Title: General Relativistic Magnetohydrodynamics Simulations of Accreting Supermassive Black Hole Binaries

Speakers: Manuela Campanelli

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

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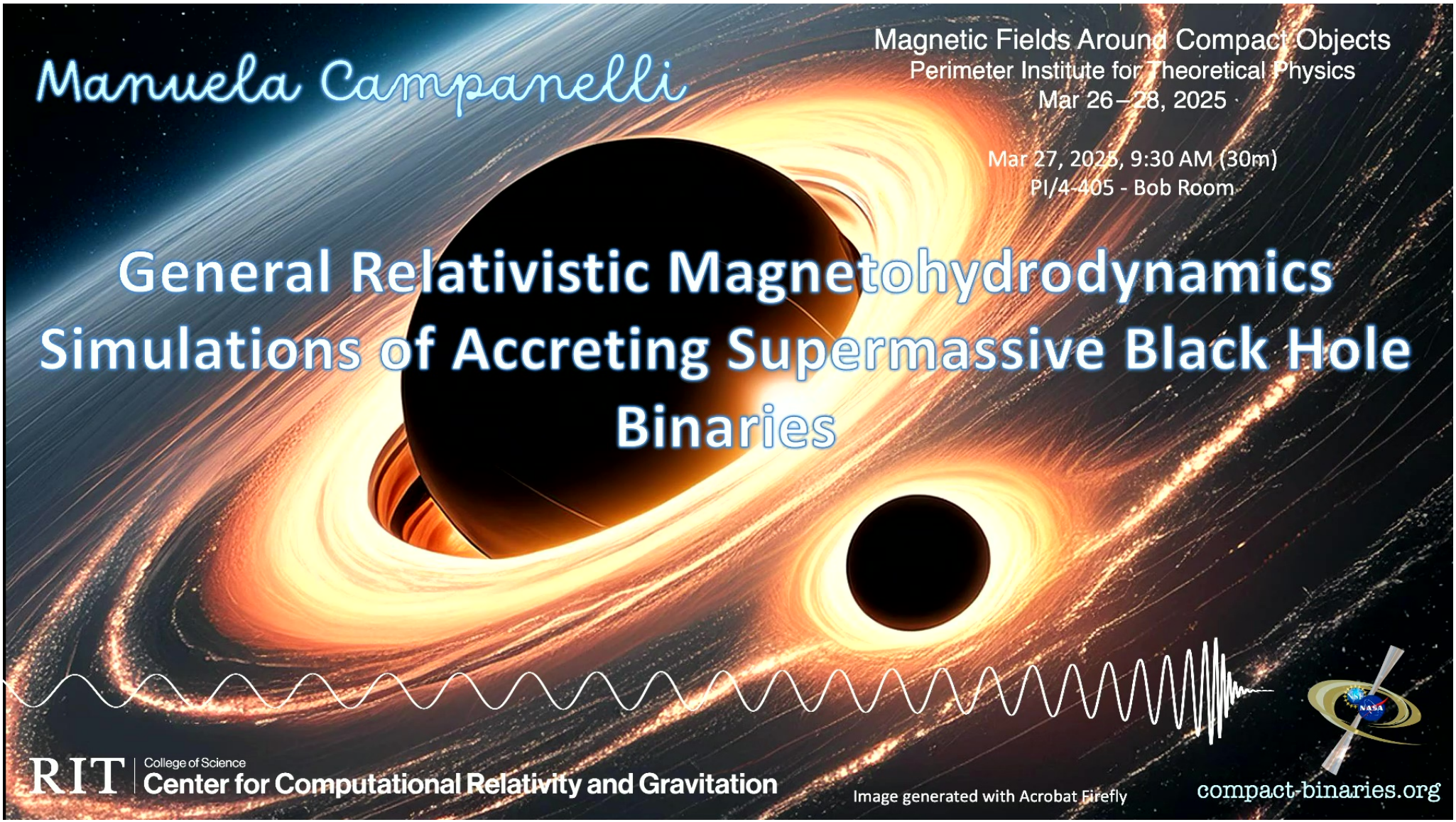
Abstract:

Supermassive black hole mergers represent a spectacular cosmic event with immense energy implications, emitting gravitational waves equivalent to the total light output of stars in the entire Universe within a brief timespan. These mergers play a crucial role in shaping the overall mass distribution of supermassive black holes across the cosmos. However, capturing visual evidence of these mergers remains elusive due to uncertainties surrounding the type of light emissions accompanying gravitational waves during these events. To address this challenge, novel General Relativistic Magnetohydrodynamics (GRMHD) simulations are being conducted to gain detailed insights into the astrophysical environments surrounding supermassive black hole binaries as they progress towards merger. By employing sophisticated computational techniques capable of accurately capturing the intricate dynamics of accretion within circumbinary disks and the relativistic flow of magnetized matter around each black hole, these simulations reveal the behavior of gas flows near binary systems, particularly when both black holes exhibit spin. These simulated scenarios provide critical data for predicting the electromagnetic and gravitational wave signatures produced by supermassive binary black holes, guiding future observational strategies utilizing advanced missions like LISA and other upcoming astronomical facilities. Ongoing initiatives are focused on refining computational tools to deepen our understanding of supermassive black hole behavior within binary systems and its interactions.


Manuela Campanelli
Magnetic Fields Around Compact Objects
Perimeter Institute for Theoretical Physics
Mar 26–28, 2025
Mar 27, 2025, 9:30 AM (30m)
PI/4-405 - Bob Room
General Relativistic Magnetohydrodynamics Simulations of Accreting Supermassive Black Hole Binaries
RIT
College of Science
Center for Computational Relativity and Gravitation
Image generated with Acrobat Firefly
compact-binaries.org

Theory and Computational Astrophysics Network (TCAN)
"BBHdisk Collaboration"

Mark Avara (Gtech)
Manuela Campanelli (RIT)
Federico Cattorini (Milano-Bicocca U.)
Luciano Combi (PI)
Michail Chabanov (RIT)
Maria Chiara De Simone (RIT)
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Jay V. Kalinani (RIT)
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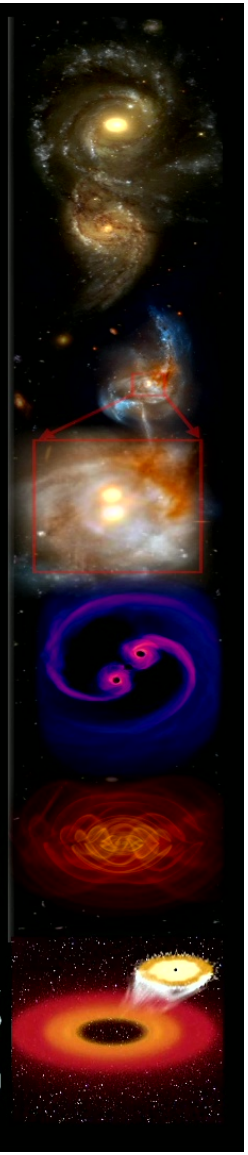
Yosef Zlochower (RIT)
Zach Nusbickel (RIT)
Allen Wen (RIT)

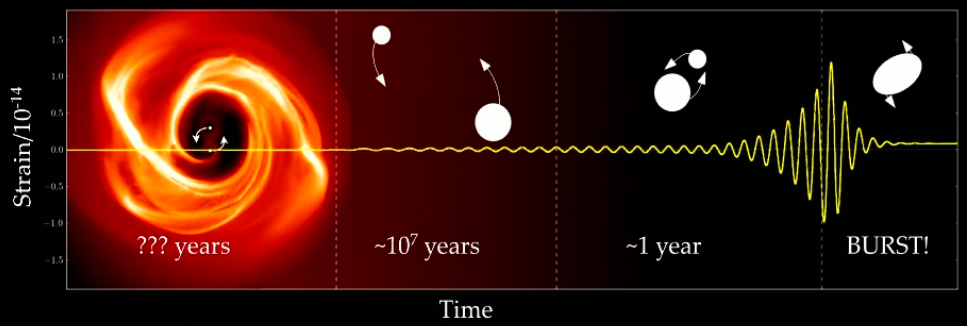
+ Einstein Toolkit Coll.: Roland Haas (NCSA),
Erick Schnetter (PI) +

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)
- And they should be EM bright: $L_{Edd} \sim 1.26 \times 10^{45} \frac{M}{M_\odot}$ erg/s
- 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 ($M_{BH} \sim 10^6\ M_\odot$) and PTA ($M_{BH} \sim 10^9\ M_\odot$).
- EM signatures can be used to localize GW events in the sky and to study their astrophysical environment.
- Finding SMBBHs now, before LISA launch, would significantly reduce the uncertainty in estimates of the potential LISA source population.

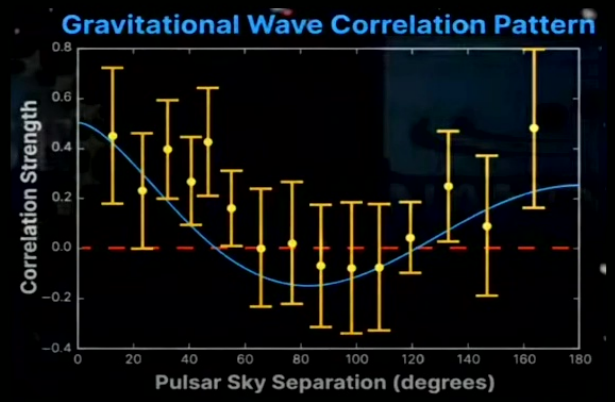


The hunt for low frequency GWs ...

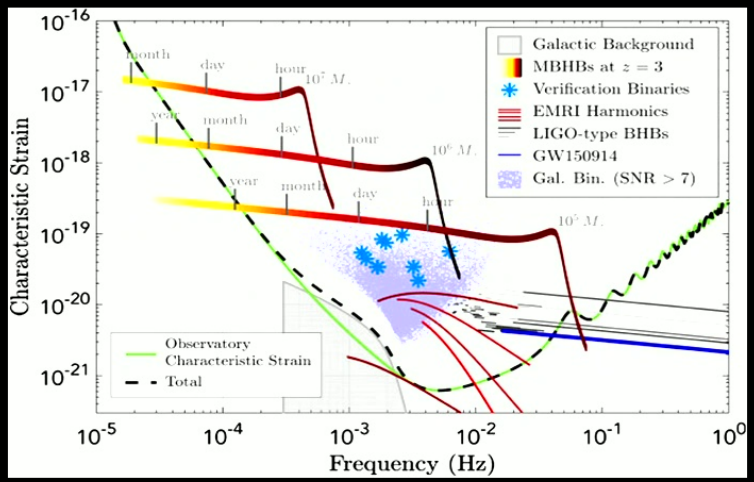


S. Burke-Spolaor +2018

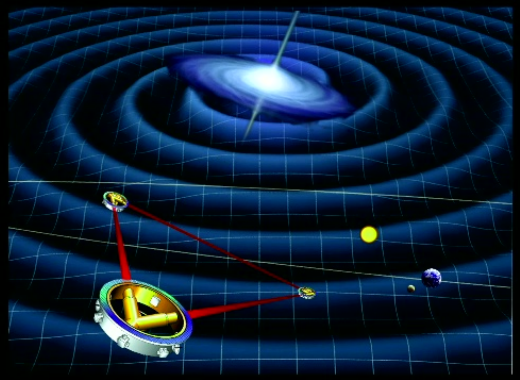
PTA has indicated that there exists a population of SMBBH inspirals ~$10^9 M_{sun}$



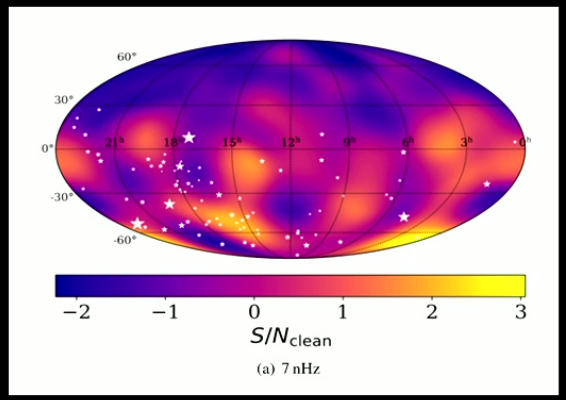
15-year correlation data
Antoniadis+NANOGrav coll. (2023)



LISA sensitity curve - Sesana+2021
NANOGrav coll. (2023)



LISA will target lower mass SMBBH mergers ~$10^6 M_{sun}$

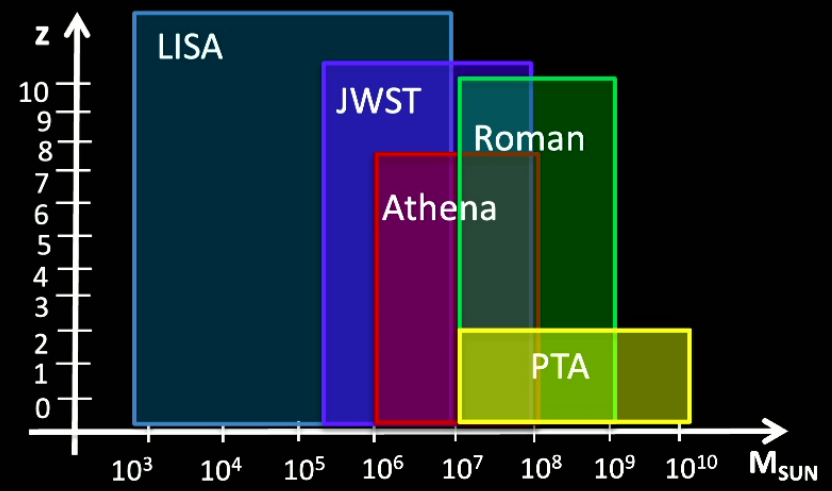


Is the PTA signal anisotropically distributed? -Grunthal++2024

SMBBHs as Multimessenger sources across cosmic epochs …

- Hierarchical galactic assembly models predict large populations of binary-AGNs across all cosmic epochs - e.g. Volonteri+ 2003.
- Hundreds of EM-distinguishable of them are in the PTA range - Krolik+2019
- Mergers are at relatively low redshifts, advantageous for EM identification – Casey-Clyde+2021, Li+2022
- Quasars are "more likely" to host more massive SMBBHs - Casey-Clyde+2024

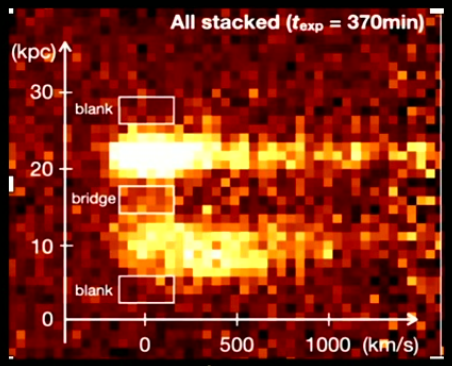
- EM signatures can be used to localize GW events in the sky and to study their astrophysical environments – finding them will be challenging but not impossible …



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

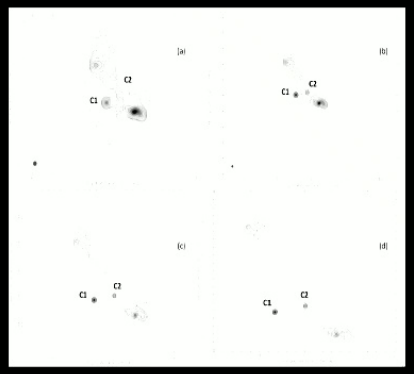
Can we distinguish EM signals SMBBH from single AGN?

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



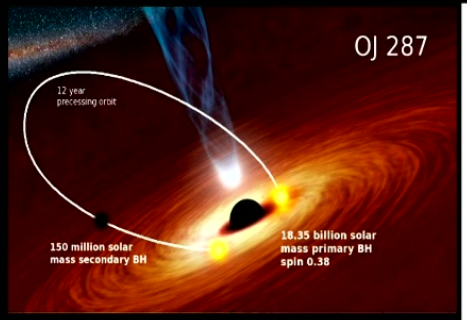
Many are binary quasars at z=6.05, separated by 12 kpc Matsuoka+2024;

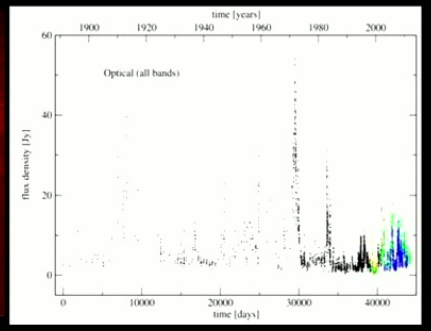
In the local universe: UGC 4211, z= 0.03,and at 230 pc separation- Koss+2024



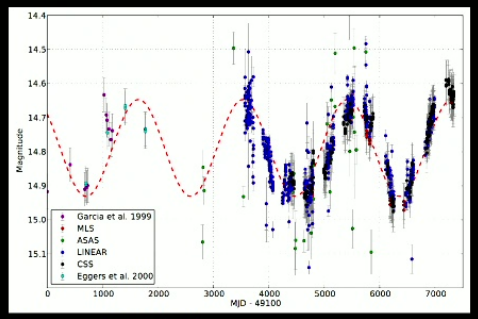
Double nuclei (radio) orbiting! 0402+379 - Bansal+2017, 12 years of multi-frequency VLBI observations

How can we detect them?

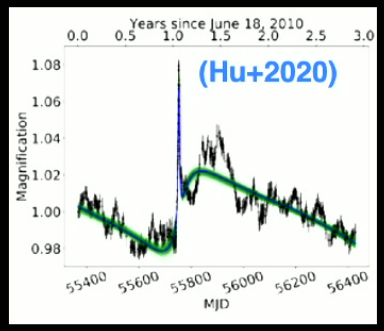




Periodic flares; OJ287 (Valtonen et al. 1988)



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

Can we distinguish EM signals SMBBH from single AGN?

There are
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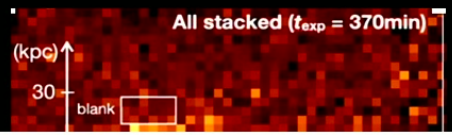
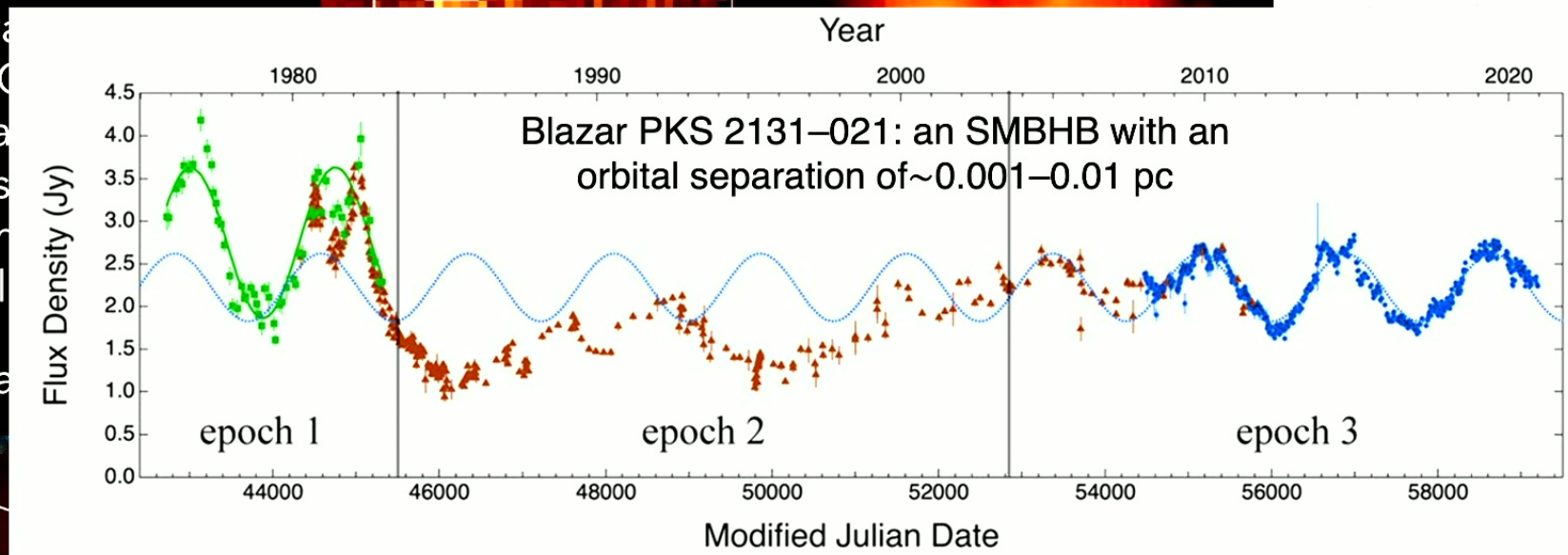
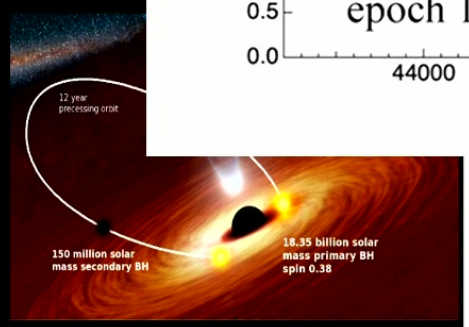
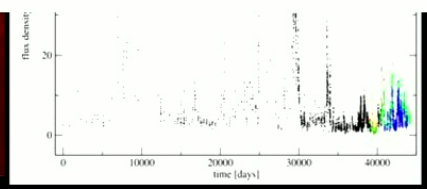
How ca









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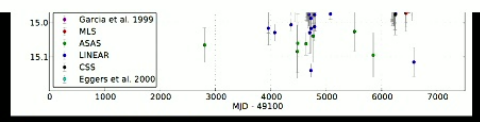

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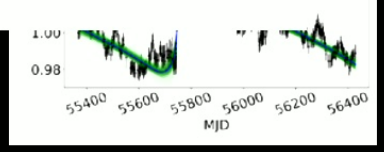
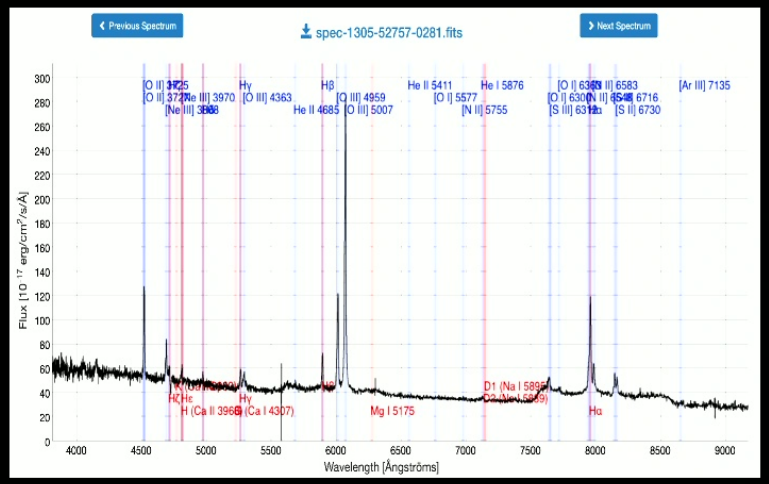


Self-lensing? D'Orazio+ 2017, Smith+2018, Ingram+ 2021,Davelaar+ 2022

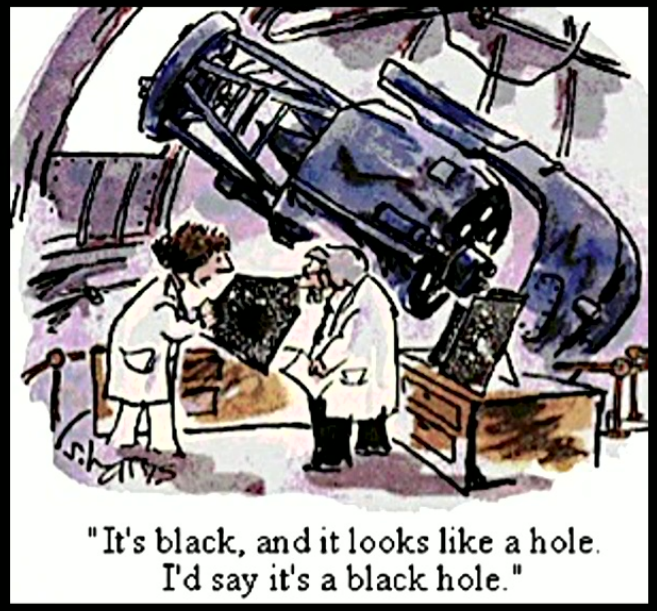
Without knowing what to look for, identification will be hard!

- 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

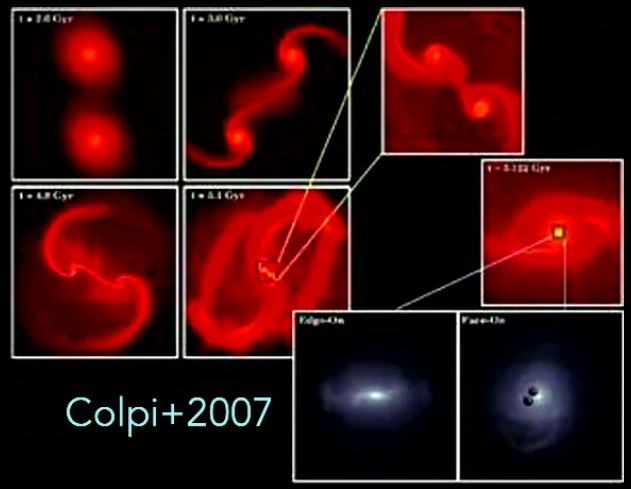


We need realistic theoretical models that can produce detailed EM spectra and lighcurves!

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.



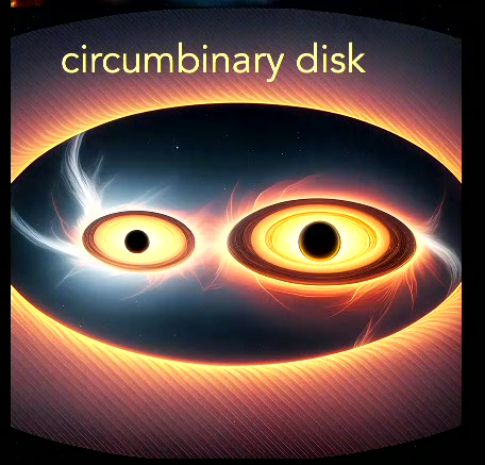
Colpi+2007

- 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

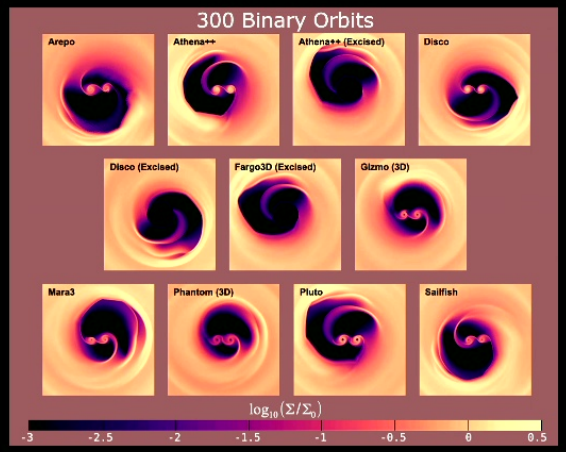
Brief History of Simulations

- 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.

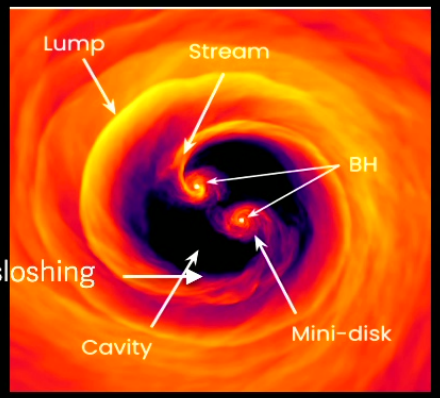
- Modern 2d (vertically integrated) and 3d Newtonian hydrodynamical simulations find that the binary torque "dam" does not hold, allowing accretion to continue, and minidisks form around each BHs - e.g. Milosavljevic & MacFadyen, 2008, D'Orazio+ 2013; Farris +2014; Ryan+2016, Tang+2018, Duffel++2024

- 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.

- 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

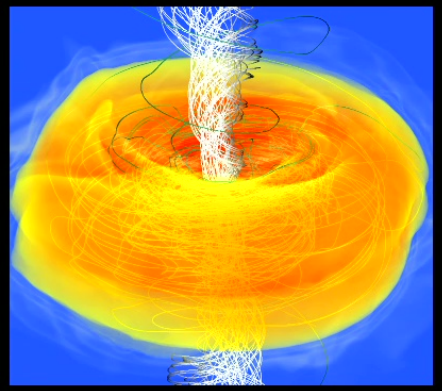


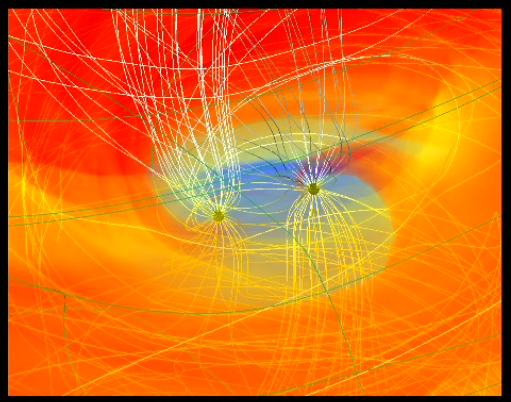
3d GRMHD ``picture'': Gutierrez, Combi, Ryan "New Frontiers in GRMHD Simulations'' 2024

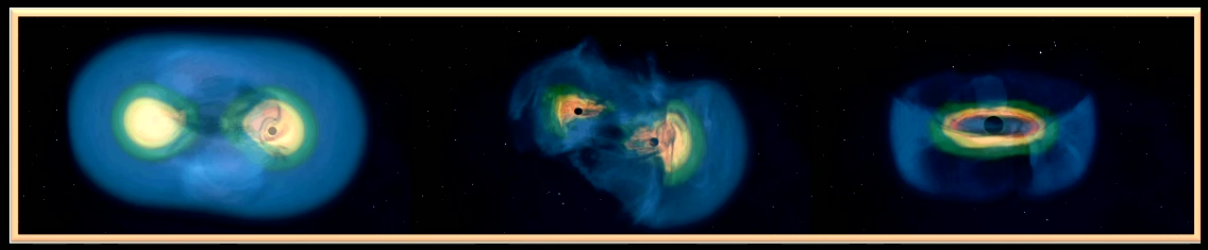
Numerical Relativity Simulations

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.

However 3d GRMHD with radiation is hard…

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

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

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

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

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

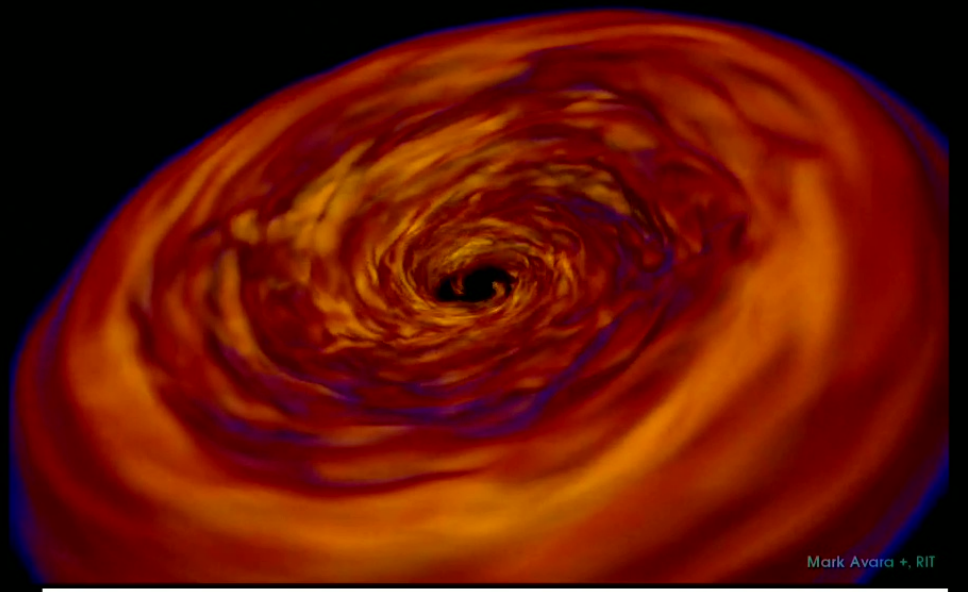
$$\nabla_\nu F^{\mu\nu} = I^\mu\,, \qquad \nabla^*_\nu F^{\mu\nu} = 0\,, \quad \text{(Maxwell equations)}$$

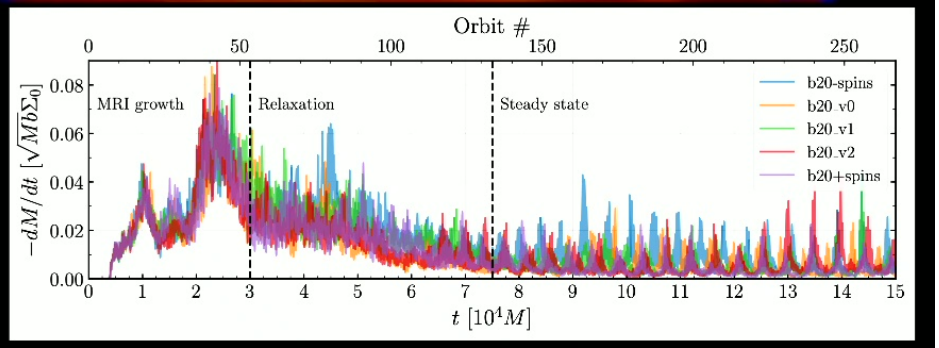
$$\nabla_\mu T^{\mu\nu}_{\text{rad}} = S^\nu\,, \quad \text{(radiative losses)}$$

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

A computational approach to long-term 3d GRMHD simulations

- Perform a long-term GRMHD simulation a circumbinary disk (CBD) for hundred of orbits to resolve the physics of the gas, i.e. until the CBD reach the quasi-steady state of accretion and turbulence
  - ❖ Spherical coordinates are optimal angular momentum transport with an excised central region around the binary for computational efficiency – Noble+2012, Lopez-Armengol+ 2021, Combi+2022
  - ❖ Analytical BBH spacetime in the relativistic inspiral regime with PN trajectories are efficient and accurate here – Noble+2012, Mundim+2014, Ireland+2014, Nakano 2014+, Lopez-Armengol+ 2021, Combi+2022,, 2024
- Then, ``hand-off '' the simulation data to a GRMHD simulations designed to resolve the physics near each BH (AMR grids) and evolve from inspiral to merger. – Bowen+2019, 2020, Avara+2024, Ennoggi+2025





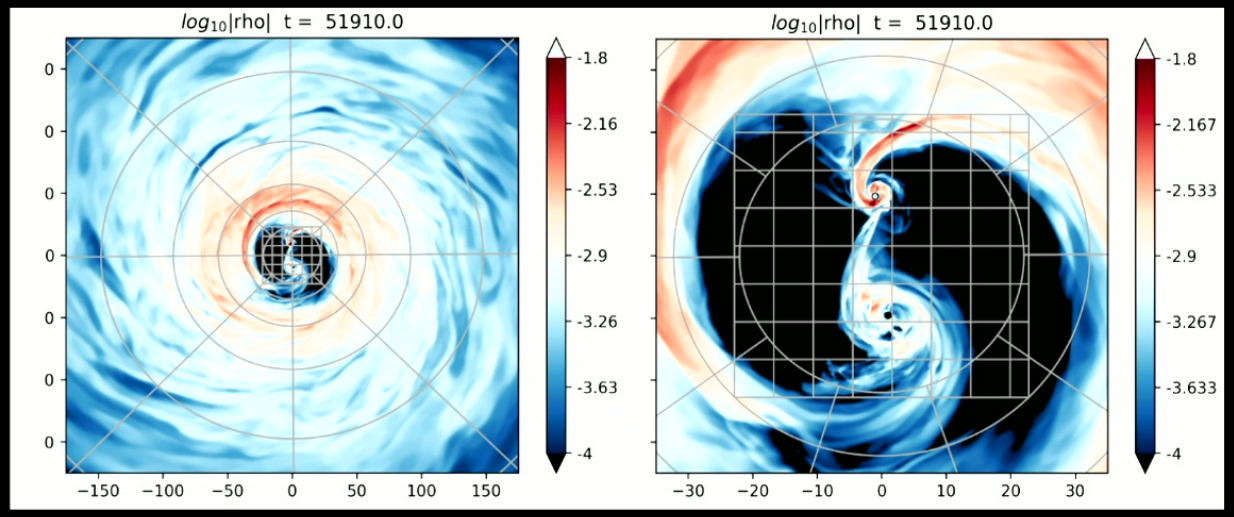
Lopez-Armengol+ 2021

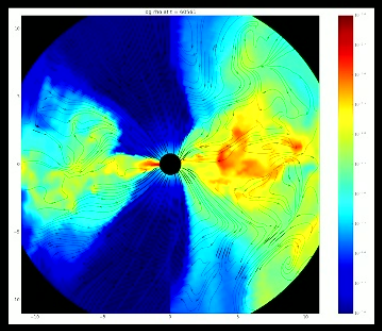
Accretion into a SMBBH approaching merger …

Noble++2012, Bowen+2017, 2018, 2019, Noble+2021,Combi+2022, Avara+2023, Noble+2024 in prep

- Minidisks forms quickly and the cycle of periodic depletion and refill of the gas is dominated by the CBD "lump" through the streams …

- Rich 3d structure of accretion disks

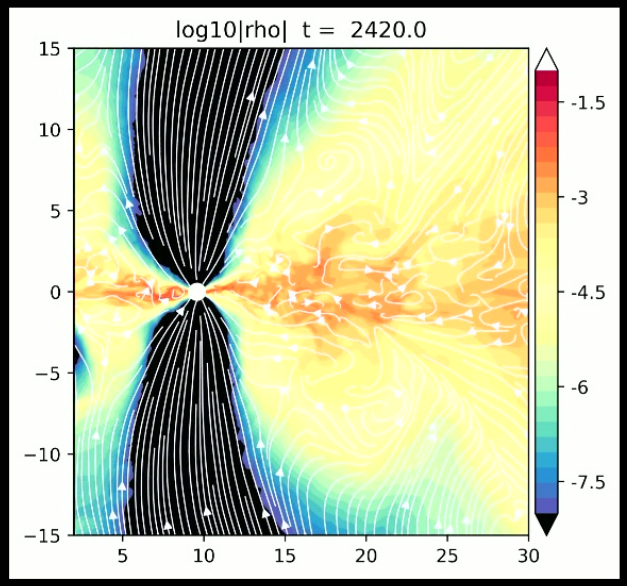




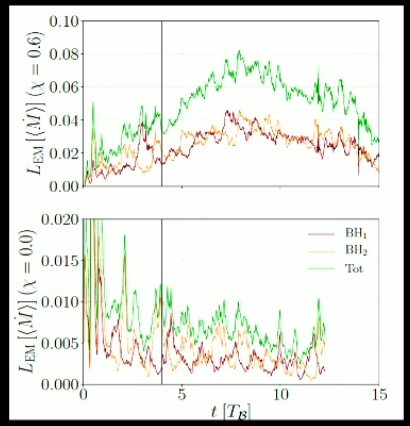
- Accreting streams fall in the cavity mostly due to gravity and shock against the BH minidisk, which deplete and refill periodically at time scale close to one orbital period.

- The minidisks form quickly and exchange mass through a periodic "sloshing". Mini-disks accretion nothing alike single BH accretion!

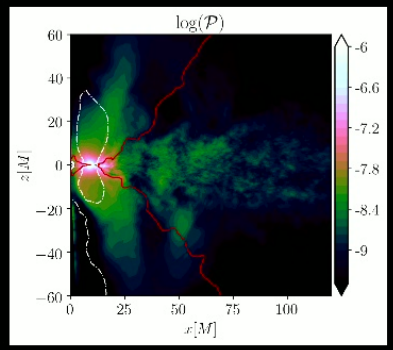
Hints of interesting dynamics with BH Spins!



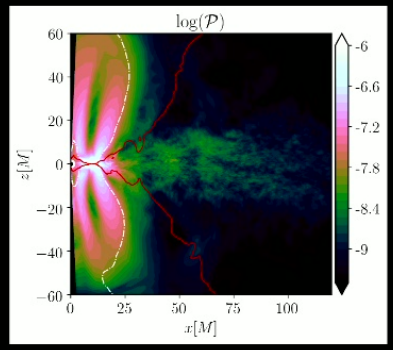
More magnetized mass + BH ergospheres means more jet-like structure!



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

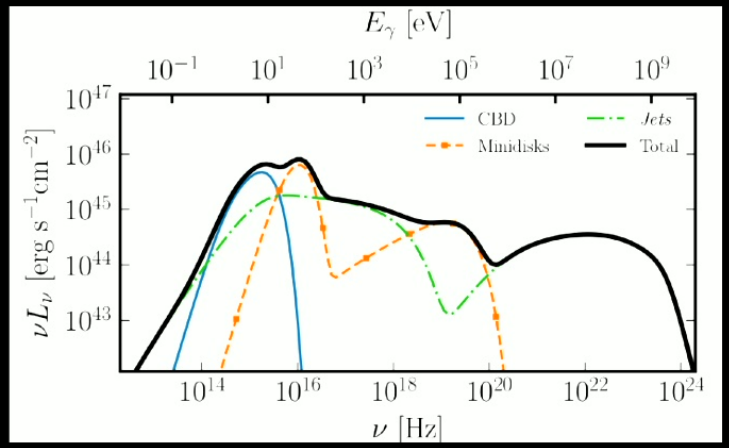


No-spins



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

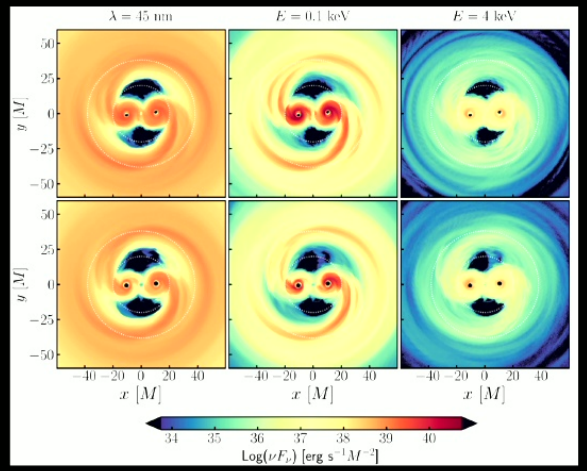
A simple Radiative Prescription …

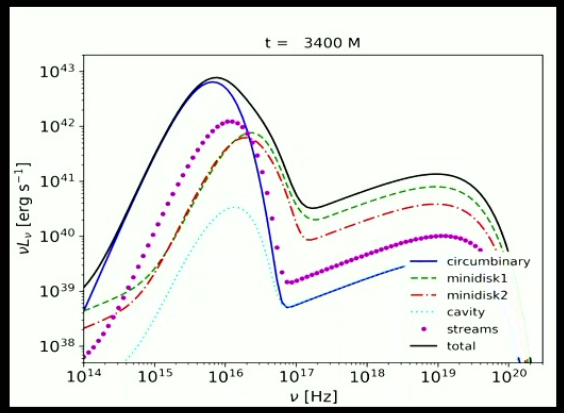
- Bound material cooled to target entropy based on a location dependent timescale – Noble+ 2012,

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

- 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.

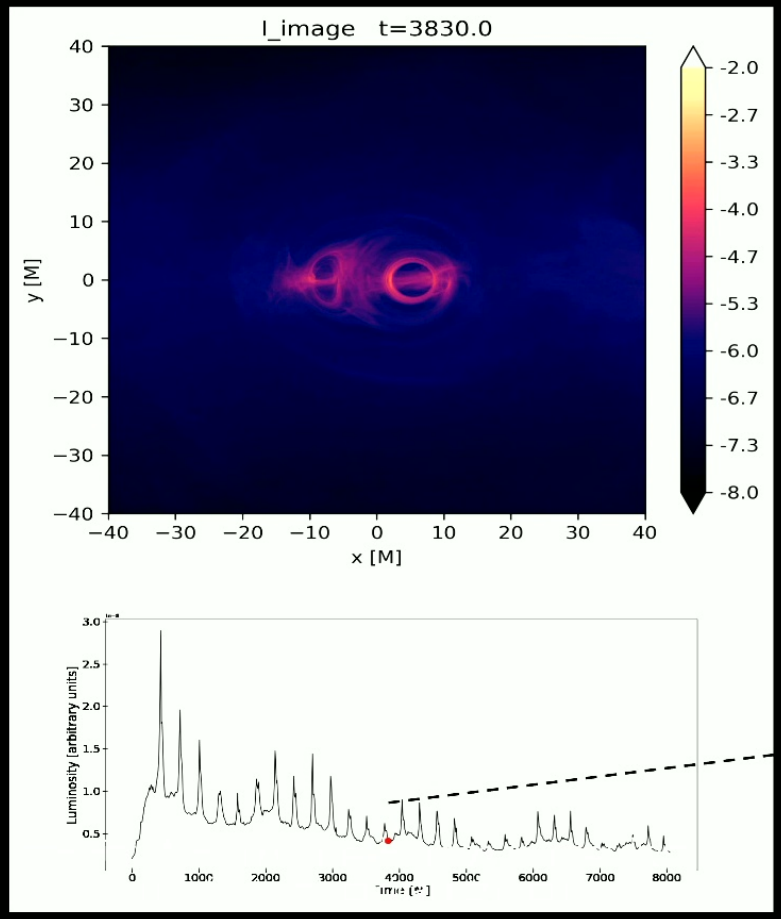
- Spectra time variability, different components at different frequencies.

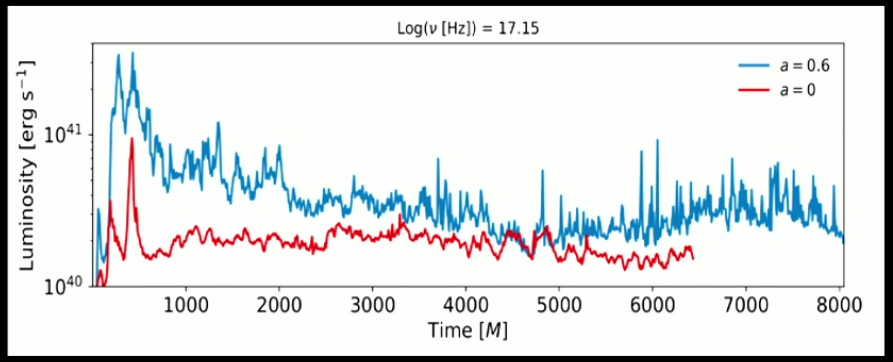




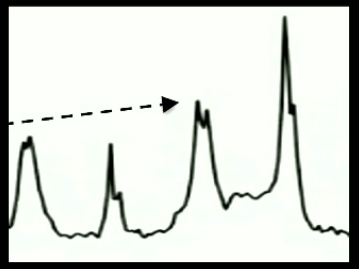
Spectral energy distribution - Gutierrez+2022

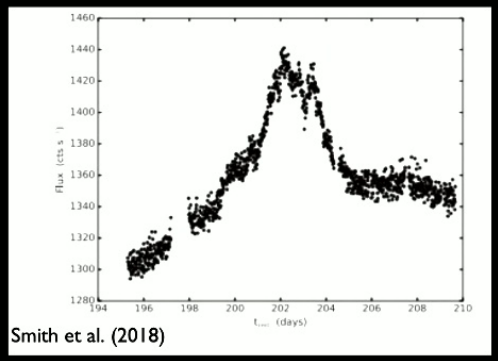
Light Curves display Self-lensing features?





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





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

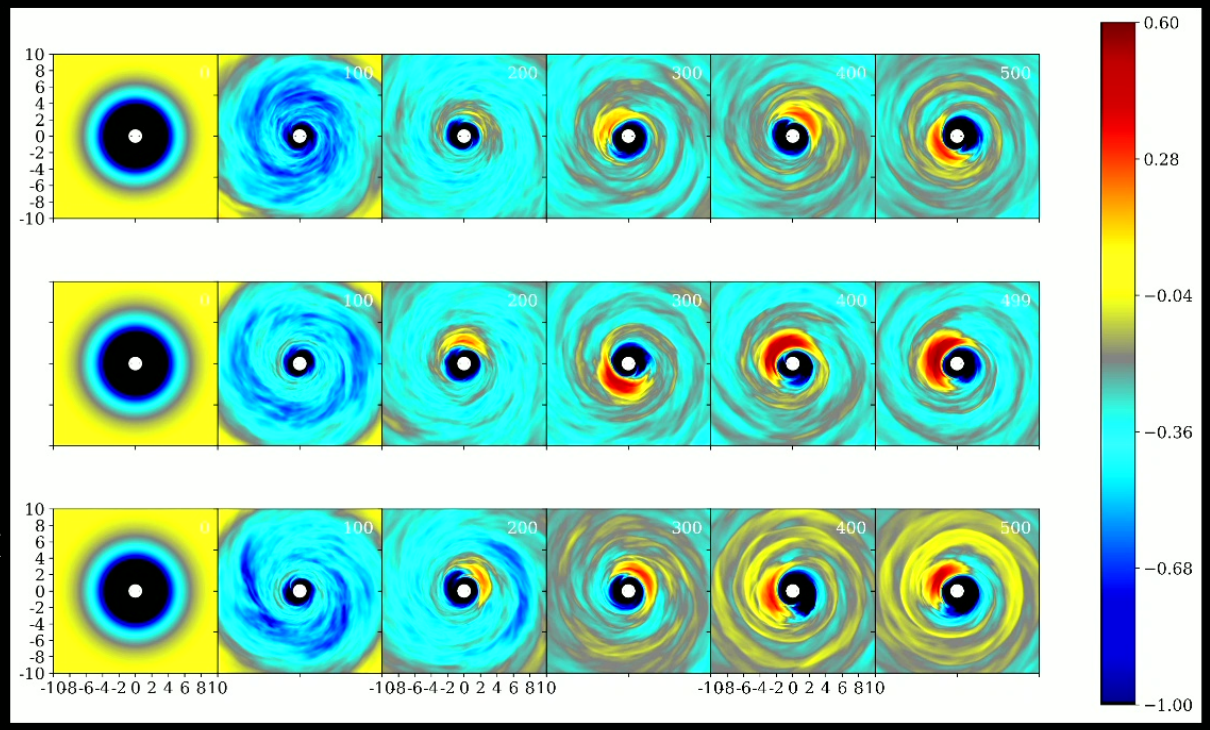
Exploring the CBD dynamics as a function of binary separation …

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!

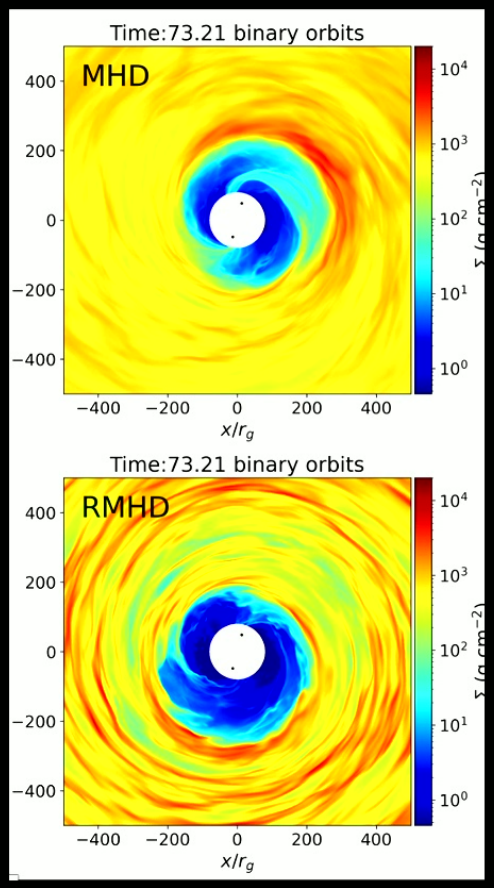
Accretion rate diminishes as cooling rate diminishes → hotter disks accrete more slowly than cooler disks.



No sign of decoupling so far!

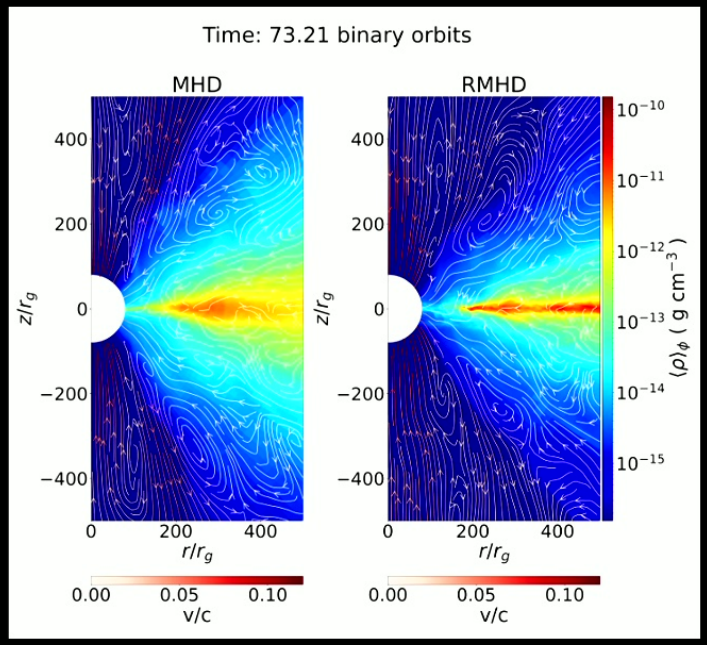
Noble+ 2024, in prep; P21
GRMHD with HARM3D on PN

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.

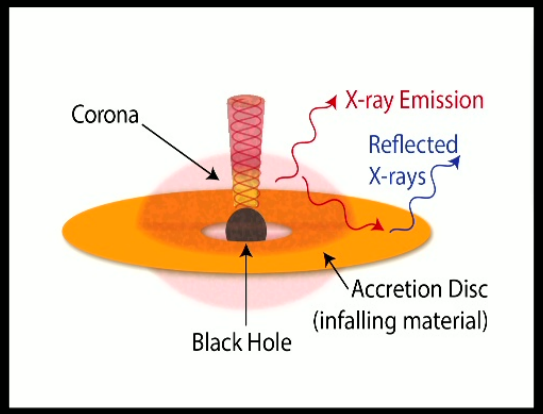


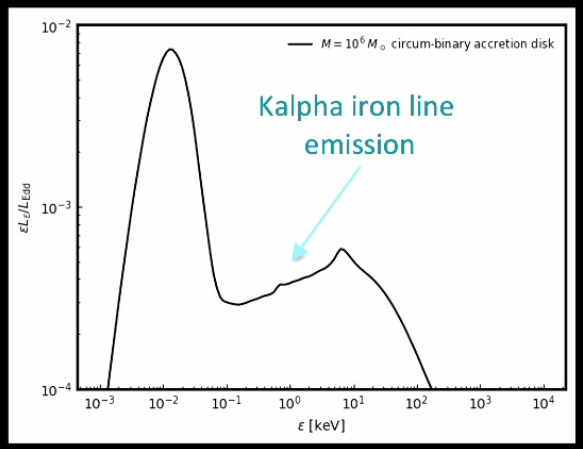
Radiation Forces and Radiated Spectra

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.

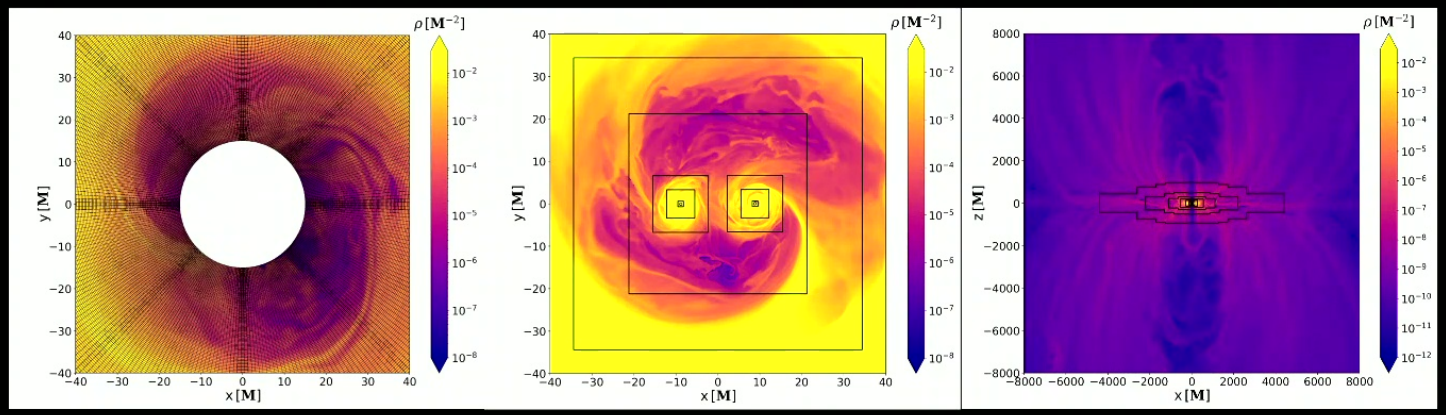




CBD spectra with PTRANX - Nagele+ 2025, in prep

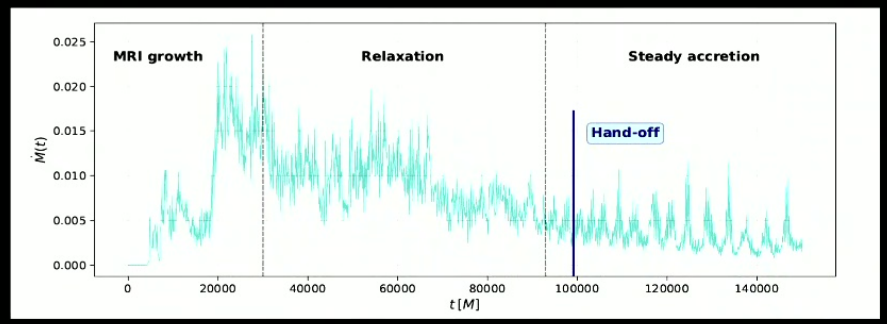
GRMHD simulations in full Numerical Relativity

Code ``Hand-off" Framework:



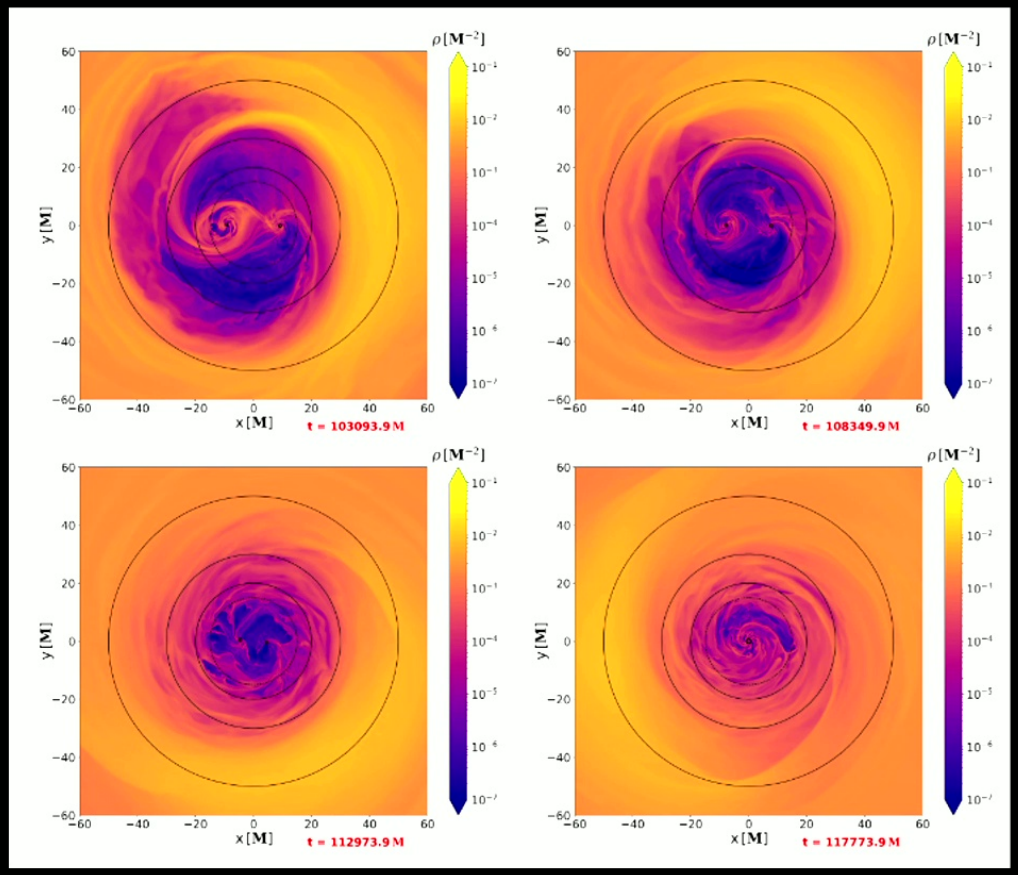
Armengol+2021, Ennoggi+ 2025

- 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)



See Ennoggi's talk this afternoon!

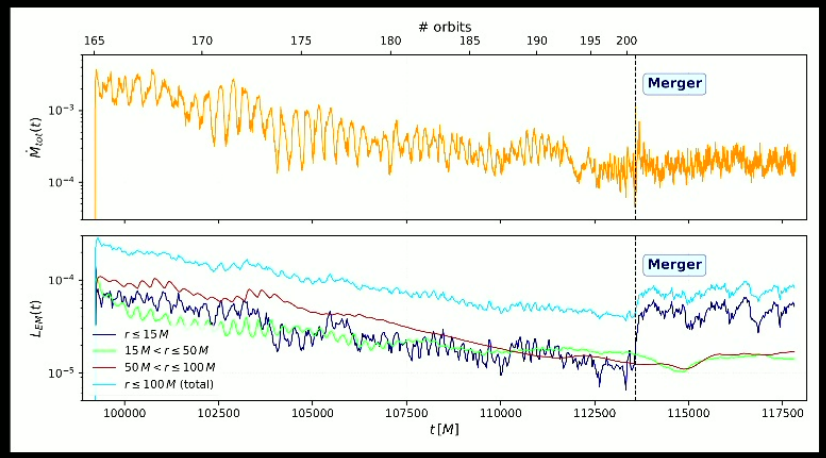
What happens at merger?



First full NR+GRMHD simulation of non-spinning, equal-mass black holes completing 200 inspiral orbits from $20r_g$ separation:

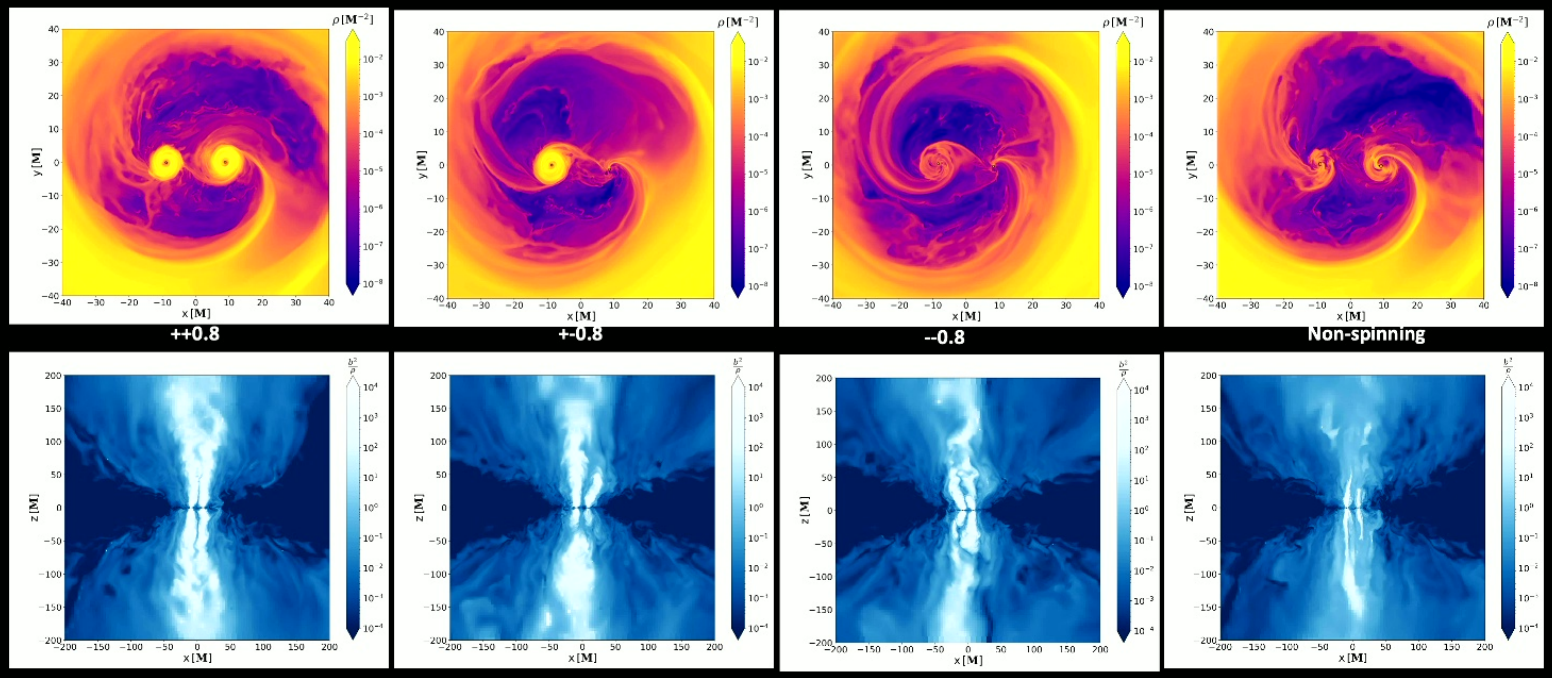
- Minidisks dissolve as the binary compresses just prior merger …
- Luminosity briefly drops only by a factor a few, then spikes by 50% at merger with an abrupt change in spectrum.

Ennoggi+2025



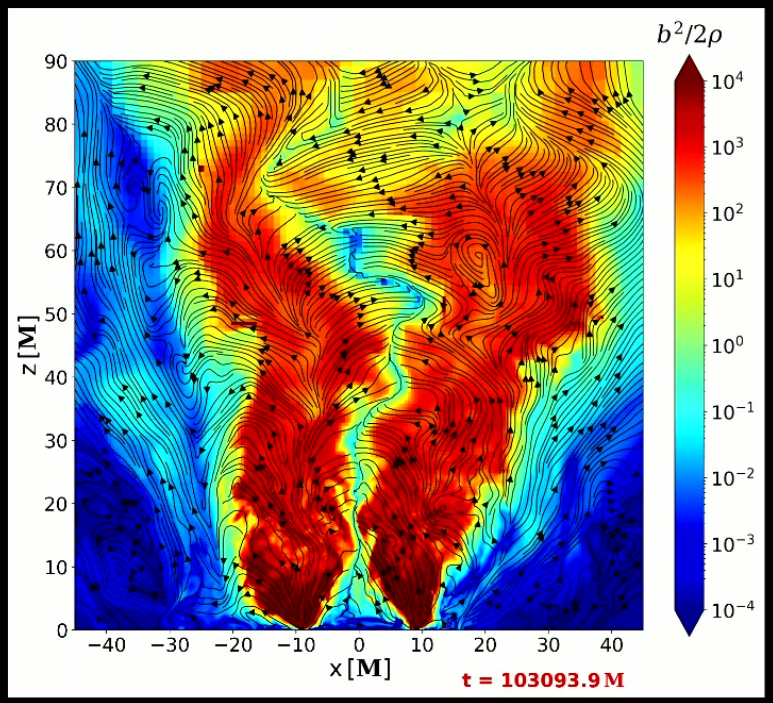
The effect of spins on minidisks and jets launching

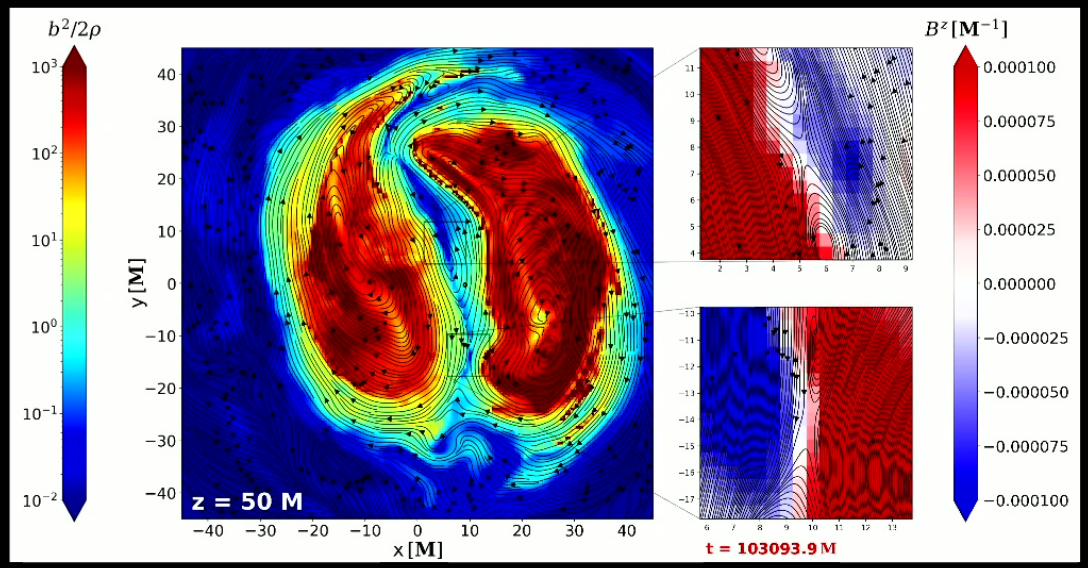
- Minidiscs physics strongly affected by BH spins – Ennoggi+2025, in prep
- The magnitude and direction of the spins affects orbital dynamics via spin-orbit interactions – Campanelli+2007



Dual Jet Interaction in Aligned Spinning SMBBH

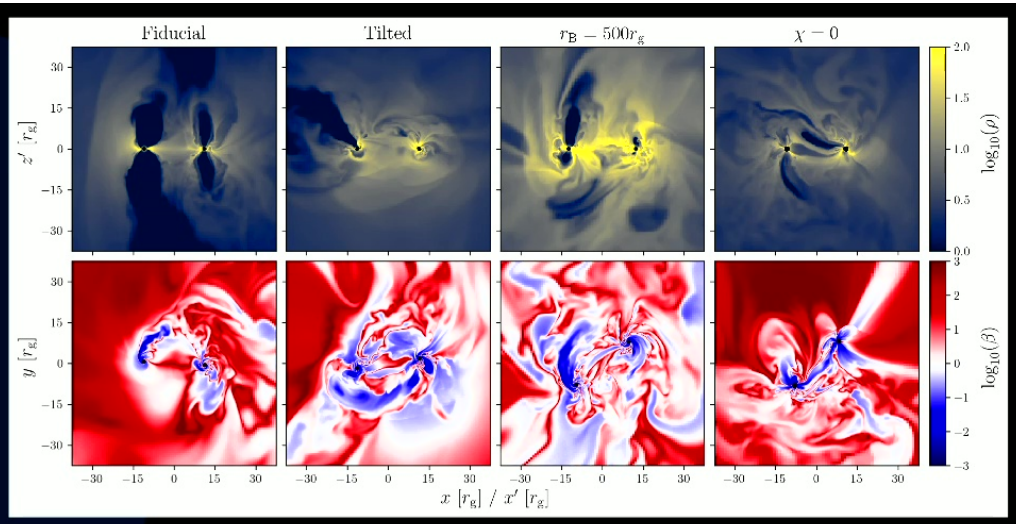
Twisted magnetic field lines accreted by both BHs due to BZ effect, displaying magnetic reconnection – Ennoggi+ 2025, in prep

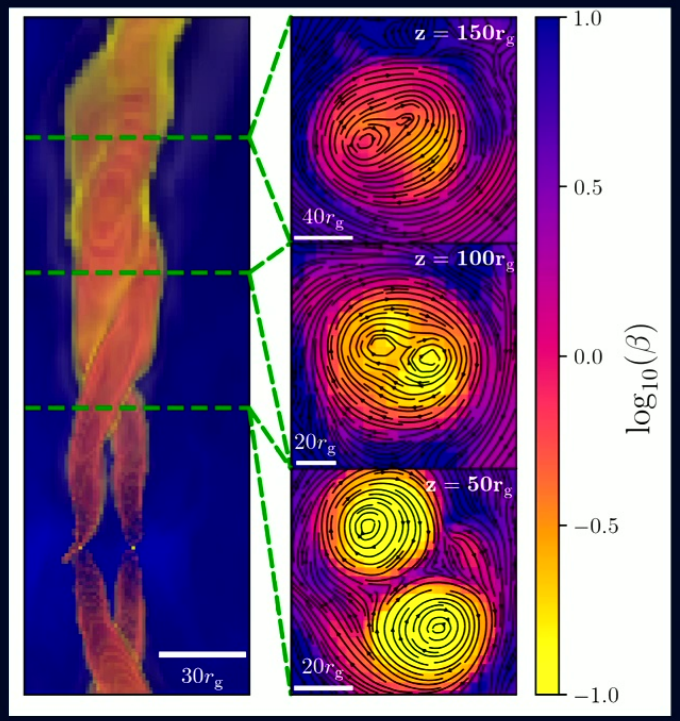




See Ennoggi's talk this afternoon!

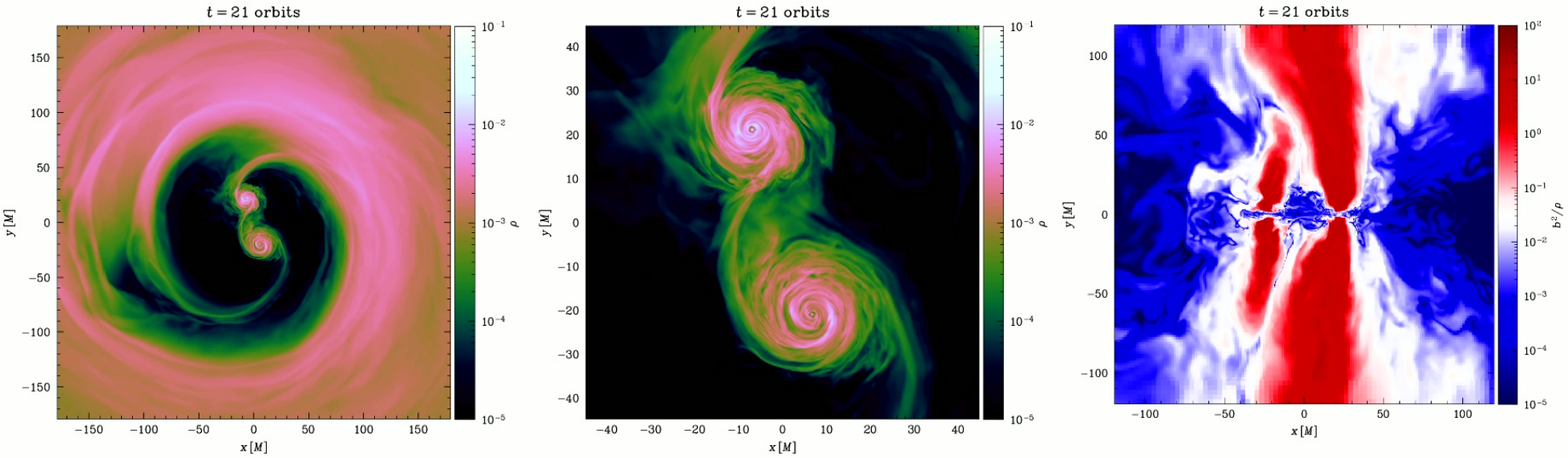
Flares and Dual Jets from Magnetically Arrested Flows in Merging SMBBH





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



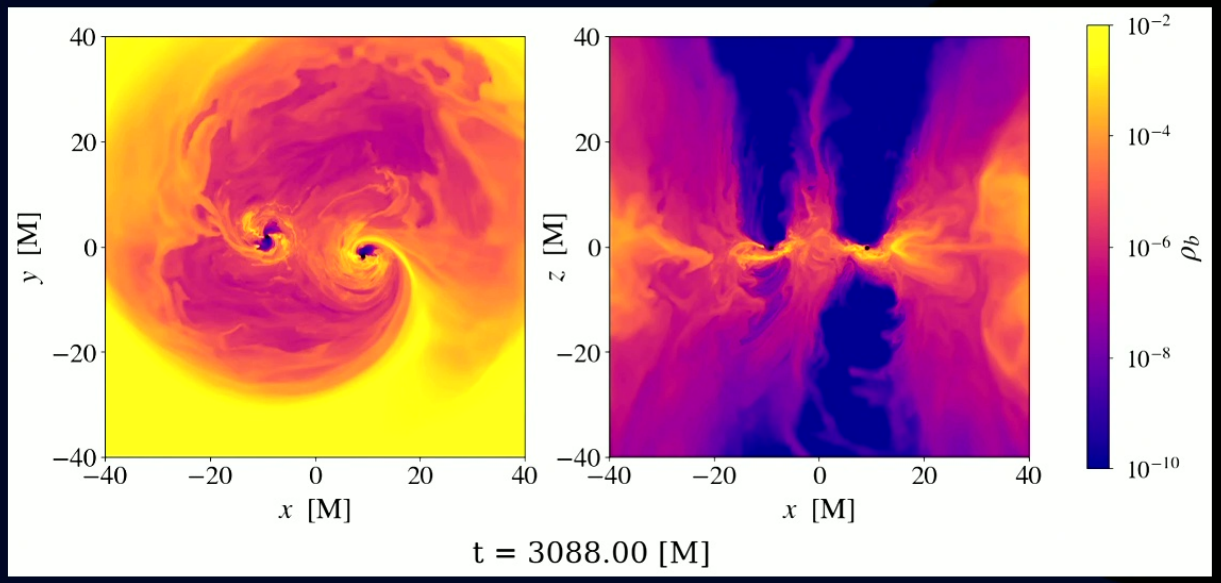
More on dual Jet Interaction from larger separations

Combi+2025, work in progress

- 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 …
- Use a semi-analytical spacetime treatment based on superimposed Kerr-Schild BHs and PN trajectories – Combi+2021, 2022
- What are the initial conditions at closer separations? e.g. $\sim 20r_g$

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

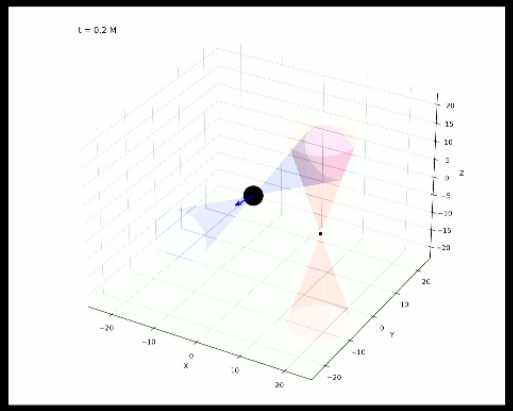
Efficient rGRMHD for Dynamical Spacetimes!

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

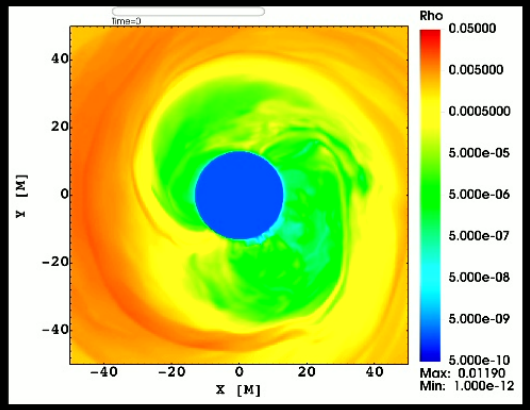
- And GPUs can make simulations 15 times faster on exascale computers – e.g. AsterX + SpacetimeX as part of the Einstein Toolkit – Kalinani+ 2024, now using subcycling time integration - Ji+2025

  See Liwei Ji+ Talk

- 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

Concluding Remarks

M87*

- 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.
- GW observations with LISA and PTA will lead us to surprising discoveries about supermassive binary black holes and their populations and ``whereabout" …
- Black holes have so far matched our expectations, but we must be ready to face the possibility that the universe can still surprise us a great deal!

. 50 μas

Sgr A*

- EM astrophysics is crucial for understanding how gas is accreted and how jets are launched. Hence, GRMHD simulations will play an increasingly central role in interpreting multi-messenger observations of compact object sources.
- 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!