RIT Rochester Institute of Technology

Probing Supermassive Black Hole Mergers with General Relativistic Magnetohydrodynamic Simulations

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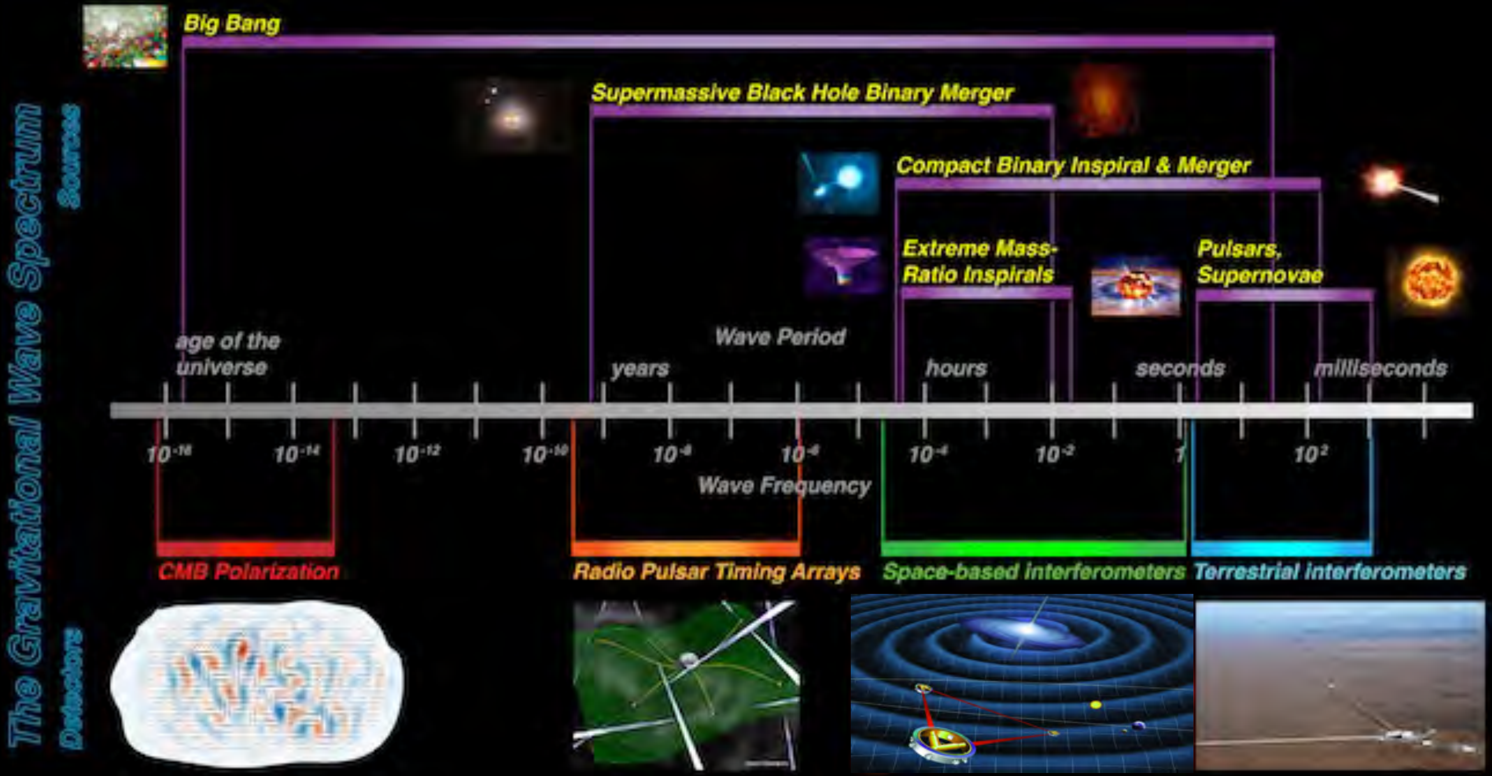
Black Hole Binaries span the entire GW spectrum

BBH mergers are essential for probing strong gravity, stellar evolution, and the cosmic growth of SMBHs.



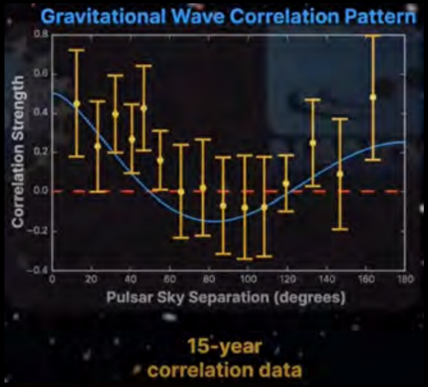
PTA ongoing

LISA launch ~2035

LIGO + 3G ground based detector

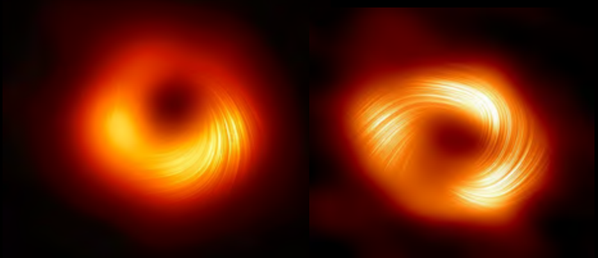
A bright Multimessenger future for BBHs

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



Stochastic GW background likely from SMBBHs (NANOGrav+2023)

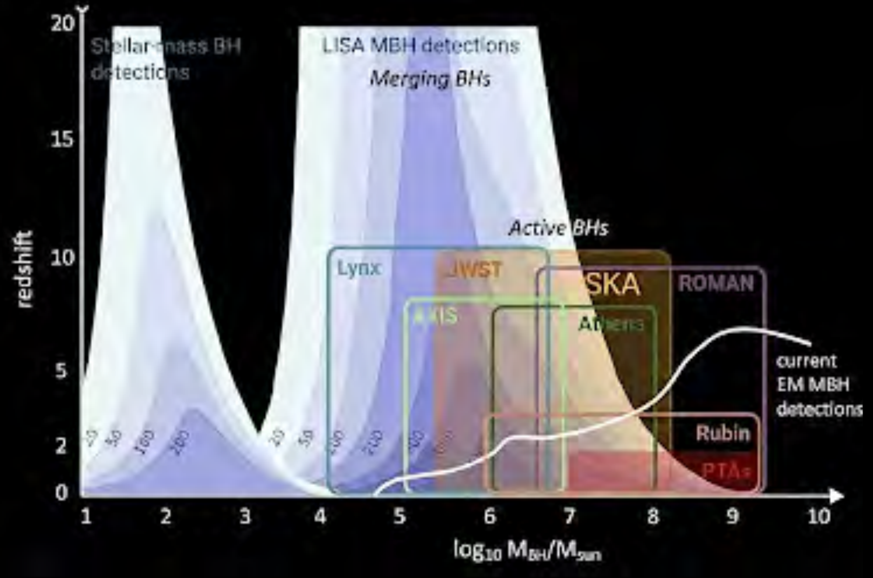
→ SKA & next-gen PTAs will resolve individual SMBBHs.



EHT: M87 & Sgr A*

EHT → ngEHT & BHEX will resolve horizon-scale dynamics & jet launching.

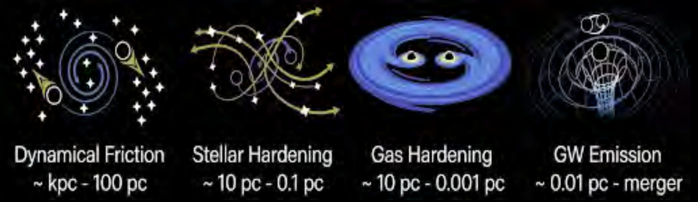
- JWST, Vera Rubin/LSST, Athena, Roman, etc., will uncover "many" binary-AGN in the upcoming decade or two…



Adapted from LISA Living Review (LISA Astrophysics Working Group, 2023)

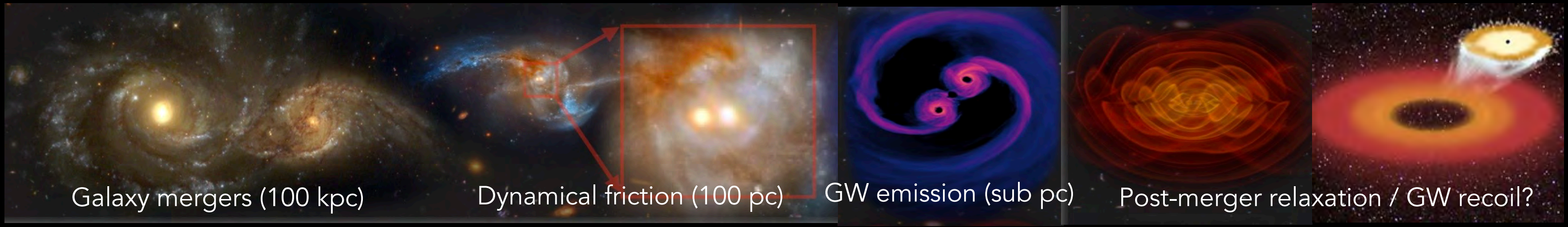
Mergers of SMBBHs

- Supermassive black hole binaries (SMBBH) should form from post-galaxy-mergers; once in the AGN core they can accrete hot gas, emit powerful jets (Begelman+1980)
- Dual-AGNs should merge within Hubble time via dynamical friction, gas torques, etc.



- Once they are in the GW regime, SMBBHs become optimal GW sources for both LISA ($M_{\rm BH} \sim 10^6\ M_\odot$) and PTA ($M_{\rm BH} \sim 10^9\ M_\odot$).
- Mergers due to GW emission, leading to recoils in some cases, are expected to occur in gas-rich environments leading to **EM emission:**

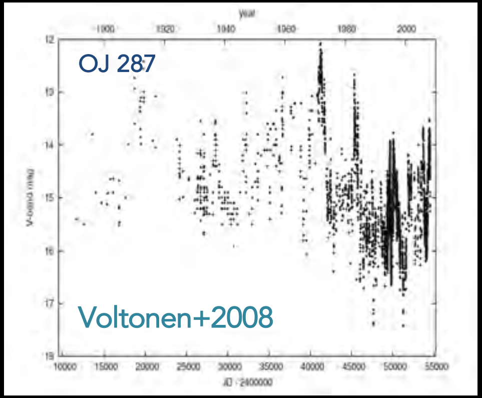
$$L_{\rm Edd} \sim 1.26 \times 10^{45} \frac{M}{10^7\ M_\odot} \text{ erg/s}$$

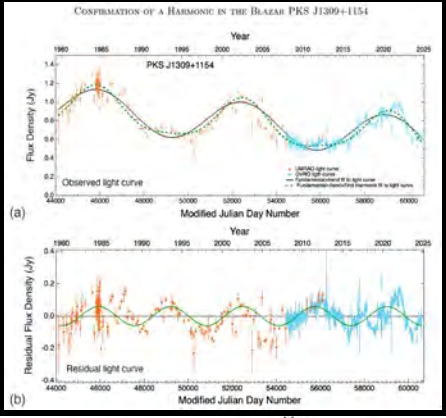


Can we distinguish EM signals of SMBBHs from single AGN?

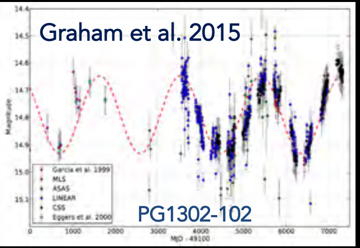
Numerous dual-AGN systems are seen, but confirmed sub-pc binaries stay rare — how do we detect them?

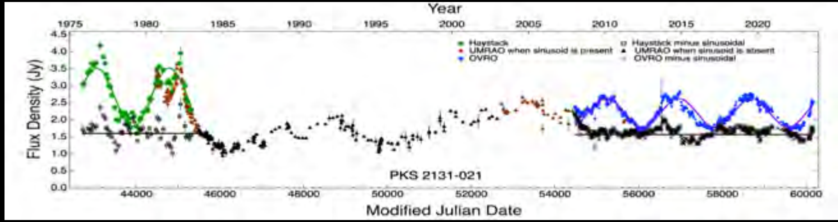
- ➢ Direct VLBI imaging of double nuclei
- ➢ **Quasi-periodic** variability in quasar / blazar light curves
- ➢ Doppler-shifted emission lines in AGN spectra
- ➢ Self-lensing & reverberation mapping



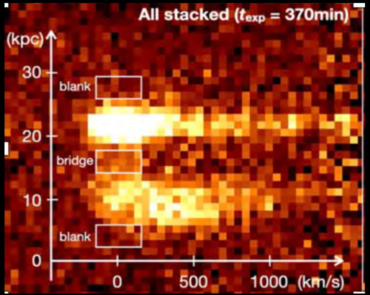


PKS J1309+1154: 17.9-year period, phase-coherent ~9-year harmonic, 2.5 cycles — ReadHead+2025



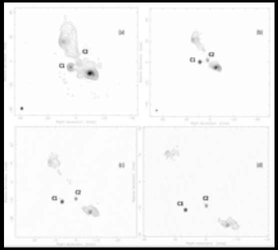


PKS 2131-021: 1.4-year period, 10 cycles — Kielhmann et al. 2024

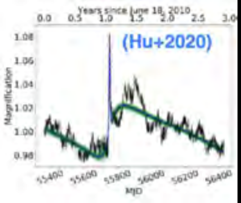


A binary quasar pair at z=6.05, separated by 12 kpc Matsuoka+2024;

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

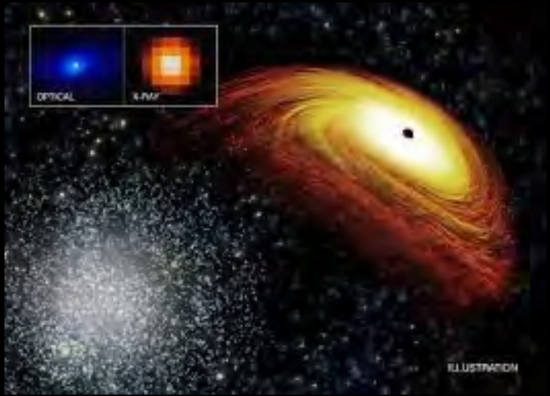


Self-lensing candidate

The case for recoiling BHs

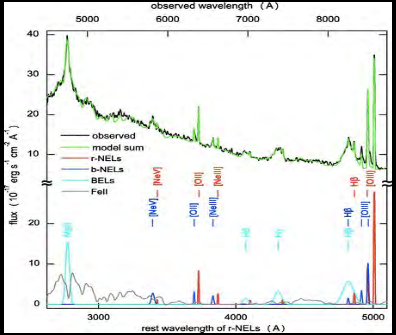
- In 2007, numerical-relativity calculations predicted large recoil kicks for BBH merger remnants (e.g., Campanelli+2007).

- If large enough, the final BH remnant could be kicked out of the galaxy, impacting many astrophysical scenarios including SMBH formation models.

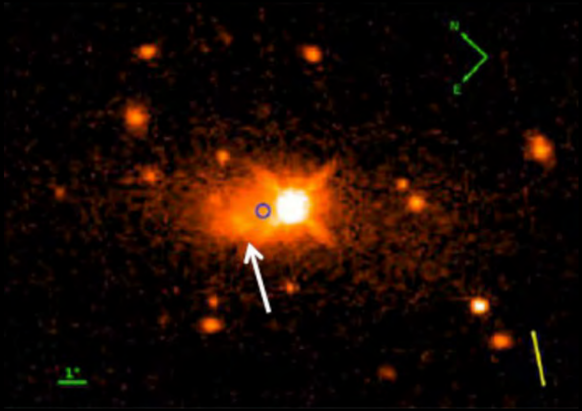


A recoiling SMBH in an AGN can retain the inner part of its accretion disk (e.g., Loeb 2007; Shields+2007)

Astronomers have searched for a number of possible signatures: double-peaked emitters, offset galactic nuclei, populations of galaxies without SMBHs, X-ray afterglows, feedback trails, etc.

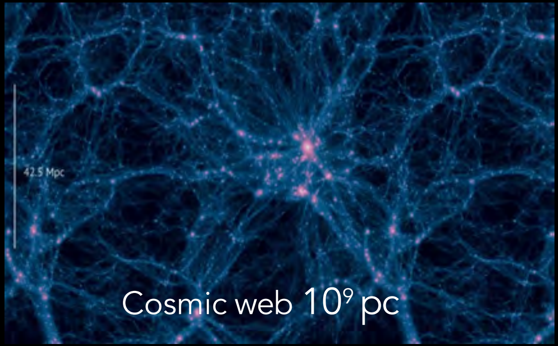


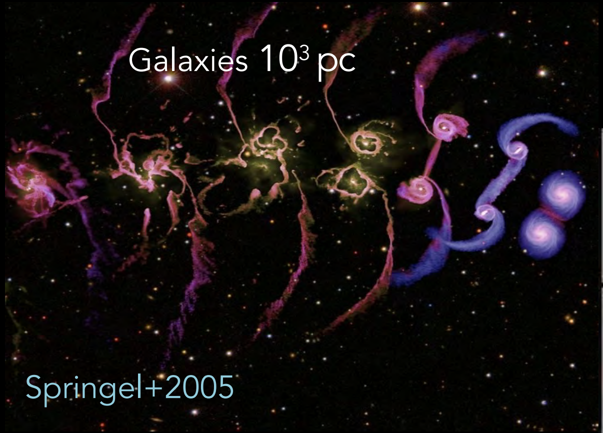
SDSS J0927+2943:
The BLR (from the gas tightly bound to and moving with the BH) are "shifted" relative to the NLR (which trace the ambient gas of the host galaxy). (e.g., Komossa+2008)



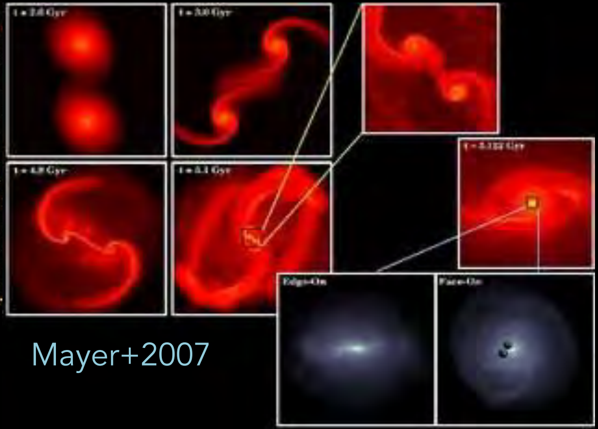
3C186 spatial offset (11kpc from galaxy core) + velocity shift from BLR shifted from NLR by 2000km/s
Chiaberge+2017, 2025; Lousto+2018

Modeling SMBBH in gaseous environments is challenging ...

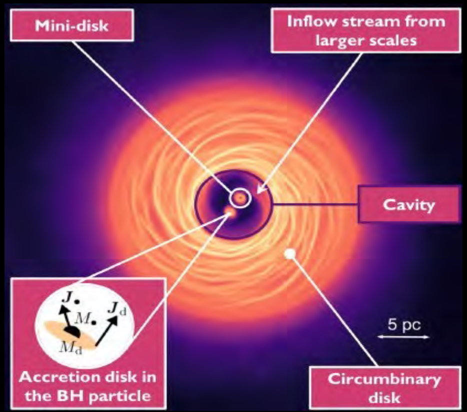




- Hierarchical galactic assembly models predict large populations of binary-AGNs across all cosmic epochs - e.g. Volonteri+2003
- Models must incorporate accurate environmental physics across the full dynamical range, from kiloparsecs down to sub-parsec levels.

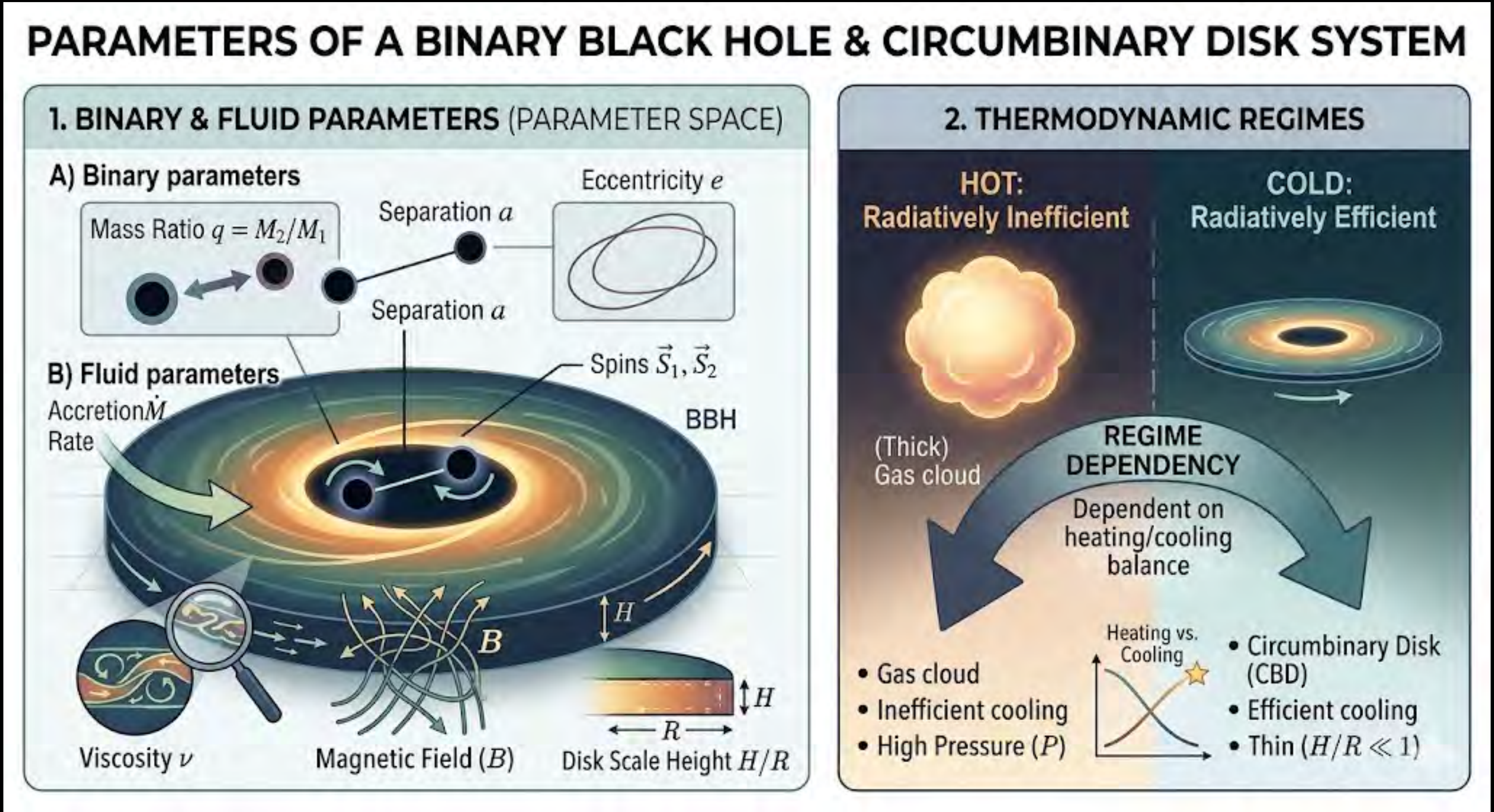


Mayer+2007



Bourne+2024

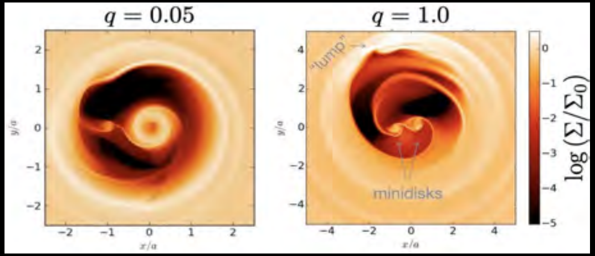
This talk: < 10^{-6} pc


PARAMETERS OF A BINARY BLACK HOLE & CIRCUMBINARY DISK SYSTEM
1. BINARY & FLUID PARAMETERS (PARAMETER SPACE)
A) Binary parameters
Mass Ratio $q = M_2/M_1$
Separation a
Eccentricity e
Separation a
B) Fluid parameters
Spins $\vec{S}_1, \vec{S}_2$
Accretion $\dot{M}$ Rate
BBH
H
B
H
R
Viscosity ν
Magnetic Field (B)
Disk Scale Height H/R
2. THERMODYNAMIC REGIMES
HOT: Radiatively Inefficient
COLD: Radiatively Efficient
(Thick) Gas cloud
REGIME DEPENDENCY
Dependent on heating/cooling balance
Heating vs. Cooling
• Gas cloud
• Inefficient cooling
• High Pressure (P)
• Circumbinary Disk (CBD)
• Efficient cooling
• Thin ($H/R \ll 1$)

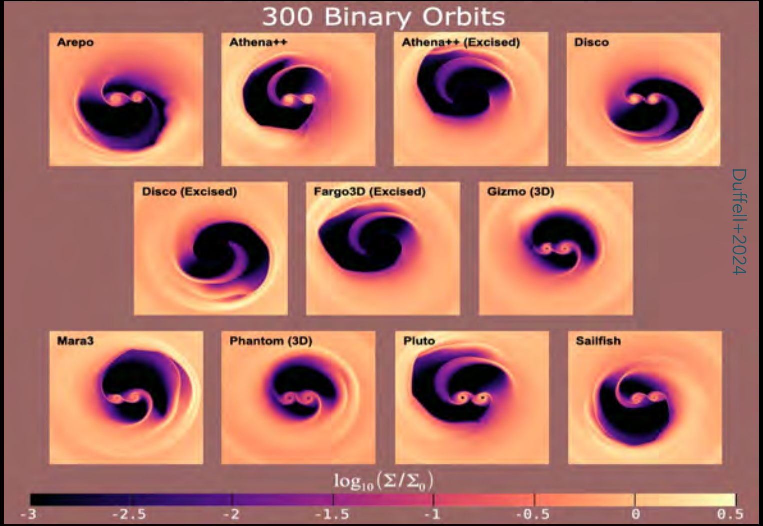
A very brief Overview on Newtonian Hydro Simulations

- **Early 1D Models**: binaries carve empty cavities (r ~2a) and effectively halt accretion (Pringle 1991; Artymowicz & Lubow 1996; Armitage+2002).

- **Modern 2D Simulations:**
  Consensus across 11 codes reveals a "leaky" barrier where streams feed minidisks (Milosavljevic & MacFadyen 2008; D'Orazio+2013; Farris+2014; Ryan+2016; Tang+2018; Dittmann+2023; Duffell+2024 etc).
- **Useful to explore parameter space but limited:**
  - **Binary**: Mass ratio q, separation a, eccentricity e, spins $S_{1,2}$
  - **Fluid**: thin disks, hydro or alpha-viscosity ν, no magnetic field (B), →no MRI driven accretion rate $\dot{M}$
  - Simple thermodynamics, constant temperature, no cooling, no radiation transport



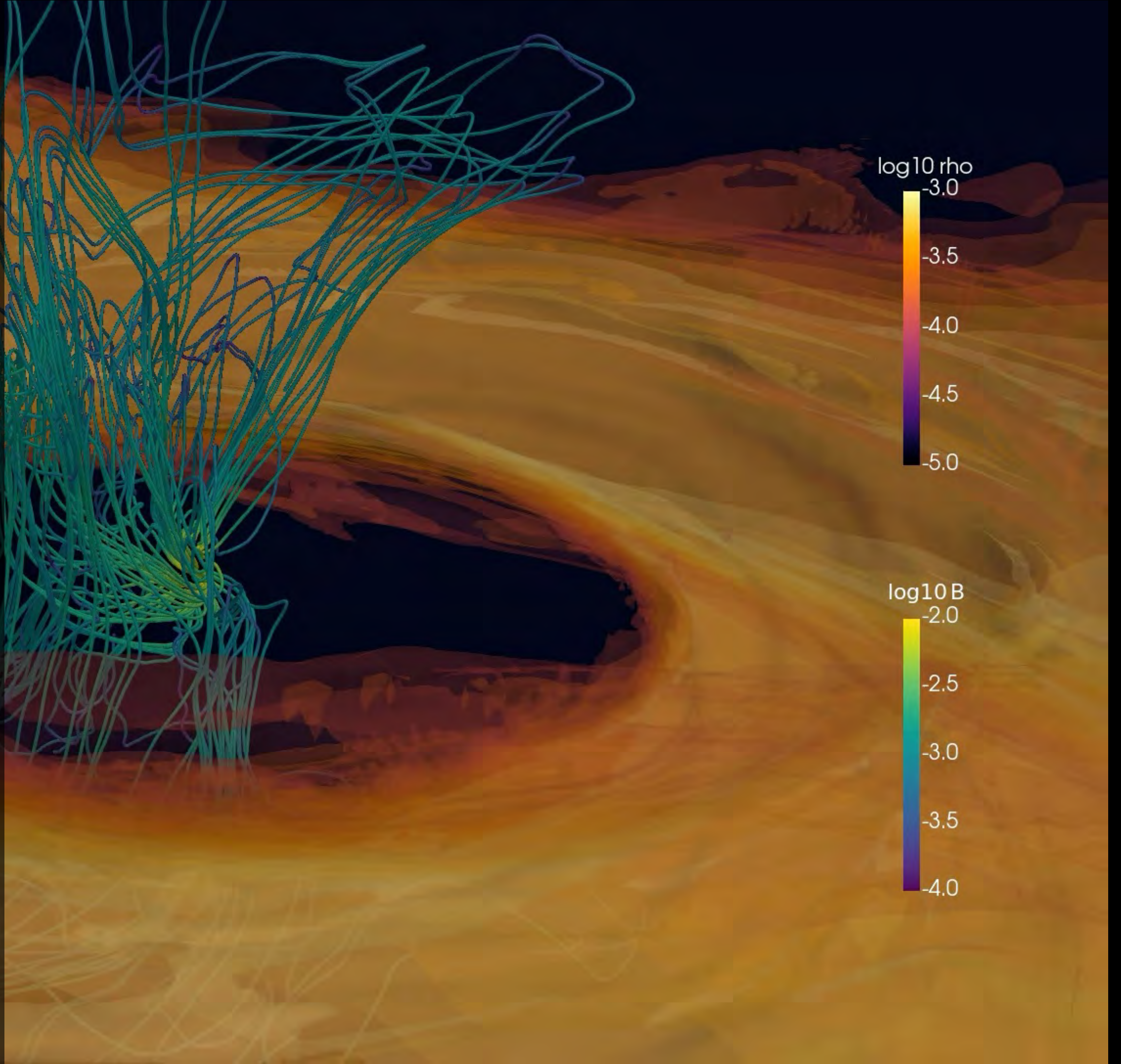
D'Orazio+2023



Duffell+2024

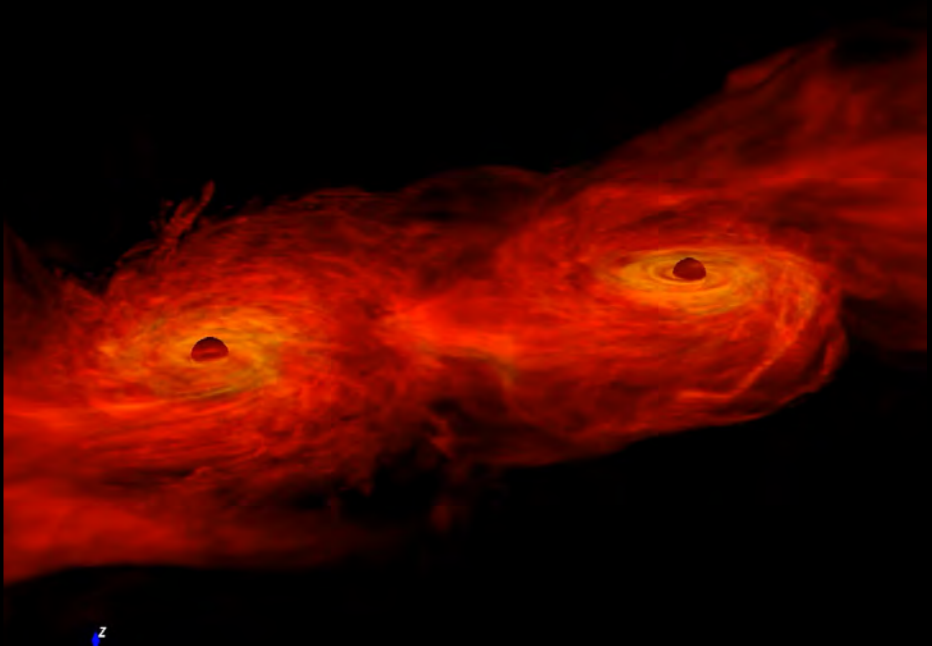
Inside the Engine with GRMHD

Full 3D GRMHD simulations in dynamical GR are essential to resolve accretion dynamics (Balbus & Hawley 1991), near-horizon physics, spin coupling, and jet formation to identify unique EM signals



Modeling SMBBH in the relativistic regime with GRMHD

What is the amount and state of the gas available to be heated at merger?



Video: Combi+2026 (in prep ApJ)

To answer this question, we need: general relativity; GRMHD (accurate at the scale of MRI/turbulence); realistic thermodynamics, plasma physics, and radiation transport.

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

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

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

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

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

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

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

GRMHD simulations approaching merger …

- **GR framework:** Post-Newtonian inspiral regime (Mundim+2014; Combi+2022, 2024)

- SANE circumbinary disk (CBD), MRI driven (Noble+2012)
  - ➢ truncation at ~2a, radiatively efficient (H/R~0.1, cooling to target entropy), initially threaded with single poloidal magnetic field

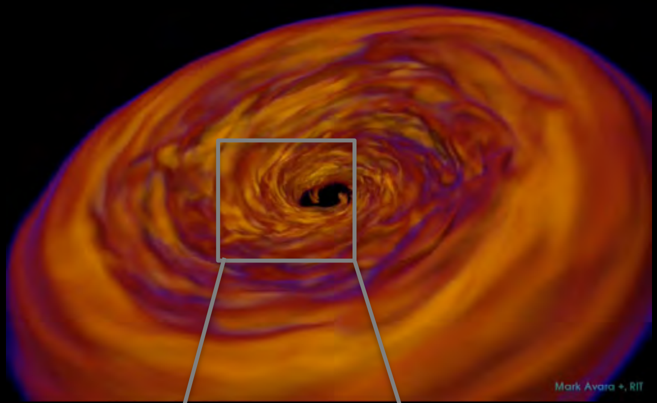
$$\beta = p_{\rm gas}/p_{\rm mag} \geq 100$$

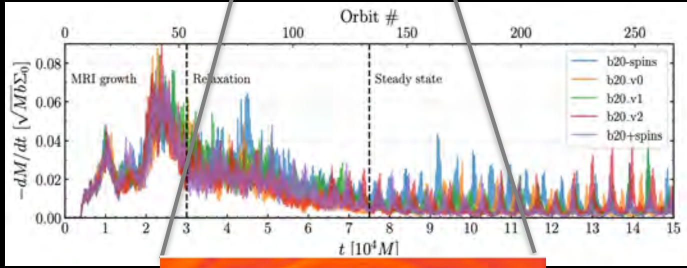
- **Robust dynamical features:**
  - ➢ **Lump** — overdensity at inner edge, period ~5 $P_{\rm bin}$ (Noble+2012, 2021; Shi+2012; D’Orazio+2013; Armengol+2021)
  - ➢ **Minidisks** — form around each BH; periodic accretion at $P_{\rm bin}$ → beat frequency (Bowen+2017–2019; Combi+2022; Avara+2024)
  - ➢ **Sloshing** — mass exchange between the two BHs (Bowen+2017; Westernacher-Schneider+2024)

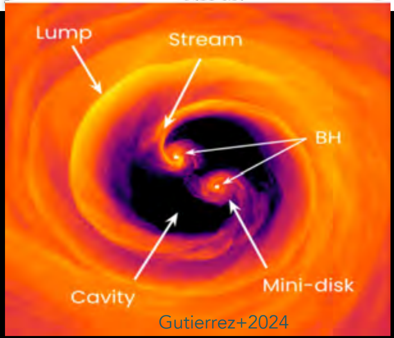
Disk equilibration for ≥ 250 orbits

Handoff

Inspiral and Merger







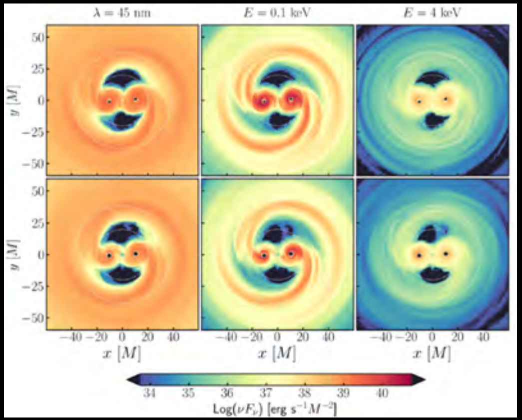
Radiation Transfer Model

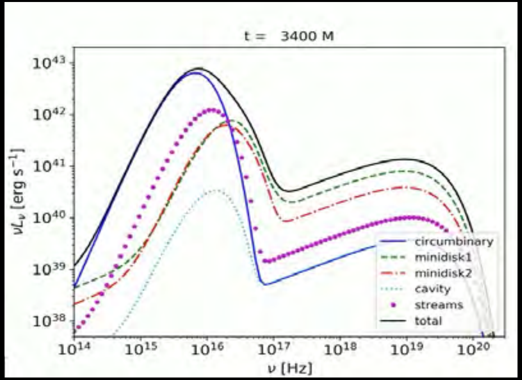
- Bound material cooled to target entropy based on a location dependent timescale (Noble+2012)

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

- Ray-tracing from GRMHD simulation snapshots – d'Ascoli+2018, Gutierrez+2022, 2024.
    - ➢ Optically thick → blackbody
    - ➢ Optically thin → AGN-like X-rays
    - ➢ Jets → Synchrotron (sub-mm)

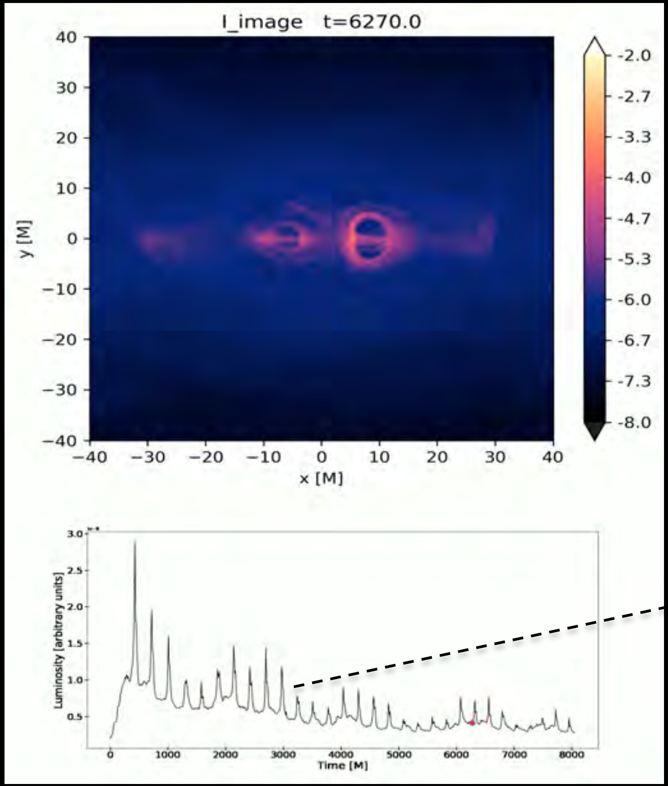
- **Time-variable spectra**, distinct components per frequency band:
    - ➢ CBD ~ truncated Shakura-Sunyaev disk
    - ➢ Minidisks brighter in X-rays
    - ➢ "Notch" (Tanaka+2012; Roedig+2014) absent — cavity filled by streams/sloshing at close separations



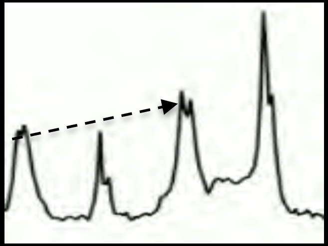


Spectral energy distribution - Gutierrez+2022

Light Curves display Self-lensing features

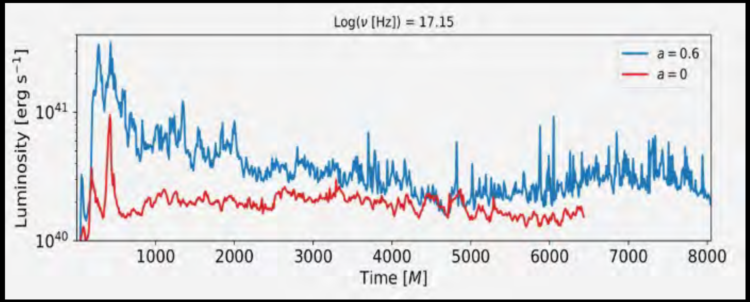


Intensity of X-rays (log scale) edge on (top), light curve (bottom), optically thin case
Gutierrez+2022

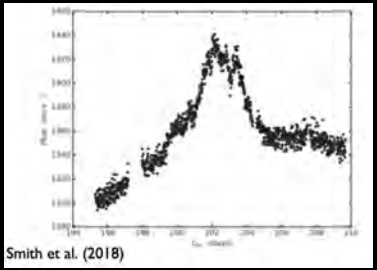


BH spins enhance the EM emission
Combi+2022, Gutierrez+2022

Close horizon physics essential!



Ray-tracing simulations
How self-lensing features depend on mass ratios, spins, accretion rates, etc
– Porter+2025

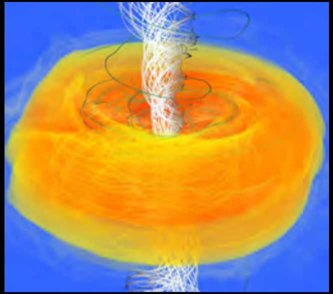


Possible observation of SLF from AGN source known as Spikey — Smith+2018

Numerical Relativity plus GRMHD

Pioneering using both circumbinary disk and gas clouds models (Van Meter+2010, Farris+2010, Giacomazzo+2012; Gold+2012, 2014; Paschalidis+2021, Cattorini+2022, Bright+2023, Ruiz+2023, Fedrigo+2024, Ennoggi+2025)

- Identified complex dynamics, including the double jets, and minidisks.
- High costs restricted the simulations to short durations and a limited parameter space (mass ratio, spin, eccentricity).
- The initial conditions (e.g. CBD) were simplified and may not reflect realistic astrophysical scenarios (mostly due to large viscous time scale!)



- Full dynamical GRMHD simulations with NR are computationally expensive due to the wide range of dynamical timescales involved.

$$t_{\rm light} < t_{\rm dyn} < t_{\rm th} < t_{\rm visc}$$

Timescale	Approximate Duration	Physics Governed
Light-Crossing	$\ll$ 1 orbit	Causality / Simulation timestep
Dynamical	1 orbit	Hydrodynamics / Orbits
Thermal	10 – 100 orbits	Heating / Cooling balance
Viscous	1,000 – 100,000 orbits	Accretion / Disk density evolution

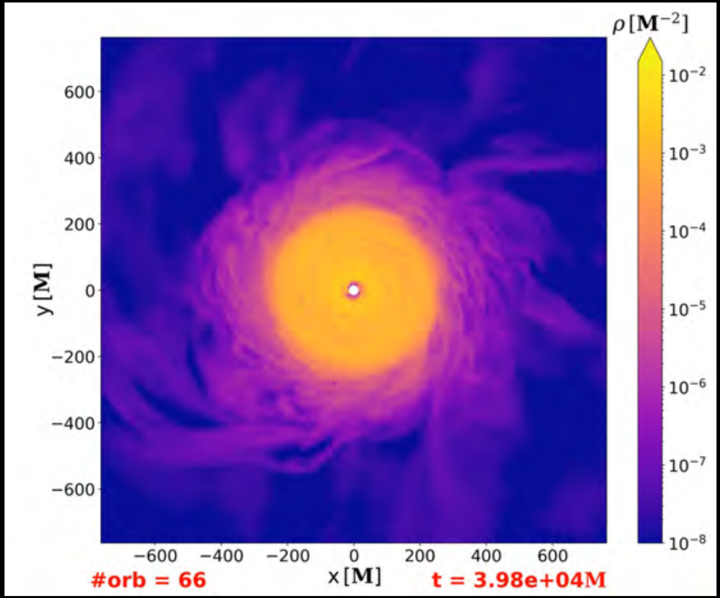
Numerical Relativity Today

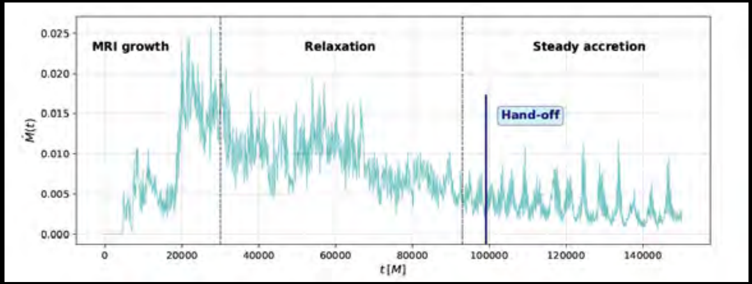
- A thriving field mostly using the moving puncture approach (Baker+2006, Campanelli+2006) .
    - ➢ Ease of Use: Rapid adoption was driven by the method's compatibility with standard 3+1 formalisms.
- Today's codes are robustly convergent and highly scalable, exceeding 10x speedups on GPUs
    - ➢ AthenaK (Stone+2024, Zhu+2024, Fields+2024) → This summer school!
    - ➢ Einstein Toolkit
        - ➢ Carpet → CarpetX
        - ➢ AsterX (Kalinani+2024, Chabanov+2025)
        - ➢ SpacetimeX (Ji+2025)
        - ➢ SphericalNR (Mewes+2019, 2020)
        - ➢ IllinoisGRMHD (Etienne+2011)

Code Asterx	Open Source	Public catalog	Formulation	Hydro	Beyond GR
AMSS-NCKU [552, 612–615]	Y	–	BSSN/Z4c	–	Y
BAM [582, 616–618]	–	[524, 619, 620]	BSSN/Z4c	Y	–
BAMPS [621–623]	–	–	GHG	Y	–
COFFEE[624, 625]	Y	–	GCFE	–	Y
Dendro-GR [626, 627]	Y	–	BSSN/CCZ4	–	Y
Einstein Toolkit [628, 629]	Y	–	BSSN/Z4c	Y	Y
*Canuda [366, 367, 630]	Y	–	BSSN	–	Y
*IllinoisGRMHD [631]	Y	–	BSSN	Y	–
*LazEv [615, 632]	–	[633–636]	BSSN/CCZ4	–	–
*Lean [637, 638]	Partially	–	BSSN	–	Y
*MAYA [639]	–	[639]	BSSN	–	Y
*NRPy+ [640]	Y	–	BSSN	Y	–
*SphericalNR [641, 642]	–	–	spherical BSSN	Y	–
*Spritz [643, 644]	Y	–	BSSN	Y	–
*THC [645–647]	Y	[649]	BSSN/Z4c	Y	–
*WhiskyMHD [648]	–	[649]	BSSN	Y	–
ExaHyPE [650]	Y	–	CCZ4	Y	–
FIL[651]	–	–	BSSN/Z4c/CCZ4	Y	–
GR-Athena++ [652]	Y	–	Z4c	Y	–
GRChombo [653–655]	Y	–	BSSN/CCZ4	–	Y
HAD [656–658]	–	–	CCZ4	Y	Y
Illinois GRMHD [659, 660]	–	–	BSSN	Y	–
MANGA/NRPy+ [661]	Partially	–	BSSN	Y	–
BH@H/NRPy+ [640, 662]	–	–	BSSN	–	–
MHDuet [663–665]	Y	–	CCZ4	Y	Y
SACRA [666–670]	–	[671]	BSSN/Z4c	Y	Y
SACRA-SFS2D [672, 673]	–	–	BSSN/Z4c	Y	–
SpEC [523, 674]	–	[521, 523, 675]	GHG	Y	Y
SpECTRE [676, 677]	Y	–	GHG	Y	–
SPHINCS_BSSN [678]		–	BSSN	SPH	–

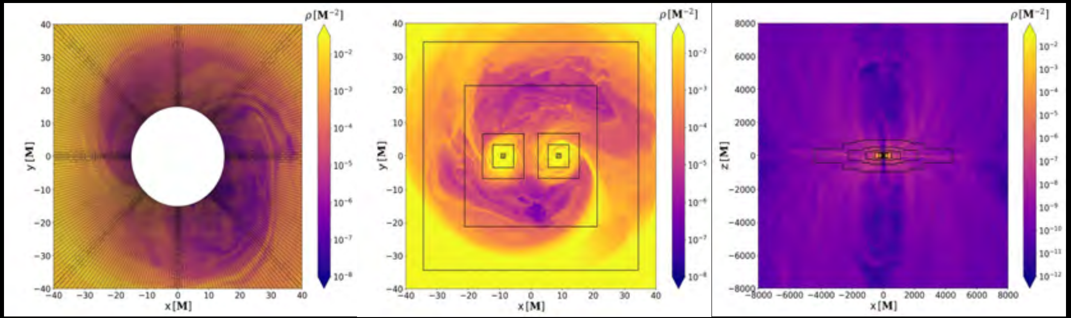
einstein toolkit

GRMHD simulations reaching merger





Lorenzo Ennoggi+2025



Initial CBD torus

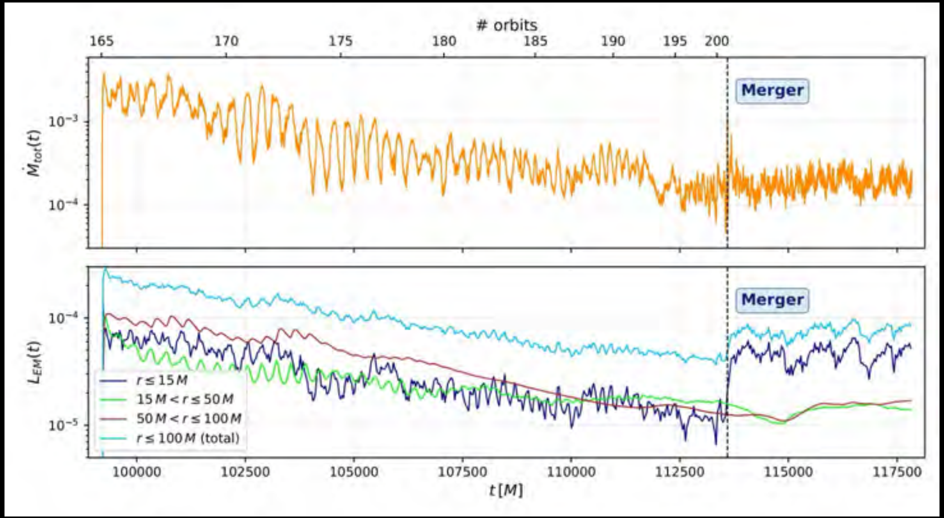
$\beta = p_{gas}/p_{mag}$ ≥100

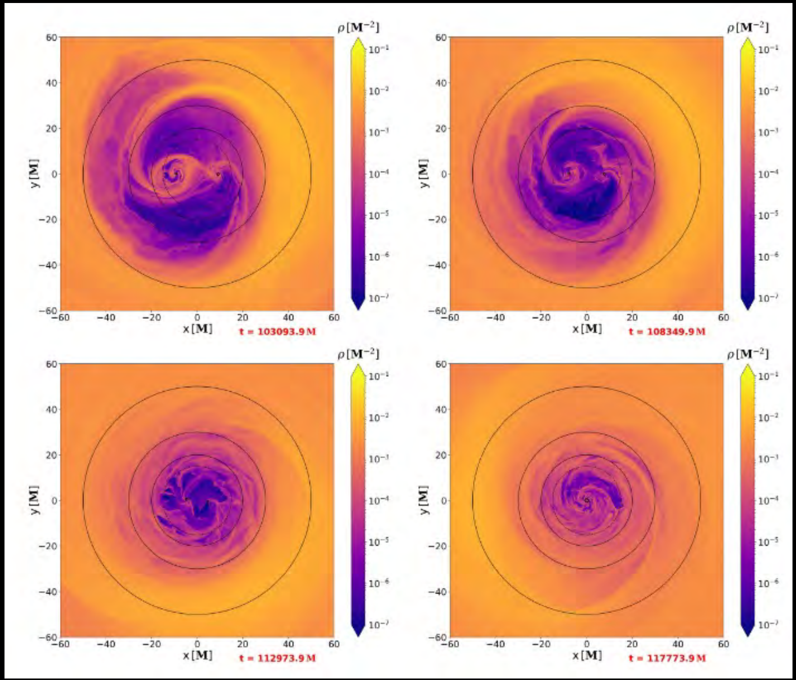
Poloidal, MRI, SANE

- Long-term circumbinary accretion (250 Orbits) with the SphericalNR code (Mewes+2018/2019, Ji+2023) - analytical PN spacetime, spherical coordinates,central excision.
- **Merger Dynamics** (50 Orbits) with IllinoisGRMHD (Etienne+2011) or AsterX (Kalinani+2024): numerical relativity, Cartesian AMR grids.

The merger of Non-spinning accreting SMBBHs

- After 200 inspiral orbits from 20M separation, the minidisks dissolve as the binary compresses just prior to merger …
- Luminosity briefly drops only by a factor of a few, then spikes by 50% at merger with an abrupt change in spectrum.
- Unlike single BHs, thermal light during the final stages is powered by strong shocks, not disk turbulence.



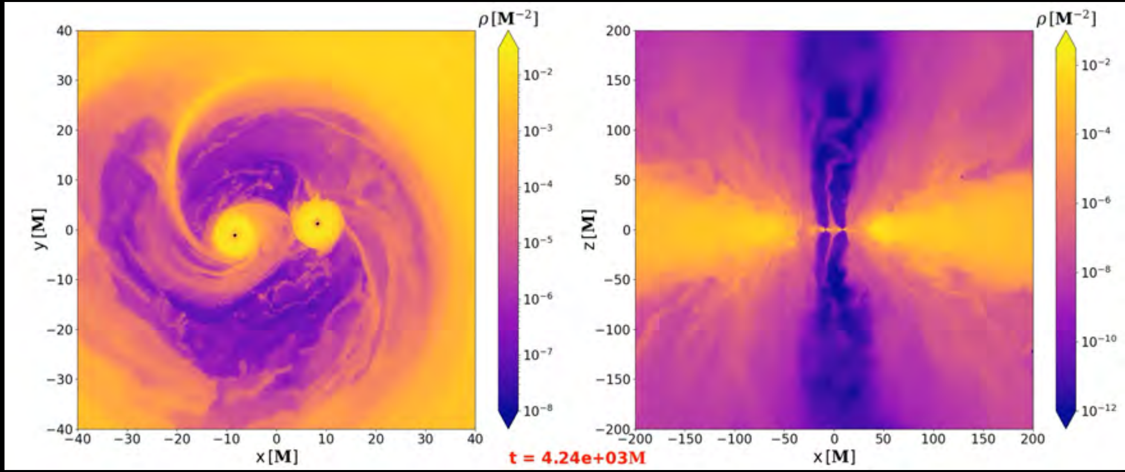


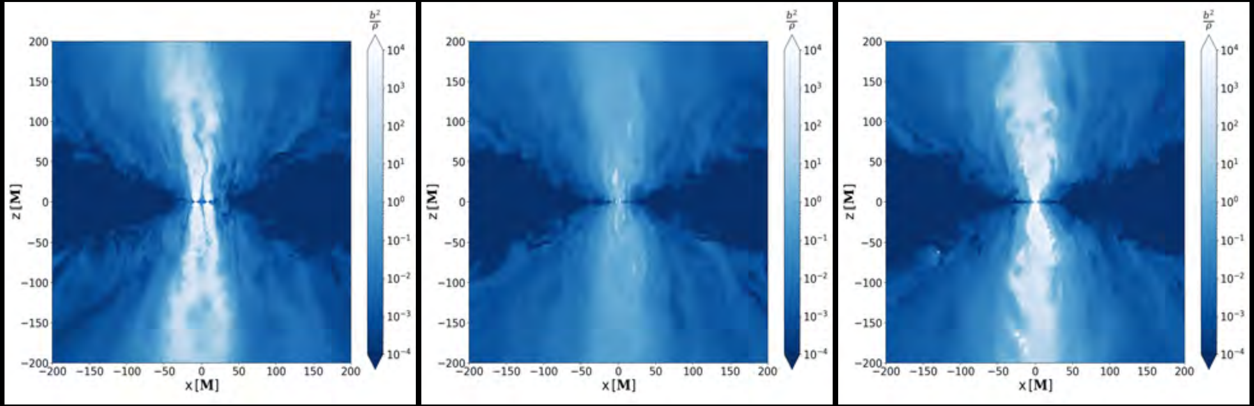
Lorenzo Ennoggi, PRD, 2025

Most of the luminosity comes from the region close to the black holes (r<15M)!

Spinning, accreting SMBBHs: luminosity at merger

- Thermal photon power is driven by strong shocks during late inspiral and merger, distinct from standard single-BH turbulent dissipation.
- Both thermal and jet power exhibit a shock-driven "dip-then-jump" luminosity feature
- Power gradually decreases pre-merger, then sharply rises to a noisy plateau at the moment of merger.



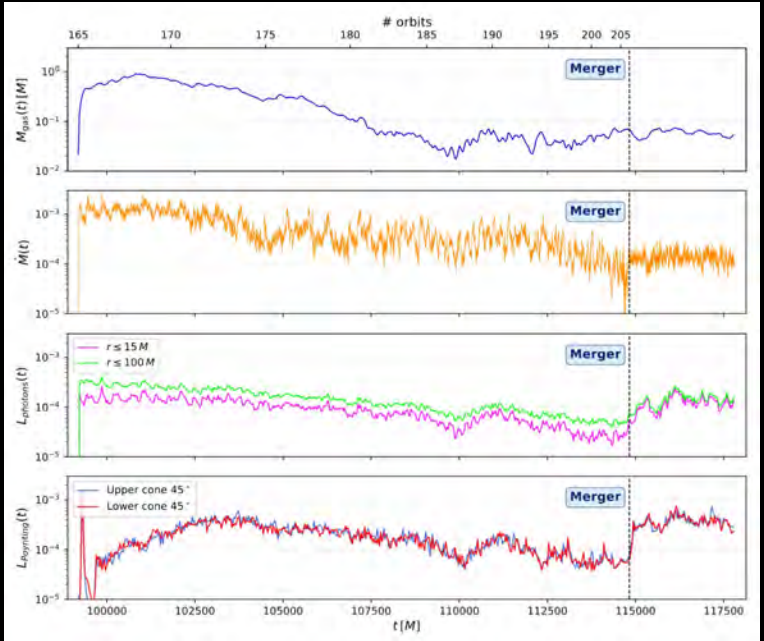


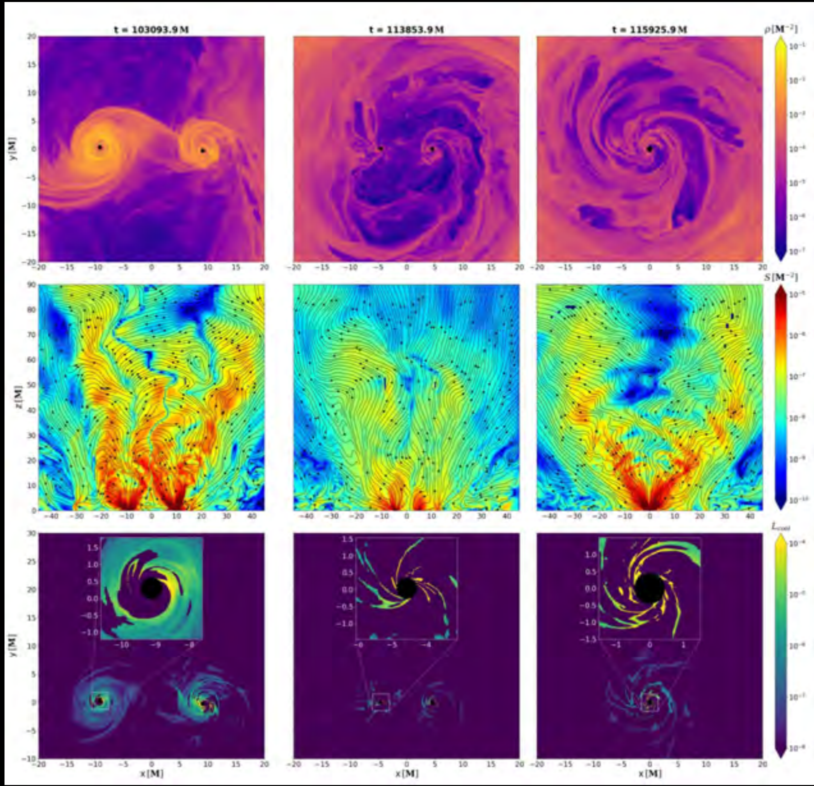
Ennoggi+PRL 2025

Spinning, accreting SMBBHs: shock-driven engine

Ennoggi+PRL 2025

Observed that luminosity is decoupled from the steady mass accretion rate; the sharp spike in power at merger is caused by a sudden increase in radiative efficiency due to strong shocks, not an increase in accreted matter.

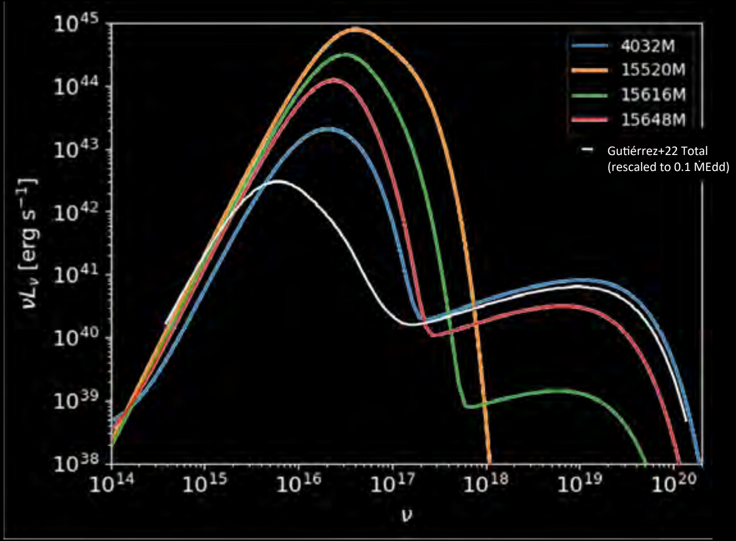




Violent shocks act as a single engine for both channels, simultaneously dissipating kinetic energy into heat (photons) and magnetic energy (jets) to create a tight temporal correlation.

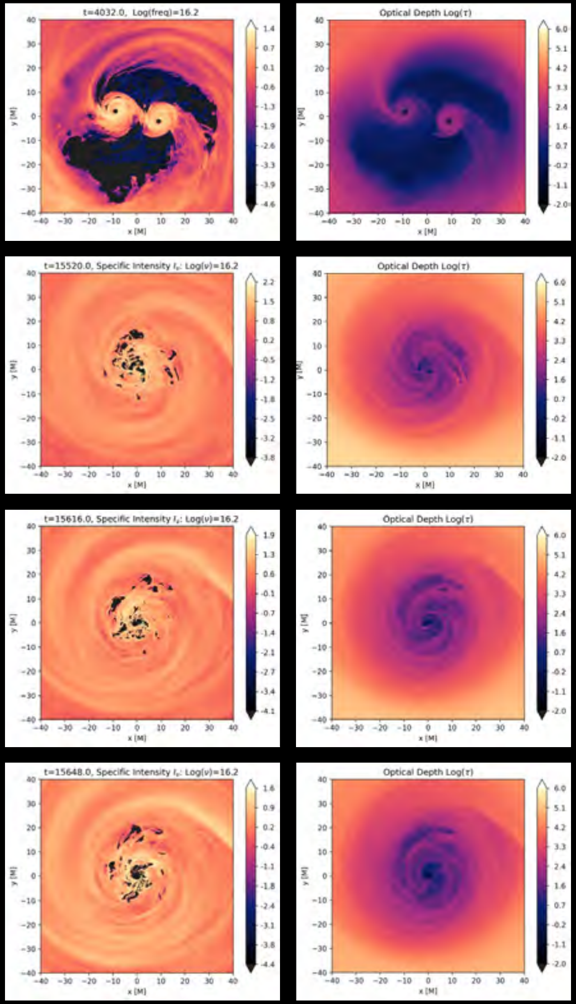
EM signatures of SMBBH mergers

GR ray-tracing framework post-processes NR GRMHD simulations to predict images, spectra & light curves through inspiral, merger & post-merger - Porter+2026



- **Black curve:** total SED from Bothros ray-tracing of the inspiral (χ = 0.6, sep. 20M), rescaled to M = 10^6 M⊙, $\dot{M} = 0.1\ \dot{M}_{edd}$ - Gutierrez+2022

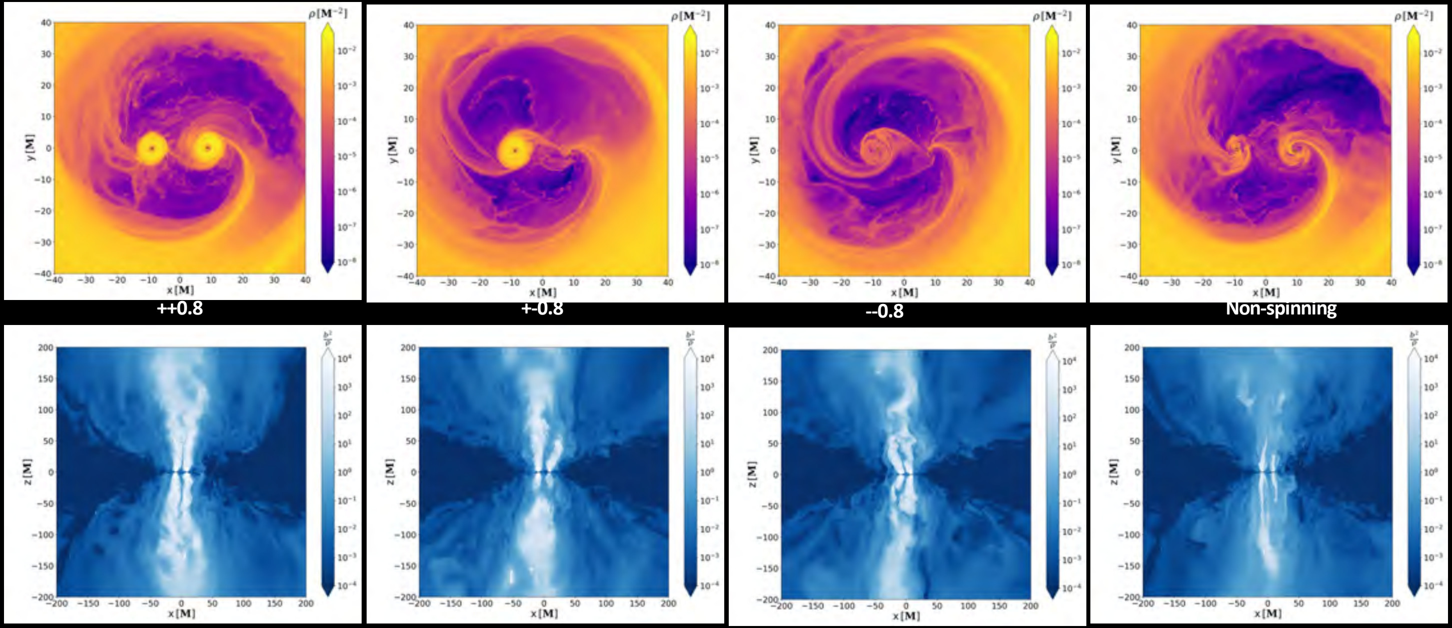
- **Thermal emission brightens** toward merger (t = 4032M, ~16M separation)
- Coronal component fades in late inspiral (15520M), weakly reappears pre-merger (15616M), recovers post-merger (15648M)
- Merger spectra: **1–2 orders of magnitude brighter** at the thermal peak than the inspiral baseline
- Peak at higher frequency (~3×10^{16} vs ~5×10^{15} Hz): **shock-heated gas**, not disk-photosphere emission
- Shock-dominated heating, **~10× higher radiative efficiency** at merger (Ennoggi et al. 2025)



Gutiérrez+22 curve digitized from their Fig. 3; L ∝ $\dot{m}$, $\nu_{thermal} \propto \dot{m}^{1/4}$ rescaling from 0.25 → 0.1 $\dot{M}_{Edd}$.

The effect of spins on minidisks and jet launching

- Minidisk physics strongly affected by BH spins – De Simone+2025, in prep
- The magnitude and direction of the spins affect orbital dynamics via spin–orbit interactions – Campanelli+2007



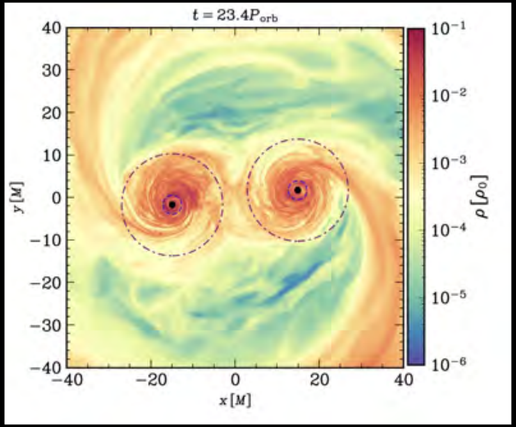
Maria Chiara De Simone, RIT

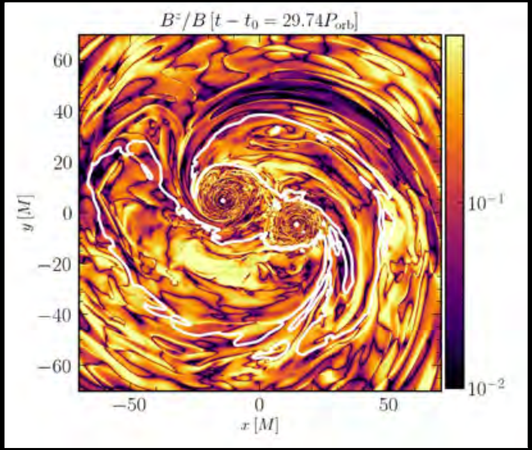
Work in Progress

Maximally spinning BBHs Inspiral

Luciano Combi, Stanford

- Equal-mass black holes with aligned spins a = 0.9; separation ~30 M, ~200 orbits.
- Boosted Kerr-Schild (SKS) BHs, PN trajectories (valid for any q, $S_{1,2}$, a and e) (Combi+2022, 2024).
- Longer inflow times stabilize minidisks, suppressing the variability seen in (Bowen+2019), except during lump accretion.
- Accretion onto the cavity happens via thin streams, causing the magnetic field to be stretched and compressed. The streams are toroidally dominated.
- However, when the field hits the minidisks, it is "reprocessed," generating a poloidal field that is then advected onto the BHs.

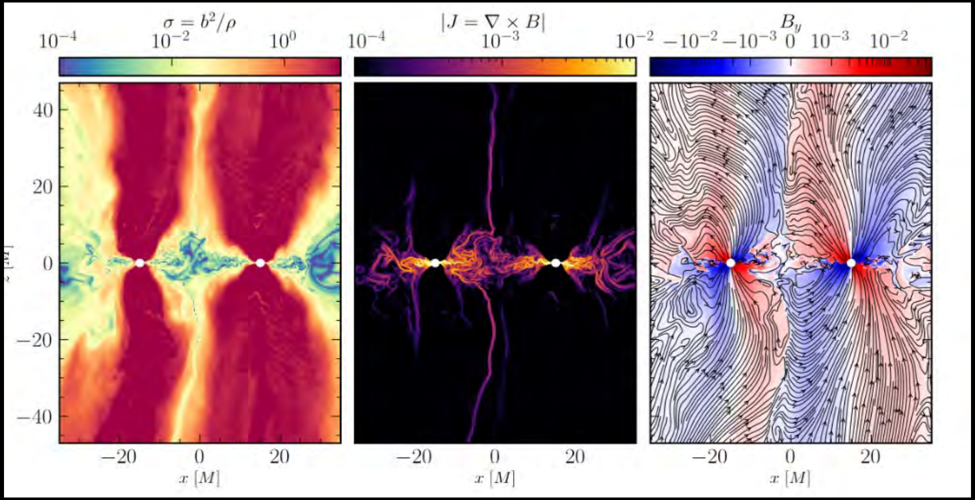


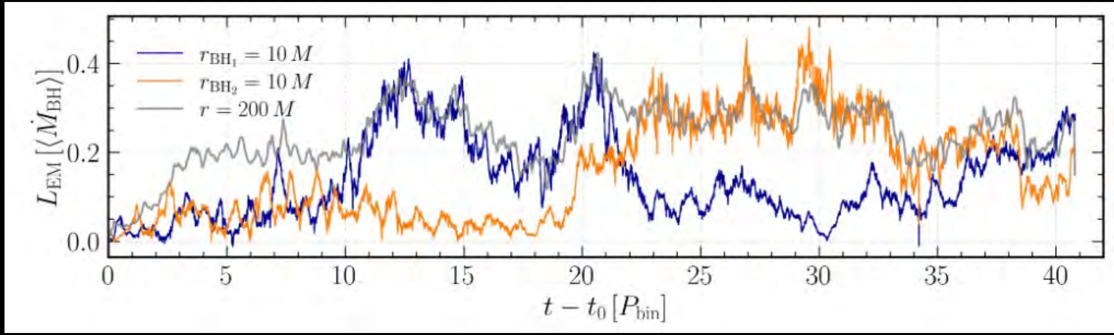


Combi, Campanelli+2026, in prep

Plasma maps and EM luminosity

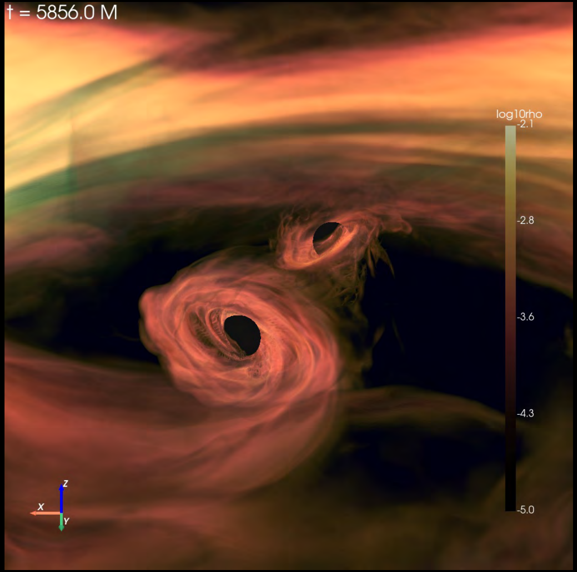
- High magnetization ($\sigma > 1$) channeled into jet funnels above each BH.
- Current sheets and reconnection sites trace |J| in the cavity and between the minidisks.
- B_y reverses sign across each BH — opposite field polarities feed the dual jets.
- Near-field (r = 10 M) EM luminosity shows large, anti-correlated fluctuations as accretion alternates between the BHs; the far-field (r = 200 M) cleanly traces the binary.





Combi, Campanelli+2026, in prep

If the spins are not aligned …



BBH can display interesting merger dynamics due to oblique spins →

warped minidisks, messy gas and jet dynamics, postmerger recoils

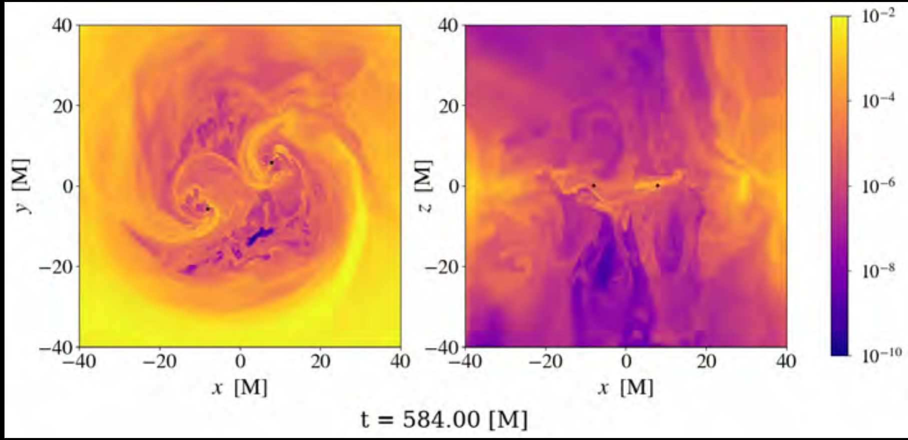
Work in progress by J.V. Kalinani, M. Chabanov, M. De Simone

- 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
- The final BH remnant after merger can get a gravitational wave recoil of several thousands km/s if the BHs have oblique spins – Campanelli+2007, Lousto+2011

BLACK HOLE KICKS

NR calculations predicted large recoil velocities if significant contribution of the total spin is in the orbital plane:

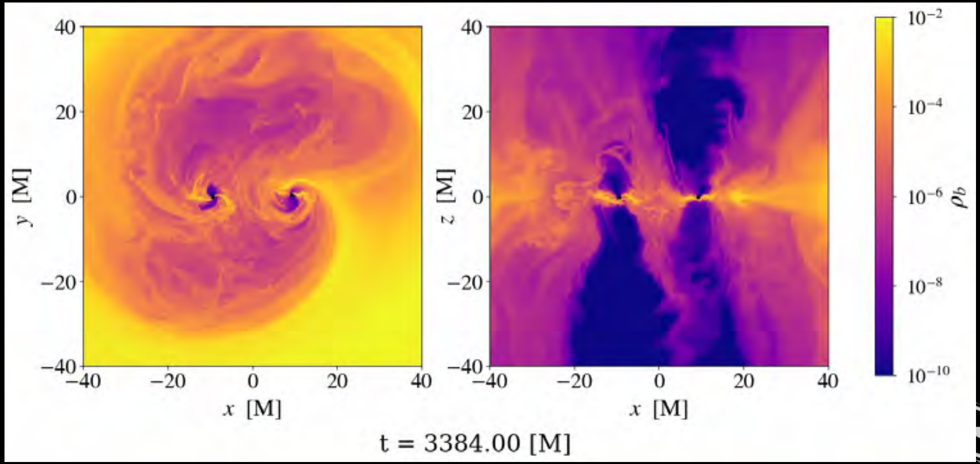
Accretion, Jets, and Recoil in Merging SMBBHs



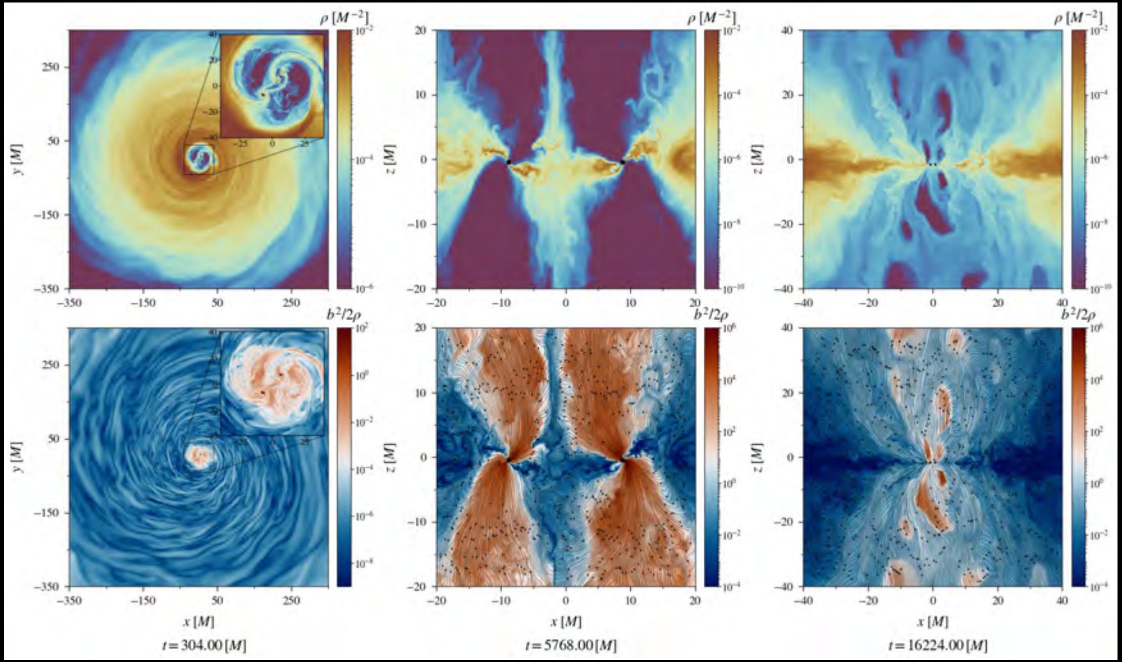
Evidence of a very messy shocked region near the BHs with the jets shocking against the CBD

Maria Chiara De Simone, RIT

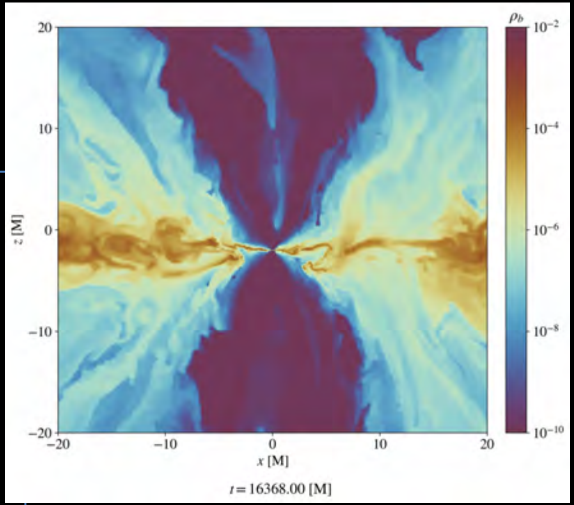
Warped minidisks persisting until close to merger and powerful jets …



Hang-Up Kick



- Recoil along the negative z-axis due to symmetries of the system: kick ~ 1,032 km/s (oblique spins)

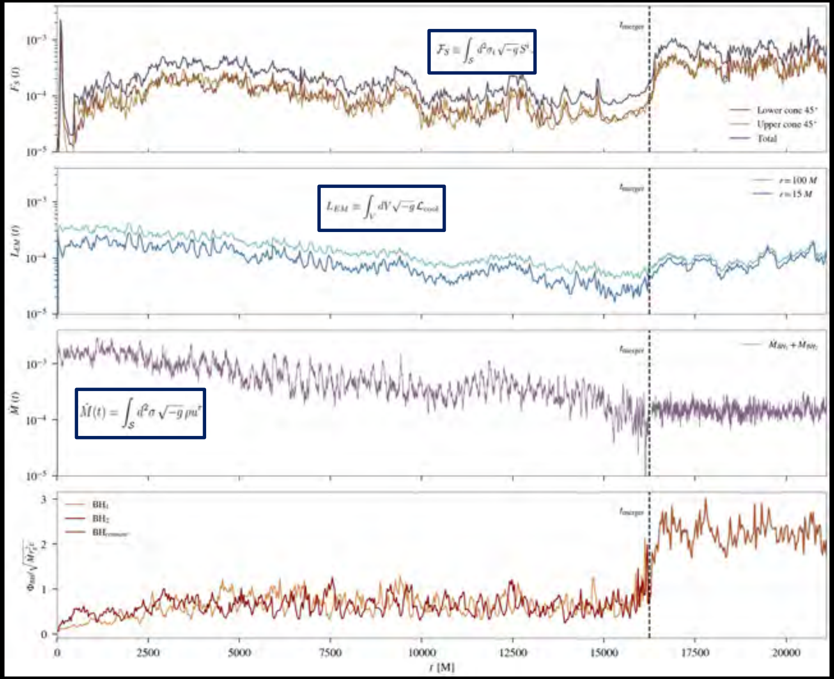


De Simone+, arXiv:2510.05883

- Minidisks tilted by 45° in a direction normal to the spin axes; very warped!
- Jet aligned with spin axis ($z<5\ M$) at close separations and aligned with orbital angular momentum at larger distances (Cattorini+2022, Kelly+2021, Ressler+2021)
- Jet quenching before merger as minidisks disappear (*Ennoggi+2025*)

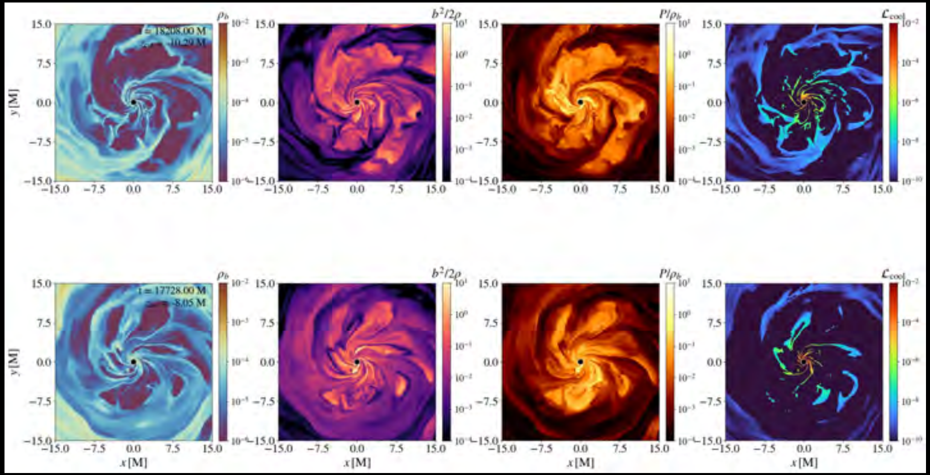
Postmerger SMBH as EM post-cursors …

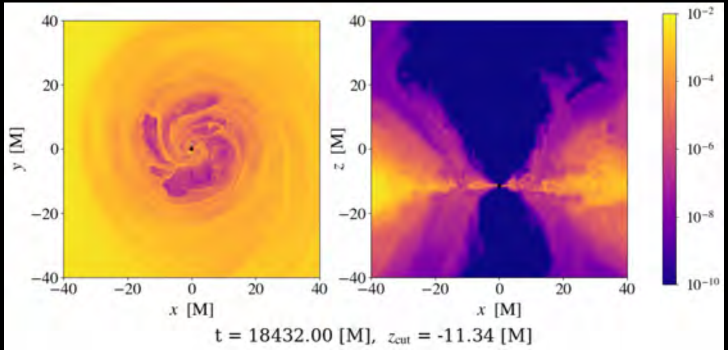
- Unique "dip-then-jump" feature is a key observational fingerprint to help identify these mergers in the EM spectrum.



De Simone+, arXiv:2510.05883

- Postmerger shocks survive for weeks → EM signal as LISA multi-messenger postcursor?





Magnetic Flux Tubes Formation in Post-merger SMBBHs

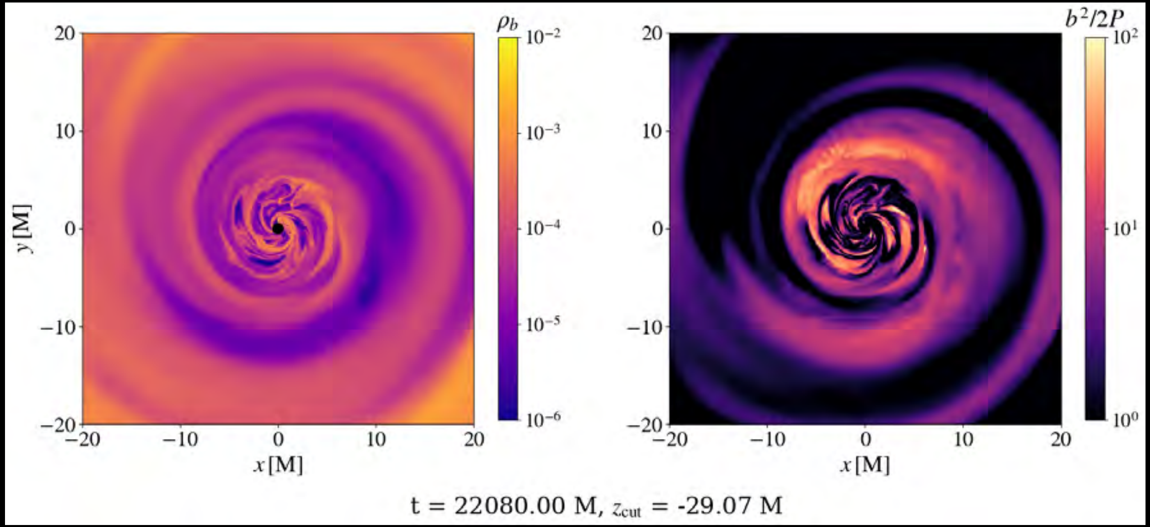
- **Magnetic bubbles and flux turbes:** Magnetic pressure locally dominates near the black hole (r~15 M), organizing into macroscopic flux tubes and bubbes with a dimensionless flux of

$$\phi = \Phi_{BH}/\sqrt{\dot{M} r_g^2 c.} \approx 10$$

- **Sustained Outflow:** These featurescpersist post-merger, anchoring a long-lived, stable relativistic jet.

- **Plasmoid-Driven Variability:** Magnetic reconnection in the equatorial current sheet generates plasmoids, driving the rapid, high-frequency flares observed within the steady outflow.

v_{kick}~340 km/s (pm08 run)

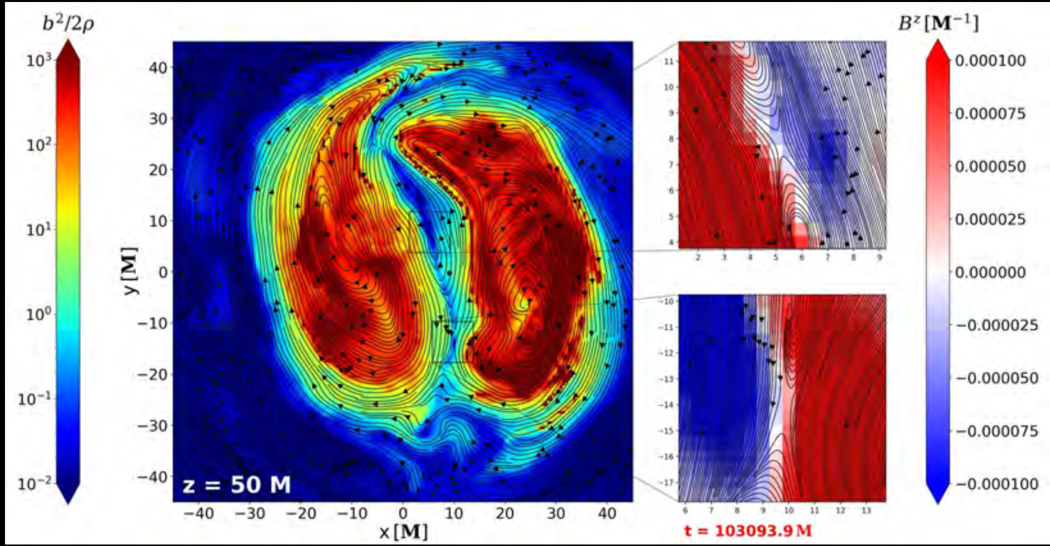


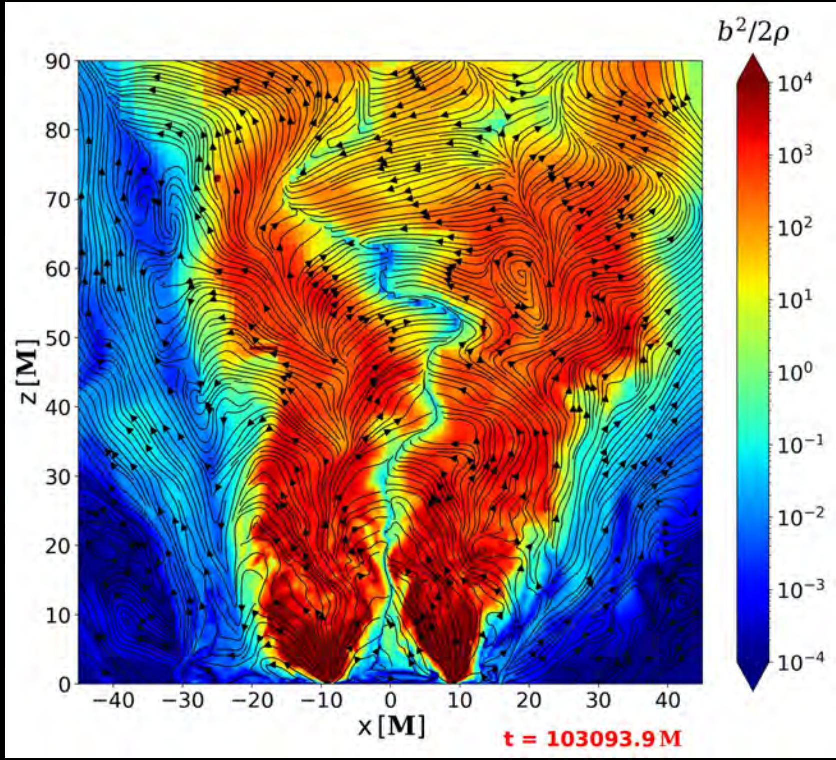
Evidence of a "intermediate MAD state" of accretion after merger?

De Simone+, 2026 in prep

Hints of Magnetic Field Reconnection

Magnetic reconnection can occur in the jet interaction region - Gutierrez+2024, Ressler+2024:

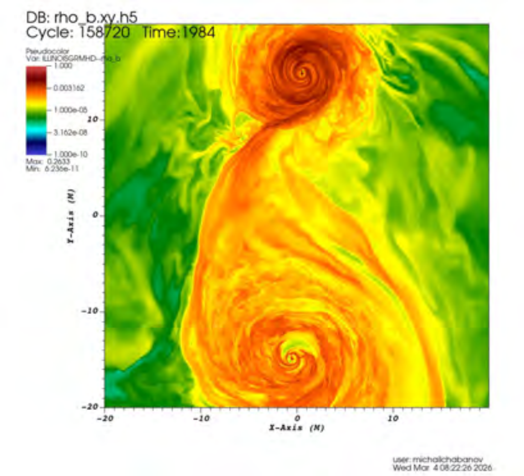


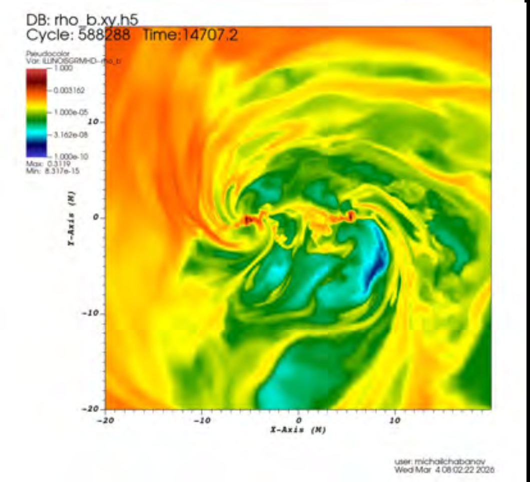


- Jet interaction: Magnetic energy converts to kinetic energy, accelerating electrons (and ions) to extreme energies along the current sheet.
- These high-energy electrons then produce synchrotron and Inverse Compton radiation.

M. Chabanov+ Extreme Resolution Simulations

Precessing spinning BBHs: spin-flip survey & MAD onset





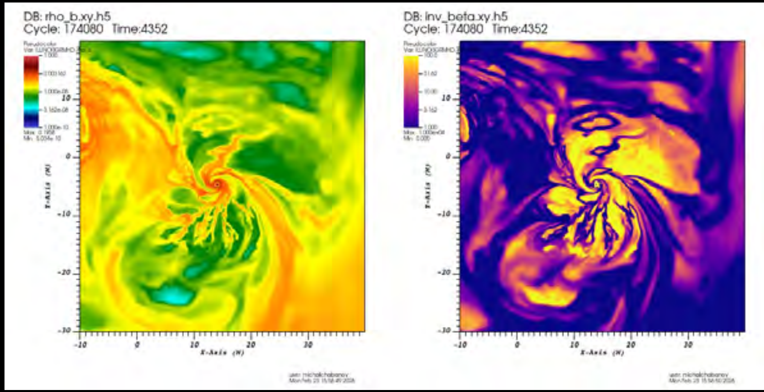
Flux-increase runs (a = 30 M)

- MAD onset within reach: large magnetization regions develop and disrupt minidisks, flux tubes, etc. (Most & Wang 2025)

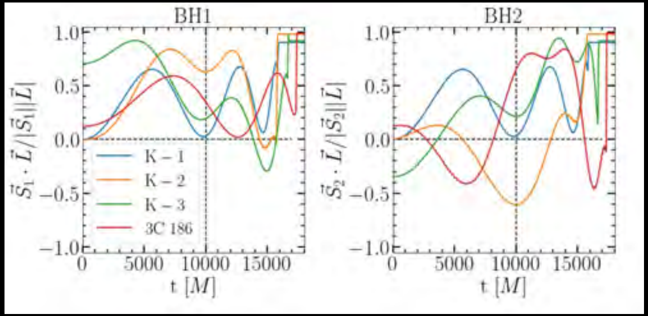
Spin-flip configurations

(Lousto+2015)

- q = 1, a = 20 M.
- Messy shocked region near each BH, jets turning on and off as spins reorient.

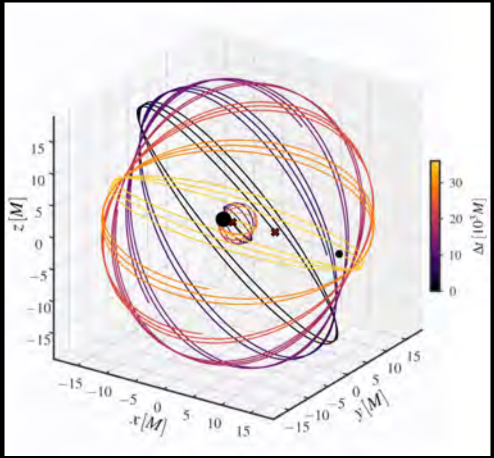


Flux-increase run at a = 30 M: magnetic energy b^2 (left) and inverse plasma beta, $1/\beta$ (right) at t ~ 8,000 M — diagnostic of approaching the MAD state.



Michael Chabanov, RIT

Precessing spinning BBHs: large-scale jet structure

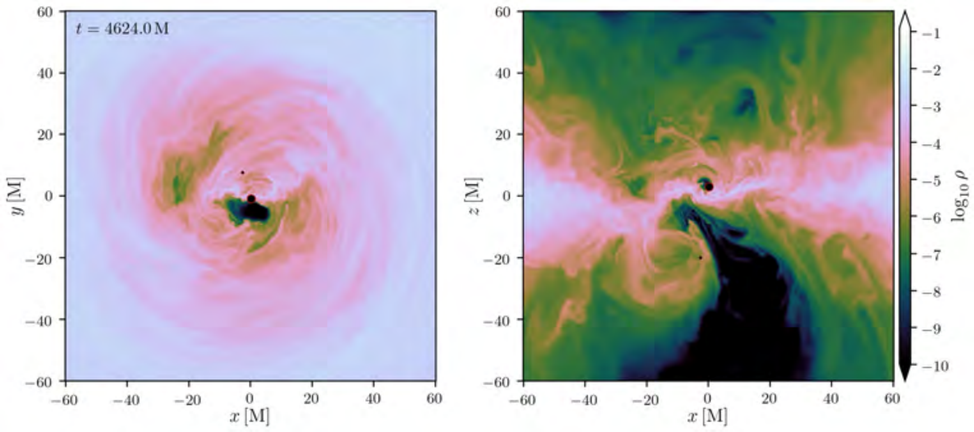


L-flip Scenario (Lousto+2018):

- Spin-orbit resonance periodically flips the primary spin orientation relative to the orbital plane (q=7, 45° initial tilt).

GRMHD simulation (Kalinani+2026, in prep)

- Primary dominates global energetics, controlling total accretion rate and horizon luminosity; secondary drives high-frequency accretion spikes.



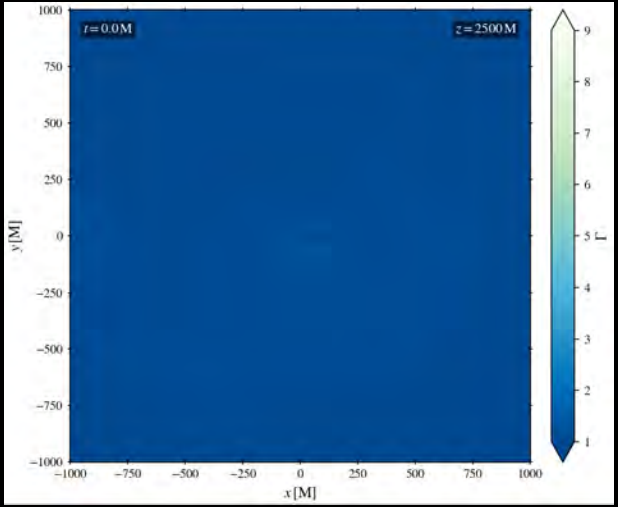
- Secondary intercepts and redirects dense cavity streams, periodically starving the primary's minidisk of fuel supply.
- BH–disk collisions provide the robust physical mechanism for periodic multi-wavelength flares in OJ 287 (Ressler+2025).

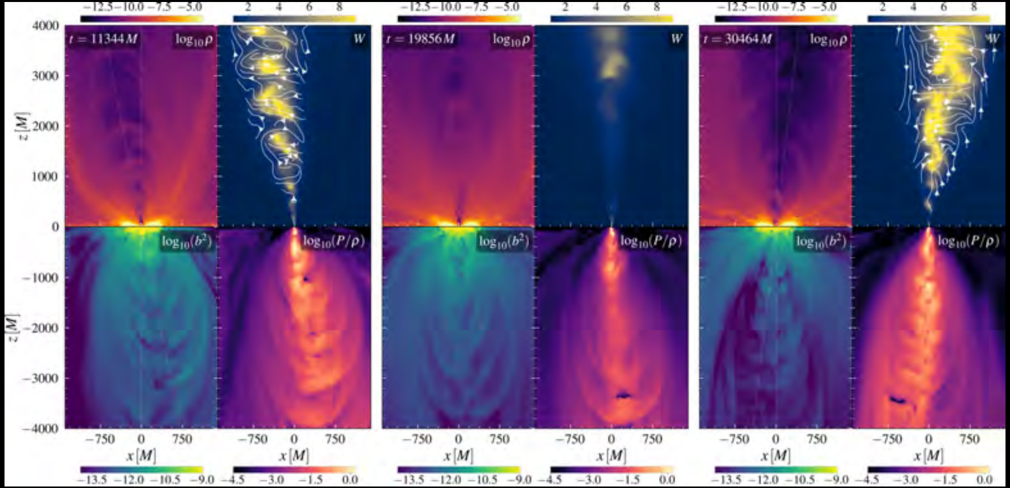
Jay V. Kalinani, RIT/UIUC

Precessing spinning BBHs: spin-flip configurations

- Jets display evidence of shocks at very large distance and are seen to precess along the orbital angular momentum.

- This could provide a physical mechanism for observed QPOs.





Large-scale meridional jet (left, to ±4000 M); three epochs of sep25M (right) show the tilted outflow weakening then recovering as the spin reorients.

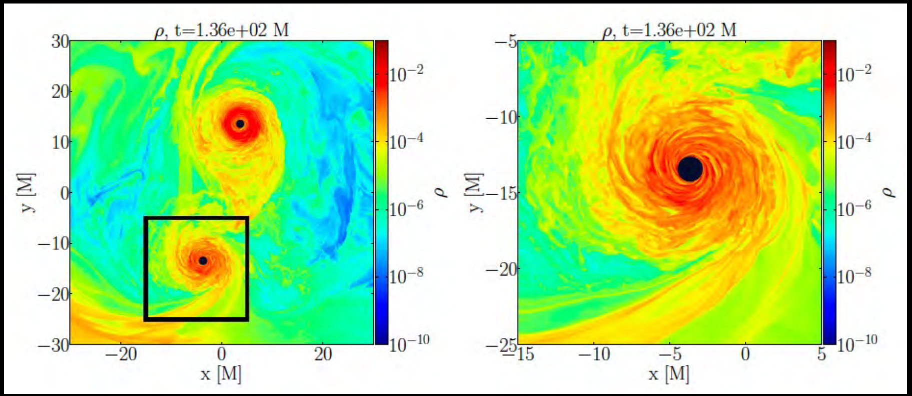
- Ordered magnetic fields and hoop stresses maintain jet collimation out to 4000M despite macroscopic wobbling.

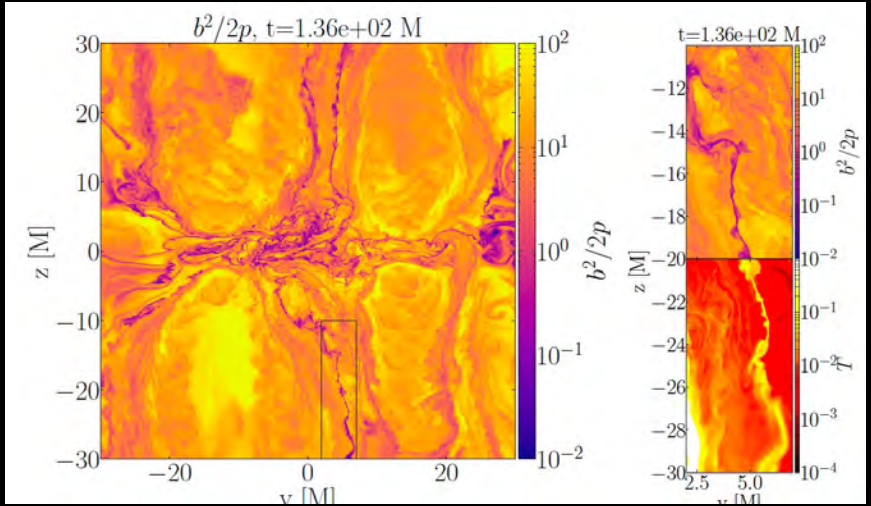
- Primary spin-flips force transient jet suppression and reverse the magnetic field, explaining observed shifts in emission polarization.

Jay V. Kalinani, RIT/UIUC

The Next Frontier: Exascale SMBBH Simulations

- **First extreme-resolution GRMHD campaign for an accreting SMBBH** — no prior study resolves near-binary reconnection physics (Chabanov +, in prep)
- **DOE Frontier (exascale):** ~958,000 node-hours on 2,048 nodes; 1.5 PB of data
- **Finest grid Δx = 0.01 M** across 10 AMR levels — ~6× beyond current state of the art
- **ER-M:** four full orbits (~2000 M); **ER-J:** resolves the ~14 M jet–jet collision layer
- **Goal:** how flux-tube eruptions and plasmoid-mediated reconnection set flare duty cycles and nonthermal emission — the physics behind Sgr A* hot spots and M87 TeV flares





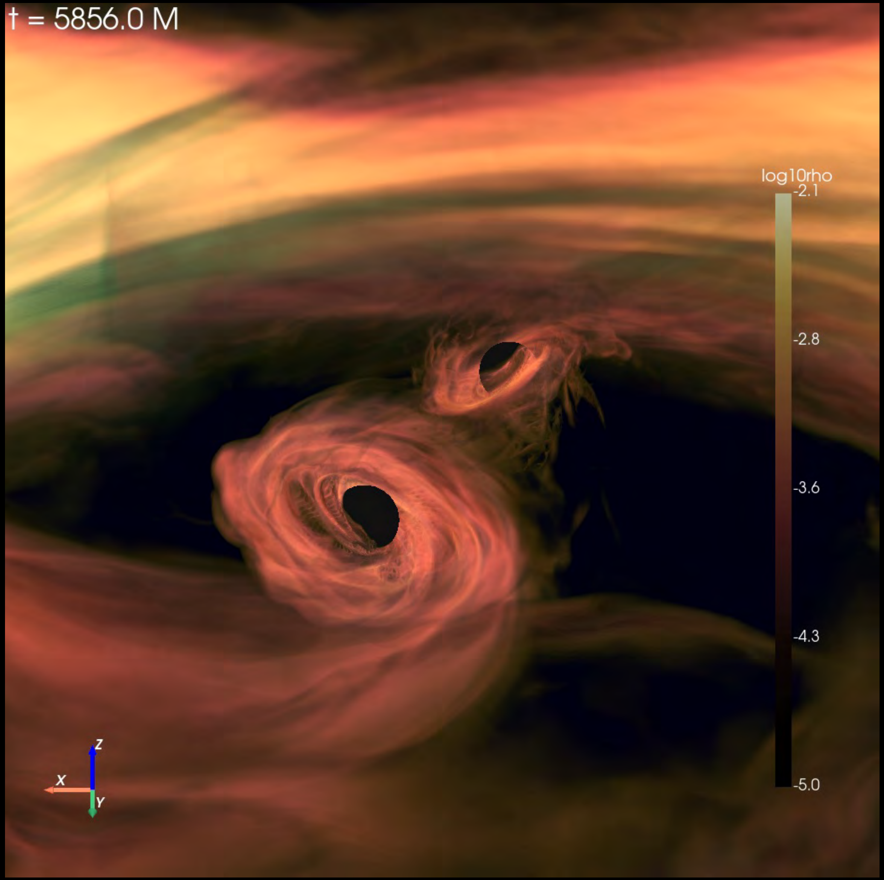
Gas density (top); plasmoid chains in b²/2p (bottom)

Credits: Chabanov+, RIT

Conclusions

- **End-to-end GRMHD** — spinning SMBBHs from CBD through merger and post-merger.
- **Merger jets & recoils** — spin-driven jets and bright displaced remnants as LISA and PTA EM post-cursors.
- **Small-q precession** — BH–disk collisions and jet flips as a natural QPO engine.
- **EM signatures** — distinctive fingerprints make SMBBHs identifiable as LISA and PTA counterparts.
- **Accurate EM predictions** — require astrophysical realism in magnetic field growth, radiation transport, and microphysics.
- **Multiscale coupling** — linking kinetic plasma physics, MHD turbulence, and global accretion dynamics across scales via next-generation methods.
- **Exascale + AI** — CPU/GPU exascale+ supercomputers, augmented by AI and superchip technology, accelerate the path to discovery.

→ *Toward a new era of multimessenger astronomy.*



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

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AsterX Collaboration
github.com/EinsteinToolkit/AsterX

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