

Towards binary boson star simulations

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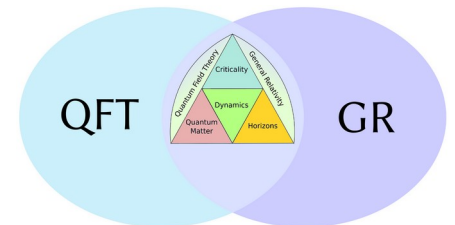
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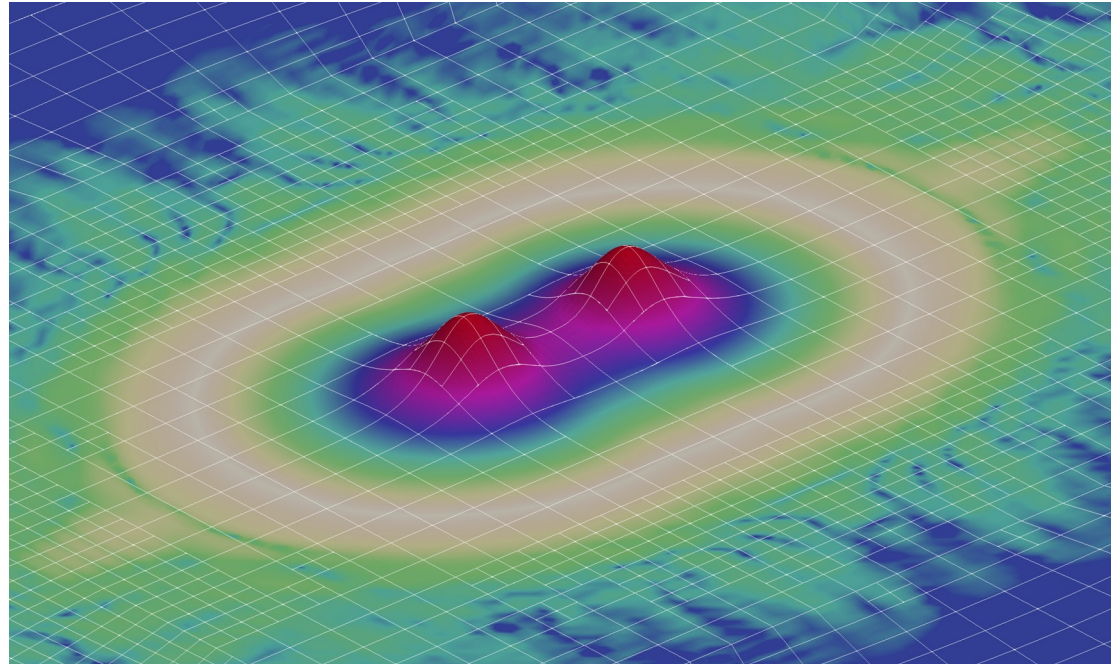


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What are boson stars?

- Inspired by Wheeler's geons [Wheeler, 1955]
- First discussed in [Kaup, 1968]
- BS \equiv complex scalar field obeying Einstein-Klein-Gordon (EKG) equations



Outline

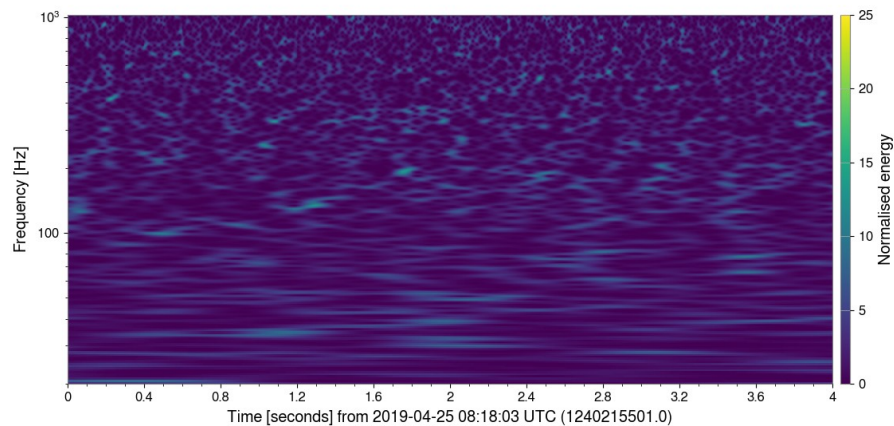
- Motivation
- Stationary Boson Star (BS) solutions
- Evolution setup and initial data (ID)
- First results
- Future directions

Motivation

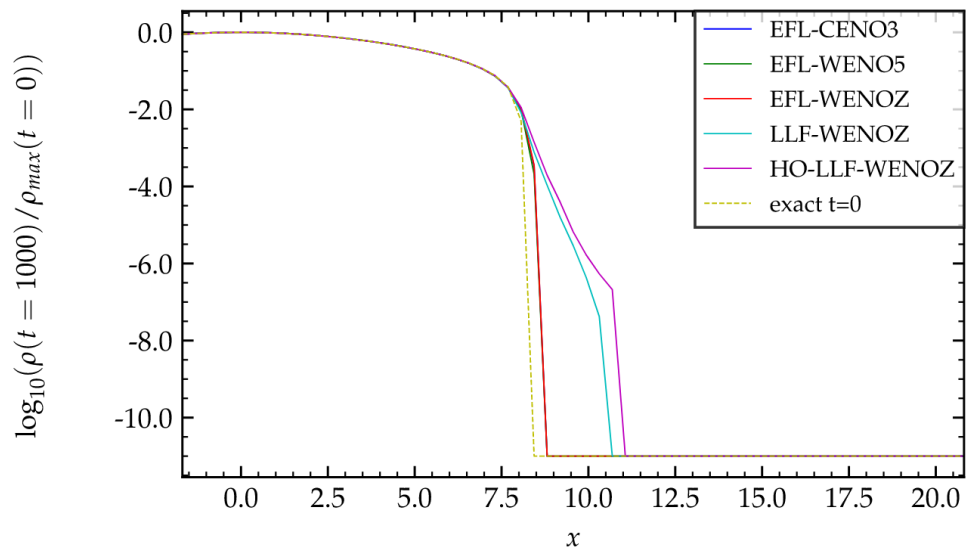
Why study boson stars?

- *Potential* candidates for GW signals without EM counterpart
- *Simpler* to evolve than BHs and NSs.

RTG Meeting, Leipzig, 6.10.2022



R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), "Open data from the first and second observing runs of Advanced LIGO and Advanced Virgo", SoftwareX 13 (2021), 100658.



DOULIS, Georgios, et al. Entropy-limited higher-order central scheme for neutron star merger simulations. arXiv preprint arXiv:2202.08839, 2022.

Stationary boson stars

Stationary BSs

- Einstein-Klein-Gordon equations

$$G_{\mu\nu} = 8\pi T_{\mu\nu}(\phi) \quad \square\phi = V'(|\phi|^2)\phi$$

- Spherical symmetry + stationarity

$$ds^2 = -e^{2\Phi(r)} dt^2 + \psi(r)^4 (dr^2 + r^2 d\Omega^2)$$

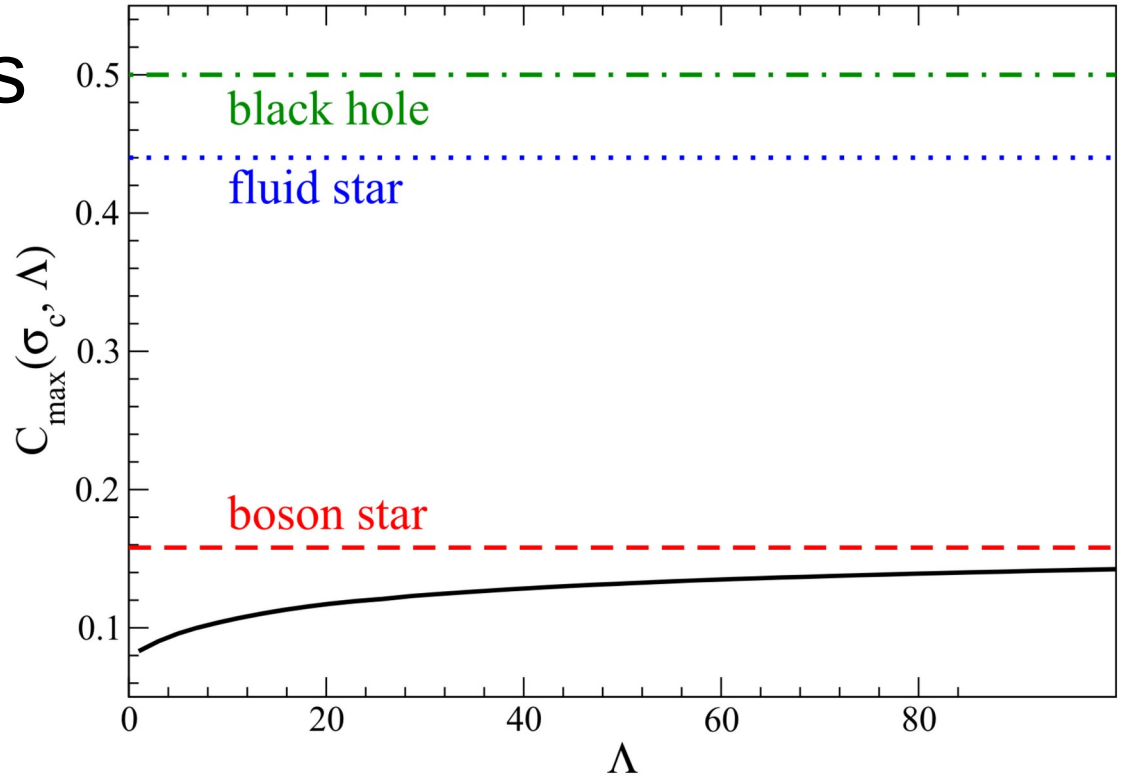
$$\phi(r, t) = A(r)e^{i\omega t}$$

BS Flavors

- Mini BS $V(|\phi|^2) = \mu|\phi|^2$

- + Quartic interactions

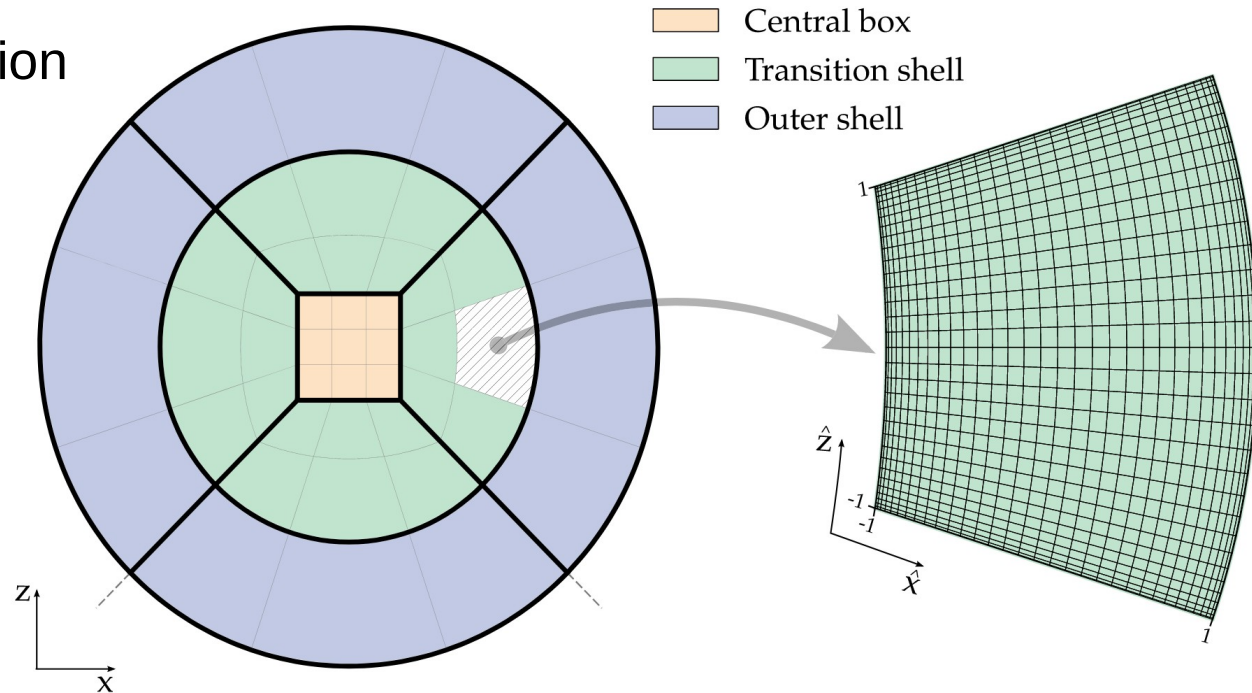
$$V(|\phi|^2) = \mu|\phi|^2 + \frac{\lambda}{2}|\phi|^4$$



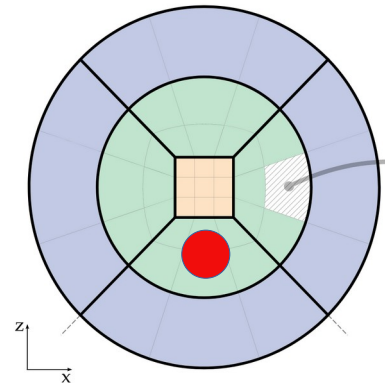
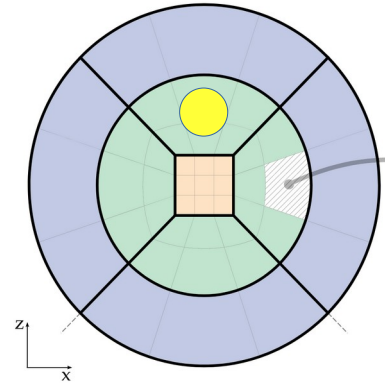
Evolution setup and initial data

bamps

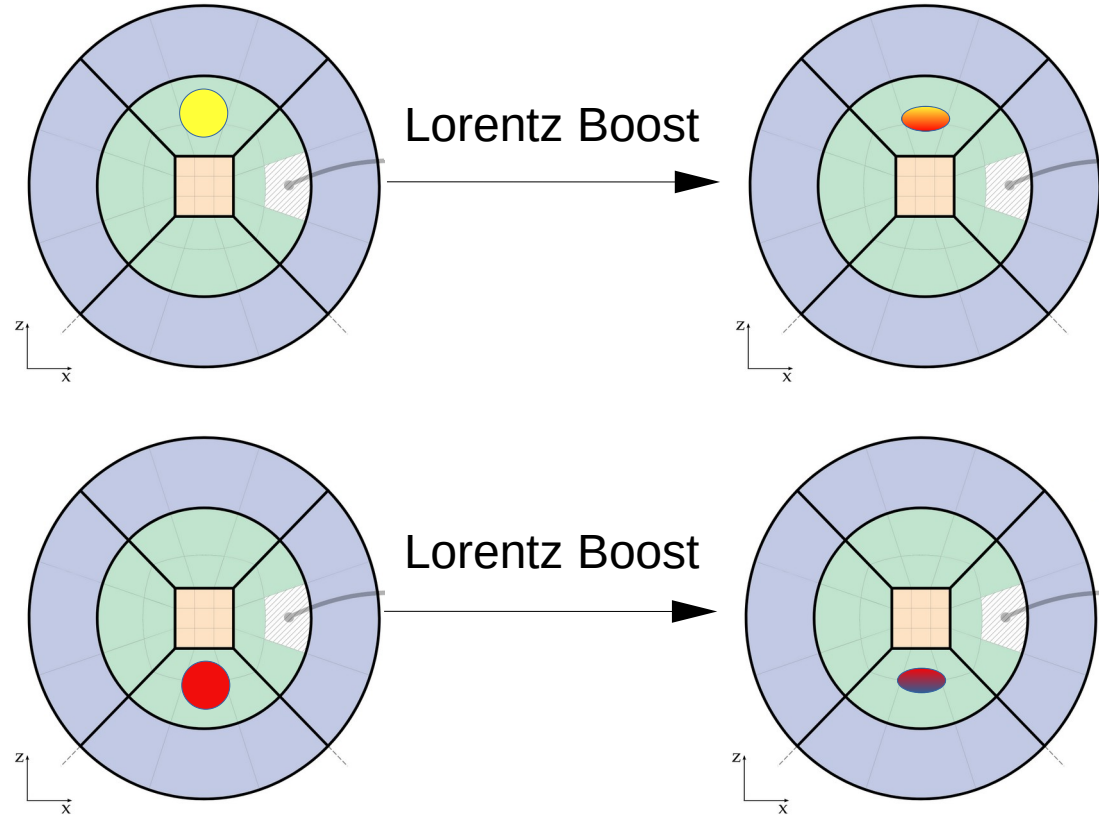
- Pseudospectral approximation in space
- Explicit stepping in time
- h- and p- aware AMR
- Shared- and distributed memory parallelization
- Successfully used for critical collapse simulations



ID construction



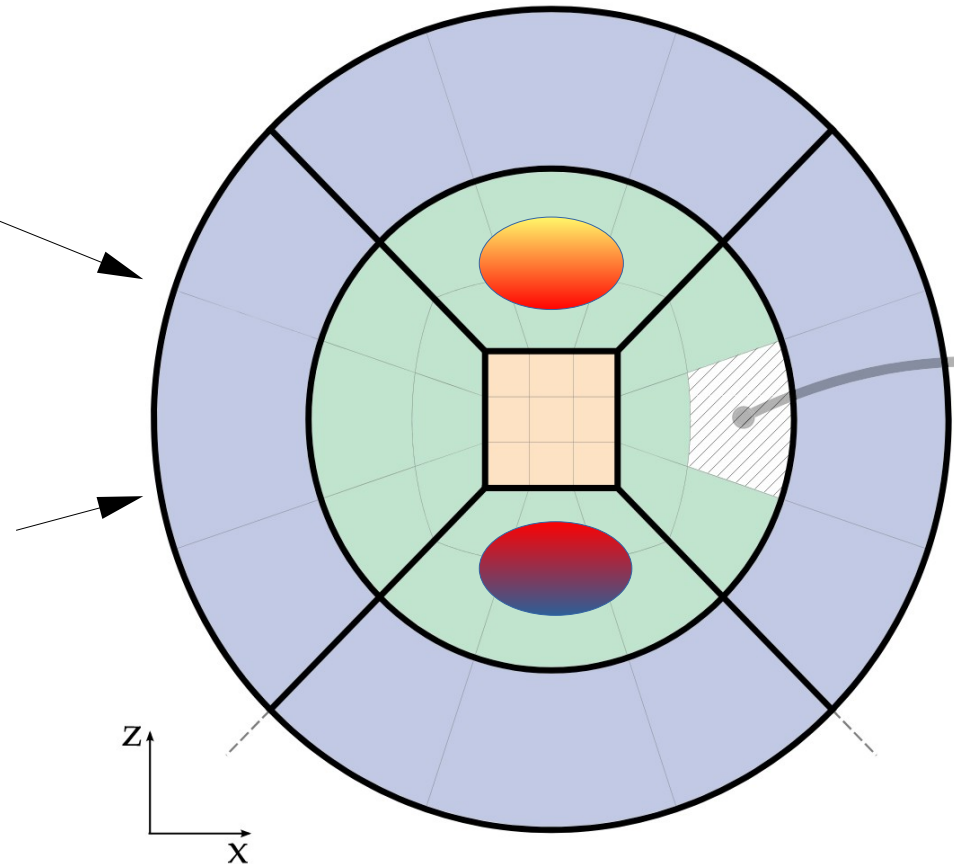
ID construction



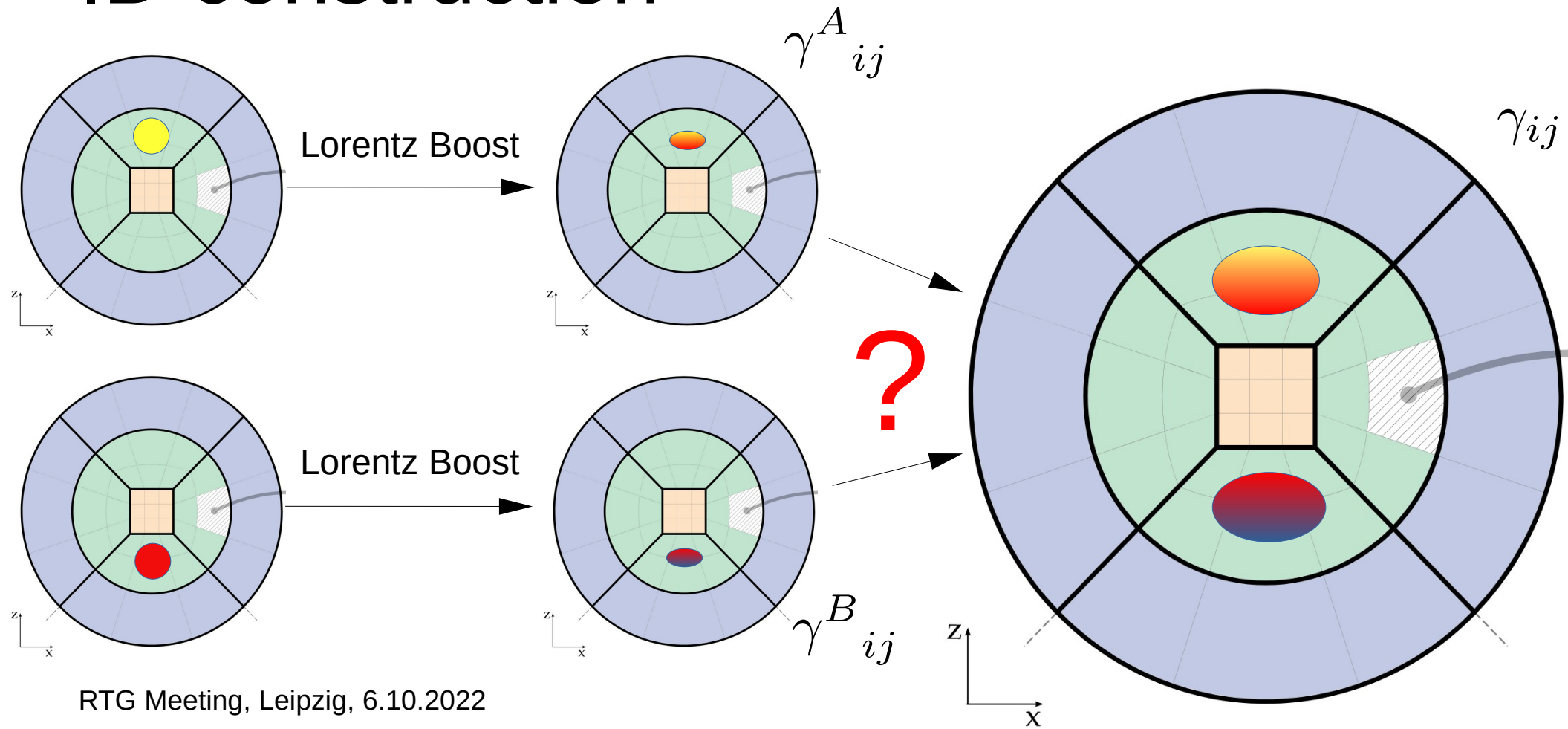
ID construction

“Naive” superposition

$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \delta_{ij}$$



ID construction



ID construction

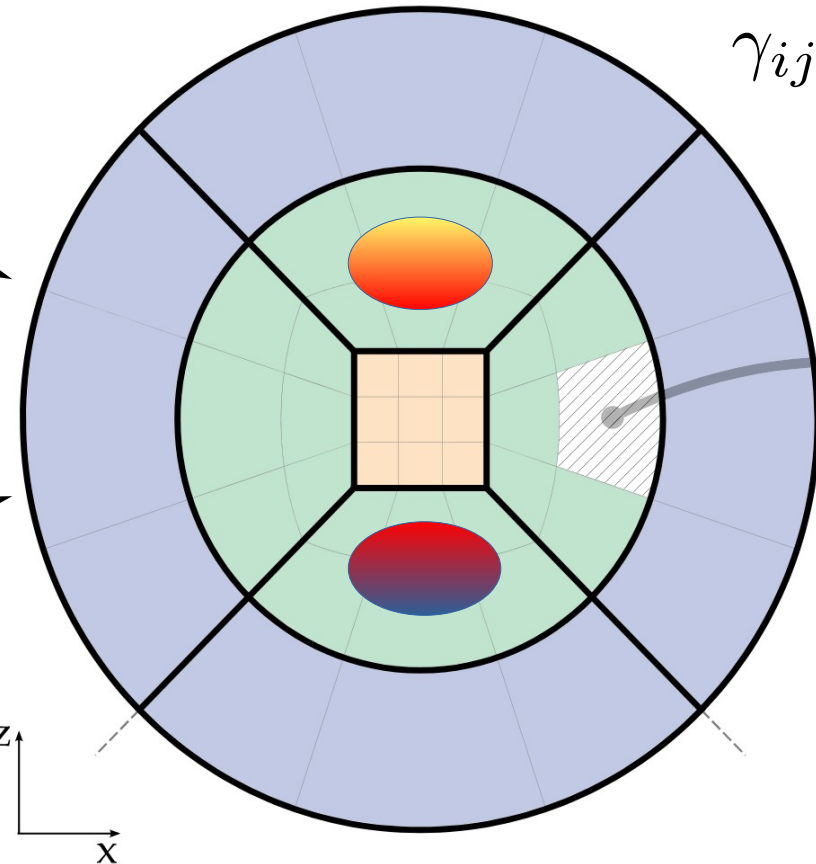
“Naive” superposition

$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \delta_{ij}$$

or

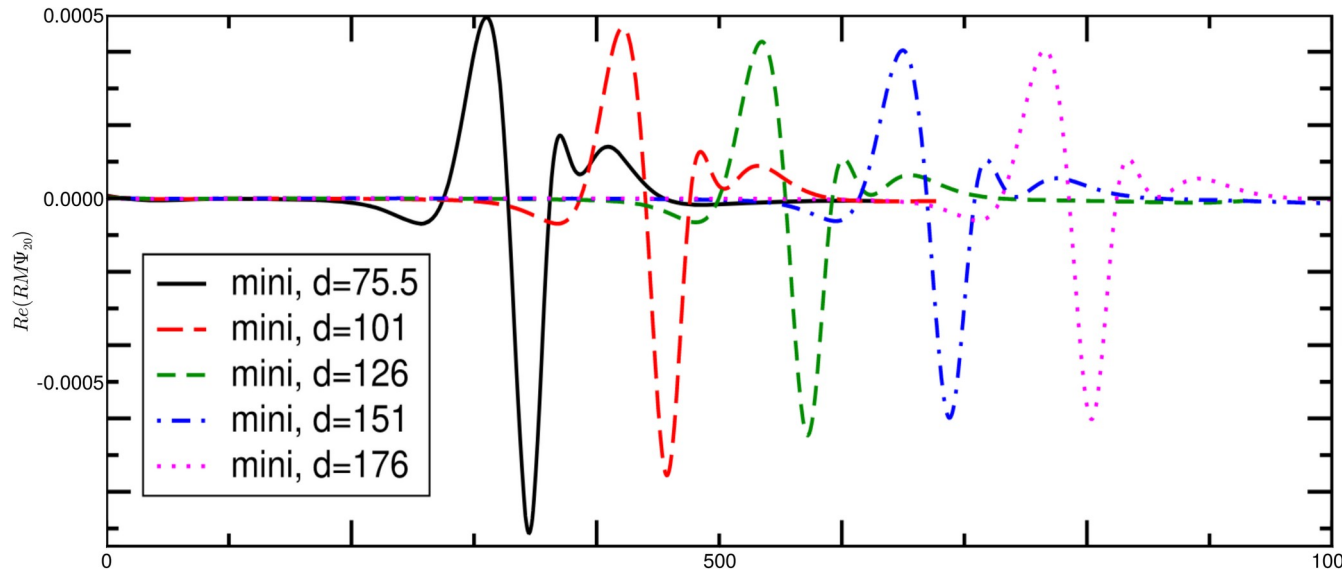
Improved superposition
[Helper et al, 2022]

$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \gamma_{ij}^A(x^B)$$

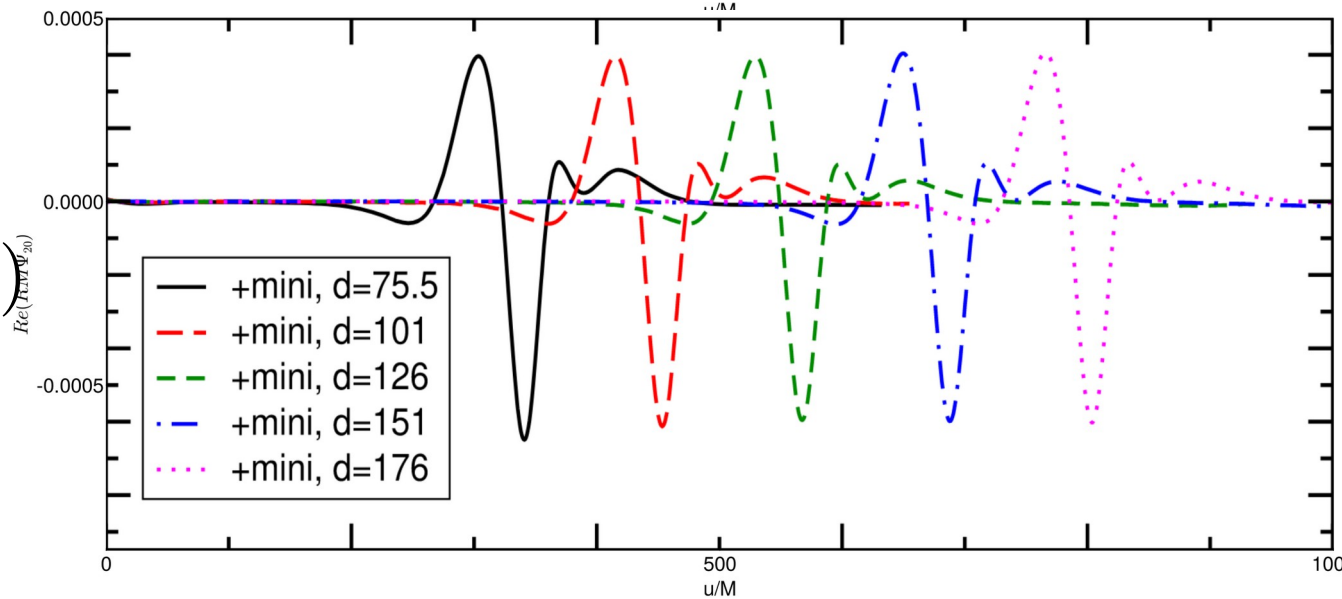


First results – Headon collisions

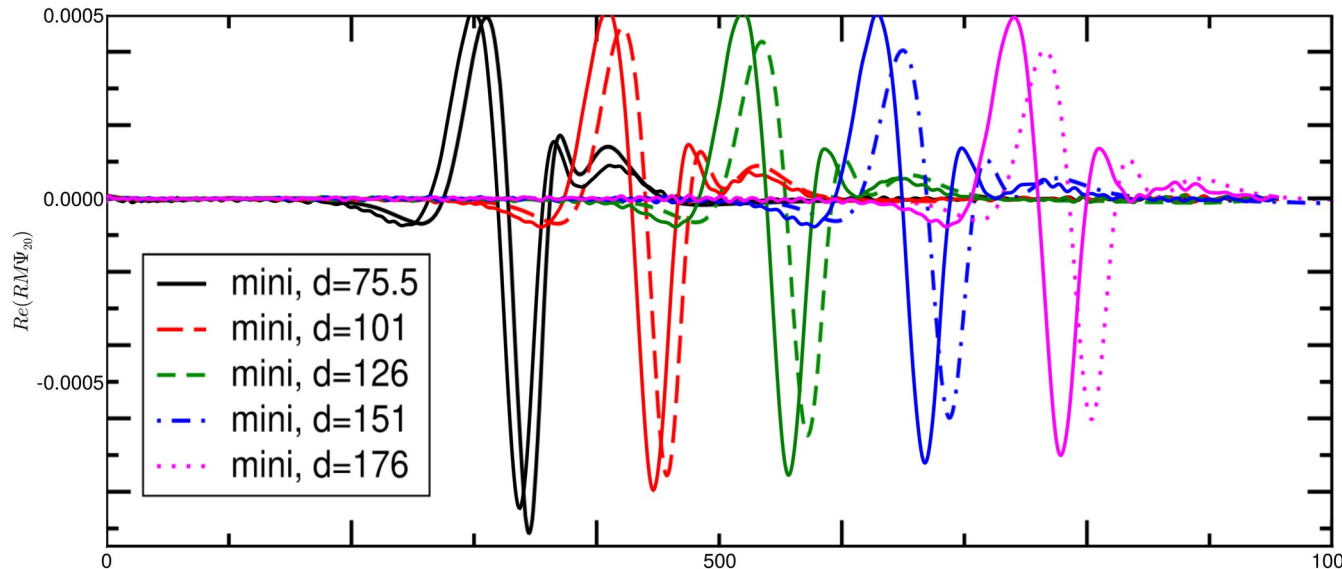
$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \delta_{ij}$$



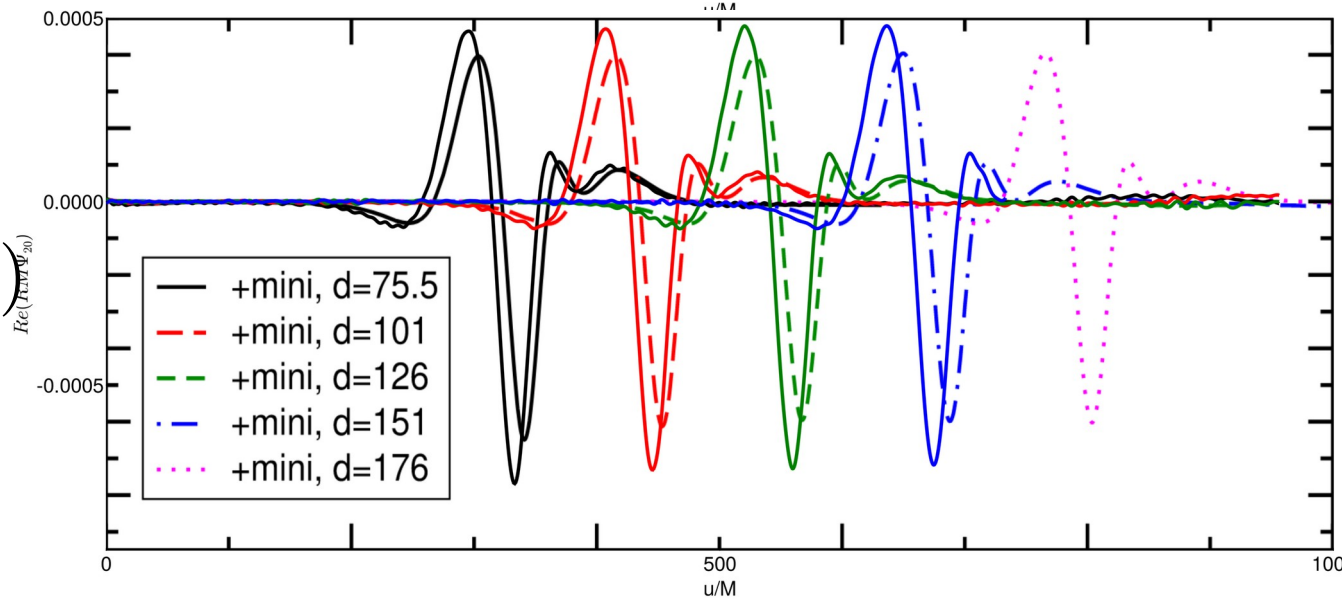
$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \gamma_{ij}^A(x^B)$$



$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \delta_{ij}$$



$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \gamma_{ij}^A(x^B)$$



Future directions

Future directions

- Near future:
 - Effect of constraint solved ID on GW signal
- Intermediate future:
 - Phenomenology
 - Unequal masses
 - BS – anti-BS $\phi(r, t) = A(r)e^{\pm i(\omega t + \delta)}$
 - Rotating BSs
- Far future: BSs in massive scalar-tensor theory

Thank you

The simplest BS

- Spherical symmetry + stationarity

$$ds^2 = -e^{2\Phi(r)} dt^2 + \psi(r)^4 (dr^2 + r^2 d\Omega^2)$$

$$\phi(r, t) = A(r) e^{i\omega t}$$

- Boundary conditions

$$r \rightarrow \infty \quad g_{\mu\nu} \rightarrow \eta_{\mu\nu}, \quad r \rightarrow 0 \quad g_{\mu\nu} \text{ regular,}$$

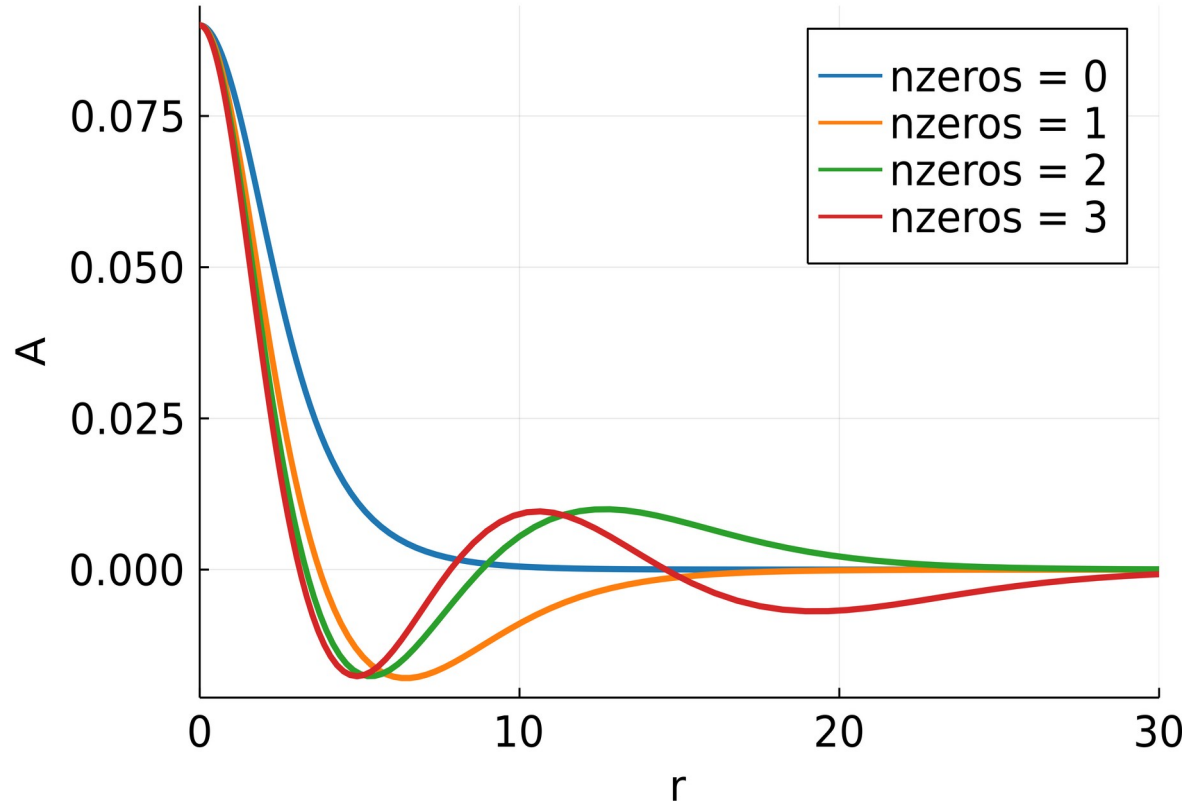
$$r \rightarrow \infty \quad |\phi| \rightarrow 0, \quad r \rightarrow 0 \quad |\phi| \rightarrow |\phi_0|.$$

Degeneracy of BSs

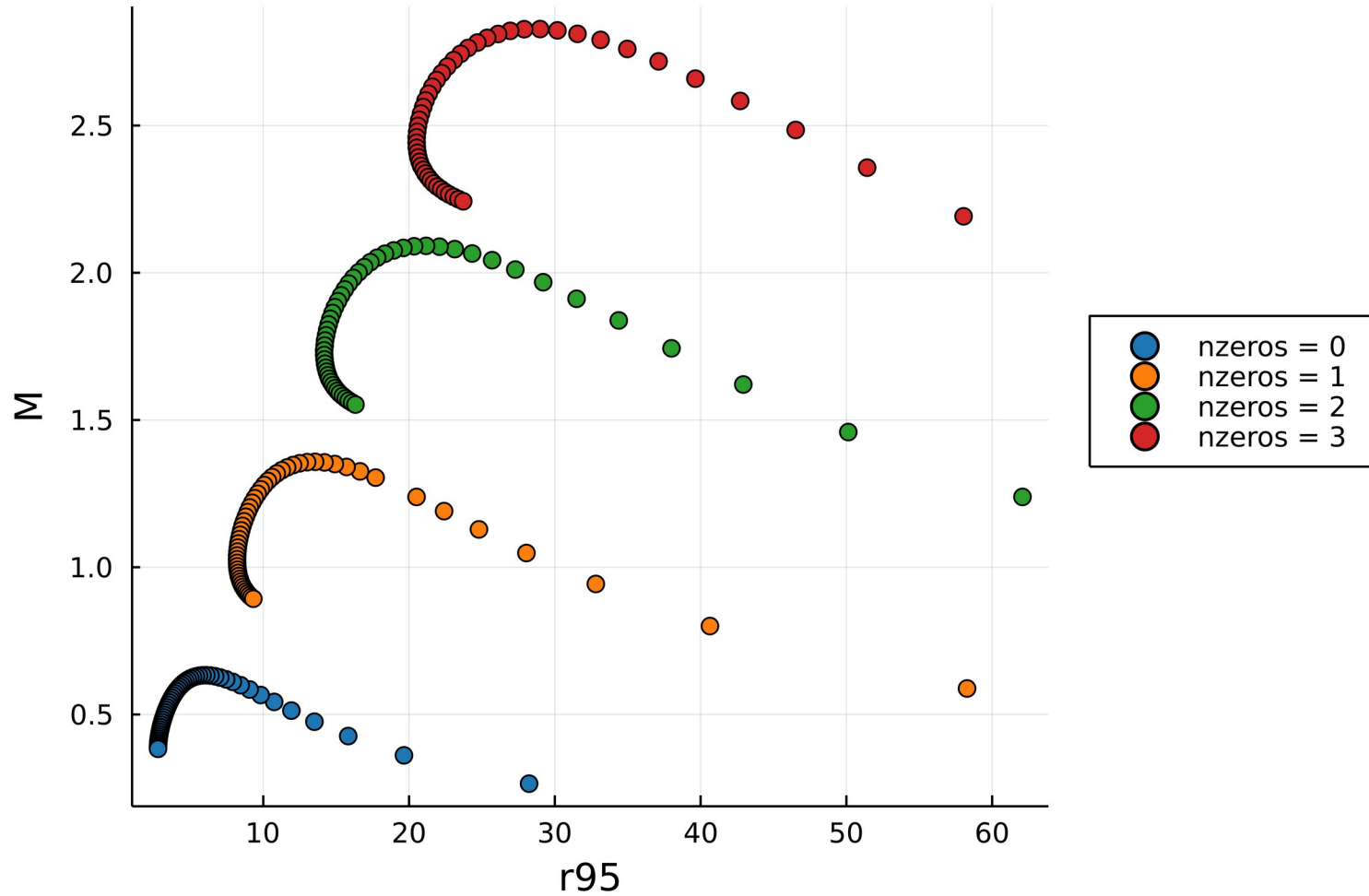
- Stationary Ansatz

$$\phi(r, t) = A(r)e^{i\omega t}$$

- We obtain family of solutions for $|\phi_0|$ with different ω



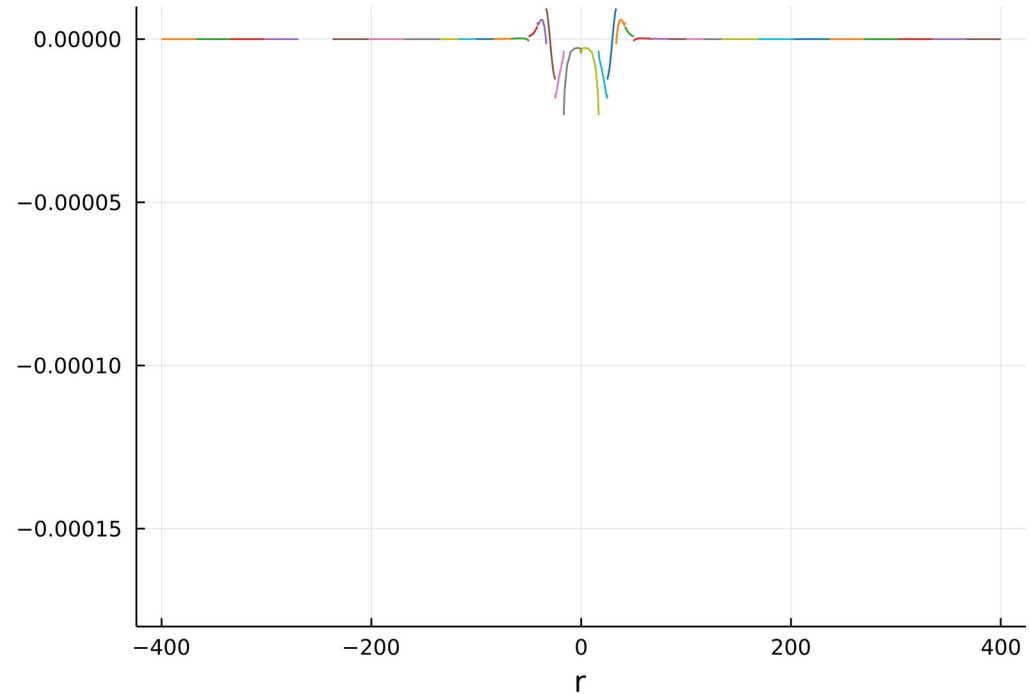
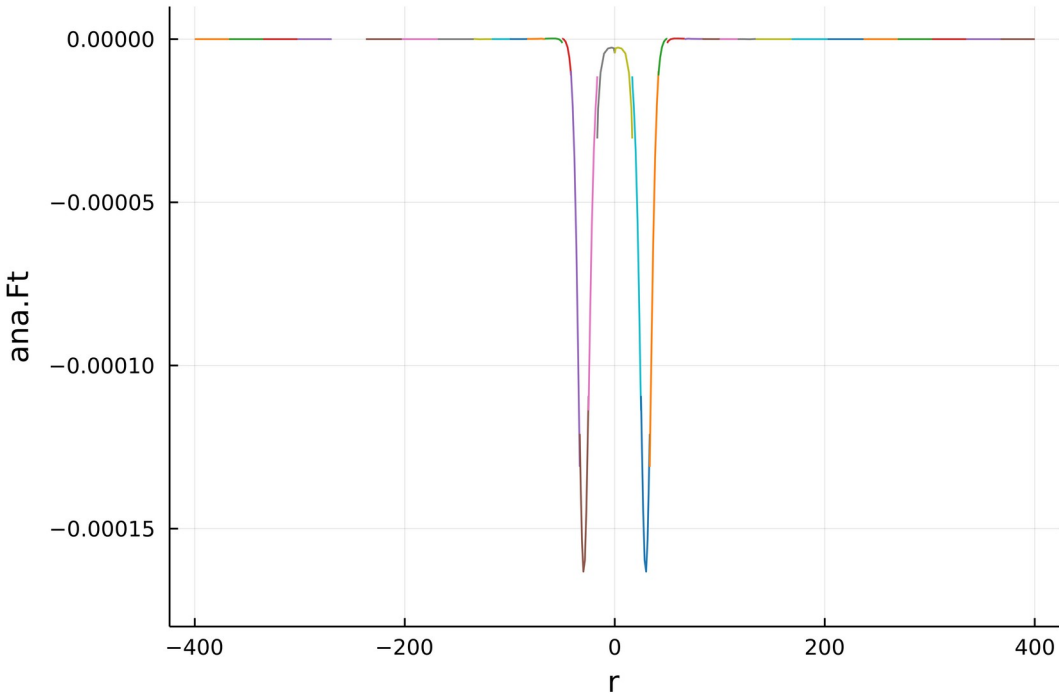
Compactness



Effects of constraint violations

$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \delta_{ij}$$

$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \gamma_{ij}^A(x^B)$$



ID construction

- Fundamental Problem: How does an initial configuration look like?
- Only guidelines we have are
 - Hamiltonian constraint (1 eq)
 - Momentum constraint (3 eqs)

