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

BW IDs: PRAC_gk5, DD_gku

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Image Credit: Mark Vanmoer (NCSA)

Based on:
- Zilhao++2015,
- Noble++in-prep,
- Bowen++in-prep.,
- Cheng++in-prep.,

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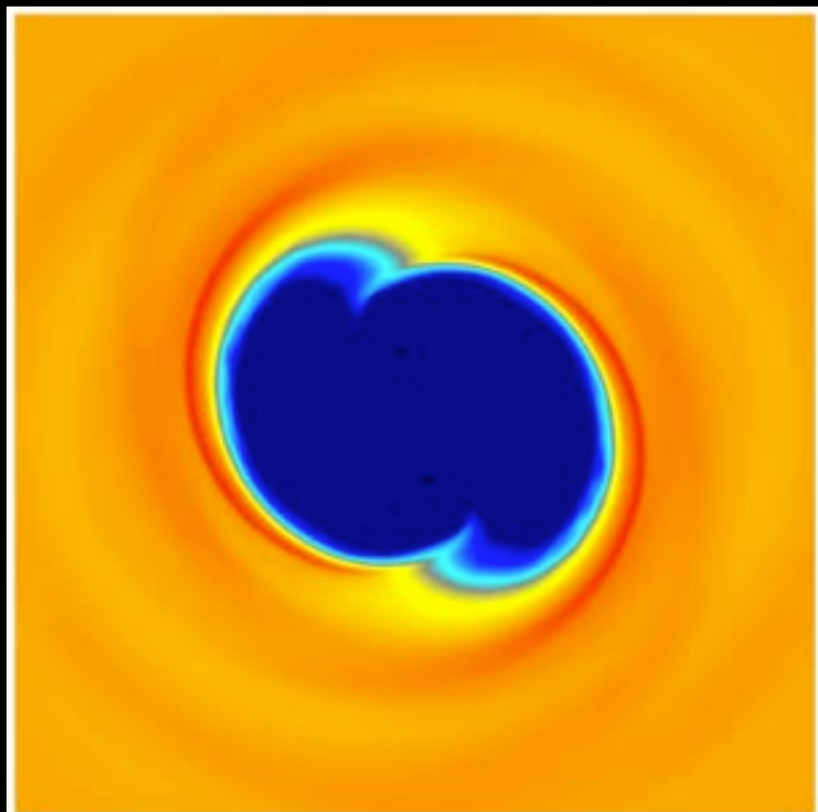
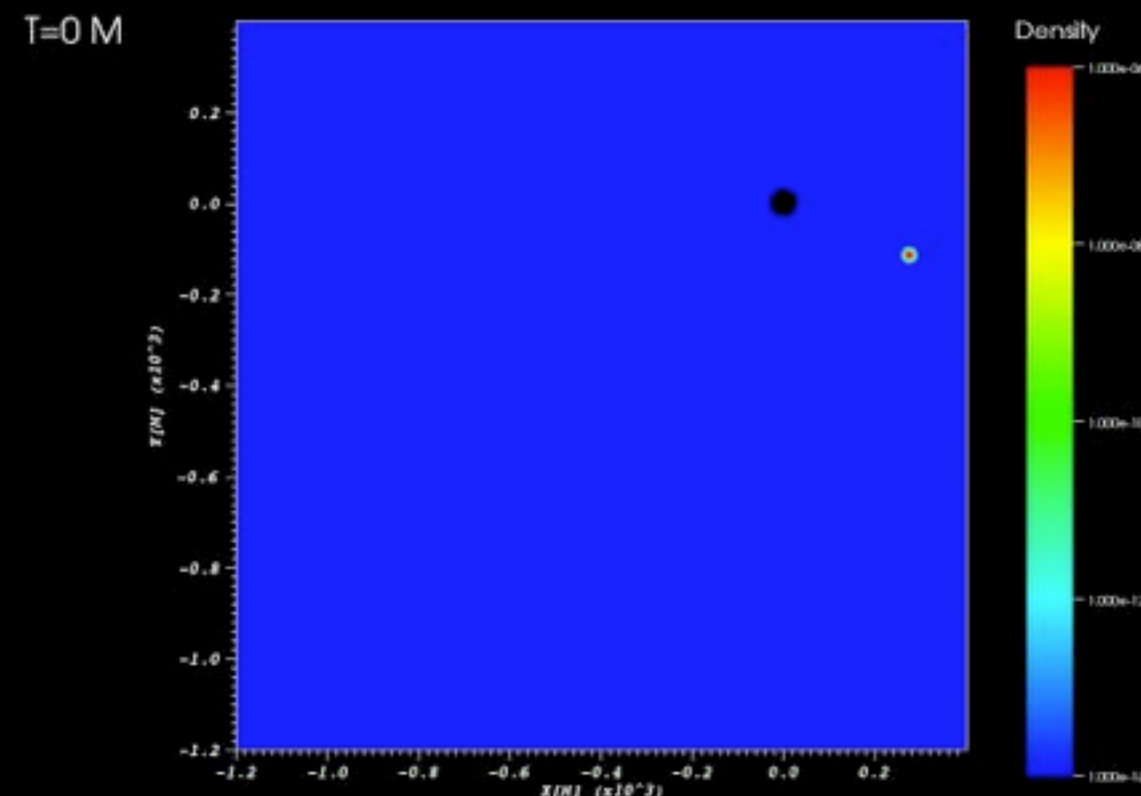
Why It Matters: Mysteries of Supermassive Black Holes

Accreting Supermassive Black Hole Binaries (SMBBHs)



- Principal source of low-frequency GWs.
- Multi-messenger astronomy offers:
  - New measurement of cosmological expansion;
  - Enhanced model constraints;

Tidal Disruption Events

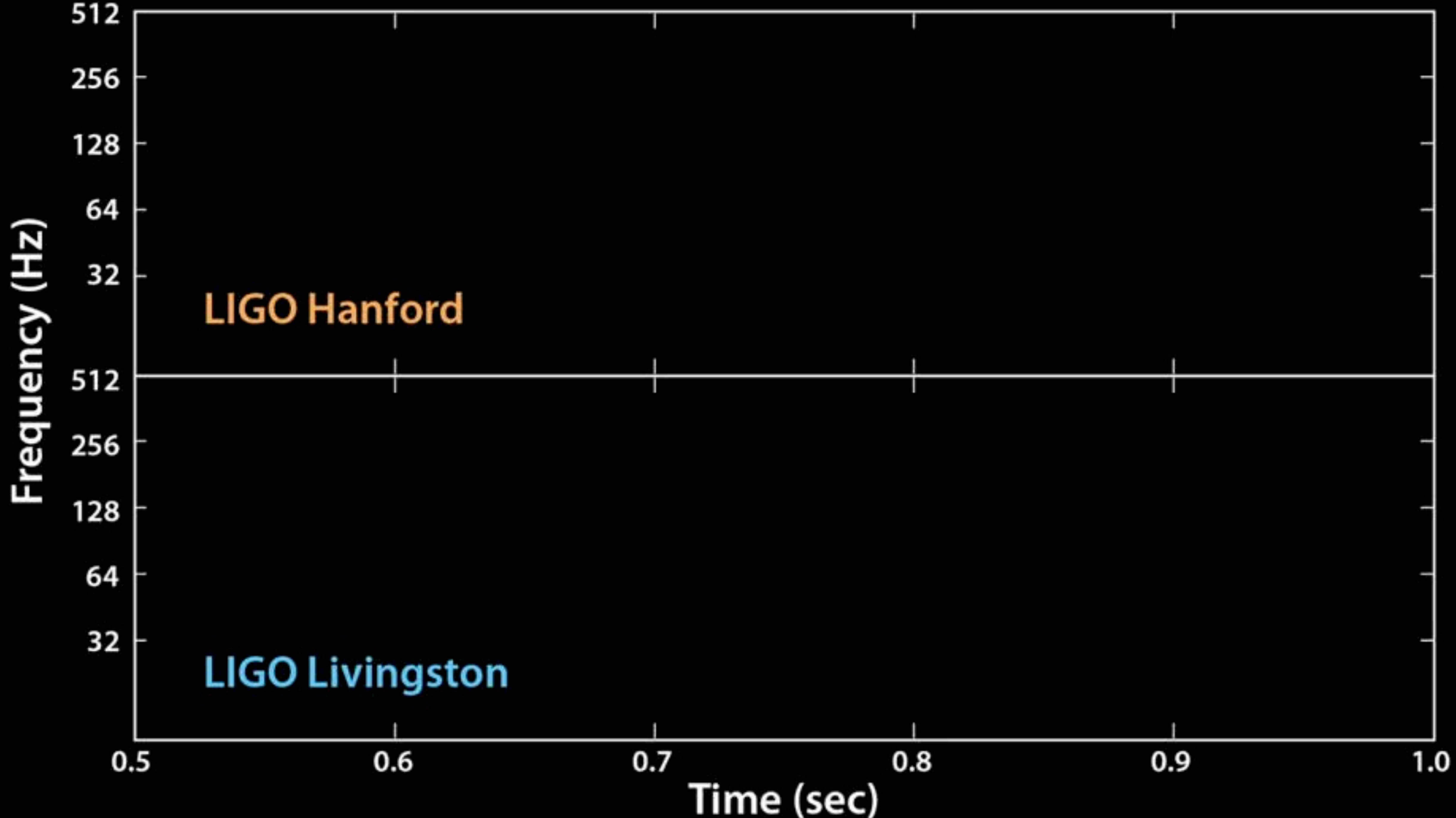


- Rare opportunity to learn how BHs become active.
- Means by which to understand feedback and stellar populations in galactic centers.

- 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)

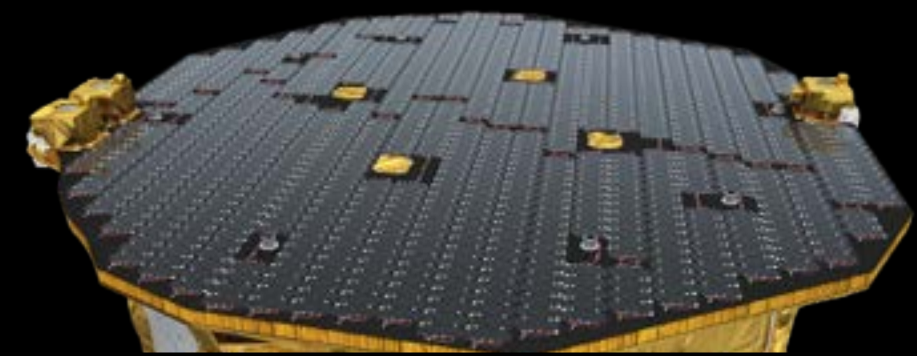
Why It Matters:

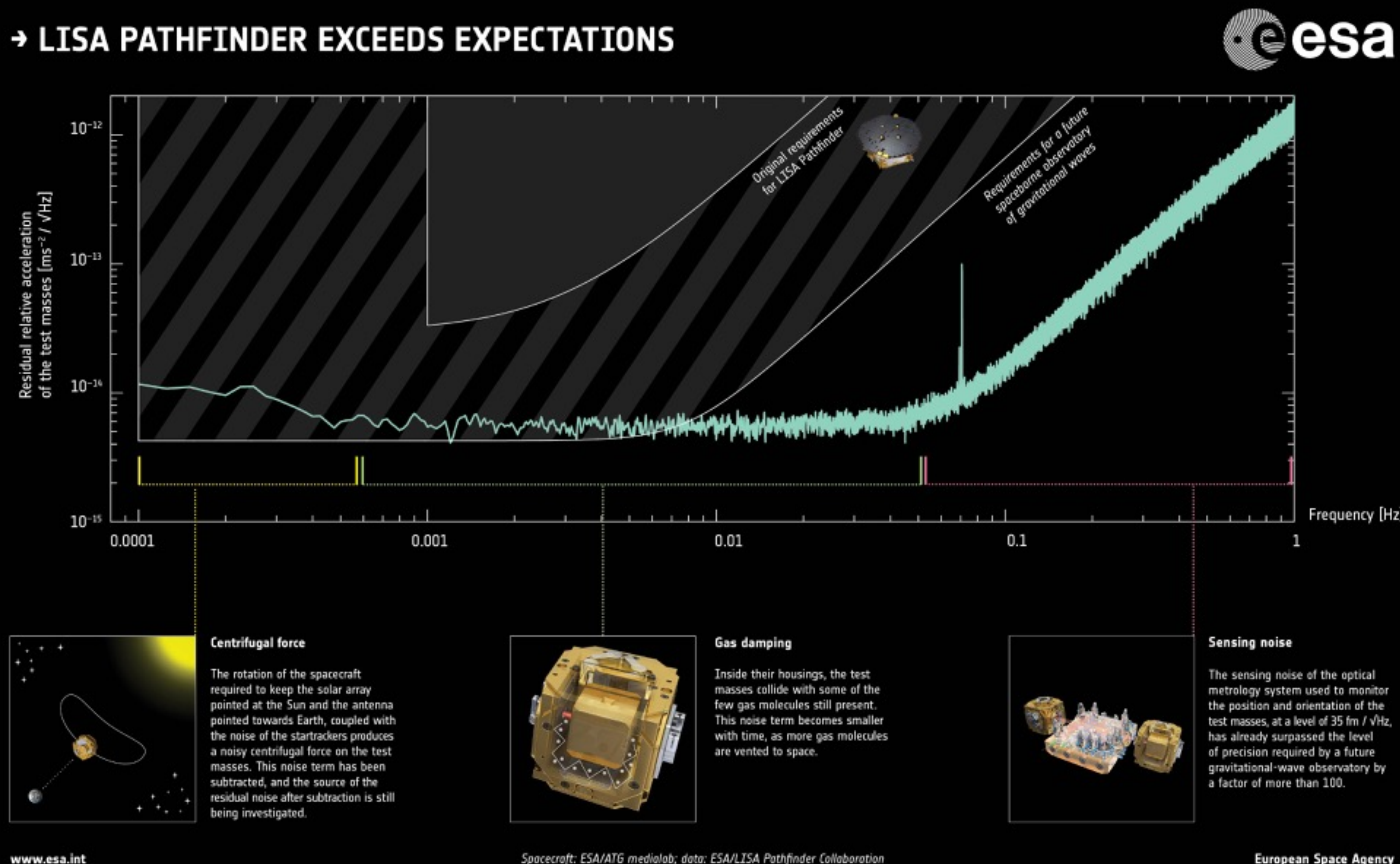
Birth of Gravitational Wave Astronomy
GW150914
Abbott++, PRL 116, 2016 advLIGO



Why It Matters:

Technology for eLISA Works!!

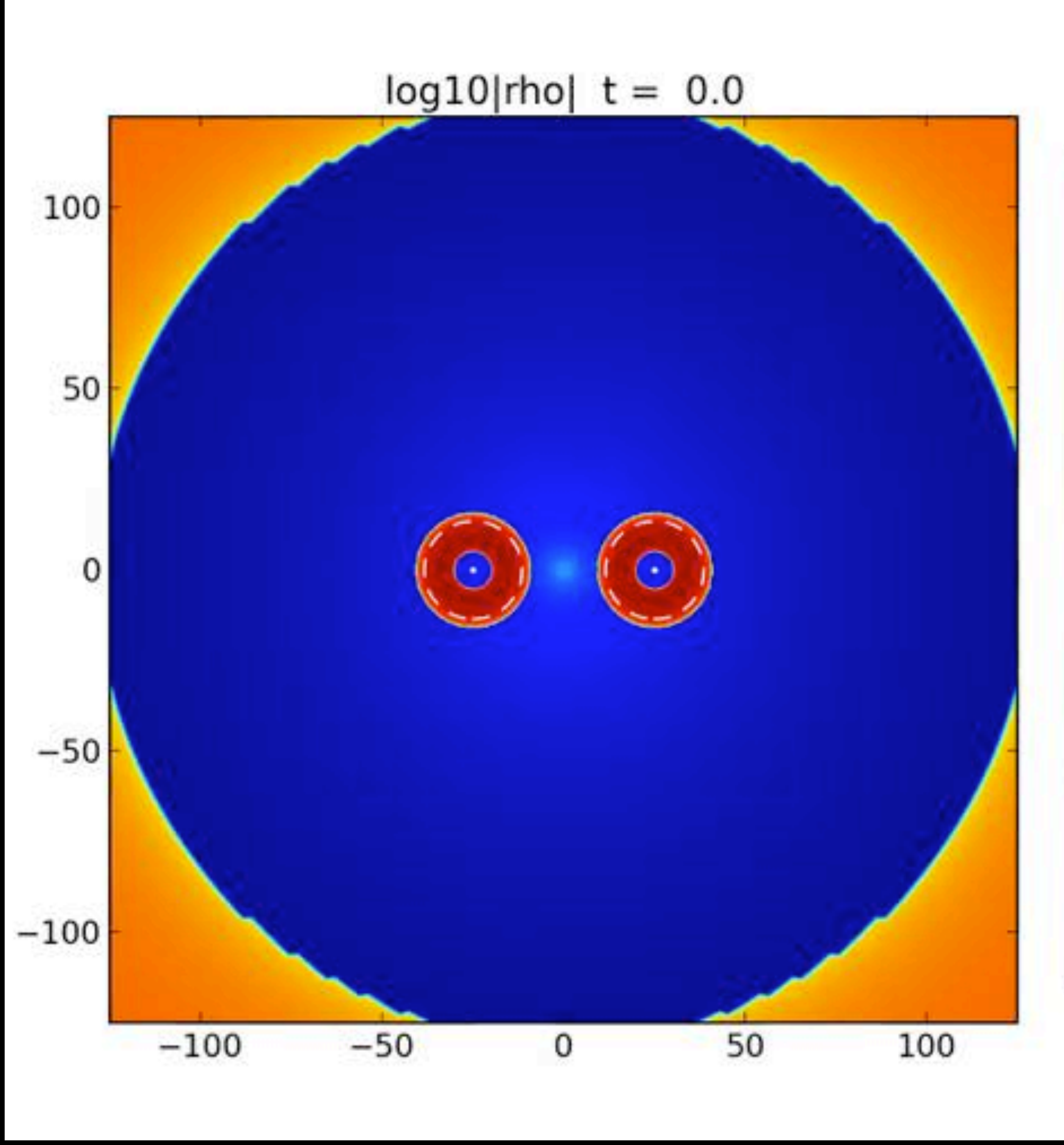




Slide made by ESA

Accomplishments:
Summary of Simulations

1. Circumbinary (SMBBH) disks (MHD)
   - BBH mass ratio survey
   - Disk size, B-field survey
   - BBH separation survey
   - Runs with BHs on the grid
   - High-resolution tests
2. Minidisk (SMBBH) runs (Hydro, BHs on grid)
   - Spacetime survey
   - BH separation survey
3. Tidal Disruption Events (hydro.)
   - First tests of the new multi-patch infrastructure

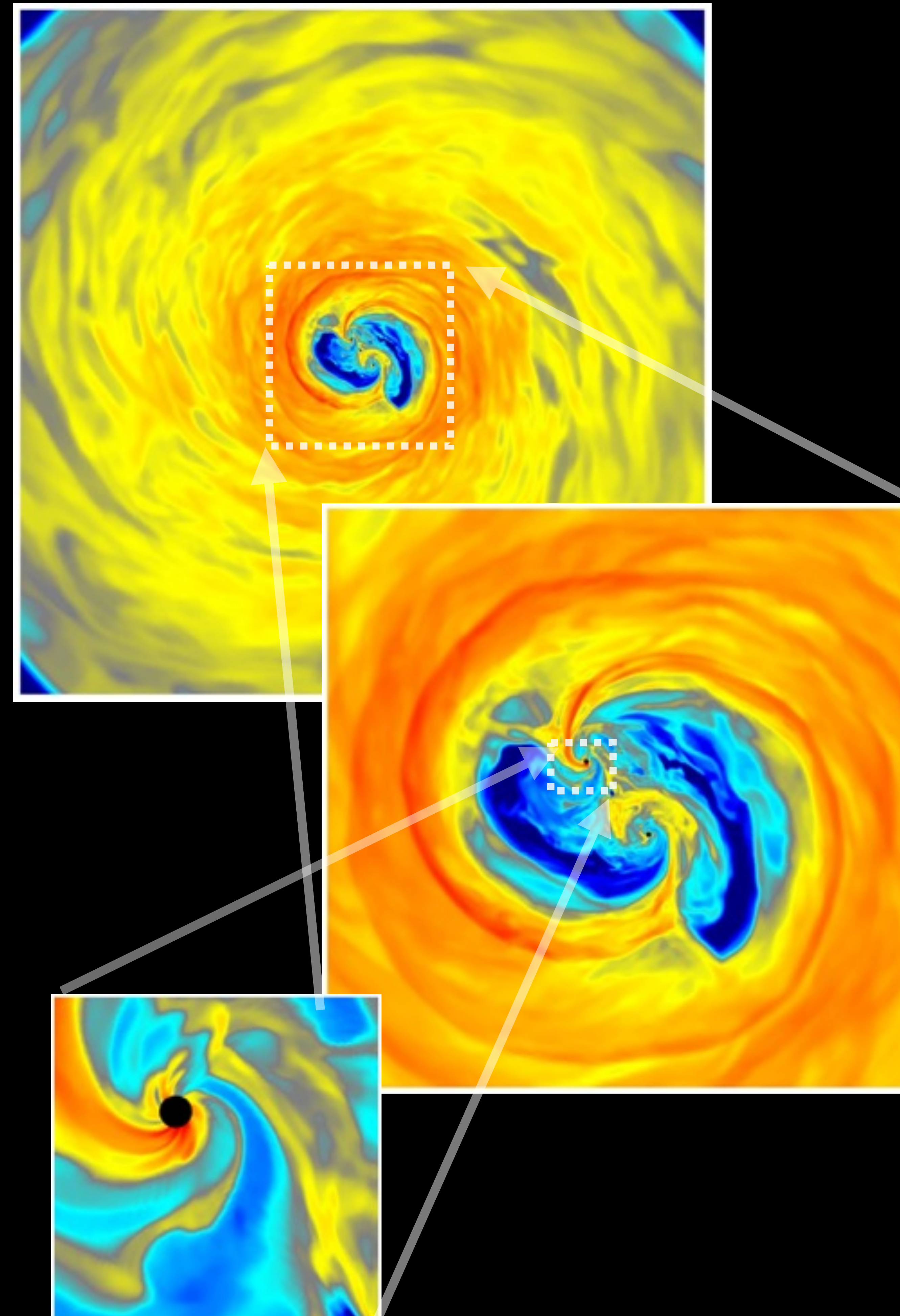


Minidisk Run:
Start with disks close to each black hole so we do not have to wait for them to fill in.

Color code: Paper in Progress
Runs in Progress

Key Challenges:

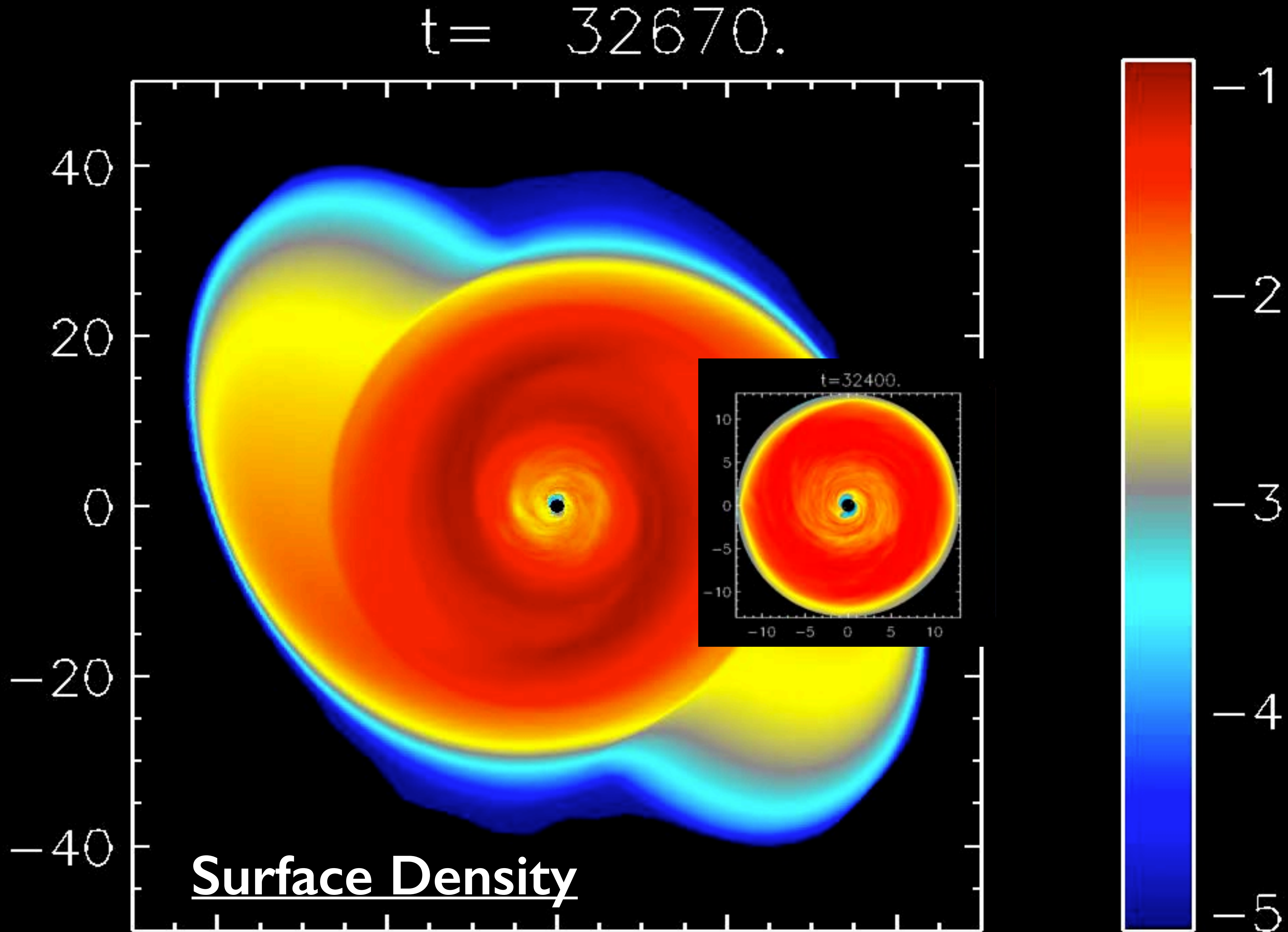
- A vast range in time scales to resolve, O(10^7) time steps:
  - Long time scales:
    - Disk equilibration time scale, O(10) orbits;
    - BBH orbital time and inspiral rate;
    - TDE debris fallback time and equilibration time;
  - Short time scales:
    - Dynamical times in small cells near the BHs;
    - Dynamical time scales near periapse passage (TDE);
- A vast range in spatial scales, O(10^7-10^8) cells:
  - Small length scales:
    - Each BH needs to be covered by at least 32 cells per dimension;
    - Tidal stream focus to thin region near periapse (TDE);
  - Large length scales:
    - Disk size >> BBH separation >> BH sizes (SMBBH);
    - Debris disk size >> 1000s BH sizes (TDE);
- Adequate treatment of the star's self-gravity is difficult in a single reference frame (TDE).



Why Blue Waters:

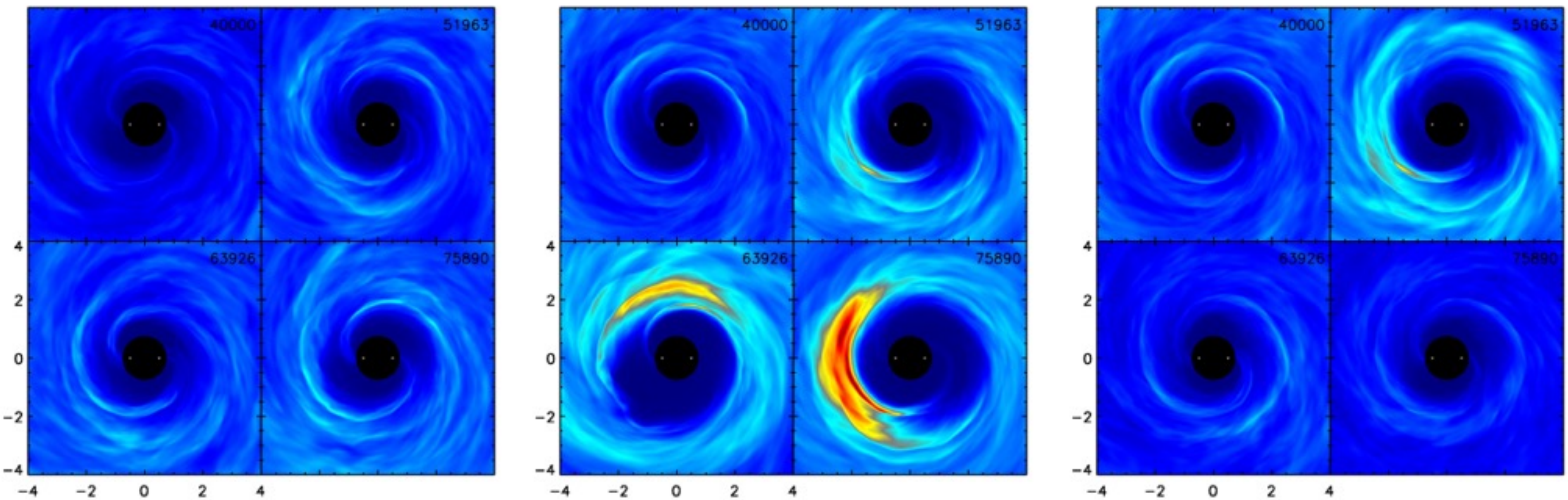
- Large core-count limit;
- Generous allocations;
- Staff to help push our codes to scale;

Circumbinary SMBBH MHD disks

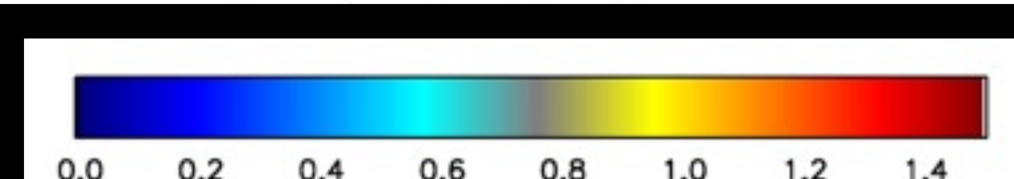


Circumbinary SMBBH MHD disks

Bigger Disk | Original | Magnetic Flux Injected



Top-down view of Surface Density



Accomplishments:

<u>More magnetic flux led to:</u>

- Less pile-up at the inner edge of the gap and smaller m=1 mode (lump);
- Therefore, less material for binary to "beat" against;
- Fluctuations arise primarily from turbulence;

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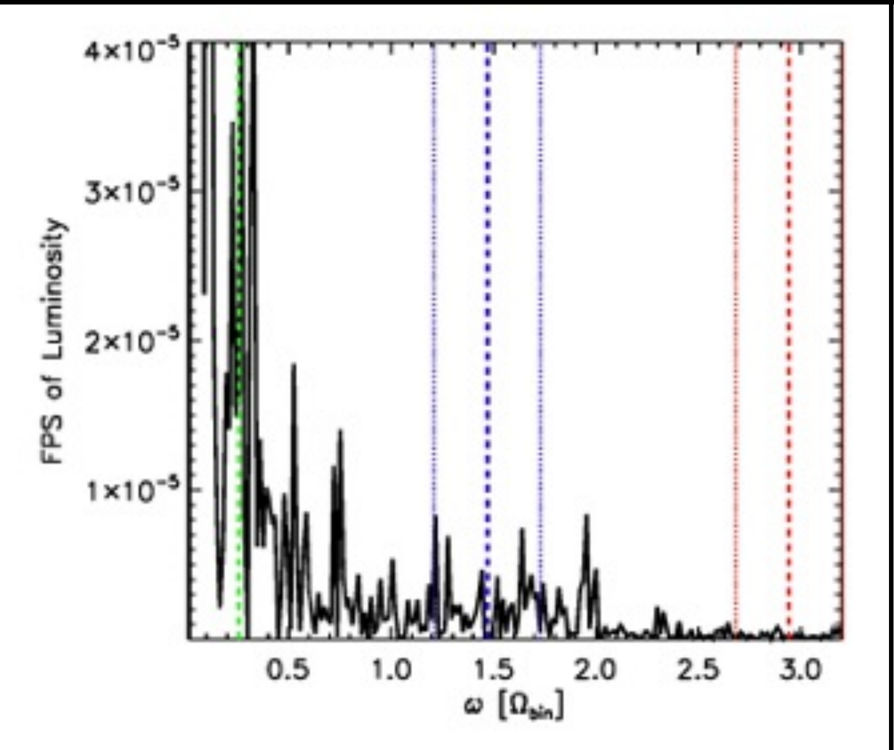
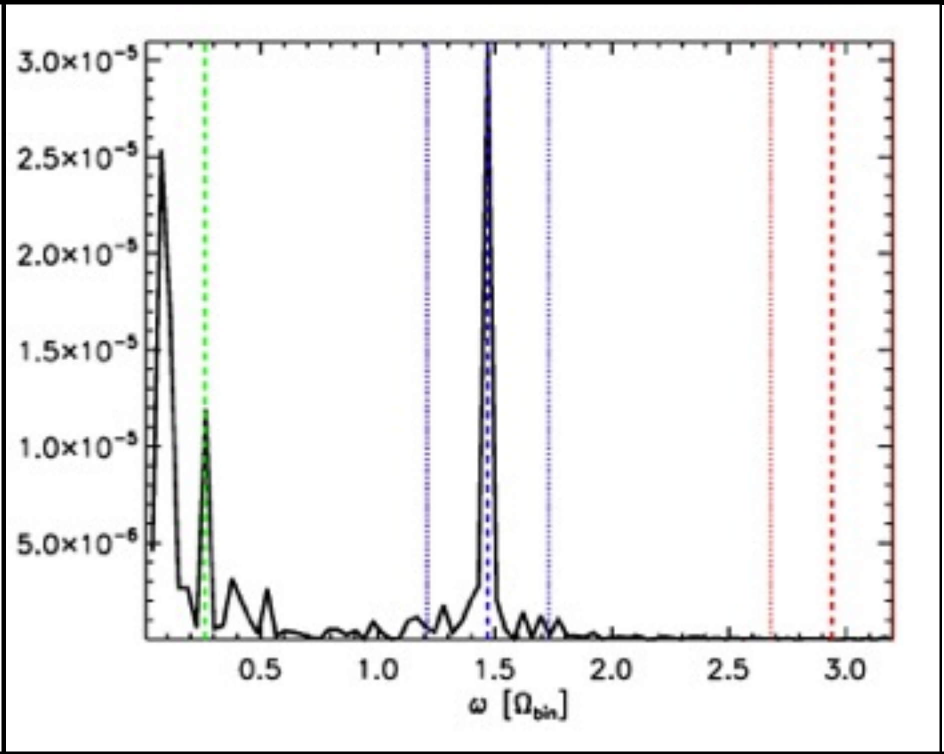
Circumbinary SMBBH MHD disks

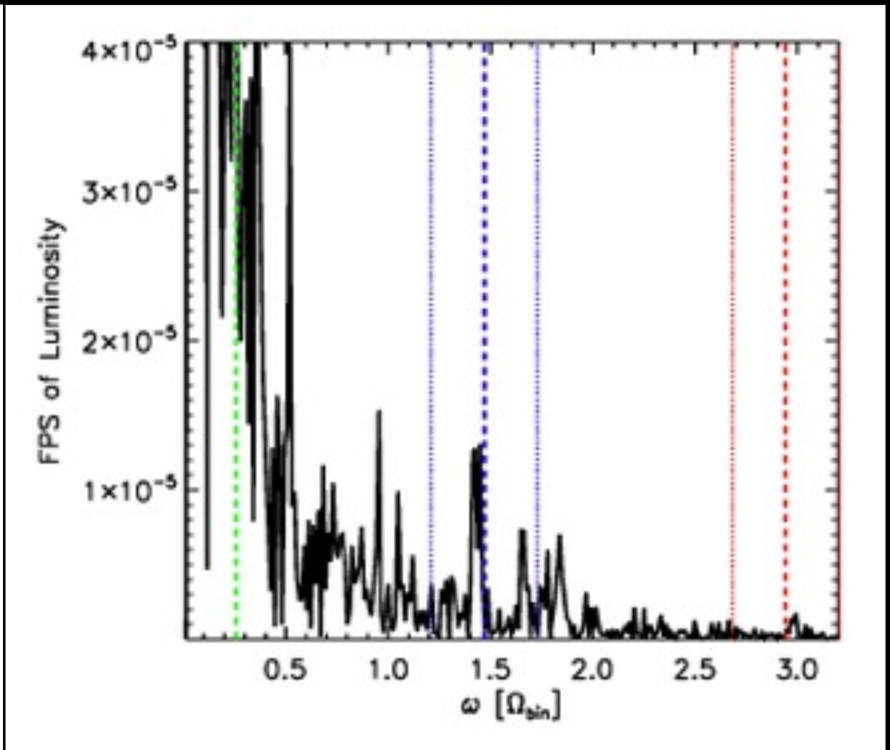
Bigger Disk



Original



Magnetic Flux-Injected



Temporal Power Spectrum

Please note different scales

Accomplishments:

More magnetic flux led to:

- Less coherent temporal power spectrum—-no more EM signal;
- Spectra resembling more a slightly bent power law, like that seen from simulations of single black hole disks;

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Hydrodynamic SMBBH Minidisks

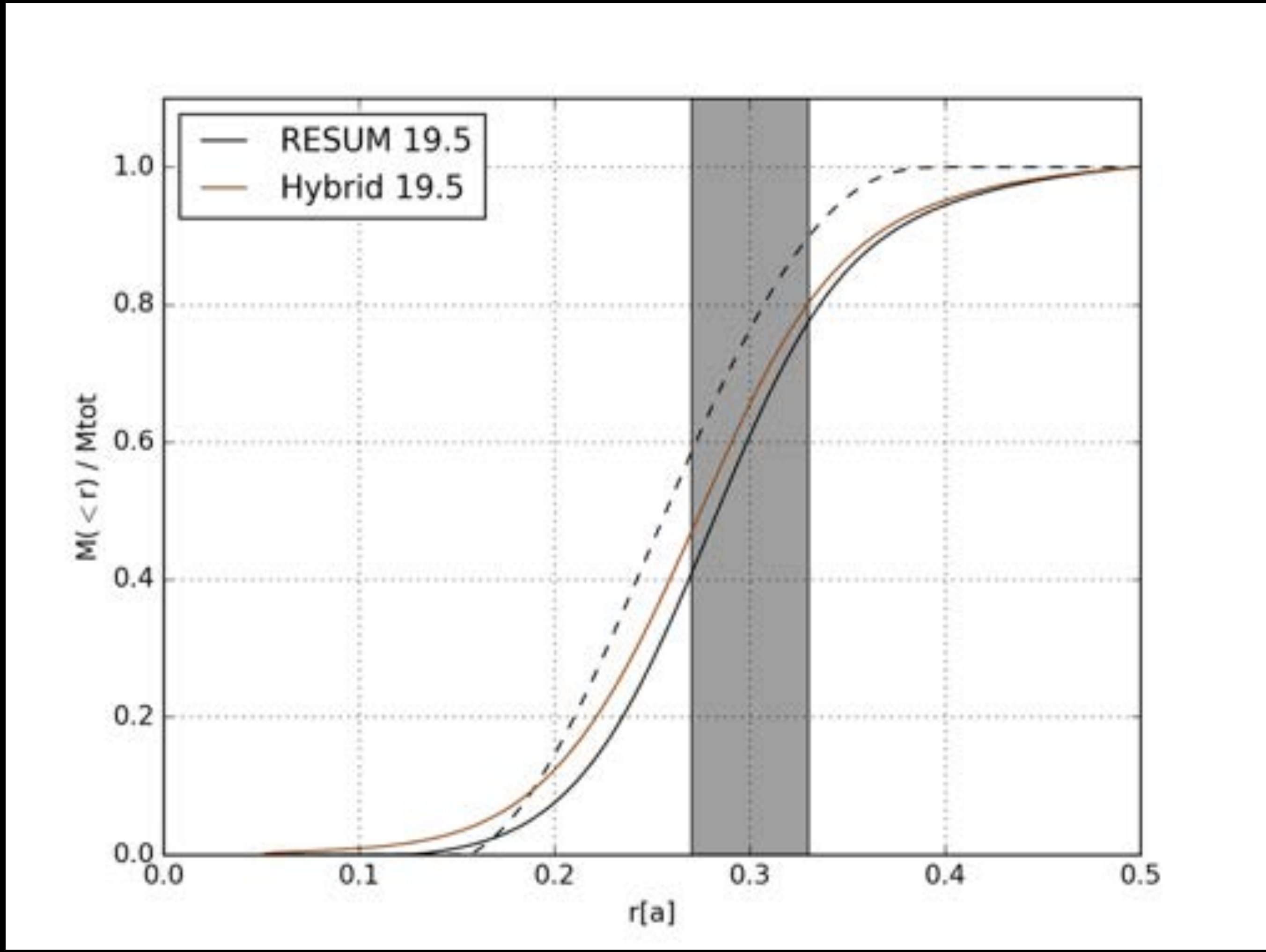
Key Challenges:

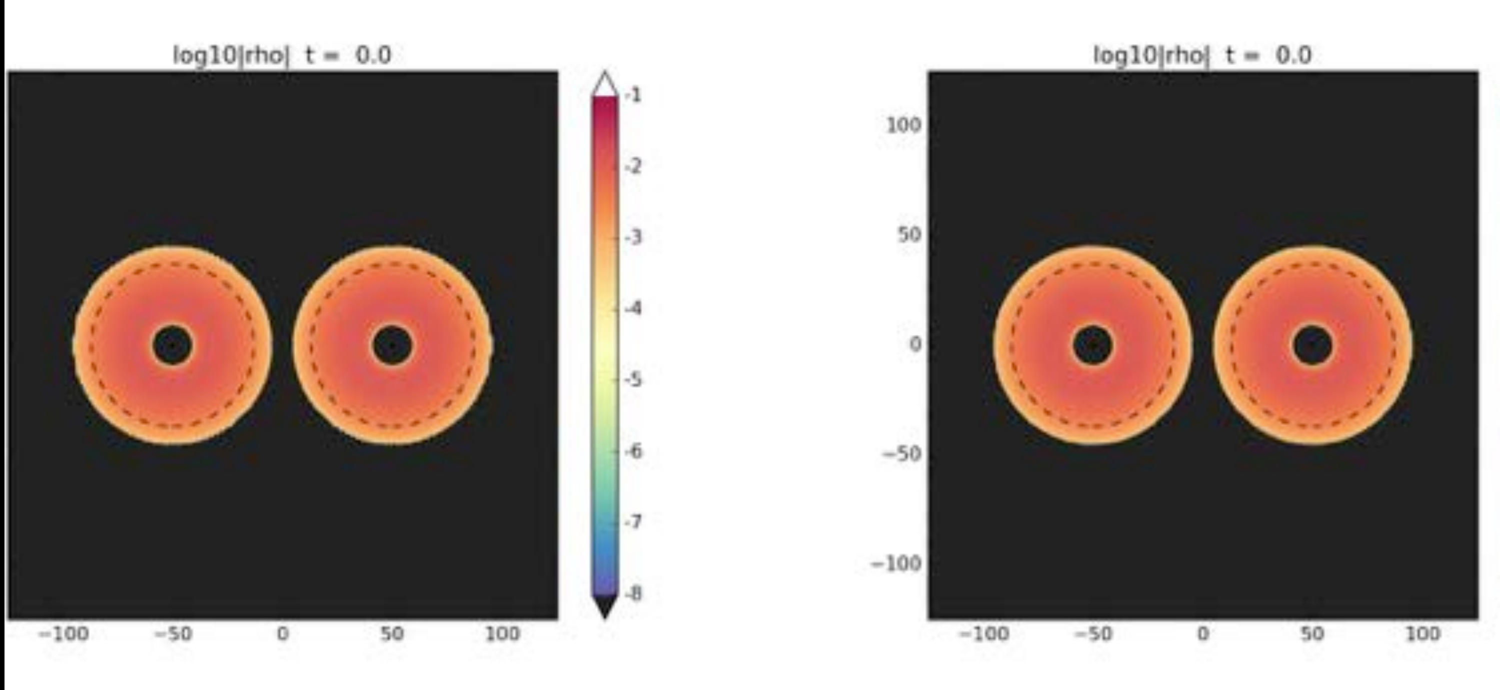
- Measure the radius at which minidisks are truncated by gravitational tidal force from companion BH, for the first time in the relativistic limit.
- Develop near-equilibrium initial data to reach steady-state quicker.

Accomplishments:

- Demonstrated stability of new minidisk initial data prescription.
- Demonstrated that Newtonian prediction

  (r_{trunc} ~= 3 a, Paczynski 1977) becomes inaccurate for BBH separations smaller than 16M or 16 BH radii, for equal-mass binaries.
- Validating new "resummed" Post-Newtonian metric that will considerably speedup calculation (x2).
- Validating system with 3-d MHD now.



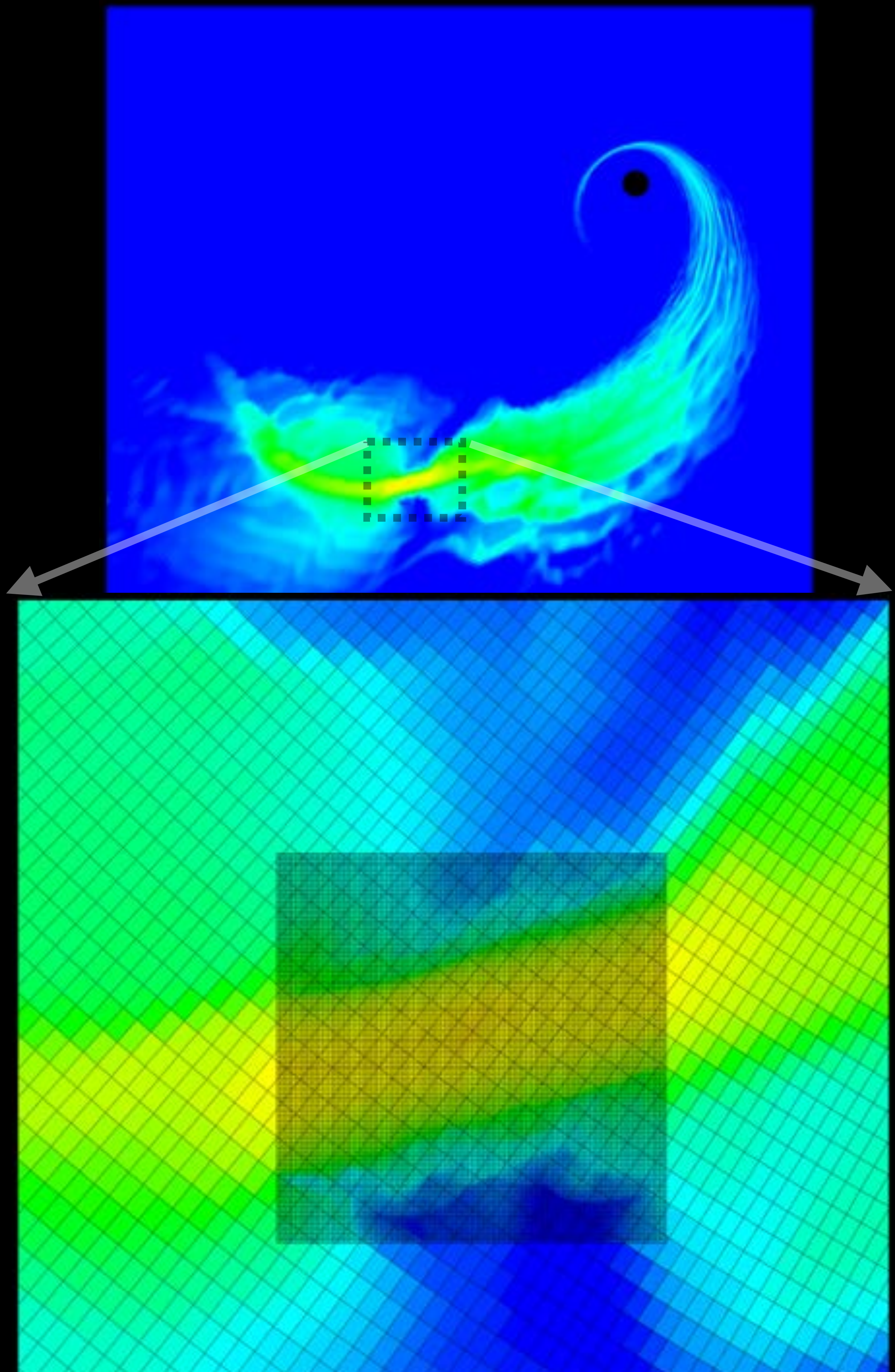


Old Hybrid **New Resum.**

Tidal Disruption Event Simulations

Key Challenges:

- Simulate TDE from capture, disruption and formation of debris disk, with the ultimate goal to perform first MHD simulations of its kind.
- Perform first production run demonstrating new multi-patch infrastructure, using multi-process/multi-data computing model.



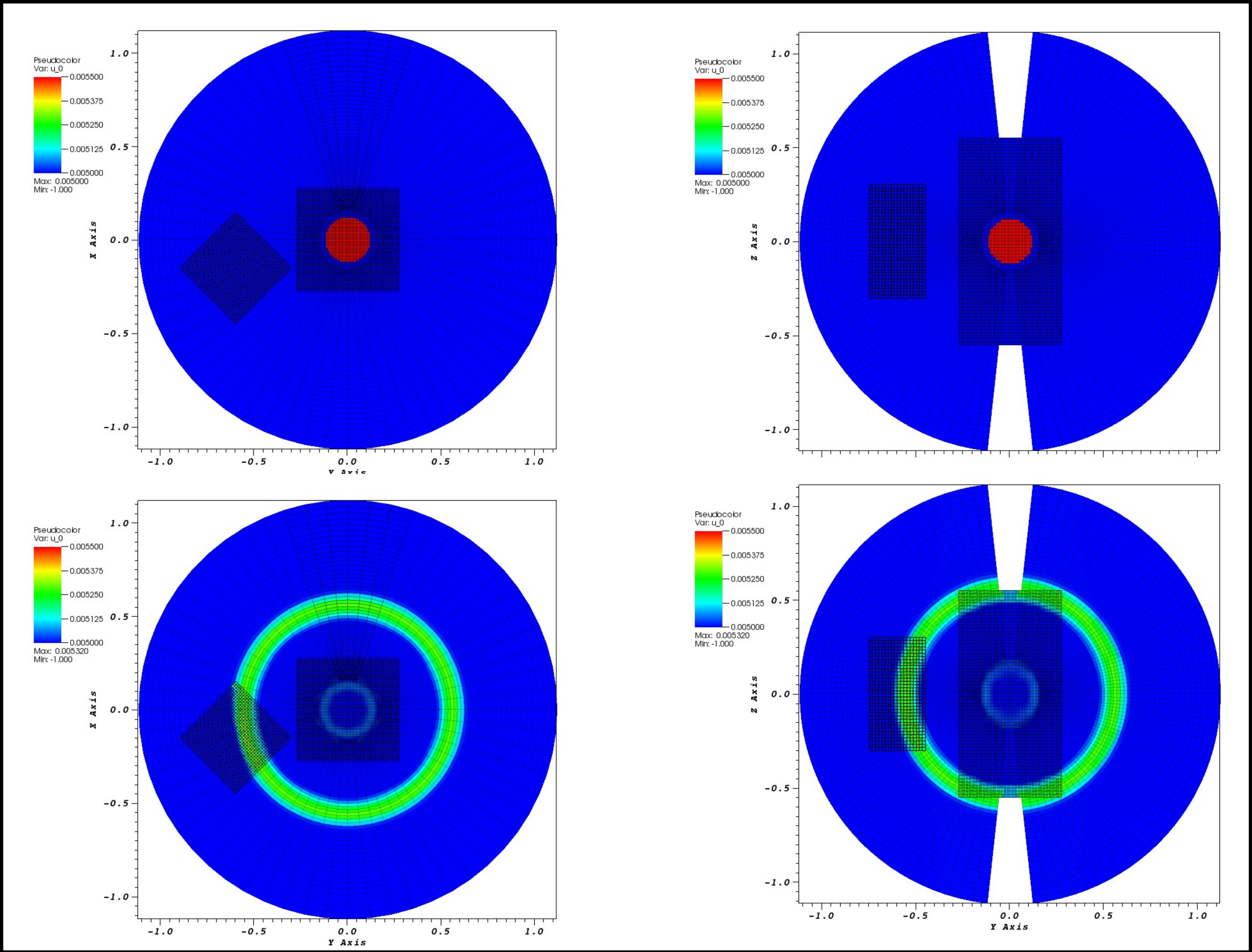
Accomplishments:

- Validated multi-patch method using patches with different:
  - Coordinate systems;
  - Resolutions;
  - Local gravity models (or spacetime metrics);
  - Time step sizes;

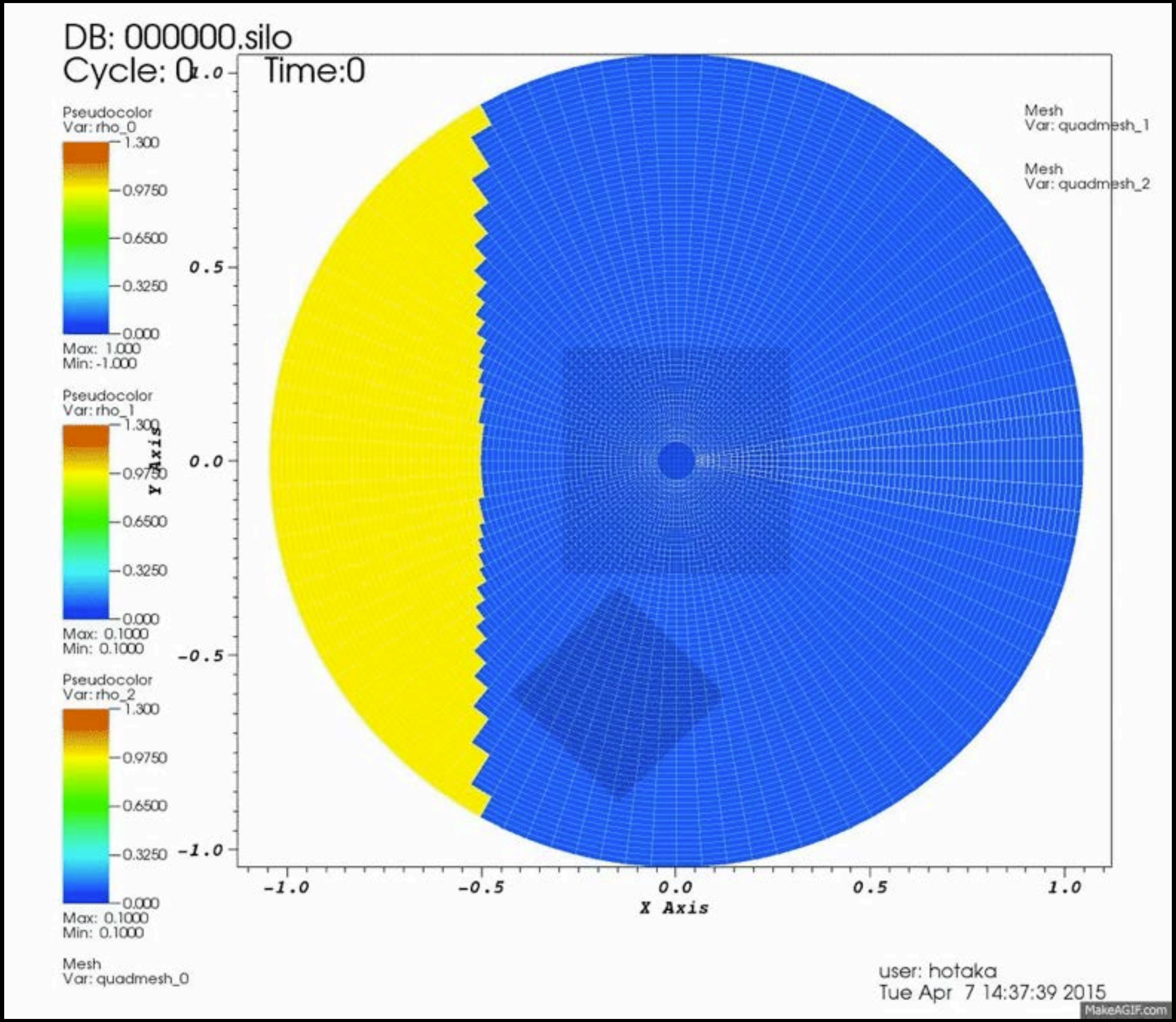
Products:

- Intend to publicly release multi-patch infrastructure code eventually, for use with other MHD codes.
- Will soon substitute our warped coordinates for multi-patch in SMBBH simulations.

Multi-Patch Example: Spherical Explosion



Multi-Patch Example: Planar Shocks Traversing Origin



Blue Waters team contributions:

PAID Project: Load Balancing with HARM3d

Team Leads: Sanjay Kale, S. Noble
Team: Nikhil Jain (UIUC), Xiang Ni (UIUC), Spencer James (Tulsa)
BW ID: DD_gku

Key Challenges:

- Nonuniform FLOP-count over domain due to harder spacetime metric evaluation near BHs (SMBBHs).
- Multi-patch evolutions with heterogenous physics and time step sizes will require an intelligent agent to dynamically balance load.
- Integrate topology awareness.

Strategies to Explore:

UIUC shared examples of three possible approaches:

Load Balancing Library:

Pros: Requires fewest changes to HARM3d;

Cons: Still in progress, not as extensible to future code developments, may not be as efficient;

AMPI:

Pros: Requires moderate number of changes to HARM3d;

Cons: Not as extensible/efficient as Charm++;

Charm++:

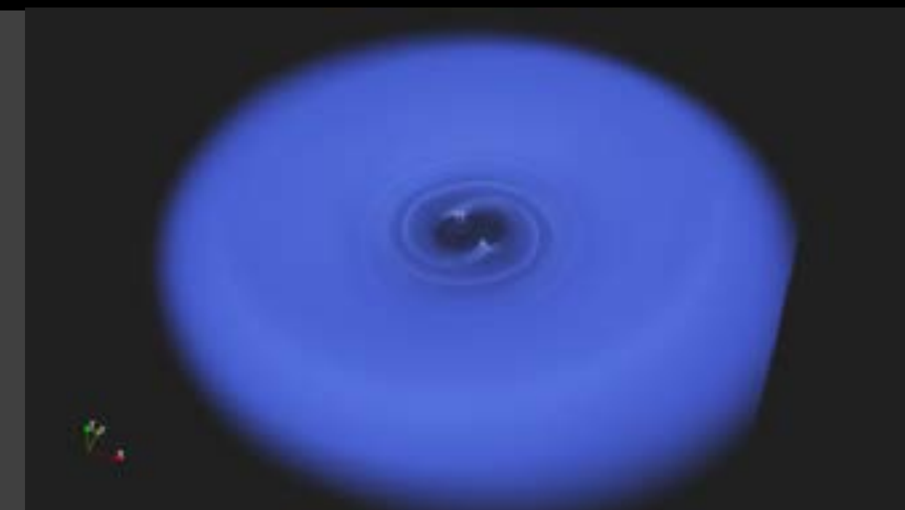
Pros: Most general approach, offers task-level distribution of effort;

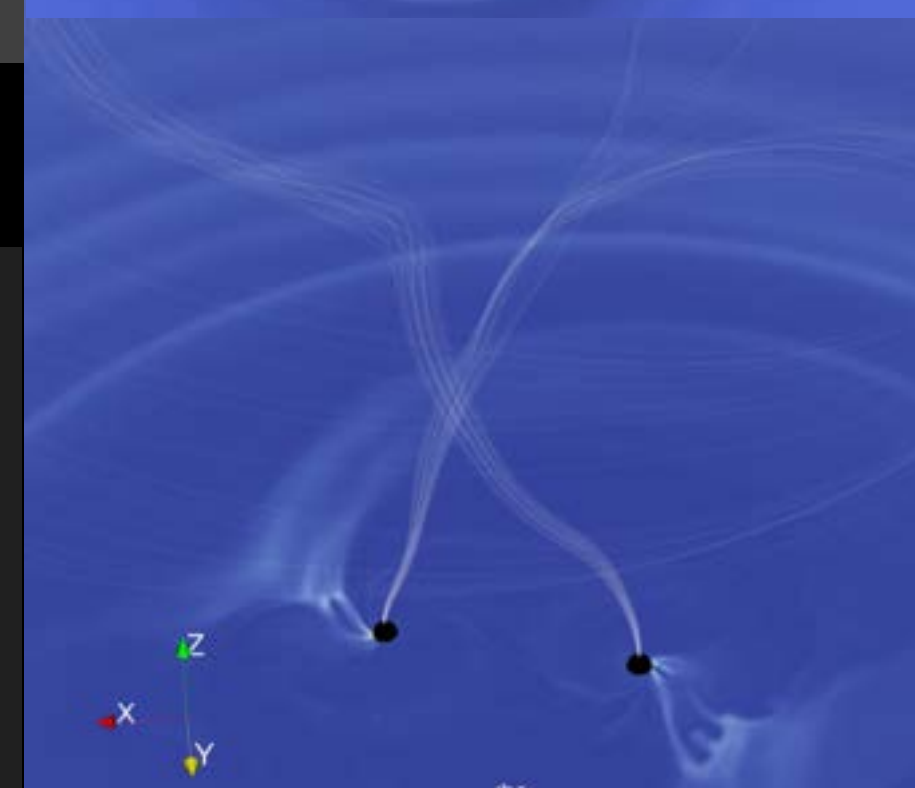
Pros: Nearly automatically extensible to future features of HARM3d, GPUs;

Cons: Will likely require most person-hours of effort, though still unclear exactly home much;

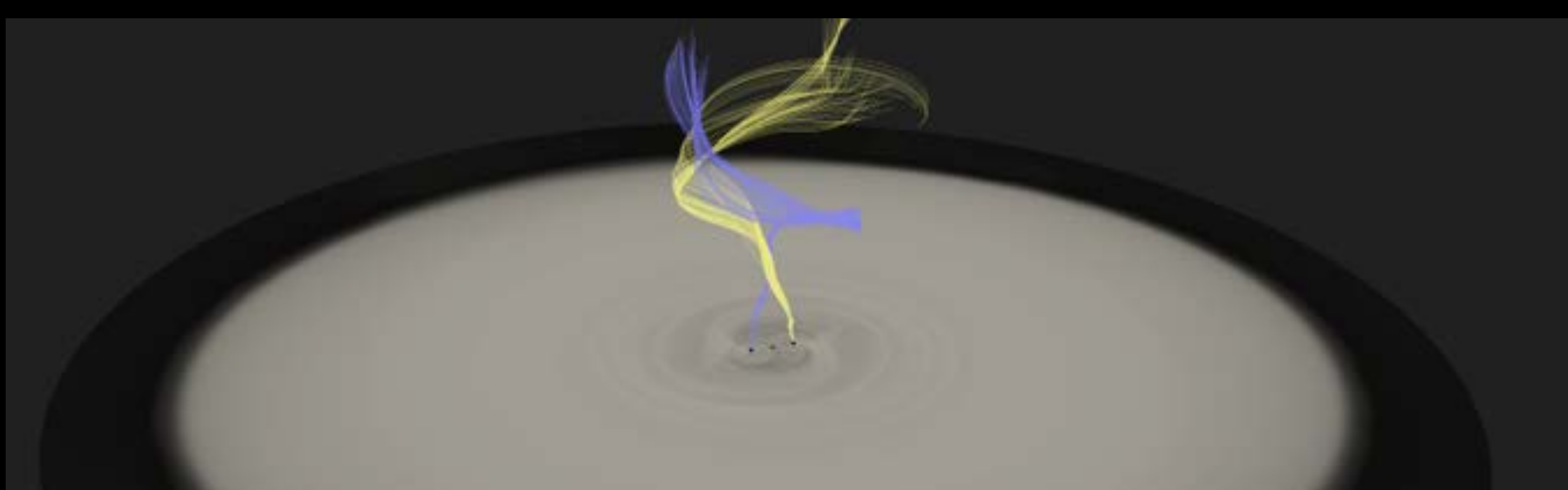
Why Blue Waters?
Blue Waters Team Contributions:
Visualizing Accreting SMBBHs

- With Mark Vanmoer and Roberto Sisneros (NCSA);
- Goal: Find optimal procedure for rendering magnetic field lines and density distributions in a time series;
- Magnetized jets from the black holes, are visualized by seeding lines at the black holes' surfaces.
- We find best results with ray-cast volume rendering of density.
- Now, we are exploring how to efficiently ray-cast with decomposed simulation data and parallelized Visit processes.





All Images by M. Vanmoer



Summary & Conclusions

- We are uncovering the conditions necessary for EM signals arising from the circumbinary disk.
- We have shown for the first time that EM signals may be tied to the level of magnetic stress in circumbinary disks.
- Demonstrated the relativistic limit of the tidal truncation radius for the first time.
- Developed and validated key, new technologies:
  - Multi-patch Infrastructure;
  - Minidisk initial data;
- Our next series of runs will include first-of-a-kind MHD TDE simulations and resolved MHD SMBBH disks with minidisks.
- PAID: Will soon be engaged aggressively to significantly improve HARM3d performance at scale.
- With Mark Vanmoer and the NCSA/BW vis team, we hope to discover new aspects of our simulations through improved visualizations.