New Techniques in NR & BNS Simulations

a discussion

Yosef Zlochower
Zachariah Etienne

New Techniques in Numerical Relativity

Why we need new techniques in numerical relativity

- Current codes don't cover all the physics we need for BNS
  - GR solver
  - Neutrino physics, advanced EOSs, nuclear physics
  - GRMHD
  - EM radiation transport

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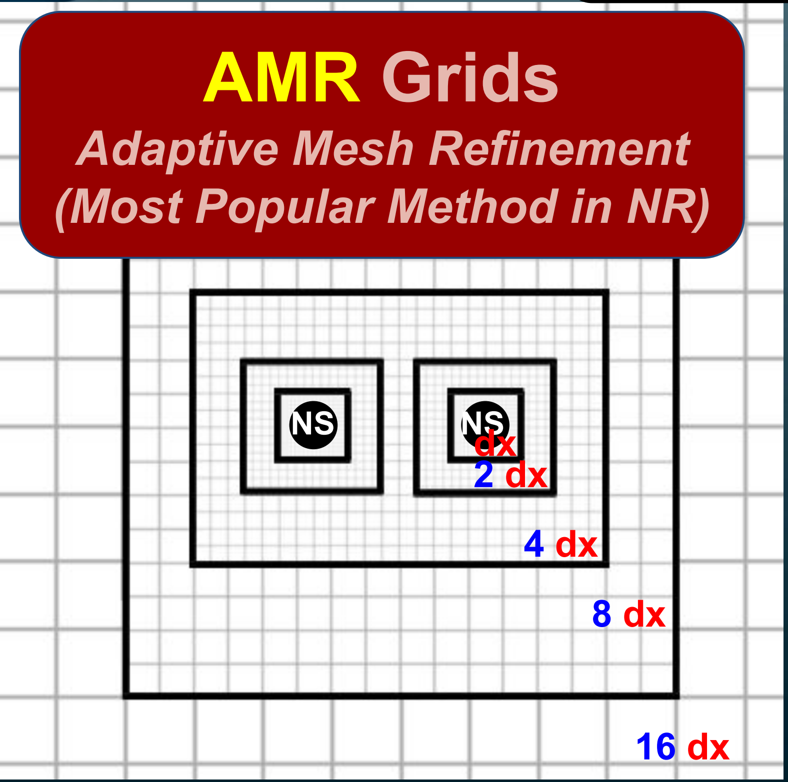
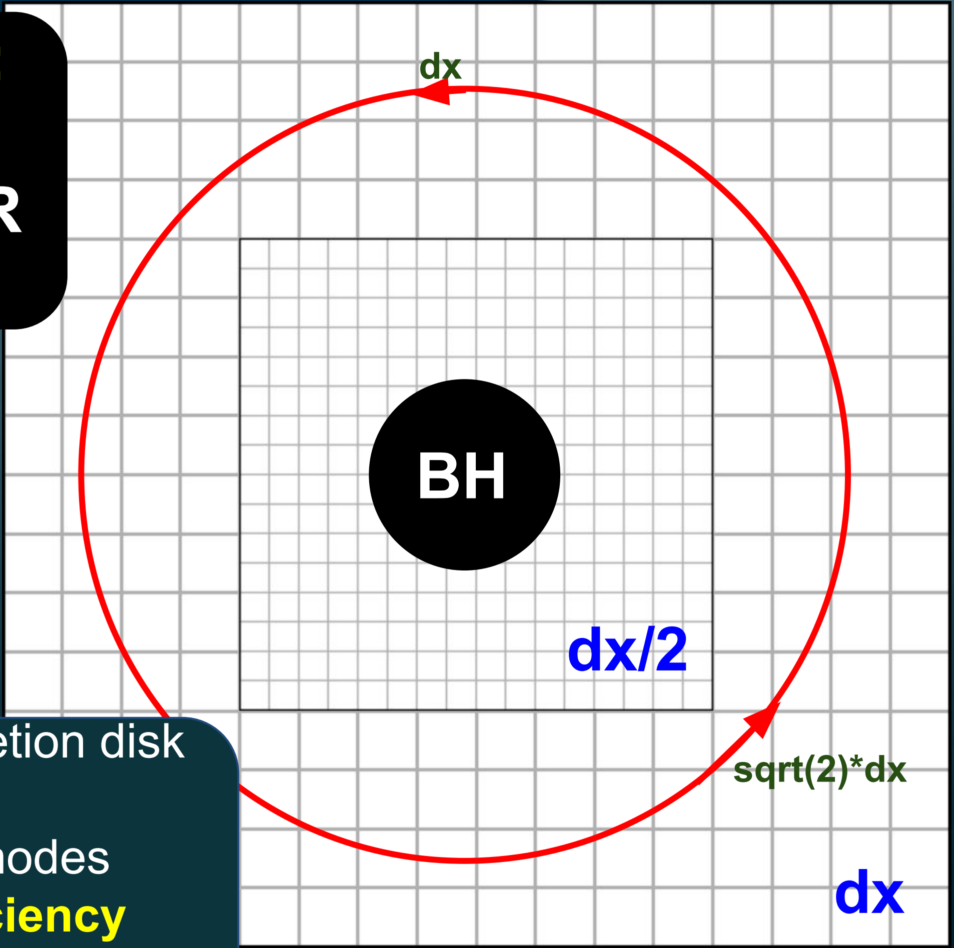
  - *All else being the same*, cost ~ # of gridpoints

Most NR codes use Cartesian AMR Grids



Most important MMA system: BH accretion disk in full 3D
Comparison of Cartesian AMR vs spherical grids



Red circle: path of fluid element in BH accretion disk
- Resolution changes by 1.4x over path
- Induces artificial high-order multipole modes

Azimuthal res. *also* ~1.4x lower: **~2x inefficiency (compared to spherical grids)**

~2x jumps in dr vs smooth dr: **~2x inefficiency**

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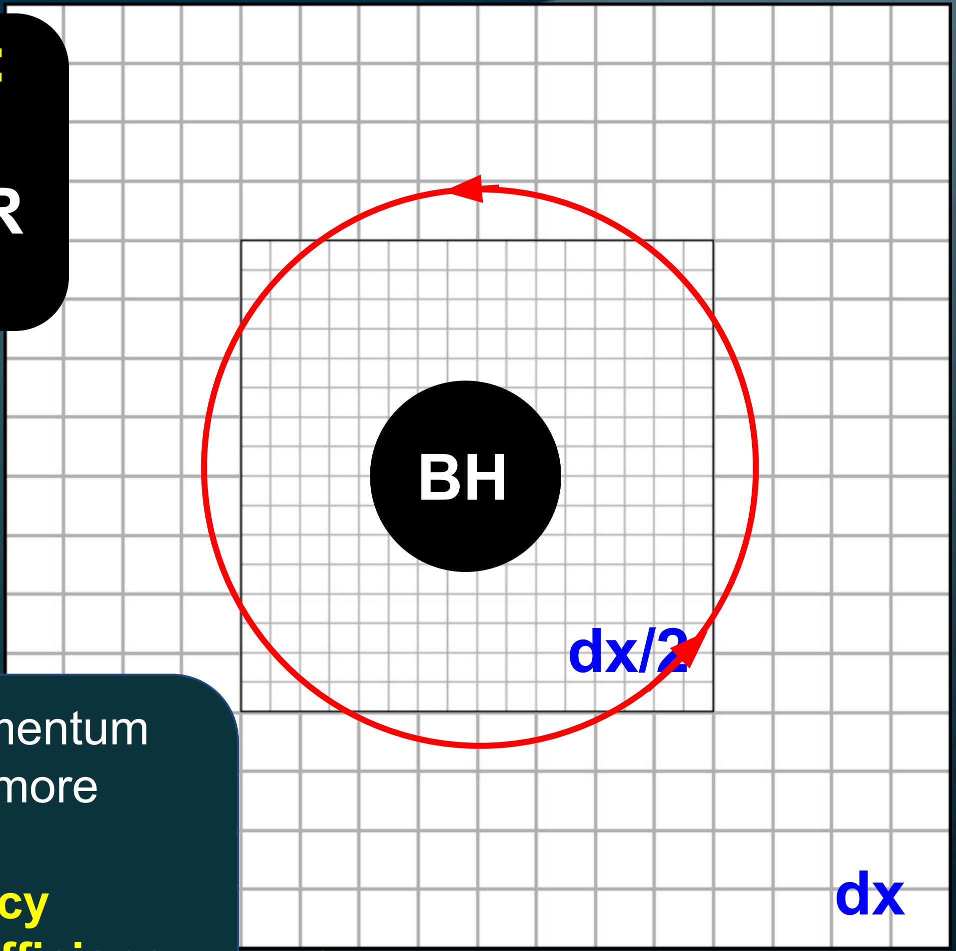

Situation becomes far worse if angular momentum transport causes fluid element to orbit more closely!

Sharp AMR corners *wasted*: **~2x inefficiency**

Coarse grid underneath fine grid: **~1.2x inefficiency**

Fine grids' wide AMR boundary: **~1.5x inefficiency**

Summary:
Cart AMR ~15x inefficient

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  - Cartesian AMR: ~15x more gridpoints than needed
    - Next-gen AMR: maybe ~1.5x improvement
    - *"Thinking outside the box"* is probably optimal

New Techniques in Numerical Relativity: Next-Generation NR Codes

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(Higher effective resolution)
DG, WENO, high-order FD

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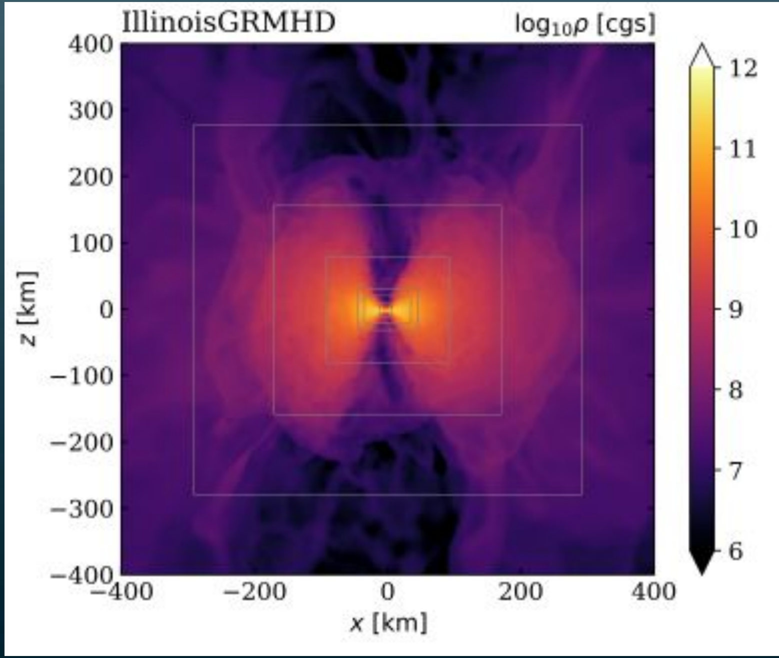
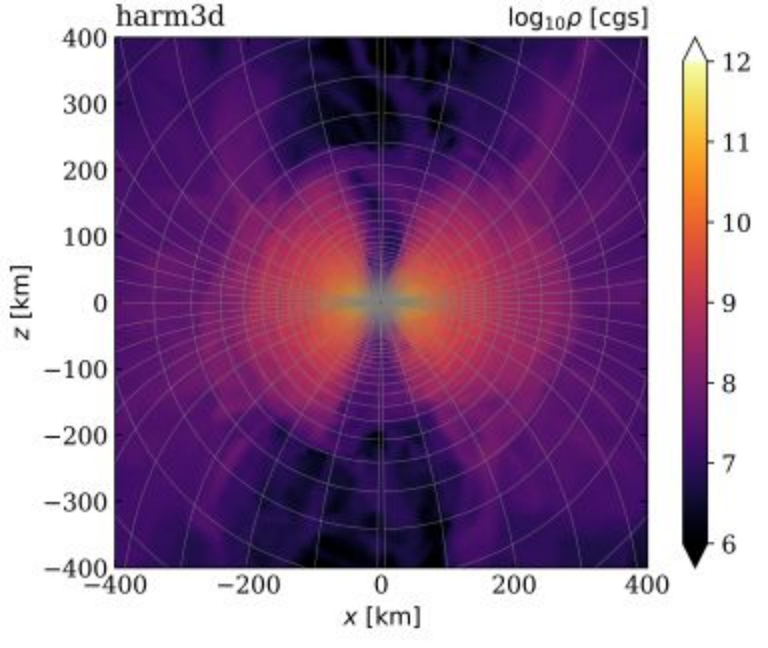
Improved post-merger BNS simulations:
Inspiral+merger using Cartesian AMR GRMHD
Very long post-merger using spherical GRMHD

Lopez Armengol, ZBE, YZ, *et al.* https://arxiv.org/abs/2112.09817
Compact-binaries.org





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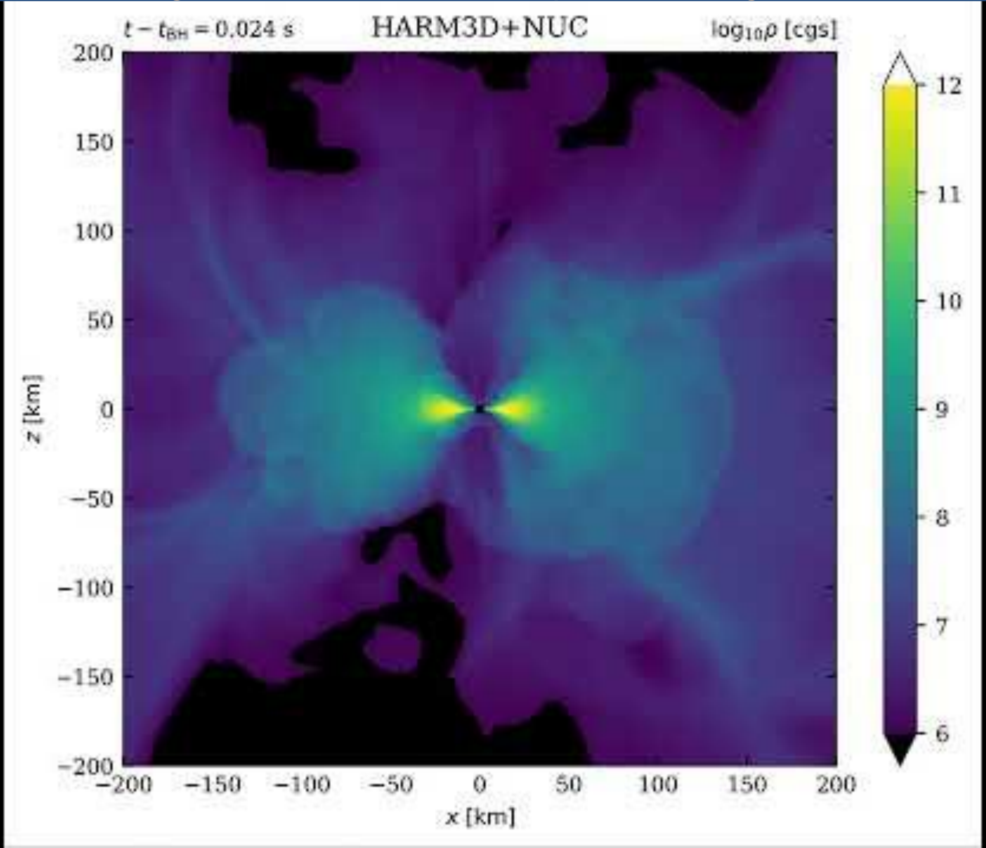

Trial run:
Magnetized BNS:
q=1
LS220/SLy4 +
postmerger neutrino
leakage

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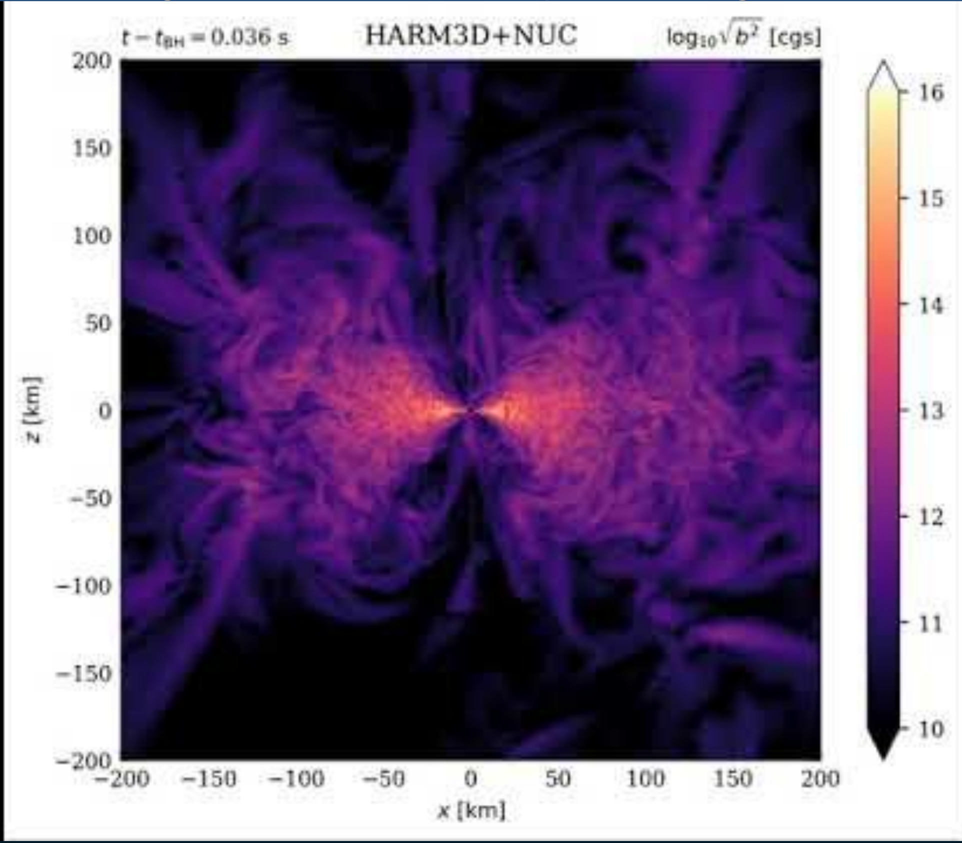

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   Just as no person can be an expert in everything, no code can/should do everything

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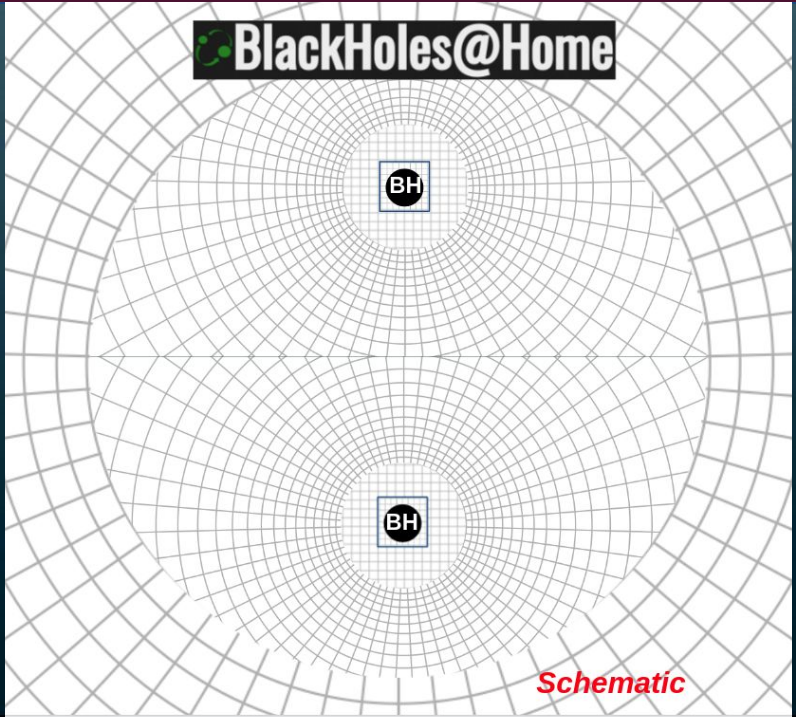
BlackHoles@Home + MANGA

BlackHoles@Home

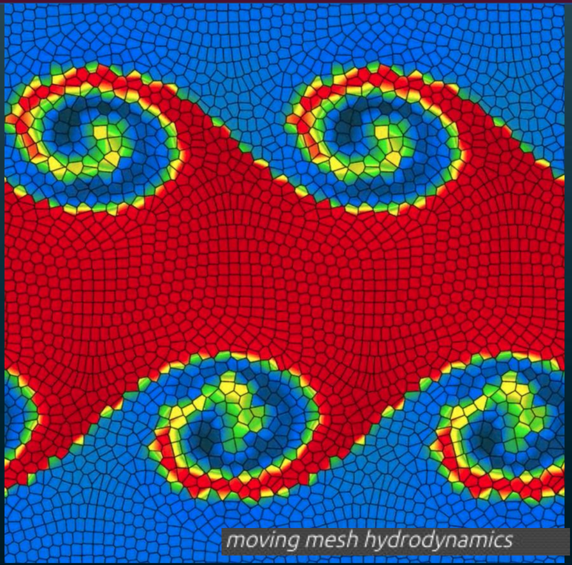
NR code with highly efficient grids (idea: *NR is the cheap part*)



MANGA

Moving-mesh Voronoi code

- Has been used to study
  - Common envelope evolution
  - Tidal disruptions
- Supports advanced EOSs, radiation hydro, GRHD in progress!



Pros and Cons of Voronoi Hydrodynamics

Pros

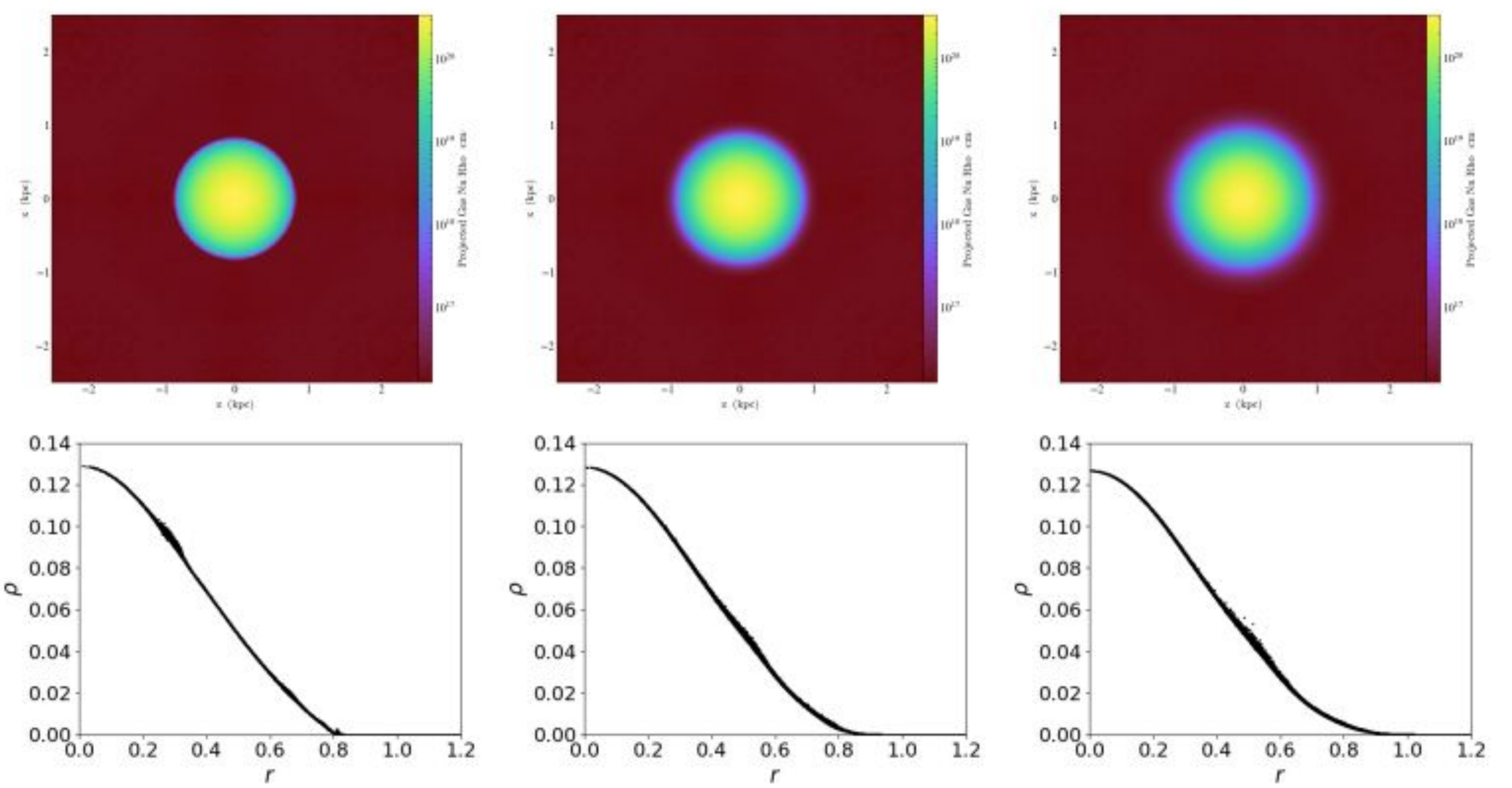
- Far better advection than Eulerian.
- Superior conservation of momentum and angular momentum compared to Eulerian schemes
- Superior shock capturing compared to SPH.
- Better capture of interface instabilities in principle.
- Continuously varying resolution – no factor of 2 or 4 jumps as in AMR.
- Almost anything solvable on Eulerian grids map to Voronoi methods.

Cons

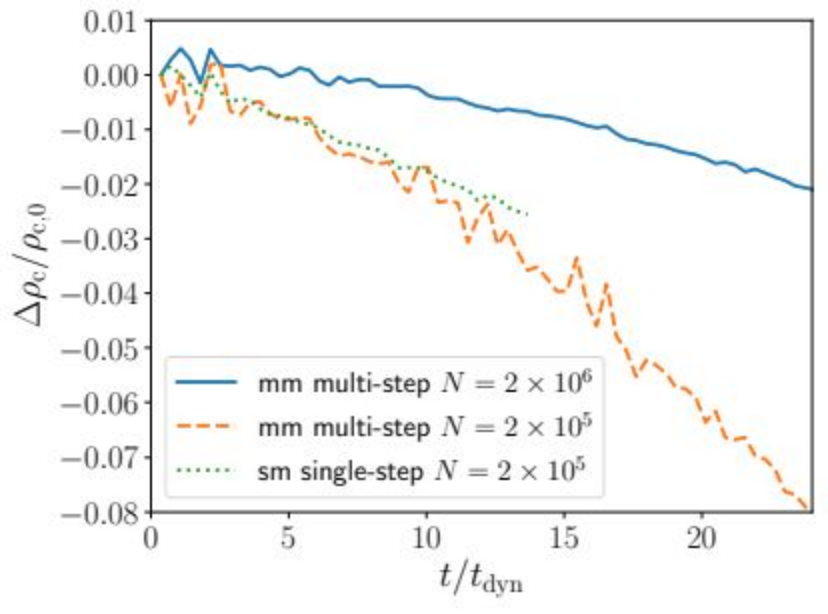
- Much more complex – combination of SPH and Eulerian + computational geometry
- Have to think about the grid (on top of everything else).
- “slower”
- MHD is divergence cleaning or vector potential based – no “staggered” CT scheme exists.
- Might be overkill for many problems

Slide courtesy Phil Chang, lead author of MANGA

General Relativistic Hydrodynamics on a Moving-mesh I: Static Spacetimes



Chang & ZBE: https://arxiv.org/abs/2002.09613 ; MNRAS 496, 1, 2020



- **Code converges as expected with increased number of mesh generating points**
  - **conv order of ~1.75**

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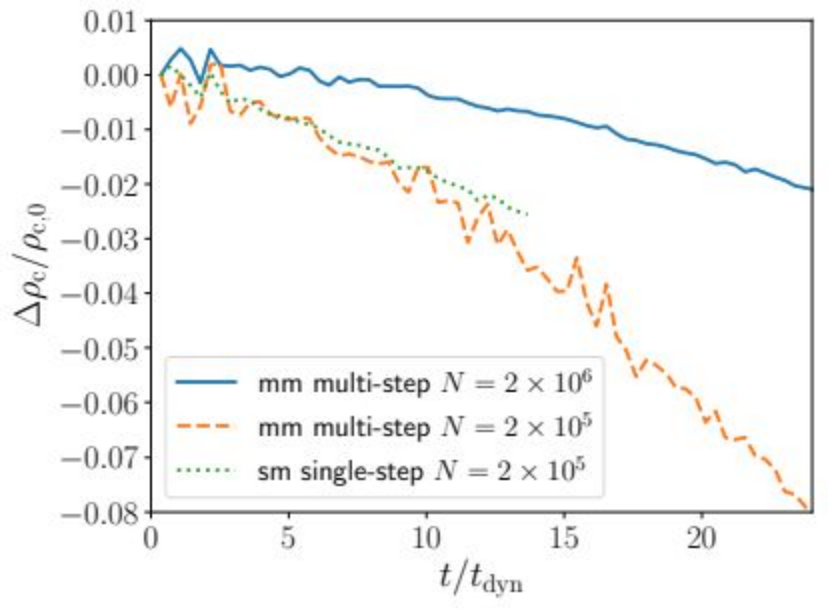

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- Current work:
  - Evolve spacetime with NRPy+
- Future work:
  - Couple to BH@H & perform BNS evolutions on moving mesh!
  - BNS with GRMHD, radiation, & advanced EOS

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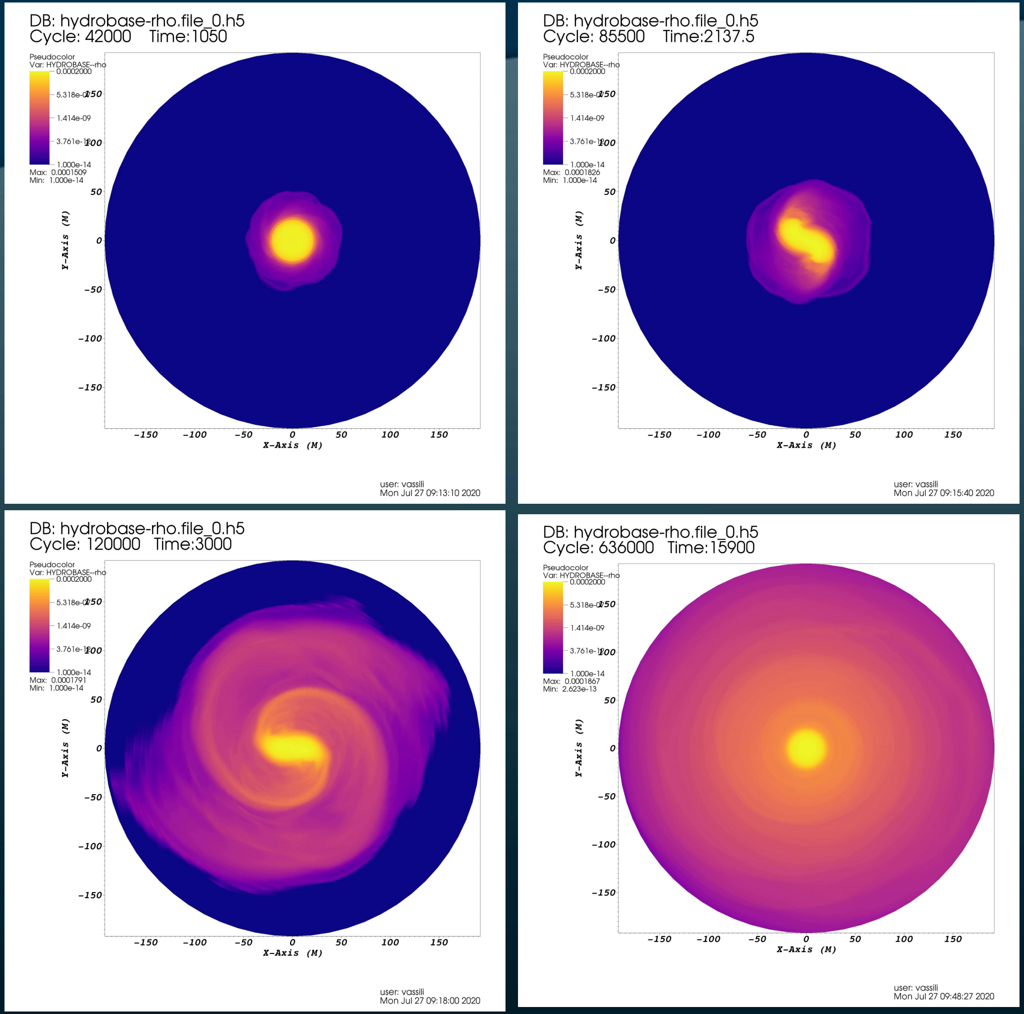
SphericalNR

- Built on top of SphericalBSSN, GRHydro, Carpet, Cactus, etc.
- NRPy+ used for code generation
- BSSN and ccZ4
- Non-staggered A field with higher-order finite differences
- WENOZ-9 reconstruction techniques
- Generic fisheye coordinates.
- Major Goals: Accuracy and Efficiency. We want the benefits of Spherical Coordinates and higher-order methods with a Courant condition dt ~ dr.

Filtering

- Developed a new filtering techniques based on 2D FFTs to suppress Courant unstable modes (V. Mewes et al).
- Fully parallelized this scheme (Liwei Ji).

- Let $\mathbf{Y}(r,\theta,\phi), 0 \leq \theta \leq \pi, 0 \leq \phi < 2\pi$ be some evolved field
- $$\mathbf{X}(r,\theta,\phi) = \begin{cases} \mathbf{Y}(r,\theta,\phi) & \theta \in [0,\pi] \\ (-1)^a \mathbf{Y}(r,\pi-\theta,\pi+\phi) & \theta \in (\pi,2\pi] \end{cases}$$
- $$\tilde{\mathbf{X}}(r,l,\phi) \to \tilde{\mathbf{X}}(r,l,\phi) L_{\mathrm{damp}}(l),$$
- $$\tilde{\mathbf{X}}(r,\theta,m) \to \tilde{\mathbf{X}}(r,\theta,m) M_{\mathrm{damp}}(m),$$
- Damping functions suppress CFL unstable modes, and don't suppress physical modes in the continuum limit.



Bar-mode unstable magnetized NS simulations (Mewes ++).

U11 from Franci et al. PRD 88 (2013) 104028 (Simulation: V. Mewes)

Open Questions
What are we missing?
How else can we address existing shortcomings?

Additional ideas

- Codes: documentation/CI standards
  - "Apples-with-apples" for BNS
- Algorithms: community library of routines

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