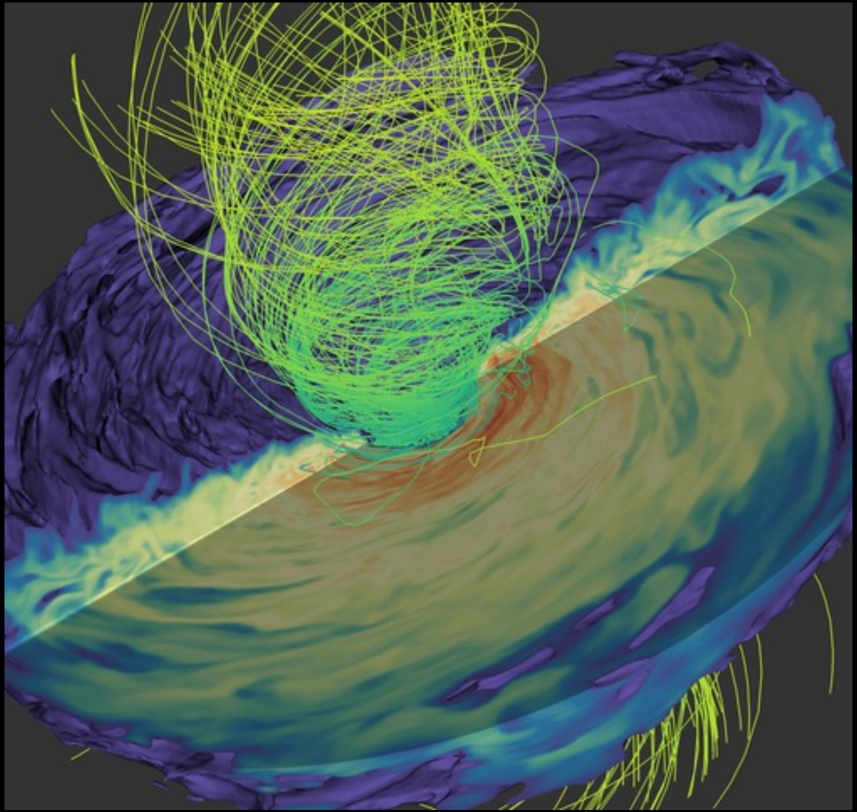
Simulations of Supermassive Black Holes Binaries Mergers

Transients 2020

Kavli-IAU Workshop

3-7 February 2020 – Cape Town



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The Lifecycle of Supermassive BH Binaries Mergers

- Supermassive BH binaries (SMBBHs) 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 …

Many implications for galaxy formation and evolution …
What is their astrophysical origin, and environment?
And what is their population across the universe as a function of the redshift?

Ideal Multi-Messenger Sources

- SMBBHs are primary GW sources for **LISA** and **PTA** campaigns.

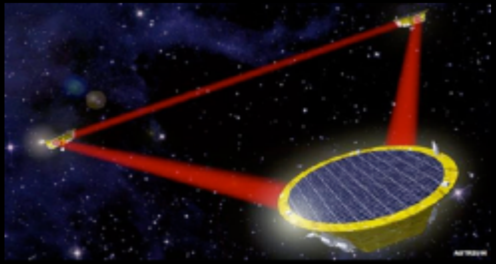
- SMBBHs in AGN are surrounded by accreting hot gas and emit powerful radio jets, so the probability of lots of accretion into binaries is enhanced by being post-galaxy-merger.

- As EM sources, they are ideal candidates for exploring plasma physics in the strongest and most dynamical regime of gravity;

"Standard Sirens" Sources for Multi-Messenger Astrophysics

Electromagnetic

Gravitational



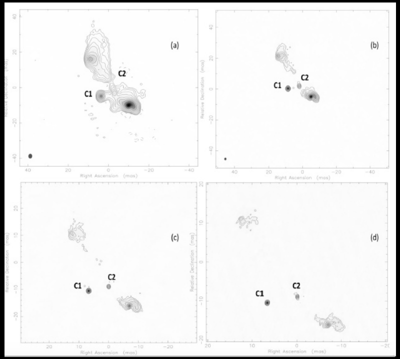
- **Realistic simulations are needed for EM identification and characterization of SMBBH mergers!**

How to distinguish binaries from single AGN?

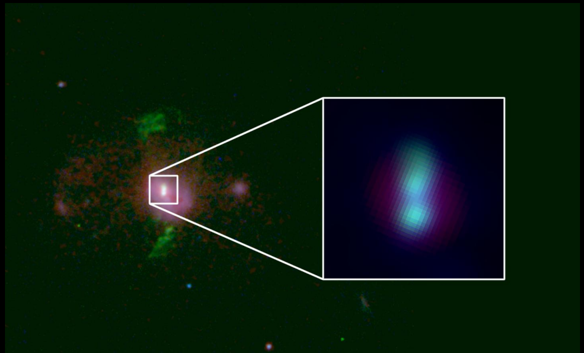
New population estimates of **EM-distinguishable binary-AGN** from galaxy evolution models and analytical theory models (supplemented by simulations) find ~10^2 sources at redshifts z~0.5-1 (at flux levels >10^{-13} erg cm^{-2} s^{-1}) -- Krolik, Volonteri, Dubois, and Devriendt, 2019

~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 Supermassive Black Hole Binaries

- Scales span several orders of magnitude from astrophysical origin to final merger; and the parameter space is absolutely huge!

- This is computationally very challenging and require sustained coordinated efforts among multiple simulation and theory efforts.

Galaxy Mergers

Binary Formation

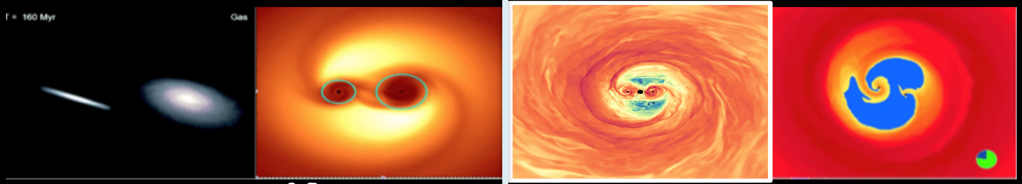
$t_{inflow} \ll t_{GW}$

Inspiral

$t_{inflow} \sim t_{GW}$

Merger:

$t_{inflow} \gg t_{GW}$



e.g. Hopkins, Hernquist

e.g. Farris++2013

Noble++2012, Bowen++2019

Farris++2011

What this require?

- ➢ Informed astrophysics input from pre-merger stages;
- ➢ Accurate 3d magnetohydrodynamics + dynamical general relativity;
- ➢ Realistic thermodynamics and radiation treatments;
- ➢ Long and accurate simulations to equilibrate the system!

Multi-Physics, Multi-scale Simulations of MMA Sources

Long, accurate, GRMHD simulations in 3d are used to both guide and interpret MM$\boldsymbol{\lambda}$, MMA observations of compact binary systems.

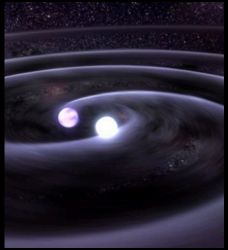
In most transients sources, GW and EM signals depends on the complex coupling among:

- ➢ Dynamical GR-MHD
- ➢ Nuclear and Neutrino Physics
- ➢ Radiation transport (photons + neutrinos)
- ➢ R-processes/nucleosynthesis

Inherently 3d problems that cannot be easily captured by Analytical Models:

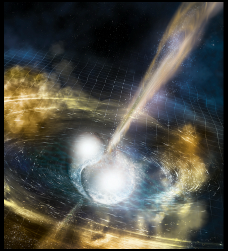
- ➢ Fluid and MHD instabilities
- ➢ multi-D structure
- ➢ multi-spatial scales

Binary Neutron Star Mergers Simulations



GW170817

+



GRB 170817A

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

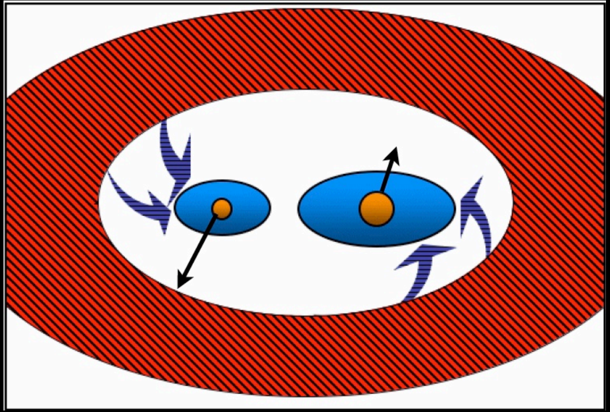
- ➢ BH + accretion disk
- ➢ Hypermassive long-lived NS + torus – delayed collapse to a BH
- ➢ Stable NS
- ➢ or anything in between?

Theoretical and Computational Astrophysics Network

NASA

A Brief Perspective on the History of SMBBHs Simulations

- Early Newtonian 1d hydrodynamics simulations 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, Palenzuela+2011, Giacomazzo+2012; Gold+ 2013.
- Modern 2d hydrodynamics and 3d MHD simulations **completely reverse this picture find a lot of accretion!** – Shi+2012, Noble+2012, D'Orazio+ 2013; Farris +2014; Ryan+2016, Tang+2018; Bowen+2017,2019, Avara+2020 …



Simple schematic Description

- The balance between angular momentum gain and lost in the accretion and binary torques is still investigated - Miranda+ 2017, Munoz+2019, Moody+2019 – but need long-term simulations, beyond simpler Newtonian gravity and alpha disk accretion theory …

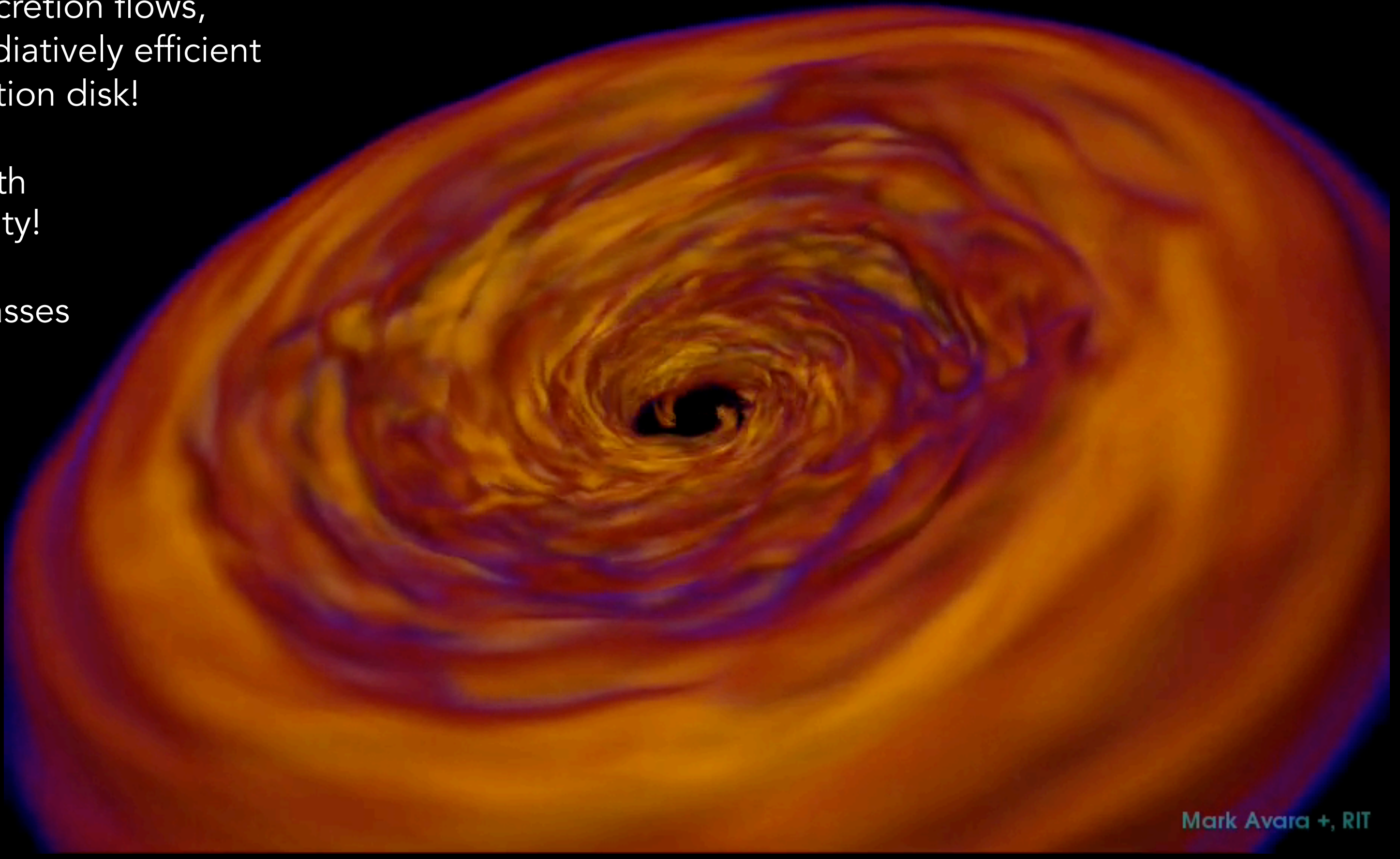
First long-term Simulations of SMBBH approaching Merger

Fully relativistic magnetohydrodynamics treatment of turbulent accretion flows, with resolved MRI and radiatively efficient (geometrically thin) accretion disk!

Binary torques treated with dynamical general relativity!

Simulations scale with masses (radiation transfer set the physical scale)

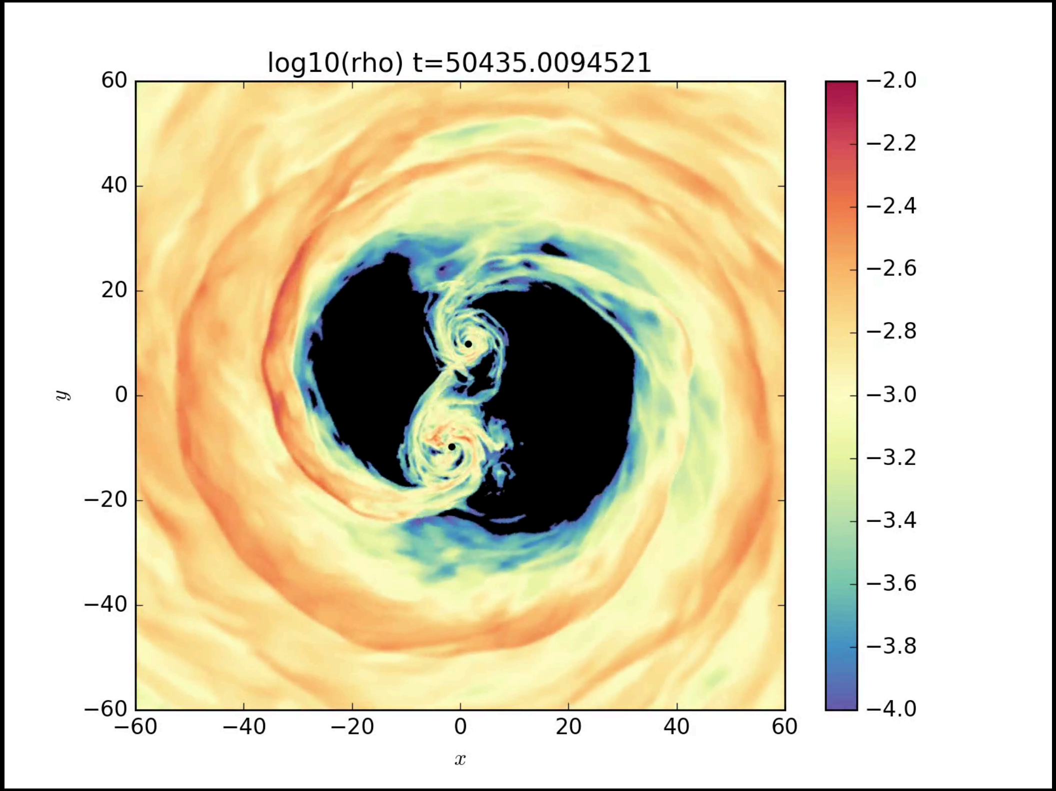
Hundred of binary orbits (GW inspiral approaching merger)



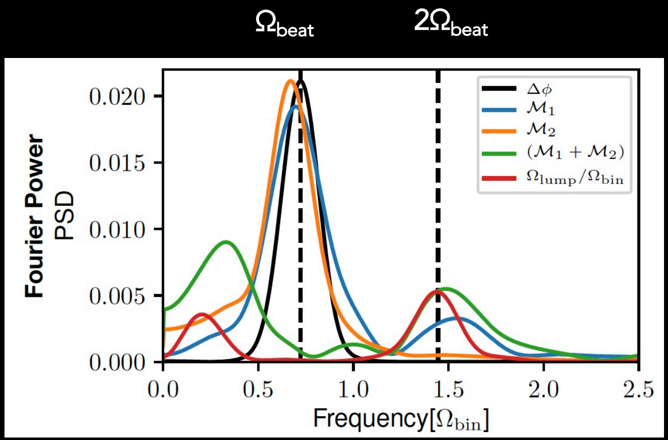
Noble+2012, Bowen+2018, 2019, Avara+2020

Dynamics in the Central Region

We discovered new dynamical interactions between the mini-disks and circumbinary disk (equal mass binary) – Noble+2012, Bowen+2018, 2019, Avara+2020



- 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, Noble, Avara, Campanelli, Krolik, ApJ 2019

Calculations of Distinct Light Signals

The first predicted time varying spectrum from accreting SMBBHs in the inspiral regime with radiation transport (ray-tracing) treatment – D'Ascoli+2018;

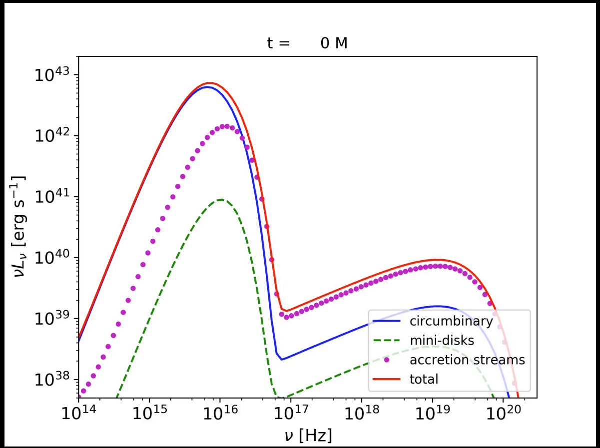
Key distinctions from single BH (AGN) systems:

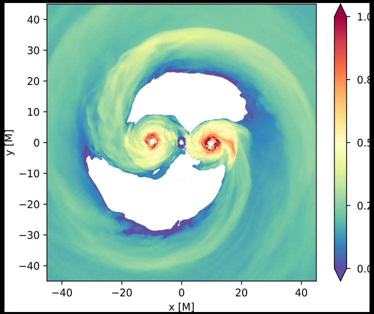
- Brighter X-ray emission relative to UV/EUV.
- Variable and broadened thermal UV/EUV peak.

Analytic theory predicts a "notch" between thermal peaks of mini-disks and circumbinary disk – e.g. Roedig+2014

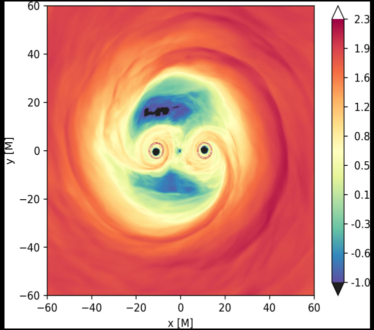
Radiative Transfer Model:

Photons starting at photosphere as black-body; above photosphere, corona emission modeled as non-thermal (Compton scattering) component with temperature 100 keV.





Map of Photosphere's Location & Temperature $\mathrm{Log}_{10}(T_{eff}/T_0)$, $T_0=5\mathrm{x}10^5$K



Log10 Optical Depth Grey Thomson Opacity

Face-on View, Optically Thick

$M_{BH}=10^6 M_\odot$

$P_{orb}\sim$ hours

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

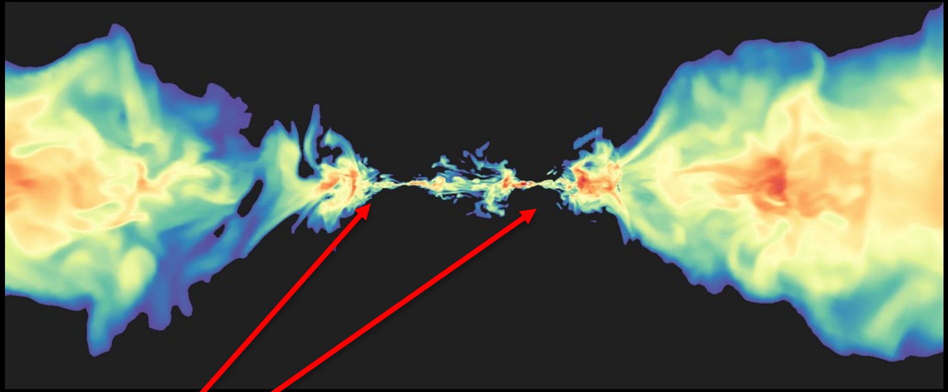
Optically Thick Case

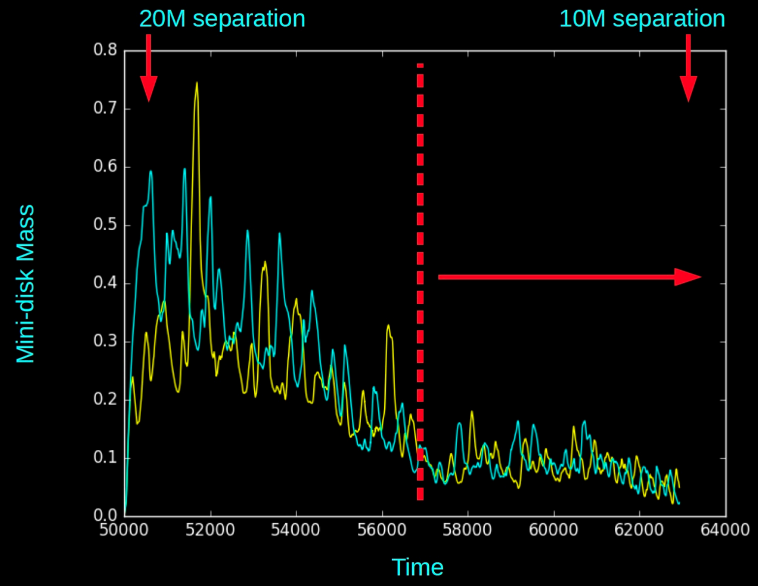
Intensity of X-rays (log scale) multiple-angle video in time

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

New 3d Accretion Dynamics

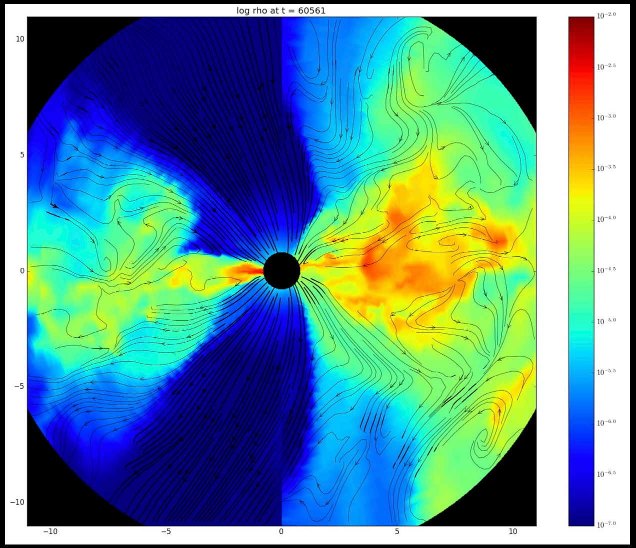
New 3d structure and dynamics of the BH mini-disks revealed – Avara+2020





Transient tilts – warped disks

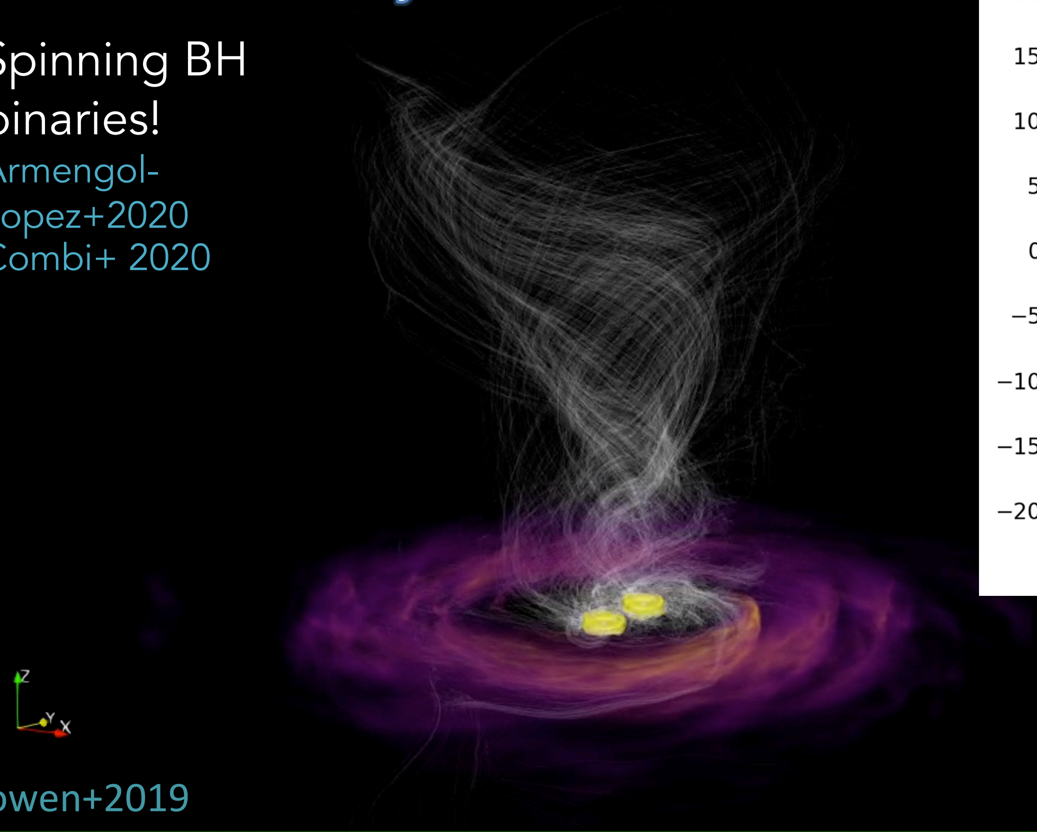
Mini-disks accretion nothing alike single BH accretion



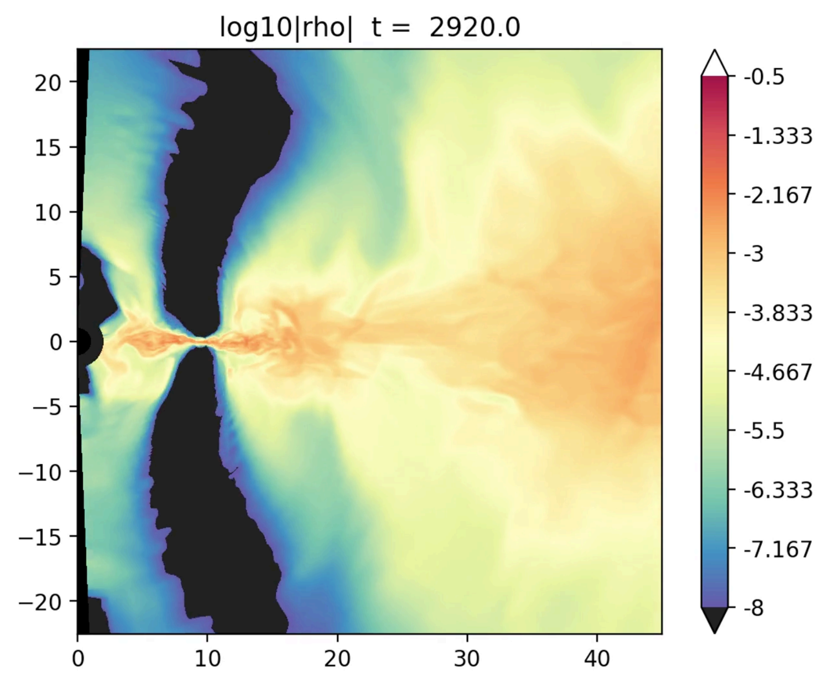
Double Jets Dynamics

Spinning BH binaries!

Armengol-Lopez+2020
Combi+ 2020



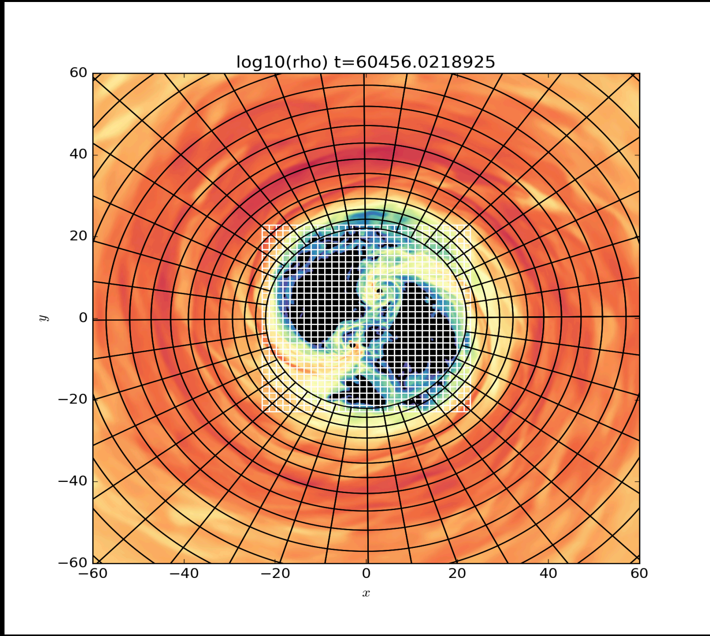
Bowen+2019

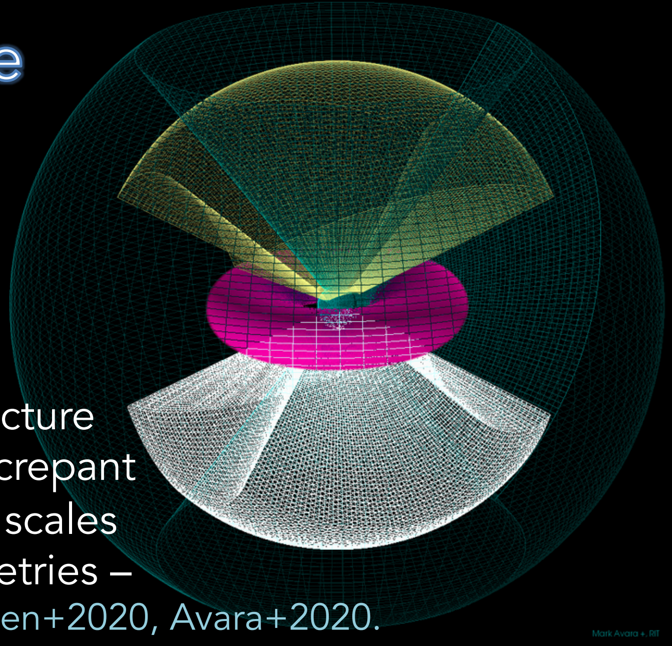


Each simulation require about 10^7 cells evaluated at approximately 10^7 time steps, using 10,000 cores (e.g. each run requires several millions CPU hours).

Multi-physics, Multi-scale Infrastructure for Exascale Computing:

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





- Multipatch infrastructure for problems of discrepant physical, temporal, scales and multiple geometries – Shiokawa+ 2018, Bowen+2020, Avara+2020.

- Alternatively approaches: AMR grids but mostly used for single grid geometry e.g. Cartesian.

- Bottleneck: load balancing and scalability among many thousands of processors!

Sustained Cyberinfrastrure is Important!

Successful Simulations require very advanced numerical algorithms, which translates into in hundred thousands lines of code!

The Advent of Supercomputers
Pioneering efforts on supercomputers at Livermore Natl Lab and NCSA by Larry Smarr in the 1970s and 80s.
Thanks to NSF support!

XSEDE

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

FRONTERA
TACC
TEXAS ADVANCED COMPUTING CENTER

- Performing such large simulations in a reasonable amount of time today is only possible on the largest Supercomputers (fast processors with peak petaflops performance, excellent interconnect, lots of memory per node);

- This is often aided by local resources (mid-scale facilities) for efficient testing and prototyping

- Collaborative research to develop core computational tools:
  - Harm3D/PatchworkMHD (TCAN)
  - WhiskyMHD+, Spritz+
  - Einstein Toolkit +IGM (open source)
  - BAM ++
  - SPEC/Spectre (SXS)

- <u>Bottlenecks</u>: load balancing and scalability, and long-term sustained efforts!

The pay-off of Numerical Relativity Simulations in GW Science

Numerical Relativity Simulations + Analytical Models (calibrated to simulations) are successfully used to match LIGO/Virgo observations, interpret and extract the parameters about the GW sources!

They are also used to test general relativity and for events visualizations
- Many Abbott+ papers

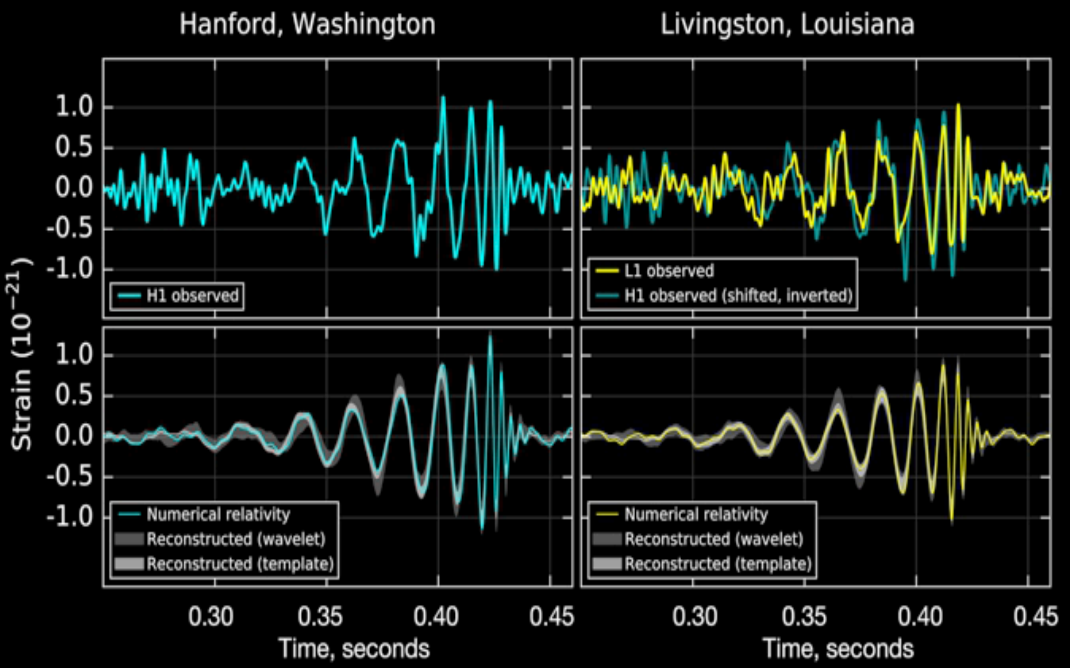


IMAGE CURTESY OF LIGO, NSF
Abbott++, 2016

"The merger phase is challenging and requires numerical relativity calculations to permit comparison between observation and theory."
Scientific Background on the Nobel Prize in Physics 2017

Catalogs of pre-calculated Waveforms!

Numerical relativity community in the LVC is working to build extensive catalogs of waveforms:

- SXS+Gatech+RIT Catalogs contain thousands of waveform;
- 8d parameter space: mass ratio, BH spins, and orbital eccentricity;

Waveforms scale in frequency and are therefore directly application to LISA as well.

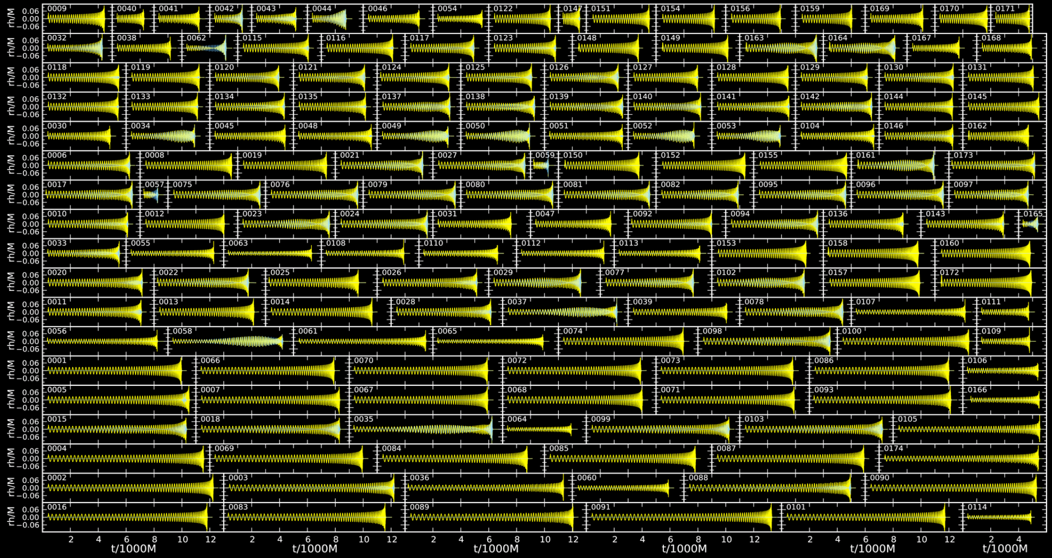
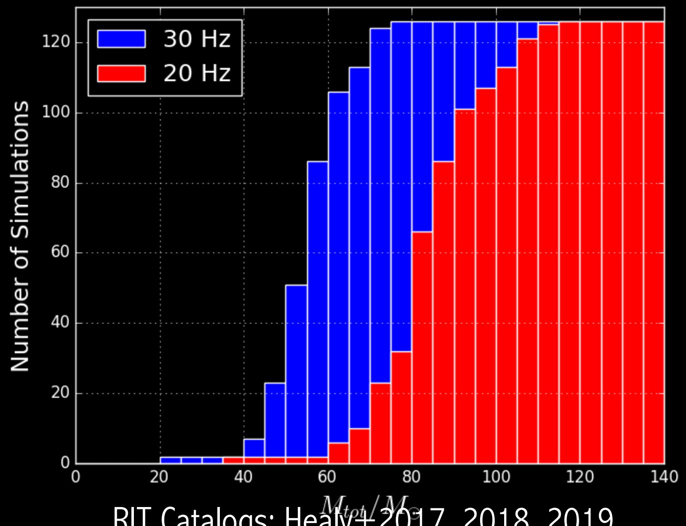


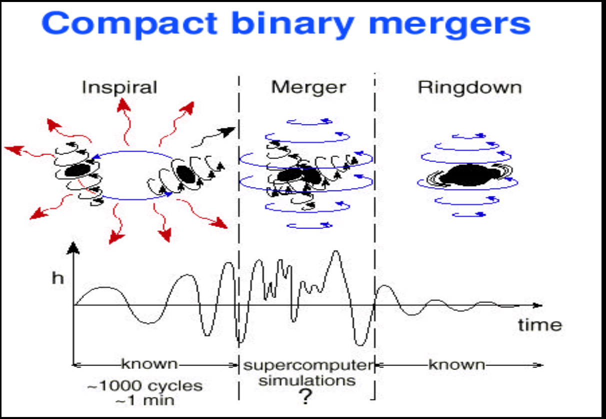
Figure courtesy: G. Lovelace for the SXS Collaboration



RIT Catalogs: Healy+2017, 2018, 2019

A Brief Lesson from History in this case:

Some theory problems are challenging!



<u>Theory vs Observations</u>

"I have bet these numerical relativists that gravitational waves will be detected from blackhole collisions before their computations are sophisticated enough to simulate them. I expect to win ... but hope to lose, because the simulation results are crucial to interpreting the observed waves."

Kip S. Thorne, 2002.

- It took more than four decades for numerical relativists to solve the problem!
- It was not an easy task - the Einstein's Field Equations of General Relativity "explicity written down" for general problems have hundreds of terms …
- **First successful simulations in 2005!** Pretorius 2005, Baker+2006, Campanelli+2006
- The field was driven by big facilities (e.g. LIGO), but mostly funded outside via single PI grants, with fewer exceptions e.g. US grand challenge. Lessons learned?

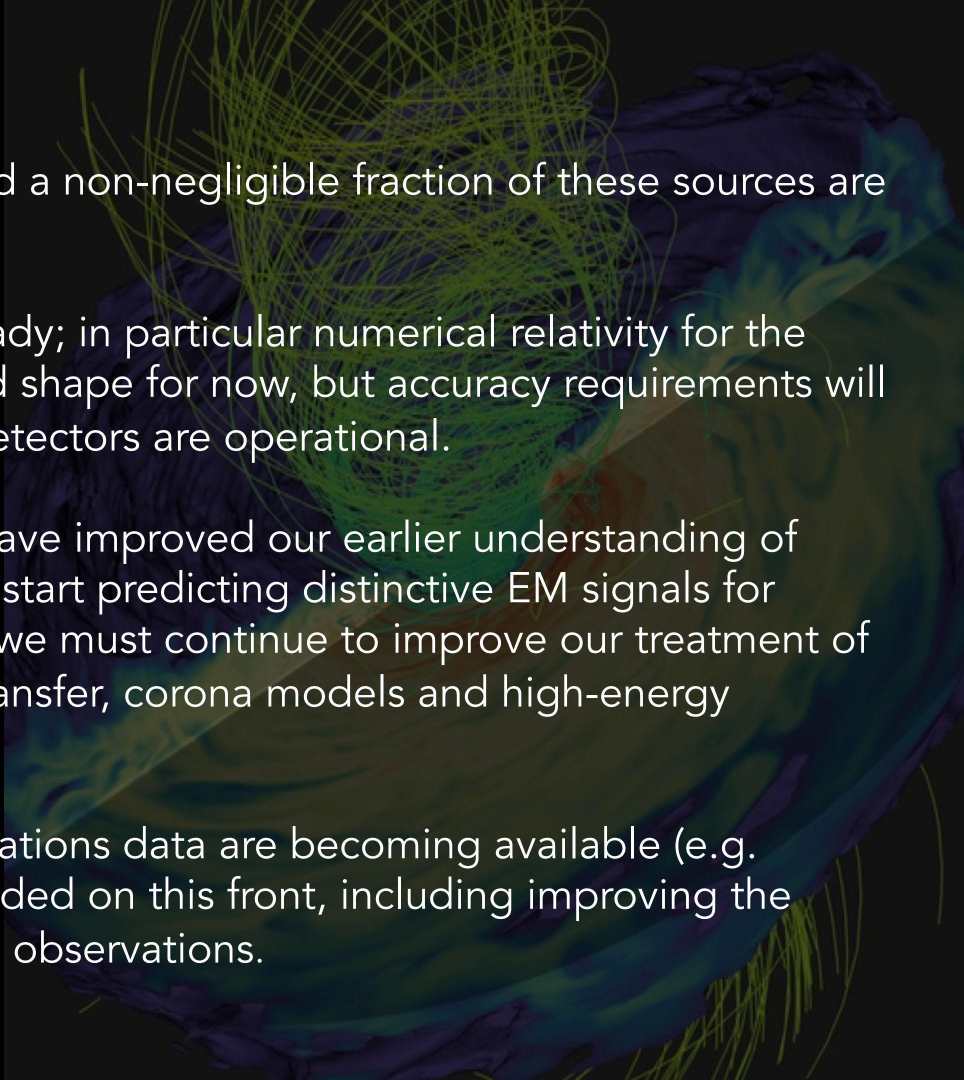
In Summary …

- SMBBH mergers are ideal MMA sources, and a non-negligible fraction of these sources are within the PTA and LISA range.

- Lots has been learned from simulations already; in particular numerical relativity for the interpretation of GW observations is in good shape for now, but accuracy requirements will increase once LISA and 3G ground based detectors are operational.

- 3d GR-MHD models of accreting SMBBHs have improved our earlier understanding of these systems, and are now long enough to start predicting distinctive EM signals for variety of astrophysical scenarios. However, we must continue to improve our treatment of magnetized and turbulent flows, radiative transfer, corona models and high-energy outflow/jet emission!

- Spectra, light curves, snapshots of key simulations data are becoming available (e.g. compact-binaries.org), but more work is needed on this front, including improving the communication barriers between theory and observations.



For further discussion later:

- Theory and simulations are key to the interpretation of observations of binary compact MMA sources.

- The demand for high-fidelity physical models will only increase as more exciting discoveries are made.
  - ➢ Need to seek complementarity between analytic and computational theory.
  - ➢ Some coordinated efforts among theory groups observing facilities would be great.

- The promise of MMA can be realized only if sufficient, sustained and community cyberinfrastructure is available!
  - ➢ Scalable software Infrastructure
  - ➢ Peta/Exascale Supercomputers
  - ➢ Workforce training and retention

White Papers: Kollmeier+2020, Allen+2020, Chang+2020


Growing Convergence Research