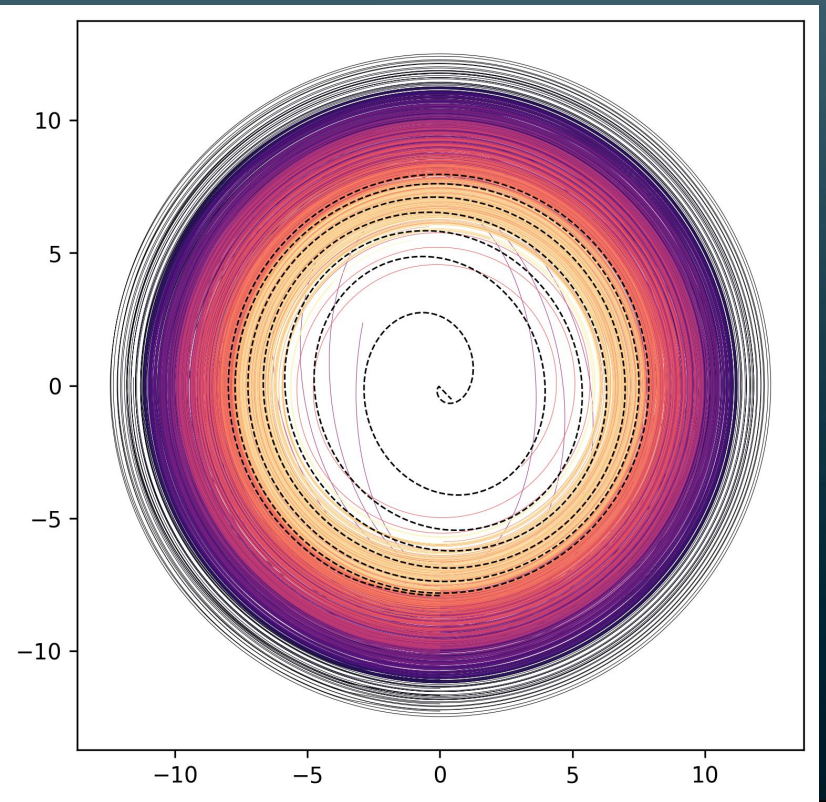
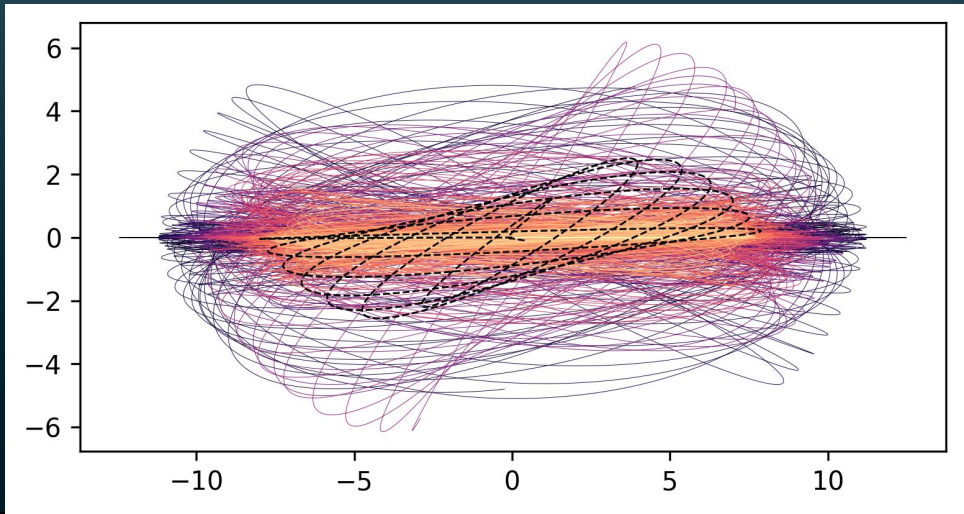
BlackHoles@Home Update





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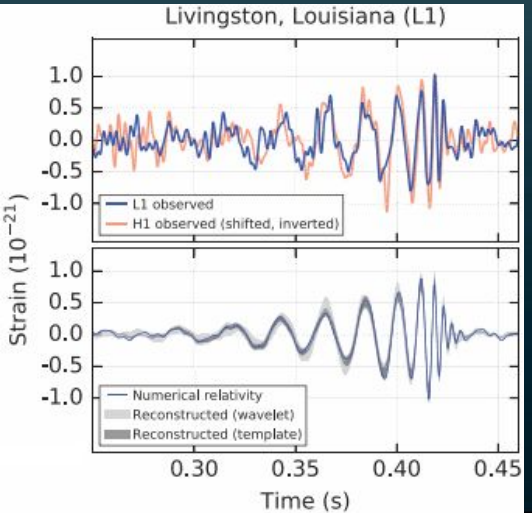
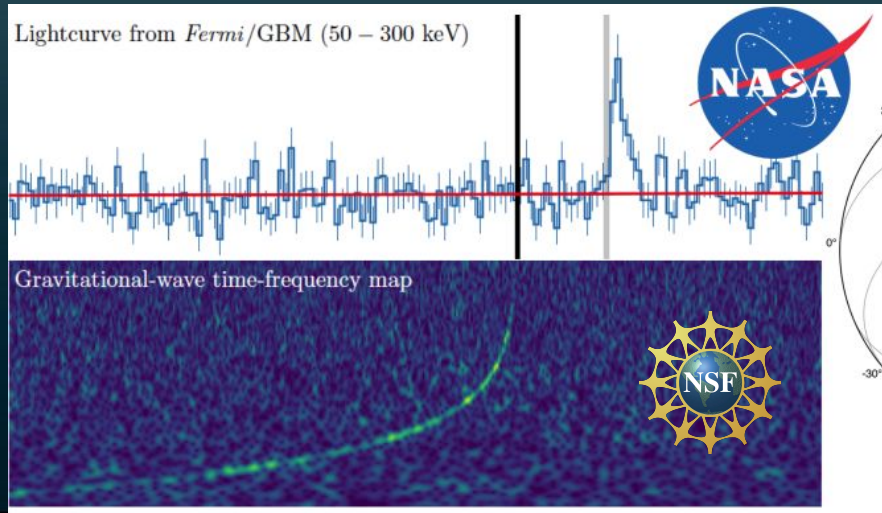
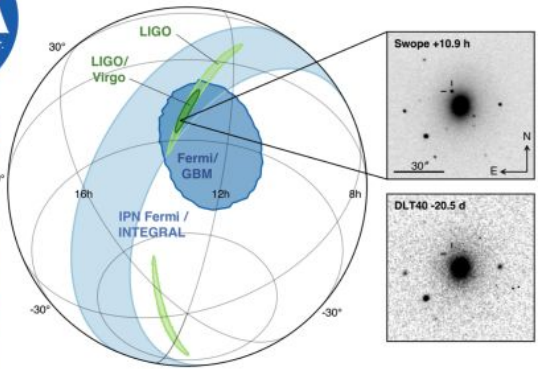
2020: Co-PI on Einstein Toolkit grant, 2022 ET School host

Importance of modeling gravitational wave and multimessenger sources

- Example: LIGO detects a gravitational wave from a black hole or neutron star binary

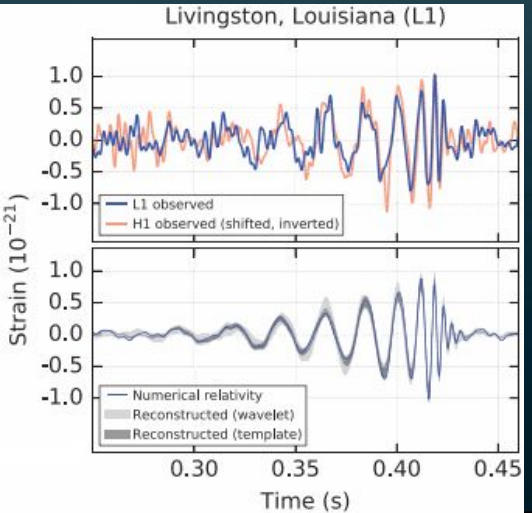


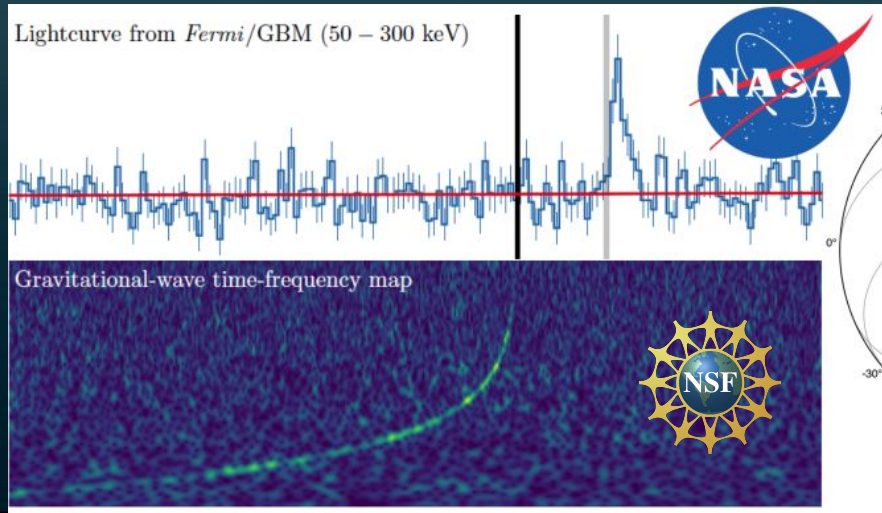


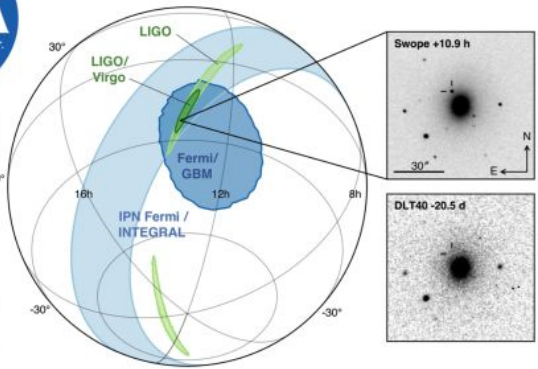


Importance of modeling gravitational wave and multimessenger sources

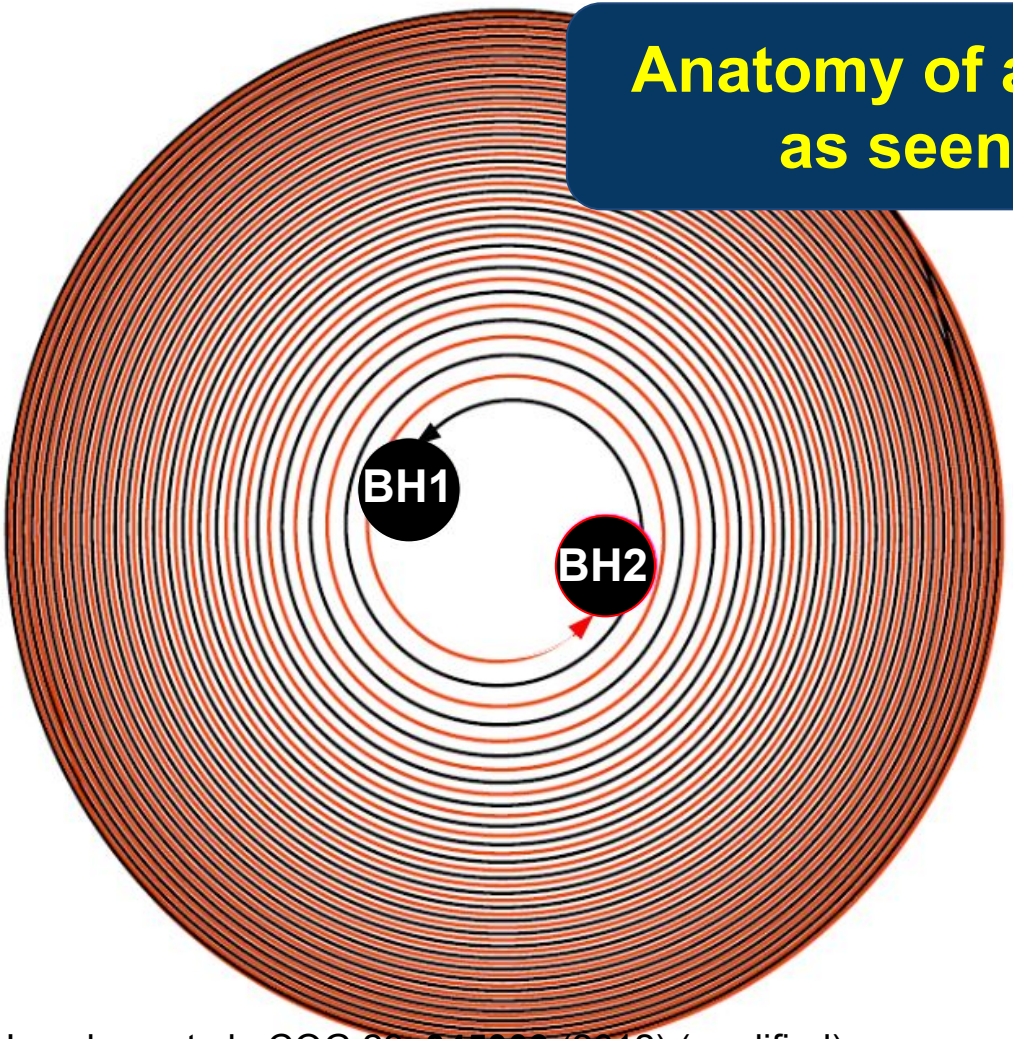
- $1B+ Question: What *exactly* caused this and *how*?
  - Answer → insights into extreme gravity and matter, pushing theor. limits.
  - To advance science, must compare observations with theoretical predictions
    - Theoretical predictions must span observ. & theor. uncertainties







Anatomy of a Binary Black Hole Merger, as seen in gravitational waves



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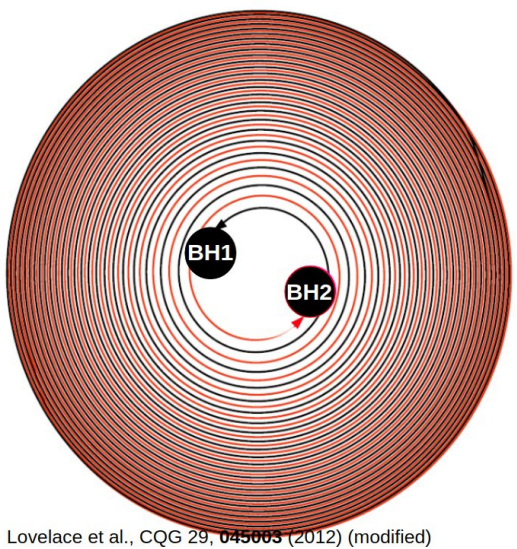

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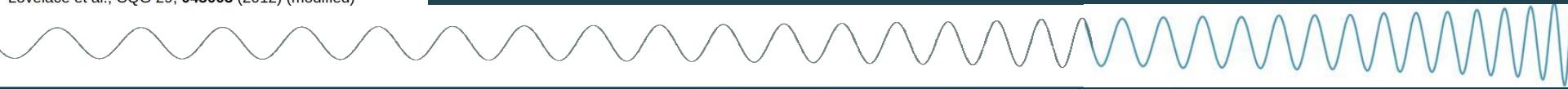

Time axis ⇨
(spans ~200ms)
Wave amplitude ⇧
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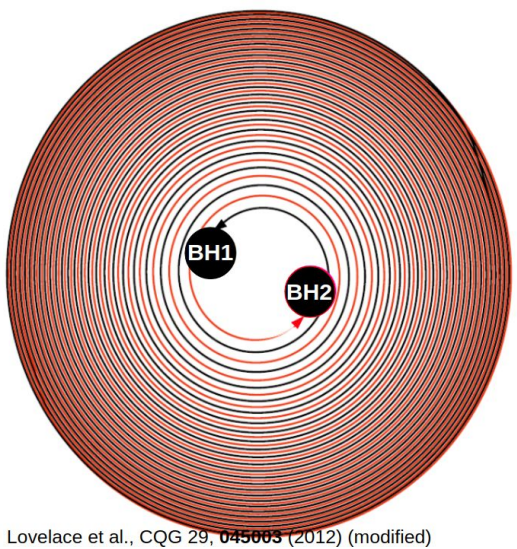

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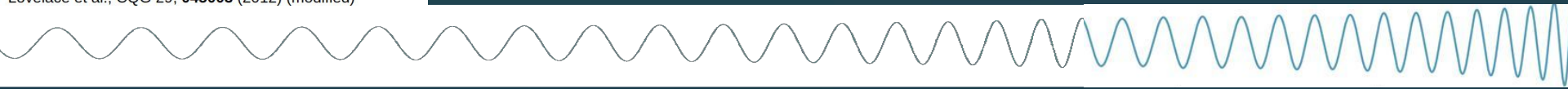

These waves encode info about masses, spins, and eccentricity of orbiting black holes

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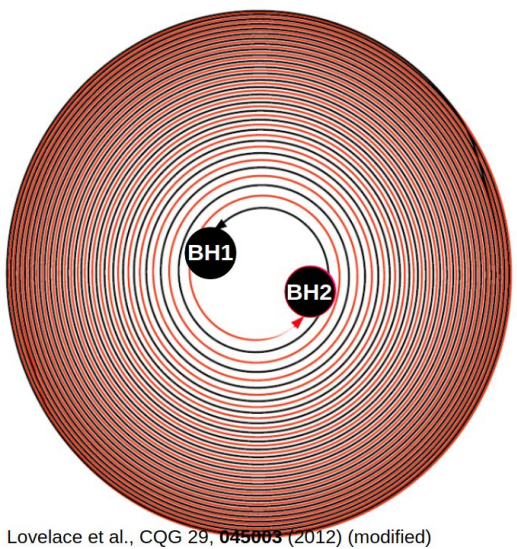

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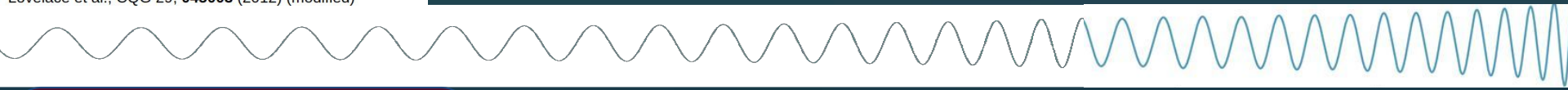

⇦ (Very) early inspiral: Perturbative solutions to Einstein gravity (GR)

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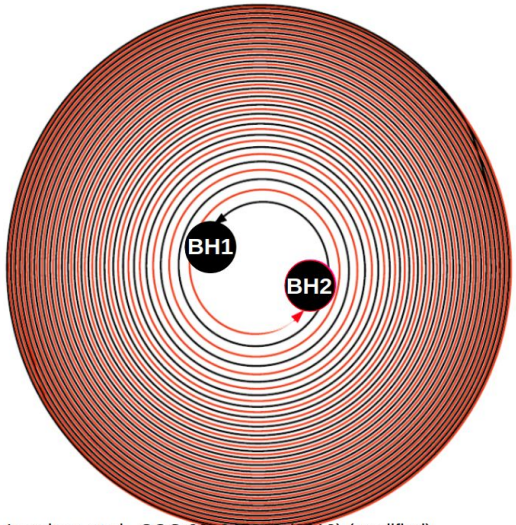

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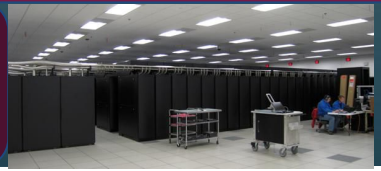
Late inspiral: Perturb. theory breaks down; **Only full GR solutions**



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$$\partial_t \bar{\gamma}_{ij} = \left[\beta^k \partial_k \bar{\gamma}_{ij} + \partial_i \beta^k \bar{\gamma}_{kj} + \partial_j \beta^k \bar{\gamma}_{ik}\right] + \frac{2}{3}\bar{\gamma}_{ij}\left(\alpha \bar{A}^k_k - \bar{D}_k \beta^k\right) - 2\alpha \bar{A}_{ij} ,$$

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$$+ e^{-4\phi}\left\{-2\alpha \bar{D}_i \bar{D}_j \phi + 4\alpha \bar{D}_i \phi \bar{D}_j \phi + 4\bar{D}_{(i}\alpha \bar{D}_{j)}\phi - \bar{D}_i \bar{D}_j \alpha + \alpha \bar{R}_{ij}\right\}^{\mathrm{TF}} ,$$

$$\partial_t \phi = \left[\beta^k \partial_k \phi\right] + \frac{1}{6}\left(\bar{D}_k \beta^k - \alpha K\right) ,$$

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$$\partial_t \beta^i = \left[\beta^j \partial_j \beta^i\right] + B^i$$

$$\partial_t B^i = \left[\beta^j \partial_j B^i\right] + \frac{3}{4}\partial_0 \bar{\Lambda}^i - \eta B^i$$

Most popular formulation

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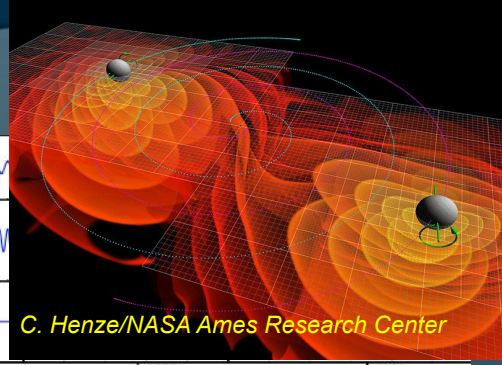

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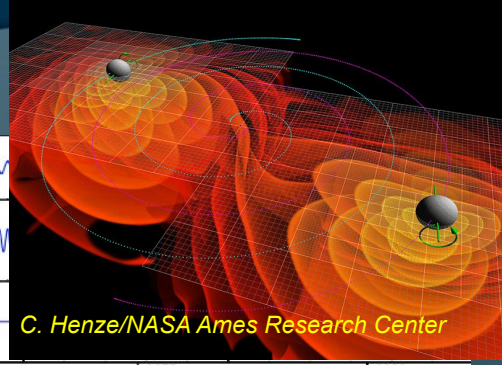

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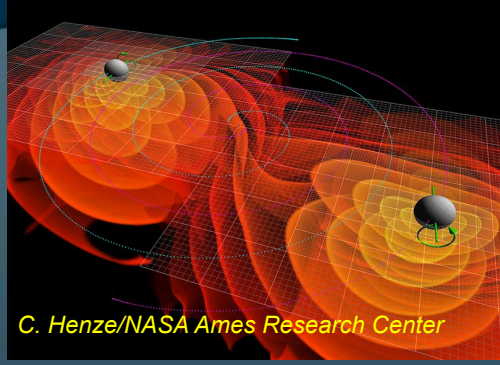

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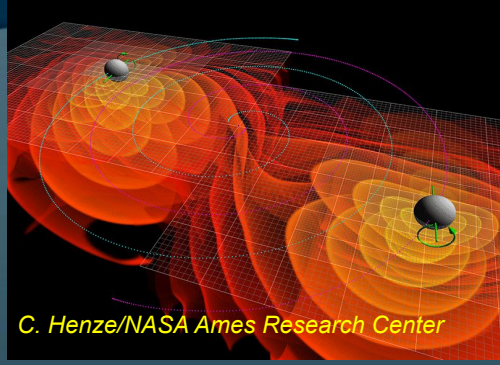

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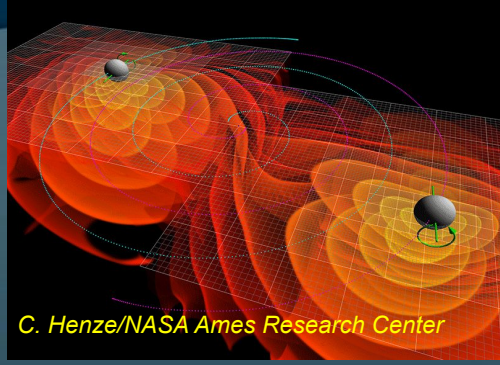

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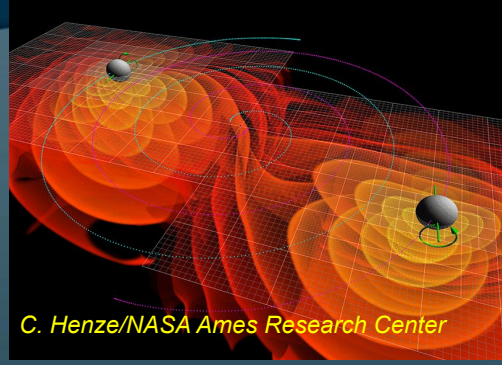

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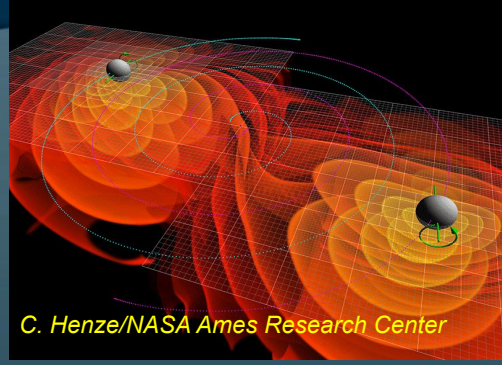

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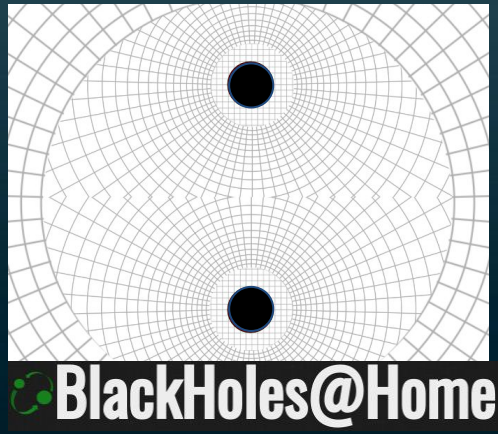

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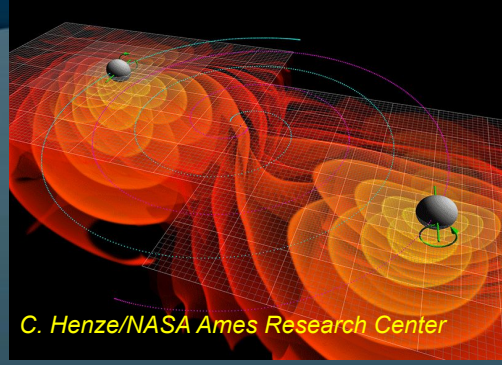

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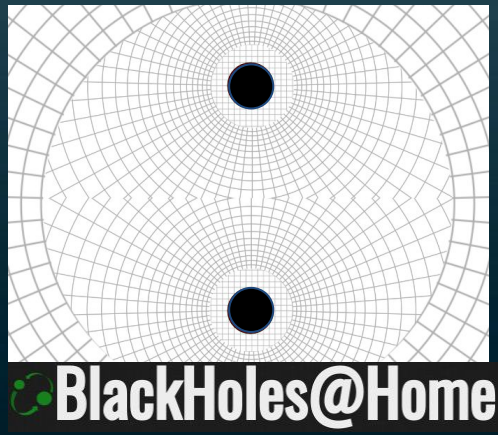

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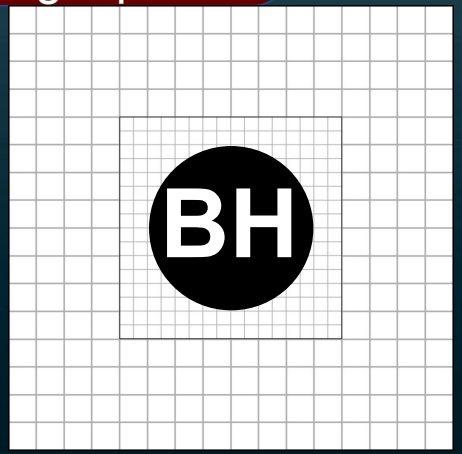

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How to address?

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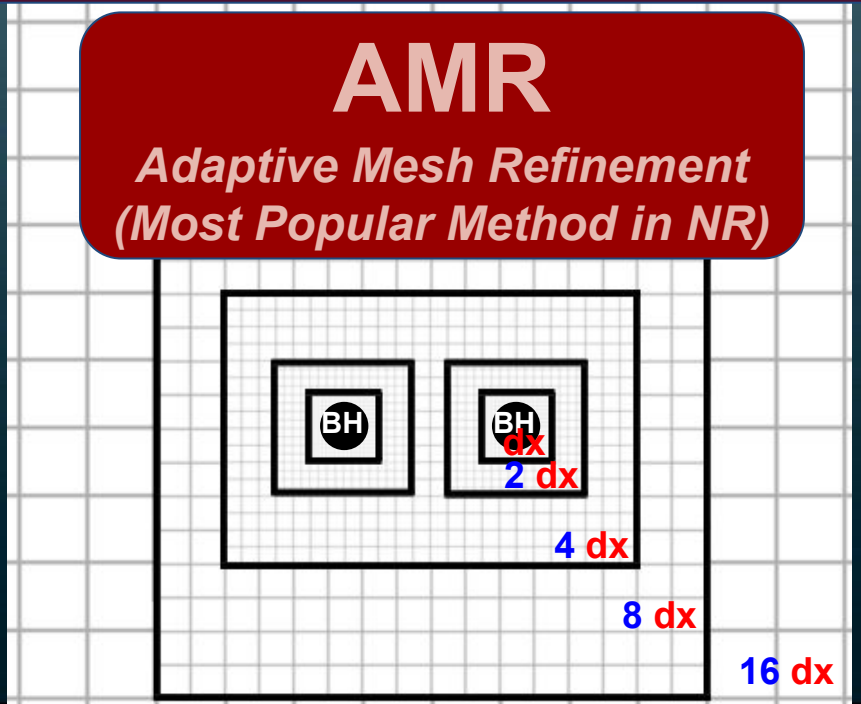

Modeling Challenges

Address (~5 orders of mag) disparity in physical scales

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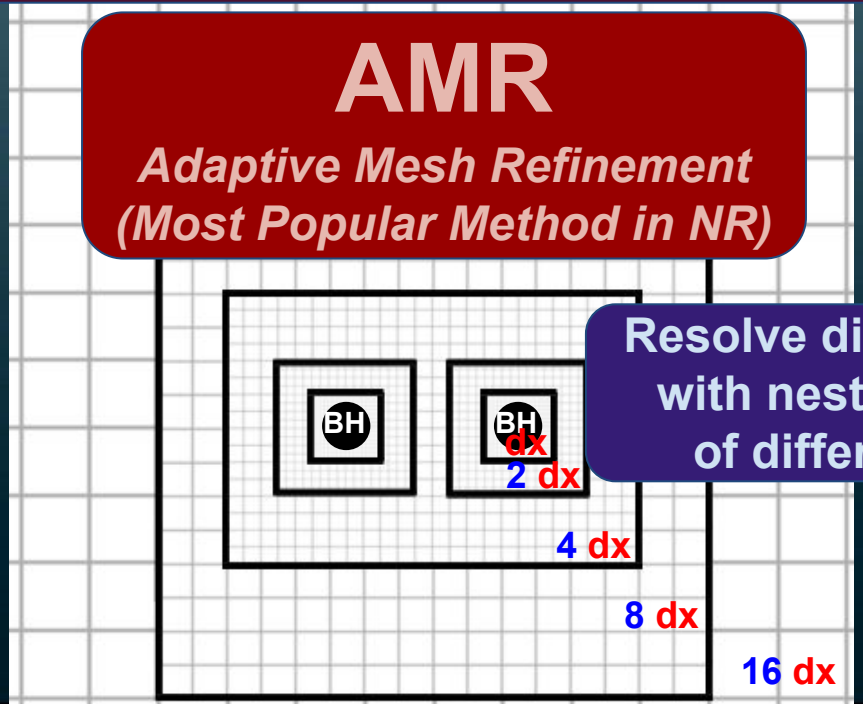

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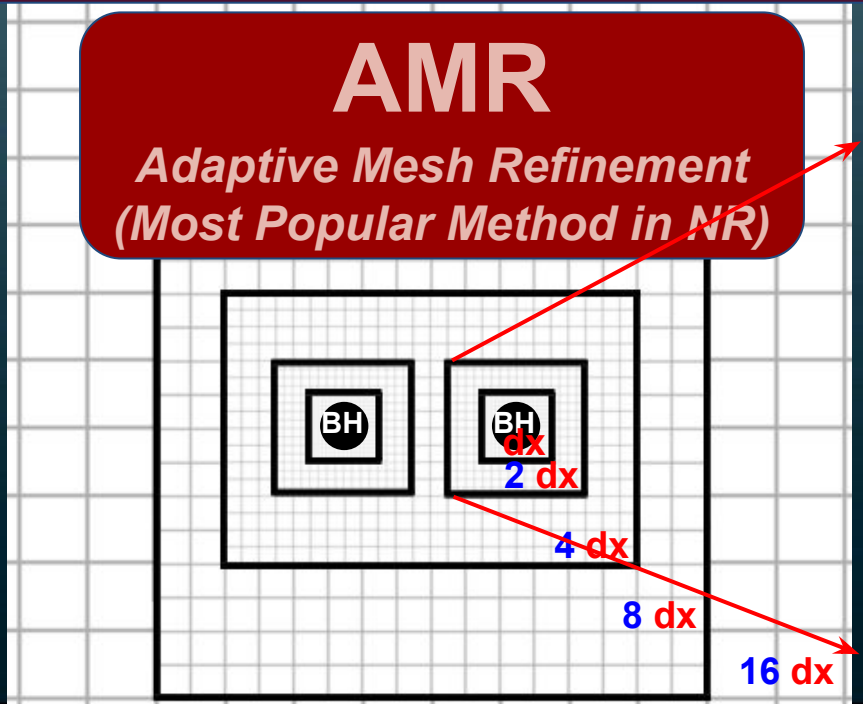

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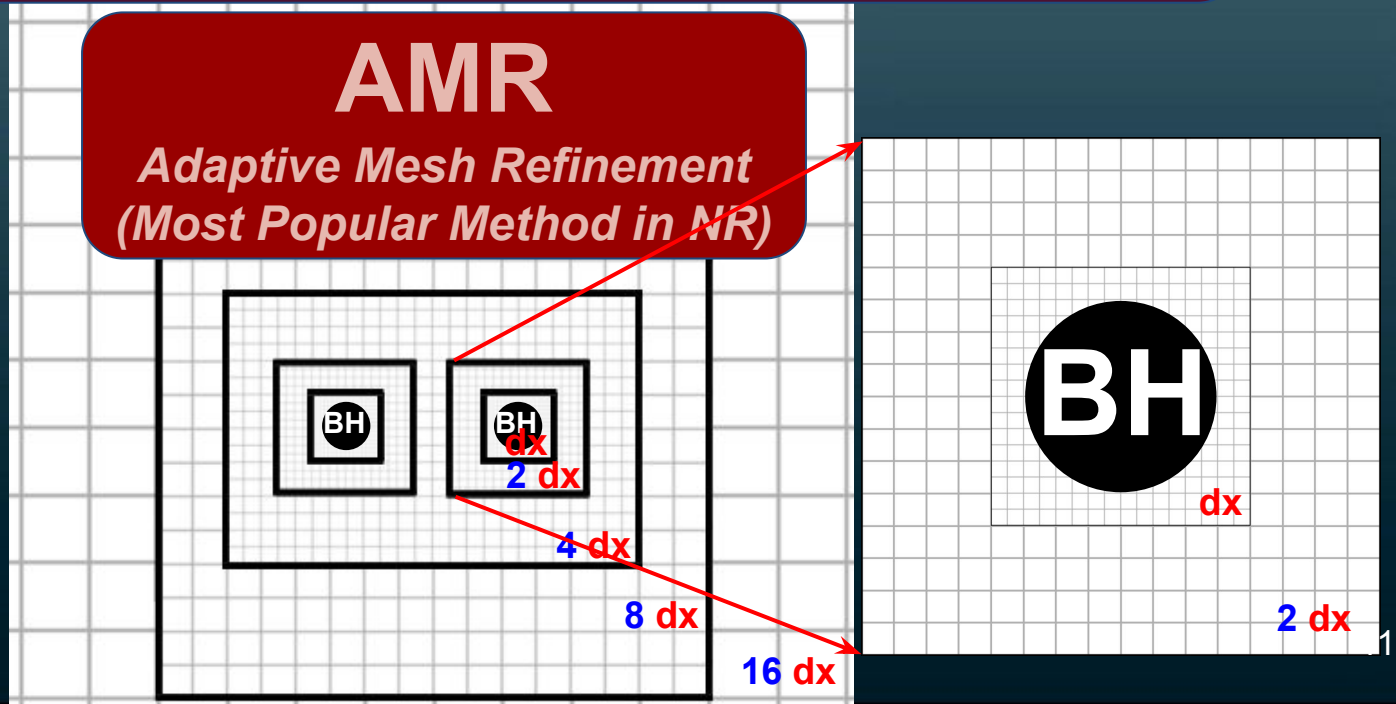

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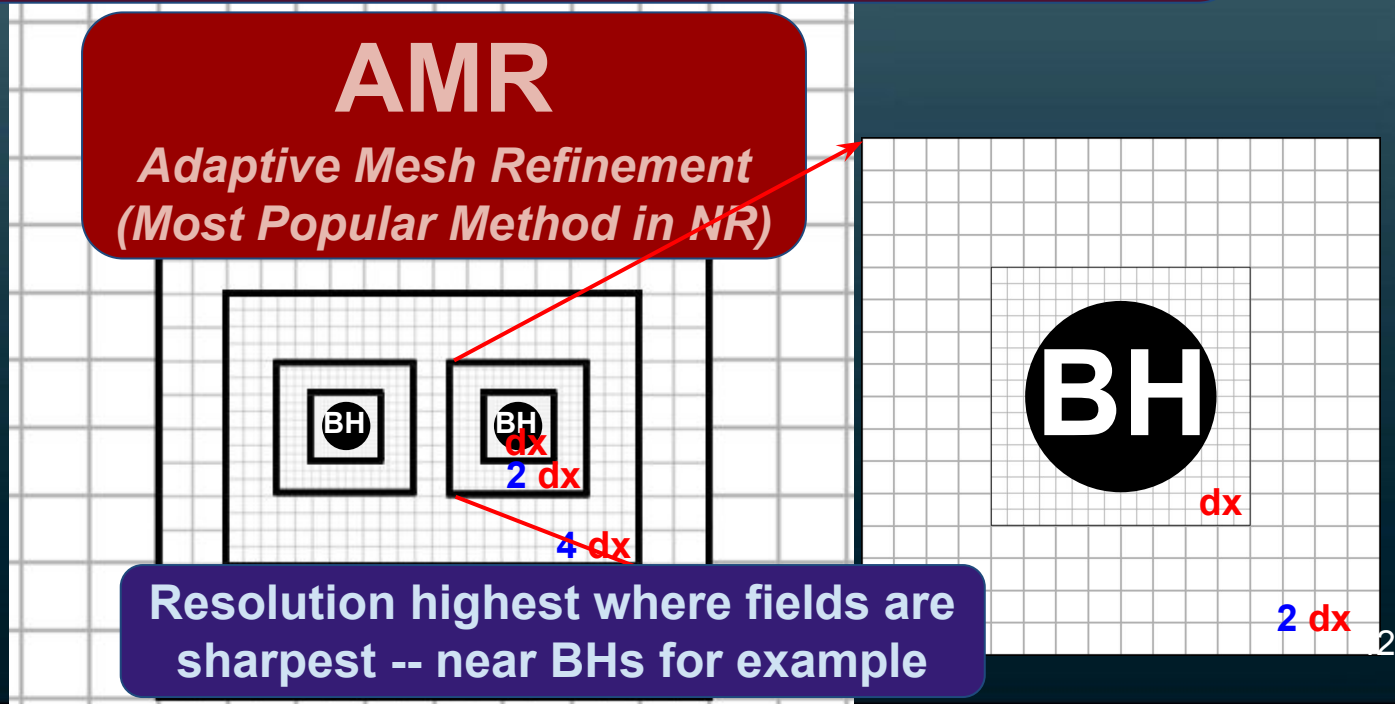
AMR

Adaptive Mesh Refinement
(Most Popular Method in NR)



Resolution highest where fields are sharpest -- near BHs for example

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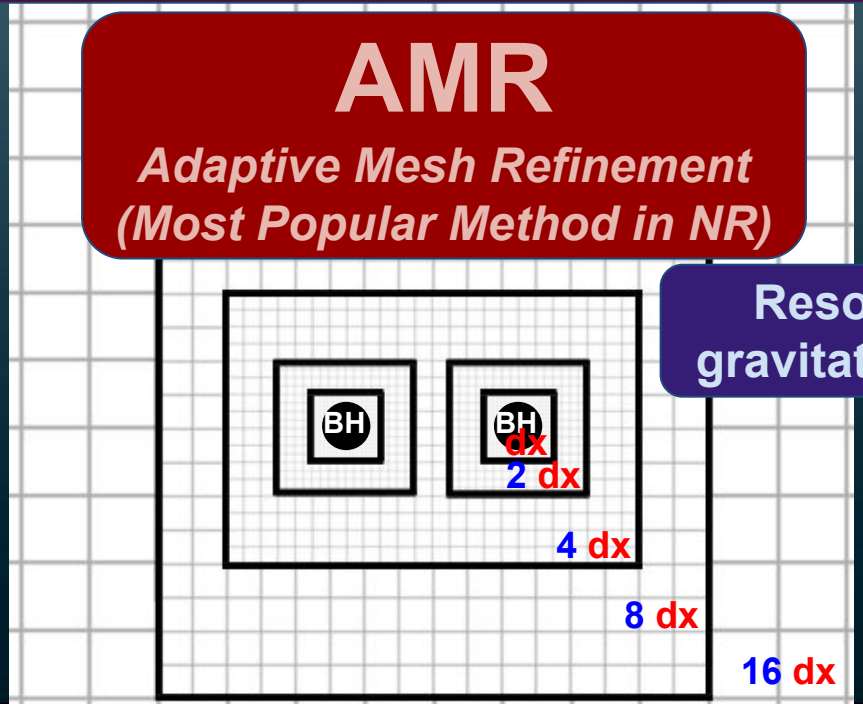

Resolution lower where gravitational waves modeled

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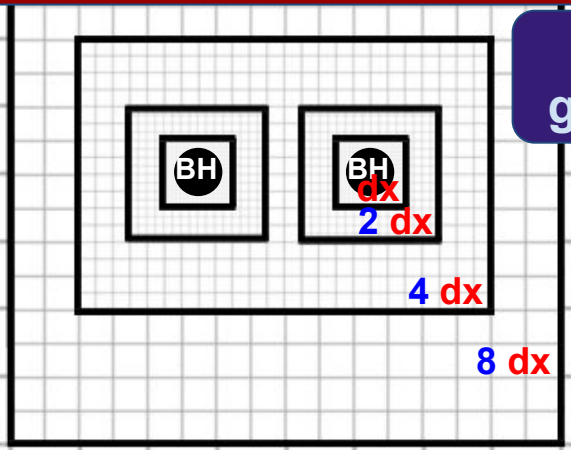

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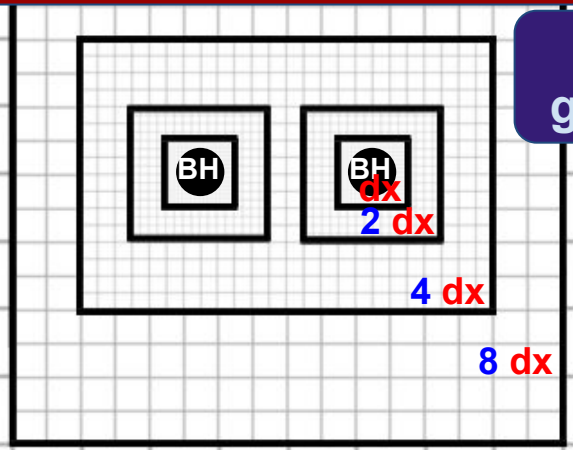

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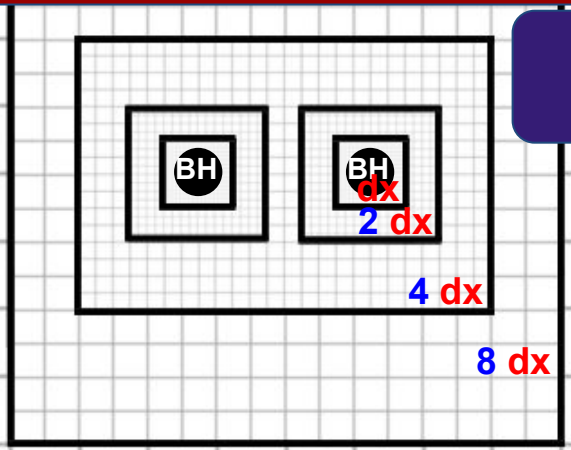

Add coarser grids to push outer boundary far away

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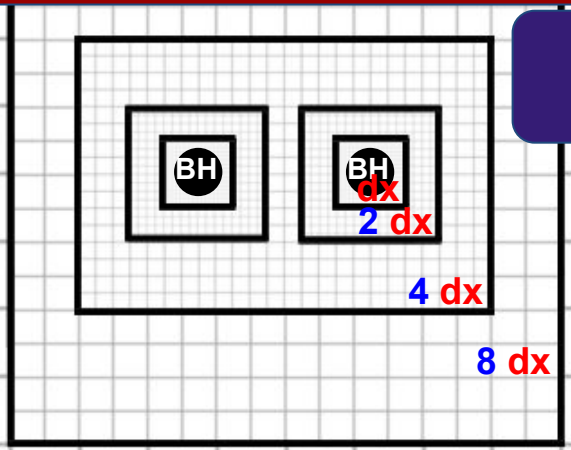

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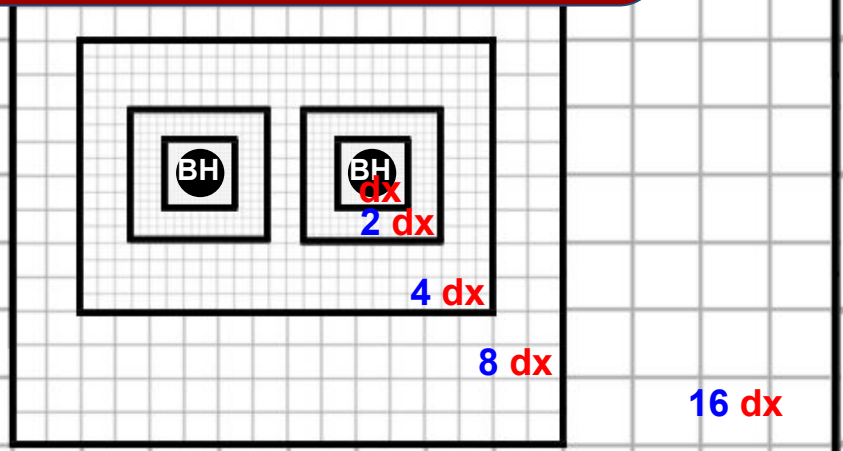

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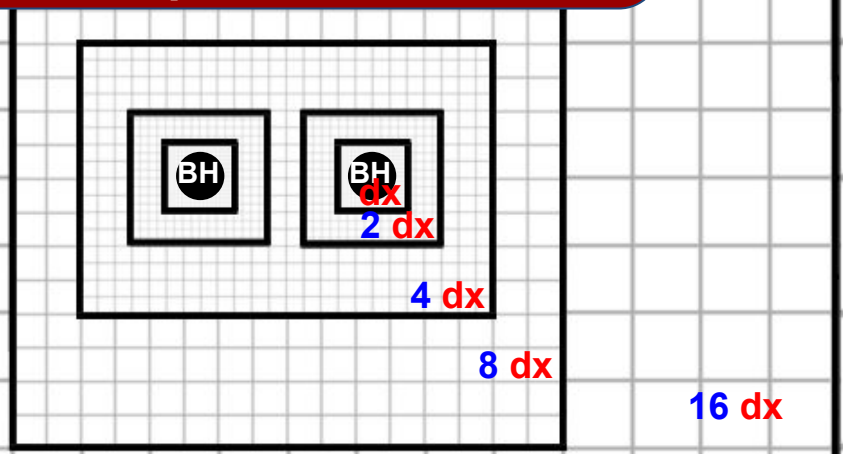

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A: Inefficient!
⇨ greater comp. cost

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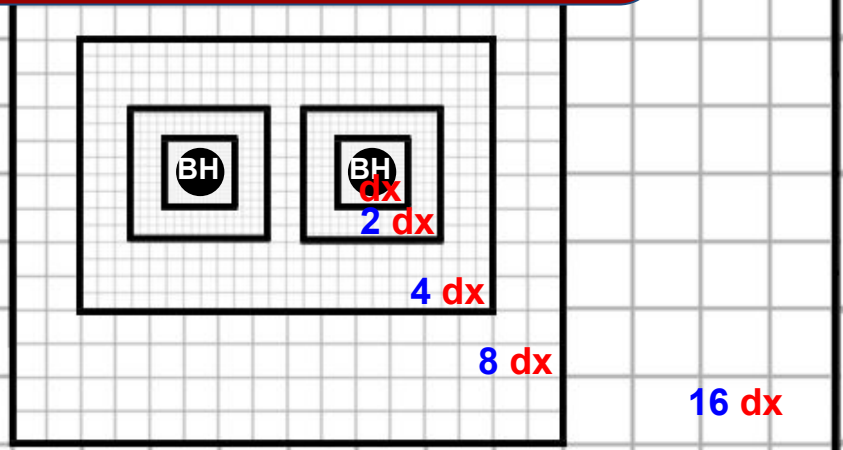

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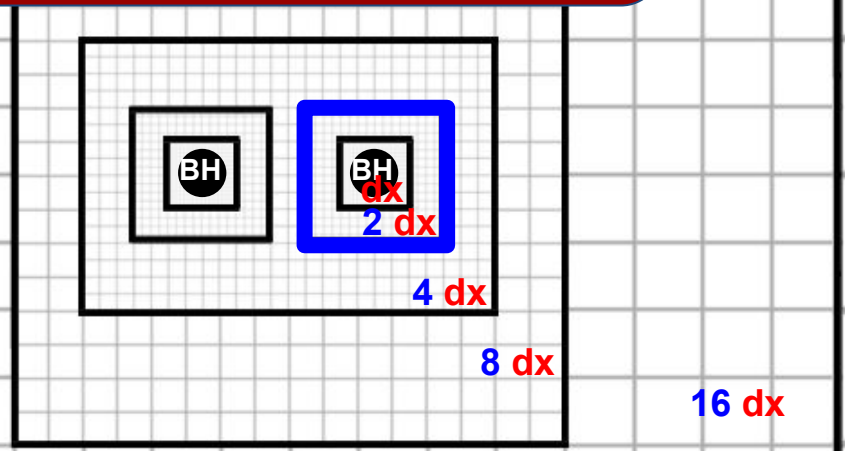

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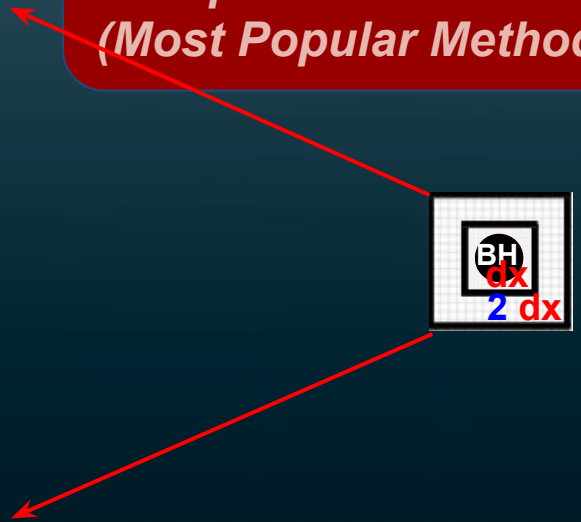

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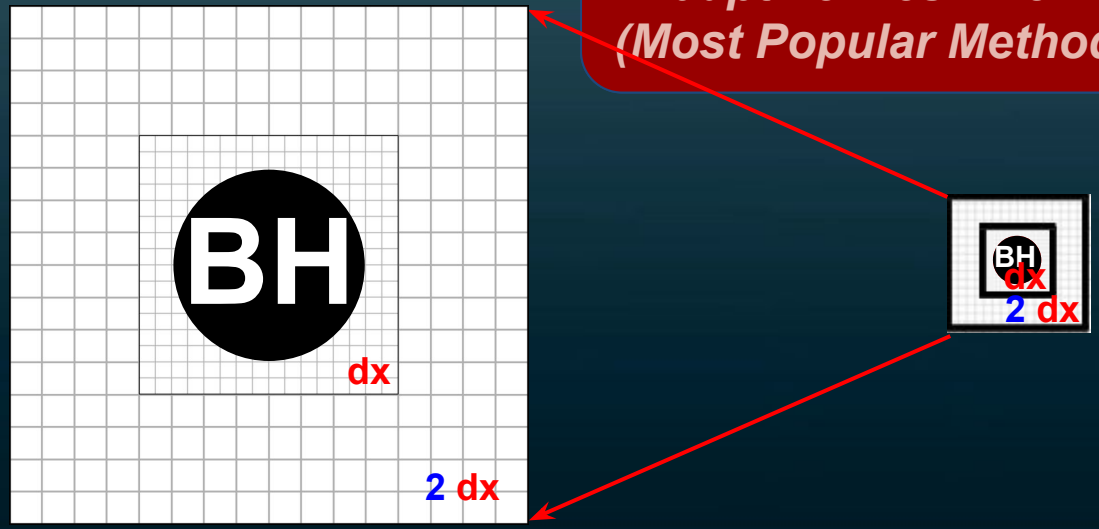

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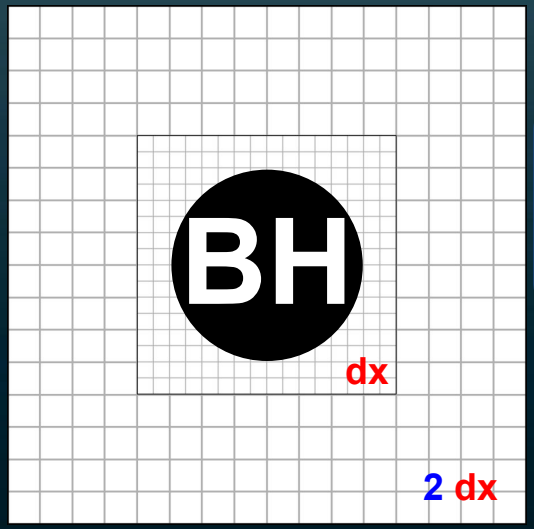

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   - ⇨ grav/matter fields drop off strongly in *radial* direction
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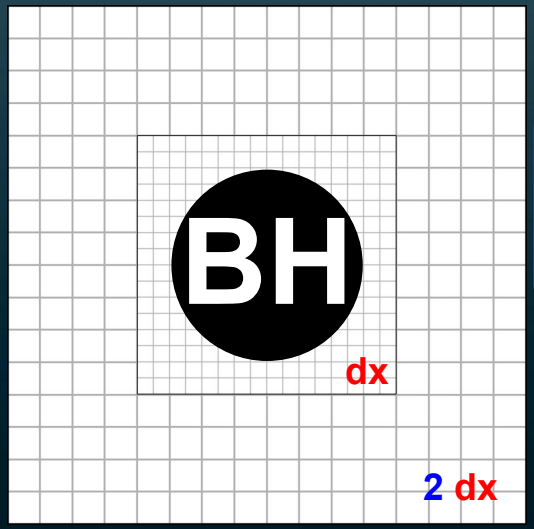

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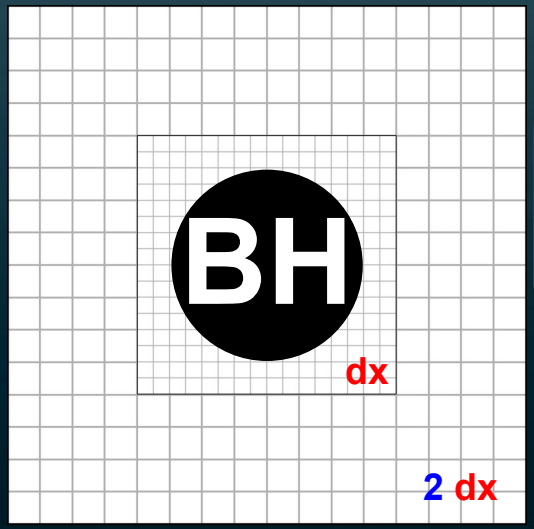

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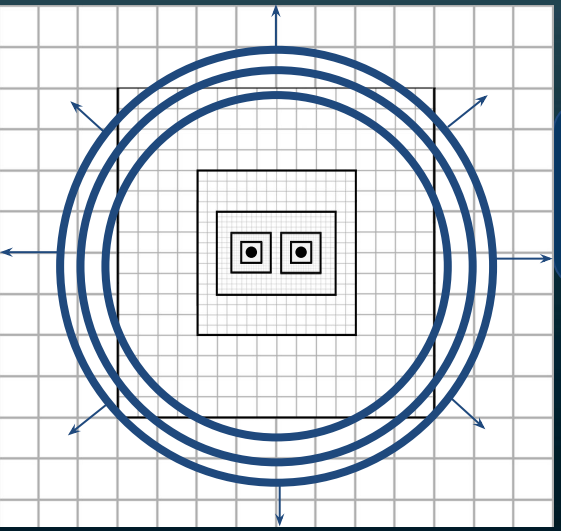

2. Gravitational waves far away nearly spherical
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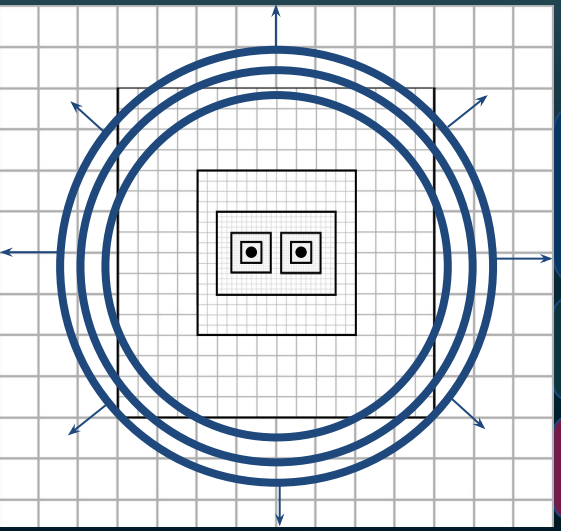

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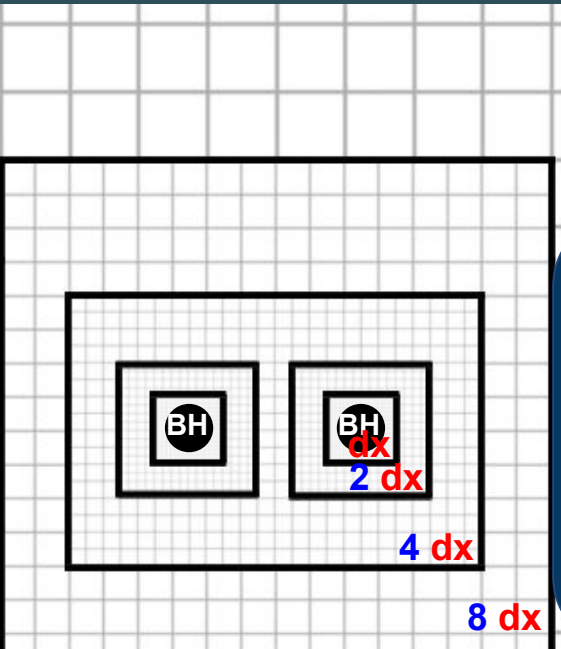

3. Grav & matter fields are mostly smooth
   - Cartesian **AMR** grids:
     - 2x jumps in resolution between boxes
     - Boxes have sharp corners
   - **Bi-spherical-like** grids: **another ~4x efficiency boost**
     - Smooth, logarithmic *r* coordinate from NSs
     - Uniform angular coordinates

BlackHoles@Home: BBHs on the Desktop
Development of Super-Efficient Grid Structures

AMR Grids

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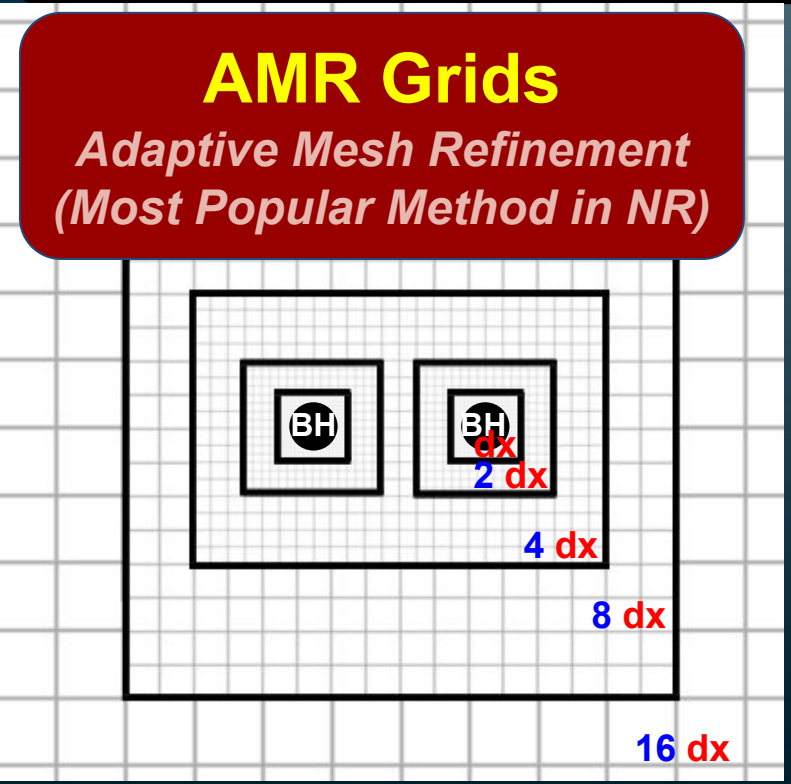

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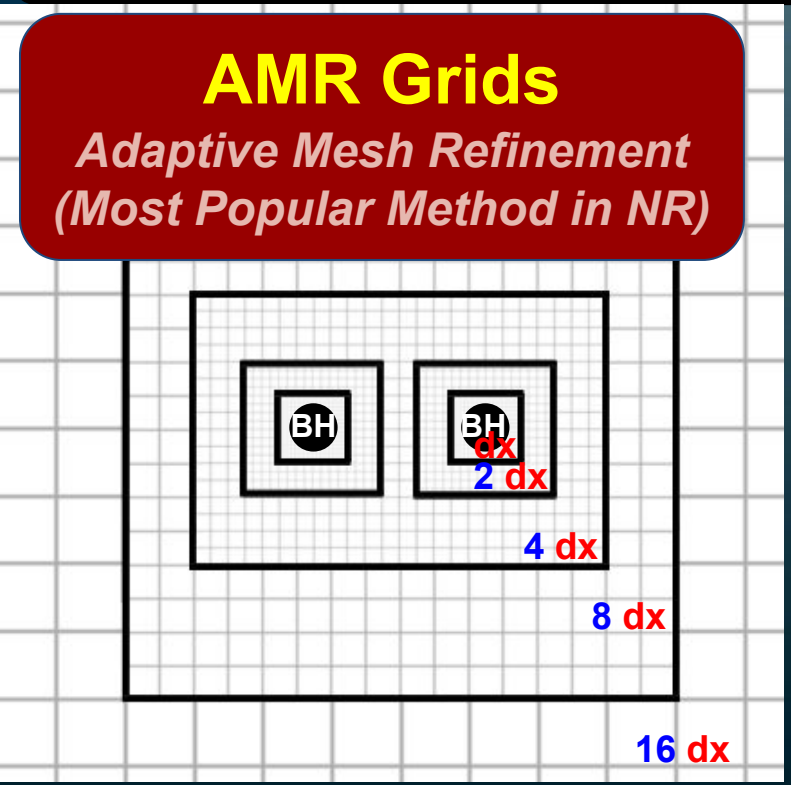

More efficient grids would...

- Employ smoother transitions in resolution
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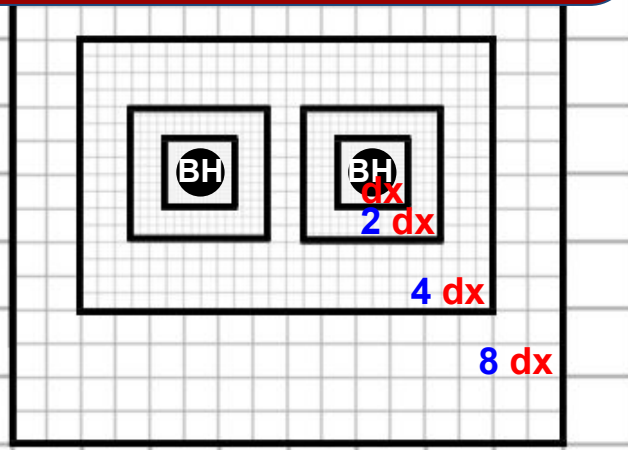

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NR in Spherical coordinates

- Brown (PRD 79, 104029, **2009**)
- Baumgarte, Montero, Cordero-Carrión, Müller (PRD 87, 044026, **2012**)

NR in Spherical-like, Cyl-like, etc.

- Ruchlin, **Etienne**, Baumgarte (PRD 97, 064036, **2018**)

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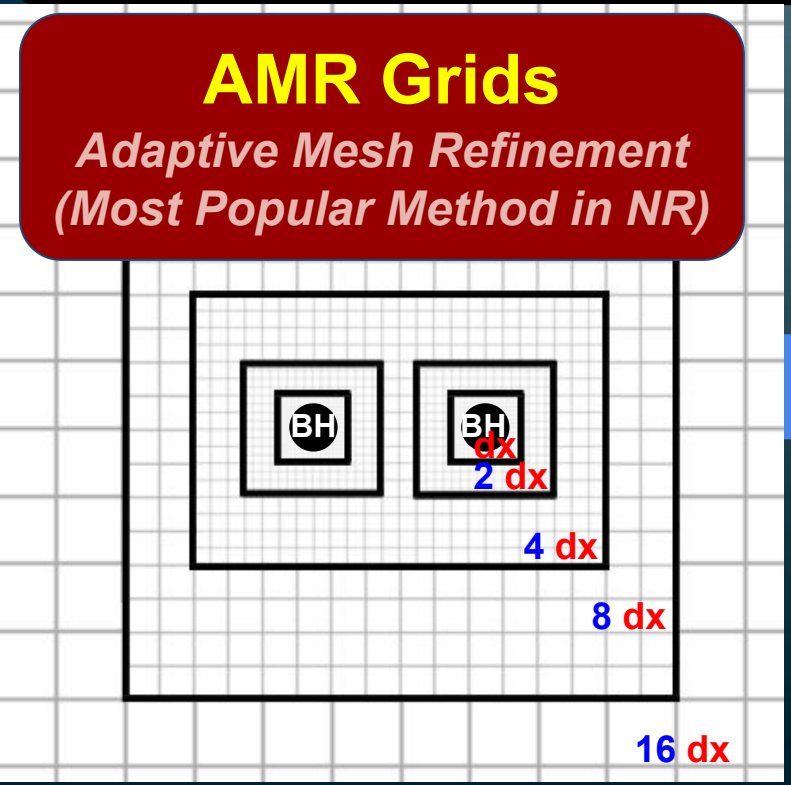
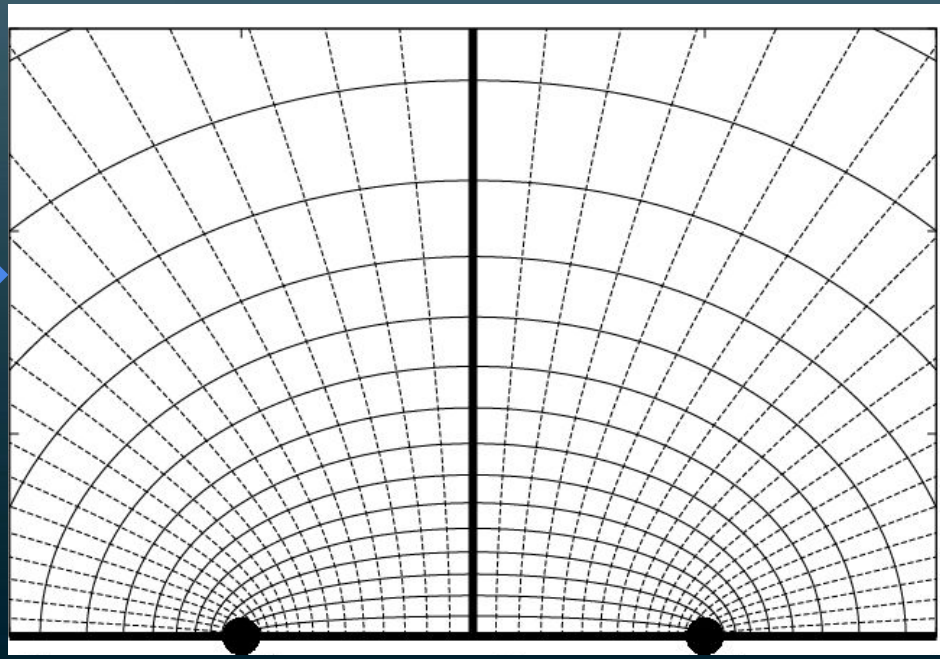


TwoPuncture Grids



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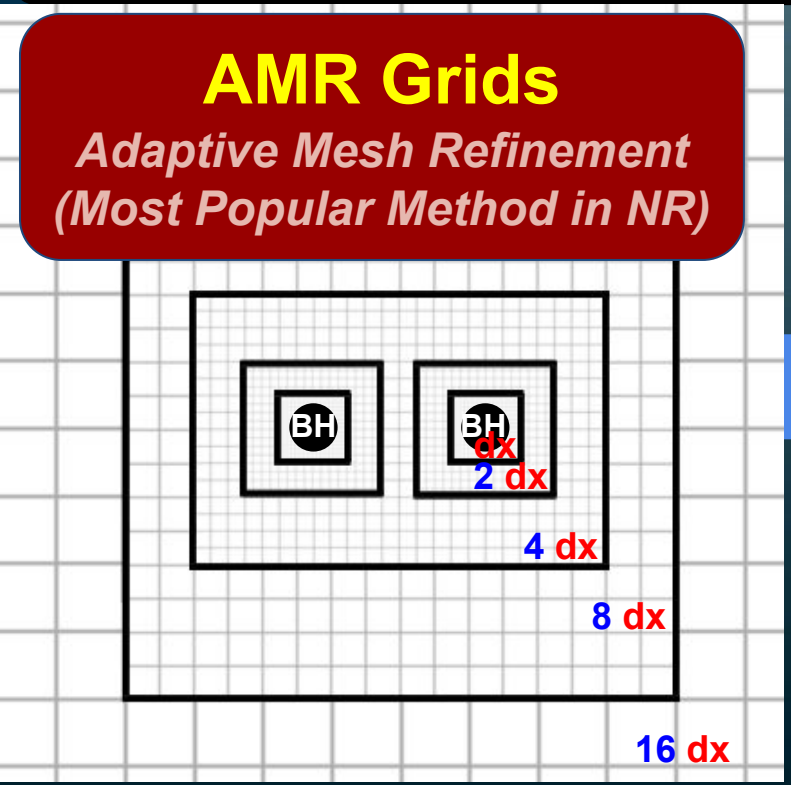

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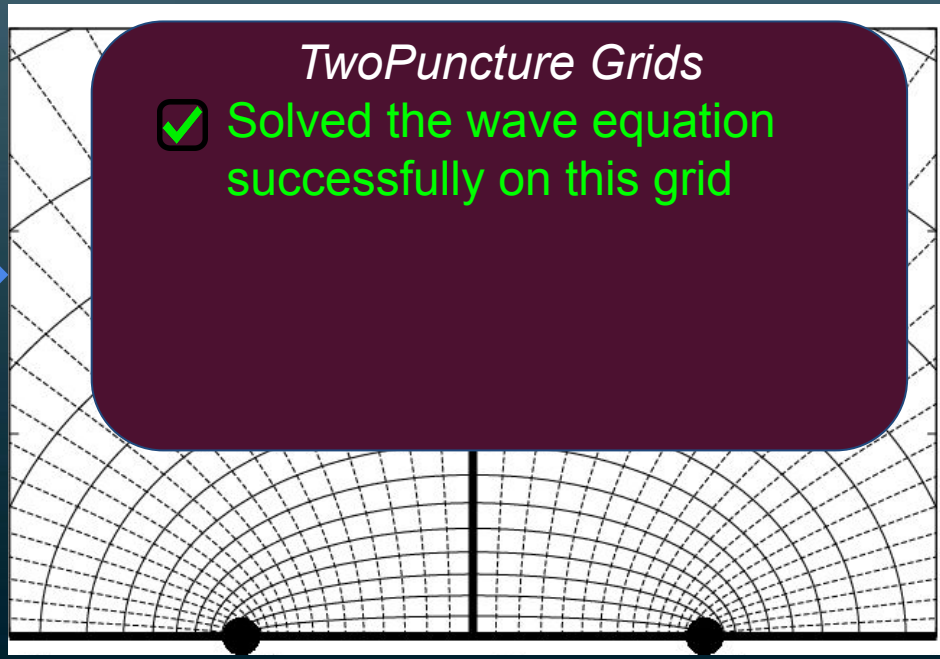

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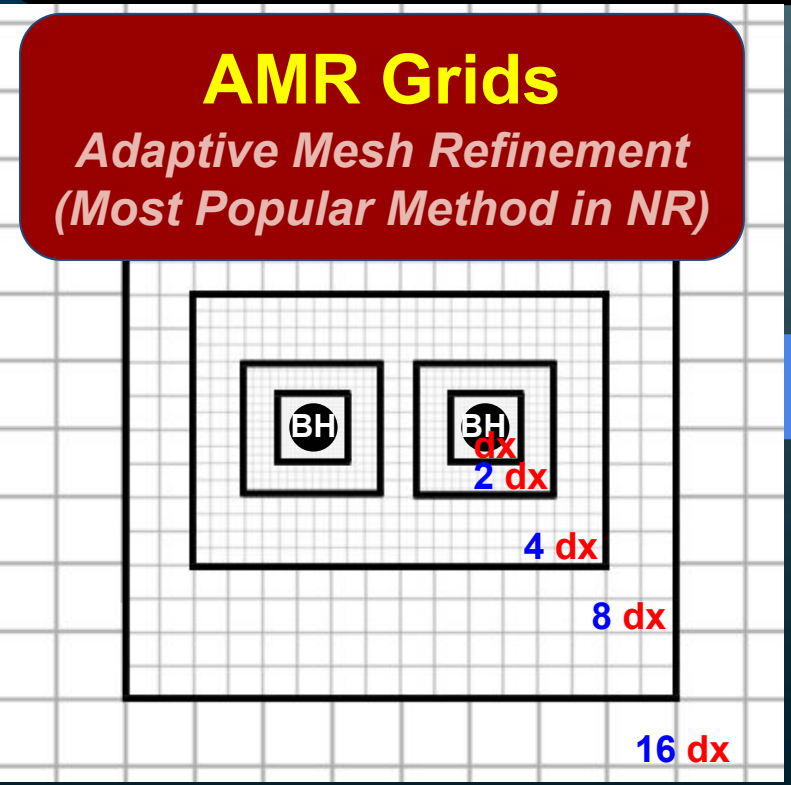

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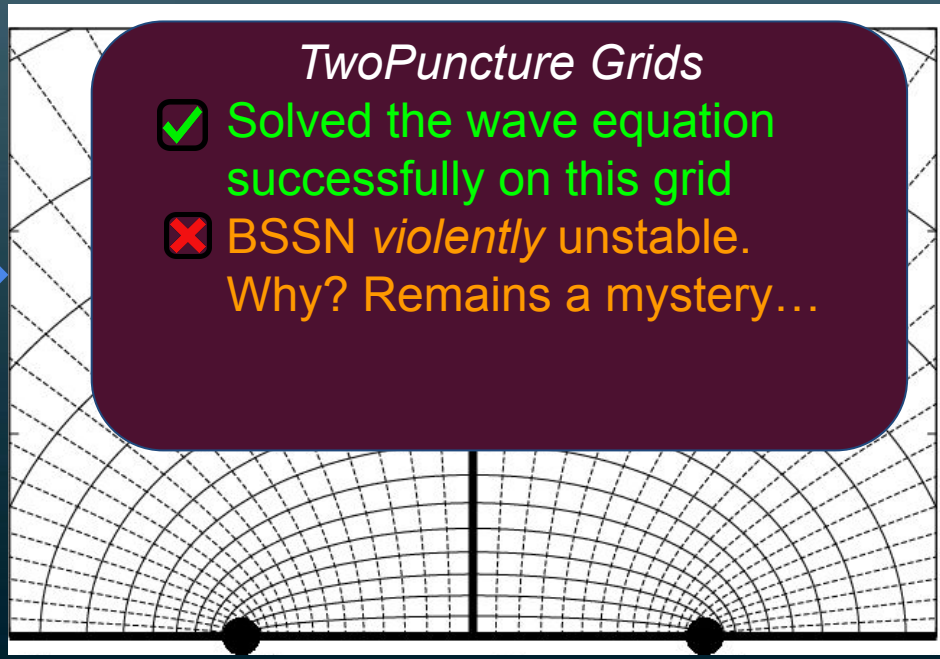
- ❌ BSSN *violently* unstable. Why? Remains a mystery…



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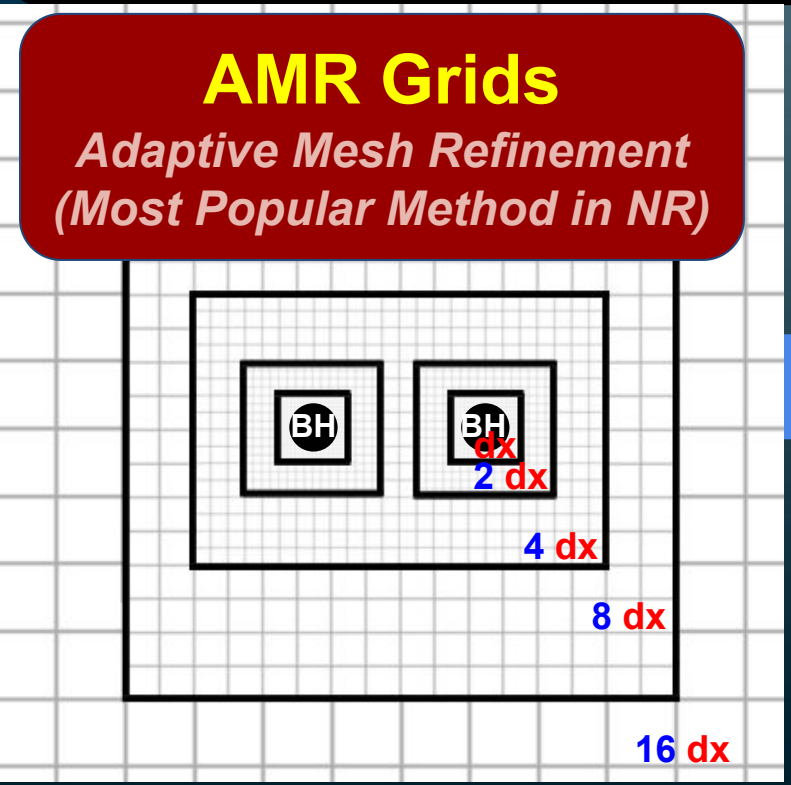

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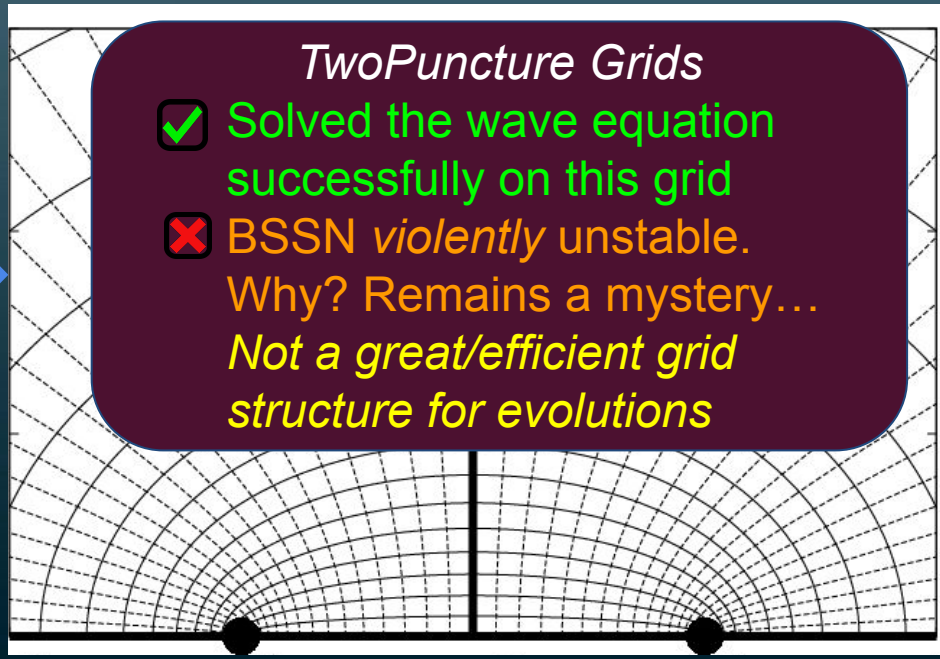
Not a great/efficient grid structure for evolutions



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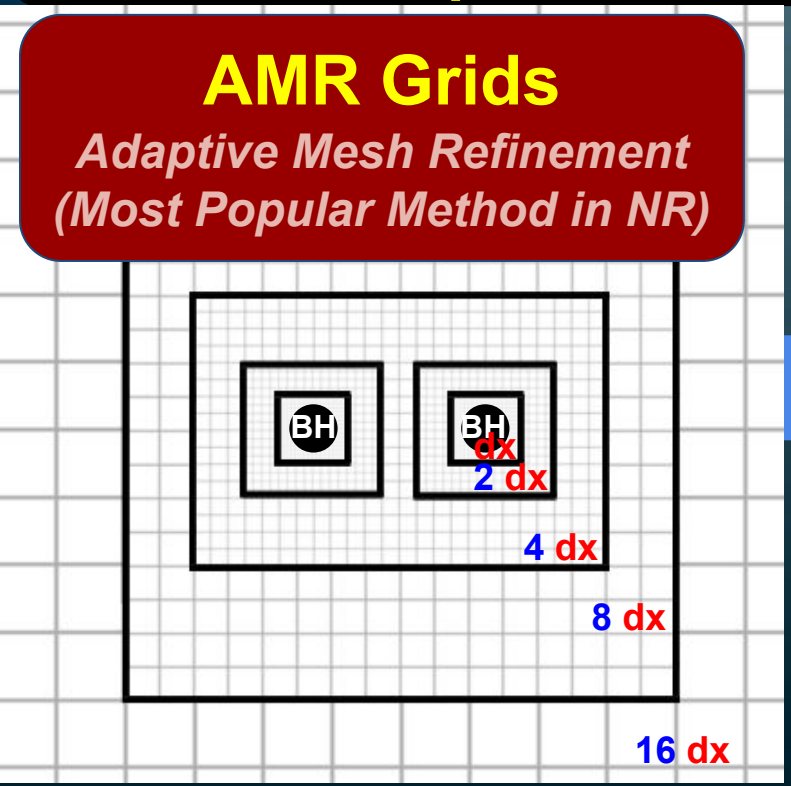
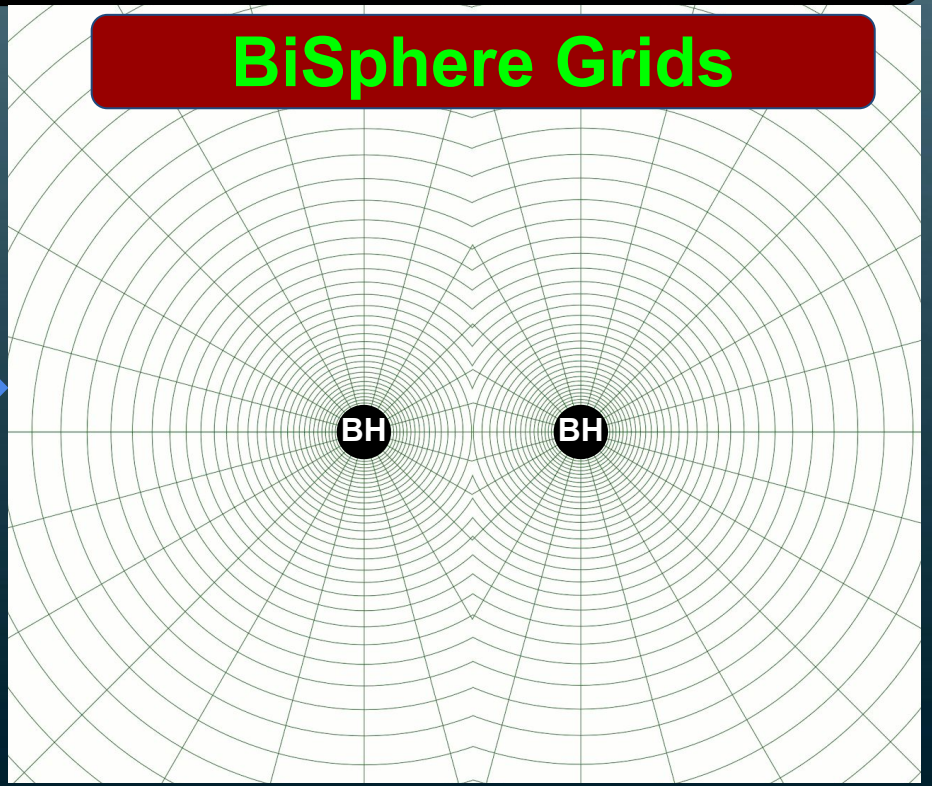


BiSphere Grids



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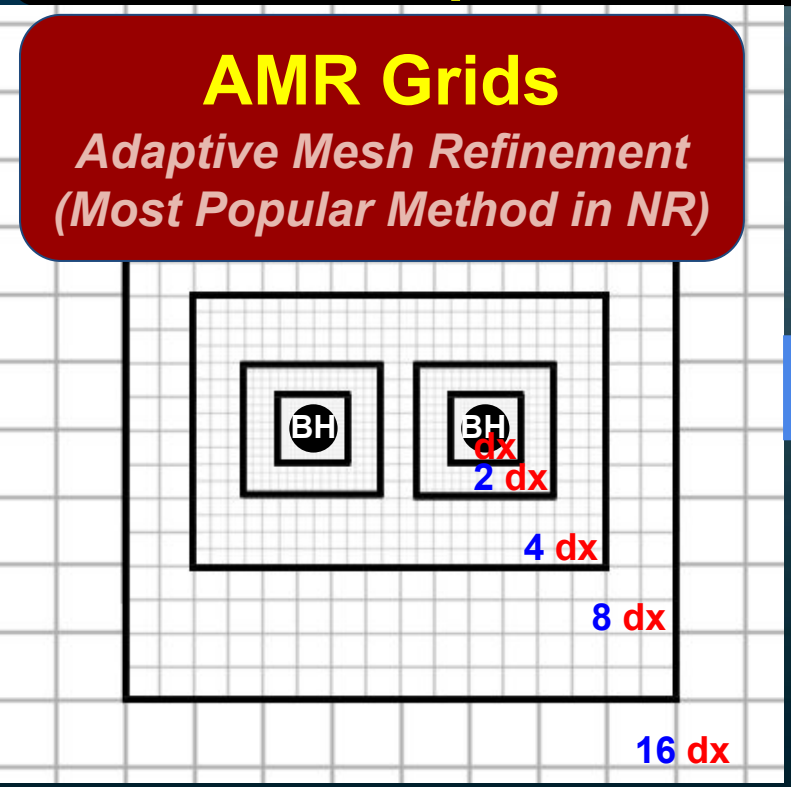
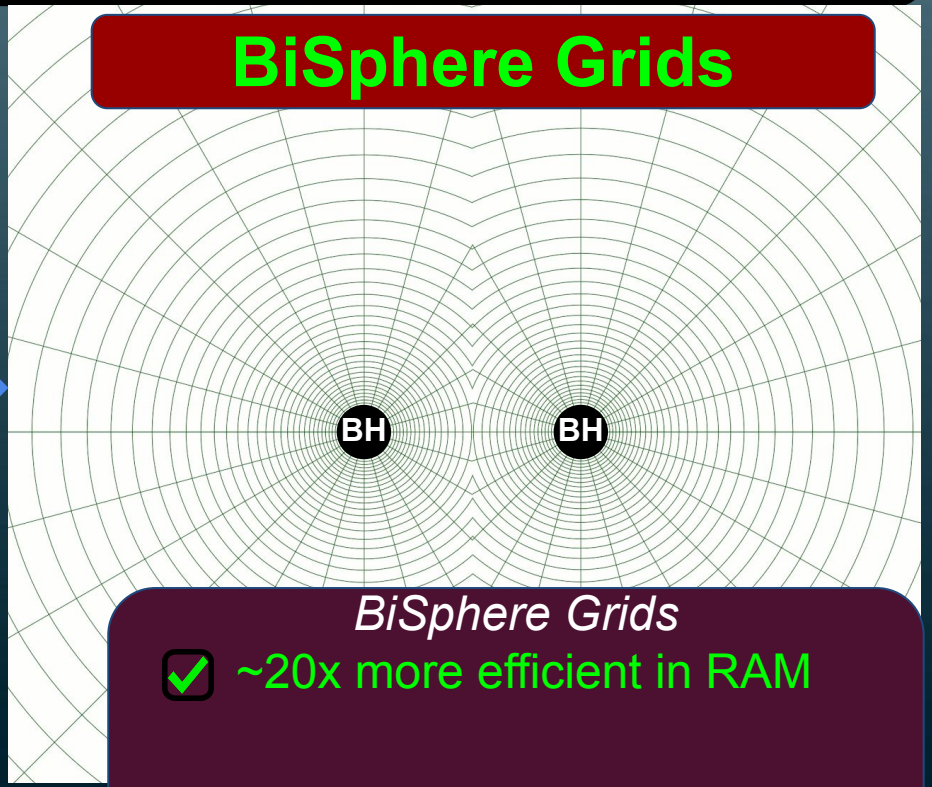


BiSphere Grids



BiSphere Grids

☑ ~20x more efficient in RAM

BlackHoles@Home: BBHs on the Desktop
Development of Super-Efficient Grid Structures

AMR Grids

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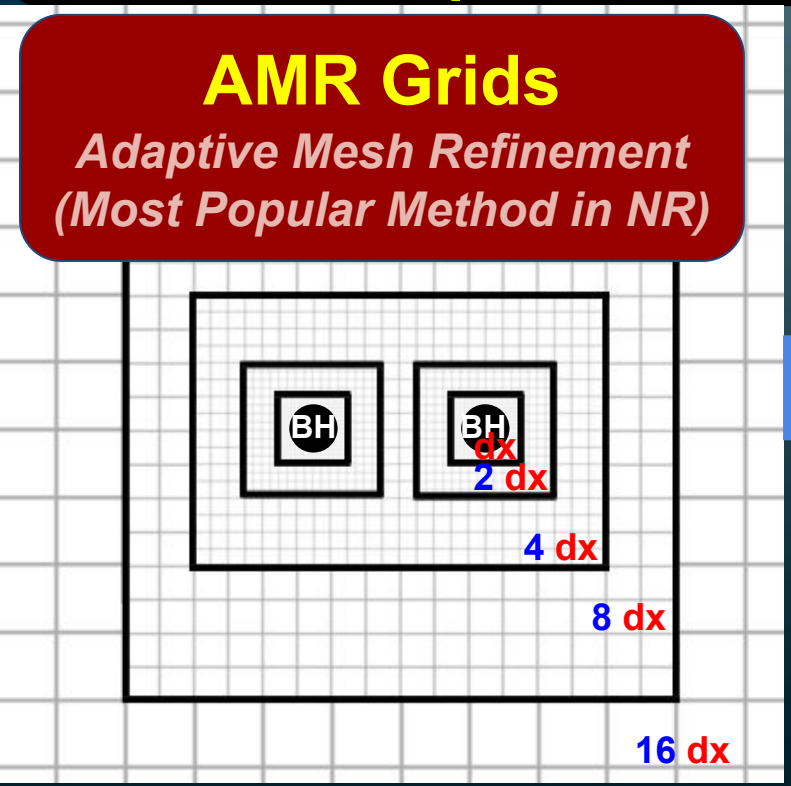

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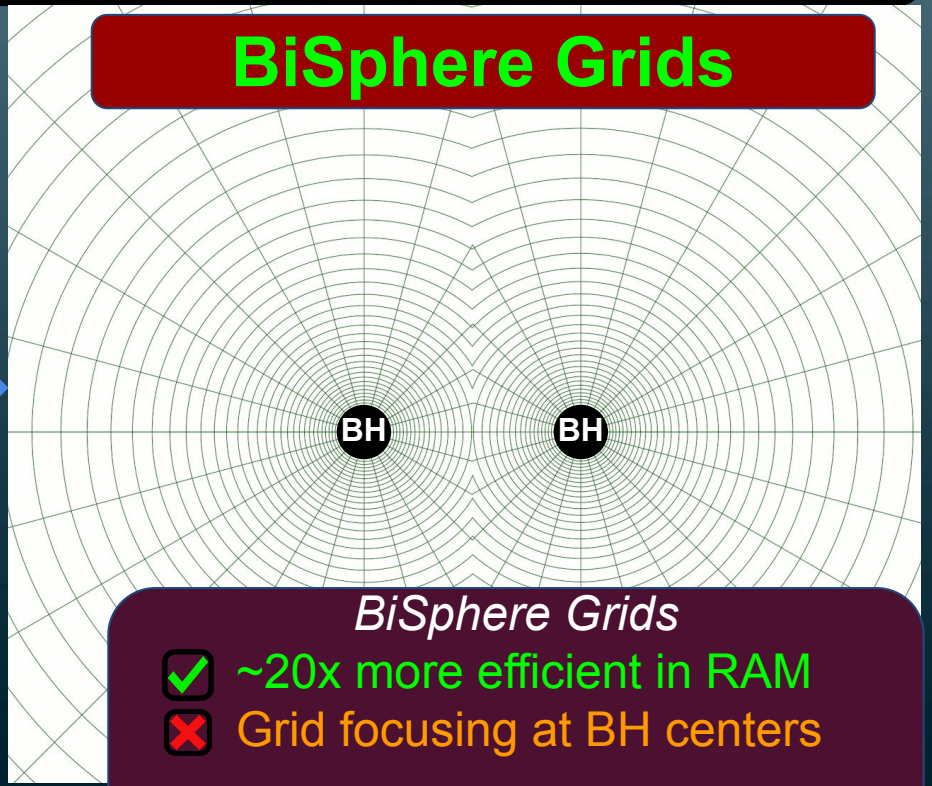

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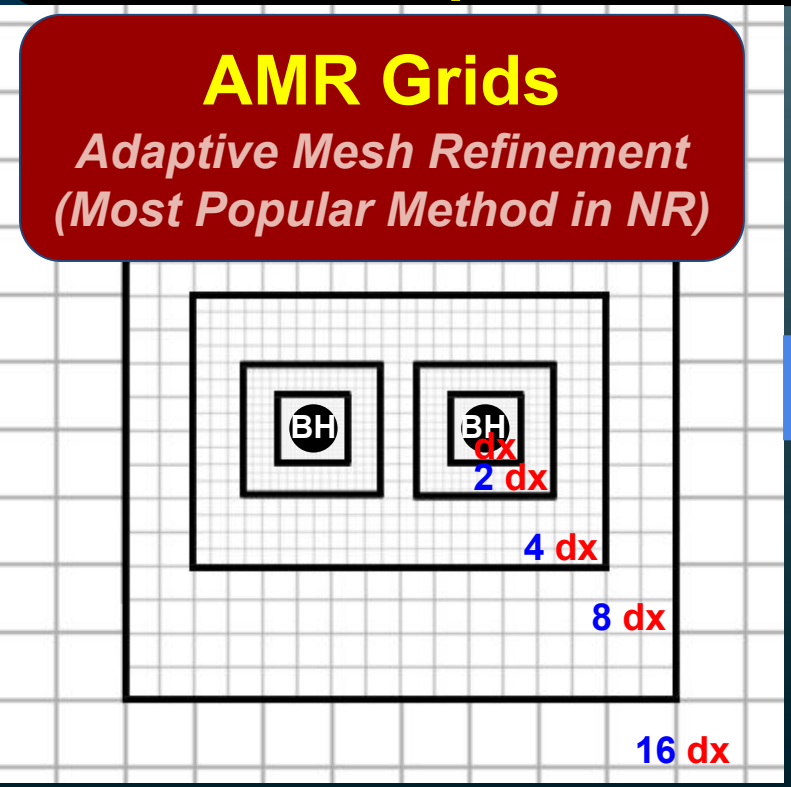

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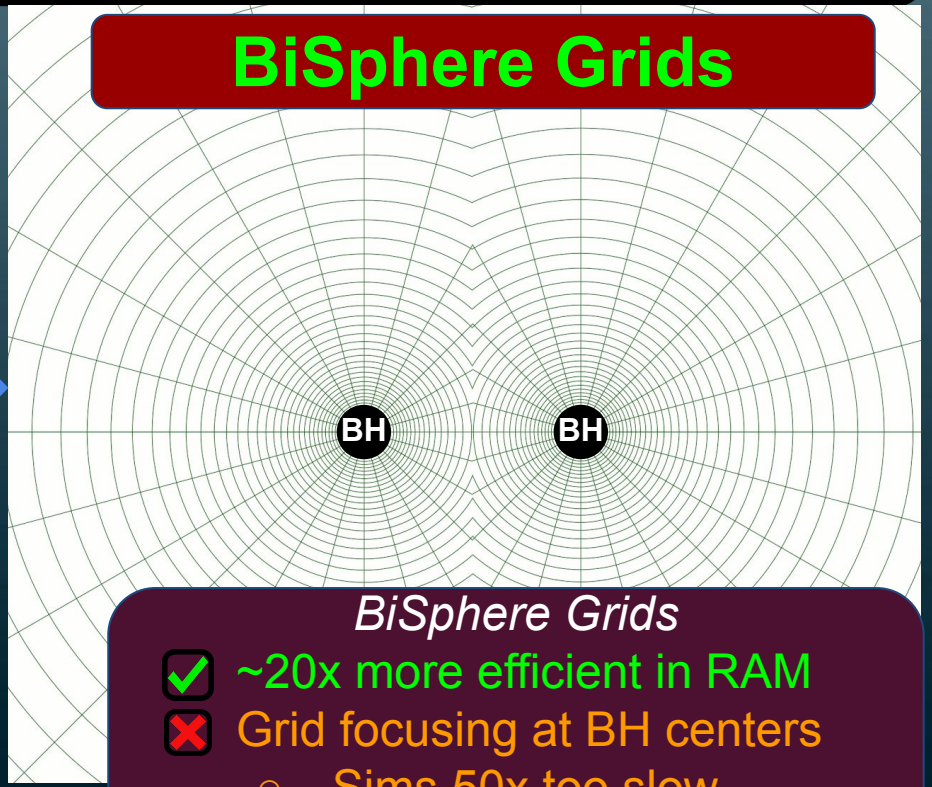

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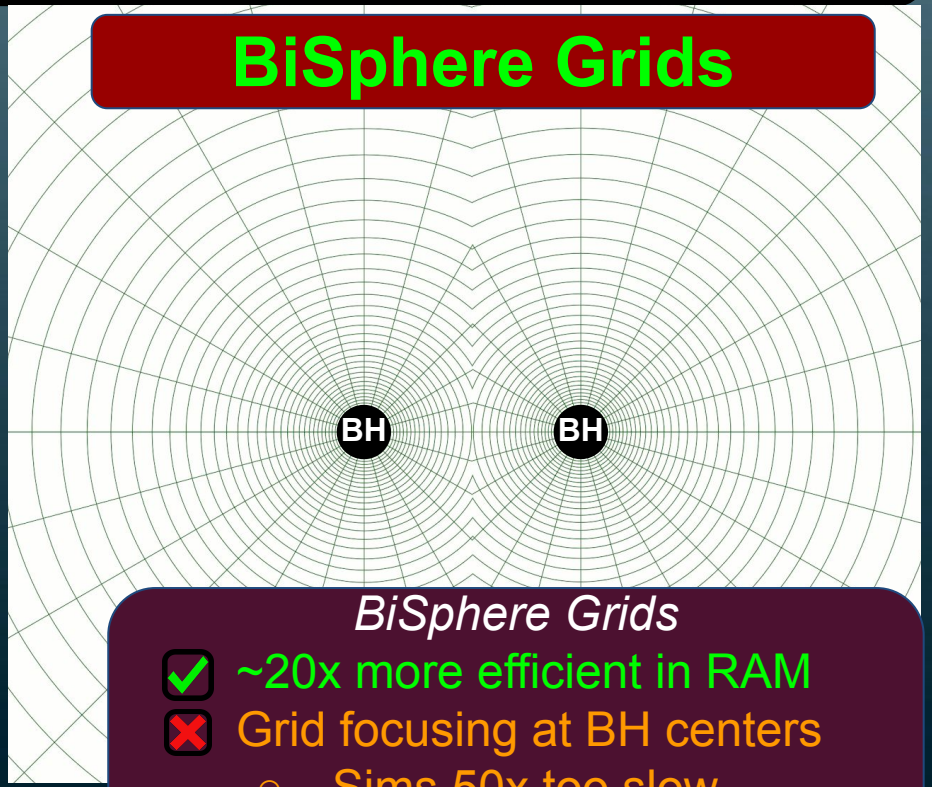

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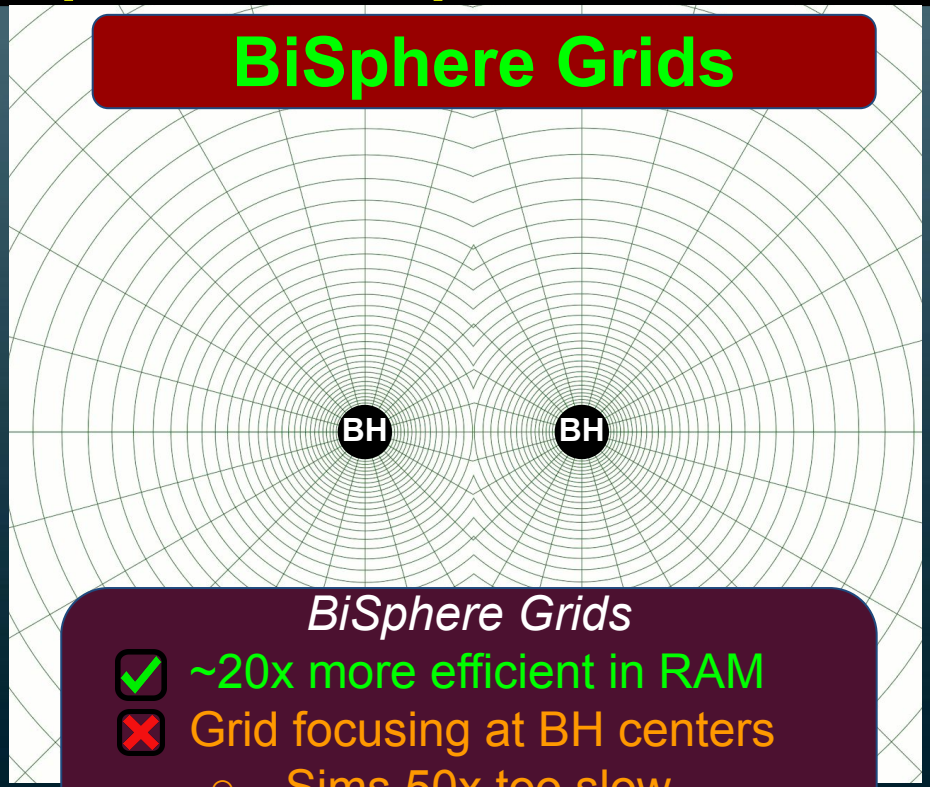

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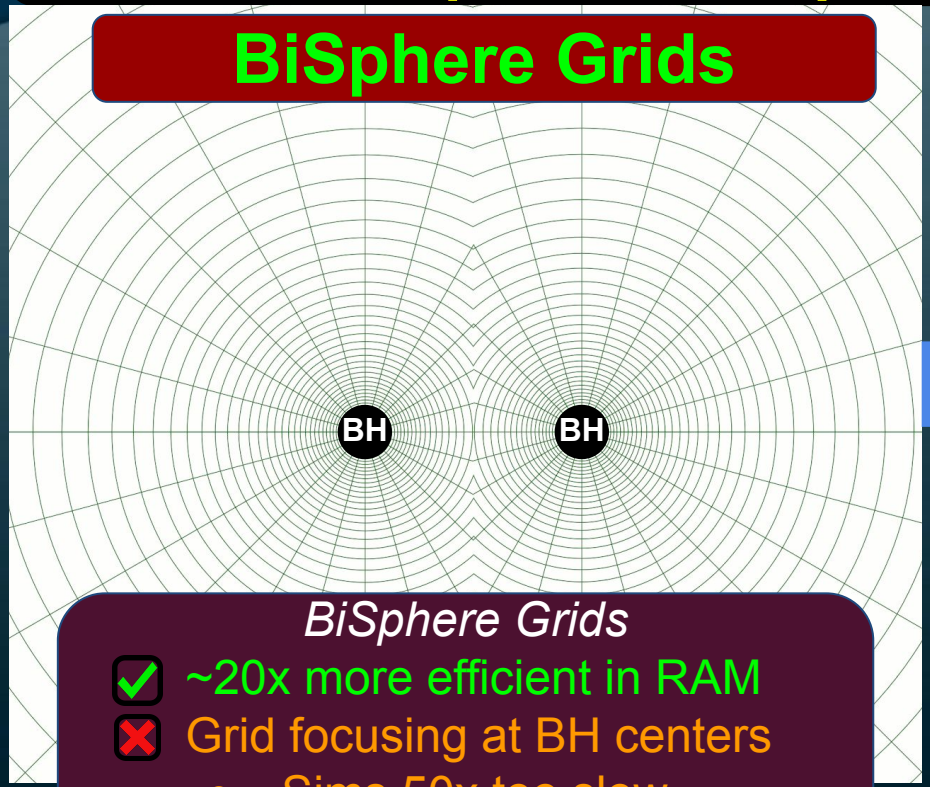

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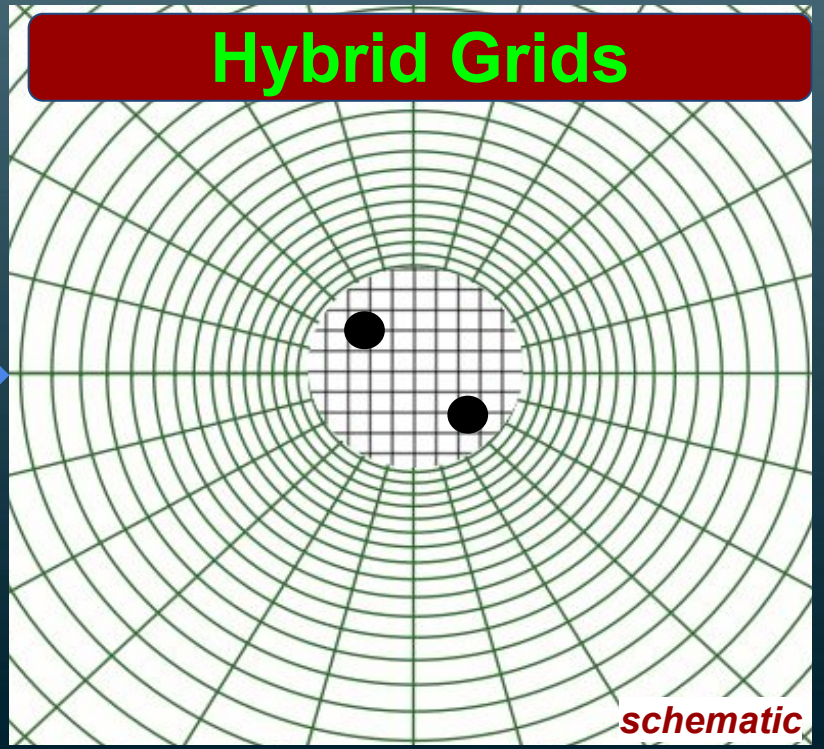

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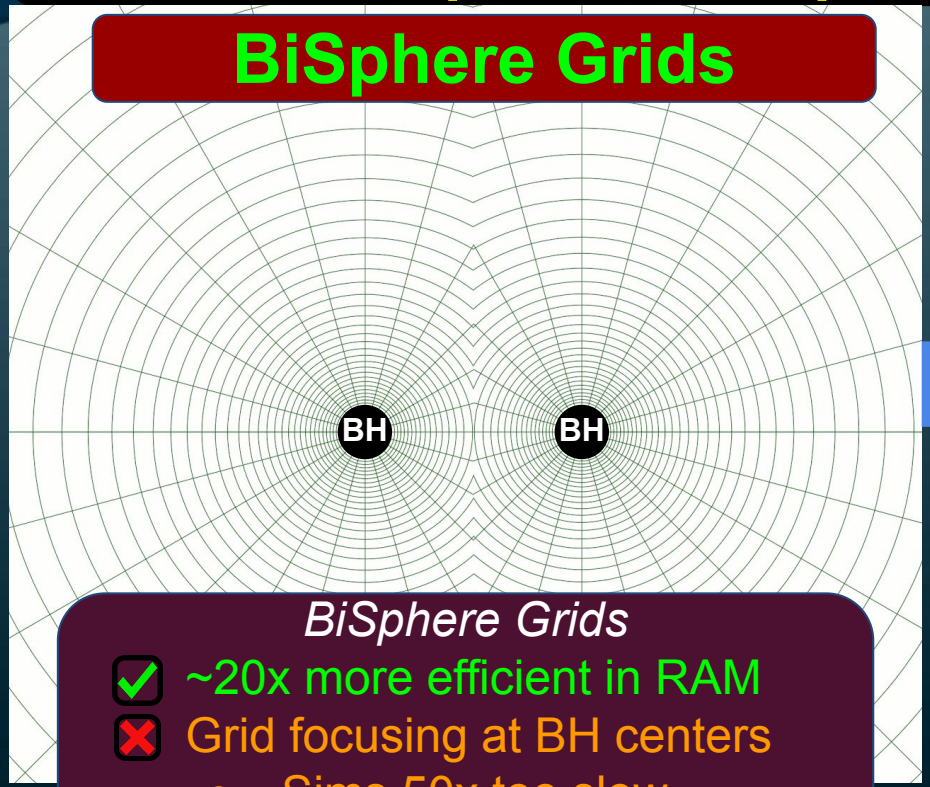

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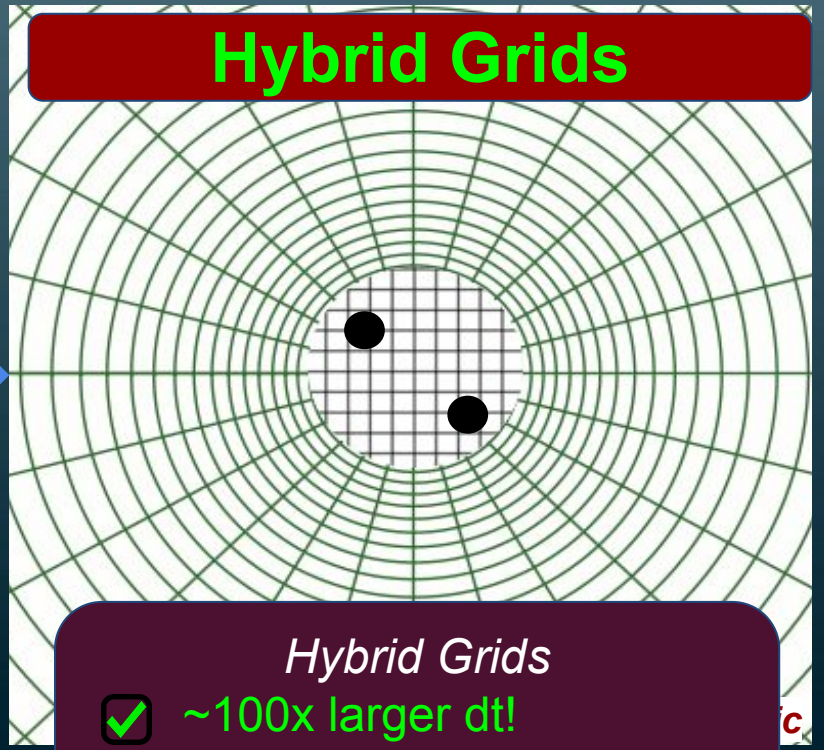

Hybrid Grids

- ✅ ~100x larger dt!

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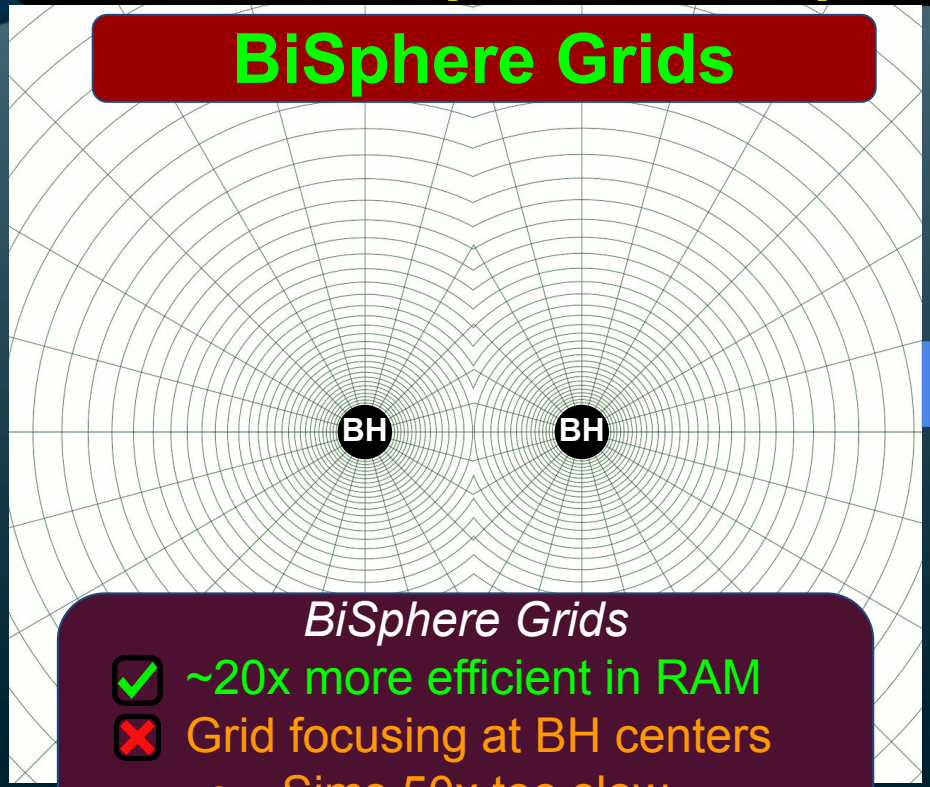

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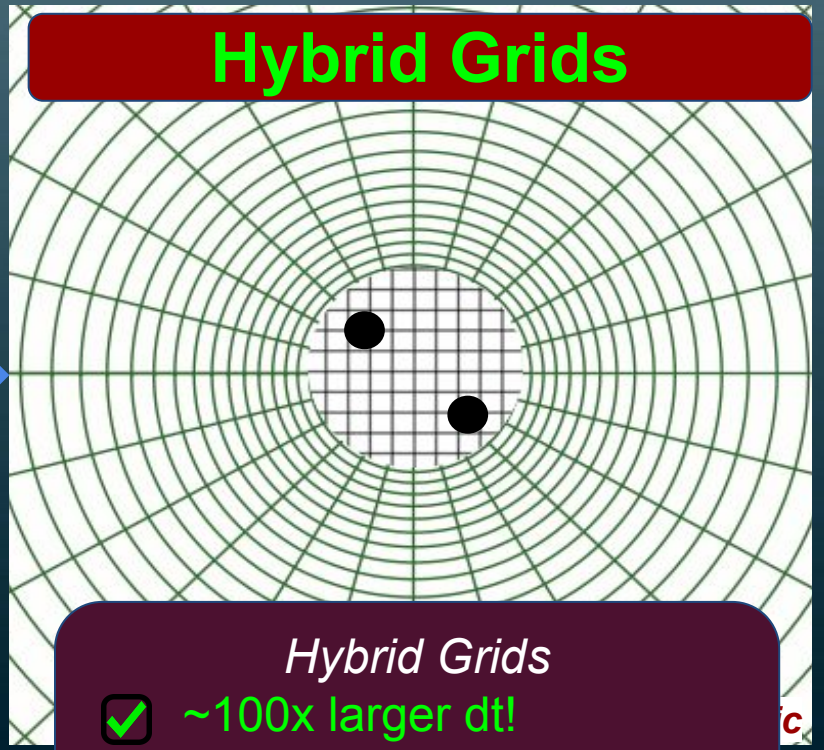
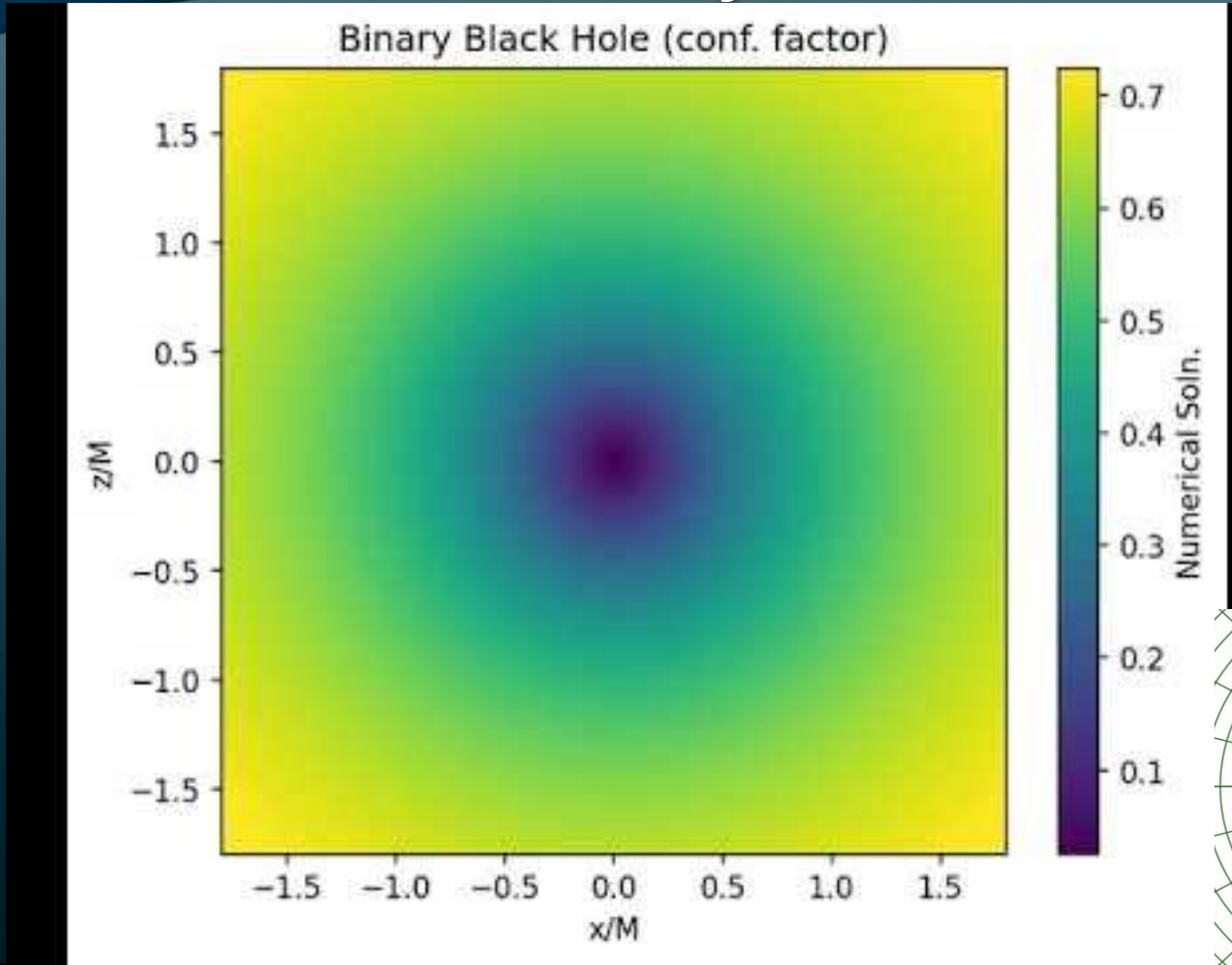
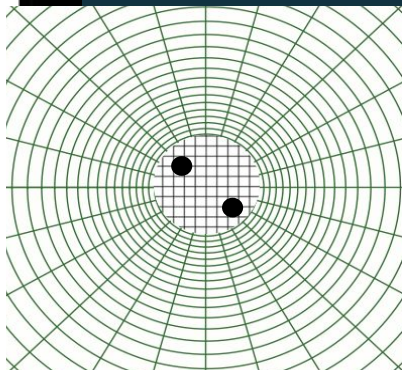


Hybrid Grids

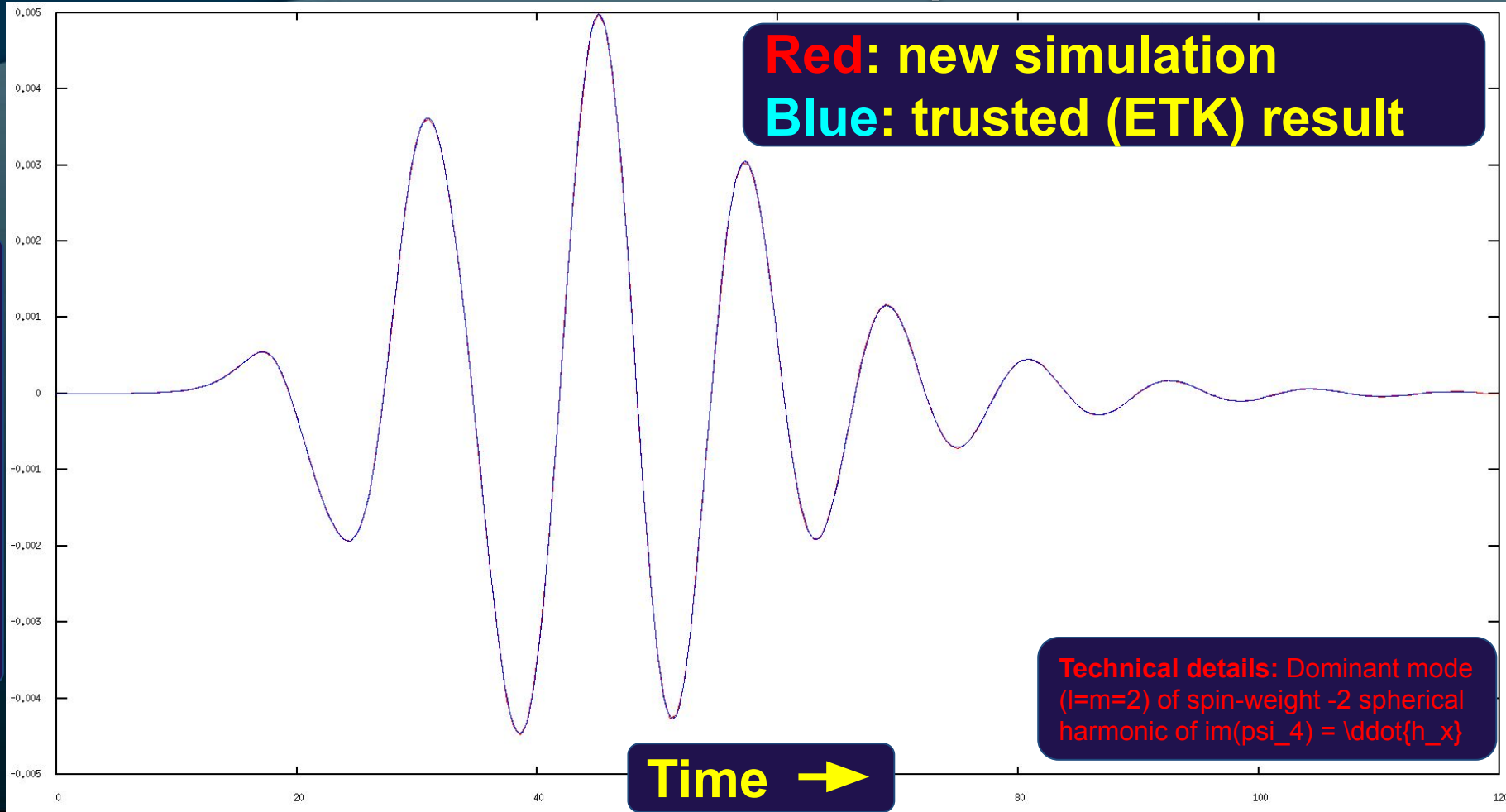
- ✅ ~100x larger dt!
- Memory usage?!
- **Will it even work?!**

Results from Hybrid Grids





Gravitational Wave Comparison



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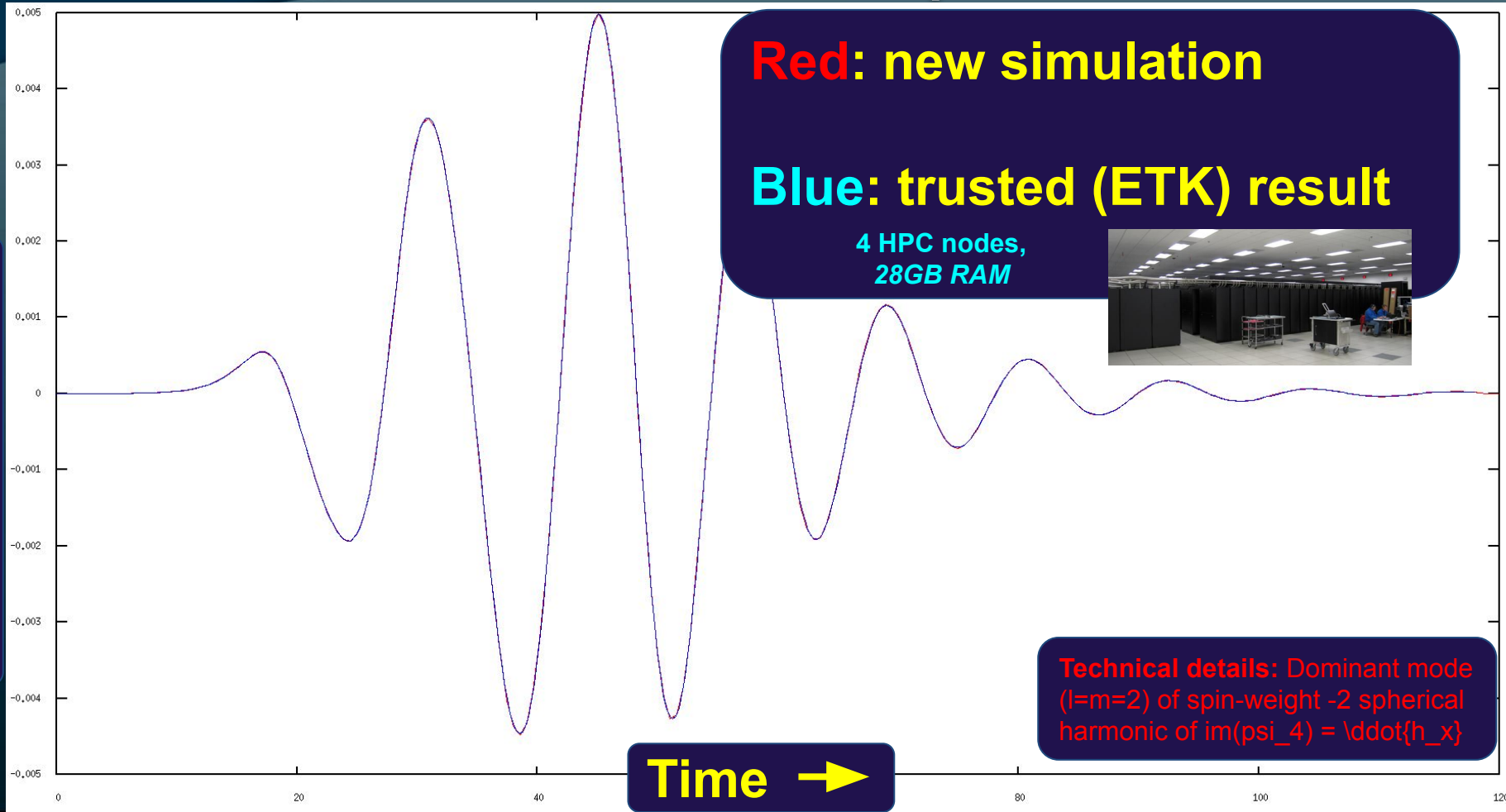

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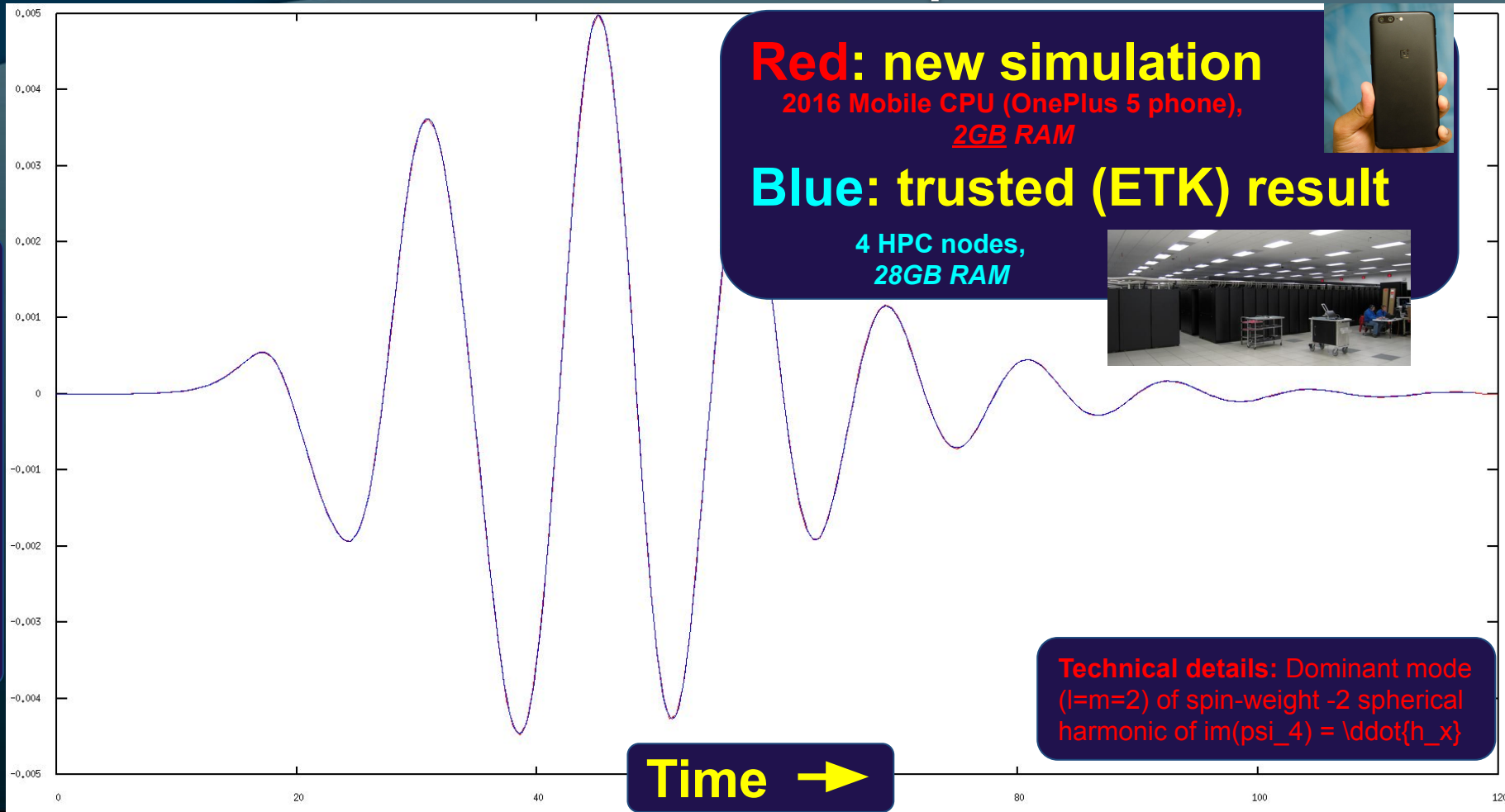

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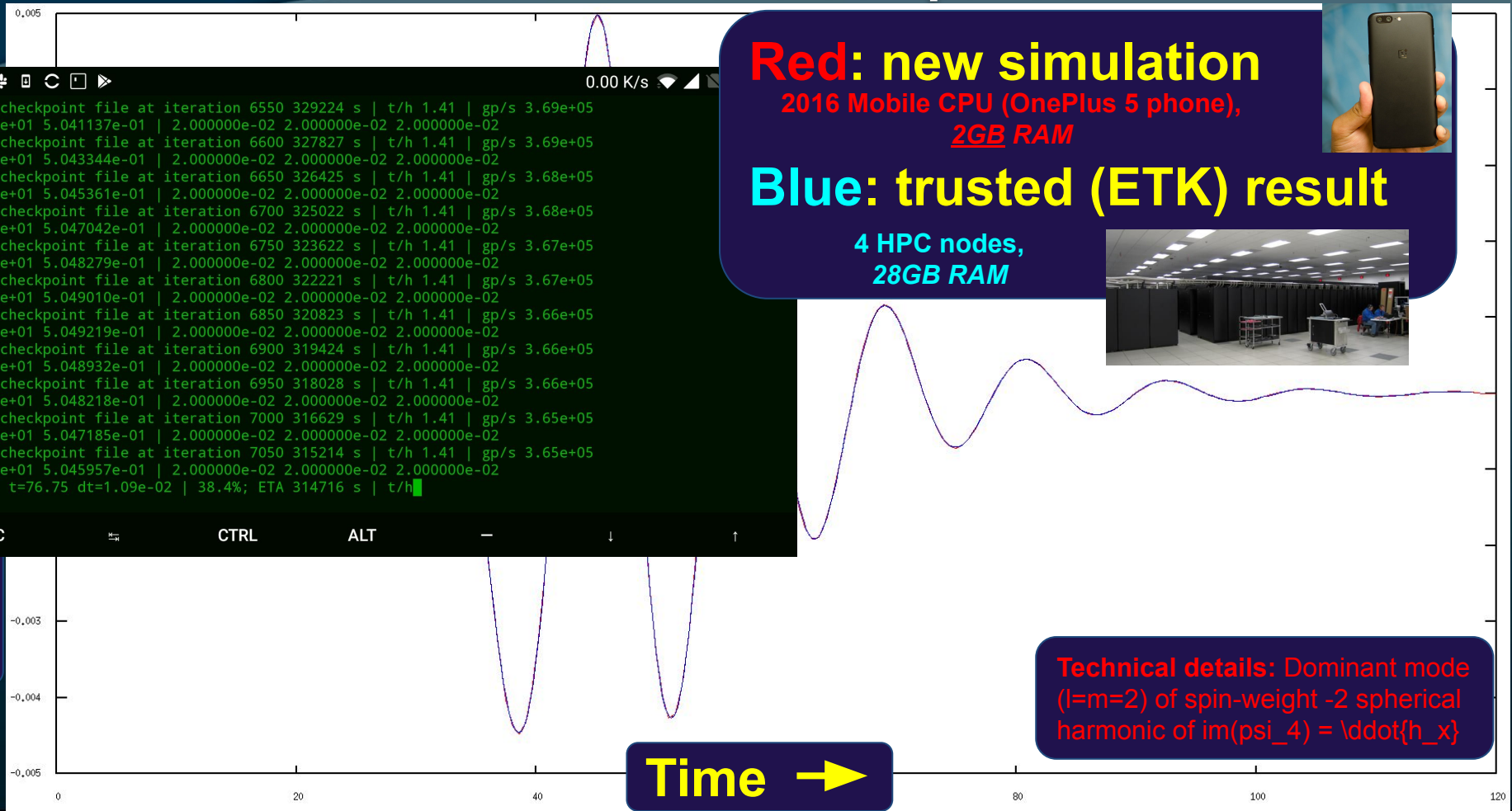


16:29 0.00 K/s

```
Writing checkpoint file at iteration 6550 329224 s | t/h 1.41 | gp/s 3.69e+05
7.114185e+01 5.041137e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 6600 327827 s | t/h 1.41 | gp/s 3.69e+05
7.168492e+01 5.043344e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 6650 326425 s | t/h 1.41 | gp/s 3.68e+05
7.222799e+01 5.045361e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 6700 325022 s | t/h 1.41 | gp/s 3.68e+05
7.277105e+01 5.047042e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 6750 323622 s | t/h 1.41 | gp/s 3.67e+05
7.331412e+01 5.048279e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 6800 322221 s | t/h 1.41 | gp/s 3.67e+05
7.385719e+01 5.049010e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 6850 320823 s | t/h 1.41 | gp/s 3.66e+05
7.440026e+01 5.049219e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 6900 319424 s | t/h 1.41 | gp/s 3.66e+05
7.494332e+01 5.048932e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 6950 318028 s | t/h 1.41 | gp/s 3.66e+05
7.548639e+01 5.048218e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 7000 316629 s | t/h 1.41 | gp/s 3.65e+05
7.602946e+01 5.047185e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
Writing checkpoint file at iteration 7050 315214 s | t/h 1.41 | gp/s 3.65e+05
7.657253e+01 5.045957e-01 | 2.000000e-02 2.000000e-02 2.000000e-02
It: 7066 t=76.75 dt=1.09e-02 | 38.4%; ETA 314716 s | t/h
```

ESC CTRL ALT

Red: new simulation

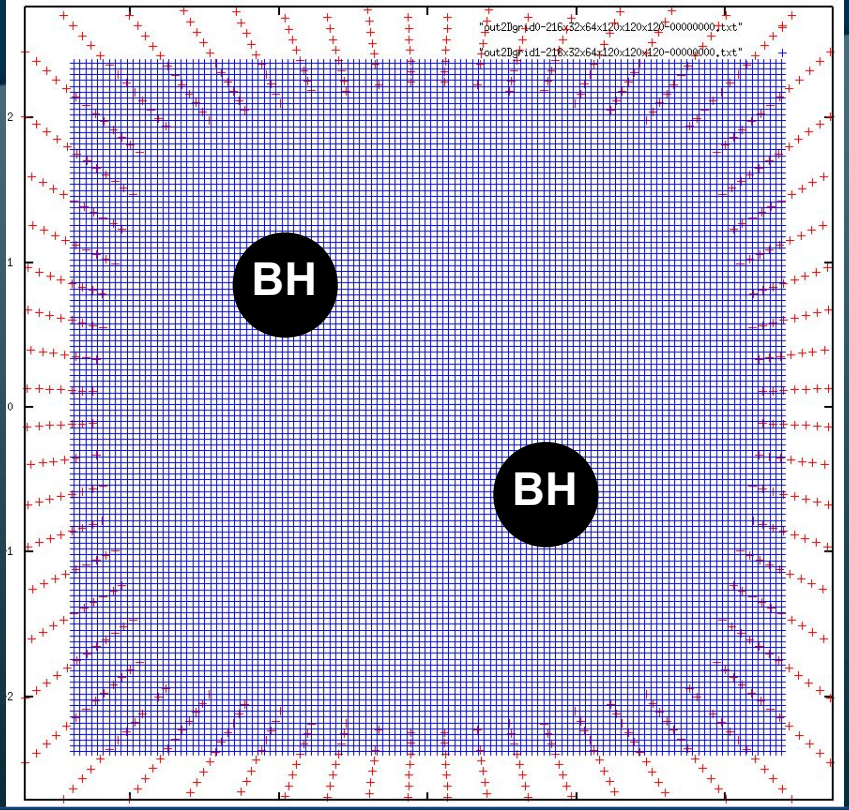
2016 Mobile CPU (OnePlus 5 phone), *2GB RAM*

Blue: trusted (ETK) result

4 HPC nodes, *28GB RAM*

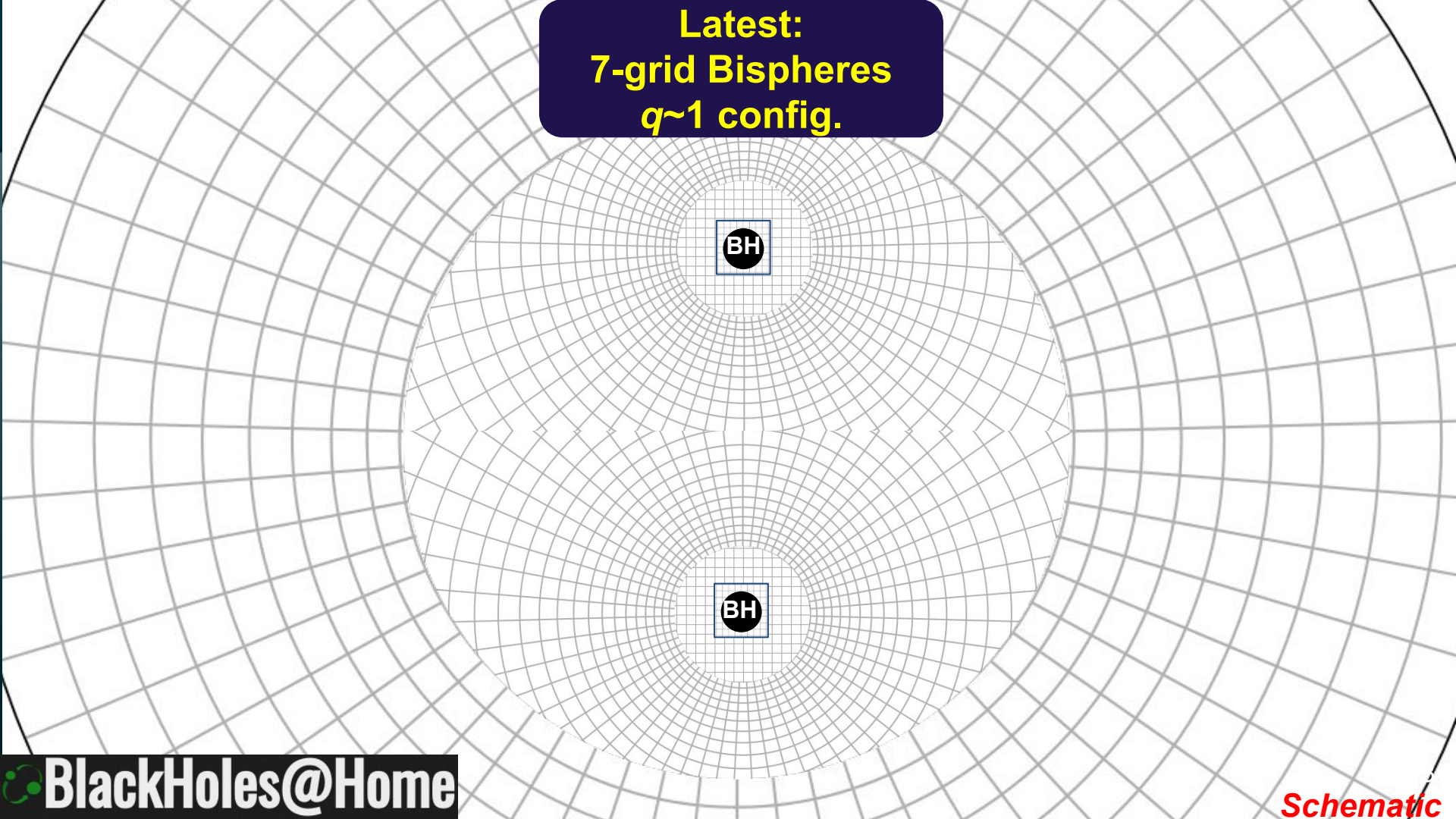
Technical details: Dominant mode (l=m=2) of spin-weight -2 spherical harmonic of im(psi_4) = \ddot{h_x}

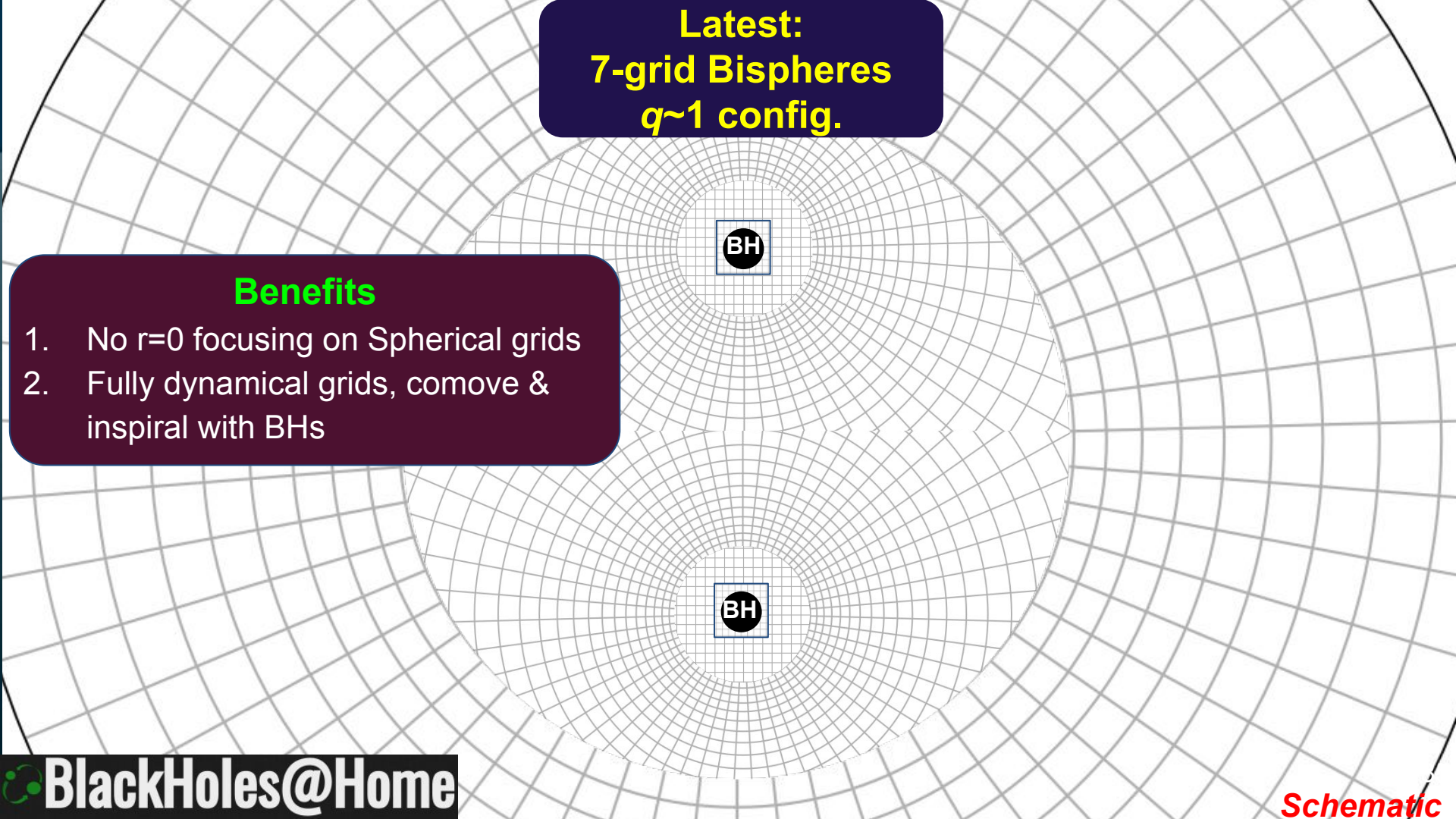
Early 2020 Results



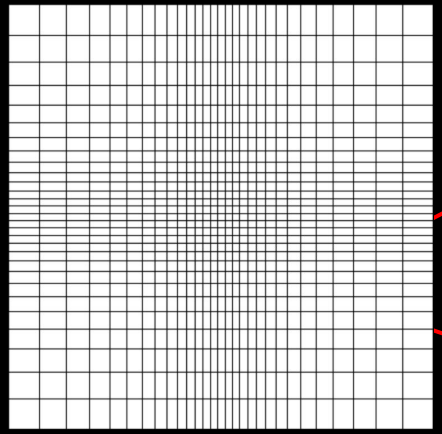
- Problem with this grid structure:
  - Only works well for two orbiting black holes ***very close* to merger**
  - Larger separations -- Cartesian grid too large -- too much memory!

- ***What to do?!***


Latest:
7-grid Bispheres
q~1 config.
BH
BH
BlackHoles@Home
Schematic


Latest:
7-grid Bispheres
q~1 config.
BH
BH
Benefits
1. No r=0 focusing on Spherical grids
2. Fully dynamical grids, comove & inspiral with BHs
BlackHoles@Home
Schematic

Latest:
7-grid Bispheres
q~1 config.



SinhCartesian focuses gridpoints along x,y,z axes.
Great for puncture BHs
AMR: *~8x in 1 refinement*

SinhCart AMR

BH

Small SinhSpherical

Small SinhSpherical

BH

SinhCart AMR

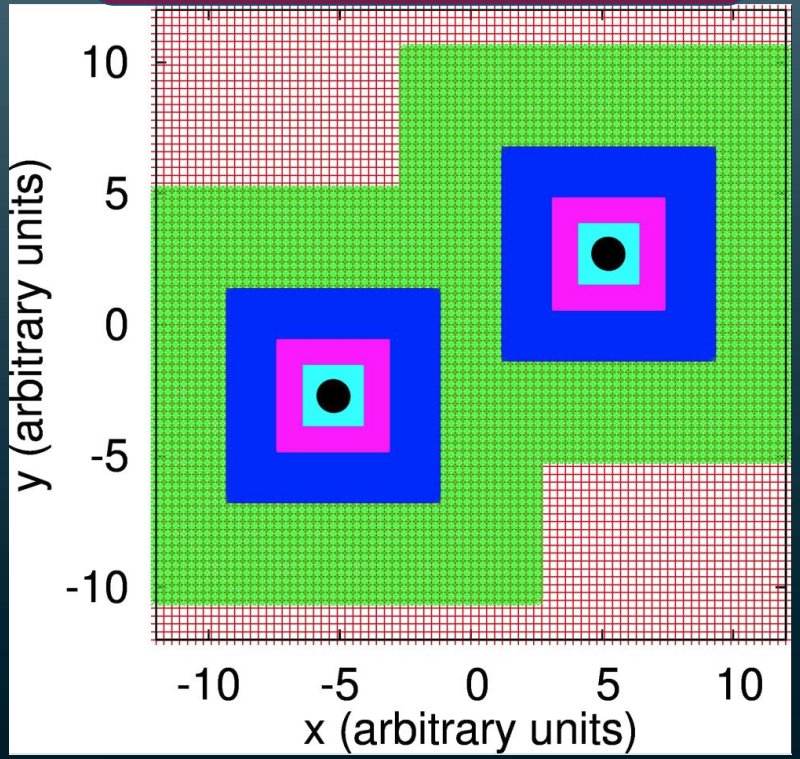
Large SinhSpherical

BlackHoles@Home

Schematic

Basic Idea:
More efficient simulation grids

Most popular grid approach:
Needs ~100GB of RAM



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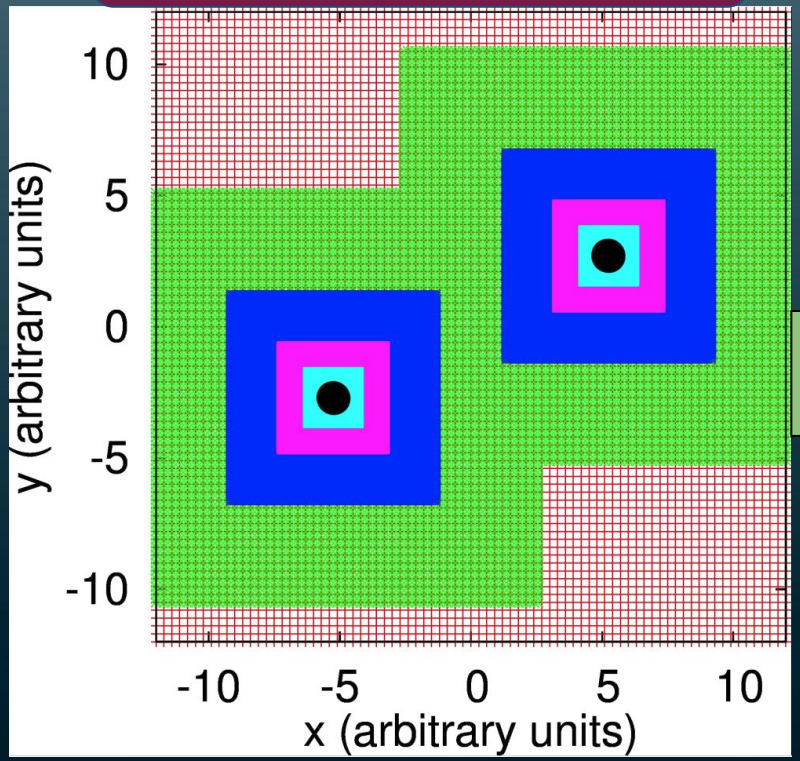
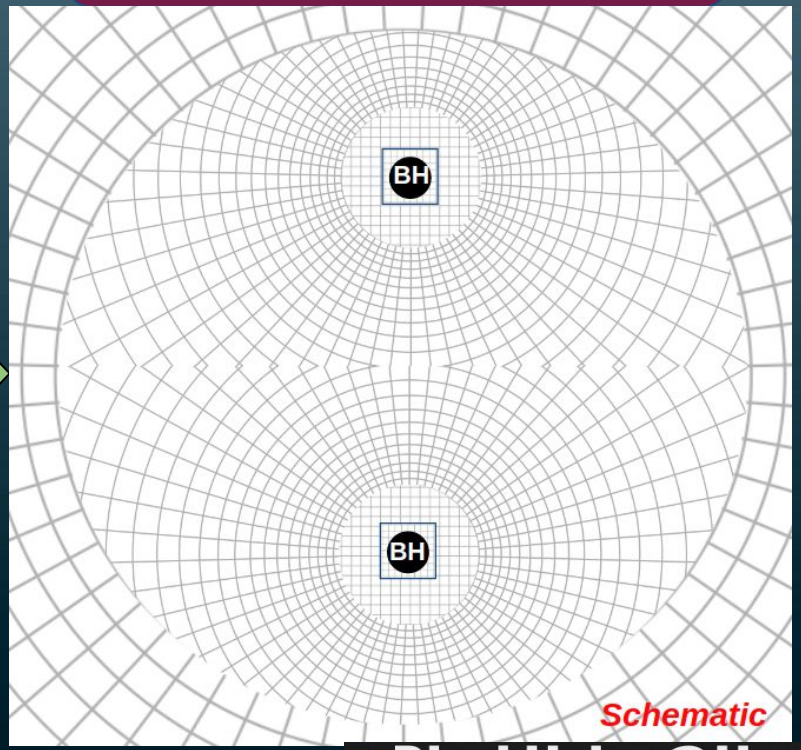


BlackHoles@Home grids:
Needs ~3GB of RAM



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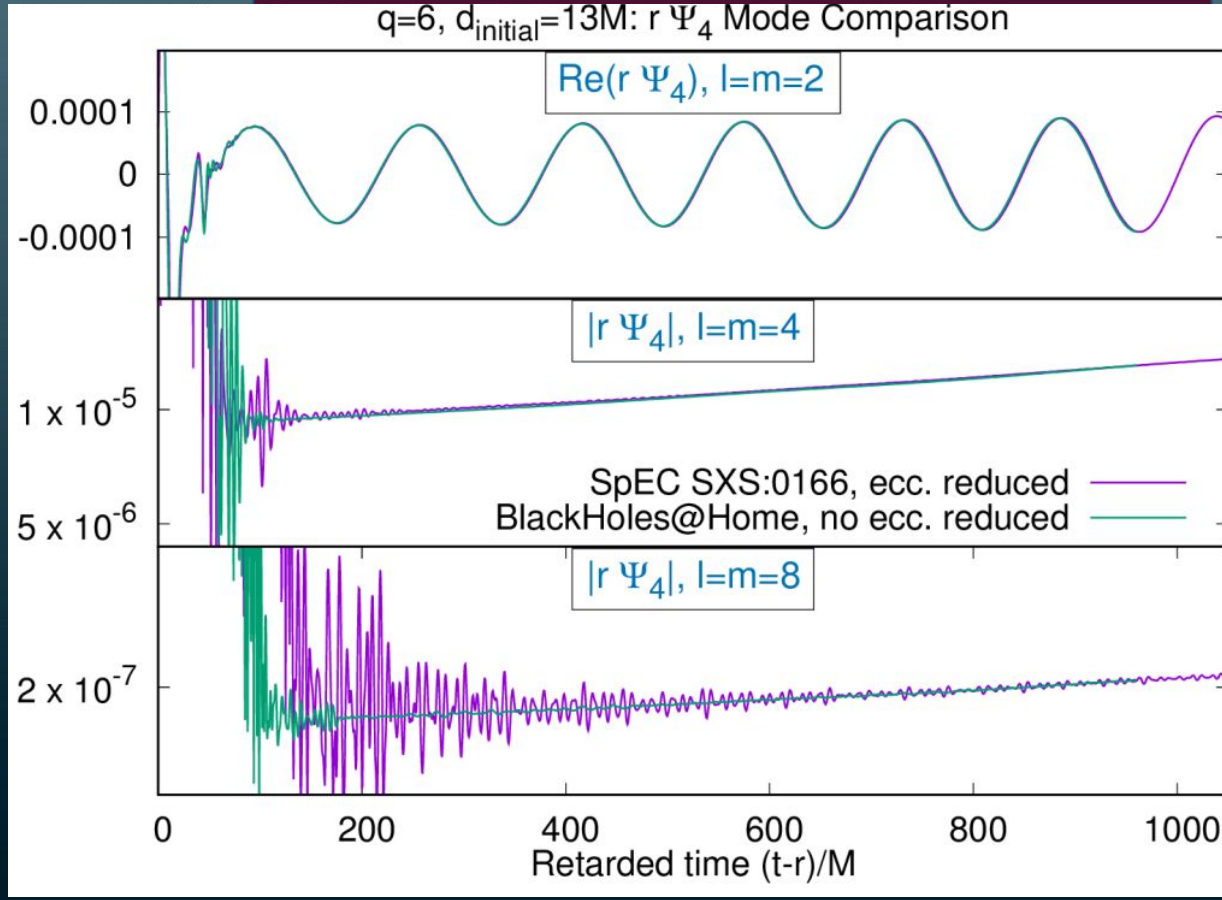
Dev. Highlights 2020-2023

- 2020-2021: 7-grid BiSpheres grids; inspirals **look great vs SpEC**



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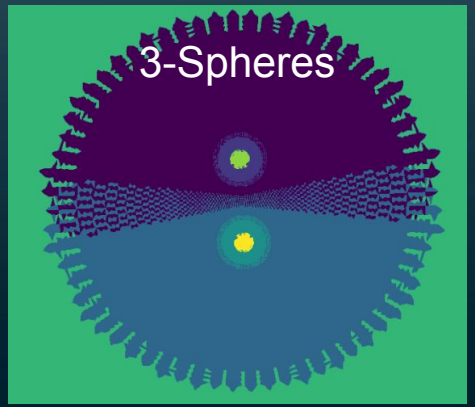
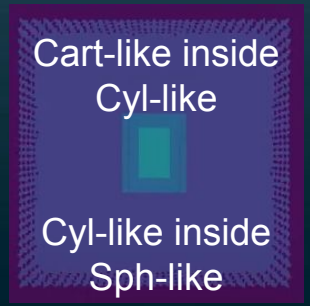
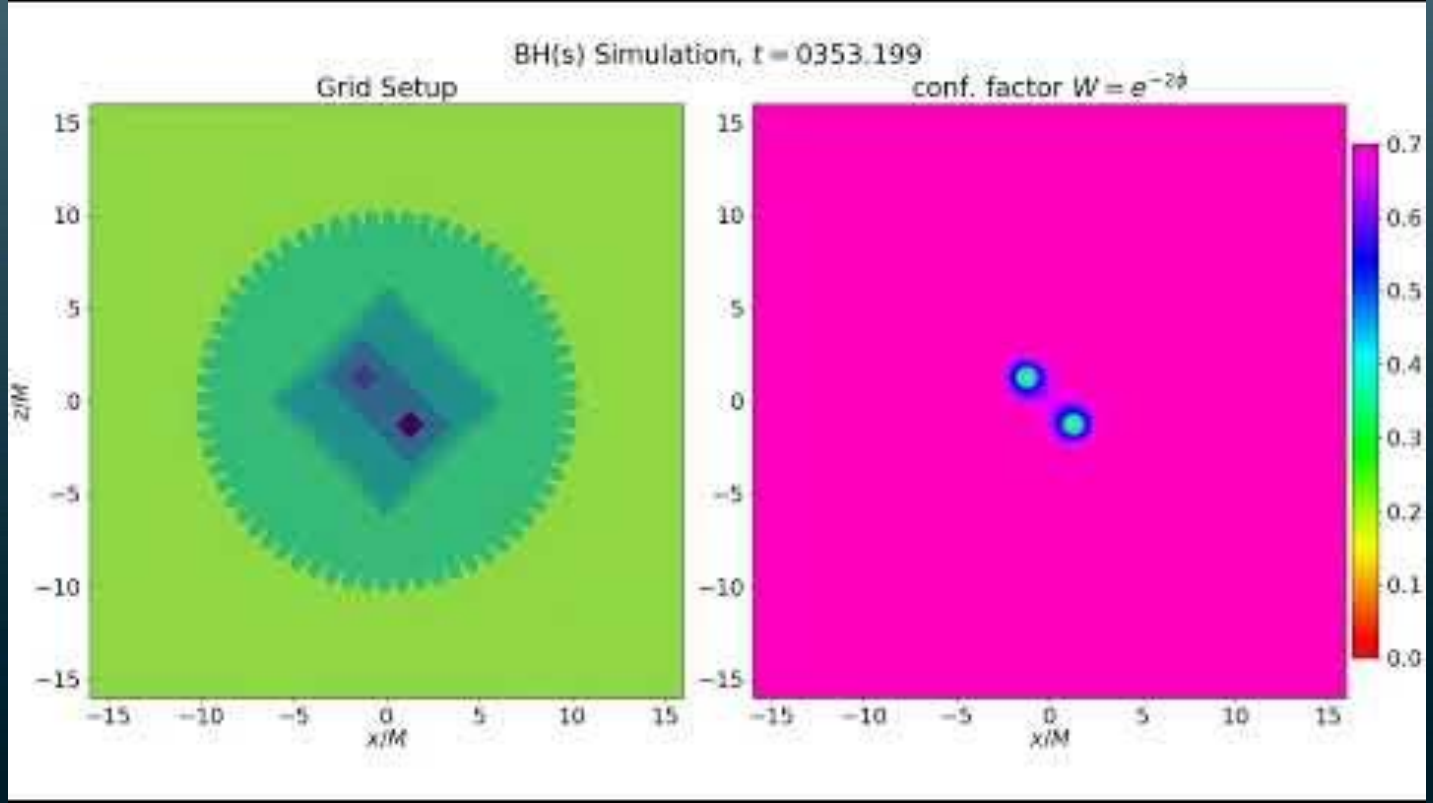




New grid structures example
q=1 nonspinning, initial sep=8M BBH



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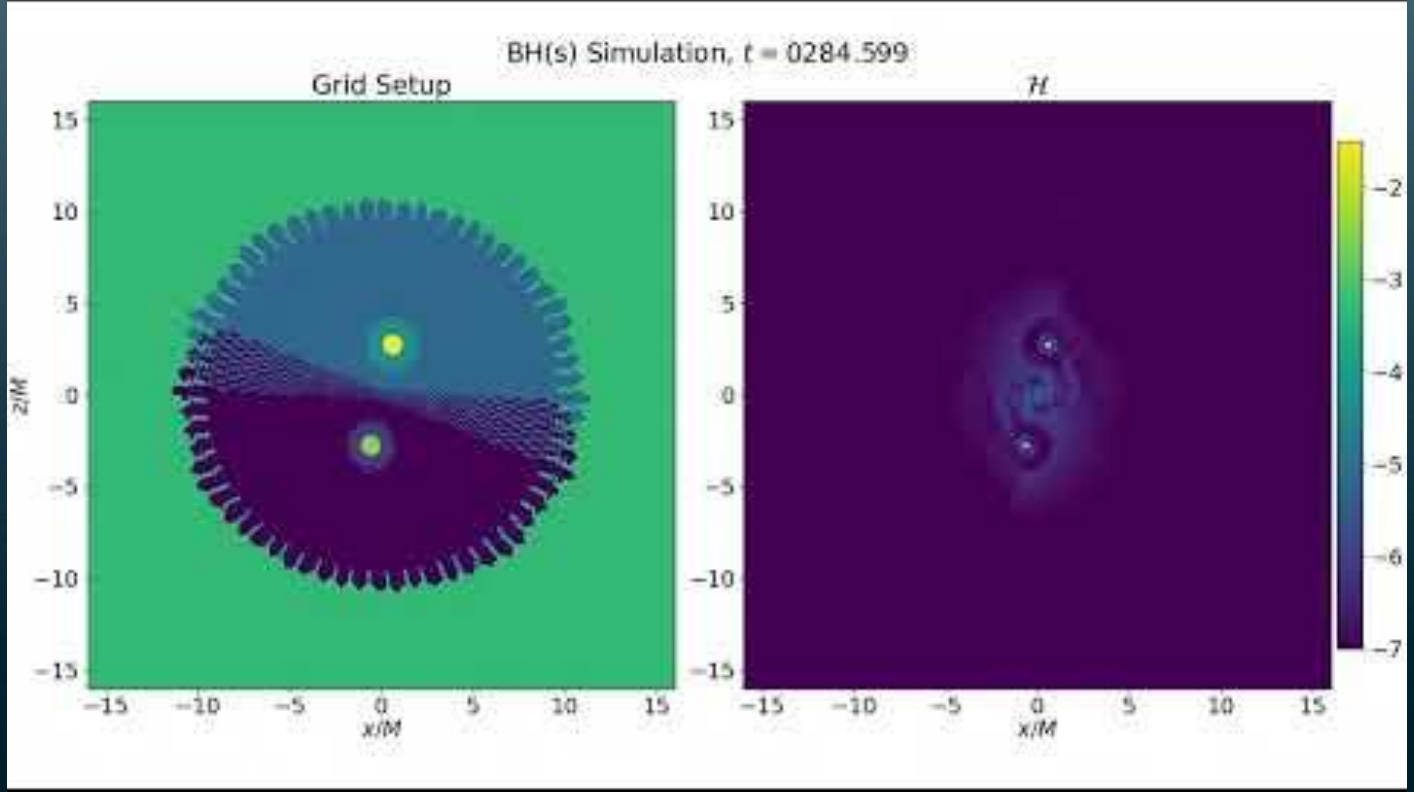

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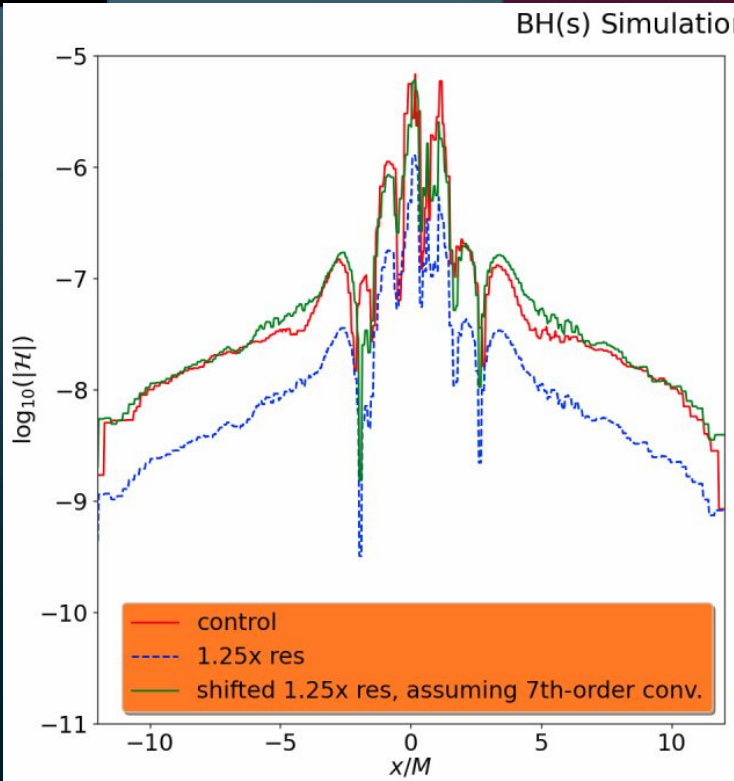

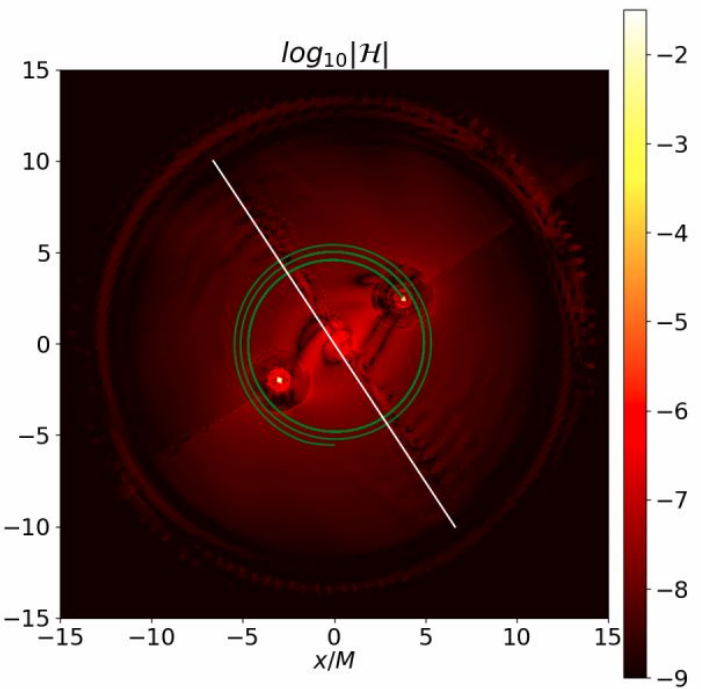

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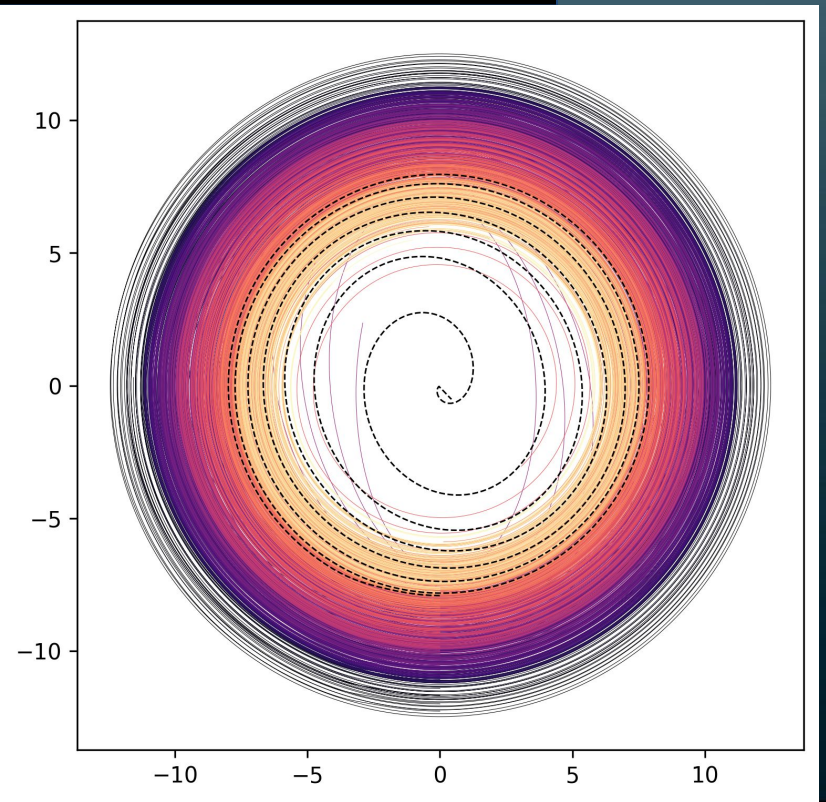
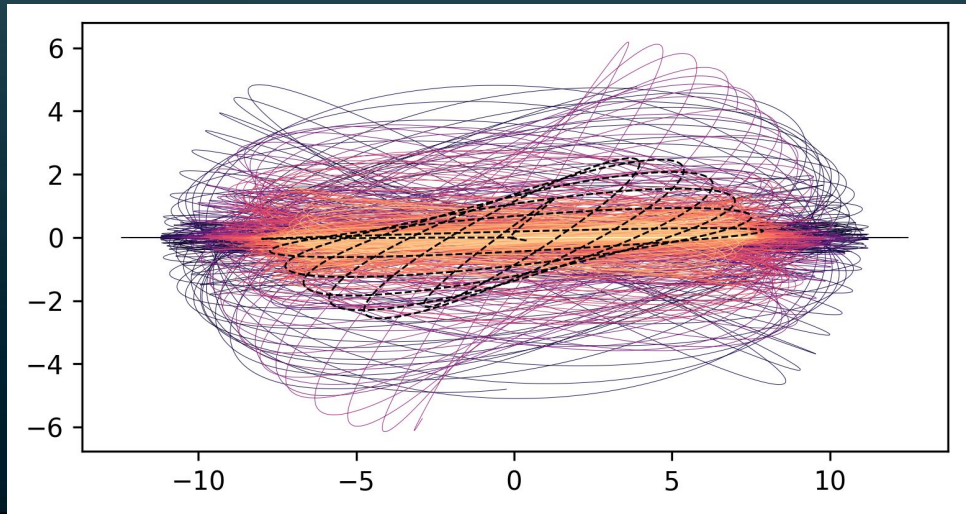
- 2022: Rewrote multipatch to handle ***mergers***; 7th order convergence!
- 2023: Performed **hundreds** of BBH simulations, found instability in ~20%





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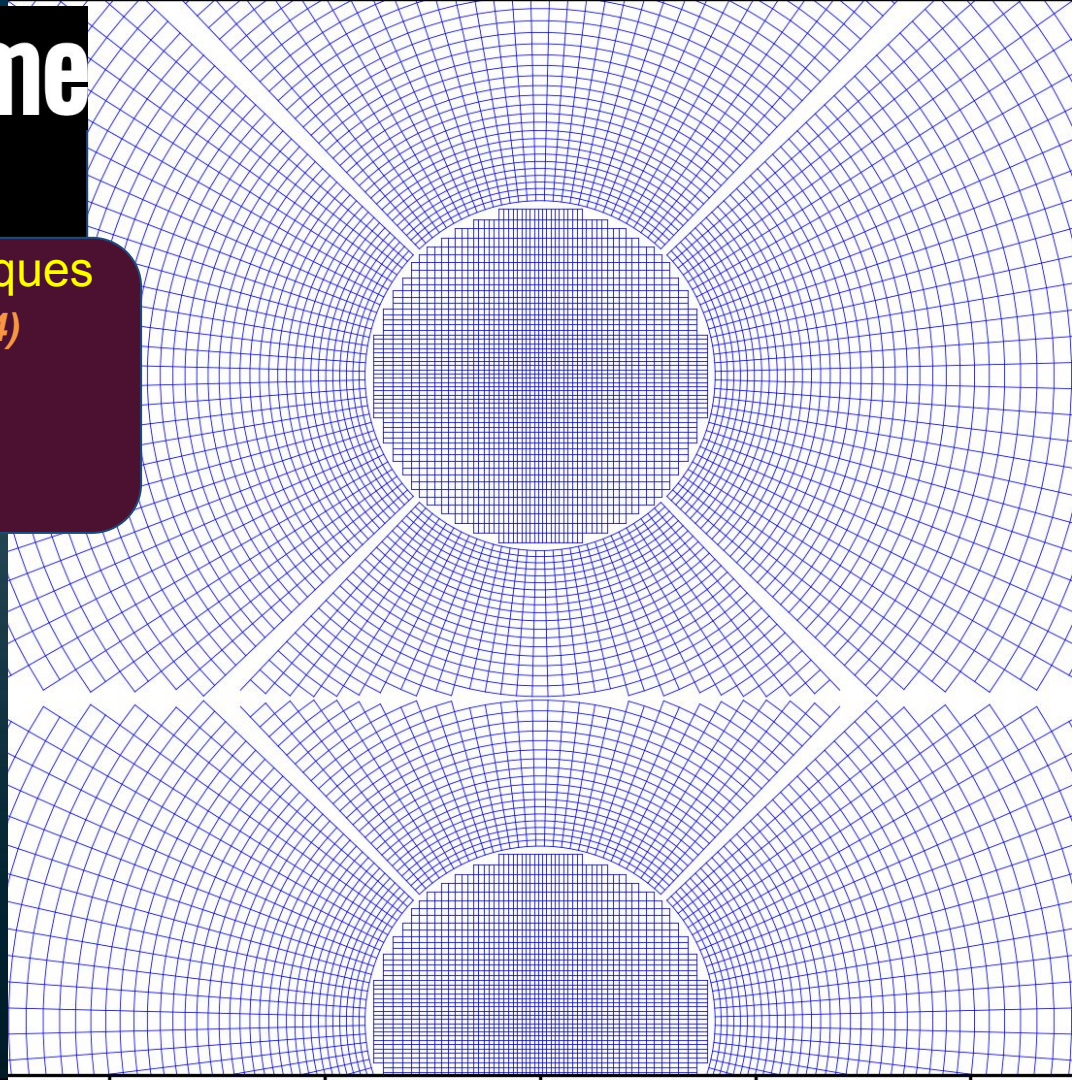
Progress over past year

1. Improved moving puncture techniques
   ***Etienne** arXiv:2404.01137 (2024)*
2. Open-sourcing BH@H in NRPy 2
   github.com/nrpy/nrpy
3. General multipatch



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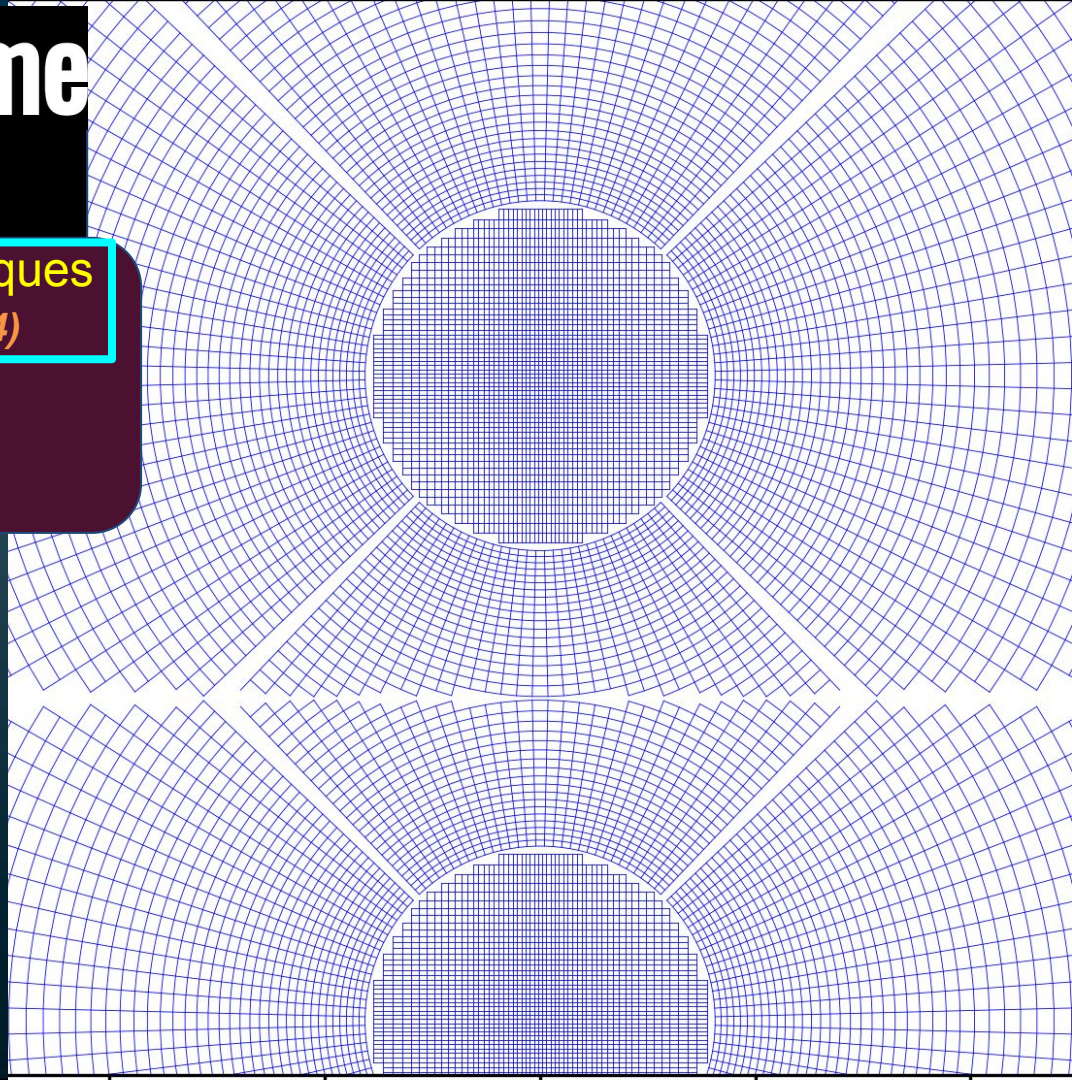

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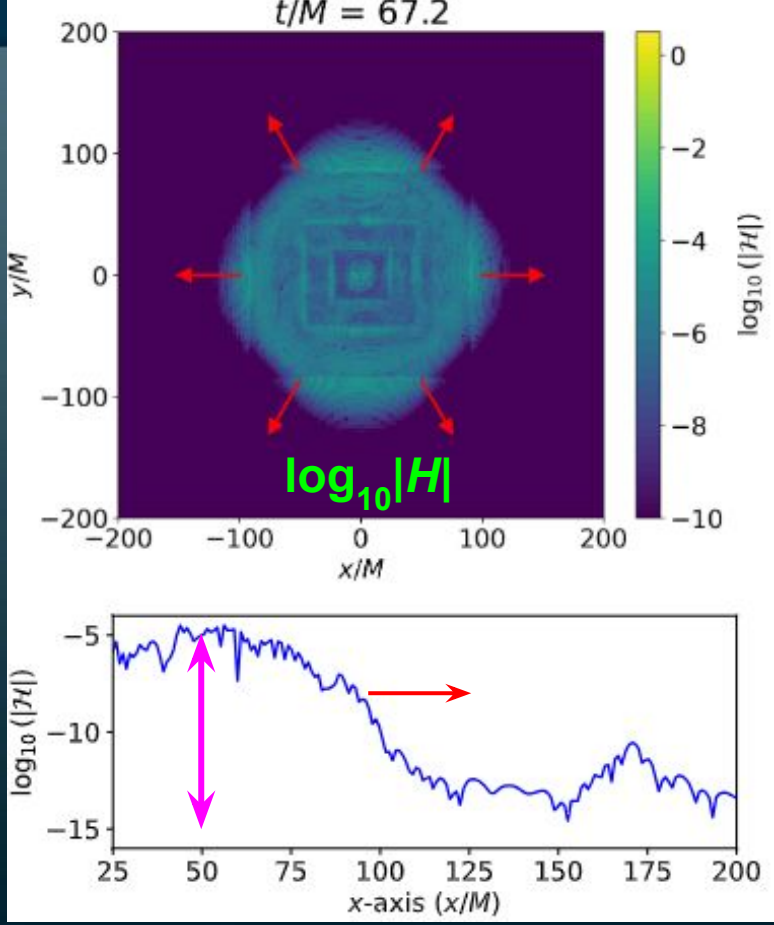
Improved Moving-Puncture Techniques

Etienne arXiv:2404.01137 (2024)

- **Improved moving puncture techniques**
  - Developed in BH@H
  - Minimal cost, infrastructure agnostic
  - Demonstrated efficacy in Einstein Toolkit (Carpet AMR) with BBH
  - Focus: curtail development & impact of sharp lapse feature
    → **~10^{10} amplification of *H***



AMR BBH simulation

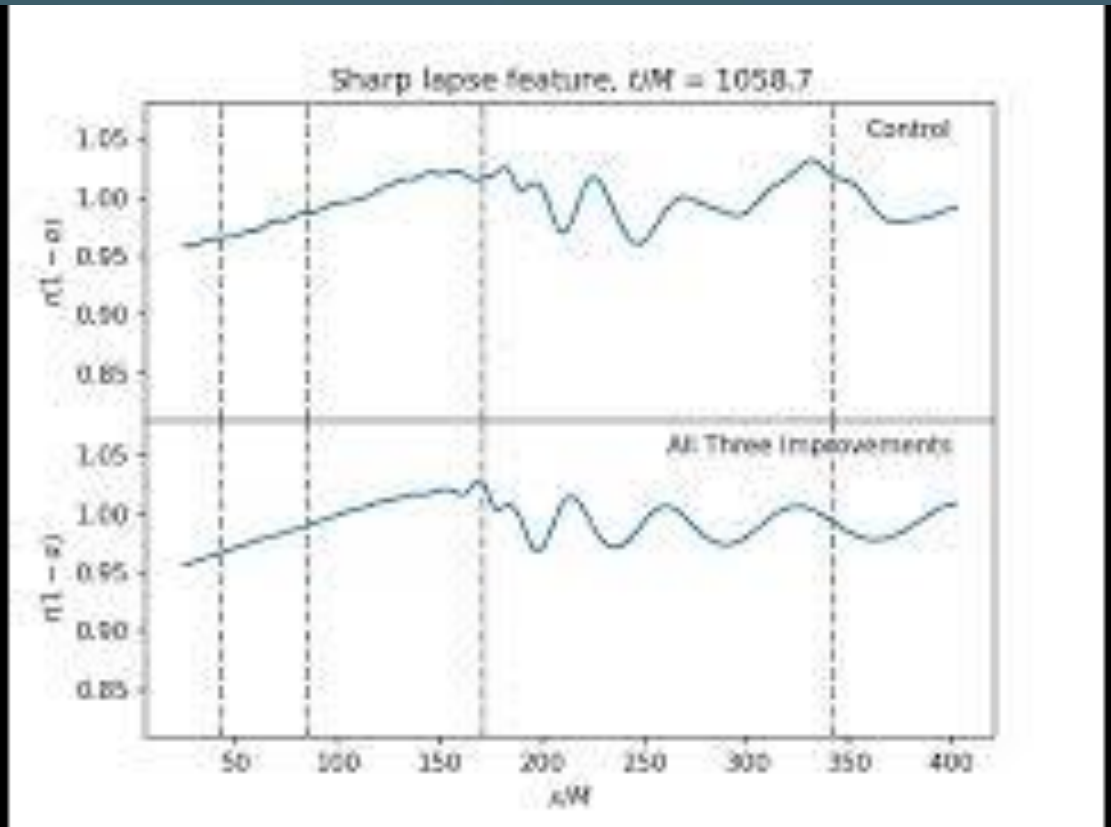
$$(1-\alpha) \propto r^{-1}, \text{ so}$$

$$r(1-\alpha) \sim \text{const.}$$

Sharp lapse feature propagates left-to-right (strong-to-weak field)

Vertical-dashed lines: AMR grid boundaries

Lapse (gauge) errors contaminate physical quantities



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    - Noise-obscured subdominant GW modes? Some now visible!

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    - M violations ~1,000x smaller
  - Weak field (wave zone):
    - H violations ~100,000x smaller
    - M violations ~100x smaller
    - Noise-obscured subdominant GW modes? Some now visible!
  - Improved convergence properties
    - → factors improve with resolution

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Improved Moving-Puncture Techniques

Etienne arXiv:2404.01137 (2024)

- **Impact on Cartesian AMR BBH sims**
  - Strong field:
    - H violations ~100x smaller
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  - Weak field (wave zone):
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⭐ **Improved ET BSSN code open sourced** ⭐

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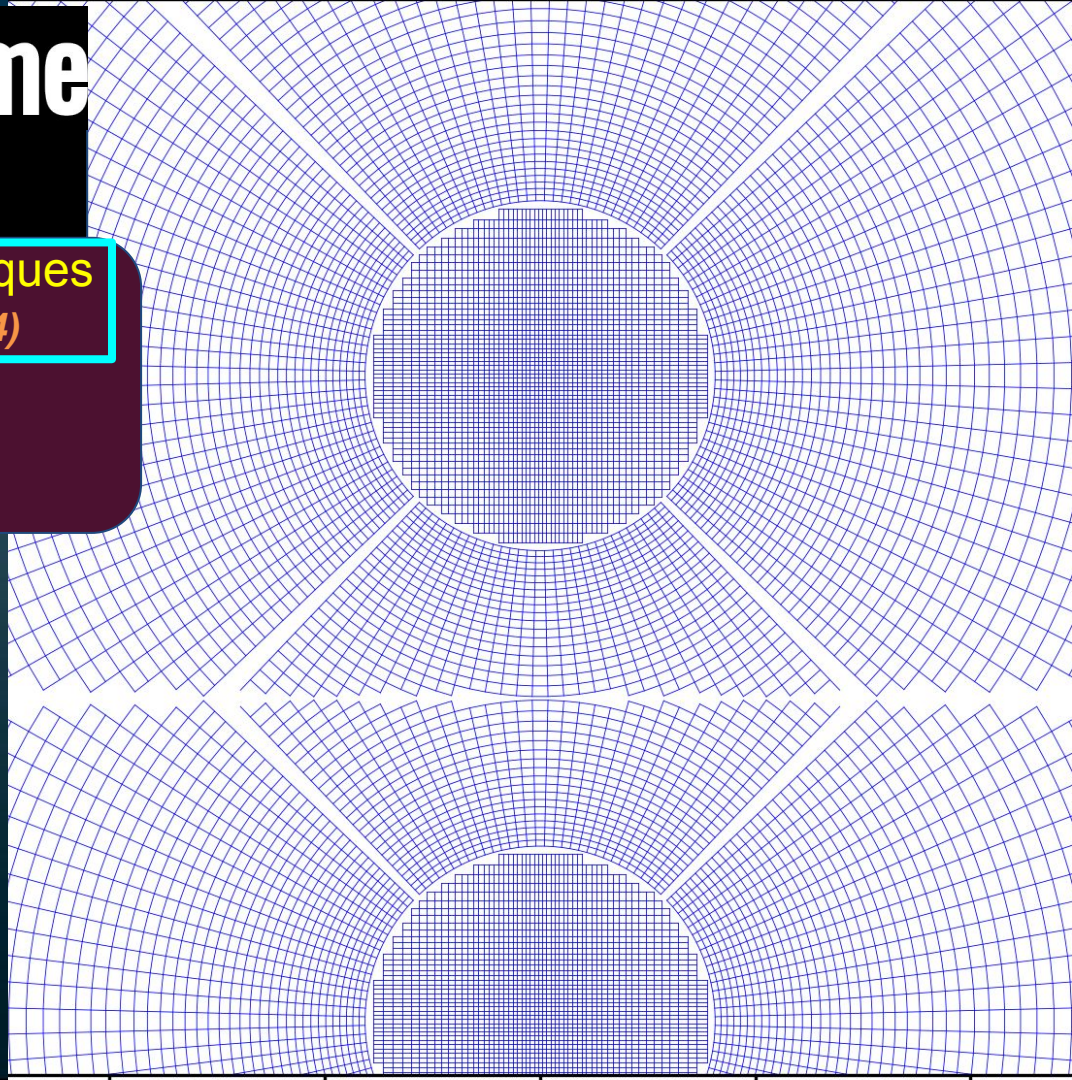
Progress over past year

1. Improved moving puncture techniques
   ***Etienne** arXiv:2404.01137 (2024)*
2. Open-sourcing BH@H in NRPy 2
   github.com/nrpy/nrpy
3. General multipatch



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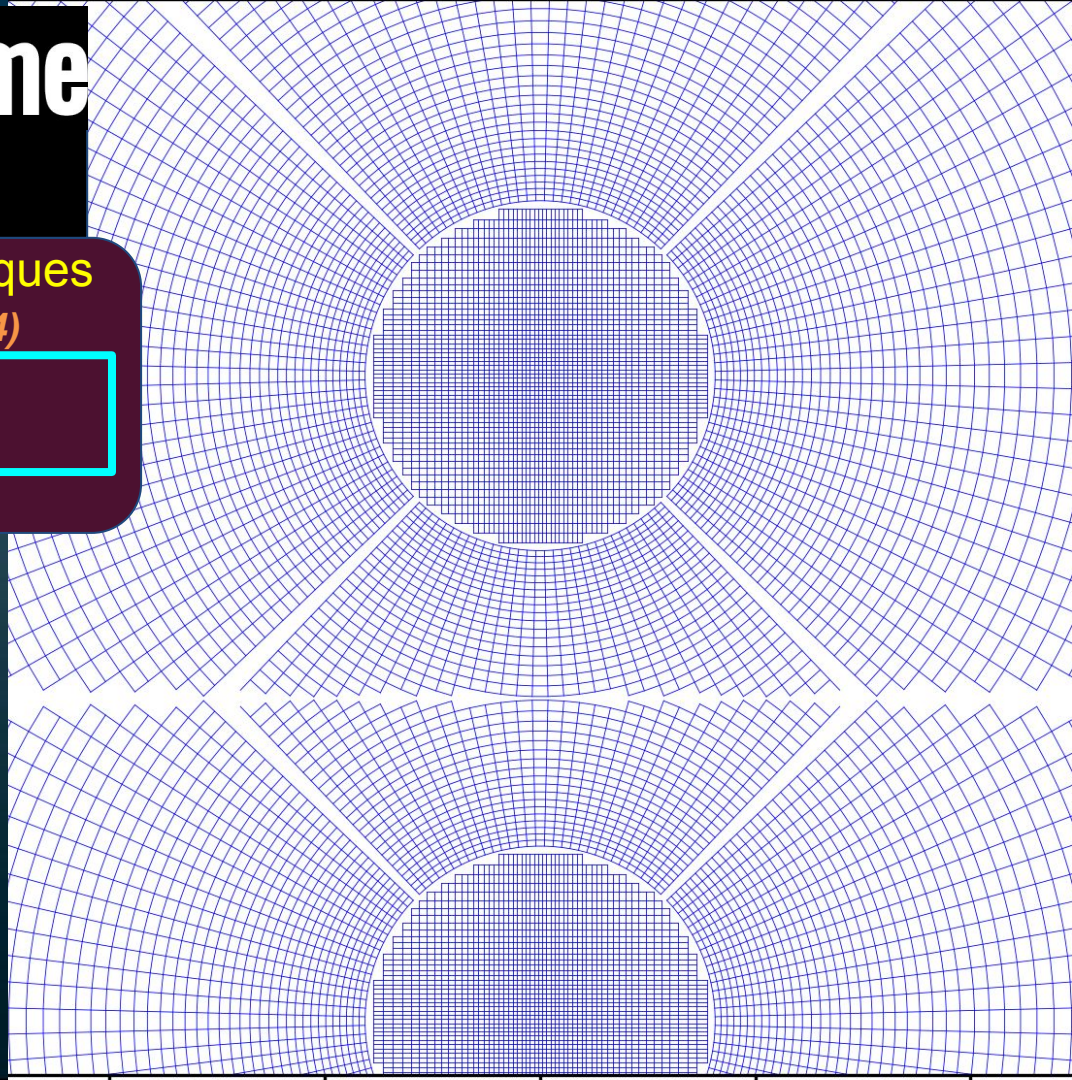

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Open-Source Progress

NRPy 2: github.com/nrpy/nrpy

BlackHoles@Home: A NRPy project

- NRPy = Python-based codegen for NR
- BH@H = NRPy-generated NR code

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Open-Source Progress

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- NRPy = Python-based codegen for NR
- BH@H = NRPy-generated NR code

NRPy 2: 2023 NRPy rewrite!

- Primary goals:
  - open source almost all of BH@H
  - modernize, address community feedback
    - `pip install nrpy`

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Open-Source Progress

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NRPy 2: 2023 NRPy rewrite!

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  - open source almost all of BH@H
  - modernize, address community feedback
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⭐ **In development: “General Multipatch”** ⭐

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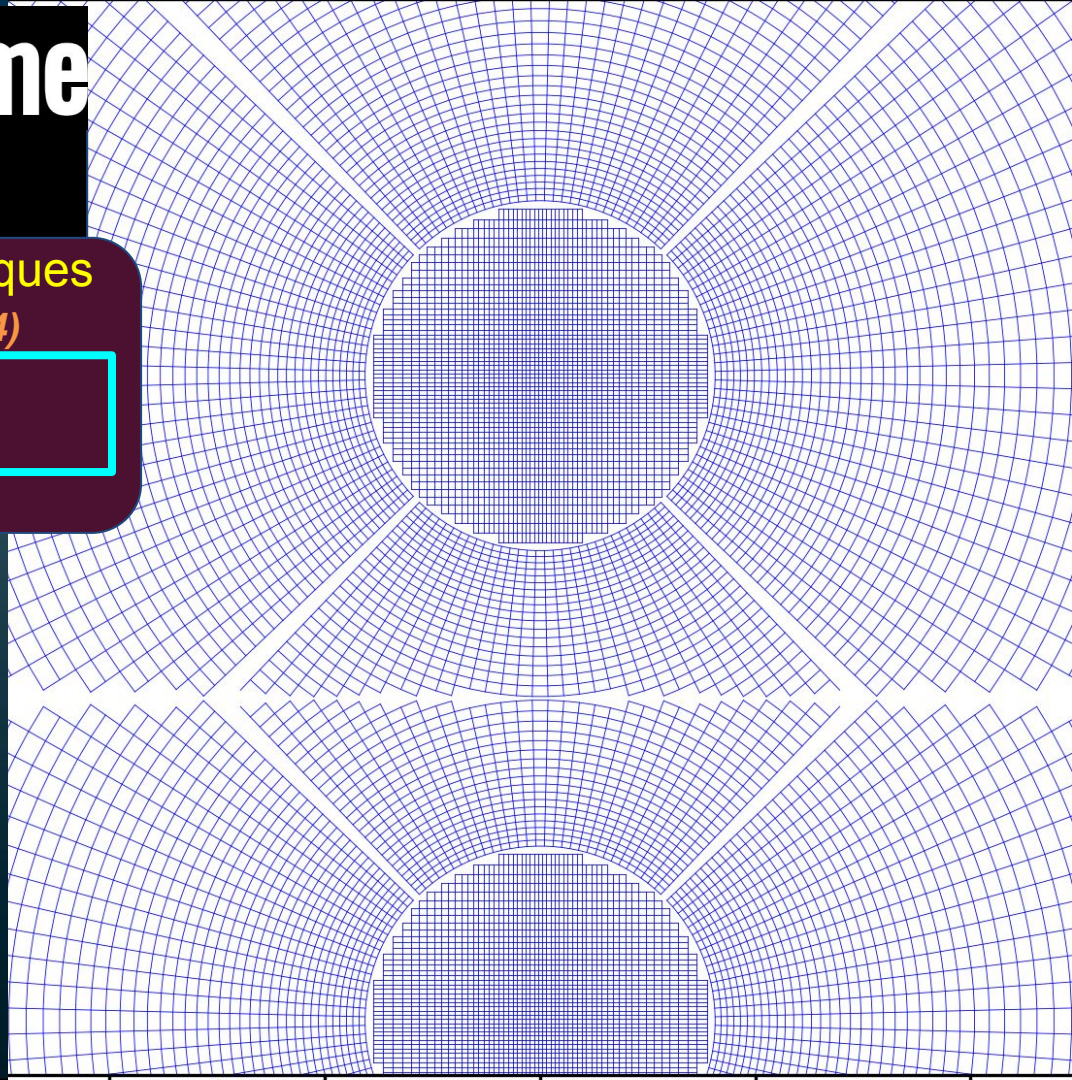

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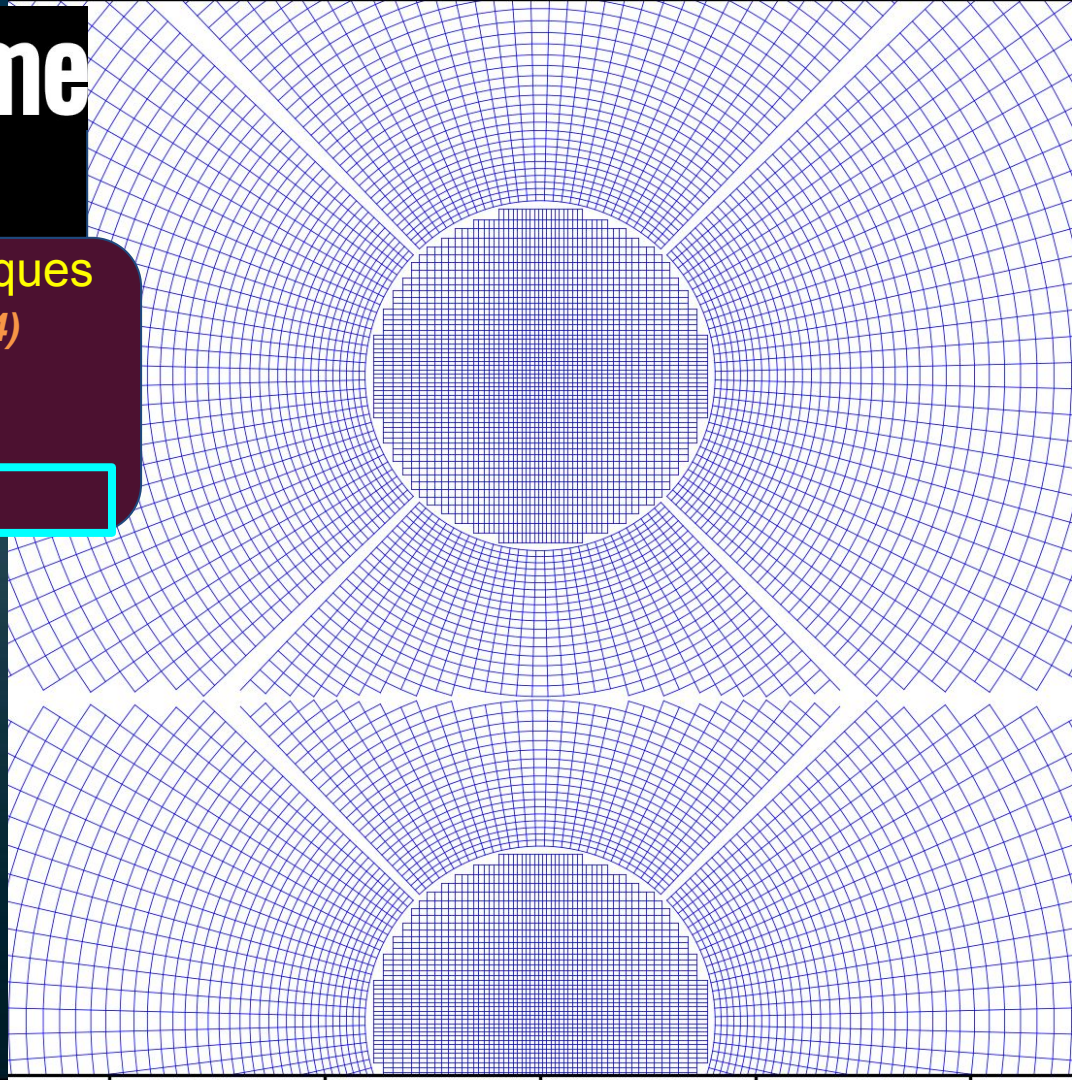

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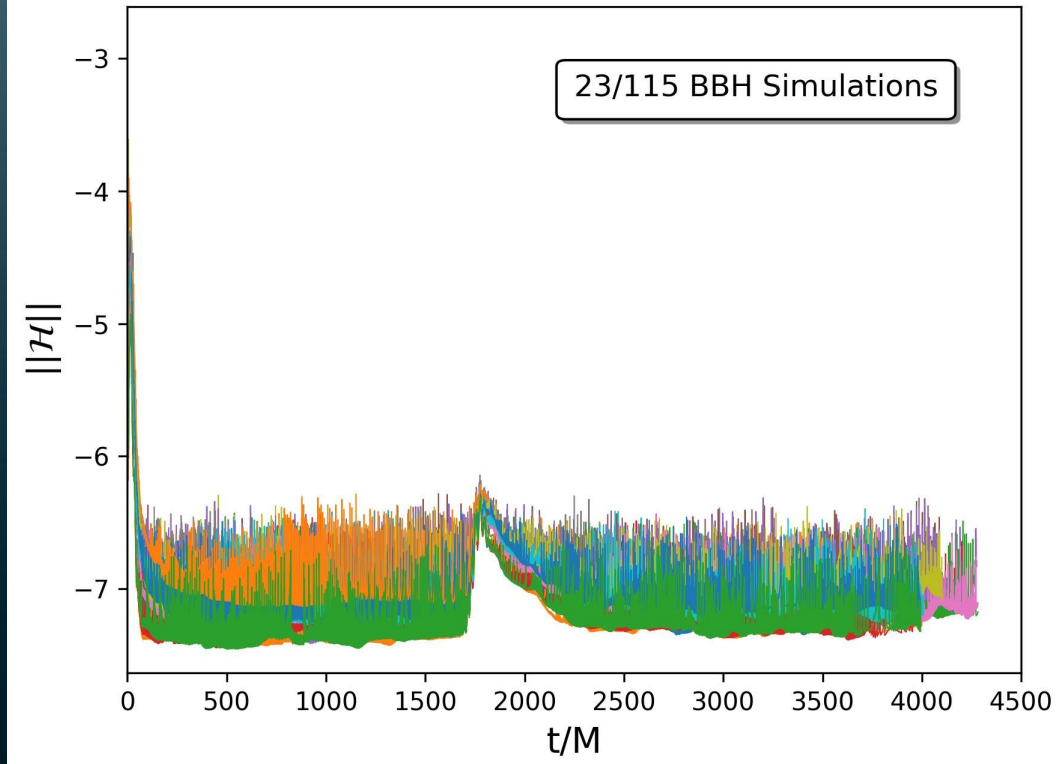
Last year: First BBH Catalog

Strong field: $||\mathcal{H}||$ in the range $0M \leq r \leq 20M$



Strong-field evolution looks great

Reproducing 115 SXS BBH Catalog Simulations

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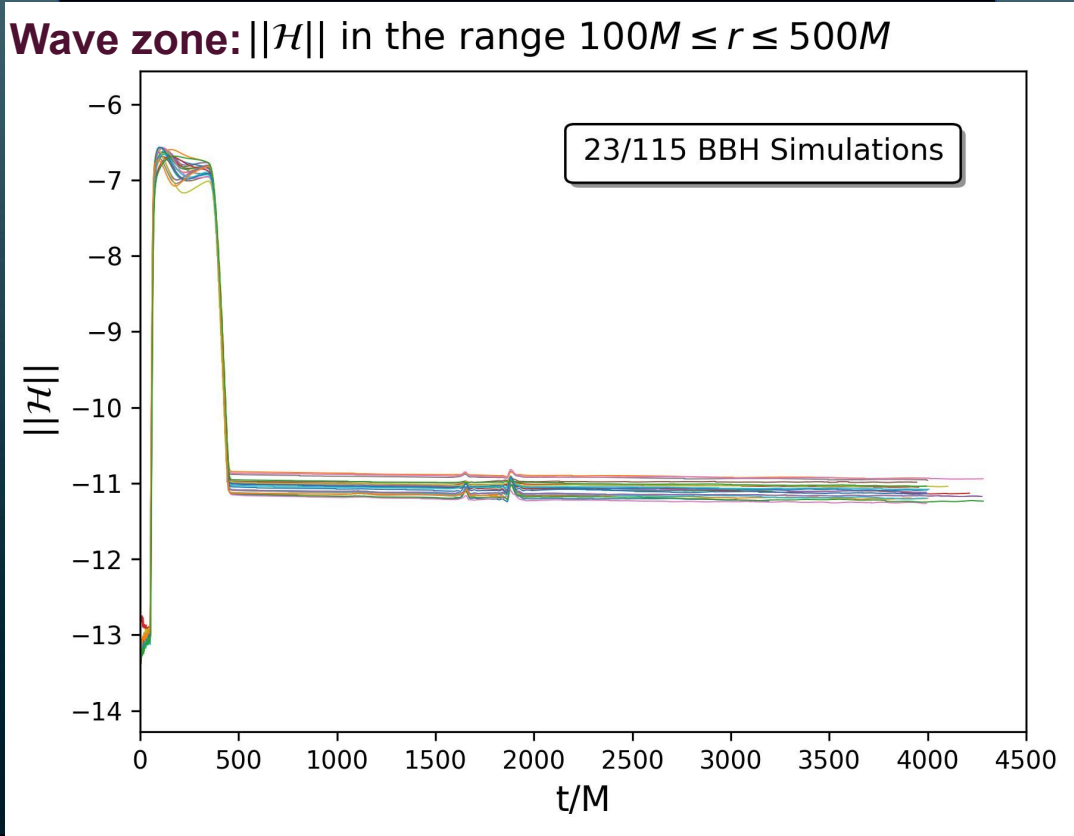
Last year: First BBH Catalog



Wave zone evolution looks great

Reproducing 115 SXS BBH Catalog Simulations

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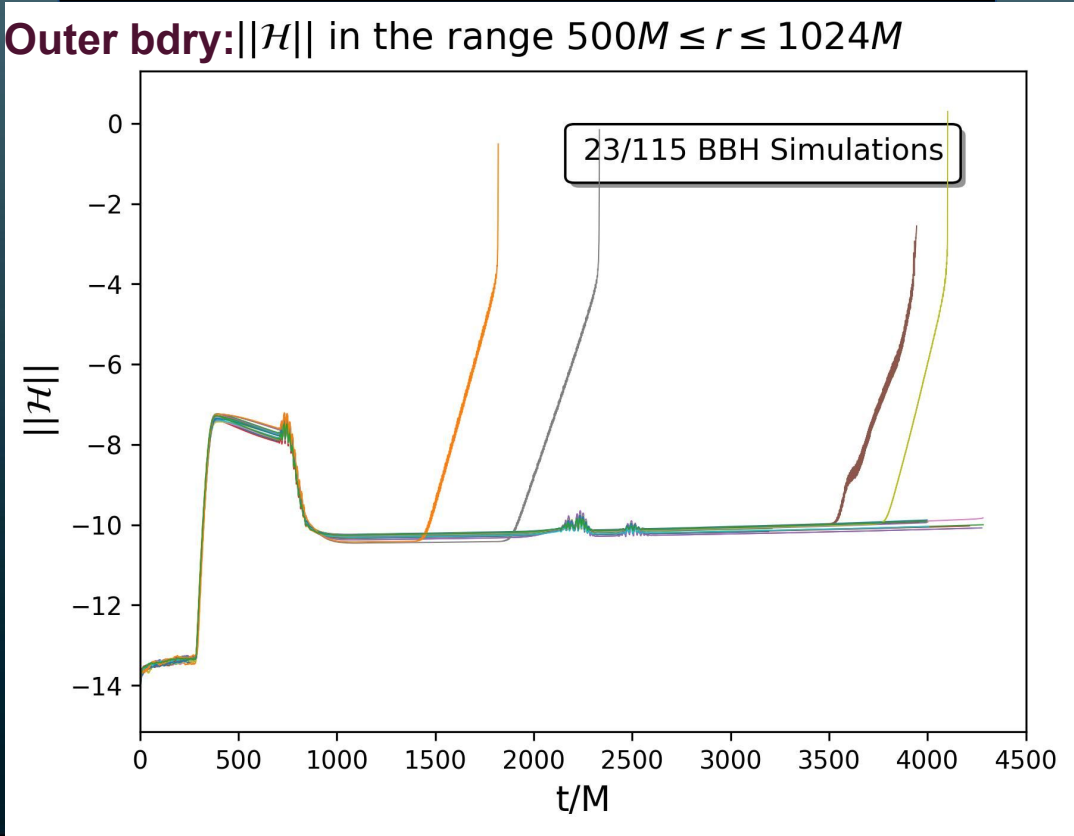
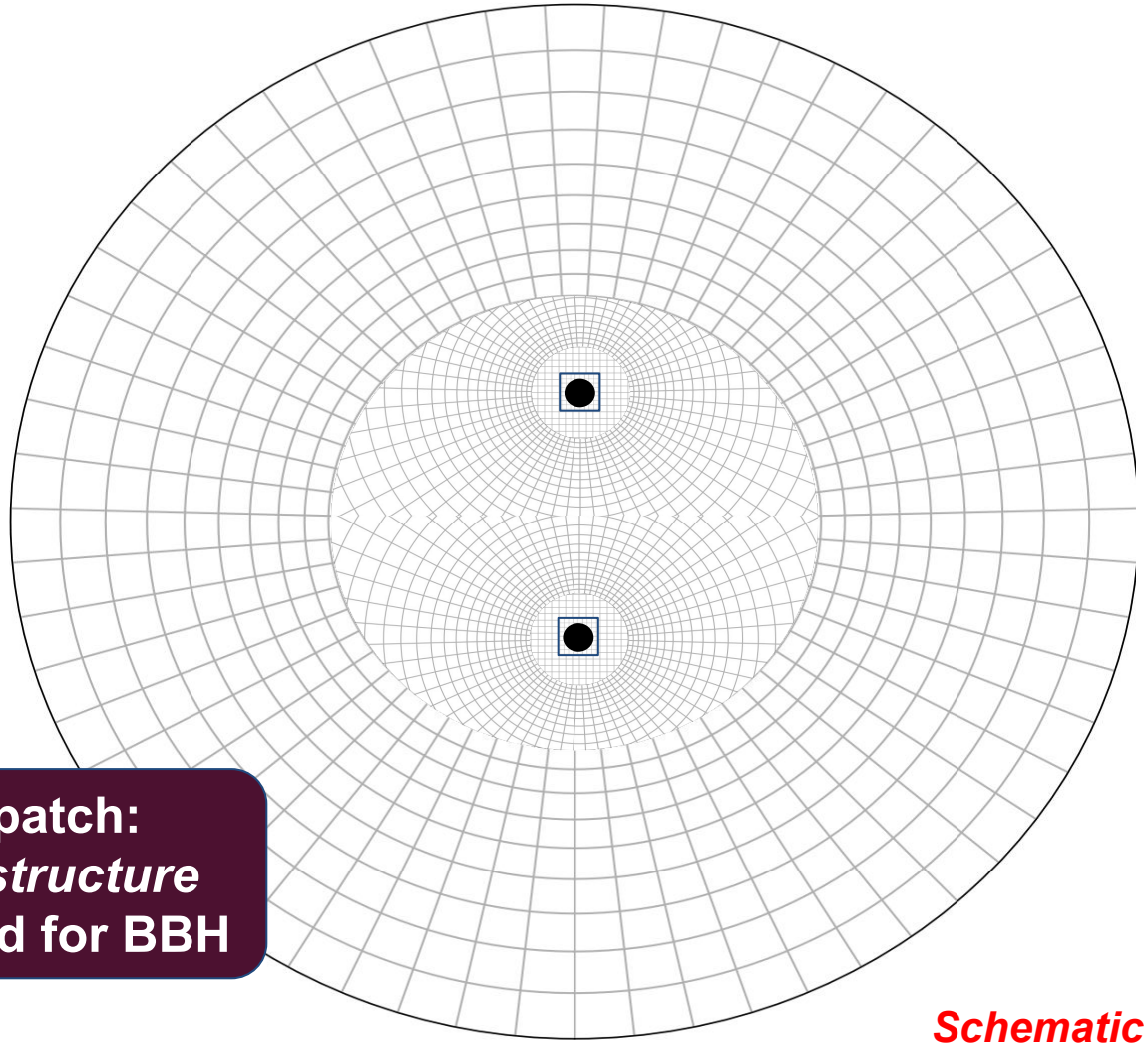
Last year: First BBH Catalog



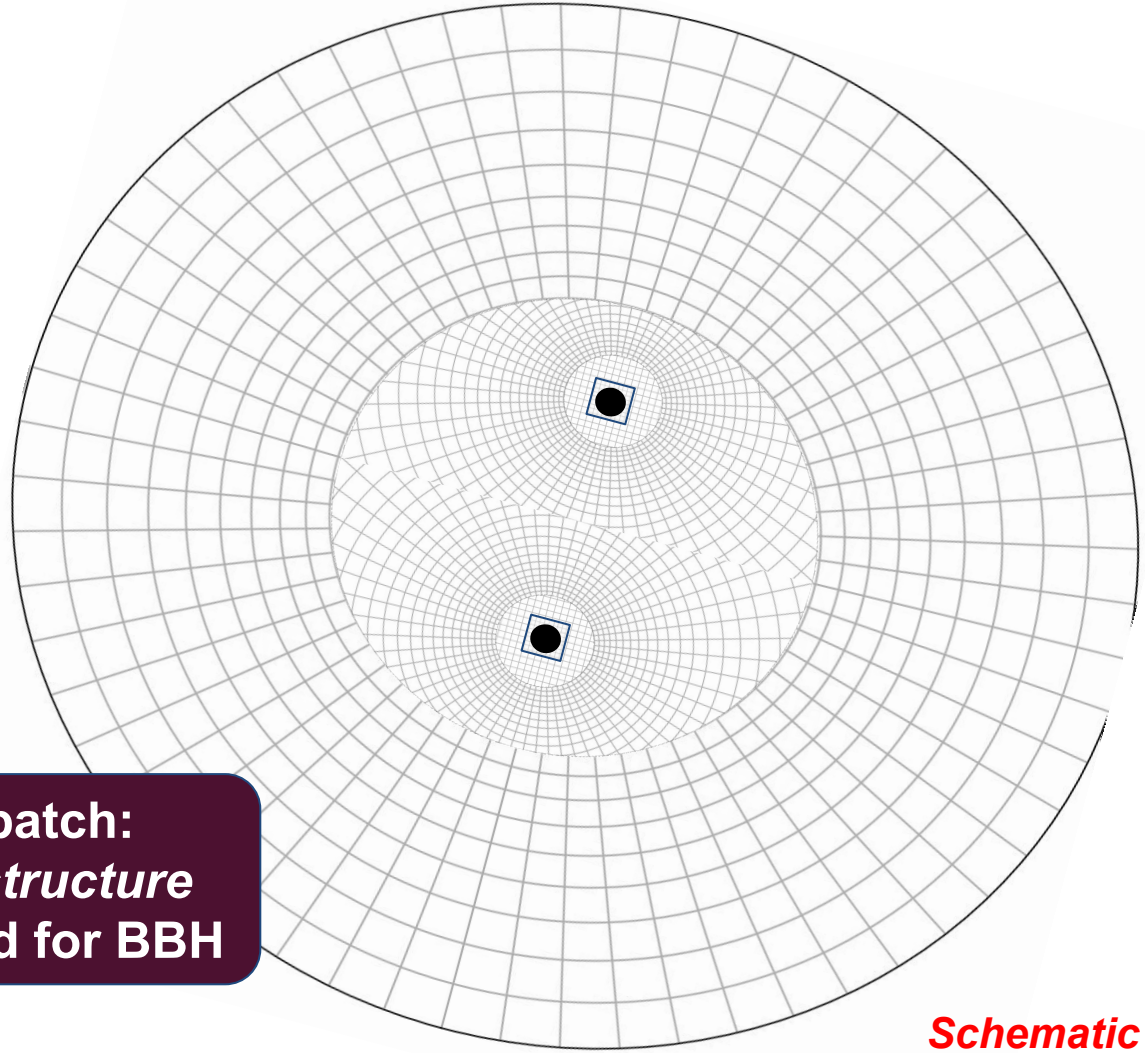
Trouble at the outer boundary

Reproducing 115 SXS BBH Catalog Simulations



Old multipatch:
Entire grid structure
is interpolated for BBH

Schematic



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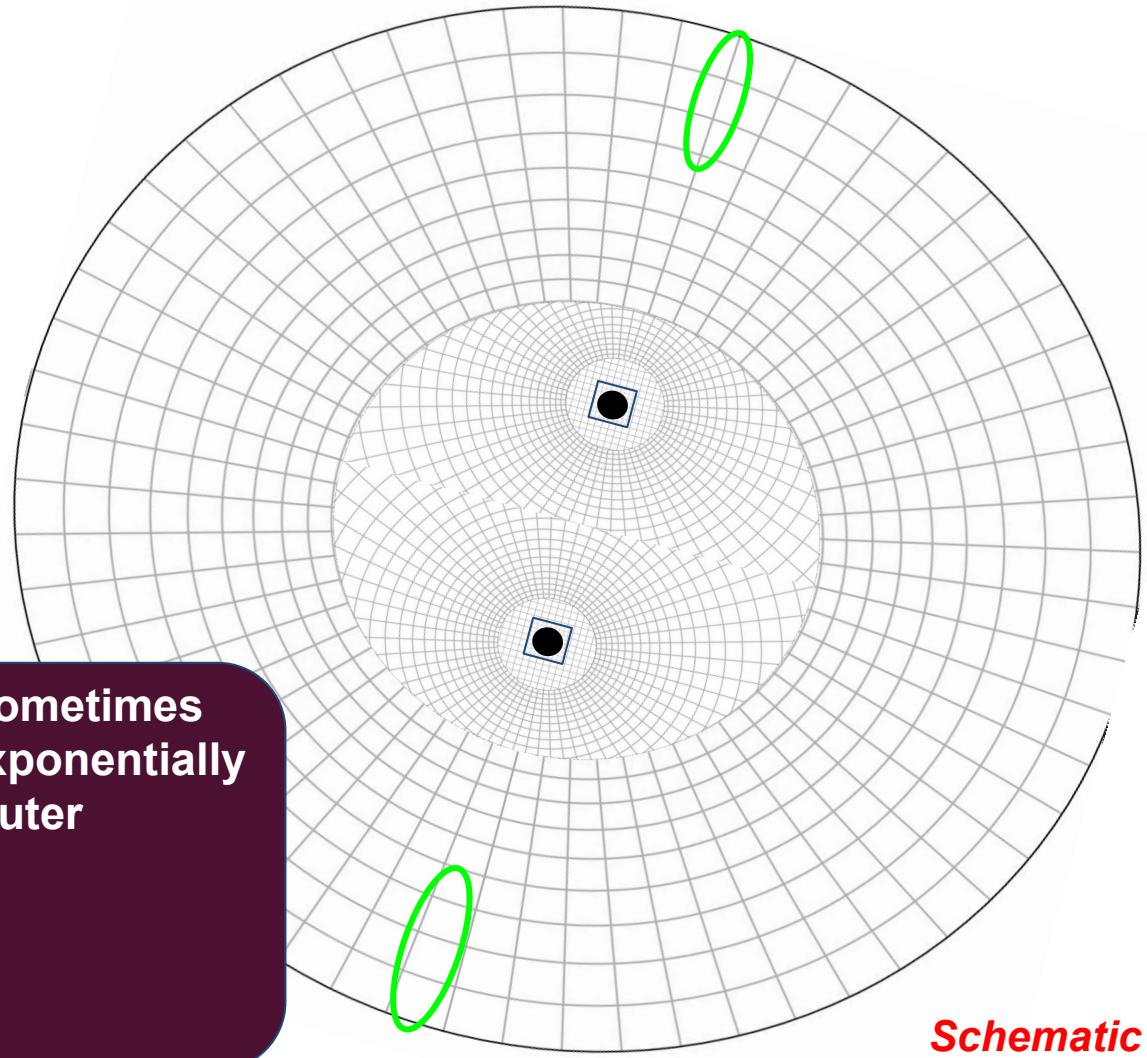
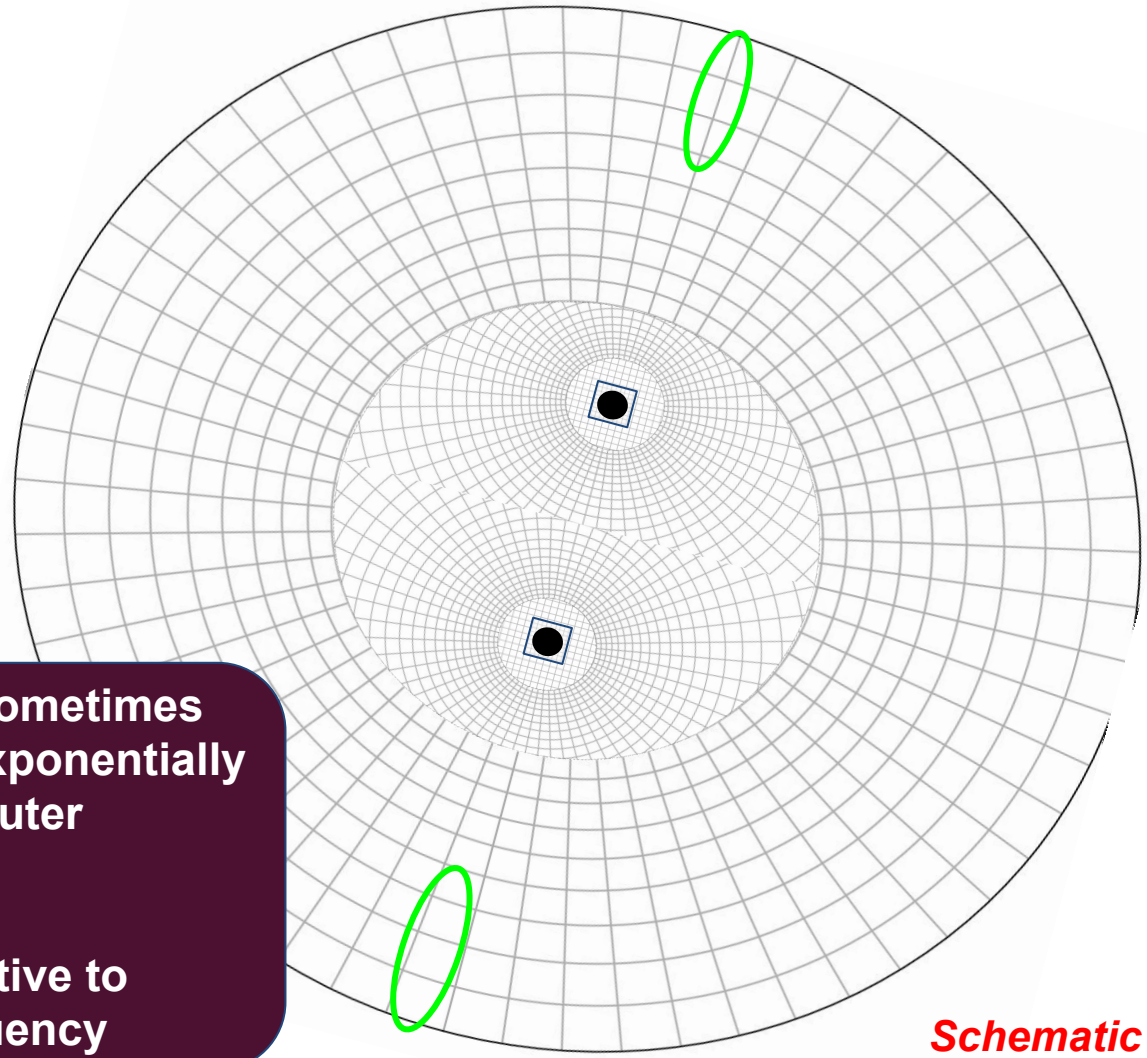


Interpolations sometimes amplify noise exponentially on z-axis near outer boundary

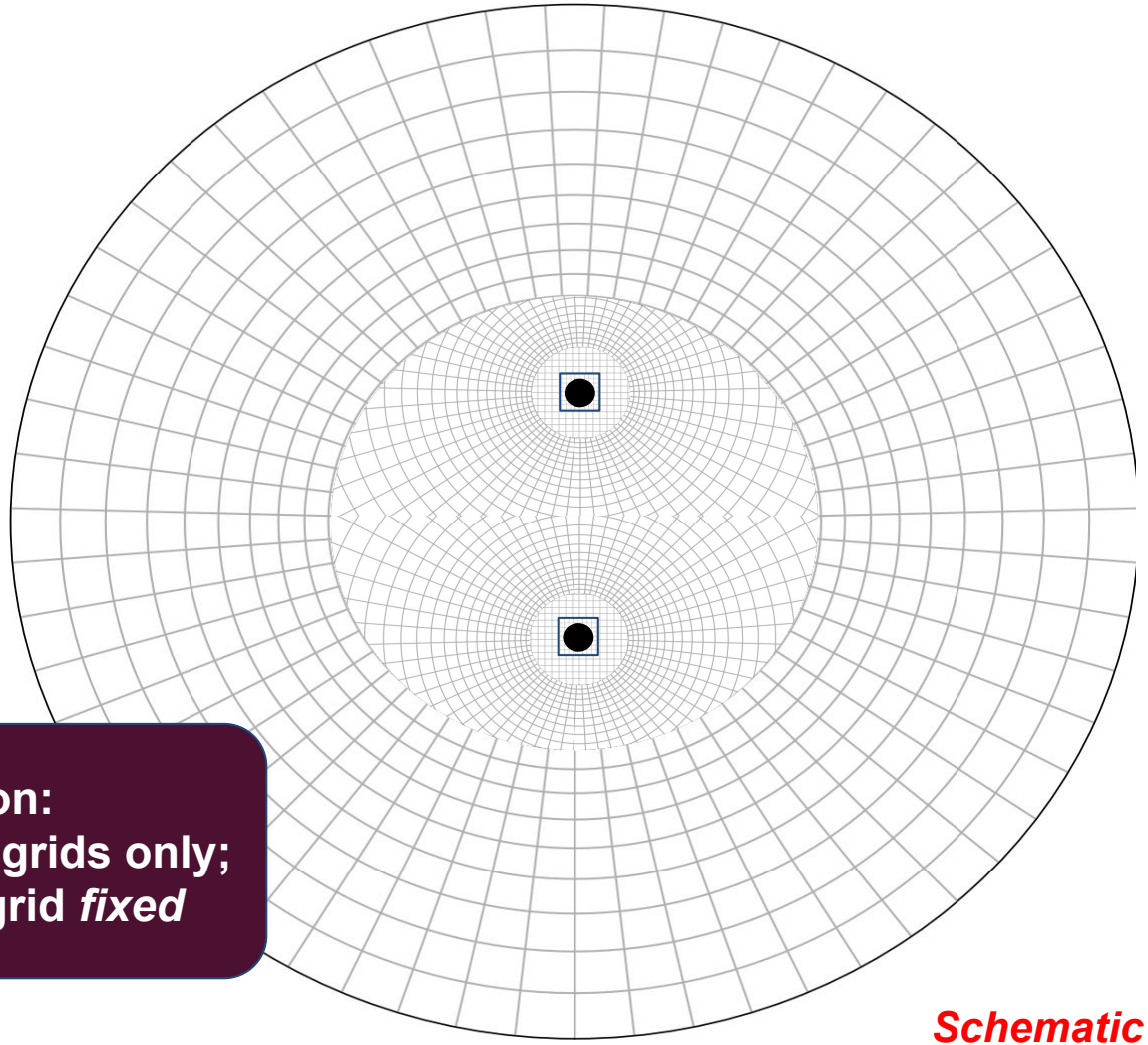
Schematic



Interpolations sometimes amplify noise exponentially on z-axis near outer boundary

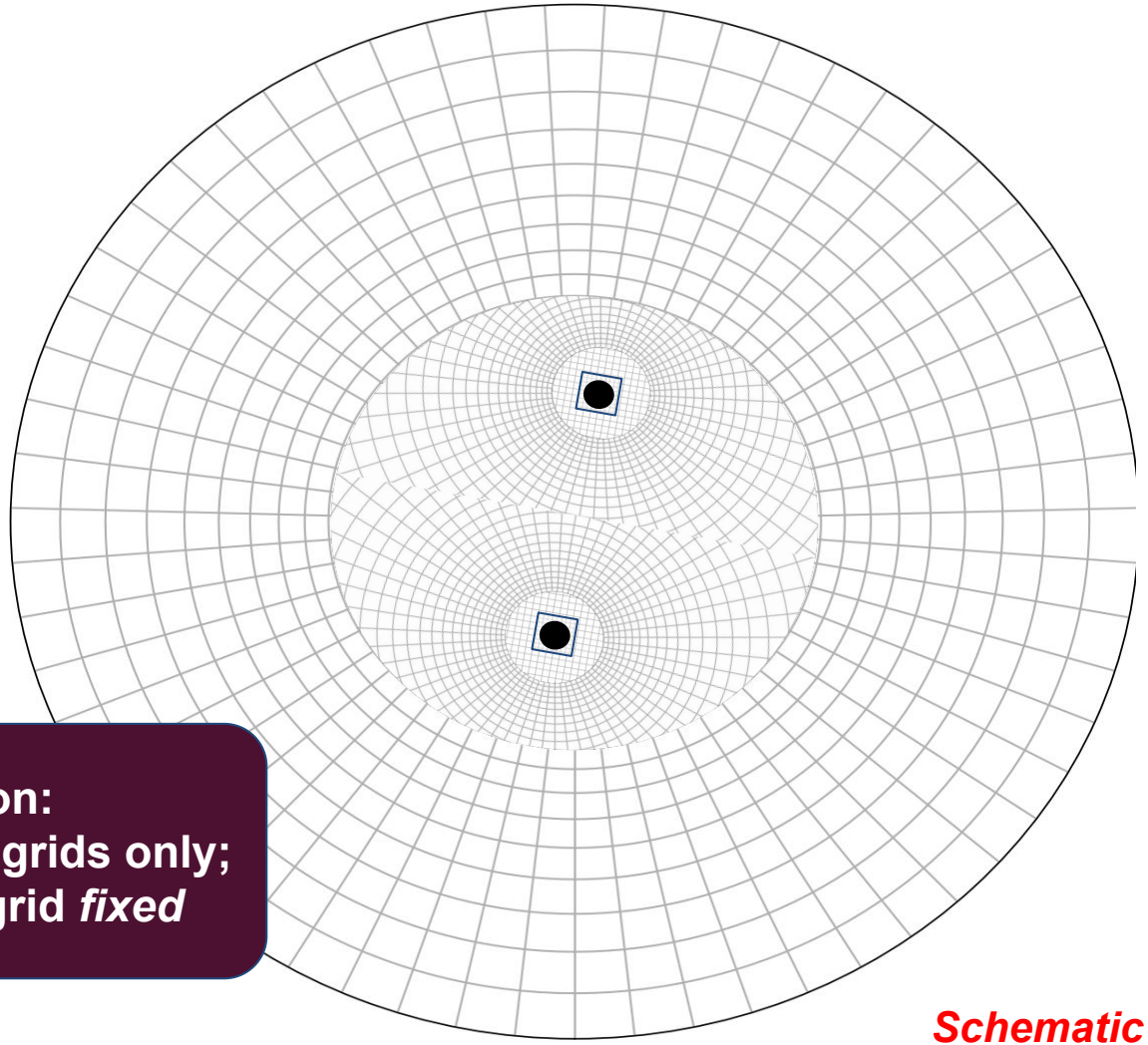
Instability sensitive to regridding frequency

Schematic



Solution:
Corotate inner grids only;
leave outer grid *fixed*

Schematic



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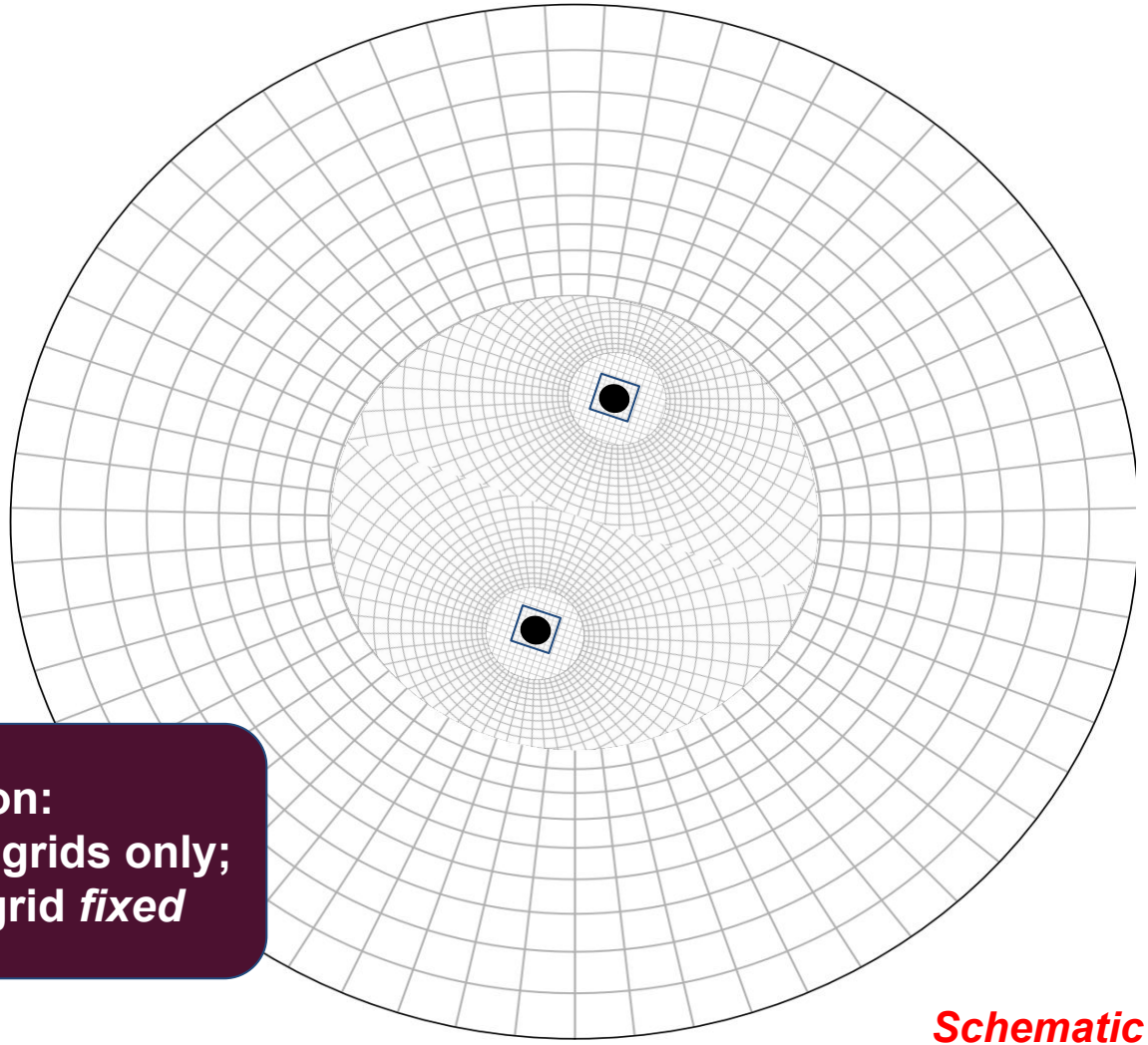

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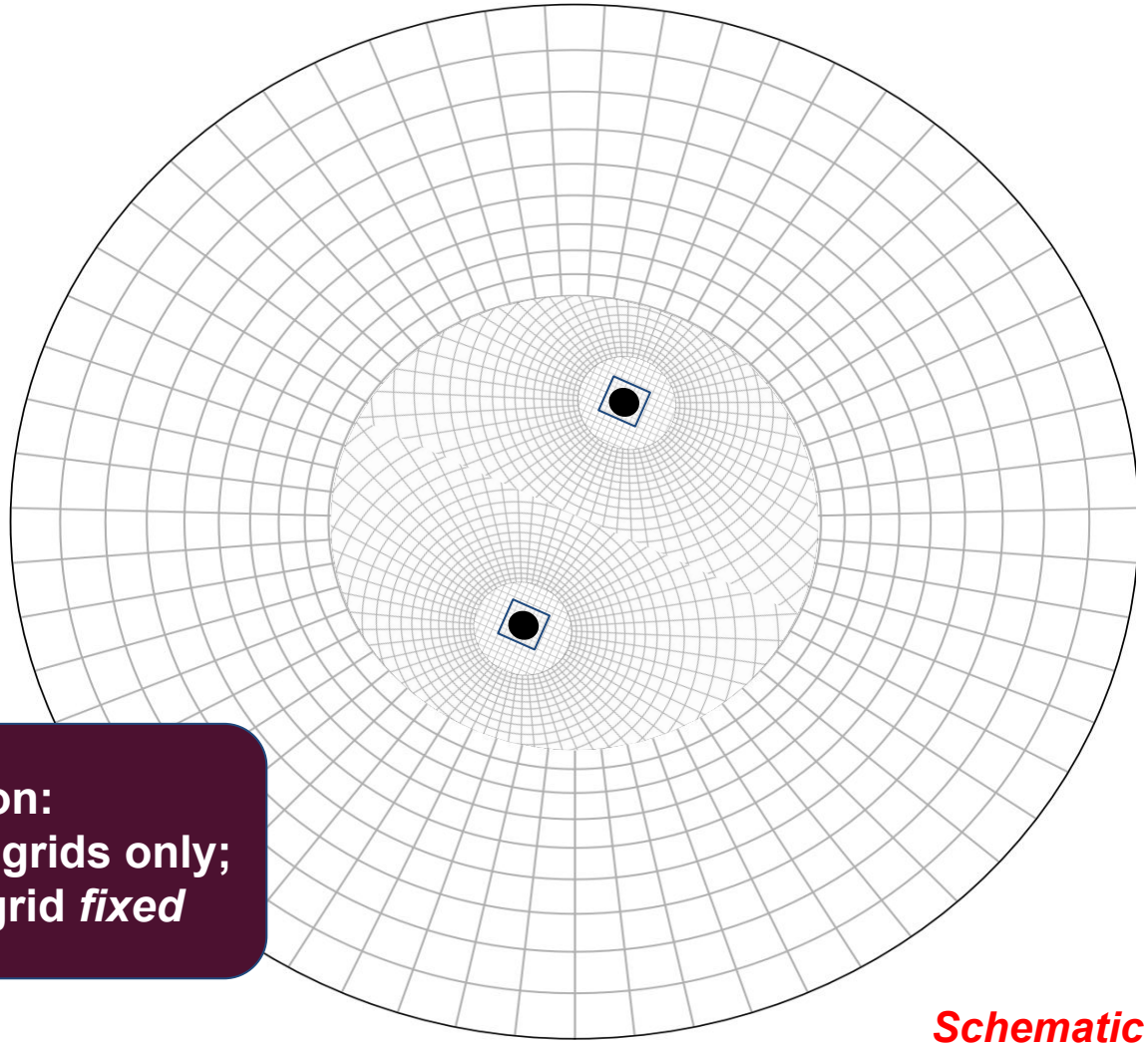

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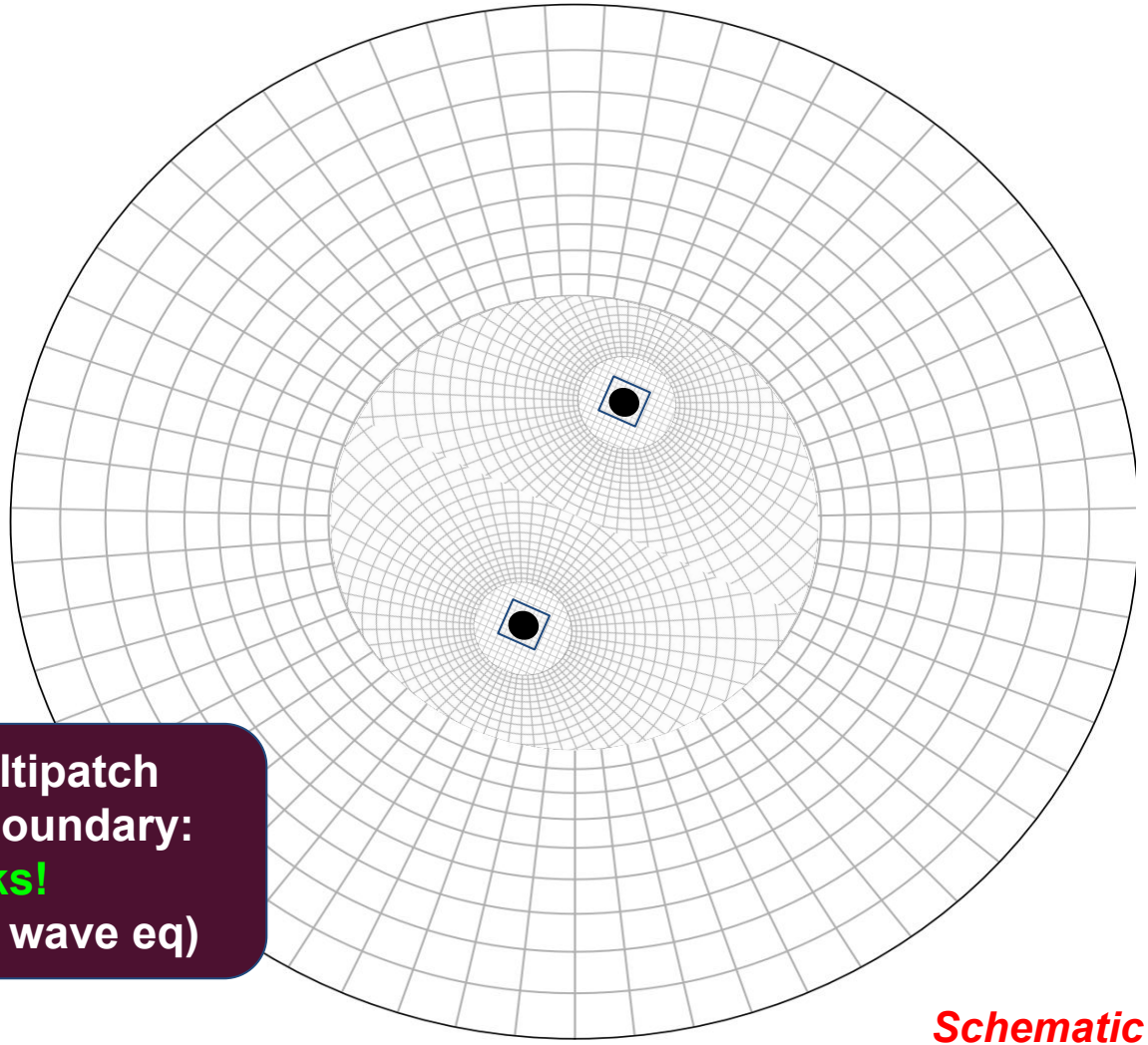

General Multipatch sliding grid boundary: It works! (validated for wave eq)

Schematic

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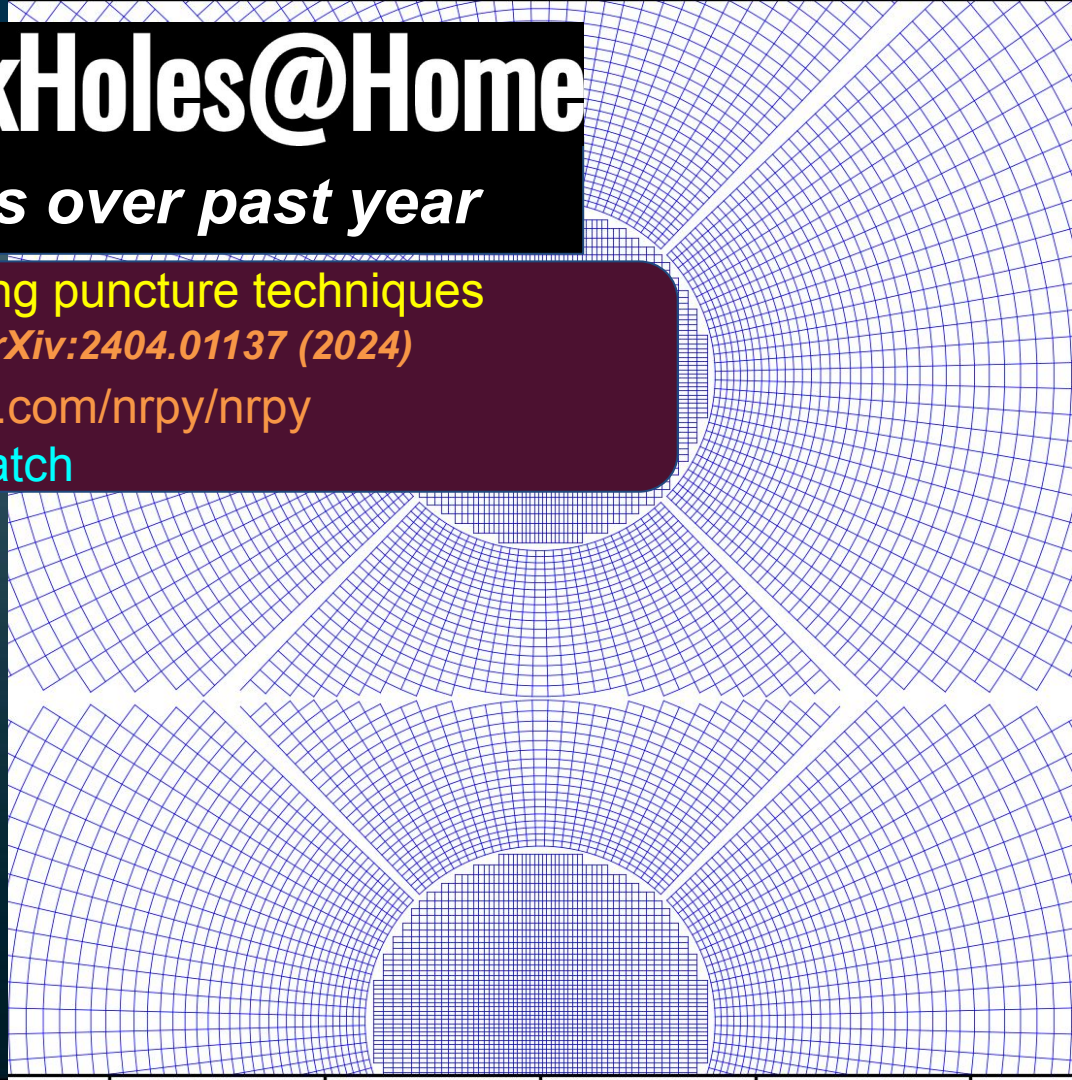

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Plans for Rest of 2024

1. Finish NRPy 2 implementation of BH@H
   (90% complete)
2. BH@H paper + open source BH@H
3. Implement SpECTRE CCE
4. Start volunteer computing work
   a. Top Priority: Reproduce SXS BBH catalog