# Light-shows from Supermassive Black Hole Mergers

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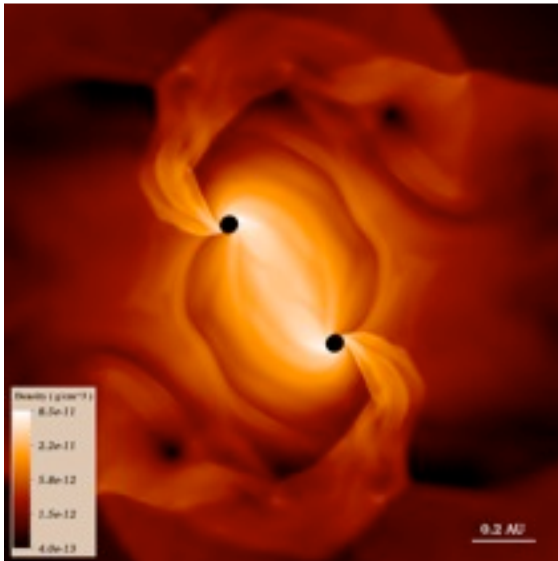
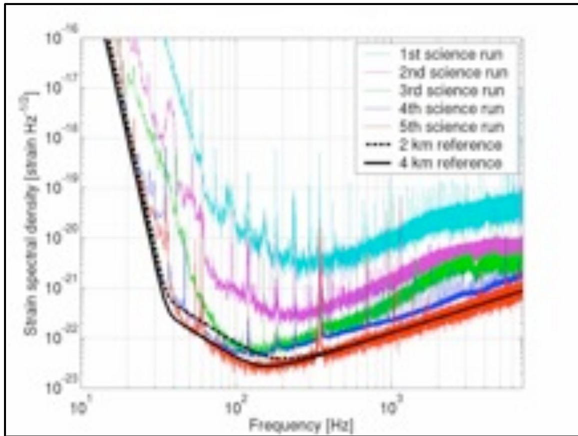
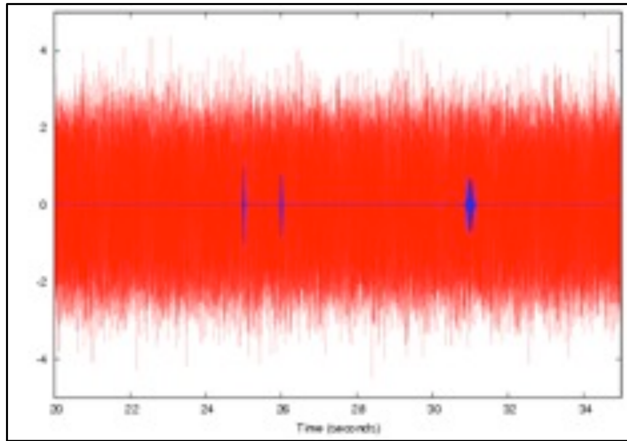


Collaborators:

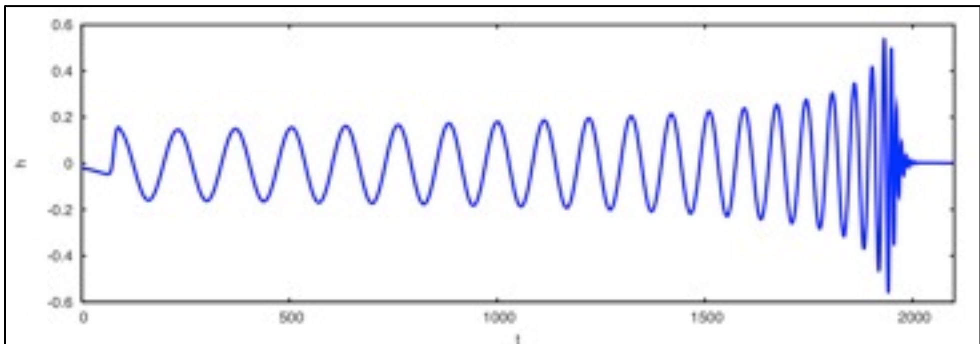
Tanja Bode, Tamara Bogdanovic (Maryland), Roland Haas, James Healy, Deirdre Shoemaker

# The Driving Force behind Numerical Relativity



*Numerical waveforms are essential on assisting to predict what to expect*



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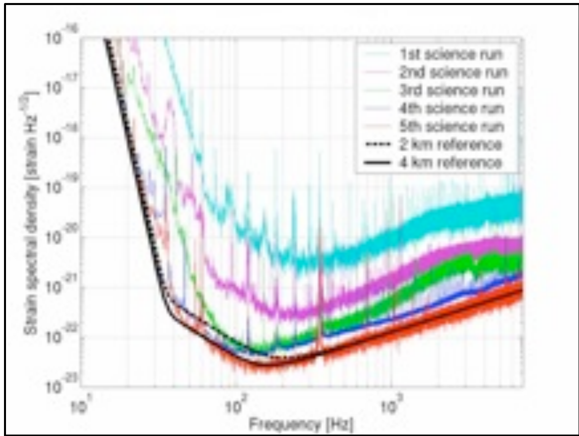


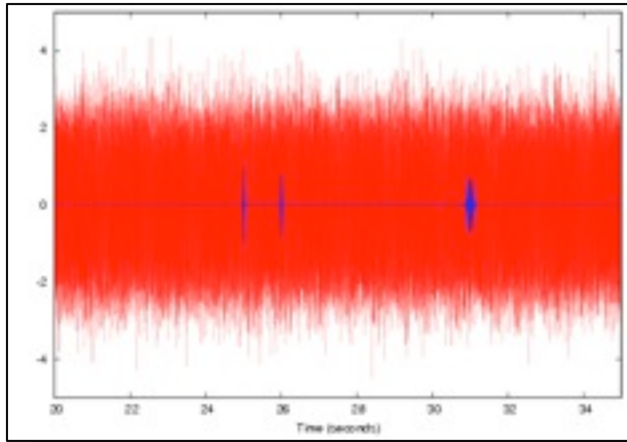

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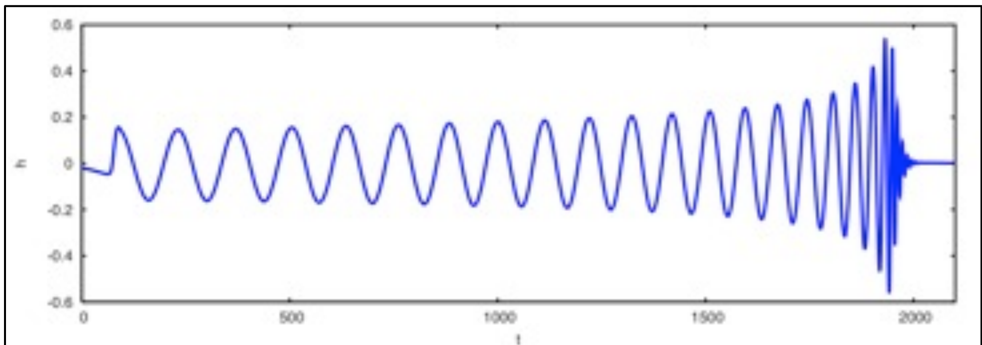


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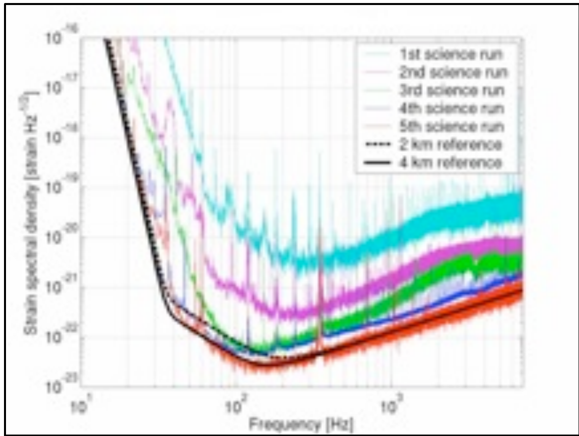


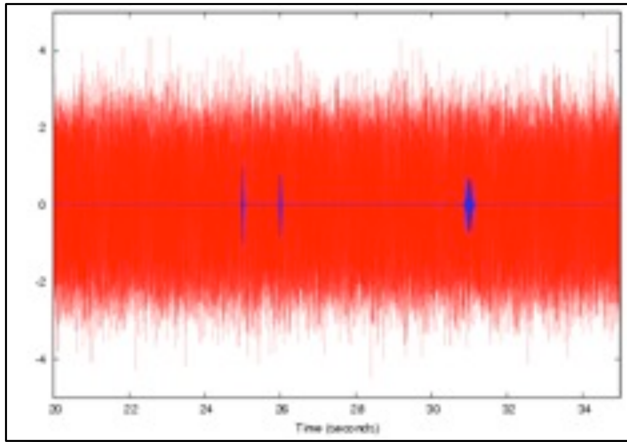

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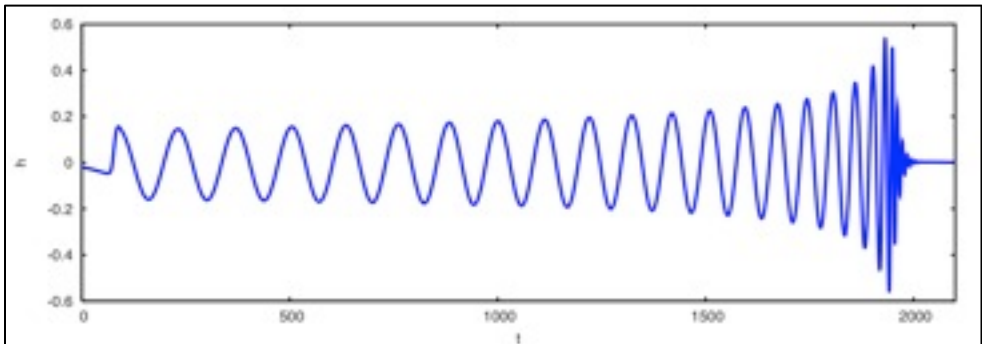
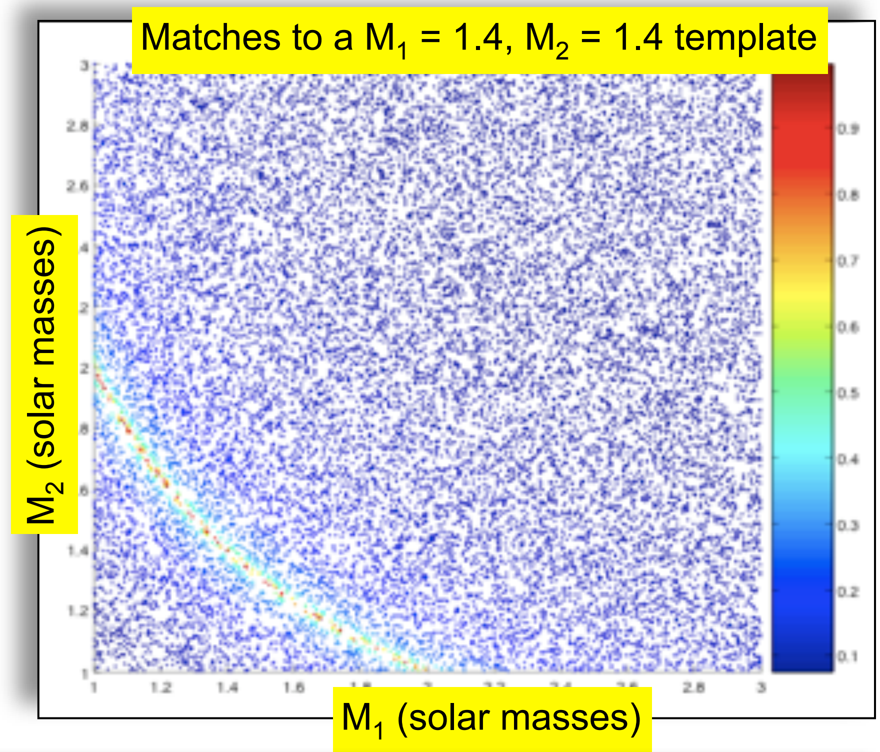


# Template Banks & Matches

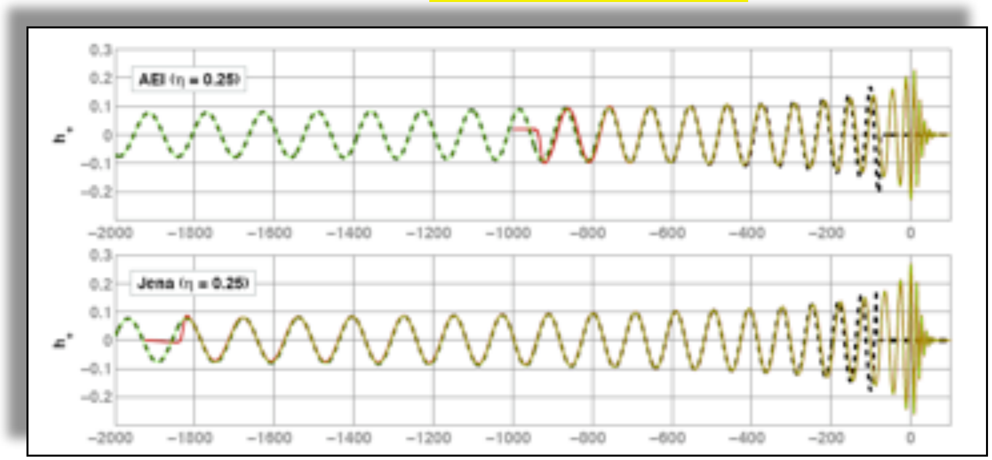
## BBH Parameter Space:

- Masses
- Spins
- Eccentricity
- Orientation
- Time of arrival
- Phase at arrival




## Dirty Laundry & Needs:

- Efficiency of codes
- Accuracy needs not known
- Limited parameter exploration
- On demand simulations



# Synergy of EM & GW signatures in SMBH Mergers

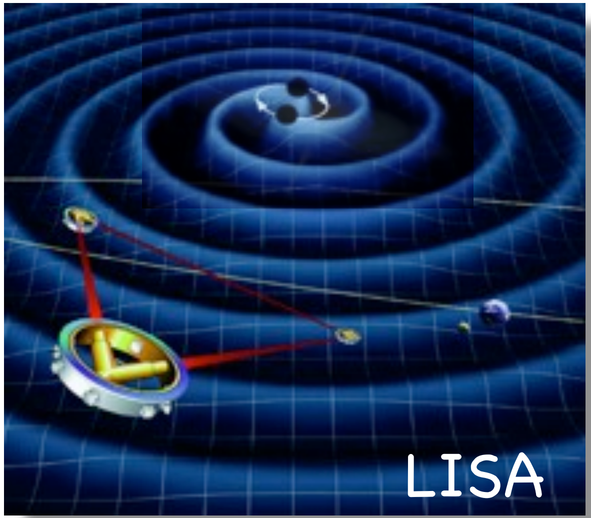
*SMBH binaries are one of the prime sources for LISA.*

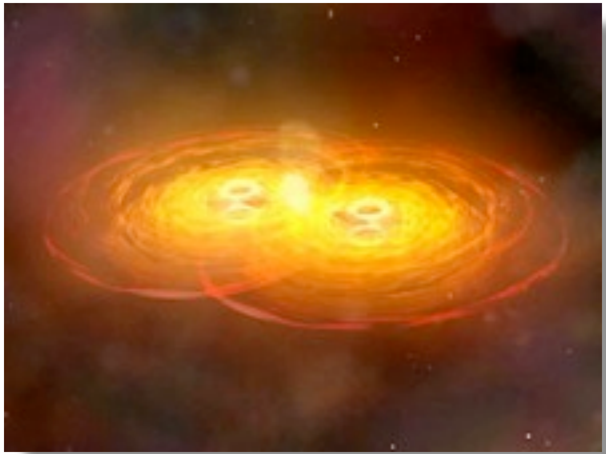
GW Data:

- Masses, spins (initial and final),
- Luminosity Distance
- Merger rates
- Mapping the spacetime

EM + GW Data:

- Improves sky localization
- Identify host galaxy morphology
- Tests of galaxy merger scenarios
- Improves GW detection rates
- Luminosity distance (GWs) and redshift (EM) yield cosmological standard sirens.
- Understanding BH accretion physics.
- Test ground for GR (e.g. graviton's speed)

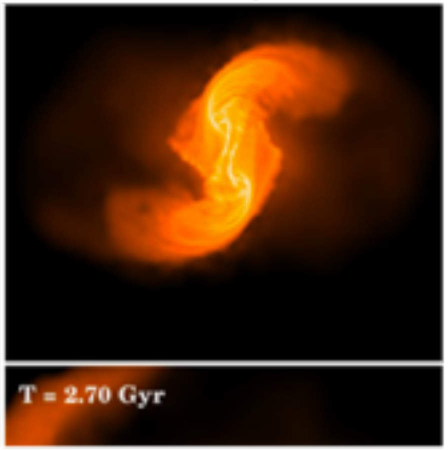


# Supermassive BH Mergers

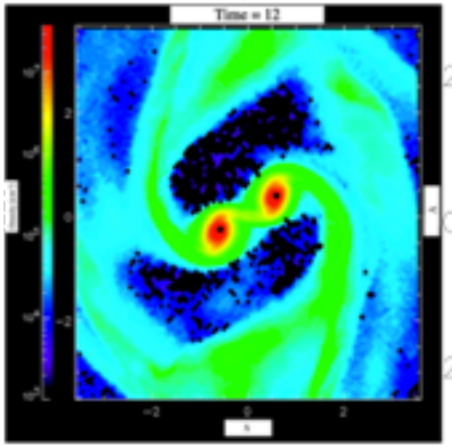
Mergers of galaxies will very often lead to SMBH coalescences.

10s kpc



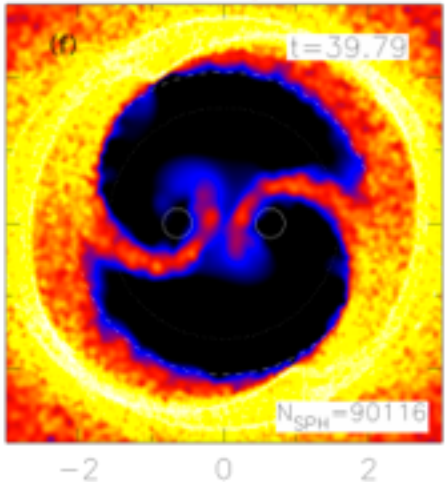

Mayer+ 07

10s pc



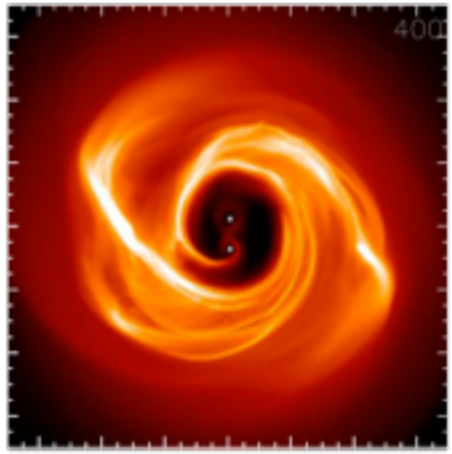

Escala+ 05

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 $\longleftrightarrow$ $10^{-5}$ pc

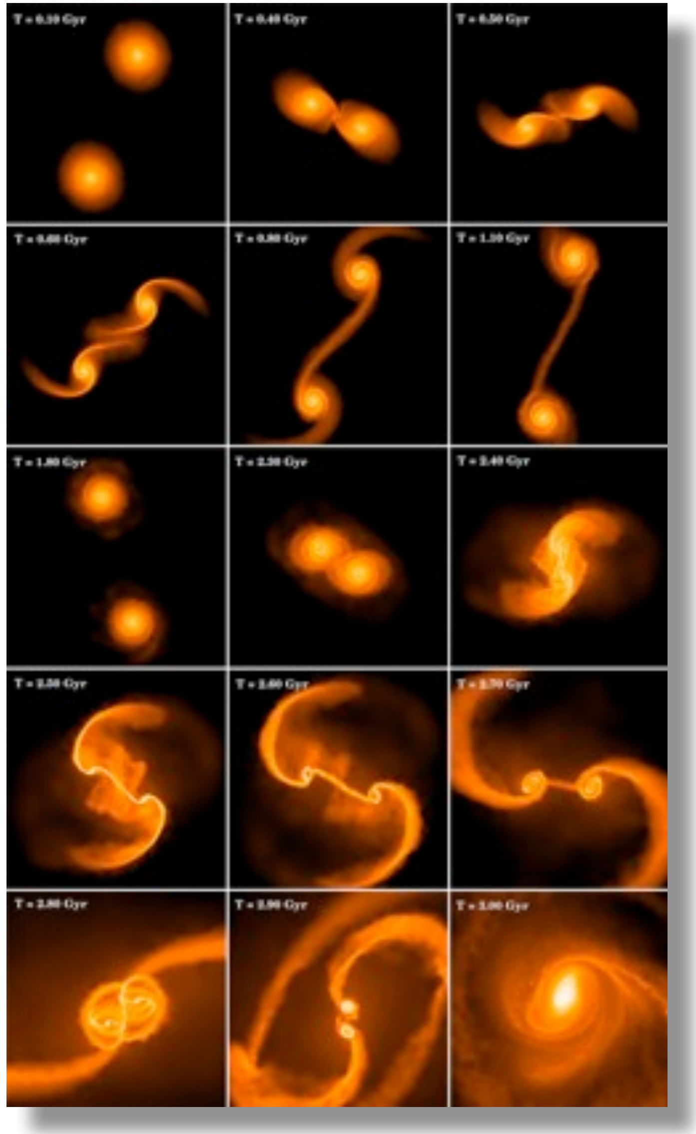
# SMBBH History in Gas-rich Environments

$r_{sep} \sim 10$ kpc:

• Galactic cores drag the BHs with them.

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

• As disks merge, gas-dynamical friction sinks the BHs to the center to form a pair.



Colpi, Callegeri, Dotti & Mayer

# SMBBH History in Gas-rich Environments

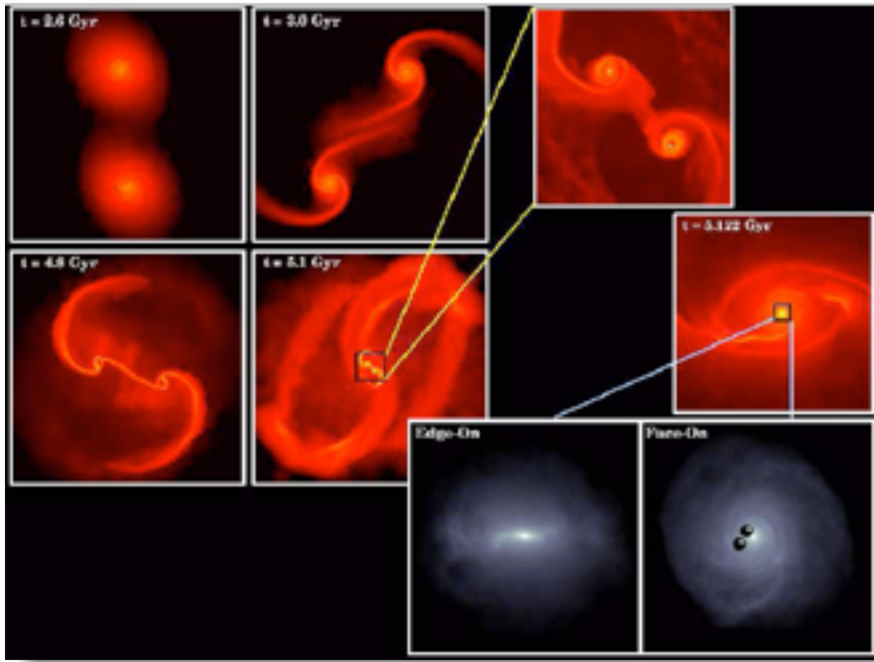
$r_{sep}$ ~ 10 pc:

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

$r_{sep}$ ~ 1 pc:

• 3-body interactions with the surrounding stars help shrinking the binary.

• Shrinking stalls when reservoir of stars is depleted (Last parsec problem).

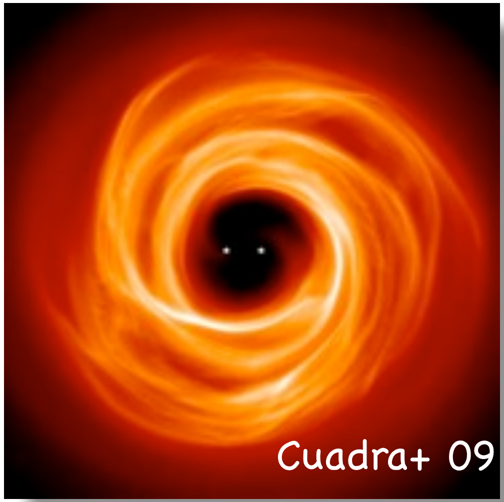



Colpi, Callegeri, Dotti & Mayer

# SMBBH History in Gas-rich Environments

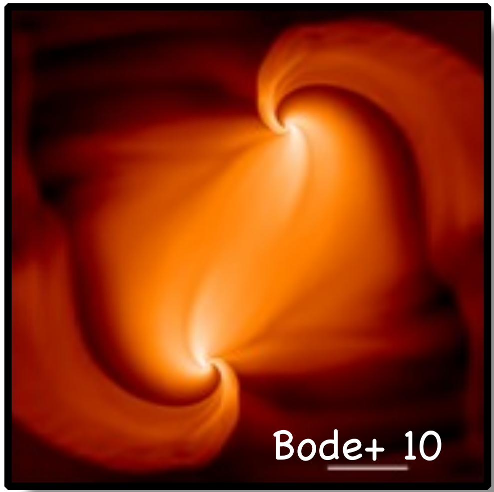
$r_{sep}$ ~ 0.01pc:

- Disk assisted binary shrinkage
- Requires thin circumbinary disks.
- More effective for un-equal mass binaries.
- Maybe a retrograde disk is more effective.




$r_{sep} < 10^{-4}$ pc:

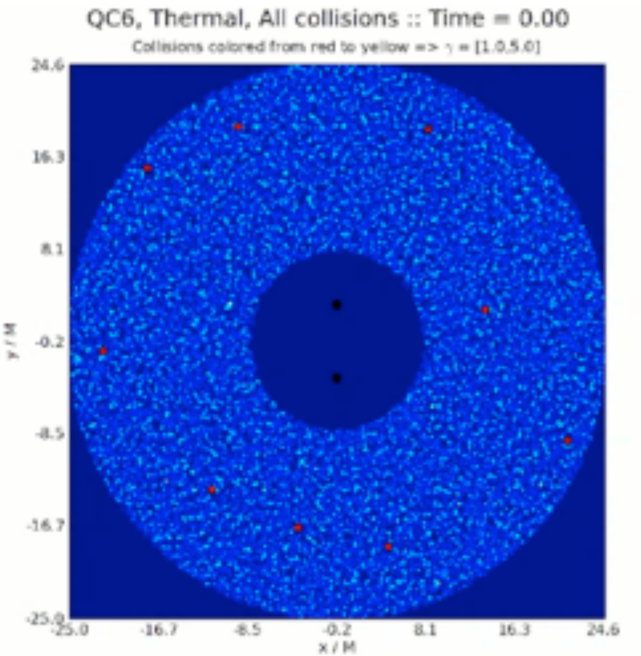
- Gravitational radiation dominates the dynamics.
- The most luminous sources of gravitational radiation in the universe (~ $10^{57}$ erg $s^{-1}$)
- An opportunity for variable or transient EM signal (multi-messenger astrophysics).

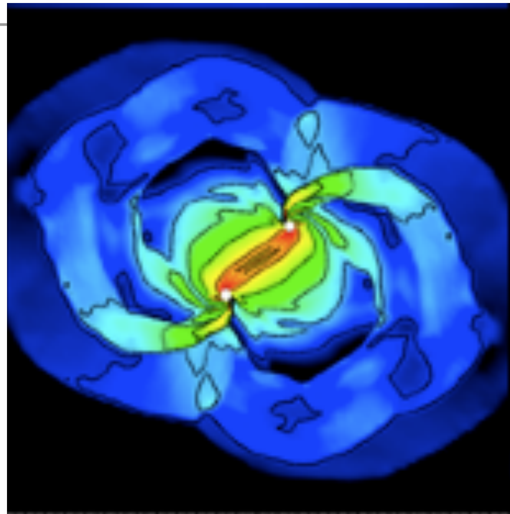


# Relativistic mergers of SBHs

Surrounded by test particles

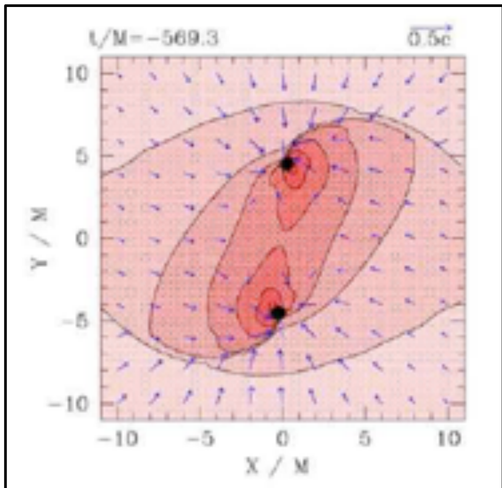
(van Meter+ 09)



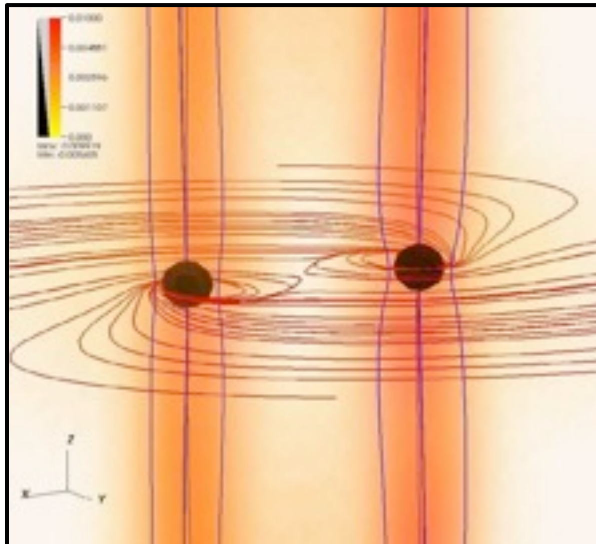
Surrounded by matter

(Bode+ 10; Farris+ 10)



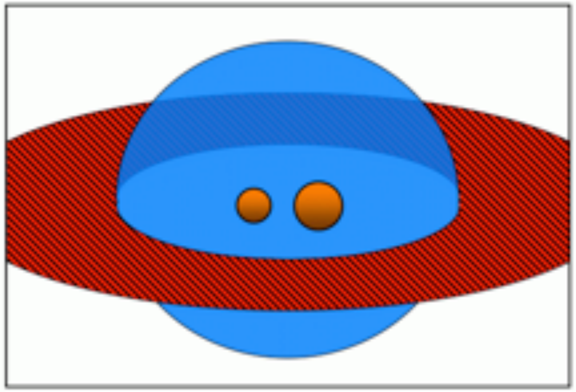

Surrounded by EM fields

(Palenzuela+ 09, 10; Mösta+ 10)

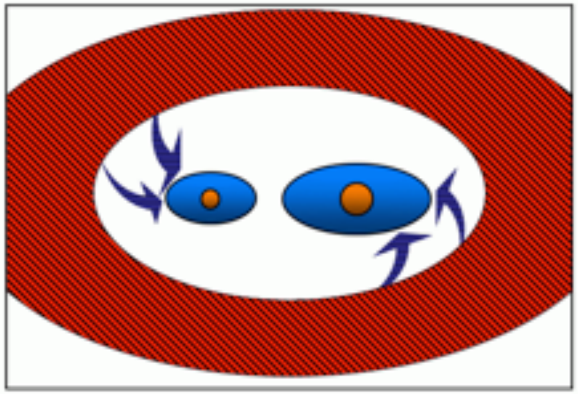


# What is the environment in the vicinity of BBHs?

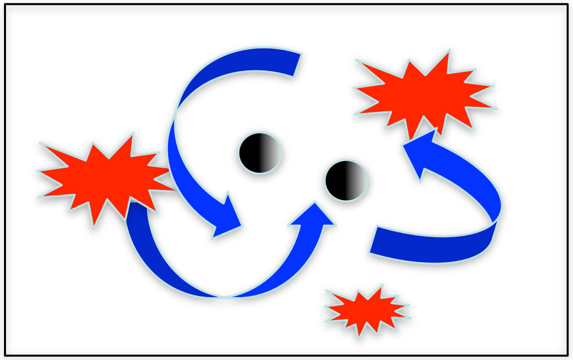
- Not well know at scales < 0.01 pc
- Two physically motivated scenarios depending on the balance of heating and cooling:



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

# We focus first on the hot gas cloud

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

| q | spins |
|---|---|
| 1 | 0 |
| 1 | ↑↑ |
| 1 | ↑↓ |

| q | spins |
|---|---|
| 1 | ↑↑ |
| 1/2 | ↑↓ |
| 1/2 | ↖↘ |

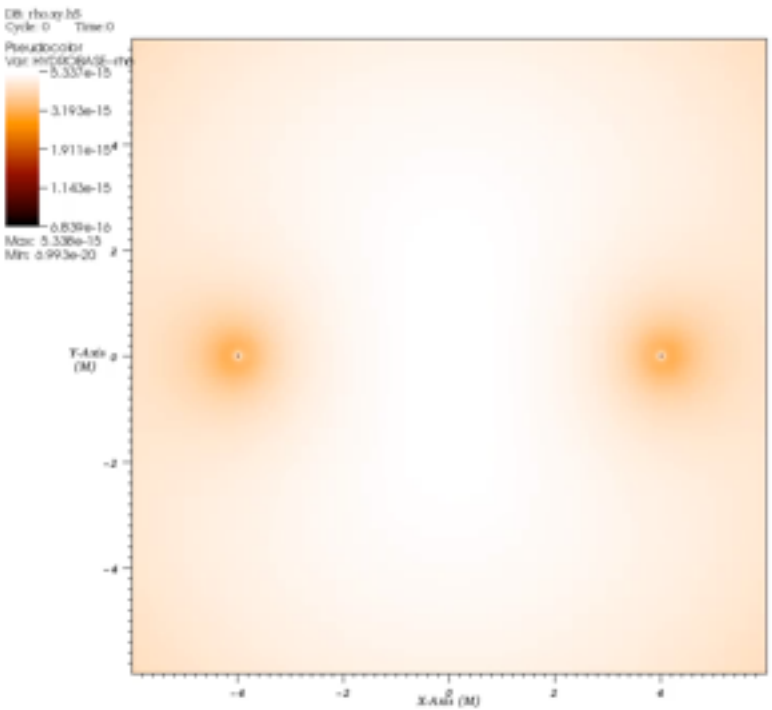
Computational Infrastructure (Maya):

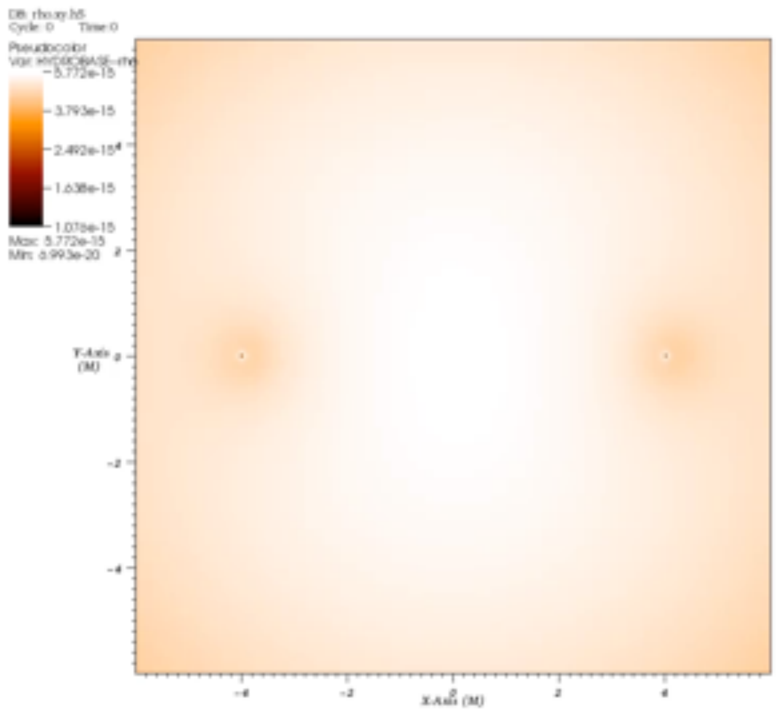
- BSSN form of Einstein Eqs
- 4th order accurate
- CACTUS (parallelization)
- CARPET (AMR, 9 refinement levels)
- WHISKY (Hydro)
- Horizon trackers
- BH spin from killing vectors
- No AGN feedback, no magnetic fields, no radiative transfer.

Dirty Laundry & Need:

- ~ 75% is spent on the Hydro
- Bottle neck, resolving BHs
- Hydro + BH AMR

# Gas Density

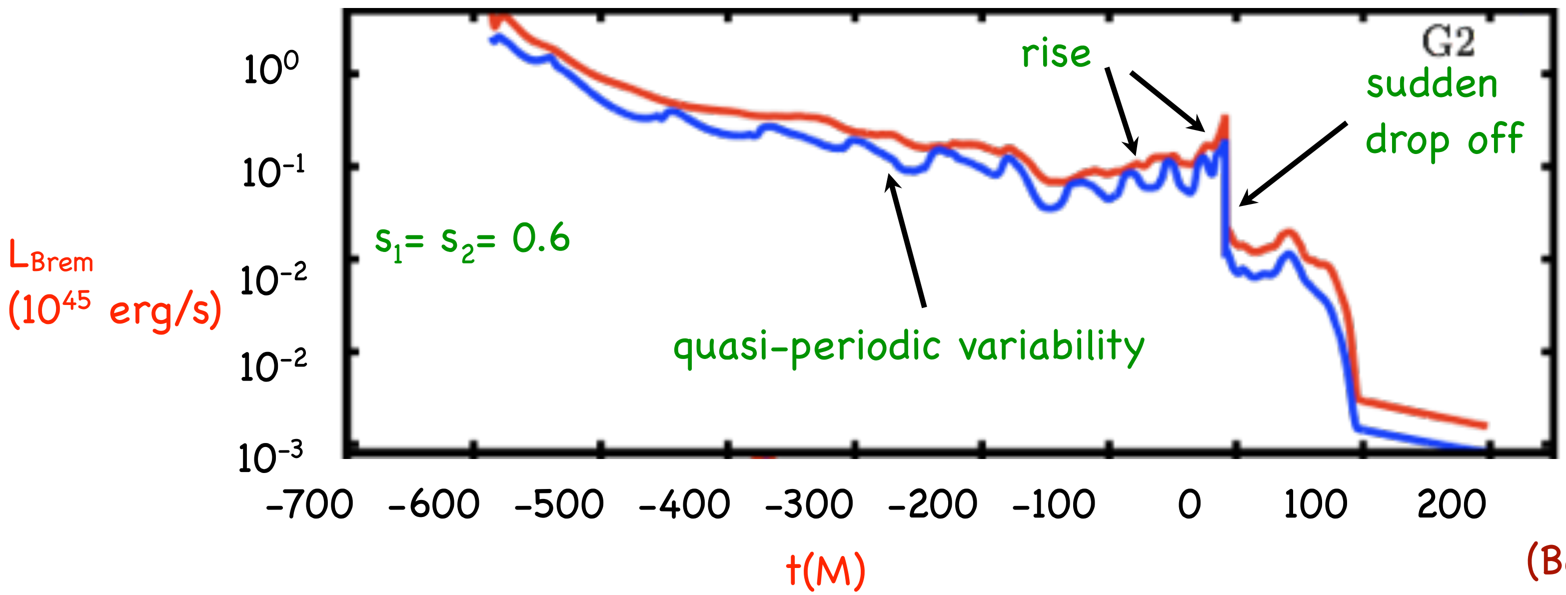



$s_1 = s_2 = 0.6$

$s_1 = -0.4 \quad s_2 = 0.4$

# Bremsstrahlung luminosity

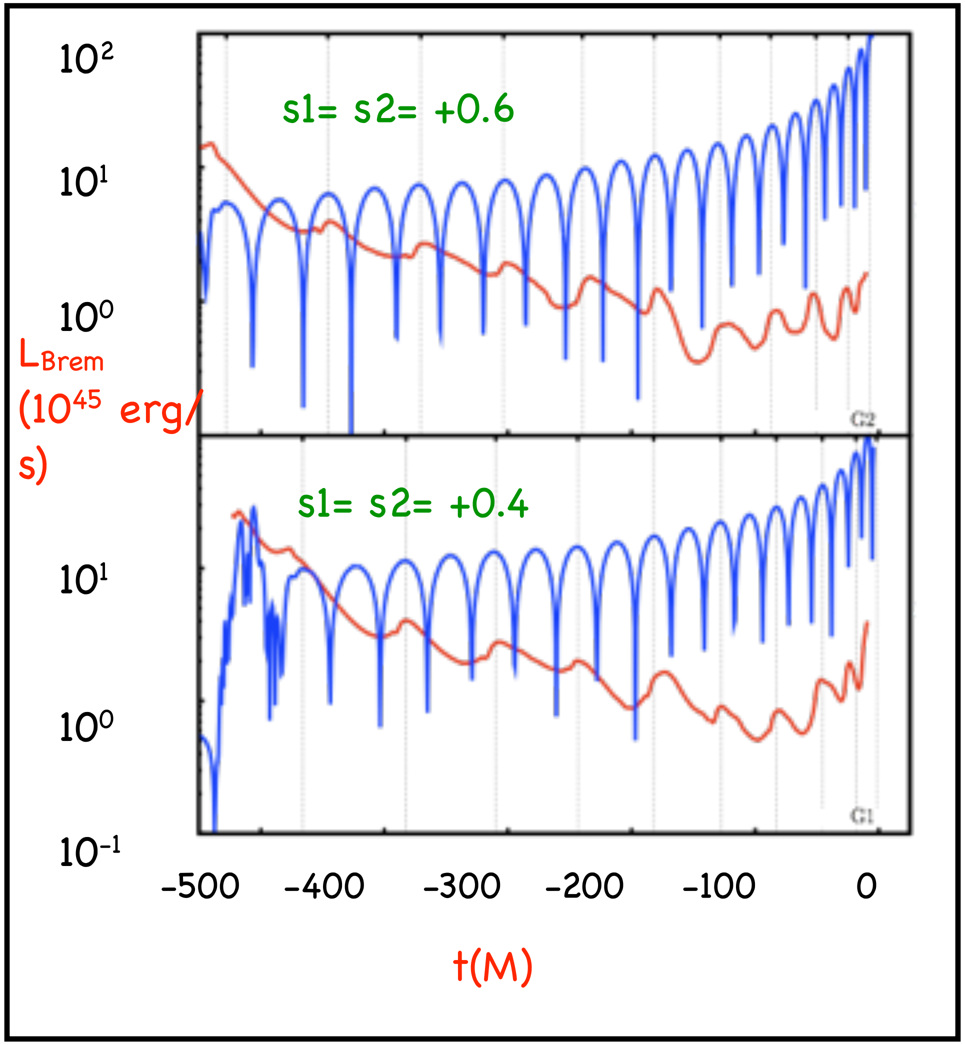



(Bode+ 09)

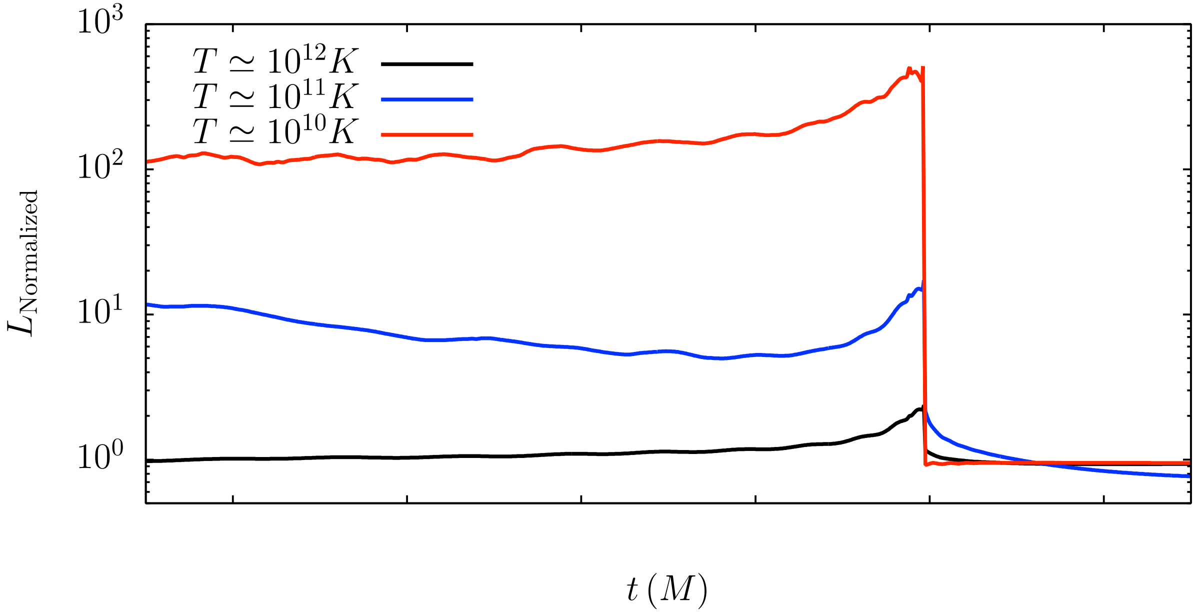
# EM & GW emission

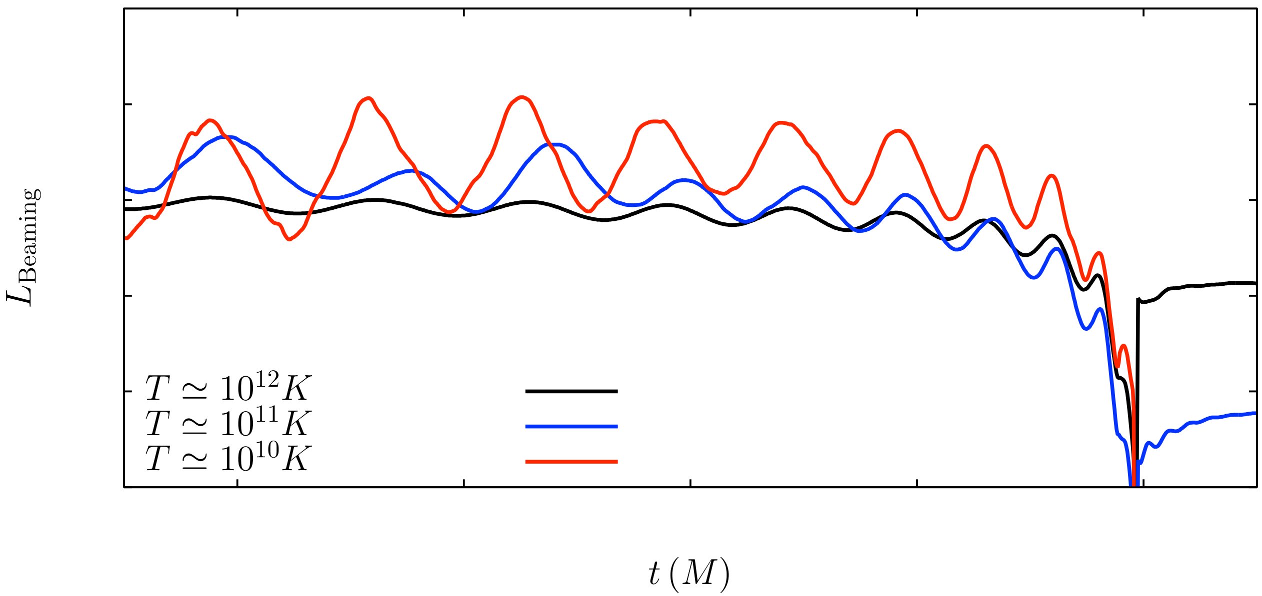
EM variability is due to relativistic beaming and boosting

(Bode+ 09)

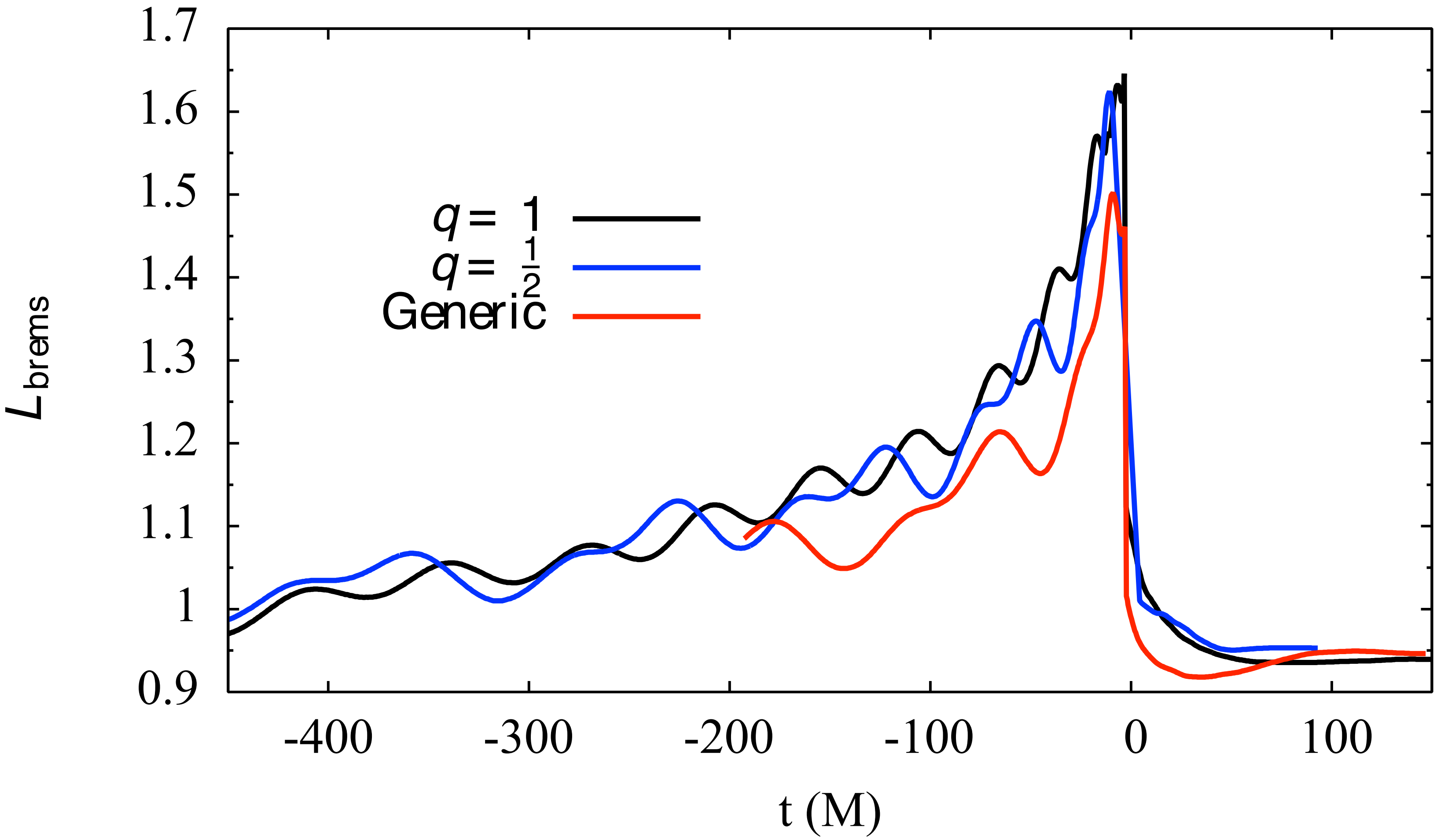


# Dependence on Temperature

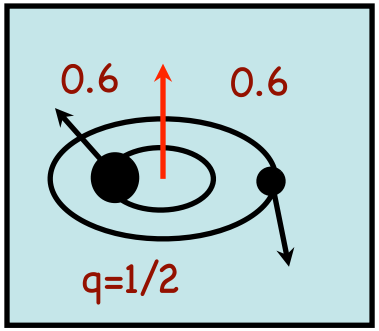


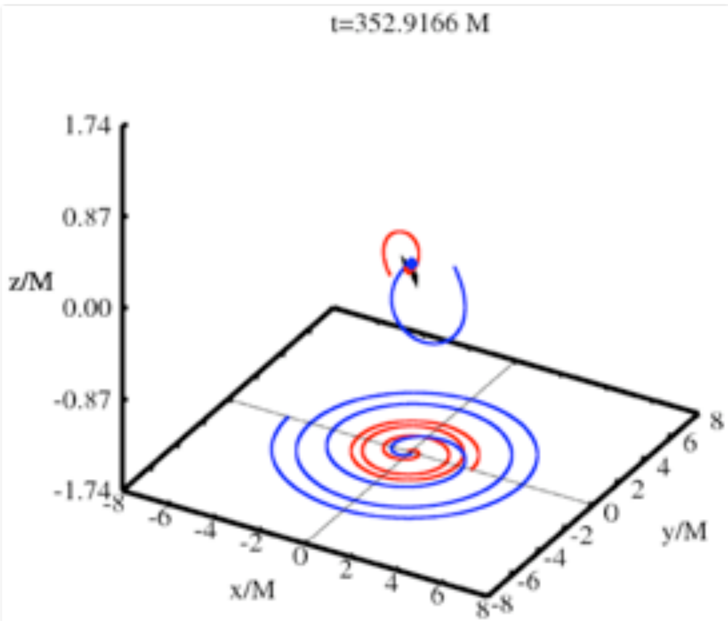



# Dependence on Mass Ratios and Spins



# Effects of unequal mass ratio and spin orientations



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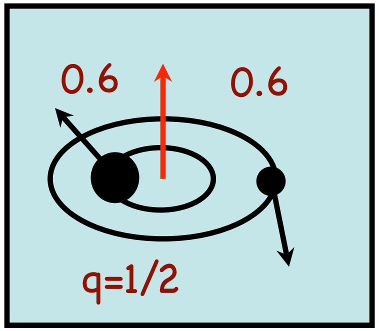


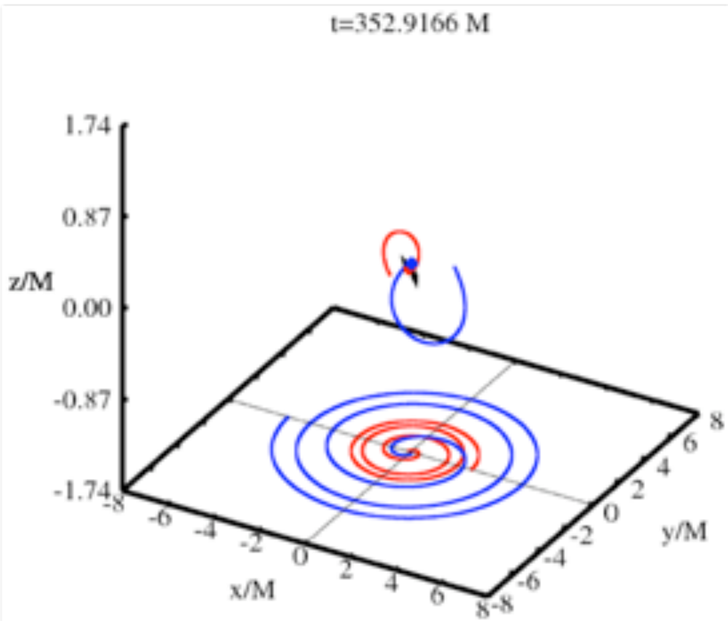


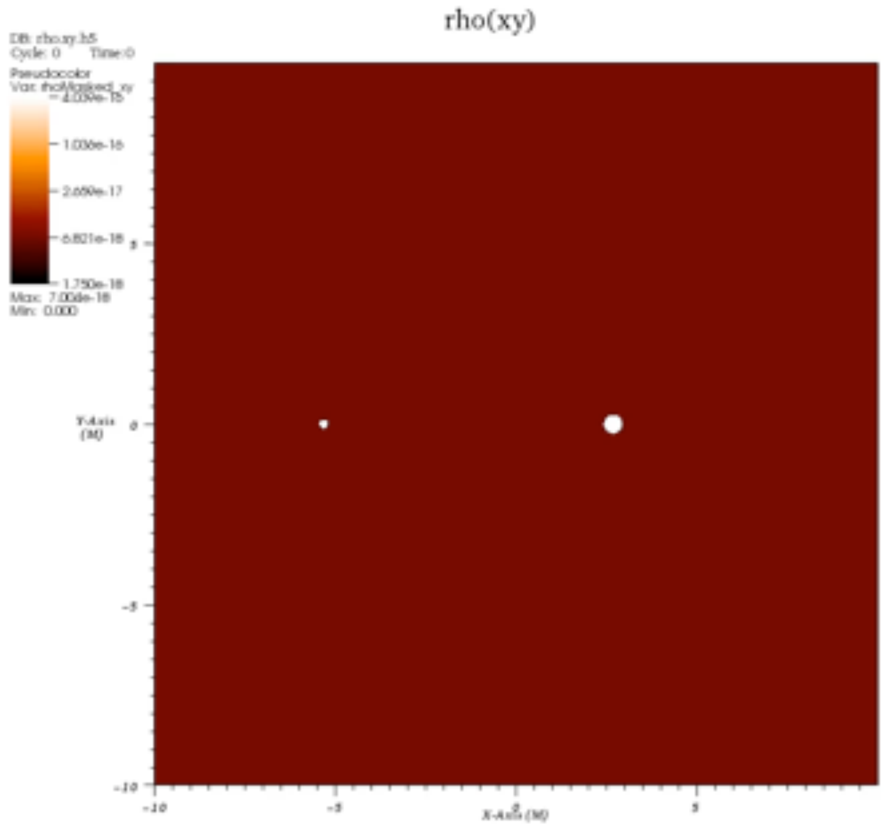

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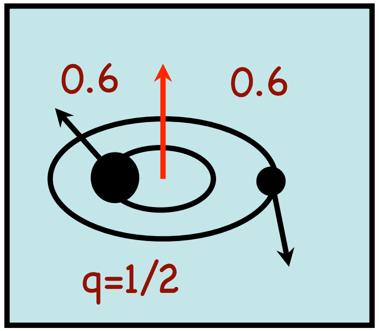
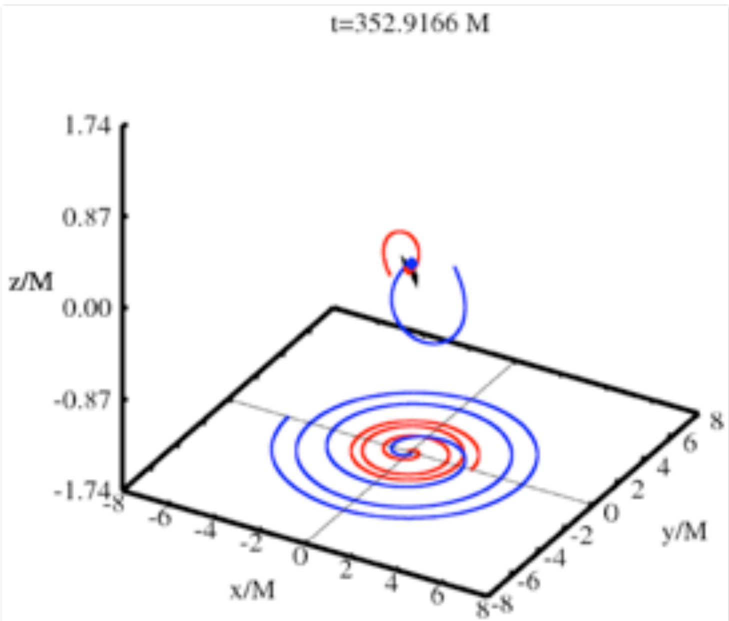


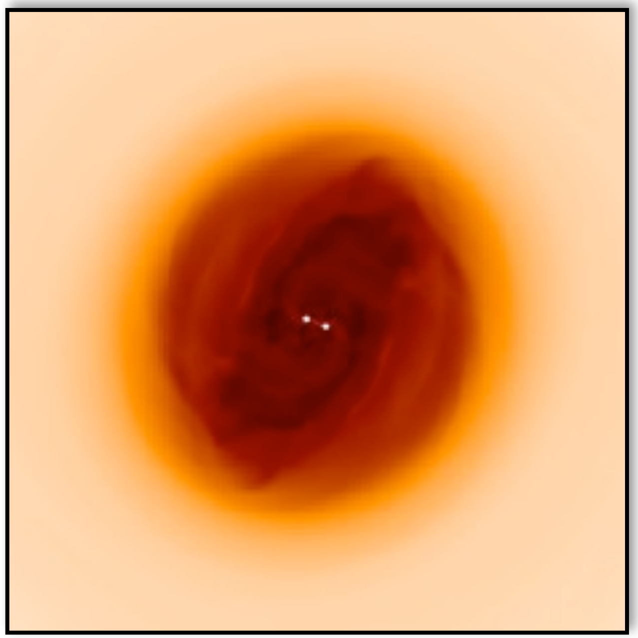
# Preview: Merger of SBHs in a circumbinary disk

- 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, inner edge at 16M
- Not modeled: AGN feedback, radiative cooling, magnetic fields, viscosity.

| q | spins |
|---|---|
| 1 | ↑↑ |
| 1/2 | ↑↑ |
| 1/2 | ↖↗ |

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

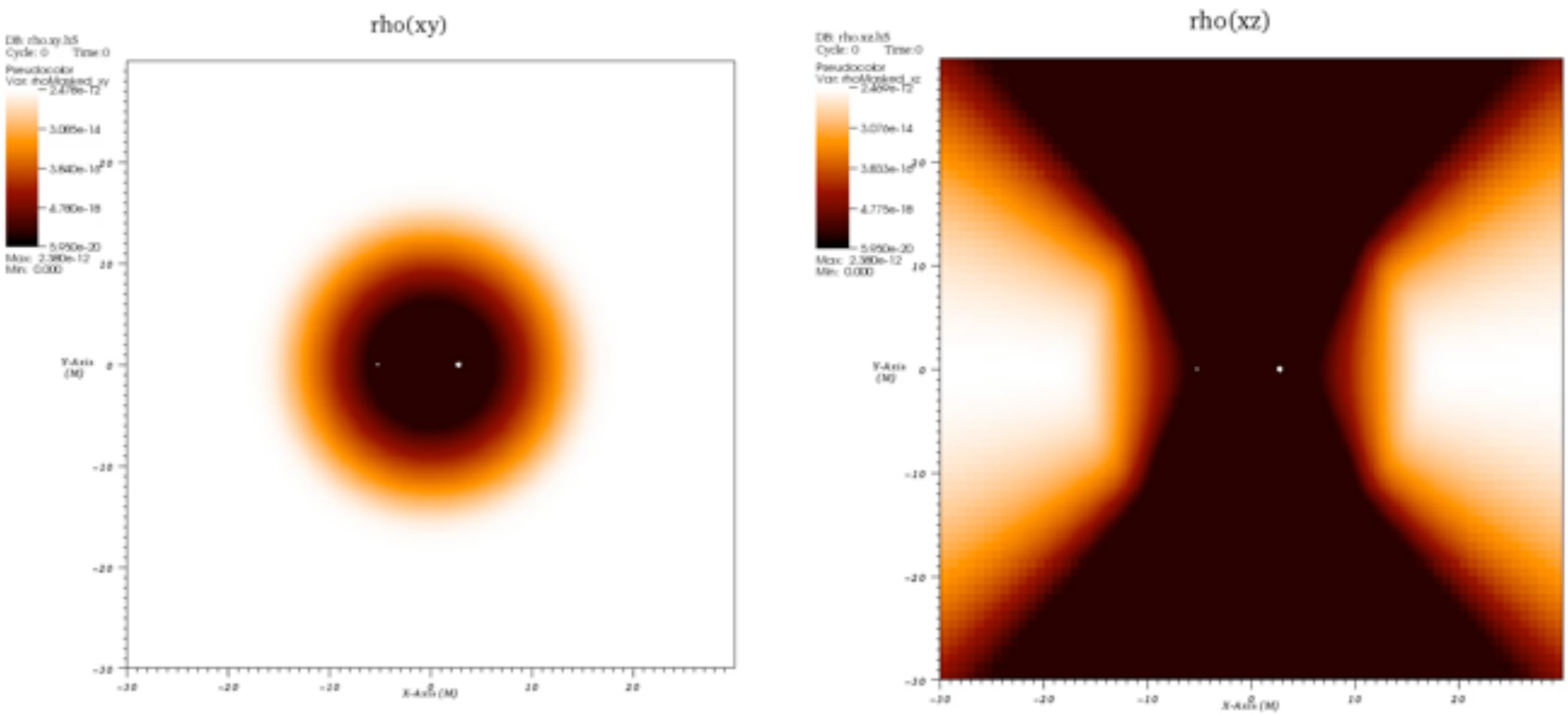
$$p(R,\theta) = \frac{M\,R\,(h/r)^2\sin^2\theta}{(R-4\,M)^2}\,\rho(R,\theta)$$



# BBH + Circumbinary Disk

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

# BBH + Circumbinary Disk

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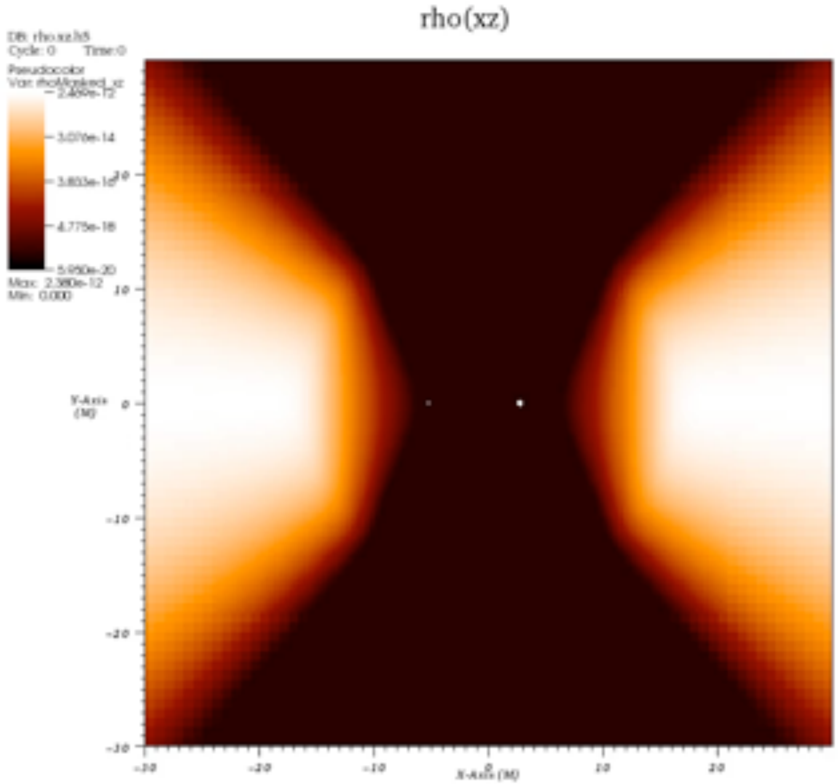
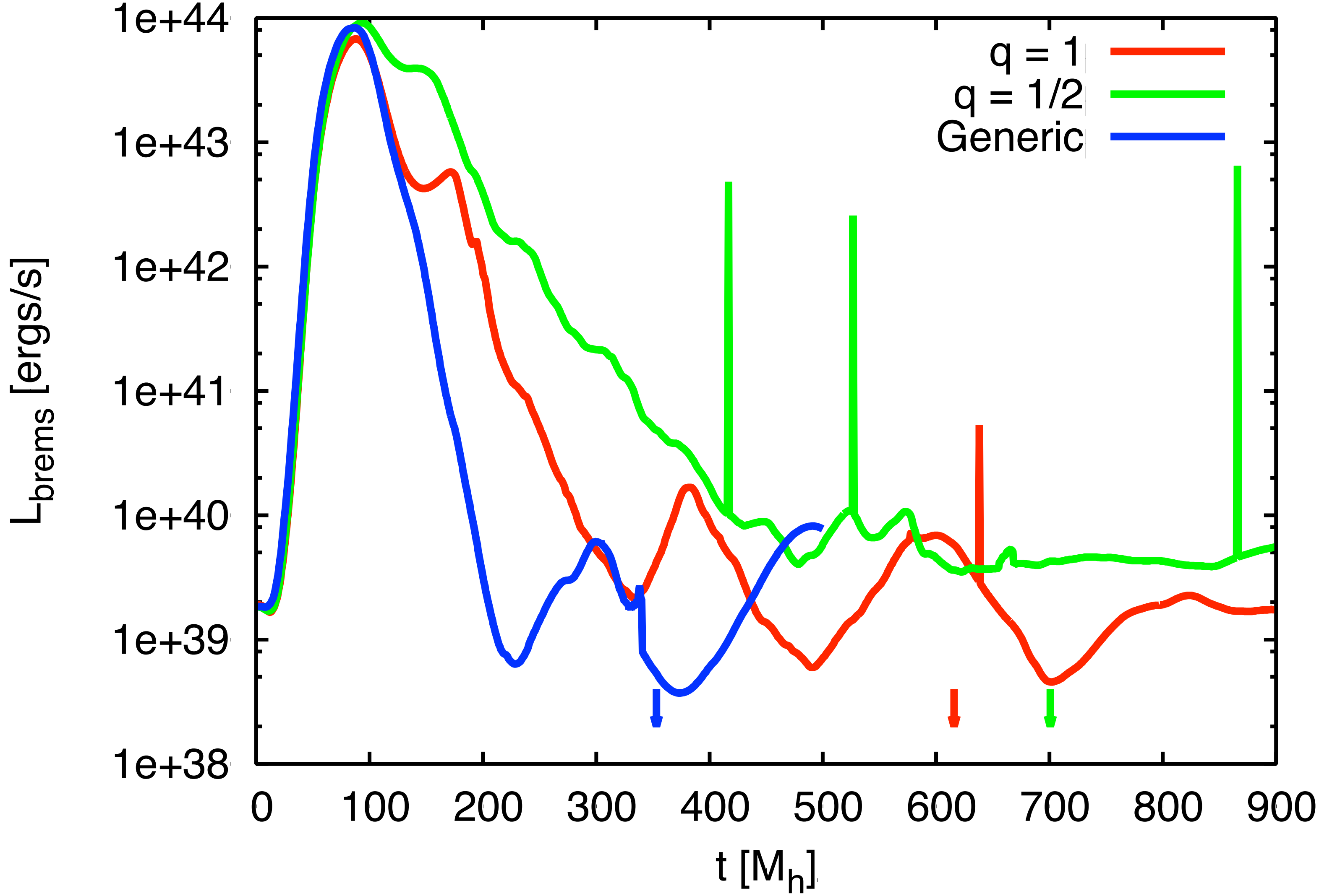



Bode, Bogdanovic, Haas, Healy, Laguna, Shoemaker, *in preparation*

# Luminosity



1e+44
1e+43
1e+42
1e+41
1e+40
1e+39
1e+38
0
100
200
300
400
500
600
700
800
900
$L_{brems}$ [ergs/s]
t [$M_h$]
q = 1
q = 1/2
Generic

# Conclusions

- Hot accretion flow:
  - Correlated EM+GW chirp-like oscillations.
  - Luminosity drop-off a robust signature.
- Circumbinary disk:
  - Binary promptly clears the gas from the central region,more pronounced for generic binary configurations.
  - Comparable luminosity from the gap region between BBH and single BH case.
- Current (lack of) observational evidence equally favors *circumbinary disk*.

# Conclusions

- We carried out fully general relativistic simulations of generic SMBH binary mergers in different astrophysical environments.

- In the absence of information regarding the environment surrounding the binary, our best option is to explore a range of scenarios and look for characteristic features (*flares, variability*).

- These are prototype simulations. Follow-up work is needed to explore more astrophysically plausible configurations (*MHD, cooling, radiative transfer*)

- The marriage between GR and Hydro needs to be improved (e.g. AMR, implicit-explicit time-stepping)