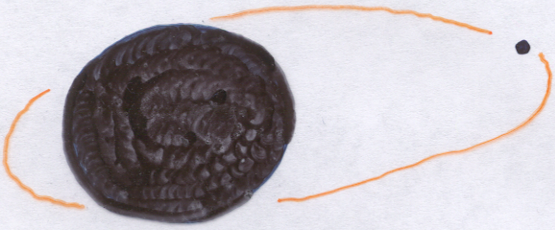
Compact Body Inspiral Into Massive Black Holes

Overview of the Worldwide Effort



$1 - 100\ M_\odot$ compact body

$10^5 - 10^7\ M_\odot$

$M_\odot$ Kerr black hole

→ LISA band gravitational waves

- Why is this interesting?
- What are the major issues?
  - When must these be understood?
- Who is doing the work?

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Scott Hughes, Inst for Theo. Physics

Why?

Inspiral of this Kind is ABUNDANT:

Events relevant to LISA are within

$$D \sim (\text{a few})\ \text{Gpc}\ (\text{small body mass}) / 10\, M_\odot$$

With massive black hole mass

$$10^5 M_\odot \lesssim M \lesssim 10^7 M_\odot$$

Estimates of the rate range from

1 inspiral/year (ultraconservative)

to (100s - 1000s)/year (new dynamical studies of galaxy cores)

POSSIBLE DANGER:

Rate may be so high that events will be confused! Need to understand how well we can extract signals in presence of a background.

Inspiral of this kind is CLEAN:

Inspiral dynamics determined entirely by GW emission in almost all galaxies.

Other major effect is drag induced by material accreting onto the massive BH:

Active galaxy: thick, hot disk of material.

➤➤ Drag forces dominate the inspiral.

Low luminosity galaxy: accreting material is very thin (eg, ADAF models)

➤➤ Drag effects NEGLIGIBLE

Vast majority of galaxies are low luminosity.

Inspiral waves encode a detailed description of the black hole spacetime:

Multipolar structure of "large body" in galactic core determines all orbital frequencies.

As small body spirals in, the GWs it emits are colored by the orbital frequencies it sweeps through.

Coherently measure these waves - track the frequency evolution - "weigh" the multipoles.

Works well because BHs have a special multipolar structure:

BH: $M_{\ell m} + i S_{\ell m} = M (ia)^\ell \delta_{m0}$

"Other": $M_{\ell m} = \int \rho r^\ell Y_{\ell m} \, dV$

$S_{\ell m} = \int \rho r^{\ell-1} (\vec{r} \times \vec{v}) Y_{\ell m} \, dV$

Wave modeling tractable because of the system's extreme mass ratio:

1. Perturbative expansion of binary's spacetime

$$g_{ab} = g_{ab}^{Kerr}(M, a) + h_{ab}(\mu)$$

$$\frac{||h_{ab}||}{||g_{ab}||} \sim \frac{\mu}{M}$$

2. Inspiral is "slow":

$$\frac{\Omega^2}{\dot{\Omega}} \propto \frac{M}{\mu}$$

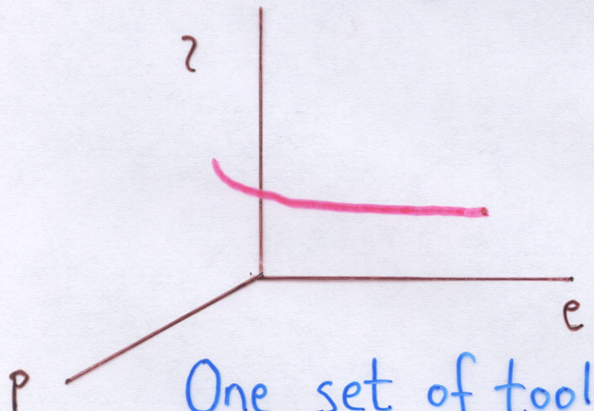
Many orbits spent near each point in orbital parameter space.

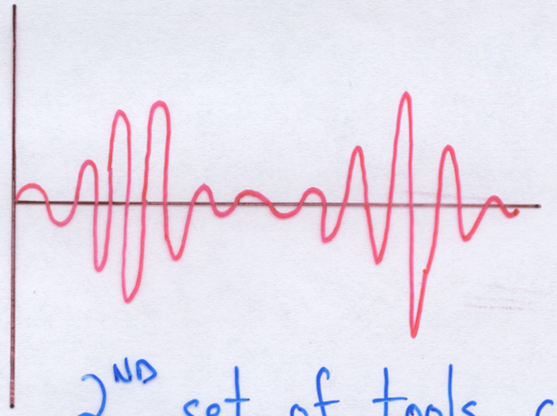
How do we do the relevant calculations?

Several toolsets developed or developing:

1. Kludge
2. Frequency domain Teukolsky equation
3. Time domain Teukolsky equation
4. Self force computation

NOTE: In this regime, it is useful to separate the radiation reaction from the wave generation:





One set of tools computes a "trajectory" through orbital parameters

2ND set of tools computes waveform generated when something spirals in on that trajectory.

Kludge Abuse weak-field radiation reaction formulae to produce strong-field inspirals

Use simple tools to build waveform

Glampedakis, Hughes, Kennefick: Developed "spiral-in" code based on quadrupole-order RR acting on exact Kerr geodesics

T. Creighton: developed crude waveform generator to make corresponding h_+, $h_\times$

Barack & Cutler: developing similar package based on post-Newtonian dynamics & RR.

Fast, simple, easy to use.

Results are wrong.

Tools for developing data analysis infrastructure.

Frequency domain Teukolsky equation

Solves perturbative version of Einstein's equation for radiative quantities

Meat of the problem involves solving ODEs - embarassingly parallelizable problem

Can get radiative evolution for 2 of 3 orbital constants; good approximation will fix the 3RD very well.

Not very good at making waveform for eccentric orbits?

Codes: Finn, Glampedakis & Kennefick, Hughes

(others exist, have not been as active recently)

Currently only handle constrained cases!

Generalization will be straightforward.

Time domain Teukolsky equation

Same underlying equation as frequency domain Teukolsky equation

Problem now is solving PDEs

Codes exist - basic formalism used in close limit BBH work (Price, Pullin, Laguna, Lousto, Baker, ...). Pennstate code can handle relevant source.

Very good way to find waveform given an inspiral trajectory.

Not such a good way to construct that trajectory?

Self-force computation

The Correct™ way to do radiation reaction. Computes the "force" associated with the small body's self-interaction.

Prime focus of an army of relativists - Mino, Nakano, Sasaki, Barack, Burko, Ori, Detweiler, Whiting, Lousto, Poisson, Wiseman, ...

Probably the only way to rigorously evolve all 3 orbital constants. Definitely the only way to evaluate non-radiative corrections to orbital motion.

DIFFICULT CALCULATION, ESPECIALLY IN KERR SPACETIME! Astrophysically relevant results not expected in the near future.

Need to scope out the magnitude of the data analysis problem <u>**NOW**</u>.

Rigorous details of radiation reaction ("Evolution of Carter's constant") and non-radiative self-force IRRELEVANT at this level. Need waveform models that faithfully capture features of inspiral waves.

PLAN: Begin building infrastructure, exploring data analysis issues with Kludge waveforms (T. Creighton; Cutler?).

Construct this infrastructure such that we can drop more sophisticated models in easily.

Push forward Teukolsky formalism codes.

My gut feeling is that a combination of time & frequency domain codes will be needed.

More People Needed!

Waveform generation code development requires post docs or advanced grad students.

Need more data analysis expertise playing with the waveforms.