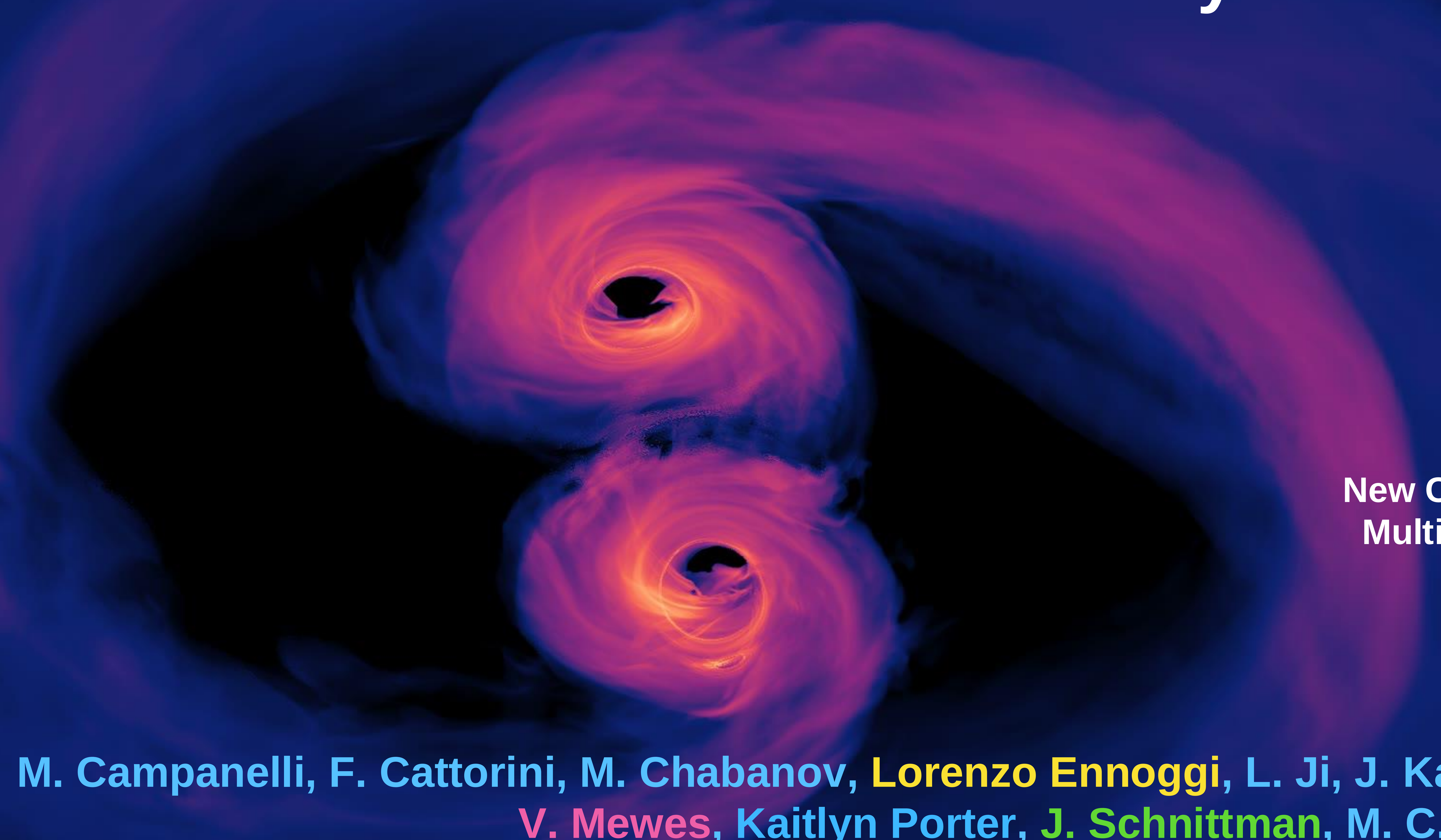
EM Counterparts of LISA Sources as Predicted by GRMHD simulations



Scott C. Noble,
(NASA-GSFC)

"10 Years to LISA:
New Challenges and Opportunities in
Multimessenger/Multiband Science"
JPL

Team:
M. Campanelli, F. Cattorini, M. Chabanov, Lorenzo Ennoggi, L. Ji, J. Kalinani, B. Kelly, J. Krolik,
V. Mewes, Kaitlyn Porter, J. Schnittman, M. C. de Simone,Y. Zlochower

RIT, JHU, ORNL, GSFC

Project Leads, RIT Grad Students

Why use General Relativistic Magnetohydrodynamics (GRMHD)?

Pros	Cons
Event horizons are the only physical inner boundary conditions, and they can launch jets naturally!	More expensive, cannot cover parameter space as inexpensively, temporal/spatial dynamic range limitations. 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, numerical dissipation at AMR grid boundaries, possible dependencies on initial distribution/topology.
3-d accommodates more realistic and consistent thermodynamics, out-of-plane dynamics, buoyancy effects, radiation physics/predictions, orientation effects, inclusion of jets, …	Many GRMHD simulations still rely on using accretion rate and Poynting flux (sometimes cooling rate) as proxies for actual synthetic observations via ray-tracing or radiation transport.
Can explore inspiral/decoupling regime using inspiral rate appropriate to physical scale of the gravitational system. Only means of exploring fully the relativistic dynamics at the time of merger.	Exploring how and where decoupling occurs in GRMHD is still challenging for more radiative efficient, geometrically thinner accretion flows.
MHD turbulence, and not viscous hydrodynamics, reproduces red-noise temporal power spectrum commonly seen in AGN.	Significant temporal dynamic range required in the simulations to ensure the binary's quasi-periodic signatures are not masked by low-frequency noise from initial data biases.

Exceptions

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

d'Ascoli, Noble, Bowen, Campanelli, Krolik, and Mewes, ApJ, 865, 140, (2018).

Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, ApJ, 928, 137, (2022).

Tiwari, Chan, Bogdanović, Jiang, Davis, and Ferrel, arXiv, arXiv:2502.18584, (2025).

Outline and Strategy

- Restrict to only GR + MHD simulations, while there are similar GR+Hydro simulations with or without viscosity;
- Group work by type of gaseous environment (e.g., radiation efficient/inefficient) or situation and in chronological order within;
- Try to point out the most salient or notable of the results, though much will be missed in such a short talk.
- Focus on forward/source modeling, ignore likelihood analysis, priors, i.e. answer "What kinds of amazing things may we see (within reason)?"
- My apologies beforehand for missing papers.

Superb Reviews of the Topic:

Gutiérrez, Combi, and Ryan, "Accretion onto supermassive black hole binaries", arXiv:2405.14843, (2024).

Bogdanović, Miller, and Blecha, "Electromagnetic counterparts to massive black-hole mergers", LRR, 25, 3, (2022).

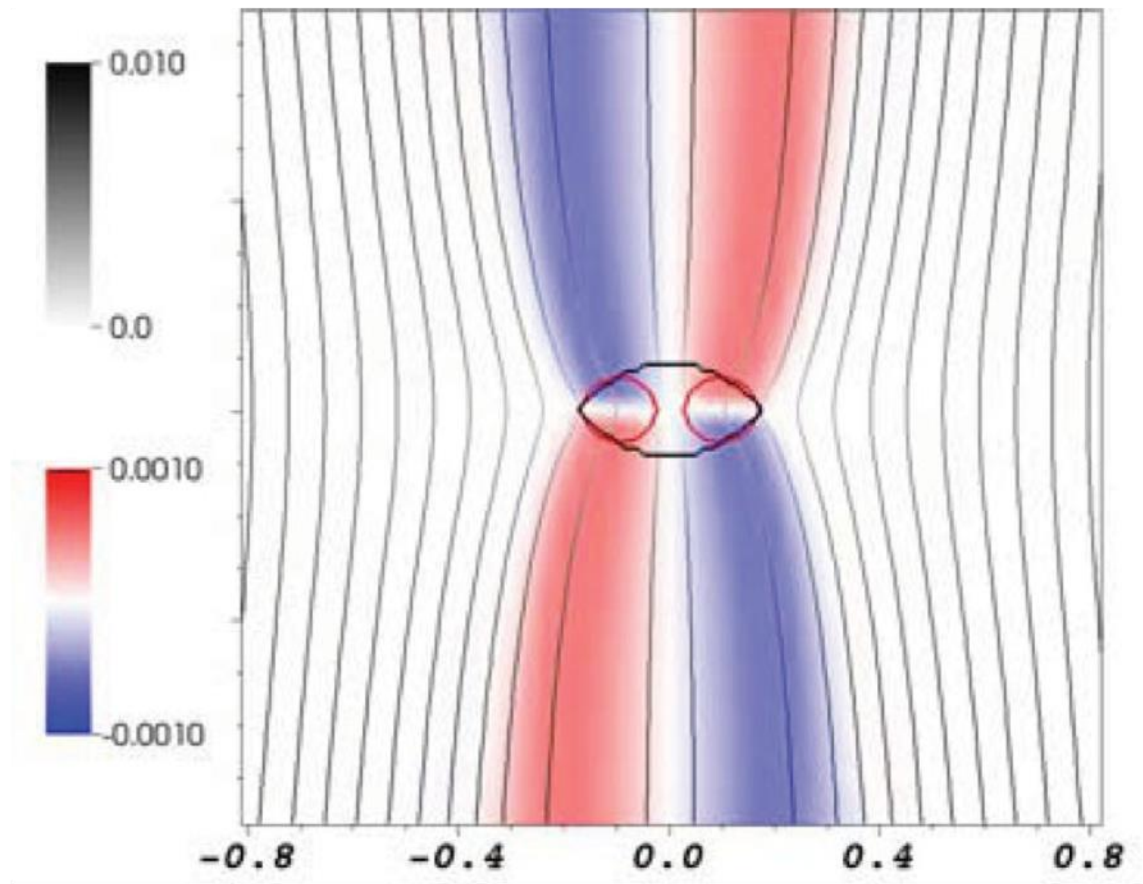
Gold, "Relativistic Aspects of Accreting Supermassive Black Hole Binaries in Their Natural Habitat: A Review", Galaxies, 7, 63, (2019).

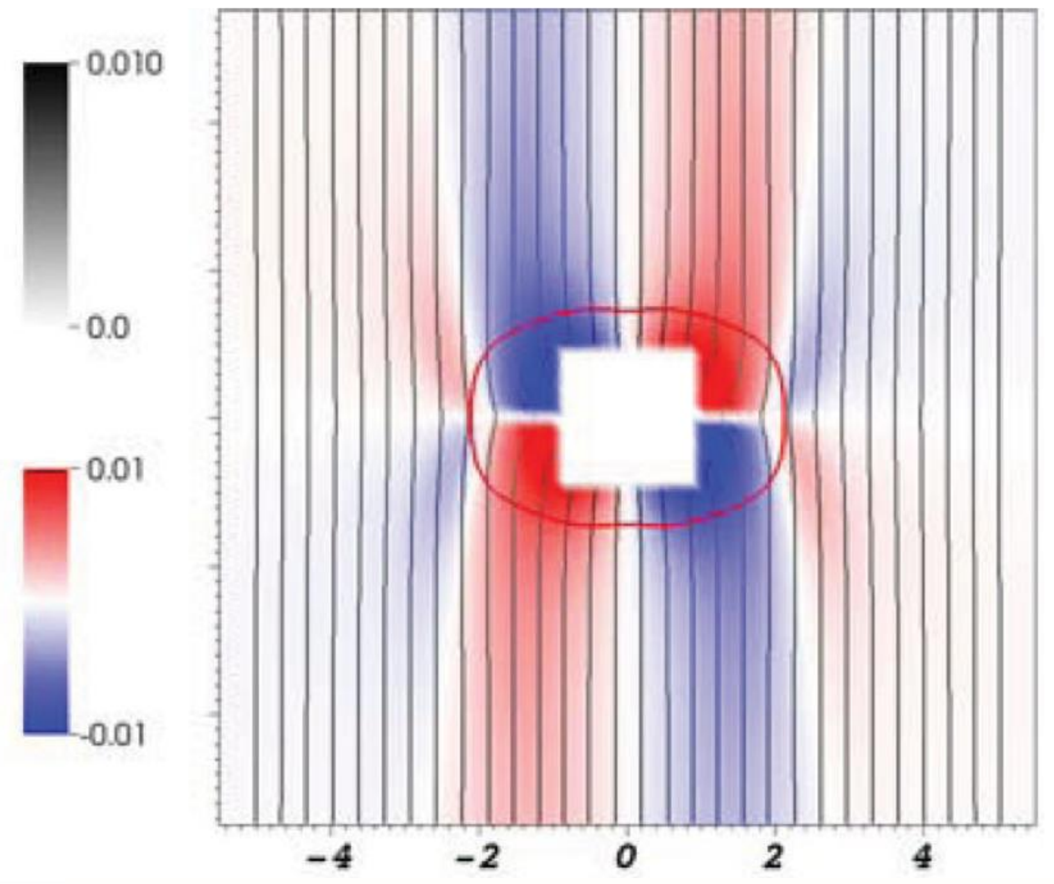
Numerical Relativity + Force-Free Evolutions

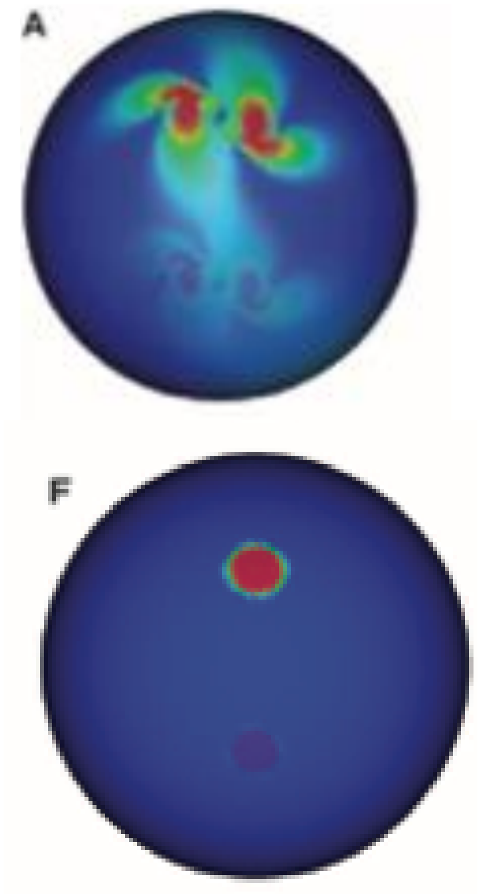
Accretion in Sparse Plasmas (Weak, e.g. ISM, Accretion)

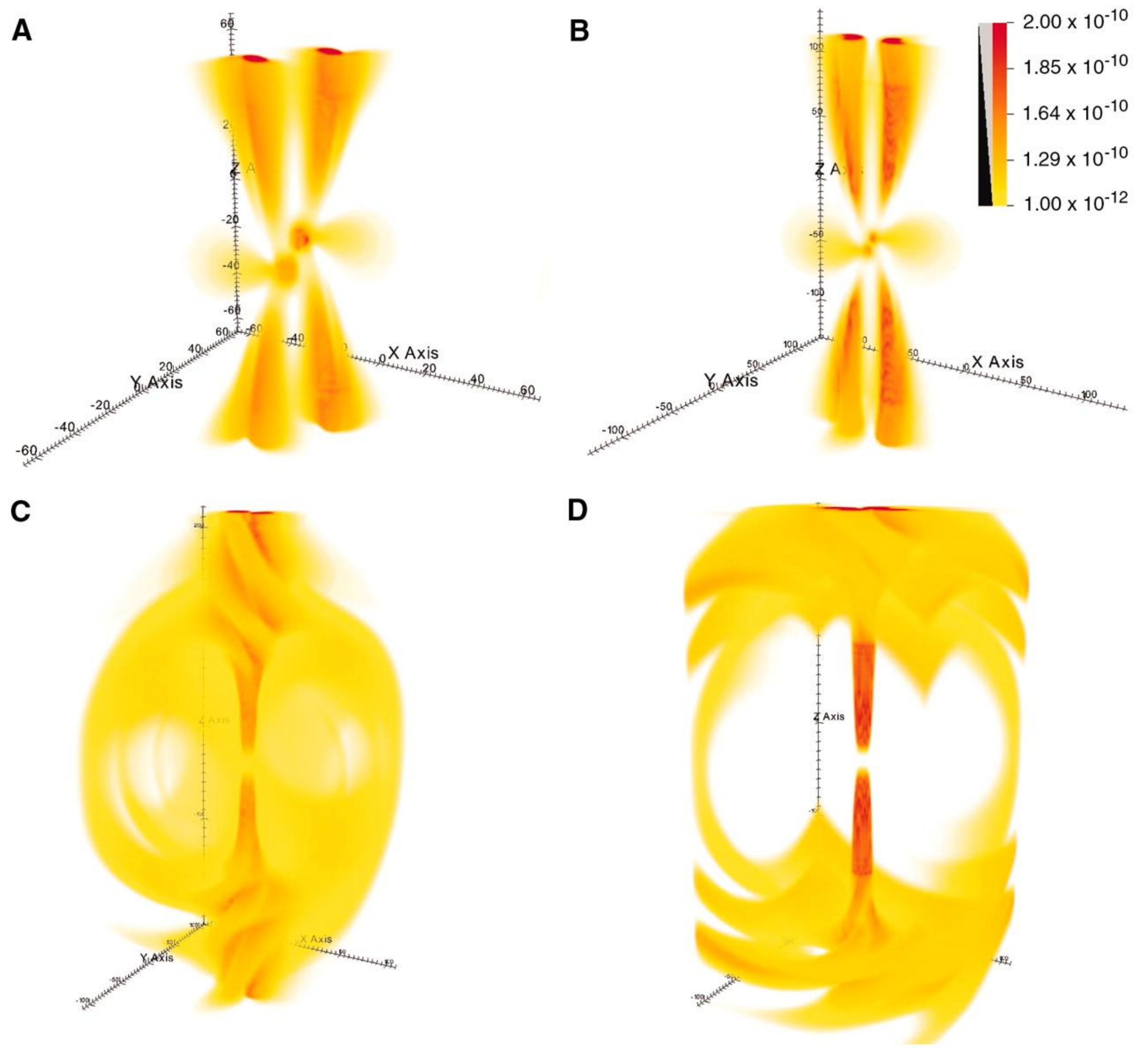
Ruiz, Palenzuela, Galeazzi, and Bona, MNRAS, 423, 1300, (2012).

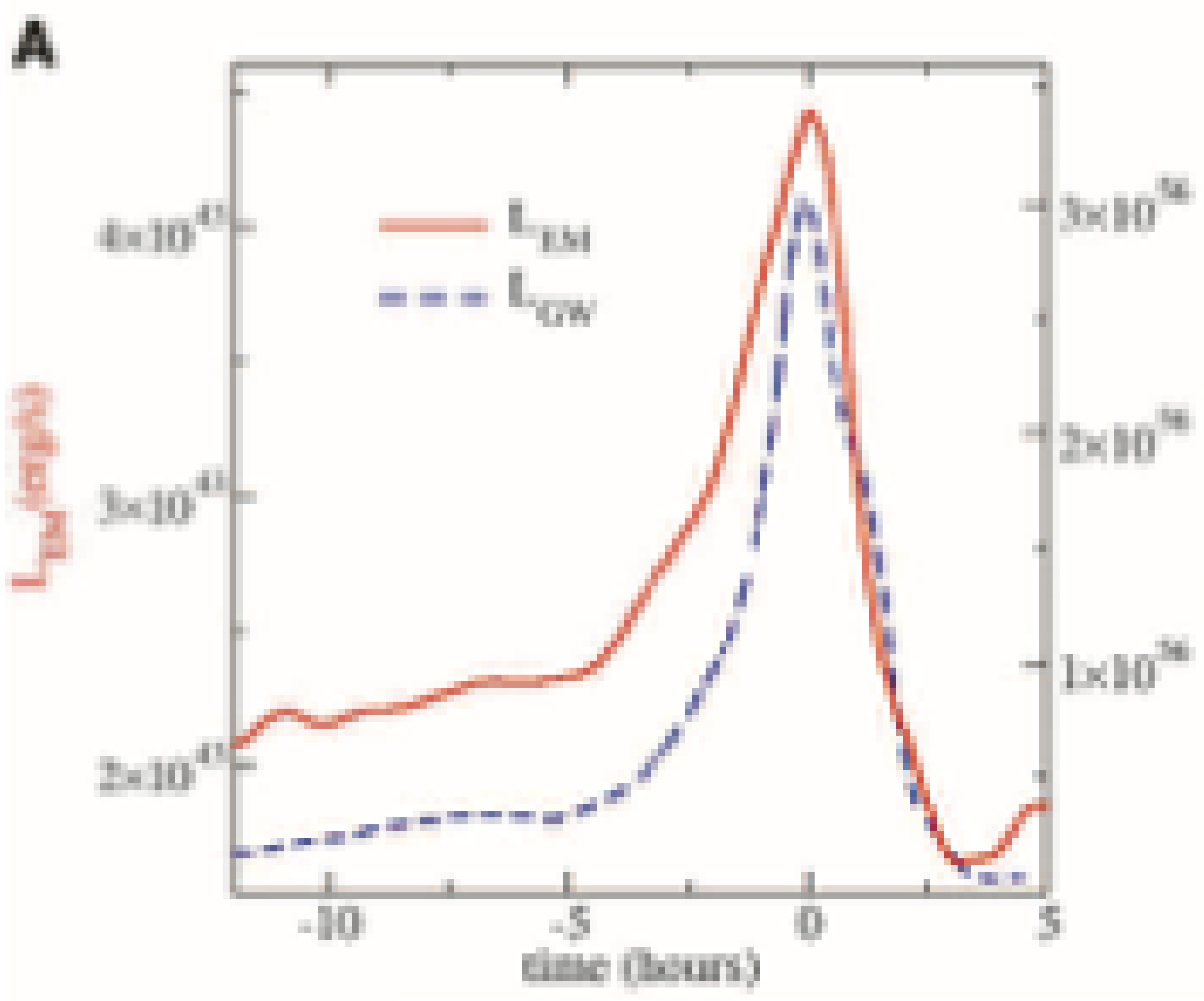
- Ergoregion —> Jets or rather Blandford-Znajek process











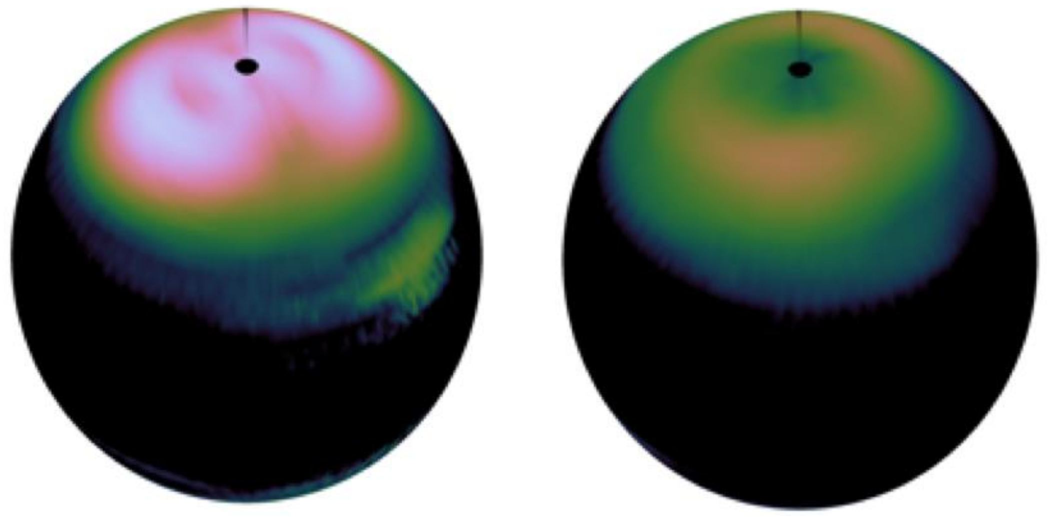
$E_{EM} = 10^{43}\ \mathrm{erg\ s^{-1}}\ (B/10^4 G)^2 (M/10^8 M_\odot)^2 (v/0.4c)^2$

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

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

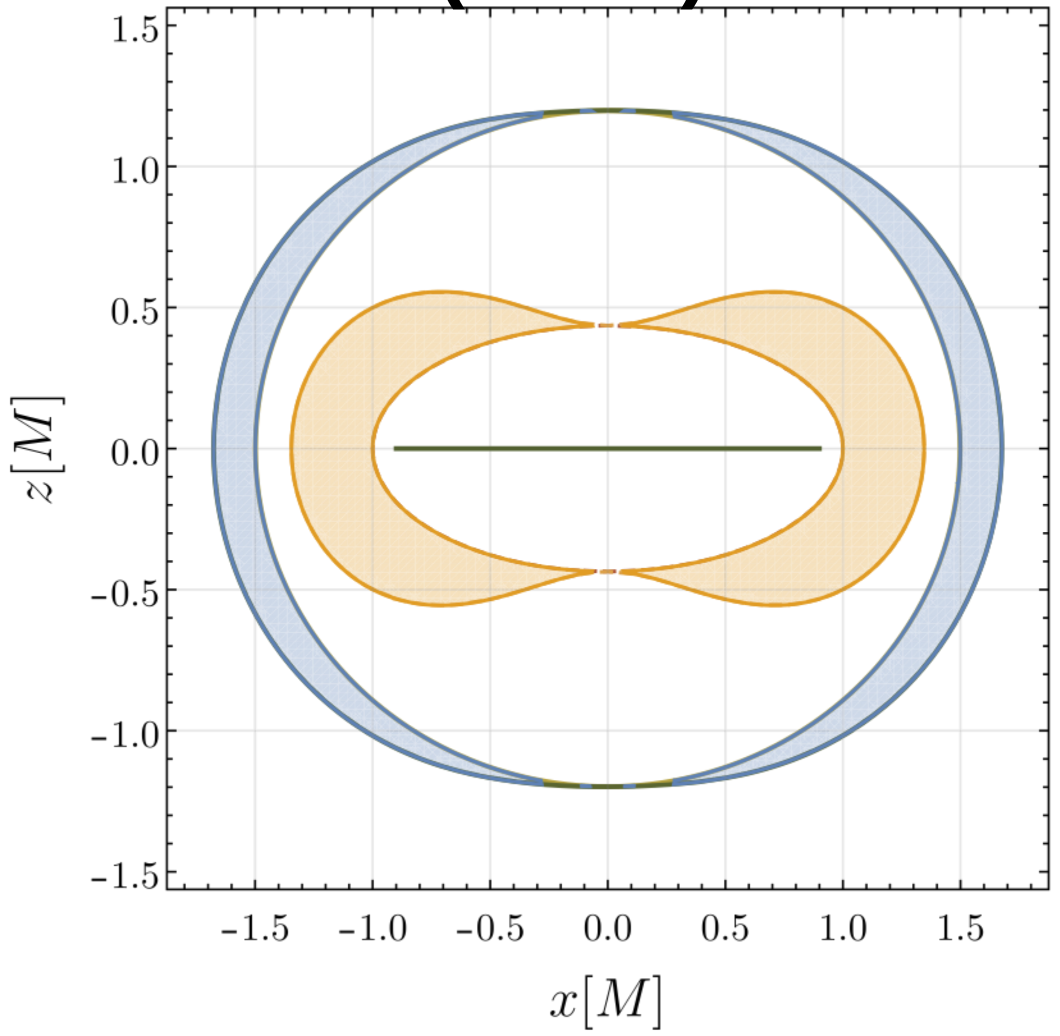
From Boosted Kerr GRMHD+mini-disk simulations:

Spins **No Spins**

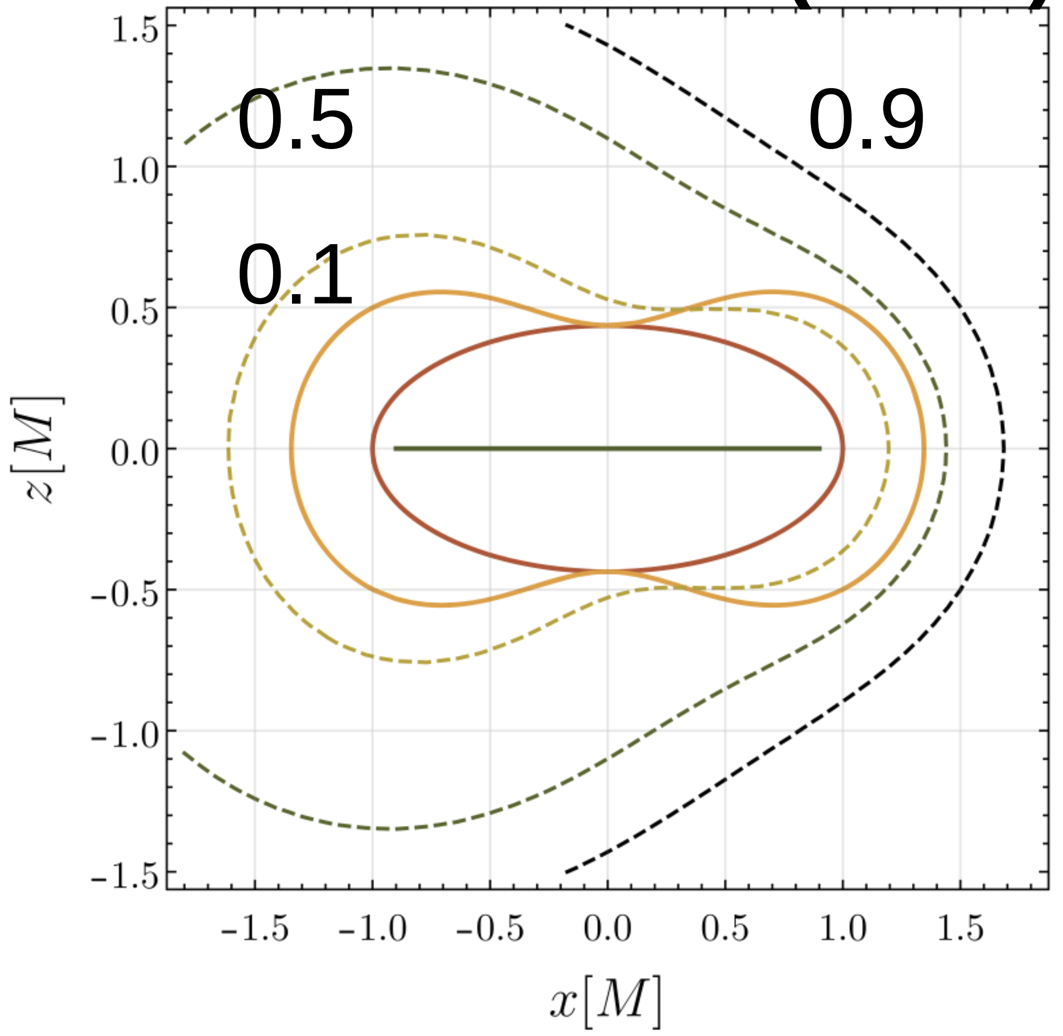


Poynting flux

Kerr (a=0.9)



Boosted Kerr (a=0.9)



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

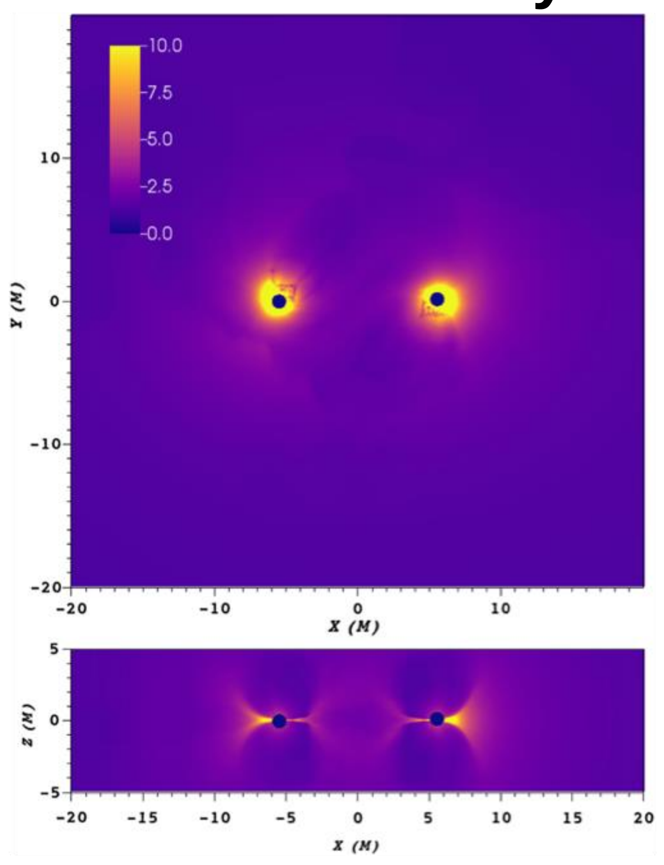
Numerical Relativity + MHD Evolutions

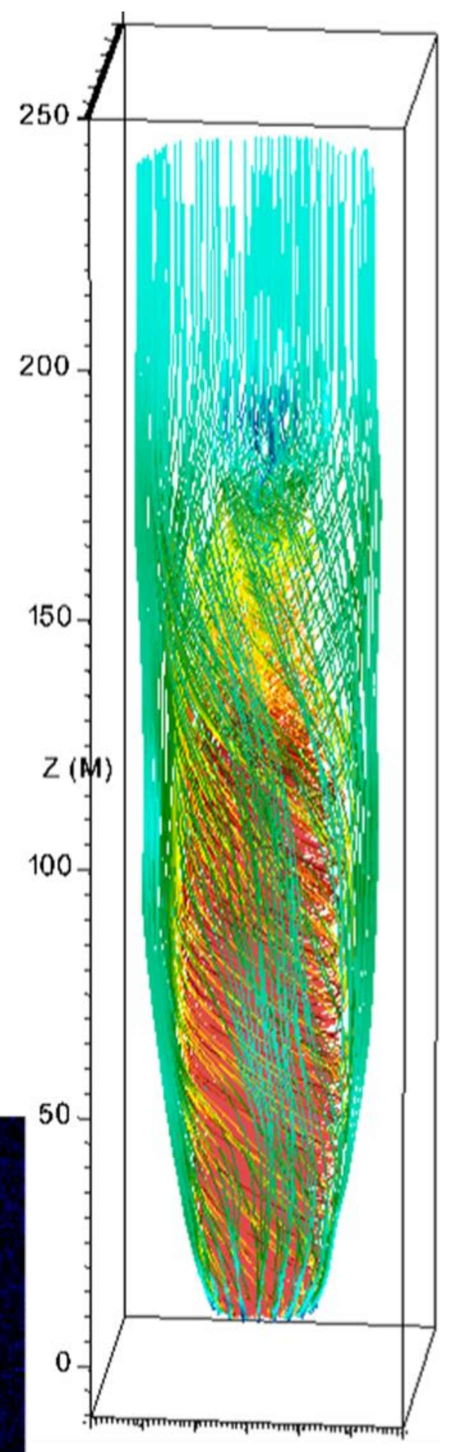
Accretion in Uniform Plasma Clouds (what if decoupling is efficient?)

Prior Art:

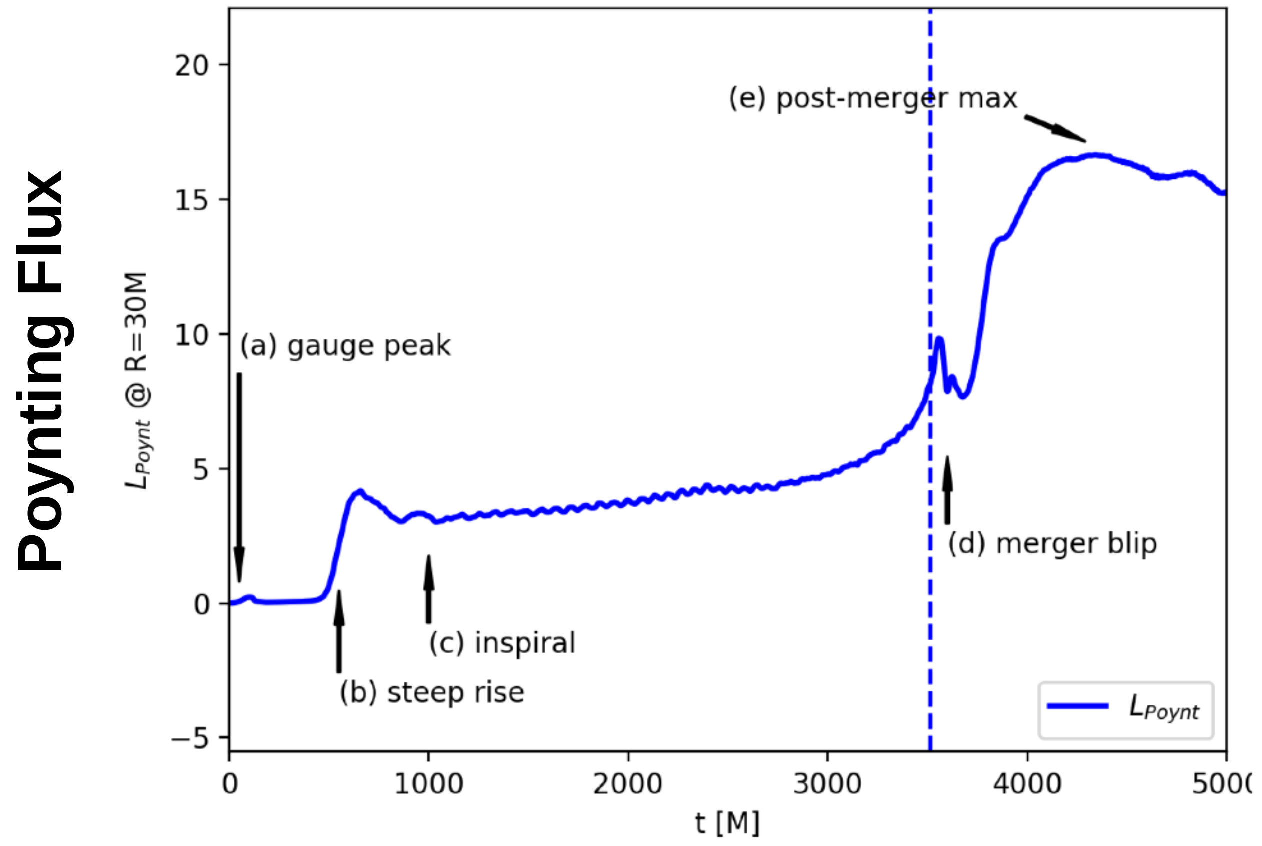
Palenzuela, Garrett, Lehner, and Liebling, PhRvD, 82, 044045, (2010)
Moesta, Alic, Rezzolla, Zanotti, and Palenzuela, ApJL, 749, L32, (2012).
Giacomazzo, Baker, Miller, Reynolds, and van Meter, ApJL, 752, L15, (2012).

Plasma Density

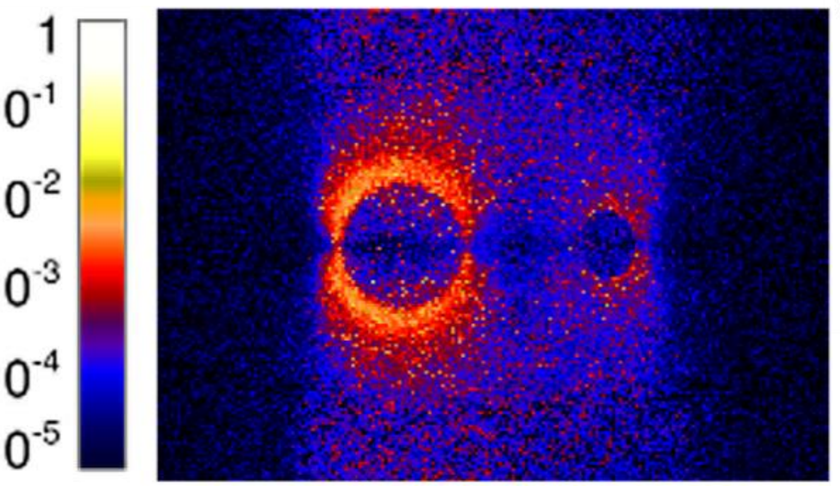


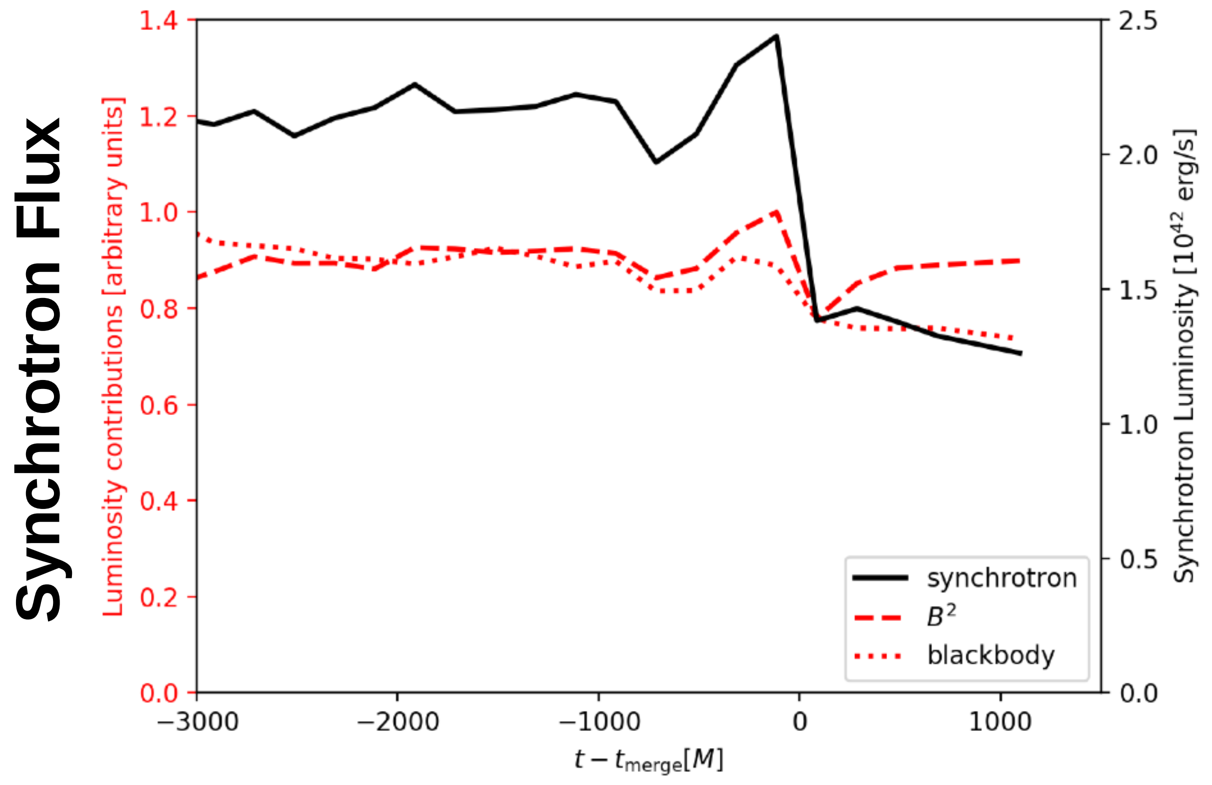


B-field Lines



Synchrotron Image





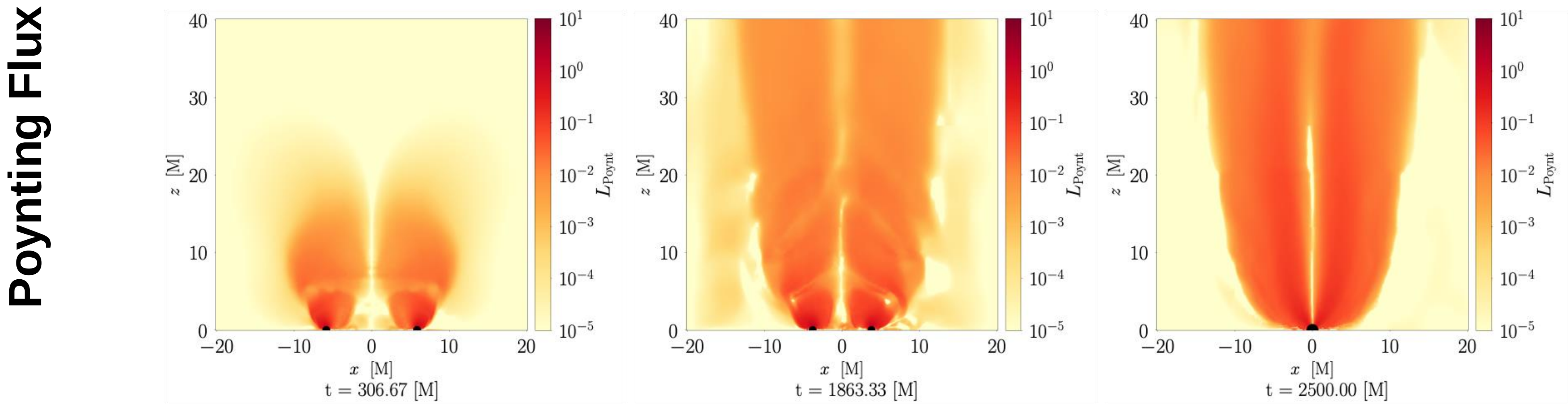
Kelly, Baker, Etienne, Giacomazzo, Schnittman, PRD 96, 123003 (2017)

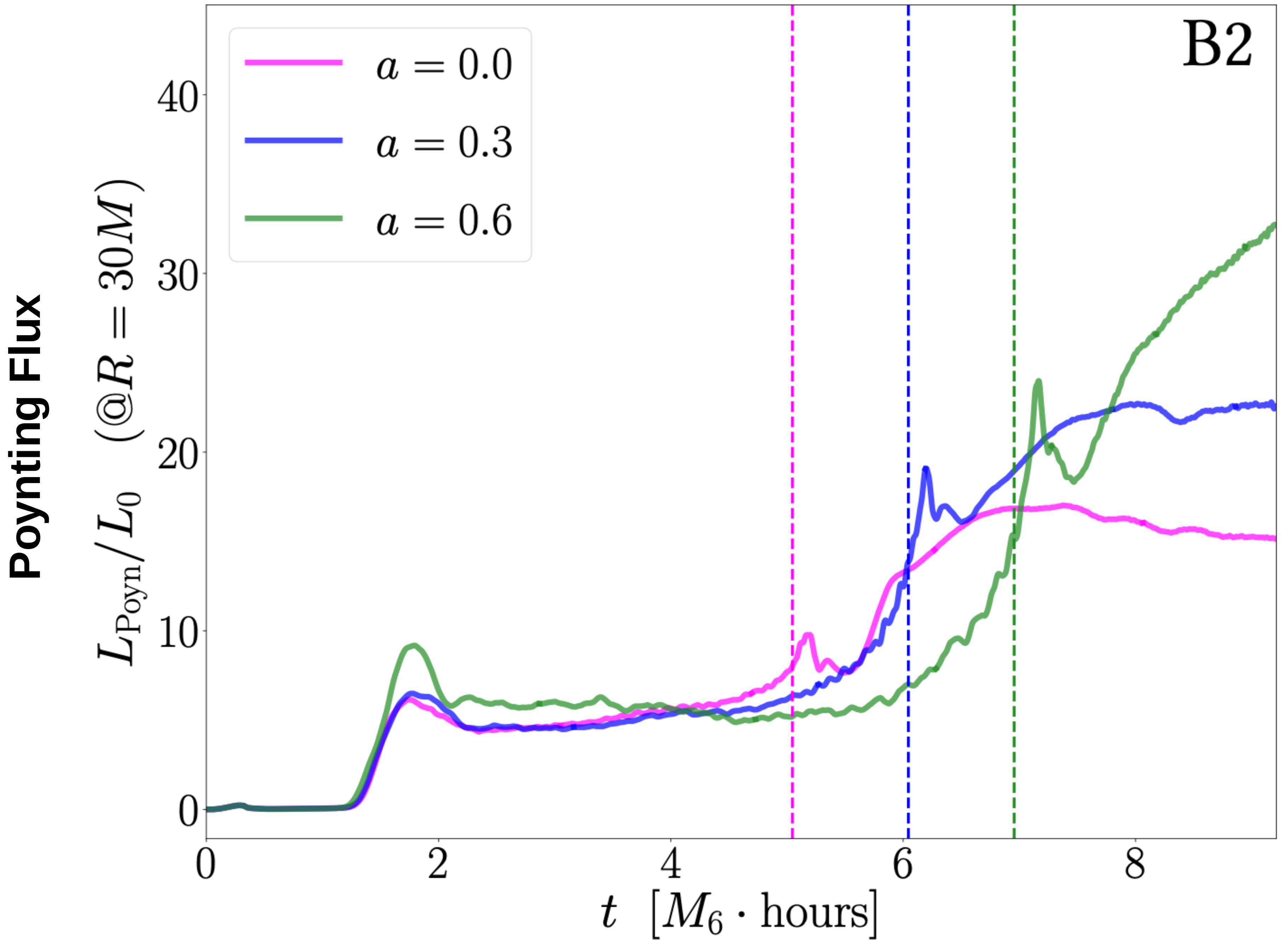
- Non-Spinning post-merger single BHs, Uniform B-field;
- Survey over magnetization, find floor value (0.01) above which runs become similar;
- Poynting flux grows in time, reaching maximum post-merger; Synchrotron plunges at merger;

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;

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



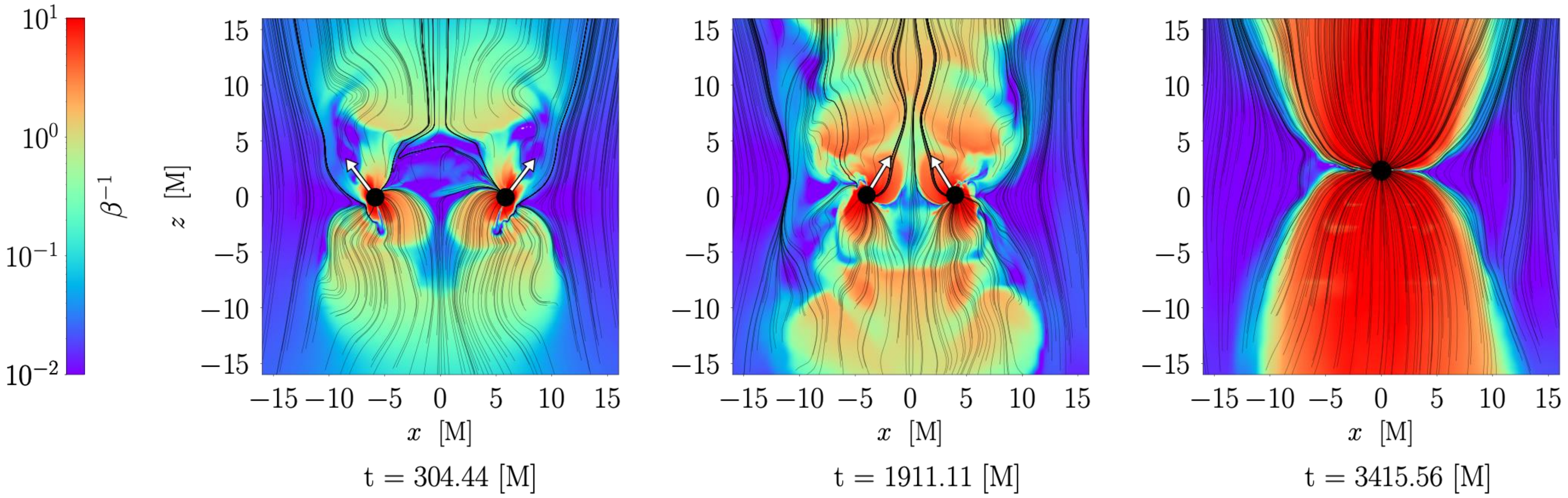


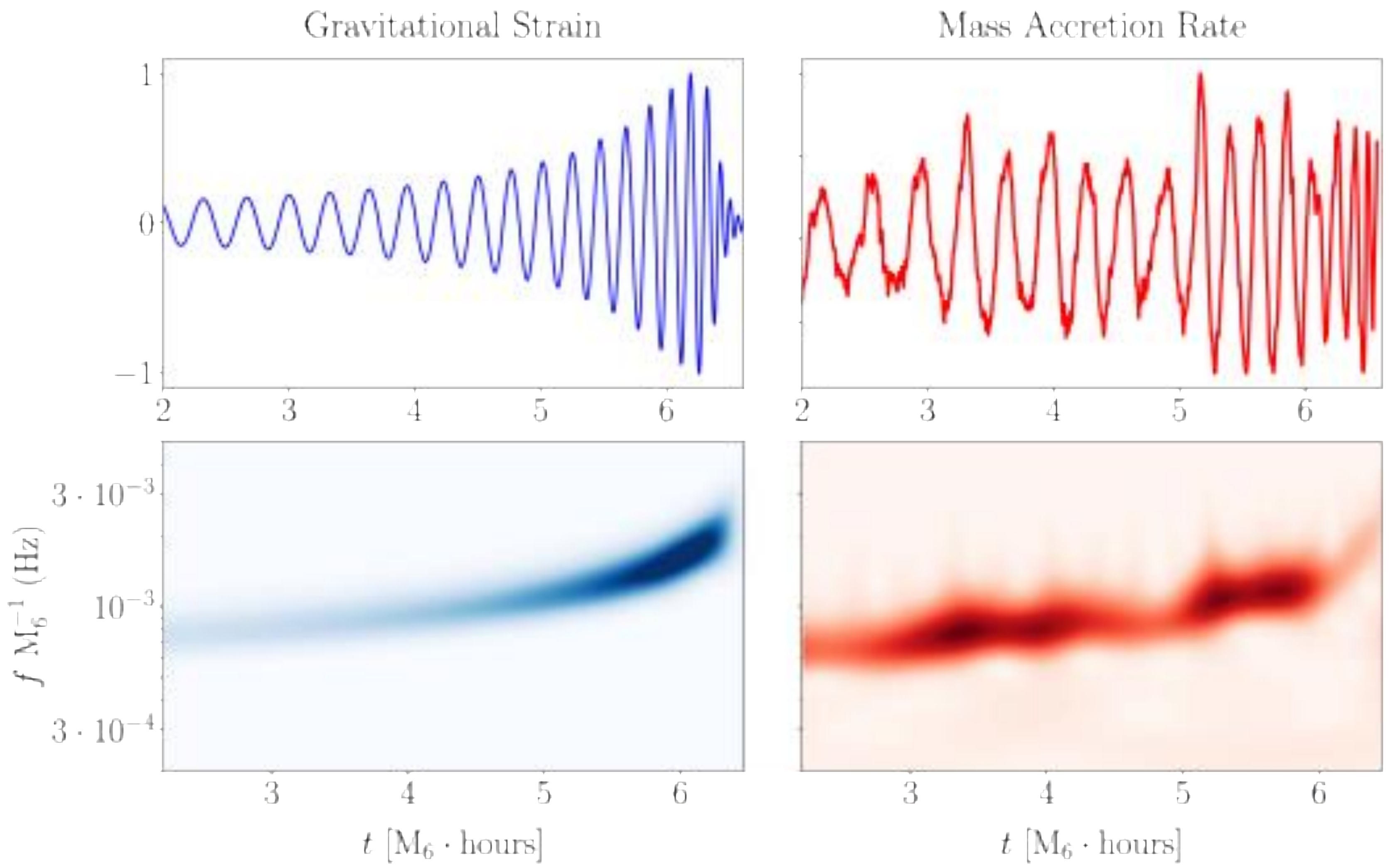
Numerical Relativity + MHD Evolutions

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

Cattorini, Maggioni, Giacomazzo, Haardt, Colpi, and Covino, ApJL, 930, L1, (2022).

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

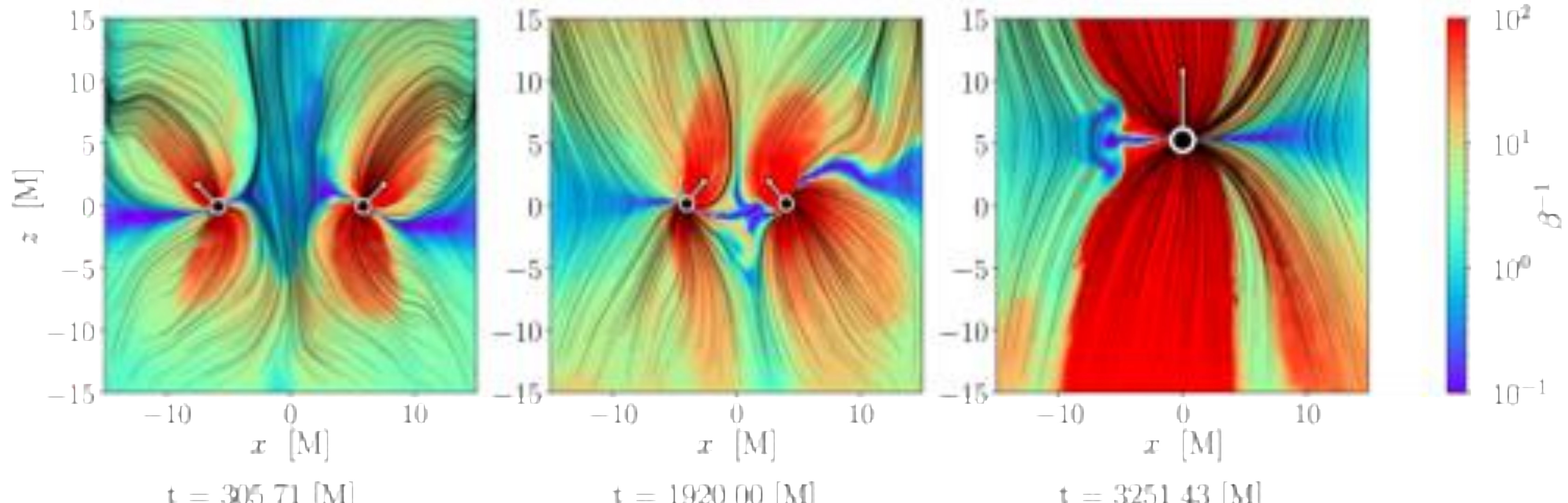




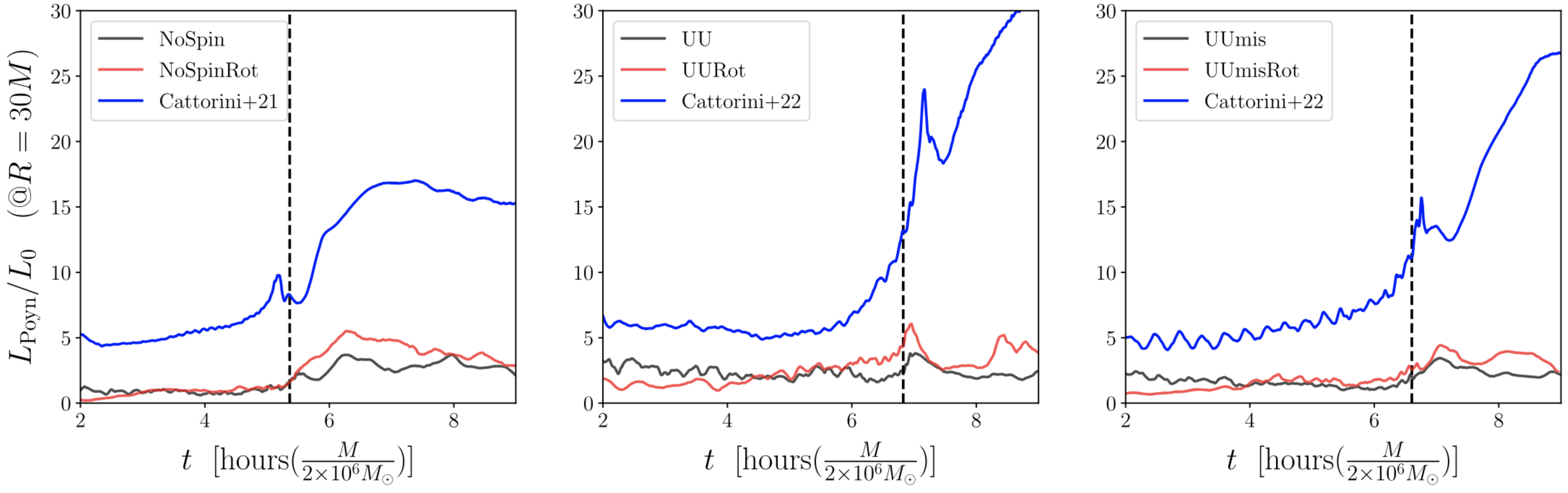
Poynting Flux Luminosity Efficiency
(Luminosity per mass accretion rate)

Accretion Type	Premerger	Postmerger
Cloud-like	5% - 10%	15—60%
Plane-like	5% - 20%	25% - 30%
Disk-like	0.5% - 5%	0.5%-100%

- 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;

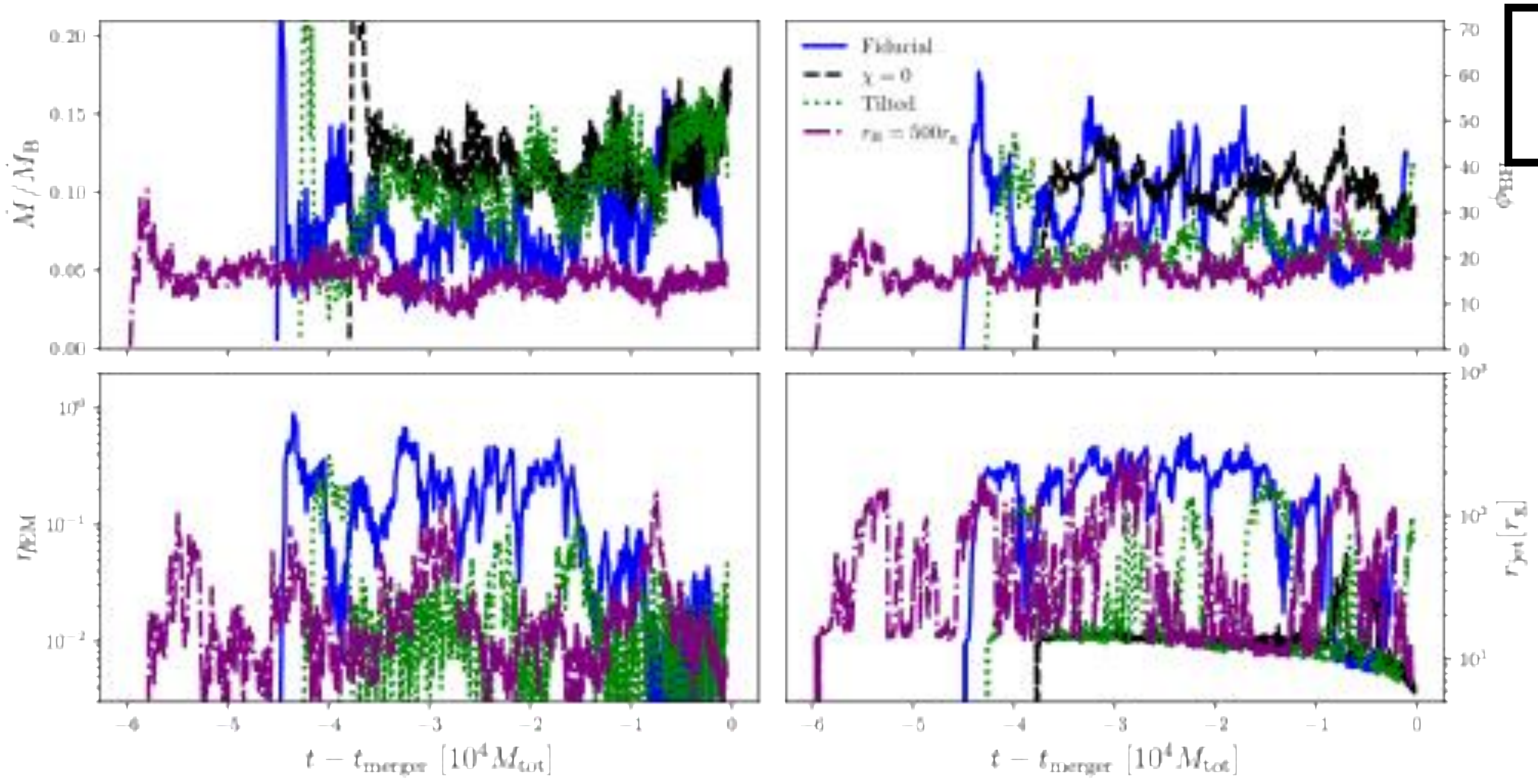


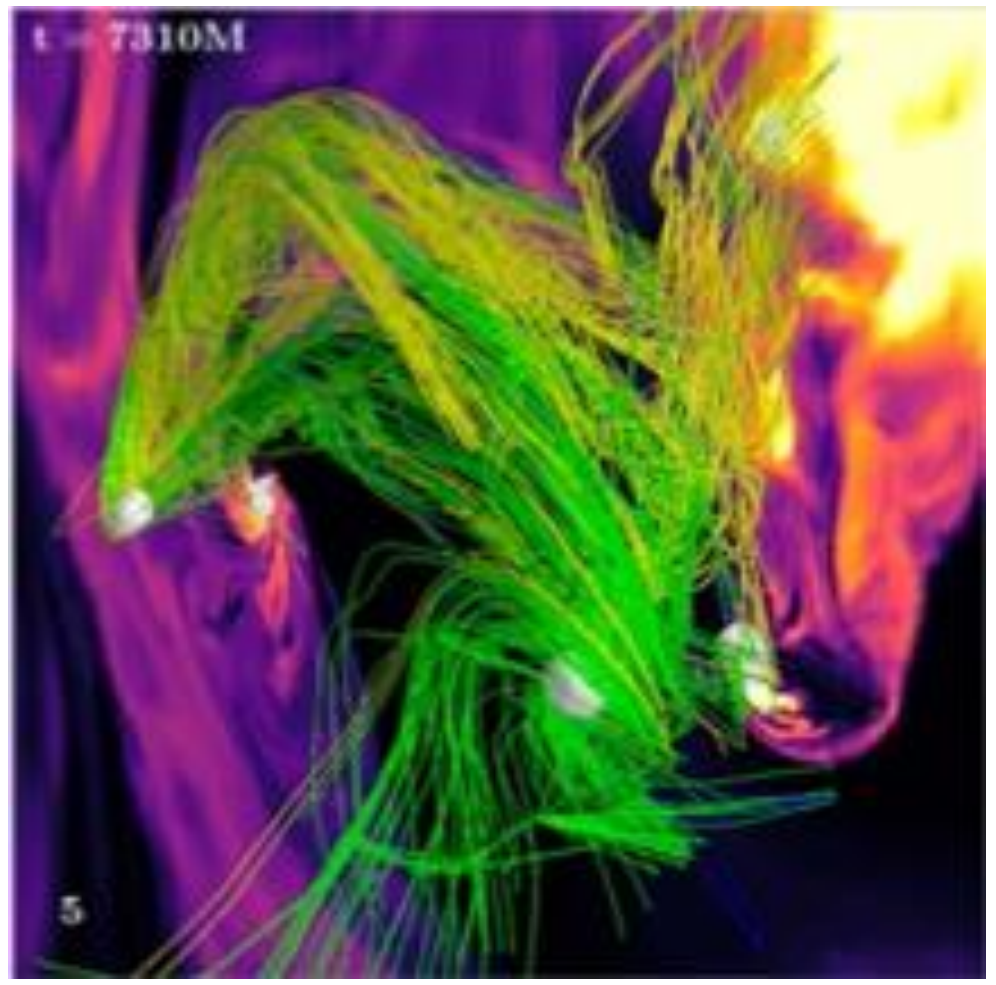
Fedrigo, Cattorini, Giacomazzo, and Colpi, PhRvD, 109, 103024, (2024).



GRMHD + Approx. Spacetimes
Dual Jets in Clouds

Ressler, Combi, Ripperda, and Most, ApJL, 979, L24, (2025).



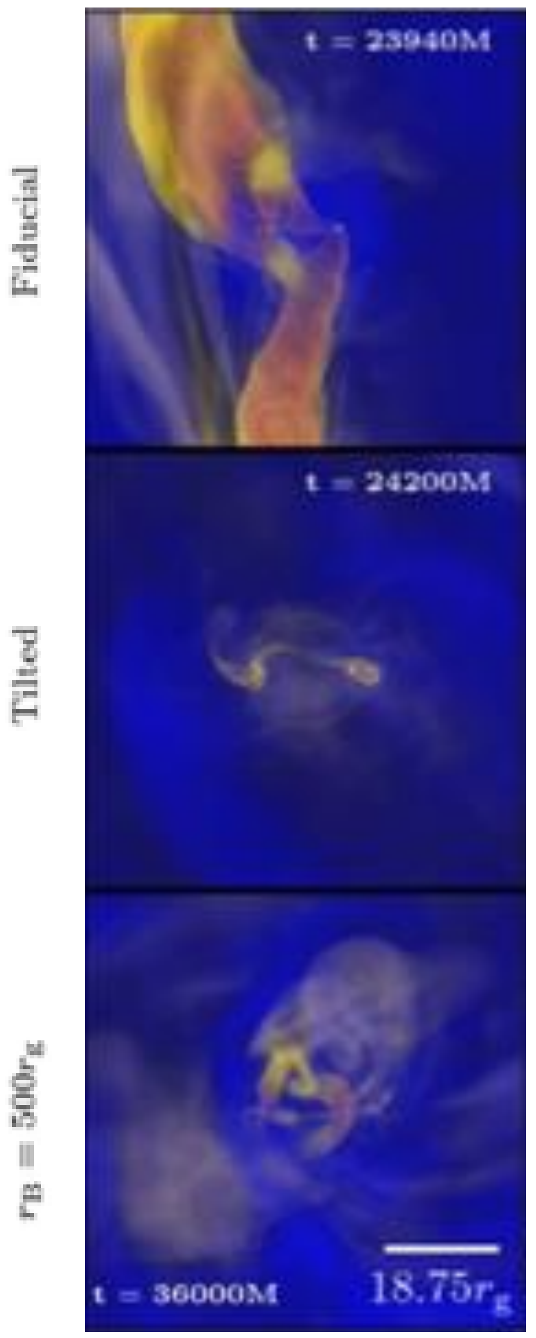


Magnetic Bridge Emission

$$\frac{(L_{rec})_{bridge}}{L} \approx 0.08 \left(\frac{u_{b,rec} r_g^2}{|\dot{M}| c} \Big/ 0.075\right)_{r=r_H} \times \left(\frac{r_H}{0.67 r_g}\right)^2 \left[\frac{\log(l_{rec}/r_H)}{2.7}\right],$$

$$(L_{rec})_{bridge} \approx 10^{43}\ \frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{u_{b,rec} r_g^2}{|\dot{M}| c} \Big/ 0.075\right)_{r=r_H} \left(\frac{r_H}{0.67 r_g}\right)^2 \times \left[\frac{\log(l_{rec}/r_H)}{2.7}\right] f_{Edd} \left(\frac{M}{10^6 M_\odot}\right) \left(\frac{\eta_{rad}}{0.1}\right)^{-1}, \quad (8)$$

$$(\nu_{synch})_{bridge} \approx 3 \times 10^{20}\ \mathrm{Hz} \left(\frac{\sigma_{bridge}}{4}\right)^2 \left(\frac{u_{b,rec} r_g^2}{|\dot{M}| c} \Big/ 0.075\right)^{1/2} \times f_{Edd}^{1/2} \left(\frac{M}{10^6 M_\odot}\right)^{-1/2} \left(\frac{\eta_{rad}}{0.1}\right)^{-1/2},$$

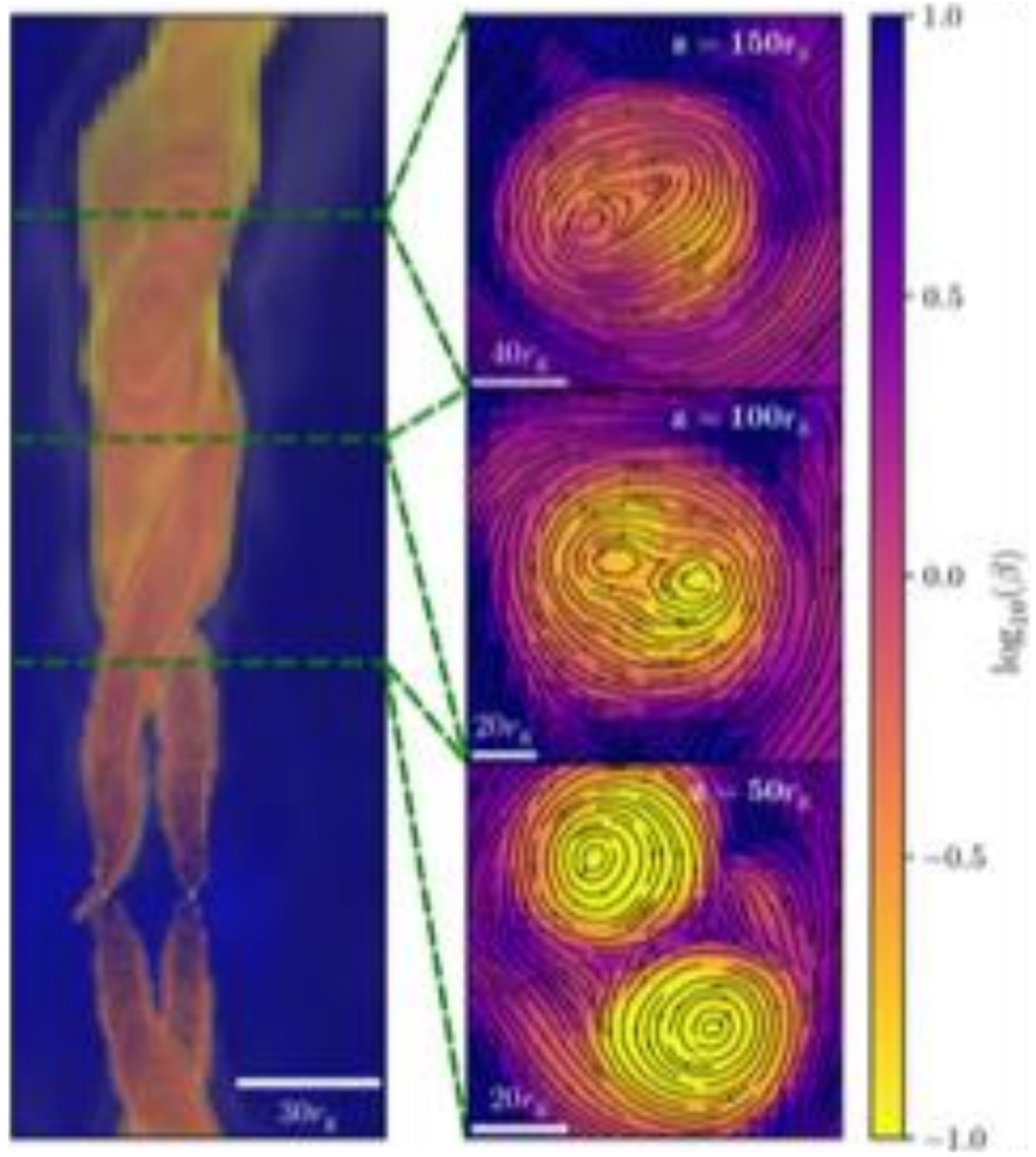


Jet-Jet Reconnection Emission

$$\frac{(L_{rec})_{jet}}{L} \approx 0.02 \left(\frac{u_{b,rec} r_g^2}{|\dot{M}| c} \Big/ 5 \times 10^{-5}\right) \left(\frac{l_{rec}}{20 r_g}\right)^2$$

$$(L_{rec})_{jet} \approx 3 \times 10^{42} \frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{u_{b,rec} r_g^2}{|\dot{M}| c} \Big/ 5 \times 10^{-5}\right) \left(\frac{l_{rec}}{20 r_g}\right)^2 \times f_{Edd} \left(\frac{M}{10^6 M_\odot}\right) \left(\frac{\eta_{rad}}{0.1}\right)^{-1},$$

$$(\nu_{synch})_{jet} \approx 2.5 \times 10^{22}\ \mathrm{Hz},$$



- Misaligned jets and less magnetized environments lead to less flux accretion, preventing it from reaching MAD levels and high-efficient jets;
- Orbital motion even keeps aligned case at sub-MAD levels, opening the possibility that binaries may not go MAD;
- Nonthermal emission predicted at reconnection sites (jet-jet, bridges) offering high-energy (1-100 MeV) avenues for detection, at few % efficiencies;

MHD Simulations Predict an EM Signature:

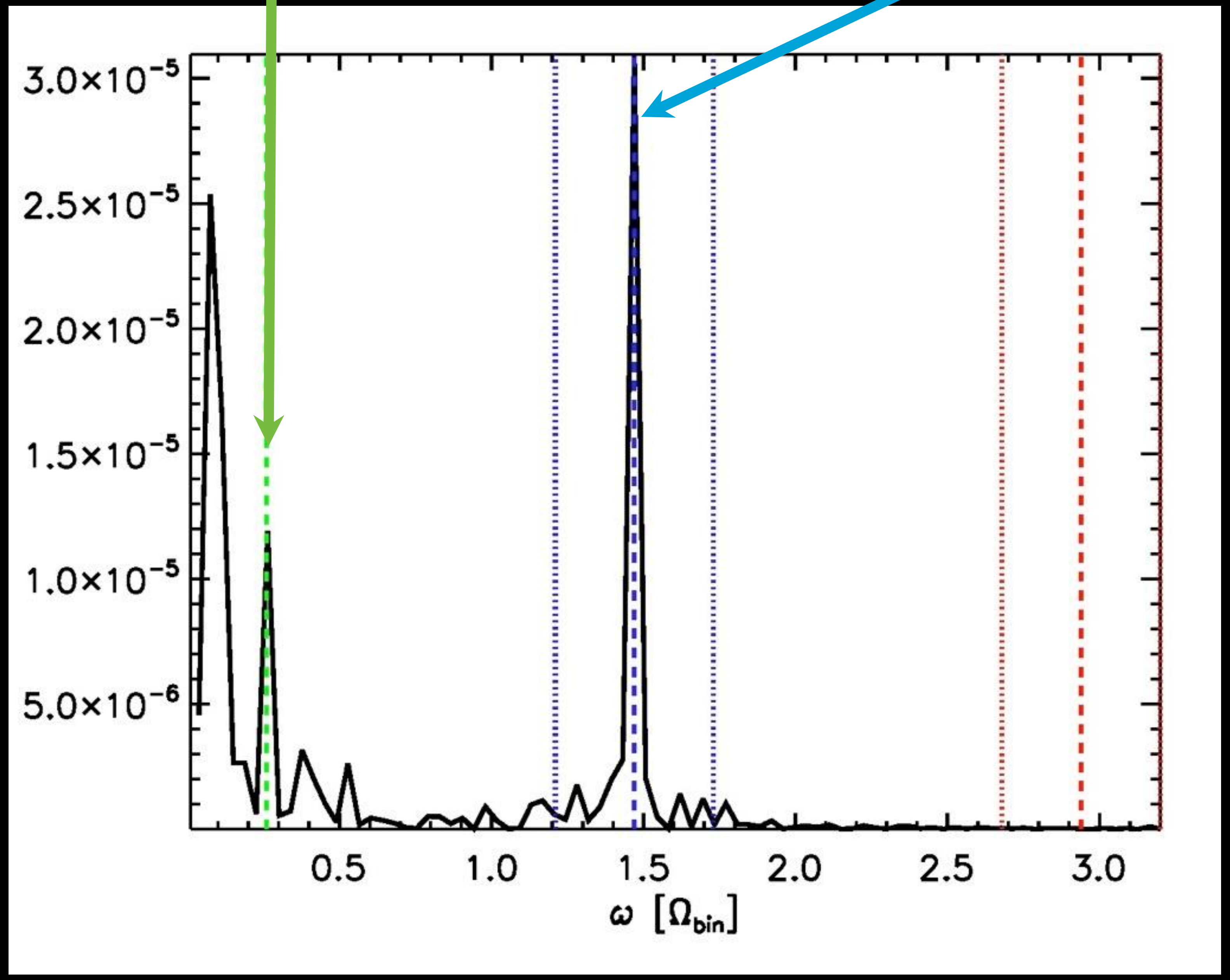
Noble++2012

Periodic Signal

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

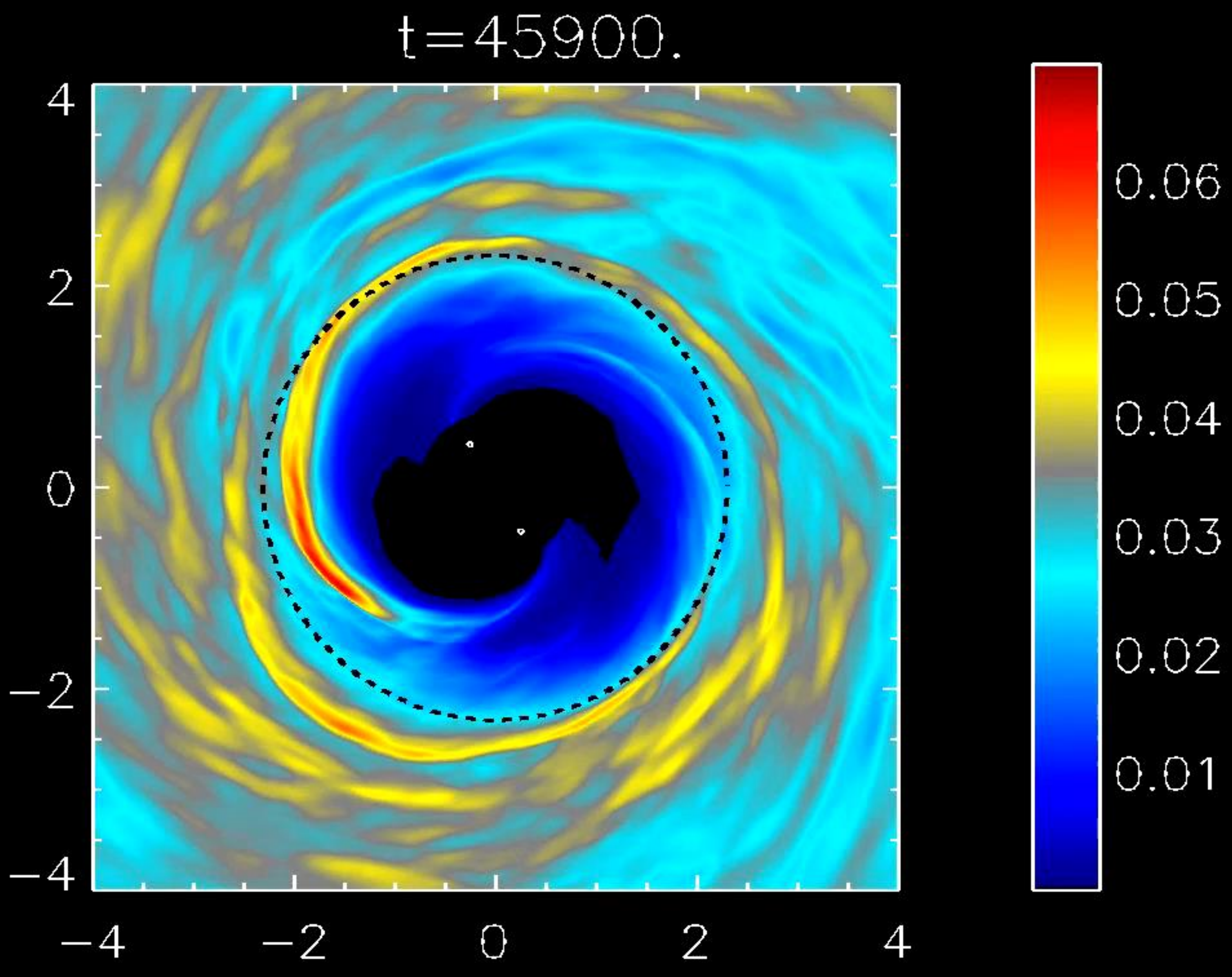
$\Omega_K(r_{\rm lump})$

$1.47\Omega_{\rm bin}$



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

Surface Density



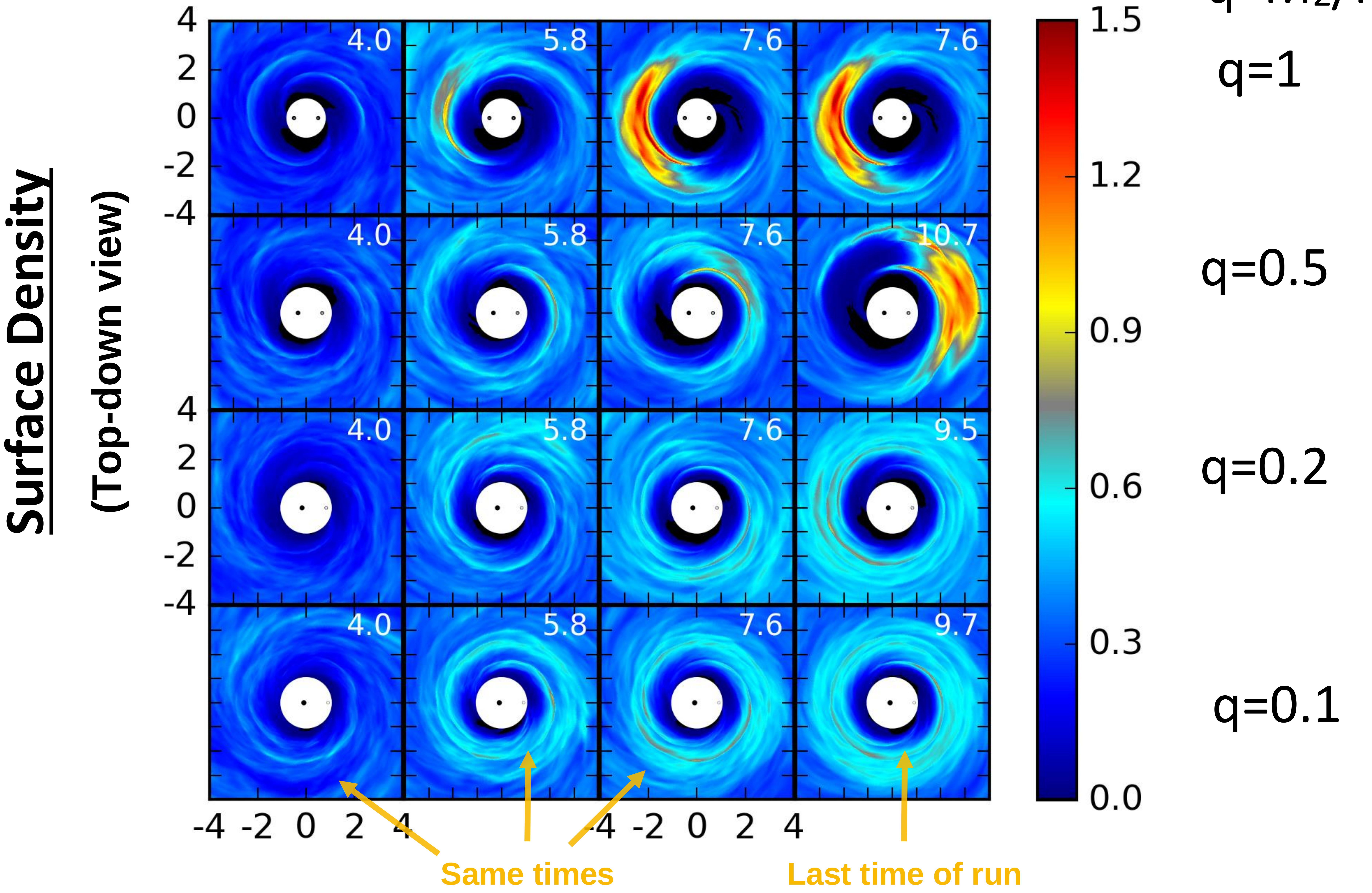
(in frame co-rotating with lump)

GRMHD + Approx. Spactime: Circumbinary Disks

a=20M

$q=M_2/M$

Noble, Krolik, Campanelli, Zlochower, Mundim, Nakano, and Zilhão, ApJ, 922, 175, (2021).



- 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.

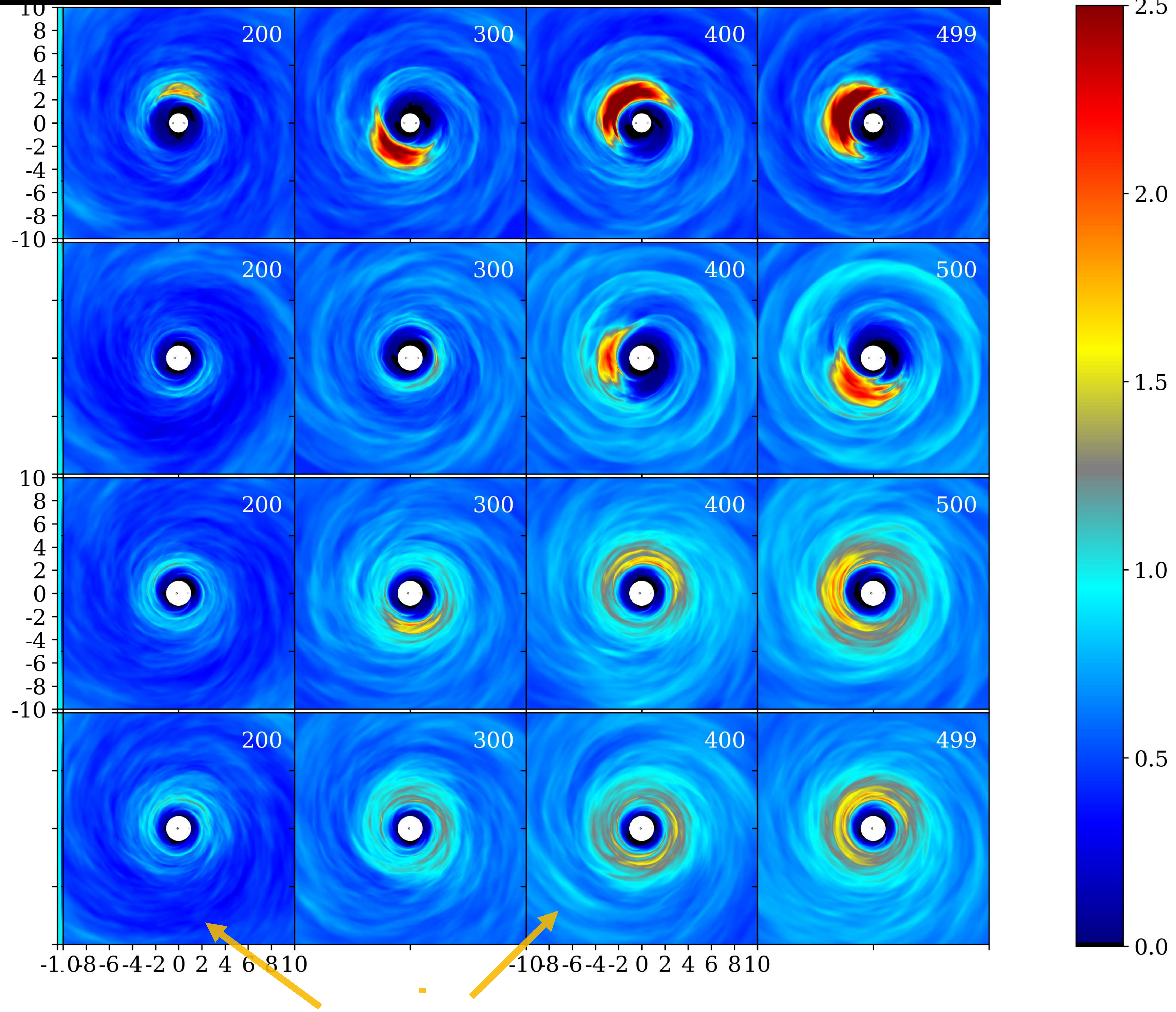
GRMHD + Approx. Spactime: Circumbinary Disks

a=50M

Noble+2025 (in prep)

Surface Density

(Top-down view)



Same times

$q=M_2/M$

q=1

q=0.5

q=0.2

q=0.1

- **Exploring binary separation and extending duration of runs out to 500 orbits to match 2d viscous hydrodynamic simulations;**
- **Lump still dominant q>0.2;**
- **Mild lump-like asymmetries exist down to q=0.1;**

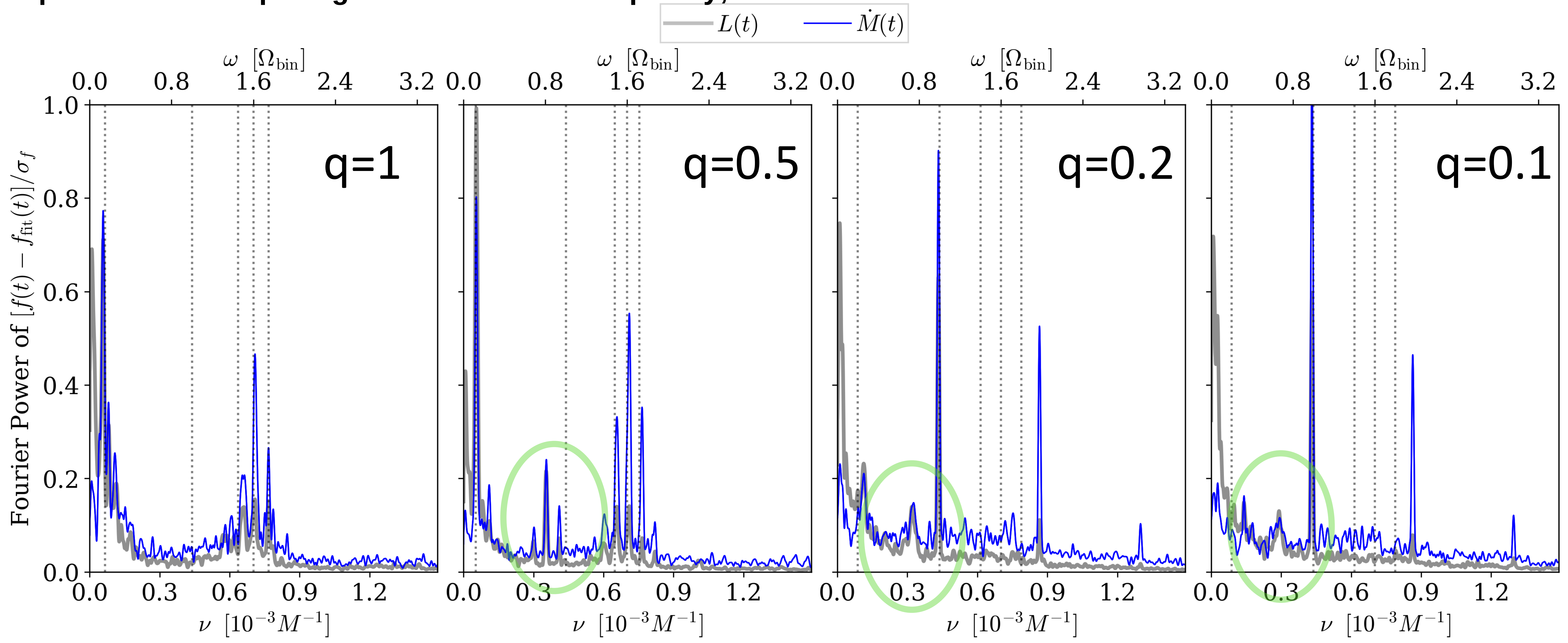
GRMHD + Approx. Spactime: Circumbinary Disks

a=50M

Noble+2025 (in prep)

- **Exploring binary separation and extending duration of runs;**
- **Lump still dominant q>0.2;**
- **For q<=0.2, orbital period dominates, though lump influence seen at low Q factor;**
- **q=0.5 shows unique signature at 1x beat frequency;**

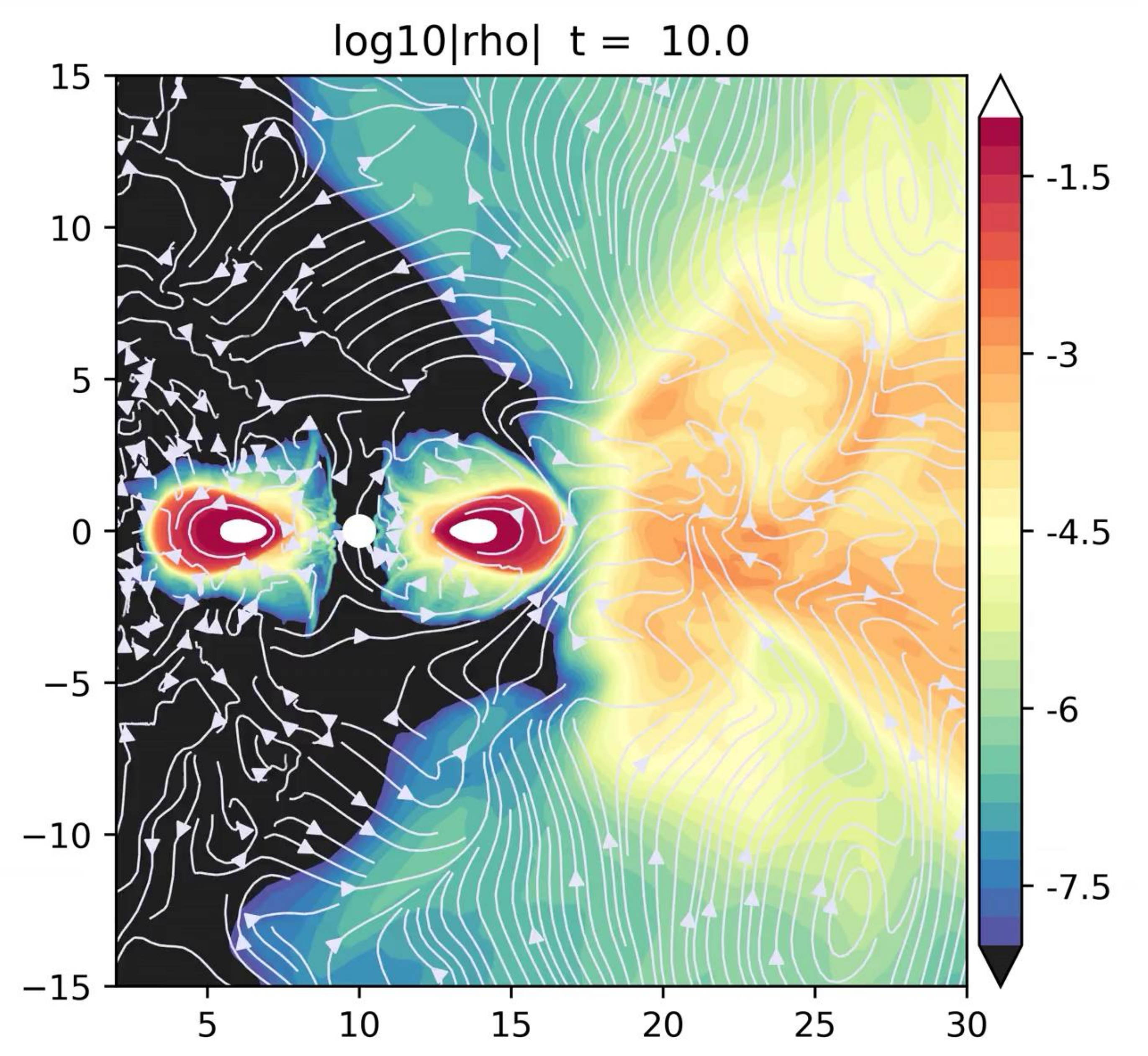
q=M₂/M

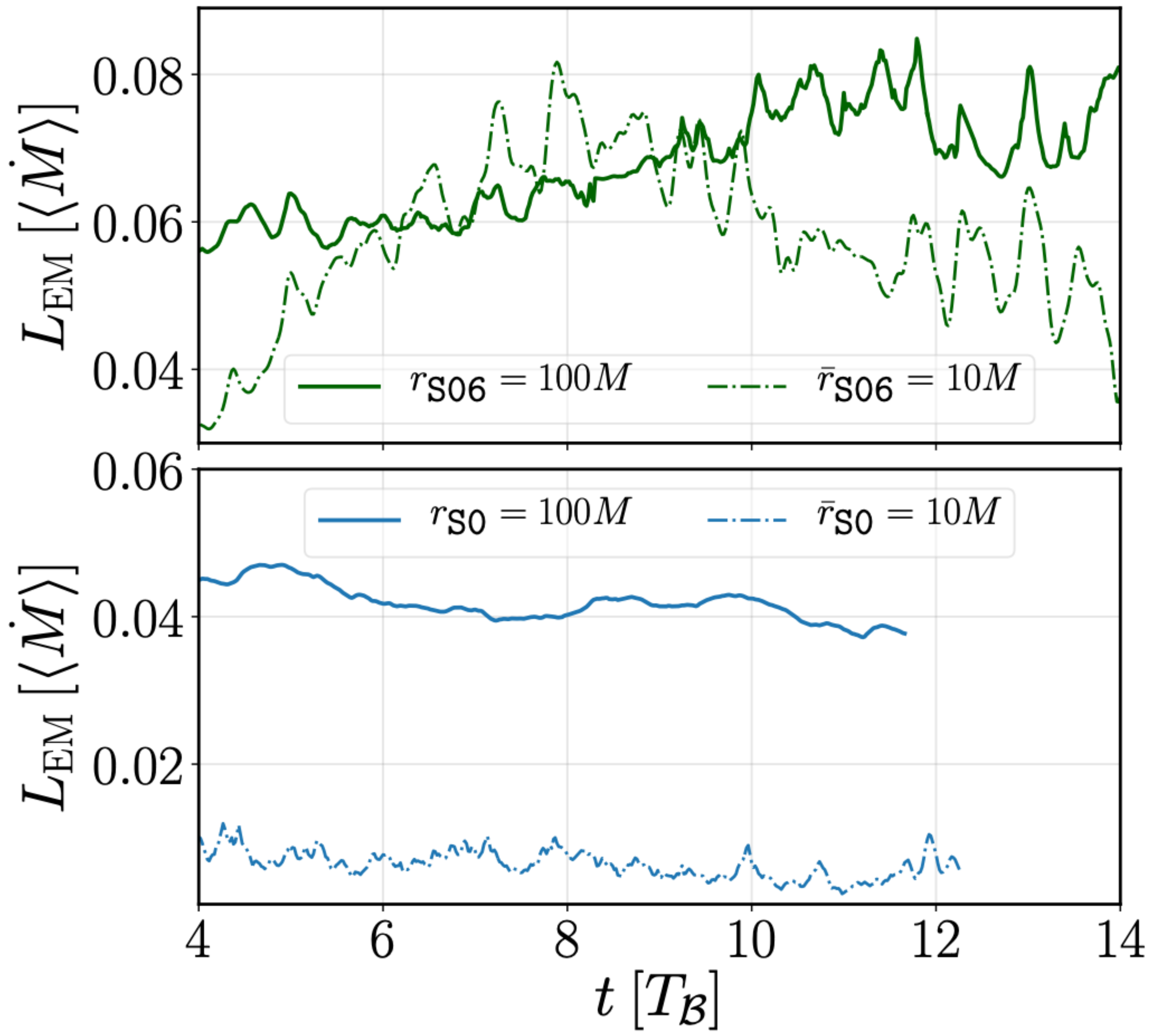


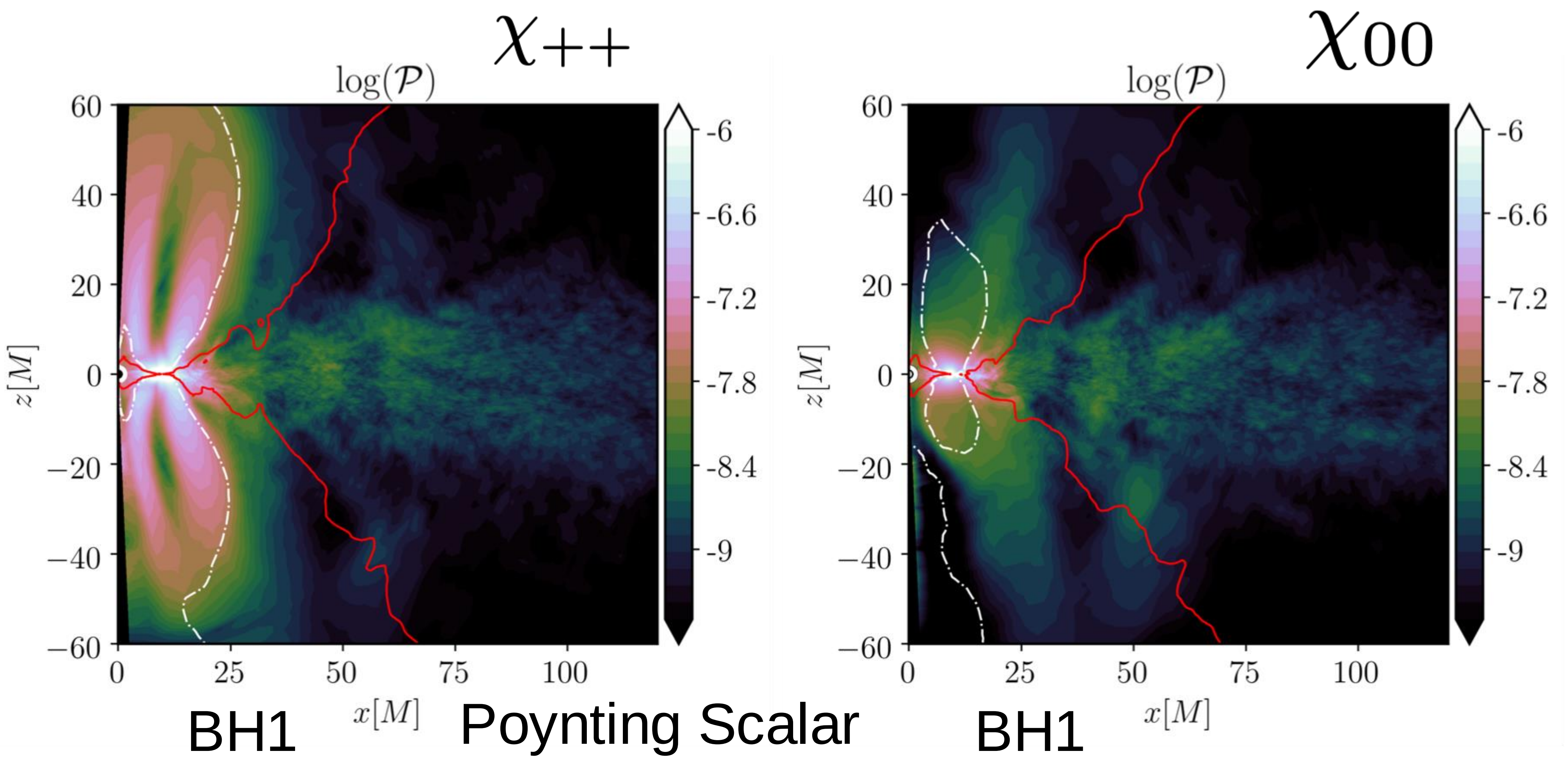
GRMHD+Approx. Spacetimes

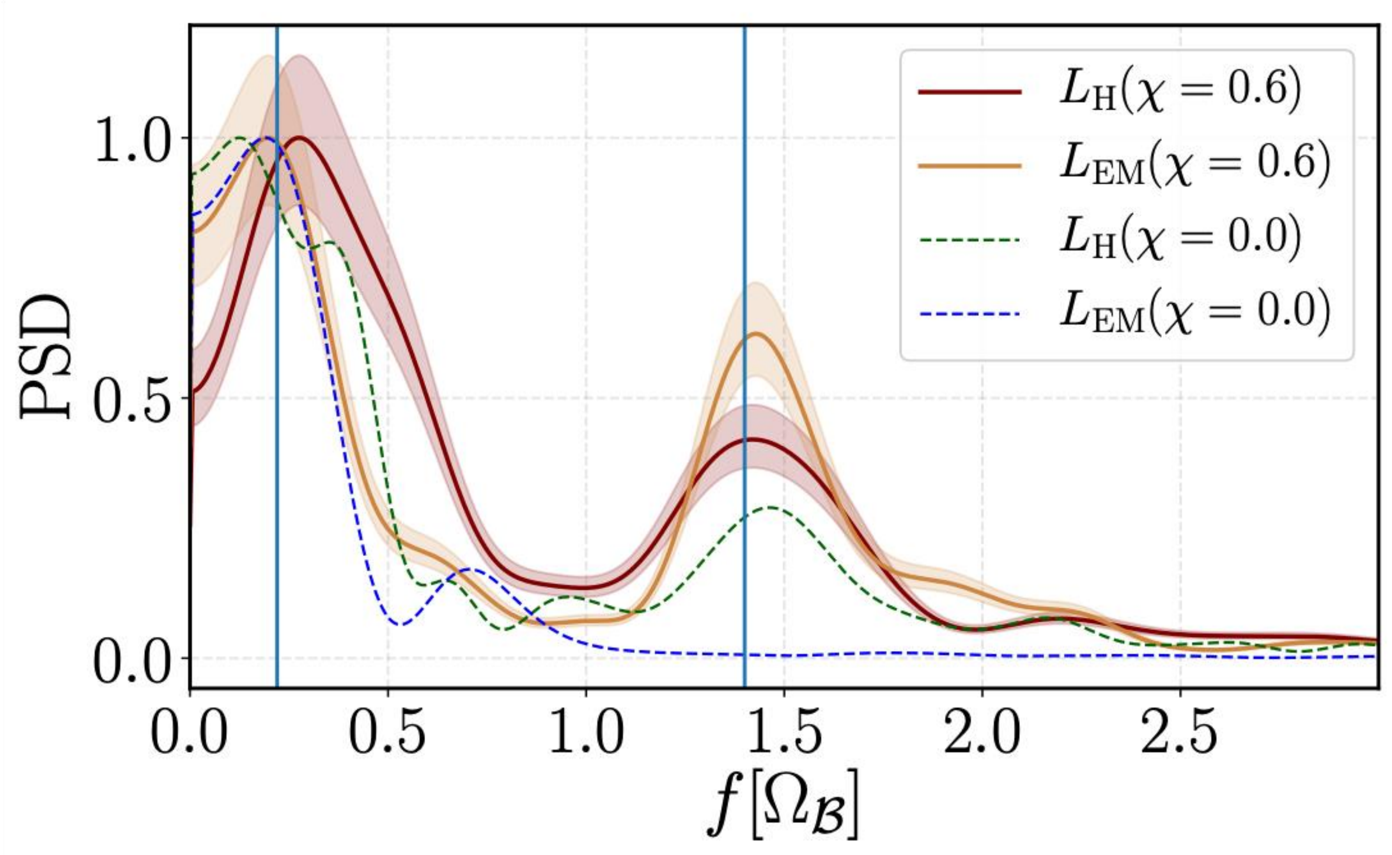
Circumbinary + Mini-Disk Regions

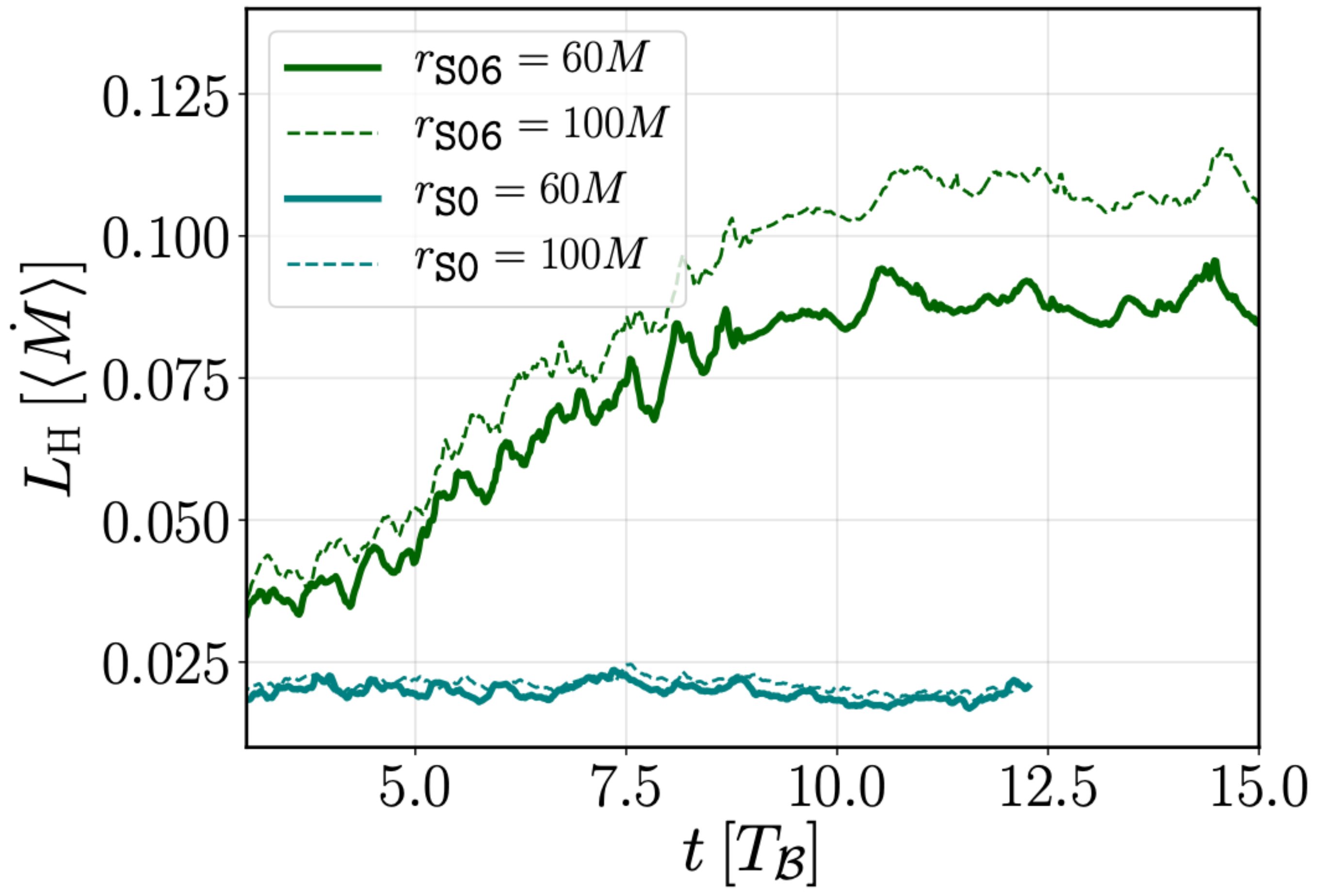
Combi, Lopez Armengol, Campanelli, Noble, Avara, Krolik, and Bowen, ApJ, 928, 187, (2022).











- **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;**

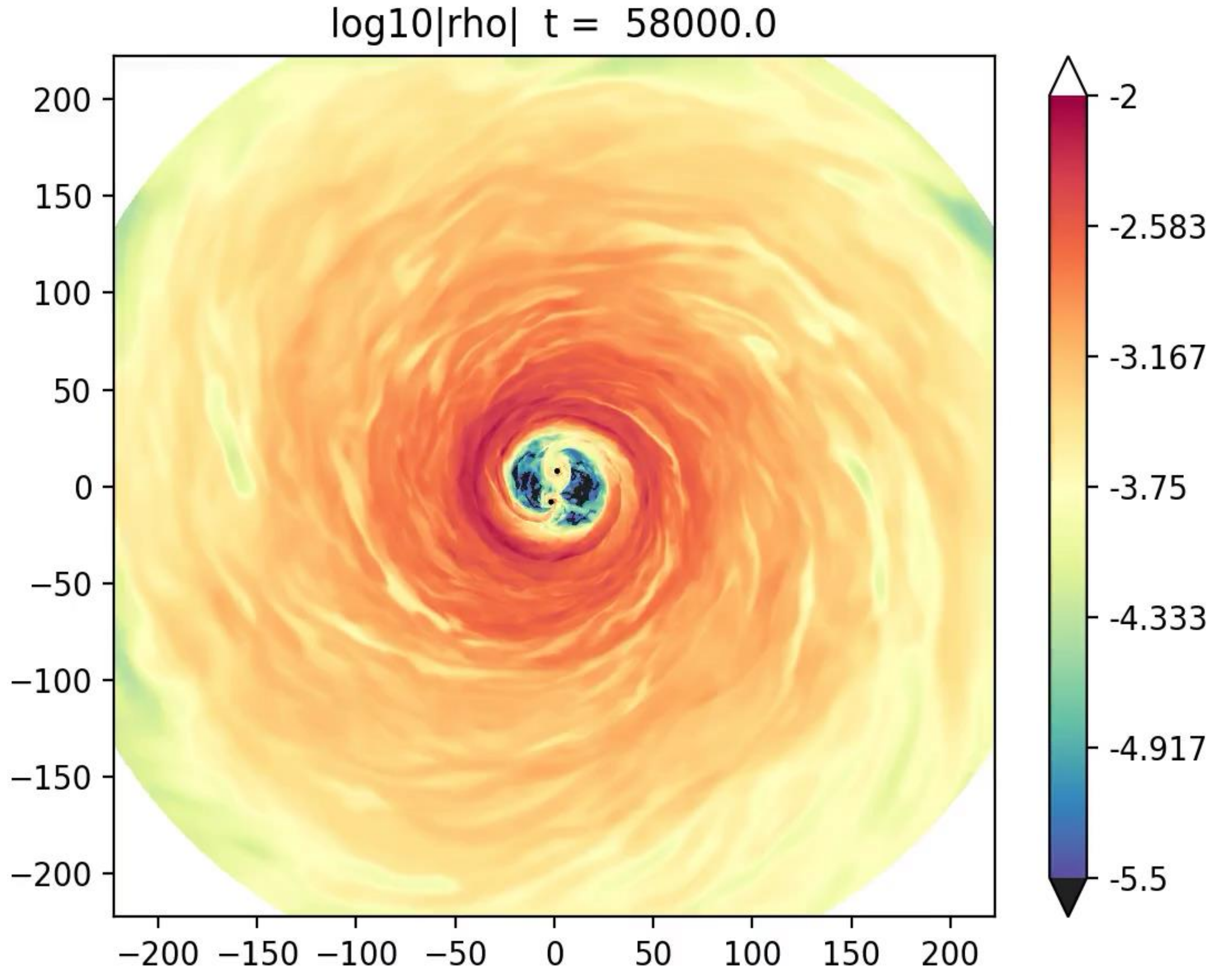
	χ_{00}	χ_{++}
$\eta_{\rm EM}$	0.5% —> 4%	5%
$\eta_{\rm H}$	2.5%	10%

Confirmed similar spin-dependent findings of Paschalidis, V., Bright, J., Ruiz, M., Gold, R., ApJL, 910, L26, (2021).

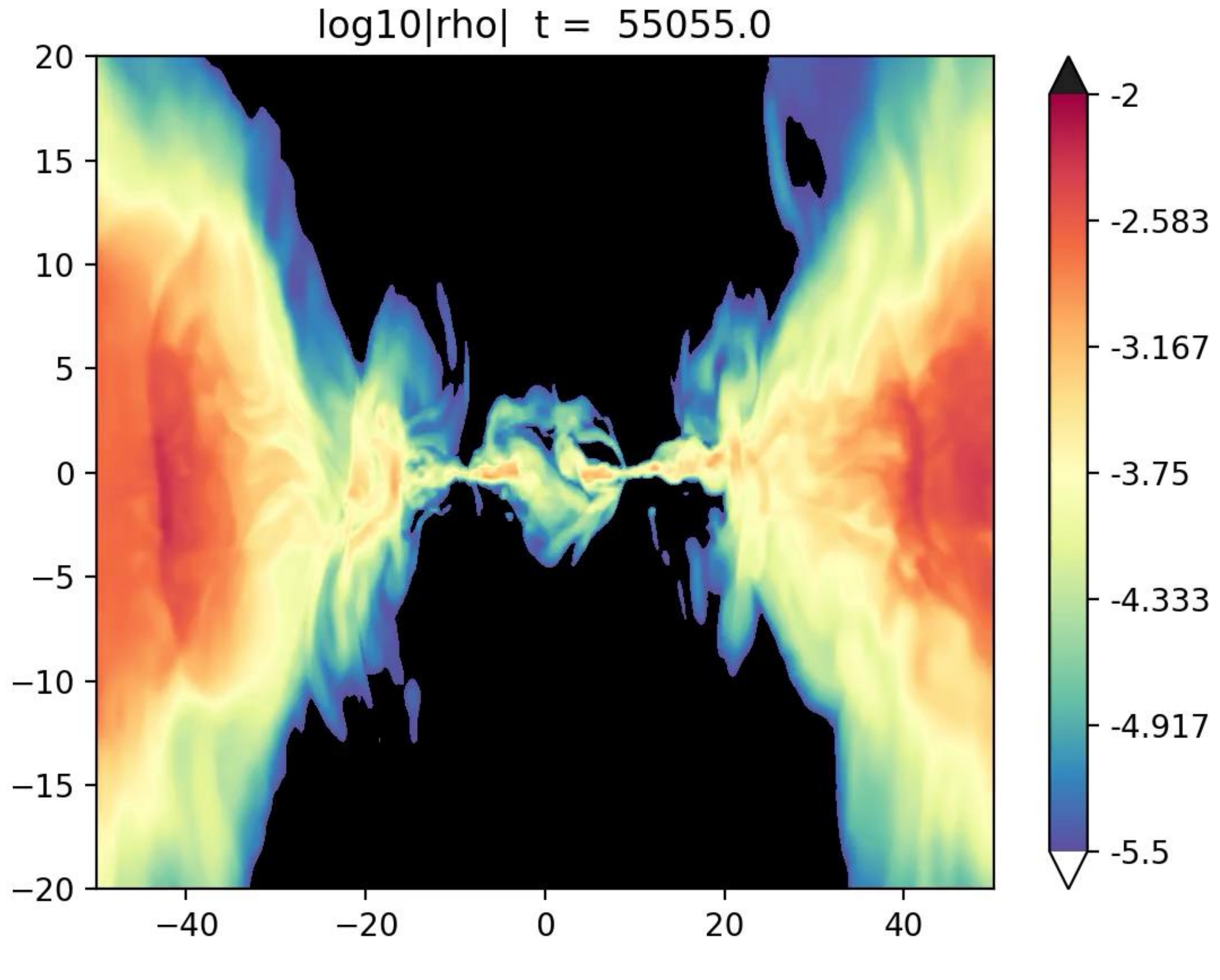
GRMHD + Approximate Spacetimes
PatchworkMHD : Mini-disks + Circumbinary Disk

- Start from only circumbinary data that has been relaxed over hundreds of binary orbits, possible only because we did not simulate the black holes on the grid.
- 34 binary orbits —> measure effects from orbital decay from gravitational radiation;
- Cartesian Patch: Uniform in x,y but graded in z.
- Spherical Patch: Same grid as circumbinary-only simulation (Noble++2012), no interpolation.

Avara, Krolik, Campanelli, Noble, Bowen, and Ryu, ApJ, 974, 242, (2024).



Top-down view



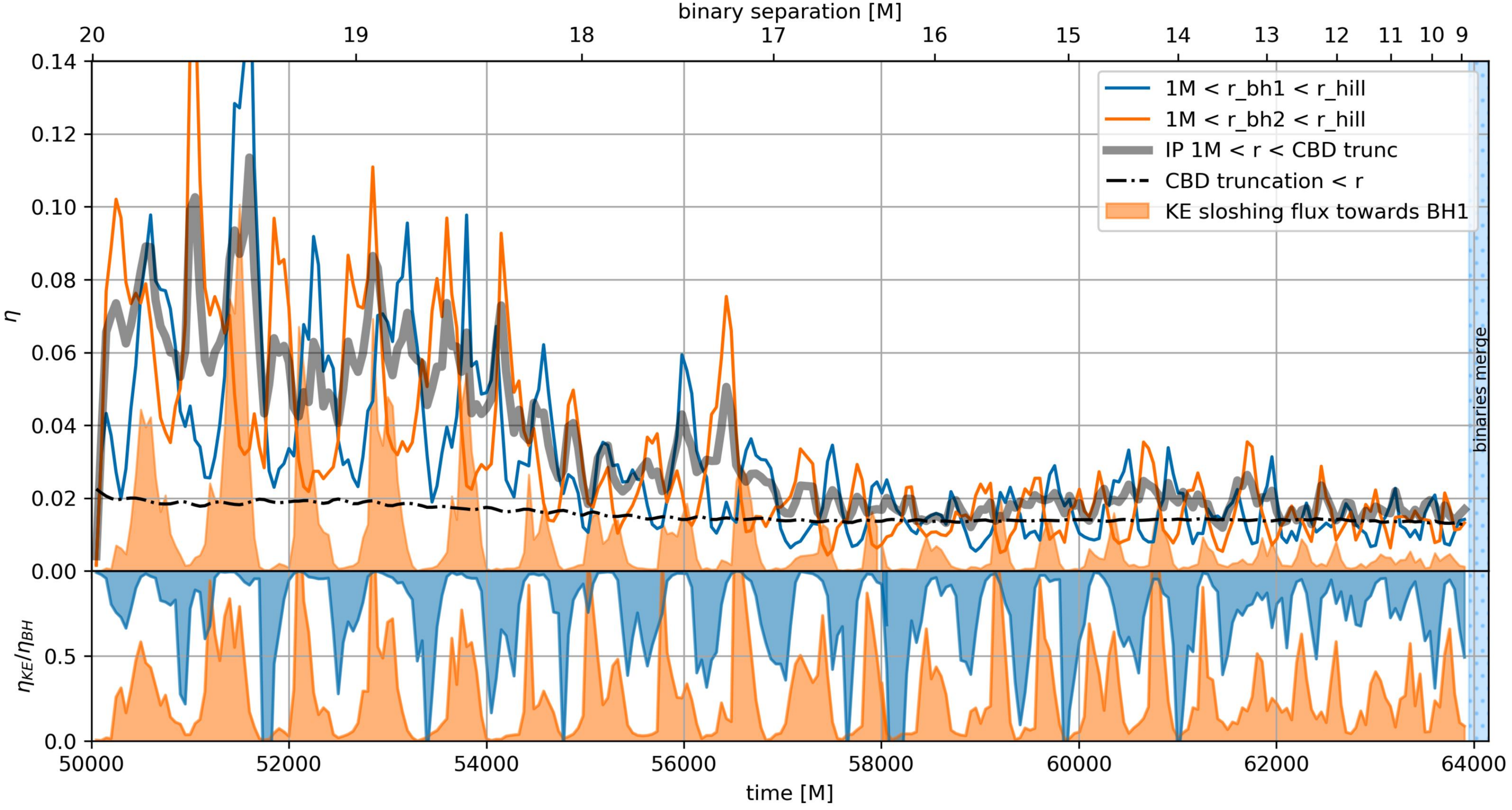
Side view

GRMHD + Approximate Spacetimes
PatchworkMHD : Mini-disks + Circumbinary Disk

Avara, Krolik, Campanelli, Noble, Bowen, and Ryu, ApJ, 974, 242, (2024).

Radiation Efficiency of Different Regions

Ratio of Sloshing Kinetic Energy to Radiative Efficiency



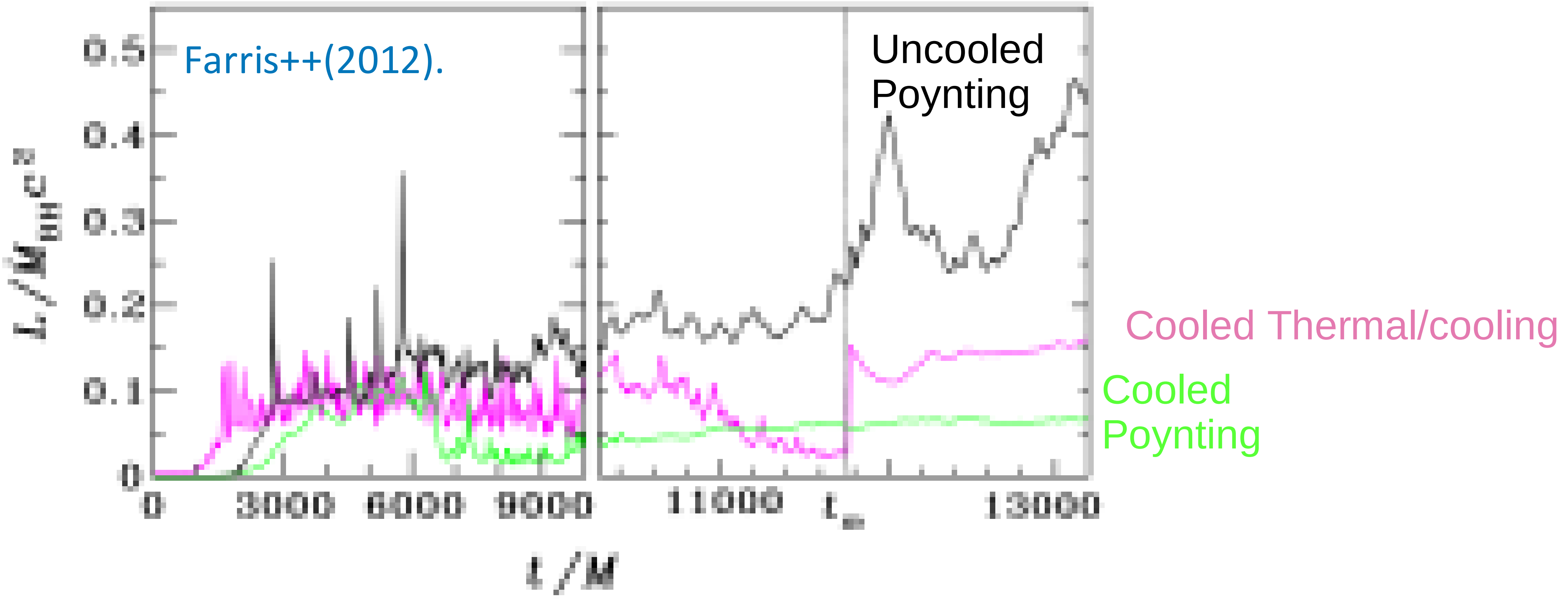
- PatchworkMHD allowed us to simulate the region between the BHs for the first time;
- Discovered that the KE of material sloshing between BHs can reach 100% of energy released from accretion;
  - New dissipative mechanism that may lead to new binary signatures (need to perform radiative transfer calculations);

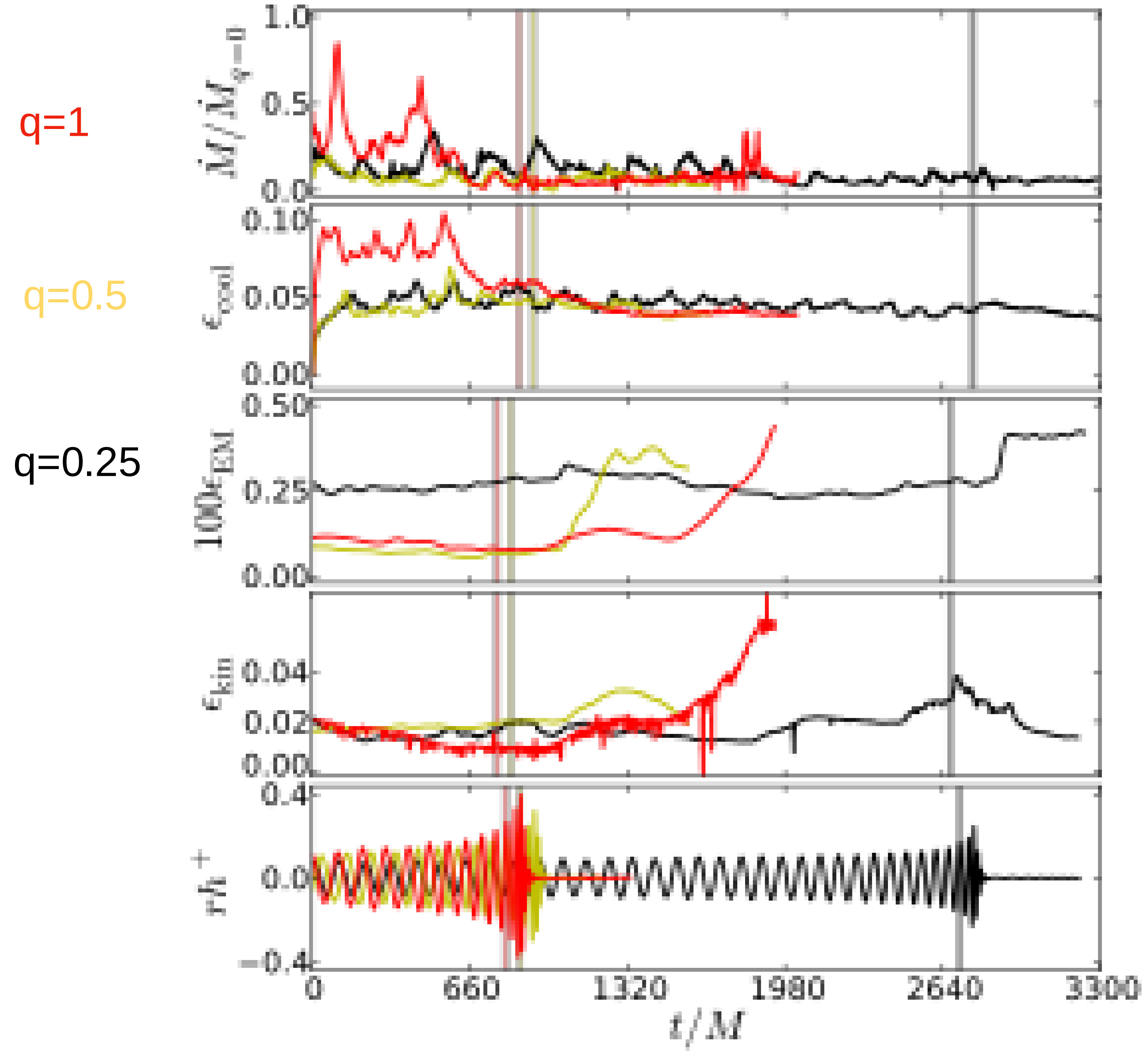
Numerical Relativity + MHD Evolutions

Accretion with Equilibrated 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).

Non-spinning, cooled & uncooled;
q = M2/M1 = 0.1 – 1.0; cooled & uncooled; Fixed separation (pre-inspiral)
q = M2/M1 = 0.1 – 1.0; cooled & uncooled; Inspiral --> Merger





$$T_{\rm eff} \sim 10^5 \left(\frac{L_b}{L_{\rm Edd}}\right)^{1/4} \left(\frac{M}{10^8 M_\odot}\right)^{-1/4} \mathrm{K}.$$

$$\nu_{bb} \sim 10^{15} \left(\frac{M}{10^8 M_\odot}\right)^{-1/4} \left(\frac{L_b}{L_{\rm Edd}}\right)^{1/4} (1+z)^{-1}\ \mathrm{Hz}.$$

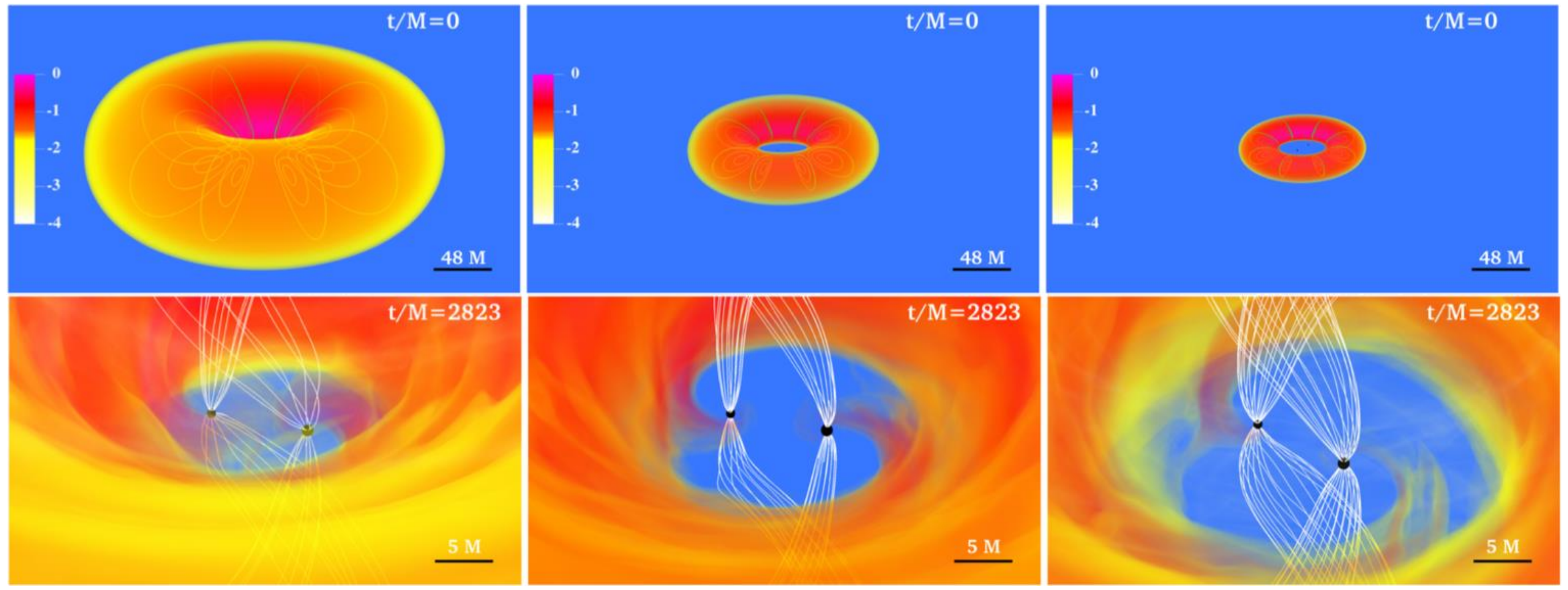
- a(t=0) ~= 13 r_g
- All use time-symmetric spacetime data interpolated from SpEC grids to IllinoisGRMHD/Carpet Cartesian block AMR grids;
- Run 45 orbits at fixed separation to equilibrate the disk;
- Geometrically thick disks: H/R ~ 0.3;
- Lump is reported to be seen, but not apparent in results;
- Cavity wall is <2a for cooling and uncooled runs;
- About 30% of radiative cooling comes from within the cavity;

- Thermal UV emission;
- Poynting flux brightens after merger;
- Radiative (cooling) flux remains steady through merger;

Numerical Relativity + MHD Evolutions

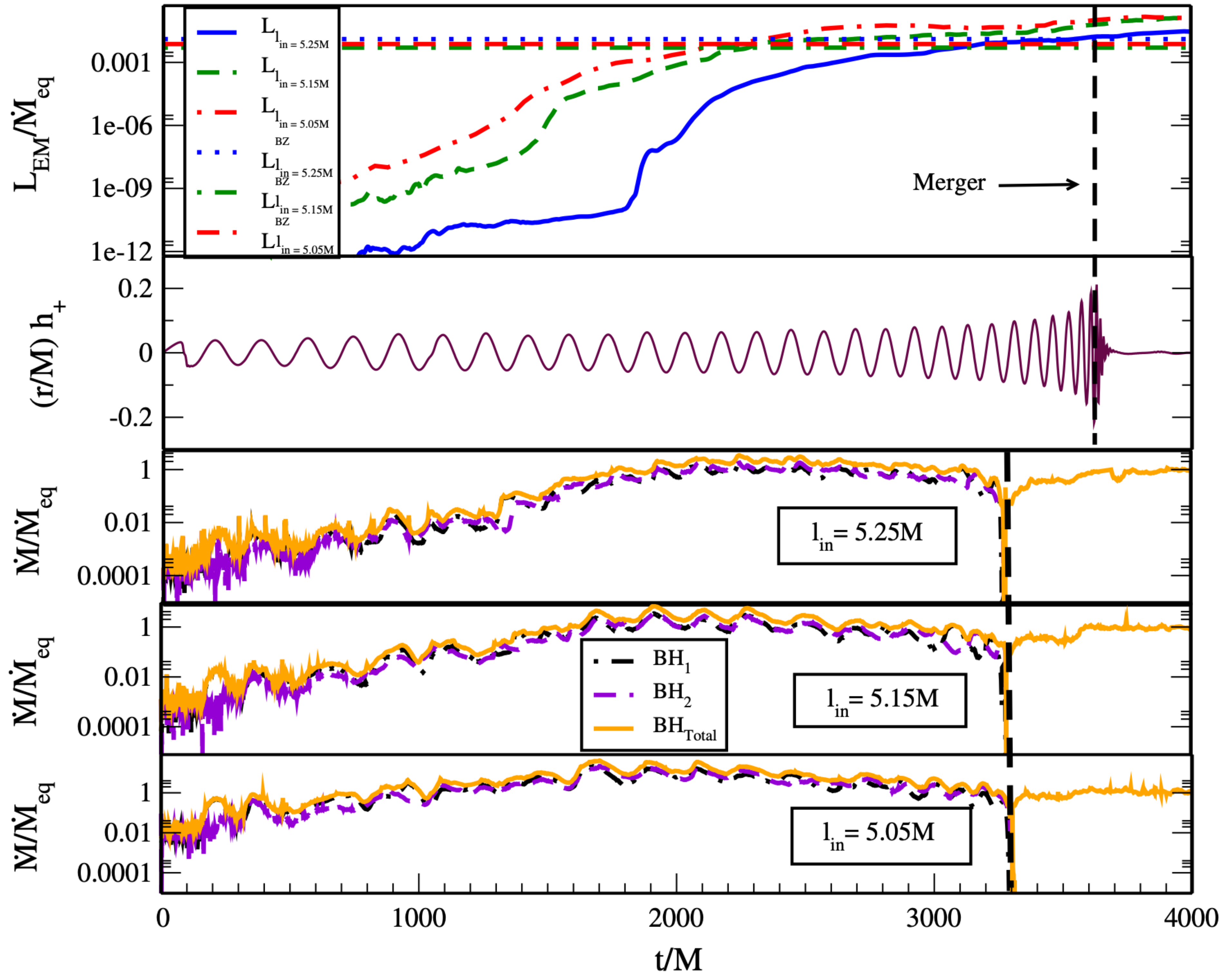
Accretion with Magnetized Hydrostationary Tori

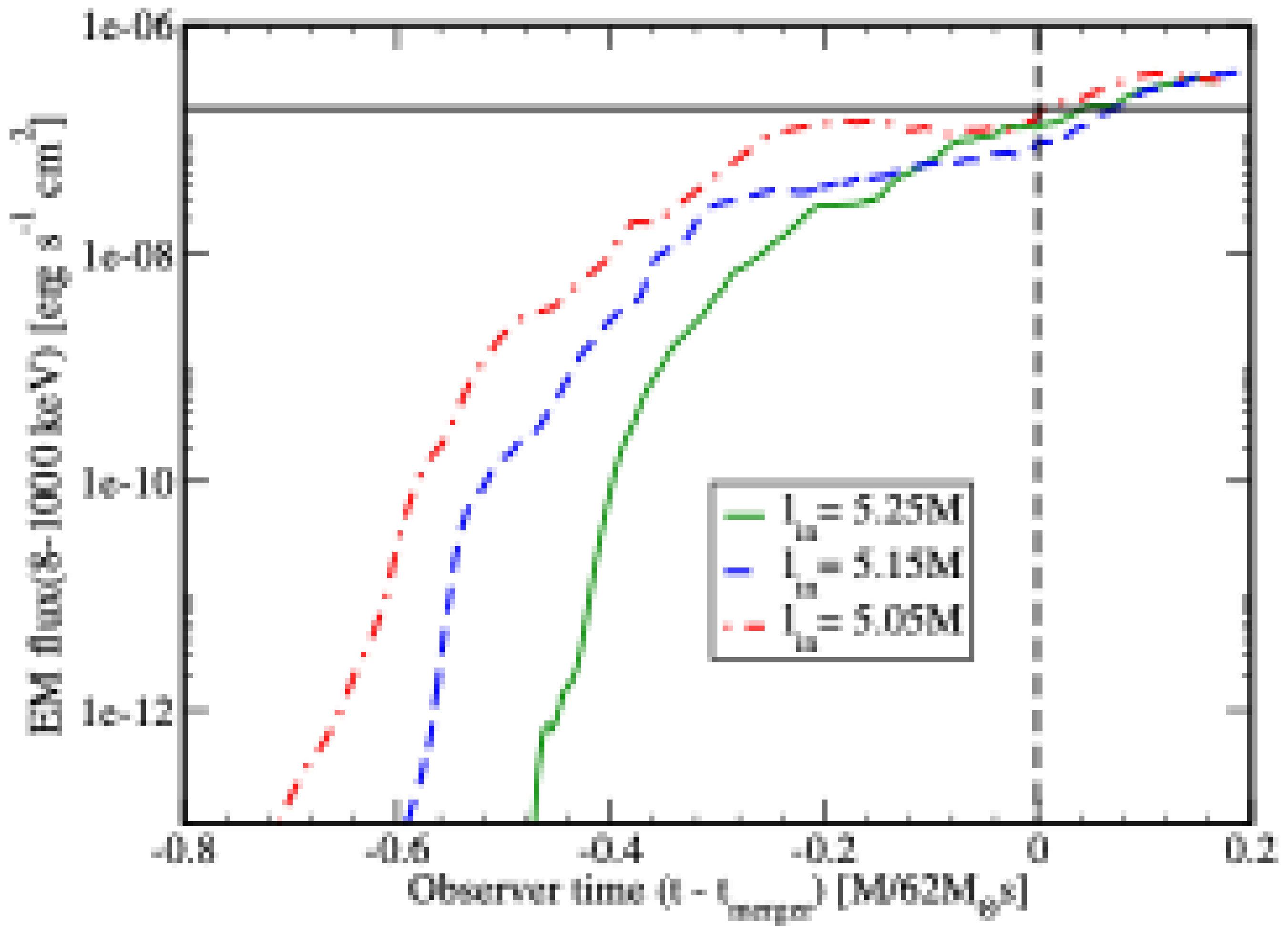
Khan, A., Paschalidis, V., Ruiz, M., Shapiro, S. L., PhRvD, 97, 044036, (2018).
Ruiz, Tsokaros, and Shapiro, PhRvD, 108, 124043, (2023).

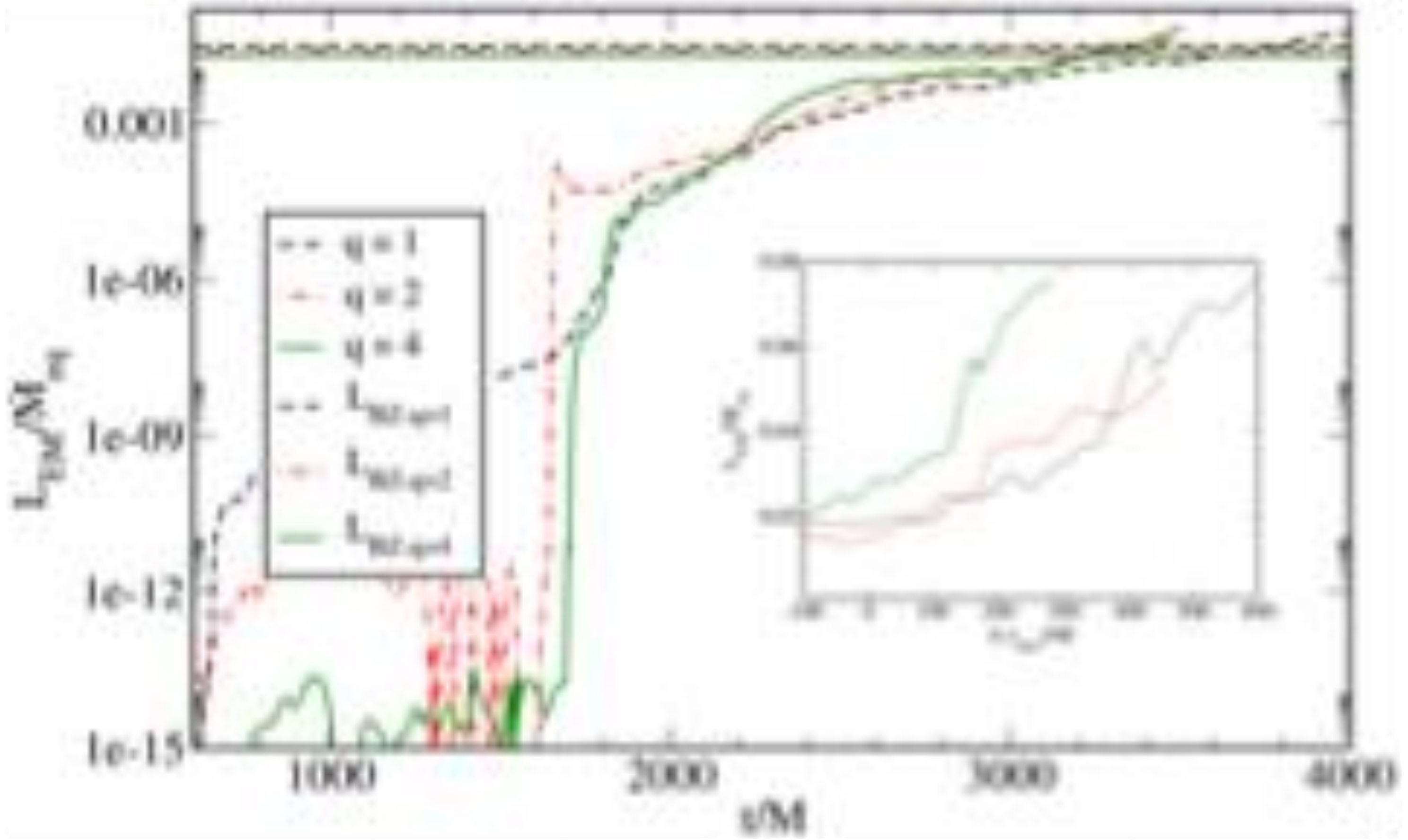


- Start from axi-symmetric hydrostationary tori at about r=1.4a;
- a(t=0) ~= 14M;
- Uncooled, H/R = 0.3;

$$\frac{a_d}{M} \approx 11.5 \left(\frac{\beta}{1.3}\right)^{3/5} \left(\frac{\eta}{1}\right)^{2/5} \left(\frac{\alpha}{0.1}\right)^{-2/5} \left(\frac{H/R}{0.3}\right)^{-4/5}$$







Case	q	$S_y/M^2_{\rm irr}$	$S_z/M^2_{\rm irr}$	a/M	ΩM	J/M^2
q1	1	0.26	0.0	14.0	1.74×10^{-2}	1.07
q2	2	0.184	0.184	13.25	1.89×10^{-2}	1.03
q4	4	0.184	0.184	12.5	2.04×10^{-2}	0.78

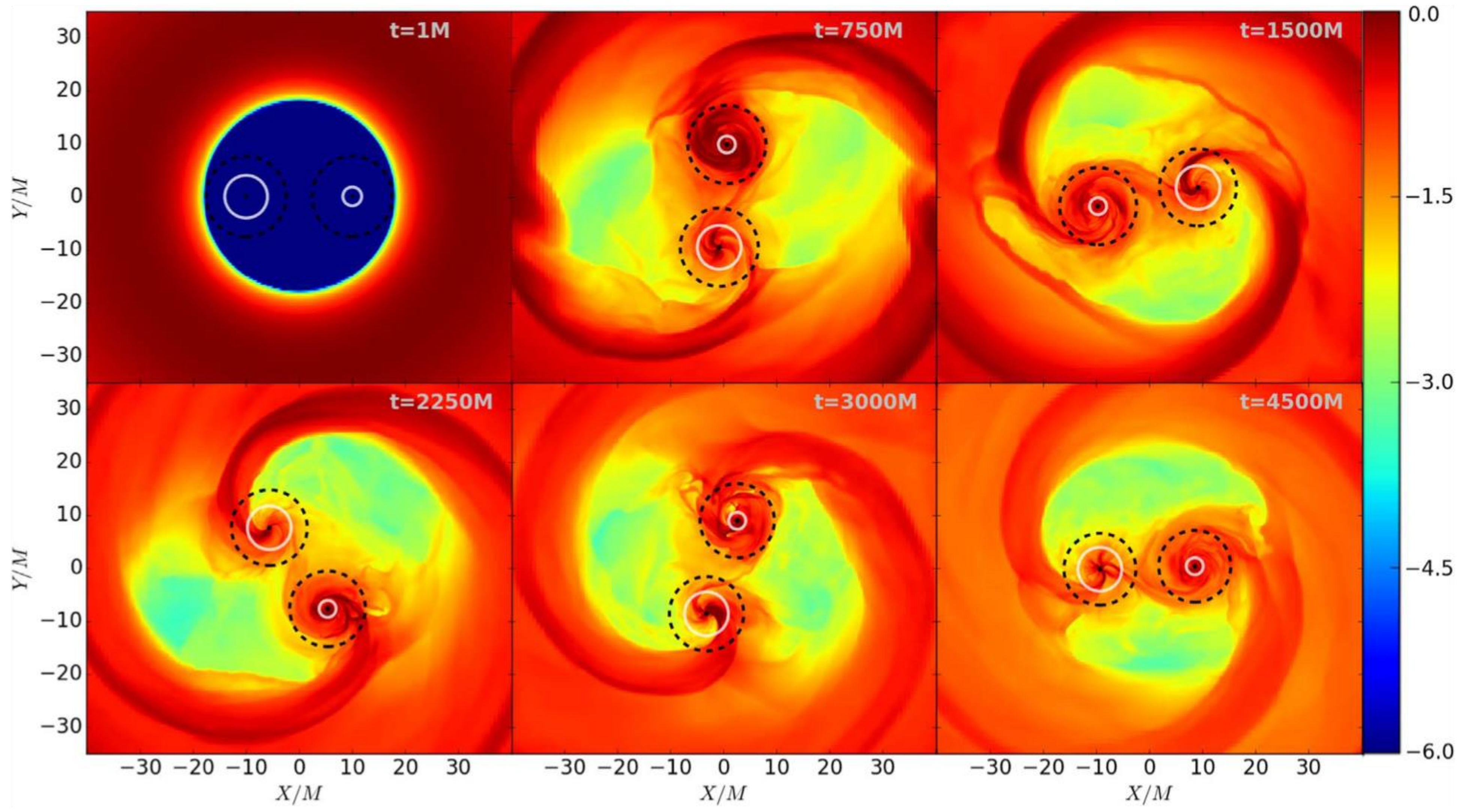
- In-plane spins lead to delayed Poynting flux brightening post-merger;
- Poynting luminosity seems insensitive to mass-ratio, continues rising thru merger;
- Accretion rate is insensitive to different initial torus sizes; though Poynting flux is not;

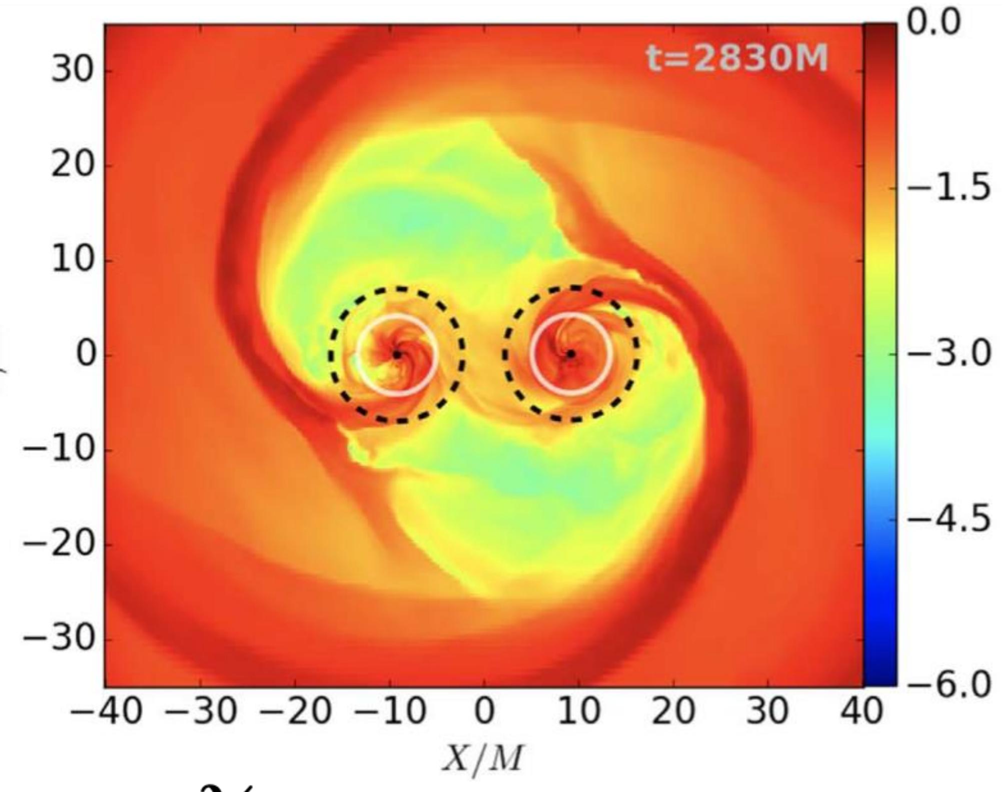
Numerical Relativity + MHD Evolutions

Accretion with Magnetized Tori + BH Spins

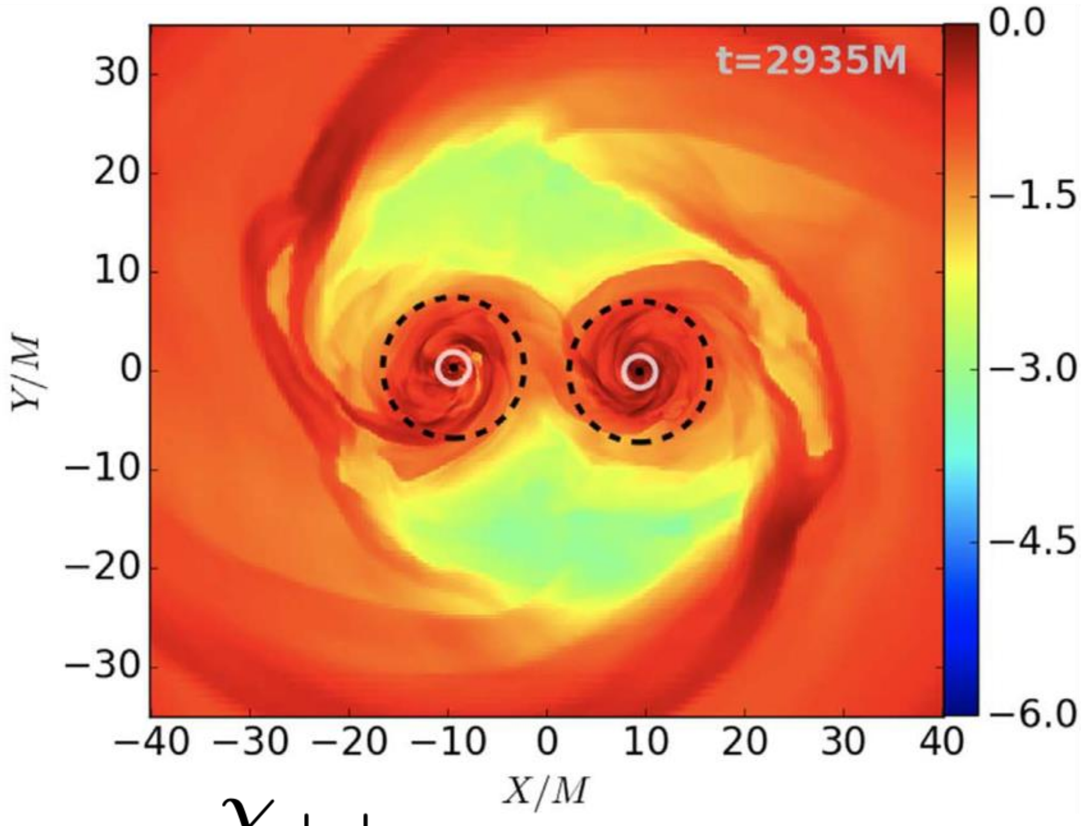
Paschalidis, V., Bright, J., Ruiz, M., Gold, R., ApJL, 910, L26, (2021).
Bright and Paschalidis, MNRAS, 520, 392, (2023).

χ_{+-}

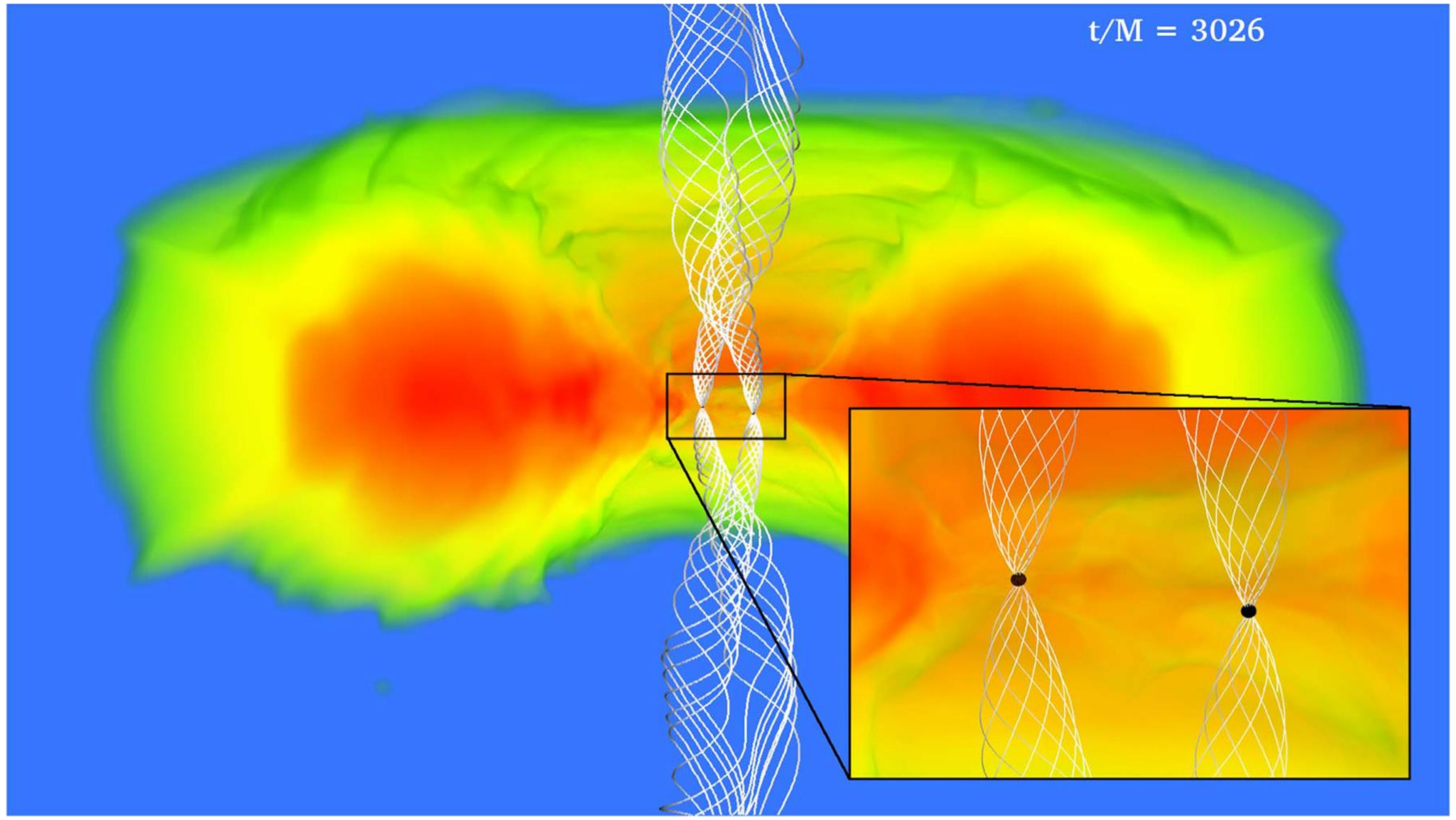




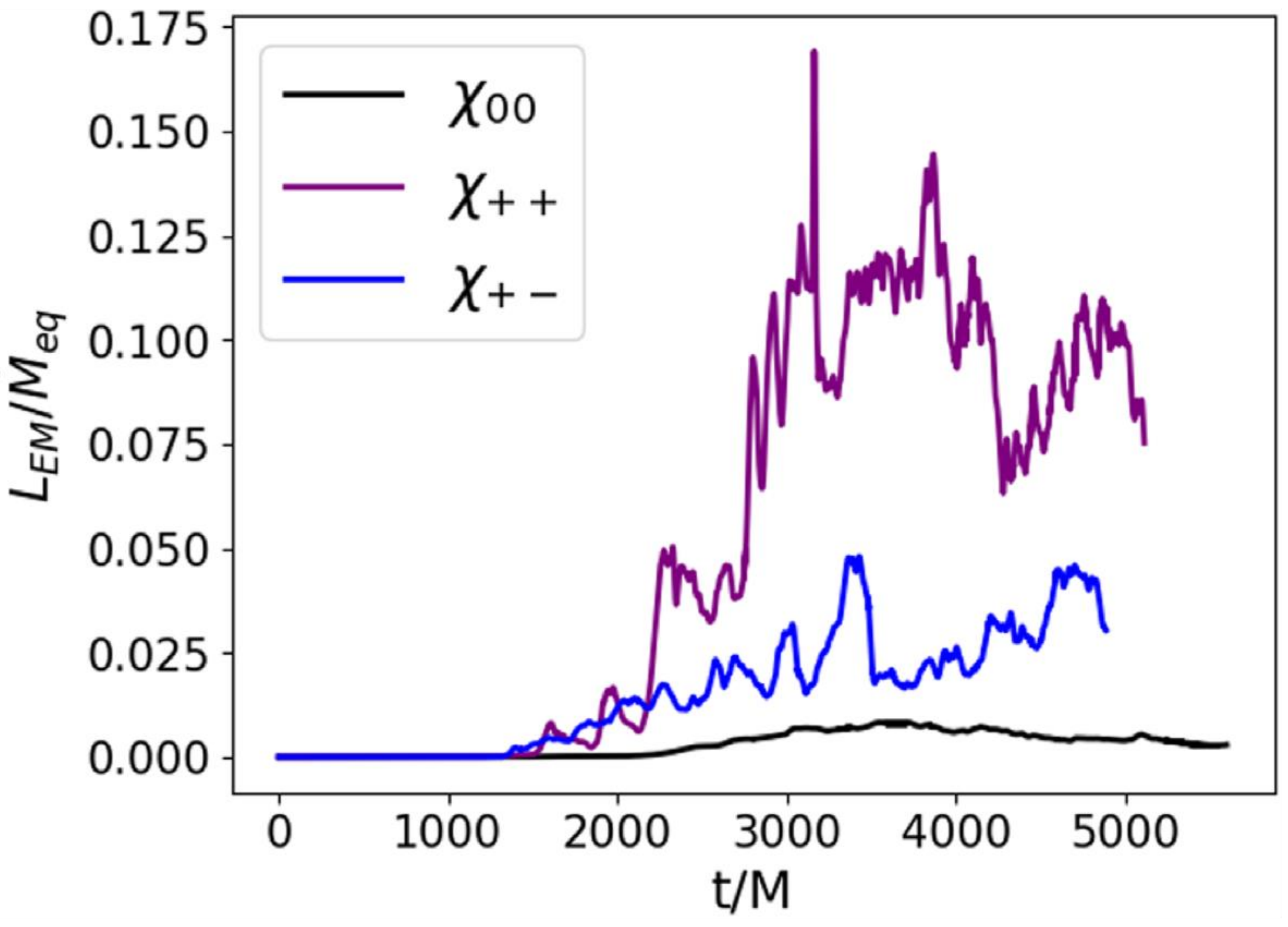
χ_{--}



χ_{++}



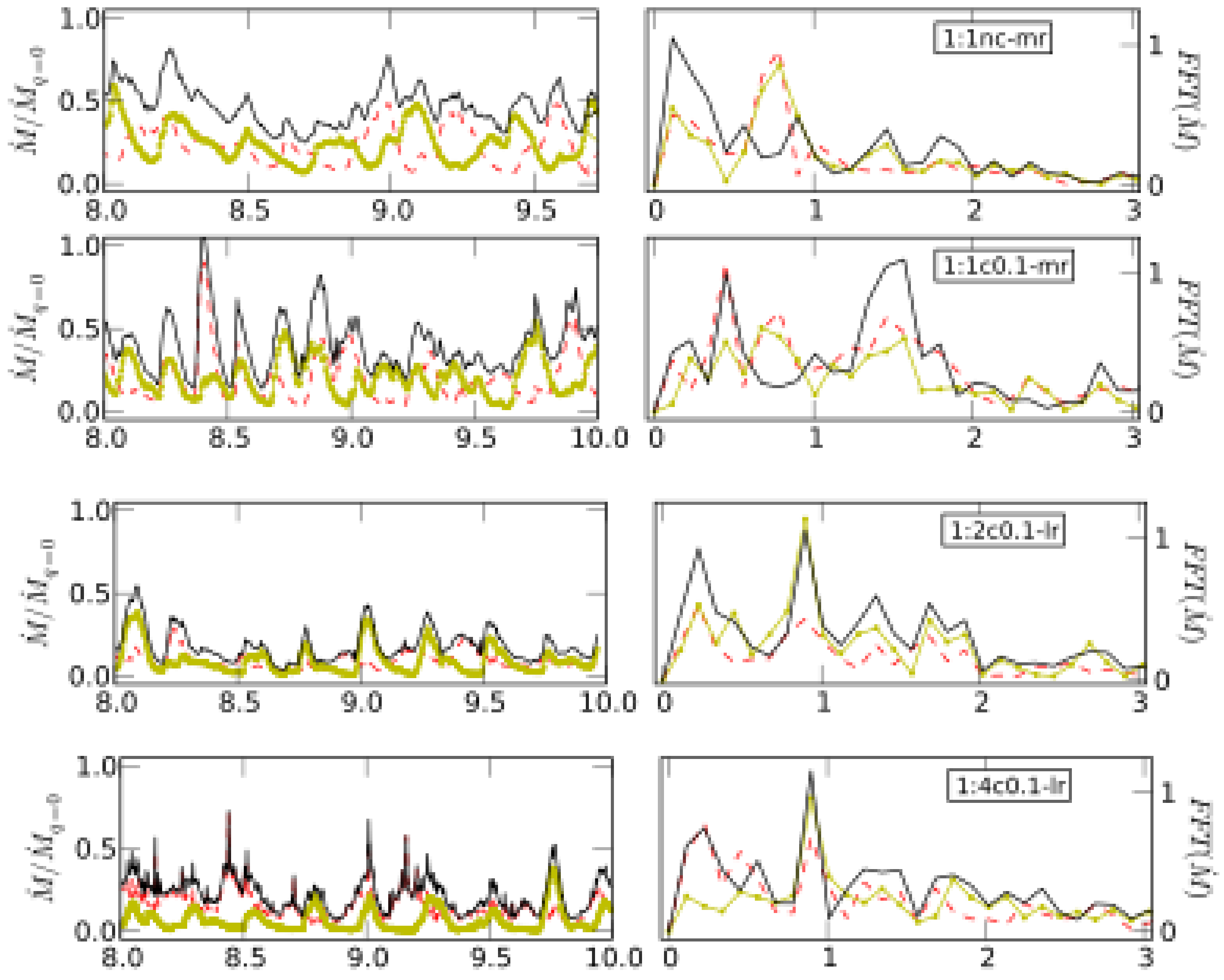
- Spinning BHs; $\chi = \pm 0.75, 0$
- a = 20M
- Larger r_{Hill}/r_{ISCO} lead to larger mini-disks;
- ☆ Spins and larger mini-disks yield larger Poynting luminosities;



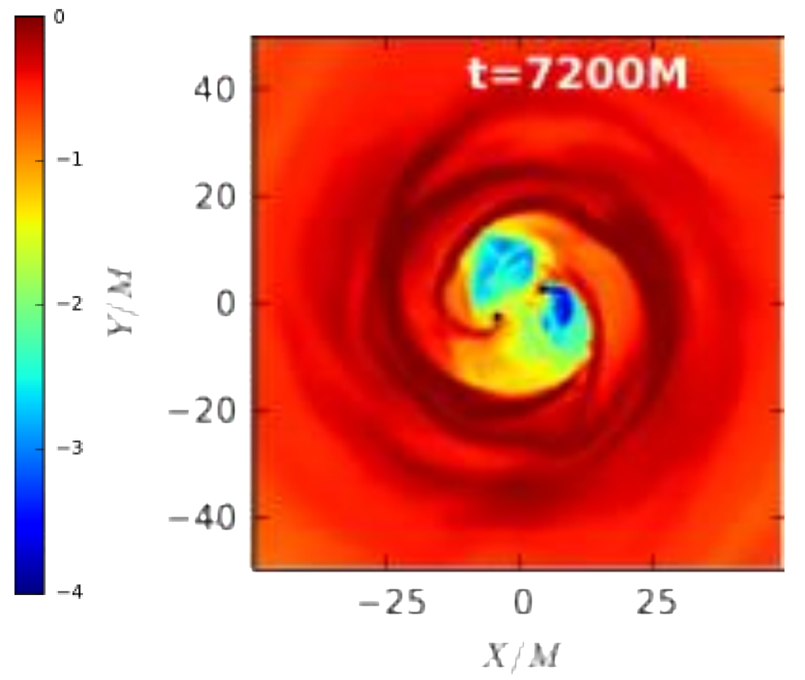
GRMHD Disk Evolutions

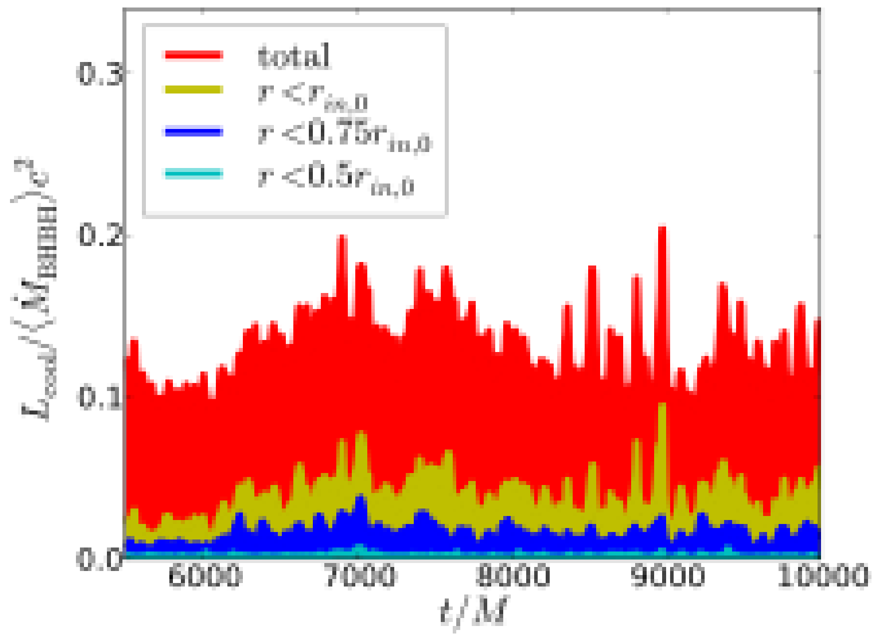
Gold, R., Paschalidis, V., Etienne, Z. B., Shapiro, S. L., Pfeiffer, H. P., PhRvD, 89, 064060, (2014).

- Cooled/uncooled disks, a~=13M, H/R ~=0.3,
- different mass ratios;



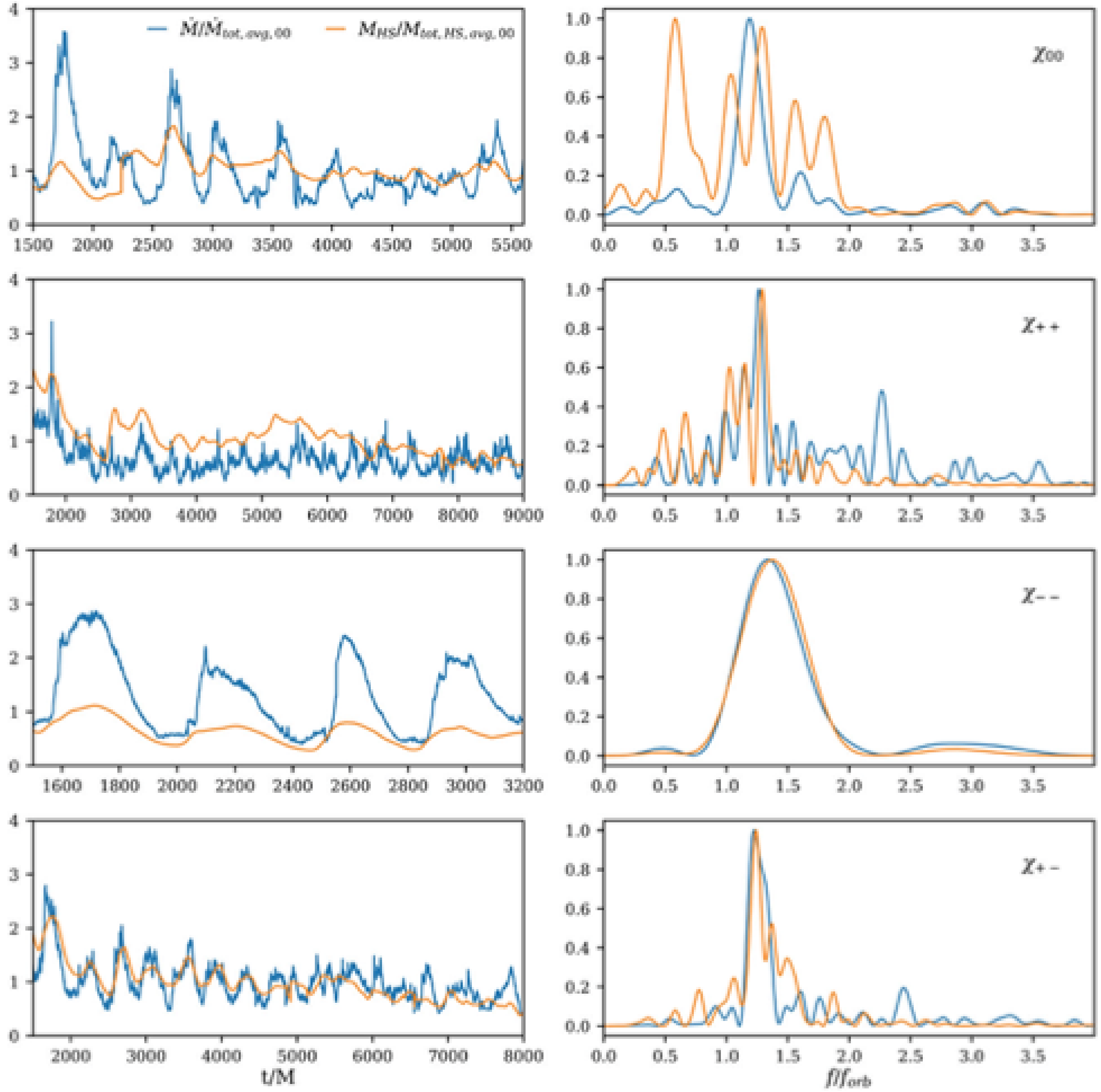
- No clear trend with mass ratio;
- Strongest peaks at binary frequency and sometimes 2xbeat;





Bright and Paschalidis, MNRAS, 520, 392, (2023).

- Uncooled disks, a~=20M, different spins: $\chi = \pm 0.75, 0$

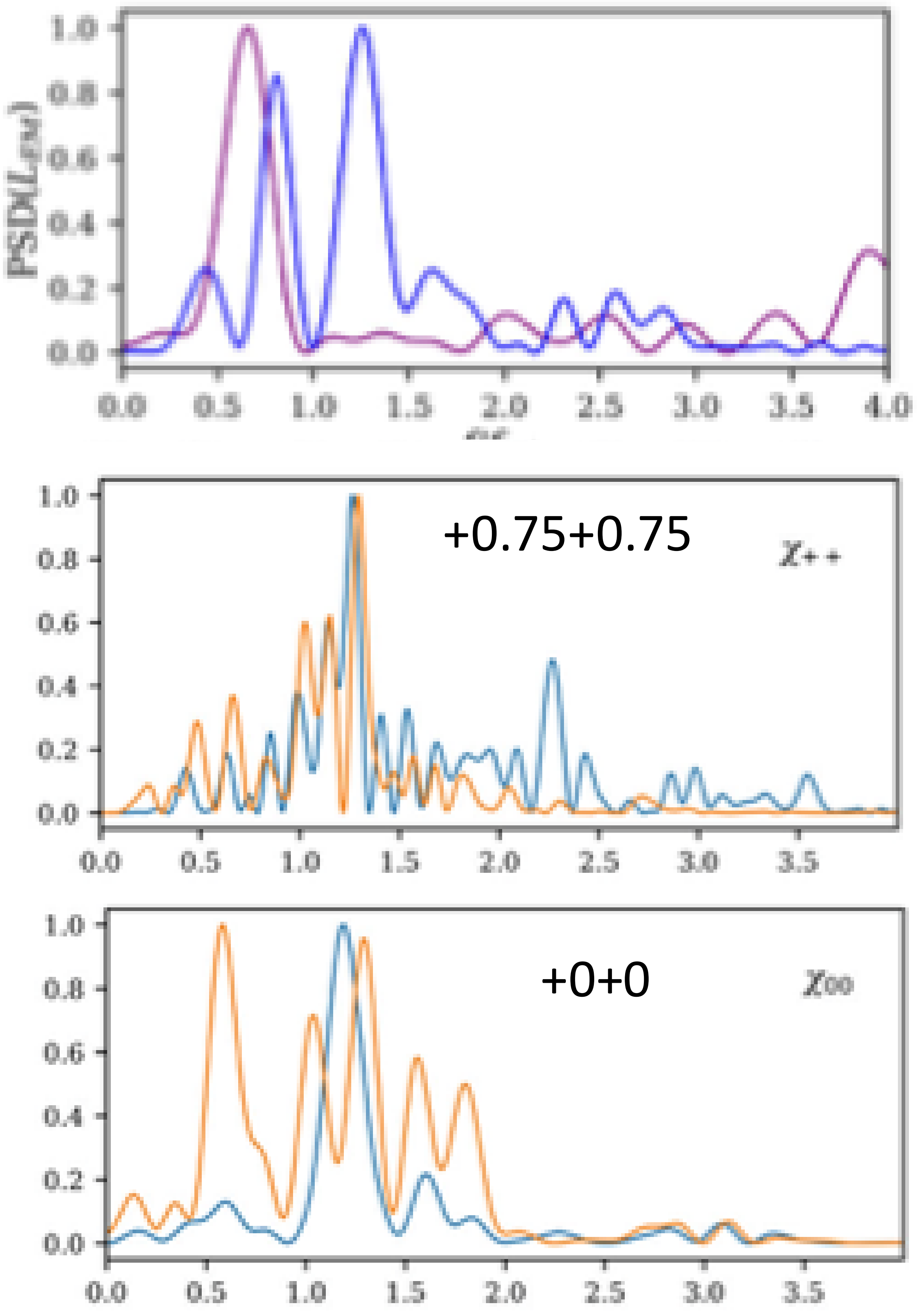


- Spins → mini-disks → steadier accretion & higher frequency variability

GRMHD Disk Evolutions

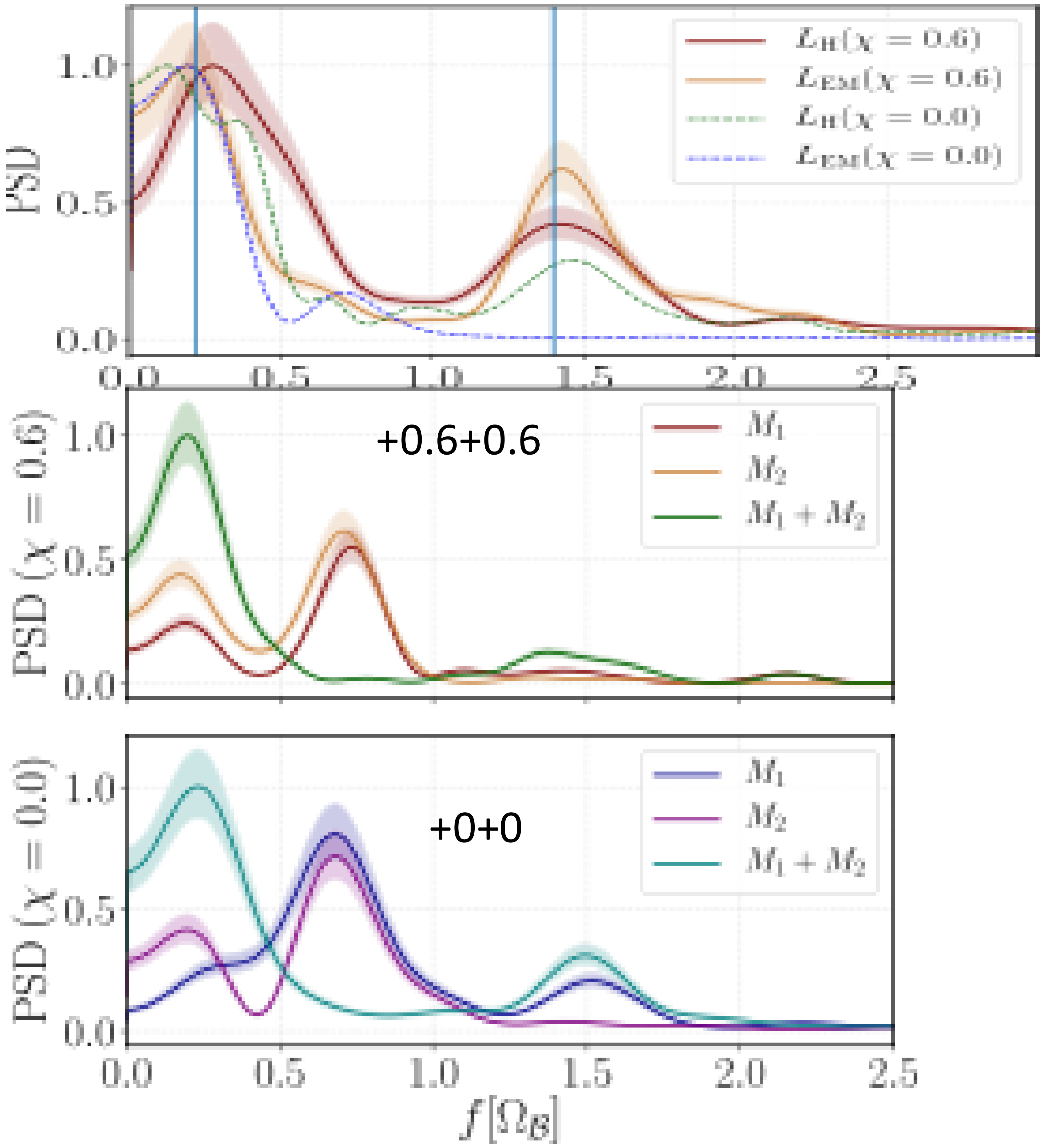
Bright and Paschalidis, MNRAS, 520, 392, (2023).

- Uncooled, H/R=0.3 disks, different spins:



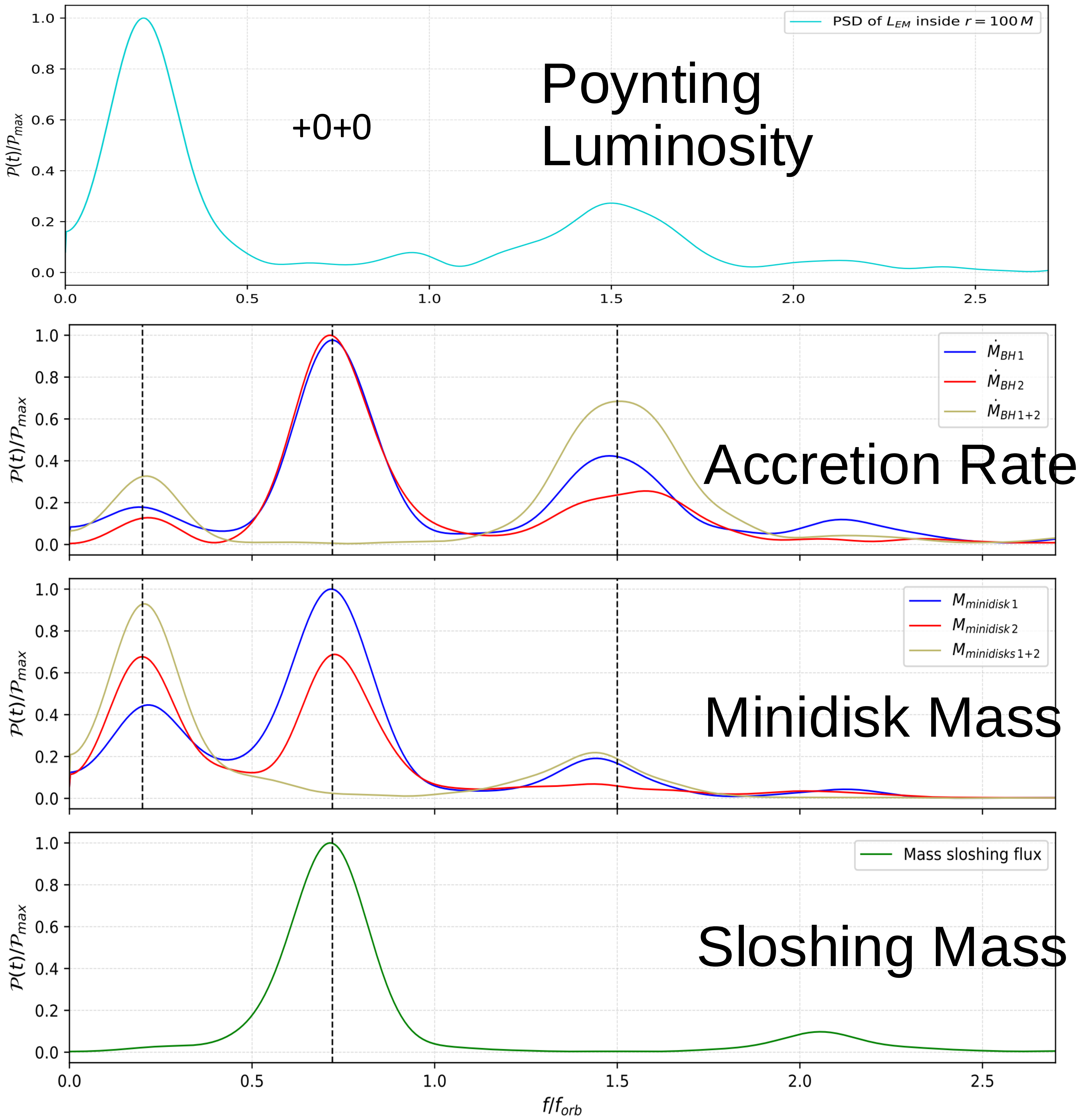
Bowen++(2018,19) cooled
Combi++(2022), cooled

- Cooled, H/R=0.1, 15 orbits down to a=15 r_g



Ennoggi++ (2025)

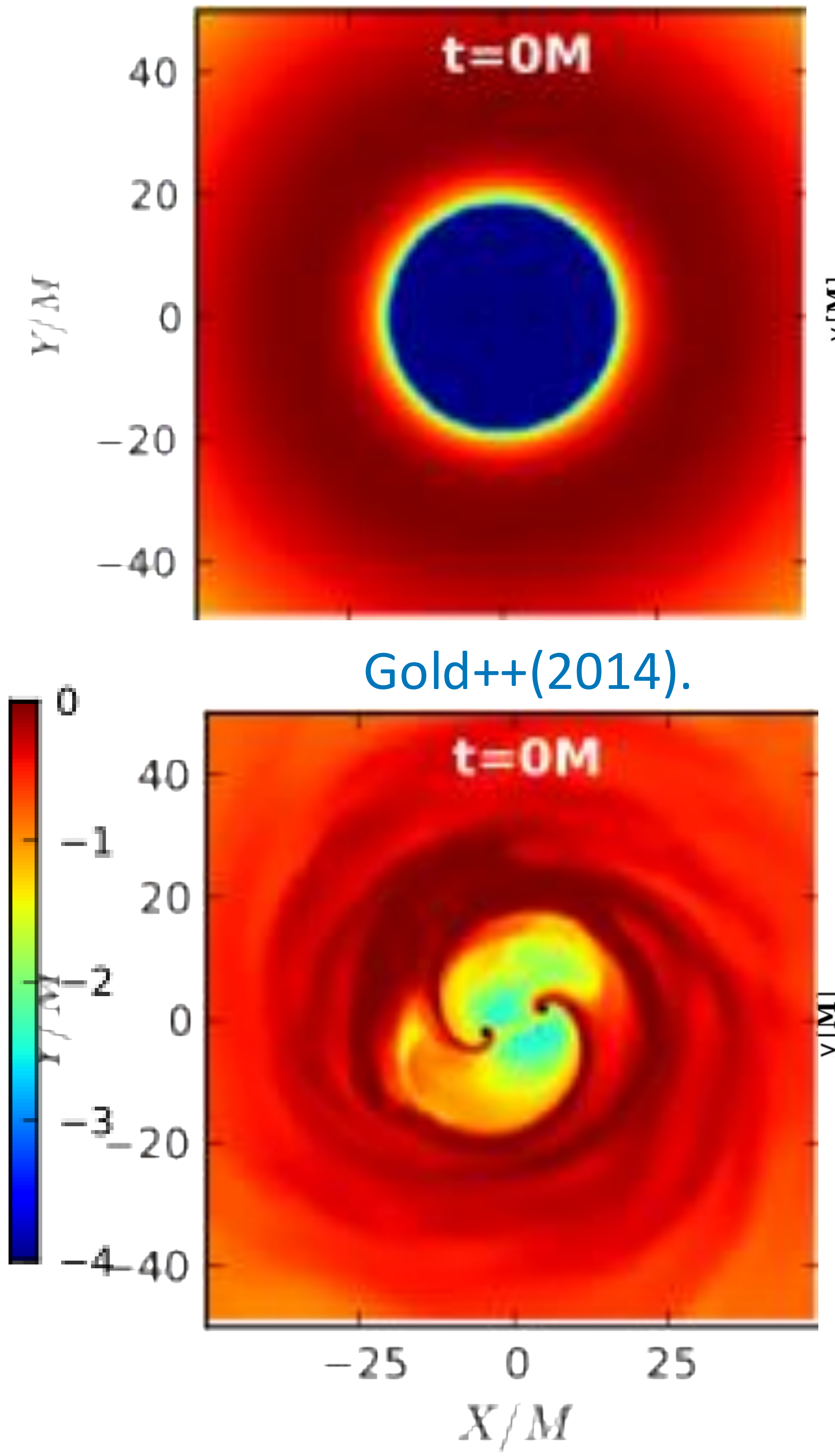
- Cooled, H/R=0.1
- From a=20r_g to merger;



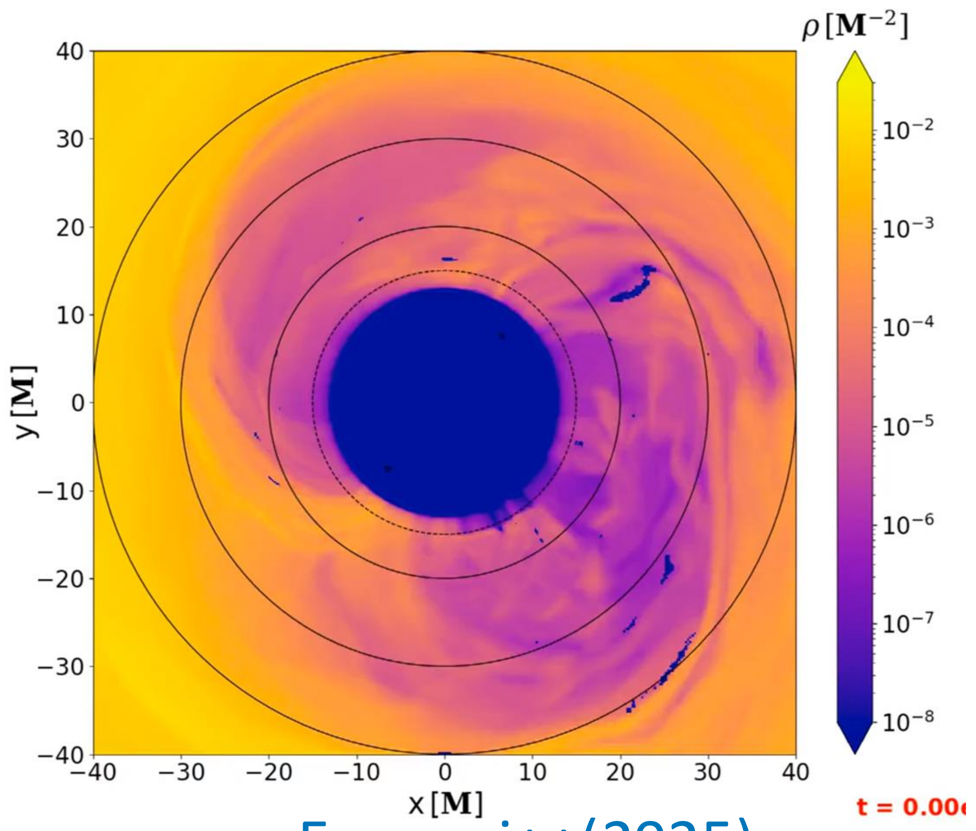
- Thicker accretion flow leads to weaker variability from lump, and most power just above the orbital frequency;
- Higher spins lead to broader power distribution;
- Thinner accretion flow simulations with similar initial data are consistent;
- Thinner disks lead to strong lump variability, even in the jet;
- New run see new 2xbeat variability for nonspinning black holes;
- Cooling and initial data may affect resultant variability signatures;

GRMHD Disk Evolutions

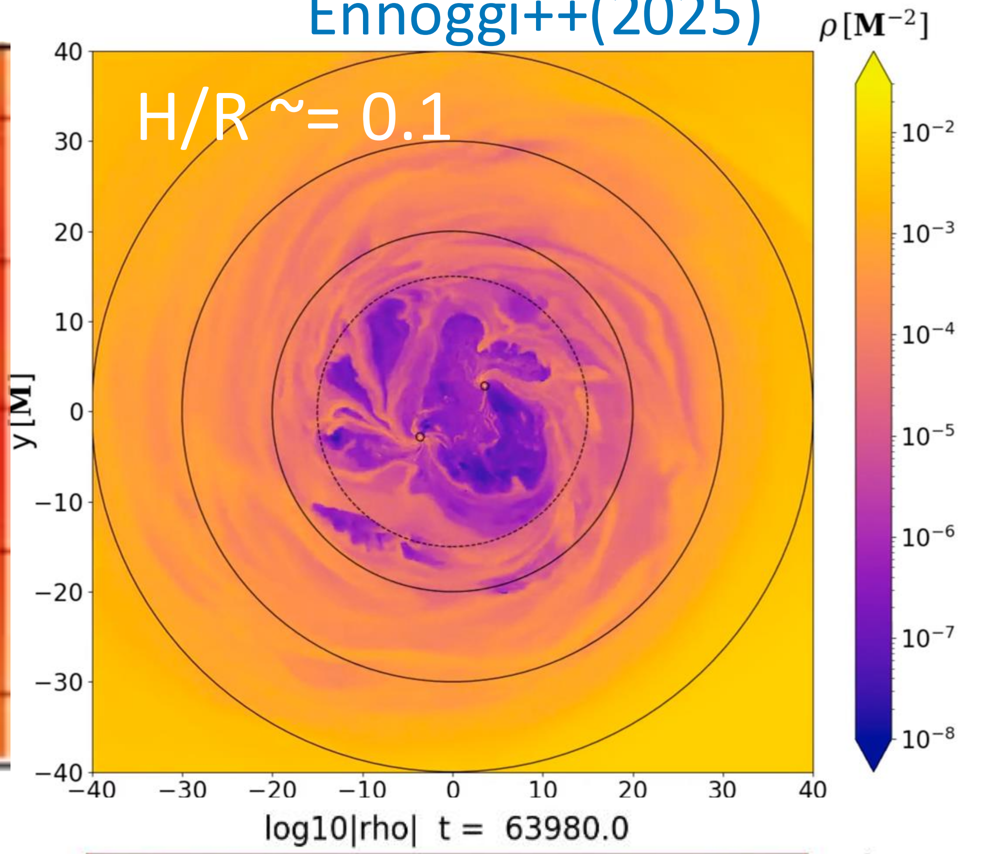
Spins = 0, Cooled, a(t) ~= 10 r_g

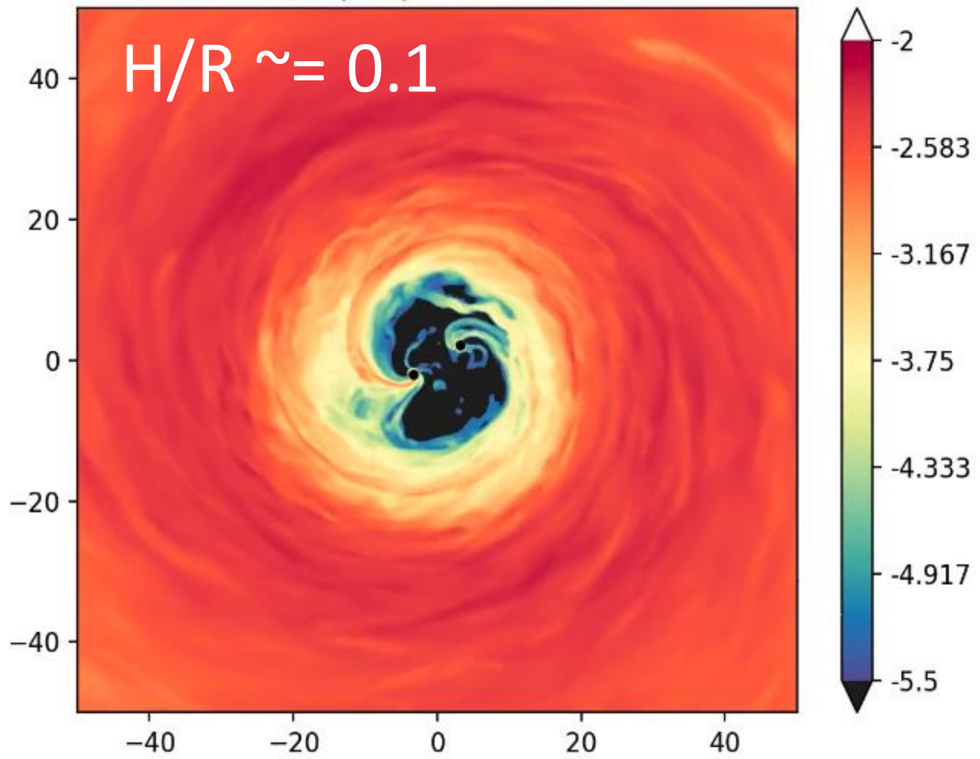


Gold++(2014).



Ennoggi++(2025)

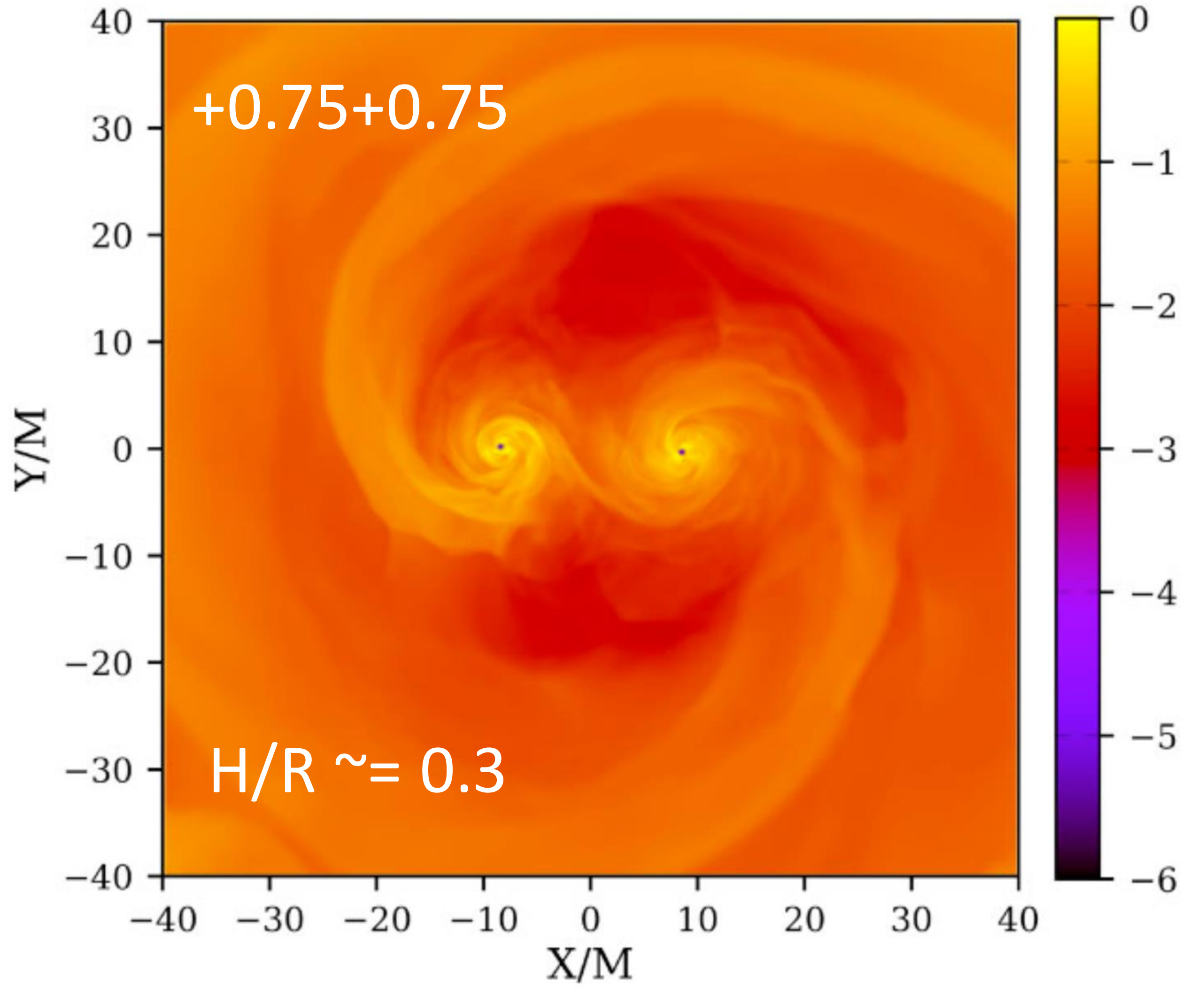




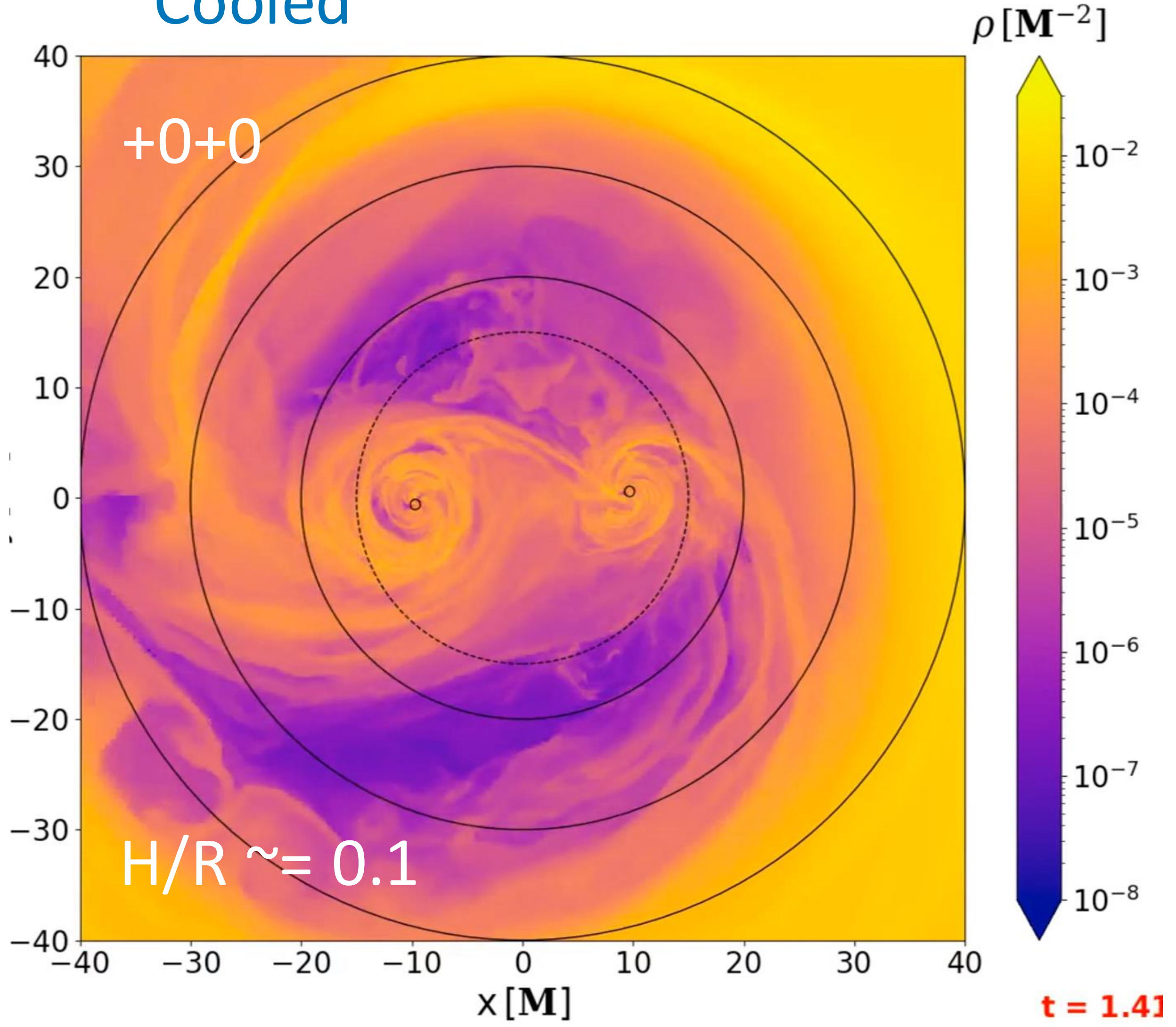
Avara++(2025)

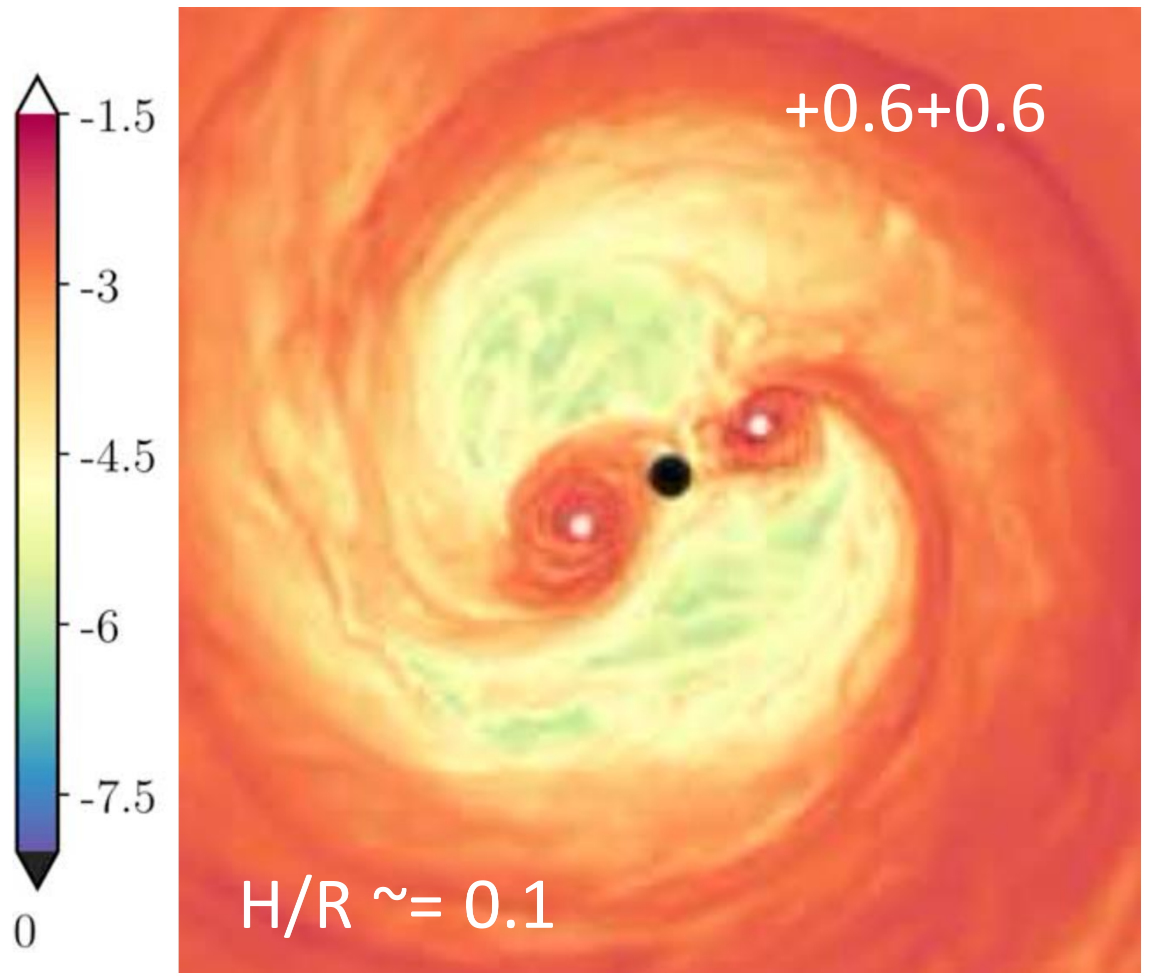
a(t) ~= 20r_g

Bright & Paschalidis (2023)
Uncooled

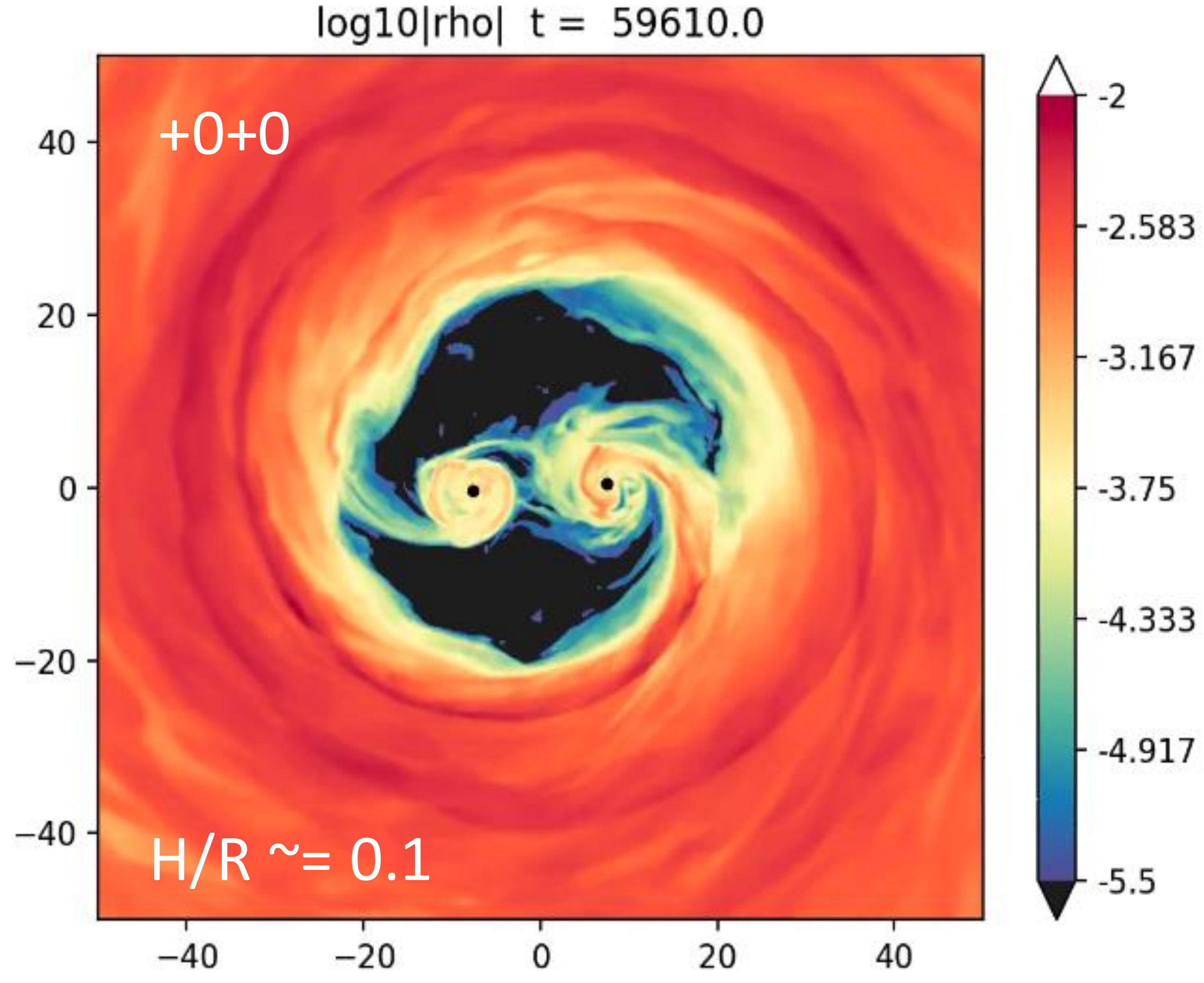


Ennoggi++ (2025)
Cooled





Combi++(2022), cooled



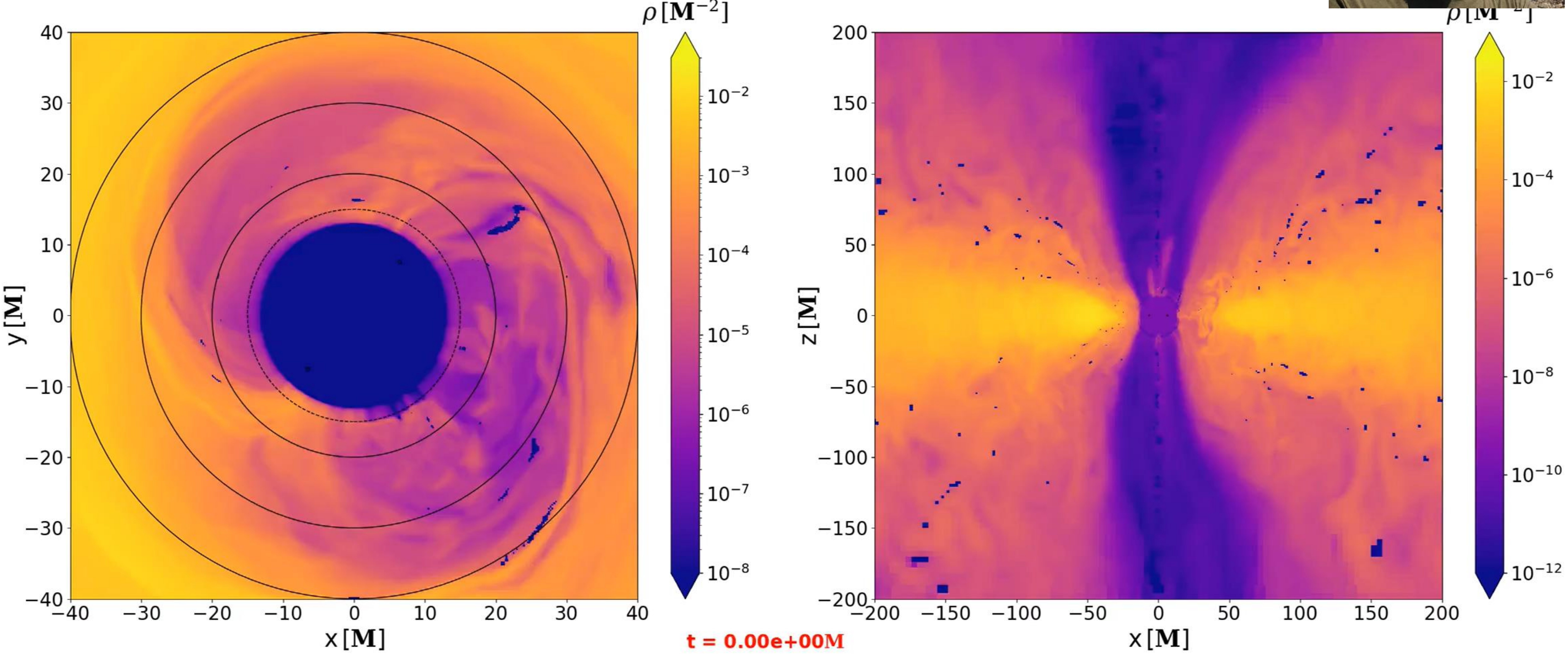
Avara++(2025), cooled

EM Signatures of Mergers: Equal-mass Non-spinning Case

First GRMHD Numerical Relativity Simulations of Accreting MBHB from Relaxed "Far-field" Circumbinary Disk

Ennoggi, Campanelli, Zlochower, Noble, Krolik, Cattorini, Kalinani, Mewes, Chabanov, Ji, and de Simone,, arXiv:2502.06389, (2025).

- Reduces influence of ad hoc choices on results;
- Particularly important since mass flow affects luminosity;

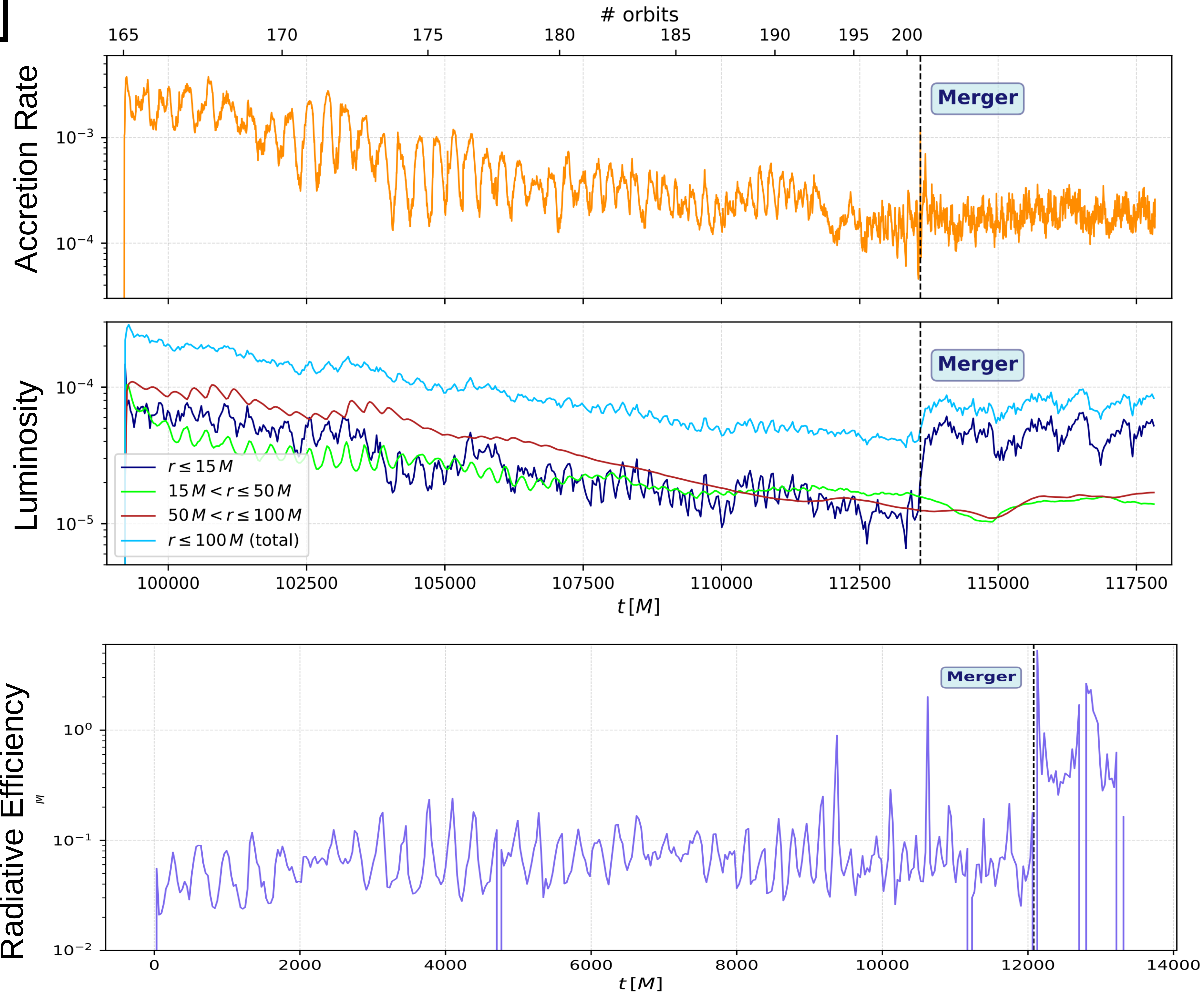


EM Signatures of Mergers

Ennoggi, Campanelli, Zlochower, Noble, Krolik, Cattorini, Kalinani, Mewes, Chabanov, Ji, and de Simone,,
arXiv:2502.06389, (2025).

- Mass accretion reaches post-merger asymptotic level prior to merger;
- Merger results in minimal uptick in accretion rate at time of merger;
- However, Poynting luminosity drops by ~4x (not as much as Mdot) prior to merger, before returning to its original luminosity post-merger;
- **Instantaneous brightening at merger** occurs as low-angular moment gas dragged by BHs suddenly finds itself in a higher radiative efficient flow in part because of the presence of a nascent spinning black hole;
- CBD's light curve is steady through merger, though no kicks in this case;
- **Binary dims a little leading up to merger, then immediately lights up at merger!**
- Inconsistent with 2d viscous hydro simulation, but similar to prior GRMHD simulations:

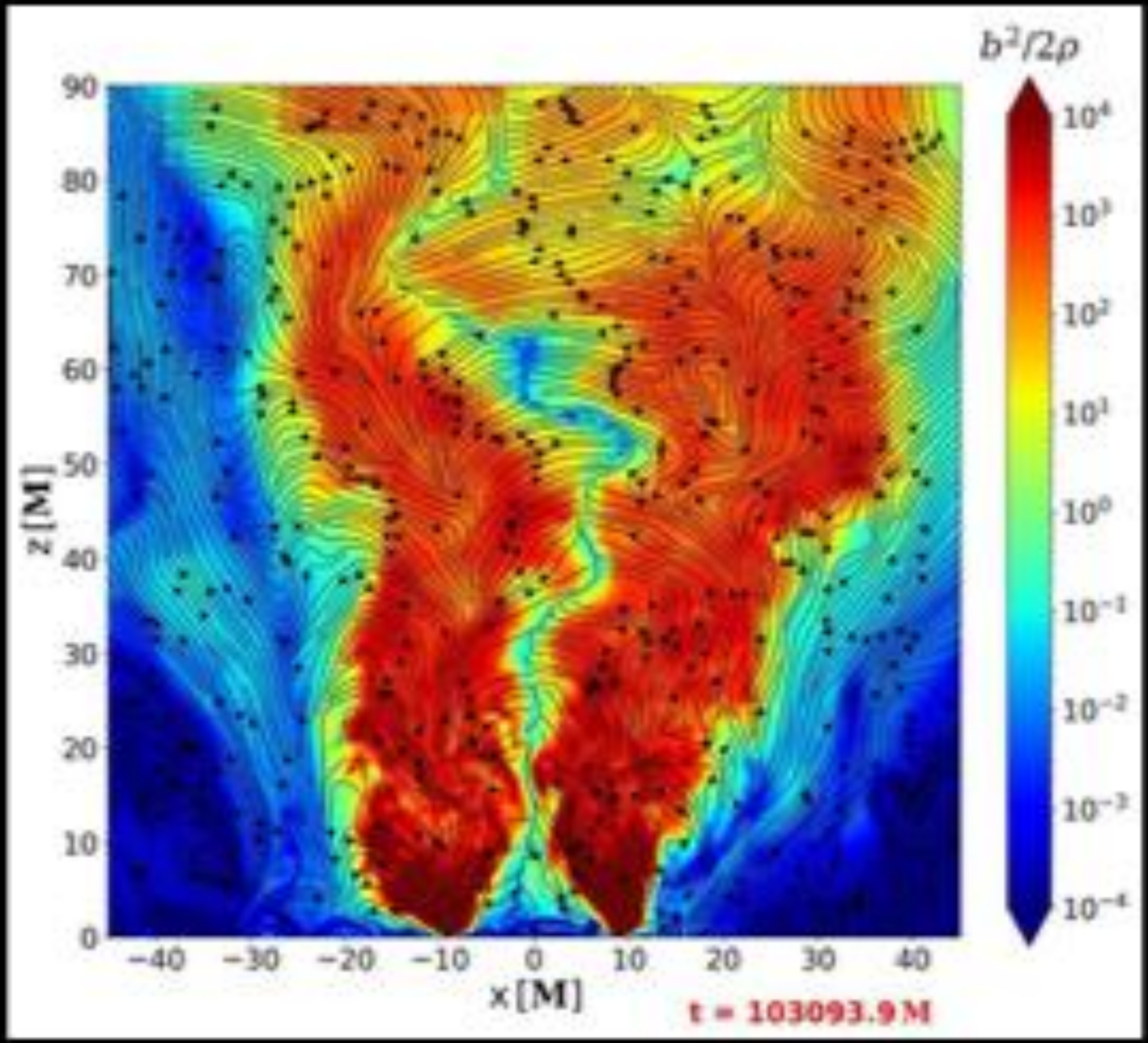
Farris++2012, Gold++2014;
Cattorini++2022,2024;
Kelly, Baker, Etienne, Giacomazzo, Schnittman, PRD 96, 123003 (2017)

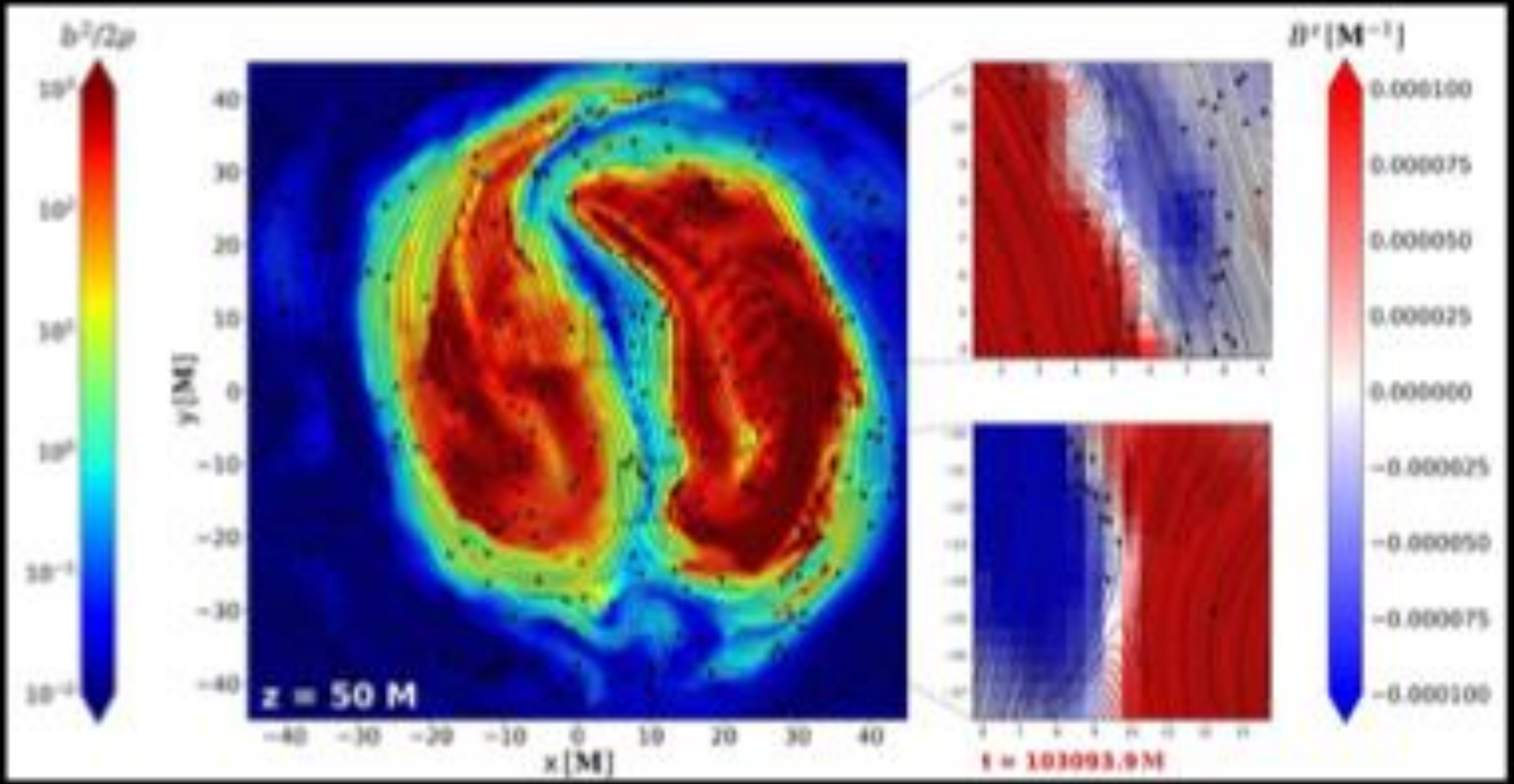


Spinning version of previous work: +0.8+0.8

Dual Jet Interaction in Aligned Spinning SMBBH

Twisted magnetic field lines accreted by both BHs due to BZ effect, displaying magnetic reconnection – Ennoggi+ 2025, in prep





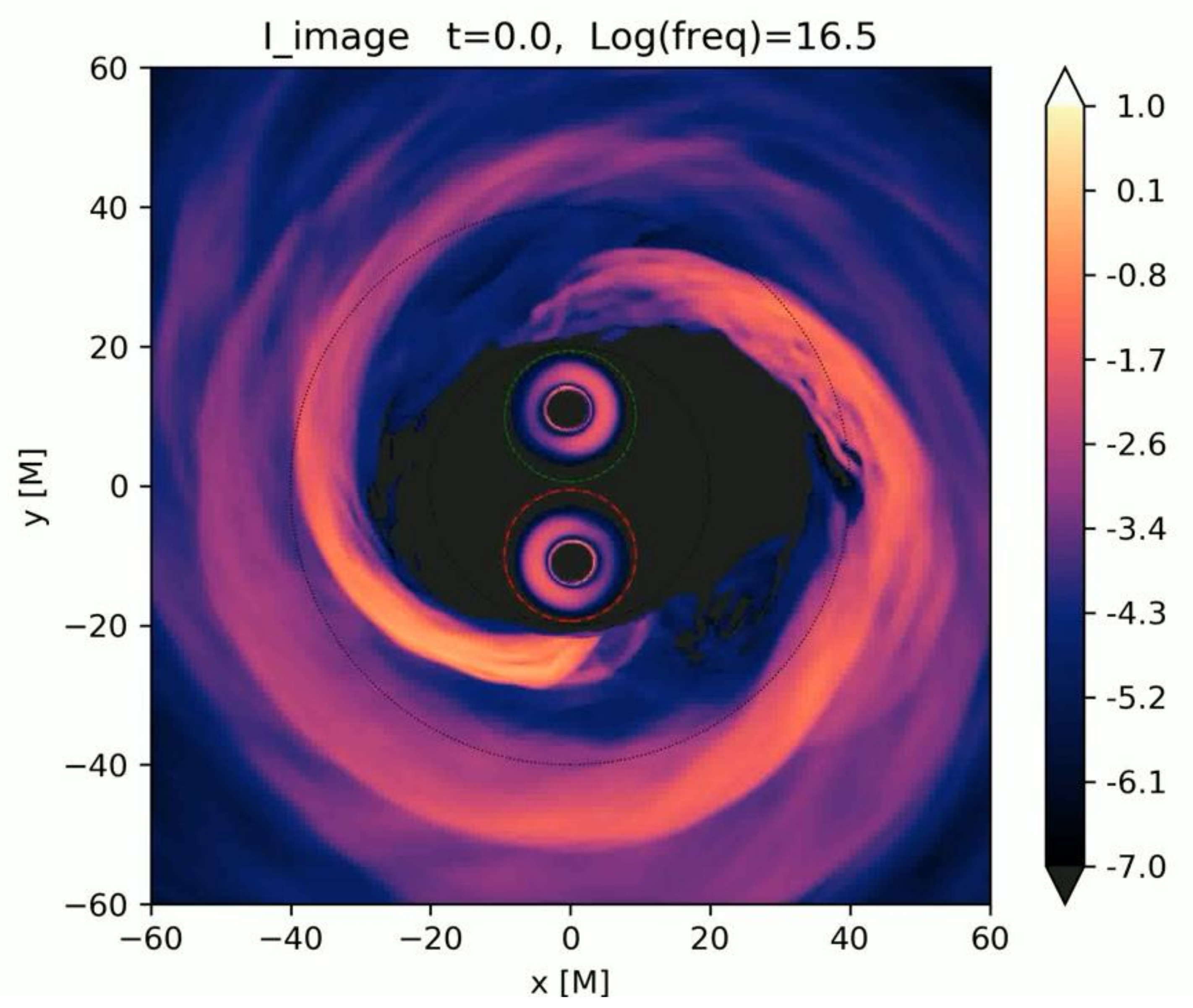
Spectra from Accretion onto Spinning BBHs

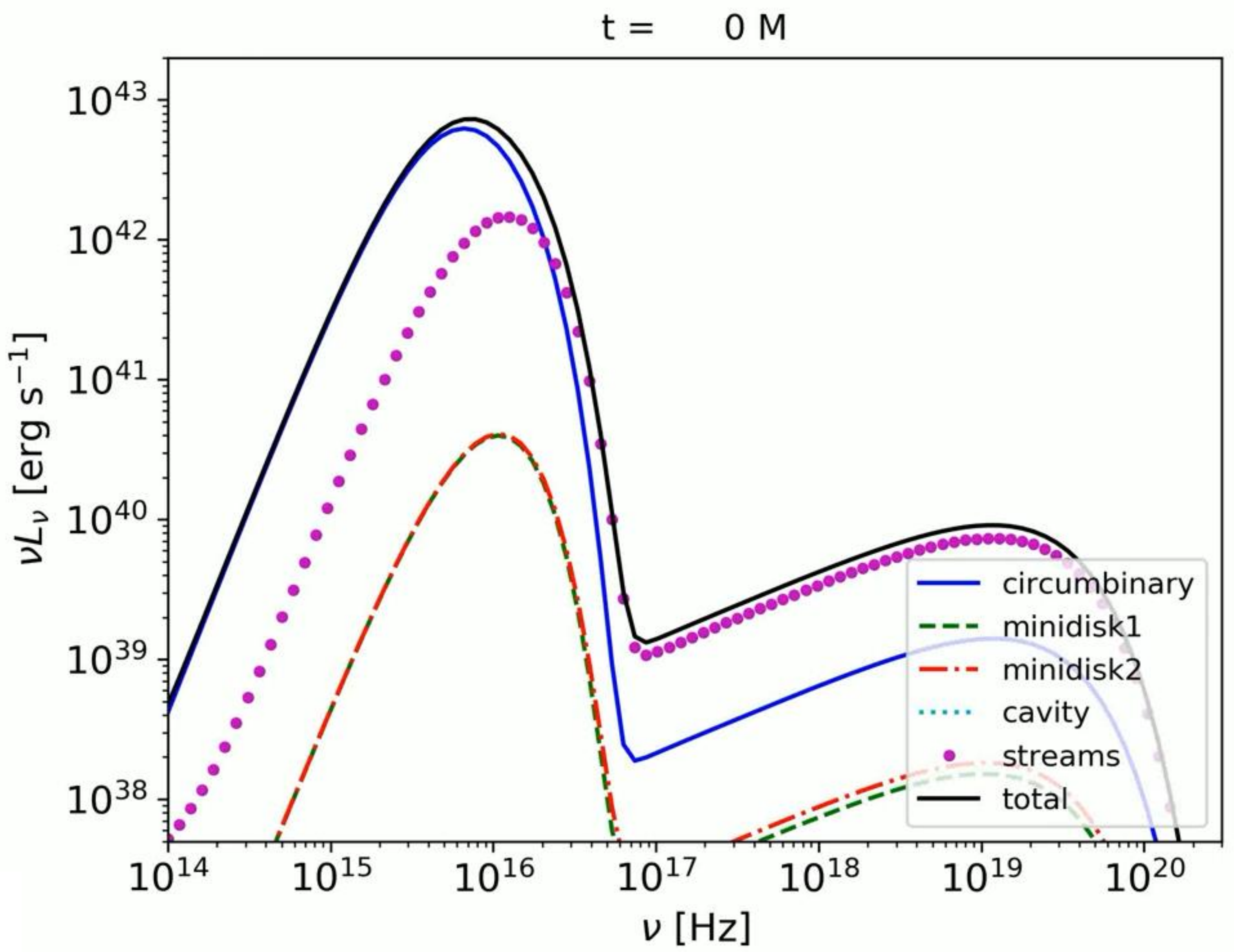
Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, ApJ, 928, 137, (2022).

- **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;**

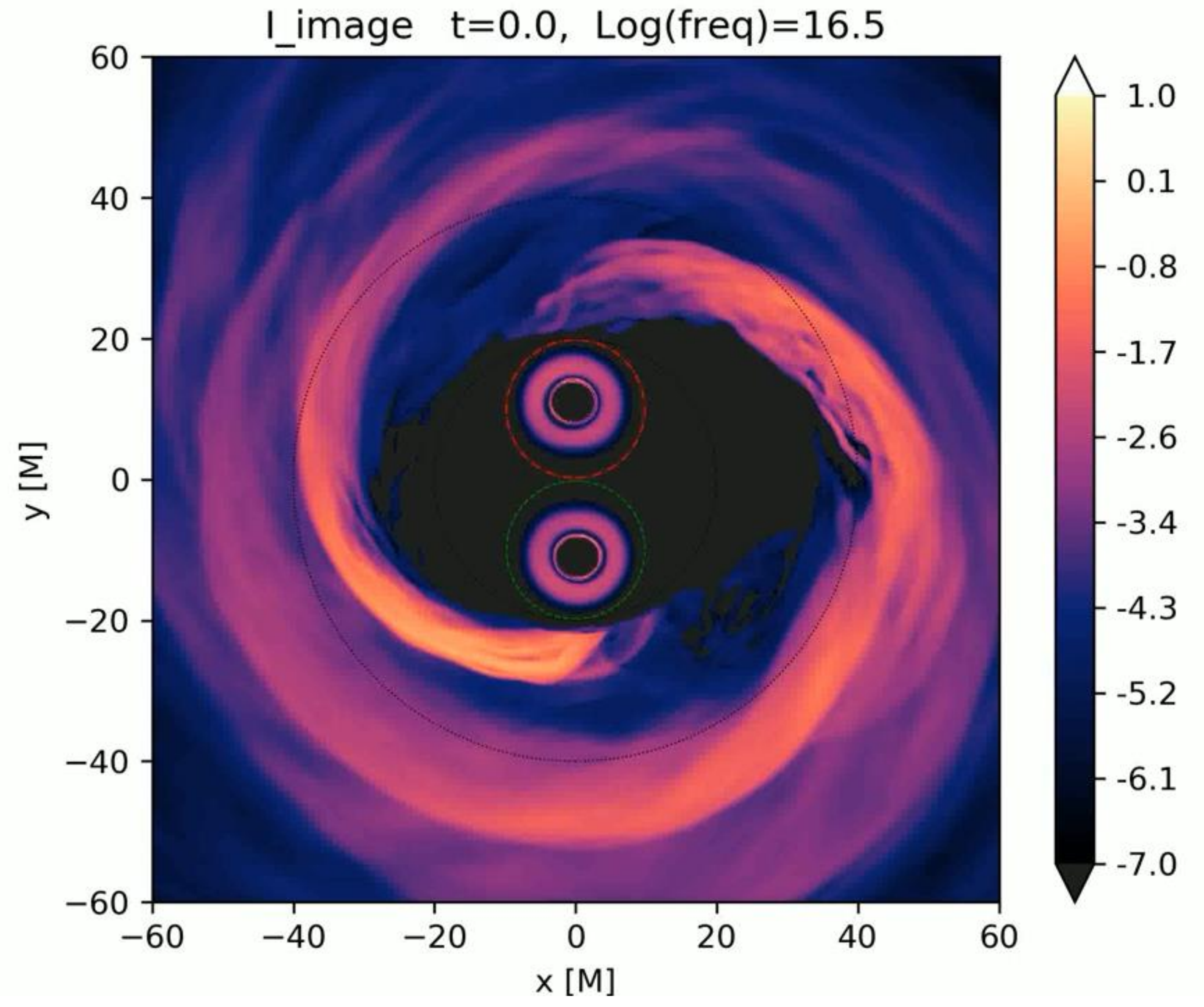
- **The spinning case provides new signatures to search for:**
  - **Broader thermal peak in optical-UV;**
  - **Variability in the UV on the binary's orbital timescale;**
  - **Stronger variability in X-rays;**

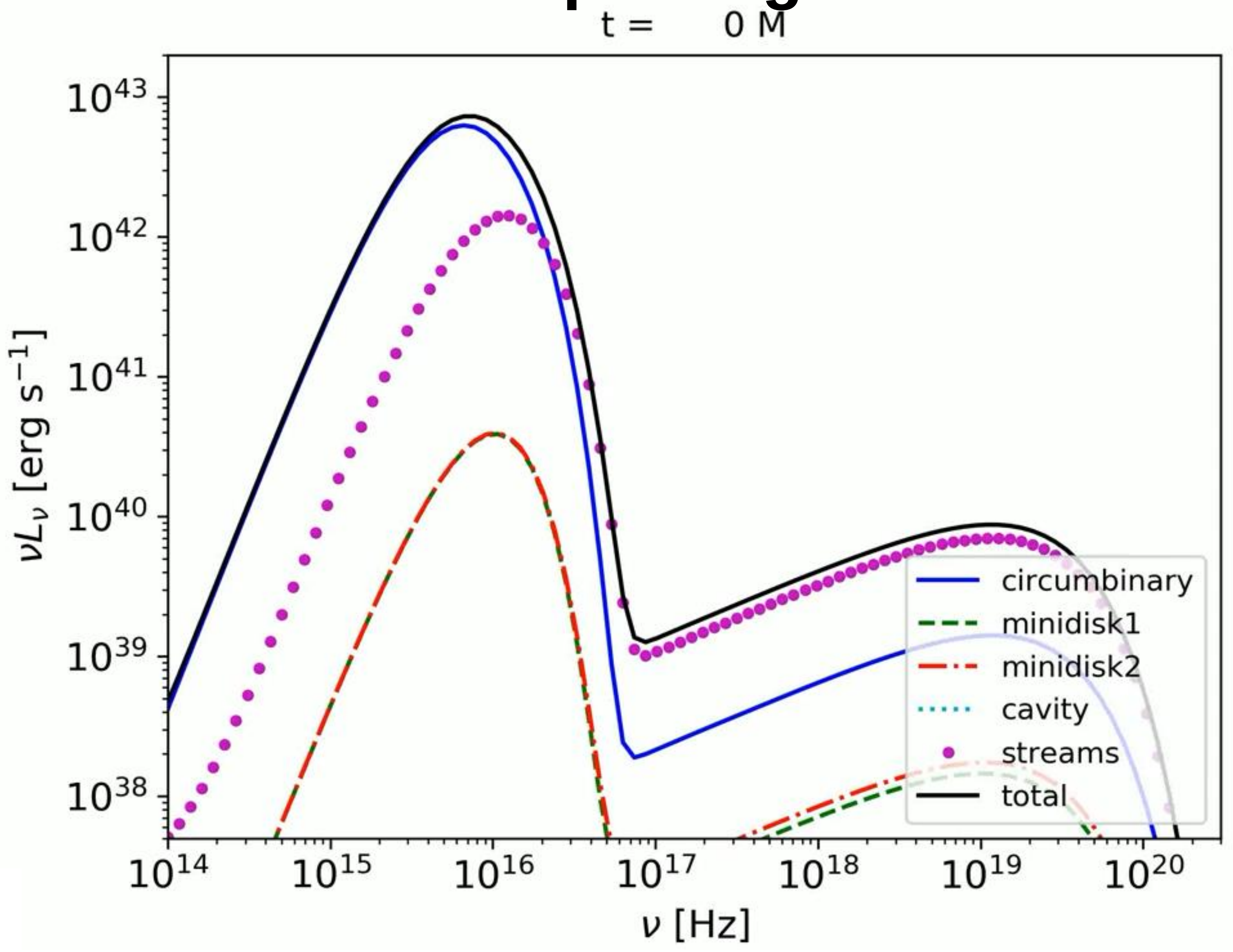
Spinning BBHs: a=0.6M, up-up





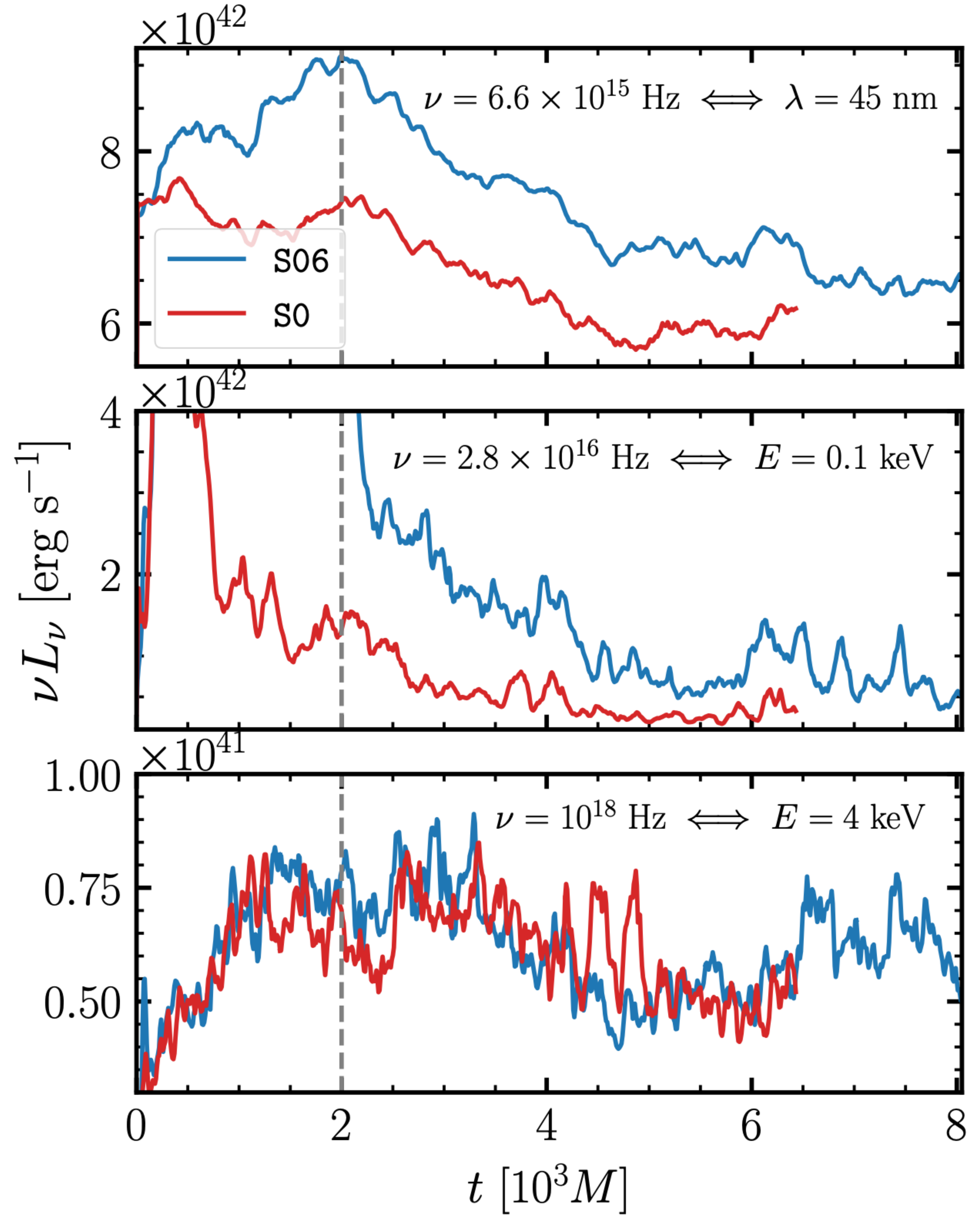
Non-Spinning BBHs

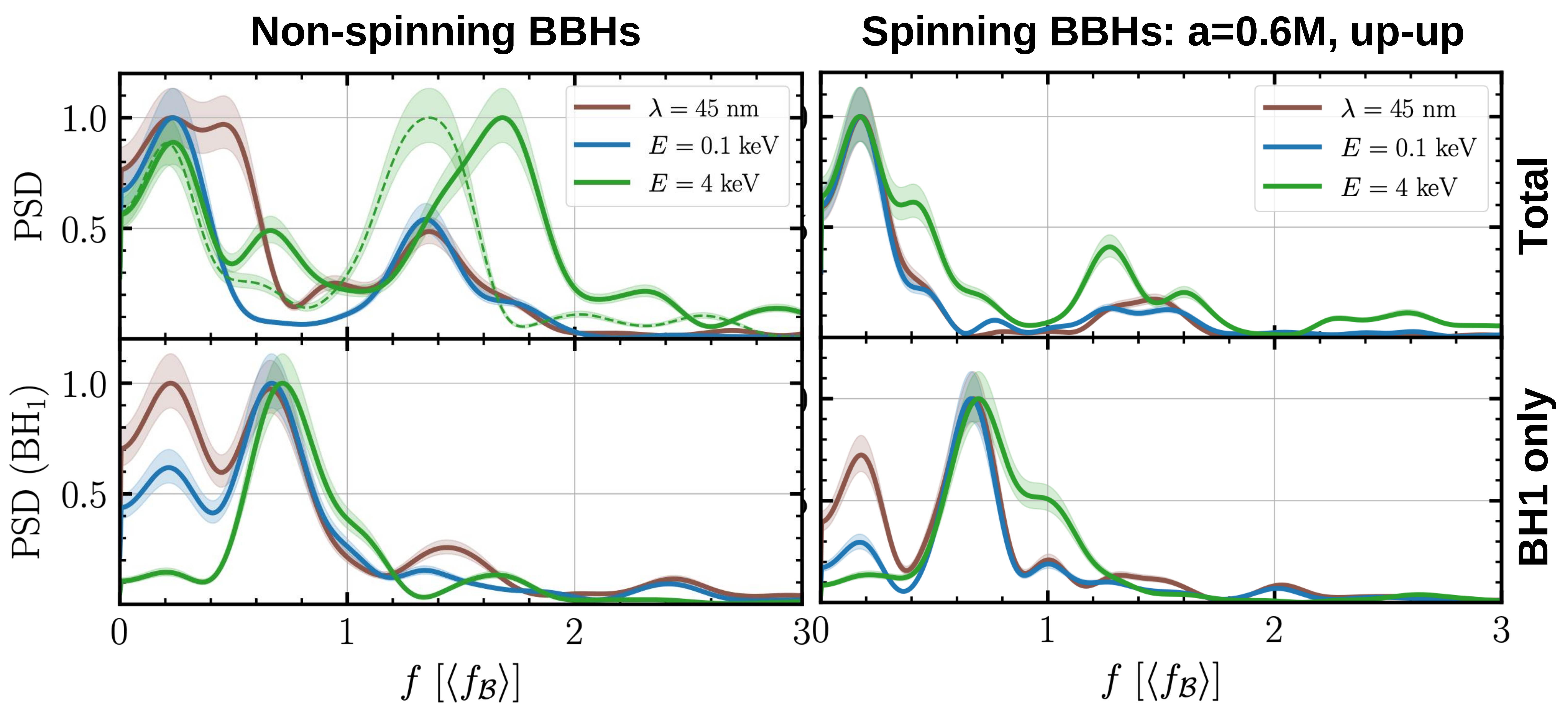




Light Curves from Accretion onto Spinning BBHs

Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, ApJ, 928, 137, (2022).



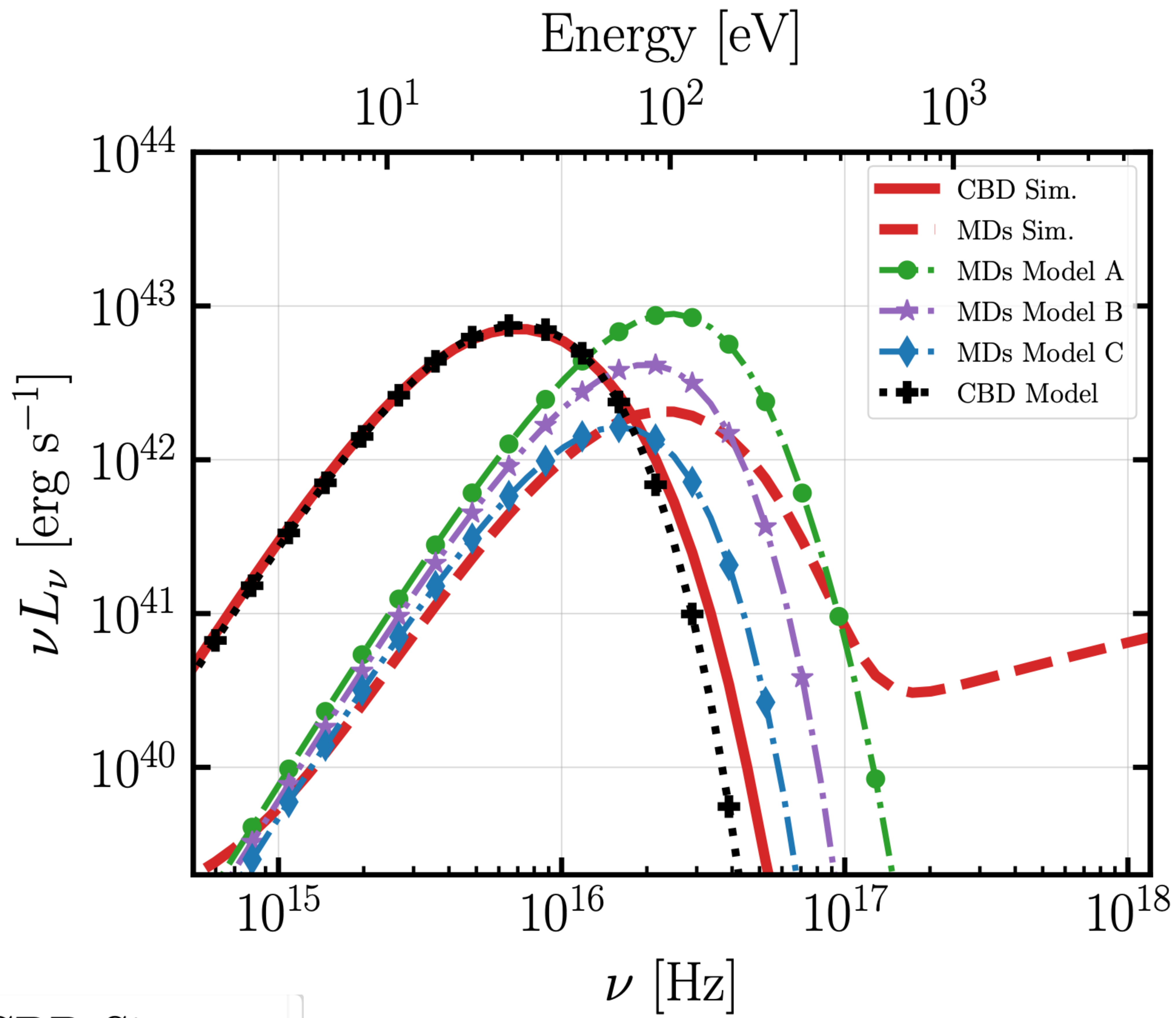


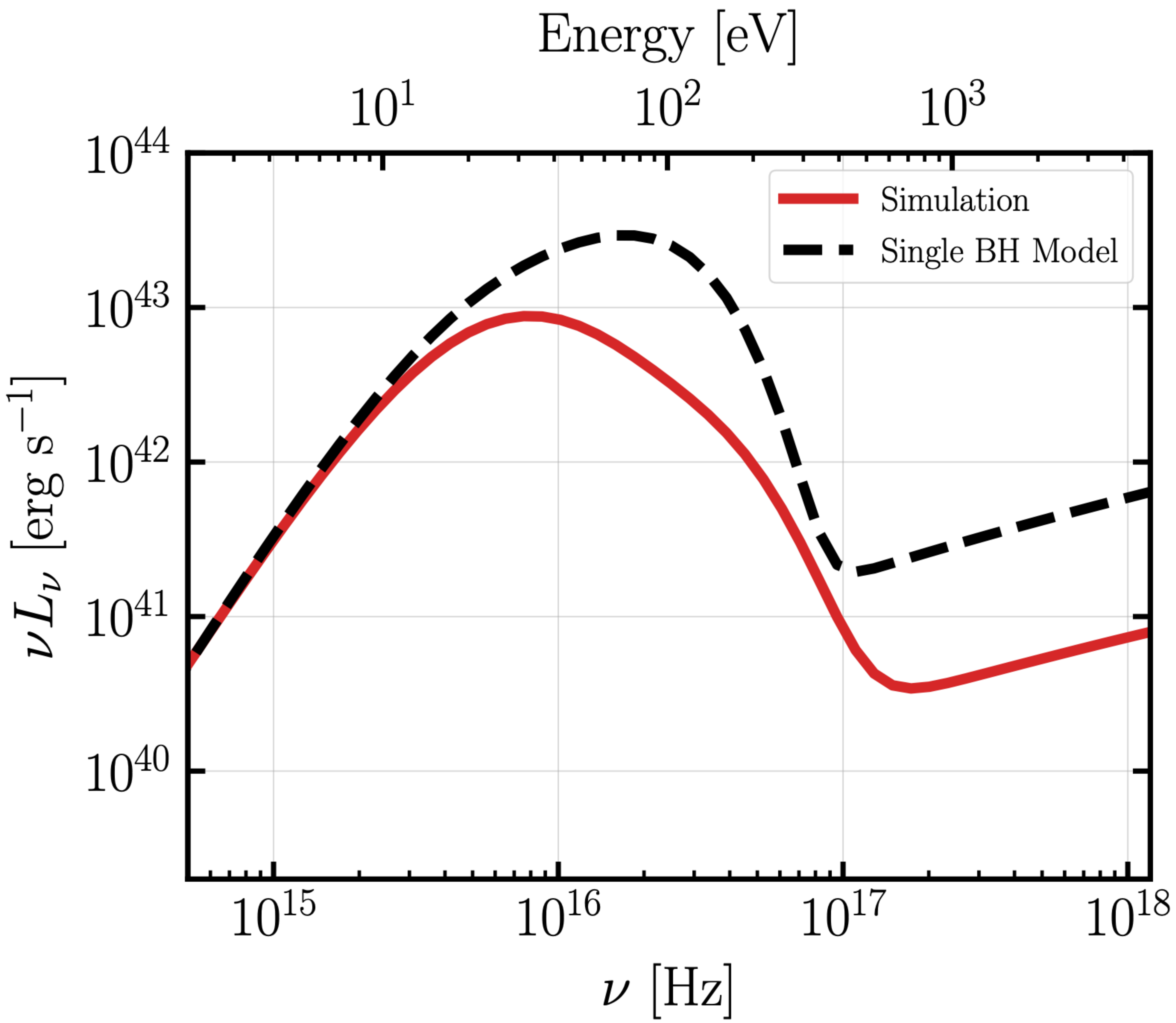
- Use thermal photosphere model plus corona model with relativistic ray-tracing;
- Prograde spinning BBHs:
  - Longer-lived mini-disks lead to relatively steadier x-ray emission and weaker signals at 2x beat freq.;
  - Individual mini-disks still suffer beat modulation;
  - Total variability in all frequencies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

See also:
d'Ascoli, Noble, Bowen, Campanelli, Krolik, and Mewes, ApJ, 865, 140, (2018)..

Spectra from Accretion onto Spinning BBHs

Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, ApJ, 928, 137, (2022).





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, $\dot{m}_1 = 6 \times 10^{-2}\dot{M}_{\rm Edd},\ \dot{m}_2 = 6.8 \times 10^{-2}\dot{M}_{\rm Edd}$
MDs Model C	2 NT, $\dot{m}_1 = 2.3 \times 10^{-2}\dot{M}_{\rm Edd},\ \dot{m}_2 = 2.7 \times 10^{-2}\dot{M}_{\rm Edd}$
CBD Model	1 NT, spin=0.6, 1e6 Msun, 2a < r < 7.5a

NT = Novikov-Thorne (1972) "thin disk"

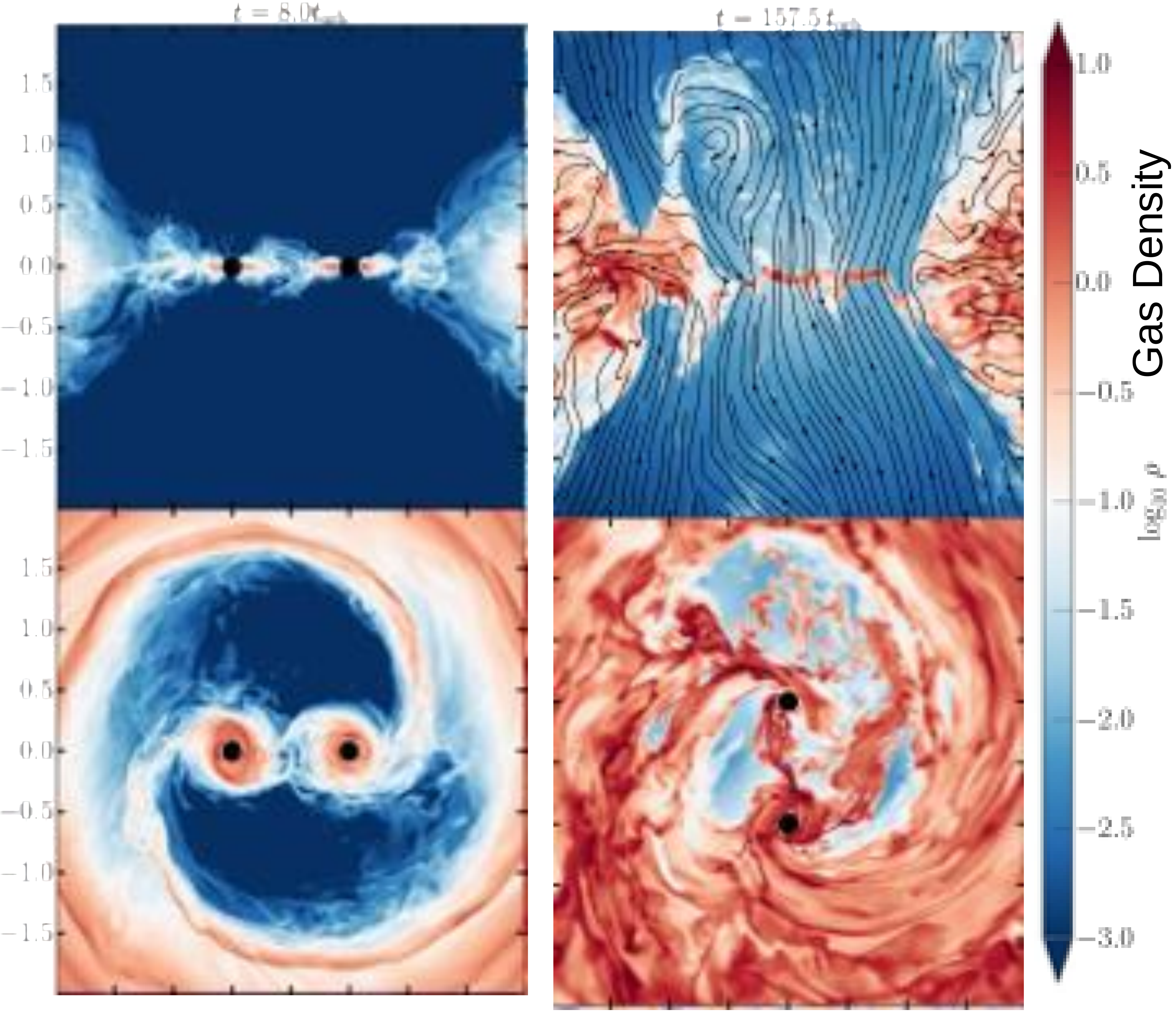
Single BH Model

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

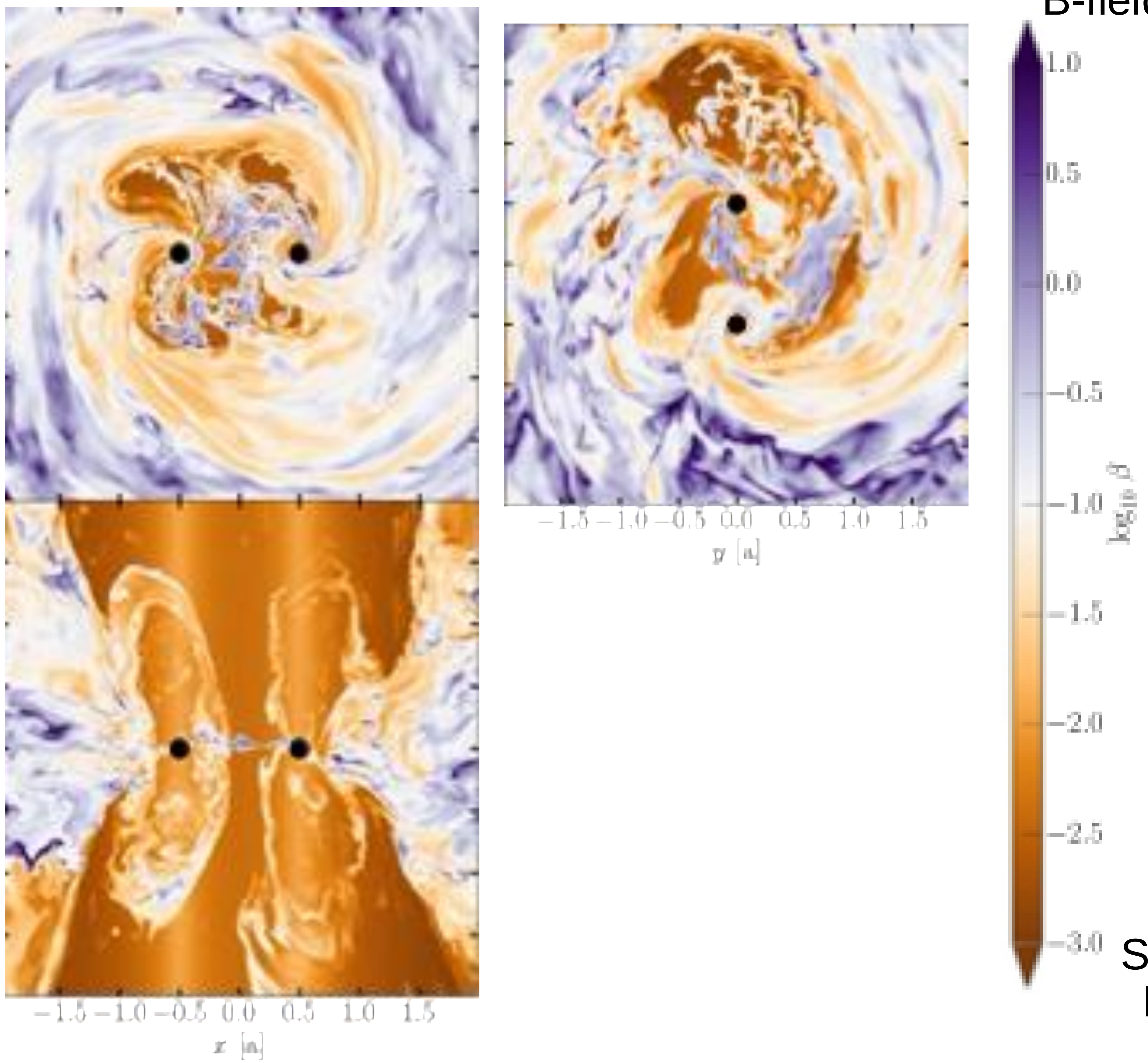
- GRMHD simulation-informed model for all spins for thin disks, same total mass and Mdot;
- **Truncated disk emission, weaker mini-disk accretion rate due to accelerated accretion via spiral shocks.**

Magnetic Arrested Disks (MAD)

Most and Wang, ApJL, 973, L19, (2024).



Weaker B-field



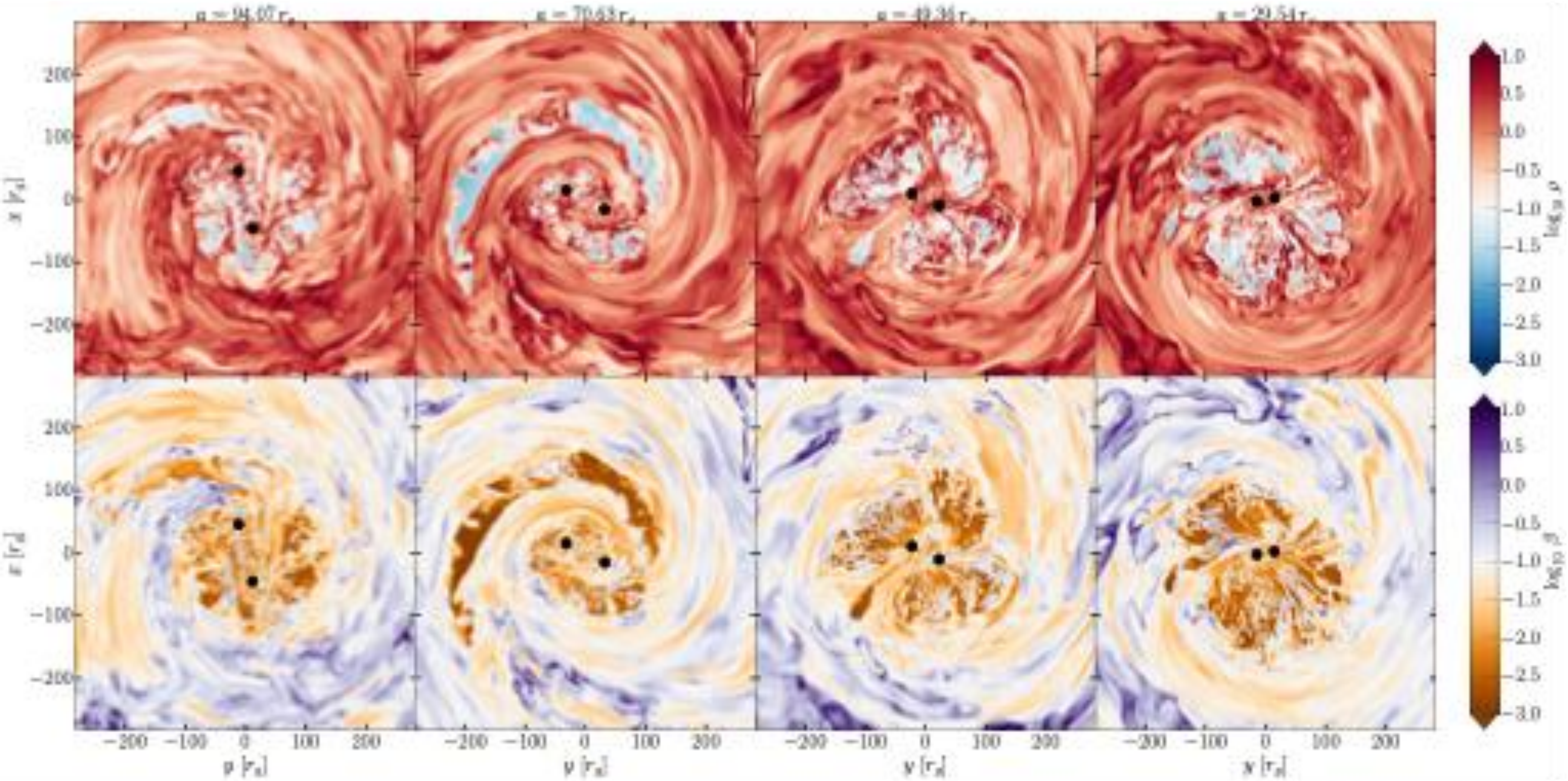
Stronger B-field

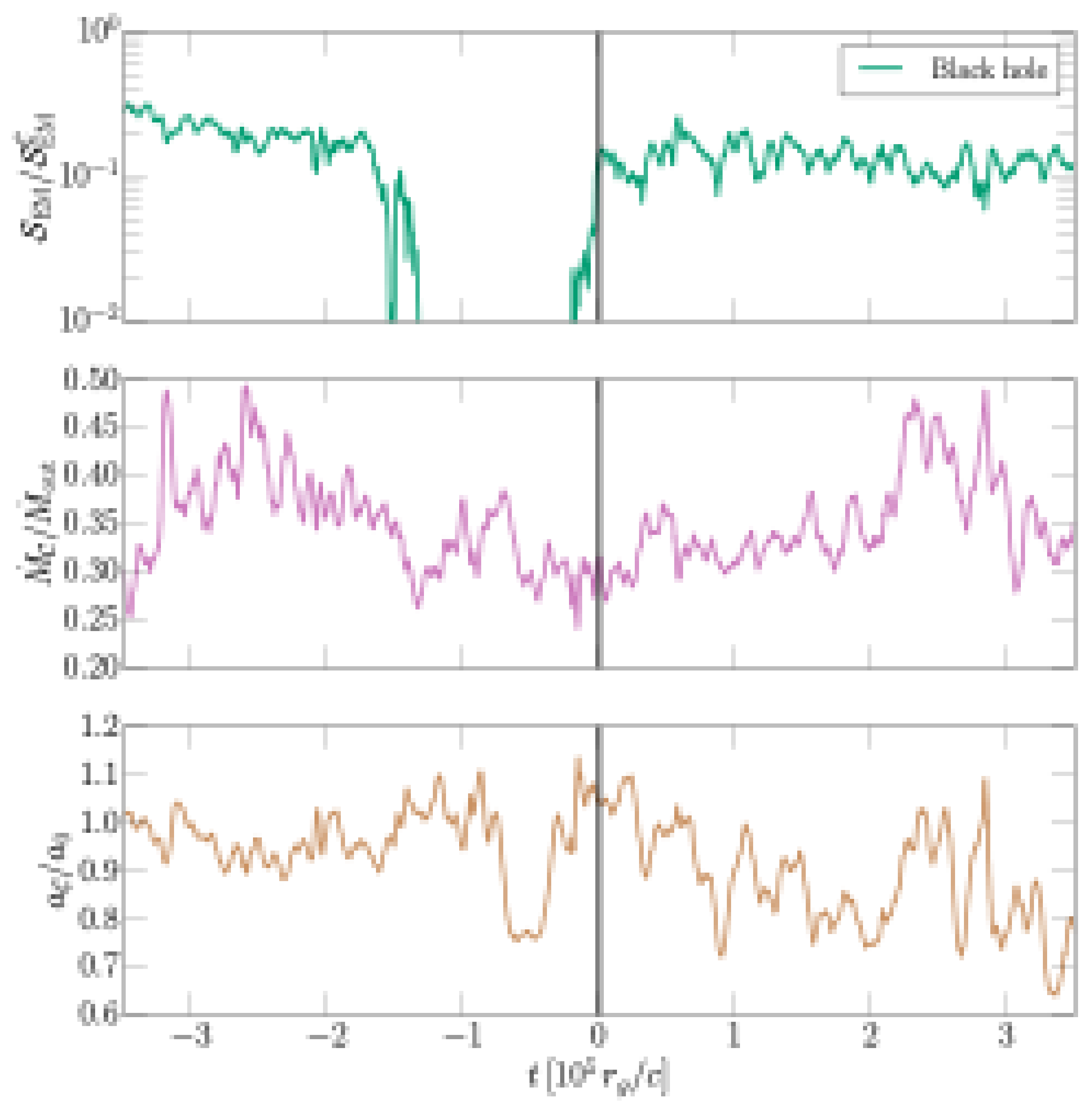
- **Newtonian MHD**, Sinks (r=0.07a) , no event horizons;
- **Isothermal EOS**, H/r ~= 0.1,
- Setup to reach MAD state;
- Separation ~ 100 r_g; (though Newtonian has no scale);

- Before MAD state begins, resembles other GRMHD work;
- Minidisks become less defined due to stifled accretion, may be due to the sink and resolution issues;
- Mass pileup leads to mag. Rayleigh Taylor accretion **NOT** connected to tidal streams;
- Reconnection of flux tubes may produce nonthermal emission;

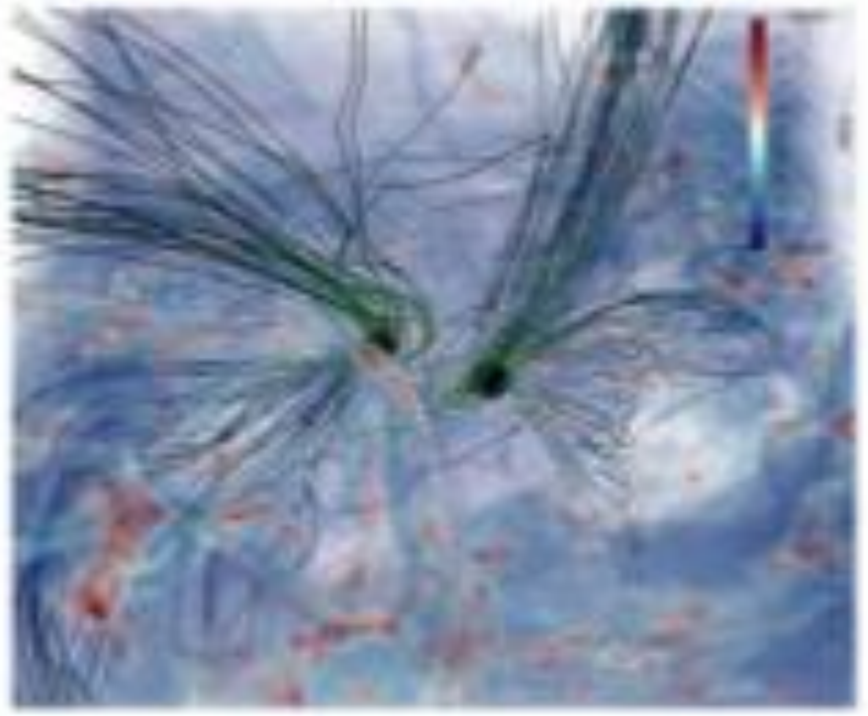
Magnetic Arrested Disks (MAD)

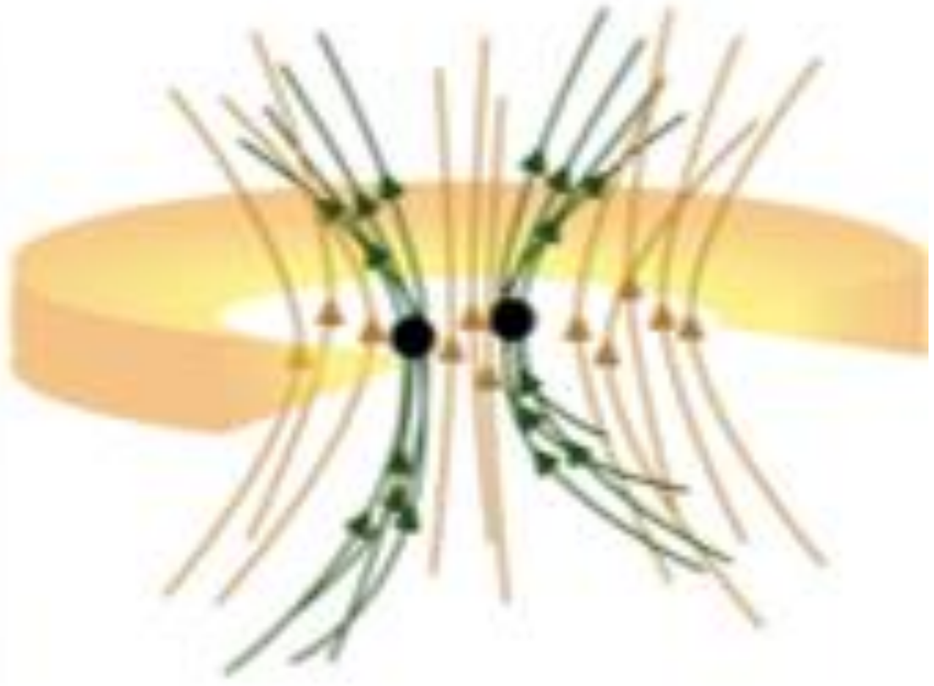
Most and Wang,, arXiv:2410.23264, (2024).





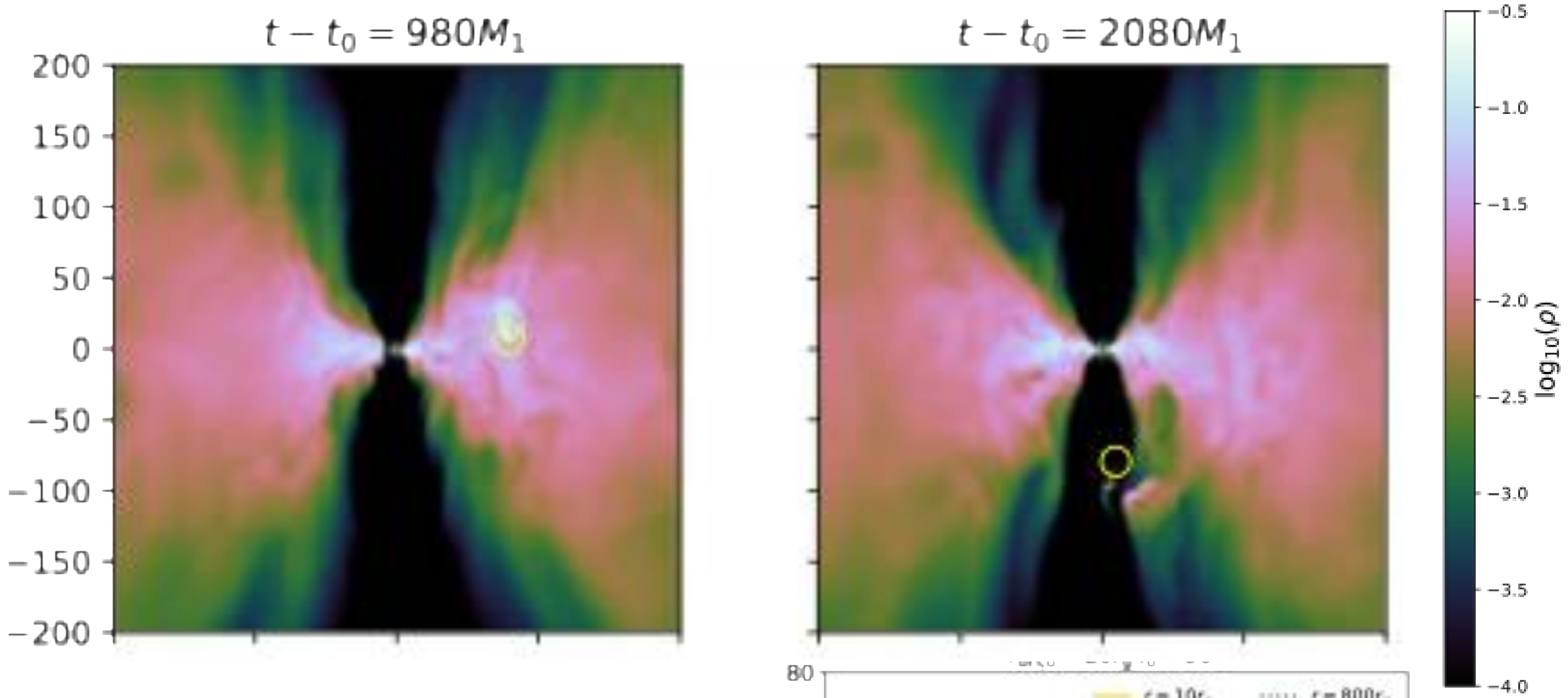
- Same as before, letting binary shrink;
- Decouples around a=50 r_g ;
- Shrinking orbit hastens interchange RTI as cavity compresses, BH Poynting flux turns off prior to merger;
- Conditions similar to uniform plasmas considered by Kelly++2017 and Cattorini++2021-2024

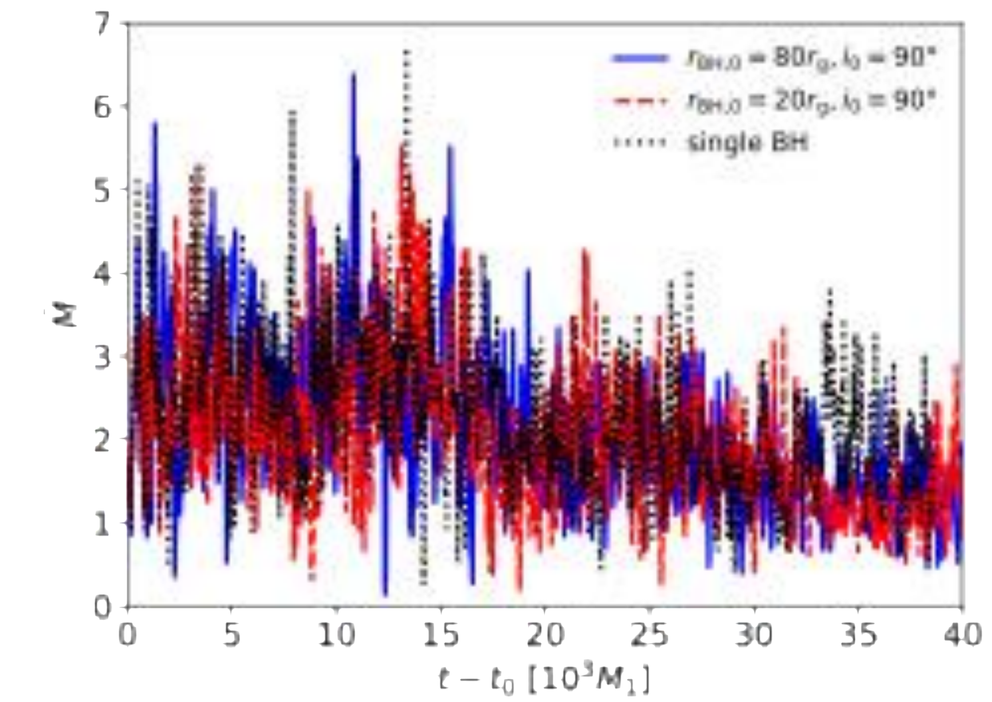


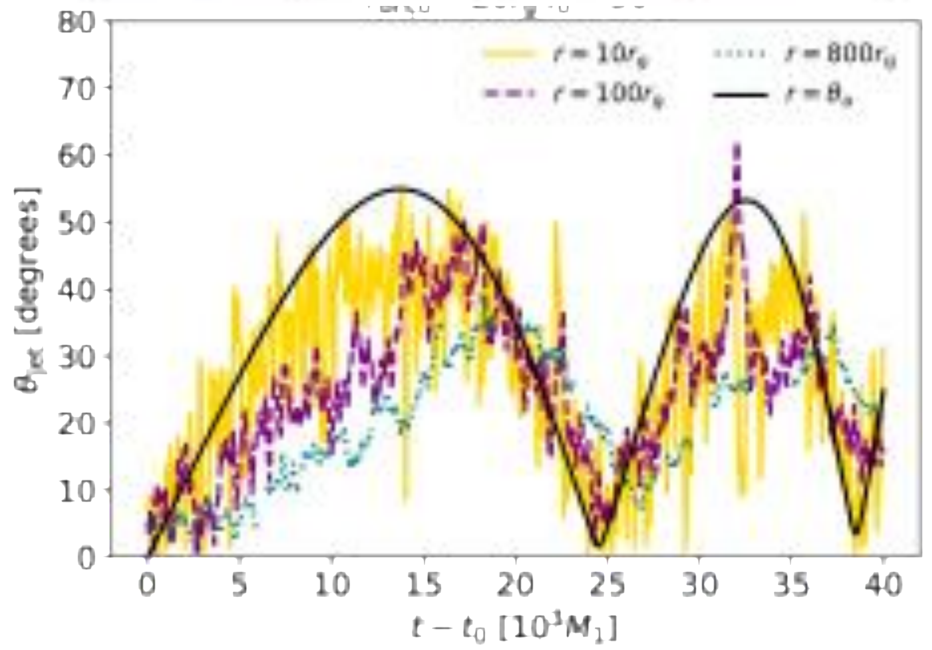


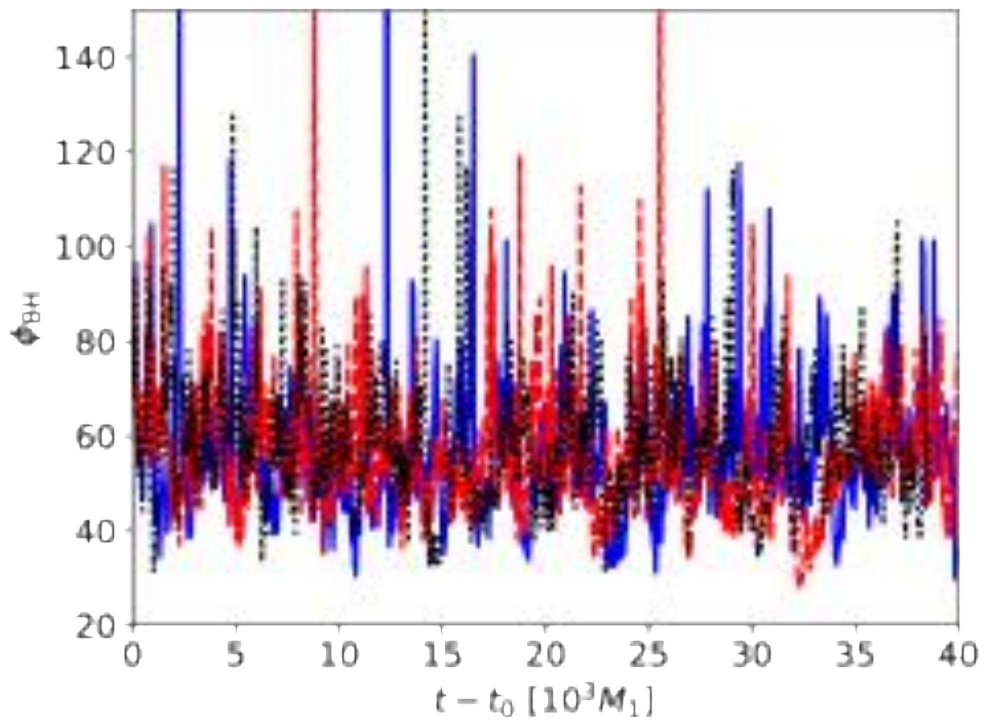
IMRI/EMRI Scenario

Ressler, Combi, Li, Ripperda, and Yang, ApJ, 967, 70, (2024).





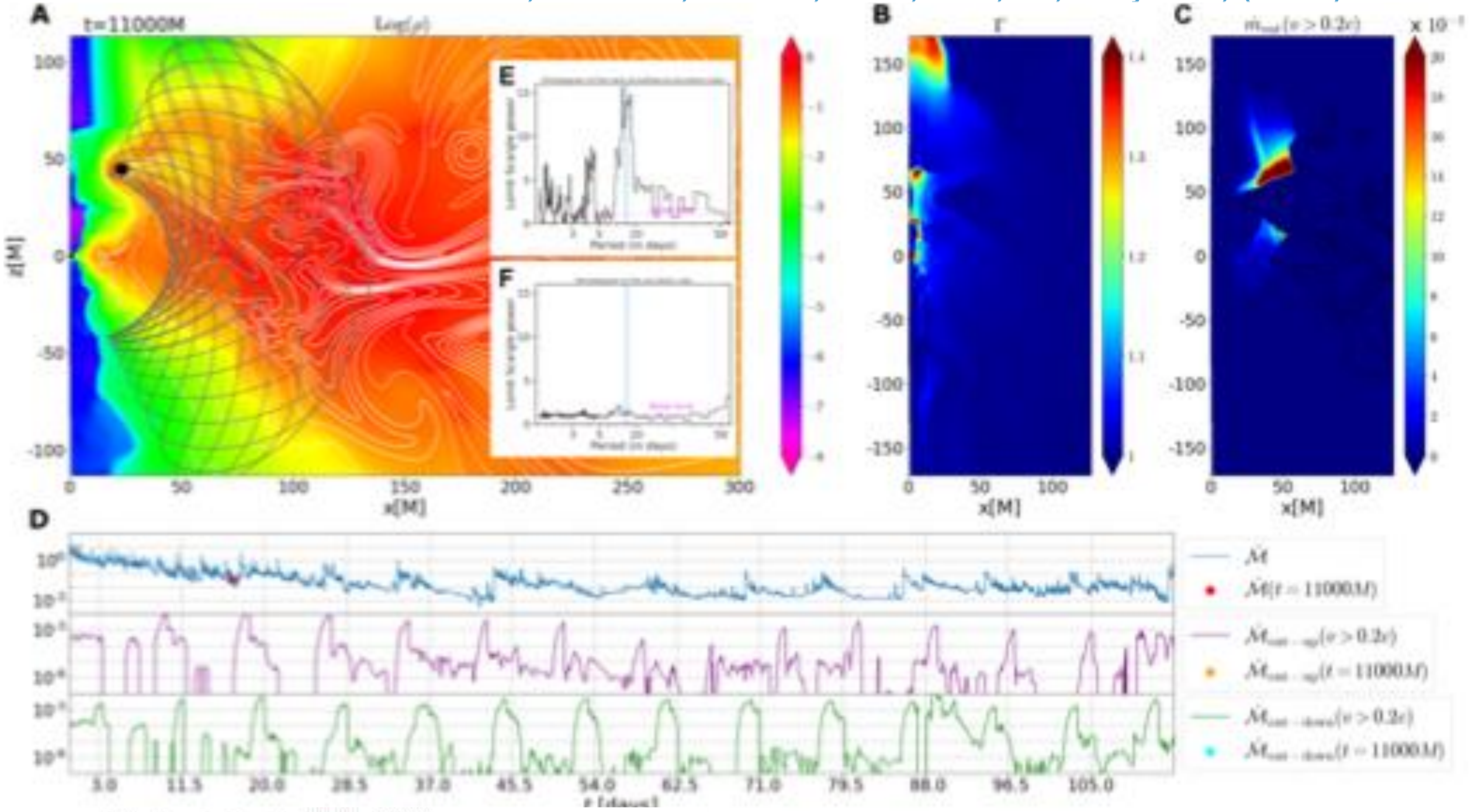


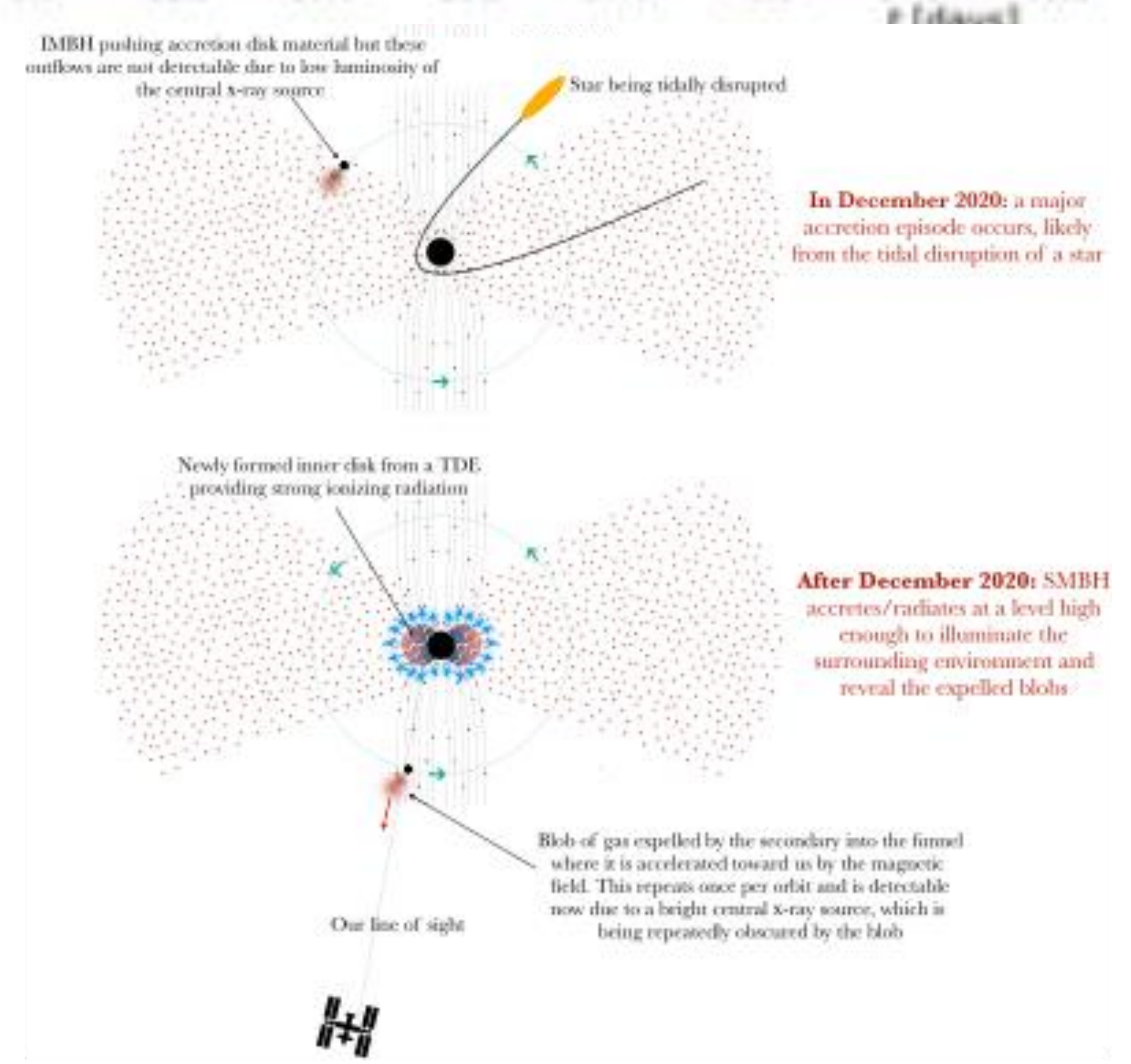


- M2/M1 = 0.1, fixed primary, orbit **inclined** 90º primary's spin axis;
- MAD disk around primary, secondary never attains MAD state;
- Secondary **insignificantly** affects Mdot and flux of primary;
- Secondary's mini-disk periodically replenishes then is ablated during passage through primary's jet;
- Most significant signature is spin-orbit evolution of the primary's jet;

X-ray Quasi-Periodic Outflows - ASASSN-20qc

Pasham, Tombesi, Suková, et al., SciA, 10, eadj8898, (2024).





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- Secondary **insignificantly** affects Mdot and flux of primary;
- Secondary's mini-disk periodically replenishes then is ablated during passage through primary's jet;
- Most significant signature is spin-orbit evolution of the primary's jet;

Summary

- Jets:
  - Nonthermal efficiences are few xMdot;
  - Pre-merger Poynting efficiencies few to several x Mdot;
  - Post-merger Poynting efficiencies are several to O(1) x Mdot;
  - Not insignificant nonthermal emission from reconnection at jet-jet interface;
  - IMRIs/EMRIs may be observable in x-rays as quasi-periodic outflows as they traverse the jet;
  - May lose Poynting flux just prior to merger for magnetically arrested flows;
  - Clouds:
    - Stronger for spinning BHs aligned with ambient large scale B-field;
    - Orbital motion hinders accumulated flux, possibly stifling large-scale jets for cloud-like situations;
    - Nonthermal emission from magnetic bridges between BHs;
  - Thick disks:
    - May keep steady through merger;
    - Accretion rate and flux imprint from secondary is insignificant q ~<= 0.1 ;
  - Thin disks:
    - May brighten suddenly through merger;
    - May be modulated by lump accretion and show variability at ~0.25f_{bin} and ~1.45f_{bin} for near equal mass binaries;

$$L \approx 10^{43} \mathrm{erg\ s^{-1}} \left(\frac{M}{10^6 M_\odot} \right)^2$$

- Thermal Emission: Efficiencies few to several xMdot;
  - Thin disk:
    - CBD peaks in UV/EUV;
    - Partial spectral gap seen arising from discontinuity in thermal spectra of CBD and minidisks;
    - Gap leads to deficit near Teff of single BH spectrum;
    - Spectrum broadly fluctuates with f_{lump} and less so at 2xf_{beat} unless binary is not spinning, in which case they are comparable only in the x-rays.
  - Thick disks:
    - Thermal (cooling) emission drops gradually toward merger, then asymptotes to single BH rate;
    - Drop is larger for more equal mass binaries;

Future Directions

- More sophisticated radiation methods:
  - Growing use of dynamic coupling between the radiation and plasma (e.g., M1 or full grey transport);
  - BHB simulations moving in this direction (Tiwari++2025);
  - Full domain problem (w/ BHs on the grid) is challenging due to the required dynamic spatial range and lack of symmetries;
  - Photo-ionization balance methods for more self-consistent spectral predictions;
- Larger spatial scale simulations of ”kicked” or post-merger disks in MHD; possibly amenable for Newtonian codes;
- Larger variety of simulations, spanning different initial data configurations, orbital eccentricity, BH spin configurations, mass accretion rates, disk thicknesses, …
- Build pipeline to create mock observations of simulations to reproduce observed cadence/depth of anticipated EM searches;
  - Observation duration matters for bquasi-periodicity detection: e.g., for 3-d hydro sims: Cocchiararo, Franchini, Lupi, and Sesana, A&A, 691, A250, (2024).

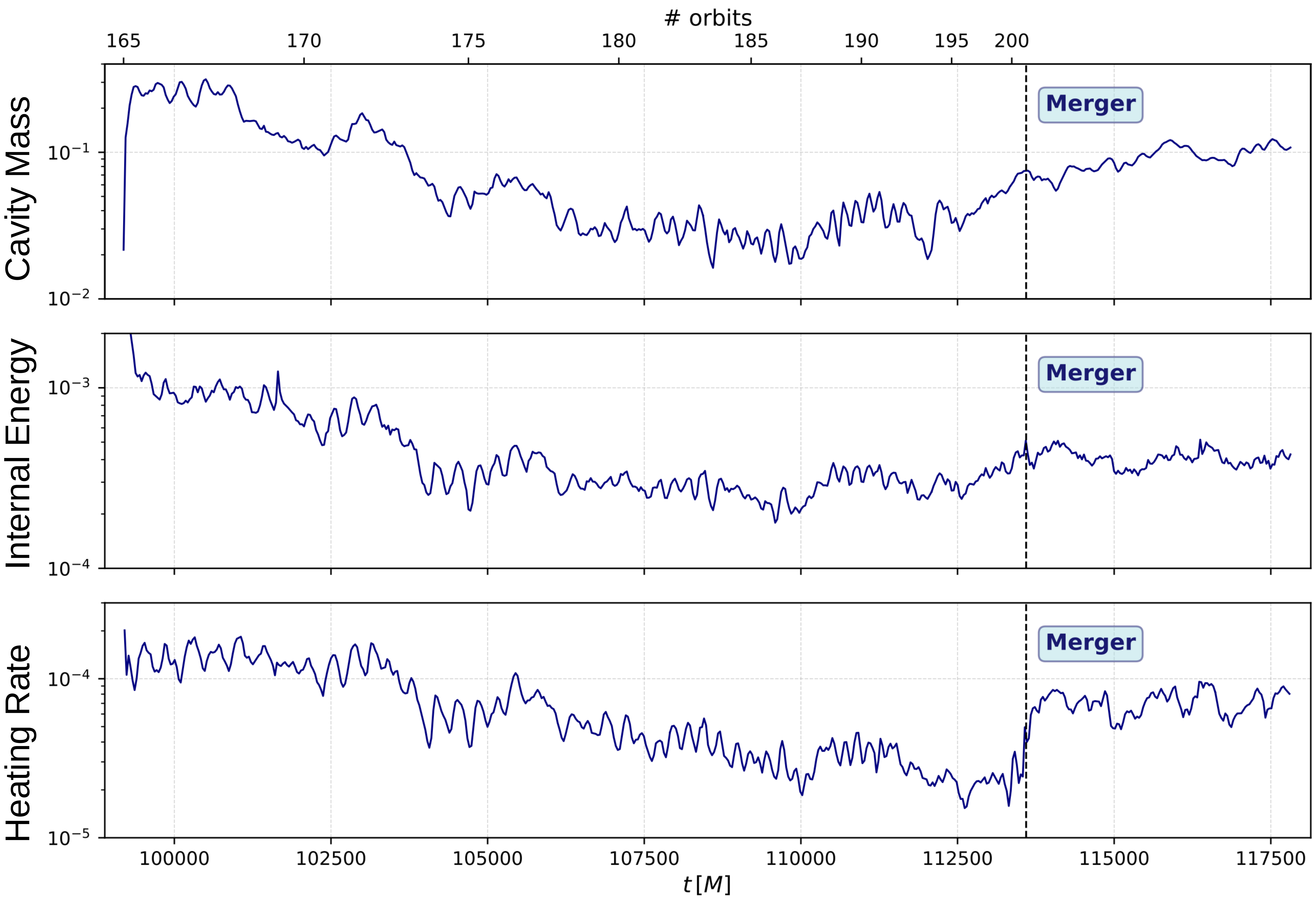
Open Questions

- How do jets from binaries and mergers manifest at large distances? Is there relic evidence of a binary in the post-merger jet properties?
- How do we connect the Newtonian scales to the relativistic regime, where do things break down?
- What impact will more radiation physics have? E.g., Tamara’s talk on Vishal++2025;
- How can we leverage viscous hydro results and connect to the GRMHD regime?
- What are good initial conditions? Are there “natural starting conditions”?
- What other binary signatures are we missing?
  - Jet-jet interactions? Jet-disk interactions?
  - Spin-orbit precession and Orbital plane flipping?

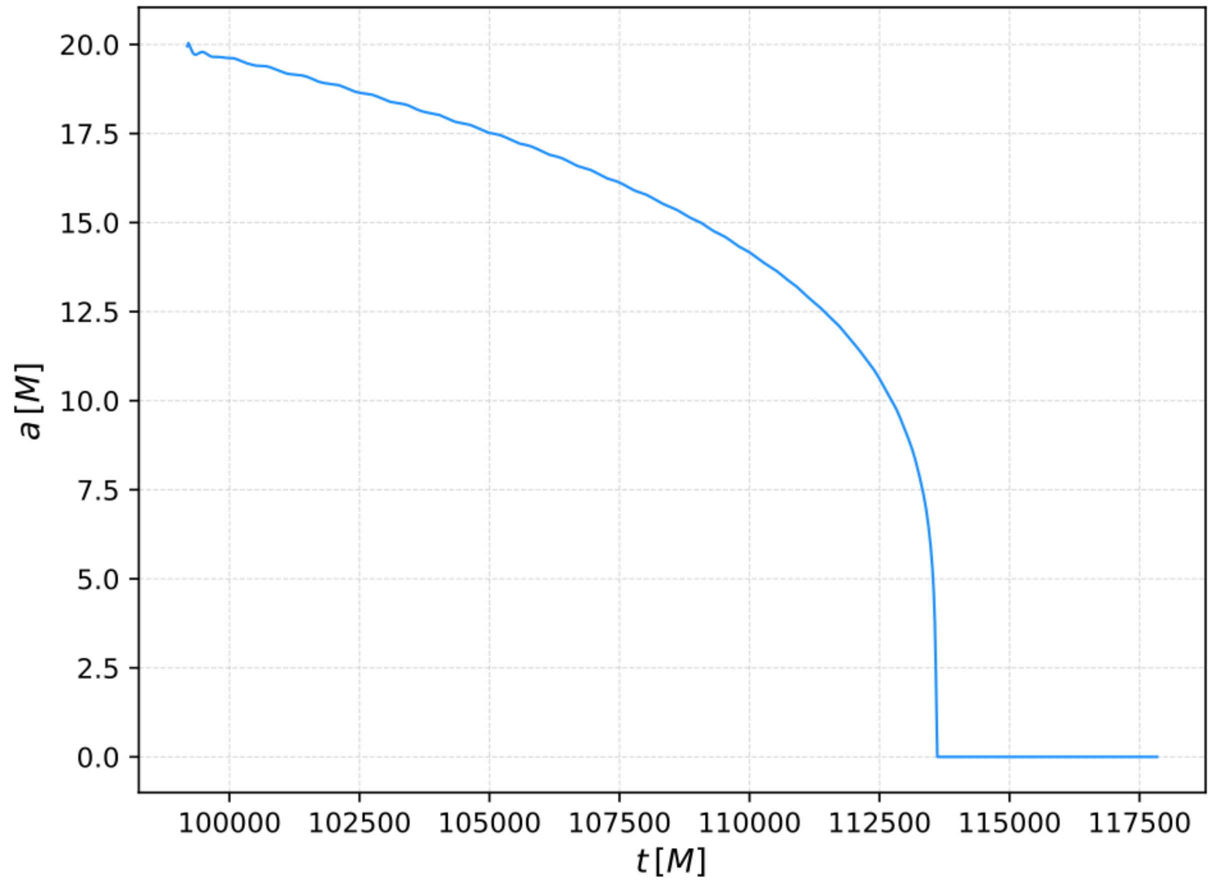
Backup Slides

EM Signatures of Mergers: Cavity Thermodynamics

Ennoggi, Campanelli, Zlochower, Noble, Krolik, Cattorini, Kalinani, Mewes, Chabanov, Ji, and de Simone,, arXiv:2502.06389, (2025).

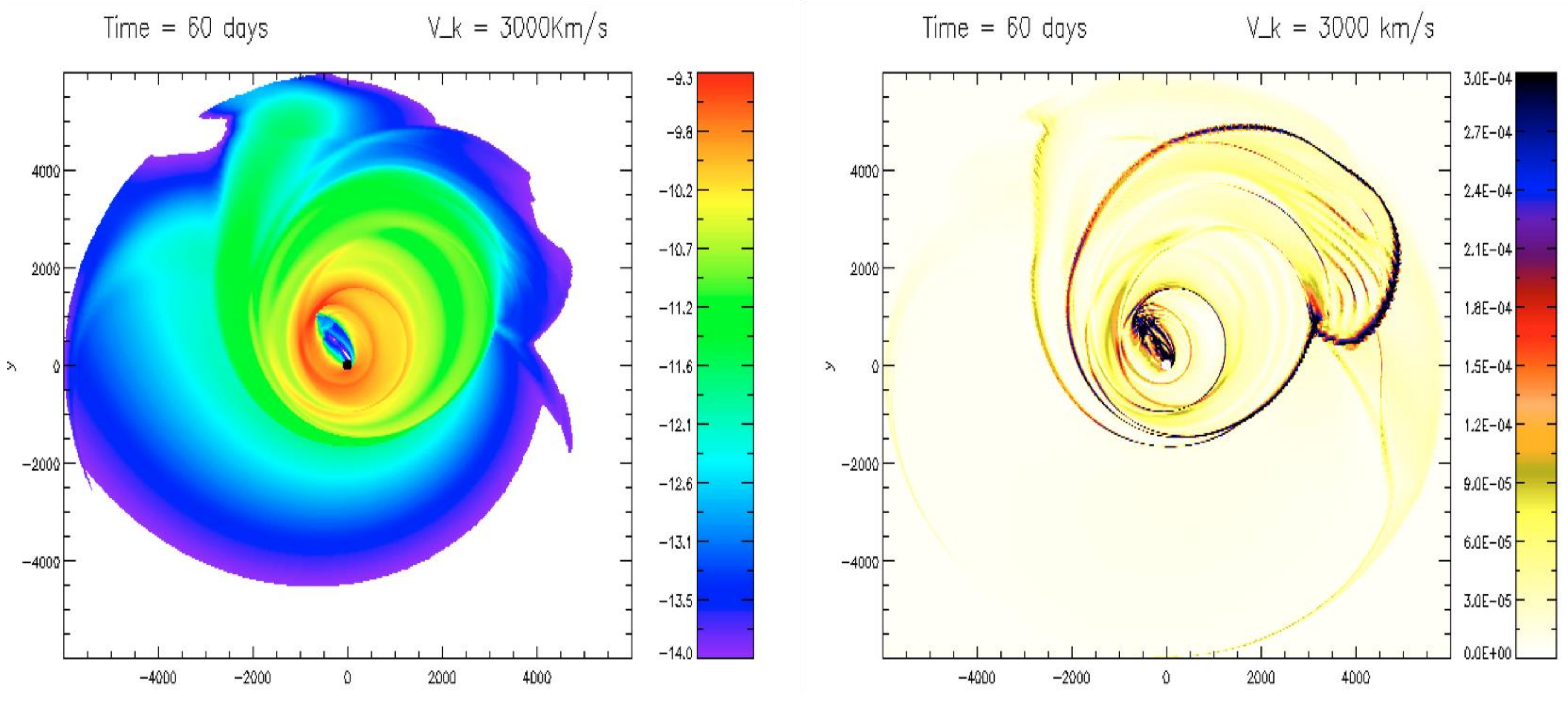


- Heat content of cavity does not decreases as much as the mass;
- Additional heat created by enhanced dissipation from the binary as its inspiral and orbit accelerate;
- **Merger triggers a suddenly heating event as the quadrupolar potential becomes monopolar;**
- Our cooling method, which cools any heat resulting from dissipation (entropy change), keeps up with heating rate;
    - —> **Luminosity tracks heating rate not accretion rate;**



Numerical Relativity + MHD Evolutions

Post-merger Aftermath: Kicks, Mass Loss, Jets

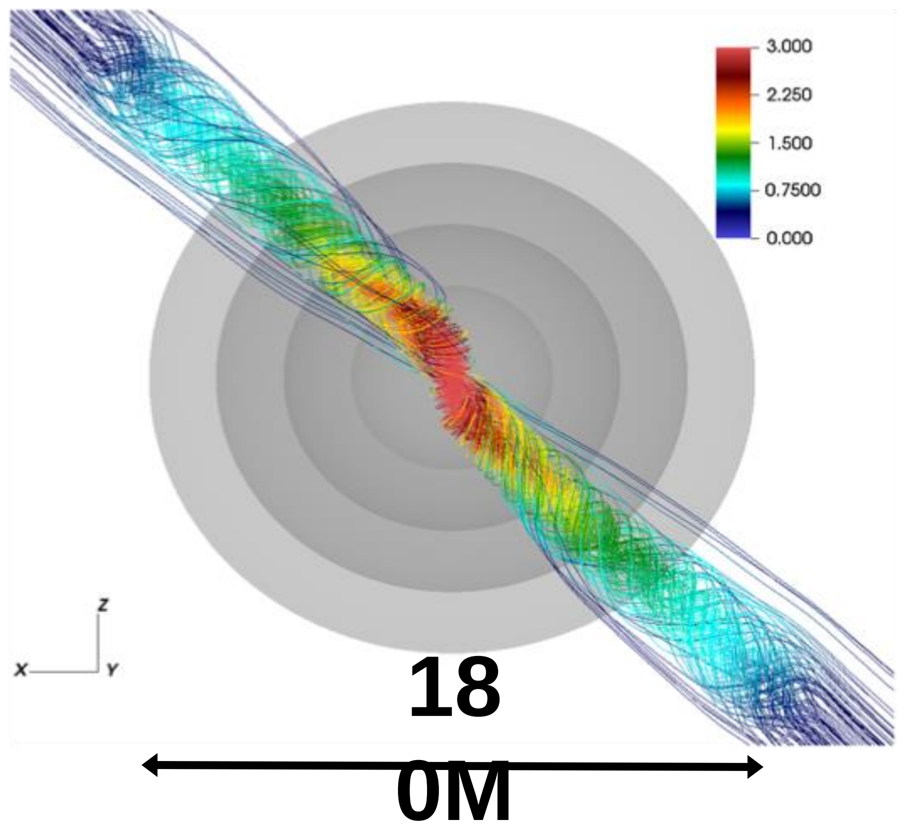


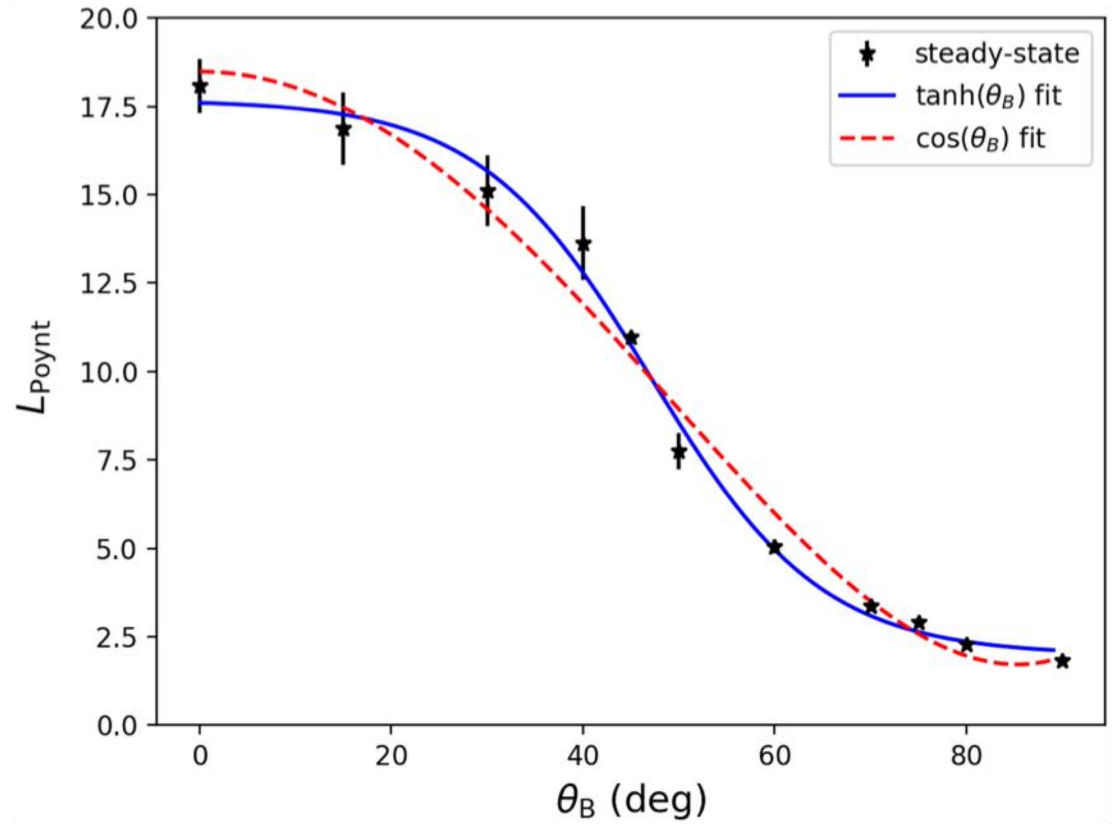
Zanotti, Rezzolla, Del Zanna, and Palenzuela, A&A, 523, A8, (2010).

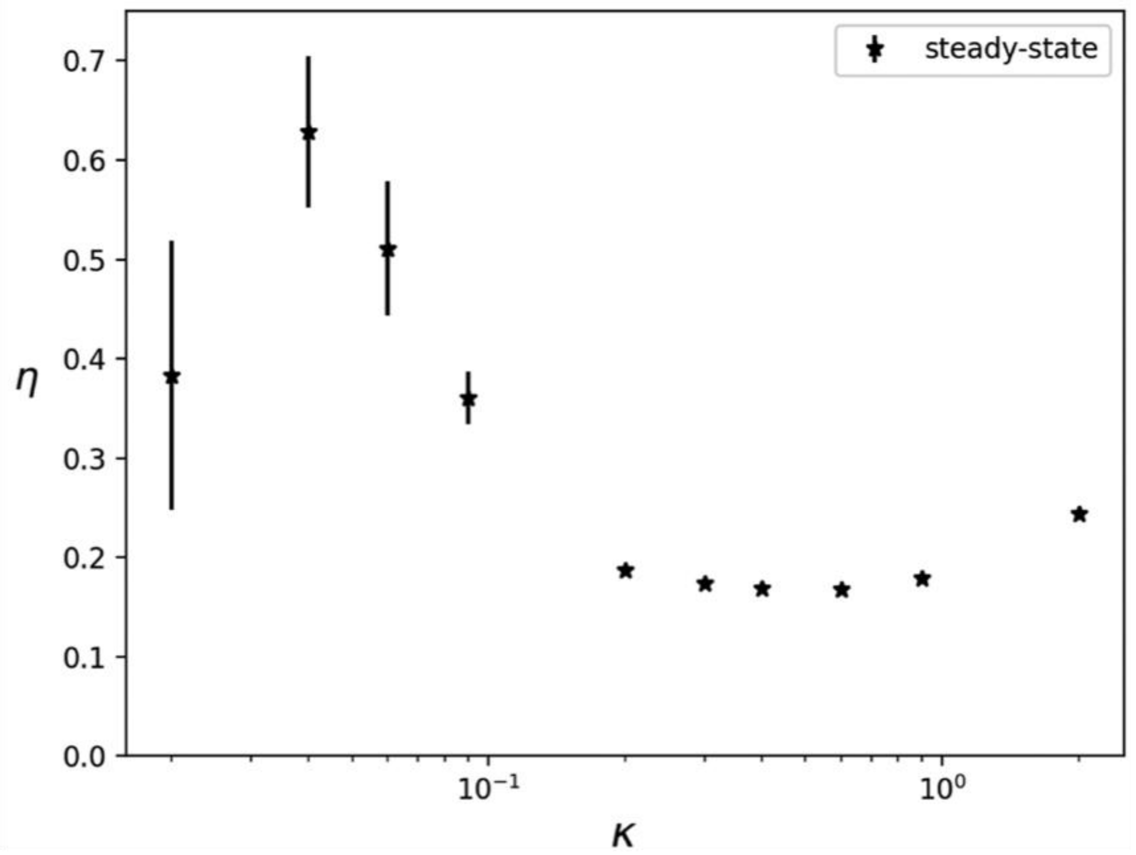
- BBH merger leads to O(100) km/s kicks on merger remnant and few-several % mass loss due to GW losses;
- Disk “adjusts” or is “kicked” by the sudden change in the gravity, often triggering eccentric shocks that dissipate change motion triggered by change in potential energy;
- Observables are often significant tens-hundreds of days post-merger for massive BBHs.

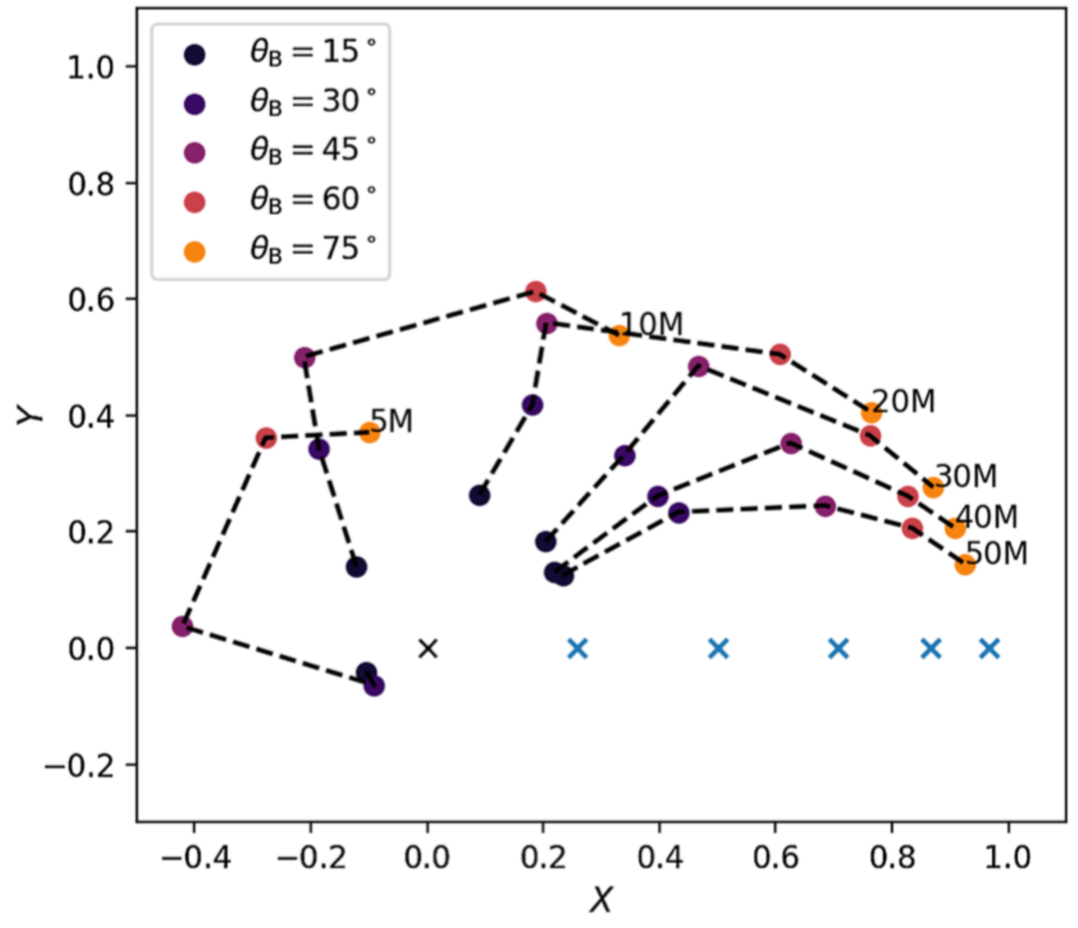
Kelly, Etienne, Golomb, Schnittman, Baker, Noble, Ryan, PRD 103, 063039 (2021)

- 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;





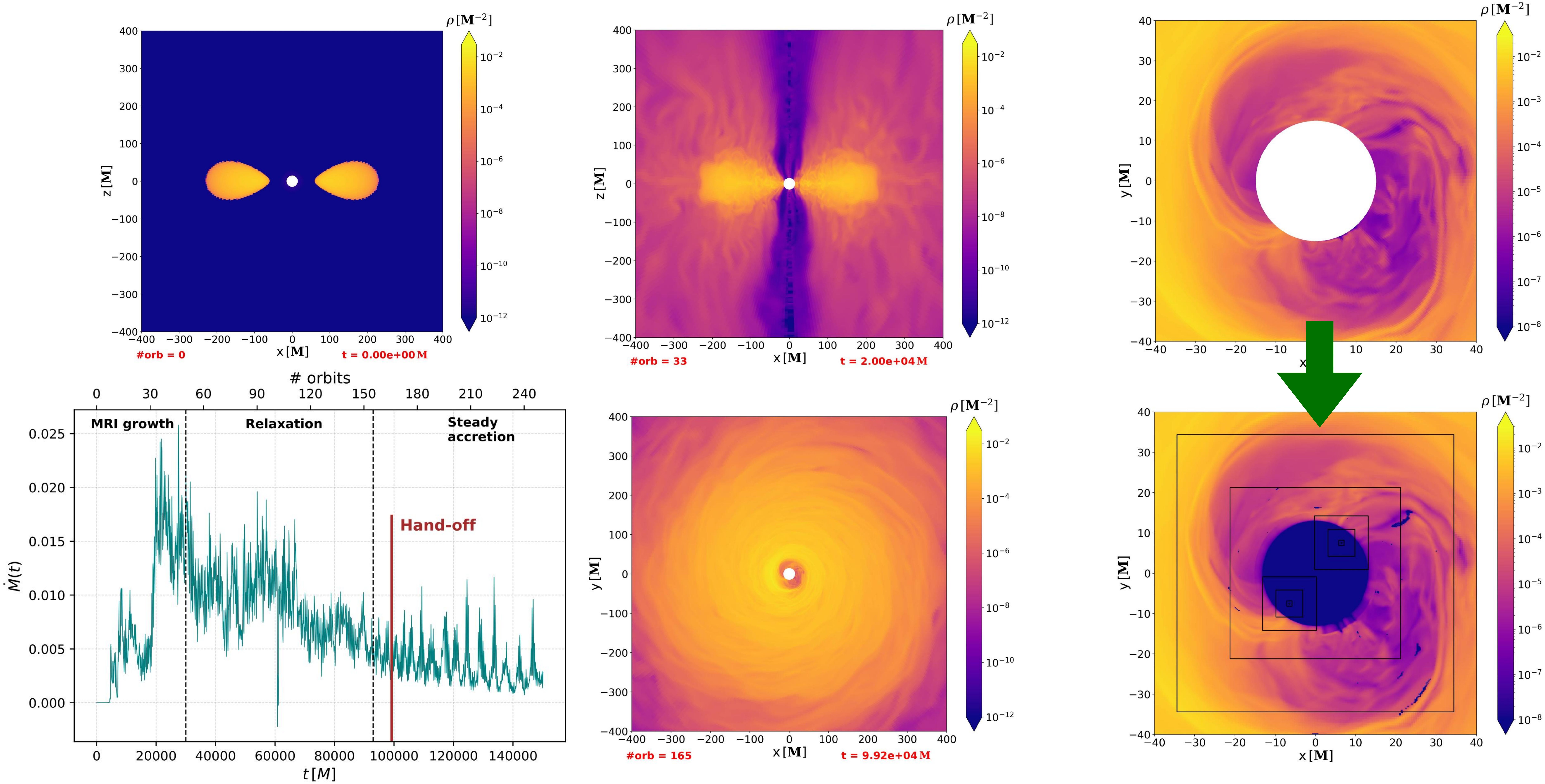




EM Signatures of Mergers: Setup

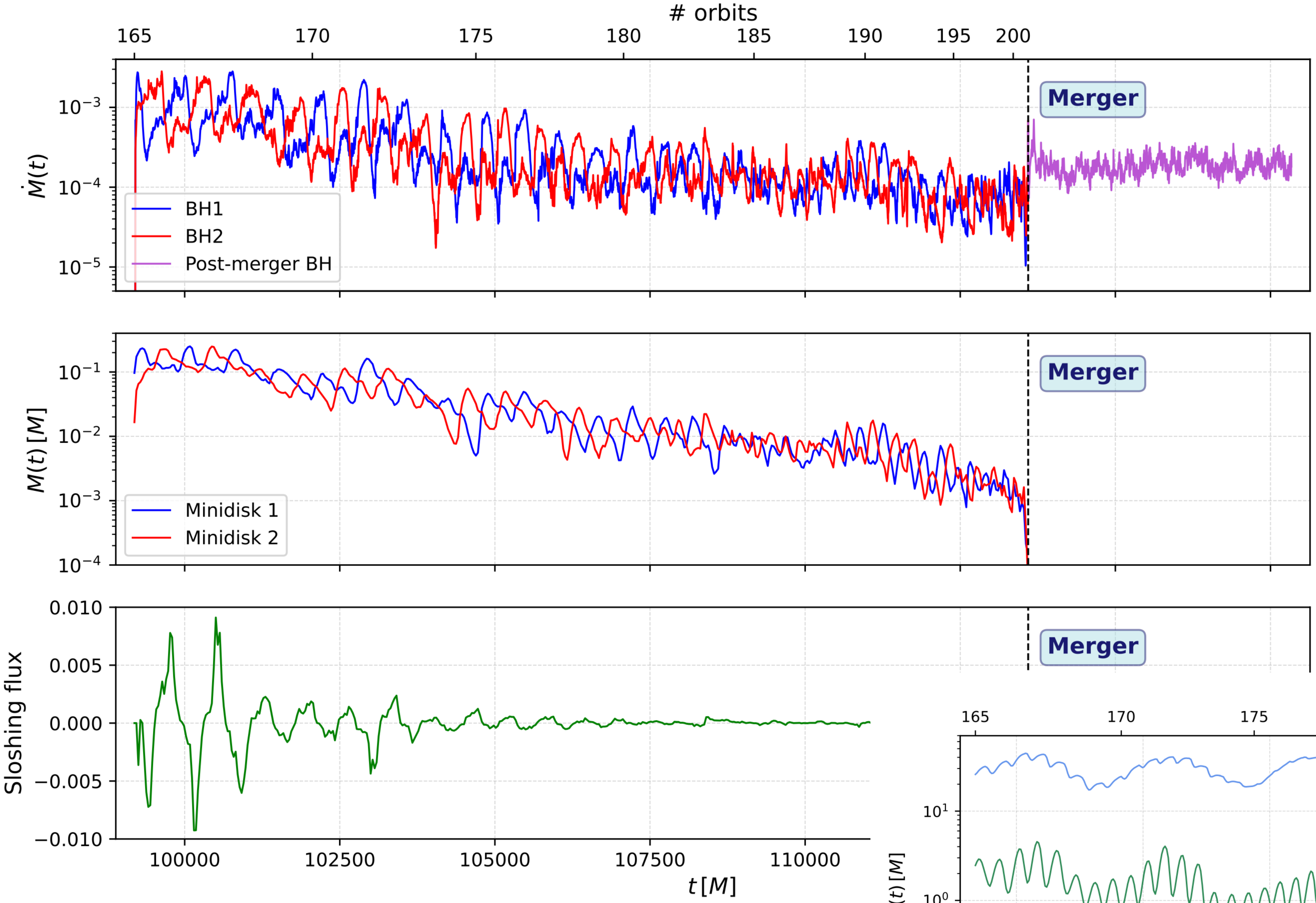
Ennoggi, Campanelli, Zlochower, Noble, Krolik, Cattorini, Kalinani, Mewes, Chabanov, Ji, and de Simone,, arXiv:2502.06389, (2025).

- CBD-only evolution with BHs excised to afford O(100) orbits using spherical Numerical Relativity code **SphericalNR**;
- CBD data from steady accretion state interpolated to AMR grid structure for merger evolution in **IllinoisGRMHD**;



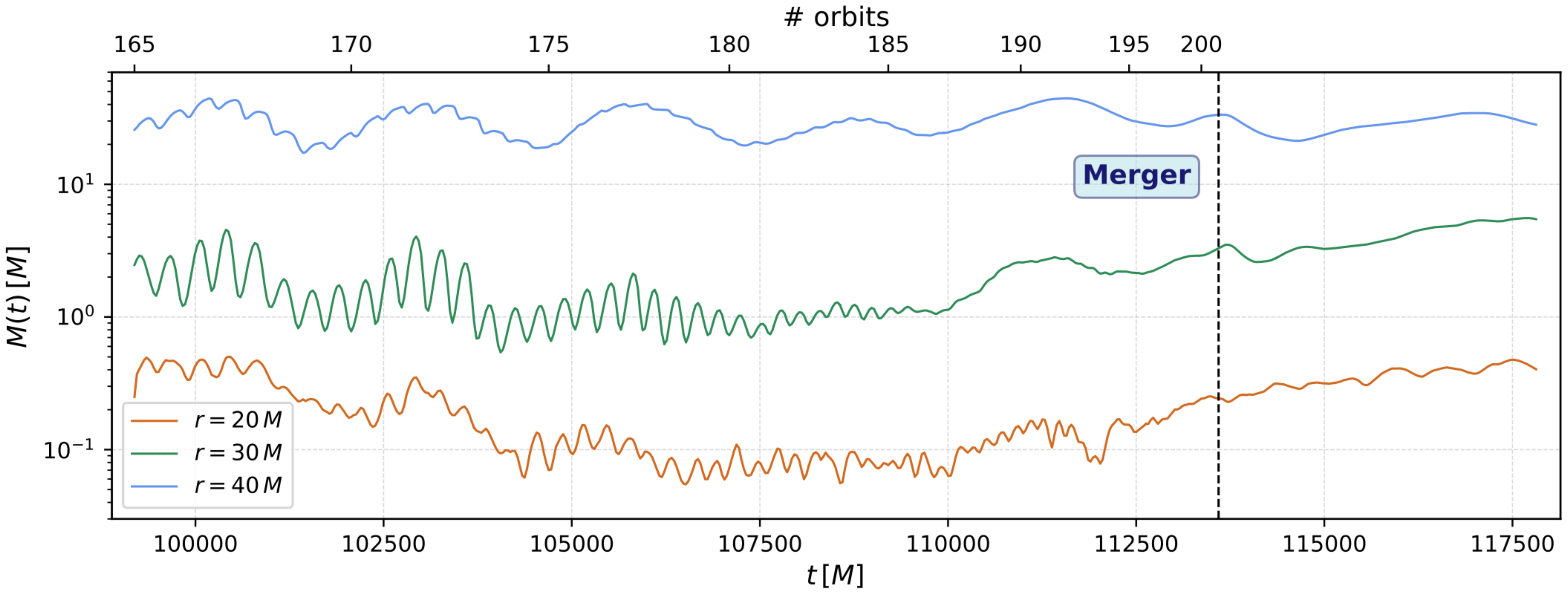
EM Signatures of Mergers

Ennoggi, Campanelli, Zlochower, Noble, Krolik, Cattorini, Kalinani, Mewes, Chabanov, Ji, and de Simone,, arXiv:2502.06389, (2025).

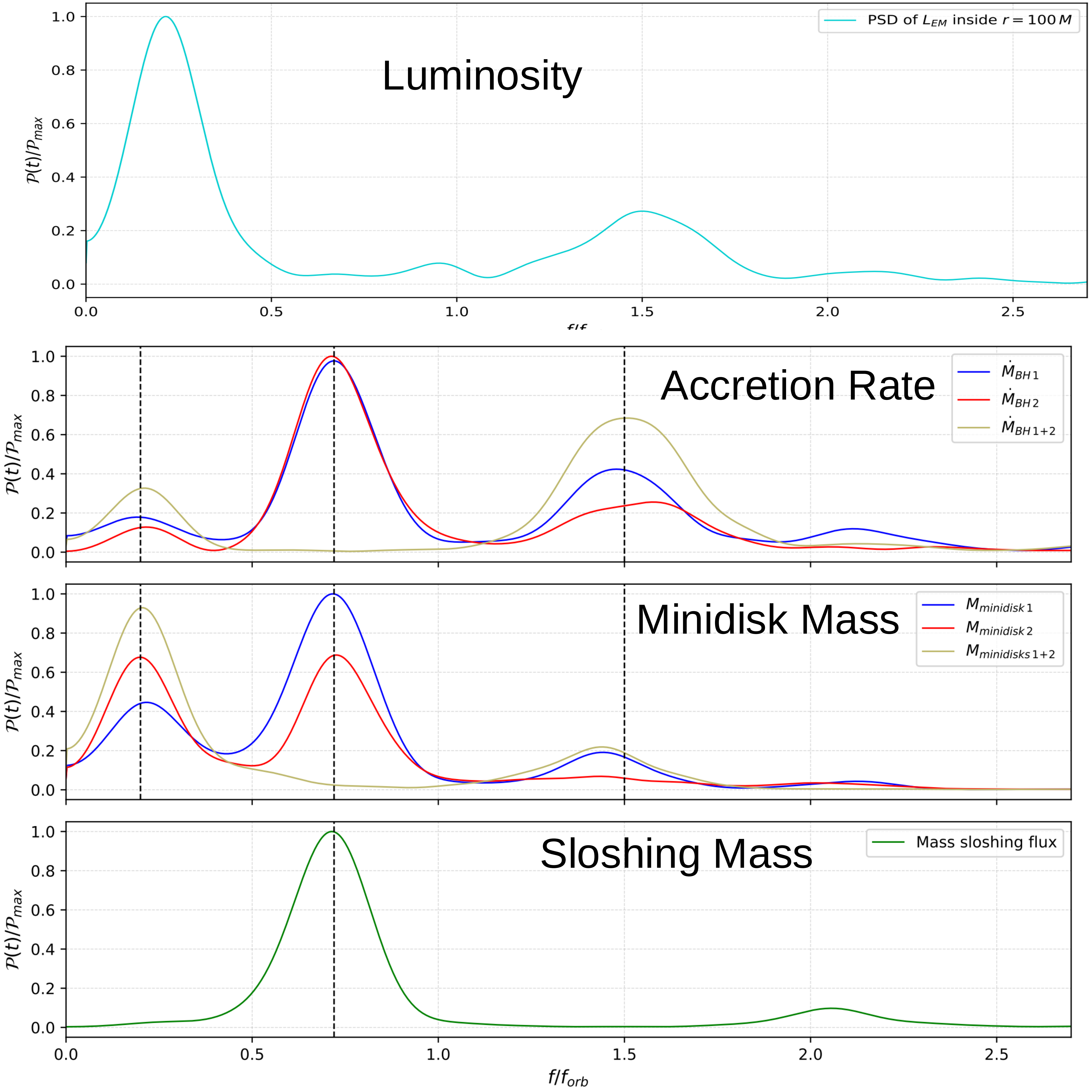


- As BHs inspiral each BH's accretion drops by a factor of a few then plateaus:
  - This drop is matched in part by disintegrating minidisks but accretion levels out through transition to stream/chaotic feeding;
  - Sloshing between BHs diminishes halfway to merger;
  - Sloshing similar to pre-merger simulations:

  Avara, Krolik, Campanelli, Noble, Bowen, and Ryu, ApJ, 974, 242, (2024).



- Mass within and near cavity wall is relatively steady throughout, though loses orbital modulation prior to merger;
- **Cavity begins to fill prior to merger;**



EM Signatures of Mergers: Variability

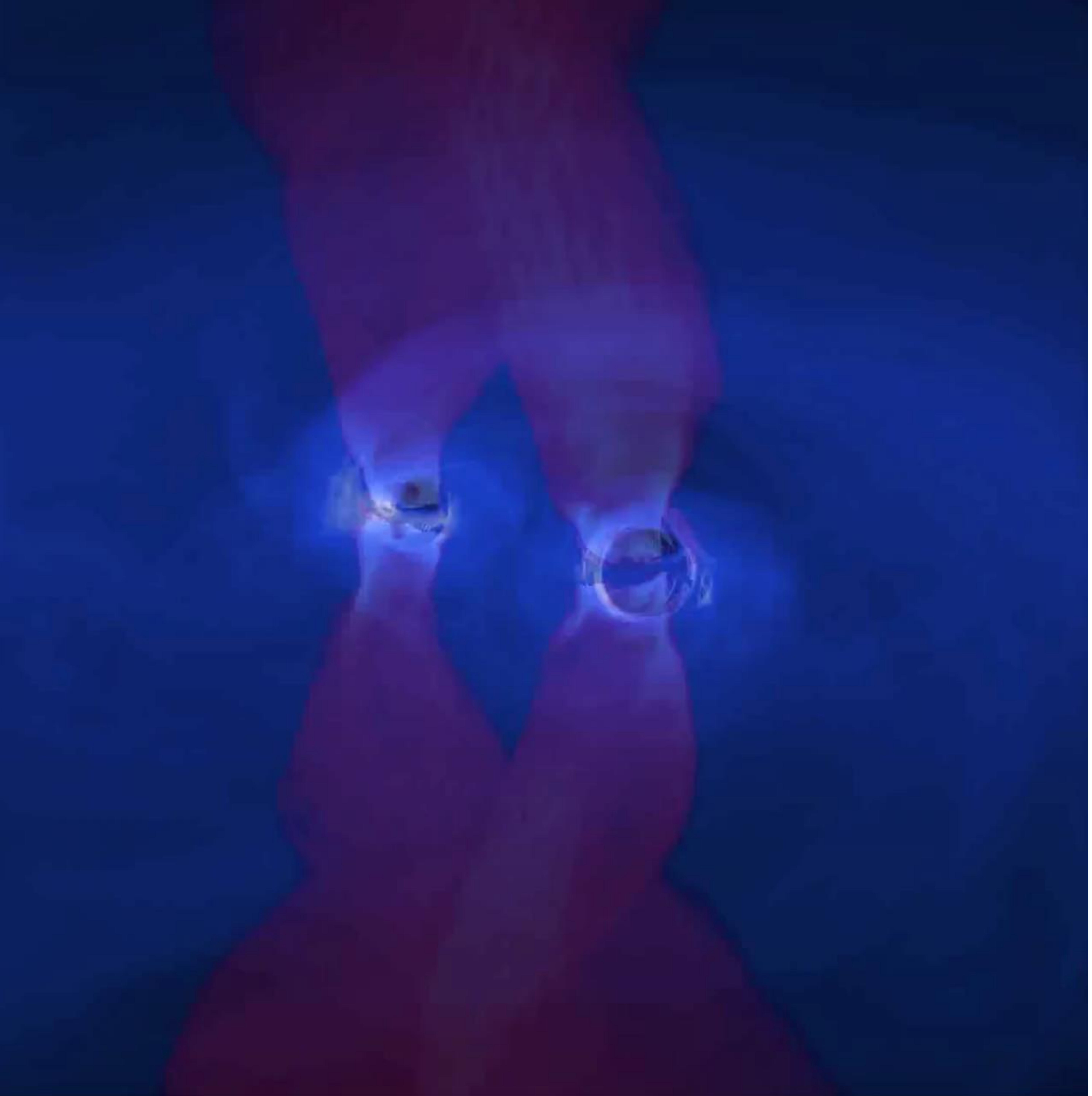
Ennoggi, Campanelli, Zlochower, Noble, Krolik, Cattorini, Kalinani, Mewes, Chabanov, Ji, and de Simone,, arXiv:2502.06389, (2025).

- Minidisk masses and sloshing mass flux all dominated by the beat frequency between the lump and the binary orbit;
  - Total minidisk mass, however only shows signal at twice the beat frequency due to symmetry in the system;

- **EM variability does not always follow mass variability!!**
- **Frequency of EM variability is not the same as the binary's orbital frequency!**
- **Majority of emission fluctuates primarily still from the lump and twice the beat frequency**, similar to CBD-only light curves and consistent with our earlier pre-merger simulations:

Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, ApJ, 928, 137, (2022).

Avara, Krolik, Campanelli, Noble, Bowen, and Ryu, ApJ, 974, 242, (2024).



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

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

Radio - Synchrotron Emission

X-ray - Corona Emission

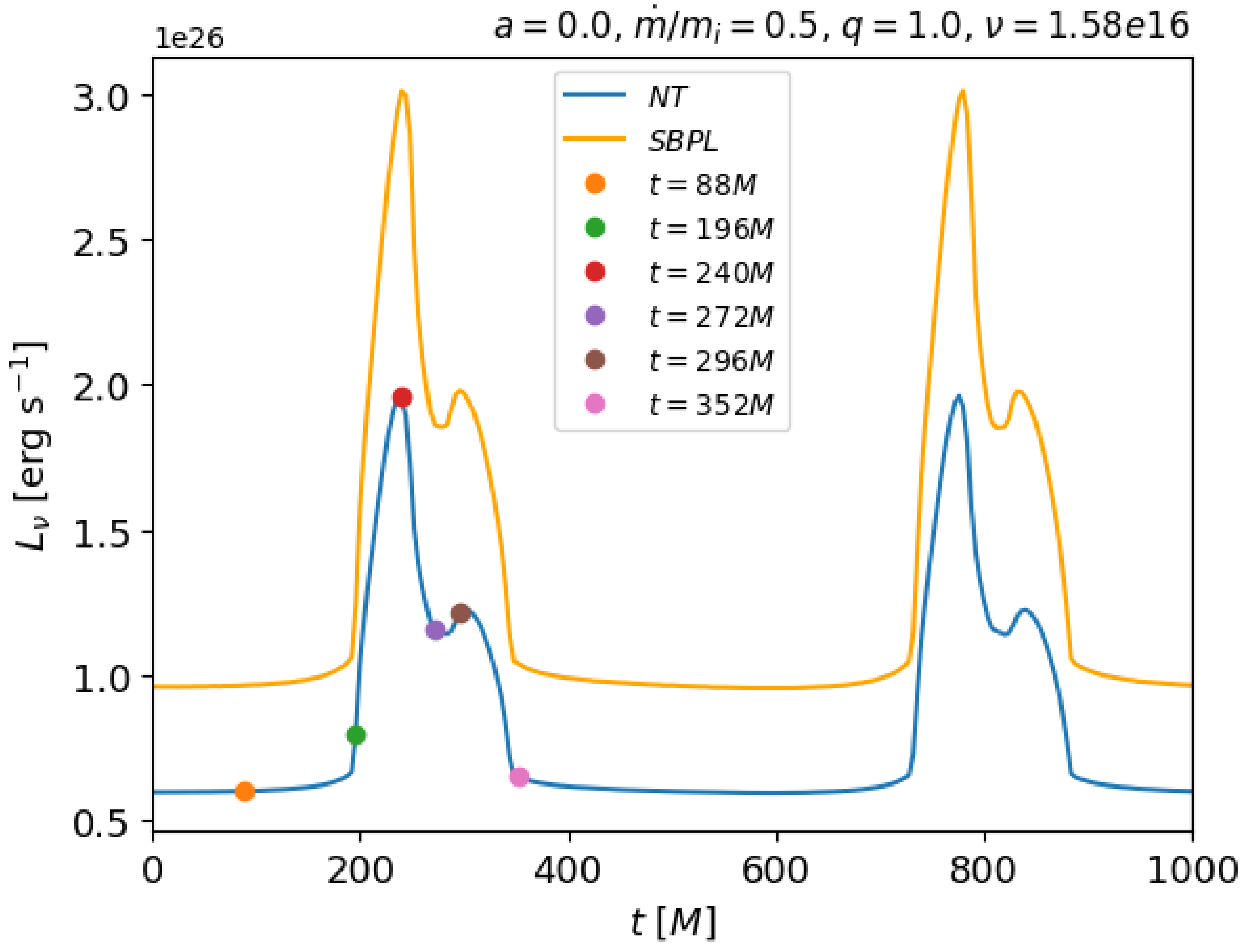
- **Binary jet phenomena;**
- **Synchrotron calculated using same emissivities used in simulations of images for the Event Horizon Telescope project.**

  Leung, Gammie, and Noble, ApJ, 737, 21, (2011).

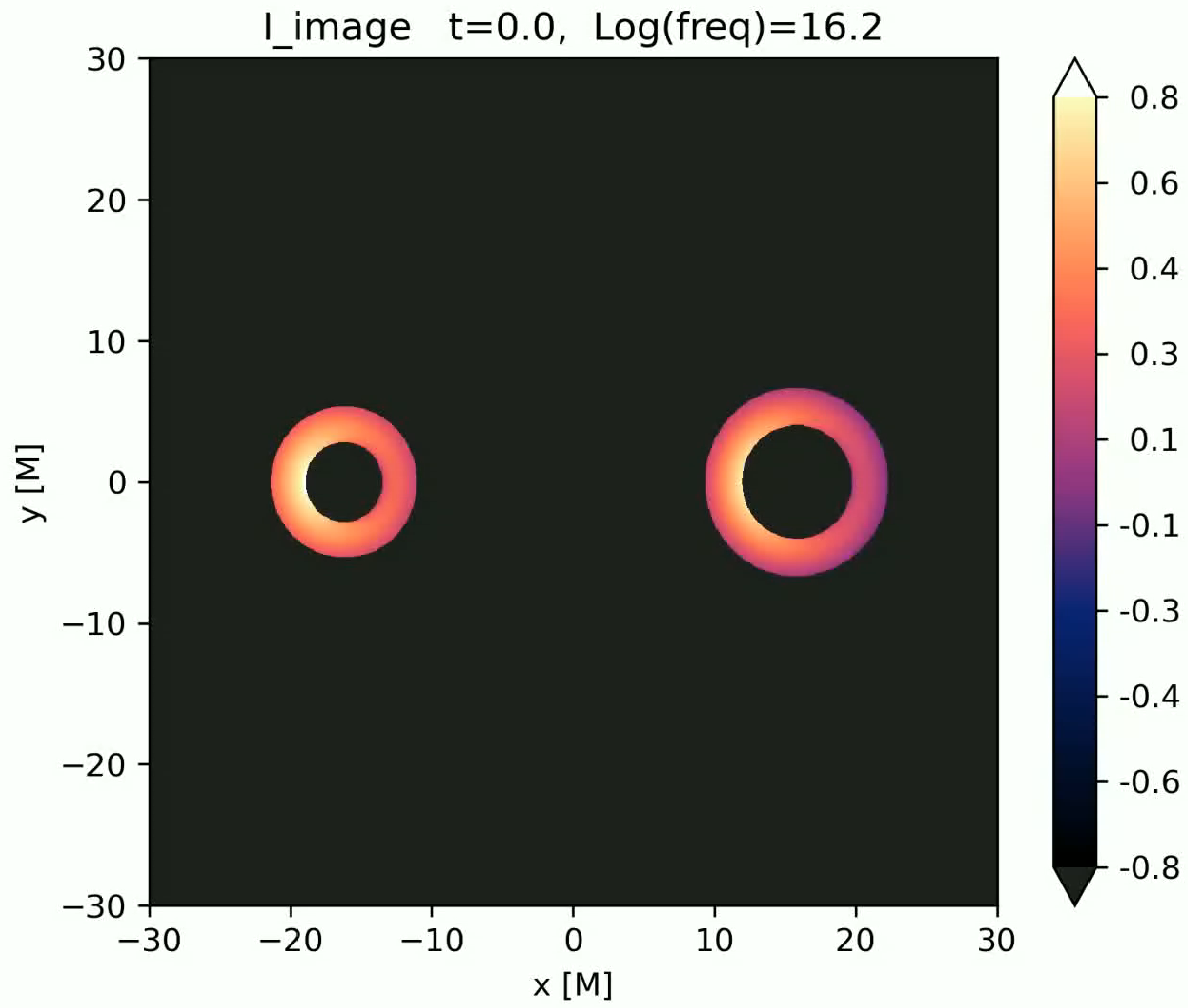
- **Predict correlated X-ray and jet variability, under certain situations, TBD.**

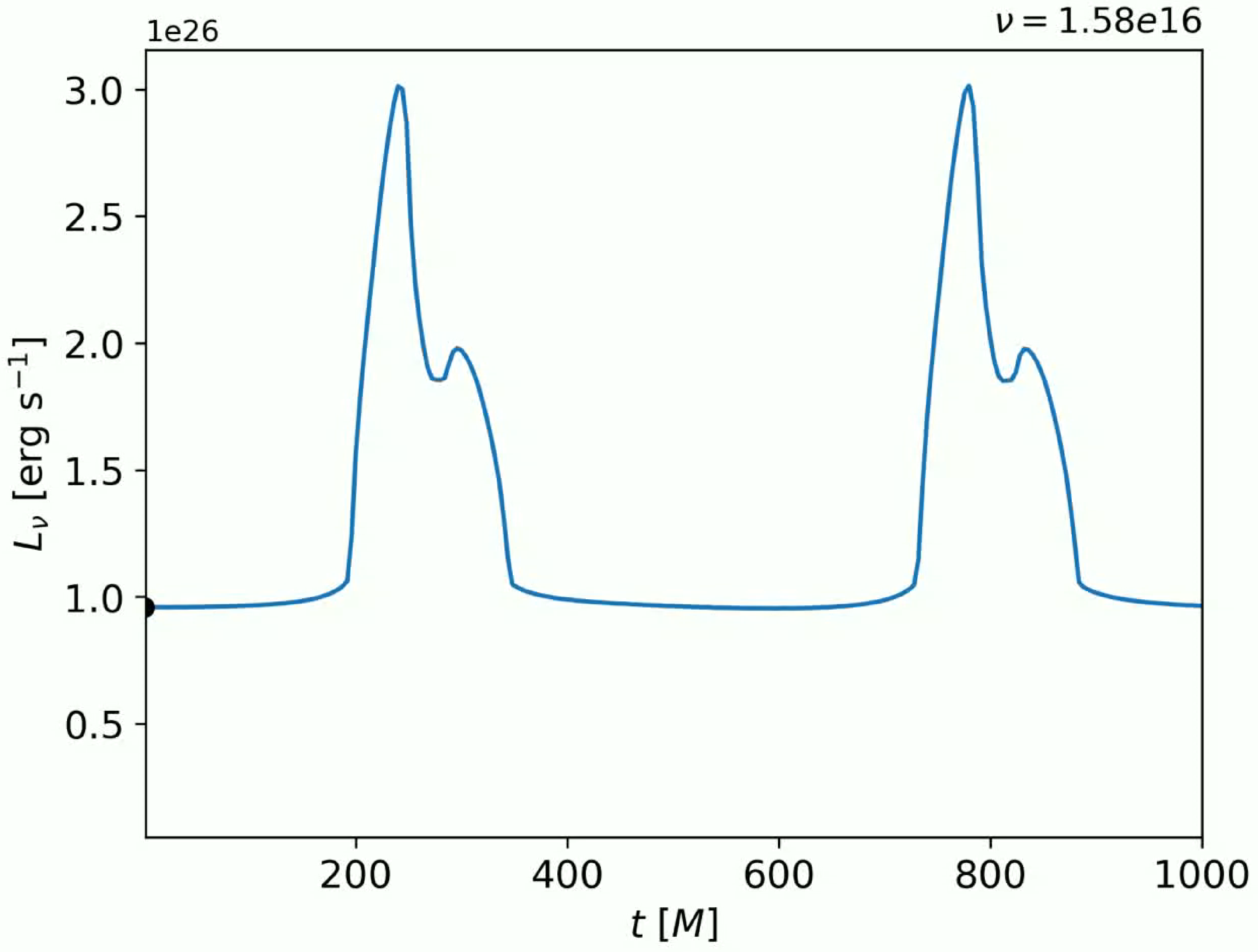
Self-lensing Flares

"A Parameter Study of the Electromagnetic Signatures of an Analytical Mini-disk Model for Supermassive Black Hole Binary Systems", **Porter**, Noble, Gutiérrez, Pelle, Campanelli, Schnittman, and Kelly, ApJ, 979, 155, (2025).



- **Superposed-Kerr-Schild spacetime, 3.5PN trajectories that include inspiral;**
- **Emission model is Novikov-Thorne + Intra-ISCO emission informed from GRMHD simulations** (Schnittman+2016);
- Survey: **mass-ratio, spin, initial separation, accretion rate, inclination angle**;
- Ultimate aim to build catalog of ray-traced light curves with simulation-fed accretion rates;
- Similar to Davelaar & Haiman 2022a,b except we transport light fully covariantly from source to observer, include intra-ISCO emission and orbital shrinkage.





Kaitlyn Porter

RIT Phd Student