Simulations of Accreting Binary Supermassive Black Holes Approaching Merger

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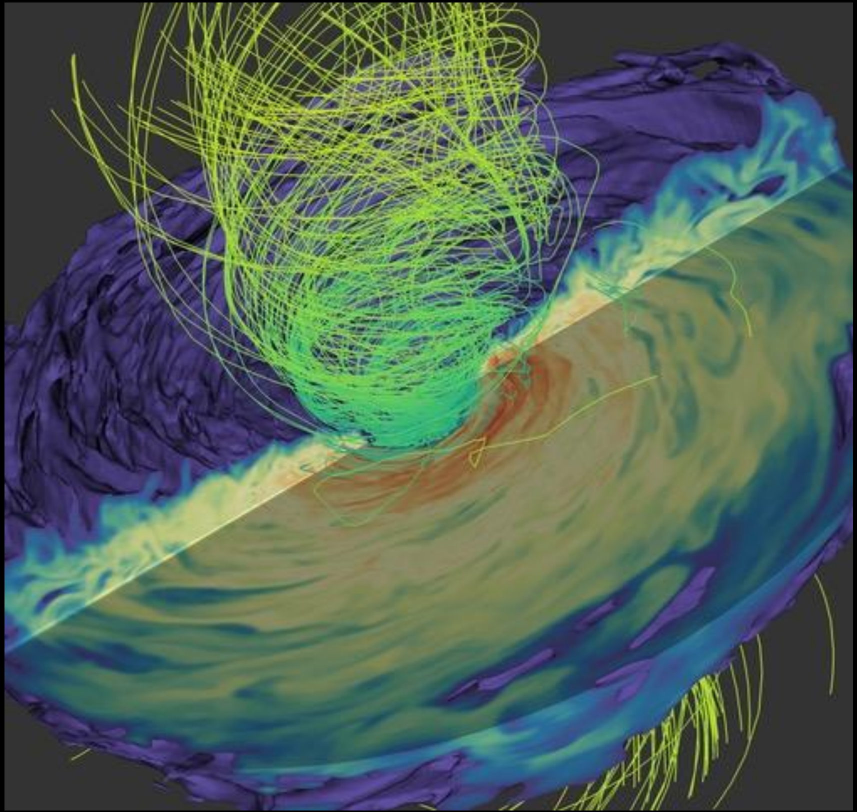

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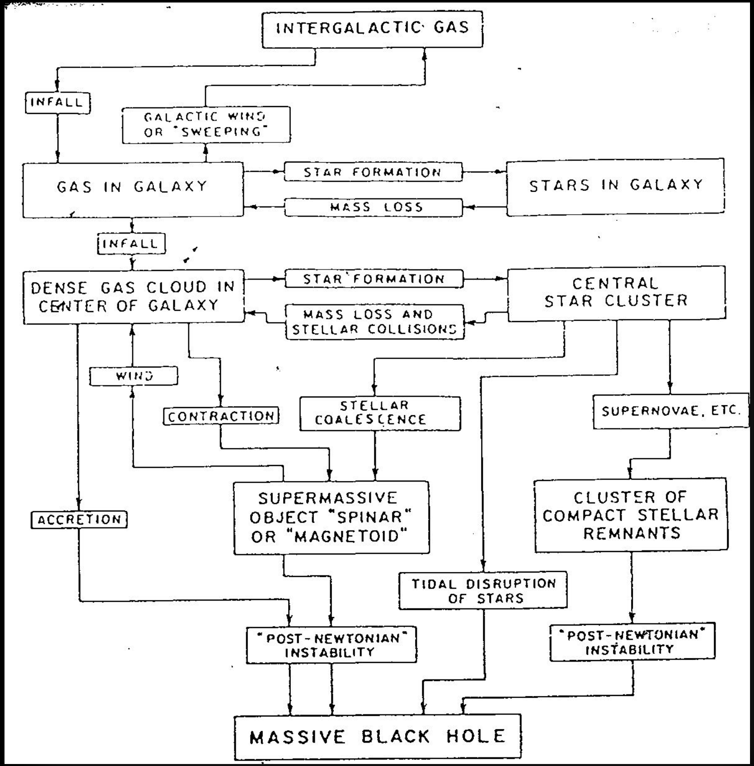
There are supermassive black holes at centers of galaxies!

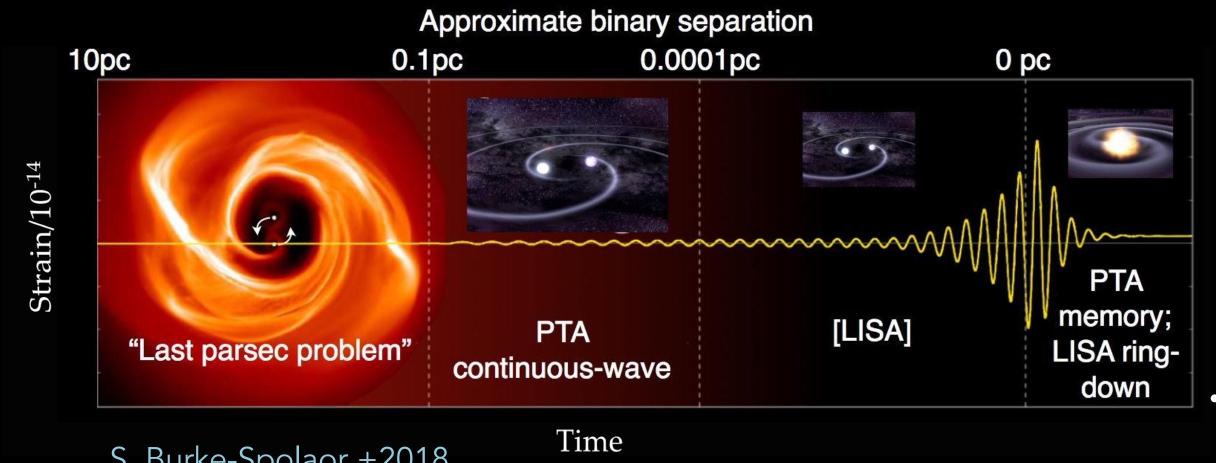


Martin Rees, 1978

There might even be two …

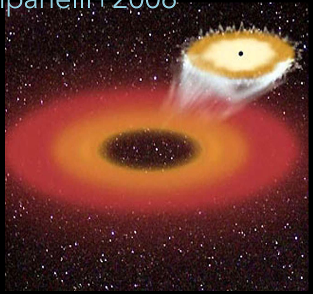
- Supermassive BH binaries should form from post-galaxy-mergers …

- And then stellar dynamical friction, torques from gas, or other processes can bring the pair to sub-pc scales, then GW should do the rest …



S. Burke-Spolaor +2018

- up to ~10% of the total mass is radiated in GW energy – e.g Campanelli+2006



- The BH remnant will **recoil** from its host structure, depending on the BH spins and masses at merger – e.g Campanelli+2007 …

Possible lifecycle of supermassive black hole binaries - Begelman, Blandford & Rees 1980. - how it happens ins still under investigation …

And they are expected to be EM – bright …

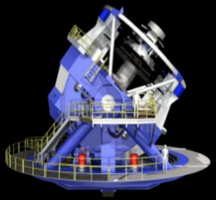
- Supermassive BHs in AGN are surrounded by accreting hot gas and emit powerful radio jets, so the probability of lots of accretion into binaries is enhanced by being post-galaxy-merger!

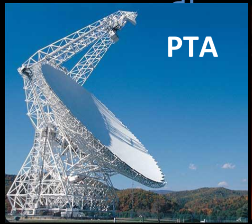
- Binary supermassive BH are primary GW sources for **LISA** and **PTA** campaigns.

- As EM sources, these binaries are ideal candidate for exploring plasma physics in the strongest and most dynamical regime of gravity.

Electromagnetic

Gravitational





Holy Grail Sources for Multi-Messenger Astrophysics!

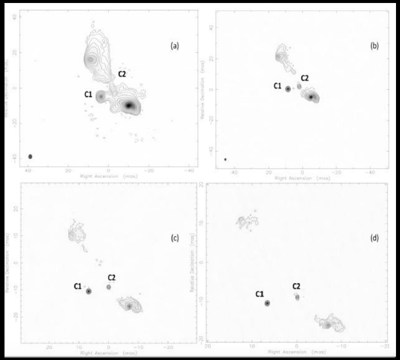
What are the EM signals associated with supermassive BH mergers?

How to distinguish binaries from single AGN?

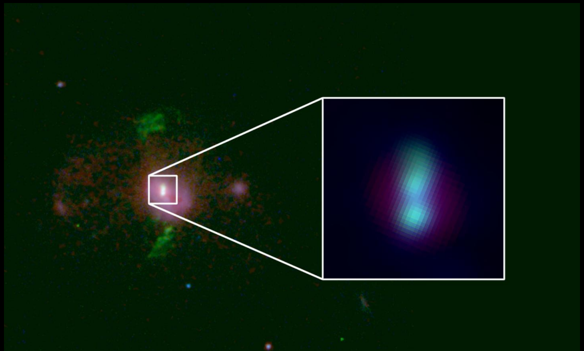
Population estimates of **EM-distinguishable binary-AGN** from galaxy evolution models find ~10^2 sources at redshifts z~0.5-1 (at flux levels >10^{-13} erg cm^{-2} s^{-1}) -- Krolik, Volonteri, Dubois, and Devriendt, 2019

~10% have periods ~ 3-5 yr, and are in the PTA range!

Identification of sub-pc SMBHBs has been challenging, but new sources will be uncovered through continued long term monitoring and new surveys and observatories,



Radio galaxy 0402+379 - Bansal+2017, 12 years of multi-frequency VLBI observations



Goulding+ ApJL 2019; HST image of SDSS J1010+1413 PTA source

e.g. LSST will study optical variability in a larger sample, so "many" binary-AGN may be uncovered in the haystack!

Modeling merging supermassive black hole binaries

Realistic simulations of the last stages of the merger are needed for EM identification and characterization!

What this requires?

Choose astrophysically motivated disk models, use GR-MHD, "realistic" thermodynamics and radiation treatment, run for **long enough** to equilibrate the system while **resolving MRI** for proper angular momentum transport in the gas – **all, considering that the spacetime is dynamically changing and must also resolve the physics close to the BH horizons!**

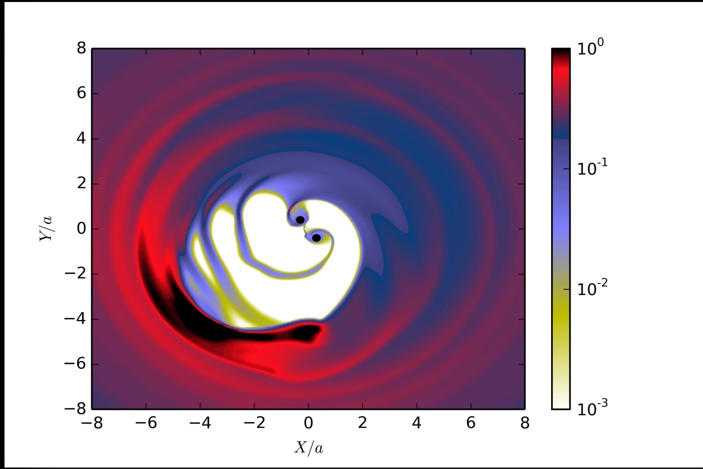
How much gas is present at merger?

- Early Newtonian HD simulations in 1D found little or no accretion close to the binary, as binary torques carve a nearly empty cavity of ~ 2a, and the circumbinary disk left behind, as the binary spirals inward fast – e.g. Pringle, 1991; Armitage+2002, Milosavljevic+2005.

- Merger simulations in full numerical relativity hint at interesting dynamics, but too short … e.g.Bode+2010; Farris+2010, Farris+2011, Giacomazzo+2012; Gold+ 2013.

- Modern 2D hydrodynamics and 3D MHD simulations **find a lot of accretion**! – Shi+2012, Noble+2012, D'Orazio+ 2013; Farris +2014; Ryan+2016, Tang+2018; Bowen+2017,2019.

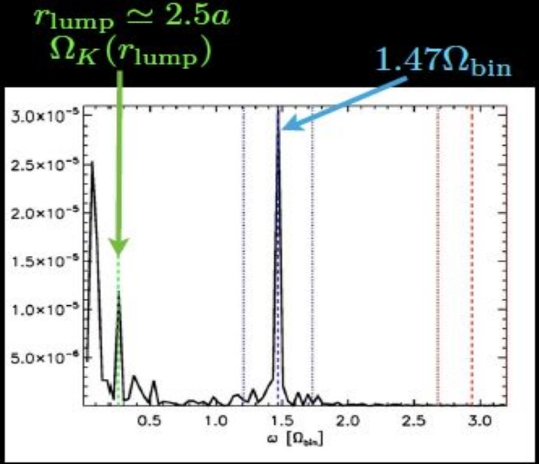
Binary torque "dam" does not hold, and accretion continues until approach to merge!



Farris+ 201a

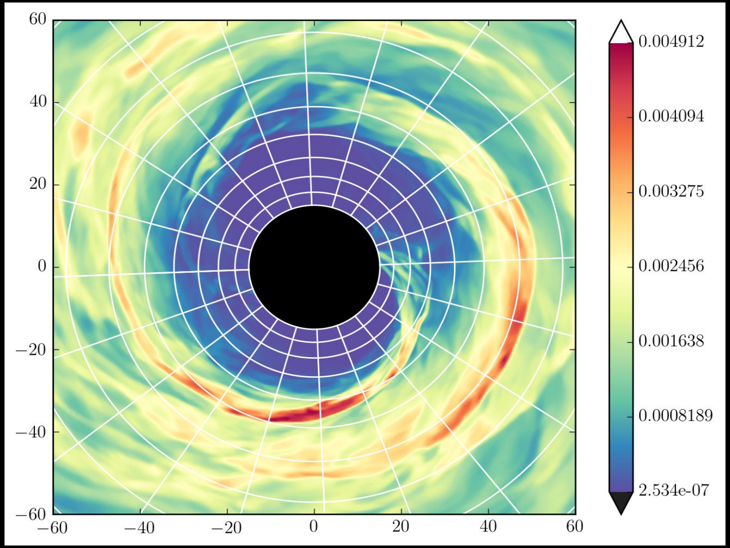
Circumbinary-disk dynamics

We found dense **accretion streams** to the BHs, and **overdensity** ("lump") in the circumbinary disk with characteristic EM signal periodicity $\Omega_{beat} = \Omega_{bin} - \Omega_{lump}$ – Shi+12, Noble+2012



Noble, Mundim, Krolik, Campanelli + ApJ 2012

Long term MHD simulations (equal-mass)
(BHs not on the grid, initial BH sep.=$20r_g$)

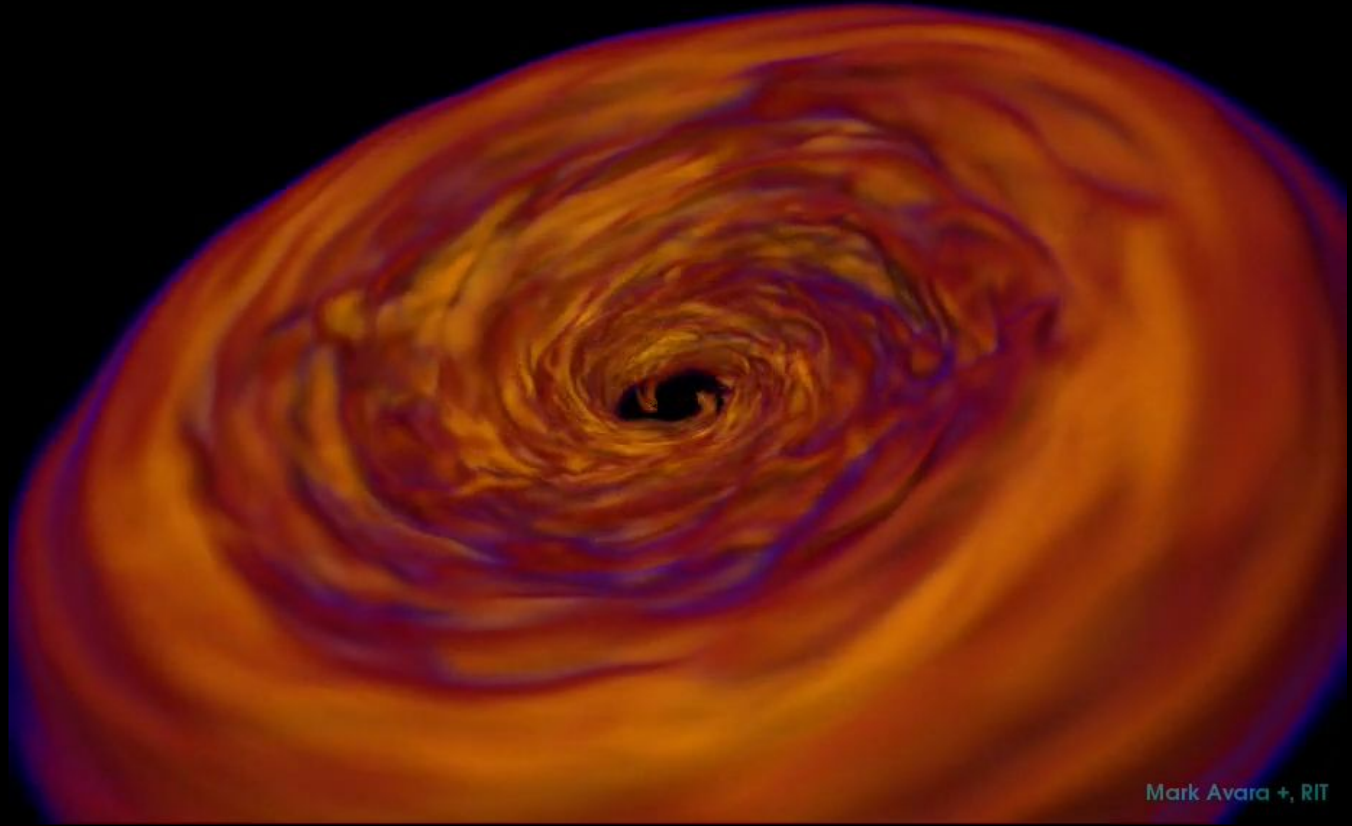


Noble +2012

This qualitative picture holds for nearly equal mass BHs and is independent of disk size or magnetization – Noble+, in prep 2019

Long-term 3 MHD simulation

Long term MHD simulations
of a tilted cicumbinary disk (~12 deg)
initial BH sep=43r_g, final BH sep=8r_g
(BHs not on the grid) – Avara+2019 in prep



Long-term, magnetohydrodynamics (MHD) simulations:

Gas evolution through conservation of mass, energy and momentum, and Maxwell's equations, on dynamical binary BH spacetime:

$$\frac{\partial}{\partial t}\mathbf{q}(\mathbf{P}) + \frac{\partial}{\partial x^i}\mathbf{F}^i(\mathbf{P}) = \mathbf{S}(\mathbf{P})$$

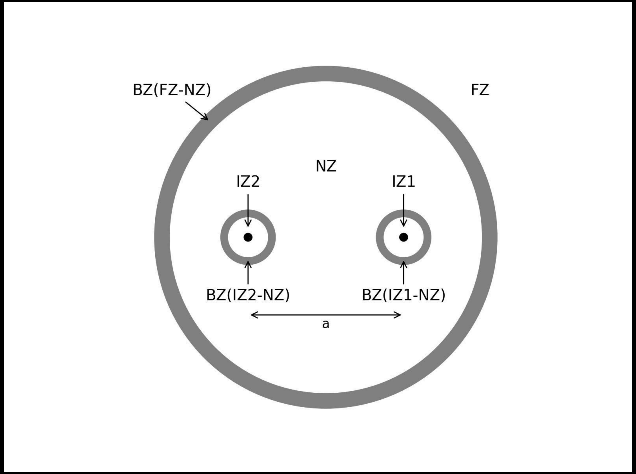
$$\frac{\partial}{\partial t}\sqrt{-g}\begin{bmatrix}\rho u^t \\ T^t{}_t + \rho u^t \\ T^t{}_j \\ B^k\end{bmatrix} + \frac{\partial}{\partial x^i}\sqrt{-g}\begin{bmatrix}\rho u^i \\ T^i{}_t + \rho u^i \\ T^i{}_j \\ \left(b^i u^k - b^k u^i\right)\end{bmatrix} = \sqrt{-g}\begin{bmatrix}0 \\ T^\kappa{}_\lambda \Gamma^\lambda{}_{t\kappa} - \mathcal{F}_t \\ T^\kappa{}_\lambda \Gamma^\lambda{}_{j\kappa} - \mathcal{F}_j \\ 0\end{bmatrix}$$

$$T_{\mu\nu} = (\rho + u + p + 2p_m)\, u_\mu u_\nu + (p + p_m)\, g_{\mu\nu} - b_\mu b_\nu$$

Mass Density; Internal Energy Density; Gas Pressure; Fluid's 4-velocity; Magnetic Pressure; Magnetic 4-vector; Radiative Energy & Momentum Loss

- Use a well-tested, **flux-conservative**, generally covariant, GR-MHD code for BH accretion disks: Harm3D – Gammie, McKinney & Toth 2003, Noble+2006
  - Ideal gas (polytropic +piecewise EOS)
  - **Isentropic cooling** (to target S_0) to keep H/r ~constant

- Code adapted to handle dynamical gravity in the relativistic GW inspiral regime – Noble+2012, Mundim+2014, Ireland+2014
  - Binary BH spacetime valid for any mass ratio and BH spins at a given initial separation.
  - BHs inspiral via the Post-Newtonian equations of motion.



Computational strategies:

Evolve accreting inspiraling BH binaries while **resolving the MRI and MHD dynamics** at the scale of the event horizons:

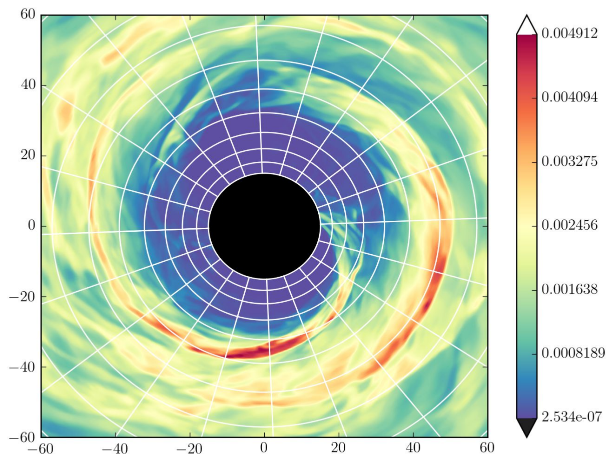
1. Perform a long-term GRMHD simulation of a thin, radiatively efficient, circumbinary accretion disk to its "quasi-steady" state:

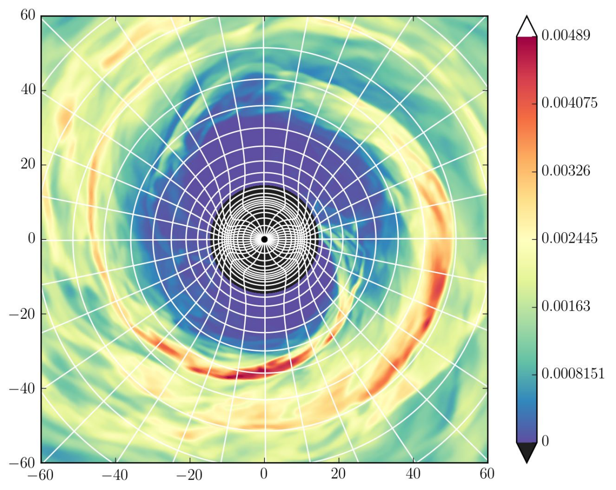
    - Use spherical polar, horizon penetrating, coords for proper angular momentum transport in the gas;
    - Remove the BHs from the grid for efficiency at this stage;

    This allow us to follow the circumbinary disk MHD dynamics for hundreds of orbits as the binary approach merger!

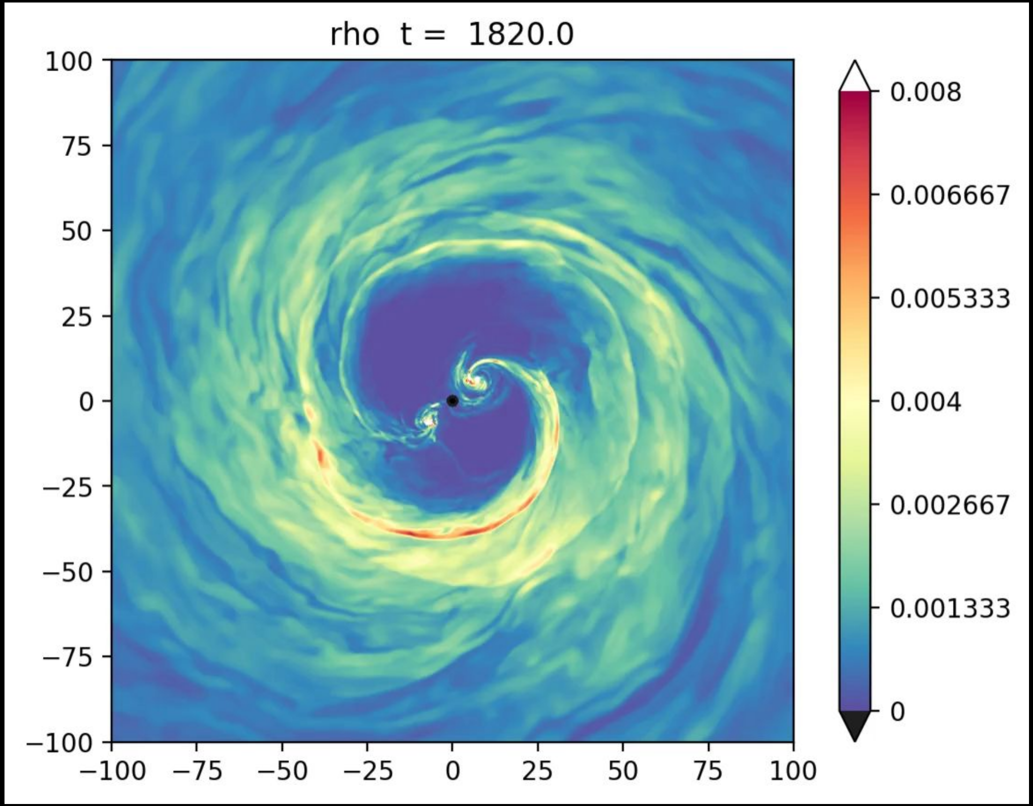
2. At "equilibration", interpolate the computational domain into a new grid designed to resolve the physics near each BHs:

    - Novel methods tailored for accuracy and efficiency e.g. dynamics warped grid – Zilhao+2014;
    - Now, augmented efficiency with a new multipatch code – Avara+2019



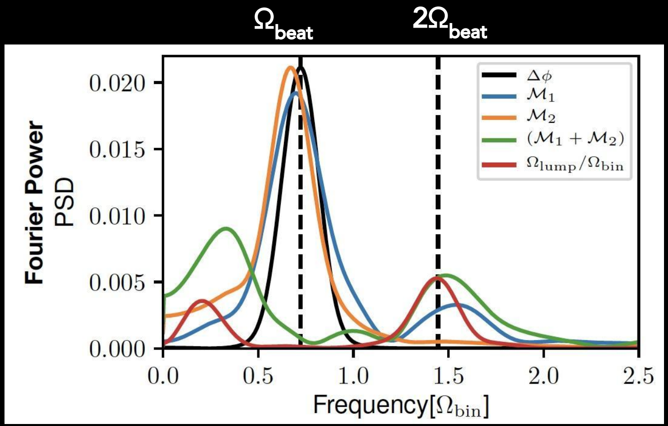


Dynamics in the central region:



We discovered new dynamical interactions between the mini-disks and circumbinary disk – Bowen+ ApJL 2018, Bowen+ ApJ 2019

- Accreting streams fall in the cavity and shock against the individual BH mini-disks.
- Mini-disks deplete and refill [the disks] periodically at time scale close to one orbital period.



Bowen, Mewes, Campanelli, Noble, Krolik, ApJL 2019

Bowen, Mewes, Noble, Avara, Campanelli, Krolik, ApJ 2019

Radiative transfer in a dynamical spacetime:

- **Bothros** - General relativistic ray-tracer for transporting radiation emitted from 3D GR-MHD simulation snapshots – Noble+2009
  - Radiative transfer integrated back into the geodesics
  - Local cooling rate = local bolometric emissivity

- **Thermal Photosphere**:
  Photons starting at photosphere start as black-body

$$\frac{\partial I}{\partial \lambda} = j - \alpha I \qquad I_\nu = B_\nu(\nu, T_{\rm eff}) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT_{\rm eff}}} - 1}.$$

Opacity: grey Thomson opacity for electron scattering

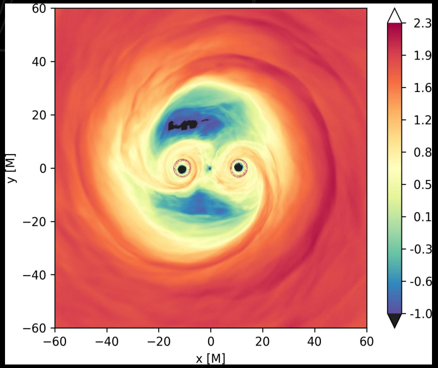
- **Above photosphere, corona emission** modeled as non-thermal (Compton scattering) component with temperature 100 keV:

$$j_\nu \propto \mathcal{W}_\nu = \left(\frac{h\nu}{\Theta}\right)^{-1/2} e^{-\frac{h\nu}{\Theta}} \qquad \Theta = kT/m_e c^2 = 0.2$$

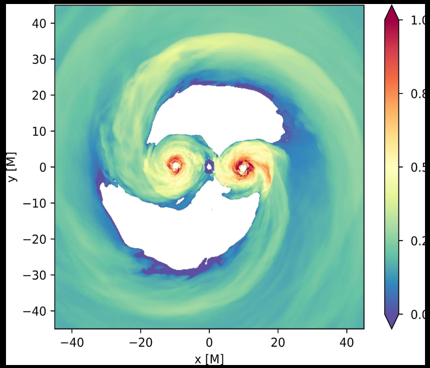
Trakhtenbrot++2017, Krolik 1999, Roedig++2014

- Explore opt. thin and thick cases: $\dot{m} = 8 \times 10^{-4}$, $\dot{m} = 0.5$

d'Ascoli, Noble, Bowen, Campanelli, Krolik, Mewes, ApJ, 2018.



Log10 Optical Depth
Grey Thomson Opacity

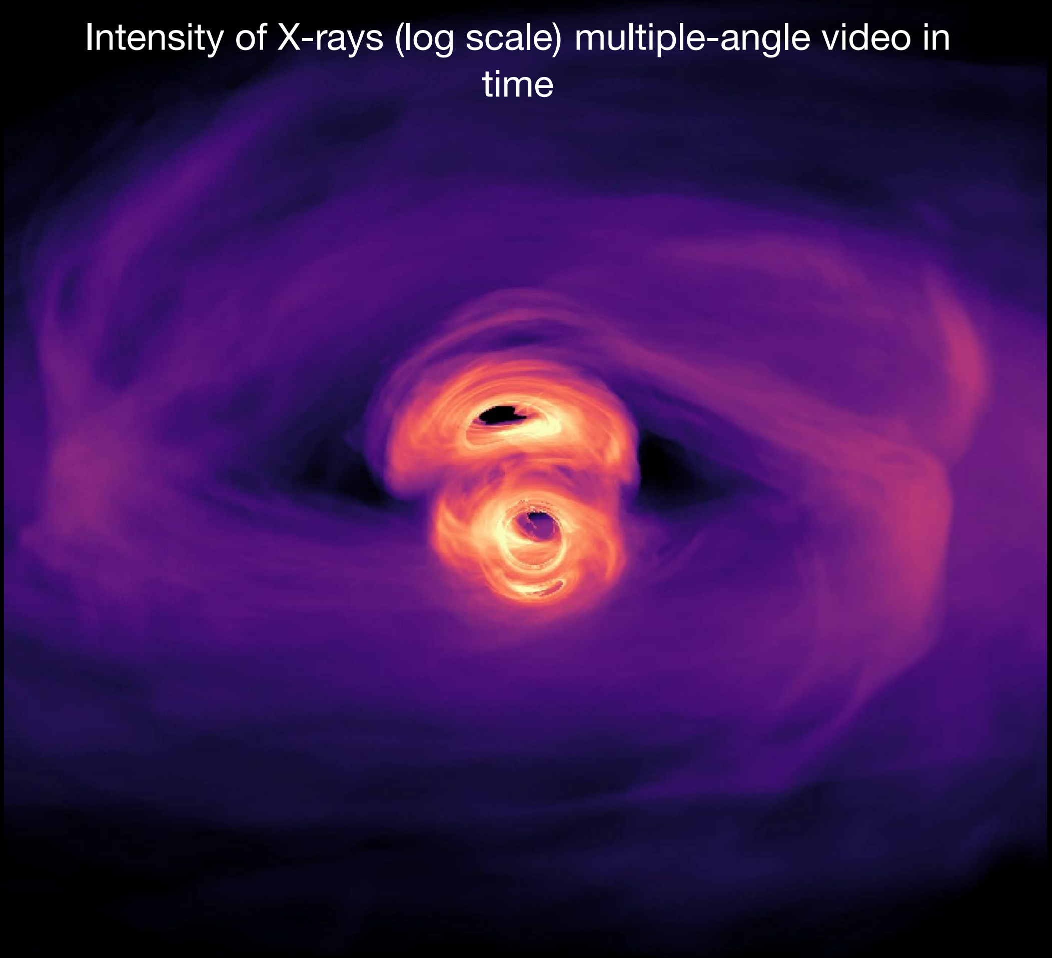


Map of Photosphere's Location & Temperature

$\log_{10}(T_{\rm eff}/T_0)$, $T_0 = 5\times10^5$K

Optically Thick Case

Intensity of X-rays (log scale) multiple-angle video in time



Credits: S. Noble (NASA) based on Bowen+2018

Calculations of distinct light signals

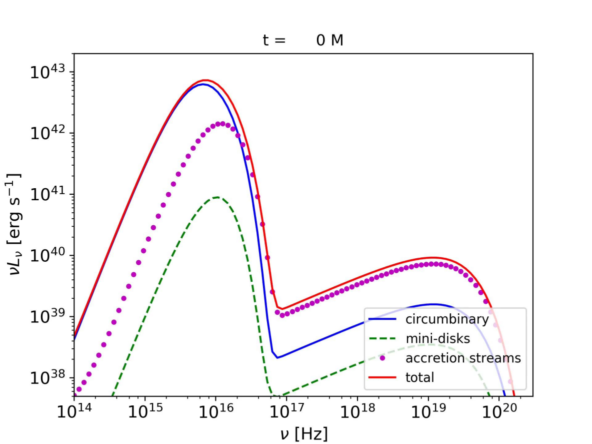
The first predicted time varying spectrum from accreting binary black holes in the inspiral regime – D’Ascoli+2018

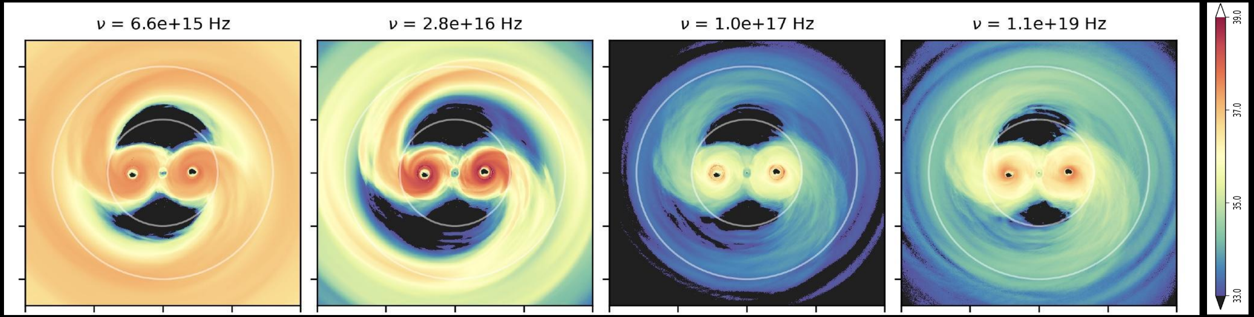
Key distinctions from single BH (AGN) systems:

- Brighter X-ray emission relative to UV/EUV.
- Variable and broadened thermal UV/EUV peak.

“Notch” between thermal peaks of mini-disks and circumbinary disk – e.g. Roedig+2014 – will likely be more visible at larger separations and for spinning BHs.

Face-on View,
Optically Thick Case
$M_{BH}=10^6 M_\odot$





Circumbinary dominated UV

Mini-disk dominated soft X-rays

X-rays near the boundary between thermal and corona dominance

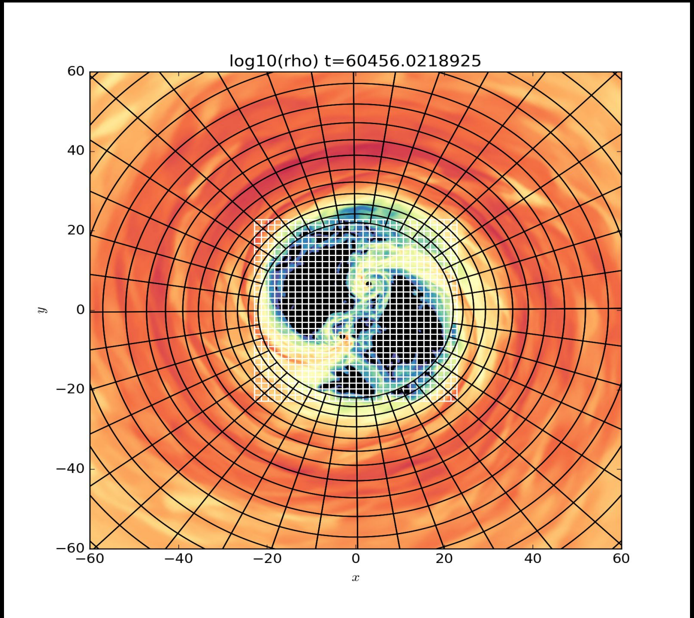
Mini-disk corona dominated hard X-rays

The systems will likely be too distant to be spatially resolved, so we need to understand their spectrum and how it varies in time.

D’Ascoli, Noble, Bowen, Campanelli, Krolik, ApJL 2019

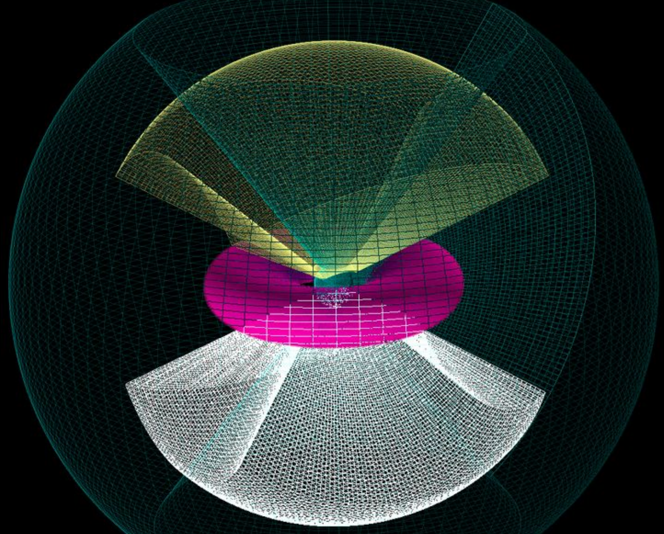
A new multi-physics, multi-scale infrastructure for exascale computing

How do we efficiently simulate 10^7-10^8 cells for 10^6-10^7 steps?



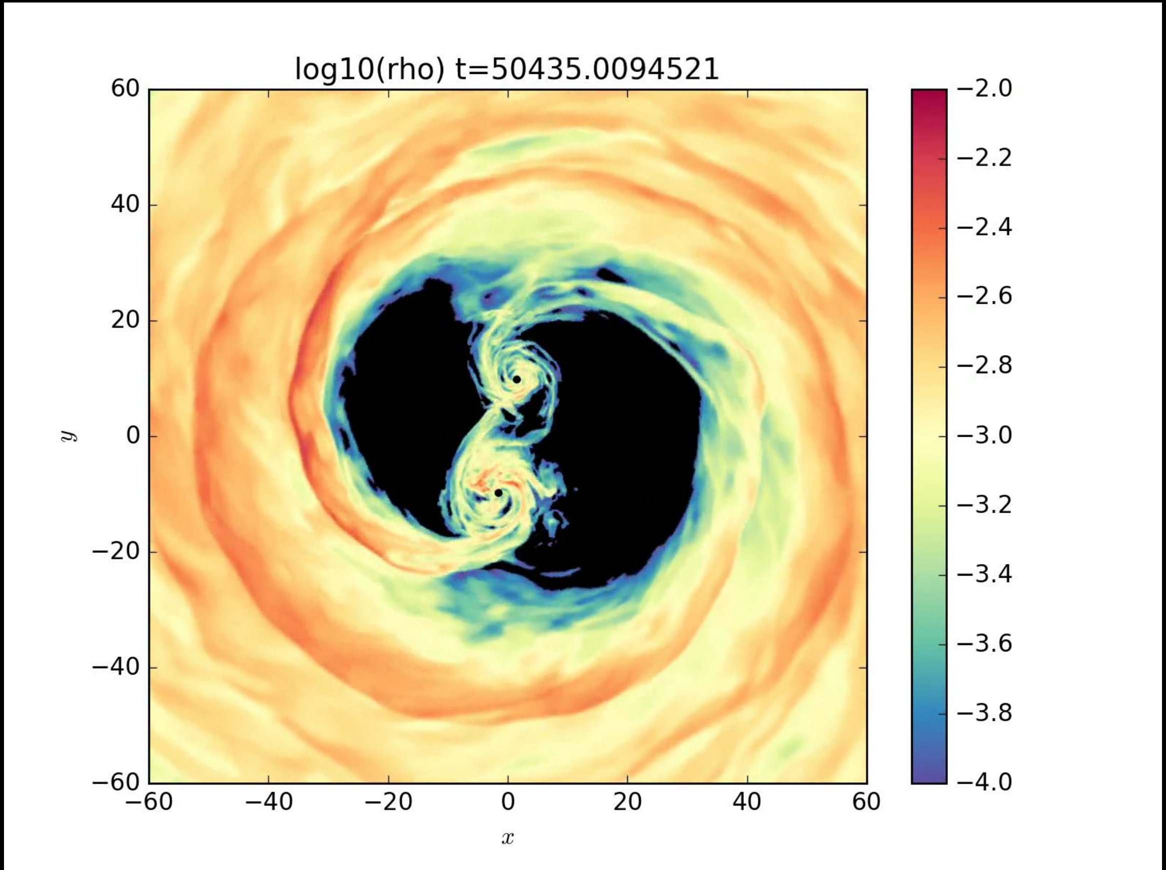
Accretion onto binary BHs

- **PatchworkMHD** – Avara+ 2019 in prep
  New software infrastructure for problems of discrepant physical, temporal, scales and multiple geometries.
- Early development (hydrodynamics only) – Shiokawa+ 2018



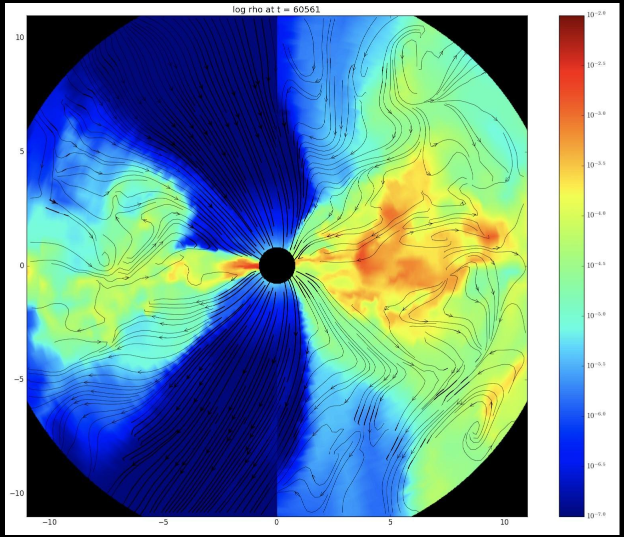
Accretion onto a single BH + Jet

First long-term global MHD simulation



- First physical parameter studies of these systems in 3D GRMHD
- Now, **30 times our prior efficiency**
- Sufficient time series data to calculate **light curve!**

Avara+2019, in prep

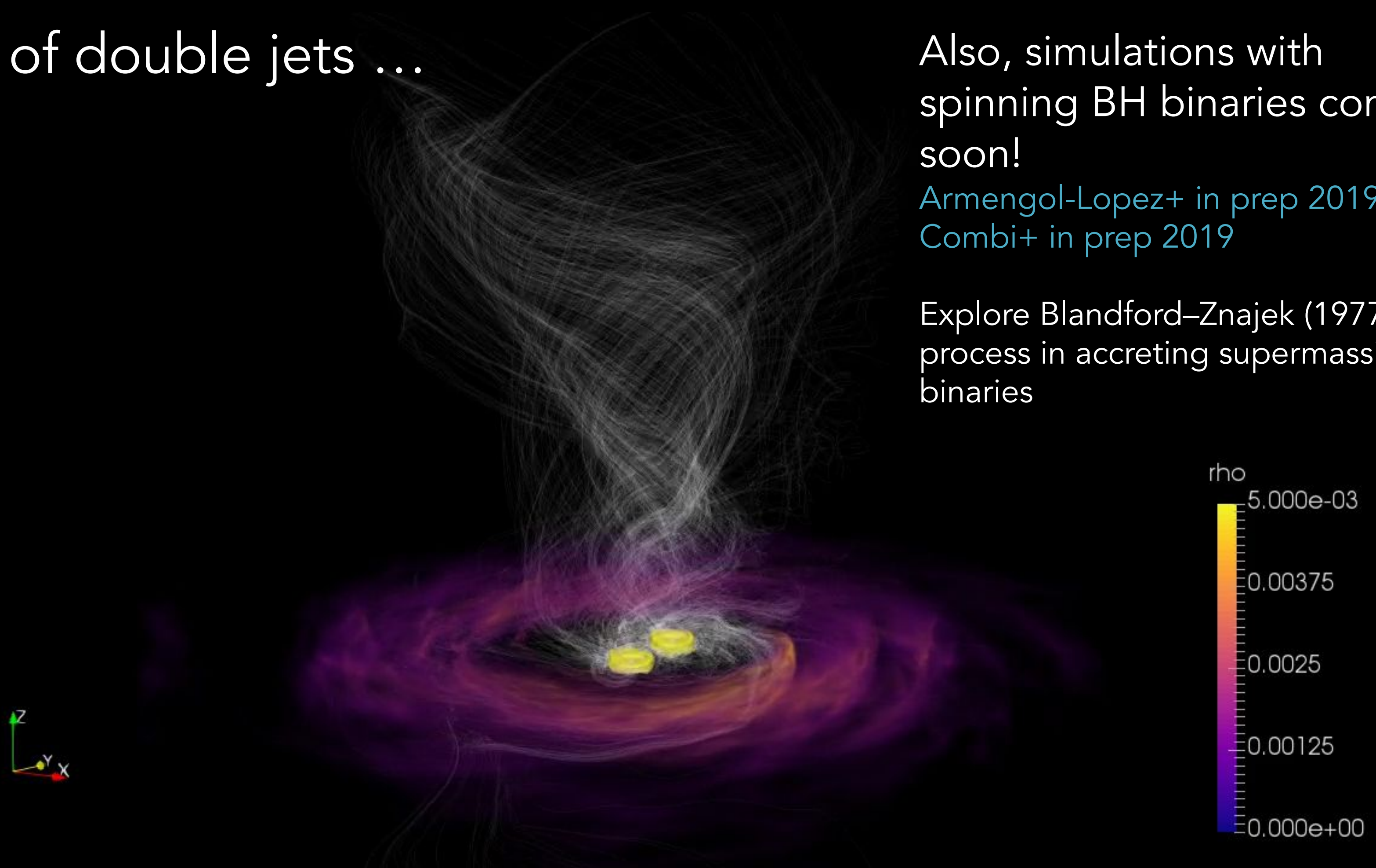


Hint of double jets …

Also, simulations with spinning BH binaries coming soon!

Armengol-Lopez+ in prep 2019
Combi+ in prep 2019

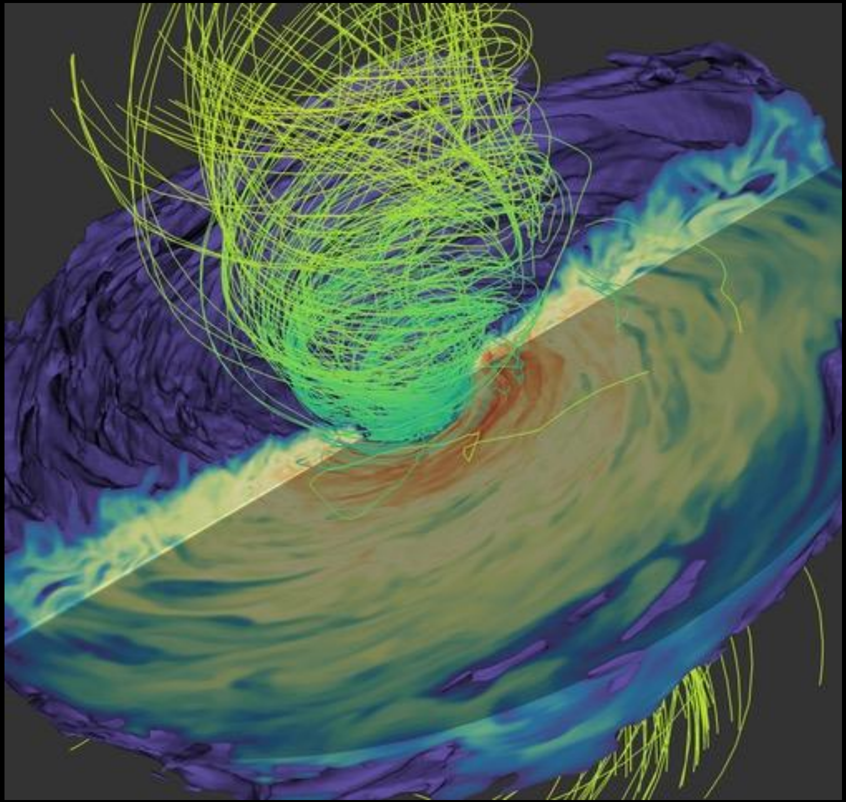
Explore Blandford–Znajek (1977) process in accreting supermassive BH binaries



Bowen++, ApJL, 2018 ; Bowen++, ApJ, 2019

Summary

- Binary black hole mergers, in particular supermassive mergers are ideal multi-messenger sources!
- A non-negligible fraction of these sources within the PTA (and LISA) GW range should also be EM observable.
- Lots has been learned already. Accurate 3d GR-MHD models are now long enough to predict distinctive EM signals for variety of astrophysical scenarios!
- Stay tuned for more results soon!



Credits: Mewes+, RIT 2019