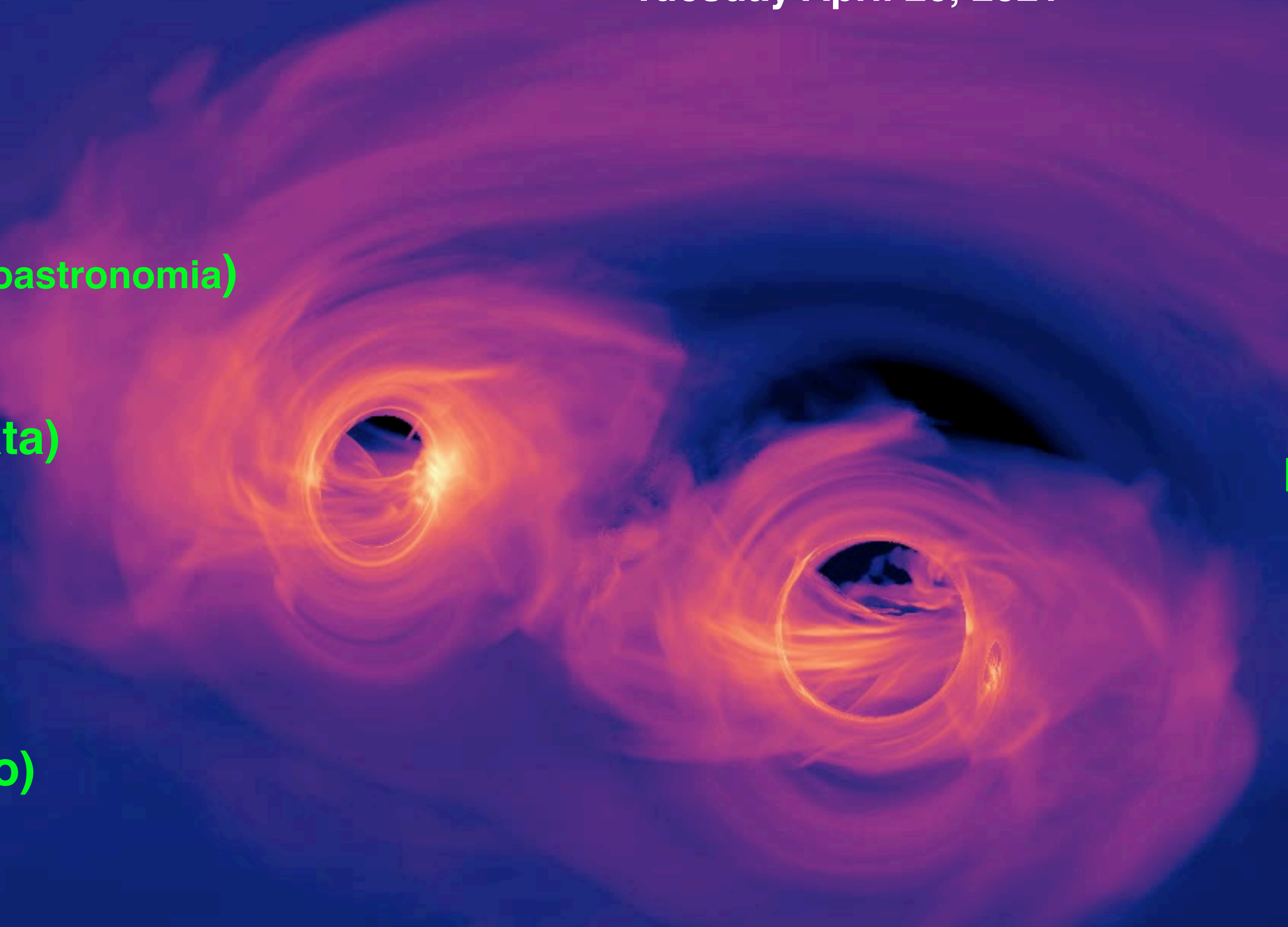
Variety in the Variability of Accreting Supermassive Binary Black Holes

APS physics APRIL MEETING 2021
Q2C quarks cosmos
APRIL 17–20 ONLINE

Session Y01: New Vistas in the Simulation of Matter in Strongly Gravitating Systems
DCOMP DGRAV
Tuesday April 20, 2021



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E. Gutierrez (Nac. Uni. La Plata)
M. Campanelli (RIT)
J. Krolik (JHU)

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V. Mewes (ORNL)
B. Mundim (SciNet/U. Toronto)
H. Nakano (Ryukoku U.)
M. Zilhao (Lisboa U.)
Y. Zlochower (RIT)

Scott C. Noble

Research Astrophysicist
Gravitational Astrophysics Lab
NASA Goddard Space Flight Center

https://arxiv.org/abs/2102.00243
https://arxiv.org/abs/2103.12100
https://arxiv.org/abs/2103.15707

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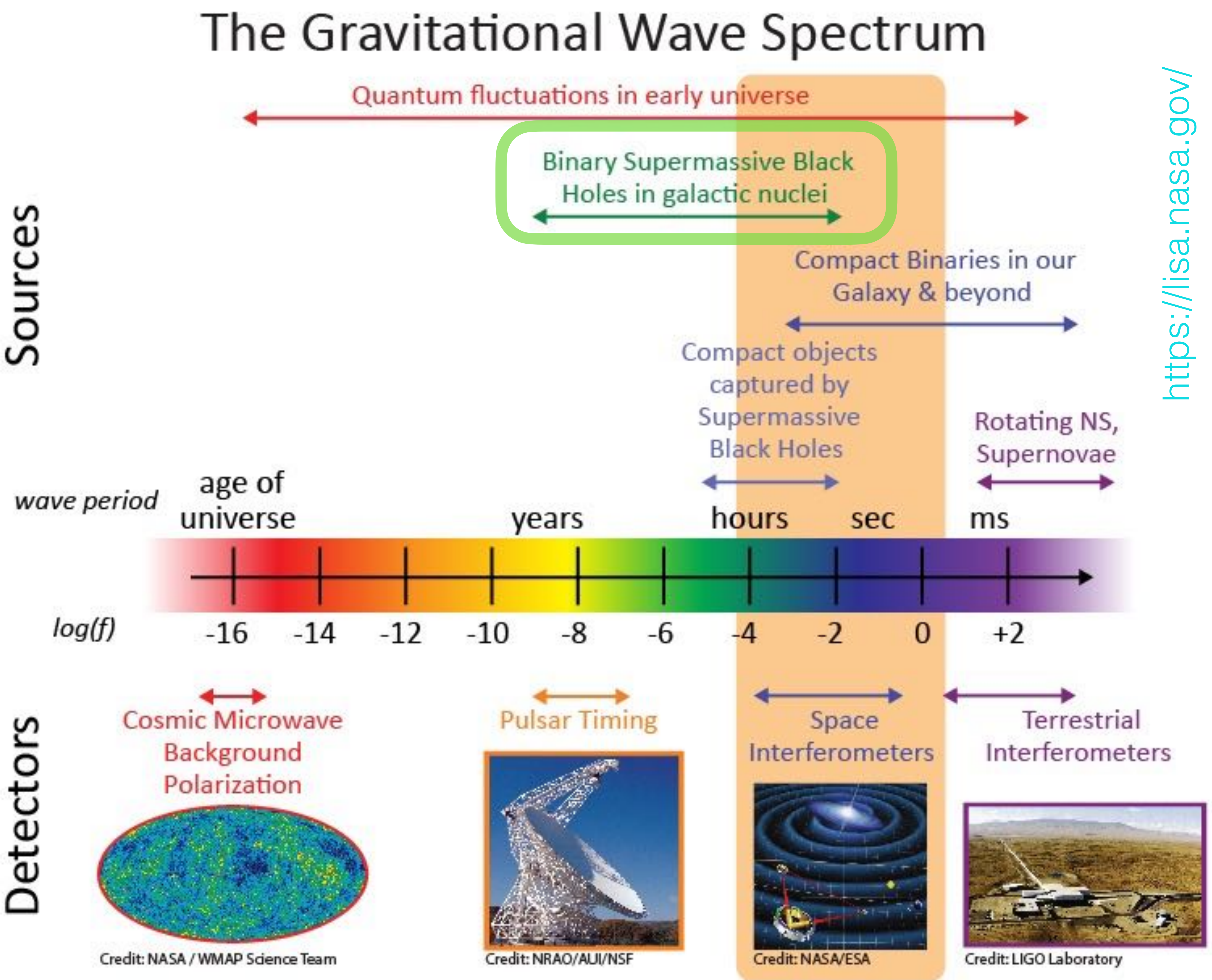
NSF PRAC ACI-1515969 & OAC-1811228, AST-1515982, AST-2009330 & PHY-2001000

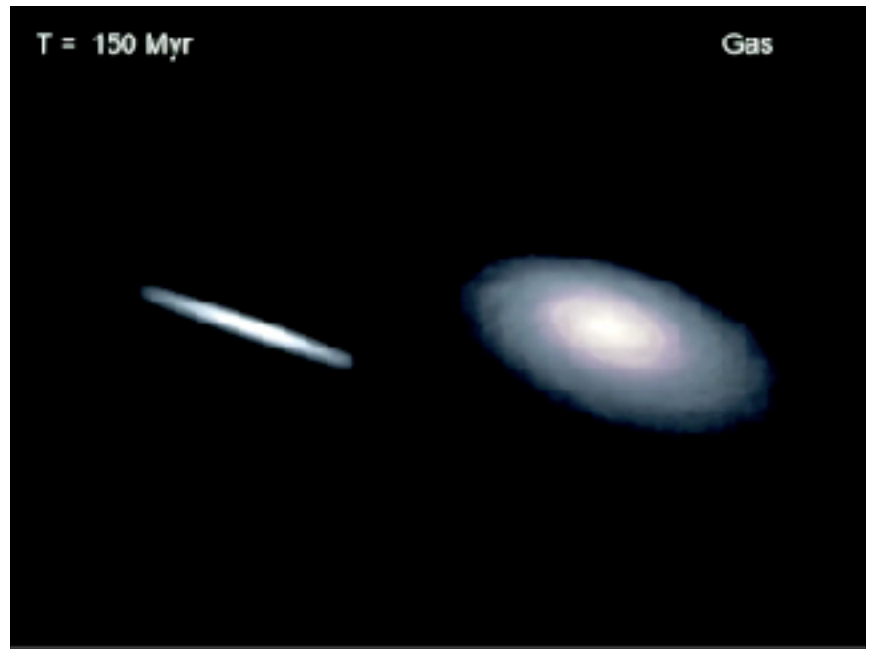
Supermassive Binary Black Holes

- Binary AGN are a primary multi-messenger source for LISA (inspirals, mergers, ringdowns) and PTA (inspirals).
- Likeliest EM-bright binary black hole system.
- Best candidate for exploring plasma physics in the strongest and most dynamical regime of gravity.
- GWs with LISA aid localization, & with smart pointing strategies with fast-slewing X-ray telescopes (e.g. Transient Astrophysics Probe) one may find O(1-5) systems before merger.
  Dal Canton++, ApJ 886 (2019).
- Only (?) likely opportunity to see EM/GW through all phases: inspiral to merger to ring-down.
- Rubin Observatory will identify 100k's of AGN, so even a "small" binary fraction implies many sources.
- EM identification will be critical for detection and characterization—> realistic simulations and their EM output are needed!



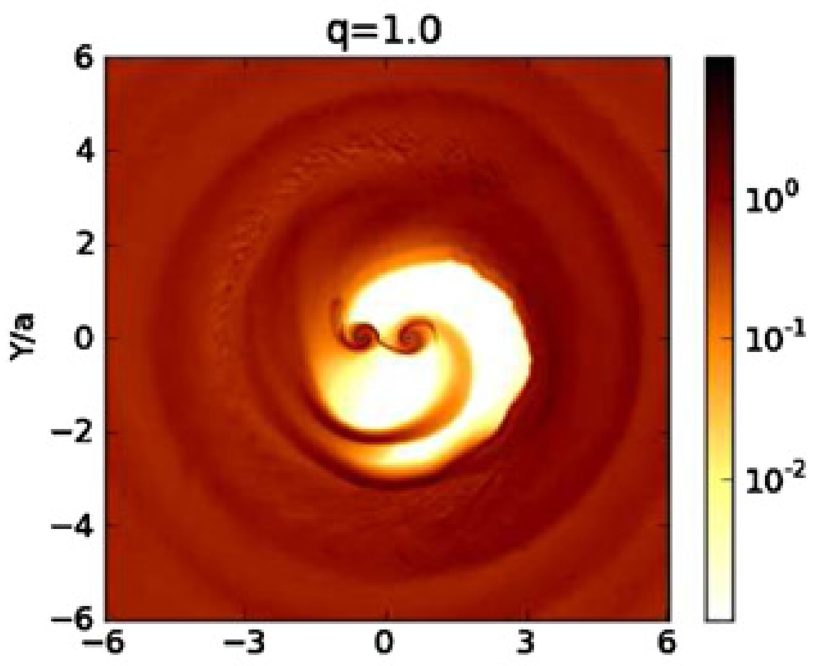
https://lisa.nasa.gov/

Strategy & Techniques



Hopkins, Hernquist, Di Matteo, Springel++

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



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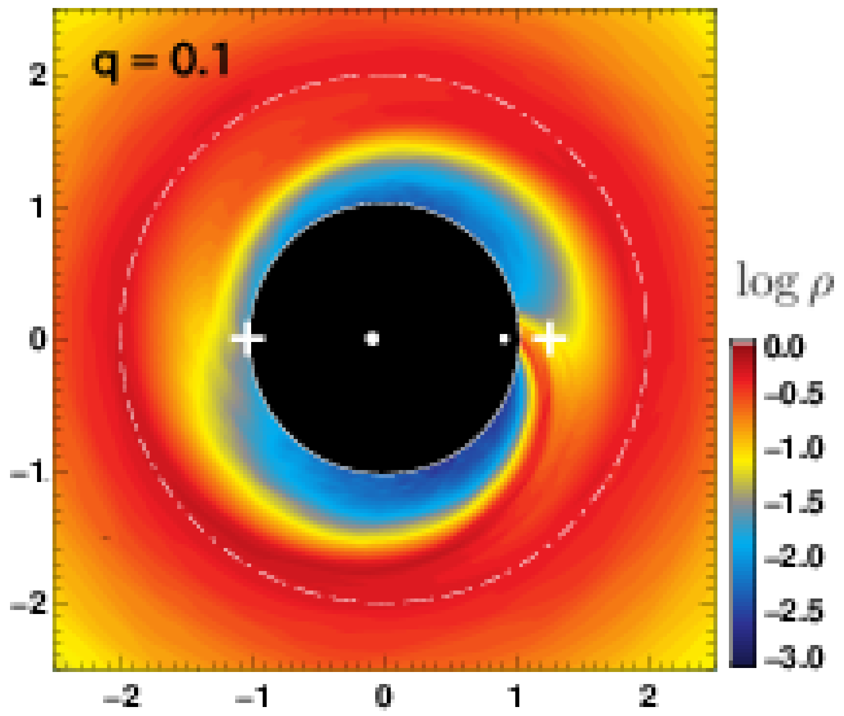
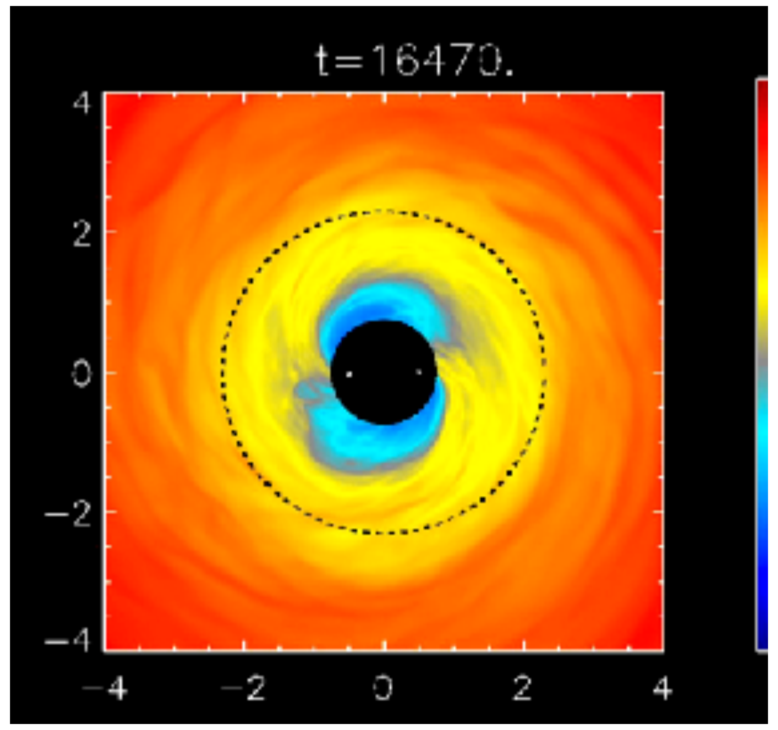
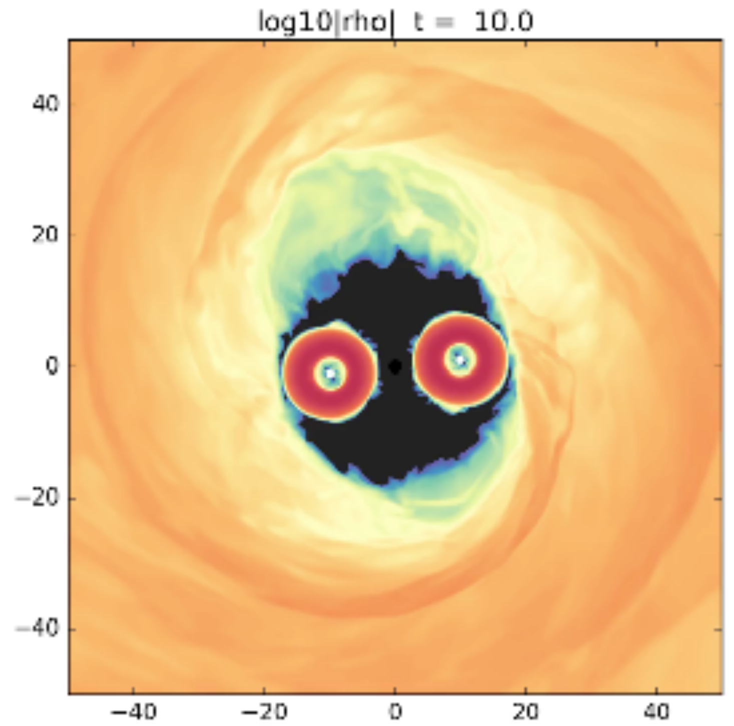


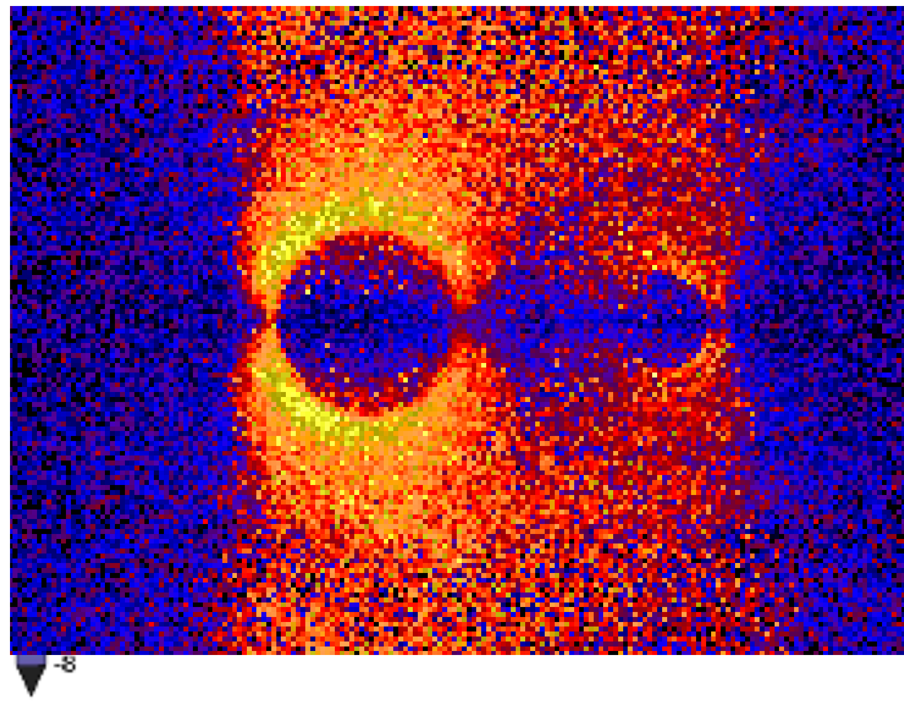
Shi & Krolik (2014-2016)
Bankert & Krolik (2015)



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



Bowen++2018, 2019
Combi++2021

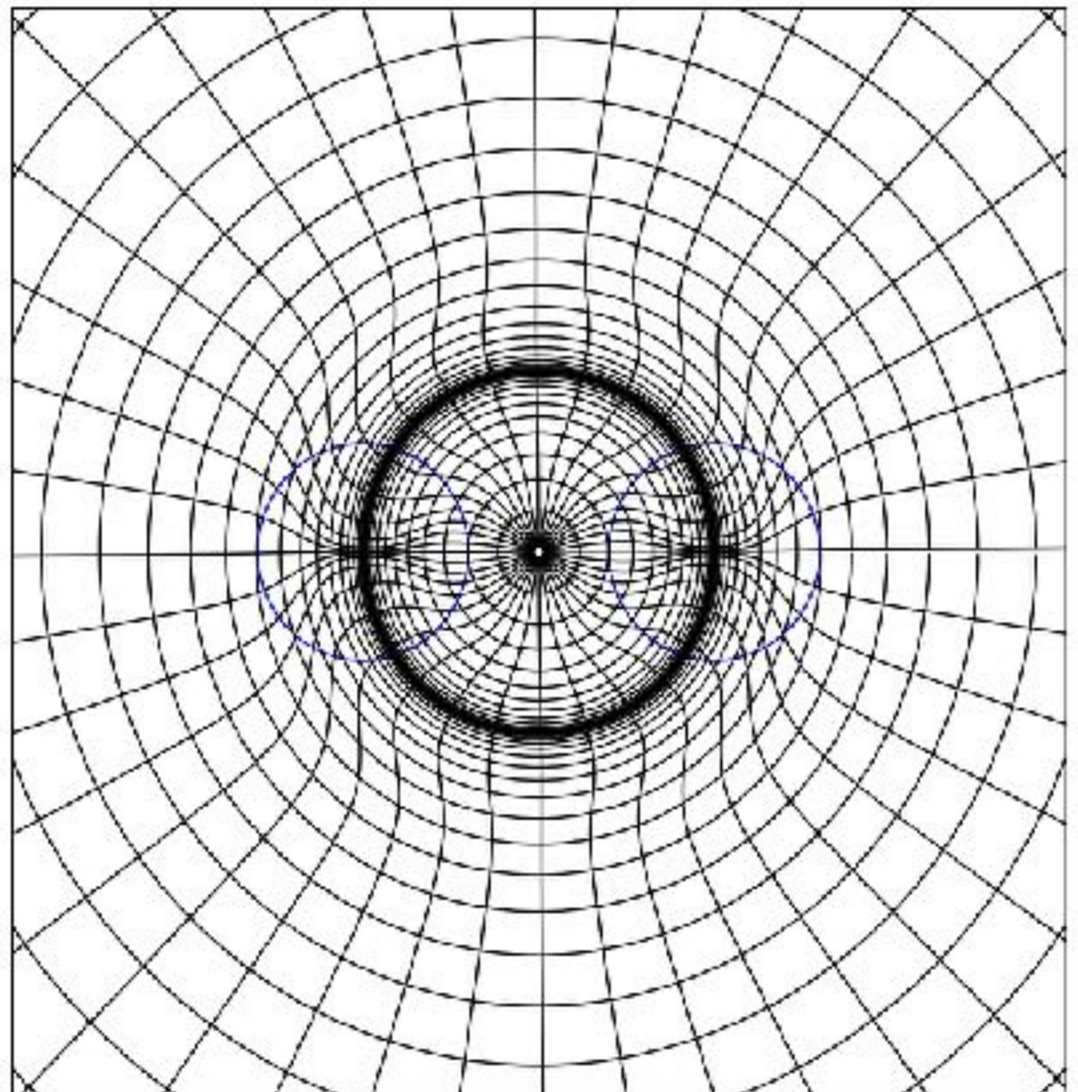


Kelly++2017, Farris++2012, Gold++2014ab, Kahn++2018, Paschalidis++2021, Cattorini++2021
Review: Gold, Galax, 7, 63, (2019)

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

- **Use well-tested GRMHD code for accretion disks: *HARM3d;***
- **Novel methods tailored for accuracy and affordability:**
  - **Dynamic warped grids;**
  - **Perturbative solutions for gravity consistent with Einstein's equations in our regime;**

➡ **Key Challenges:** **Ability to evolve accreting binaries while resolving the MRI and MHD dynamics at the scale of the event horizons in the inspiral regime—*key for establishing pre-merger conditions*.**



Newtonian Binary Accretion Systems

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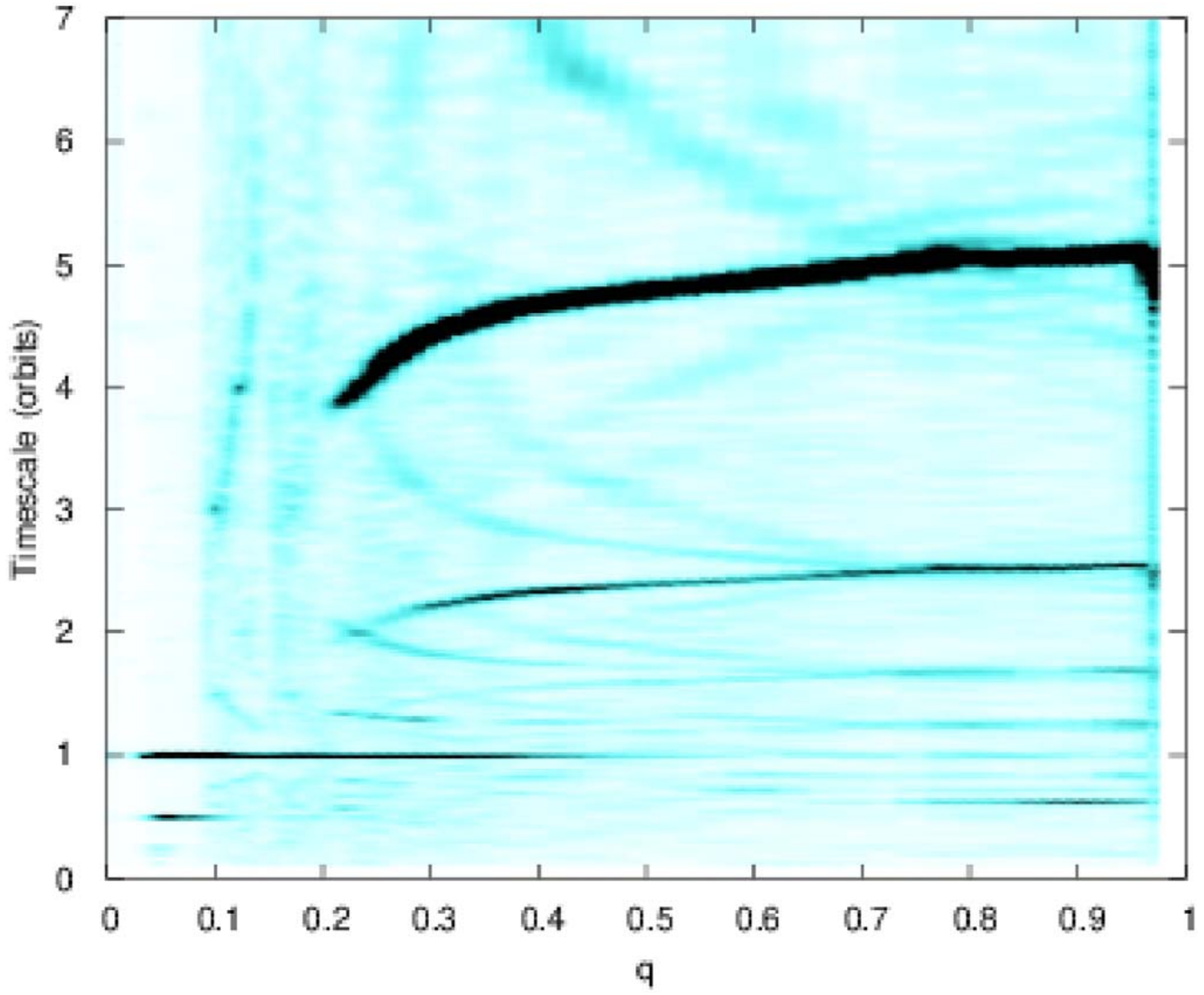
D'Orazio @APS: H03.00002



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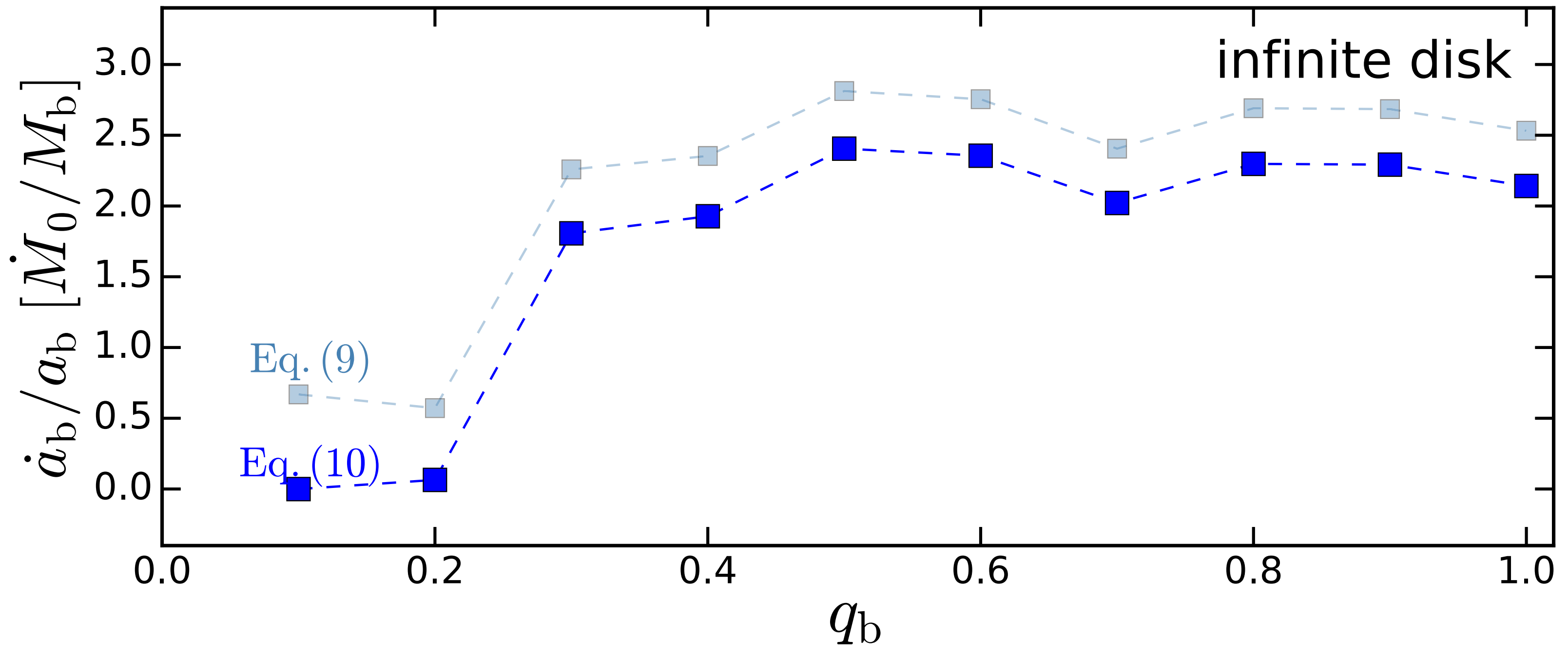
- Accretion variability becomes lump-dominated for mass-ratios above ~0.2



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- Binaries with mass-ratios above ~0.05 - 0.1 may spiral apart!

3-d Newtonian Viscous SPH

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Cuadra, J., Armitage, P. J., Alexander, R. D., Begelman, M. C., MNRAS, 393, 1423, (2009).
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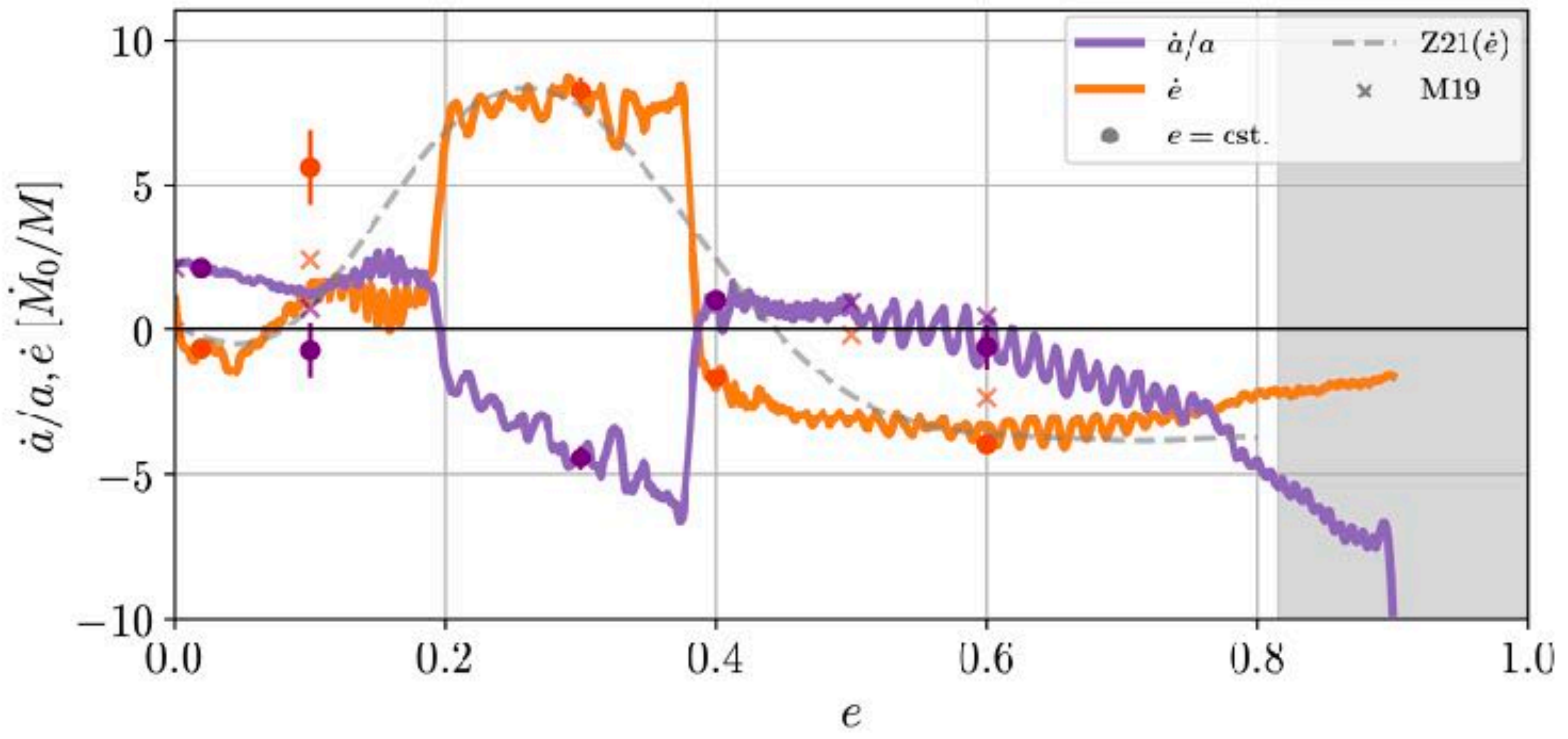

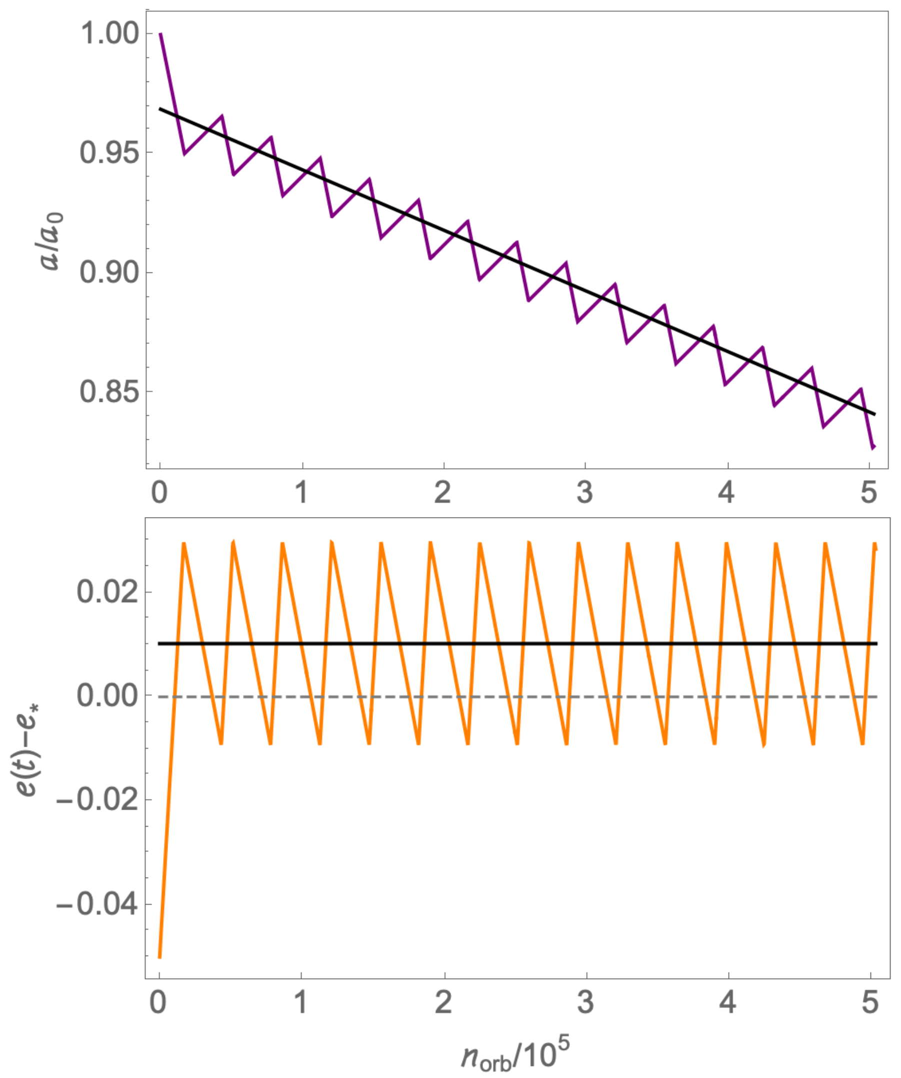

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- Eccentricity evolves with the inspiral rate;
- Sweeping over eccentricity, fixed points at e=0, 0.4;
- Careful attention to e=0.4 case shows it inspirals!

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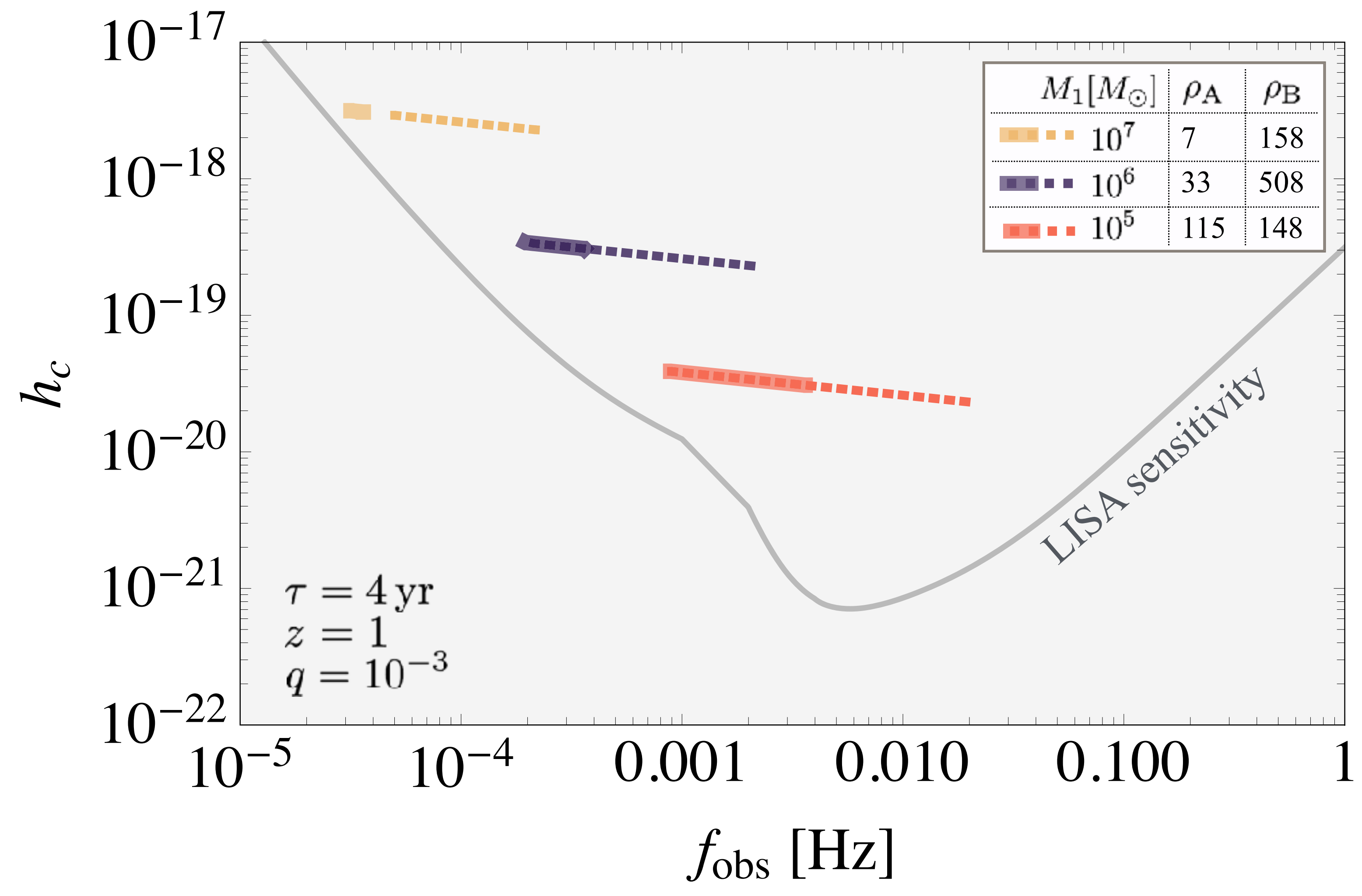

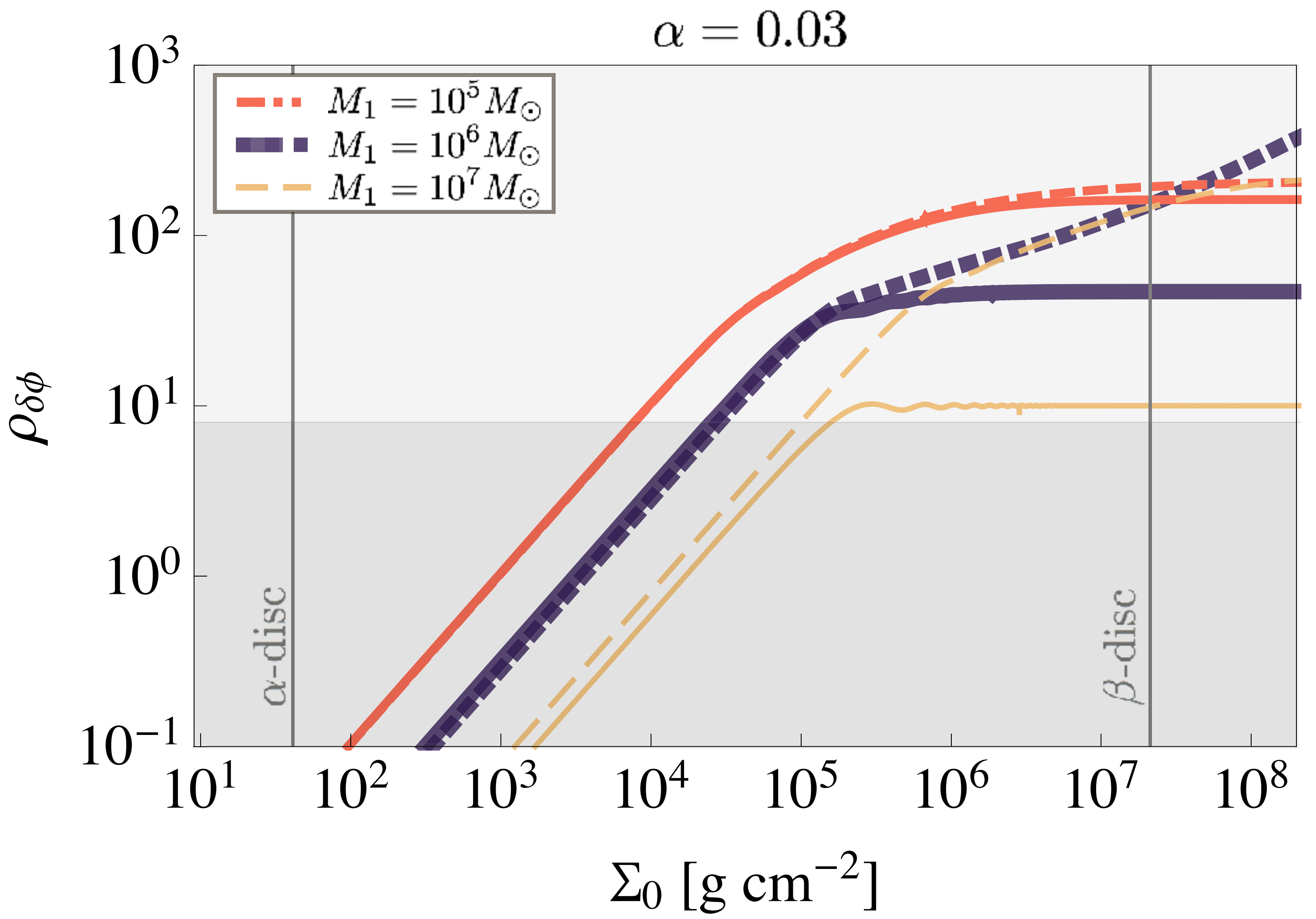

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- Gravitational torque from gas can affect SNR of EMRI LISA sources;

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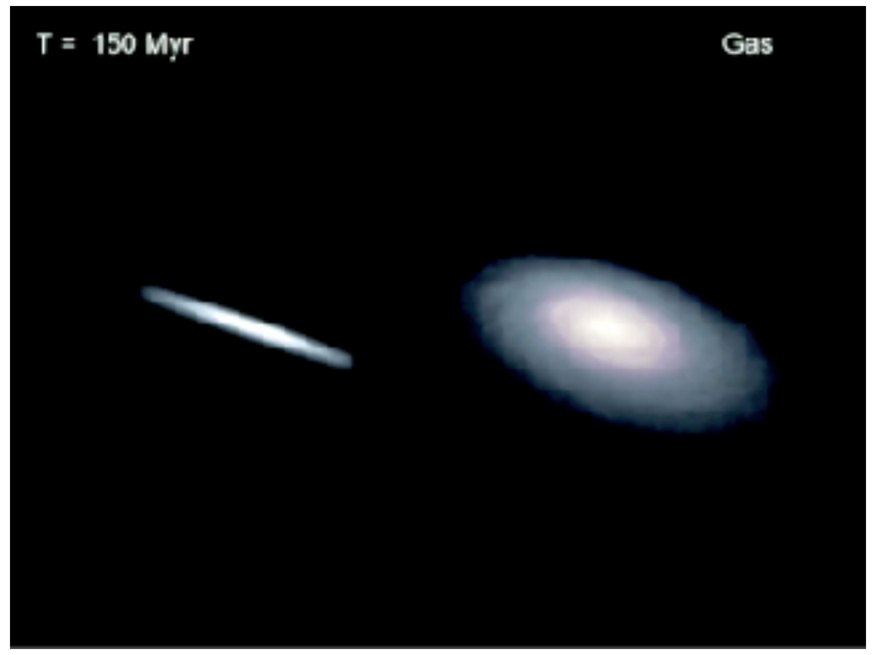
Strategy & Techniques



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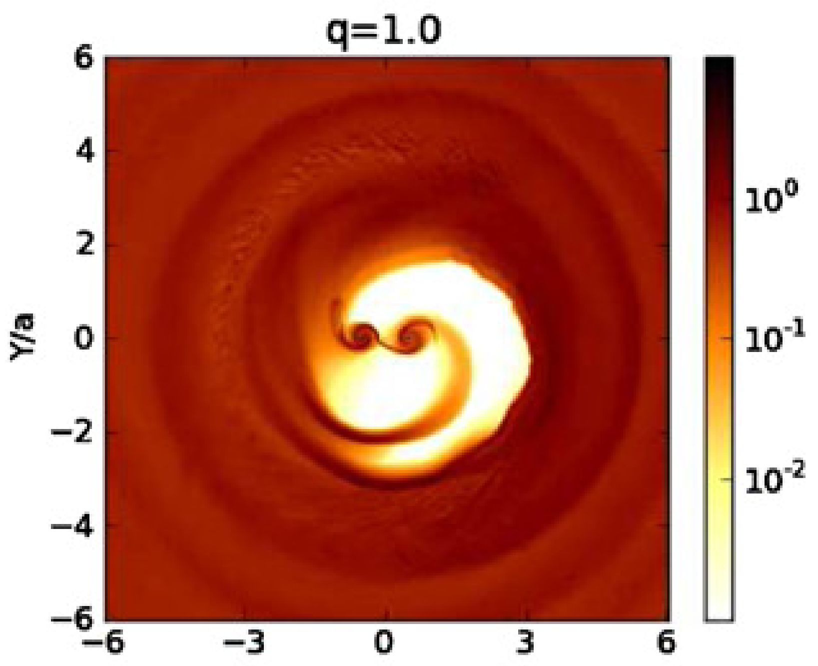

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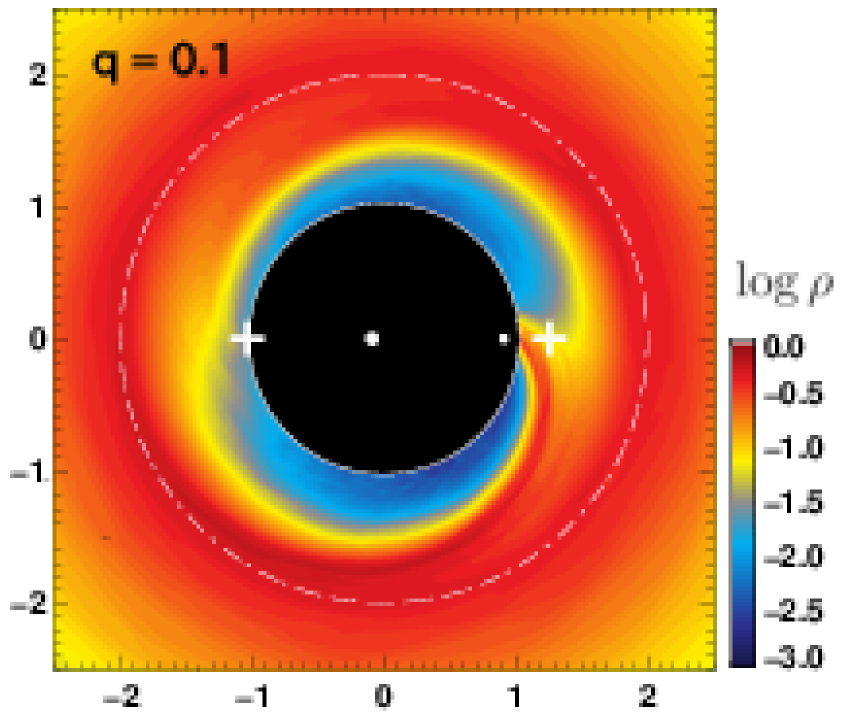

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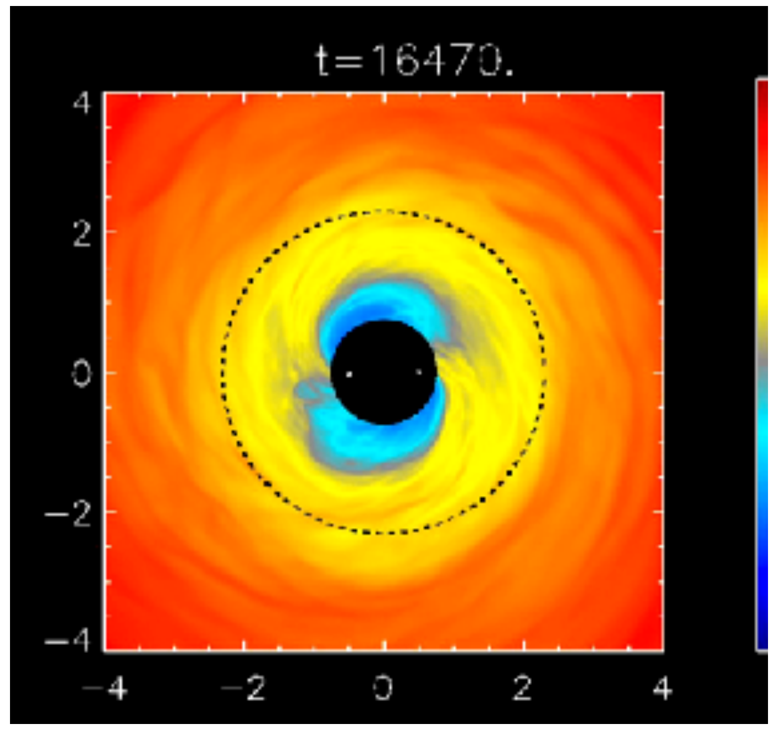

Noble++2012–15
Lopez Armengol++2021
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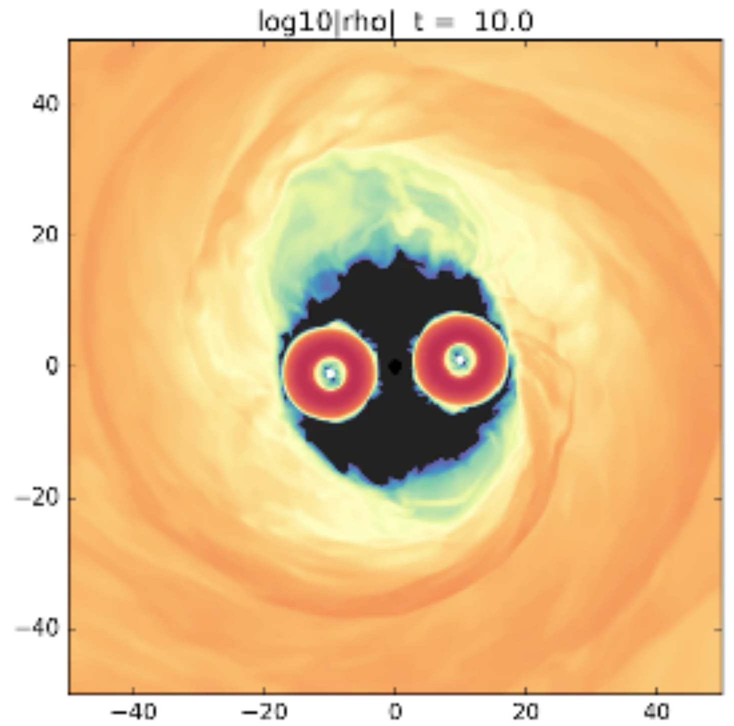

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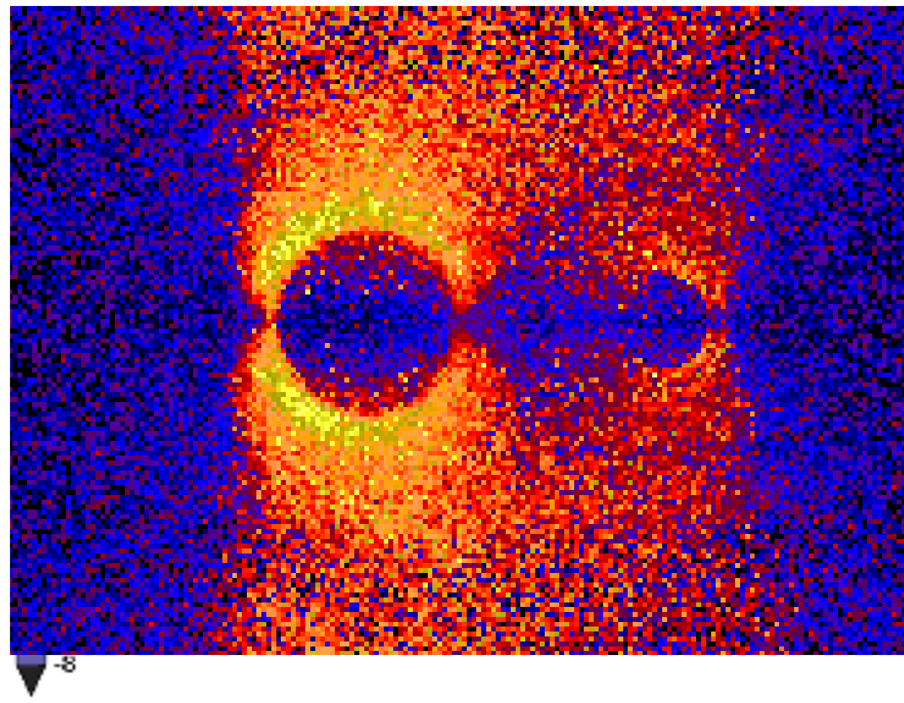
Combi++2021



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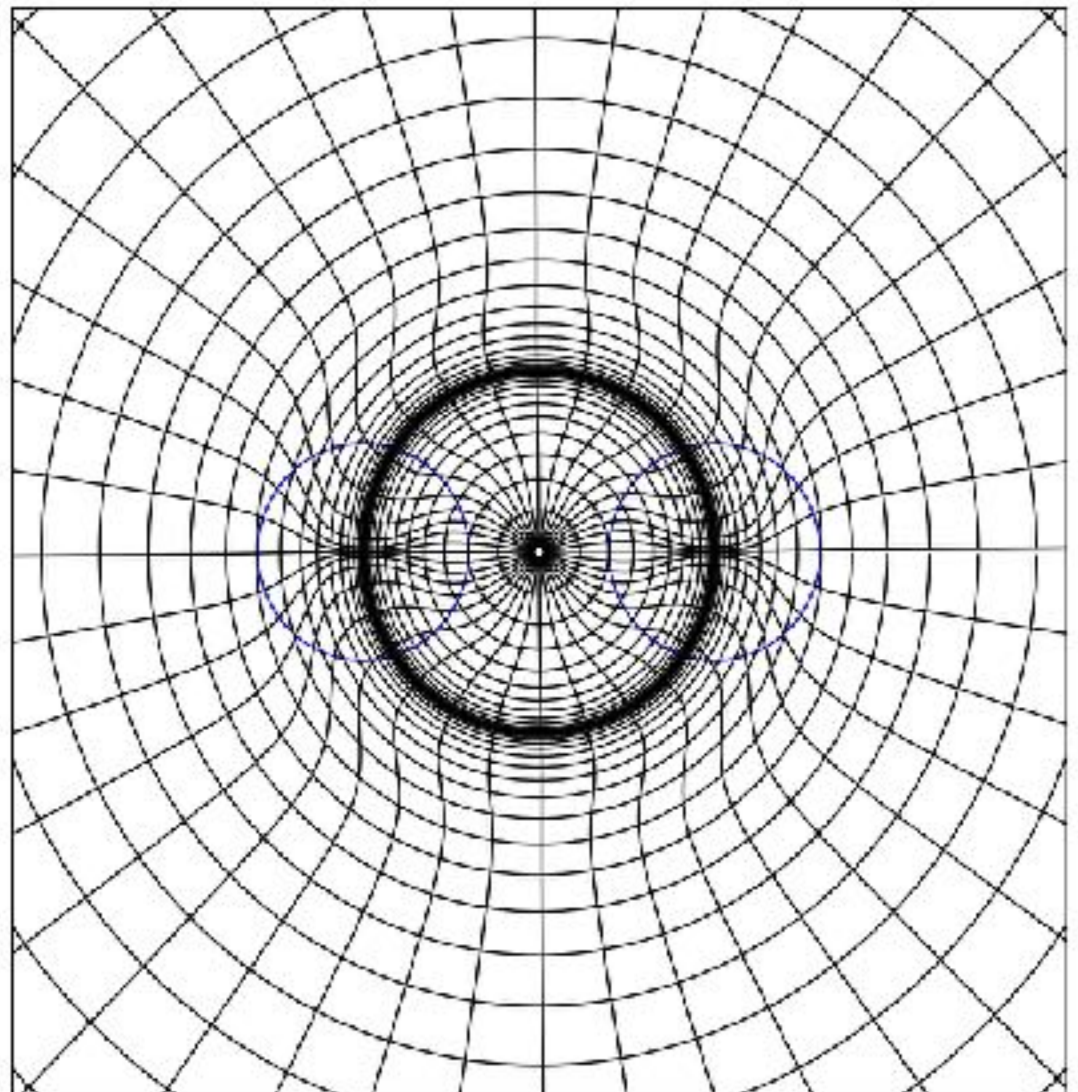
Review: Gold, Galax, 7, 63, (2019)

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

- Use well-tested GRMHD code for accretion disks: *HARM3d;*
- Novel methods tailored for accuracy and affordability:
  - Dynamic warped grids;
  - Perturbative solutions for gravity consistent with Einstein's equations in our regime;

➡ **Key Challenges:** Ability to evolve accreting binaries while resolving the MRI and MHD dynamics at the scale of the event horizons in the inspiral regime—*key for establishing pre-merger conditions*.



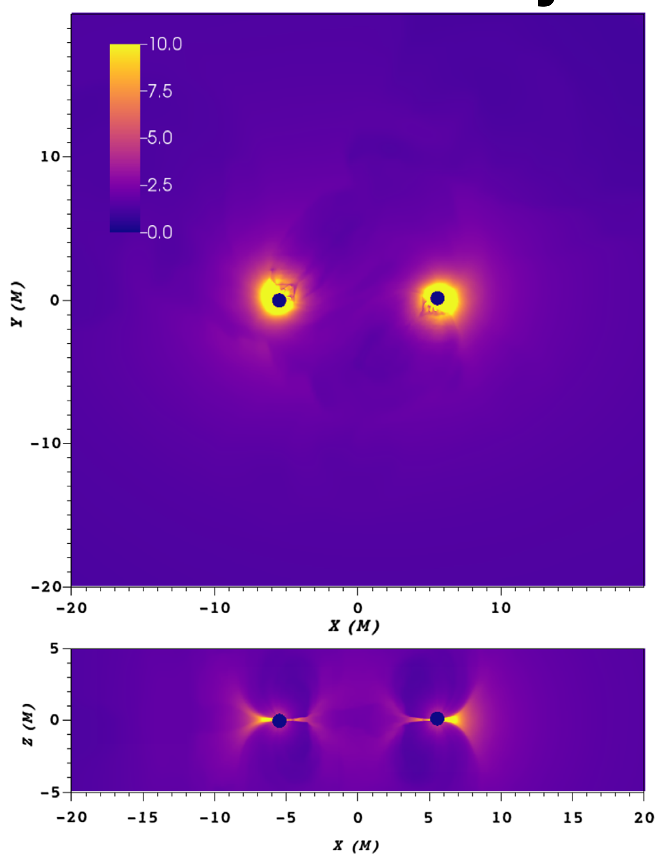
Numerical Relativity + MHD Evolutions

Accretion in Uniform Plasma

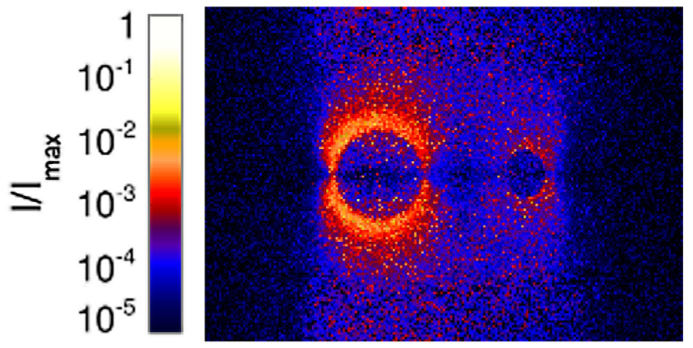
Kelly, Baker, Etienne, Giacomazzo, Schnittman, PRD 96, 123003 (2017)

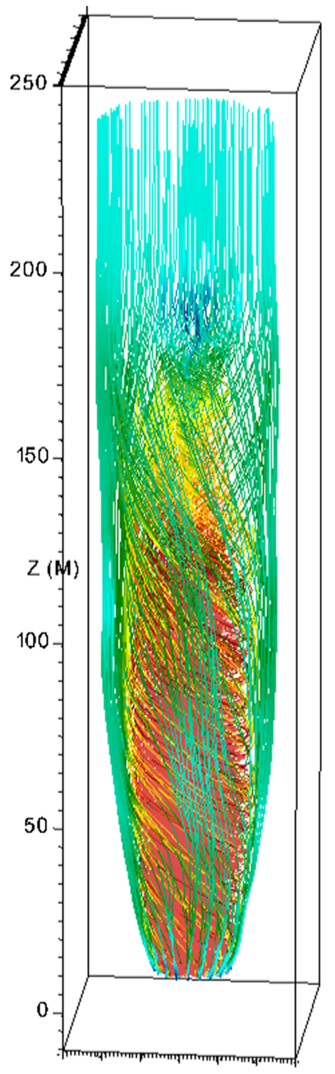
- Non-Spinning merging BHs, Uniform plasma, B-field

Plasma Density



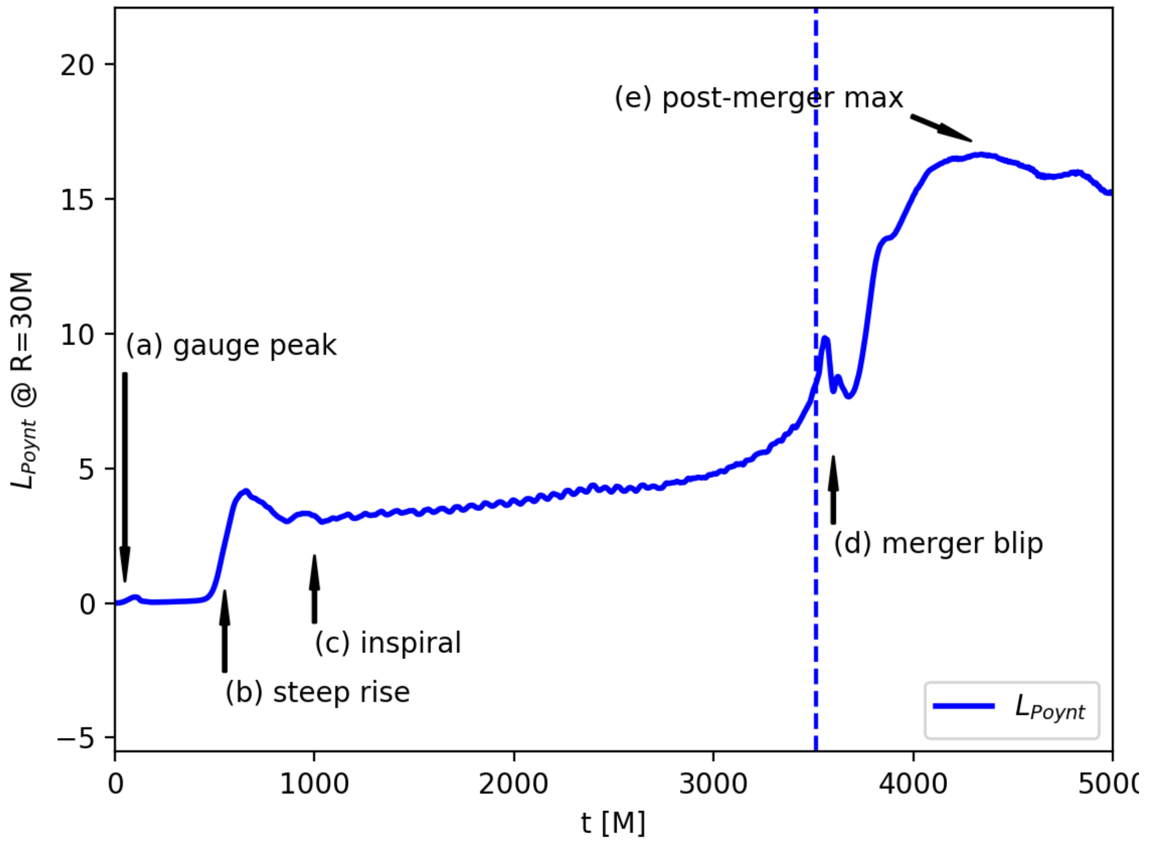
Synchrotron Image





B-field Lines

Poynting Flux



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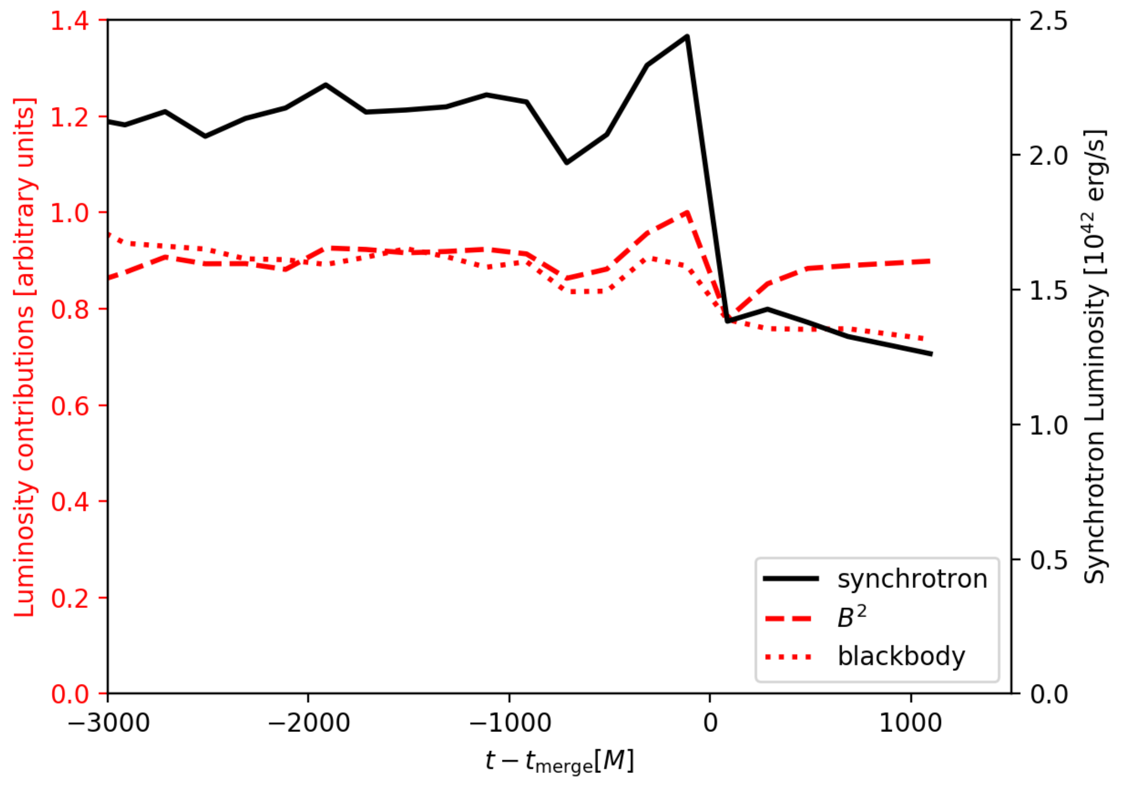

Kelly, Etienne, Golomb, Schnittman, Baker, Noble, Ryan, PRD 103, 063039 (2021)

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Cattorini, Giacomazzo, Haardt, Colpi, arxiv:2102.13166 (2021)

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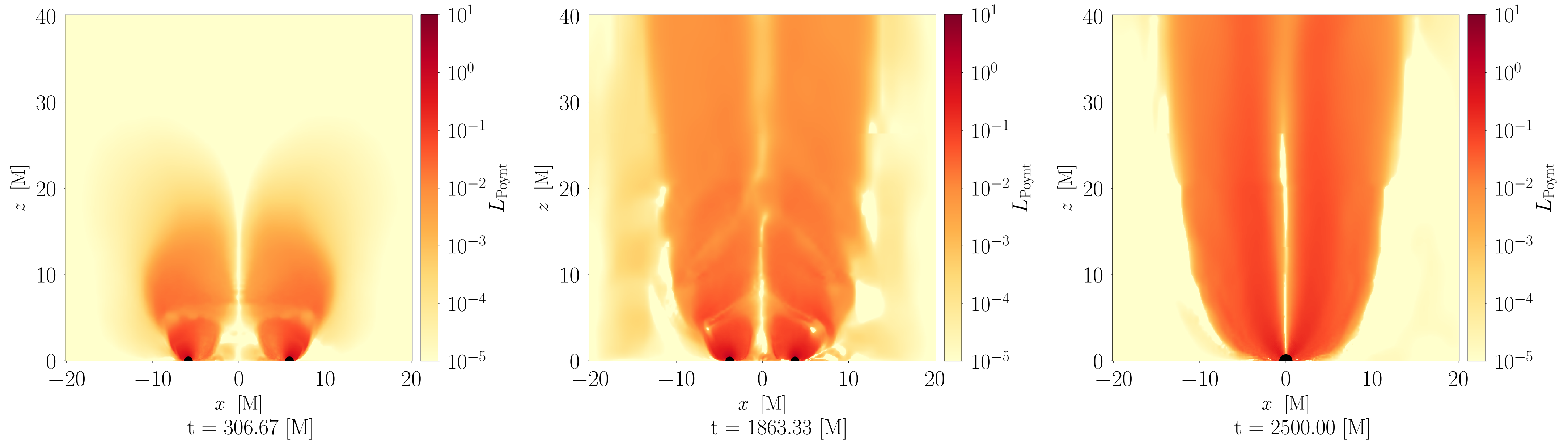

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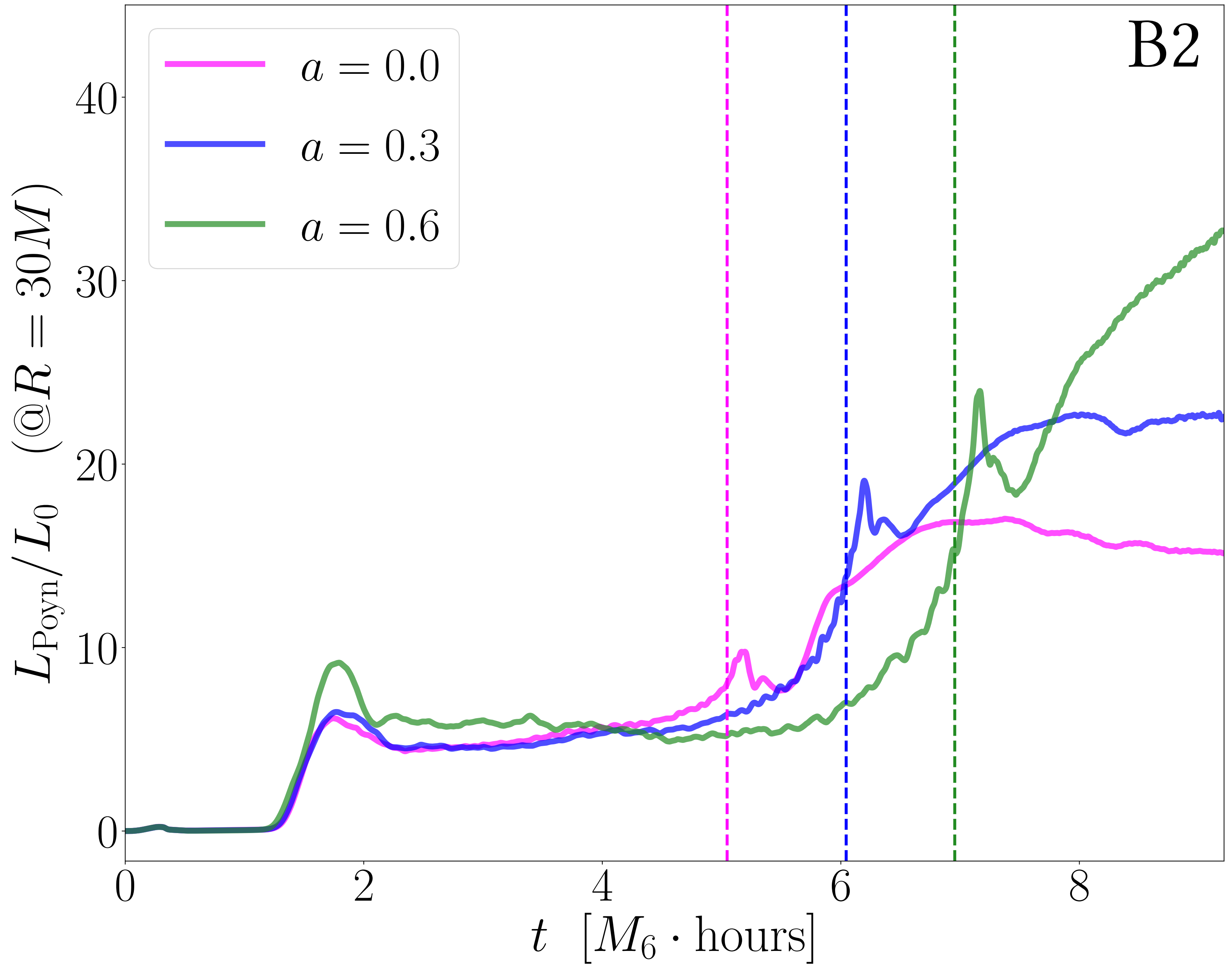

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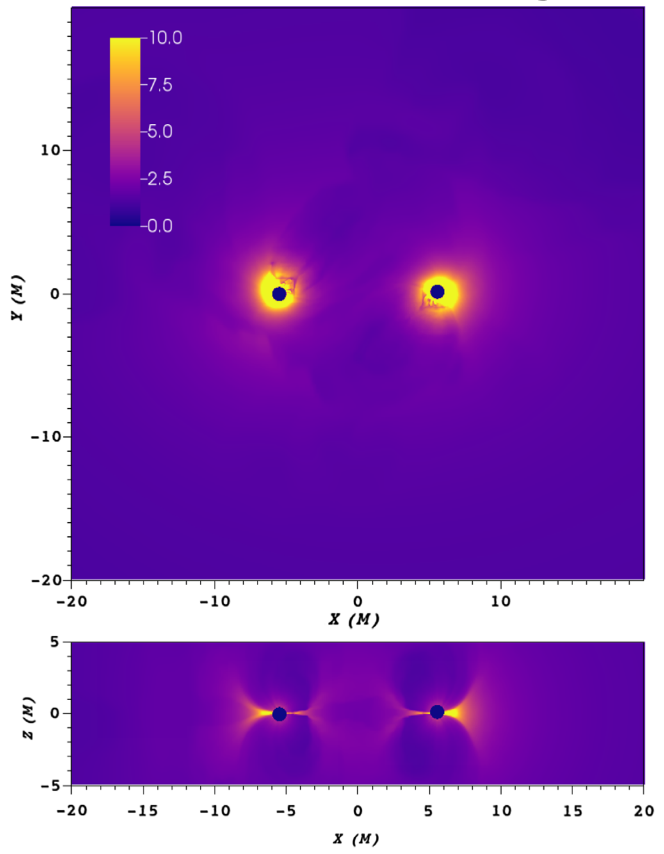

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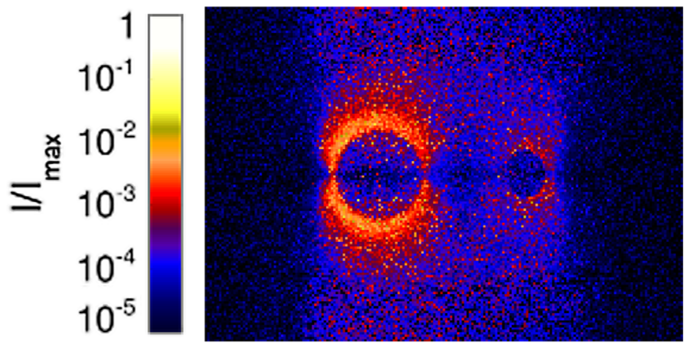

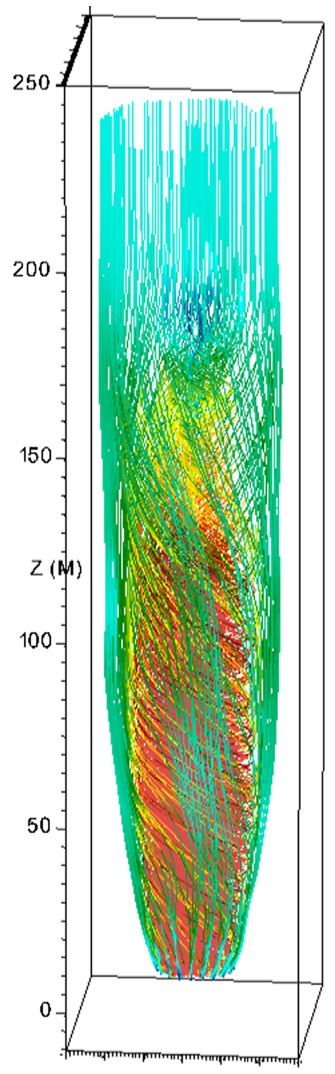

B-field Lines

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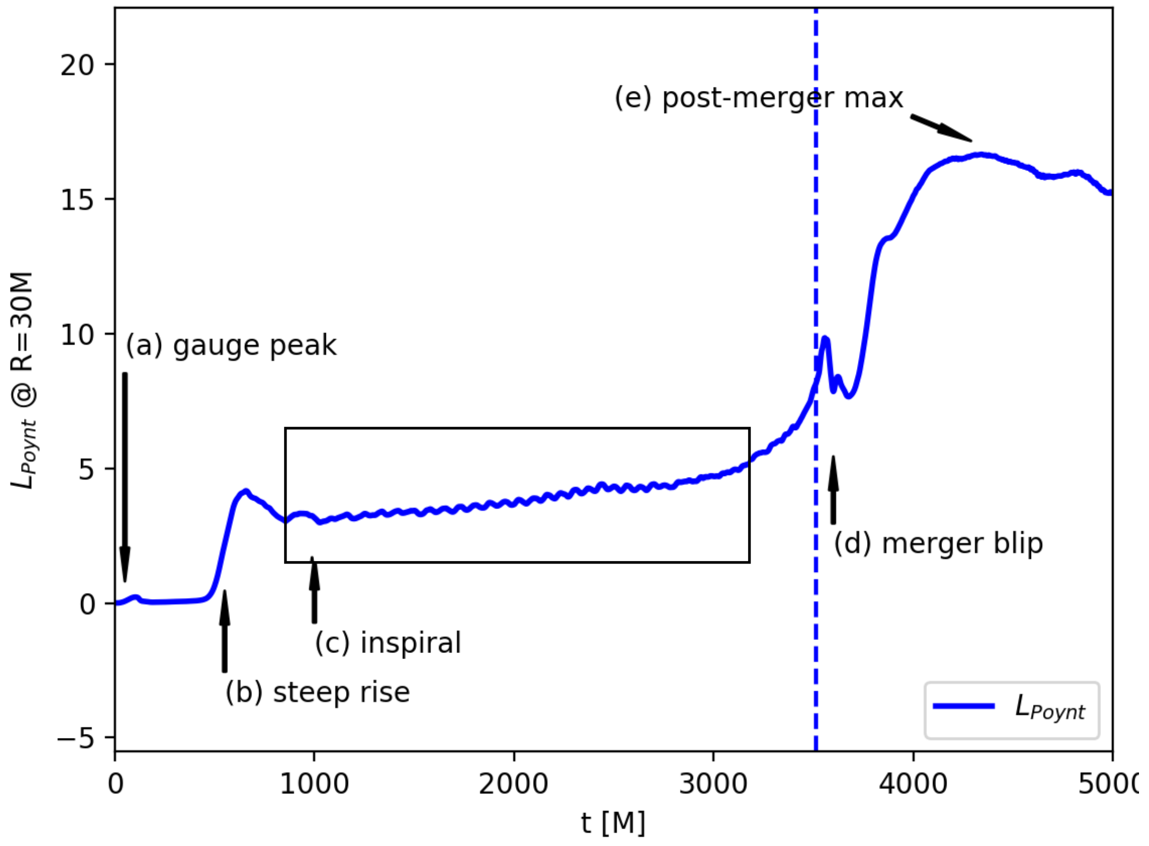

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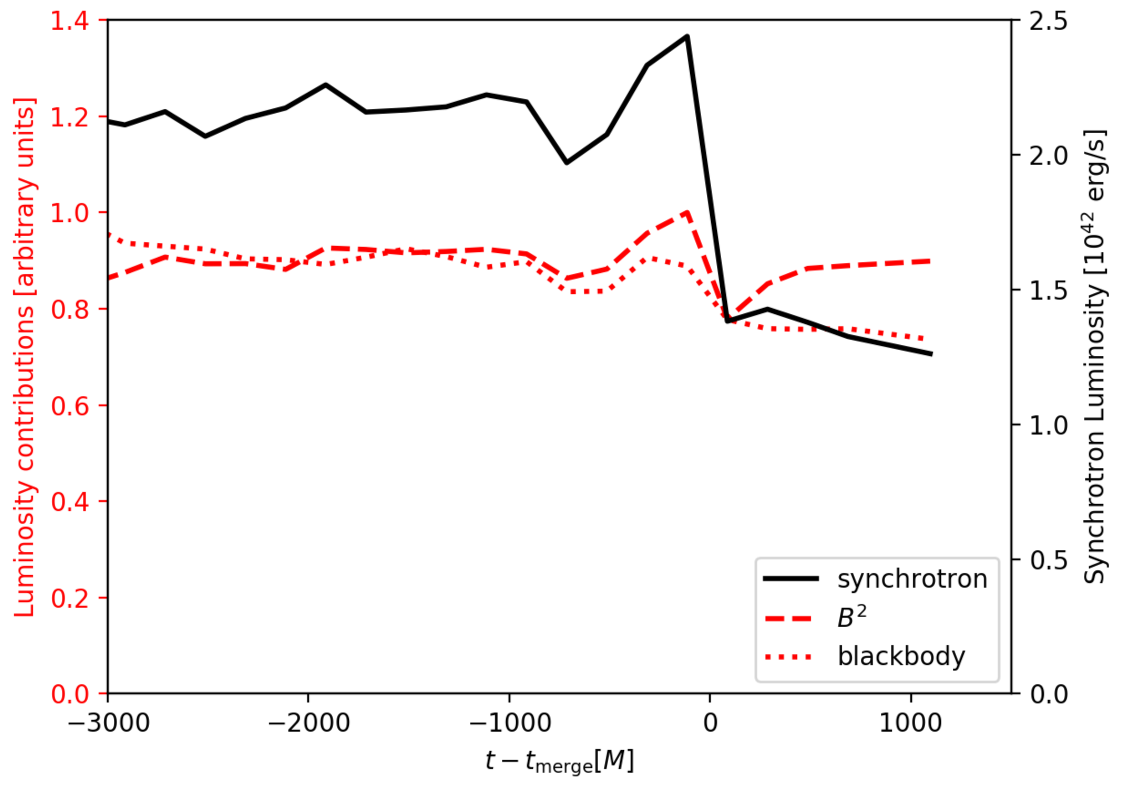

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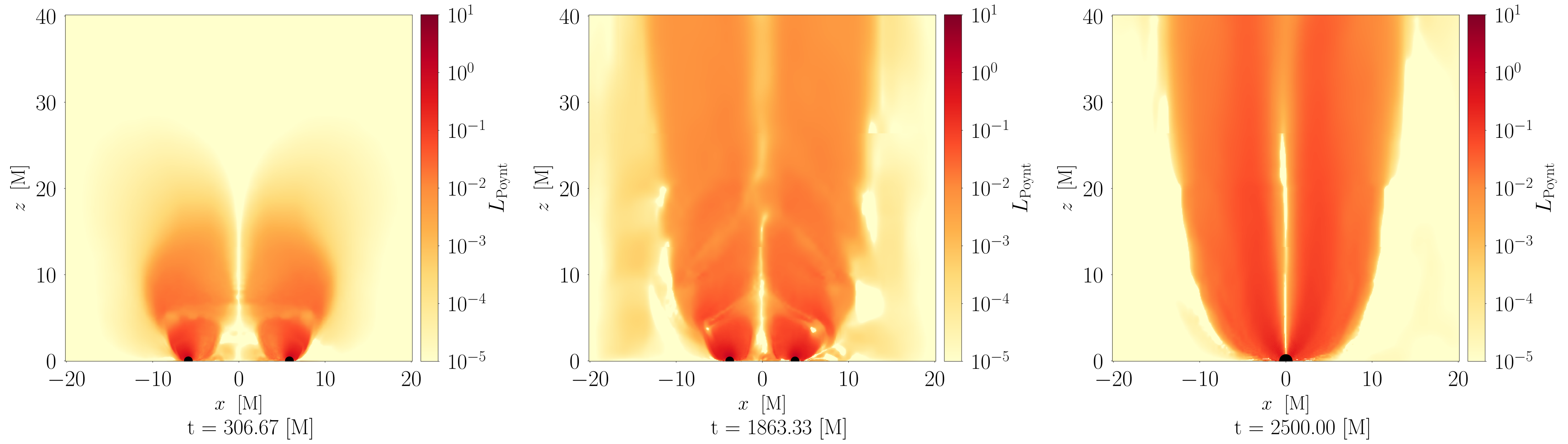

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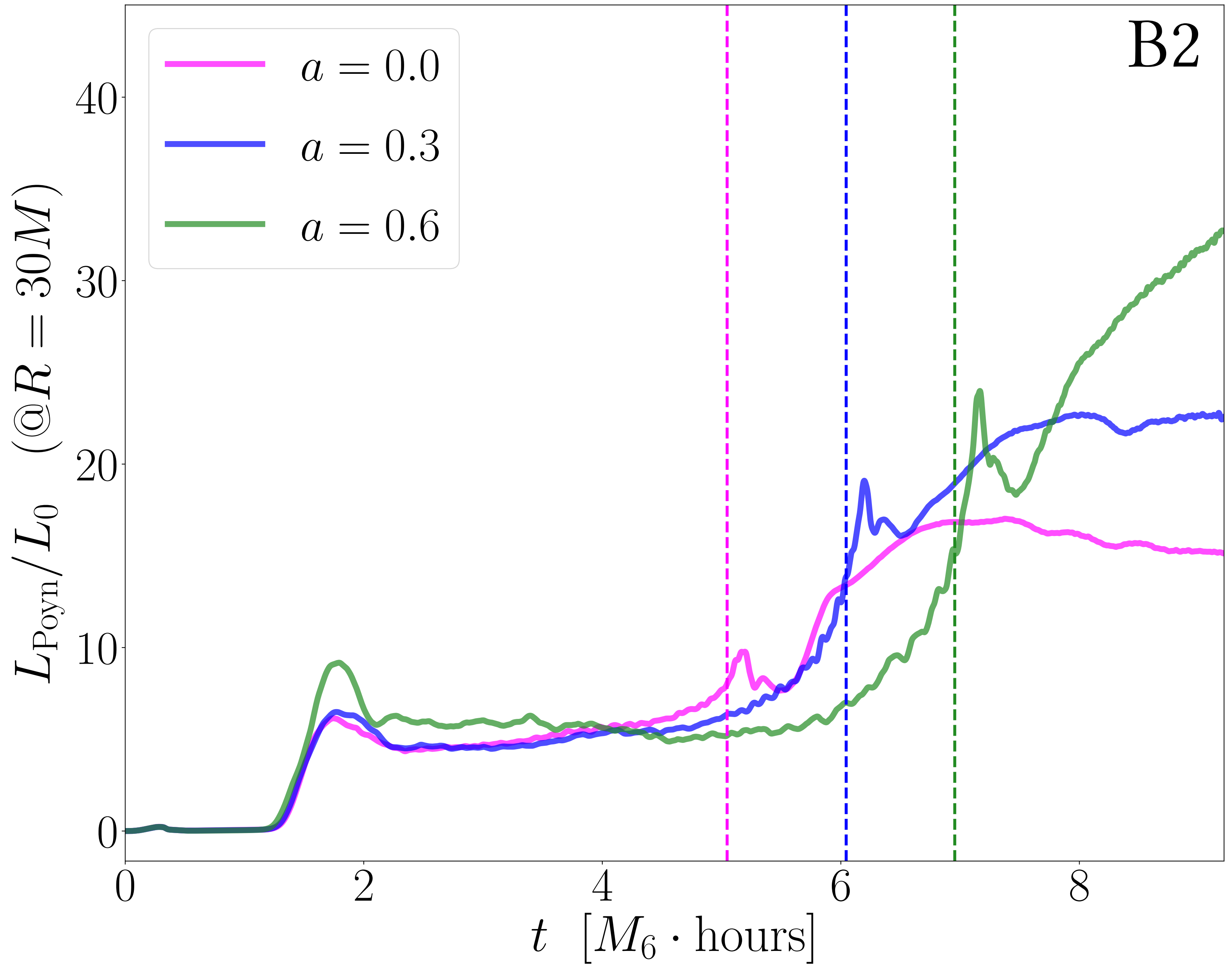

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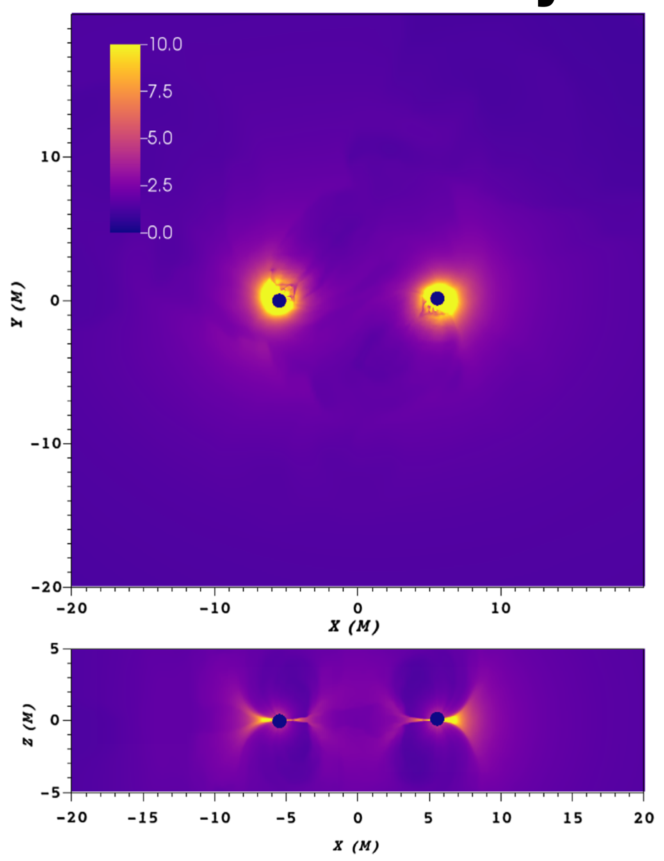

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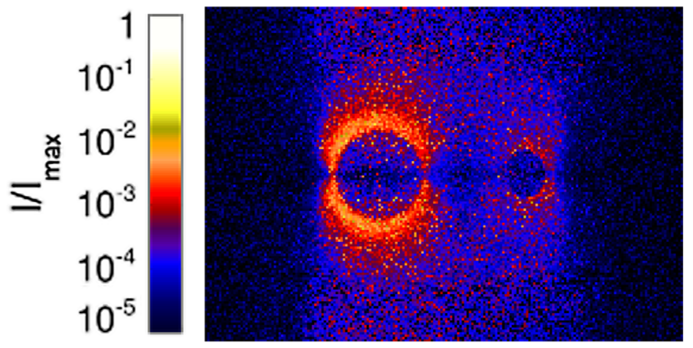

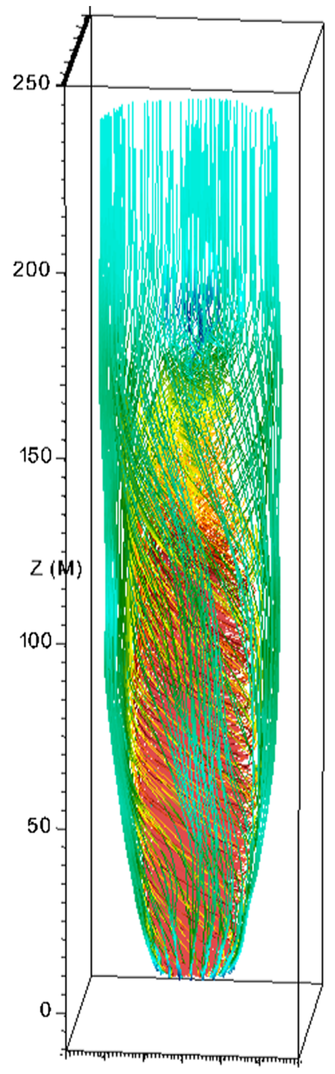

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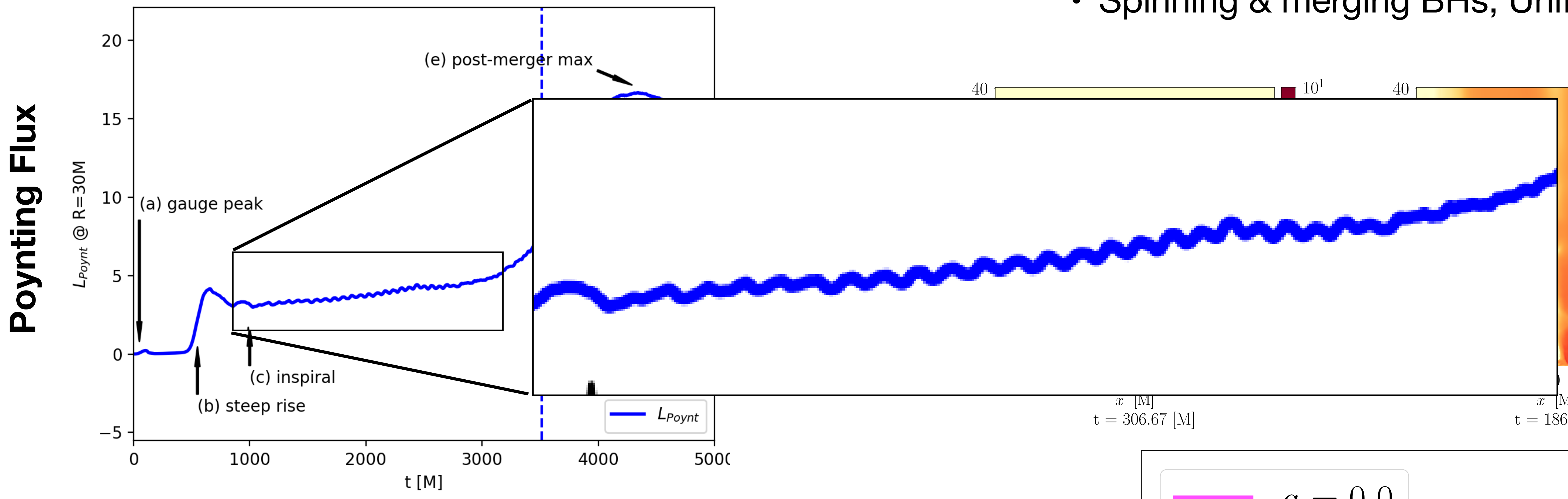

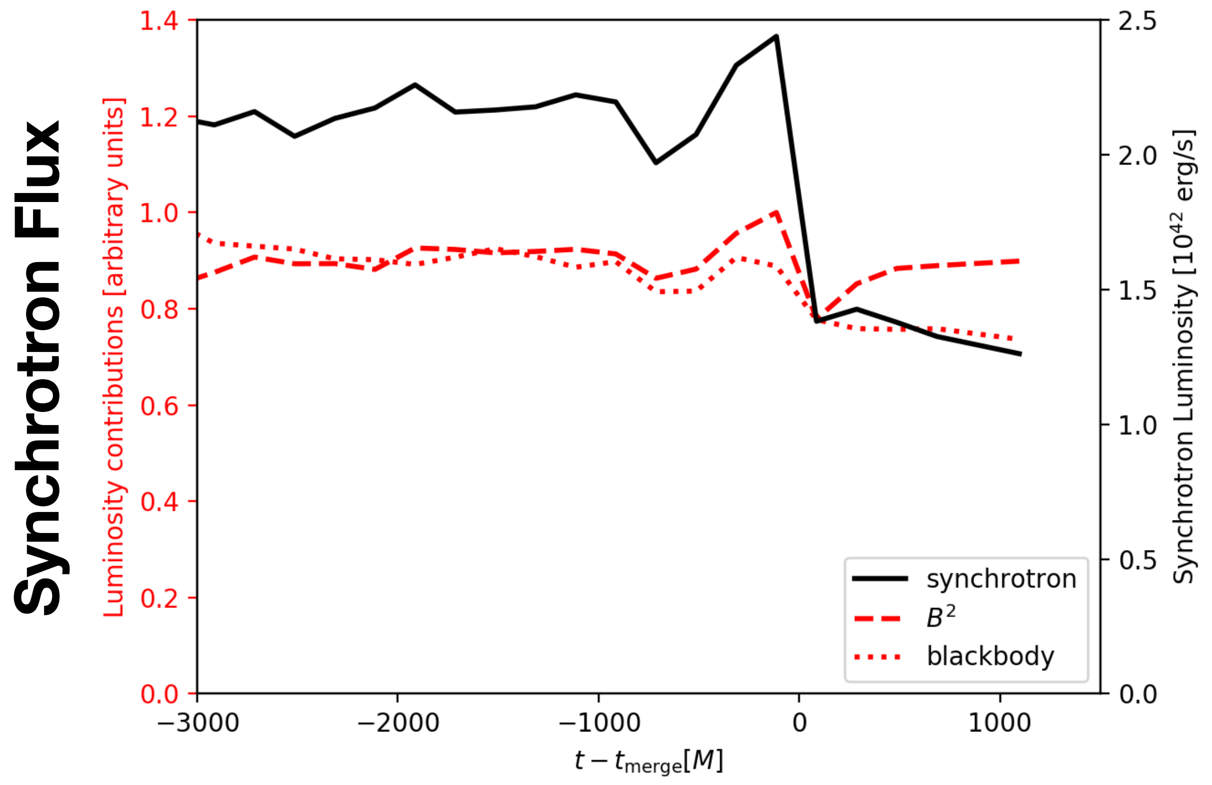

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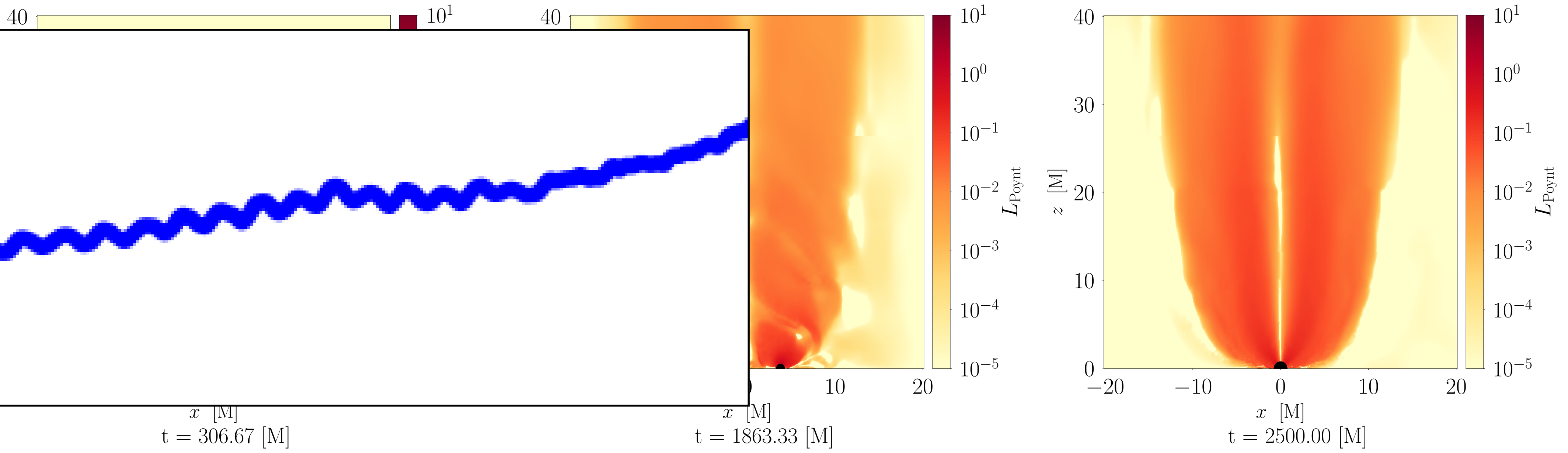

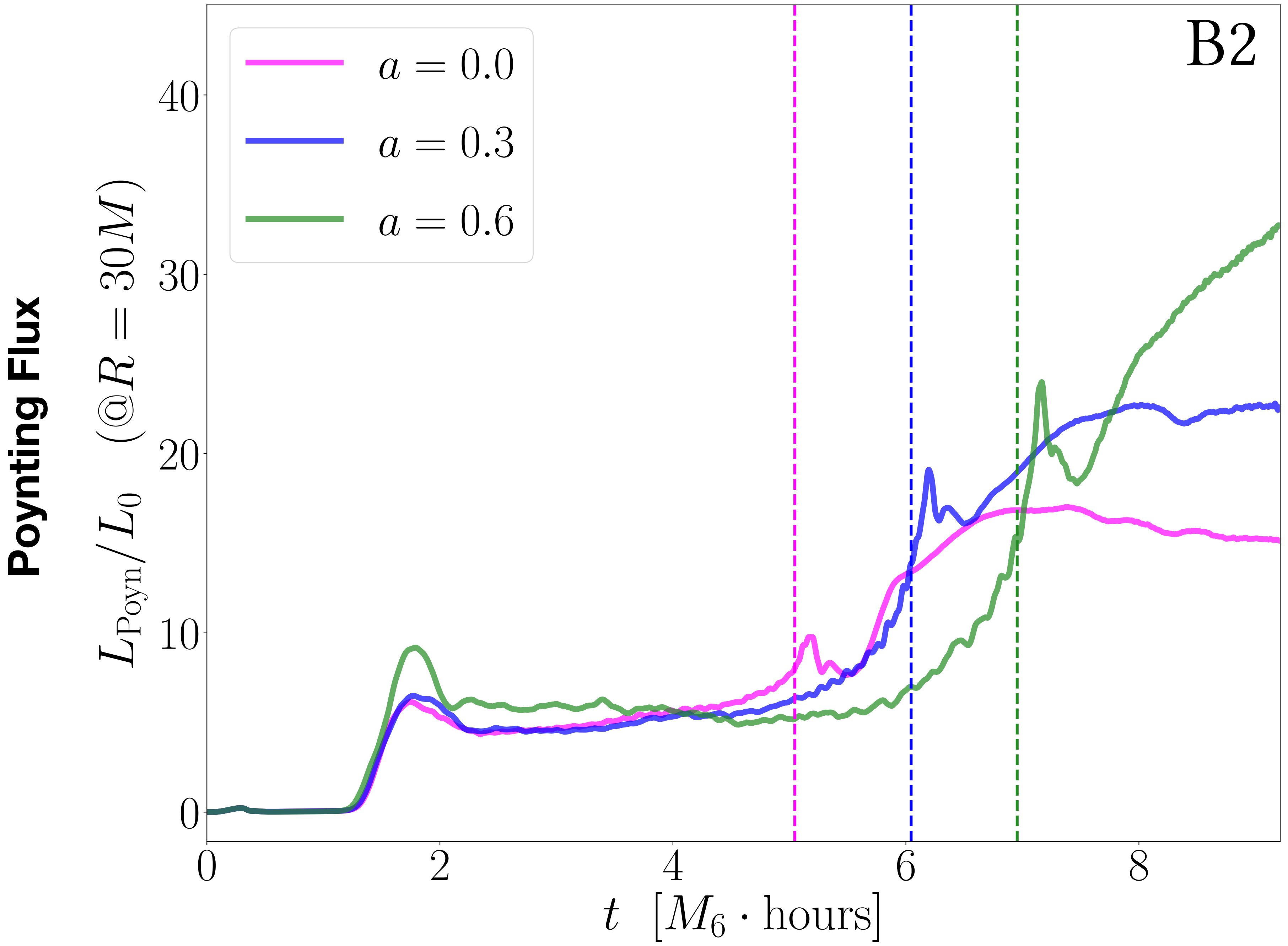

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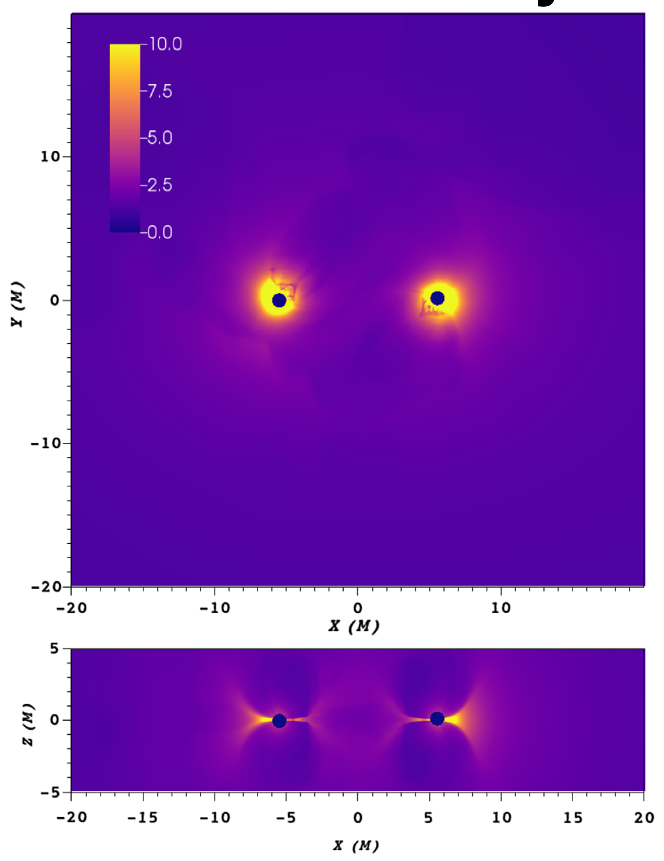
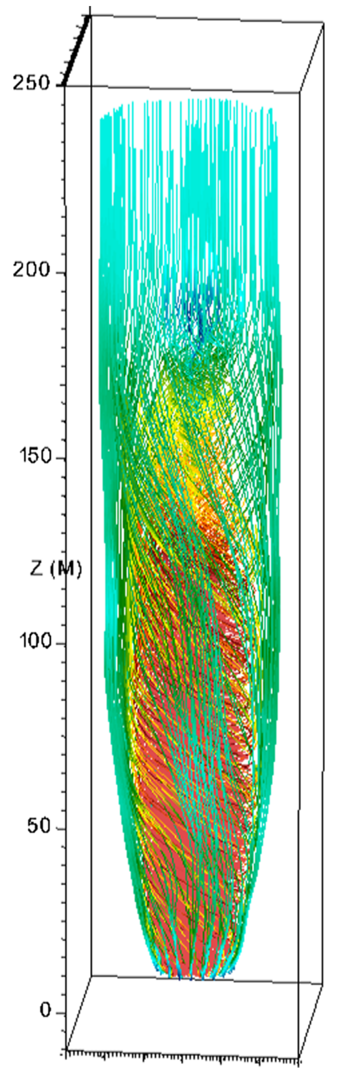
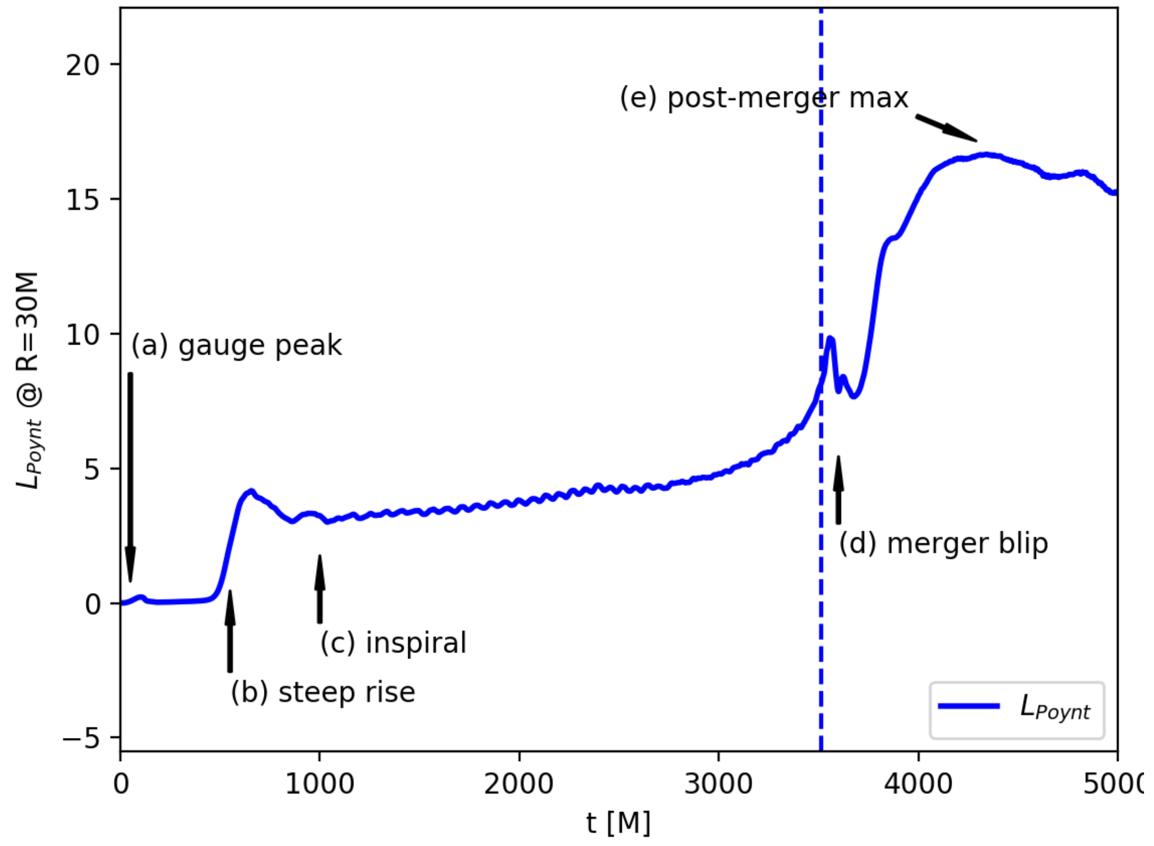


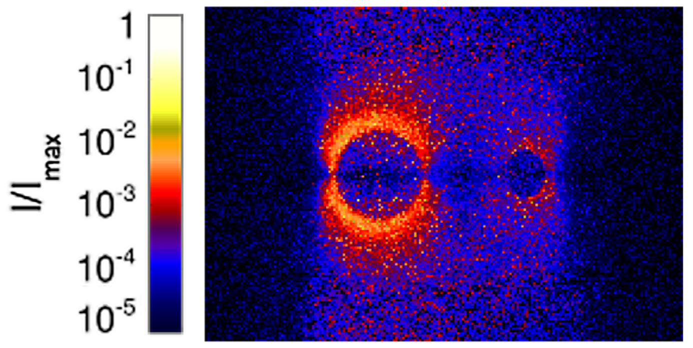


B-field Lines

Poynting Flux



Synchrotron Image



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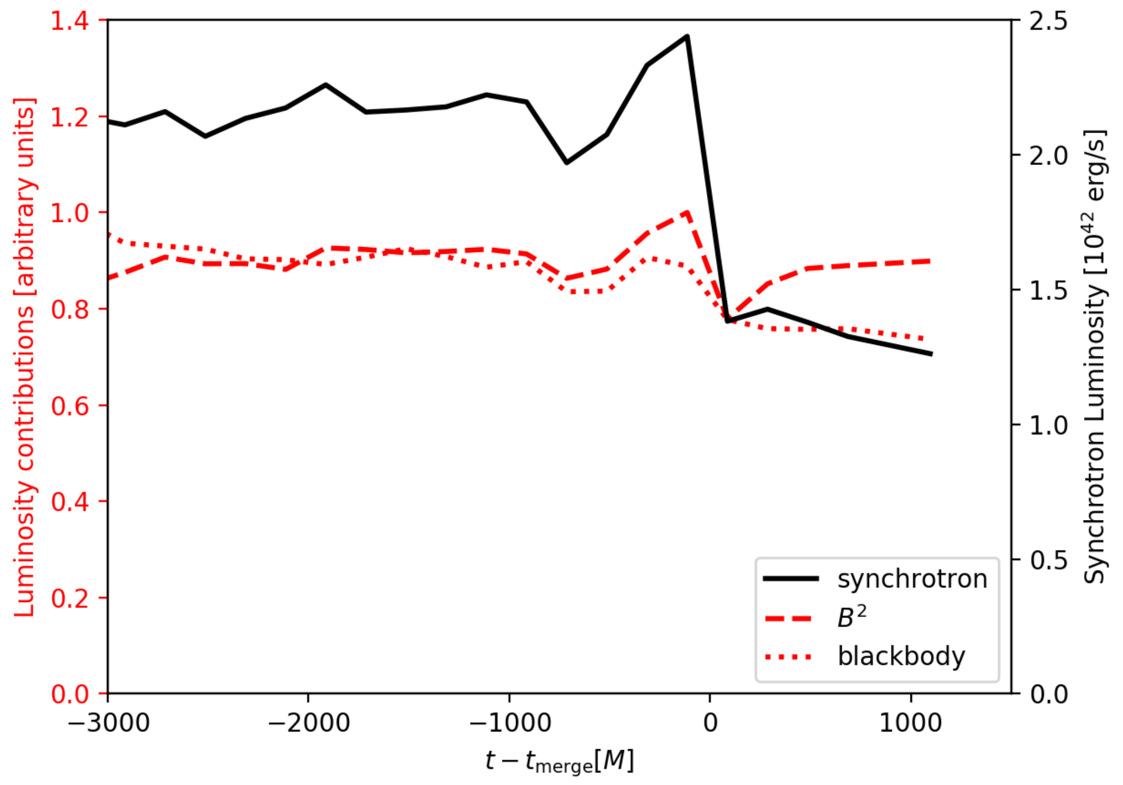

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Kelly @APS: G15.00001

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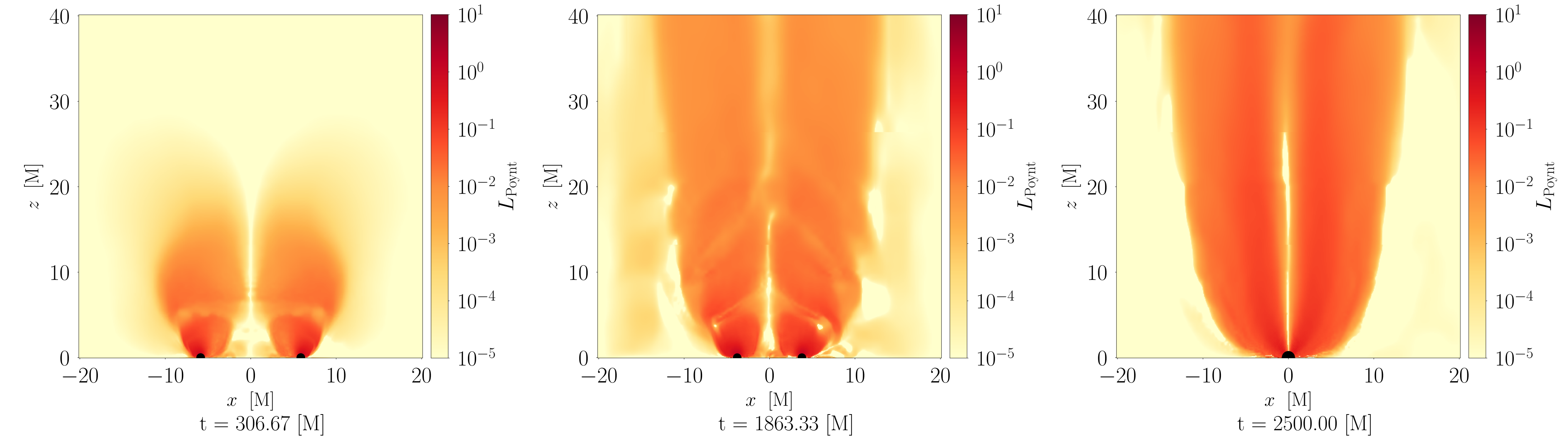

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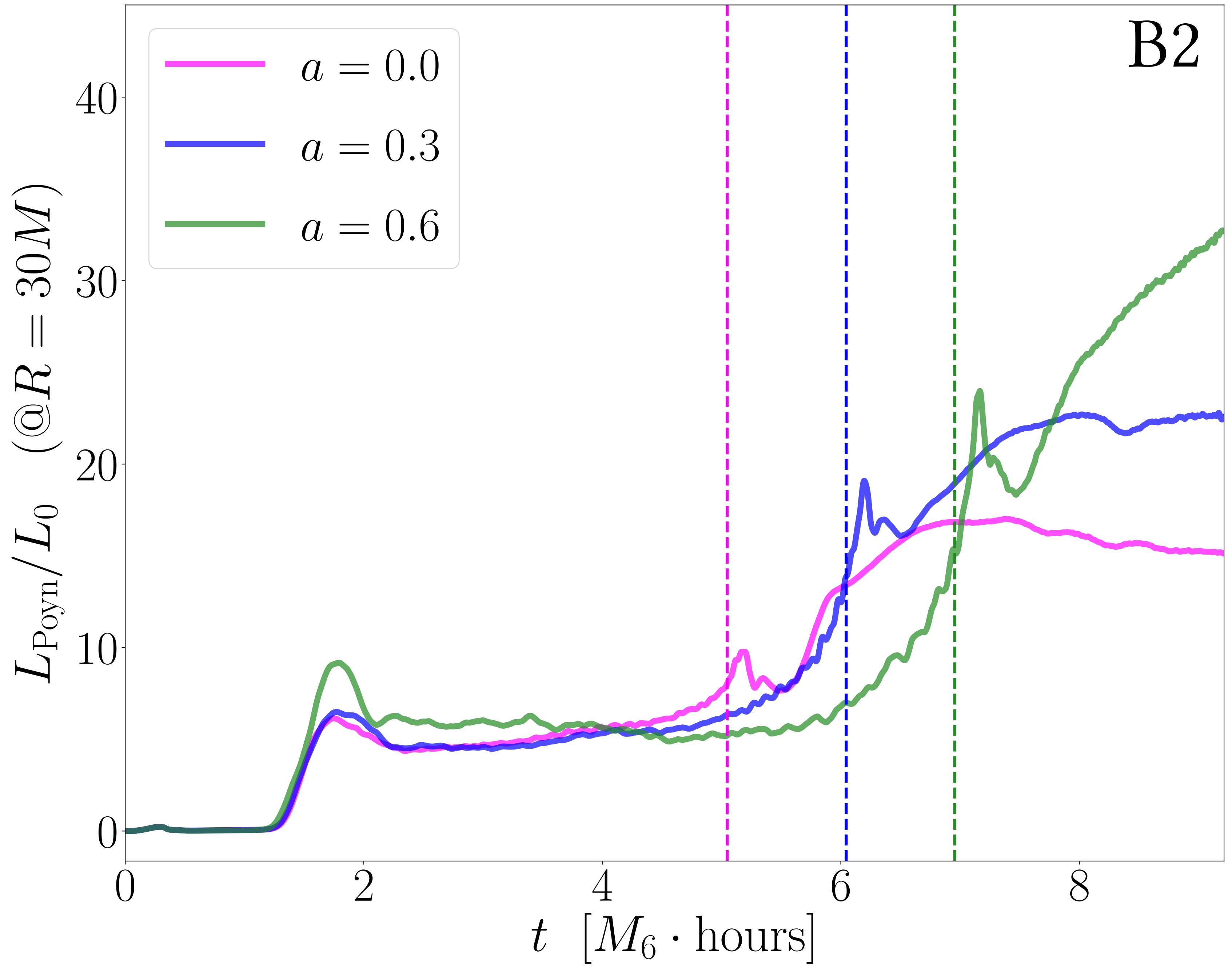
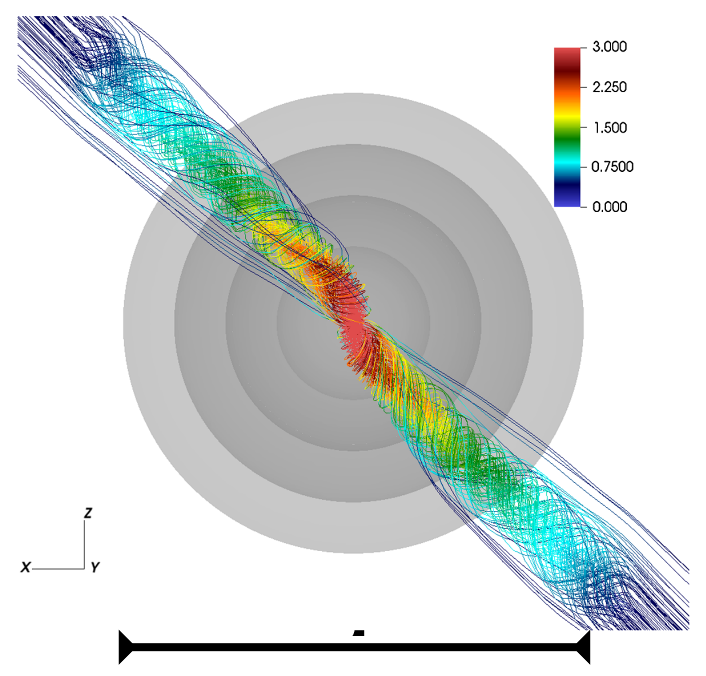


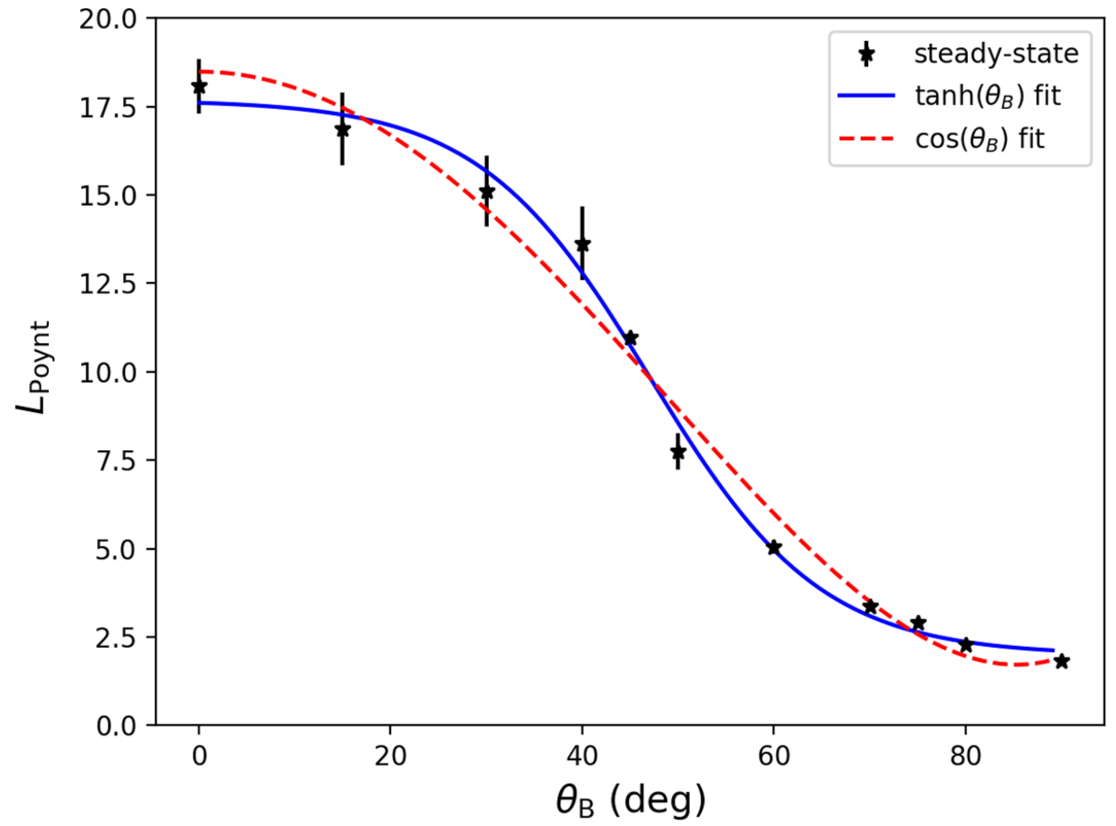
Numerical Relativity + MHD Evolutions
Accretion in Uniform Plasma

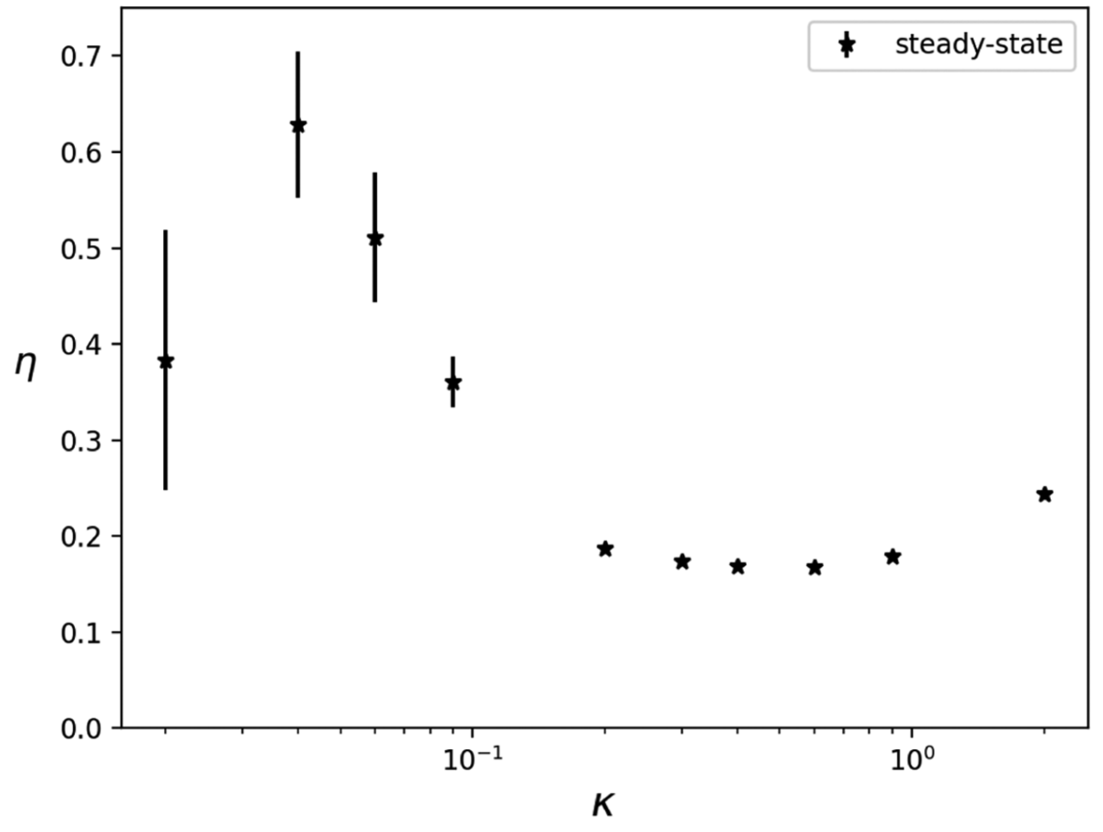
Kelly, Etienne, Golomb, Schnittman, Baker, Noble, Ryan, PRD 103, 063039 (2021)

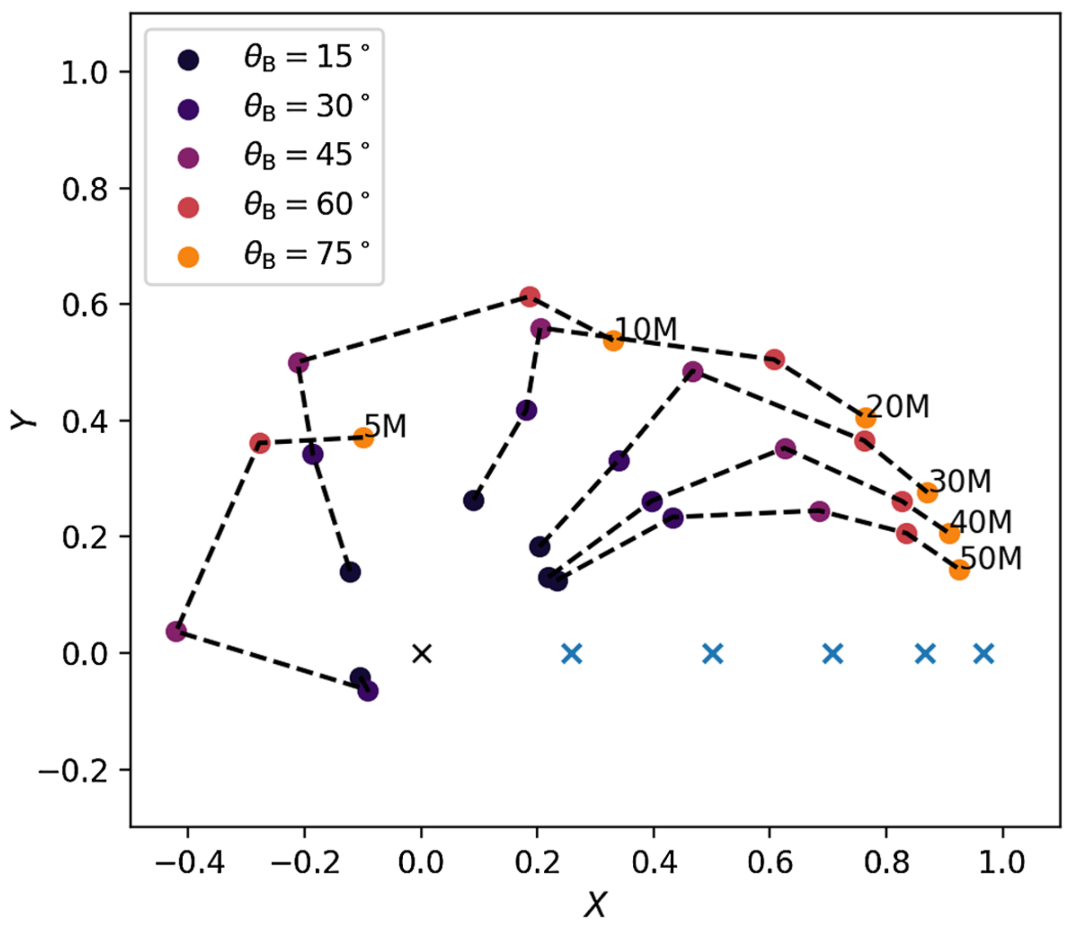
Kelly @APS: G15.00001

- 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;









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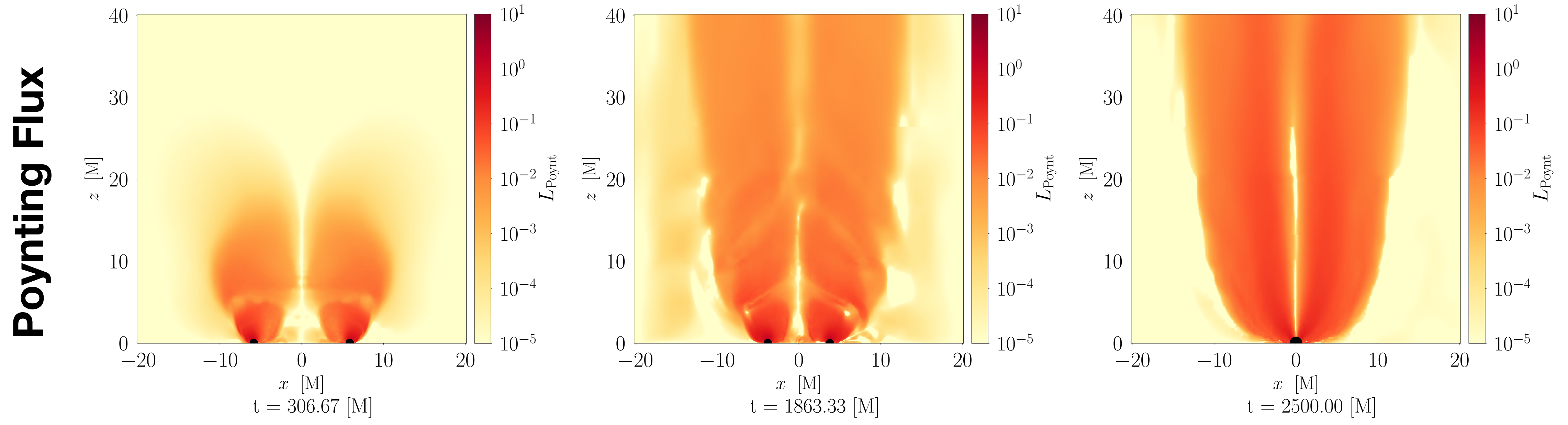
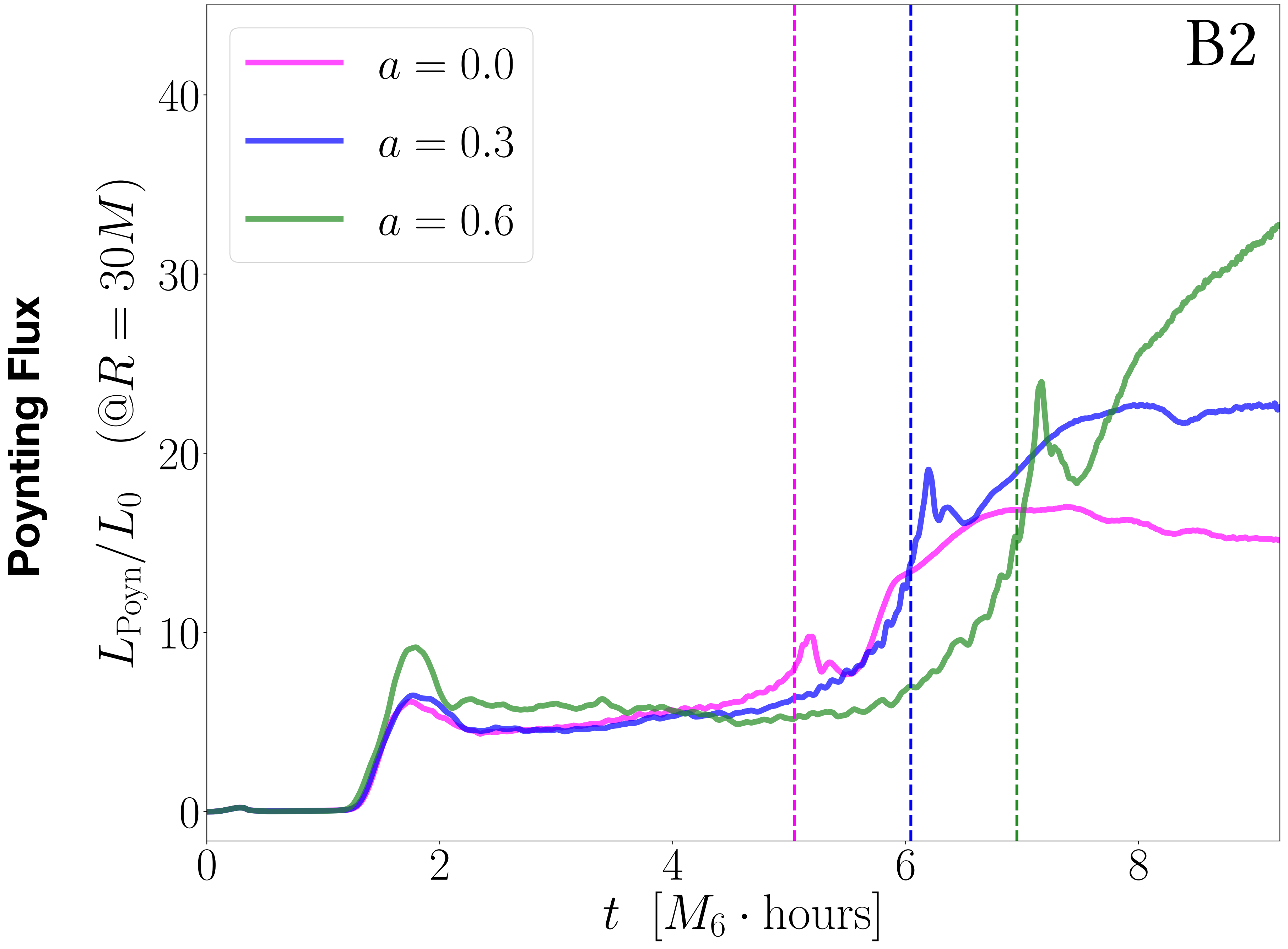




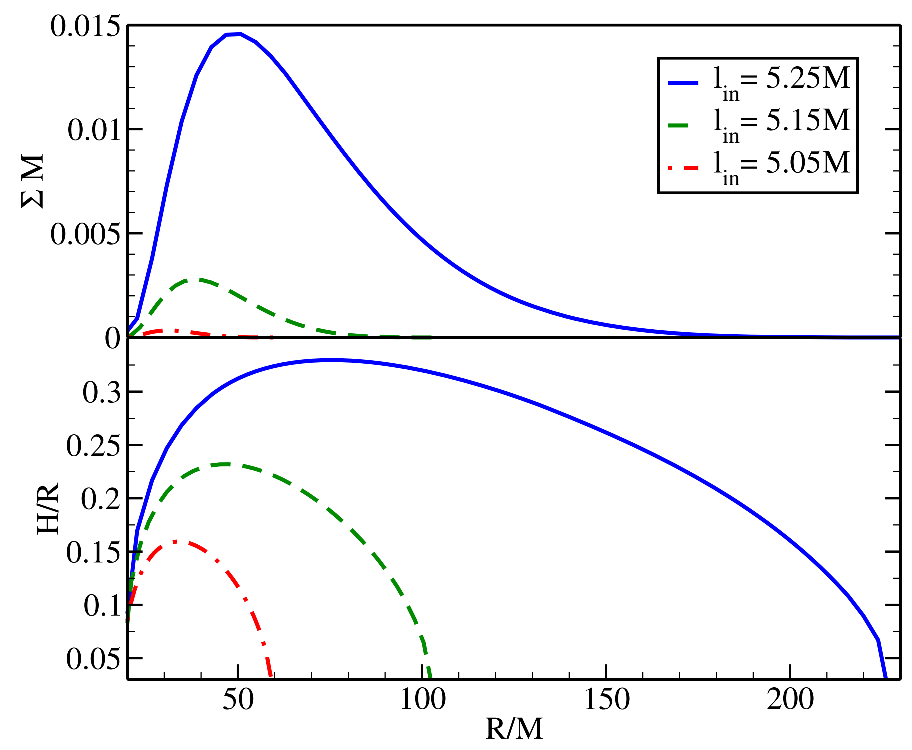
Numerical Relativity + MHD Evolutions

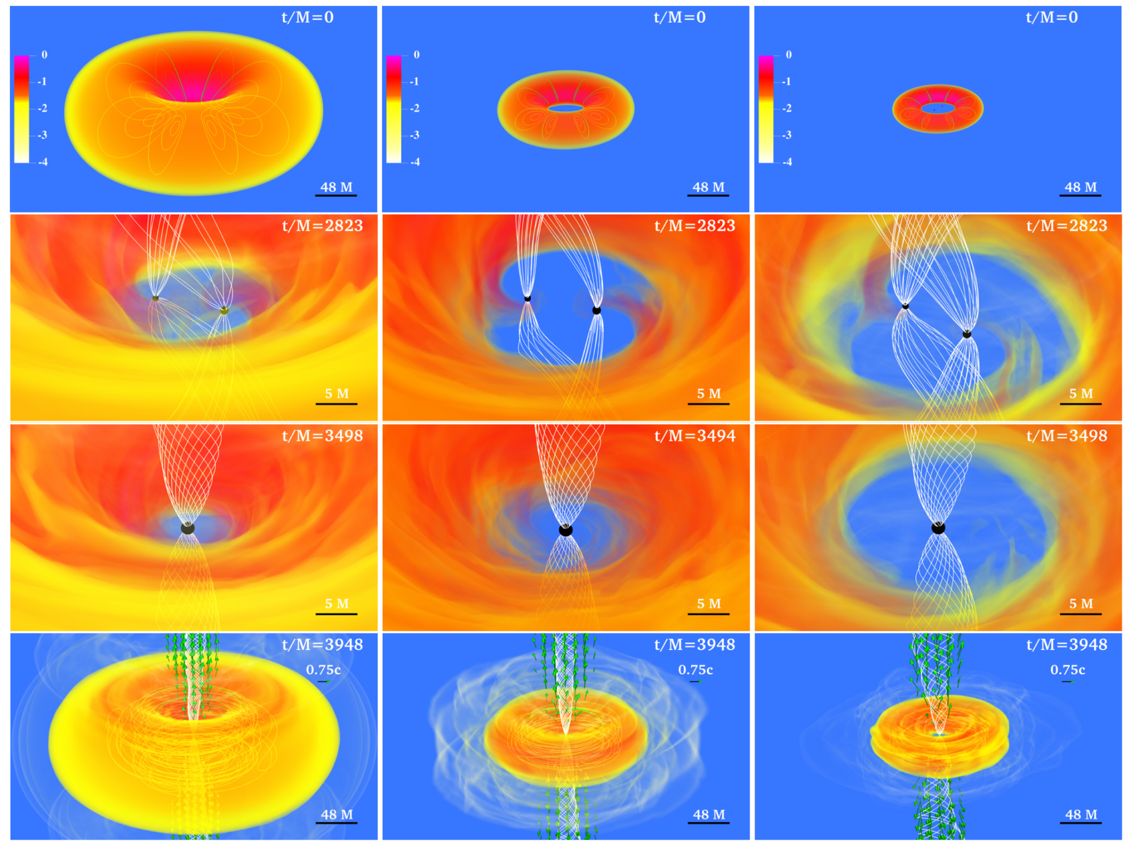
Accretion with Magnetized Tori

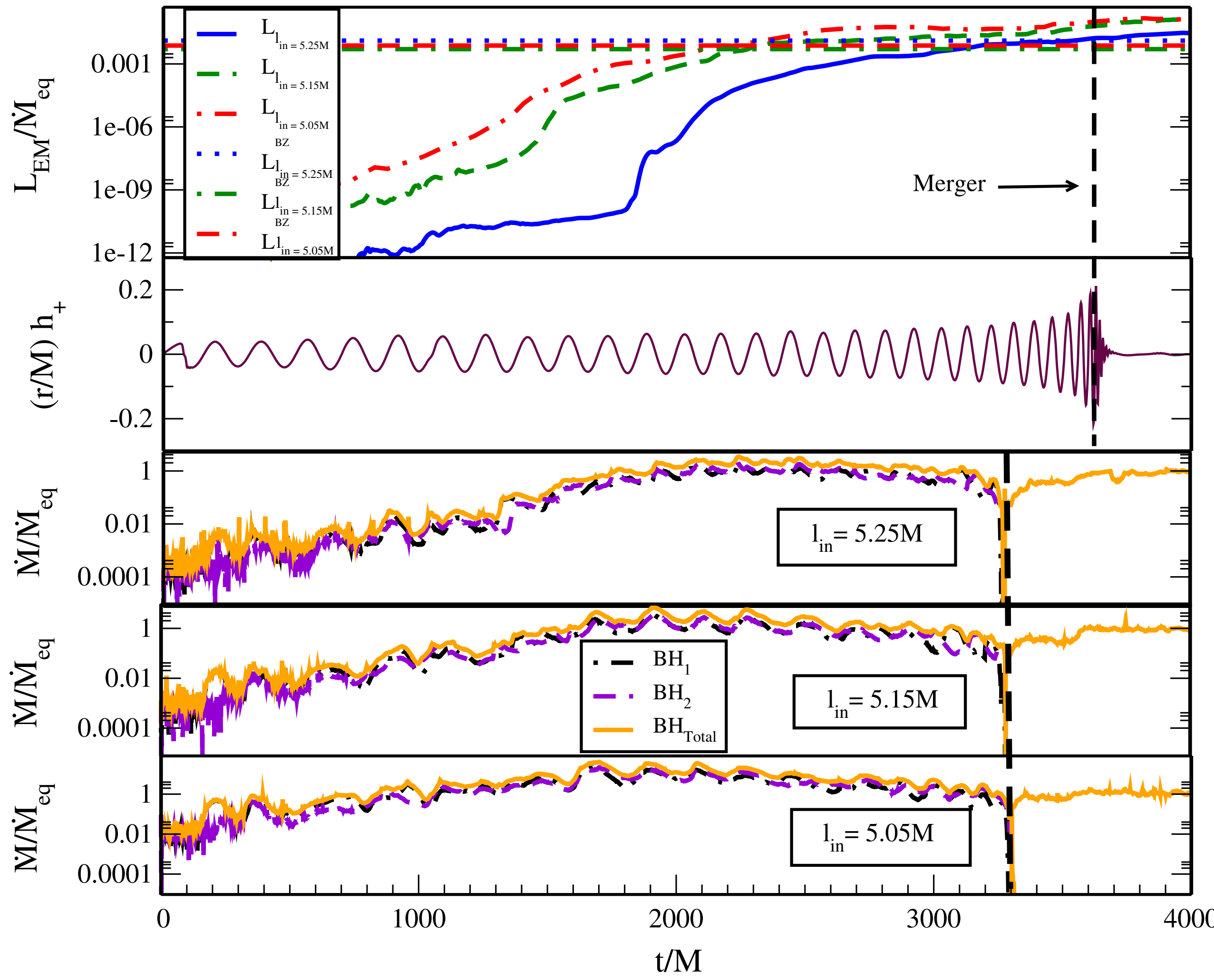
Farris, B. D., Gold, R., Paschalidis, V., Etienne, Z. B., Shapiro, S. L., PhRvL, 109, 221102, (2012).
Gold, R., Paschalidis, V., Etienne, Z. B., Shapiro, S. L., Pfeiffer, H. P., PhRvD, 89, 064060, (2014).
Gold, R., Paschalidis, V., Ruiz, M., Shapiro, S. L., Etienne, Z. B., Pfeiffer, H. P., PhRvD, 90, 104030, (2014).
Khan, A., Paschalidis, V., Ruiz, M., Shapiro, S. L., PhRvD, 97, 044036, (2018).

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

Bright @APS: L08.00001





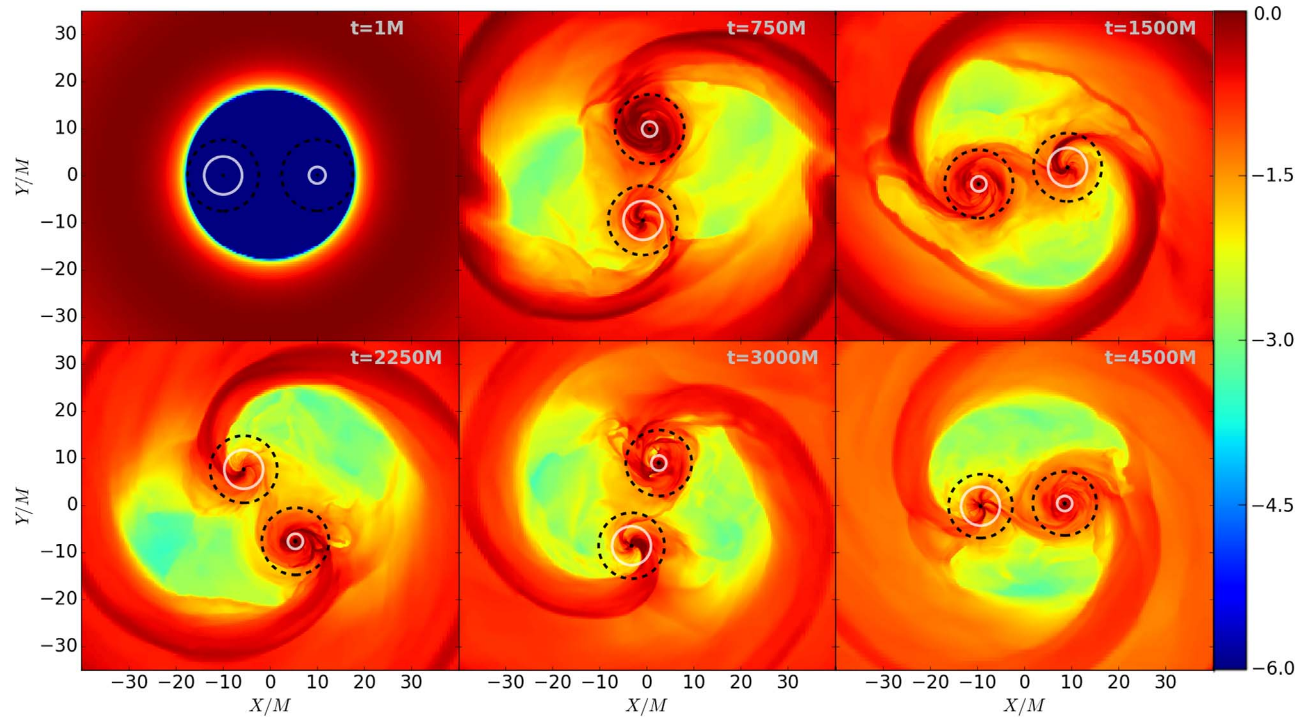


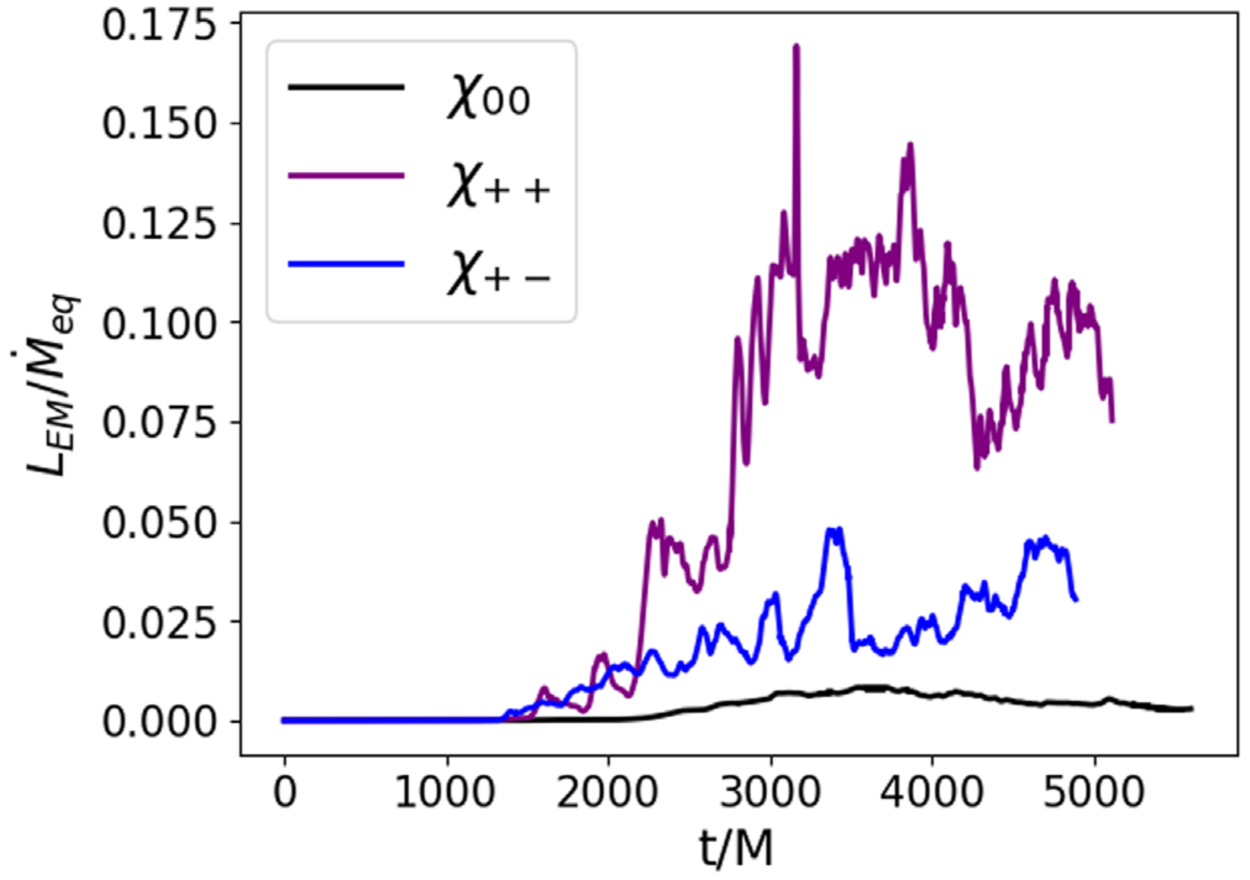
- Non-Spinning BHs;
- Survey over disk size and ang. mom. distribution;

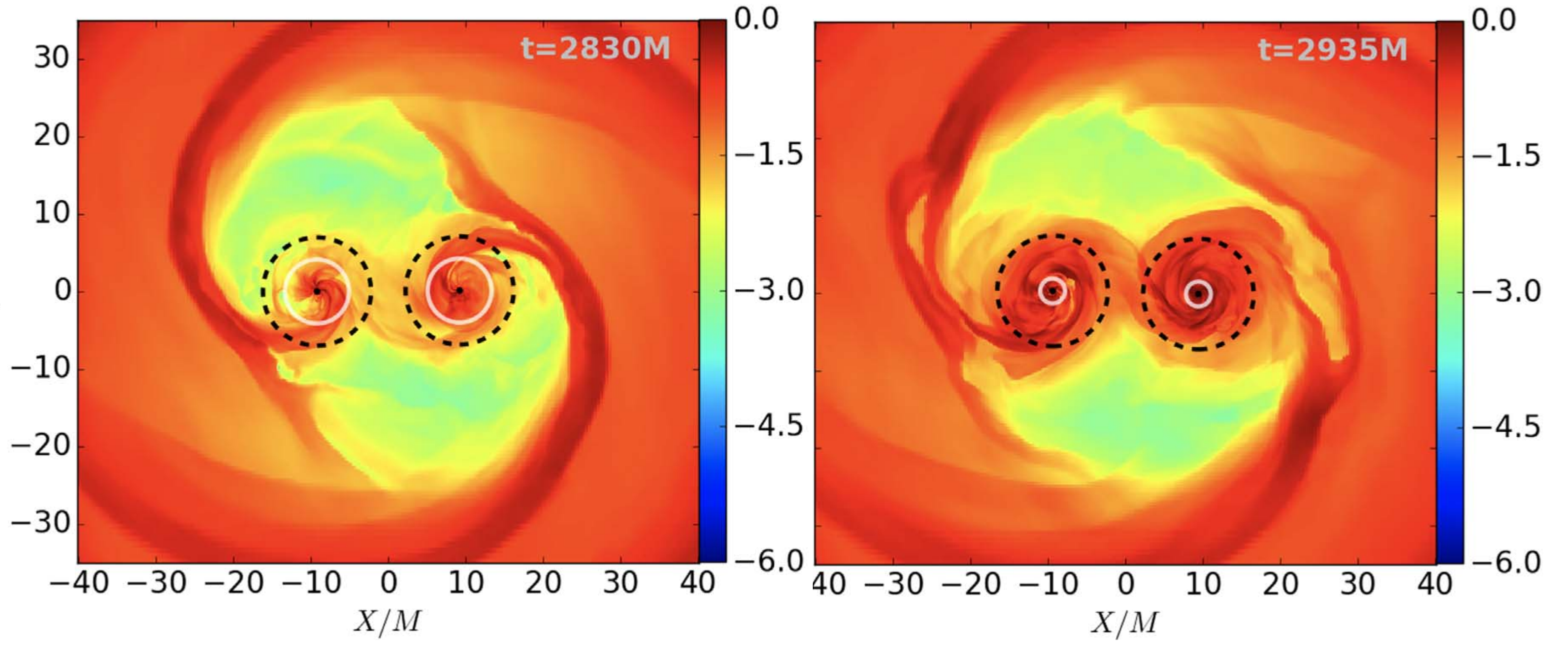
⭐Accretion rate is universal over these timescales;

⭐All lead to similar post-merger Poynting luminosities

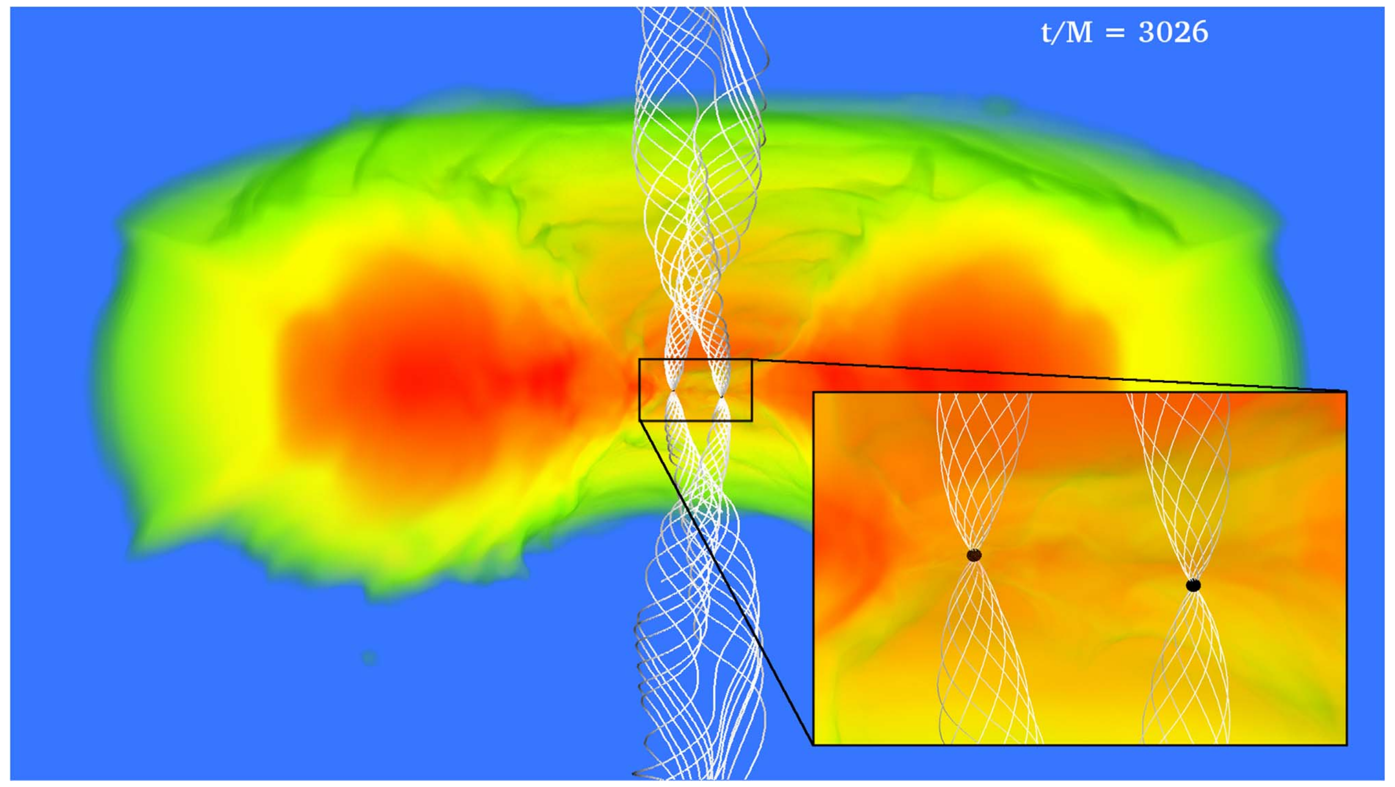
χ_{+-}







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;

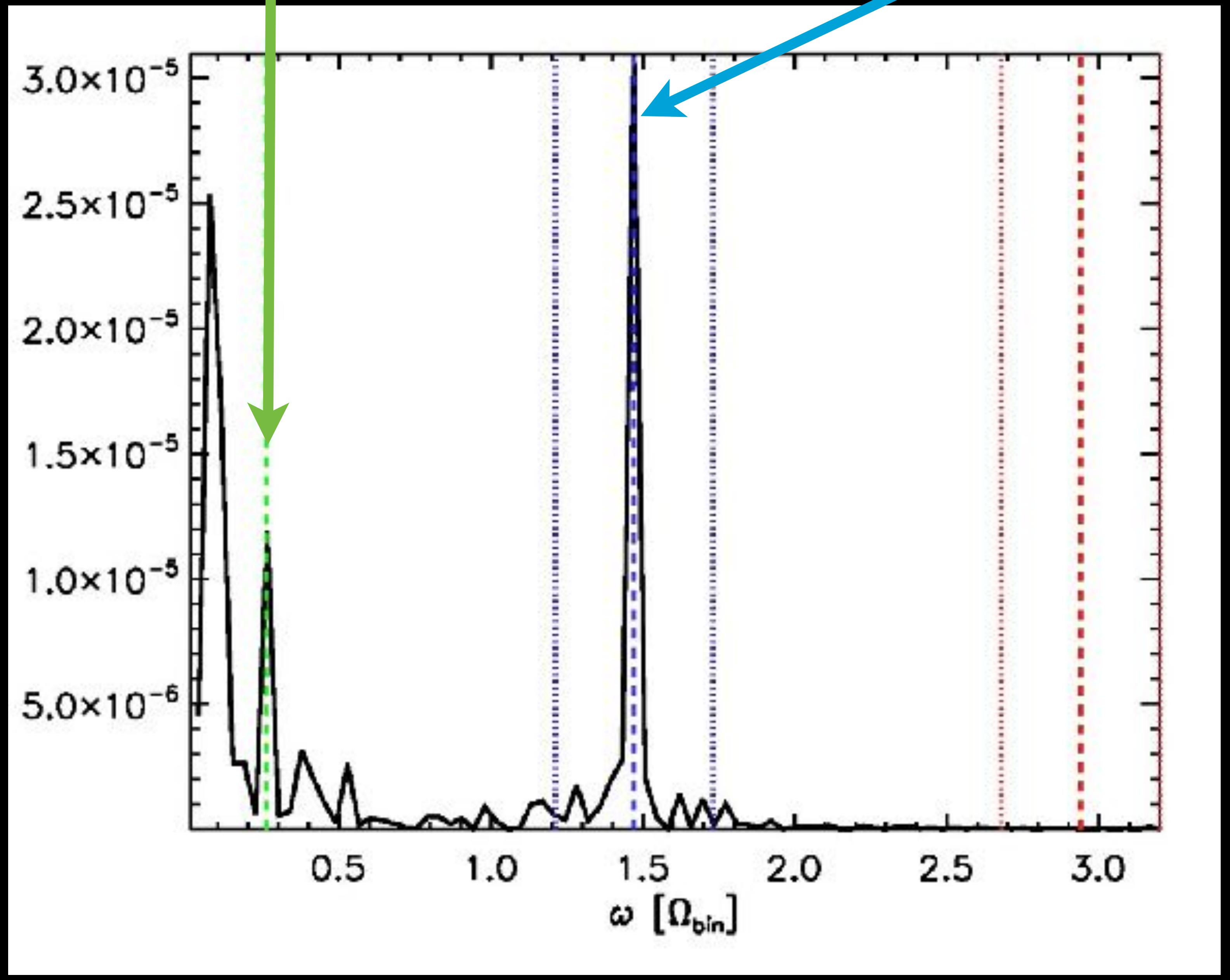
MHD Simulations Predict an EM Signature:

Noble++2012

Periodic Signal

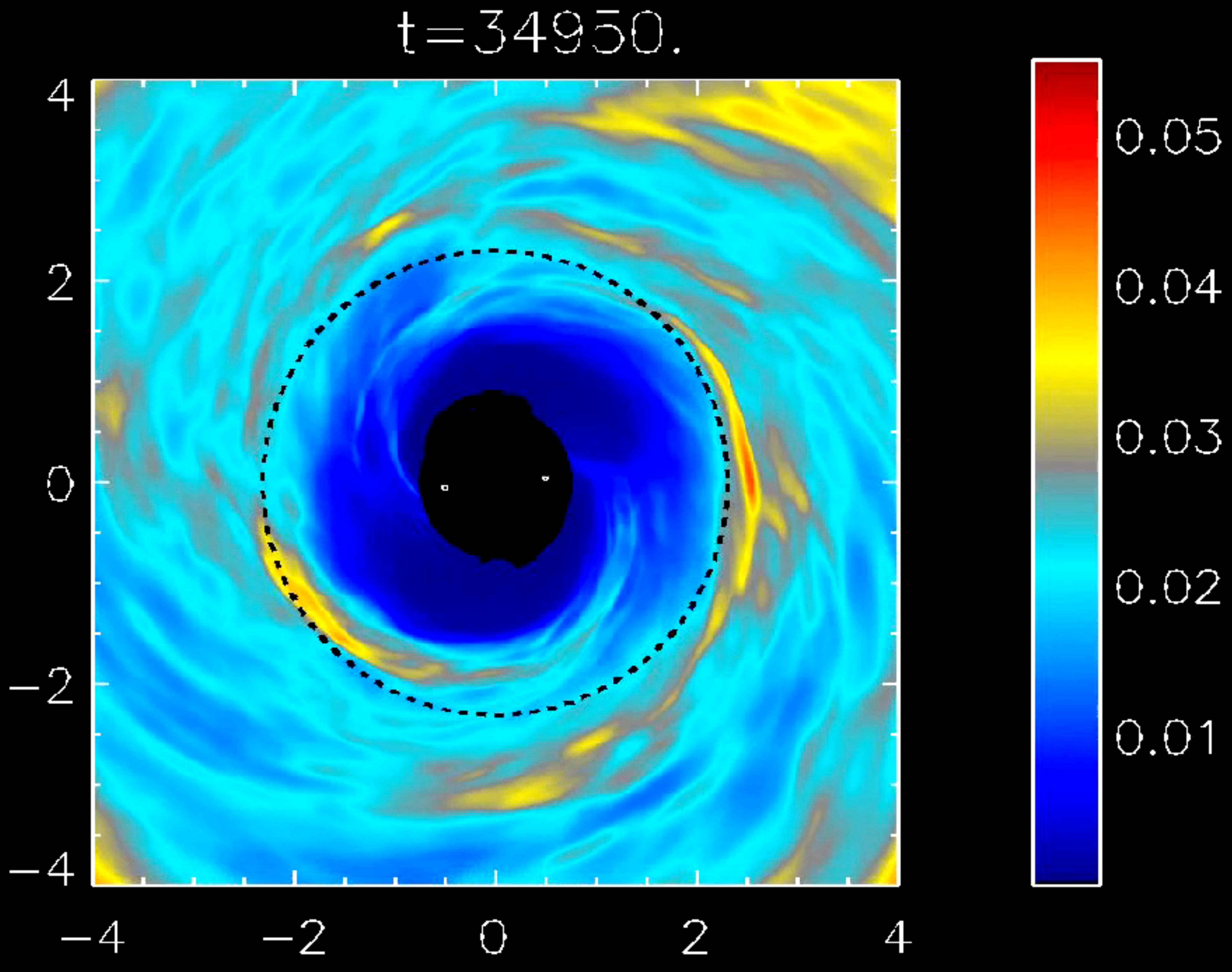
$r_{\rm lump} \simeq 2.5a$
$\Omega_K(r_{\rm lump})$

$1.47\Omega_{\rm bin}$



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

Surface Density



(in frame co-rotating with lump)

Longterm 3-d GRMHD Mini-disk Evolutions

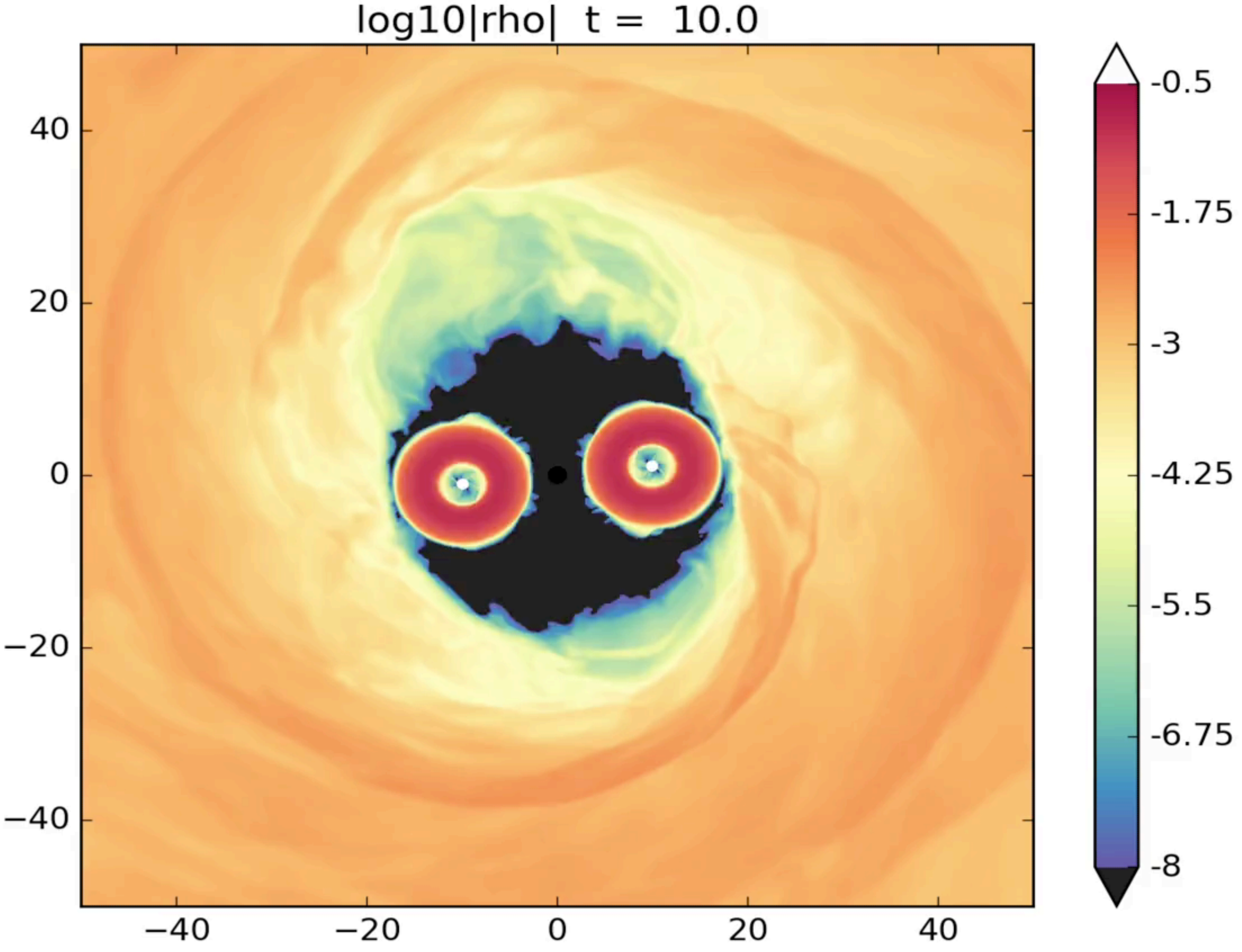
- Noble++2012 circumbinary disk plus mini-disks, with domain covering black hole region;

- Extending Bowen++2018 run from 3 orbits to 12 orbits.
  - Resolved GRMHD simulation of an accreting binary with relaxed circumbinary disk data and mini-disks evolved to *steady mini-disk phase*.

  - First measurement with GRMHD of quasi-periodic interactions in the *steady state* between mini-disks and circumbinary disks in the inspiral regime of the binary, the longest phase observable by LISA.

- Enough time series data to calculate light curve.

Bowen et. al, ApJ (2019).



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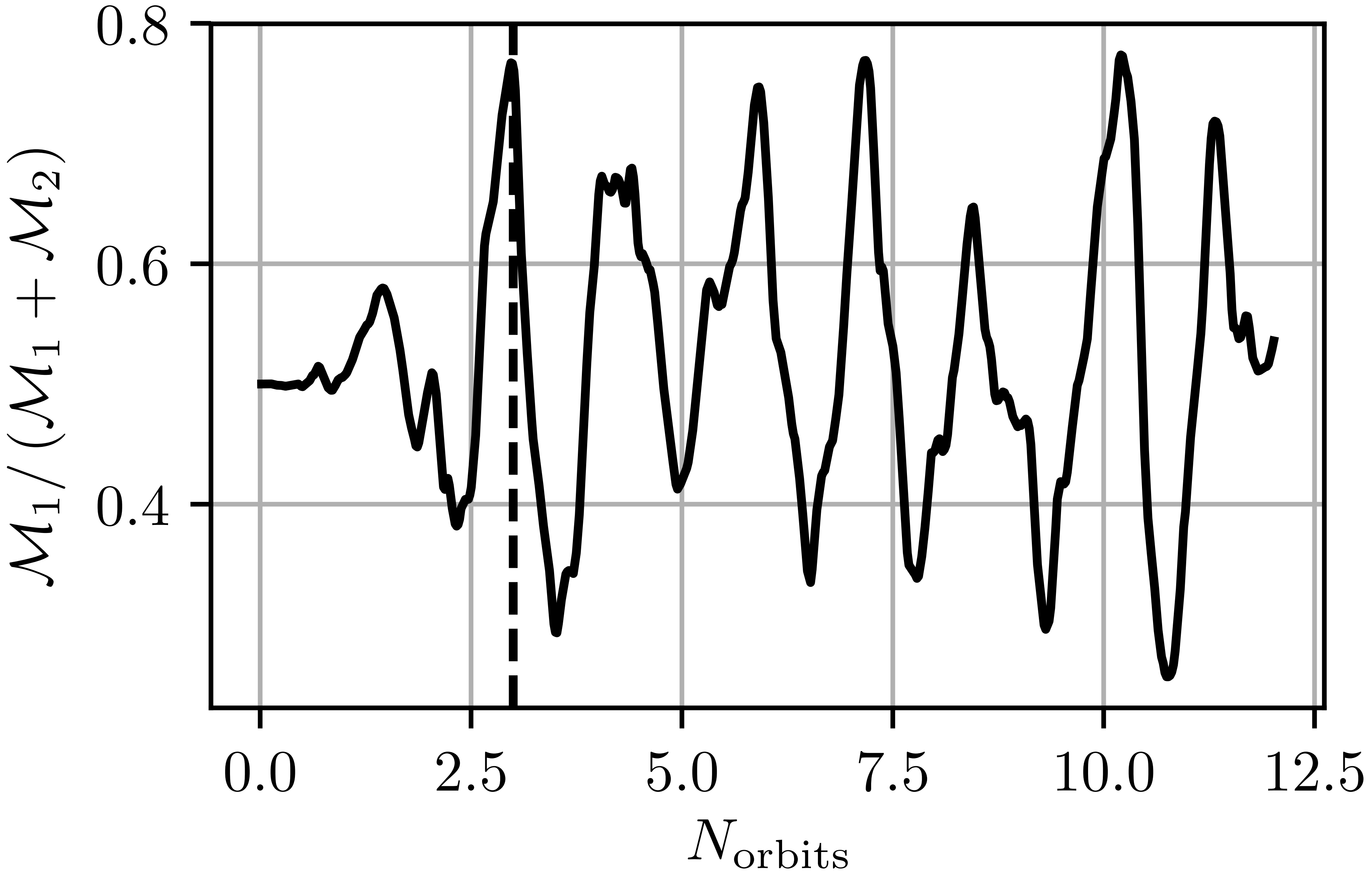
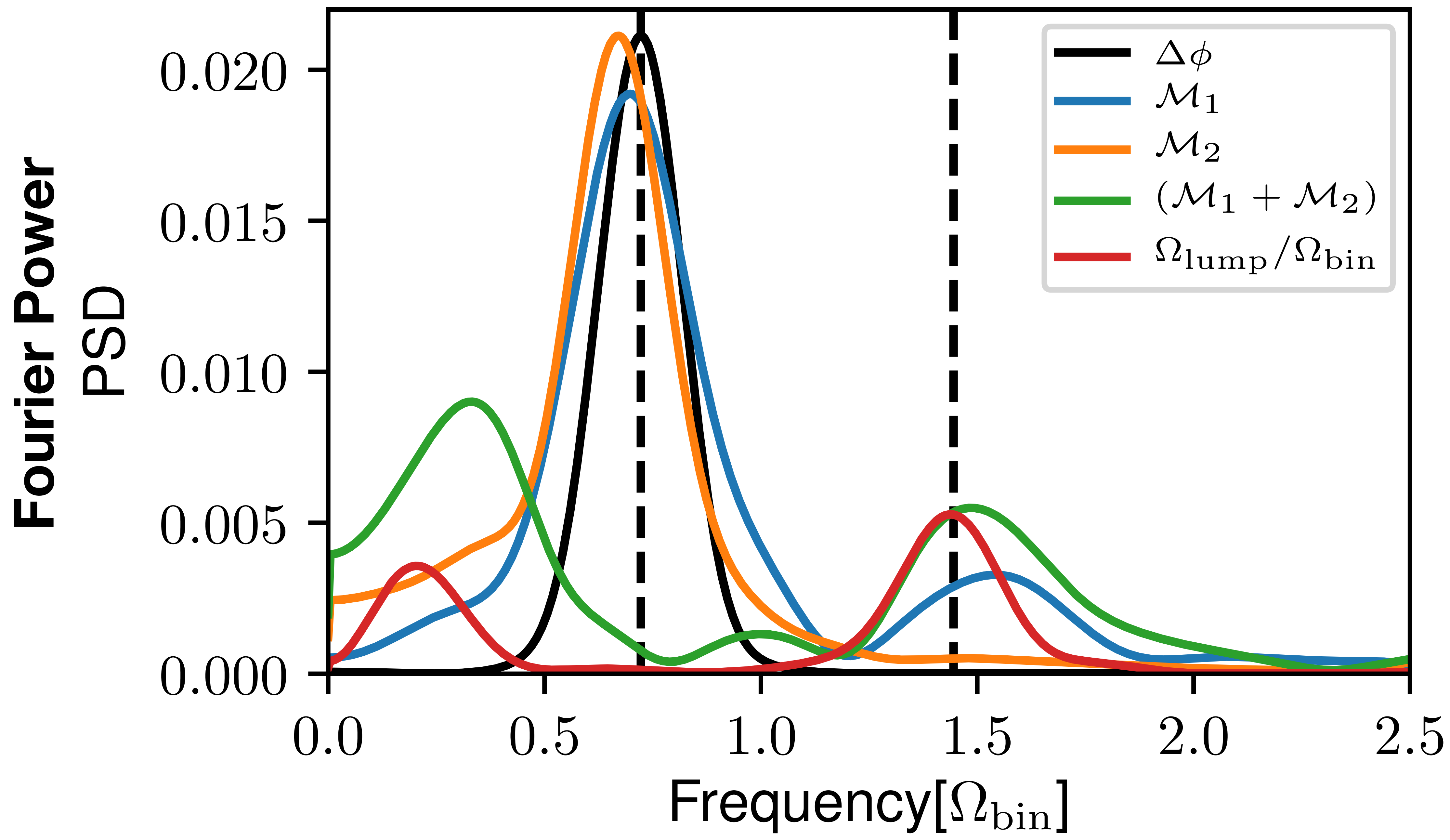




- **Mini-disks settle to a steady-state after several binary orbits.**
- **Mini-disks replenish with material in alternating fashion as they pass by the circumbinary disk's lump, then drain at time scale close to one orbit period.**
- **At these close separations and cooling rate, accretion through mini-disks is driven primarily through spiral shocks.**

- **Significant modulation in each mini-disk's mass —> possible EM signal?**
- **If light follows mass, EM period would be a ~1.5 times the binary period, the beat frequency between the orbital periods of the lump and mini-disks.**
- **Dimmer circumbinary lump modulated at the same frequency plus its local orbital rate (Noble++2012).**

Light from GRMHD Mini-disks

d'Ascoli et. al, ApJ, (2018).

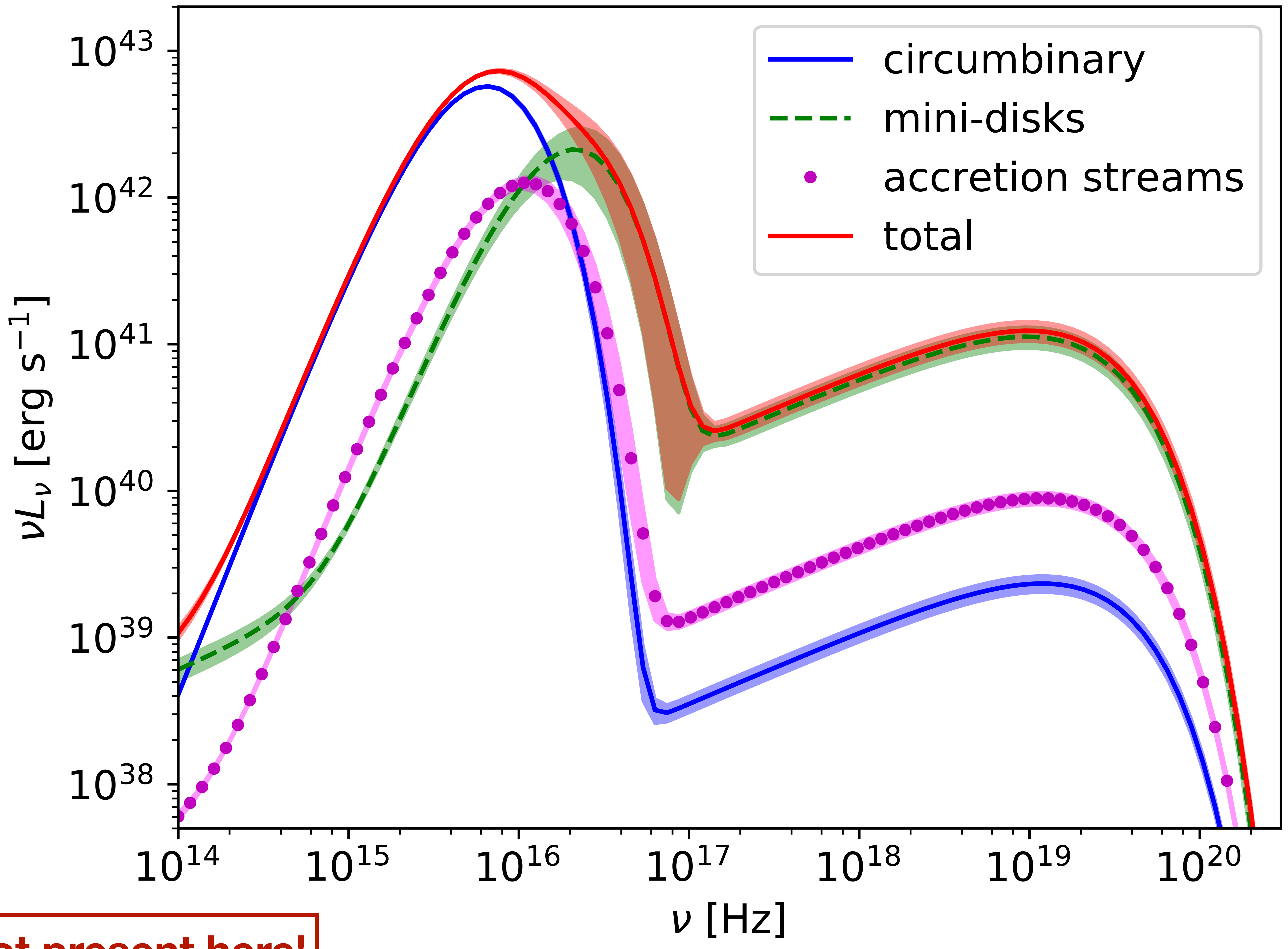
- **Predicted spectrum from accreting binary black holes in the inspiral regime.**

- **The systems will likely be too distant to be spatially resolved, so we need to understand their spectrum and how it varies in time.**

- **Key distinctions from single black hole (AGN) systems:**
  - **Brighter X-ray emission relative to UV/EUV.**
  - **Variable and broadened thermal UV/EUV peak.**
  - **"Notch" between thermal peaks of mini-disks and circumbinary disk will likely be more visible at larger separations and for spinning black holes.**

Face-on View,
Optically Thick Case

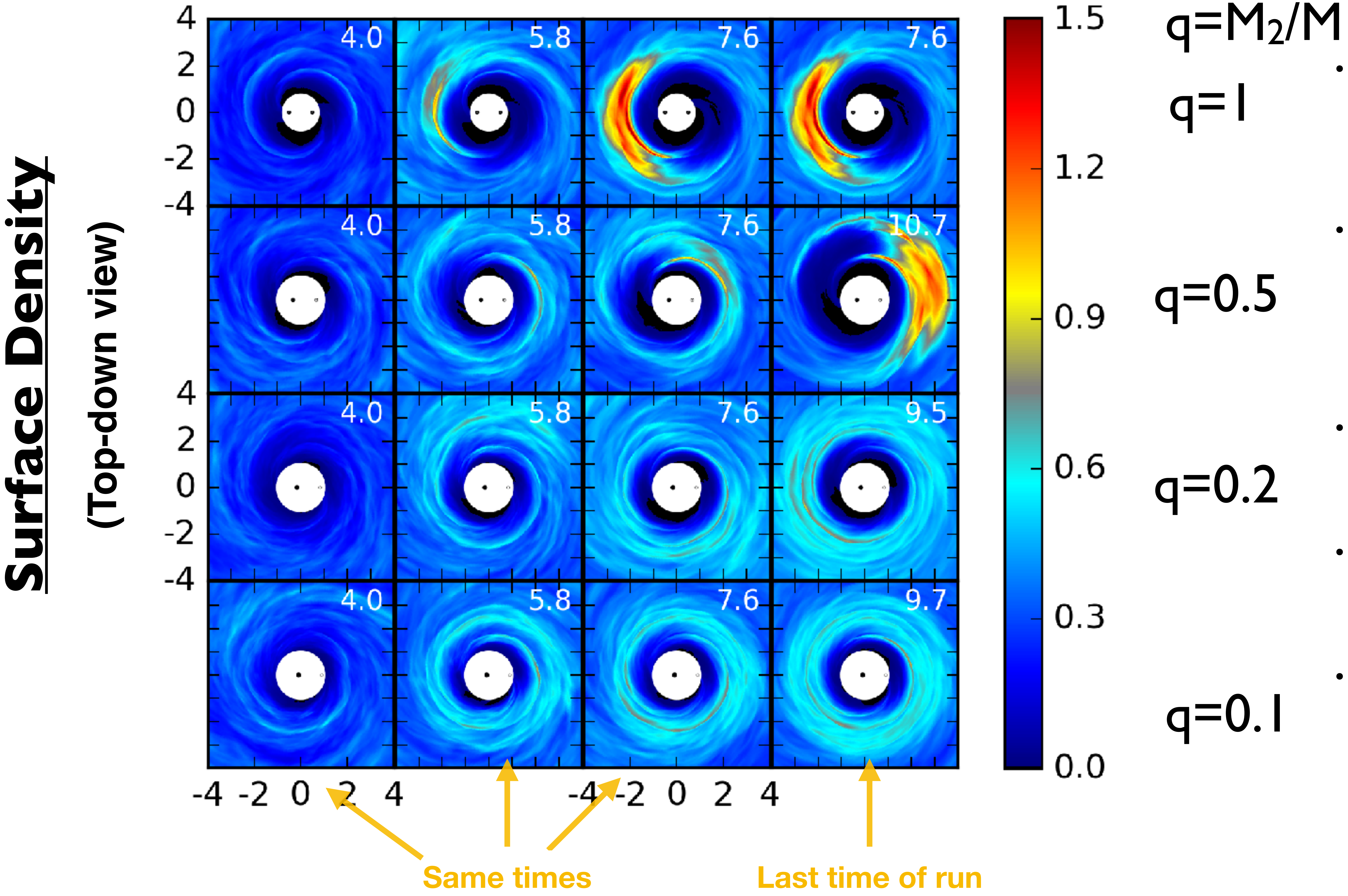
Variability over 1 orbit



Variability on longer lump's time scale not present here!

Mass Ratio Survey : Circumbinary Disks

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



- 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.

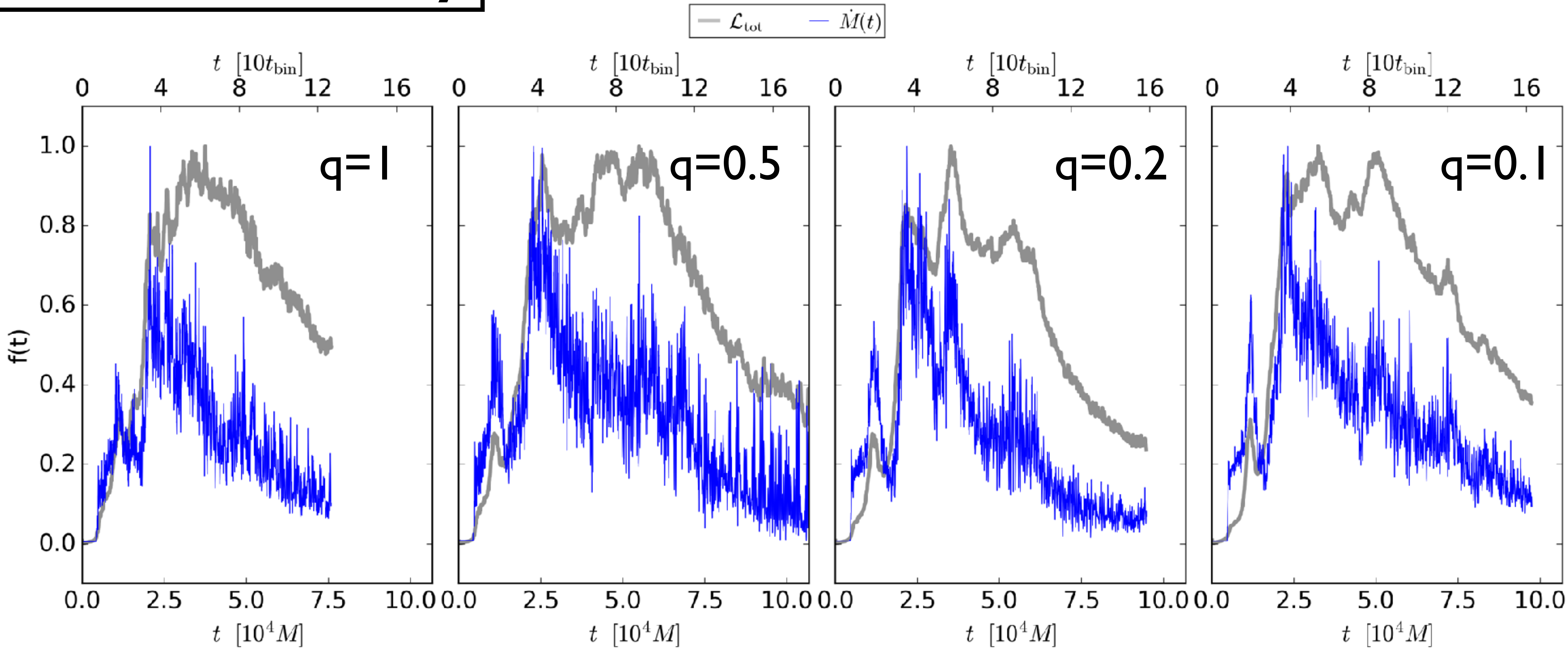
Noble, Krolik, Campanelli, Zlochower, Mundim, Nakano, Zilhao (2021)
https://arxiv.org/abs/2103.12100

- **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.**

Mass Ratio Survey

Global Trends of the Lump

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



- **Accretion rate and bolometric luminosity histories follow similar trends, largely dictated by initial data of the disk;**
- **Radiative efficiency improves over time as more mass fills the interior region, likely due to more dissipative binary torque;**

Mass Ratio Survey

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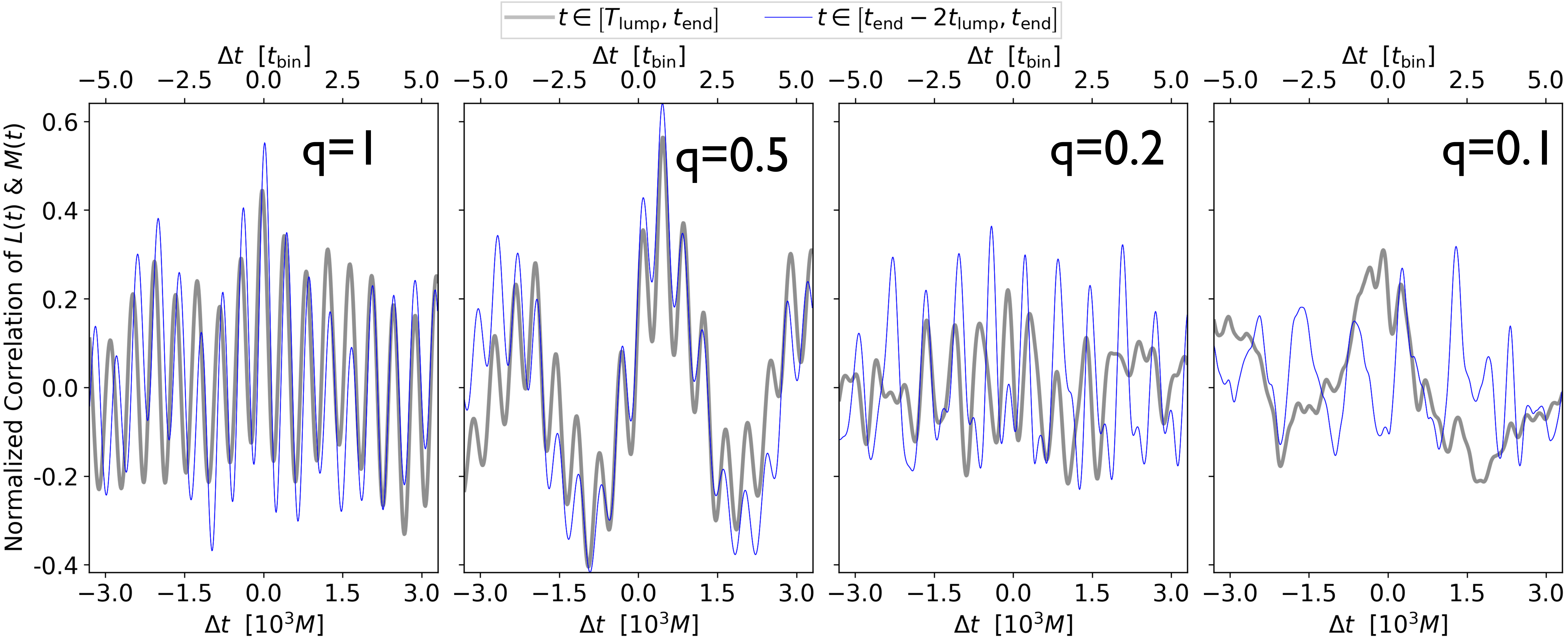
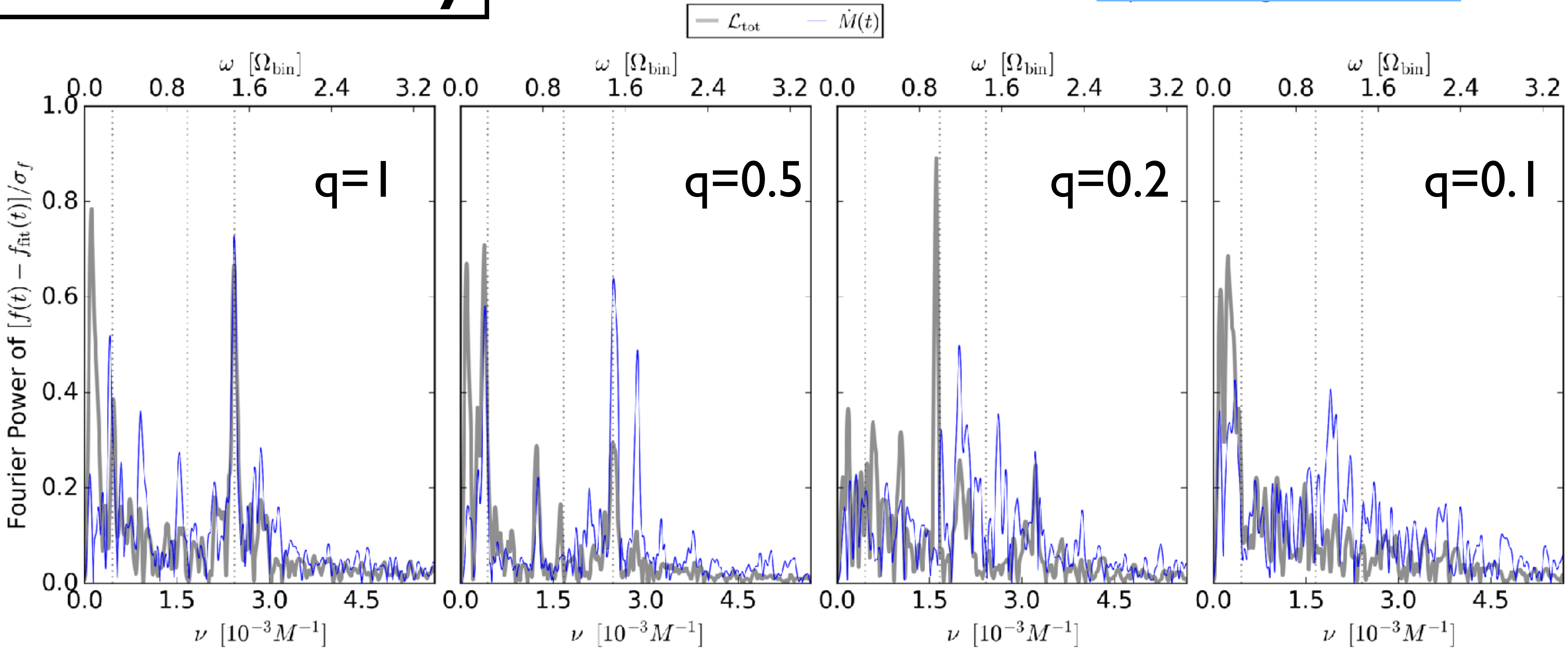


- **Lump-forming runs exhibit correlations with large amplitude oscillations at** $\Omega_{\rm lump}$ and $2\Omega_{\rm beat}$
- **Positive lags mean accretion rate leads luminosity: accretion stream is pulled in, then partially expelled and dissipated along the cavity wall;**

Mass Ratio Survey

Global Trends of the Lump

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



- **Non-trivial signals apparent in L(t) and Mdot(t) at $2\Omega_{\rm beat}$**
- **Signals in accretion rate and luminosity are not always shared;**
- **Small-q binaries show red-noise dominated power spectrum like single-BH disks;**
- **Intermediate-q binary shows strongest signal at binary frequency, as the disk interacts primarily with BH#2;**
- **Mdot modulations will likely modulate mini-disk luminosities, which are brightest high-energy component;**

Mass Ratio Survey

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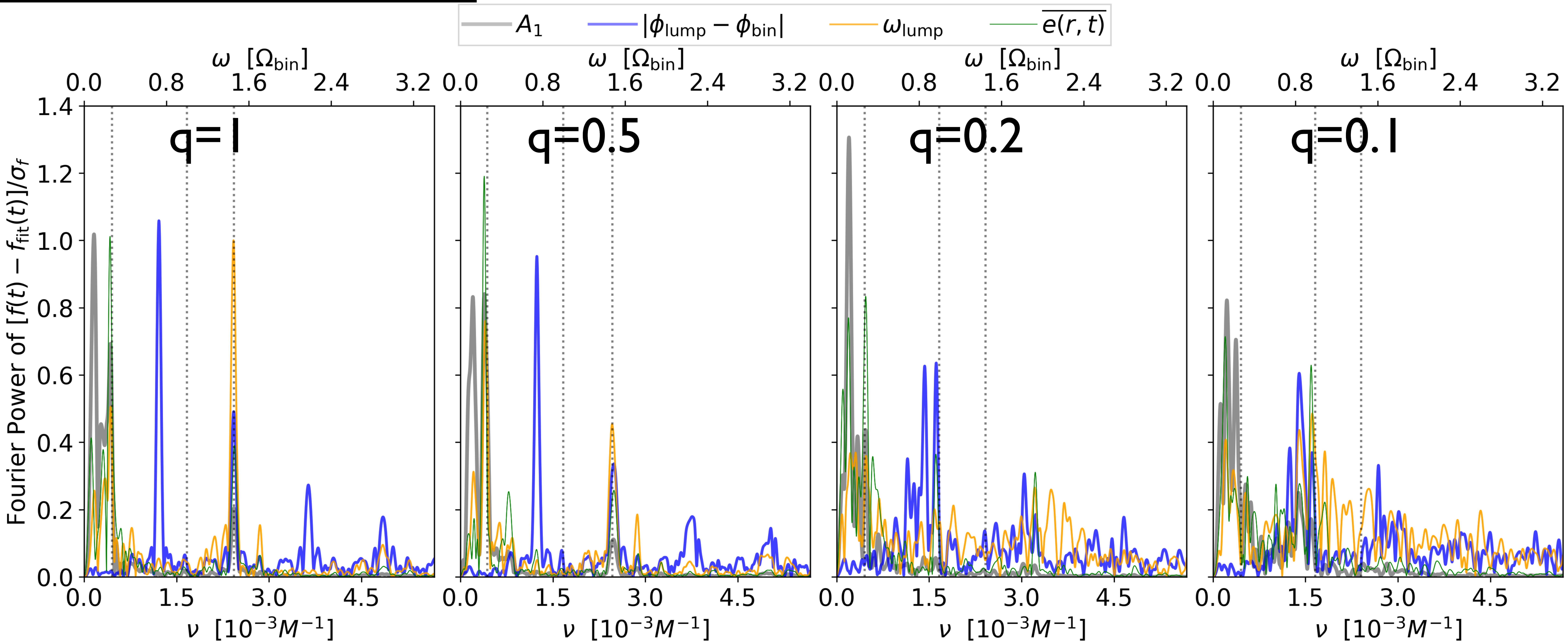


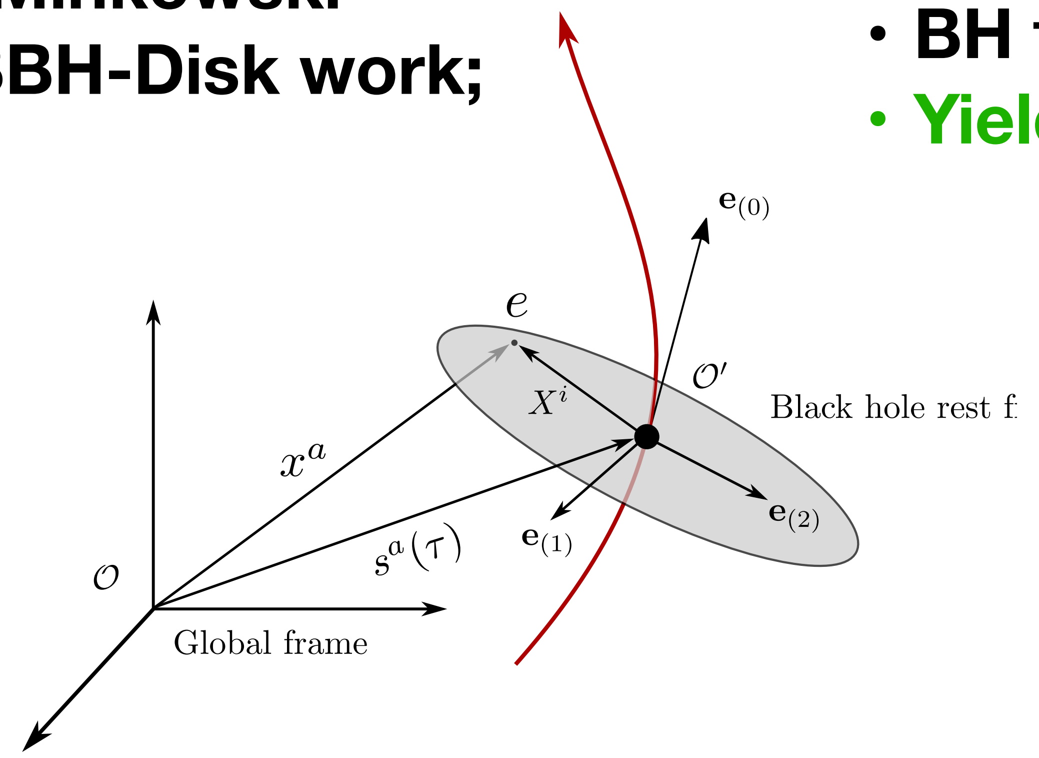
- **Kinematics of lump demonstrated through variability analysis of lump's phase, frequency, and amplitude;**
- **Variability of lump's rotation rate modulated at by each passing BH at** $2\Omega_{\rm beat}$
- **Disks's eccentricity variability strongly associated with variability of the lump (A_1);**
- **These lump signals greatly diminish for runs without a strong lump amplitude;**
- **Also in the paper: we demonstrate how lump formation is connected to local amplitude of specific magnetic stress;**

Superposed Kerr-Schild

Combi, Lopez Armengol, Campanelli, Ireland, Noble, Nakano, Bowen (2021)
https://arxiv.org/abs/2103.15707

- **Use an approximate spacetime leading up to merger to most efficiently build accretion flow to a "steady" or more natural state.**
- **Old Method: Matching : Kerr+Post-Newt.+Post-Minkowski**
  - **Non-spinning version used in all our previous BBH-Disk work;**
  - **Spinning version is too expensive:**
    - **Includes retarded time integral for all x^a;**

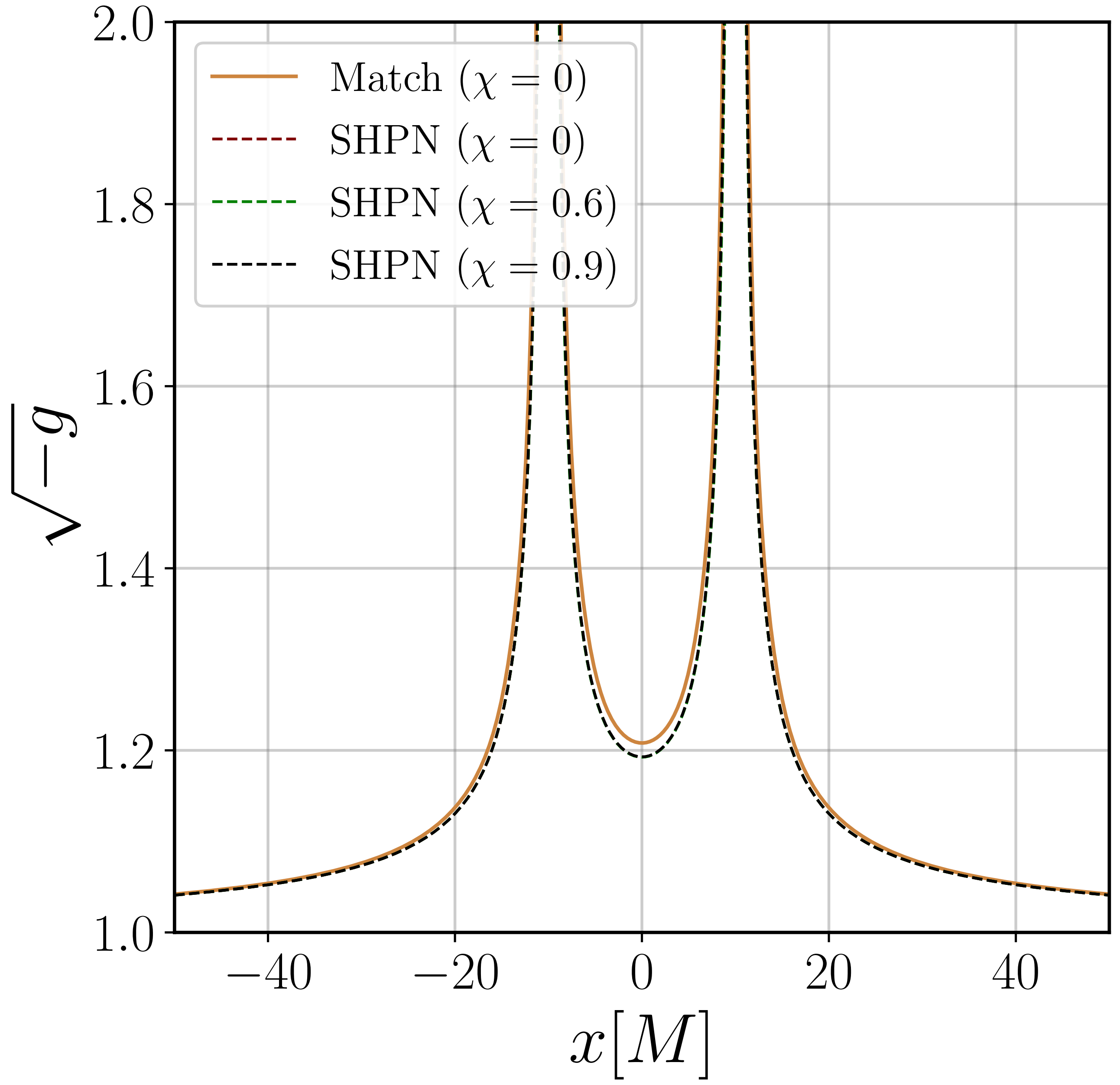
$$g_{ab} = (1 - f_{\rm FZ})\Big\{ f_{\rm NZ}\big[f_{{\rm IZ},1}\, g^{\rm (NZ)}_{ab} + (1 - f_{{\rm IZ},1})\, g^{\rm (IZ1)}_{ab}\big] + (1 - f_{\rm NZ})\big[f_{{\rm IZ},2}\, g^{\rm (NZ)}_{ab} + (1 - f_{{\rm IZ},2})\, g^{\rm (IZ2)}_{ab}\big]\Big\} + f_{\rm FZ}\, g^{\rm (FZ)}_{ab} \qquad (30)$$

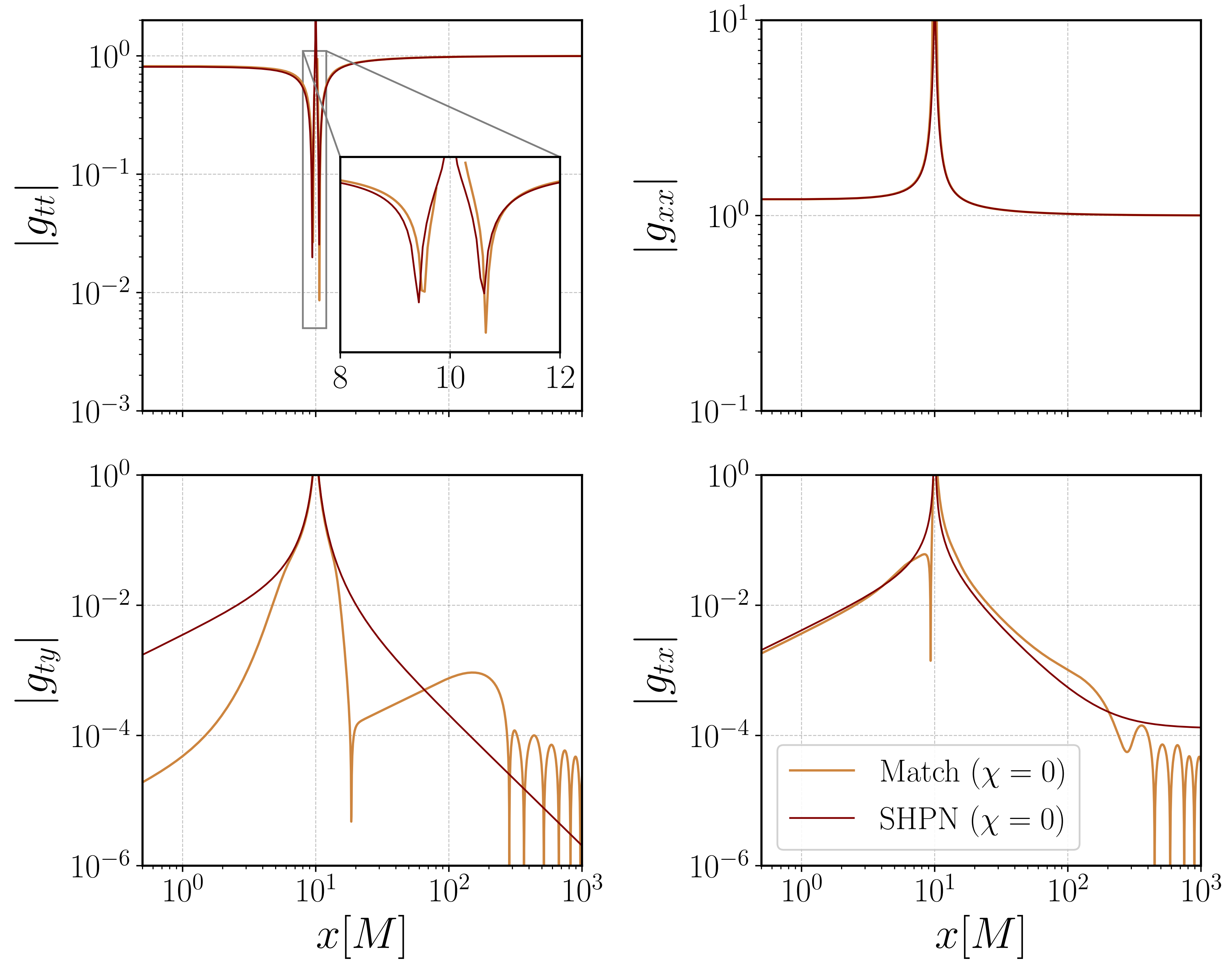


- **New Method: Superposed Kerr-Schild:**
  - **Boosted set of Spinning BHs in Harmonic Cook-Scheel coordinates;**
  - **Significantly more computationally efficient than Matching;**
  - **BH trajectories still governed by 2.5PN theory;**
  - **Yields comparable vacuum sol'n as that of Matching;**

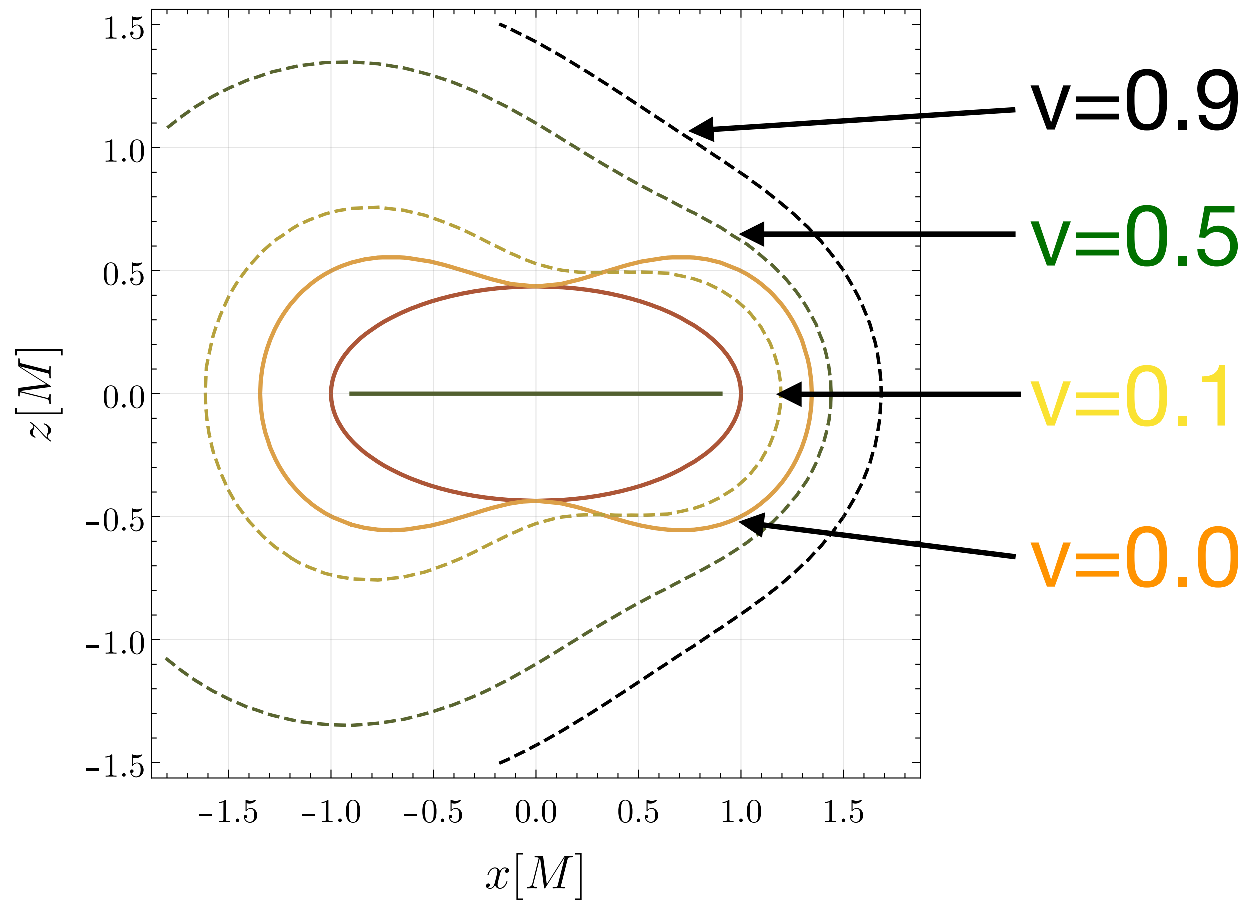
$$g_{ab} = \eta_{ab} + M_1\left(\frac{\partial X_1^{\bar a}}{\partial x^a}\frac{\partial X_1^{\bar b}}{\partial x^b}\mathcal{H}_{\bar a \bar b}\right) + M_2\left(\frac{\partial X_2^{\bar a}}{\partial x^a}\frac{\partial X_2^{\bar b}}{\partial x^b}\mathcal{H}_{\bar a \bar b}\right),$$

$$\mathcal{H}_{ab} := 2H l^H_a l^H_b + \mathcal{A}_{ab}.$$



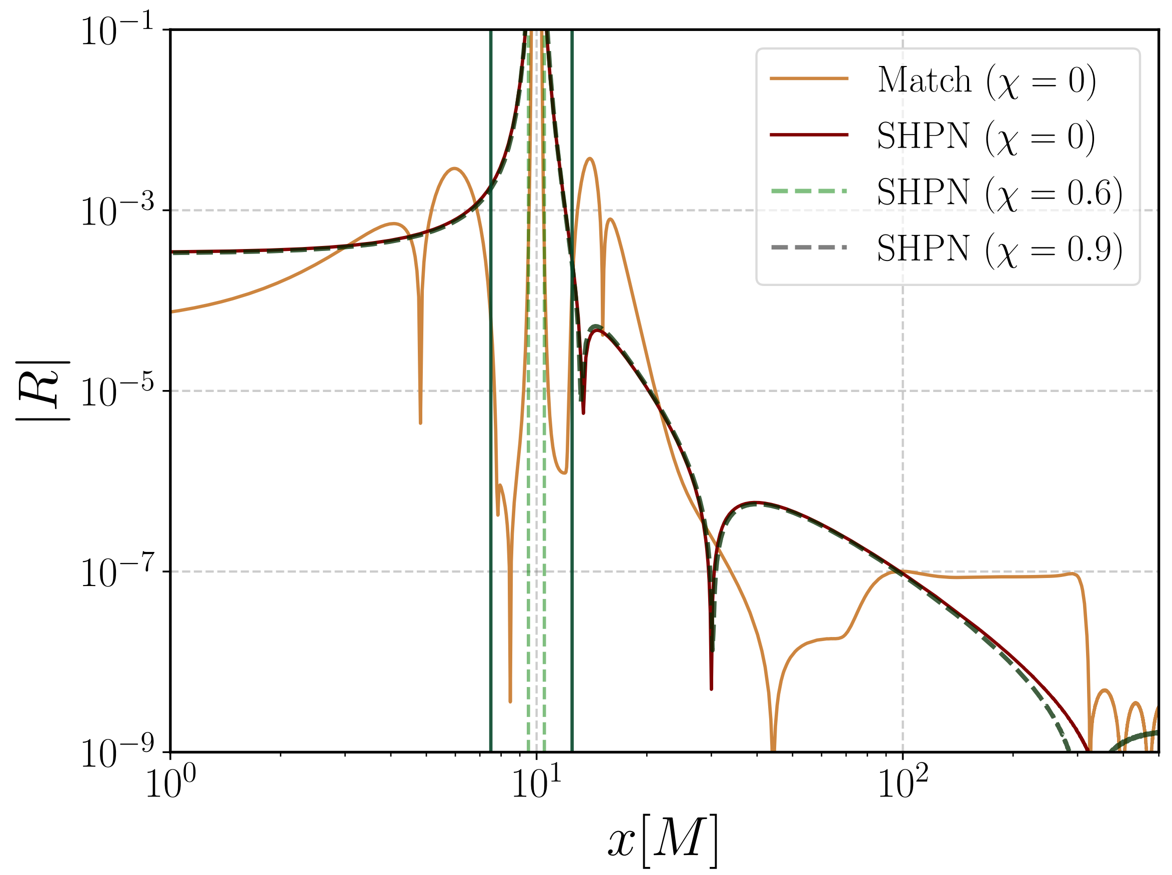


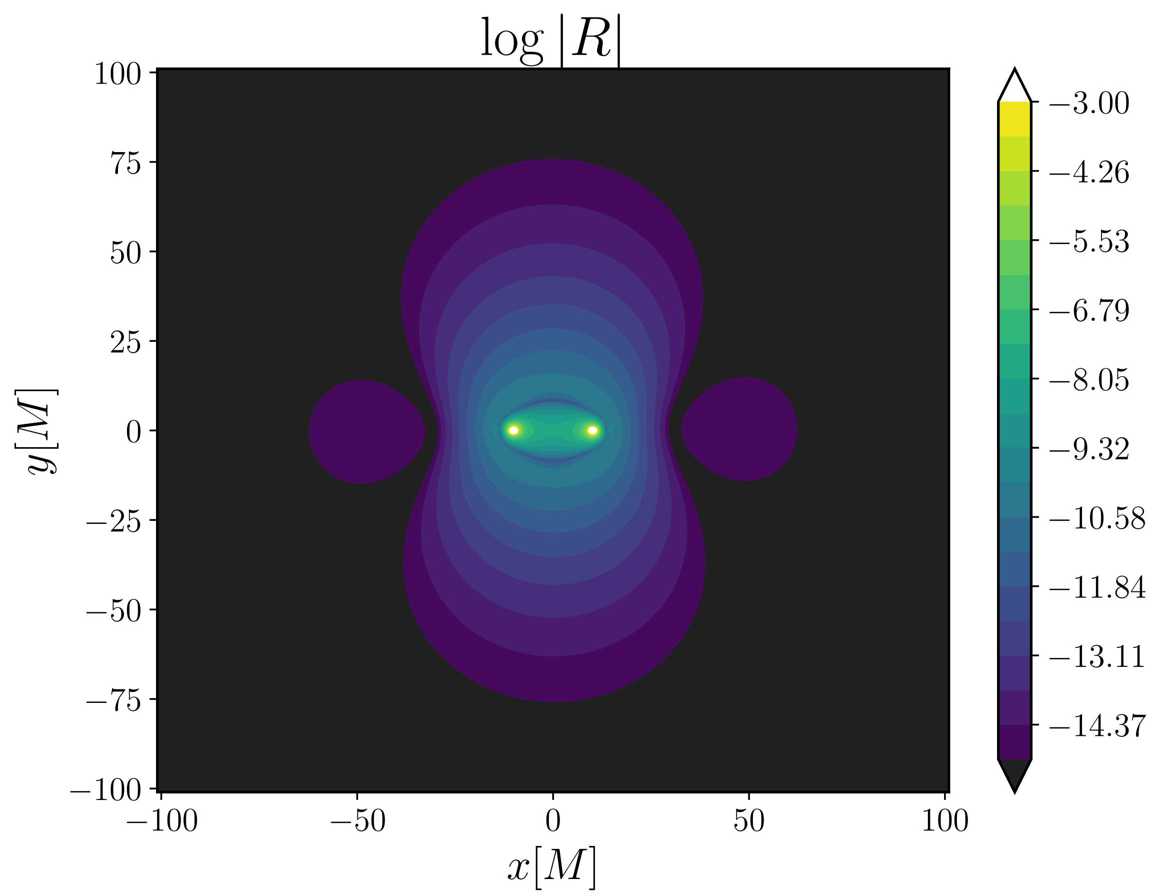
Ergoregion varies with spin and velocity:
—> Consequences to energy extraction eff.;

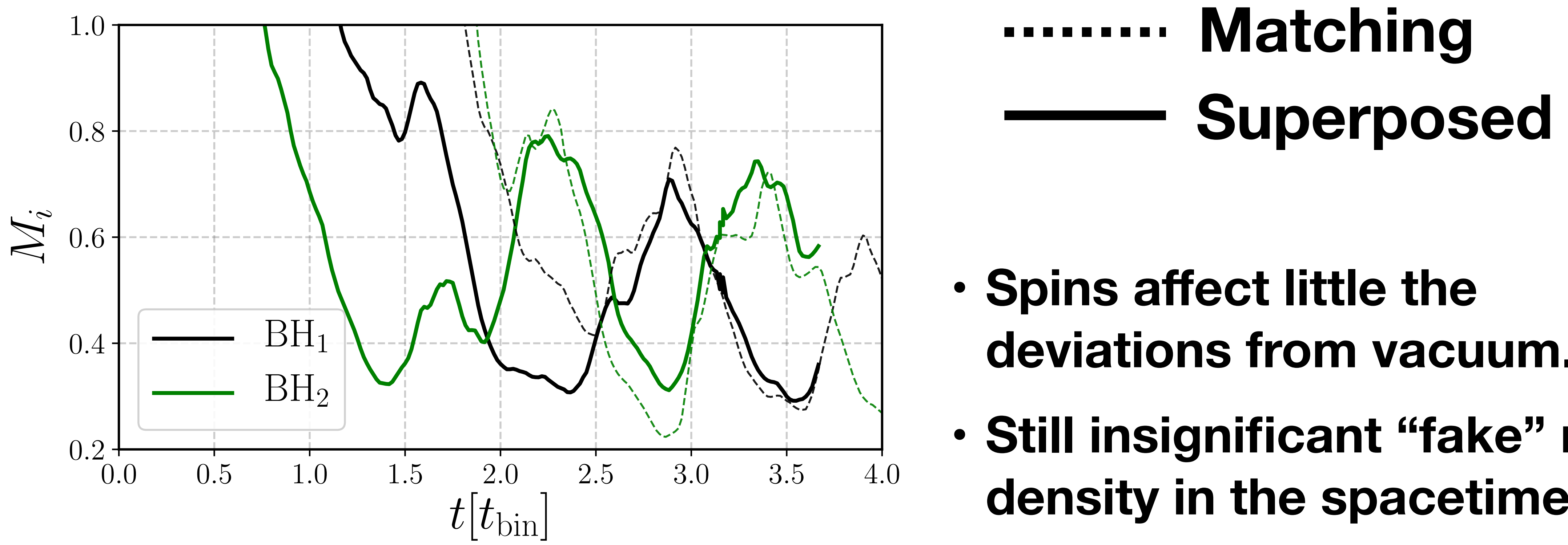


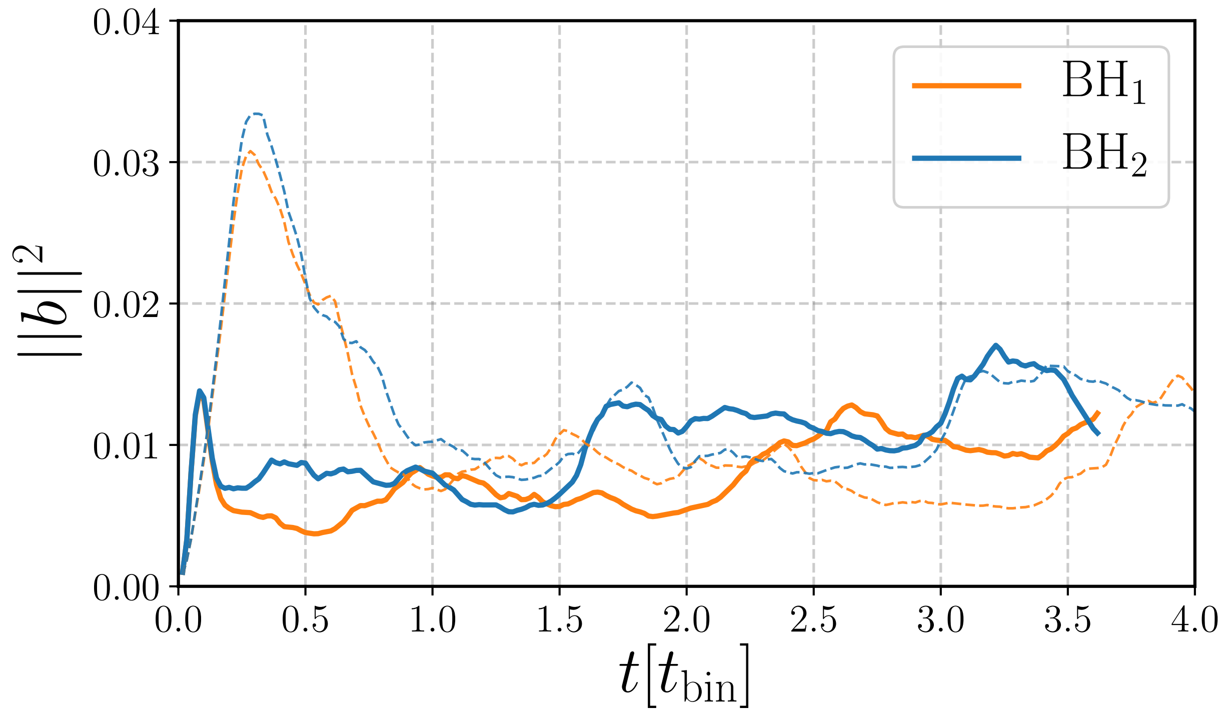
Superposed Kerr-Schild

Combi, Lopez Armengol, Campanelli, Ireland, Noble, Nakano, Bowen (2021)
https://arxiv.org/abs/2103.15707

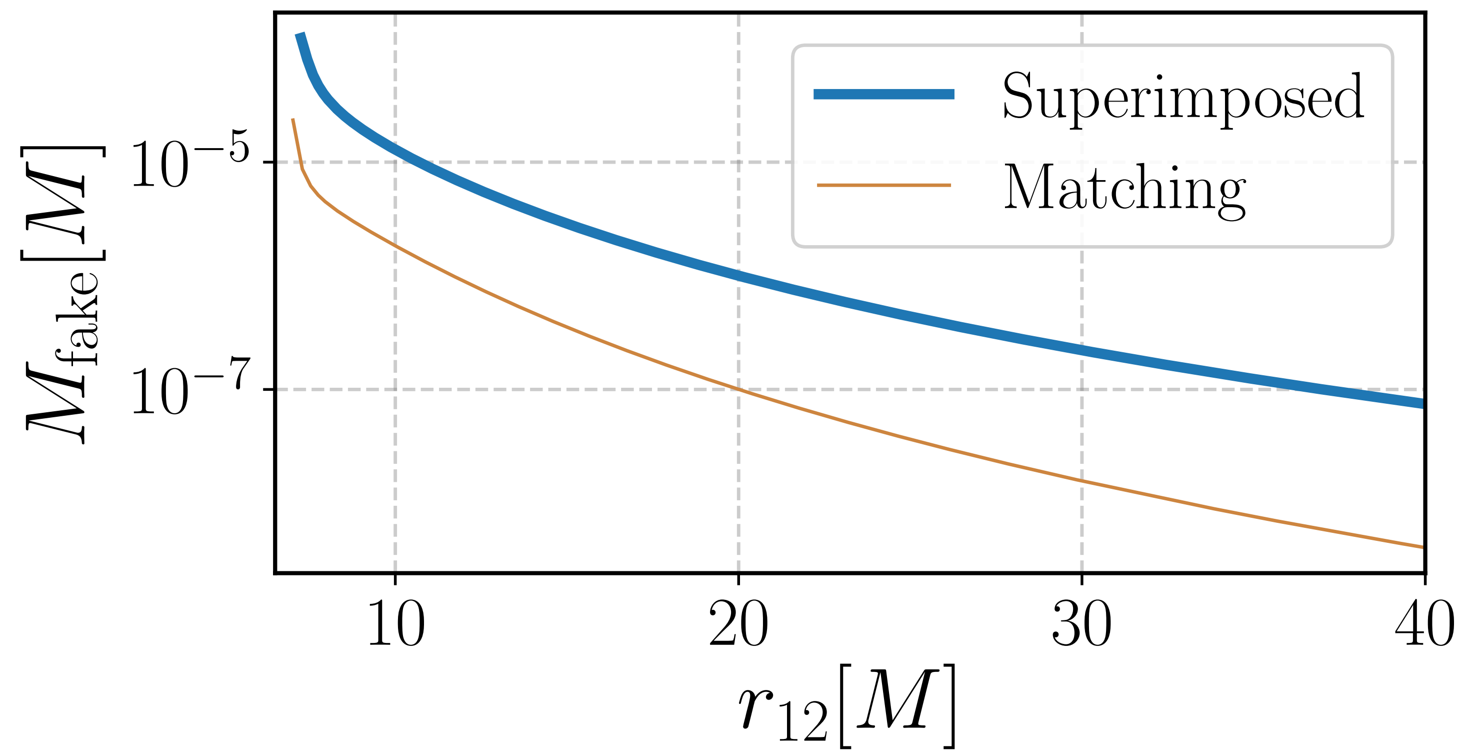






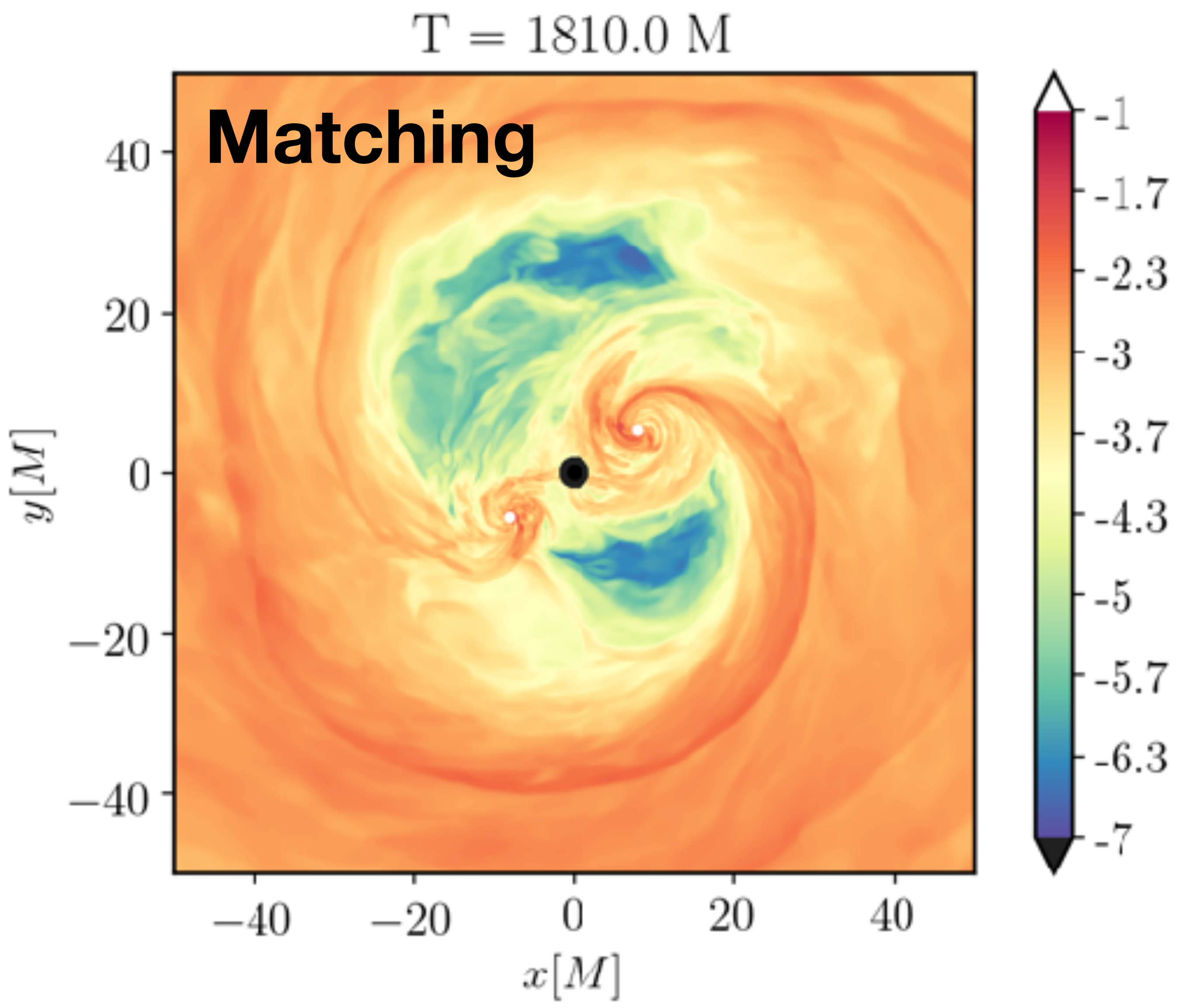


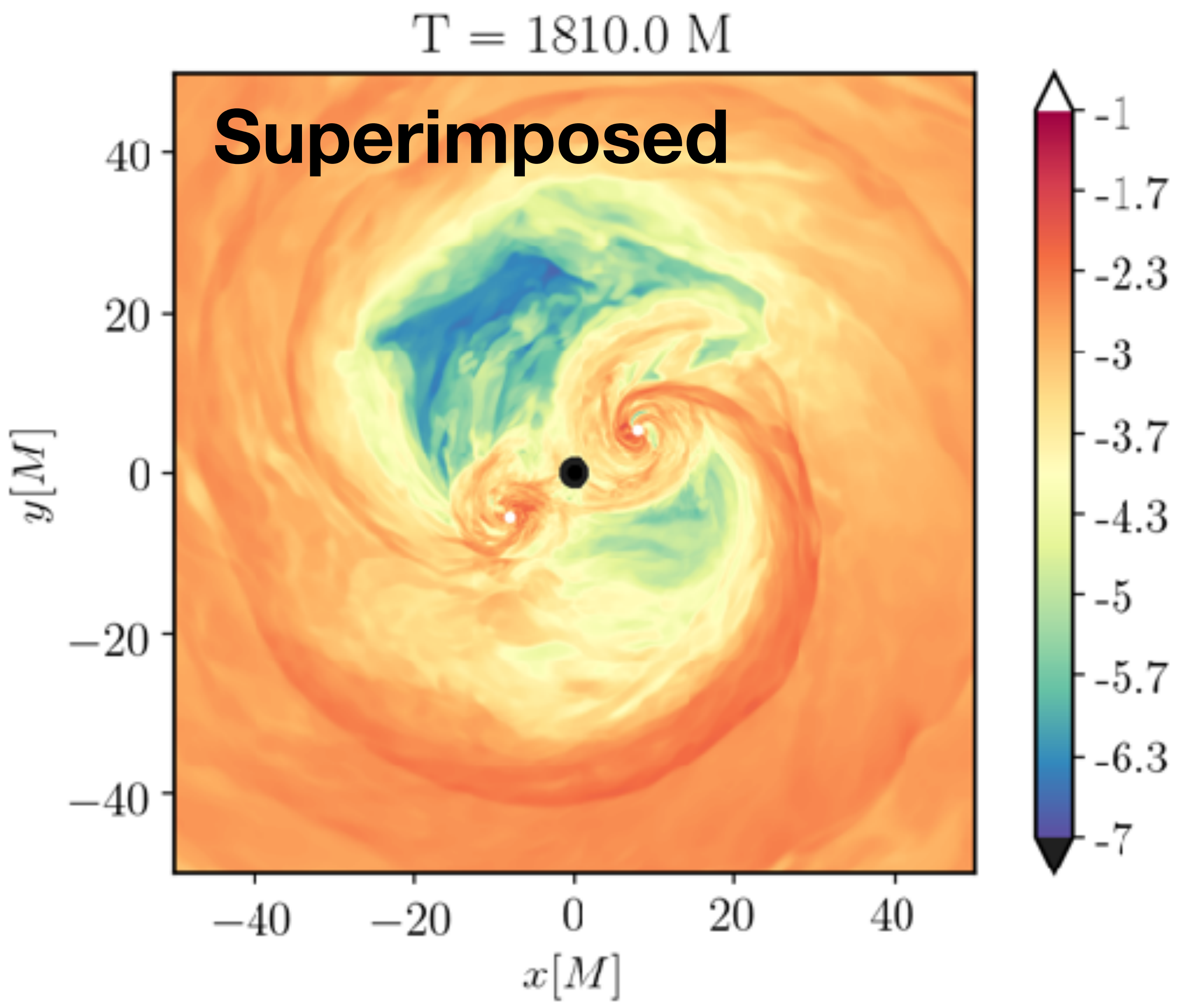
- **Spins affect little the deviations from vacuum.**
- **Still insignificant "fake" mass density in the spacetime;**
- **Insignificant consequences to the asymptotic accretion flow:**
  - **Largest differences seen during initial transient phase because the mini-disk initial data were derived using the Matching metric;**



$$\mathcal{H} := {}^3R + K - K_{ab}K^{ab} = 16\pi\tilde{\rho},$$

$$M_{\rm fake} = \frac{1}{16\pi}\int_{\mathcal{V}} \mathcal{H}\, d\mathcal{V}.$$



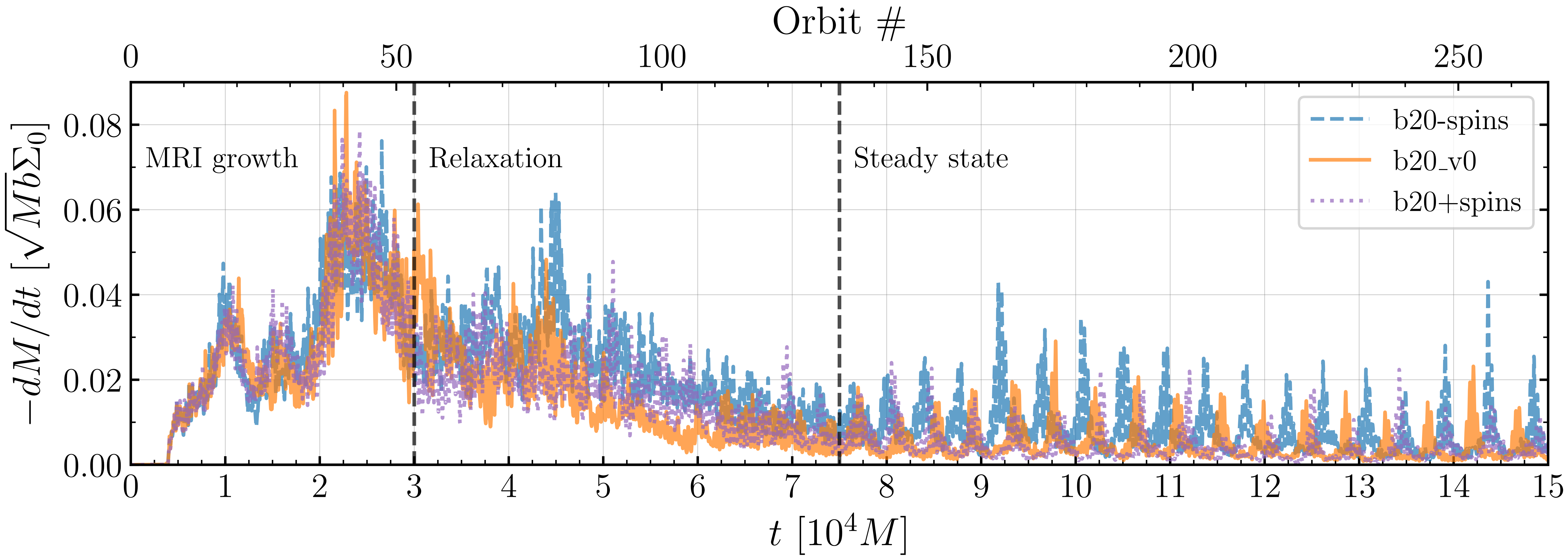


Accretion onto Spinning BBHs

Circumbinary Disk Region

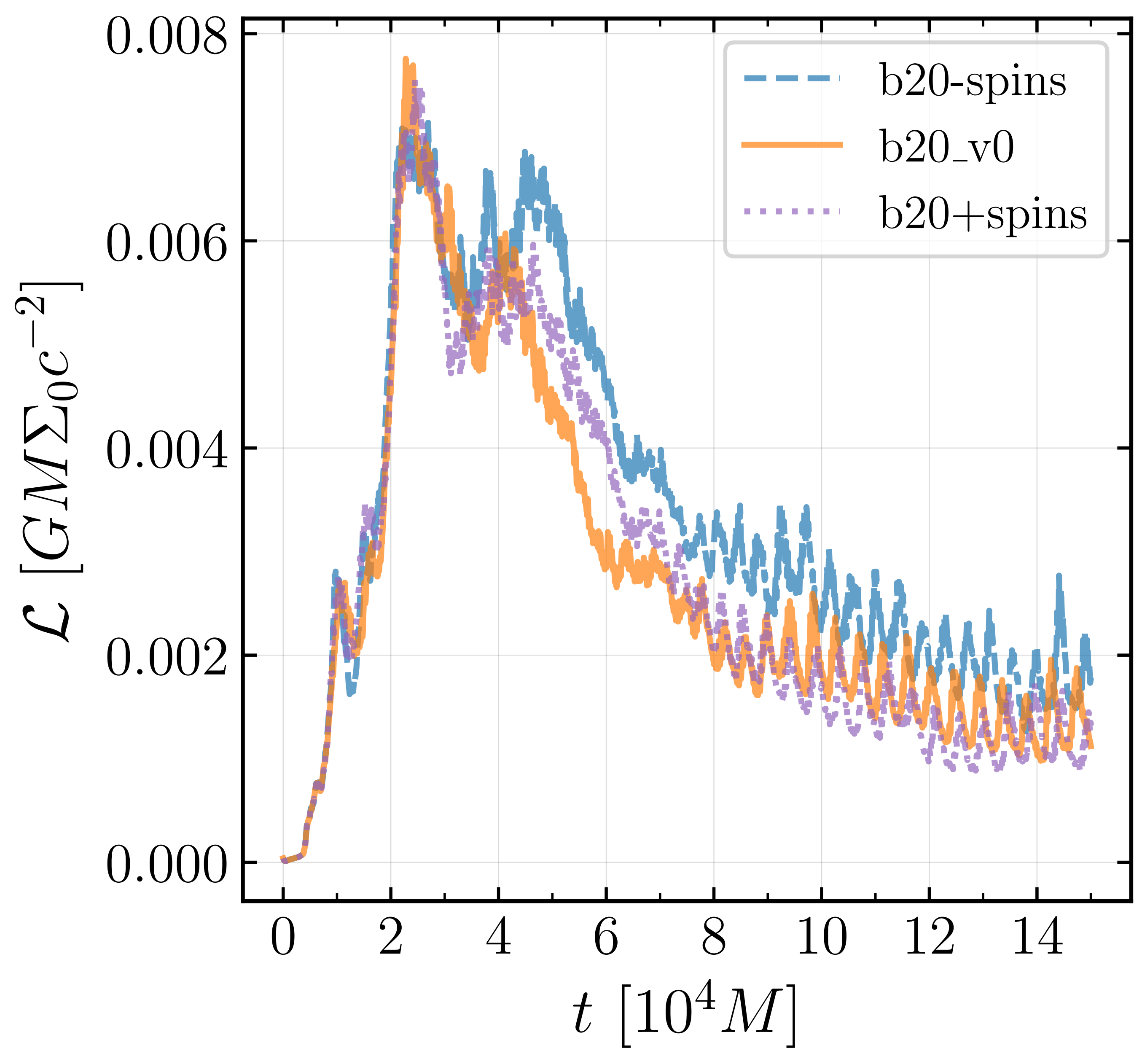
Lopez Armengol, Combi, Campanelli, Noble, Krolik, Bowen, Avara, Mewes, Nakano (2021)

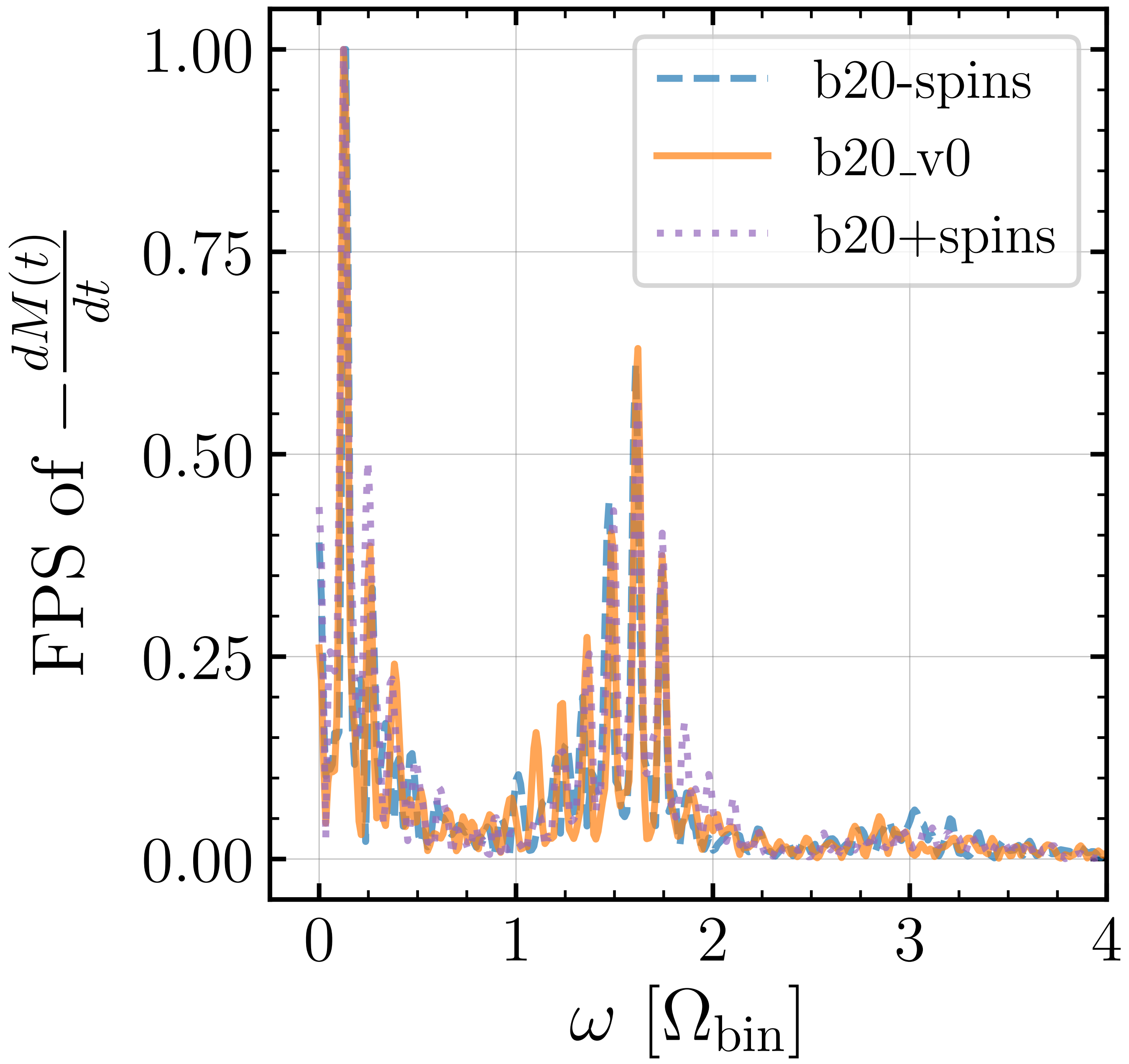
https://arxiv.org/abs/2102.00243



- "b20" = 20M separation
- "-spins" = spins retrograde to orbit
- "+spins" = spins prograde to orbit
- "v0-2" = no spins, different random 1% pressure noise

$a_{1,2}/M_{1,2}$ = +/- 0.9





- **Simulations of only circumbinary disk region, starting from Noble++2012 conditions, only changing spin and using Superposed metric; Equal masses, q=1;**
- **Ran longer than before, reached a better steady state;**
- **Circumbinary dynamics largely unaffected by spin aligned with orbital angular momentum;**
- **Again, light curve modulated by the beat mode and the lump's orbital frequency;**
- **Measured the realization variance by performing runs w/ different sets of random perturbations to the initial data;**

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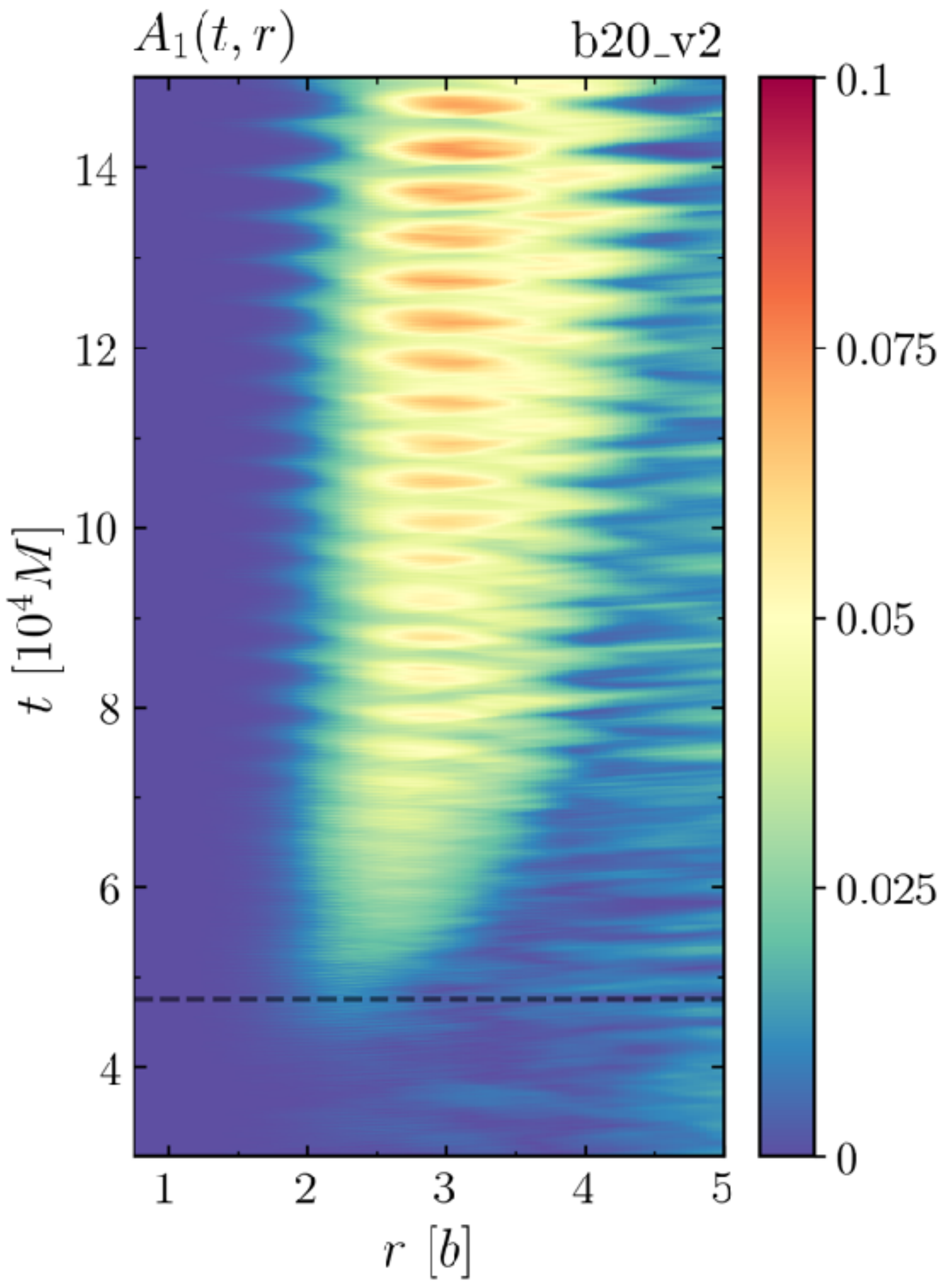
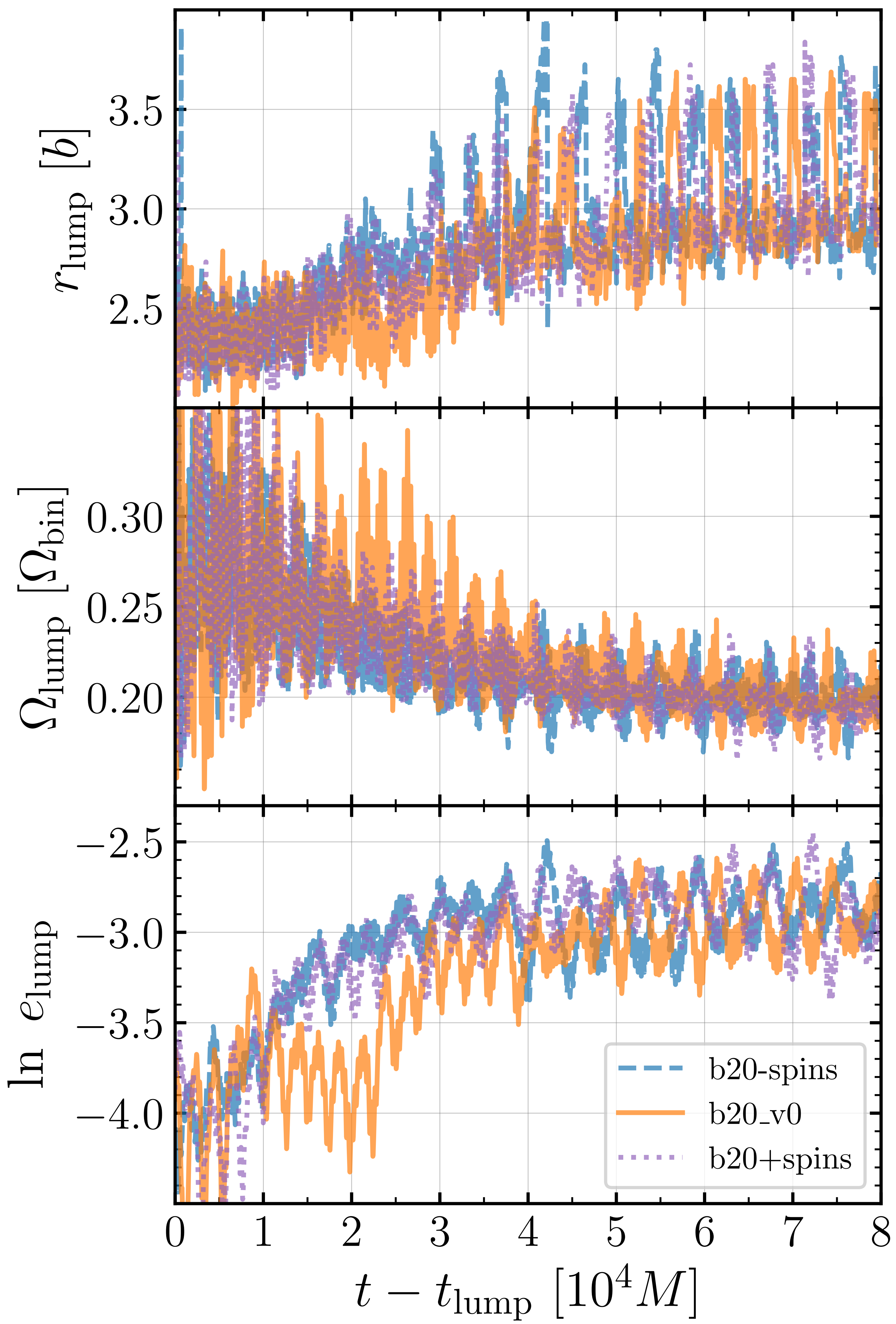


Spacetime diagram of the shell-averaged azimuthal m=1 mode amplitude of density.



- **Lump's orbit stabilizes after ~200 binary orbits;**
- **Lump's frequency is ~ 1/5 of binary's, at the background flow's local Keplerian rate at r_{lump};**
- **Lump gains eccentricity, asymptotic to 0.05,**
- **t_{lump} determined using "lump criterion" already mentioned;**
- **Even though each run yields different t_{lump}, all runs' trends coincide when displayed in reference to t_{lump} .**

—> Transition to lump dominance is stochastic, while subsequent lump dynamics is not.

—> Lump's dynamics is a relatively robust phenomenon.

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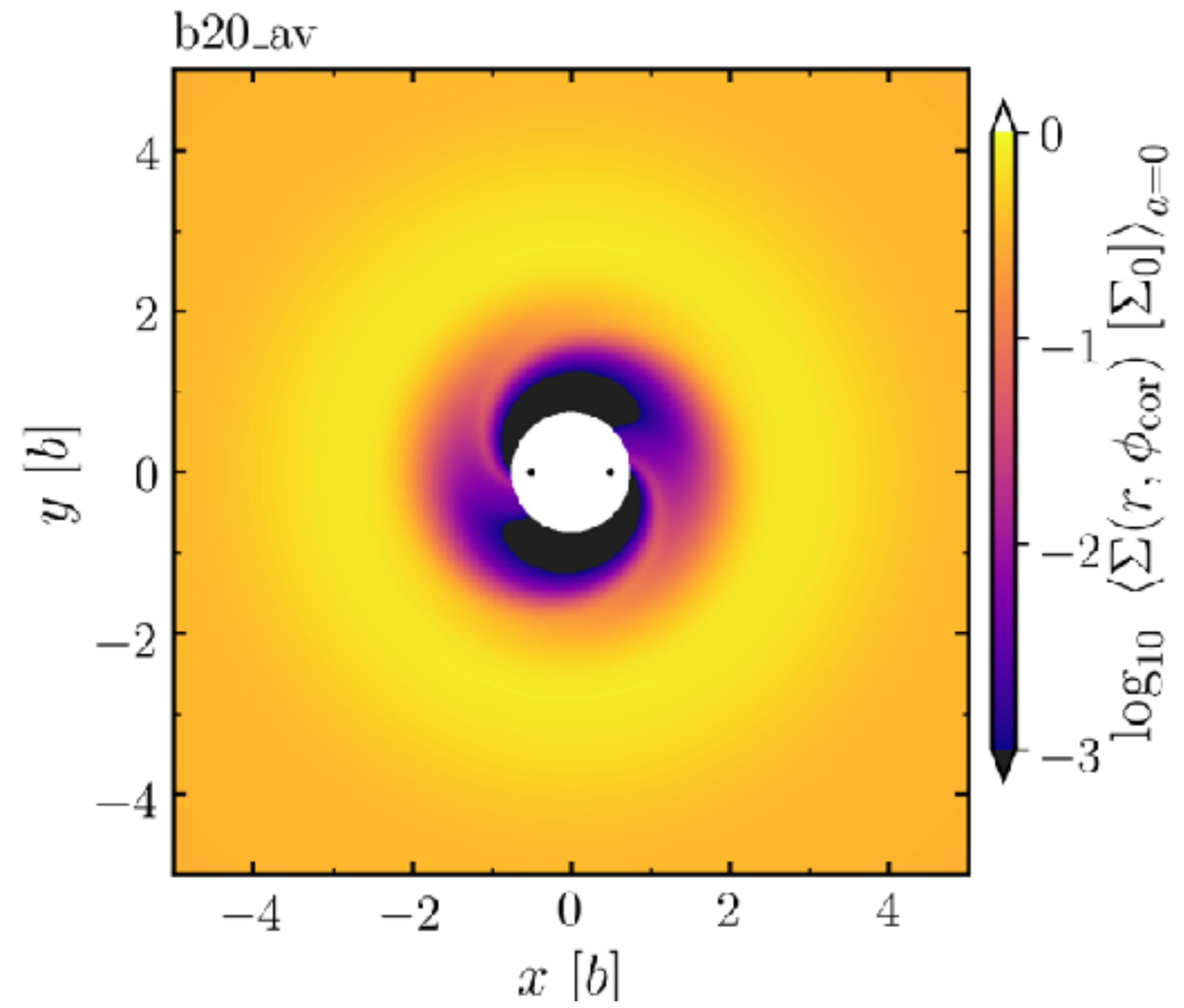
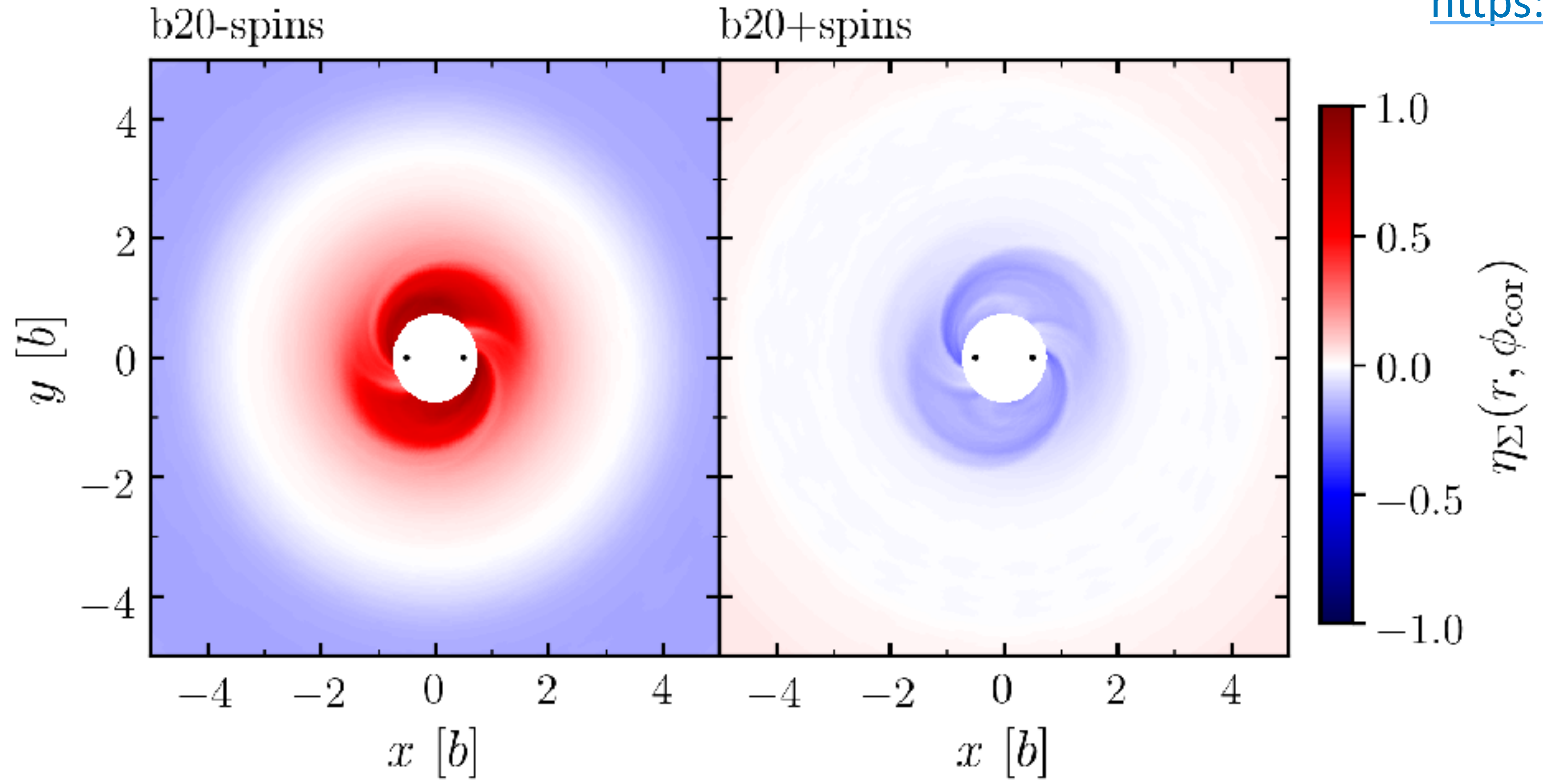
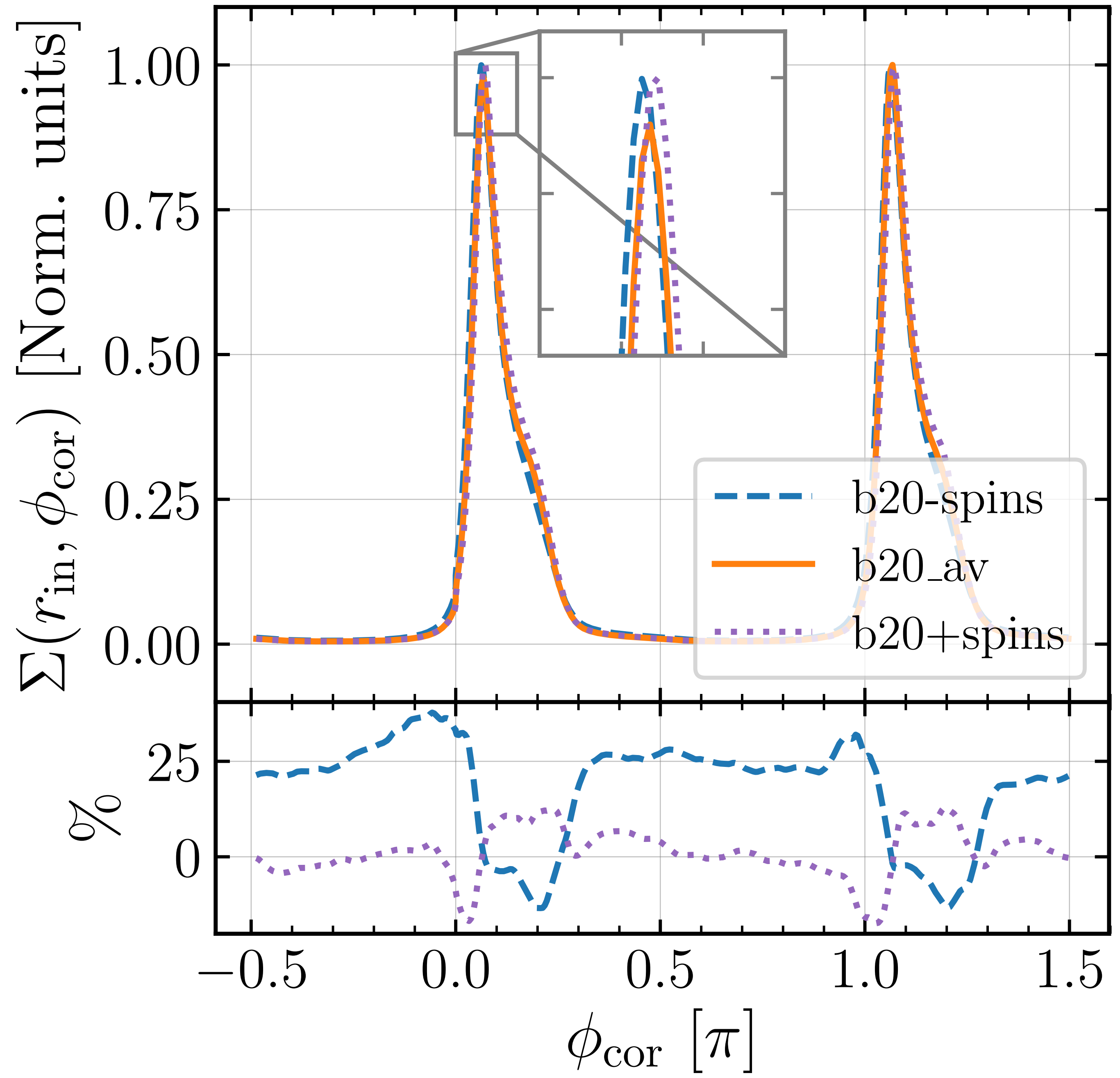






	Accretion Rate	Luminosity
Parallel Spins	86%	88%
Non-spinning	100%	100%
Anti-parallel Spins	145%	129%

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

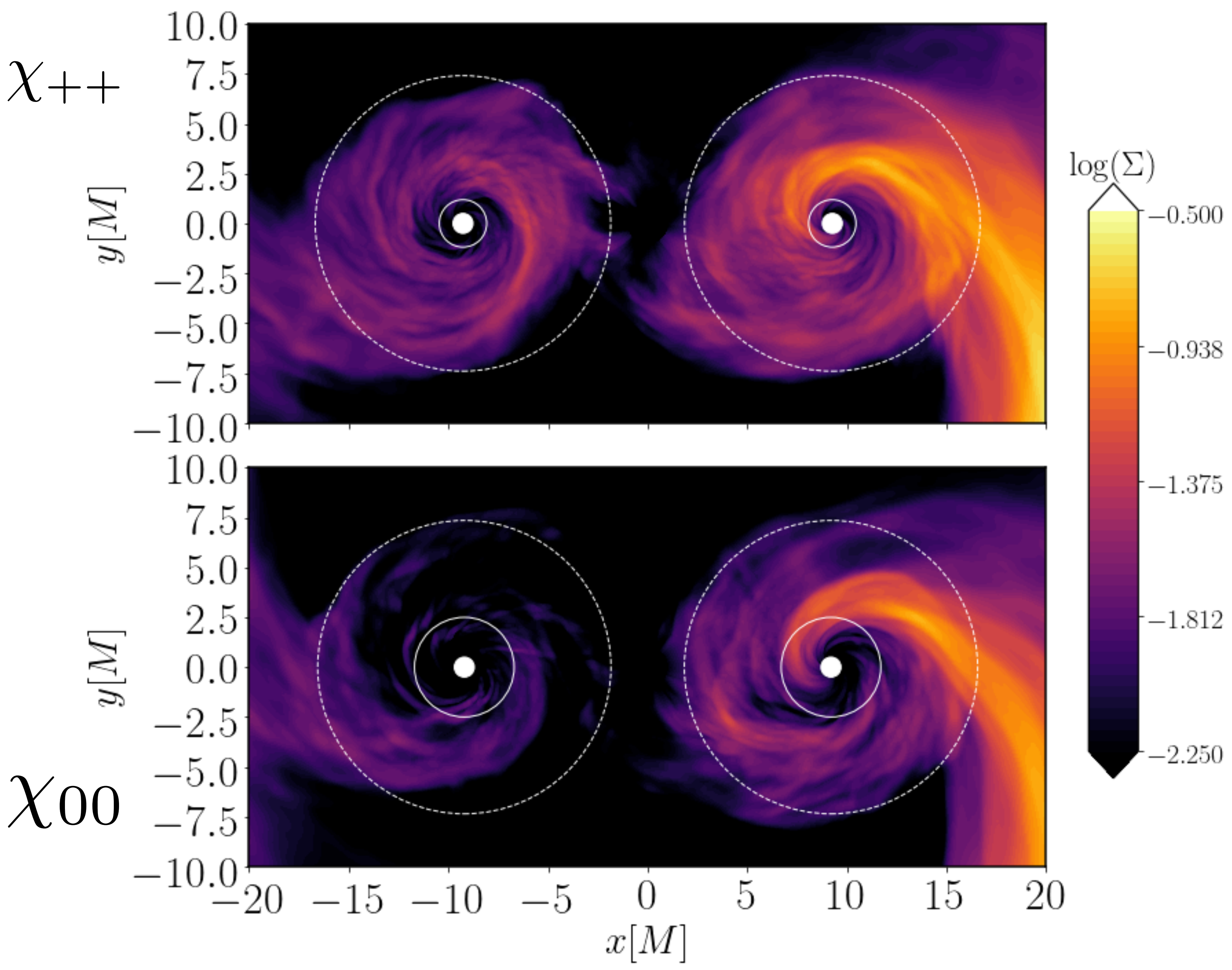
$$\Phi_{\rm Eff} = -\frac{M}{r} - \frac{1}{16}\frac{b^2 M}{r^3} + \frac{J^2}{2r^2} + \frac{MJ}{3r^3}\left(2a + \frac{L}{4}\right)$$

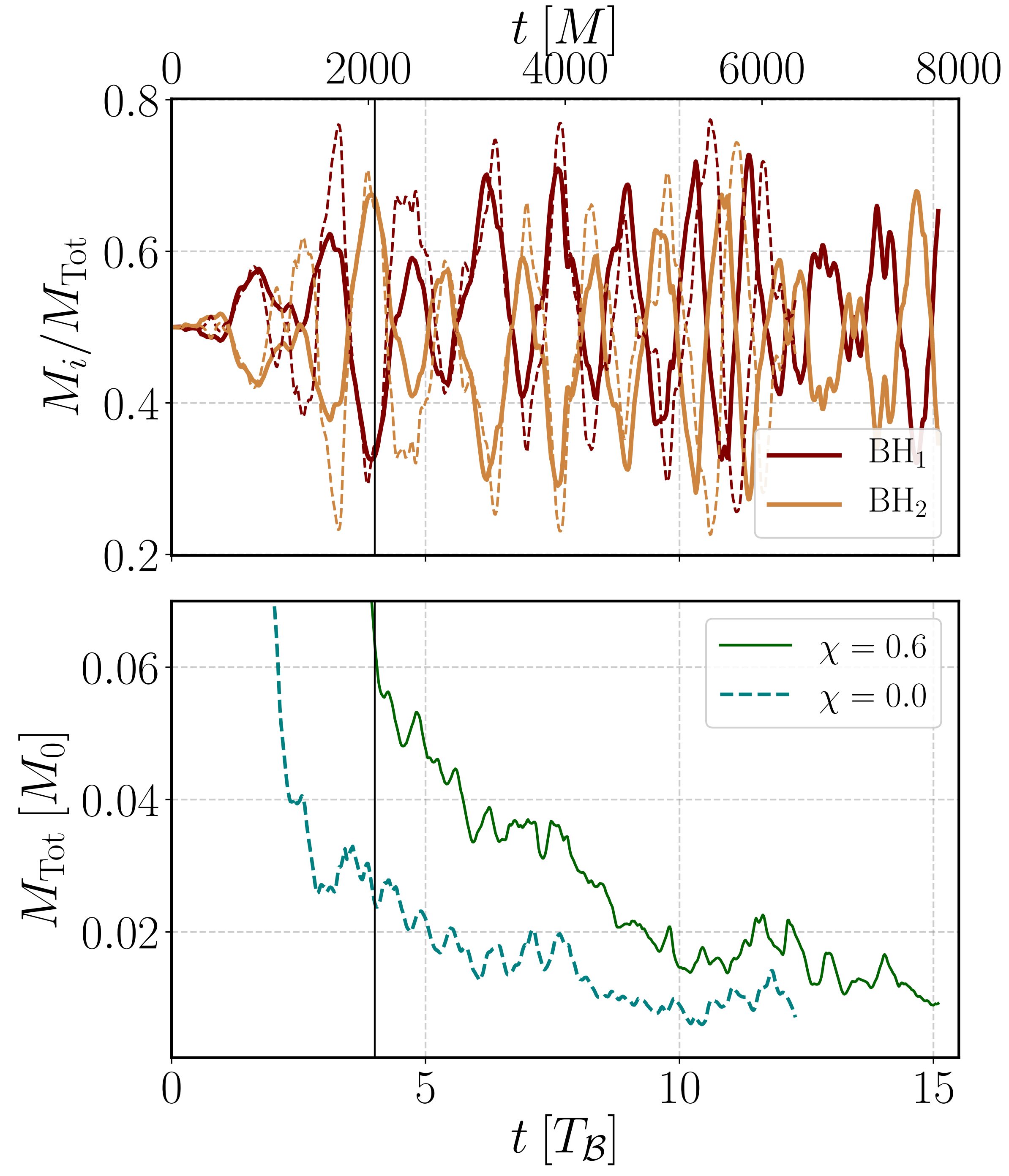
- **Frame dragging acts to lag (lead) accretion streams for anti-parallel (parallel) spins;**

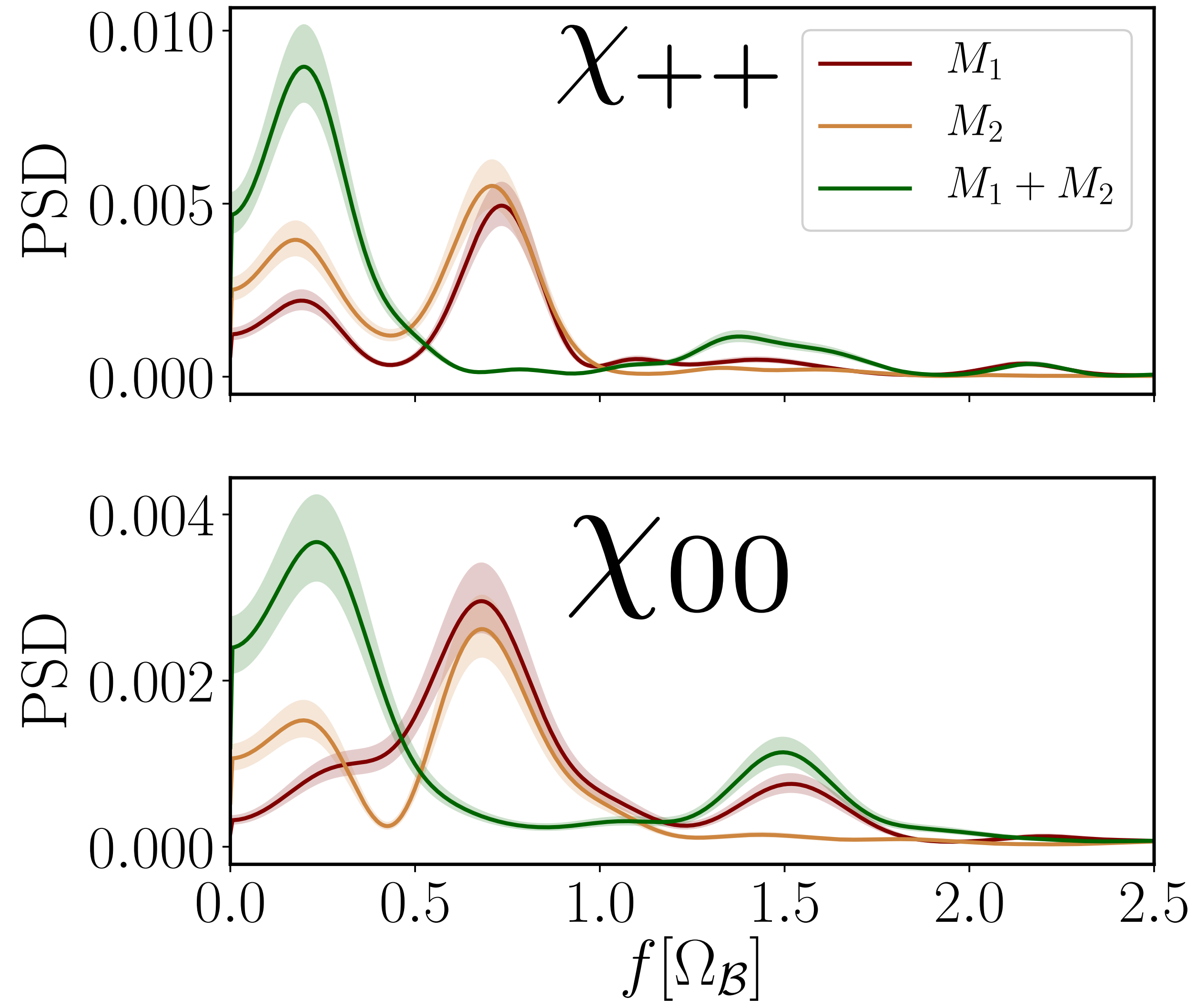
Accretion onto Spinning BBHs

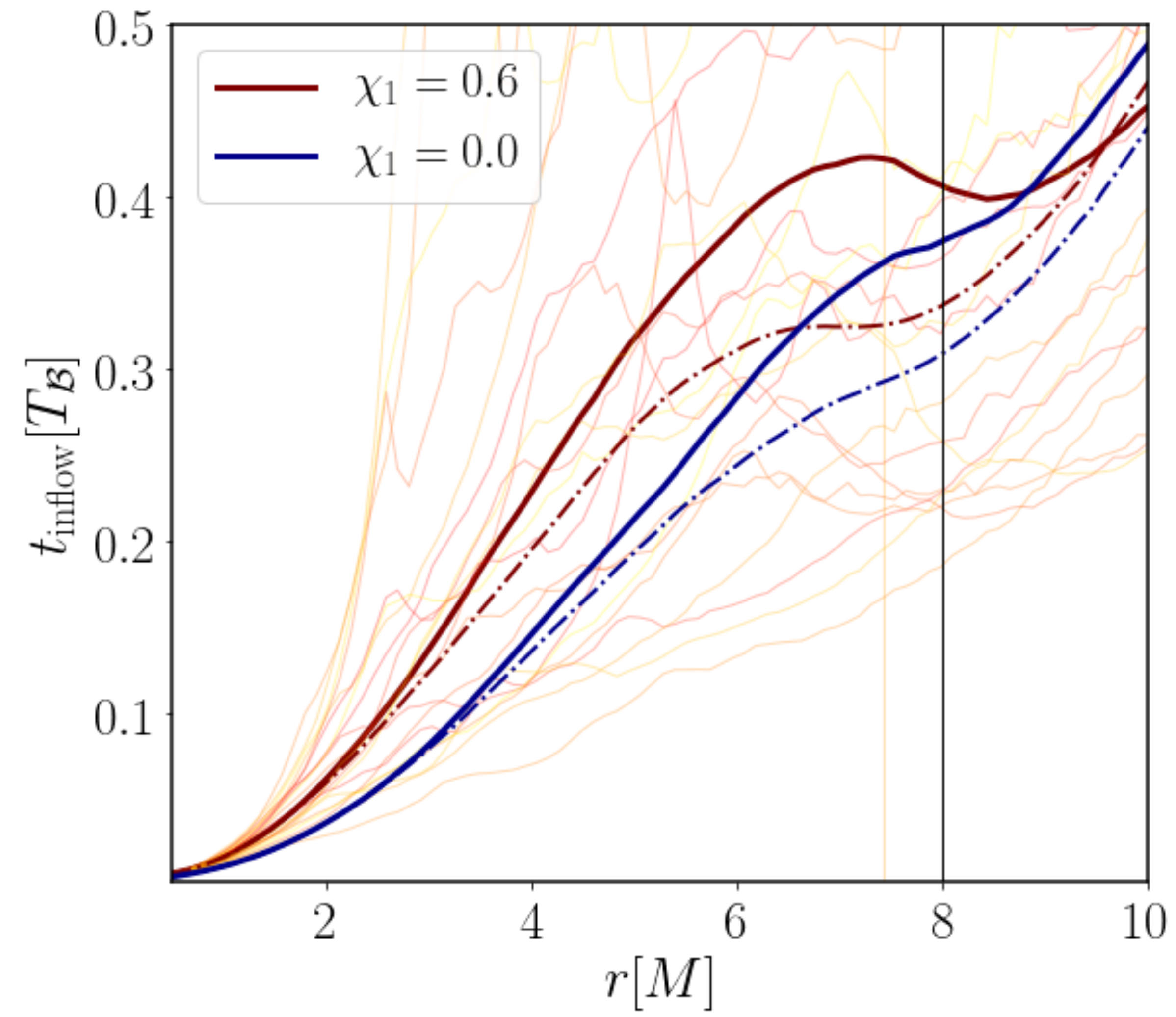
Circumbinary + Mini- Disk Regions

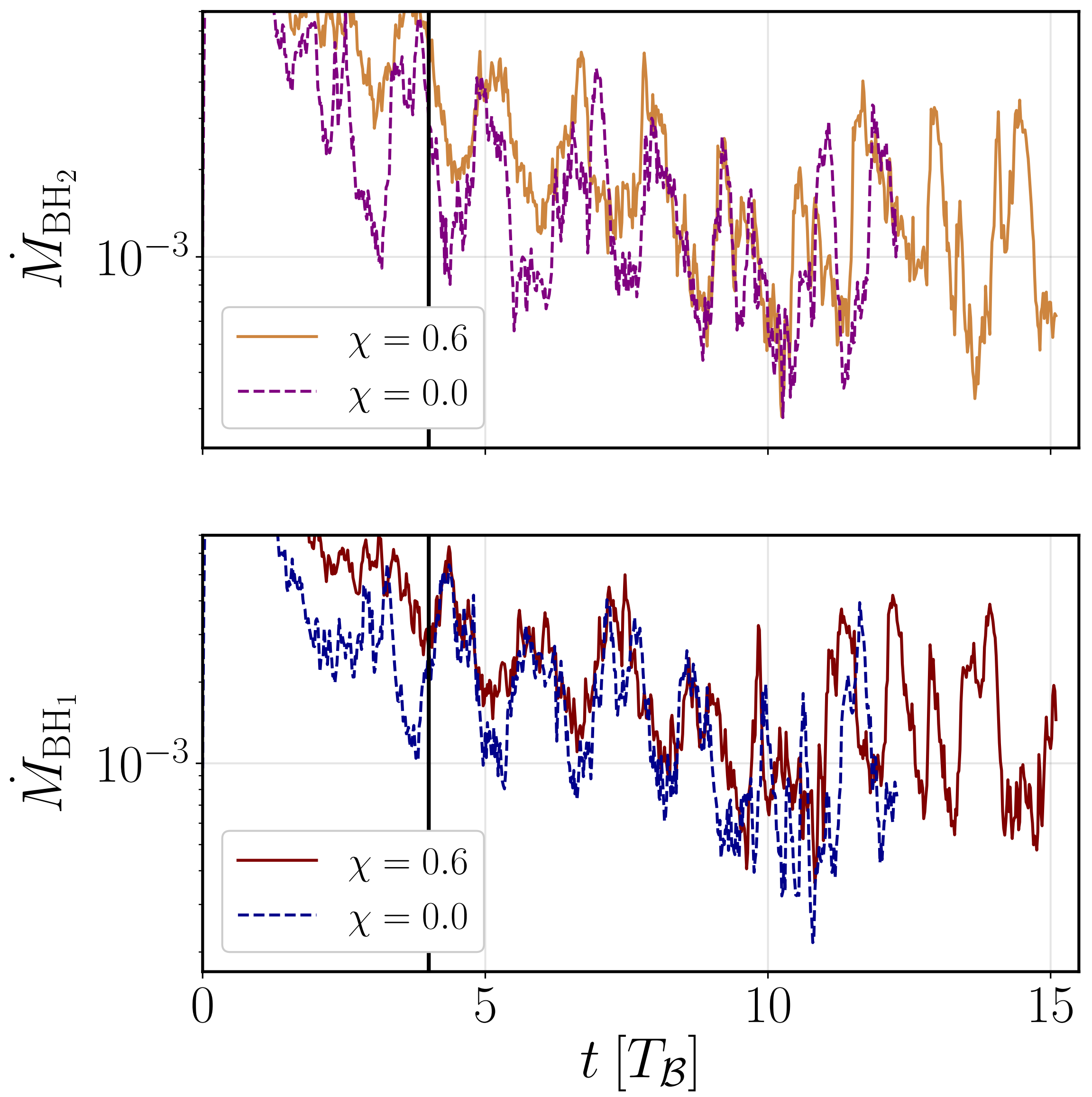
Combi, Lopez Armengol, (in prep, 2021)











$\chi = +0.6$

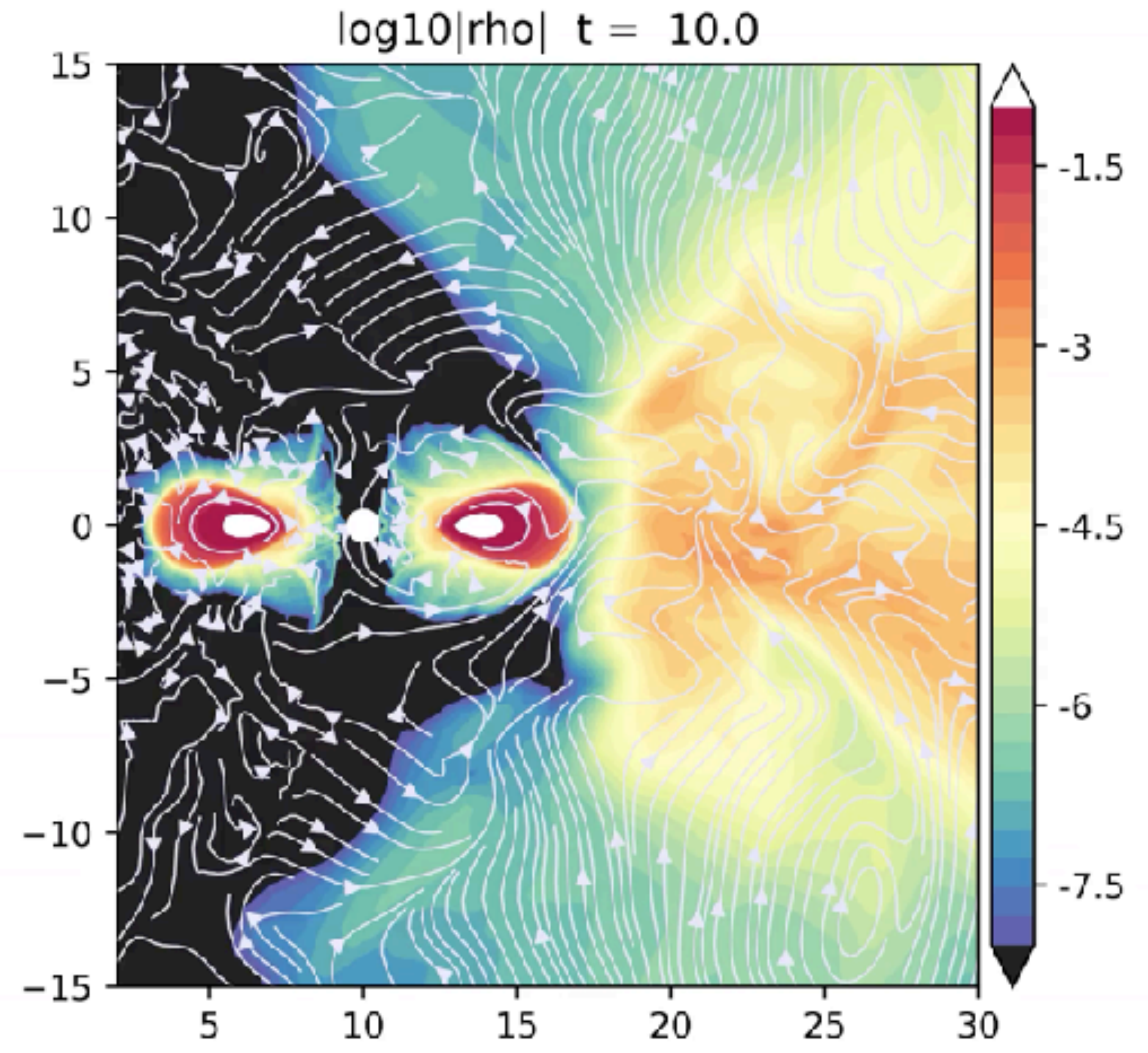
- **Starting from same initial accretion flow conditions;**
- **Because of smaller ISCO, the volume of stability in mini-disk region increases for larger (parallel) spin;**
  - **—>More persistent mini-disks;**
  - **—> Longer inflow time scales;**
  - **—> Comparable accretion rates;**
  - **—> Smaller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

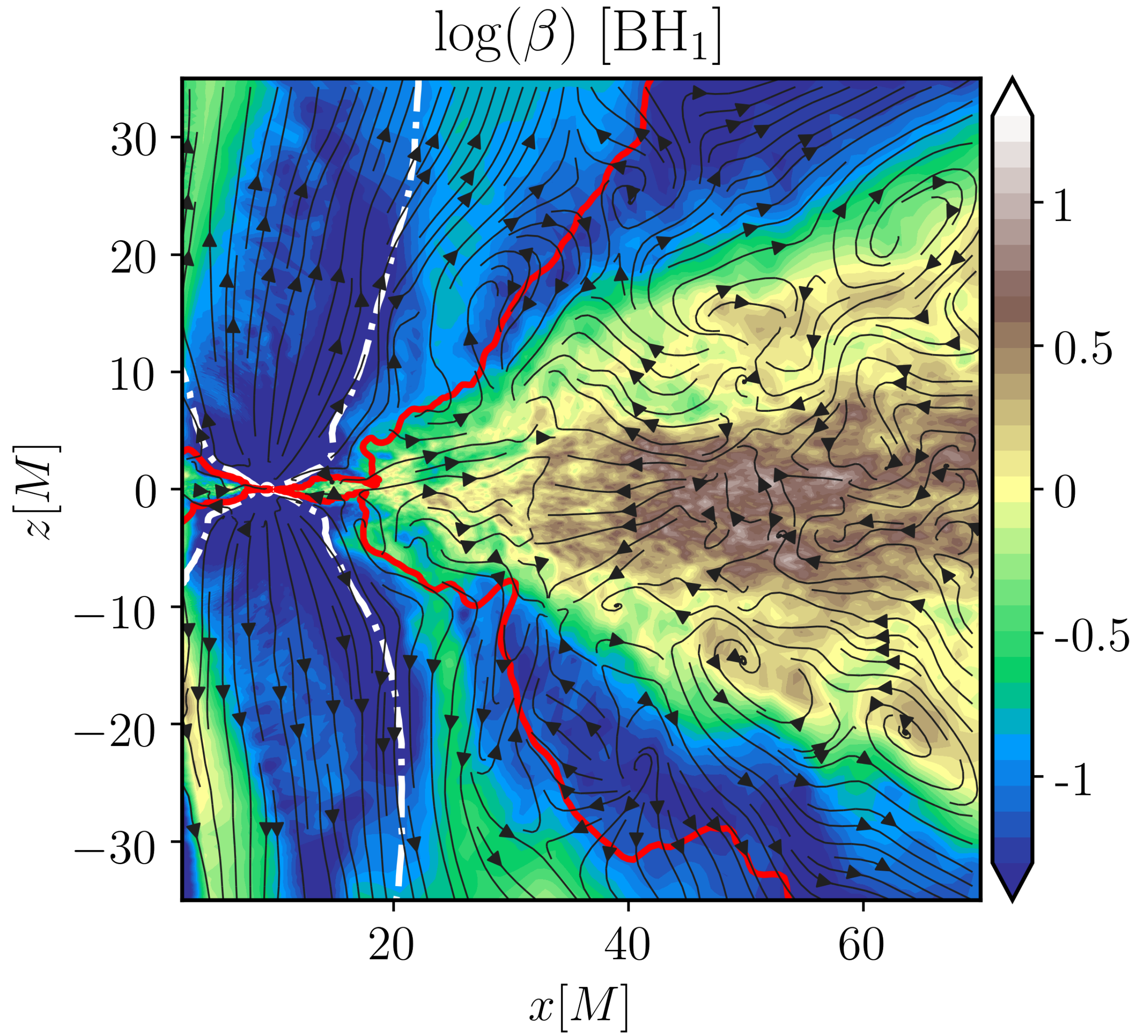
Accretion onto Spinning BBHs

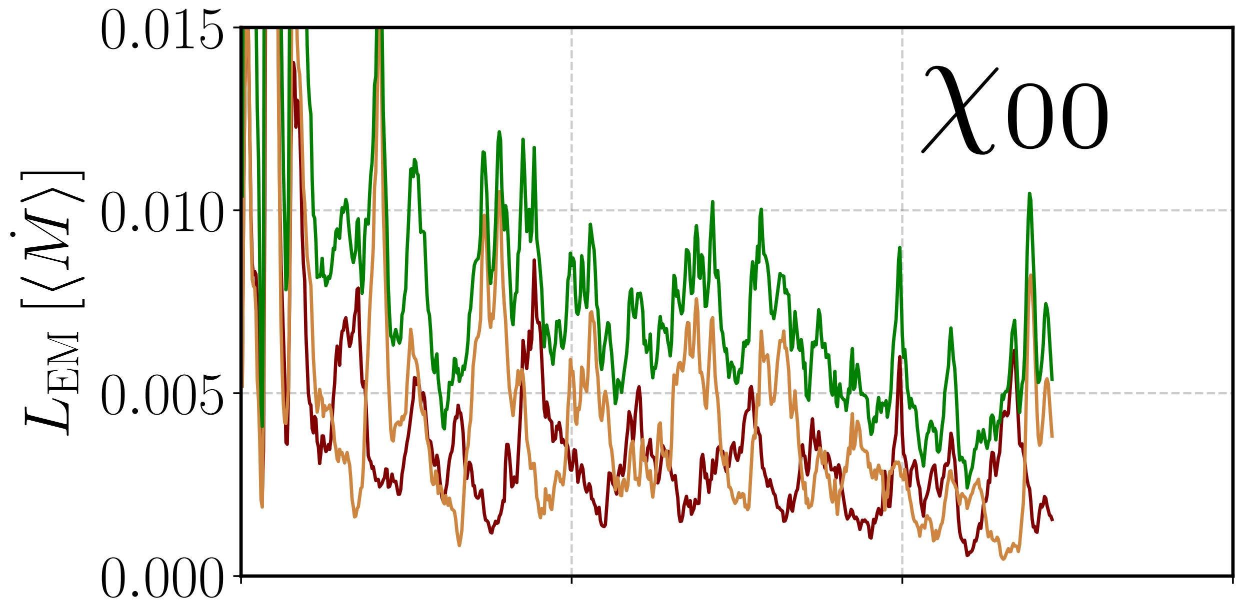
Circumbinary + Mini- Disk Regions

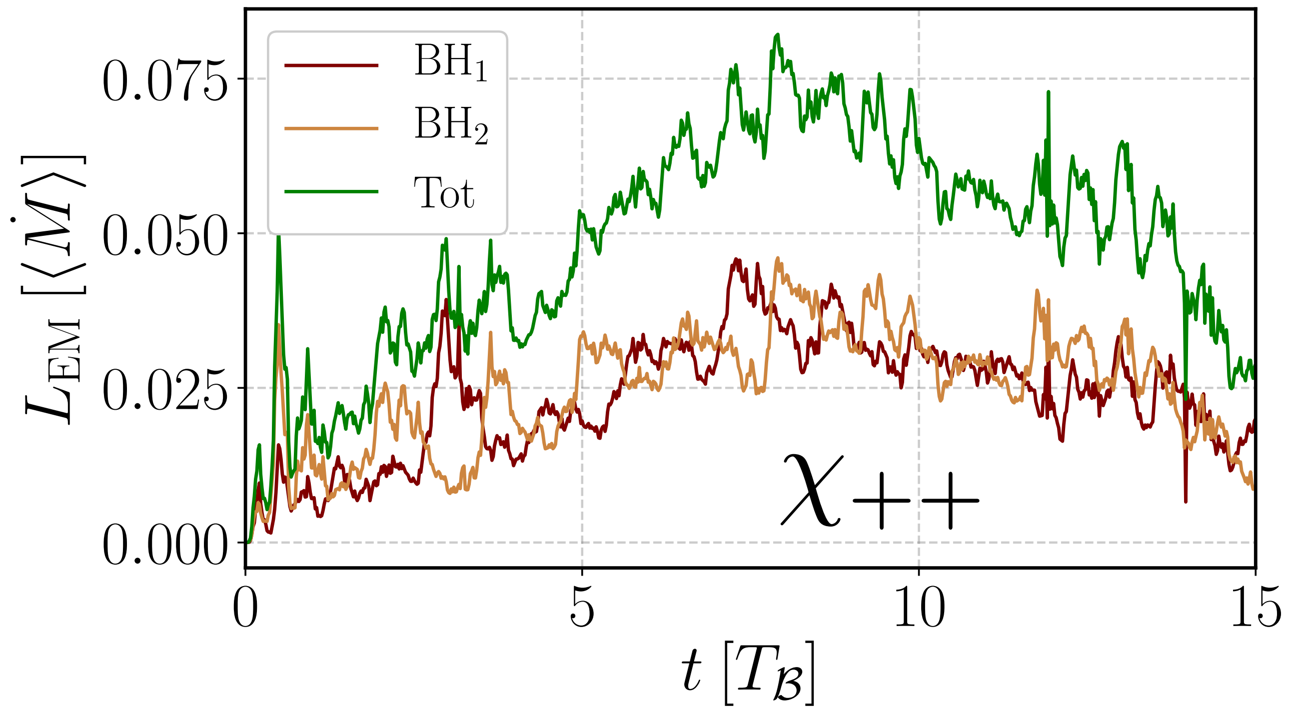
Poynting Scalar

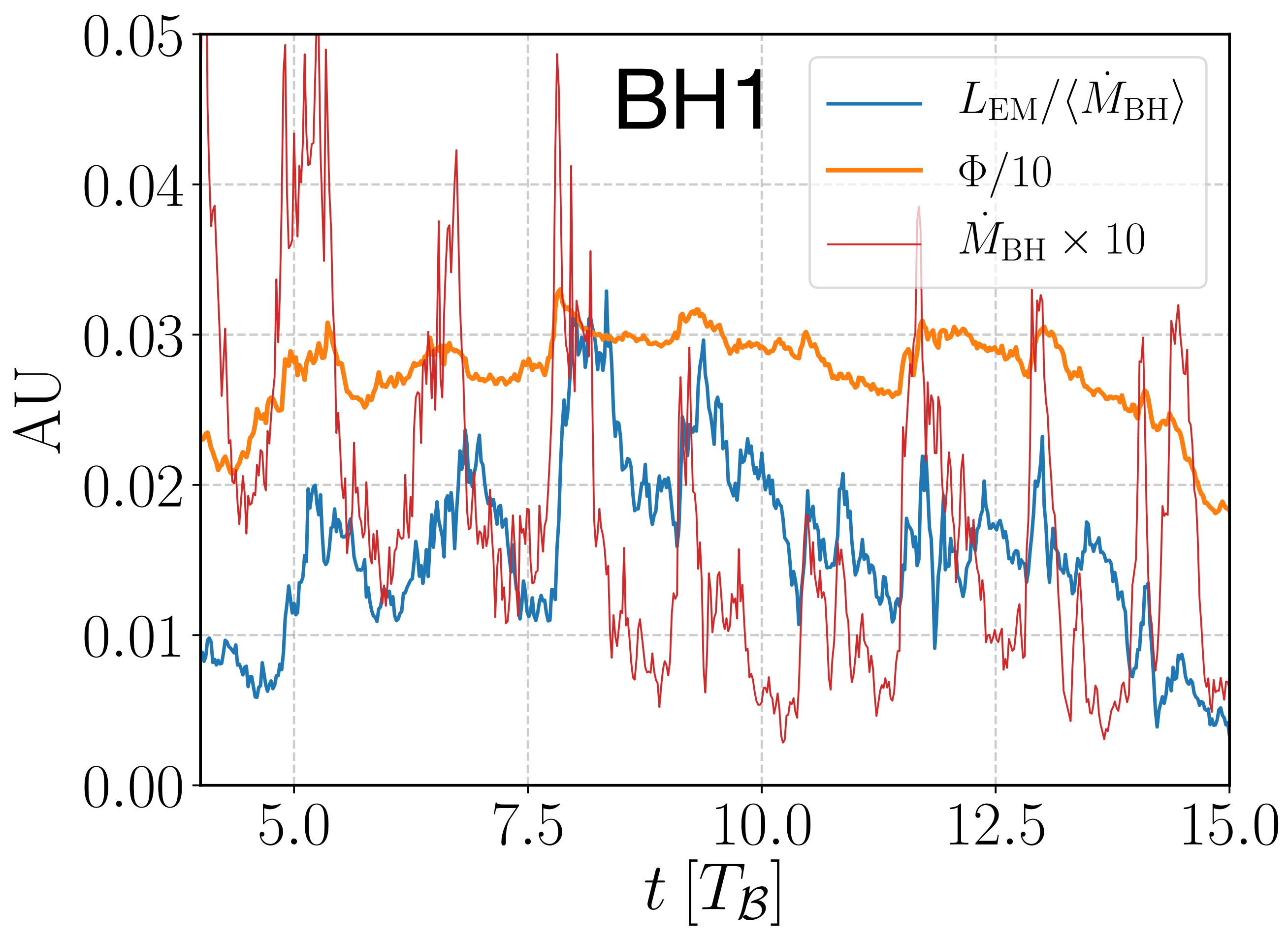
Combi, Lopez Armengol, (in prep, 2021)

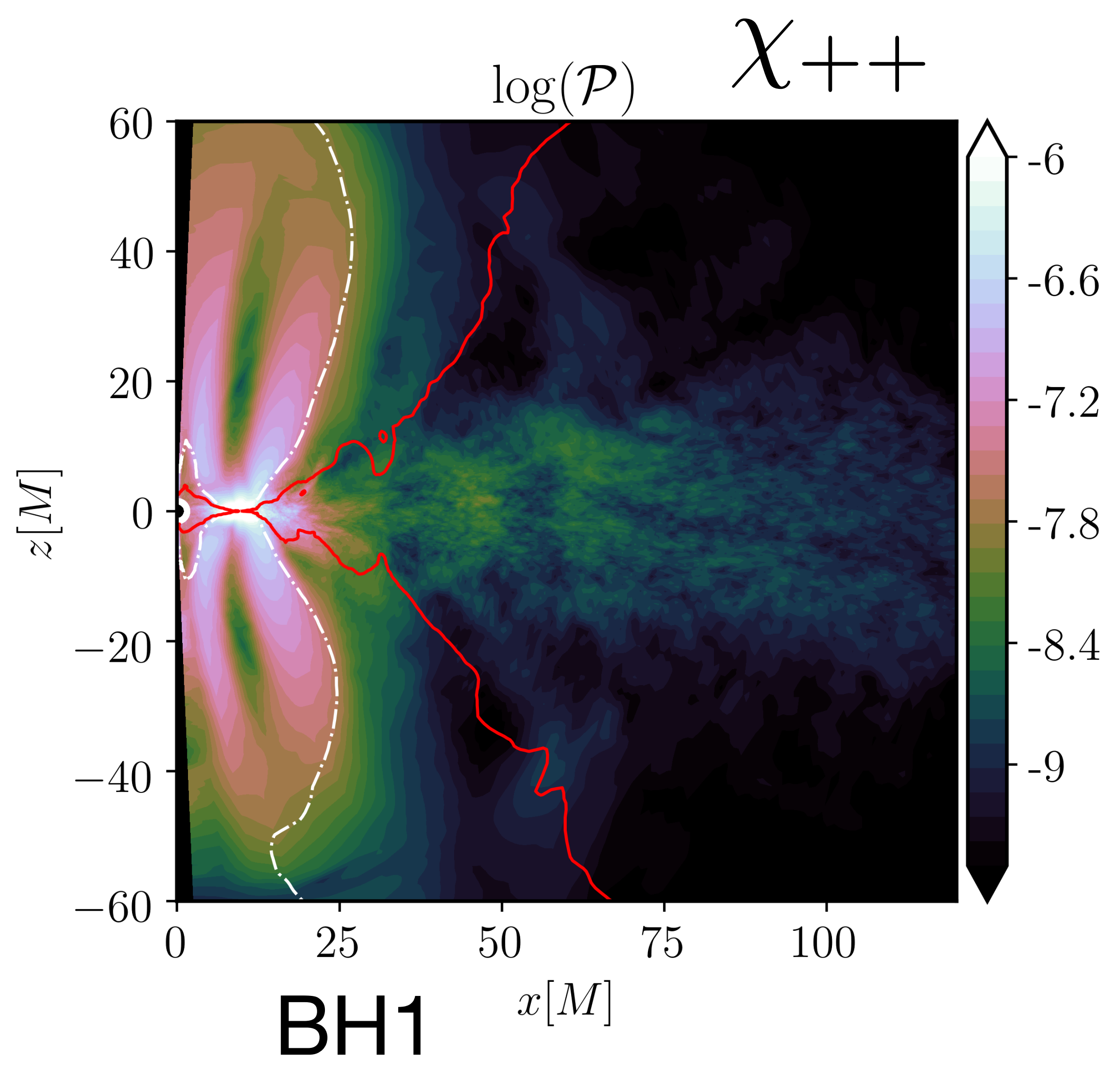


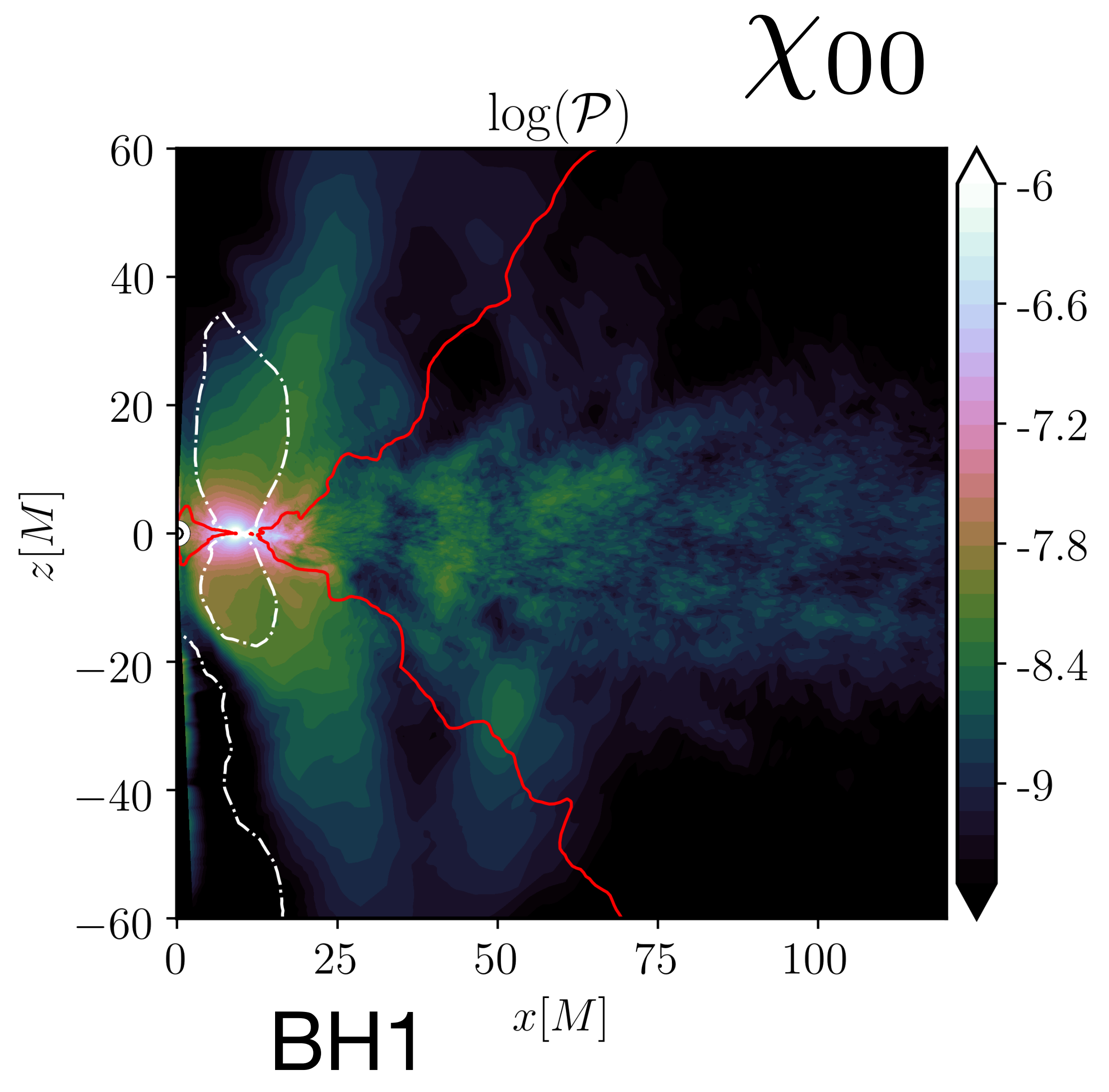












Spinning black holes launch jets!

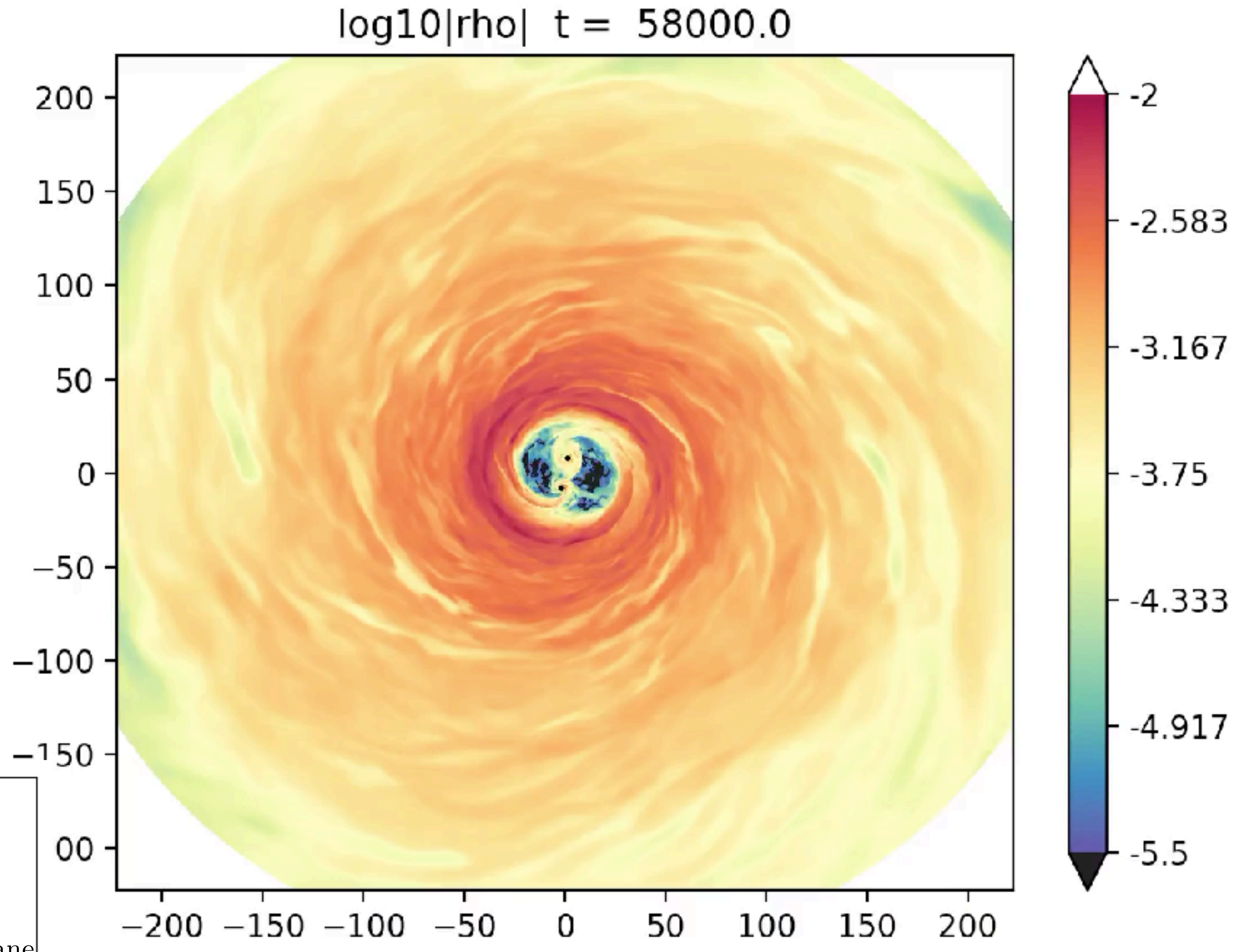
- **BH jets are powerful radio sources;**
  - **Possible signature of helical field orientation in emission's polarization?!**
- **Poynting luminosity modulated by accretion rate from circumbinary disk and accreted magnetic field flux;**
- **All sorts of exciting possibilities with binary jet dynamics!**

PatchworkMHD : Mini-disks + Circumbinary Disk

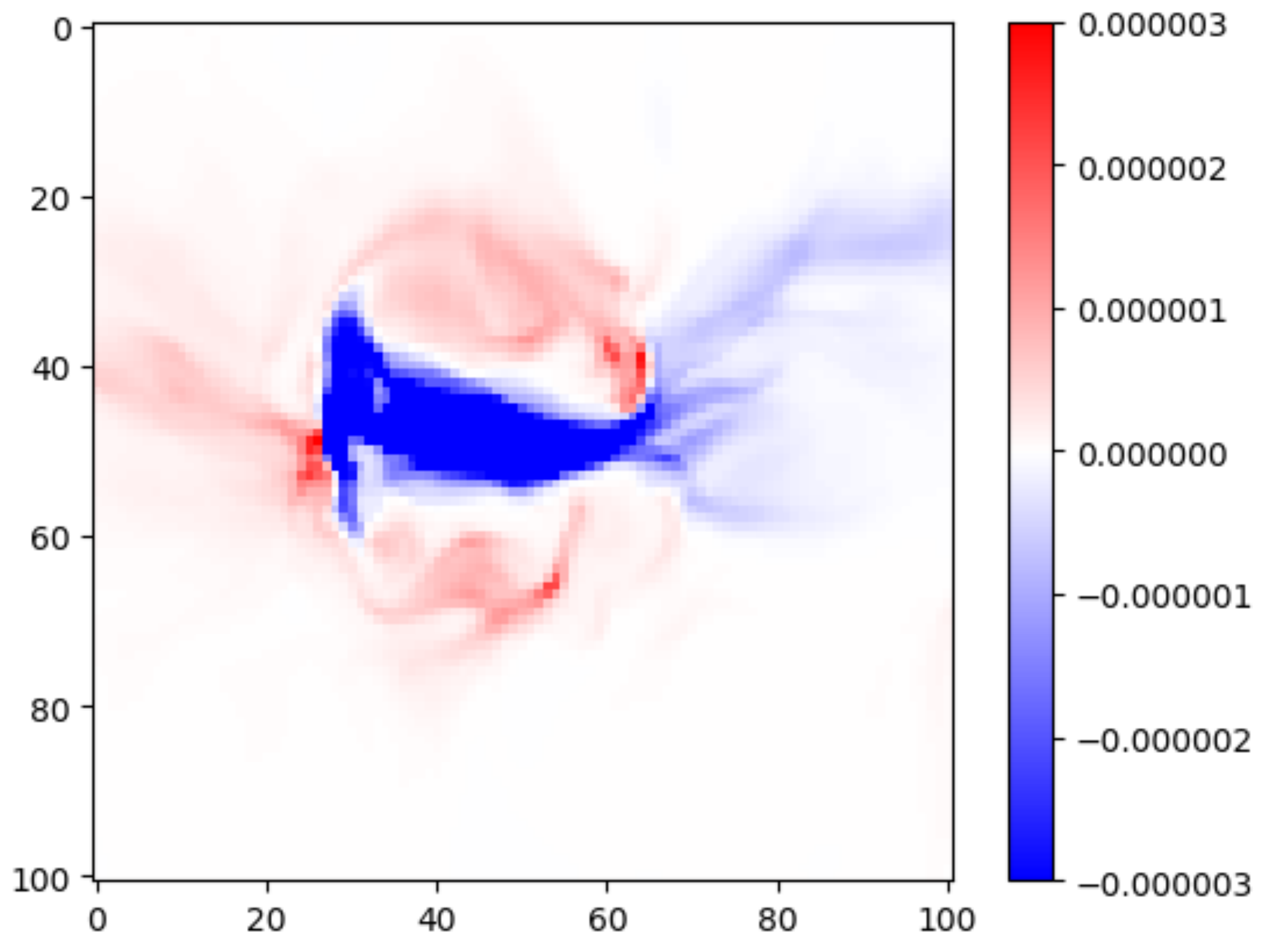
Avara et. al, (in prep)

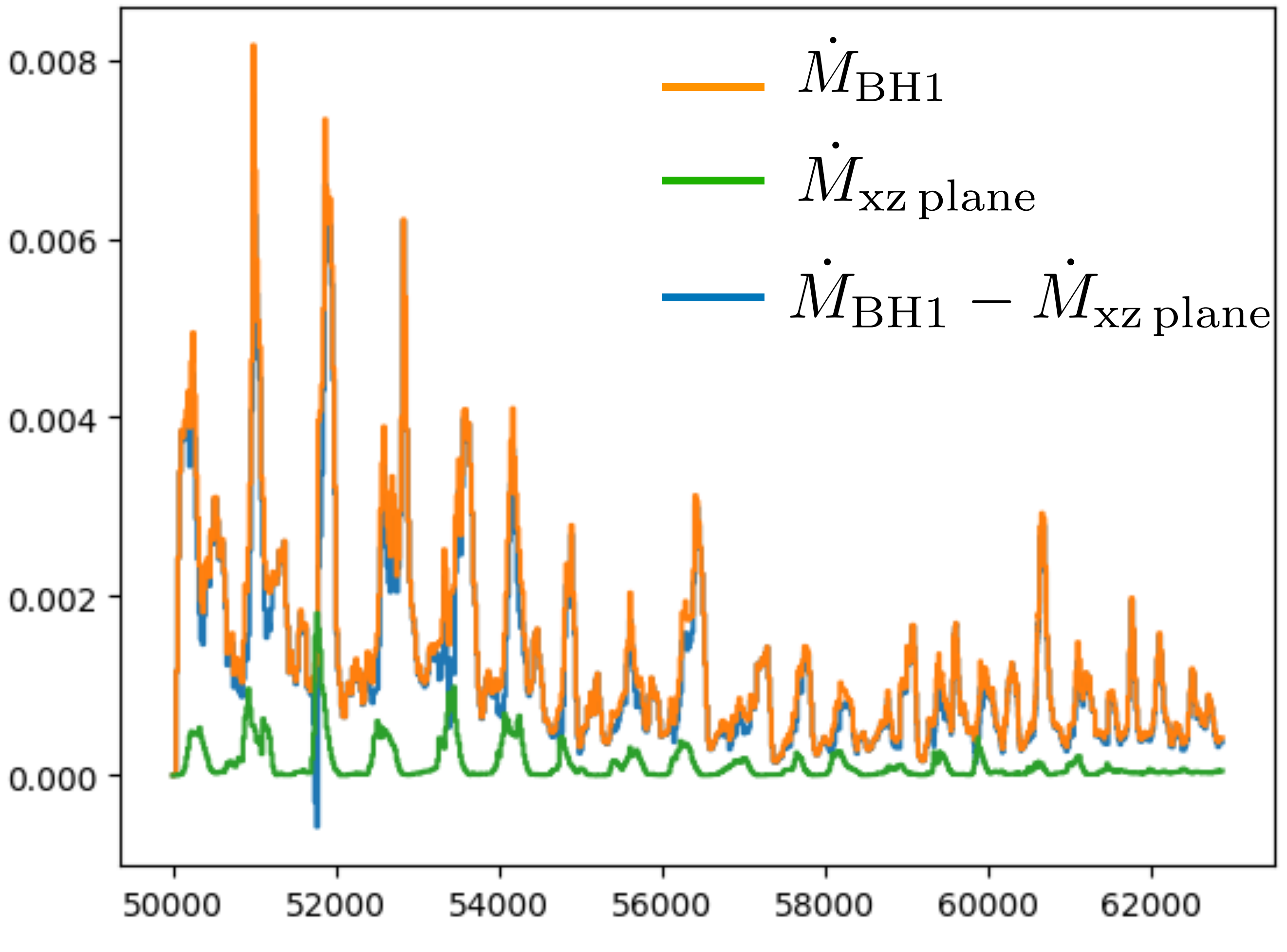
Avara @APS: H09.00006

- 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



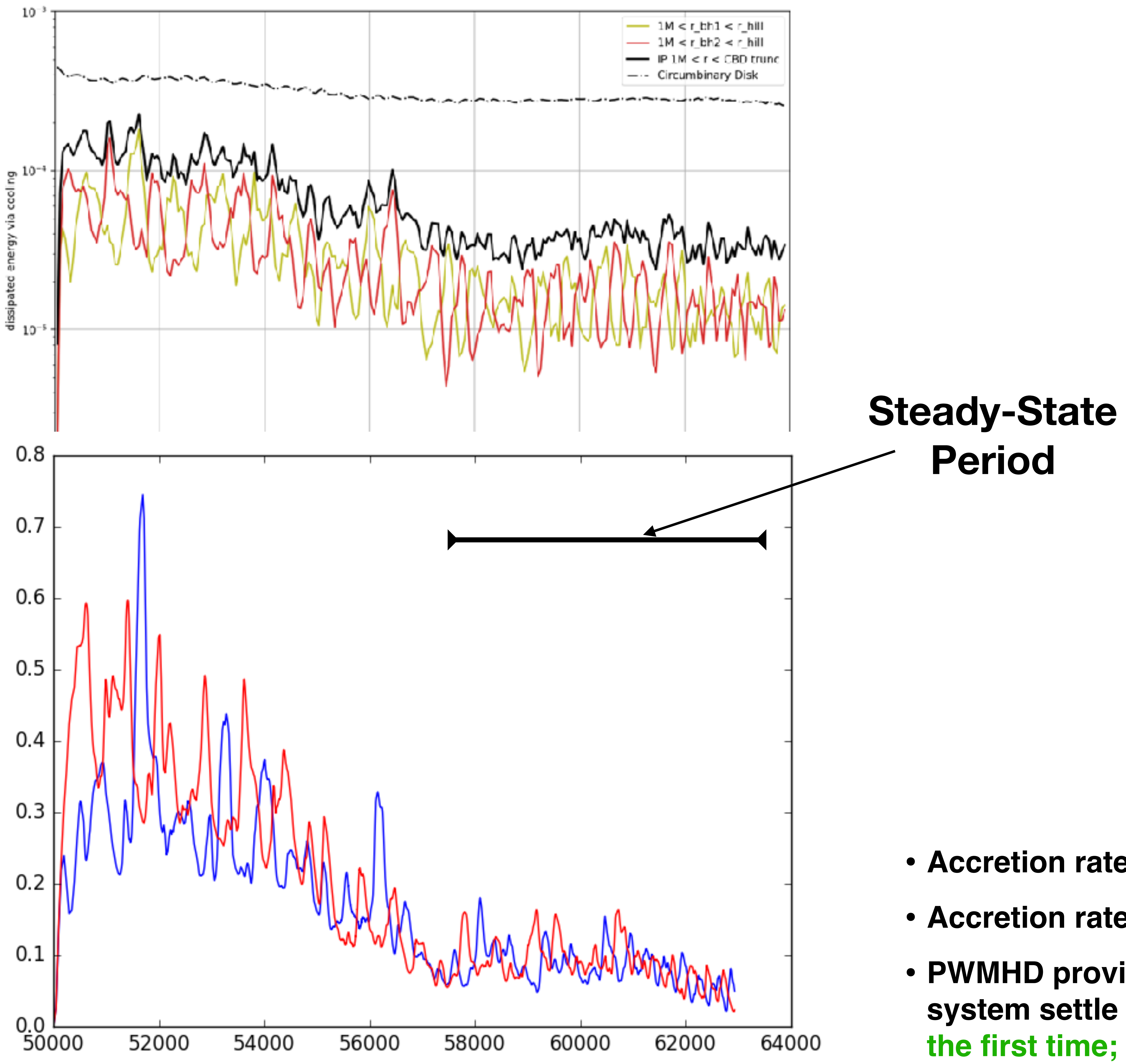


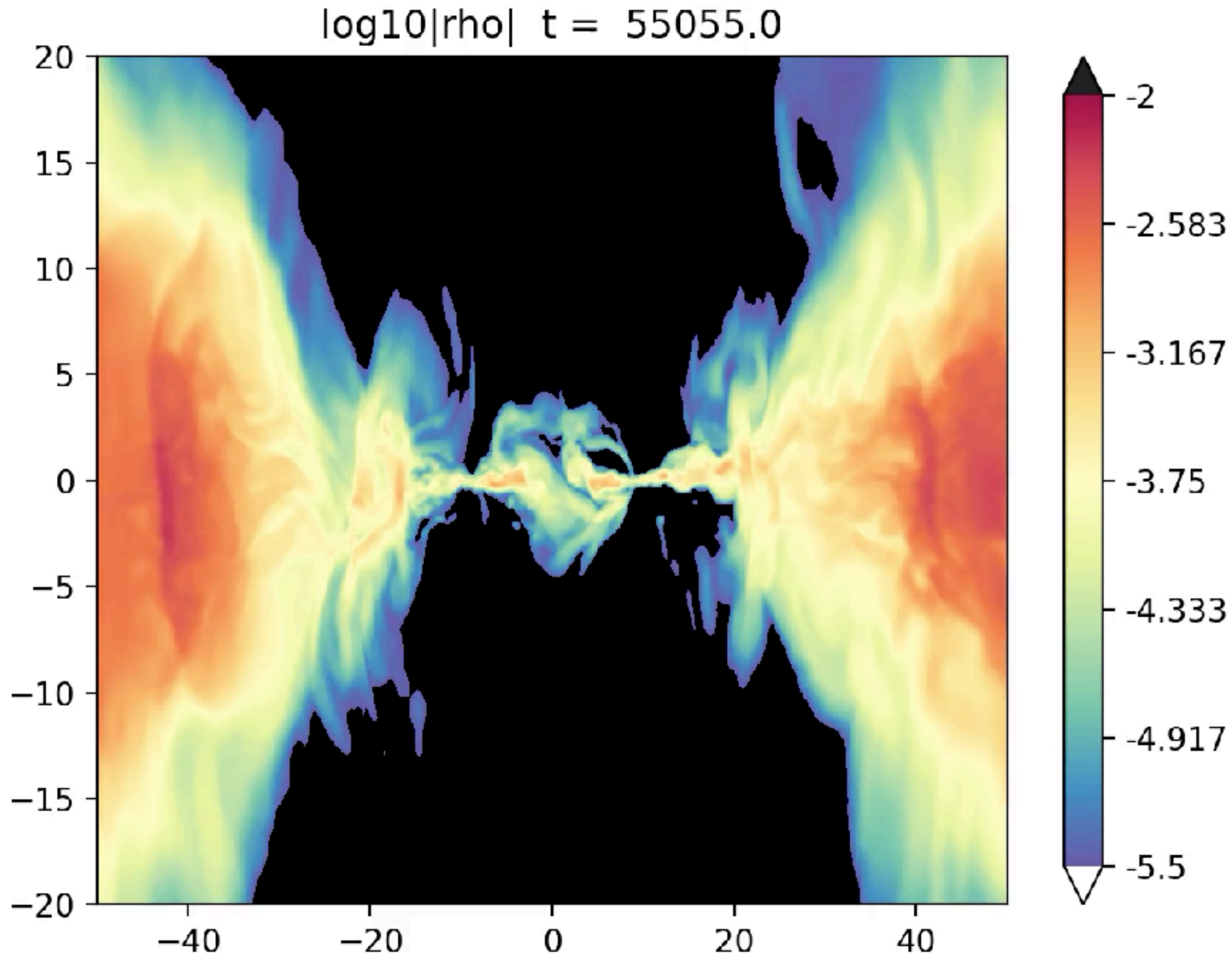
- No cutout!
  - PWMHD allows us to measure the mass exchange between mini-disks for the first time!
  - Mass flux between mini-disks is a minority contribution, though energy dissipated by mass transfer may be more significant;vers the missing volume.

PatchworkMHD : Mini-disks + Circumbinary Disk

Avara et. al, (in prep)

Avara @APS: H09.00006





- **Accretion rate onto each BH modulated by their passage near the lump.**
- **Accretion rate still significant even while BBH rapidly inspirals.**
- **PWMHD provides the affordability to runs for the O(30-40) orbits necessary to let the system settle into a steady-state, providing light curves from relaxed mini-disks for the first time;**

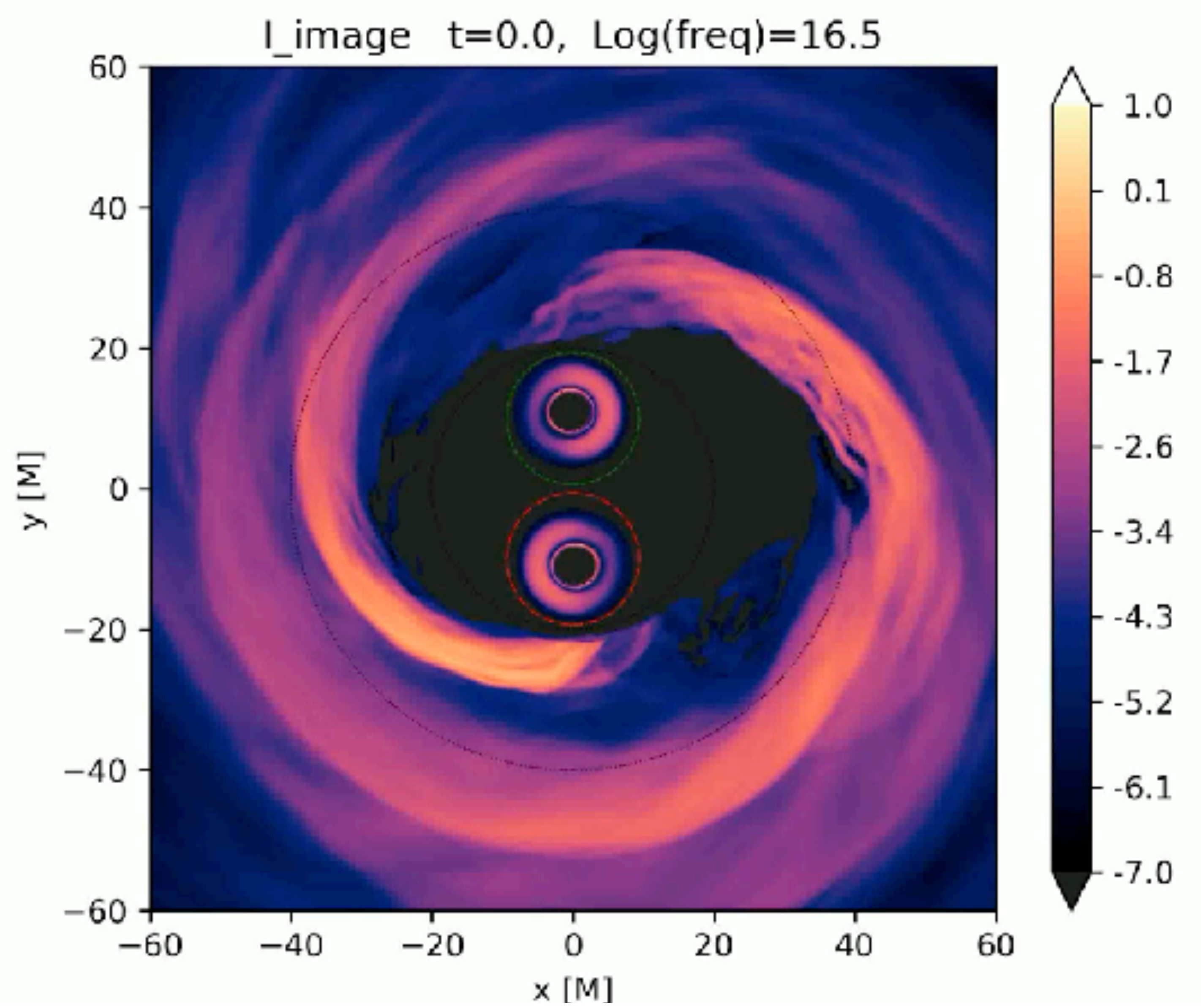
Light Curves from Accretion onto Spinning BBHs

- **Following** d'Ascoli++2018
- **Using sim data from:** Combi, Lopez Armengol, (in prep, 2021)
- **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;**

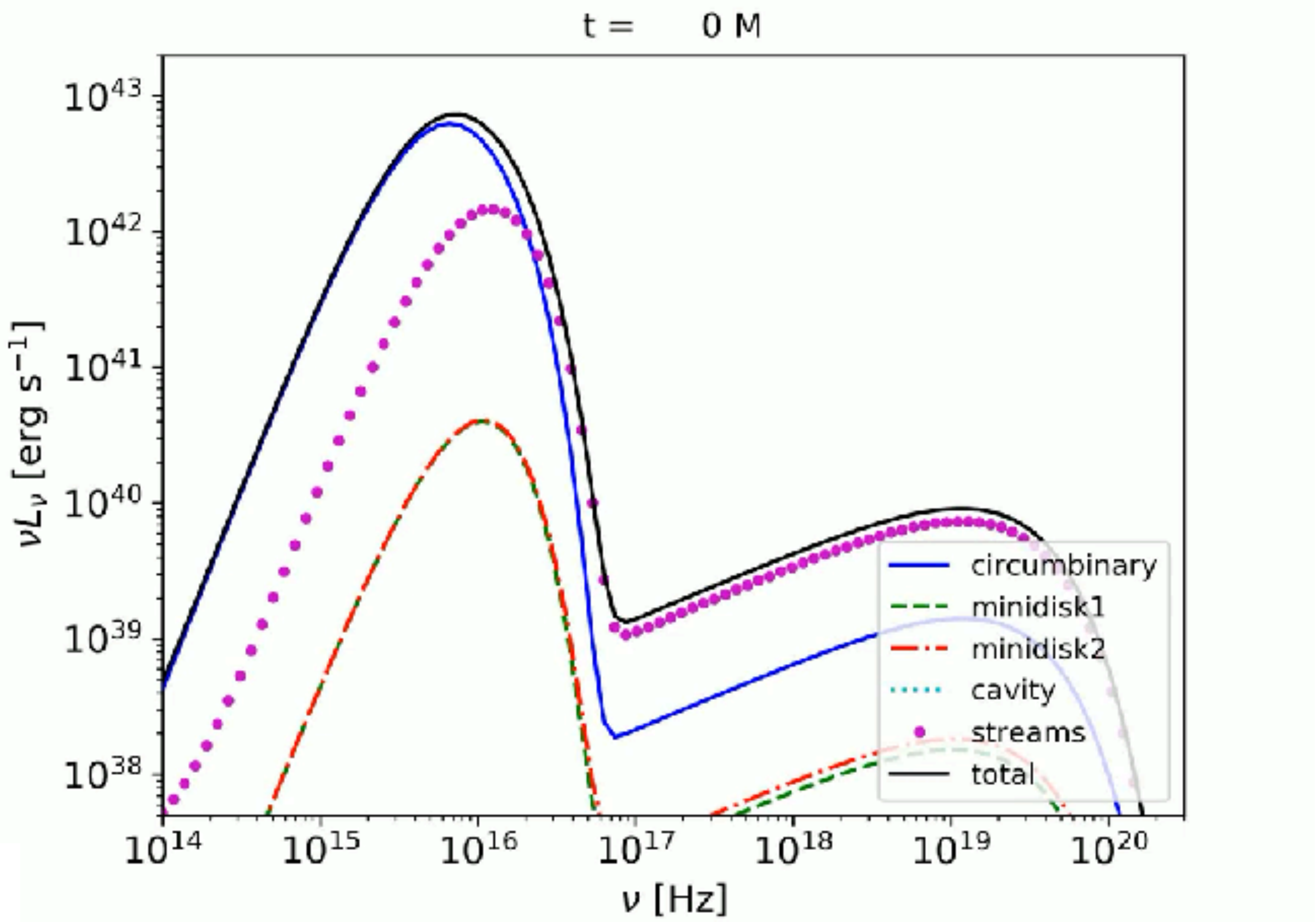
- **The spinning case provides new signatures to search for:**
  - **Broaden thermal peak in optical-UV;**
  - **Variability in the UV on the binary's orbital timescale;**
  - **Stronger variability in X-rays;**

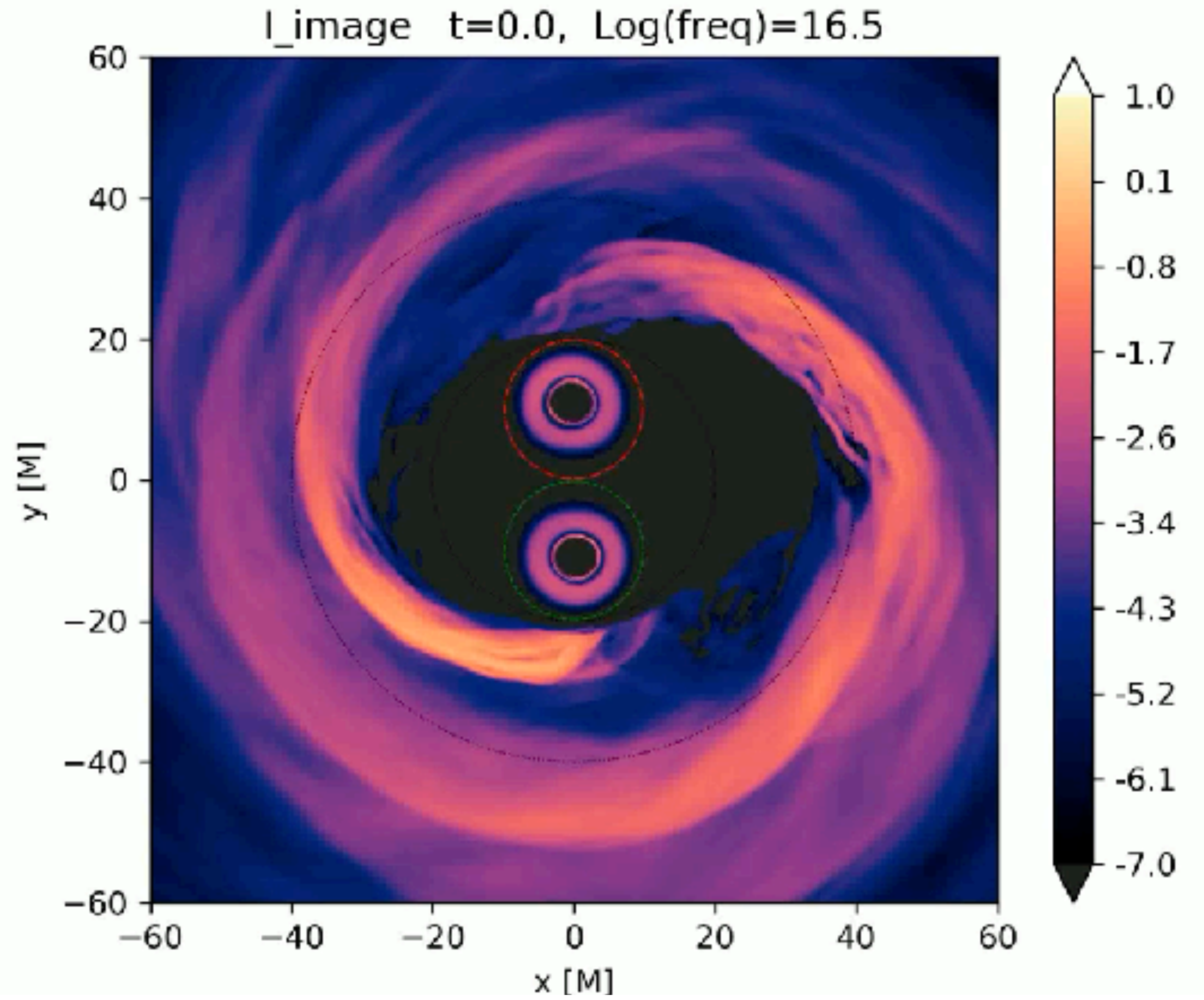
- **We expect SMBBHs, especially in gaseous environments, to be spinning even faster, these effects may be even stronger in real systems.**

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

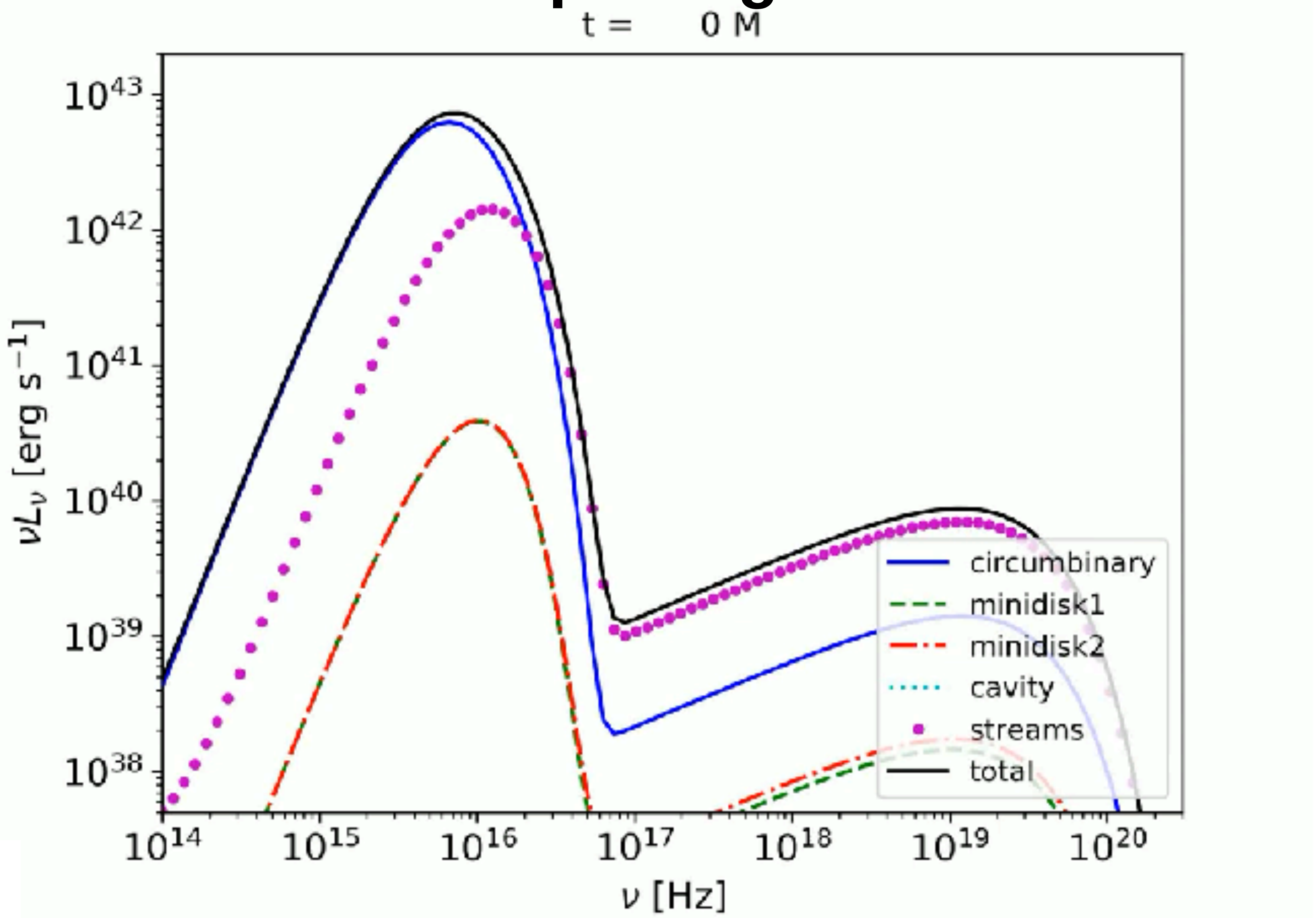


Spinning BBHs: a=0.6M, up-up





Non-Spinning BBHs

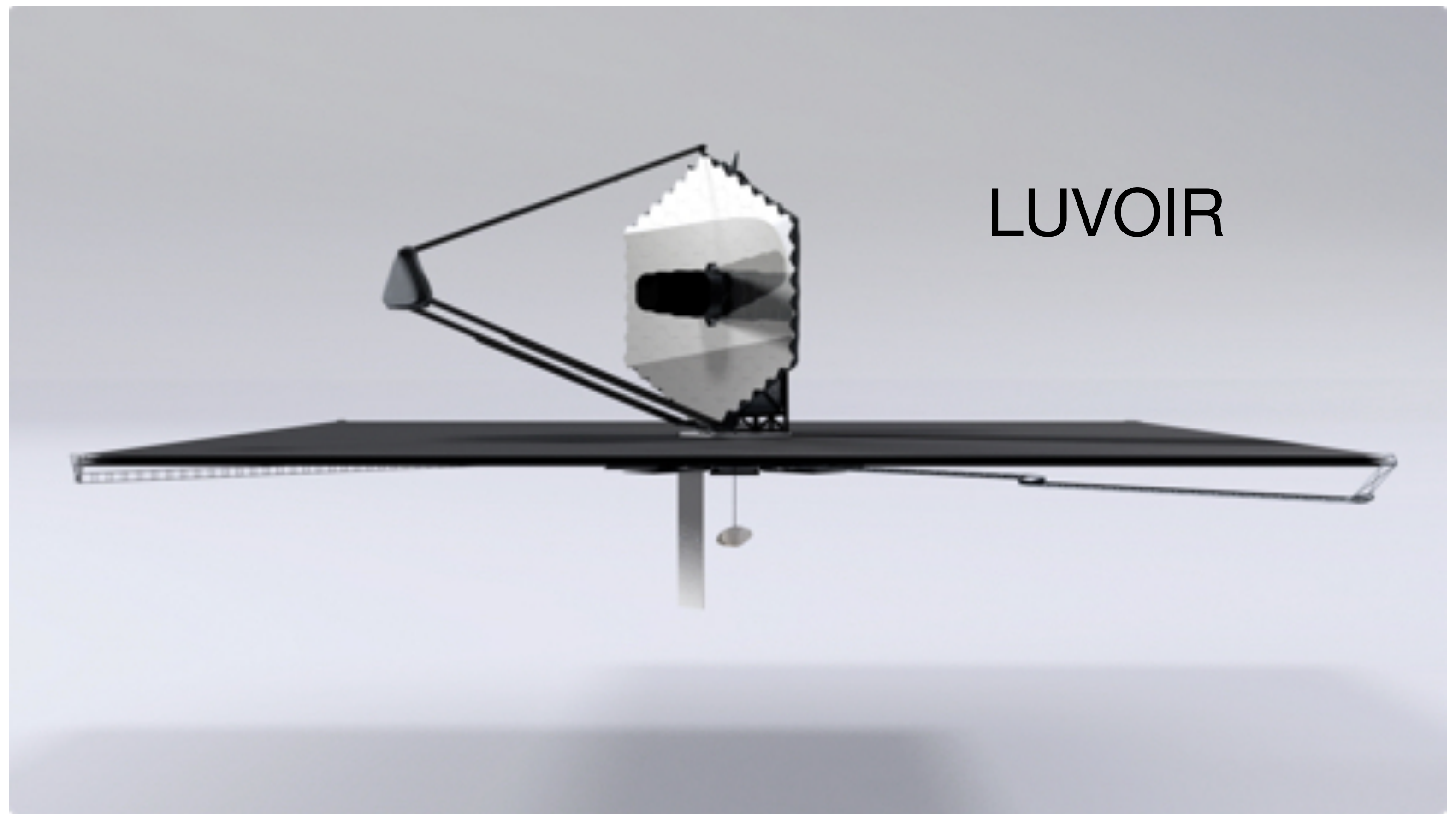


Light Curves from Accretion onto Spinning BBHs

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

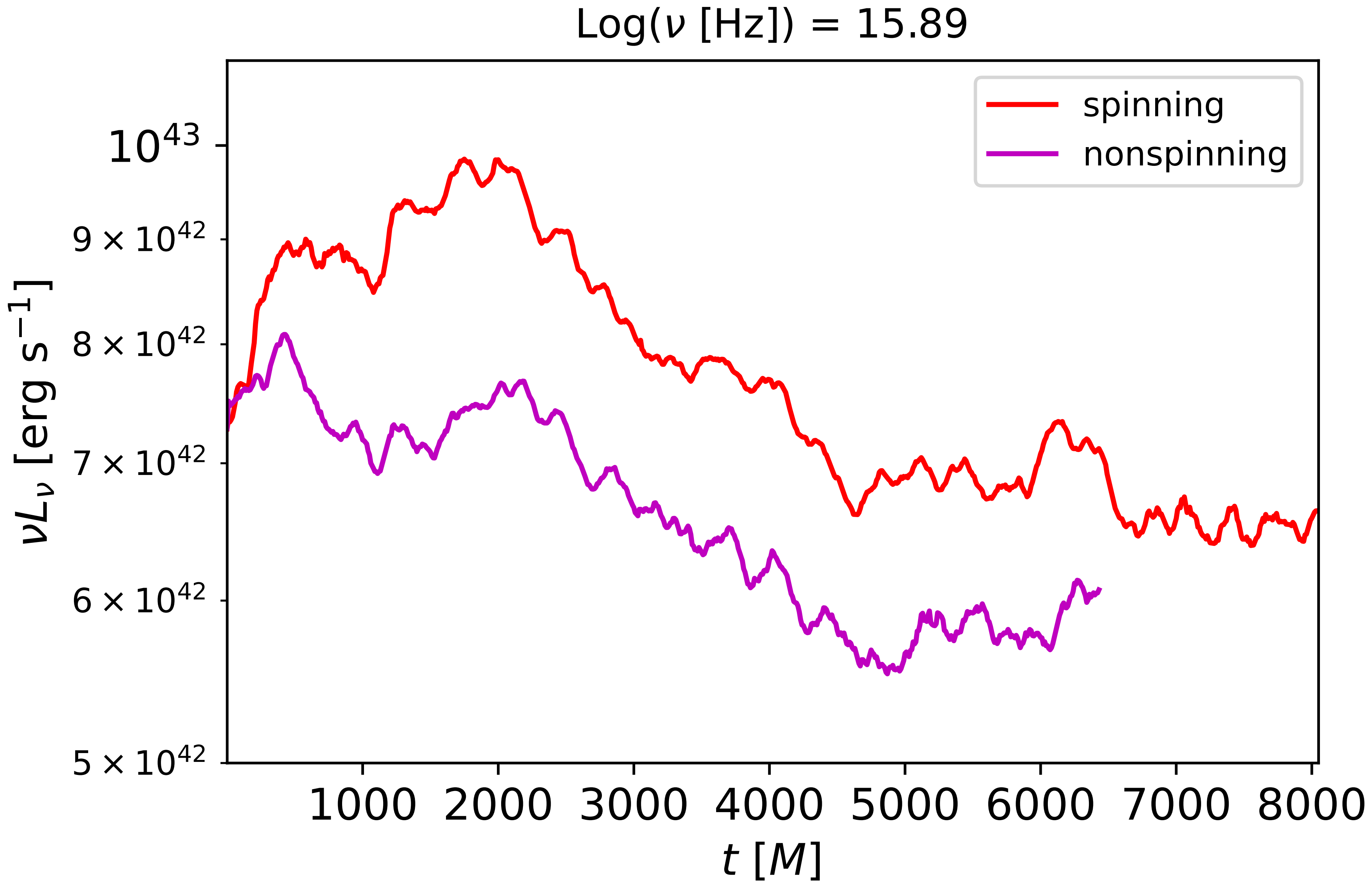
- Binary signature is most significant in X-rays;
  - TAP, Athena, LYNX, Strobe-X, AXIS…;

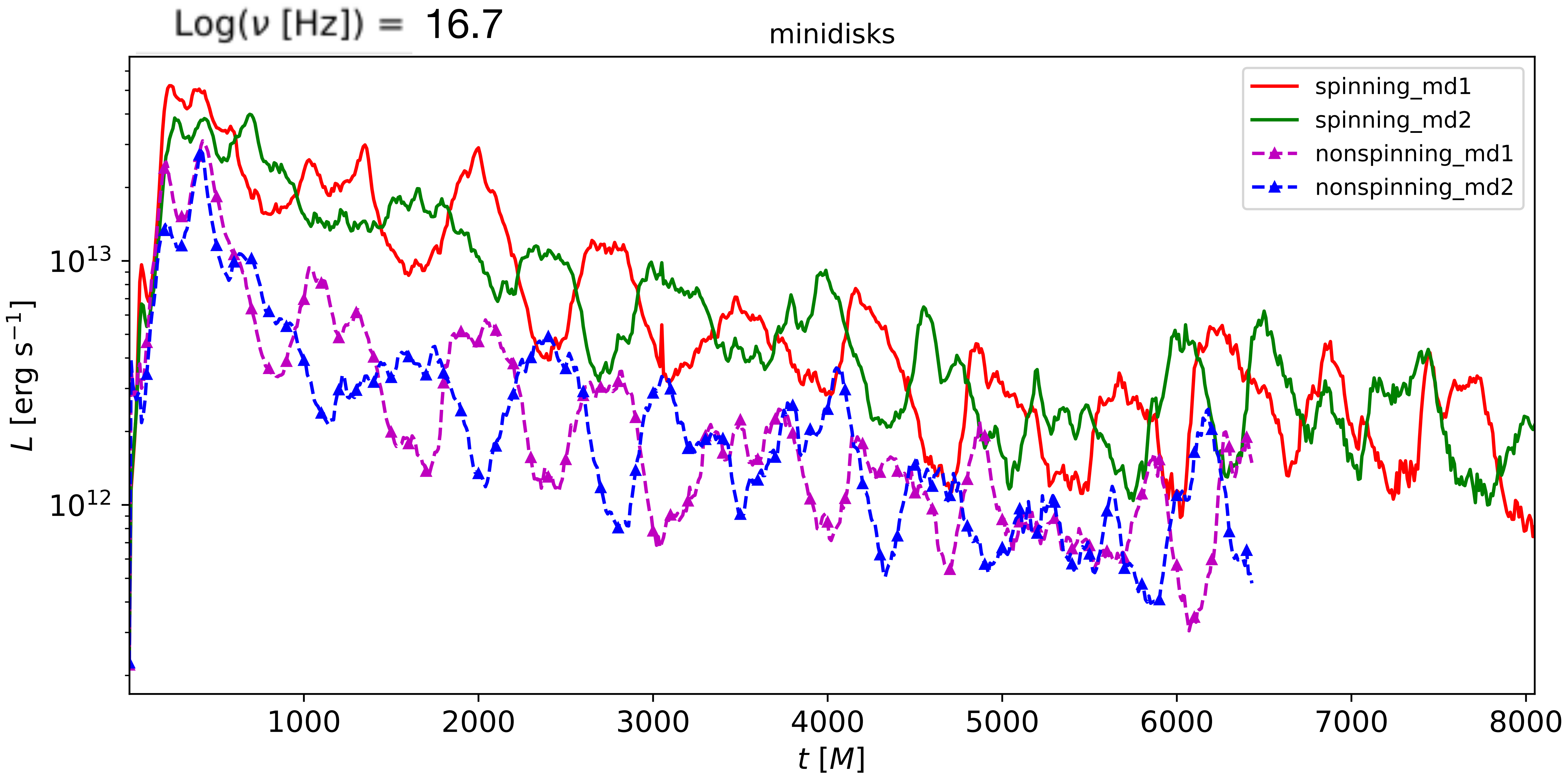
- UV offers interesting opportunity too as this is where the mini-disk's thermal disk spectrum peaks;
  - Hubble, LUVOIR, Dorado possibilities;



Spinning BBHs: a=0.6M, up-up

Total Emission





Summary & Conclusion

- Numerical GRMHD simulations are critical to predicting EM emission from SMBBH systems and establishing their multi-messenger connection.
- The circumbinary lump modulates accretion onto the BBH at O(1) levels for mass-ratios >~ 0.2, and leads to a powerful EM signature of BBHs.
- Lump formation in GRMHD simulations is generic and robust to perturbations after a relaxation period.
- Binaries with spins give rise to jets that may provide additional observational signatures of their binary-ness.
- PatchworkMHD has been demonstrated to be a powerful tool at providing the means to cover the entire domain to sufficiently resolve MHD turbulence in an efficient manner.
- Future work will explore how coupled radiation-MHD physics will alter BBH disk dynamics and their EM emission.

https://arxiv.org/abs/2102.00243
https://arxiv.org/abs/2103.12100
https://arxiv.org/abs/2103.15707

Mass Ratio Survey

Global Trends of the Lump

Noble, Krolik, Campanelli, Zlochower, Mundim, Nakano, Zilhao (2021)
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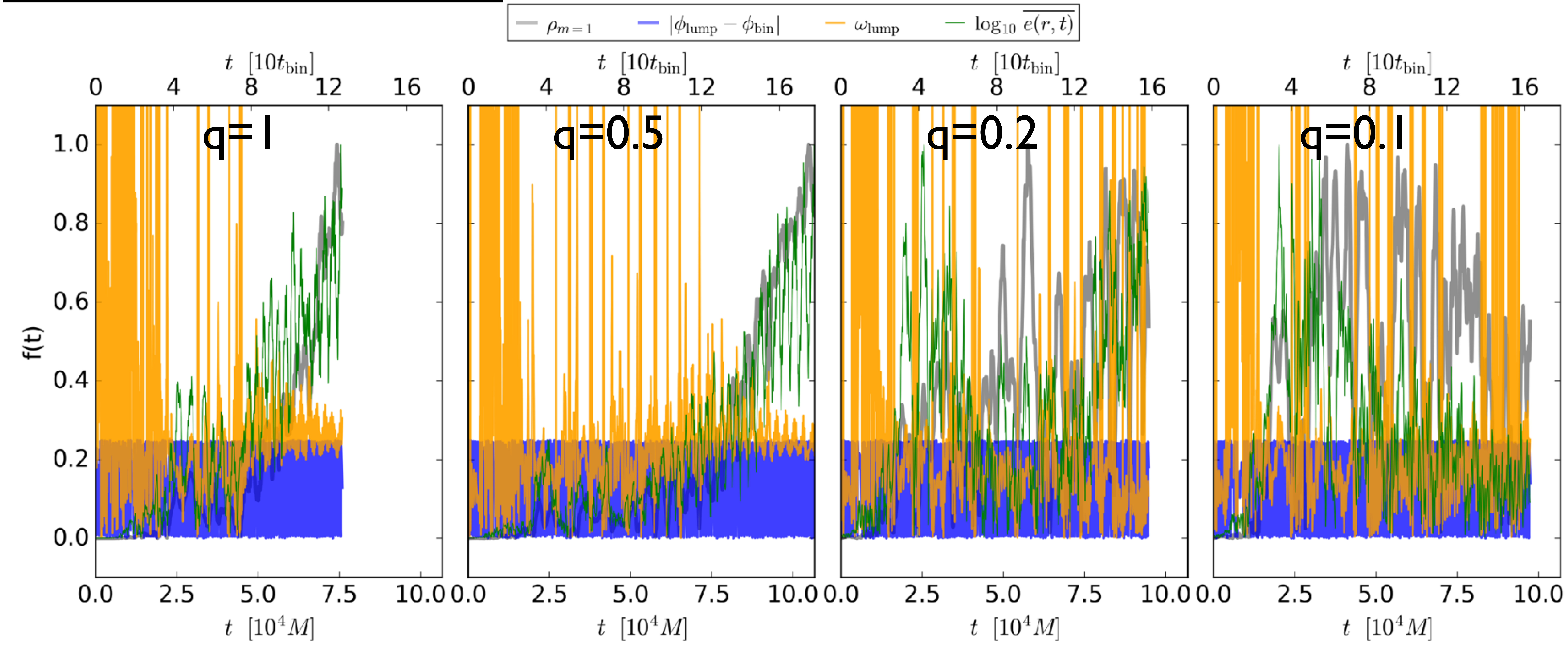
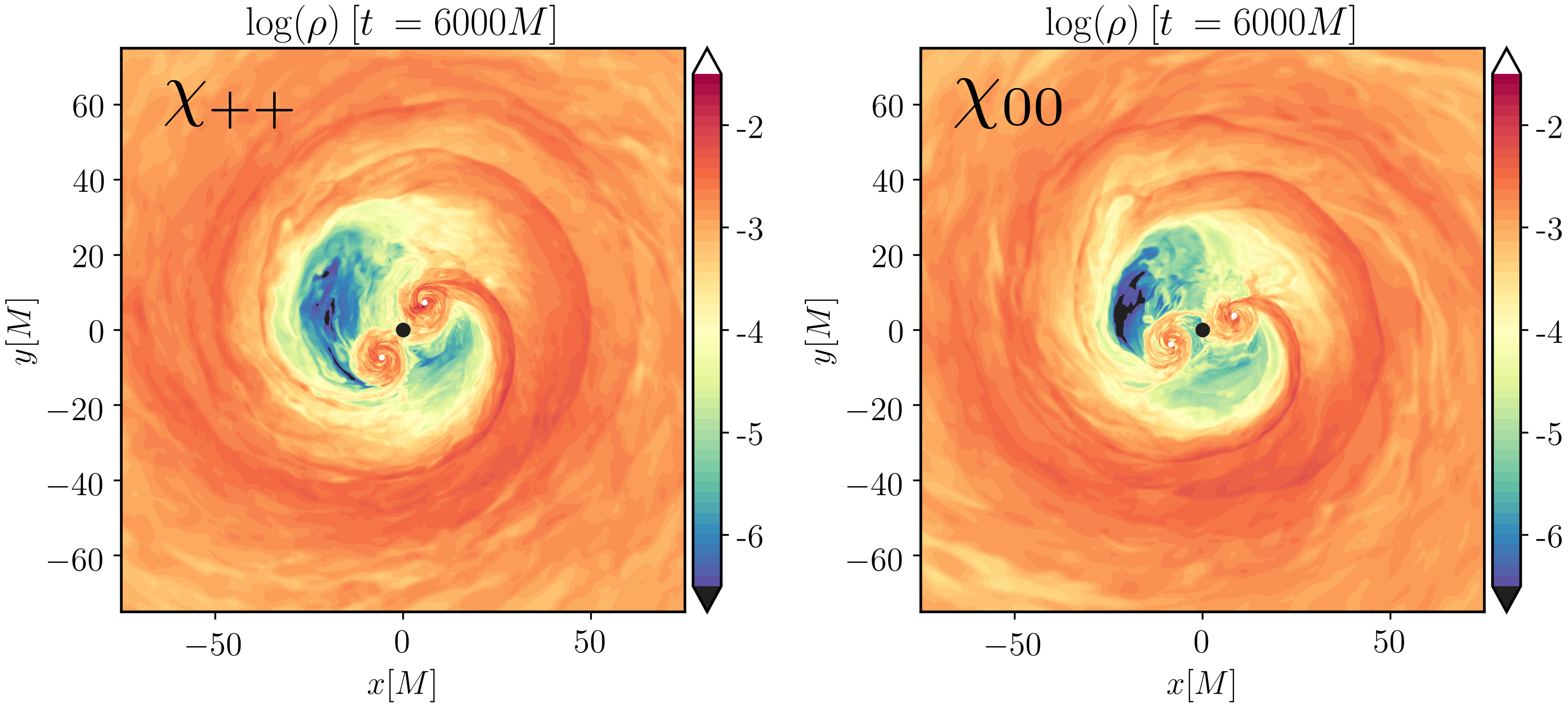


- **The lump is clearly tracked as the principal m=1 mode for q>0.2;**
- **Consistent trend exists between m=1 mode strength, eccentricity, and coherent m=1 angular velocity;**
- **All oscillate in phase, modulated by lump and binary orbital frequencies;**

Accretion onto Spinning BBHs

Circumbinary + Mini- Disk Regions

Combi, Lopez Armengol, (in prep, 2021)

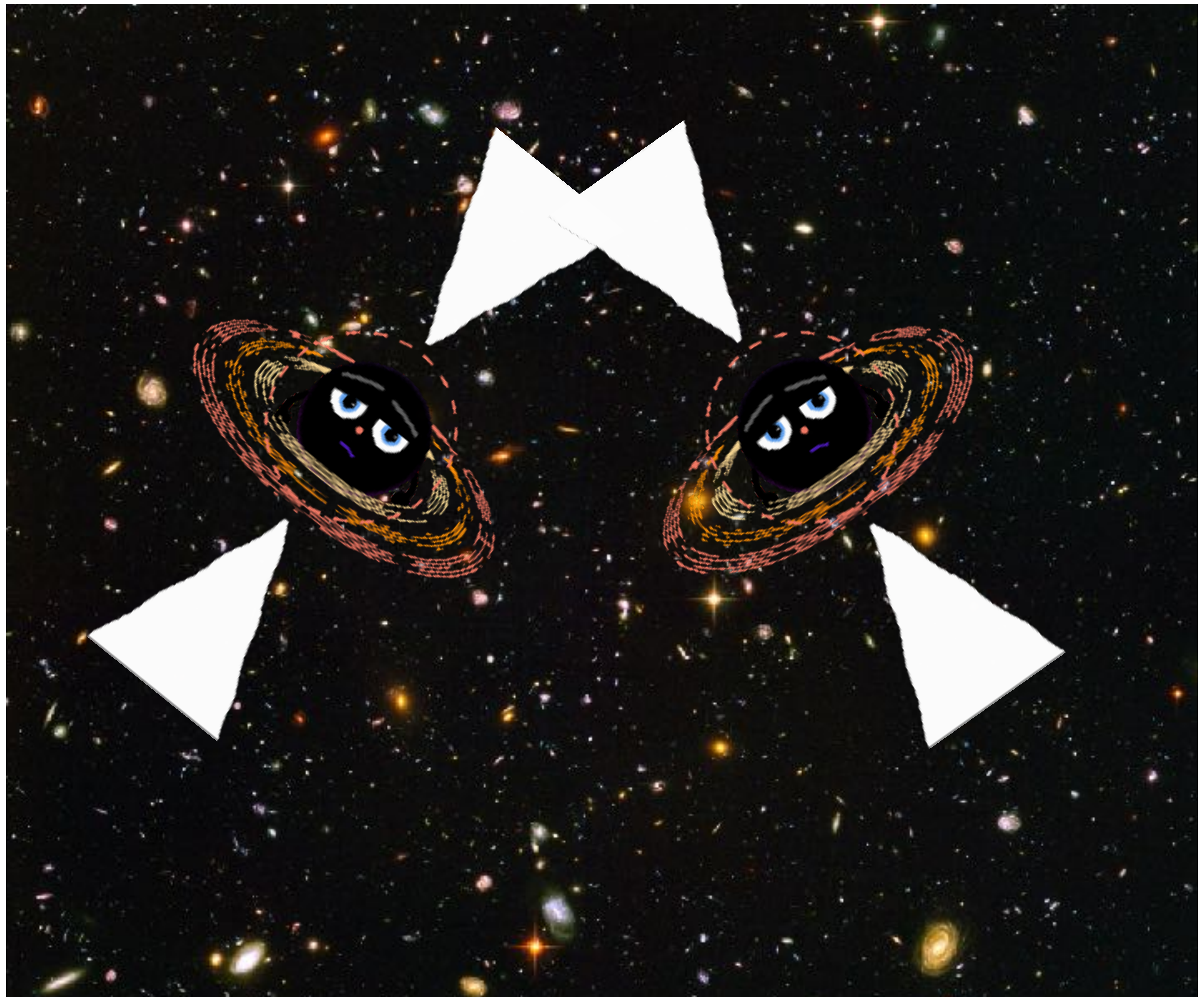


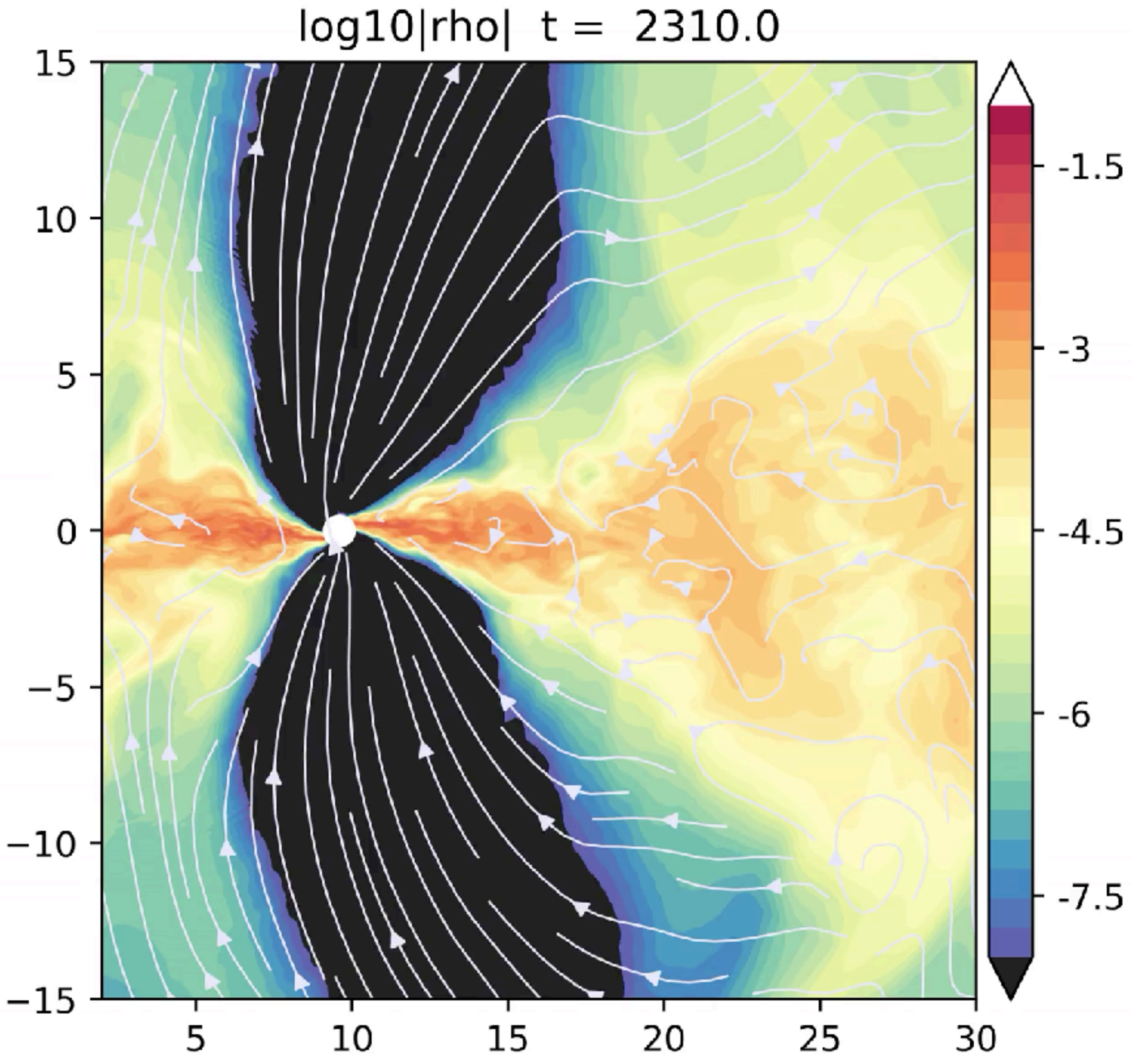
Accretion onto Misaligned Spinning BBHs

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.**



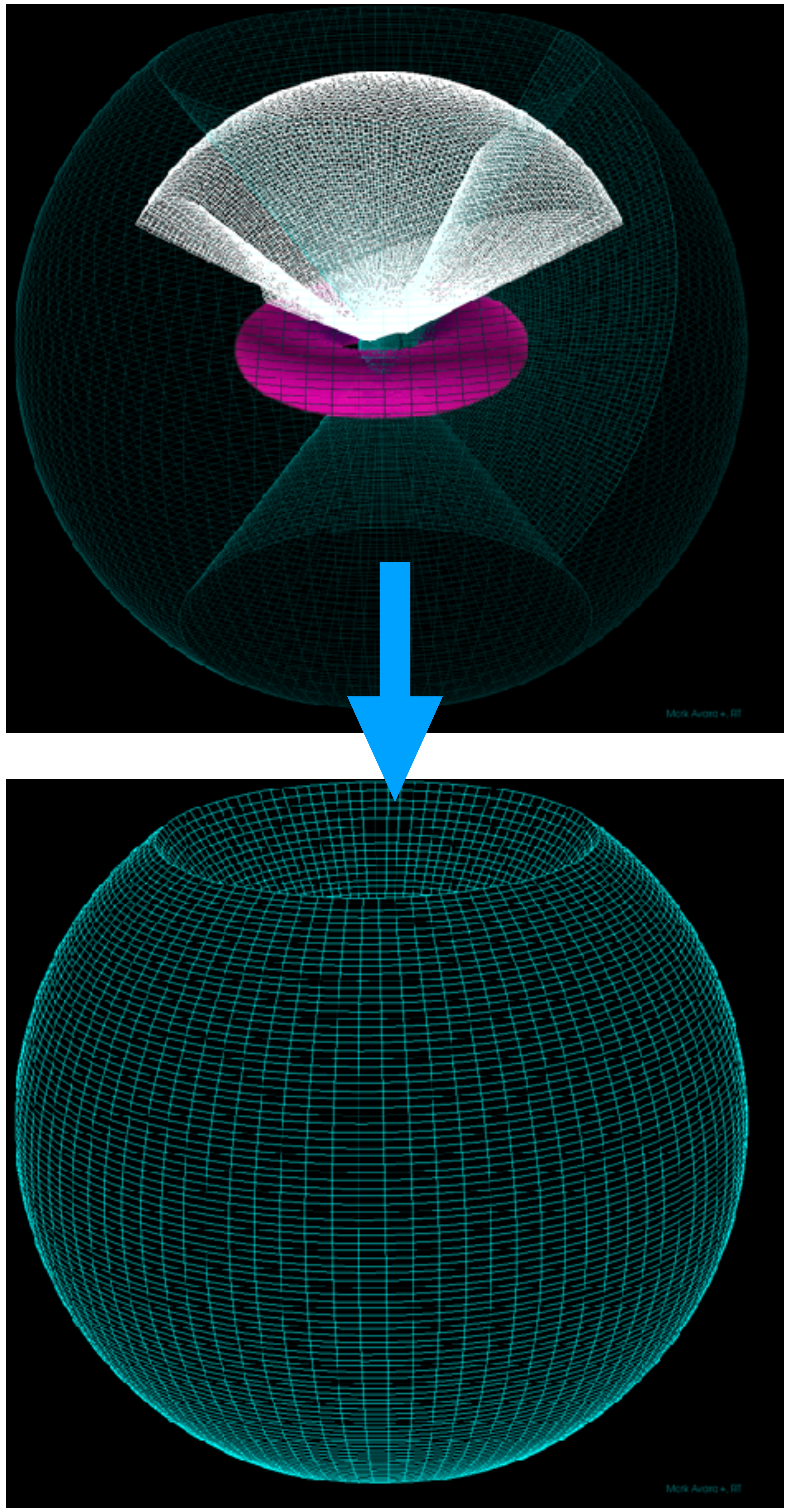


PatchworkMHD : Single BH Test

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;