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

BW IDs: PRAC_gk5, DD_gku

Blue Waters Symposium, Wednesday May 17th, 2017

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- S. James (GR, U. Tulsa)
- C. Lousto (Prof, RIT)
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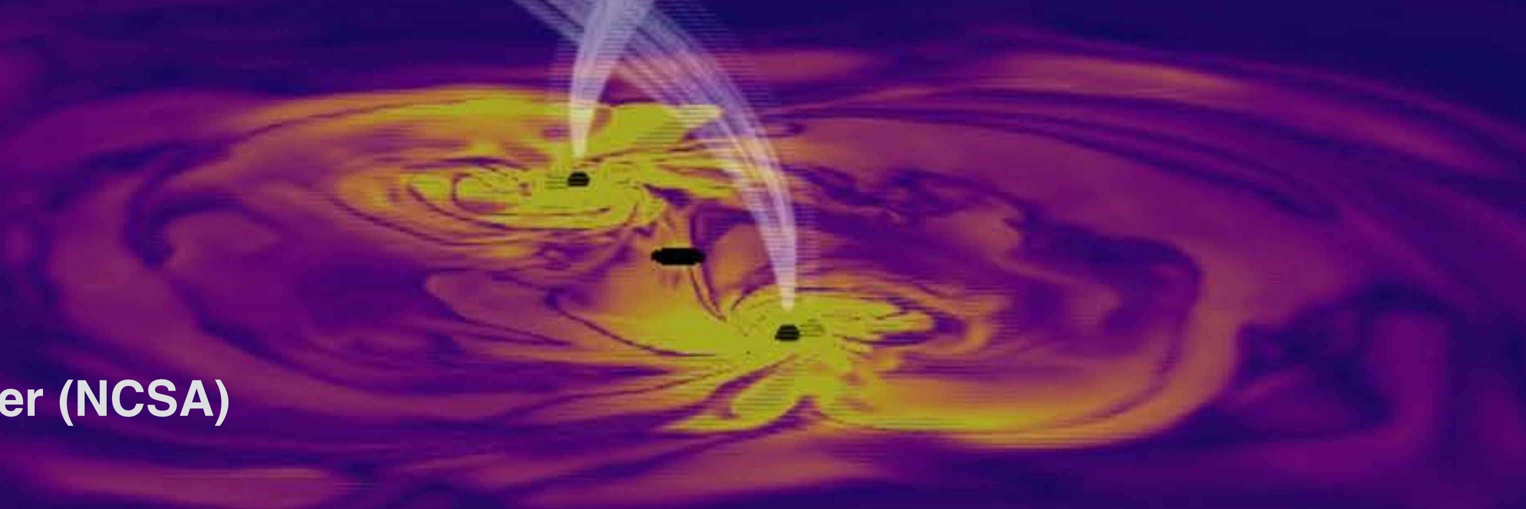
- L. Moon (UG, RIT)
- H. Shiokawa (PD, CfA)
- Y. Zlochower (Prof, RIT)

NCSA POC: Jing Li

Image Credit: Mark Vanmoer (NCSA)



Based on:

- Bowen et. al, ApJ, **838**, 42 (2017).
- Healy & Lousto, PRD, **95**, 024037 (2017)
- Healy, Lousto, Campanelli, *arXiv,* 1703.03423
- Shiokawa et al., arXiv, 1701.05610 (in review)

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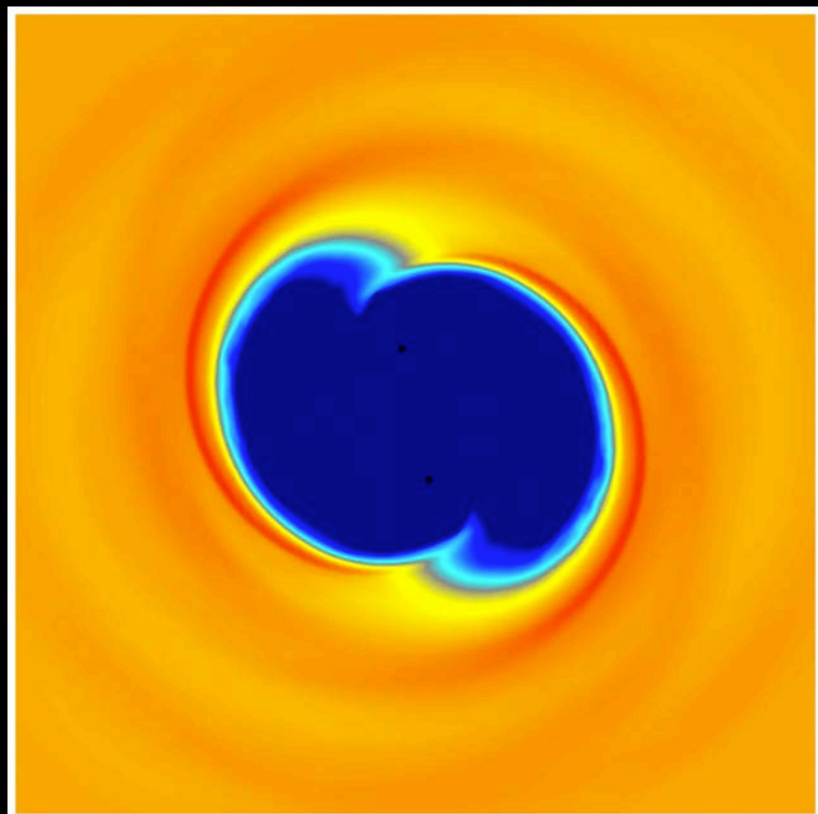
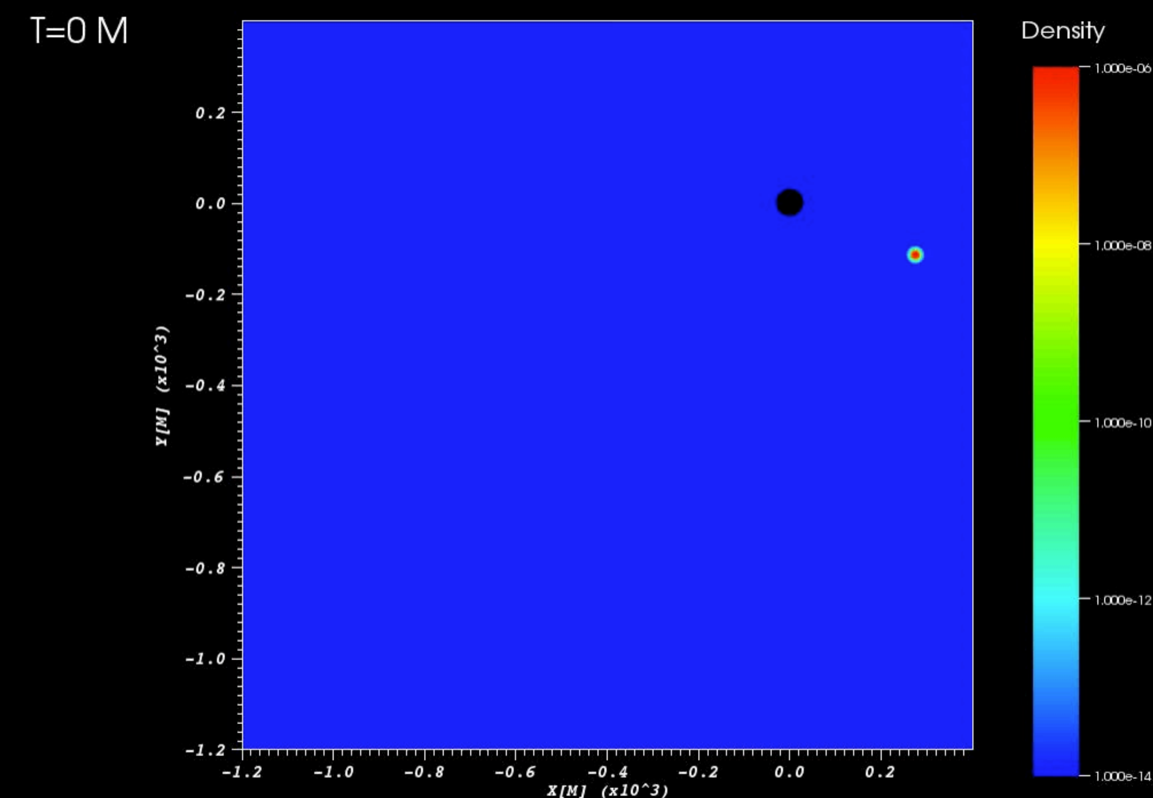
Why It Matters: Mysteries of Supermassive Black Holes

Accreting Supermassive Black Hole Binaries (SMBBHs)



- Principal source of low-frequency GWs (LISA).
- Multi-messenger astronomy offers:
  - Simul. EM/GW to probe strong-field gravity;
  - New measurement of cosmological expansion;

Tidal Disruption Events

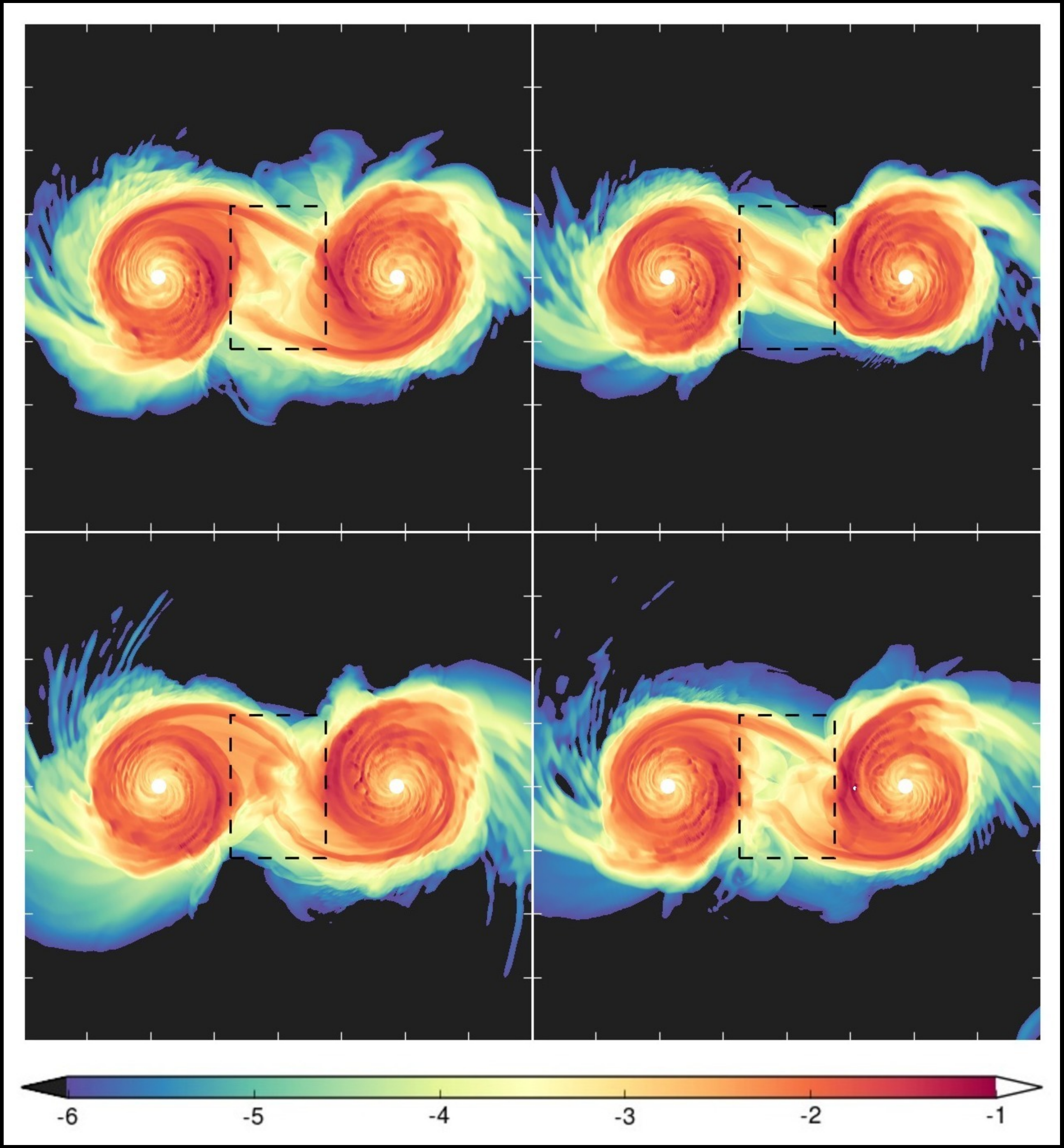


- Rare opportunity to learn how BHs become active and grow.
- Means by which to understand feedback and stellar populations in galactic centers.

- Both provide significant insight into galaxy evolution and black hole growth.
- Both lack resolved, long time-scale MHD simulations thereof in the relativistic regime.
- Both are being investigated using current high-cadence data (PAN-STARRS, Catalina RTS), and future ones like the Large Synoptic Survey Telescope (LSST).

2-d Hydrodynamic SMBBH Mini-disks

Bowen et. al, ApJ, 838, 42 (2017)



Key Challenges:

- Our novel near-equilibrium initial data allows us to reach steady-state quicker and mitigate initial data transients.
- Resolve the vast dynamic range of the problem.

Accomplishments:

- Demonstrated break down of Newtonian prediction (Paczynski 1977) of truncation radius, at separations < 20-30M for equal-mass binaries;
- Sloshing seen in previous runs using Newtonian gravity, though has not been studied closely.
- Closer binaries:

  —>Shallower potential

  —> More mass in sloshing region

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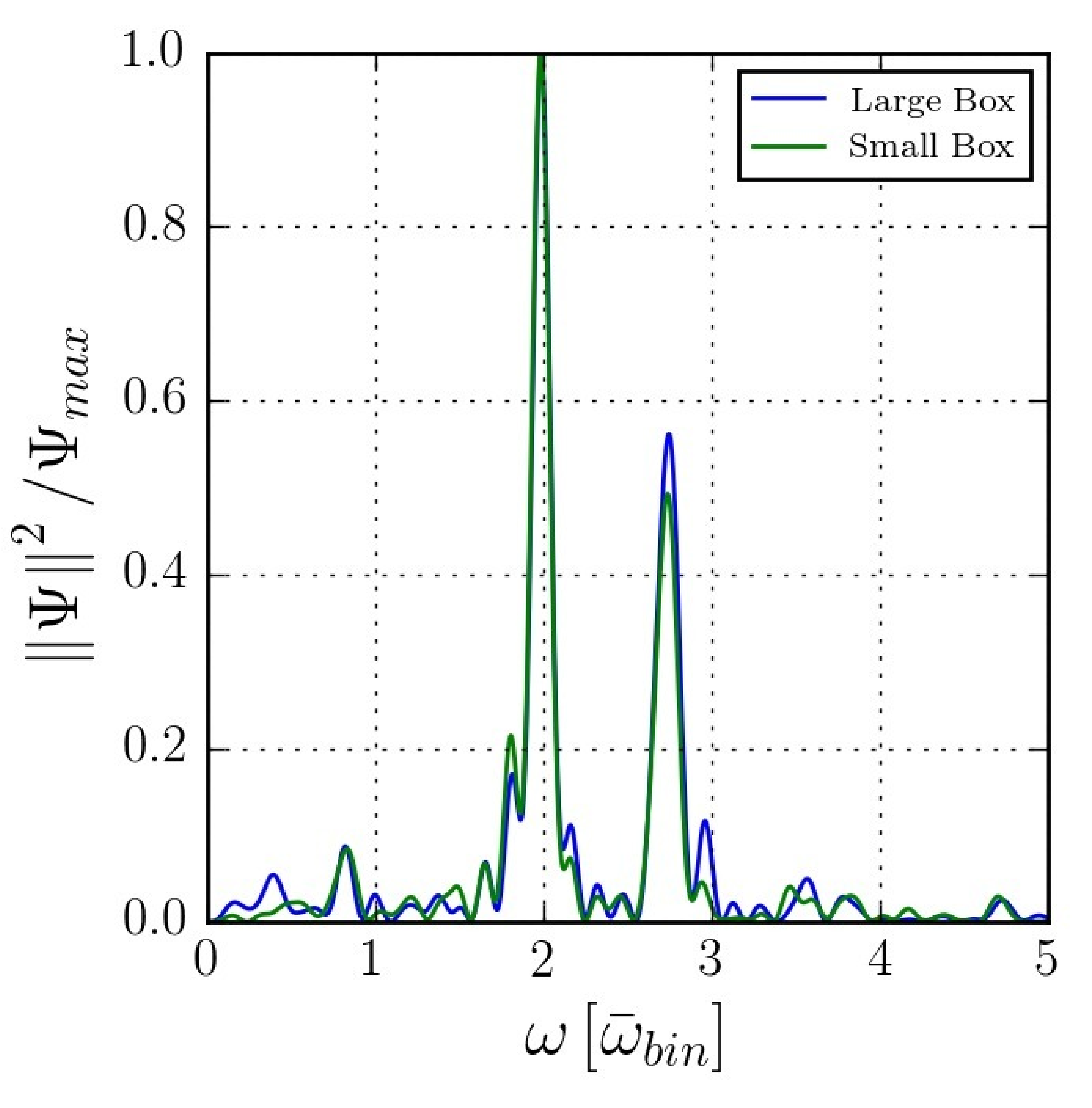


Modulation Power of Mass in Sloshing Region

Accomplishments:

- Closer binaries:
  —>Shallower potential
  —> More mass in sloshing region
- Dissipation of sloshing streams will emit significant luminosity, which can modulate the signal from the binary.
  —> Signature of strong-field gravitational dynamics.

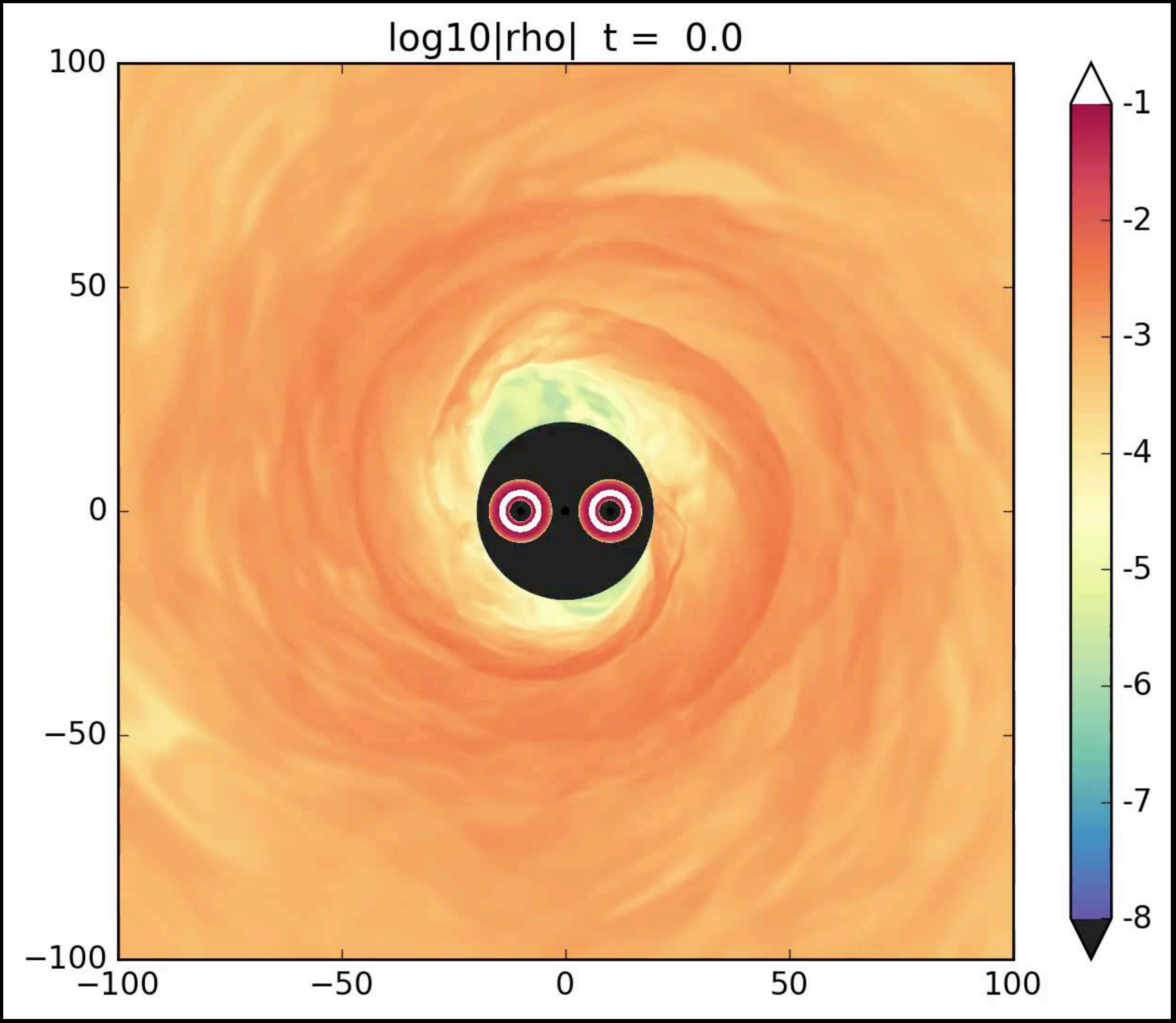
Why It Matters:

- Frequency of mass modulation not trivially connected to orbital frequency —> simulations are key!
- Modulation can help identify binaries and characterize their parameters.

3-d MHD SMBBH Mini-disks (in progress)

- First of a kind simulation: consistent GRMHD in inspiral regime.
- Will 2-d hydro. results carry over to more realistic scenario?
- 3-d also allows us to maintain consistent thermodynamics with radiated power, useful exploring relativistic beaming, gravitational redshift effects on observables.
- Discover the significance of relativistic outflows (jets).

Top-down, large scale view



Why Blue Waters?

- The run is an "intermediate"-sized job requiring more than a month of sustained run time:
  - 600x160x640 (6e7) cells.
  - 600 nodes for 40 days.
- Unaffordable on other systems.
- Difficult to push through the queue quickly because of its size and BW's queue's priorities.

BW Team Contributions:

- David King and Jing Li (and others) both helped setup reservations for the 3-d runs to accelerate the jobs through the queue.

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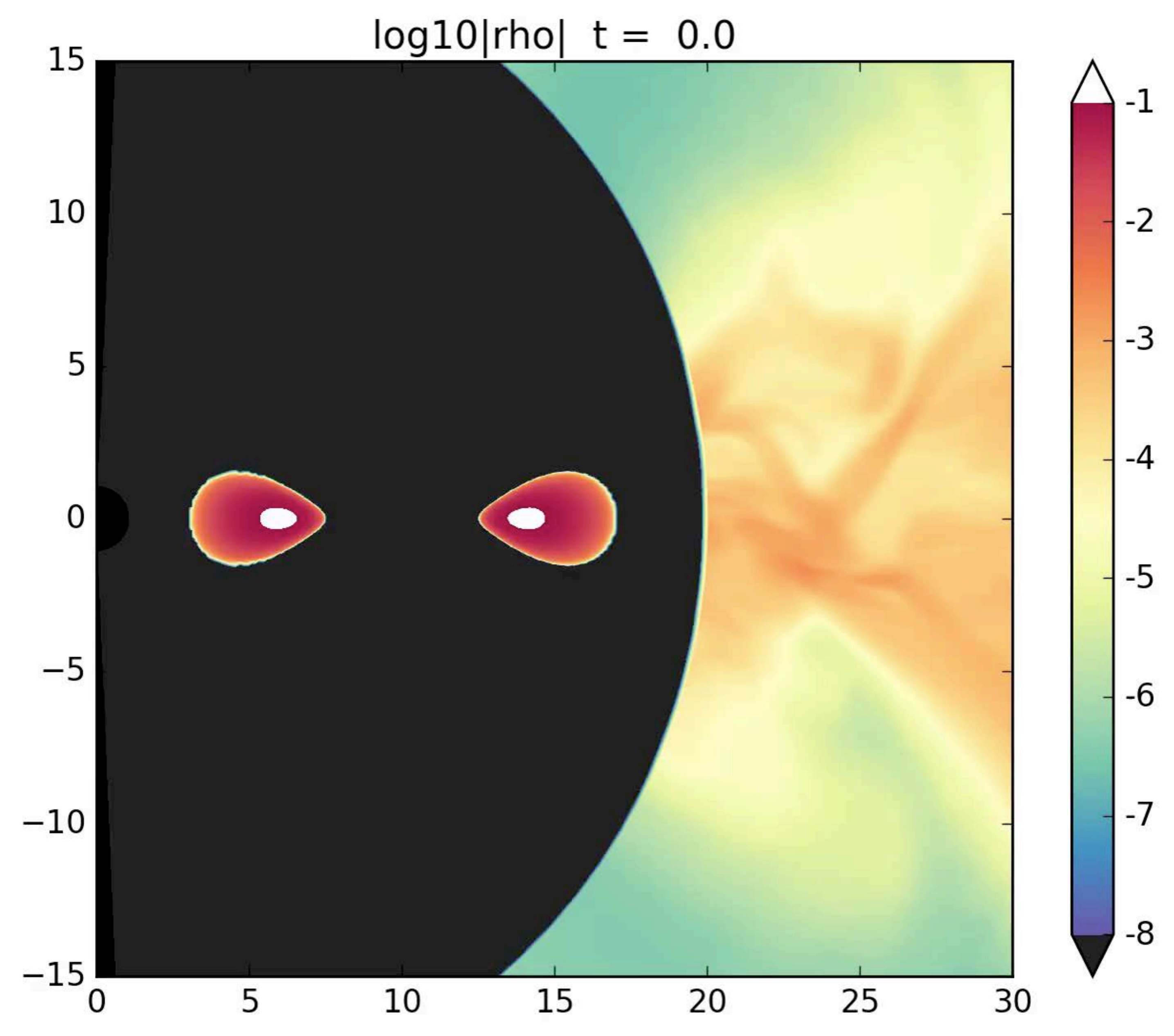

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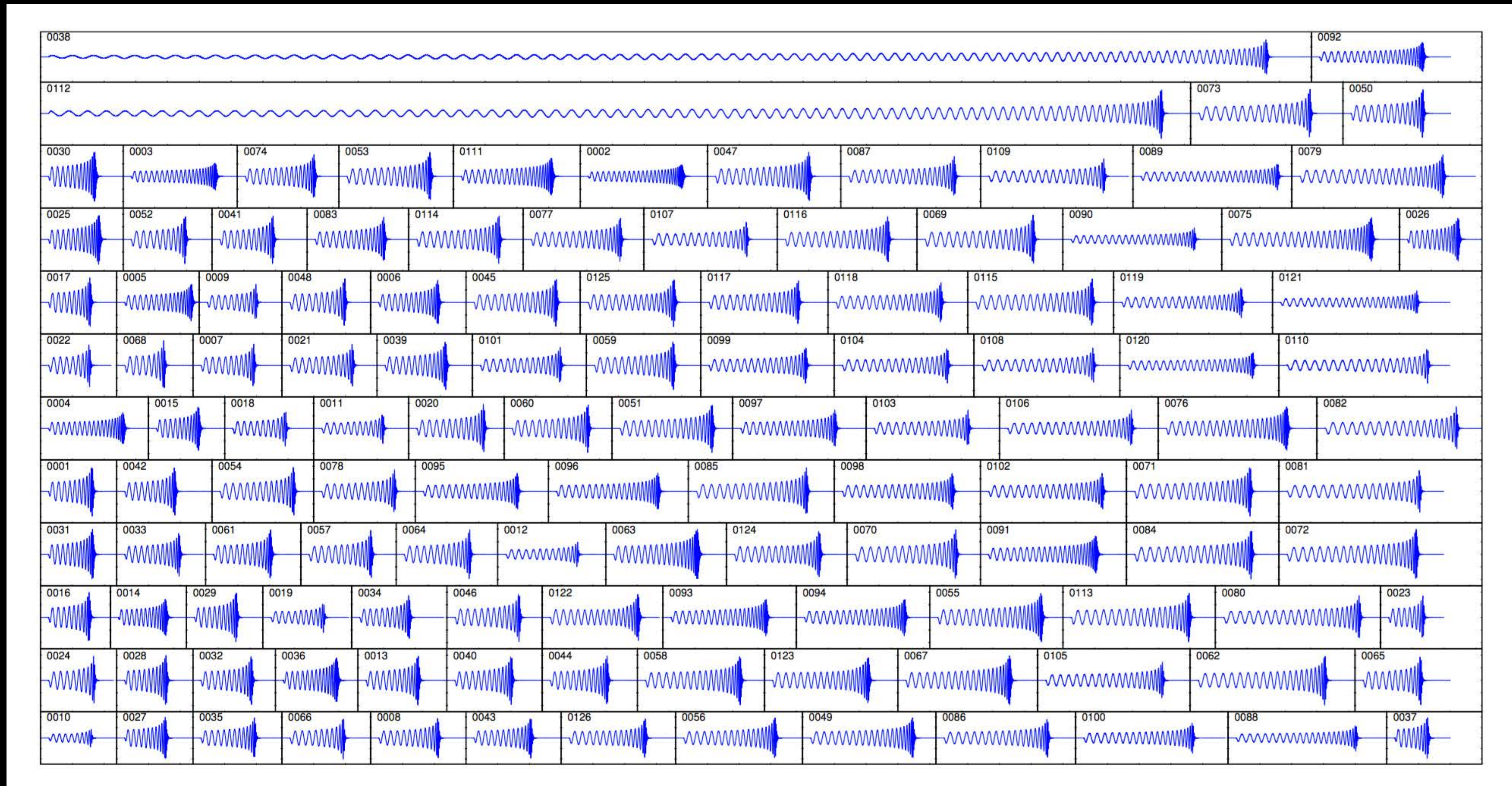
Numerical Relativity (vacuum) Binary Black Simulations

Healy & Lousto, PRD, 95, 024037 (2017)
Healy et al., *arXiv,* 1703.03423



Products & Broader Impacts:

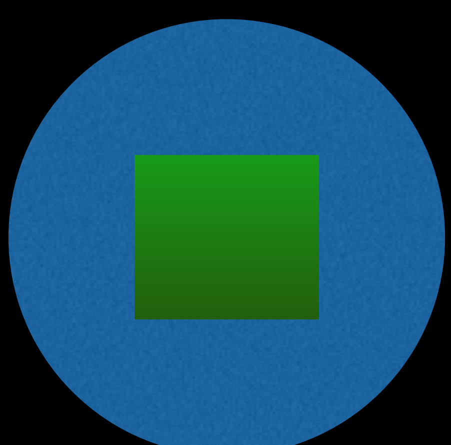
- RIT's public catalog of NumRel gravitational waveforms:
  - 16 of 126 waveforms were done on BW for first public catalog.
  - 60 more in progress, for a total of 76 out of 300 waveforms in the next catalog.
  - Used in LIGO's Algorithm Library for use in matched filtering GW signals.
  - Used to improve fitting formula for final BH mass, spin, kick velocity, GW luminosity, etc.
- Additional simulations include those of GW151226 and LVT151012 LIGO events.

Patchwork: a Multipatch Infrastructure for Multiphysics/Multiscale/Multiframe Fluid Simulations

Shiokawa et al., arXiv, 1701.05610 (in review)

Accomplishments:

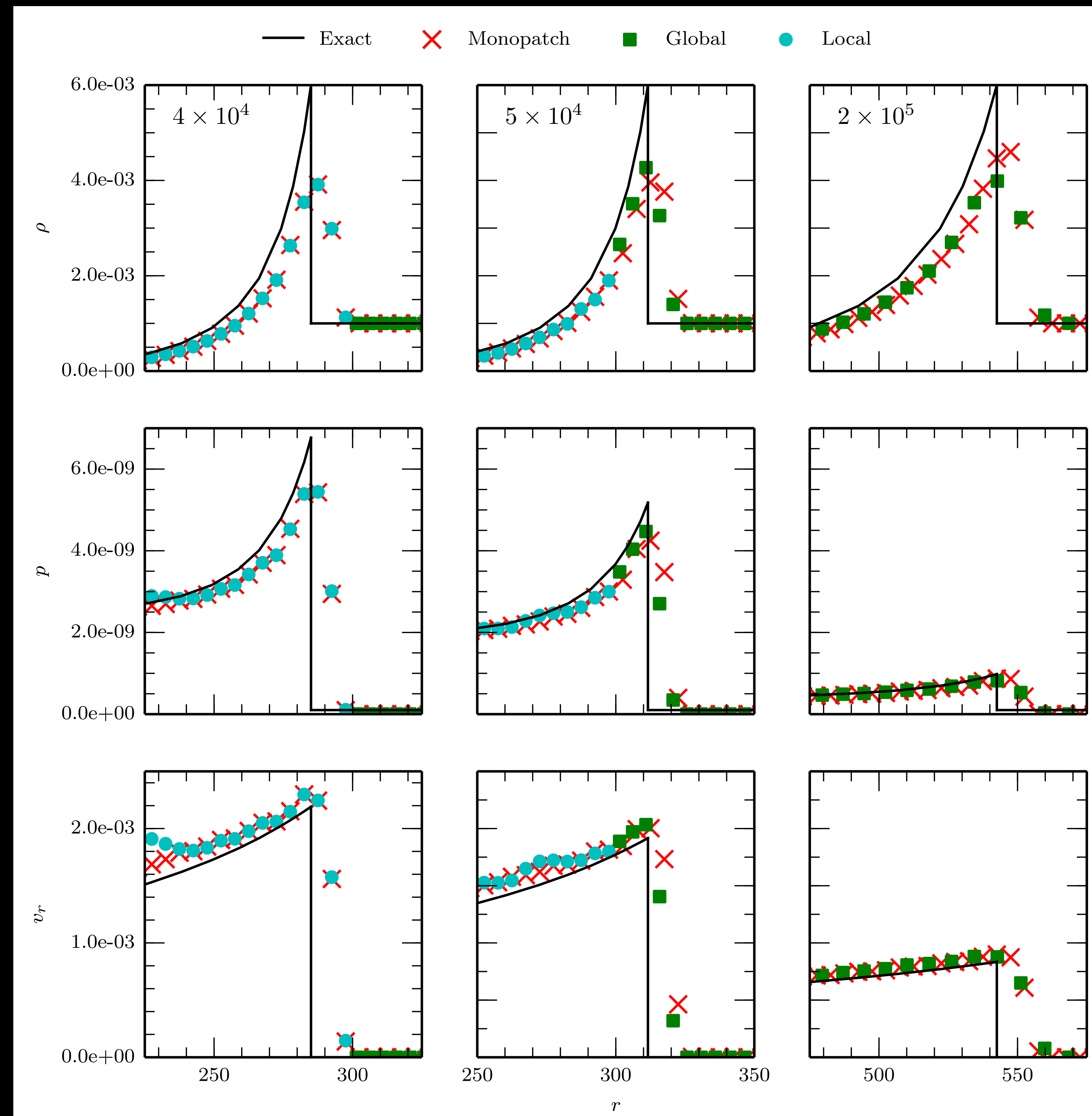
- Validated multi-patch method using patches with different:
  - Coordinate systems;
  - Resolutions;
  - Local gravity models;
  - Time step sizes;
- Various tests;
  - Shock tube;
  - **Spherical Sedov-Taylor blast wave;**
  - Linear waves;



Multipatch

vs.

Monopatch



Sedov-Taylor blast wave

Patchwork: a Multipatch Infrastructure for Multiphysics/Multiscale/Multiframe Fluid Simulations

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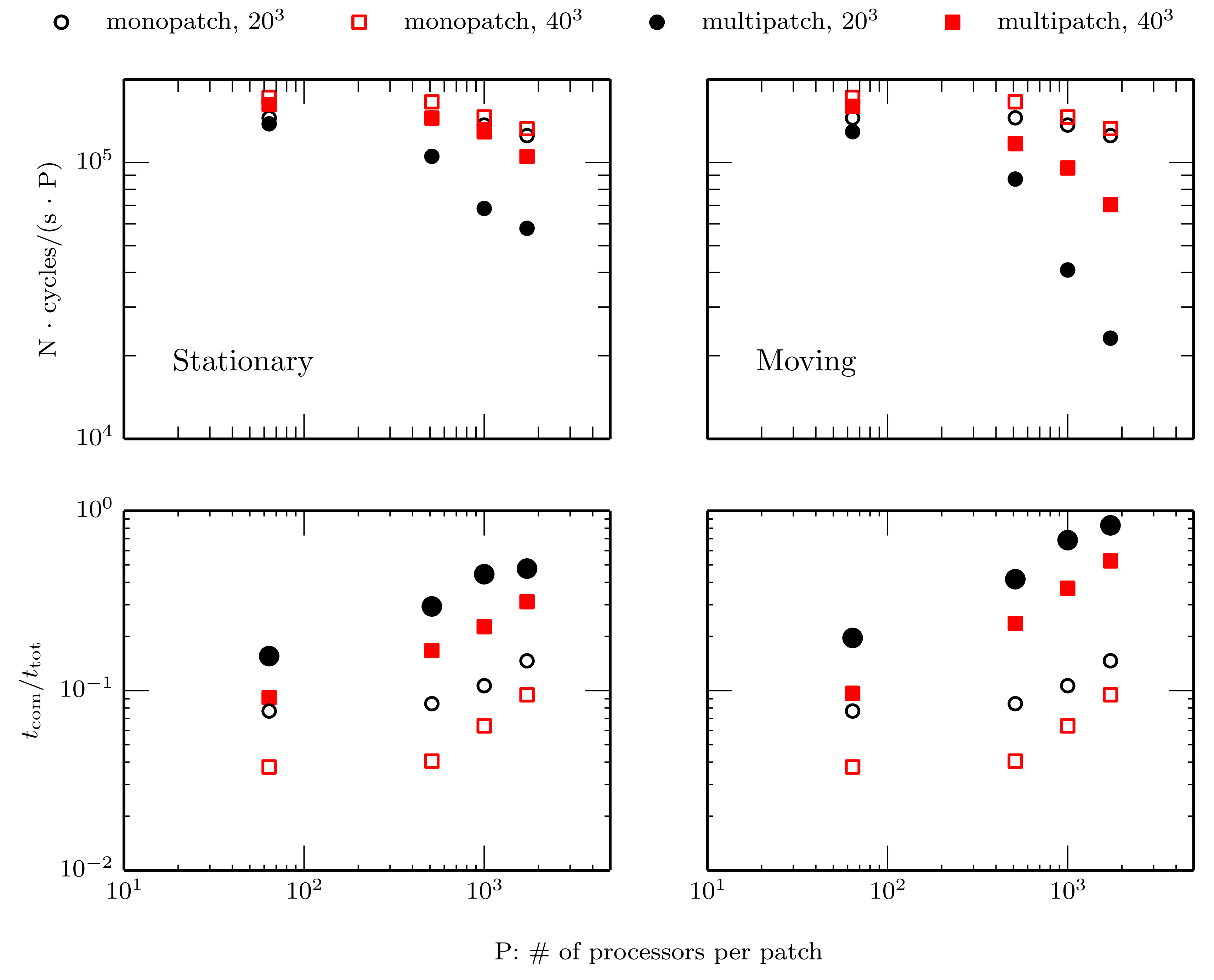
Accomplishments:

- Scaling Performance:
  - Communication load insignificant up to ~10^3 cores per patch;
  - Improves with smaller surface/volume ratio;
  - Moving patches add overhead as inter-patch connections need to be updated more often.
  - Still using naive, unoptimized communication strategy;
  - Heterogenous time stepping yields **2-3x speedup!**

Products:

- Intend to publicly release Patchwork code eventually as soon as possible.



Weak & Strong Scaling Performance
(Stampede scaling shown, BW scaling in progress)

Blue Waters Team Contributions:
Visualizing Accreting SMBBHs

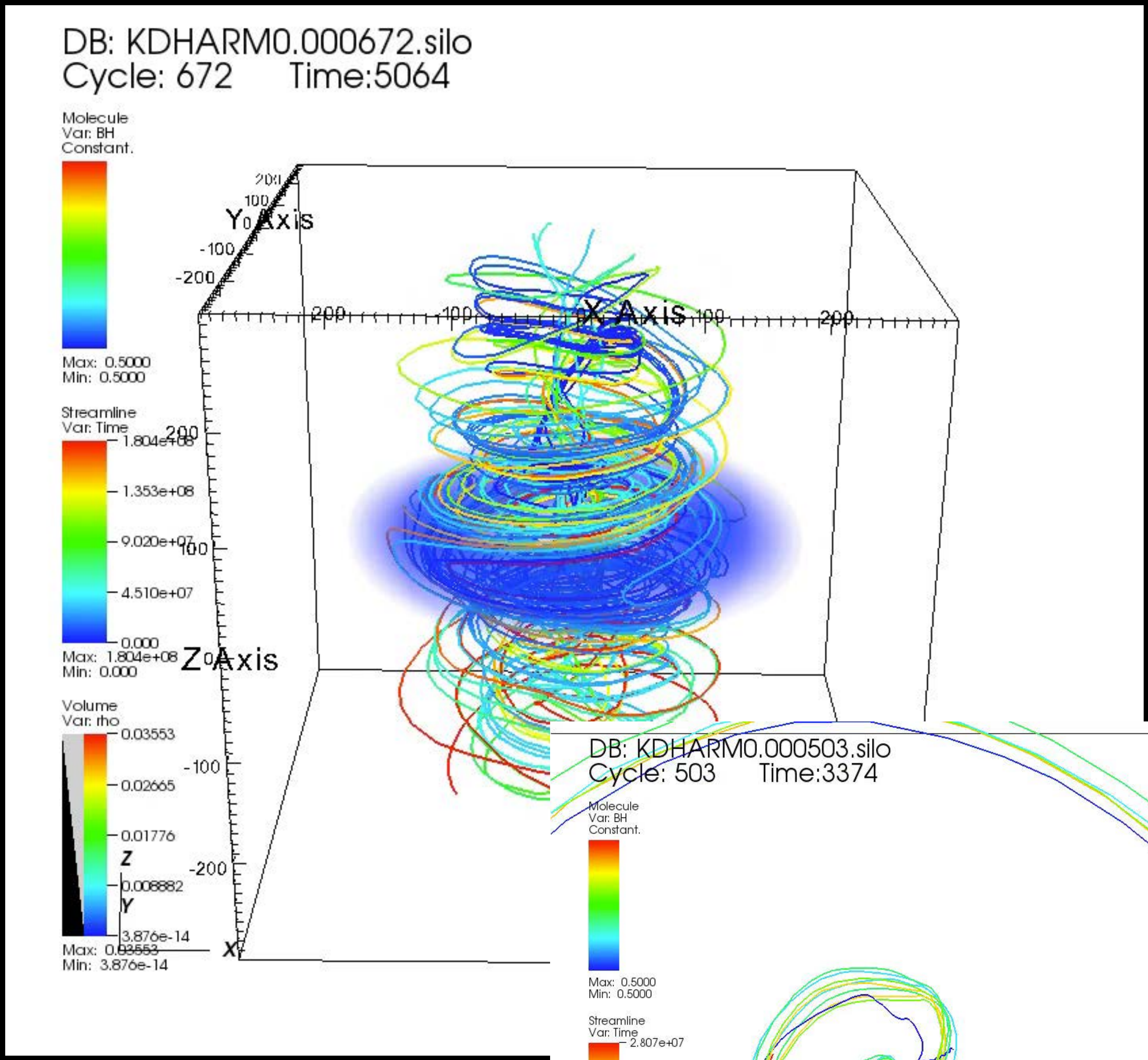
Orbiting Black Holes
Magnetohydrodynamics

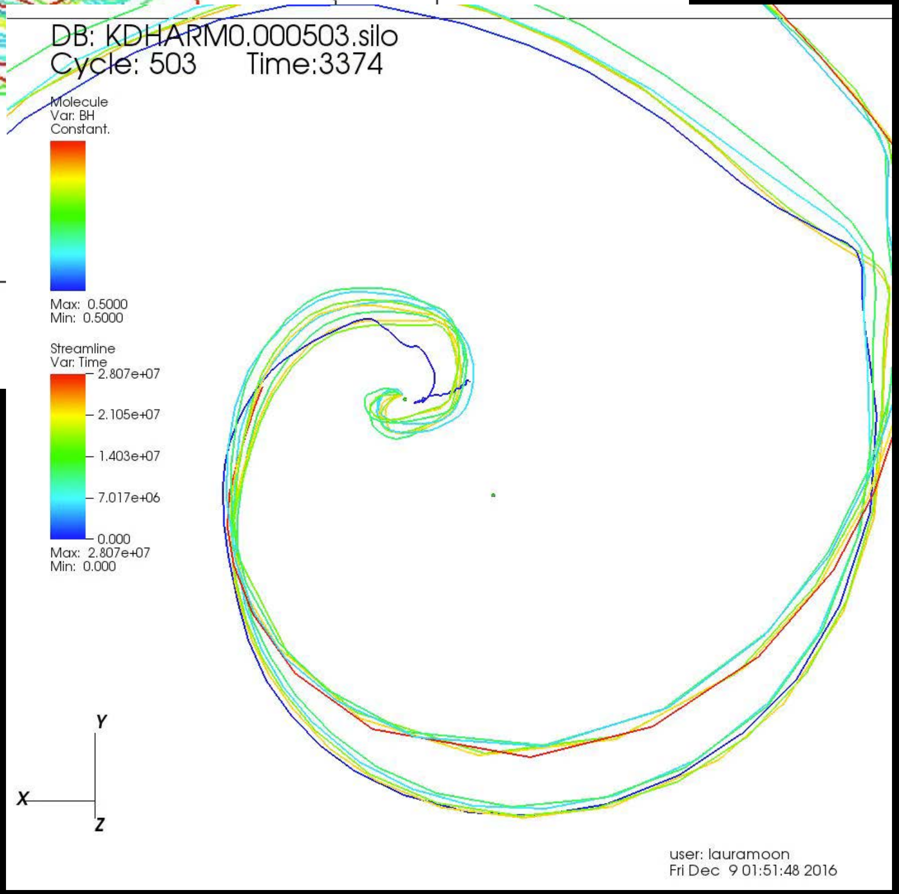
PI: Scott Noble, Tulsa
Vis: Mark Van Moer, NCSA

M. Van Moer, S. Noble, and R. Sisneros. "Orbiting Black Holes Magnetohydrodynamics." Presented at the Visualization Showcase. XSEDE16 Conference on Diversity, Big Data, and Science at Scale. Miami, USA. July 17-21, 2016.

Broader Impacts & Blue Waters Team Contributions:
Educating the Next-generation of Scientific Visualizers

- With Mark Van Moer and Roberto Sisneros (NCSA), Manuela Campanelli (RIT), S. Noble (Tulsa);
- Undergraduate Students:
  - Laura Moon (Chemical Eng., RIT)
  - Brennan Dell (Software Eng., RIT)
- Goals:
  - Provide advanced scientific visualization education to undergraduate students, using Visit and Python.
  - Discover the particular distribution, topology and evolution of magnetic field lines near accreting binary black holes.
  - Advance current practices on animating the same set of field lines continuously in time.
- Student Results:
  - Learned how to use Python scripts to interface with Visit and control camera position/movement, and field line seed point locations.
  - Have begun exploring how to advect the seed points in time to maintain field line continuity.





All Images by
L. Moon and B. Dell (RIT)

Blue Waters Team Contributions:
PAID Project: Load Balancing with HARM3d

Team Leads: Sanjay Kale, S. Noble
Team: Spencer James (Tulsa), Sam White (UIUC), Juan Galvez (UIUC),
BW ID: DD_gku
(see my PAID talk Thursday afternoon)

Key Challenges:

- Nonuniform FLOP-count over domain due to harder spacetime metric evaluation near BHs (SMBBHs), or multi-patch evolutions.
- Include topology awareness.
- Use Charm++/AMPI tools to provide solution within a year's time.

Accomplishments:

- Thread Local Storage solution proved incompatible with migrating HARM3d;
- Implemented "work around" using AMPI's "Pack-UnPack" framework to explicitly instruct how data is migrated, allocated, and deallocated during migrating virtual processes.
- Required moving global variables into a dynamically allocated structure which is passed in function arguments.
- Rewrite resulted in insignificant performance impact.
- Validated (load balanced) single black hole disk configuration.
- Verified success of AMPI's load balancer with artificially imbalanced single BH disk configuration, leading to ~50% SU savings.
- Currently testing MHD binary black hole configuration.

Summary & Conclusions

Key Science Achievements:

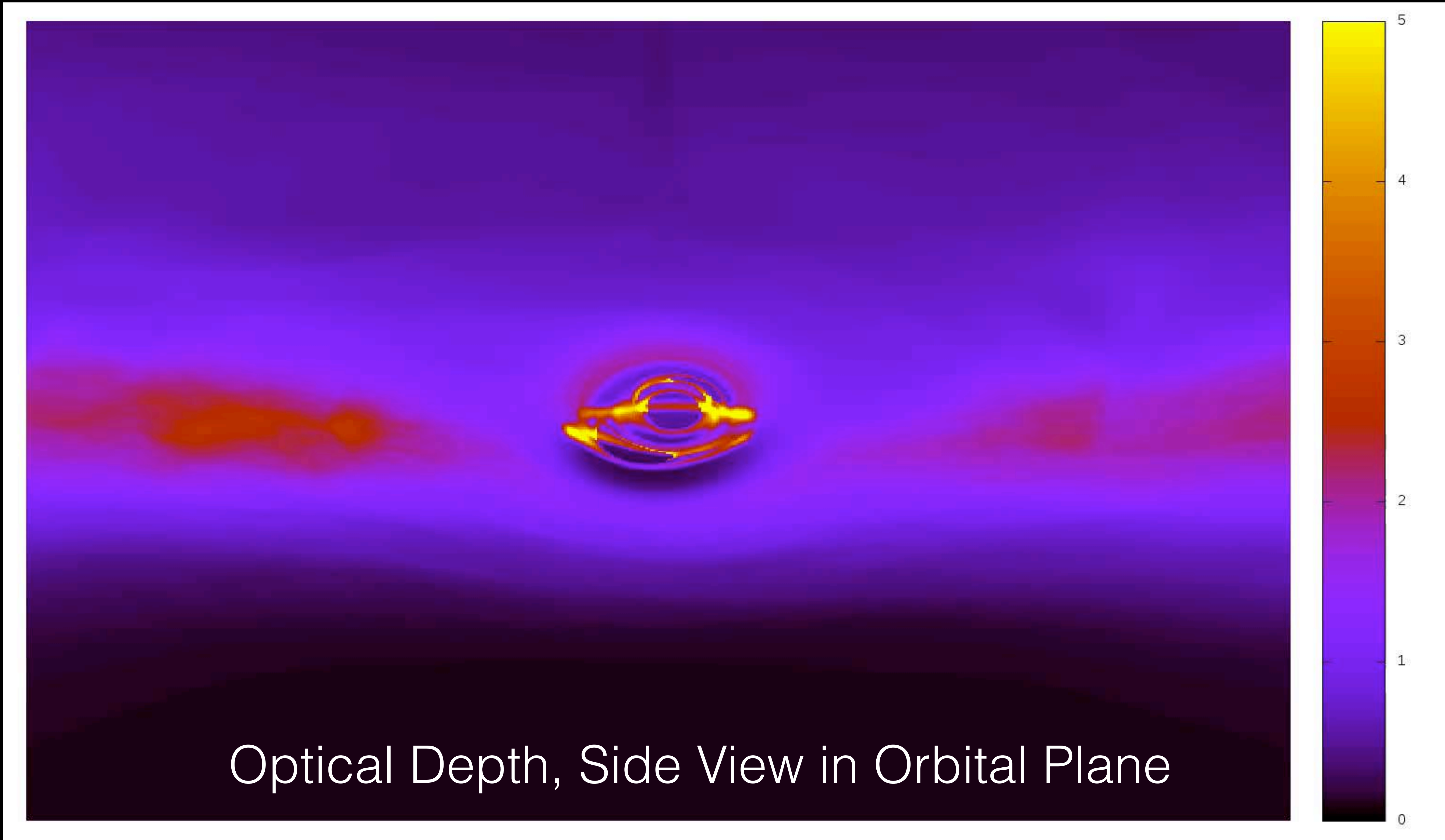
- First of a kind GRMHD **mini-disk** simulations of inspiral SMBBHs;
  - BW is essential for this project;
  - Have reached critical mass of person-power —> great things to come as long as the SUs are there:
    - Dynamic GR radiative transfer;
    - Spinning/precessing/merging binaries;
    - Relaxation of circumbinary disk, long-term signature of merger;
- Developed ***Patchwork*** code for future public use;
- Contributing gravitational waveforms and improved parameter estimation formulae to the LIGO Scientific Community;

Benefits of Blue Waters:

- Necessary SUs and reliability for the job;
- Helpful staff and resources (e.g., queue througput, PAID);
- Expert and enthusiastic visualization staff for creating innovative scientific imagery and animations;
- PAID program provides a rare resource for focusing effort on code improvements;

Teaser trailer for next year:

Time-dependent Post-process GR Radiative Transfer of SMBBH



by Stephane d'Ascoli (RIT)