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GW Notes was born from the need for a journal where the distinct communites involved in gravitation wave research might gather. While these three communities - Astrophysics, General Relativity and Data Analysis - have made significant collaborative progress over recent years, we believe that it is indispensible to future advancement that they draw closer, and that they speak a common idiom.

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Editorial

What our old friend the photon cannot and will never see

Looking into the dark side of the Universe

The joint ESA-NASA Laser Interferometer Space Antenna, LISA, will not just be a gravitational wave detector, but a gravitational wave *observatory*. This means that we not only expect to be able to directly detect gravitational waves, but to completely decode the information about the astrophysical systems which generate them.

LISA's holy grail is the detection and full characterisation of supermassive black hole binaries. The data we will be provided with are impossible to obtain with traditional electromagnetic Astronomy. Furthermore, the *accuracy* of the results obtained from the data will be unprecedented in the history of Astrophysics; e.g., we believe we will be able to resolve the masses, sky position and luminosity with an accuracy of less than 1%.

In this regard, LISA will be the most powerful telescope ever constructed. However, a telescope working not with photons, but with gravitational waves.

Data analysis of LISA sources

In the next few years, Gravitational Wave astrophysics will take a similar path to the one Cosmology once did. As the Cosmologist Max Tegmark put it,

'Cosmology, which used to be a data-starved science, is now experiencing a formidable explosion of data in the form of both CMB maps and galaxy redshift surveys.'

Unavoidably, an impressive breakthrough in scientific discoveries will come along with the data. Obviously, the priority of the development of data analysis algorithms which will allow us to fully decode the information, must be *efficiency*, i.e. a combination of speed and accuracy.

The development of data analysis algorithms for LISA is a young, but quickly developing field. Until now the efforts have been focused at obtaining accurate search results in the **Mock LISA Data Challenge**. These have been very satisfactory in terms of detection and characterisation, but the data Nature will provide us with will be more complicated than we possibly expect it to be. The datastream we will have to cope with will include signals, and possibly also noise, which we have not thought of. It is easy to think that we will have to develop not only accurate, but *fast* algorithms to deal with the complications which may arise.

Therefore, obtaining a good result in our data analysis using a beowulf cluster for a month is not equivalent to obtaining the same result using a laptop for a couple of hours. The *speed* of the algorithm is almost as important as its accuracy. Whilst it is good to have a robust algorithm that provides us with accurate results, one should only resort to this to calibrate the quicker searches using more approximative, though faster schemes. A reason for this is cross-communication with the Astrophysics community in the combined detection of a source with GW and electromagnetic radiation. If the analysis of a source takes too long, there is not much hope in EM follow-ups.

Astrophysics is a science which has a long tradition of data analysis and source modelling. When one wants, for example, to model a galactic nucleus or a globular cluster taking into account the stellar dynamics of the system including relaxation, the most accurate numerical techniques at our disposal are the direct-summation $N-$body integrators, such as the family of direct $N-$body codes of Sverre Aarseth or `Starlab`, developed by Steve McMillan and also Simon Portegies Zwart. Nevertheless, the price of accuracy is performance. We cannot do statistics using direct-summation techniques. If one wants to do statistics, one resorts to faster, though more approximate numerical tools, such as Fokker-Planck codes. Again, in this case, the direct-summation results are used to calibrate the Fokker-Planck results. A compromise are Monte Carlo programmes, such as the one written by Marc Freitag, which relies on the Hénon technique. It provides us with more accurate results than Fokker-Planck codes and is much faster than direct $N-$body.

We believe that this is the correct approximation and path to follow in the next years of development of data analysis techniques. The bottom line is that it is not only accuracy which counts, but *speed*.

For this GW Notes issue we have asked Edward Porter to write an introduction to existing algorithms and search techniques in the the data analysis of LISA sources, a pre-MLDC 3 status of algorithms, for our highlight article.

Pau Amaro-Seoane & Bernard F. Schutz, editors

GW Notes highlight article

Data Analysis

AN OVERVIEW OF LISA DATA ANALYSIS ALGORITHMS

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Abstract

The development of search algorithms for gravitational wave sources in the LISA data stream is currently a very active area of research. It has become clear that not only does difficulty lie in searching for the individual sources, but in the case of galactic binaries, evaluating the fidelity of resolved sources also turns out to be a major challenge in itself. In this article we review the current status of developed algorithms for galactic binary, non-spinning supermassive black hole binary and extreme mass ratio inspiral sources. While covering the vast majority of algorithms, we will highlight those that represent the state of the art in terms of speed and accuracy

Contents

1 Introduction

The ESA-NASA Laser Interferometer Space Antenna (LISA) will be able to detect the emitted gravitational waves (GWs) from a number of sources. Amongst the strongest sources will be the inspiral and merger of comparable mass supermassive black holes, the inspiral of stellar mass black holes or neutron stars into central massive black holes and the galaxy containing tens of millions of quasi-monochromatic white dwarf binary systems. The LISA detector is composed of three spacecraft which form an equatorial triangle and will work in the frequency range $10^{-5} \leq f/Hz \leq 1$. The center of mass of the constellation traces out a circular orbit around the Sun at a distance of 1 AU and lies about 20^o behind the Earth. The three spacecraft cartwheel in retrograde motion as they move around the Sun with a period of one year. This motion induces amplitude, frequency and phase modulations in the gravitational wave signal. The amplitude modulation is caused by the antenna pattern being moved across the sky. Because LISA can be thought of as two separate detectors, measuring different polarizations of the GW, the phase modulations are cause by combinations of the polarizations. Finally, the frequency or Doppler modulations are caused by the motion of the detector with respect to the source.

While a lot of algorithms have been developed and tested on in-house data, a more communal way of algorithm testing exists. The Mock LISA Data Challenges (MLDC[1]) were initiated by the LISA International Science Team (LIST) at the end of 2005. A taskforce exists which decides on the severity of the challenge, the types and number of sources etc. and also conducts the analysis of entries at the end of each challenge. A challenge data set is regularly issued with a deadline ranging from six to twelve months. These challenges are open to everyone within the GW community, and allow the community to simulate a realistic data analysis effort where the number of input sources and parameters are (relatively) unknown.

2 Galactic binaries

Binary systems consisting of pairs of white dwarves are expected to be one of the major sources of GWs in the LISA detector. While we expect may tens of millions of such systems in the galaxy, only approximately 25,000 of these sources will actually resolvable (Timpano et al., 2006). The other sources remain in the data stream as an extra source of noise called *confusion noise*. While detection of the so-called verification binaries will produce a good metric of our ability to conduct parameter estimation using gravitational waves, it is also imperative that we are able to successfully and confidently remove as many galactic binaries as is possible from the data stream. It is possible that an untreated galaxy of galactic binaries could effect the success of parameter estimation for supermassive black hole binaries (SMBHBs)

[1] http://www.tapir.caltech.edu/dokuwiki/listwg1b:home

and even the detection of extreme mass ratio inspirals (EMRIs), as in general, these sources will lie below the noise floor that includes the galaxy.

The GWs from a galactic binary are described by an eight parameter set $\vec{\lambda} = \{A_0, \iota, \psi, \varphi_0, f_0, \dot{f}_0, \theta, \phi\}$, where A_0 is a constant amplitude, ι is the inclination of the orbital plane of the binary, ψ is the GW polarization, φ_0 is the initial phase of the GW, $(f_0, \dot{f}_0)$ are the monochromatic frequency and first time derivative of the frequency and (θ, ϕ) are the sky coordinates for the source. Each polarization of the GW is characterized by

$$h_+ = A_0\left(1 + \cos^2\iota\right)\cos(\varphi_0 + \Phi(t)),$$
$$h_\times = -2A_0\cos\iota\sin(\varphi_0 + \Phi(t)),$$

where the phase term is described by

$$\Phi(t) = 2\pi f_0 t + \pi \dot{f}_0 t^2 + 2\pi\left(f_0 + \dot{f}_0\right) R_\oplus \sin\theta\cos\left(2\pi f_m t - \phi\right). \tag{1}$$

The final term in the above expression describes the Doppler modulation to the phase due to the motion of the LISA detector about the sun. The quantity $R_\oplus$ corresponds to the light crossing time for one AU (i.e. ~500 seconds) and f_m=1/year is the LISA modulation frequency. The frequency derivative is described (to leading order) by

$$\dot{f}_0 = \frac{96}{5}\pi^{8/3} f_0^{11/3} M_c^{5/3}, \tag{2}$$

where $M_c = m\eta^{3/5}$ is the chirp mass, $m = m_1 + m_2$ is the total binary mass and $\eta = m_1 m_2/m^2$ is the symmetric reduced mass ratio. In detatched binaries the frequency derivative is only resolvable in the higher frequency sources. Because of this, most galactic binary systems are sufficiently described by a seven parameter set.

2.1 Search algorithms for galactic binaries

It was shown quite early on that LISA data analysis would need the development of new search techniques. The most commonly used algorithm within the ground based community is the construction of a template bank (Owen, 1996 et Owen et Sathyaprakash, 1999). This is a grid of theoretical waveforms, or templates, placed in the parameter space. Each intersection of the grid corresponds to a certain combination of parameters and represents a waveform solution. In general, the templates are placed such that the minimal match between a template and a source achieves a preset threshold. The problem with standard template banks is the number of templates needed scales geometrically with the number of parameter dimensions. Once we have more than two dimensions, the number of templates quickly blows up. It was shown by Cornish & Porter (Cornish et Porter, 2005) that using an F-Statistic (Jaranowski et al., 1998) maximised template grid, the search for a galactic binary assuming a minimal match of 97% required between 10^6 and 10^{10} templates, depending on the monochromatic frequency. This study also showed that the scaling of template number with frequency changed from $f_0^{1.25}$ to $f_0^{5.88}$ beyond a frequency of $f_0 = 1.6 \times 10^{-3}$ Hz due to a change in dimensionality of the problem, as $\dot{f}_0$ now becomes resolvable. As the F-Statistic will be mentioned a lot in this article, it deserves further explanation. The F-Statistic allows us to write the detector response in a single channel

$$h(t) = h_+(t)F^+(t) + h_\times(t)F^\times(t), \tag{3}$$

in the form

$$h(t) = \sum_{i=1}^{4} a_i\left(\iota, \psi, A_0, \varphi_0\right) A^i\left(t; f_0, \dot{f}_0, \theta, \phi\right), \tag{4}$$

where the response is now composed of four quantities a_i which are a function of the extrinsic parameters (i.e. those parameters that are dependent of the detector) and four time dependent A^i's that are a function of the intrinsic parameters (i.e. parameters that describe the dynamics of the system). Now assuming the detector output is a combination of a signal plus noise, i.e. $s(t) = h(t) + n(t)$, the noise weighted inner product between the data $s(t)$ and a template $h(t)$ is written

$$\langle h \,|s\rangle = 2\int_0^\infty \frac{df}{S_n(f)}\left[\tilde{h}(f)\tilde{s}^*(f) + \tilde{h}^*(f)\tilde{s}(f)\right], \tag{5}$$

where

$$\tilde{h}(f) = \int_{-\infty}^{\infty} dt\, h(t)e^{2\pi\iota f t}, \tag{6}$$

is the Fourier transform of the time domain waveform $h(t)$ and $S_n(f)$ is the one sided noise power spectral density. Now defining four constants $N^i = \left\langle s \,\middle|A^i\right\rangle$, we can find a solution for the a_i's in the form

$$a_i = M_{ij}N^j, \tag{7}$$

where the M-Matrix is defined by

$$M_{ij} = \left(M^{ij}\right)^{-1} = \left\langle A^i \,\middle|A^j\right\rangle^{-1}. \tag{8}$$

We can now write the F-statistic as

$$\mathcal{F} = \frac{1}{2}M_{ij}N^iN^j, \tag{9}$$

which automatically maximizes the log-likelihood over the extrinsic parameters and reduces the search space to the sub-space of intrinsic parameters. Once we have numerical solutions for the four a_i's, we can analytically maximize over the extrinsic parameters. Furthermore, the F-Statistic is related to the SNR by $\mathcal{F} \approx SNR^2/2$.

In the last few years a number of different algorithms have been developed to search for monochromatic binaries. A full list of these algorithms is given by Arnaud et al., 2007a, 2007b et Babak et al., 2008, but we will mention a few of the more successful methods here : a number of refined template grid methods have been used that use the F-Statistic to minimize the number of search parameters. One method developed by Królak & Blaut used the optimal placement of templates on a hypercubic lattice (Arnaud et al., 2007a, 2007b et Babak et al., 2008). Another algorithm developed by Prix & Whelan used a hierarchical method that searched for enforced trigger coincidences between TDI variables, followed by a coherent search using noise orthogonal TDI combinations (Prix et Whelan, 2007 et Whelan et al., 2008). Crowder, Cornish & Reddinger developed a genetic algorithm where the different parameter set combinations for the GW waveform are treated as organisms in the parameter space and are allowed to “evolve" by means of various biological rules (Crowder et al., 2006).

However, the most successful algorithms developed thus far (for all sources), have been based on Markov chain Monte Carlo (MCMC) methods. Due to the success of these algorithms we describe in a little more detail the mechanics of MCMC methods.

2.2 Metropolis-Hastings & Markov Chain Monte Carlo

The MCMC is a stochastic method which is ideal for searching through high dimensional spaces. It works by constructing a chain of solution points in parameter space drawn from a proposal distribution that we believe to be close to the target density we are trying to model. If the chain is run long enough then we are guaranteed to eventually map out the target density. There are a number of types of MCMC. The most popular being a Gibbs algorithm (where we update one parameter at a time) or a Metropolis-Hastings algorithm (where we update all parameters at the same time). A Gibbs Markov chain is very simple to get up and running as it requires no a priori knowledge of the system. However, as all proposals are accepted, it is possible to end up random-walking through the parameter space. Also, Gibbs chains can get stuck on likelihood peaks if there is almost perfect (anti)correlation between parameters, or if our solution represents a single high peak in an otherwise featureless likelihood space.

The Metropolis-Hastings sampling method is a variant on the Markov Chain Monte Carlo method , and works as follows : starting with data $s(t)$ and some initial template $h(t, \vec{x})$, where $\vec{x}$ is a starting random combination of the system parameters, we then draw from a proposal distribution and propose a jump to another point in the space $\vec{y}$. In order to compare both points, we evaluate the Metropolis-Hastings ratio

$$H = \frac{\pi(\vec{y})\, p(s|\vec{y})\, q(\vec{x}|\vec{y})}{\pi(\vec{x})\, p(s|\vec{x})\, q(\vec{y}|\vec{x})}. \quad (10)$$

Here $\pi(\vec{x})$ are the priors of the parameters, $q(\vec{x}|\vec{y})$ is the proposal distribution and $p(s|\vec{x})$ is the likelihood defined by

$$p(s|\vec{x}) = C\, e^{-\langle s-h(\vec{x})|s-h(\vec{x})\rangle/2}, \tag{11}$$

where C is a normalization constant. This jump is then accepted with probability $\alpha = min(1, H)$, otherwise the chain stays at $\vec{x}$. While the Metropolis-Hastings algorithm requires more effort, in that we need to tailor the proposal distributions to the problem at hand, it has a much faster convergence rate than Gibbs sampling. Another way to improve convergence is to ensure that we are jumping along eigendirections rather than coordinate directions. This is achieved by using the eigenvalues and eigenvectors of the Fisher information matrix (FIM), i.e.

$$\Gamma_{\mu\nu} = \left\langle \partial_\mu h | \partial_\nu h \right\rangle, \tag{12}$$

to provide the scale and directionality of the jump.

At present a number of flavours of MCMC are being used within the GW community. Some of these involve reverse jump MCMC (Cornish et Littenberg, 2007 et Littenberg et Cornish, 2009) (where one can change the dimensionality of the search within the algorithm. This is useful if we are also trying to carry out a model selection in terms of source number), delayed rejection MCMC (Trias et al., 2009a, 2009b) (here one proposes a move to a new point. If the point is not accepted, instead of rejecting it straight away, it is kept and information from this point is used to aid proposal of another possible solution) and parallel tempered MCMC (Littenberg et Cornish, 2009 et Key et Cornish, 2009) (here, instead of running one chain, a number of cross-communicating chains of different temperatures are run simultaneously, allowing wider exploration the the hotter chains, and local exploration with the cold chains).

The MLDCs have become a way of testing algorithms within the gravitational wave community, especially in the case of galactic binaries. The most important challenge thus far, in terms of displaying the capabilities of various algorithms, was MLDC 2. In this challenge the groups were faced with two data sets. One with a bare galaxy of approximately 30 million individually modelled galactic binaries, and a second set with again approximately 30 million galactic binaries, but also with between 4-6 SMBHBs in the data stream. Of the groups that returned full parameter sets (i.e. all seven required parameters), the template grid of Królak & Blaut found 404 sources in the bare galaxy challenge. The hierarchical grid search developed by Prix & Whelan did somewhat better with 1777 sources detected in the bare galaxy test, and 1737 sources in the galaxy plus SMBHB test. However, by far, the most successful algorithm for the detection and extraction of parameters for galactic binaries was the Block Annealed Metropolis-Hastings or *BAM* algorithm developed by Crowder & Cornish (Crowder et Cornish, 2004, 2007a, 2007b et Cornish et Crowder, 2005).

2.3 BAM algorithm

The BAM algorithm works by dividing the frequency search band into equal sized blocks. The algorithm then sequentially steps through the blocks, simultaneously updating the sources within the blocks. Once all the blocks are updated, they are shifted by one half a block width for the next round. By breaking the band into blocks, fewer search templates are needed as compared to searching the entire frequency band at once.

The main issue, as always, with breaking up data streams, is the treatment of edge effects. However, the BAM algorithm circumvents the problems in a number of ways. Firstly, in each search region, two concepts entitled “wings" and “acceptance window" are introduced. The acceptance window is, in effect, a safe region where one can be sure that search templates are finding reliable sources. The wings have the job of dealing with the effects of the regions between the edge of the acceptance window and the boundaries of the search region. One of their main jobs is to lessen the effect of bright sources that exist outside the search area and are bleeding power into the region of interest. These sources cause an effect called “slamming" where search templates are drawn to the boundary of the search area due to the bleeding power. This can result in the templates missing other dimmer signals within the search area, and providing inaccurate estimations for the parameter values. While these templates are recognizable due to large amplitudes and a high degree of (anti)correlation between the templates, they still represent a problem. To overcome this problem, the authors introduced another concept called “wing noise”. This is an exponential increase in the noise spectral density at the edge of the acceptance window. This noise weights matches between templates and a signal less in the wings than in the acceptance window, thus encouraging templates to stay within the acceptance window.

A number of techniques were used to increase the speed of convergence of the algorithm. The first was an exploitation in certain symmetries which exist within the problem and the construction of corresponding proposal distributions. This first is the fact that there is an antipodal sky solution due to the LISA response at approximately

$$\theta \to \pi - \theta, \quad \phi \to \phi \pm \pi. \tag{13}$$

This symmetry allows one to force the algorithm to explore both hemispheres. A second more subtle symmetry can be seen by Figure ??. On the left hand side of this figure, we plot the power spectrum of two galactic binaries that are identical, except that the frequency of one is shifted by one LISA modulation frequency f_m. On the right hand side of the figure, we plot the SNR obtained by keeping all parameters constant, except for the frequency of the template which we slide by $\pm 10 f_m$. We can see that there are symmetric peaks at distances of approximately $1 f_m$ separation across the band. The authors used this information to “island hop" through frequency space. One of the other non-Markovian steps used by the authors was, if one island hop is accepted, immediately try another in order to converge as quickly as possible.

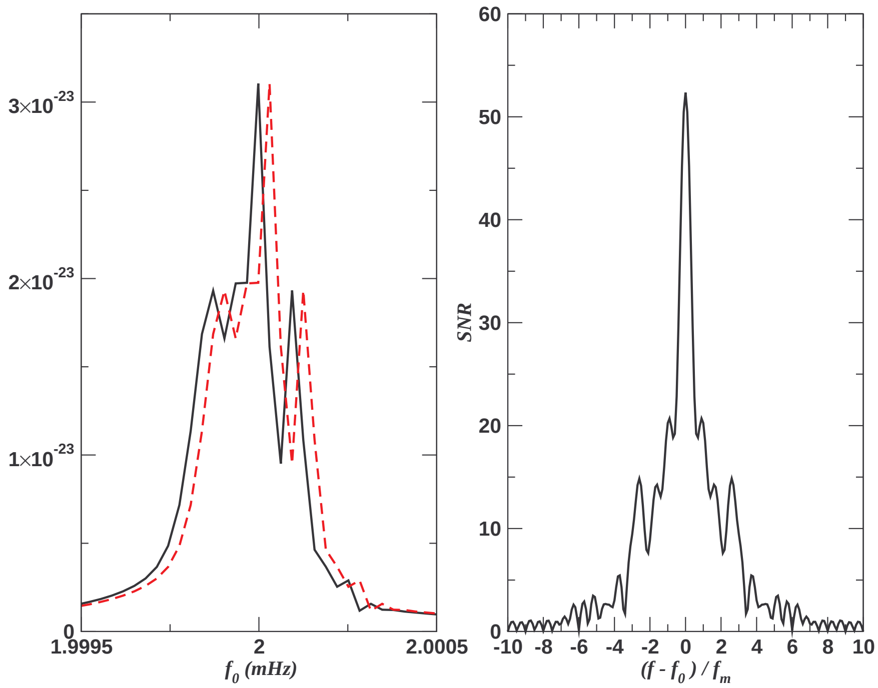


Fig. 1 On the left, we plot the same galactic binary at frequencies of $f_0 = 2$ and $f_0 = 2 + f_m$ mHz. On the right, we plot the SNR as a function of frequency modulation offsets from $-10 \leq (f - f_0)/f_m \leq 10$. We can see that an offset of $\pm 1 f_m$ produces secondary peaks in the SNR. In general these, and other peaks, are separated at approximately $\pm n f_m$, where n is an integer number

One of the issues with the convergence of any MCMC algorithm is the tendency for a chain to stay at a local maximum for a long time before moving on. Simulated annealing is a common way of softening features on the likelihood surface which cause a chain to get stuck, and thus allow wider exploration and faster convergence. This is implemented by multiplying the noise weighted inner product by an inverse temperature

$$\beta = \frac{1}{T} = \begin{cases} \beta_0 \left(\frac{1}{\beta_0}\right)^{i/Nc} & \text{if } 0 \leq i \leq N_c \\ 1 & \text{if } i > N_c \end{cases}$$

where β_0 is the heat-index defining the initial heat, i is the number of steps in the chain and N_c is the cooling schedule. Normally, simulated annealing is used to accelerate the chain to a stationary solution, after which the heat is set to unity and a fully Markovian chain is used. It is also useful as it allows a chain to explore the likelihood surface faster as it is unlikely to get stuck on a secondary maximum while the heat is high. The hope is that as we cool to unit temperature, the chain is already close enough to the true solution that it only has to walk uphill to the top of the central peak. Some of the issues with simulated annealing include the fact there is no a priori information on what the value of the initial temperature should be. If it is too high, we kill all features on the likelihood surface and waste a large number of computer cycles conducting a random walk in parameter space. If it is too low, we very quickly find a local maximum and never move again within the timescale of the chain. Also, with simulated annealing, one needs to cool the likelihood surface slowly, as too quick a cooling can again trap a chain on a local maximum.

In Figure 2 we plot the log likelihood for a template across a frequency band of $\pm 5 f_m$ for four different values of the temperature T. We can see that for $T = 10$, only feature visible is the central peak. However, as we cool from $T = 10$ to 1, we can see the peaks in the likelihood surface becoming visible again. Simulated annealing allows the chain to visit regions it may not otherwise go to. For example, in the figure, we can see that a uniform temperature chain at $\pm 3 f_m$ is unlikely to move to the central peak in any reasonable amount of time due to the deep minima at $\pm 1.5 f_m$. While a MCMC can move to areas of lower likelihood, it doesn't happen very often. However, it is clear that these minima are not an issue for a chain with temperature $T = 10$ and are easily traversable.

In the previously mentioned MLDC 2, the *BAM* algorithm performed extremely well. In the bare galaxy test, 19,324 sources were recovered, while in the galaxy plus SMBHB test, 18,461 sources were found. These numbers are approaching the theoretical estimate for the number of recoverable sources. Furthermore, the algorithm is very fast taking less than two weeks to process the entire galaxy using a 128 node cluster.

2.4 Outstanding issues for galactic binaries

It has become clear from the full galaxy challenges of the MLDC that there are two important questions to be answered. While the questions are from different points of view, they are inextricably linked : what does one use as a termination criterion and how exactly does one evaluate many thousand possible sollutions simultaneously? The common factor linking both questions is that we have no idea just how many sources will actually be resolvable, or what their parameter values will be. On top of this, it is very difficult to even define the notions of false positives and false dismissals. Some of the algorithms available today only return the intrinsic parameters, while others return all system parameters. However, it is always possible to to get a better fit to a model with more parameters, so there may be cases where some algorithms are overfitting the data. A number of groups have started to investigate Bayesian model selection for GW sources (Cornish et Littenberg, 2007, Littenberg et Cornish, 2009 et Veitch et Vecchio, 2008a, 2008b), but the works are too detailed to discuss here.

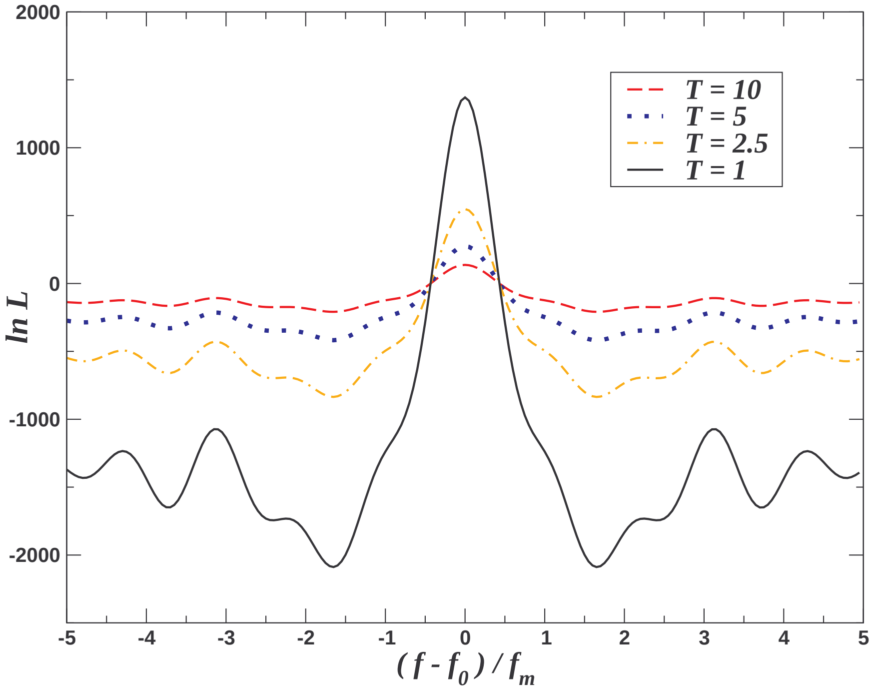


Fig. 2 A plot of the log-likelihood at frequency modulation offsets from $-5 \leq (f - f_0)/f_m \leq 5$ with different simulated annealing temperatures. We can see that a heat of 10 essentially flattens all peaks on the likelihood surface apart from the main peak. As we cool the surface, we begin to see the other peaks arising

3 Non-spinning supermassive black hole binaries

In this section we focus on algorithms for non-spinning SMBHBs. A number of algorithms have now been developed that can successfully search for and extract the parameters from these inspiralling binaries. In virtually all cases, the work has focused on restricted post-Newtonian binaries (i.e. while the phase is evolved to 2-PN order, the amplitude is kept at the dominant Newtonian level). The SMBHB polarizations are given by

$$h_+ = \frac{2Gm\eta}{c^2 D_L}\left(1 + \cos^2\iota\right) x \cos(\Phi),$$
$$h_\times = -\frac{4Gm\eta}{c^2 D_L} \cos\iota\, x \sin(\Phi).$$

Here D_L is the luminosity distance from the source to detector. The invariant PN velocity parameter is defined by $x = \left(Gm\omega/c^3\right)^{2/3}$, where

$$\omega(t) = \frac{c^3}{8Gm}\left[\Theta^{-3/8} + \left(\frac{743}{2688} + \frac{11}{32}\eta\right)\Theta^{-5/8} - \frac{3\pi}{10}\Theta^{-3/4} + \left(\frac{1855099}{14450688} + \frac{56975}{258048}\eta + \frac{371}{2048}\eta^2\right)\Theta^{-7/8}\right]$$

is the 2 PN order orbital frequency for a circular orbit formally defined as $\omega = d\Phi_{orb}/dt$, and $\Phi = \varphi_c - \varphi(t) = 2\Phi_{orb}$ is the gravitational wave phase which is defined as

$$\Phi(t) = \varphi_c - \frac{2}{\eta}\left[\Theta^{5/8} + \left(\frac{3715}{8064} + \frac{55}{96}\eta\right)\Theta^{3/8} - \frac{3\pi}{4}\Theta^{1/4} + \left(\frac{9275495}{14450688} + \frac{284875}{258048}\eta + \frac{1855}{2048}\eta^2\right)\Theta^{1/8}\right].$$

The quantity $\Theta(t; t_c)$ is related to the time to coalescence of the wave, t_c, by

$$\Theta(t; t_c) = \frac{c^3\eta}{5Gm}(t_c - t)\,. \tag{14}$$

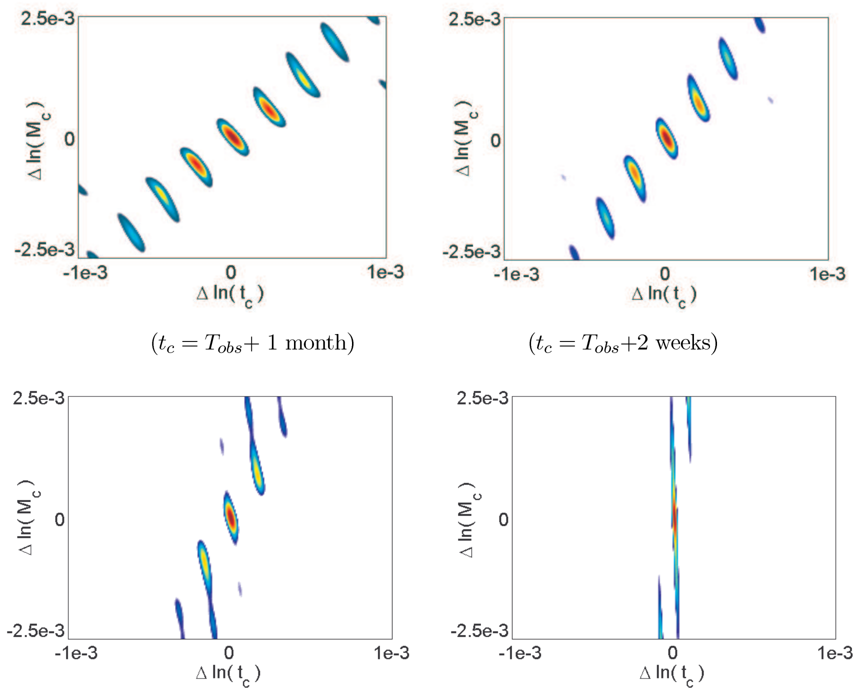
In the search for SMBHBs, groups have used algorithms based on stochastic template banks (Farr et al., 2009 et Babak, 2008), time-frequency tracks (Arnaud et al., 2007b), user-refined grids (Arnaud et al., 2007a) and a three step method combining time-frequency analysis, a template grid and a Metropolis-Hastings based Markov chain (Brown et al., 2007).

However, we present here three methods that have excelled in terms of speed and precision.

3.1 Metropolis-Hastings Monte Carlo search algorithm

The Metropolis-Hastings Monte Carlo search algorithm (MHMC) was developed by Cornish & Porter (Cornish et Porter, 2006, 2007a, 2007b, 2007c). Similar to the BAM algorithm, it used a number of tailored proposal distributions and techniques to speed up convergence of the waveform. The first method of acceleration was that a version of the F-Statistic exists for non-spinning SMBHBs (Cornish et Porter, 2007b). This allows us to separate the parameter set into intrinsic $\{\ln M_c, \ln\mu, \ln t_c, \theta, \phi\}$ and extrinsic $\{\iota, \psi, \varphi_c, \ln D_L\}$ subsets, thus reducing the dimensionality of the search space form nine to five.

The second measure used was to accelerate the convergence of the algorithm by maximizing over the time-of-coalescence during the search and cooling phase of the chain. For these sources, this parameter is the most important one to find. Once t_c is found, due to the fact that the parameters are highly correlated, the mass parameters are usually found very soon after. Strictly, this is not a correct step to use as it assumes that LISA is stationary. However, during the annealing phase t_c is treated as being a quasi-extrinsic parameter and searched over separately. Once the cooling phase has finished this maximization is stopped. The advantage of including this step in the search is that it manages to tie t_c down to a restricted search range very



($t_c = T_{obs}$+ 1 month) ($t_c = T_{obs}$+2 weeks)

($t_c = T_{obs}$+1 week) ($t_c = T_{obs}$+1 day)

Fig. 3 This Figure displays the evolution for the island chain of maxima on a $\ln(M_c) - \ln(t_c)$ slice through the Likelihood surface for coalescence times that exceed the observation time

quickly. The t_c maximization is carried out using a modified F-Statistic search. Using the usual Fourier domain t_c maximization, the equations for the F-Statistic take on a slightly different form. This time instead of defining the four constants N_i, we define the matrix

$$N^{ij} = 4 \sum_{i=1}^{n} \sum_{j=1}^{4} \left(N_I^{ij} + N_{II}^{ij} \right), \tag{15}$$

where n is the number of elements in the waveform array. The above equation describes the four constants at different time lags. We can now solve for the time independent amplitudes

$$a_{ij} = \sum_{i=1}^{n} \sum_{j=1}^{4} \sum_{k=1}^{4} M_{jk} N^{ik} \tag{16}$$

where the M-Matrix is the same as the one defined previously. Inverting the M-Matrix, the F-Statistic is now a vector over different time lags.

$$\mathcal{F}_i = \sum_{i=1}^{n} \sum_{j=1}^{4} \sum_{k=1}^{4} M_{jk} N^{ij} N^{ik} \tag{17}$$

This vector array is then searched through to find the value of t_c that maximizes the F-Statistic. While it is possible to carry out a search without this maximization, it takes much longer to converge. In fact, with t_c maximization the algorithm has found the time to coalescence of the SMBHB in as little as 10 steps of the chain for certain sources.

A lot of the success of this algorithm was due to exploiting symmetries in the detector response, as well as features on the likelihood surface. As in the case of galactic binaries, proposal distributions were used that forced the chain to explore the antipodal sky solution. It was also found that, similar to the galactic binaries, "island chains" in the likelihood surface could be exploited. In Figure 3 we plot a slice through the $\ln(M_c) - \ln(t_c)$ surface. We can see how the islands elongate and the island chains rotate as we approach coalescence. While the authors were unable to precisely work out the distance between islands, a proposal distribution was developed that allowed them to successfully exploit these island chains.

One of the outcomes from the study of the island chains was that truncating the waveform before the coalescence changes both the shape, position and number of islands within a certain distance of the true solution. We can see from Figure 3 that movement along the islands is a lot easier the further we are out from coalescence. This, and the fact that it is very difficult to fit parameters for the most relativistic cycles at the end of the waveform, led the authors to develop an acceleration technique called *frequency annealing*. With this scheme, the waveform at a particular iteration is generated to a cut-off frequency, f_{cut}, which is less than the maximum search bandwidth frequency, f_{max}. This maximum bandwidth frequency is determined as a function of the lowest total mass in the priors. The initial upper cut-off frequency is chosen to be a multiple (at least 2, but in most cases 4) of the lower frequency cutoff of LISA. Then, by defining a growth parameter

$$B = \log\left(\frac{f_{max}}{a\, f_{cut}}\right) \quad a \geq 2, \tag{18}$$

we evolve the upper cut-off frequency according to

$$f_{\rm cut} = \begin{cases} 10^{-B\left(1-\frac{i}{N_c}\right)} f_{\rm max} & \text{if } f < f_{\rm max} \\ f_{\rm max} & \text{if } f \geq f_{\rm max} \end{cases}$$

This annealing scheme allows us to fit the early less relativistic cycles easily, thus constraining the parameters. In practice, as we approach the point where we are generating full templates, the waveform parameters are already close to the correct values. This is due to the fact that terminating the templates early manages to surpress a lot of the features on the likelihood surface that would normally present an obstacle to the chain. In this respect, the frequency annealing acts as a form of simulated annealing as it changes the structure of the likelihood surface. One of the main advantages of this scheme is that the first few thousand iterations of the chain are achieved in less than ten minutes. This allows us to give a very quick confirmation of a detection.

The final refinement used was to introduce a *thermostated* heat factor. As the frequency annealing is a progressive algorithm (i.e. it does not see the full signal until very late in the run) it is important the algorithm does not get stuck on a secondary maximum. To get around this, the authors used a thermostated heat defined by

$$\delta = \begin{cases} 1.0 & \text{if } 0 \leq SNR \leq SNR_0 \\ \left(\frac{SNR}{SNR_0}\right)^2 & \text{if } SNR > SNR_0 \end{cases}$$

which ensures that once a SNR of greater than SNR_0 is attained, the effective SNR never exceeds this value (this value is chosen a priori by the user, but it was found that setting $SNR_0 = 20$ usually suffices). This thermostated heat means that the chain explores the parameter space more aggressively and as the algorithm approaches using the full templates, there is enough heat in the system to prevent the chain from getting stuck. This stage is carried out for a certain number of iterations and then cooled using standard simulated annealing.

One other thing worth mentioning here is the ability of this algorithm to also map out the posterior density functions (pdfs) for each solution. It was shown that on the projected 5-D parameter space of the intrinsic parameters, the pdfs obtained from the MCMC were a very good match to the predictions of the FIM. However, using the full parameter set, there were cases where the MCMC displayed a deviation from the predictions of the FIM due to high correlations between the parameters. This showed that, while in many cases we can take the estimations of the FIM as a good approximation, there are sometimes when it (under)overestimates the error. We refer the reader to a paper by Vallisneri (Vallisneri, 2008) on the validity of the FIM in GW astronomy. The authors also showed that when trying to map out the pdfs for sources where we do not see coalescence, the large uncertainty in the phase at coalescence φ_c causes the chains to go on a random walk, and the mapping of the pdf takes a very long time. To circumvent this, the authors used a *mini F-Statistic* where only the luminosity distance and phase at coalescence are maximized over. Expanding the detector response in terms of φ and φ_c we obtain

$$\begin{aligned} h(t) &= \frac{\cos(\varphi_c)}{D_L}\left[A_+F^+\cos(\varphi) - A_\times F^\times \sin(\varphi)\right] \\ &+ \frac{\sin(\varphi_c)}{D_L}\left[A_+F^+\sin(\varphi) + A_\times F^\times \cos(\varphi)\right]. \end{aligned}$$

The square bracket terms in the above expression correspond to the responses $h(t;\varphi_c = 0)$ and $h(t;\varphi_c = \pi/2)$ respectively, with the luminosity distance set to unity, which allows us to write the mini F-Statistic in the form

$$\begin{aligned} h(t) &= \frac{\cos(\varphi_c)}{D_L} h(t;\varphi_c = 0, D_L = 1) + \frac{\sin(\varphi_c)}{D_L} h(t;\varphi_c = \pi/2, D_L = 1) \\ &= \sum_{k=1}^{2} a_k A^k, \end{aligned}$$

where

$$a_1 = \frac{\cos(\varphi_c)}{D_L} \quad , \quad a_2 = \frac{\sin(\varphi_c)}{D_L}, \tag{19}$$

and

$$A^1 = h(t; \varphi_c = 0, D_L = 1) \quad , \quad A^2 = h(t; \varphi_c = \pi/2, D_L = 1). \tag{20}$$

Repeating the steps from the generalized F-Statistic, one can obtain the numerical values for the quantities a_k. The maximized values of φ_c and D_L are then found using the expressions

$$\varphi_c = \arctan\left(\frac{a_2}{a_1}\right), \tag{21}$$

$$D_L = \left[a_1^2 + a_2^2\right]^{-1/2}. \tag{22}$$

The above process greatly improved the convergence of the chains for the non-coalescing sources.

In both user trials and blind MLDC challenges, this algorithm performed exceptionally well. Parameters were always estimated to within a 5σ error. However, the main attraction of the algorithm was the fact that the total run-time was 4-5 hours on a laptop. While one would always run multiple chains to ensure detection and parameter estimation, this algorithm does not require the use of a cluster and is thus easily accessible to others.

3.2 Hybrid evolutionary algorithm

The MHMC algorithm described above is an iterative algorithm in that it first finds the brightest source, removes that source and then searches for another. The Hybrid Evolutionary Algorithm (HEA) was developed by Gair & Porter (Gair et Porter, 2009) in an effort to simultaneously find multiple mode solutions for multiple sources. The algorithm uses a combination of Metropolis-Hasting, Nested Sampling and evolutionary rules to solve the problem. The version of Metropolis-Hastings used is slightly different from the one described above in that the Metropolis-Hastings ratio is now decided by

$$H = \begin{cases} 1 & \text{if } \mathcal{L}(\Theta') > \mathcal{L}_i \text{ and } \pi(\Theta') > \pi(\Theta) \\ \pi(\Theta')/\pi(\Theta) & \text{if } \mathcal{L}(\Theta') > \mathcal{L}_i \text{ and } \pi(\Theta') \leq \pi(\Theta) \\ 0 & \text{otherwise} \end{cases}$$

where again $\pi(\Theta)$ are the priors based on the parameters Θ, and $\mathcal{L}(\Theta)$ denote the likelihood. Nested Sampling was introduced by Skilling (Skilling, 2004) as a tool for evaluating the Bayesian evidence, by employing a set of live points that climb together through nested contours of increasing likelihood. At each step, the algorithm attempts to find a point with a likelihood higher than the lowest likelihood point in the live point set and then replaces the lowest likelihood point with the new point. Nested sampling has already been applied to the issue of model selection for ground based observations of gravitational waves (Veitch et Vecchio, 2008b)

The HEA algorithm works as follows : a number of organisms (trial solutions) and a predefined number of cluster centroids are dropped onto the likelihood surface. The initial organisms must satisfy a fitness criterion to survive (i.e. their initial SNR must be greater than some threshold). After that each successive organism is required be fitter than the mean fitness of the group. Once the initial selection has been made, the organisms are given the chance to improve their fitness, before being allowed to evolve through the system by using the Metropolis-Hastings, Nested Sampling algorithm or by using rules from evolutionary computation such as birth, death, altruism etc. At preset points the organisms are clustered according to the Euclidean distance from the center of mass of a cluster and either stay where they are, or join a new cluster of solutions. The centroids, while initially dropped randomly, are then assigned to the center of mass of each cluster. While we are interested in the evolution of each individual organism, it is the evolution of each centroid that we are truly interested in. The HEA uses some of the same simulated and thermostated annealing concepts from the MHMC algorithm. As each cluster needs to evolve at its own pace, we divide the parameter space into *Voronoi regions*. This associates a certain amount of the parameter space with a particular cluster. The temperature in each Voronoi region is then linked to the fittest member of each cluster. This allows some clusters to evolve faster than others, but also means that the temperature associated with an extremely bright source does not kill the features associated with a dimmer source.

The algorithm was tested on a data set with two SMBHBs. While there were only two sources, things were complicated by the fact that there was a bright coalescing source, plus a dimmer non-coalescing source. The algorithm was informed that there were between two and eight possible solutions and 80 live points were used in the search. In Figure ?? we focus on the search over sky parameters (due to known degeneracies in the parameter space) and plot the performance of the algorithm at four different snapshots. We can see that the algorithm converges very quickly. It not only finds the primary modes associated with each source (i.e. true and antipodal), but also manages to find a number secondary modes as well. For both sources, the intrinsic parameters were all found to within 5σ of the true values. As with the MHMC algorithm, the HEA again requires no more than a laptop to search for non-spinning sources, with a run time of about 10 hours.

3.3 MultiNest

One of the problems with the Nested Sampling algorithm is, given a position in parameter space, the hard constraint of randomly finding a better point within the prior volume. At the start of an algorithm when we are far away from the true solution, this is not that much of a constraint, but as we get closer to the true solution this becomes more and more difficult. As a result, the acceptance rate of proposals starts to rapidly decrease, and the runtime begins to increase accordingly. MultiNest is a multimodal nested sampling algorithm designed by Feroz, Hobson & Bridges (Feroz et al., 2008) to efficiently evaluate the Bayesian evidence and return

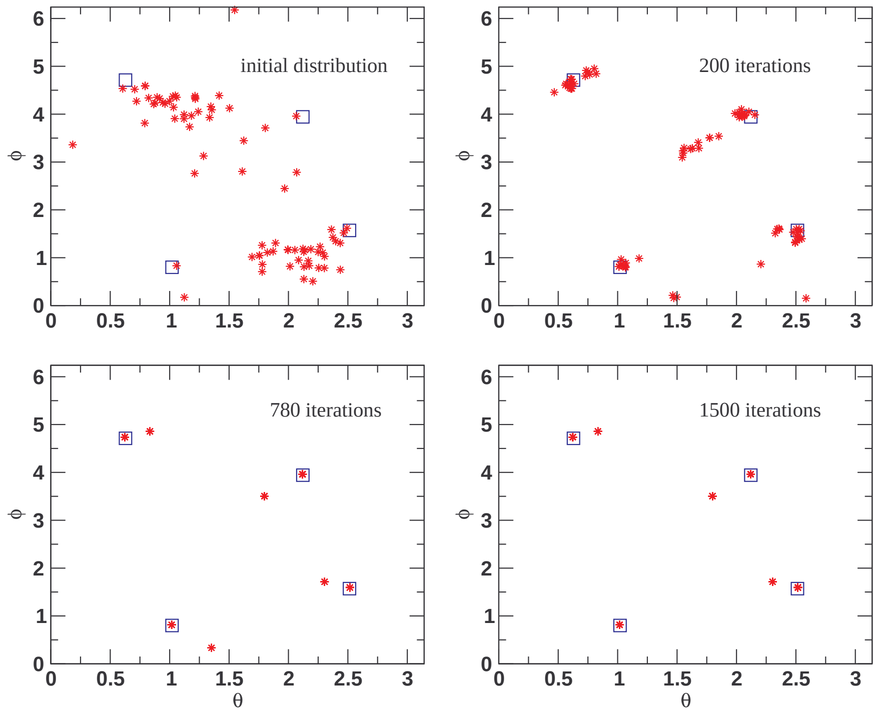


Fig. 4 A plot of the HEA sky search at four different times. In each cell, the square represent the true solutions, while the stars represent the organisms. We plot (going from top-left to bottom-right) the initial distribution after the initial selection and uphill climber improvement phase, and then at 200, 780 and 1500 iterations. We see that not only does the algorithm find the two primary sky solutions (i.e., real and antipodal) for both sources, but also a bunch of secondary solutions at almost 90 degrees to the primaries

posterior probability densities for likelihood surfaces containing multiple secondary modes in Cosmology and particle physics. It solves the problem of likelihood evaluation by using the current set of live points as a model of the shape of the likelihood surface. The algorithm uses an ellipsoidal rejection sampling scheme by enclosing the live point set into a set of (possibly overlapping) ellipsoids and then uniformly draws a new point from the region enclosed by these ellipsoids. This allows highly correlated pdfs to be broken into a number of smaller regions of overlapping ellipsoids. The other main advantage of the MultiNest algorithm is that it allows both the local and global evidence to be evaluated.

MultiNest was recently applied to GW astronomy for non-spinning black holes by Feroz, Gair, Hobson & Porter (Feroz et al., 2009). The algorithm was run on the same two sources that were used for the HEA, using approximately 1000 live points. The MultiNest algorithm is model independent in that it only requires calculation of the likelihood, and is therefore very fast. In the initial part of the search, an F-Statistic was used to reduce the parameter space to five dimensions. The algorithm found eleven modes in total, including the seven modes found by the HEA. A second stage was also run, where the extrinsic parameters were also searched for. In all cases the parameters were again found to with 5σ, and just like the other two algorithms described above, could be run on a laptop with a runtime of ~ 3 hours.

3.4 Outstanding issues for SMBHBs

The binary black hole problem is much simpler than the galactic binary problem in that we do not expect to have very many SMBHBs in the data stream at any one time. Even if we are faced with a number of simultaneous sources, it was shown by Cornish & Porter (Cornish et Porter, 2007b) that SMBHBs will be invisible to each other, so we will not have to contend with a confusion problem between sources. At present, there are a number of end to end, or multiple stage algorithms that can detect and extract the parameter sets for both individual and multiple non-spinning massive black hole binaries. However, in recent years it has been shown by Hughes & Lang (Lang et Hughes, 2006, 2008) that the inclusion of spin will have a dramatic improvement on the estimation of parameters. More recently, it has been shown by a number of groups (see for example : Porter & Cornish (Porter et Cornish, 2008), Trias & Sintes (Trias et Sintes, 2008a, 2008b), Arun et al (Arun et al., 2007)) that the corrections to the waveforms from higher harmonics break correlations between parameters and can also improve parameter estimation. Therefore, at some point, algorithms that can search for spinning SMBHBs with higher harmonic corrections will be needed for LISA. While we have not covered it here, blind tests for spinning SMBHBs have already started in MLDC 3. Finally, all existing algorithms search for the inspiral phase only. In reality, we will need to develop algorithms that will search for signals that also include a merger and ringdown phase. While the ringdown phase is quite easily modelled (Berti et al., 2007), we must wait until numerical relativity has increased in accuracy, sufficient for the development of LISA waveforms.

4 Extreme mass ratio inspirals

The inspiral of a stellar mass black hole or neutron star into a supermassive black hole can provide a richness of information due to the fact that the compact object spends a large fraction of its observable life in the highly relativistic region close to the massive black hole. It has been suggested that due to the large number of observable GW cycles, EMRIs can be used to test General Relativity by mapping out the strong-field spacetime around the central black hole. For a more detailed overview of EMRI astrophysics and detection with LISA, we refer the reader to an article by Amaro-Seoane et al (Amaro-Seoane et al., 2007).

However, due to the highly relativistic nature of the source, it is extremely difficult to model the compact object's orbit. While advanced methods exist to approximate the inspiral, the generation time for these waveforms puts any data analysis effort currently out of reach. In recent years the community has been using the analytical kludge waveforms of Barack & Cutler (Barack et Cutler, 2004). These are phenomenological waveforms that capture the complexity of true EMRI signals and importantly, have the correct number of paramters. In general, this model is described by a 14-D parameter set : the mass of the central black hole M, the mass of the compact object μ, the luminosity distance to the source D_L, the initial frequency ν_0 or plunge time t_p, the initial(final) eccentricity $e_0(e_p)$, the spin of the central black hole S, the position of the source in the sky (θ_S, ϕ_S), orientation of the black hole spin (θ_k, ϕ_k), inclination of orbit λ and three initial orbital phases $(\Phi_0, \alpha_0, \gamma_0)$.

With modern computing abilities we are restricted to searching within a very narrow range of priors for EMRI sources. This is due to a number of issues. Presently, the waveform generation codes for the MLDCs take many minutes to generate a two year data set, as the waveforms contain many harmonics. Even something as simple as calculating the likelihood becomes a time consuming chore with this waveform. Things get rapidly worse if we need to calculate the FIM, as we need to generate 28 waveforms to calculate the derivatives of the waveforms with respect to the parameters. It is clear that this kind of time consumption is clearly unusable. A lot of the recent effort has been made in efforts to speed up the generation of the waveforms. This has involved restricting the number of waveform harmonics, approximating Bessel functions etc. A waveform code developed by Cornish (Cornish, 2008) is now orders of magnitude faster than the codes used for the MLDC data generation and makes data analysis a reality.

It was shown by Gair et al (Gair et al., 2004) that a reasonable template grid search for EMRIs is clearly out of reach as it would require approximately 10^{40} templates. At present two approaches have been used to search for individual EMRIs buried in instrumental noise : a time-frequency analysis and a Metropolis-Hastings based algorithm. We will look at each in detail later on. As we said earlier, the convergence of the MH based algorithm can be greatly improved if we jump along eigendirections rather than coordinate directions. This requires frequent calculation of the FIM. As well as the time constraints on the generation of the FIM, it was found that one has to be very careful with the numerical methods used for inverting the FIM. The FIM for EMRIs is highly singular with a large condition number. As the FIM is calculated and inverted numerically, it was found that while we achieved convergence for the elements of the FIM, the elements of the inverse could differ by orders of magnitude. Alot of work has been done in the last year or so by Cornish, Gair & Porter[2] on the numerical stability of the FIM inversion as part of the LISA Parameter Estimation Taskforce.

There is still a lot of work to do for EMRI sources. We are not yet in a situation where we have algorithms as developed as in the case of galactic binaries or non-spinning

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2 http://www.tapir.caltech.edu/dokuwiki/lisape:home

SMBHBs. However, algorithms exist that can detect and carry out parameter estimation for isolated high SNR EMRIs embedded in instrumental noise. We discuss the two current approaches below.

4.1 Time-frequency methods

The time-frequency method for EMRI searches (Wen et Gair, 2005, Gair et Wen, 2005, Wen et al., 2006 et Gair et Jones, 2007) works by dividing the data into a number of segments. Each segment is Fourier transformed to produce a spectrogram of the data. One then searches the spectrogram for features. One of the first methods used was the Hierarchical Algorithm for Clusters and Ridges (HACR). This algorithm was shown by Gair & Jones (Gair et Jones, 2007) to have a 10-15% higher detection rate than a simple excess power algorithm. However, after the MLDC 2, the authors improved the algorithm by introducing an EMRI tuned track search called the Chirp-based Algorithm for Track Searches (CATS) (Gair et al., 2008a, 2008b). In this algorithm, one constructs a 3-D grid in the the $(f, \dot{f}, \ddot{f})$ parameters space. At each point, a potential track is constructed, and the power in each pixel along the track is added to give the total track power. The brightest track is then claimed as a detection. The power in the pixels of this track are then set to a large negative value to prevent intersection with future tracks.

In the MLDCs, the time-frequency algorithm worked quite well. The only drawback with this type of search is that while cheap to use computationally, there is a corresponding loss in resolution. The algorithm only returns the intrinsic parameters, so may only work as a first step algorithm. Also, it is unclear how the algorithm will perform when we have many overlapping sources plus a galaxy.

4.2 Metropolis-Hastings based algorithms

To this point, two groups have developed MH based search algorithms for EMRIs (Cornish, 2008, Gair et al., 2008c et Babak et al., 2009). The two algorithms are very close in function, due to having a common starting point in the BAM and MHMC algorithms. The current problem with EMRI algorithms is the time it takes for development. As the galactic binary and SMBHB waveforms were very quick to generate (i.e. many hundreds per second), the development of these algorithms was also quite rapid. It could be seen in a matter of minutes/hours that there was a feature on the likelihood surface that was trapping the chain. A proposal distribution could quickly be formulated to bypass this problem and the development continued. With the EMRIs however, the situation is a lot more complicated. Due to the frequency of the MLDCs, there hasn't been time to properly explore the EMRI likelihood surface. Also, the chains take a long time to run, sometimes up to weeks at a time, so it is very hard to quickly see if there are obstacles to convergence.

However, progress has been made on this front. As already mentioned, the current algorithms use the aforementioned concepts of simulated and thermostated annealing. The main difference compared to other searches, is that the current algorithms are fundamentally hierarchical due to the time restrictions detailed above. Shorter waveforms (3~4 months duration) are used to improve on the starting point in parameter space. The best points from this initial stage are then taken as starting points for the next round, where the length of a template is possibly increased. While a true F-Statistic is not available for EMRI waveforms, it is possible to optimize over the luminosity distance, the plunge time and the three initial phases using a combination of methods described in the SMBHB section above. By matching individual harmonics, it is also possible to now conduct some "island hopping" in the parameter space.

Both algorithms have thus far been tested in situations where we have isolated EMRIs buried in instrumental noise. In this case both algorithms have successfully detected and carried out parameter estimation for these sources. However, we should mention once again, that due to computational constraints, the parameter priors are very narrow and it is impossible to extrapolate the performance of each algorithm to a wide prior search. More recently, the algorithms have been applied to overlapping EMRIs in the third MLDC, so it will be interesting to see how each algorithm performs.

4.3 Outstanding issues for EMRIs

As said, we still have nowhere near the same comprehension of the likelihood surface for EMRIs that we have for other sources. This requires serious study in order to further improve the current algorithms. While the Barack-Cutler waveforms capture the complexity of EMRI orbits, at some point a transition to more exact numerical waveforms will have to be made. It could be that a different waveform model could introduce (or remove) features on the likelihood surface that will dramatically effect the convergence of algorithm. Finally, it is still not clear how the algorithms will perform once we widen the parameter priors or begin to have some EMRI confusion due to a high number of sources in the data stream.

5 Conclusions

We have presented here an overview of the current state of the art algorithms for LISA data analysis. While a number of different approaches have been used, we focused on those that were superior in terms of both accuracy and speed. At present an algorithm exists for galactic binary analysis that is already approaching the theoretical limits for the resolution of binaries in the galaxy. While the algorithm can be used on a desktop, it can process an entire galaxy of ~30 million binaries in under two weeks on a cluster. We also presented three detection and parameter estimation algorithms for non-spinning SMBHBs that currently require no more than a laptop to run on. These algorithms provide very accurate parameter estimation and search over wide priors in less than half a day. Finally, we introduced the currently available algorithms for EMRI data analysis. This is the area with the least amount of development. This is due to the complexity of the problem, the time taken to carry out the analysis and a not very advanced understanding of the likelihood surface for these sources. Even so, the current algorithms are able to detect and extract the parameters for isolated EMRIs buried in instrumental noise. We again caution the reader that it is too early to make predictions of the effectiveness of these algorithms as a lot more work is required.

With approximately a decade to go before the planned LISA launch date, we are in a very good state concerning LISA data analysis. There has been a significant progression from year to year in the methods and algorithms used to search for and detect various sources. Lessons that have been learned from previous algorithms, have fed into the next generation of development, allowing more and more sophisticated techniques to be used. While some methods have passed by the way, the good news is that new algorithms are always popping up. And, while we still have a long way to go, given the current algorithms, we can proceed with a certain amount of confidence.

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Selected abstracts

April to June 2009

Gravitational self-force correction to the innermost stable circular orbit of a Schwarzschild black hole

Authors: Barack, Leor; Sago, Norichika

Eprint: http://arxiv.org/abs/0902.0573

Keywords: EMRI; radiation reaction; self force

Abstract: The innermost stable circular orbit (ISCO) of a test particle around a Schwarzschild black hole of mass M is located at $r_{\rm isco} = 6MG/c^2$ (Schwarzschild coordinate radius). If the particle is endowed with mass $\mu(\ll M)$, it experiences a gravitational self-force whose conservative piece alters the location of the ISCO. Here we calculate the resulting shifts $\Delta r_{\rm isco}$ and $\Delta\Omega_{\rm isco}$ in the ISCO's radius and frequency, at leading order in the mass ratio μ/M. We obtain $\Delta r_{\rm isco} = -3.27\mu G/c^2$ (in the Lorenz gauge) and $\Delta\Omega_{\rm isco}/\Omega_{\rm isco} = 0.487\mu/M$ (gauge invariant). We discuss the implications of our result within the context of extreme mass-ratio binary inspirals.

Predicting the direction of the final spin from the coalescence of two black holes

Authors: Barausse, Enrico; Rezzolla, Luciano

Eprint: http://arxiv.org/abs/0904.2577

Keywords: astrophysics; general relativity; spin; numerical relativity; cosmology

Abstract: The knowledge of the spin of the black hole resulting from the merger of a generic binary system of black holes is of great importance to study the cosmological evolution of supermassive black holes. Several attempts have been recently made to model the spin via simple expressions exploiting the results of numerical-relativity simulations. While these expressions are in good agreement with the simulations, they are intrinsically imprecise when predicting the final spin direction, especially if applied to binaries with separations of hundred or thousands of gravitational radii. This is due to neglecting the precession of the orbital plane of the binary, and is a clear drawback if the formulas are employed in cosmological merger-trees or N-body simulations, which provide the spins and angular momentum of the two black

holes when their separation is of thousands of gravitational radii. We remove this problem by proposing an expression which is built on improved assumptions and that gives, for any separation, a very accurate prediction both for the norm of the final spin and for its direction. By comparing with the numerical data, we also show that the final spin direction is very accurately aligned with the total angular momentum of the binary at large separation. Hence, observations of the final spin direction (e.g. via a jet) can provide information on the orbital plane of the binary at large separations and could be relevant, for instance, to study X-shaped radio sources.

Bounding the mass of the graviton with gravitational waves: Effect of higher harmonics in gravitational waveform templates

Authors: Arun, K G; Will, Clifford M

Eprint: http://arxiv.org/abs/0904.1190

Keywords: post-Newtonian theory; waveforms; massive binaries of black holes

Abstract: Observations by laser interferometric detectors of gravitational waves from inspiraling compact binary systems can be used to search for a dependence of the waves' propagation speed on wavelength, and thereby to bound the mass or Compton wavelength of a putative graviton. We study the effect of including higher harmonics, as well as their post-Newtonian amplitude corrections, in the template gravitational waveforms employed in the process of parameter estimation using matched filtering. We consider the bounds that could be achieved using advanced LIGO, a proposed third generation instrument called Einstein Telescope, and the proposed space interferometer LISA. We find that in all cases, the bounds on the graviton Compton wavelength are improved by almost an order of magnitude for higher masses when amplitude corrections are included.

LISA as a dark energy probe

Authors: Arun, K G; Mishra, Chandra Kant; Broeck, Chris Van Den; Iyer, B R; Sathyaprakash, B S; Sinha, Siddhartha

Eprint: http://arxiv.org/abs/0810.5727

Keywords: massive binaries of black holes; cosmology

Abstract: Recently it was shown that the inclusion of higher signal harmonics in the inspiral signals of binary supermassive black holes (SMBH) leads to dramatic improvements in parameter estimation with the Laser Interferometer Space Antenna (LISA). In particular, the angular resolution becomes good enough to identify the host galaxy or galaxy cluster, in which case the redshift can be determined by electromagnetic means. The gravitational wave signal also provides the luminosity distance with high accuracy, and the relationship between this and the redshift depends sensitively on the cosmological parameters, such as the equation-of-state parameter $w = p_{\mathrm{DE}}/\rho_{\mathrm{DE}}$ of dark energy. With a single binary SMBH event at $z < 1$ having appropriate masses and orientation, one would be able to constrain w to within a few percent. We show that, if the measured sky location is folded into the error analysis, the uncertainty on w goes down by an additional factor of 2-3, leaving weak lensing as the only limiting factor in using LISA as a dark energy probe.

Massive black hole binary evolution in gas-rich mergers

Authors: Colpi, M.; Callegari, S.; Dotti, M.; Mayer, L.

Eprint: http://arxiv.org/abs/0904.0385

Keywords: astrophysics; cosmology

Abstract: We report on key studies on the dynamics of black holes (BHs) in gas-rich galaxy mergers that underscore the vital role played by gas dissipation in promoting BH inspiral down to the smallest scales ever probed with use of high-resolution numerical simulations. In major mergers, the BHs sink rapidly under the action of gas-dynamical friction while orbiting inside the massive nuclear disc resulting from the merger. The BHs then bind and form a Keplerian binary on a scale of 5 pc. In minor mergers, BH pairing proceeds down to the minimum scale explored of 10-100 pc only when the gas fraction in the less massive galaxy is comparatively large to avoid its tidal and/or ram pressure disruption and the wandering of the light BH in the periphery of the main halo. Binary BHs enter the gravitational wave dominated inspiral only when their relative distance is typically of 0.001 pc. If the gas preserves the degree of dissipation expected in a star-burst environment, binary decay continues down to 0.1 pc, the smallest length-scale ever attained. Stalling versus hardening below 0.1 pc is still matter of deep investigations.

Rightsizing LISA

Authors: Stebbins, R. T.

Eprint: http://arxiv.org/abs/0904.1029

Keywords: instruments; detectors; interferometers

Abstract: The LISA science requirements and conceptual design have been fairly stable for over a decade. In the interest of reducing costs, the LISA Project at NASA has looked for simplifications of the architecture, at downsizing of subsystems, and at descopes of the entire mission. This is a natural activity of the formulation phase, and one that is particularly timely in the current NASA budgetary context. There is, and will continue to be, enormous pressure for cost reduction from both ESA and NASA, reviewers and the broader research community. Here, the rationale for the baseline architecture is reviewed, and recent efforts to find simplifications and other reductions that might lead to savings are reported. A few possible simplifications have been found in the LISA baseline architecture. In the interest of exploring cost sensitivity, one moderate and one aggressive descope have been evaluated; the cost savings are modest and the loss of science is not.

Harmonic Gravitational Wave Spectra of Cosmic String Loops in the Galaxy

Authors: DePies, Matthew R; Hogan, Craig J

Eprint: http://arxiv.org/abs/0904.1052

Keywords: bursts; cosmology

Abstract:

A new candidate source of gravitational radiation is described: the nearly-perfect harmonic series from individual loops of cosmic string. It is argued that theories with light cosmic strings give rise to a population of numerous long-lived stable loops, many of which cluster gravitationally in galaxy halos along with the dark matter. Each cosmic string loop produces a spectrum of discrete frequencies in a nearly perfect harmonic series, a fundamental mode and its integer multiples. The gravitational wave signal from cosmic string loops in our Galactic halo is analyzed numerically and it is found that the for light strings, the nearest loops typically produce strong signals which stand out above confusion noise from Galactic binaries. The total population of cosmic string loops in the Milky Way also produces a broad signal that acts as a confusion noise. Both signals are enhanced by the clustering of loops gravitationally bound to the Galaxy, which significantly decreases the average distance from the solar system to the nearest loop. Numerical estimates indicate that for dimensionless string tension $G\mu < 10^{-11}$, many loops are likely to be found in the Galactic halo. Lighter strings, down to $G\mu = 10^{-19}$, are detectable by the Laser Interferometer Space Antenna (LISA). For these light strings, the fundamental and low-order harmonics of typical loops often lie in the band where LISA is sensitive,

0.1 to 100 mHz. The harmonic nature of the cosmic string loop modes leaves a distinct spectral signature different from any other known source of gravitational waves.

The Population of Viscosity- and Gravitational Wave-Driven Supermassive Black Hole Binaries Among Luminous AGN

Authors: Haiman, ZoltÃąn; Kocsis, Bence; Menou, Kristen

Eprint: http://arxiv.org/abs/0904.1383

Keywords: astrophysics; massive binaries of black holes; cosmology

Abstract:

Supermassive black hole binaries (SMBHBs) in galactic nuclei are thought to be a common by-product of major galaxy mergers. We use simple disk models for the circumbinary gas and for the binary-disk interaction to follow the orbital decay of SMBHBs with a range of total masses (M) and mass ratios (q), through physically distinct regions of the disk, until gravitational waves (GWs) take over their evolution. Prior to the GW-driven phase, the viscous decay is in the stalled "secondary-dominated" regime. SMBHBs spend a non-negligible fraction of 10^7 years at orbital periods $t_v ar$ between a day and a year. A dedicated optical or X-ray survey could identify coalescing SMBHBs statistically, as a population of periodically variable quasars, whose abundance $N_v ar$ is proportional to t_{var}^{α}, in a range of periods t_{var} around tens of weeks. SMBHBs with $M < 10^7 M_\odot$, with $0.5 < \alpha < 1.5$, would probe the physics of viscous orbital decay, whereas the detection of a population of higher-mass binaries, with $\alpha = 8/3$, would confirm that their decay is driven by GWs. The lowest mass SMBHBs ($M < 10^{5-6} M_\odot$) enter the GW-driven regime at short orbital periods, in the frequency band of the Laser Interferometric Space Antenna (LISA). While viscous processes are strongly sub-dominant in the last few years of coalescence, they could reduce the amplitude of any unresolved background of near-stationary LISA sources. We discuss constraints on the SMBHB population available from existing data, and the sensitivity and sky coverage requirements for a detection in future surveys. SMBHBs may also be identified from velocity shifts in their spectra; we discuss the expected abundance of SMBHBs as a function of their orbital velocity.

Use of the MultiNest algorithm for gravitational wave data analysis

Authors: Feroz, Farhan; Gair, Jonathan R; Hobson, Michael P; Porter, Edward K

Eprint: http://arxiv.org/abs/0904.1544

Keywords: search algorithms; data analysis

Abstract: We describe an application of the MultiNest algorithm to gravitational wave data analysis. MultiNest is a multimodal nested sampling algorithm designed to efficiently evaluate the Bayesian evidence and return posterior probability densities for likelihood surfaces containing multiple secondary modes. The algorithm employs a set of live points which are updated by partitioning the set into multiple overlapping ellipsoids and sampling uniformly from within them. This set of live points climbs up the likelihood surface through nested iso-likelihood contours and the evidence and posterior distributions can be recovered from the point set evolution. The algorithm is model-independent in the sense that the specific problem being tackled enters only through the likelihood computation, and does not change how the live point set is updated. In this paper, we consider the use of the algorithm for gravitational wave data analysis by searching a simulated LISA data set containing two non-spinning supermassive black hole binary signals. The algorithm is able to rapidly identify all the modes of the solution and recover the true parameters of the sources to high precision.

Energy Dissipation through Quasi-Static Tides in White Dwarf Binaries

Authors: Willems, B.; Deloye, C. J.; Kalogera, V.

Eprint: http://arxiv.org/abs/0904.1953

Keywords: astrophysics

Abstract: We study tidal interactions in white dwarf binaries in the limiting case of quasi-static tides. The formalism is valid for arbitrary orbital eccentricities and therefore applicable to white dwarf binaries in the Galactic disk as well as globular clusters. In the quasi-static limit, the total perturbation of the gravitational potential shows a phase shift with respect to the position of the companion, the magnitude of which is determined primarily by the efficiency of energy dissipation through convective damping. We determine rates of secular evolution of the orbital elements and white dwarf rotational angular velocity for a 0.3 solar mass helium white dwarf in binaries with orbital frequencies in the LISA gravitational wave frequency

band and companion masses ranging from 0.3 to 10^5 solar masses. The resulting tidal evolution time scales for the orbital semi-major axis are longer than a Hubble time, so that convective damping of quasi-static tides need not be considered in the construction of gravitational wave templates of white dwarf binaries in the LISA band. Spin-up of the white dwarf, on the other hand, can occur on time scales of less than 10Myr, provided that the white dwarf is initially rotating with a frequency much smaller than the orbital frequency. For semi-detached white dwarf binaries spin-up can occur on time scales of less than 1Myr. Nevertheless, the time scales remain longer than the orbital inspiral time scales due to gravitational radiation, so that the degree of asynchronism in these binaries increases. As a consequence, tidal forcing eventually occurs at forcing frequencies beyond the quasi-static tide approximation. For the shortest period binaries, energy dissipation is therefore expected to take place through dynamic tides and resonantly excited g-modes.

Response of a spaceborne gravitational wave antenna to solar oscillations

Authors: Polnarev, A. G.; Roxburgh, I. W.; Baskaran, D.

Eprint: http://arxiv.org/abs/0904.1943

Keywords: instruments; detectors; interferometers

Abstract: We investigate the possibility of observing very small amplitude low frequency solar oscillations with the proposed laser interferometer space antenna (LISA). For frequencies ν below 3×10^{-4}Hz the dominant contribution is from the near zone time dependent gravitational quadrupole moments associated with the normal modes of oscillation. For frequencies ν above 3×10^{-4}Hz the dominant contribution is from gravitational radiation generated by the quadrupole oscillations which is larger than the Newtonian signal by a factor of the order $(2\pi r\nu/c)^4$, where r is the distance to the Sun, and c is the velocity of light.

The low order solar quadrupole pressure and gravity oscillation modes have not yet been detected above the solar background by helioseismic velocity and intensity measurements. We show that for frequencies $\nu \lesssim 2 \times 10^{-4}$Hz, the signal due to solar oscillations will have a higher signal to noise ratio in a LISA type space interferometer than in helioseismology measurements. Our estimates of the amplitudes needed to give a detectable signal on a LISA type space laser interferometer imply surface velocity amplitudes on the sun of the order of 1-10 mm/sec in the frequency range $1 \times 10^{-4} - 5 \times 10^{-4}$Hz. If such modes exist with frequencies and amplitudes in this range they could be detected with a LISA type laser interferometer.

Extreme- and Intermediate-Mass Ratio Inspirals in Dynamical Chern-Simons Modified Gravity

Authors: Sopuerta, Carlos F.; Yunes, Nicolas

Eprint: http://arxiv.org/abs/0904.4501

Keywords: EMRI; general relativity; IMRI; tests of alternative theories

Abstract: [abridged] Chern-Simons (CS) modified gravity is a 4D effective theory that descends both from string theory and loop quantum gravity, and that corrects the Einstein-Hilbert action by adding the product of a scalar field and the parity-violating, Pontryagin density. In this theory, the gravitational field of spinning black holes is described by a modified Kerr geometry whose multipole moments deviate from the Kerr ones only at the fourth multipole, $l = 4$. We investigate possible signatures of this theory in the gravitational wave emission produced in the inspiral of stellar compact objects into massive black holes, both for intermediate- and extreme-mass ratios. We use the semi-relativistic approximation, where the trajectories are geodesics of the massive black hole geometry and the gravitational waveforms are obtained from a multipolar decomposition of the radiative field. The main CS corrections to the waveforms arise from modifications to the geodesic trajectories, due to changes to the massive black hole geometry, and manifest themselves as an accumulating dephasing relative to the general relativistic case. We also explore the propagation and the stress-energy tensor of gravitational waves in this theory. We find that, although this tensor has the same form as in General Relativity, the energy and angular momentum balance laws are indeed modified through the stress-energy tensor of the CS scalar field. These balance laws could be used to describe the inspiral through adiabatic changes in the orbital parameters, which in turn would enhance the dephasing effect. Gravitational-wave observations of intermediate- or extreme-mass ratio inspirals with advanced ground detectors or with LISA could use such dephasing to test the dynamical theory to unprecedented levels.

Multiwavelength periodicity study of Markarian 501

Authors: Roedig, Constanze; Burkart, Thomas; Elbracht, Oliver; Spanier, Felix

Eprint: http://arxiv.org/abs/0904.4392

Keywords: astrophysics

Abstract: Context: Active Galactic Nuclei are highly variable emitters of electromagnetic waves from the radio to the gamma-ray regime. This variability may be periodic, which in turn could be the signature of a binary black hole. Systems of

black holes are strong emitters of gravitational waves whose amplitude depends on the binary orbital parameters as the component mass, the orbital semi-major-axis and eccentricity.

Aims: It is our aim to prove the existence of periodicity of the AGN Markarian 501 from several observations in different wavelengths. A simultaneous periodicity in different wavelengths provides evidence for bound binary black holes in the core of AGN.

Methods: Existing data sets from observations by Whipple, SWIFT, RXTE, VERITAS and MAGIC have been analysed with the Lomb-Scargle method, the epoch folding technique and the SigSpec software.

Results: Our analysis shows a 72-day period, which could not be seen in previous works due to the limited length of observations. This does not contradict a 23-day period which can be derived as a higher harmonic from the 72-day period.

Nature of X-shaped sources

Authors: Lal, D. V.; Hardcastle, M. J.; Kraft, R. P.; Cheung, C. C.; Lobanov, A. P.; Zensus, J. A.; Bhatnagar, S.; Rao, A. P.

Eprint: http://arxiv.org/abs/0904.2725

Keywords: astrophysics; cosmology

Abstract: The nature of X-shaped sources is a matter of considerable debate: it has even been proposed that they provide evidence for black hole mergers/spin reorientation, and therefore constrain the rate of strong gravitational wave events (Merritt & Ekers 2002). Based on morphological and spectral characteristics of these sources, currently a strong contender to explain the nature of these sources is the 'alternative' model of Lal & Rao (2007), in which these sources consist of two pairs of jets, which are associated with two unresolved AGNs. Detailed morphological and spectral results on milliarcsecond-scales (mas) provide a crucial test of this model, and hence these sources are excellent candidates to study on mas; *i.e.*, to detect he presence/absence of double nuclei/AGNs, signs of helical/disrupted jets, thereby, to investigate spatially resolved/unresolved binary AGN systems and providing clues to understanding the physics of merging of AGNs on mas. We conducted a systematic study of a large sample of known X-shaped, comparison FR II radio galaxies, and newly discovered X-shaped candidate sources using Giant Metrewave Radio Telescope and Very Large Array at several radio frequencies. In our new observations of 'comparison' FR II radio galaxies we find that almost all of our targets show standard spectral steepening as a function of distance from the hotspot. However, one source, 3C 321, has a low-surface-brightness extension that shows a flatter

spectral index than the high-surface-brightness hotspots/lobes, as found in 'known' X-shaped sources.

An Efficient Numerical Method for Computing Gravitational Waves Induced by a Particle Moving on Eccentric Inclined Orbits around a Kerr Black Hole

Authors: Fujita, Ryuichi; Hikida, Wataru; Tagoshi, Hideyuki

Eprint: http://arxiv.org/abs/0904.3810

Keywords: EMRI; general relativity

Abstract: We develop a numerical code to compute gravitational waves induced by a particle moving on eccentric inclined orbits around a Kerr black hole. For such systems, the black hole perturbation method is applicable. The gravitational waves can be evaluated by solving the Teukolsky equation with a point like source term, which is computed from the stress-energy tensor of a test particle moving on generic bound geodesic orbits. In our previous papers, we computed the homogeneous solutions of the Teukolsky equation using a formalism developed by Mano, Suzuki and Takasugi and showed that we could compute gravitational waves efficiently and very accurately in the case of circular orbits on the equatorial plane. Here, we apply this method to eccentric inclined orbits. The geodesics around a Kerr black hole have three constants of motion: energy, angular momentum and the Carter constant. We compute the rates of change of the Carter constant as well as those of energy and angular momentum. This is the first time that the rate of change of the Carter constant has been evaluated accurately. We also treat the case of highly eccentric orbits with $e = 0.9$. To confirm the accuracy of our codes, several tests are performed. We find that the accuracy is only limited by the truncation of ℓ-, k- and n-modes, where ℓ is the index of the spin-weighted spheroidal harmonics, and n and k are the harmonics of the radial and polar motion, respectively. When we set the maximum of ℓ to 20, we obtain a relative accuracy of 10^{-5} even in the highly eccentric case of $e = 0.9$. The accuracy is better for lower eccentricity. Our numerical code is expected to be useful for computing templates of the extreme mass ratio inspirals, which is one of the main targets of the Laser Interferometer Space Antenna (LISA).

Response of a spaceborne gravitational wave antenna to solar oscillations

Authors: Polnarev, A. G.; Roxburgh, I. W.; Baskaran, D.

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Keywords: instruments; detectors; interferometers

Abstract: We investigate the possibility of observing very small amplitude low frequency solar oscillations with the proposed laser interferometer space antenna (LISA). For frequencies ν below 3×10^{-4}Hz the dominant contribution is from the near zone time dependent gravitational quadrupole moments associated with the normal modes of oscillation. For frequencies ν above 3×10^{-4}Hz the dominant contribution is from gravitational radiation generated by the quadrupole oscillations which is larger than the Newtonian signal by a factor of the order $(2\pi r\nu/c)^4$, where r is the distance to the Sun, and c is the velocity of light.

The low order solar quadrupole pressure and gravity oscillation modes have not yet been detected above the solar background by helioseismic velocity and intensity measurements. We show that for frequencies $\nu \lesssim 2 \times 10^{-4}$Hz, the signal due to solar oscillations will have a higher signal to noise ratio in a LISA type space interferometer than in helioseismology measurements. Our estimates of the amplitudes needed to give a detectable signal on a LISA type space laser interferometer imply surface velocity amplitudes on the sun of the order of 1-10 mm/sec in the frequency range $1 \times 10^{-4} - 5 \times 10^{-4}$Hz. If such modes exist with frequencies and amplitudes in this range they could be detected with a LISA type laser interferometer.

Enhanced tidal disruption rates from massive black hole binaries

Authors: Chen, X.; Madau, P.; Sesana, A.; Liu, F. K.

Eprint: http://arxiv.org/abs/0904.4481

Keywords: astrophysics; massive binaries of black holes; cosmology

Abstract: "Hard" massive black hole (MBH) binaries embedded in steep stellar cusps can shrink via three-body slingshot interactions. We show that this process will inevitably be accompanied by a burst of stellar tidal disruptions, at a rate that can be several orders of magnitude larger than that appropriate for a single MBH. Our numerical scattering experiments reveal that: 1) a significant fraction of stars initially bound to the primary hole are scattered into its tidal disruption loss cone by gravitational interactions with the secondary hole, an enhancement effect that is more pronounced for very unequal-mass binaries; 2) about 25% (40%) of all strongly interacting stars are tidally disrupted by a MBH binary of mass ratio q=1/81 (q=1/243) and eccentricity 0.1; and 3) two mechanisms dominate the fueling of the tidal disruption loss cone, a Kozai non-resonant interaction that causes

the secular evolution of the stellar angular momentum in the field of the binary, and the effect of close encounters with the secondary hole that change the stellar orbital parameters in a chaotic way. For a hard MBH binary of 10^7 solar masses and mass ratio 0.01, embedded in an isothermal stellar cusp of velocity dispersion sigma*=100 km/s, the tidal disruption rate can be as large as 1/yr. This is 4 orders of magnitude higher than estimated for a single MBH fed by two-body relaxation. When applied to the case of a putative intermediate-mass black hole inspiraling onto Sgr A*, our results predict tidal disruption rates ~ 0.05-0.1/yr.

Images of the radiatively inefficient accretion flow surrounding a Kerr black hole: application in Sgr A*

Authors: Yuan, Ye-Fei; Cao, Xinwu; Huang, Lei; Shen, Zhi-Qiang

Eprint: http://arxiv.org/abs/0904.4090

Keywords: astrophysics; supermassive black holes; accretion discs

Abstract: In fully general relativity, we calculate the images of the radiatively inefficient accretion flow (RIAF) surrounding a Kerr black hole with arbitrary spins, inclination angles, and observational wavelengths. For the same initial conditions, such as the fixed accretion rate, it is found that the intrinsic size and radiation intensity of the images become larger, but the images become more compact in the inner region, while the size of the black hole shadow decreases with the increase of the black hole spin. With the increase of the inclination angles, the shapes of the black hole shadows change and become smaller, even disappear at all due to the obscuration by the thick disks. For median inclination angles, the radial velocity observed at infinity is larger because of both the rotation and radial motion of the fluid in the disk, which results in the luminous part of the images is much brighter. For larger inclination angles, such as the disk is edge on, the emission becomes dimmer at longer observational wavelengths (such as at 7.0mm and 3.5mm wavelengths), or brighter at shorter observational wavelengths (such as at 1.3 mm wavelength) than that of the face on case, except for the high spin and high inclination images. These complex behaviors are due to the combination of the Lorentz boosting effect and the radiative absorption in the disk. We hope our results are helpful to determine the spin parameter of the black hole in low luminosity sources, such as the Galactic center. A primary analysis by comparison with the observed sizes of Sgr A* at millimeters strongly suggests that the disk around the central black hole at Sgr A* is highly inclined or the central black hole is rotating fast.

Integrated Sachs-Wolfe Effect for Gravitational Radiation

Authors: Laguna, Pablo; Larson, Shane L.; Spergel, David; Yunes, Nicolas

Eprint: http://arxiv.org/abs/0905.1908

Keywords: astrophysics; general relativity; numerical relativity

Abstract: Gravitational waves are messengers carrying valuable information about their sources. For sources at cosmological distances, the waves will contain also the imprint left by the intervening matter. The situation is in close analogy with cosmic microwave photons, for which the large-scale structures the photons traverse contribute to the observed temperature anisotropies, in a process known as the integrated Sachs-Wolfe effect. We derive the gravitational wave counterpart of this effect for waves propagating on a Friedman-Robertson-Walker background with scalar perturbations. We find that the phase, frequency and amplitude of the gravitational waves experience Sachs-Wolfe type integrated effects, this in addition to the magnification effects on the amplitude from gravitational lensing. We show that for supermassive black hole binaries, the integrated effects could account for measurable changes on the frequency, chirp mass and luminosity distance of the binary, thus unveiling the presence of inhomogeneities, and potentially dark energy, in the Universe.

The search for spinning black hole binaries using a genetic algorithm

Authors: Petiteau, Antoine; Yu, Shang; Babak, Stanislav

Eprint: http://arxiv.org/abs/0905.1785

Keywords: search algorithms; data analysis; spin; massive binaries of black holes

Abstract: We use a genetic algorithm to analyze the data from the third round of the mock LISA data challenge. These data consist of gaussian stationary instrumental noise, a Galactic background and four to six signals from the inspiralling spinning BHs in quasi-circular orbits. We present a particular implementation of the genetic algorithm which uses properties of the signal and the response function. We discuss the results of a preliminary search for a single signal in the instrumental noise.

Growing the first bright quasars in cosmological simulations of structure formation

Authors: Sijacki, Debora; Springel, Volker; Haehnelt, Martin G.

Eprint: http://arxiv.org/abs/0905.1689

Keywords: astrophysics; N-body; cosmology

Abstract: We employ cosmological hydrodynamical simulations to study the growth of massive black holes (BHs) at high redshifts subject to BH merger recoils from gravitational wave emission. We select the most massive dark matter halo at z=6 from the Millennium simulation, and resimulate its formation at much higher resolution including gas physics and a model for BH seeding, growth and feedback. Assuming that the initial BH seeds are relatively massive, of the order of $10^5 M_\odot$, and that seeding occurs around z$\sim$ 15 in dark matter haloes of mass $10^9 - 10^{10} M_\odot$, we find that it is possible to build up supermassive BHs (SMBHs) by z=6 that assemble most of their mass during extended Eddington-limited accretion periods. The properties of the simulated SMBHs are consistent with observations of z=6 quasars in terms of the estimated BH masses and bolometric luminosities, the amount of star formation occurring within the host halo, and the presence of highly enriched gas in the innermost regions of the host galaxy. After a peak in the BH accretion rate at z=6, the most massive BH has become sufficiently massive for the growth to enter into a much slower phase of feedback-regulated accretion. We explore the full range of expected recoils and radiative efficiencies, and also consider models with spinning BHs. In the most 'pessimistic' case where BH spins are initially high, we find that the growth of the SMBHs can be potentially hampered if they grow mostly in isolation and experience only a small number of mergers. Whereas BH kicks can expel a substantial fraction of low mass BHs, they do not significantly affect the build up of the SMBHs. On the contrary, a large number of BH mergers has beneficial consequences for the growth of the SMBHs by considerably reducing their spin. [Abridged]

Stirring, not shaking: binary black holes' effects on electromagnetic fields

Authors: Palenzuela, Carlos; Anderson, Matthew; Lehner, Luis; Liebling, Steven L.; Neilsen, David

Eprint: http://arxiv.org/abs/0905.1121

Keywords: numerical relativity; numerical methods; EM counterparts

Abstract: In addition to producing gravitational waves (GW), the dynamics of a binary black hole system could induce emission of electromagnetic (EM) radiation by affecting the behavior of plasmas and electromagnetic fields in their vicinity. We here study how the electromagnetic fields are affected by a pair of orbiting black holes through the merger. In particular, we show how the binary's dynamics induce a variability in possible electromagnetically induced emissions as well as a possible enhancement of electromagnetic fields during the late-merge and merger epochs. These time dependent features will likely leave their imprint in processes generating detectable emissions and can be exploited in the detection of electromagnetic counterparts of gravitational waves.

Nonthermal transient phenomena around rotating black holes

Authors: van Putten, Maurice H. P. M.

Eprint: http://arxiv.org/abs/0905.3367

Keywords: astrophysics; EM counterparts

Abstract: Ultra-high energy cosmic rays (UHECRs) and gamma-ray bursts (GRBs) are the most exceptional nonthermal transient events, that appear to be associated with black holes. Here, we describe radiation mechanisms induced by turbulent flows around rapidly rotating black holes: high-energy emissions from a relativistic capillary effect along the black hole spin-axis and low-energy emissions by catalytic conversion of spin-energy. High-energy emissions arise, concurrently, in photons and, upstream of an outgoing Alfvén front, in ionic contaminants by linear acceleration. The latter develop into ultra-high energy cosmic rays (UHECRs) about the Greisen-Zatsepin-Kuzmin (GZK) threshold in low-luminosity, intermittent active galactic nuclei. These may include Seyfert galaxies and Cen A suggested by detections of UHECRs by the Pierre Auger Observatory and, for the latter, also of Very High Energy (VHE) gamma-rays by the High Energy Stereoscopic System (HESS). Nearly complete spin-down of stellar mass black holes is common to collapsars and mergers of neutron stars with another neutron star or companion black hole. Thus, long GRBs from rotating black holes explain events with and without supernovae and a diversity in their X-ray afterglows. Their intrinsic exponential decay is remarkably consistent with the average of 600 light curves of long GRBs, whose total output agrees with observed peak and true energies in gamma-rays. We conclude that long GRBs are spin-powered. Gravitational radiation from turbulent flows in SgrA* might be of interest to the planned Laser Interferometric Space Antenna (LISA) and, for stellar mass black holes in GRBs, should be detectable by LIGO-Virgo. Long GRBs from naked inner engines produced in mergers produce

long-duration radio-burst that may be seen in all-sky surveys by the Low Frequency Array (LOFAR).

A second black hole candidate in a M31 globular cluster is identified with XMM-Newton

Authors: Barnard, R.; Kolb, U.

Eprint: http://arxiv.org/abs/0905.3278

Keywords: astrophysics; intermediate-mass black holes (IMBH); massive binaries of black holes

Abstract: We use arguments developed in previous work to identify a second black hole candidate associated with a M31 globular cluster, Bo 144, on the basis of X-ray spectral and timing properties. The 2002 XMM-Newton observation of the associated X-ray source (hereafter XBo 144) revealed behaviour that is common to all low-mass X-ray binaries (LMXBs) in the low-hard state. Studies have shown that neutron star LMXBs exhibit this behaviour at 0.01-1000 keV luminosities *leq*10% of the Eddington limit ($L_{\rm Edd}$). However, the unabsorbed 0.3-10 keV XBo 144 luminosity was $\sim 0.30 L_{\rm Edd}$ for a 1.4 $M_\odot$ neutron star, and the expected 0.01-1000 keV luminosity is 3-7 times higher. We therefore identify XBo 144 as a black hole candidate. Furthermore, it is the second black hole candidate to be consistent with formation via tidal capture of a mean sequence donor in a GC; such systems were previously though non-existent, because the donor was thought to be disrupted during the capture process.

Perturbed disks get shocked. Binary black hole merger effects on accretion disks

Authors: Megevand, Miguel; Anderson, Matthew; Frank, Juhan; Hirschmann, Eric W.; Lehner, Luis; Liebling, Steven L.; Motl, Patrick M.; Neilsen, David

Eprint: http://arxiv.org/abs/0905.3390

Keywords: astrophysics; gravitational recoil; accretion discs; numerical methods; massive binaries of black holes

Abstract: The merger process of a binary black hole system can have a strong impact on a circumbinary disk. In the present work we study the effect of both central

mass reduction (due to the energy loss through gravitational waves) and a possible black hole recoil (due to asymmetric emission of gravitational radiation). For the mass reduction case and recoil directed along the disk's angular momentum, oscillations are induced in the disk which then modulate the internal energy and bremsstrahlung luminosities. On the other hand, when the recoil direction has a component orthogonal to the disk's angular momentum, the disk's dynamics are strongly impacted, giving rise to relativistic shocks. The shock heating leaves its signature in our proxies for radiation, the total internal energy and bremsstrahlung luminosity. Interestingly, for cases where the kick velocity is below the smallest orbital velocity in the disk (a likely scenario in real AGN), we observe a common, characteristic pattern in the internal energy of the disk. Variations in kick velocity simply provide a phase offset in the characteristic pattern implying that observations of such a signature could yield a measure of the kick velocity through electromagnetic signals alone.

Signatures of black hole spin in galaxy evolution

Authors: Garofalo, David

Eprint: http://arxiv.org/abs/0905.4782

Keywords: astrophysics; accretion discs; spin

Abstract: We explore the connection between black hole spin and AGN power by addressing the consequences underlying the assumption in the recent literature that the gap region between accretion disks and black holes is fundamental in producing strong, spin-dependent, horizon-threading magnetic fields. Under the additional assumption that jets and outflows in AGN are produced by the Blandford-Znajek and Blandford-Payne mechanisms, we show that maximum jet/outflow power is achieved for accretion onto black holes having highly retrograde spin parameter, an energetically excited yet unstable gravitomagnetic configuration.

Extension of the LTP temperature diagnostics to the LISA band: first results

Authors: Sanjuan, J; Ramos-Castro, J; Lobo, A

Eprint: http://arxiv.org/abs/0905.4881

Keywords: instruments; interferometers

Abstract: High-resolution temperature measurements are required in the LTP, i.e., 10 uK/sqrt(Hz) from 1 mHz to 30 mHz. This has been already accomplished with thermistors and a suitable low noise electronics. However, the frequency range of interest for LISA goes down to 0.1 mHz. Investigations on the performance of temperature sensors and the associated electronics at frequencies around 0.1 mHz have been performed. Theoretical limits of the temperature measurement system and the practical on-ground limitations to test them are shown demonstrating that 1/f noise is not observed in thermistors even at frequencies around 0.1 mHz and amplitude levels of 10 uK/sqrt(Hz).

ADC non-linear errors correction in thermal diagnostics for the LISA mission

Authors: Sanjuan, J.; Lobo, A.; Ramos-Castro, J.

Eprint: http://arxiv.org/abs/0905.3165

Keywords: instruments; interferometers

Abstract: Low-noise temperature measurements at frequencies in the milli-Hertz range are needed in the LISA and LISA PathFinder (LPF). The required temperature stability for LISA is around 10 uK/sqrt(Hz) at frequencies down to 0.1 mHz. In this paper we focus on the identification and reduction of a source of excess noise detected when measuring time-varying temperature signals. This is shown to be due to non-idealities in the ADC transfer curve, and degrades the measurement by about one order of magnitude in the measurement bandwidth when the measured temperature exhibits drifts of uK/s. In a suitable measuring system for the LISA mission, this noise needs to be reduced. Two different methods based on the same technique have been implemented, both consisting in the addition of dither signals out of band to mitigate the ADC non-ideality errors. Excess noise of this nature has been satisfactorily reduced by using these methods when measuring temperature ramps up to 10 uK/s .

Studying stellar binary systems with the Laser Interferometer Space Antenna using Delayed Rejection Markov chain Monte Carlo methods

Authors: Trias, Miquel; Vecchio, Alberto; Veitch, John

Eprint: http://arxiv.org/abs/0905.2976

Keywords: data analysis; Metropolis-Hastings

Abstract: Bayesian analysis of LISA data sets based on Markov chain Monte Carlo methods has been shown to be a challenging problem, in part due to the complicated structure of the likelihood function consisting of several isolated local maxima that dramatically reduces the efficiency of the sampling techniques. Here we introduce a new fully Markovian algorithm, a Delayed Rejection Metropolis-Hastings Markov chain Monte Carlo method, to efficiently explore these kind of structures and we demonstrate its performance on selected LISA data sets containing a known number of stellar-mass binary signals embedded in Gaussian stationary noise.

Post-Circular Expansion of Eccentric Binary Inspirals: Fourier-Domain Waveforms in the Stationary Phase Approximation

Authors: Yunes, Nicolas; Arun, K. G.; Berti, Emanuele; Will, Clifford M.

Eprint: http://arxiv.org/abs/0906.0313

Keywords: post-Newtonian theory; waveforms; general relativity

Abstract: We lay the foundations for the construction of analytic expressions for Fourier-domain gravitational waveforms produced by eccentric, inspiraling compact binaries in a post-circular or small-eccentricity approximation. The time-dependent, "plus" and "cross" polarizations are expanded in Bessel functions, which are then self-consistently re-expanded in a power series about zero initial eccentricity to eighth order. The stationary phase approximation is then employed to obtain explicit analytic expressions for the Fourier transform of the post-circular expanded, time-domain signal. We exemplify this framework by considering Newtonian-accurate waveforms, which in the post-circular scheme give rise to higher harmonics of the orbital phase and amplitude corrections both to the amplitude and the phase of the Fourier domain waveform. Such higher harmonics lead to an effective increase in the inspiral mass reach of a detector as a function of the binary's eccentricity e_0 at the time when the binary enters the detector sensitivity band. Using the largest initial eccentricity allowed by our approximations ($e_0 < 0.4$), the mass reach is found to be enhanced up to factors of approximately 5 relative to that of circular binaries for Advanced LIGO, LISA, and the proposed Einstein Telescope at a signal-to-noise ratio of ten. A post-Newtonian generalization of the post circular scheme is also discussed, which holds the promise to provide "ready-to-use" Fourier-domain waveforms for data analysis of eccentric inspirals.

Gravitational wave backgrounds and the cosmic transition from Population III to Population II stars

Authors: Marassi, Stefania; Schneider, Raffaella; Ferrari, Valeria

Eprint: http://arxiv.org/abs/0906.0461

Keywords: astrophysics; noise: instrumental; cosmology

Abstract: Using the results of a numerical simulation which follows the evolution, metal enrichment and energy deposition of both Population III and Population II stars, we predict the redshift dependence of the formation rate of black hole remnants of Population III stars with masses 100- 500Msun and of neutron stars(black holes) remnants of Population II stars with masses 8-20Msun (20-40Msun). We describe the gravitational wave spectrum produced by Population III and Population II sources adopting the most appropriate signals available in the literature and we compute the stochastic backgrounds resulting from the cumulative emission of these sources throughout the history of the Universe. With the aim of assessing whether these backgrounds might act as foregrounds for signals generated in the Inflationary epoch, we compare their amplitudes with the sensitivity of currently planned and future ground/space-based interferometers.

Binary dynamics near a massive black hole

Authors: Hopman, Clovis

Eprint: http://arxiv.org/abs/0906.0374

Keywords: astrophysics; EMRI

Abstract: We analyze the dynamical evolution of binary stars that interact with a static background of single stars in the environment of a massive black hole (MBH). All stars are considered to be single mass, Newtonian point particles. We follow the evolution of the energy E and angular momentum J of the center of mass of the binaries with respect to the MBH, as well as their internal semi-major axis a, using a Monte Carlo method. For a system like the Galactic center, the main conclusions are the following: (1) The binary fraction can be of the order of a few percent outside 0.1 pc, but decreases quickly closer to the MBH. (2) Within $\sim$ 0.1 pc, binaries can only exist on eccentric orbits with apocenters much further away from the MBH. (3) Far away from the MBH, loss-cone effects are the dominant mechanism that disrupts binaries with internal velocities close to the velocity dispersion. Closer to the MBH, three-body encounters are more effective in disrupting binaries. (4) The rate at which hard binaries become tighter is usually less than the rate at which a

binary diffuses to orbits that are more bound to the MBH. (5) Binaries are typically disrupted before they experience an exchange interaction; as a result, the number of exchanges is less than one would estimate from a simple "nvσestimate". We give applications of our results to the formation of X-ray binaries near MBHs and to the production rates of hyper-velocity stars by intermediate mass MBHs.

Quasinormal modes of black holes and black branes

Authors: Berti, Emanuele; Cardoso, Vitor; Starinets, Andrei O.

Eprint: http://arxiv.org/abs/0905.2975

Keywords: astrophysics; waveforms; numerical relativity; no-hair conjecture; parameter estimation

Abstract: Quasinormal modes are eigenmodes of dissipative systems. Perturbations of classical gravitational backgrounds involving black holes or branes naturally lead to quasinormal modes. The analysis and classification of the quasinormal spectra requires solving non-Hermitian eigenvalue problems for the associated linear differential equations. Within the recently developed gauge-gravity duality, these modes serve as an important tool for determining the near-equilibrium properties of strongly coupled quantum field theories, in particular their transport coefficients, such as viscosity, conductivity and diffusion constants. In astrophysics, the detection of quasinormal modes in gravitational wave experiments would allow precise measurements of the mass and spin of black holes as well as new tests of general relativity. This review is meant as an introduction to the subject, with a focus on the recent developments in the field.

Black hole mergers: can gas discs solve the 'final parsec' problem?

Authors: Lodato, G.; Nayakshin, S.; King, A. R.; Pringle, J. E.

Eprint: http://arxiv.org/abs/0906.0737

Keywords: astrophysics; numerical methods; massive binaries of black holes

Abstract: We compute the effect of an orbiting gas disc in promoting the coalescence of a central supermassive black hole binary. Unlike earlier studies, we consider a finite mass of gas with explicit time dependence: we do not assume that the gas necessarily adopts a steady state or a spatially constant accretion rate, i.e. that the merging black hole was somehow inserted into a pre–existing accretion disc. We

consider the tidal torque of the binary on the disc, and the binary's gravitational radiation. We study the effects of star formation in the gas disc in a simple energy feedback framework. The disc spectrum differs in detail from that found before. In particular, tidal torques from the secondary black hole heat the edges of the gap, creating bright rims around the secondary. These rims do not in practice have uniform brightness either in azimuth or time, but can on average account for as much as 50 per cent of the integrated light from the disc. This may lead to detectable high–photon–energy variability on the relatively long orbital timescale of the secondary black hole, and thus offer a prospective signature of a coalescing black hole binary. We also find that the disc can drive the binary to merger on a reasonable timescale only if its mass is at least comparable with that of the secondary black hole, and if the initial binary separation is relatively small, i.e. $a_0 \lesssim 0.05$ pc. Star formation complicates the merger further by removing mass from the disc. In the feedback model we consider, this sets an effective limit to the disc mass. As a result, binary merging is unlikely unless the black hole mass ratio is 0.001. Gas discs thus appear not to be an effective solution to the 'last parsec' problem for a significant class of mergers.

Fossil Gas and the Electromagnetic Precursor of Supermassive Binary Black Hole Mergers

Authors: Chang, P.; Strubbe, L. E.; Menou, K.; Quataert, E.

Eprint: http://arxiv.org/abs/0906.0825

Keywords: astrophysics; massive binaries of black holes; EM counterparts

Abstract: Using a one-dimensional height integrated model, we calculate the evolution of an unequal mass binary black hole with a coplanar gas disk that contains a gap due to the presence of the secondary black hole. Viscous evolution of the outer circumbinary disk initially hardens the binary, while the inner disk drains onto the primary (central) black hole. As long as the inner disk remains cool and thin at low $\dot{M}_{\rm ext}$ (rather than becoming hot and geometrically thick), the mass of the inner disk reaches an asymptotic mass typically $\sim 10^{-3} - 10^{-4} M_\odot$. Once the semimajor axis shrinks below a critical value, angular momentum losses from gravitational waves dominate over viscous transport in hardening the binary. The inner disk then no longer responds viscously to the inspiraling black holes. Instead, tidal interactions with the secondary rapidly drive the inner disk into the primary. Tidal and viscous dissipation in the inner disk lead to a late time brightening in luminosity $L \propto t_{\rm minus}^{5/4}$, where $t_{\rm minus}$ is the time prior to the final merger. This late time brightening peaks ~ 1 day prior to the final merger at $\sim 0.1 L_{\rm Edd}$. This behavior is relatively robust because of self regulation in the coupled viscous-gravitational evolution of such

binary systems. It constitutes a unique electromagnetic signature of a binary supermassive black hole merger and may allow the host galaxy to be identified if used in conjunction with the Laser Interferometric Space Antenna (LISA) localization.

New analytical methods for gravitational radiation and reaction in binaries with arbitrary mass ratio and relative velocity

Authors: Galley, Chad R.; Hu, Bei-Lok

Eprint: http://arxiv.org/abs/0906.0968

Keywords: post-Newtonian theory; general relativity; self force

Abstract: We present a new analytical framework for describing the dynamics of a gravitational binary system with unequal masses moving with arbitrary relative velocity, taking into account the backreaction from both compact objects in the form of tidal deformation, gravitational waves and self forces. Allowing all dynamical variables to interact with each other in a self-consistent manner this formalism ensures that all the dynamical quantities involved are conserved on the background spacetime and obey the gauge invariance under general coordinate transformations that preserve the background geometry. Because it is based on a generalized perturbation theory and the important new emphasis is on the self-consistency of all the dynamical variables involved we call it a gravitational perturbation theory with self-consistent backreaction (GP-SCB).

As an illustration of how this formalism is implemented we construct perturbatively a self-consistent set of equations of motion for an inspiraling gravitational binary, which does not require extra assumptions such as slow motion, weak-field or small mass ratio for its formulation. This case should encompass the inspiral and possibly the plunge and merger phases of binaries with otherwise general parameters (e.g., mass ratio and relative velocity) though more investigation is needed to substantiate it.

In the second part, we discuss how the mass ratio can be treated as a perturbation parameter in the post-Newtonian effective field theory (PN-EFT) approach, thus extending the work of Goldberger and Rothstein for equal mass binaries to variable mass ratios. We provide rough estimates for the higher post-Newtonian orders needed to determine the number of gravitational wave cycles, with a specified precision, that fall into a detector's bandwidth.

Quasi-Periodic Flares from Star-Accretion Disc Collisions

Authors: Dai, Lixin; Fuerst, Steven V.; Blandford, Roger

Eprint: http://arxiv.org/abs/0906.0800

Keywords: astrophysics; general relativity; accretion discs; EM counterparts

Abstract: We present simulated results of quasi-periodic flares generated by the inelastic collisions of a star bound to a super-massive black hole (SMBH) and its attendant accretion disc. We show that the behavior of the quasi-periodicity is affected by the mass and spin of the black hole and the orbital elements of the stellar orbit. We also evaluate the possibility of extracting useful information on these parameters and verifying the character of the Kerr metric from such quasi-periodic signals. Comparisons are made with the observed optical outbursts of OJ287, infrared flares from the Galactic center and X-ray variability in RE J1034+396.

Analytical solutions of bound timelike geodesic orbits in Kerr spacetime

Authors: Fujita, Ryuichi; Hikida, Wataru

Eprint: http://arxiv.org/abs/0906.1420

Keywords: post-Newtonian theory; EMRI; general relativity

Abstract: We derive the analytical solutions of the bound timelike geodesic orbits in Kerr spacetime. The analytical solutions are expressed in terms of the elliptic integrals using Mino time λ as the independent variable. Mino time decouples the radial and polar motion of a particle and hence leads to forms more useful to estimate three fundamental frequencies, radial, polar and azimuthal motion, for the bound timelike geodesics in Kerr spacetime. This paper gives the first derivation of the analytical expressions of the fundamental frequencies. This paper also gives the first derivation of the analytical expressions of all coordinates for the bound timelike geodesics using Mino time. These analytical expressions should be useful not only to investigate physical properties of Kerr geodesics but more importantly to applications related to the estimation of gravitational waves from the extreme mass ratio inspirals.

On post-Newtonian orbits and the Galactic-center stars

Authors: Preto, Miguel; Saha, Prasenjit

Eprint: http://arxiv.org/abs/0906.2226

Keywords: N-body; EMRI; stellar dynamics; astrophysics; supermassive black holes; numerical methods

Abstract: Stars near the Galactic center reach a few percent of light speed during pericenter passage, which makes post-Newtonian effects potentially detectable. We formulate the orbit equations in Hamiltonian form such that the $O(v^2/c^2)$ and $O(v^3/c^3)$ post-Newtonian effects of the Kerr metric appear as a simple generalization of the Kepler problem. A related perturbative Hamiltonian applies to photon paths. We then derive a symplectic integrator with adaptive time-steps, for fast and accurate numerical calculation of post-Newtonian effects. Using this integrator, we explore relativistic effects. Taking the star S2 as an example, we find that general relativity would contribute tenths of mas in astrometry and tens of kms^{-1} in kinematics. (For eventual comparison with observations, redshift and time-delay contributions from the gravitational field on light paths will need to be calculated, but we do attempt these in the present paper.) The contribution from stars, gas, and dark matter in the Galactic center region is still poorly constrained observationally, but current models suggest that the resulting Newtonian perturbation on the orbits could plausibly be of the same order as the relativistic effects for stars with semi-major axes $\gtrsim$ 0.01 pc (or 250 mas). Nevertheless, the known and distinctive *time dependence* of the relativistic perturbations may make it possible to disentangle and extract both effects from observations.

Spacetime constraints on accreting black holes

Authors: Garofalo, David

Eprint: http://arxiv.org/abs/0906.2398

Keywords: accretion discs; spin; EM counterparts

Abstract: We study the spin dependence of accretion onto rotating Kerr black holes using analytic techniques. In its linear regime, angular momentum transport in MHD turbulent accretion flow involves the generation of radial magnetic field connecting plasma in a differentially rotating flow. We take a first principles approach, highlighting the constraint that limits the generation and amplification of radial magnetic fields, stemming from the transfer of energy from mechanical to magnetic form. Because the energy transferred in magnetic form is ultimately constrained by gravitational potential energy or Killing energy, the spin-dependence of the latter allows us to derive spin-dependent constraints on the success of the accreting plasma to expel its angular momentum and accrete. We find an inverse relationship between this ability and black hole spin. If this radial magnetic field generation forms the basis for angular momentum transfer in accretion flows, accretion rates involving Kerr black holes are expected to be lower as the black hole spin increases in the prograde sense.

LISA technology and instrumentation

Authors: Jennrich, O.

Eprint: http://arxiv.org/abs/0906.2901

Keywords: instruments; interferometers

Abstract: This article reviews the present status of the technology and instrumentation for the joint ESA/NASA gravitational wave detector LISA. It briefly describes the measurement principle and the mission architecture including the resulting sensitivity before focussing on a description of the main payload items, such as the interferomtric measurement system, comprising the optical system with the optical bench and the telescope, the laser system, and the phase measurement system; and the disturbance reduction system with the inertial sensor, the charge control system, and the micropropulsion system. The article touches upon the requirements for the different subsystems that need to be fulfilled to obtain the overall sensitivity.

A theorem on central velocity dispersions

Authors: An, Jin H.; Evans, N. Wyn

Eprint: http://arxiv.org/abs/0906.3673

Keywords: astrophysics; supermassive black holes; stellar dynamics

Abstract: It is shown that, if the tracer population is supported by a spherical dark halo with a core or a cusp diverging more slowly than that of a singular isothermal sphere, the logarithmic cusp slope 'g' of the tracers must be given exactly by g=2b where b is their velocity anisotropy parameter at the center unless the same tracers are dynamically cold at the center. If the halo cusp diverges faster than that of the singular isothermal sphere, the velocity dispersion of the tracers must diverge at the center too. In particular, if the logarithmic halo cusp slope is larger than two, the diverging velocity dispersion also traces the behavior of the potential. The implication of our theorem on projected quantities is also discussed. We argue that our theorem should be understood as a warning against interpreting results based on simplifying assumptions such as isotropy and spherical symmetry.

Correlation of Black Hole-Bulge Masses by AGN Jets

Authors: Soker, Noam

Eprint: http://arxiv.org/abs/0905.2702

Keywords: astrophysics; supermassive black holes; accretion discs

Abstract: I propose a feedback model to explain the correlation between the supermassive black hole (SMBH) mass and the host galaxy bulge mass. The feedback is based on narrow jets that are launched by the central SMBH, and expel large amounts of mass to large distances. The condition is that the jets do not penetrate through the inflowing gas, such that they can deposit their energy in the inner region where the bulge is formed. For that to occur, the SMBH must move relative to the inflowing gas, such that the jets continuously encounter fresh gas. Taking into account the relative motion of the SMBH and the inflowing gas I derive a relation between the mass accreted by the SMBH and the mass that is not expelled, and is assumed to form the bulge. This relation is not linear, but rather the SMBH to bulge mass ratio increases slowly with mass. The same mechanism was applied to suppress star formation in cooling flow clusters, making a tighter connection between the feedback in galaxy formation and cooling flows.

Bounding the mass of the graviton with gravitational waves: Effect of spin precessions in massive black hole binaries

Authors: Stavridis, Adamantios; Will, Clifford M.

Eprint: http://arxiv.org/abs/0906.3602

Keywords: general relativity; spin; massive binaries of black holes

Abstract:

Observations of gravitational waves from massive binary black hole systems at cosmological distances can be used to search for a dependence of the speed of propagation of the waves on wavelength, and thereby to bound the mass of a hypothetical

graviton. We study the effects of precessions of the spins of the black holes and of the orbital angular momentum on the process of parameter estimation using matched filtering of gravitational-wave signals vs. theoretical template waveforms. For the proposed space interferometer LISA, we show that precessions, and the accompanying modulations of the gravitational waveforms, are effective in breaking degeneracies among the parameters being estimated, and effectively restore the achievable graviton-mass bounds to levels obtainable from binary inspirals without spin. For spinning, precessing binary black hole systems of equal masses (10^6 solar masses) at 3 Gpc, the bounds on the graviton Compton wavelength achievable are of the order of 5×10^{16} km.

Constraining alternative theories of gravity by gravitational waves from precessing eccentric compact binaries with LISA

Authors: Yagi, Kent; Tanaka, Takahiro

Eprint: http://arxiv.org/abs/0906.4269

Keywords: parameter estimation; waveforms; intermediate-mass black holes; general relativity; EMRI; IMRI

Abstract:

We calculate how strong one can put constraints on the alternative theories of gravities such as Brans-Dicke and massive graviton theories with LISA. We consider the inspiral gravitational waves from NS/IMBH binaries in Brans-Dicke theory and SMBH/BH binaries in massive graviton theories. We use the 2PN waveforms including spins. We also take both precession and small eccentricity of the orbit into account. We neglect the spin of one of the binary object so that we can apply the so-called *simple precession*. We perform the Monte Carlo simulations of 10^4 binaries, whose parameters include the Brans-Dicke parameter $\omega_{\rm BD}$ and the graviton Compton length λ_g. We find that including both the spin-spin coupling σ and the small eccentricity into the binary parameters reduces the determination accuracy by an order of magnitude for the Brans-Dicke case, whilst it has less influence on massive graviton theories. On the other hand, including precession enhances the constraint on $\omega_{\rm BD}$ only 20% but it increases the constraint on λ_g by several factors. For $(1.4 + 1000)M_\odot$ NS/BH binaries of SNR=10, one can put $\omega_{\rm BD} > 7040$, whilst for $(10^7 + 10^6)M_\odot$ BH/BH binaries at 3Gpc, one can put $\lambda_g > 4.24 \times 10^{21}$cm, on average. This is four orders of magnitude stronger than the one obtained from the solar system experiment. From these results, it is understood that the effects of precession and eccentricity cannot be neglected in the parameter estimation analysis.

Application of Graphics Processing Units to Search Pipeline for Gravitational Waves from Coalescing Binaries of Compact Objects

Authors: Chung, Shin Kee; Wen, Linqing; Blair, David; Cannon, Kipp; Datta, Amitava

Eprint: http://arxiv.org/abs/0906.4175

Keywords: waveforms; numerical methods; massive binaries of black holes

Abstract: We report a novel application of graphics processing units (GPUs) for the purpose of accelerating the search pipelines for gravitational waves from coalescing binaries of compact objects. A speed-up of 16 fold has been achieved compared with a single central processing unit (CPU). We show that substantial improvements are possible and discuss the reduction in CPU count required for the detection of inspiral sources afforded by the use of GPUs.

On the dissolution of star clusters in the Galactic centre. I. Circular orbits

Authors: Ernst, Andreas; Just, Andreas; Spurzem, Rainer

Eprint: http://arxiv.org/abs/0906.4459

Keywords: N-body; intermediate-mass black holes; EMRI; stellar dynamics; astrophysics; supermassive black holes

Abstract: We present N-body simulations of dissolving star clusters close to galactic centres. For this purpose, we developed a new N-body program called nbody6gc based on Aarseth's series of N-body codes. We describe the algorithm in detail. We report about the density wave phenomenon in the tidal arms which has been recently explained by Kuepper et al. (2008). Standing waves develop in the tidal arms. The wave knots or clumps develop at the position, where the emerging tidal arm hits the potential wall of the effective potential and is reflected. The escaping stars move through the wave knots further into the tidal arms. We show the consistency of the positions of the wave knots with the theory in Just et al. (2009). We also demonstrate a simple method to study the properties of tidal arms. By solving many eigenvalue problems along the tidal arms, we construct numerically a 1D coordinate system whose direction is always along a principal axis of the local tensor of inertia.

Along this coordinate system, physical quantities can be evaluated. The half-mass or dissolution times of our models are almost independent of the particle number which indicates that two-body relaxation is not the dominant mechanism leading to the dissolution. This may be a typical situation for many young star clusters. We propose a classification scheme which sheds light on the dissolution mechanism.

Massive Binary Black Holes in the Cosmic Landscape

Authors: Colpi, M.; Dotti, M.

Eprint: http://arxiv.org/abs/0906.4339

Keywords: massive binaries of black holes

Abstract: Binary black holes occupy a special place in our quest for understanding the evolution of galaxies along cosmic history. If massive black holes grow at the center of (pre-)galactic structures that experience a sequence of merger episodes, then dual black holes form as inescapable outcome of galaxy assembly. But, if the black holes reach coalescence, then they become the loudest sources of gravitational waves ever in the universe. Nature seems to provide a pathway for the formation of these exotic binaries, and a number of key questions need to be addressed: How do massive black holes pair in a merger? Depending on the properties of the underlying galaxies, do black holes always form a close Keplerian binary? If a binary forms, does hardening proceed down to the domain controlled by gravitational wave back reaction? What is the role played by gas and/or stars in braking the black holes, and on which timescale does coalescence occur? Can the black holes accrete on flight and shine during their pathway to coalescence? N-Body/hydrodynamical codes have proven to be vital tools for studying their evolution, and progress in this field is expected to grow rapidly in the effort to describe, in full realism, the physics of stars and gas around the black holes, starting from the cosmological large scale of a merger. If detected in the new window provided by the upcoming gravitational wave experiments, binary black holes will provide a deep view into the process of hierarchical clustering which is at the heart of the current paradigm of galaxy formation. They will also be exquisite probes for testing General Relativity, as the theory of gravity. The waveforms emitted during the inspiral, coalescence and ring-down phase carry in their shape the sign of a dynamically evolving space-time and the proof of the existence of an horizon.

On the Prospect of Constraining Black-Hole Spin Through X-ray Spectroscopy of Hotspots

Authors: Murphy, K. D.; Yaqoob, T.; Dovčiak, M.; Karas, V.

Eprint: http://arxiv.org/abs/0906.4713

Keywords: astrophysics; supermassive black holes; accretion discs; spin

Abstract: Future X-ray instrumentation is expected to allow us to significantly improve the constraints derivedfrom the Fe K lines in AGN, such as the black-hole angular momentum (spin) and the inclination angle of the putative accretion disk. We consider the possibility that measurements of the persistent, time-averaged Fe K line emission from the disk could be supplemented by the observation of a localized flare, or "hotspot", orbiting close to the black hole. Although observationally challenging, such measurements would recover some of the information loss that is inherent to the radially-integrated line profiles. We present calculations for this scenario to assess the extent to which, in principle, black-hole spin may be measured. We quantify the feasibility of this approach using realistic assumptions about likely measurement uncertainties.

Density and kinematic cusps in M54 at the heart of the Sagittarius dwarf galaxy: evidence for a $10^4 M_\odot$ Black Hole?

Authors: Ibata, R.; Bellazzini, M.; Chapman, S. C.; Dalessandro, E.; Ferraro, F. R.; Irwin, M.; Lanzoni, B.; Lewis, G. F.; Mackey, A. D.; Miocchi, P.; Varghese, A.

Eprint: http://arxiv.org/abs/0906.4894

Keywords: intermediate-mass black holes; observations; astrophysics; IMRI

Abstract: We report the detection of a stellar density cusp and a velocity dispersion increase in the center of the globular cluster M54, located at the center of the Sagittarius dwarf galaxy (Sgr). The central line of sight velocity dispersion is 20.2 +/- 0.7 km/s, decreasing to 16.4 +/- 0.4 km/s at 2.5" (0.3 pc). Modeling the kinematics and surface density profiles as the sum of a King model and a point-mass yields a black hole (BH) mass of $\sim 9400 M_\odot$. However, the observations can alternatively be explained if the cusp stars possess moderate radial anisotropy. A Jeans analysis of the Sgr nucleus reveals a strong tangential anisotropy, probably a relic from the formation of the system.

Gravitational waves production from stellar encounters around massive black holes

Authors: De Laurentis, M.; Capozziello, S.

Eprint: http://arxiv.org/abs/0906.4923

Keywords: EMRI; supermassive black holes; parameter estimation; stellar dynamics

Abstract: The emission of gravitational waves from a system of massive objects interacting on elliptical, hyperbolic and parabolic orbits is studied in the quadrupole approximation. Analytical expressions are then derived for the gravitational wave luminosity, the total energy output and gravitational radiation amplitude. A crude estimate of the expected number of events towards peculiar targets (i.e. globular clusters) is also given. In particular, the rate of events per year is obtained for the dense stellar cluster at the Galactic Center.

Intention and purpose of GW Notes

A succinct explanation

The electronic publishing service **arXiv** is a dynamic, well-respected source of news of recent work and is updated daily. But, perhaps due to the large volume of new work submitted, it is probable that a member of our community might easily overlook relevant material. This new e-journal and its blog, **The LISA Brownbag**, both produced by the AEI, propose to offer scientist of the Gravitational Wave community the opportunity to more easily follow advances in the three areas mentioned: Astrophysics, General Relativity and Data Analysis. We hope to achieve this by selecting the most significant e-prints and list them in abstract form with a link to the full paper in both a single e-journal (GW Newsletter) and a blog (The LISA Brownbag). Of course, *this also implies that the paper will have its impact increased, since it will reach a broader public*, so that we encourage you to not forget submitting your own work

In addition to the abstracts, in each PDF issue of GW Notes, we will offer you a previously unpublished article written by a senior researcher in one of these three domains, which addresses the interests of all readers.

Thus the aim of The LISA Brownbag and GW Notes is twofold:

- Whenever you see an interesting paper on GWs science and LISA, you can submit the **arXiv** number to our **submission page**. This is straightforward: No registration is required (although recommended) to simply type in the number in the entry field of the page, indicate some keywords and that's it

- We will publish a new full article in each issue, if available. This "feature article" will be from the fields of Astrophysics, General Relativity or the Data Analysis of gravitational waves and LISA. We will prepare a more detailed guide for authors, but for now would like to simply remind submitters that they are writing for colleagues in closely related but not identical fields, and that cross-fertilization and collaboration is an important goal of our concept

Subscribers get the issue distributed in PDF form. Additionally, they will be able to submit special announcements, such as meetings, workshops and jobs openings, to the list of registered people. For this, please register at the **registration page** by filling in your e-mail address and choosing a password.

The Astro-GR meetings

Past, present and future

Sixty two scientists attended the **Astro-GR@AEI** meeting, which took place September 18-22 2006 at the **Max-Planck Institut für Gravitationsphysik (Albert Einstein-Institut)** in Golm, Germany. The meeting was the brainchild of an AEI postdoc, who had the vision of bringing together Astrophysicists and experts in General Relativity and gravitational-wave Data Analysis to discuss sources for **LISA**, the planned Laser Interferometer Space Antenna. More specifically, the main topics were EMRIs and IMRIs (Extreme and Intermediate Mass-Ratio Inspiral events), i.e. captures of stellar-mass compact objects by supermassive black holes and coalescence of intermediate-mass black holes with supermassive black holes.

The general consensus was that the meeting was both interesting and quite stimulating. It was generally agreed that someone should step up and host a second round of this meeting. Monica Colpi kindly did so and this led to **Astro-GR@Como**, which was very similar in its informal format, though with a focus on all sources, meant to trigger new ideas, as a kind of brainstroming meeting.

Also, in the same year, in the two first weeks of September, we had another workshop in the Astro-GR series with a new "flavour", namely, the **Two Weeks At The AEI (2W@AEI)**, in which the interaction between the attendees was be even higher than what was reached in the previous meetings. To this end, we reduced the number of talks, allowing participants more opportunity to collaborate. Moreover, participants got office facilities and we combined the regular talks with the so-called "powerpointless" seminar, which will were totally informal and open-ended, on a blackboard.

The next one will be held in Barcelona in 2009 at the beginning of September:

LISA Astro-GR@BCN (Barcelona, Monday 7th to Friday, September 11th 2009)

Pau Amaro-Seoane, Priscilla Cañizares, Carlos F. Sopuerta, Alberto Lobo and Bernard F. Schutz will organise it and it will be held at the ICE (CSIC-IEEC) in Barcelona from Monday 7th to Friday, September 11th 2009

After that, **the next one will be in Paris in 2010, at the APC**.

If you are interested in hosting in the future an Astro-GR meeting, please contact us. We are open to new formats, as long as the *Five Golden Rules* are respected.

A proper Astro-GR meeting **MUST** closely follow the *Five Golden Rules*:

I. Bring together Astrophysicists, Cosmologists, Relativists and Data Analysts

II. Motivate new collaborations and projects

III. Be run in the style of Aspen, ITP, Newton Institute and Modest meetings, with plenty of time for discussions

IIII. Grant access to the slides in a cross-platform format, such as PDF and, within reason, to the recorded movies of the talks in a free format which everybody can play like **Theora**, for those who could not attend, following the good principles of **Open Access**

~~IIII~~. Keep It Simple and... Spontaneous