Massive black hole binaries: dynamics, accretion, and electromagnetic counterparts

Binary formation and evolution from kpc to sub-pc scales

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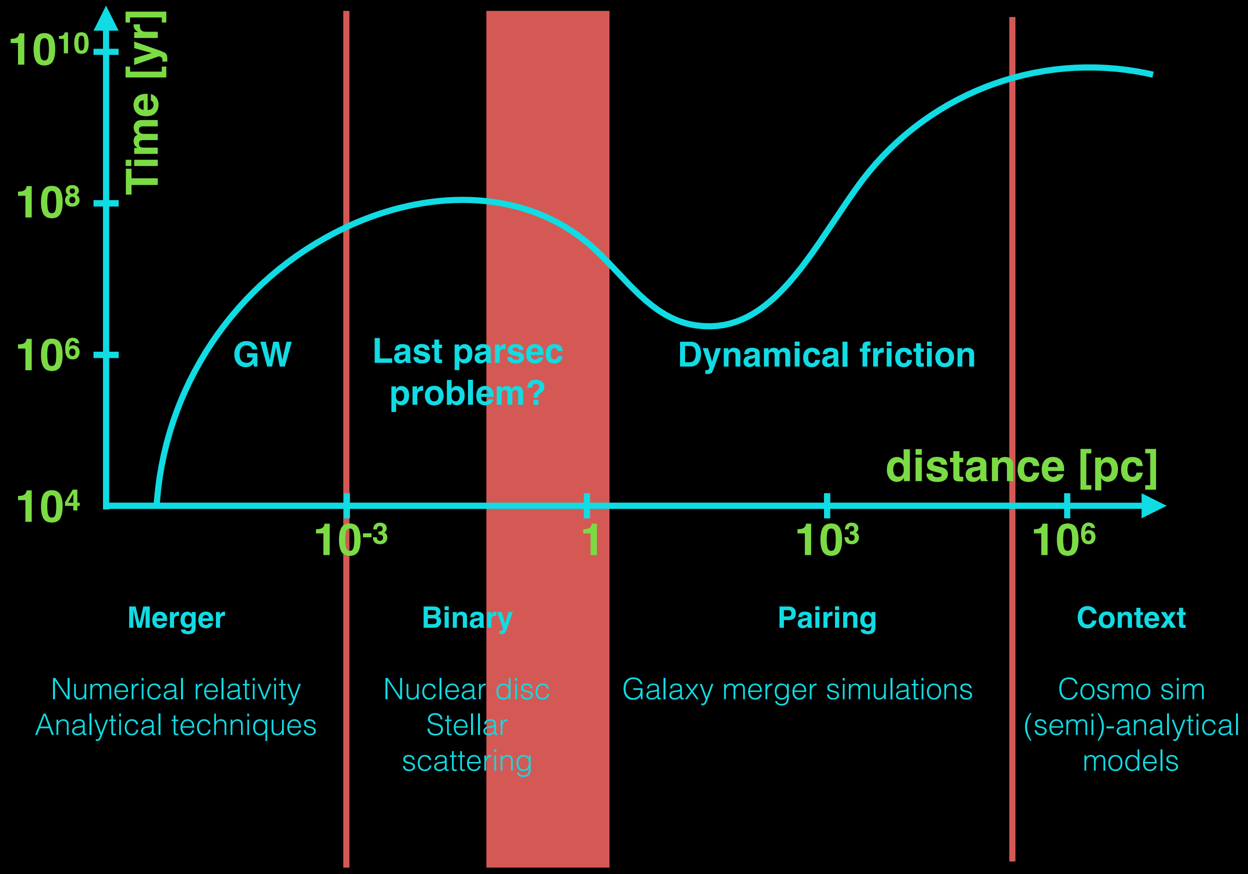
A step back: binary formation



(Begelman, Blandford & Rees 1980)

Phase I:
DF (gas/stars/DM)

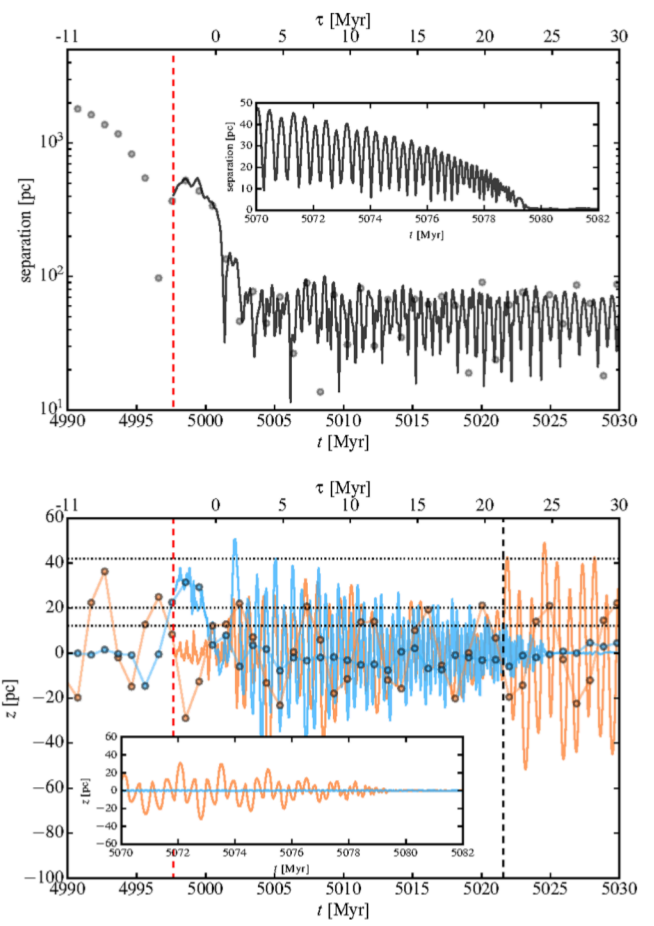
Phase II:
three-body encounters
gas-driven evolution
…

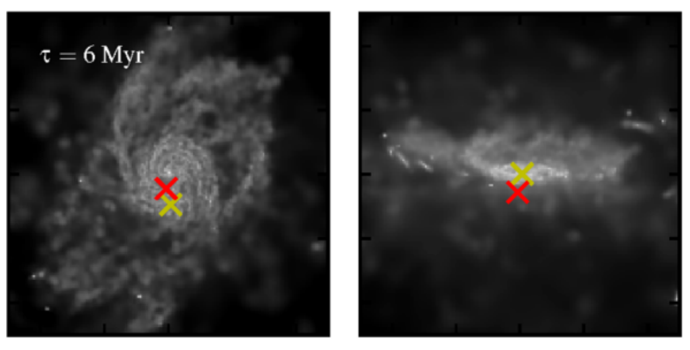
Phase III:
GW-driven inspiral

A step back: how efficiently binaries form?

Clump scattering

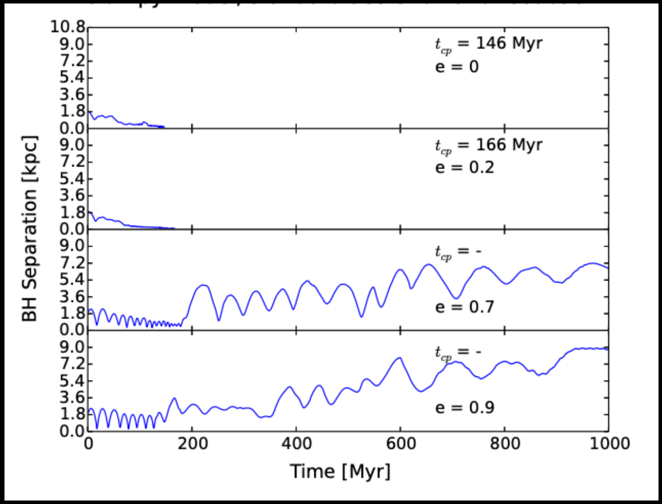
During the late stages of a galaxy merger, tidal shocks inject energy in the nuclei, causing one or both nuclei to be disrupted and leaving their BH ‘naked’, without any bound gas or stars.

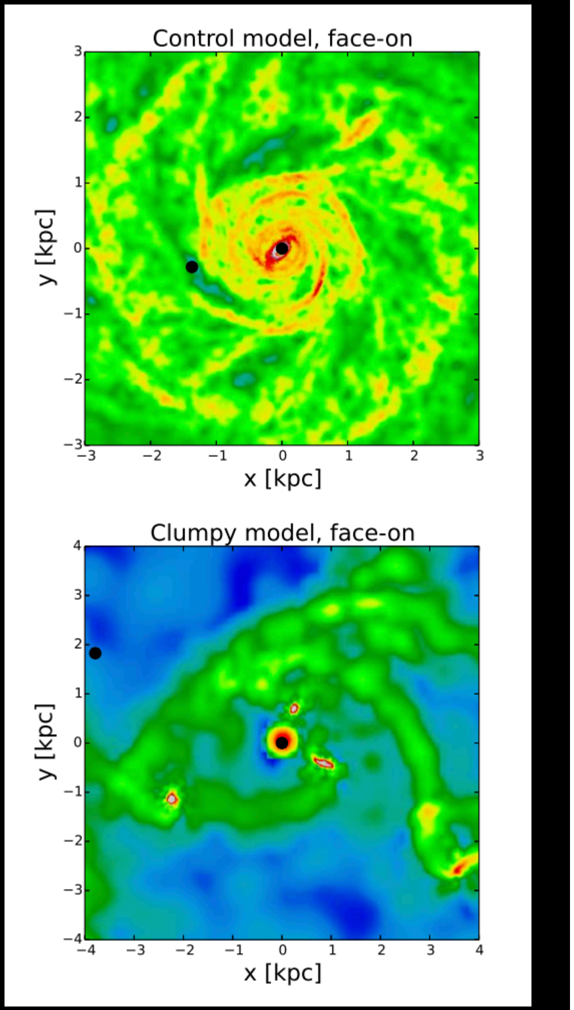




(Roskar et al. 2015)

(Tamburello et al. 2016)

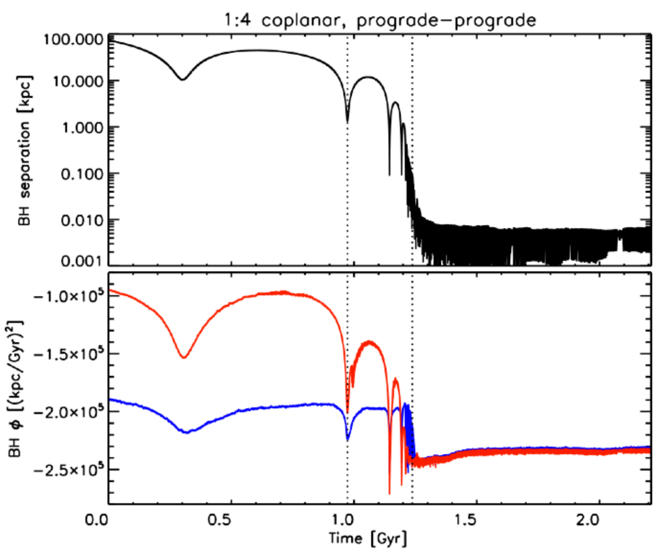




A step back: how efficiently binaries form?

Nuclear coups

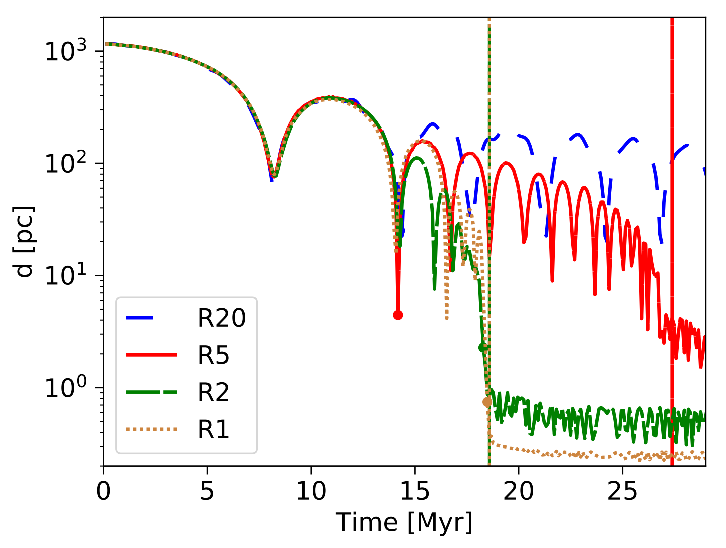
If star formation grows a denser nuclear cusp in the smaller galaxy, the nucleus that is ultimately disrupted is that of the larger galaxy (‘nuclear coup’; van Wassenhove et al. 2014).



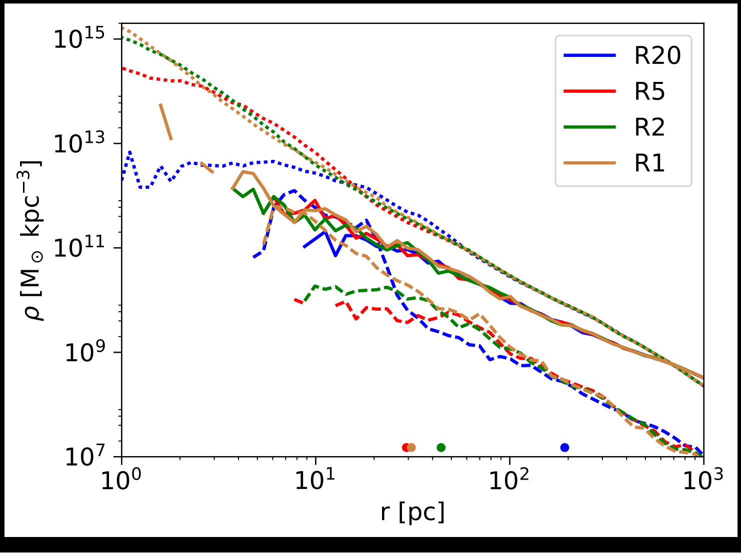
(Capelo et al. 2015)

Resolution

(from 20pc to 1pc)



(Pfister, **Lupi** et al. 2017)



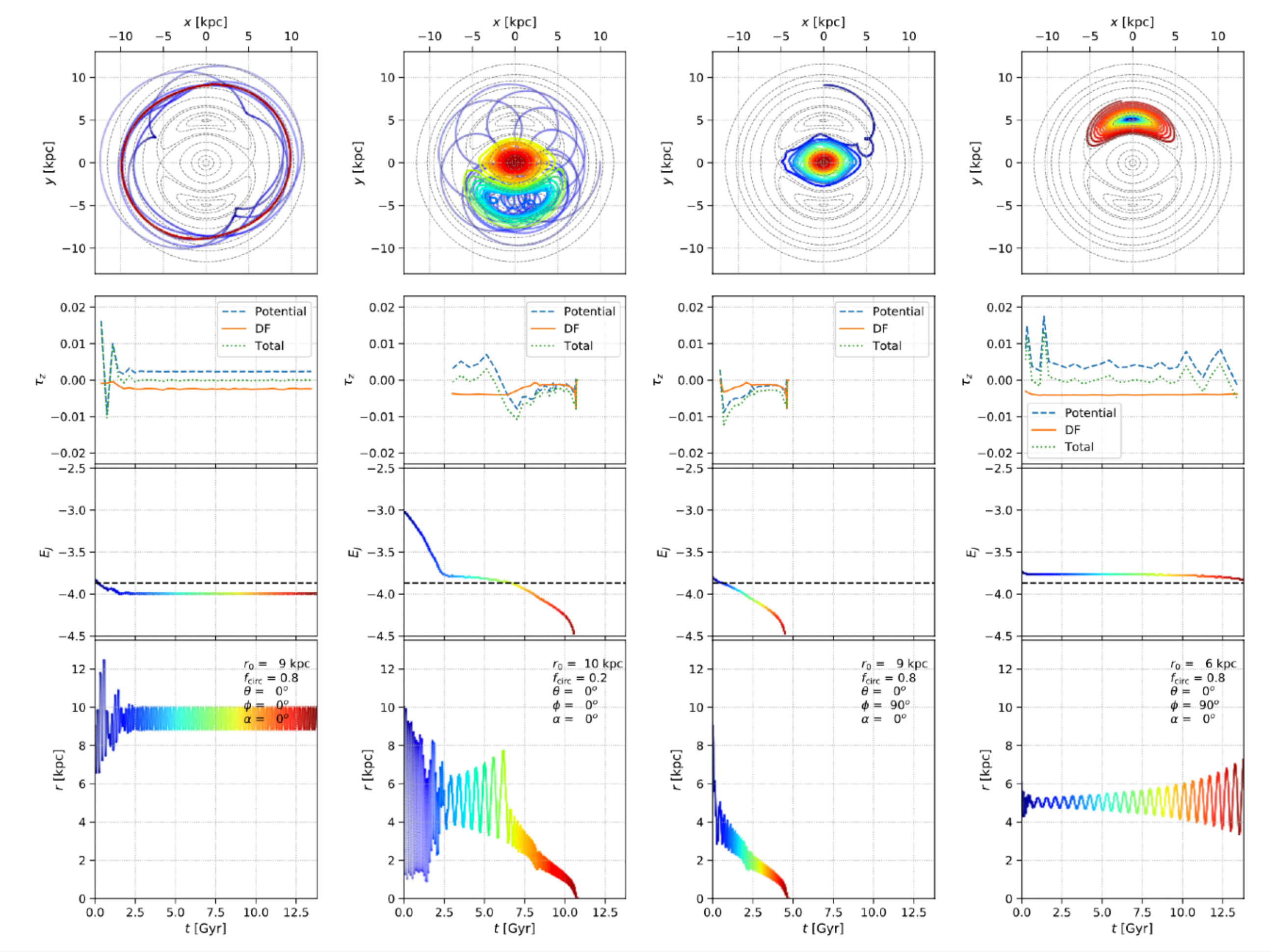
A step back: how efficiently binaries form?

Bar-induced torques

A significant fraction of observed galaxies appears to host a central bar. Due to their nature, these non-axisymmetric features can significantly alter the dynamics of decaying MBHs via torques.

(Bortolas, Bonetti, Dotti, **Lupi** et al. 2022; see also Bortolas et al. 2020)

Typical LISA BHs are likely to be more affected by bar structures, especially in the case of minor mergers, resulting in potentially delayed or completely hindered binary formation

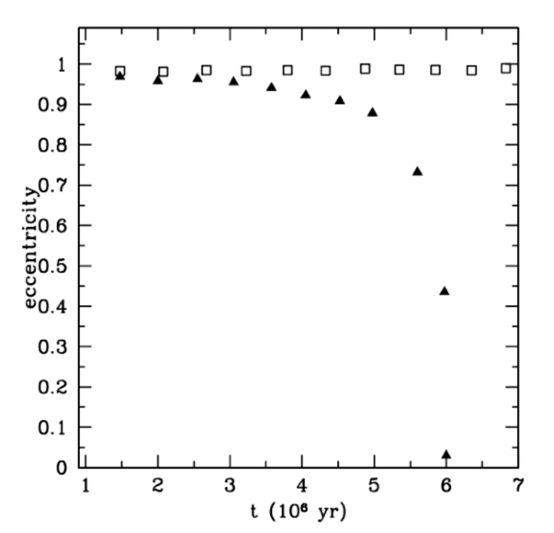


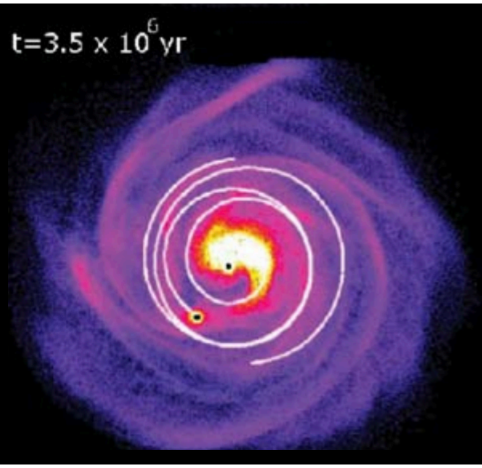
The initial binary eccentricity

Drag toward circularisation

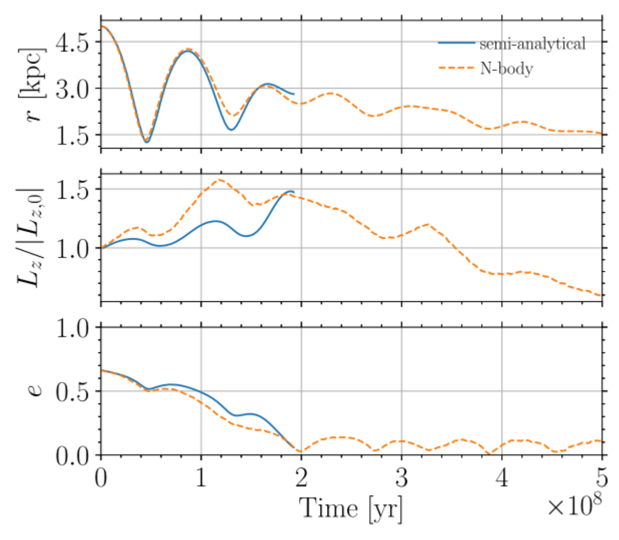
Unlike in elliptical galaxies, dynamical friction in rotating discs significantly affects the initial eccentricity of BH binaries

Dotti et al. (2006) studied binary formation in smooth gaseous circum-nuclear discs



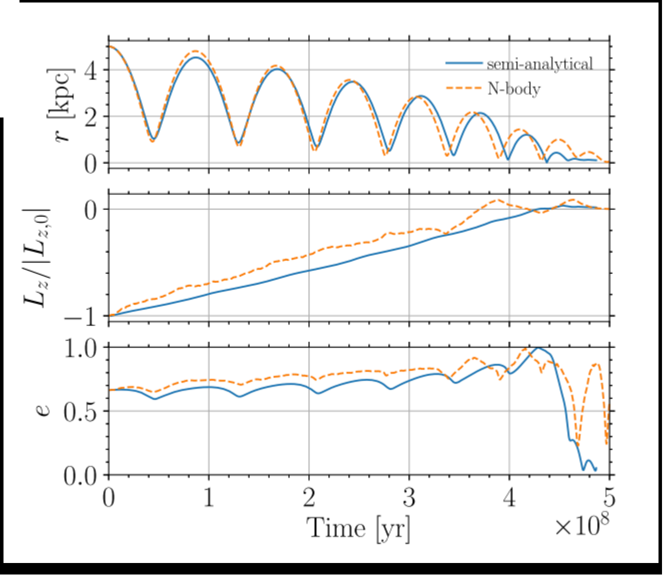


Bonetti, Bortolas, **Lupi** et al. (2020) explored the evolution on galactic scales



co-rotating

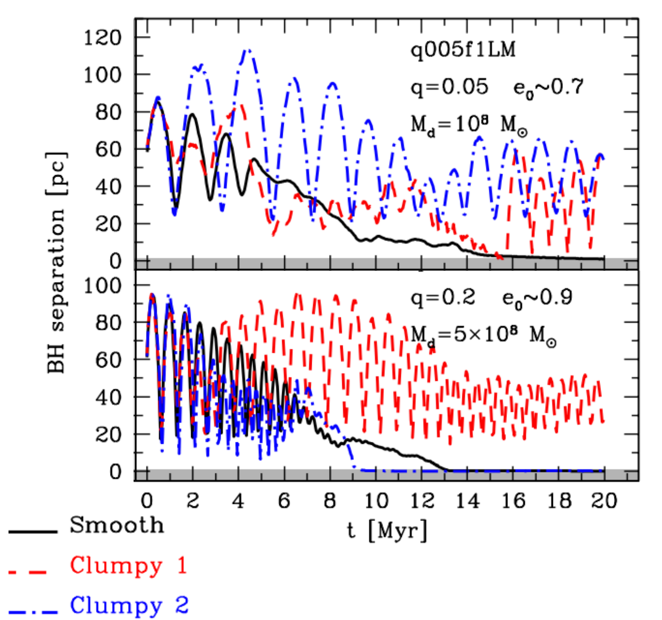
counter-rotating

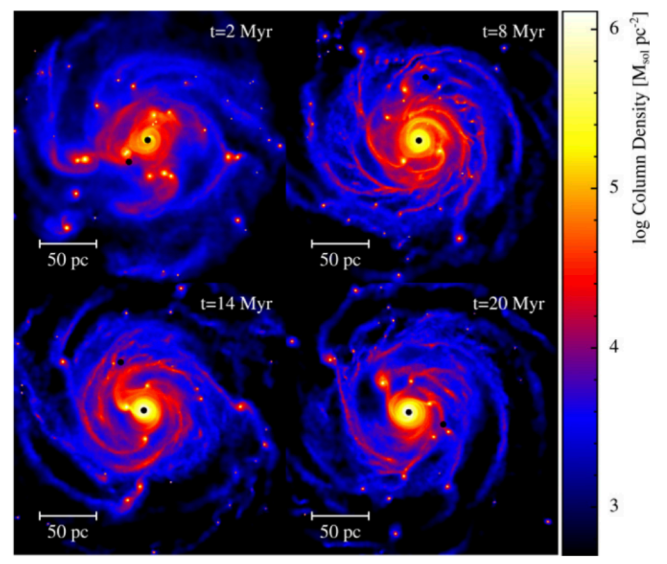


MBHBs forming in disc galaxies are likely to have low eccentricity at formation

Binary formation in circum nuclear discs

The role of long-lived clumps





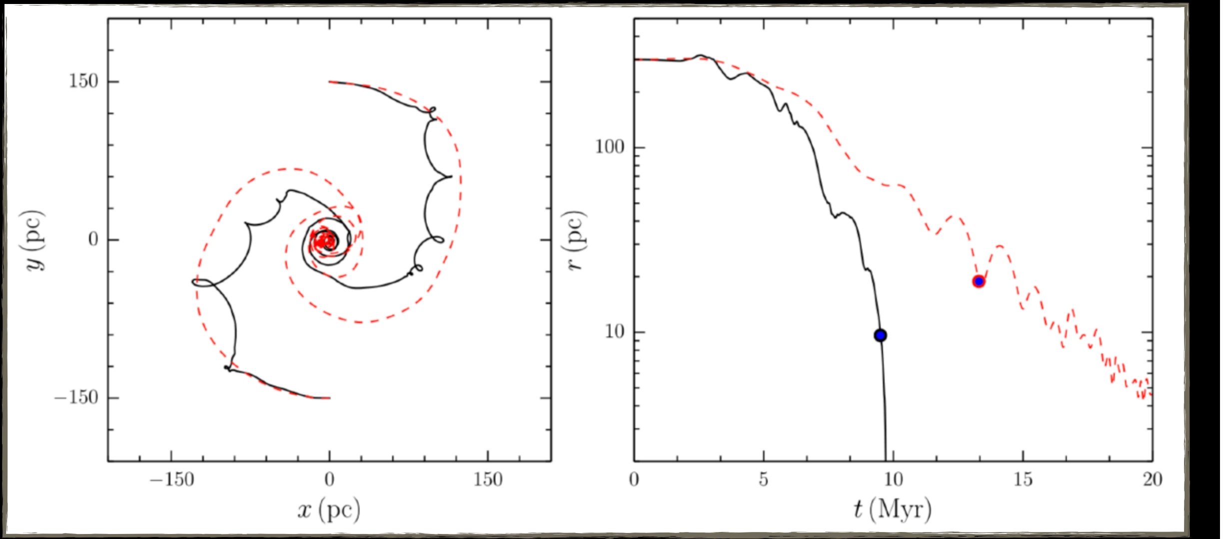
(Fiacconi et al. 2013)

SPH simulations:

0.5 pc resolution
No SF/SN feedback
No cooling during the run

Lupi et al. (2015a,b): AMR simulations of two equal mass discs initially on eccentric orbits.

Impact of SN feedback: the survival of massive and dense clumps significantly alters the pairing time-scale



Similar results found by del Valle et al. (2015), using different SF models

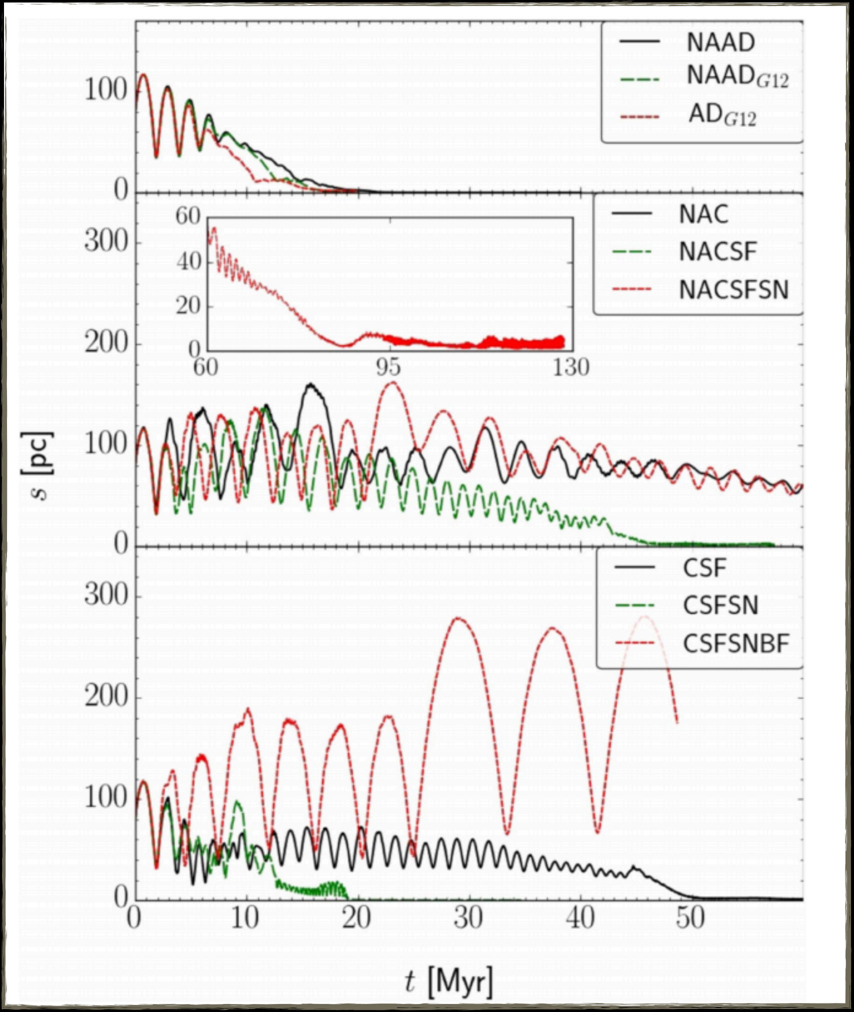
Binary formation in circum nuclear discs

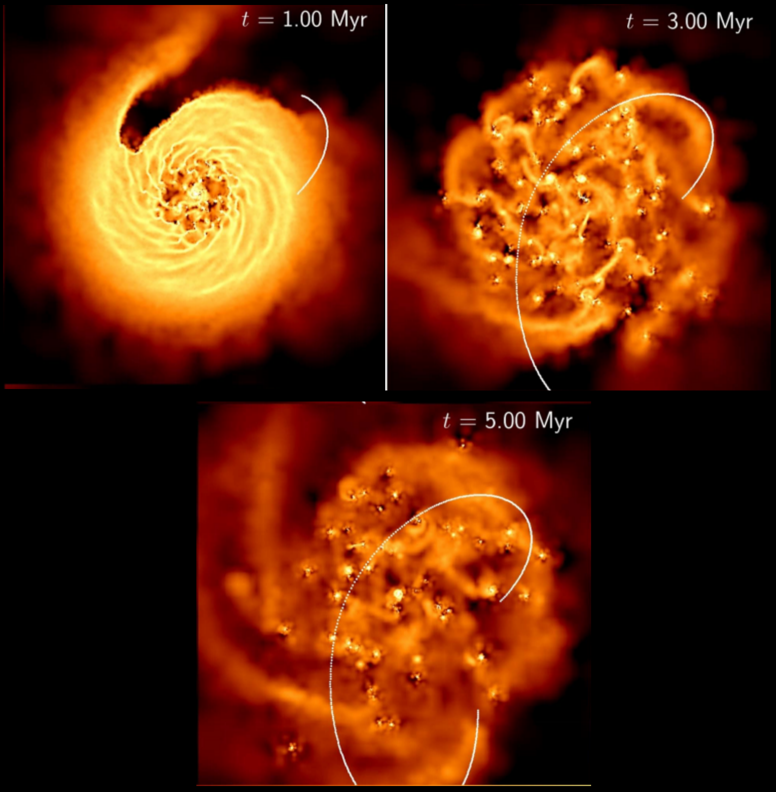
What about BH accretion and feedback?

(Souza-Lima et al. 2017)

SPH simulations:

0.5 pc resolution
Cooling/SF/SN feedback
+ BH accretion and feedback





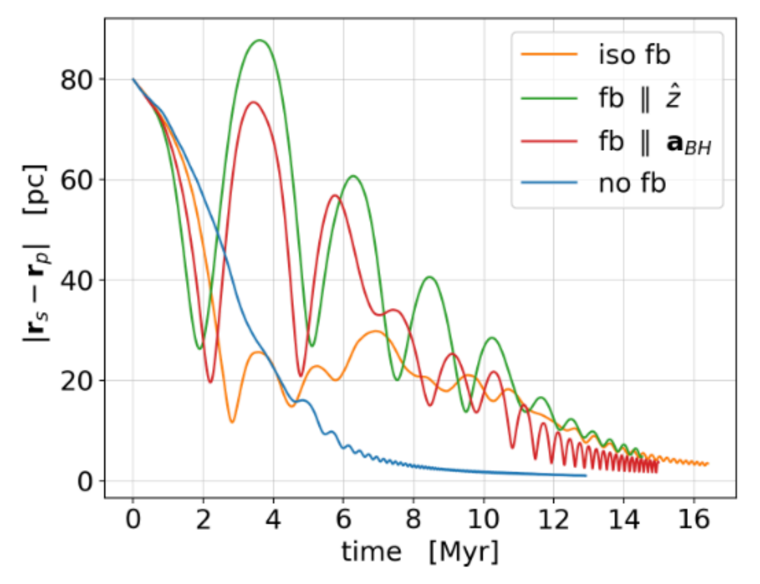
Binary formation in circum nuclear discs

What about BH accretion and feedback?

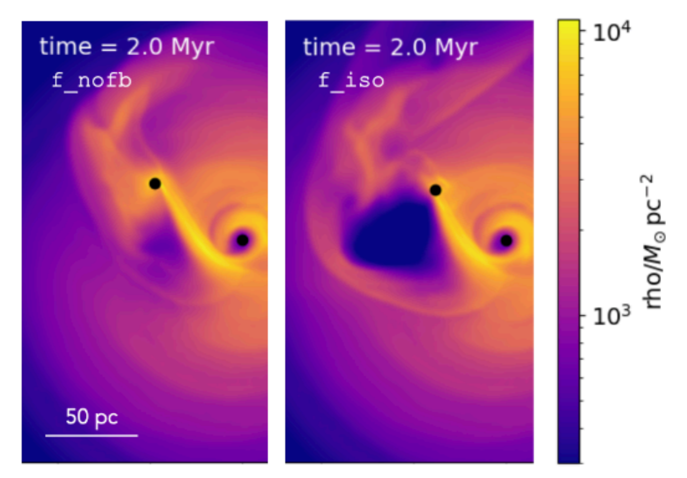
(Bollati, **Lupi** et al. in preparation)

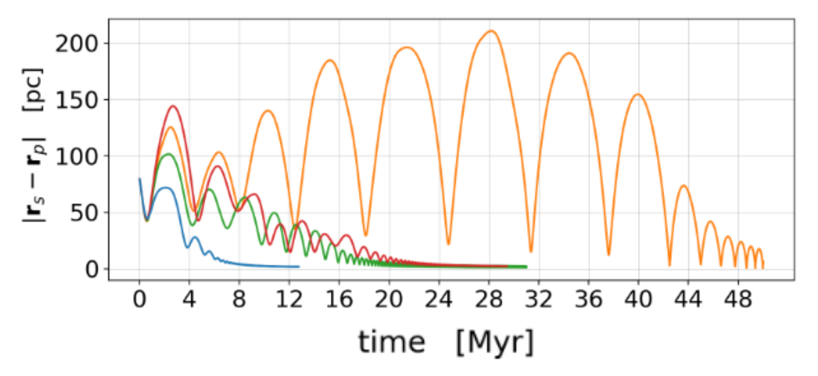
GIZMO MFM simulations:

0.1 pc resolution
spin-dependent BH accretion and feedback

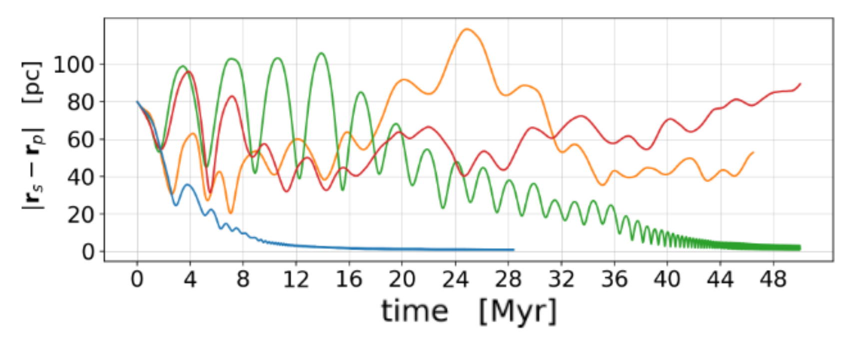


q=1/2 e=0





q=1/2 e=0.5



q=1/4 e=0

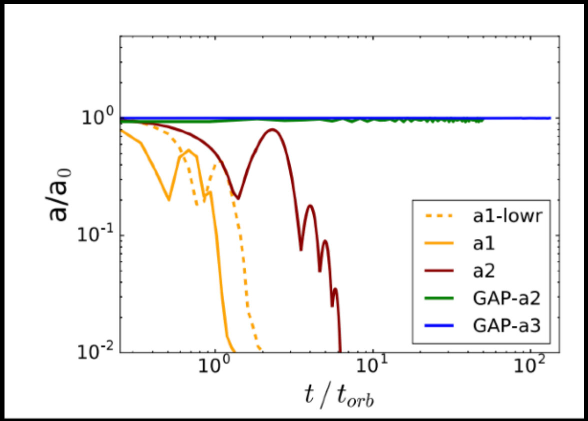
Binaries in gaseous circumbinary discs

Cavity opening: torques vs feedback

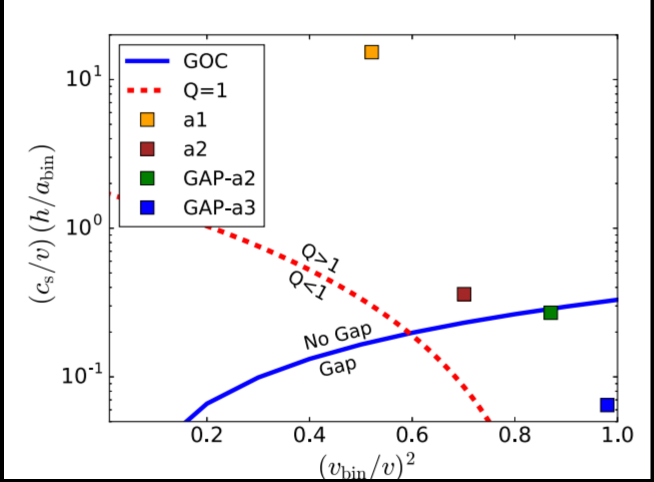
del Valle & Volonteri (2018) explore binary evolution in self-gravitating circumbinary discs in which AGN feedback affects the disc itself

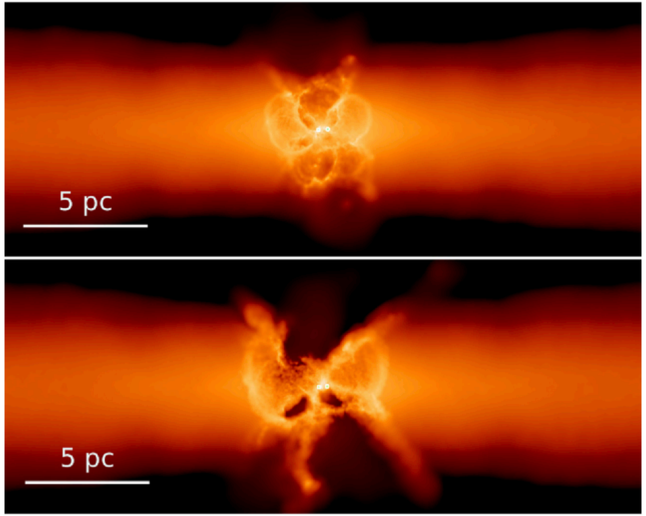
del Valle & Escala (2014)

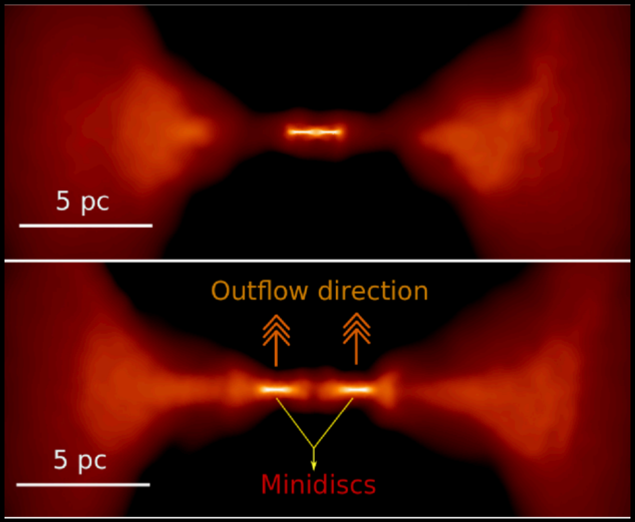
$$\frac{1}{0.33}\left(\frac{v}{v_{\mathrm{bin}}}\right)^2\left(\frac{c_s}{v}\right)\left(\frac{h}{a_{\mathrm{bin}}}\right) \leq 1$$

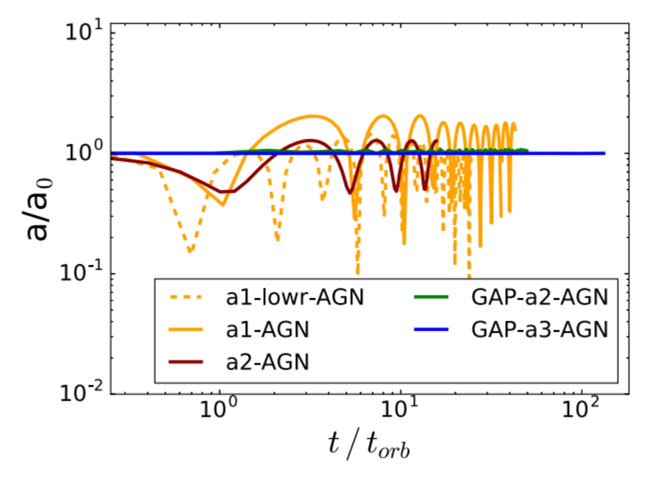


No feedback: no-cavity vs cavity runs with different binary separations







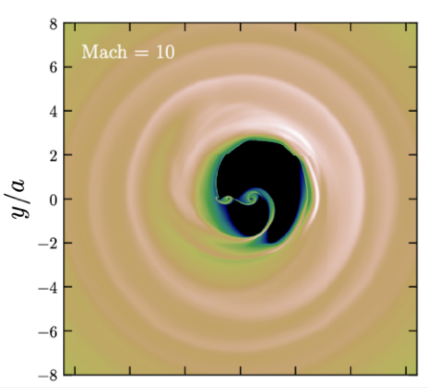


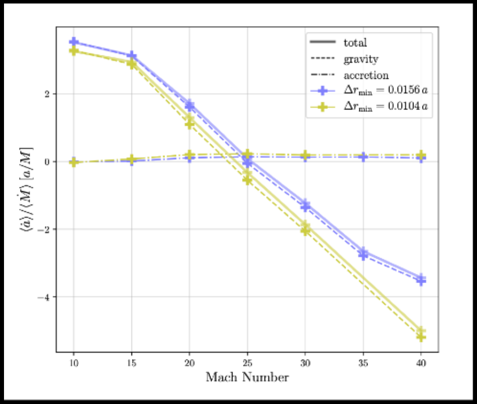
Binary shrinking vs expansion

Is there a maximum H/R above which binaries expand?

Several works have recently pointed out that thick discs result in binary expansion, thus significantly affecting the number of source potentially detectable by LISA

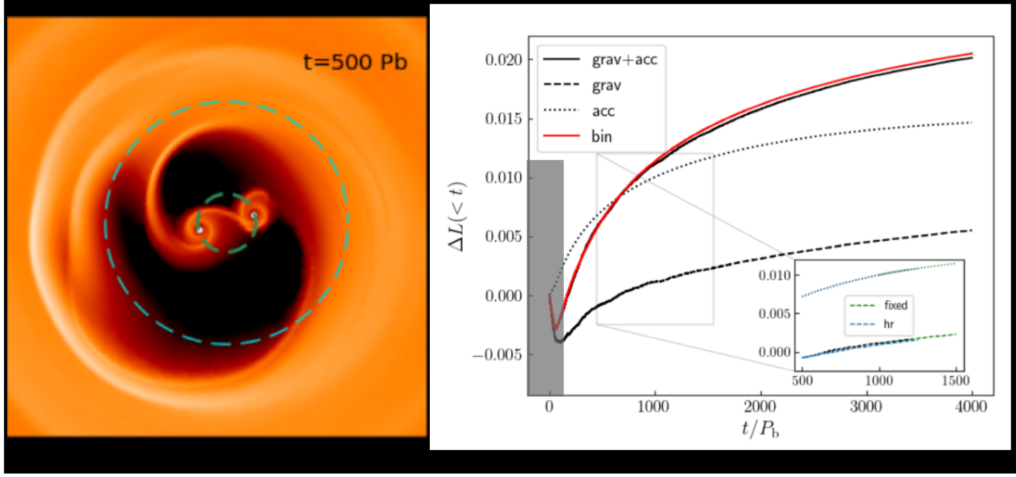
Fixed binary orbit - grid or moving mesh simulations
2D: Munoz et al. (2019, 2020), Duffell et al. (2020)
3D: Moody et al. (2019)

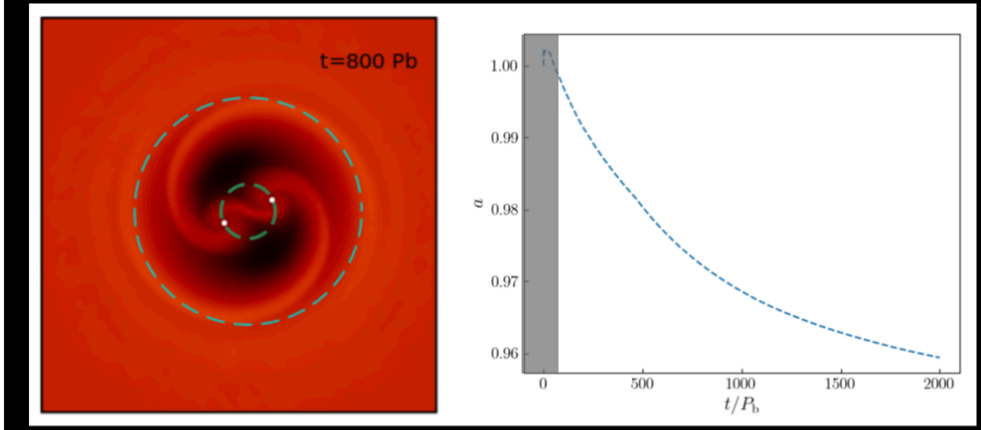




- Tiede et al. (2020): critical H/R~0.04
- Heath & Nixon (2020), using 3D SPH simulations with a live binary, found a critical H/R~0.2

Franchini, Lupi and Sesana (2022), using adaptive particle splitting, have resolved in 3D the dynamics inside the cavity with a resolution comparable to 2D simulations: expansion occurs in a very specific regime



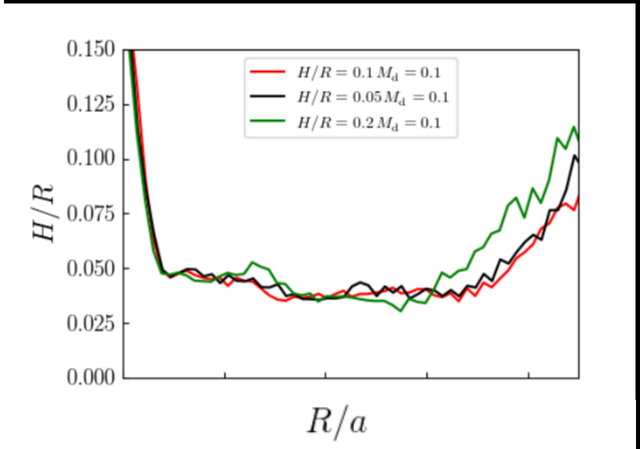


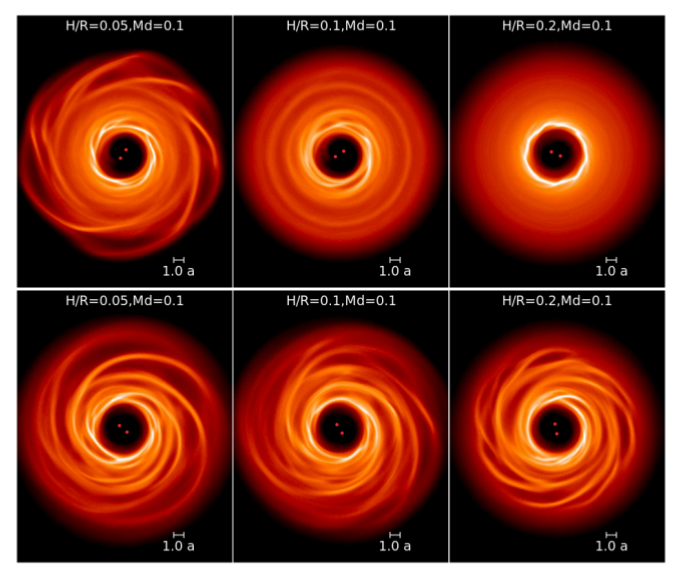
Binary shrinking vs expansion

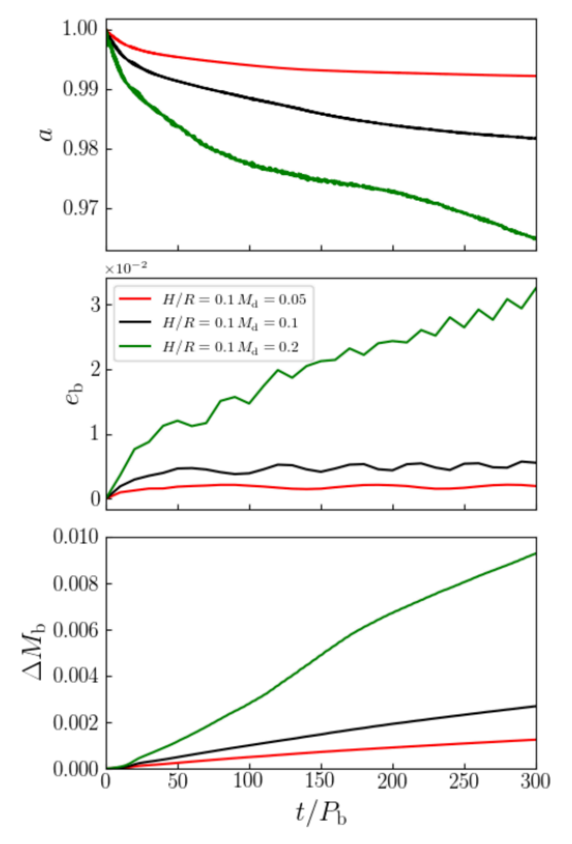
How does the picture change when self-gravity is included?

Roedig et al. (2012) and more recently Franchini et al. (2021) explored the impact of self-gravity on the evolution of binaries

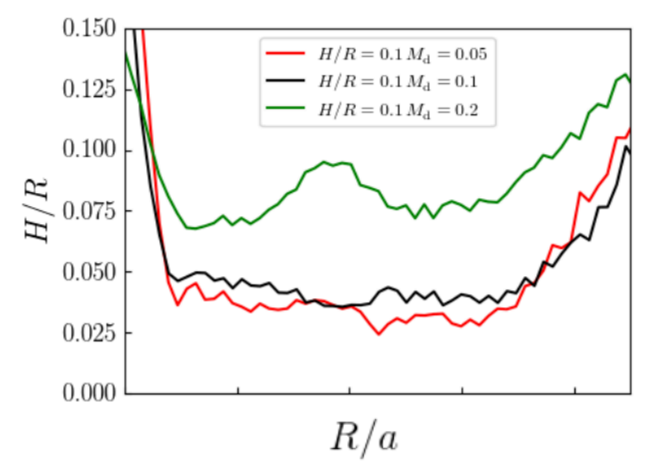
Beta cooling in the disc reduces H/R to ~0.05, always resulting in binary shrinking







For more massive discs, H/R can remain closer to 0.1, but $\dot{M}$ and $\dot{e}$ are higher, and the shrinking is faster



Gas vs stars: who wins?

While gas-driven processes are extremely important in the case the loss-cone is emptied (last-parsec problem), most up-to-date studies have shown that realistic merger remnants are triaxial, which means that the loss-cone is continuously refilled, driving binaries to shrink via 3-body interactions.

Bortolas et al. (2021) investigated the relative importance of gas-driven and stellar-driven binary evolution

Sesana & Khan (2015)

$$\dot{a}_\star = -\frac{HG\rho}{\sigma}\,a^2$$

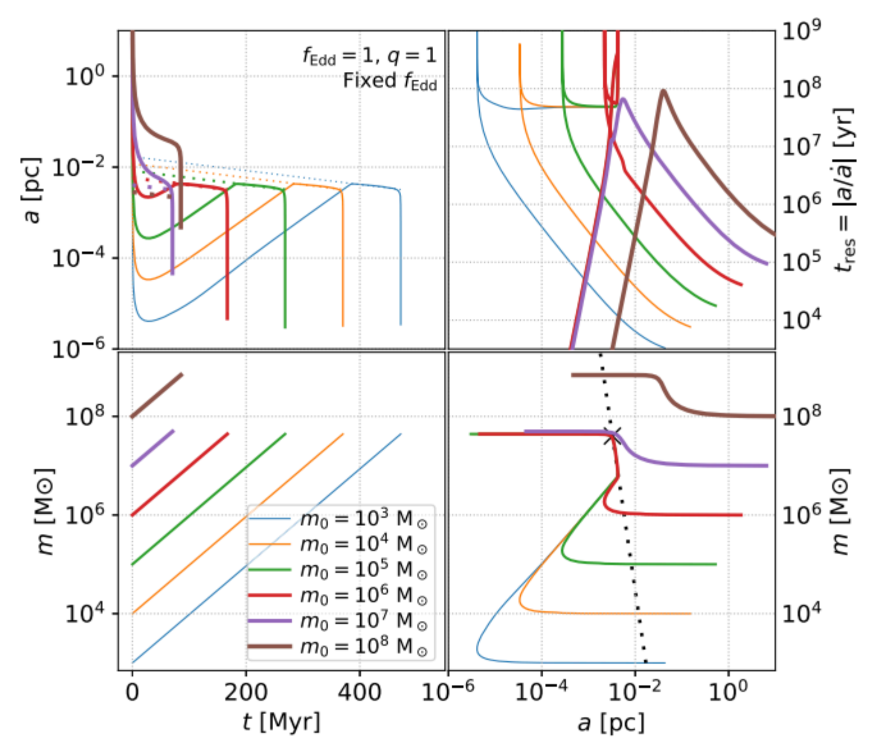
Peters (1964)

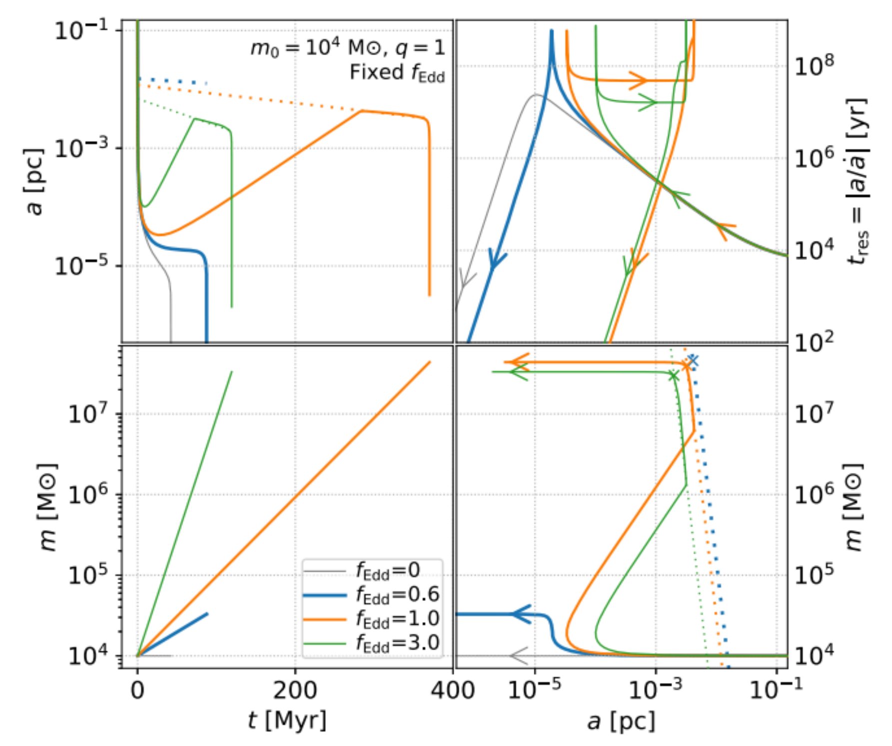
$$\dot{a}_{\rm GW} = -\frac{64}{5}\frac{G^3}{c^5}\frac{q}{(1+q)^2}\frac{m^3}{a^3}$$

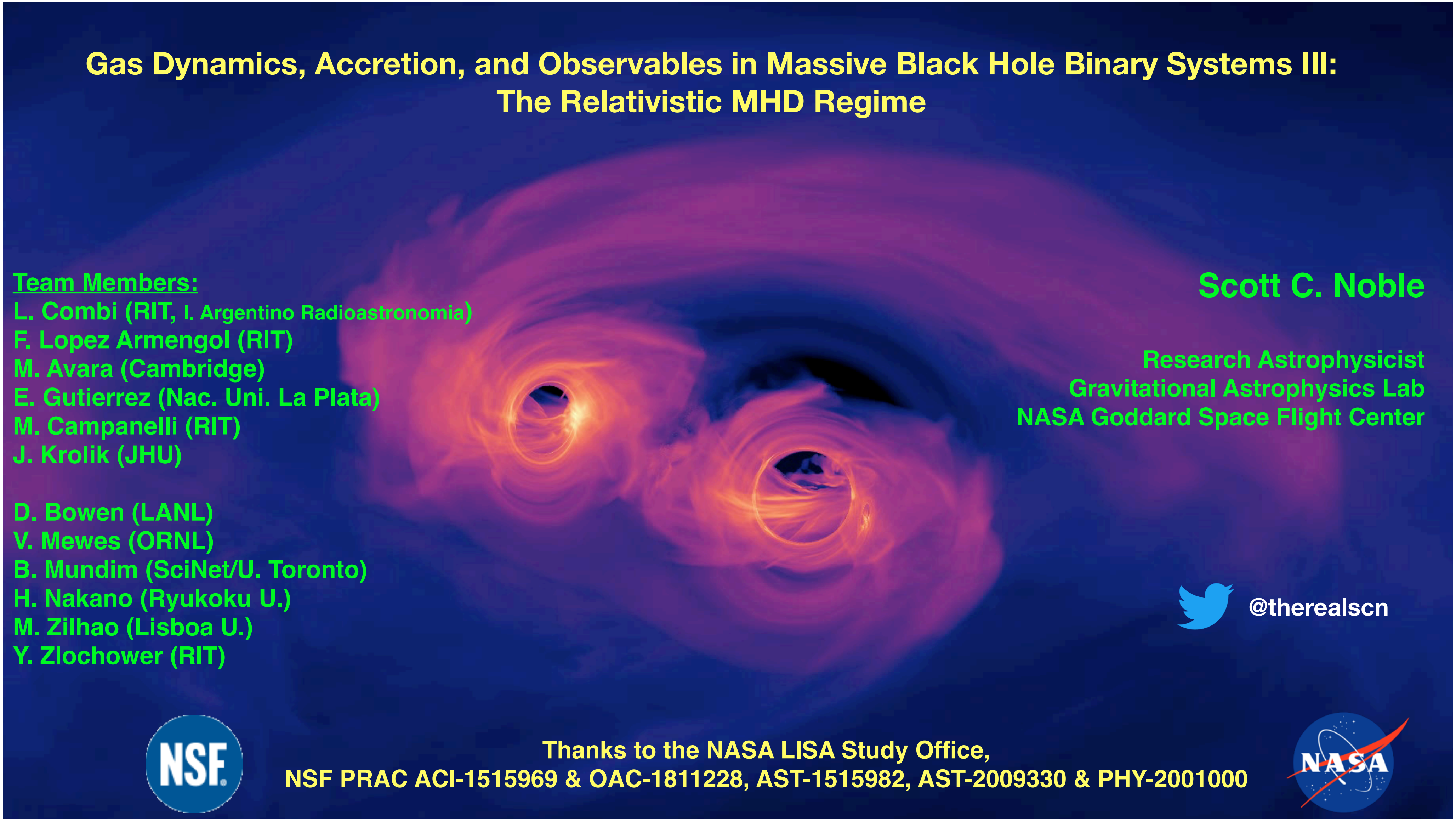
Muñoz et al. (2020)

$$\dot{a}_{\rm gas} = 2.68\frac{\dot{m}}{m}a,$$

for q>~0.1







Gas Dynamics, Accretion, and Observables in Massive Black Hole Binary Systems III: The Relativistic MHD Regime

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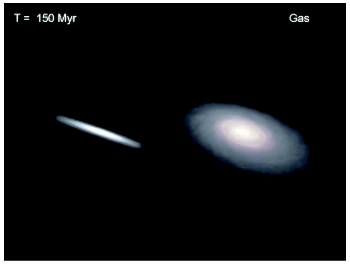
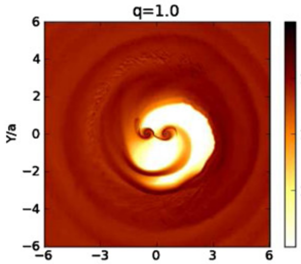
Strategy & Techniques

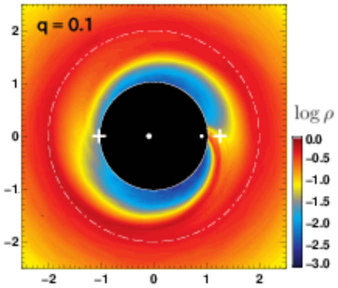


Hopkins, Hernquist, Di Matteo, Springel++

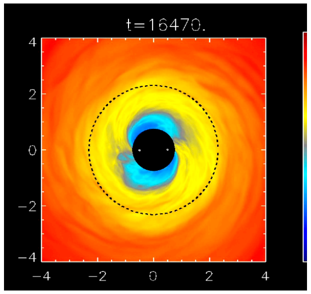
e.g., Sayeb, Blecha, Kelley, Gerosa, Kesden, and Thomas, MNRAS (2020)



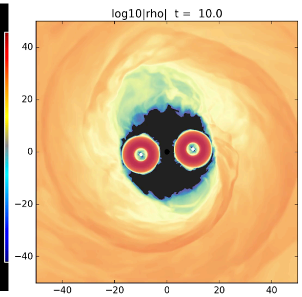
Farris++2014, d'Orazio++2015—, Munoz, Miranda, Lai (2017-2020), Moody++(2019), Tang++(2017-2019) Samsing++2020, Zrake++2020, ….



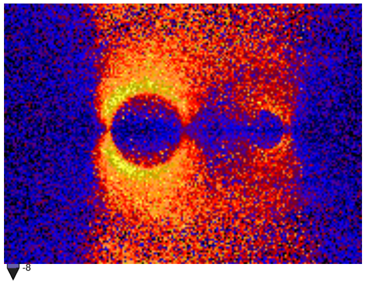
Shi & Krolik (2014-2016)
Bankert & Krolik (2015)



Noble++2012–15
Lopez Armengol++2021
Noble++2021



Bowen++2018, 2019
Combi++2021



Kelly++2017,
Farris++2012, Gold++2014ab,
Kahn++2018, Paschalidis++2021,
Cattorini++2021,2022
Review: Gold, Galax, 7, 63, (2019)

Matter:	**Viscous Hydro.**	**MHD**	**GR MHD**	**GR MHD**
Gravity:	**Newtonian**	**Newtonian**	**Post-Newtonian**	**Numerical Relativity**

Advantages/Disadvantages of Rel. MHD regime:

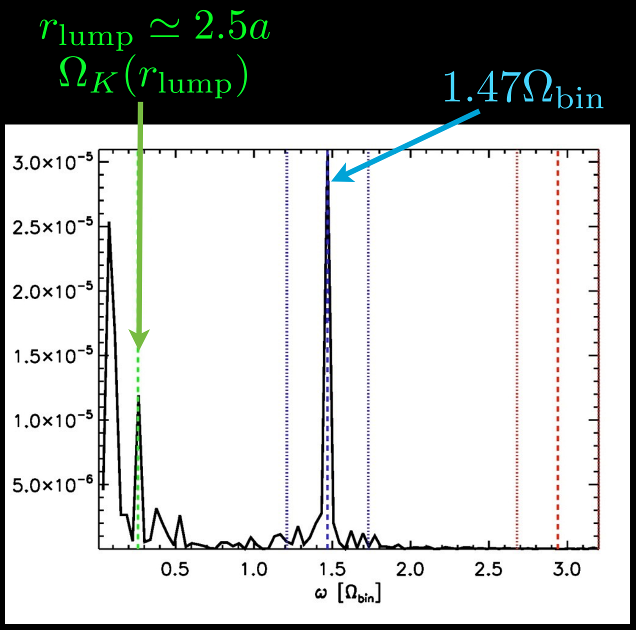
Pros	Cons
Event horizons are physical inner boundary conditions, and can launch jets naturally!	Sometimes the binary region still needs to be excised to afford longer evolutions of the CBD.
Internal magnetic stress is a physically motivated agent for angular momentum transport.	Magnetic fields introduce other issues: monopoles, possible dependencies on initial distribution/topology.
3-d accommodates more realistic thermo., radiation physics/predictions, orientation effects, etc.	More expensive, cannot cover parameter space as inexpensively, temporal/spatial dynamic range limitations.
Can explore inspiral/decoupling regime using inspiral rate appropriate to physical scale of the gravitational system.	Needs further exploration, TBD.

GIGO:
"Garbage In —> Garbage Out"

Non-trivial EM Periodicity from the Lump:

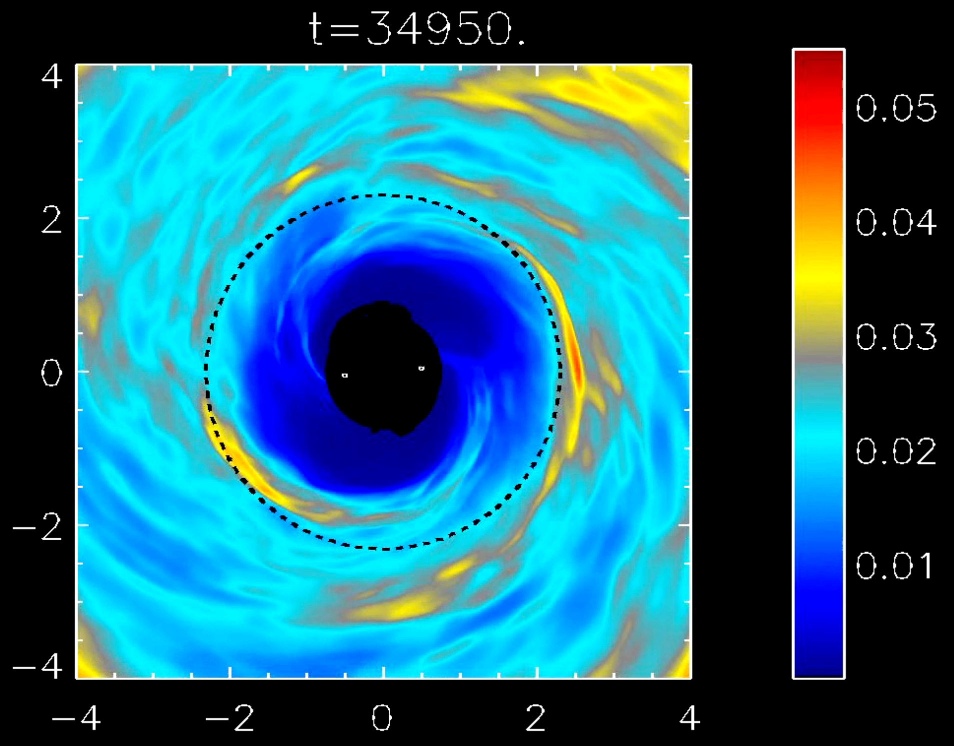
Noble, Mundim, Nakano, Krolik, Campanelli, Zlochower, and Yunes, ApJ, 755, 51, (2012).

Periodic Signal



$$\omega_{\rm peak} = 2\left(\Omega_{\rm bin} - \Omega_{\rm lump}\right)$$

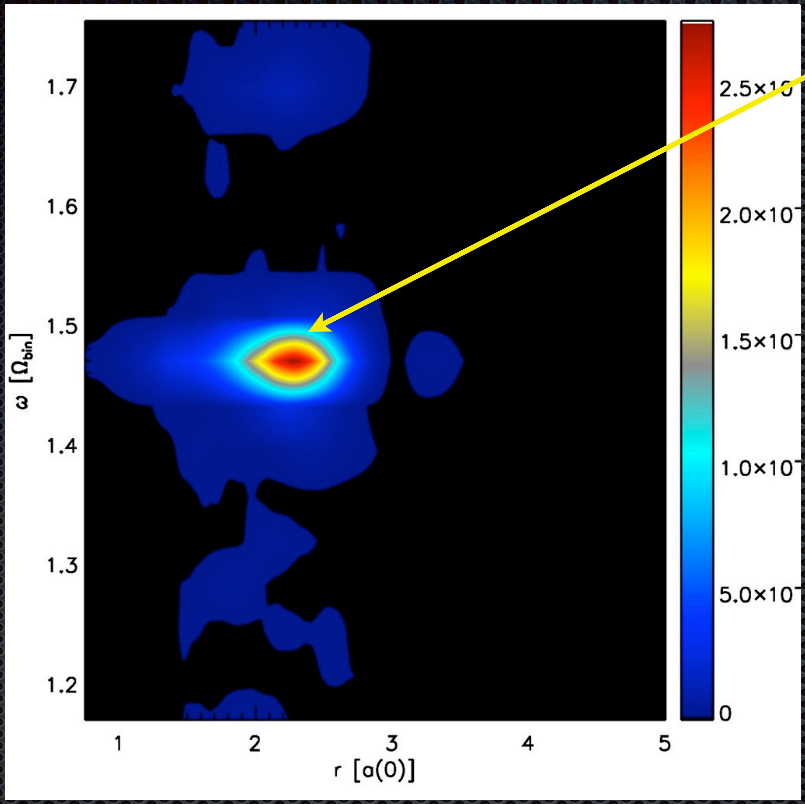
Surface Density



(in frame co-rotating with lump)

Variability

FFT close-up

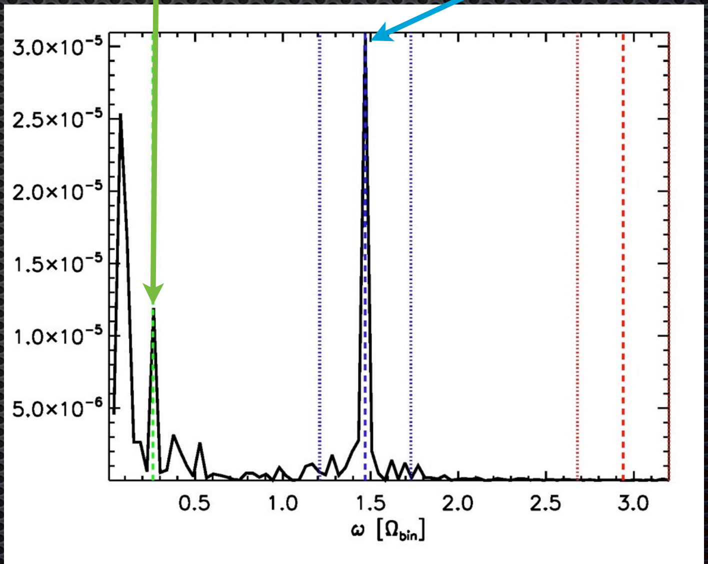


$r_{\rm peak} \simeq 2.3a$

$r_{\rm lump} \simeq 2.5a$

$\Omega_K(r_{\rm lump})$

$1.47\Omega_{\rm bin}$

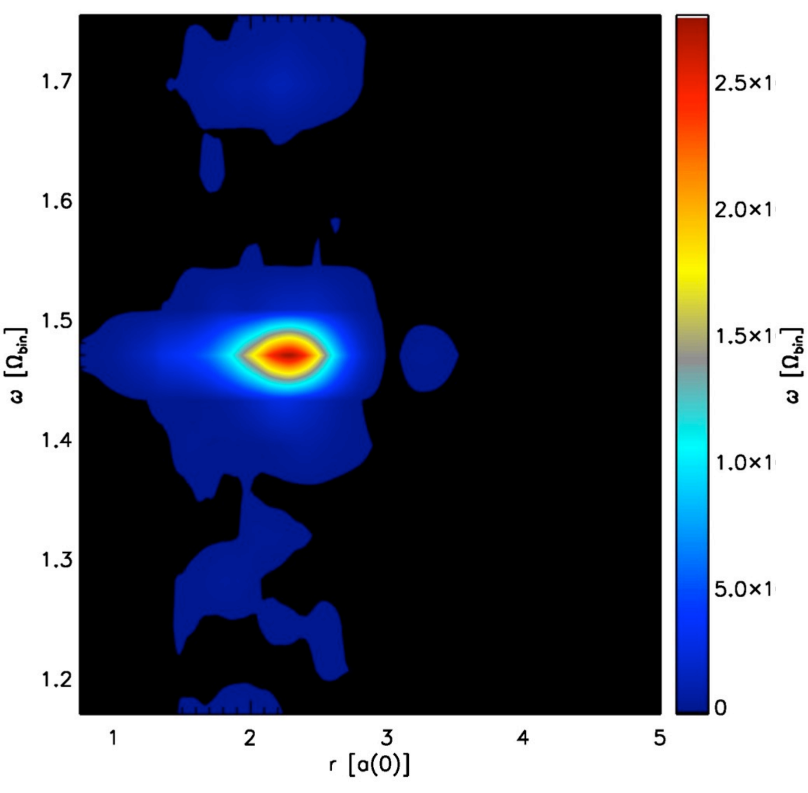


(r ,ω) space

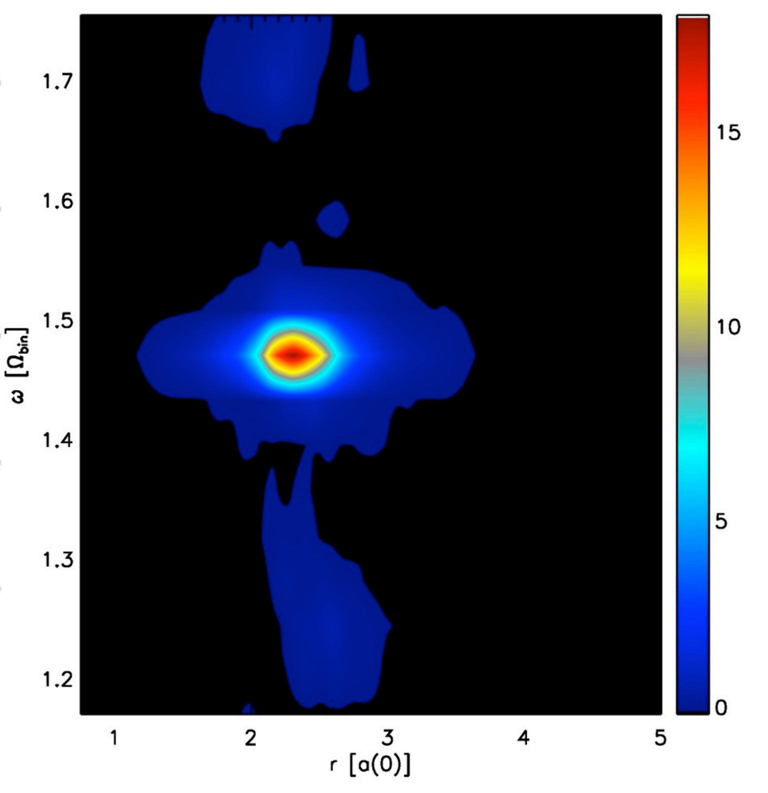
integrated over radius

Variability

FFT close-up



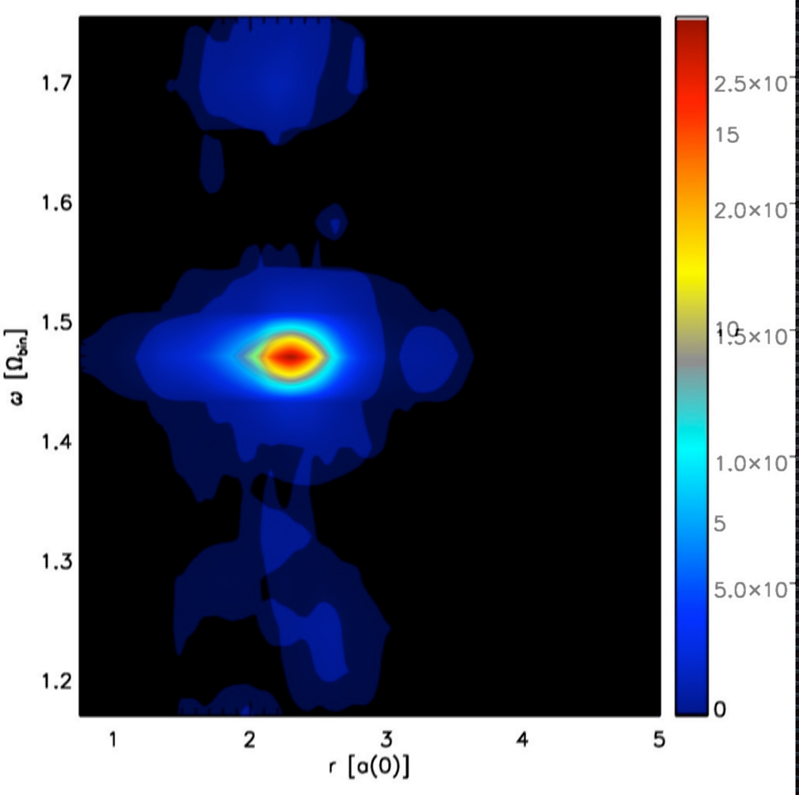
Luminosity



Surface Density

Variability

FFT close-up

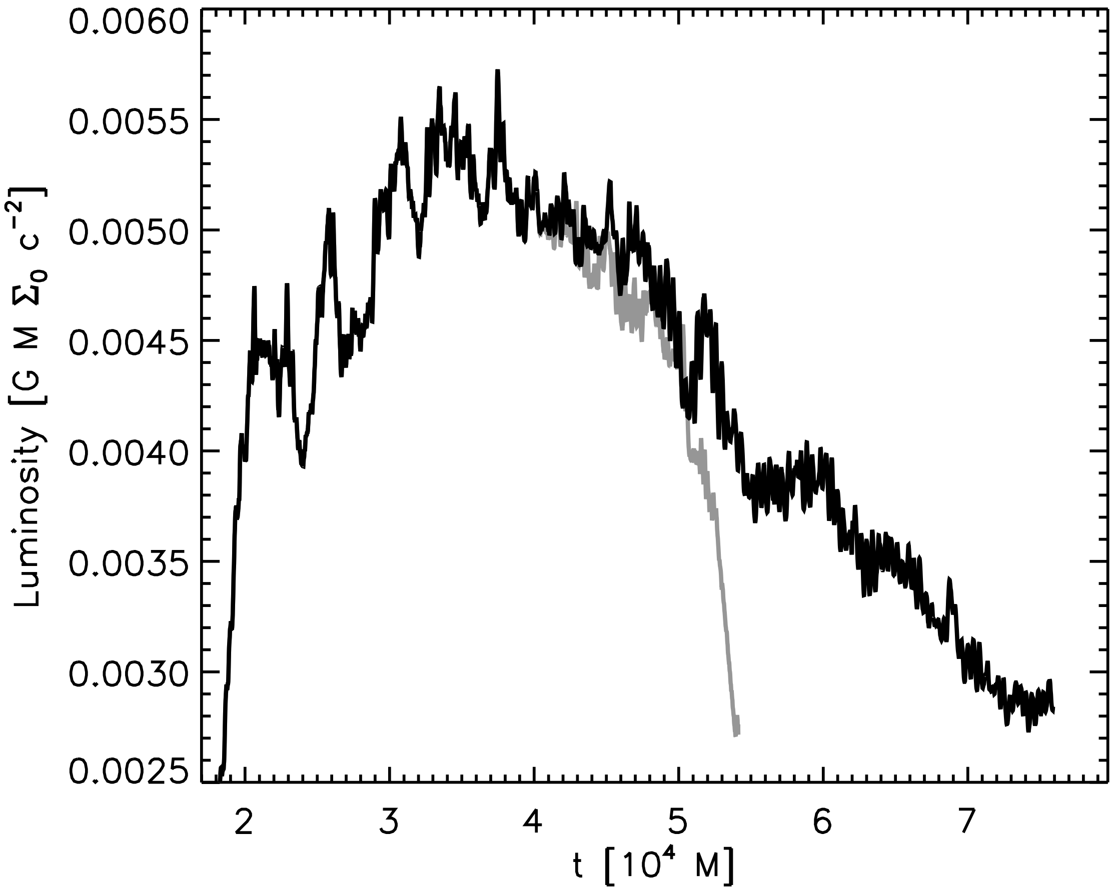


Luminosity

Surface Density

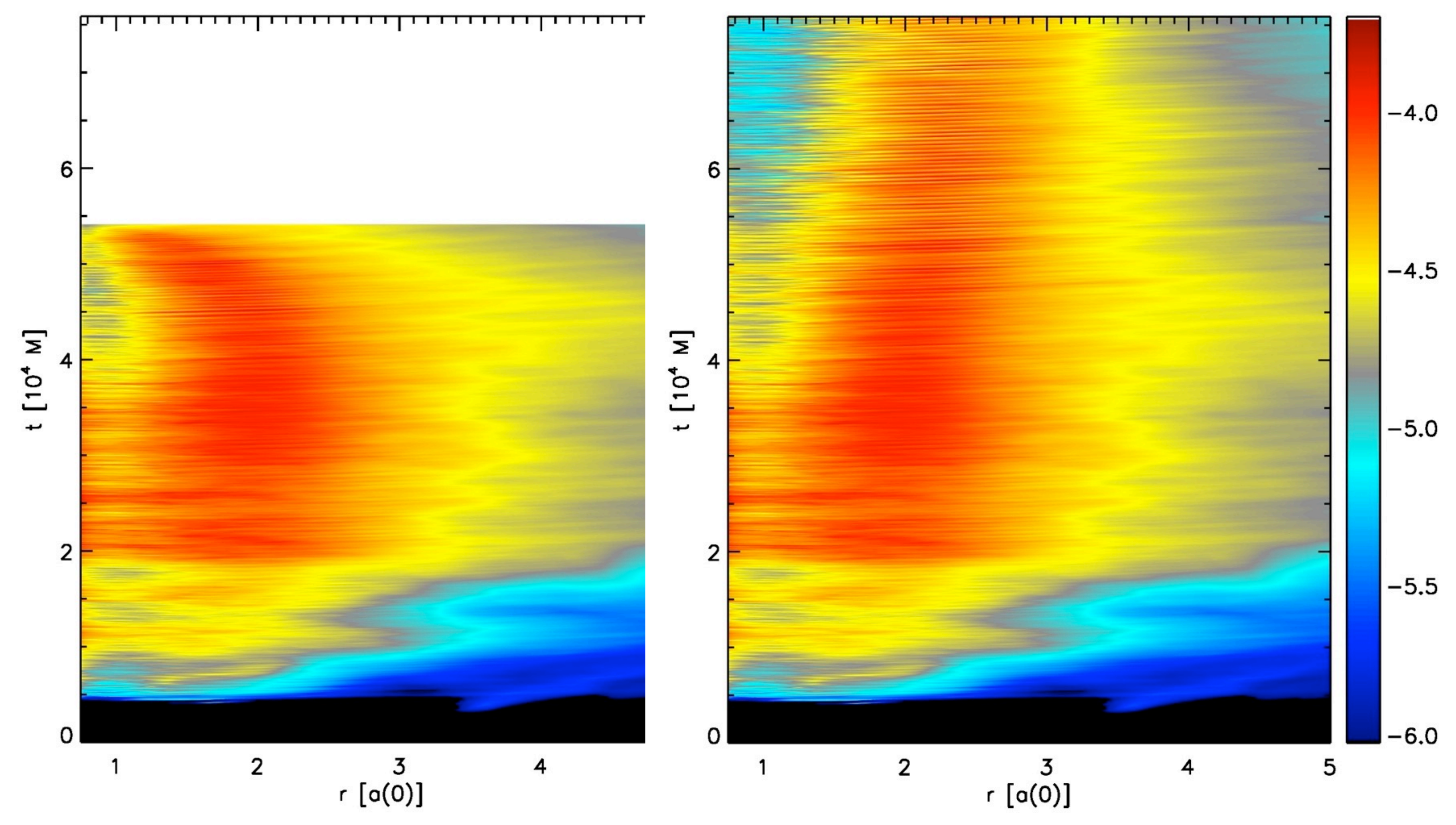
Decoupling

Noble, Mundim, Nakano, Krolik, Campanelli, Zlochower, and Yunes, ApJ, 755, 51, (2012).

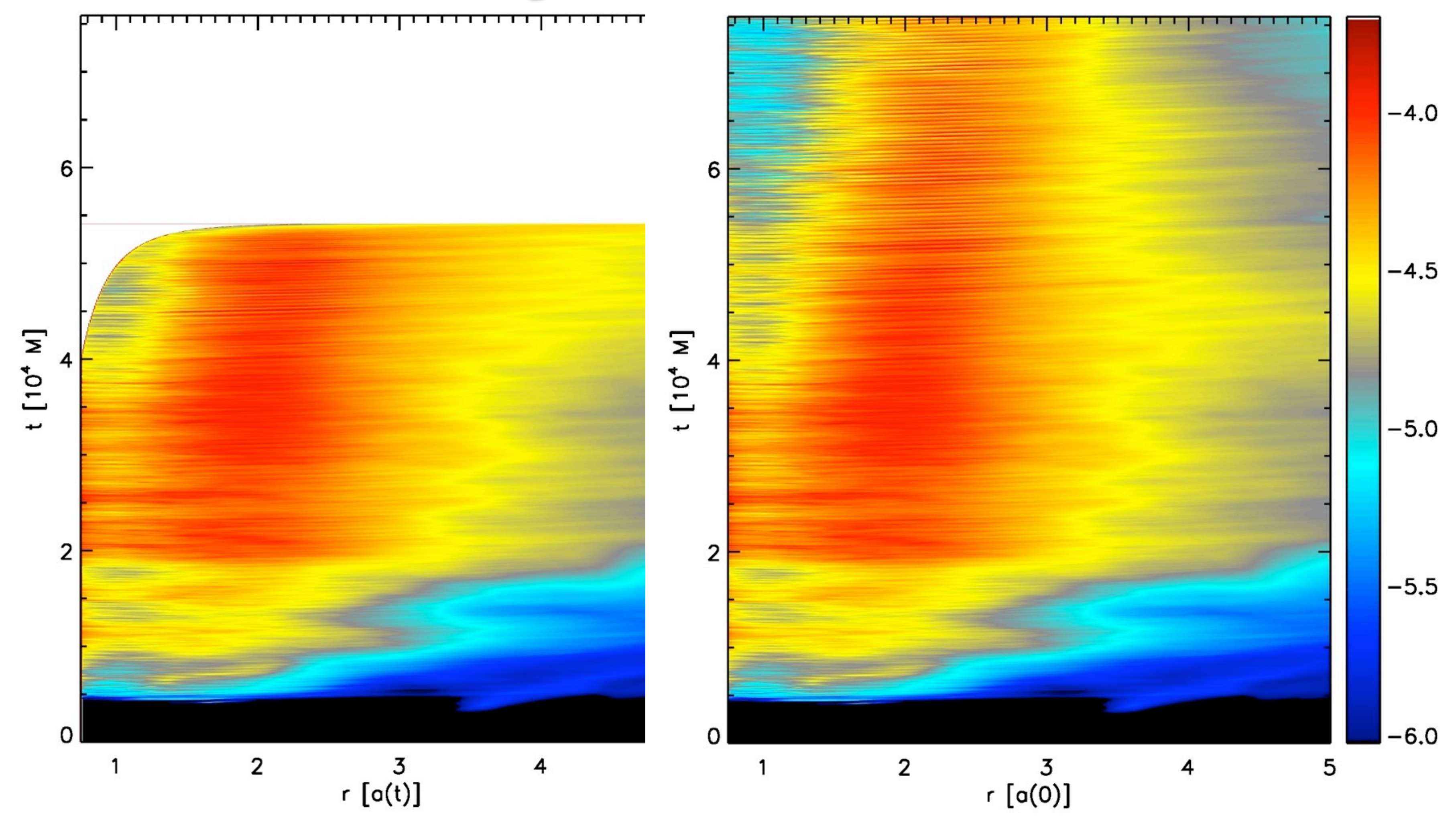


- Decoupling at t=40,000M.
- Post-decoupling luminosity tracks fixed separation continuation closely.
- Departures only at later time.
- Still need to experiment with large separations so we can track the inspiral longer.

Luminosity : time vs. radius

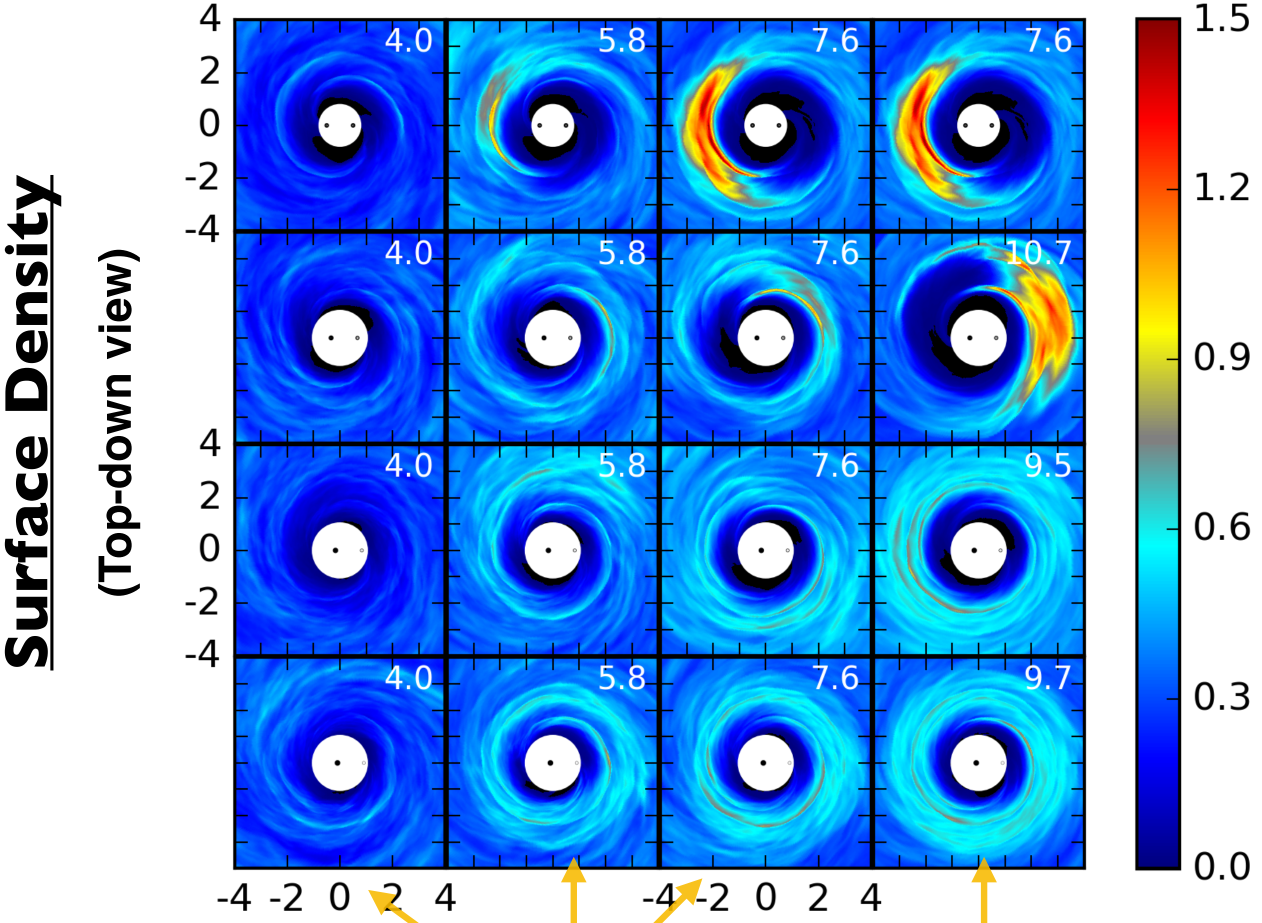


Luminosity : time vs. radius



Mass Ratio Survey : Circumbinary Disks

Noble, Krolik, Campanelli, Zlochower, Mundim, Nakano, Zilhao (2021)
https://arxiv.org/abs/2103.12100



Same times

Last time of run

$q=M_2/M$

$q=1$

$q=0.5$

$q=0.2$

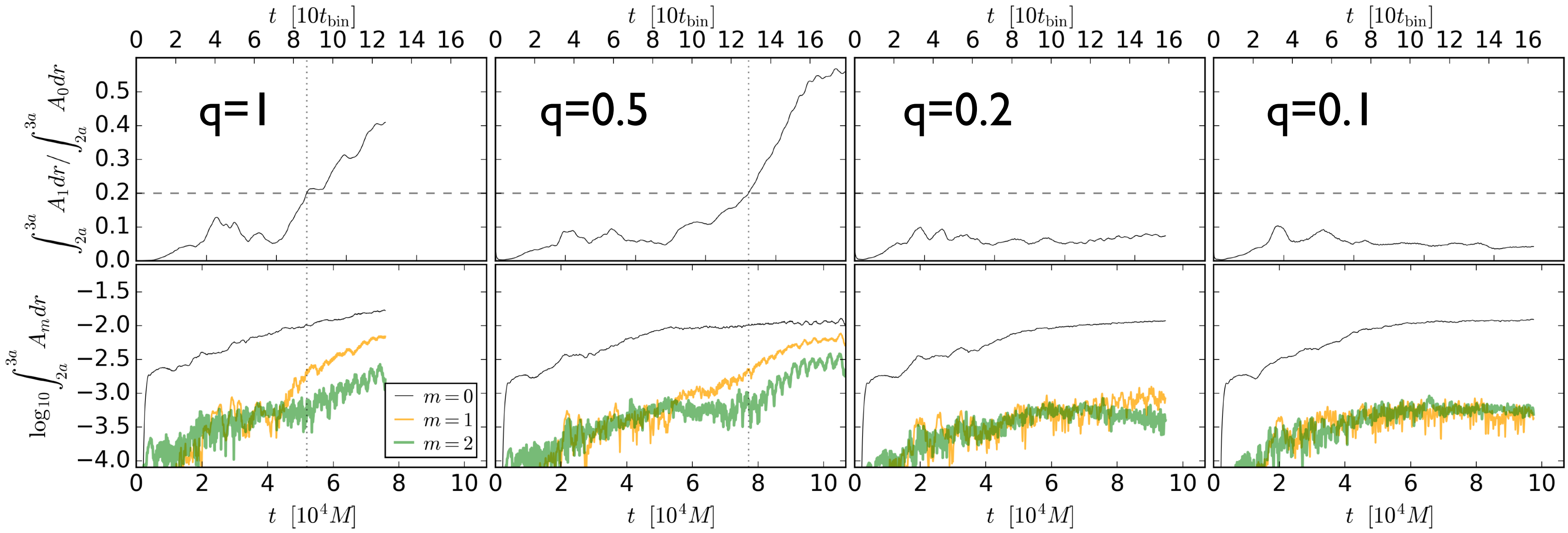
$q=0.1$

- **Simulations of only circumbinary disk region, starting from Noble++2012 conditions, only changing q.**
- **As mass-ratio diminishes, so does gravitational torque density of the binary, asymptoting to “single BH” disk;**
- **Weaker torques also diminish strength of the lump feature.**
- **Weaker torques (smaller mass ratio binaries) take longer to form lumps.**
- **Duffel++2019, see transition in lump’s relevance at q~0.2 for viscous Newtonian hydro. disks; See also Shi & Krolik 2016, Munoz+2019, Moody+2019.**

Mass Ratio Survey

Lump Formation Criterion:
Ratio of m=1 to m=0 Amp.

Noble, Krolik, Campanelli, Zlochower, Mundim, Nakano, Zilhao (2021)
https://arxiv.org/abs/2103.12100



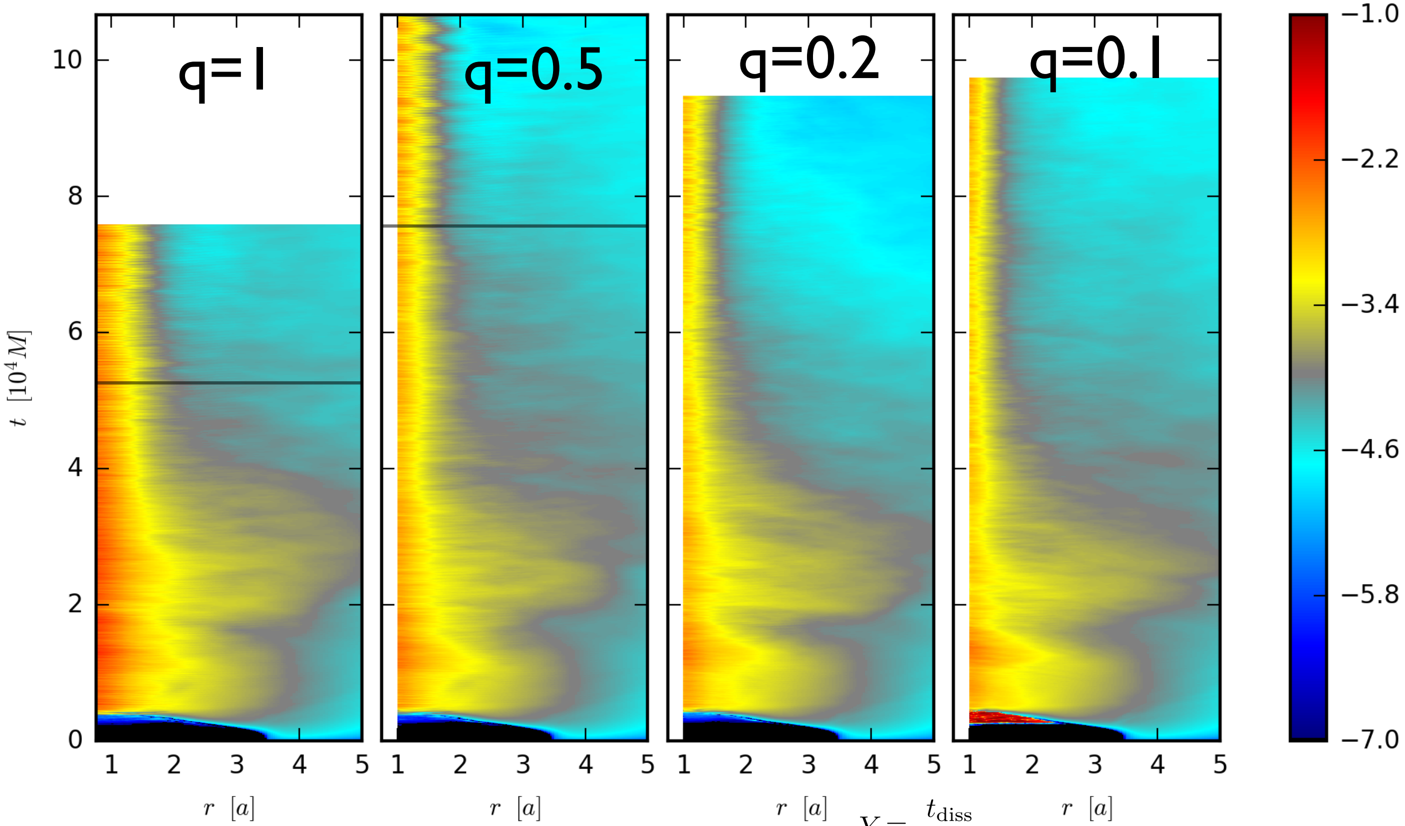
- **Lump is well-described by relatively stronger m=1 azimuthal mode amplitude.**
- **A quantitative threshold is found for the m=1 relative amplitude above which the lump continues to at least persist or grow.**
- **Threshold value is consistent across different mass ratios and initial disk configurations.**
- **Provides a quantifiable means of recognizing the lump's genesis and strength.**

Do viscous hydro simulations find similar mode strengths?

Mass Ratio Survey

Magnetic Stress per Mass

Noble, Krolik, Campanelli, Zlochower, Mundim, Nakano, Zilhao (2021)
https://arxiv.org/abs/2103.12100



- Lump formation observed to occur after specific magnetic stress asymptotes to certain value;
- Trend observed across all runs, even those in which magnetic flux was injected to dissipate the lump;
- Competition between:
  - Rate of dissipation of field from binary's gravitational torque expelled stream into lump;
  - Rate of magnetic field advected into the lump region;
- Lump forms when: $Y < 1$.

1. Replenished material torqued outward from accretion stream;
2. Returning material leads to weaker shear stress:
   1. It is corotating with material there so differential rotational velocity diminishes, weakening hydro viscosity or MRI;
   2. MHD: magnetic field is dissipated there too, possibly resulting in even more significant lump formation.

$$W^r{}_\phi = \frac{\{M^r{}_\phi\}}{\{\rho\}}$$

$$W^r{}_\phi \simeq r\Omega_K(r)\langle u^r\rangle_\rho$$

$$\Delta t_{\rm adv} = \frac{\Delta r_{\rm lump}}{\langle u^r\rangle_\rho} = \left.\frac{\Delta r_{\rm lump}\, r\, \Omega_K(r)}{W^r{}_\phi}\right|_{r=r_{\rm lump}}$$

$$\Omega_{\rm diss} = 2\left(\Omega_{\rm bin} - \Omega_K(r_{\rm lump})\right) \simeq \tfrac{3}{2}\Omega_{\rm bin}$$

$$t_{\rm diss} = \frac{2\pi}{\Omega_{\rm diss}} \simeq \frac{2}{3} t_{\rm bin}$$

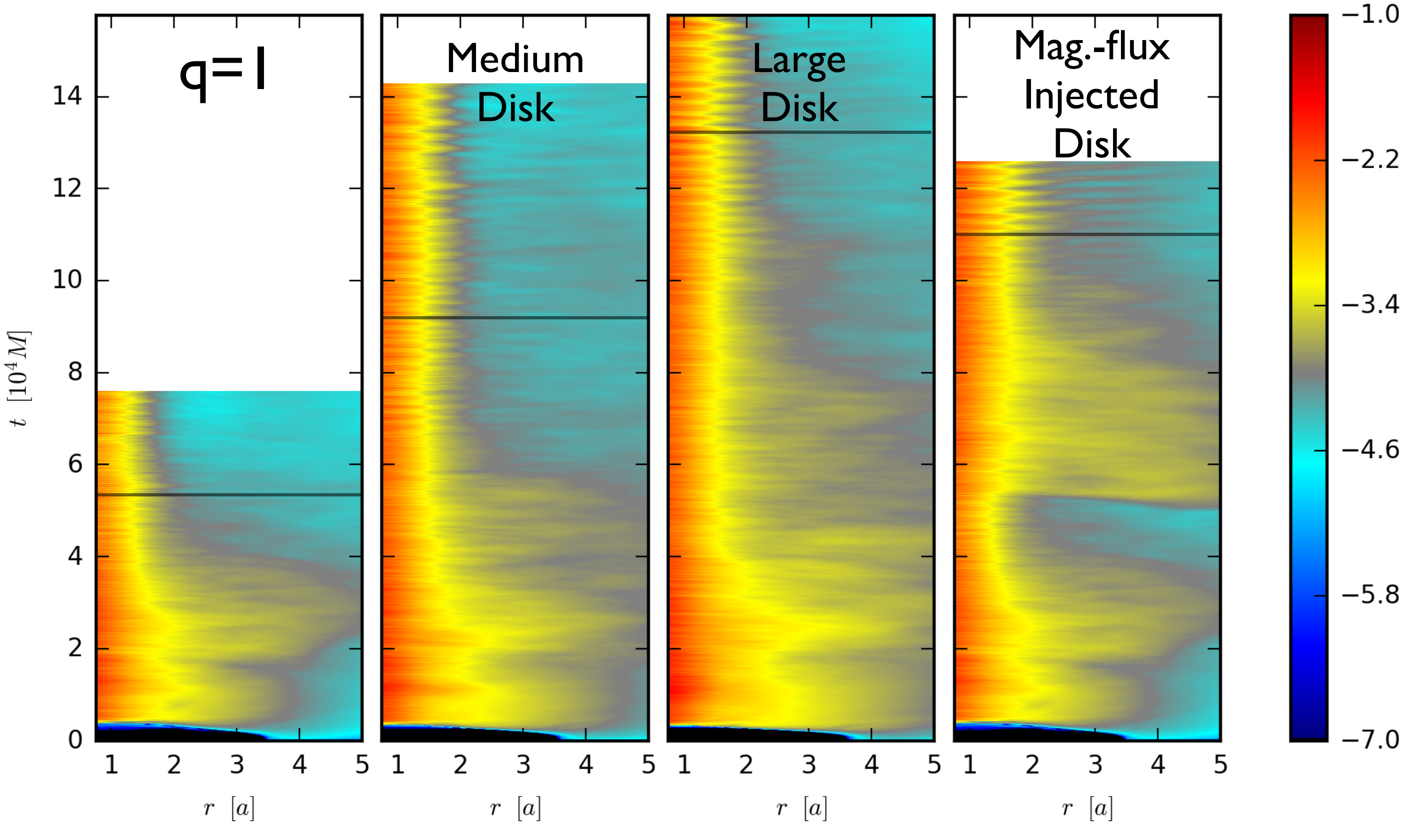
$$Y \equiv \frac{t_{\rm diss}}{\Delta t_{\rm adv}}$$

$$\simeq 0.13\left(\frac{\Delta r_{\rm lump}}{0.1a}\right)^{-1}\left(\frac{r_{\rm lump}}{2.5a}\right)^{-\frac{1}{2}} \times \left(\frac{a}{20{\rm M}}\right)\left(\frac{W^r{}_\phi}{10^{-4}}\right).$$

Mag. Flux Survey

Magnetic Stress per Mass

Noble, Krolik, Campanelli, Zlochower, Mundim, Nakano, Zilhao (2021)
https://arxiv.org/abs/2103.12100



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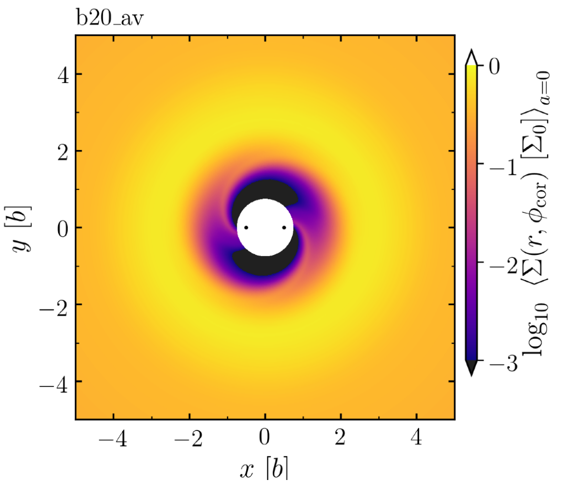
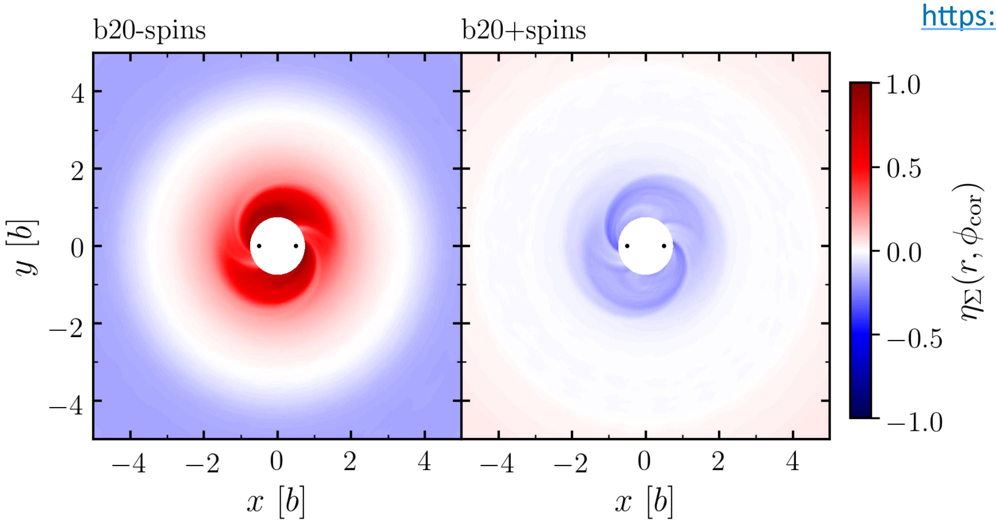
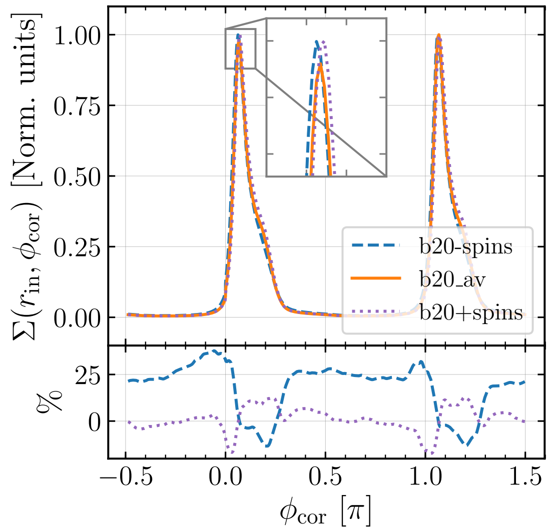
Accretion onto Spinning BBHs

Circumbinary Disk Region

Lopez Armengol, Combi, Campanelli, Noble, Krolik, Bowen, Avara, Mewes, Nakano (2021)
https://arxiv.org/abs/2102.00243







	Accretion Rate	**Luminosity**
Parallel Spins	86%	88%
Non-spinning	100%	100%
Anti-parallel Spins	145%	129%

- **Anti-parallel spins enhance:**
  - **Accretion rate;**
  - **Luminosity;**
  - **Surface density;**
- **Enhancement due to deepening of effective potential as spins grow negative:**

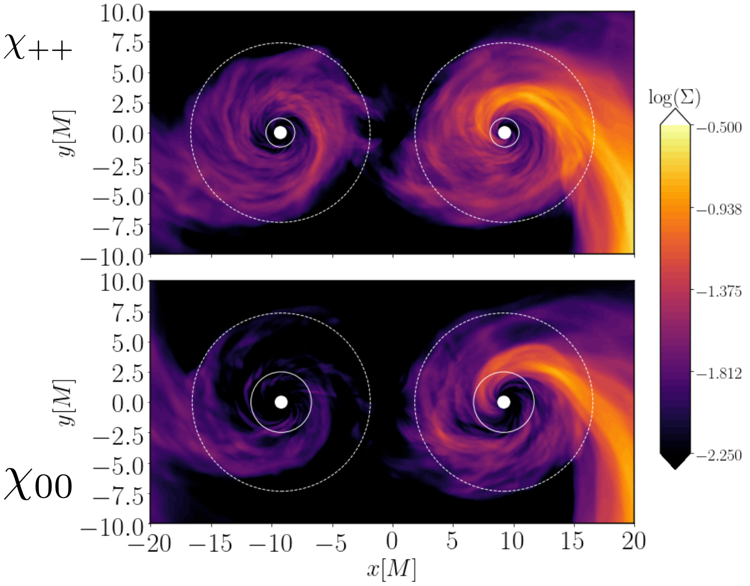
$$\Phi_{\rm Eff} = -\frac{M}{r} - \frac{1}{16}\frac{b^2 M}{r^3} + \frac{J^2}{2r^2} + \frac{MJ}{3r^3}\left(2a + \frac{L}{4}\right)$$

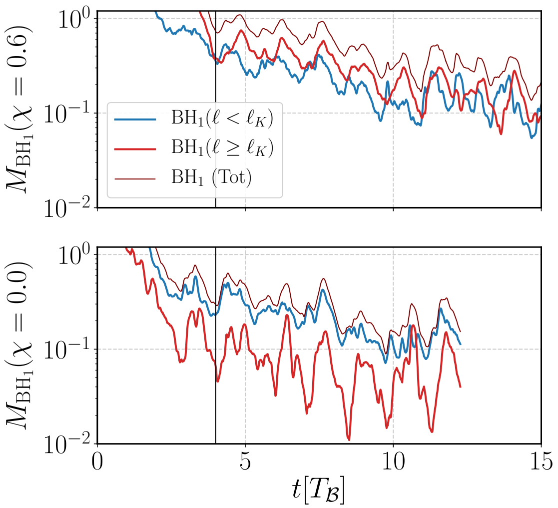
- **Frame dragging acts to lag (lead) accretion streams for anti-parallel (parallel) spins;**

Accretion onto Spinning BBHs

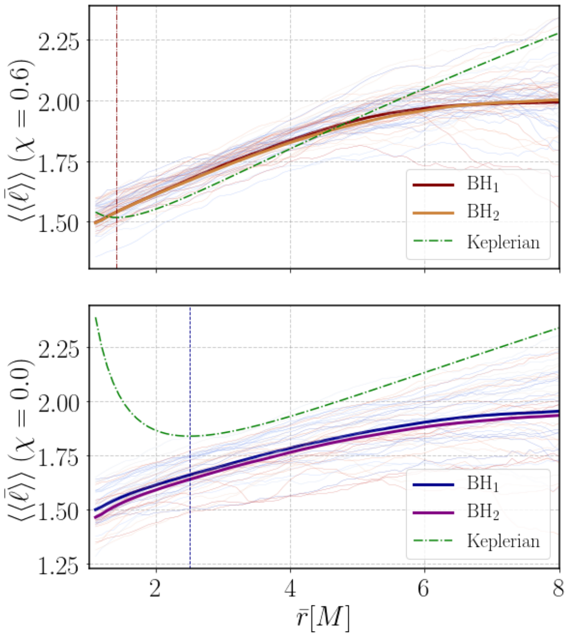
Circumbinary +
Mini- Disk Regions

Combi, Lopez Armengol, Campanelli, Noble, Avara, Krolik, and Bowen, arXiv, arXiv:2109.01307, (2021).





$\chi = +0.6$

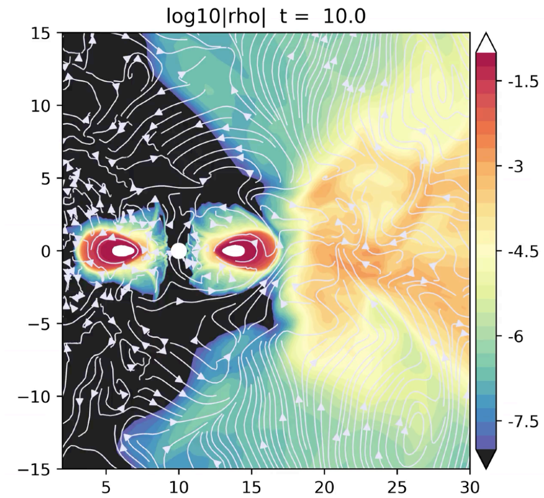


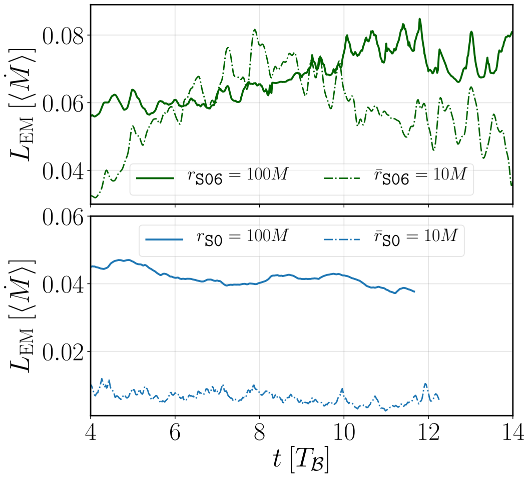
- **Starting from same initial accretion flow conditions;**
- **Because of smaller ISCO, the volume of stability in mini-disk region increases for larger (parallel) spin;**
  - **—>More persistent mini-disks;**
  - **—> Longer inflow time scales;**
  - **—> Comparable accretion rates;**
  - **—> Smaller fluctuations at 2x beat freq.**

- **Faster spins change the potential so that the accretion streams are no longer sub-Keplerian, allowing for gas to accumulate;**
- **Mini-disks are 2x as massive with spins than without.**

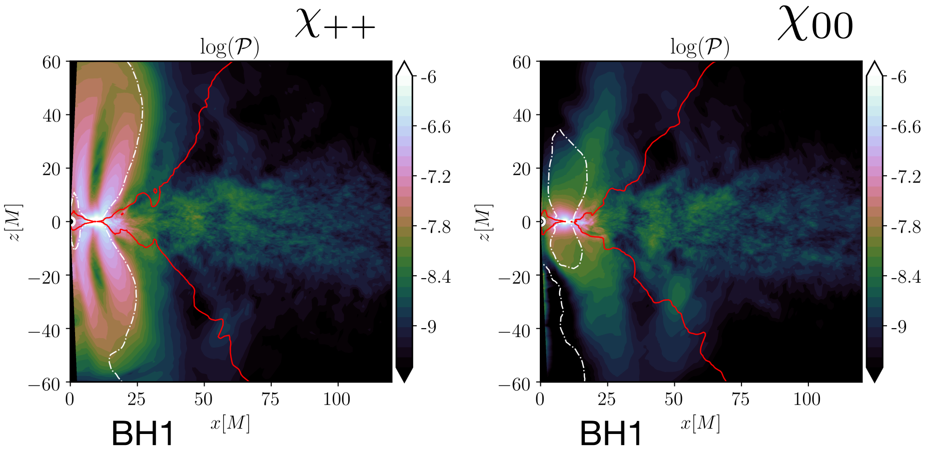
Accretion onto Spinning BBHs

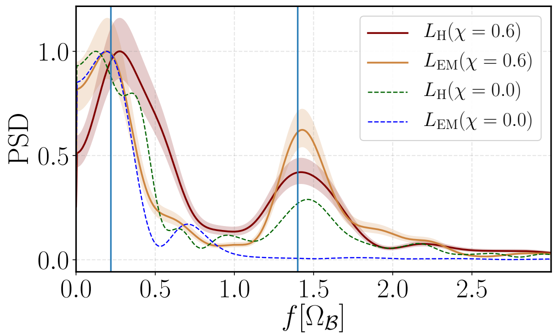
Circumbinary +
Mini- Disk Regions

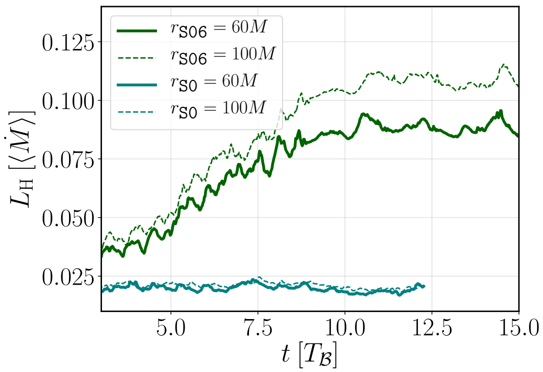




Poynting Scalar







- **Hydro and EM fluxes are both larger with spins;**
  - **Possible signature of helical field orientation in emission's polarization?!**
- **Poynting luminosity modulated at 2x beat freq. w/ lump;**

	χ_{00}	χ_{++}
$\eta_{\rm EM}$	0.5% —> 4%	5%
$\eta_{\rm H}$	2.5%	10%

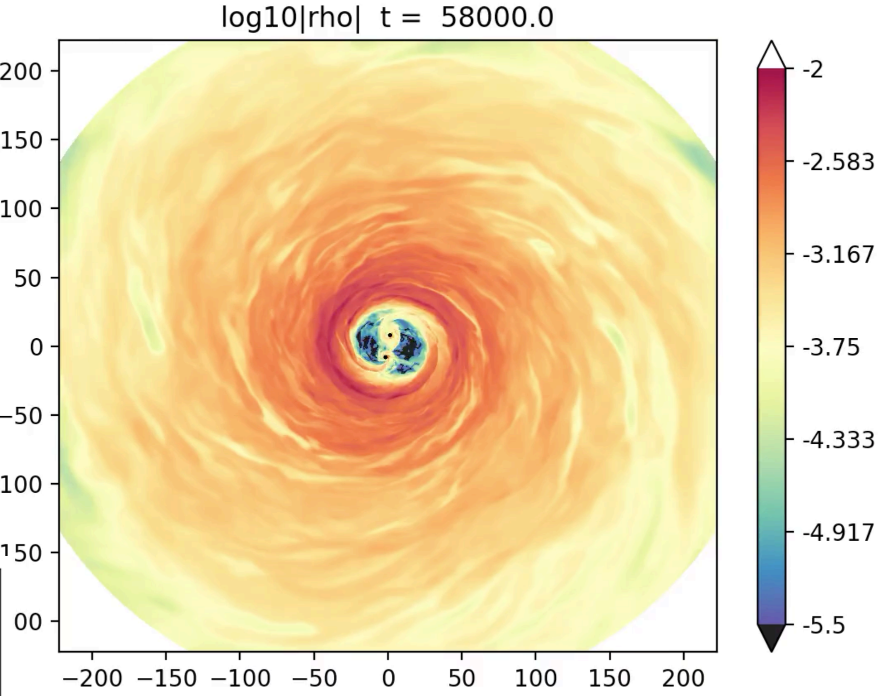
Combi, Lopez Armengol, Campanelli, Noble, Avara, Krolik, and Bowen, arXiv, arXiv:2109.01307, (2021).

PatchworkMHD : Mini-disks + Circumbinary Disk

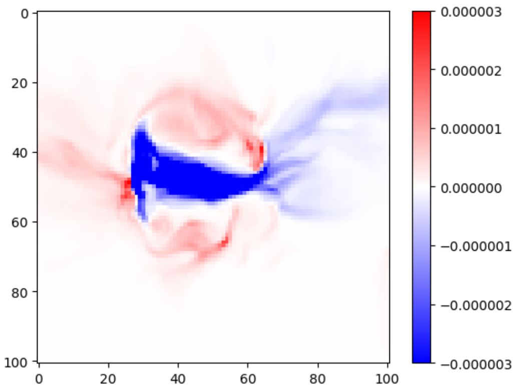
Avara et. al, (in prep)

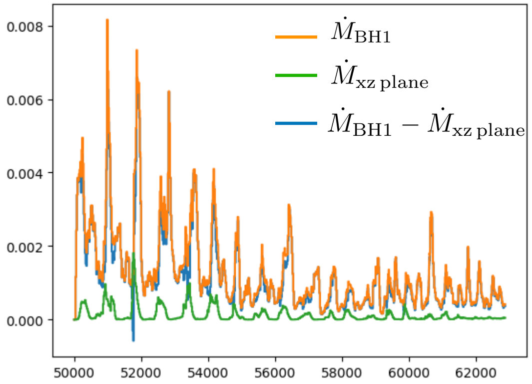
Avara @binary_c22: Thursday 2PM

- **Key Challenges: How do we efficiently simulate 10^7-10^8 cells for 10^6-10^7 steps? PatchworkMHD!**
- **Starting from CBD data of Noble++2012, let mini-disks fill in.**
- **34 binary orbits;**
- **Cartesian Patch: Uniform in x,y but graded in z.**
- **Spherical Patch: Same grid as Noble++2012, no interpolation.**
- **Cartesian patch avoids the focusing of cells near the origin and axis, increasing the size of time steps we can take, plus covers the missing volume.**
- **???**



Mass flux through xz plane toward BH1





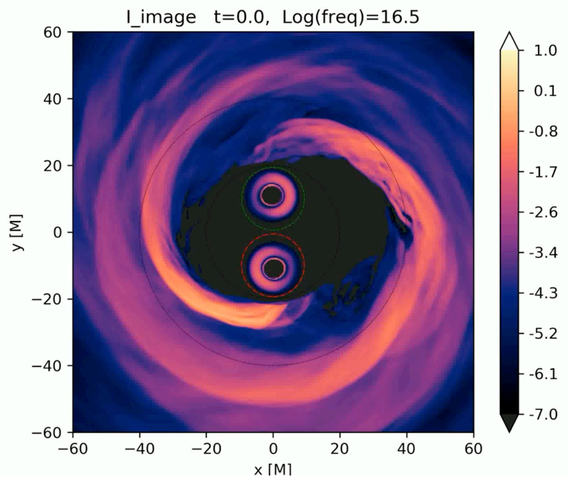
- **No cutout!**
  - **PWMHD allows us to measure the mass exchange between mini-disks for the first time!**
  - **Mass flux between mini-disks is a minority contribution, though energy dissipated by mass transfer may be more significant.**

Spectra from Accretion onto Spinning BBHs

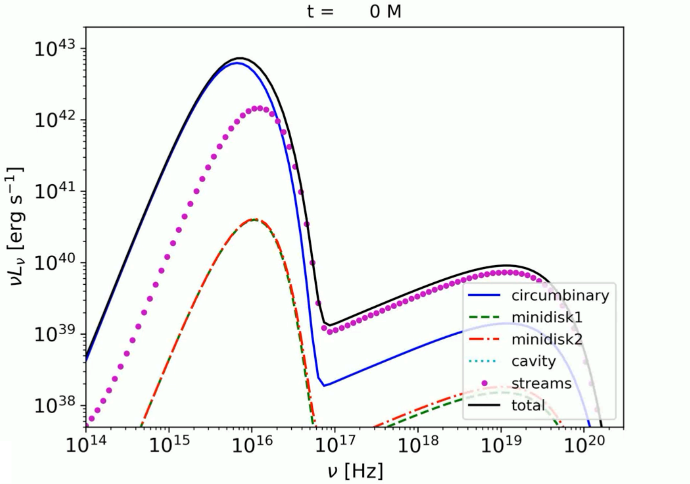
Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, arXiv:2112.09773, (2021).

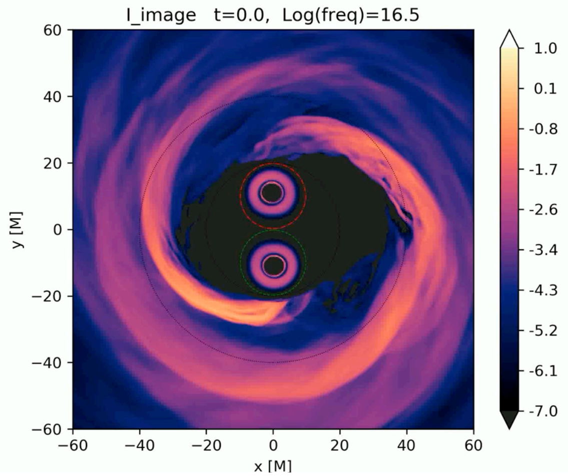
- **Following** d'Ascoli++2018
- **Using sim data from:**
- **BH spins (even at these modest values):**
  - **Brighter mini-disks;**
  - **More variable mini-disks;**
  - **More substantial mini-disks broaden the circumbinary disk's thermal peak;**

- **The spinning case provides new signatures to search for:**
  - **Broader thermal peak in optical-UV;**
  - **Variability in the UV on the binary's orbital timescale;**
  - **Stronger variability in X-rays;**

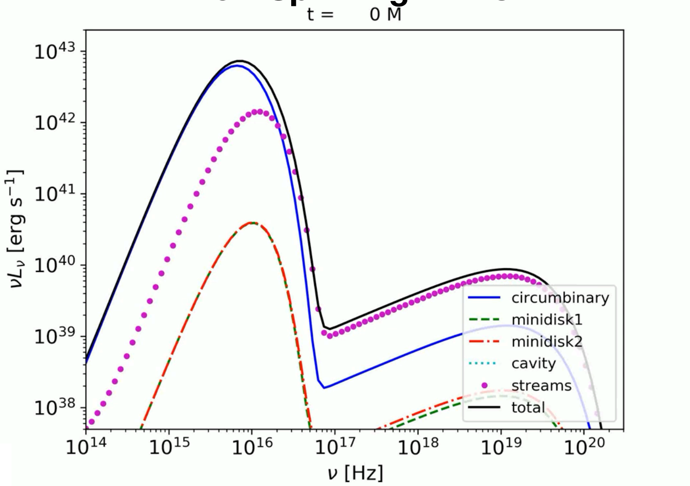


Spinning BBHs: a=0.6M, up-up





Non-Spinning BBHs



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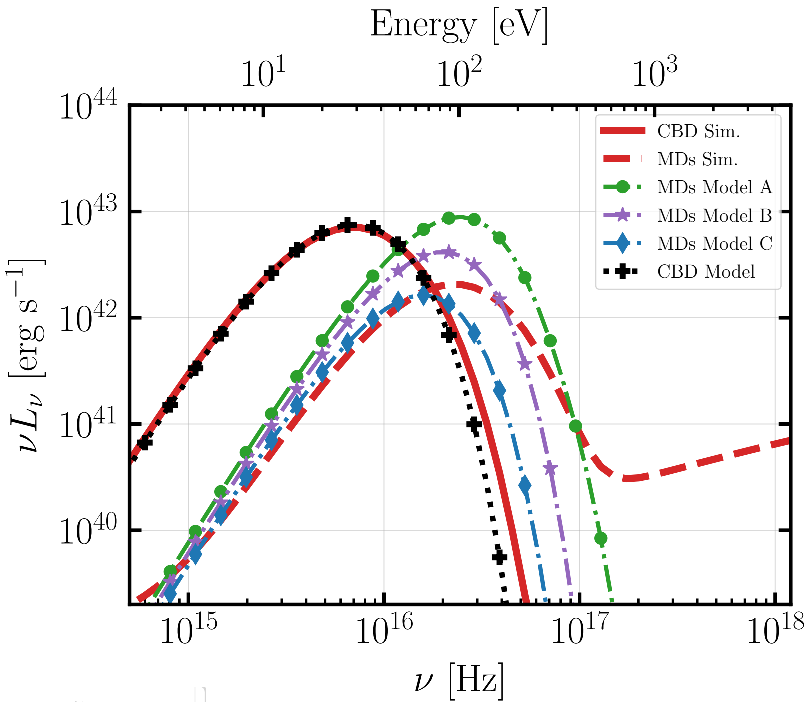
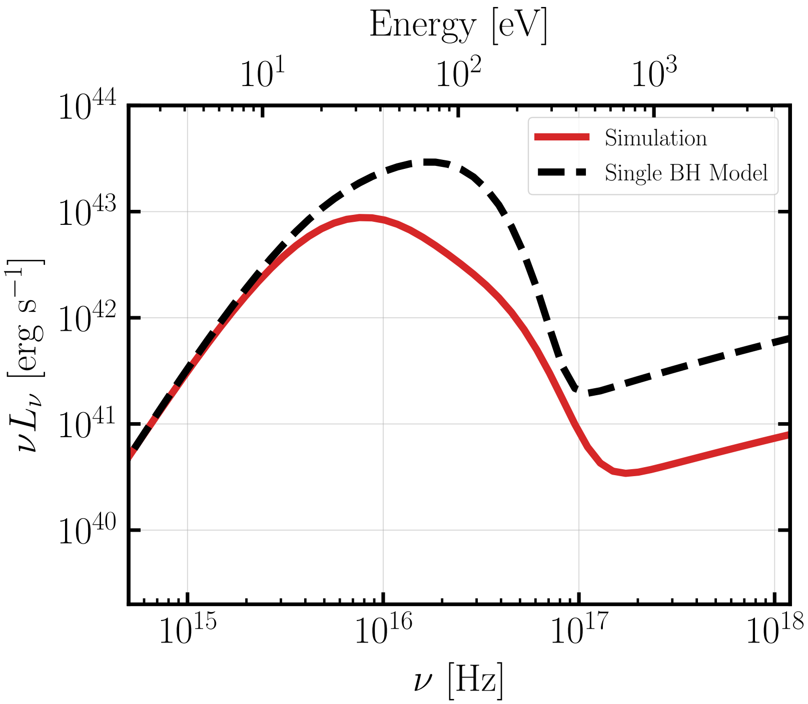




Spinning BBHs

━━ CBD Sim.	CBD portion of simulation.
╍╍ MDs Sim.	Mini-disk portion of simulation.
-●- MDs Model A	2 NT, $\dot{m}_1 = \dot{m}_2 = 0.125\dot{M}_{\rm Edd}$
-★- MDs Model B	2 NT, $\dot{m}_1 = 6\times10^{-2}\dot{M}_{\rm Edd},\ \dot{m}_2 = 6.8\times10^{-2}\dot{M}_{\rm Edd}$
-◆- MDs Model C	2 NT, $\dot{m}_1 = 2.3\times10^{-2}\dot{M}_{\rm Edd},\ \dot{m}_2 = 2.7\times10^{-2}\dot{M}_{\rm Edd}$
·✚· CBD Model	1 NT, spin=0.6, 1e6 Msun, 2a < r < 7.5a

NT = Novikov-Thorne (1972) “thin disk”

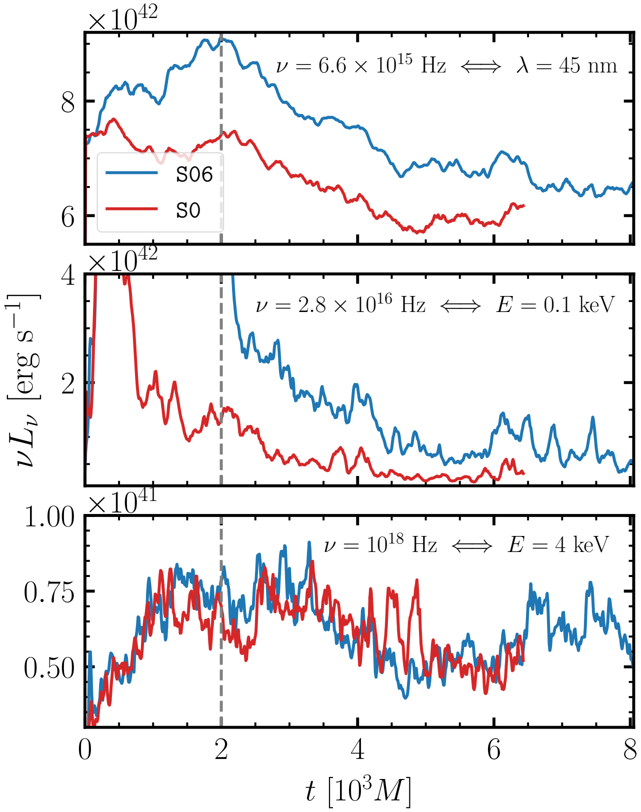
╍╍ Single BH Model

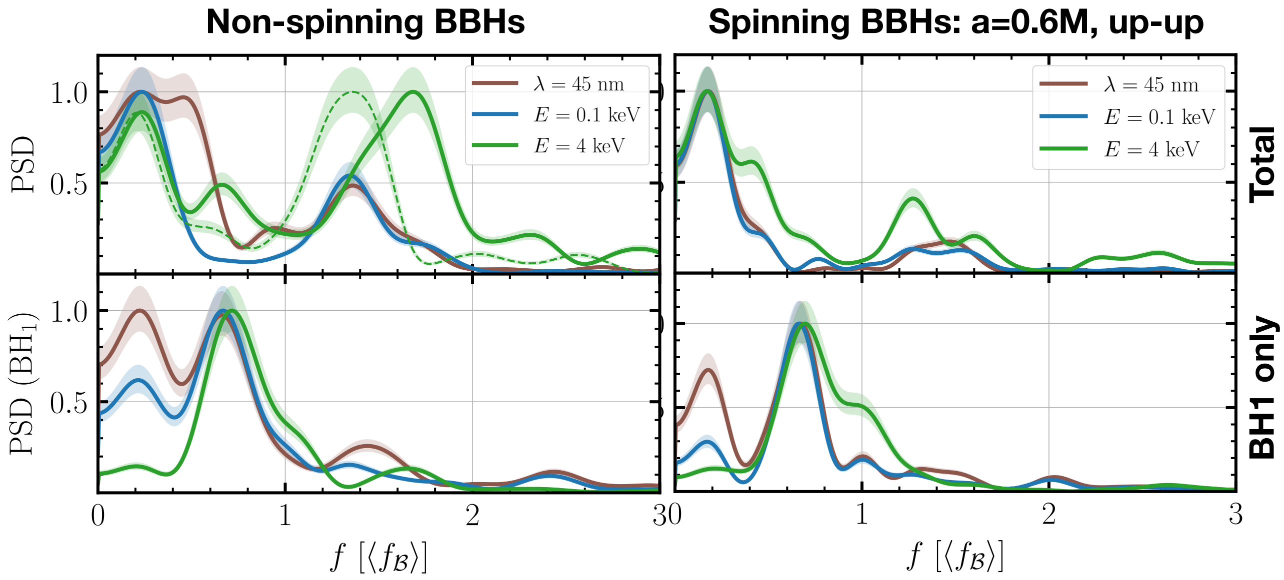
Schnittman, Krolik, and Noble, ApJ, 819, 48, (2016).

- GRMHD simulation-informed model for all spins for thin disks, same total mass and Mdot;
- Truncated disk emission, weaker mini-disk accretion rate due to accelerated accretion via shocks.

Light Curves from Accretion onto Spinning BBHs

Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, arXiv:2112.09773, (2021).





Non-spinning BBHs

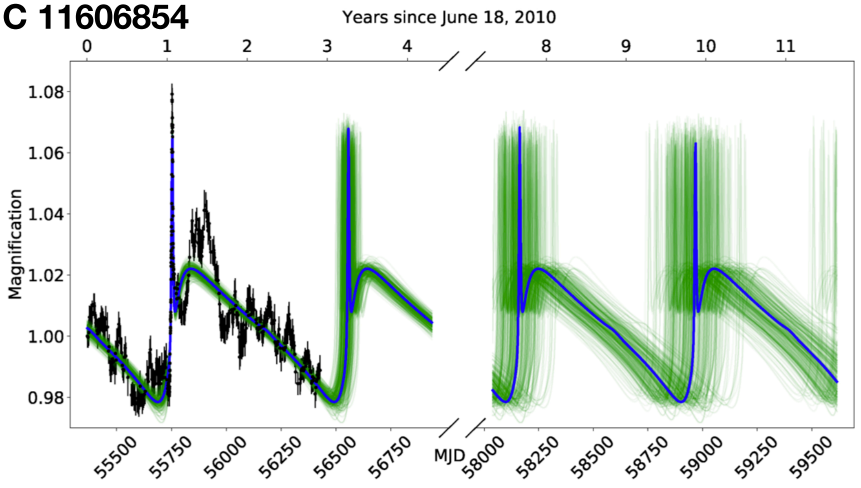
Spinning BBHs: a=0.6M, up-up

- Prograde spinning BBHs:
  - Longer-lived mini-disks lead to relatively steadier x-ray emission and weaker signals at 2x beat freq.;
  - Individual mini-disks still suffer beat modulation;
  - Total variability in all frequencies modulates by lump's orbital frequency, radial epicyclic oscillation;
- Predict spinning BBHs will be predominantly varying at lower-frequencies than gravitational waves;

“Spikey”

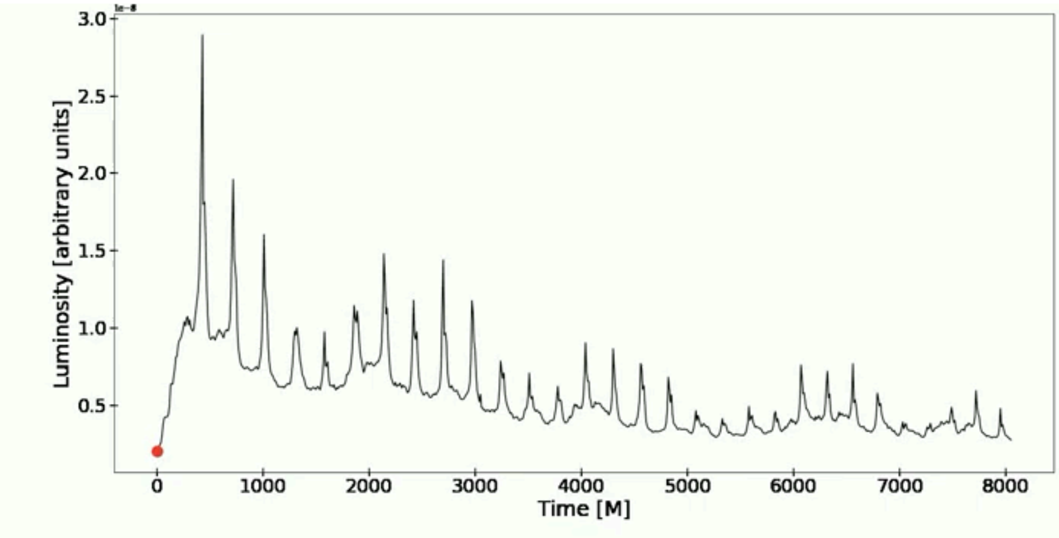
Hu, D'Orazio, Haiman, Smith, Snios, Charisi, and Di Stefano, MNRAS, 495, 4061, (2020).

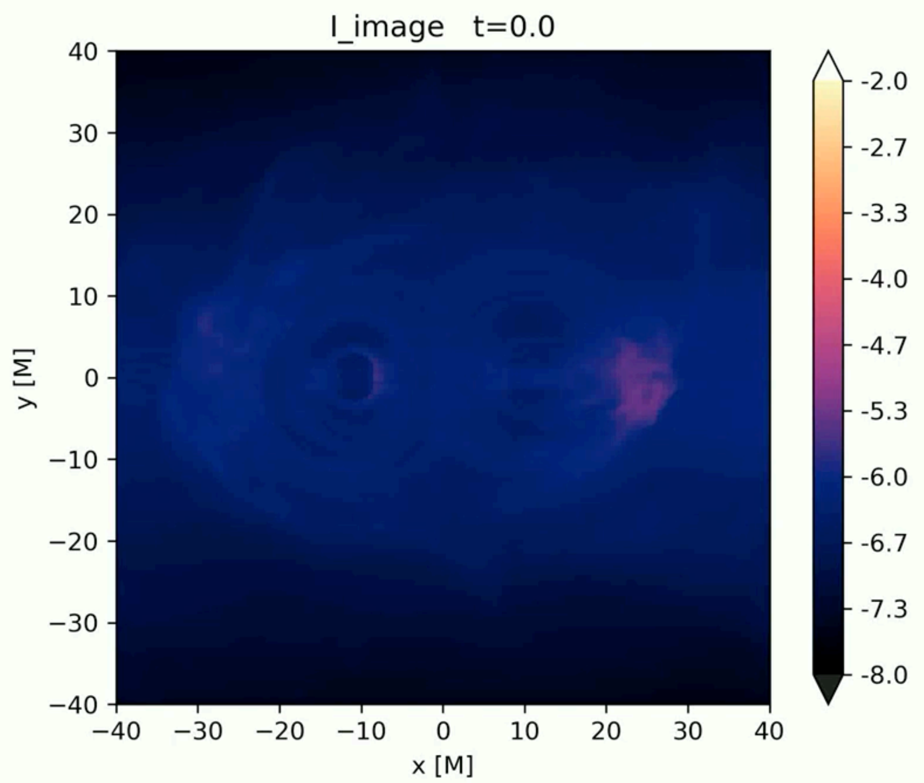
KIC 11606854

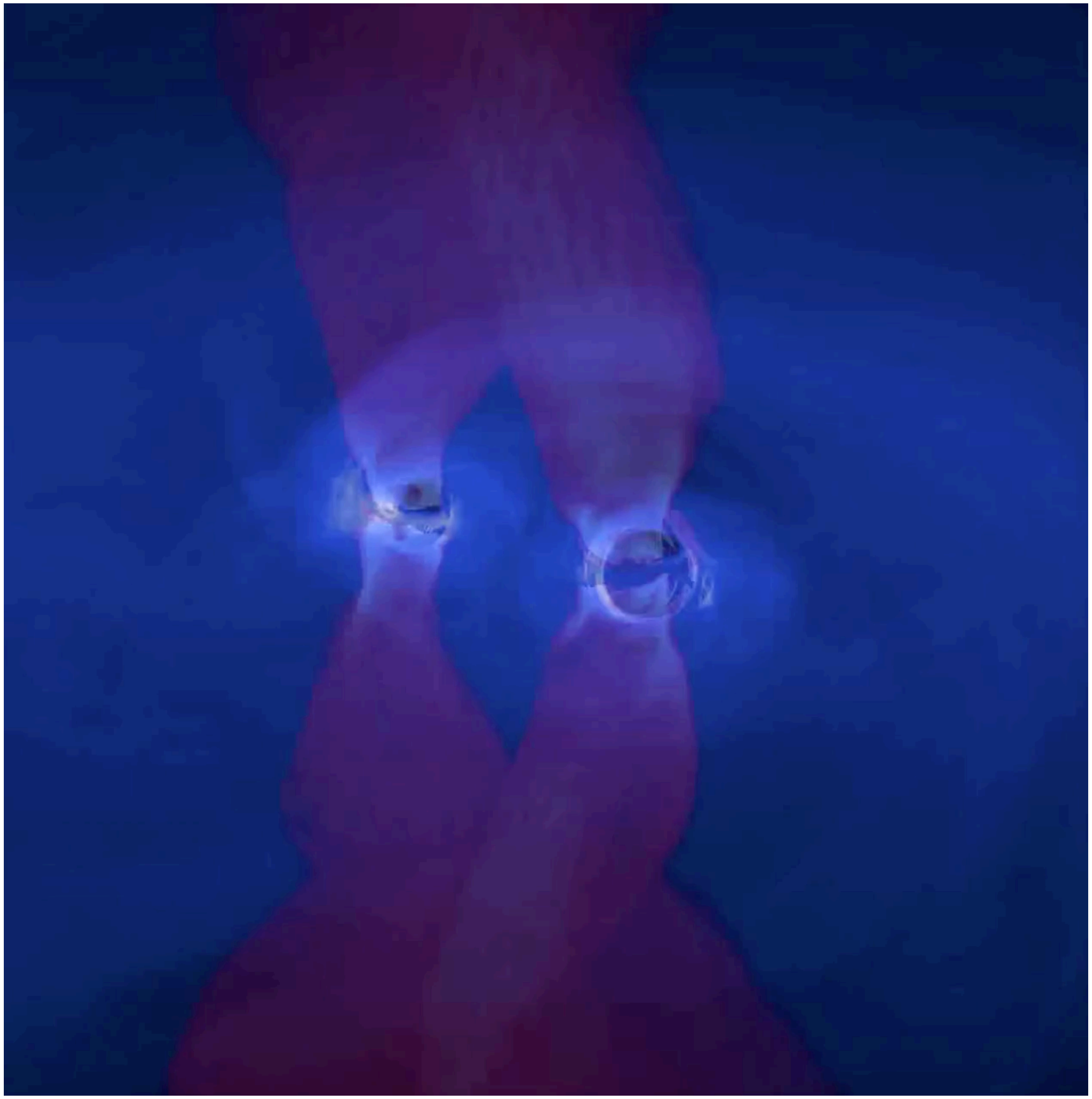


Light Curves from Accretion onto Spinning BBHs

Gutierrez, Combi, Lopez Armengol++(in prep)







Simultaneous Images of Synchrotron Jets and Optically Thin X-ray Emission

Gutierrez, Combi, Lopez Armengol++(in prep)

Radio - Synchrotron Emission

X-ray - Corona Emission

- **Dual jet phenomena;**
- **Synchrotron calculated using same emissivities used in simulations of images for the Event Horizon Telescope project.**

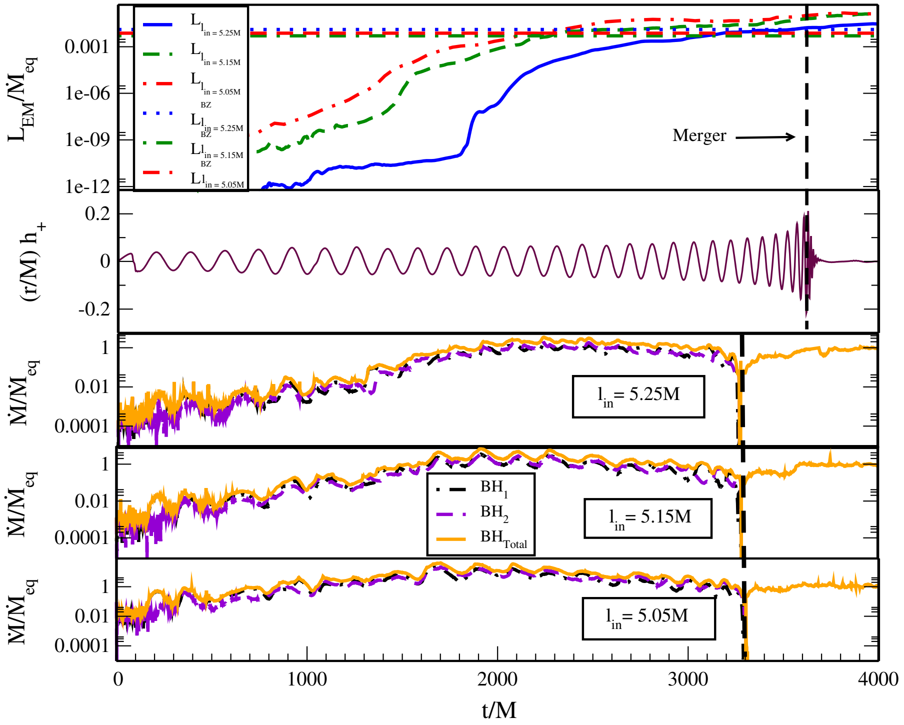
  Leung, Gammie, and Noble, ApJ, 737, 21, (2011).
- **Predict correlated X-ray and jet variability, under certain situations, TBD.**

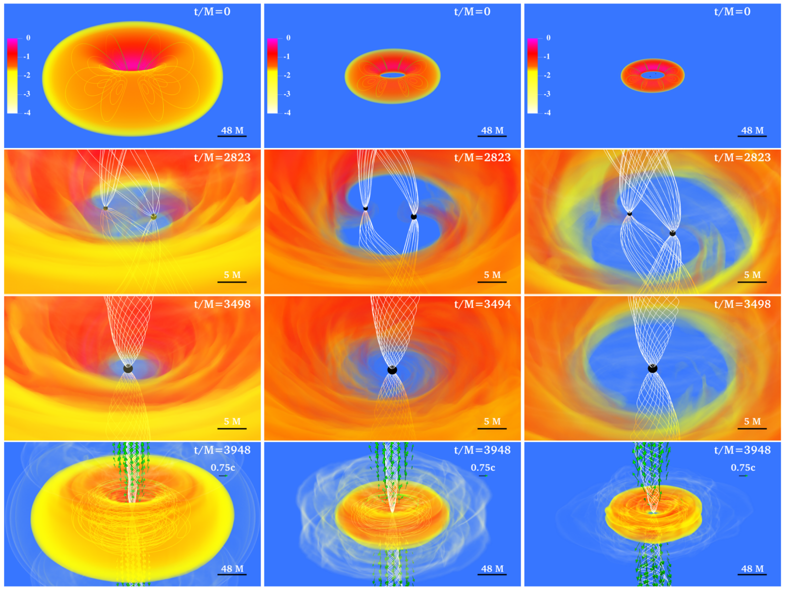
Numerical Relativity + MHD Evolutions

Accretion with Magnetized Tori

Farris, B. D., Gold, R., Paschalidis, V., Etienne, Z. B., Shapiro, S. L., PhRvL, 109, 221102, (2012).
Gold, R., Paschalidis, V., Etienne, Z. B., Shapiro, S. L., Pfeiffer, H. P., PhRvD, 89, 064060, (2014).
Gold, R., Paschalidis, V., Ruiz, M., Shapiro, S. L., Etienne, Z. B., Pfeiffer, H. P., PhRvD, 90, 104030, (2014).

Khan, A., Paschalidis, V., Ruiz, M., Shapiro, S. L., PhRvD, 97, 044036, (2018).





- Non-Spinning BHs;
- Survey over disk size and ang. mom. distribution;
- ☆Accretion rate is universal over these timescales;
- ☆All lead to similar post-merger Poynting luminosities

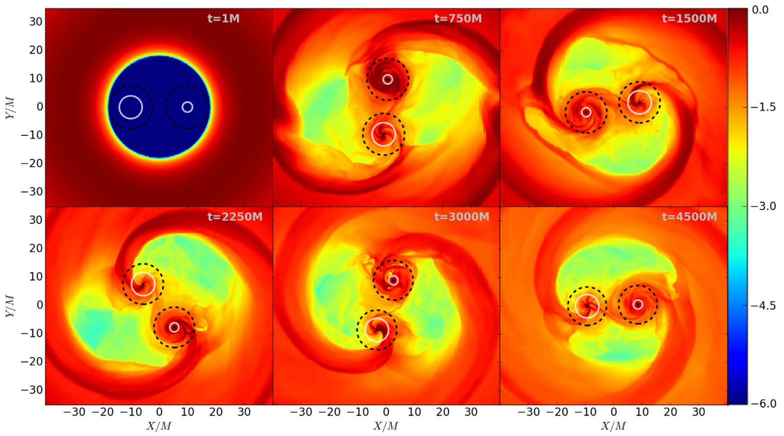
The other work shows little dependence on mass-ratio, insignificant lumps, and small differences on cooling rate, likely because these short-duration simulations are only sensitive to the amount of gas accreted in transient phase of evolution before disk equilibrates.

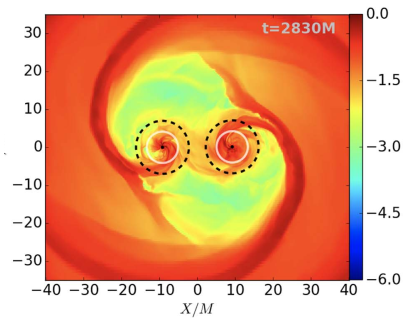
Numerical Relativity + MHD Evolutions

Accretion with Magnetized Tori

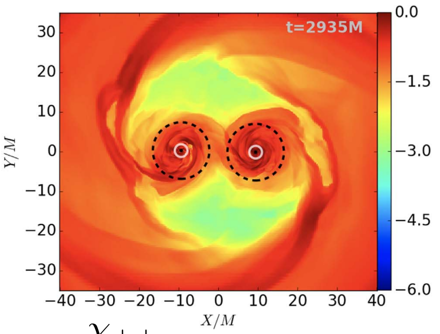
Paschalidis, V., Bright, J., Ruiz, M., Gold, R., ApJL, 910, L26, (2021).

χ_{+-}

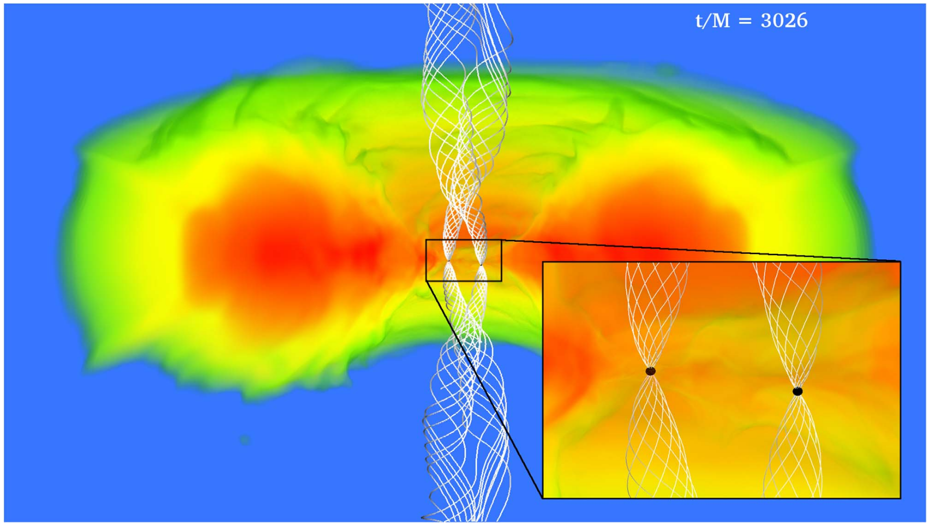




χ_{--}



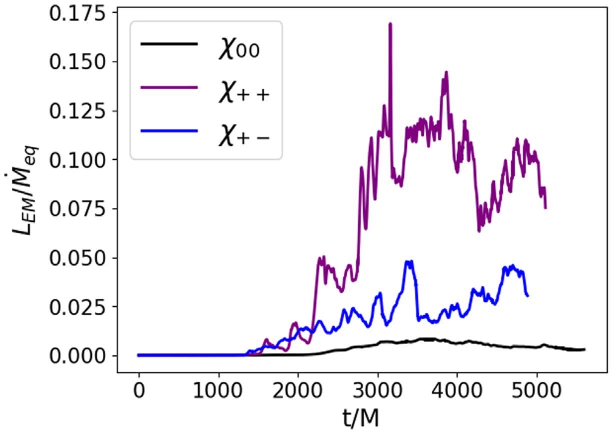
χ_{++}



- Spinning BHs; $\chi = \pm 0.75, 0$
- Larger r_{Hill}/r_{ISCO} lead to larger mini-disks;

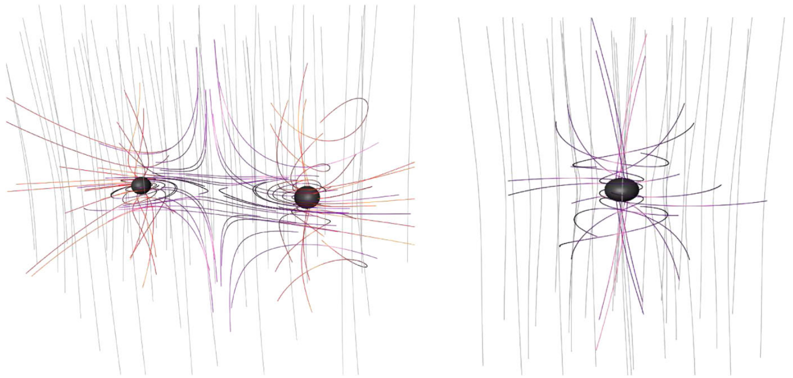
☆Spins and larger mini-disks yield larger Poynting luminosities;

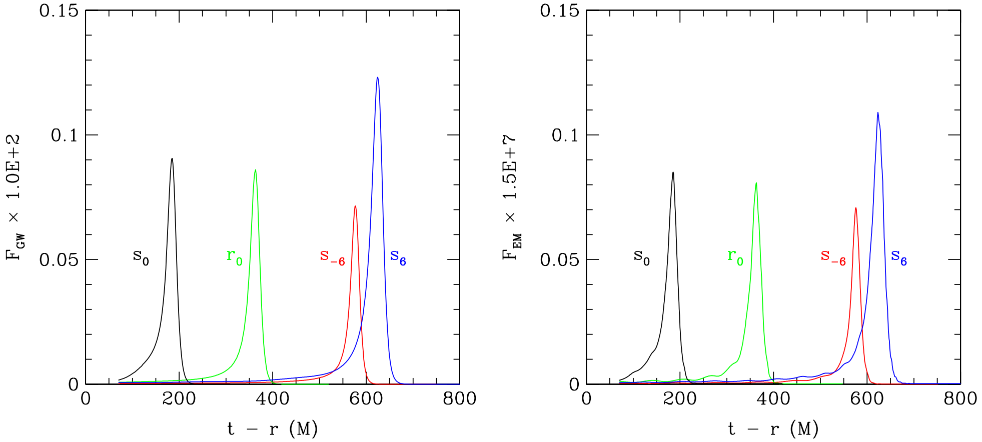
☆Mini-disks evaporate prior to merger;



Numerical Relativity + MHD Evolutions

Accretion in Vacuum + Electromagnetic Field





Mösta, Palenzuela, Rezzolla, Lehner, Yoshida, and Pollney, PhRvD, 81, 064017, (2010).

$$E^{\rm rad}_{\rm EM}/M \simeq 10^{-15}(M/10^8 M_\odot)^2(B/10^4 {\rm G})^2$$

- Radiative efficiences are only significant for large magnetic fields;
- Wavelength of the emission is same as gravitational wave, so very long;
  - Not clear how EM flux is reprocessed to be observable, or maybe use LOFAR?

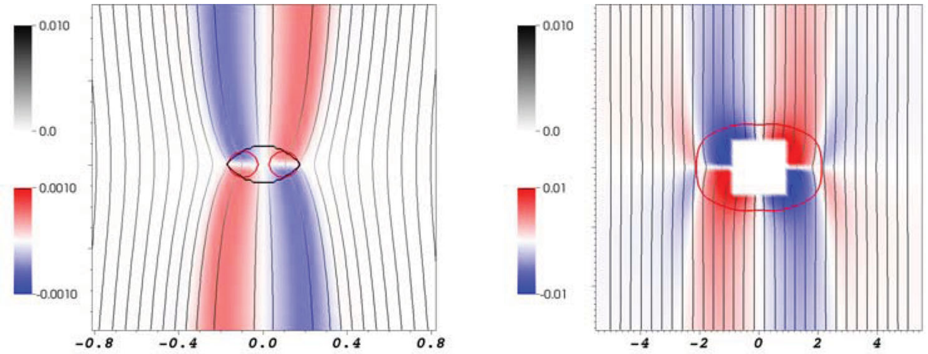
Palenzuela, Lehner, and Yoshida, PhRvD, 81, 084007, (2010).
Mösta, Palenzuela, Rezzolla, Lehner, Yoshida, and Pollney, PhRvD, 81, 064017, (2010).

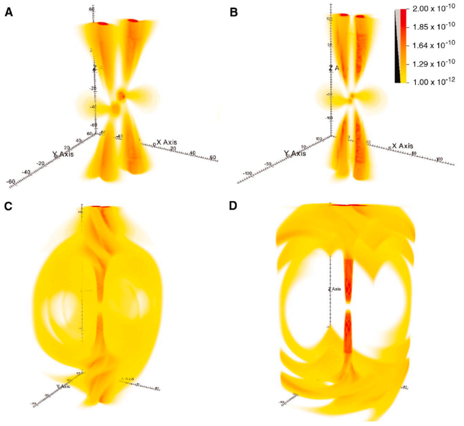
Numerical Relativity + EM Evolutions

Accretion in Vacuum + Electromagnetic Field

Ruiz, Palenzuela, Galeazzi, and Bona, MNRAS, 423, 1300, (2012).

- Ergoregion —> Jets or rather Blandford-Znajek process



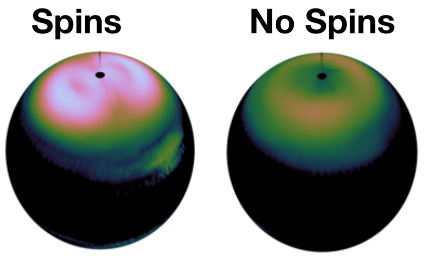


$$\frac{E^{\rm em}_{\rm rad}}{Mc^2} = 10^{-14}\left(\frac{M}{10^8\ M_\odot}\right)^2\left(\frac{B}{10^4\ {\rm G}}\right)^2$$

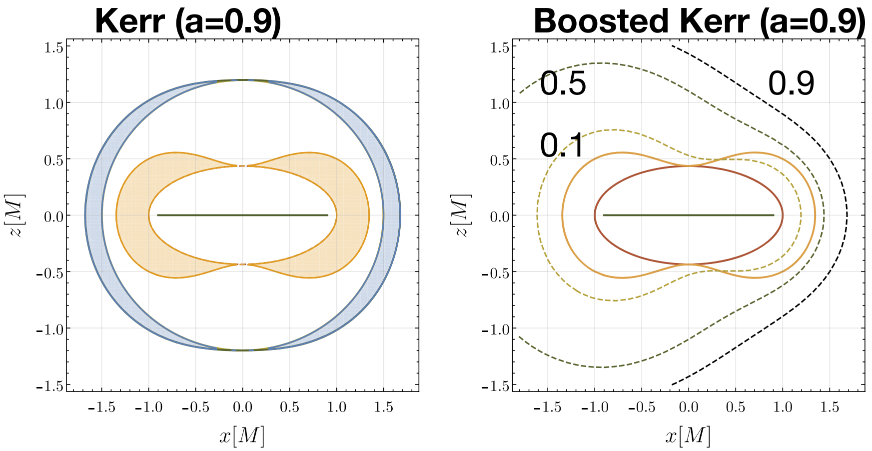
Palenzuela, Lehner, and Liebling, Sci, 329, 927, (2010).

Combi, Lopez Armengol, Campanelli, Noble, Avara, Krolik, and Bowen, arXiv:2109.01307, (2021).

From Boosted Kerr GRMHD+mini-disk simulations:



Poynting flux



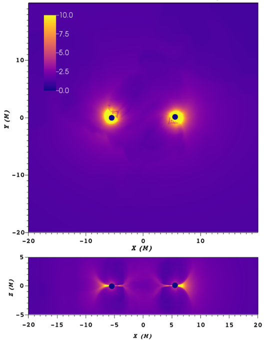
Combi, Armengol, Campanelli, Ireland, Noble, Nakano, and Bowen, PhRvD, 104, 044041, (2021).

Numerical Relativity + MHD Evolutions

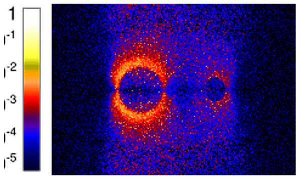
Accretion in Uniform Plasma (what if decoupling is efficient?)

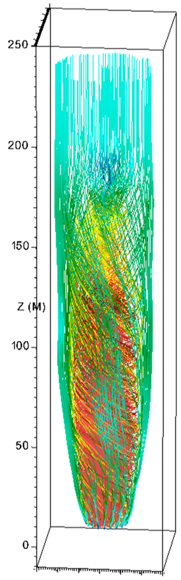
Prior Art:
Palenzuela, Garrett, Lehner, and Liebling, PhRvD, 82, 044045, (2010)
Moesta, Alic, Rezzolla, Zanotti, and Palenzuela, ApJL, 749, L32, (2012).

Plasma Density



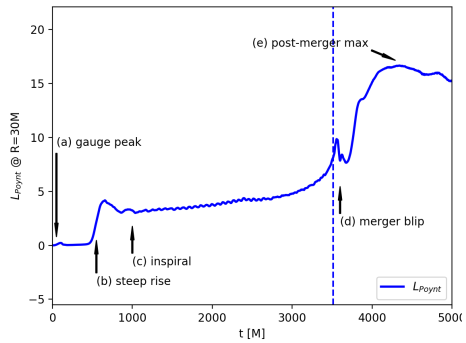
Synchrotron Image



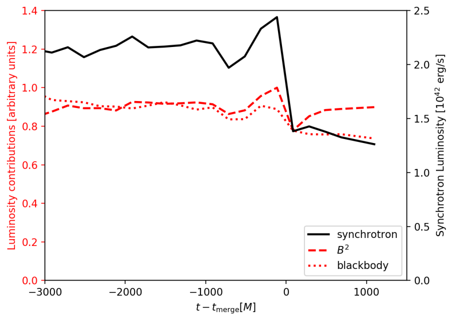


B-field Lines

Poynting Flux



Synchrotron Flux



Kelly, Baker, Etienne, Giacomazzo, Schnittman, PRD 96, 123003 (2017)

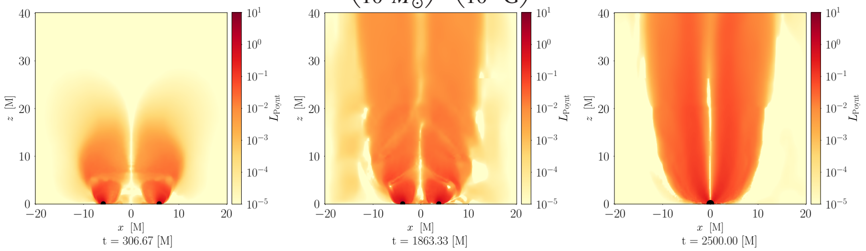
- Non-Spinning post-merger single BHs, Uniform B-field;
- Survey over magnetization, find floor value (0.01) above which runs become similar;
- Poynting flux grows in time, reaching maximum post-merger; Synchrotron plunges at merger;

Cattorini, Giacomazzo, Haardt, and Colpi, PhRvD, 103, 103022, (2021).

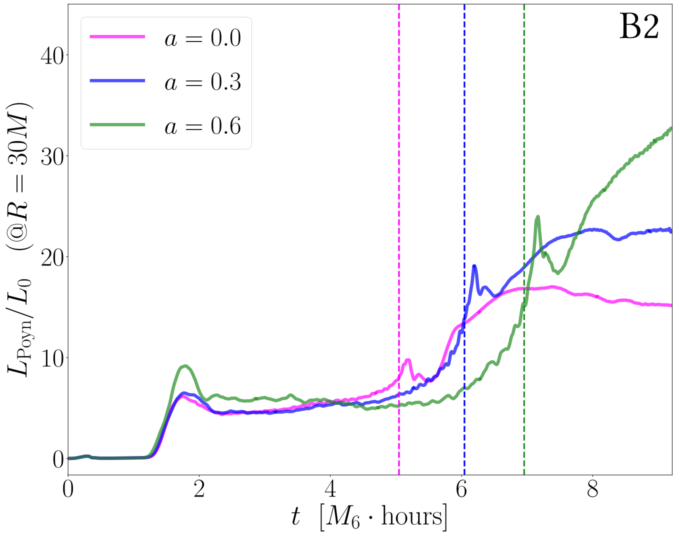
- Spinning & merging BHs, Uniform aligned B-field
- Find consistent Poynting flux levels pre-merger,
- Difference seen mostly post-merger as B-Z flux scales with a^2;

$$L_{\rm BZ} \sim 10^{43}\ {\rm erg\ s^{-1}} (a)^2 \left(\frac{M}{10^6 M_\odot}\right)^2 \left(\frac{B}{10^6\ {\rm G}}\right)^2 .$$

Poynting Flux



Poynting Flux

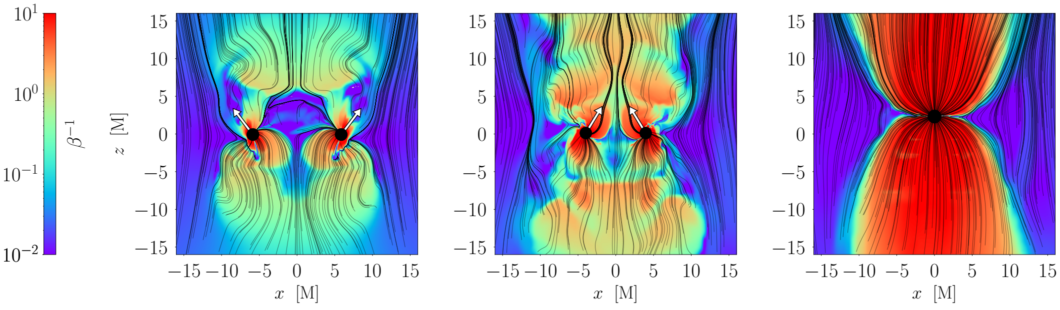


Numerical Relativity + MHD Evolutions

Accretion in Uniform Plasma (what if decoupling is efficient?)

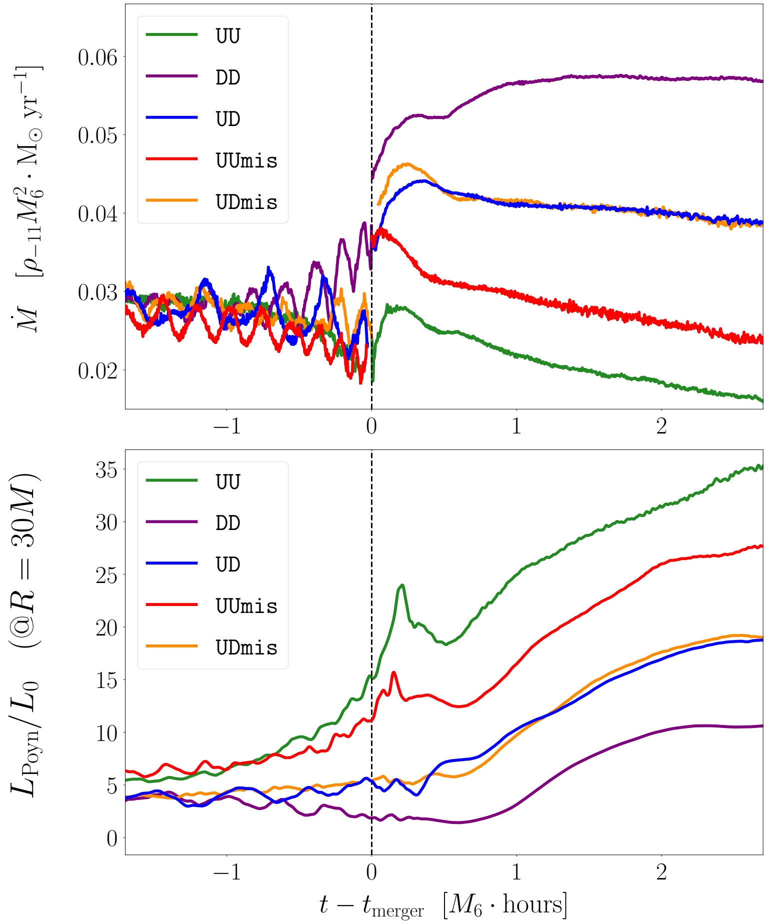
Cattorini, Maggioni, Giacomazzo, Haardt, Colpi, and Covino, arXiv, arXiv:2202.08282, (2022).

- Spinning & merging BHs, Uniform aligned B-field
- Aligned and Misaligned spins



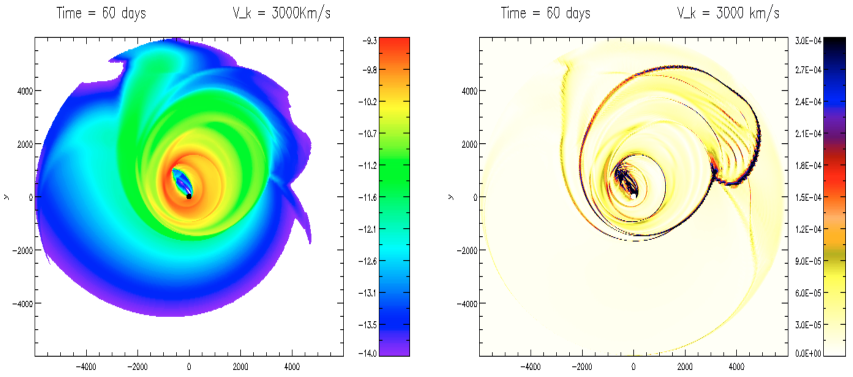
t = 304.44 [M] t = 1911.11 [M] t = 3415.56 [M]

- Retrograde spinning BHs accrete faster but produce weaker "jets";
- Misalignment can hurt the Prograde+prograde configuration (UU), but not the mixed-grade case;
- If Poynting flux is observable, the slope of the relative brightening may help estimate pre-merger spin orientation and magnitude;



Numerical Relativity + MHD Evolutions

Post-merger Aftermath: Kicks, Mass Loss, Jets



Zanotti, Rezzolla, Del Zanna, and Palenzuela, A&A, 523, A8, (2010).

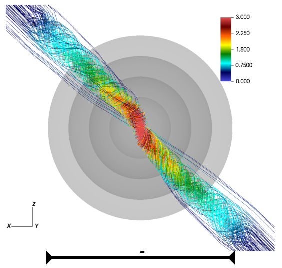
- BBH merger leads to O(100) km/s kicks on merger remnant and few-several % mass loss due to GW losses;
- Disk "adjusts" or is "kicked" by the sudden change in the gravity, often triggering eccentric shocks that dissipate change motion triggered by change in potential energy;
- Observables are often significant tens-hundreds of days post-merger for massive BBHs.
- What's going on in this topic? Are we waiting for better initial data? Is that necessary? Are there any outstanding issues, aspects here?

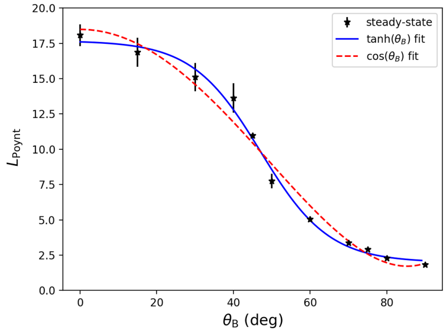
Kelly, Etienne, Golomb, Schnittman, Baker, Noble, Ryan, PRD 103, 063039 (2021)

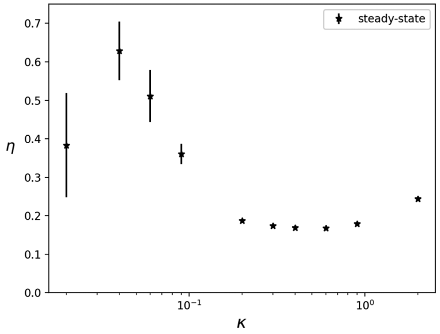
- Spinning post-merger single BHs, Uniform plasma;
- Survey over angle between B-field and spin;
- Survey over temperature;

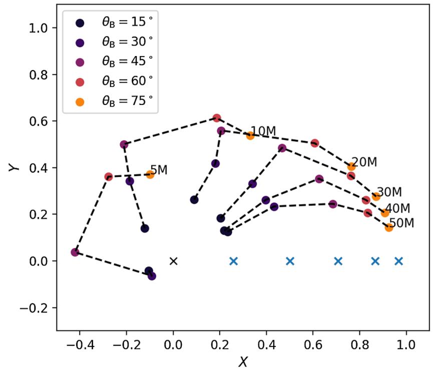
☆Jet starts aligned with spin, then aligns with B-field;

☆Poynting luminosity strongest when aligned;

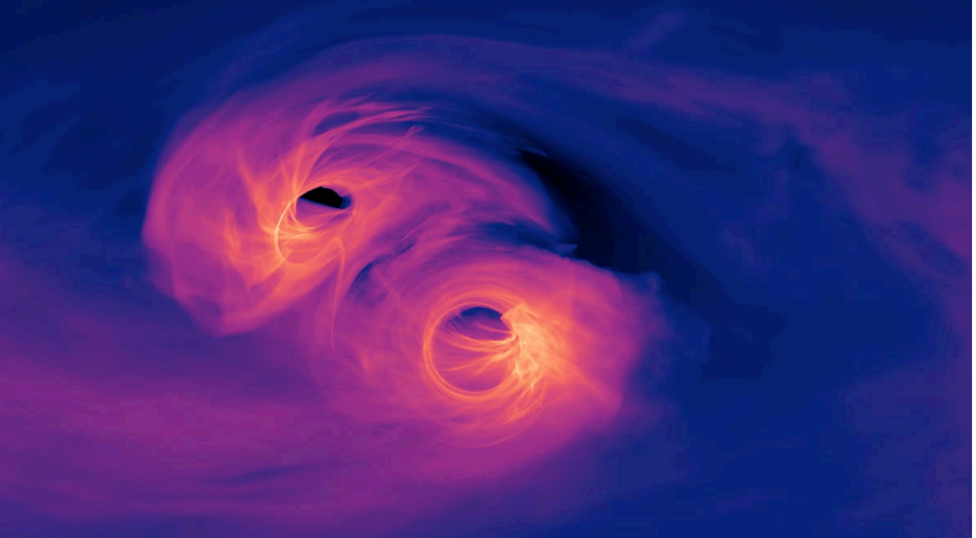








Open Questions



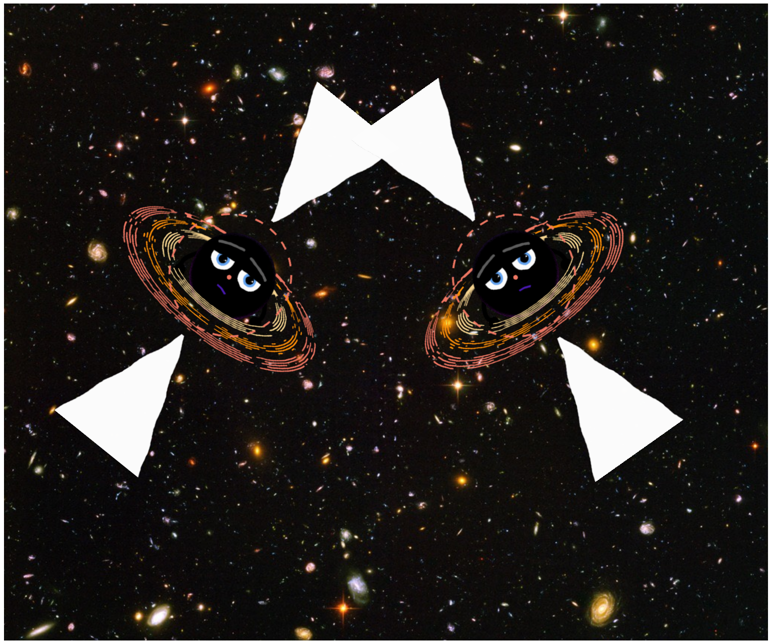
- How is Poynting flux reprocessed? Or how do predictions of Poynting flux turn into observables?
- Even though jets are seen to form in mergers, are they likely to reach large distances in post-merger environments? Is there relic evidence of a binary in the post-merger jet properties?
- How do we connect the Newtonian scales to the relativistic regime?
- At what separations must inspiral simulations start from?
  Decoupling radius?
  Or when is $a / (da/dt) \gg t_{\text{inflow}}$?
- How can we leverage viscous hydro results and connect to the GRMHD regime?
- Modulation: what are the differences in the lump between Newtonian vs. GR, viscous hydro vs. MHD?
- What other binary signatures are we missing?

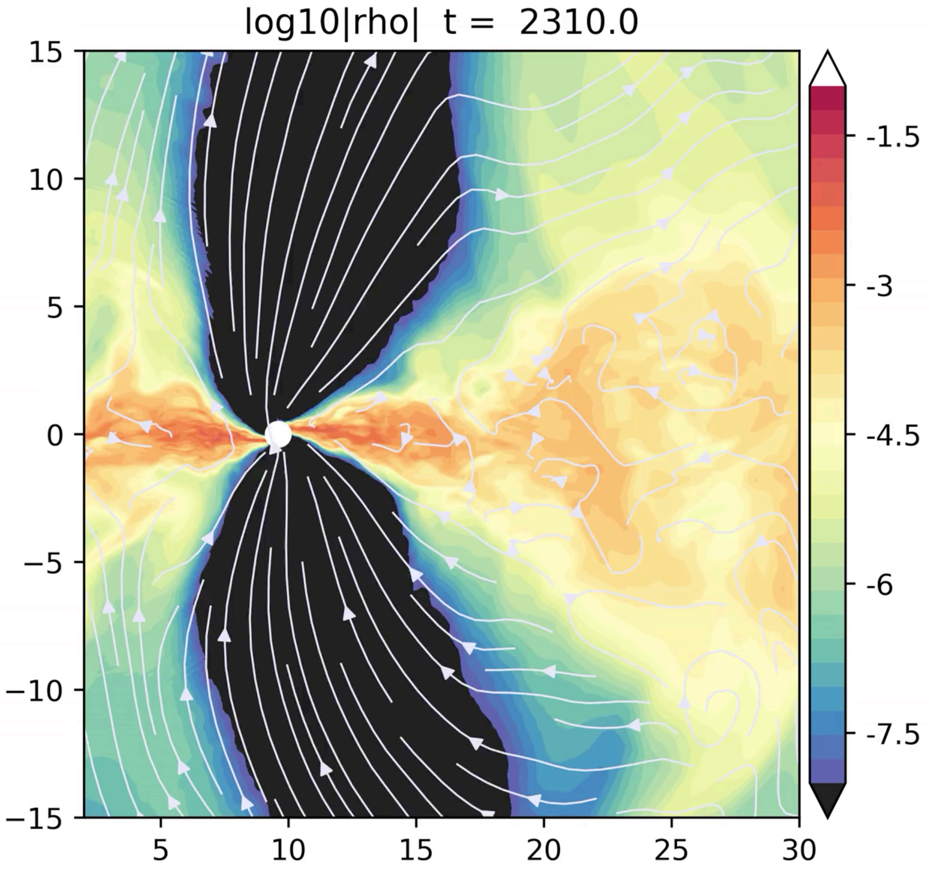
Accretion onto **Misaligned** Spinning BBHs

Circumbinary + Mini- Disk Regions

Combi, Gutierrez, Lopez Armengol++(in prep)

- **Jet Interaction?!**
- **Additional variability in the emission possible from hot spots in collisions between jet-wind, or jet-jet regions.**
- **Inclined BH spins to circumbinary disk leads to tilted mini-disks, complicating mini-disk replenishment cycle and modulation.**





PatchworkMHD : Single BH Test

Avara et. al, (in prep)

Avara @APS: H09.00006

- Allows us to stitch together coordinate patches that follow local symmetries efficiently and eliminate coordinate singularities that arise in spherical/cylindrical coordinates.
- Adding support for MHD and preservation of solenoidal (aka “no magnetic monopoles”) constraint into the hydrodynamic *Patchwork* code (Shiokawa++2018).
- Generalize *Patchwork* for the wide range of coordinate systems and patch situations (e.g., patch motion/rotation/overlap) desirable to execute our planned simulations.
- Developed method to adjust fluxes along patch boundaries to dissipate monopoles and flux differences.

- Test: Single accreting black hole.
- 3 spherical patches:
  - 1 aligned with z-axis;
  - 2 aligned with x-axis covering the poles;
- Avoids coordinate singularity along the z-axis and admits larger time steps;