Merging black hole binaries: accretion dynamics and outflows

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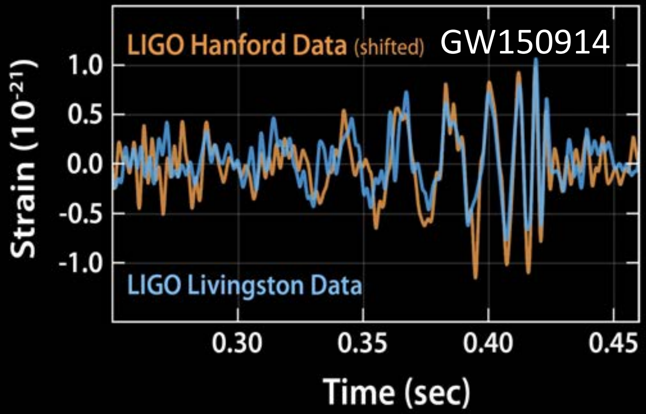
Computational Challenges in
Multi-Messenger Astrophysics

Institute for Pure and Applied Mathematics
(IPAM)

OCTOBER 4 - 8, 2021

Windows onto the Universe!

Recent gravitational-wave discoveries by LIGO …



… have opened an unprecedented observational window into binary black holes and neutron stars!

… as well as recent progress in X-ray, gamma ray and radio observations …

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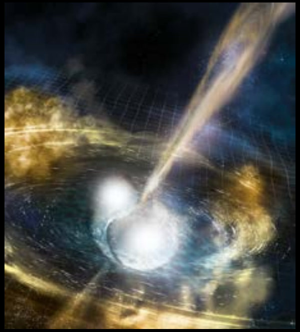


GW170817

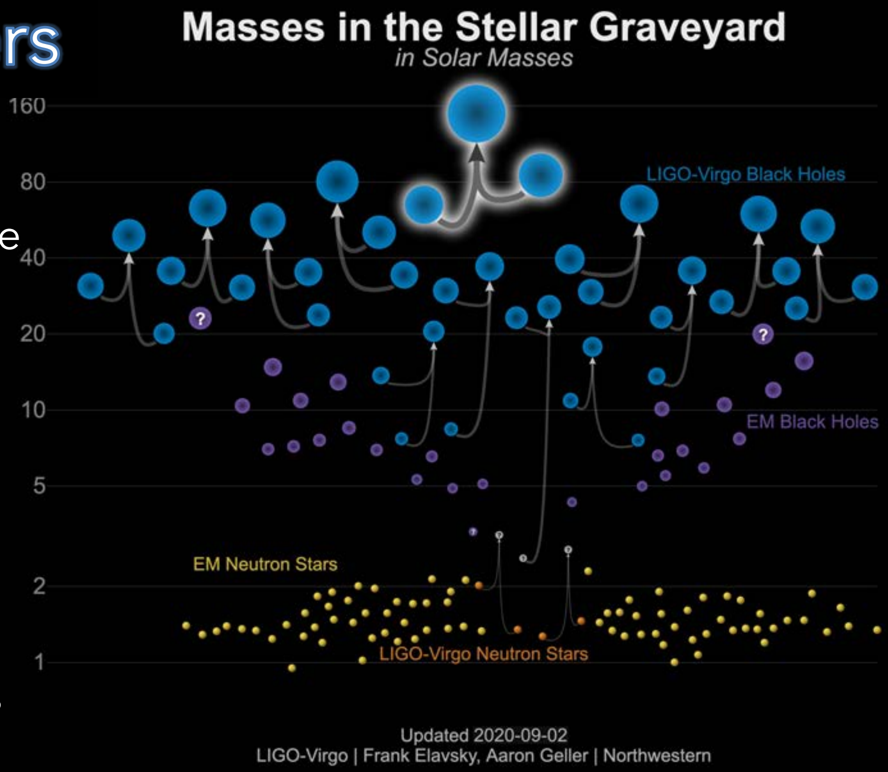
GRB 170817A

LIGO/Virgo BBH Mergers

Models and numerical relativity GW calculations are currently used to infer source parameters such as masses, effective spins, distance, etc.

They critical to our understanding of these sources:

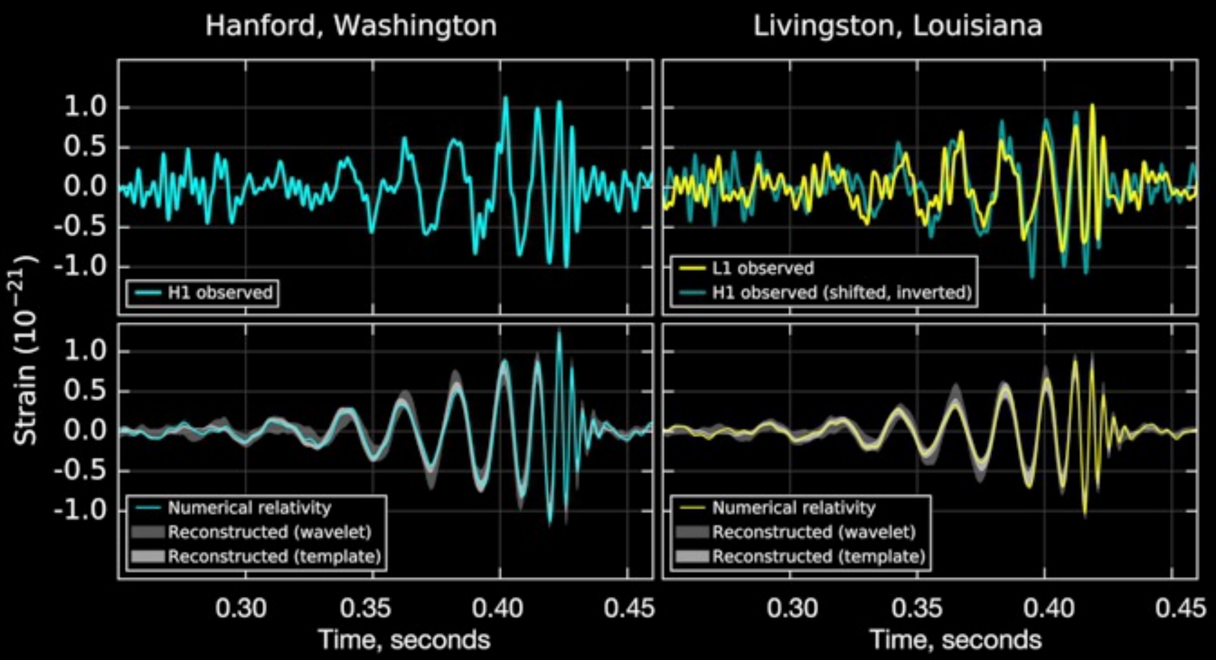
- What is their astrophysical origin, and environment?
- What are the stellar evolution processes leading to the formation of these sources?
- What is their population across the universe as a function of the redshift?



Multi-Spectrum GW observations 3G + LISA could distinguish **formation channels** - Vitale+2017, 2018++ Sesana, 2016, Breivik+2016, Rodriguez+2017 ...

The Predictive Role of Modeling and Simulations in LIGO Observations

The serendipitous GW150914



Abbott et al, Phys. Rev. Lett. **116**, 061102 (2016)

It took more than four decades for researchers to solve the BBH problem with numerical relativity. We did it in 2005!

Pretorius 2005, Campanelli+ 2006, Baker+2006

LIGO and Gravitational Waves, III: Nobel Lecture, December 8, 2017, Kip Thorne

See also IPAM Talk by Dr. Carlos Lousto

Multi-Messenger Sources

Compact object mergers in strong field gravity with matter, e.g. binary neutron star mergers and accreting black hole binaries, can produce powerful electromagnetic signals, high-energy particles, in addition to gravitational waves.

Current facilities give us only a glimpse on new potential MMA discoveries.
Several new major observational facilities are coming online soon!

Theory and computational astrophysics models are critical to interpret MMA observations.

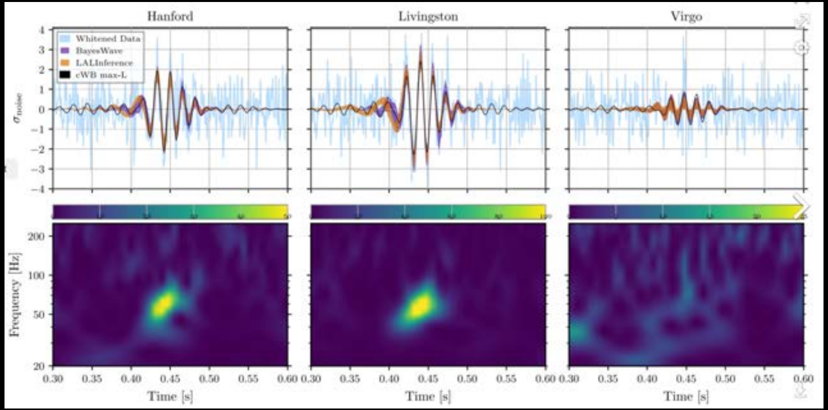
Could any of LIGO BBH mergers also be EM bright?

Mergers of stellar/intermediate BBH do not typically emit any detectable light, but there could be possible gas dragging in galactic nuclear disk – McKernan+2019

ZTF candidate S190521g* - Graham+2020

Recoiling BH moving at ~ 200 km/s through the accretion disk of an nearby SMBBH could disrupt the disk material and producing a flare of light.

Caveats: Super Eddington luminosity hard to explain … Also, there are many possible sources in 765 deg^2 area.



The GW event GW190521 observed by the LIGO Hanford (left), LIGO Livingston (middle), and Virgo

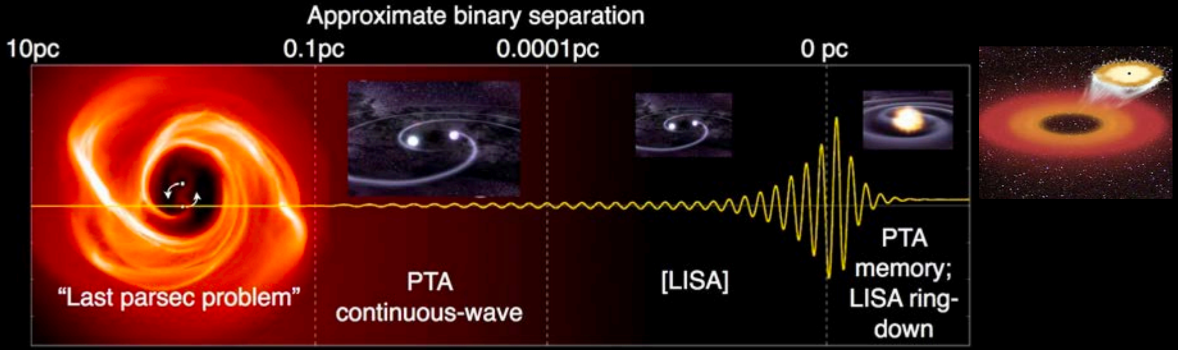
Using hundreds of NR simulations, we find that GW190521 is best explained by a high-eccentricity, precessing model with e~0.7, pointing to 2G cluster merger object Gayathri++, arXiv:2009.05461 leading to a 240km/s recoiling BH …

On the more massive end of the spectrum …

- 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!

- Stellar dynamical friction, torques from gas, or other processes can bring the pair to sub-pc scales, then GW should do the rest making these primary GW sources for **LISA** and **PTA**.

S. Burke-Spolaor +2018

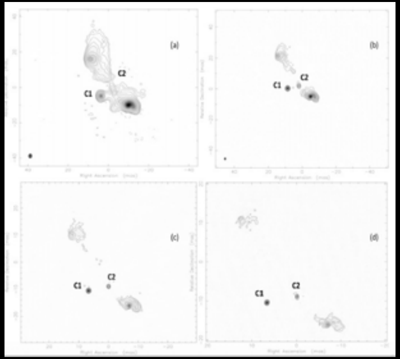


- up to ~10% of the total mass is radiated in GW energy – e.g Campanelli+2006
- BH remnant **is kicket out** from its host structure, depending on the BH spins and masses at merger – e.g Campanelli+2007 …

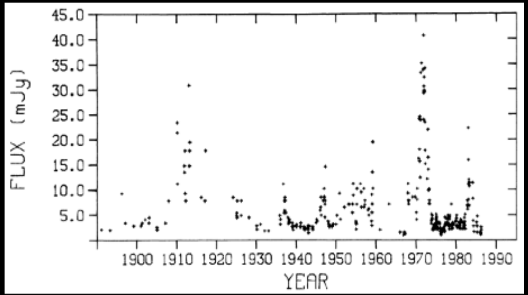
As MMA sources, they **are also important cosmological "standard candles" and** ideal laboratories for exploring plasma physics in the strongest and most dynamical regime of gravity.

So far, a handful of sub-pc EM candidates ...

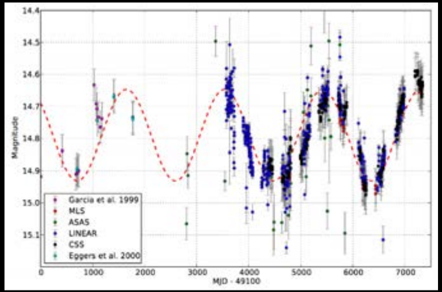
Identification of sub-pc SMBHBs has been challenging, but new sources will be uncovered through continued long term monitoring and new surveys and observatories:



Direct Imaging of double nuclei Radio galaxy 0402+379 - Bansal+2017, 12 years of multi-frequency VLBI observations, $P_{orb} \sim 10^2$

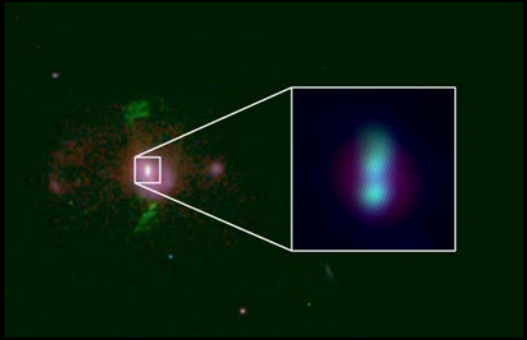


Periodic flares; OJ287 (Valtonen et al. 1988)



Sinusoidal light curves: PG1302-102 (Graham et al. 2015)

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



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

Population estimates of **EM-distinguishable binary-AGN** from galaxy evolution models find $\sim 10^2$ sources at redshifts z~0.5-1 - Krolik, Volonteri, Dubois, and Devriendt, 2019

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

Supermassive Black Hole Binaries

What are the electromagnetic signals associated with these mergers?

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

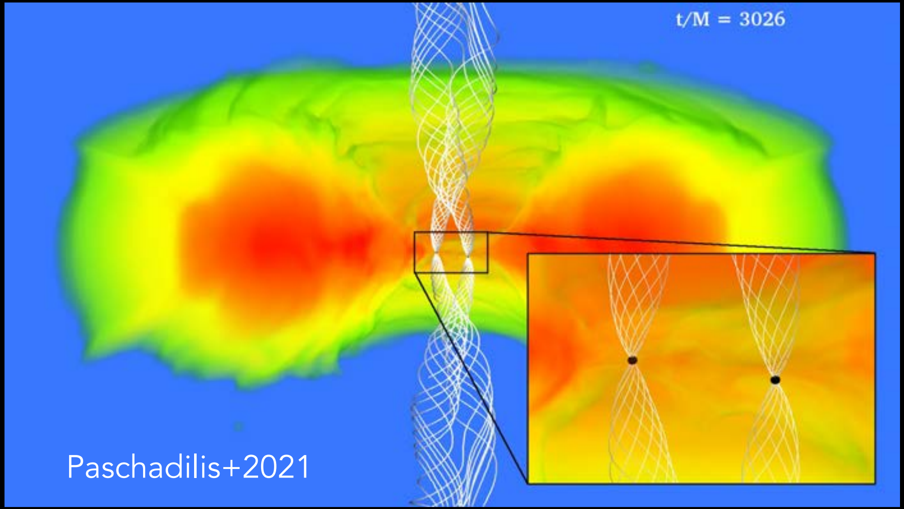
- Huge dynamical scales starting from astrophysically motivated disk models …
- Must resolve the scale MRI/turbulence for proper angular momentum transport in the gas.
- Need realistic thermodynamics, plasma physics and radiation transport.
- Must account that the spacetime is dynamically changing according to Einstein's equations of general relativity, and must also resolve the physics close to the black hole 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.

- Modern 2D hydrodynamics and 3D MHD simulations **find that binary torque "dam" does not hold, and accretion continues until approach to merge!** Shi+2012, Noble+2012, D'Orazio+ 2013; Farris +2014; Ryan+2016, Tang+2018; Bowen+2017,2019.

- Merger simulations in full numerical relativity hint at interesting dynamics, but are either too short or do not start from astrophysical initial conditions …
  e.g.Bode+2010; Farris+2010, Farris+2011, Giacomazzo+2012; Gold+ 2013; Paschadilis+2021, Cattorini+2021.



Full 3d GR-MHD in Inspiral Regime

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

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

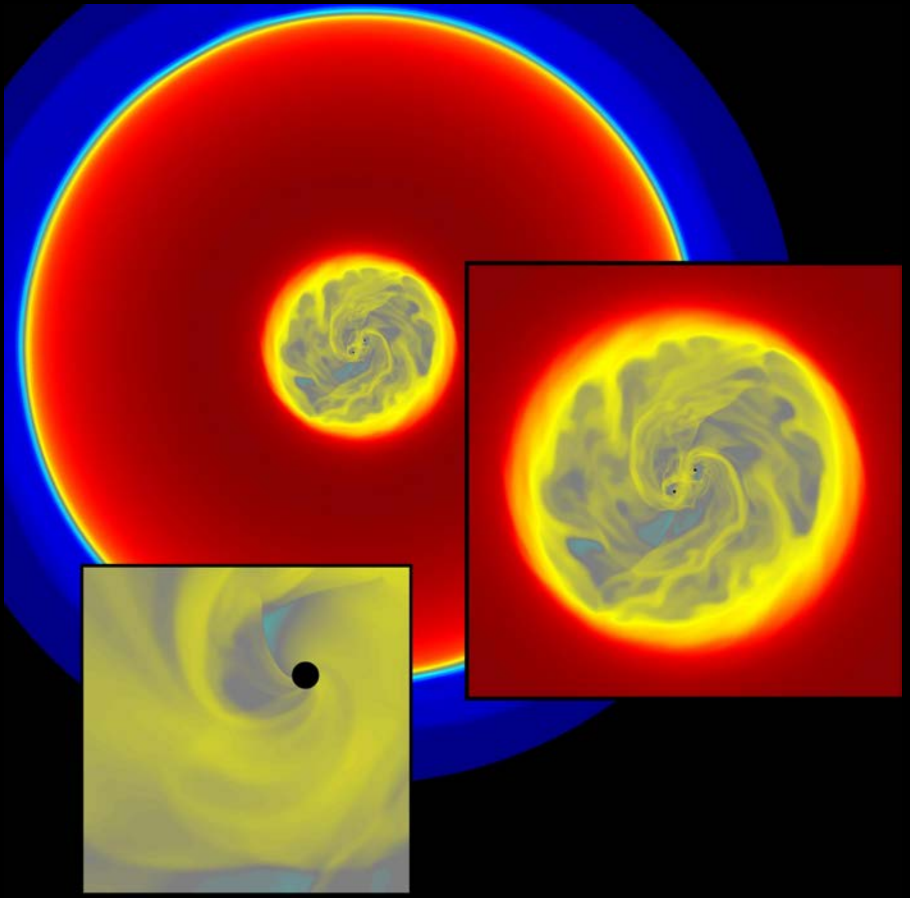
$$T_{\mu\nu} = \left(\rho + u + p + 2p_m\right) u_\mu u_\nu + \left(p + p_m\right) g_{\mu\nu} - b_\mu b_\nu$$

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

Modified to handle generic dynamical BH binary systems in the relativistic GW inspiral regime (use 3.5PN trajectories) – Noble+2012, Mundim+2014, Ireland+2014, Nakano 2014+, Lopez-Armengol+ in prep, 2020, Combi+ in prep 2020.

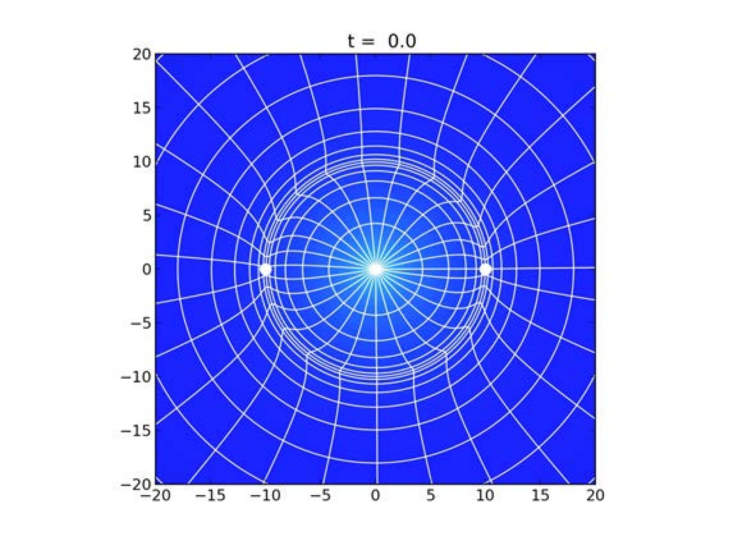


GR-MHD in Dynamical Gravity

Modified to handle generic dynamical BH binary systems in the relativistic GW inspiral regime (use 3.5PN trajectories) – Noble+2012, Mundim+2014, Ireland+2014, Nakano 2014+, Lopez-Armengol+ in prep, 2020, Combi+ in prep 2020.

- Binary BH spacetime valid for any mass ratio, BH spins (and eccentricity) at a given initial separation.
- BHs inspiral via the 3.5 Post-Newtonian equations of motion.

Simulations quickly unaffordable without a clever choice of the grid, especially in the central cavity, near each BHs



Warped curvilinear grids – Zilhão+2014

Novel Multipatch Scheme (later)

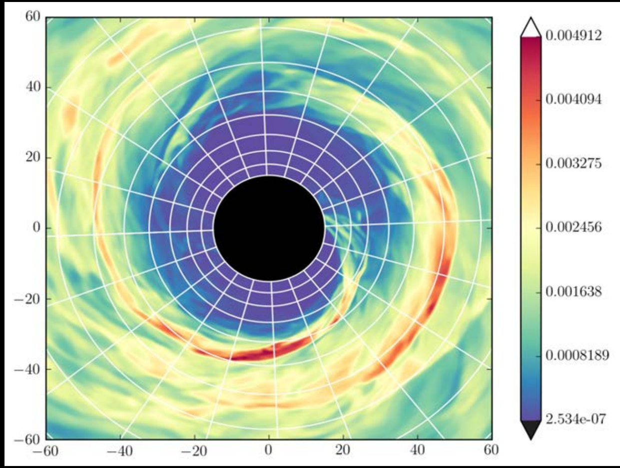
Computational strategies:

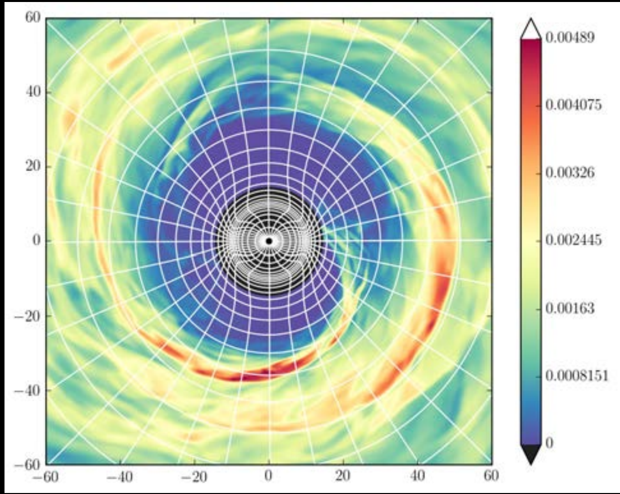
Evolve accreting inspiraling BH binaries while **resolving the MRI and MHD dynamics** at the scale of the event horizons:

1. Perform a long-term GRMHD simulation with a excised central spherical cutout containing the BHs in order to afford longer evolutions so we achieve statistically steady circumbinary disks.

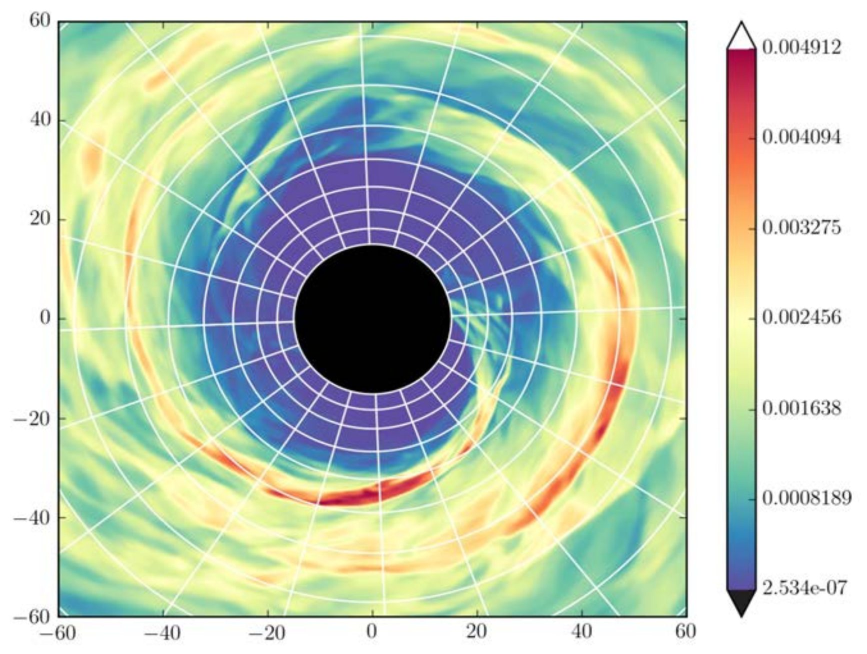
2. At "equilibration", interpolate the computational domain into a new grid designed to resolve the physics near each BH.

Each run requires approx. 10^7 cells, 10^7 time steps, 10^7 integer-core-hours e.g. 20,000 cores!





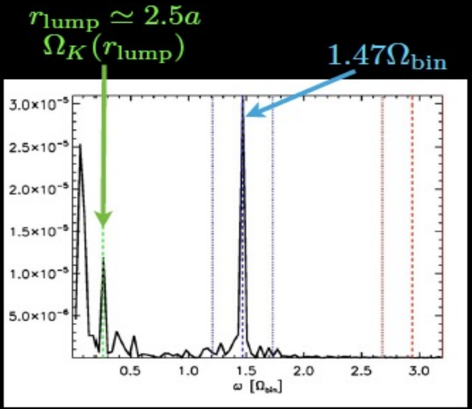
Circumbinary disk dynamics in the GW inspiral regime



circuminary disk simulations (equal-mass)
(BHs not on the grid, sep=20M)

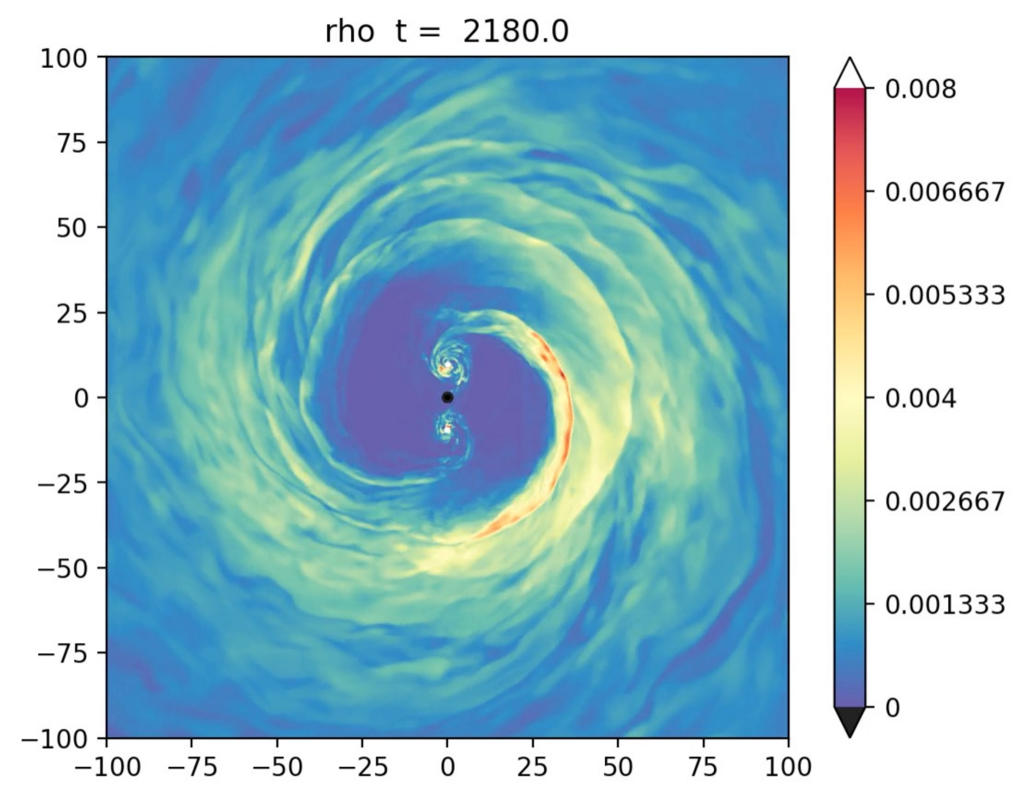
Noble, Mundim, Krolik, Campanelli + ApJ 2012

We found dense **accretion streams** to the BHs, and **overdensity** or "lump" leading to a characteristic periodicity $\Omega_{beat} = \Omega_{bin} - \Omega_{lump}$ – Noble+2012, also see in Shi+2012



The lump's qualitative picture holds for nearly equal mass BHs and is independent of disk size, but depends on mass-ratio and magnetization – Noble+, ApJ 2021

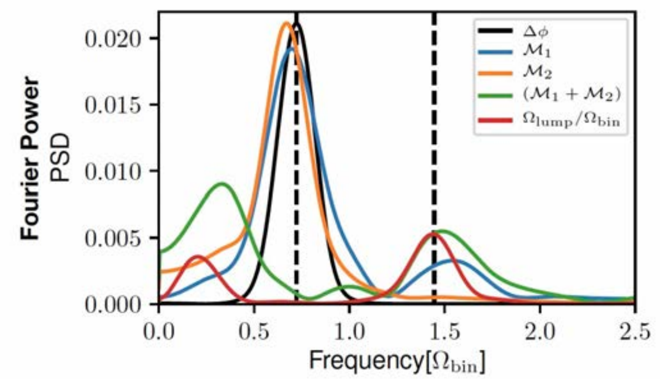
Mass Exchange between the BHs



We discovered new dynamical interactions between the black minidisks and circumbinary disk – Noble+2012, Bowen+2018, 2019

Accreting streams fall in the cavity and shock against the individual minidisks.

Mini-disks deplete and refill periodically at time scale close to one orbital period.



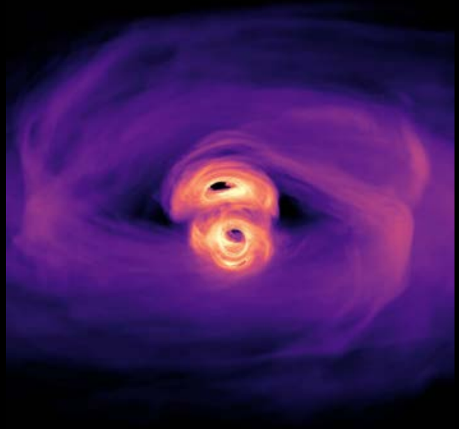
BLUE WATERS
SUSTAINED PETASCALE COMPUTING
ILLINOIS
NCSA | National Center for Supercomputing Applications

Credits: Bowen (RIT/LANL) 2019

First calculations of light signals

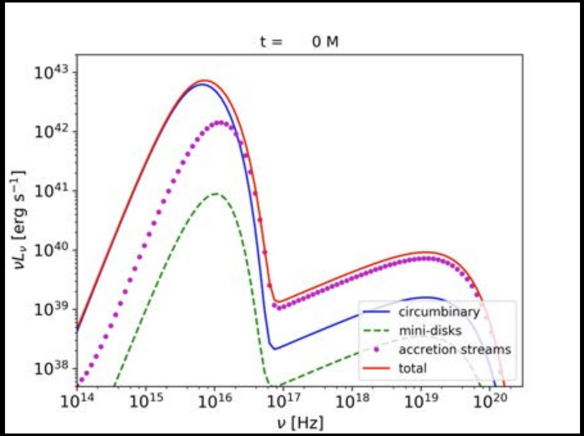
- The first predicted time varying spectrum from accreting binary black holes approaching merger – D'Ascoli+2018 with data from Bowen+2019

- We found that the minidisks around each of the black holes are the hottest features emitting bright X-rays relative to UV/EUV



Intensity of X-rays (log scale) multiple-angle video in time, optically thin case

videos Scott Noble (GSFC)



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

Bothros - general relativistic ray-tracing code for transporting radiation emitted from 3d GR-MHD simulation snapshots - Noble+2009

Camera-to-source approach

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\lambda}\frac{dx^\beta}{d\lambda} = 0$$

Geodesic equation

$$\frac{\partial I}{\partial \lambda} = j - \alpha I$$

Radiative transport equation

High-accretion rate systems **(Opt. thick)**

$$\dot{M} = 0.5\dot{M}_{\rm Edd}$$

Low-accretion rate systems **(Opt. thin)**

$$\dot{M} = 8\times 10^{-4}\dot{M}_{\rm Edd}$$

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

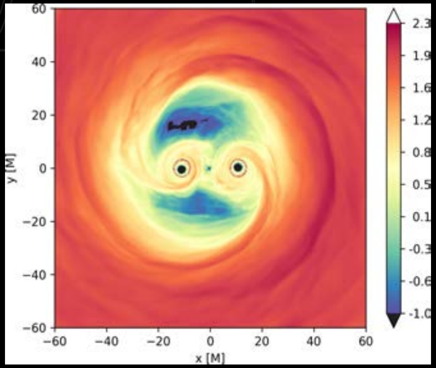
- **Above photosphere, corona emission** modeled as non-thermal (Compton scattering) component with temperature 100 keV:

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

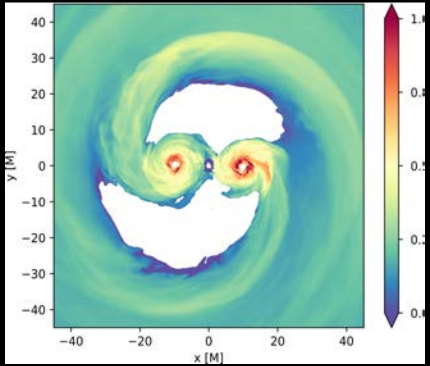
Trakhtenbrot++2017, Krolik 1999, Roedig++2014

- 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



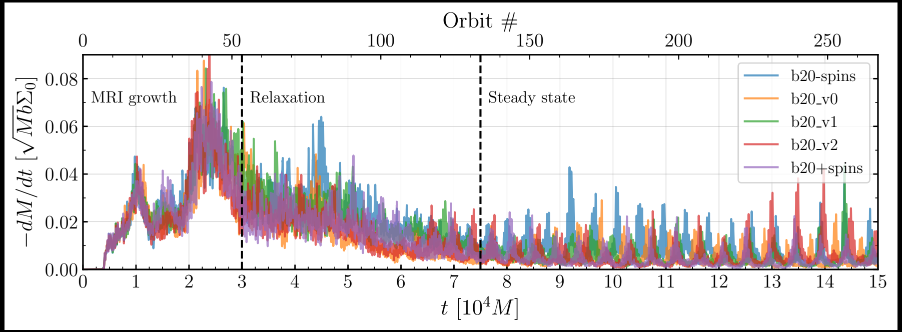
Map of Photosphere's Location & Temperature

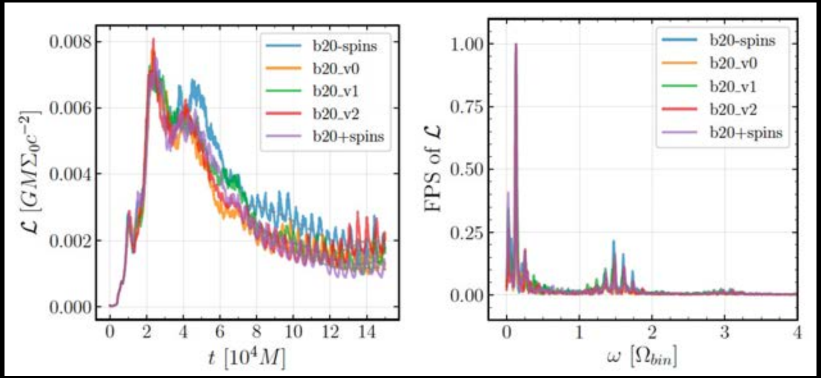
$\mathrm{Log}_{10}(T_{\rm eff}/T_0)$, $T_0 = 5\times10^5$K

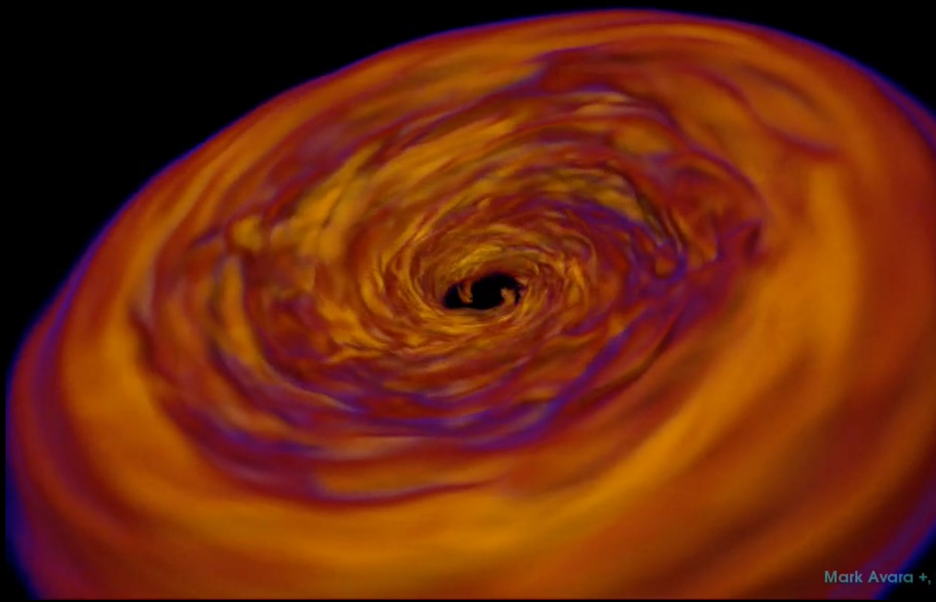
Circumbinary Disk Dynamics in Spinning Black hole Binaries

It takes time to equilibrate the disk in the region near the cavity (hundreds of orbits) – Noble+, ApJ 2012

Integrated luminosity in the circumbinary disk enhanced when spins are anti-aligned due to relativistic gravity - Lopez-Armengol+, ApJ 2021

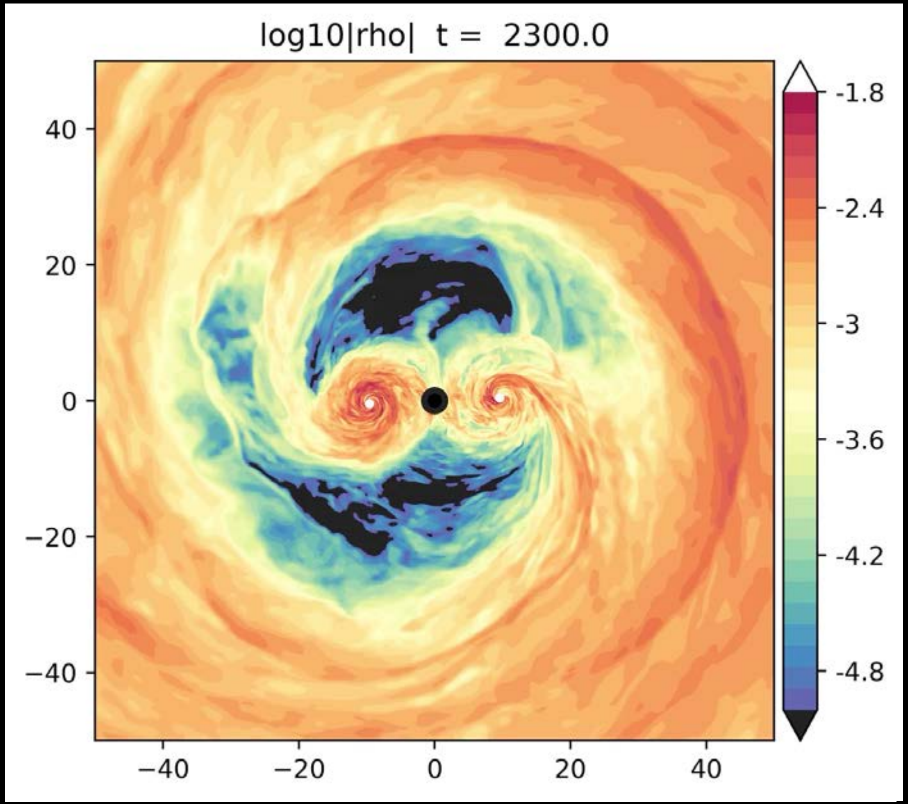






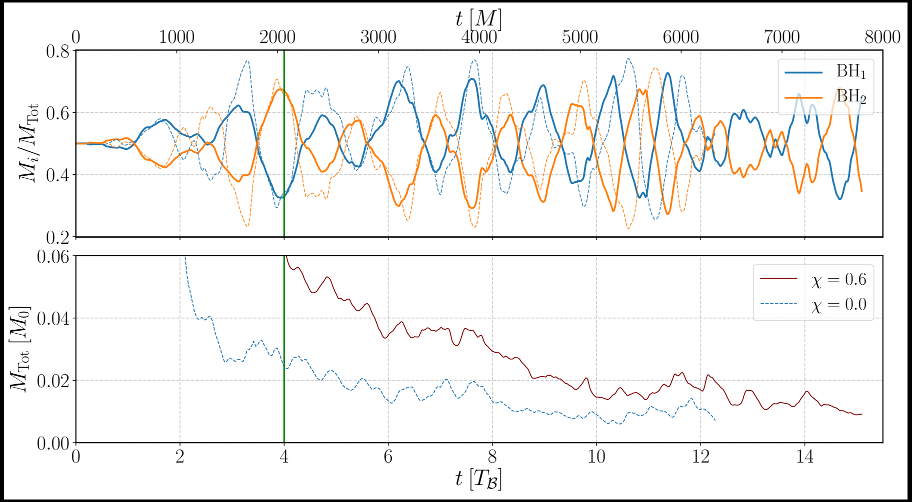
Video Credits: Mark Avara + RIT

On the effect of the BH spins …



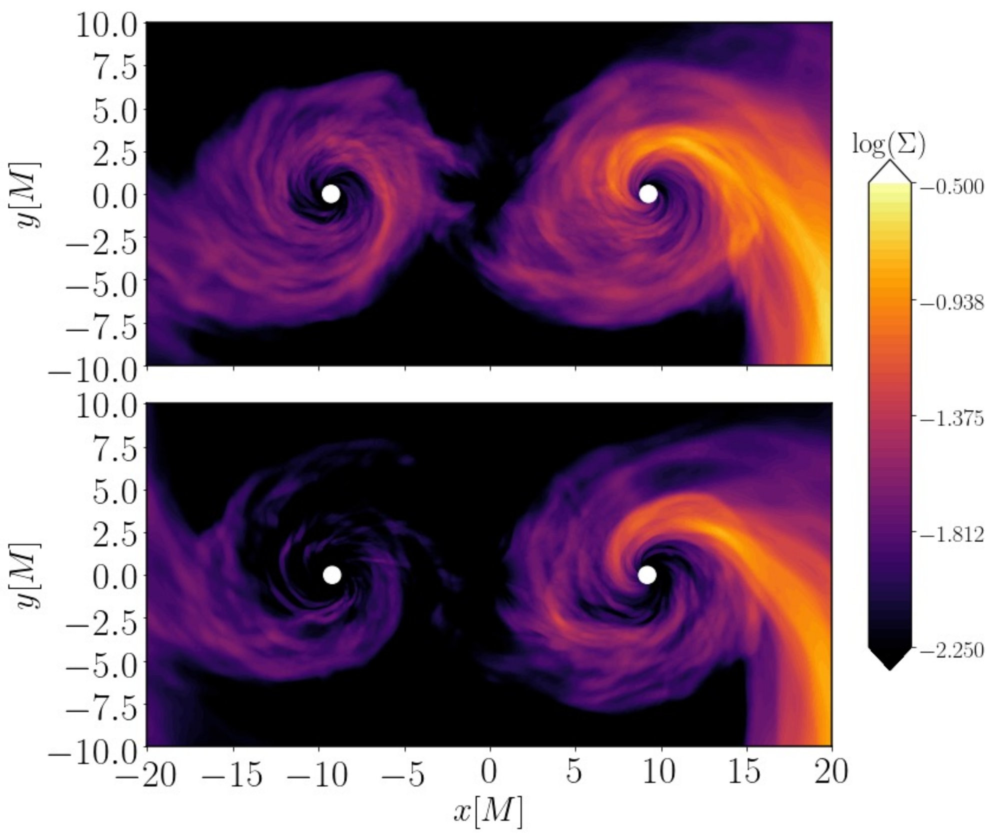
Credits: Luciano Combi (RIT/IAR)

Mini-disks deplete and refill periodically at time scale close to one orbital period, exchanging more mass than in the non-spinning case when the spins are aligned with the orbital angular momentum.



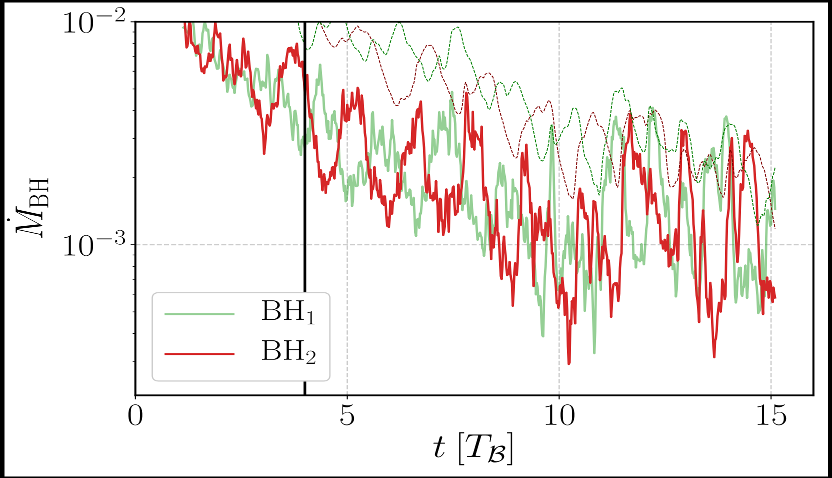
Combi+ 2021, arXiv:2109.01307

On the effect of the BH spins …



Formation of massive and circular minidisks structures with material piling up close to black holes – Combi+, 2021; arXiv:2109.01307

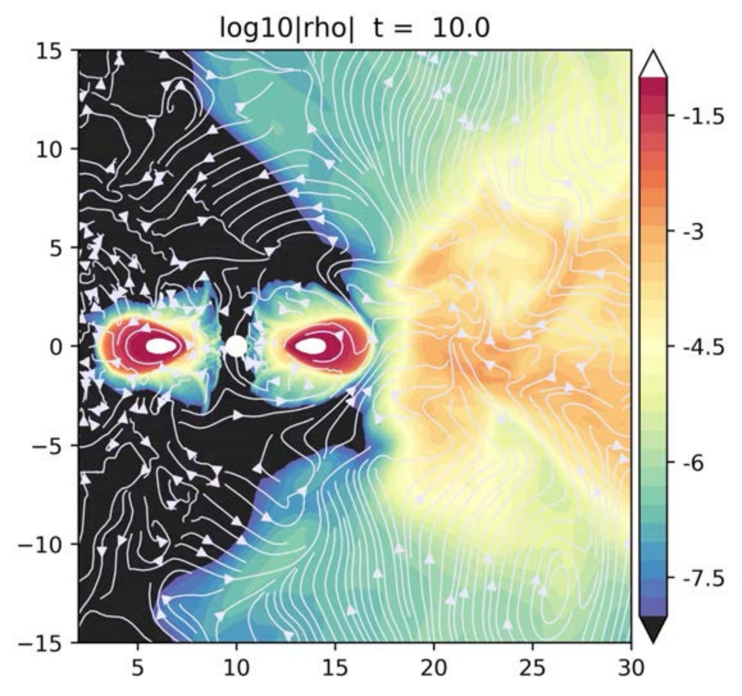
Accretion rate follow filling and refilling of the minidiscs …

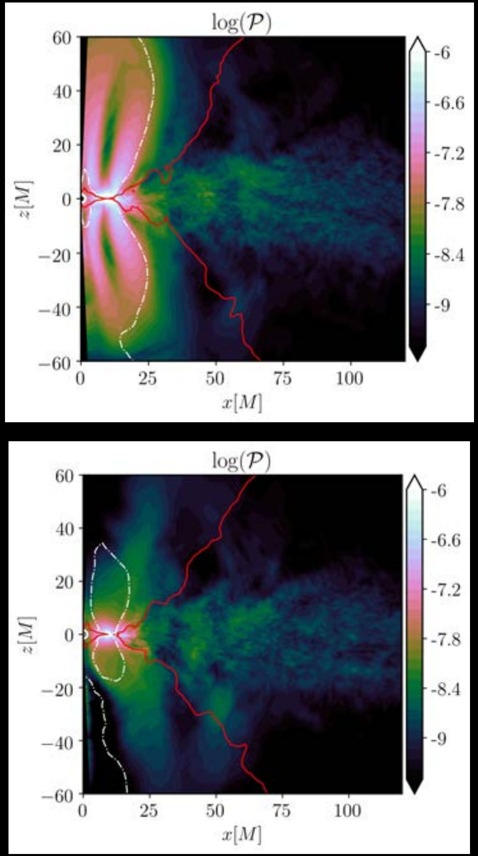


Credits: Luciano Combi (RIT/IAR)

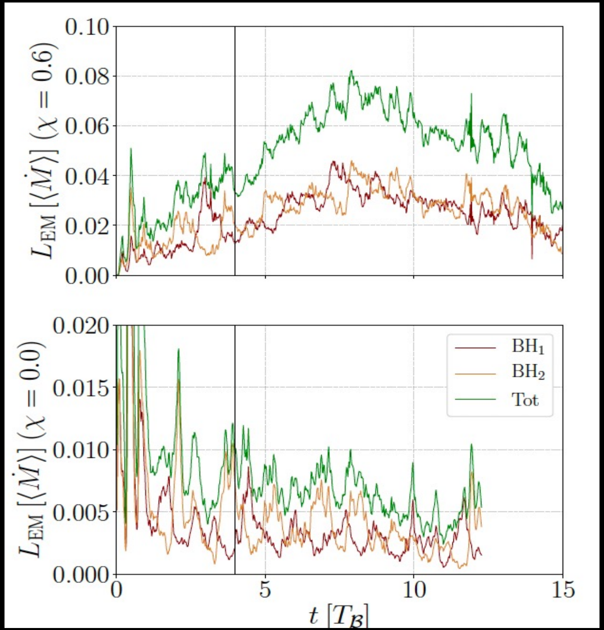
BH Spins and Jets!

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





Jet power modulated with the same periodic behavior that the filling/depletion cycle!



Combi+ 202; arXiv:2109.01307

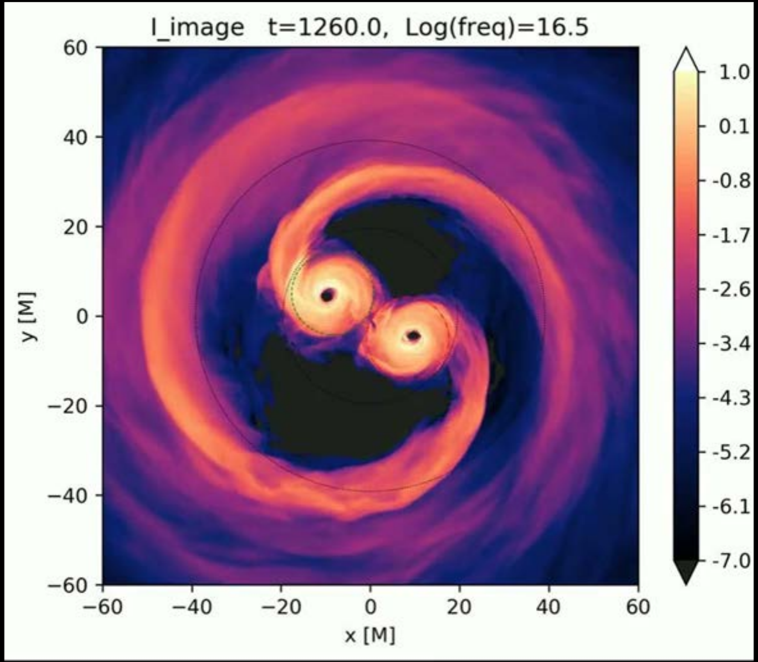
Outfows are nearly 10 times stronger than the non-spinning case!

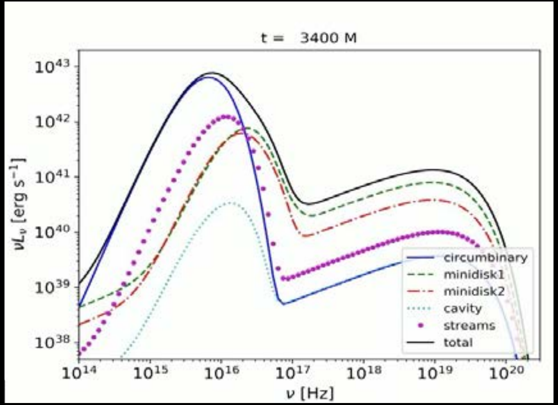
Imaging Accreting Spinning Black Holes

Gutierrez+ in prep 2021, based on spinning BBH (a=0.6) data from Combi+ 2021

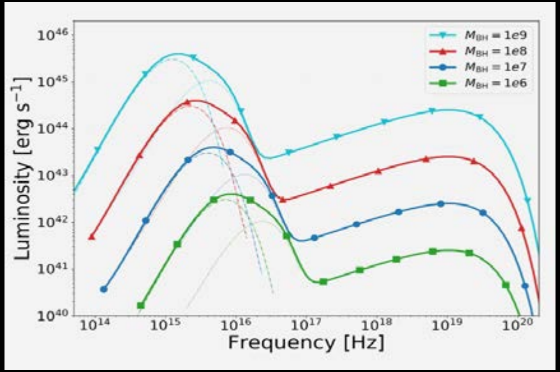
Using Bothros, Optically thick scenarios:

Blackbody emission from the photosphere, and Inverse Compton emission from the corona.





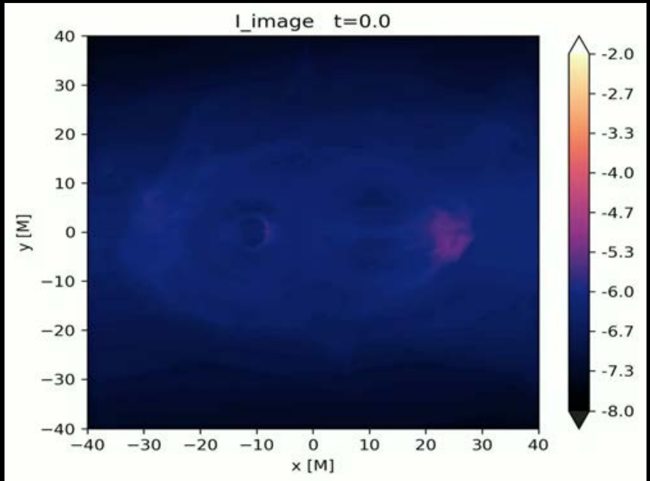
Spectra time variability, different components at different frequencies (top), different masses (bottom).

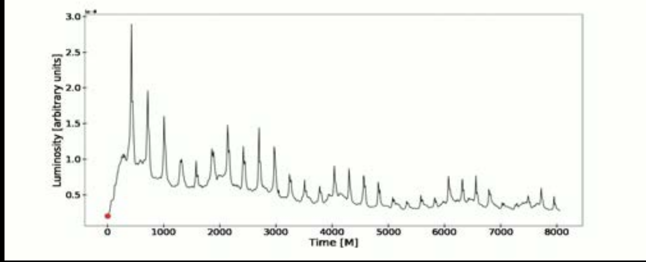


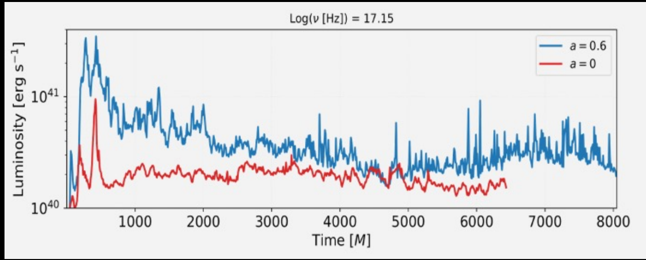
Light Curves from Accreting Spinning Black Holes

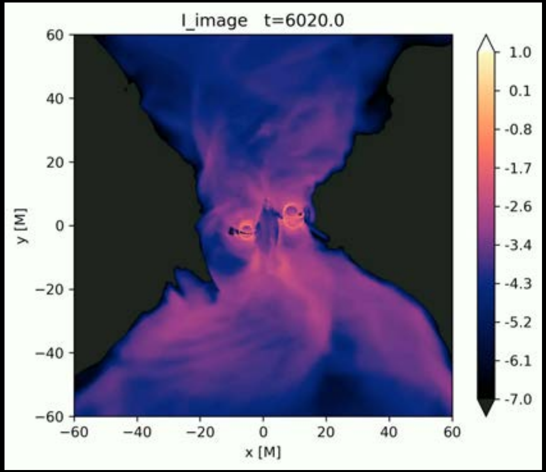
Gutierrez+ in prep 2021

Optically thin Case:
Inverse Compton emission from the hot plasma (hard X-rays) and Synchrotron emission (sub-mm) from the jets.

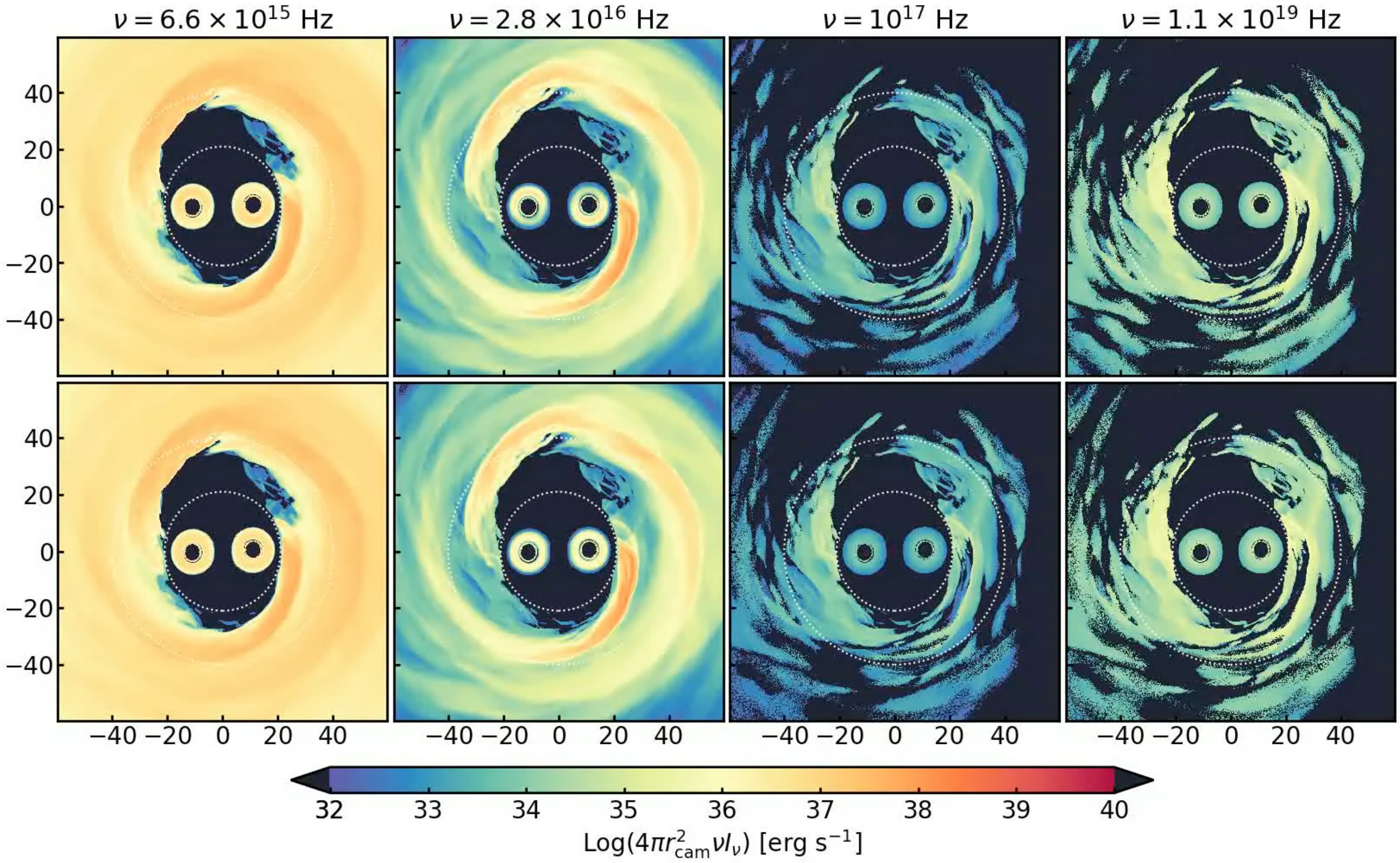








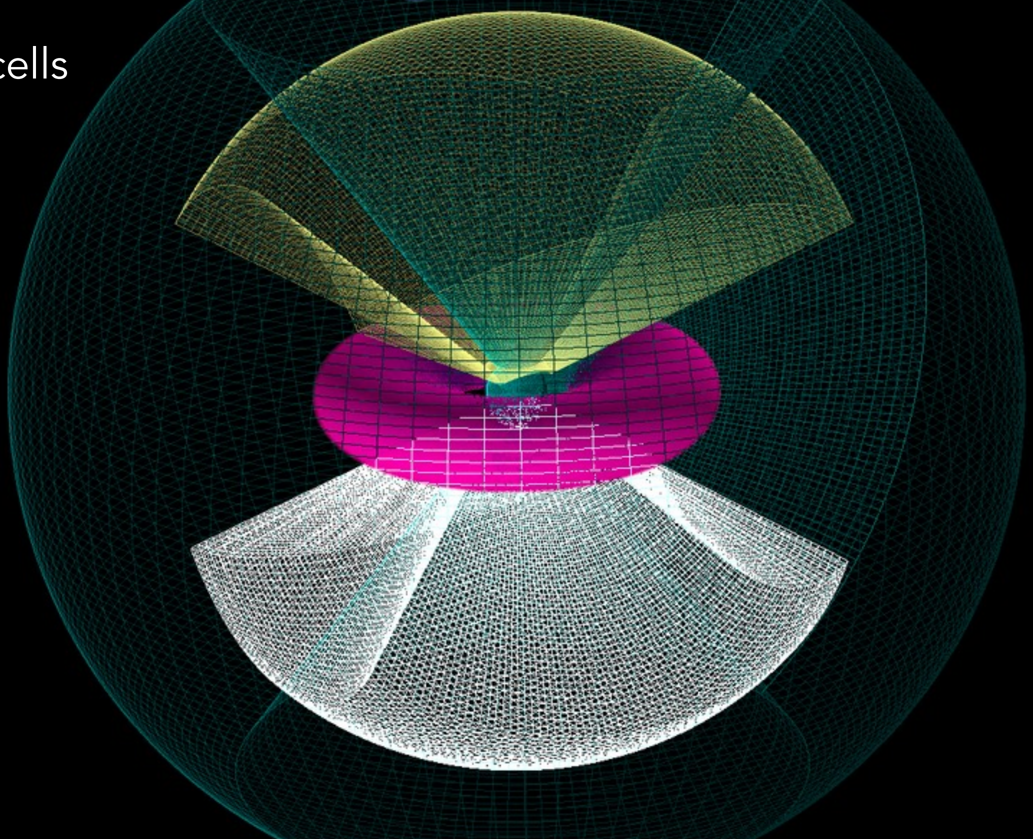
- Mini-disks around spinning BBH are brigther and produce more variability in X-rays
- Variability in the light curves and outflows follows that of accretion rate!


$\nu = 6.6 \times 10^{15}$ Hz
$\nu = 2.8 \times 10^{16}$ Hz
$\nu = 10^{17}$ Hz
$\nu = 1.1 \times 10^{19}$ Hz
40
20
0
−20
−40
−40 −20 0 20 40
32
33
34
35
36
37
38
39
40
$\mathrm{Log}(4\pi r_{\mathrm{cam}}^2 \nu I_\nu)$ [erg s^{-1}]

A new Multi-Patch Scheme for Accreting BBH + Jets

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

- **PatchworkMHD** – Avara+ 2021 in prep New software infrastructure for problems of discrepant physical, temporal, scales and multiple geometries.
- Early development (hydrodynamics only) – Shiokawa+ 2018



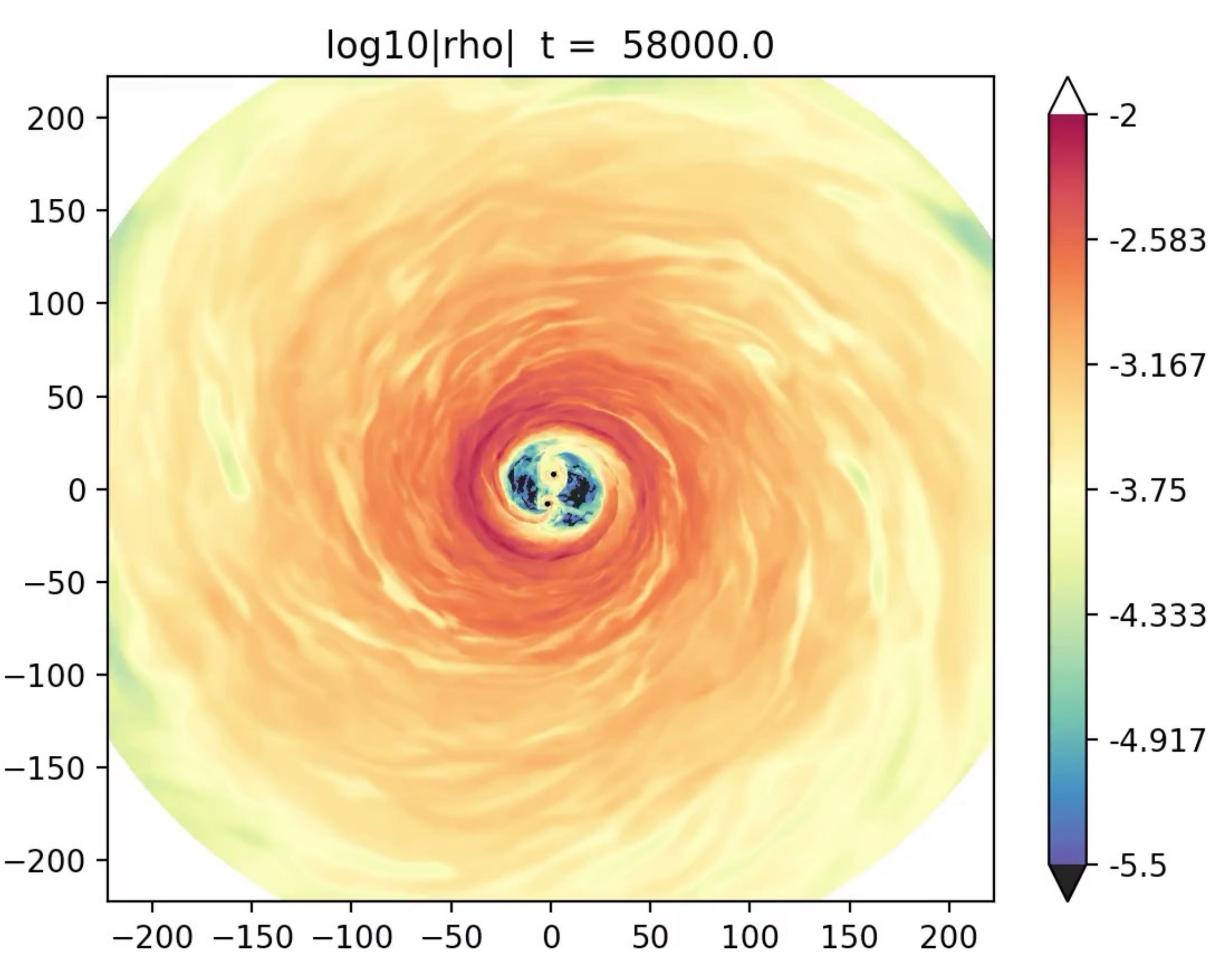
Accretion onto a single BH + Jet

Mark Avara +, RIT

The first successful PWMHD Simulation of Black Hole Binaries

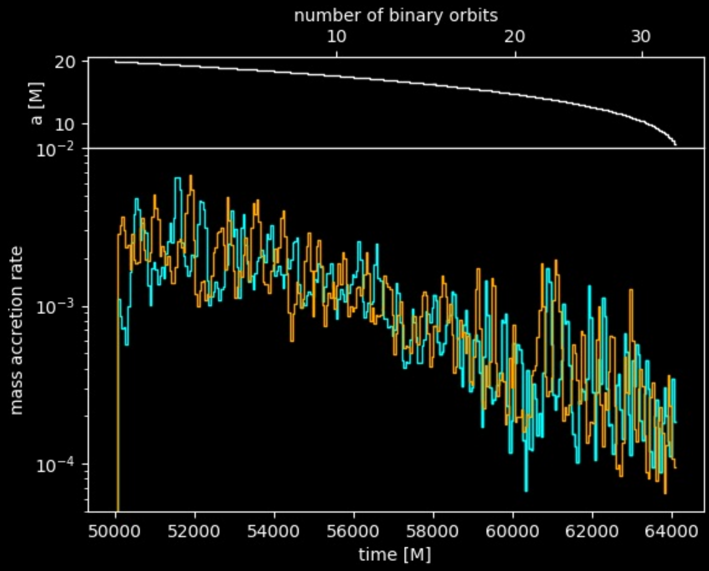
Long term simulation of non-spinning BBH covering the full domain with PWMHD, now 30 times our prior efficiency

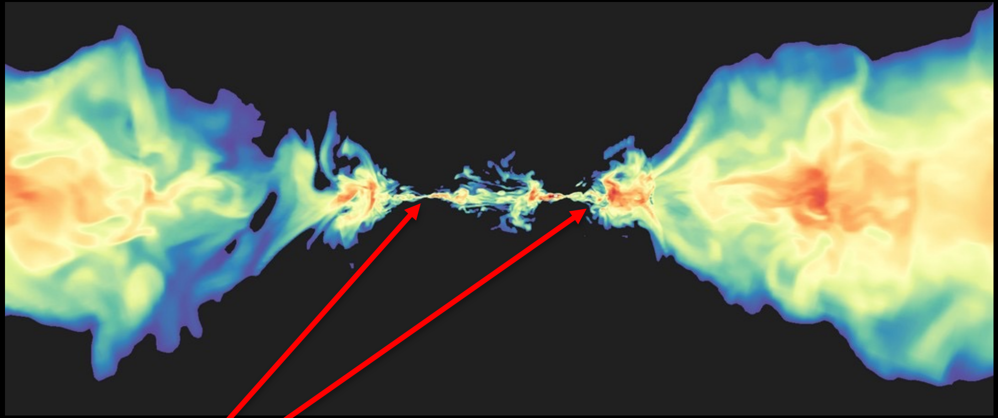
Avara+2021, in prep



New BH Minidisk physics

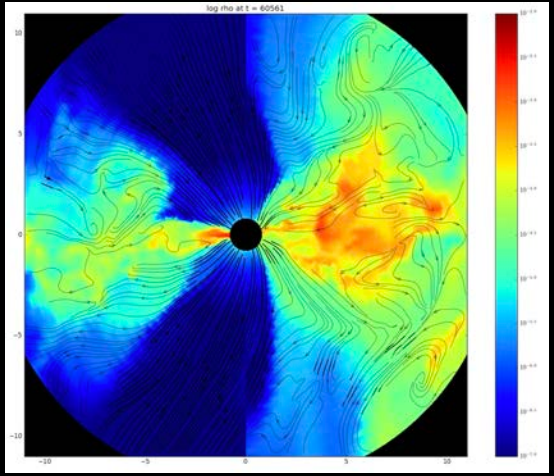
New 3d structure and dynamics of the BH mini-disks revealed – Avara+2021 in prep





Transient tilts

Mini-disks accretion nothing alike single BH accretion



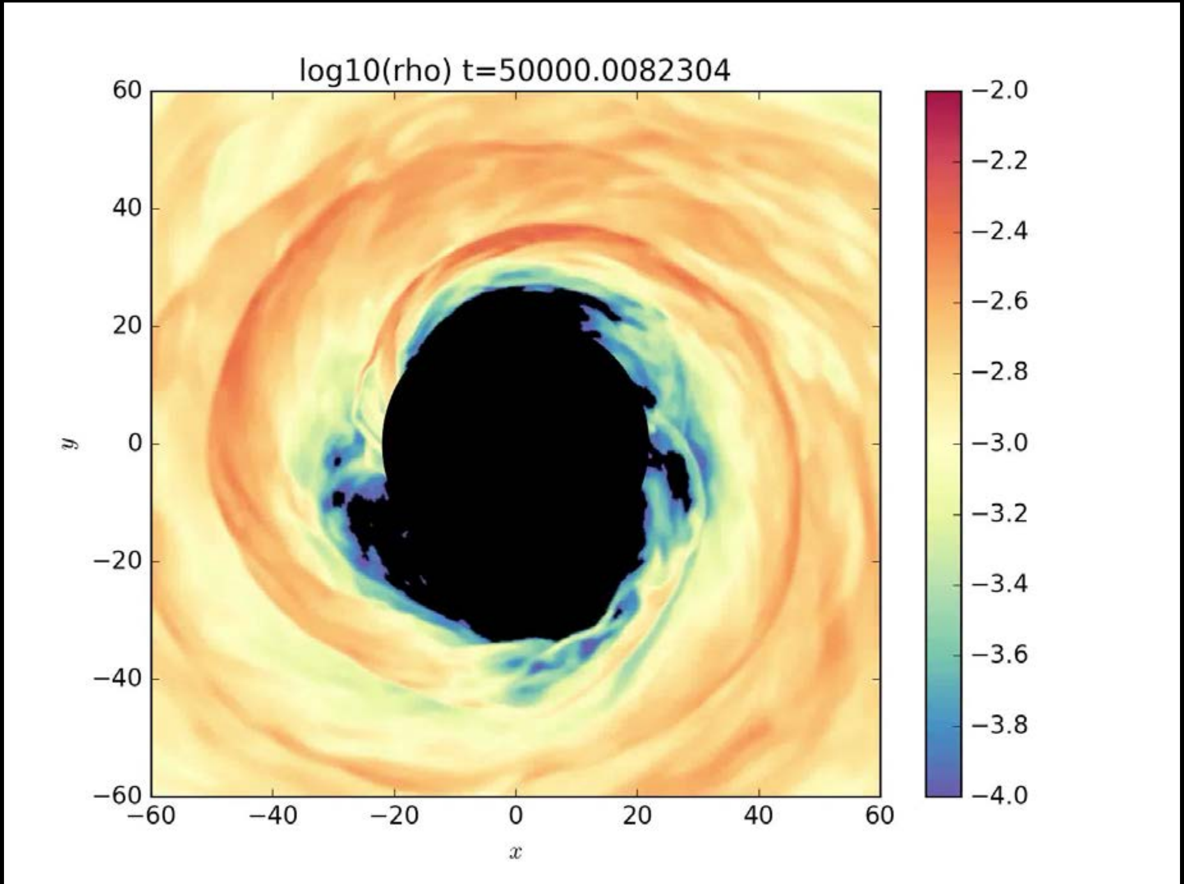
Getting closer to merger!
Adding BH Spins (and oblique jets)!

Exploring the parameter space BH spins, masses, eccentricity, tilted disks, thermodynamics properties, radiation treatments, etc, with PWMHD

Our goal: Find robust characteristic periodic signatures distinguishable from single AGN variability

Spinning BBH in progress …

Rueda Berecil++2022, in prep

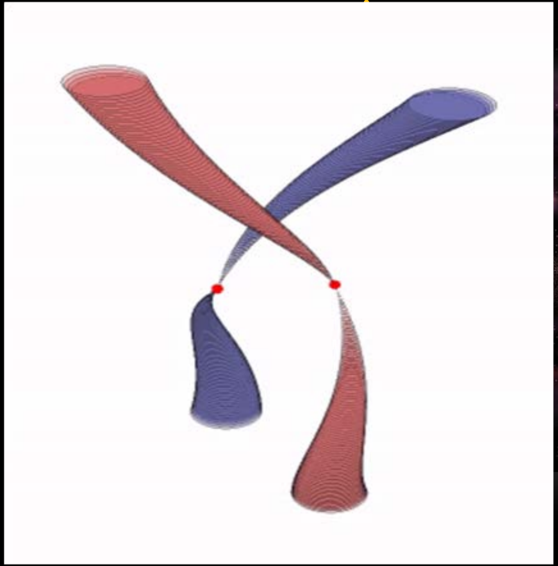


Stay Tuned!

More on BH Spins and Jets!

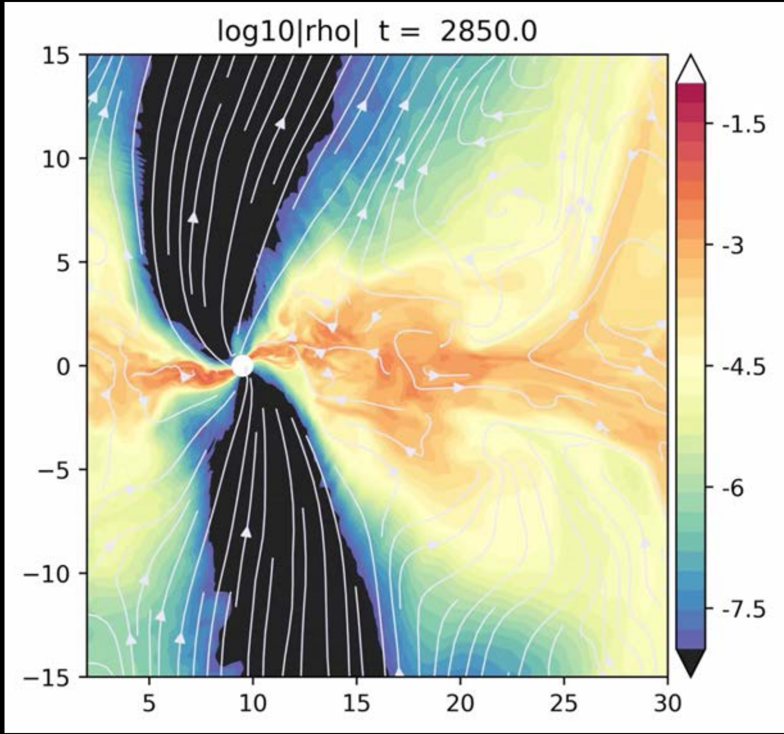
More magnetized mass + BH ergospheres means more jet-like structure!

Interesting things could happens if the BH spins are oblique … Combi+ in prep 2021, Gutierrez+ in prep 2021



… as the BHs approach merger … at merger and post-merger …

See spin-flips, X-shaped morphology …



Credits: Luciano Combi and Eduardo Mario Gutierrez

Stay Tuned!

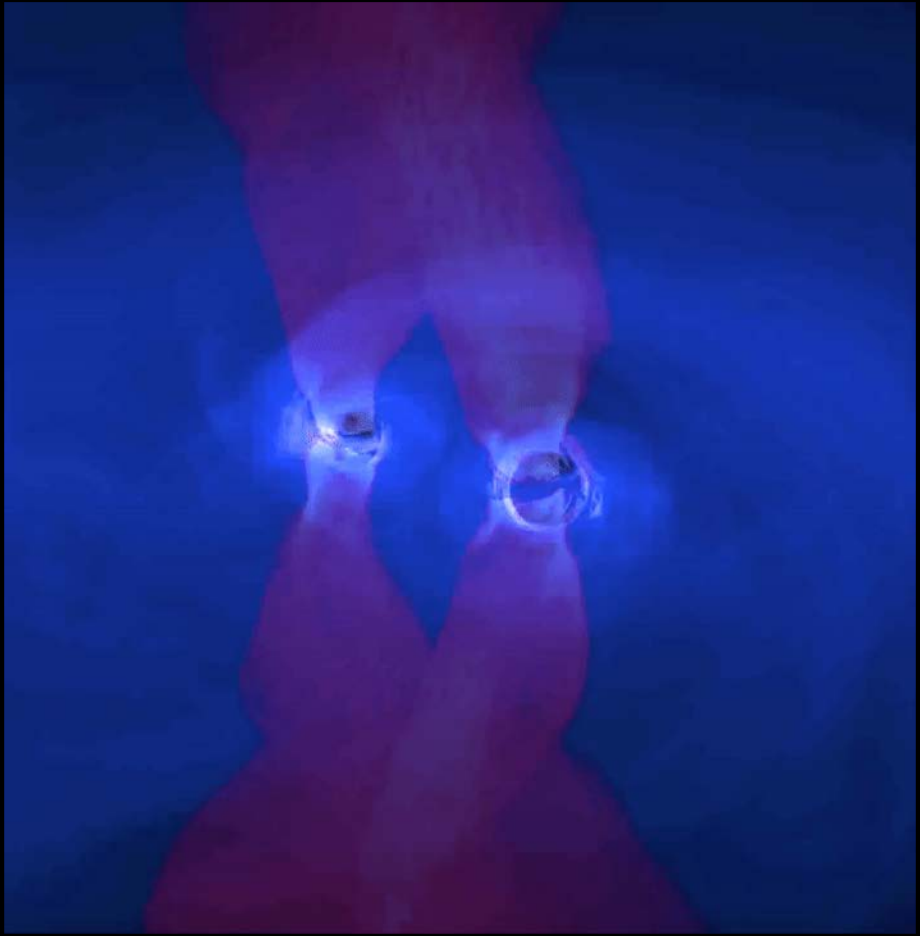
Summary

- Supermassive BH mergers are ideal multi-messenger sources!

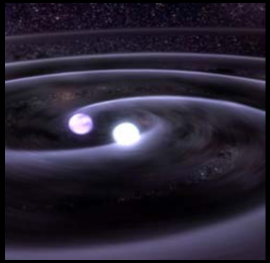
- A non-negligible fraction of these sources within the PTA (and LISA) GW range should also be EM observable.

- Accurate 3d GR-MHD models are now long enough to predict distinctive EM signals for variety of astrophysical scenarios!

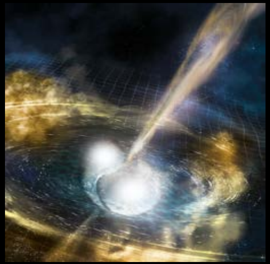
- This could resolve many interesting open questions around the origin of these BHs and AGN variability!



About Binary Neutron Star simulations …



+



GW170817

GRB 170817A

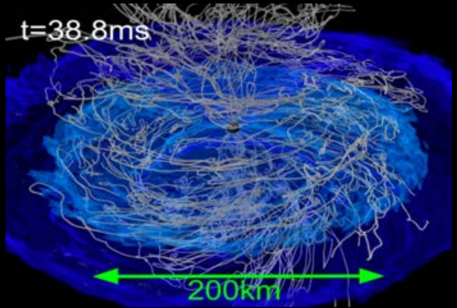
What is the central engine of a sGRB?
How is the jet launched?
What is the nature of the remnant?

BH + accretion disk
Hypermassive long-lived NS
+ torus – delayed collapse to a BH
Stable NS

Long, accurate, GRMHD BNS and BH/NS simulations are required in full **3d**

- NR + GRMHD
- Nuclear and Neutrino Physics, EOS
- Neutrino/photon transport
- R-processes/nucleosynthesis

And they are inherently **multi-physics**, **multi-scale**!



resolution of 17.5 m for 4--5 ms after the onset of the merger

Kenta Kiuchi+ 2015

Need to simulate ~1 sec after the onset of the merger with resolutions of the scale of the MRI!

Theory and Computational Astrophysics Network on Binary Neutron Star Mergers

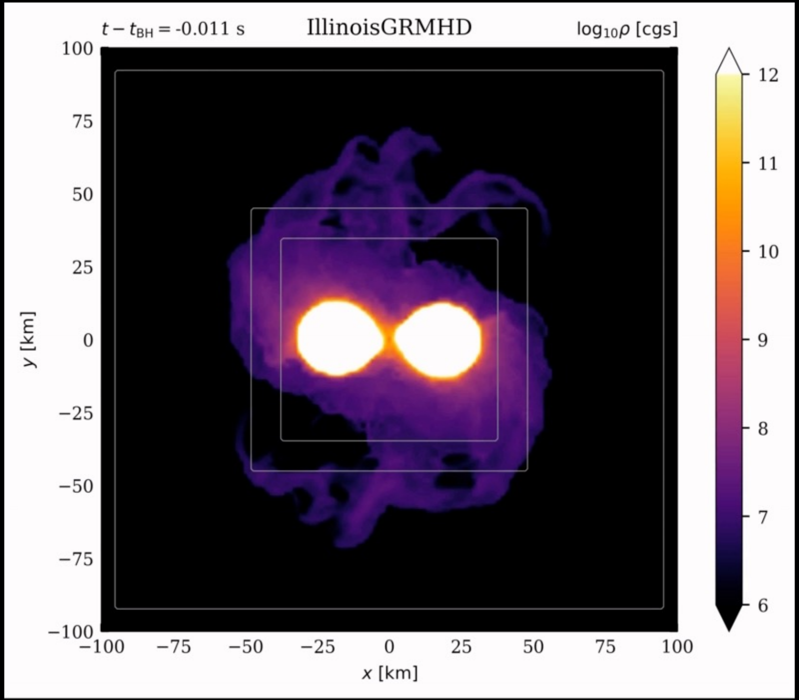
TCAN collaboration
compact-binaries.org

Divide problem according to physical characteristics; different codes for different regimes!

- Solve "handoff" algorithmic differences e.g. atmosphere treatment, common EOS, neutrino physics, and treatment of MHD - Lopez-Armengol+ in prep, 2021

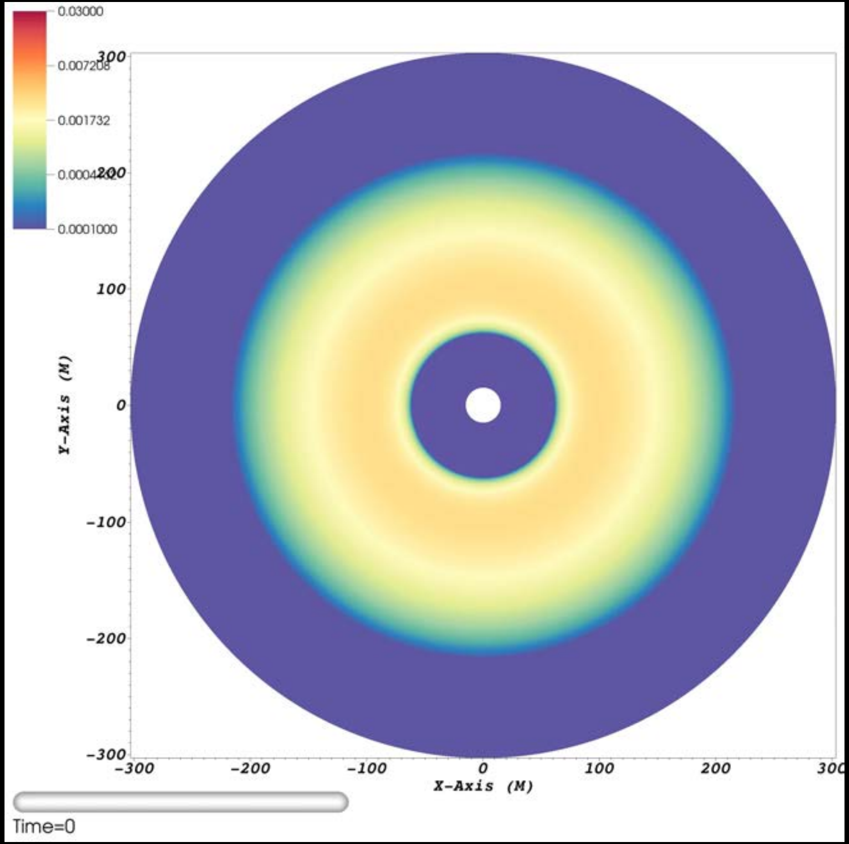
- Now complete and postmerger simulations with tabulated EOS and neutrinos (Murguia-Berthier+ 2021) are underway on TACC's Frontera supercomputer.

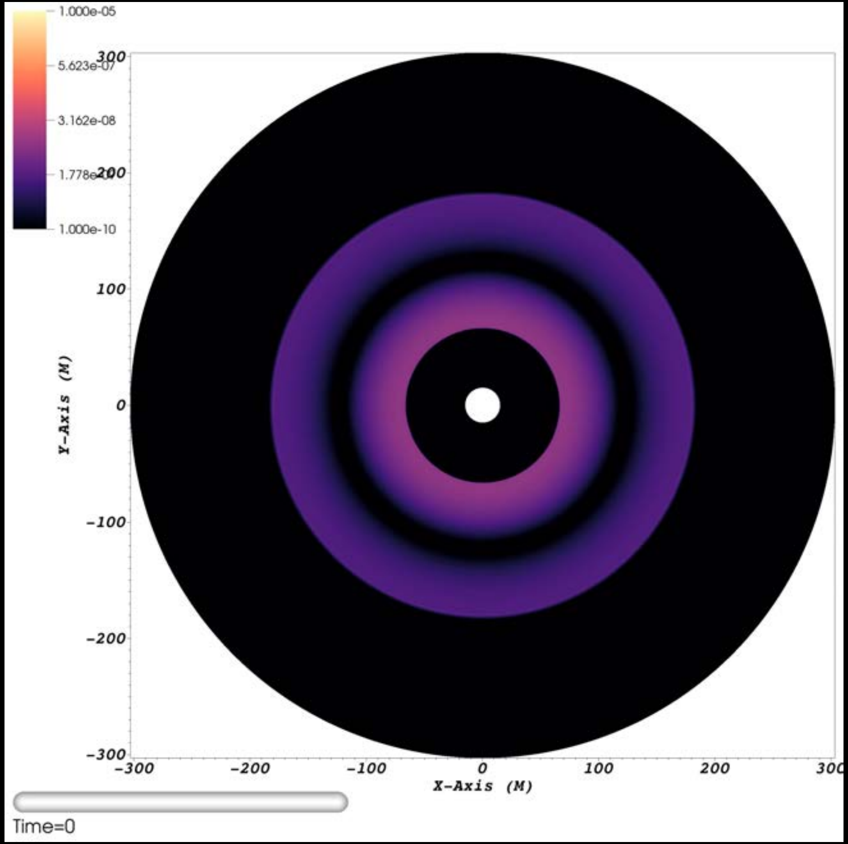
Stay Tuned for more soon!



See also IPAM Talk by Dr. Ariadna Murguia Berthier

Numerical Relativity in Spherical Coordinates in the ETK:





Mewes et al, 2019, 2020 and in prep 2021