10 years to LISA
JPL, April 1-3, 2025

Manuela Campanelli

Insights and Predictions from GRMHD Simulations of Supermassive Black Hole Mergers: Shaping Future Observational Strategies

RIT College of Science
Center for Computational Relativity and Gravitation

Image generated with Acrobat Firefly

compact-binaries.org

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Supermassive black hole binaries

- Supermassive black hole binaries (SMBBH) should form from post-galaxy-mergers; once into the AGN core they should accrete hot gas and emit powerful jets … - Begelman, Blandford, & Rees (1980)

- Dual-AGN should reach sub-pc scales and merge within Hubble time, via stellar dynamical friction, torques from gas …

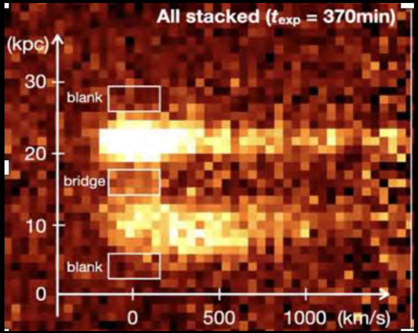
- Once they are in the GW regime, SMBBH become optimal GW sources for both LISA ($M_{\rm BH} \sim 10^6\ M_\odot$) and PTA ($M_{\rm BH} \sim 10^9\ M_\odot$).

- And they should be EM bright: $L_{\rm Edd} \sim 1.26 \times 10^{45} \frac{M}{M_\odot}$ erg/s

- EM signatures can be used to localize GW events in the sky and to study their astrophysical environments – finding them as LISA precursors is going to be challenging but not impossible …

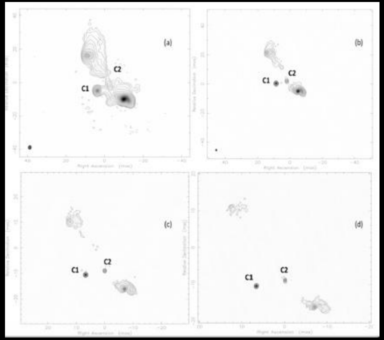
Can we distinguish EM signals SMBBH from single AGN?

There are ``numerous" observations of dual AGN systems with pairs of SMBHs; however, confirmed binaries are still rare …



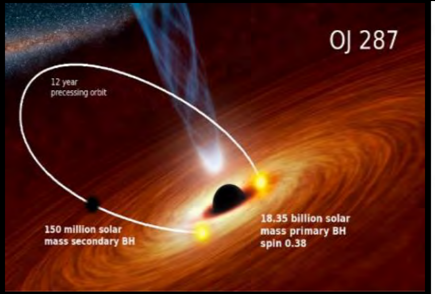
Many are binary quasars at z=6.05, separated by 12 kpc Matsuoka+2024;

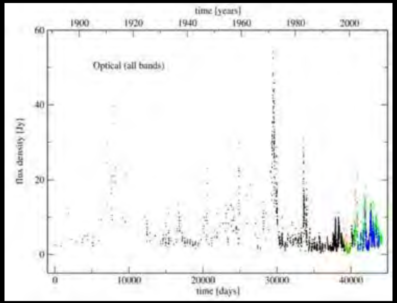
In the local universe: UGC 4211, z= 0.03,and at 230 pc separation- Koss+2024



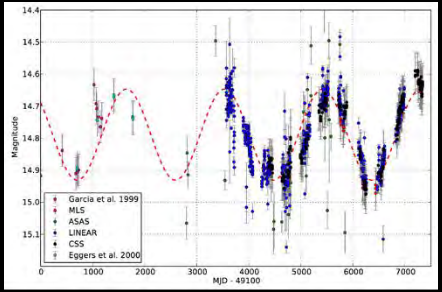
Double nuclei (radio) orbiting! 0402+379 - Bansal+2017, 12 years of multi-frequency VLBI observations

How can we detect them?

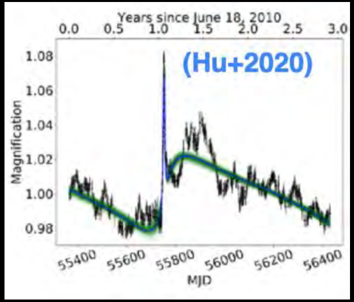




Periodic flares; OJ287 (Valtonen et al. 1988)



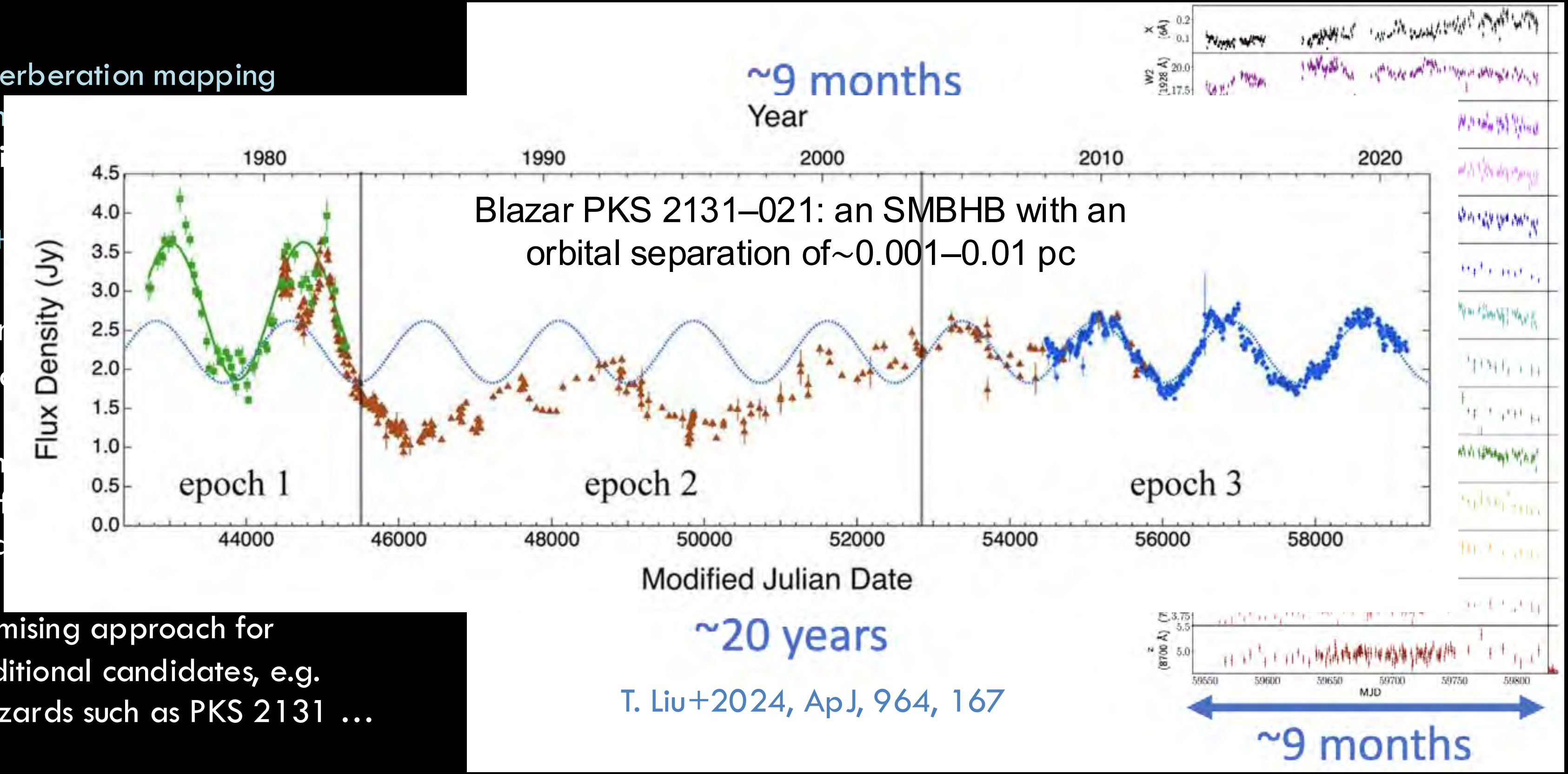
Sinusoidal light curves: SMBBH or statistical red-noise? PG1302-102 (Graham et al. 2015)



Self-lensing? D'Orazio+ 2017, Smith+2018, Ingram+ 2021,Davelaar+ 2022

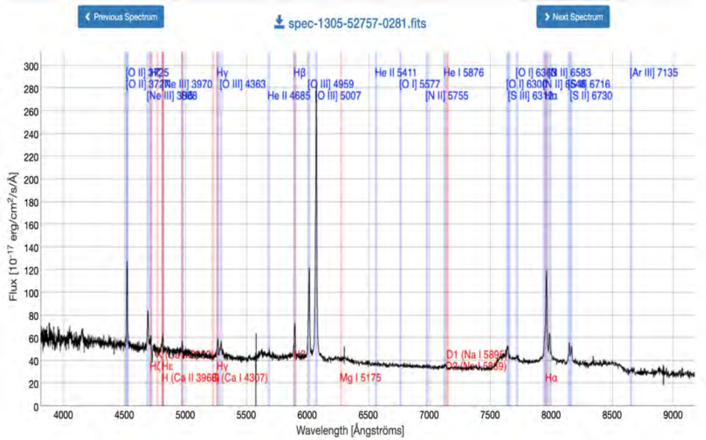
Catching SMBBH with light echoes …

- Reverberation mapping tech… peri… the Liu+…
- Ca… am…
- Ca… Swi… evi…
- Promising approach for additional candidates, e.g. blazards such as PKS 2131 …



Without knowing what to look for, identification will be hard!

- NR calculations predicted recoiling merger remnants of thousands of km/s from spinning BBH mergers – e.g. Campanelli+2007,Gonzalez+2007, Lousto+2011
- Astronomers searched for EM signals such as double-peaked emitters, off-set galactic nuclei, population of galaxies without SMBHs, x-rays afterglows, feedback trails, etc



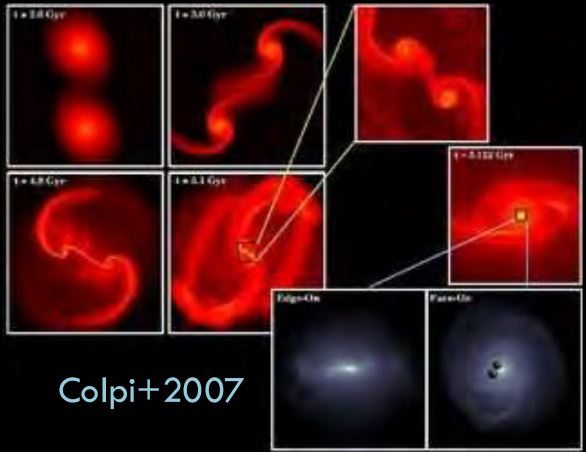
SDSS Extremely Weird Object
(extreme double-peaked lines in SDSS J0942+0900 and SDSS J1417+6141) - Emily Temple, RIT

We need realistic theoretical models of EM spectra and lighcurves!

Modeling SMBBH is challenging …

- Models need to cover an extensive range of dynamical scales and should be integrated with astrophysically accurate representations of the environments surrounding SMBBHs.

- They must incorporate essential physics at each scale, from kiloparsecs (kpc) down to sub-parsec (sub-pc) levels.



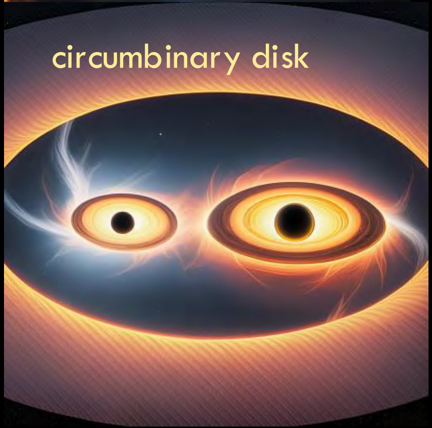
Colpi+2007

- Accretion flow scenarios for close SMBBH could be quite different from what we know of single BH accretion disks …

- Wider parameter space: accretion rate ($\dot{M}$), total mass (M), disk scale height (H/R), equation of state, viscosity (ν), magnetic field (B), binary separation (a), BH mass ratio (q), orbital eccentricity (e), BH spins (S1, S2), etc.

- Depending on the balance of heating and cooling mechanisms:

  - Gas cloud (hot radiatively inefficient)
  - Circumbinary disk (cold, radiatively efficient)



Images created with Acrobat Firefly AI

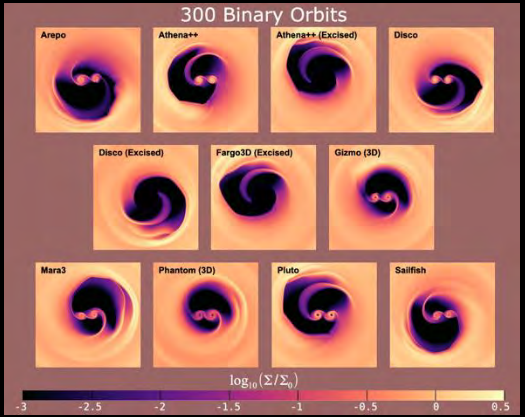
Brief History of Simulations

- First calculation (Pringle 1991), followed by early 1d Newtonian simulations (e.g Artymowicz & Lubow, 1996, Armitage+2002) found little or no accretion close to the SMBBHs, as binary torque carves a nearly empty cavity of 2a, and the CBD is left behind, as the binary spirals inward fast (``decoupling") – Milosavljevic+2005.

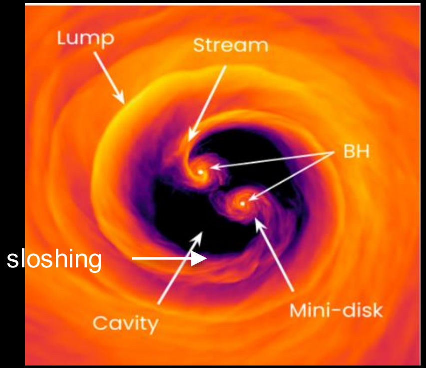
- Modern 2d (vertically integrated) and 3d Newtonian hydrodynamical simulations find that the binary torque "dam" does not hold, allowing accretion to continue, and minidisks form around each BHs - e.g. Milosavljevic & MacFadyen, 2008, D'Orazio+ 2013; Farris +2014; Ryan+2016, Tang+2018, Duffel++2024

- 3d GRMHD simulations in dynamical GR are essential to describe accretion physics close to the BHs and to treat the GW inspiral, merger and postmerger regimes. MHD – Balbus &Hawley 1991

- Are there distinticve EM signals associated with the dynamics of the minidisks, streams, shoshing, lumps and dual jets during a binary merger and right after?



Comparison among 2d and 3d HD simulations - Duffel++2024

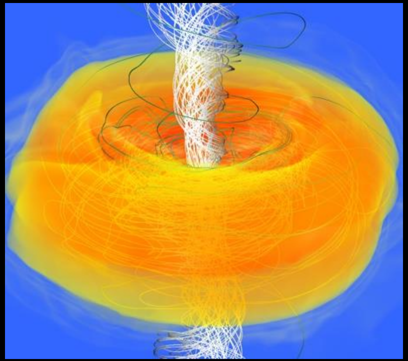


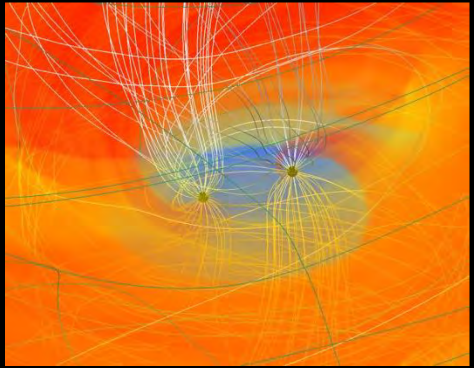
3d GRMHD ``picture": Gutierrez, Combi, Ryan "New Frontiers in GRMHD Simulations" 2024

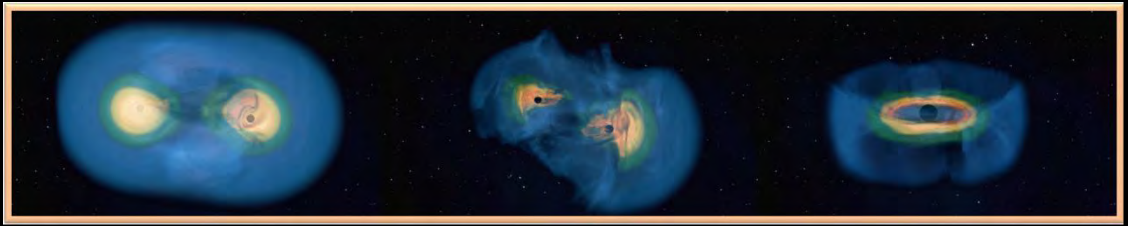
Numerical Relativity Simulations

Pioneering 3d GRMHD using numerical relativity (NR) simulations explored SMBBH in both circumbinary disk and gas clouds models

See Cattorini+2024 for a review







Explored a relatively small range of the parameter space, such as mass ratio, spins and even eccentricity, and their preliminary results included decoupling phase prior merger, double jets, minidisk dynamics, etc. However, they were so far generally limited in total duration due to the computational cost – e.g. van Meter+ 2010, Farris+2010, Giacomazzo+2012; Gold+ 2012,2014; Paschadilis+2021, Cattorini+2022, Bright+2023, Ruiz+2023, Fedrigo+2024, Ennoggi+2025.

Computational endeavor: 3d radiative GRMHD

Must include Essential Physics:

- Dynamically changing spacetime according to Einstein's equations of general relativity (GR).
- GRMHD (accurate at the scale of MRI/turbulence).
- Realistic thermodynamics, plasma physics, and radiation transport.

Numerical algorithms must resolve physics in the CBD, minidisks and near black hole horizons.

This means solving the GR equations coupled with MHD fluids, EoS, radiation transport …

See Fergusson's talk on Numerical Relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} \,, \text{ (Einstein equations)}$$

$$\nabla_\mu T^{\mu\nu} = 0 \,, \quad \text{(cons. energy/momentum)}$$

$$\nabla_\mu (\rho u^\mu) = 0 \,, \quad \text{(cons. rest mass)}$$

$$p = p(\rho, \epsilon, Y_e, \ldots) \,, \quad \text{(equation of state)}$$

$$\nabla_\nu F^{\mu\nu} = I^\mu \,, \qquad \nabla_\nu^* F^{\mu\nu} = 0 \,, \quad \text{(Maxwell equations)}$$

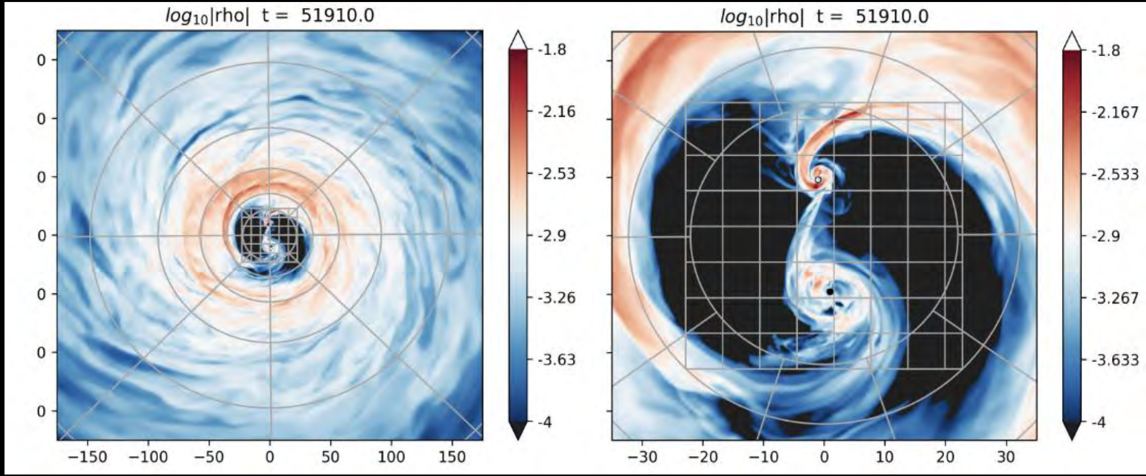
$$\nabla_\mu T^{\mu\nu}_{\rm rad} = S^\nu \,, \quad \text{(radiative losses)}$$

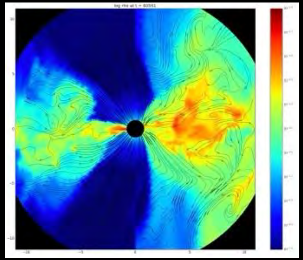
$$T_{\mu\nu} = T^{\rm fluid}_{\mu\nu} + T^{\rm EM}_{\mu\nu} + T^{\rm rad}_{\mu\nu} + \ldots \quad \text{(energy} - \text{momentum tensor)}$$

GRMHD simulations of SMBBHs approaching merger …

Noble++2012, Bowen+2017, 2018, 2019, Noble+2021,Combi+2022, Avara+2024

- Minidisks forms quickly and the cycle of periodic depletion and refill of the gas is dominated by the CBD "lump" through the streams …
- Using analytical spacetime in the relativistic inspiral regime with PN trajectories – Mundim+2014, Combi+2022, 2024

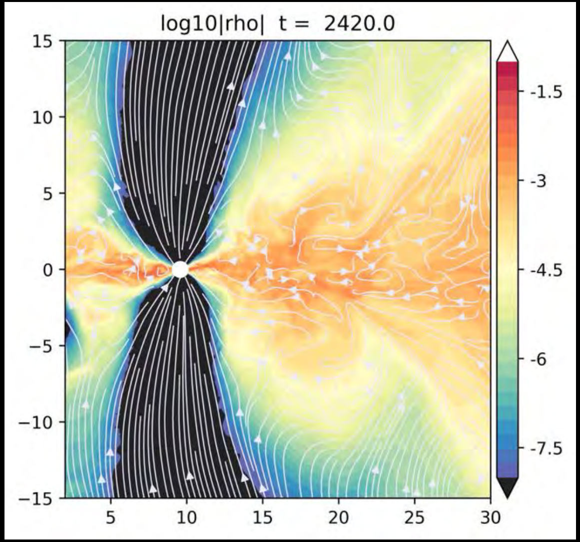




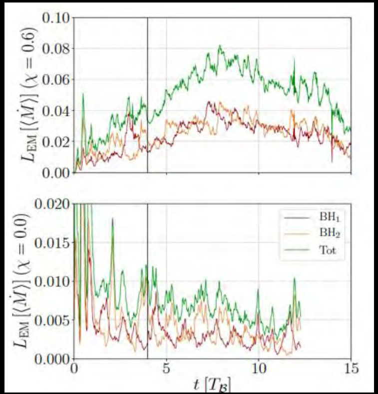
- Rich 3d structure of accretion disks

- Accreting streams fall in the cavity mostly due to gravity and shock against the BH minidisk, which deplete and refill periodically at time scale close to one orbital period.
- The minidisks form quickly and exchange mass through a periodic "sloshing". Mini-disks accretion nothing alike single BH accretion!

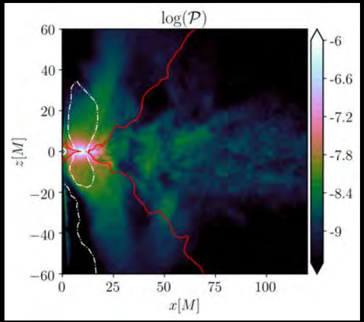
Hints of interesting dynamics with BH Spins!



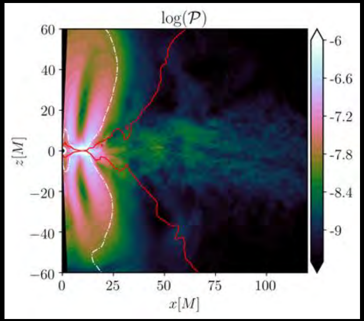
More magnetized mass + BH ergospheres means more jet-like structure!



Jet power modulated with the same periodic behavior that the filling/depletion cycle: Periodicities? Flaring behavior?

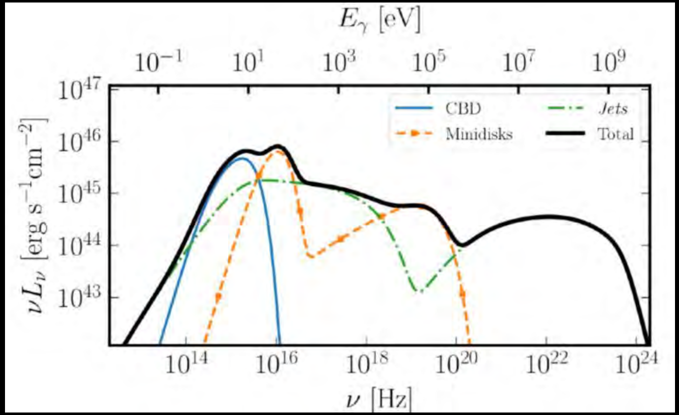


No-spins



Spins = 0.6

Outfows are nearly 10 times stronger than the non-spinning case - Combi+ 2022; Gutierrez+2022



Spectral energy distribution with a dual jet contribution - Gutierrez+2024

Radiative Output

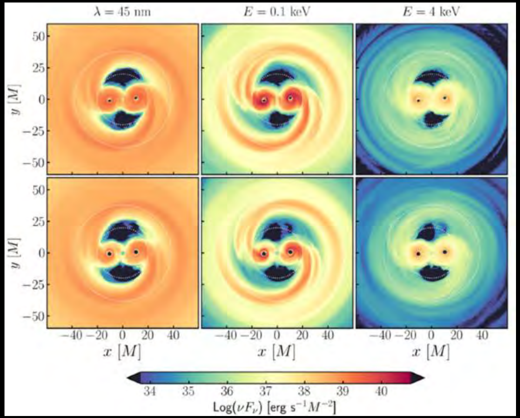
- Bound material cooled to target entropy based on a location dependent timescale – Noble+ 2012,

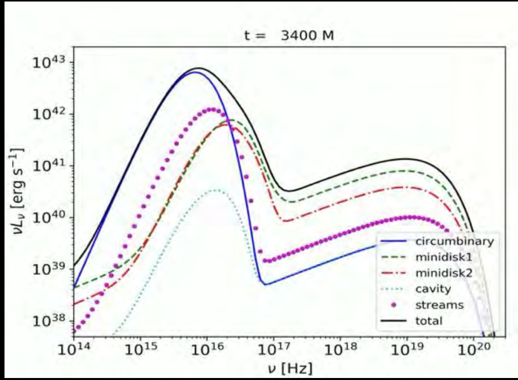
$$\nabla_\mu T^{\mu\nu} = -L_{cool} u^\mu$$

- Ray-tracing from GRMHD simulation snapshots –d'Ascoli+2028, Gutierrez+2022, 2024.

  - ❖ Optically thick material emitting a blackbody spectrum.
  - ❖ Optically thin material emitting an X-ray spectrum like AGNs.
  - ❖ Synchrotron emission (sub-mm) from the jets.

- Spectra time variability, different components at different frequencies.
  - ❖ CBD ``similar'' to truncated Shakura-Sunyaev disk …
  - ❖ **Mini-disks brigther in X-rays**
  - ❖ 'Notch' (Tanaka+2012, Roedig+2014) absent due smaller ``cavity'' filled with streams and sloshing at $20r_g$ separation

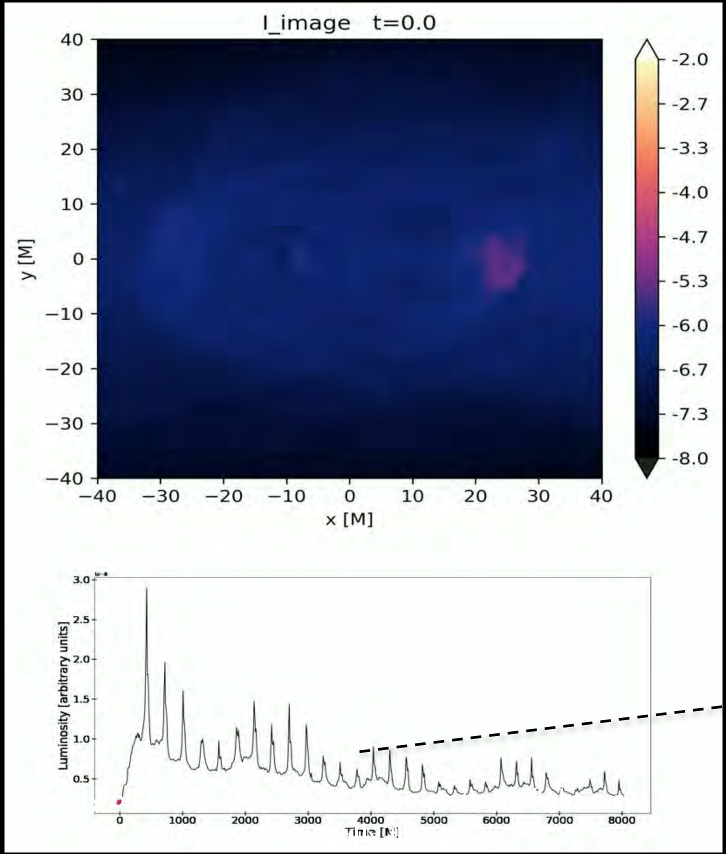


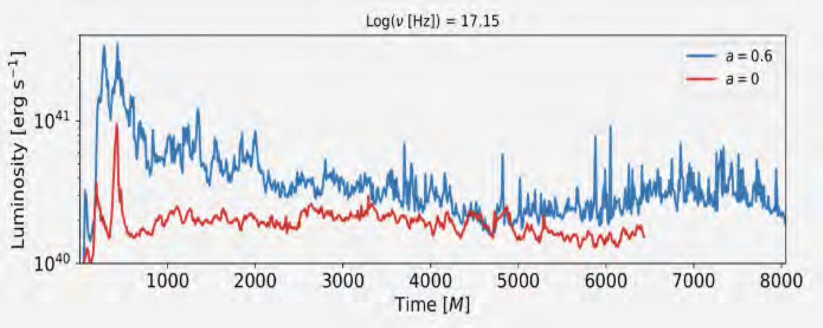


Spectral energy distribution - Gutierrez+2022

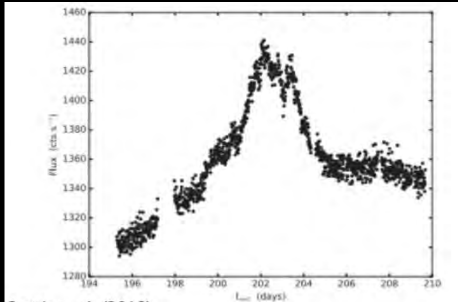
See also Scott Noble talk

Light Curves display Self-lensing features





How self-lensing features depends on mass ratios, spins, accretion rates, etc – Porter+2024



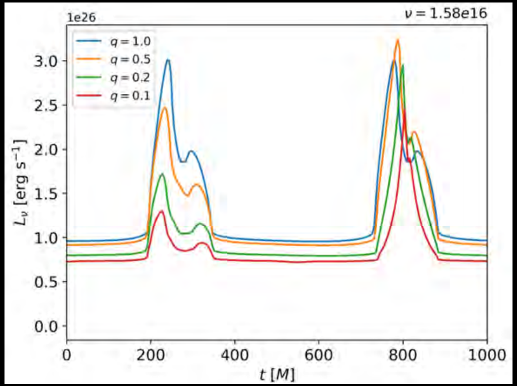
Smith et al. (2018)

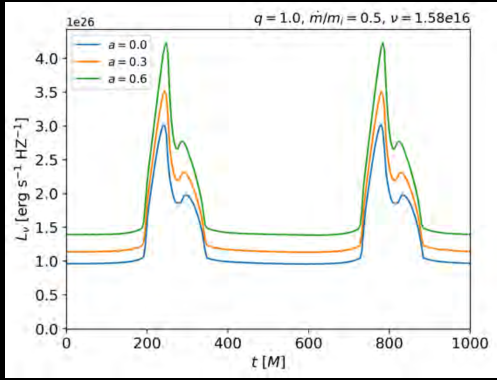
Possible observation of SLF from AGN source known as Spikey, - Smith+2018

Catalogs of Light Curves

Kaitlyn Porter talk, GRA@RIT

- Analytical models to explore dependence on binary parameters - D'Orazio+2017, Davelaar+2022, Porter+2024
- For inspirilling SMBBHs, Porter+ 2024 explored effects of mass-ratio, spins and separations on light curves and self-lensing features





- EM spectra from these models now used to identify unique signatures of SMBBHs compared to single SMBH from the SDSS quasar catalog - Ziming Ji+ WIP, GRA@RIT

Exploring the CBD dynamics as a function of binary separation

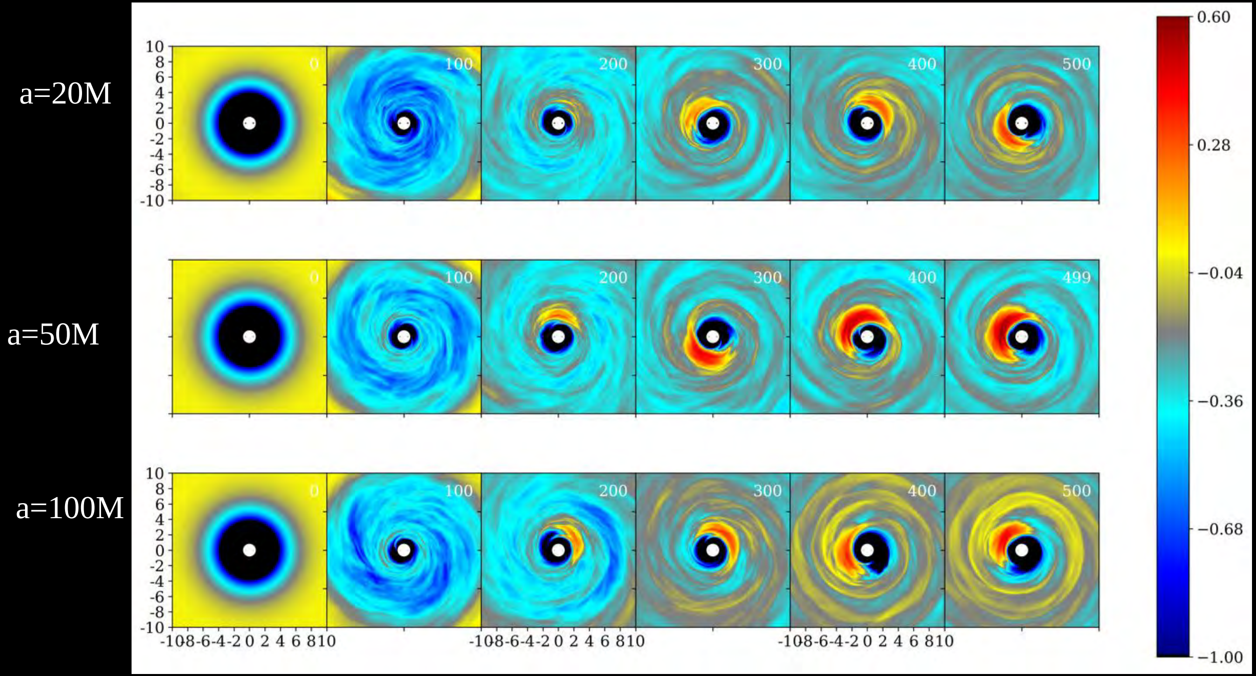
Sequence of radiatively efficient ``thin disks'' H/R~ 0.1

...

Sequence of CBDs reaching the quasi-steady state of accretion at different separations.

Accretion rates in CBD are approximately independent of separation, and the lump is persistent for q>0.2!

Accretion rate diminishes as cooling rate diminishes → hotter disks accrete more slowly than cooler disks.

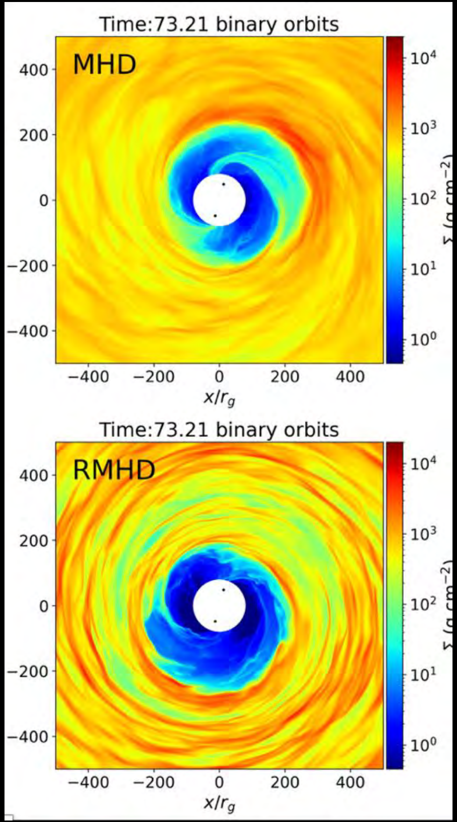


No sign of decoupling so far!

Noble+ 2024, in prep; P21

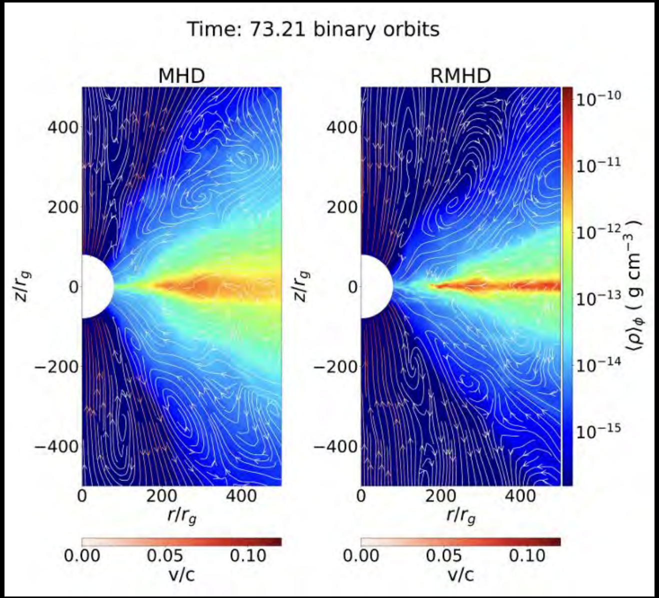
GRMHD with HARM3D on PN

Is the Lump really a generic feature?



Radiative MHD Simulation of sub-Eddington (L_{EM}~$0.1L_{Edd}$) accreting CBD SMBBH (10^7 $M_\odot$) at $100r_g$ with Athena++ - Tiwari+2025

- Find denser, thinner disk compared to MHD, lower accretion rate, weaker streams and lump.
- Variability induced by the binary-CBD interaction is distinguishable in the optical/UV band, where CBD shines at about 1% of the Eddington luminosity.

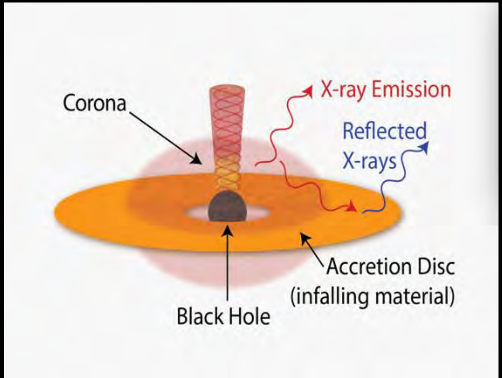


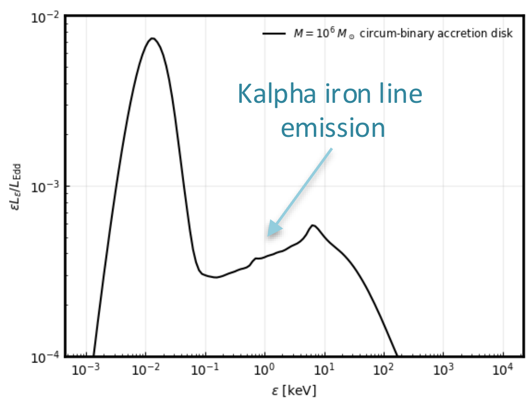
Radiation Forces and Radiated Spectra

Radiating regions range from relatively cool and thermal deep inside the accretion flow to extremely hot in coronae and shocks

- Use a more realistic treatment for radiation transport to accurately capture the effects of radiation forces on the fluid …
  - Leakage scheme for photons – Combi+, Minjae Kim+, work in progress
  - Guided Moments approach – Izquierdo+ 2024 – a cost-effective solution combining M1 closure (in the optically thick regions), MC (in the optically thin regions); energy-dependent emissivities and opacities.
  - Full direct integration transport in Athena++/AthenaK - see J. Stone talk

- EM spectra from Monte-Carlo (MC) approach with PTRANSX - Schnittman+2013, Kinch+2021, 2022 (on GitHub)
  - Post-processing toolkit from rGRMHD snapshots
  - Compton-scattering transport in coronal region.
  - Full photoionization and thermal physics of the disk atmosphere.



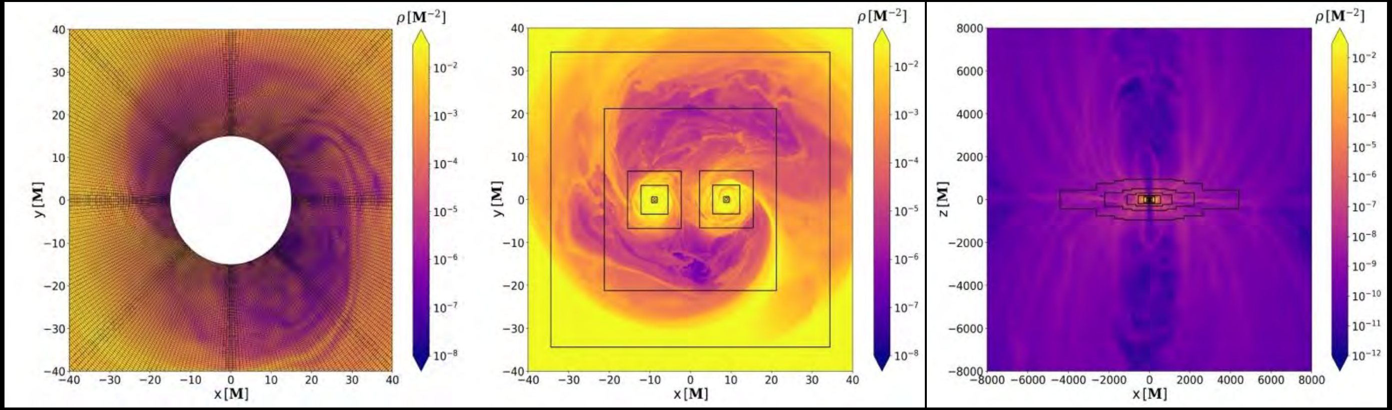


CBD spectra with PTRANX - Nagele+ 2025, in prep

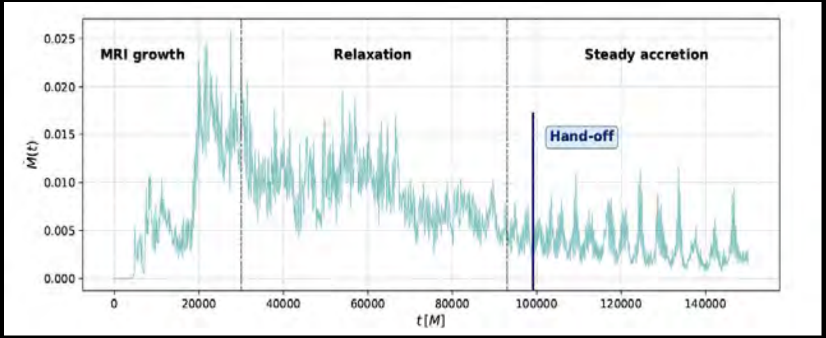
GRMHD simulations in full Numerical Relativity

Code ``Hand-off" Framework:

Armengol+2021, Ennoggi+ 2025



- Long-term CBD evolution in spherical coords – SphericalNR - Mewes+2018 &2019, Ji+202
- Global `` CBD + Minidisks" in Cartesian coords using AMR grids – IllinoisGRMHD (Etienne+2011) or AsterX (Kalinani+2024)



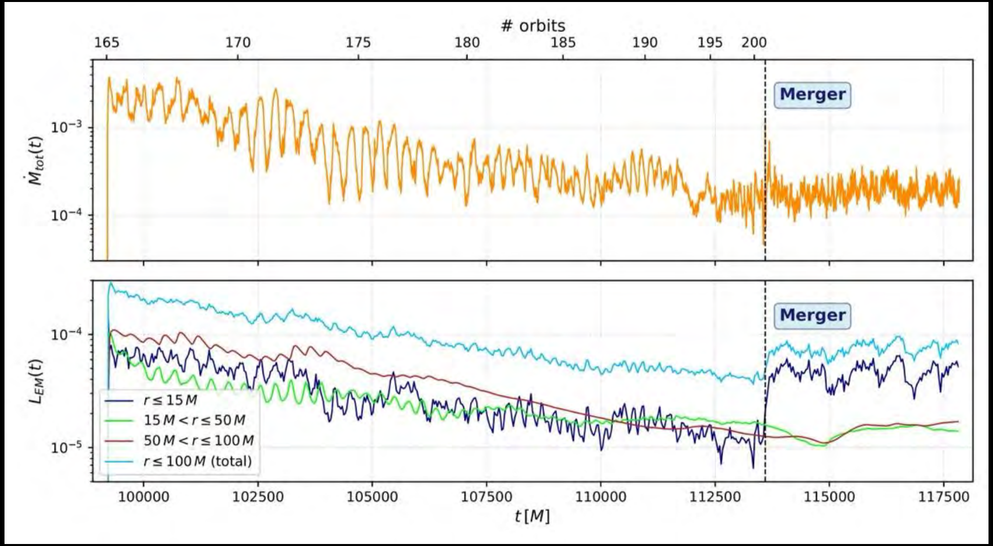
What happens at merger?

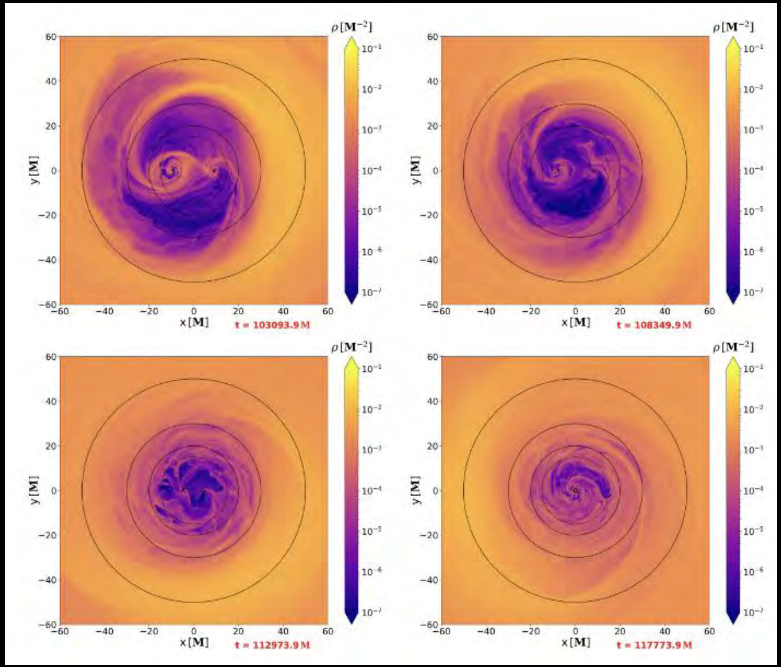
Ennoggi+2025

First full NR+GRMHD simulation of non-spinning, equal-mass black holes:

- Decoupling at merger? After 200 inspiral orbits from $20r_g$ separation, the minidisks dissolve as the binary compresses just prior merger …

- Luminosity briefly drops only by a factor a few, then spikes by 50% at merger with an abrupt change in spectrum.

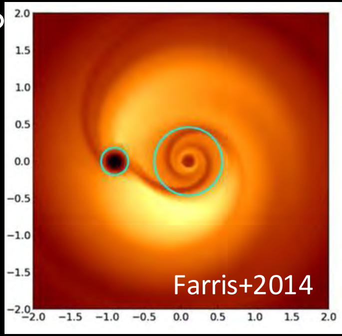


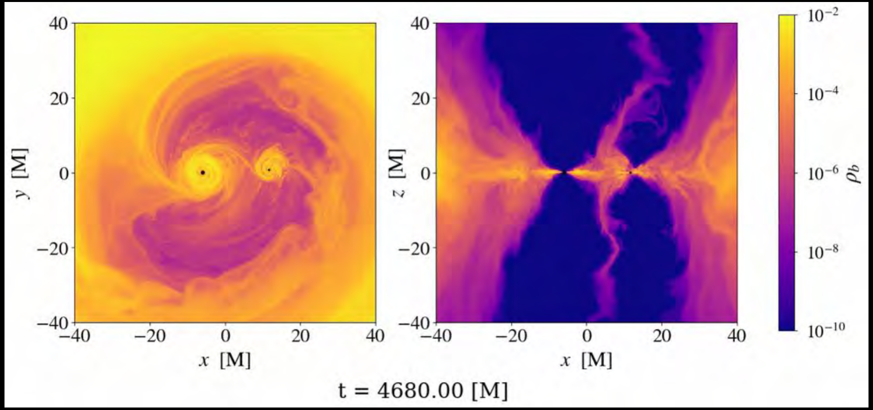


Anatomy of an SMBBH …

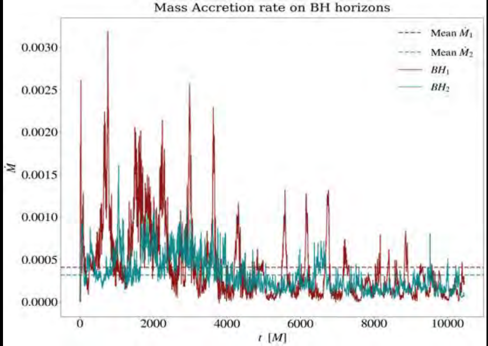
In an unequal-mass system:

- Mass is preferentially accreted onto the secondary …
- The secondary BH carries a smaller (but brighter) minidisk

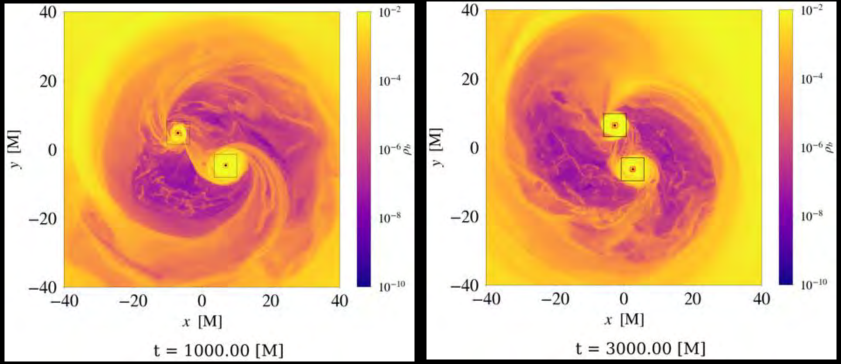




1:2 mass ratio



Eccentric orbits can produce with episodic accretion into minidisks

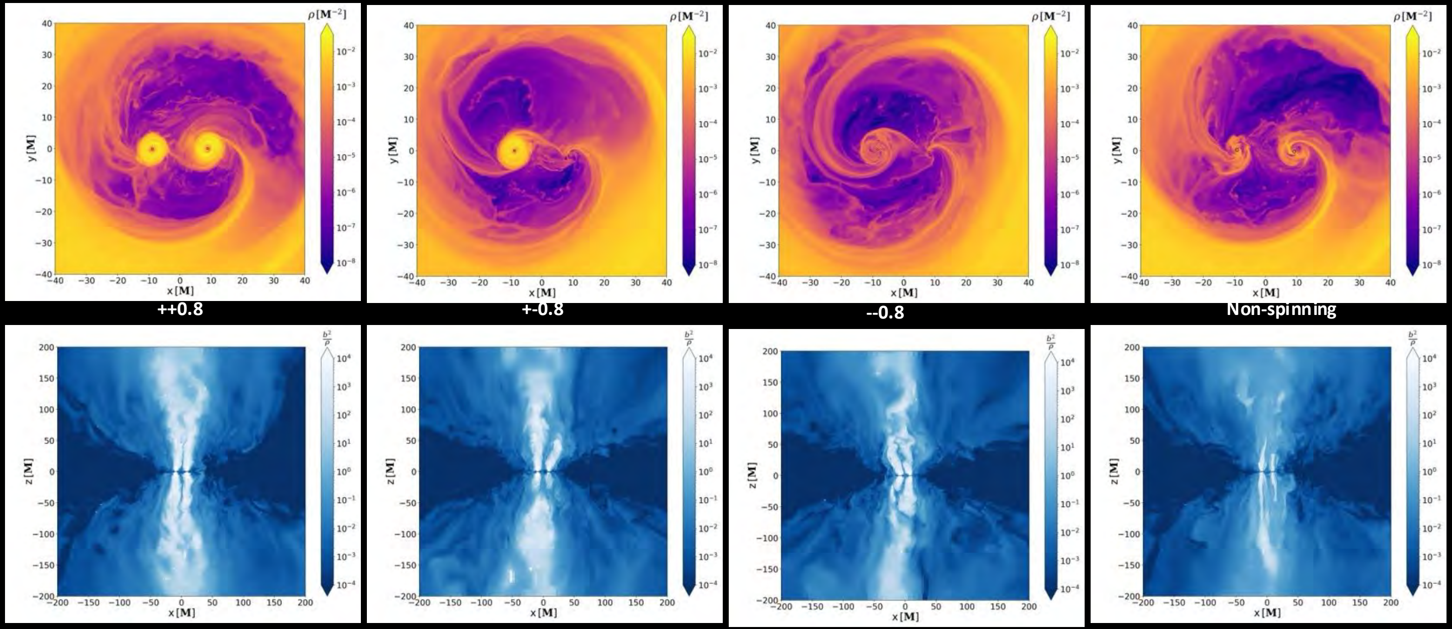


Eccentric orbit with e=0.1

Work in progress
Maria Chiara De Simone, RIT

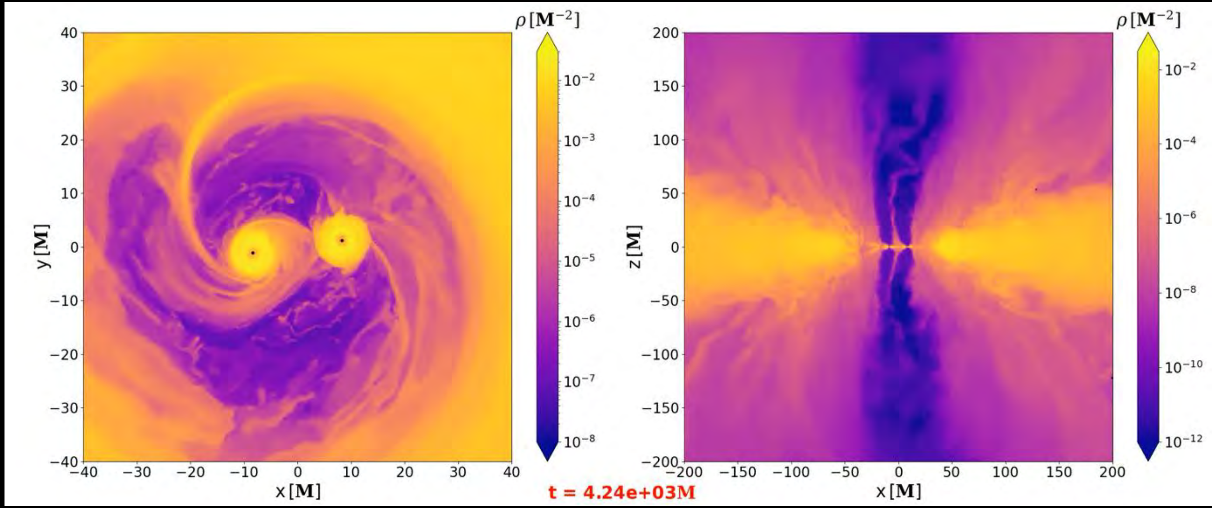
The effect of spins on minidisks and jets launching

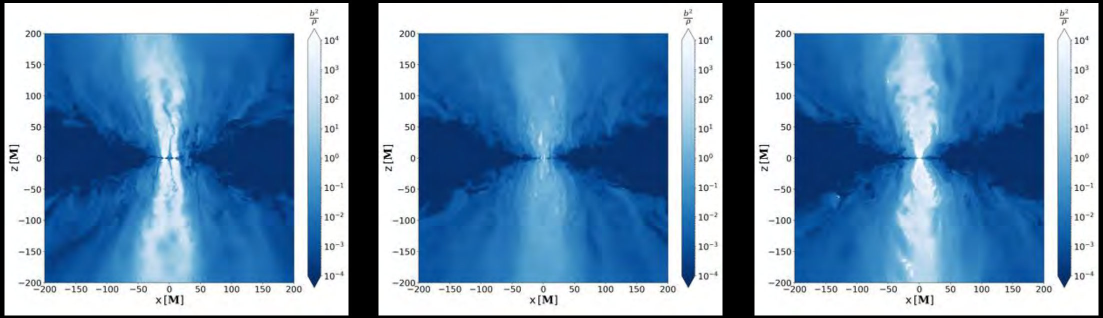
- Minidiscs physics strongly affected by BH spins – Ennoggi+2025, in prep
- The magnitude and direction of the spins affects orbital dynamics via spin-orbit interactions – Campanelli+2007



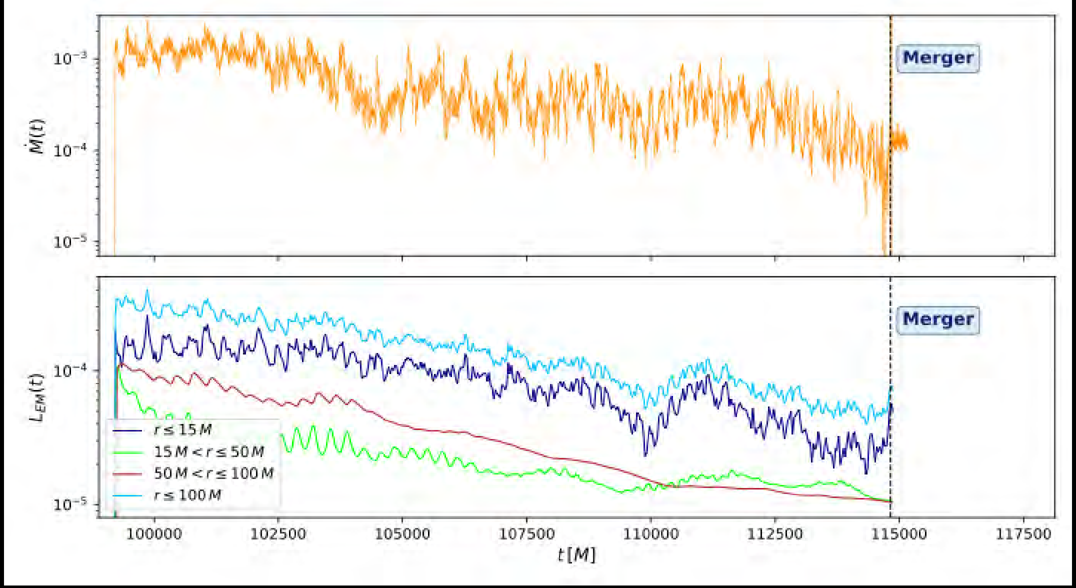
Aligned spins case: Jet quenching and re-ignition!

Ennoggi+2025 in prep



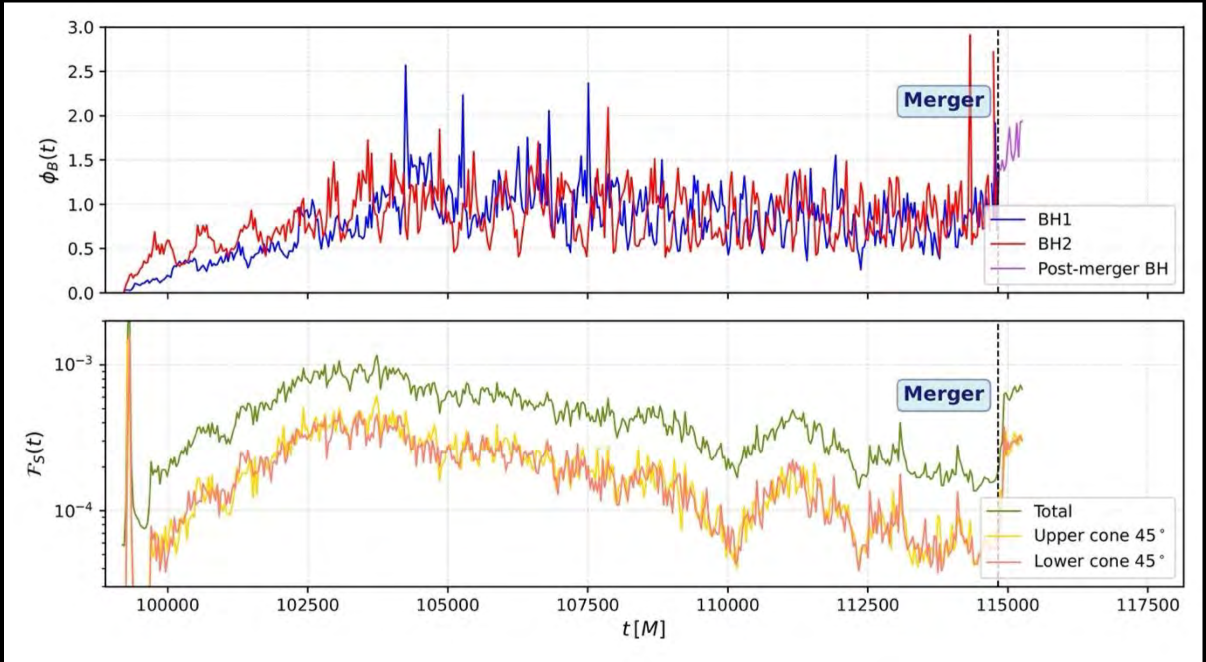


Minidisks form around each BH and relativistic jets are powered. Close to merger, we observe the minidisk being disrupted and the jets being quenched; then, a single jet is re-ignited just after merger.



- Spins have a strong effects on the overall dynamics and luminosity.
- Luminosity close to the binary dominates!
- Luminosity displays characteristics signatures during inspiral, prior merger (modulation due to the lump) and after merger … (simulations still ongoing).

- The minidisks disrupt in they appoach merger, as in the non-spinning case, but then rebuilt (due to the BH spins) until they disappear again prior disappearing.



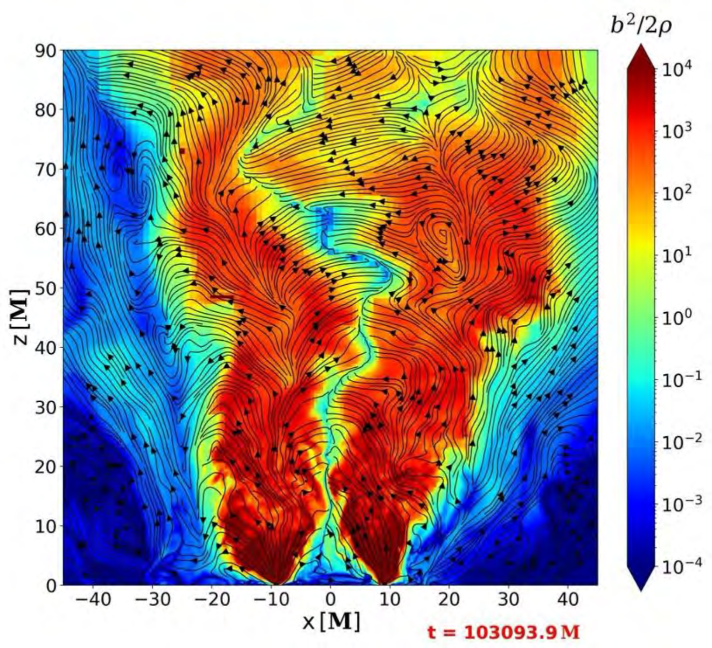
More massive minidisks and jet power due to BZ effect.

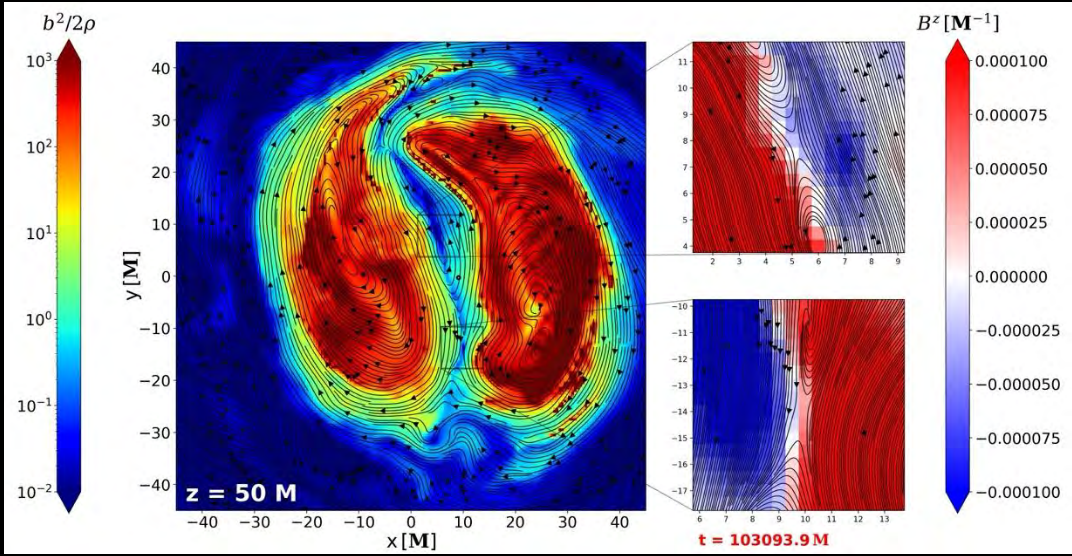
Jet quenching and reignition

- Poynting luminosity displays characteriscs signatures during inspiral, prior merger (modulation due to the lump) and after merger.
- The minidisks disrupt in they approach merger, as in the non-spinning case, but then rebuilt (due to the BH spins) until they disappear again prior disappearing.

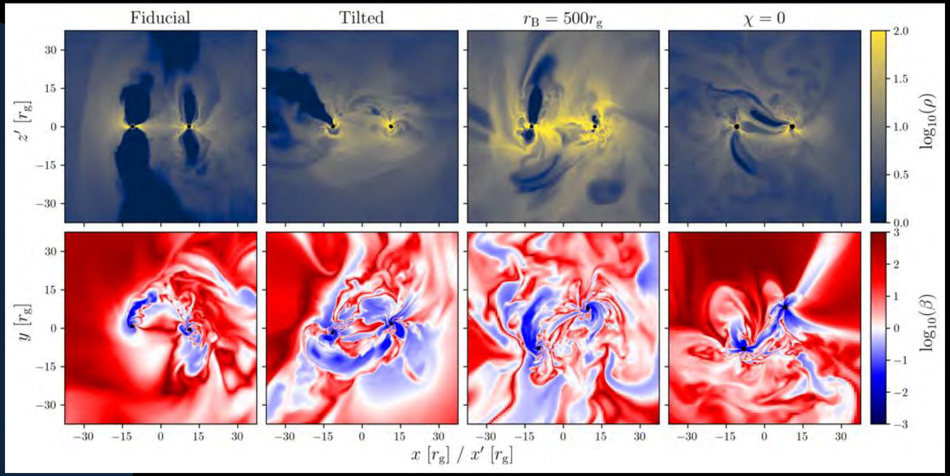
Dual Jet Interaction in Aligned Spinning SMBBH

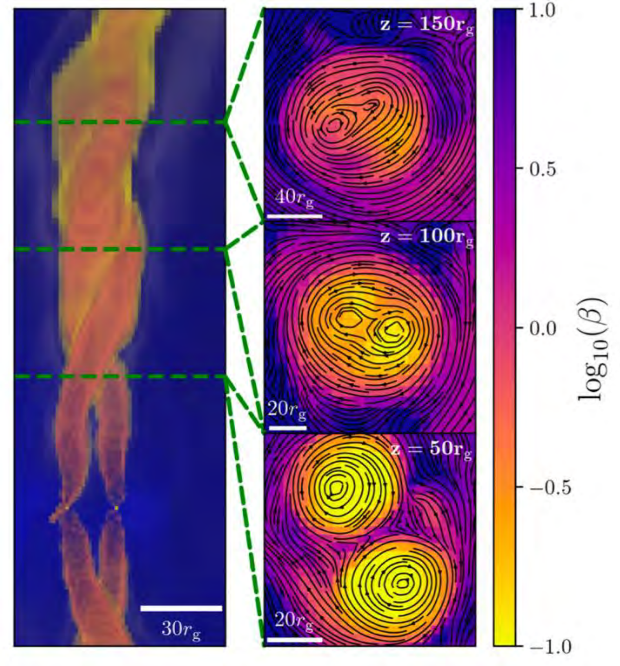
Twisted magnetic field lines accreted by both BHs due to BZ effect, displaying magnetic reconnection, could enhance the EM signals from the jets – Ennoggi+ 2025, in prep





Flares and Dual Jets from Magnetically Arrested Flows in Merging SMBBH





Magnetic field reconnection among jets, magnetic tubes and "Magnetic bridges" - Ressler+2024

- MAD accretion flows around each BH halt, causing the cavity wall to become unstable and ejecting magnetic flux in large bursts - Moest+2024

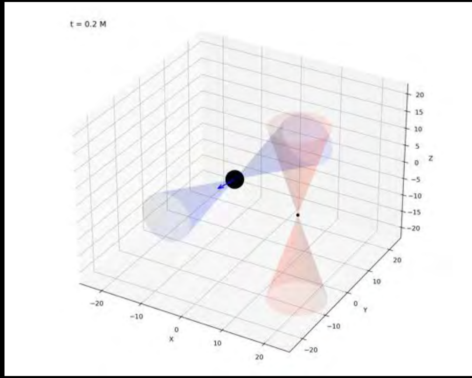
- In highly magnetized thin disk, some of the BZ power goes into the disk/corona - Agol & Krolik 2000; Krolik+2005; Noble+ 2009, Dhang+2024

Efficient rGRMHD for Dynamical Spacetimes!

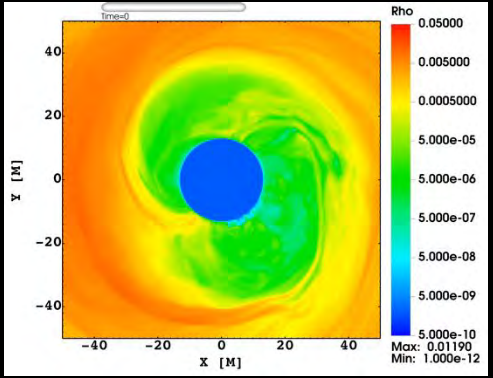
- Semi-analytical spacetime treatment has enabled early explorations of potentially interesting physics. It's a factor 5 faster than full NR! – Combi & Ressler, 2024

- And GPUs can make simulations 15 times faster on exascale computers – e.g. AsterX + SpacetimeX as part of the Einstein Toolkit – Kalinani+ 2024, now using subcycling time integration - Ji+2025

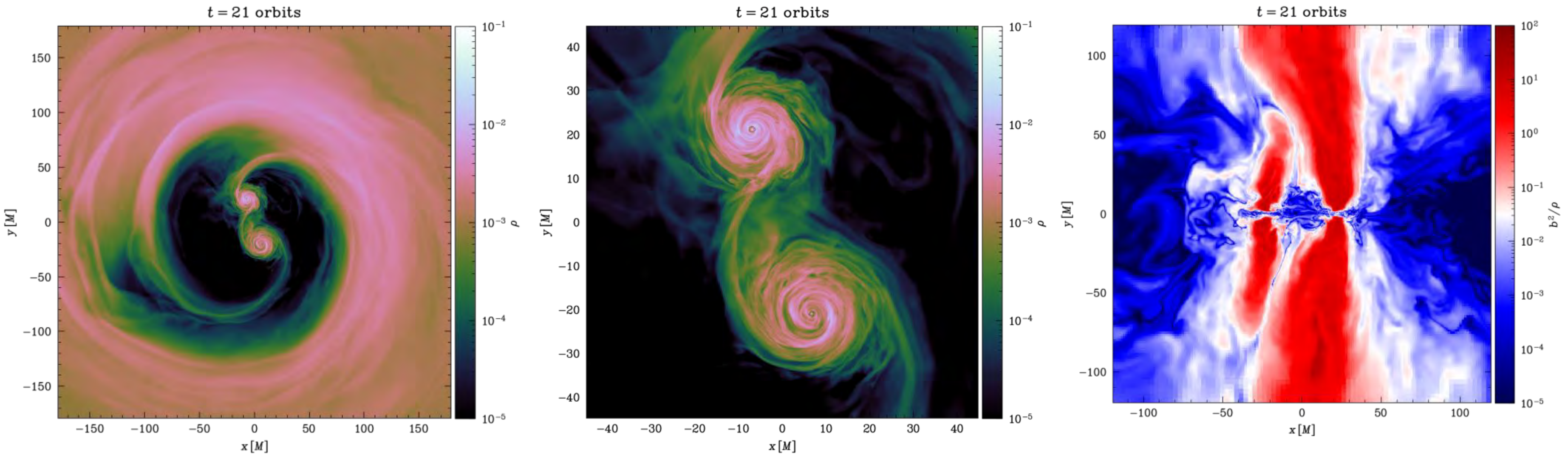
- This will allow us to use a more realistic treatment for radiation transport making Radiative GRMHD for dynamical spacetimes affordable!



L-flip - Kalinani+ 2025, work in progress



S-Flip - Chabanov+ 2025, work in progress



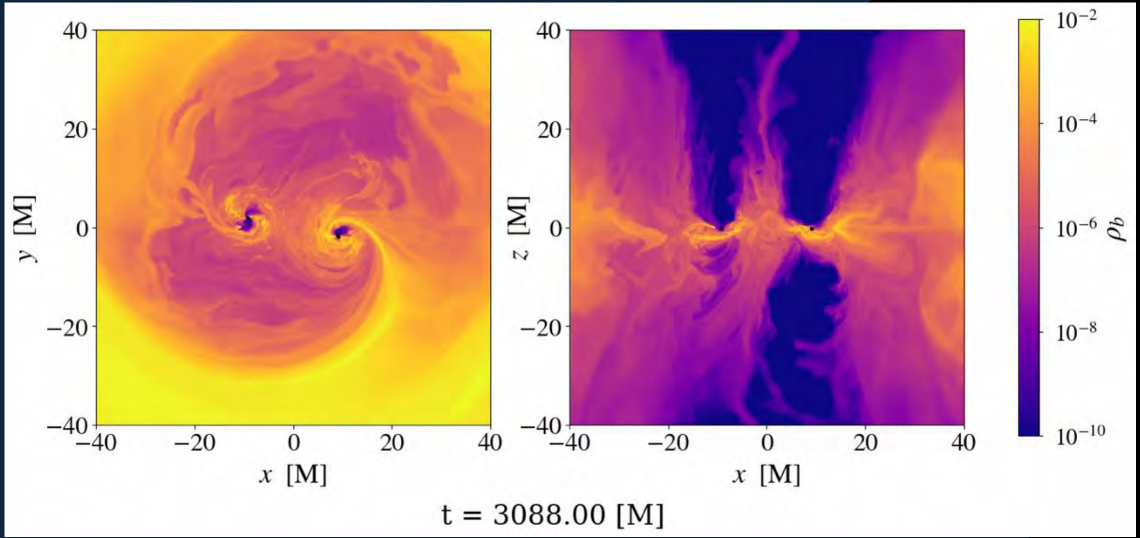
More on dual Jet Interaction from larger separations

- Explore accretion dynamics starting from larger binary separations e.g. $\geq 30r_g$
- We find persistent minidisks, magnetic field close to saturation, very strong jets with BH spins parameter 0.9 …
- Modeling Blazards signals!

Combi+MC+2025, work in progress

If the BH Spins are oblique …

BBH can display interesting merger dynamics due to precessing spins



Maria Chiara De Simone +, GRA @ RIT, work in progress

- ``Superkicks” and ``Hang-up Kicks”: the final BH remnant after merger can get a gravitational wave recoil of several thousands km/s is the BHs have oblique spins – Campanelli+2007, Lousto+2015
- BH spin – flip: Flip the spin of one of the BHs with respect to the orbital angular momentum **L** – Lousto & Healy, 2015
- L – Flip: 1:10 mass ratio BBH with spin of larger BH pointing down at oblique angle – Lousto & Healy, 2018
- Flares from dual Jet interaction … – Gutierrez+2024, Ressler+2024

Concluding Remarks

- In the next decade or two, there will be a revolution black hole astrophysics and GW science, unveiling populations of black holes, including binaries, across all cosmic epochs, and revealing their origins.

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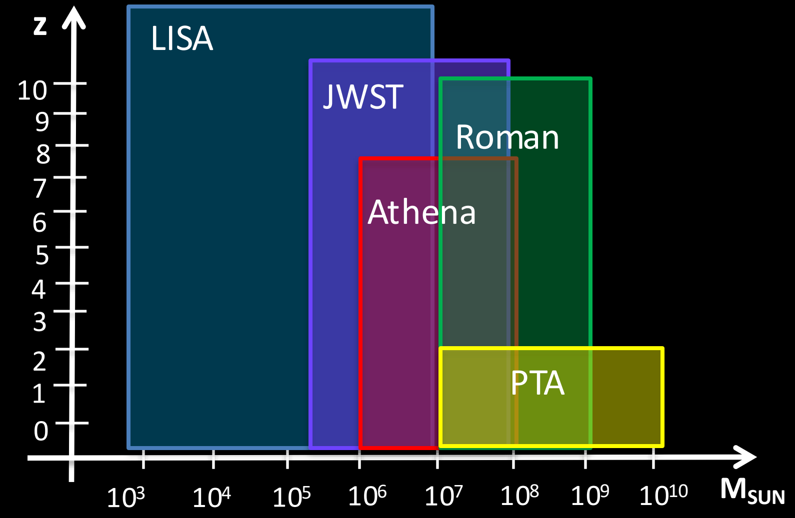

- JWST, Vera Rubin/LSST, Athena, Roman might uncover "many" binary-AGN in the haystack in the upcoming decade or two …

- We need to achieve better astrophysical realism and accuracy for magnetic field growth, radiation, microphysics treatments.

- The advent of CPU/GPU powered exascale+ supercomputers, augmented by AI and superchip technology, will only accelerate us in the path to discovery!