Title: Relativistic Gas Accretion onto Supermassive Black Hole Binaries from Inspiral through Merger

Speakers: Lorenzo Ennoggi

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

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Abstract:

Accreting supermassive black hole binaries are powerful multimessenger sources emitting both gravitational and electromagnetic (EM) radiation. Understanding the accretion dynamics of these systems and predicting their distinctive EM signals is crucial to informing and guiding upcoming efforts aimed at detecting gravitational waves produced by these binaries. To this end, accurate numerical modeling is required to describe both the spacetime and the magnetized gas around the black holes. In this talk, I will outline two key advancements in this field of research.

On the one hand, I will present a novel 3D general relativistic magnetohydrodynamics (GRMHD) framework that combines multiple numerical codes to simulate the inspiral and merger of supermassive black hole binaries starting from realistic initial data and running all the way through merger. Throughout the evolution, we adopt a simple but functional prescription to account for gas cooling through the emission of photons.

On the other hand, I will present the application of our new computational method to following the time evolution of a circular, equal-mass, non-spinning black hole binary of total mass ${M}$ for ${\sim\!200}$ orbits starting from a separation of ${20\,r_g\equiv 20\,M}$ and reaching the post-merger evolutionary stage of the system. Our simulation has confirmed the predictions of previous works about the early inspiral phase, but has also revealed phenomena specific to the late-inspiral and merger so far undocumented in the literature. Perhaps our most striking finding is that, although the accretion rate onto the black holes is approximately constant from ${\sim\!3000\,M}$ before merger onward, the EM luminosity undergoes a sharp increase around the time of merger. This effect is caused by the sudden lack of binary torque, which allows the gas in the immediate vicinity of the remnant to quickly fall in, thus compressing and heating up as it shocks. Secondly, the magnetic flux brought to the ${\sim\!0.68\text{-spinning}}$ merger remnant is able to drive a relativistic, Poynting-flux-dominated jet.

These dynamics could lead to potentially observable EM signals, supporting upcoming multimessenger observational campaigns.

Relativistic Gas Accretion onto Supermassive Black Hole Binaries from Inspiral Through Merger

PI meeting 2025

Lorenzo Ennoggi

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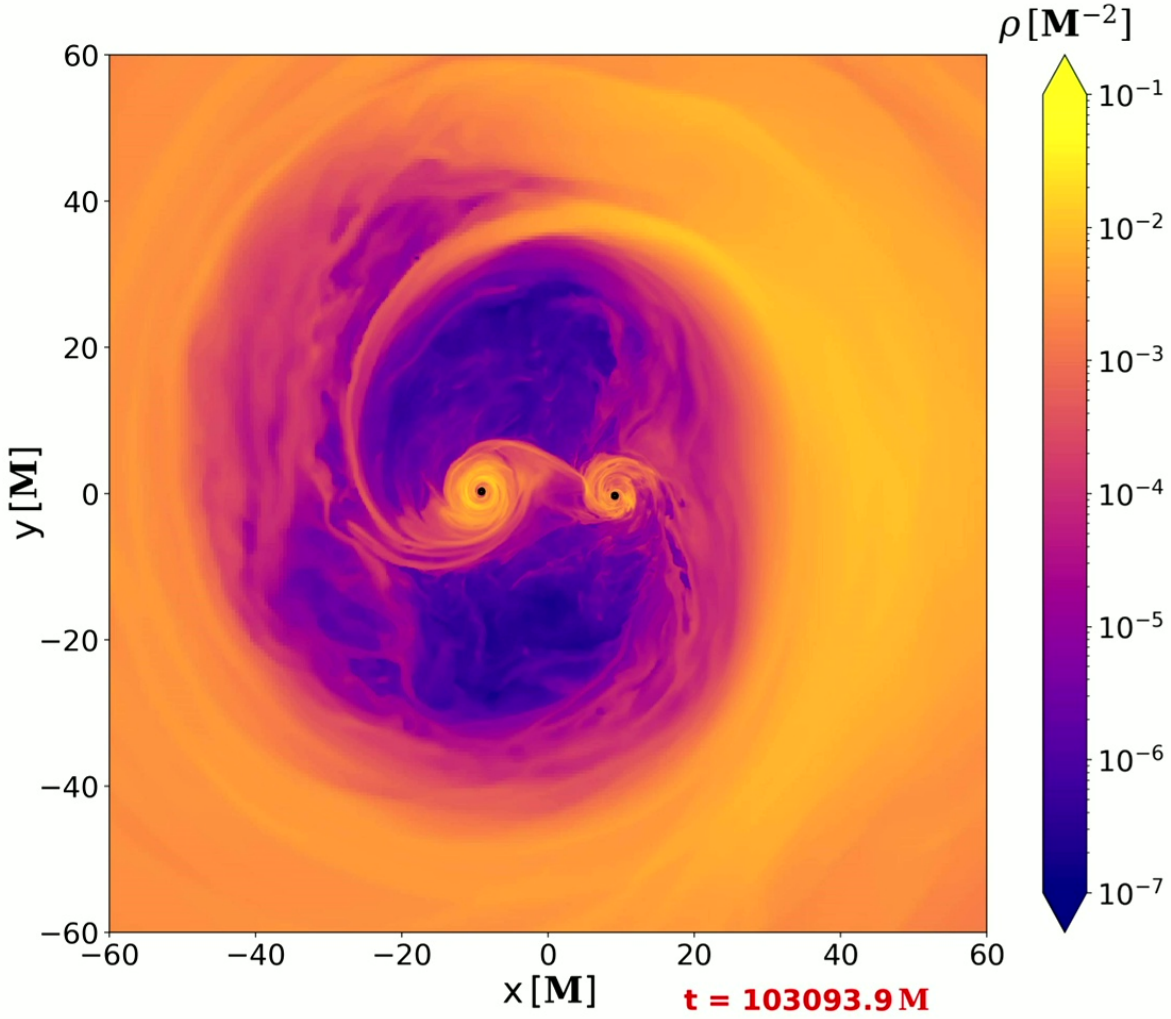
Motivation

- The coalescence of **supermassive binary black hole (SMBBH)** systems in a **gas-rich environment** can take place after two galaxies have merged
- SMBBH are multimessenger sources
  - Detectable by current/future **GW campaigns (PTAs, LISA)**
  - They emit **EM radiation and jets**
    - How can we find their EM signatures among AGN observations?
    - EM signatures can guide GW observations and provide insight into the galactic environment hosting the black holes
- We need **GRMHD simulations** of accreting SMBBH to predict the expected EM features

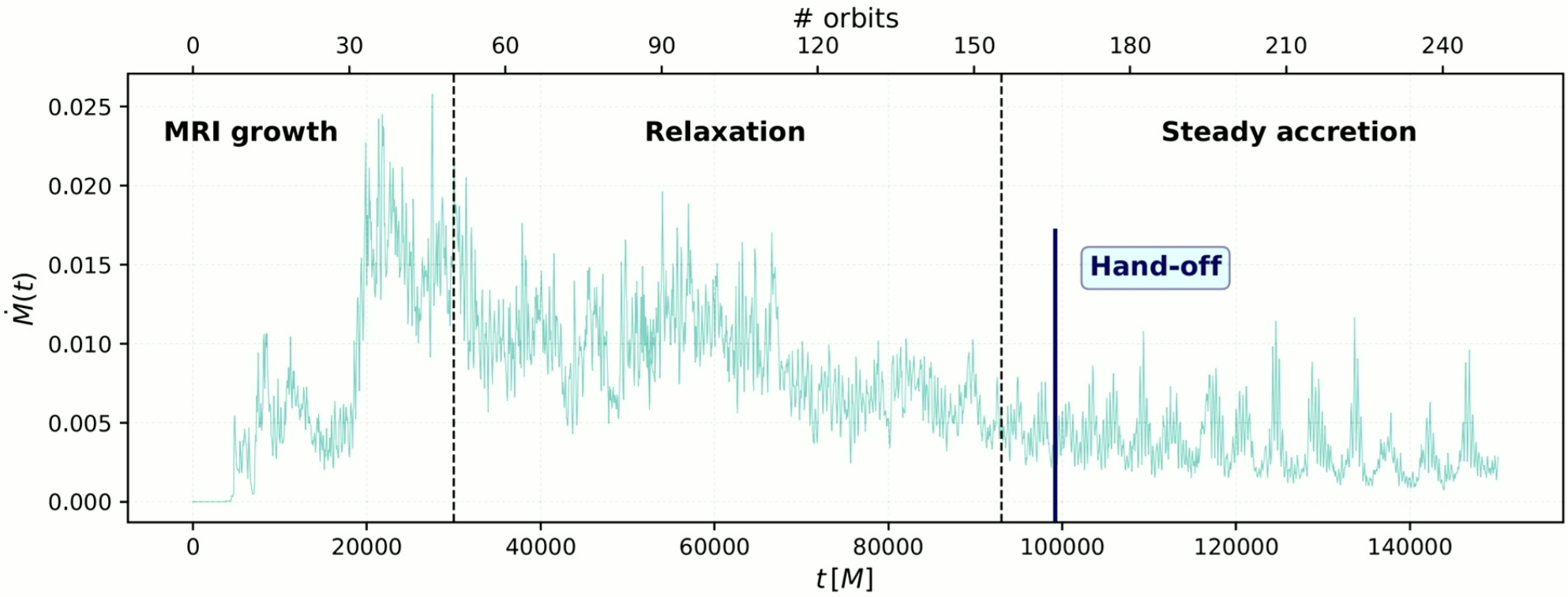
Inspiralling SMBBHs: what we know



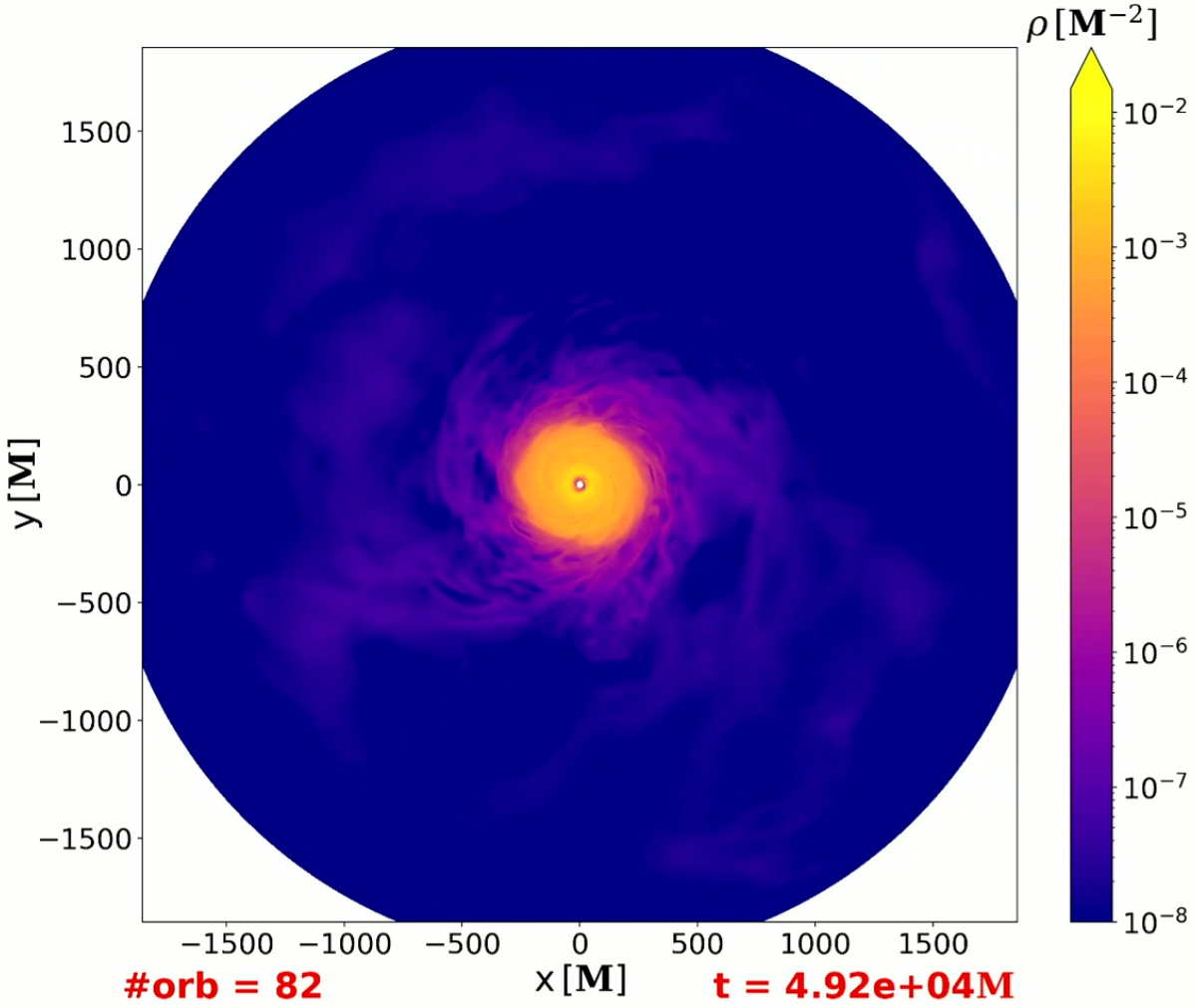
Previous work done by the ***BBHDisk collaboration:***

- **Circumbinary disk (CBD)** in quasi-steady accretion state
- **Overdensity ('lump')** near the inner edge of the CBD *(Shi+2012, Noble+ 2012, Lopez Armengol+ 2021*)
- **Minidisks** periodically filled and emptied through the streams (*Bowen+ 2018, 2019*)
- **Sloshing:** mass exchange between minidisks (*Bowen+ 2017*)
- **Periodic EM emission** (x rays/UV) (*d'Ascoli+ 2018, Gutiérrez+ 2022*)

Steadily accreting CBD



The ‘hand-off’ technique

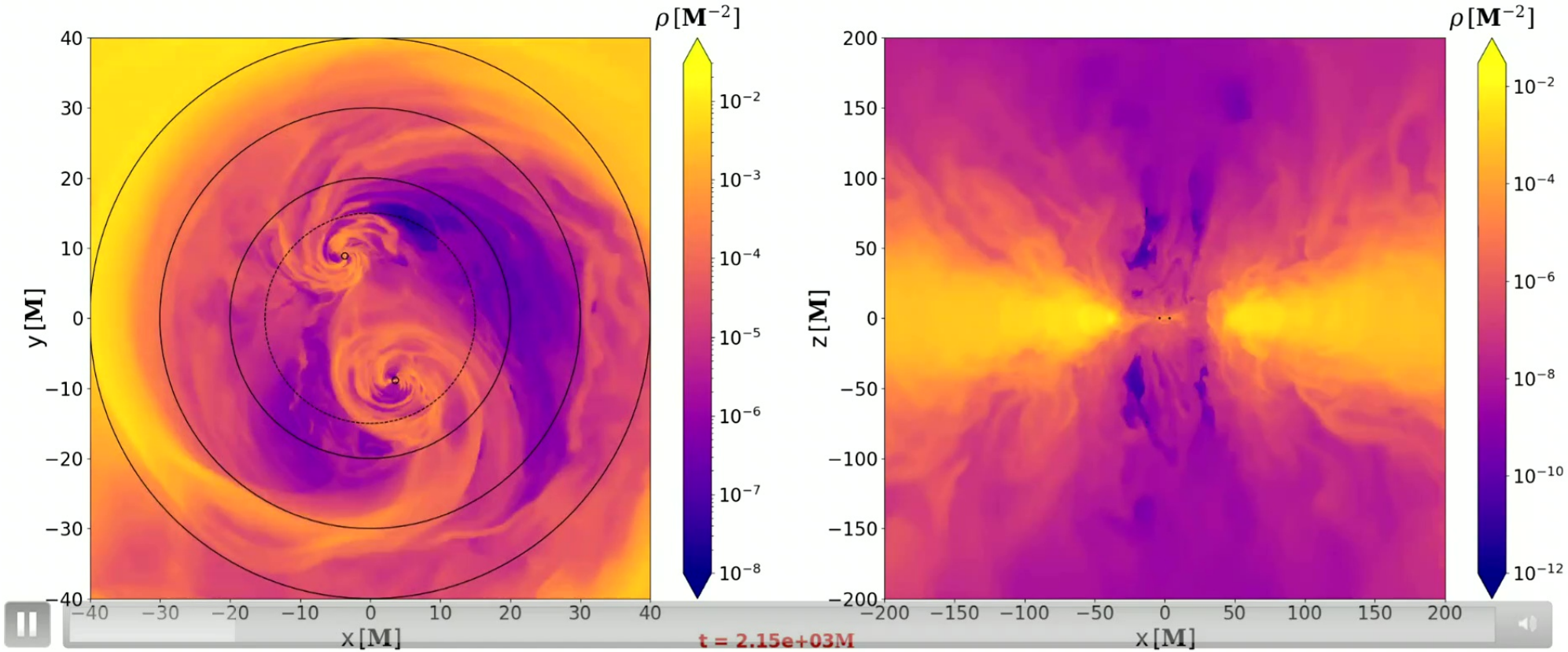


1. [Long-term CBD evolution](#) with **SphericalNR** (*Mewes+ 2018, 2020*) until quasi-steady accretion and turbulence
   - **Spherical coordinates** → Good angular momentum transport
   - **Approximate spacetime** metric (PN)
   - Central region is **excised** (computational efficiency)
2. [‘Hand-off’](#) to **IllinoisGRMHD**
   - **Cartesian grid** with box-in-box mesh refinement
   - **Fill the central cavity** with atmosphere
   - Put the **punctures** on the grid
3. Evolve down to [merger in full GR](#)

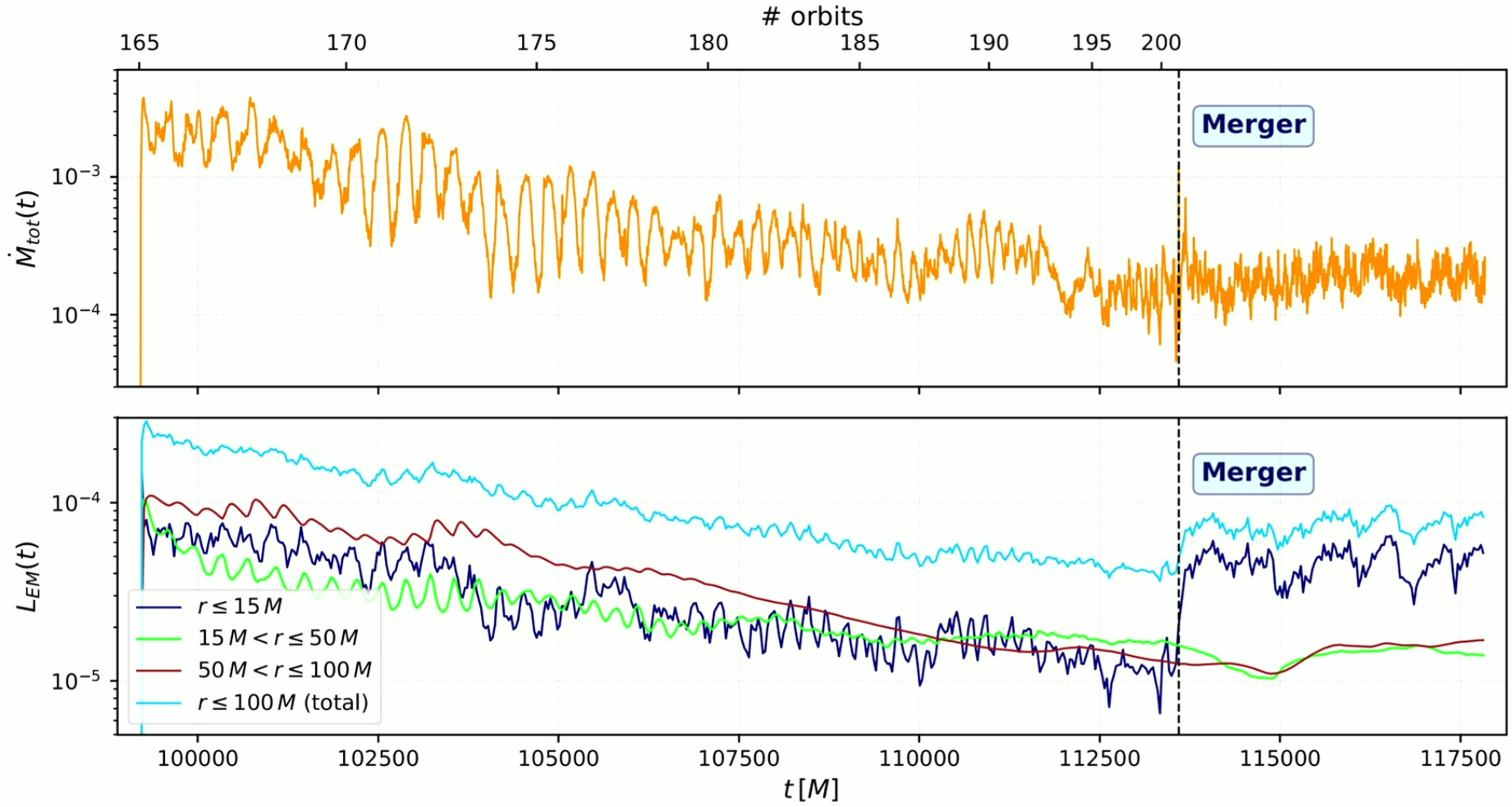
✓ **Radiative cooling** down to a target entropy (*Noble+ 2012*)

✓ Vector potential evolution → **No magnetic monopoles** introduced by the handoff

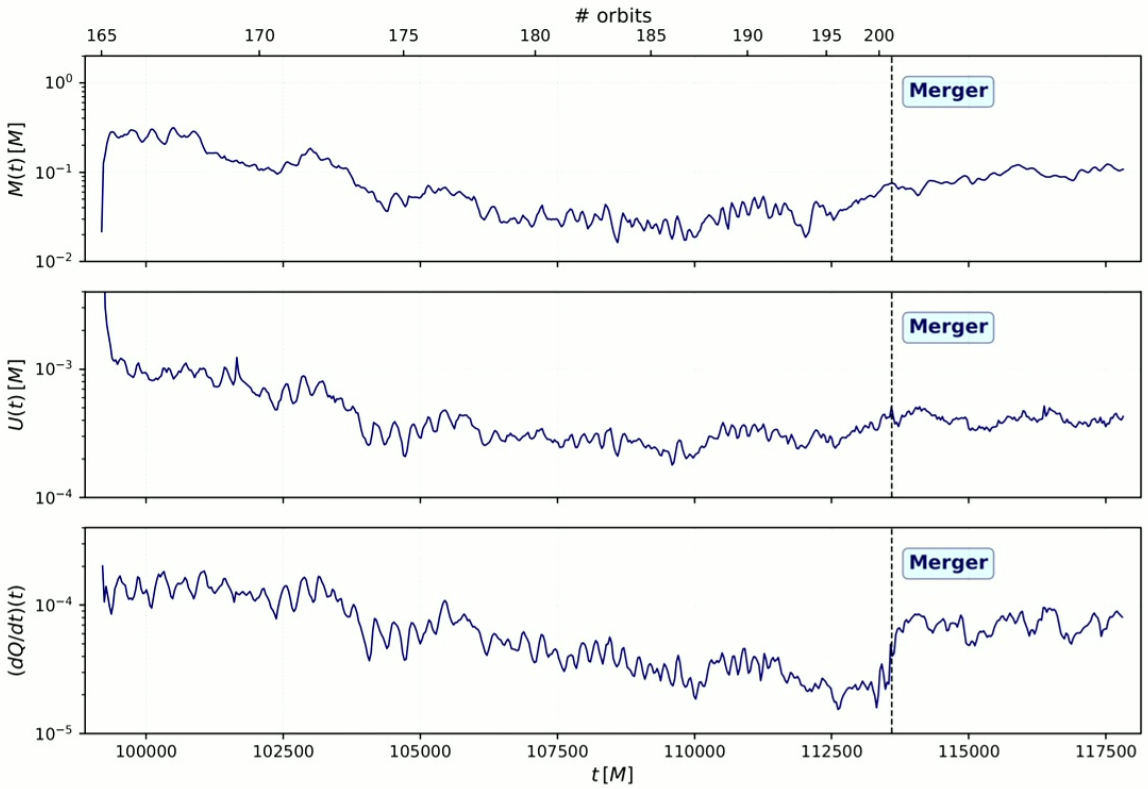
Non-spinning BBH

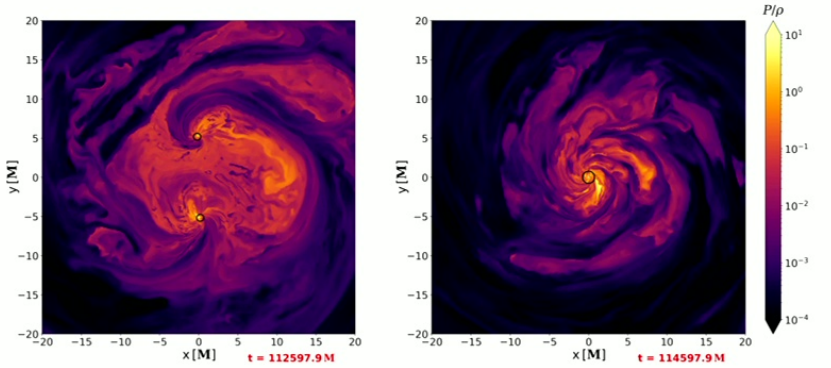


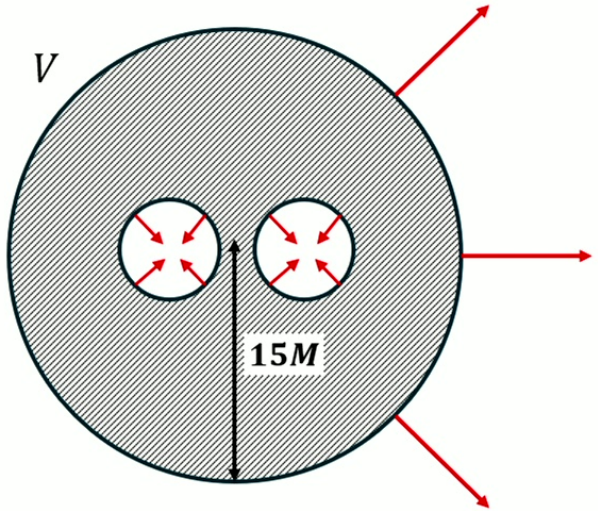
Merger dynamics: luminosity [1]



Merger dynamics: luminosity [2]

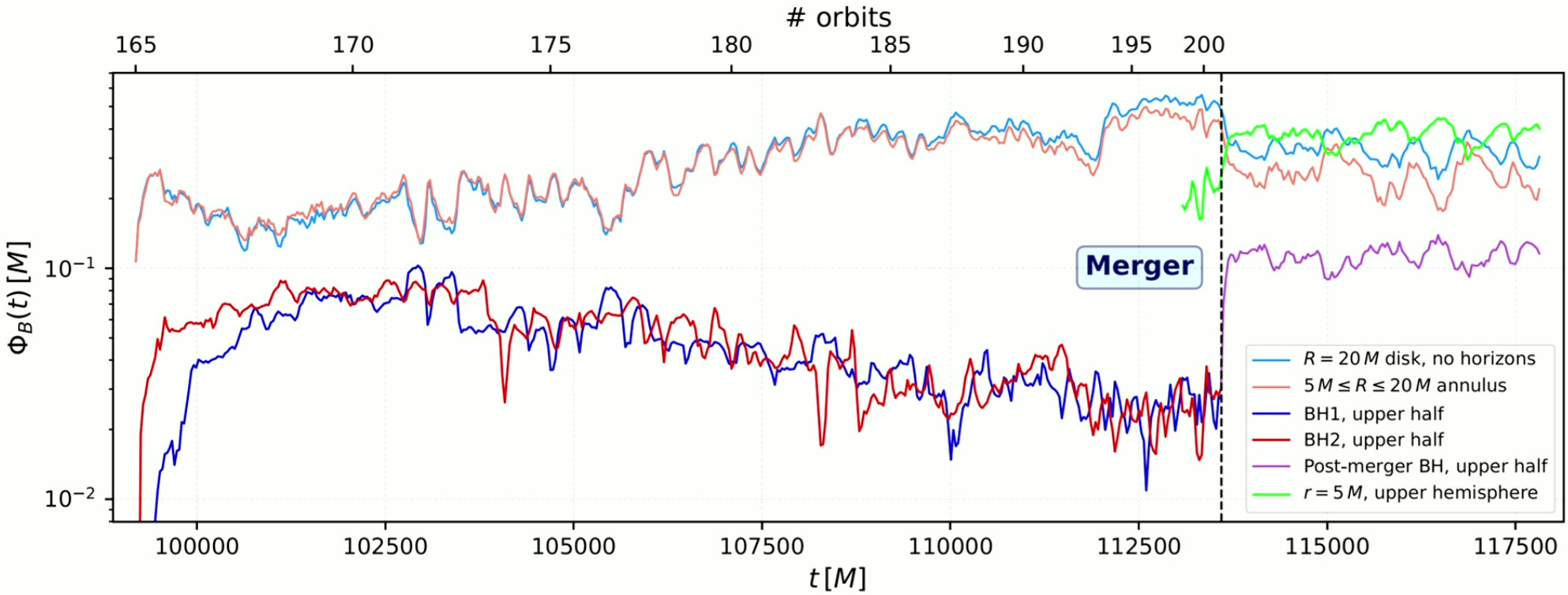




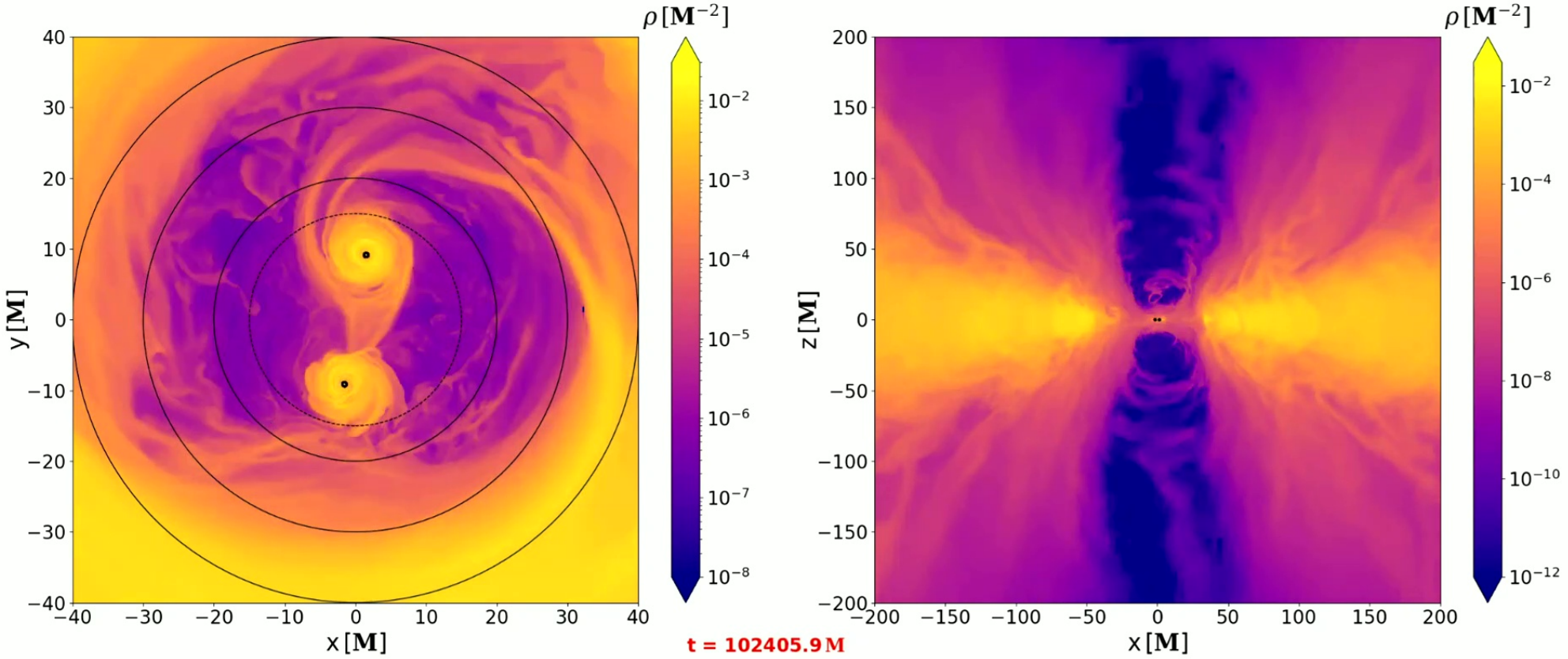


$$\frac{dU}{dt} = -\int_{\partial V} d^2\sigma \sqrt{-g}\, \rho\epsilon u^r - \int_V dV \sqrt{-g}\, L_{cool} + \frac{dQ}{dt}$$

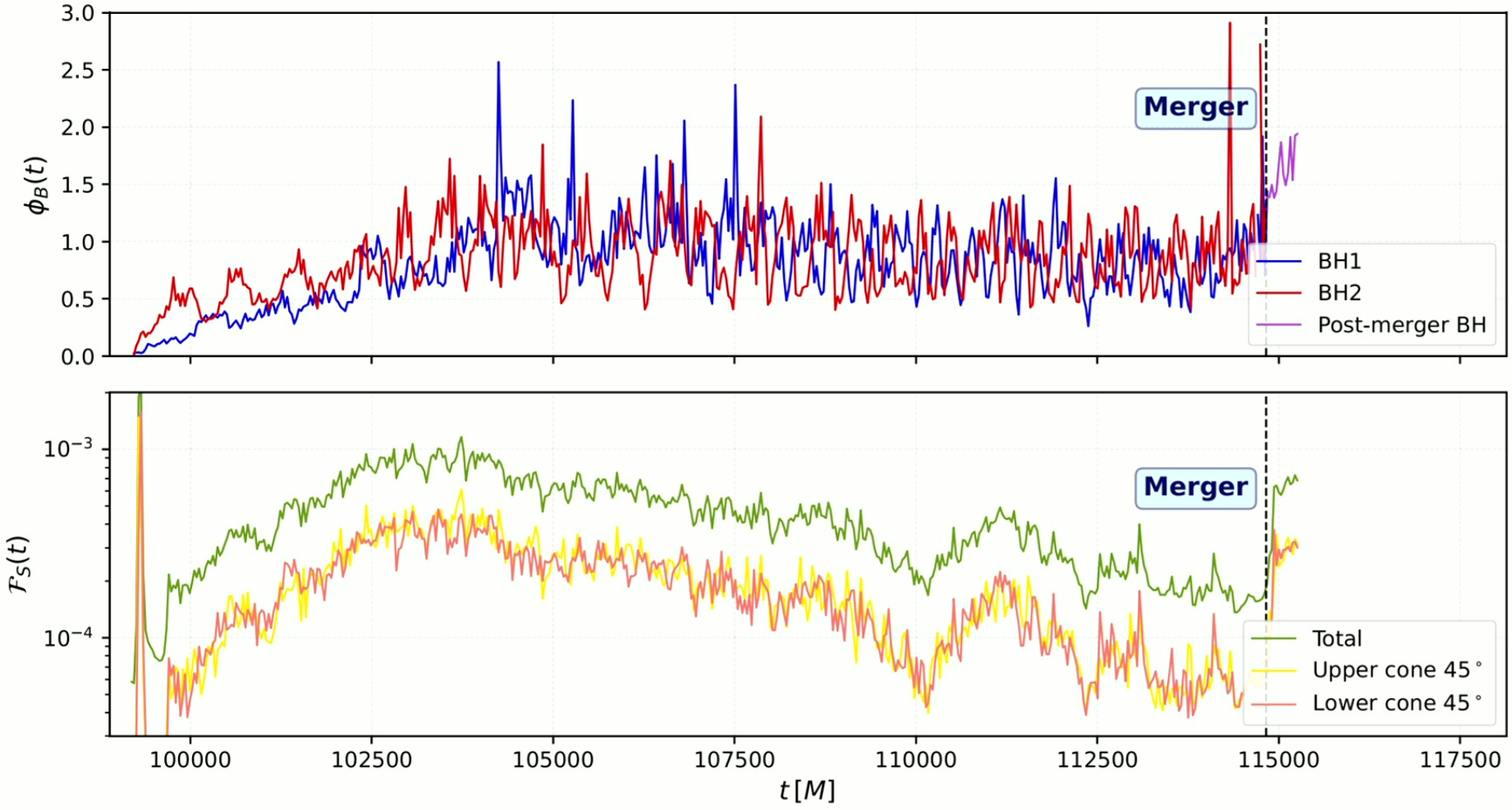
Merger dynamics: magnetic field



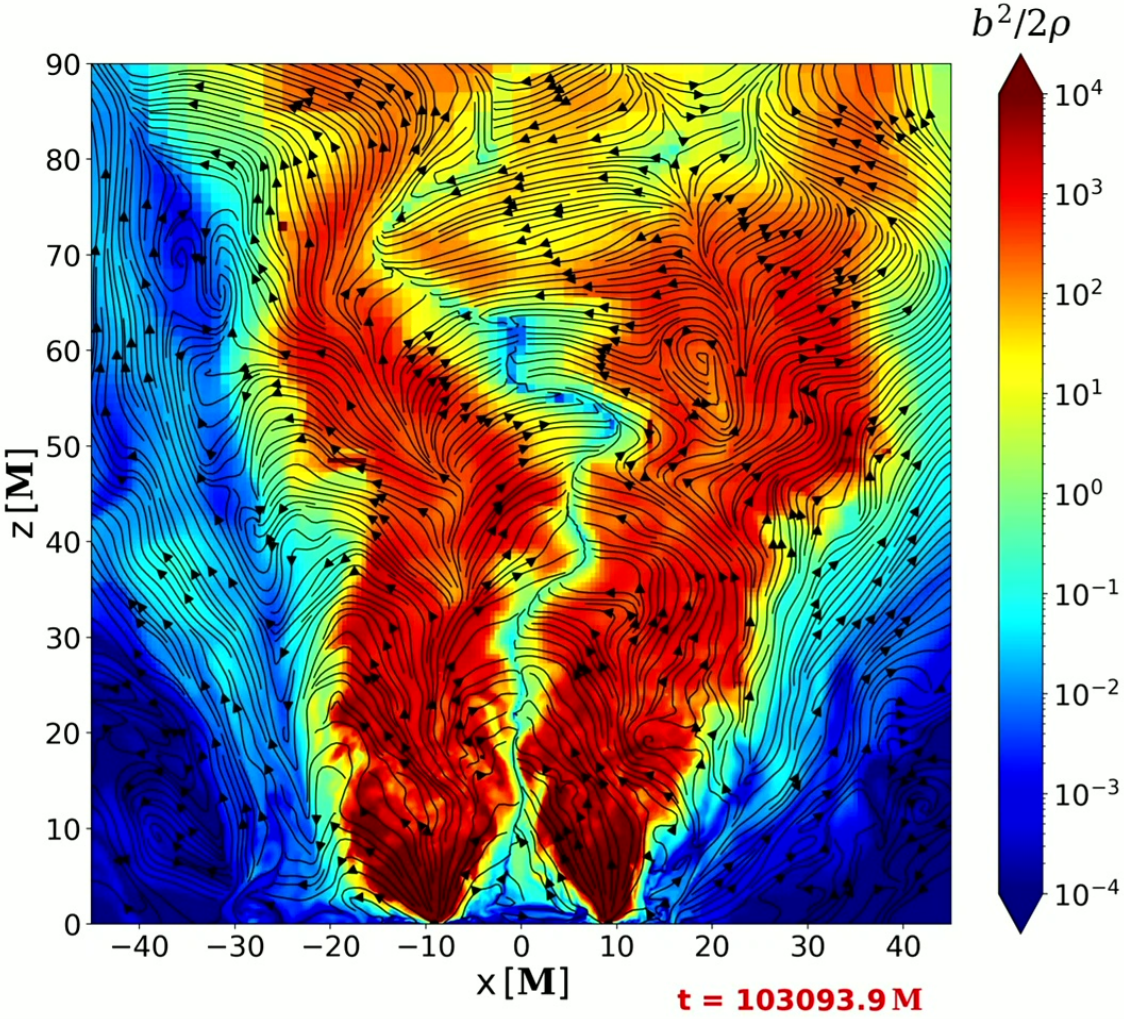
++0.8 spinning BBH



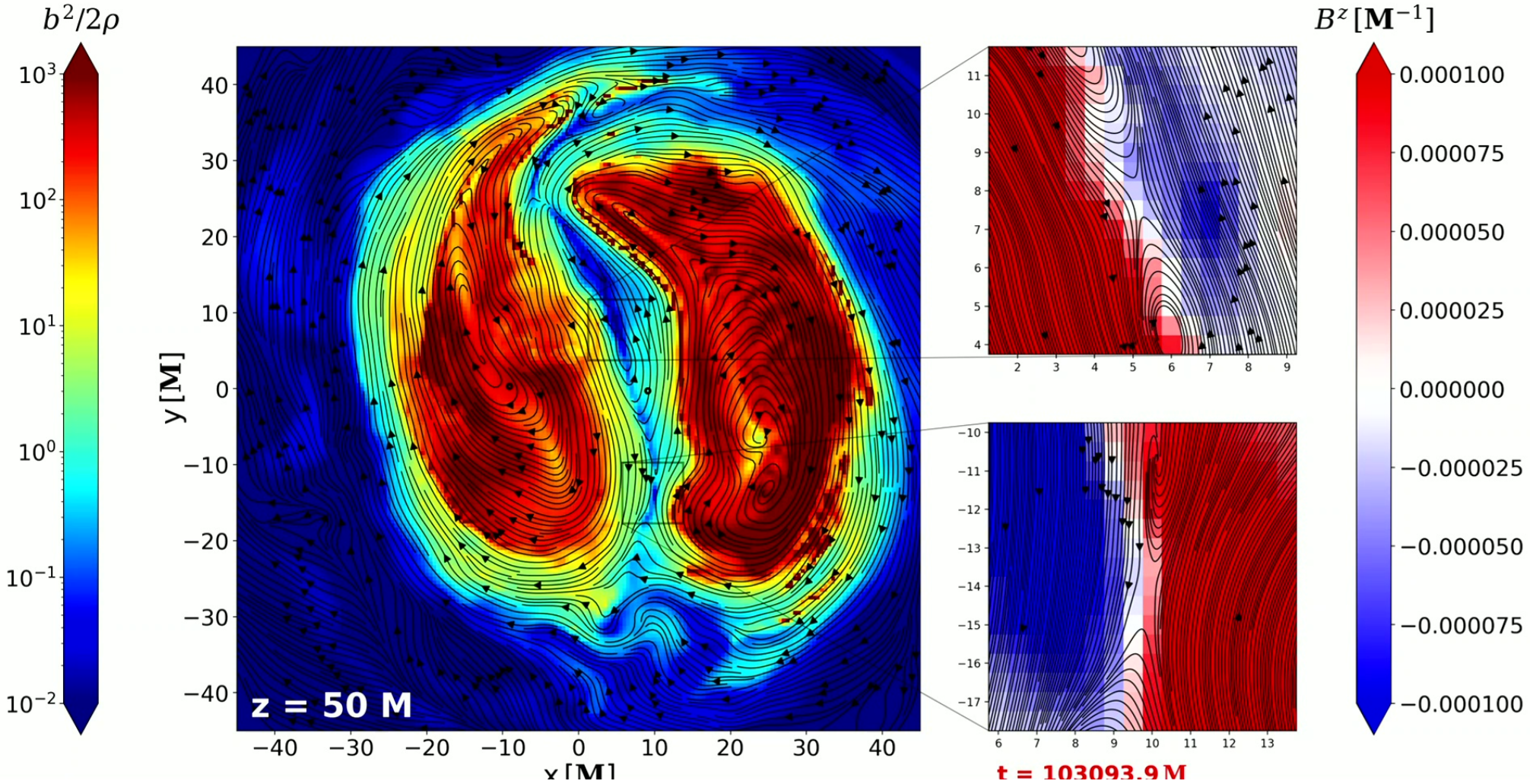
Jet quenching and reignition



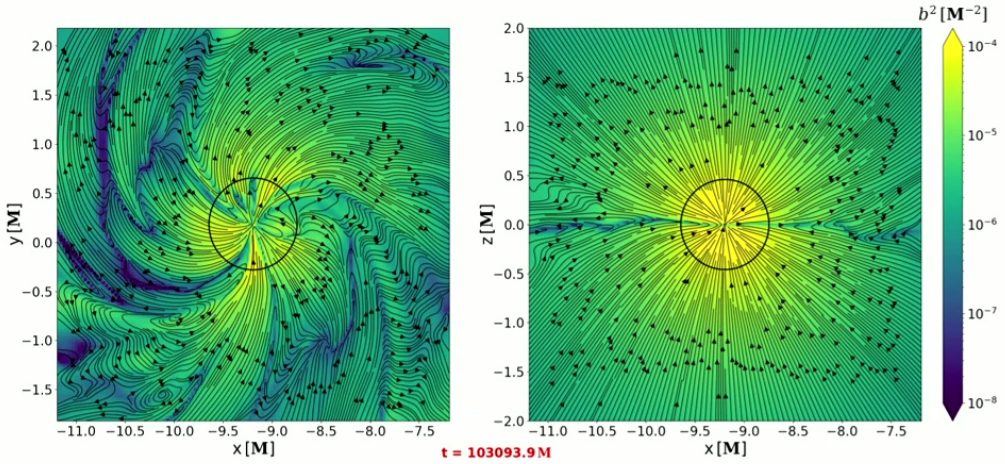
Interactions between the jets



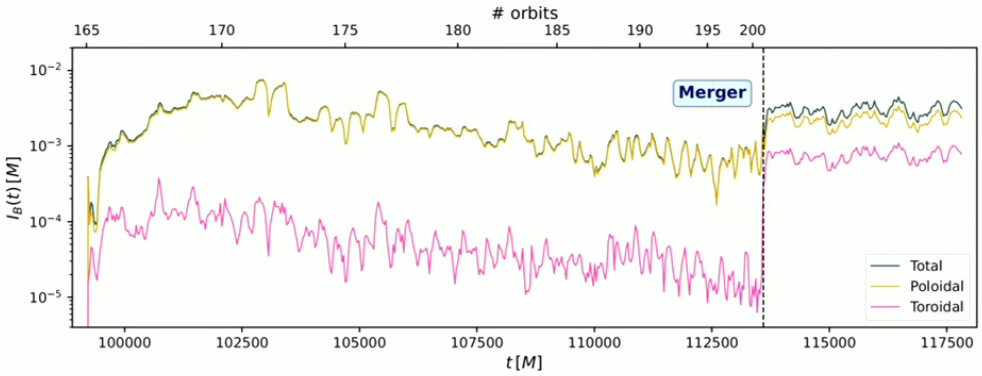
Interactions between the jets

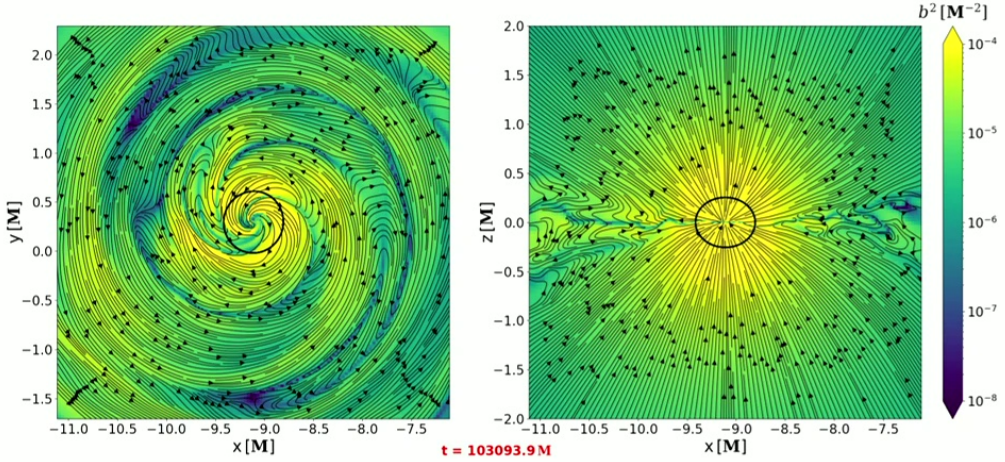


Magnetic field close to the BHs

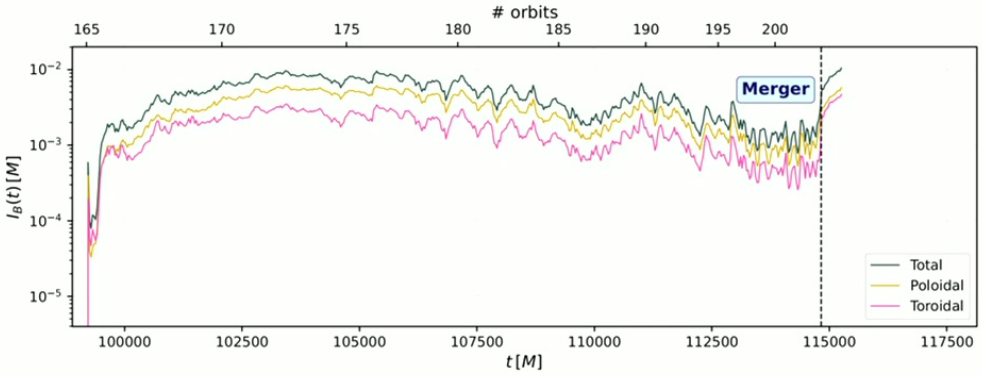


Non-spinning





++0.8



Conclusions

Simulations of SMBBH mergers in a gas-rich environment starting from **realistic initial data** with **radiative cooling**

- **Methods + Non-spinning BBH paper:** https://arxiv.org/abs/2502.06389
- **++0.8 BBH paper** out soon
- **Improved radiation treatment** underway -> EM spectra, light curves
- Explorations of **unequal masses, eccentricity, larger separations** underway
- Improved simulation efficiency via the new **GPU-enabled** code **`AsterX`** (`AMReX/CarpetX`-based, *Kalinani+2024, https://github.com/jaykalinani/AsterX*)