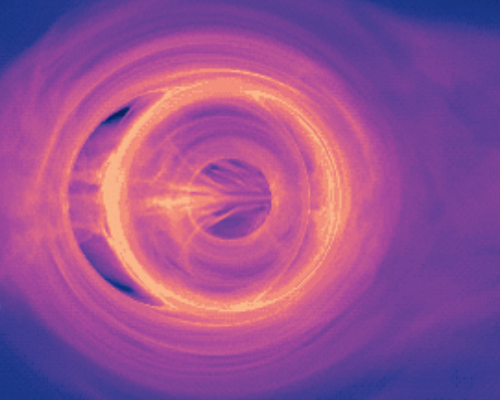
Simulations of Binary Supermassive Black Holes Approaching Merger

Accretion Dynamics, Jets and Electromagnetic Signals



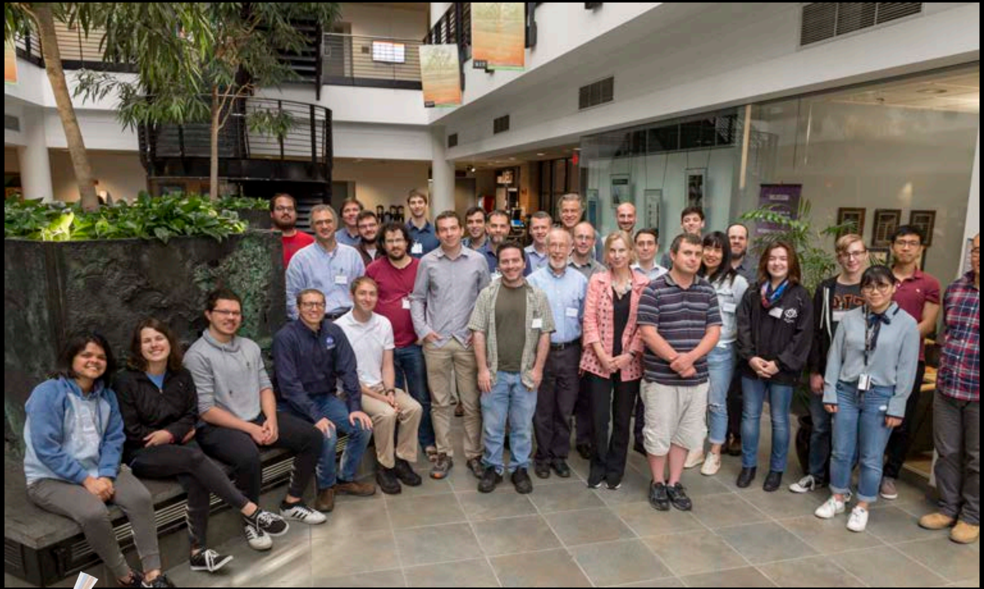
Manuela Campanelli

RIT | College of Science
Center for Computational Relativity and Gravitation

FRONTERA 21

2021 Frontera User Meeting
January 28-29, 2021

NSF
LRAC PHY20010
LSCP AST20021
NASA



Compact-binaries.org

Four site PI institutions (RIT, JHU, GSFC, WVU) and multiple international partners (Berkeley, ORNL, LANL, UCSC, Penn State, INFN, ORNL, LANL, U.Milan, Technion, IAR-Ar, etc)

NSF AST-2009330, AST-1028087, AST-1516150 and PHY-1707946, OAC-1550436; NASA TCAN 80NSSC18K1488.

LRAC AST20021
Total: 4121001 SUs
Current: 2501000 SUs
(2019-2022)

FRONTERA

Users

1. Manuela Campanelli (manuela) ★ PI
2. Scott Noble (tg458565) ☆ Delegate
3. Ariadna Murguia Berthier (armurgui)
4. Bernard Kelly (bernardk)
5. Bruno Giacomazzo (bgiacoma)
6. Eduardo Gutierrez (emgsma)
7. Federico Cipolletta (fcipolle)
8. Federico Lopez Armengol (flopezar)
9. James Healy (healy)
10. Jesus Rueda-Becerril (jmruebec)
11. Joshua A. Faber (tg455526)
12. Luciano Combi (lcombi)
13. Mark Avara (mark_ava)
14. Taeho Ryu (tg863319)
15. Vassilios Mewes (vass)
16. Yosef Zlochower (tg801986)
17. Zachariah Etienne (tg455525)

+ Julian Krolik, Tsvi Piran, Ben Margalit, David Radice,
Sebastiano Bernuzzi, Riccardo Ciolfi,
(40+ in total)
https://compact-binaries.org/people-cb

LSCP AST20021
Total: 1000000 SUs
(2020-2022)

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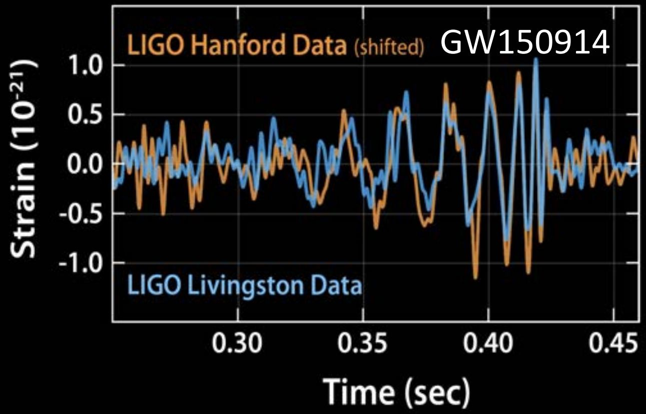
6. Federico Lopez Armengol (flopezar)
7. Leonardo Werneck (werneck)
8. Lorenzo Ennoggi (lennoggi)
9. Mark Avara (mark_ava)
10. Vassilios Mewes (vass)
11. Yosef Zlochower (tg801986)
12. Yossef Zenati (yfree18)
13. Zachariah Etienne (tg455525)

Windows onto the Universe!

Recent gravitational-wave discoveries by LIGO …



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

+

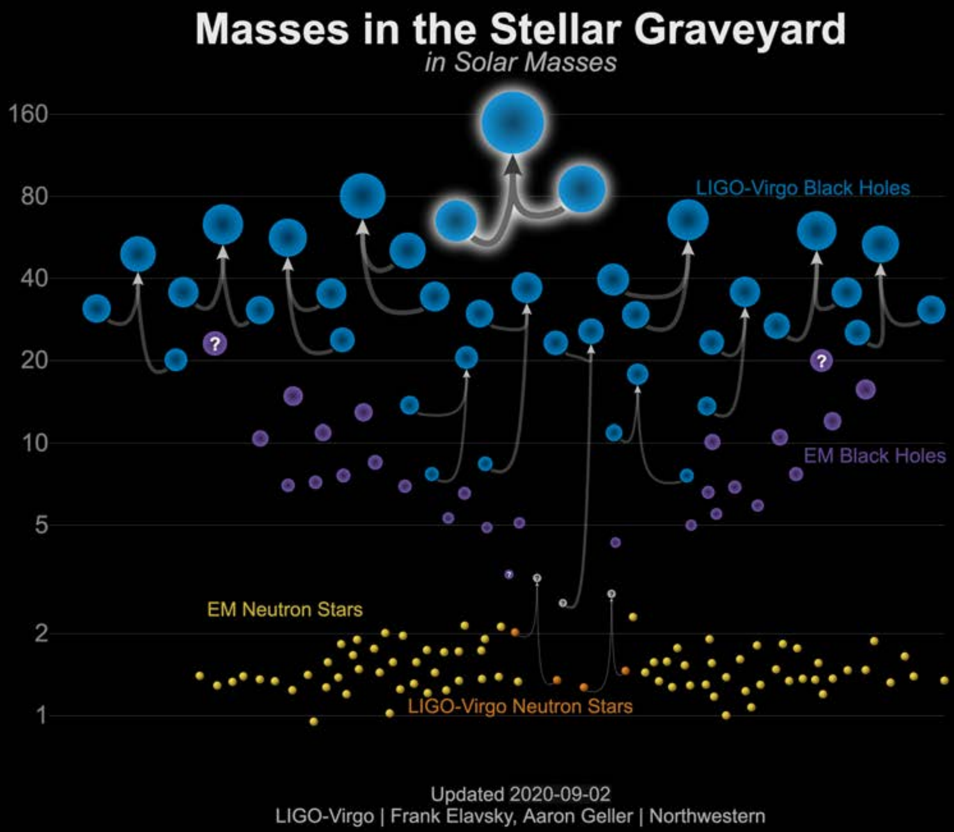
Aug 2017

GW170817

GRB 170817A

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

Compact Binaries Mergers



Many implications for stellar astrophysics, such as production of heavy elements, galaxy formation and cosmology …

What is their population across the universe as a function of the redshift?

What is their astrophysical origin, and environment?

How nature manage to produce black hole binaries with a variety of masses, and spins?

What is the state of matter inside a neutron star? And what power a gamma ray burst?

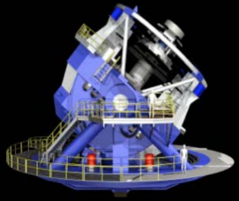
How are jet launched? What is the nature of the merger remnants?

Multi-Messenger Sources

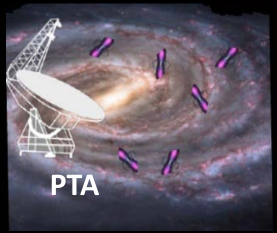
Many of these sources, e.g. accreting binary black holes and binary neutron star mergers, can produce powerful electromagnetic signals and high-energy particles, in addition to gravitational waves.

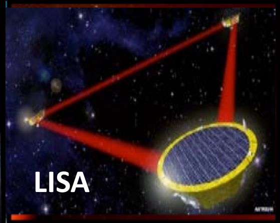
Multi-messenger astrophysics is a new revolutionary field of science in very rapid expansion.

Electromagnetic



Gravitational





Current facilities, such as LIGO/Virgo, 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 demand for high-fidelity physical models will only increase as more exciting discoveries are made.

Supermassive Black Hole Binaries

Supermassive black hole binaries in active galactic nuclei are the primary gravitational wave sources for the **LISA** and **PTA** campaigns. These black holes are also surrounded by accreting magnetized hot gas, and emit powerful radio jets!

What are the electromagnetic signals associated with these mergers?

We need long-term, accurate, GR-MHD simulations to answer this question:

- 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!

Full 3d GR-MHD in Dynamical Gravity

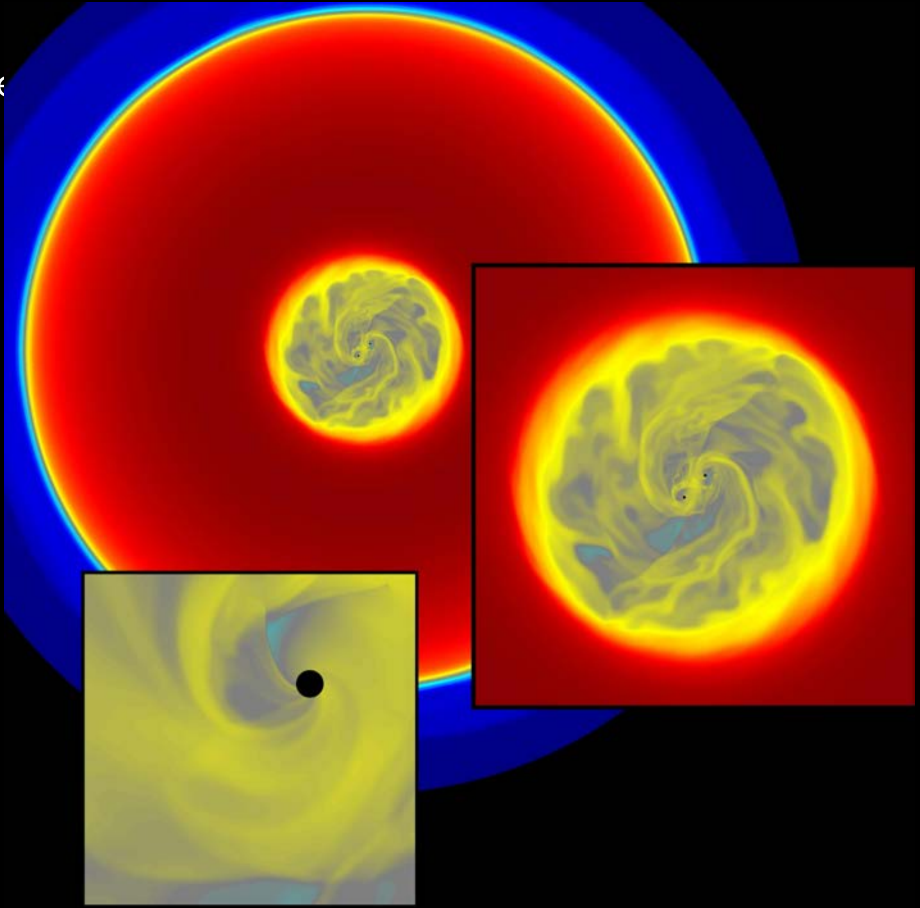
Use, Harm3d, a well-tested, **flux-conservative**, generally covariant, GR-MHD code for black hole accretion disks – Gammie+ 2003, Noble+2006

Modified to handle dynamical spacetimes, radiation and neutrino cooling losses, realistic equation of state of matter - Noble+2012, Murguia Berthier+ in prep 2021.

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

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

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



Scale well on ~1000s nodes …

Our computational strategy for long-term simulations:

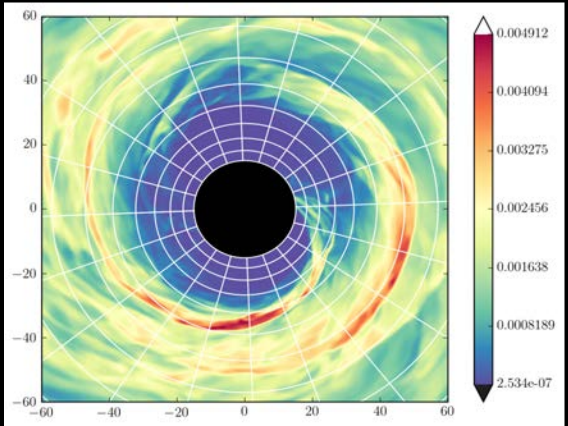
Evolve accreting inspiraling black holes binaries while **resolving angular momentum transport in the disk** and physics near black hole horizons:

1. Perform a long-term GRMHD simulation with a excised central spherical "cut-out" containing the black holes in order to afford longer evolutions so we achieve steady accreting circumbinary disks.

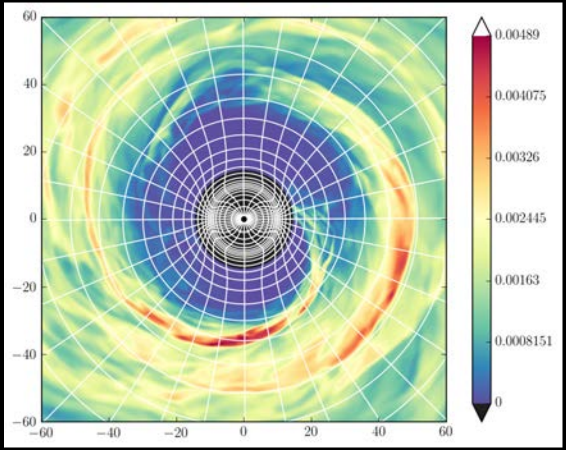
2. At "equilibration", interpolate the computational domain into a new grid designed to resolve the physics near each black holes.

Use warped curvilinear grids – Zilhão+2014, multipatch scheme Avara+ in prep 2021

Each run requires~ 10^7 cells, 10^7 time steps



20,000+ SUs
250+ binary orbits
20+ days



400,000+ SUs
15+ binary orbits
60+ days

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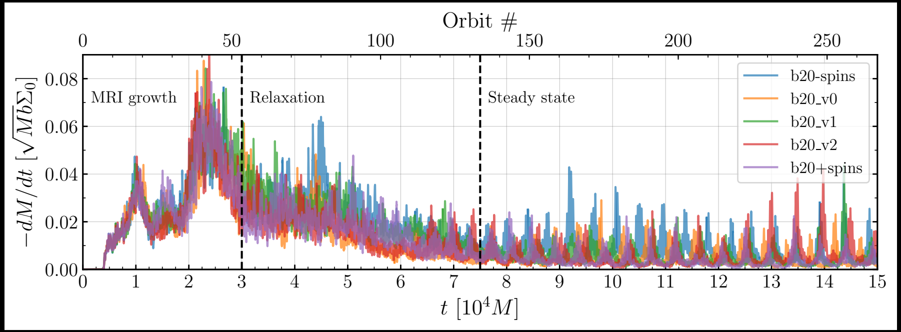
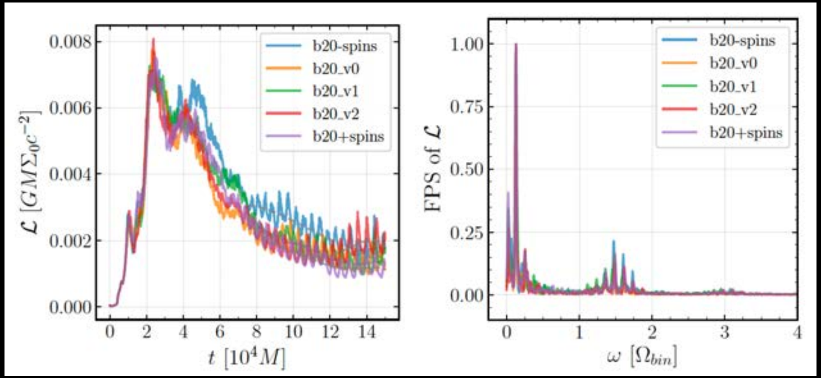
TEXAS ADVANCED COMPUTING CENTER

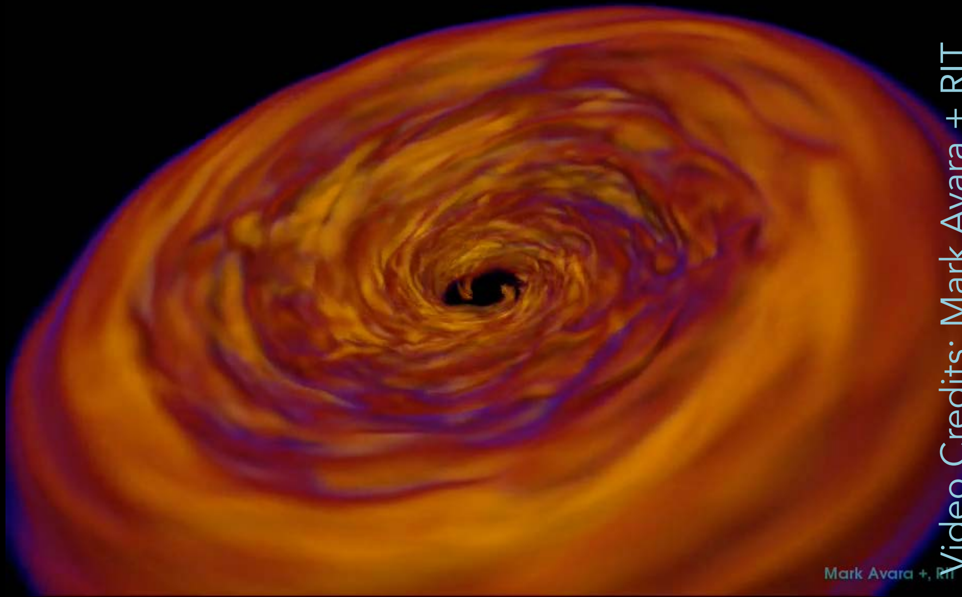
Circumbinary Disk Dynamics in Spinning Black hole Binaries

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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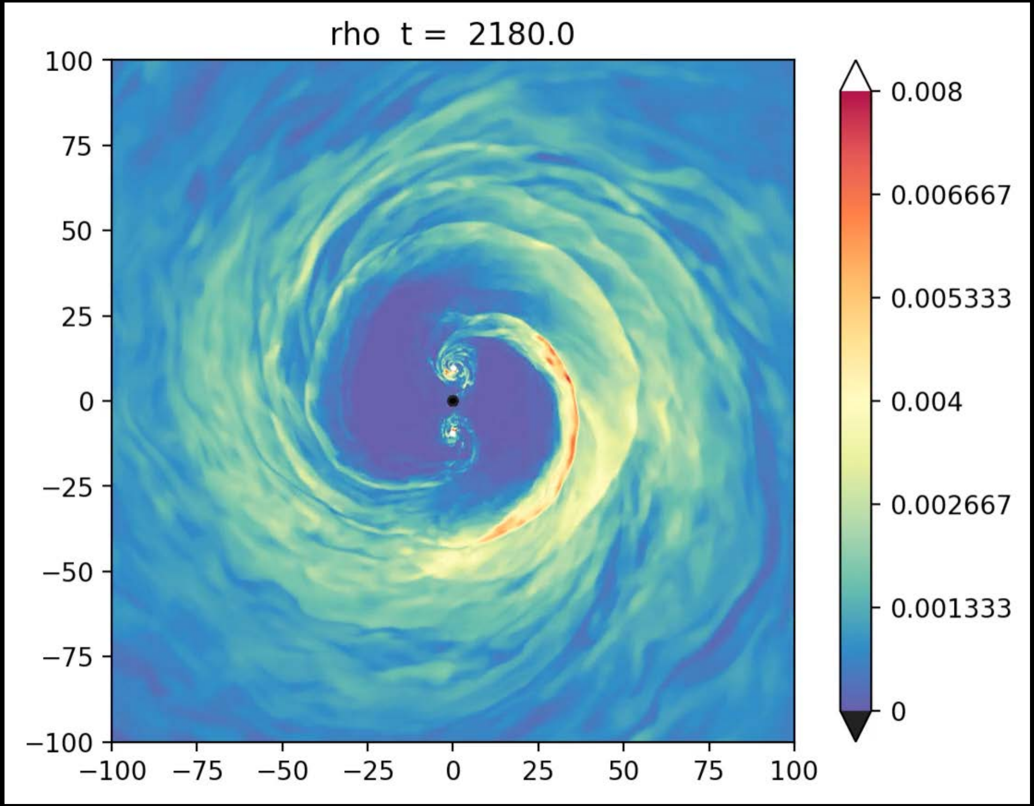
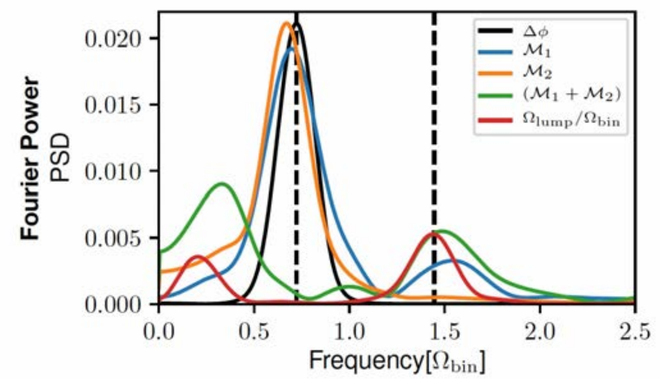
Mass Exchange between the BHs



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

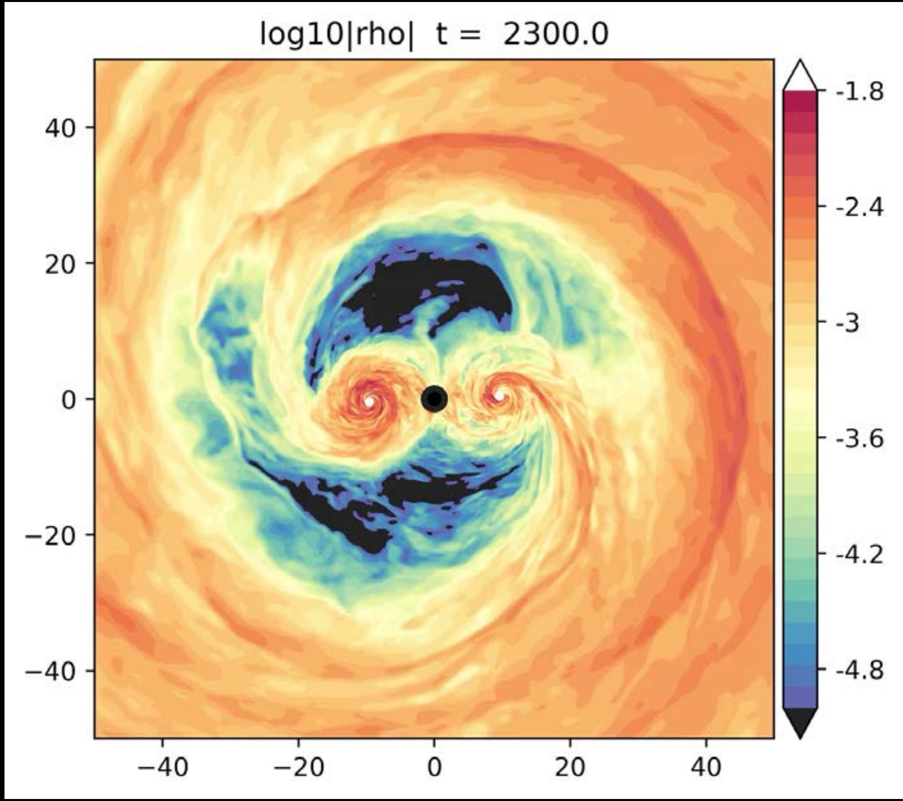
Accreting streams fall in the cavity and shock against the individual minidisks.

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



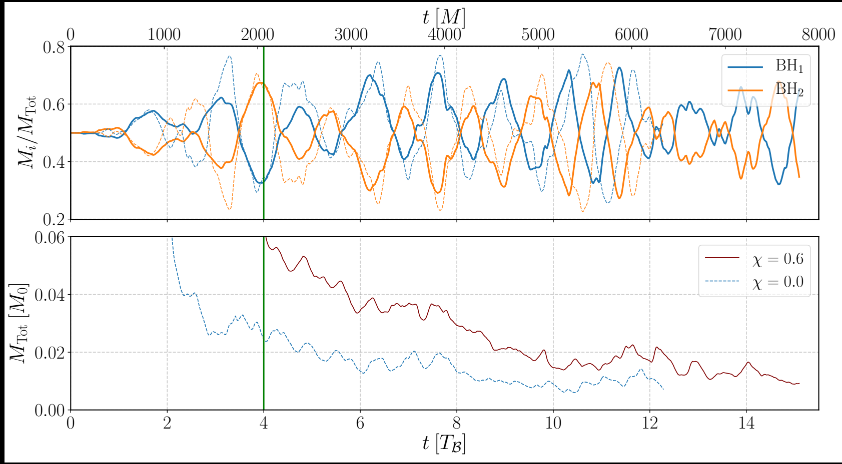
Credits: Bowen (RIT/LANL) 2019

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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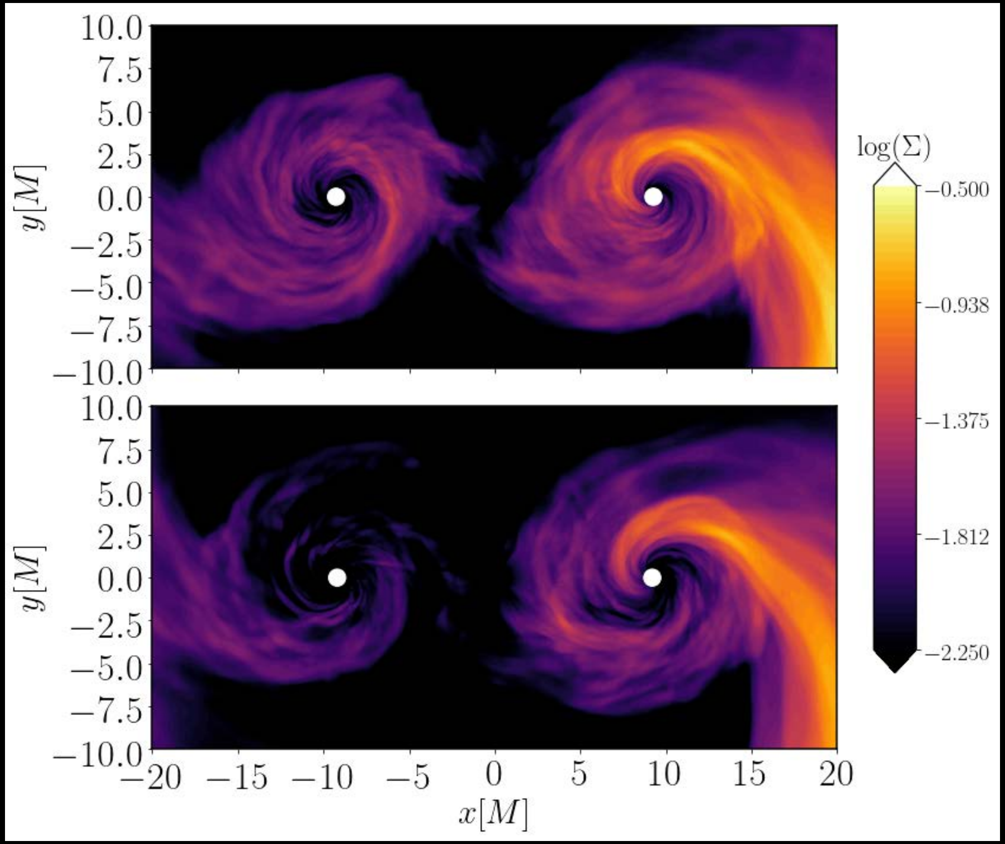
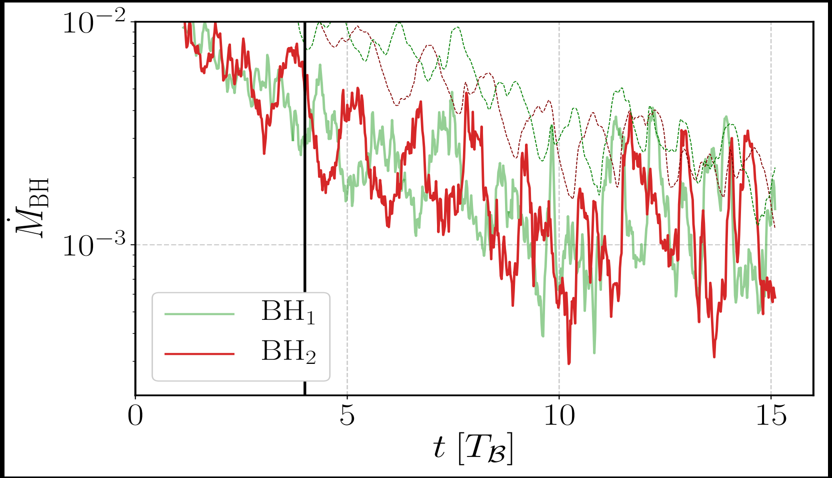
On the effect of the BH spins …



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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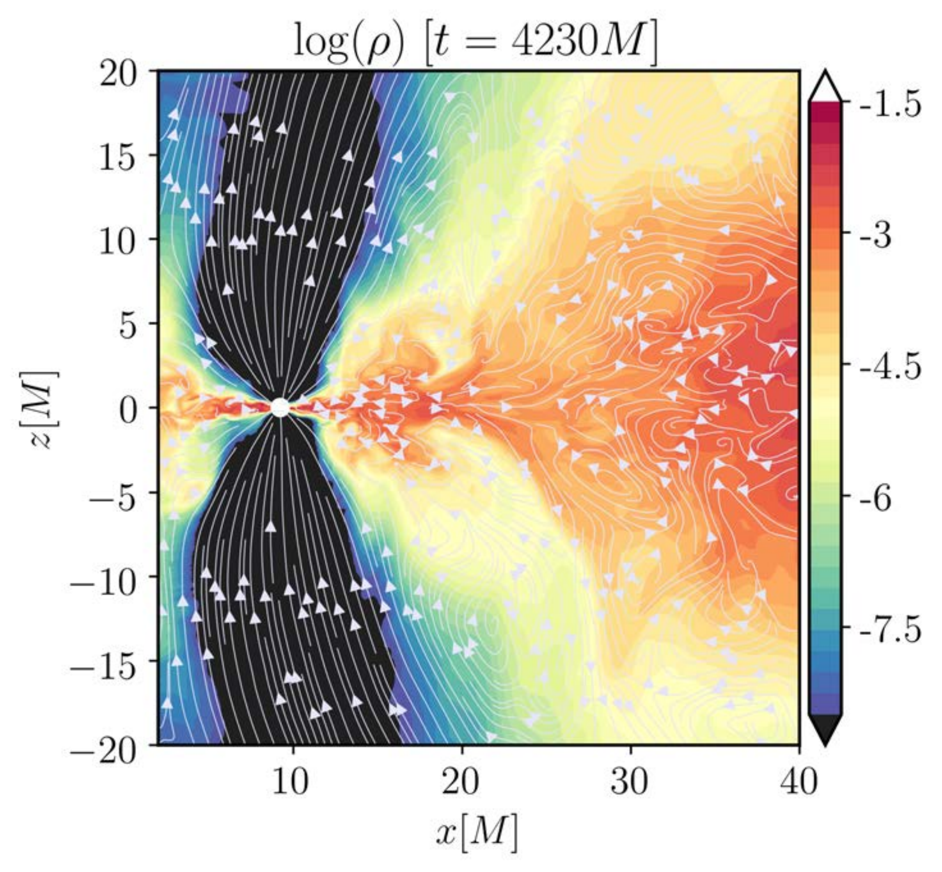
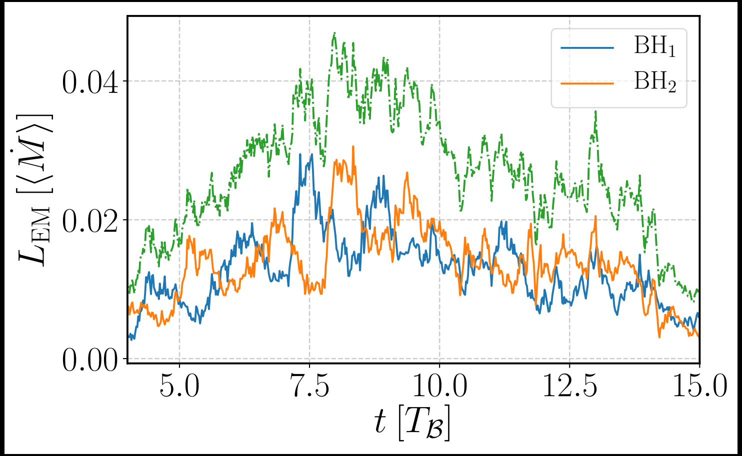
BH Spins and Jets!



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

Credits: Luciano Combi + (RIT/IAR)

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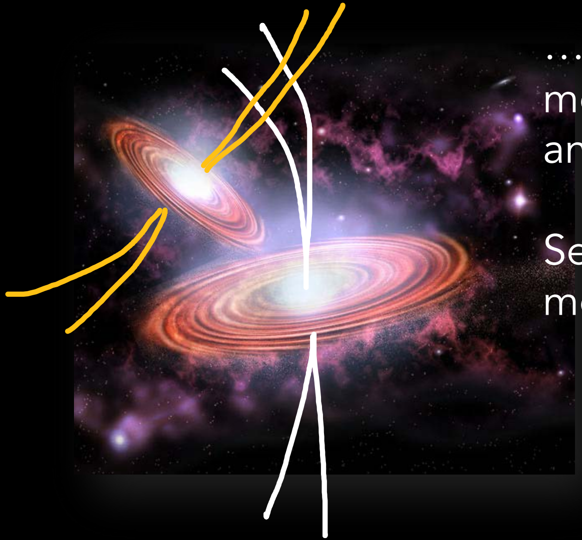
More on BH Spins and Jets!

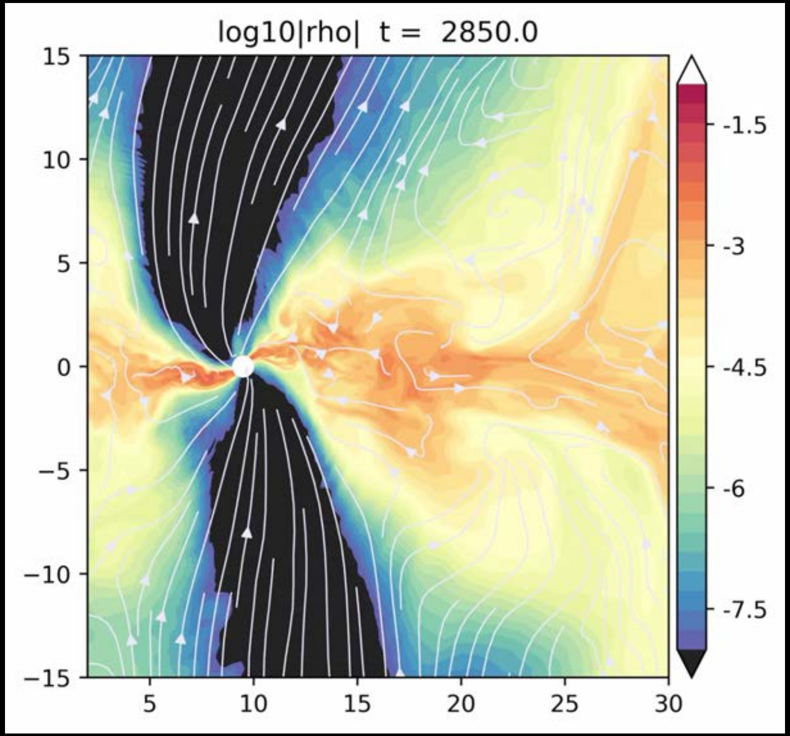
More magnetized mass + BH ergospheres means more jet-like structure!

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

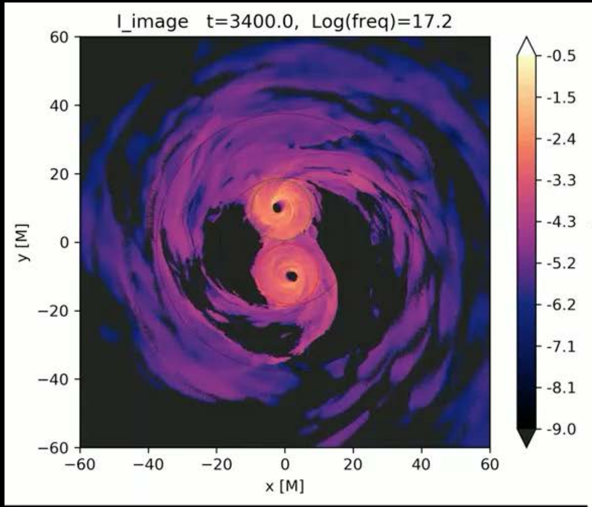
Intensity of X-rays (log scale) multiple-angle video in time

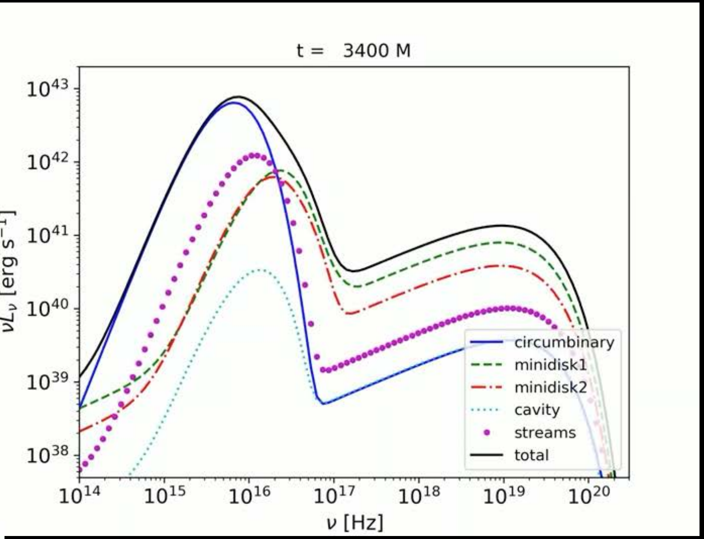
Credits: S. Noble (NASA/RIT)

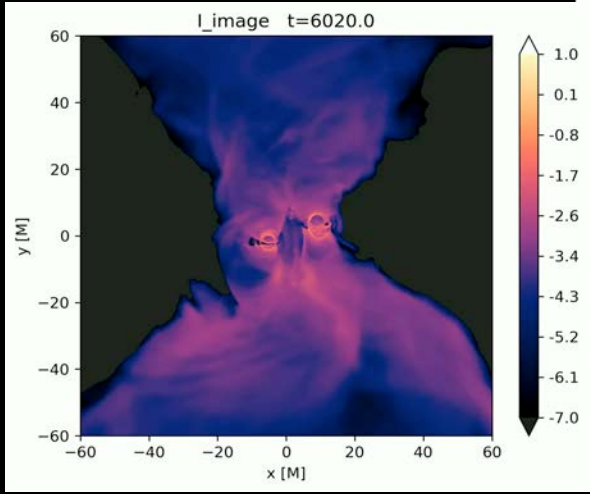
Light Signals from Spinning Black Hole Binaries

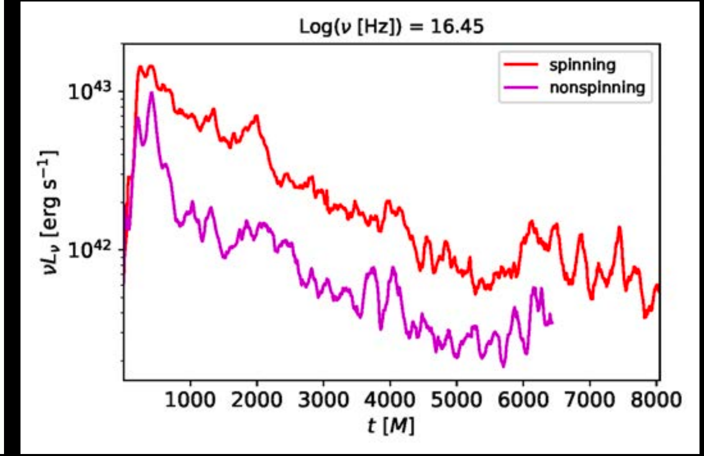
Gutierrez+ in prep 2021

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









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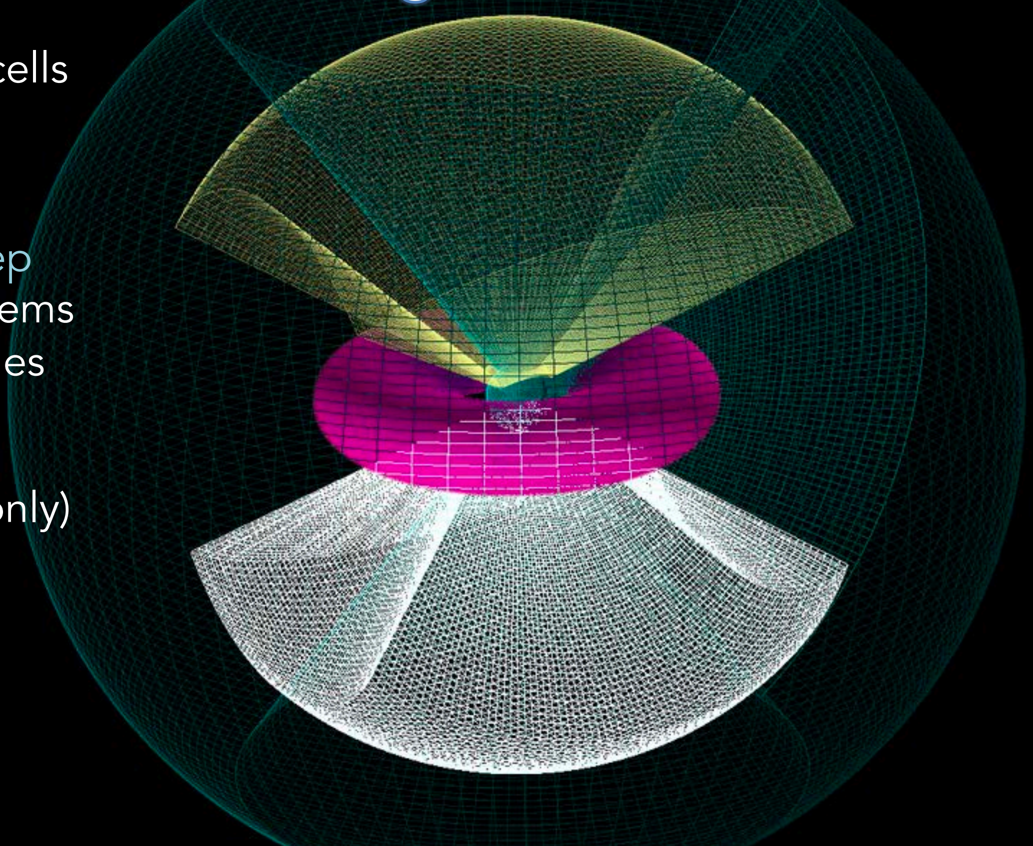
Credits: Gutierrez (RIT), based on Combi+ 2021

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

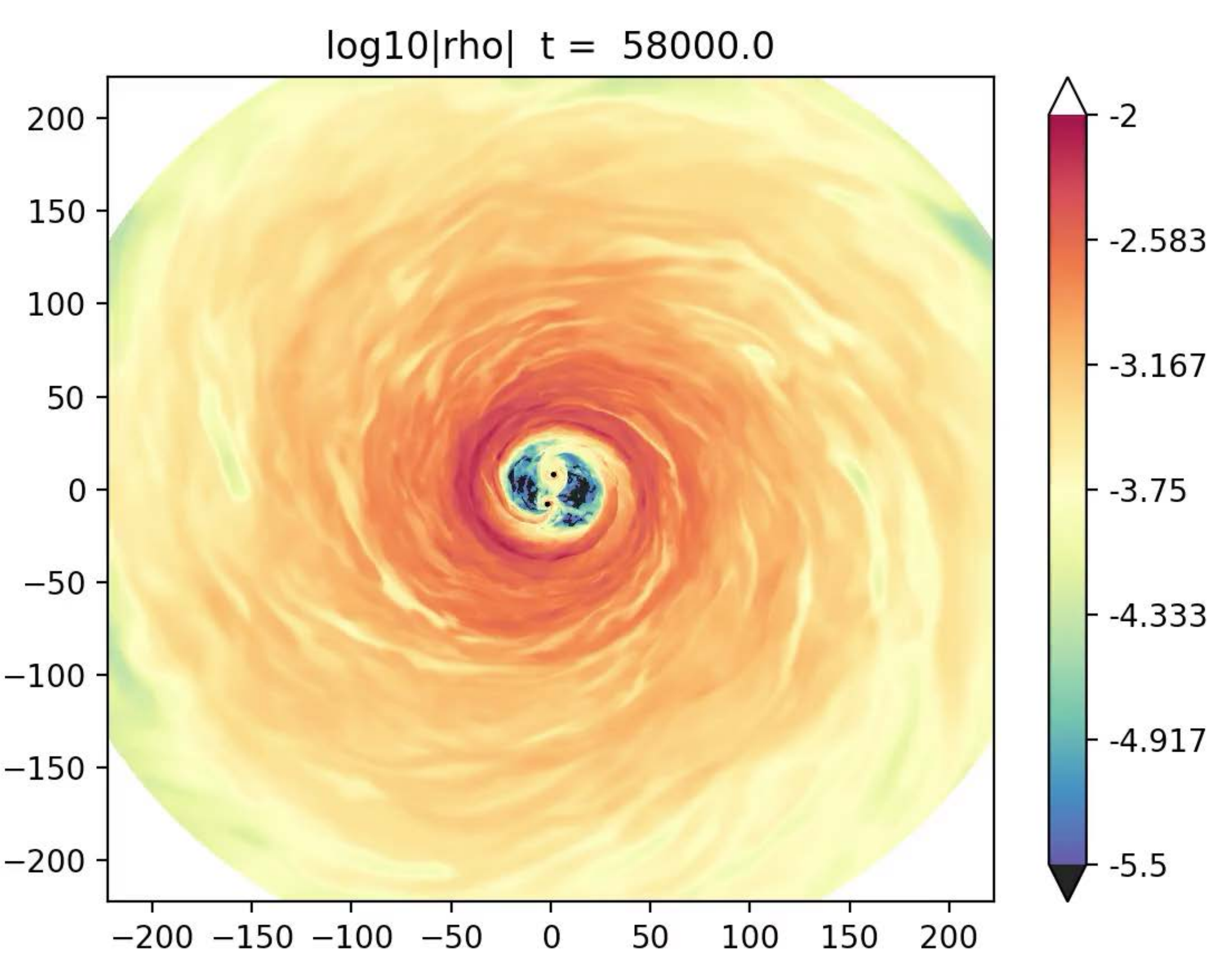


Accretion onto a single BH + Jet

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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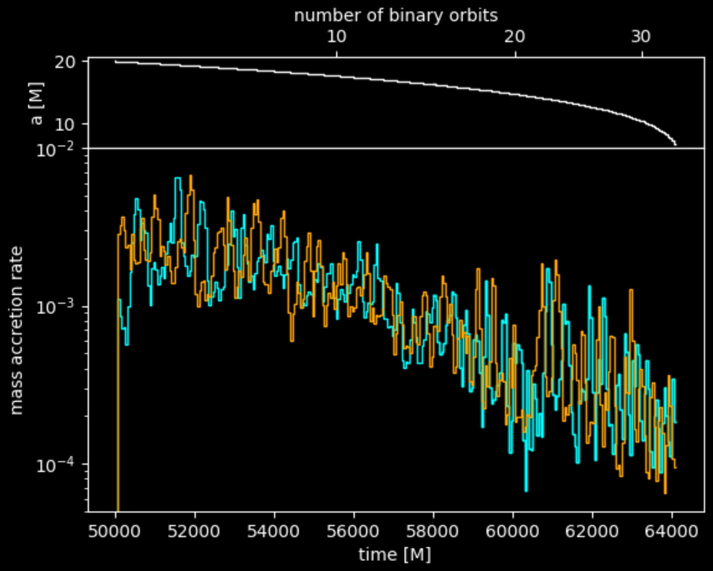
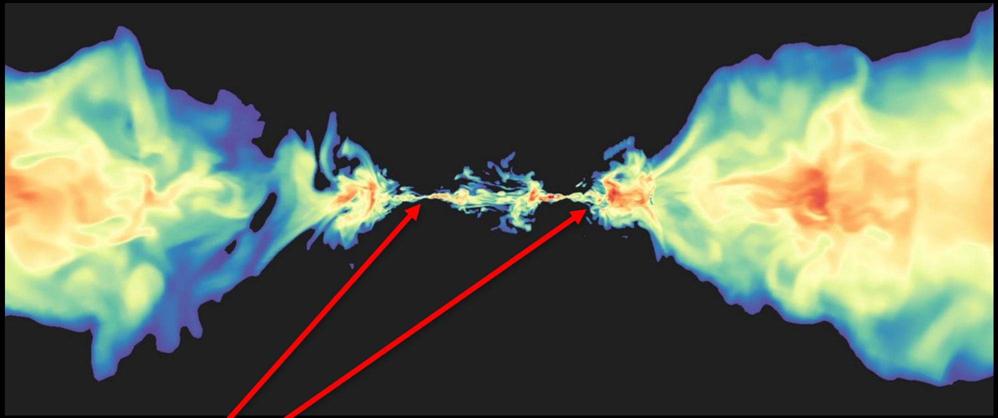
New BH Minidisk physics

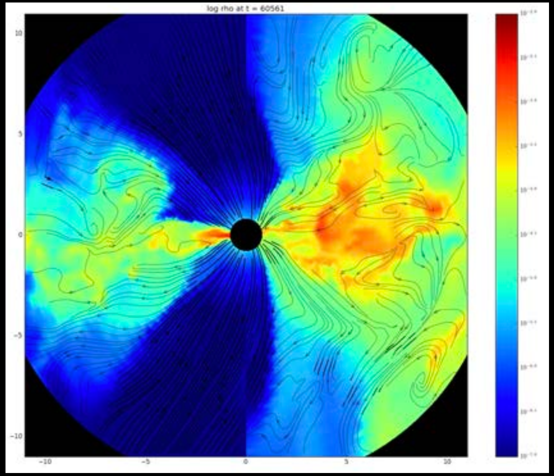
New 3d structure and dynamics of the BH mini-disks revealed – Avara+2021 in prep



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



Transient tilts



Mini-disks accretion nothing alike single BH accretion

Stay Tuned!

Cyberinfrastructure Challenges:

Successful Simulations require very advanced numerical algorithms, which scale well on the lagest petascale/exascale supercomputer

A lot of computing time, fast processors with peak petaflops performance, excellent interconnect, lots of memory per node!

XSEDE

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

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Mid-scale (local) facilities are also required for code development and testing, and to perform a range of data analysis projects.

Need 21st century tools for multi-scale, multi-physics simulation!

We need to continue to improve our software bottlenecks due data exchange between processors and inefficiencies due to load-unbalances.

Open Source Scalable software Infrastructure.

Discussion:

The promise of multi-messenger can be realized only if sufficient, sustained and community cyberinfrastructure is available!

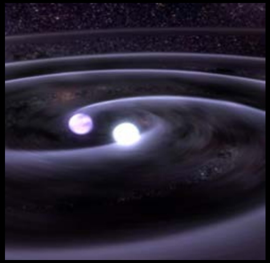
- Multi-domain expertise of astrophysicists, physicists and software engineers.
- Sustained ecosystem of collaborative, scalable, software Infrastrucure.
- Continued access to Peta/Exascale Supercomputers, such as Frontera, with user support.
- Public, coordinated, data/code repositories and common portal /hub to share simulation products with the larger scientific community and observers.
- Workforce training and retention.

About BNS simulations ...

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

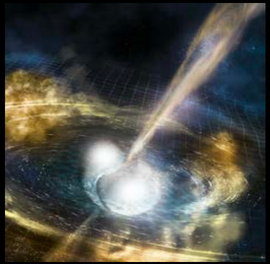
- ➢ NR + GRMHD
- ➢ Nuclear and Neutrino Physics, EOS
- ➢ Neutrino/photon transport
- ➢ R-processes/nucleosynthesis

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



GW170817

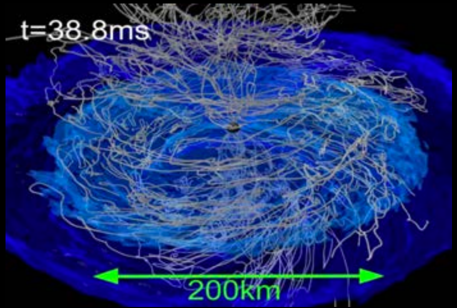
+



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



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

Kenta Kiuchi+ 2015

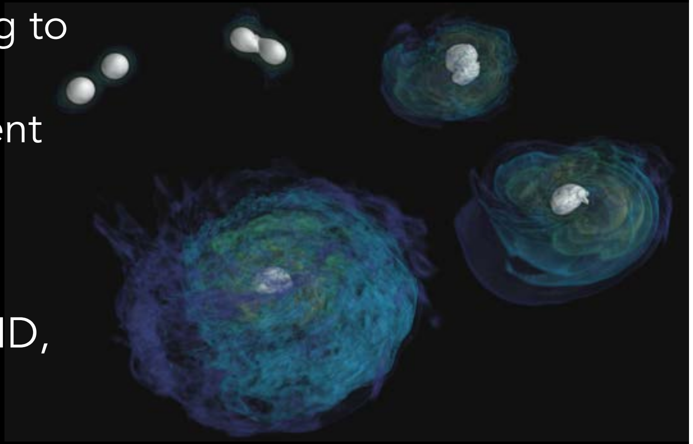
Need to simulate ~1 sec after the onset of the merger with resolutions of the scale of the MRI!

TCAN: Building an Integrated set of Computational Tools for the entire Binary Neutron Star mergers

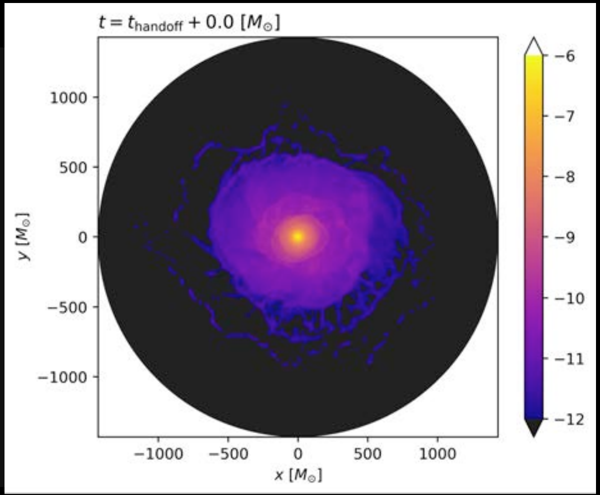
Advancing Computational Methods to Understand the Dynamics of Ejection, Accretion, Winds and Jets in Neutron Star Mergers

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

- Implementing the most advanced physics (GRMHD, EOS, neutrinos) with the needed consistency for stable data hand-off from one code to another.



Ciolfi+2019



Lopez-Armengol+ in prep 2021
Murguia Berthier+ in prep 2021

LSCP AST20021

Now complete, and merger/postmerger BNS simulations are underway on TACC's Frontera.