Multi-Messenger Signatures from Supermassive Binary Black Hole Mergers

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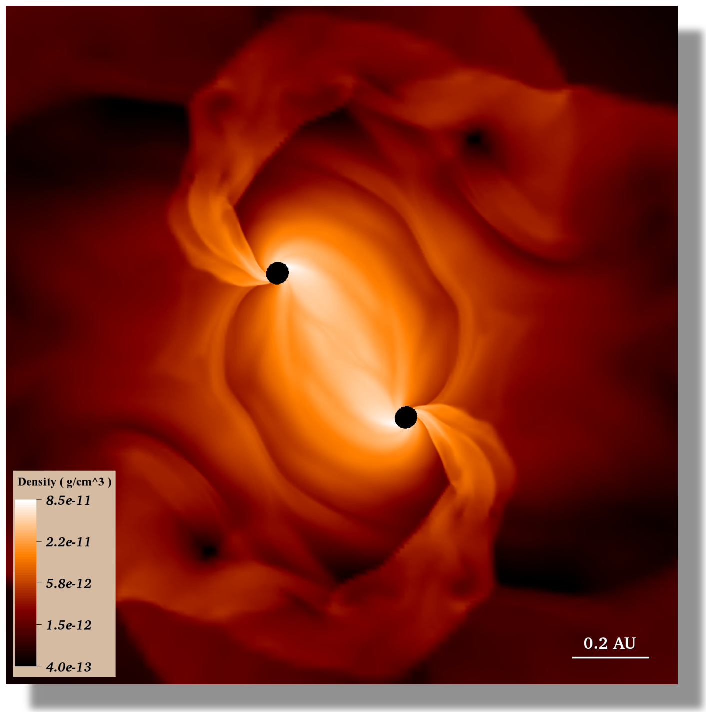
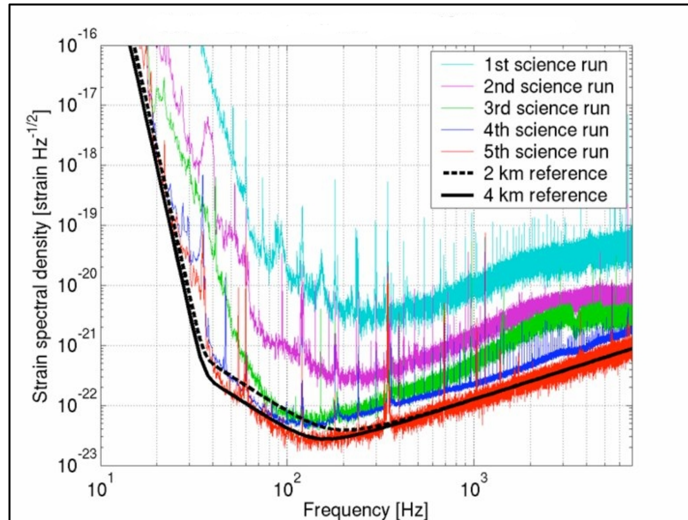
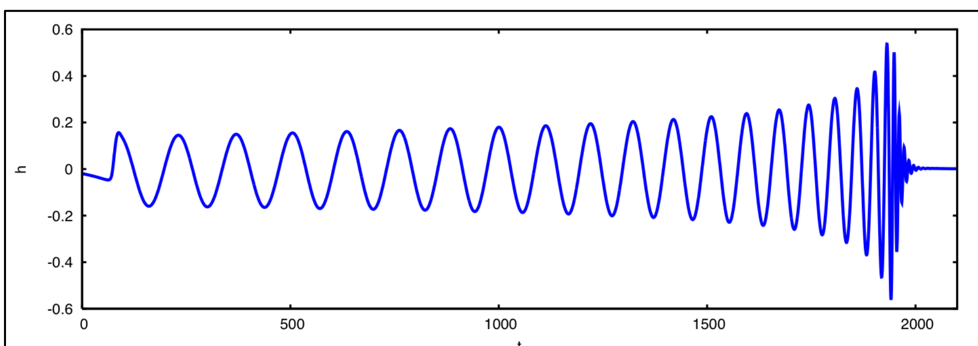


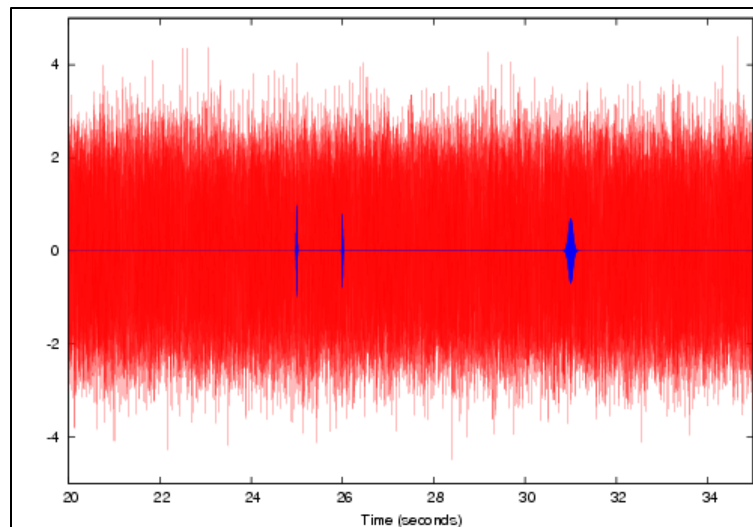
Collaborators:
Tanja Bode, Tamara Bogdanovic (Maryland), Roland Haas, Deirdre Shoemaker

Numerical Relativity
as a Tool of Astrophysical Discovery

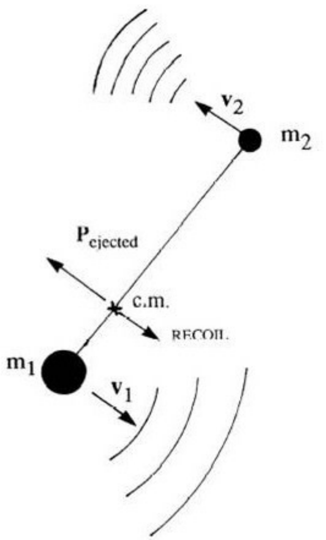


numerical waveforms are essential on assisting to predict what to expect (NINJA & NRAR)



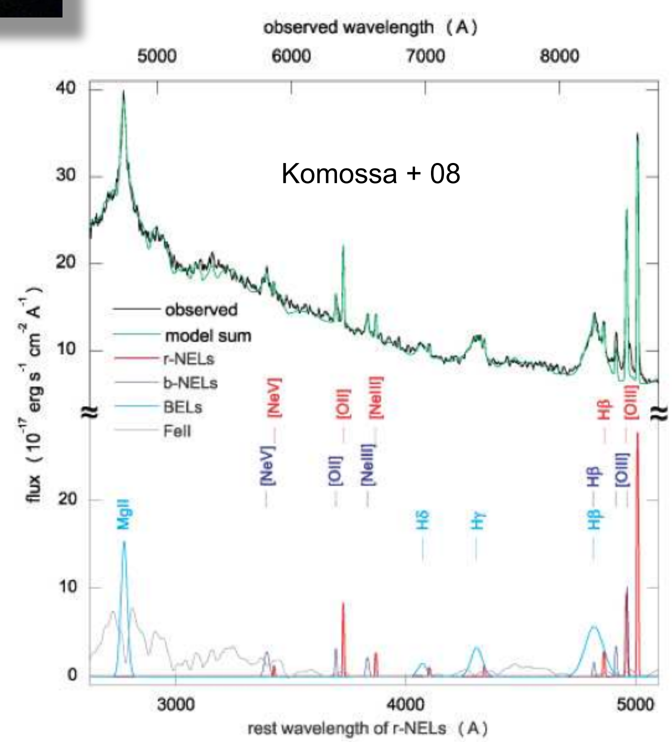


Gravitational Recoil or BH kicks



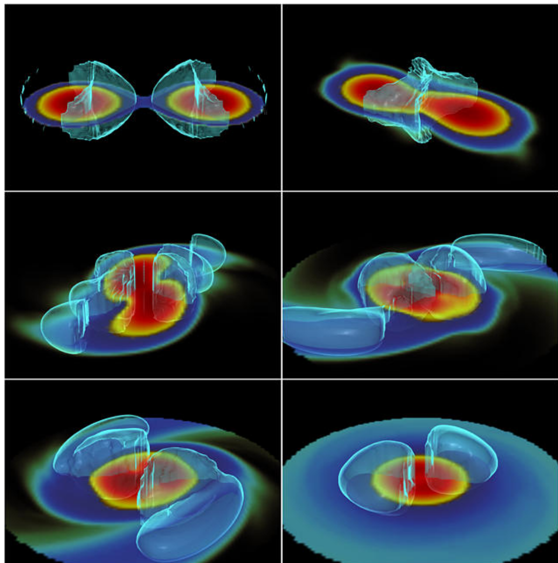
Superkicks ~ 2,400 km/s

Sperhake+ 08 & Campanelli+ 08

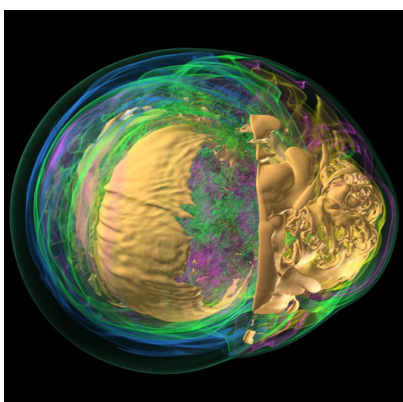


The r.h.s. of the Einstein Equations

The Heavy Side

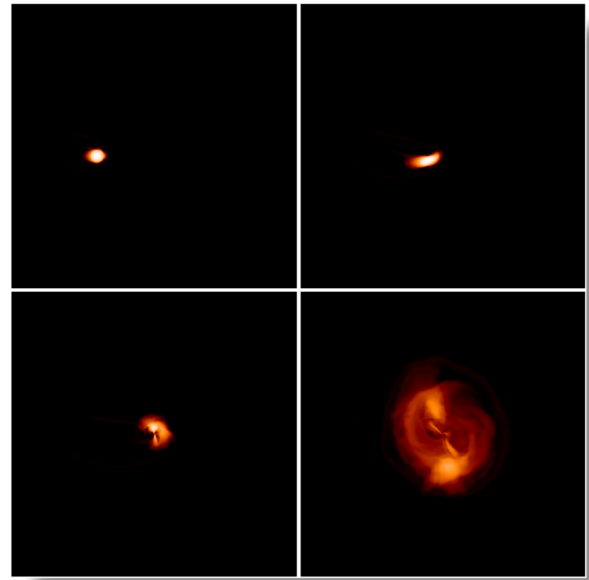


NS+NS

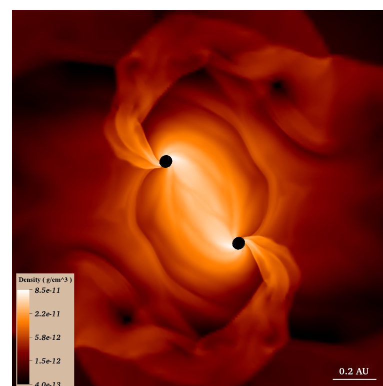


Core Collapse SN

The Light Side



Tidal Disruptions



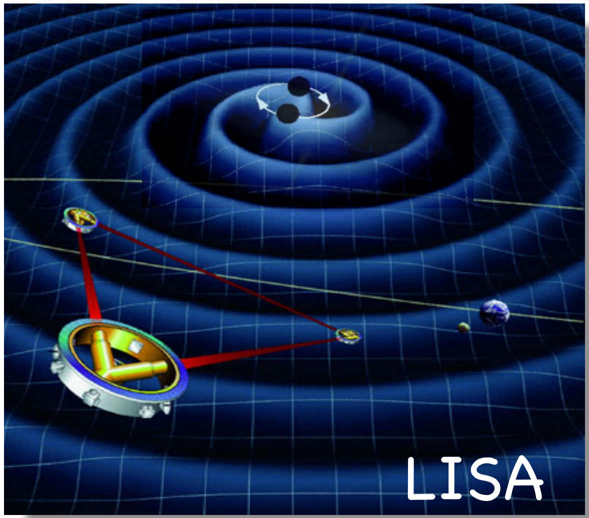
BBH + Gas

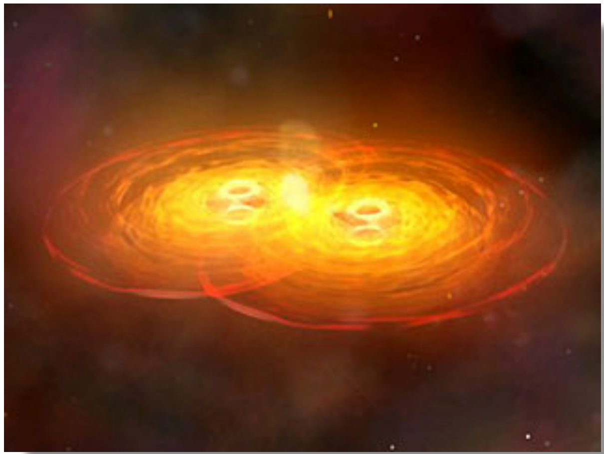
Synergy of EM & GW signatures in SMBH Mergers

GW Data: Masses, spins (initial and final), distances, merger rates, spacetime dynamics

EM + GW Data:

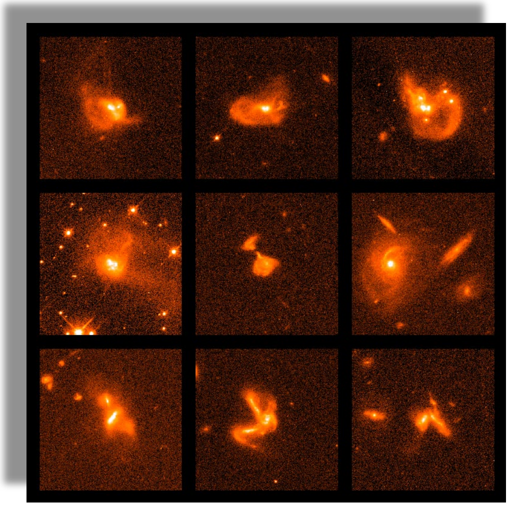
- Improves sky localization
- Identify host galaxy morphology
- Tests of galaxy merger scenarios
- Rates of detection for GW experiments
- Luminosity distance (GWs) and redshift (EM) yields cosmological standard sirens. D. E. Holz and S. A. Hughes, Astrophys. J. 629, 15 (2005)
- BH accretion physics. 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)

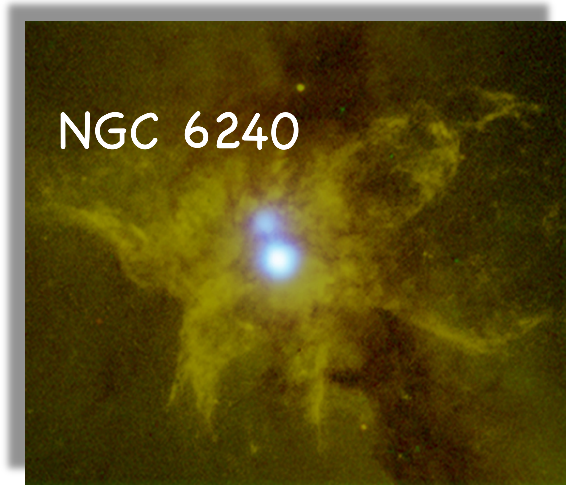




Supermassive BH Mergers

Galaxies merge and very often host a massive BH, leading to massive BHs coalescences.





- 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?
- It depends on the environment

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

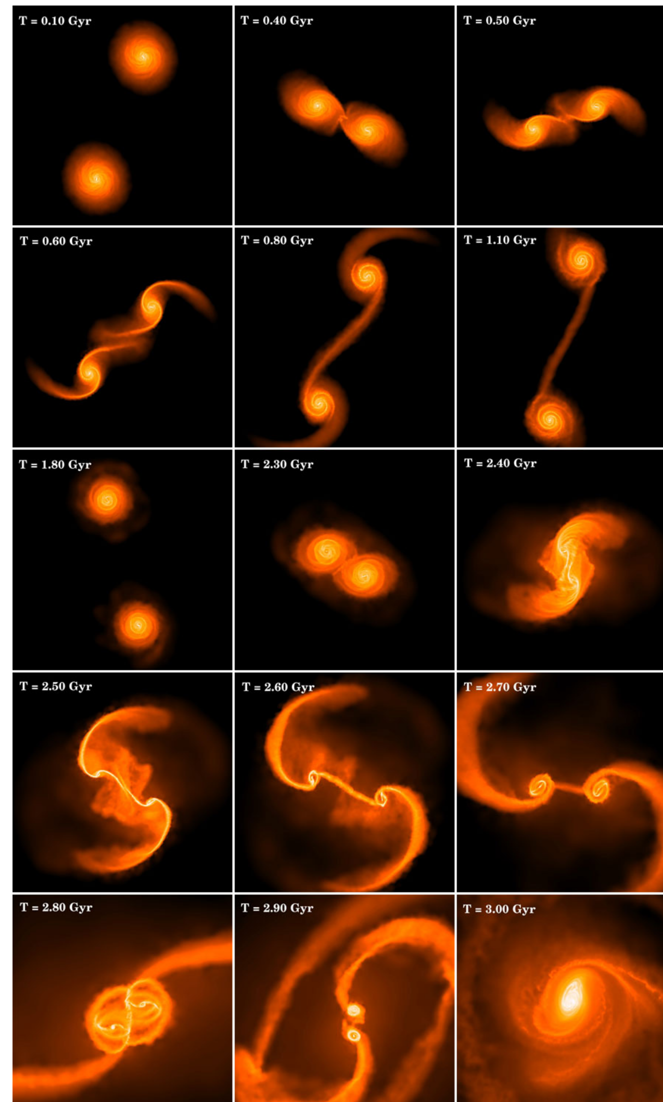
SMBBH History in Gas-rich Environments

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 and form a BH pair.

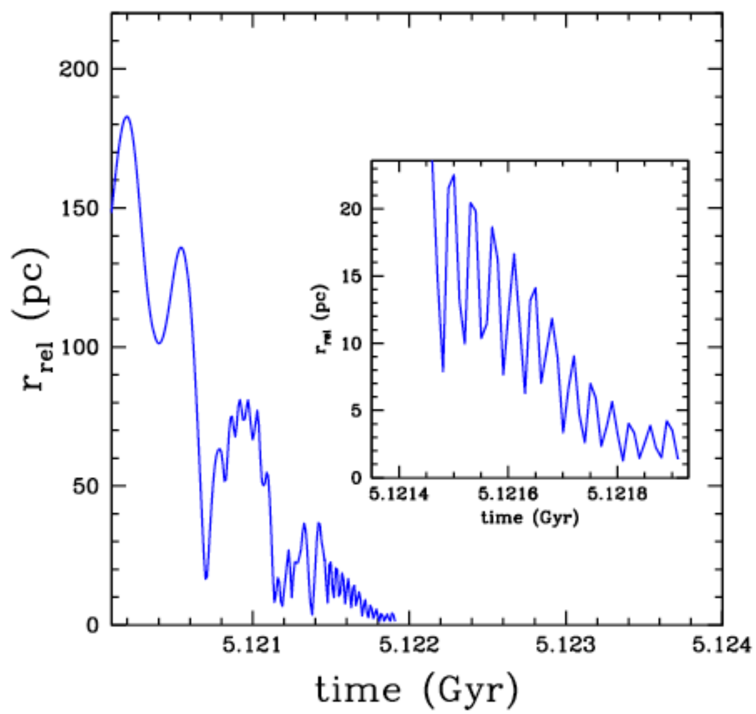


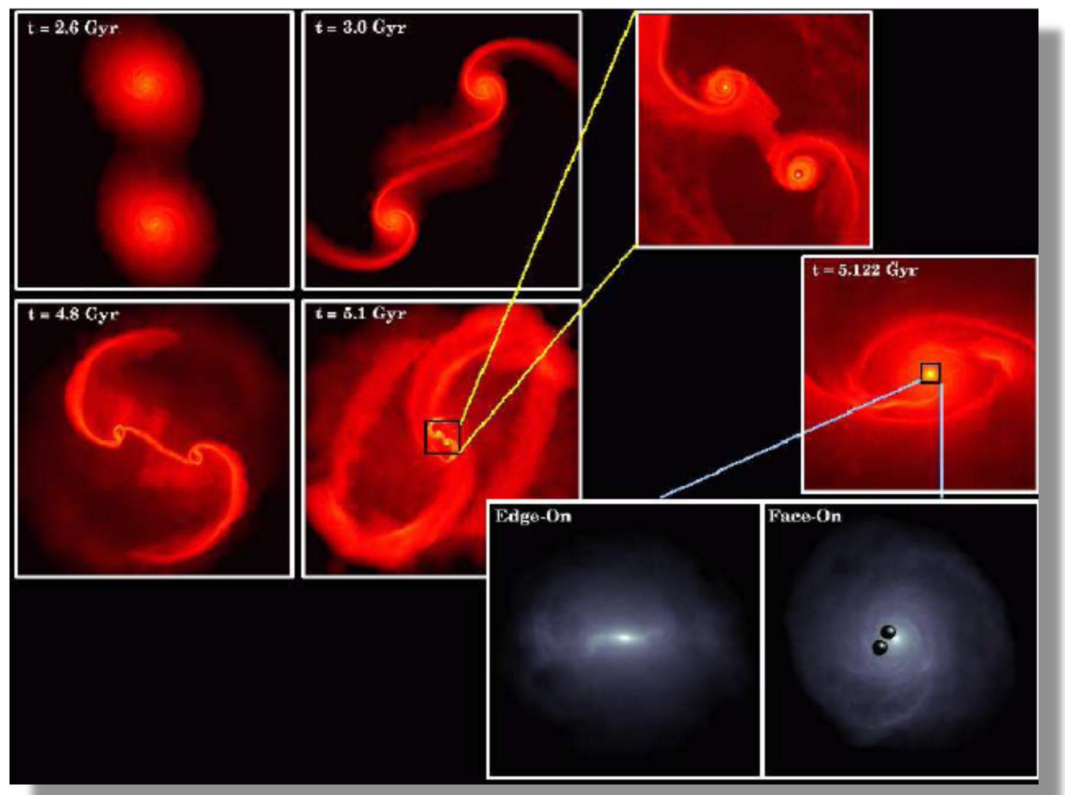
Colpi, Callegeri, Dotti & Mayer

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.





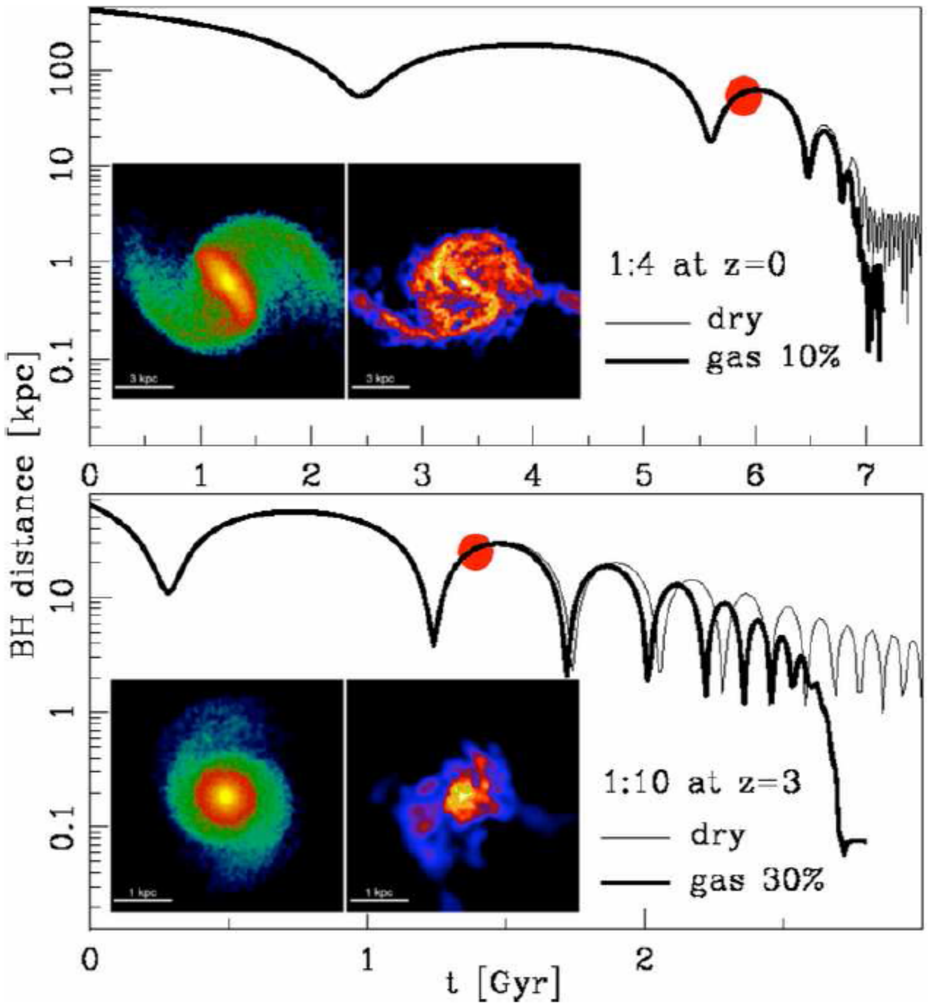
Colpi, Callegeri, Dotti & Mayer

SMBBH History in Gas-rich Environments

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

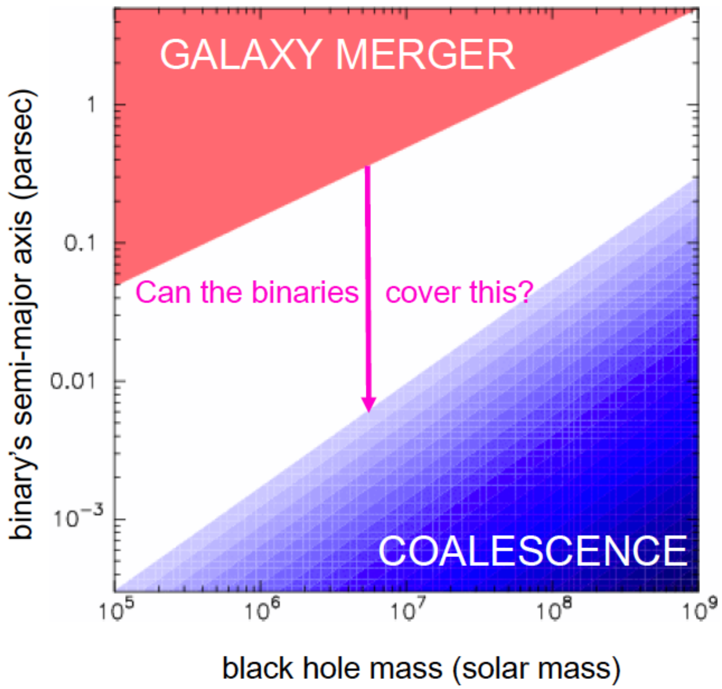
• 3-body interactions with the surrounding stars also contributes to shrink the BBH separation.

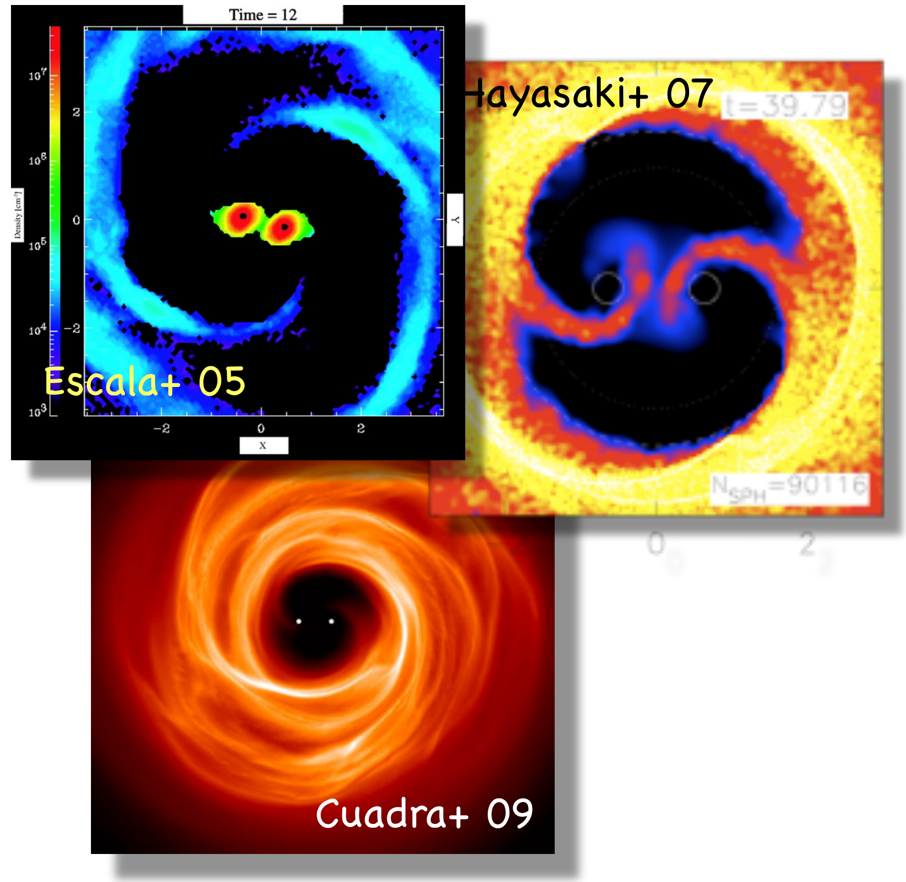
• However, shrinking stalls when reservoir of stars is depleted.



Colpi, Callegeri, Dotti & Mayer

The Last Parsec Problem



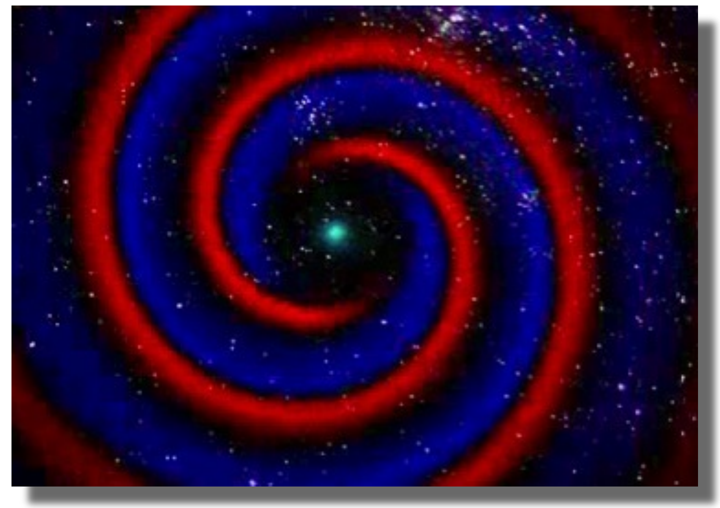


Disk assisted binary shrinkage:

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

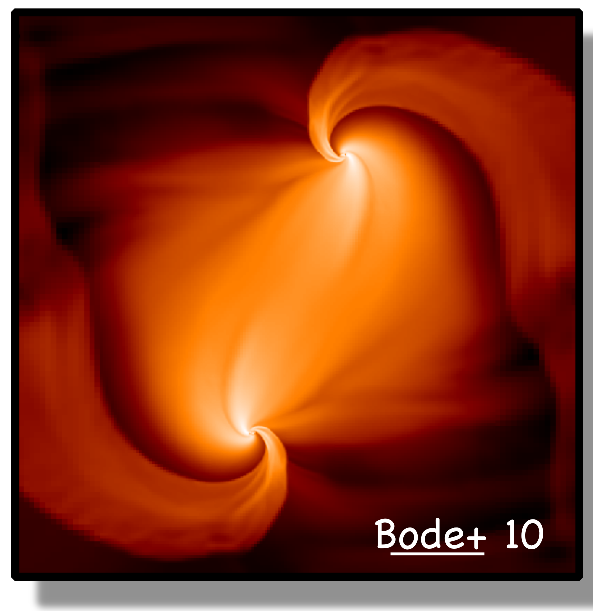
SMBBH History in Gas-rich Environments

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})

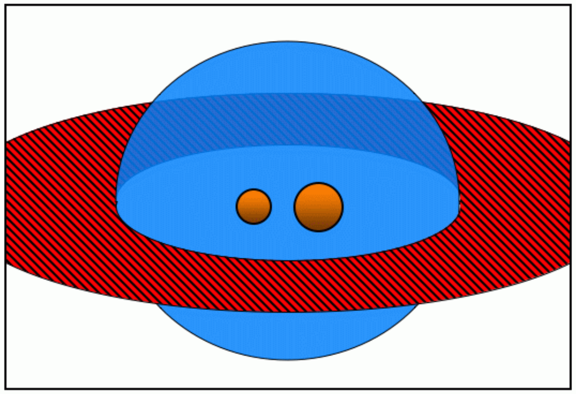


• The coalescence could in addition produce a variable or transient EM signal.

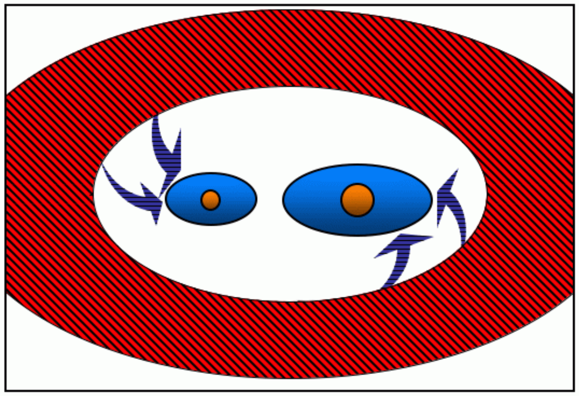
• A unique opportunity for multi-messenger astrophysics.

What is the environment in the vicinity of BBHs?

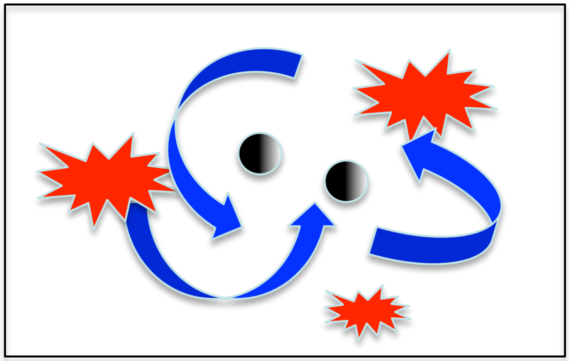
- Not well know at scales < 0.01 pc
- Two physically motivated scenarios depending on the balance of heating and cooling:



Radiatively Inefficient Hot Gas: If cooling is inefficient, the BBH is immersed in a pressure supported, geometrically thick torus or cloud.



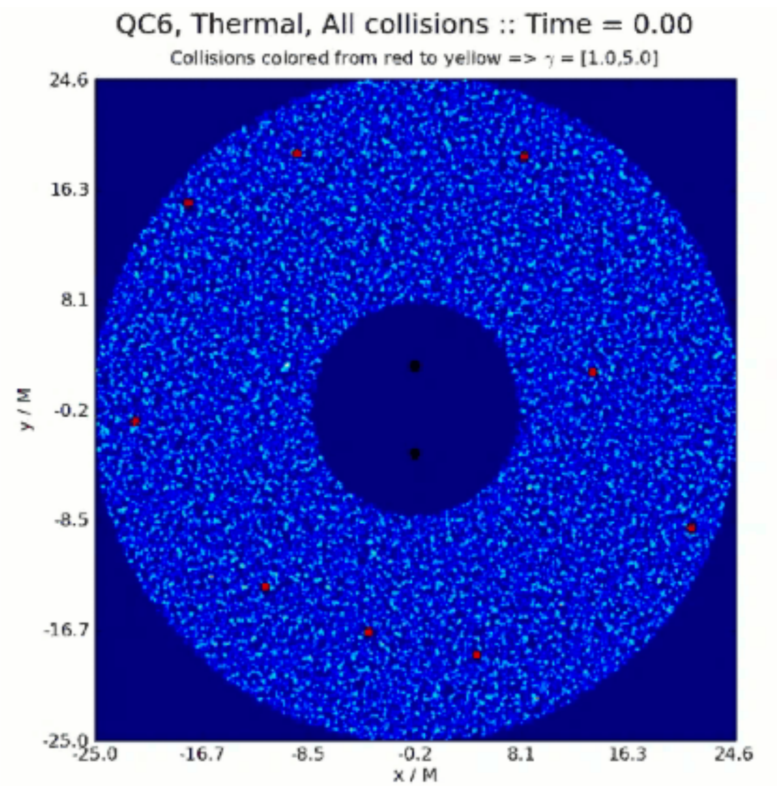
Circumbinary Disk: If cooling is relatively efficient, the gas settles into a rotationally supported geometrically accretion disk around the BBH.

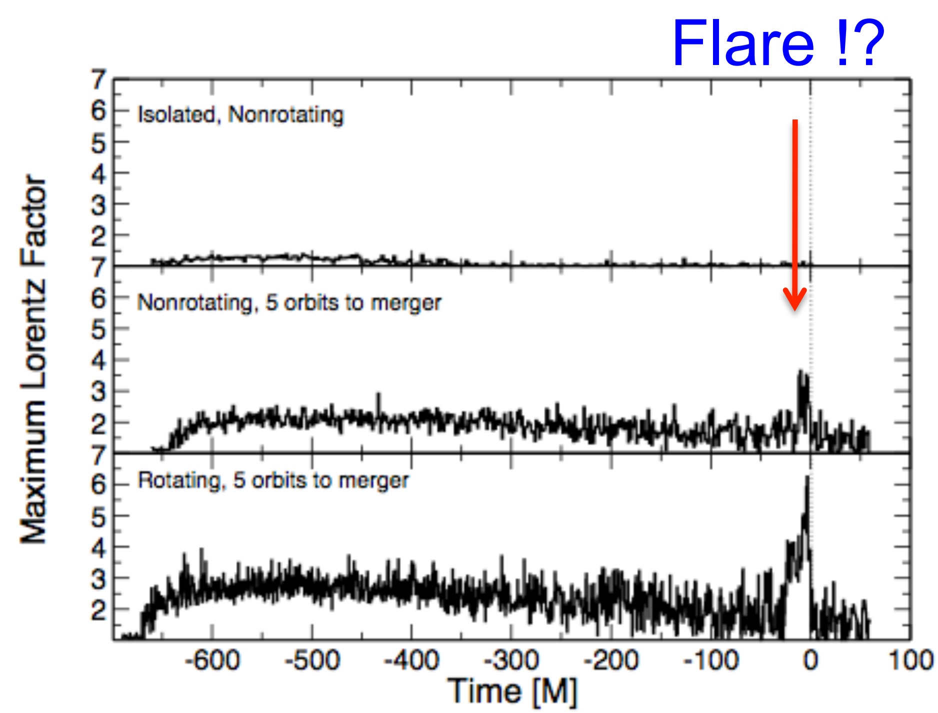


Chaotic Central Accretion: sequence of randomly oriented disks.

Modeling Matter in the Vicinity of BH Mergers

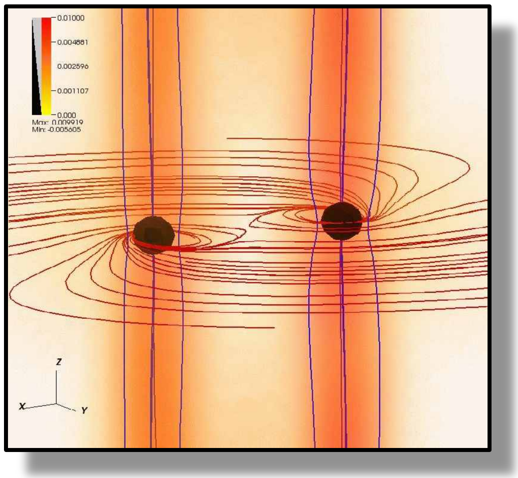
- *Goal:* For astrophysical relevant systems, one only need to model gas and magnetic fields in the *dynamical* spacetime of merging BHs
- *First step:* Map the flow of test particles around the merging BHs and estimate energetics of the flow from "collisions"
- *Setup:* 25,000 particles, uniformly distributed, velocities Keplerian with random directions

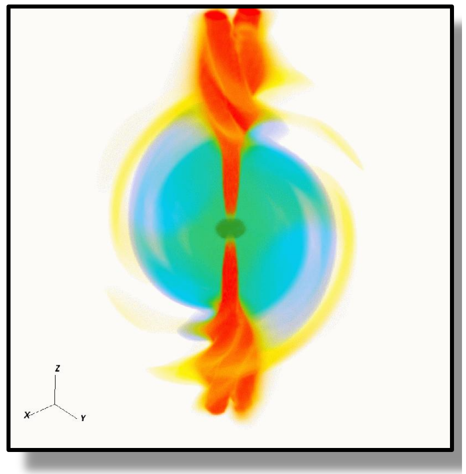


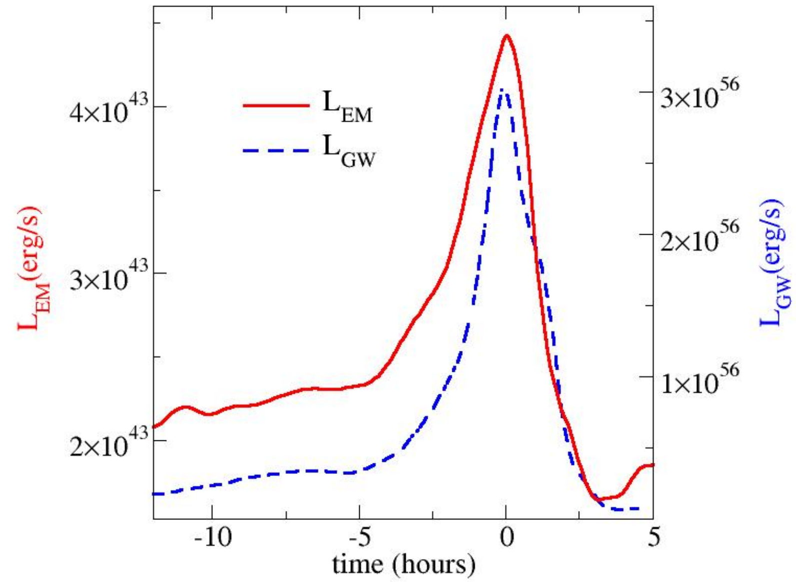


Van Meter et al arxiv:0908.0023

SMBH Mergers Surrounded by EM Fields





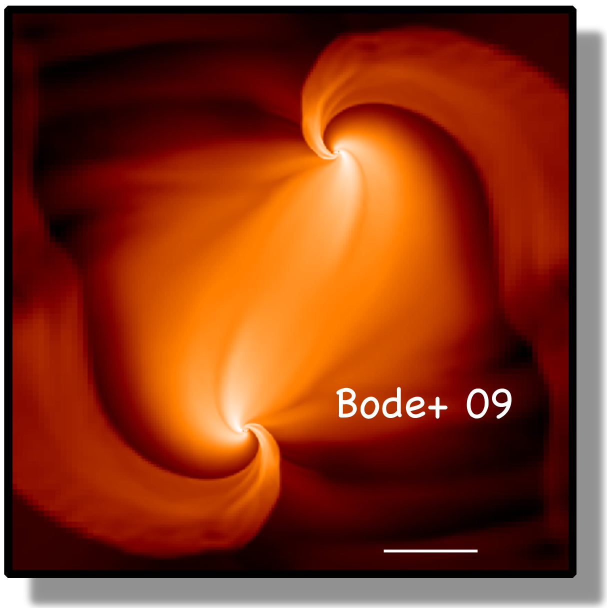


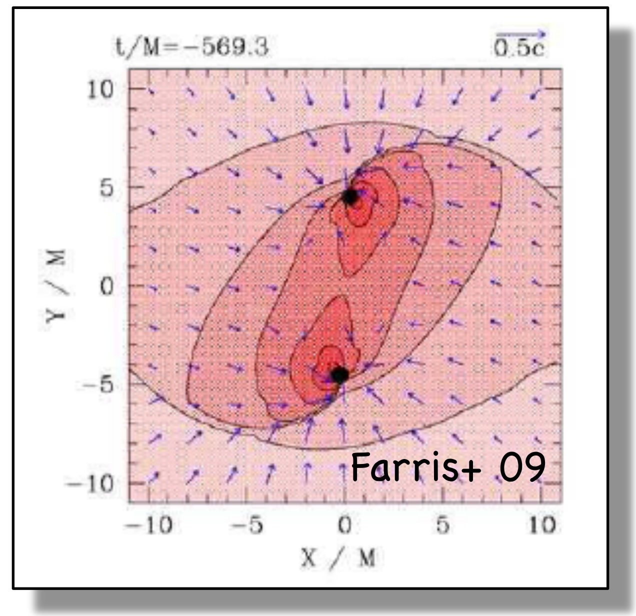
(Palenzuela, Lehner Liebling 09a, 09b, 10; Mösta+ 09)

$$\frac{E_{\rm em}}{E_{\rm gw}} \approx 10^{-13} \left(\frac{M}{10^8\, M_\odot}\right)^2 \left(\frac{B}{10^4\,{\rm G}}\right)^2 \qquad f_{\rm em} \approx 10^{-4} \left(\frac{M}{10^8\, M_\odot}\right)^{-1} {\rm Hz}$$

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

SMBH Mergers Surrounded by Gas



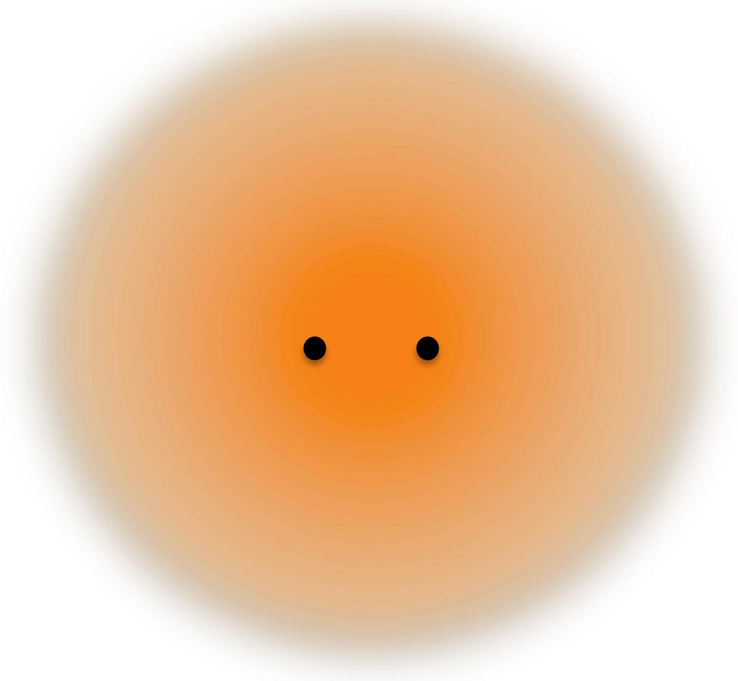


Relativistic Mergers of Supermassive Black Holes and their Electromagnetic Signatures
Bode, Haas, Bogdanovic, Laguna, Shoemaker

Properties of Accretion Flows Around Coalescing Supermassive Black Holes
Bogdanovic, Bode, Haas, Laguna, Shoemaker

Binary Black Hole Mergers in Gaseous Environments: "Binary Bondi" and "Binary Bondi-Hoyle-Lyttleton" Accretion
Farris, Liu, Shapiro

We focus on the hot gas cloud case



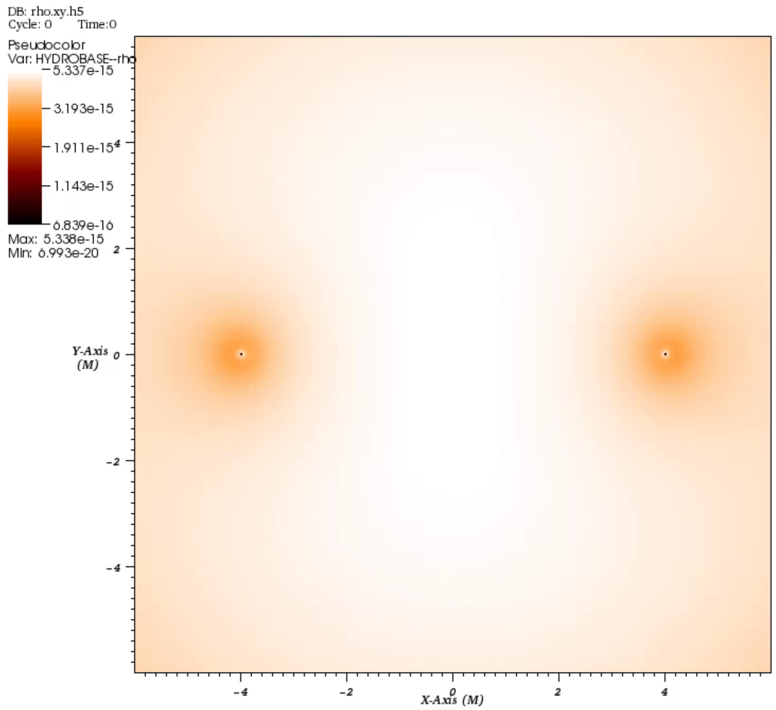
$$
\begin{aligned}
M &= 10^7 M_\odot \\
d &= 8\,M = 10^{-5} M_7\,\mathrm{pc} \\
\rho_c &= 7 \times 10^{-12}\mathrm{g\,cm^{-3}}\, M_7^{-2} \\
T_p &= 10^{12}\mathrm{K} \\
T_e &= 10^{10}\mathrm{K}
\end{aligned}
$$

Computational Infrastructure (Maya):

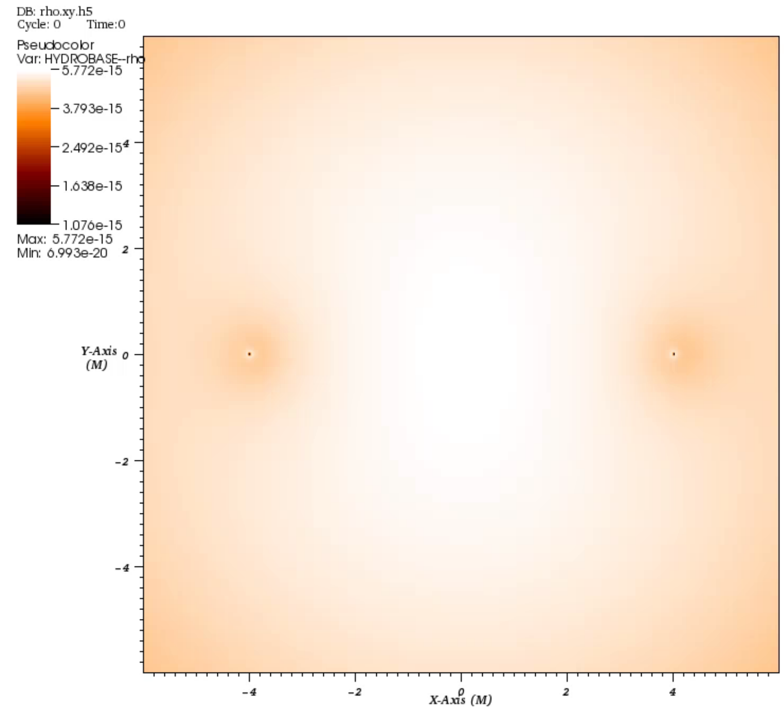
- BSSN form of Einstein Eqs
- 4th order accurate
- CACTUS (parallelization)
- CARPET (AMR, 9 refinement levels)
- WHISKY (Hydro)
- Horizon trackers
- BH spin from killing vectors
- No AGN feedback, no magnetic fields, no radiative transfer.

runs	s_1	s_2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4

Gas Density

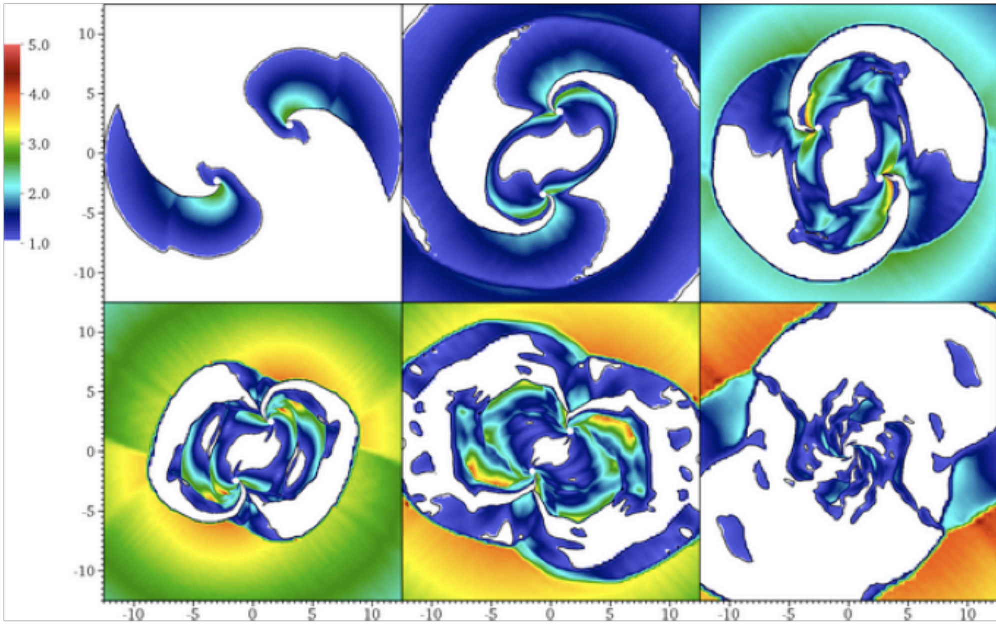


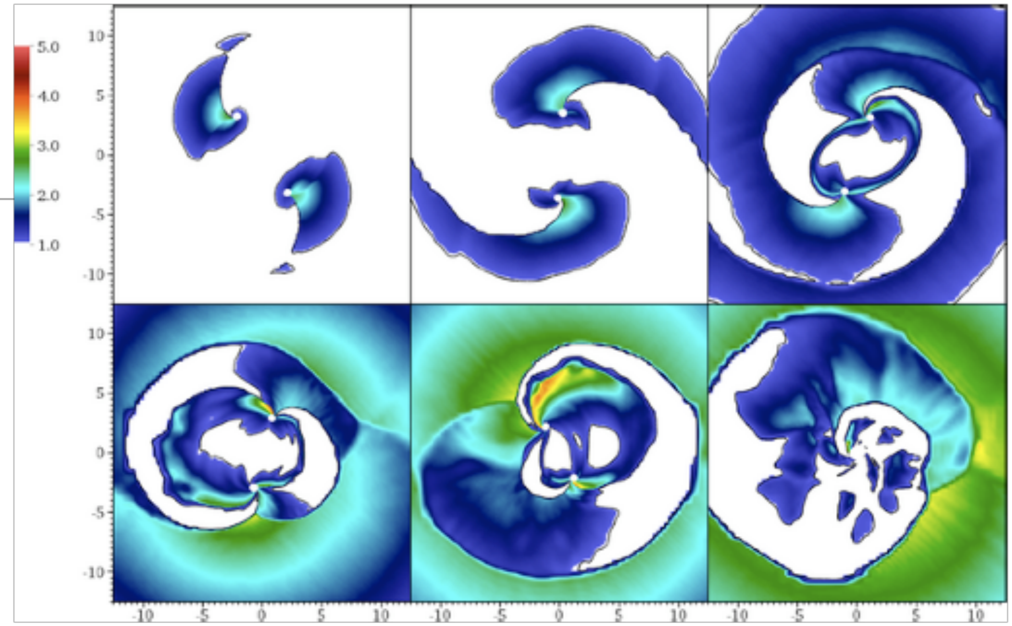
$s_1/m^2 = s_2/m^2 = 0.6$



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

Mach number ≥ 1

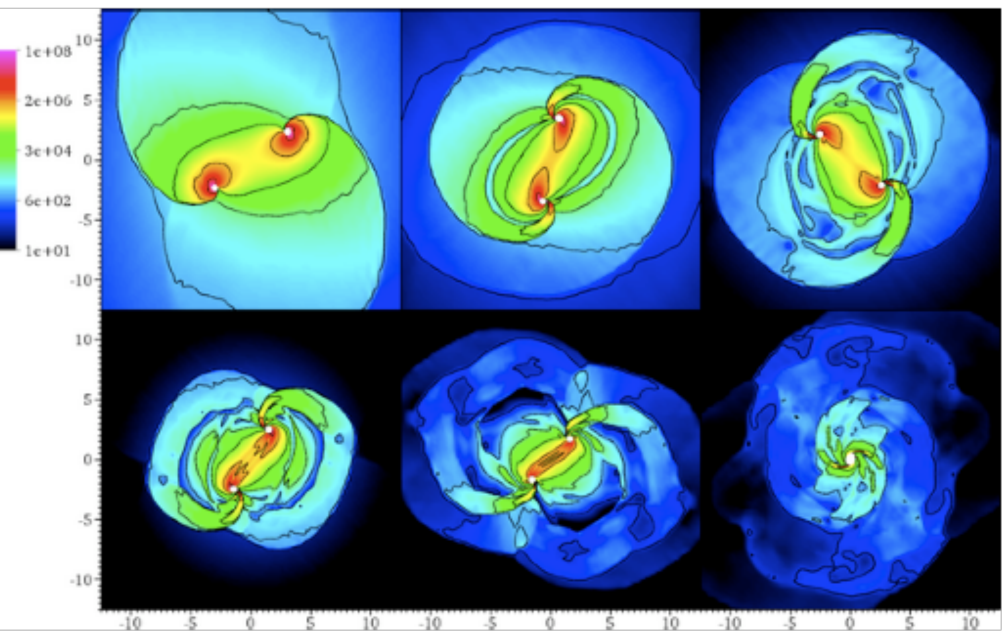


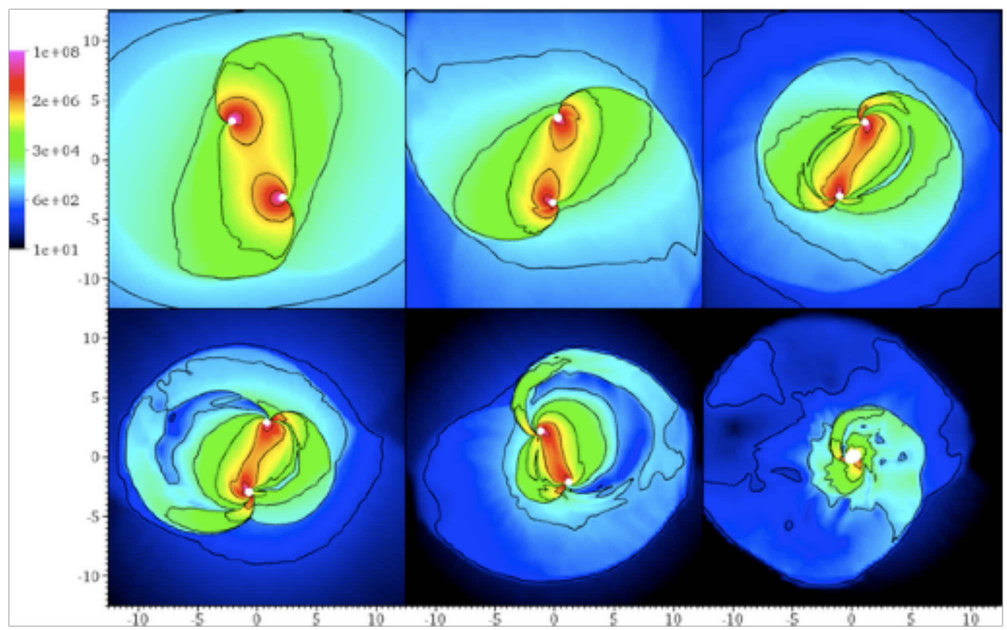


s1= s2= +0.6

Temperature

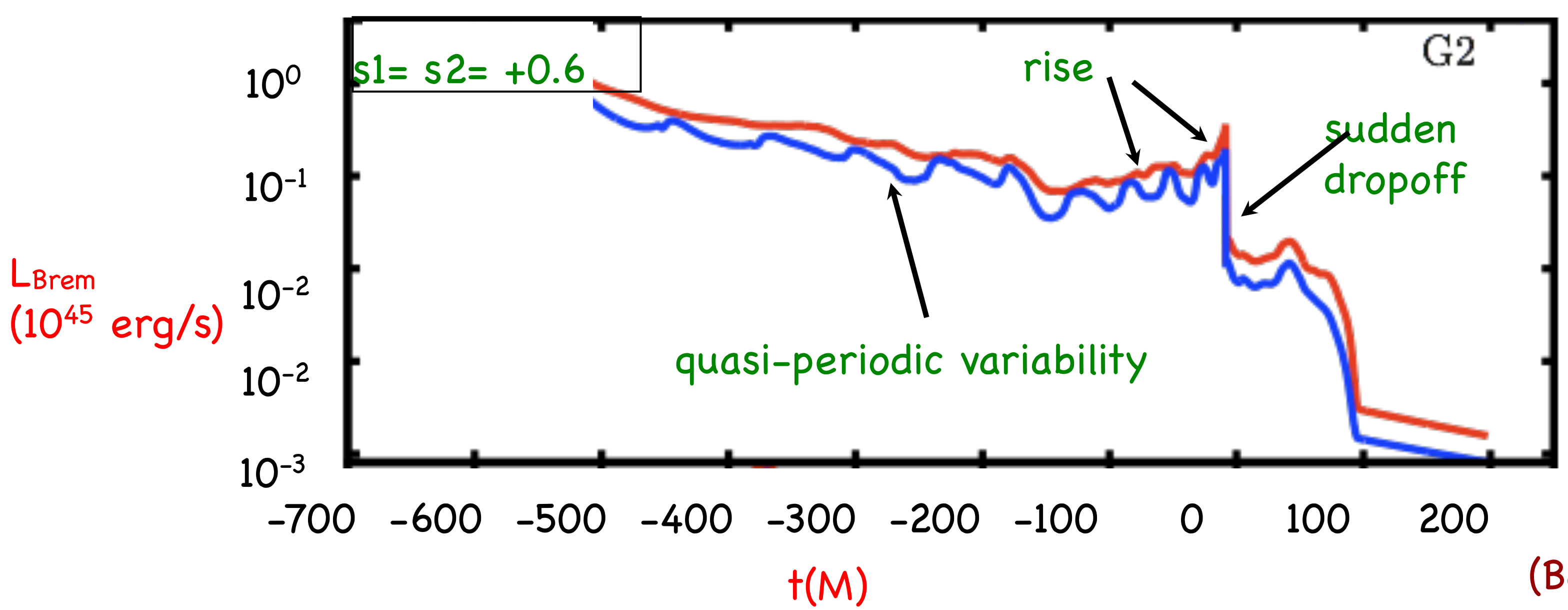
s1= +0.4 s2= -0.4





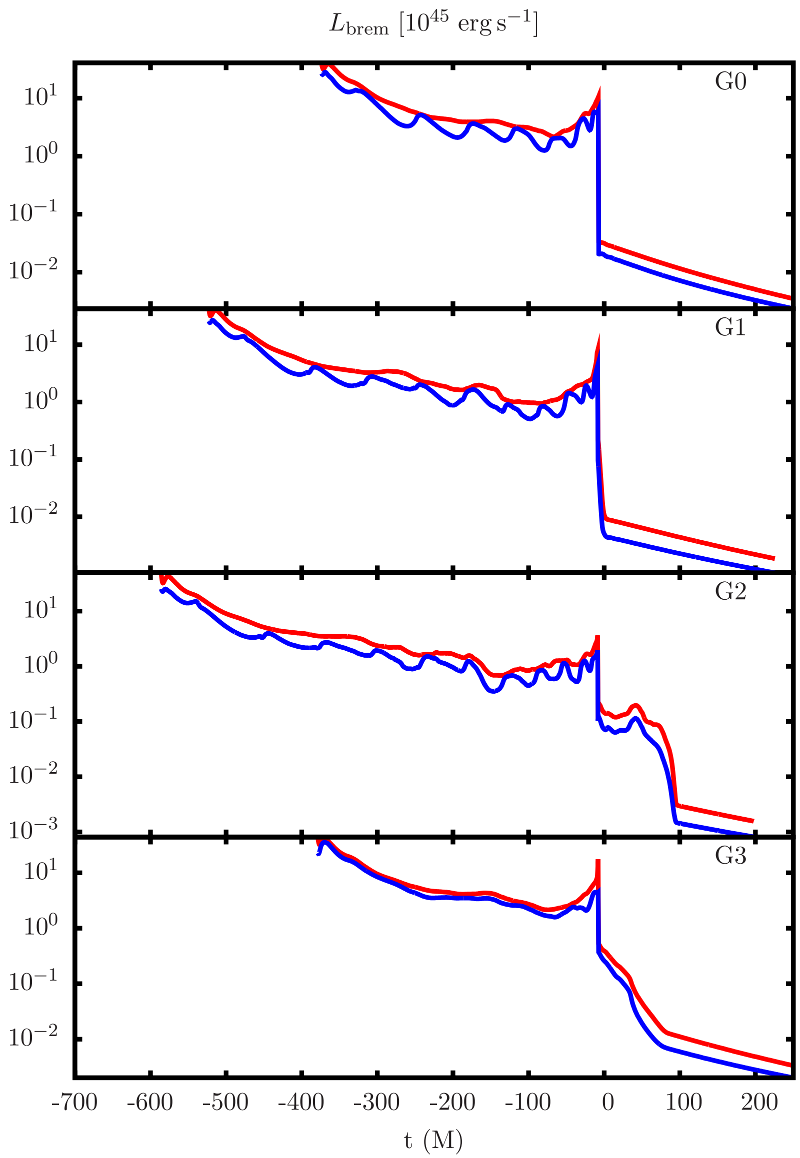
Bremsstrahlung luminosity

$$
\begin{aligned}
L_{\rm Brem} &\approx 1\times10^{44}\,{\rm erg\,s^{-1}}\left(\frac{\rho_c}{10^{-11}{\rm g\,cm^{-3}}}\right)^2\left(\frac{T_p}{10^{12}\,{\rm K}}\right)^{-3}\left(\frac{T_e}{10^{10}\,{\rm K}}\right)^{1/2}\\
&\times\left[1+4.4\times\left(\frac{T_e}{10^{10}\,{\rm K}}\right)\right]_{5.4} M_7^6\\
L_{\rm Sync} &\approx 2\times10^{36}\,{\rm erg\,s^{-1}}\left(\frac{\rho_c}{10^{-11}{\rm g\,cm^{-3}}}\right)\left(\frac{T_p}{10^{12}\,{\rm K}}\right)^{-3}\left(\frac{B}{1G}\right)^2 M_7^6\\
L_{\rm IC} &\approx 8\times10^{-9}\,L_{\rm soft}\left(\frac{\rho_c}{10^{-11}{\rm g\,cm^{-3}}}\right)\left(\frac{T_p}{10^{12}\,{\rm K}}\right)^{-3}\left(\frac{R_{\rm tran}}{10^5 M}\right)^{-2} M_7^4\\
L_{\rm Edd} &\approx 1.3\times10^{45}\,{\rm erg\,s^{-1}}\,M_7
\end{aligned}
$$

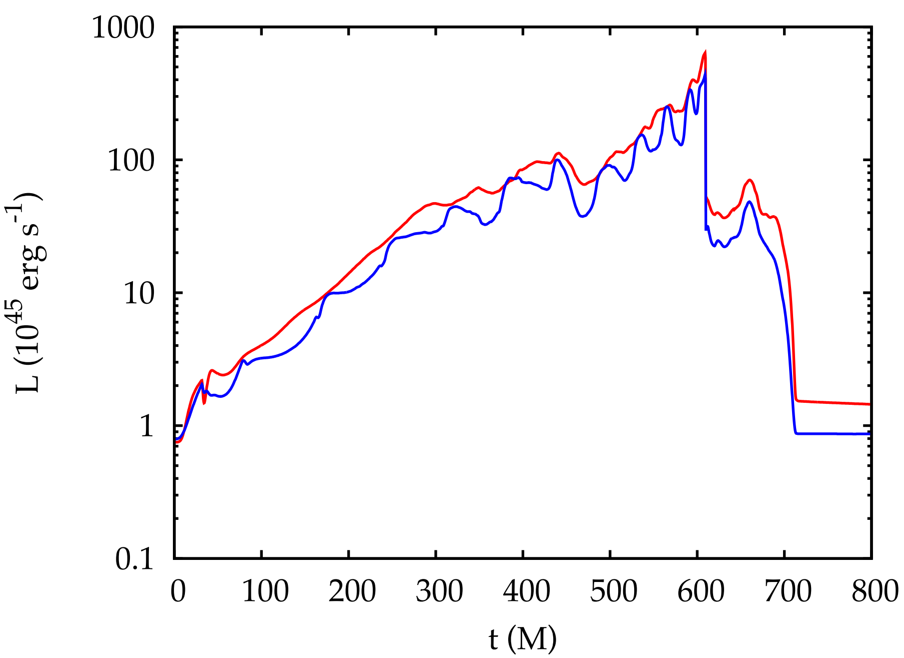


(Bode+ 09)

Bremsstrahlung luminosity



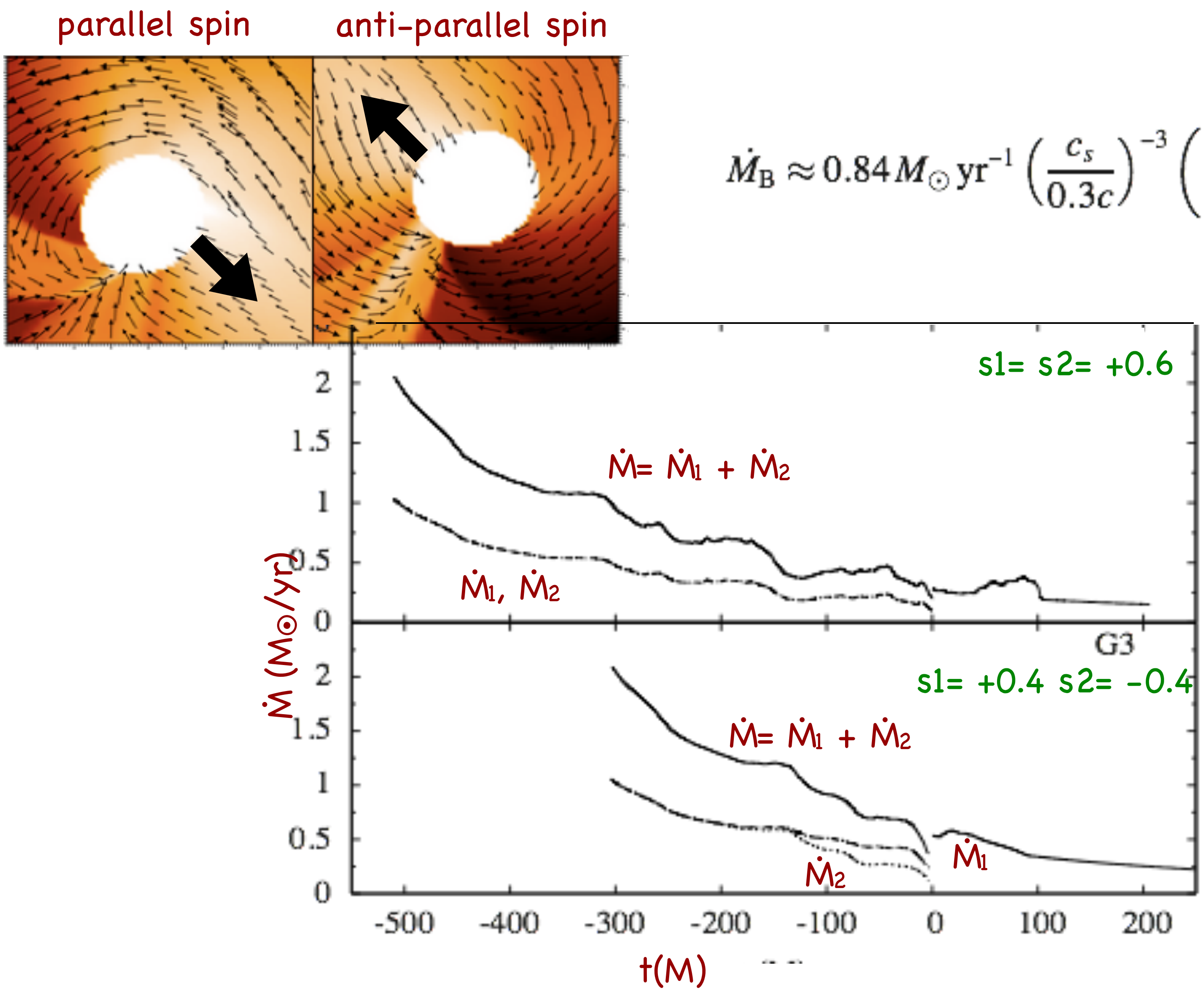
runs	s_1	s_2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4



Accretion onto the BHs

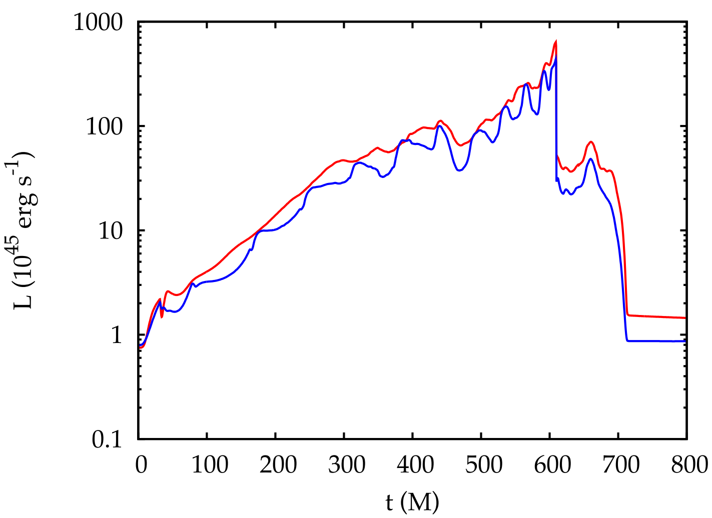
(Bode+ 09)

$$\dot{M}_B \approx 0.84\, M_\odot\, \mathrm{yr}^{-1} \left(\frac{c_s}{0.3c}\right)^{-3} \left(\frac{\rho}{10^{-11}\,\mathrm{g\,cm^{-3}}}\right) M_7^2$$

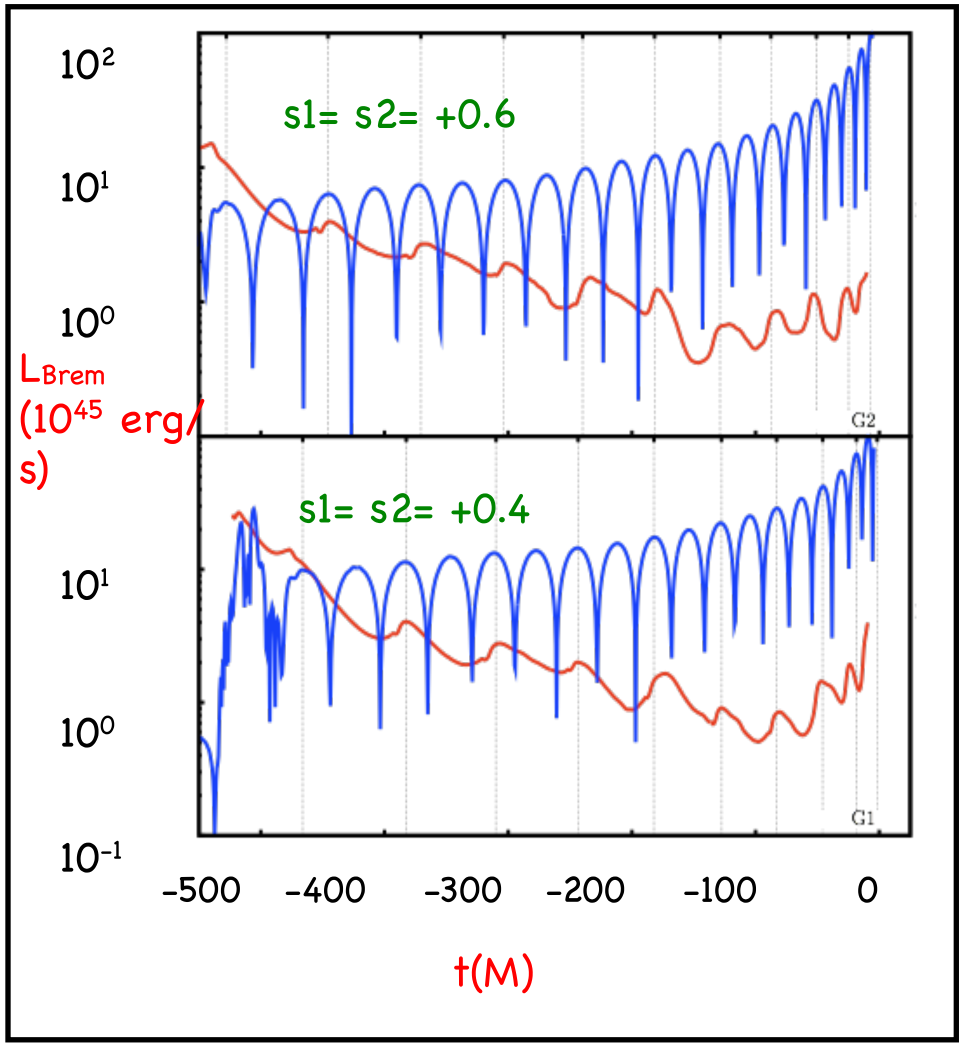


EM & GW emission

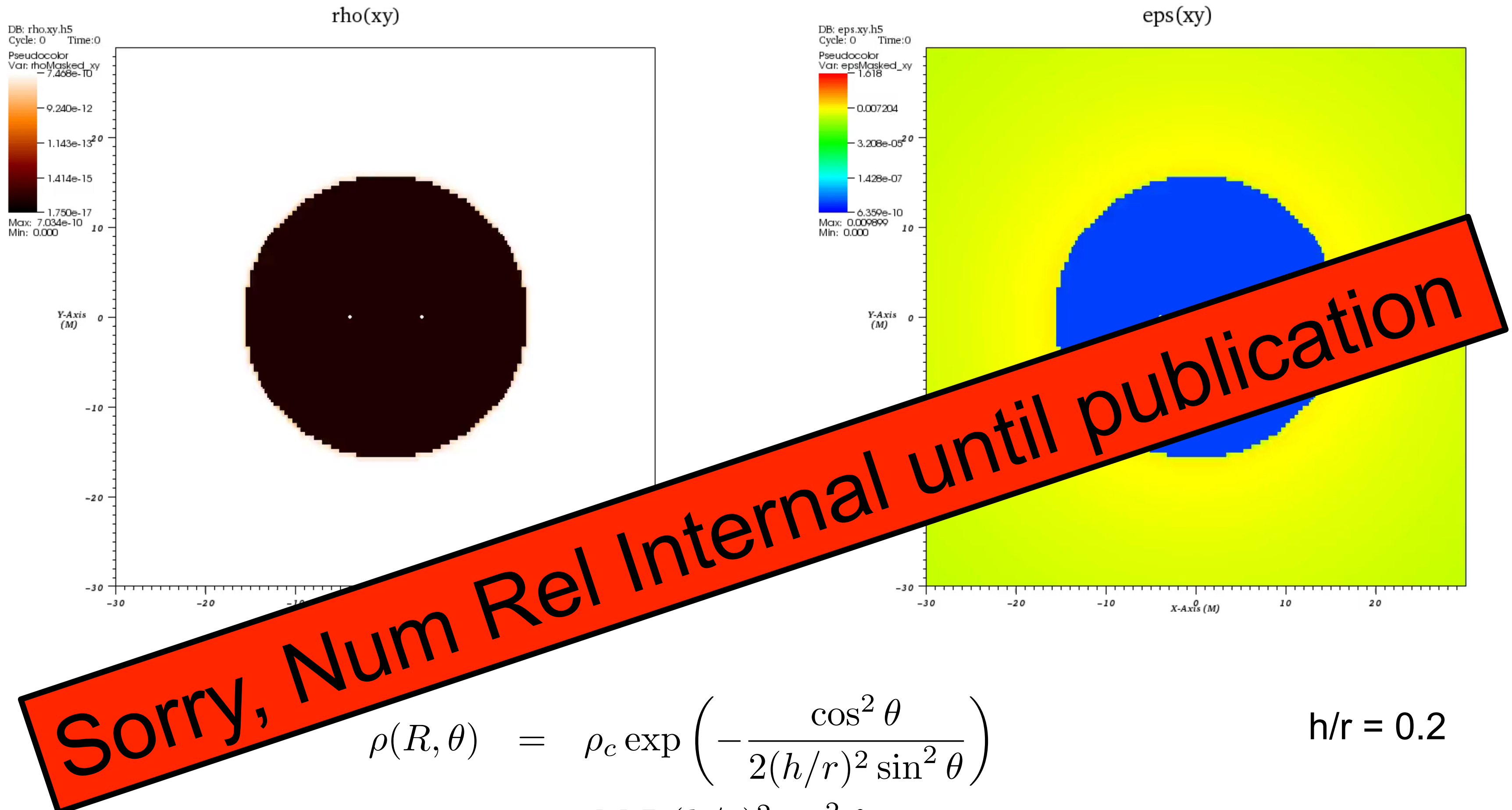
- Correlated variability can occur due to the effect of relativistic beaming and boosting
- Other characteristic features: rise and sudden drop off of luminosity



(Bode+ 09)



BBH + Circumbinary Disk



$$\rho(R,\theta) = \rho_c \exp\left(-\frac{\cos^2\theta}{2(h/r)^2\sin^2\theta}\right)$$

$$p(R,\theta) = \frac{M\,R\,(h/r)^2\sin^2\theta}{(R-4\,M)^2}\,\rho(R,\theta)$$

h/r = 0.2

Bode, Bogdanovic, Haas, Healy, Laguna, Shoemaker, *in preparation*

Conclusions and Prospects

- In the absence of information regarding the physical properties of the gaseous environment surrounding a binary before and during coalescence our best option is to explore a range of scenarios and look for characteristic features.
- For a radiatively inefficient hot gas, correlated EM+GW variability or a sudden drop of EM emission can provide the smoking gun.
- These are prototype simulations. More follow-up work is needed in order to explore more astrophysically plausible configurations (i.e. MHD, cooling, radiative transfer?