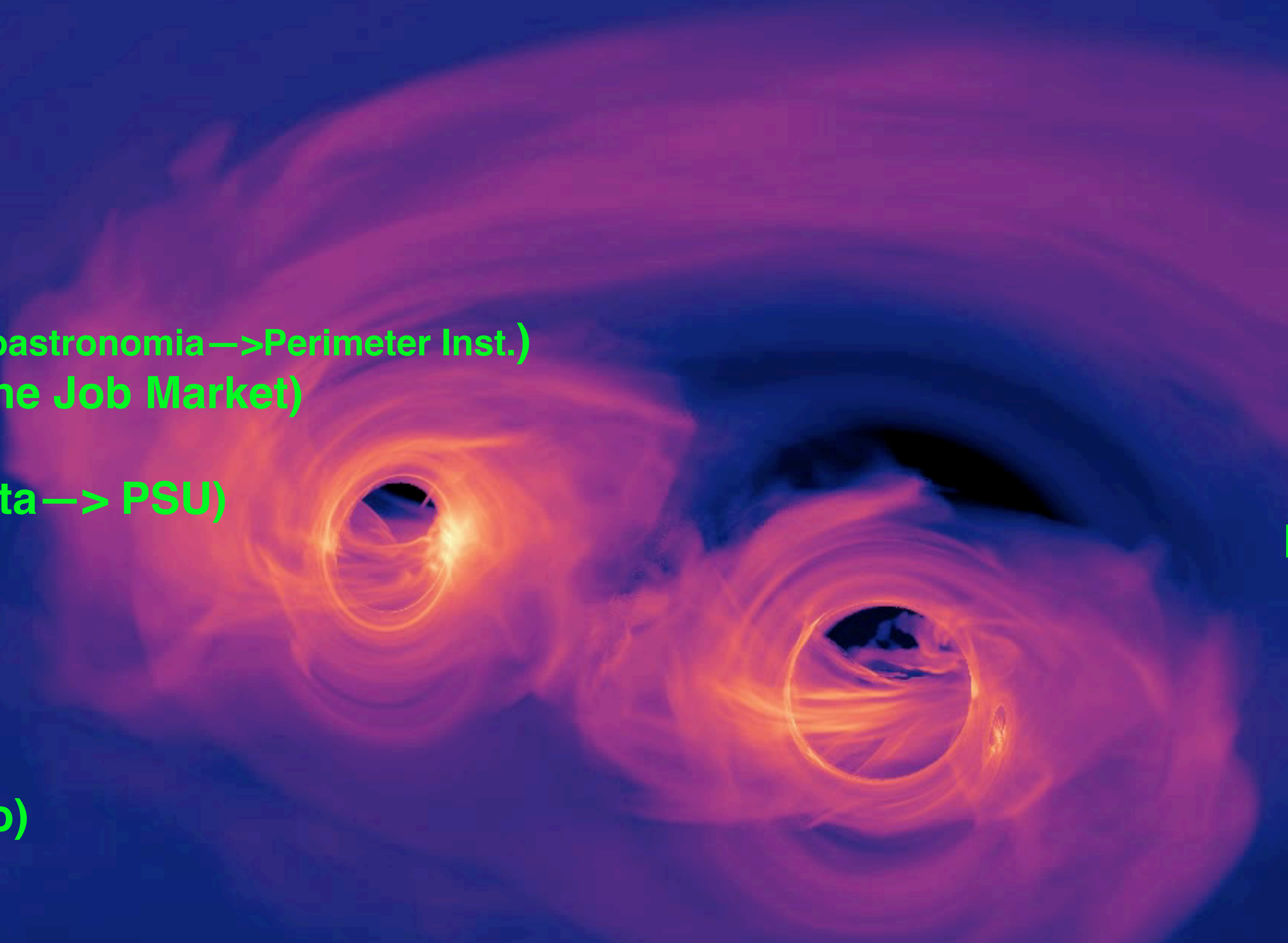
Electromagnetic Time and Wavelength Domain Predictions for Accreting Binary Black Holes



__Team Members:__
L. Combi (RIT, I. Argentino Radioastronomia—>Perimeter Inst.)
F. Lopez Armengol (RIT, On the Job Market)
M. Avara (Cambridge)
E. Gutierrez (Nac. Uni. La Plata—> PSU)
M. Campanelli (RIT)
J. Krolik (JHU)

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

Scott C. Noble

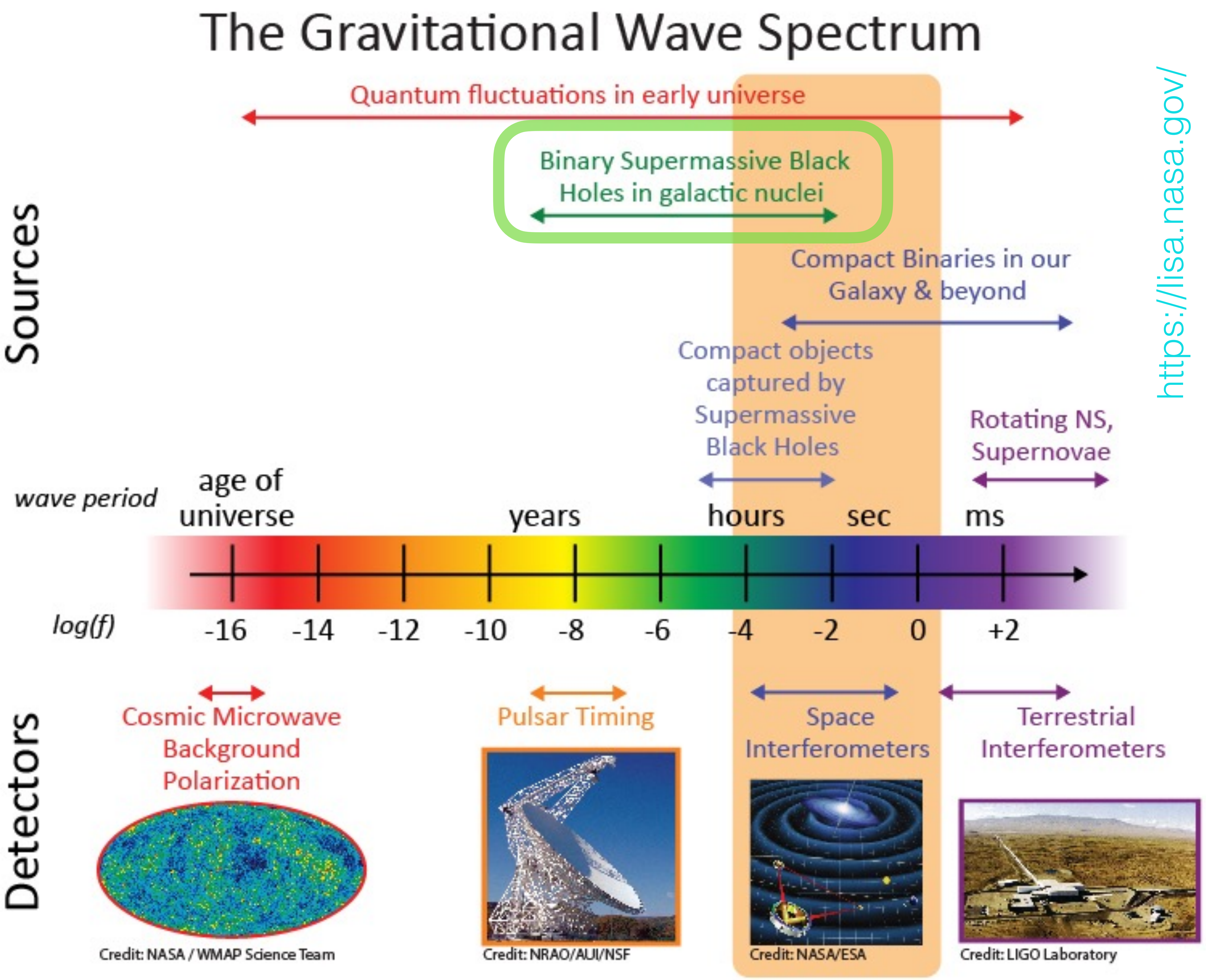
Research Astrophysicist
Gravitational Astrophysics Lab
NASA Goddard Space Flight Center

@therealscn

Thanks to the NASA LISA Study Office,
NSF PRAC ACI-1515969 & OAC-1811228, AST-1515982, AST-2009330 & PHY-2001000

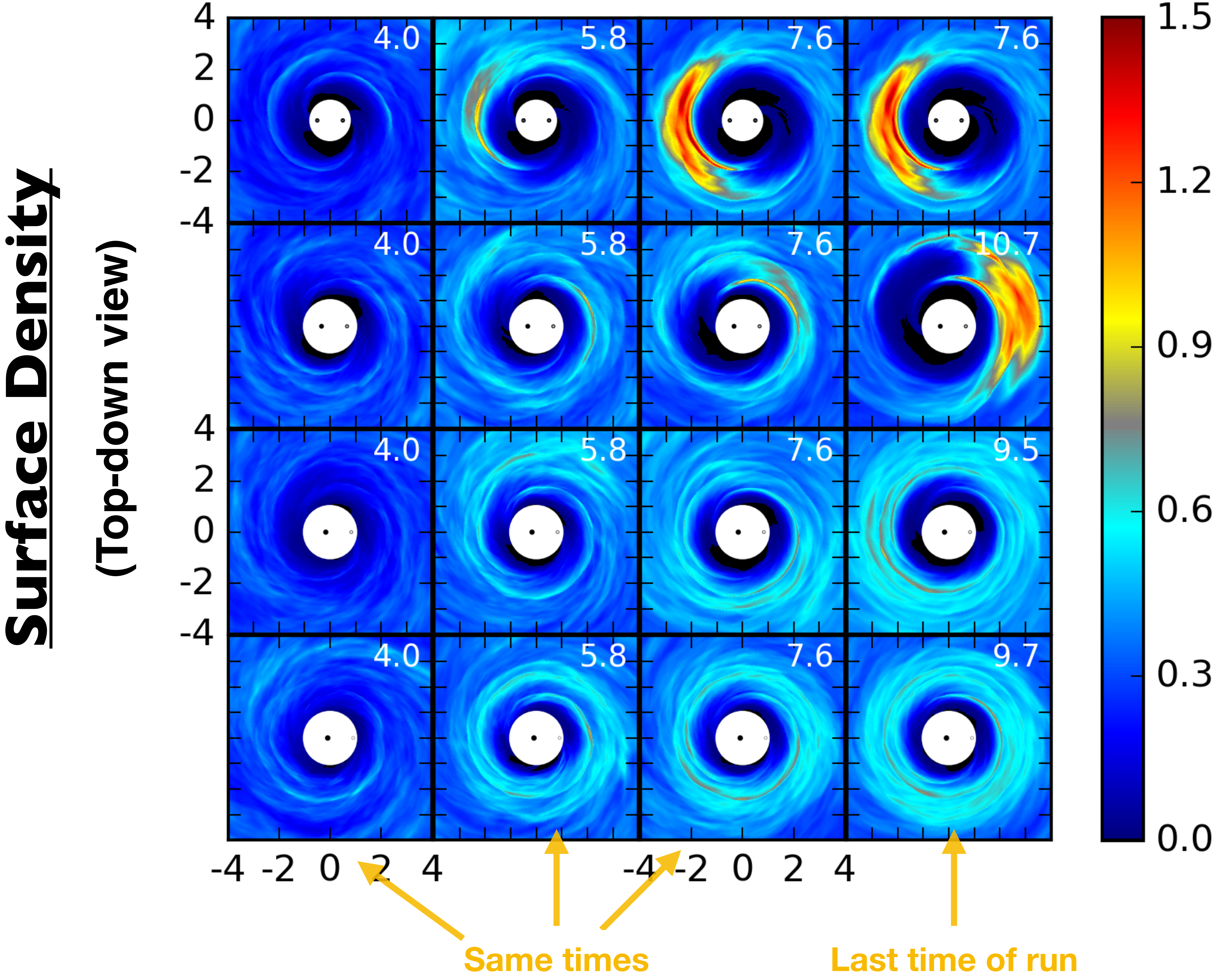
Supermassive Binary Black Holes

- 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 (?) 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!



Mass Ratio Survey : Circumbinary Disks

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



$q=M_2/M$

q=1

q=0.5

q=0.2

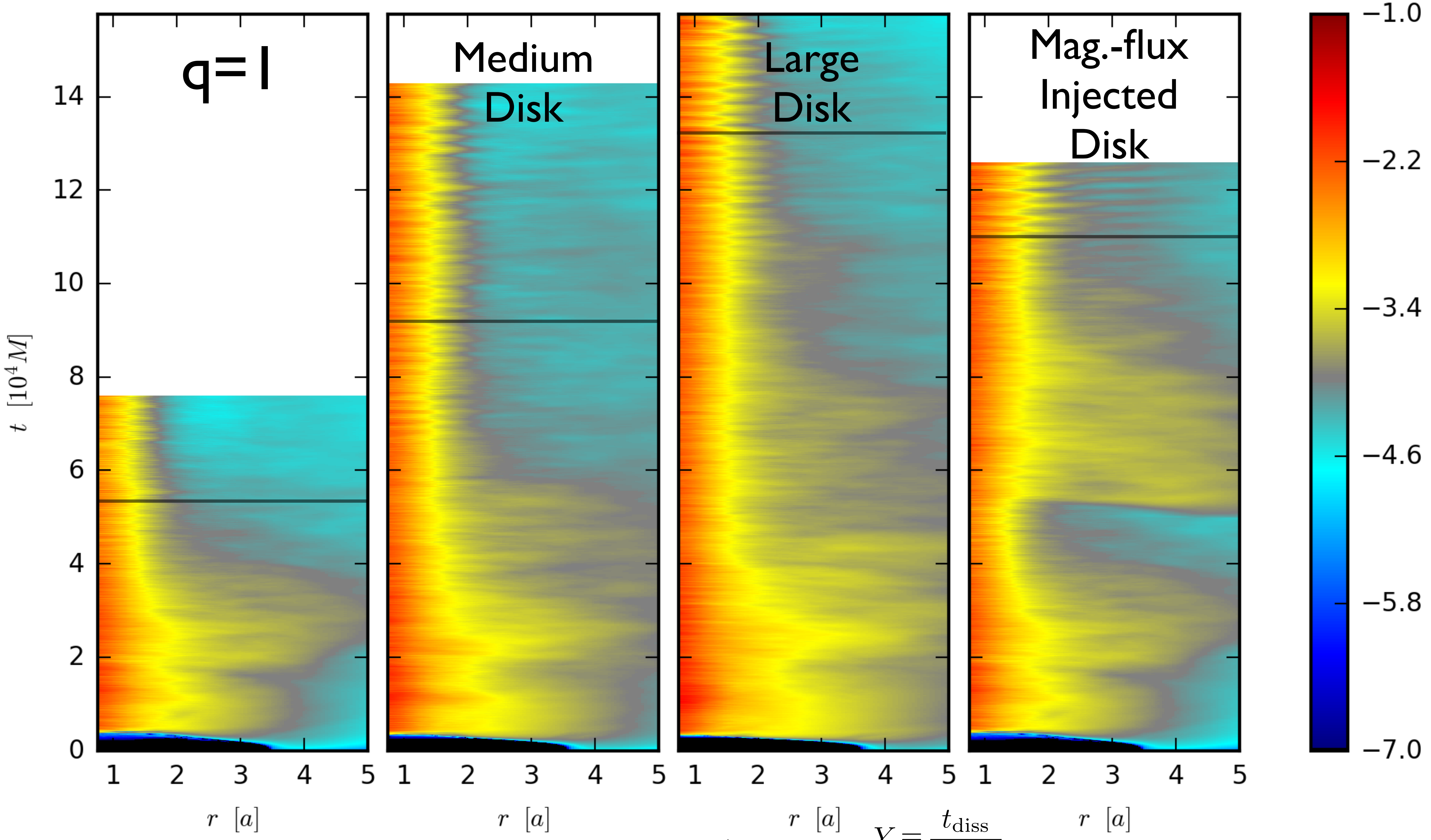
q=0.1

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

Mag. Flux Survey

Magnetic Stress per Mass

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



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

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

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

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

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

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

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

1. Replenished material torqued outward from accretion stream;

2. Returning material leads to weaker shear stress:

   1. It is corotating with material there so differential rotational velocity diminishes, weakening hydro viscosity or MRI;

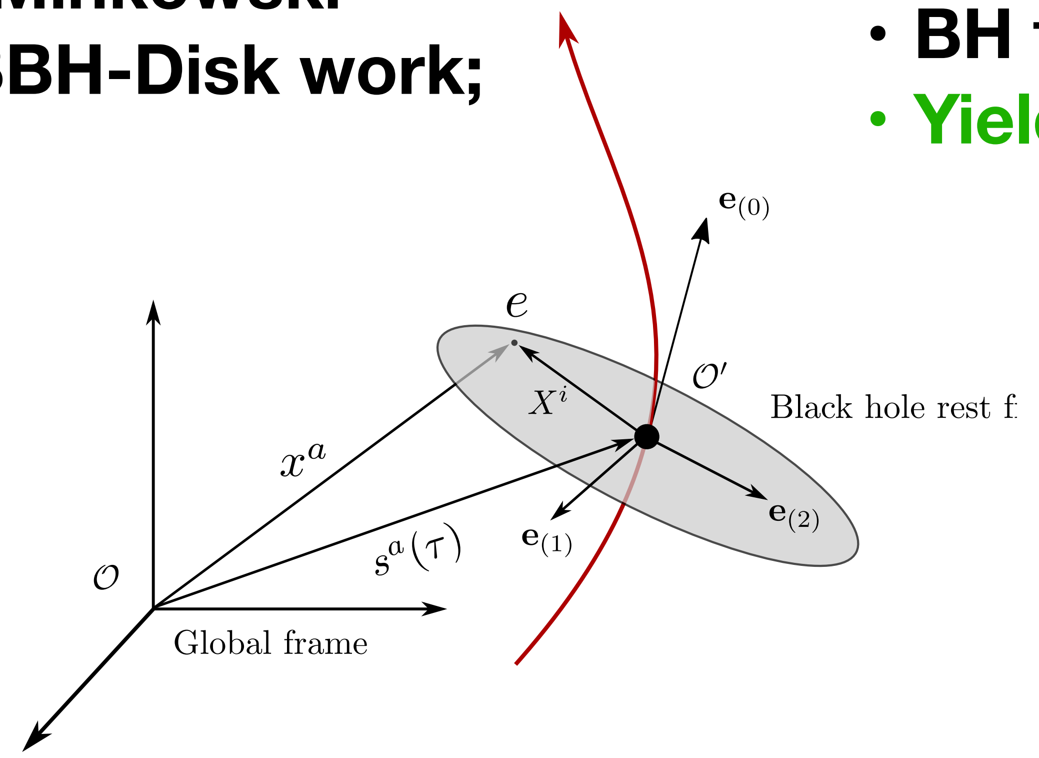
   2. MHD: magnetic field is dissipated there too, possibly resulting in even more significant lump formation.

Superposed Kerr-Schild

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

- **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;**

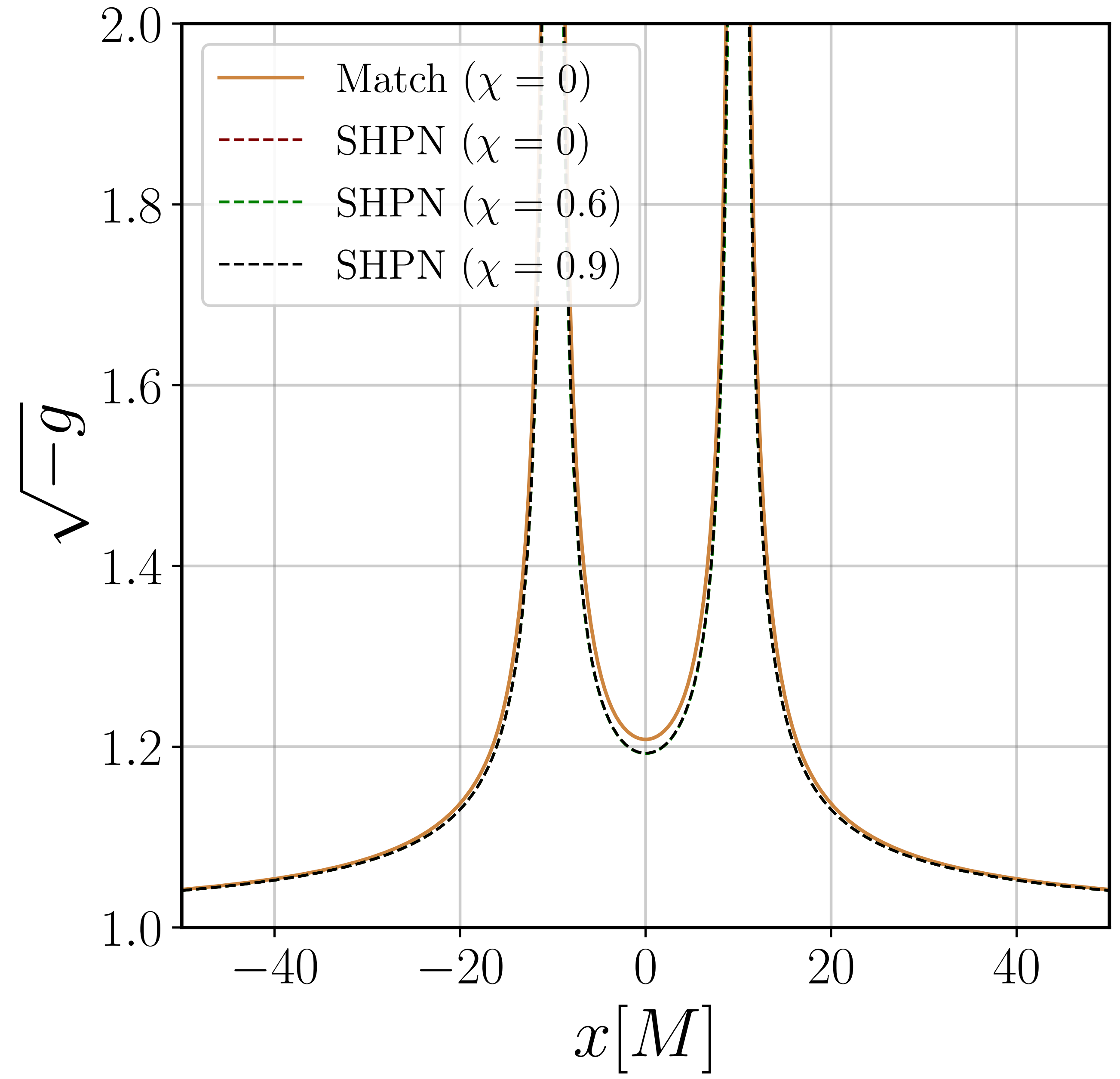
$$g_{ab} = (1 - f_{\rm FZ})\Big\{ f_{\rm NZ}\big[f_{{\rm IZ},1}\, g_{ab}^{\rm (NZ)} + (1 - f_{{\rm IZ},1})\, g_{ab}^{\rm (IZ1)}\big] + (1 - f_{\rm NZ})\big[f_{{\rm IZ},2}\, g_{ab}^{\rm (NZ)} + (1 - f_{{\rm IZ},2})\, g_{ab}^{\rm (IZ2)}\big]\Big\} + f_{\rm FZ}\, g_{ab}^{\rm (FZ)} \quad (30)$$

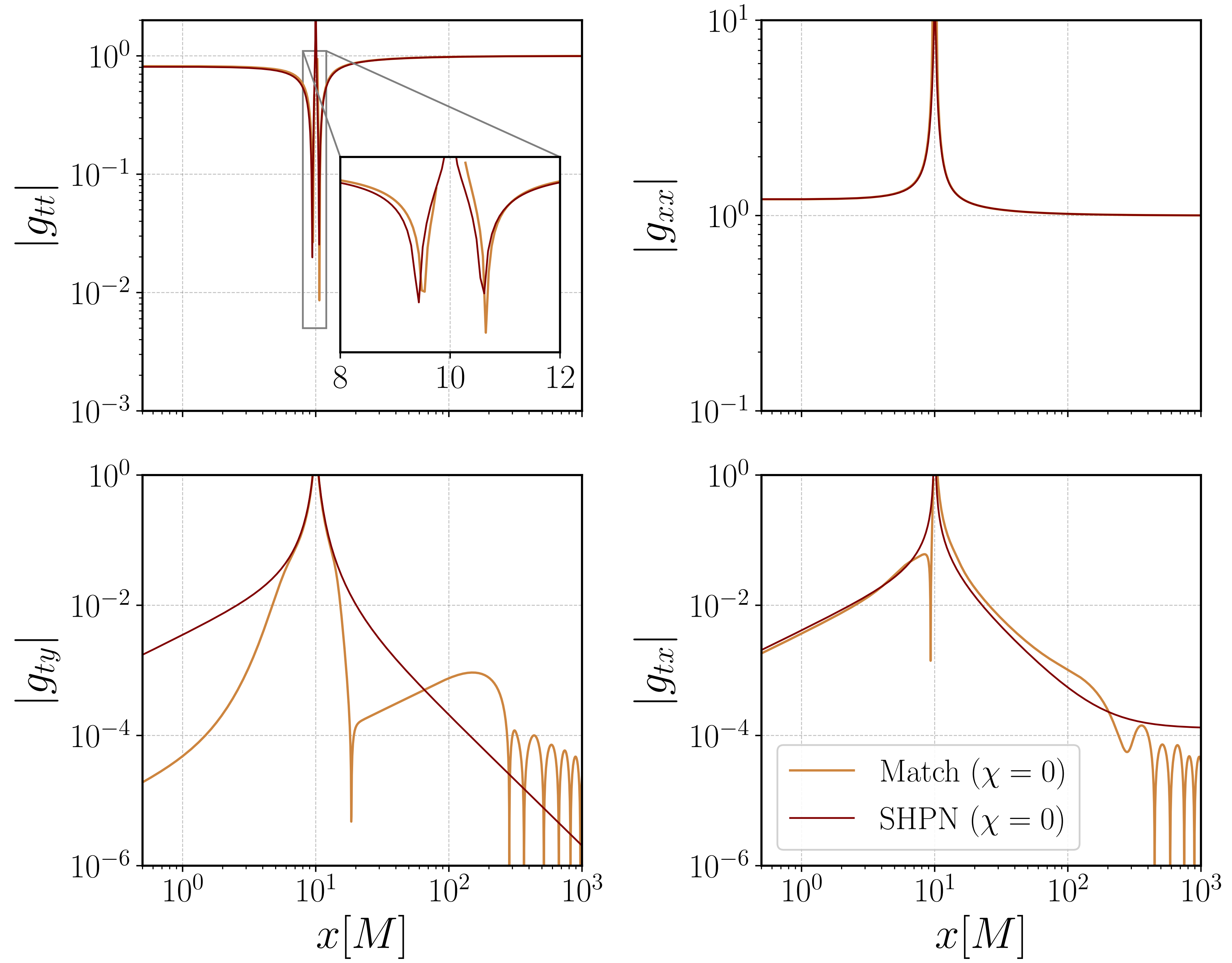


- **New Method: Superposed Kerr-Schild:**
  - **Boosted set of Spinning BHs in Harmonic Cook-Scheel coordinates;**
  - **Significantly more computationally efficient than Matching;**
  - **BH trajectories still governed by 2.5PN theory;**
  - **Yields comparable vacuum sol'n as that of Matching;**

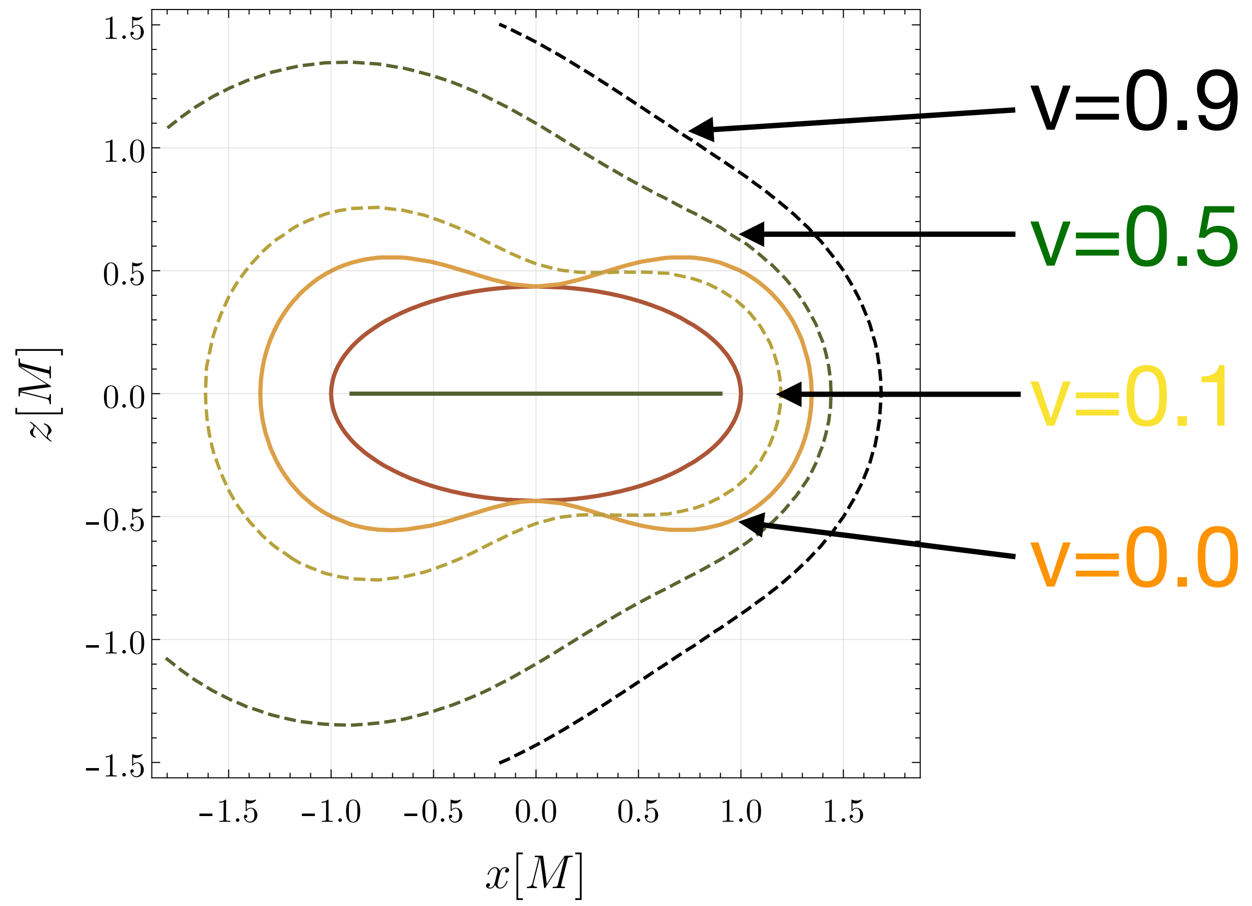
$$g_{ab} = \eta_{ab} + M_1\left(\frac{\partial X_1^{\bar a}}{\partial x^a}\frac{\partial X_1^{\bar b}}{\partial x^b}\mathcal{H}_{\bar a \bar b}\right) + M_2\left(\frac{\partial X_2^{\bar a}}{\partial x^a}\frac{\partial X_2^{\bar b}}{\partial x^b}\mathcal{H}_{\bar a \bar b}\right),$$

$$\mathcal{H}_{ab} := 2H l_a^H l_b^H + \mathcal{A}_{ab}.$$





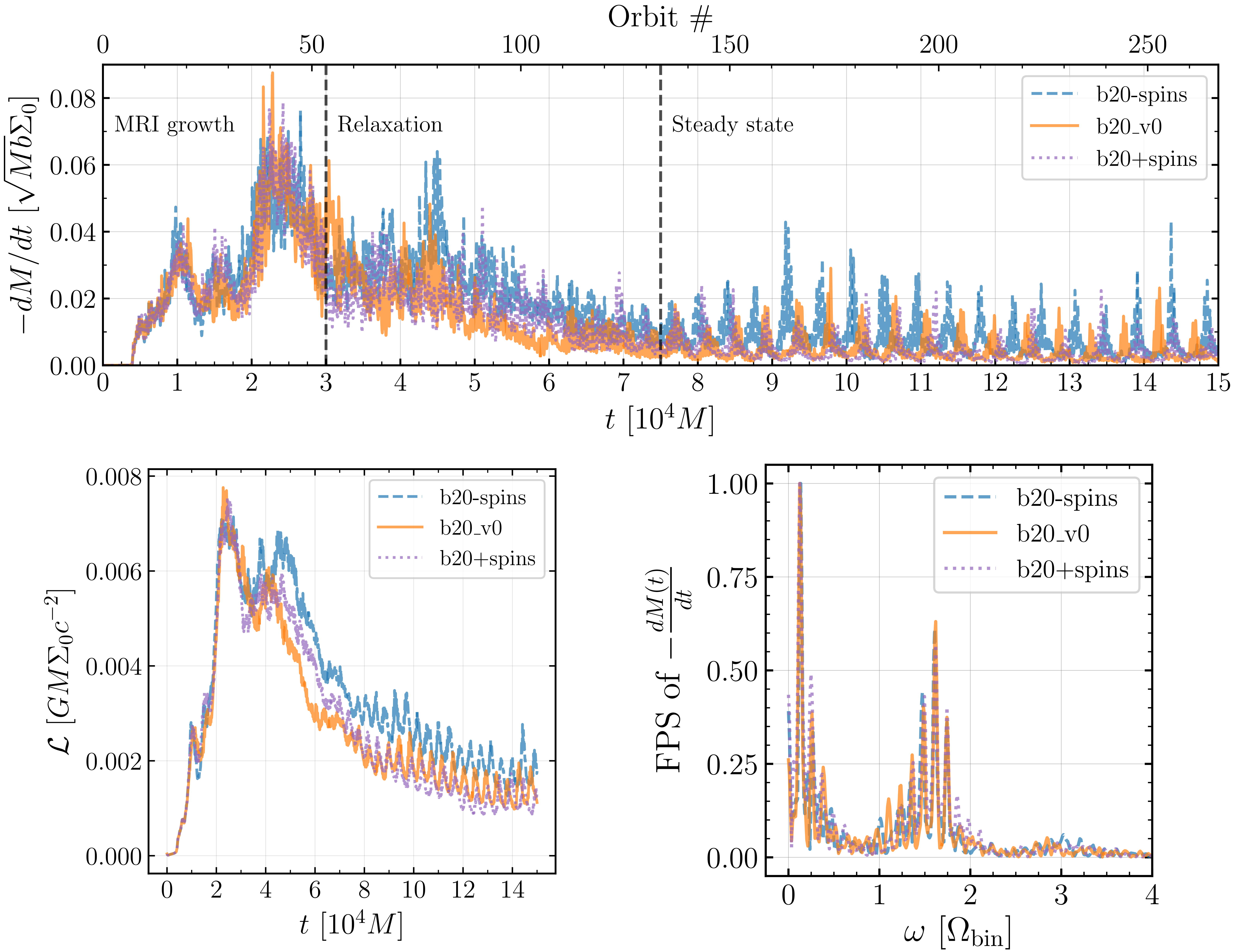
Ergoregion varies with spin and velocity:
—> Consequences to energy extraction eff.;



Accretion onto Spinning BBHs

Circumbinary Disk Region

Lopez Armengol, Combi, Campanelli, Noble, Krolik, Bowen, Avara, Mewes, and Nakano, ApJ, 913, 16, (2021).



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

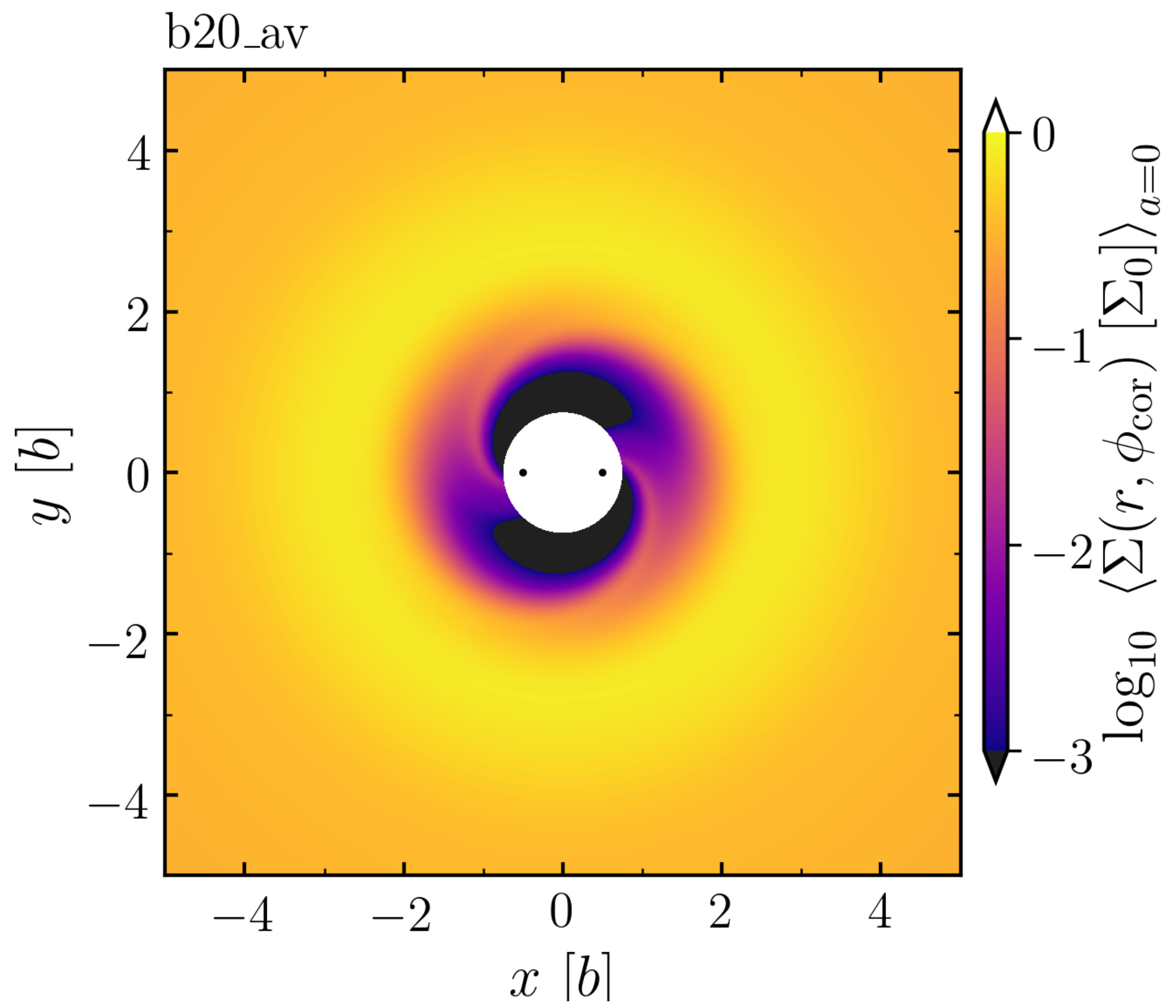
$a_{1,2}/M_{1,2}$ = +/- 0.9

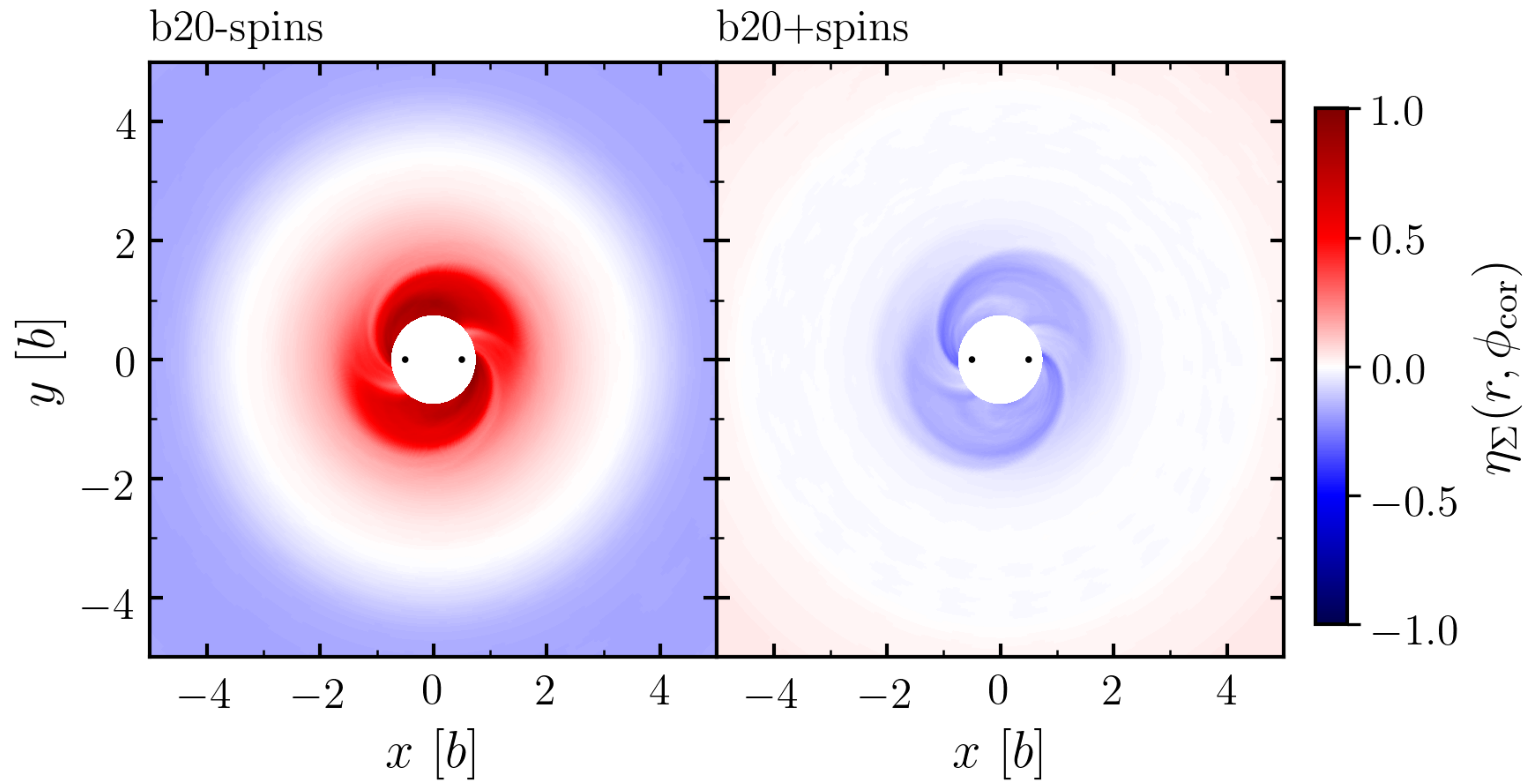
- **Simulations of only circumbinary disk region, starting from Noble++2012 conditions, only changing spin and using Superposed metric; Equal masses, q=1;**
- **Ran longer than before, reached a better steady state;**
- **Circumbinary dynamics & lump largely unaffected by spin aligned with orbital angular 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;**

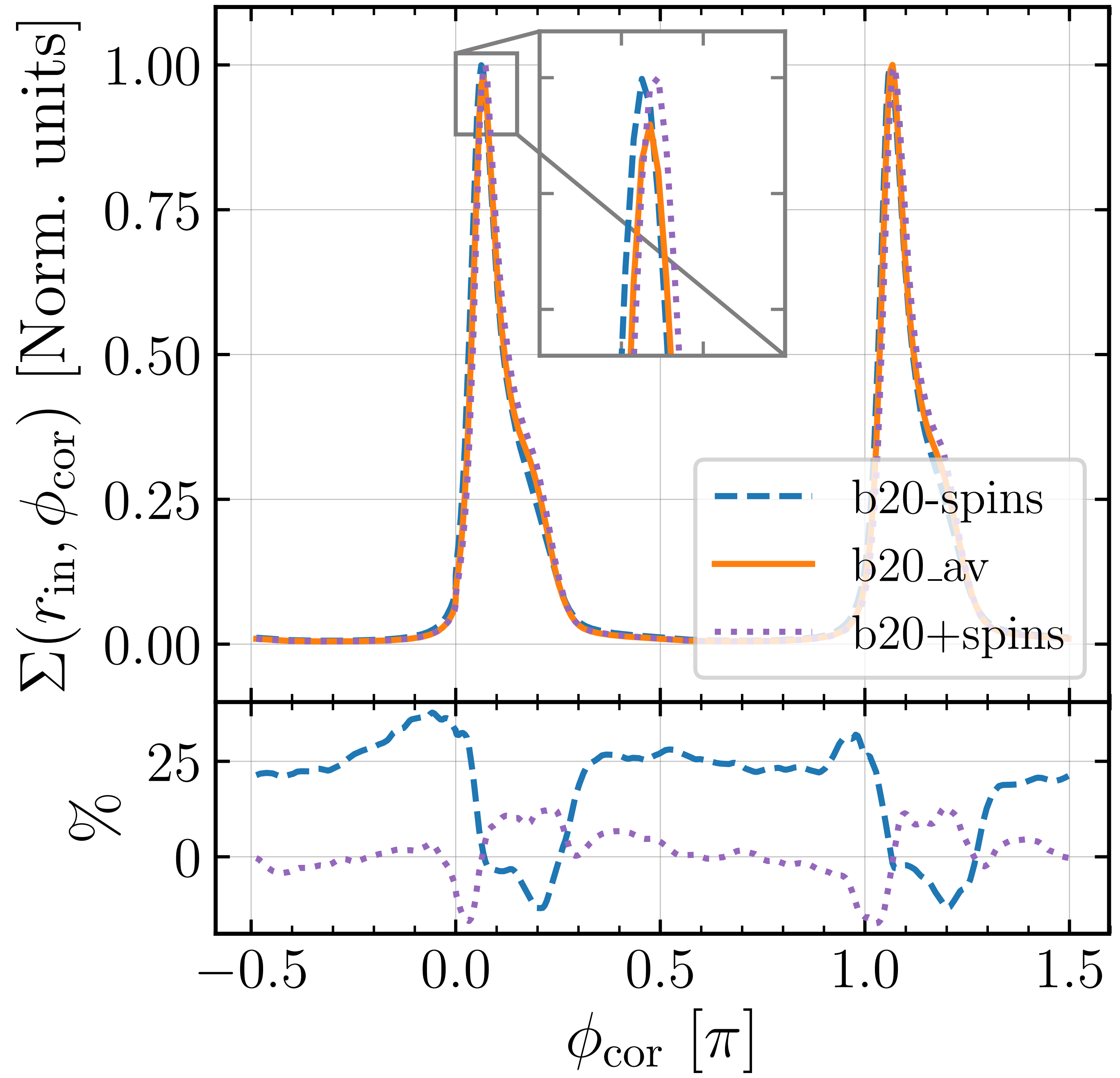
Accretion onto Spinning BBHs

Circumbinary Disk Region

Lopez Armengol, Combi, Campanelli, Noble, Krolik, Bowen, Avara, Mewes, and Nakano, ApJ, 913, 16, (2021).







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

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

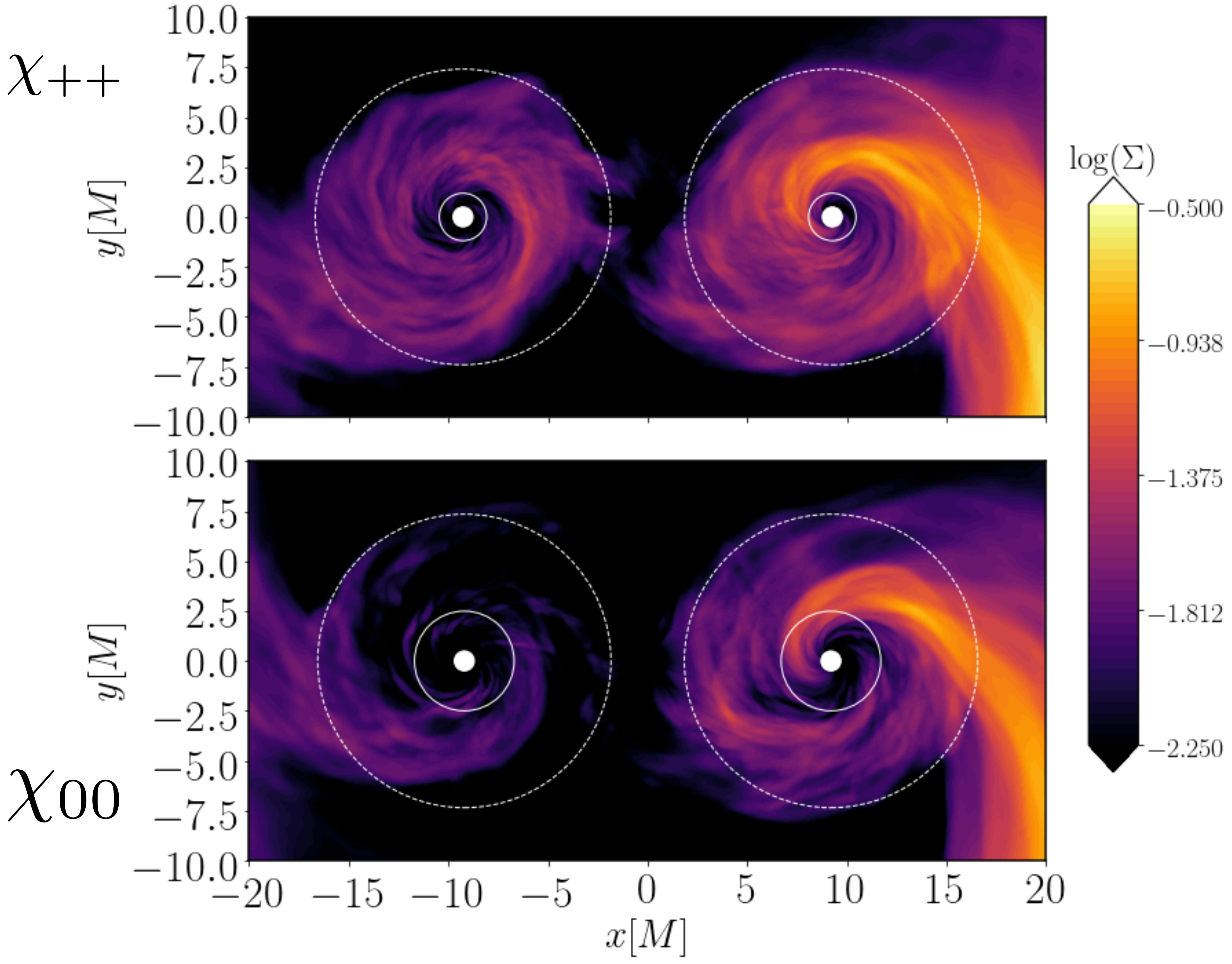
$$\Phi_{\rm Eff} = -\frac{M}{r} - \frac{1}{16}\frac{b^2 M}{r^3} + \frac{J^2}{2r^2} + \frac{MJ}{3r^3}\left(2a + \frac{L}{4}\right)$$

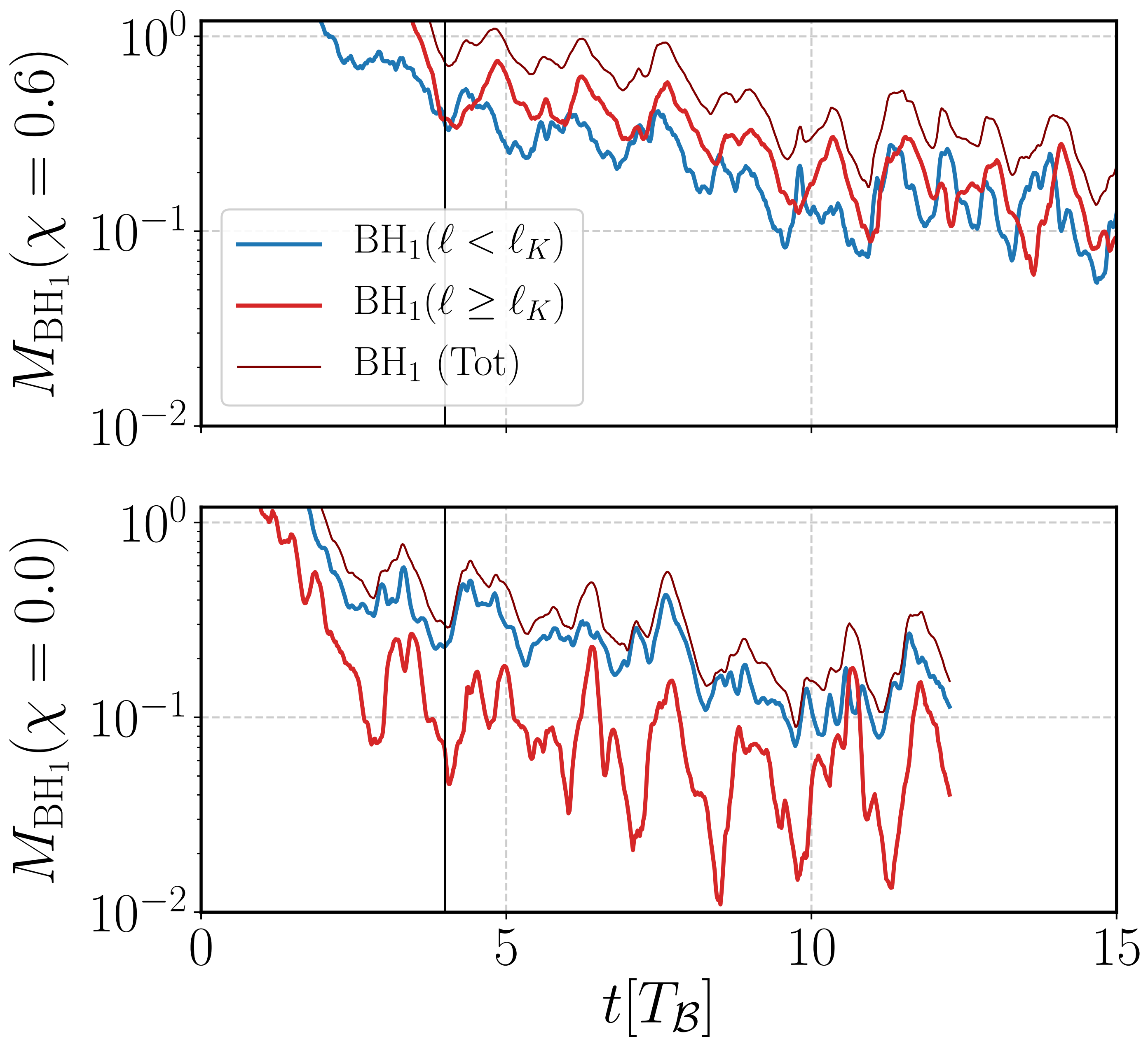
- **Frame dragging acts to lag (lead) accretion streams for anti-parallel (parallel) spins;**

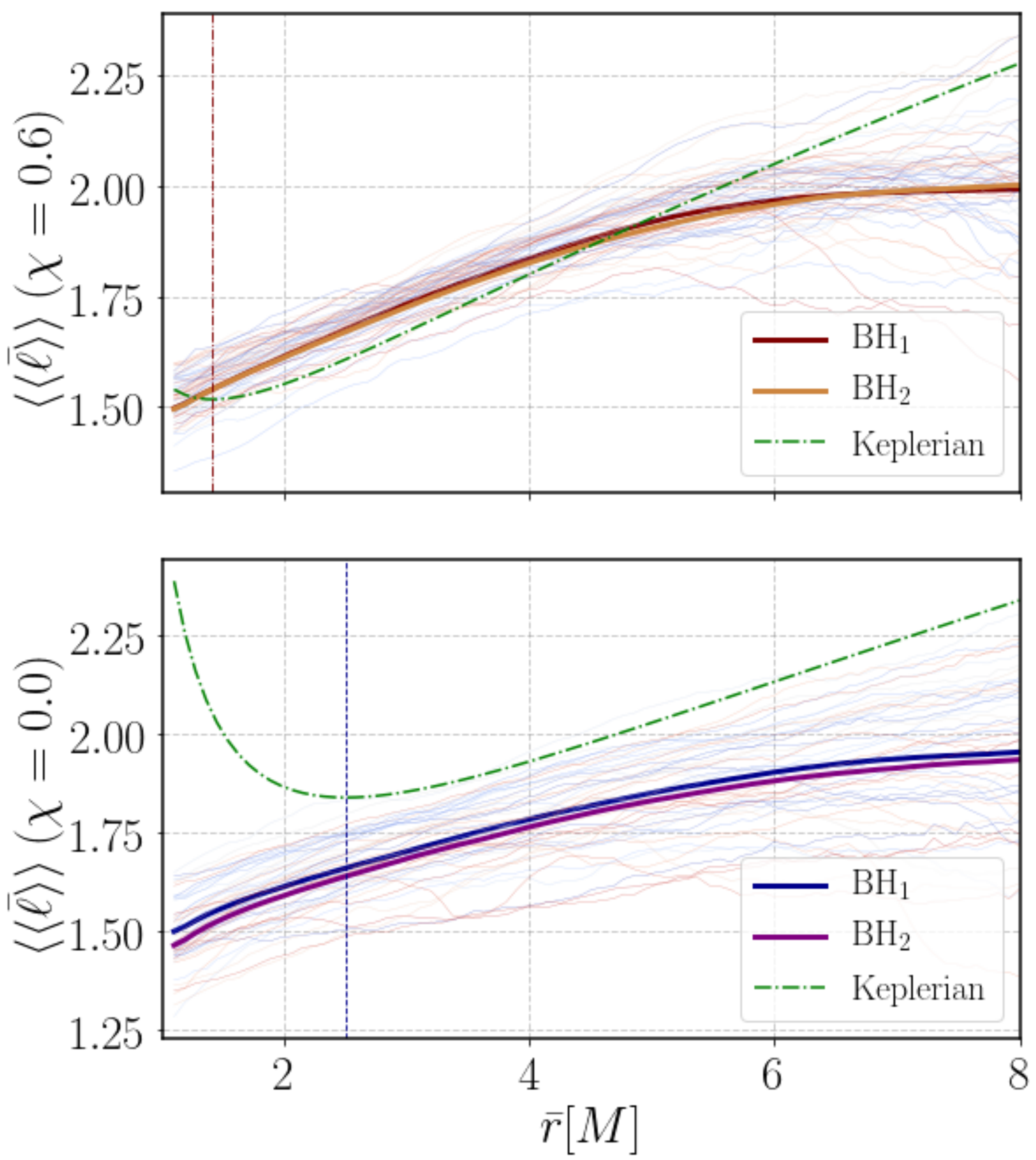
Accretion onto Spinning BBHs

Circumbinary + Mini- Disk Regions

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







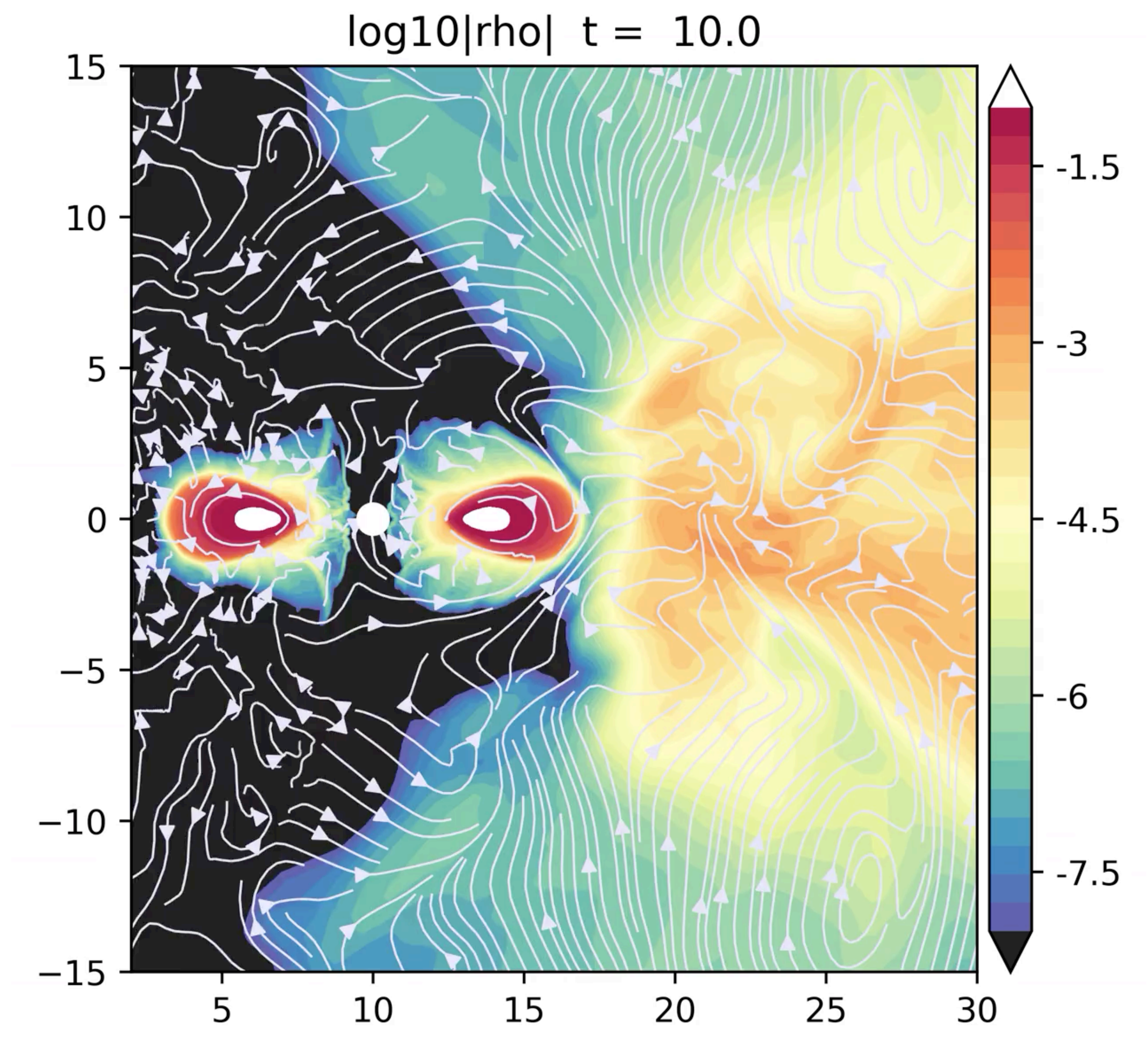
- **Starting from same initial accretion flow conditions;**
- **Because of smaller ISCO, the volume of stability in mini-disk region increases for larger (parallel) spin;**
  - **—>More persistent mini-disks;**
  - **—> Longer inflow time scales;**
  - **—> Comparable accretion rates;**
  - **—> Smaller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

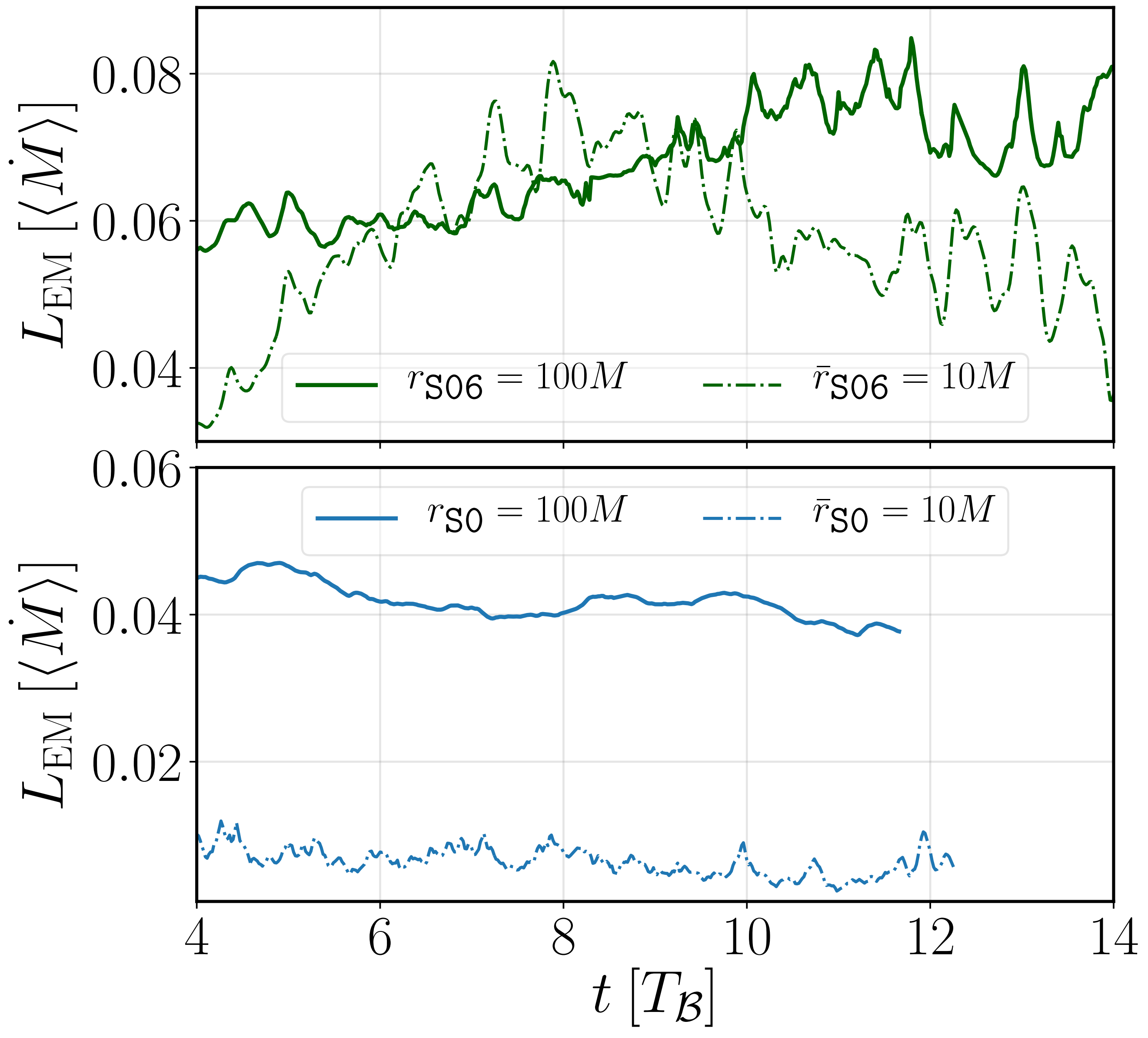
$$\chi = +0.6$$

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

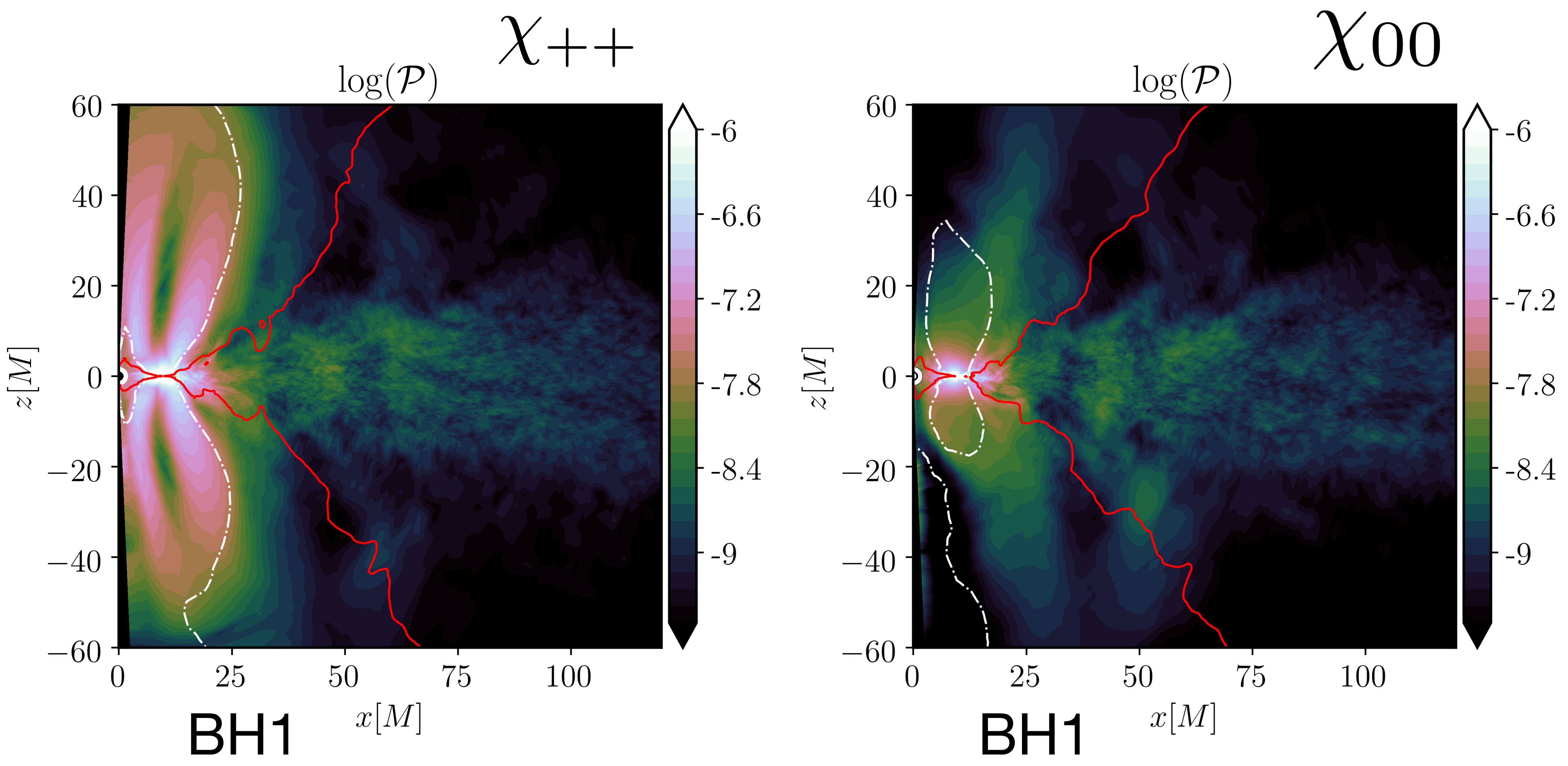
Accretion onto Spinning BBHs

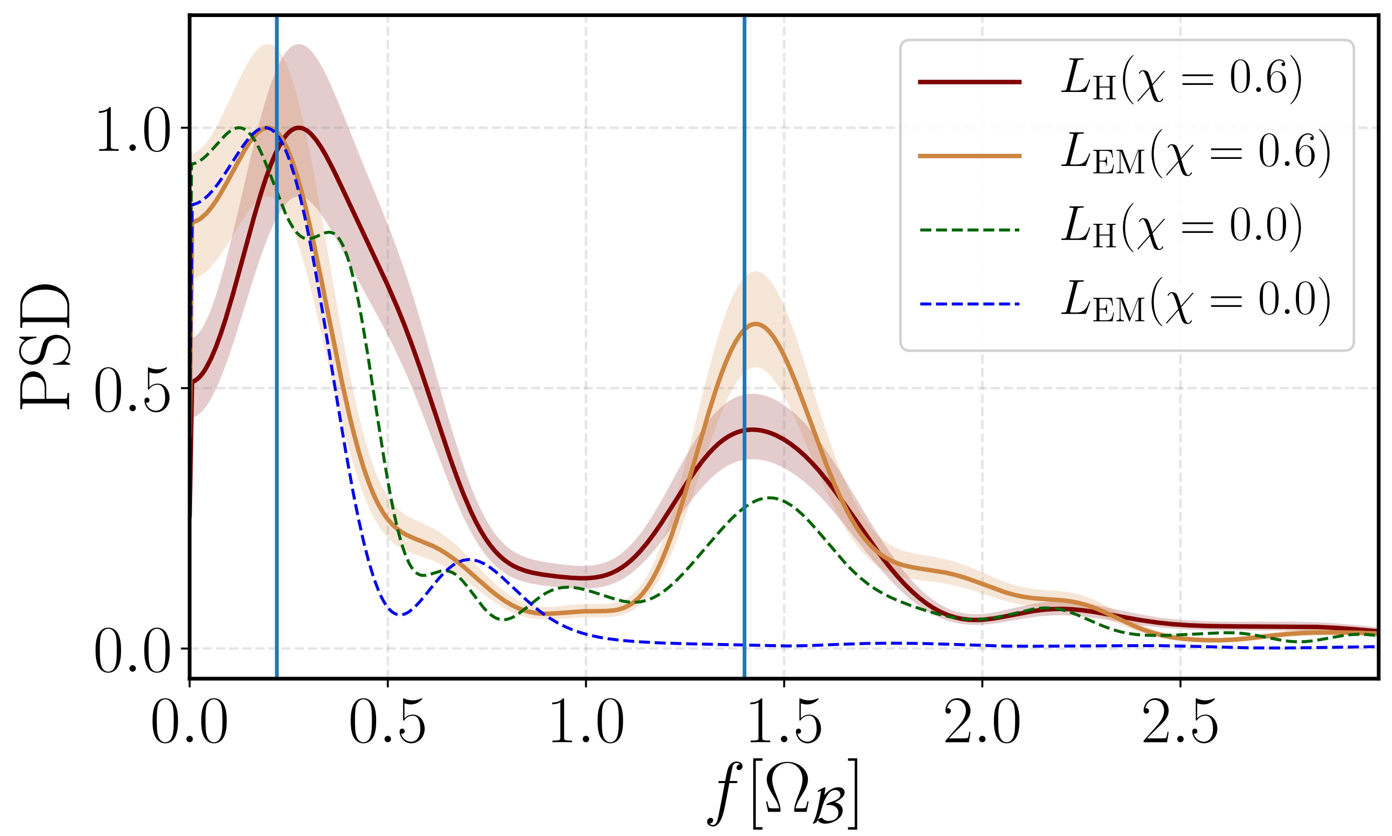
Circumbinary + Mini- Disk Regions

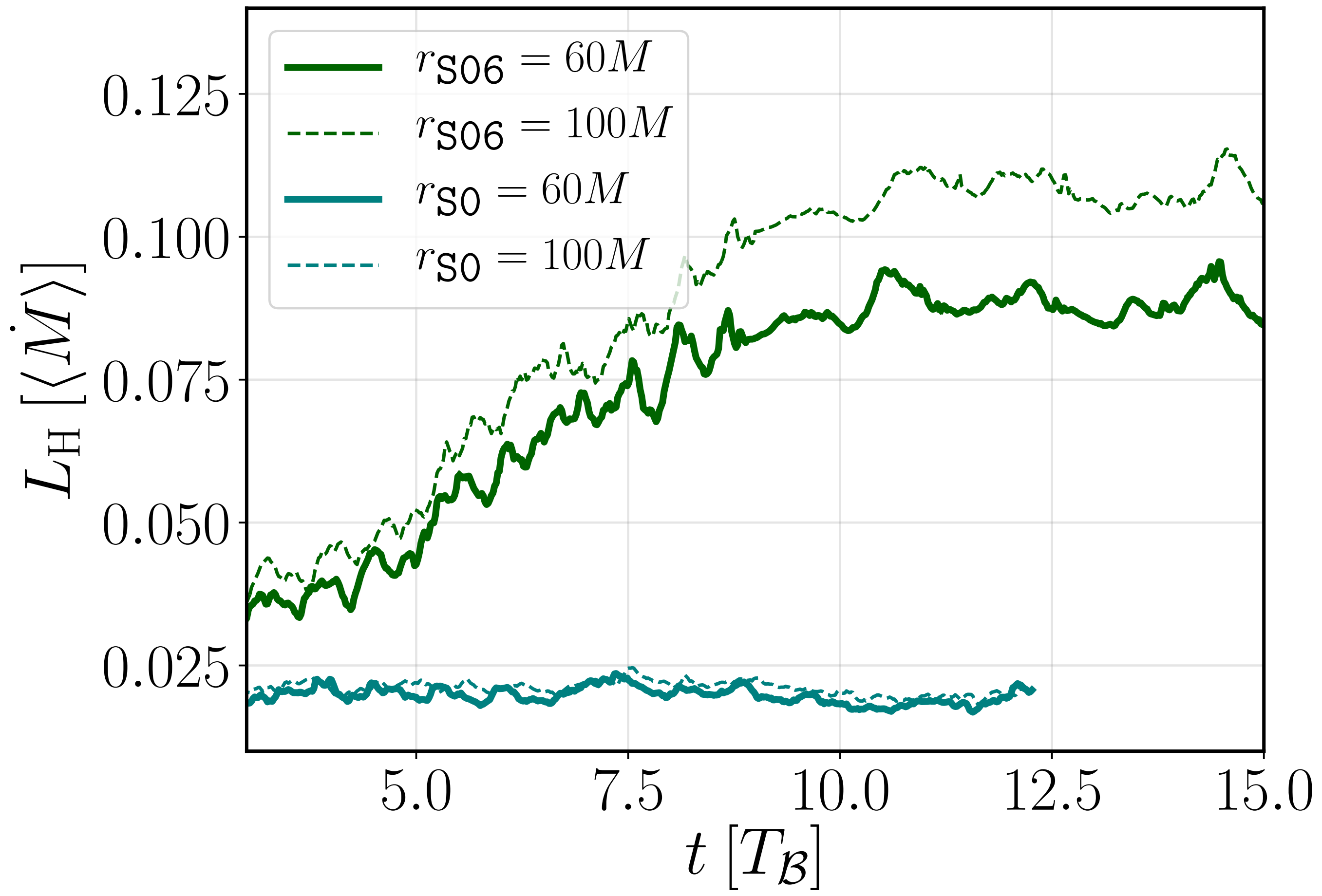




Poynting Scalar







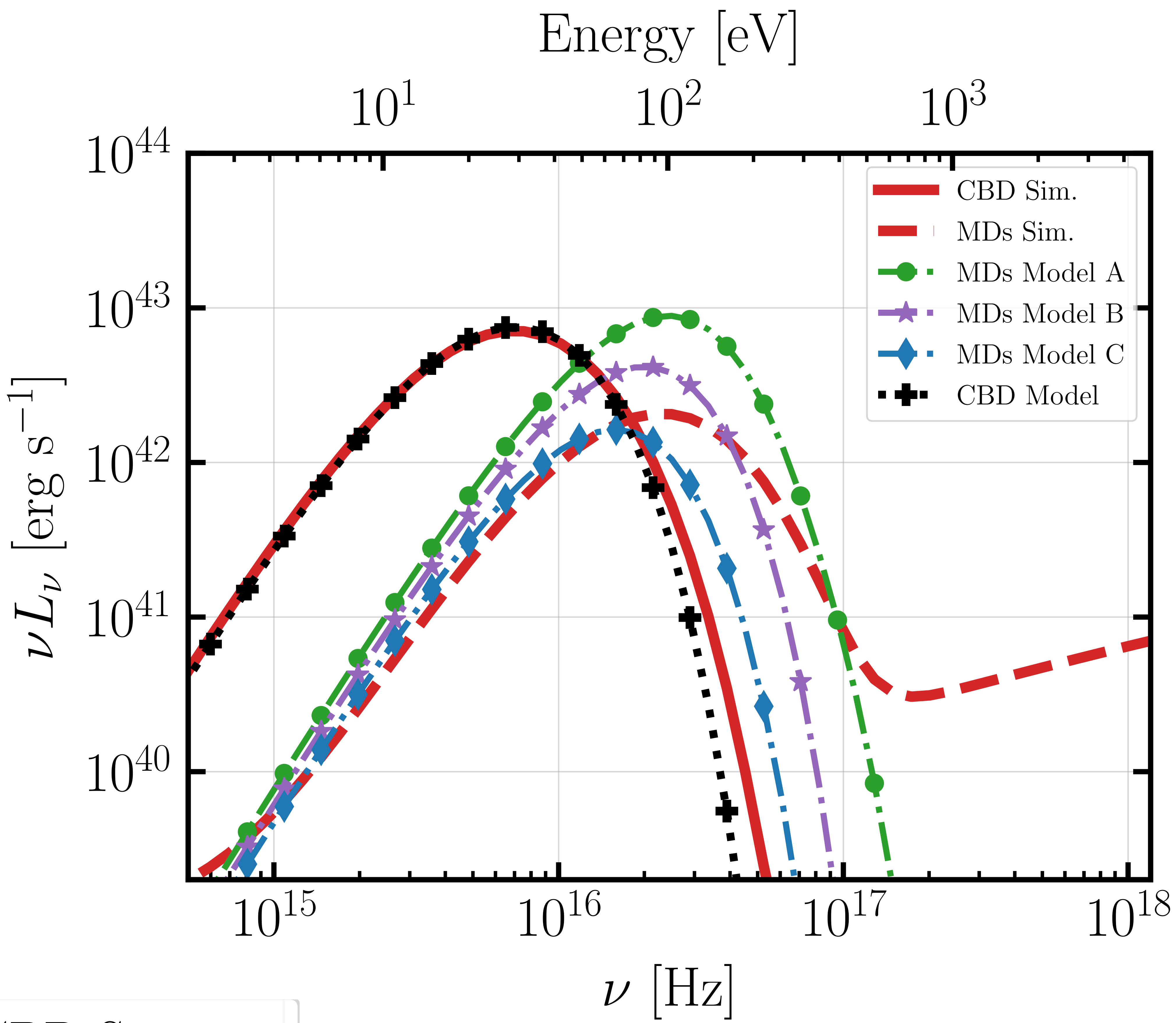
- **Hydro and EM fluxes are both larger with spins;**
  - **Possible signature of helical field orientation in emission's polarization?!**
- **Poynting luminosity modulated at 2x beat freq. w/ lump;**

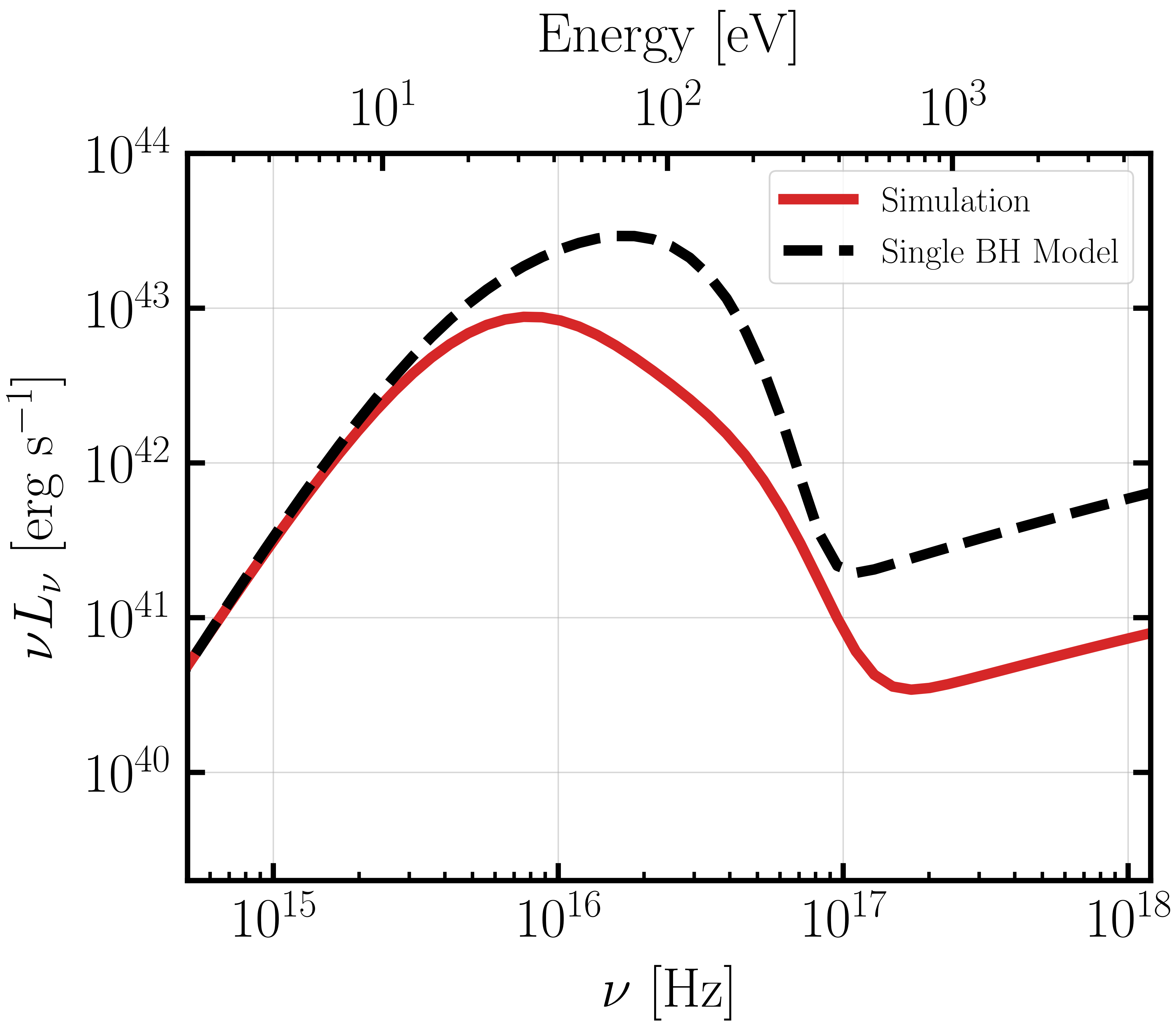
	χ_{00}	χ_{++}
$\eta_{\rm EM}$	0.5% —> 4%	5%
$\eta_{\rm H}$	2.5%	10%

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

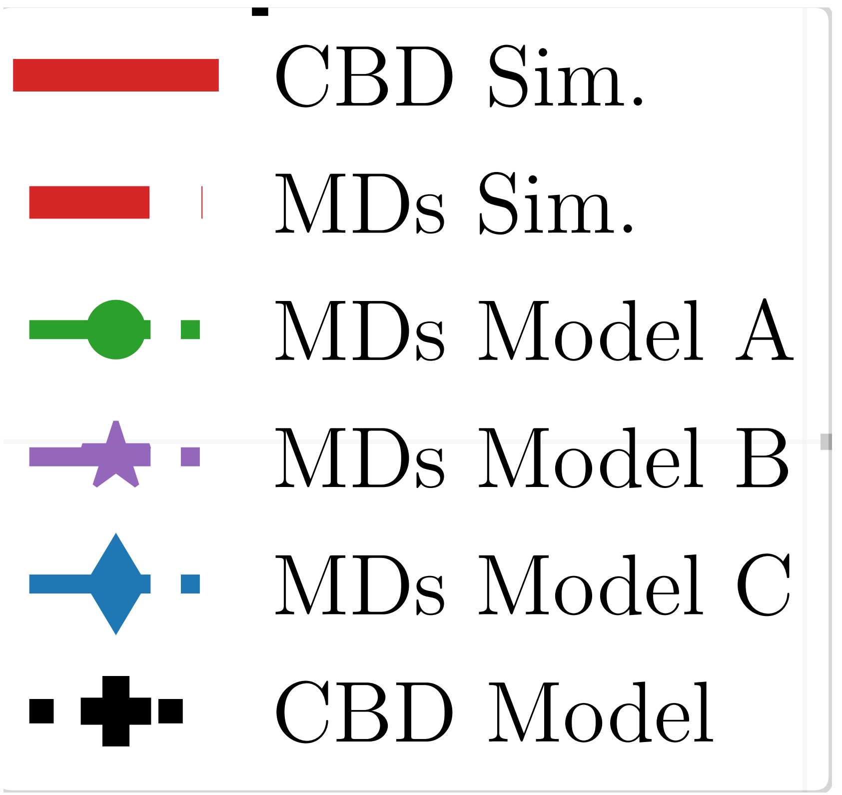
Spectra from Accretion onto Spinning BBHs

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





Spinning BBHs



CBD portion of simulation.

Mini-disk portion of simulation.

2 NT, $\dot{m}_1 = \dot{m}_2 = 0.125\dot{M}_{\rm Edd}$

2 NT, $\dot{m}_1 = 6 \times 10^{-2}\dot{M}_{\rm Edd},\ \dot{m}_2 = 6.8 \times 10^{-2}\dot{M}_{\rm Edd}$

2 NT, $\dot{m}_1 = 2.3 \times 10^{-2}\dot{M}_{\rm Edd},\ \dot{m}_2 = 2.7 \times 10^{-2}\dot{M}_{\rm Edd}$

1 NT, spin=0.6, 1e6 Msun, 2a < r < 7.5a

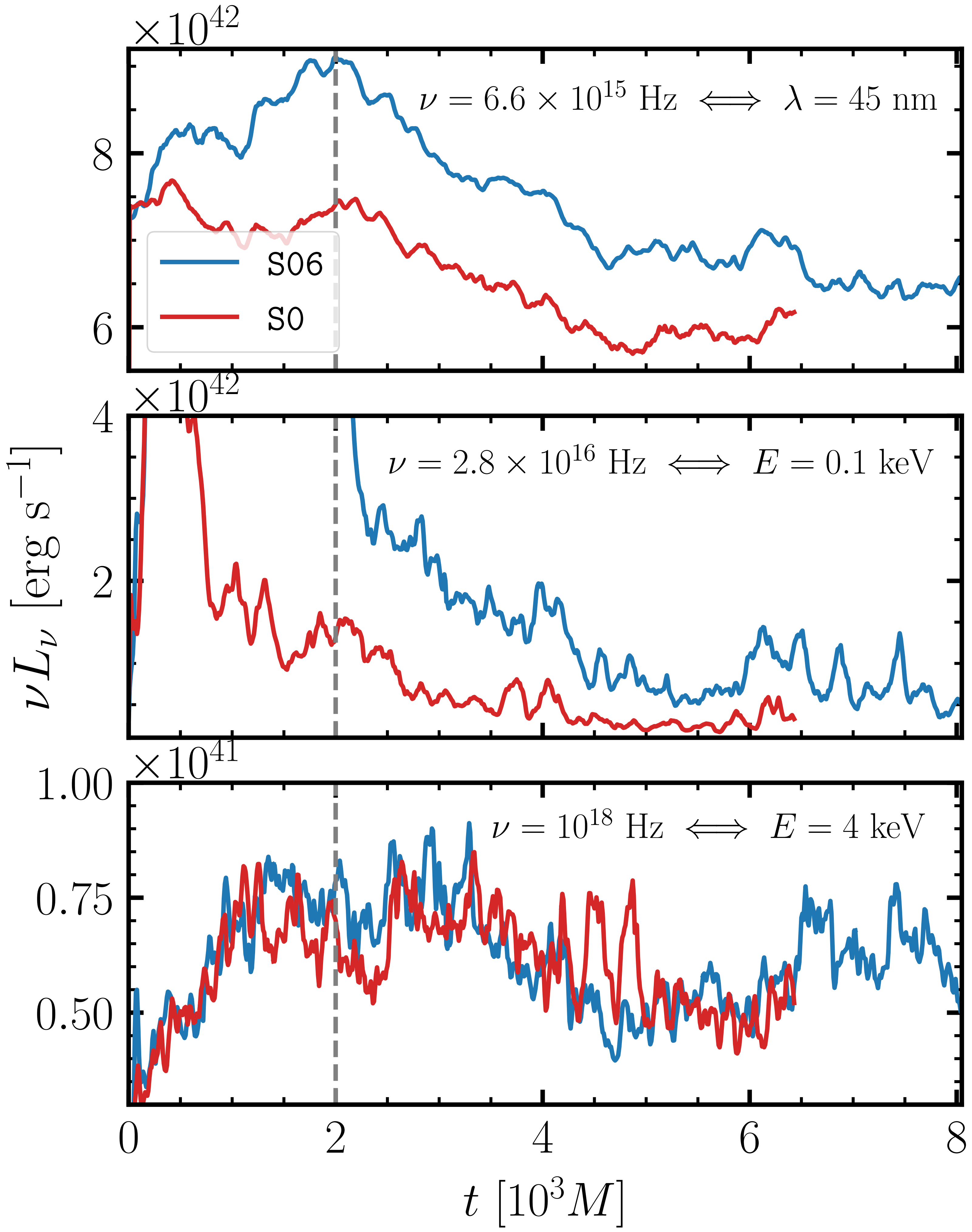
NT = Novikov-Thorne (1972) “thin disk”

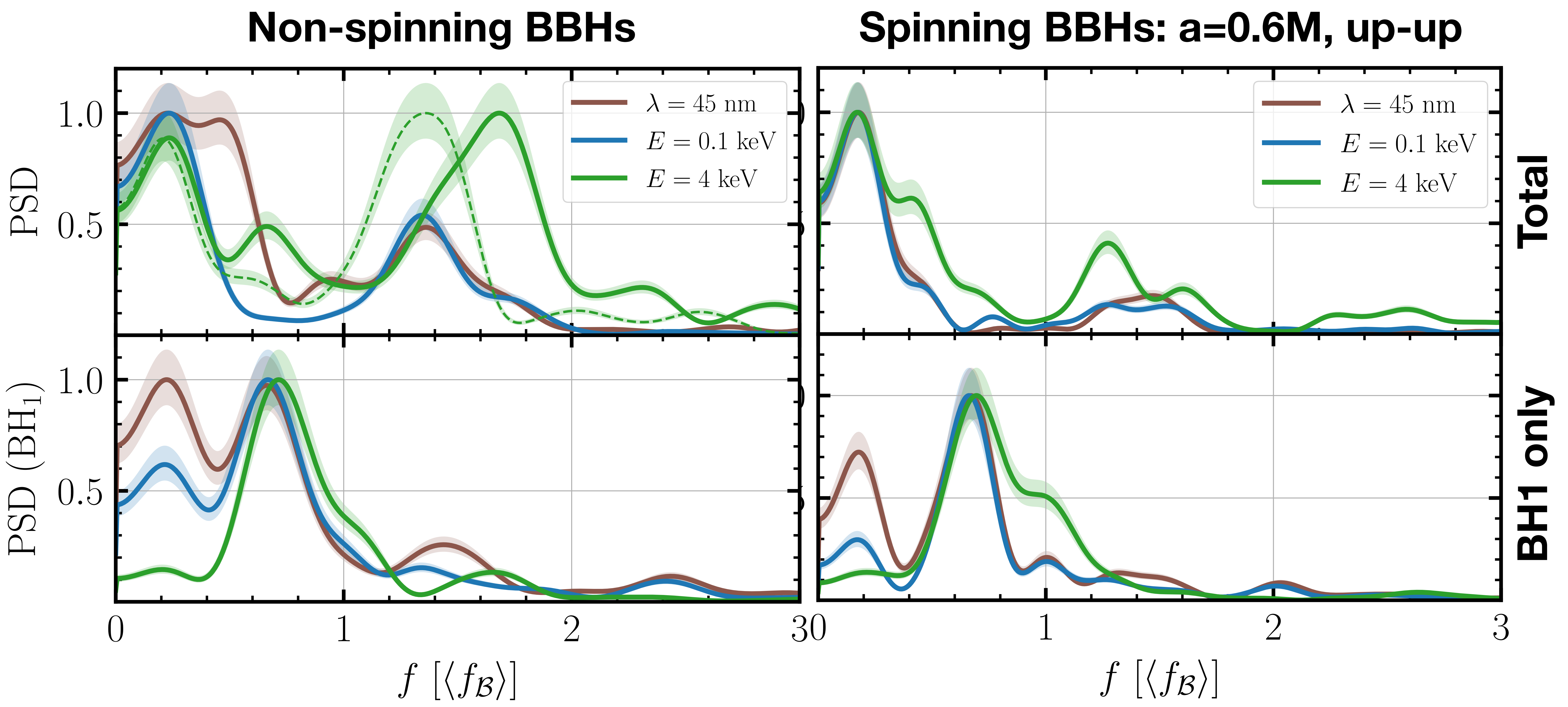
Schnittman, Krolik, and Noble, ApJ, 819, 48, (2016).

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

Light Curves from Accretion onto Spinning BBHs

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

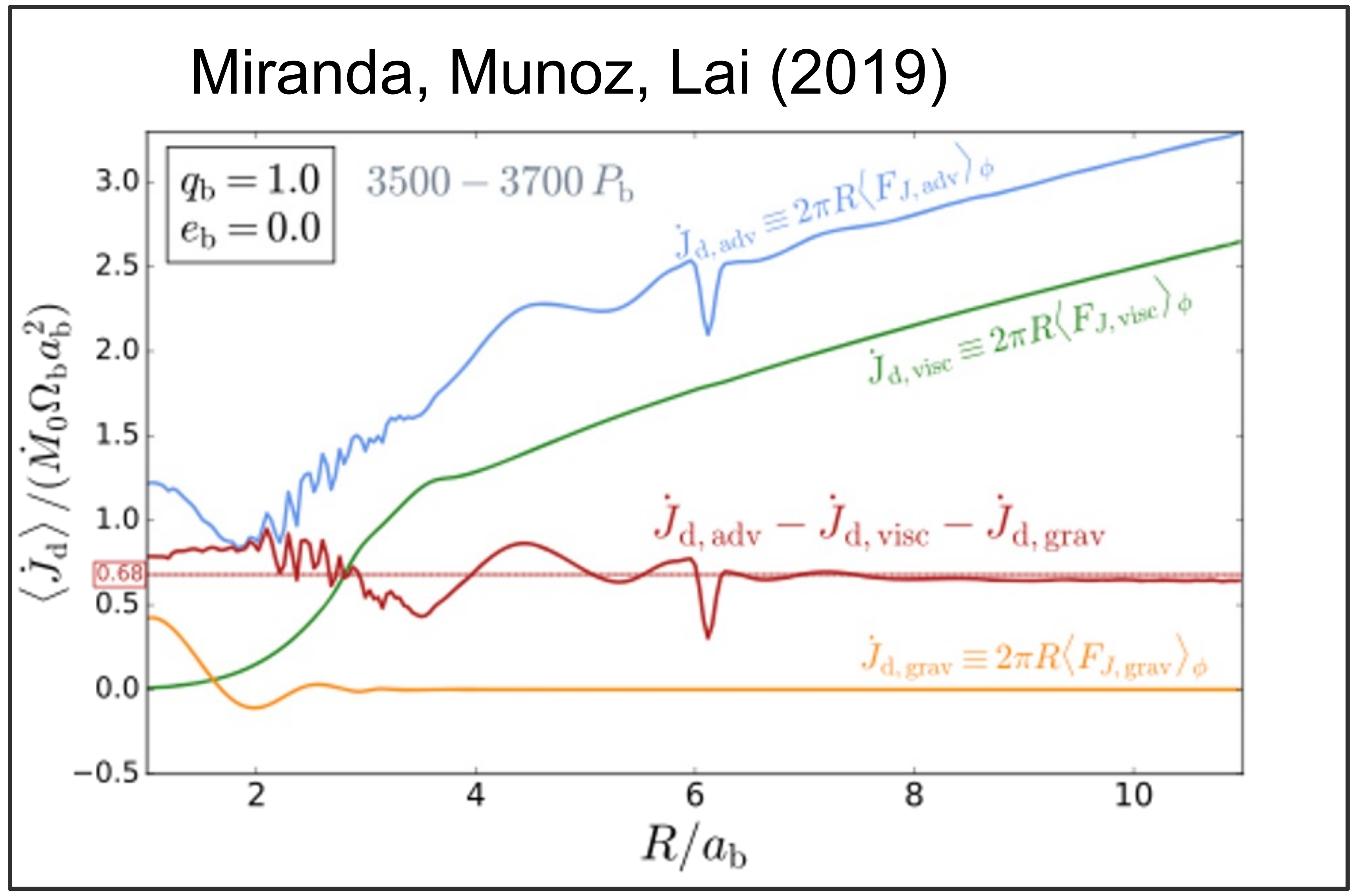




- Prograde spinning BBHs:
  - Longer-lived mini-disks lead to relatively steadier x-ray emission and weaker signals at 2x beat freq.;
  - Individual mini-disks still suffer beat modulation;
  - Total variability in all frequencies modulates by lump's orbital frequency, radial epicyclic oscillation;
-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

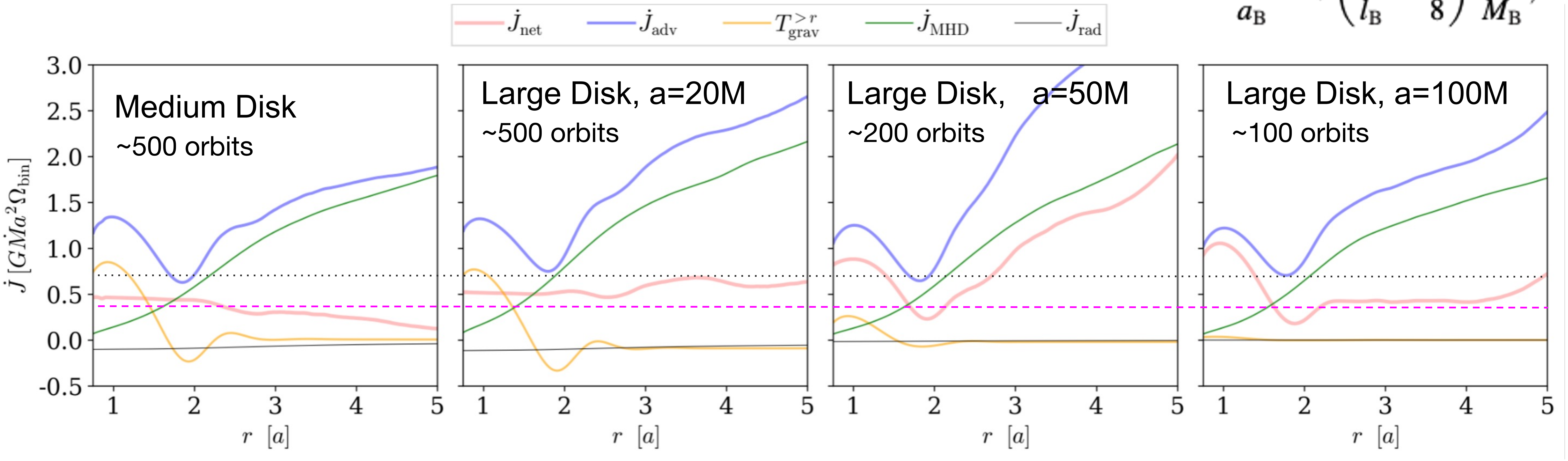
GR to Newtonian Scales

Gladkova, SCN++ in progress



- Does inspiral vs. outspiral depend on separation? MHD vs. viscosity?
- How do we reconcile need for mass inflow equilibrium and the likely fact that AGN have "short" periods of activity and may have stochastic feeding processes (e.g., TDEs, misaligned annuli, …) ?

$$\frac{\dot{a}_B}{a_B} = 8\left(\frac{l_0}{l_B} - \frac{3}{8}\right)\frac{\dot{M}_B}{M_B},$$



Open Questions

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