Lighting up Supermassive Binary Black Holes: Probing the Dynamical Spacetimes of Mergers

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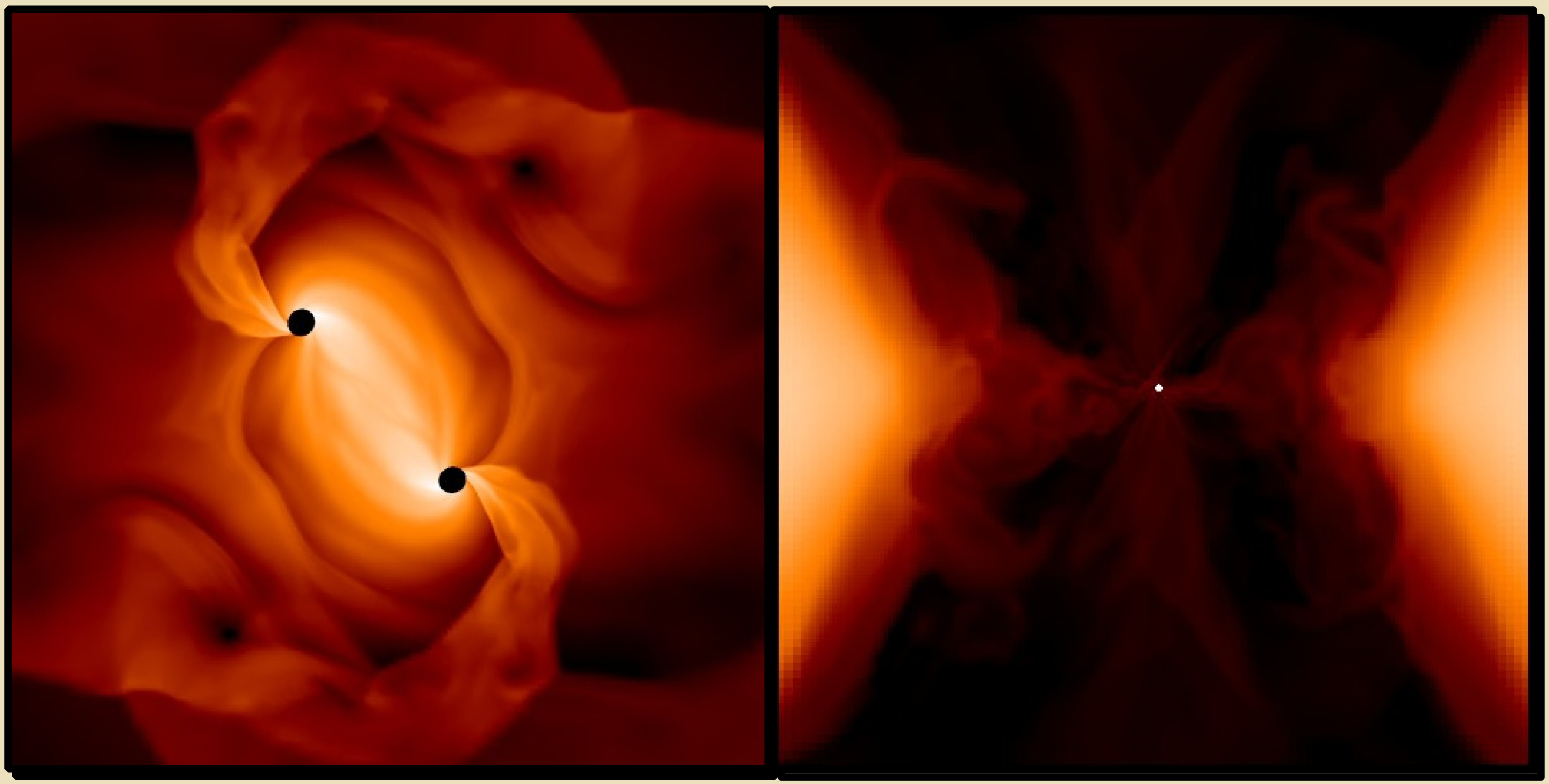


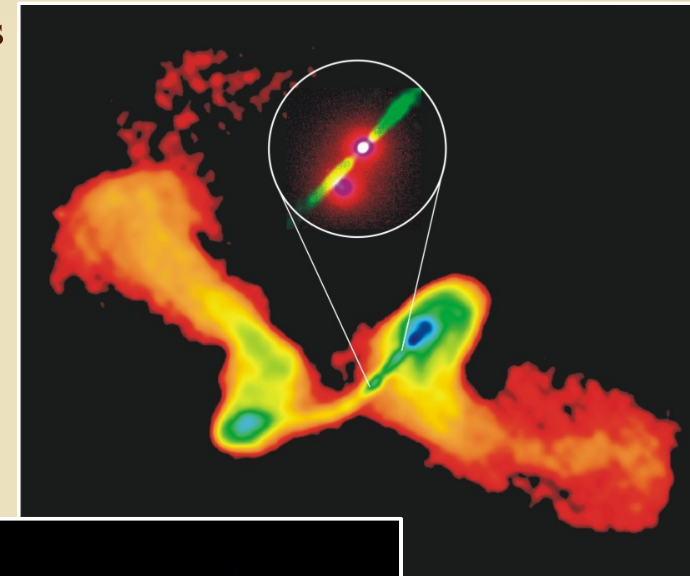
Collaborators: T. Bogdanović, R. Haas, J. Healy, P. Laguna, D. Shoemaker

4. September 2013
Connections for Women: Mathematical General Relativity
Mathematical Sciences Research Institute

EM Signatures Through BBH Lifetime

Galaxy Mergers
R ~ Mpc

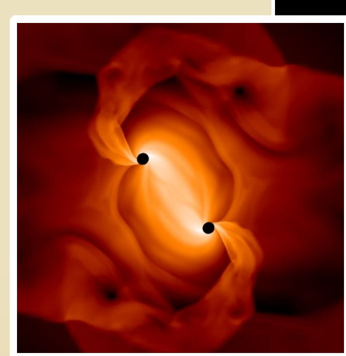
X-Shaped Lobes
t ~ Myrs



Dual AGN
R ~ kpc

Relaxing Disk
t ~ yrs

Circumbinary Disks
R ~ pc



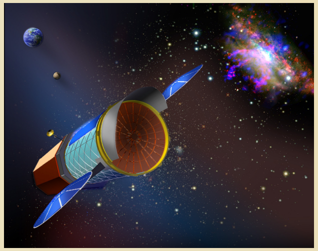
Immediate
t ~ ± hrs
r < 10^{-5} pc

See Schnittman *(arXiv:1307.3542)* for a good review

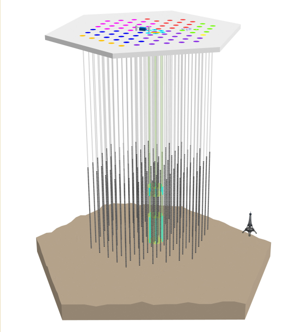
Multi-Messenger Astronomy

Credit: *NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and K. Noll (STScI)*

Credit: NASA



Credit: LIGO Laboratory



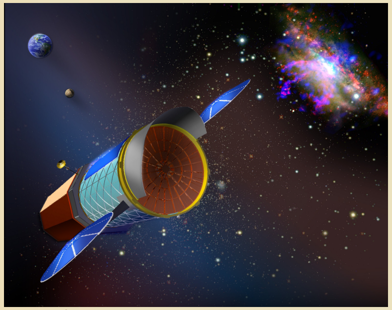
Synergistic Measurements → Extra Information → "Standard Sirens"

- Source Localization: EM better than GW
- Indep. Redshift & Luminosity distances
- Galactic Evolution & Nuclei Environments
- Supermassive BH growth methods

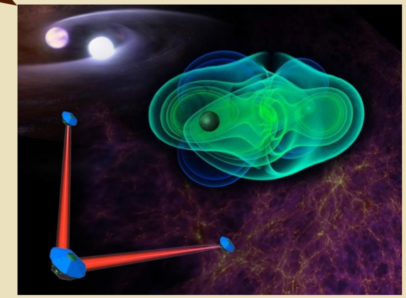
See e.g., Schutz ('86). Holz & Hughes (2005)

EM + GW Detections
Sight & Sound

Credit: *NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and K. Noll (STScI)*



Credit: NASA



Credit: eLISA/NGO

Supermassive Black Holes

- 10^6-10^7 M_{sun} → edge of eLISA/NGO (2028) frequency band
- Fiducial $q = m_1/m_2 \leq 2$ binaries, whose vacuum solutions are thoroughly studied

Galactic Nuclei

Gap in evolutionary studies of SMBH systems ($\mathbf{10^{-2} - 10^{-5}}$ pc) → uncertainties in environment

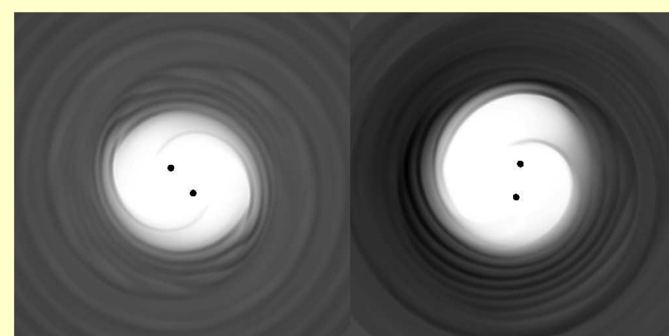
Inefficient Cooling → **ADAFs** (Advection Dominated Accretion Flows) / **RIAFs**

NASA/CXC/MIT/Frederick K. Baganoff et al.

Like Sgr A*, observations point to SBH environments where accretion is suppressed below its expected rate for the surrounding material.

Efficient Cooling → **Circumbinary Disk**

Suggested configuration from Newtonian, N-Body, and SPH simulations. Binary torques evacuate the central region.


MacFadyen and Miloasavljević, ApJ 672, 83 (2008)

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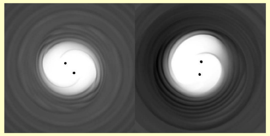
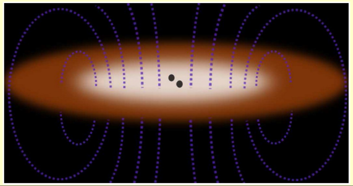


Magnetic Fields



Since 2009, just over a dozen studies have started exploring these parameters in full GR
Solve matter evolution when it's fully coupled to a proper, fully dynamic spacetime..

Fully-Coupled Numerical Relativistic Hydro Simulations

→ ***Dynamic*** coupled spacetime, though gas too tenuous to affect binary on these timescales.

$$G_{\alpha\beta} = 8\pi T_{\alpha\beta} \qquad \nabla_\alpha T^{\alpha\beta} = 0$$
$$\nabla_\alpha \left(\rho u^\alpha\right) = 0$$

→ ***Physics Assumptions***

– Perfect fluid and/or Maxwell stress energy tensor

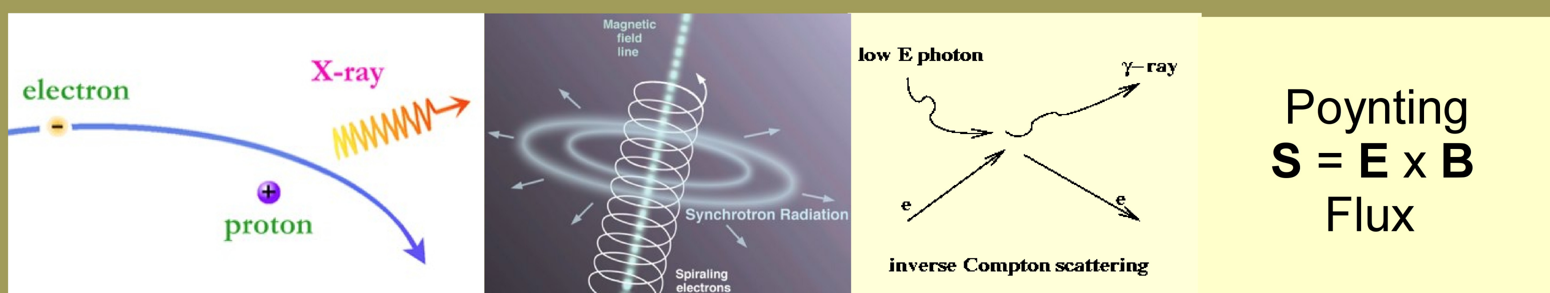
– Ideal Gas Equation of State $P(\rho, \epsilon) = \rho\epsilon(\Gamma - 1),$ or Polytrope (MHD)

– Heating of the gas via radiative feedback from the central AGN or cooling due to radiation during the simulated time range around merger is negligible

Luminosity from Hydro/MHD Fields

Extrapolating from an evolved ideal gas distribution to observable light curves and spectra.

- First Generation
  - Emissivity of a region, ε(ρ, T,B)
  - Luminosity is ∫ ε(ρ,T,B) dV
  - Optically thin hot accretion flow & regions outside CB disk



- Second Generation
  - Ray tracing to capture e.g. photon orbits, redshifts
  - Radiation Transport

Luminosity from Hydro/MHD Fields

- Relativistic Thermal Free-Free Emission (a.k.a. Bremsstrahlung)

$$\varepsilon_{\rm brem} = 2.8\times10^4 {\rm erg\,s^{-1}\,cm^{-3}} \left(\frac{\rho}{10^{-11}{\rm g\,cm^{-3}}}\right)^2 \left(\frac{T_e}{10^{10}\,{\rm K}}\right)^{1/2} \left\{1+4.4\times\left(\frac{T_e}{10^{10}\,{\rm K}}\right)\right\}$$

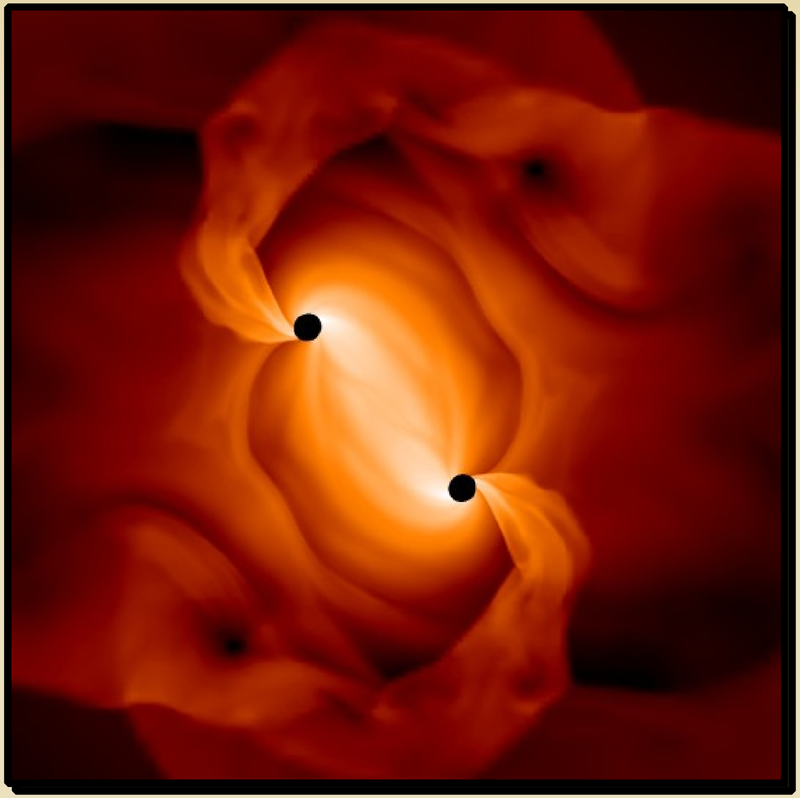
$$L_{\rm brem} \approx 4\times10^{44}\,{\rm erg\,s^{-1}} \left(\frac{\rho}{10^{-11}{\rm g\,cm^{-3}}}\right)^2 \left(\frac{R}{10M}\right)^3 M_7^3 \left(\frac{T_e}{10^{10}\,{\rm K}}\right)^{1/2} \left[1+4.4\times\left(\frac{T_e}{10^{10}\,{\rm K}}\right)\right]_{5.4}$$

- Synchrotron

$$L_{\rm synchro} \approx 8\times10^{36}\,{\rm erg\,s^{-1}} \left(\frac{\rho}{10^{-11}{\rm g\,cm^{-3}}}\right) \left(\frac{R}{10M}\right)^3 \left(\frac{B}{1G}\right)^2 M_7^3$$

- Inverse Compton

$$L_{\rm IC} \approx 3\times10^{-8}\,L_{\rm soft} \left(\frac{\rho}{10^{-11}{\rm g\,cm^{-3}}}\right) \left(\frac{R}{10M}\right)^3 \left(\frac{R_{\rm tran}}{10^5\,M}\right)^{-2} M_7$$



Hot Accretion Flows

Hot Accretion Flows

- Astronomical basis – RIAFs

  → Low-luminosity AGN (e.g., Elitzur and Ho 2009)

  → Sgr A* (e.g., Narayan *et al*. 1995, 1998)

- 2 - Temperature ($T_e \ll T_p$) Ideal Gas

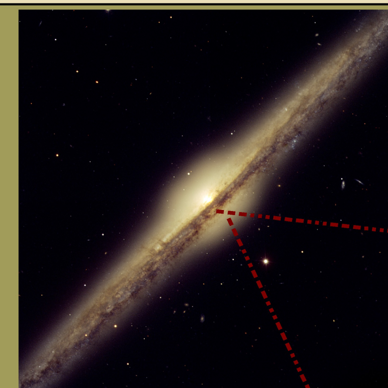
  $t_{\mathrm{Coulomb}} \gtrsim t_{\mathrm{inflow}}$

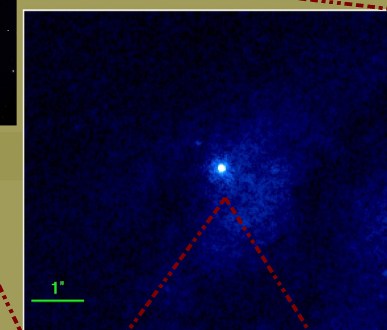
- Mass of flow motivated by an external circumbinary disk at much larger radii:

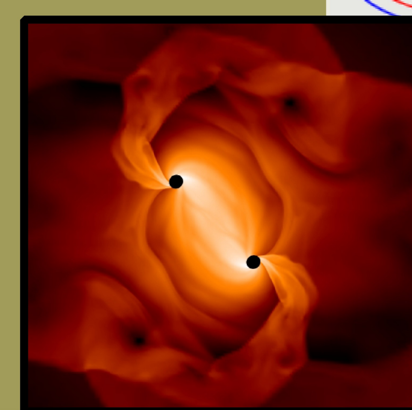
  M_{gas} up to ~ 1% M_{BH} at decoupling (Colpi *et al.* 2007)

- Environment parameters

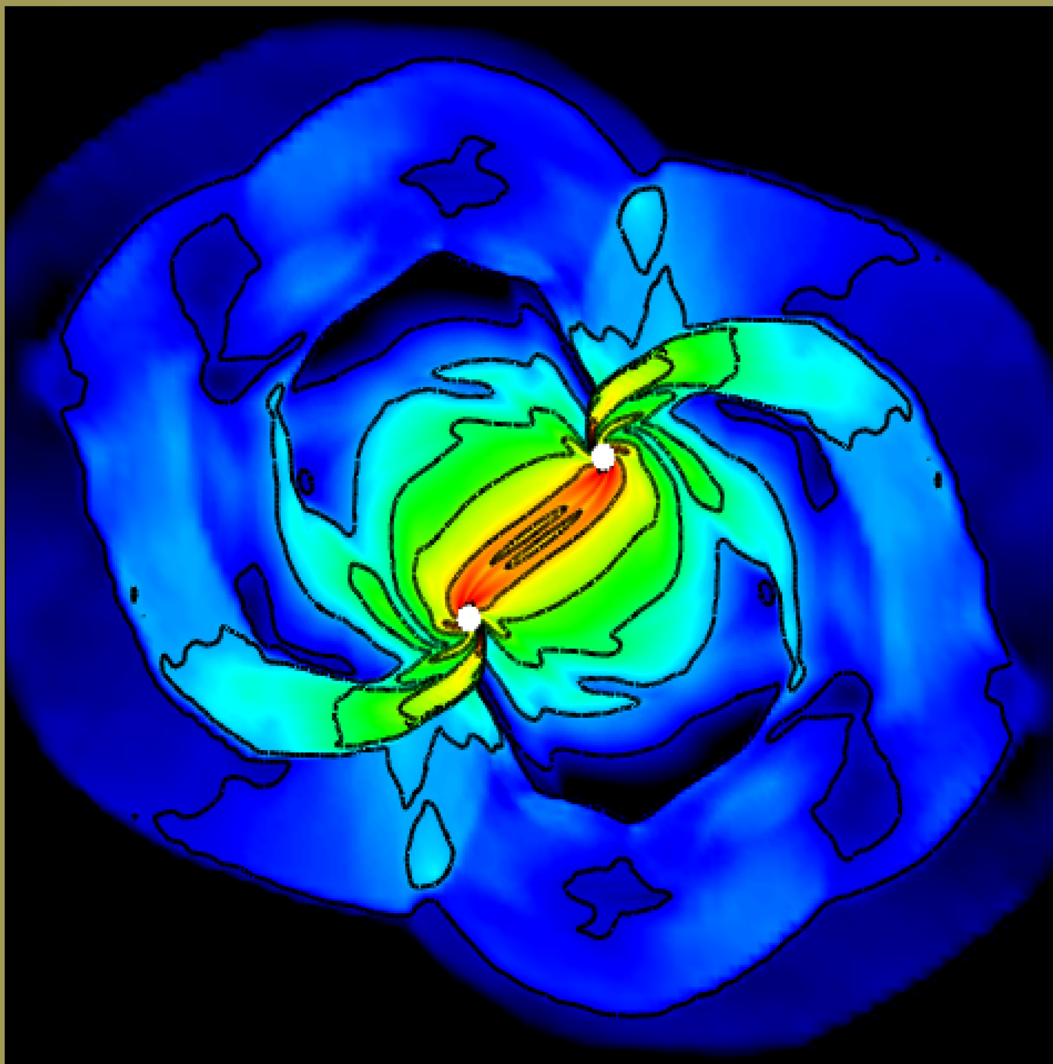
  Density, Temperature, & Equation of State
  BBH parameters


NGC 4565, ESO VLT FORS

HST. Chiaberge et al 2006




Hot Accretion Flows: Basic Features



Emissivity,

- **Interbinary Bar**

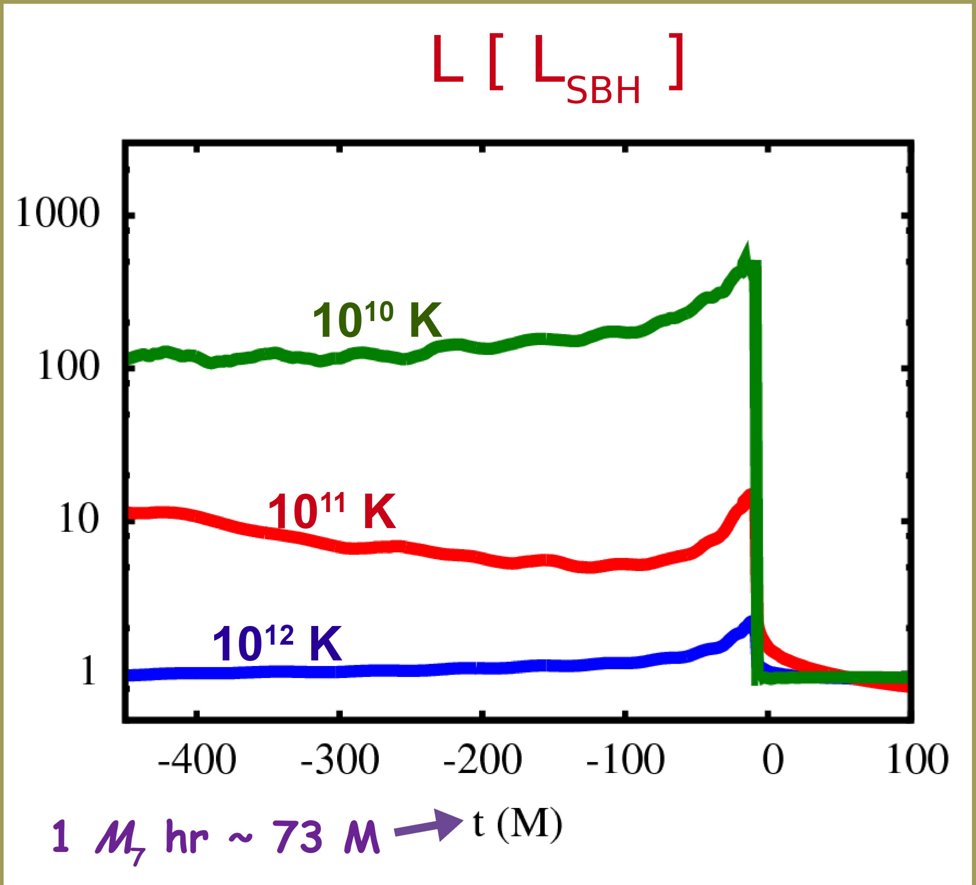
  Gas falls into interbinary region, creating a dense, hot bar.

- **Density Wakes**

  Moving BHs shock the gas as they move through and accrete the surrounding gas, creating trailing wakes wrapped around the BHs by their spin.

(Bode* et al *'10, '12
Farris* et al *'10)

Hot Accretion Flows: Temperature dependence



(Bode **et al** *2012)*

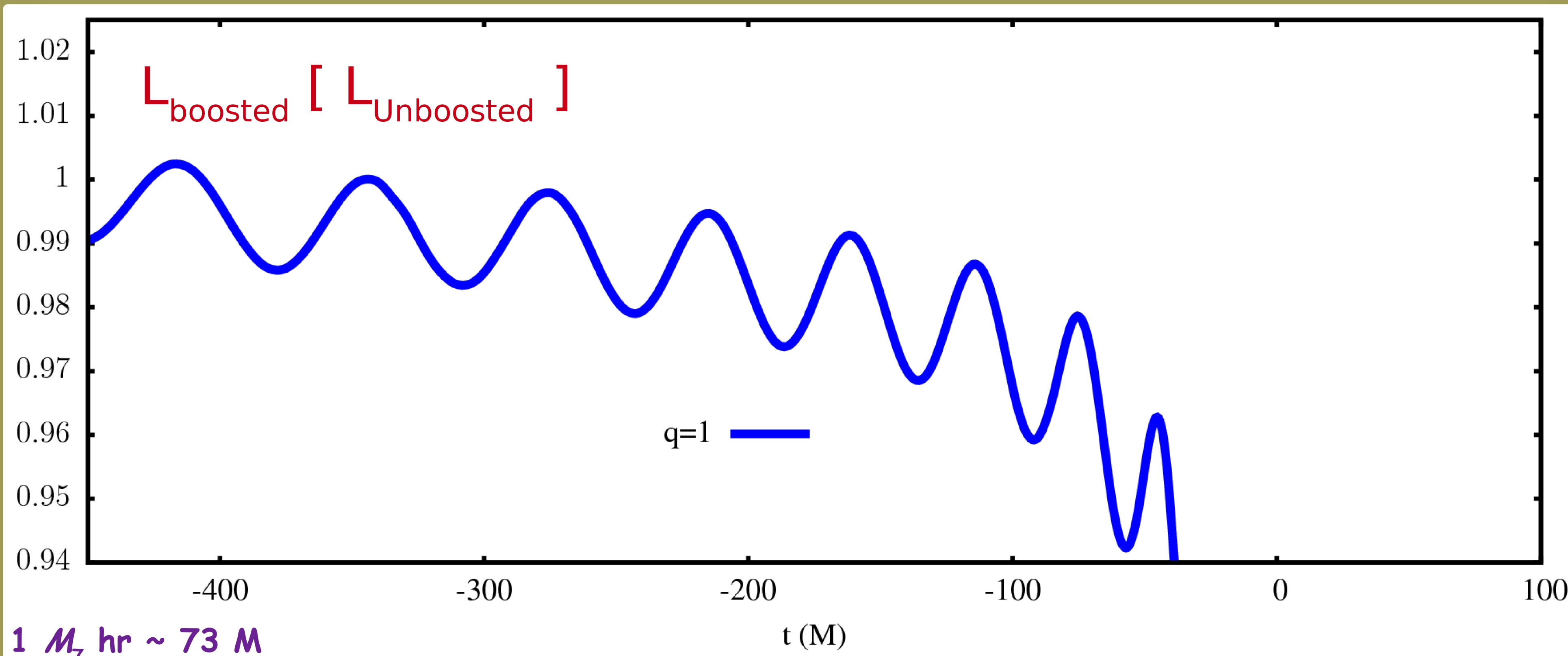
Temperature affects the pressure and hence support against both shocking (density wakes) and infall to the interbinary bar.

Lower temperature flows (~ 10^{10} K) accumulate more matter, while remaining in the approximate RIAF regime.

Pre-merger Flare & Post-merger Drop-off

Cooler Gas → Higher peak (emissivity ~ density²)

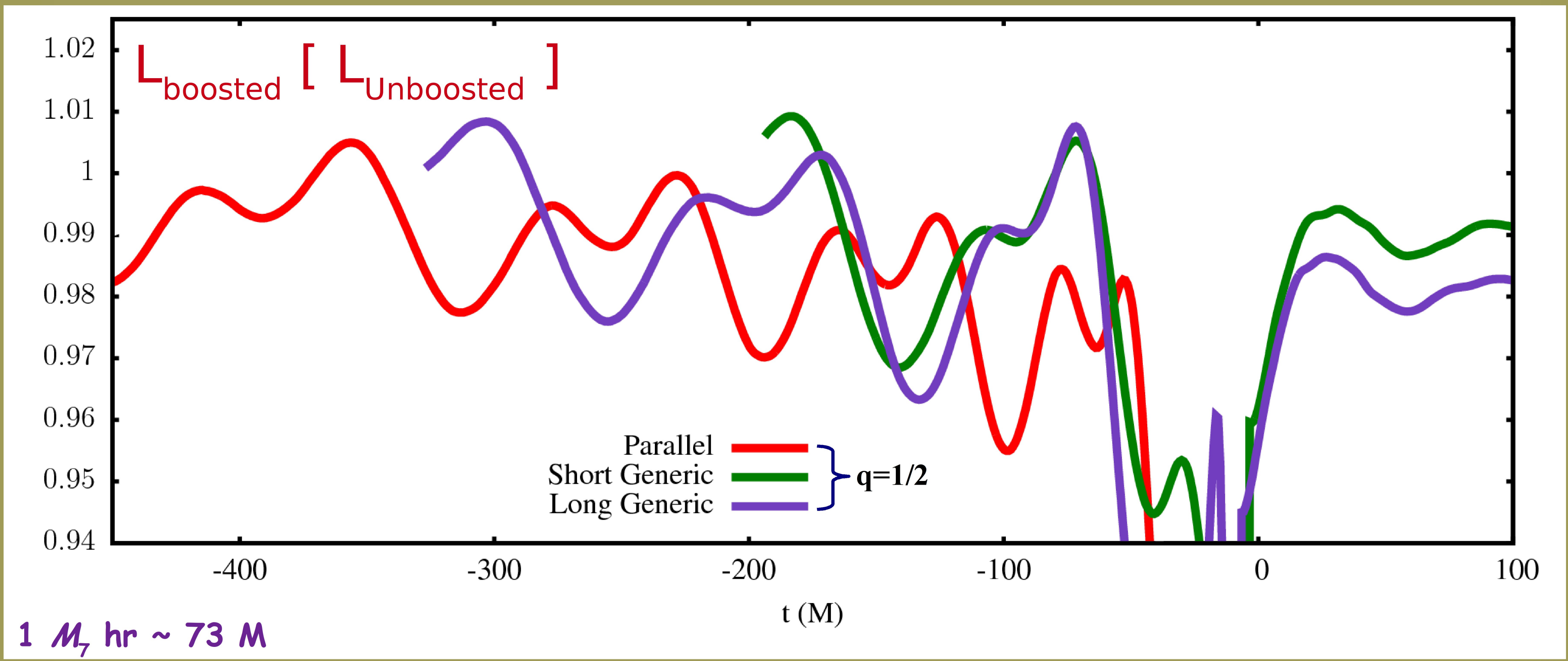
Hot Accretion Flows:
Pre-merger Luminosity Oscillations



Relativistic beaming accentuates geometry of inner region for some aspect angles

Equal-mass binary → Smooth, regular oscillations (~ few %)

Hot Accretion Flows:
Pre-merger Luminosity Oscillations

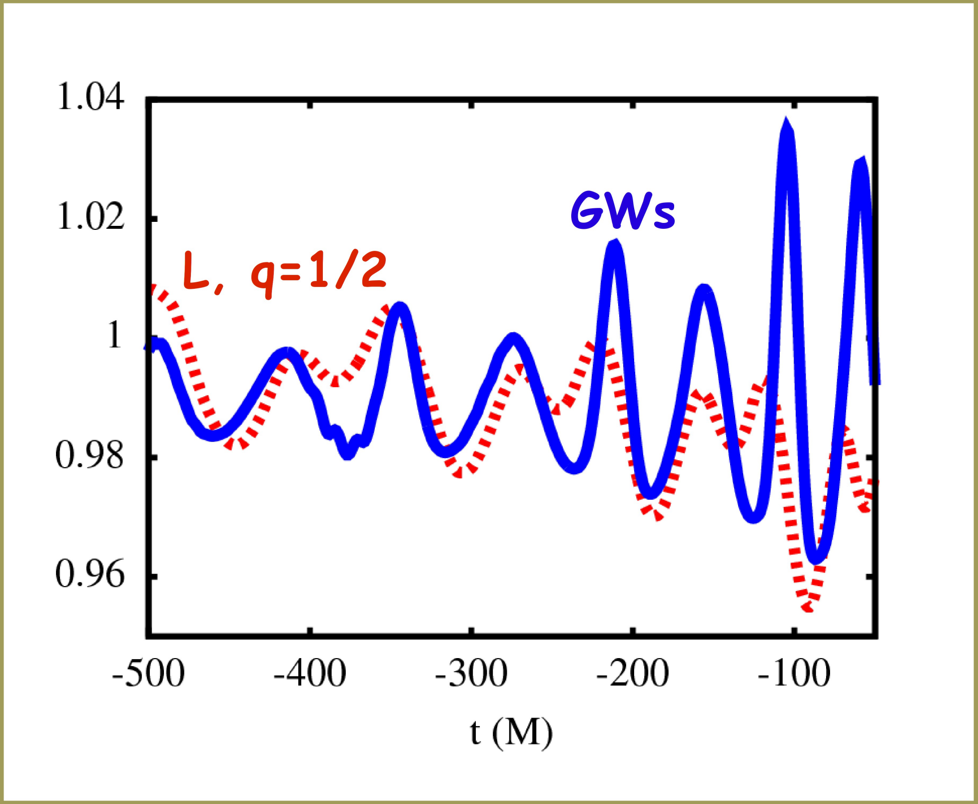


Unequal-mass Binary breaks π – symmetry

$q = m_2 / m_1 = ½$ → *Double-peaked oscillations*

(Bode *et al.* '12)

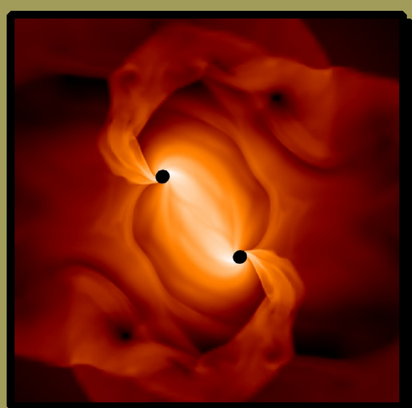
Hot Accretion Flows: Pre-merger Oscillations



Both boosted L and GWs connected to orbital frequency.
Correlated Counterpart! (Though challenging to observe)

Hot Accretion Flow Simulation Samples

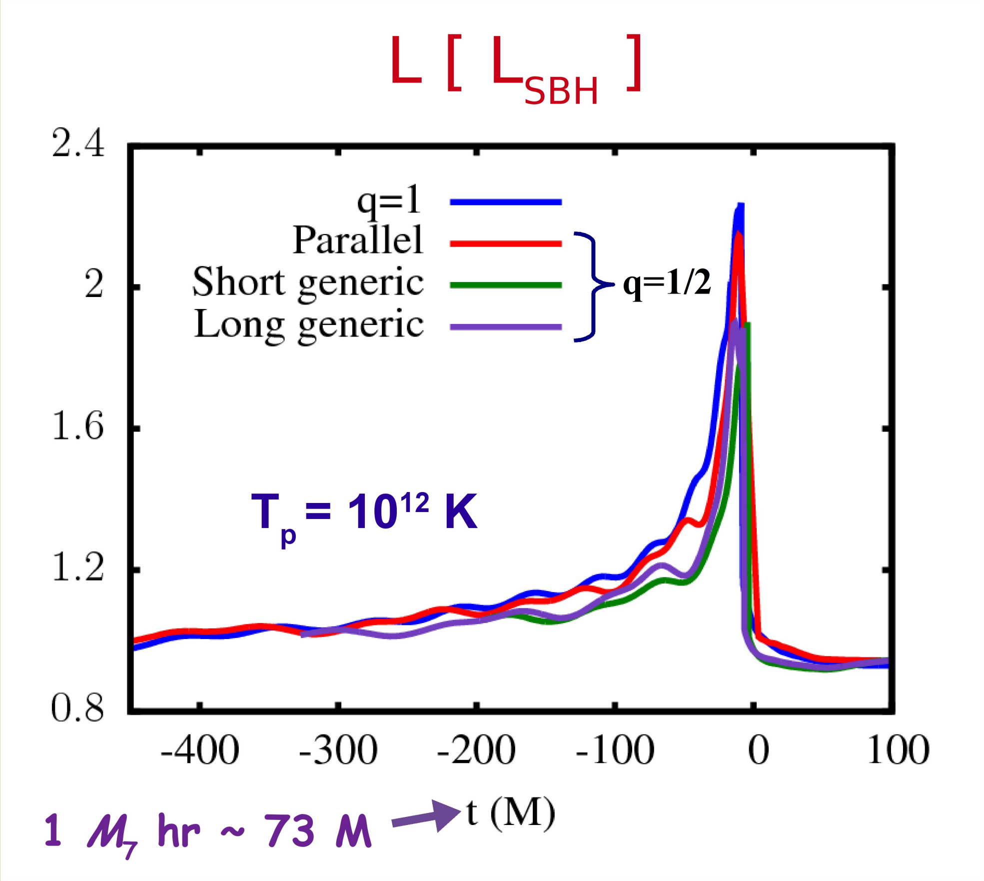
Examples:
Equal-mass,
varying spin



Qualitative Features
→ Interbinary bars
→ Density wakes

Hot Accretion Flows: Black Hole Parameter Dependence

Bode **et al.**
2010, 2012

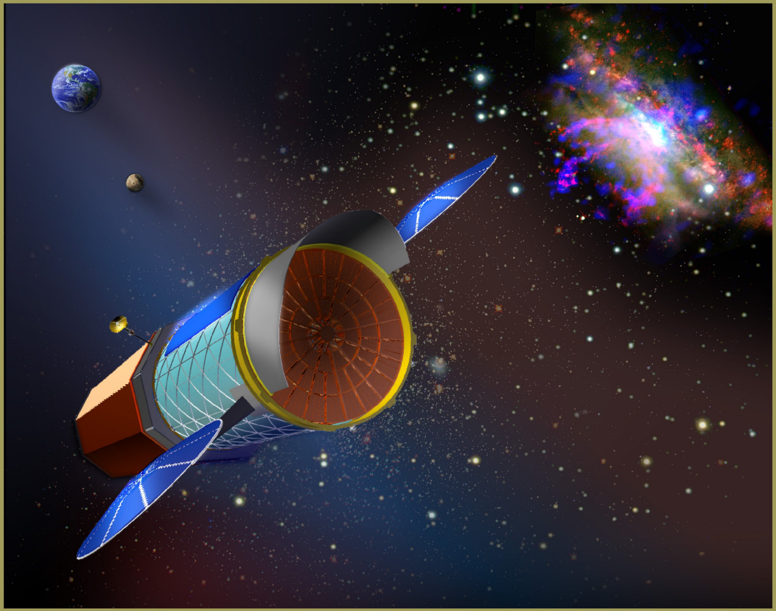


$$M_7 = \left(\frac{M_{sys}}{10^7\, M_\odot}\right)$$

Pre-merger ***Flare*** & Post-merger ***Drop-off***

At high T, flare not strongly influenced by binary parameters

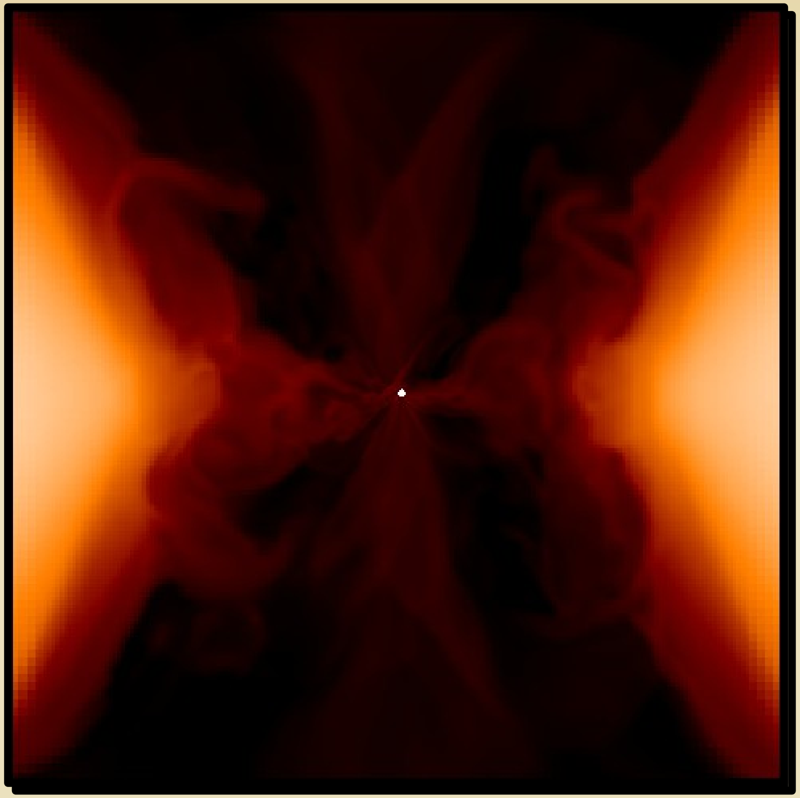
Observability



Artist's Conception of IXO, Credit: NASA

For an AGN with RIAF at z~1, $L_{\mathrm{X-ray}} \simeq L_{\mathrm{bol}}/15.8$, $F_{\mathrm{X-ray}} \sim 10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$
Pre-merger flares visible by planned International X-ray Observatory (IXO)
& Energetic X-ray Imaging Survey Telescope (EXIST)

- High-luminosity obscured AGN out to z~2.5
- Low-luminosity AGN (LLAGN) out to z~0.5



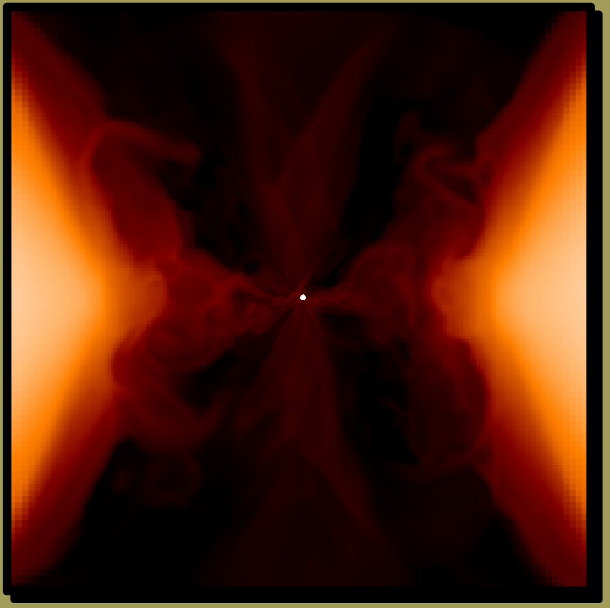
Circumbinary Disk

Circumbinary Disk

With enough viscosity, disk can decouple much closer to merger and follow the binary inwards as it heads to merger

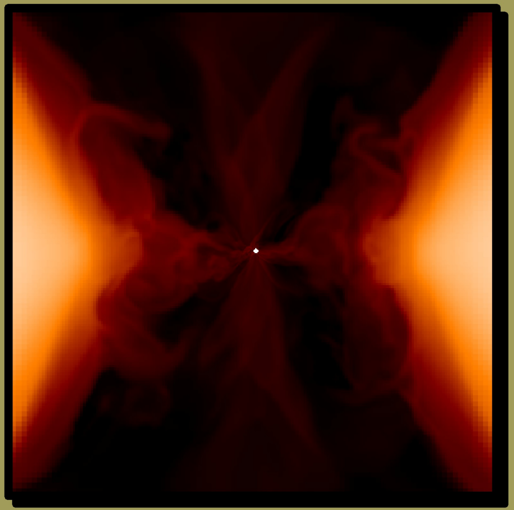
- GW shedding of orbital eccentricity dominates for $a \leq 120$ M, so quasi-circular orbits
- Inner edge at r ~ semi-major axis
- Environmental Parameters

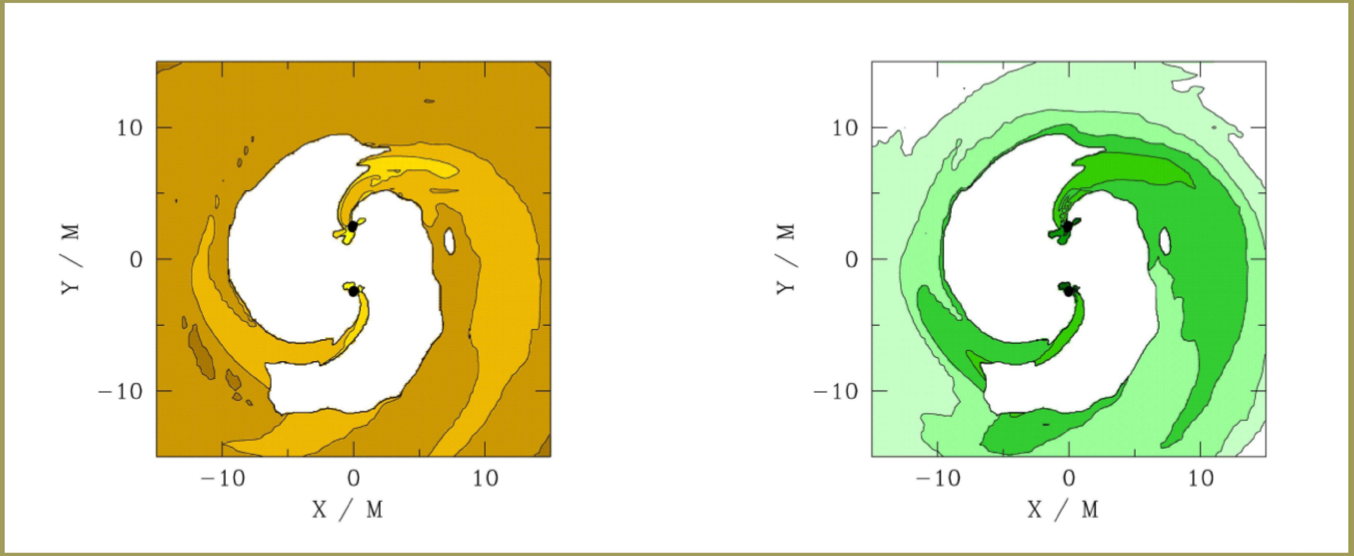
  Thickness (H/R), Inner Edge, Equation of State
  BBH Parameters
- Emission from disk vs gap compete



Circumbinary Disk in HD

Thick(-ish) Disks (H/R = 0.11, 0.2, 0.4)





Qualitative Features

→ Shock-heated tenuous inner region
→ No interbinary bar this time
→ Accretion-based emission decreases with time as gas depletes
→ Thick disk too hot, washes out perturbations to the disk
→ Interaction w/ Inner Edge particularly with unequal masses close to merger

Farris et al '11, Bode *et al.* '12

Circumbinary Disk: Inner Gap Luminosities

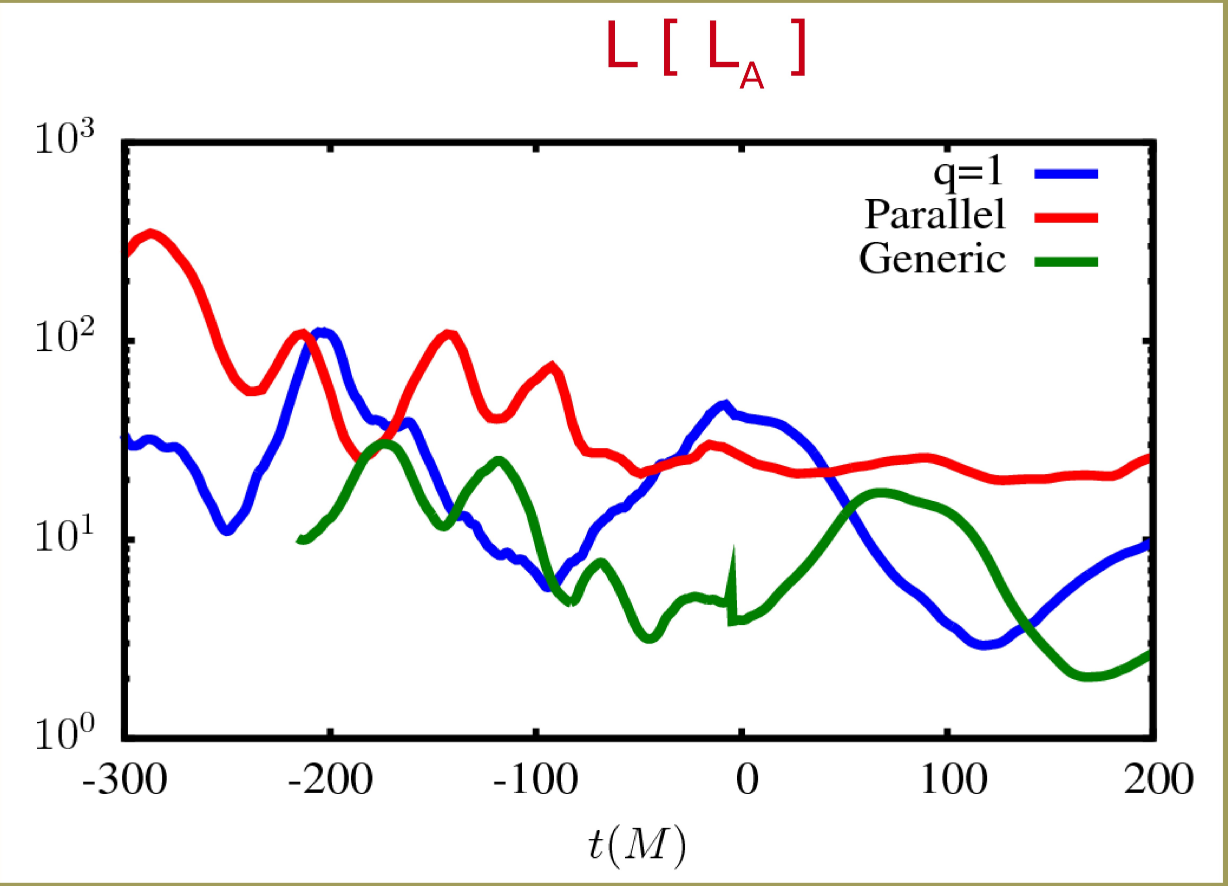
*(**Bode** et al '12)*

Hot, tenuous, dynamic gas in inner region *(like RIAFs)*

$f_{gas} = \rho_{gap}/\rho_{disk} \sim 10^{-5}$ *(H/R=0.2)*

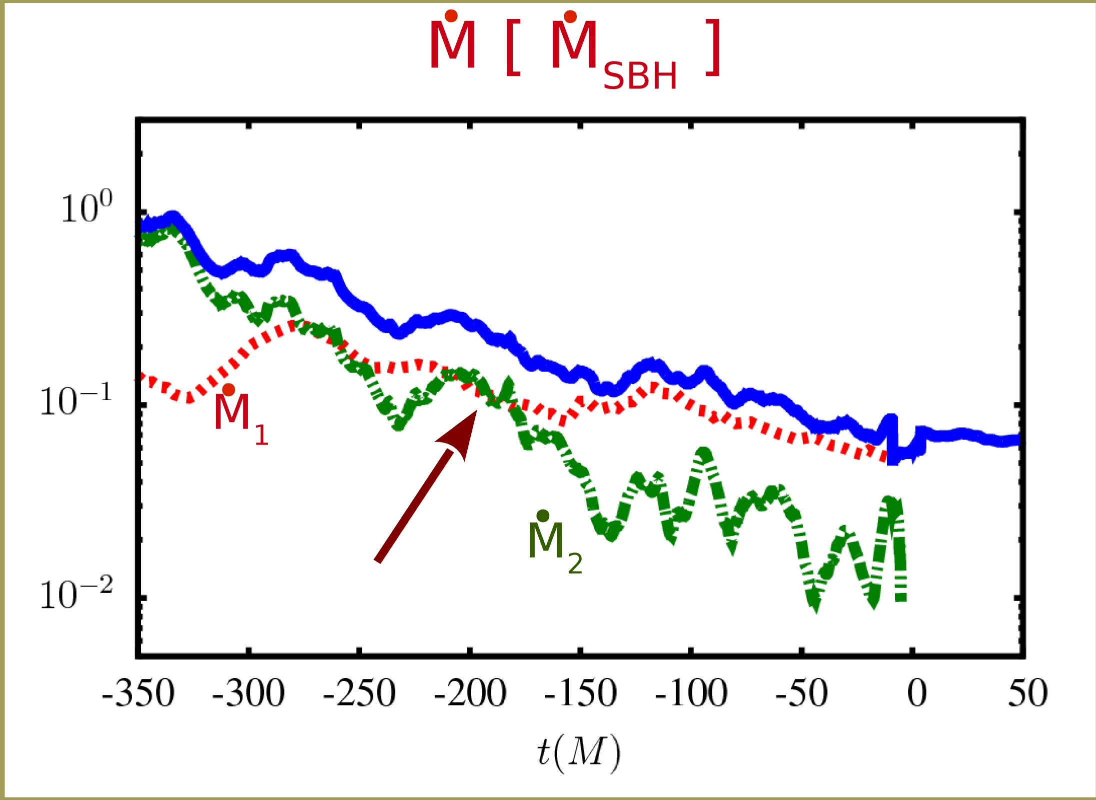
$f_{gas} \sim 10^{-4}$ *(H/R=0.4)*

Highly variable L, no flare



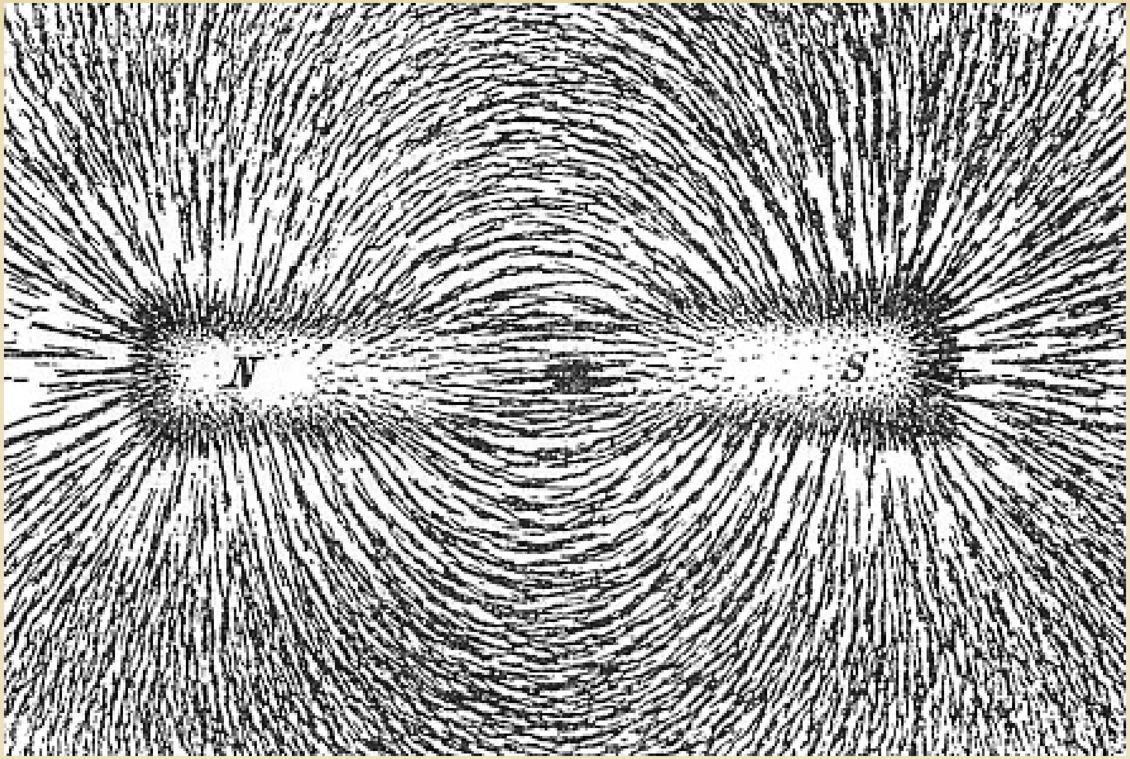
Circumbinary Disk: Unequal Mass Binary Accretion Signature

(Bode et al *2012)*



Accretion rate switch for unequal mass ratio → Spectrum transient to lower energies

Observability: Challenging, must be visible above surrounding disk luminosity and variability. Requires specific aspect angle for signature to escape.

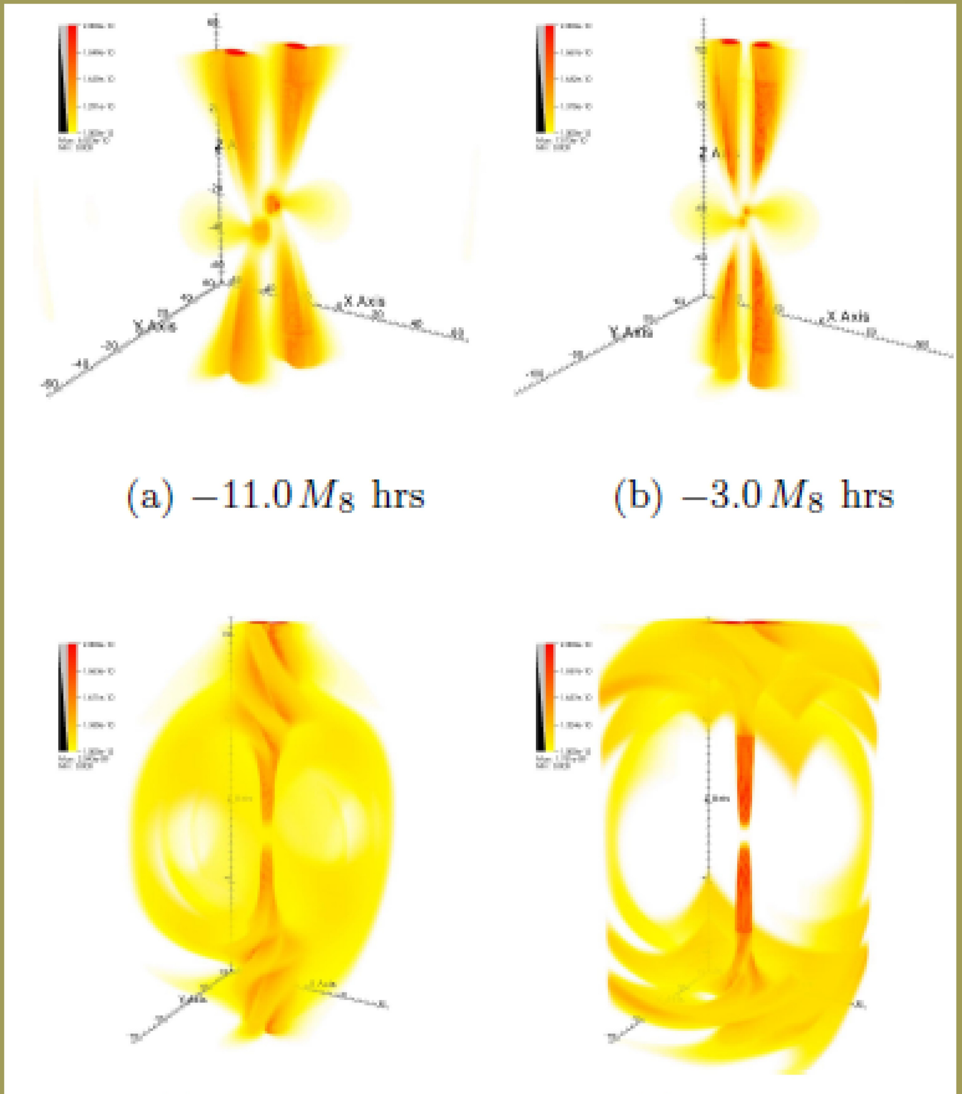


Magnetic Fields

Vacuum EM / Force-Free

EM fields in vacuum (threaded from distant circumbinary disk) and force-free magnetically dominated plasmas (10^4 M_8 G)

Poynting flux collimated outwards at BH poles, regardless of BH spin
(Mösta+ '10, '11, Palenzuela+ '09, '10, Alic+ '12)



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

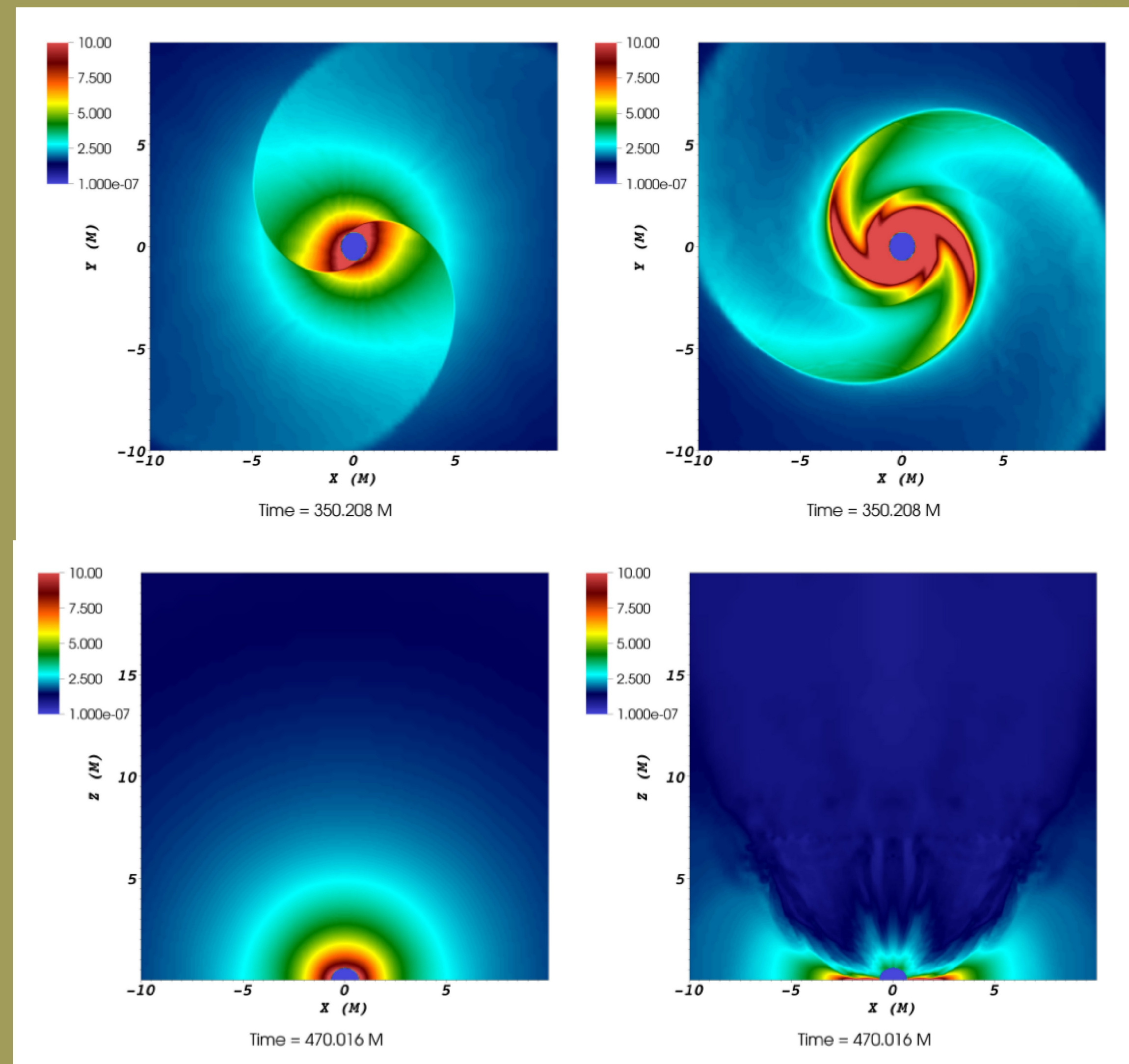
(c) $4.6\,M_8$ hrs (d) $6.8\,M_8$ hrs

EM / Force-free (Mösta *et al.* '11)

Degrees of Magnetic Influence

- Ideal MHD – Infinite conductivity limit
  - Magnetic fields increase pressure support

- Force-free – Magnetically dominated regime
  - Amplified magnetic field, amplified synchrotron radiation

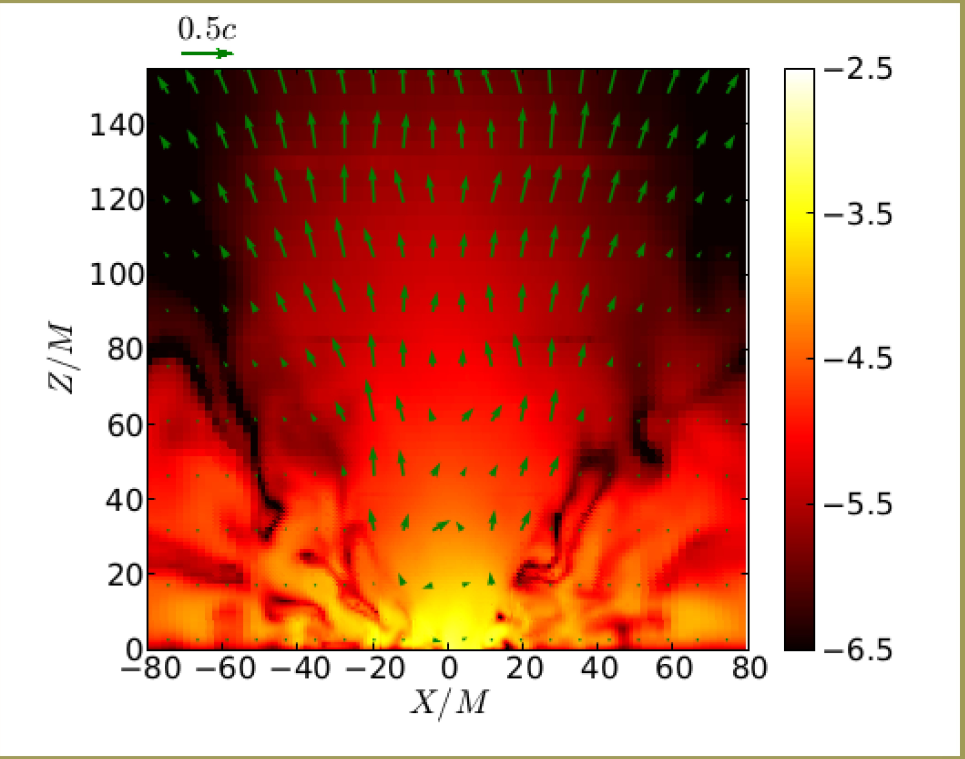


(Giacomazzo '12)

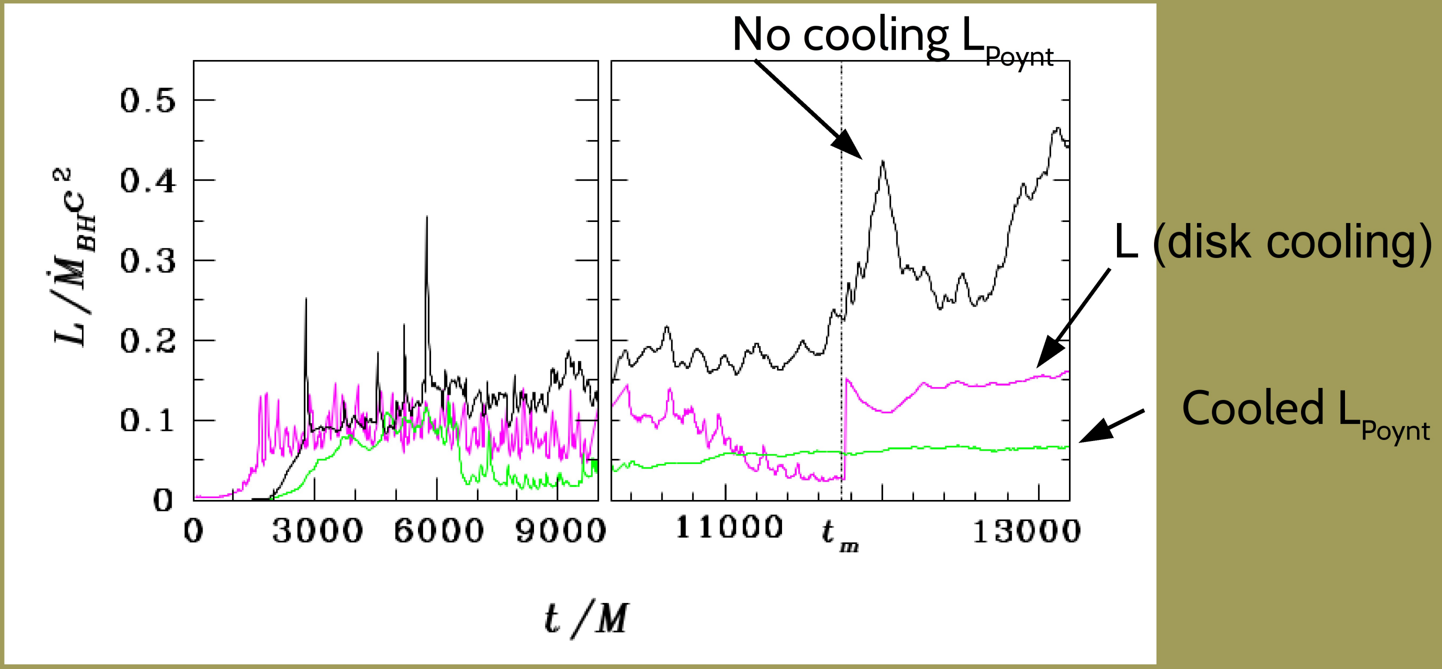
Magnetized Circumbinary Disks

GRMHD, MRI-based
magnetized circumbinary disks

→ Poynting flux collimates outwards
at BH poles.
(Farris+ '12)



Magnetized Circumbinary Disks



Magnetized Disks – Post-merger Poynting Flux flare-up due to outflows, noteworthy if cooling present
(Farris et al 2012)

Summary

- **Hot Accretion Flows**: *hot, tenuous gaseous environment (e.g. Sgr A*)*
  - *Pre-merger flare* – Brightening wakes and region within orbits, T dependent
  - *Post-merger drop-off* – Bright regions hidden behind new horizon, wakes disperse
  - *Inspiral Oscillations* – Correlated with GW oscillations, ~ few % variability (challenging)

- **Circumbinary Disks**:
  - *Decreasing luminosity* after decoupling from inner edge
  - *Shifting Spectra* → Pre-merger accretion hierarchy switch
  - *Post-merger Brightening* → Accretion disk falls into merged BH potential
  - *Observability* → Confusable with intrinsic AGN variability, possibly buried by disk emissions

- **Magnetic Possibilties**
  - Collimated outflows in polar region, regardless of initial gas distribution