

GW Source Modeling

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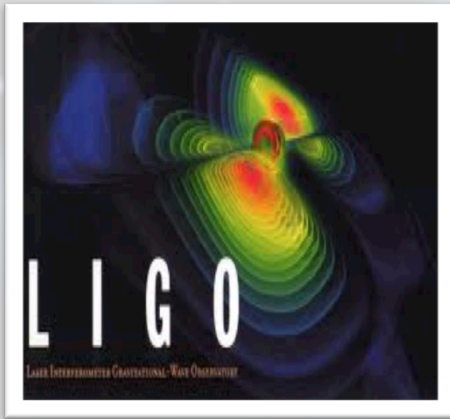


TESTING GRAVITY 2015

15-17 JANUARY 2015, SFU HARBOUR CENTER, VANCOUVER, BC, CANADA



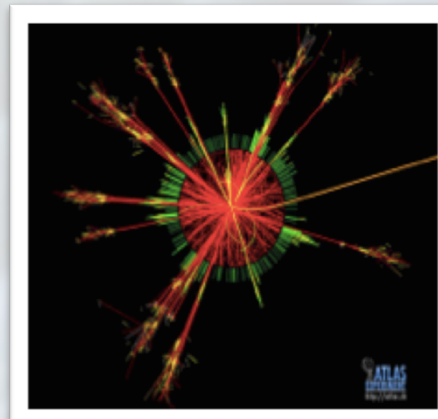
GW Source Modeling Today



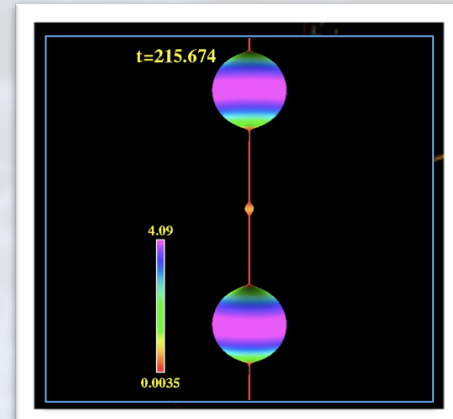
Gravitational Wave
Astronomy



Astrophysics



High-Energy Physics

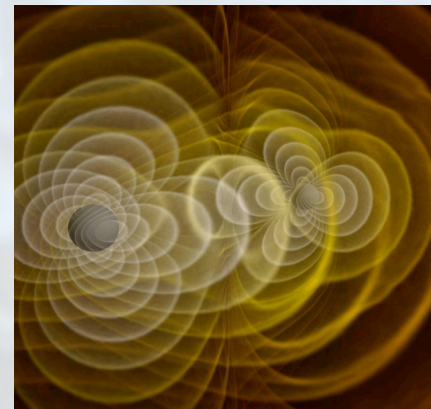


Fundamental Physics

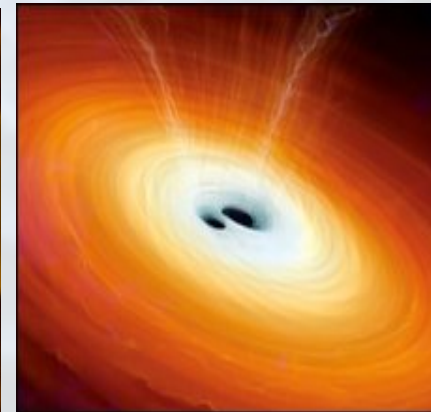
I will focus on applications of numerical relativity (NR) to:

- predict and characterize sources of GWs
- unveil other strong-field gravity astrophysical phenomena in the universe

I will restrict to **Binary Black-Hole (BBH)** systems



BBH + GWs



... + gas + EM

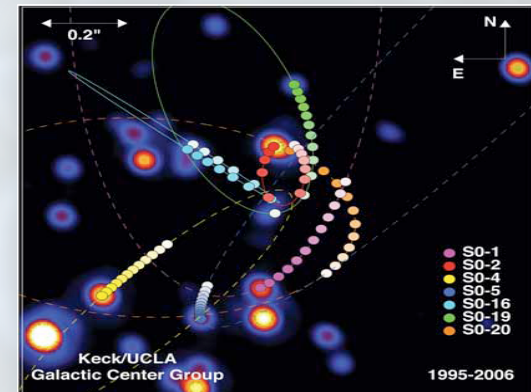
There are "Black Holes"



"It's black, and it looks like a hole.
I'd say it's a black hole."

SMBHs $\sim 10^6 \dots 10^9 M_{\odot}$

Stellar dynamics near galactic centers, iron emission line profiles, AGN engines



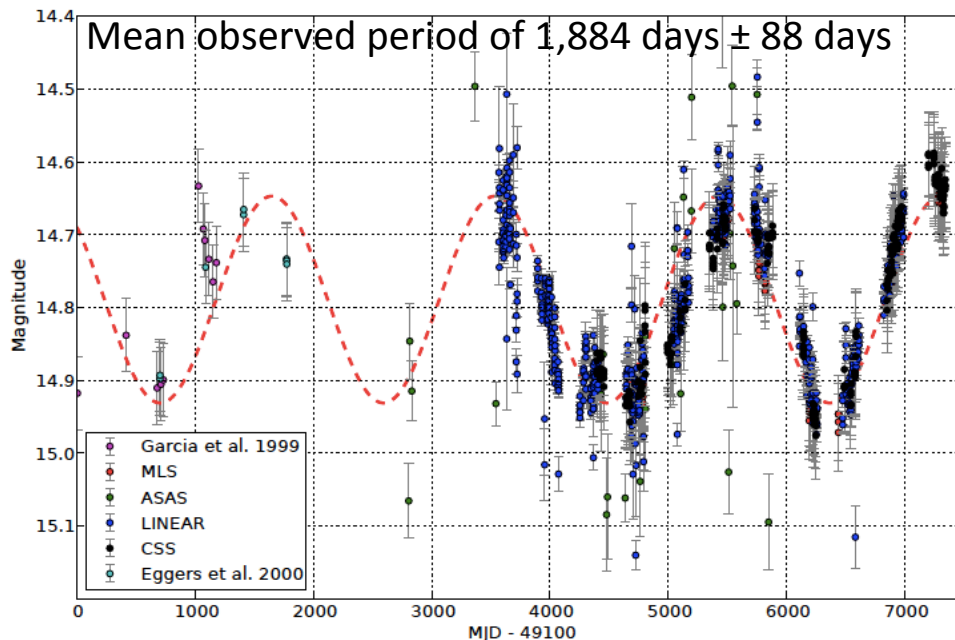
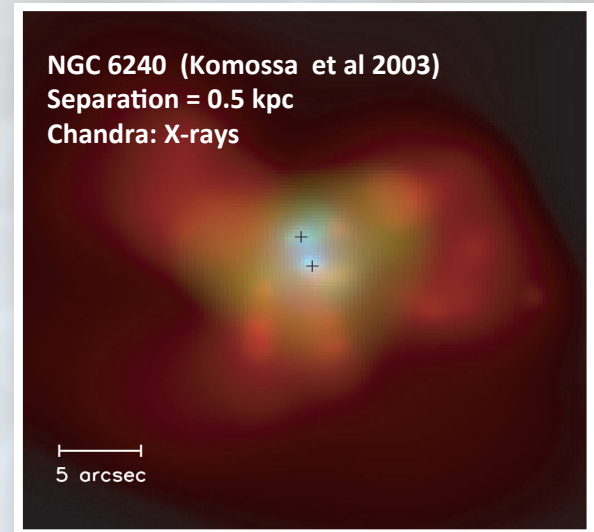
Stellar Mass BHs $\sim 3-50 M_{\odot}$

X-ray binaries, MS star + compact star, e. g. Cygnus X-1 (1964)

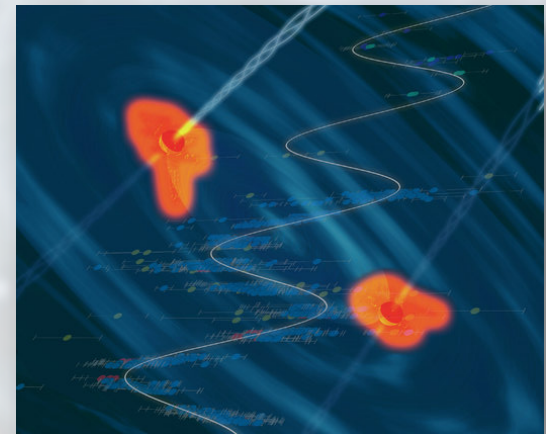


But what about Binary Black Holes ?

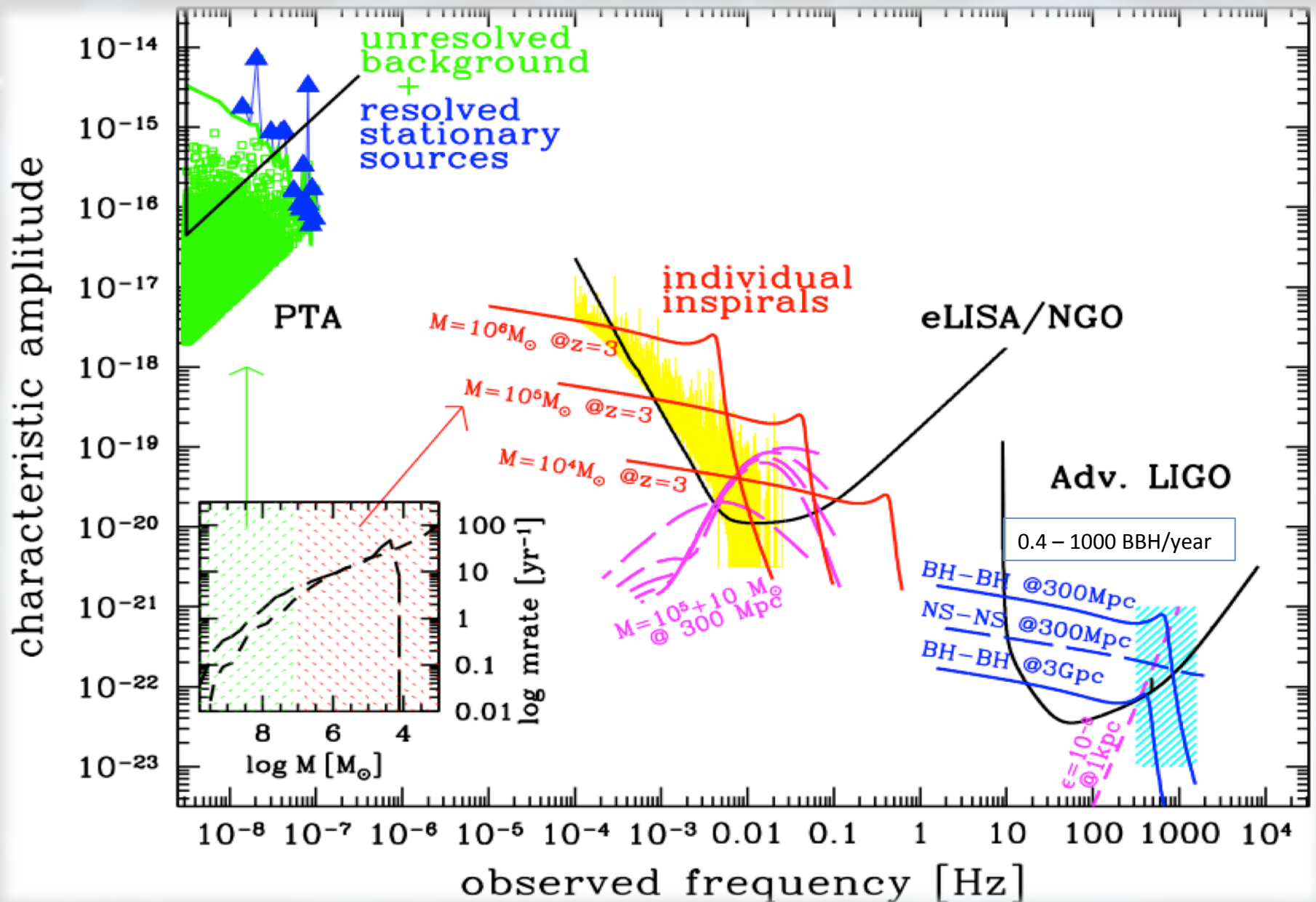
- Hierarchical build-up of galaxies from smaller structures (Λ CDM) $\rightarrow$ galaxies merger $\rightarrow$ dual black hole systems
- Few observations of resolved subkpc dual nuclei ...
- Torques from gas, stellar dynamical friction, gravitational slingshot bring the pair to sub-pc scales in the GW regime (separation < 0.1 pc)



**Quasars variability from Catalina
Real-time Transient Survey (CRTS) $\rightarrow$
PG 1302-102 (Graham et al Nature 2015)**



Gravitational Wave Spectrum



The benefits of EM Observations

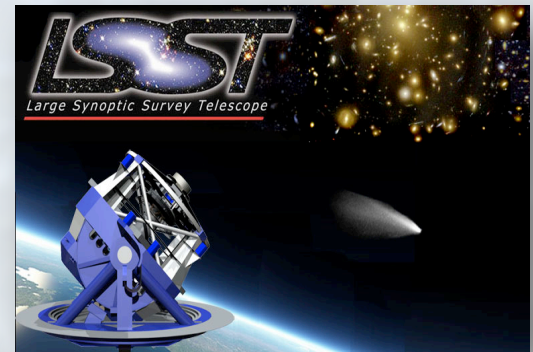
- High-cadence, all-sky survey astronomy data could differentiate BBH from single AGNs or Quasars in the near future:
 - GW Detection/Localization $\Rightarrow$ EM Detection/Localization
 - Distance vs Redshift $\Rightarrow$ Cosmological Standard Sirens (Schutz 1986, Holz & Hughes 2005)
 - Implications for gravity models, relativistic accretion, jet formation, etc
- **Need accurate predictions of the sources temporal variability and energy spectrum as most sources are spatially unresolved ...**



Pan-STARRS

2010-??

4 skies per month



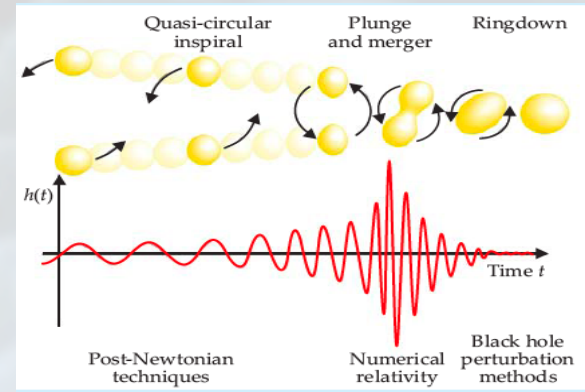
Large Synoptic Survey Telescope (LSST)

2021-2032

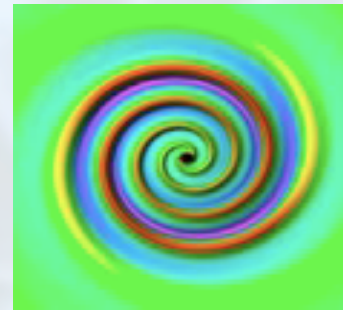
1 sky every 3 days

Modeling BBH in Strong Field GR

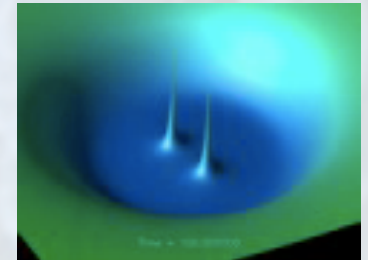
- In order to study BBH mergers and gravitational radiation, we need to evolve the GR Equations.
- There has been an ongoing effort since the 60's to do this ...
- Only in the last 9 years has it actually been possible to evolve multiple BH spacetimes
- Modern Numerical Relativity Tools are now available to the scientific community at large and have produced a wealth of new results:
 - Spectral Einstein Code (SpEC)
 - Moving Punctures
 - GR-MHD



Artistic representation, Baumgarte & Shapiro (Physics Today 2011)



Pretorius PRL 2005



Baker+ PRL 2006;
Campanelli+ PRL 2006

einstein
toolkit



Waveform Catalogs

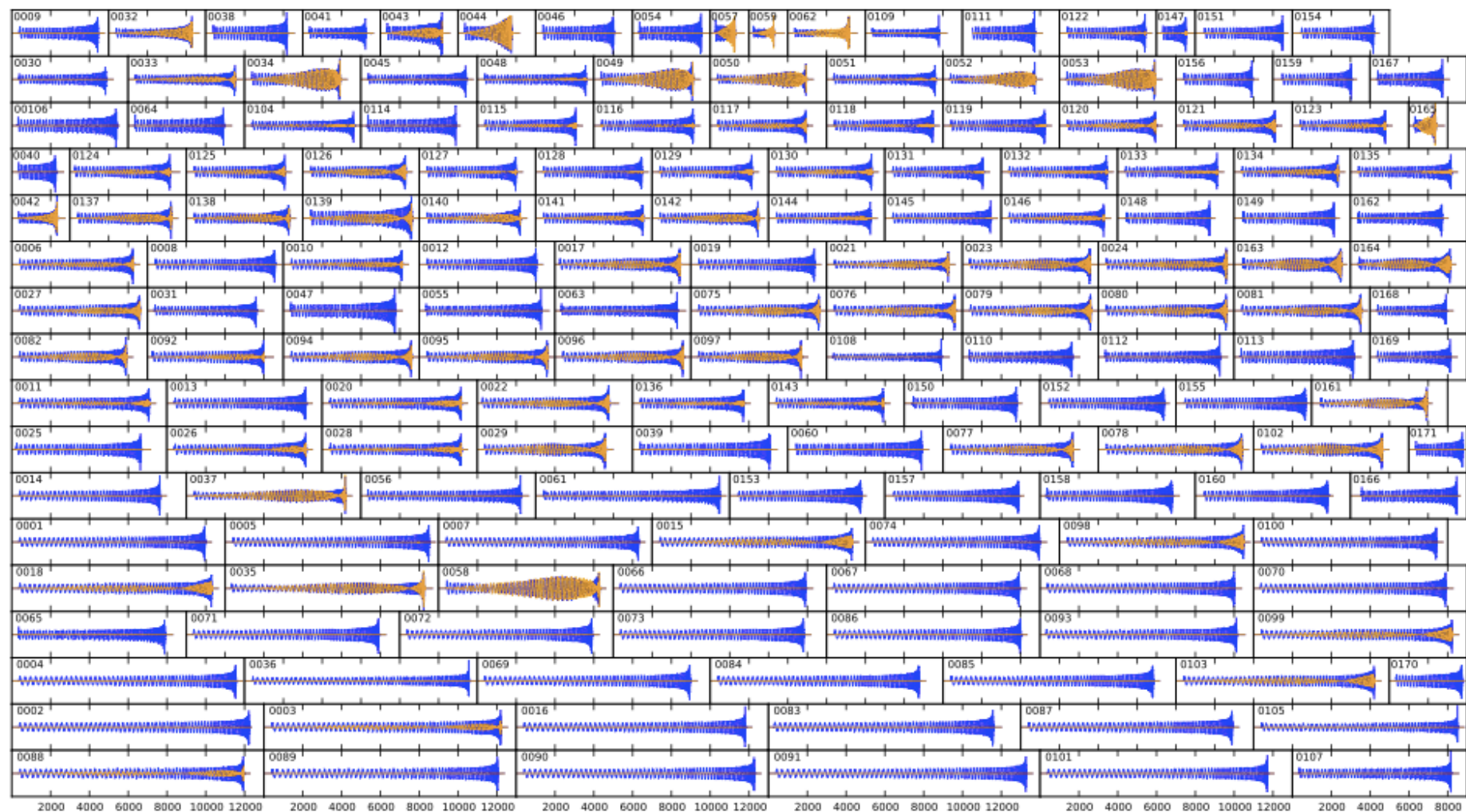
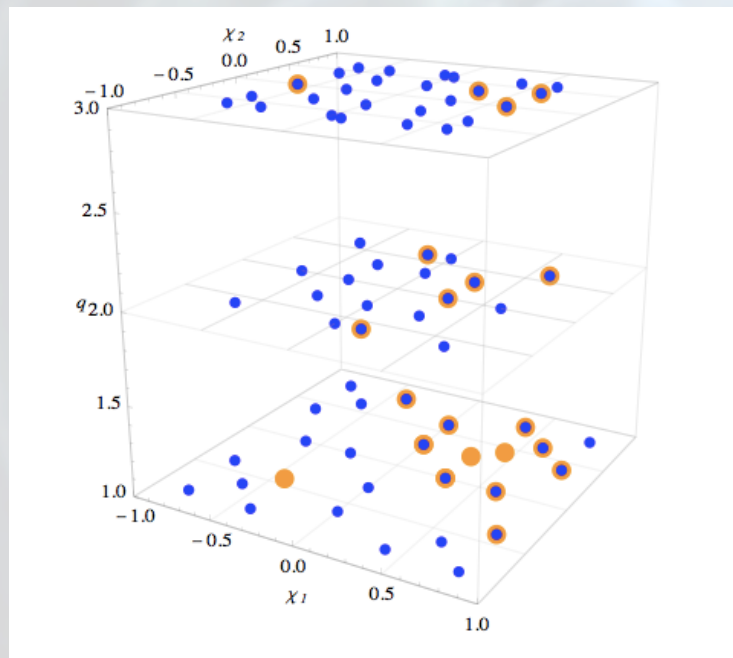


FIG. 3. Waveform polarizations h_+ (blue) and $h_\times$ (orange) in a sky direction parallel to the initial orbital plane of each simulation. All plots have the same horizontal scale, with each tick representing a time interval of $2000M$ (equal to 0.2 s for a $20M_\odot$ BBH).

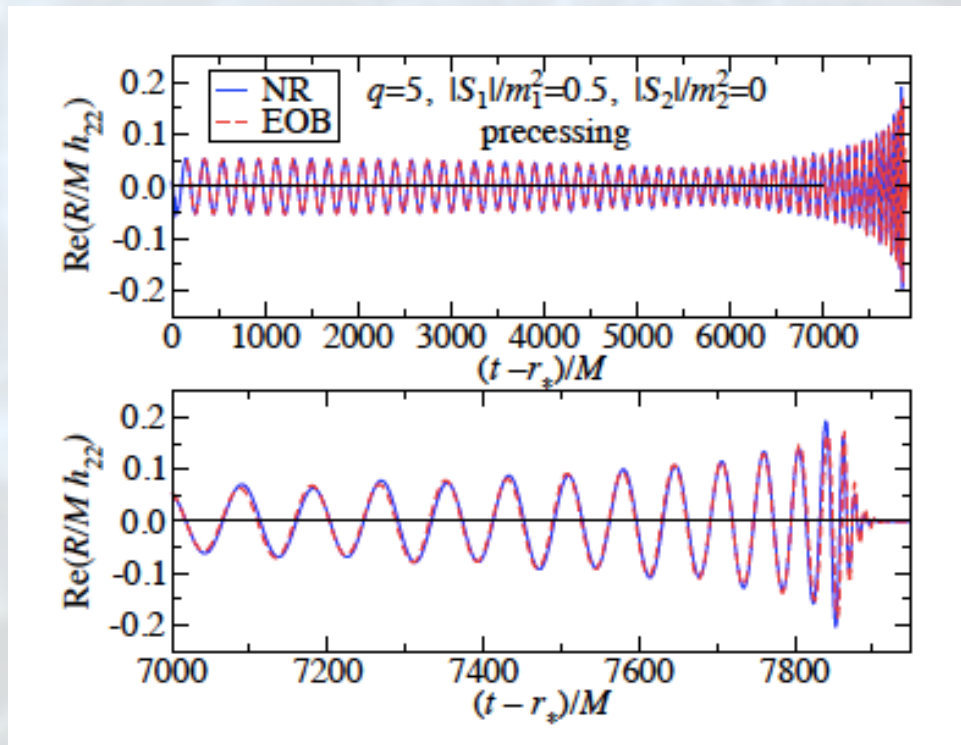
GW Templates for Spinning, Non-Precessing BBH

Effective-one-body (EOB) phenomenological waveforms have overlaps above 99% with spinning, non-precessing BBH waveforms from NR simulations produced by the **NRAR** (Hinder et al 2013) and **SXS** (Taracchini et al 2014) collaborations.

- Consider mass ratios $<1:10$, and spin magnitudes up to 98% of extremality
- Obtain negligible loss in event rate due to the modeling errors (below 3%)



Hinder et al 2013



Taracchini et al 2014

Spin Dynamics

Campanelli+, Phys Rev D, 2006

Orbital-hangup effect: When spins are aligned with L , repulsive spin-orbit coupling delays the merger, maximizing the amplitude of gravitational radiation, and leaving behind a submax Kerr BH (Cosmic censorship at work!)

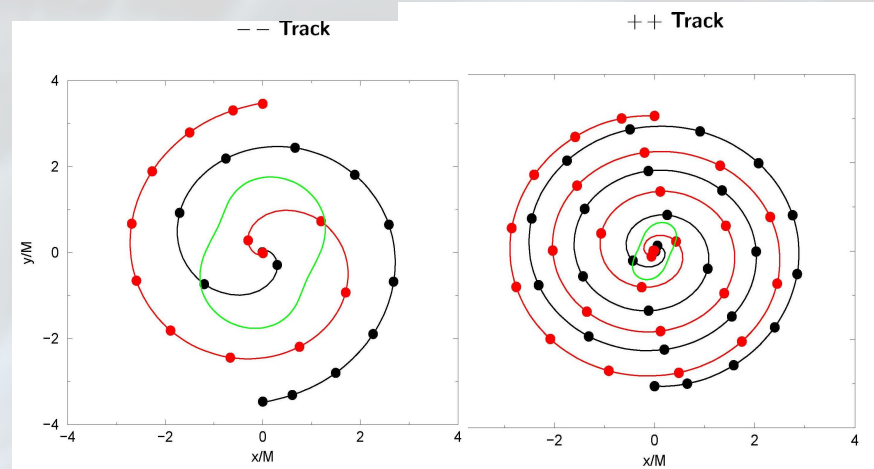
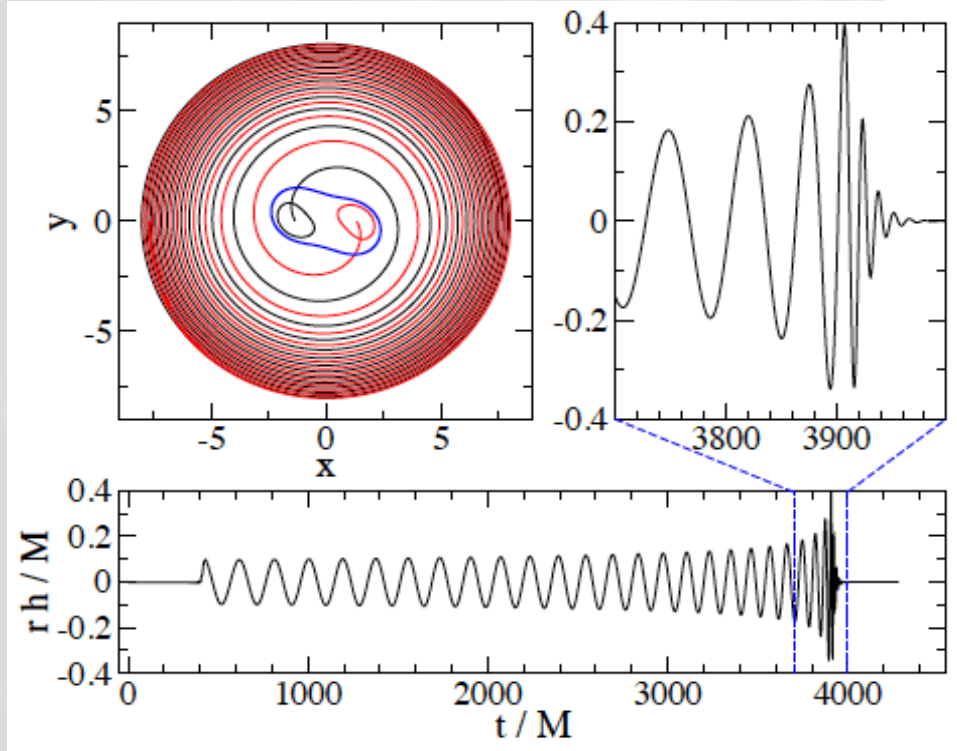


Figure 4: Puncture tracks for the -- configuration. Figure 6: Puncture tracks for the ++ configuration.



Lovelace+, Phys. Rev. D, 2011

Make a 12 orbits evolution of BBH with spins=0.97.
Radiates over 10% of its mass in GW. The brightest source in the entire Universe!

Recoiling Black Holes

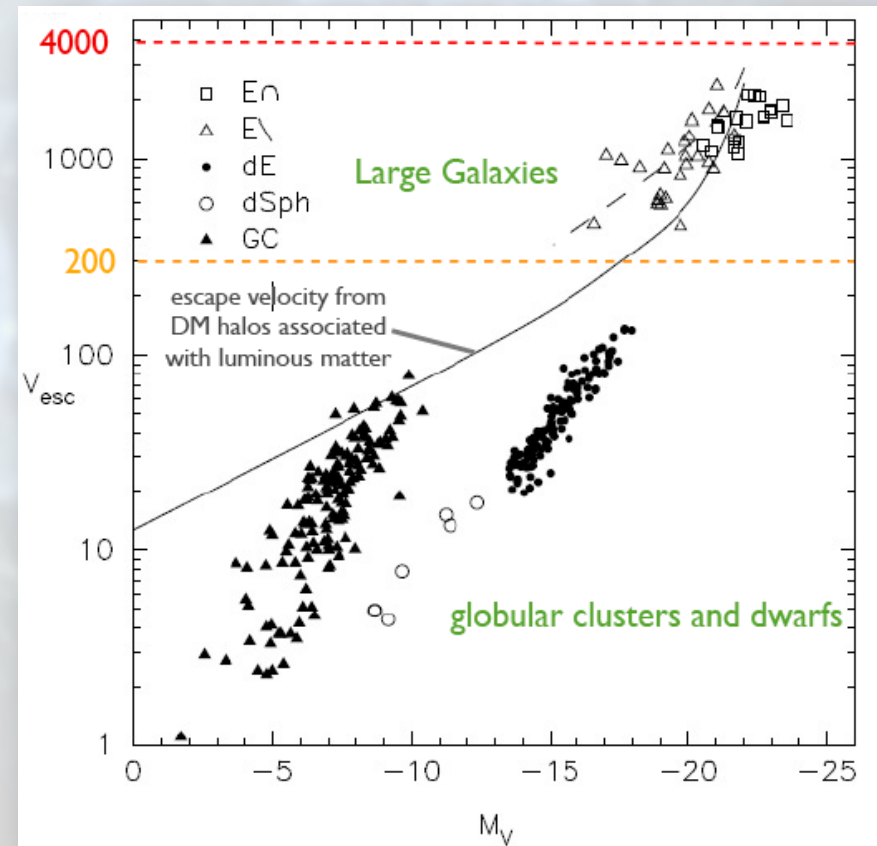
The asymmetric beaming of GW radiation at merger can cause the BH remnant to recoil, and “escape” from its host structure



Ideal calculation for NR!

$$\frac{dP_i}{dt} = \lim_{r \rightarrow \infty} \left[\frac{r^2}{16\pi} \int_{\Omega} \ell_i \left| \int_{-\infty}^t \Psi_4 d\tilde{t} \right|^2 d\Omega \right]$$

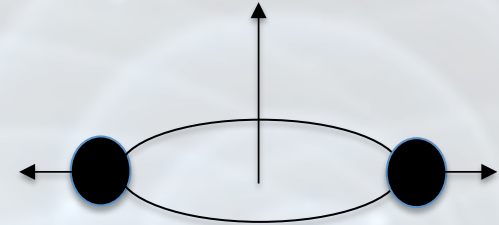
Consequences for growth of SMBHs in galaxies and IMBH formation in globular clusters



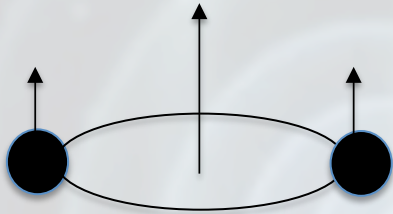
Super Large Kicks from Spinning BBH

Superkicks (Campanelli + 2007, González + 2007)

- Moderate GW generation
- $v_{\text{max}} \sim 4000 \text{ km/s}$

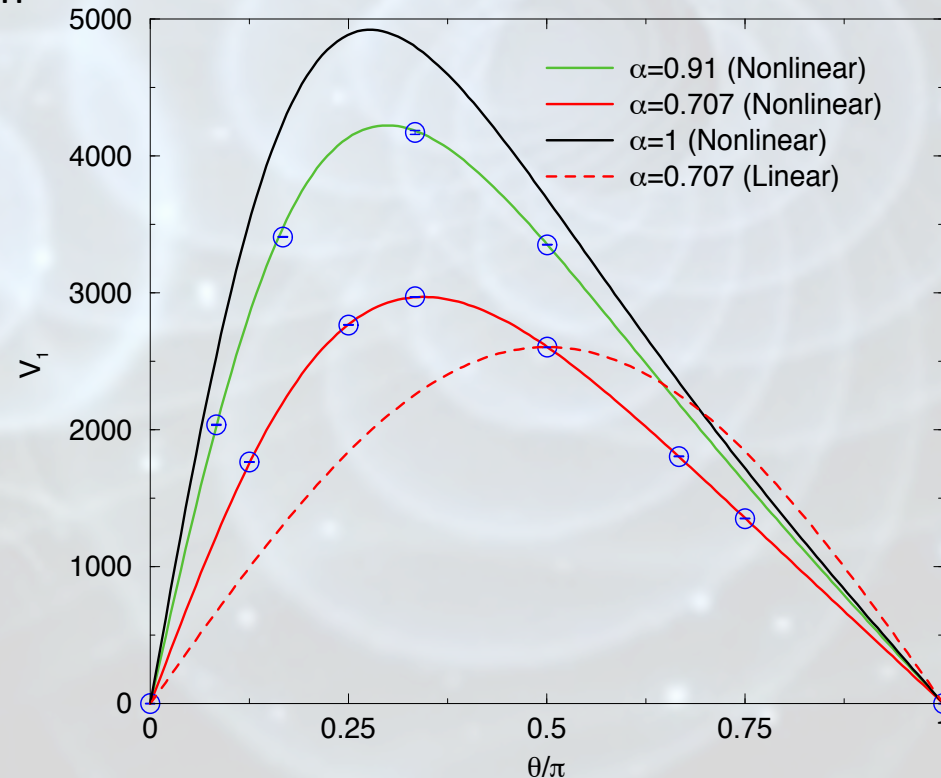
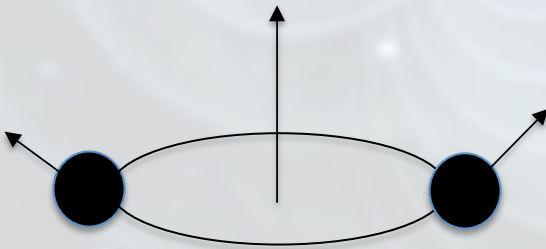


Unequal-mass, non-spinning BBH $\sim 200 \text{ km/s}$ (Bruegmann++,2006)



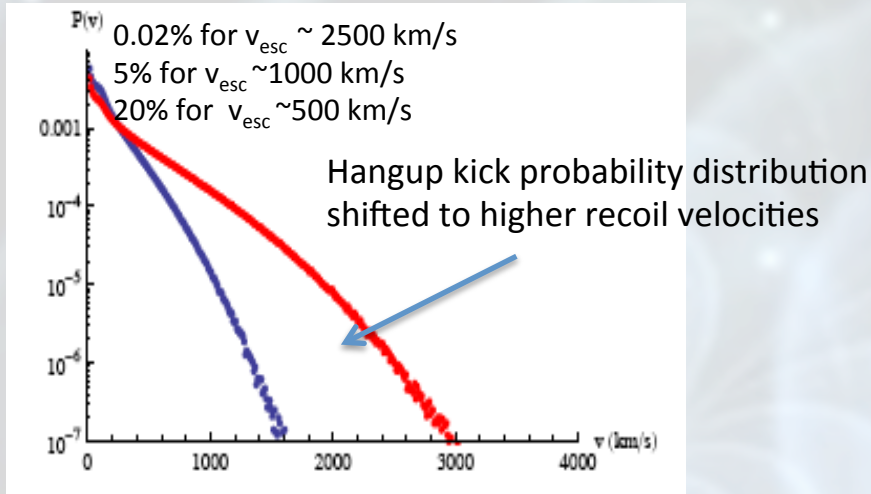
Strong GW generation
No kicks

Hang-Up Kicks $v_{\text{max}} \sim 5000 \text{ km/s}$ Lousto & Zlochower+ 2007



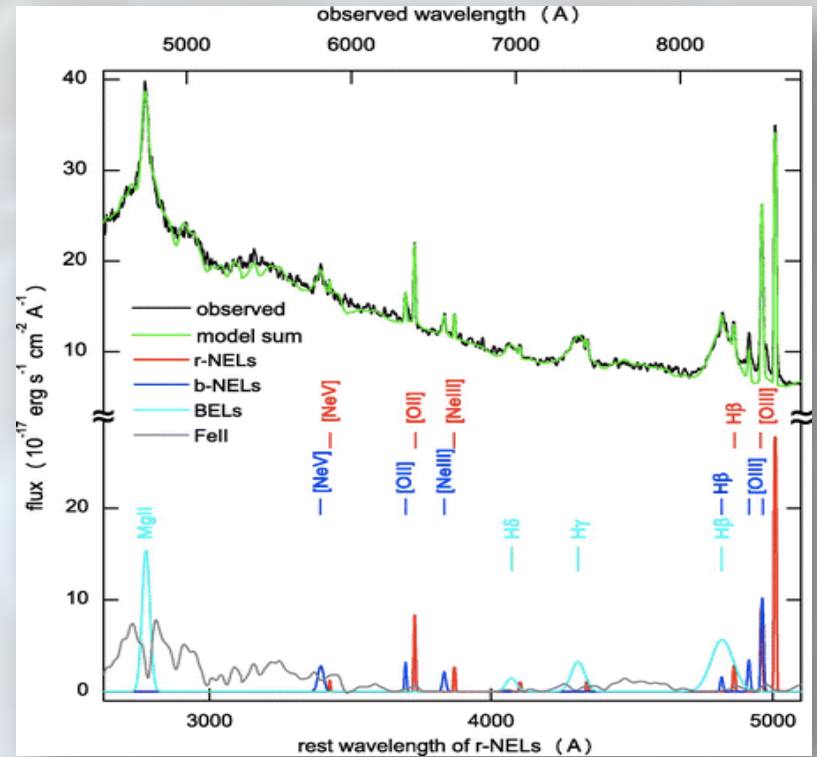
But Recoiling BH are still Elusive ...

Probabilities that remnant BH recoils in any direction from host structure (Lousto++2011)



Suppression via spin alignment due to:

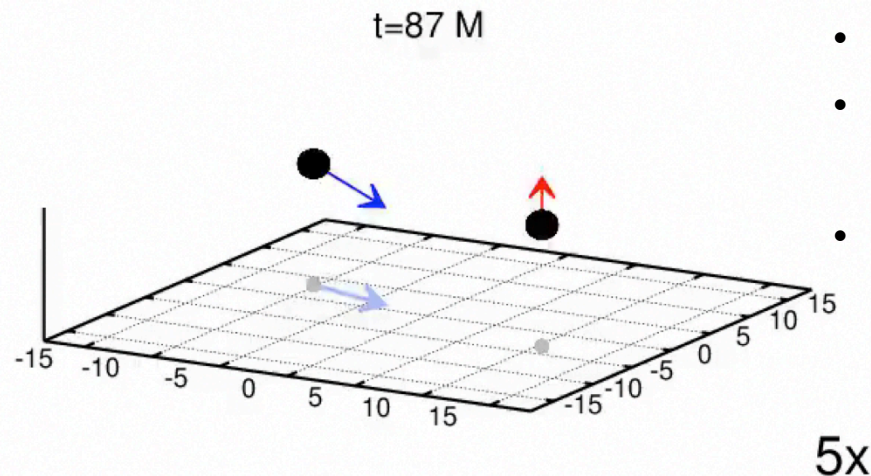
- accretion torques from gas
Schnittman, 2004
Bogdanovic'z, Reynolds & Miller, 2007
Sorathia, Krolik & Hawley 2013 (Bardeen-Petterson in MHD)
Miller & Krolik 2013 (Spin and Orbital Alignment)
- and resonance effects in inspiral
Kesden++ 2010



Komossa, 2008 (Double-peaked NRL emitters)

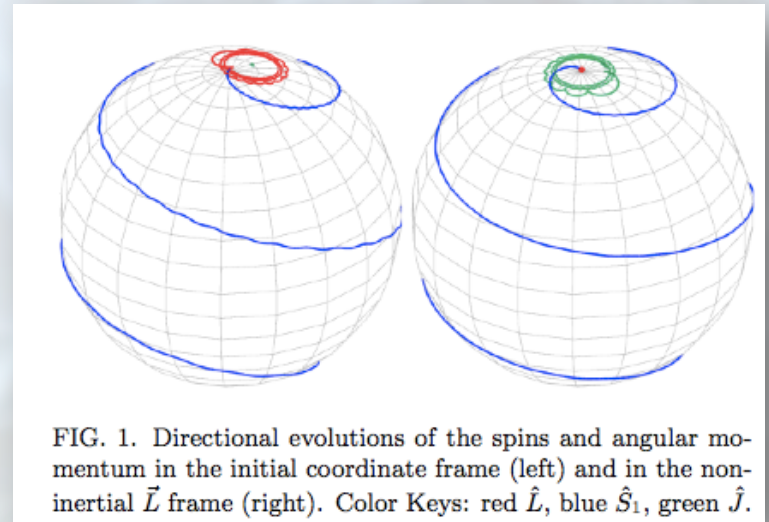
Other possible observations: off-set galactic nuclei, displaced active galactic nuclei, population of galaxies without SMBHs, x-rays afterglows, feedback trails

More on Spin Dynamics and Astrophysics



Spin Flip-Flop: (Lousto & Healy, arXiv:1410.3830)

- 2PN spin-spin effect (leading order)
- Excellent agreement with 3.5PN waveform (phase error $< 0.2\%$, amplitude $< 2\%$)
- Improved waveform extraction (Nakano arXiv:1501.02890)



Consequences for astrophysics of BBH mergers:

- accretion into each BH (minidisk) from prograde to retrograde in ~ 100 -200 of orbits
- effect shorter than accretion-driven spin alignment mechanisms

Binary Black Holes in a Gaseous Environment

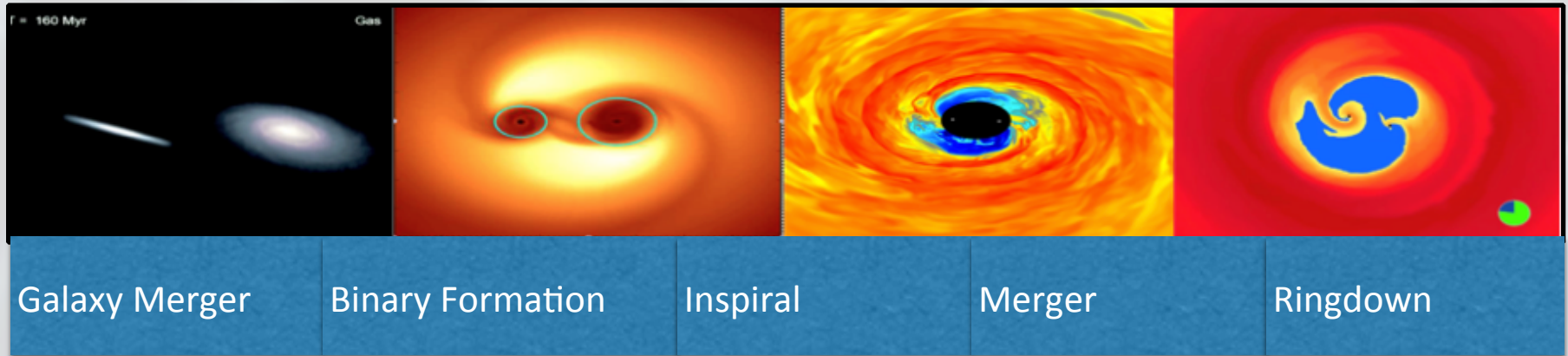
- Grand Challenge Problem → scales range from 10^5 pc to 10^{-5} pc
- Not well understood at subpc scales, and more so close to merger e.g. < 0.01 pc

Hopkins, Hernquist, Springer et al

Farris++2013

Noble++2012

Farris++2011



Dynamical Gravity + Covariant Magnetohydrodynamics + Radiation Treatment

Newtonian Gravity

Eulerian, high-resolution/shock-capturing, 3-d, ideal MHD, dynamical GR, HLL fluxes, parabolic reconstruction, dynamical FMR

Post-Newtonian

Harm3d

Numerical Relativity

Static GR

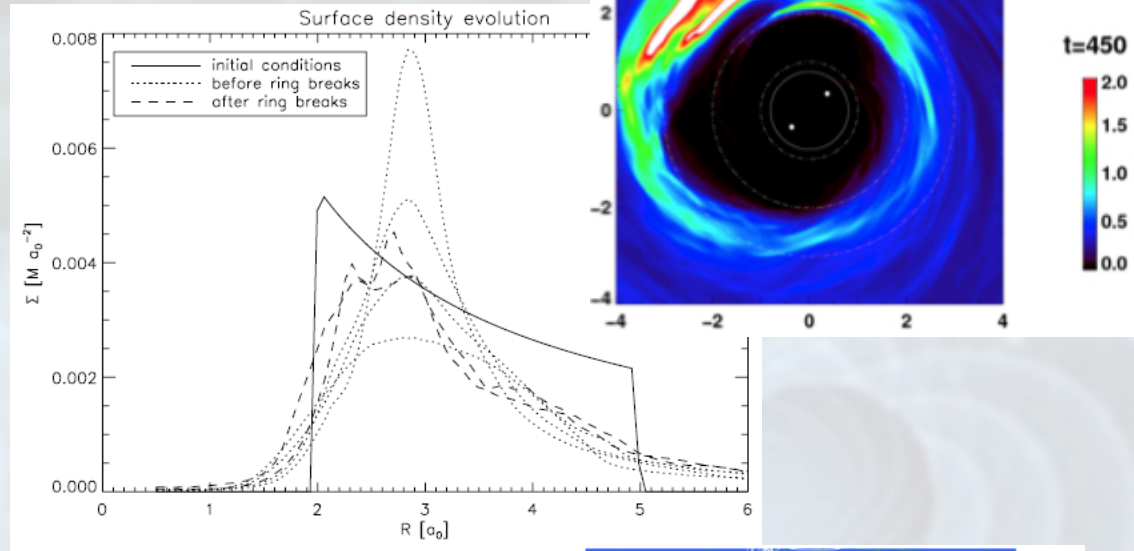
Harm3d

Status of this Affair

Newtonian Hydrodynamics

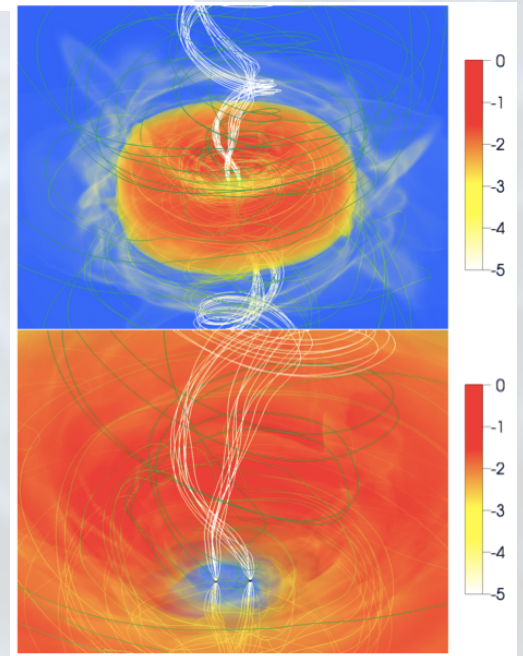
($t_{\text{merger}} \gg t_{\text{inflow}}$, $a > 1000M$)

- 2D Hydro: Gap formation near $r \approx 2a$, essentially due to binary torque (MacFadyen & Milosavljevic 2008, Cuadra+2009)
- MHD: Build-up of late-time surface density maximum near the gap edge with faster accretion (due to MHD stresses) (Shi +11)



GRHydro and GR-MHD ($t_{\text{merger}} \ll t_{\text{inflow}}$, $a < 12M$)

- Correlation EM/GW signals (Bode+2010)
- Stronger shock heating with MHD (Giacomazzo+2012)
- Quick refilling of the cavity (Gold++ 2013)
- Very dense accretion streams near BHs (Farris+2010, Farris+2011)
- Jets emerging from both BH horizons and merging into one
- common jet at large distance (Palenzuela++ 2010-11, Gold++ 2013)



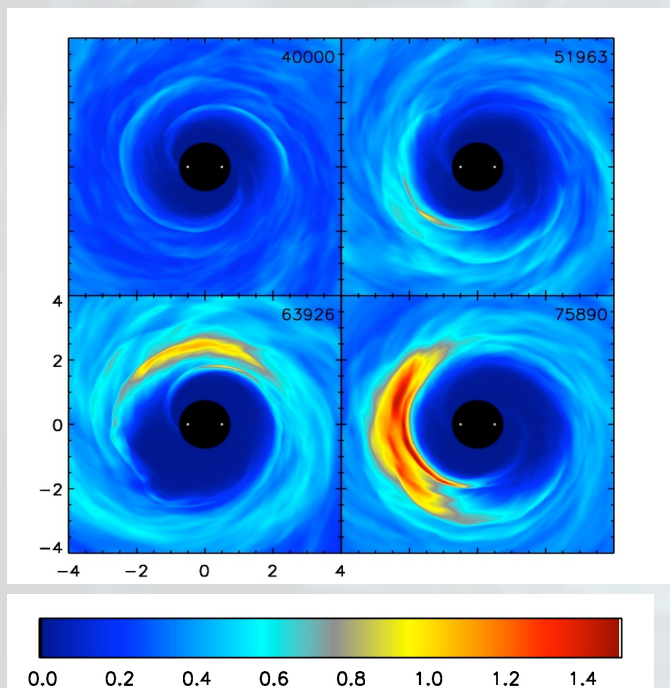
Status of this Affair

The amount of gas available to be heated at merger depends from the balance of BBH torques and MHD stresses!

GW driven Inspiral + GRMHD

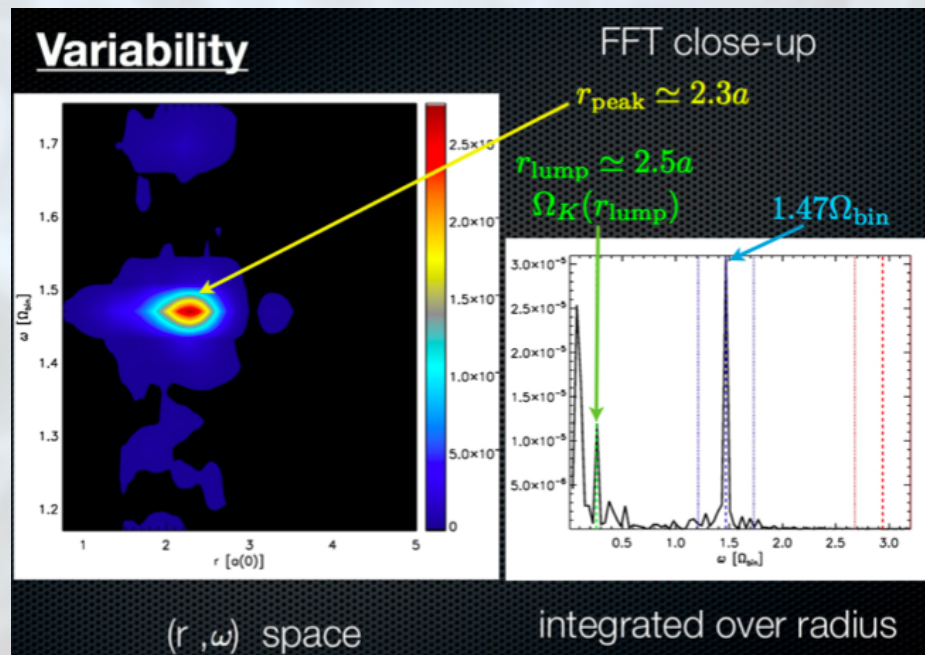
$t_{\text{inflow}} \approx t_{\text{merger}}$, $a \approx 20\text{-}100M$

- Evolve 3.5 PN BBH for hundreds of orbits in a radiatively efficient, circumbinary (geometrically thin) accretion disk (Noble+2012)

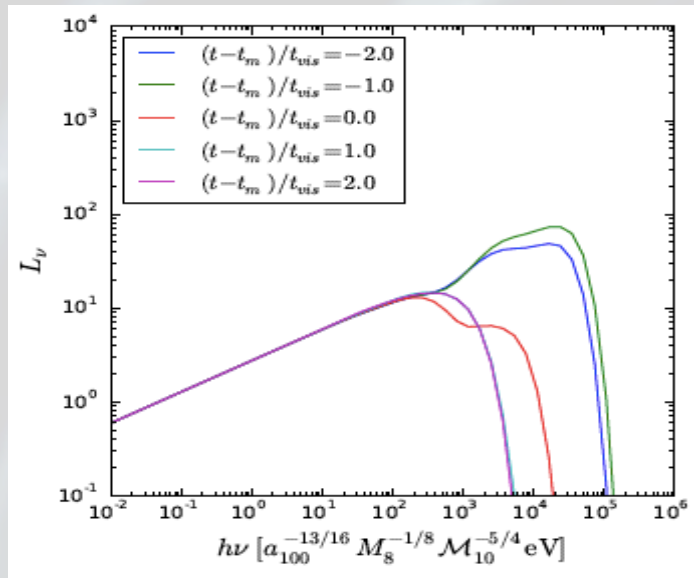


$$\Sigma(r, \phi) \equiv \int d\theta \sqrt{-g\rho} / \sqrt{g_{\phi\phi}}$$

- Accretion “**Streams**” to and from BHs
- Disk follow the BBH inspiral until decoupling
- Find “**Lump**” with characteristic EM signal periodicity = beat between the orbital freq. of the disk’s surface density max and the binary orbital freq. (dimmer with high mass-ratio BBH, work in progress)
- Luminosity characteristic of AGN (near Eddington, UV)

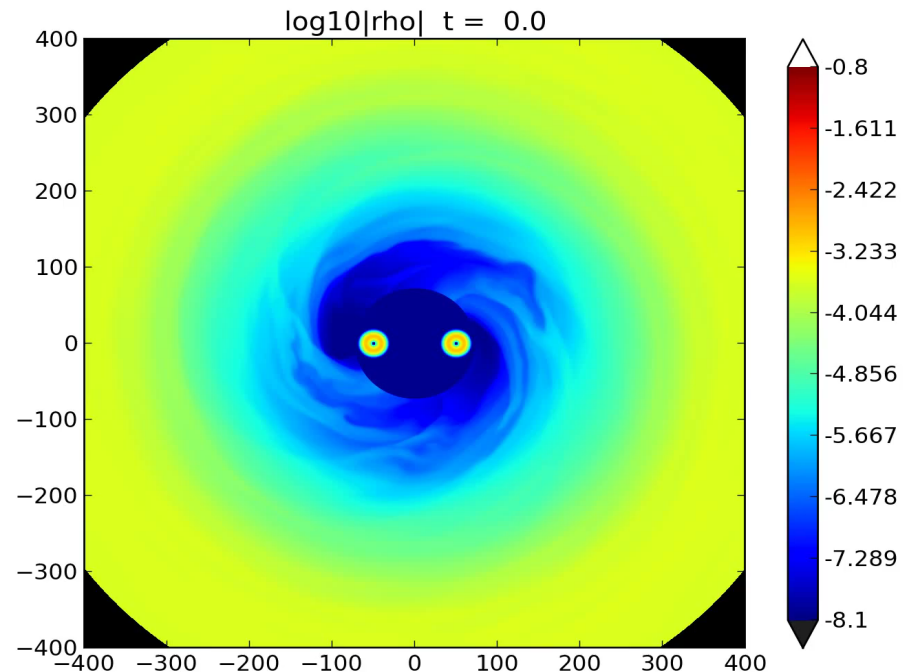


“Shedding Light” during BBH Inspiral and Mergers



2D viscous hydro with radiative cooling
(Farris++, 2014)

- orbital energy converted into heat via strong shocks inside the cavity, and radiated away → Luminosity in X-rays higher prior to the merger



Bowen, Noble, MC, Krolik, 2015

- Binary's inspiral at the rate set by GW emission (Gallouin+, 2012, Mundim ++ 2013)
- GRMHD simulation currently underway...

Stay Tuned!

Summary and Conclusions

BBH mergers are a perfect laboratory to test gravity in its strongest grip

They radiate up to 10% of total mass through gravitational radiation!

Produce many astrophysically interesting effects with potentially interesting observational consequences

Modeling efforts focuses on producing accurate gravitational waveform templates for current GW detection, and GRMHD simulations to calculate EM counterparts

