



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)

Based on:

- Bowen et. al, *ApJ*, (accepted) (2019).
- Bowen et. al, *ApJ*, 853, L17 (2018).
- d'Ascoli et al., *ApJ* (2018).

Thanks to NSF PRAC OCI-0725070, NSF CDI AST-1028087, NSF PRAC
ACI-1515969, NSF AST-1515982, NSF PRAC OAC-1811228

NCSA POC: Jing Li



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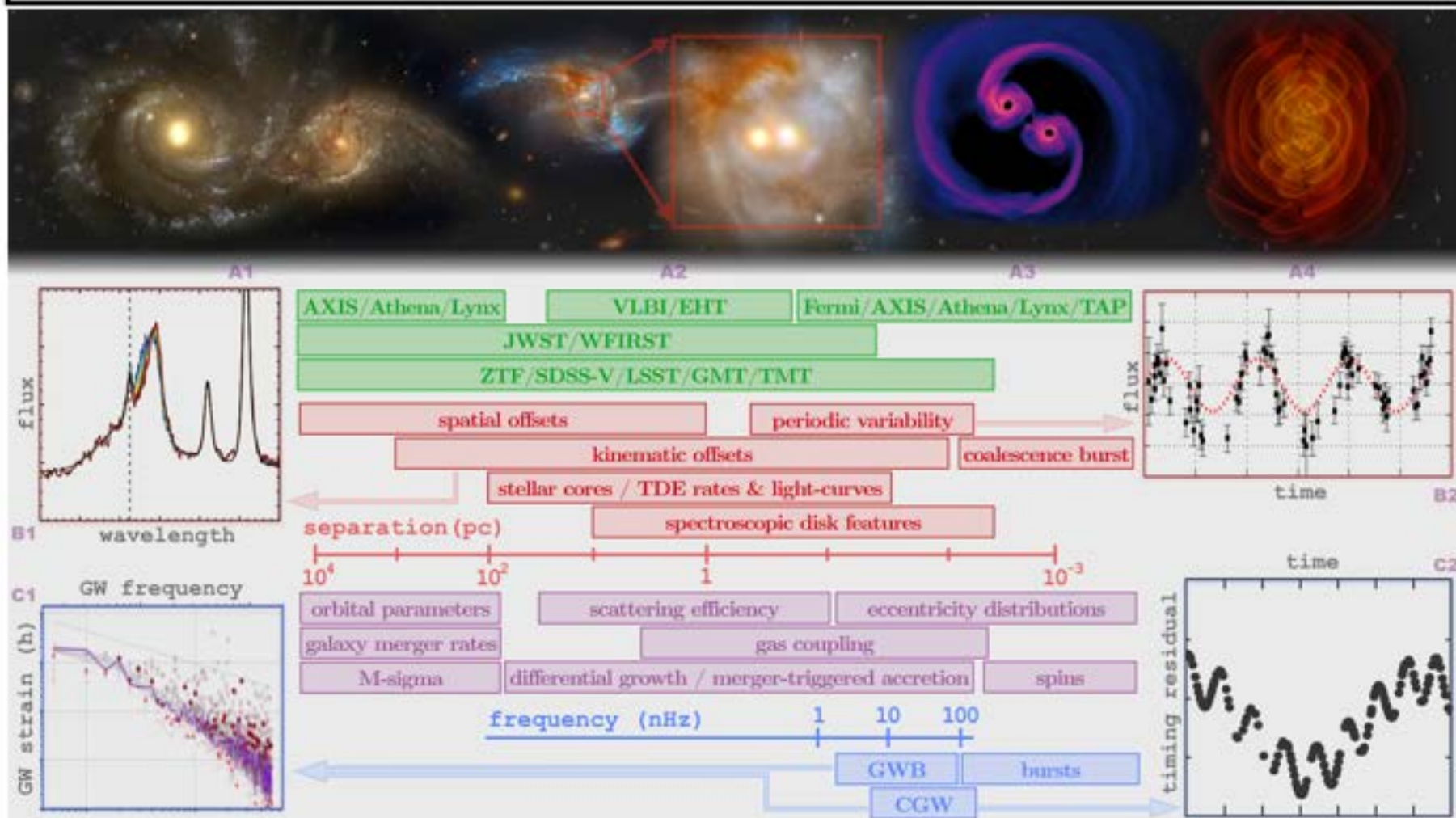
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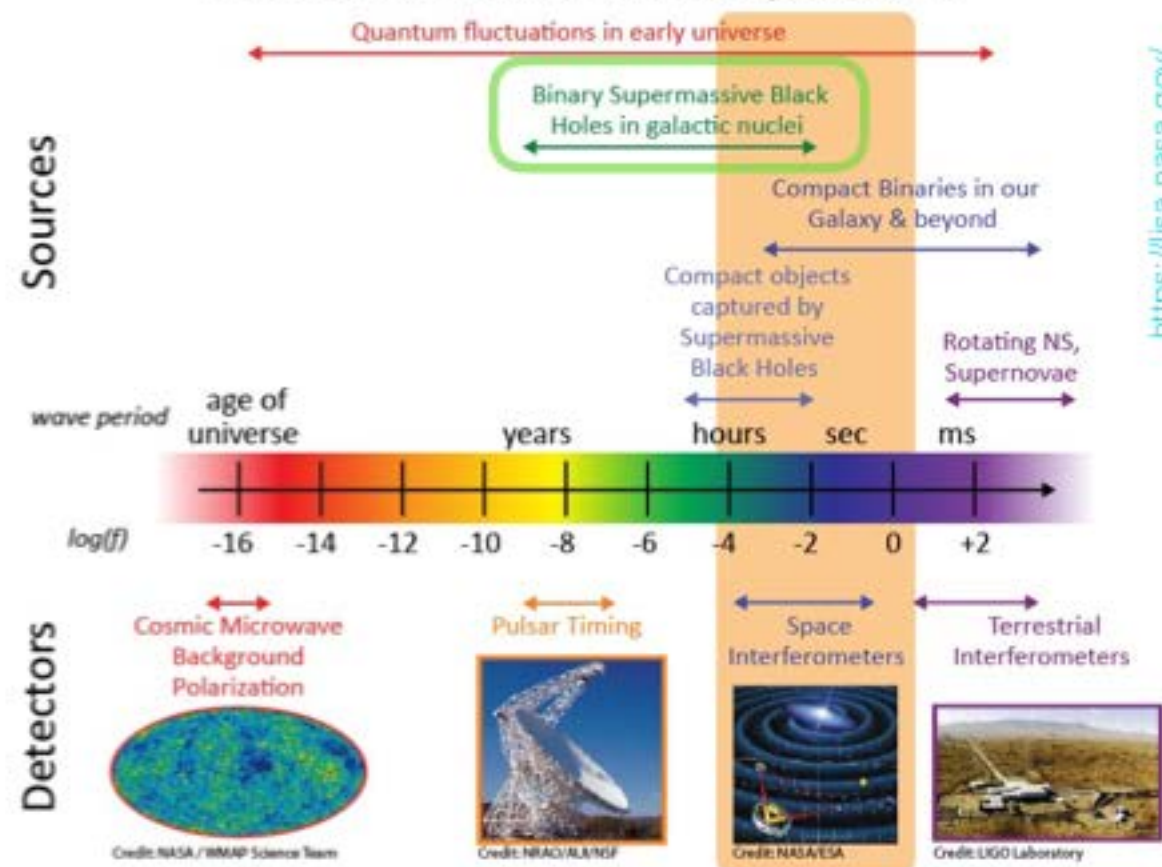
Broader Impact: Inspiring a Field: Multi-Messenger Astrophysics



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!

The Gravitational Wave Spectrum



Broader Impact: Inspiring a Field: Multi-Messenger Astrophysics

Astro2020 Decadal Review

X-ray follow-up of extragalactic transients

Thematic Areas
Formation and Evolution of Compact Objects
Multi-Messenger Astronomy and Astrophysics

Principal Author:

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Eris Kara, NASA GSFC
Regina Caputo, NASA GSFC
Derek Fox, Penn State University
Scott Noble, University of Texas, NASA GSFC
Richard Mushotzky, University of Maryland
John Ruan, McGill University
Daryl Haggard, McGill University
Geoffrey Ryan, University of Maryland
David Burrows, Penn State University

* early career scientist (pre-tenure faculty/postdoc)

Primary Thematic Science Area: Multi-Messenger Astronomy and Astrophysics
Secondary Areas: Cosmology and Fundamental Physics, Galaxy Evolution, Formation and Evolution of Compact Objects

Multimessenger science opportunities with mHz gravitational waves

John Baker,^{1,2} **Zoltan Haiman**,³ **Elena Maria Rossi**,⁴
Edo Berger,⁵ **Niel Branch**,⁶ **Elmè Brendt**,⁷ **Katerlyn Breivik**,⁸ **Maria Charisi**,⁹ **Andrea D'Orlando**,¹⁰ **Daniel J. D'Orazio**,¹¹ **Saurik Ford**,^{12,13} **Jenny E. Greene**,¹² **J. Colin Hill**,^{13,14}
Kelly Holley-Bockelmann,¹⁵ **Joey Shapiro Key**,¹⁶ **Bence Kocsis**,¹⁷ **Thomas Kupfer**,¹⁸ **Shane Larson**,¹⁹ **Piero Madau**,²⁰ **Thomas Marsh**,²¹ **Barry McKernan**,^{22,23} **Sean T. McWilliams**,²²
Priyavada Natarajan,²⁴ **Samaya Nissanke**,²⁵ **Scott Noble**,^{25,1} **E. Sterl Pittney**,⁸ **Gavin Raaijmakers**,²⁶ **Jeremy Schnittman**,¹ **Alberto Sotani**,^{27,28} **David Shoemaker**,²⁹ **Nicholas Stone**,¹
Silvia Toonen,^{30,27} **Benny Trakhtenbrot**,³¹ **Alesey Vikhlinin**,³ and **Marta Volonteri**³²

¹NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

MULTI-MESSENGER ASTROPHYSICS WITH PULSAR TIMING ARRAYS Astro2020 Science White Paper

Thematic Areas ■ Multi-Messenger Astronomy and Astrophysics
■ Galaxy Evolution ■ Cosmology and Fundamental Physics

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S. Burke-Spolaer,¹ **J. Simon**,² **L. Shroder**,³ **T. Bagchi**,⁴ **M. Cohn**,⁵ **J. Connerford**,⁶ **D. D'Orazio**,⁷ **M. Dozzi**,⁸ **M. Evans**,⁹ **M. Graham**,¹⁰ **J. Greene**,¹¹ **Z. Haiman**,¹² **K. Holley-Bockelmann**,^{13,14} **E. Kara**,^{15,16} **R. Kelly**,^{17,18} **S. Komara**,¹⁹ **S. Larson**,²⁰ **X. Liu**,²¹ **C.-P. Ma**,²² **S. Noble**,^{23,24} **V. Paschalidis**,²⁵ **R. Rafferty**,²⁶ **V. Ravi**,²⁷ **J. Romano**,²⁸ **A. Sotani**,^{29,30} **D. Stern**,³¹ **M. A. Stron**,³² **Y. T.**,³³ **M. Volonteri**,³⁴ & the **NANOGrav Collaboration**
¹Harvard University, ²Center for Gravitational Waves and Cosmology, ³UMass Lowell, ⁴North Carolina State University, ⁵Princeton University, ⁶California Institute of Technology, ⁷University of Florida, ⁸University of Illinois, ⁹University of Michigan, ¹⁰University of California, ¹¹University of Maryland, ¹²University of Texas, ¹³Northwestern University, ¹⁴University of California, ¹⁵University of Maryland, ¹⁶MIT, ¹⁷University of California, ¹⁸University of Illinois, ¹⁹University of California, ²⁰University of California, ²¹University of California, ²²University of California, ²³University of California, ²⁴University of California, ²⁵University of California, ²⁶University of California, ²⁷University of California, ²⁸University of California, ²⁹University of California, ³⁰University of California, ³¹University of California, ³²University of California, ³³University of California, ³⁴University of California

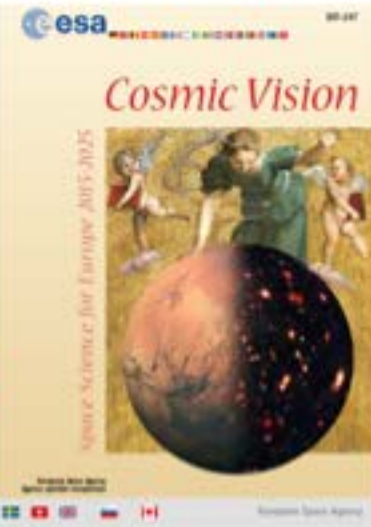
<https://youtu.be/lpkPh6H8p4M>

Athena and LISA synergy

- The hot and violent universe: Strong gravity produces high energy radiation and gravitational waves.
- "Bringing sound to the movies": crucial orthogonal information on physical processes, e.g. compact object mergers.
- Black holes may contribute to the elusive Dark Matter, solving two riddles simultaneously.

We encourage the Athena and LISA teams to jointly work on a study about these synergies.

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Changing Science Strategies: ESA's Rethinking Launch Schedules

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

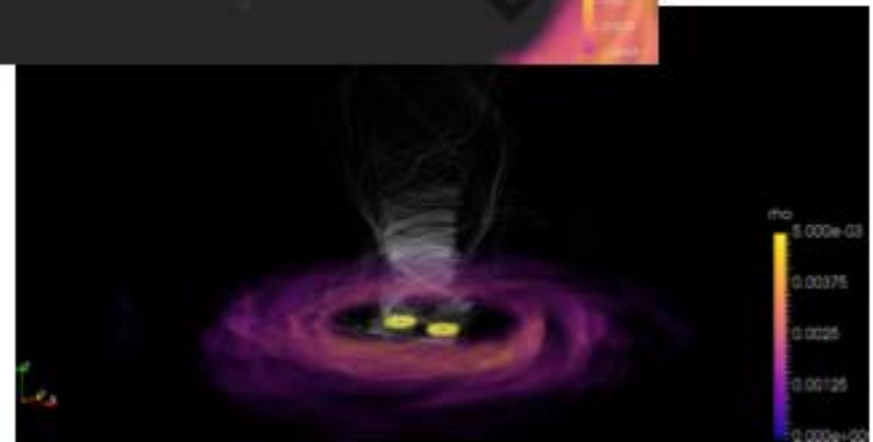
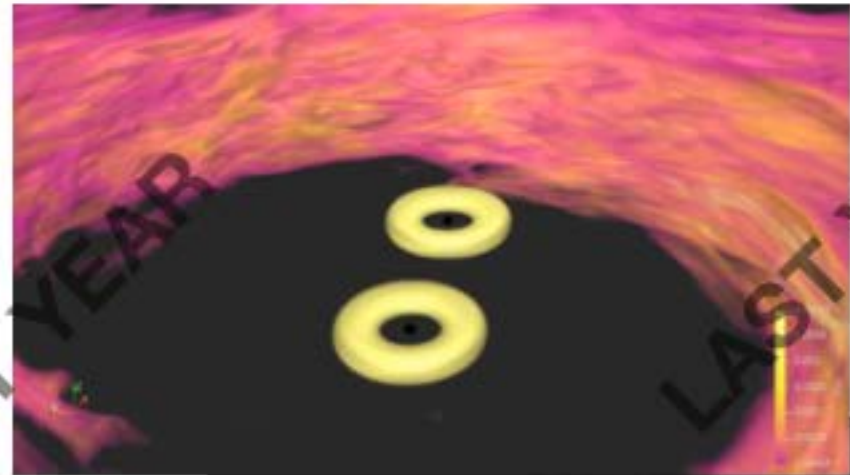
Accomplishments of GRMHD Mini-disk Evolution

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.



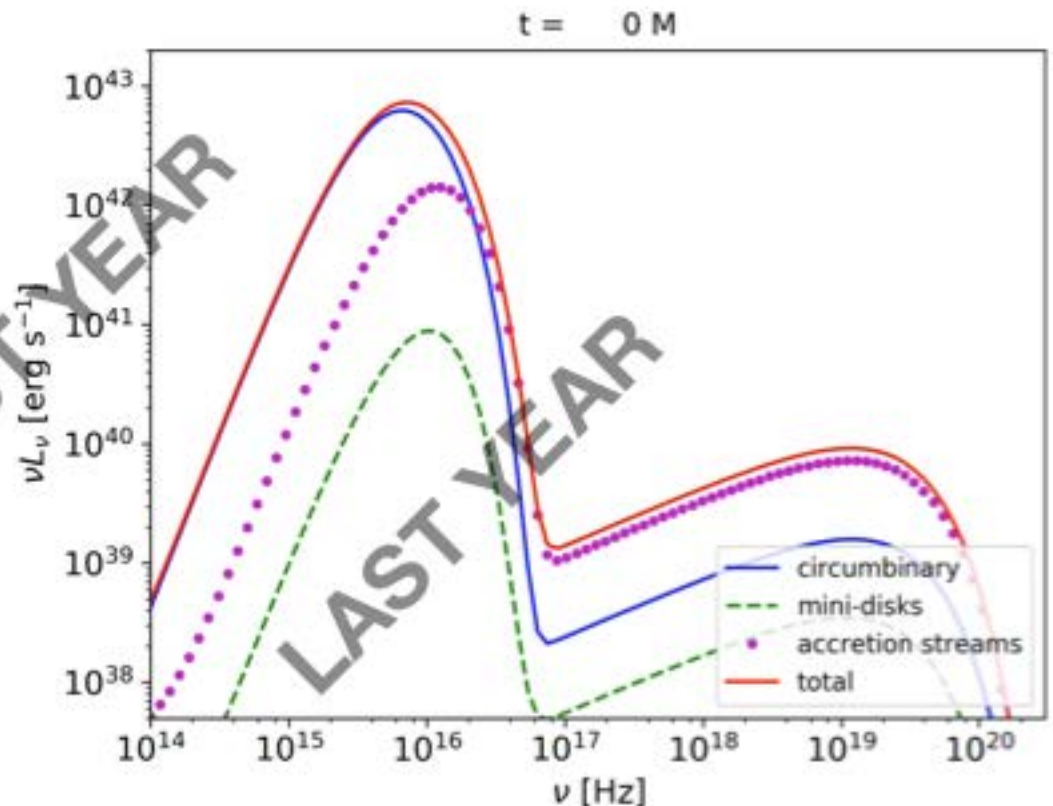
Blue Waters Team Contributions:

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.



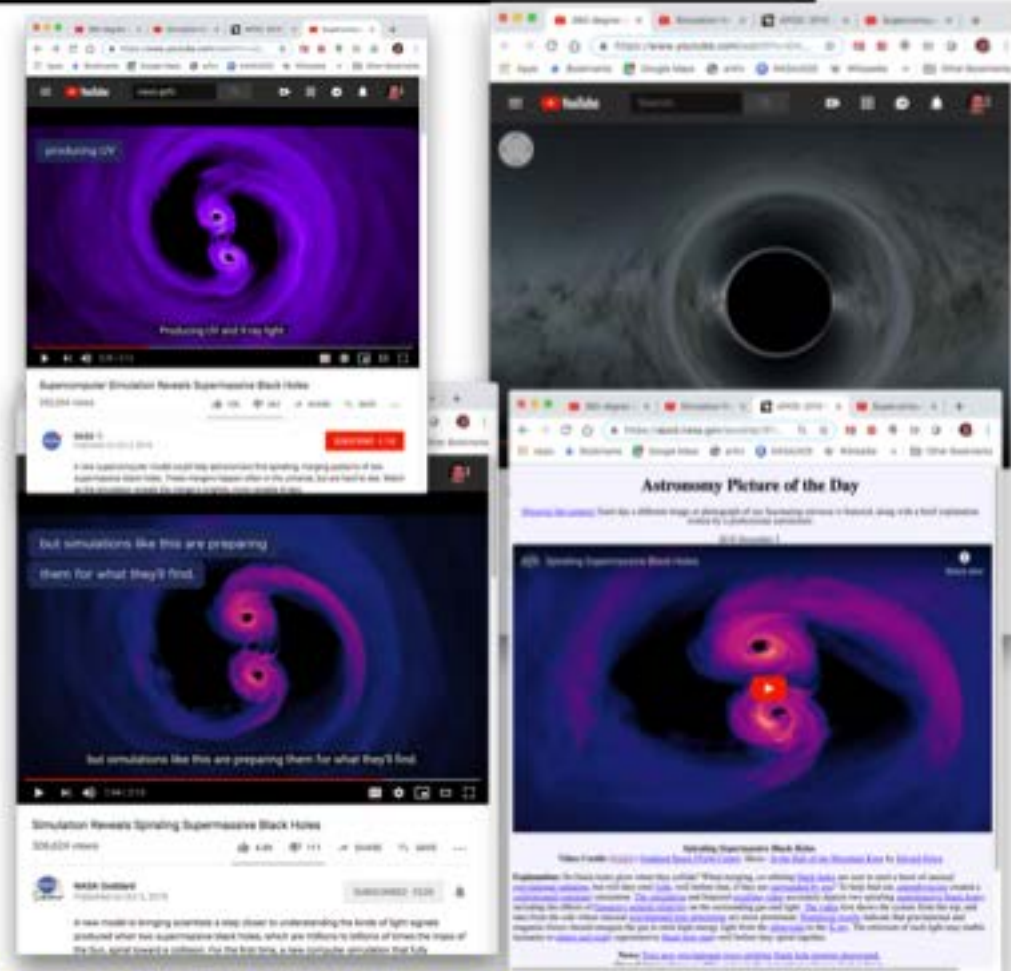
Broader Impact: Science Communication

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>



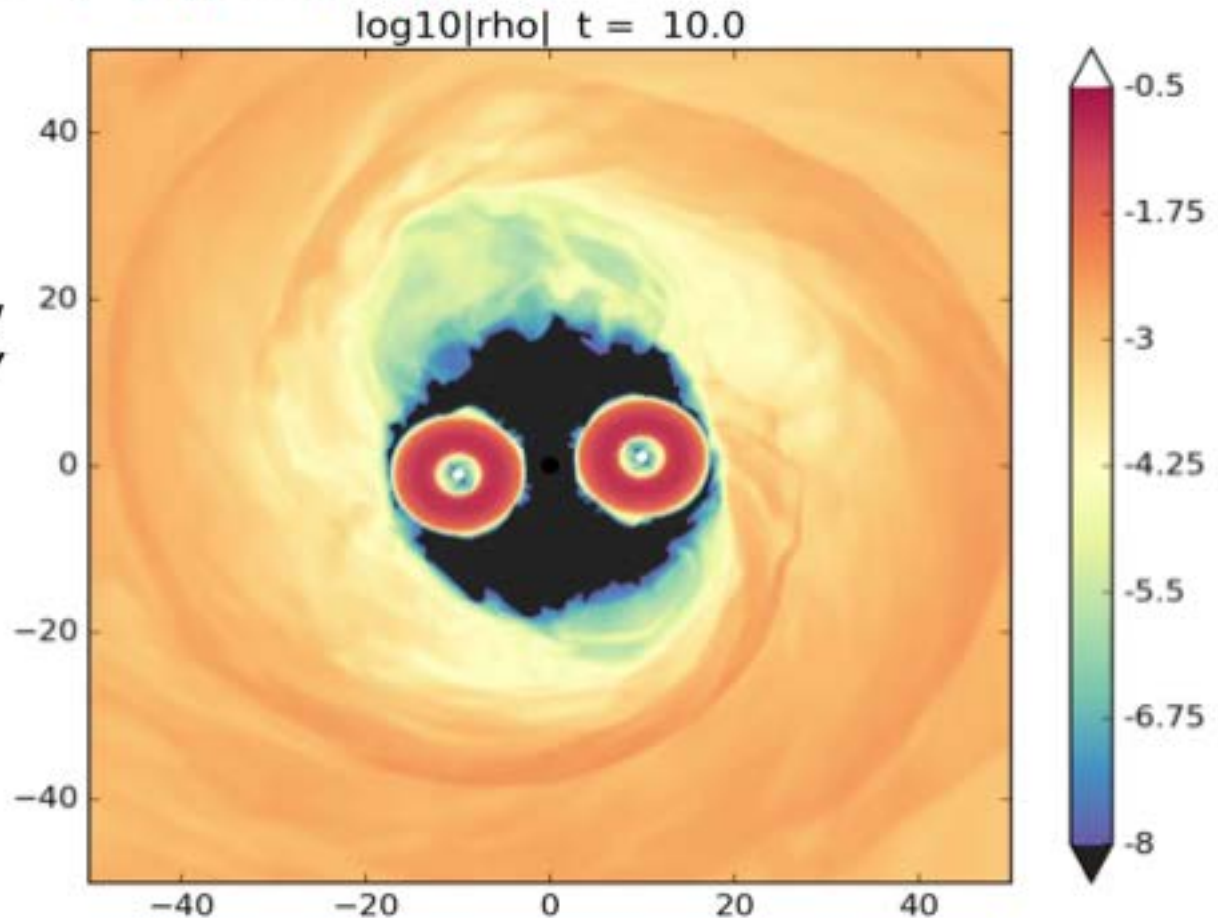
Accomplishments: *Longterm* 3-d GRMHD Mini-disk Evolutions

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

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

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- **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).



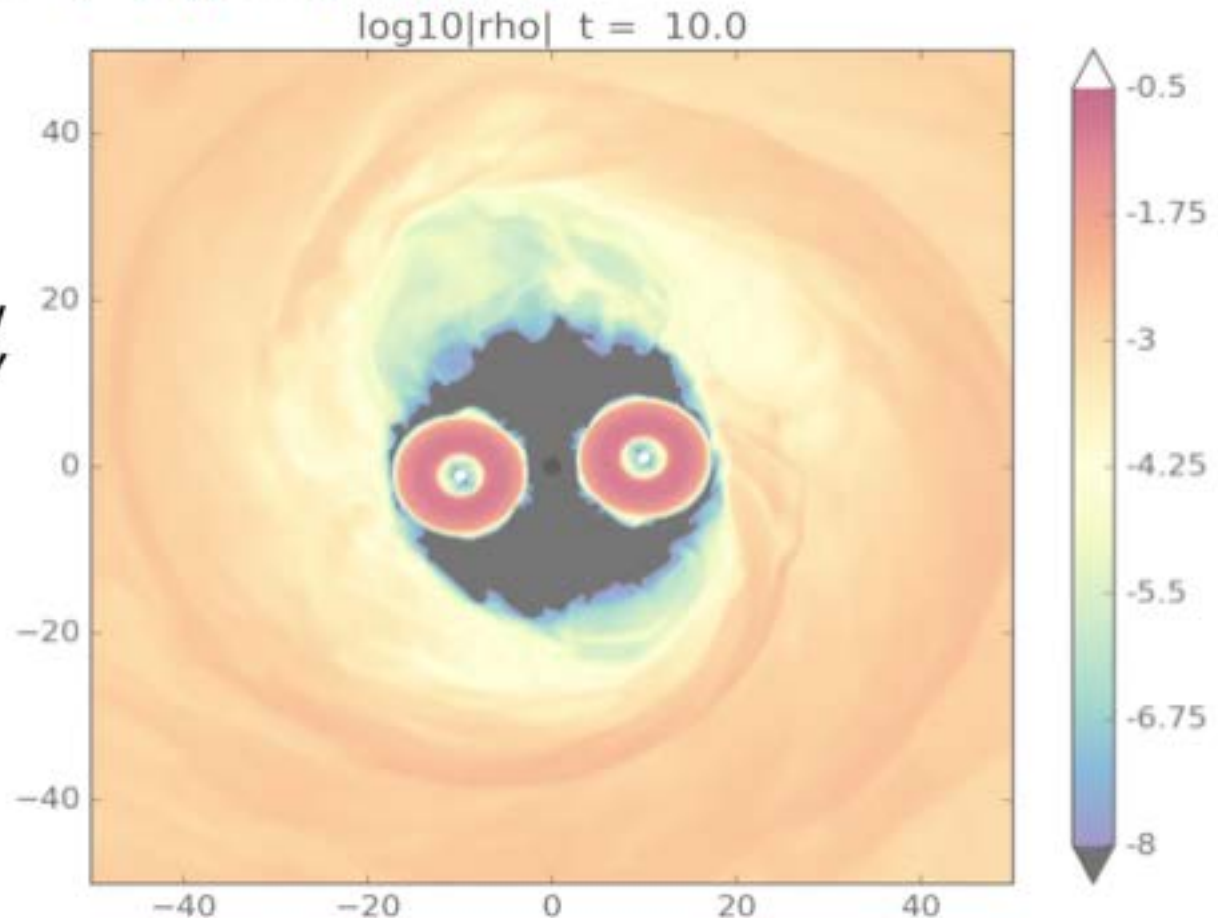
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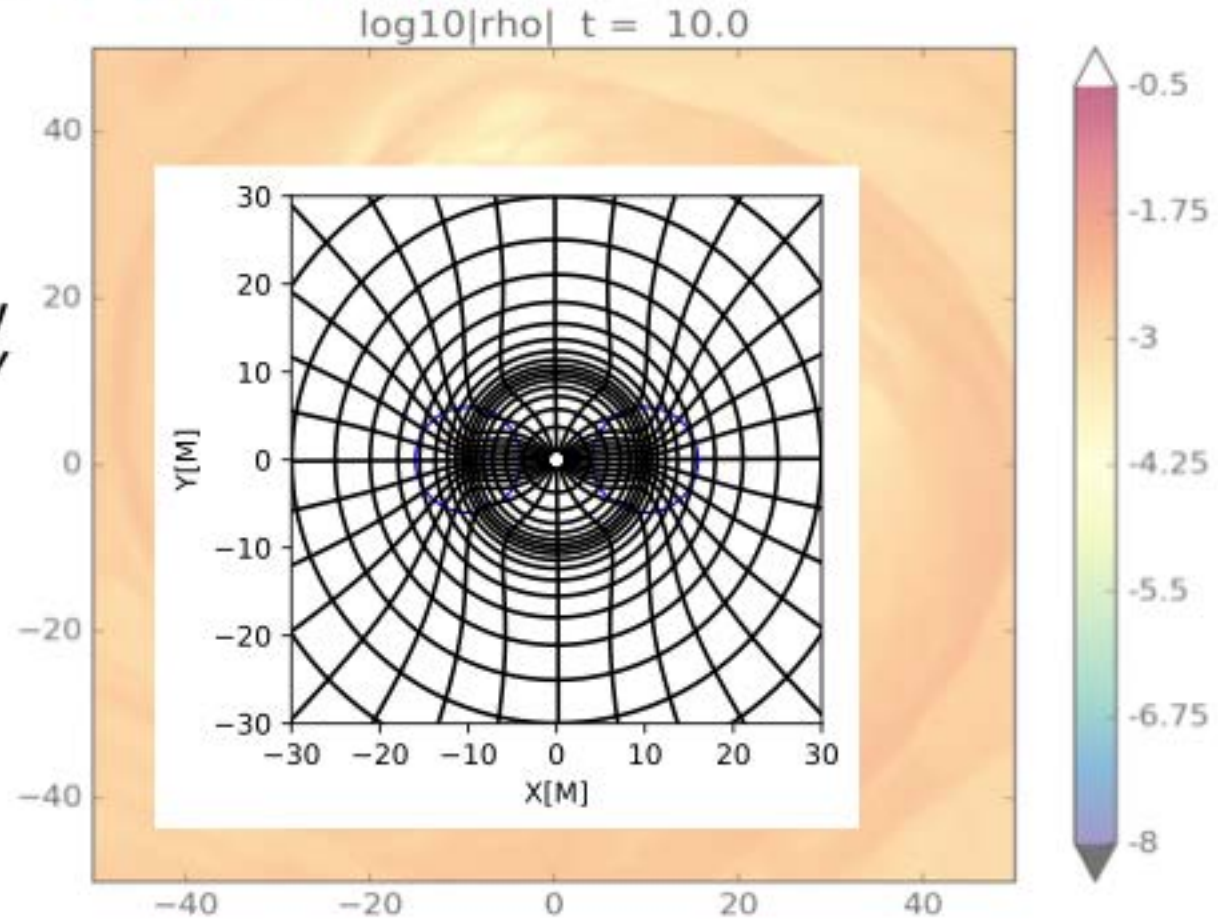
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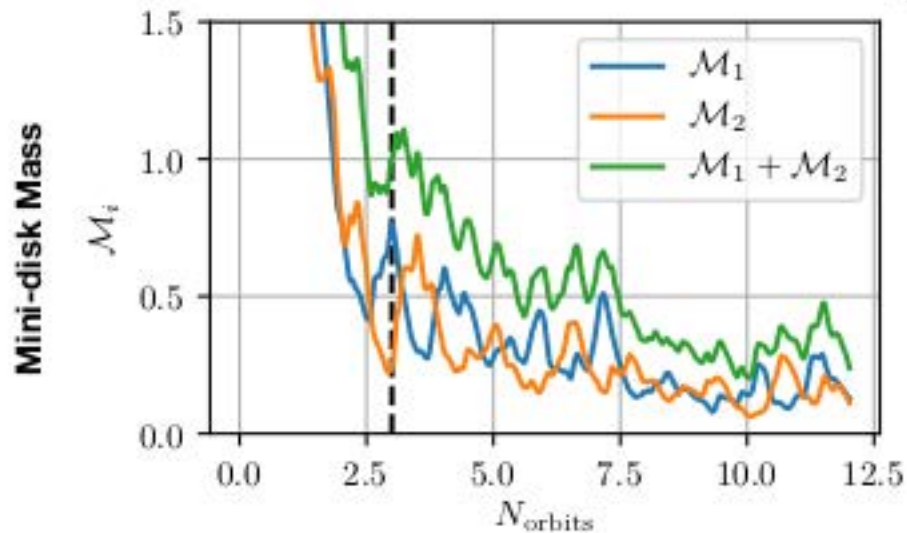
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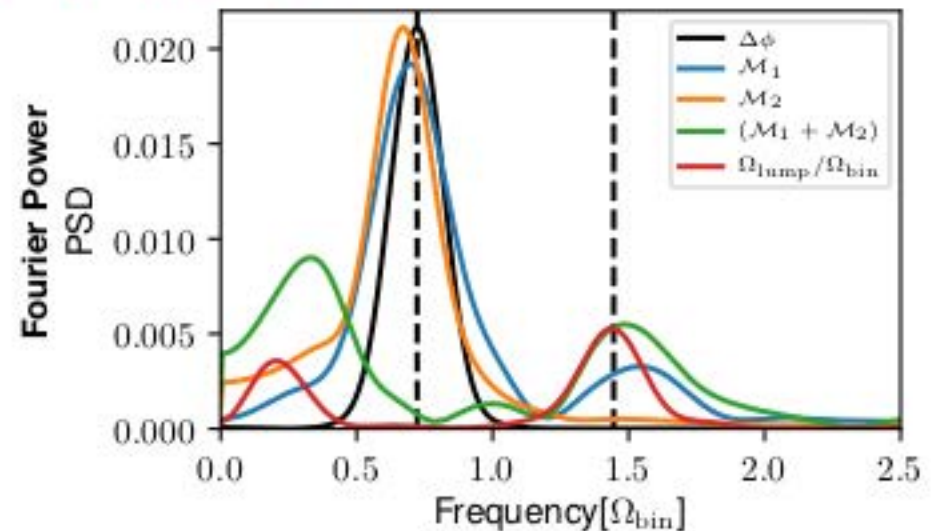


Accomplishments: Longterm 3-d GRMHD Mini-disk Evolutions

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



- 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.

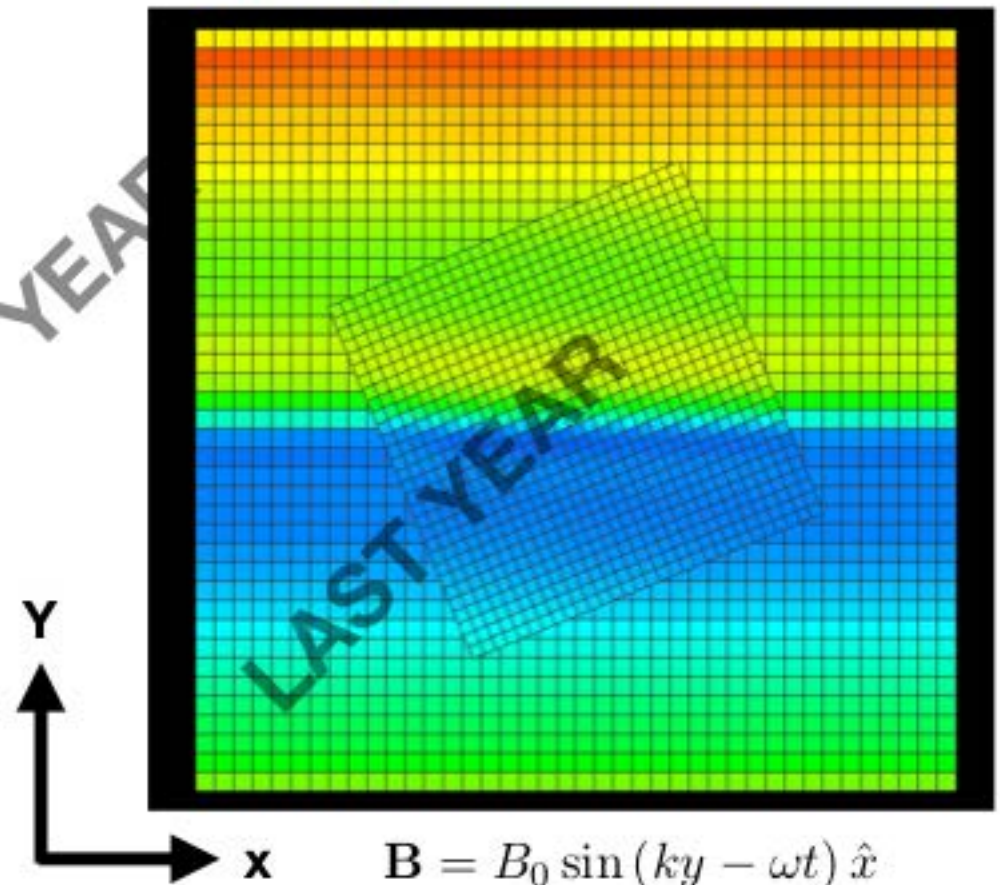


- Significant modulation in each mini-disk's mass \rightarrow possible EM signal?
- If light follows mass, EM period would be a ~ 1.5 times the binary period, the beat frequency between the orbital periods of the lump and mini-disks.
- Dimmer circumbinary lump modulated at the same frequency plus its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

Accomplishments, Product: MHD Patchwork

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

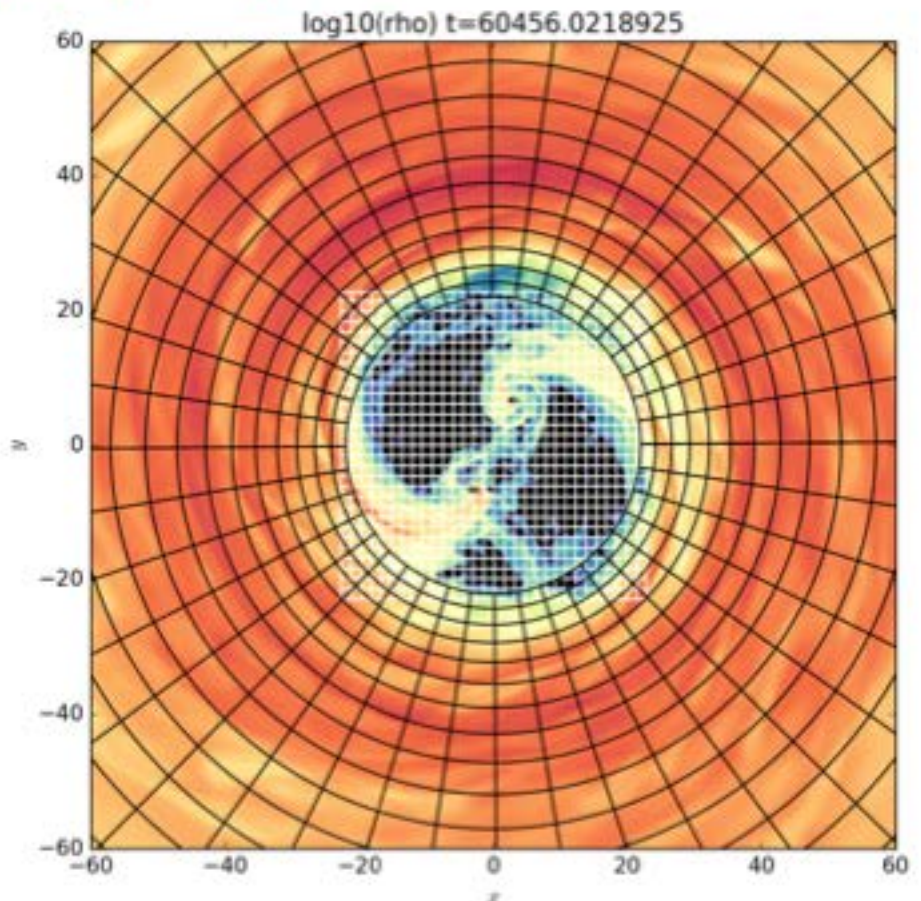
- **Key Challenges:** Adding support for MHD and preservation of solenoidal (aka “no magnetic monopoles”) constraint into the hydrodynamic *Patchwork* code.
- **Key Challenges:** Generalize *Patchwork* for the wide range of coordinate systems and patch situations (e.g., patch motion/rotation/overlap) 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.



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.



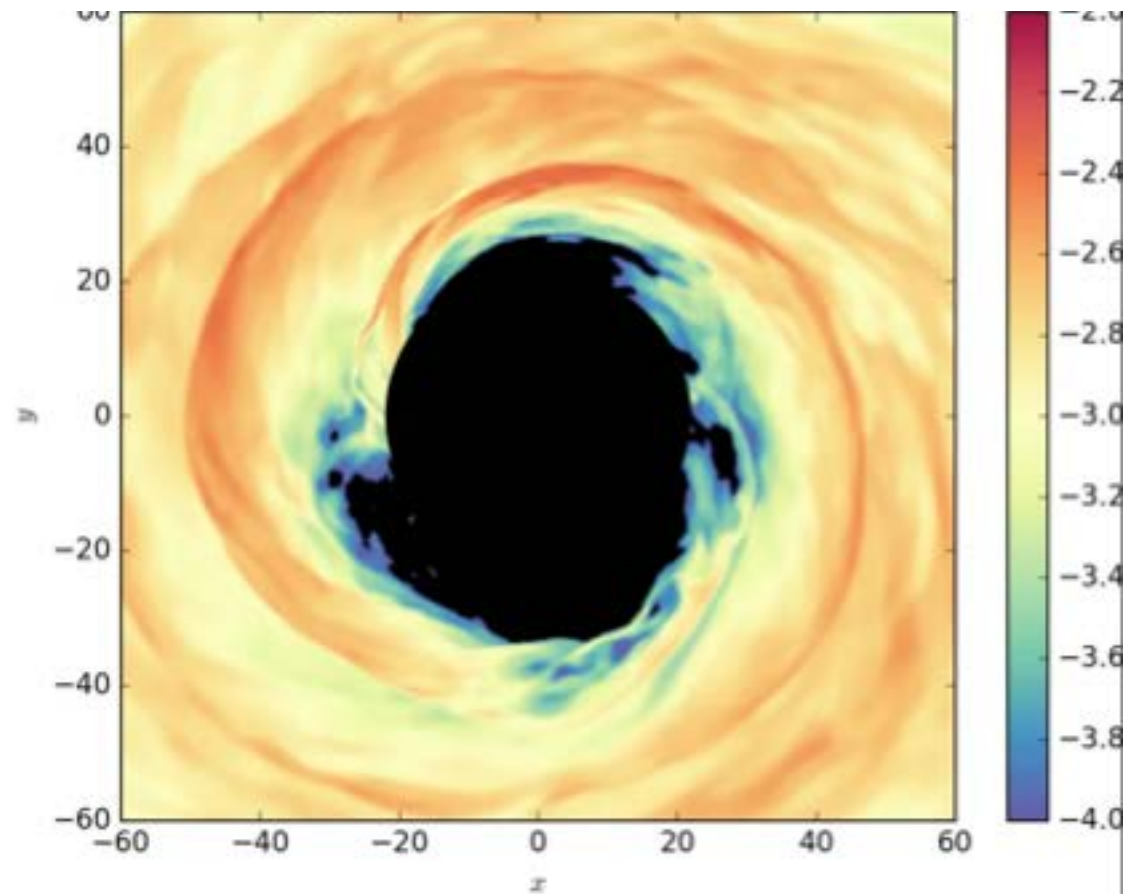
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log₁₀(rho) t=50000.0082304

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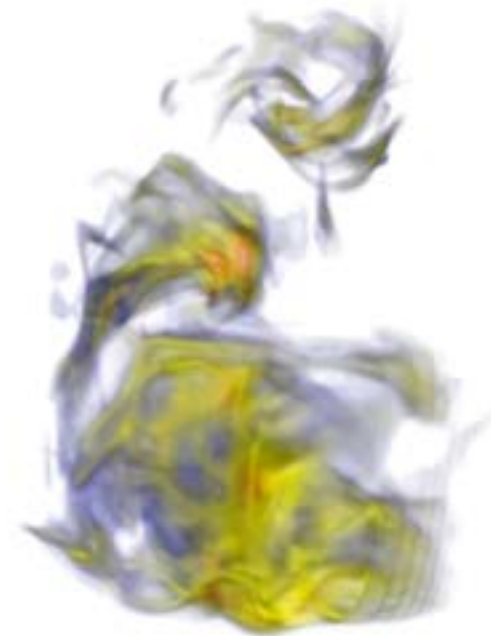
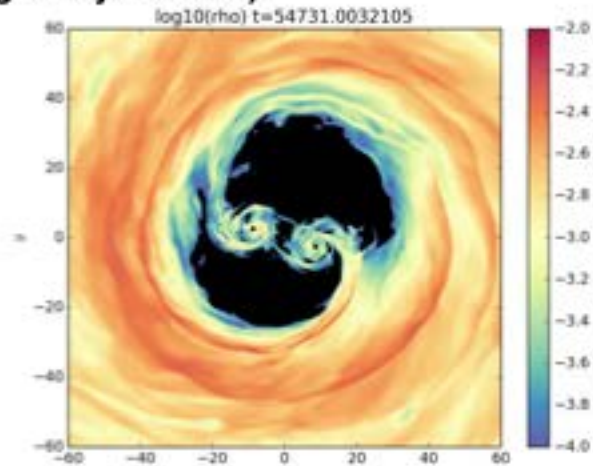
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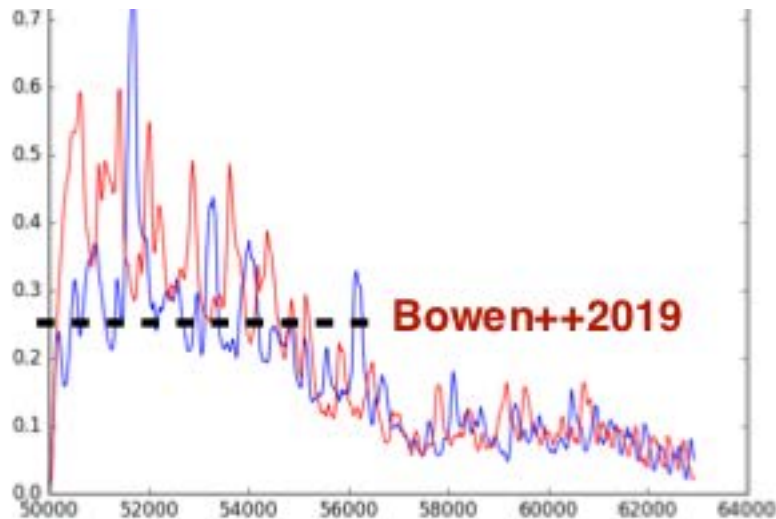


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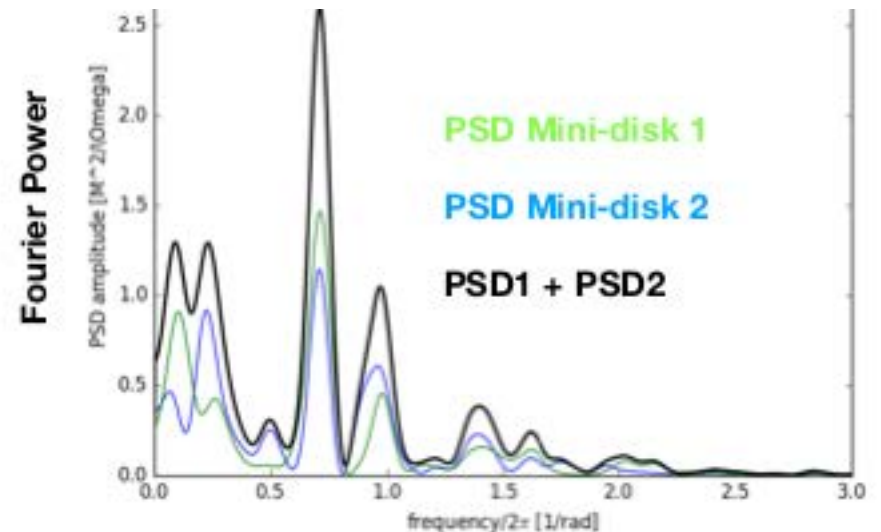
Accomplishments: *Patchwork* Mini-disk Evolutions

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





- 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;

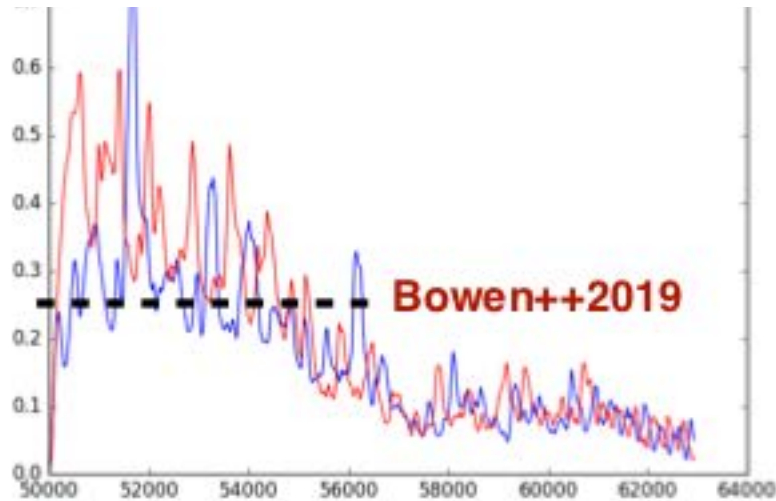


- Signals in mini-disk mass are also reminiscent.
- Mini-disks still oscillate at beat frequency, and lump oscillates at its local orbital rate.
- Now see signal at 1x and 2x the binary orbital frequency, possibly from “sloshing”.
- More scenarios in progress at different resolutions, mass ratios, separations...

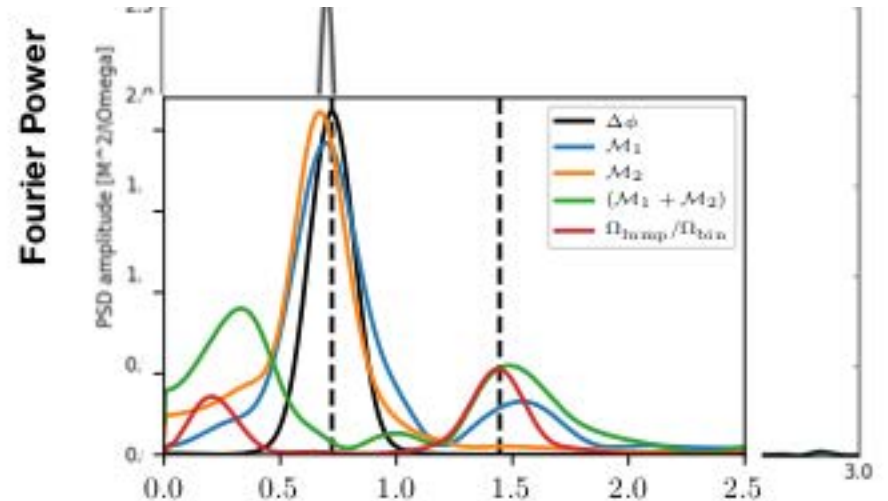
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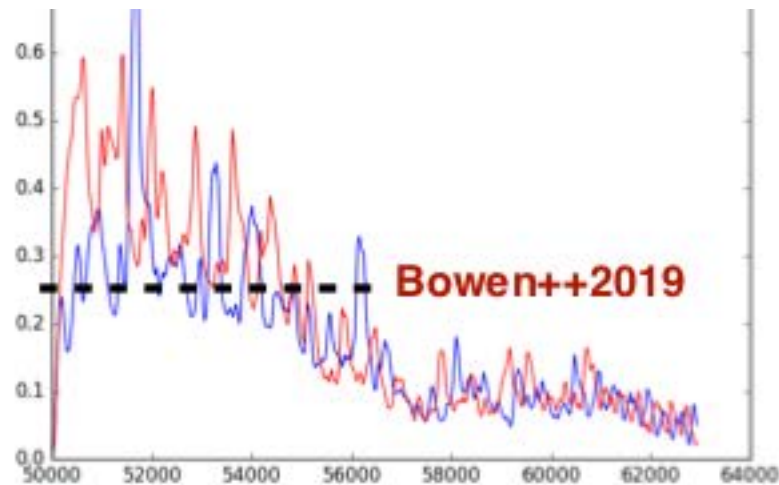


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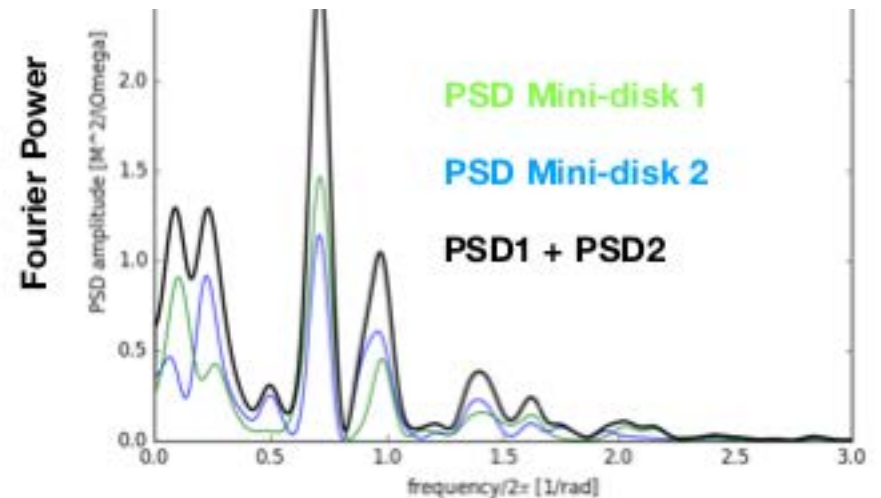
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The Event Horizon General Relativistic Magnetohydrodynamic Code Comparison Project

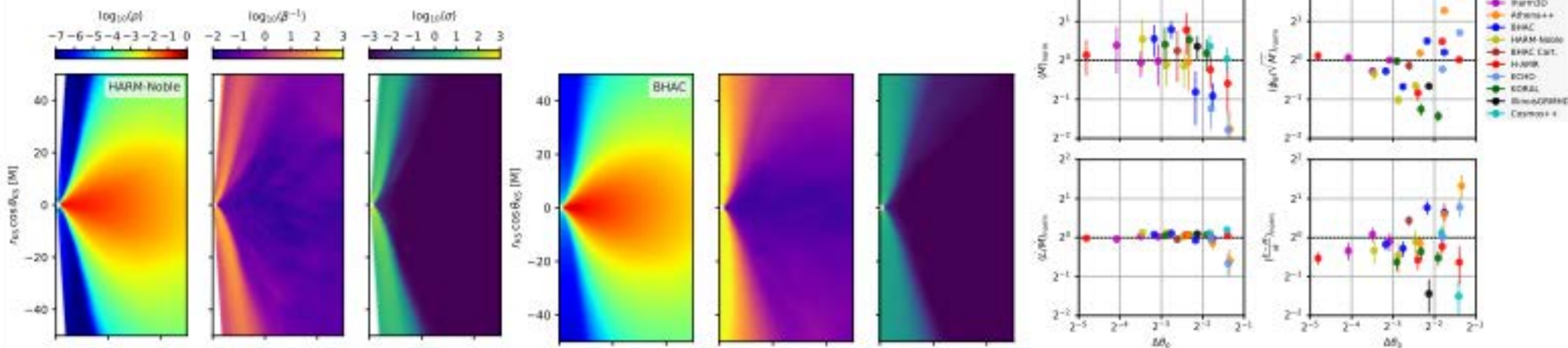
OLIVER PORTH,^{1,2} KUSHIK CHATTERJEE,¹ RAMESH NARAYAN,^{3,4} CHARLES F. GAMMIE,⁵ YOSUKE MIZUNO,²
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 ZIRI YOUNSI^{29,2}

KAZUNORI AKIYAMA,^{30,31,32,4} ANTON ALBERDI,³³ WALTER ALEF,³⁴ KEIICHI ASADA,³⁵ REBECCA AZULAY

<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.

