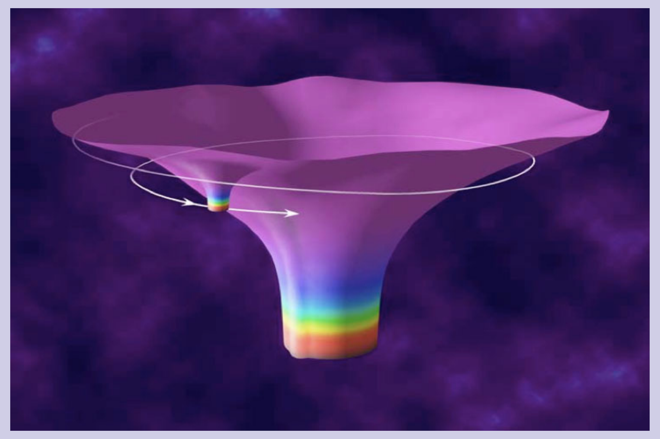

Production of EMRIs in Supermassive Black Hole Binaries

In prep. : Near final draft available from Chris Wegg (wegg@caltech.edu)

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1 Introduction

An Extreme Mass Ratio Inspiral (EMRI) is the gravitational radiation driven inspiral and merger of a SMBH with a compact object such as a stellar mass black hole, a neutron star, or a white dwarf. LISA (or a LISA like mission) should be able to detect EMRI waveforms to $z \sim 1$ and will be most sensitive to $\sim 10^6 M_\odot$ black holes.

- The canonical picture is that EMRIs are produced by stars scattering via star-star scattering onto highly eccentric orbits where GW loss is significant.
- But during SMBH binary formation, while inspiraling, the secondary SMBH would scatter stars and compact objects into the near vicinity of the primary where the compact objects could emit gravitational radiation and become EMRIs. Quantifying this production method is the aim of this work.

If EMRIs are produced LISA may be able to detect the presence of the secondary SMBH at a separation of ~ 1 pc extending the parameter space probed by LISA (Yunes et al 2011).

2 Simulations of Stars Around SMBH Binaries

Simulations evolve a star under the influence of three components:

1. Primary SMBH
2. Surrounded by η-model cusp
   $$\rho(r) = \frac{GM_1\eta}{2\pi r_c^3}\frac{1}{(r/r_c)^{3-\eta}(1+r/r_c)^{1+\eta}}$$
   Source of initial conditions of star
   Source of non-Keplerian potential
3. Secondary SMBH spirals in.
   Inspiral path fitted to dynamical friction, stellar ejection and stalling

Same setup as Wegg and Bode (2011; other poster at this workshop)

To include GR we:

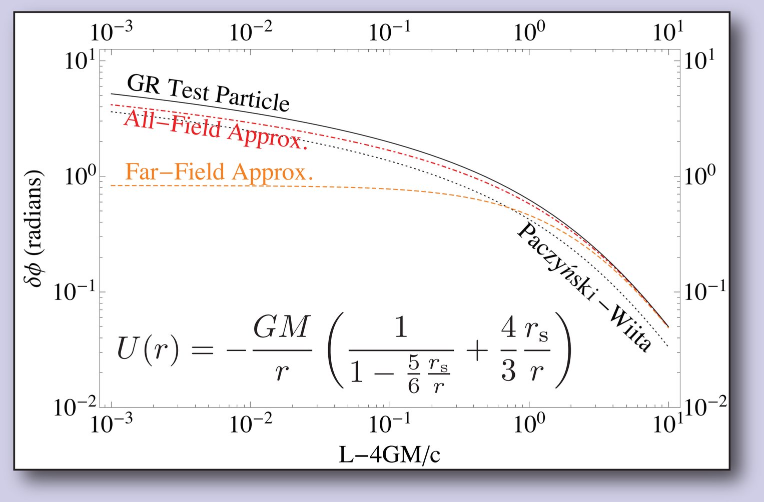
- Accurately subtract energy and angular momentum loss at periapse
- Use a pseudo-Newtonian potential to mimic GR precession

NEW IMPROVED! Added for this work

Paczyński-Wiita potential produces incorrect precession by 50% everywhere – It is useful for accretion disks not galactic dynamics.

We 'derived' our own potential which:

- Has the correct precession in the far field
- Logarithmically diverges at the correct angular momentum – we can reproduce zoom-whirl orbits



3 Numbers of EMRIs from SMBH Binaries

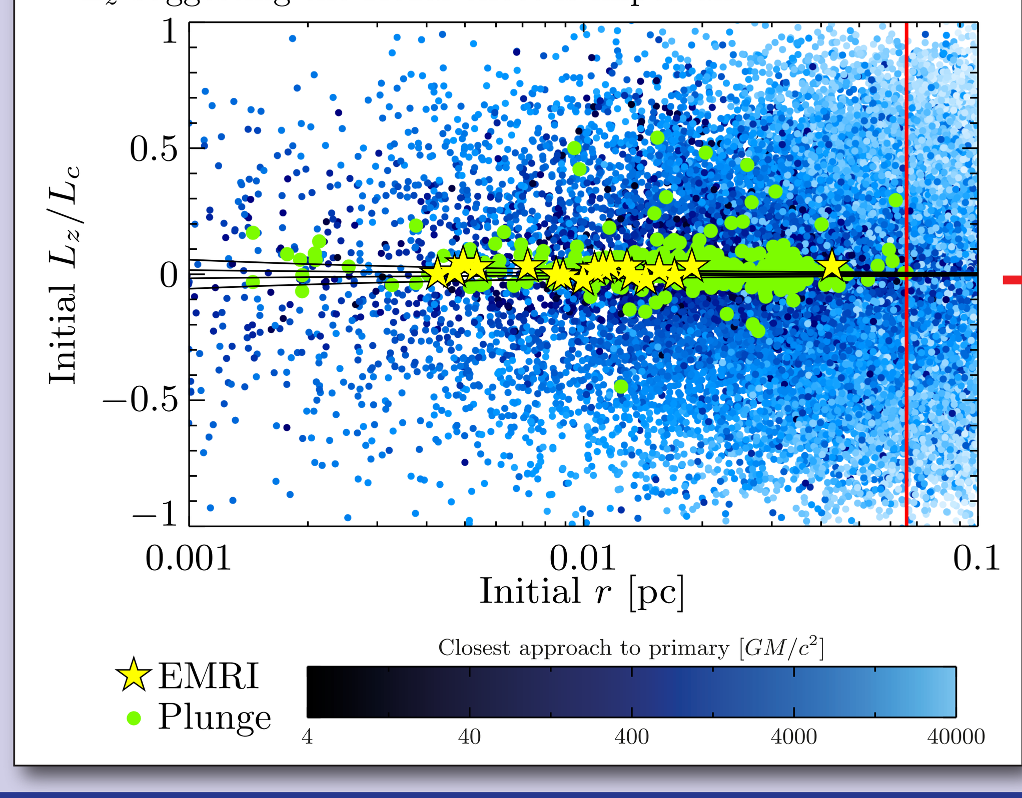
We find ~ 10 EMRIs are produced during each major merger of binary SMBH systems containing a $10^6 M_\odot$ black hole provided the stellar cusps are initially relaxed and mass segregated such that the majority of the stellar mass at 0.01 pc is in the form of stellar mass ($\sim 10 M_\odot$) black holes.

For the original LISA design this should result in the detection of several SMBH binaries at their stalling radius. This would allow LISA to probe a new region of SMBH binary space outside its original design.

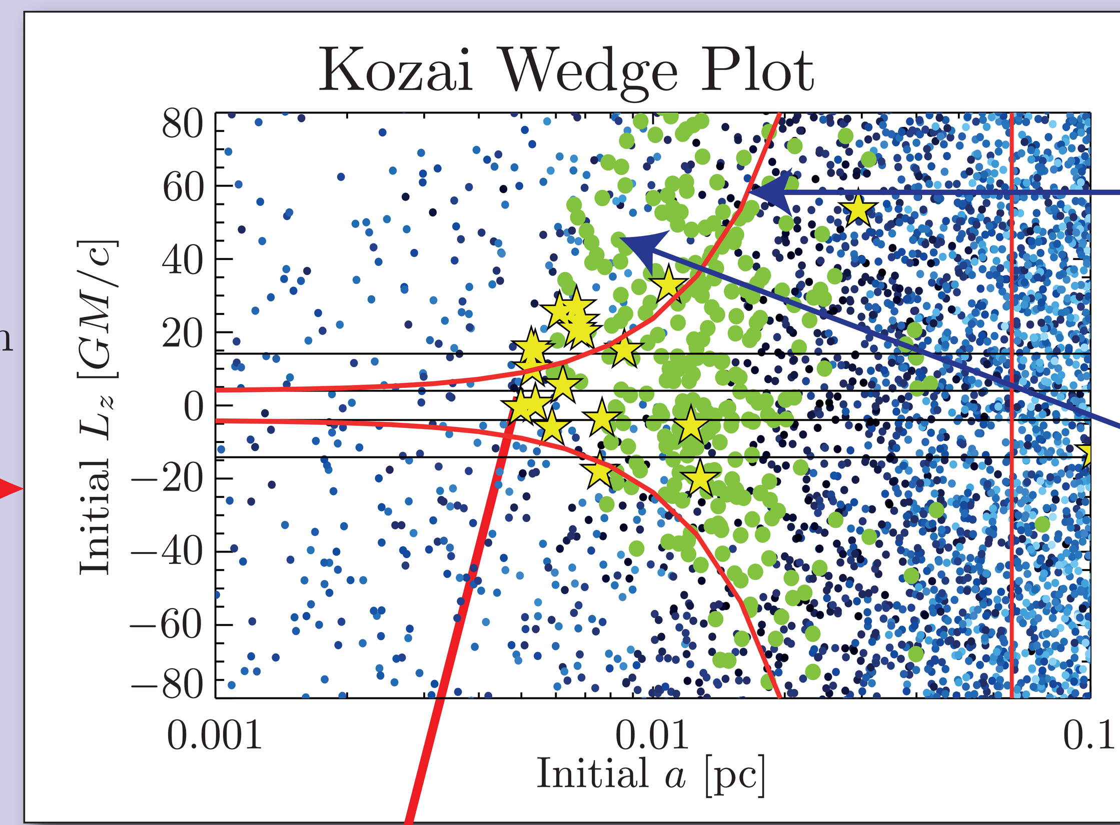
4 Kozai Effect?

- The secondary secularly perturbs the orbit of the star in a manner known as the Kozai effect.
- Highly inclined orbits can evolve to very high eccentricity and become EMRIs.
- In this process L_z is conserved so we expect EMRIs and plunges which need a low total L to come from low L_z.

The EMRIs and plunges occur from stars with initially low L_z suggesting the Kozai effect is important:



Zooming in though things are more complex

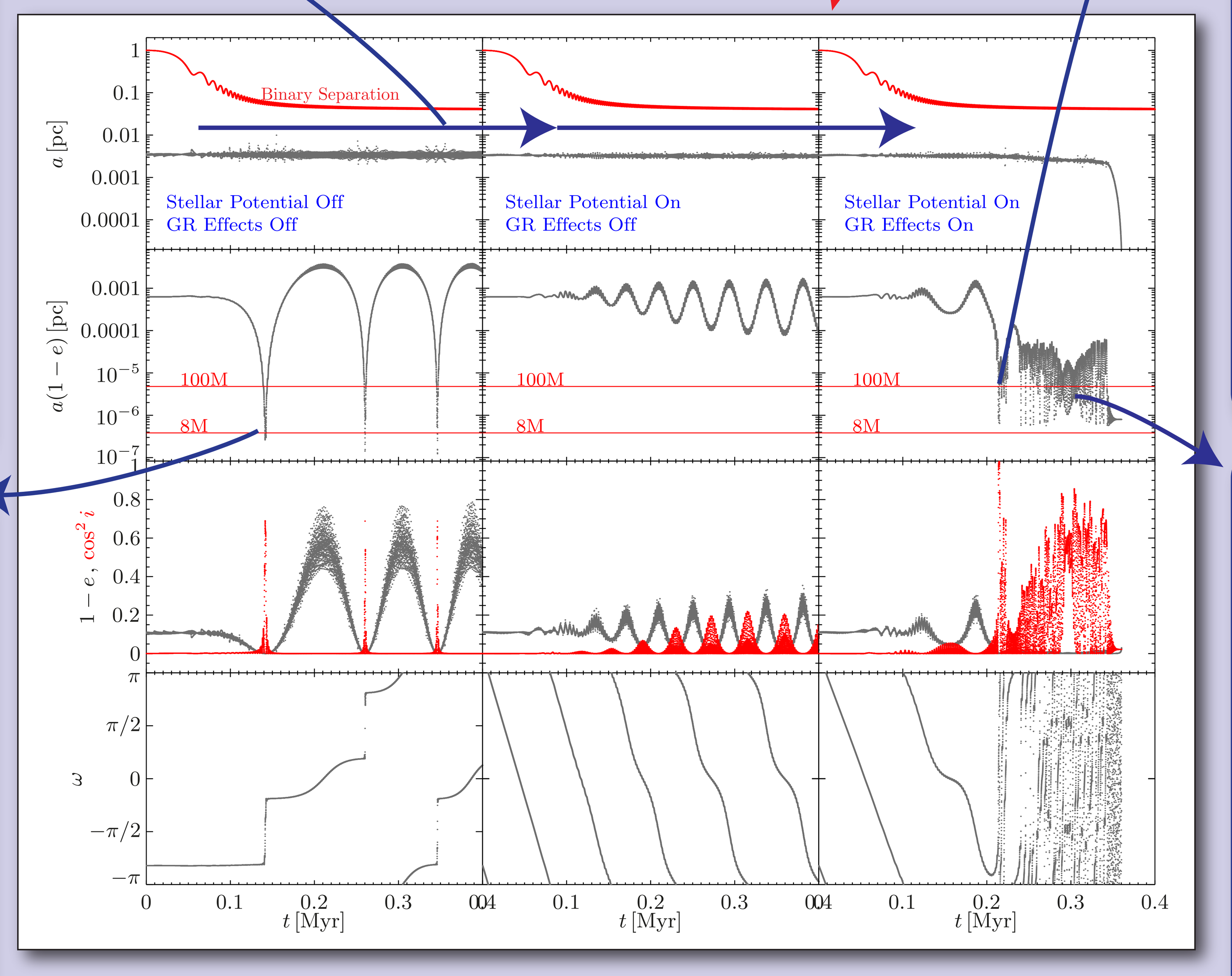


Size of Kozai wedge increased by oscillations on SMBH binary orbital timescale, see panel 5b

Asymmetry caused by the direction of the secondary's orbit compared to the stars. See panels 5c and 5d.

And looking at an individual star we see some interesting effects

5 Very Interesting Dynamics!

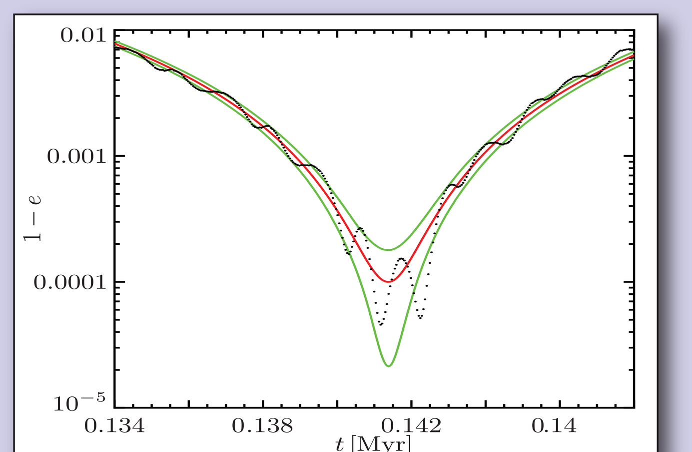


a Precession

- With no precession there are large Kozai oscillations in periapsis distance, $a(1-e)$
- Turning on the stellar potential causes a precession faster than the Kozai timescale, reducing oscillations in $a(1-e)$
- GR precession is in the opposite direction to stellar precession causing increased oscillations
- The GW loss in the close approaches reduces the semi-major axis of the star and it becomes an EMRI

b Binary Timescale

- Oscillations on the orbital timescale of the SMBH binary are vitally important.
- This is not included in purely secular approaches, such as the 'Double Averaging' in the Kozai effect – this result is the red line in the plot below.
- The size of the oscillations can be calculated and is shown in green. This causes an increase in the size of the Kozai wedge shown in red in panel 4.



c 'Reverse Kozai Effect'

- The analysis of the Kozai effect assumes precession is small
- In regions the GR precession timescale is shorter than the binary orbital timescale
- In the rotating frame, where the star's elliptical orbit is stationary, the secondary appears to obit in the reverse direction but off-axis
- This results in a modified Kozai effect with a shorter timescale, and smaller oscillations
- We have termed this 'reverse Kozai'

d 'Resonant Kozai Effect'?

- Some simulated stars display long periods where their Kozai timescale is very close to the secondary SMBH's orbital period
- This is possible because the Kozai timescale is shortened due to GR precession
- We are still investigating this situation