Working Group for EMRIs

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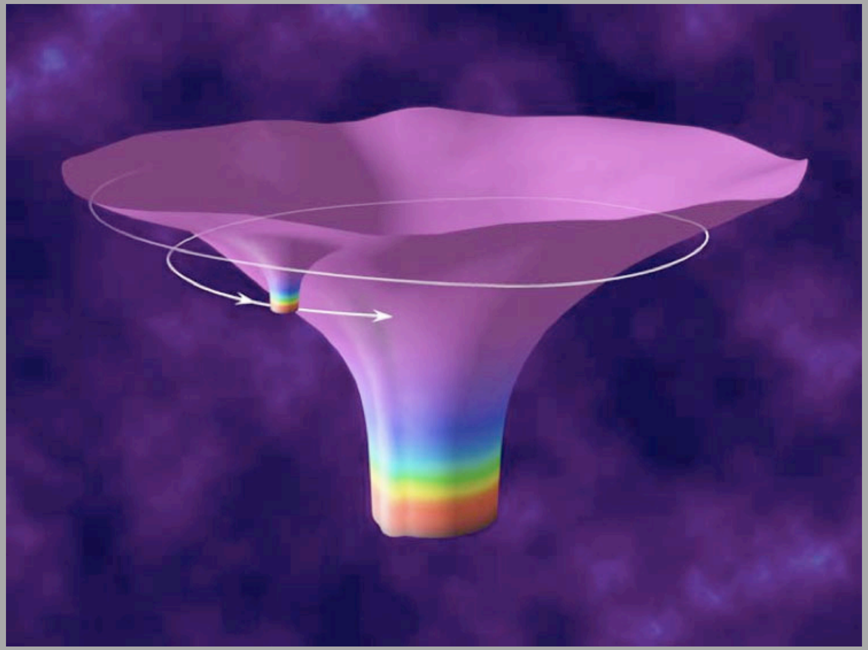
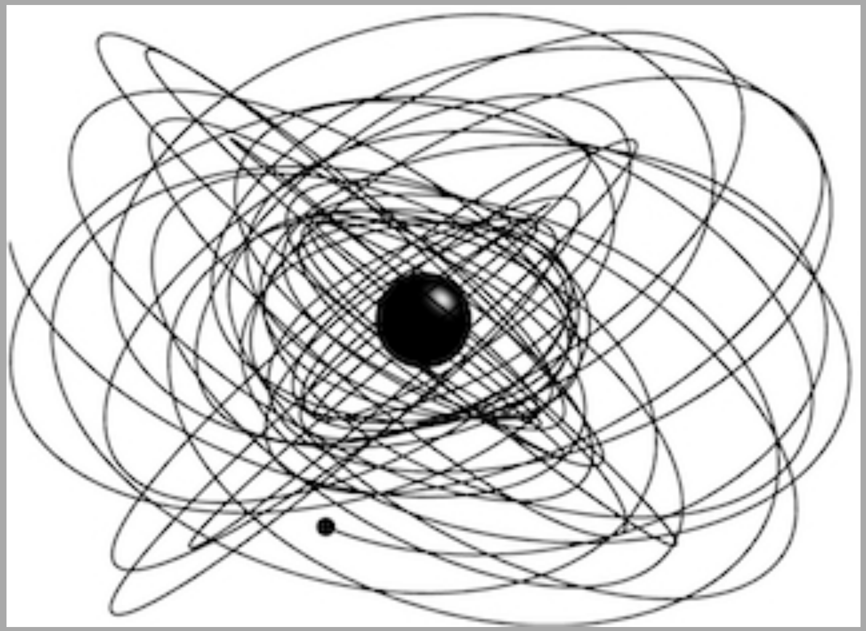


Outline

- EMRI Formation Mechanisms/Event Rates
- Modeling
- Science Potential
- IMRIs
- Synergies

Extreme-Mass-Ratio Inspirals (EMRIs)

- Extreme- and Intermediate mass ratio inspirals (EMRIs and IMRIs) are binary systems whose evolution is driven by Gravitational-Wave (GW) emission and such the mass ratio between their components is in the range:



$$q = \frac{m_*}{M_\bullet} = \begin{cases} \sim 10^{-7} - 10^{-4} & \text{for EMRIs} \\ \sim 10^{-4} - 10^{-2} & \text{for IMRIs} \end{cases}$$

Extreme-Mass-Ratio Inspirals (EMRIs)

- The astrophysical systems we have in mind are:

  * EMRIs : Stellar Compact Object + Central Massive Object
  (SCO: MSS,WD,NS,BH) Massive Black Hole
  (MBH: BHs at Galactic Centers)
  (eLISA)

  * IMRIs : Intermediate MBH (IMBH) + MBH
  (eLISA)

  SCO + IMBH
  (Ground-Based Detectors)

See: Amaro-Seoane, arXiv:1205.5240 (submitted to Living Reviews in Relativity) for astrophysical questions about E/IMRIs.

Extreme-Mass-Ratio Inspirals (EMRIs)

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  - Quality of these GW Cycles. The SCO orbits are very complex: high eccentricity and inclined (precesional effects). Moreover, they can get very close to the MBH Horizon:

$$\frac{9GM_\bullet}{c^2}\ \left(\text{for } \frac{a}{M_\bullet} = -1\right) \ \geq\ r_{\text{Last Stable Orbit}} \ \geq\ \frac{GM_\bullet}{c^2}\ \left(\text{for } \frac{a}{M_\bullet} = 1\right)$$

EMRI Formation Mechanisms/Event Rates

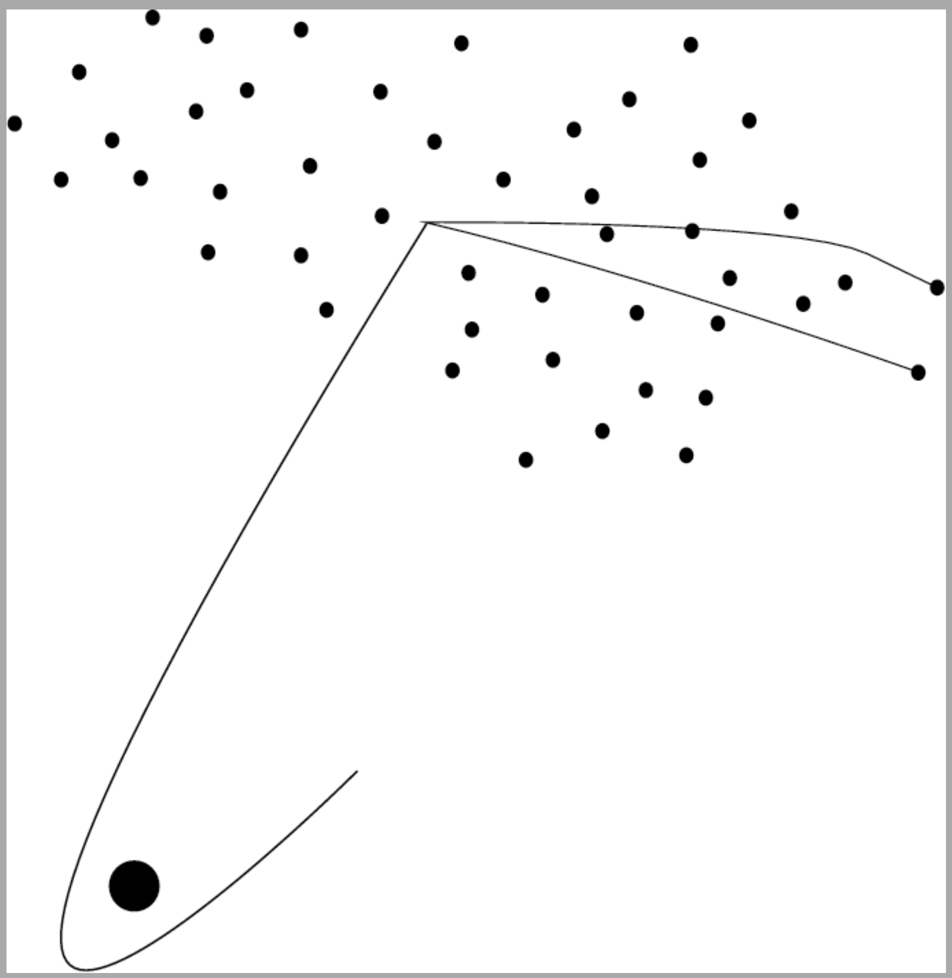
- Main Goals:

1) To identify all possible astrophysical mechanisms (channels) that can produce EMRIs in the eLISA GW band.

2) To estimate, for each channel, the expected number of events during the eLISA mission lifetime.

EMRI Formation Mechanisms/Event Rates

- Main channel: Single capture mechanism:



  - Scattering of a Stellar-mass Compact Object (through 2-body or multi-body encounters) to highly eccentric orbits around a MBH:

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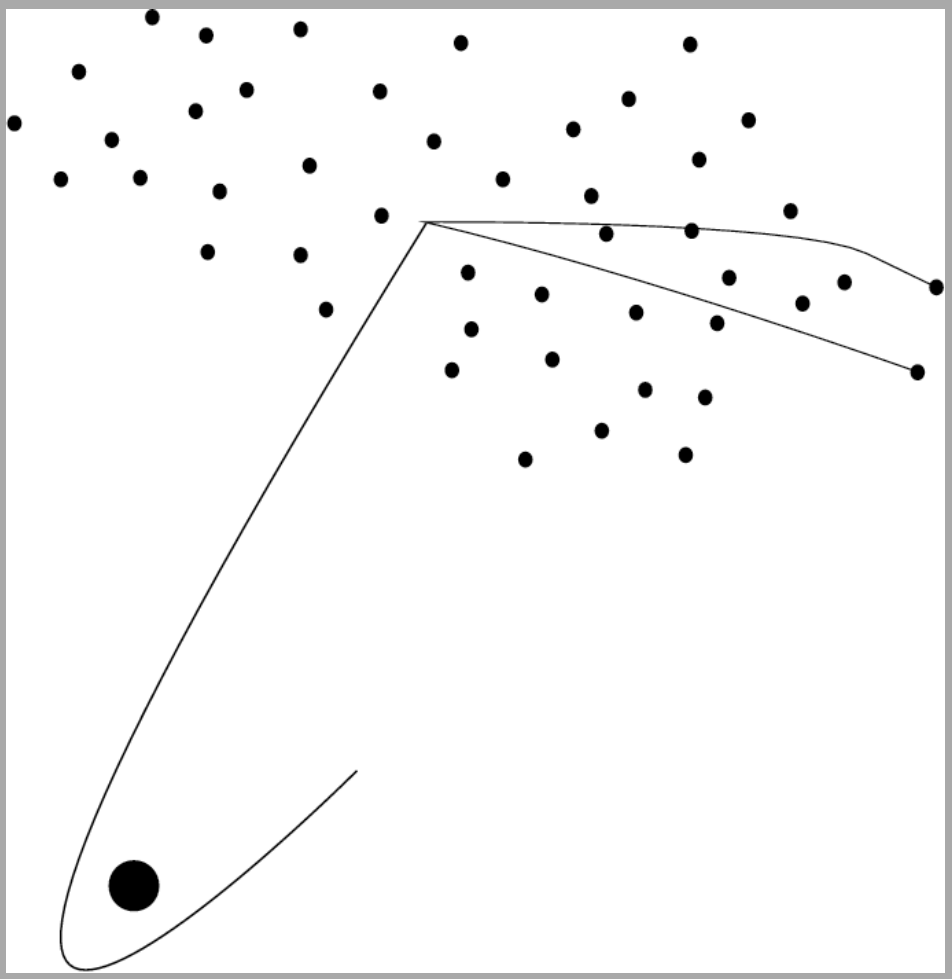

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- They expend the last year before plunging inside the LISA band [Finn & Thorne (2000)]:

$$e \sim 0.5 - 0.9\,, \quad \text{no. cycles} \sim 10^5\,.$$

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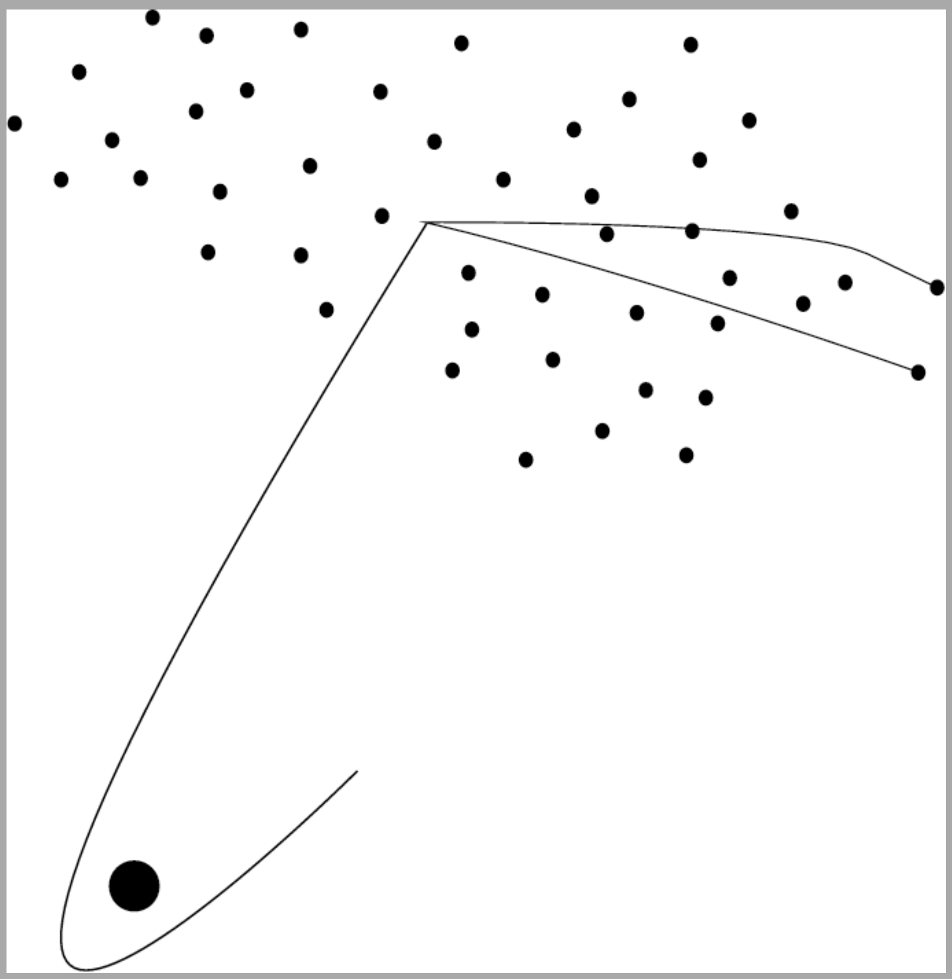

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Expected NGO EMRI events (from NGO YB)

Waveform model	Teukolsky with black hole spin $a_\bullet = 0$	Teukolsky with black hole spin $a_\bullet = 0.5$	Teukolsky with black hole spin $a_\bullet = 0.9$	Analytic Kludge
Number of events	30	35	55	50

EMRI Formation Mechanisms/Event Rates

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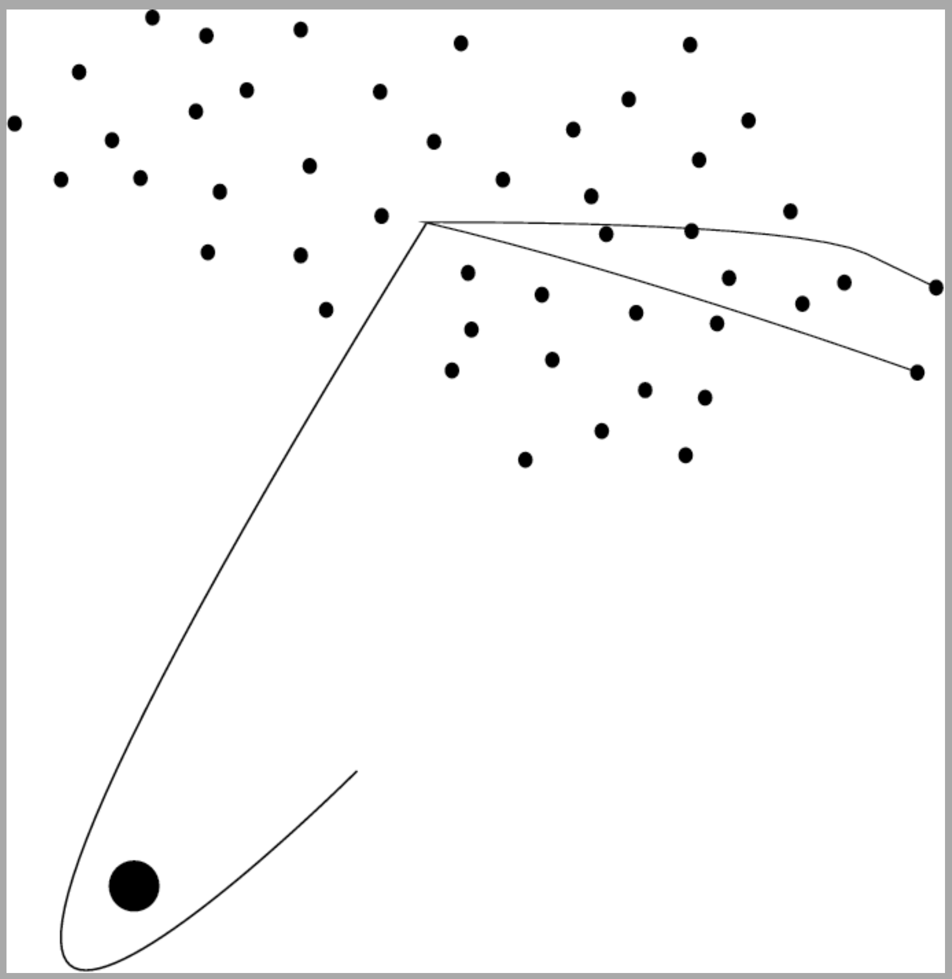
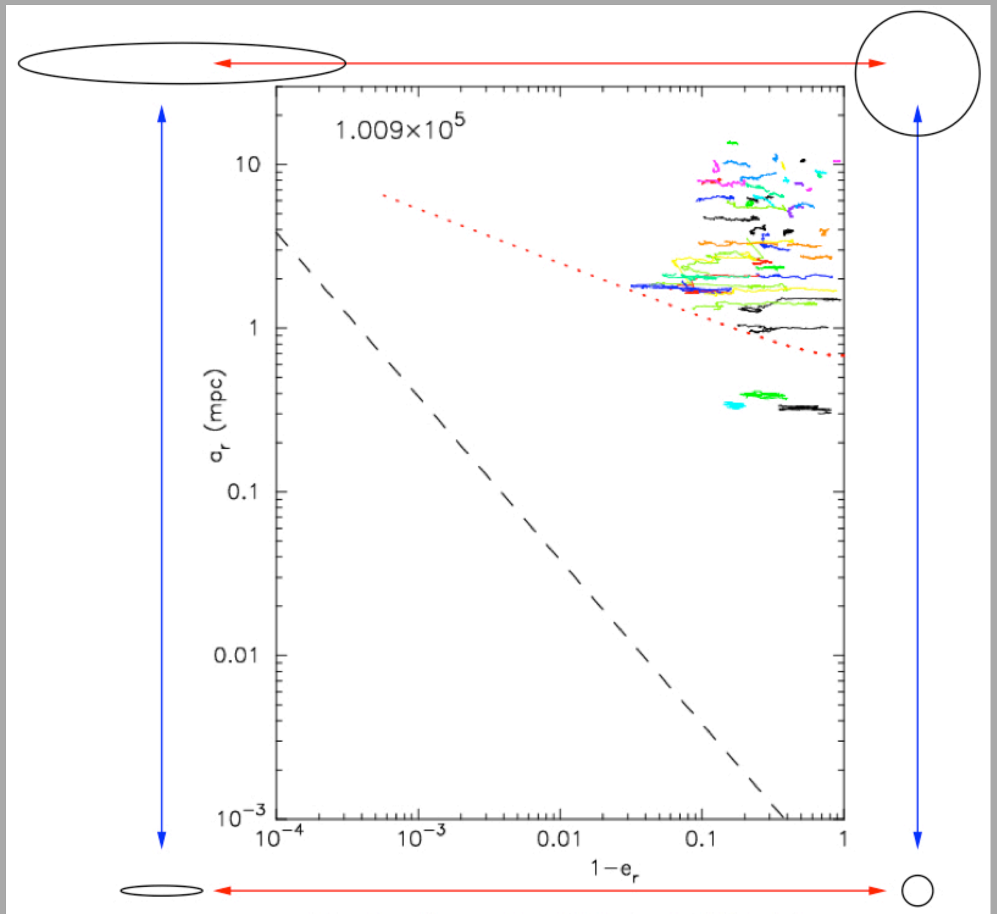


- Some questions/problems:

-Do stars around the galactic center form a cusp or a core?

-Role of Resonant Relaxation & GR effects (precesion): Schwarzschild barrier:

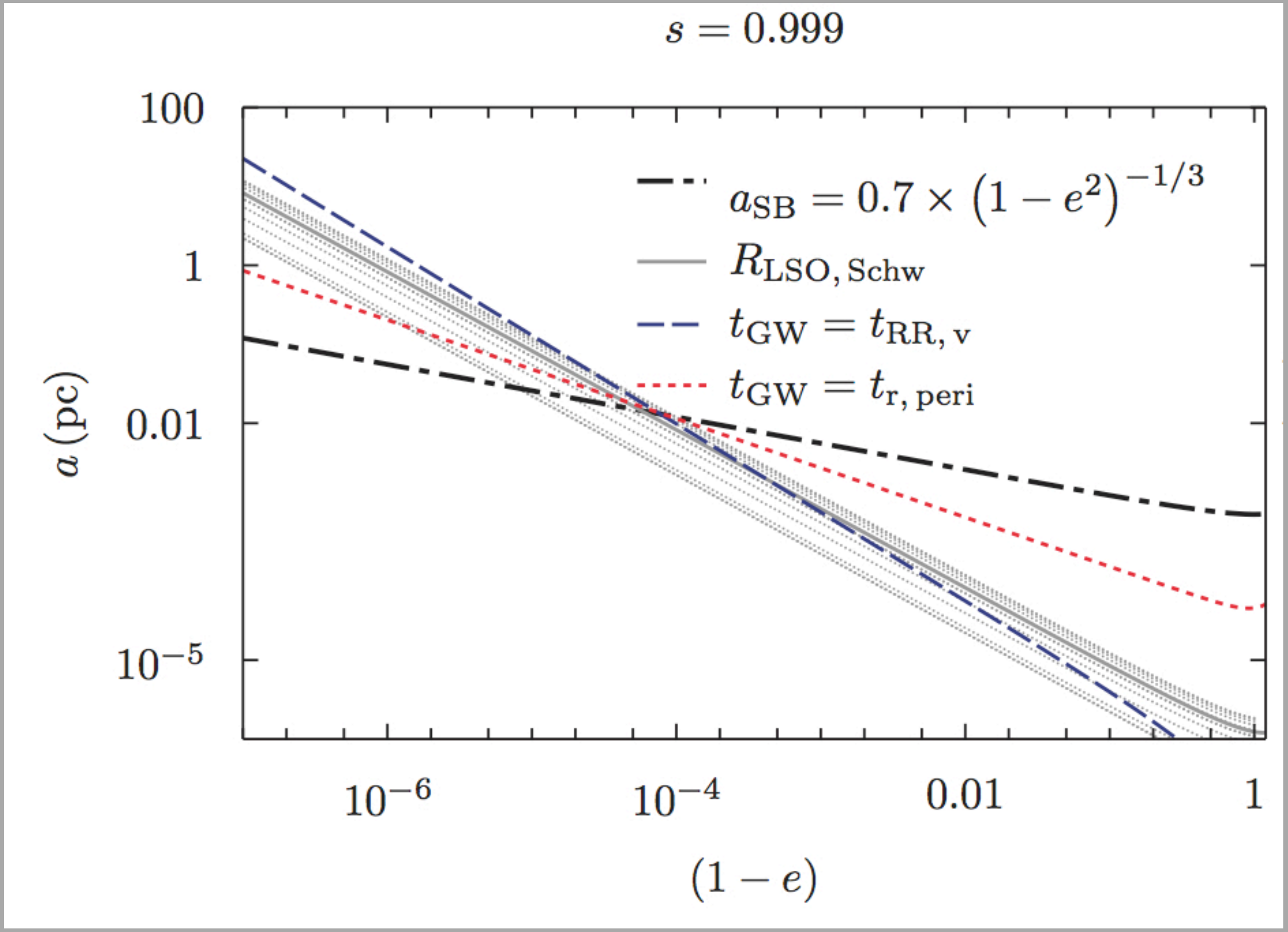


Merritt, Alexander, Mikkola & Will 2011

EMRI Formation Mechanisms/Event Rates

- Main channel: Single capture mechanism:

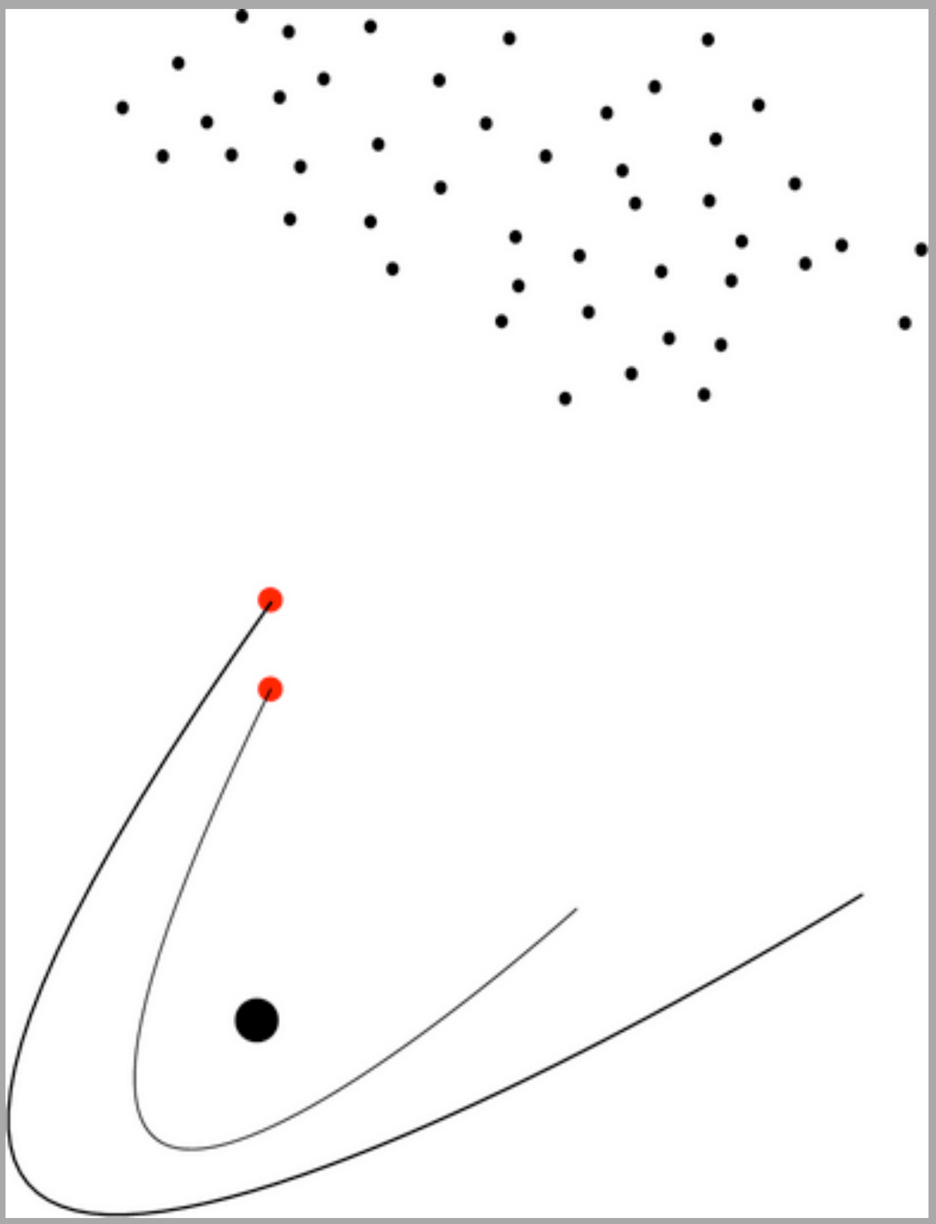
  - Schwarzschild barrier and the effect of the MBH spin:



Amaro-Seoane, Brem & CFS; Amaro-Seoane, CFS & Freitag (2012)

EMRI Formation Mechanisms/Event Rates

- Other EMRI channels:



- Disruption of a compact binary by a MBH (Hills mechanism [Hills (1988,1991); Miller et al (2005)]).
- The eccentricity when the bound object enters the eLISA band is almost zero (Zero-Eccentricity events).
- High event rates? Depending on the binary population near the MBH they may even dominate the EMRI event rate.

- Connection with hypervelocity stars.

EMRI Formation Mechanisms/Event Rates

- Other EMRI channels:
- Capture of cores of giant stars close to the MBH by tidal stresses [Davies & King (2005); Di Stefano et al (2001)].
- Inspiral of black holes produced in an accretion disc around the MBH (at distances 0.1-1 pc). They would have equatorial co-rotating circular orbits [Levin (2007)].
- Extreme-Mass-Ratio Bursts (EMRBs): long-period, nearly-radial encounters of compact objects with a central MBH. The gravitational radiation emitted during periapse passages may be seen as GW bursts by eLISA [Rubbo, Holley-Bockelmann & Finn (2006); Yunes, CFS, Holley-Bockelmann & Rubbo (2008); Berry & Gair (2012)].
- . . . ASTRO-GR meetings provide an arena for discussion (P. Amaro-Seoane).

Modeling

- Main Goals:

1) To understand all the details of the GR dynamics of EMRIs.

2) To construct efficient algorithms to produce EMRI waveforms good enough for detection and precise parameter estimation.

Modeling

- Where we are?

- The SCO is modelled as a particle orbiting a MBH whose inspiral is a consequence of the gravitational backreaction. This is described in terms of a local force (the self-force).

- The first-order self-force is known for generic orbits around non-spinning MBHs [Barack et al].

- There is work in progress for the spinning case.

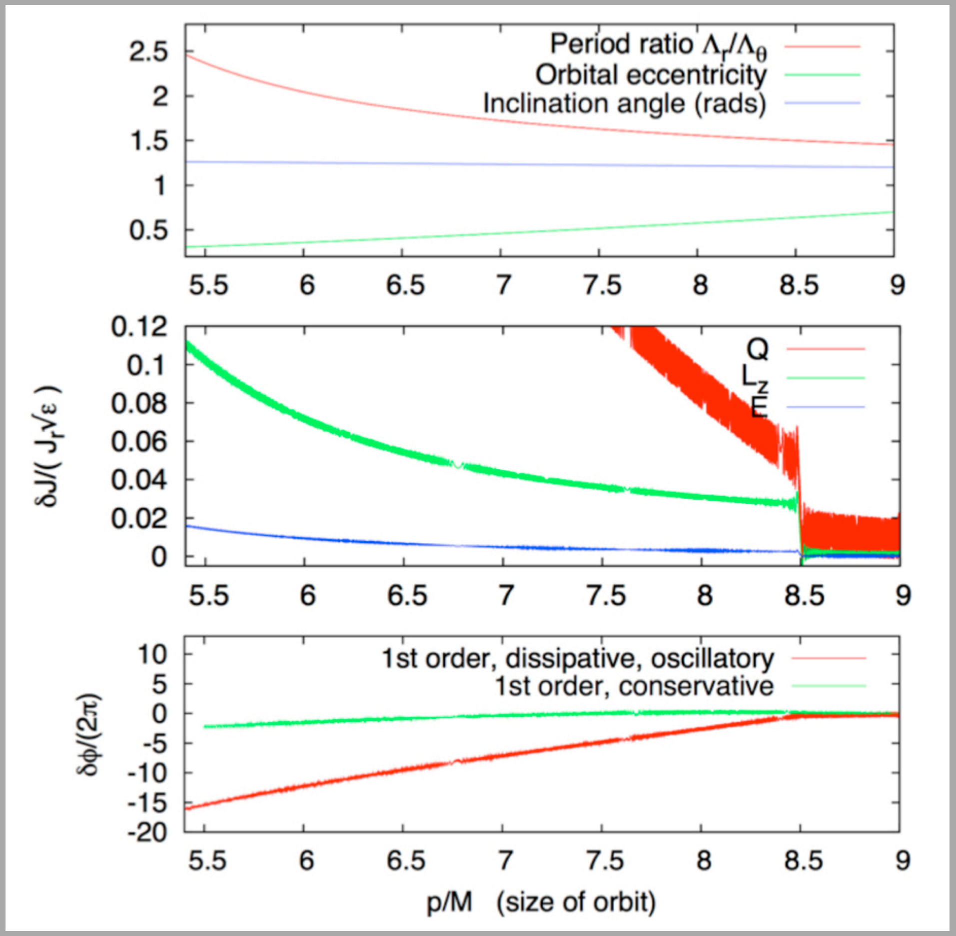
- There is a group of people working on the problem which meet at the CAPRA RANCH MEETINGS ON RADIATION REACTION.

Modeling

- Some open problems:
- Self-consistent EMRI evolution scheme with the self-force and waveform production.
- Are first-order computations good enough for the scientific goals of eLISA?
- It may also be that some finite-size effects become non-negligible near plunge.
- Resonances in the strong field regime [Hinderer & Flanagan (2010)]:

$$\frac{\Omega_\theta}{\Omega_r} \rightarrow \frac{3}{2}$$

$$\Delta\phi \sim \sqrt{q^{-1}}$$



Modeling

- Towards the construction of waveform models:
- At present there is a number of approximate methods to produce EMRI waveforms (not yet good enough for data analysis purposes): Analytic Klugde [Barack & Cutler], Numerical Kludge [Babak, Gair et al], Teukolsky-based waveforms [Hughes et al], EOB [Yunes et al], Chimera [CFS & Yunes], etc.

$$h_{+,\times}(t) = \sum_{k,m,n} h^{(+,\times)}_{k,m,n}(t)\, e^{-i\,(k\,\Omega_r(t)+m\,\Omega_\theta(t)+n\,\Omega_\phi(t))\,t}$$

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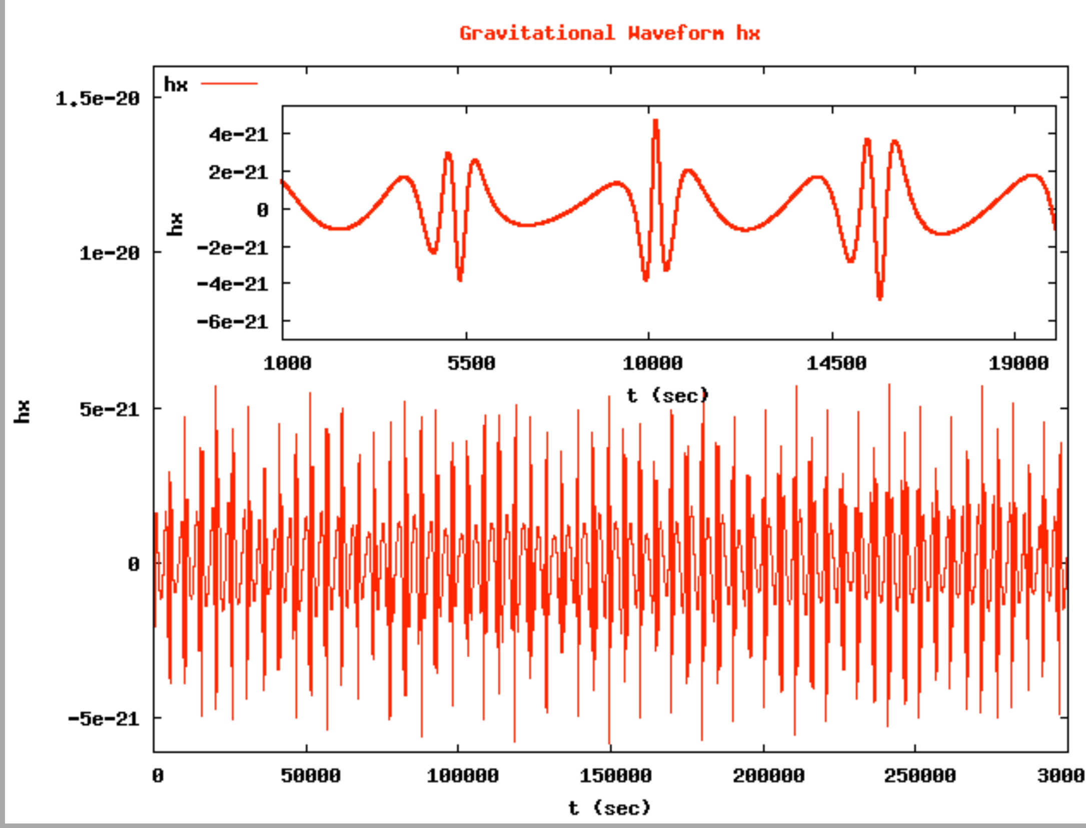

Modeling

- Others:

- Including in the modeling non-standard EMRI parameters [outside the 14 parameters required by the standard picture]. For instance: Deviations from the BH paradigm; Deviations from GR; effect of accretion disks around the MBH; presence of a third body; etc. -> PARAMETER ESTIMATION STUDIES.

- . . .

Science Potential

- Main Goals:

1) To produce theoretical developments to exploit eLISA EMRI observations.

Science Potential

- Main Scientific Goals [From NGO YB]:

NGO will bring a new revolutionary perspective to the study of galactic nuclei. NGO will offer the deepest view of galactic nuclei, exploring regions to which we are blind using current electromagnetic techniques and probing the dynamics of stars in the space-time of a Kerr black hole, by capturing the gravitational waves emitted by stellar black holes orbiting the massive black hole.

The detection of EMRI will allow us to infer properties of the stellar environment around a massive black hole, so that our understanding of stellar dynamics in galactic nuclei will be greatly improved.

Detection of EMRIs from black holes in the NGO mass range, that includes black holes similar to the Milky Way's, will enable us to probe the population of central black holes in an interval of masses where electromagnetic observations are challenging. NGO's EMRIs can be detected up to $z \simeq 0.5 - 0.7$ allowing to explore a volume of several tens of Gpc^3 and discover massive black holes in dwarf galaxies that are still elusive to electromagnetic observations. NGO will also measure the mass of the stellar black hole. This will provide invaluable information on the mass spectrum of stellar black holes, and on the processes giving rise to compact stars.

NGO will detect EMRI events out to redshift $z \sim 0.7$ in normal galaxies with high SNR and in the mass interval $10^4\,\mathrm{M}_\odot \lesssim M \lesssim 5 \times 10^6\,\mathrm{M}_\odot$. NGO will measure the mass and spin of the large, massive black hole with a precision to better than a part in 10^4. This will enable us to characterise the population of central massive black holes in an interval of masses where electromagnetic observations are poor, incomplete or even missing, providing information also on their spins. NGO will also measure with equivalent precision the mass of the stellar black hole in the EMRI event, and also the orbital eccentricity at plunge. These observations will provide insight on the way stars and their remnants are forming and evolving in the extreme environment of a galactic nucleus.

IMRIs

- Main Goals:

1) Modeling: Heritage from EMRI modeling and numerical relativity.

2) Science: Rates (if IMBHs exist), scientific output of the observations.

IMRIs

- IMRI signals are stronger than EMRI ones but sweep in the band faster too.

- IMRI modeling more complex: Non-linearities are much more important and the spin of the SCO cannot be neglected.

- The SNR of IMRIs (MBH+IMBH with M. = 10^5) for eLISA, in a given frequency bin, may be around 10 or more. Could they be followed without full templates?

- There are additional time scales (spin-orbit and spin-spin interactions) -> More fundamental frequencies.

Synergies

- Exchange with Data Analysis WG -> EMRI data analysis strategies can set the EMRI modeling needs.
- Exchange with Tests of Fundamental Laws WG -> EMRIs have a lot of potential but these studies require waveform models with more parameters.
- Connection to Galactic Center observation groups and people studying stellar dynamics in galactic nuclei and globular clusters.

- The parameter error estimations are [Barack & Cutler, PRD, **69**, 082005 (2004)]:

$$\Delta(\ln M_\bullet)\,,\quad \Delta\left(\ln m_\star\right)\,,\quad \Delta\left(\frac{S_\bullet}{M_\bullet^2}\right)\;\sim\;10^{-4}$$

$$\Delta e_0\;\sim\;10^{-(3-4)}\,,\quad \Delta\left(\ln\frac{m_\star}{D_{\rm L}}\right)\;\sim\;10^{-(1-2)}$$

For EMRIs with:

$$M_\bullet = 10^6 M_\odot\,,\quad m_\star = 10 M_\odot\,,\quad \mathrm{SNR}\sim 30$$

- Barack & Cutler extended their study [PRD, **75**, 042003 (2007)] to consider a central object with a mass quadrupole. The error estimations for this parameter (using generic orbits) are in the range:

$$\Delta\left(\frac{M_2}{M_0^3}\right) \sim 10^{-(2-4)}$$

which is a considerably better error estimate than Ryan's estimate.