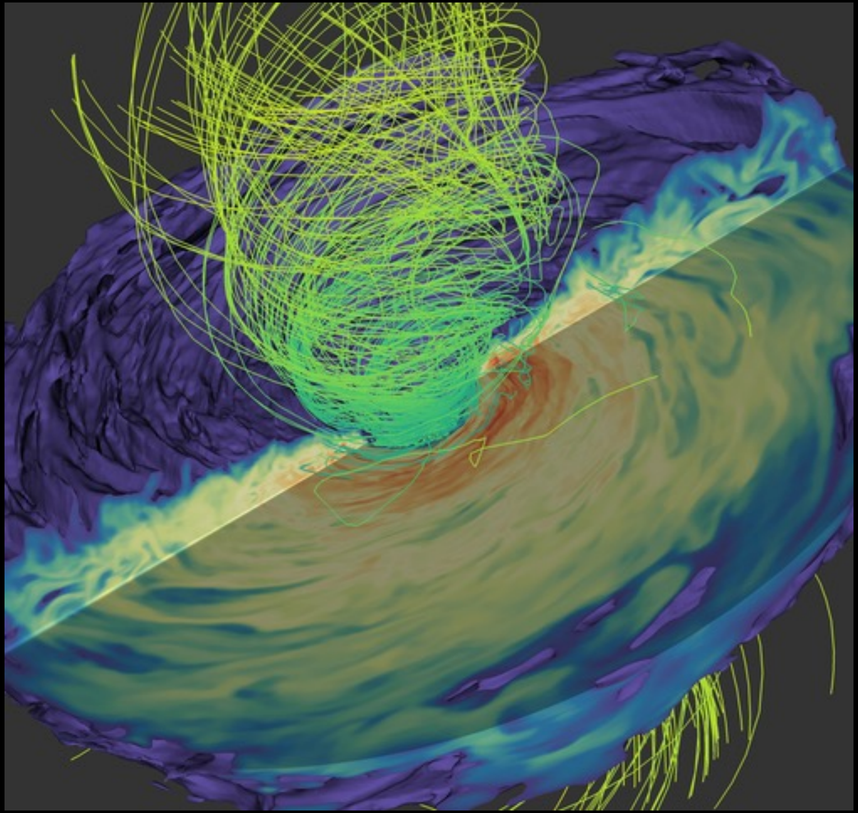
Simulations of Accreting Binary Supermassive Black Holes Approaching Merger



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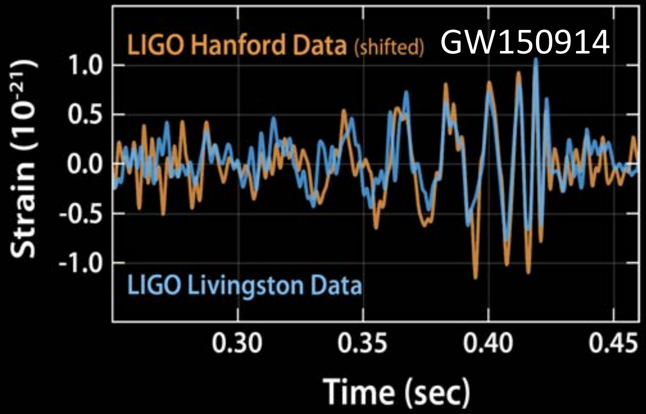
Windows onto the Universe!

Recent gravitational-wave discoveries by LIGO …

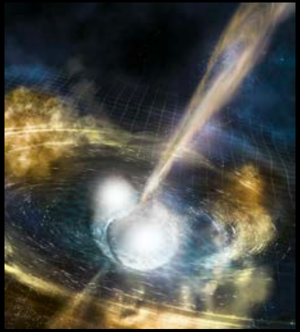


… have opened an unprecedented observational window into black holes and neutron stars!

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

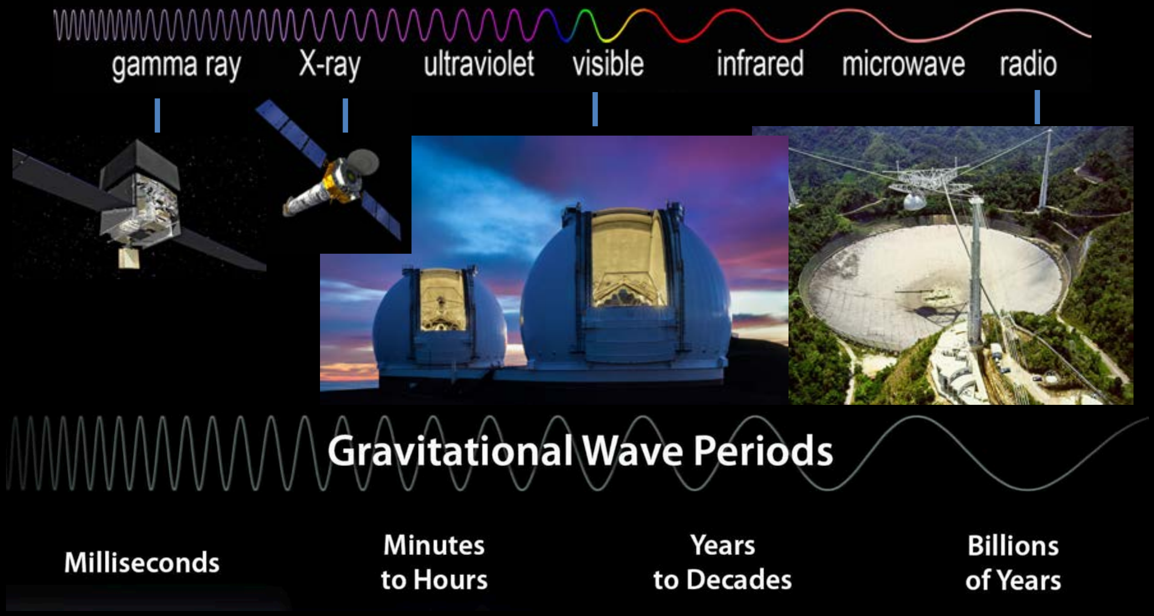
GW170817

+



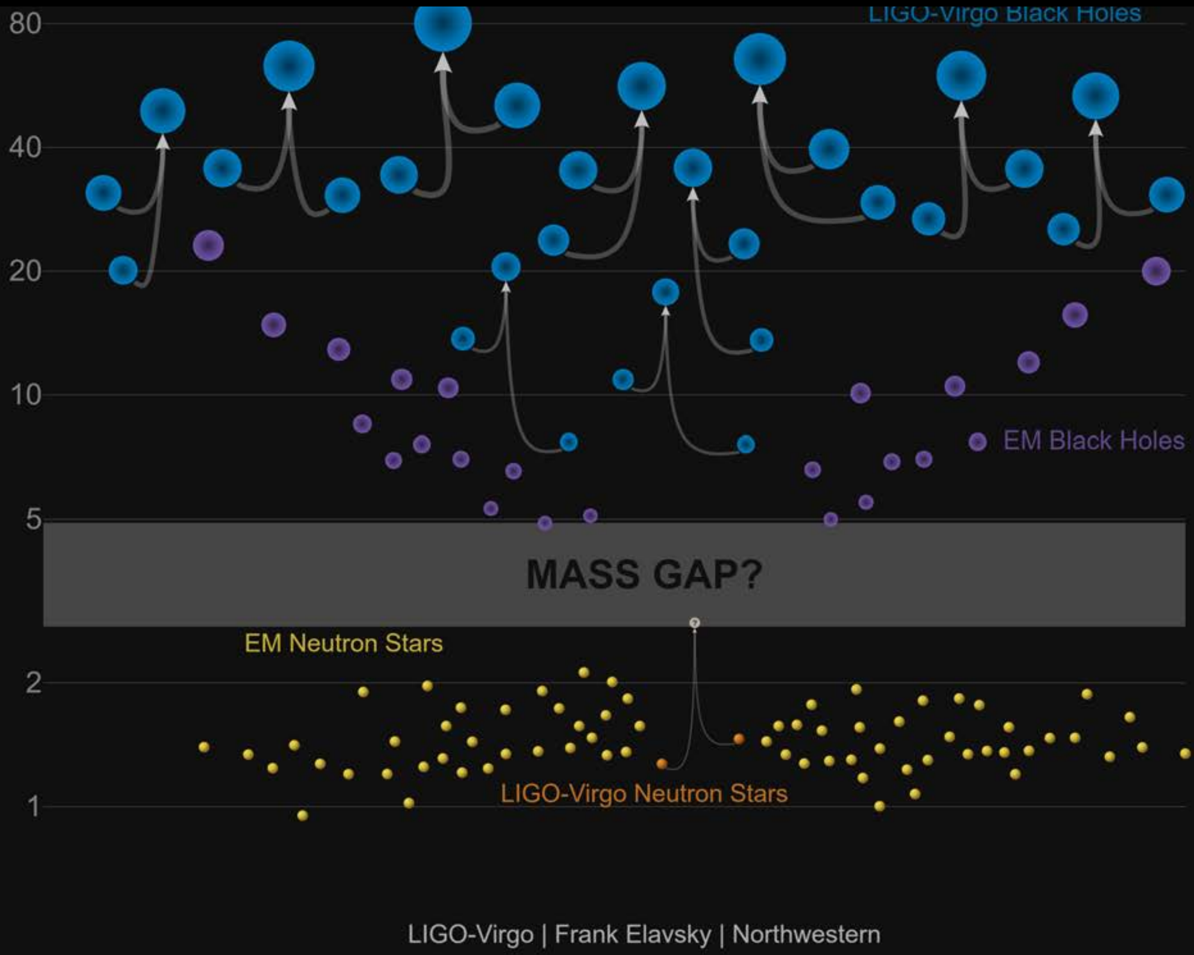
GRB 170817A

The Dawn of a New Kind of Astronomy



New MMA facilities coming soon online, e.g. LSST (see 48+ Astro2020 white papers!)

A few words about stellar–size binaries



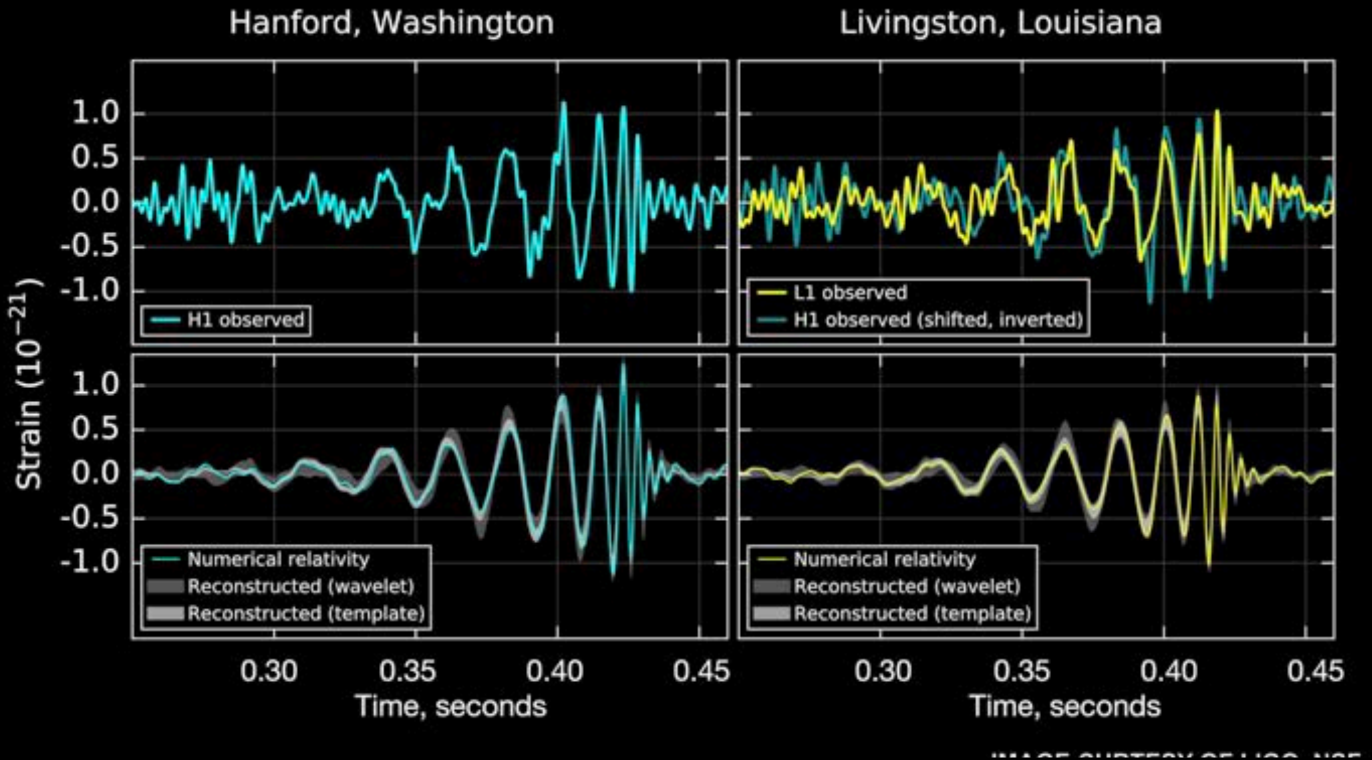
- LIGO GW public database: **23 events** so far
  gracedb.ligo.org
  17 BBH (>94-99%)
  1 BNS (>99%)
  1 NSBH (>99%)
- What is their population across the universe?
  - Mass gaps, really?
  - GW vs EM spins …
- What are the stellar evolution processes leading to the formation of these binary systems?

A theorist's point of view …

"It's black, and it looks like a hole. I'd say it's a black hole."

Black hole overload!

The Role of Theoretical Modeling and Numerical Simulations in LIGO discoveries

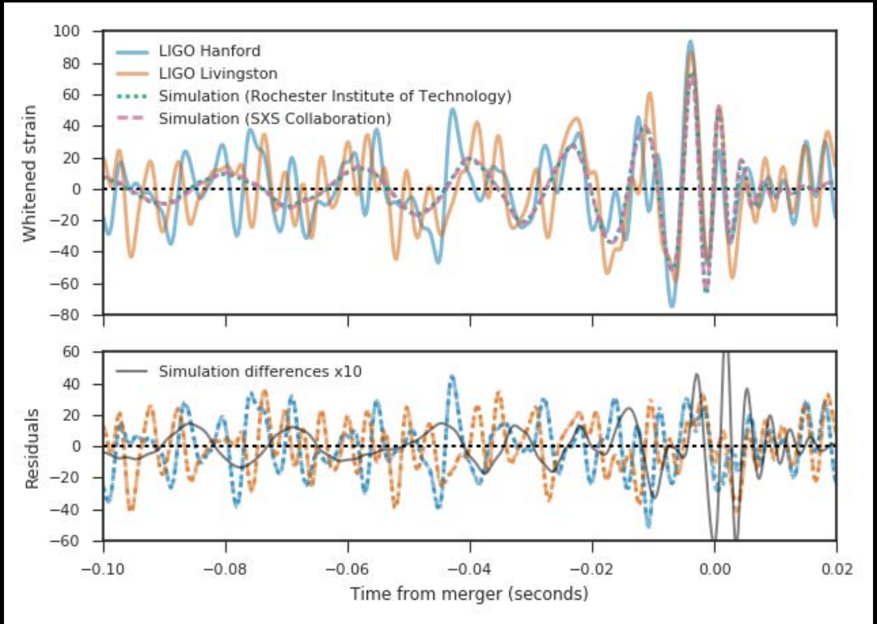


The serendipitous GW150914

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

How well does numerical relativity calculations match the real data today?

Targeted numerical simulations of binary black holes for **GW170104**



Excellent agreement among totally independent codes and totally independent methods!

Excellent match with LIGO data!

Healy+ 2018, Lange+2018

Catalogs of pre-calculated waveforms!

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

- 8-D parameter space (mass ratio, value and direction of each individual BH spins, and eccentricity of the orbit)
- SXS+Gatech+RIT Catalogs contain 3000+ waveforms

XSEDE

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

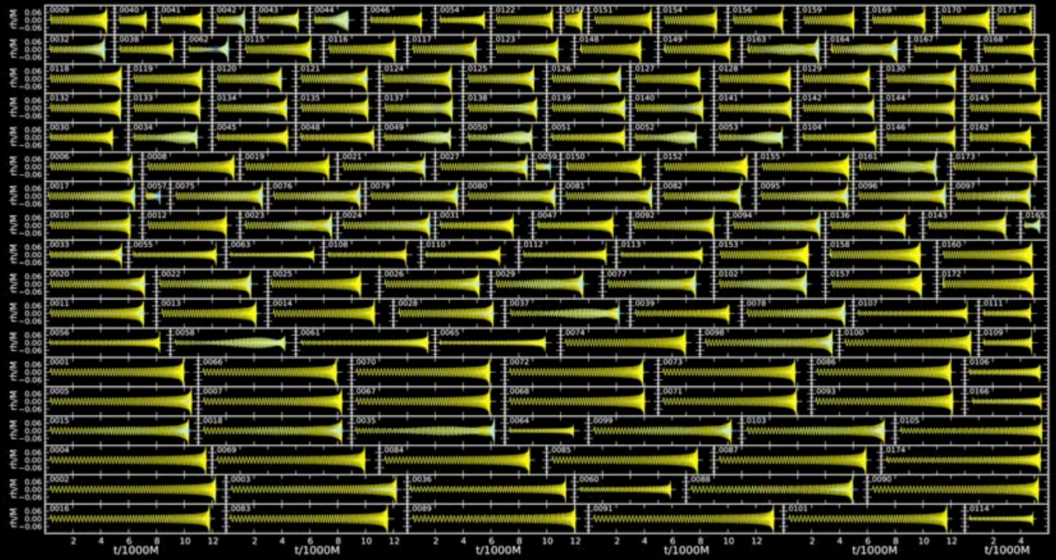
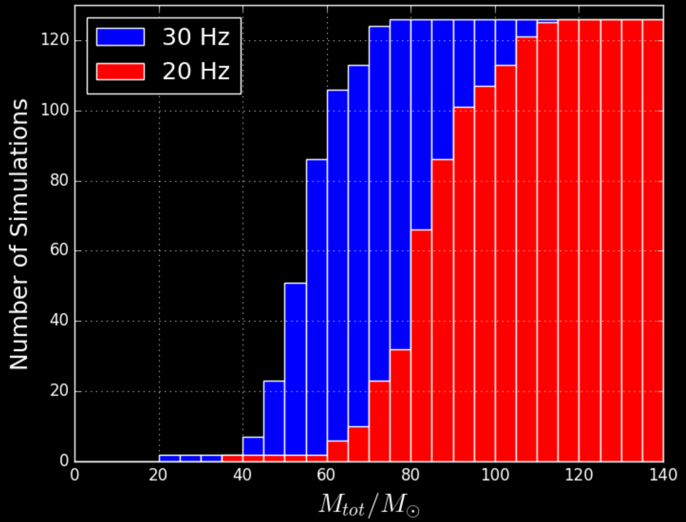
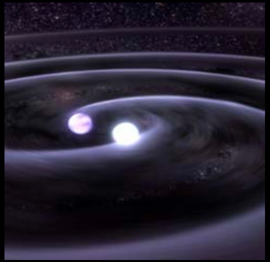


Figure courtesy: G. Lovelace for the SXS Collaboration



RIT Catalogs: Healy+2017, 2018, 2019

About Neutron Star Mergers …



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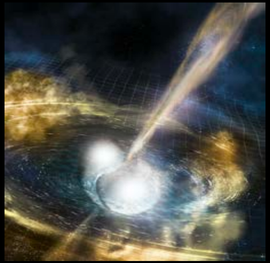


GW170817

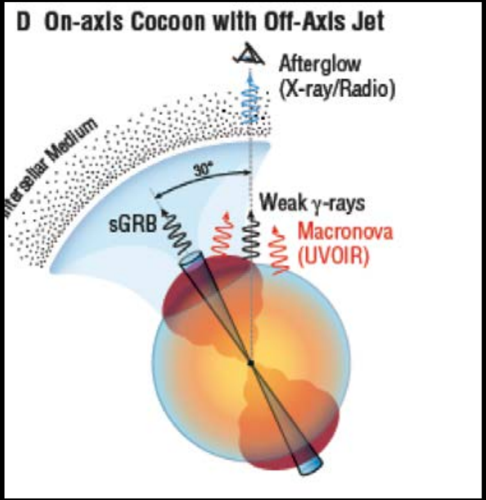
GRB 170817A

Best Interpretation, so far …

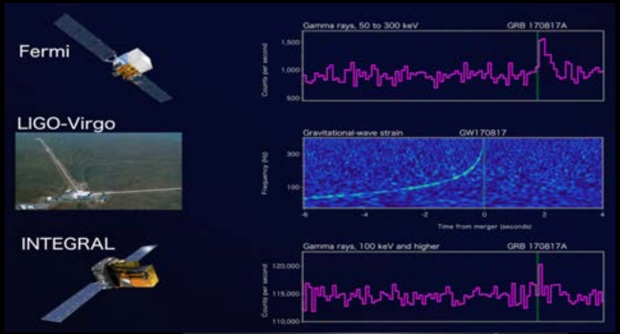
- Radio shows narrow powerful off-axis jet (E_{iso}~10^{52} ergs)
- With on-axis emission of weak gamma rays, that explode into the surrounding stellar media (kilonova or macronova).
- R-process associated with the production of heavy elements

Worldwide, astronomy follow-up observations!

First, demonstration that MMA is can be done in real-time on a global scale!



Credits: Tsvi Piran

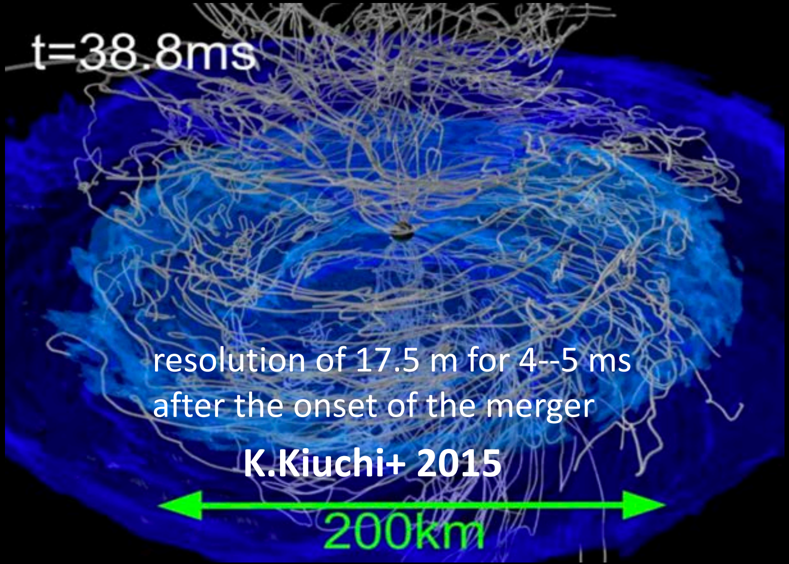


Best Indirect proof of the association of NS mergers and sGRBs that we have today!

A Multi-Physics Computational Grand Challenge!

GW and EM signals depends on the complex coupling among:

- GR-MHD
- Nuclear and Neutrino Physics
- Neutrino transport
- R-processes/nucleosynthesis



GRMHD BNS simulations are the primary tool to understand SGRB jet launching mechanism and central engine (BH vs NS), but need to resolve:

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

Going to ~1 sec after the onset of the merger with MRI resolved MHD postmerger simulations

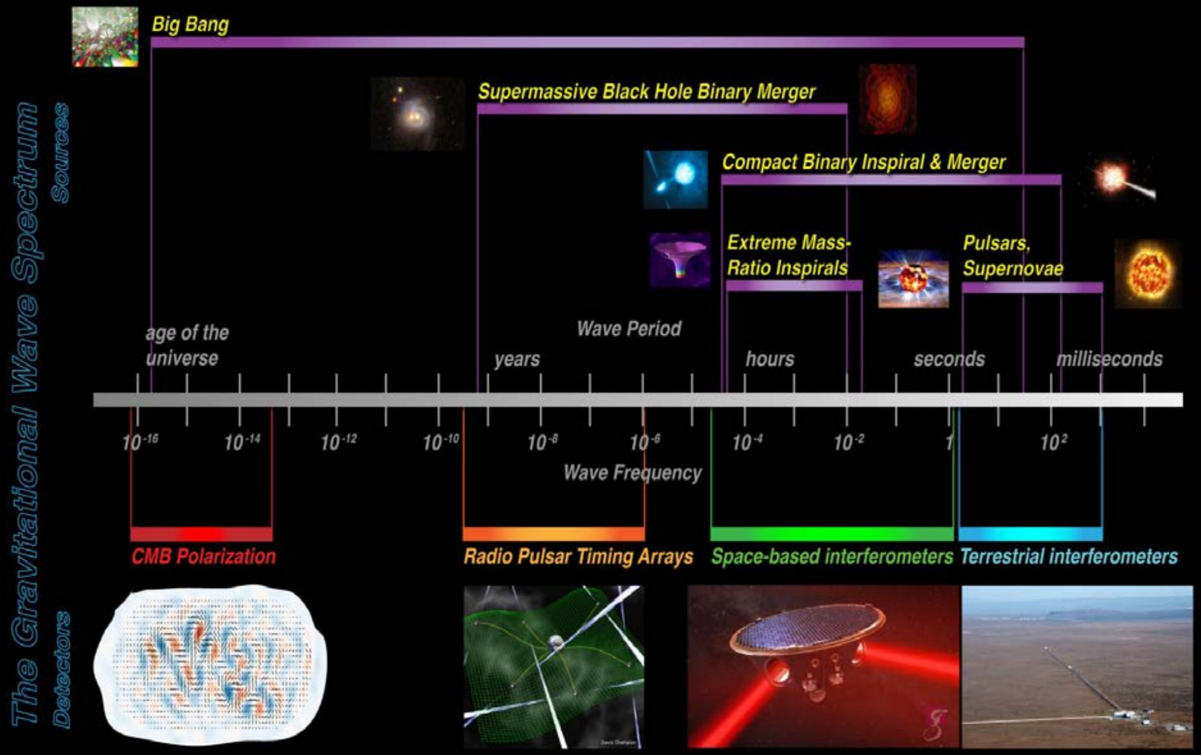
TCAN

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

Stay Tuned for more soon!

Gravitational Waves from Merging Black Hole Binaries

Black hole binaries are spanning over a large portion of the GW spectrum:

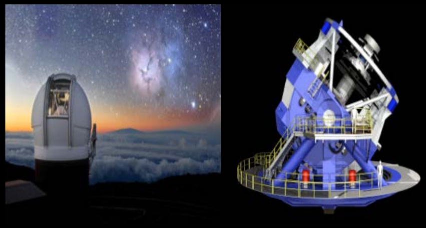


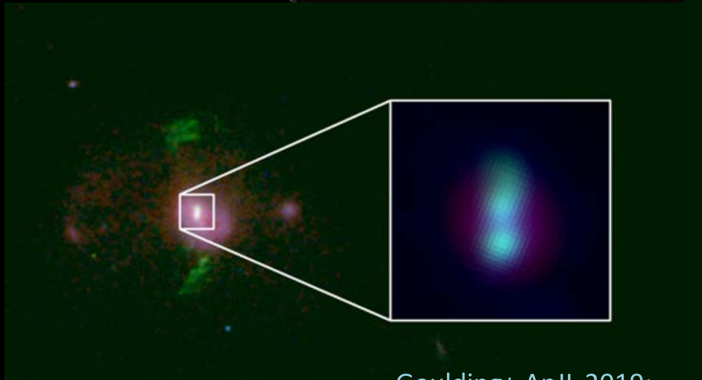
- Are these the same type of compact objects?
- How nature manage to produce them with a variety of masses, and spins?
- And what is their population across the universe as a function of the redshift?
- What is their astrophysical origin, and environment?
- How does physics change at the extremes?

Merging Supermassive Black Hole Binaries

- Supermassive BHs in AGN/Quasars are surrounded by accreting hot gas and emit powerful radio jets.
- Following from galaxy mergers, SMBBH mergers should be EM-bright.
  - ❖ **What are the EM signals associated with SMBBH merger?** Holy Grail for **Multi-Messenger Astrophysics!**

Electromagnetic　　　Gravitational





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

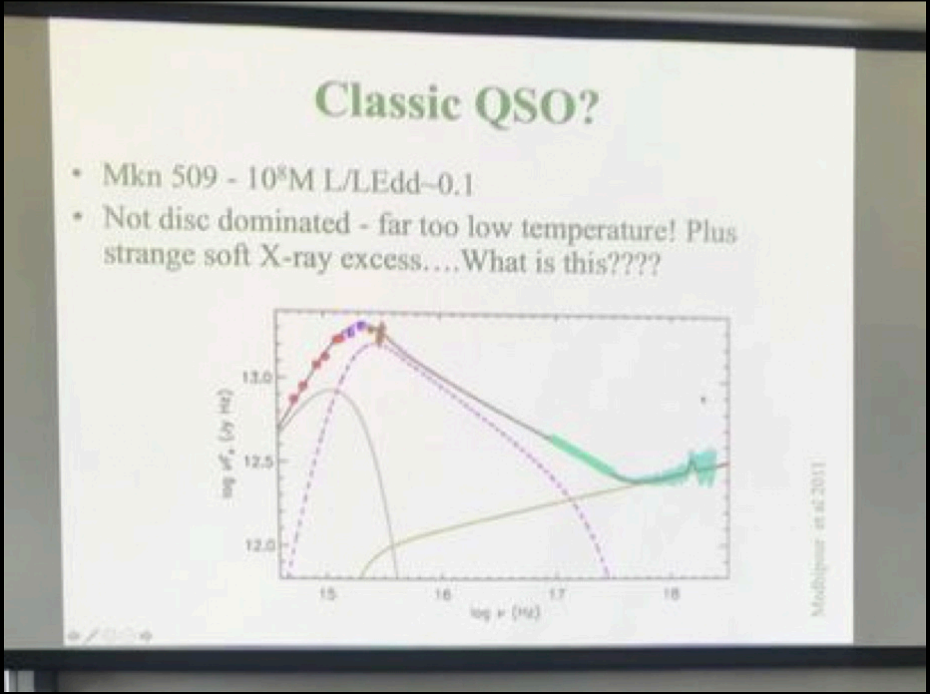
- ➢ Binary supermassive BH are primary GW sources for LISA and PTA campaigns.
- ➢ As EM sources, they are ideal candidate for exploring plasma physics in the strongest and most dynamical regime of gravity.

Quasars/AGN in Crisis?!

QUASARS IN CRISIS
THE ROYAL OBSERVATORY, EDINBURGH
AUGUST 6-9, 2019

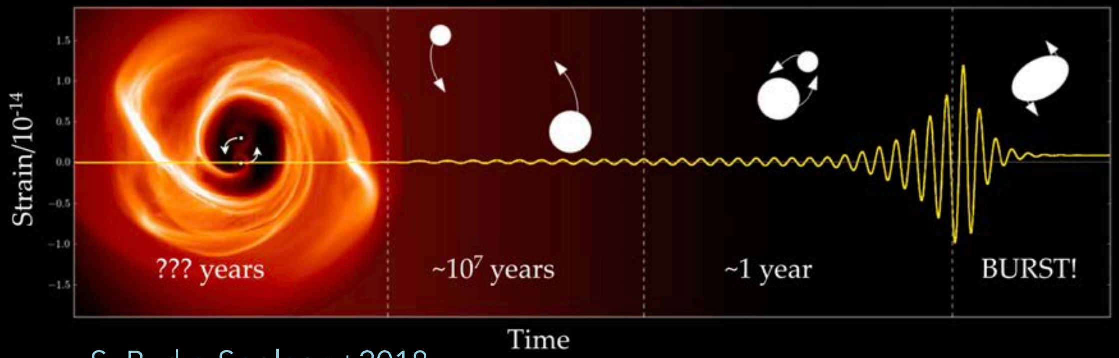
"Changing" AGNs and Quasars created a crisis in the astronomy community:

- Focus on Surveys and Classifications is leading to more confusion, too many unique variable AGNs e.g.Mrk1018, Mrk 509
- Multi-wavelength needed to understand the observations.
- GW (e.g. LISA and PTA) could help to solve some puzzles around the BH binary (Hussleman+2019) and recoiling interpretation (Kim+2018).
- Need to understand underlying high-energy physics



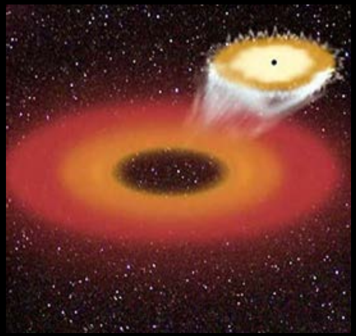
The Lifecycle of Supermassive Black Hole Binaries

- What is the population of supermassive BH binary mergers across the universe?
- What are the binary dynamics that take the BHs from galaxy merger scales to the GW scale?
- What about the remnant BH? e.g. postmerger recoil?



S. Burke-Spolaor +2018

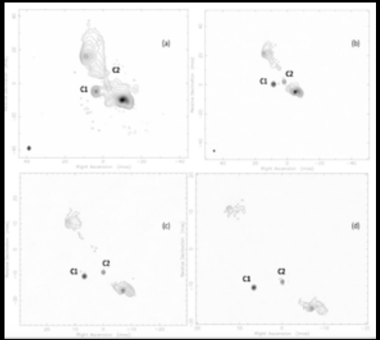
- ➢ up to 10+% of the total mass is radiated in GW energy – e.g Campanelli+2006



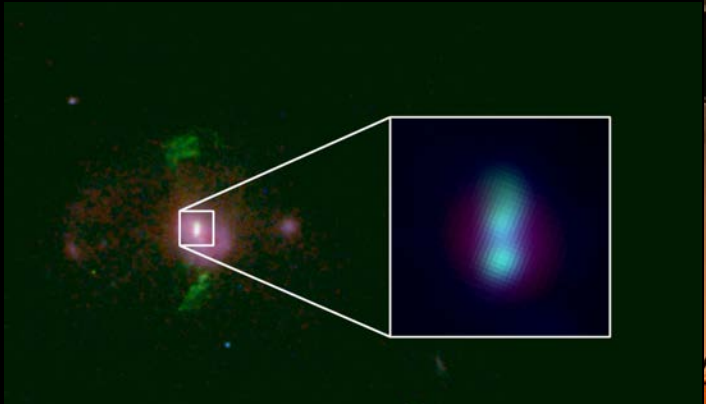
- ➢ Assume an optimistic rate of 1-10 mergers per year, but there are still many caveats about their full lifecycle.
- ➢ Assume that stellar dynamical friction, torques from gas, or other processes can bring the pair to sub-pc scales, then GW should do the rest …

- ➢ The BH remnant will **recoil** from its host structure, depending on the BH spins and masses at merger – e.g Campanelli+2007 …

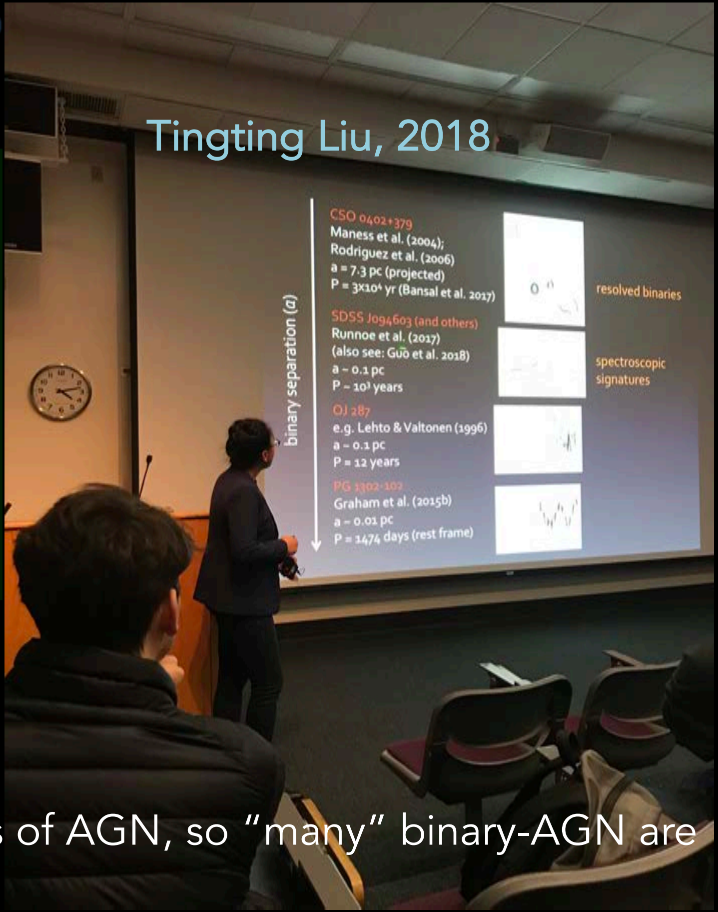
So far, a handful of Candidates …



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



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



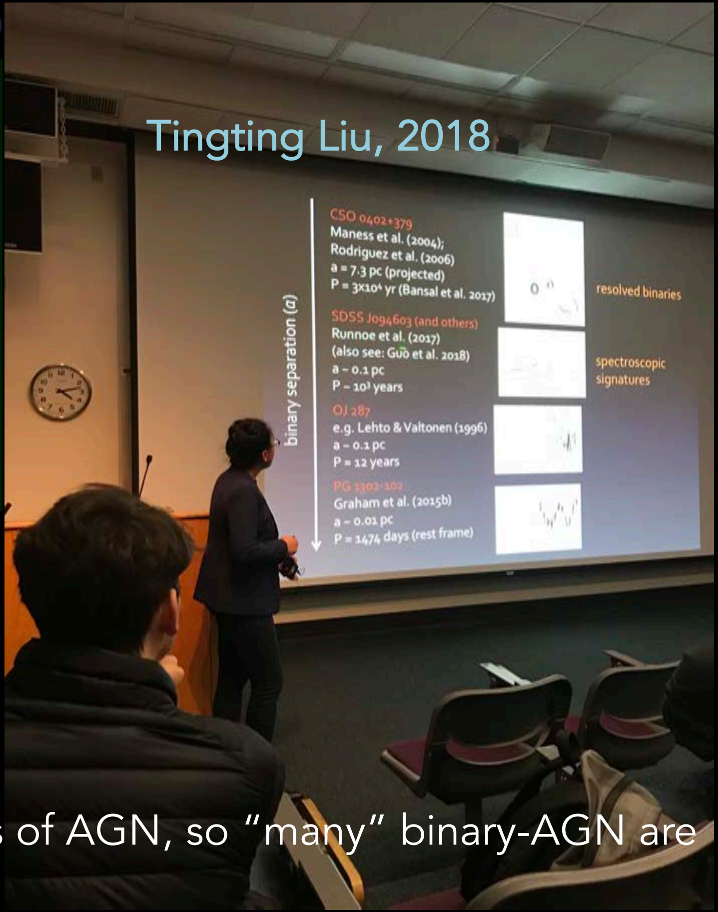
Future astronomical surveys, e.g. LSST, will identify 100k's of AGN, so "many" binary-AGN are expected to be uncovered in the haystack!

So far, a handful of Candidates …

Table 5. Spectroscopic Measurements and Inferred Binary Parameters

PS1 Designation	Spectroscopy	M_{BH} Estimator	f_λ [erg s^{-1}cm^{-2}Å^{-1}]	FWHM [km s^{-1}]	log (M_{BH}) [$M_\odot$]	z	P_{rest} [day]	a [pc]	a [R_s]
PSO J35.7068–4.23144	SDSS	MgII	1.4×10^{-17}	5185	8.7	1.564	167	0.002	47
PSO J35.8704–4.0263	SDSS	MgII	3.3×10^{-17}	3810	8.8	1.916	284	0.004	55
PSO J52.6172–27.6268	GS16B	MgII	1.3×10^{-17}	7384	9.2	2.134	317	0.005	32
PSO J129.4288+43.8234	SDSS	MgII	4.5×10^{-17}	3744	8.3	0.959	160	0.002	80
PSO J130.9953+43.7685	SDSS	MgII	4.1×10^{-17}	3850	8.4	0.986	361	0.003	133
PSO J131.1273+44.8582	SDSS	MgII	1.6×10^{-17}	2450	8.3	2.011	280	0.002	126
PSO J131.7789+45.0939	SDSS	MgII	2.0×10^{-17}	6773	8.8	1.233	312	0.004	58
PSO J148.8485+1.8124	SDSS	MgII	7×10^{-18}	5402	8.9	2.378	242	0.003	45
PSO J149.4989+2.7827	SDSS	CIV	3.4×10^{-17}	5173	9.1	2.376	284	0.004	38
PSO J149.2447+3.1393	GS15B	MgII	8.6×10^{-17}	1955	8.5	1.859	283	0.003	94
PSO J149.9400+1.5090	SDSS	MgII	2.4×10^{-17}	3715	8.3	1.106	198	0.002	102
PSO J149.6873+1.7192	DCT17Q1	MgII	1.3×10^{-17} (n)	5755	8.6	1.354	348	0.004	85
PSO J150.9191+3.3880	SDSS	MgII	6.9×10^{-17}	1995	7.7	0.719	431	0.002	426
PSO J160.6037+56.9160	SDSS	MgII	3.7×10^{-17}	3251	8.5	1.445	404	0.004	119
PSO J161.2980+57.4038	DCT17Q1	MgII	2.0×10^{-17}(n)	3043	8.5	1.798	351	0.003	114
PSO J163.2331+58.8626	DCT17Q1	CIV	6.7×10^{-17}(n)	5611	9.2	2.165	316	0.005	33
PSO J185.8689+46.9752	SDSS	MgII	1.3×10^{-17}	6070	8.9	1.681	357	0.004	59
PSO J213.9985+52.7527	SDSS	MgII	1.5×10^{-17}	4123	8.7	1.867	253	0.003	67
PSO J214.9172+53.8166	SDSS	MgII	1.5×10^{-17}	4907	8.4	1.169	462	0.004	142
PSO J242.5040+55.4391	DCT17Q1	MgII	1.9×10^{-17} (n)	5547	8.9	1.780	310	0.004	53
PSO J242.8039+54.0585	SDSS	MgII	3.6×10^{-17}	6581	8.8	0.960	375	0.004	70
PSO J243.5676+54.9741	DCT16Q3	MgII	3.5×10^{-17}(n)	2041	8.0	1.268	434	0.002	280
PSO J333.0298+0.9687	DCT15Q3	Mg II	2.4×10^{-17}	8851	9.2	1.284	244	0.004	28
PSO J333.9833+1.0242	SDSS	MgII	4.2×10^{-17}	6157	9.5	2.234	144	0.003	13
PSO J334.2028+1.4075	GS15A	Mg II	1.9×10^{-17}	5492	9.1	2.070	182	0.003	28
PSO J351.5679–1.6795	DCT17Q2	MgII	10.7×10^{-17}	4702	8.9	1.156	373	0.005	59

Note—Those flux measurements that were made from the re-normalized Deveny spectra are indicated by (n).



Future astronomical surveys, e.g. LSST, will identify 100k's of AGN, so "many" binary-AGN are expected to be uncovered in the haystack!

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.

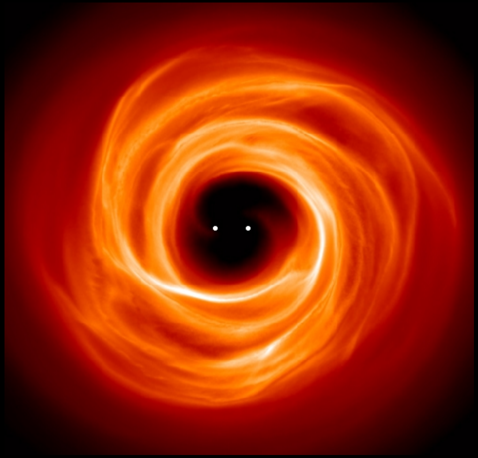
Key Challenges

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!**

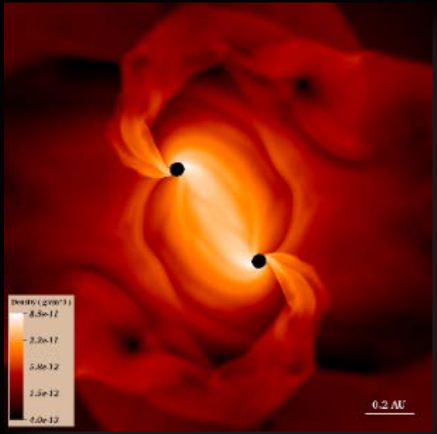
There is Reason for Increased Optimism!

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:

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

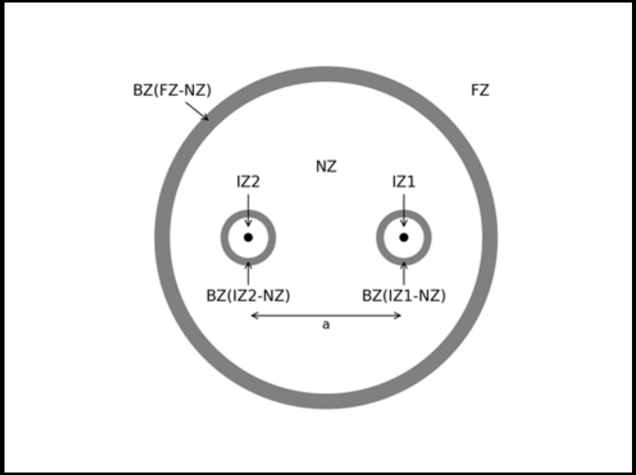
$$\frac{\partial}{\partial t}\sqrt{-g}\begin{bmatrix} \rho u^t \\ T^t{}_t + \rho u^t \\ T^t{}_j \\ B^k \end{bmatrix} + \frac{\partial}{\partial x^i}\sqrt{-g}\begin{bmatrix} \rho u^i \\ T^i{}_t + \rho u^i \\ T^i{}_j \\ \left(b^i u^k - b^k u^i\right) \end{bmatrix} = \sqrt{-g}\begin{bmatrix} 0 \\ T^\kappa{}_\lambda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

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

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:

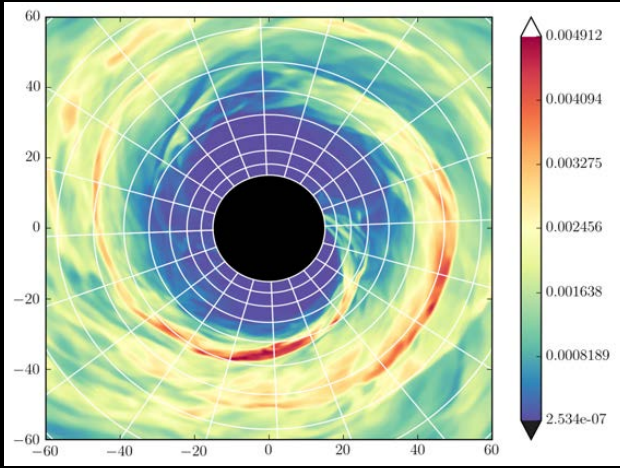
1. Perform a long-term GRMHD simulation of a thin, radiatively efficient, circumbinary accretion disk to its "quasi-steady" state:

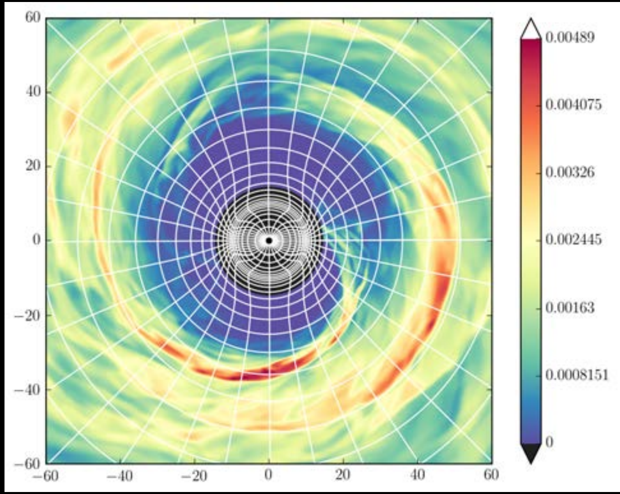
   - ➢ Use spherical polar, horizon penetrating, coords for proper angular momentum transport in the gas;
   - ➢ Remove the BHs from the grid for efficiency at this stage;

   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:

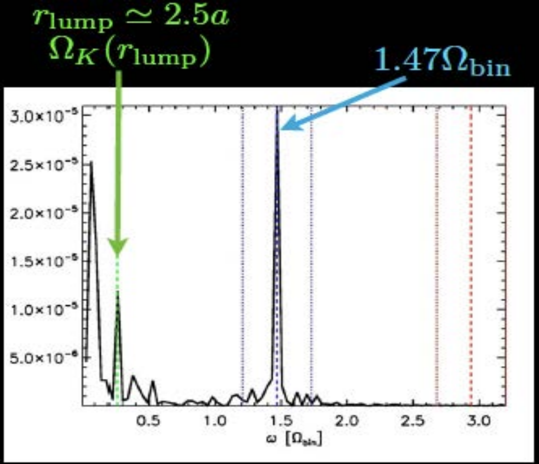
   - ➢ Novel methods tailored for accuracy and efficiency e.g. dynamics warped grid – Zilhao+2014;
   - ➢ Now, augmented efficiency with a new multipatch code – Avara+2019





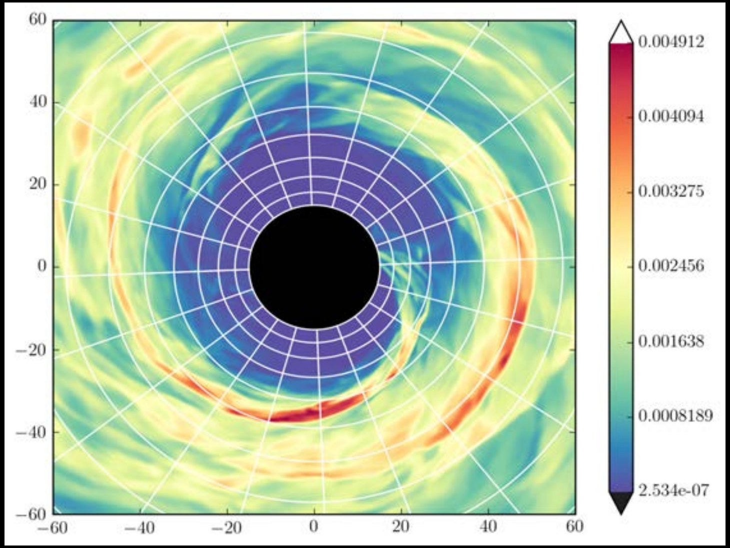
Circumbinary Disk Dynamics

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.=$20r_g$)

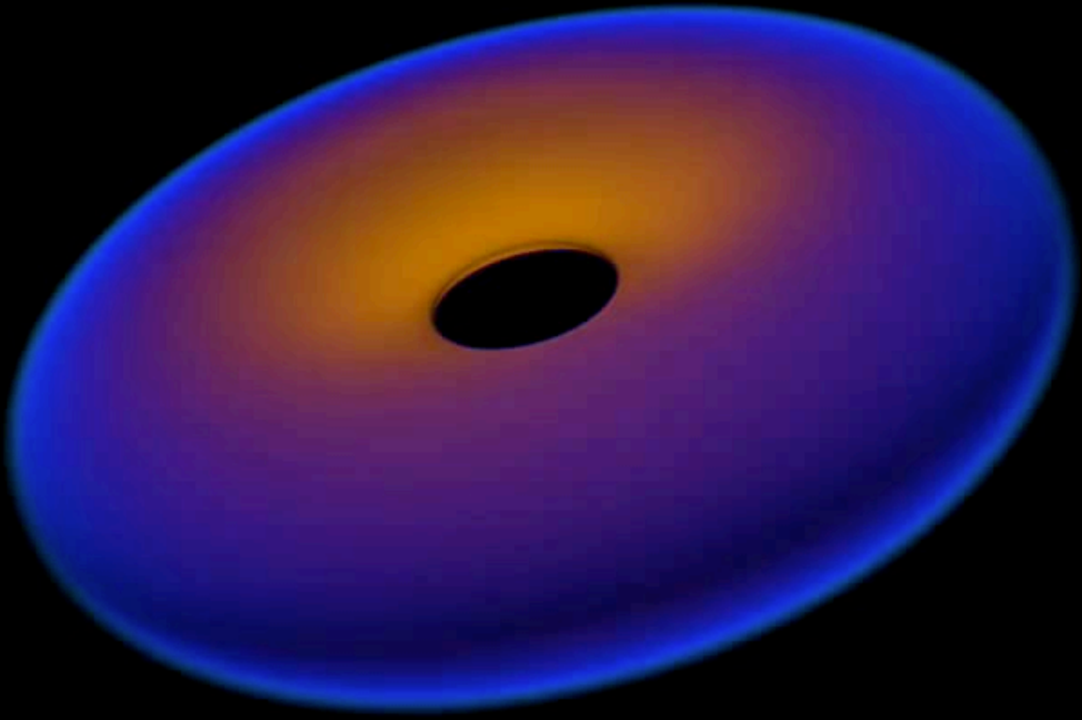


Noble +2012

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!

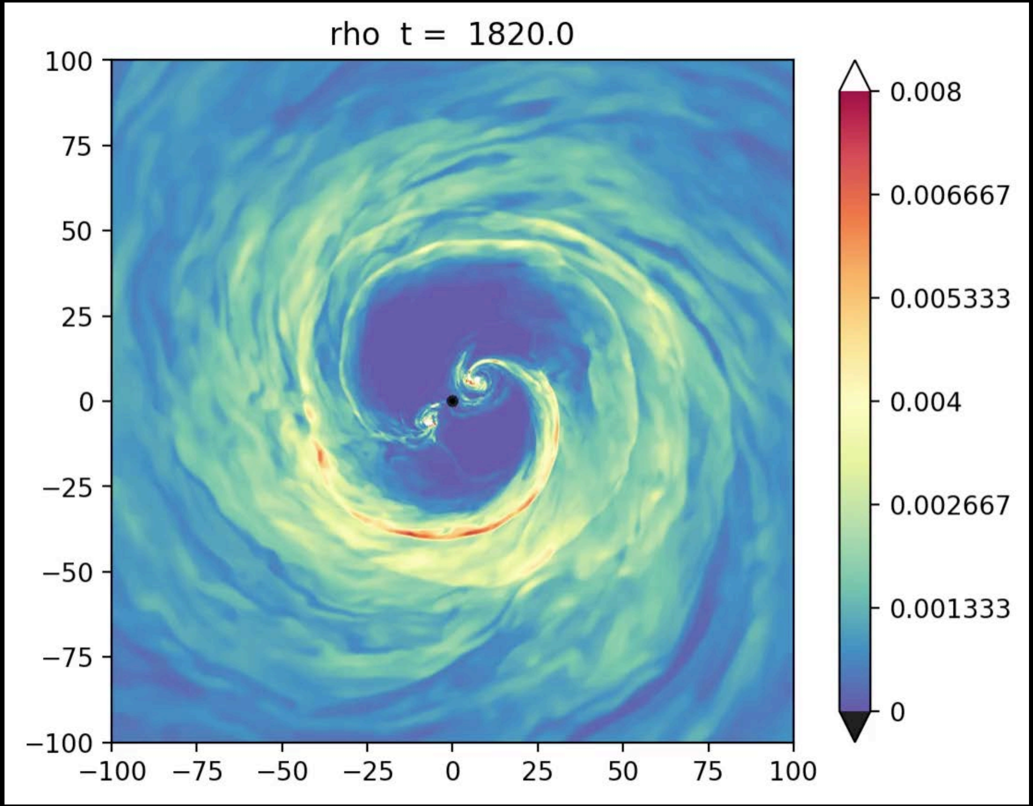
Circumbinary Disk Dynamics



Mark Avara + RIT

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

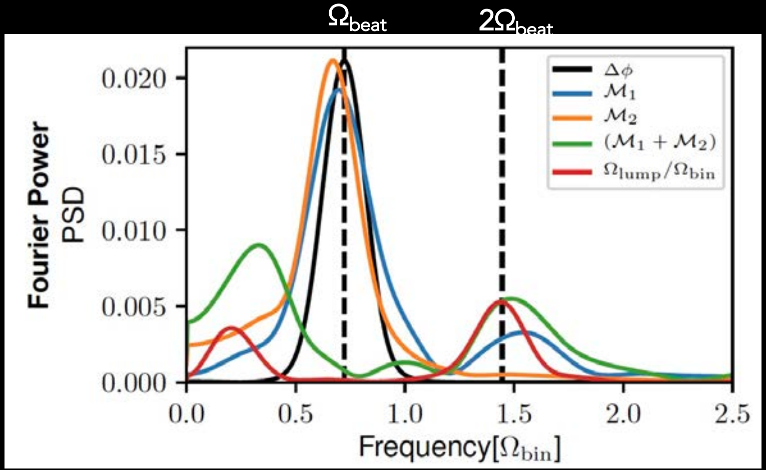
Dynamics in the Central Region



Bowen, Mewes, Campanelli, Noble, Krolik, ApJL 2019

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, 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

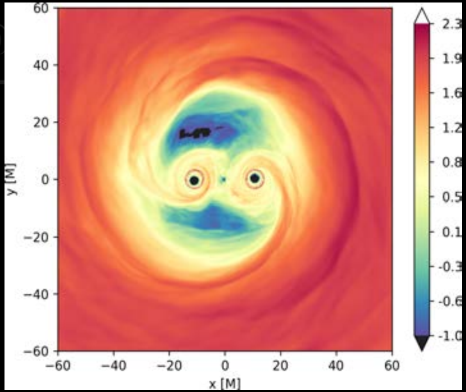
- **Above photosphere, corona emission** modeled as non-thermal (Compton scattering) component with temperature 100 keV:

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

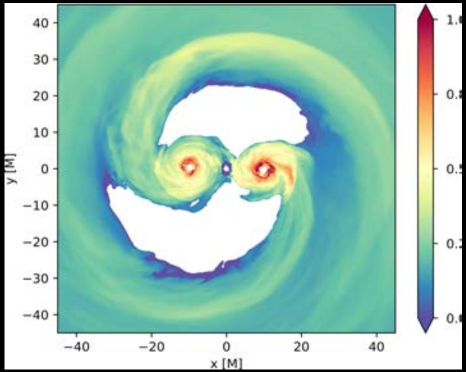
Trakhtenbrot++2017, Krolik 1999, Roedig++2014

- 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

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

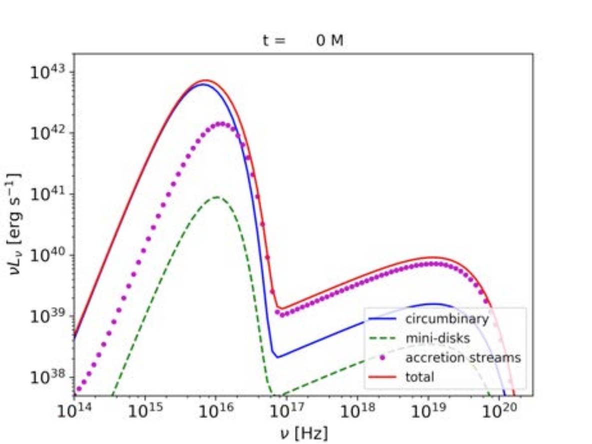
Looking for Distinct Light Signatures

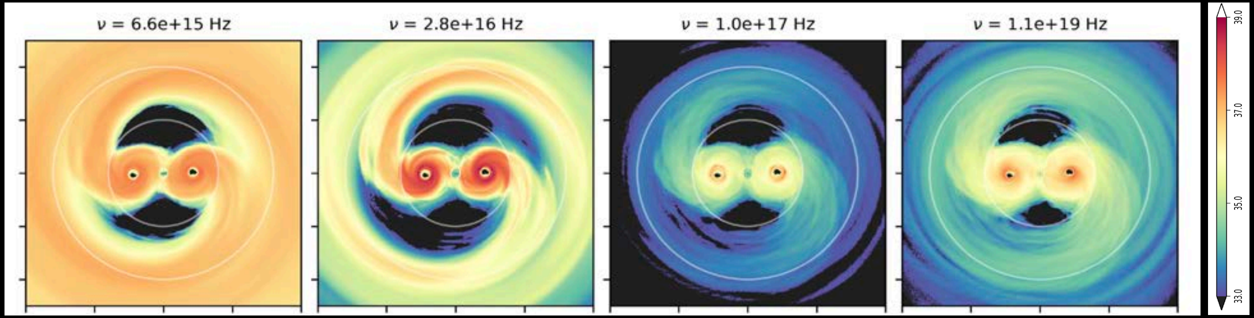
Face-on View,
Optically Thick Case
$M_{BH}=10^6 M_\odot$

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

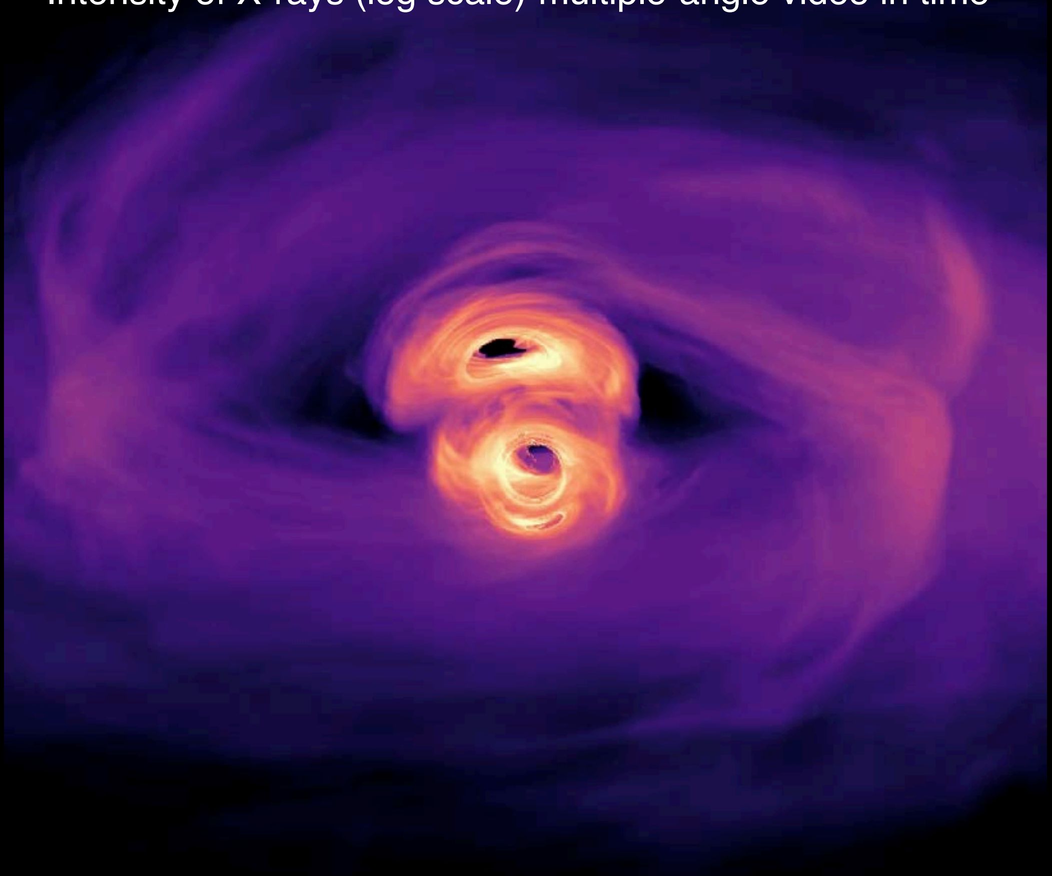
Mini-disk corona dominated hard X-rays

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

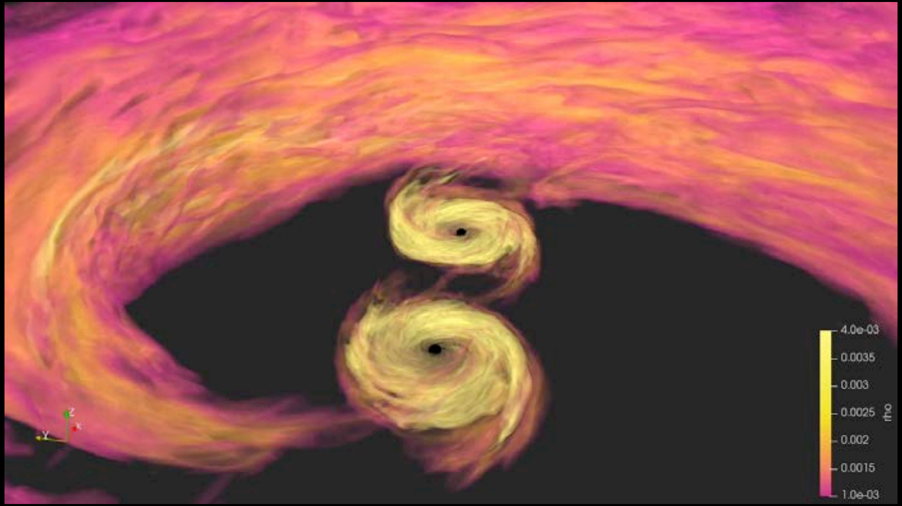
Intensity of X-rays (log scale) multiple-angle video in time

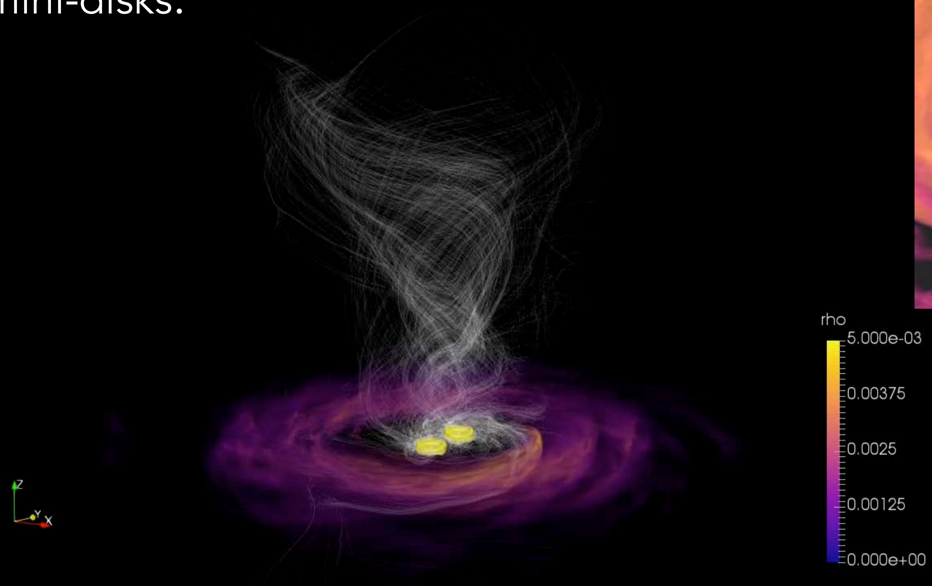


Credits: S. Noble (NASA) based on Bowen+2018

A Few Words on Computational Aspects:

First long-term GR-MHD simulation of accreting supermassive binary black holes, with circumbinary disk data and resolved mini-disks.



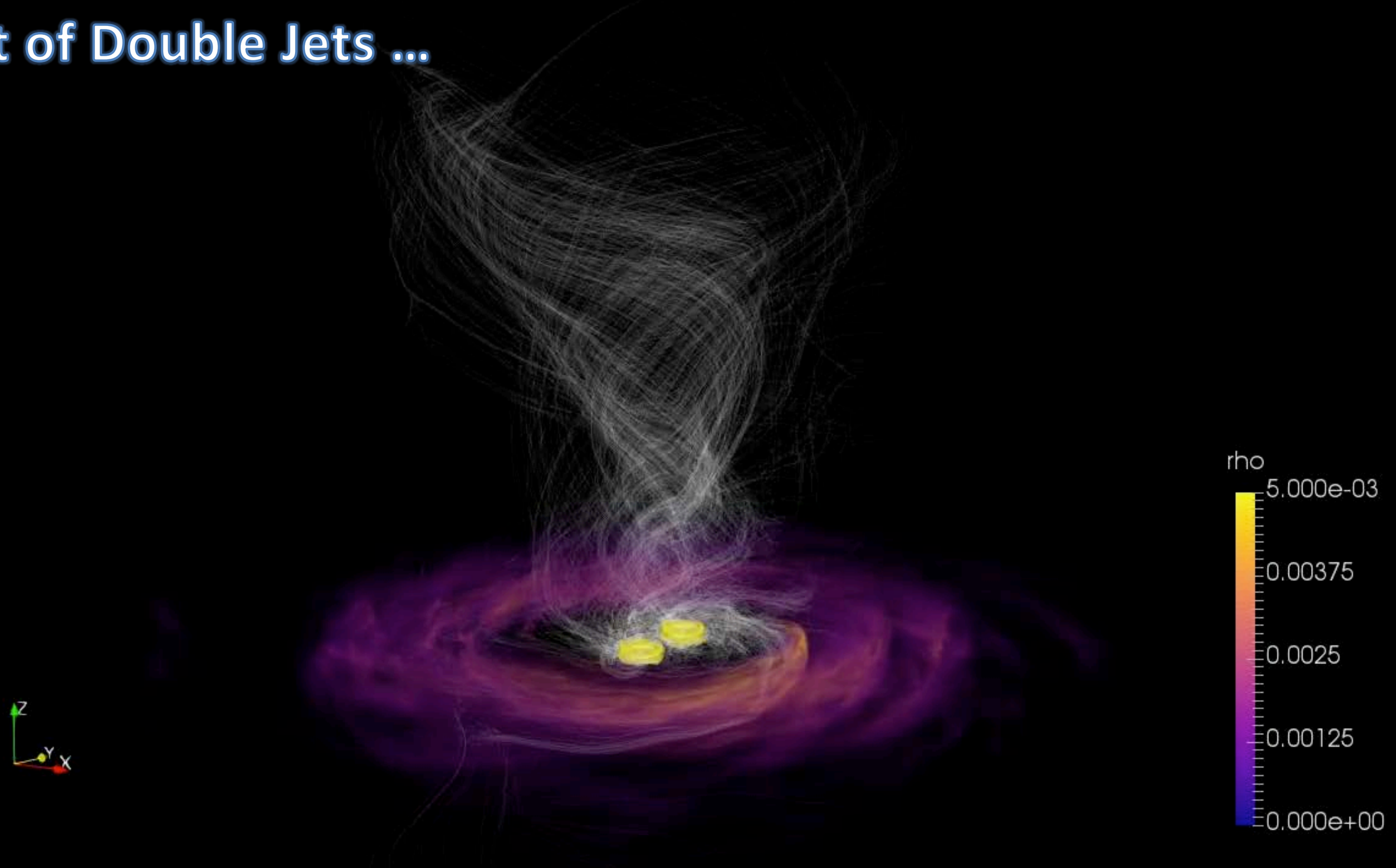


Each simulation require about 10^7 cells evaluated at approximately 10^7 time steps, using 10,000 cores (e.g. each run requires several millions CPU hours).

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

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

Hint of Double Jets …

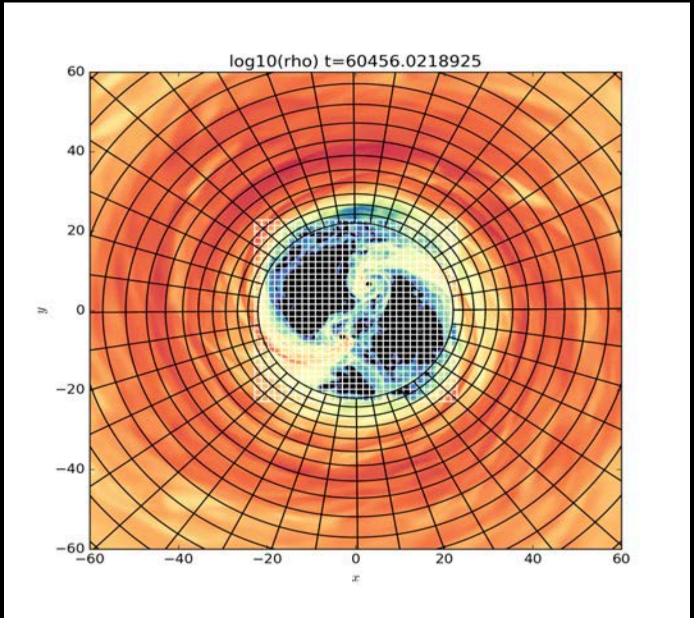


Bowen++, ApJL, 2018 ; Bowen++, ApJ, 2019

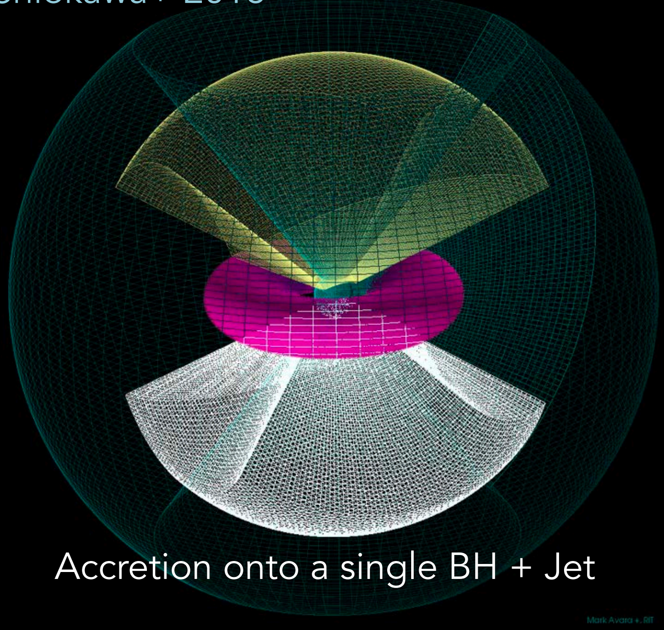
A new Multi-Physics, Multi-scale Infrastructure for Exascale Computing

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

- **PatchworkMHD** – Avara+ 2019 in prep
  New software infrastructure for problems of discrepant physical, temporal, scales and multiple geometries.
- Early development (hydrodynamics only) – Shiokawa+ 2018

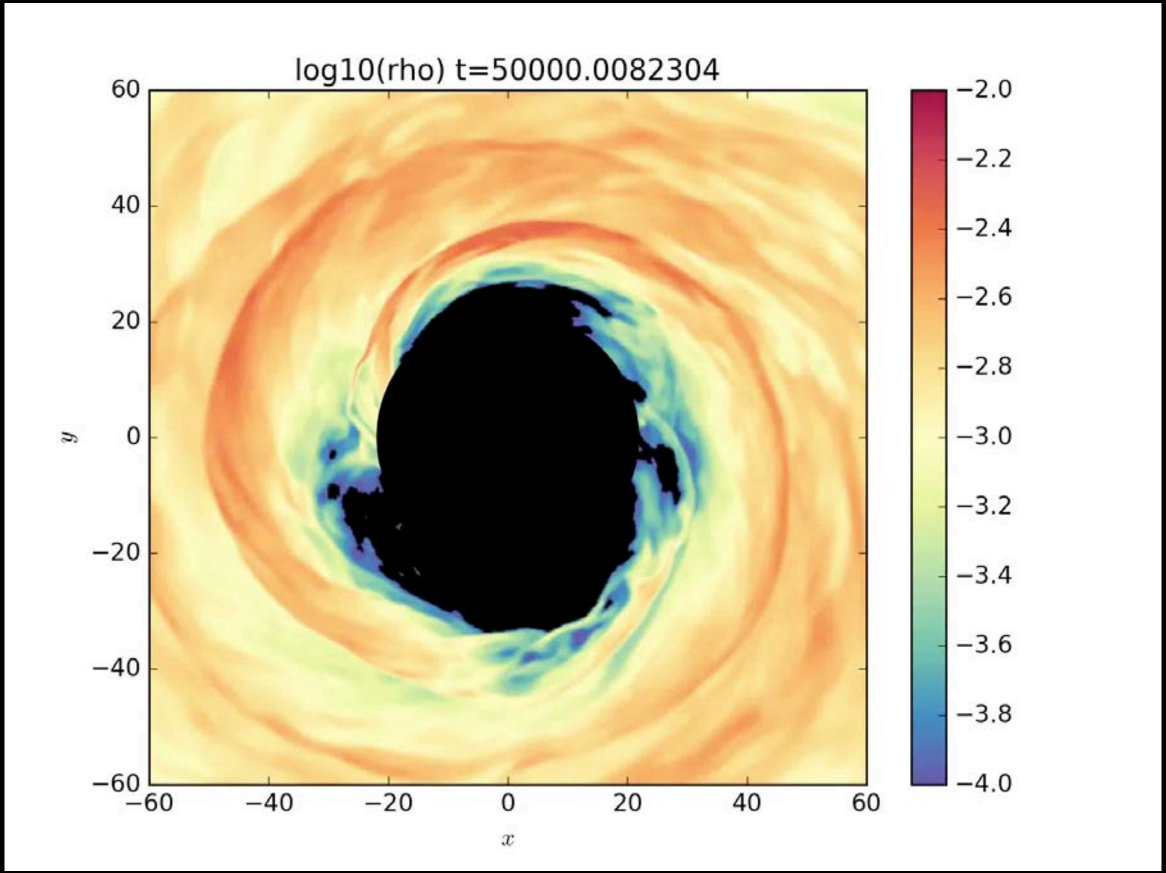


Accretion onto binary BHs



Accretion onto a single BH + Jet

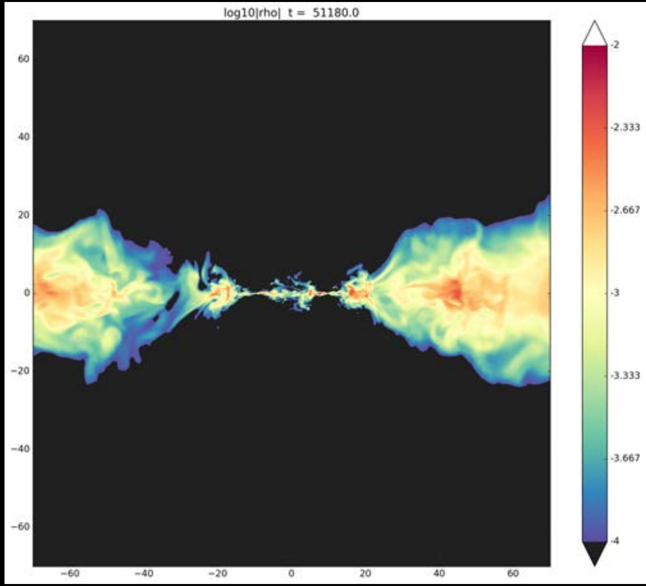
First Glimpse at the full Dynamics



Avara+2019, in prep

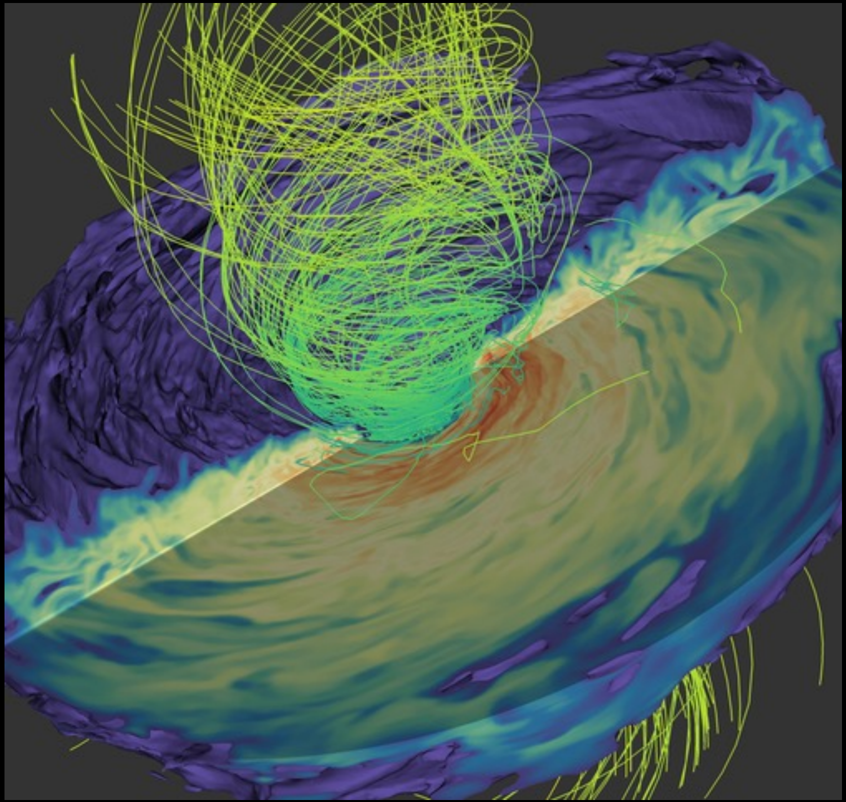
Ongoing PatchworkMHD Simulation on Blue Water –

- 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)



Summary

- Simulations are playing a major role, in both the analysis and interpretation of binary mergers, detected by advanced LIGO, and future gravitational wave detectors
- Binary black hole mergers, in particular supermassive mergers are ideal multi-messenger sources!
- Accurate 3d GRMHD models are necessary to predict characteristic signals.
- We produced the first electromagnetic spectrum from 3D simulations, essential for astronomical search campaigns and understanding systems to be discovered soon.
- Black holes are "hot", but there is still a lot that we don't know about them. There might be surprises awaiting for us!



Credits: Mewes+, RIT 2019

Collaborative Research

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NCSA's Blue Waters
TACC's Frontera
Xsede

Co-Is: Julian Krolik (JHU), Scott Noble (NASA GSFC), Yosef Zlochower (RIT
Investigators: M. Avara (PD, RIT) D. Bowen (PD, RIT/LANL) S. d'Ascoli (GR, RIT, ENS-Paris), B. Drachler (GR, RIT), James Healy, V. Mewes (PD, RIT).

Advancing Computational Methods to Understand the Dynamics of Ejection, Accretion, Winds and Jets in Neutron Star Mergers, NASA's TCAN Award 2018-2022.

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