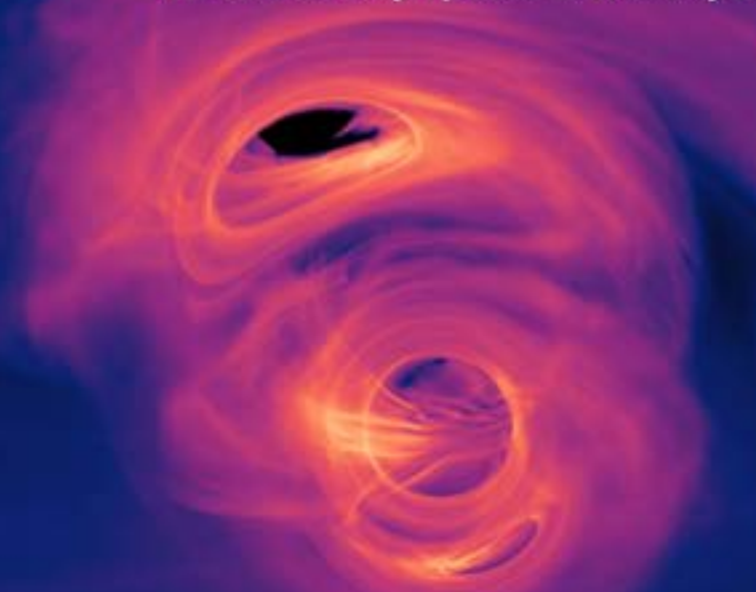
I use Blue Waters to calculate the...

Photons from Binary Black Hole Inspirals

BW ID: PRAC_baqi (now PRAC_bayh)

Blue Waters Symposium, Tuesday June 4th, 2019



Scott C. Noble, co-I
(U. Tulsa, NASA-GSFC)

PI: M. Campanelli (RIT)
co-I: J. Krolik (JHU)
Investigators:
M. Avara (PD, RIT)
D. Bowen (PD, RIT)
S. d'Ascoli (GR, RIT, ENS-Paris)
B. Drachler (GR, RIT)
V. Mewes (PD, RIT)

NCSA POC: Jing Li

Based on:

- Bowen et. al, ApJ, (accepted) (2019).
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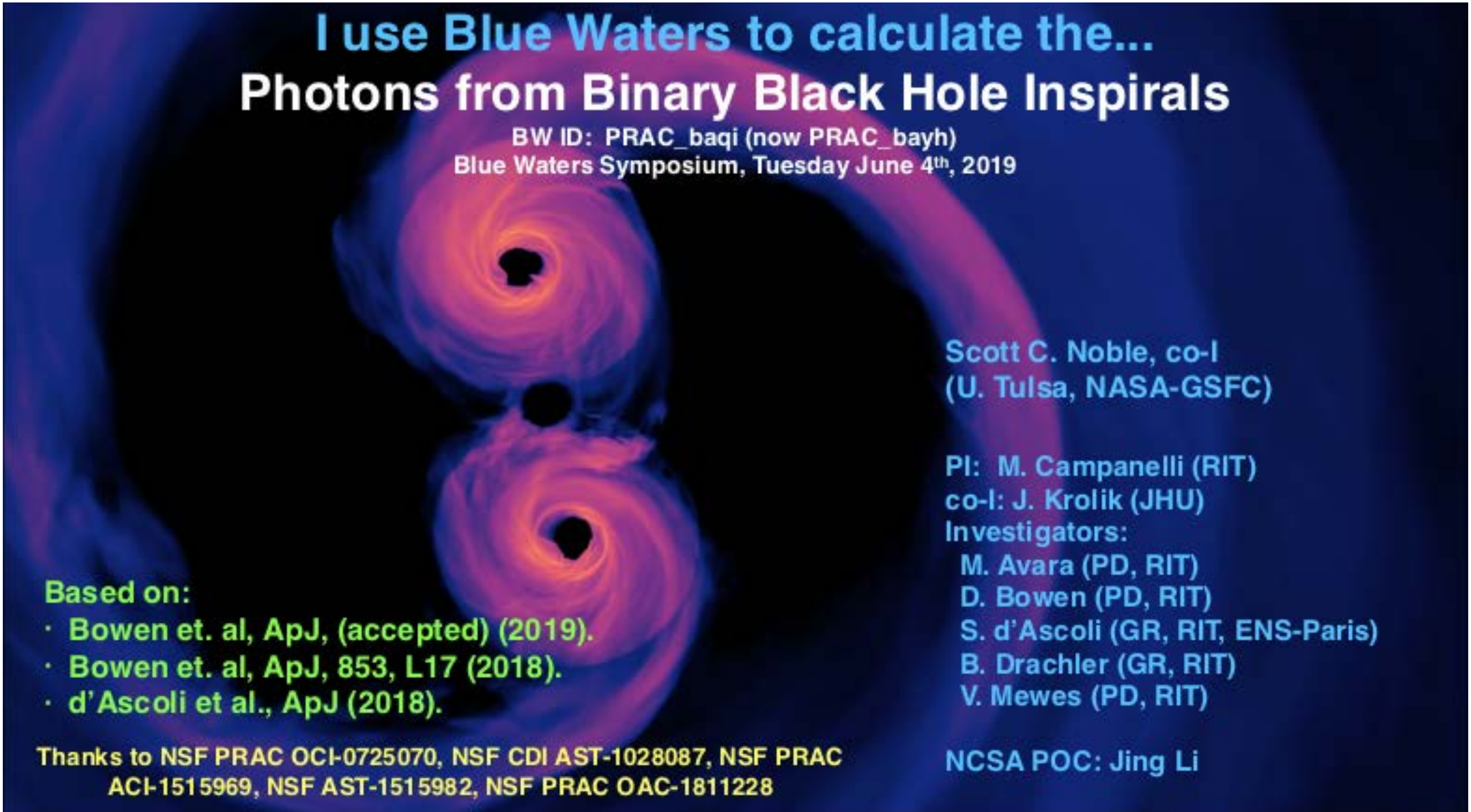
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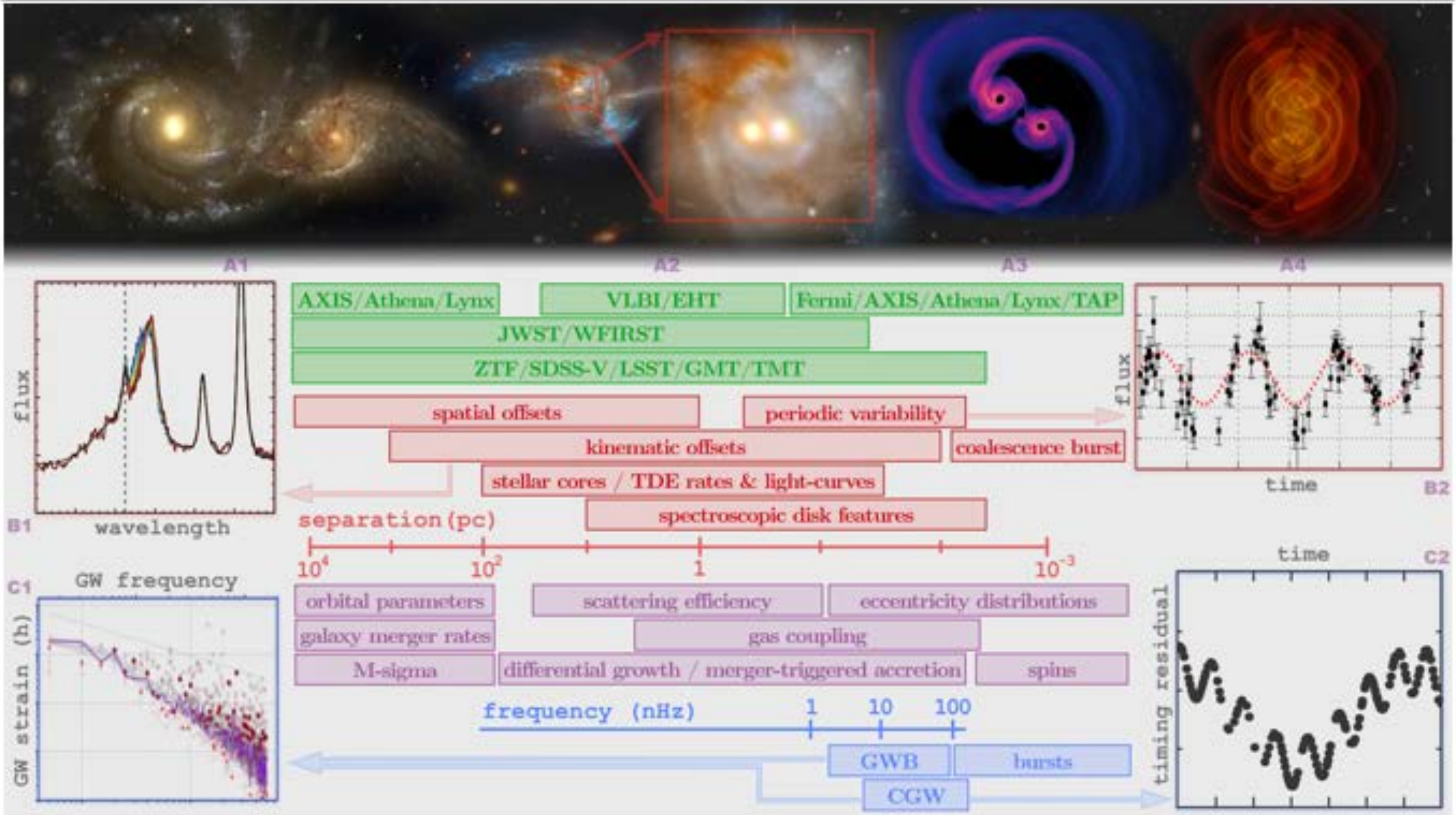
Broader Impact: Inspiring a Field: Multi-Messenger Astrophysics

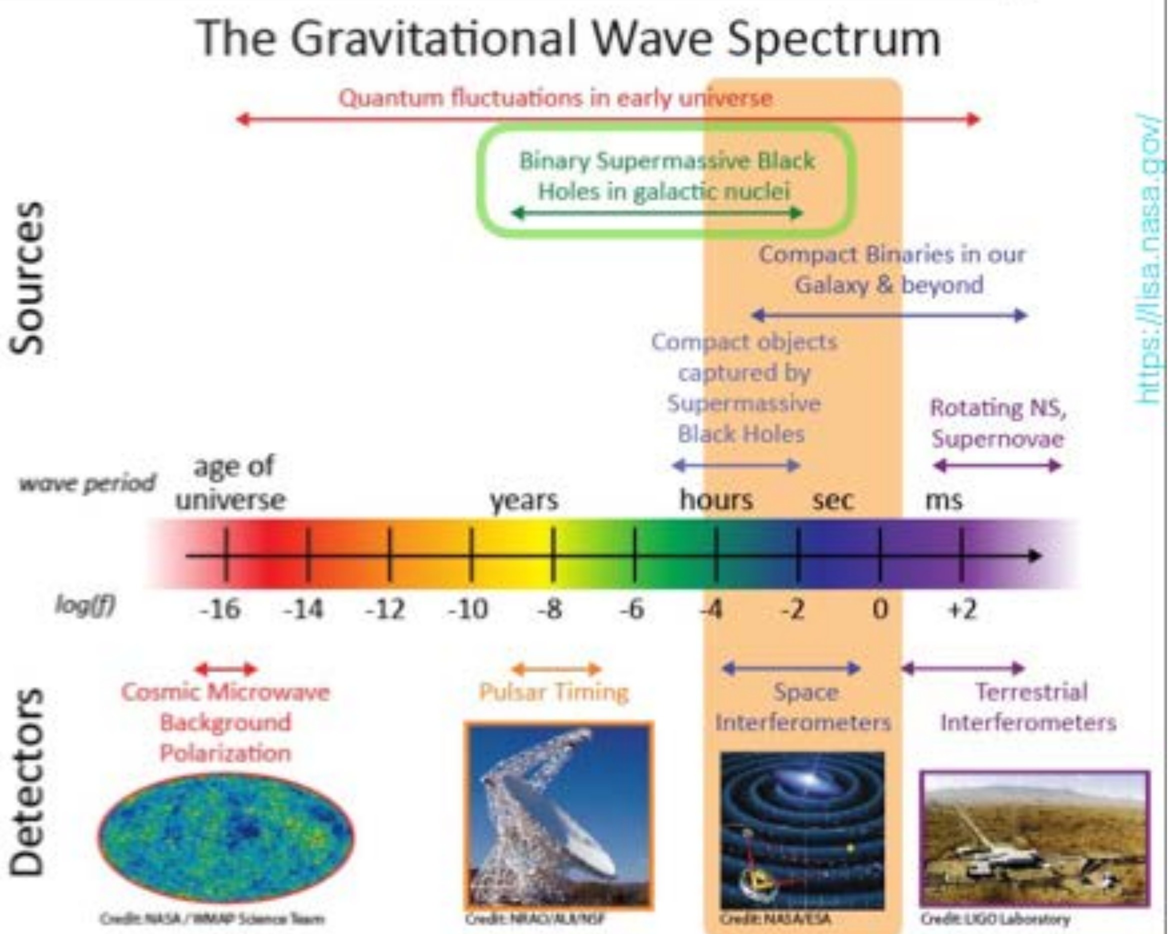


Kelley, Charisi++2019—Astro2020 Whitepaper

Why It Matters: Mysteries of Supermassive Black Holes

- Binary AGN are a primary multi-messenger source for LISA and PTA campaigns.
- Likeliest EM-bright binary black hole system, as embedded binaries in AGN disks may be too dim w.r.t. their host.

  ➡Best candidate for exploring plasma physics in the strongest and most dynamical regime of gravity.
- Even though GWs can aid localization (e.g., GW170817), the source volume increases significantly with LISA/PTA events.
- LSST will identify 100k's of AGN, so "many" binary-AGN are expected to be uncovered in the haystack.
- EM identification will be critical for detection and characterization—> realistic simulations and their electromagnetic output are needed!



Broader Impact: Inspiring a Field: Multi-Messenger Astrophysics

Astro2020 Decadal Review

https://youtu.be/IpkPh6H8p4M

Changing Science Strategies: ESA's Rethinking Launch Schedules

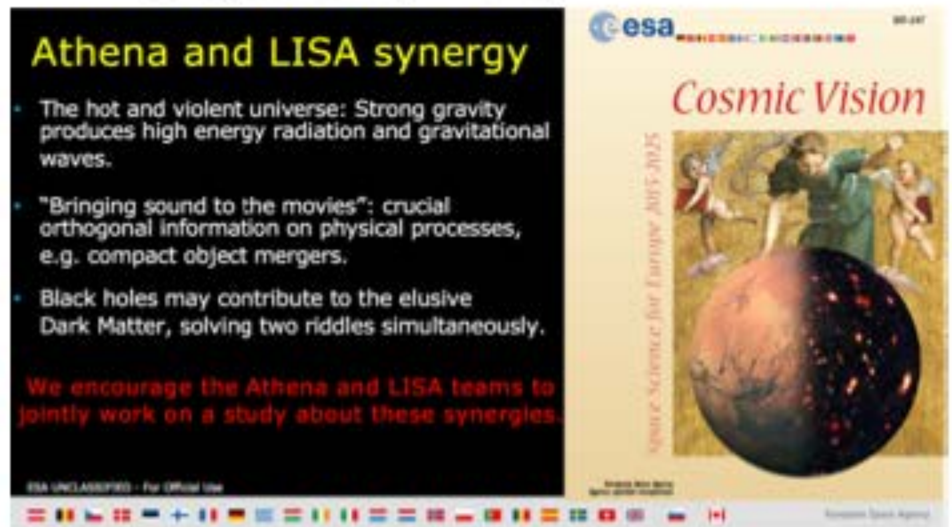


Chart is from presentation by Guenther Hasinger, ESA Director of Science, at LISA Symposium

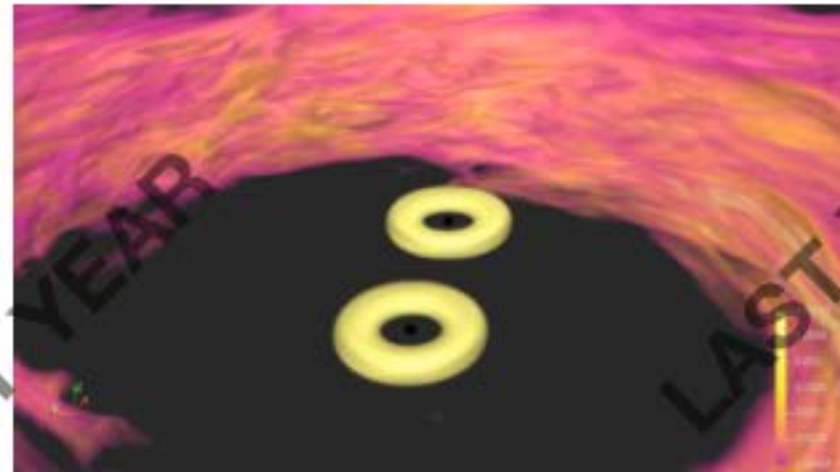
Accomplishments: 3-d GRMHD Mini-disk Evolutions

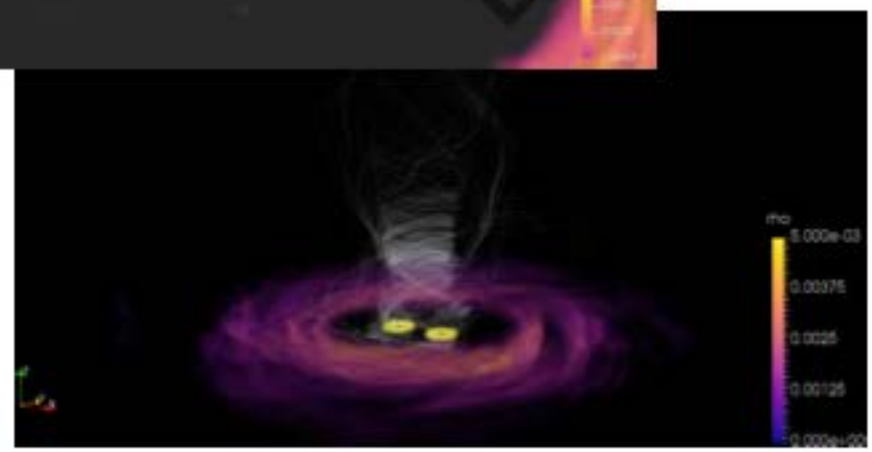
Bowen et. al, ApJ, 853, L17 (2018).

Why It Matters:

- **First** simulation of resolved GRMHD simulations of an accreting binary with relaxed circumbinary disk data and mini-disks.
- **First** exploration of interactions between mini-disks and circumbinary disks in the inspiral regime of the binary, the longest phase observable by LISA.
- **First** mini-disk simulations in 3-d, or with event horizons, or both.

- **Product:** Arbitrary grid-to-grid interpolator with magnetic monopole cleaner for preserving the solenoidal constraint.





Blue Waters Team Contributions:
Visualizations by Mark Van Moer (NCSA)

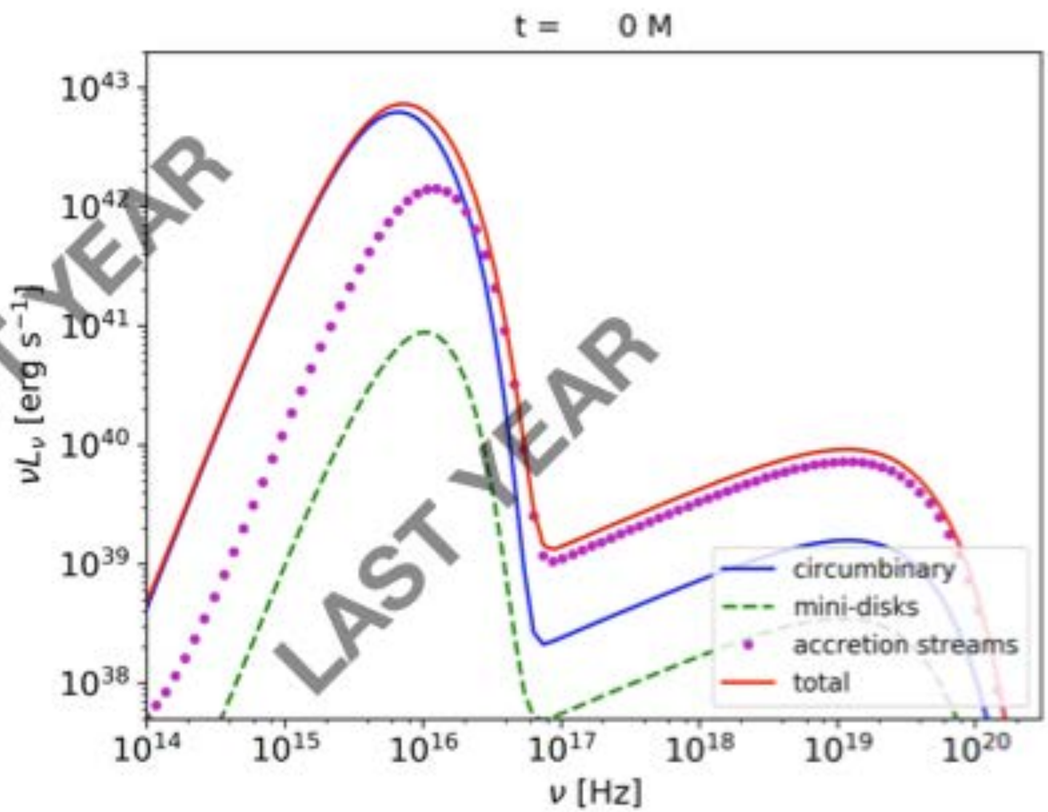
Accomplishments: Light from GRMHD Mini-disks

d'Ascoli et. al, ApJ, (2018).

- **Why It Matters: First predicted spectrum from accreting binary black holes in the inspiral regime.**

- **Why It Matters: The systems will likely be too distant to be spatially resolved, so we need to understand their spectrum and how it varies in time.**

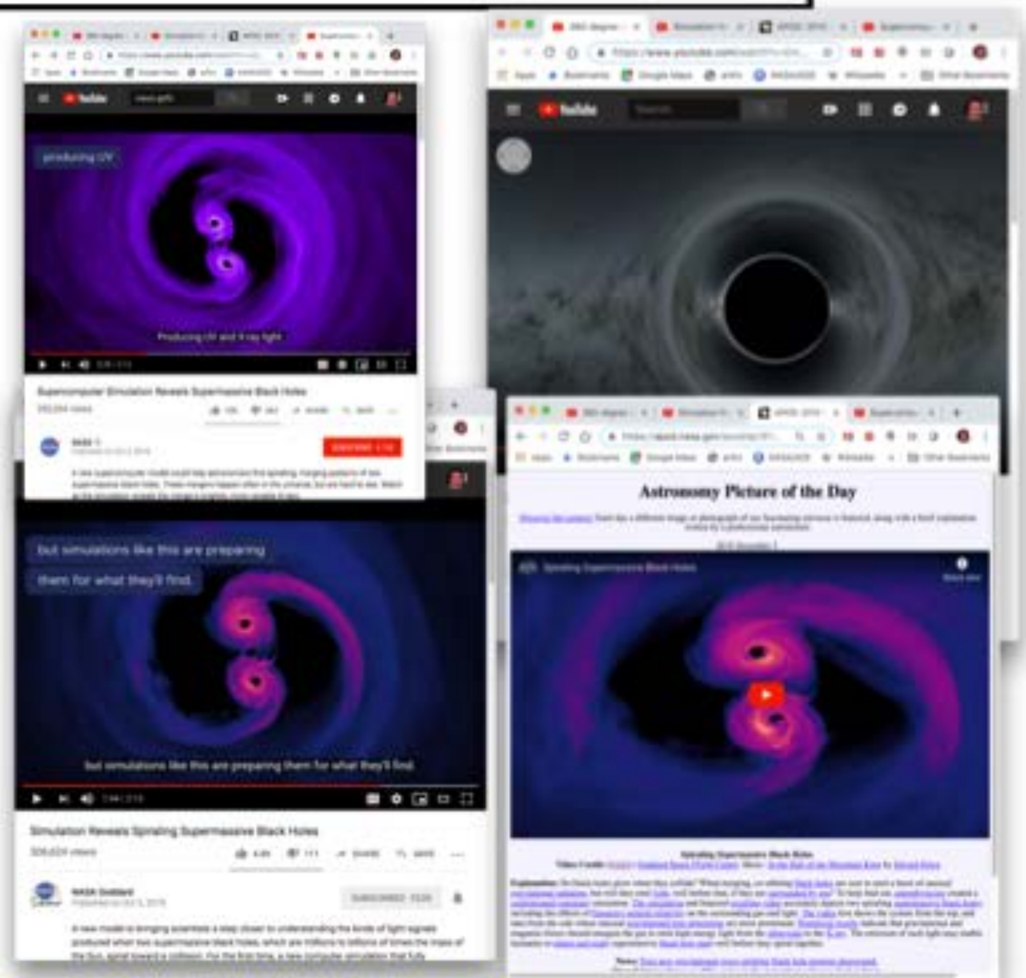
- **Key distinctions from single black hole (AGN) systems:**
  - **Brighter X-ray emission relative to UV/EUV.**
  - **Variable and broadened thermal UV/EUV peak.**
  - **"Notch" between thermal peaks of mini-disks and circumbinary disk will likely be more visible at larger separations and for spinning black holes.**



Broader Impact: Science Communication

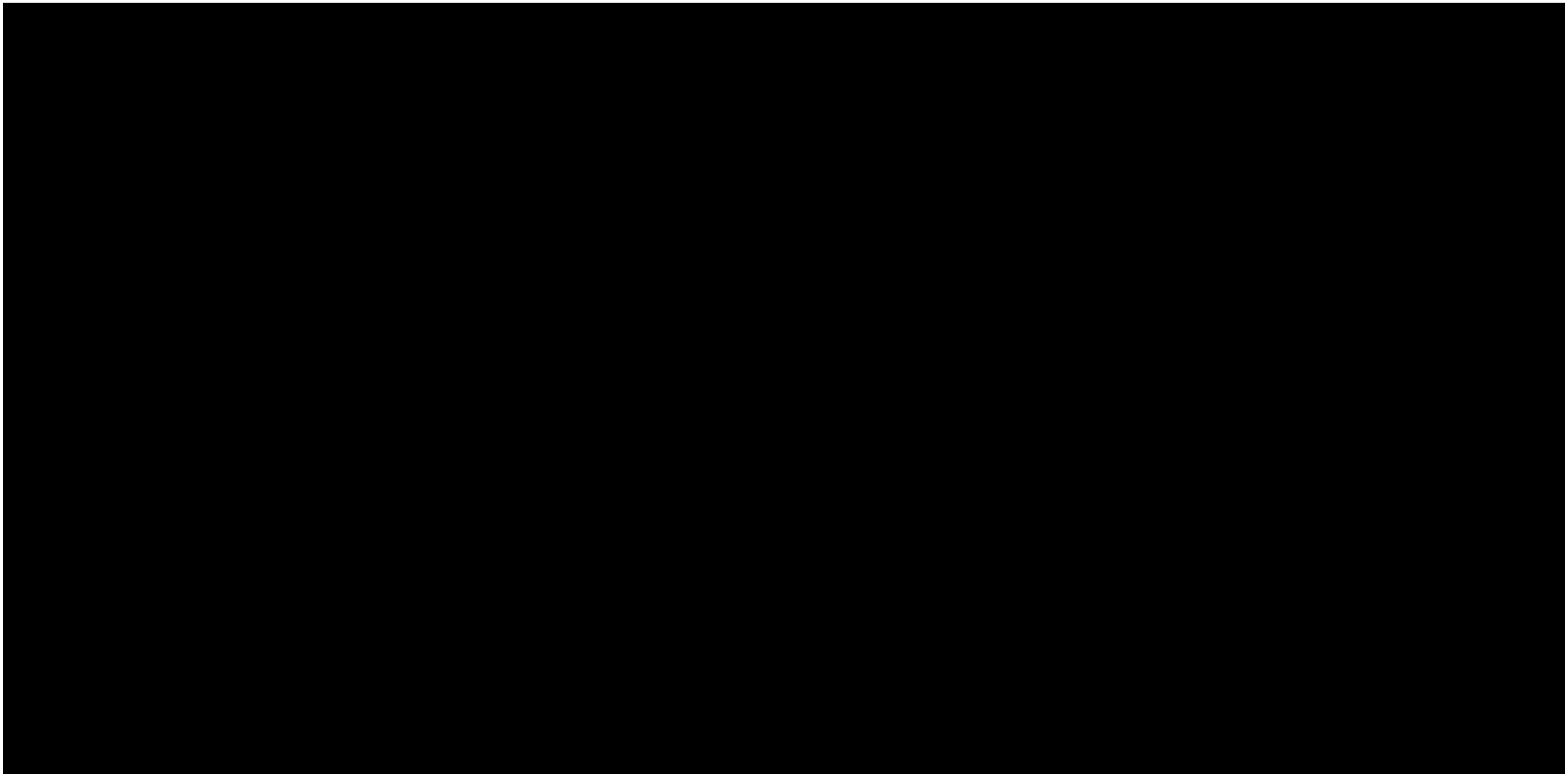
d’Ascoli et. al, ApJ, (2018).

- **Blue Waters Team Contributions:** Jing Li helped us develop a strategy to maximize queue throughput so we would meet publication announcement deadline (e.g. bundle small jobs into bigger ones, etc.).
- **Why Blue Waters:** Level of resources and availability to large number of nodes provided the creative freedom to think big and execute ray-tracing process quickly.
  - 4K resolution, ~ 10M pixels per frame, $O(10^3)$ frames, each needing geodesic and rad. transf. Integrations.
- **Broader Impact:** Shared visualizations with more than 840,000 views through NASA YouTube channels.
- 360 deg. VR Movie: https://youtu.be/Em4OFLjMux0



https://svs.gsfc.nasa.gov/13043

https://www.nasa.gov/feature/goddard/2018/new-simulation-sheds-light-on-spiraling-supermassive-black-holes



Accomplishments: ***Longterm*** **3-d GRMHD Mini-disk Evolutions**

Bowen et. al, ApJ, (accepted) (2019).

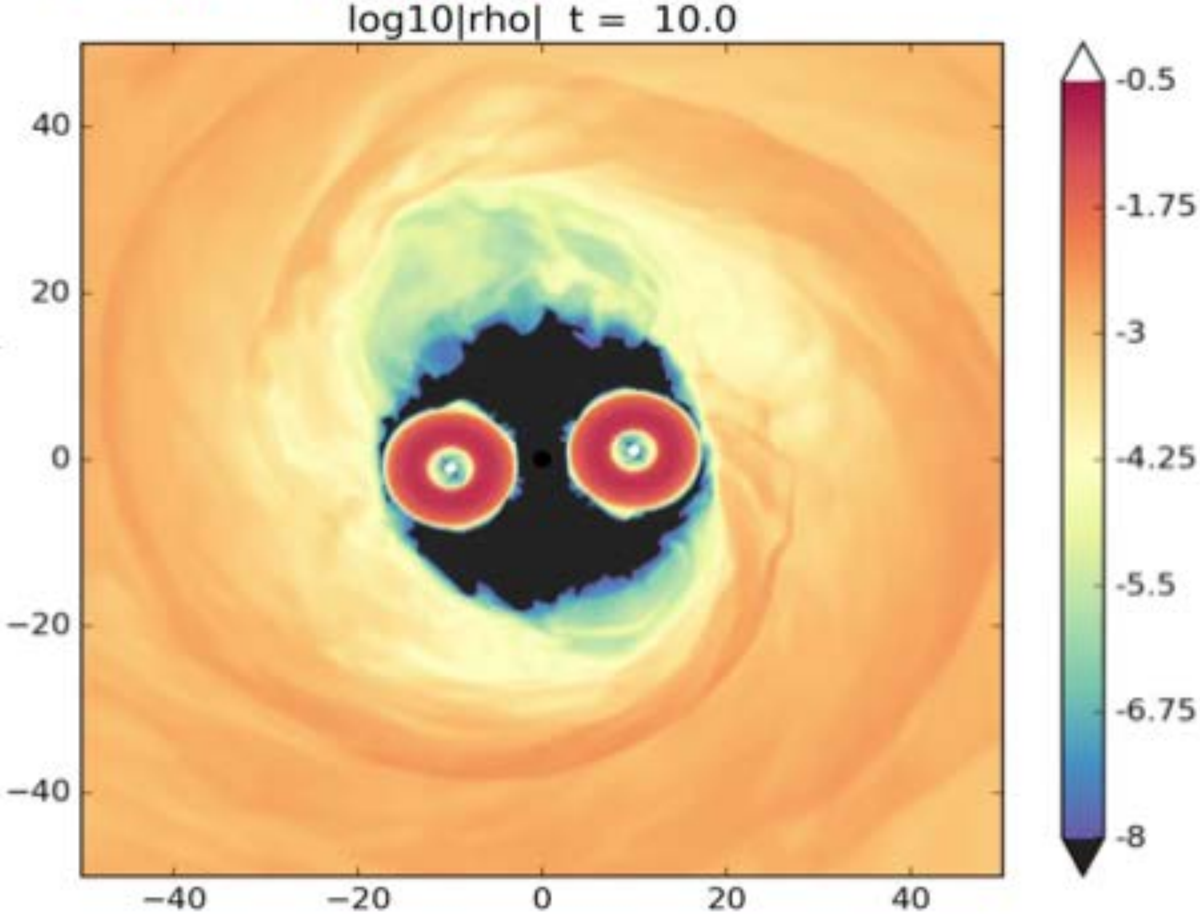
- Extending Bowen++2018 run from 3 orbits to 12 orbits.

Why It Matters:

- **First** resolved GRMHD simulation of an accreting binary with relaxed circumbinary disk data and mini-disks evolved to *steady mini-disk phase*.

- **First** measurement of quasi-periodic interactions in the *steady state* between mini-disks and circumbinary disks in the inspiral regime of the binary, the longest phase observable by LISA.

- **Product:** Enough time series data to calculate light curve (being analyzed now).



Accomplishments: *Longterm* 3-d GRMHD Mini-disk Evolutions

Bowen et. al, ApJ, (accepted) (2019).

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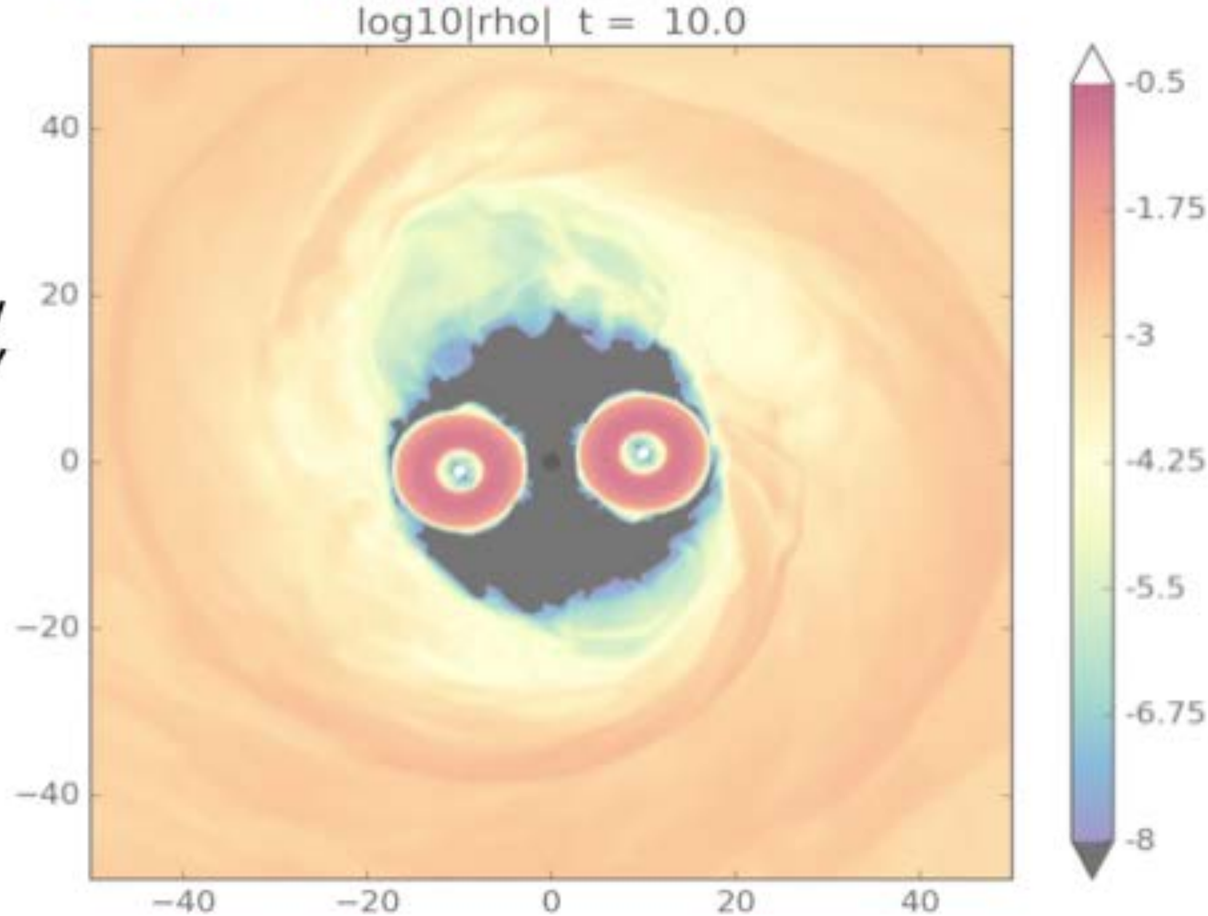

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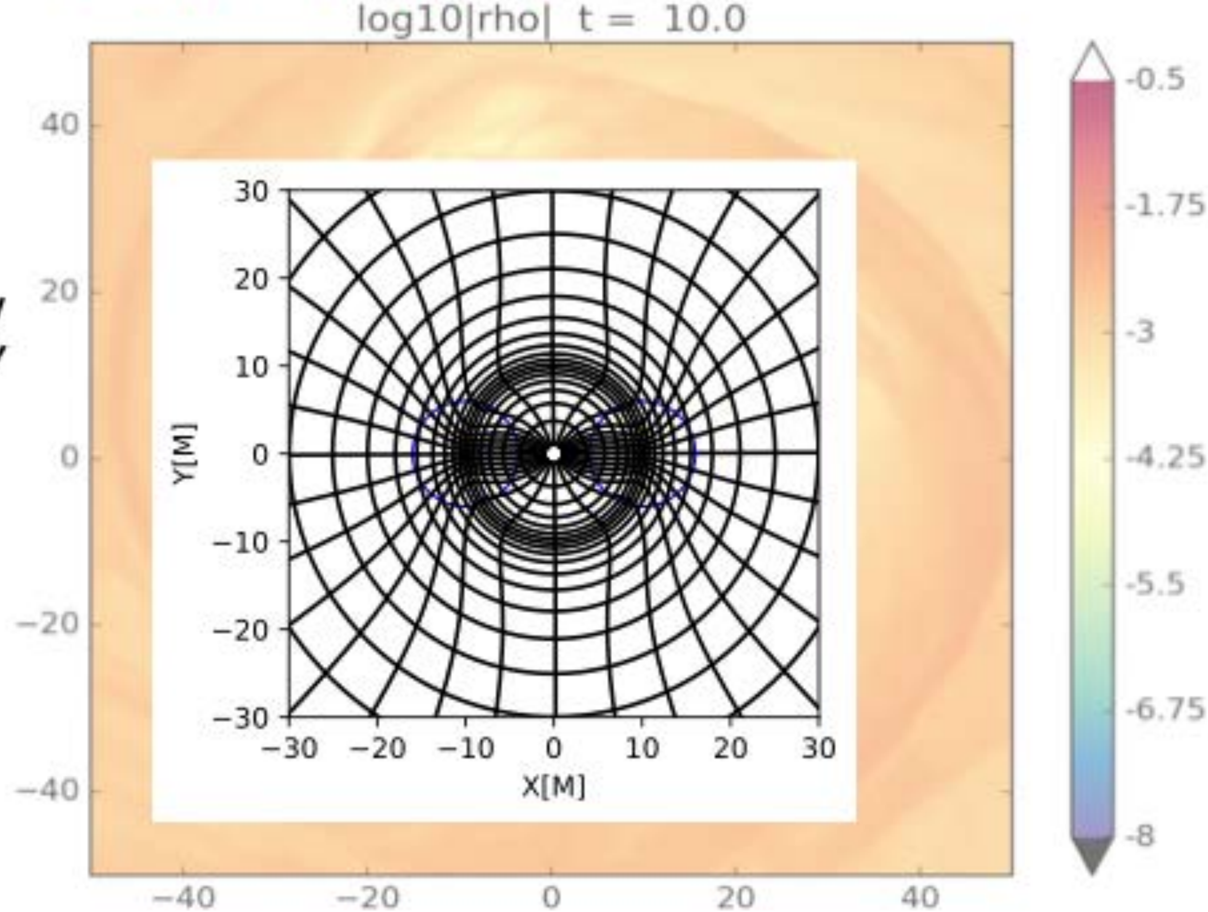

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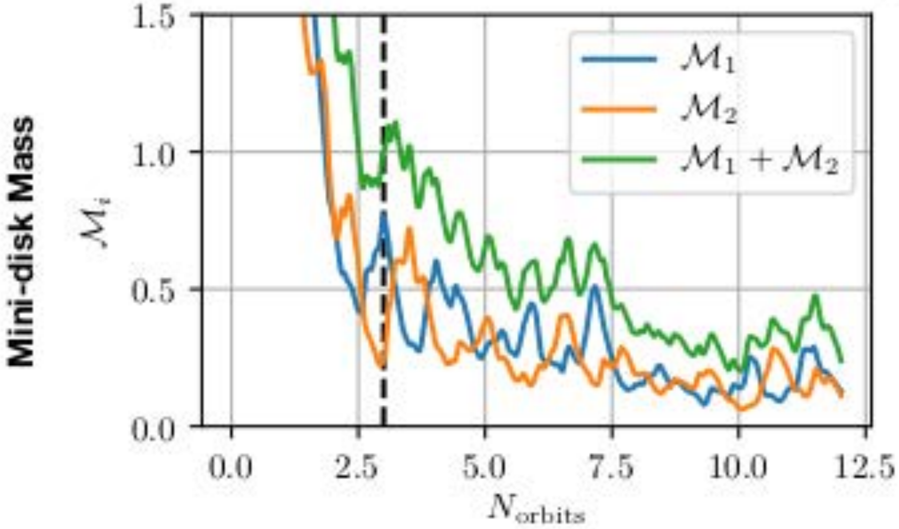
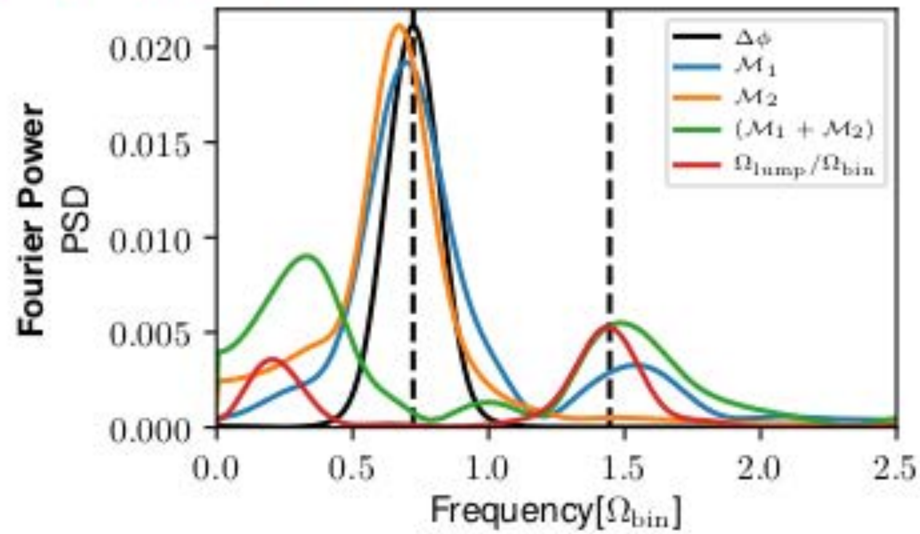




- Mini-disks settle to a steady-state after several binary orbits.
- Mini-disks replenish with material in alternating fashion as they pass by the circumbinary disk's lump, then drain at time scale close to one orbit period.
- At these close separations and cooling rate, accretion through mini-disks is driven primarily through spiral shocks.

- Significant modulation in each mini-disk's mass —> possible EM signal?
- If light follows mass, EM period would be a ~1.5 times the binary period, the beat frequency between the orbital periods of the lump and mini-disks.
- Dimmer circumbinary lump modulated at the same frequency plus its local orbital rate (Noble++2012).

Accomplishments, Product: MHD *Patchwork*

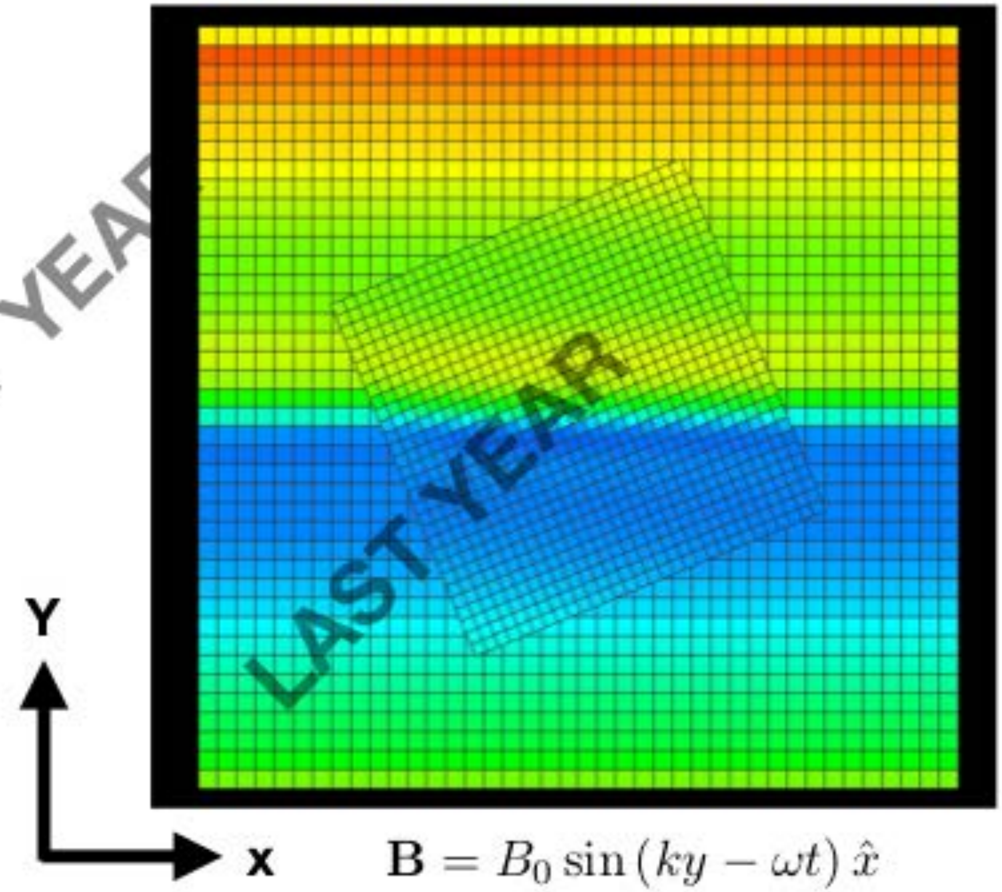
Avara et. al, to be submitted (2019).

- **Key Challenges:** Adding support for MHD and preservation of solenoidal (aka "no magnetic monopoles") constraint into the hydrodynamic *Patchwork* code.

- **Key Challenges:** Generalize *Patchwork* for the wide range of coordinate systems and patch situations (e.g., patch motion/rotation/overlap) desirable to execute our planned simulations.

- **Product:** Developed method to adjust fluxes along patch boundaries to dissipate monopoles and flux differences.

- **Why It Matters:** Allows us to stitch together coordinate patches that follow local symmetries efficiently and eliminate coordinate singularities that arise in spherical/cylindrical coordinates.

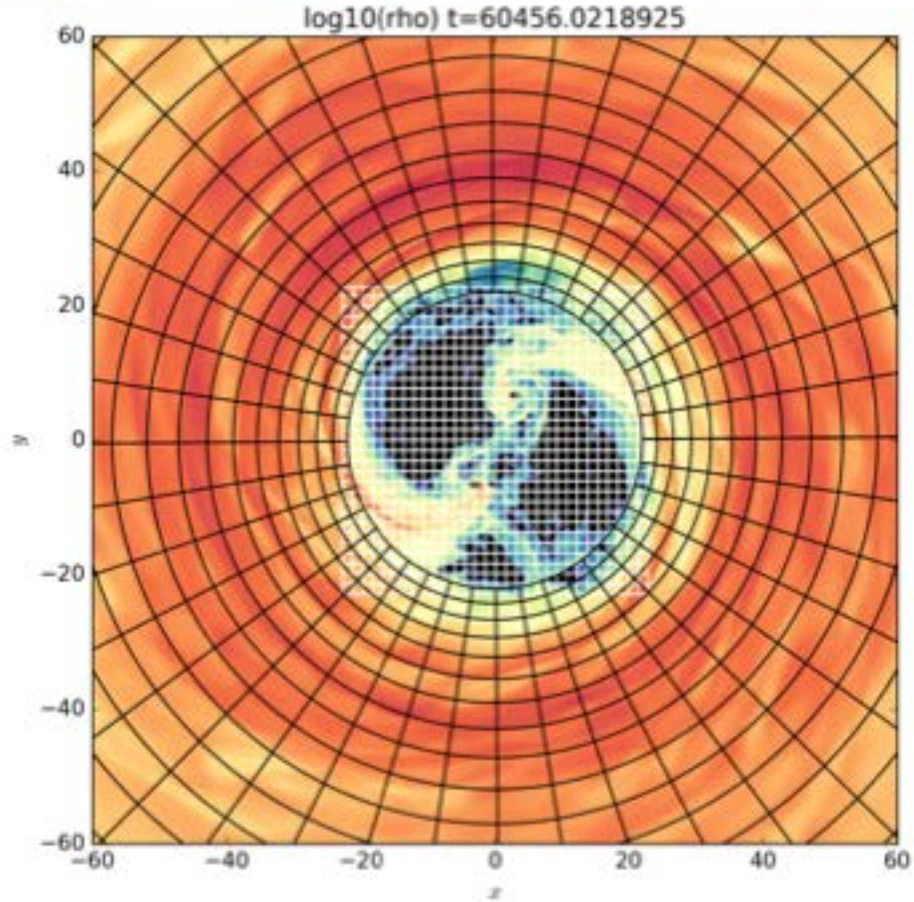


$$\mathbf{B} = B_0 \sin(ky - \omega t)\,\hat{x}$$

Accomplishments: *Patchwork* Mini-disk Evolutions

Avara et. al, ApJ, (in progress) (2019).

- **Key Challenges**: How do we efficiently simulate 10^7-10^8 cells for 10^6-10^7 steps?
- Starting from circumbinary disk data of **Noble++2012**, let mini-disks fill in since mini-disks drain in about one binary orbit.
- **Product**: Use new PatchworkMHD code (Avara++2019, in progress).
- 31 binary orbits (from 12 orbits before);
- Grid the domain dictated by local symmetries/ asymmetries of the solution.
- Cartesian Patch: 300x300x200 cells
  - Uniform in x,y but graded in z.
- Spherical Patch: 300x160x400 cells
  - Same grid as Noble++2012, no interpolation required.
- Cartesian patch avoids the focusing of cells near the origin and axis, increasing the size of time steps we can take, plus covers the missing volume.



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log10(rho) t=50000.0082304

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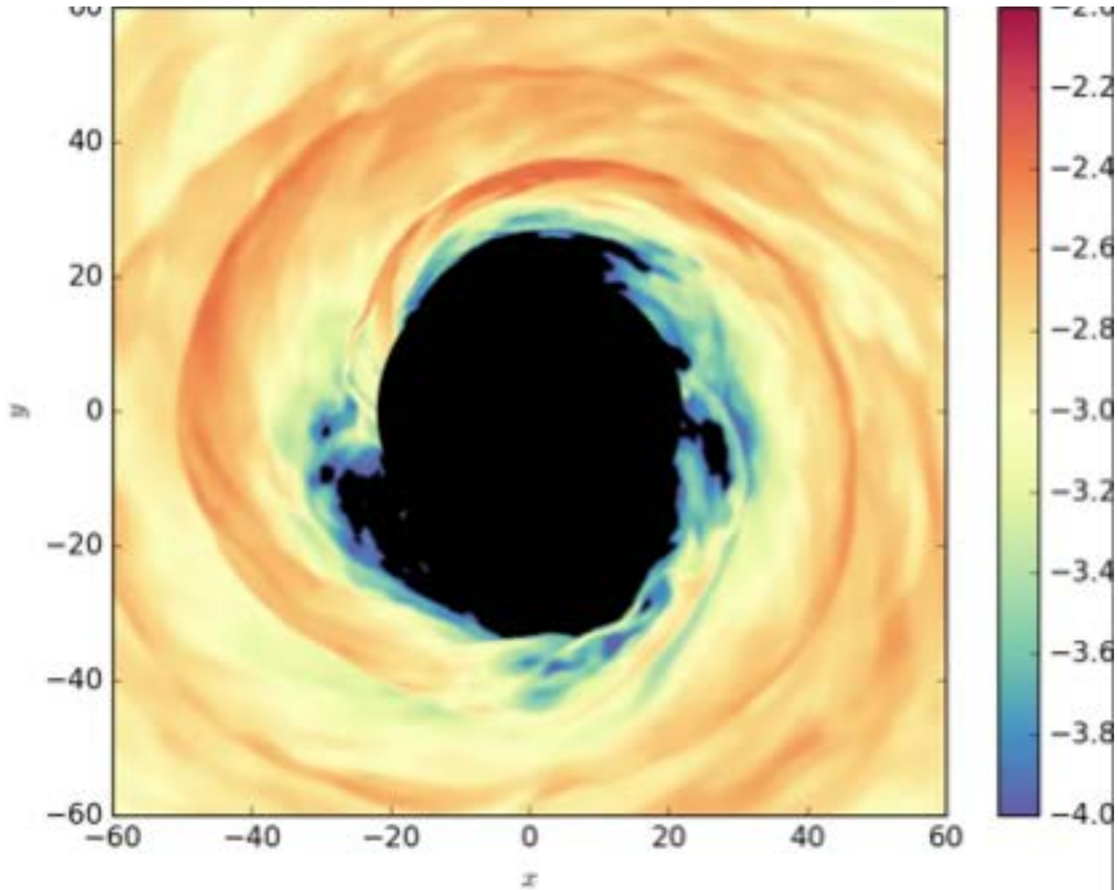

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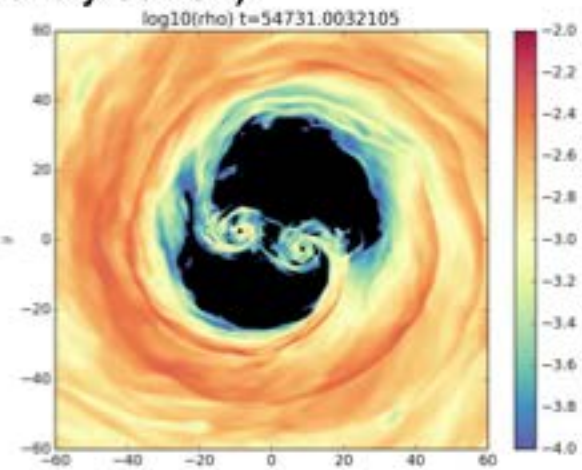

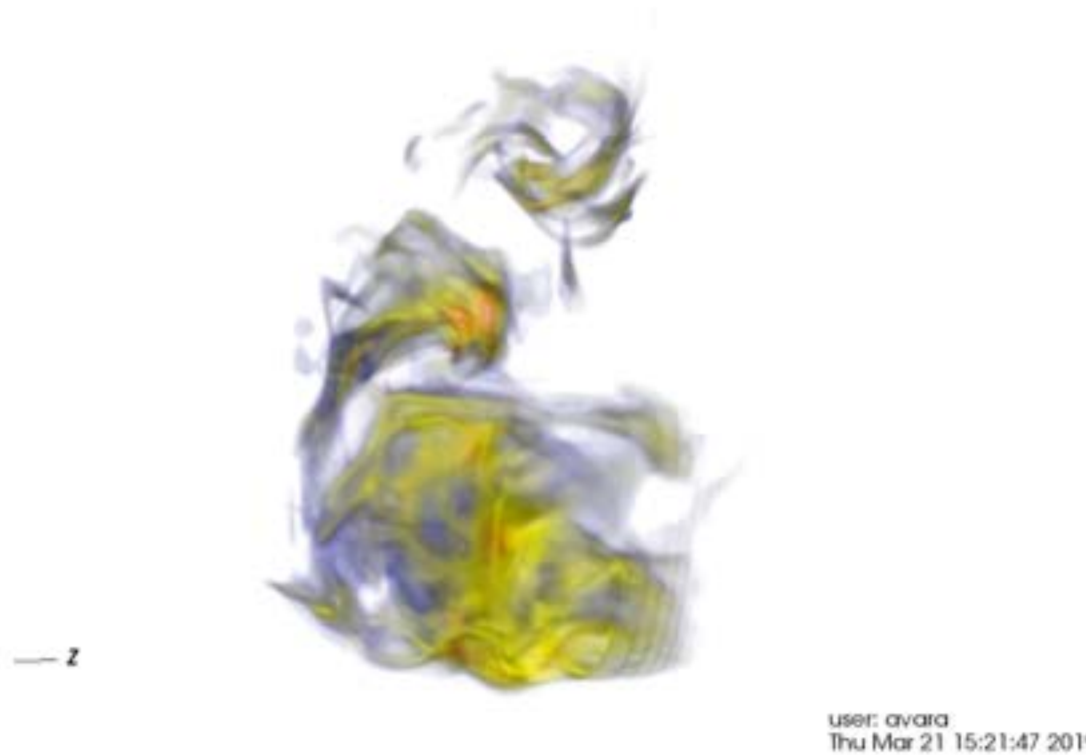

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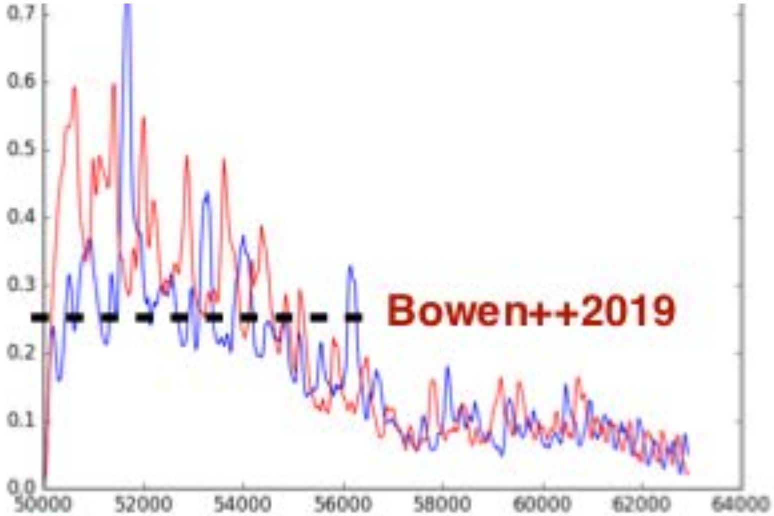
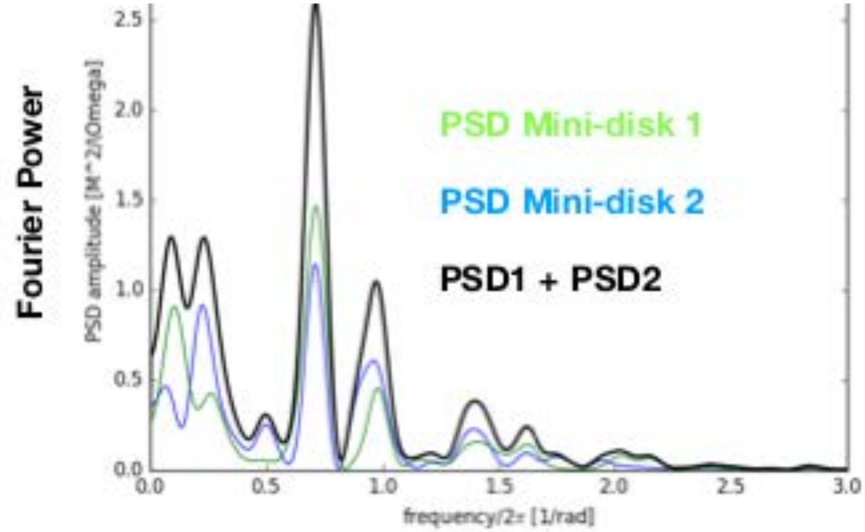


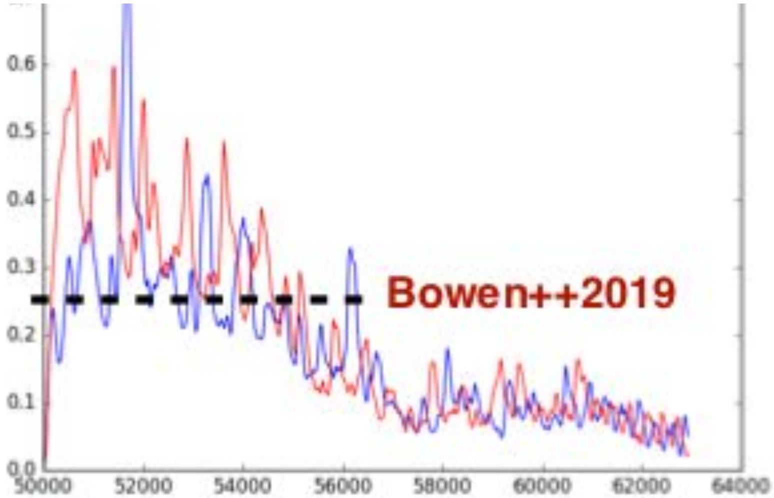


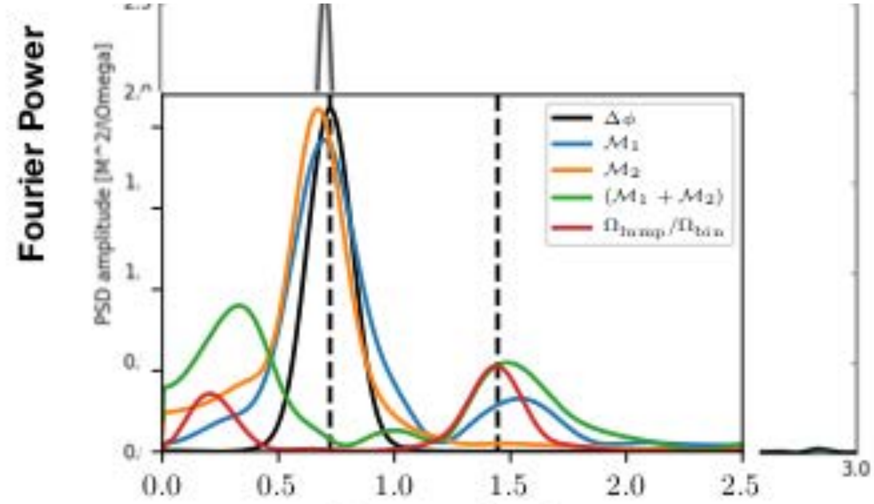
- **Mini-disks again settle to a steady-state after several binary orbits, though now from below.**
- **Confirms prior results with "warped" grid:**
  - **Existence of spiral shocks dominating mini-disk accretion;**
  - **Draining/replenishing cycle and rate;**
  - **Primary time scales of variability in mini-disk masses;**

- **Signals in mini-disk mass are also reminiscent.**
- **Mini-disks still oscillate at beat frequency, and lump oscillates at its local orbital rate.**
- **Now see signal at 1x and 2x the binary orbital frequency, possibly from "sloshing".**
- **More scenarios in progress at different resolutions, mass ratios, separations…**

Accomplishments: *Patchwork* Mini-disk Evolutions

Avara et. al, ApJ, (in progress) (2019).





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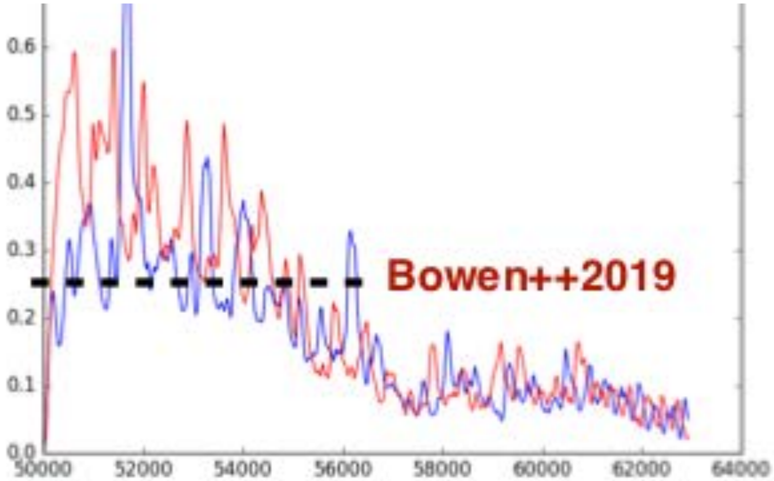

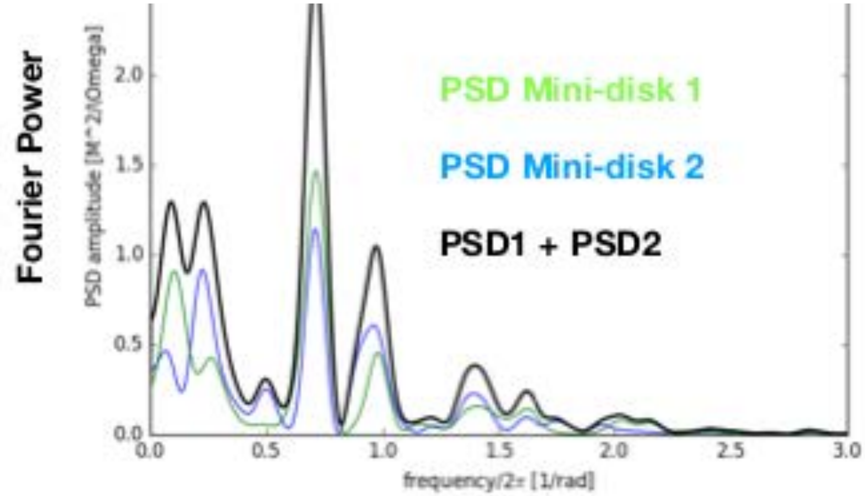

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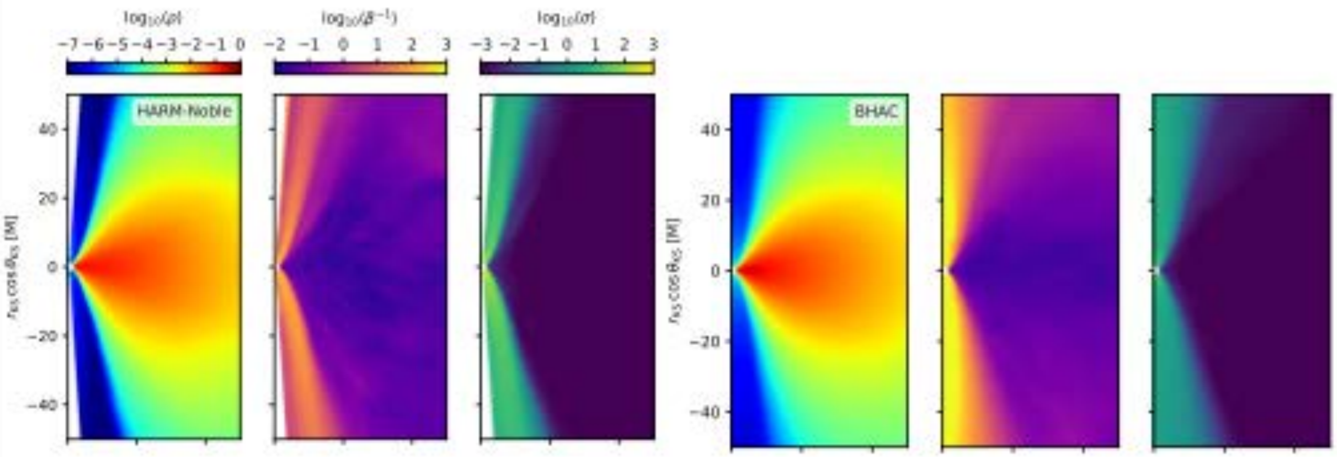
The Event Horizon General Relativistic Magnetohydrodynamic Code Comparison Project

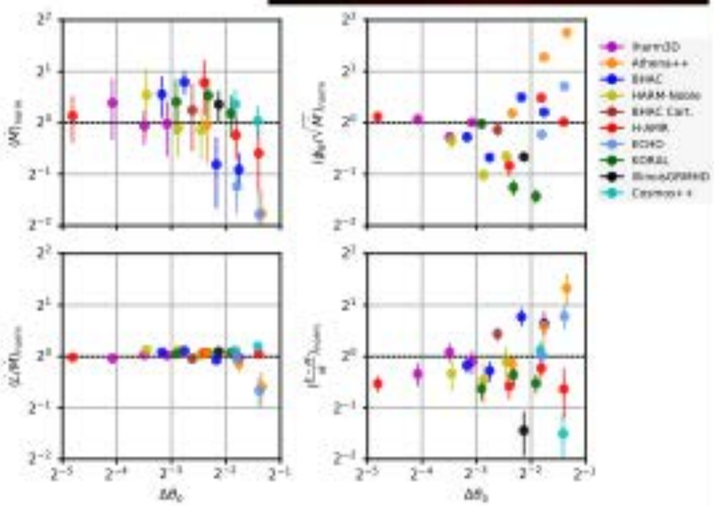
Oliver Porth,[1,2] Koushik Chatterjee,[1] Ramesh Narayan,[3,4] Charles F. Gammie,[5] Yosuke Mizuno,[2] Peter Anninos,[6] John G. Baker,[7,8] Matteo Bugli,[9] Chi-kwan Chan,[10,11] Jordy Davelaar,[12] Luca Del Zanna,[13,14] Zachariah B. Etienne,[15,16] P. Chris Fragile,[17] Bernard J. Kelly,[18,19,7] Matthew Liska,[1] Sera Markoff,[20] Jonathan C. McKinney,[21] Bhupendra Mishra,[22] Scott C. Noble,[23,7] Héctor Olivares,[2] Ben Prather,[24] Luciano Rezzolla,[2] Benjamin R. Ryan,[25,26] James M. Stone,[27] Niccolò Tomei,[13,14] Christopher J. White,[28] and Ziri Younsi[29,2]

KAZUNORI AKIYAMA,[30,31,32,4] ANTXON ALBERDI,[33] WALTER ALEF,[34] KEIICHI ASADA,[35] REBECCA AZ

https://arxiv.org/abs/1904.04923 **(and many more ......)**

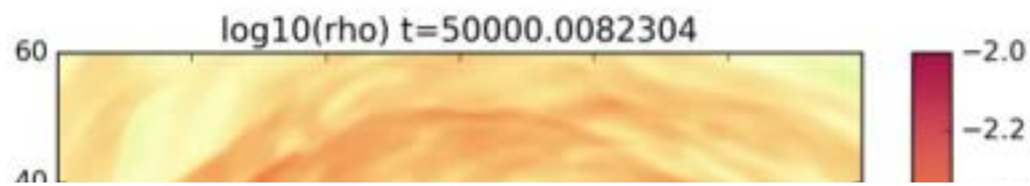
Software: `Athena++`, White et al. (2016); `BHAC`, Porth et al. (2017); `Cosmos++`, Anninos et al. (2005); Fragile et al. (2012, 2014); `ECHO`, Del Zanna et al. (2007); `H-AMR`, Liska et al. (2018a); Chatterjee et al. (2019); `HARM-Noble`, (Gammie et al. 2003; Noble et al. 2006, 2009); `iharm3D`, Gammie et al. (2003); Noble et al. (2006, 2009); `IllinoisGRMHD`, Etienne et al. (2015); `KORAL`, (Sądowski et al. 2013, 2014)





Summary and Conclusions

- **Produced a number of first-of-a-kind simulations involving accreting supermassive binary black holes, made possible by the generous resources of Blue Waters.**



- Discovered periodicities in the masses of different components of the accretion flow suggesting a means for identifying and characterizing these relatively hard to find systems.
  - Provides renewed optimism for gravitational wave and EM searches and follow-ups.
  - Providing input to future space missions (TAP, LISA, Athena).
- Demonstrated technical developments will add versatility to how we design our simulations and enable a real change in how we model relativistic astrophysical sources.

- Why Blue Waters: The incredible resources and level of support provided by Blue Waters have motivated us to challenge ourselves to solve problems and develop tools we may not have done otherwise.