Glimpse of Light from the Deep Universe: Supermassive Black Holes Approaching Merger

Compact-binaries.org:

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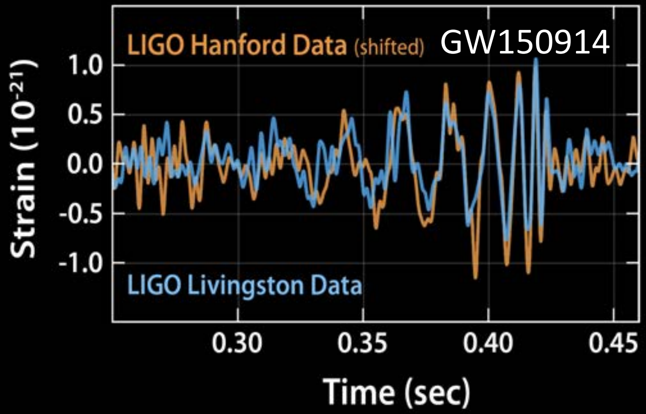
INTERNATIONAL SCHOOL DANIEL CHALLONGE-HECTOR DE VEGA
MARCH 17, 2021



Erice, Italy, 1992

Windows onto the Universe!

Recent gravitational-wave discoveries by LIGO …



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

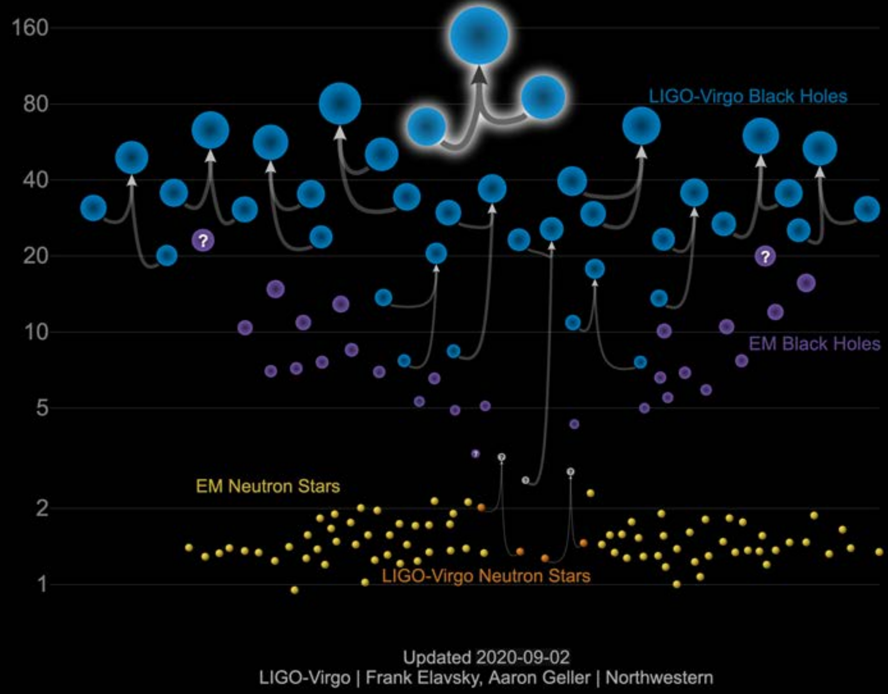
… have opened an unprecedented observational window into binary black holes and neutron stars!

GW170817

+

GRB 170817A

LIGO/Virgo BBH Mergers



- What is their population across the universe as a function of the redshift?
- What is their astrophysical origin, and environment?
- What are the stellar evolution processes leading to the formation of these sources?
- How nature manage to produce black hole binaries with a variety of masses, and spins?

- 3G ground based GW detectors could get them all!- Vitale+2017, 2018++
- **Multi-Spectrum GW** observations 3G + LISA could distinguish **formation channels -** Sesana, 2016, Breivik+2016, Rodriguez+2017 …

Multi-Messenger Sources

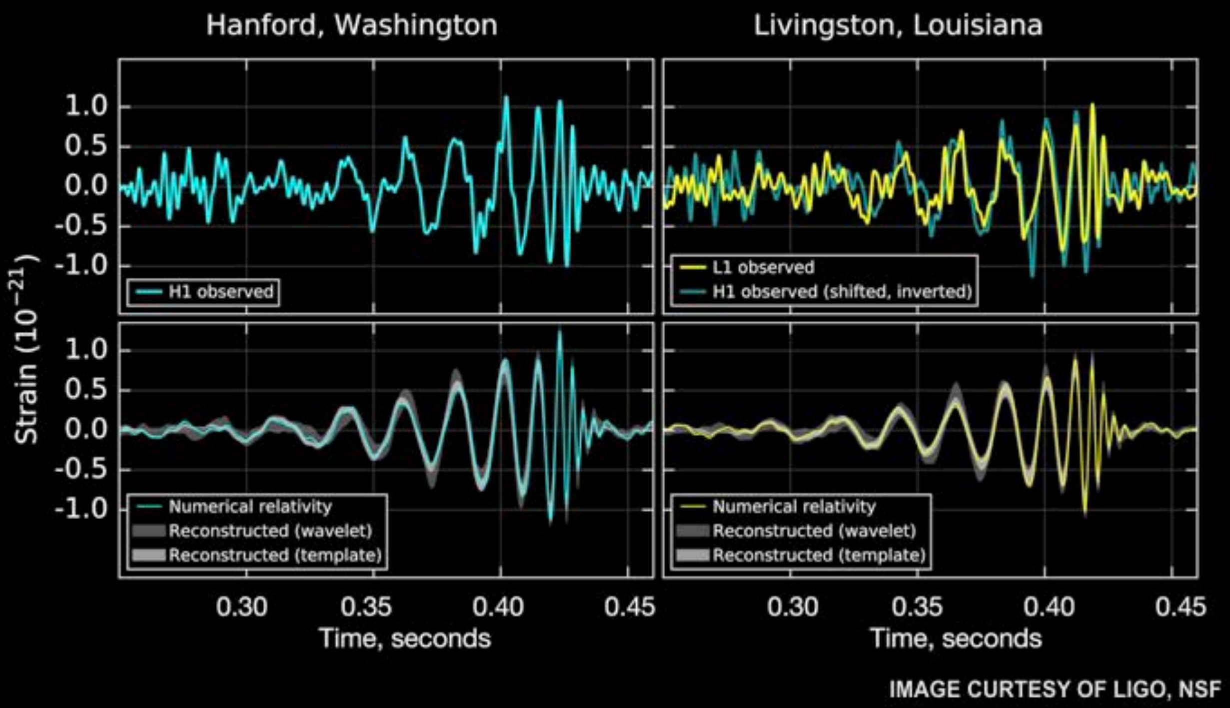
Many of these sources, e.g. accreting binary black holes and binary neutron star mergers, can produce powerful electromagnetic signals and high-energy particles, in addition to gravitational waves.

Multi-messenger astrophysics is a new revolutionary field of science in very rapid expansion.

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

Theory and computational astrophysics models are critical to interpret multi-messenger observations.

The Role of Theoretical Modeling and Numerical Simulations in LIGO discoveries



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

The serendipitous GW150914

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

Talk by Dr. Carlos Lousto

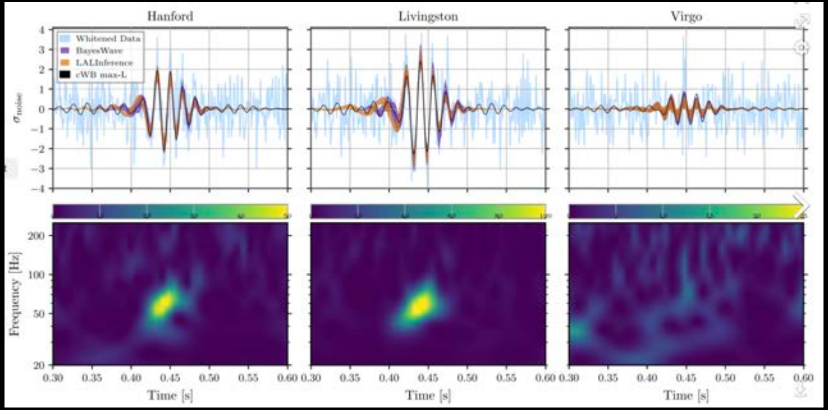
Could any of these BBH mergers also be EM bright?

Mergers of stellar/intermediate BBH do not typically emit any 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!

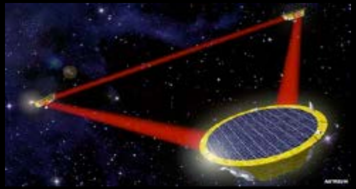
Stellar dynamical friction, torques from gas, or other processes can bring the pair to sub-pc scales, then GW should do the rest …

- 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 …

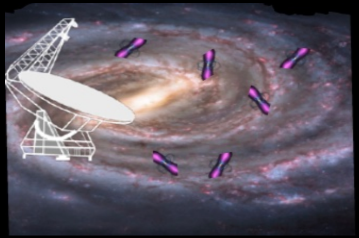
On the more massive end of the spectrum …

SMBBH are primary GW sources for **LISA** and **PTA** campaigns.

- How nature manage to produce BH binaries with a variety of masses, and spins?
- And what is their population across the universe as a function of the redshift?
- What is their astrophysical origin, and environment?
- Many implications for galaxy formation and evolution …



LISA
[Launches in 2030s]
10^4-10^7 M_{sun}
P_{orb}~ hours-days



PTA
[first discovery 2020s?]
10^8-10^{11} M_{sun}
P_{orb}~ weeks-decades

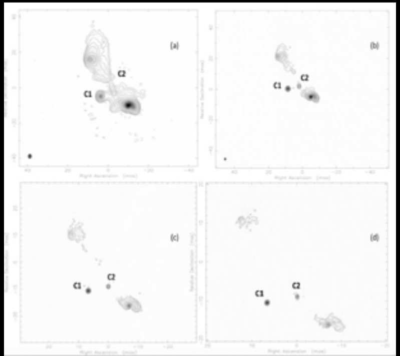
As MMA sources, they **are also important cosmological "standard candles" and i**deal laboratories for exploring plasma physics in the strongest and most dynamical regime of gravity.

What is the EM signal associated with SMBH Mergers?

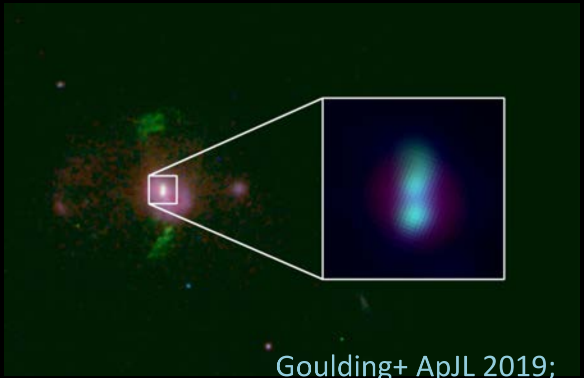
Population estimates of **EM-distinguishable binary-AGN** from galaxy evolution models find ~10^2 sources at redshifts z~0.5-1 (at flux levels >10^{-13} erg cm^{-2} s^{-1}) -- Krolik, Volonteri, Dubois, and Devriendt, 2019

~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!

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!

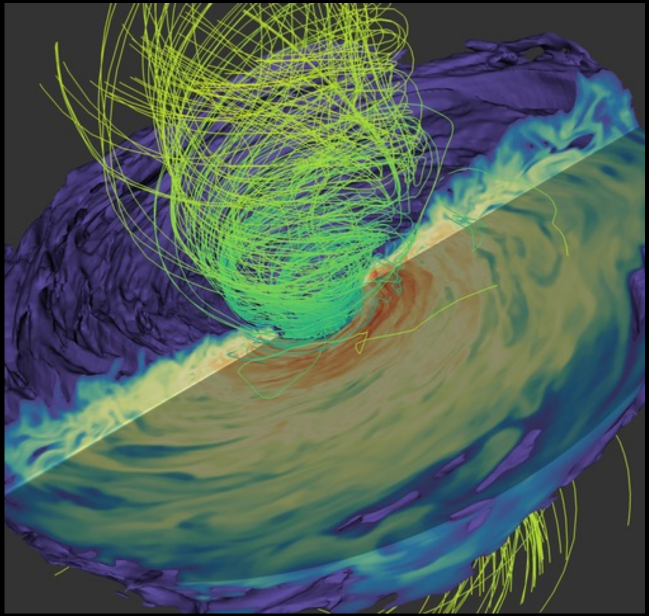
How much gas is present at merger?

- 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.

- 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!



Bowen+, 2019. Movie: Mewes

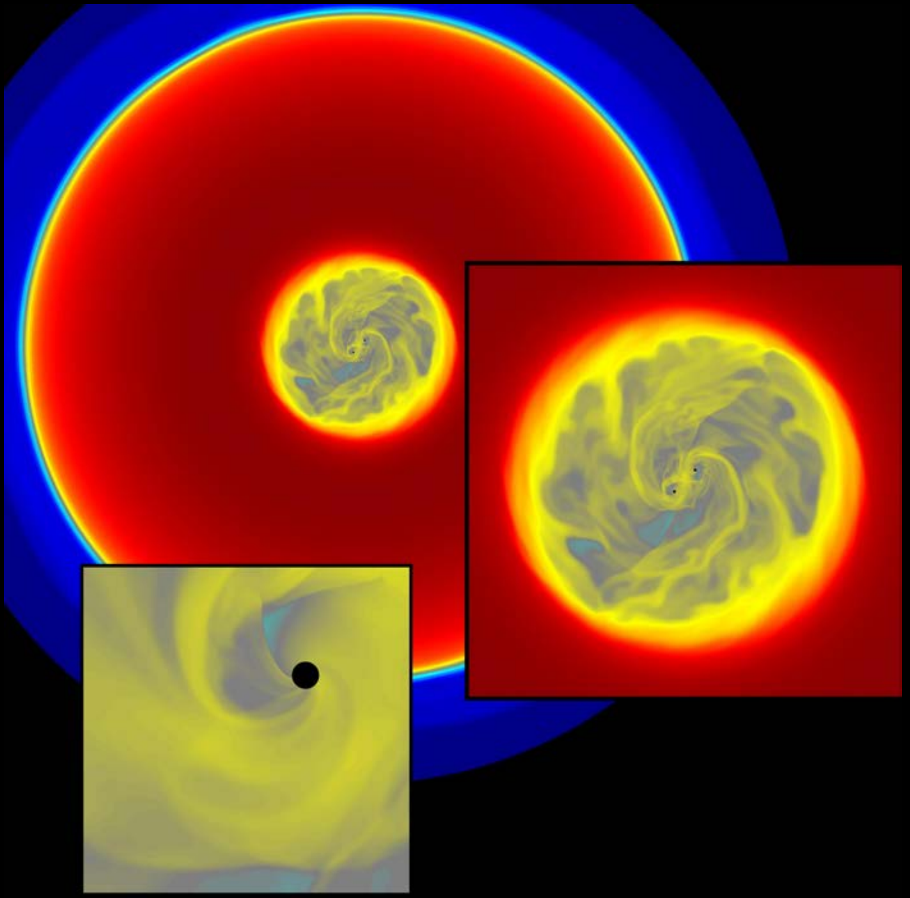
Full 3d GR-MHD in Dynamical Gravity

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

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

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

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



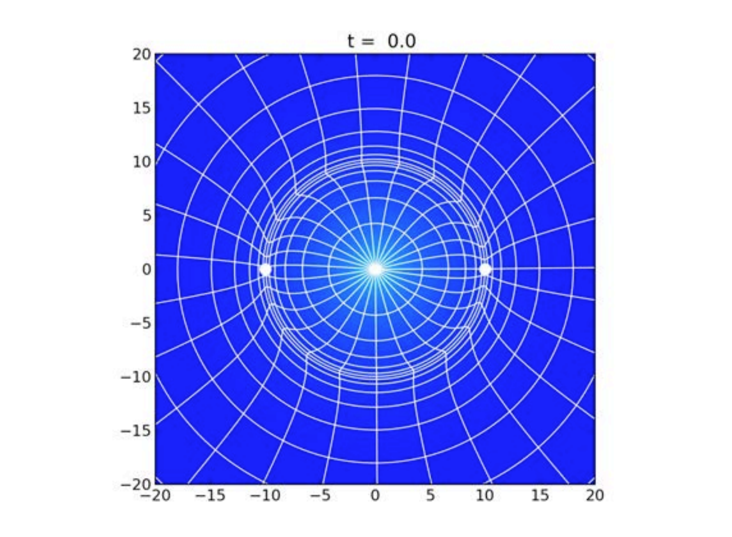
Use a well-tested, **flux-conservative**, generally covariant, GR-MHD code for BH accretion disks: Harm3D – Gammie, McKinney & Toth 2003, Noble+2006

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.

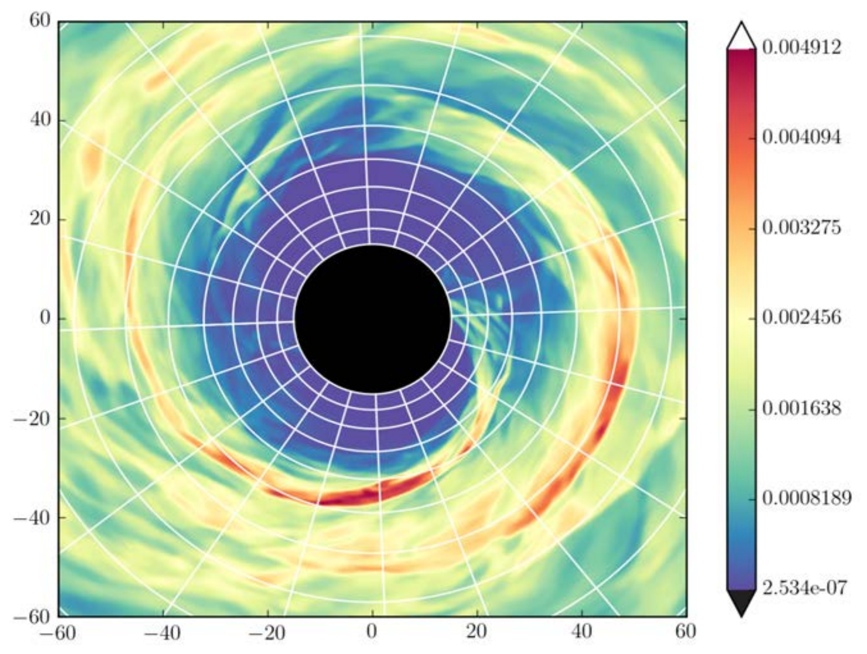
Simulations quickly unaffordable without a clever choice of the grid, especially in the central cavity, near each BHs



Warped curvilinear grids – Zilhão+2014

Novel Multipatch Scheme (later)

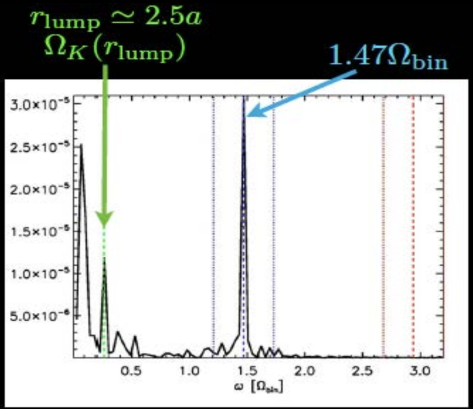
Circumbinary disk dynamics in the GW inspiral regime



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+, in prep 2020

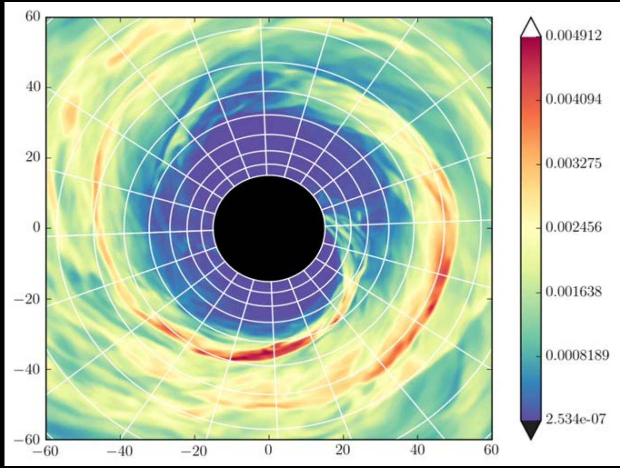
Computational strategies:

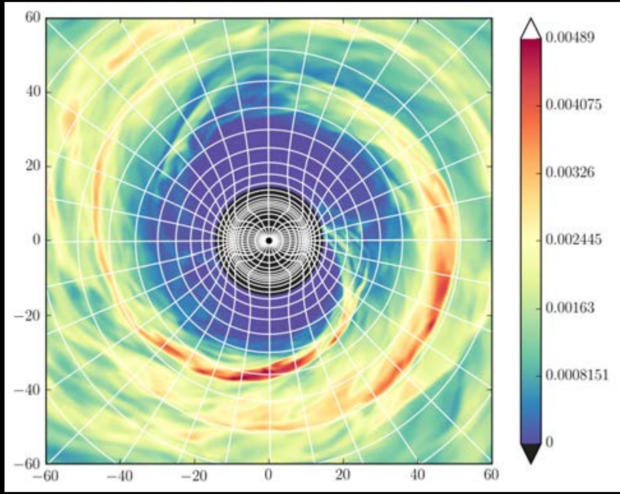
Evolve accreting inspiraling BH binaries while **resolving the MRI and MHD dynamics** at the scale of the event horizons:

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!

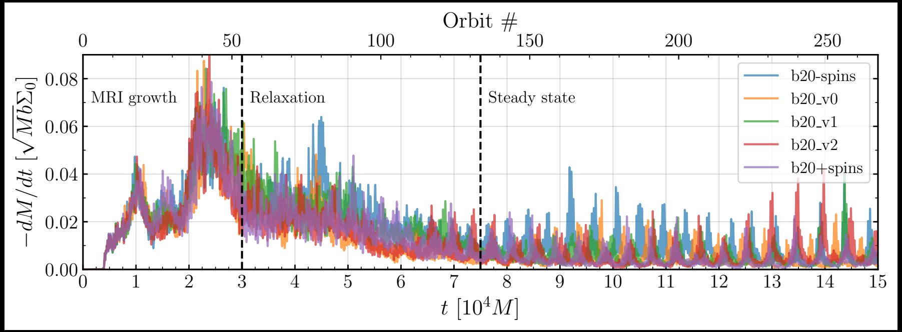


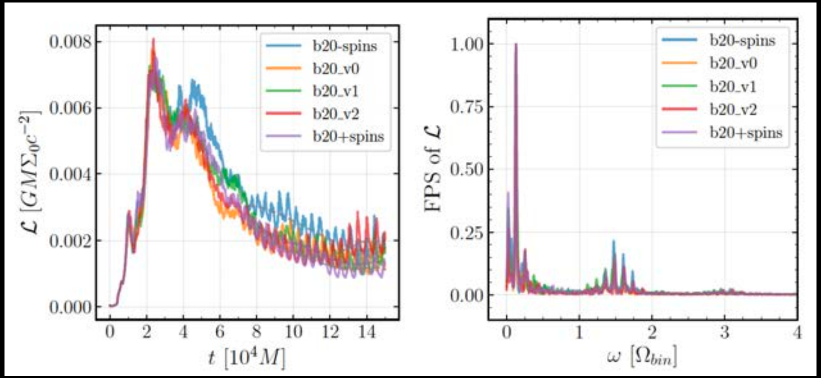


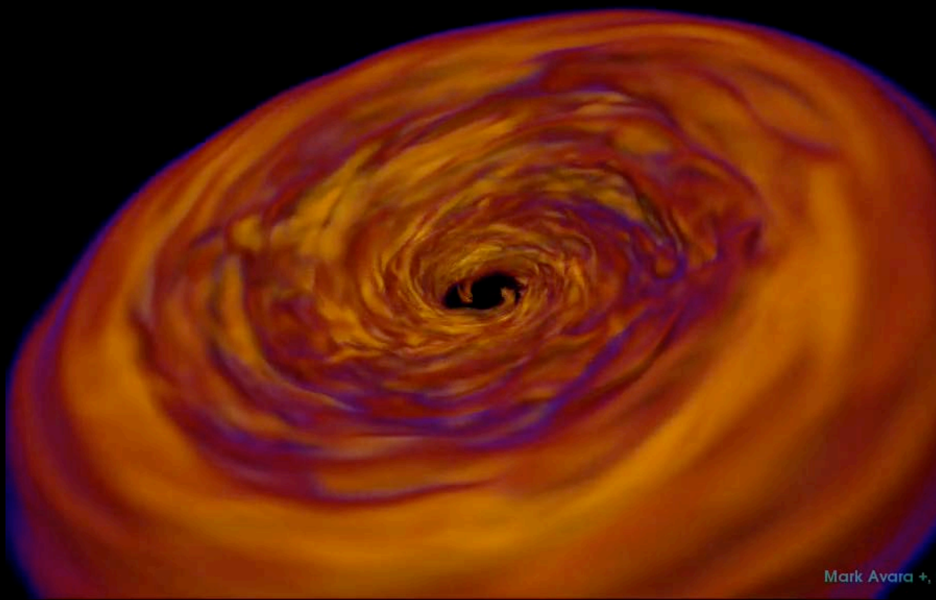
Circumbinary Disk Dynamics in Spinning Black hole Binaries

It takes time to equilibrate the disk in the region near the cavity (hundreds of orbits) – Noble+2012, Lopez-Armengol+ 2021

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







Video Credits: Mark Avara + RIT

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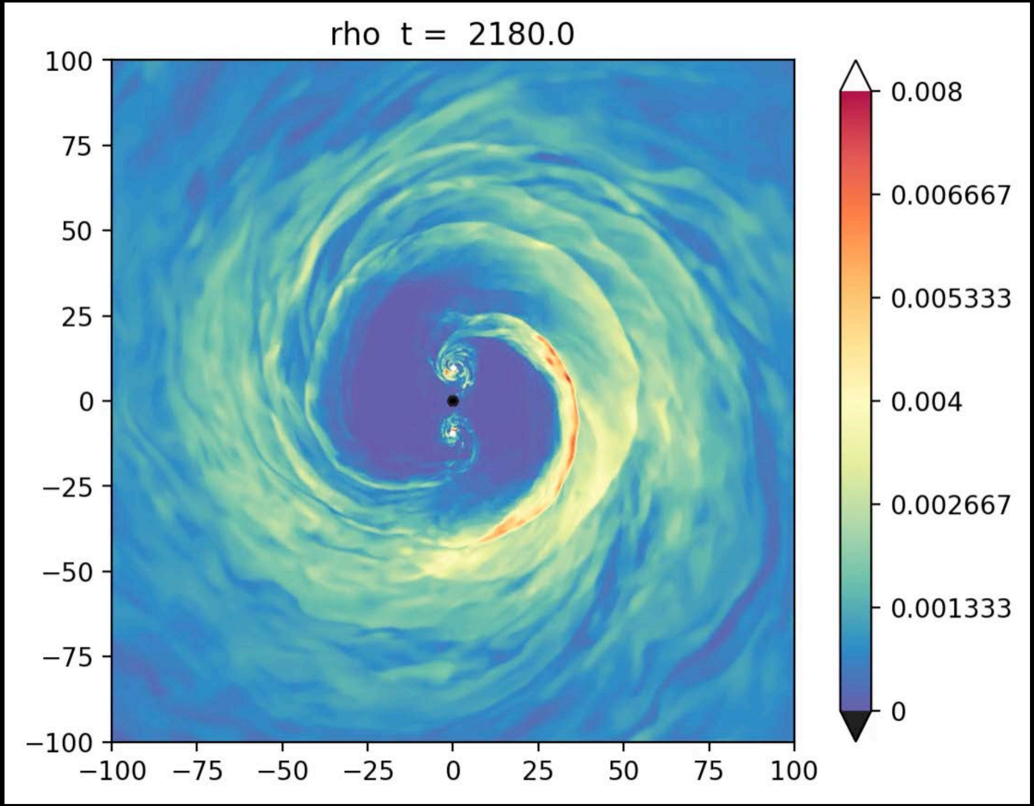
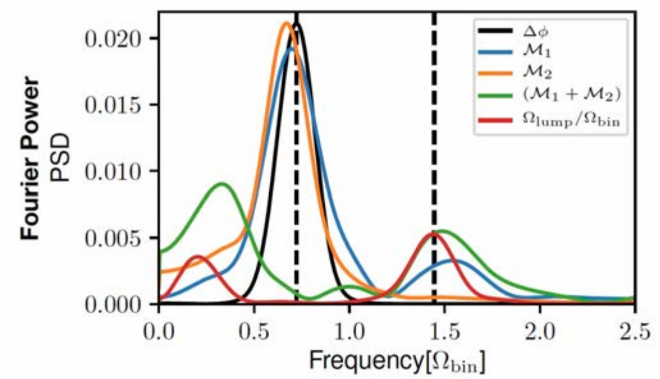
Mass Exchange between the BHs



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.

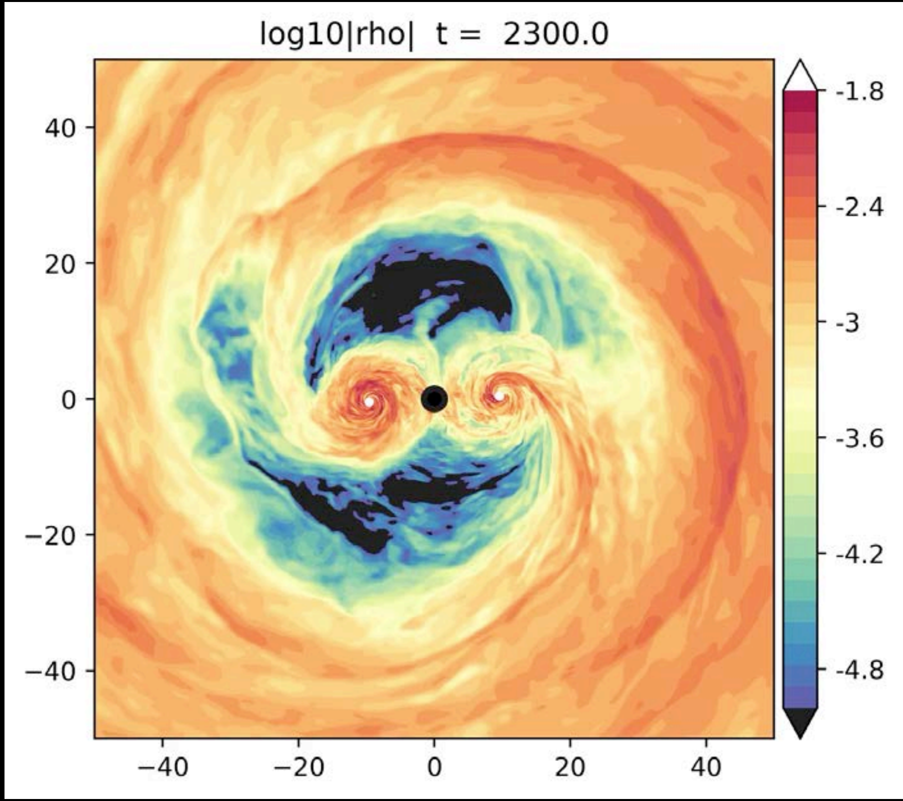
Mini-disks deplete and refill periodically at time scale close to one orbital period.



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

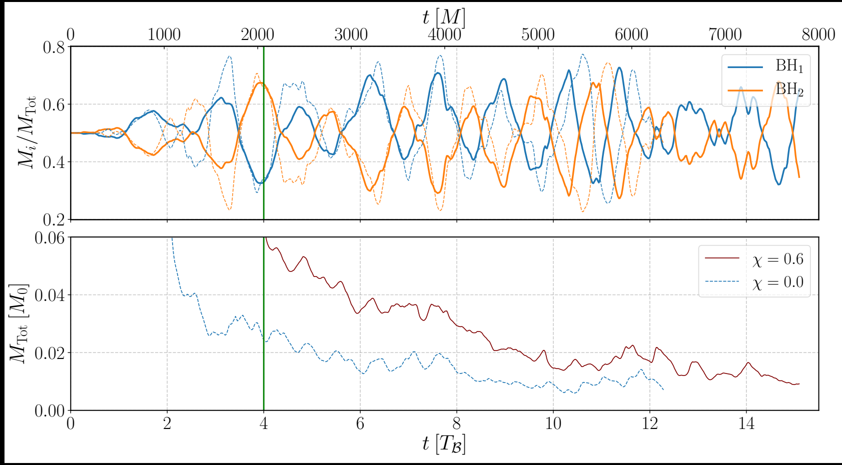
Credits: Bowen (RIT/LANL) 2019

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+ in prep 2021



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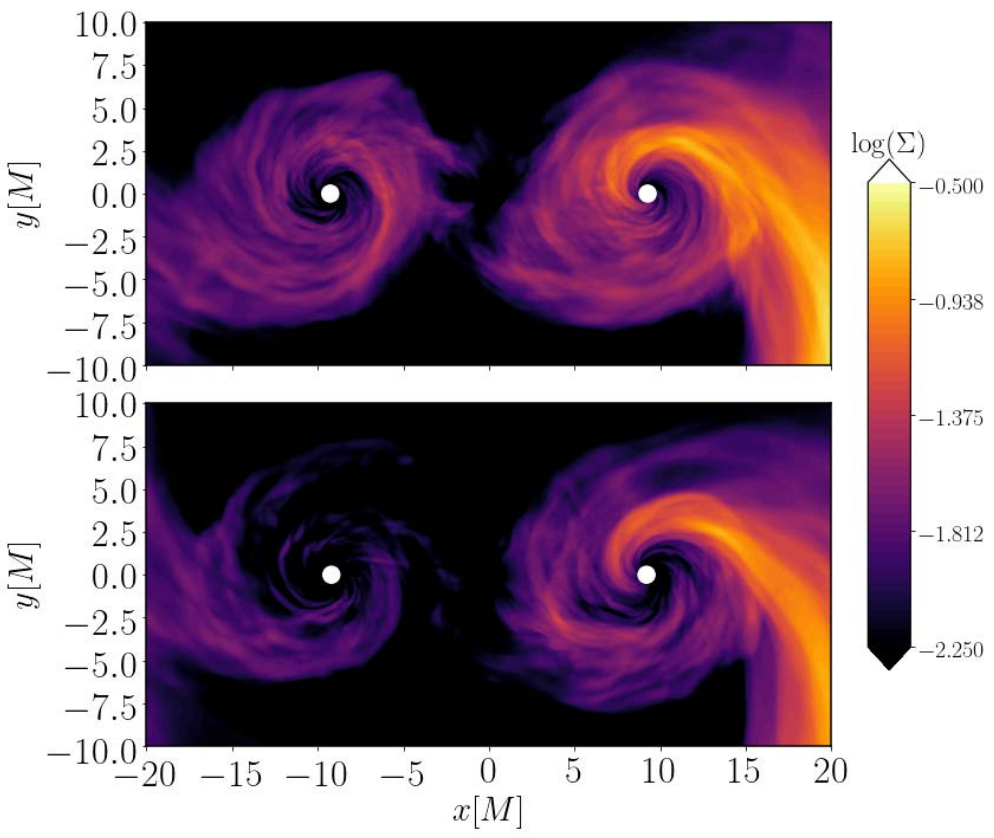
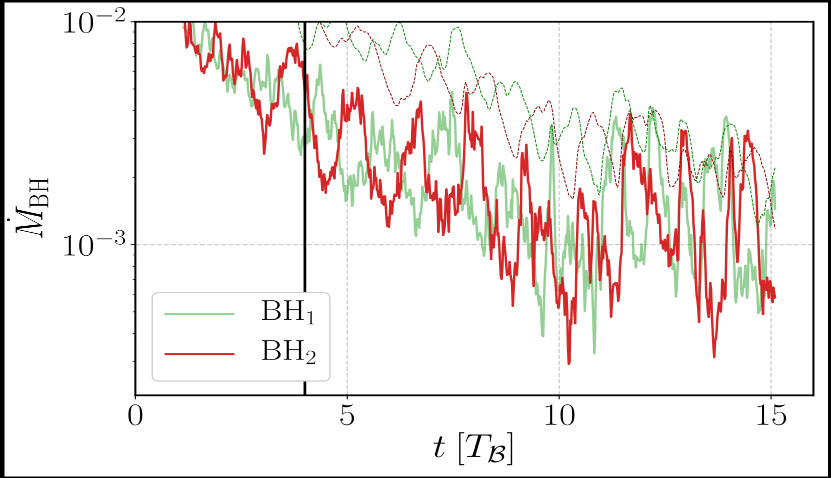
On the effect of the BH spins …



Formation of massive and circular minidisks structures with material piling up close to black holes – Combi+ in prep 2021

Accretion rate follow filling and refilling of the minidiscs …



Credits: Luciano Combi (RIT/IAR)

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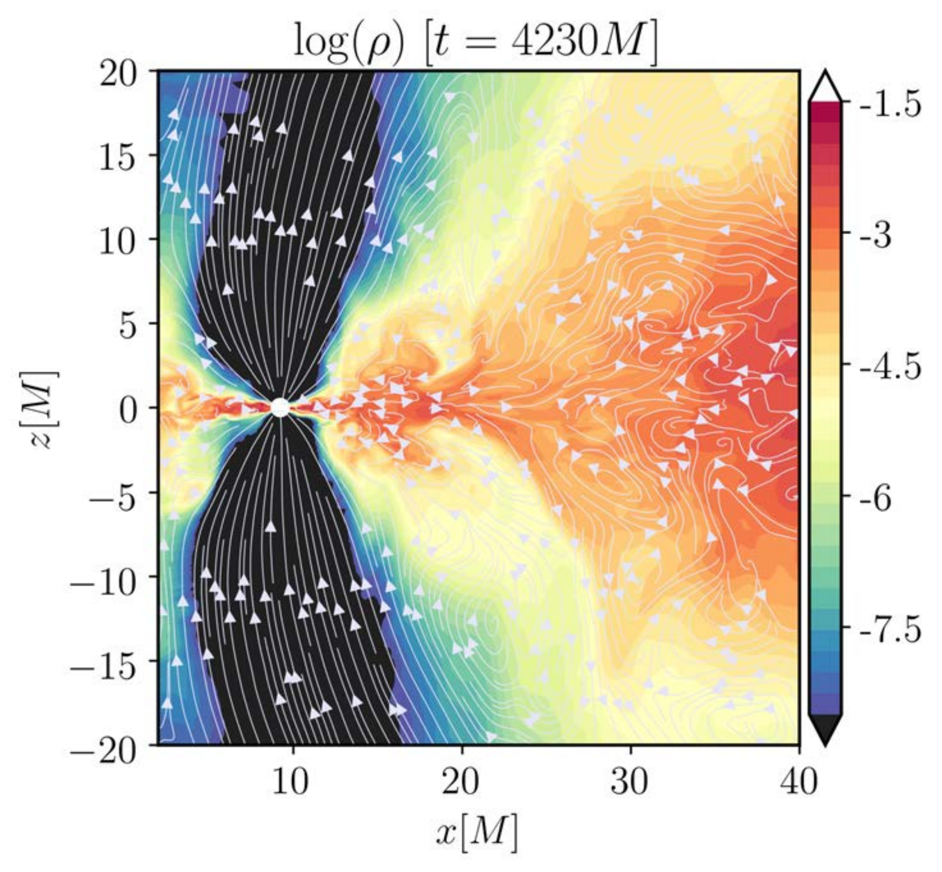
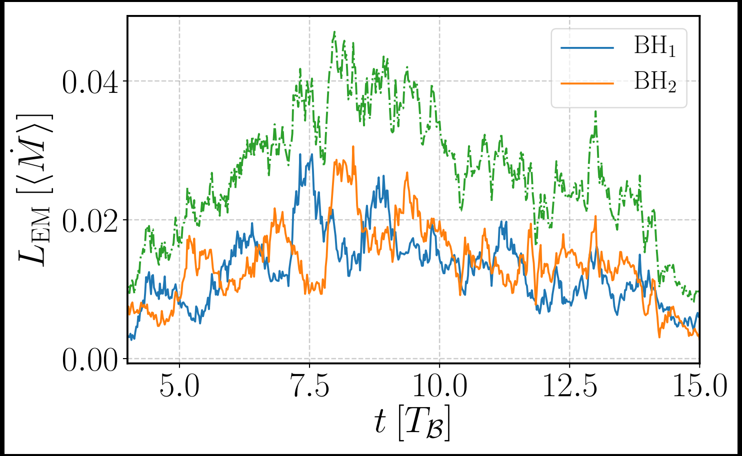
BH Spins and Jets!



Credits: Luciano Combi + (RIT/IAR)

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



Jet power modulated with the same periodic behavior that the filling/depletion cycle - Combi+ in prep 2021

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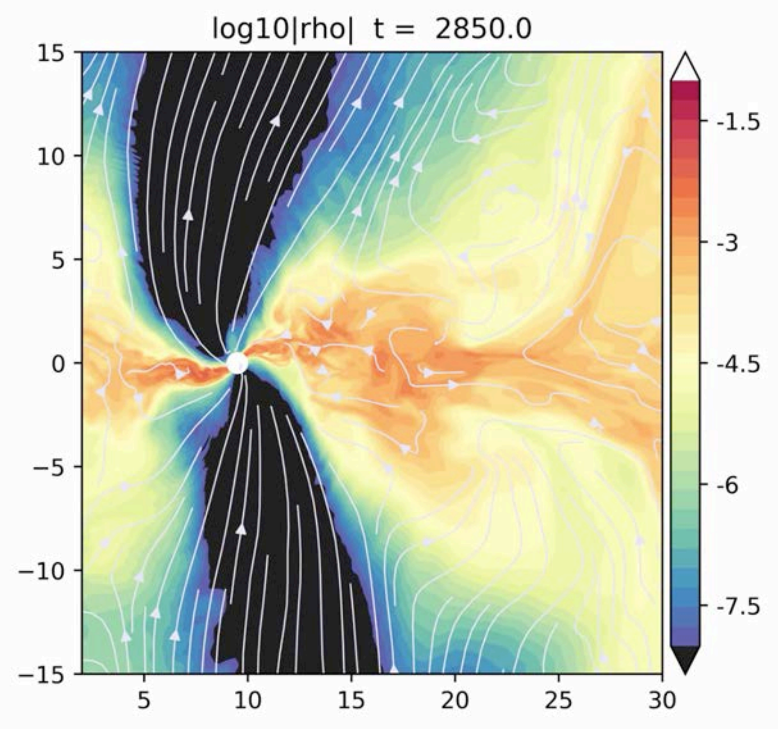
More on BH Spins and Jets!

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

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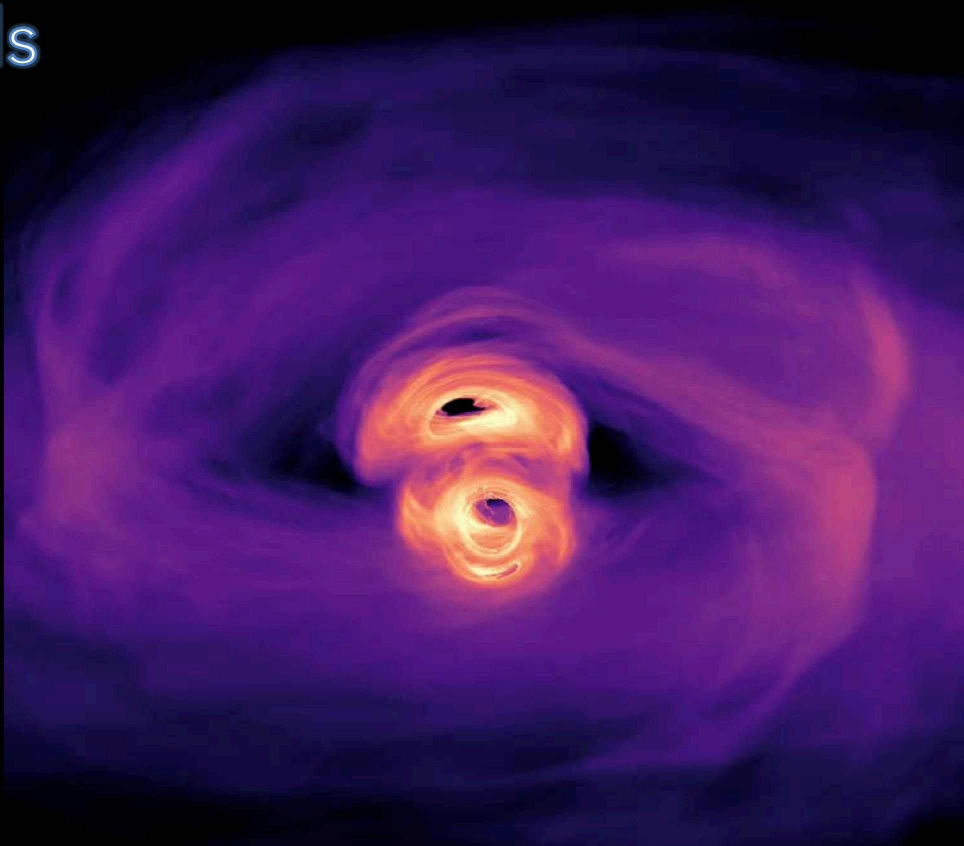
Stay Tuned!

Calculations of light signals

The first predicted time varying spectrum from accreting binary black holes approaching merger – D'Ascoli+2018

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

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



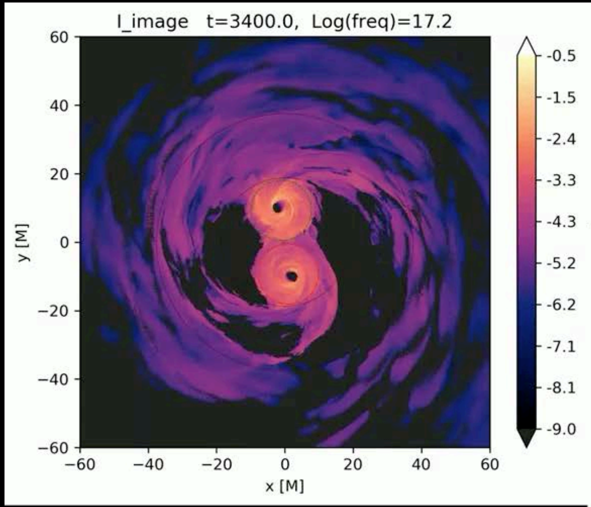
Intensity of X-rays (log scale) multiple-angle video in time

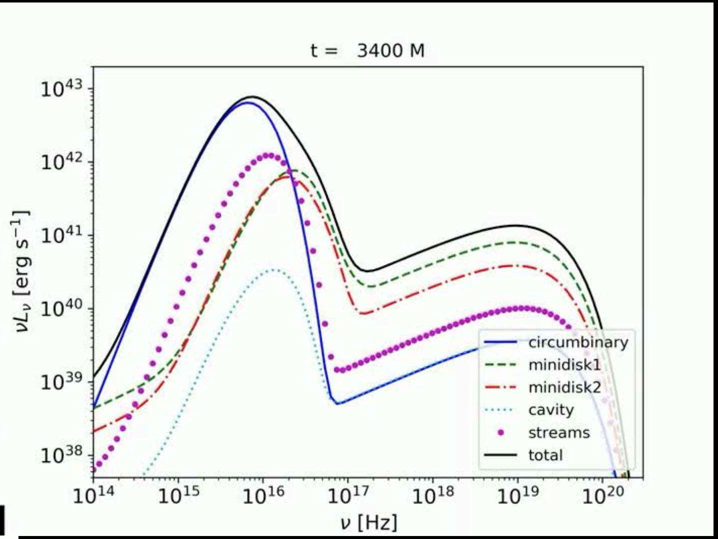
Credits: S. Noble (NASA/RIT)

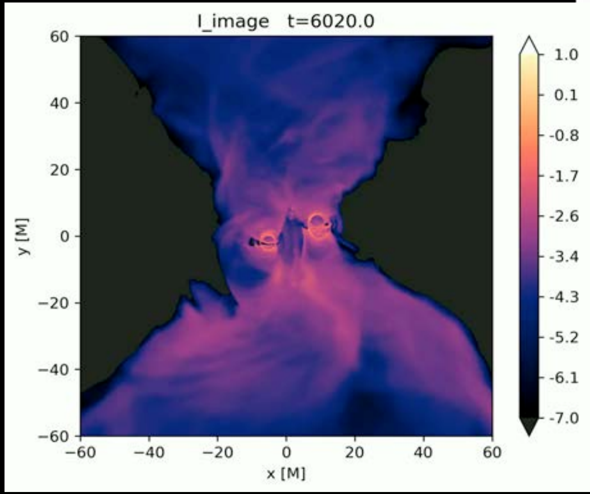
First Calculations Light Signals from Spinning Black Hole Binaries

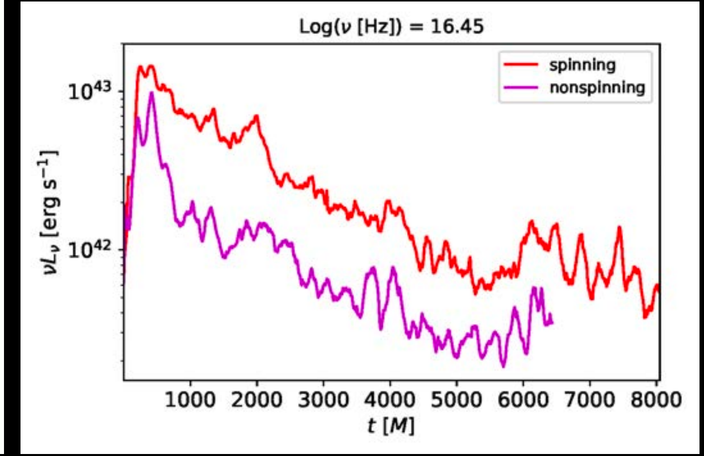
Gutierrez+ in prep 2021

Optically thick case (top)
Optically thin case (bottom)









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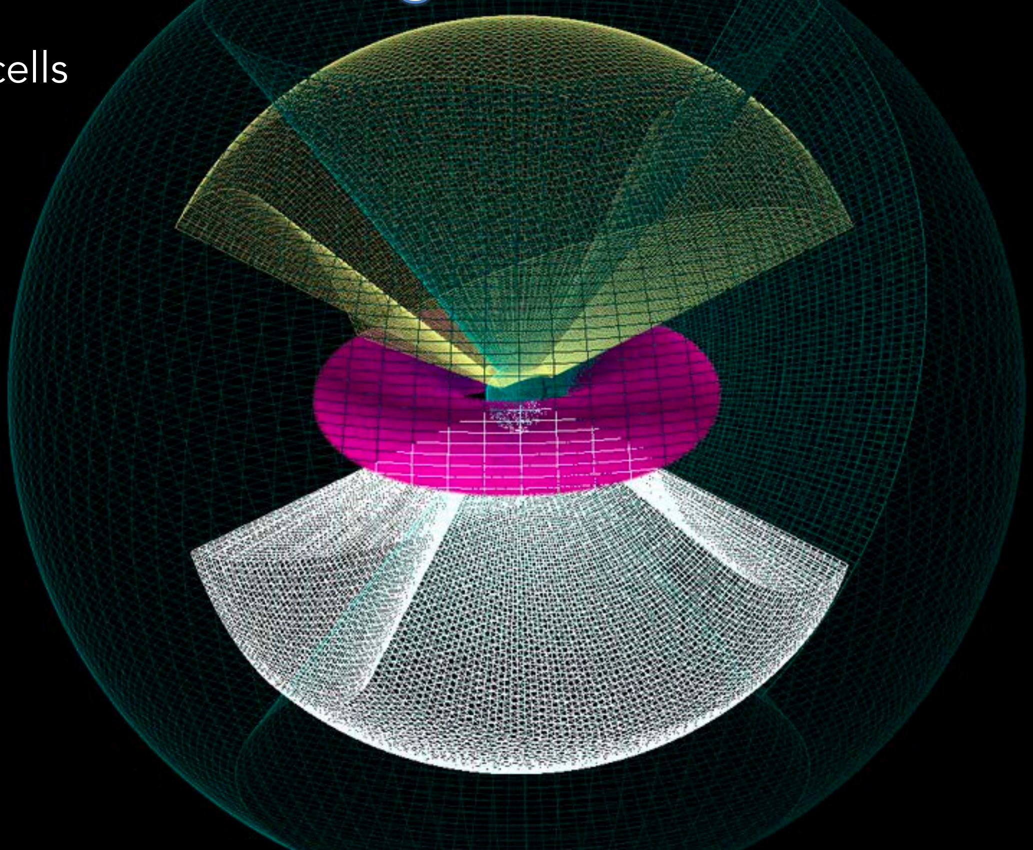
Credits: Gutierrez (RIT), based on Combi+ 2021

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+ 2020 in prep New software infrastructure for problems of discrepant physical, temporal, scales and multiple geometries.
- Early development (hydrodynamics only) – Shiokawa+ 2018

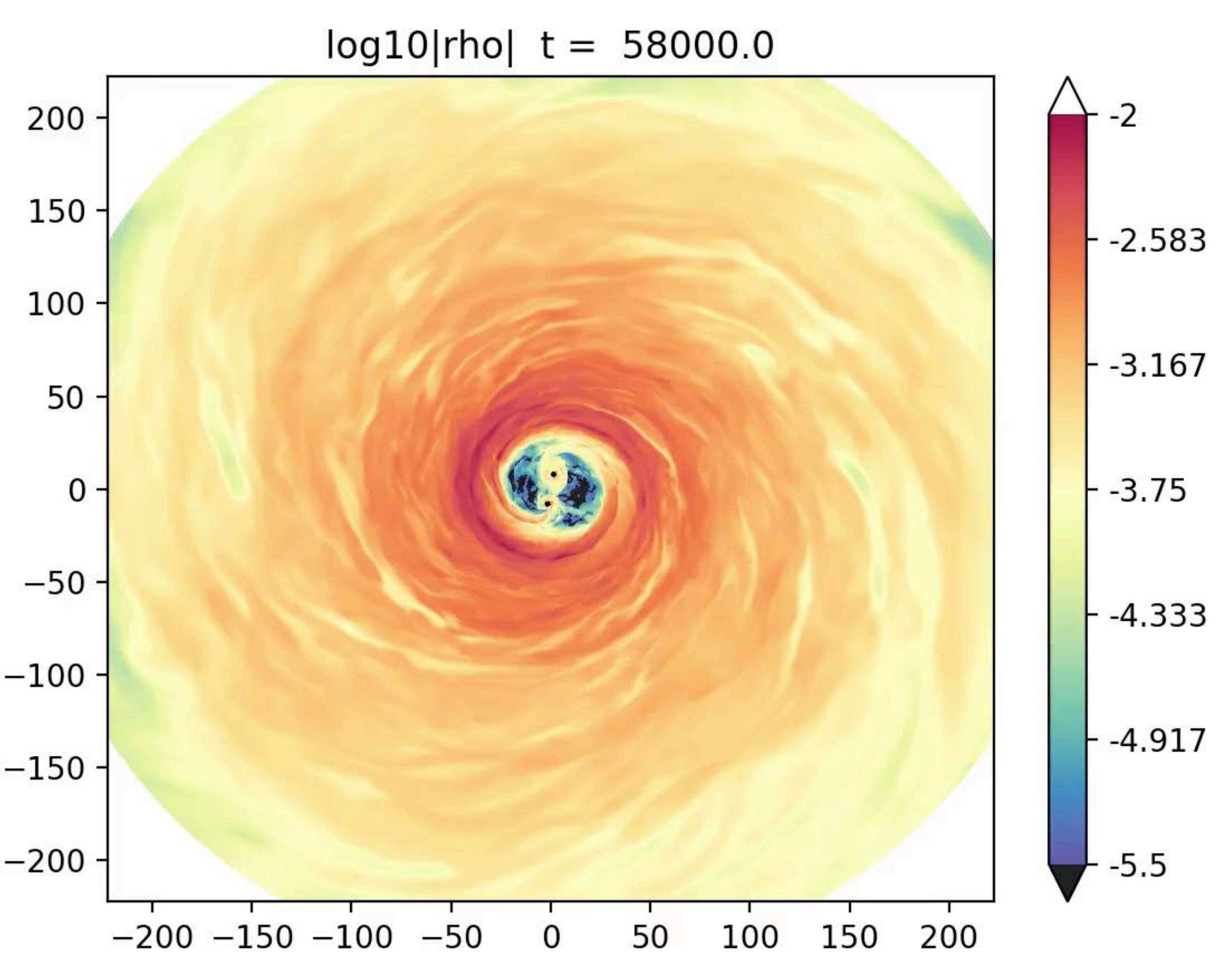


Accretion onto a single BH + Jet

The first successful PWMHD Simulation of Black Hole Binaries

Long term simulation covering the full domain with PWMHD, now 30 times our prior efficiency

Avara+2021, in prep



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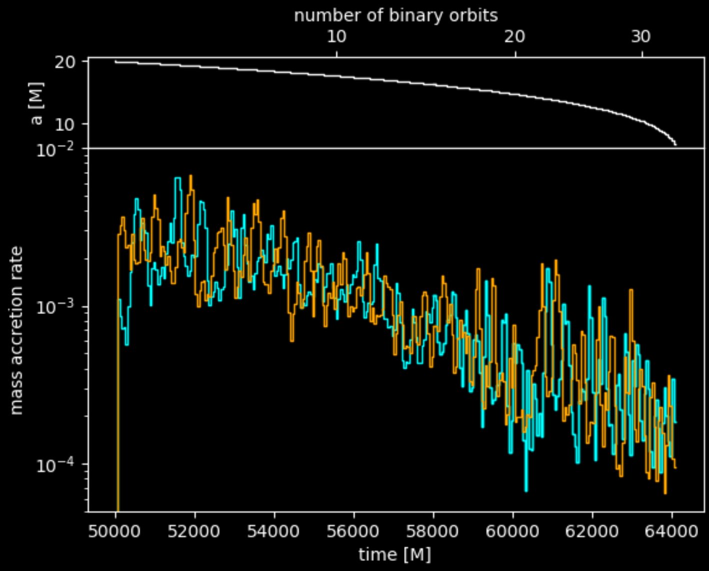
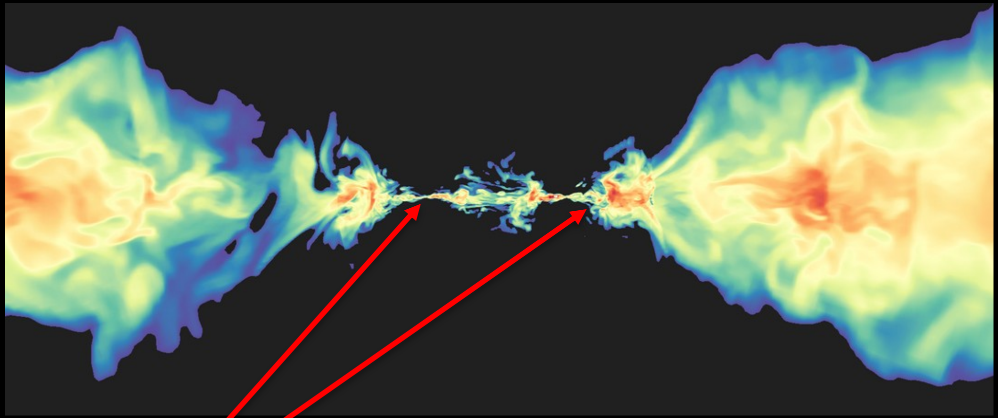
New BH Minidisk physics

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

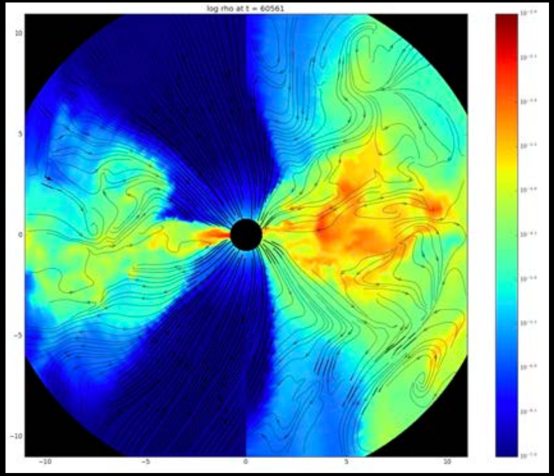


Getting closer to merger!
Adding BH Spins (and oblique jets)!



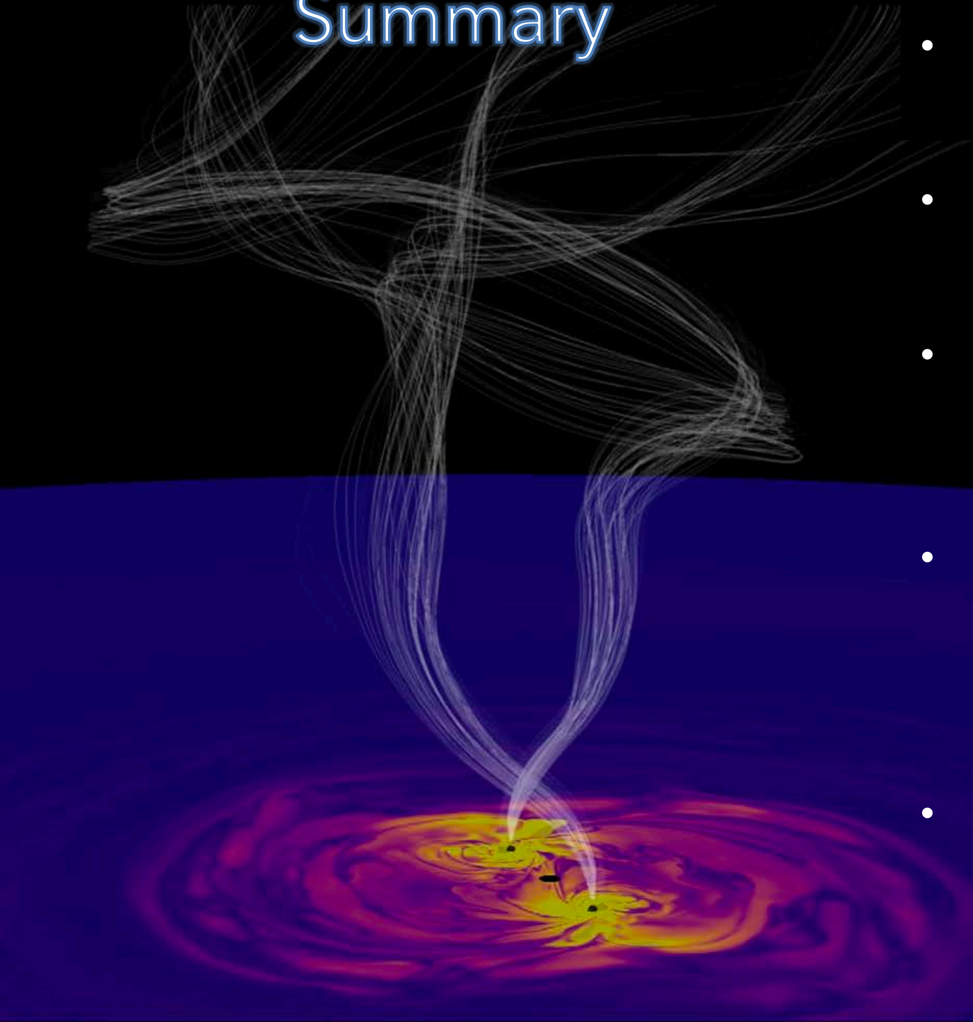
Transient tilts

Mini-disks accretion nothing alike single BH accretion



Stay Tuned!

Summary



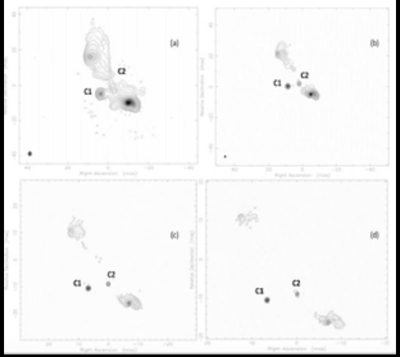
- A lot of binary compact mergers from GW observations, and most are binary black holes!
- Supermassive BH mergers are ideal multi-messenger sources!
- A non-negligible fraction of these sources within the PTA (and LISA) GW range should also be EM observable.
- Lots has been learned already. Accurate 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!

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

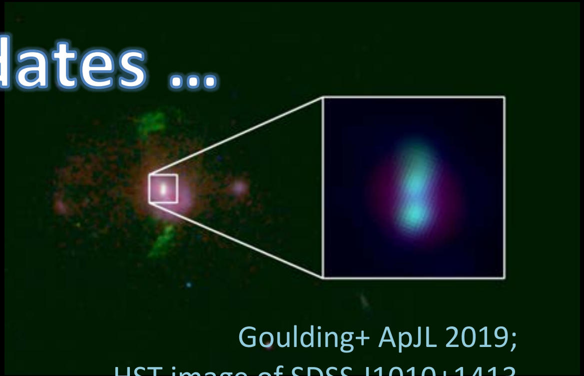
- Direct (e.g. VLBI) imaging:
  Double nuclei (~1 candidate)
  P_{orb}~10^2

- Spectroscopy:
  Offset broad emission lines
  (~100 candidates
  P_{orb} ~ 10s —100s years

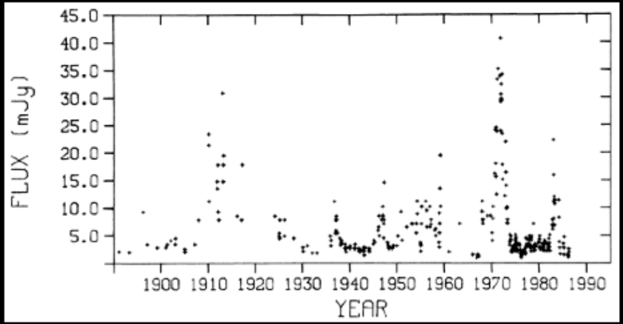
- Photometry:
  Quasi-periodic variability
  (~150 candidates)
  P_{orb} ~ few —10 years



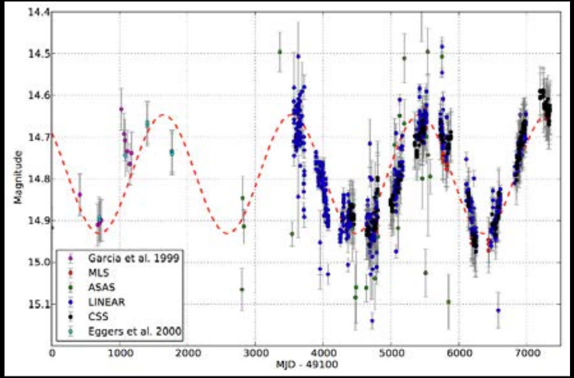
Radio galaxy 0402+379 - Bansal+2017, 12 years of multi-frequency VLBI observations



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



Periodic flares; OJ287 (Valtonen et al. 1988)



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

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

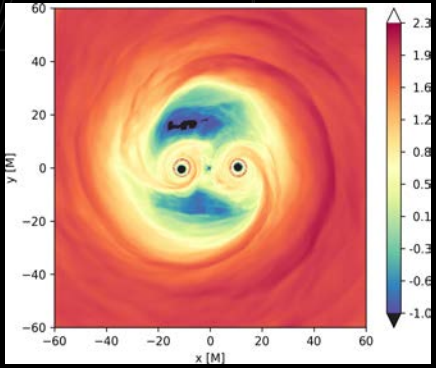
- **Above photosphere, corona emission** modeled as non-thermal (Compton scattering) component with temperature 100 keV:

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

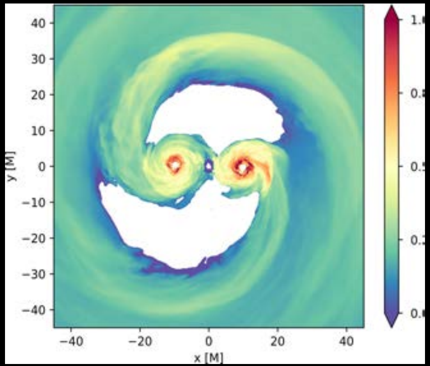
Trakhtenbrot++2017, Krolik 1999, Roedig++2014

- 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