Predicting the Transient Signals from Galactic Centers: Circumbinary Disks and Tidal Disruptions Around Black Holes Year 3

BW ID: PRAC_gk5

Blue Waters Symposium, Wednesday June 6th, 2018

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Based on:

- Bowen et. al, ApJ, 838, 42 (2017).
- Bowen et. al, ApJ, 853, L17 (2018).
- d’Ascoli et al., submitted ApJ (2018).

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Why It Matters: Mysteries of Supermassive Black Holes

- **Binary AGN are a primary multi-messenger source for LISA and PTA campaigns.**

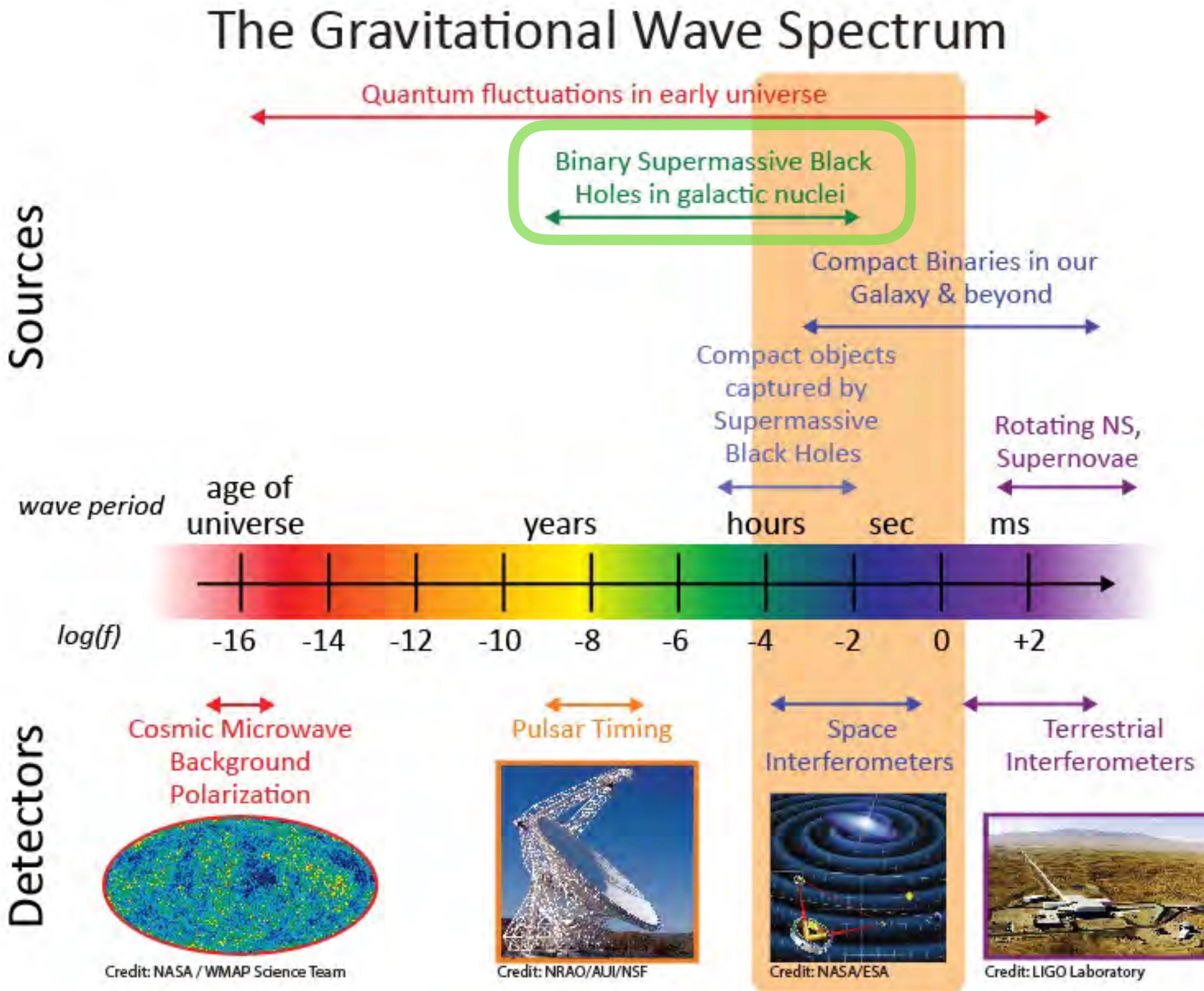
- **Likeliest EM-bright binary black hole system, as embedded binaries in AGN disks may be too dim w.r.t. their host.**

  ➡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.**

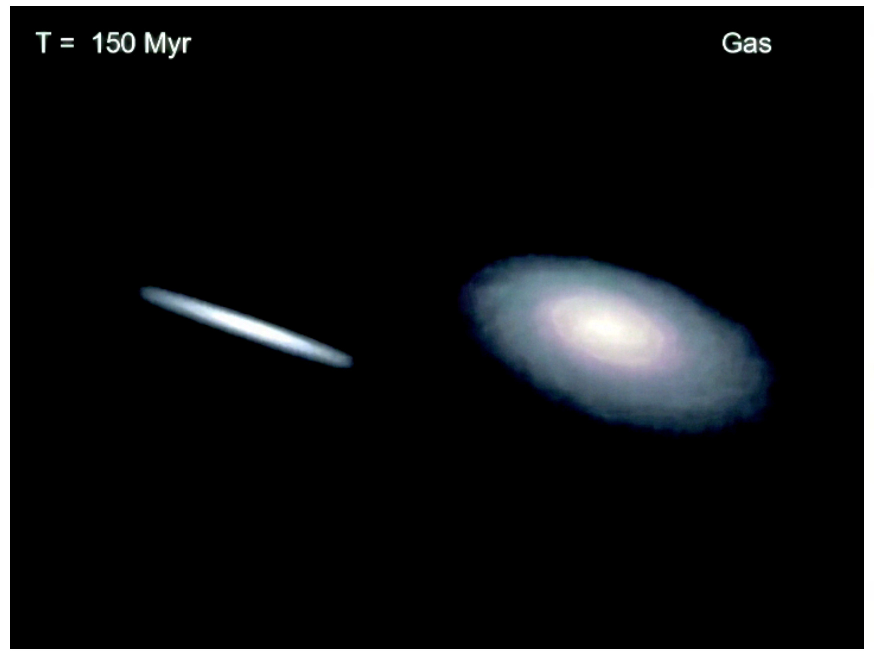
- **LSST will identify 100k's of AGN, so "many" binary-AGN are expected to be uncovered in the haystack.**

- **EM identification will be critical for detection and characterization—> realistic simulations and their electromagnetic output are needed!**

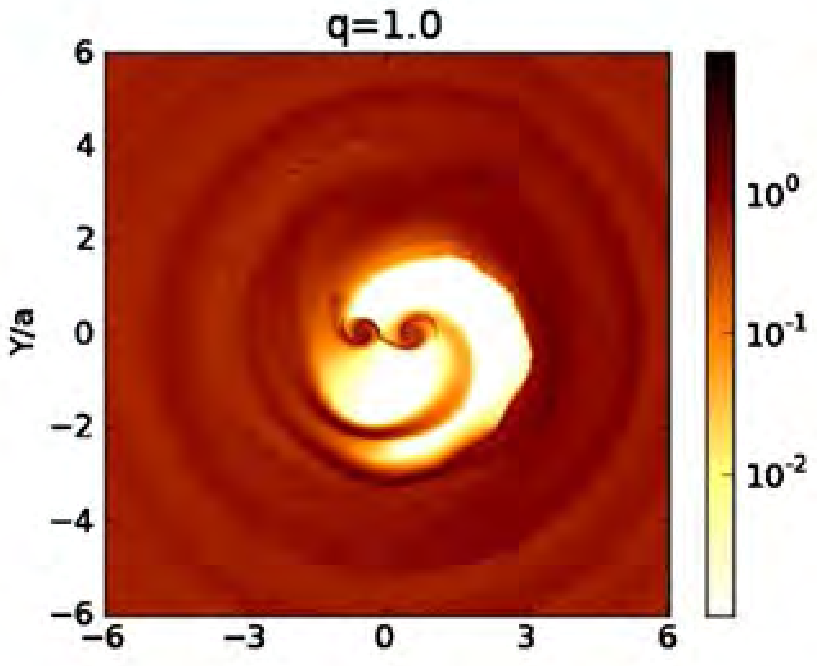


https://lisa.nasa.gov/

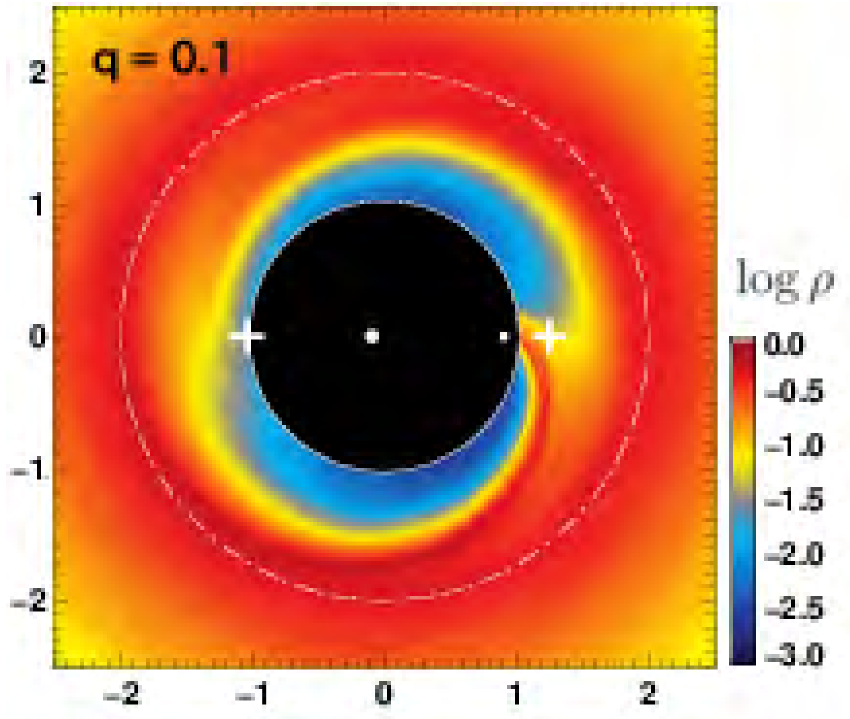
Products: Strategy & Techniques



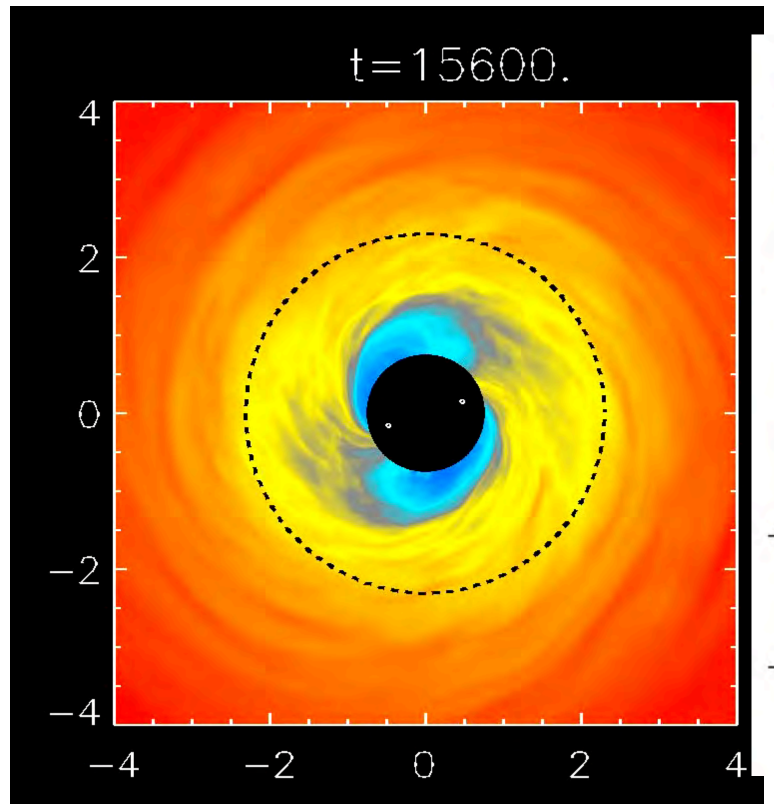
Hopkins,Hernquist,
Di Matteo, Springel++



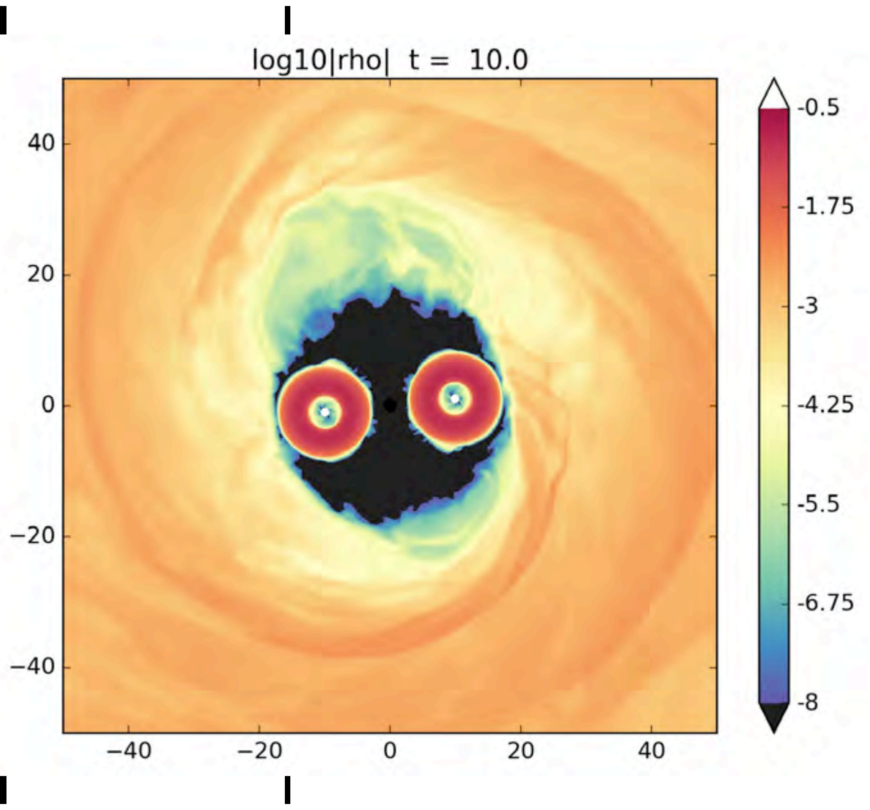
Farris++2014



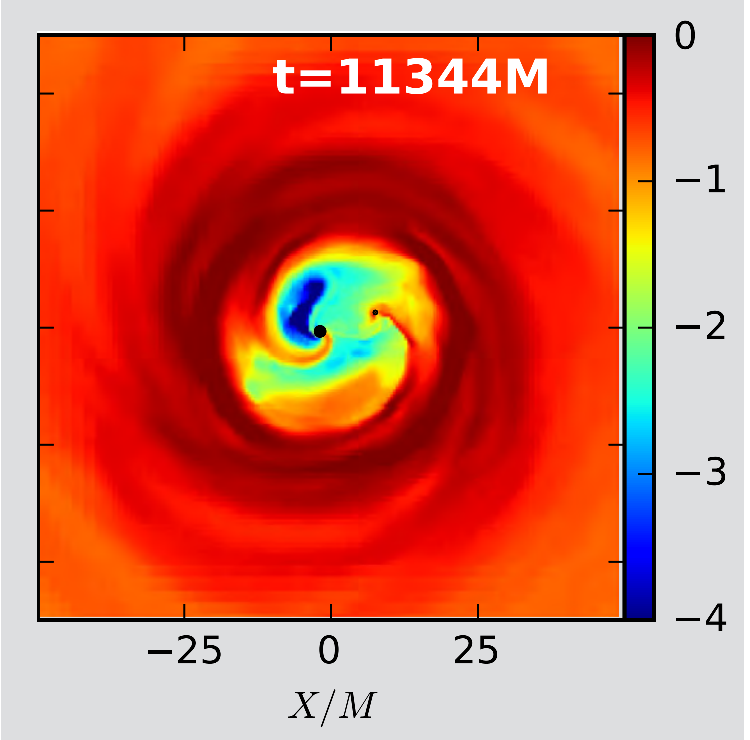
Shi++2014



Noble++2012



Bowen++2018

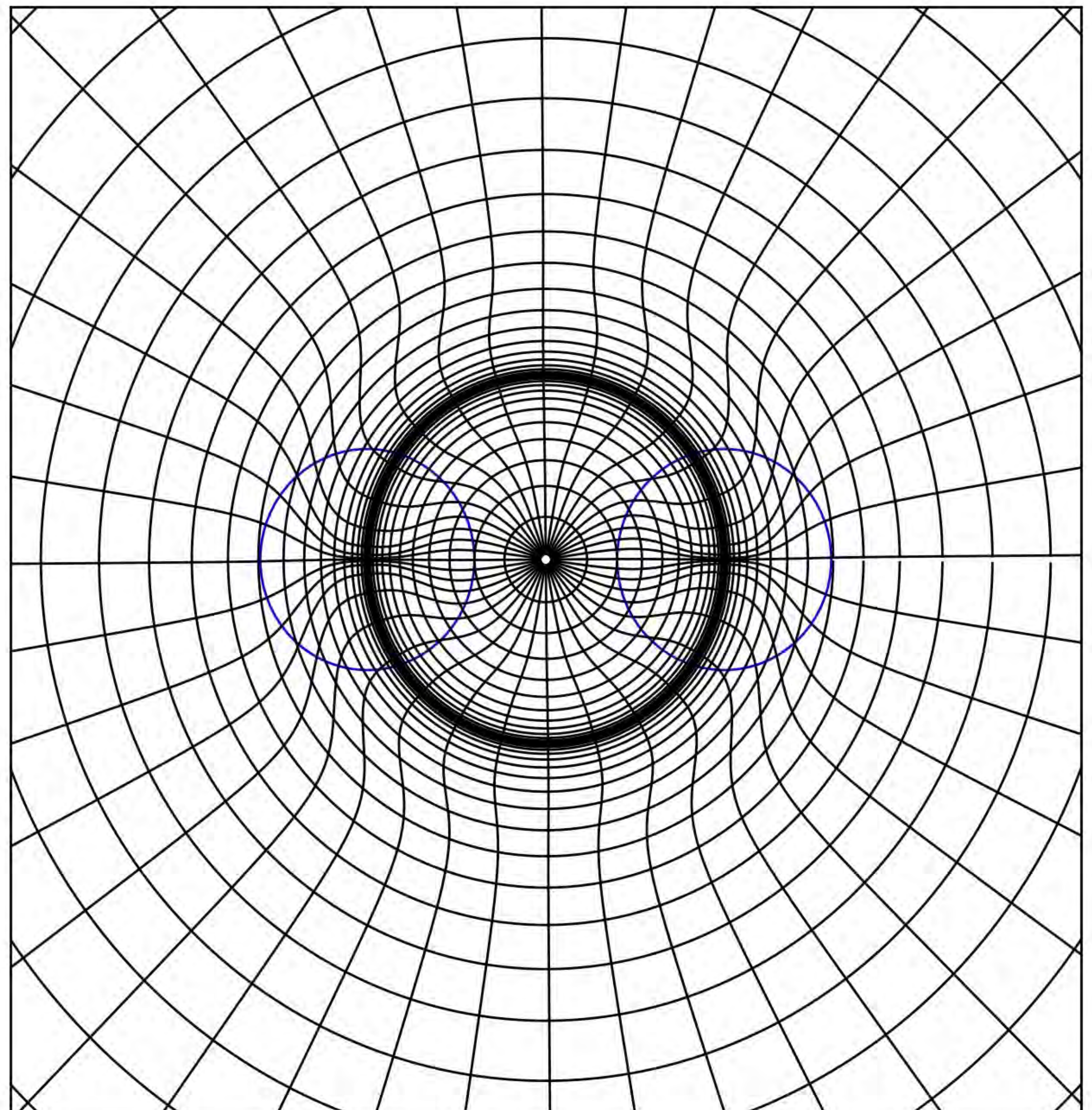


Gold++2014

Matter:	Viscous Hydro.	MHD	GR MHD	GR MHD
Gravity:	Newtonian	Newtonian	Post-Newtonian	Numerical Relativity

- **Use well-tested GRMHD code for accretion disks: *HARM3d;***
- **Novel methods tailored for accuracy and affordability:**
  - **Dynamic warped grids;**
  - **Perturbative solutions for gravity consistent with Einstein's equations in our regime;**

➡ **Key Challenges:** **Ability to evolve accreting binaries while resolving the MRI and MHD dynamics at the scale of the event horizons in the inspiral regime—*key for establishing pre-merger conditions*.**

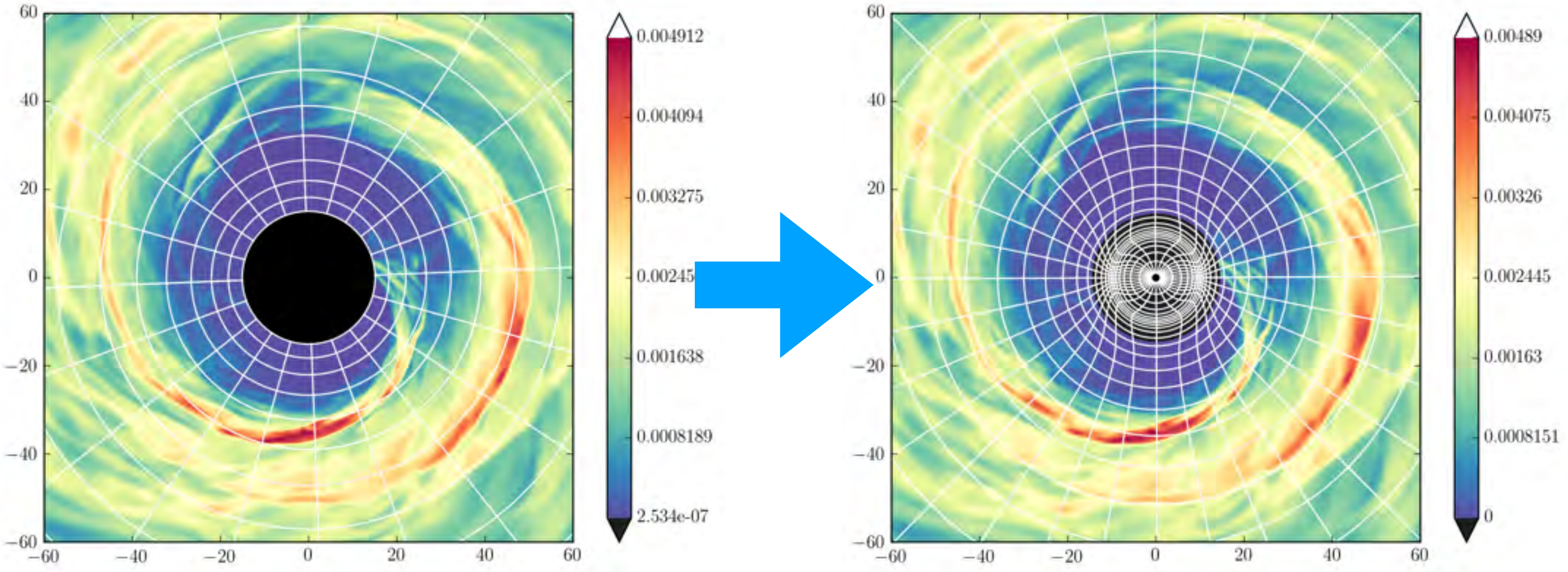


Accomplishments: 3-d GRMHD Mini-disk Evolutions

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.



- Late-time (t=50,000M) snapshot from long-term (~120 orbits) simulations with BHs excised.

- Data interpolated onto new grid that includes the BHs.
- Requires "cleaning" the magnetic monopoles off the grid before we begin the evolution.

Why Blue Waters: Visualizations by Mark Van Moer (NCSA)

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

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Accomplishments: 3-d GRMHD Mini-disk Evolutions

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

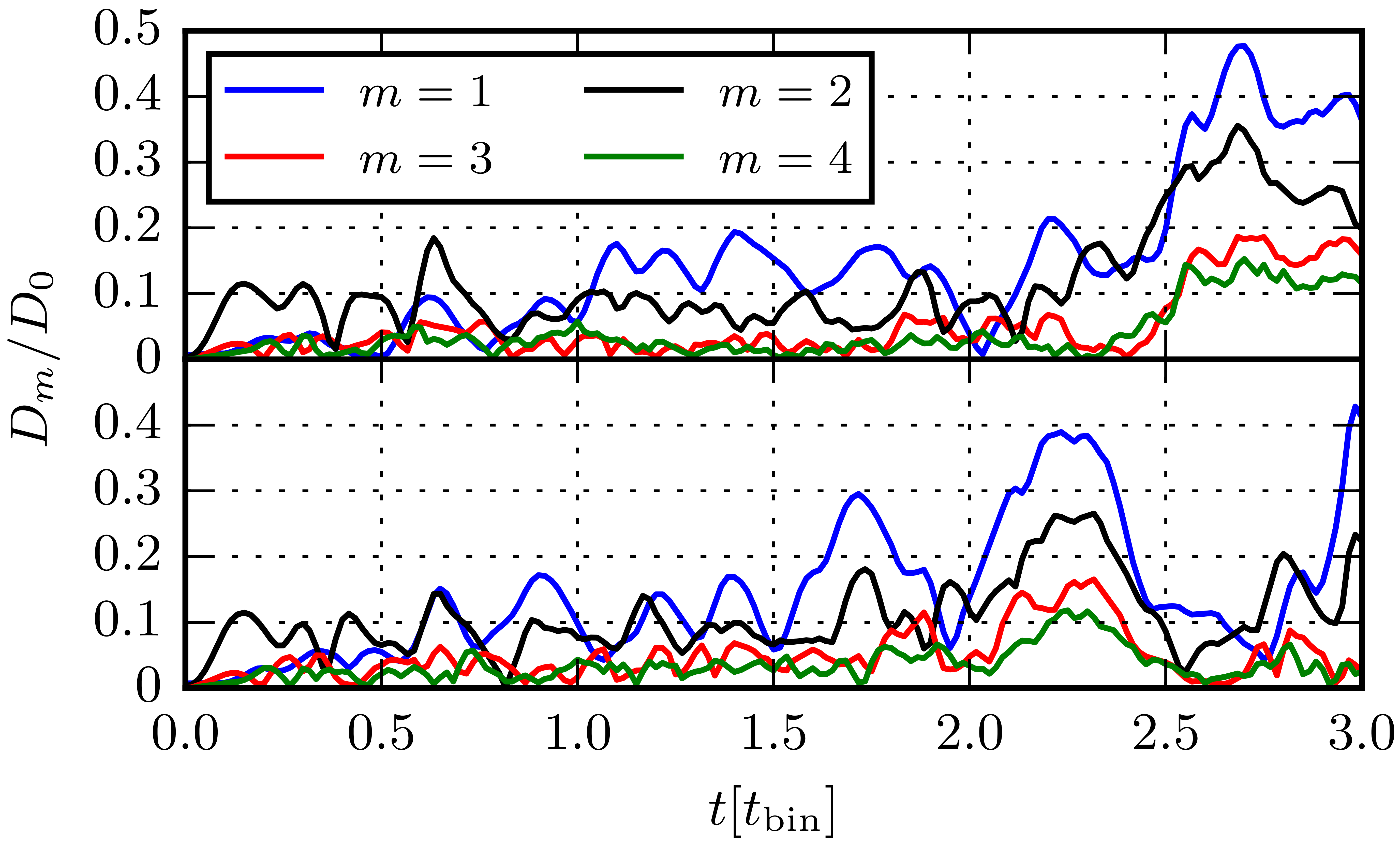
- All azimuthal modes strengthen in time.

- The two lowest order modes are the strongest, quantifying the development of spiral density waves.

- Spiral shocks accelerate angular momentum transfer and accretion onto the black hole, contributing to the depletion of the mini-disks.

- The fact that the m=1 mode is the strongest differs from what others have seen with simulations of solitary mini-disks at larger separation.

  - May indicate how spiral mode structure evolves as the separation shrinks and becomes relativistic.

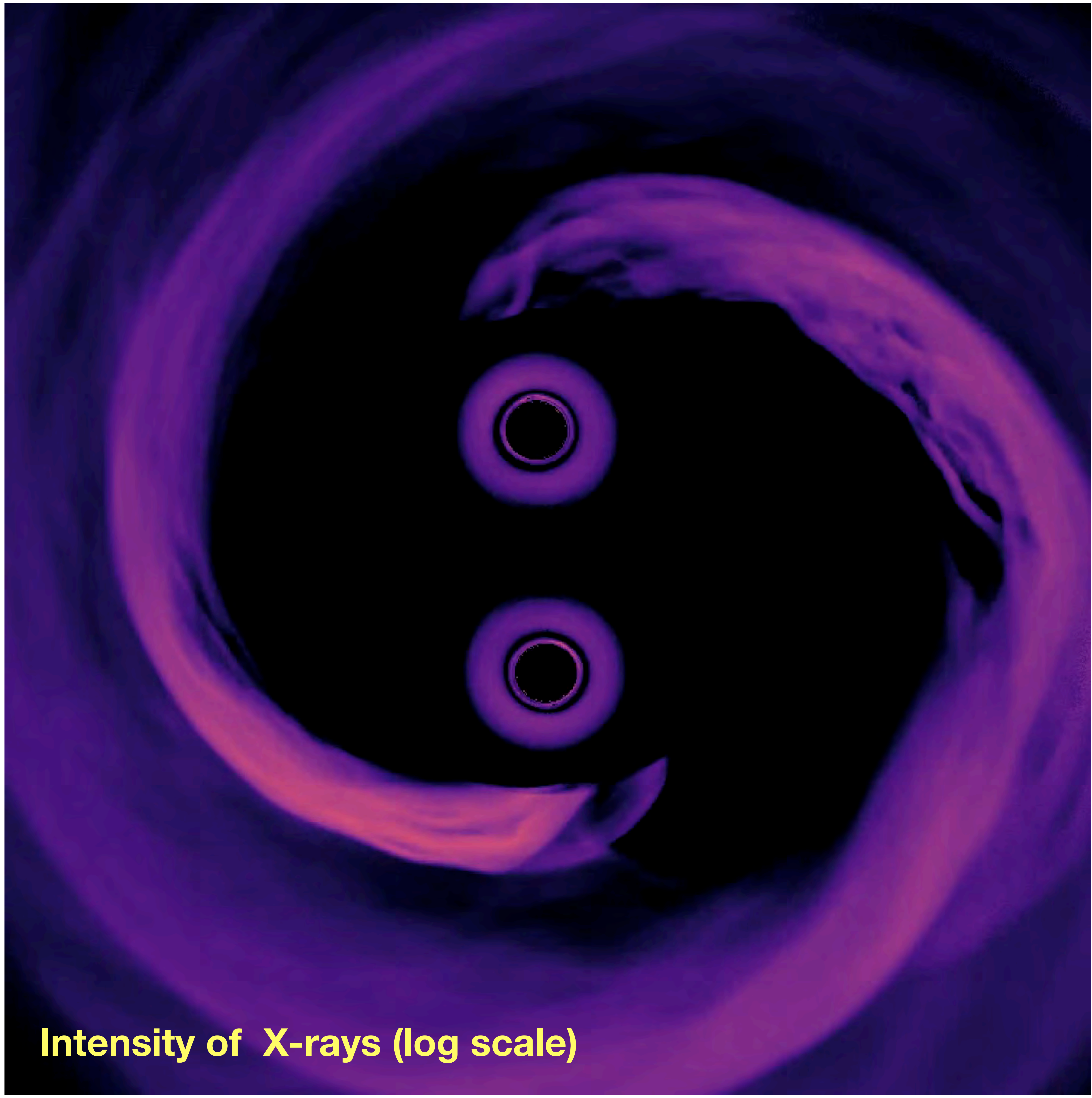


Relative azimuthal mode strength over time, where “m” is the mode number or the number of nodes in a wave.

Accomplishments: Light from GRMHD Mini-disks

d'Ascoli et. al, *submitted to* ApJ, (2018).

- Why It Matters: First calculation of the light emitted by accreting binary black holes in the inspiral regime of their evolution.
- Why It Matters: Critical to demonstrating how complicated mini-disk dynamics translates into electromagnetic emission and reliable predictions.
- Radiative transfer integrated back along geodesics.
- Photons starting at photosphere start as black-body.
- Above photosphere, corona emission modeled as non-thermal component with temperature 100 keV.
- Explore optically thin and thick cases.



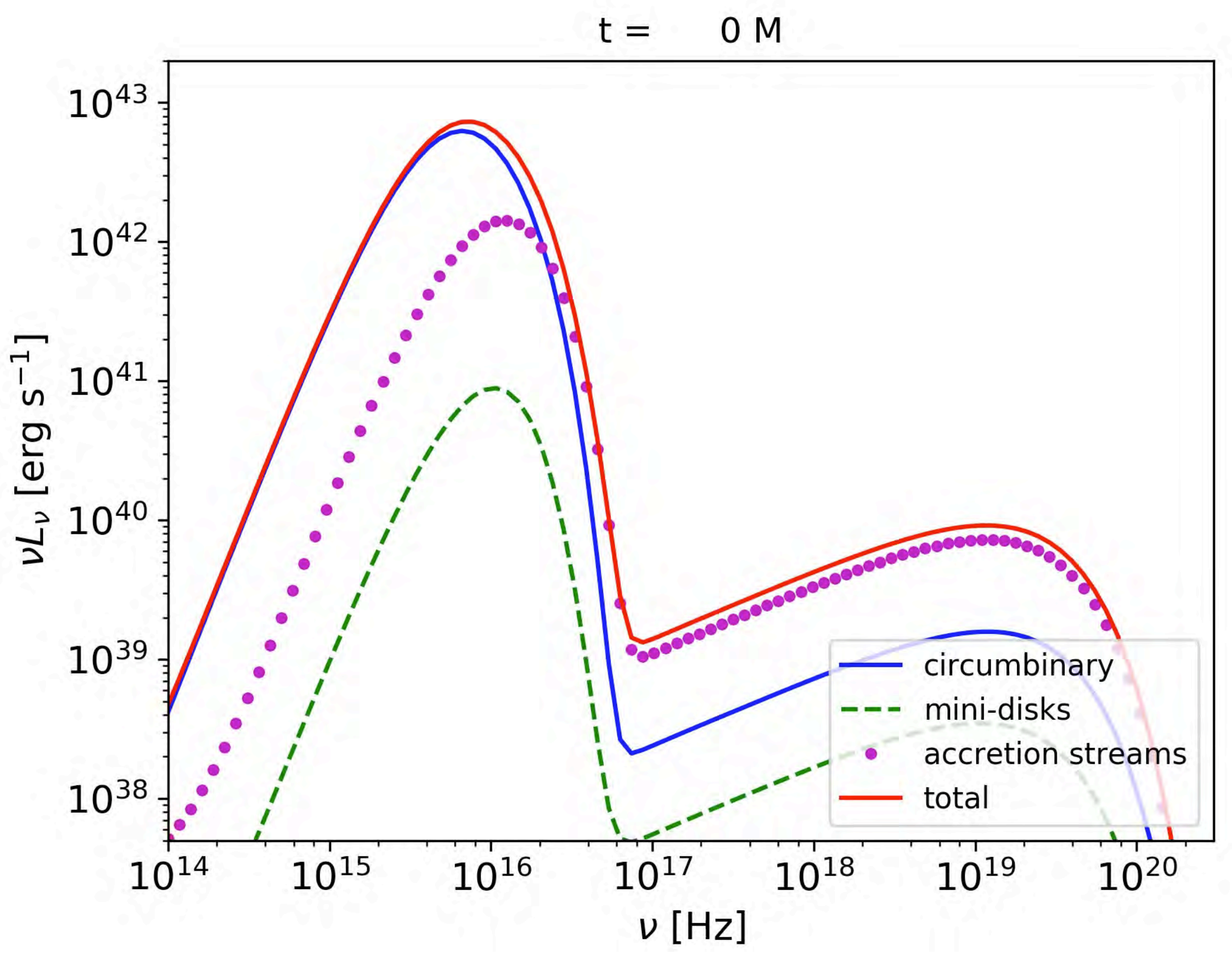
Accomplishments: Light from GRMHD Mini-disks

d'Ascoli et. al, *submitted to* 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.**

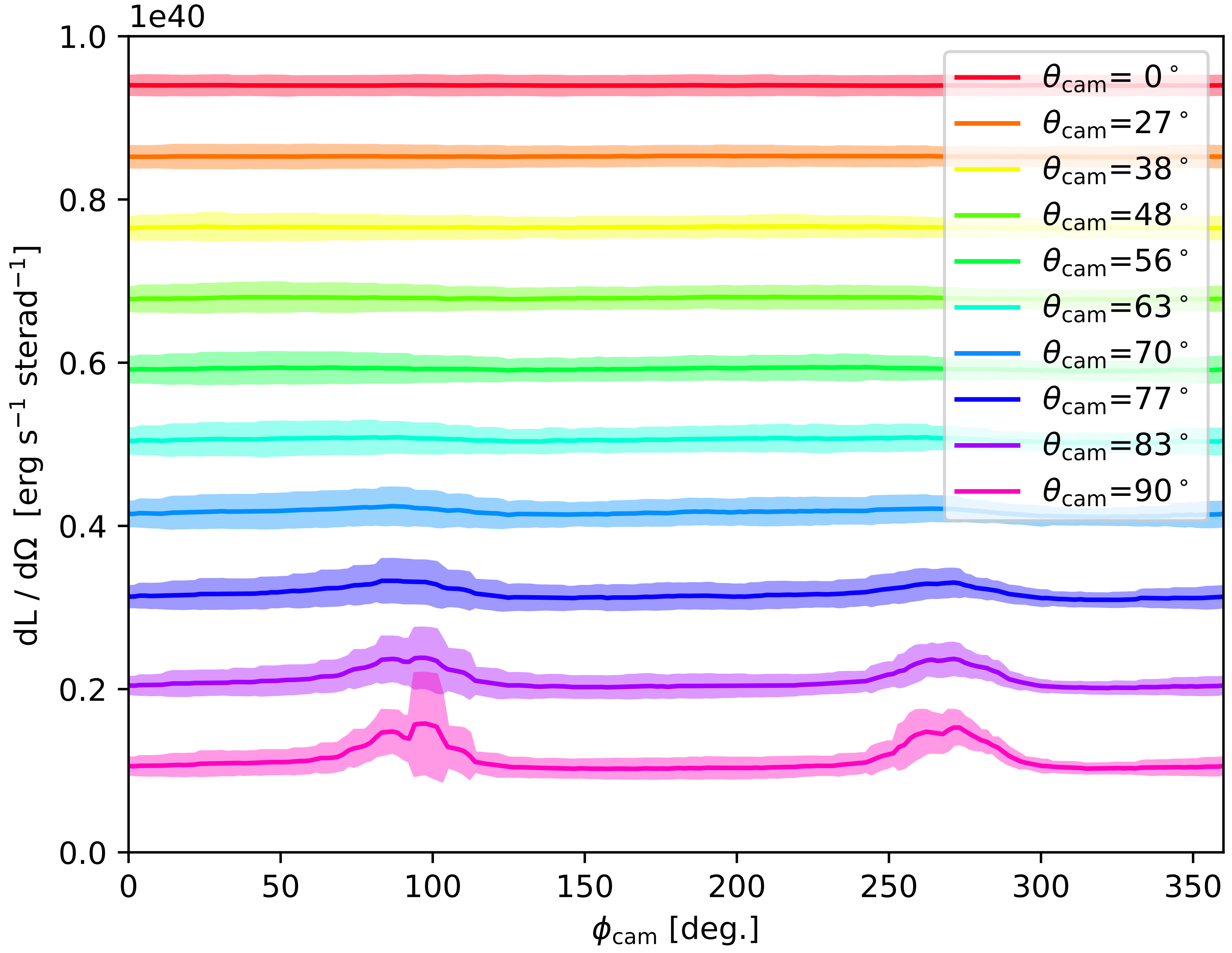
- **Key distinctions from single black hole (AGN) systems:**
  - **Brighter X-ray emission relative to UV/EUV.**
  - **Variable and broadened thermal UV/EUV peak.**
  - **"Notch" between thermal peaks of mini-disks and circumbinary disk will likely be more visible at larger separations and for spinning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



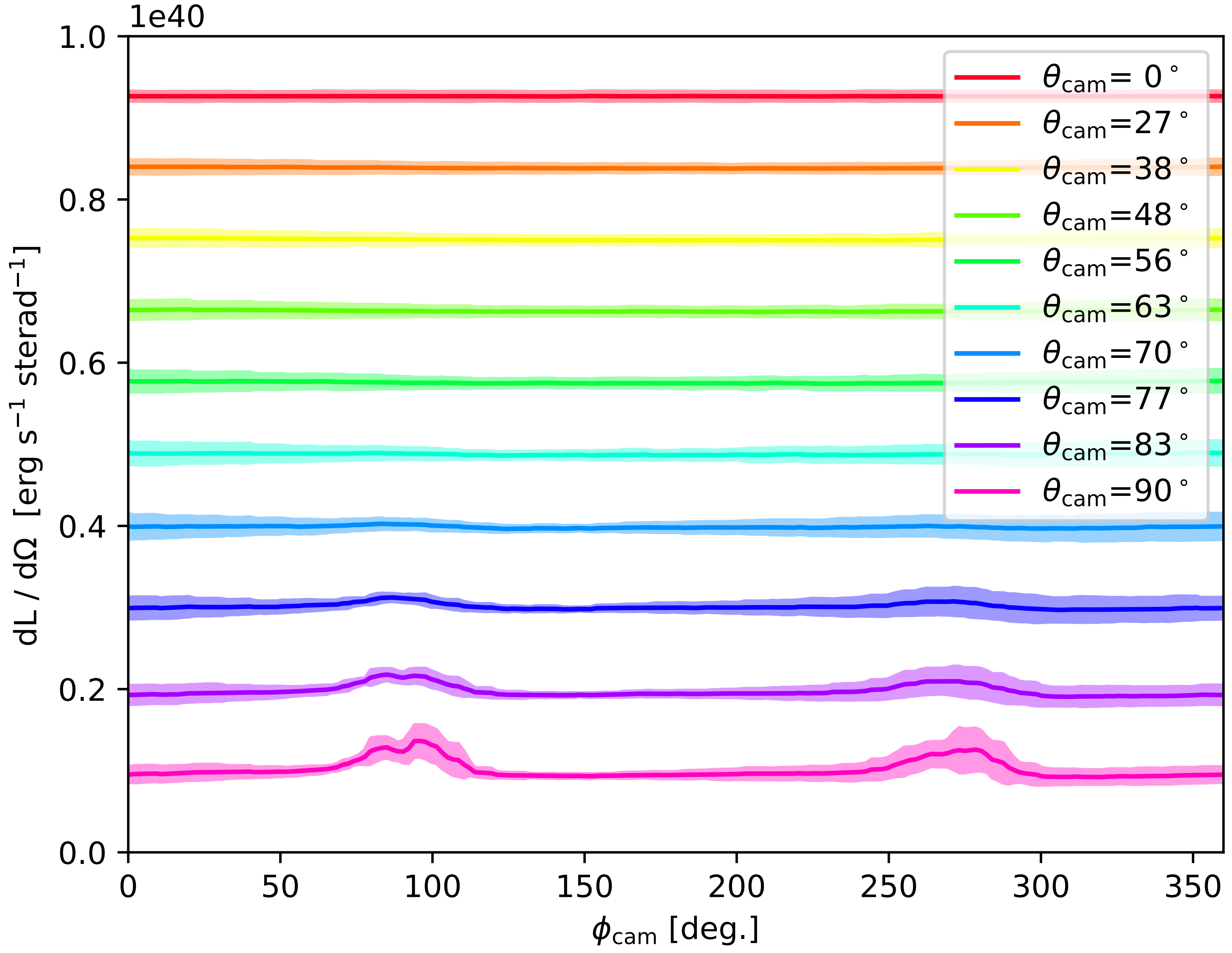
Accomplishments: Light from GRMHD Mini-disks

d'Ascoli et. al, *submitted to* ApJ, (2018).

Time Averaged over 2nd Orbit



Time Averaged over 3rd Orbit



- **Use orbital phase as a proxy to the time-dependence because our system has not sufficiently equilibrated in time.**
- **Thickness of lines show 1 standard deviation variability over each period. Lines are shifted vertically distinguish them.**

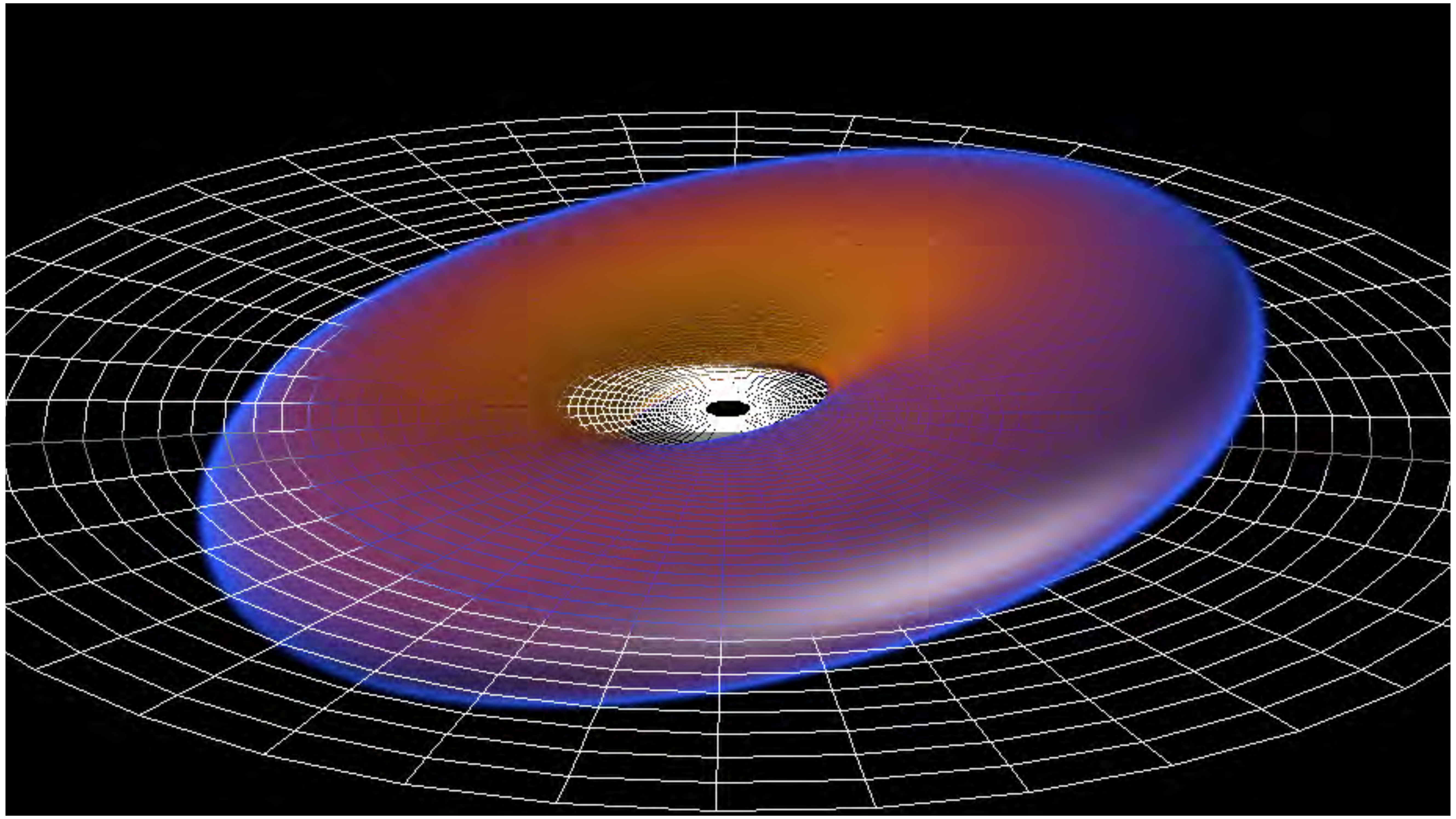
- **Why It Matters: Largest fluctuations from lensing of background mini-disk by foreground black hole.**
- **Why Blue Waters 2: Future longer simulations will explore O(10) orbits to yield actual time-dependence.**

Accomplishments: Tilted Disks about Binary Black Holes

Avara et. al, to be submitted (2018).

Credit: M. Avara

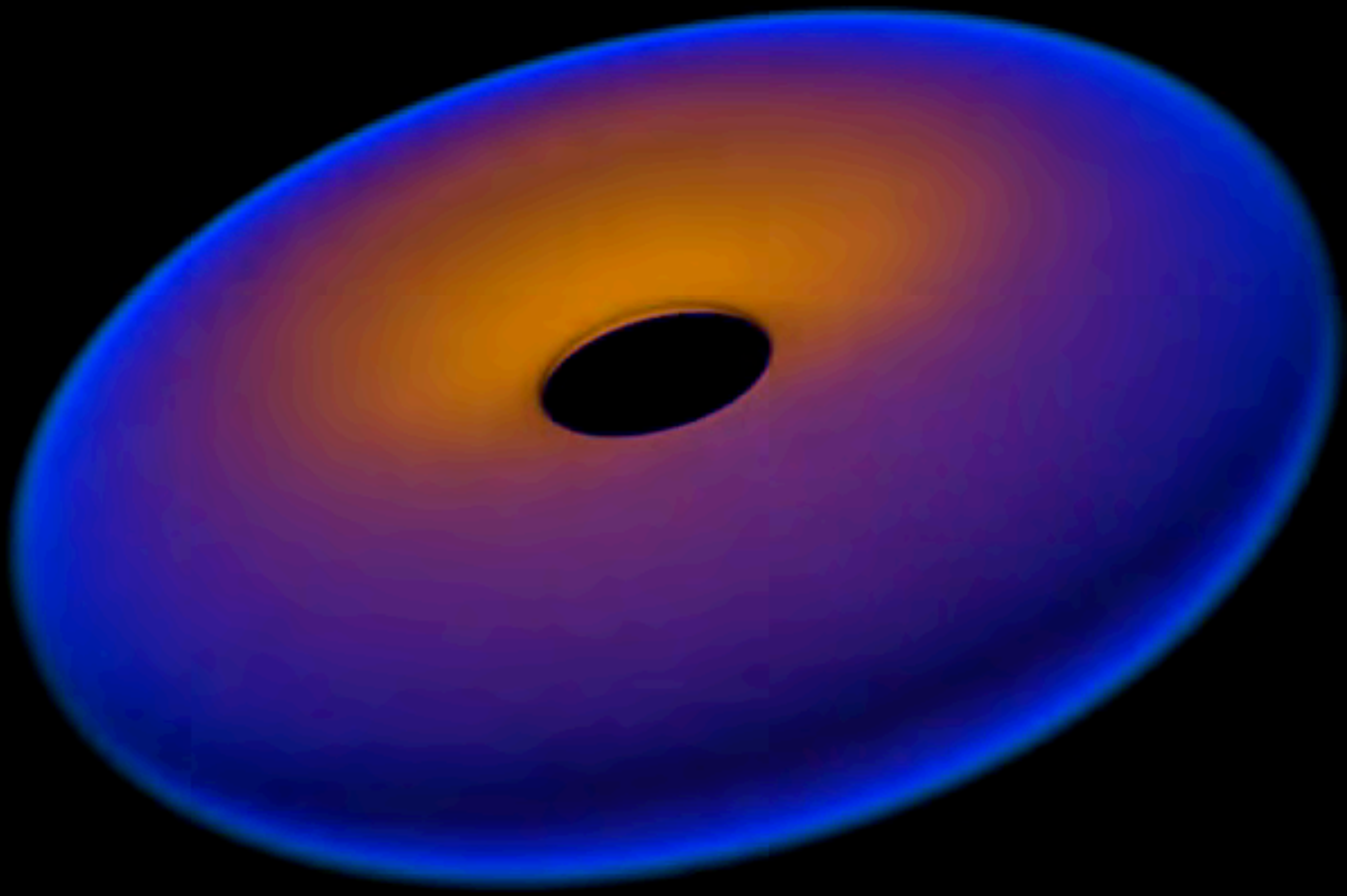
- Why It Matters:
  - Disks in nature may naturally arise misaligned, or 3-body encounters may misalign an already aligned system. Misaligned disks act different.
  - Gas on tilted orbits undergo differential precession from binary torques, similar to a misaligned disk about a single spinning black hole (see Tchekhovskoy's talk).
  - Differential precession lead to pressure gradients and shear stress that may dissipate it, acting to align disk.
  - Therefore it is important to use MHD since it is nature's source of shear stress.
  - At what radius does the alignment end?



- First simulations of resolved GRMHD simulations of tilted circumbinary disks.
  - Tilts (variety of resolutions for each):
    - 0 deg. (aligned),
    - 6 deg. (almost nonlinear),
    - 12 deg. (nonlinear);

- Disks have aspect ratio H/R ~ 0.1 ;
- Binary separation shrinks: 43M —> 12.5M
- Grid dynamically shrinks with the binary.
- 450x340x400 cells, O(10^7) time steps, 500 nodes for ~30 days;
- 300,000 M of problem time with a shrinking time step as the binary inspirals;

Avara et. al, to be submitted (2018).



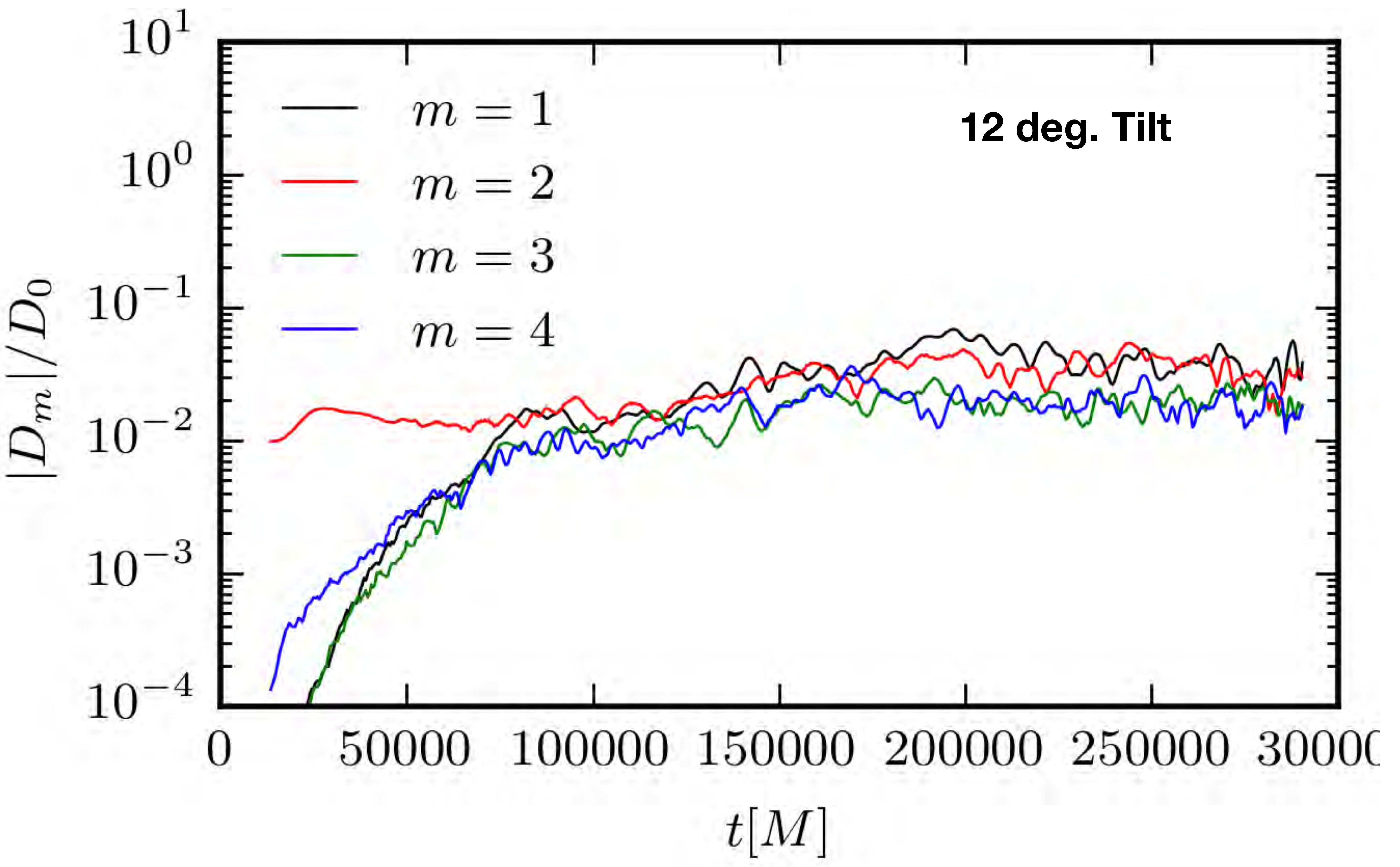
12 deg. Tilt

Mark Avara +, RIT

Accomplishments: Tilted Disks about Binary Black Holes

Avara et. al, to be submitted (2018).

- **Why It Matters:**
  - How do all our existing aligned results change when the disk is tilted? And with what tilt angle dependence?
  - Does alignment happen in the same way as in single spinning BH systems? Time-averaged binary spacetime resembles highly spinning black hole spacetime.
  - Does the circumbinary disk's overdensity develop with the same strength?
  - Simulations have just finished, analyzing now…



Relative azimuthal mode strength over time, where "m" is the mode number or the number of nodes in a wave.

Accomplishments, Product: MHD *Patchwork*

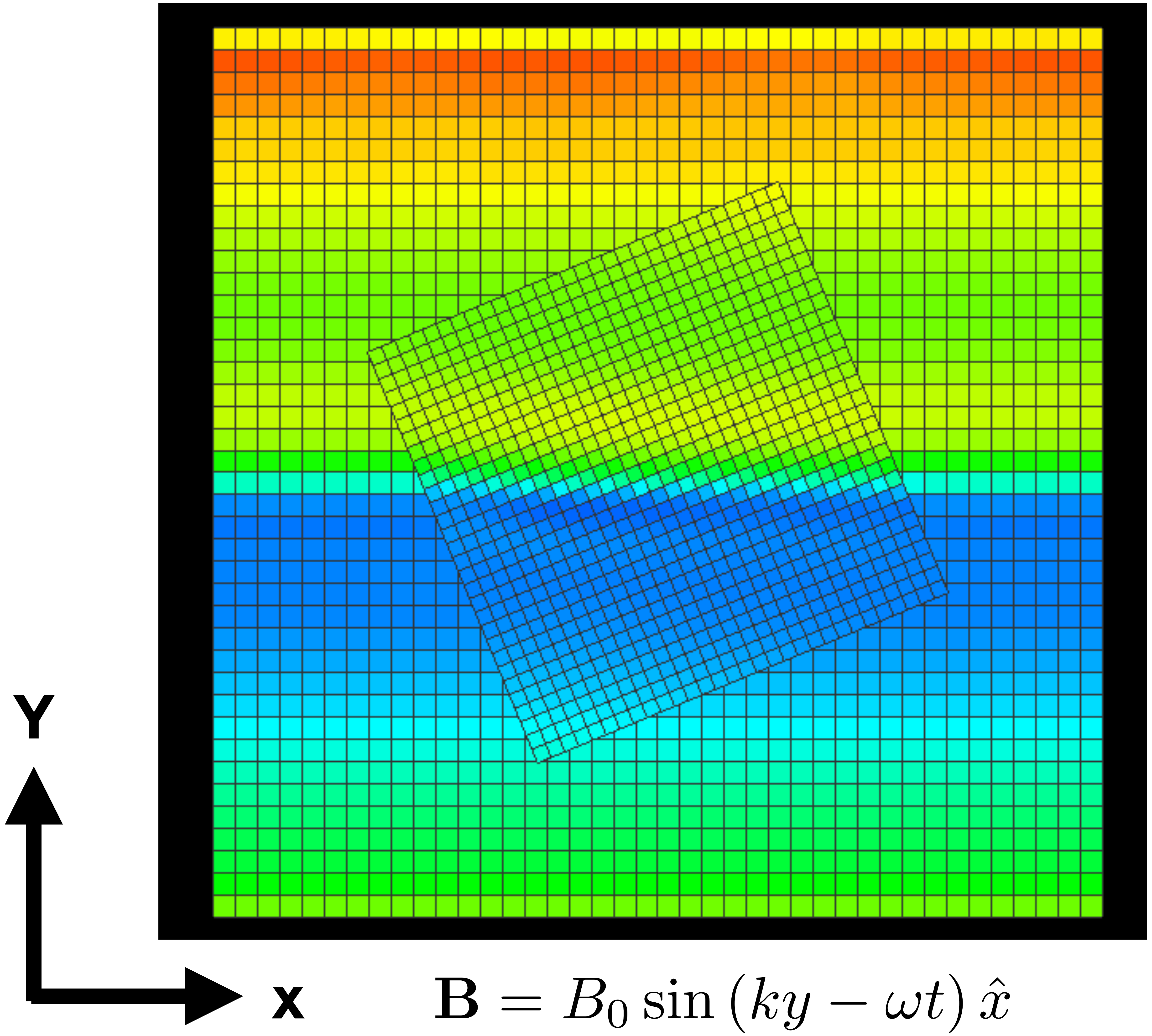
Avara et. al, to be submitted (2018).

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

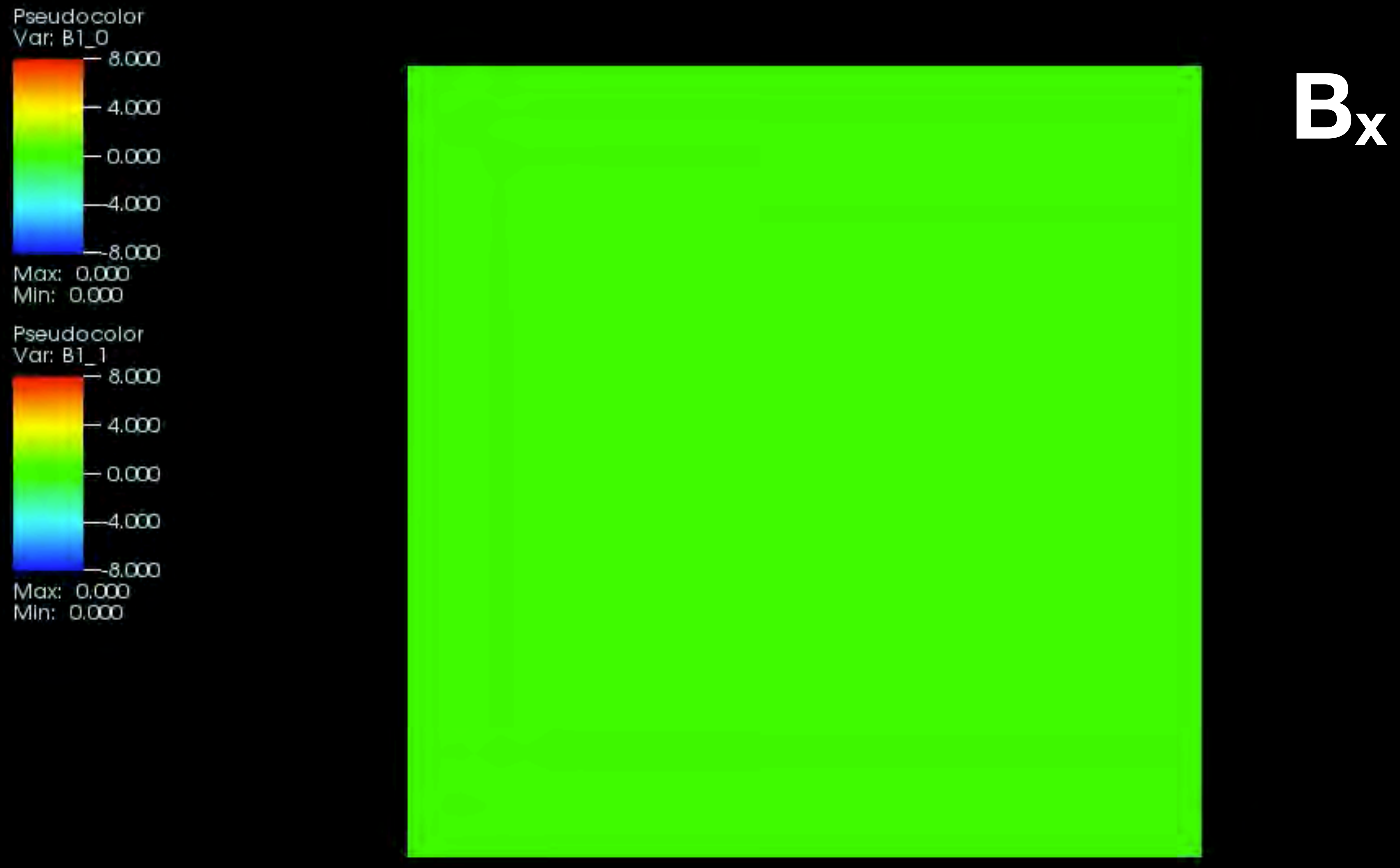
- **Key Challenges:** Generalize *Patchwork* for the wide range of coordinate systems and patch situations (e.g., patch motion/rotation/overlap) desirable to execute our planned simulations.

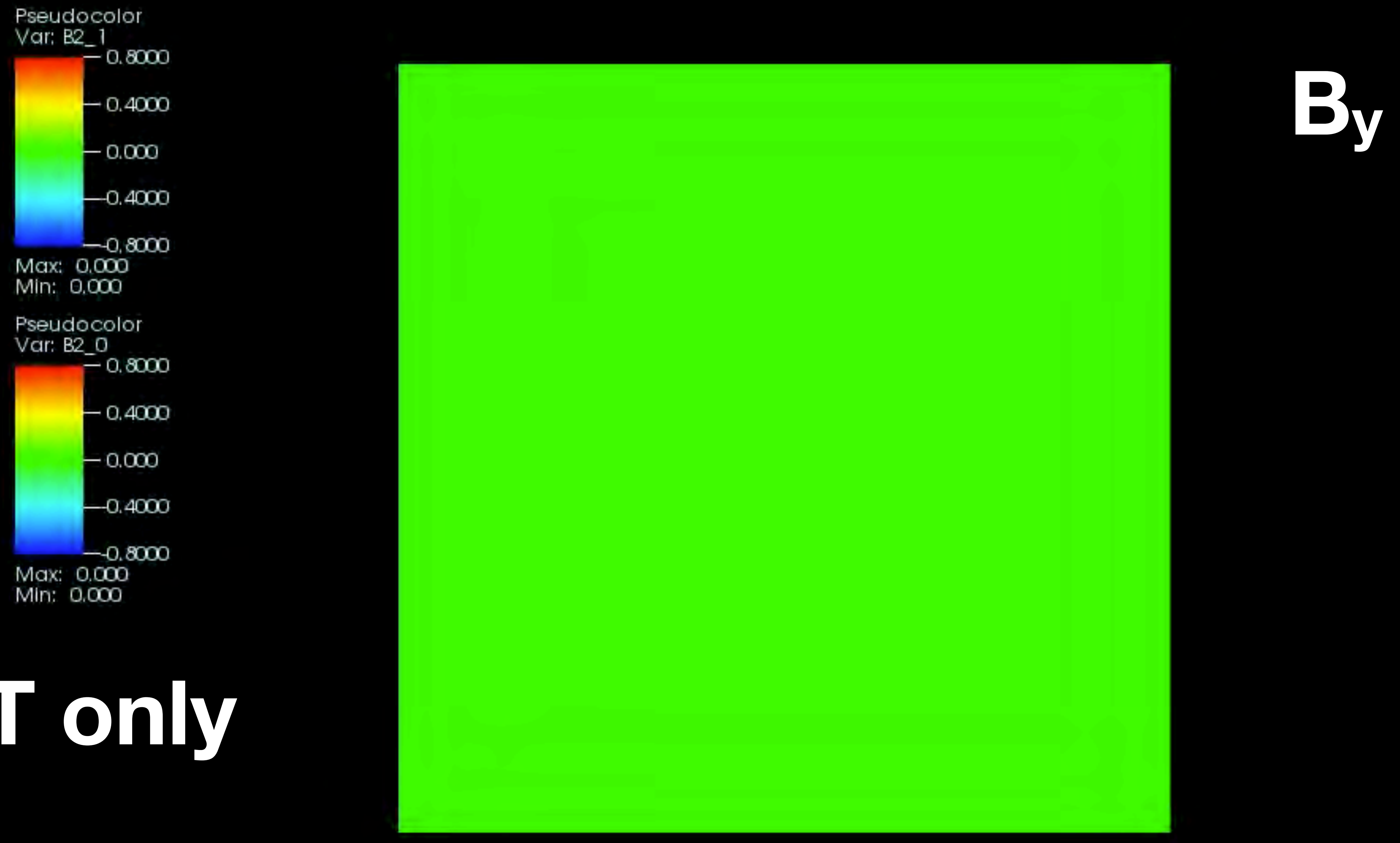
- **Product:** Developed method to adjust fluxes along patch boundaries to dissipate monopoles and flux differences.

- **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.



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





FluxCT only

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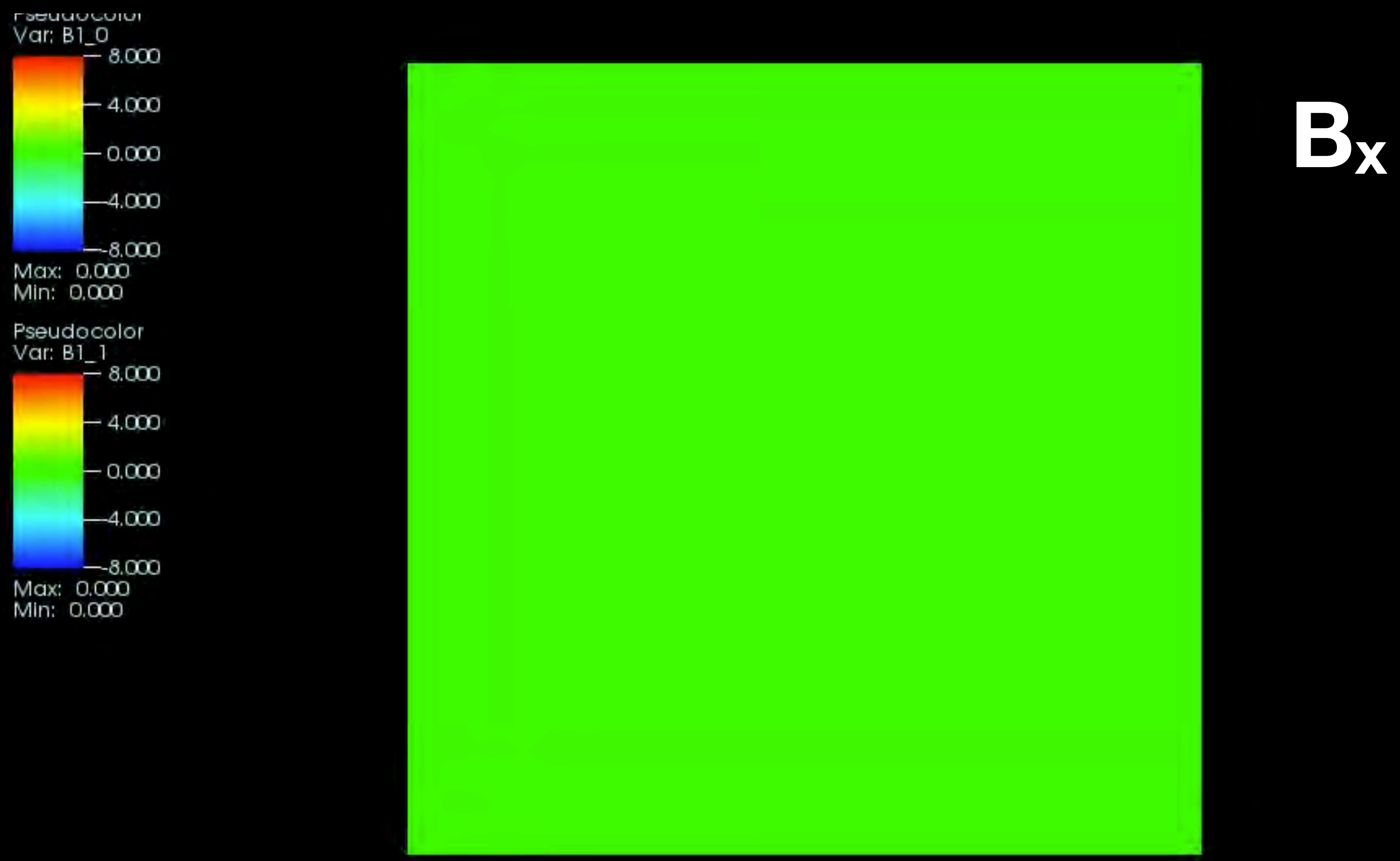
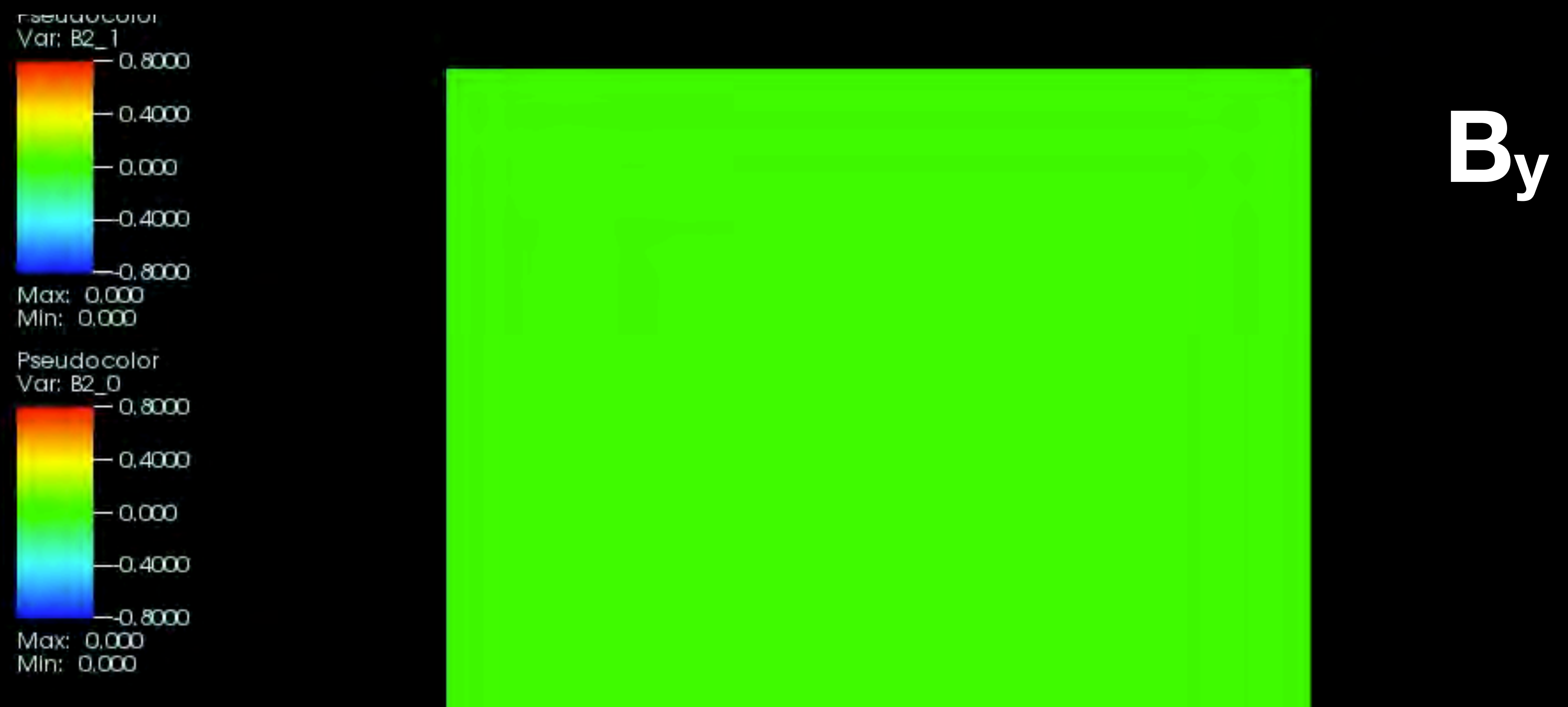
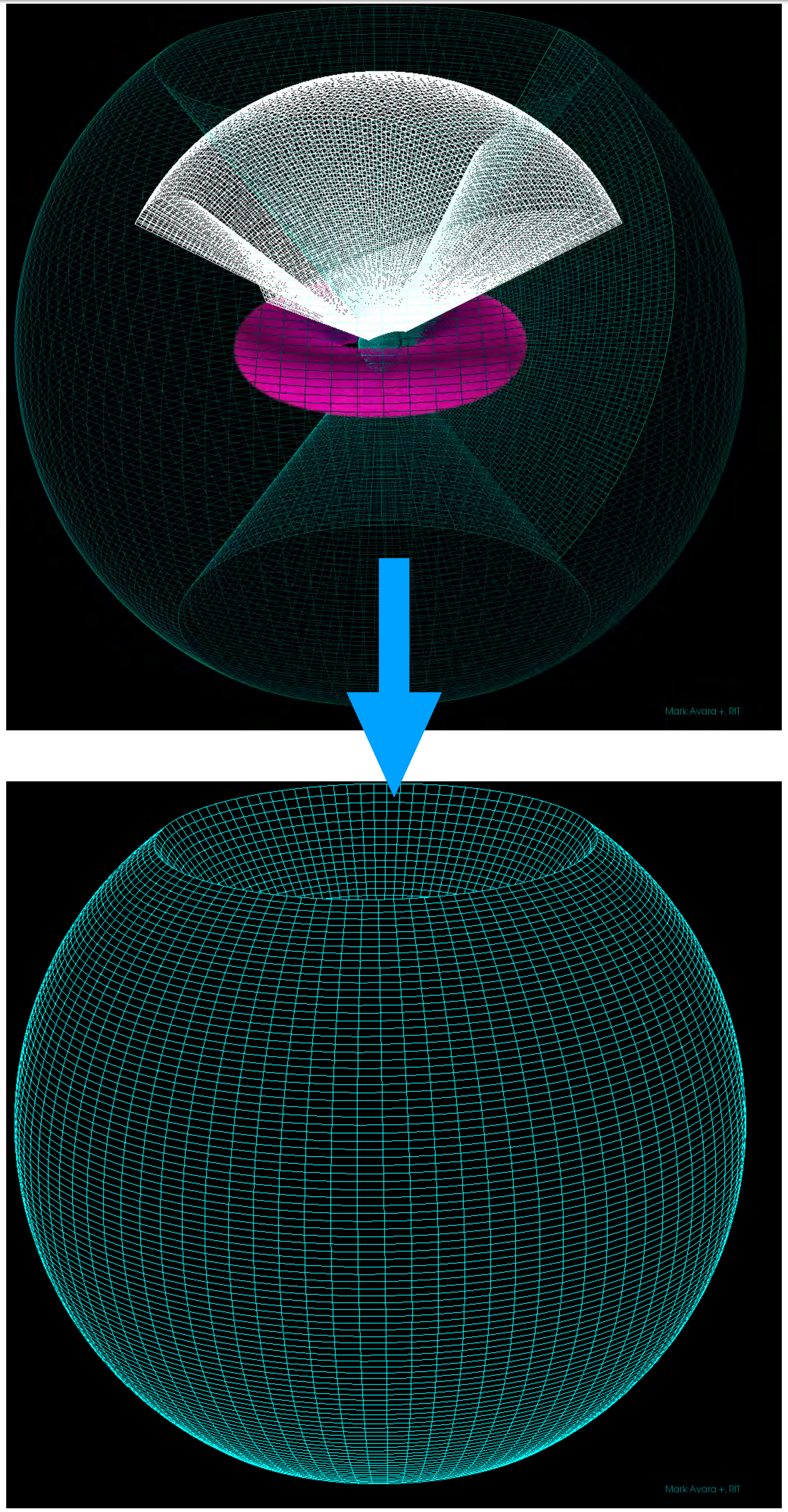


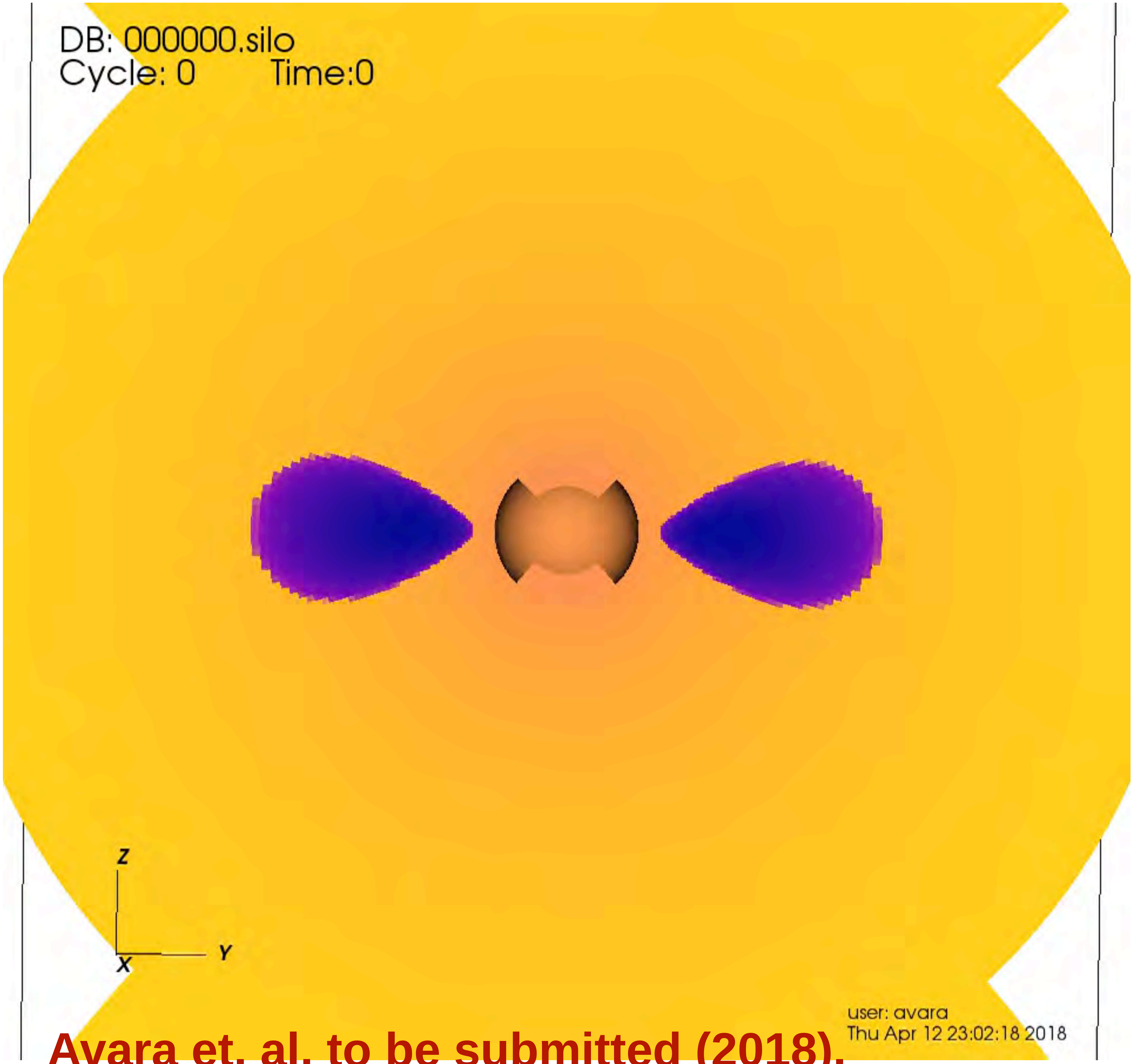


FluxCT
With Flux Fix

Accomplishments, Product: MHD *Patchwork*

- Test: Single accreting black hole.
- 3 spherical patches:
  - 1 aligned with z-axis;
  - 2 aligned with x-axis covering the poles;
- Now testing many-patch setup for BBH Disk simulations, that will be used for simulations in our next allocation.





Avara et. al, to be submitted (2018).

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 new dynamical interactions between the mini-disks and circumbinary disks of the flow.

    - Produced the first electromagnetic spectrum from 3-d simulations, essential for astronomical search campaigns and understanding systems to be discovered soon.

- Tilted circumbinary disk simulations are broadening these predictions and will be used in future mini-disk simulations.

- New 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 and unique resources—both computational and support—Blue Waters provides has really motivated us to aim high and challenge ourselves to solve problems and develop tools we may not have done otherwise.