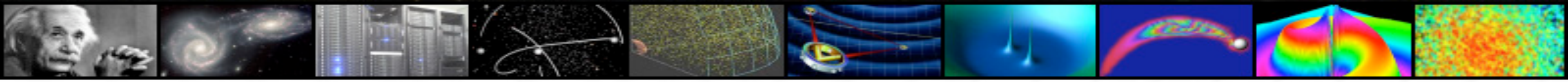
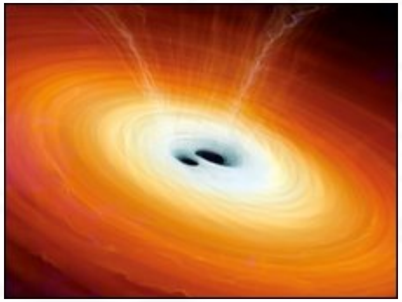


Black Hole Mergers



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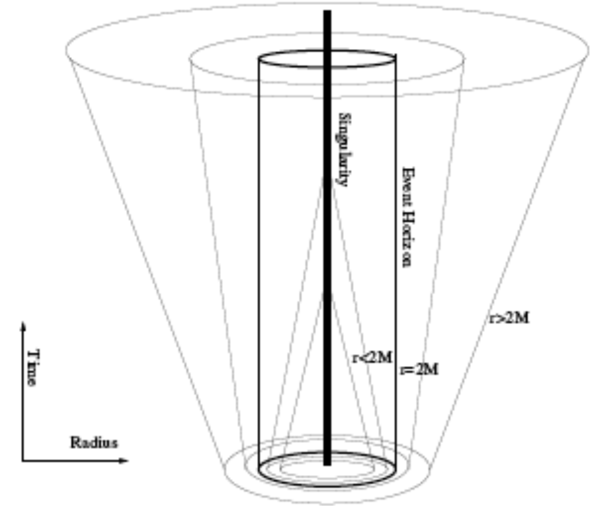
Department of Physics
Duke University
Feb 15-17, 2012

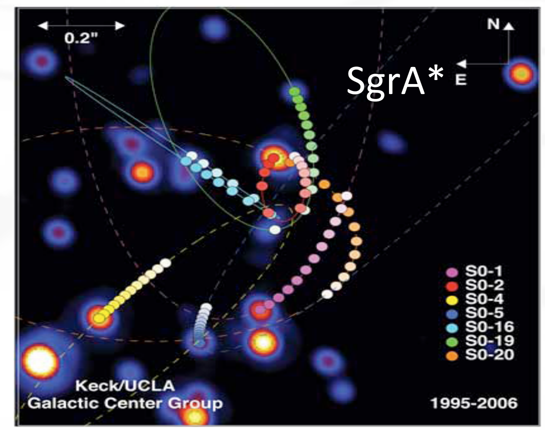
Black Holes

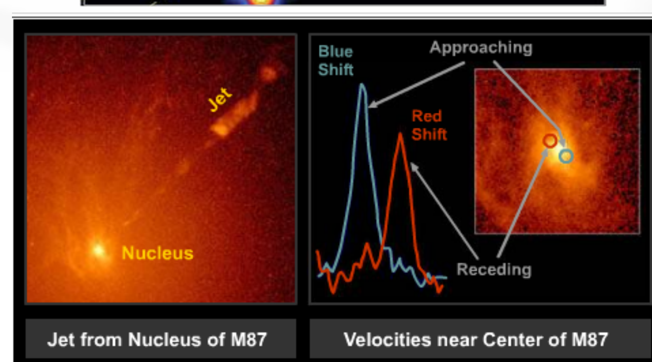
- In General Relativity (GR), Black Holes (BHs) are completely described by three quantities (no-hair theorem):
  - mass *M*,
  - angular momentum *J=aM*, a spin parameter
  - electric charge *Q* (rapidly depleted by surrounding plasma)

- BHs singularities are expected to be covered by an horizon (cosmic censorship a/M<1), located at $r_+=M+(M^2-a^2)^{1/2}$

- There is indirect evidence that BHs exist in the Universe, with a vast range of masses from few tens to $10^9\ M_\odot$
  - Stellar-mass BHs (3-30$M_\odot$) should form from the collapse of massive stars …
  - IMBHs (10^2-$10^4 M_\odot$) may assemble in globular clusters …
  - MBHs (10^4-$10^7 M_\odot$) and SMBHs (10^7-$10^9 M_\odot$) are observed in galactic cores (motion of stars and/or gas),





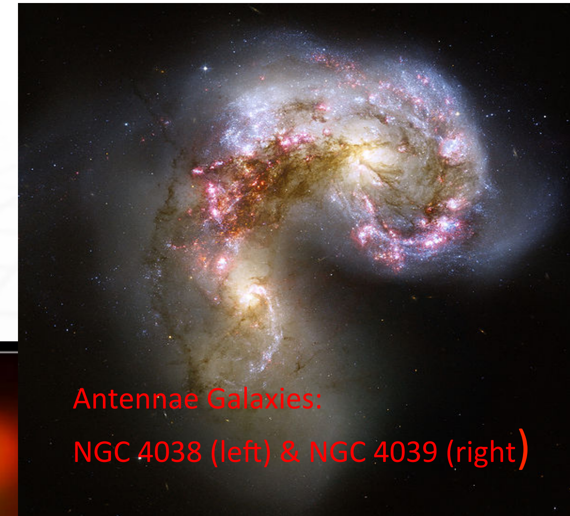


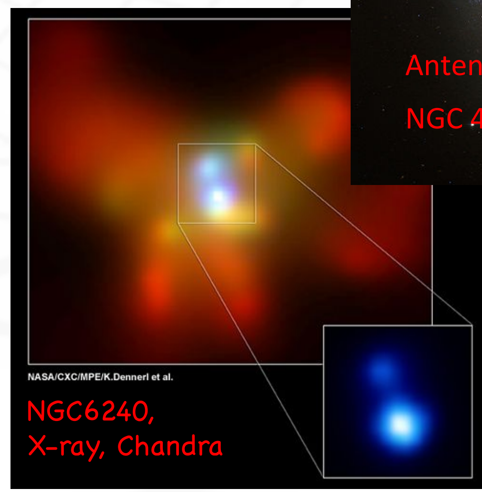
Jet from Nucleus of M87

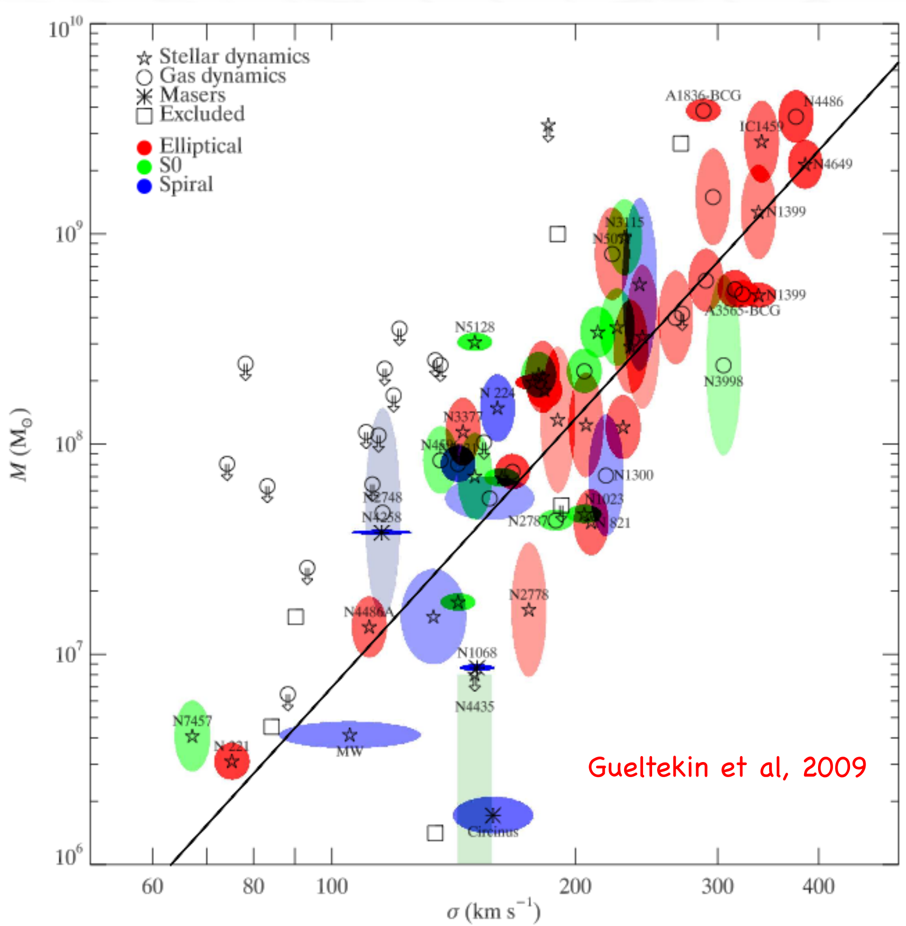
Velocities near Center of M87

Supermassive Black-Hole Binaries

- SMBHs are observed at the centers of all galaxies with bulges
- Understanding them is of paramount importance because they are connected to the host galaxy evolution/history (**M-Sigma relation**)
- There are also observational candidates of "close" (a few pc) SMBHs starting to merge



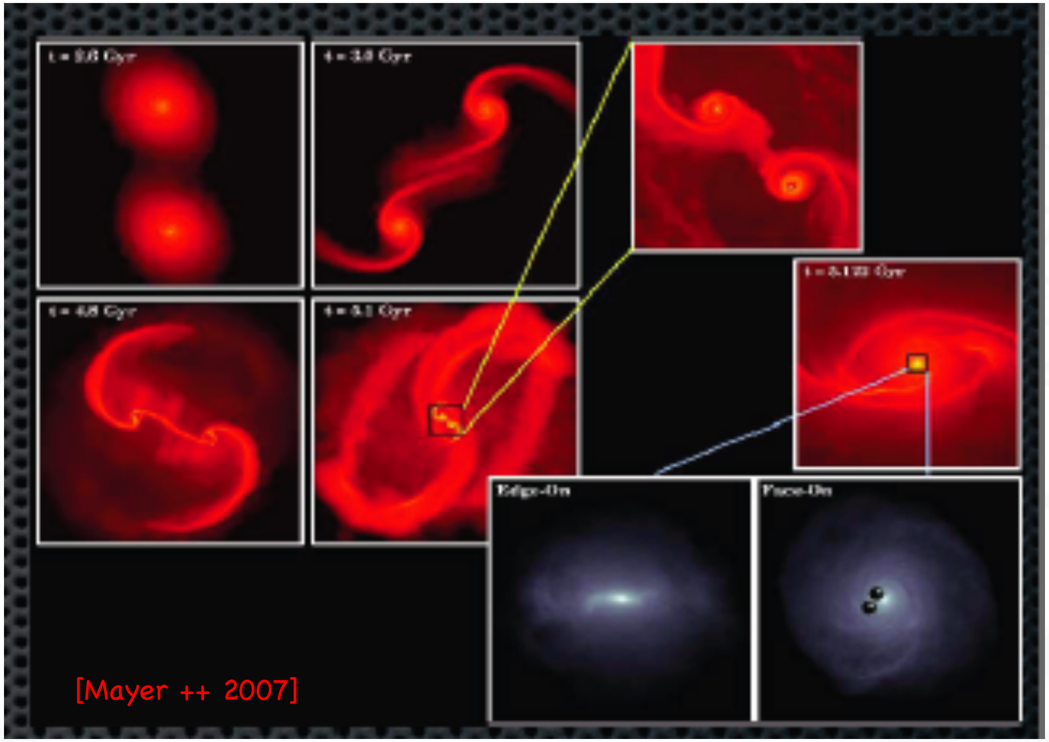




- ΛCDM models of cosmic structure formation feature hierarchical build-up of galaxies from smaller structures, suggest that most galaxy have undergone at least one merger
  ➔ ***binary black hole mergers***
- Merger Rates: expect ~ 0.1-10s per year (Schnittman & Krolik, 2008), depends on size of BH seeds, accretion, stellar effects …

Binary Black-Hole Mergers in Astrophysics

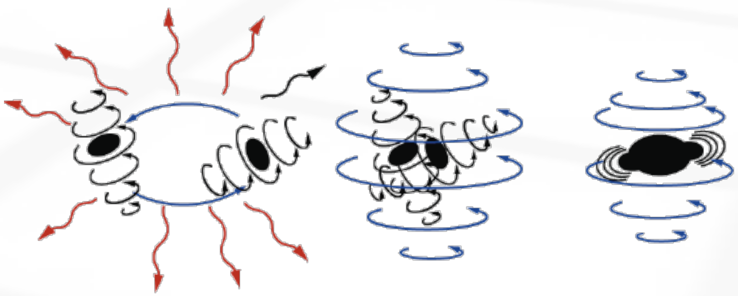
- Torques from gas, stellar dynamical friction, gravitational slingshot bring the pair to interact gravitationally (sub-pc scales)



- In the final stage of the collision (<< 1 pc scale), gravitational wave (GW) emission drive the BHBs to merge

- In the final merger event 3-10% of the total mass is radiated in gravitational waves (GWs).

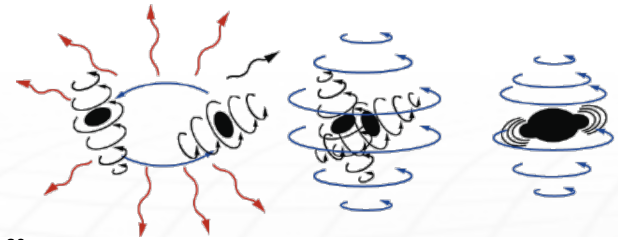
$L_{GW} \sim 10^{57}$ erg/s



Artistic representation By Kip Thorne (Caltech)

- If a circumbinary disk is present, then SMBH mergers could also be observable in the electromagnetic (EM) spectrum …

Merging Black-Hole Binaries and Gravitational Waves



- Coalescing BH Binaries are very loud source of GWs

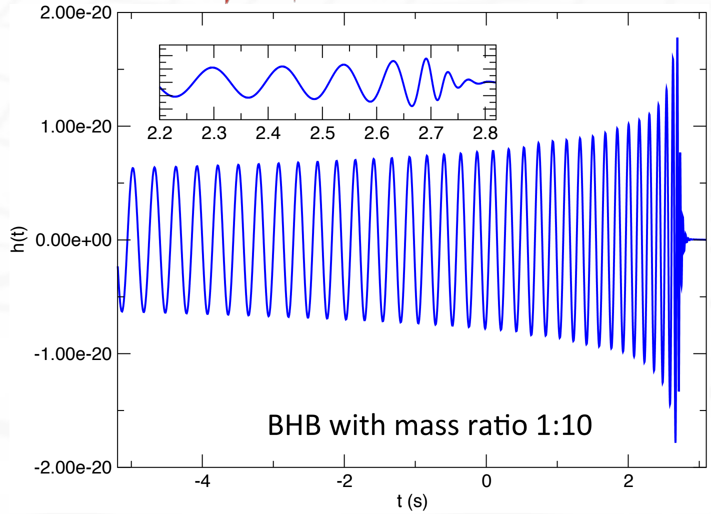
- GWs are quadrupolar (two polarizations):

$$h \sim \frac{G}{c^4}\frac{\ddot{Q}}{r} \sim \frac{GM_{\rm quad}}{rc^2}\frac{v^2}{c^2}, \qquad h = h_+ + ih_\times$$

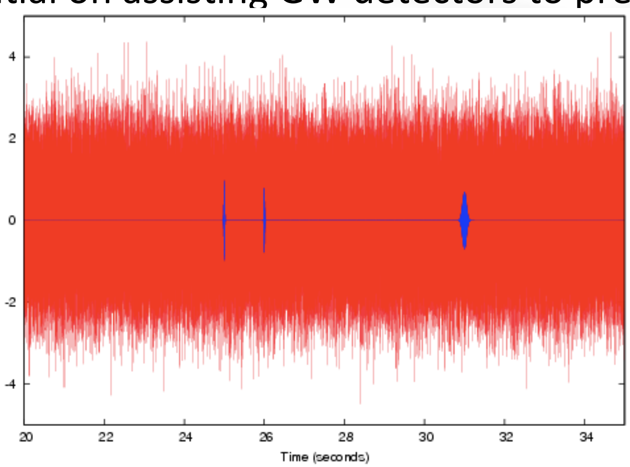
- Waveforms carry information on BH masses, spins (initial and final), distances, merger rates, spacetime dynamics.

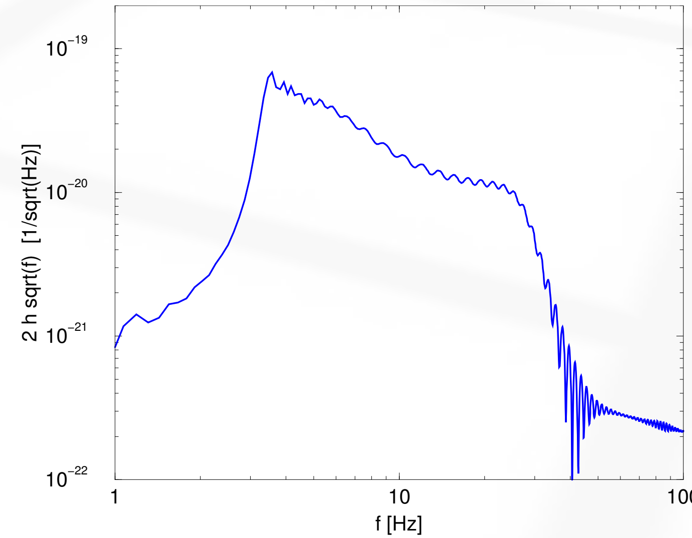
$$h \sim \frac{M_c^{5/3}(f_{orb}(1+z))^{2/3}}{D(z)}, \quad M_c = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}$$

$$\dot{f} \sim \frac{M_c^{5/3}(f_{orb}(1+z))^{11/3}}{D(z)} + (M_1, M_2, S_1, S_2)_{rel.corr}$$



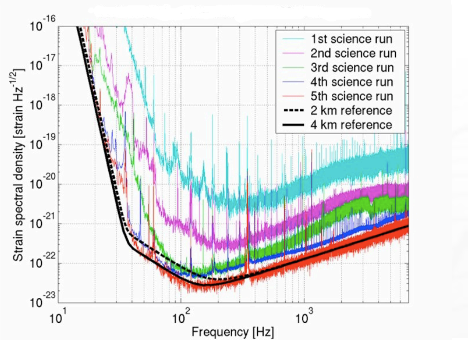
- And they are essential on assisting GW detectors to predict what to expect



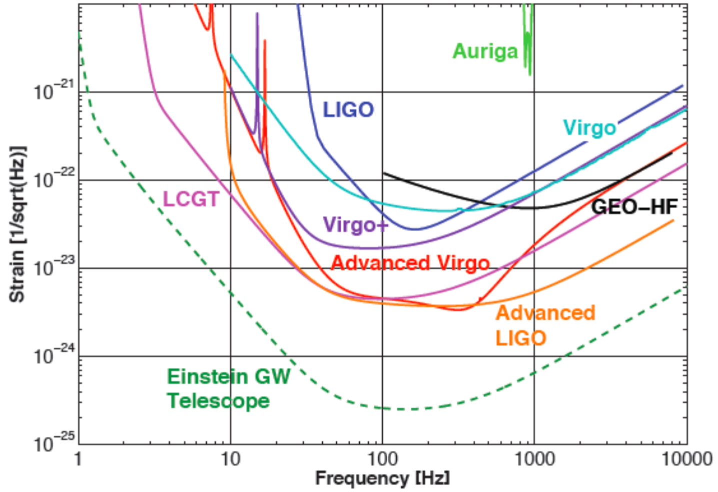


Searching for Binary Black-Holes Coalescences with Gravitational Wave Detectors

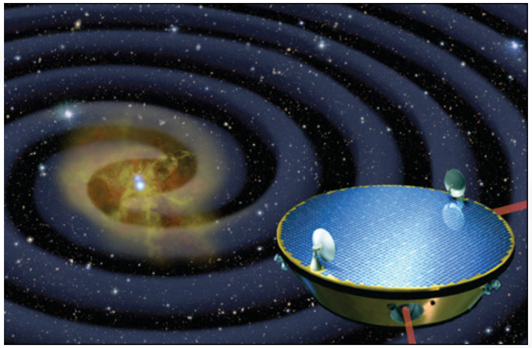
- Merging BH binaries the ideal target for all GW detectors



- Network of ground-based detectors, sensitive at high frequency (~1-10^4 Hz)
  - LIGOs, Virgo, TAMA300 (~2005-2010):
    - design sensitivity, upper limits …
  - Advanced LIGO and LCGT (2015+):
    - 10 × increase in sensitivity, 10^3 × increase in event rates
  - Future 3G detectors, e.g. Einstein Telescope (2027+):
    - 100 × increase in sensitivity, 10^6 × increase in event rates
    - Target sources to cosmological distances
    - GW Astrophysics at 1-10 Hz, EOS of NS-NS, BH-NS mergers, IMBH



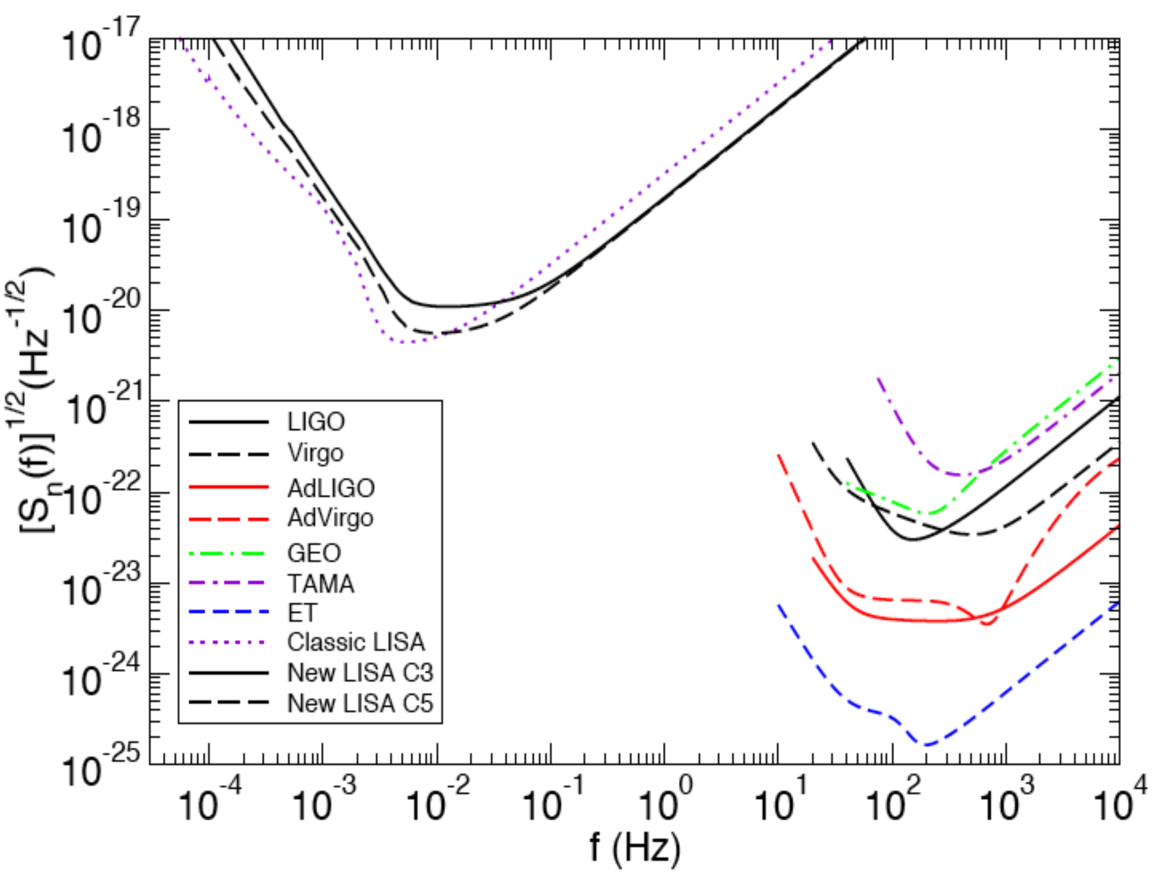
- Future space-based mission, sensitive at low frequencies (~10^{-4}-10^{-1} Hz)?
  - LISA was canceled by NASA, after Astro decadal ranking (2025+) and US FY12 Budget (April 8th, 2011).
  - New science goals and mission concept as part of an ESA-led mission launching in the early 2020's
  - MBH binary merger events, history of hierarchical galaxy mergers, and the growth of MBHs over time



The Detection Challenge

Observing the universe with gravitational waves is a tremendous challenge:

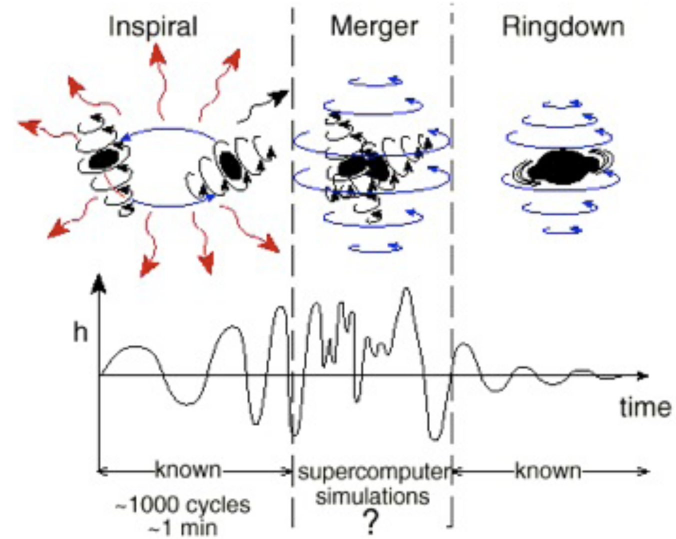
- Initial LIGO demonstrated that we can measure displacements of 10^{-19} m
- Advanced LIGO is expected to detect GWs from compact binary sources (NS-NS, BH-NS, BH-BH) up to 250 Mpc
- “LISA” could measure SMBH mergers up to z=6.

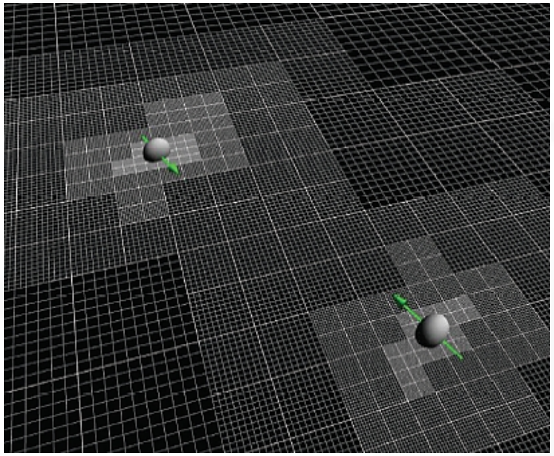


Noise curve generated by Emanuele Berti

Simulation of Black-Hole Binaries with Full Numerical General Relativity

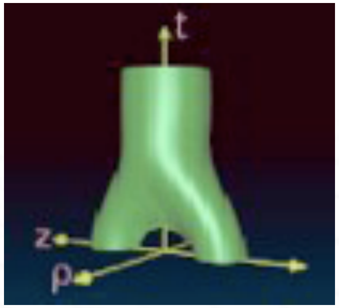
- Numerical Relativity:
  - Solve numerically Einstein's GR eqs for dynamical spacetime, in strong gravity where no approximations hold.
  - Very difficult problem …
- Goals:
  - Understand gravity at its strongest manifestation
  - Inform gravitational wave detection
  - Determine characteristics of compact objects (final black hole)
- Challenges:
  - Several scales required for physics
    - Mass of the smallest BH, BH spins, etc
    - Wavelength of the waveform in the wave zone
  - Long waveforms matching early PN inspiral
  - Large parameter space: mass ratio, spins, eccentricity …

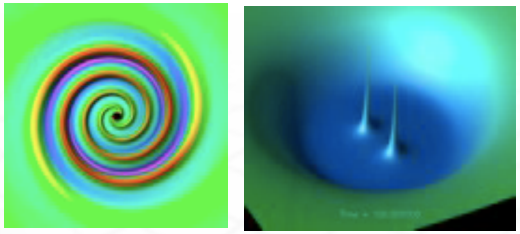


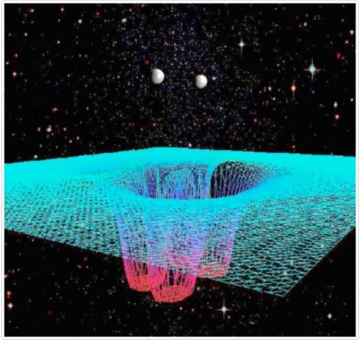


Credits: NASA GSFC group, 2007

A Brief Historical Perspective







40+years of hard labor:

1964 First Simulation (Hahn & Lindquist)

… then LIGO …

1990s Grand Challenge

- BSSN-NOK evolution system
- Puncture Initial Data (Brandt-Bruegmann)
- Gauge: Fixed Punctures (Alcubierre et al.)
- Lazarus (Campanelli et al)

2004 One Orbit (Buegman et al.)

Breakthrough:

2005 Binary Inspiral and Merger

Pretorius, PRL 95

2005-06 Moving Punctures

Campanelli et al PRL 96 (RIT)

Baker et al PRL 96 (NASA)

Results:

2006+ GW Waveforms & Orbits,

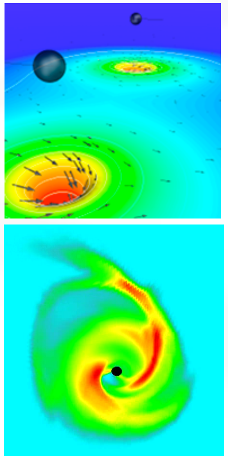
Spin dynamics, Mass ratios, GW Recoils, BH remnants, BHs multiplets

2009+ Community Collaborations

2010+ Extreme BH Binaries

BH Binaries in a gaseous environment

Numerical Relativity Today



Spectral Einstein Code (SpEC):

Generalized Harmonic, but 1st order

Physical BCs

Highly-accurate, but less flexible (care needed to get BH-BH merger)

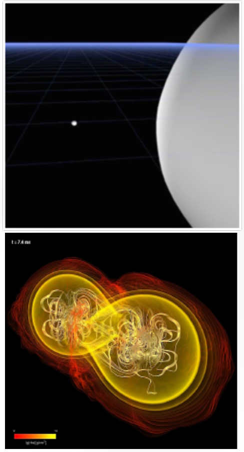
Extended to GRMHD (BH-NS, Duez)

Moving Puncture Codes:

BSSN + Punctures, AMR

Less-accurate, but more flexible and robust (BH-BH mergers)

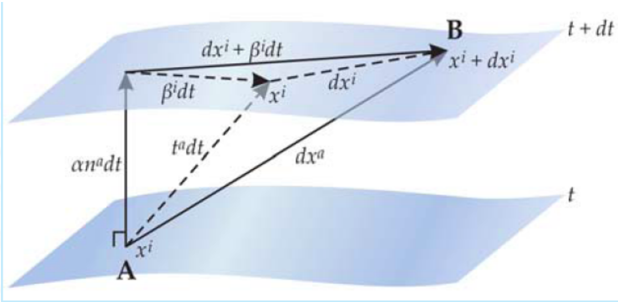
Community Codes, including GRMHD (http://einsteintoolkit.org)



The Moving Puncture Approach

- 3+1 formalism [Arnowitt, Deser and Misner, 1962] and BHs as punctures [Brandt and Brügmann, 1997]

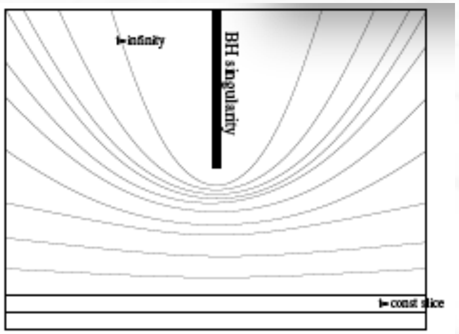
- Strongly hyperbolic BSSN evolution system [Nakamura-Oohara-Kojima (1987), Shibata-Nakamura (1995), Baumgarte-Shapiro (1999)]
  - 17 variables g_{ij}, $A_{ij} \sim \partial_t g_{ij}$, Φ, K, Γ^i



- New variables that regularize the puncture: $W = e^{-2\phi}$

- Modified Gauges to allow punctures to move across grid
  - Singularity avoiding
  - Coordinate not too distorted
  - Gridpoint should resolve region of interest

$$(\partial_t - \beta^i \partial_i)\alpha = -2\alpha K$$
$$\partial_t \beta^i = 3/4 \tilde{\Gamma}^i - \eta \beta^i$$

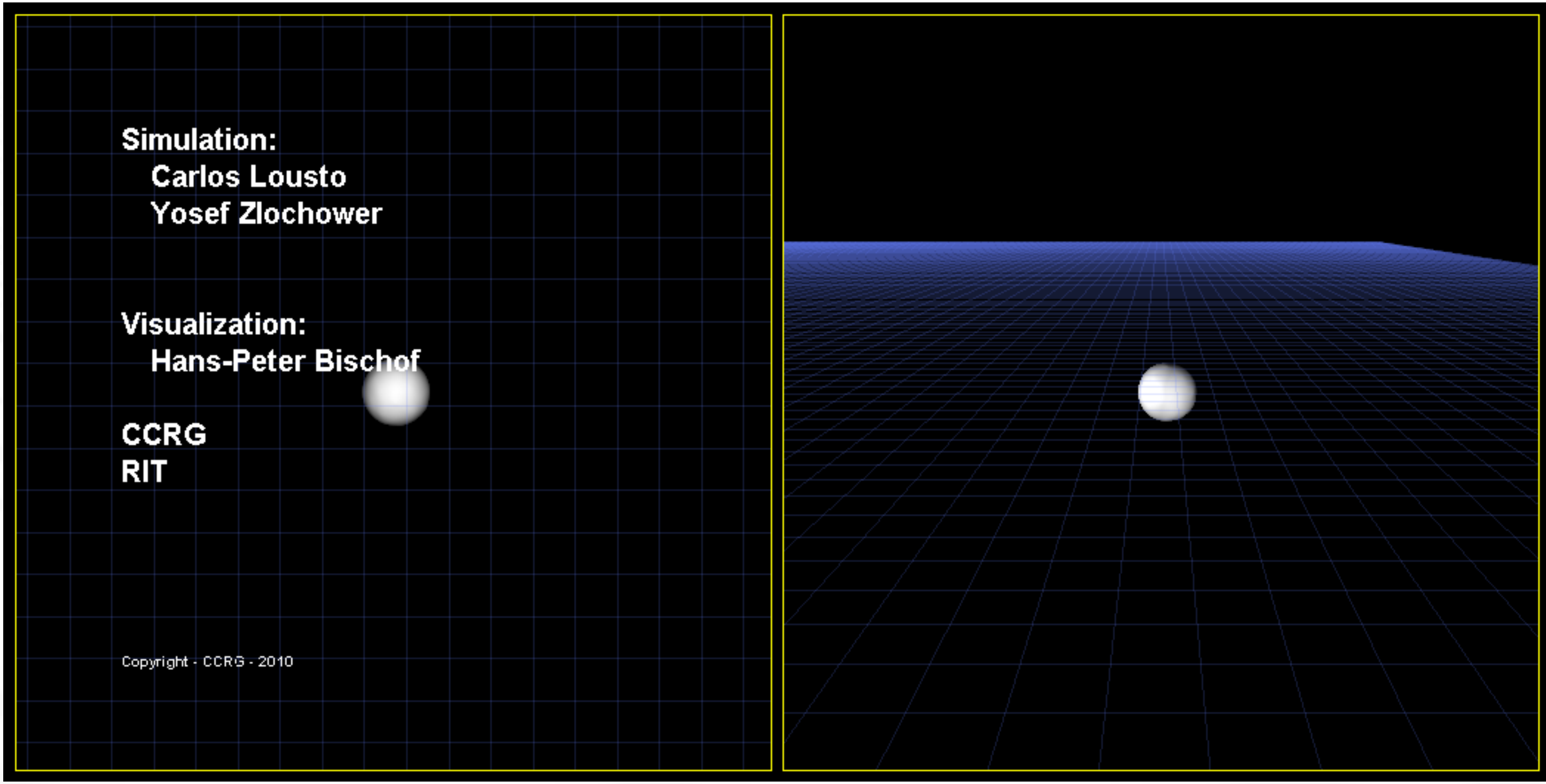


- Numerics:
  - Method of Lines Integration: RK4 time integration, 8th-order spatial finite differencing, with Kreiss-Oliger dissipation.
  - Many Scales in the problem: parallelization (MPI) and AMR techniques (moving boxes).

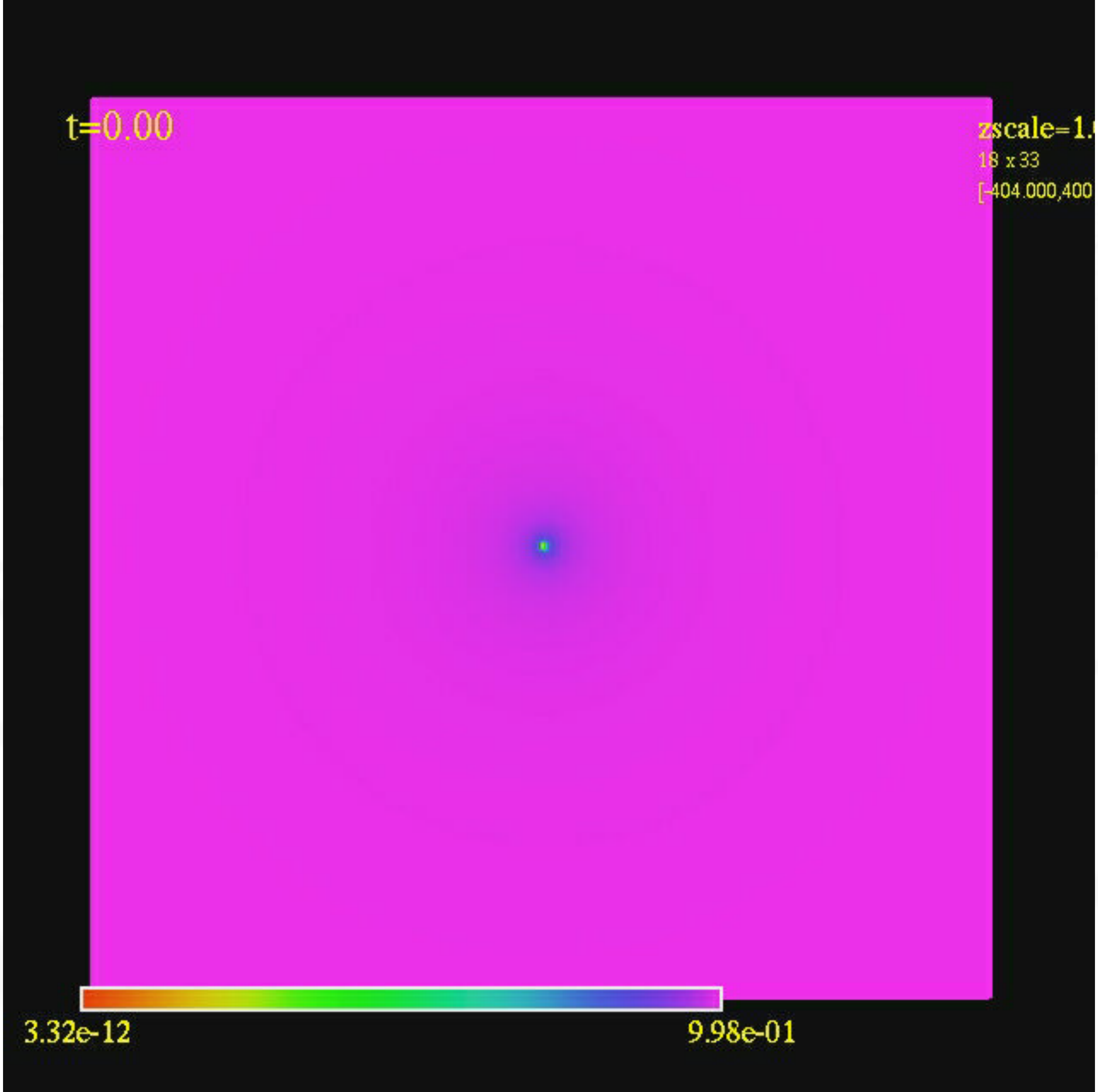
- Open Source Codes: The einsteintoolkit.org, ~ 30 groups worldwide, Caltech/Gatech/LSU/RIT as lead institutions

- Extraction of physics quantities "at infinity" and at the BH horizons, such as conserved masses, momenta and spins, as well as radiation waveform, energy, angular and linear momenta.

Vacuum GR Simulation Challenge



Very challenging GR simulation of 1:100 mass ratio BH binary, with 16 levels of refinements in AMR and intelligent input from BH perturbation theory on where to place the refinement boundaries [Lousto & Zlochower, PRL 2011]



t=0.00
zscale=1.
18 x 33
[-404.000,400
3.32e-12
9.98e-01

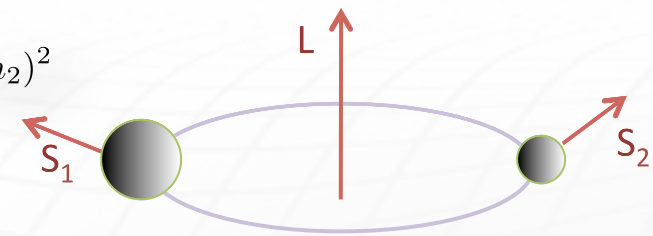
Parameter Space of Gravitational Waveforms

- BH binaries span over a large parameter space:

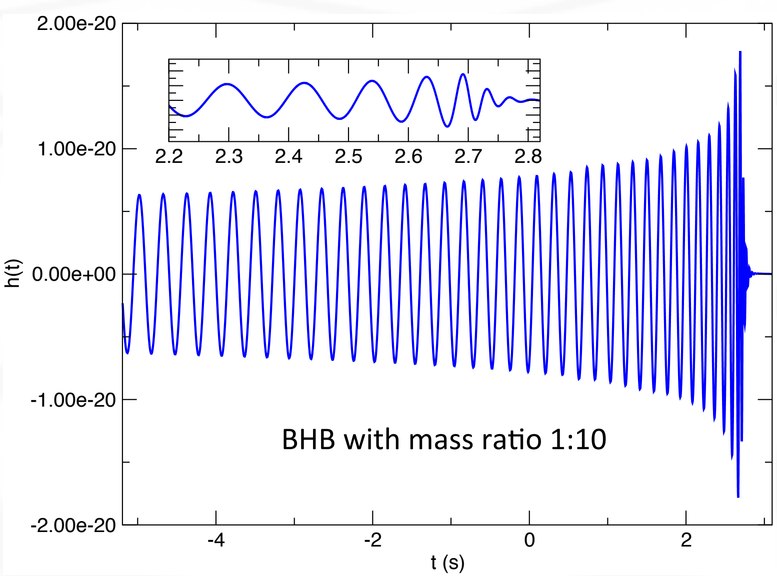
mass ratio (1 parameter) : $q = m_1/m_2 \leq 1, \quad \nu = \eta = m_1 m_2/(m_1+m_2)^2$

spin (6 parameters) : $\vec{S}_i = m_i^2 \vec{\alpha}_i, \quad |\vec{\alpha}_i| \leq 1$

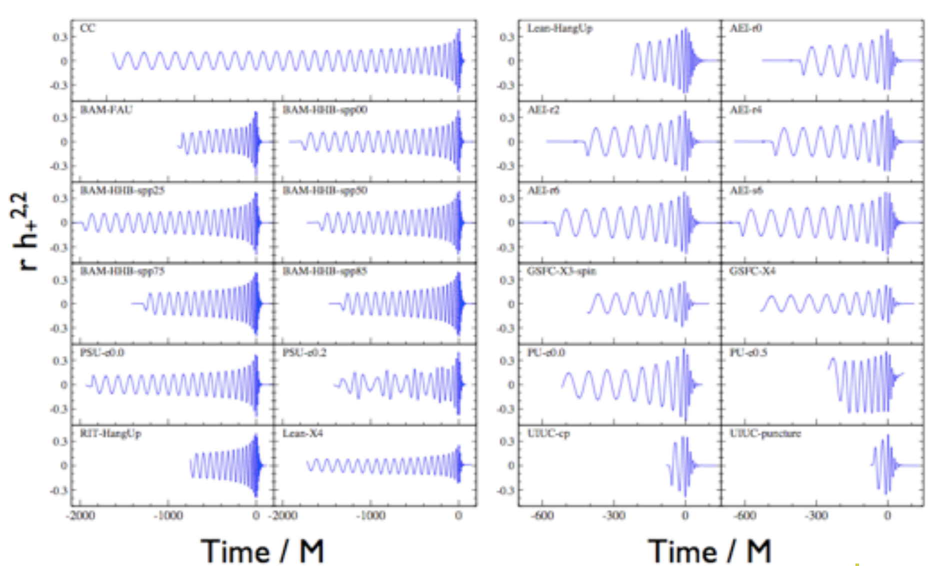
eccentricity (1 parameters) : e



- Waveforms encode information about the BH parameters (mass, spins), distance, merger rates, etc, and are essential on assisting GW detectors to predict what to expect and for physical information extraction



[Lousto++ (MC) 2010]

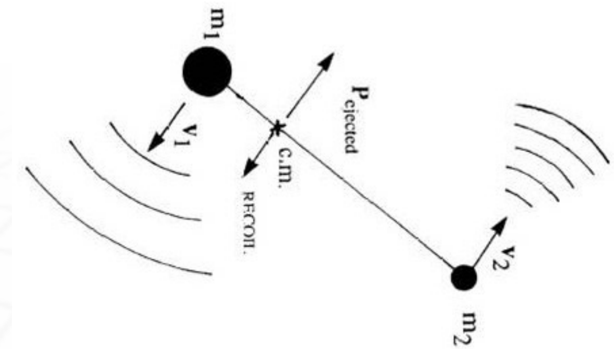


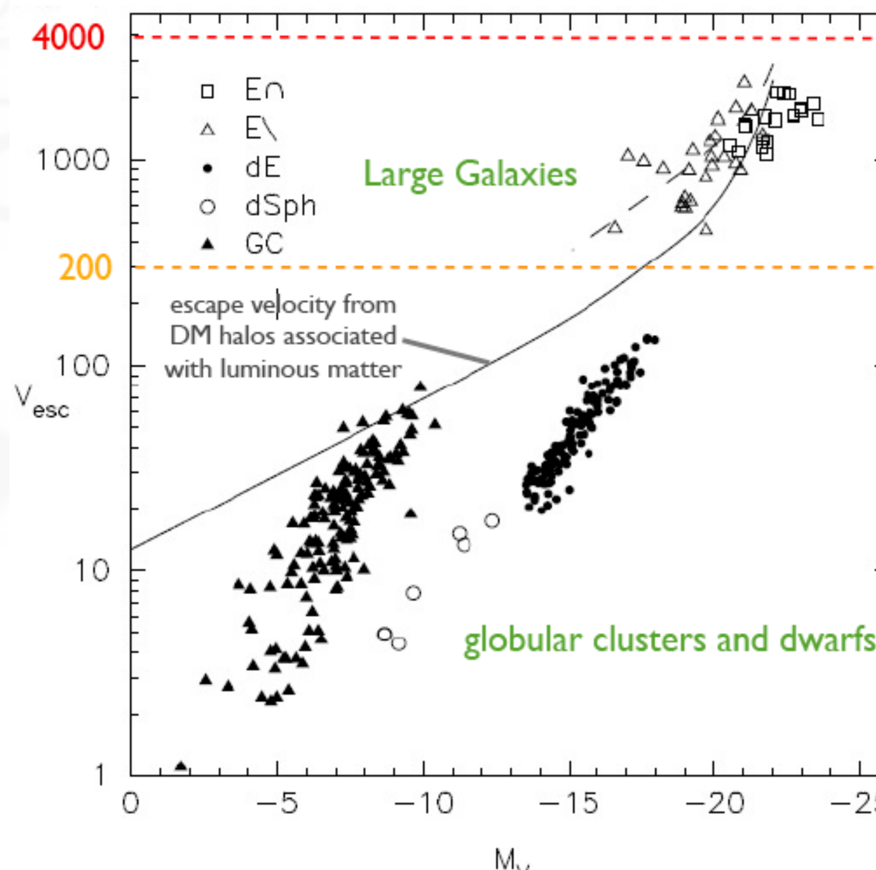
https://www.ninja-project.org/

Gravitational Radiation Recoils

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

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





Spin-Orbit Dynamics

- Repulsive spin-orbit interaction maximizes radiation (up to 10%) and produce “hang-up” orbits before merger when spins are aligned with L [Campanelli, Lousto, Zlochower, 2006]

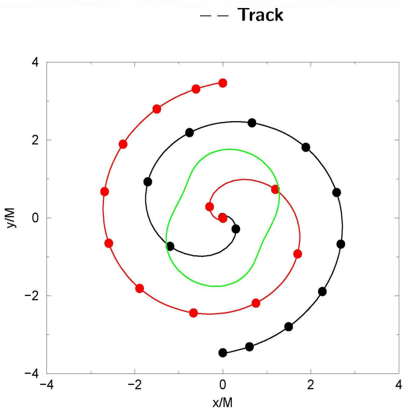


Figure 4: Puncture tracks for the – – configuration

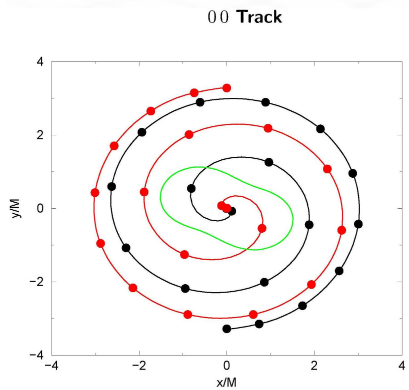


Figure 5: Puncture tracks for the 0 0 configuration.

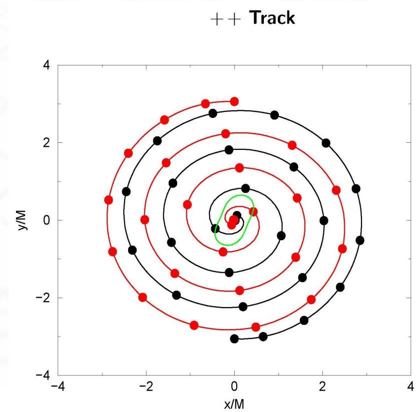
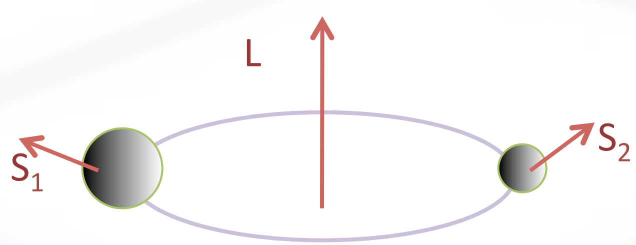
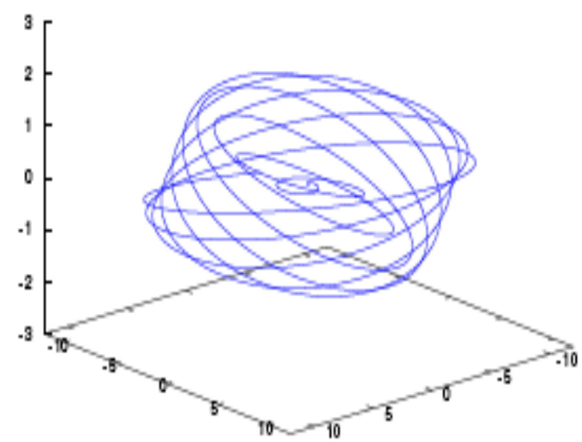


Figure 6: Puncture tracks for the + + configuration.

- Merger of generic, precessing BH binary [Campanelli, Lousto, Zlochower, 2009]





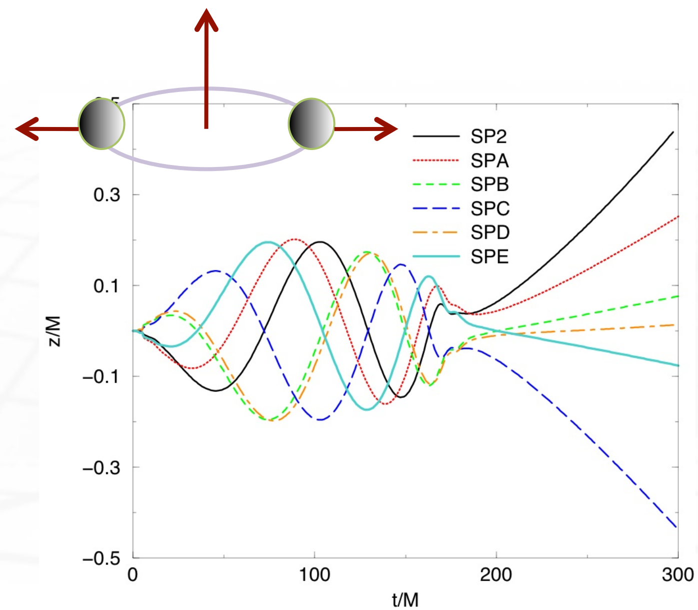
Spins Dynamics and Gravitational Radiation Recoils

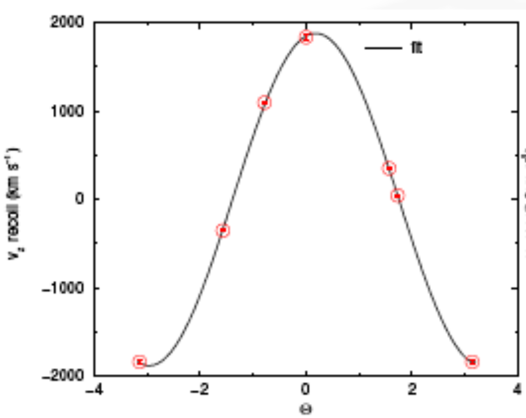
- Campanelli et al (2007, ApJL and PRL), Gonzalez et al (2007, PRL): found recoils up to 4,000 km/s, when the BH spins are within the orbital plane, equal in magnitude, but opposite in direction (SuperKicks).

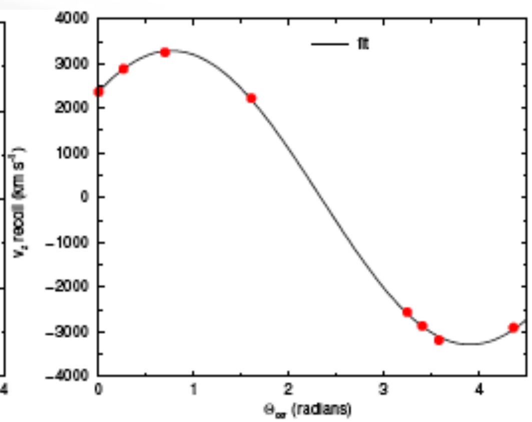
- The bobbing of the orbit (due to spin-orbit coupling) causes an asymmetric beaming of the radiation and the net asymmetry is balanced by a recoil at the moment of merger

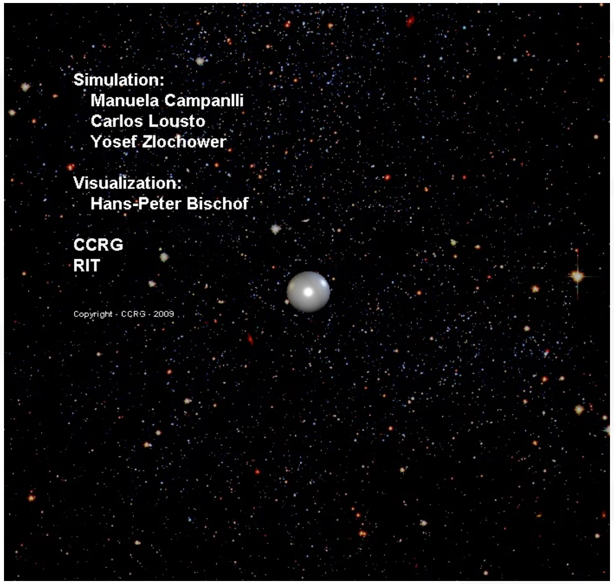
- The recoil was modeled by an semi-empirical formula which depends sinusoidally on the initial phase of the binary, and linearly (at leading order) on the spin magnitude:

$$
\begin{aligned}
V &= V_1 \cos(\phi - \phi_1) + V_3 \cos(3\phi - 3\phi_3),\\
V_1 &= V_{1,1}\alpha + V_{1,3}\alpha^3,\\
V_3 &= V_{3,1}\alpha + V_{3,3}\alpha^3,
\end{aligned}
$$





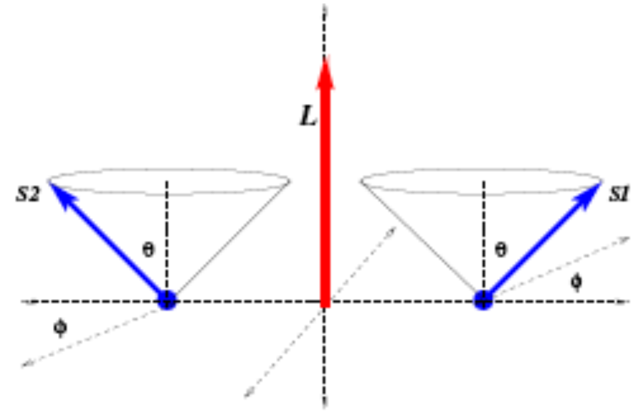




[Campanelli et al, ApJL 2007, Campanelli et al, PRL 2007, Lousto & Zlochower, PRD, 2010]

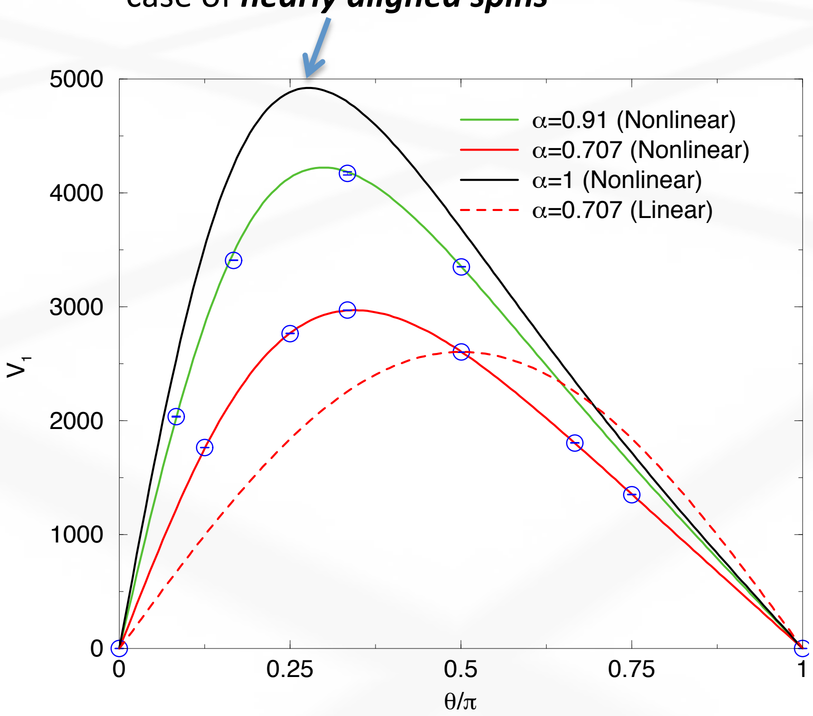
New Calculations of GW Recoils

Hangup: repulsive spin-orbit interaction maximizes radiation (up to 10%) and orbits before merger when spins are aligned with L [Campanelli, Lousto, Zlochower, 2006]

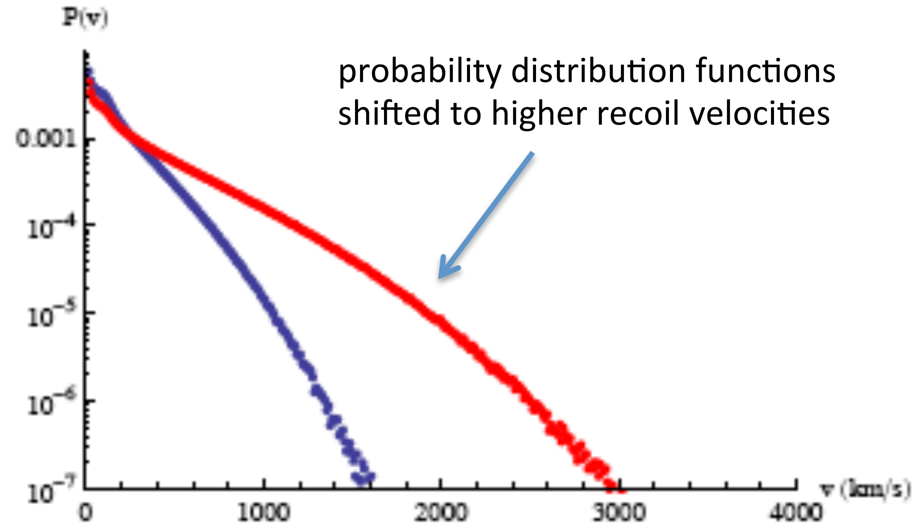


Lousto & Zlochower PRL 2011: nonlinear combination of the hangup effect and superkicks (higher order spin terms) can lead to very large recoils:

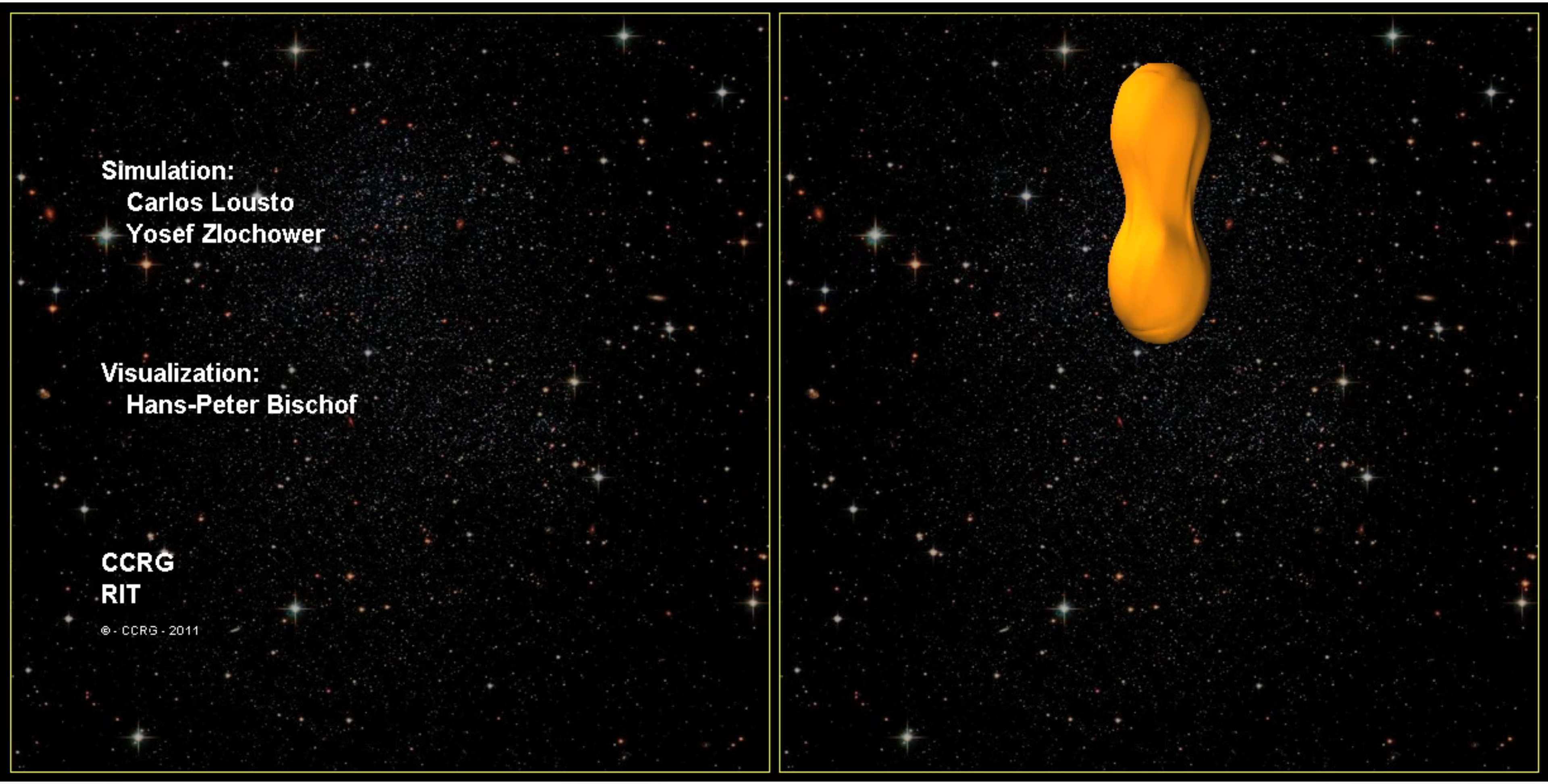
peak occurs at 5000 km/s in the case of ***nearly aligned spins***



Partial alignment of the spins by gas accretion cannot inhibit large recoils as conjectured in [Bogdanovic et al (2007), Dotti et al. (2010)]

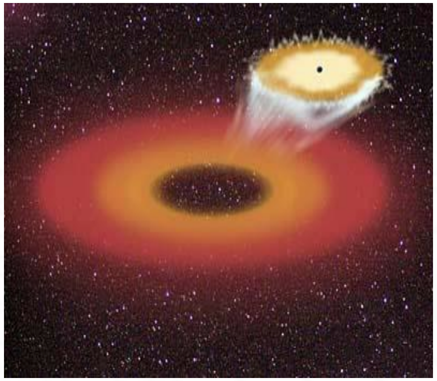


New Superkick Movie



Super-Hang-Up Kick (Left) and Radiated Power (Right)
[Lousto & Zlochower, PRL (2011)], visualization by H.P. Bischof

Astronomical Candidates of Recoiling Black Holes



• The recoiling BH can retain an accretion disk while the it wanders far from the galactic nucleus

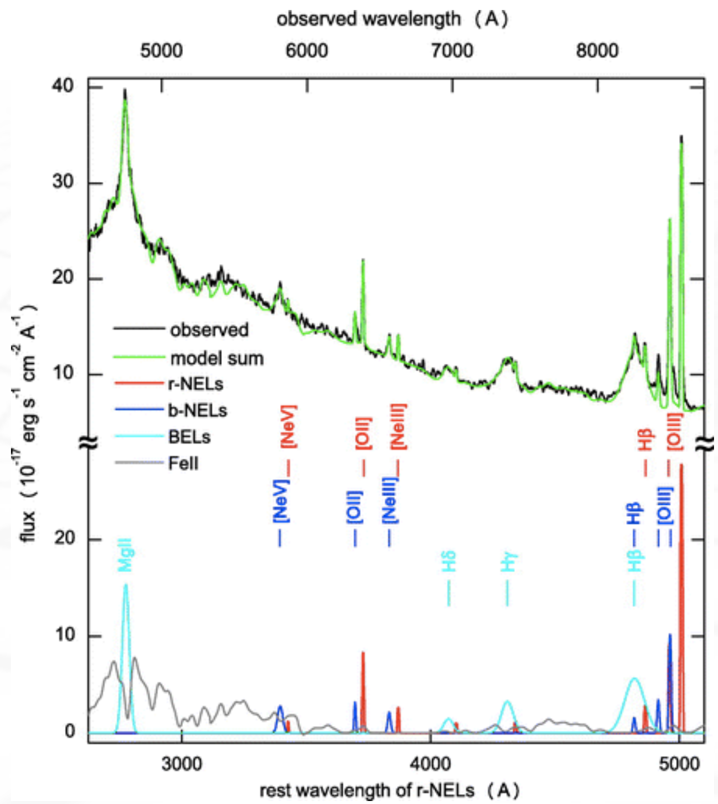
•This could explain some observational results …

• Double-peaked NRL emitters [Komossa et al. (2008); Shields et al, (2009; Civano et al, (2010)]

• New surveys:

- Eracleous et al (2011): DV>1000km/s. 88 objects, 68 spectra -14 binaries
- Tsalmantza et al (2011), SDSS, 32 objects -9 binaries

These observations could be a confirmation of the highly dynamic, nonlinear (strong field), predictions of GR.



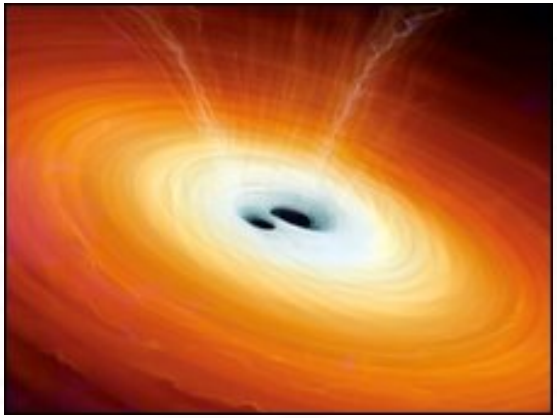
SDSS J0927 + 2943, BLR shifted 2600 km/s

Kick interpretation: Blue system is kicked hole, with blue NLR due to expanding gas from edge of bound disk. Red NLR is in host galaxy ionized by kicked AGN.

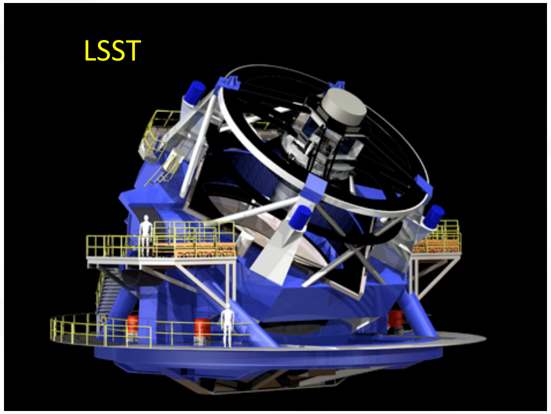
Light Signatures from SMBBH Mergers

- SMBBH mergers could yield detectable light signals from the surrounding gas

- Depending on the merger stages one could look for EM variability in prompt Optical, UV signals, X-ray flares, year-timescale events in IR and other bands
  - Distinguish from single SMBH AGNs variability
  - High-time resolution astronomy (ALMA, LSST, Pan-Starr, JWST, etc)



- A coordinated GW and EM astronomy will allow -
  - Redshift / distance determination for cosmology
    Standard Sirens [Schutz 1986, Holz & Hughes 2005]
  - Understand SMBH dynamics and evolution
  - Merger scenarios -- Highly relativistic plasma

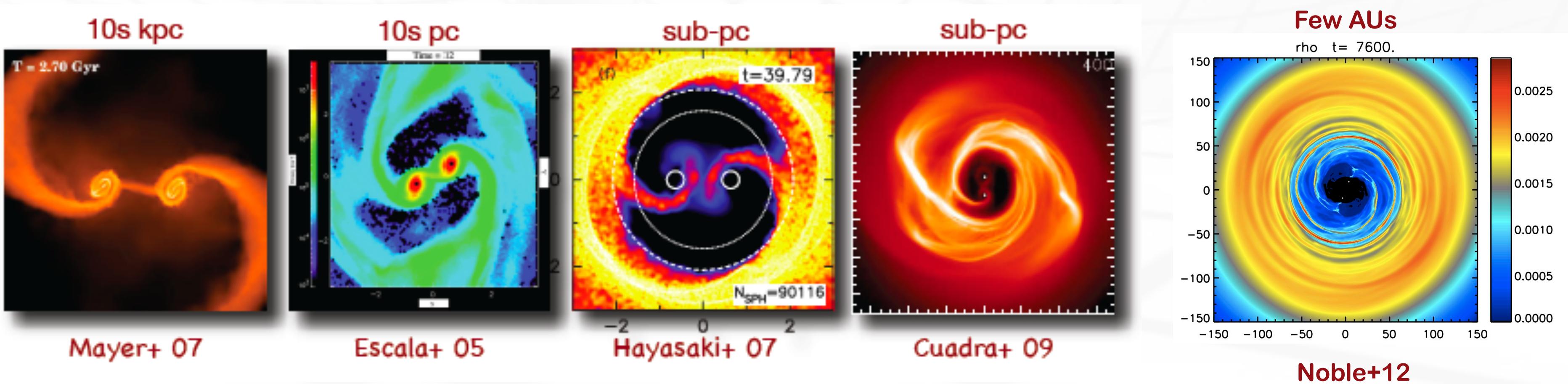


- We need robust theoretical models of SMBBHs in their surrounding astrophysics environments to predict source variability accurately, with good accretion disk physics and MHD dynamics

Modeling SMBBH Mergers in Astrophysics

- Overall, the problem is too big to handle even for the fastest supercomputers (scales ranges from 10^5 pc to 10^{-5} pc)

- Then do systematic studies of each stage of the coalescence, bridging the gaps among simulations:

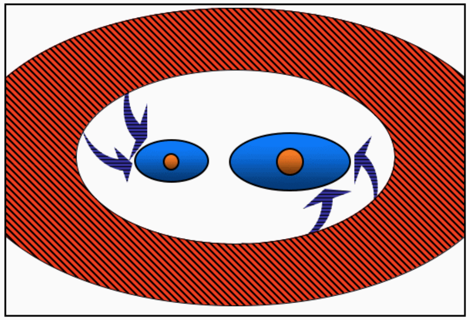


Newtonian Hydrodynamical Simulations → GR-MHD Simulations

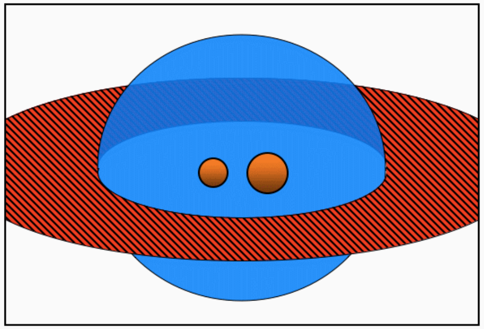
- Need astrophysically realistic model for BBH dynamics and accretion disk physics
  - Gravity: Newtonian (Kpc-sub-pc), Post-Newtonian and GR (AU)
  - Matter: Hydrodynamics and MHD (kp-pc), relativistic MHD (sub-pc-AU)

Modeling the Environment during the inspiral and merger proper of SMBHs

Not well know at scales < 0.01 pc, but there are several possible physically motivated scenarios depending on the balance of heating and cooling:



- Circumbinary Radiatively Efficient Thin Disk:
  If cooling is relatively efficient, the gas settles into a rotationally supported geometrically thin accretion disk around the BBH. kT ~ 0.1–1 MeV (hard X-ray, γ-ray)



- Radiatively Inefficient Hot Gas:
  If cooling is inefficient, the BBH is immersed in a pressure supported, geometrically thick torus or cloud. kT ~10–100 eV (UV, optical)

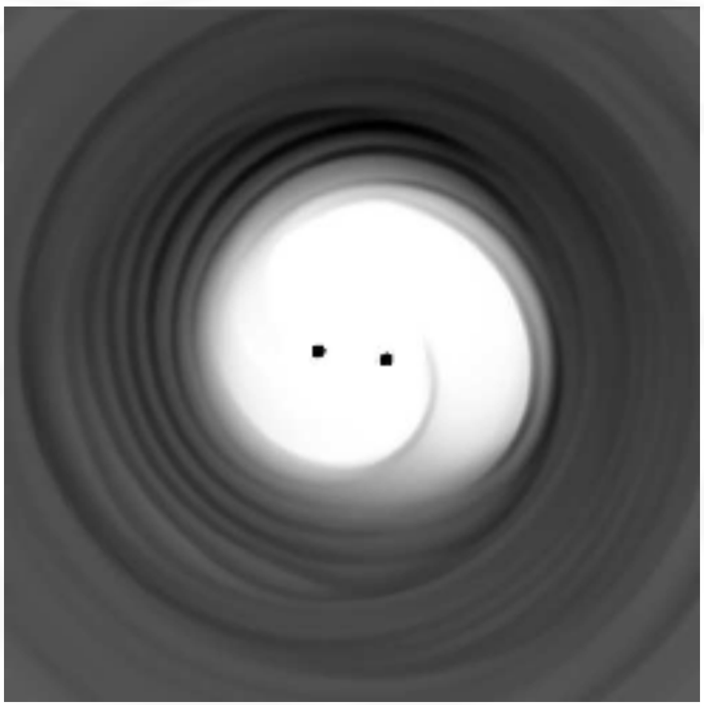
- Chaotic Central Accretion:
  Sequence of randomly oriented disks.

We adopt here the first scenario based on accretion disks models around stellar-mass rotating black-holes (McClintock++, 2011)

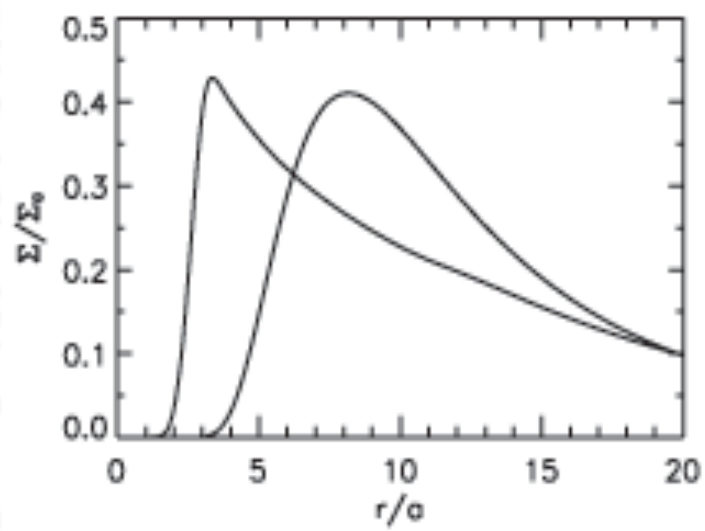
Newtonian Simulations of Circumbinary Disks

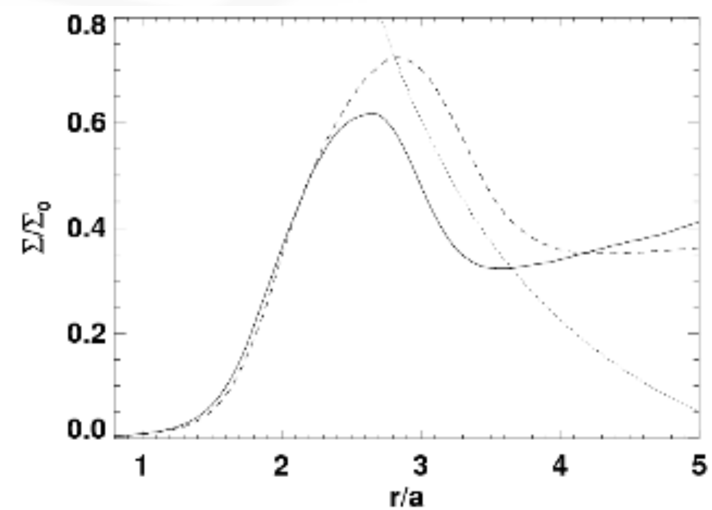
- Hydrodynamical simulations show that a gap is forming at $r \approx 2a$ (where a is the binary separation) due to the torque exerted by the binary [MacFadyen & Milosavljevic 2008, Cuadra et al, 2009]

- MHD torques (and MRI) seem to be able to accrete more material through the gap, but gap still exists [Shi ++ 2011]



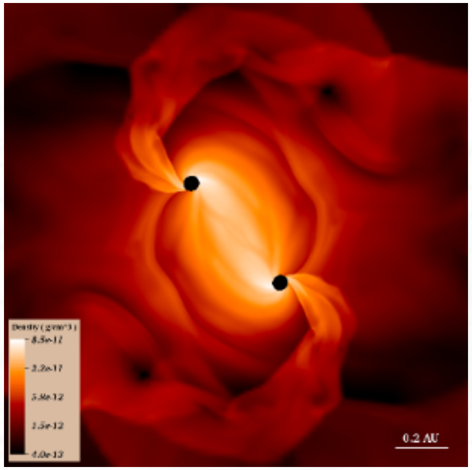
Surface density tends to buildup at $r \sim 2a$



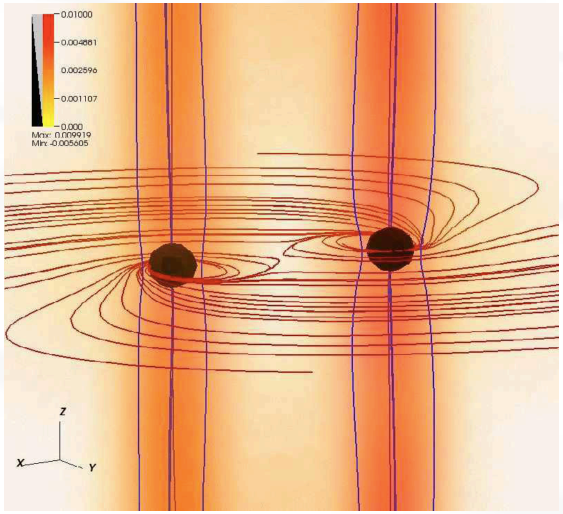


GR Simulations of BBH in Gaseous Environments

- Collisions of test-particles [Van Meter++ 2009]
  - Larger Lorentz factor near merger
- Dynamics of EM fields [Palenzuela++ 2010; Palenzuela++ 2011]
  - Double Jets, Enhanced EM fields
- Hydrodynamics of hot gas clouds [Bode++ 2010; Farris++ 2010], and circumbinary disks [Farris++ 2011]
  - Streams near BHs, Enhanced Luminosity at merger
  - Larger effects with Spins



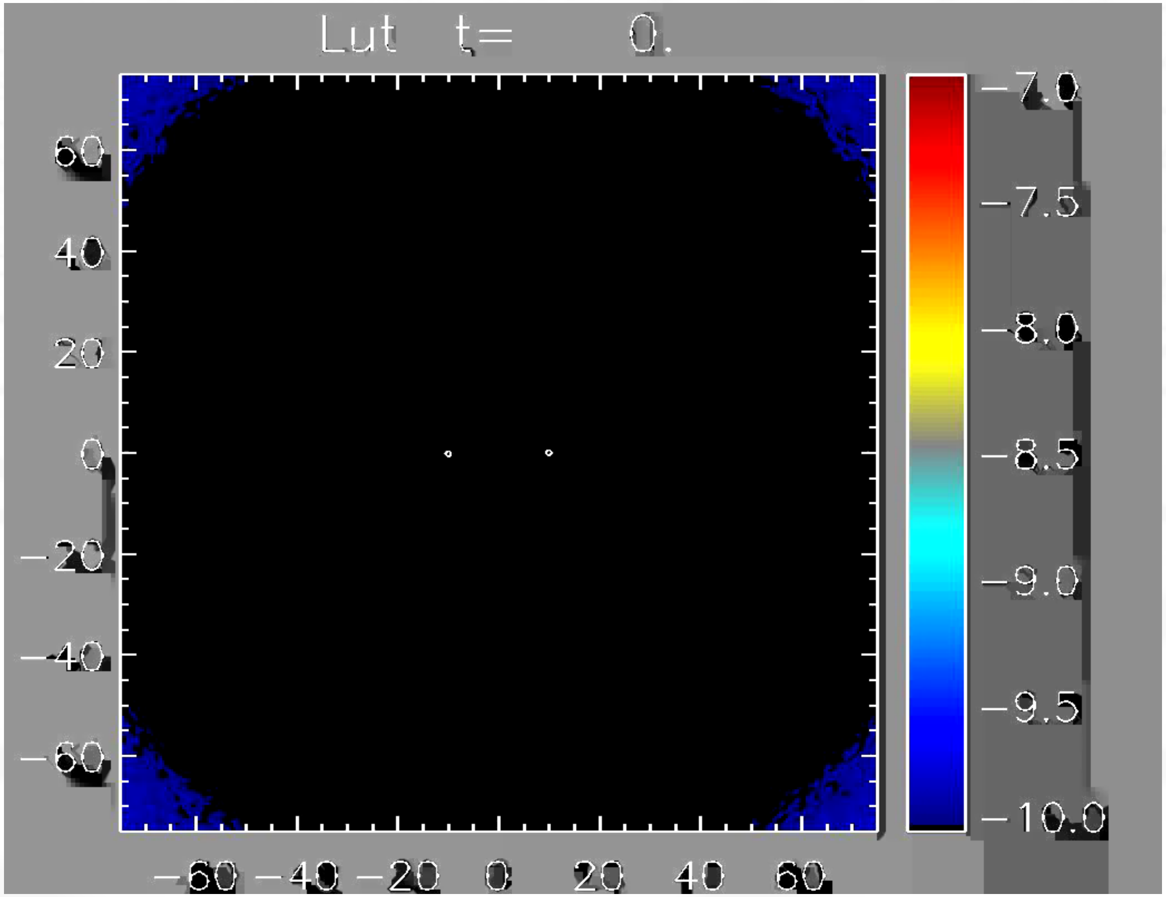
However, the amount of gas available to be heated in a merger is determined by a competition between the internal MHD stresses (and MRI) that drive inflow and the binary torques that tend to keep gas at away from the merging black holes.



Needs longer orbital dynamics and MHD to determine the balance between these competing effects

Cicumbinary MHD Accretion into Inspiraling Black Holes

First relativistic MHD simulation of circumbinary accretion disk into binary black hole inspirals



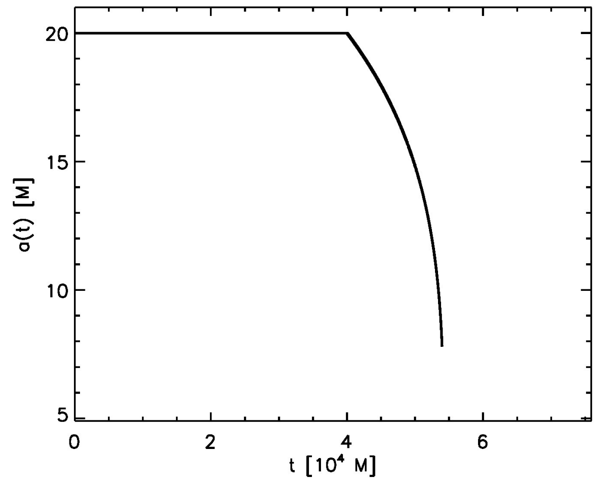
- Cold thin circumbinary accretion disk with a flux conservative GR-MHD code (HARM3D) [Noble++ 2008], adpated to evolve dynamical BBH spacetime
- BBH spacetime based on Post-Newtonian (PN) expansion of GR equations of motion in $(v/c)^2$ and/or $GM/(rc^2)$, where motions are slow compared to the speed of light and where gravitational fields are weak.

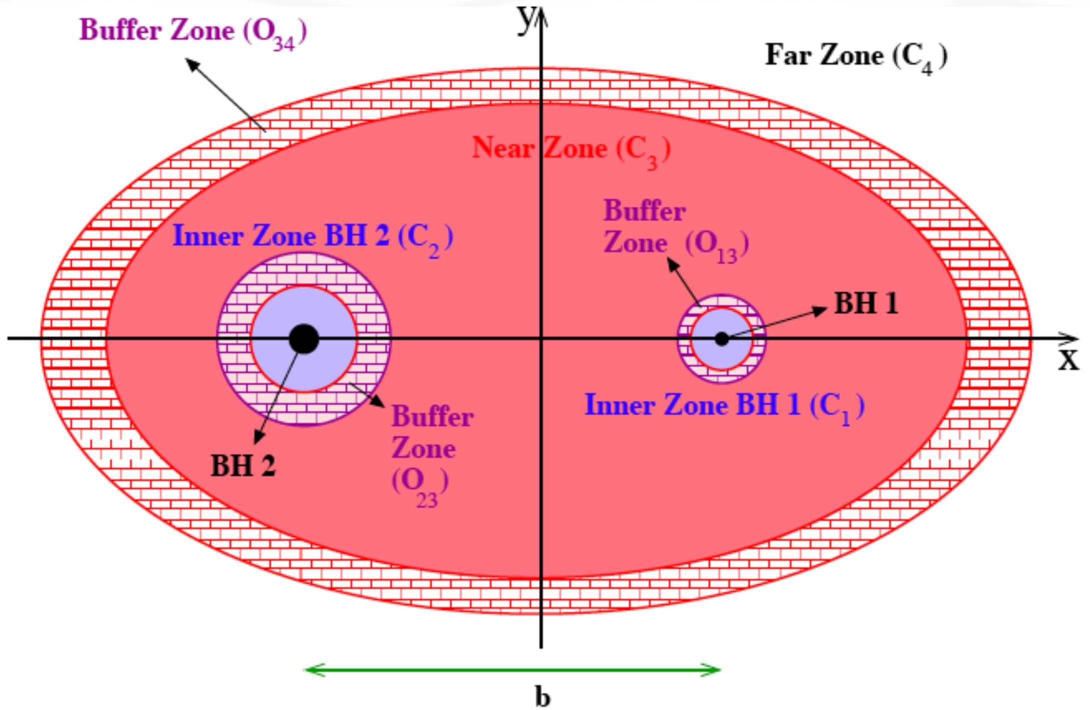
[Noble, Mundim, Nakano, Krolik, Campanelli, Zlochower and Yunes, in prep for ApJ, 2012]

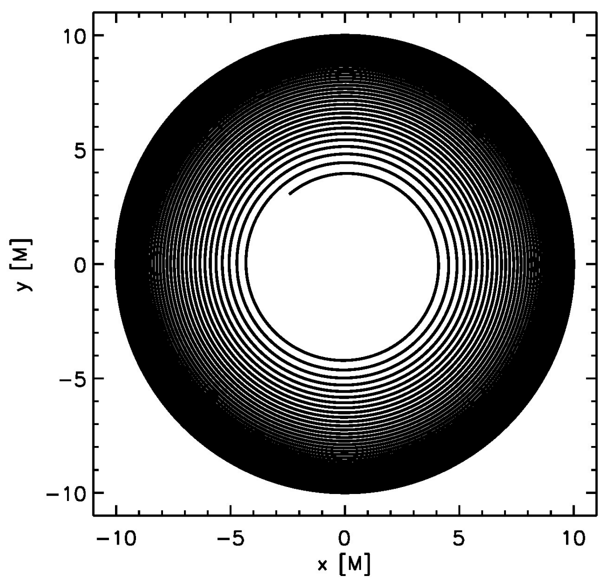
Spacetime Model

- BBH spacetime based on Post-Newtonian (PN) approximate model [Johnson-McDaniel, 2009]. That is, one solves Einstein's field equations perturbatively, expanding in $(v/c)^2$ and/or $GM/(rc^2)$ (motions are slow compared to the speed of light and where gravitational fields are weak).

- Evolve PN equation of motion evolution for ~200 orbits
  - Keep binary at fixed separation (a_0 = 20M) until t = 40,000 M
  - For t > 40,000M, let BBH inspiral according to 3.5 PN

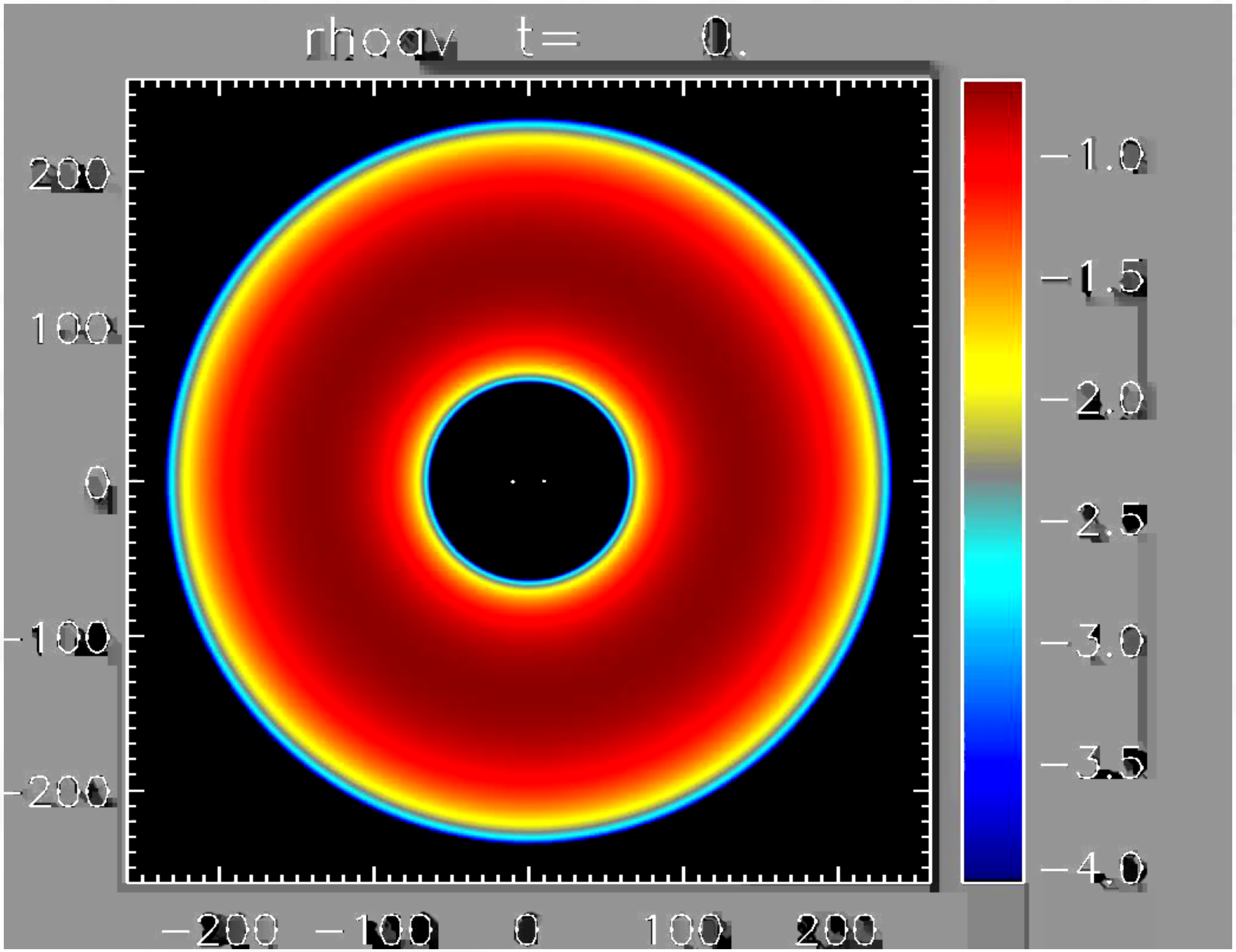


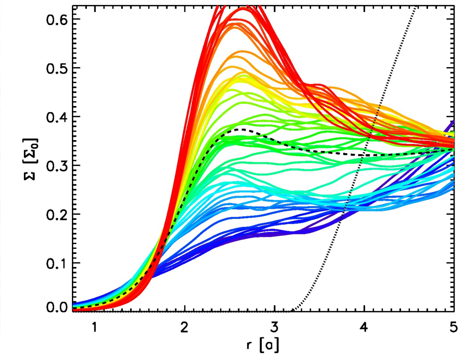


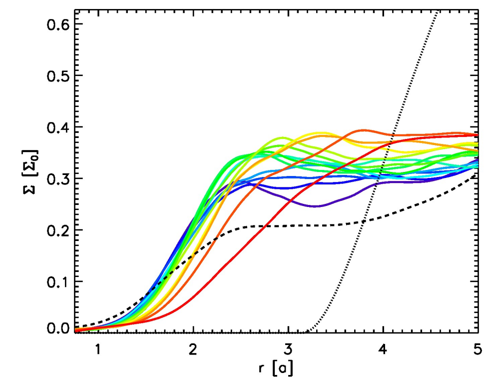


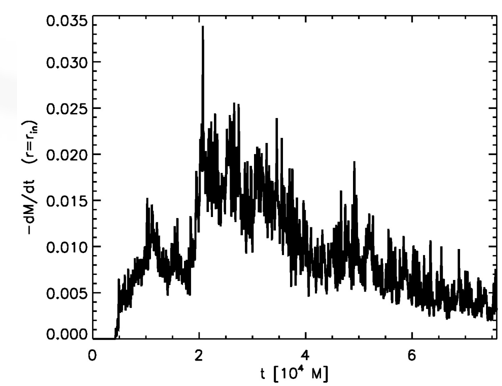
"How much mass would one expect close to a black hole merger?"

- Unlike Newtonian simulations where matter builds up at ~2.5 a, here more than 70% of the matter slides in as the binary inspiral inward until merger. Accretion rate shows little contrast in how much matter actually gets into the domain of the binary whether it's shrinking fast or not at all.









The future …

- Black Hole binary mergers are excellent laboratories for testing the extremes of astrophysics
  - Testing GR in the very-strong-field regime
  - Massive bursts of GR radiation (10^8 M_{sun} in a few days) -- very large Recoils and superkicks
  - Some of of the most strongly relativistic matter and MHD phenomena -- Enhanced EM emission, Jet production

- The field of Numerical Relativity has made tremendous steps forward and it continues to lead us to many exciting results, contributing to our understanding of the strong-field merger process in binary BHs.

- What shall we expect in the next 5 or 10 years, and beyond?

- Our understanding of gravity will soon be challenged, with advanced LIGO right at our door, and a possible future space mission …

- Deeper understanding of fundamental gravitational wave astrophysics

- Development of more efficient, reliable (open-source), GRMHD codes to model astrophysical sources of GWs

- Correlated GW and EM Astronomy and Physics!