Binary Black Holes in Astrophysical Environments

Pablo Laguna
Center for Relativistic Astrophysics
Georgia Tech, USA

NEB 15 - *Recent Developments in Gravity*
22 June 2012, Chania, Greece

EM counterparts of GW Sources

Source	GW data	GW+EM data
NS-BH, NS-NS (LIGO)	Masses, spins, NS radius, EOS, orbit inclination and orientation	Gamma-rays, jet and outflow (afterglow) properties as a function of GW & neutrinos
Supernovae (LIGO)	Extreme core (magneto) hydrodynamics and instabilities, rotation & bars	Relation of core dynamics to explosion type, progenitors, BH vs NS remnant
Radio and X-ray pulsars, low-mass X-ray binaries (LIGO)	Spin, interior structures, NS mountains and mass multipole moments induced by interior magnetic fields or accretion	Accretion rate, spin up/ down, exterior magnetic field, detection of core-crust differential rotation, thermal properties

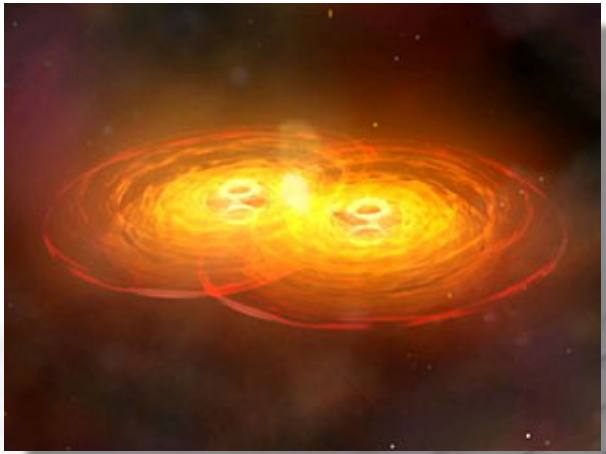
E. Phinney arXiv:0903.0098

EM counterparts of GW Sources

Source	GW data	GW+EM data
WD-WD, WD-NS (LIGO, LISA)	Final NS or BH mass, radius, spin	Nucleosynthesis, outflow energetics, explosion vs remnant?, magnetic field of remnant
EMRI (LISA)	Mass, spin of massive BH, mass of compact object, distance, high-precision spacetime, merger rate and dead star mass function in local universe, orbit eccentricity, inclination, orientation	Redshift, host galaxy ID, properties and dynamics of host nucleus, GW advance notice for EM study of tidal disruption of WD, brown dwarfs of known M,R.
Massive BBH (LISA)	Eccentricity, component masses and spins, distances, orbit inclination and orientation, formation rate, merger rate	Accretion rates, magnetic fields, dual jets, variability, disk perturbations

E. Phinney arXiv:0903.0098

Massive BH mergers



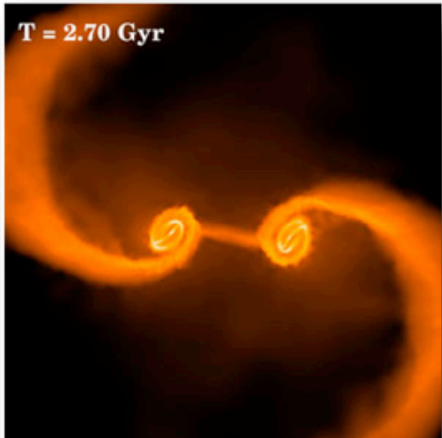
LISA

EM + GW Data:

- Improves sky localization
- Identify host galaxy morphology
- Tests of galaxy merger scenarios
- Rates of detection for GW experiments
- Luminosity distance (GWs) and redshift (EM) yields cosmological standard sirens. D. E. Holz and S. A. Hughes, Astrophys. J. 629, 15 (2005)
- BH accretion physics. B. Kocsis, Z. Frei, Z. Haiman, and K. Menou, Astrophys. J. 637, 27 (2006)
- Test ground for GR (e.g. graviton’s speed) B. Kocsis, Z. Haiman, and K. Menou, Astrophys. J. 684, 870 (2008)

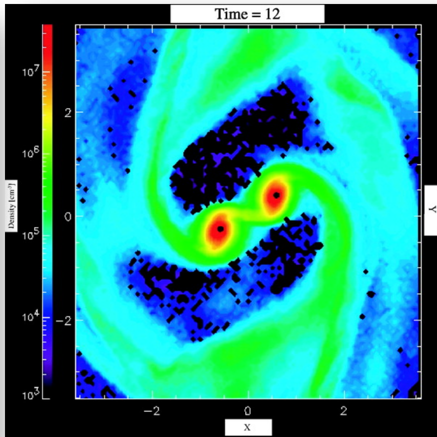
The Grand Challenge of Modeling SMBH Mergers

10s kpc



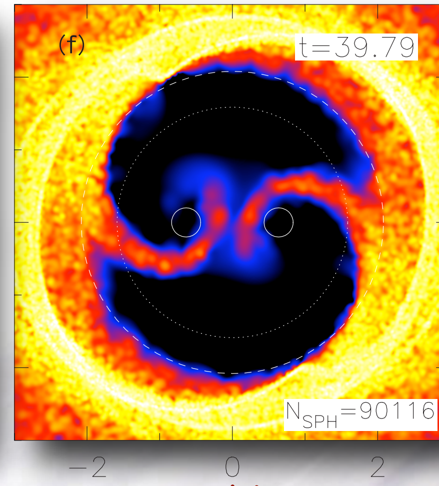
Mayer+ 07

10s pc



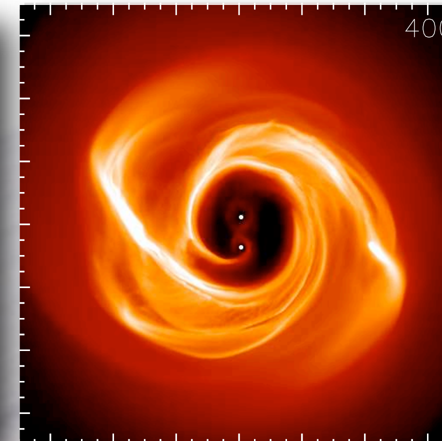
Escala+ 05

sub-pc



Hayasaki+ 07

sub-pc



Cuadra+ 09

- Galactic mergers scales: 10^2 kpc scales
- BH binaries scales: few pc when binding and AU near coalescence
- How do BHs reach the gravitational wave inspiral regime?
- What is the role of the environment?

Tremendous computational modeling grand challenge!
10^5 pc ⟷ 10^{-5} pc

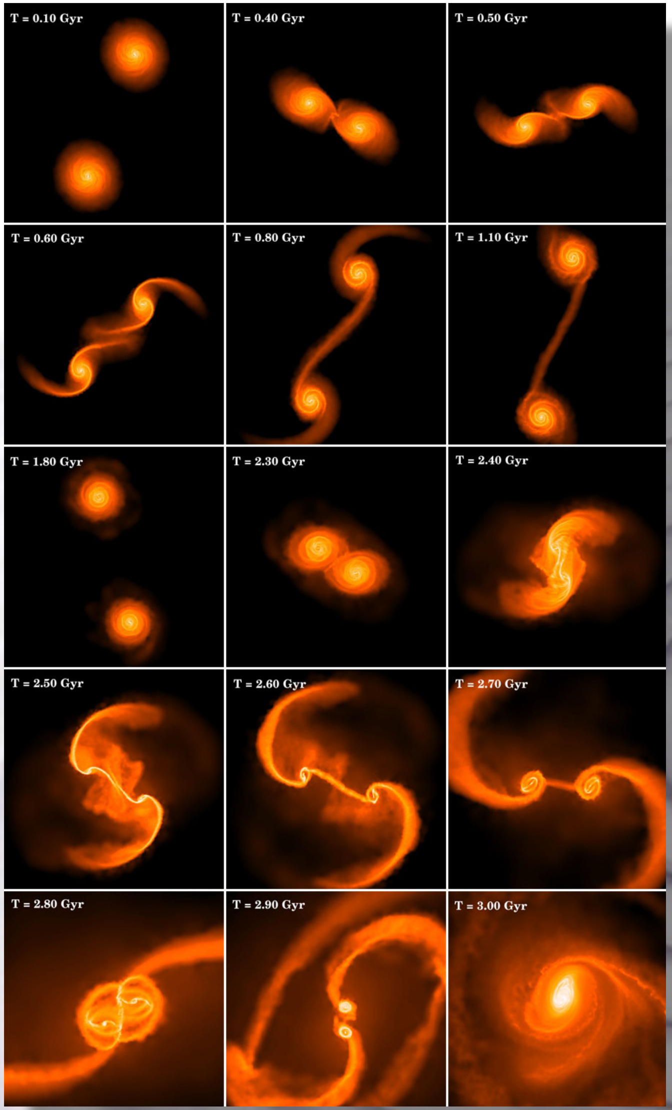
SMBBH History in Gas-rich Environments

STAGE I:

• Galactic cores drag the BHs with them.

• Each BH (e.g.10^6 M_{sun}) is surrounded by a stellar and gaseous disk (10^8 M_{sun}).

• Disk merge, and gas-dynamical friction sinks the BHs to the center.

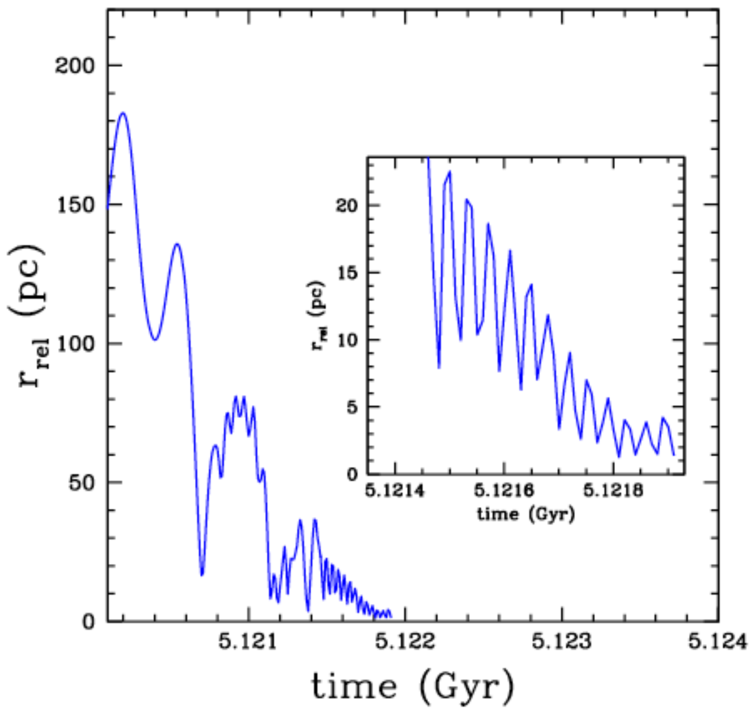


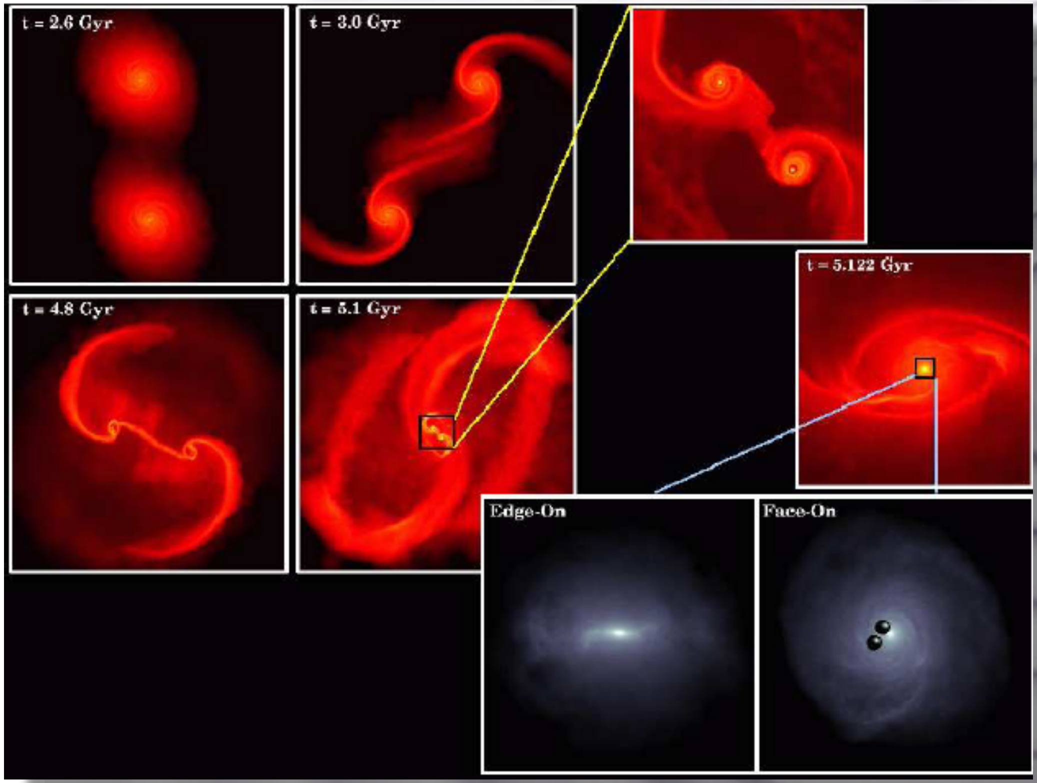
Colpi, Callegeri, Dotti & Mayer

SMBBH History in Gas-rich Environments

STAGE II (r_{sep} < 10.0 pc) :

When the mass within their separation is less than the binary mass, the BHs bind and form a Keplerian binary.





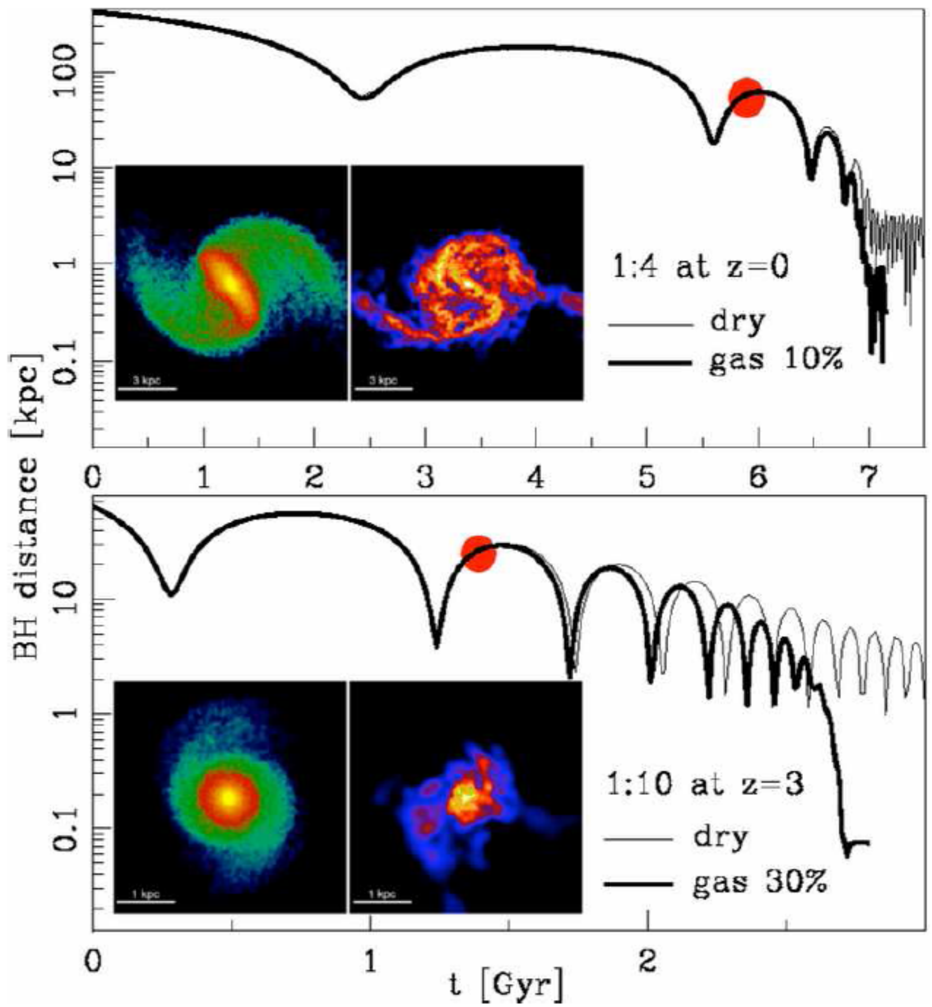
Colpi, Callegeri, Dotti & Mayer

SMBBH History in Gas-rich Environments

STAGE III (r_{sep} < 1.0 pc) :

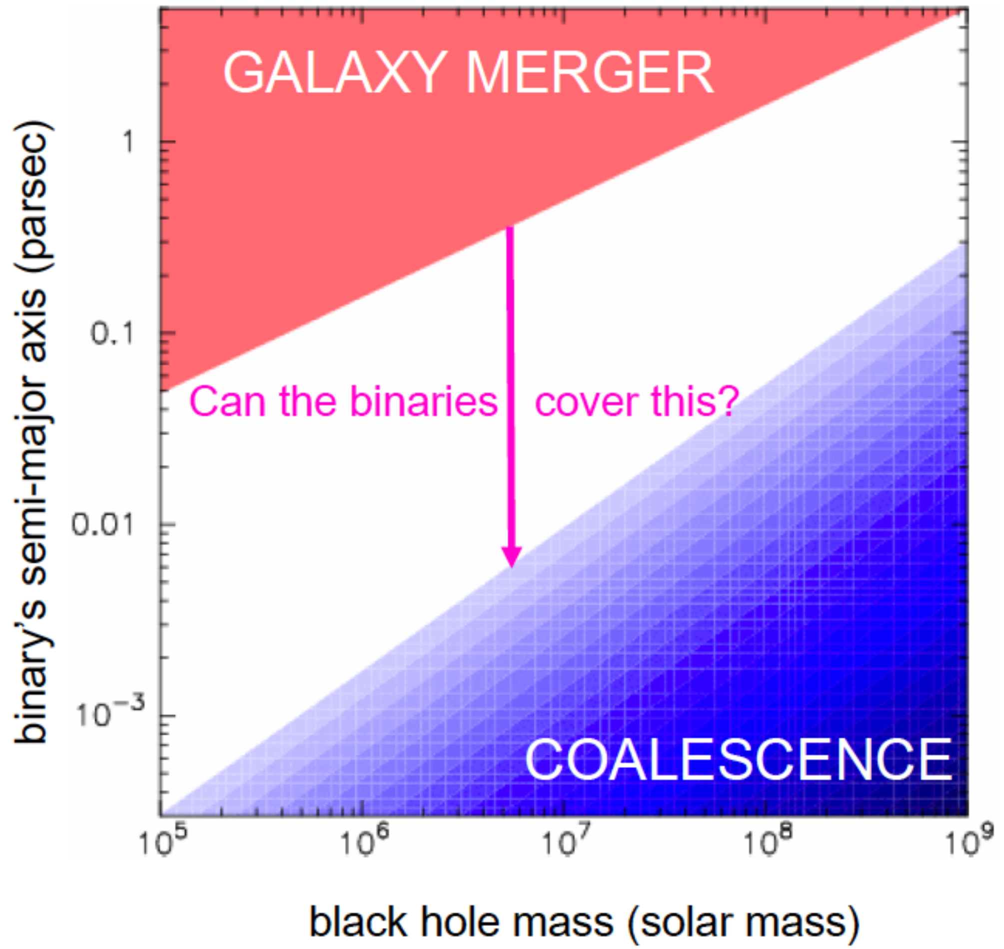
• 3-body interactions with the surrounding stars also contributes to shrink the BBH separation.

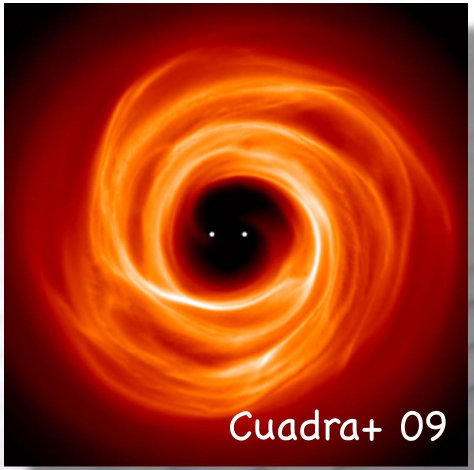
• However, shrinking stalls when reservoir of stars is depleted.



Colpi, Callegeri, Dotti & Mayer

The Last Parsec Problem





Disk assisted binary shrinkage:

- Requires a geometrically-thin circum-binary accretion disk.
- More effective for un-equal mass binaries.

SMBBH History in Gas-rich Environments

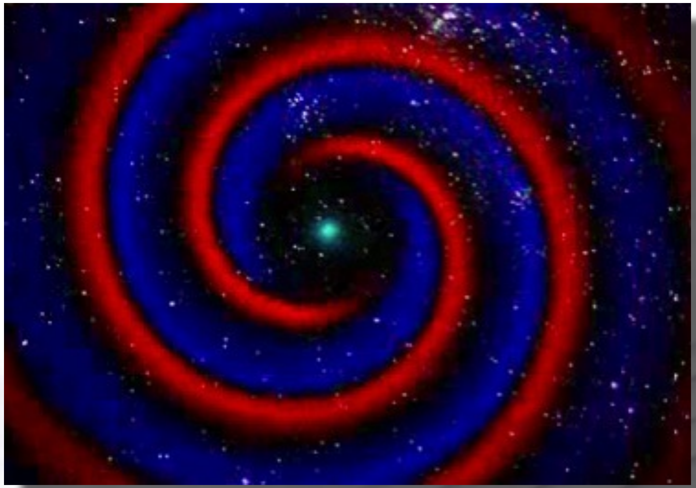
STAGE IV ($r_{sep} < 10^{-3}$ pc):

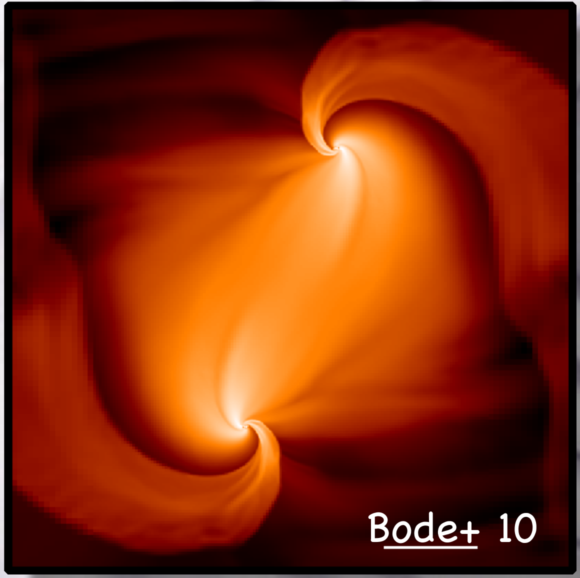
• Gravitational radiation dominates the BBH dynamics.

• The most luminous sources of gravitational radiation in the universe (~ 10^{57} erg s^{-1})

• The coalescence could in addition produce a variable or transient EM signal.

• A unique opportunity for multi-messenger astrophysics.

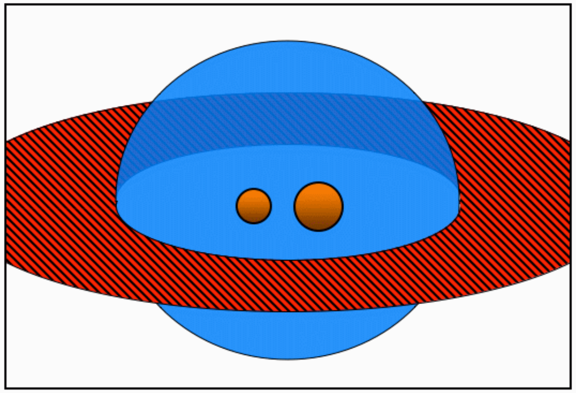




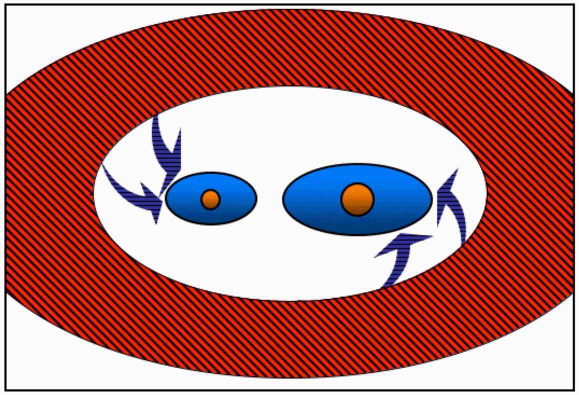
What is the environment during the late inspiral and merger of BBHs?

- Not well know at scales < 0.01 pc
- Two physically motivated scenarios depending on the balance of heating and cooling:

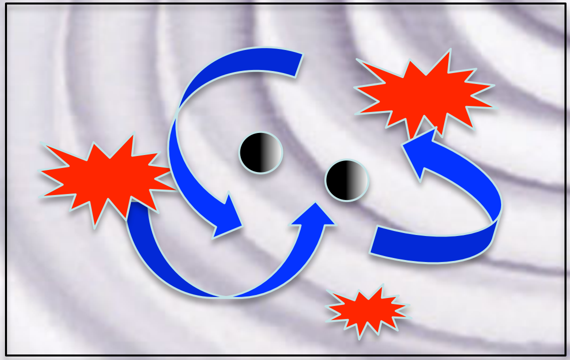
Radiatively Inefficient Hot Gas: If cooling is inefficient, the BBH is immersed in a pressure supported, geometrically thick torus or cloud. kT ~10−100 eV (UV, optical)



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



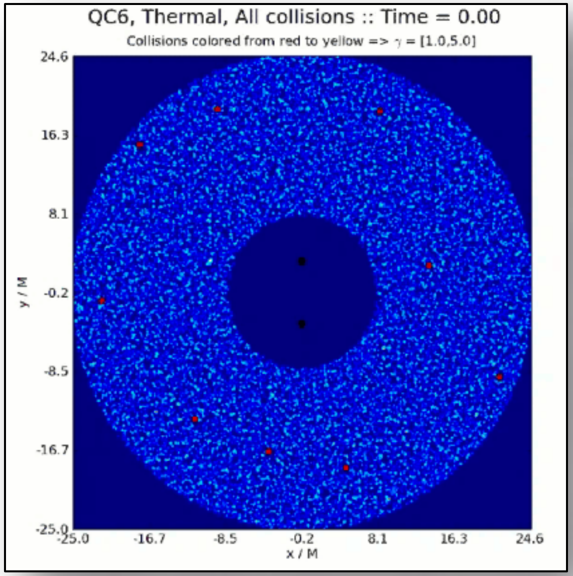
Chaotic Central Accretion: sequence of randomly oriented disks.

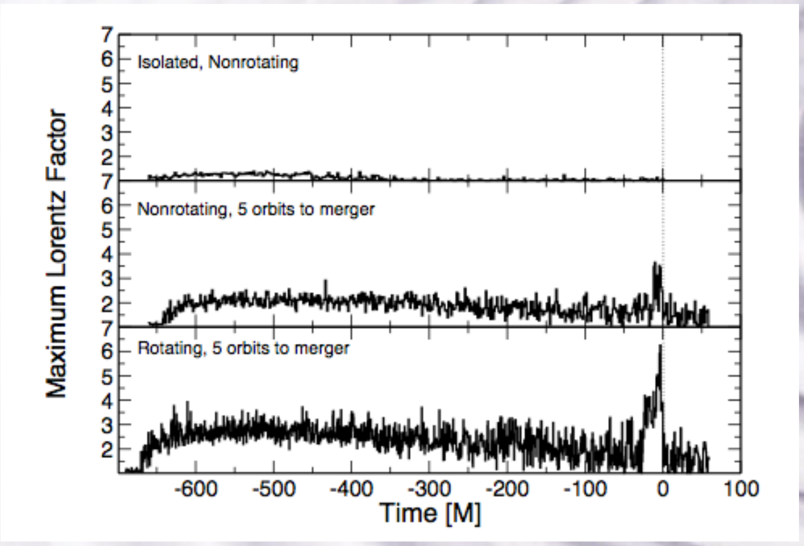


Test particles around merging BBH

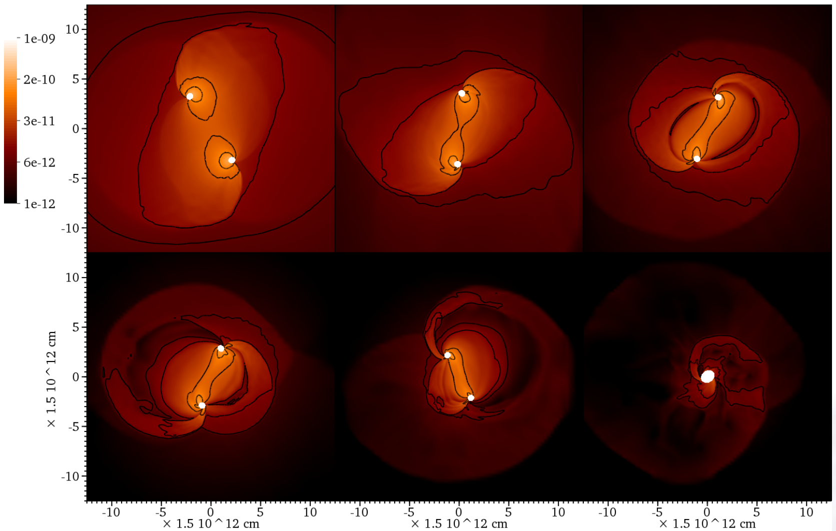
van Meter et al Ap J Letters, 711, L89 (2010)

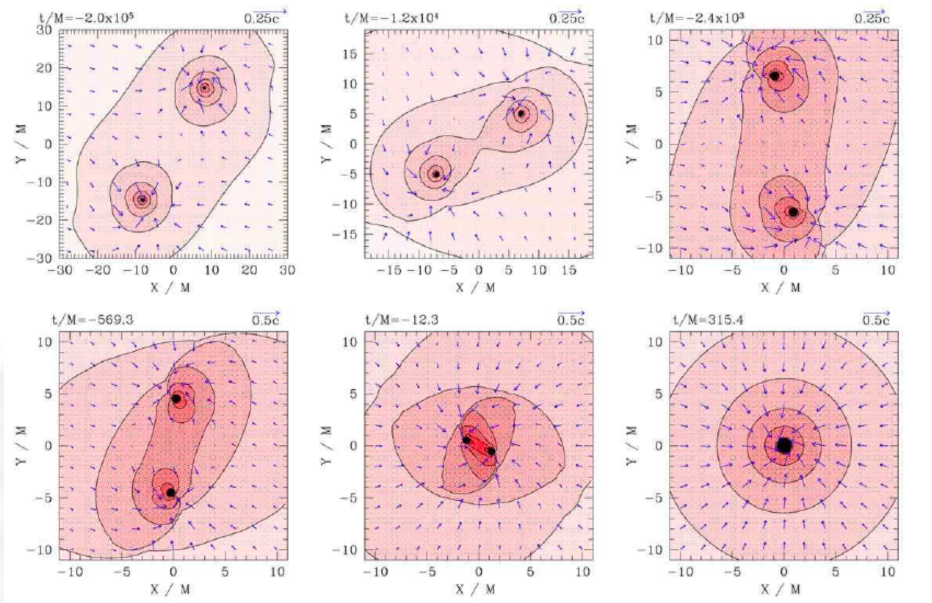
- *Simulations:* Track geodesic motion of particles in the dynamical spacetime of merging BHs:
- *Goal:* Identify high speed outflows and “particle collisions,” hinting where shocks would develop.
- *Setup:* 75,000 particles, in random “isotropic” and random “orbital” configurations.





SMBH Mergers in Hot Gas Environments

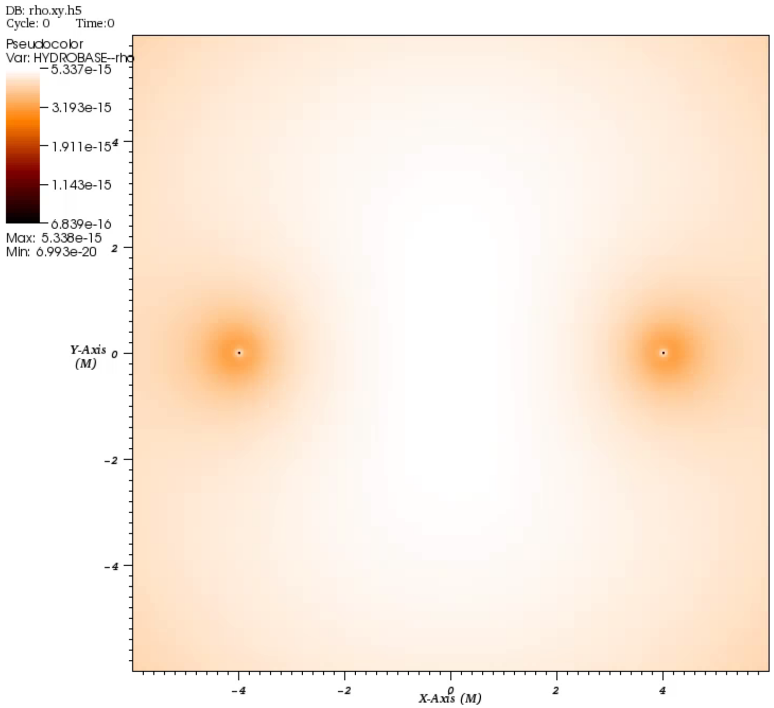


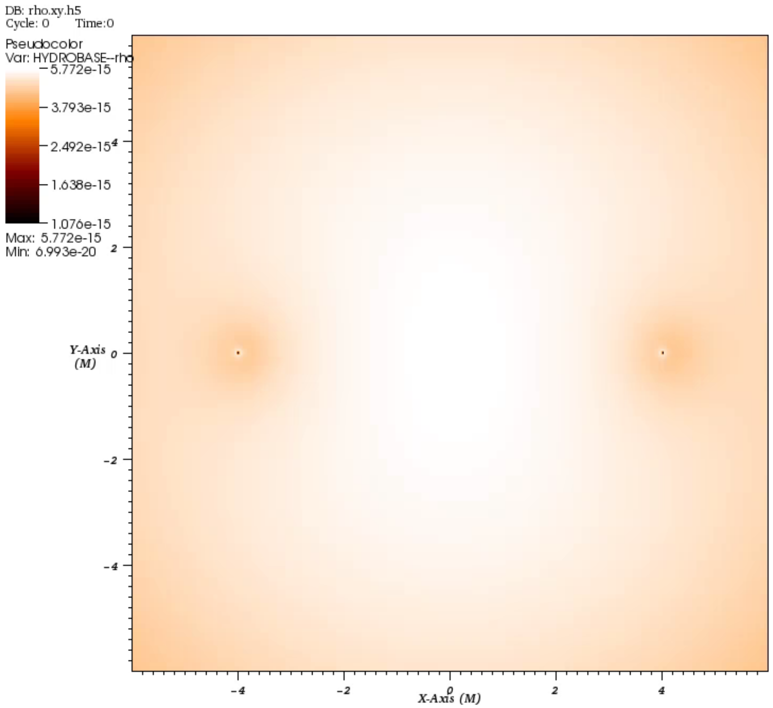


Relativistic Mergers of Supermassive Black Holes and their Electromagnetic Signatures
Bode, Bogdanovic, Haas, PL, Shoemaker Ap J 715, 1117 (2010)

Binary Black Hole Mergers in Gaseous Environments: "Binary Bondi" and "Binary Bondi-Hoyle-Lyttleton" Accretion
Farris, Liu, Shapiro, Phys Rev D, 81, 084008 (2010)

Gas Density

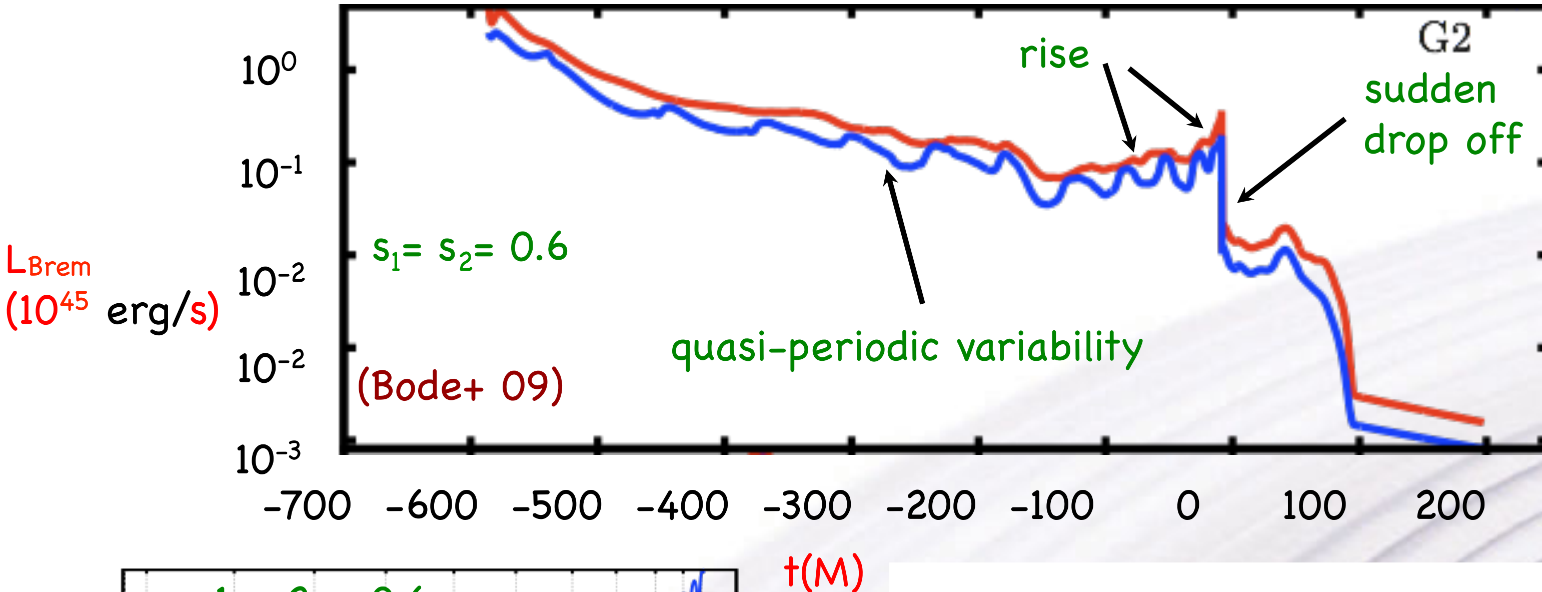


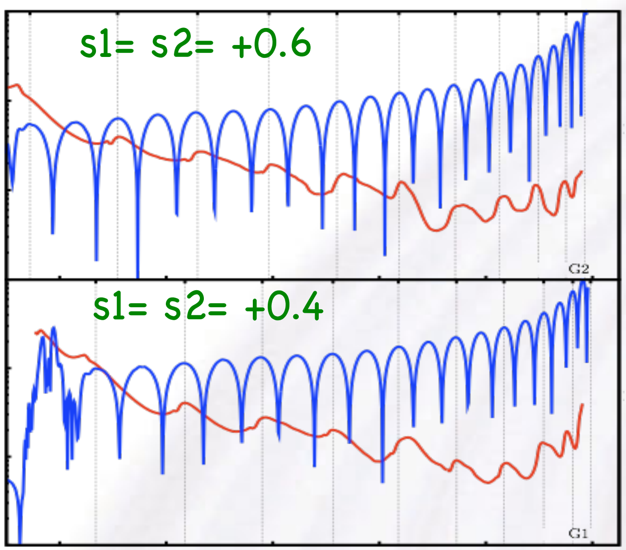


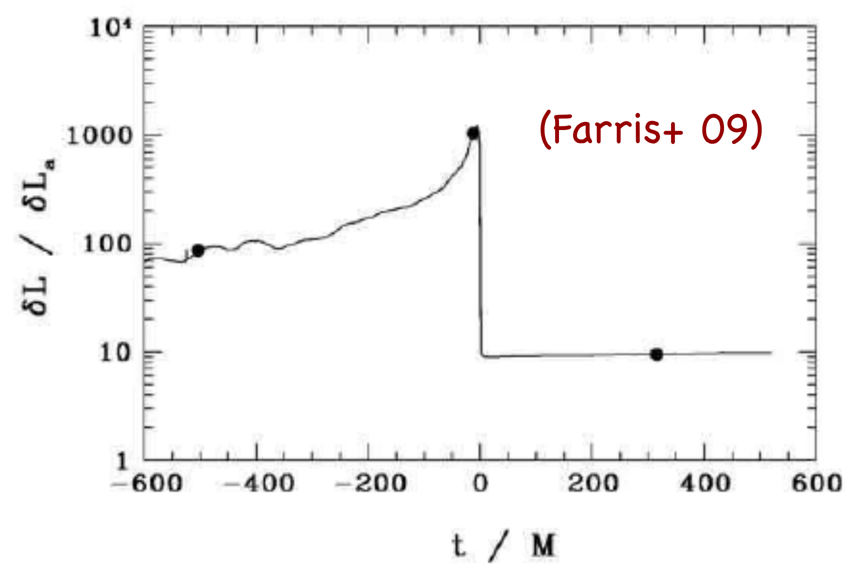
$s_1/m^2 = s_2/m^2 = 0.6$

$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$

Bremsstrahlung luminosity

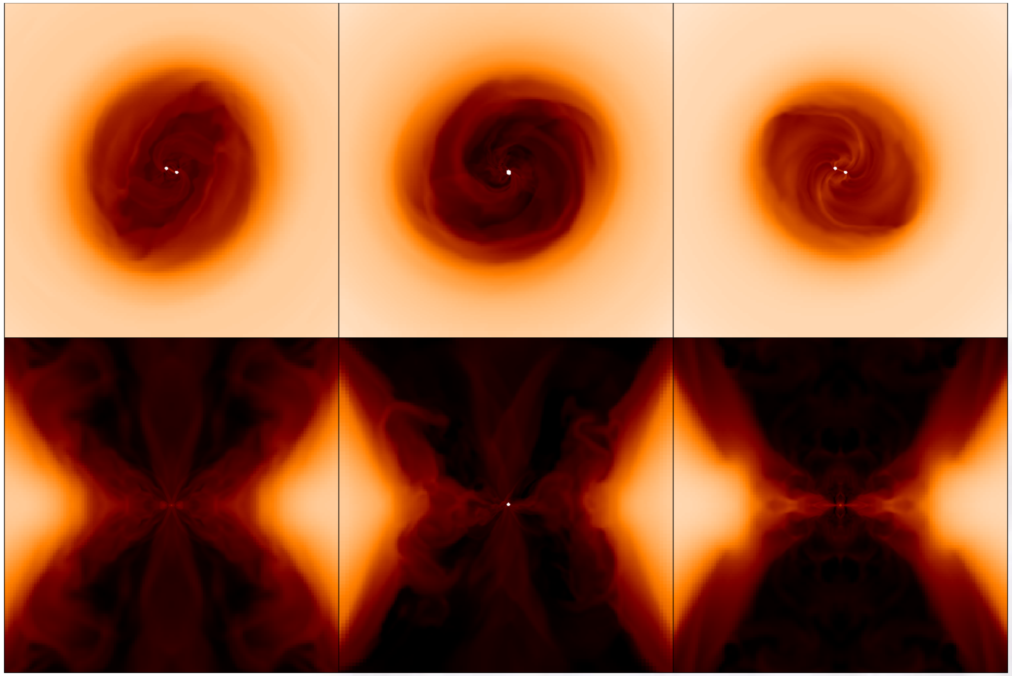




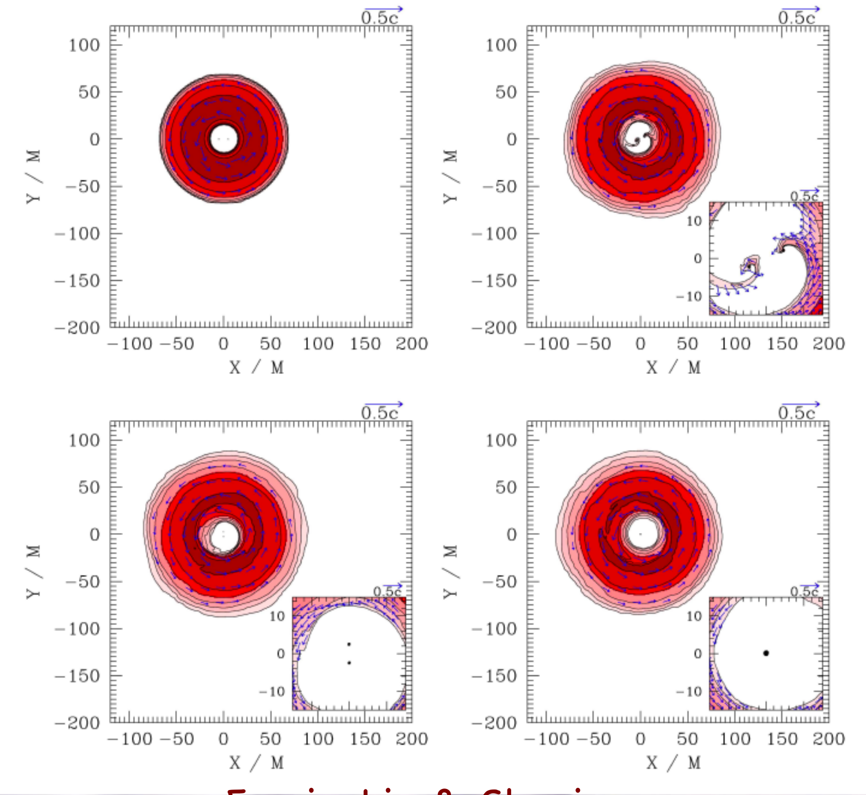


Merger of SBHs in a circumbinary disk

- Late inspiral and merger (BH separation 8M)
- Equal and unequal mass, spinning BHs
- Initially, orbital plane in the plane of the disk
- Pressure supported disk, h/r = 0.2, 0.4 inner edge at 16M
- Not modeled: AGN feedback, radiative cooling, magnetic fields, viscosity.

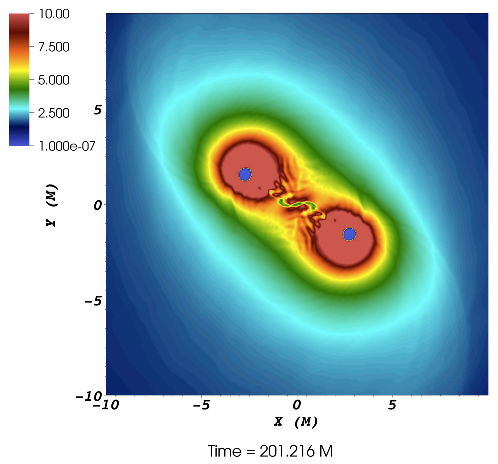


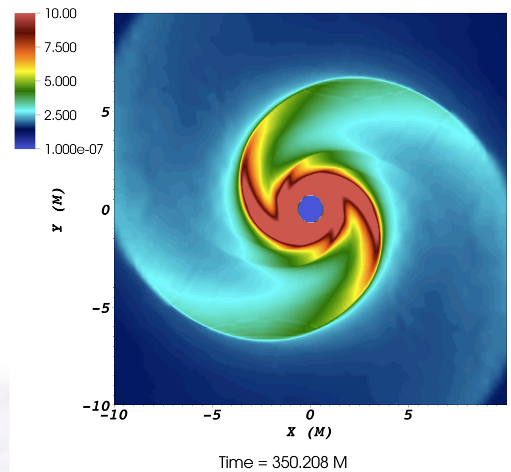
Bode, Bogdanovic, Haas, PL, Shoemaker

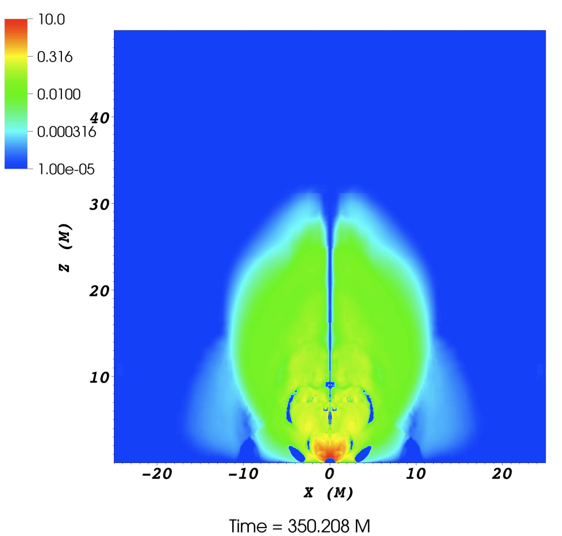


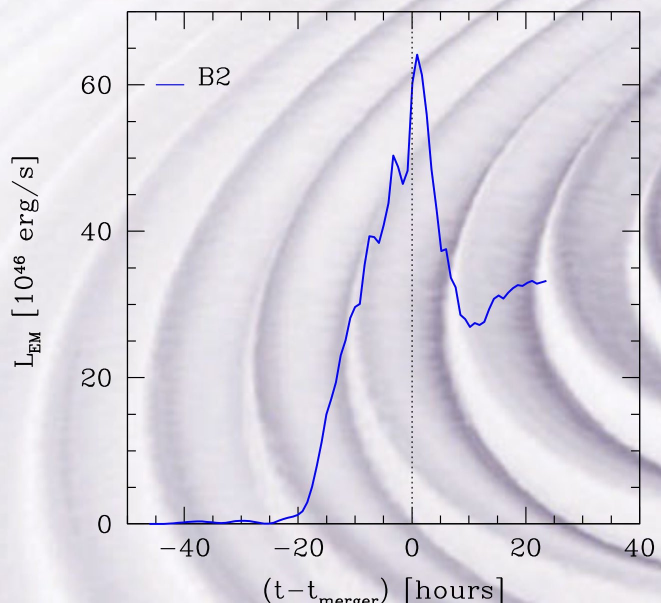
Farris, Liu & Shapiro

Circumbinary MHD Disks



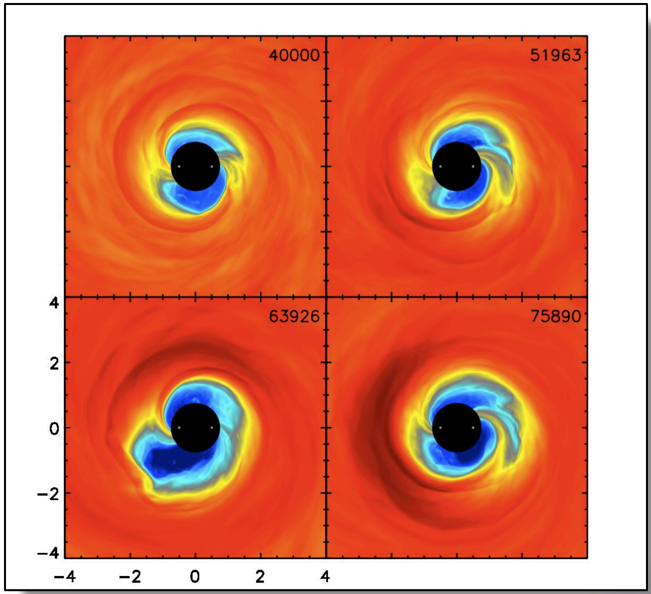


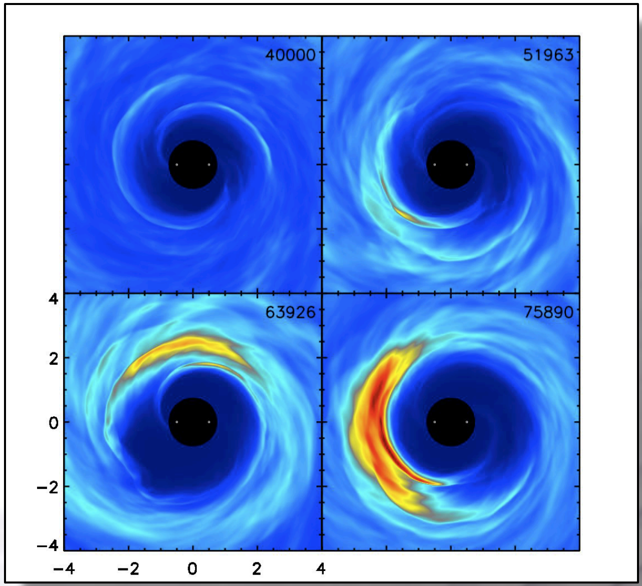


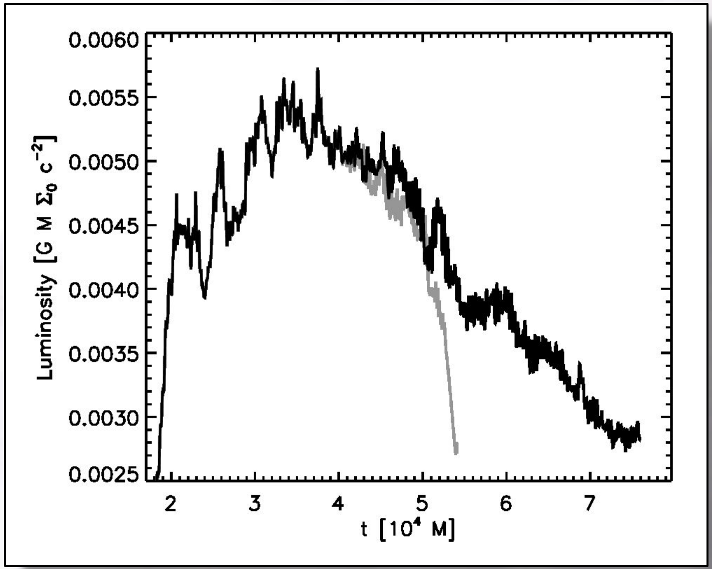


Giacomazzo et al arXiv:1203.6108

Circumbinary MHD Disks

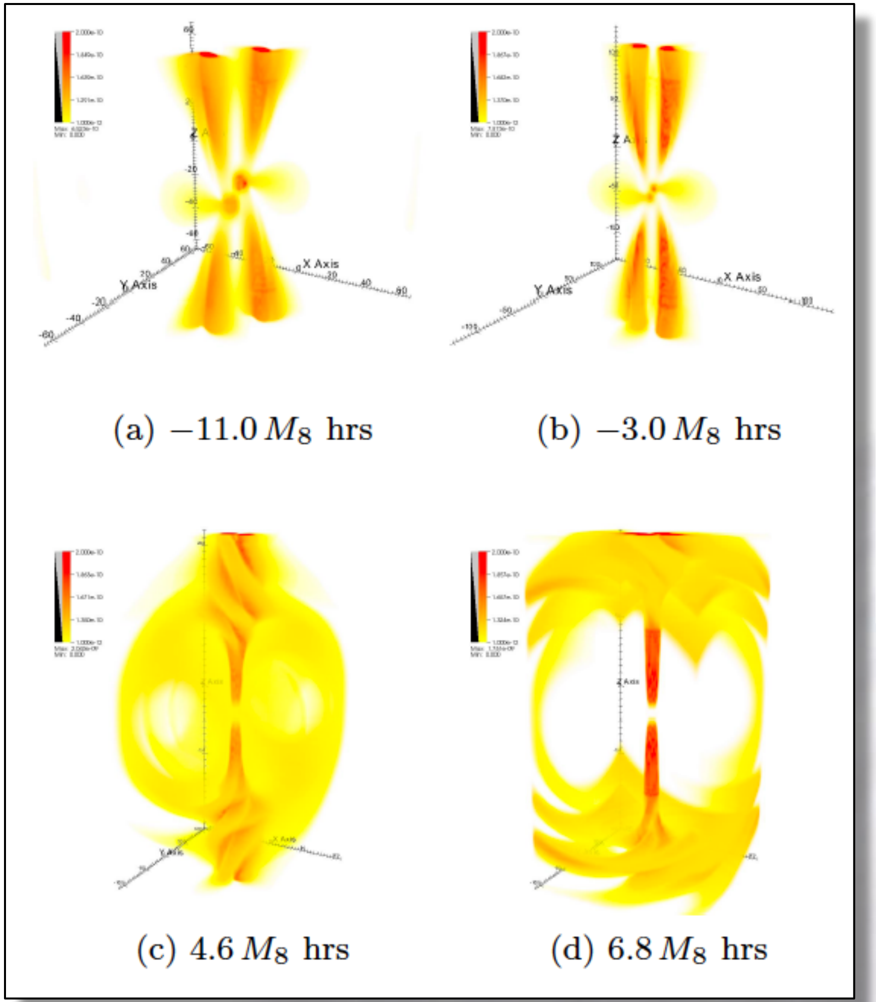






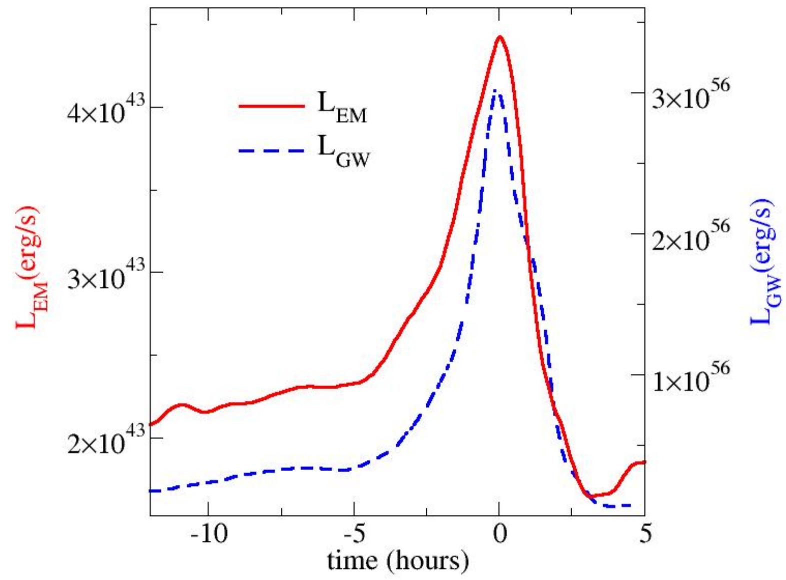
Noble et al arXiv:1204.1073

SMBH Mergers Surrounded by EM Fields



(a) $-11.0\,M_8$ hrs (b) $-3.0\,M_8$ hrs

(c) $4.6\,M_8$ hrs (d) $6.8\,M_8$ hrs

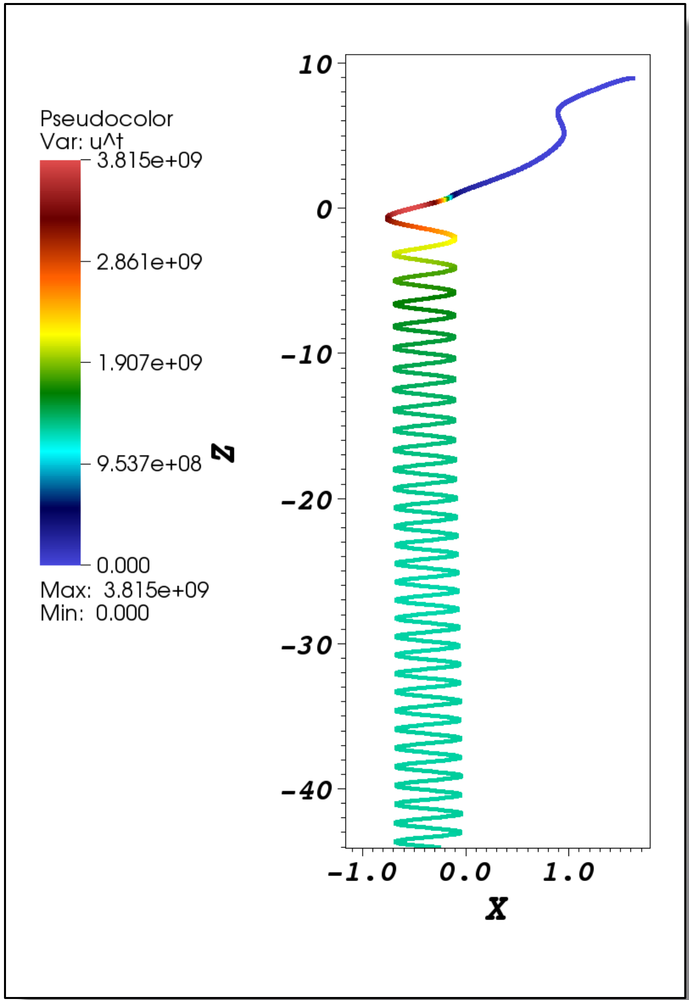


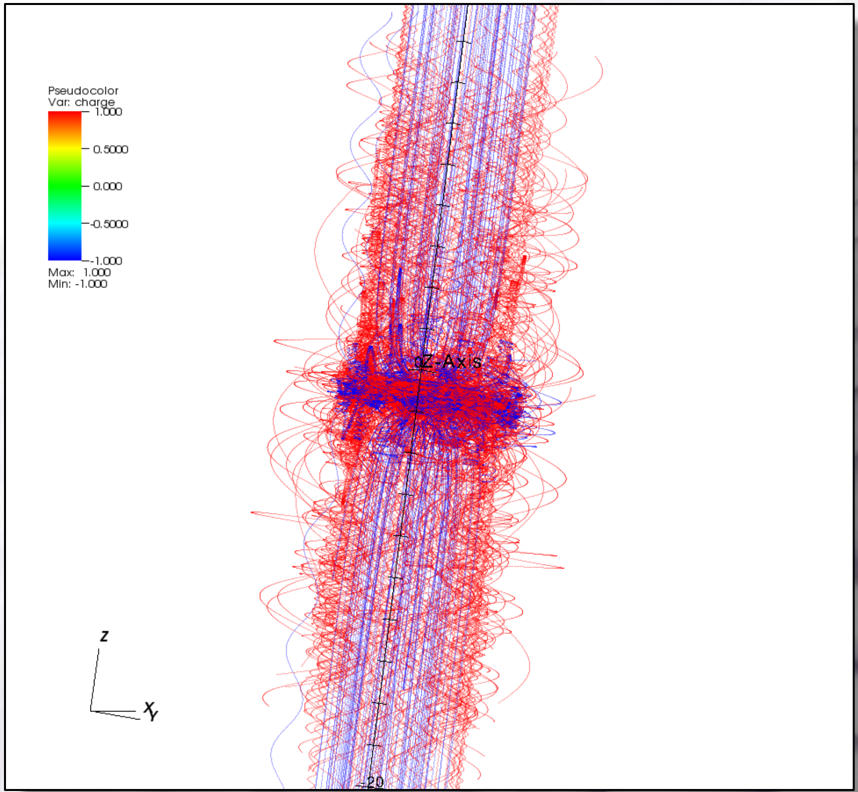
- Unlikely that this EM emission can be detected directly.
- The EM emission could be observable indirectly from its effects on the BH accretion rate.

(Palenzuela, Lehner Liebling 09a, 09b, 10; Mösta+ 09)

Particle Acceleration by BBH

Kinsey, Heally, Bogdanovic, PL & Shoemaker (in preparation)





Conclusions and Prospects

- Correlated variability EM-GW and characteristic features in the EM light can provide convincing evidence for an impending SBH merger.
- Most massive binaries will be EM visible out to z=1.
- GRMHD circumbinary simulations show promising EM signatures
- These are still prototype simulations. More follow-up work is needed in order to explore more astrophysically plausible configurations.

Ευχαριστώ