Matter in Binary Black Hole Simulations

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Rattle and Shine: GW & EM Studies of Compact Binary Mergers
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Massive BH mergers

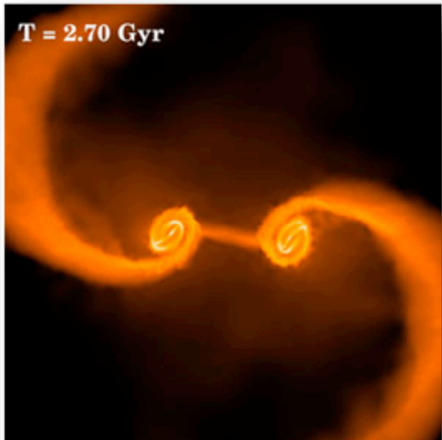
GW data	EM data
Eccentricity, component masses and spins, distances, orbit inclination and orientation, formation rate, merger rate	Accretion rates, magnetic fields, dual jets, variability, disk perturbations

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.
- BH accretion physics.
- Tests of GR (e.g. graviton's speed)

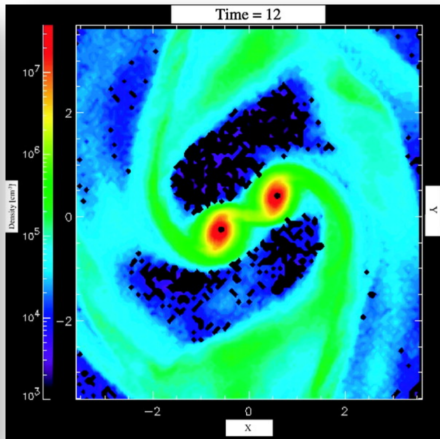
The Modeling Grand Challenge

10s kpc



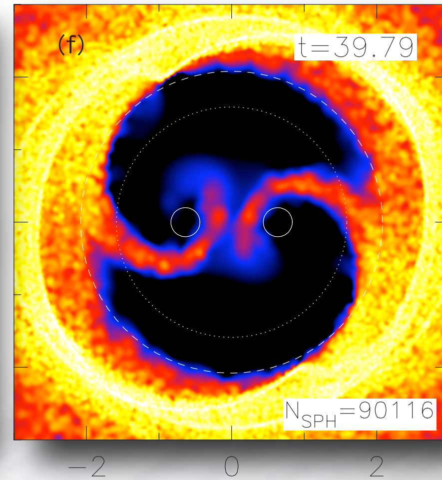
Mayer+ 07

10s pc



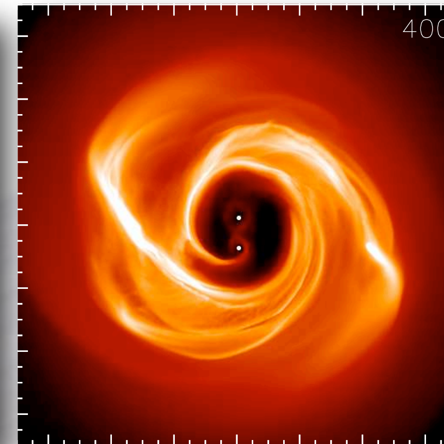
Escala+ 05

sub-pc



Hayasaki+ 07

sub-pc

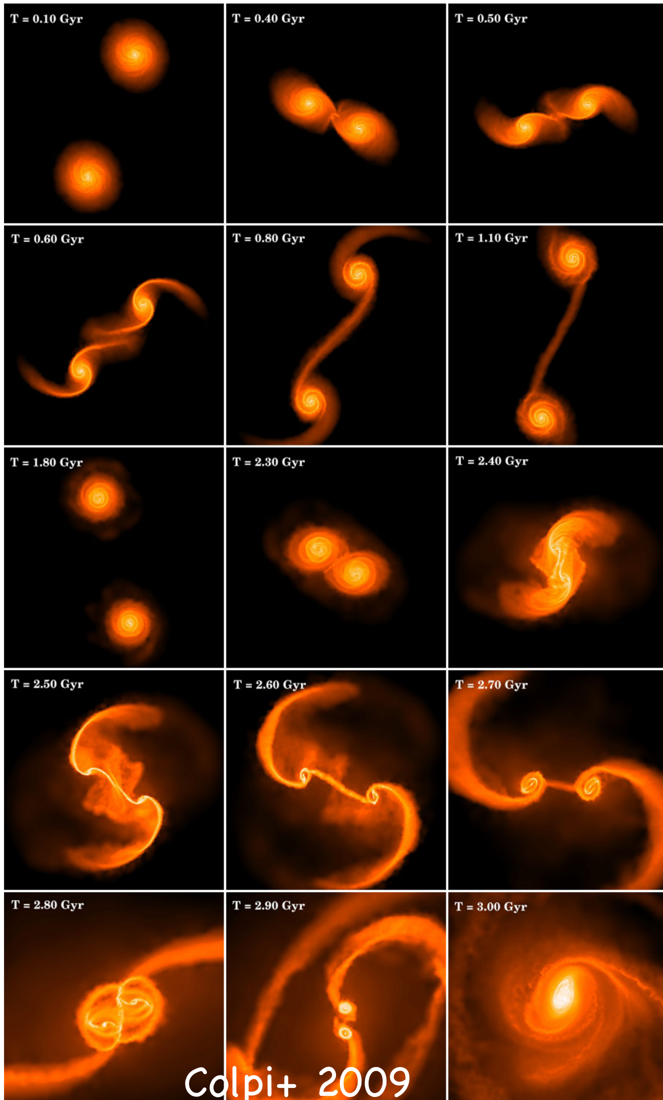


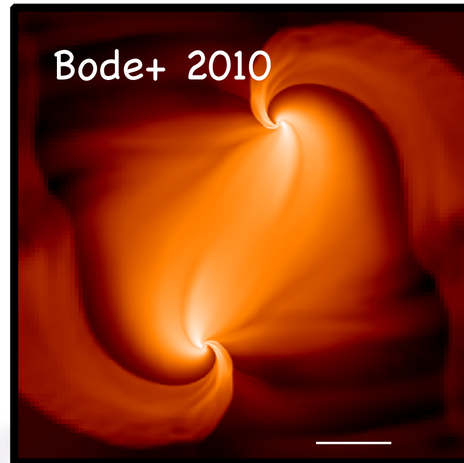
Cuadra+ 09

- Galactic mergers: 10^2 kpc
- BH binaries forms: 10 pc
- BBH & circumbinary disk: 0.01
- BH late inspiral and coalescence: 10^{-5} pc ~ AU

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

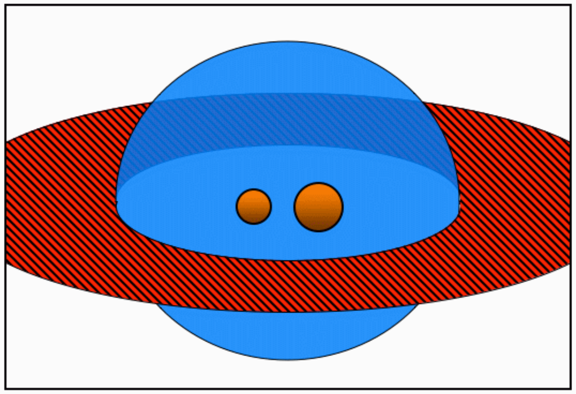
10^{5} pc ↔ 10^{-5} pc





- How does the binary reach the GW driven regime?
- What is the role of the environment?
- What is the BH spin orientation at merger?
- Are the orbits circular or eccentric?
- Are there dual jets?
- Does the merger perturb the circumbinary disk?
- Are there observational signatures from a recoil?

Num Rel BBH in Matter Scenarios

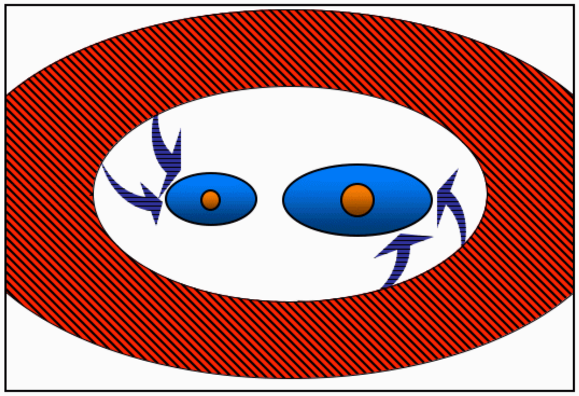


Hot Gas Clouds

Bode, Bogdanovic, Haas, PL, Shoemaker Ap J 715, 1117 (2010)

Farris, Liu, Shapiro, Phys Rev D, 81, 084008 (2010)

Giacomazzo et al ApJ 752 L15 (2012)



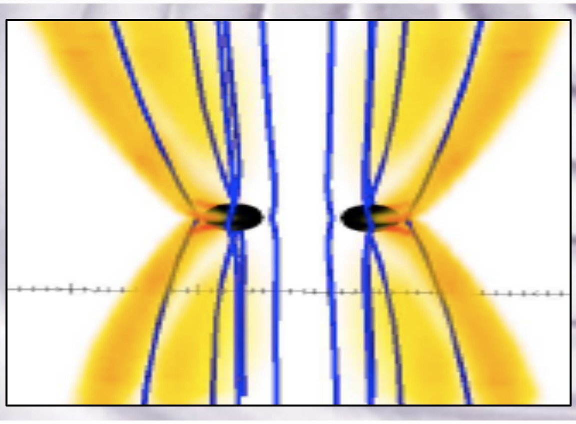
Circumbinary Disk:

Bode, Bogdanovic, Haas, Laguna, Shoemaker, Astrophys.J. 744 (2012) 45

Farris, Gold, Paschalidis, Etienne, Shapiro, arXiv:1207.3354

Farris, Liu, Shapiro, Phys.Rev.D84:024024,2011

Noble, Mundim, Nakano, Krolik, Campanelli, Zlochower, Yunes, arXiv: 1204.1073



Maxwell Fields:

Alic, Modesta, Rezzolla, Zanotti, Jarramillo, ApJ, 754, 36, 2012

Modesta, Alic, Rezzola, Zanotti, Palenzuela ApJ, 749, L32, 2012

Palenzuela, Garrett, Lehner, Liebling, Phys. Rev. D 82, 044045 (2010)

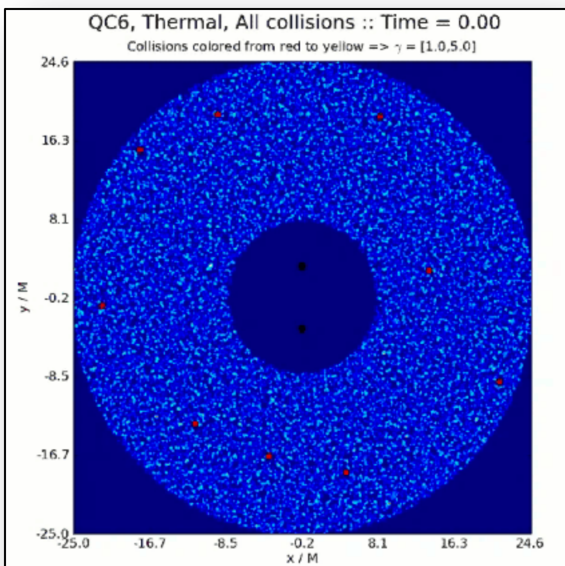
Palenzuela, Lehner, Liebling, Science V329, 927 (2010)

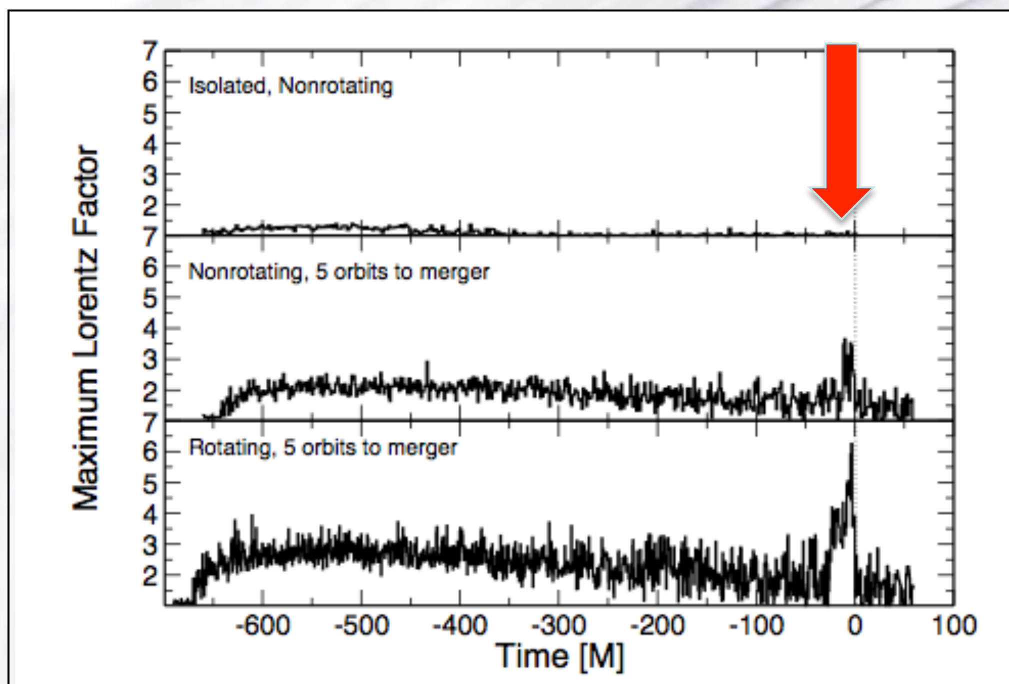
Palenzuela, Anderson, Lehner, Liebling, Neilsen, Phys.Rev.Lett. 103:081101,2009

Test particles around merging BBH

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

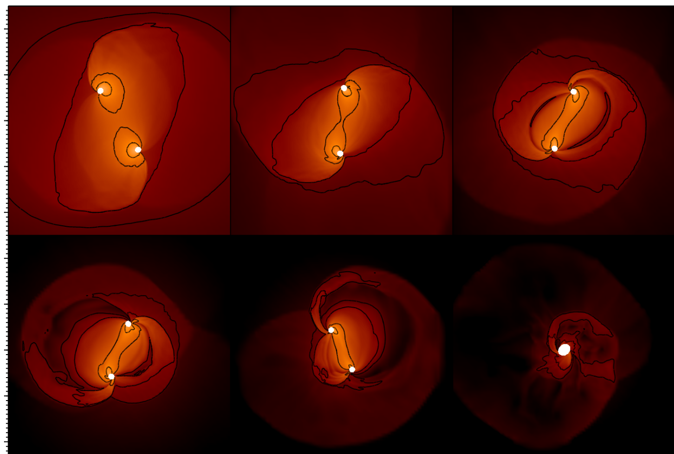
- *Setup:* 75,000 particles, in random "isotropic" and random "orbital" configurations
- *Simulations:* Track geodesic motion of the particles in the dynamical spacetime of merging BHs:
- *Goal:* Identify high speed outflows and "particle collisions," hinting where shocks would develop.



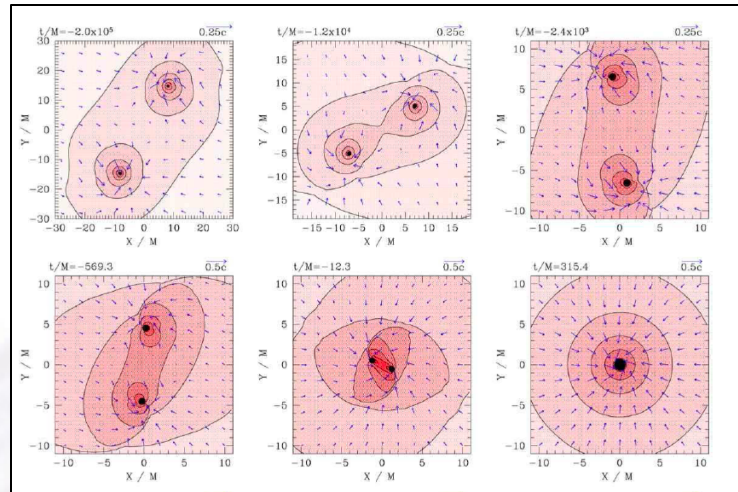


BBH Mergers in Hot Gas Environments

Bode, Bogdanovic, Haas, PL, Shoemaker
Ap J 715, 1117 (2010)

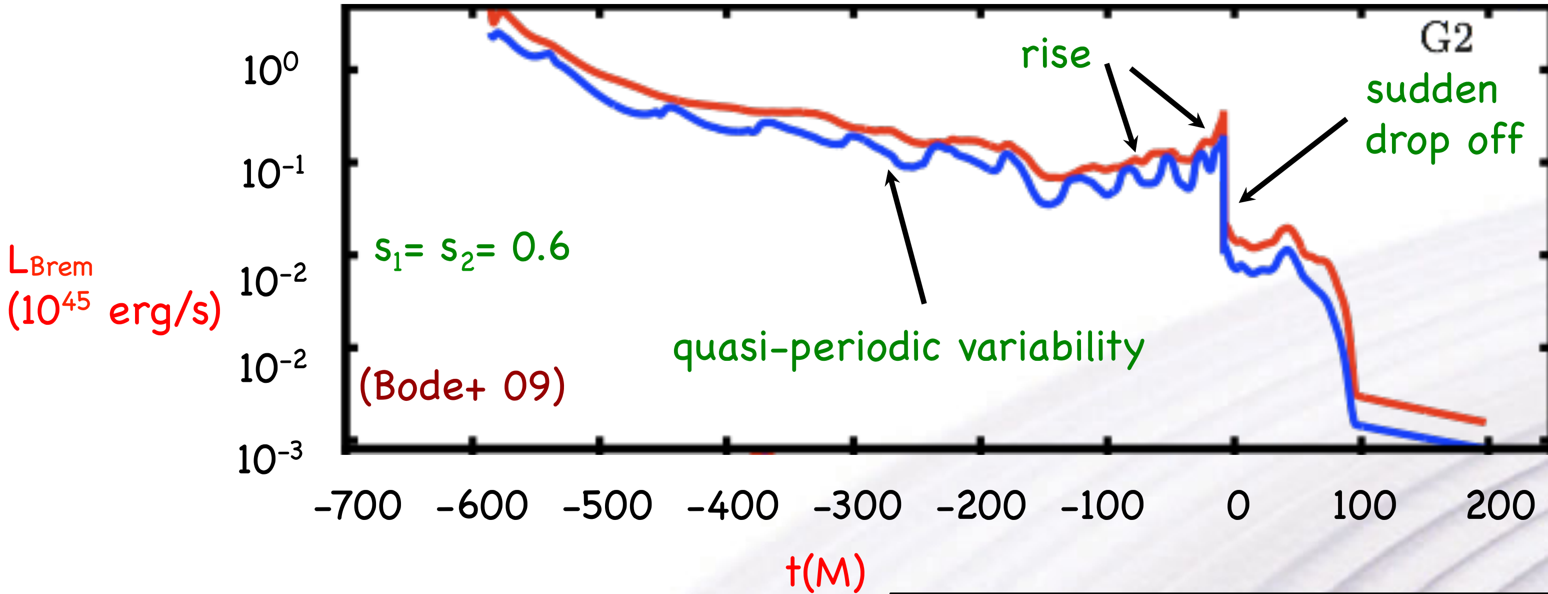


Farris, Liu, Shapiro, Phys Rev D, 81, 084008 (2010)

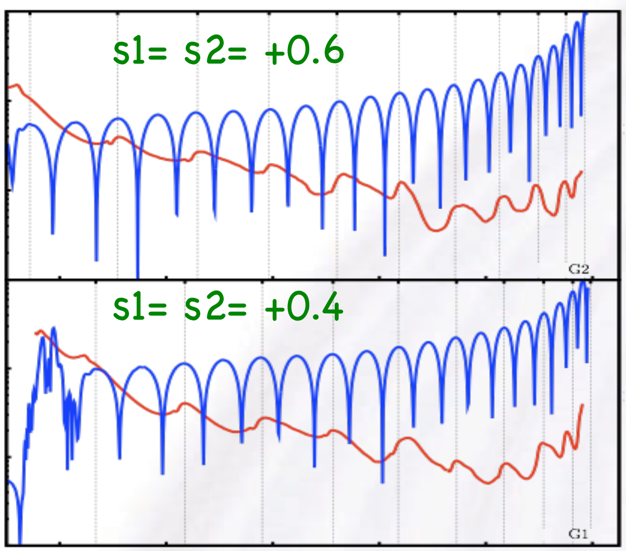


- Cloud density ~ 10^{-12} g cm^{-3}, T ~ 10^{12} K
- Evidence for significant enhancements in dM/dt and L over values for a single BH.
- Detectable by LSST for a 10^6 M_{sun} binary at z ~1, reaching a maximum of L~ 10^{43} erg s^{-1}
- The flare could last for 10^4 s with the emission peaking in the X-ray band.

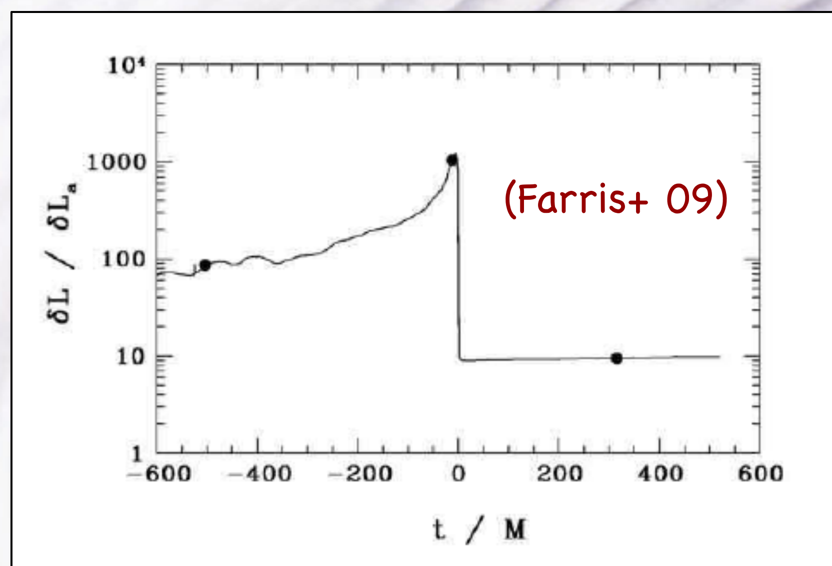
Luminosity



G2
rise
sudden
drop off
s1= s2= 0.6
quasi-periodic variability
(Bode+ 09)
LBrem
(10^45 erg/s)
10^0
10^-1
10^-2
10^-2
10^-3
-700 -600 -500 -400 -300 -200 -100 0 100 200
t(M)

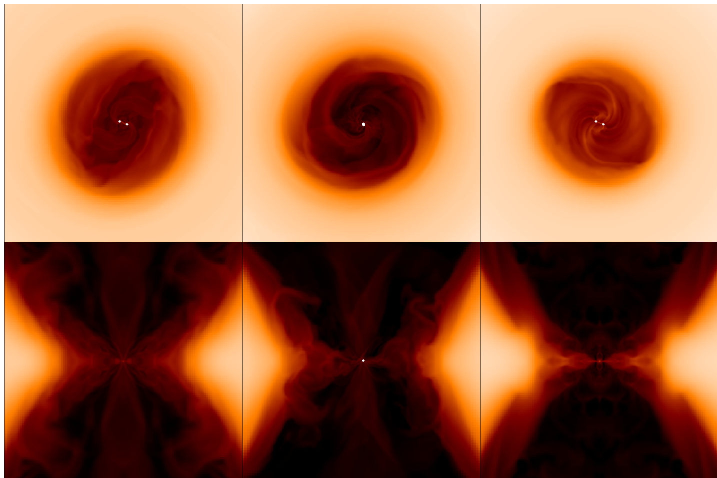


s1= s2= +0.6
G2
s1= s2= +0.4
G1

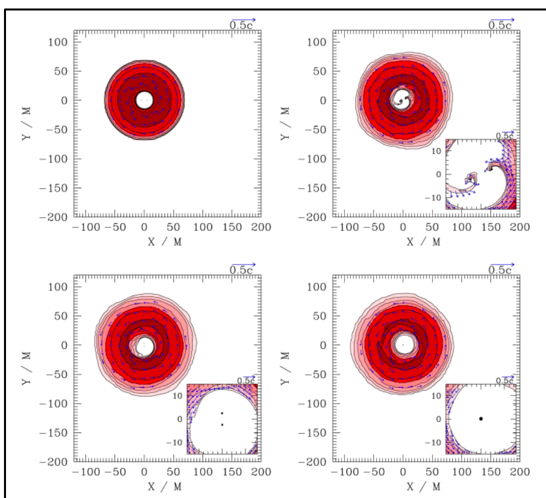


(Farris+ 09)
δL / δLa
10^4
1000
100
10
1
-600 -400 -200 0 200 400 600
t / M

Merger of SBHs in a circumbinary disk



Bode, Bogdanovic, Haas, PL, Shoemaker

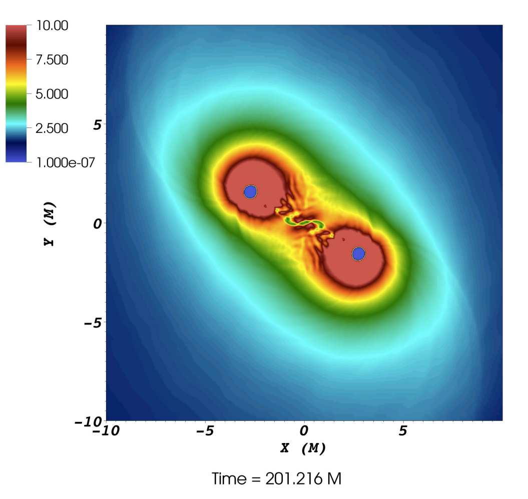


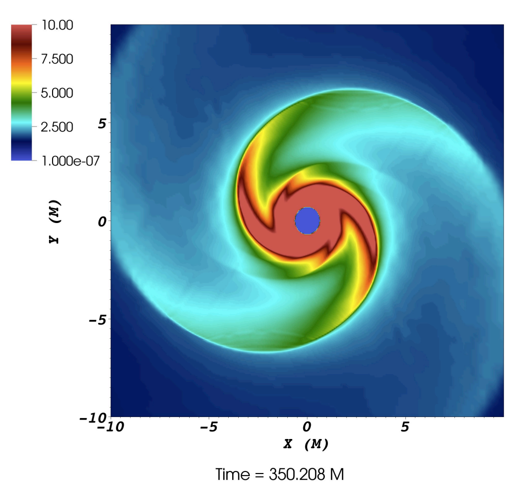
Farris, Liu & Shapiro

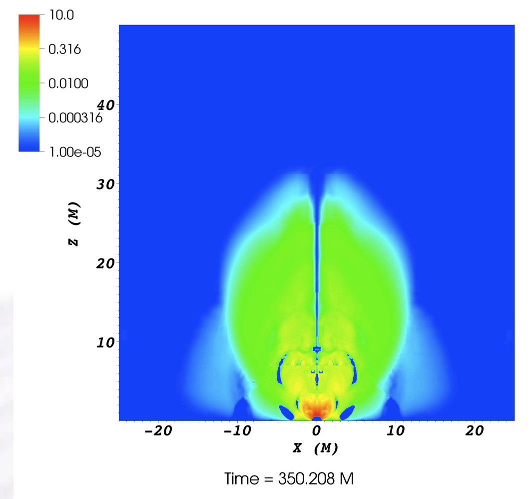
- Late inspiral and merger (BH separation 8M)
- Pressure supported disk, h/r = 0.3, inner edge at 16M, density n ~10^{12} cm^{-3}
- Not modeled: AGN feedback, radiative cooling, magnetic fields, viscosity.
- The synchrotron component of the luminosity peaks at L ~ 10^{45} erg s^{-1} in the infrared band, lasting ~ 100 hrs
- Detectable by WFIRST and possibly the LSST for a 10^8 M_{sun} binary at z ~1
- Difficult to separate spurious effects from the initial data setup.

BBH in Magnetized Plasmas

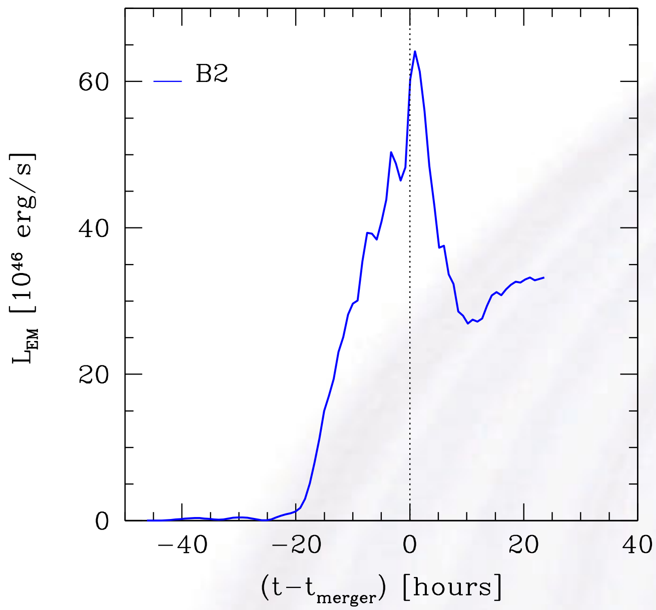
Giacomazzo et al ApJ 752 L15 (2012)





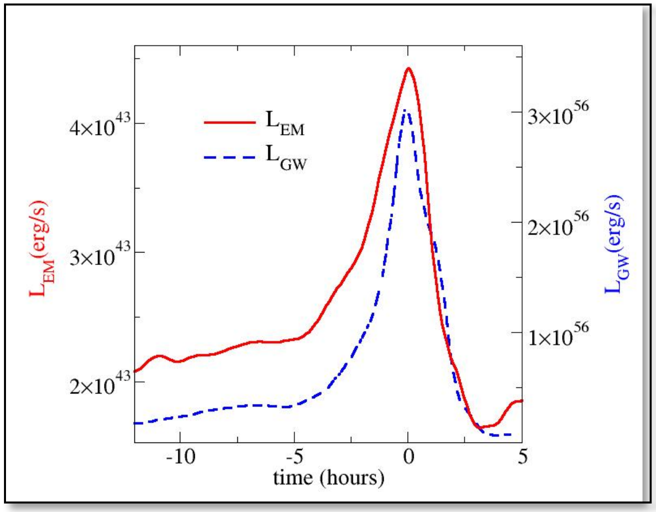


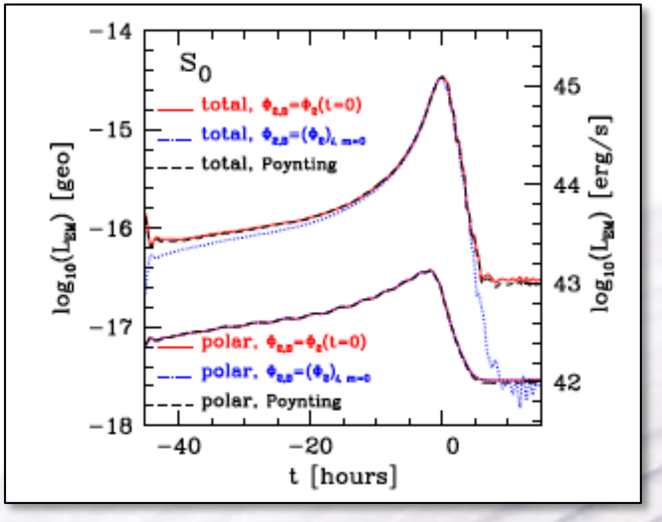
Pointing Flux



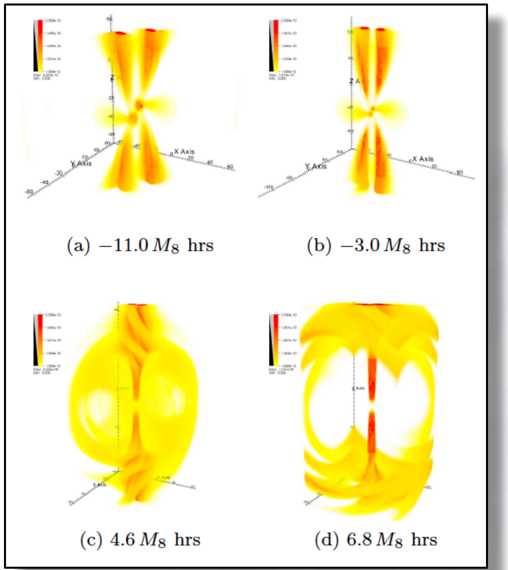
- BBH ~ 10^8 M_{sun}
- Plasma density ~ 10^{-11} g cm^{-3}
- P_{mag}/P_{gas} = 2.5 x 10^{-2} (initial)
  P_{mag}/P_{gas} = 0.1 (jet)
- B ~ 10^4 G (initial)
  B ~10^6 G (final)
- B-field lines are compressed and twisted
- L ~ 10^{47} erg s^{-1}, 10^4 higher than force-free calculations

BBH in EM Fields





(Palenzuela, Lehner Liebling 09a, 09b, 10; Mösta+ 09; Alic+ 12)



(a) $-11.0\, M_8$ hrs (b) $-3.0\, M_8$ hrs (c) $4.6\, M_8$ hrs (d) $6.8\, M_8$ hrs

- Force-free simulations with B ~ 10^4 G and BBH ~ 10^8 M_{sun}
- Dual jets form!
- Unfortunately energetically sub-dominant (by a factor 100) with respect to the non-collimated emission, thus unlikely to be detectable (Alic, et al arXiv:1204.2226)
- Scaling with orbital frequency

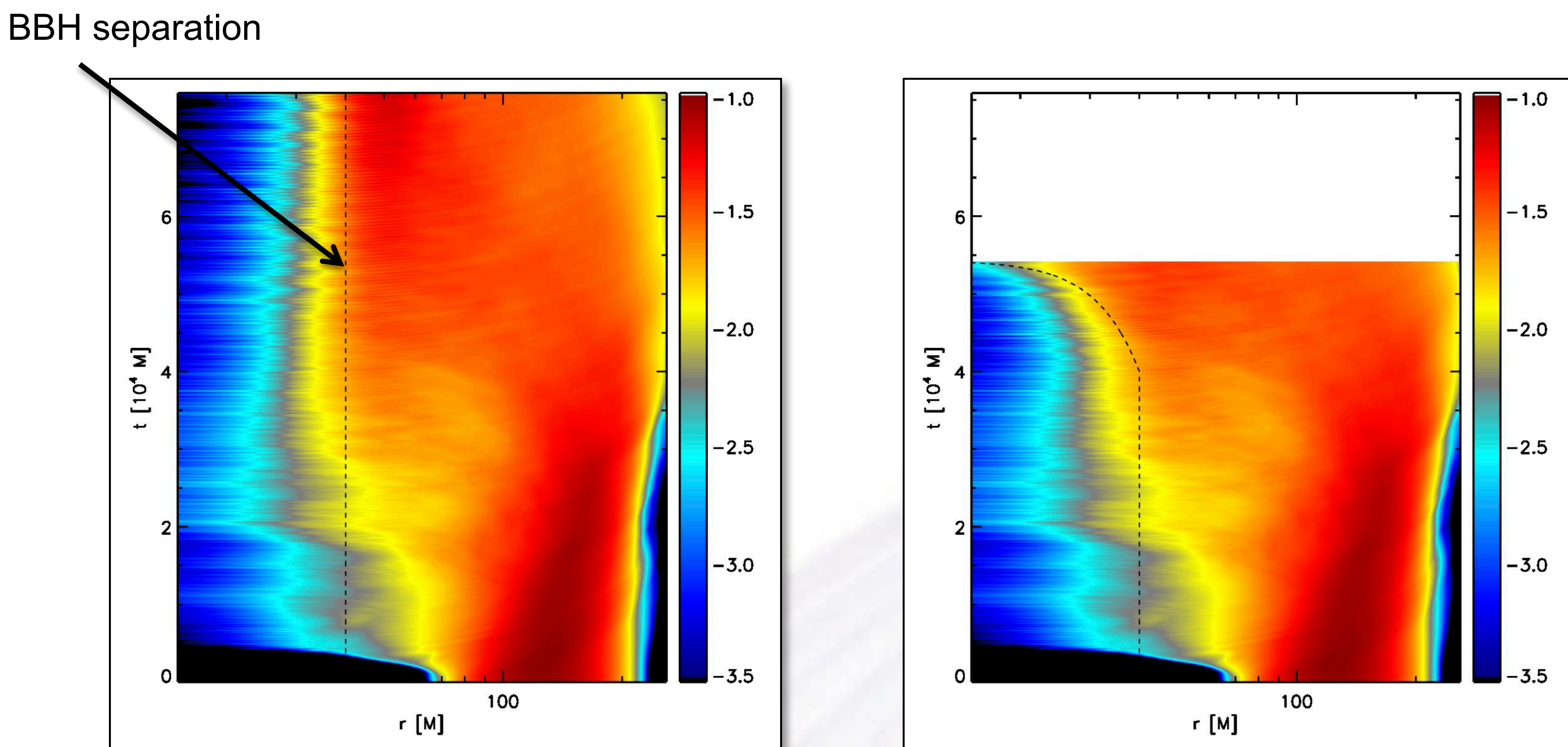
$$L_{EM}^{non-coll} \approx \Omega^{10/3-8/3}$$

$$L_{EM}^{coll} \approx \Omega^{5/3-6/3}$$

More in Palenzuela's talk

Circumbinary MHD Disks

Noble et al arXiv:1204.1073

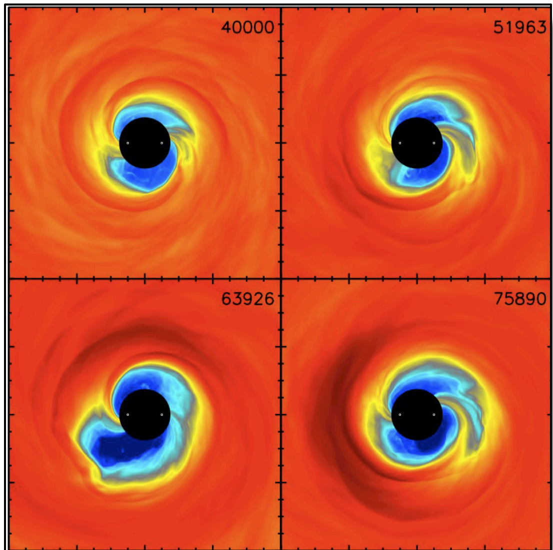


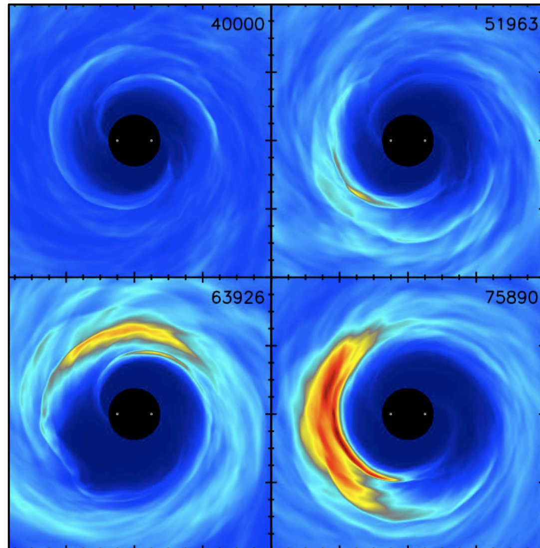
Surface Density

- Modeled phase prior to the late inspiral and merger
- Case I: Space-time frozen and PN approximated for 76,000 M with BBH separation of 20 M
- The goal is to construct a “secularly evolving” disk
- Case II: PN approximation with BBH shrinking until separation 8 M

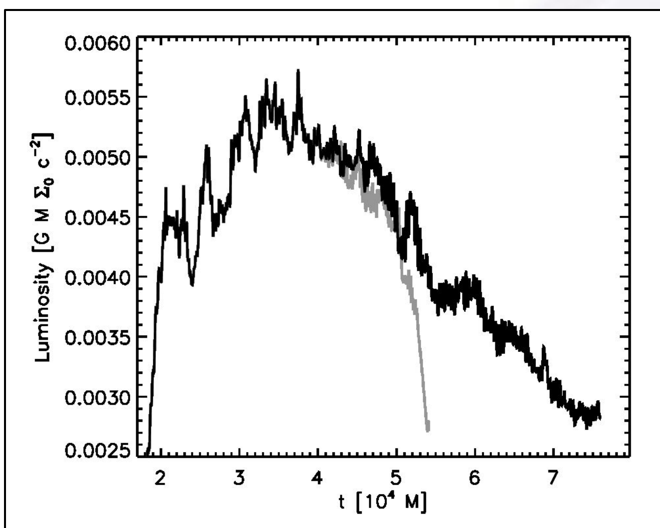
Circumbinary MHD Disks

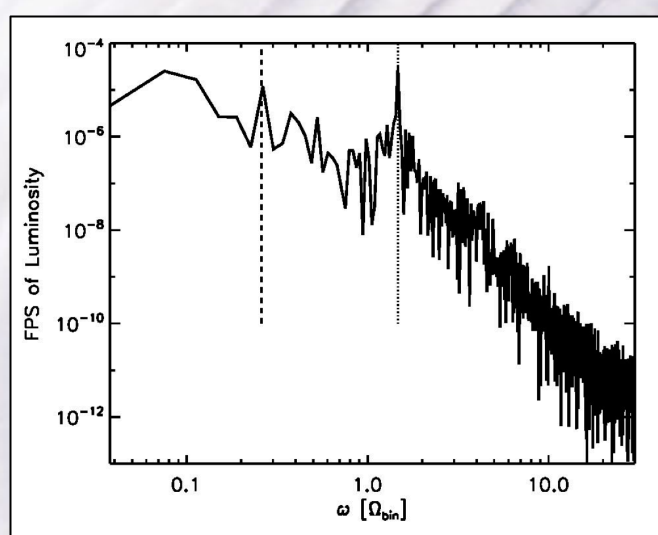
Noble et al arXiv:1204.1073





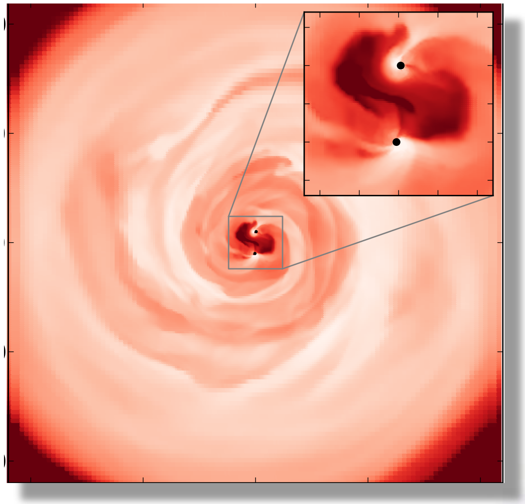
- Binary decouples at separation smaller than previous estimates
- Modulation develops but it is not clear if it will be observable
- Accretion rate for the frozen case is 20-30% higher.



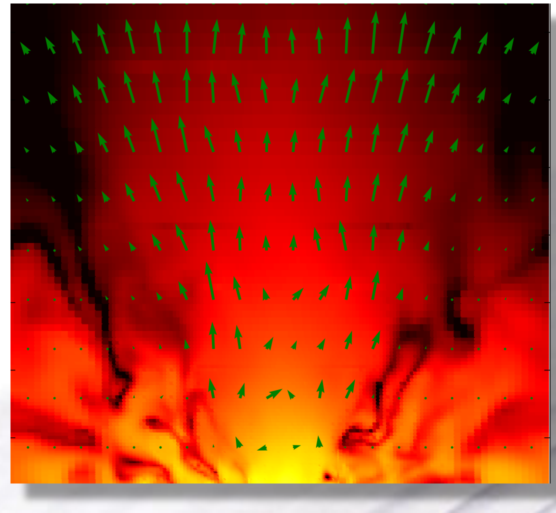


Circumbinary MHD Disks

Farris et al arXiv:1207.3354



Relaxed disk after 10,000 M

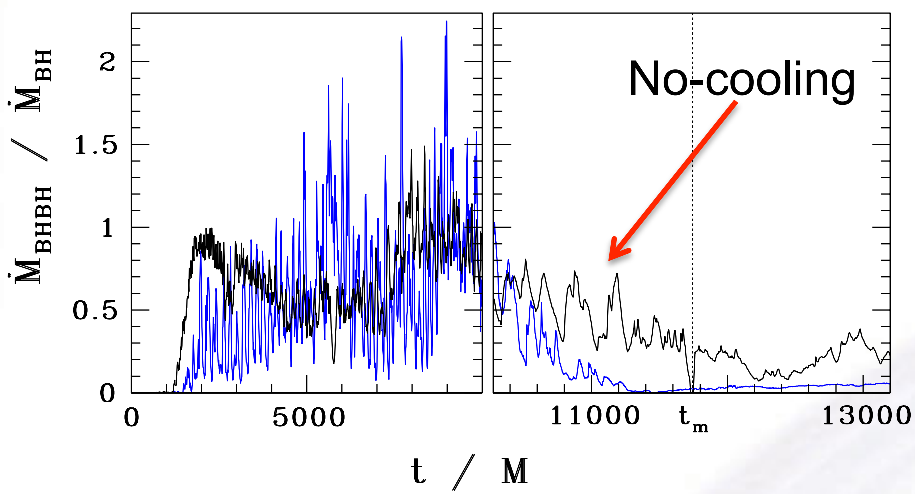


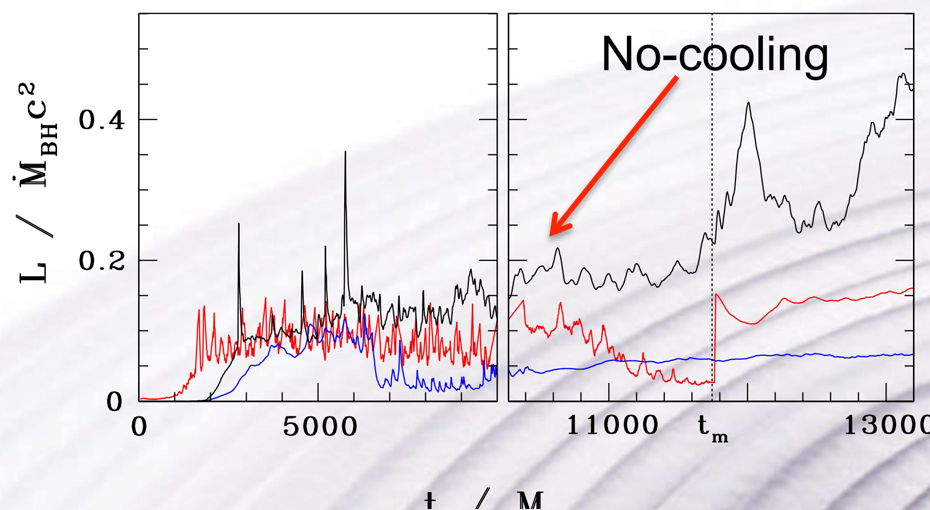
Magnetic pressure after 10,000 M with no cooling

- Modeled both the pre-decoupled and post-decoupled phase
- Pre-decoupled phase: Frozen conformal thin-sandwich space-time for about 10,000M (45 orbits)
- Post-decoupled phase: Cooling is added via an effective local emissivity
- Prior to decoupling, persistent, magnetized collimated outflows (v > 0.5 c)

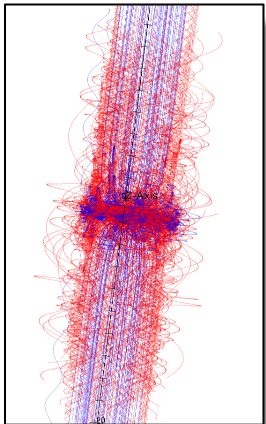
Circumbinary MHD Disks

Farris et al arXiv:1207.3354



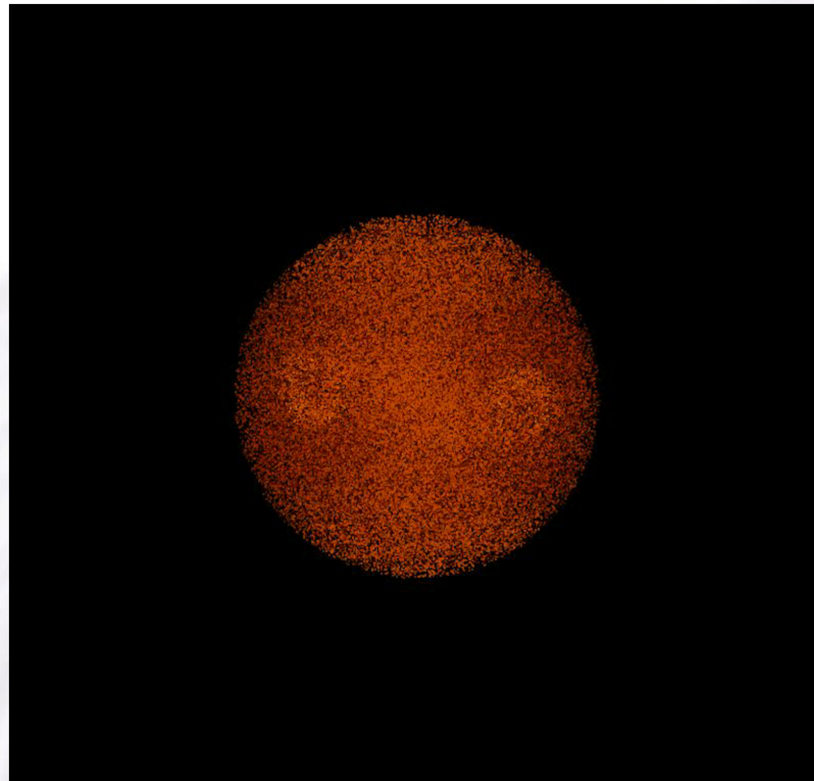


- Prior to decoupling, accretion rates are comparable to those from a single BH
- Accretion streams remain present until merger for the non-cooling case.
- The enhancement in luminosity from the no-cooling case is due to shock heating

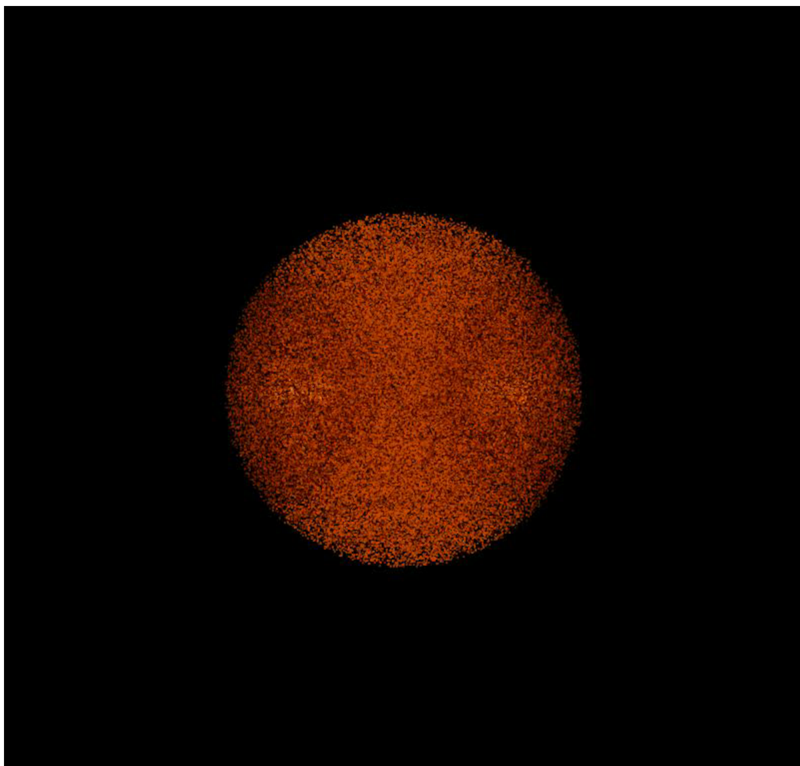


Particle Acceleration by Dual Jets in BBH

Matt Kinsey, Healy, Bogdanovic, PL & Shoemaker (in preparation)



Face-on



Edge-on

Conclusions and Prospects

- Correlated variability of EM emission with GWs could in principle provide convincing evidence for an impending massive BBH merger.
- Even in the absence of GWs, characteristic features in the EM emission will hopefully give us signatures of strong and/or dynamical gravity.
- Most massive binaries will be EM visible out to z=1.
- In particular, GRMHD circumbinary simulations show promising EM signatures
- However, these are still prototype simulations. More follow-up work is needed to explore more astrophysically plausible configurations.