GRMHD Simulations of Accretion Flows onto Merging SuperMassive BHs

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Supermassive Black Hole Binary Mergers

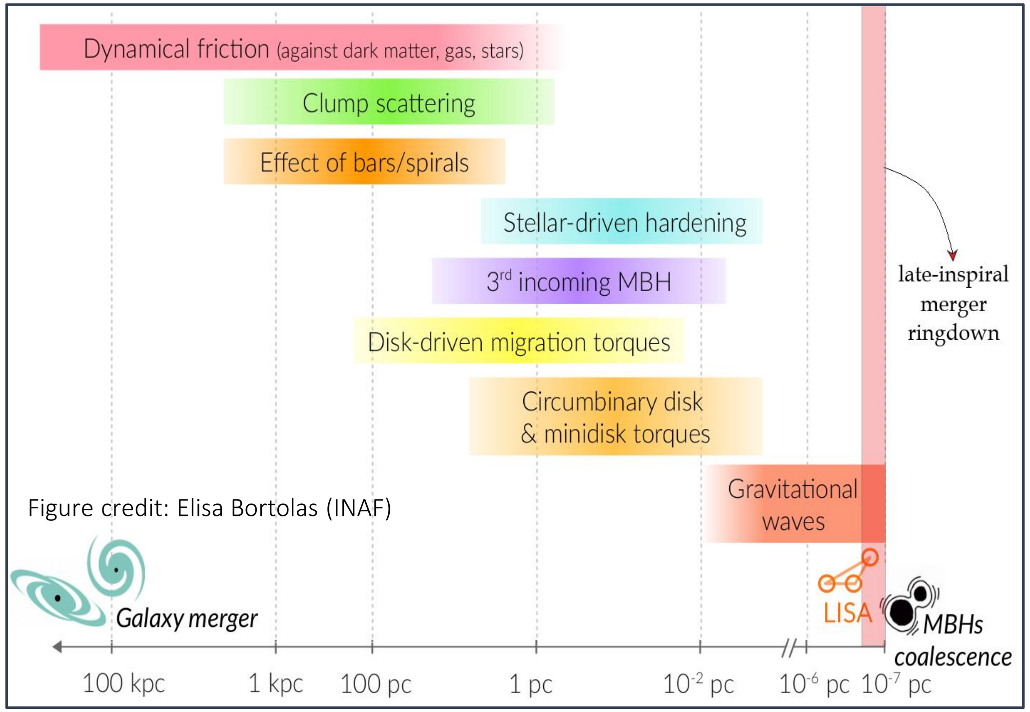
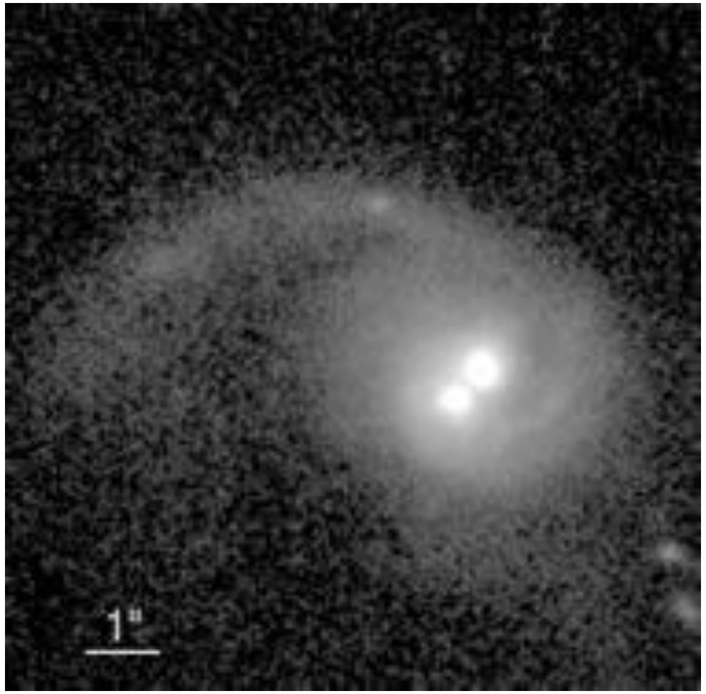


Figure credit: Elisa Bortolas (INAF)

- They can form after galaxy mergers
- They may be surrounded by accreting matter:
  - **Circumbinary Disk Model**
  - **Gas Cloud Model**
- When magnetized, the gas may lead to powerful ejecta and bright EM radiation together with the GW emission from the BH-BH binary.

Supermassive Black Hole Binary Mergers



Cromerford et al 2009

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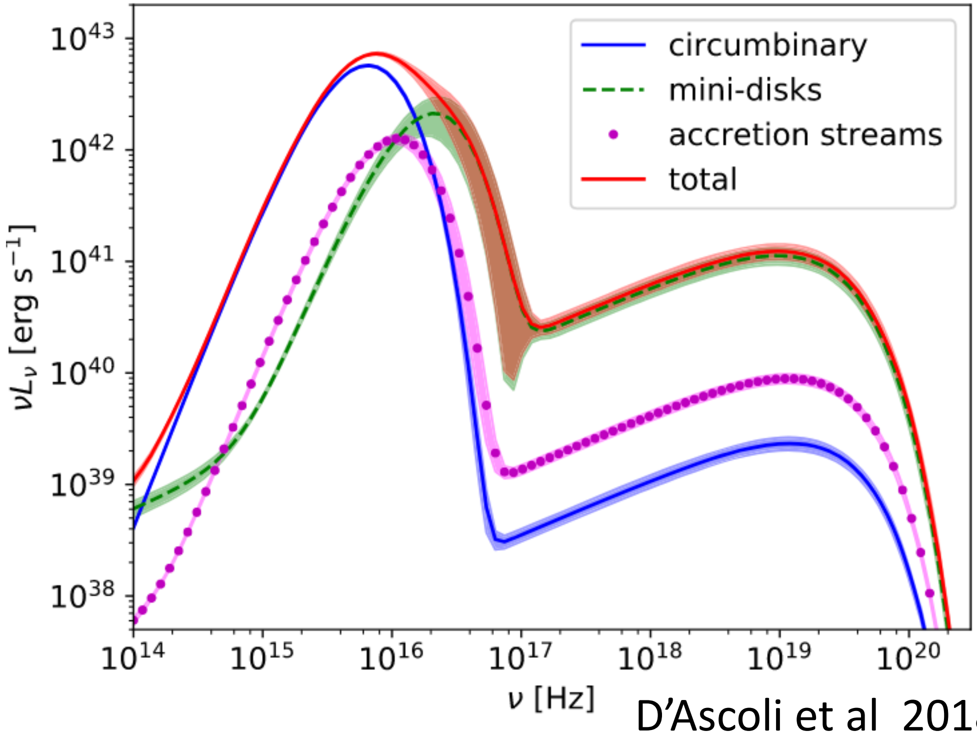

D'Ascoli et al 2018

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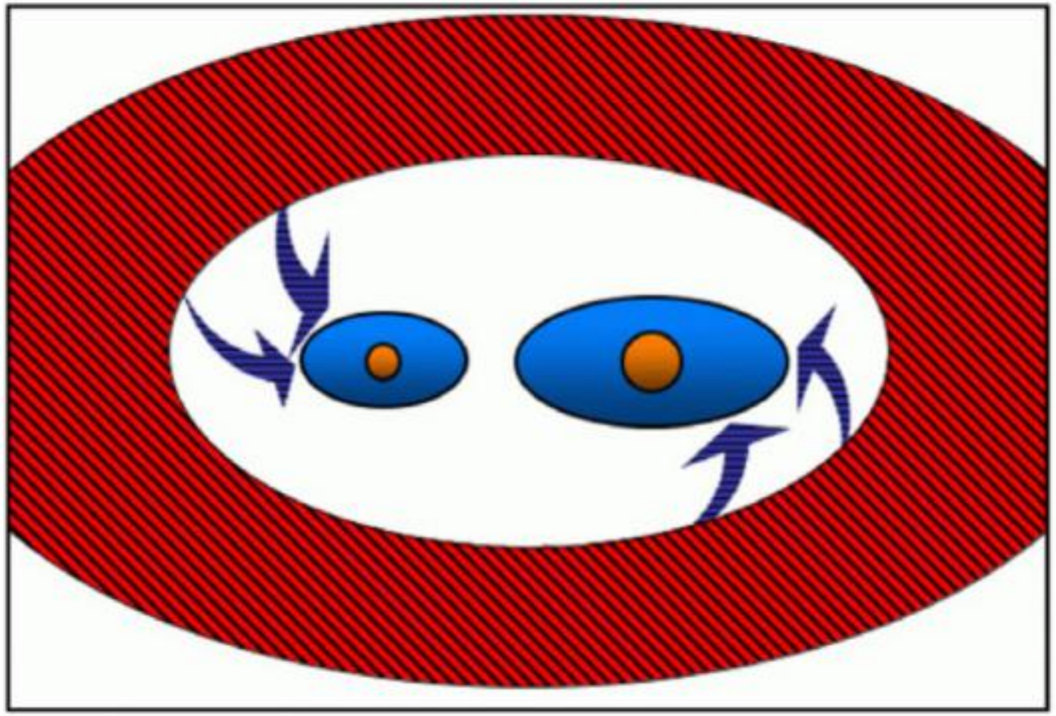
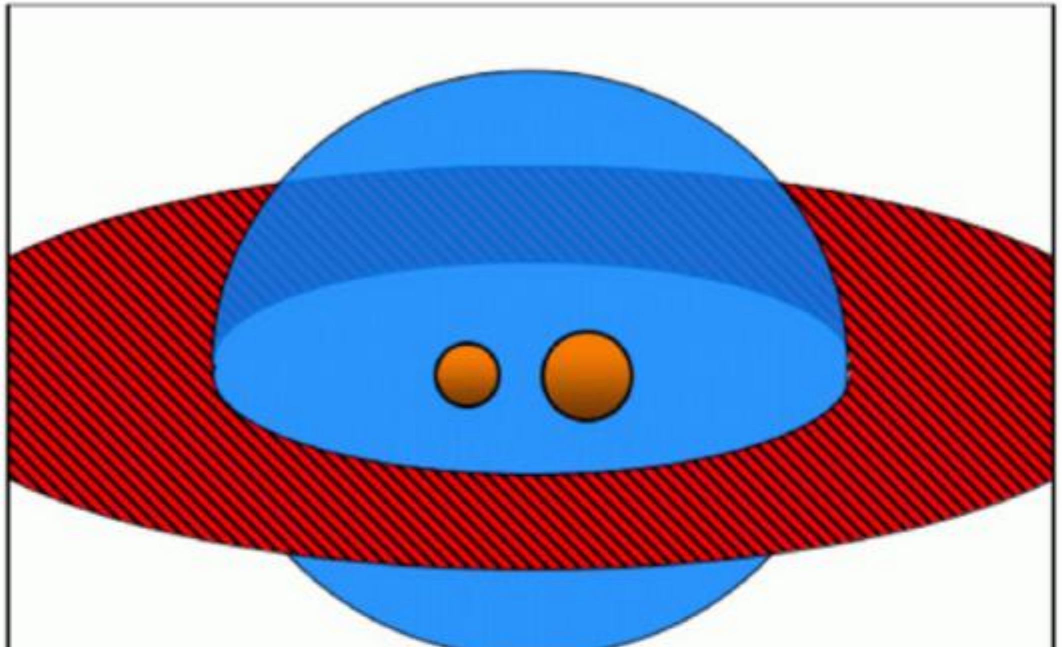
Gas Configurations

Circumbinary Disk



Gas Cloud



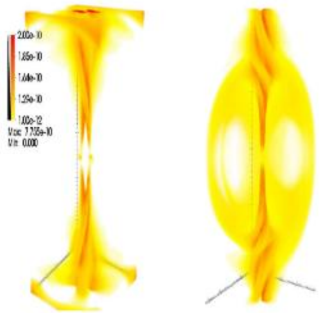
Bogdanović et al 2011

See also Cattorini & Giacomazzo 2024 for a recent review
https://doi.org/10.1016/j.astropartphys.2023.102892

Binary configurations

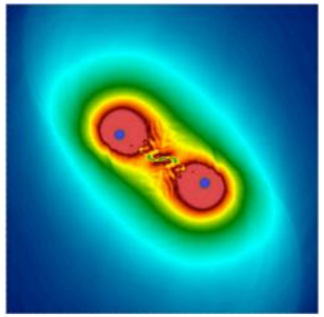
- SMBH binaries, quasicircular orbits, spin aligned/misaligned to the orbital angular momentum
- B field anchored to a circumbinary disk outside the computational domain

+ FF electrodynamics



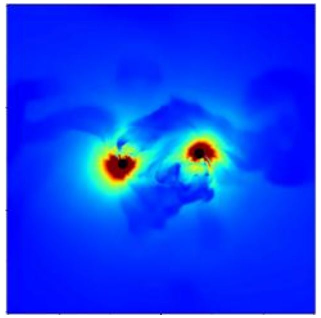
Palenzuela+10

+ ideal GRMHD



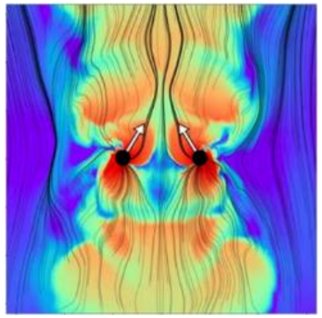
Giacomazzo+12

+ spinning BHs



Cattorini+21

+ misaligned spins



Cattorini+22

- Force-free electrodynamics (Palenzuela++, Science 329, 929 (2010), Moesta++, ApJL 749:L32 (2012))
- Ideal MHD (Giacomazzo++, ApJ 752, L15 (2012), Kelly++, PRD 96, 123003 (2017))
- Binaries of spinning BHs, aligned (Cattorini++, PRD 102, 103022 (2021)) and misaligned (Cattorini++, ApJL 930, L1 (2022)) with the orbital angular momentum
- Unequal-mass ratios, different gas profiles (Cattorini++, PRD 109, 043004 (2024), Fedrigo++, PRD 109, 103024 (2024))

Progressive increase in physical complexity

Equations

Einstein Equations

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

Hydro Equations

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\nabla_\mu J^\mu = 0$$

$$P = P(\rho, \epsilon)$$

$$J^\mu = \rho u^\mu$$

$$T^{\mu\nu} = (\rho h + b^2) u^\mu u^\nu + \left(p + \frac{b^2}{2}\right) g^{\mu\nu} - b^\mu b^\nu$$

Maxwell Equations

$$\nabla_\nu {}^*F^{\mu\nu} = 0$$

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Maxwell Equations

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Initial Data (part 1)

We extended previous works on the gas cloud model including (for the first time in GRMHD) the effect of BH spins (aligned and misaligned).

- F. Cattorini, **B. Giacomazzo**, F. Haardt, M. Colpi 2021, PRD 103, 103022:
  - Non spinning ($a \equiv J/M^2$=0) and spinning (a=0.3 and a=0.6) equal-mass configurations (both spins parallel to the orbital angular momentum)
- F. Cattorini, S. Maggioni, **B. Giacomazzo**, F. Haardt, M. Colpi, S. Covino 2022, APJL 930, L1:
  - All equal-mass models with spin a=0.6
  - 3 models with spins parallel or antiparallel to orbital angular momentum (UU, UD, DD)
  - 2 models with spins misaligned (UUMIS, UDMIS)

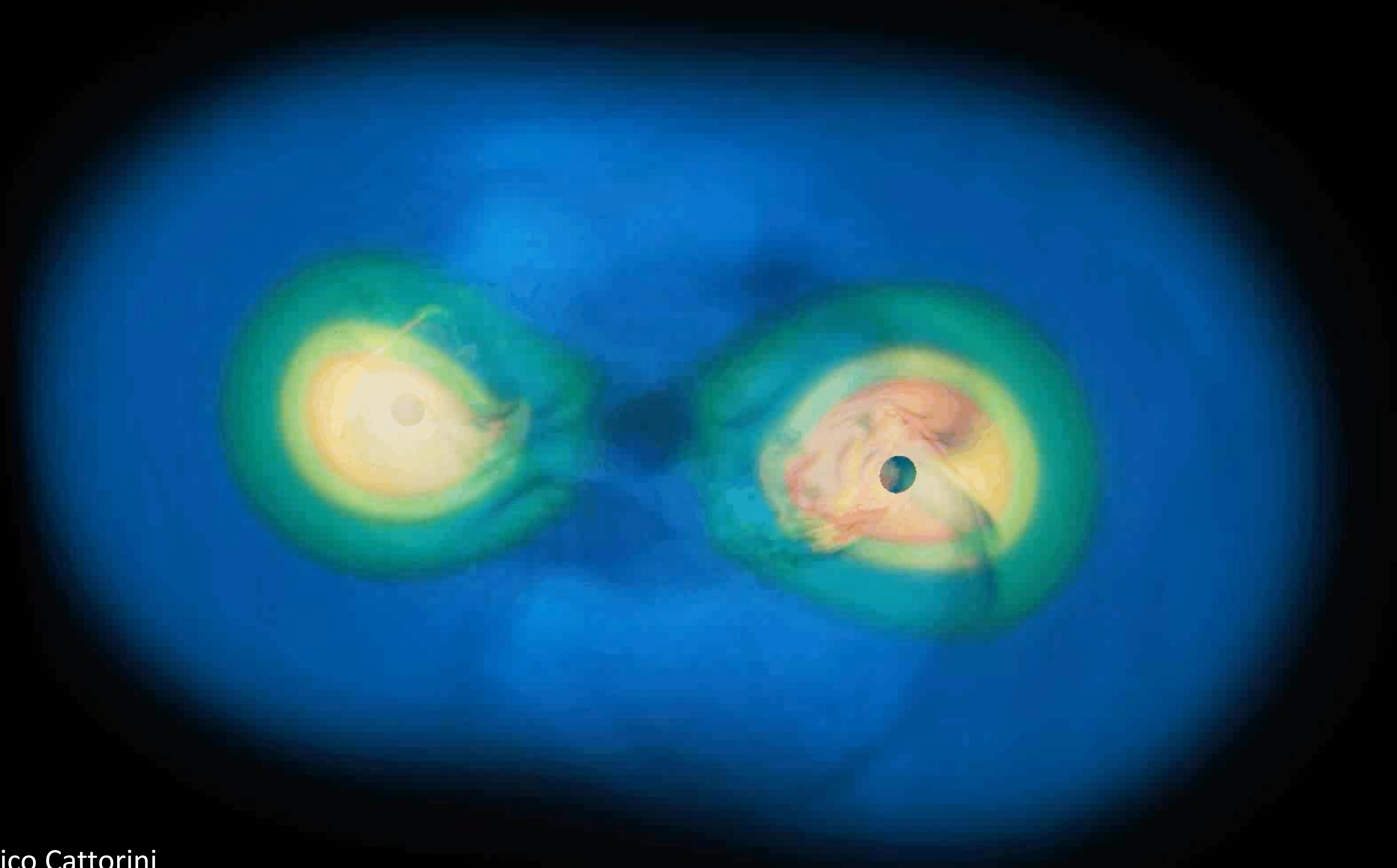
In both papers an ideal gas law ($\Gamma = 4/3$) was used ($T \sim 10^{12} K$).

Initially uniform plasma and magnetic field with $\beta^{-1} \approx 0.3$ ($B \sim 10^5 G$).

For our simulations we used the publicly available IllinoisGRMHD code

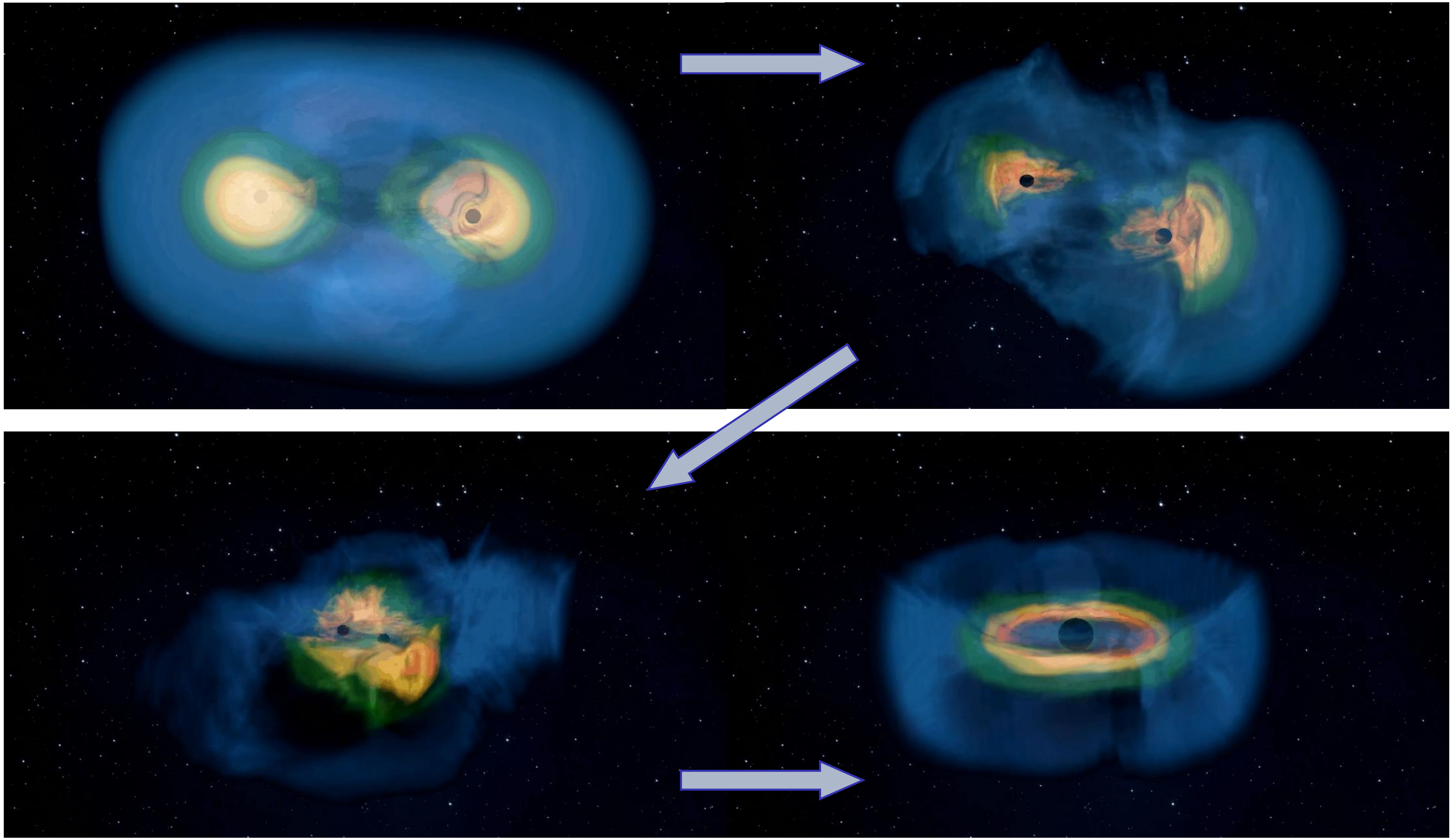
(included in the Einstein Toolkit)

www.einsteintoolkit.org



UUMIS model
Movie by Federico Cattorini
Cattorini et al 2022

https://youtu.be/ln-b0ZXnYLg



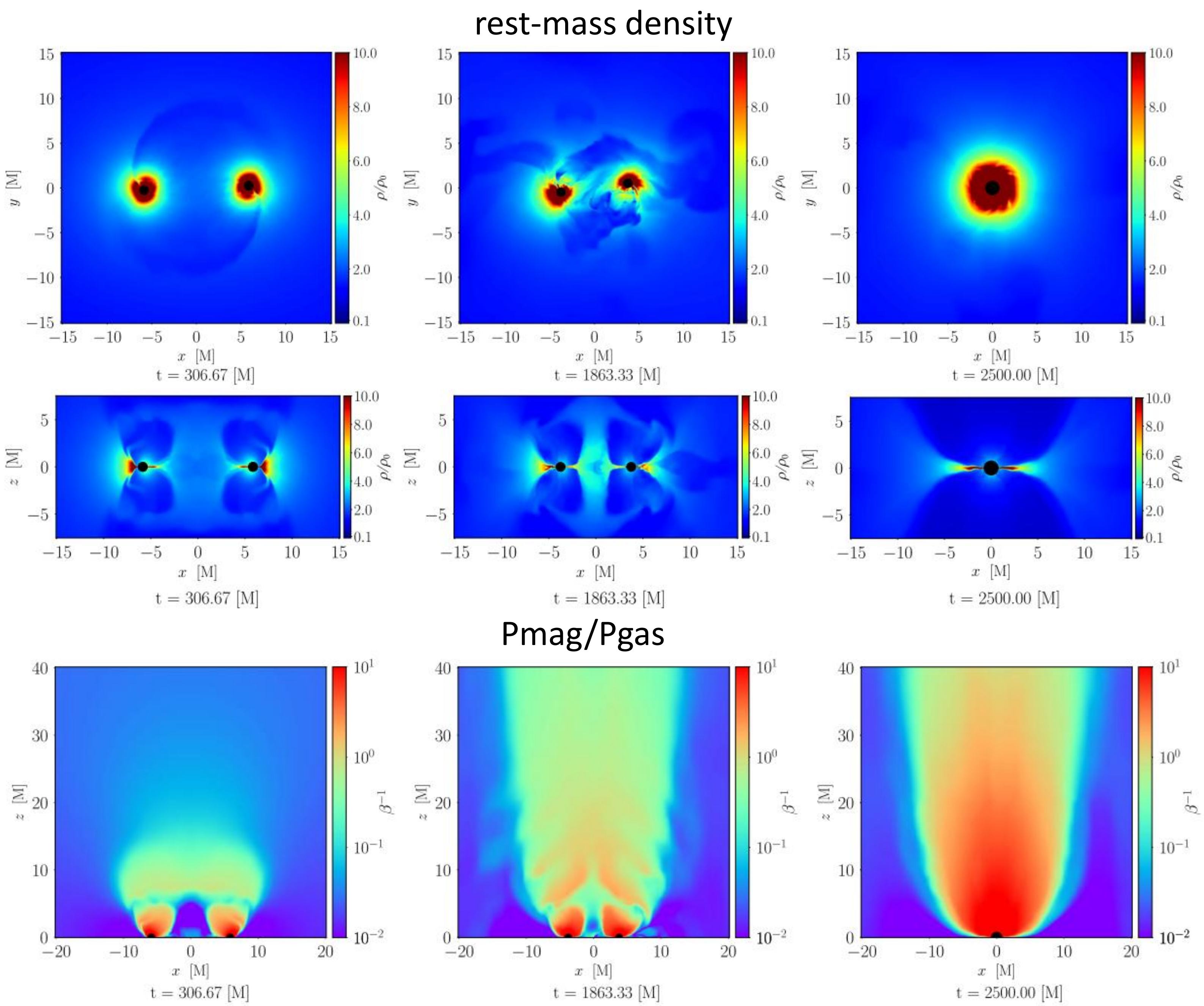
Aligned Spins

Accretion rates in magnetized models found to be smaller by up to ~3 times.

Aligned spins also reduce accretion by up to ~50%.

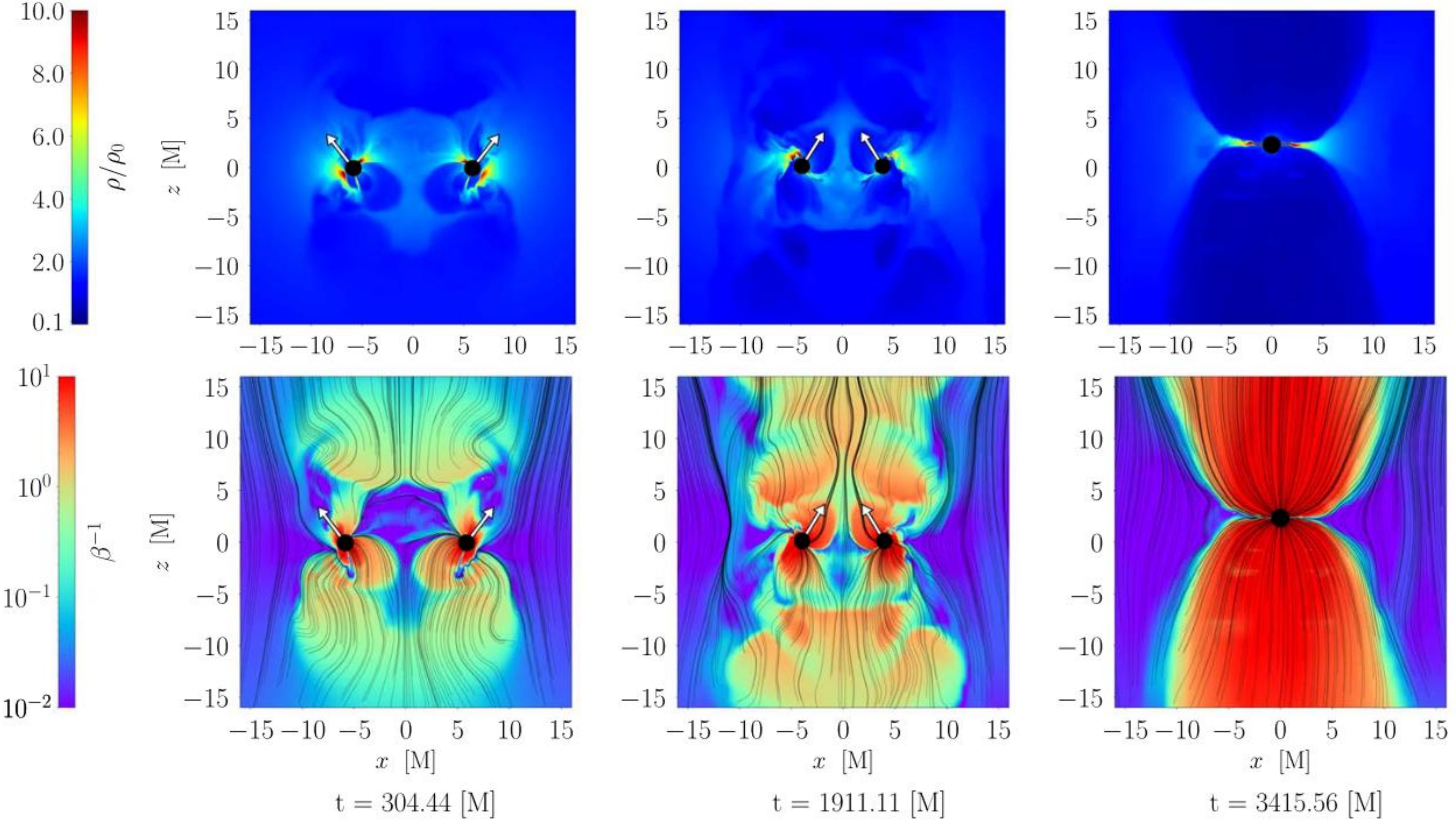
Aligned spins increase Poynting luminosity by a factor ~2.

Both spins and magnetic fields affect the dynamics of these systems.



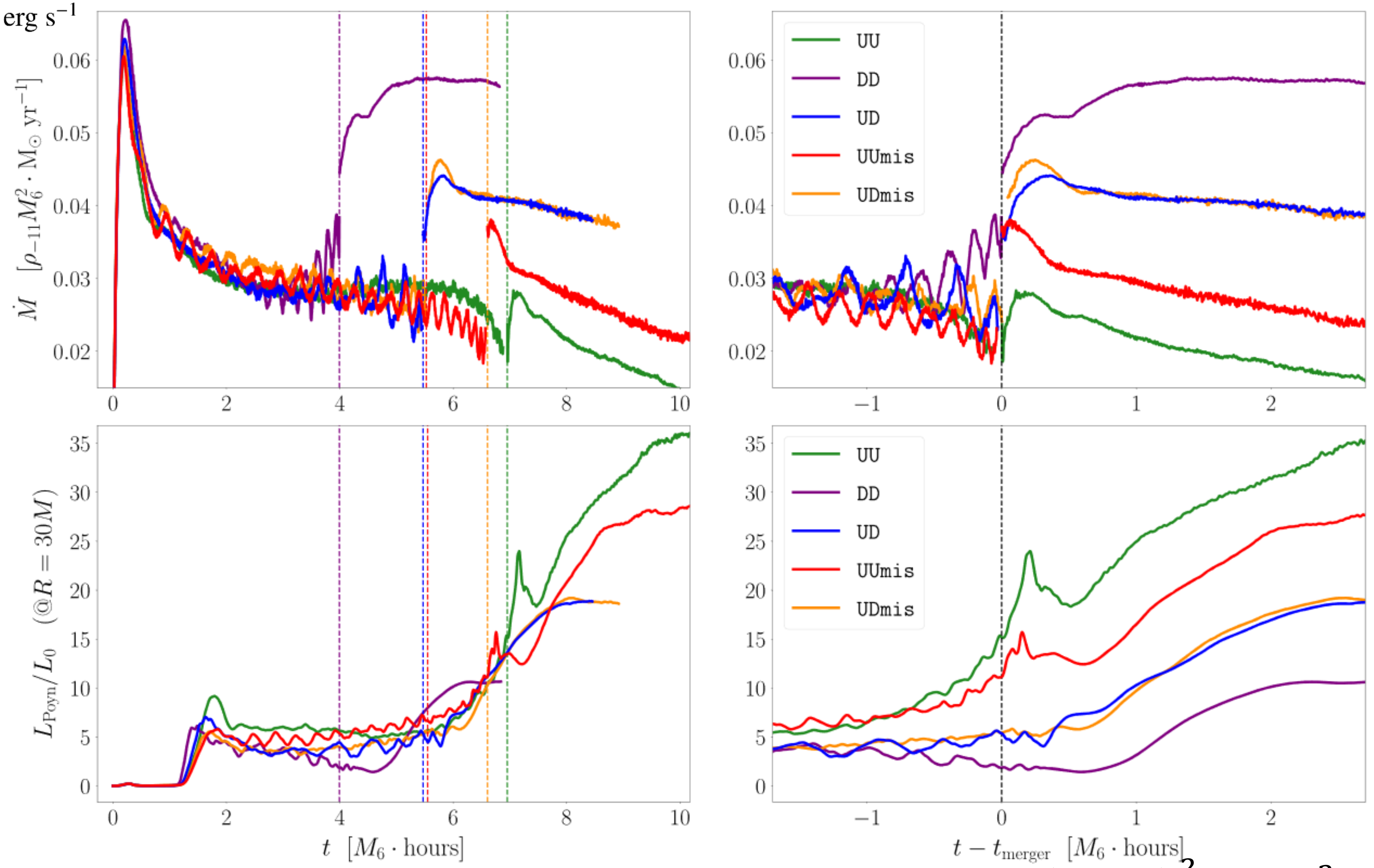
Cattorini et al 2021

UUMIS run



Cattorini et al 2022

$L_0 \simeq 5.9 \times 10^{42} \rho_{-11} M_6^2$ erg s^{-1}

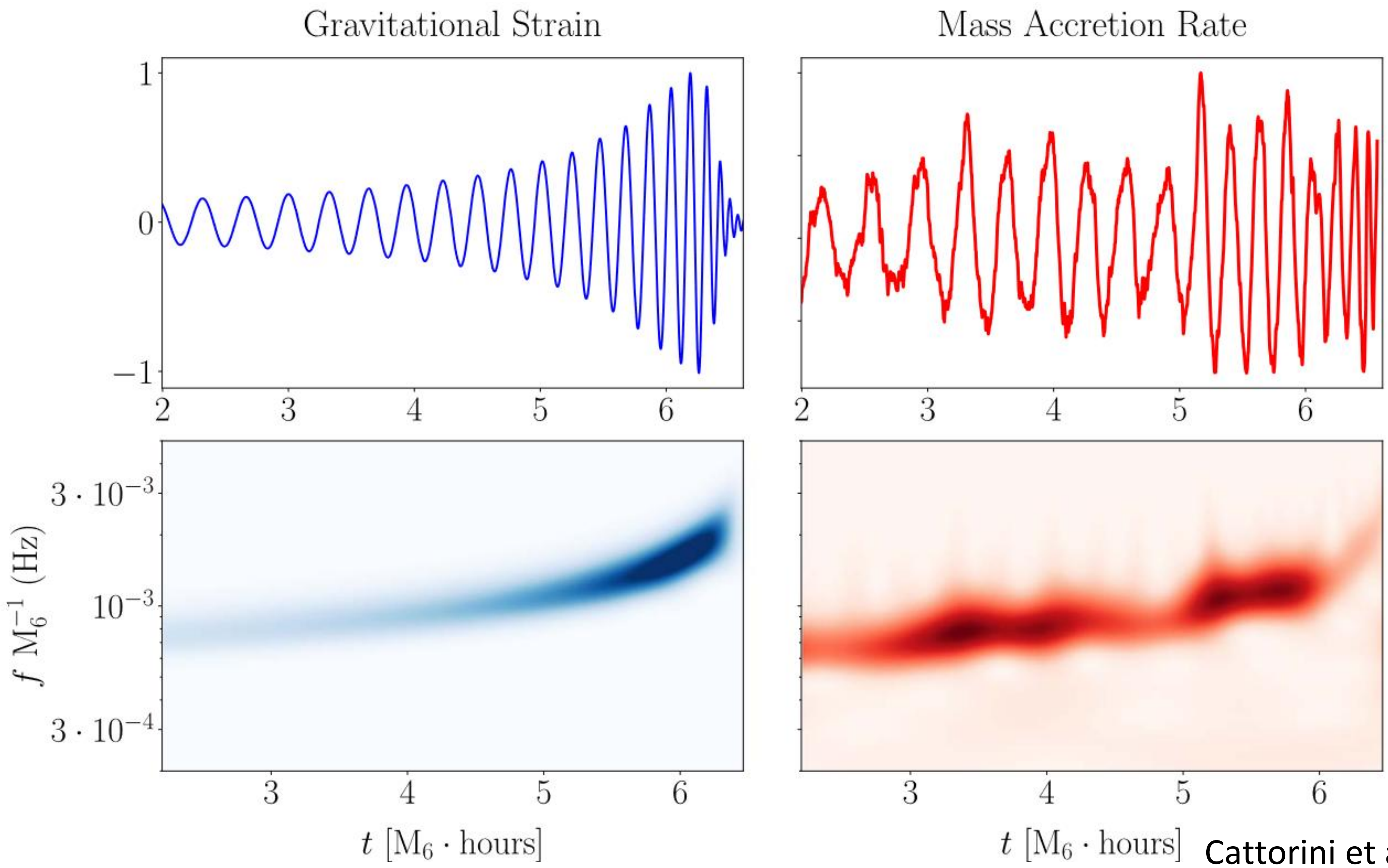


Cattorini et al 2022

Results consistent with Blandford-Znajek mechanism $L_{BZ} \sim 10^{43} erg\ s^{-1} (a)^2 \left(\frac{M}{10^6 M_\odot}\right)^2 \left(\frac{B}{10^6 G}\right)^2$

Postmerger luminosity is little sensitive to initial magnetization, but increases up to a factor ~5 for higher spin values.

UUMIS run



Cattorini et al 2022

Accretion rate displays a «chirp» analogous to the gravitational one.
Possible means for identifying MBHBs in the late-inspiral? Pre-merger multimessenger possibility?

Initial Data (part 2)

We also considered precessing binaries and different gas configurations.

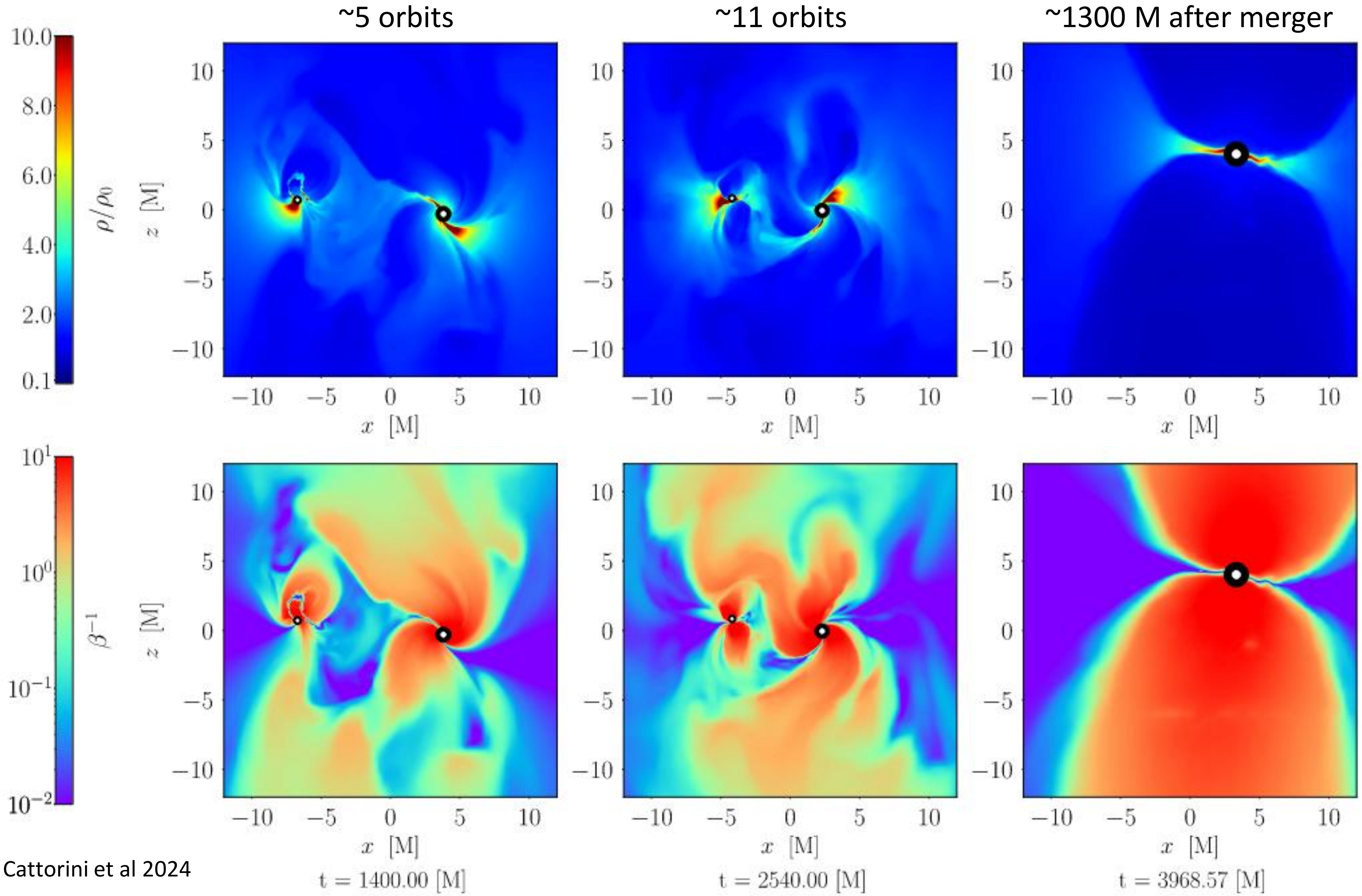
- F. Cattorini, **B. Giacomazzo**, M. Colpi, F. Haardt, 2024, PRD 109, 043004:
  - 8 unequal-mass (q=0.6) spinning (a=0.6) BBH simulations with different spin inclinations causing orbital precession
- G. Fedrigo, F. Cattorini, **B. Giacomazzo**, M. Colpi 2024, PRD 109, 103024:
  - All equal-mass models embedded in a gas slab (instead of a gas cloud)
  - 2 non spinning models, 2 with spin aligned (UU), 2 with spin misaligned (UUMIS)
  - 2 models with spins misaligned (UUMIS, UDMIS)

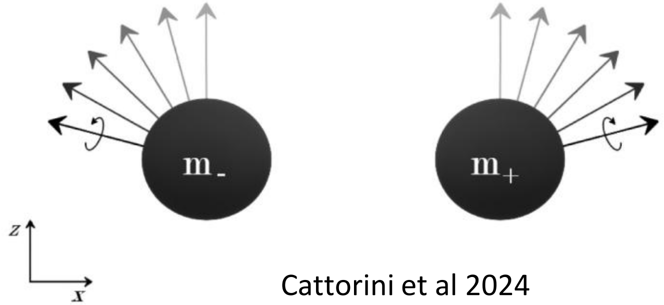
We used an ideal gas law with $\Gamma = 4/3$ (also $\Gamma = 5/3$ and $\Gamma = 13/9$ in the first paper).

Initially uniform plasma and magnetic field with $\beta^{-1} \approx 0.3$ ($B \sim 10^5 G$).

The publicly available IllinoisGRMHD code (included in the Einstein Toolkit) was used.

Precessing Binaries

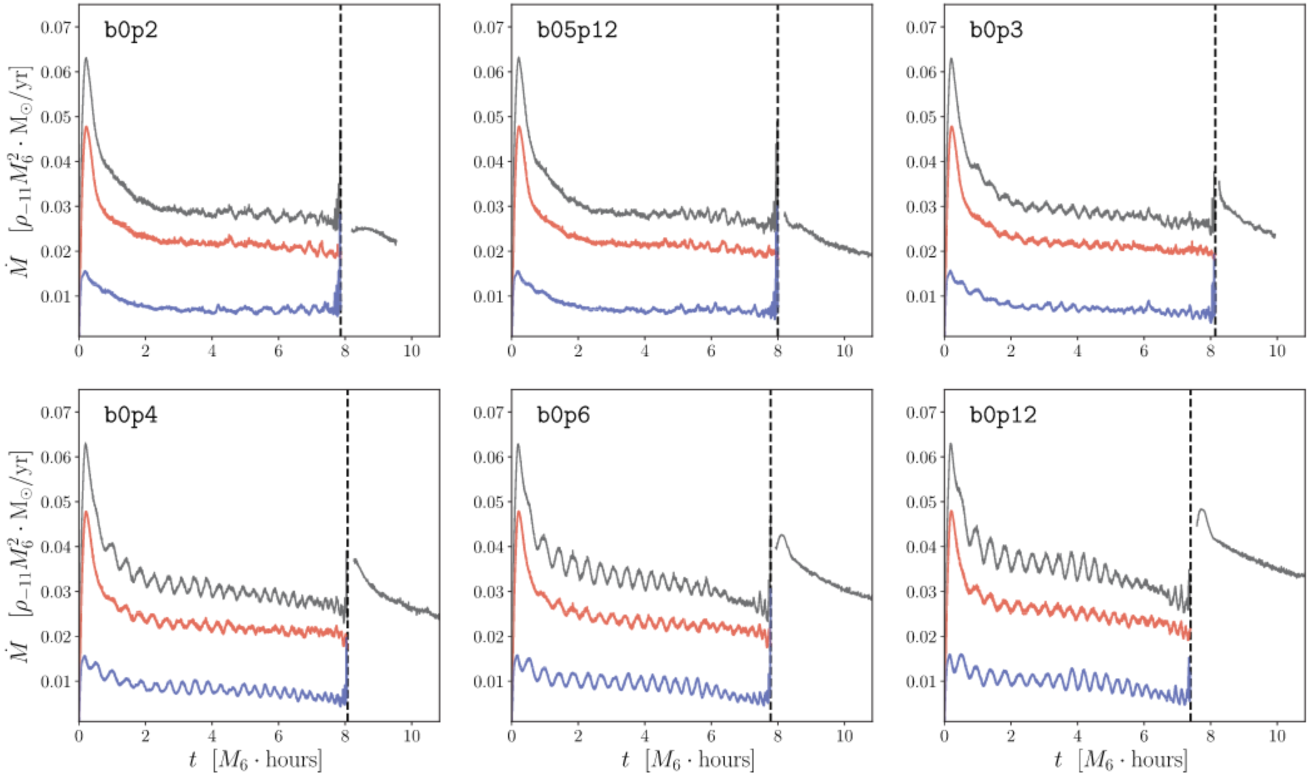




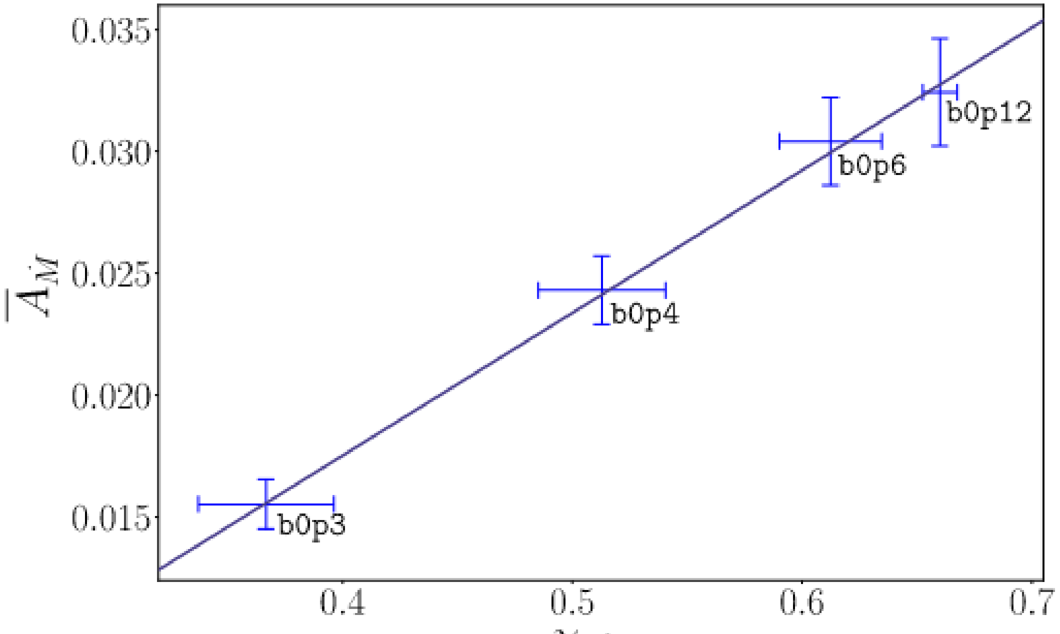
Cattorini et al 2024

Cattorini et al 2024

Precessing Binaries



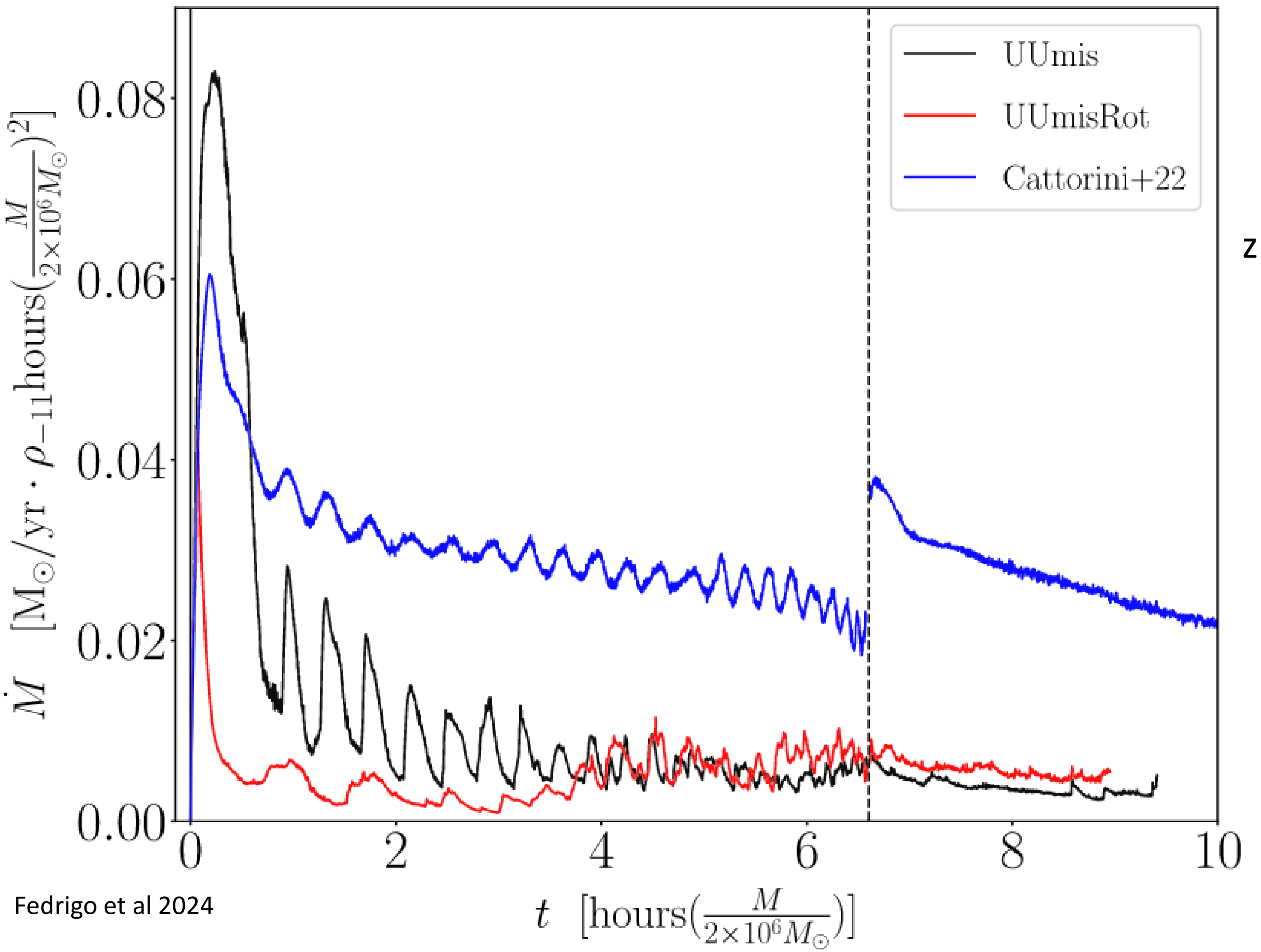
Cattorini et al 2024



Cattorini et al 2024

Correlation between modulation amplitude and the effective precession parameter χ_p

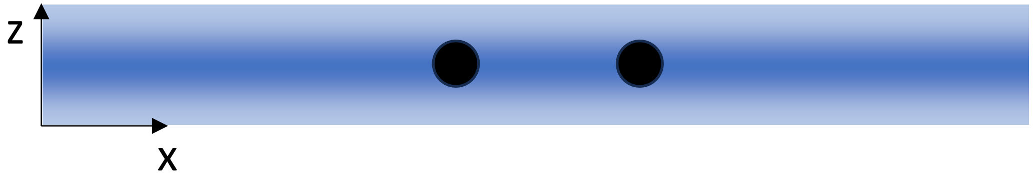
Gas Slab



Fedrigo et al 2024

Gas slab configuration:

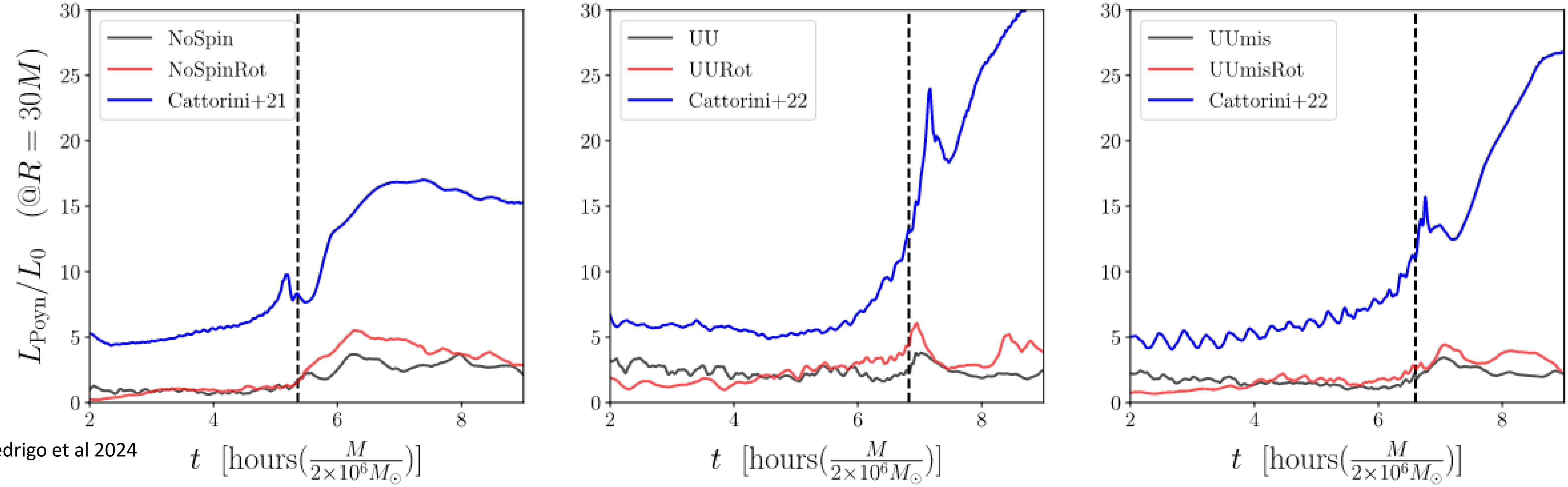
$$\rho(r,z) = \rho_0 \exp\left(-\frac{z^2}{2\sigma_{slab}^2}\right)$$



Modulations are present also in this case, but no strong peak at merger.

$L_0 \simeq 5.9 \times 10^{42} \rho_{-11} M_6^2 \text{ erg s}^{-1}$

Gas Slab

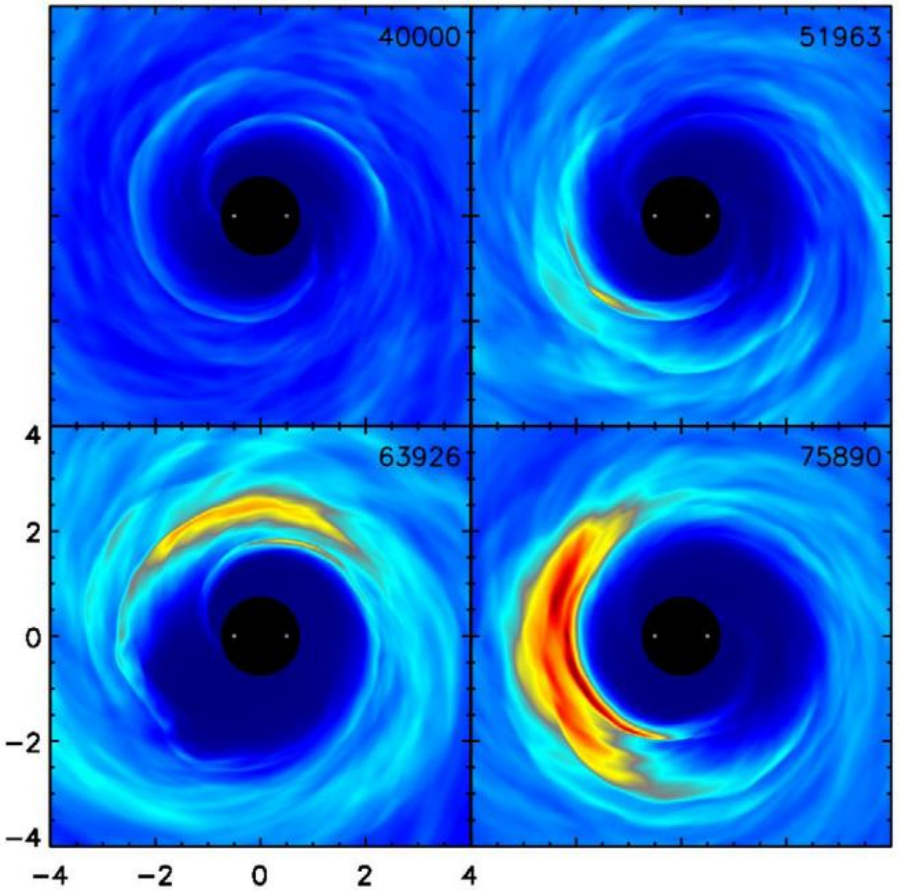


Fedrigo et al 2024

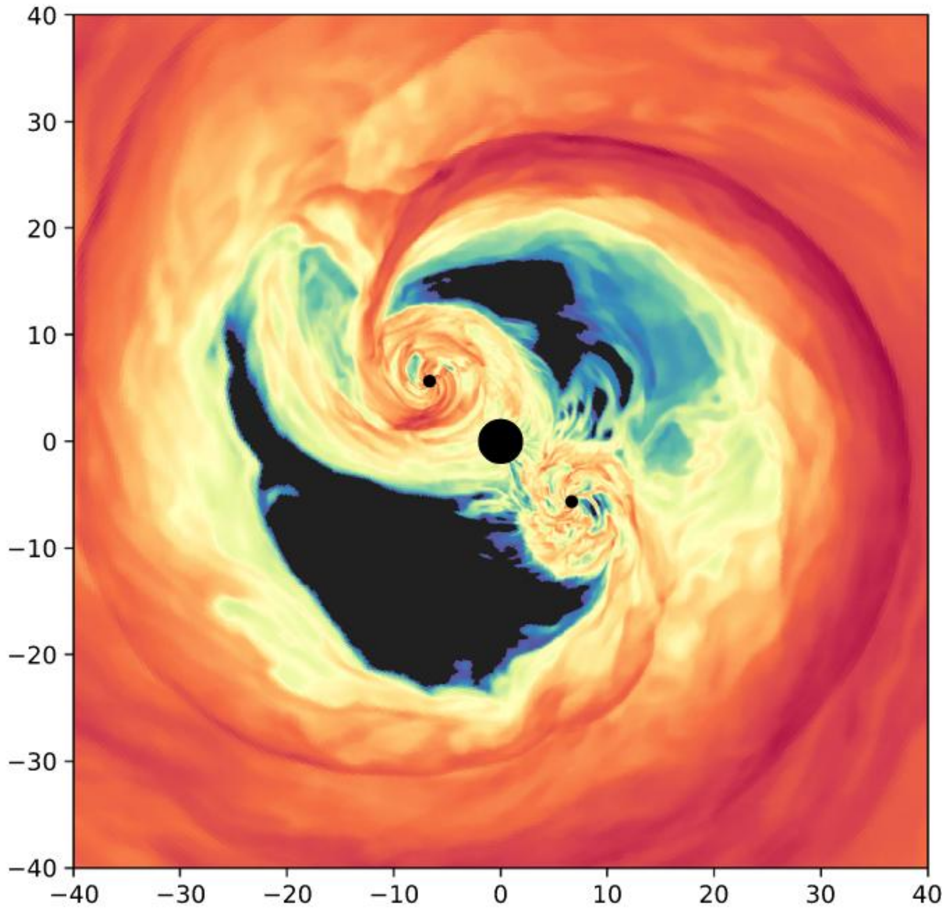
Lower Poynting luminosity L_{Poyn} than the gas cloud scenario

No peak at merger in L_{Poyn}

Modulations in Circumbinary Disk Models

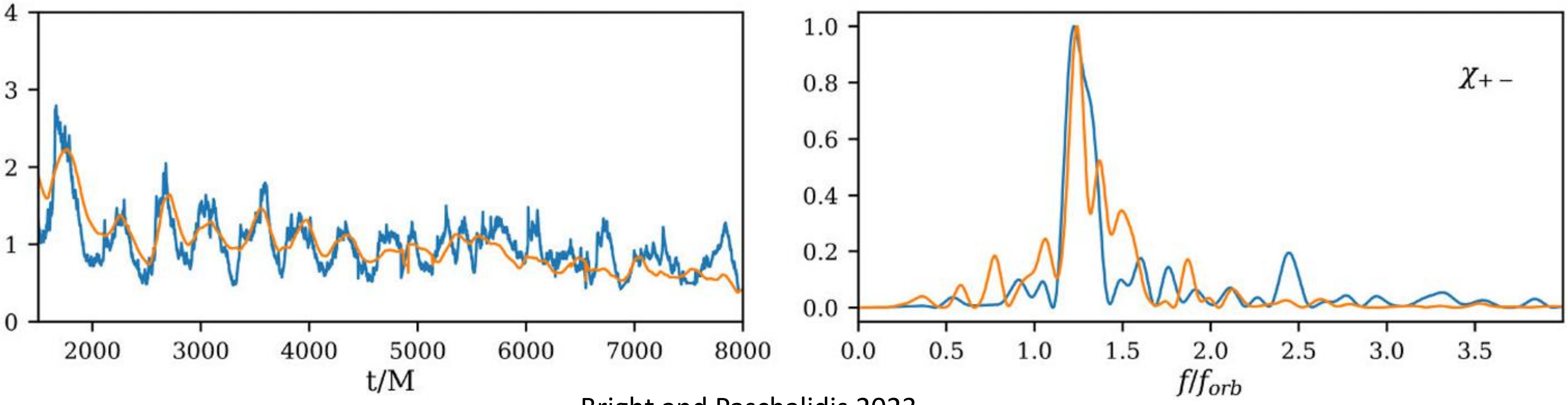


Noble et al 2012



Bowen et al 2019

Modulations in Circumbinary Disk Models



Bright and Paschalidis 2023

Modulations in the accretion rate observed also in this case.
They may also be present in the EM emission (e.g., see Gutiérrez et al 2022).

Conclusions

- Magnetic fields and BH spin can impact significantly the accretion process (higher magnetic fields and higher spins -> lower accretion rates)
- Magnetic fields can be amplified of ~2 orders of magnitude and easily produce magnetically dominated regions above and below the BHs
- Misaligned spins + magnetic fields introduce modulations in accretion rate (EM precursors to merger?)
- Modulations are stronger in the case of precessing binaries and correlate well with χ_p
- Modulations can be observed also in other gas configurations, but peak in L_{Poyn} and $\dot{M}$ is not always present at merger

Adv: Federico Cattorini and I wrote a recent review on GRMHD studies of accreting massive black hole binaries in astrophysical environments (Cattorini & Giacomazzo 2024 https://doi.org/10.1016/j.astropartphys.2023.102892)