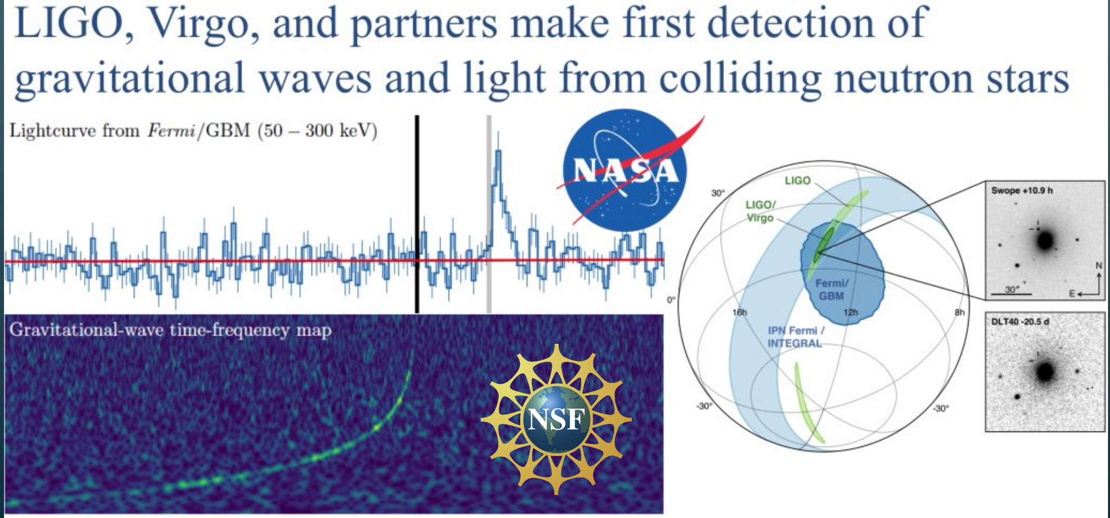
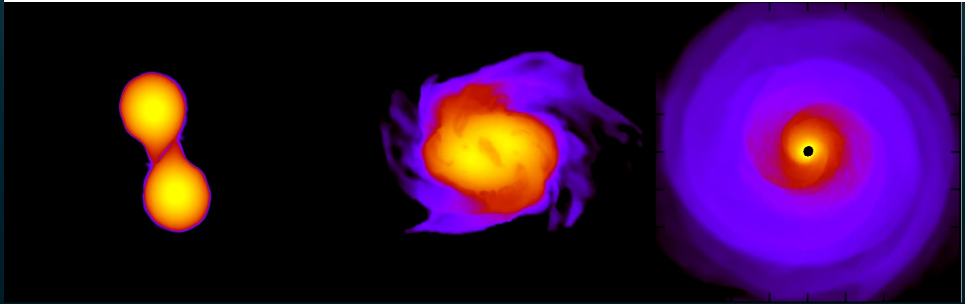
Advancing Multimessenger Astrophysics with Next-Generation Black Hole and Neutron Star Binary Merger Simulations

Zach Etienne





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80NSSC18K1488 (TCAN, 2018-2021)

NSF awards

PHY-1806596 (Grav theory, 2018-2021)

PHY-1607405 (LIGO research, 2016-2019)

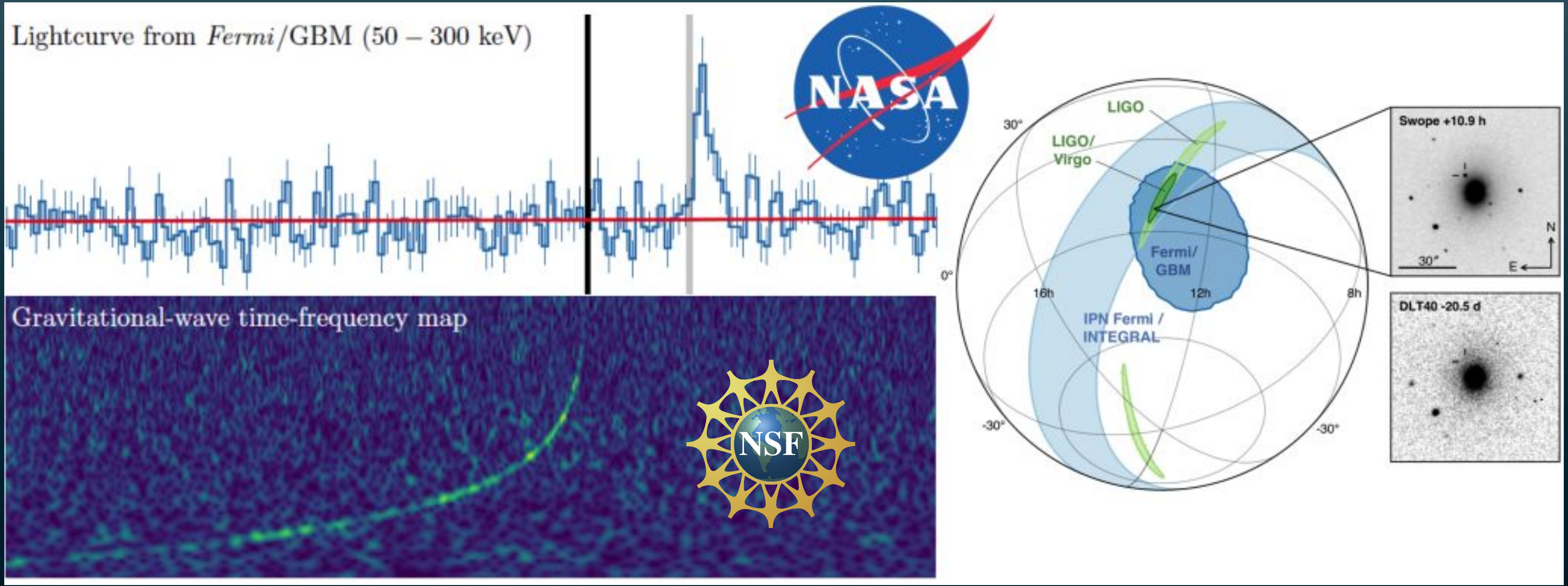
PHY-1912497 (LIGO research, 2019-2021)

PHY-1757005 (Grav expmt, 2017-2020)

EPSCoR-1458952 (2015-2020)

Outline

- Part 1: **When Neutron Stars Collide!**
  - GW170817 / GRB170817A: **How two bright stars lived and died**



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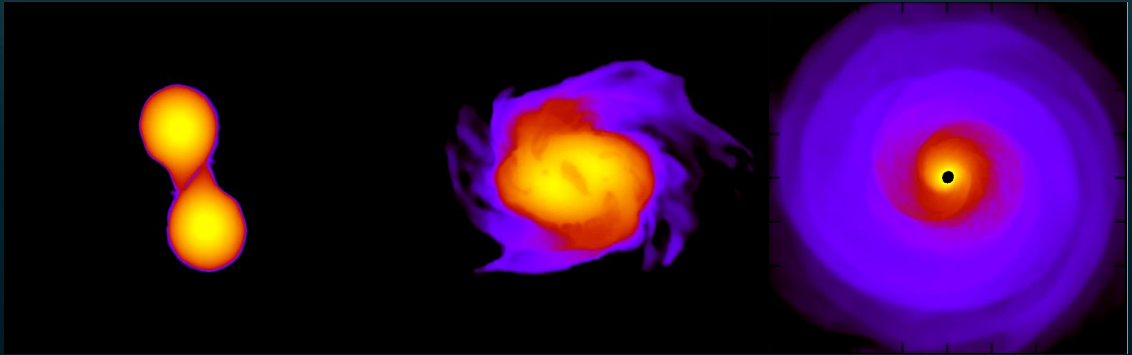
- Part 2: **Extracting Science from the Observations**
  - The **importance** and **challenges** of modeling gravitational wave and multimessenger sources



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A long time ago in a galaxy far,
far away....

~130M years ago

A long time ago in a galaxy far, far away….

NGC 4993

NEUTRON STARS

http://www6.flamingtext.com/logo/Design-Death-Star

NEUTRON STARS

GW170817
GRB170817A

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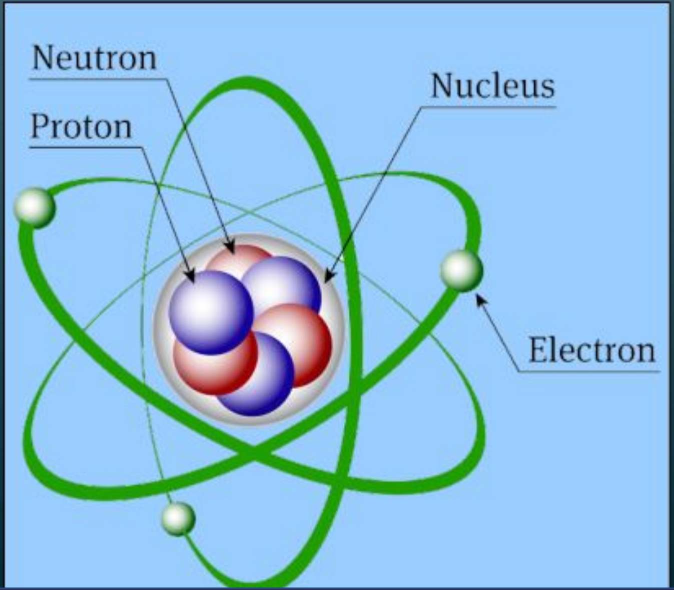
What is a Neutron Star?
A: A large ball of neutrons



Atom: mostly empty space

- Imagine nucleus @ 30cm diameter →electrons ~5km away!

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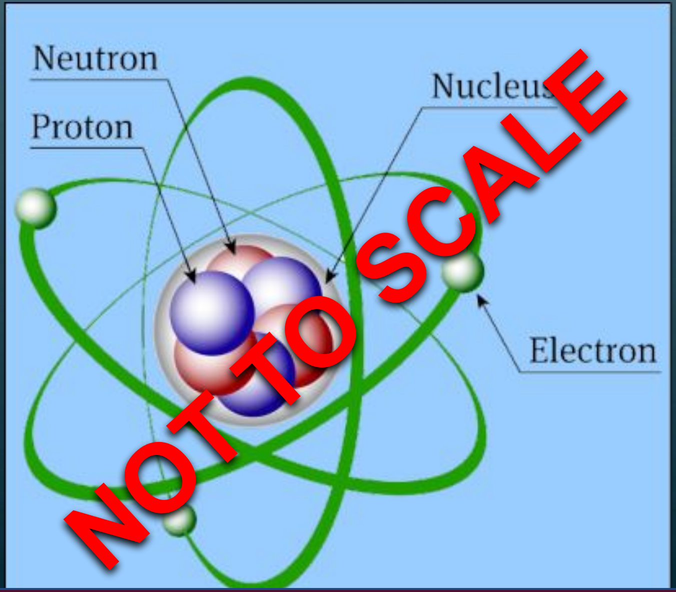

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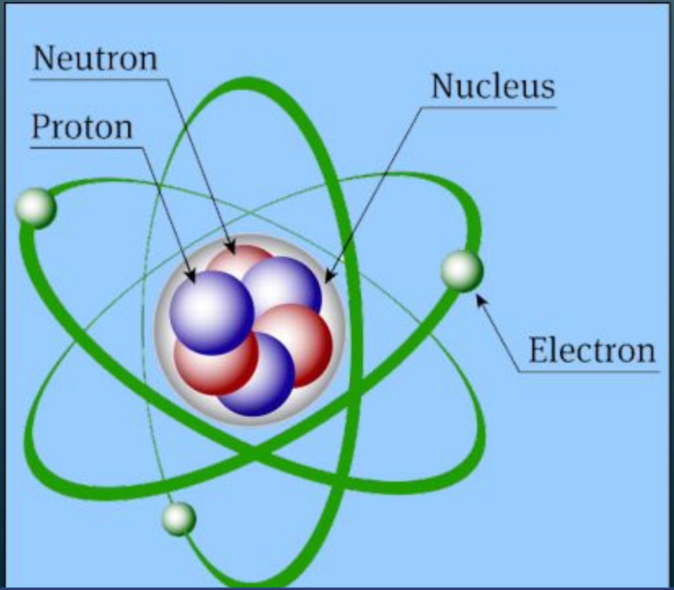

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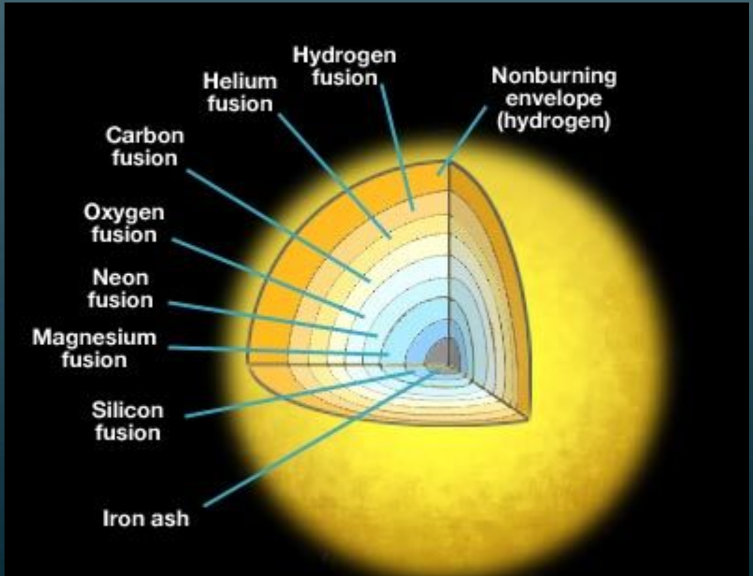
- Imagine nucleus @ 30cm diameter
  →electrons ~5km away!
  →nuclei, NSs are **SUPER** dense

How to make a Neutron Star?



Old Massive Star

- Like all stars, heat from fusion pushes out, gravity pulls in

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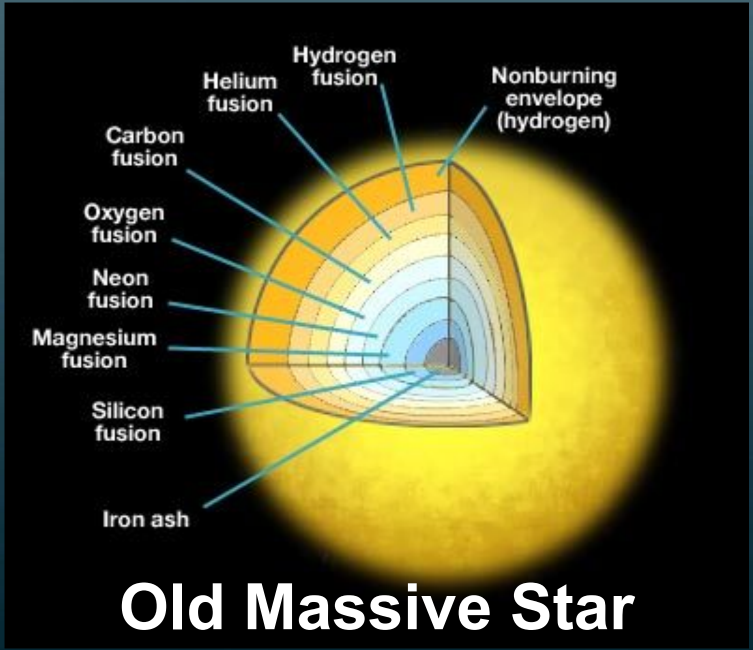

- Like all stars, heat from fusion pushes out, gravity pulls in
- Massive stars burn bright & hot; fusion up to nickel & iron

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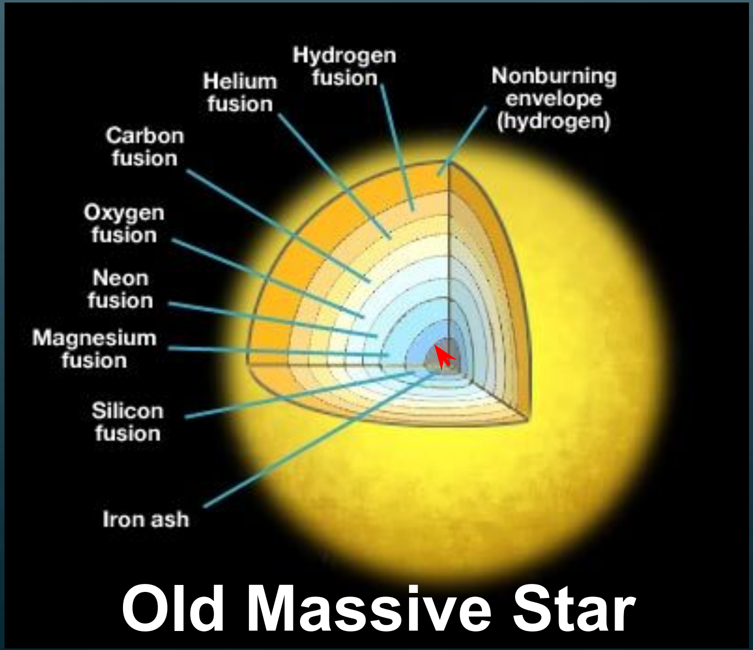

- Growing nickel-iron core pushes back outer layers (*e*-degen pressure)

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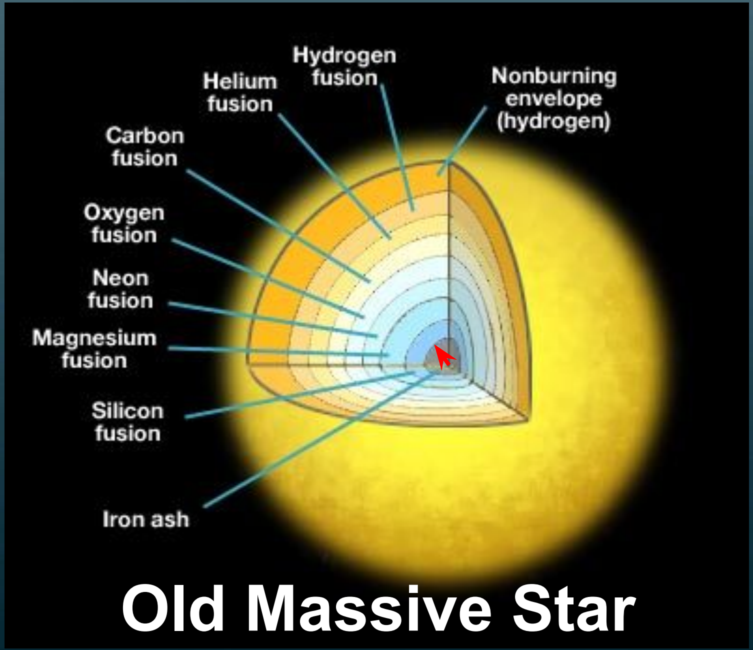

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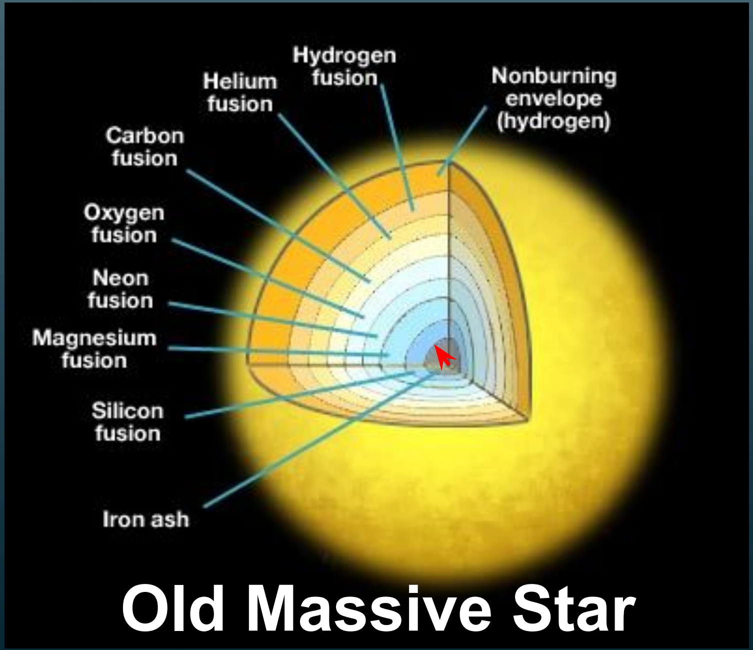

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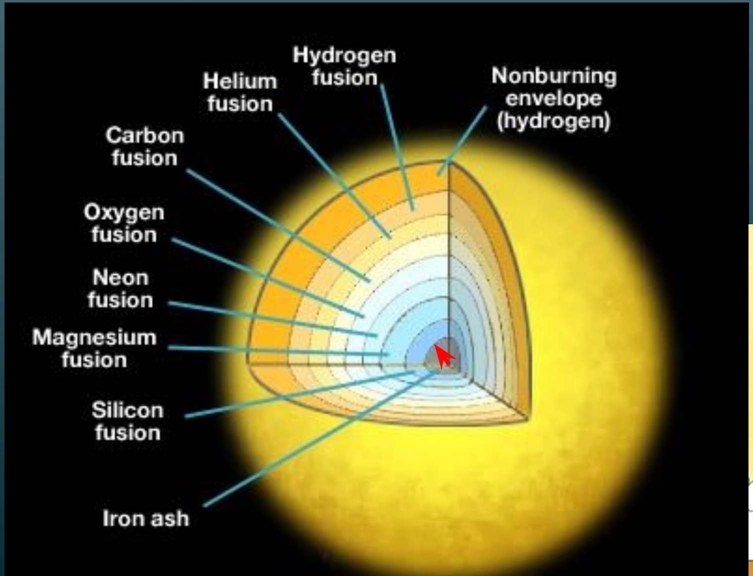

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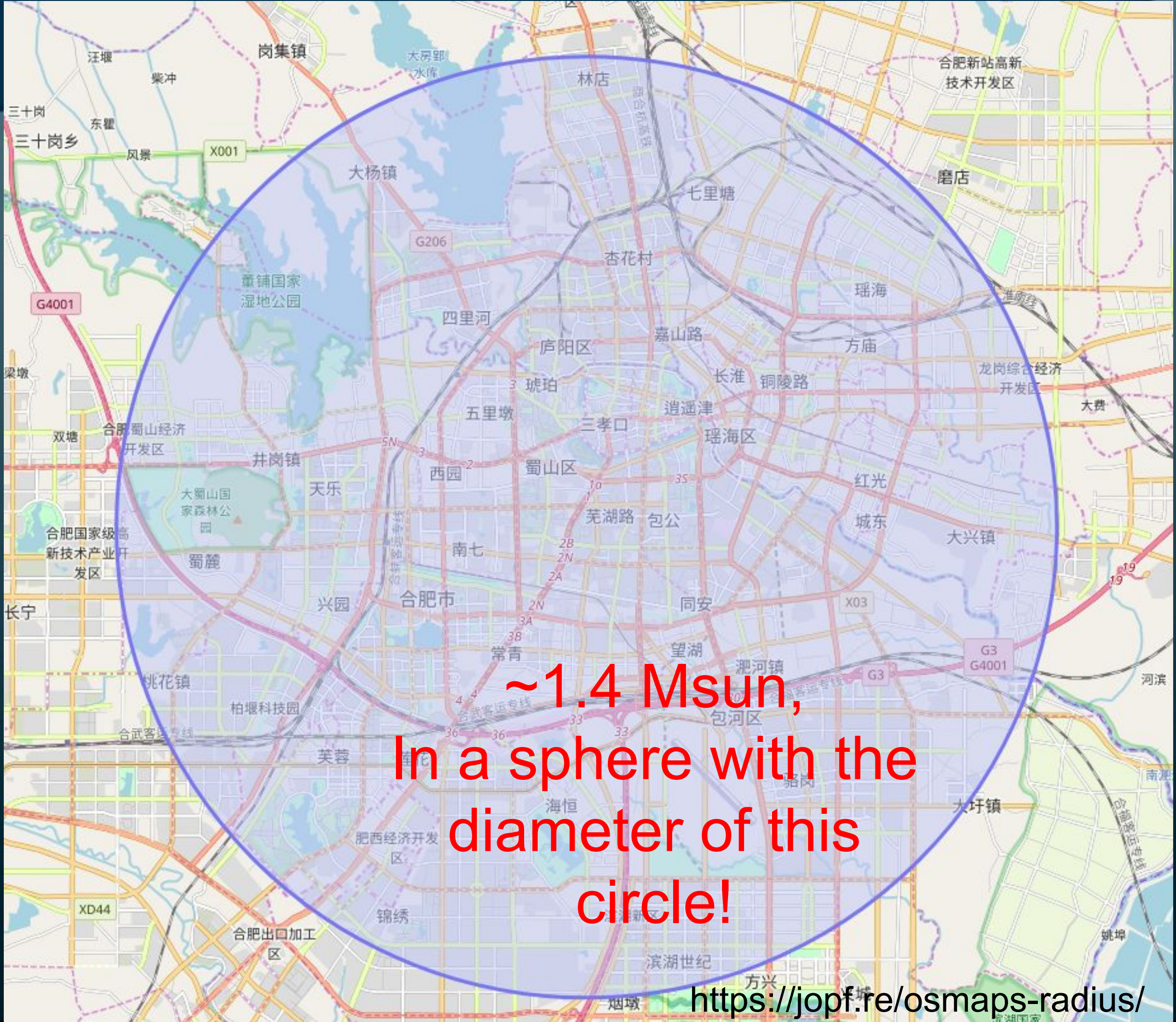
Neutron star:
~1.4 Msun
~24km diameter



~1.4 Msun,
In a sphere with the diameter of this circle!

https://jopf.re/osmaps-radius/

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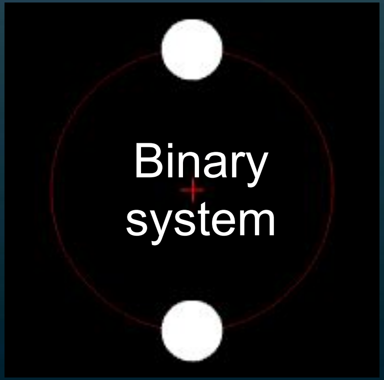

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Moving toward you

Moving away from you

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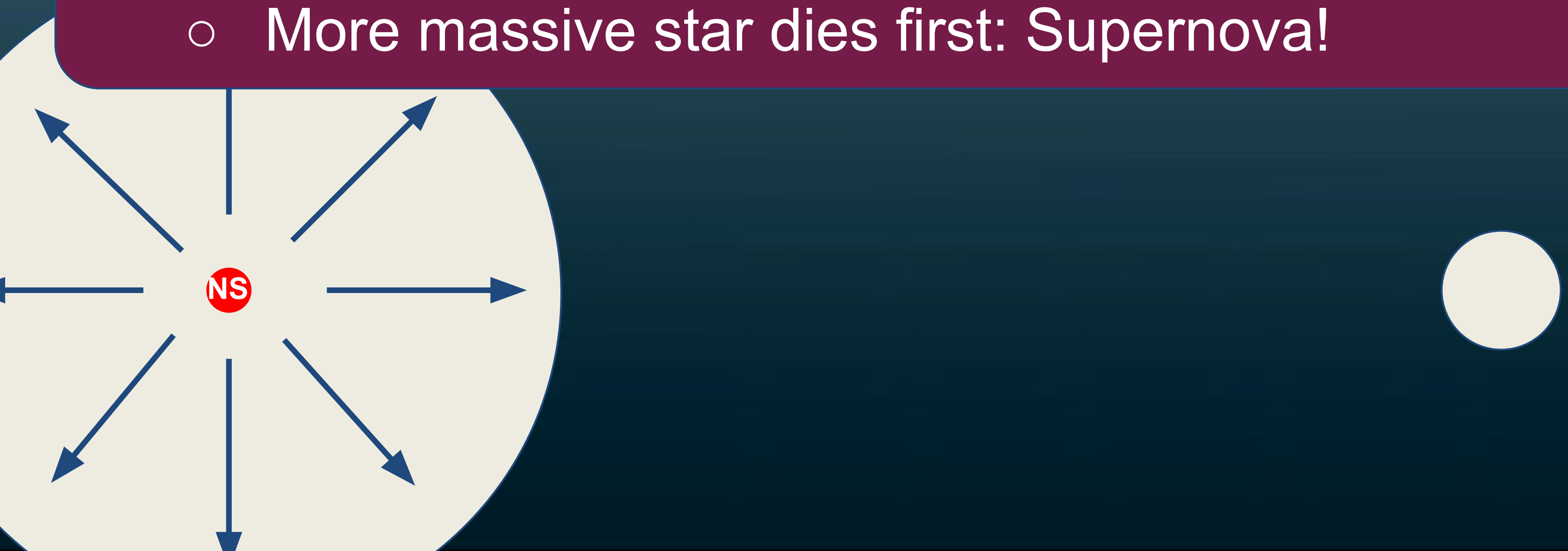

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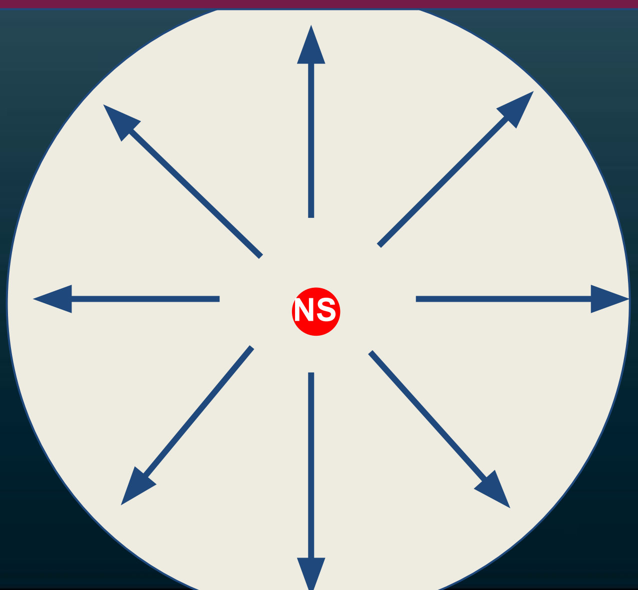

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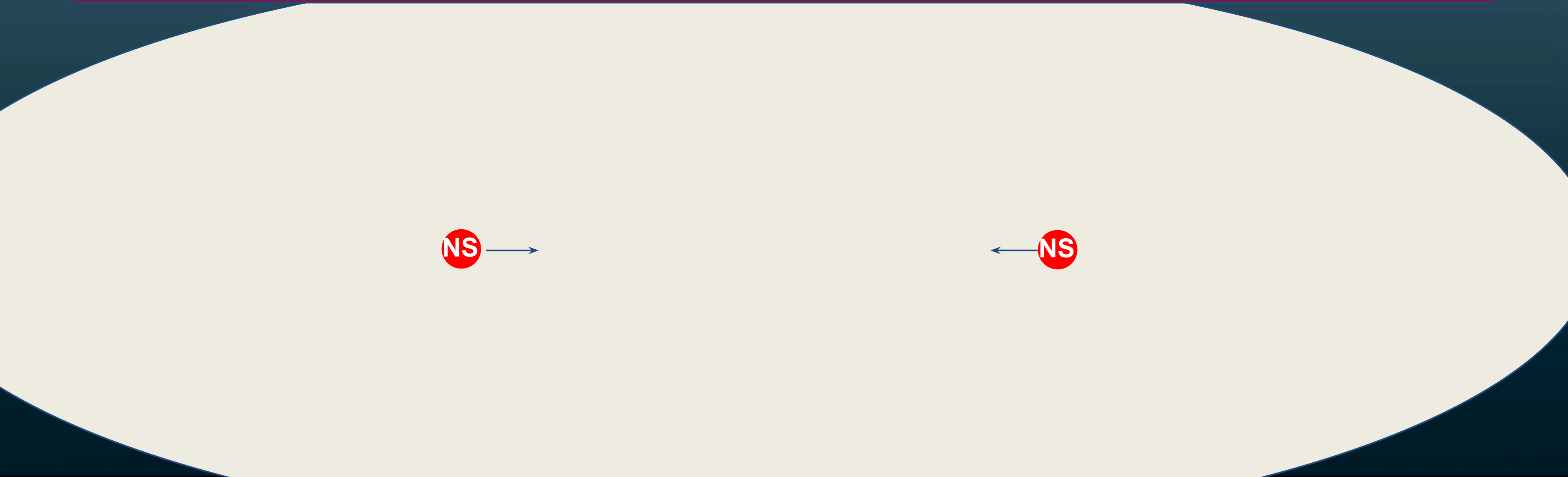

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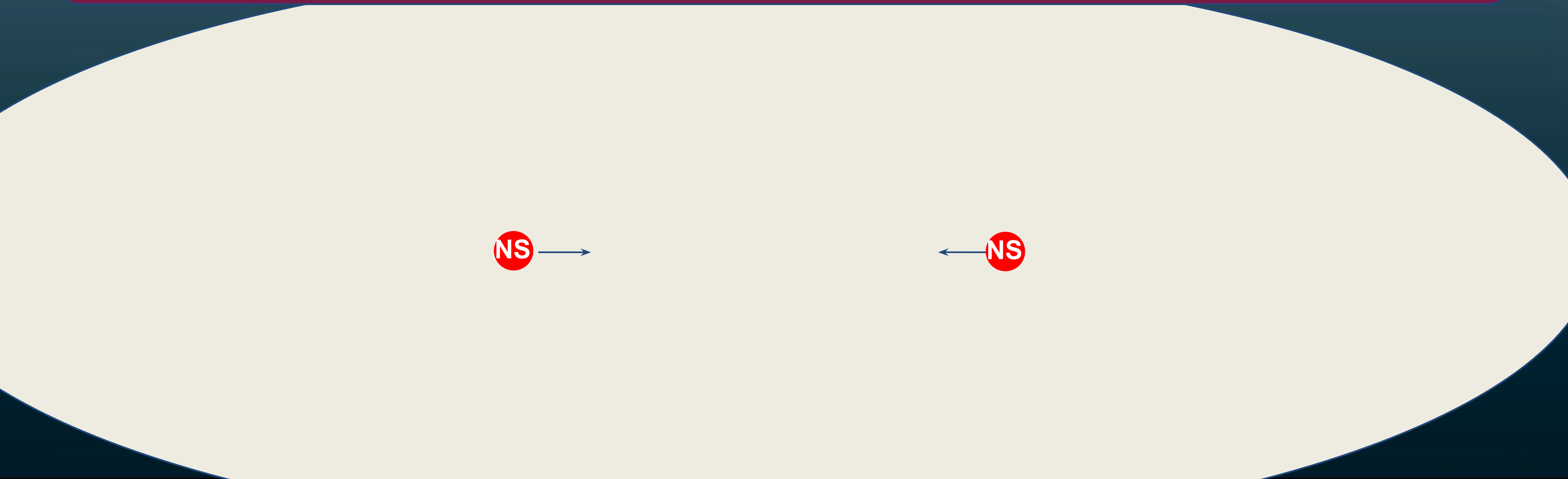

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- This two-supernova process has led to two neutron stars orbiting *very* closely

Disclaimer: This is just one plausible binary-neutron-star formation scenario; there are others

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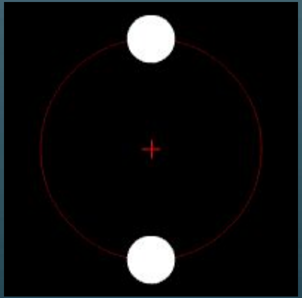

Newton's theory of gravity

- Point-like masses can orbit forever, *never colliding*

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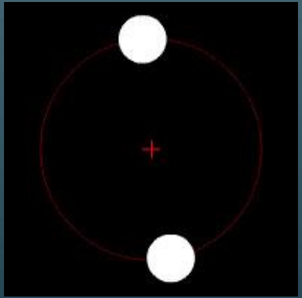

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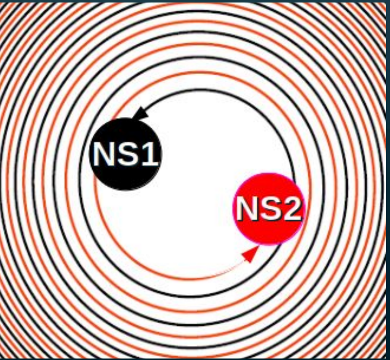

Lovelace et al.,
CQG 29, 045003 (2012) (modified)

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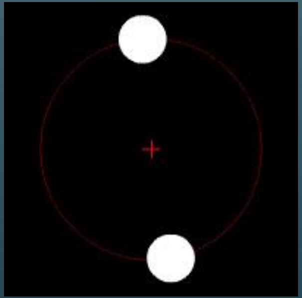

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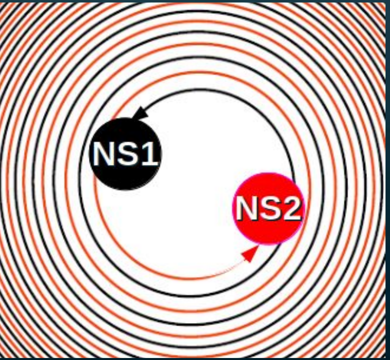

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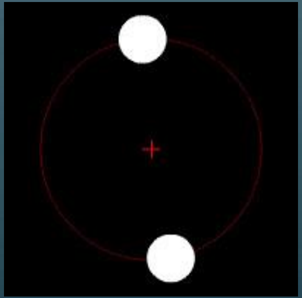

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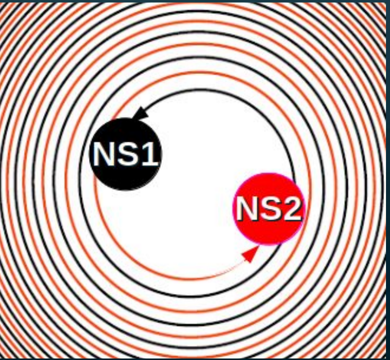

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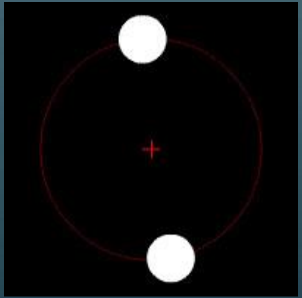

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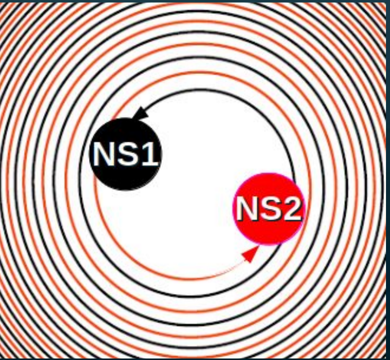

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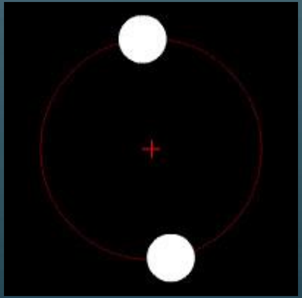

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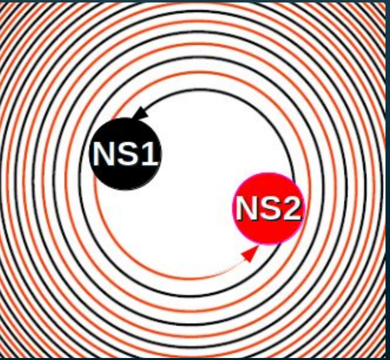

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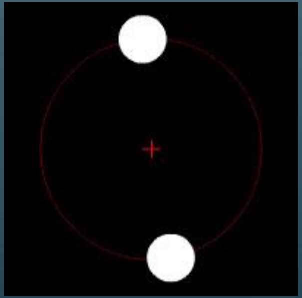

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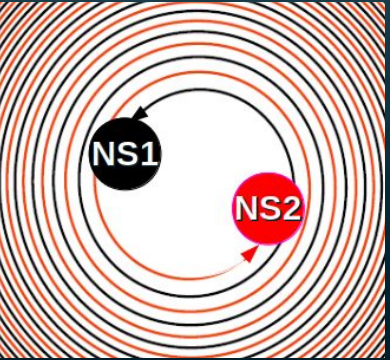

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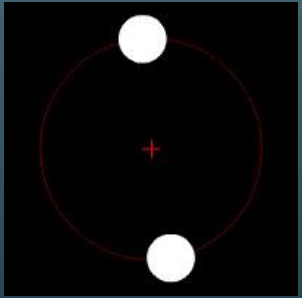

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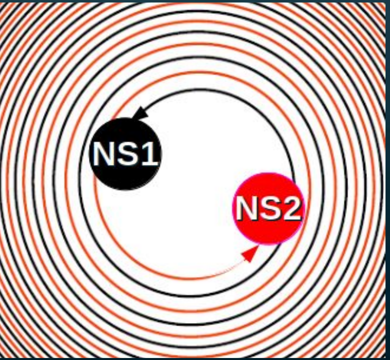

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⇨ **relativistic death spiral to collision!**

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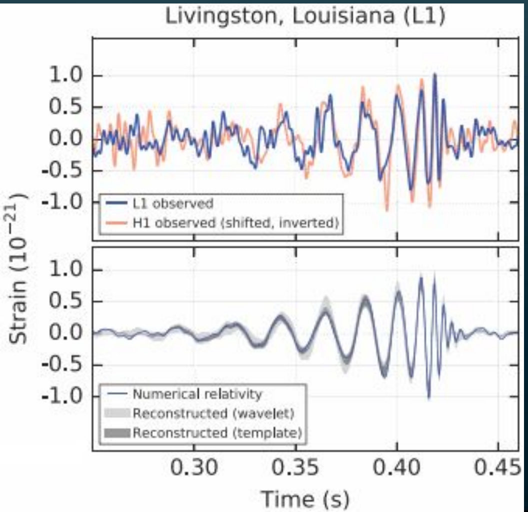
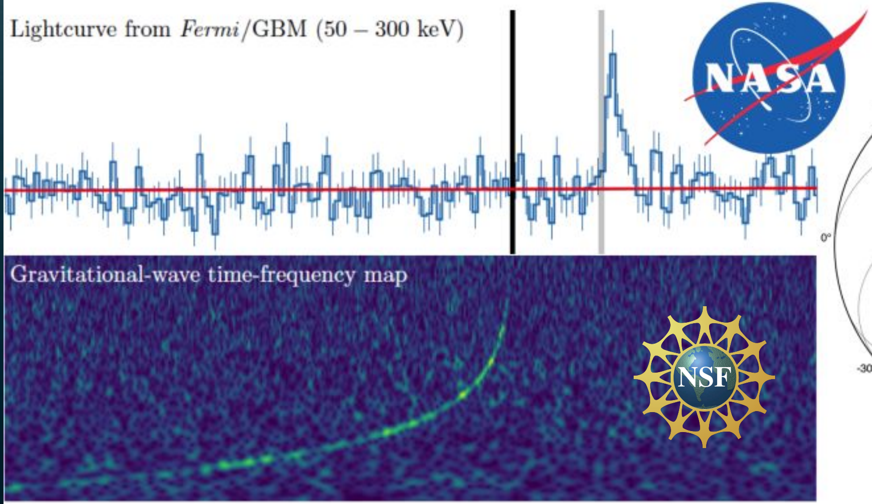
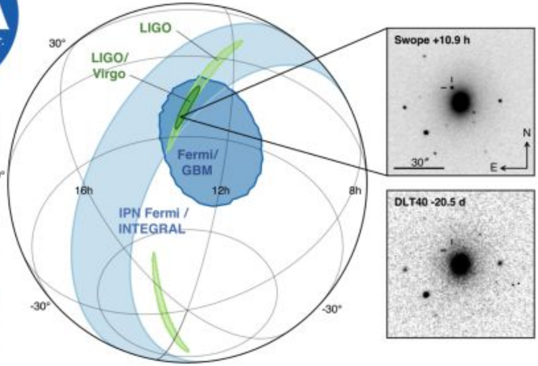
<u>Importance</u> of modeling gravitational wave and multimessenger sources

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

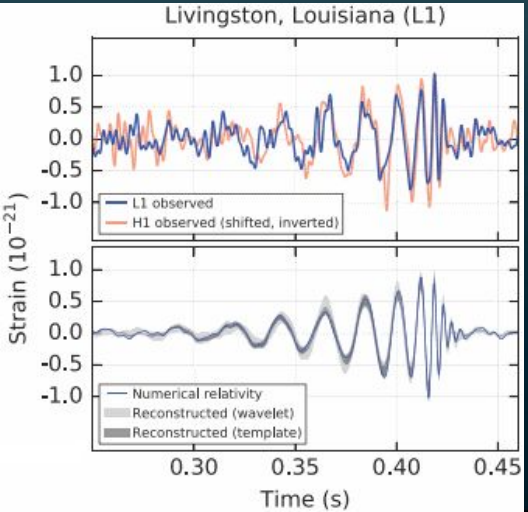


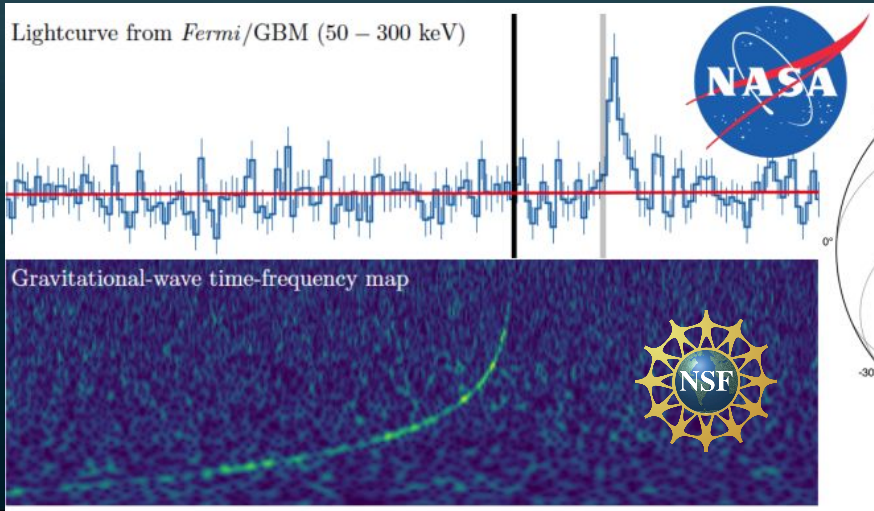


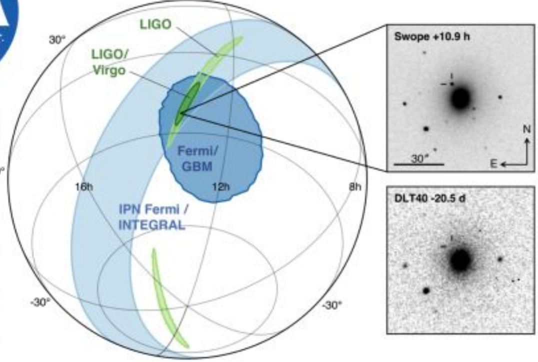


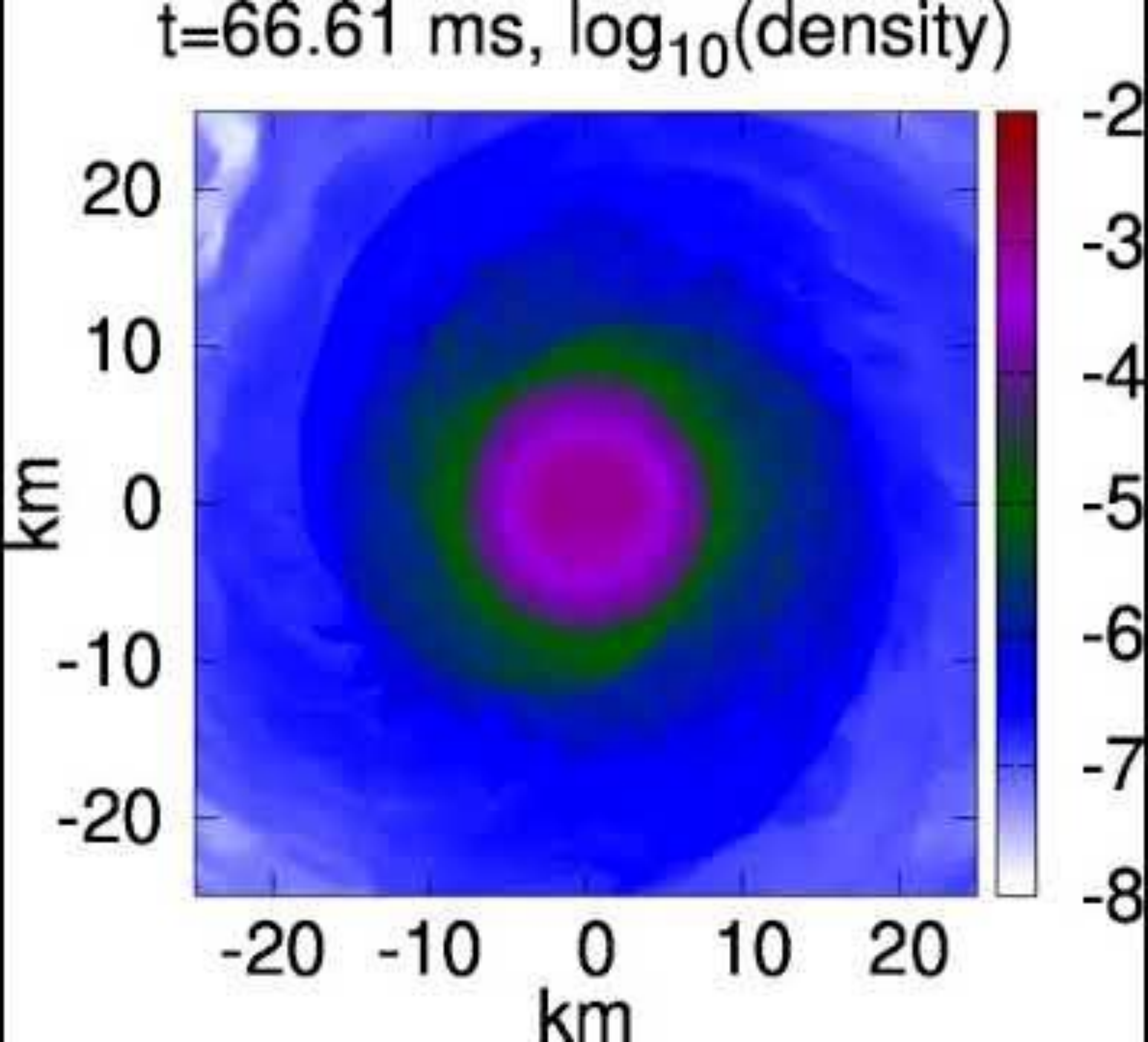
Importance of modeling gravitational wave and multimessenger sources

- $1B+ Question: What *exactly* caused this and *how*?
  - Answer can provide deep insights into extreme gravity & extreme matter, testing theories beyond current limits
  - To advance science, must compare observations with theoretical predictions
    - Theoretical predictions need to span observ. & theor. uncertainties





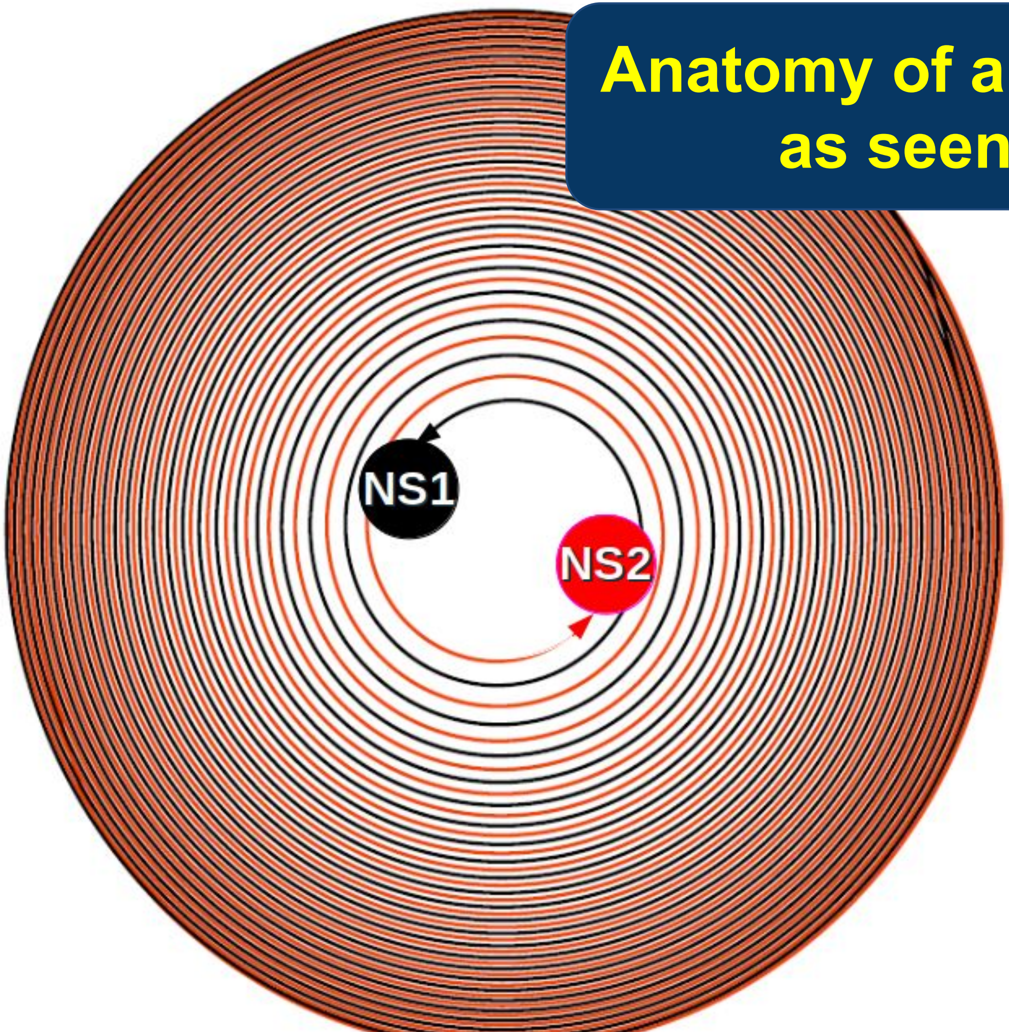




Nuclear density: -3.5 in these log units

Anatomy of a Binary Neutron Star Merger, as seen in gravitational waves

- Gravitational-wave driven "Relativistic death spiral"



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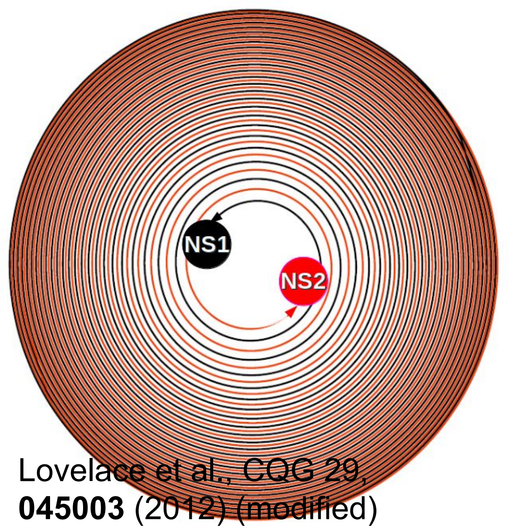

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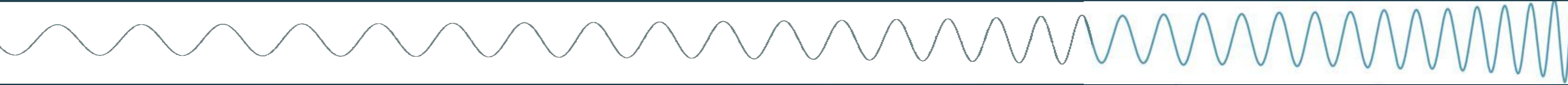
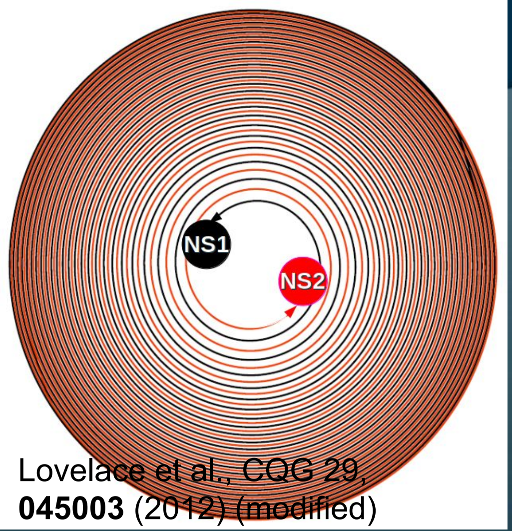
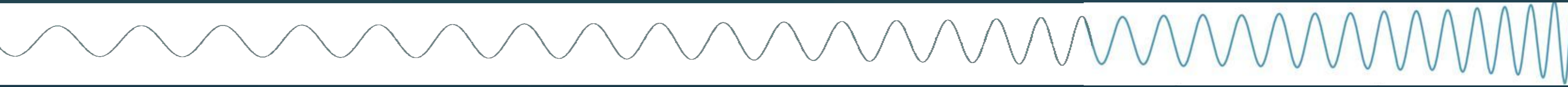


Time axis ⇨
(spans ~200ms)
Wave amplitude ⇧
(wave strain, arb. units)

Anatomy of a Binary Neutron Star Merger, as seen in gravitational waves



- Gravitational-wave driven "Relativistic death spiral"



These waves encode info about masses, spins, and composition of NSs

Time axis ⇨
(spans ~200ms)
Wave amplitude ⇧
(wave strain, arb. units)

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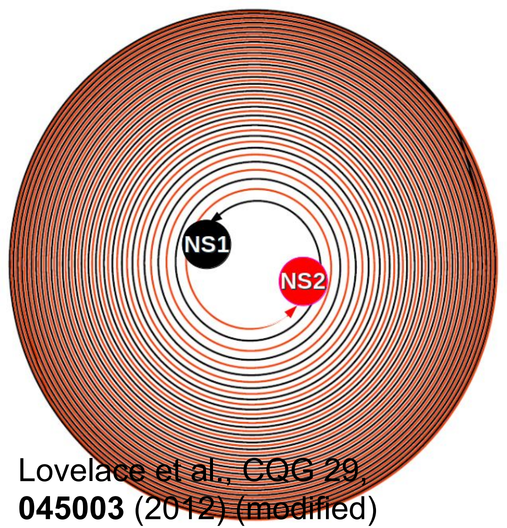

Lovelace et al., CQG 29, **045003** (2012) (modified)

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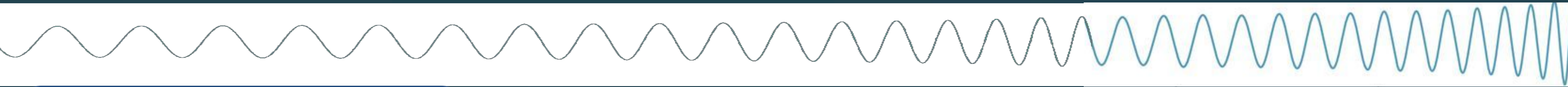

⇦ (Very) early inspiral: Perturbative solutions to Einstein gravity (GR)

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(wave strain, arb. units)

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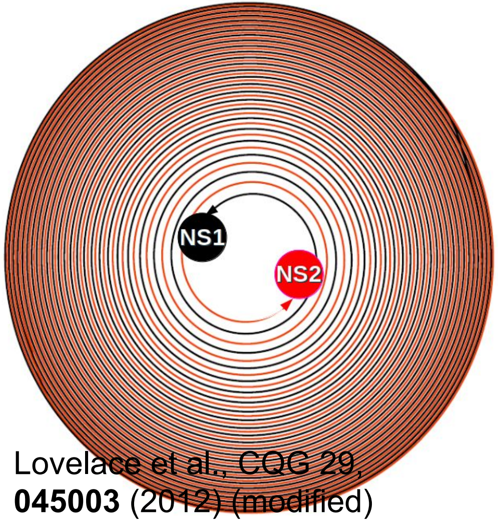

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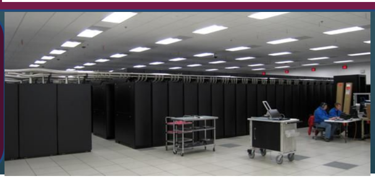

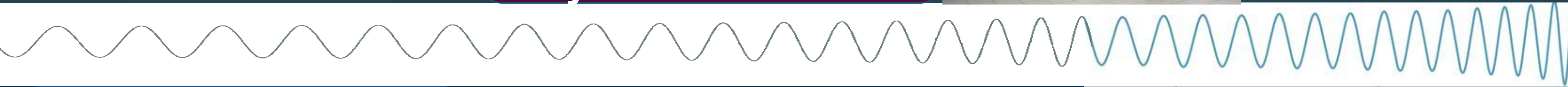

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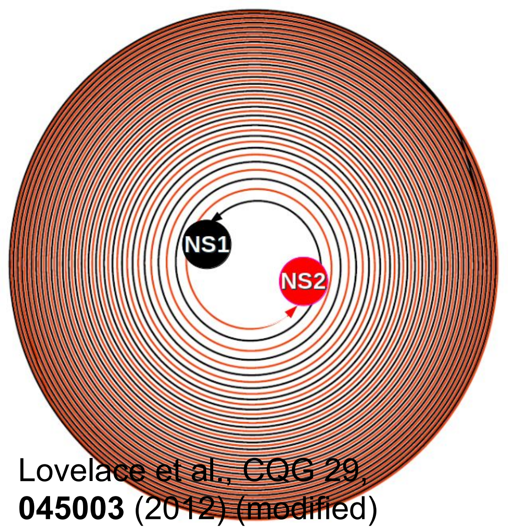

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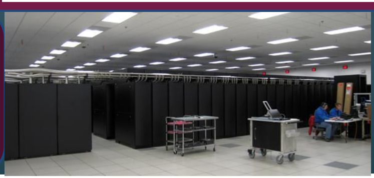

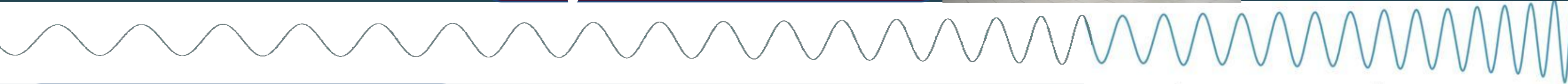

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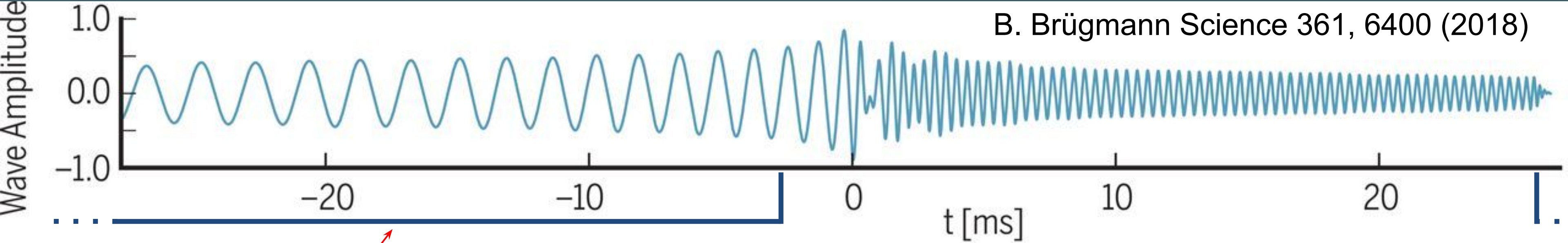
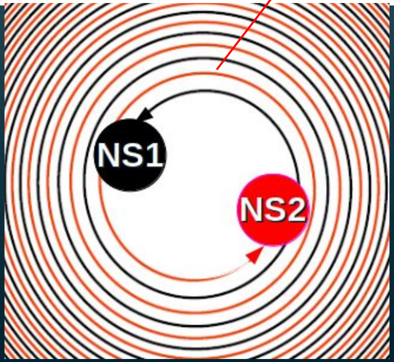
Next: modeling merger

Anatomy of a Binary Neutron Star Merger, as seen in gravitational waves

B. Brügmann Science 361, 6400 (2018)





Inspiral

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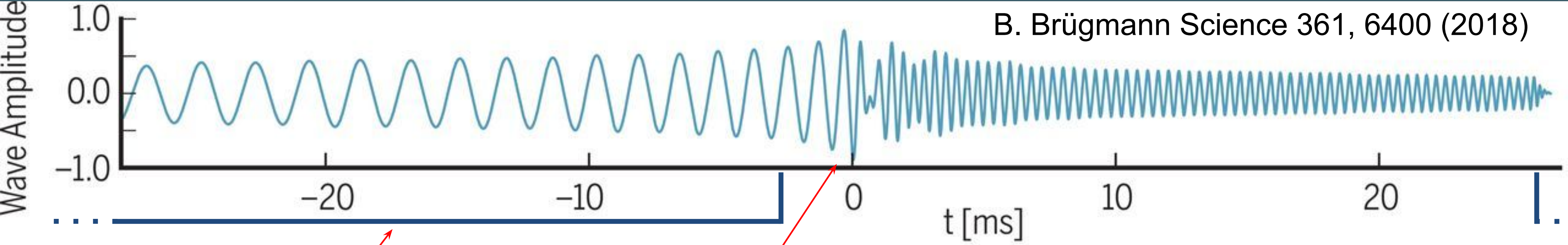

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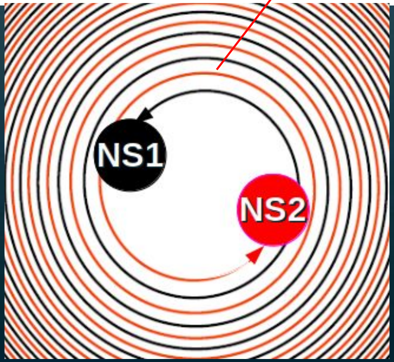

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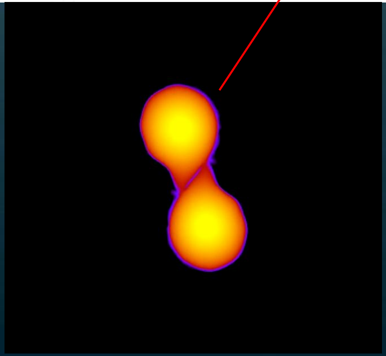

Merger

Magnetized BNS merger
Z. Etienne (2019)

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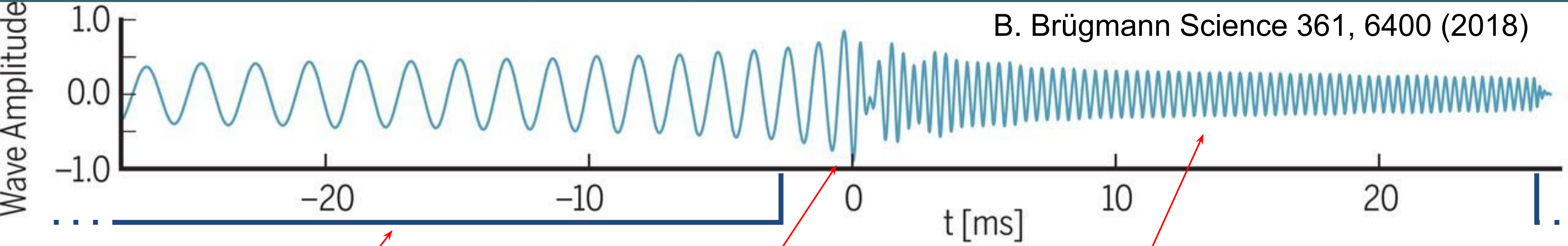

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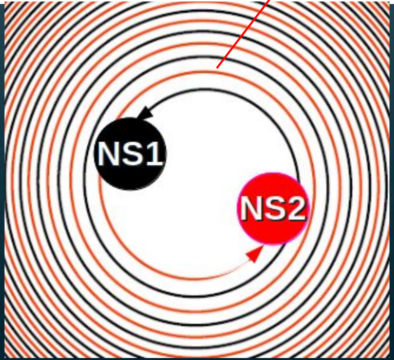

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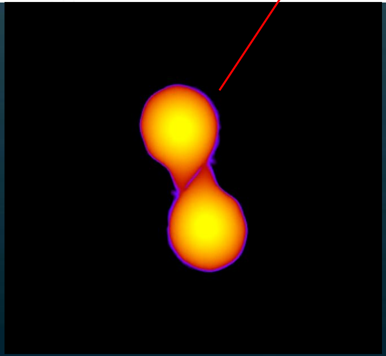

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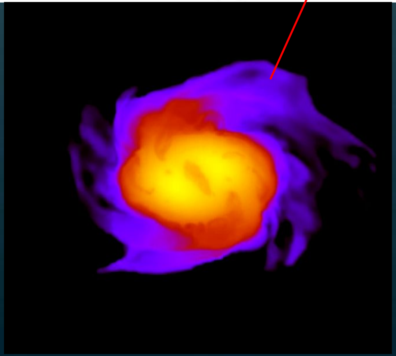

Hypermassive NS

Lovelace et al., CQG 29, 045003 (2012) (modified)

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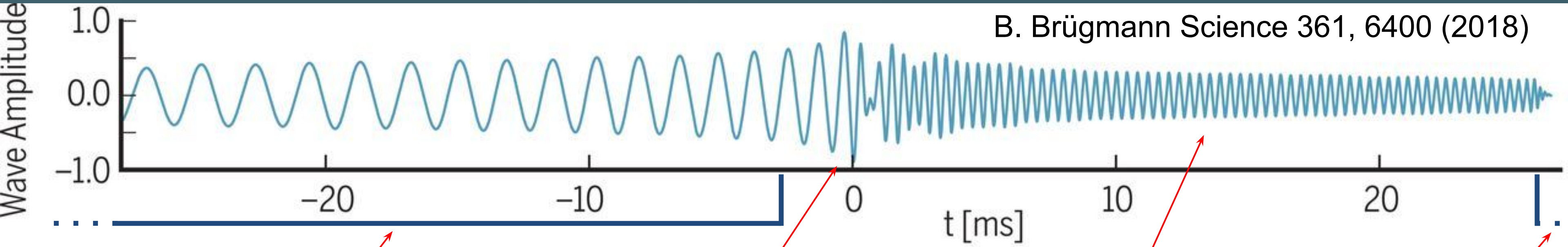

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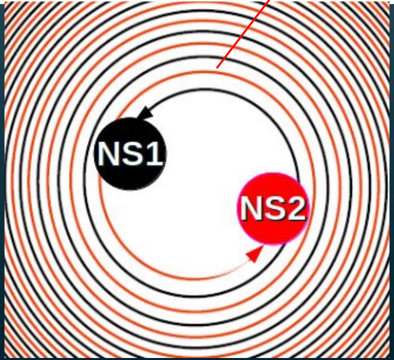

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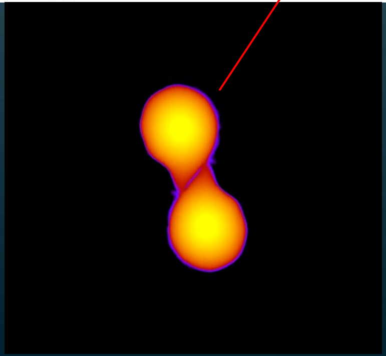

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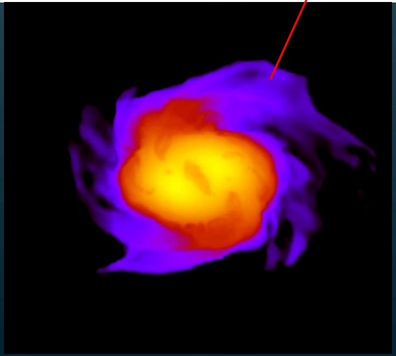

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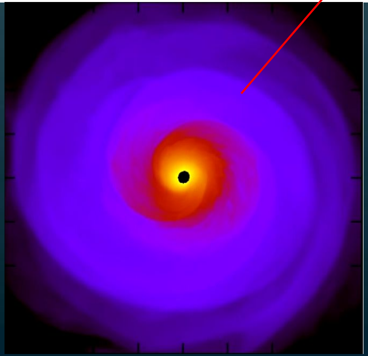


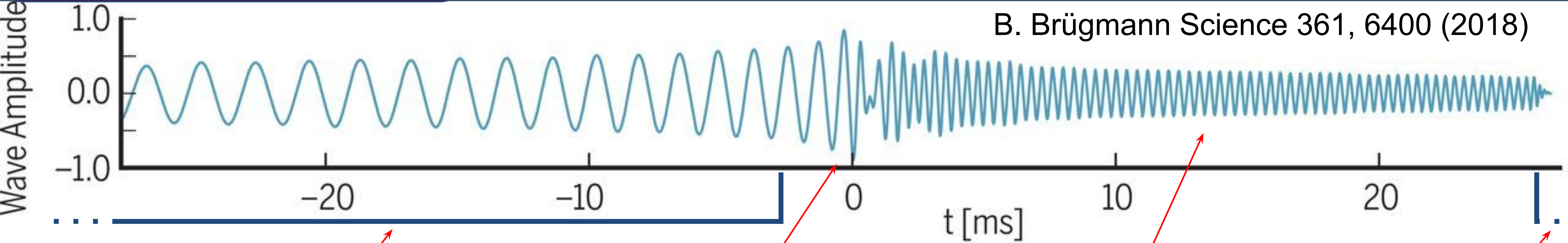
BH+disk

Lovelace et al., CQG 29, 045003 (2012) (modified)

Magnetized BNS merger
Z. Etienne (2019)

Anatomy of a Binary Neutron Star Merger, as seen in gravitational waves

Consistent model of merger to BH+disk: **must be full GR sim.**



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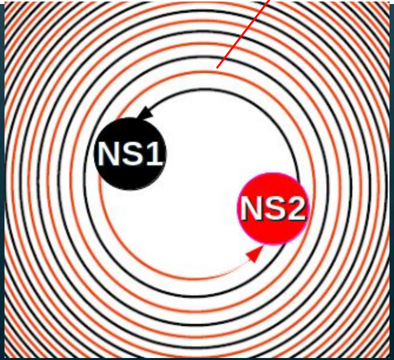
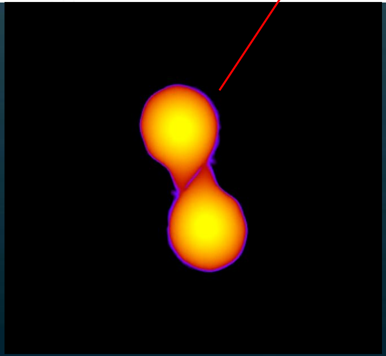


Inspiral



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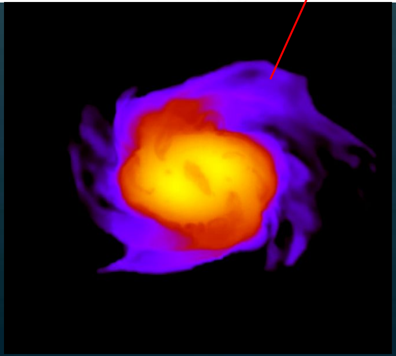

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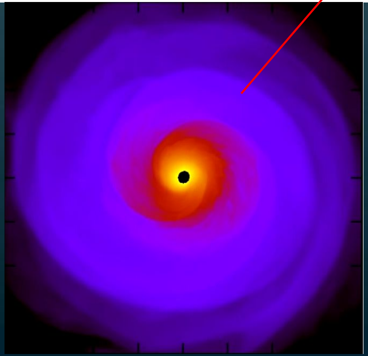

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Modeling Challenges

Reformulate Einstein's theory of gravity for the computer

1. **Stability**, even when simulating BHs
2. **Reliability**: numerical errors small and well-understood

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GR Equations are complex;
Solving the 2-body problem (two orbiting point masses) in GR took <u>90 years</u> (1915-2005)

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

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

$$\partial_t K = \left[\beta^k \partial_k K\right] + \frac{1}{3}\alpha K^2 + \alpha \bar{A}_{ij}\bar{A}^{ij} - e^{-4\phi}\left(\bar{D}_i \bar{D}^i \alpha + 2\bar{D}^i \alpha \bar{D}_i \phi\right) ,$$

$$\partial_t \bar{\Lambda}^i = \left[\beta^k \partial_k \bar{\Lambda}^i - \partial_k \beta^i \bar{\Lambda}^k\right] + \bar{\gamma}^{jk}\hat{D}_j \hat{D}_k \beta^i + \frac{2}{3}\Delta^i \bar{D}_j \beta^j + \frac{1}{3}\bar{D}^i \bar{D}_j \beta^j$$
$$- 2\bar{A}^{ij}\left(\partial_j \alpha - 6\partial_j \phi\right) + 2\alpha \bar{A}^{jk}\Delta^i_{jk} - \frac{4}{3}\alpha \bar{\gamma}^{ij}\partial_j K$$

$$\partial_t \alpha = \left[\beta^i \partial_i \alpha\right] - 2\alpha K$$

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

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

Most popular formulation

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Model all the necessary physical processes

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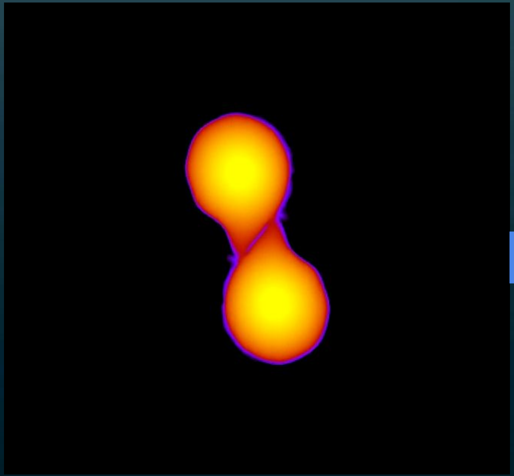
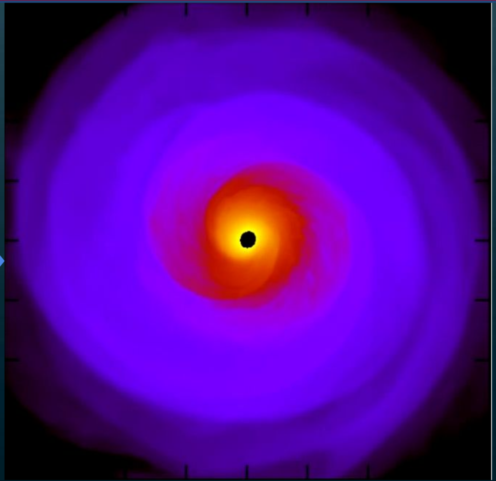
- *E.g., gamma-ray bursts thought to originate from magnetized fluid dynamics around BH+disk remnant*



Binary NS Merger



BH+disk

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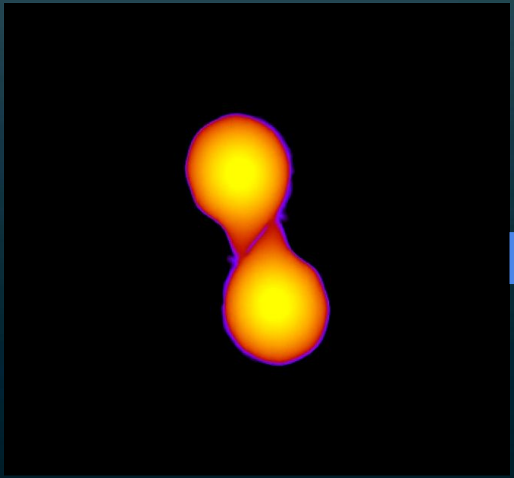

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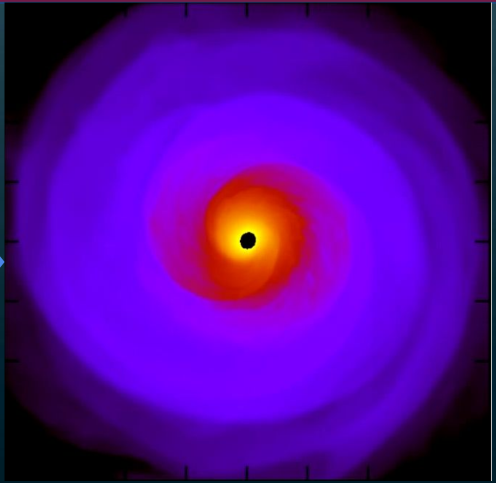

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Current state-of-the-art

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

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2. Model **long-wavelength** gravitational waves far away
3. Push outer boundary very far away (due to approx. BCs)

Outline

- Part 1: **When Neutron Stars Collide!**
  - GW170817 / GRB170817A: How two bright stars lived and died
- Part 2: **Extracting Science from the Observations**
  - The importance and challenges of modeling gravitational wave and multimessenger sources
- Part 3: **A Promising New Approach!**
  - Addressing challenges to unlock next-generation models of multimessenger sources

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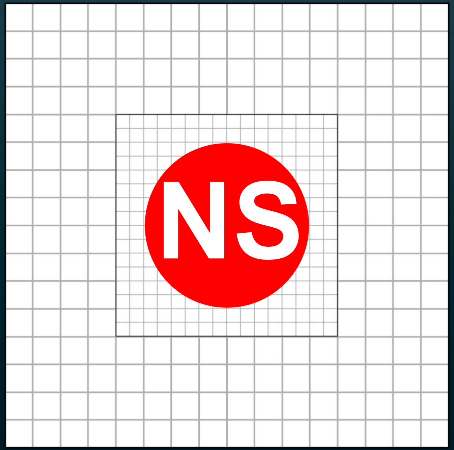
So why not just use dense grids everywhere?



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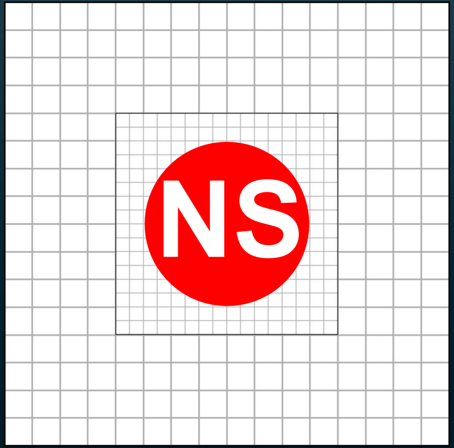
A: Wasteful and impractical; supercomputers are not "super" enough.



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How to address?

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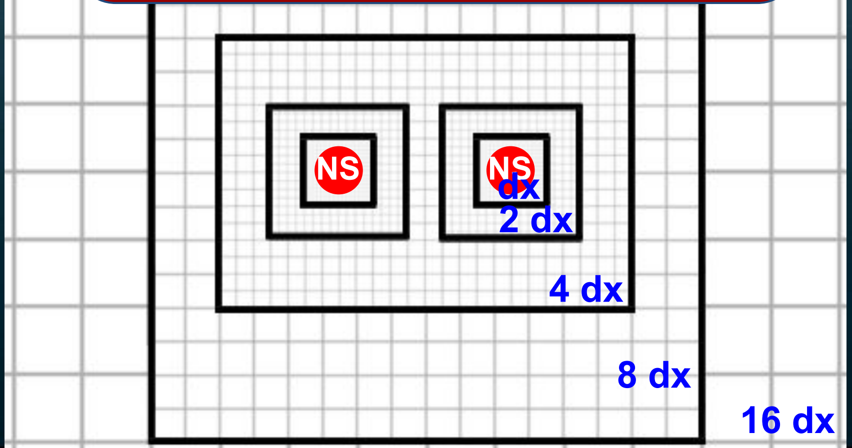
AMR

Adaptive Mesh Refinement

(Most Popular Method in NR)



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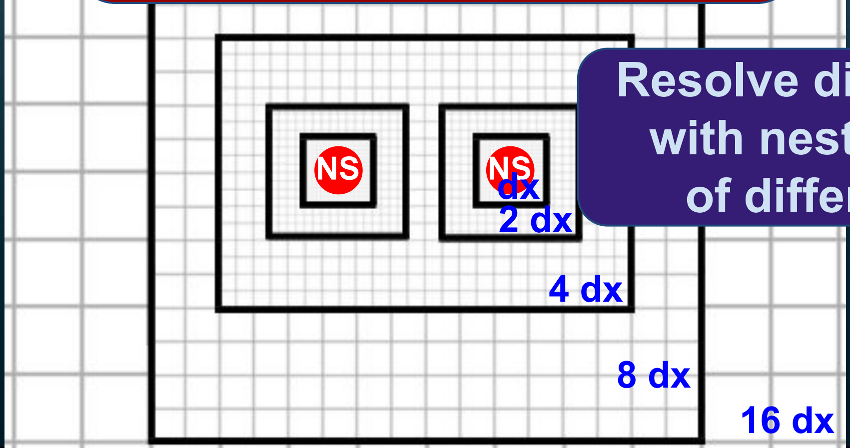

Resolve disparate lengthscales with nested Cartesian cubes of differing grid spacings

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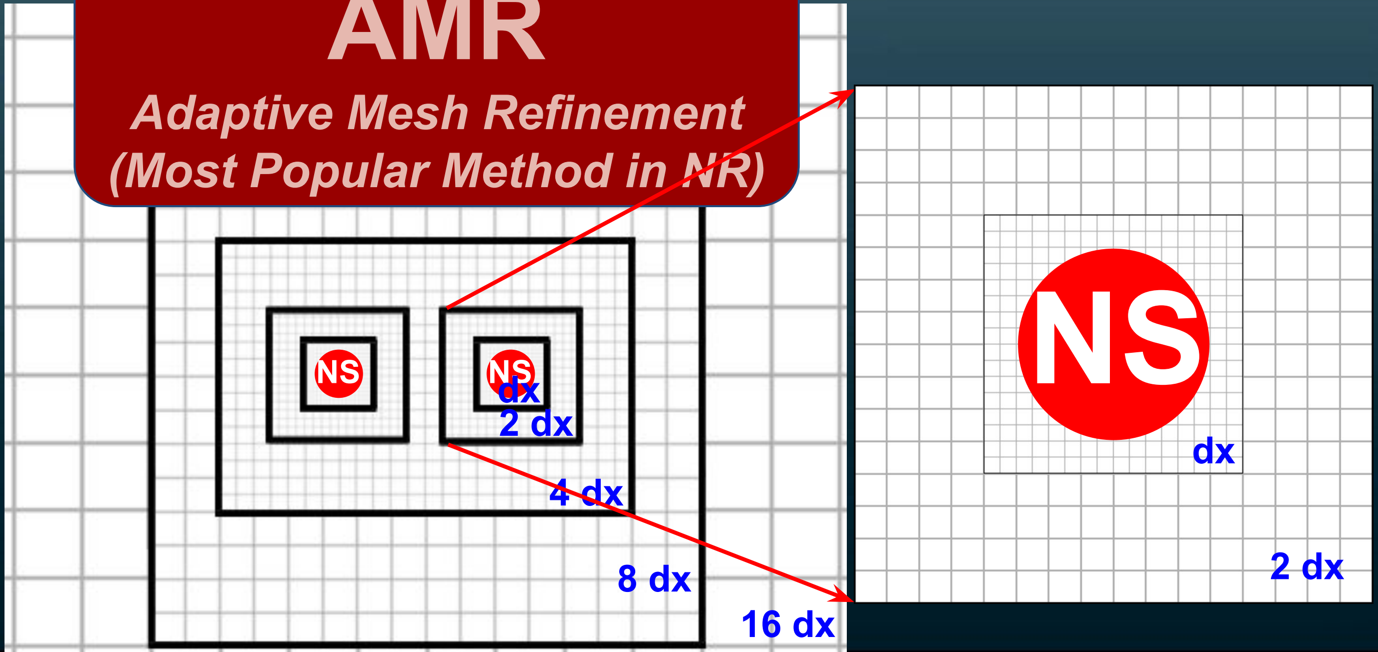

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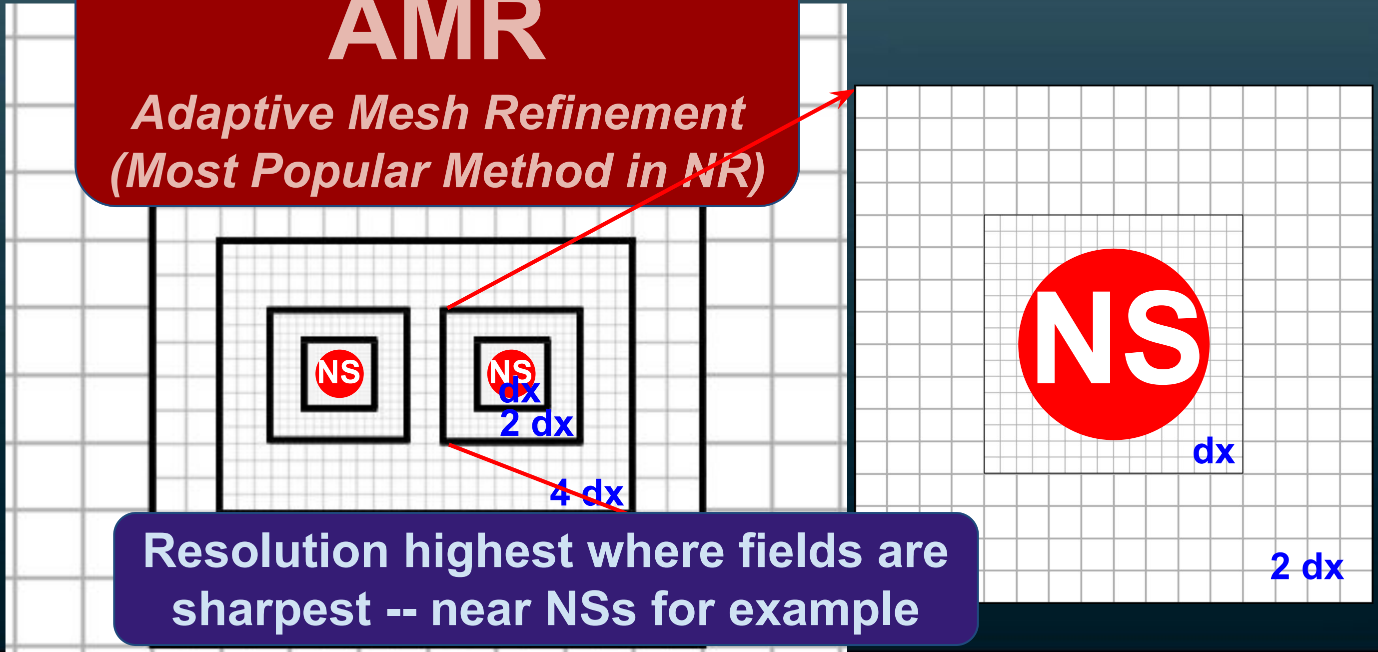

Resolution highest where fields are sharpest -- near NSs for example

Modeling Challenges

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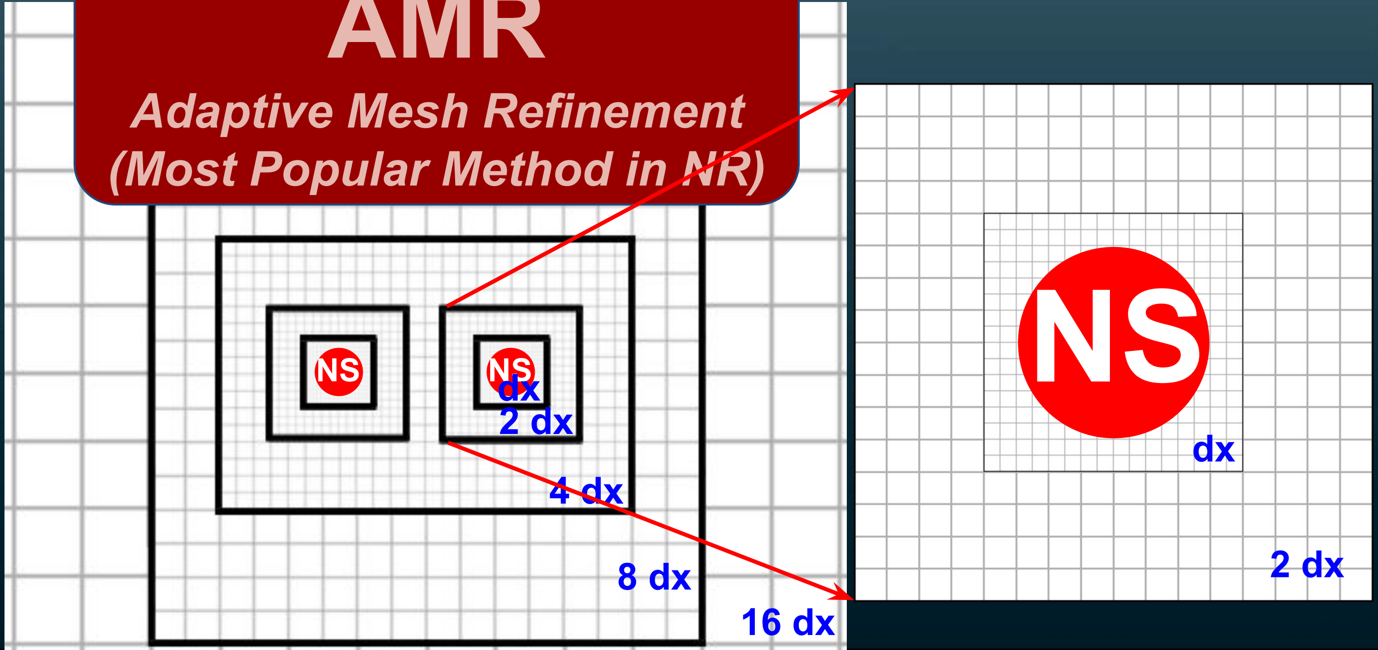
AMR

Adaptive Mesh Refinement
(Most Popular Method in NR)



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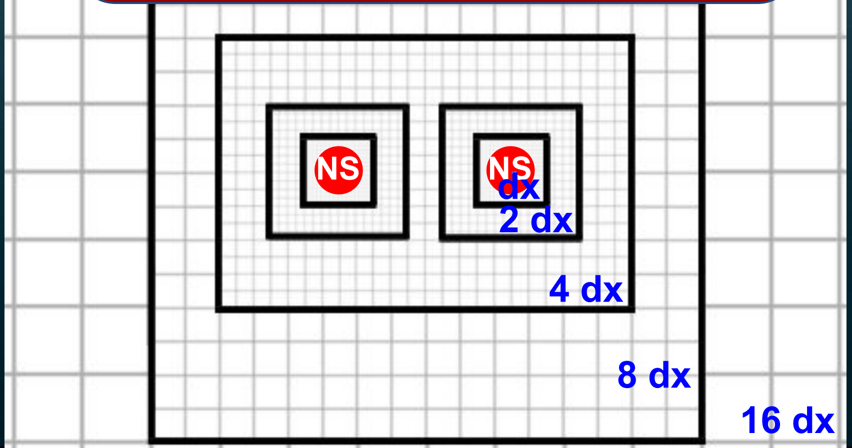

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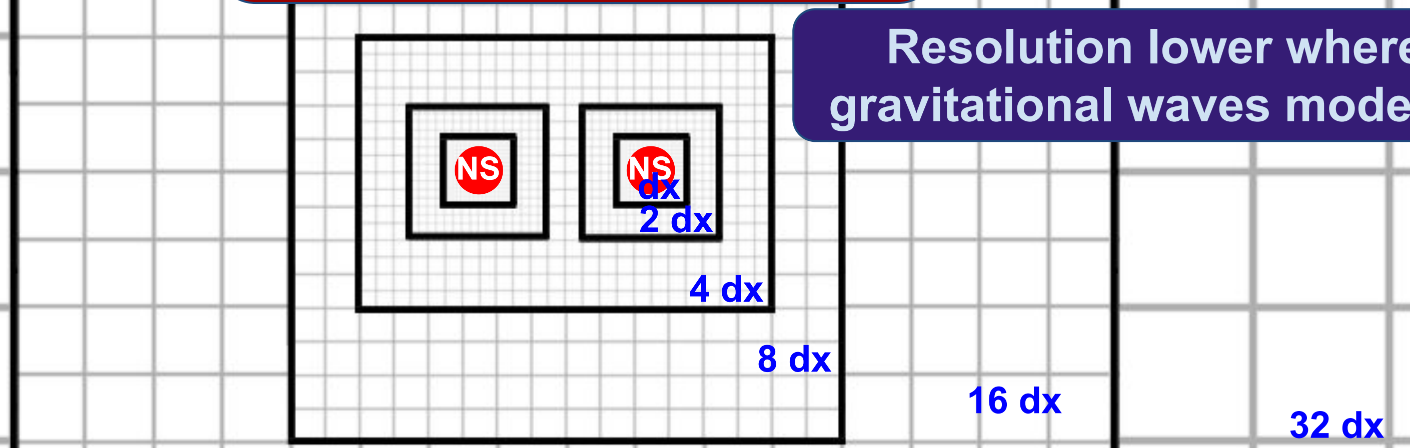
Resolution lower where gravitational waves modeled



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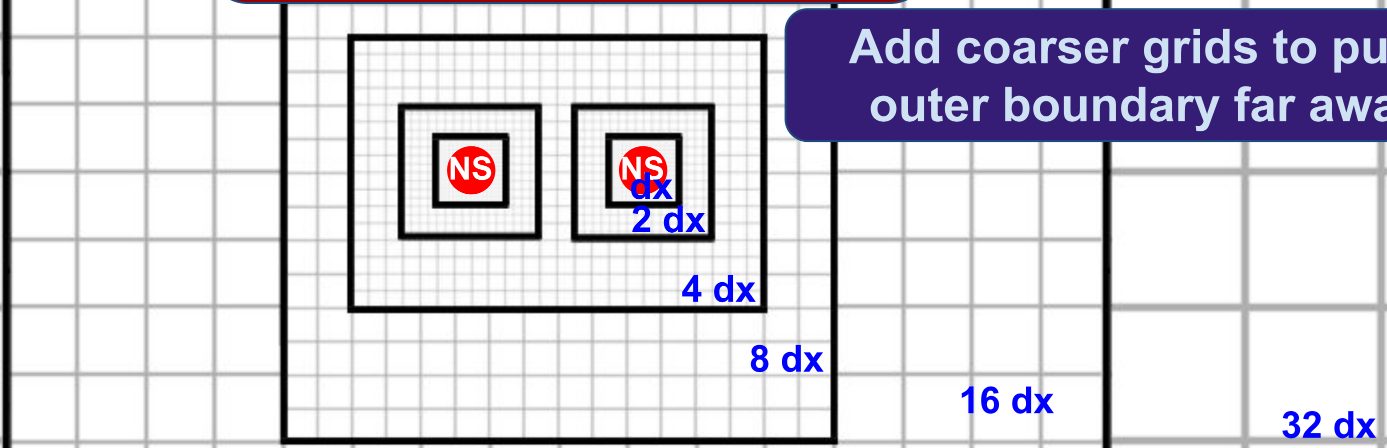
Add coarser grids to push outer boundary far away



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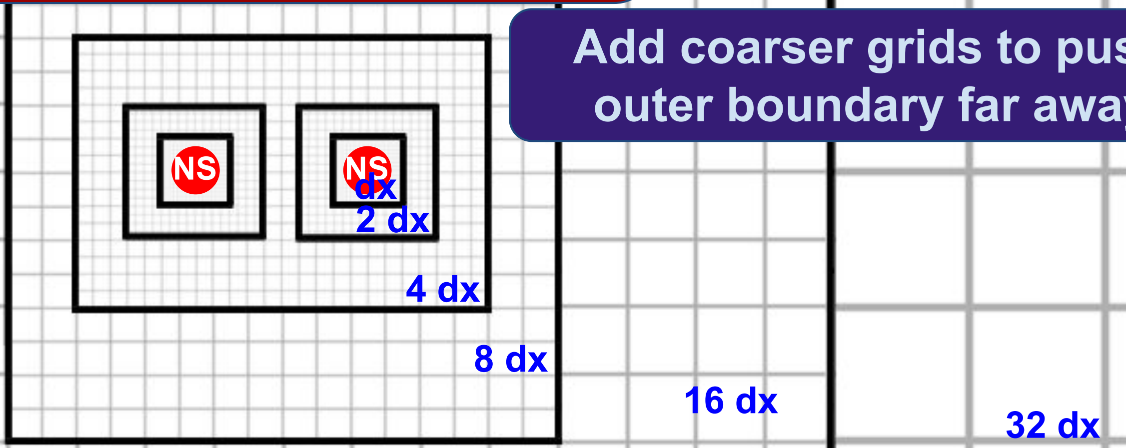

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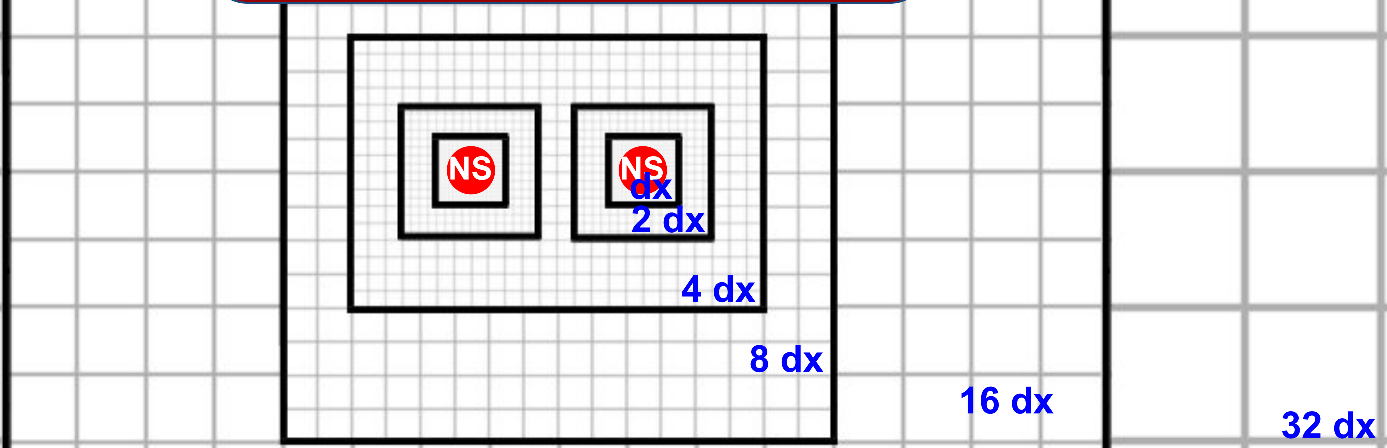

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What's the problem?

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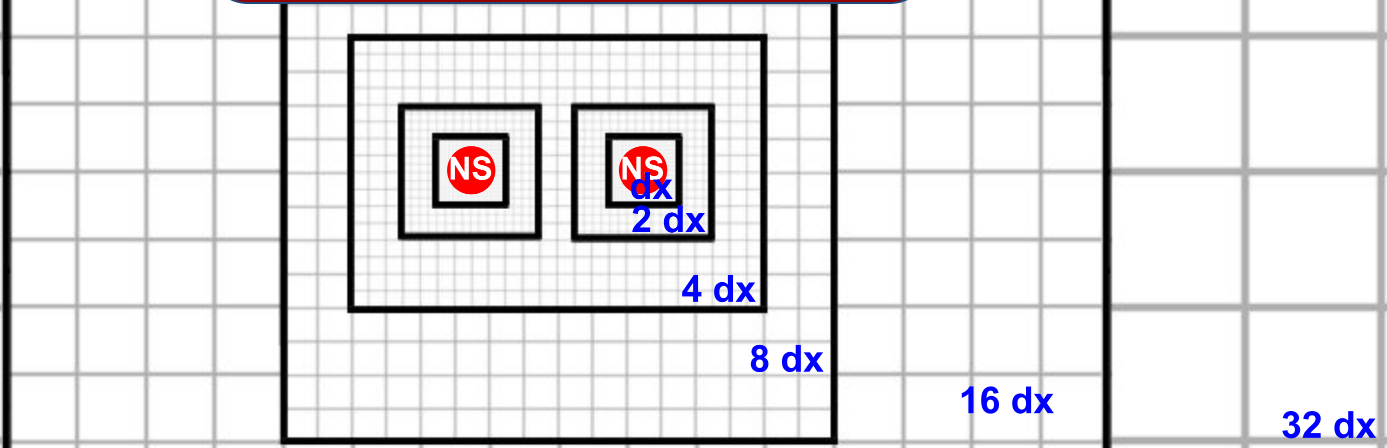

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What's the problem?

A: Inefficient!
➪ greater comp. cost

AMR

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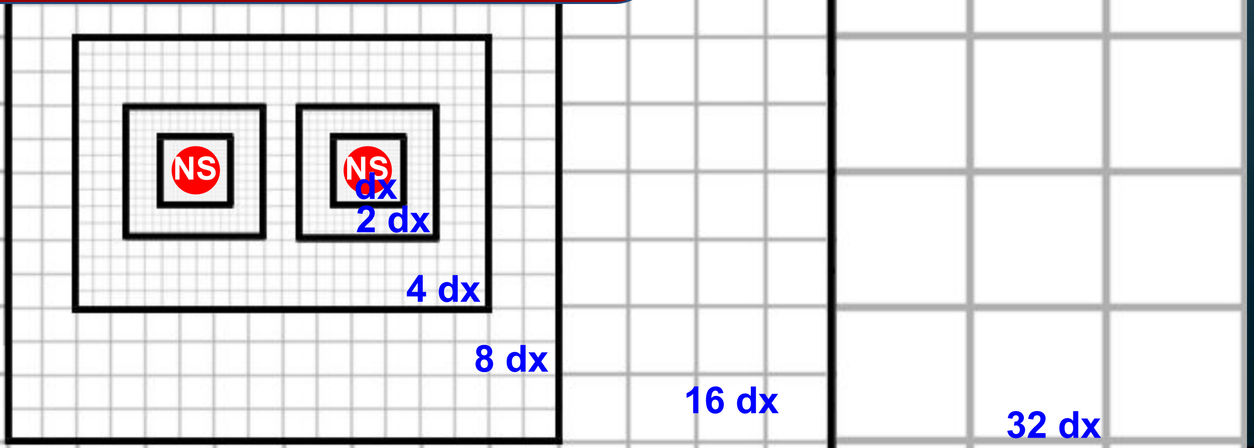

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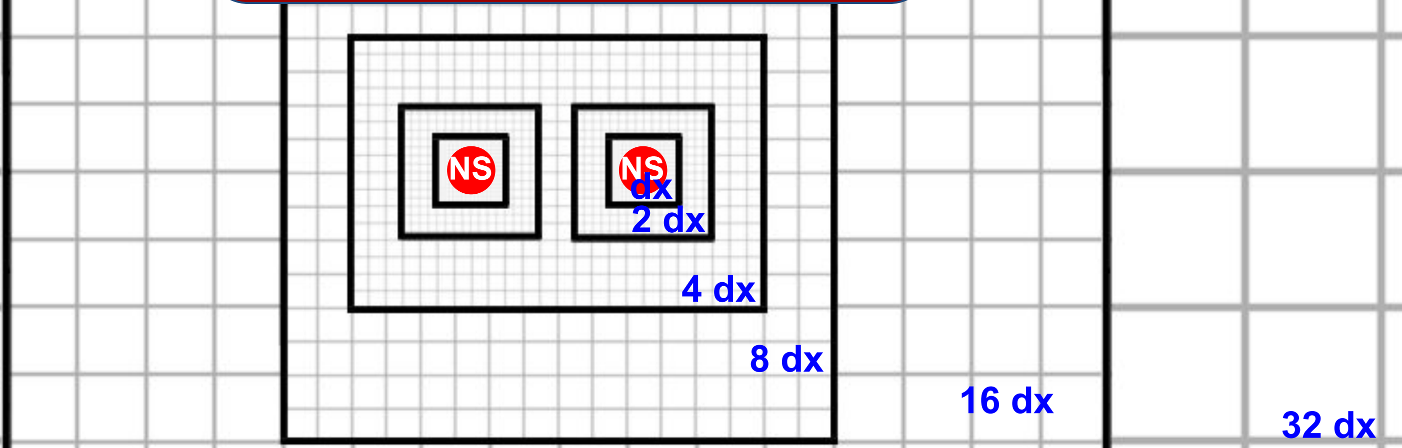

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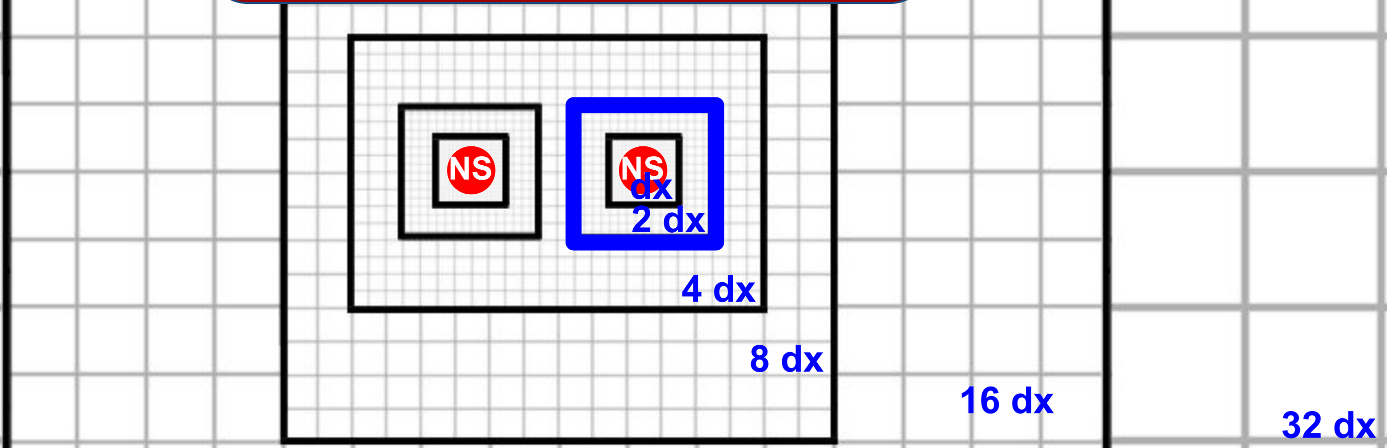

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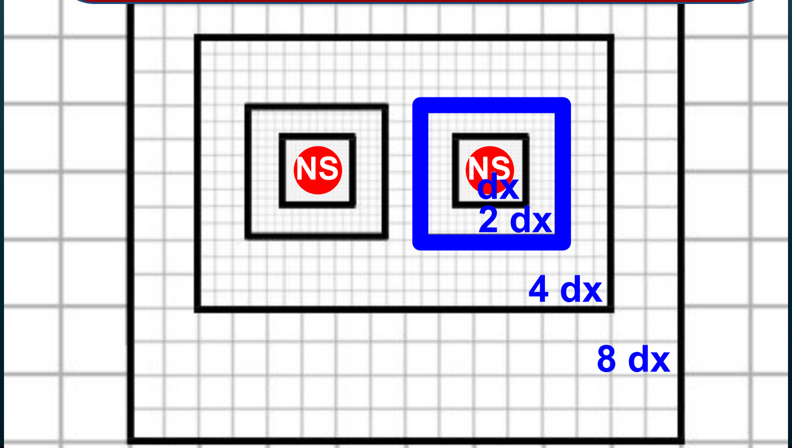

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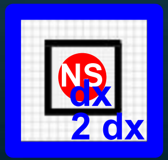

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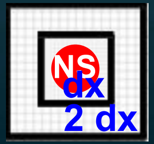

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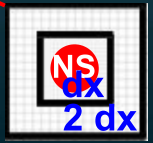

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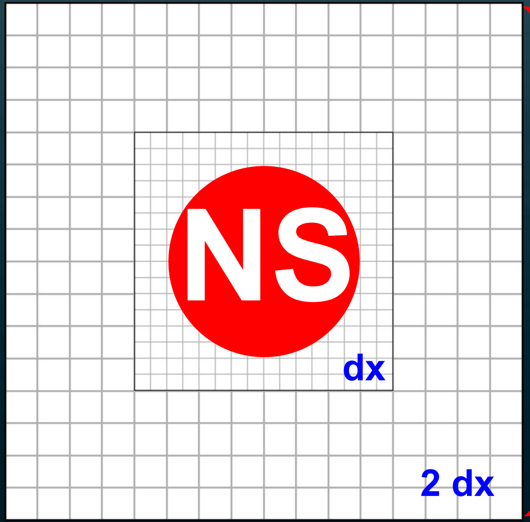

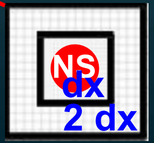

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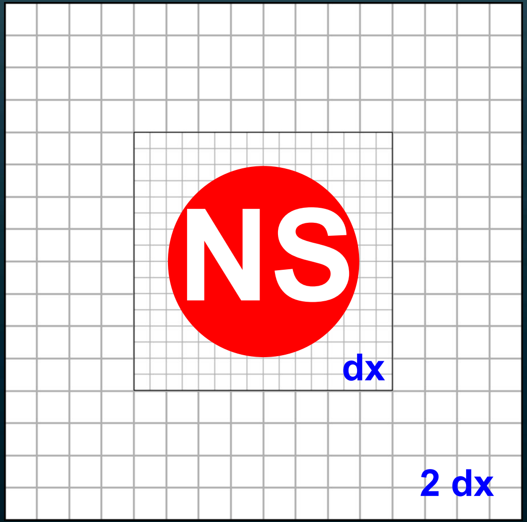

1. Black holes & neutron stars:
   nearly spherical/axisymmetric
   - ⇨ grav/matter fields drop off strongly in *radial* direction
     ⇨ <u>need highest sampling in *r* direction</u>

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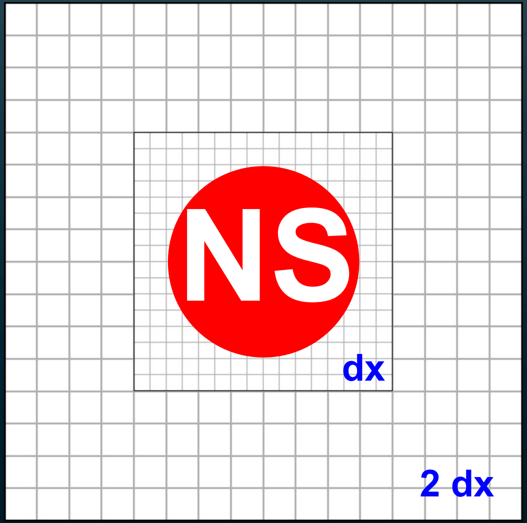

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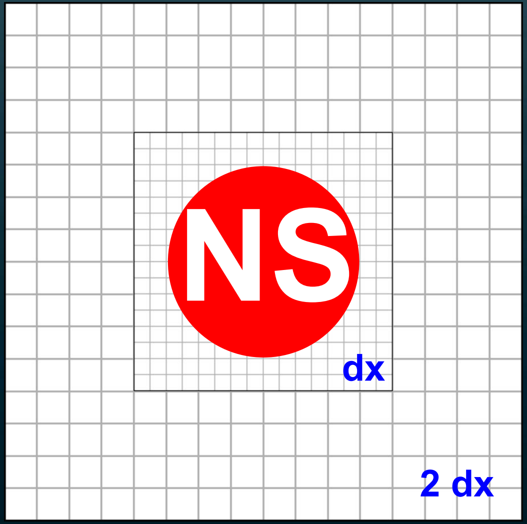

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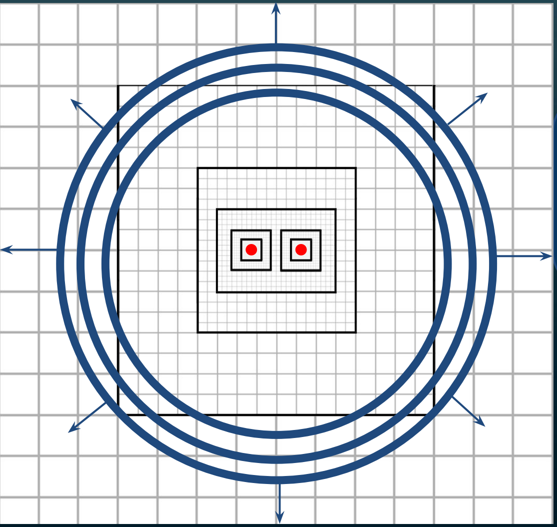

2. Gravitational waves far away nearly spherical
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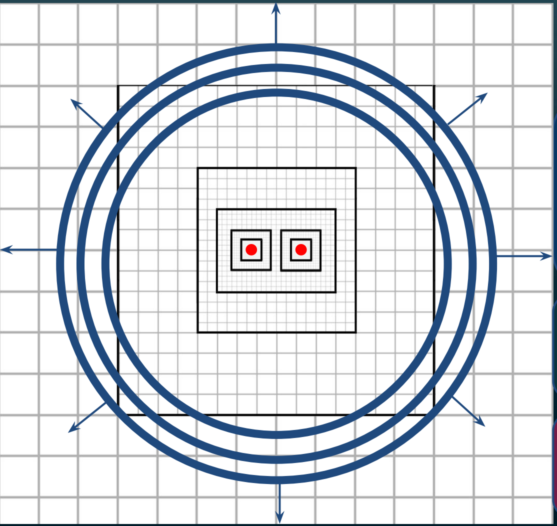

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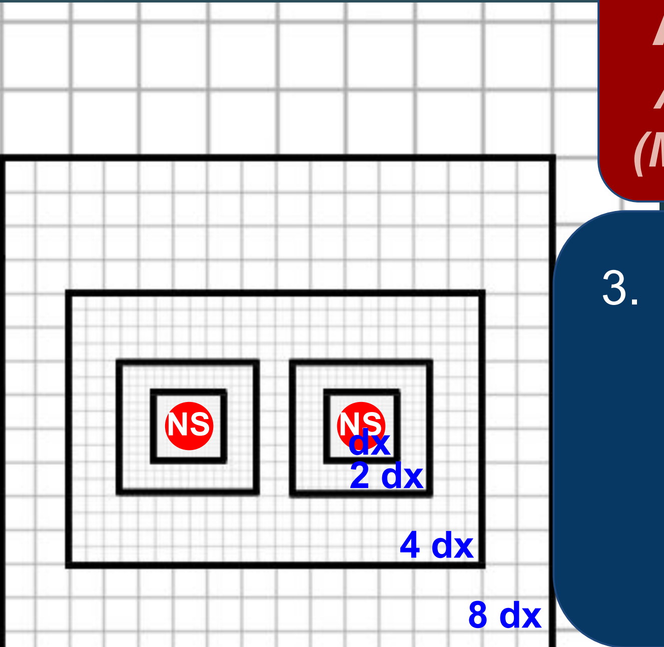

AMR Inefficiencies

Adaptive Mesh Refinement
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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

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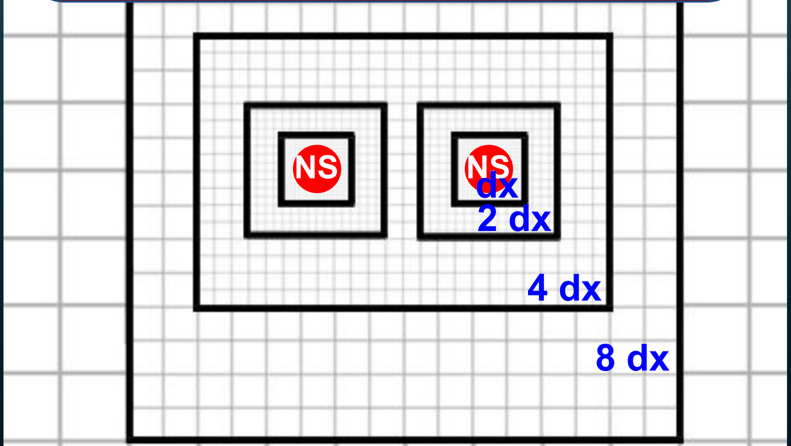

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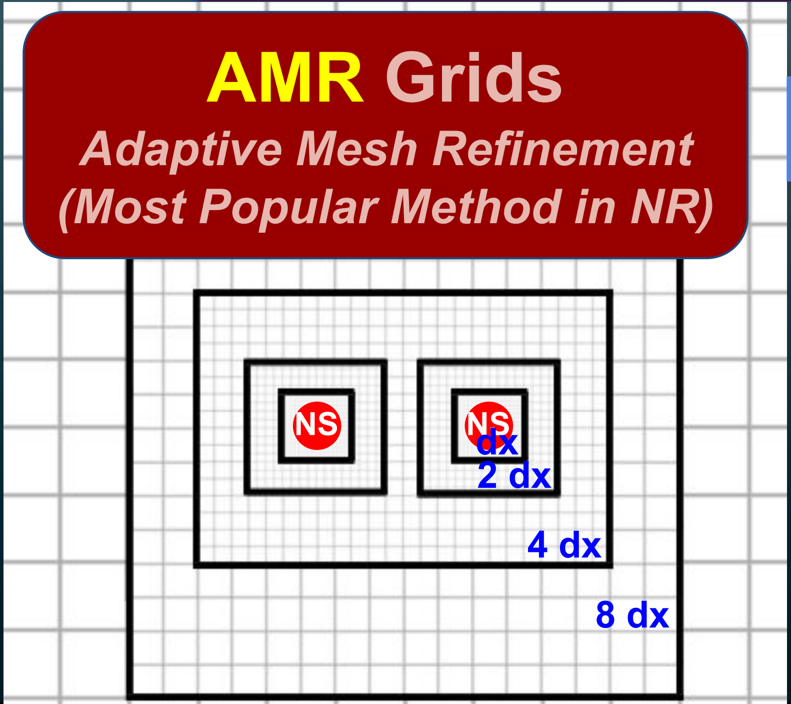
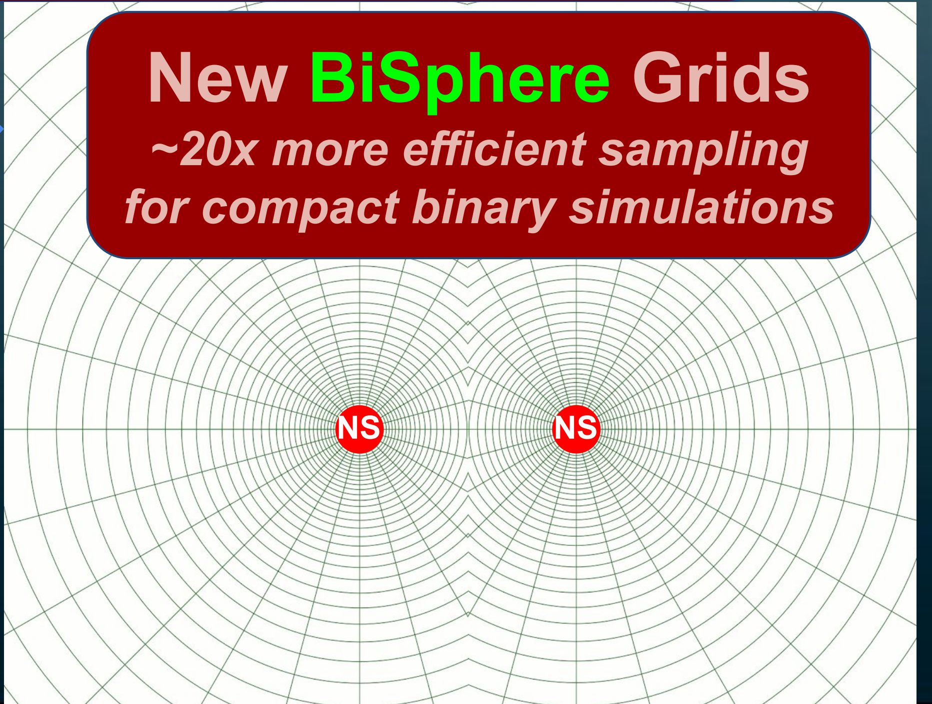


New BiSphere Grids

~20x more efficient sampling
for compact binary simulations



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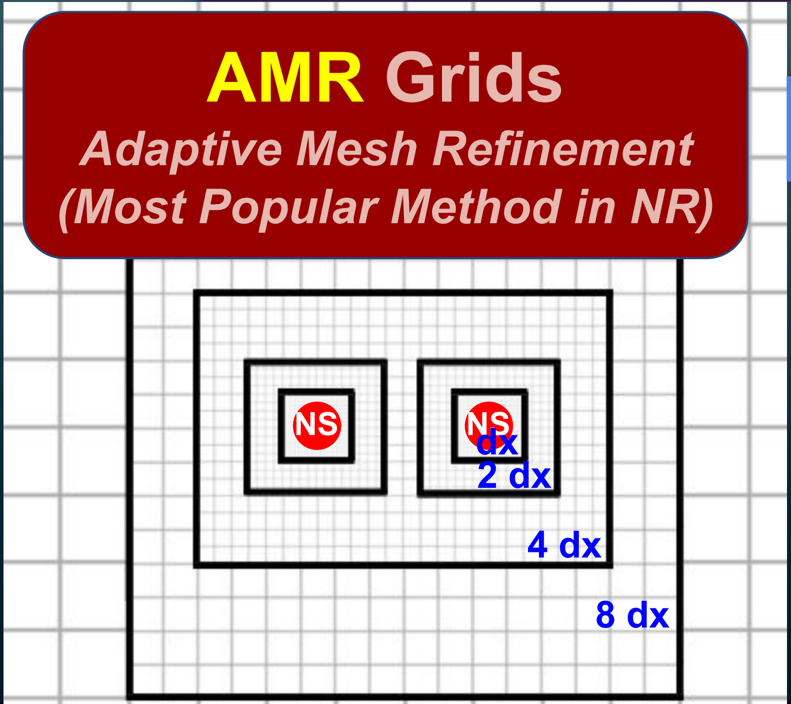

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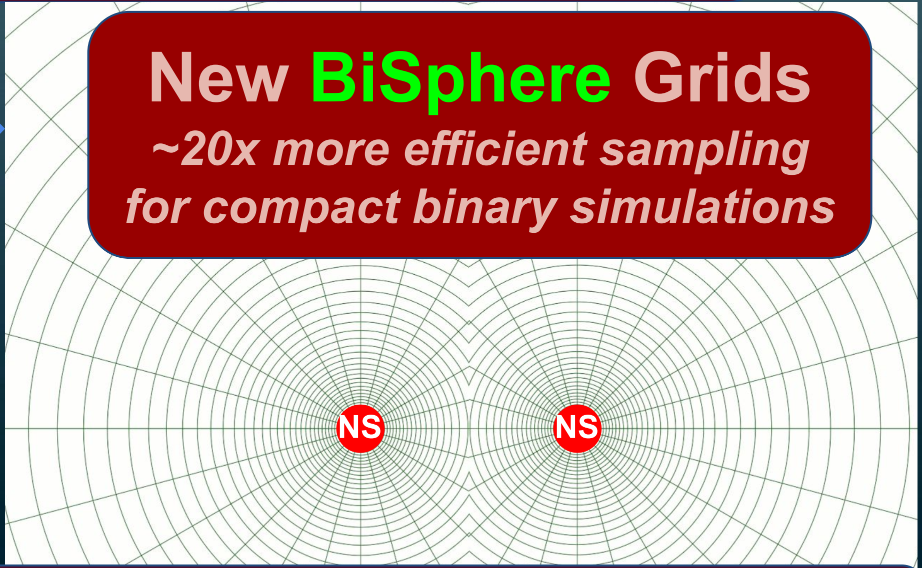

- Exploits near-symmetries (~5x)
- Smooth transitions in resolution (~4x)

BiSphere Challenges

1. Formulate general relativity in <u>single</u> log-radial spherical polar coordinates; **must be as numerically stable & robust as Cartesian**
   a. **Ordinary spherical polar: done!**
      Baumgarte, Montero, Cordero-Carrión, Müller (PRD 87, 044026, **2012**), built upon covariant BSSN formulation of Brown (PRD 79, 104029, **2009**)
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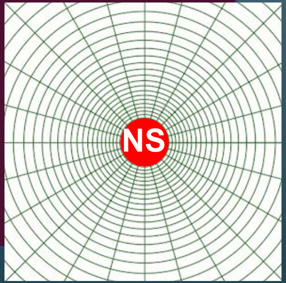

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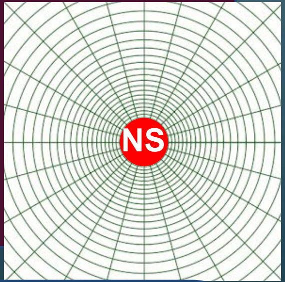

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   a. <u>**Interpolate between spheres; make spheres "orbit"**</u>
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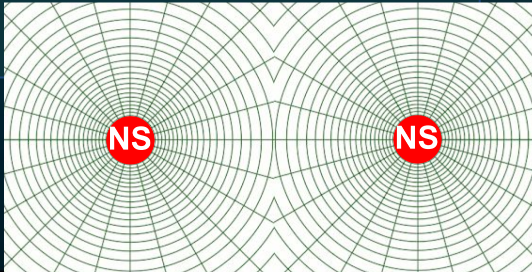

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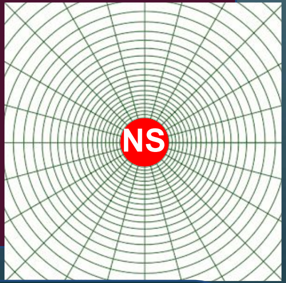

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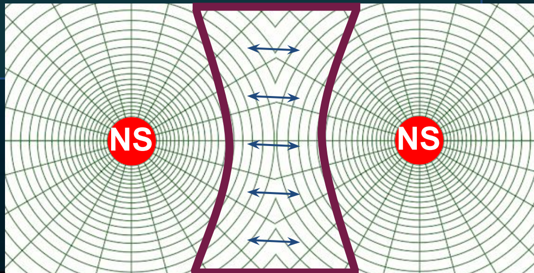
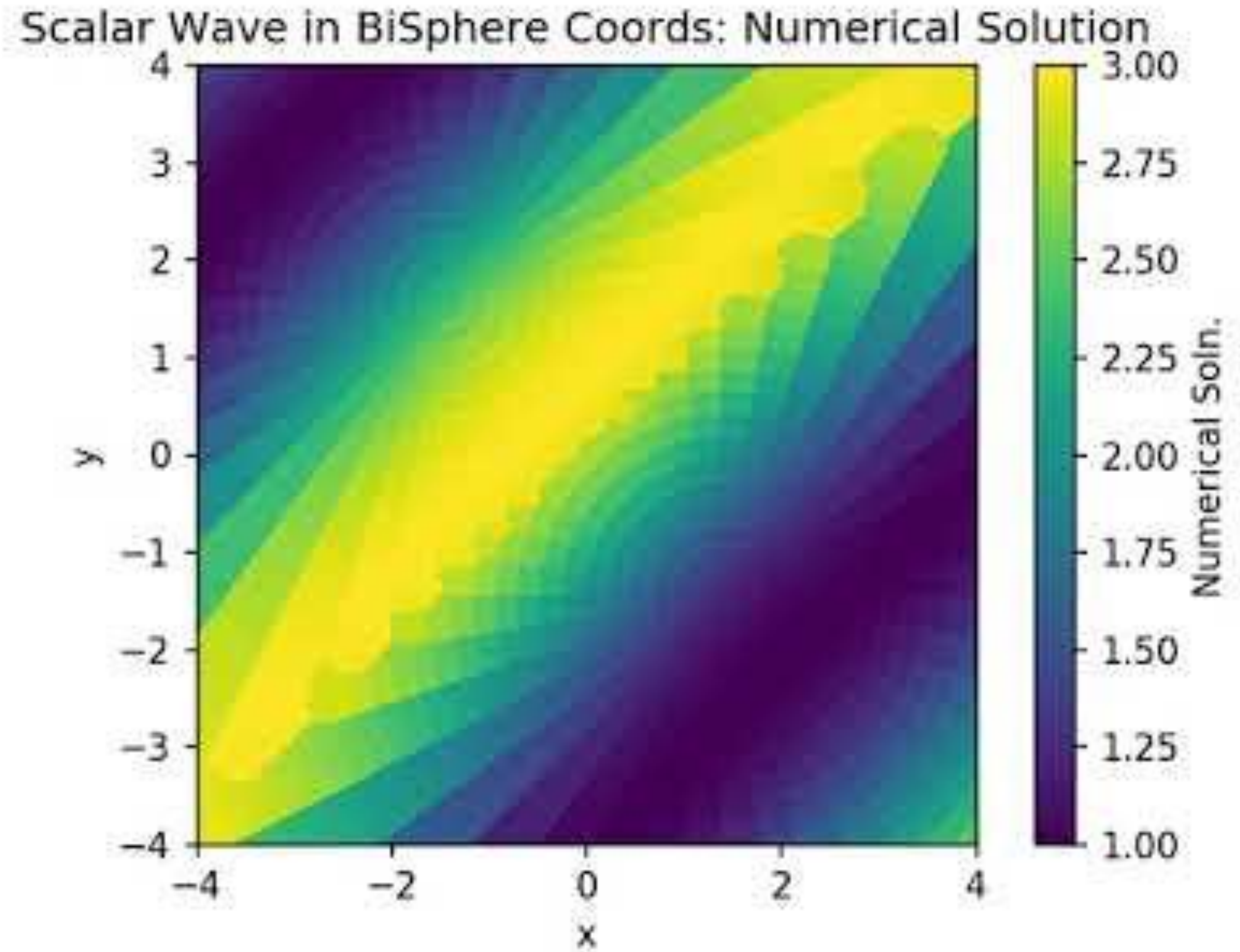
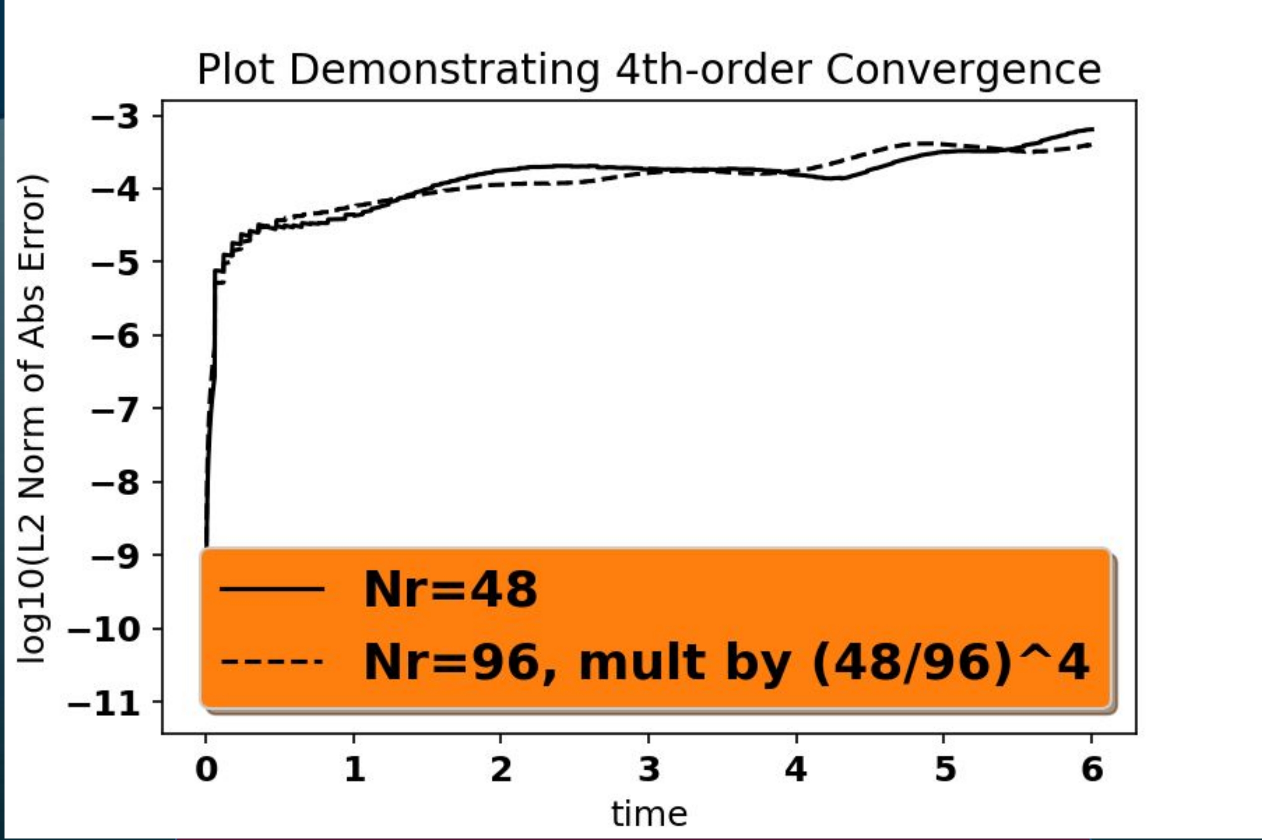



Scalar Wave in BiSphere Coords: Numerical Solution
y
x
Numerical Soln.
4
3
2
1
0
−1
−2
−3
−4
−4
−2
0
2
4
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00



Finding from wave test:
Numerical errors small and converge to zero at expected rate

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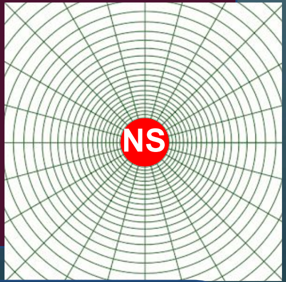

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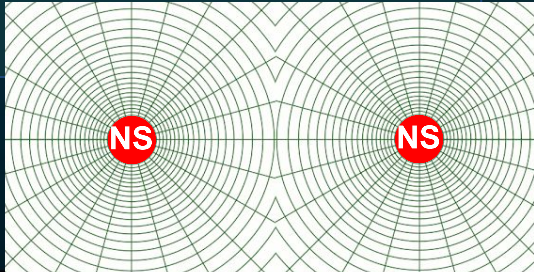

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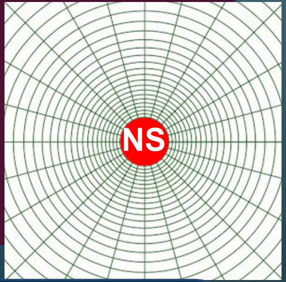

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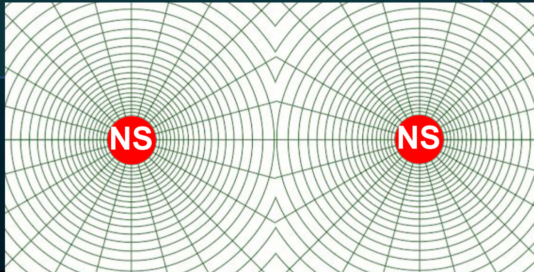
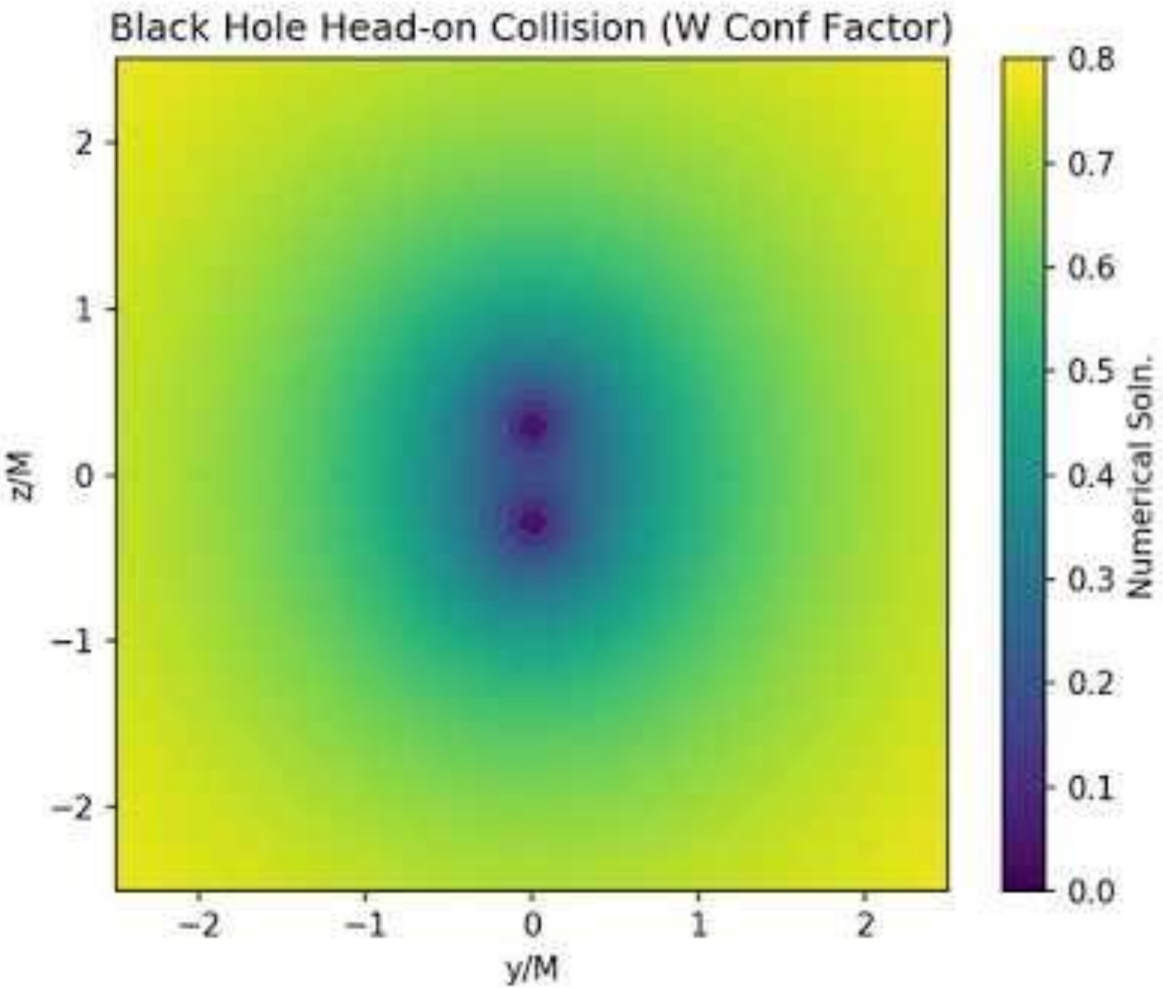
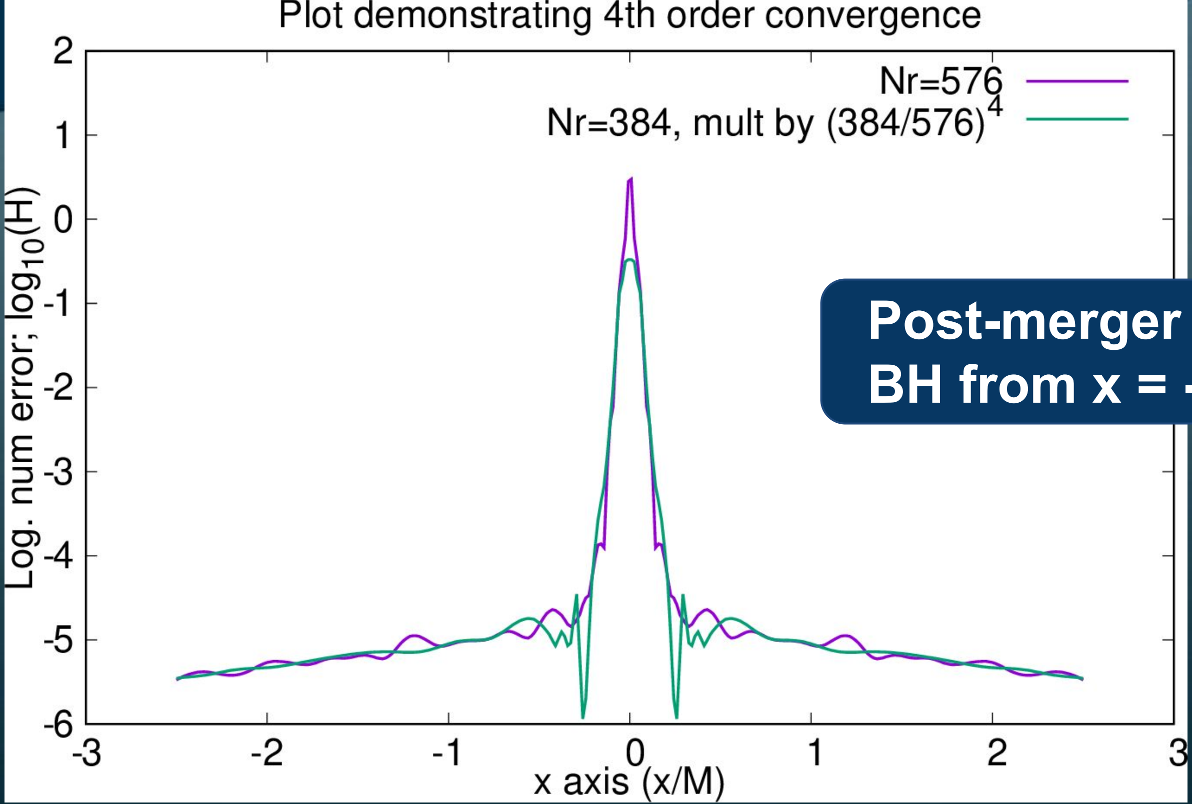




Black Hole Head-on Collision (W Conf Factor)
z/M
y/M
Numerical Soln.
−2
−1
0
1
2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

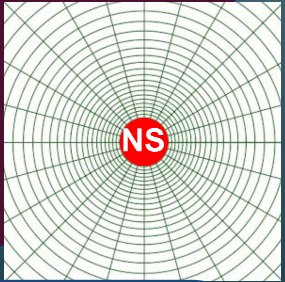


Post-merger num error, BH from x = -0.5 to +0.5

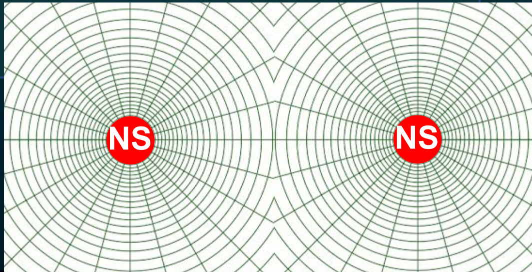
Finding from BH collision test: Numerical errors small and converge to zero at expected rate

BiSphere Challenges

1. Formulate general relativity in single log-radial spherical polar coordinates; **must be as numerically stable & robust as Cartesian**
   a. **Ordinary spherical polar: done!**
      Baumgarte, Montero, Cordero-Carrión, Müller (PRD 87, 044026, **2012**)
   b. **Generic-radius spherical polar (incl. log-radial): done!**
      Ruchlin, **Etienne**, Baumgarte (PRD 97, 064036, **2018**)



2. Need approach for performing simulation on two such coordinate systems, which ***co-move*** with orbiting binary system
   a. **Interpolate between spheres; make spheres "orbit": done!** **(late Jan 2019)**
   b. **Adjust directions of vectors & tensors when interpolating**
      (basis transforms; Jacobians): **done!** **(late Jan 2019 + 3d)**



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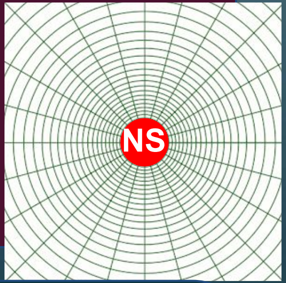

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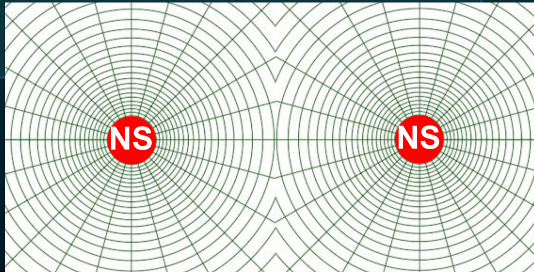
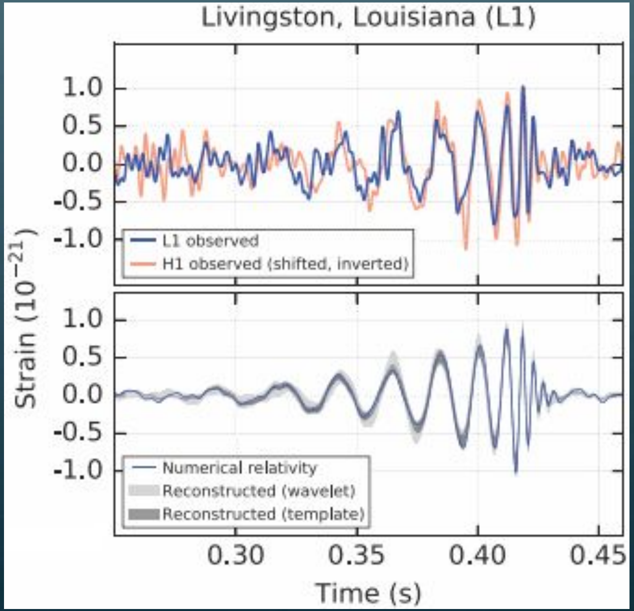


Still a work-in-progress, stay tuned!

Next Step: Colliding BHs on the Desktop!

Two black holes merge, gravitational waves detected
The $1B question: What exactly caused this?



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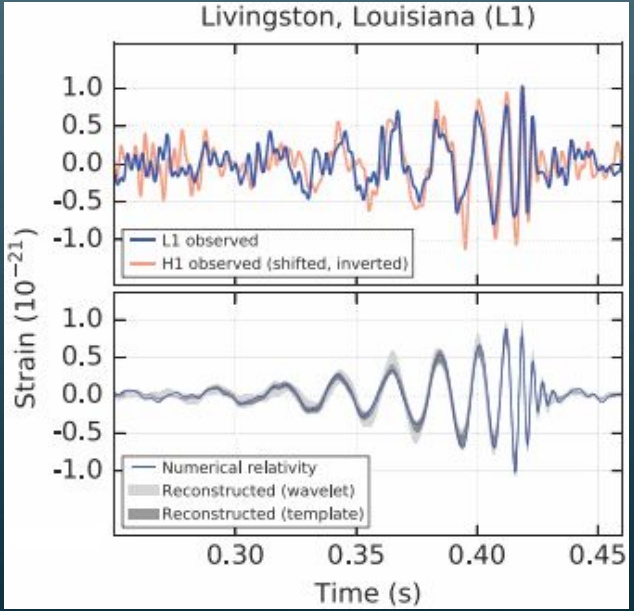
- Inferring source properties from grav. waves *tough*
  - Black hole binaries: 7 dims of parameters!
  - All existing full-GR simulation catalogs:
    - ~3000 theoretical gravitational waveforms
      - About 3 points per dimension
      - Enough for first detections (low SNR), but ***not enough*** moving forward!



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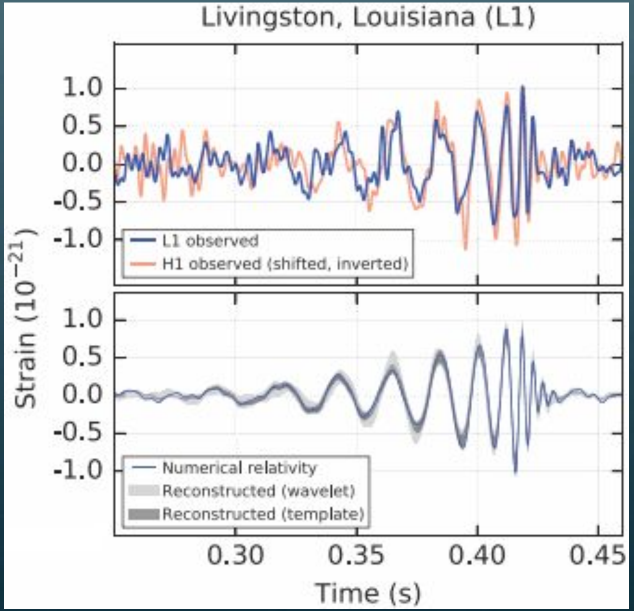
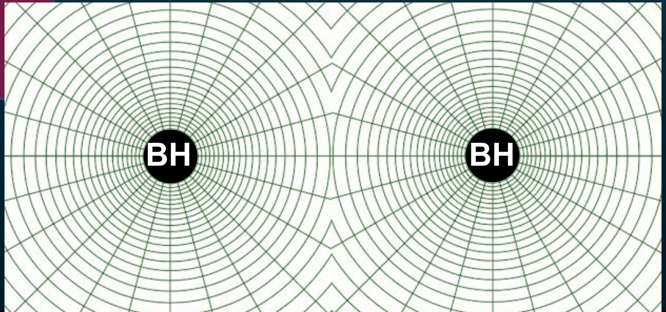


- BH binary sims need 4 supercomputing nodes
- BiSpheres grids use 1/20x memory
  - ⇨ Can fit simulation on desktop!



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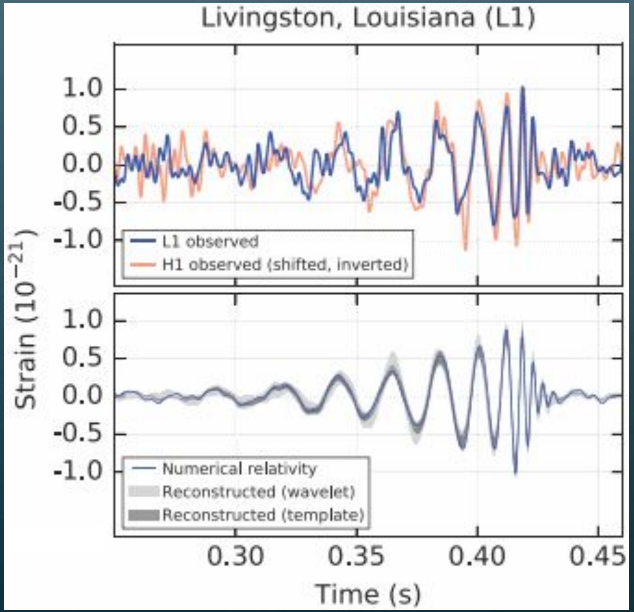
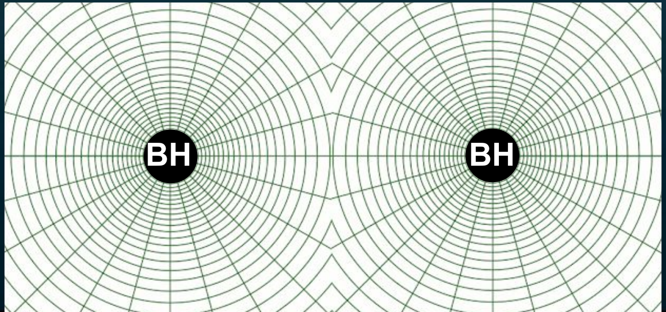


BlackHoles@Home

https://blackholesathome.net

- BiSphere: BH binary sims on desktop computer
- Like SETI@Home, public helps with science
  - Expect at least 20k waveforms in first year

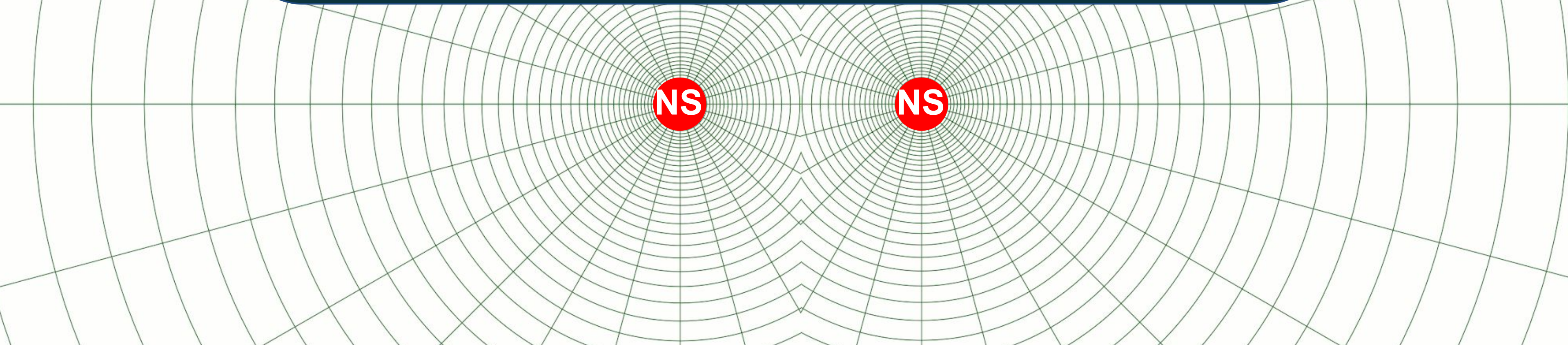


Beyond BlackHoles@Home

https://blackholesathome.net

Implement BiSpheres grids with neutron star binaries

- Neutron star binary simulations need supercomputers!
  - BiSpheres grids should scale on modern supercomputers far better than Cartesian AMR
  - Use efficiency boost to, e.g.,
    - model physical processes lacking in current state-of-the-art simulations



Addressing Issues with Singular Coordinates

Baumgarte, Montero, Cordero-Carrión, Müller (PRD 87, 044026, **2012**)

1. **Tensor components can be singular** (→0 or ∞) **at coord singularities**
   - Use cell-centered grids to avoid exact overlap with singularities
   - Singular pieces are multiplicative and known analytically:
     i. Scale out singular pieces & handle spatial derivs analytically
     ii. Promote rescaled tensors to evolved quantities

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- *Example*: Smooth spacetime quantity Λ^i
  - **Cartesian**: all components regular; no coord singularities

$$
\begin{aligned}
\bar{\Lambda}^x &= [\text{smooth}] \\
\bar{\Lambda}^y &= [\text{smooth}] \\
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- *Example*: Smooth spacetime quantity Λ^i
  - **Cartesian**: all components regular; no coord singularities
  - **Spherical**: e.g., ϕ component diverges at coord singularity
    - **Idea**: where needed, only take numer. derivatives of smooth part, λ^ϕ
    - Perform *exact* differentiation on singular terms like $1/(r \sin \theta)$

$$\bar{\Lambda}^\phi = \frac{1}{r\sin\theta} \times [\text{smooth part}] = \frac{1}{r\sin\theta} \times \lambda^\phi$$

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   - E.g., 1D scalar wave equation:

$$\partial_t^2 u = \partial_r^2 u + \boxed{\frac{2}{r}} \partial_r u$$

   - $2/r$ term "stiffens" the equation
   - Even with cell-centered grids, RK2 timestepping is unstable
     1. Can use PIRK2 (original formulation), but
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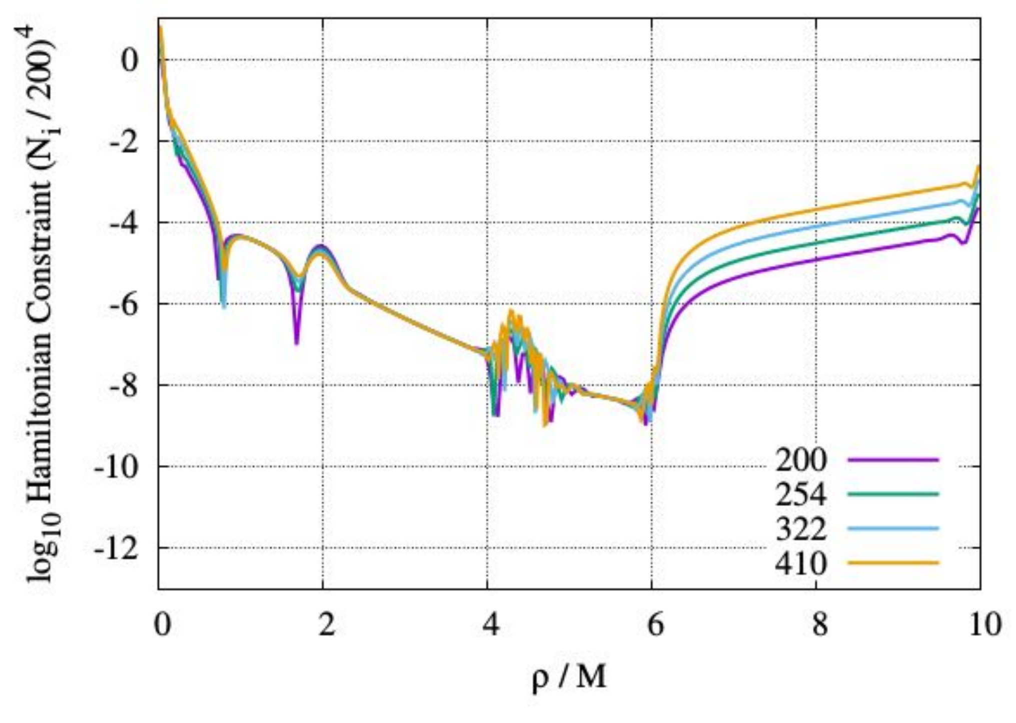
***Net result*: Stability & convergence properties**
***on par* with Cartesian grids**

SENR/NRPy+: Code Validation

http://blackholesathome.net

- Black hole simulation
  - Wormhole initial data
  - Cylindrical coordinates
  - Fourth-order finite differencing
- Excellent convergence
  - at t = 5M, in region unaffected by outer boundary (at r=10M)

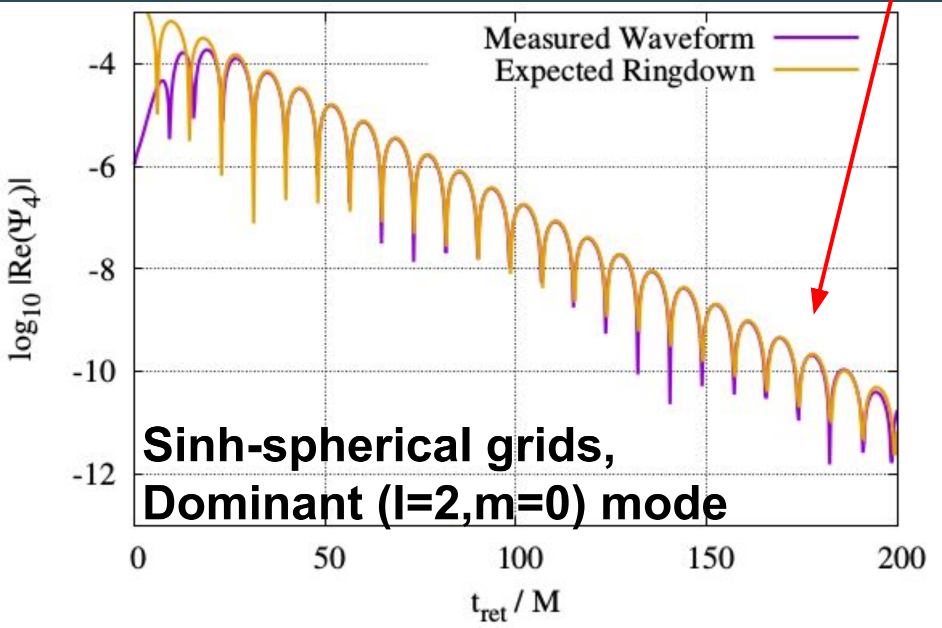


SENR/NRPy+:
BH Spectroscopy from Head-on BH Collision

- Dual black hole simulation
  - Brill-Lindquist initial data
  - Moving puncture gauge
  - Sinh-spherical coordinates
  - Moderate resolution

BH perturbation theory prediction

- **Agreement to ~7 decades!**



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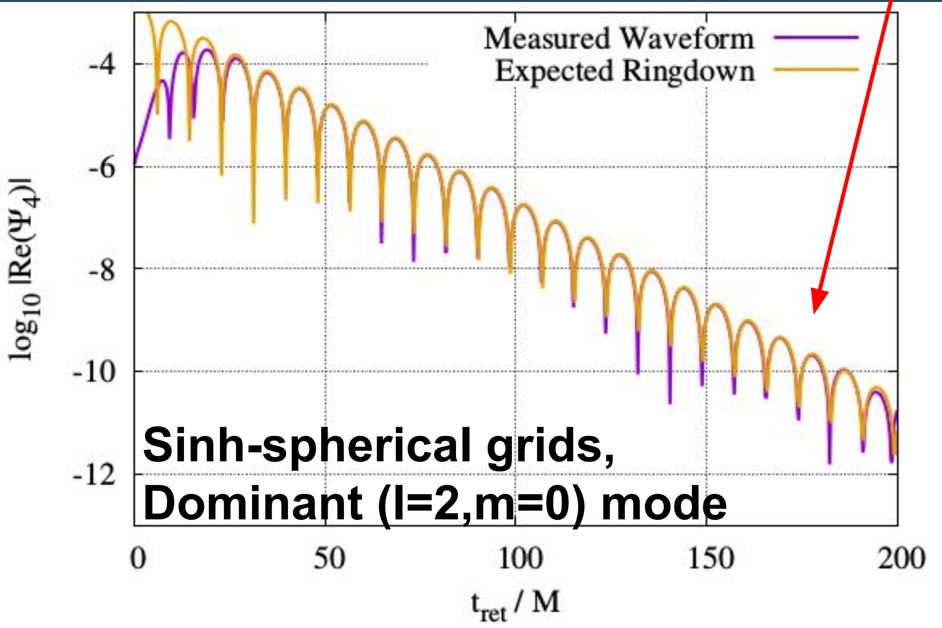
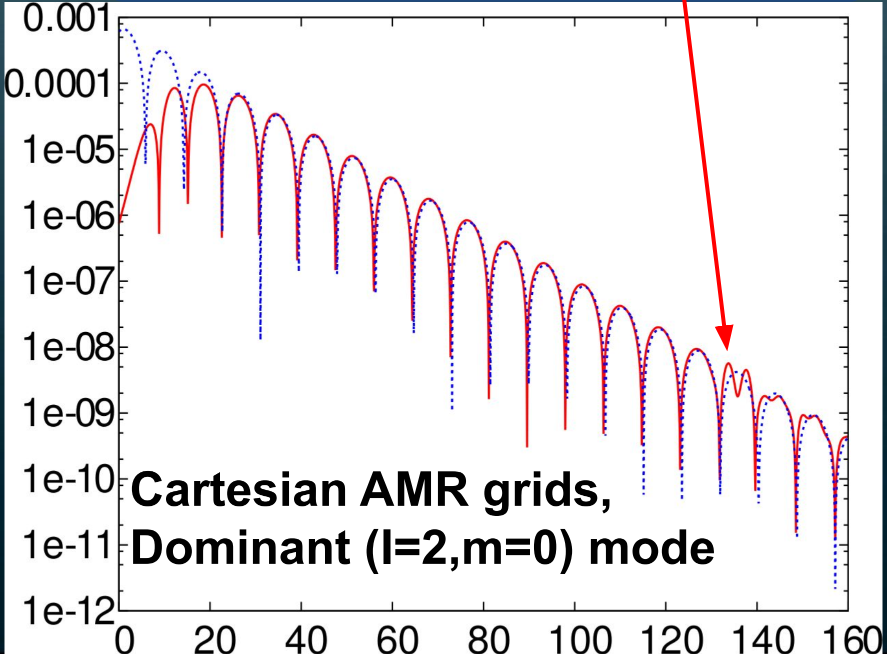
Cartesian AMR Grids
- **Only ~4 decades of agreement**





Research Seminar: Ongoing/Planned Projects

- Add neutrino & photon physics to IllinoisGRMHD

  80NSSC18K0538 (ISFM, 2017-2020)
  80NSSC18K1488 (TCAN, 2018-2021)

- BiSpheres grids for GR fields + moving-mesh Voronoi tessellations for hydro, MHD, and radiation
  - Project with Phil Chang, UWM
- BlackHoles@Home outreach opportunities
- Measuring *G*; big data, modeling

  PHY-1757005 (Grav expmt, 2017-2020)

- LIGO proposal: greatly improved GW approximants
- Make simulations with BiSphere grids >50x faster, submit PRL, begin BlackHoles@Home

  PHY-1806596 (Grav theory, 2018-2021)

Original GRMHD code of Illinois NR group

- Highly robust
- Written by experts, for experts
- Takes ~3 years to master

<u>IllinoisGRMHD</u>

- Same robustness
- Well documented
- ~months to master

Community

- Released in 2014, part of the Einstein Toolkit
- 14 research groups around the world use IllinoisGRMHD, and growing
- 5 publications using IllinoisGRMHD, two not from our group
    - New patches from users add new features & expedite development!
- IllinoisGRMHD Working Group of the Einstein Toolkit
    - User-support telecons every ~month

https://illinoisgrmhd.net

Einstein Toolkit as Funding Source (NSF-CSSI)

- I will be Co-PI on next grant in 2019. E.g., use Toolkit's infrastructure to develop BiSpheres grids for massively parallel BNS simulations

Adding Neutrino Physics to BNS Simulations: IllinoisGRMHD + Pandurata

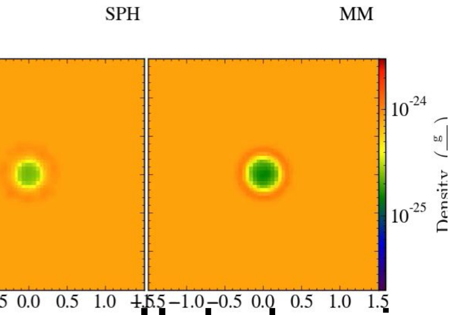
80NSSC18K0538 (ISFM, 2017-2020)
80NSSC18K1488 (TCAN, 2018-2021)

- **Pandurata**: a Monte Carlo code for radiation transport in full GR
- **IllinoisGRMHD**: a GRMHD code for modeling, e.g., binary neutron star mergers with magnetic fields

- **Idea**: combine Pandurata & IllinoisGRMHD to incorporate live photon & neutrino feedback into magnetized BNS simulations
- **Difficulty**: N interpolations must be performed to track N photons/neutrinos at each step in their trajectories
  - Approach: Reduce cost of interpolations (reuse interp stencils) using BiSpheres-like grids
- **Progress**:
  - Interpolation routines ready to go! Pandurata being modified so that all photons/neutrinos propagated in lockstep with IllinoisGRMHD simulation

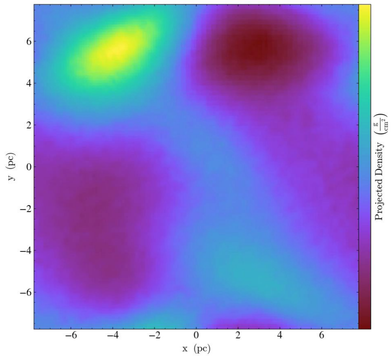
MANGA - A Moving Mesh Solver for ChaNGa

Philip Chang (UWM), Sean Couch (MSU), Shane Davis (UVa), Zach Etienne (WVU),
Yan-Fei Jiang (KITP), Logan Prust (UWM), Tom Quinn (UW), James Wadsley (McMaster)



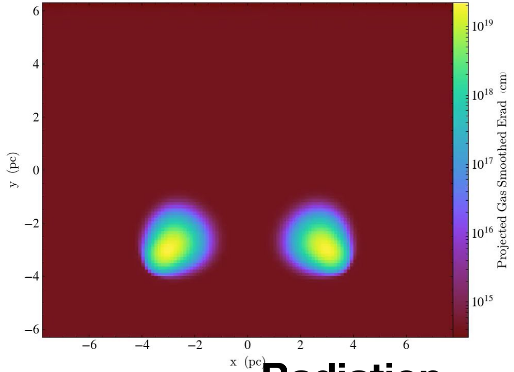
Hydrodynamics

Sedov-Taylor Explosion



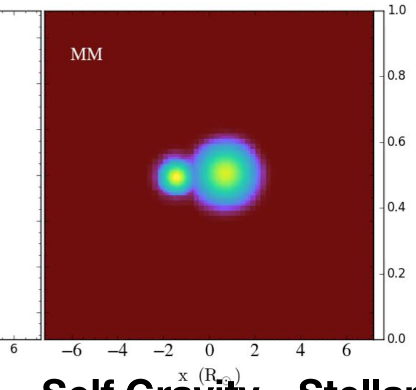
Magnetic Fields

Magnetic turbulence

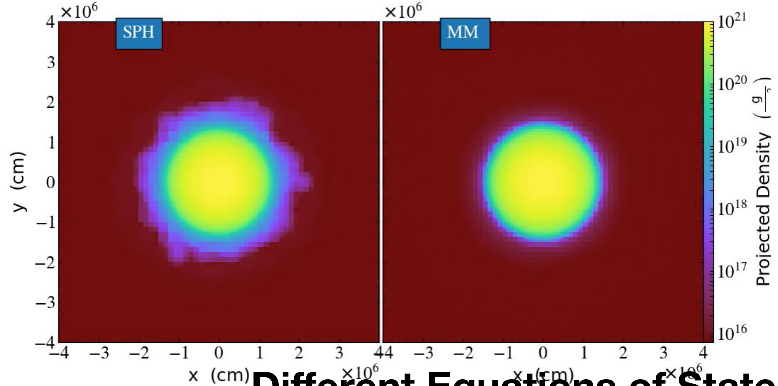


Radiation

Crossing beam test



Self Gravity - Stellar merger



Different Equations of State

Example of a neutron star equation of state.

MANGA - A Moving Mesh Solver for ChaNGa

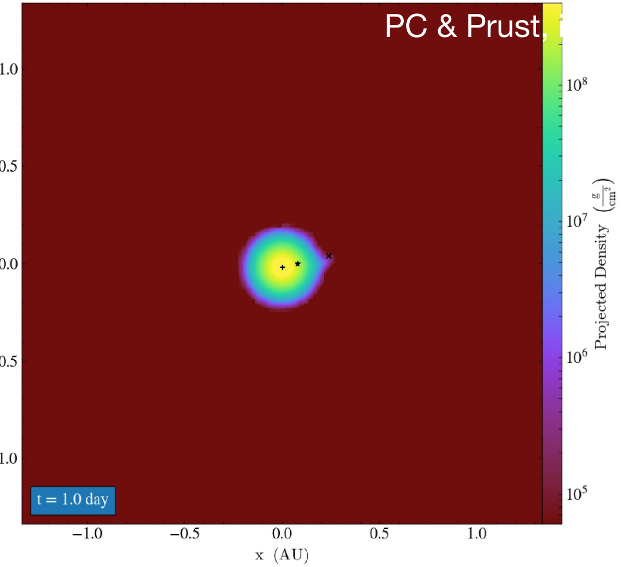
Current Features

- Hydrodynamics on Voronoi Mesh, Self-gravity, Entropy or Energy solving (Chang, Quinn & Wadsley 2017)
- Multistepping (Chang & Prust, in preparation)
- Radiation Hydrodynamics (Chang, Davis \& Jiang, submitted)
- Quiet Problem Generator — reduced Poisson noise
- MHD — constrained transport scheme, not fully tested (Chang, in prep)

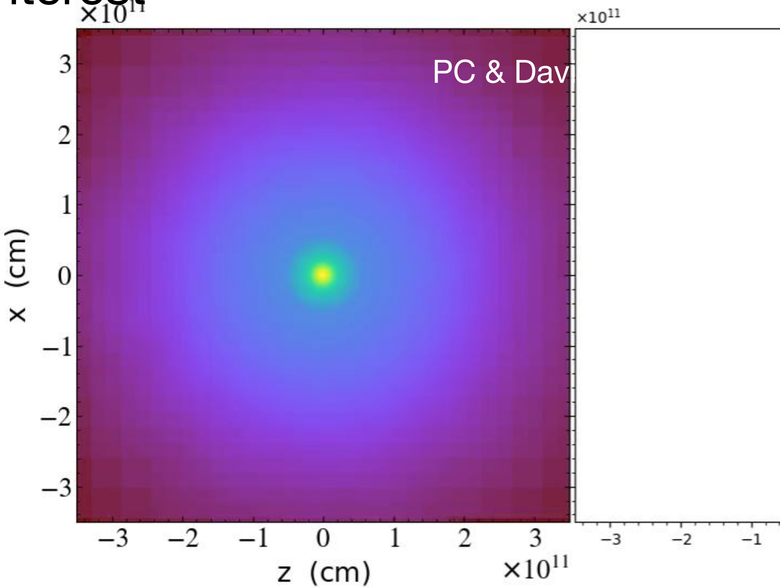
Future Goals (1-2 years)

- Relativity — GRHydro on a moving Voronoi mesh (w. Z. Etienne)
- Point source radiation (w. T. Abel)

MANGA Problems of Interest



Common Envelope/Stellar Mergers



Tidal Disruption Events

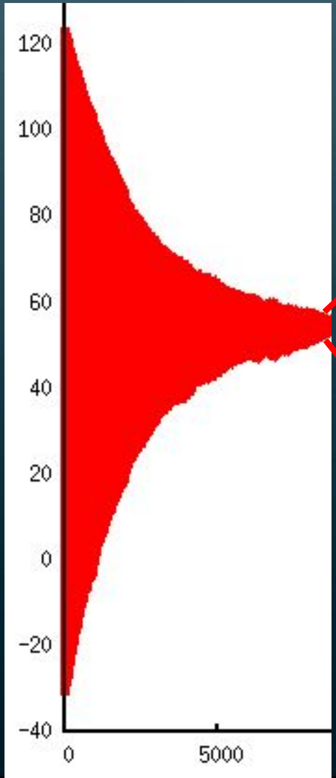
Binary Mergers of NS/NS and NS/BH in Full GR

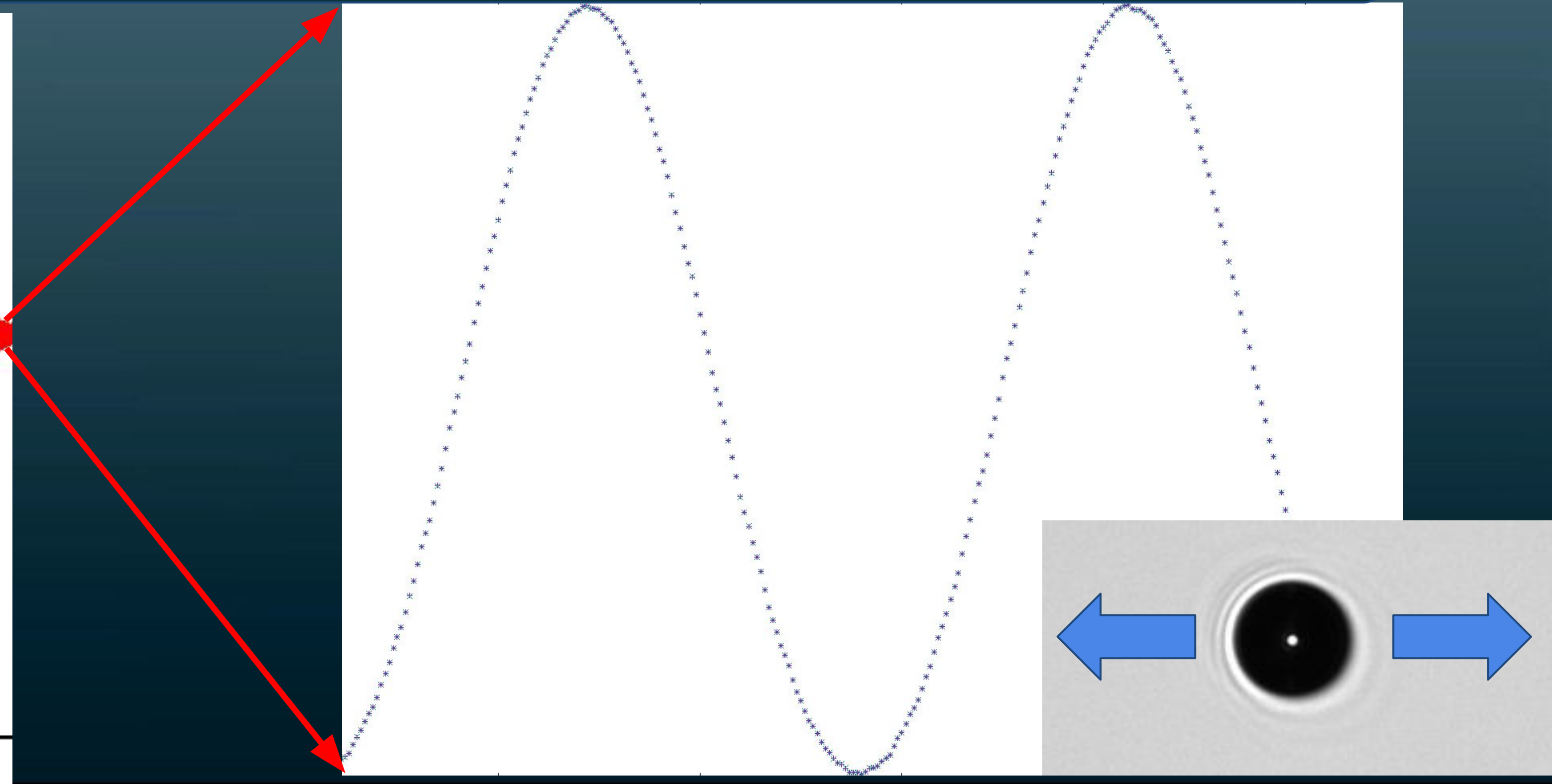
Core collapse supernova

Theor Support for Measuring *G* Experiment

PHY-1757005 (Grav expmt, 2017-2020)

- Magnetically-suspended microsphere in harmonic trap oscillates
- Oscillation phase changes if field masses added -> *G*!





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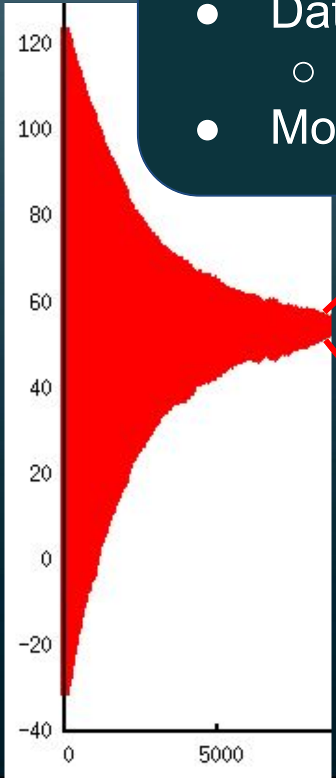
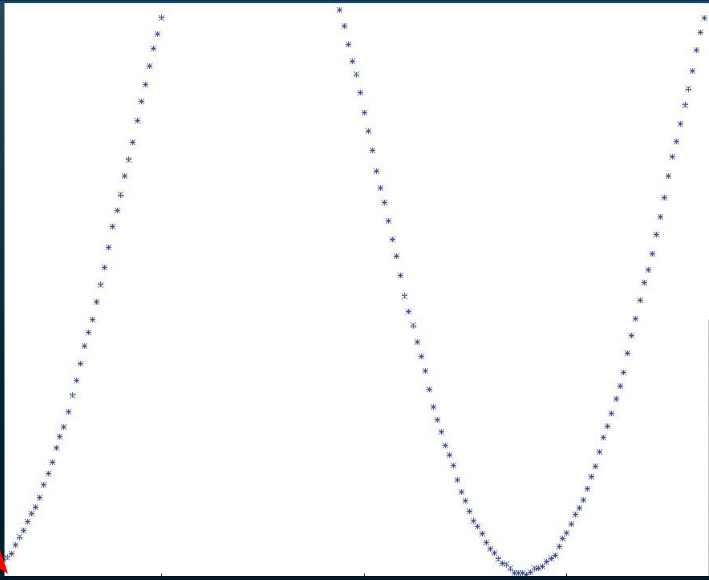
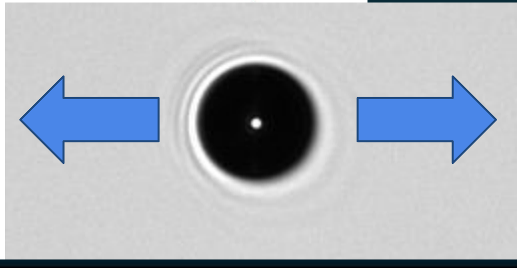
- Magnetically-suspended microsphere in harmonic trap oscillates
- Oscillation phase changes if field masses added -> *G*!
- Data: 8.6M frames of data in 24h, each image x-correlated
  - “Big Data”! Need supercomputer.
- Modeling: Geometry of field masses to minimize anharmonicity

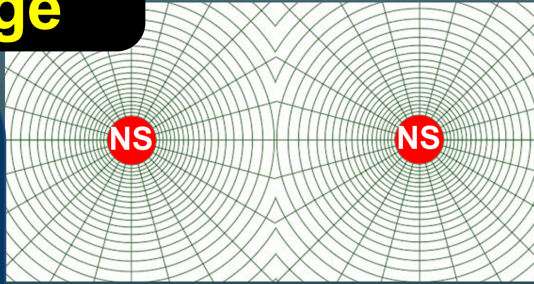


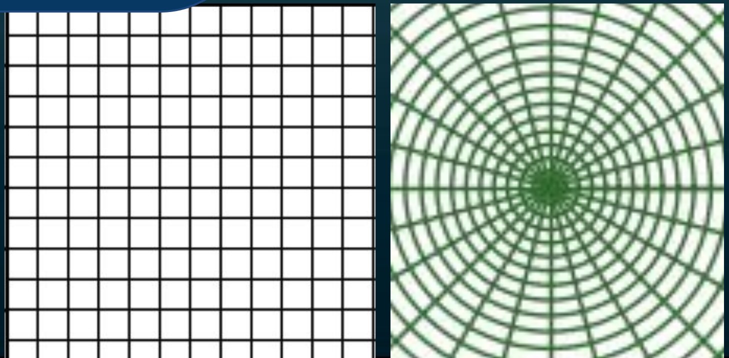




Small Timesteps,
The Last BiSphere Challenge

- BH binary on desktop now, but ~50x *too slow*
  - About 3x can be gained through software optimz.
- Problem:
  - <u>Simulation timestep $\propto$ min dist between gridpoints</u>
  - Spherical coords focus gridpoints at r=0, z-axis





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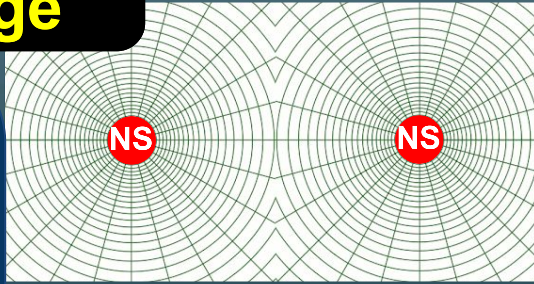

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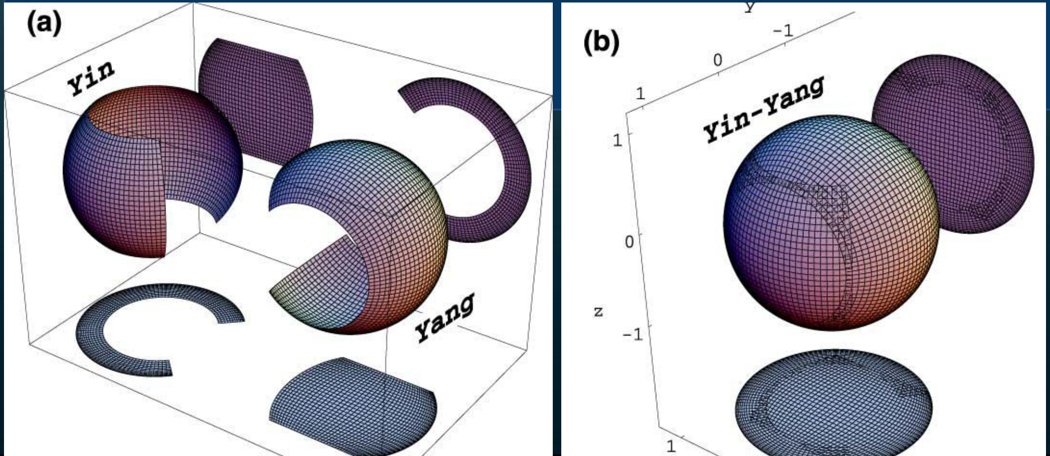
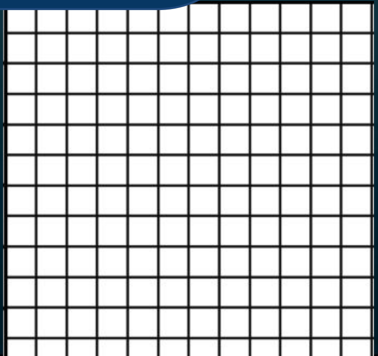
  - Yin-yang grids (~10x faster) Kageyama & Sato 2004





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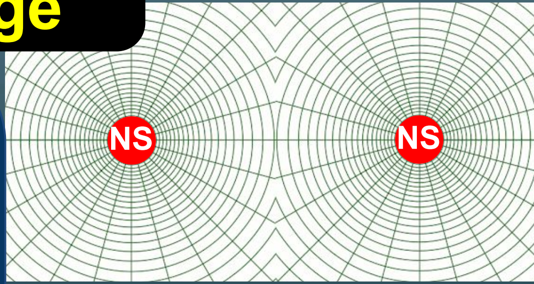
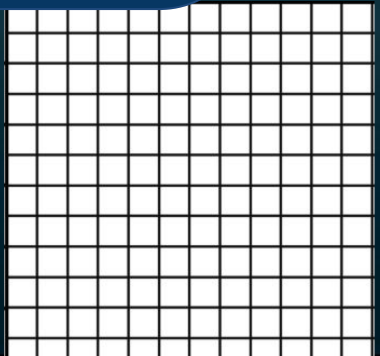
  - Replace data inside BHs (~40x faster, only BHs) **Etienne**, Faber, Liu, Shapiro, Baumgarte, 2007





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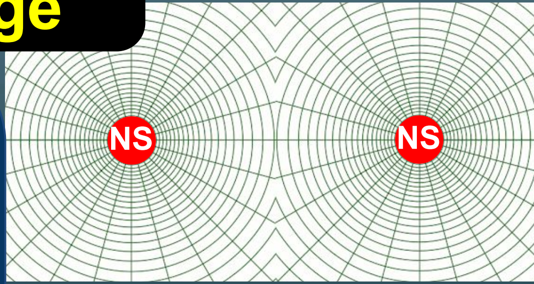
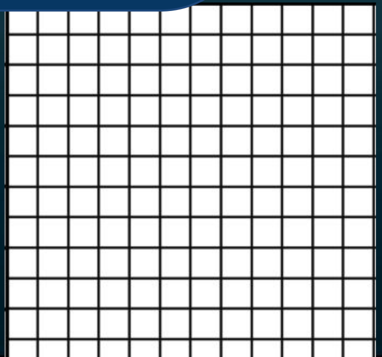
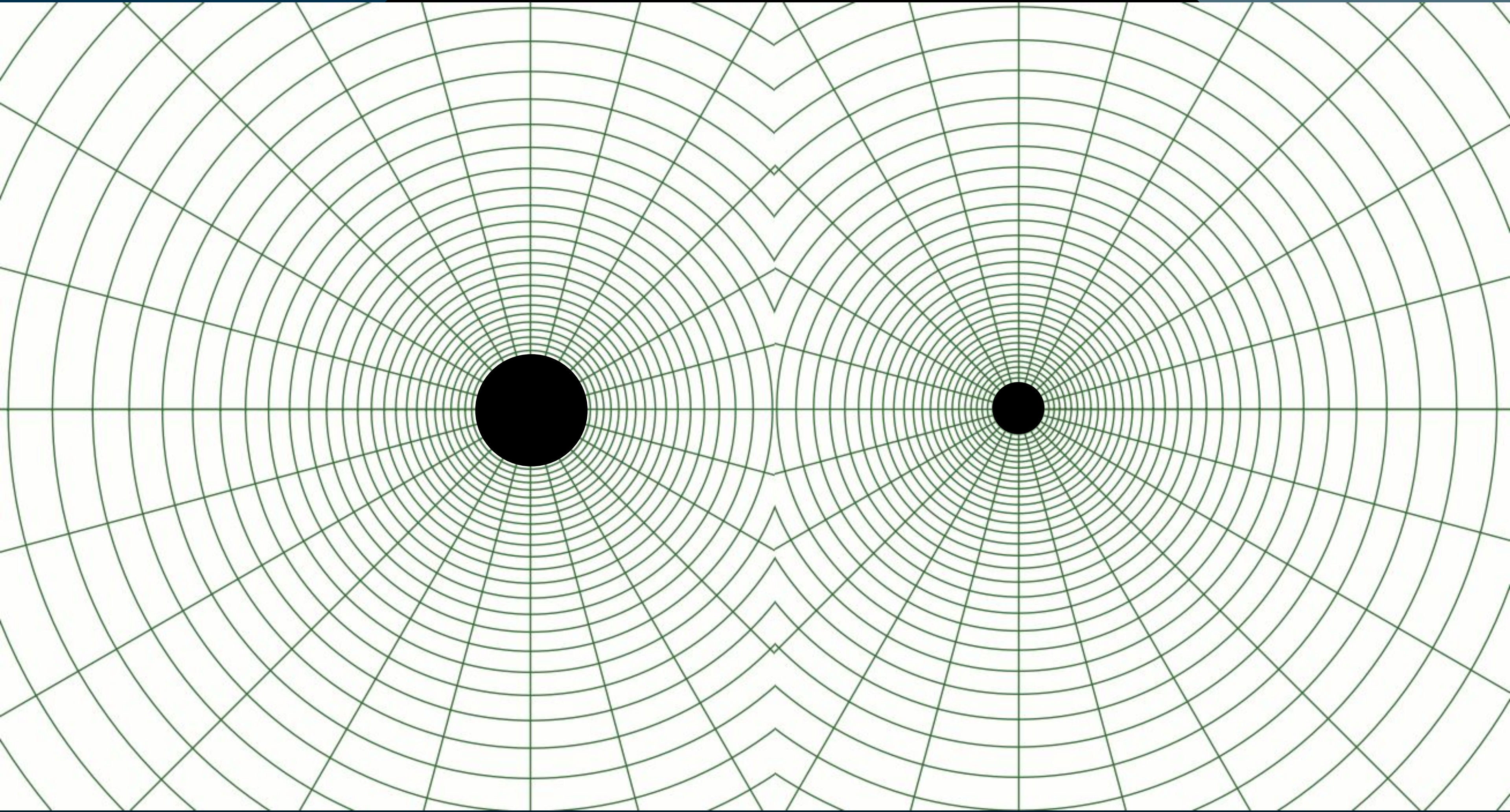
The Last BiSphere Challenge

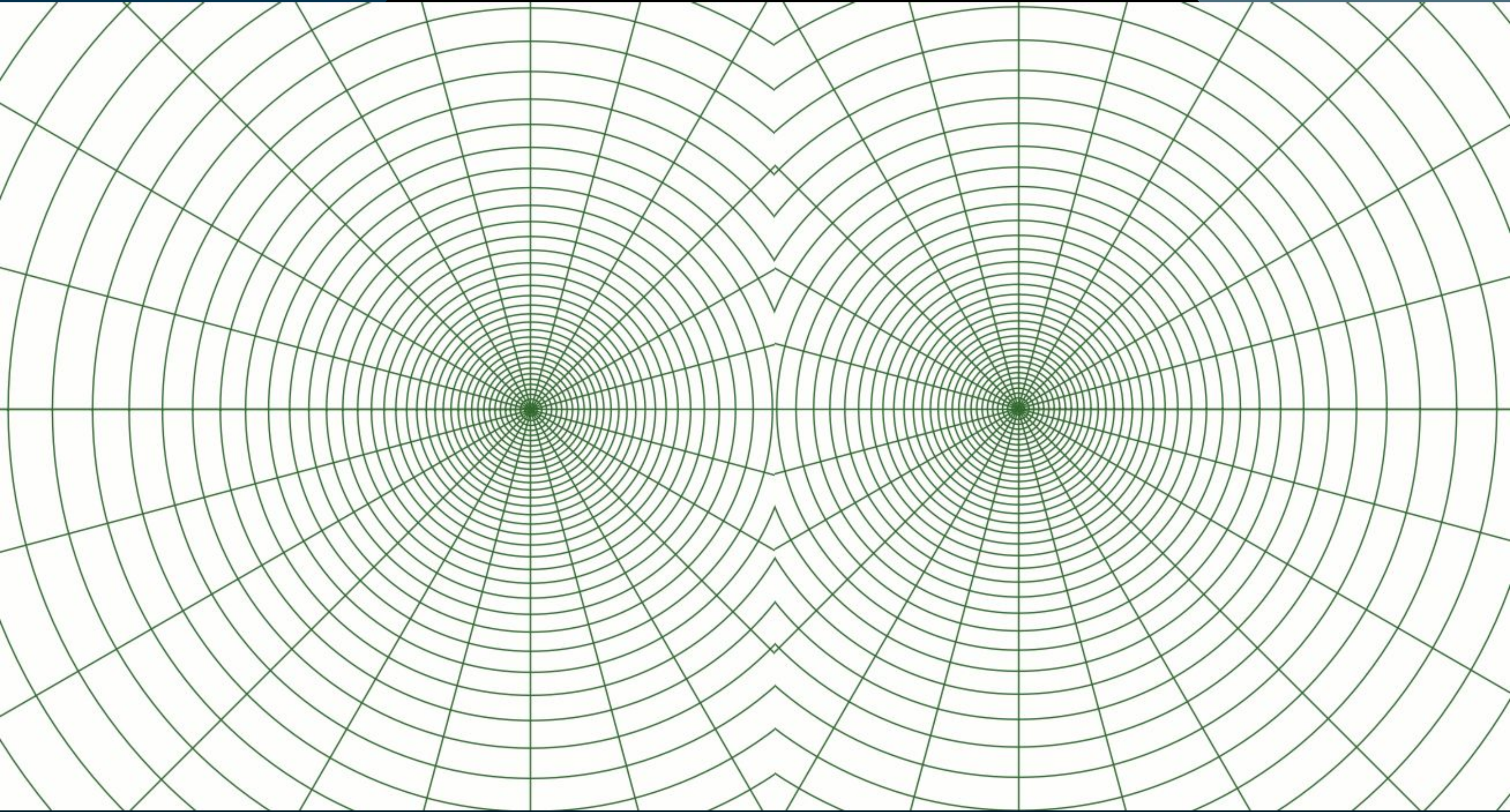


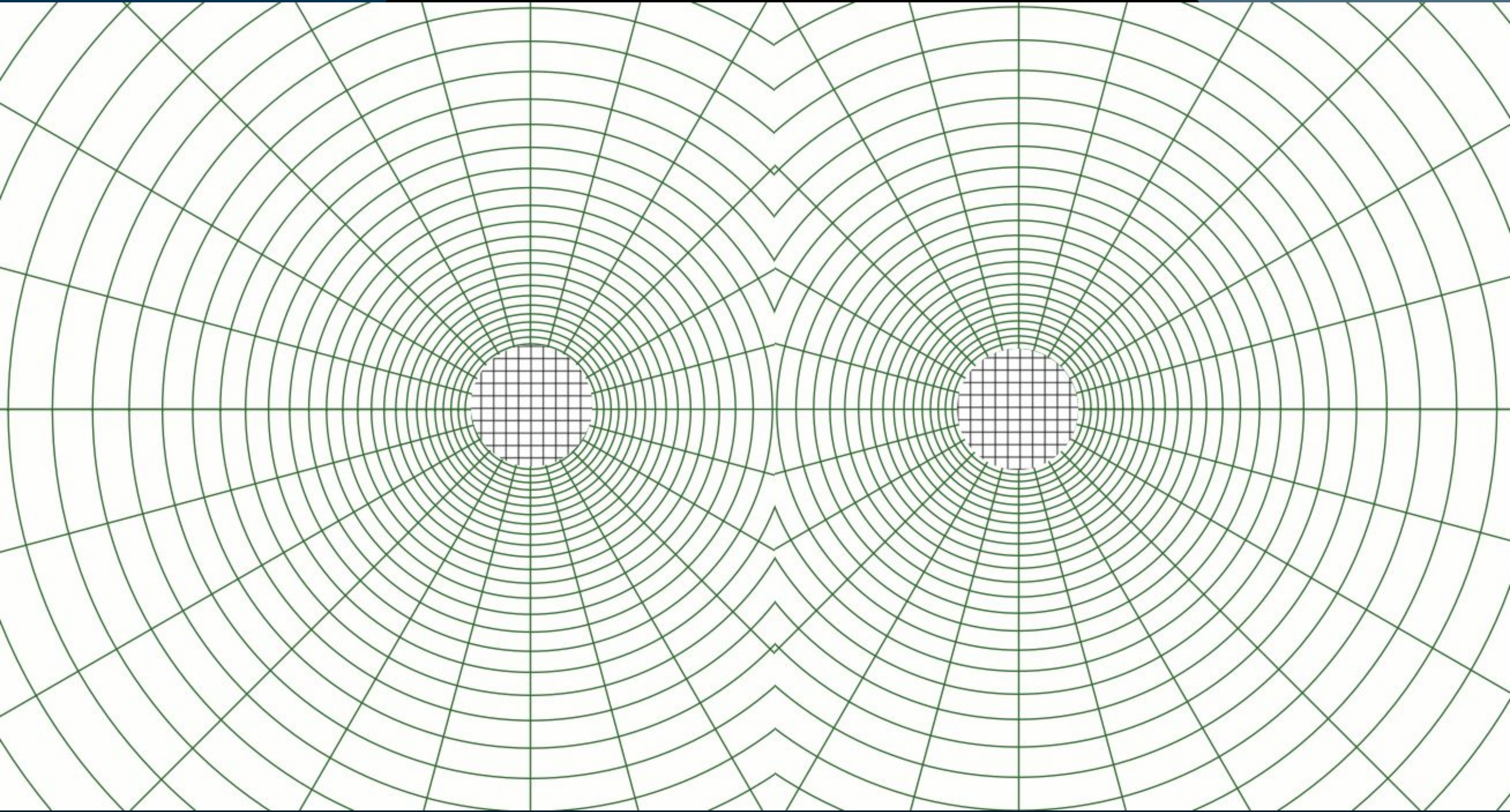
- BH binary on desktop now, but ~50x *too slow*
  - About 5x can be gained through software optimz.
- Problem:
  - Simulation timestep ∝ min dist between gridpoints
  - Spherical coords focus gridpoints at *r*=0, *z*-axis
- Well-known problem! Multiple solutions:
  - Yin-yang grids (~10x faster) Kageyama & Sato 2004
  - Replace data inside BHs (~40x faster, only BHs)
  - High-res Cartesian filter/grid at *r*=0 (~100x faster)

Etienne, Faber, Liu, Shapiro, Baumgarte, 2007









Importance of modeling gravitational wave and multimessenger sources

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    - Built upon careful observations and experiments

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My job: provide theoretical predictions needed to advance science

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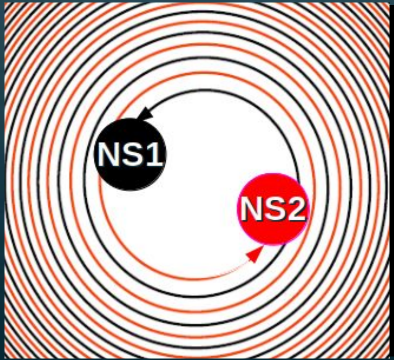
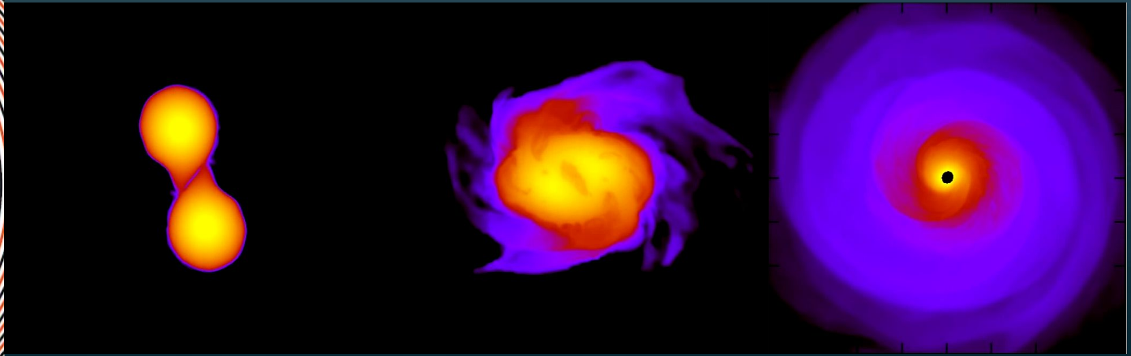


Lovelace et al., CQG 29, 045003 (2012) (modified)



Magnetized BNS merger
Z. Etienne (2019)

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- Theoretical predictions (based in simulations) must incorporate needed physics *and* span both observational and theoretical uncertainties

Modeling Challenges

Model all the necessary physical processes

- *E.g., gamma-ray bursts thought to originate from magnetized fluid dynamics around BH+disk remnant*
  a. **Gravitational fields** (general relativity)
  b. **Hydrodynamics + magnetic fields** (GRMHD/GRFFE)
  c. **Neutrinos**
  d. **Photons**

Maxwell's equations in MHD limit

GR

$$\partial_j\left(\sqrt{\gamma}B^j\right)=0$$

$$\partial_t(\sqrt{\gamma}B^i)+\partial_j\left[\sqrt{\gamma}\left(v^jB^i-v^iB^j\right)\right]=0$$

Newtonian

$$\nabla\cdot B=0$$

$$\partial_t B=\nabla\times(v\times B)$$

Fluid equations

GR

$$\partial_t\rho_*+\partial_j\left(\rho_* v^j\right)=0$$

$$\partial_t S_i+\partial_j\left(\alpha\sqrt{\gamma}T^j{}_i\right)=\frac{1}{2}\alpha\sqrt{\gamma}T^{\alpha\beta}\partial_i g_{\alpha\beta}$$

$$\partial_t\tau+\partial_j\left(-n_\mu\alpha\sqrt{\gamma}T^{\mu i}-\rho_* v^j\right)=s$$

Newtonian

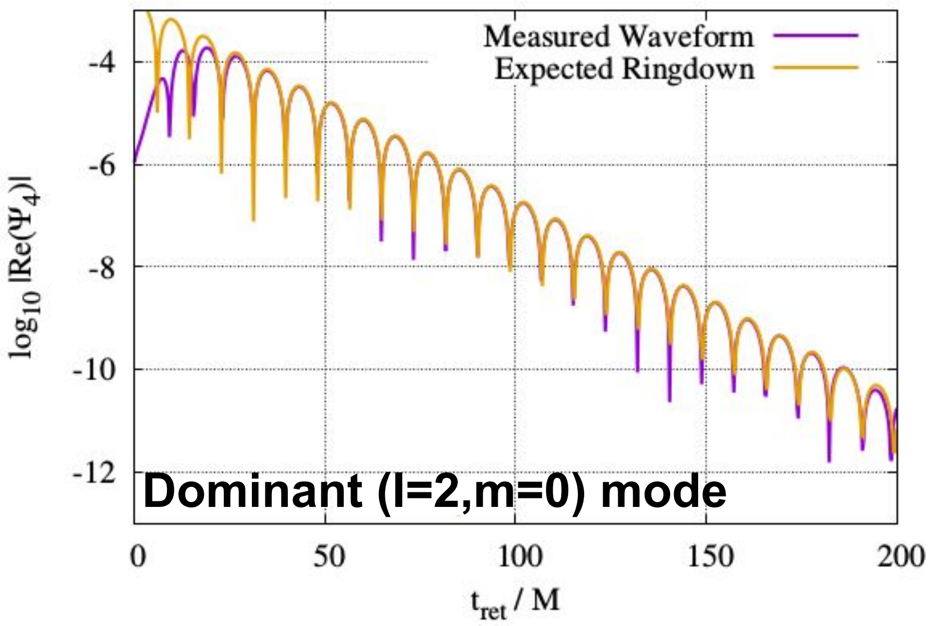
$$\partial_t\rho+\nabla\cdot(\rho v)=0$$

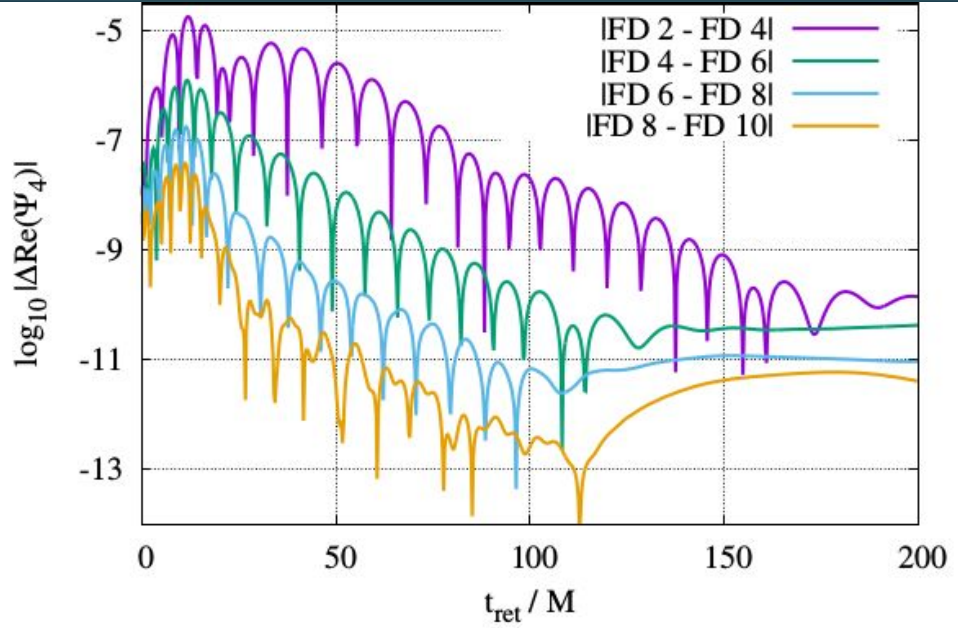
$$\rho\left(\partial_t v+v\cdot\nabla v\right)=-\nabla\left(P+\frac{B^2}{8\pi}\right)+\frac{B\cdot\nabla B}{4\pi}-\rho\nabla\Phi$$

$$\rho\left(\partial_t\varepsilon+v\cdot\nabla\varepsilon\right)+P\nabla\cdot v=0$$

SENR/NRPy+: BH Spectroscopy from Head-on BH Collision

- Dual black hole simulation
  - Brill-Lindquist initial data
  - Moving puncture gauge
  - Sinh-spherical coordinates
  - Moderate resolution
- BH perturbation theory prediction
  - **Agreement to ~ 7 decades!**
- Increase FD order, grids fixed
  - Nearly exp. convergence in WFs





Advancing Multimessenger Astrophysics with Next-Generation Black Hole and Neutron Star Binary Merger Simulations

Zach Etienne

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PHY-1912497 (LIGO research, 2019-2021)

PHY-1757005 (Grav expmt, 2017-2020)

EPSCoR-1458952 (2015-2020)