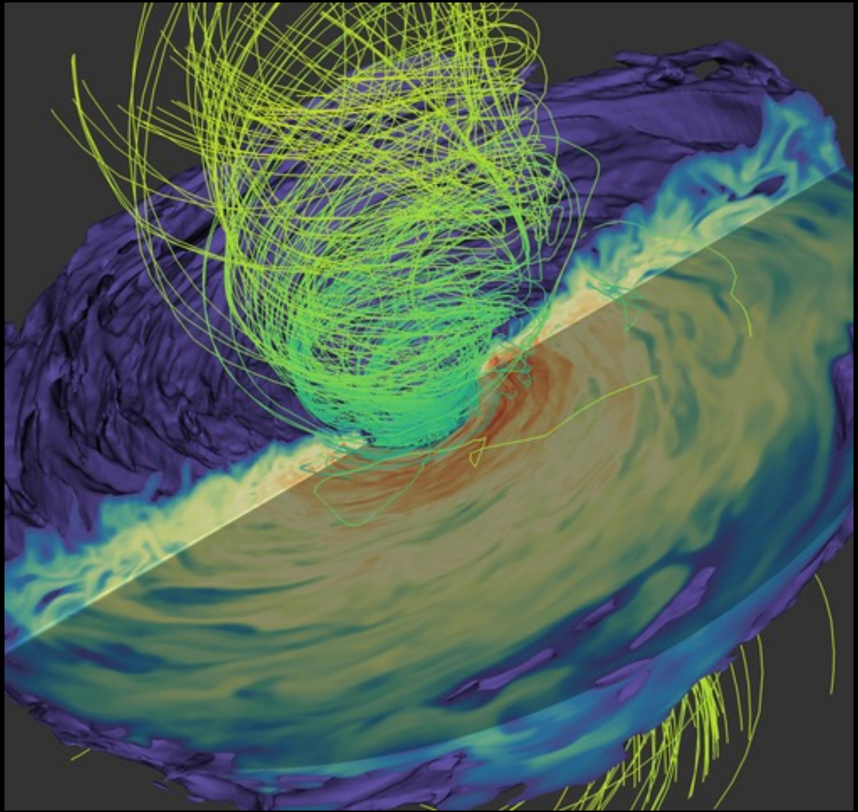
Simulations of Accreting Binary Supermassive Black Hole Approaching Merger



Collaborators:
M. Avara (PD, RIT)
D. Bowen (GRA/PD, RIT)
S.C. Noble (U. Tulsa, NASA GSFC)
V. Mewes (RIT)
J. Krolik (JHU)
J. Schnittman (GSFC)

NSF NASA

Manuela Campanelli

RIT | College of Science
Center for Computational Relativity and Gravitation

QUASARS IN CRISIS
THE ROYAL OBSERVATORY, EDINBURGH
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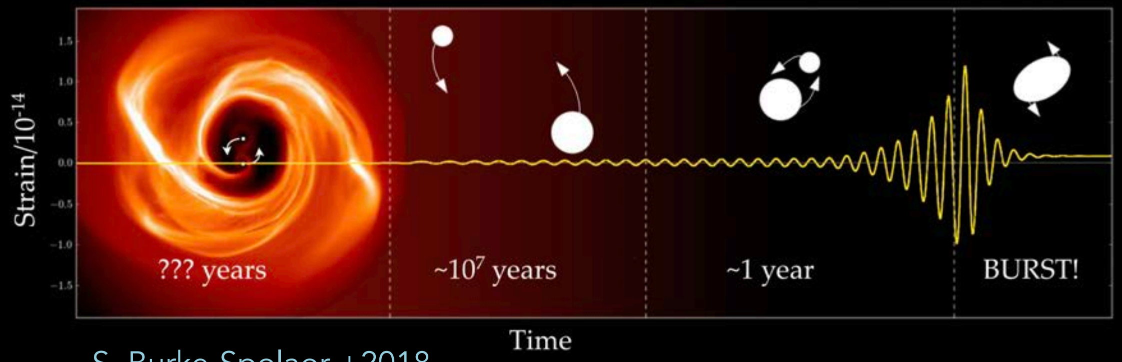
A theorist's point of view …

Modeling Merging Supermassive Black Hole Binaries

- SMBBH are primary GW sources for LISA and PTA campaigns.
- As EM sources, they are ideal candidate for exploring plasma physics in the strongest and most dynamical regime of gravity.
- **Realistic simulations and their electromagnetic output** are needed for EM identification and characterization in this regime.



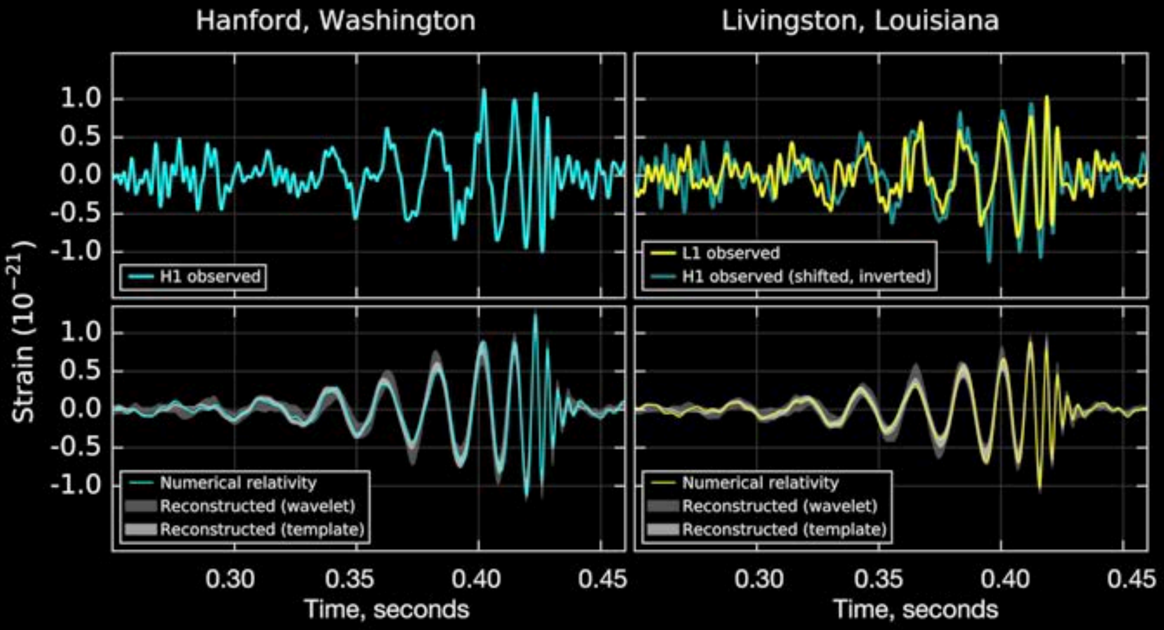
S. Burke-Spolaor +2018

Key Challenges:

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

Numerical Simulations can have predictive power!

To directly compare them to LIGO data, and extract information about the sources!



Abbott + 2016

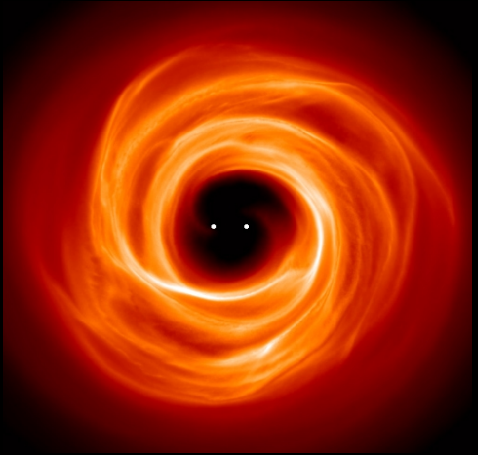
IMAGE CURTESY OF LIGO, NSF

Today, we have catalogs containing 3000+ cakculated waveforms!

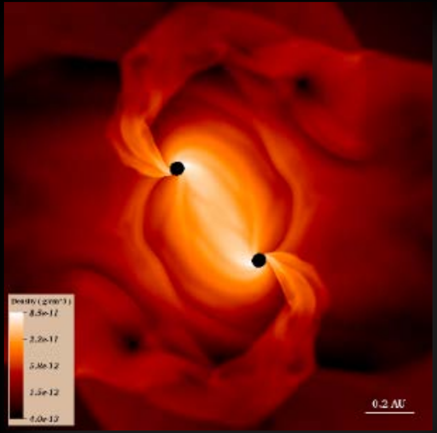
There is Reason for Increased Optimism!

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

Early Newtonian hydrodynamics in 1D and 2D 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. e.g. Pringle, 1991; Armitage & Natarajan 2002, 2005, Milosavljevic & Phinney 2005, Cuadra+2009.



Cuadra+2009



Bode+2010

Merger simulations in full GRMHD hint at interesting dynamics, but too short … e.g.Bode+2010; Farris+2010, Farris+2011, Giacomazzo+2012; Gold+ 2013; Kelly+2017.

Modern 3D GRMHD completely reverse this picture – binary torque "dam" does not hold, and accretion continues until approach to merger – e.g. Noble+12, Bowen+18,19

Long-term GR-MHD simulations

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

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

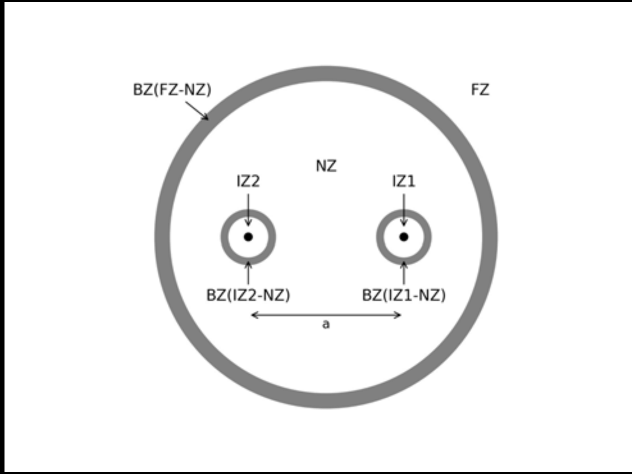
$$\frac{\partial}{\partial t}\sqrt{-g}\begin{bmatrix}\rho u^t \\ T^t{}_t + \rho u^t \\ T^t{}_j \\ B^k\end{bmatrix} + \frac{\partial}{\partial x^i}\sqrt{-g}\begin{bmatrix}\rho u^i \\ T^i{}_t + \rho u^i \\ T^i{}_j \\ \left(b^i u^k - b^k u^i\right)\end{bmatrix} = \sqrt{-g}\begin{bmatrix}0 \\ T^\kappa{}_\lambda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

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

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, GRMHD 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:

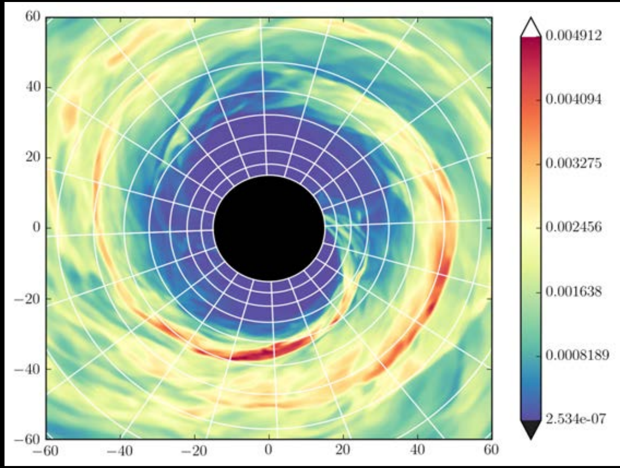
1. Perform a long-term GRMHD simulation of a thin, radiatively efficient, circumbinary accretion disk to its "quasi-steady" state:

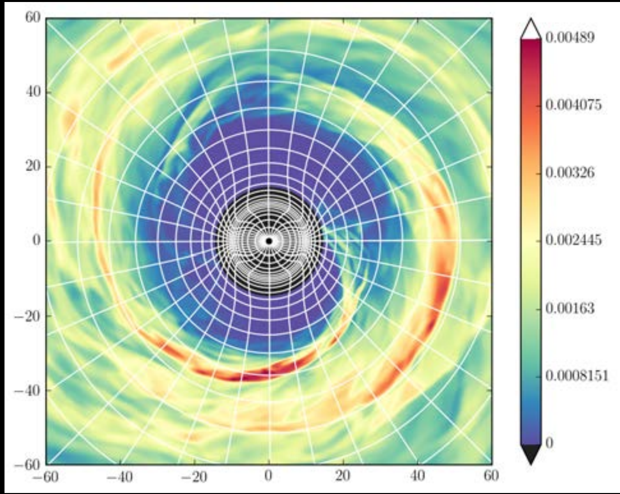
   - ➢ Use spherical polar, horizon penetrating, coords for proper angular momentum transport in the gas;
   - ➢ Remove the BHs from the grid for efficiency at this stage;

   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:

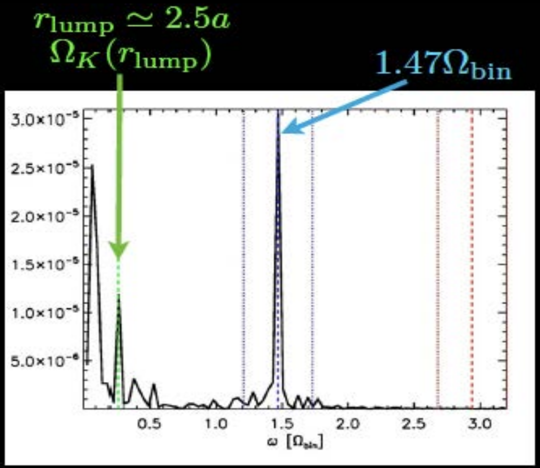
   - ➢ Novel methods tailored for accuracy and efficiency e.g. dynamics warped grid – Zilhao+2014;
   - ➢ Now, augmented efficiency with a new multipatch code – Avara+2019





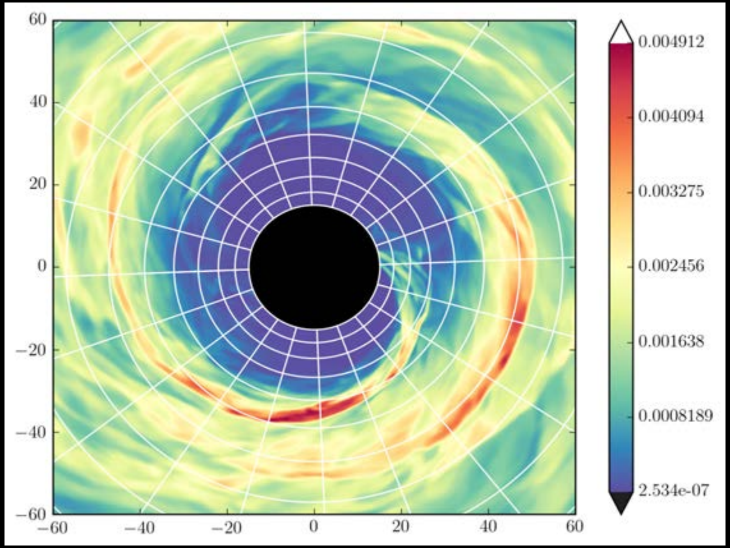
Circumbinary Disk Dynamics

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



Noble, Mundim, Krolik, Campanelli + ApJ 2012

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



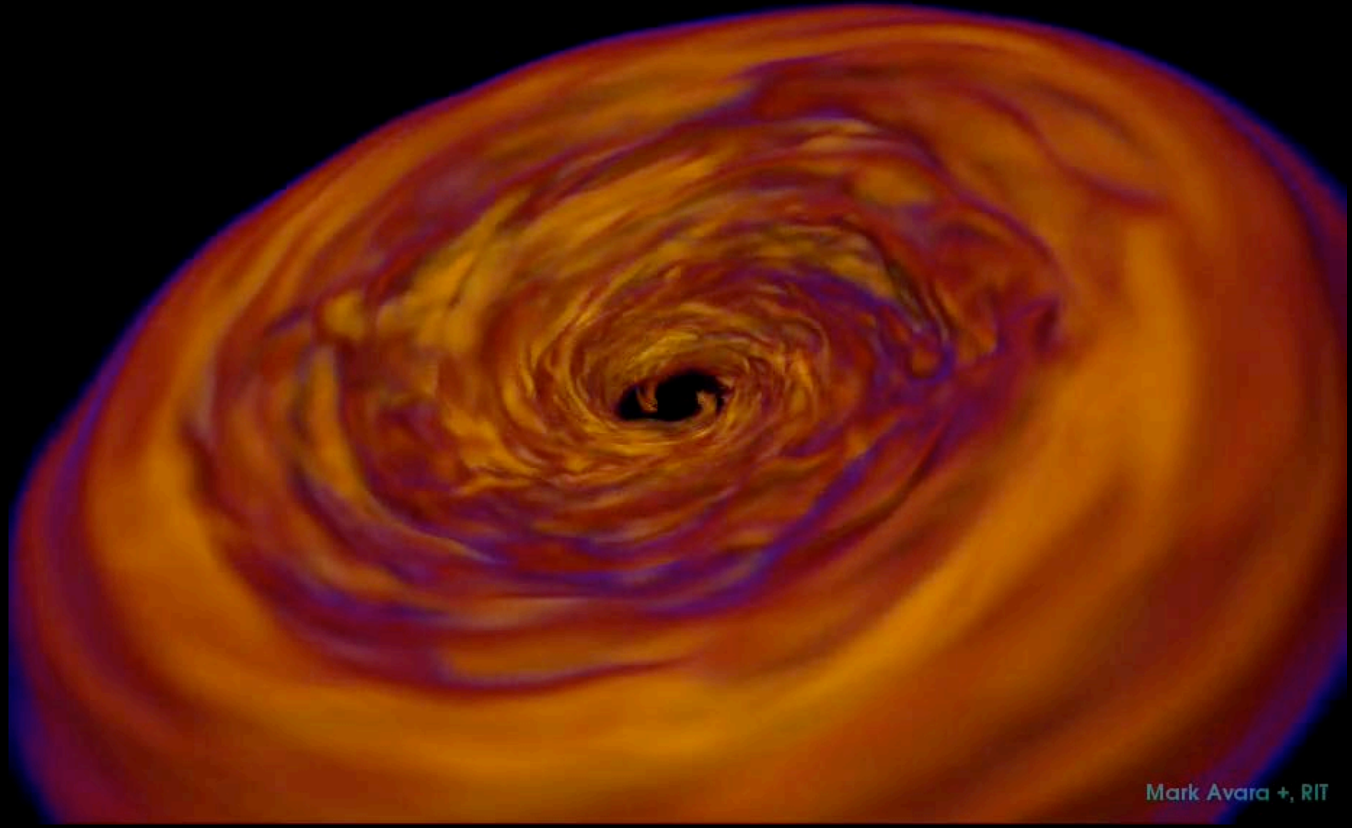
Noble +2012

This qualitative picture holds for nearly equal mass BHs (q >= 1/5), and is independent of disk size or magnetization – Noble+, in prep 2019

Do not see a lump for ~1:10 mass ratio!

Circumbinary Disk Dynamics

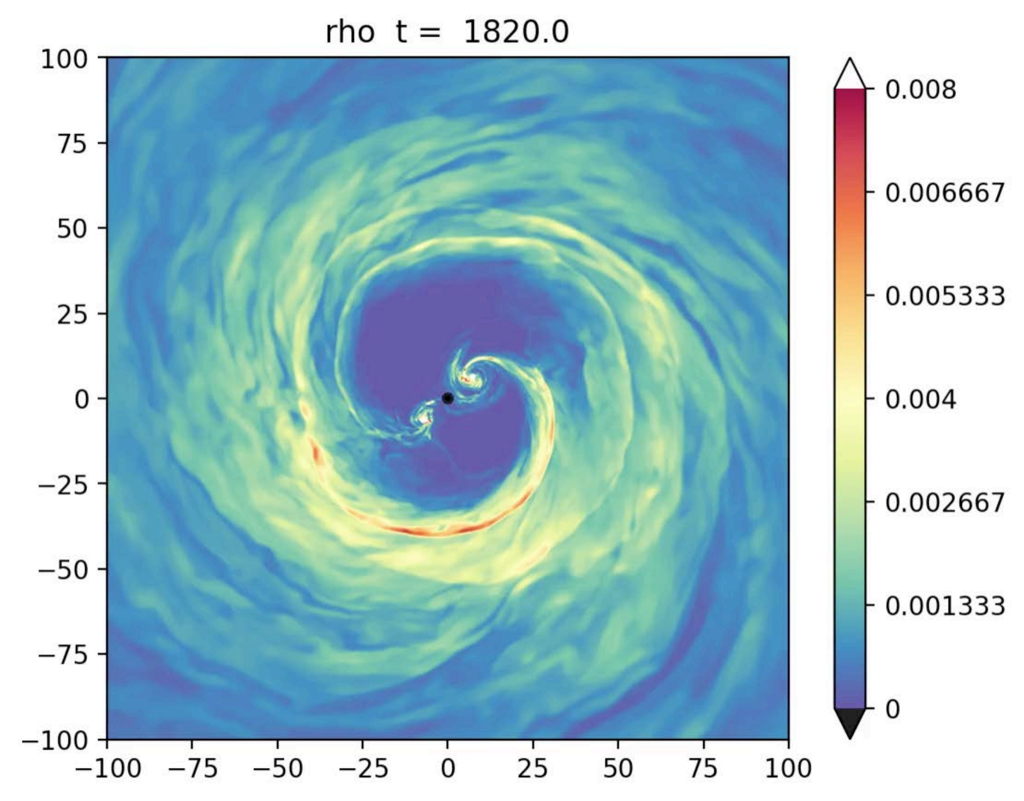
Long term MHD simulations
of a tilted cicumbinary disk (~12 deg)
initial BH sep=43r_g , final BH sep=8r_g
(BHs not on the grid) – Avara+2019 in prep

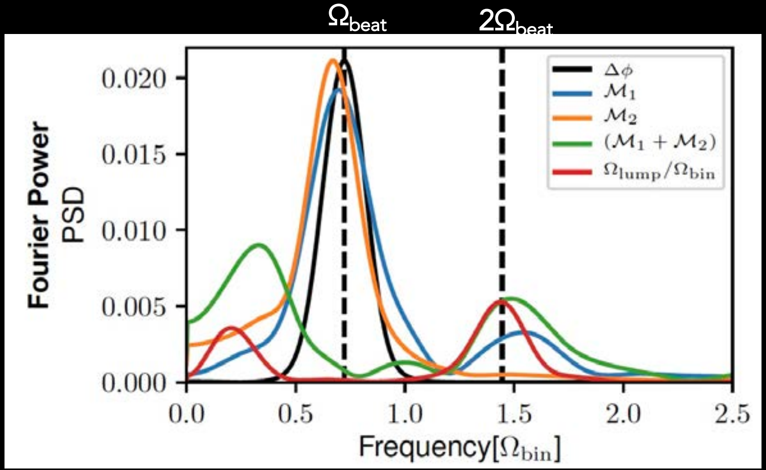


Dynamics in the Central Region

We discovered a 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

General Relativistic Radiative Transfer:

- **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

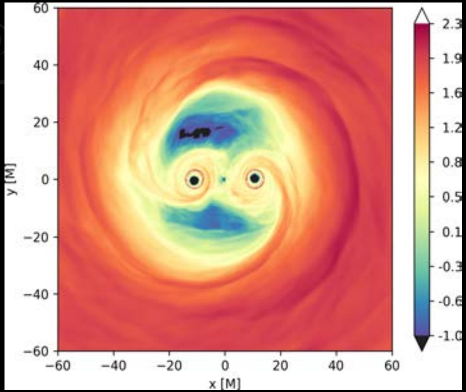
- **Above photosphere, corona emission** modeled as non-thermal (Compton scattering) component with temperature 100 keV:

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

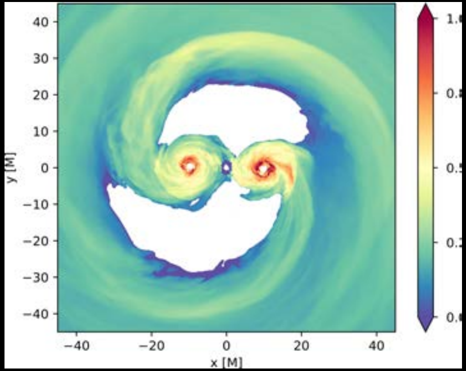
Trakhtenbrot++2017, Krolik 1999, Roedig++2014

- Emissivity ignored in low-density regions in which scattering processes are important (and unavailable to us for now);

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



Log10 Optical Depth
Grey Thomson Opacity



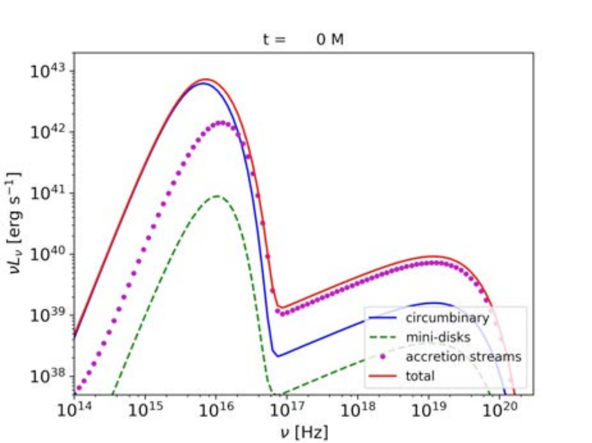
Map of Photosphere's Location & Temperature

$\mathrm{Log}_{10}(T_{\rm eff}/T_0)$, $T_0 = 5\mathrm{x}10^5$K

Looking for Distinct Light Signatures

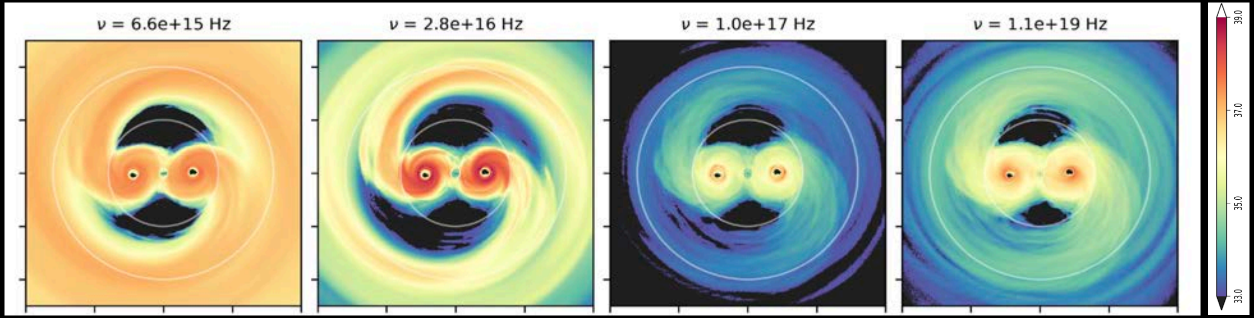
Face-on View,
Optically Thick Case
$M_{BH}=10^6 M_\odot$

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. e.g. Roedig+2014 – will likely be more visible at larger separations and for spinning black holes.



Circumbinary dominated UV

Mini-disk dominated soft X-rays

X-rays near the boundary between thermal and corona dominance

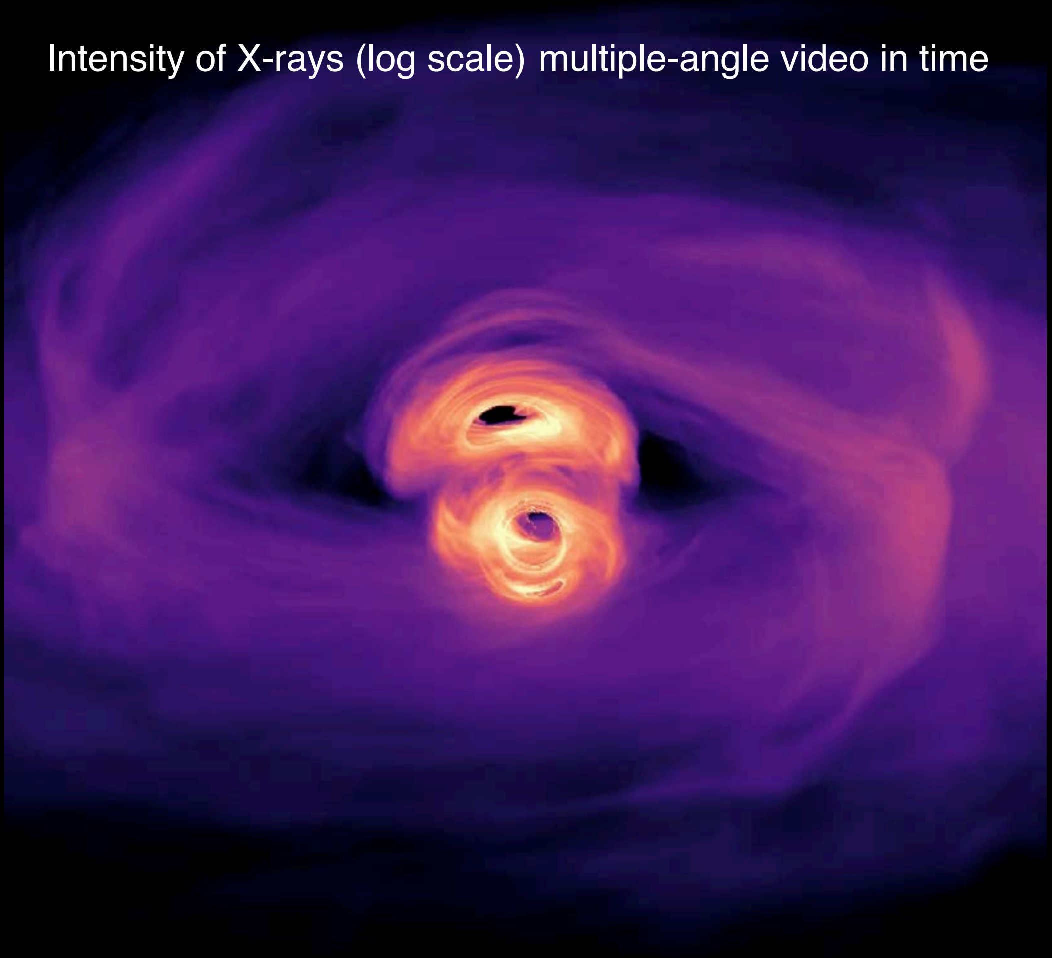
Mini-disk corona dominated hard X-rays

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

Optically Thick Case

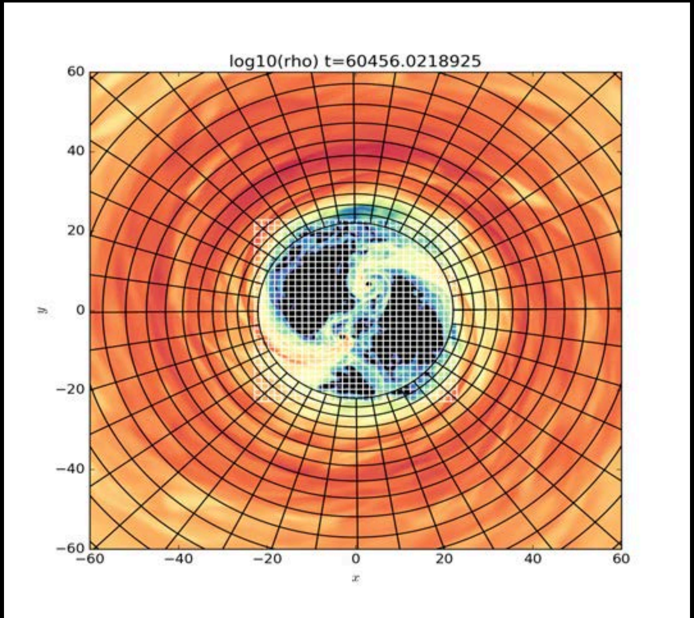
Intensity of X-rays (log scale) multiple-angle video in time



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

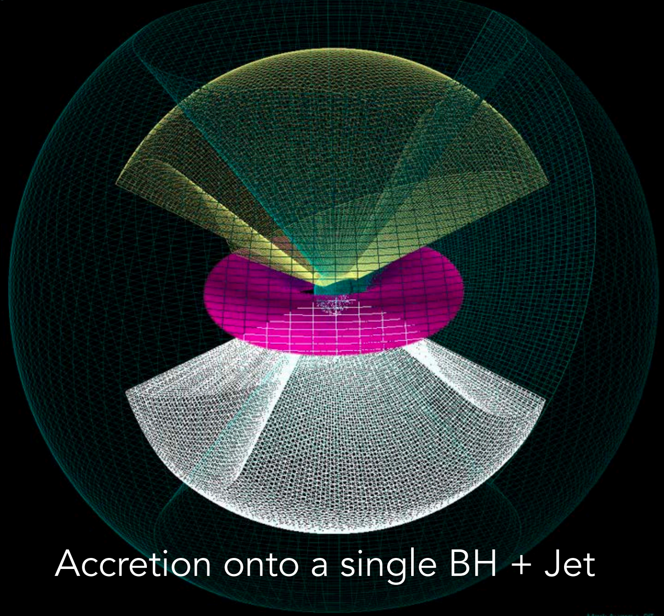
A new Multi-Physics, Multi-scale Infrastructure for Exascale Computing

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



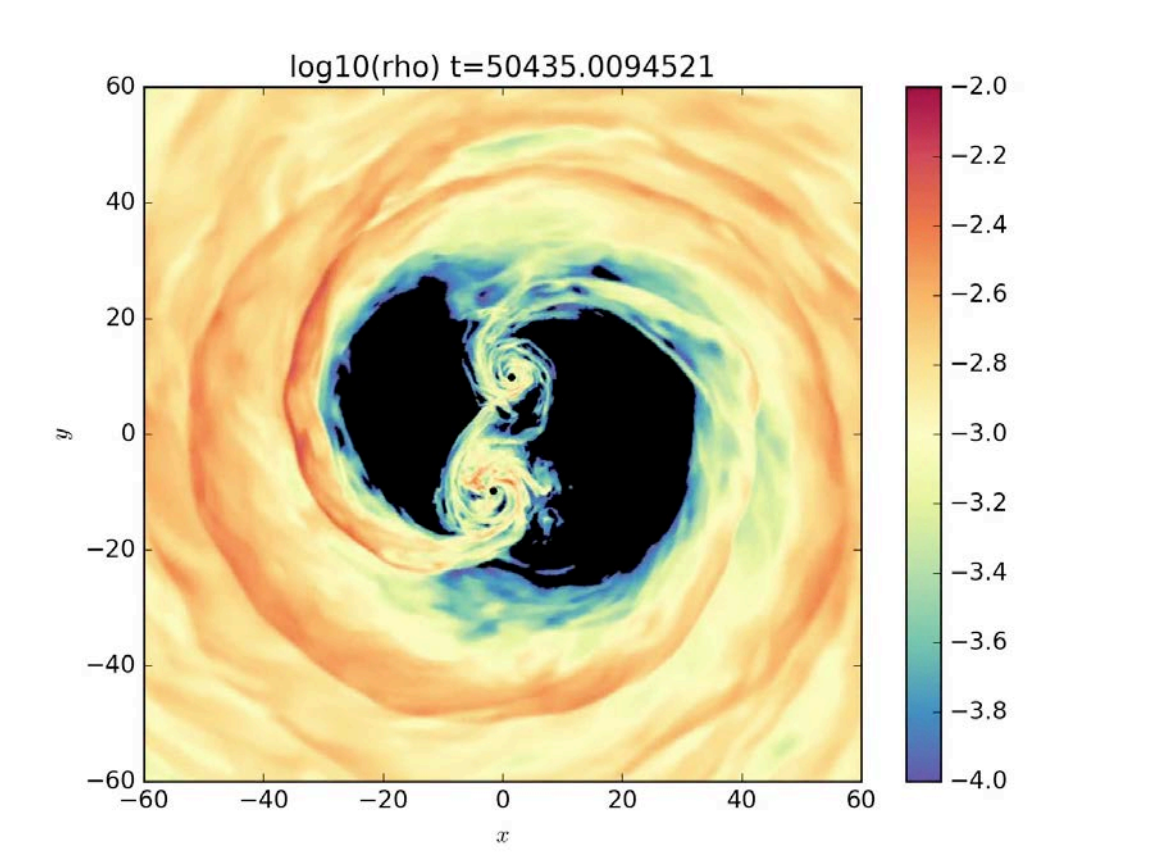
Accretion onto binary BHs

- **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

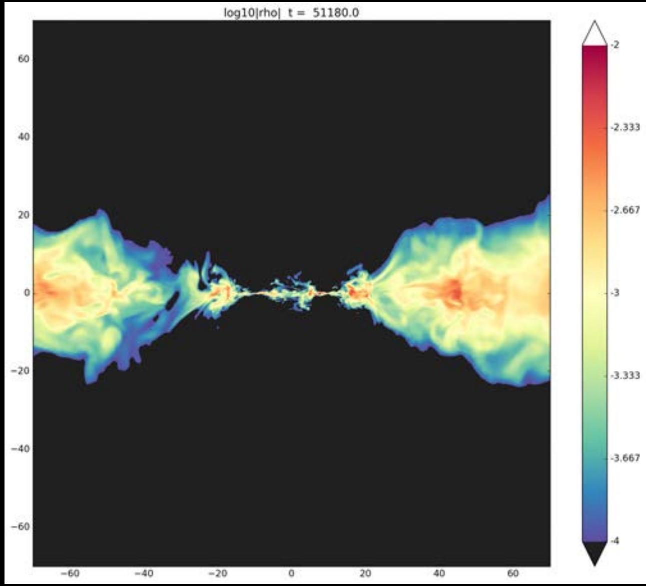
First Glimpse at the full Dynamics



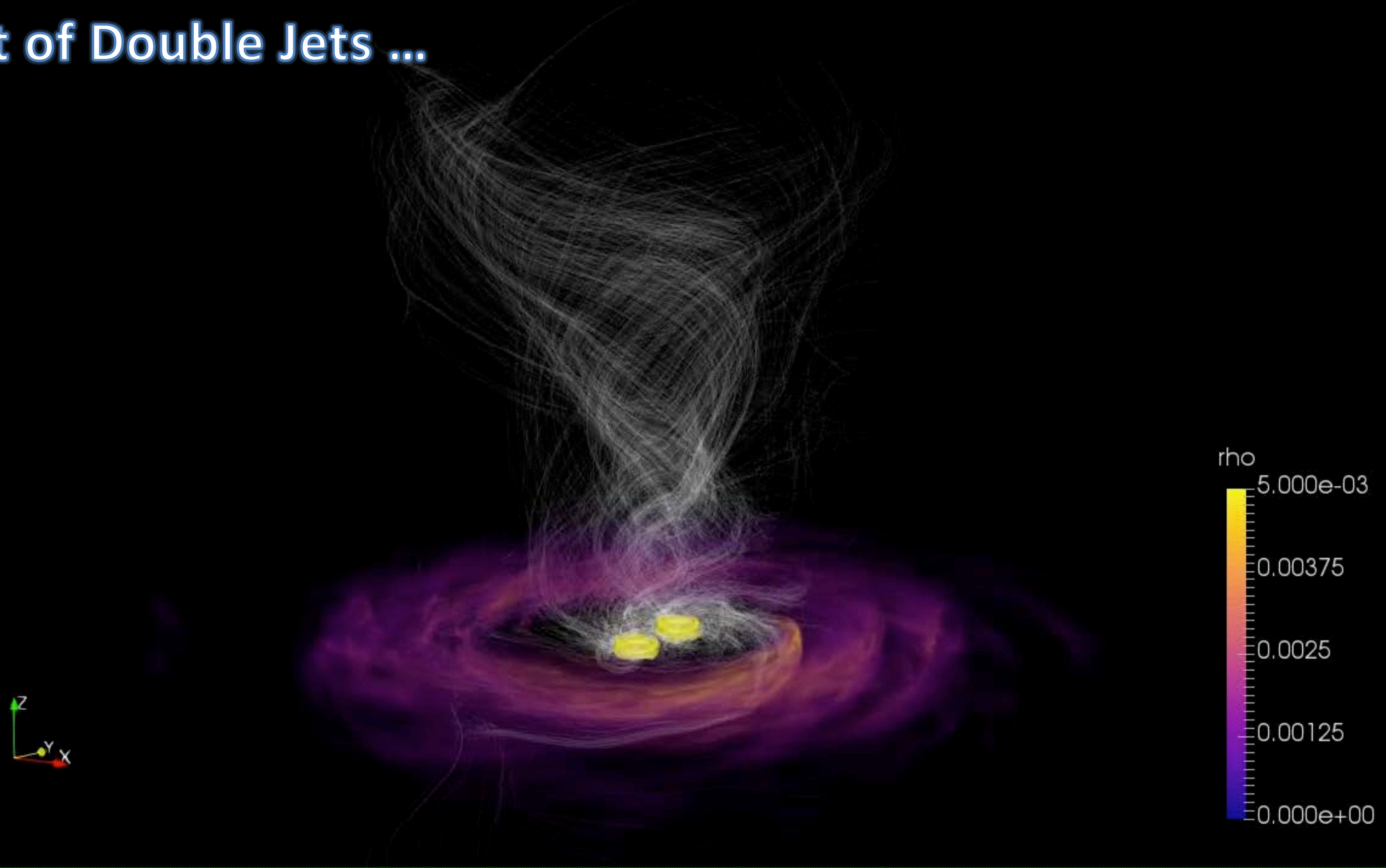
Avara+2019, in prep

Ongoing PatchworkMHD Simulation on Blue Water –

- First physical parameter studies of these systems in 3D GRMHD
- Now **30 times our prior efficiency**
- Sufficient time series data to calculate **light curve** (being analyzed now)



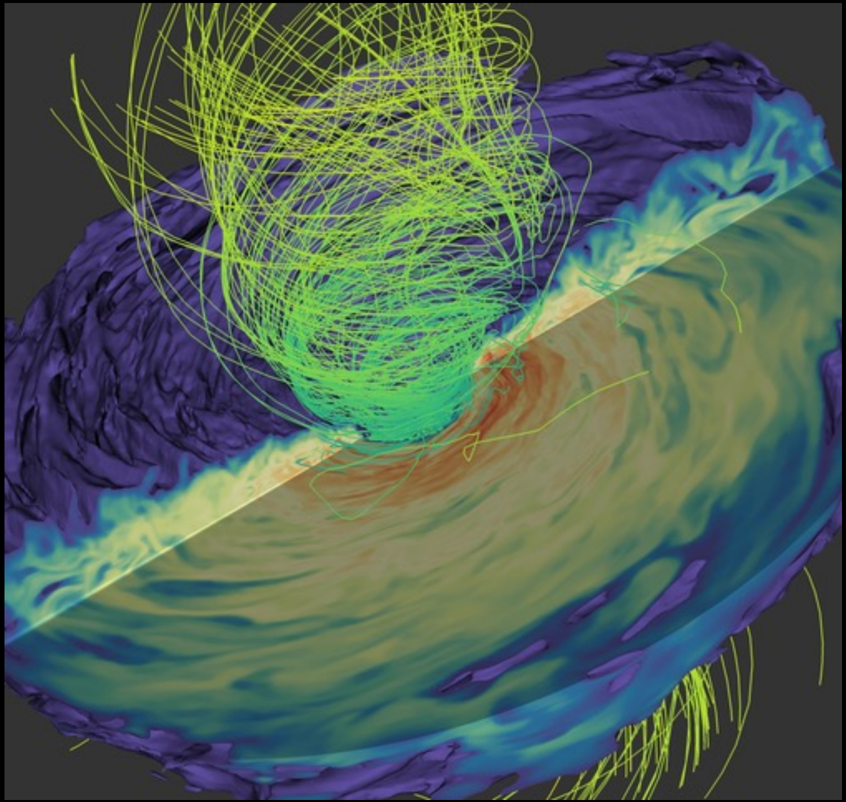
Hint of Double Jets …



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

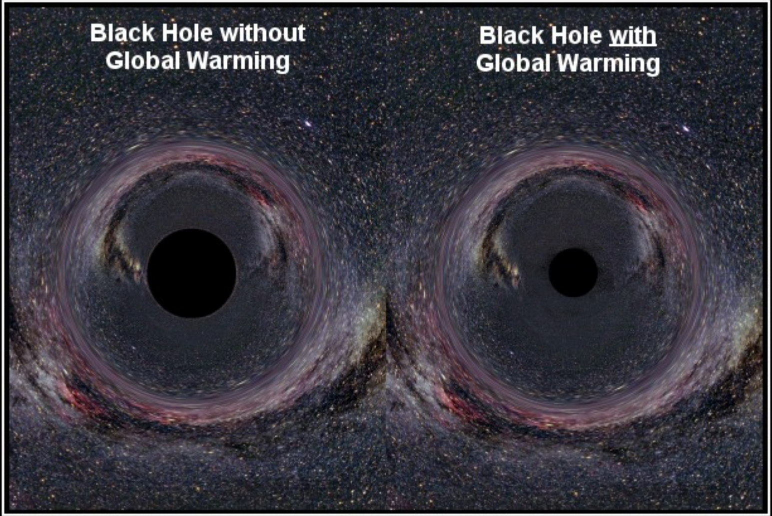
Summary

- First long-term, accurate, GR-MHD simulations involving accreting binary AGN/supermassive black holes in the GW inspiral stage.
- Contrarily, to what previously believed, we discovered a new dynamical interactions between the mini-disks and circumbinary disks of the flow.
- We produced the first electromagnetic spectrum from 3D simulations, essential for astronomical search campaigns and understanding systems to be discovered soon.
- New technical developments will add versatility to how we design our simulations and enable a real change in how we model relativistic astrophysical sources.
- Stay tuned for more soon!



Credits: Mewes+, RIT 2019

The SMBBH Crisis …



GLOBAL WARMING

A force so powerful, it stunts black holes

Takamitsu Tanaka - *The New Scientist, June 9 2012*

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 21 August 2018 (MN LaTeX style file v2.2)

X-ray emission from high-redshift miniquasars: self-regulating the population of massive black holes through global warming

Takamitsu Tanaka[1⋆], Rosalba Perna[2], and Zoltán Haiman[3]

[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany*

[2] *JILA and Department of Astrophysical and Planetary Science, University of Colorado at Boulder, 440 UCB, Boulder, CO, 80309, USA*

[3] *Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027, USA*

arXiv:1205.6467v2 [astro-ph.CO] 16 Jul 2012

21 August 2018

ABSTRACT

Observations of high-redshift quasars at $z \gtrsim 6$ imply that supermassive black holes (SMBHs) with masses $M \gtrsim 10^9$ $M_\odot$ were in place less than 1 Gyr after the Big Bang. If these SMBHs assembled from "seed" BHs left behind by the first stars, then they must have accreted gas at close to the Eddington limit during a large fraction ($\gtrsim 50\%$) of the time. A generic problem with this scenario, however, is that the mass density in $M \sim 10^6$ $M_\odot$ SMBHs at $z \sim 6$ already exceeds the locally observed SMBH mass density by several orders of magnitude; in order to avoid this overproduction, BH seed formation and growth must become significantly less efficient in less massive protogalaxies through some form of feedback, while proceeding unabated in the most massive galaxies that formed first. Using Monte-Carlo realizations of the merger and growth history of BHs, we show that X-rays from the earliest accreting BHs can provide such a feedback mechanism, on a global scale. Our calculations paint a self-consistent picture of *black-hole-made climate change*, in which the first miniquasars—among them the ancestors of the $z \sim 6$ quasar SMBHs—globally warm the intergalactic medium and suppress the formation and growth of subsequent generations of BHs. We present two specific models with global miniquasar feedback that provide excellent agreement with recent estimates of the $z = 6$ SMBH mass function. For each of these models, we estimate the rate of BH mergers at $z > 6$ that could be detected by the proposed gravitational-wave observatory *eLISA*/NGO.

Key words: black hole physics – cosmology: theory – galaxies: formation – quasars: general – gravitational waves

1 INTRODUCTION

The discovery of bright quasars at redshifts $z \gtrsim 6$ in the Sloan Digital Sky Survey (see the review by Fan 2006), the Canada-France High-z Quasar Survey (Willott et al. 2010a), and the current redshift record-holder at $z = 7.08$ in the UKIDSS (Mortlock et al. 2011) indicates that supermassive

onto a pre-existing smaller seed BH (e.g. Volonteri & Rees 2005), or by going through the interim state of a very massive star (e.g. Bond, Arnett & Carr 1984), a rapidly accreting massive "proto-star" (Begelman, Volonteri & Rees 2006; Hosokawa, Omukai & Yorke 2012) or a dense stellar cluster (Omukai, Schneider & Haiman 2008; Devecchi & Volonteri 2009). These models rely on