# Boson star head-on collisions

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# What are boson stars and why?

- BS ≡ soliton-like solutions to Einstein-Klein-Gordon (EKG) equations

  Kaup, 1968
  Liebling, Palenzuela, 2023 (review)

$$S = \int \sqrt{-g} x^4 \left[ \frac{R}{16\pi} - \frac{1}{2} g^{\mu\nu} \nabla_\mu \bar{\phi} \nabla_\nu \phi + V(|\phi|^2) \right]$$

$$G_{\mu\nu} = 8\pi T_{\mu\nu} \qquad \Box\phi = \phi \frac{dV(|\phi|^2)}{d|\phi|^2}$$

# What are boson stars and why?

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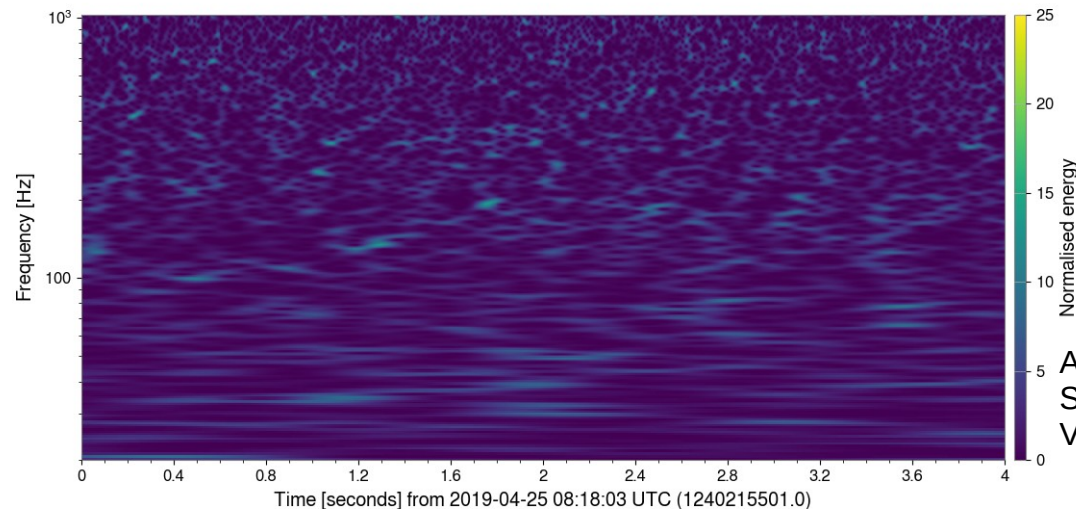
- This talk – mini boson stars:

- Need templates for GW search

$$S = \int \sqrt{-g}x^4 \left[ \frac{R}{16\pi} - \frac{1}{2}g^{\mu\nu}\nabla_\mu\bar{\phi}\nabla_\nu\phi + V(|\phi|^2) \right]$$

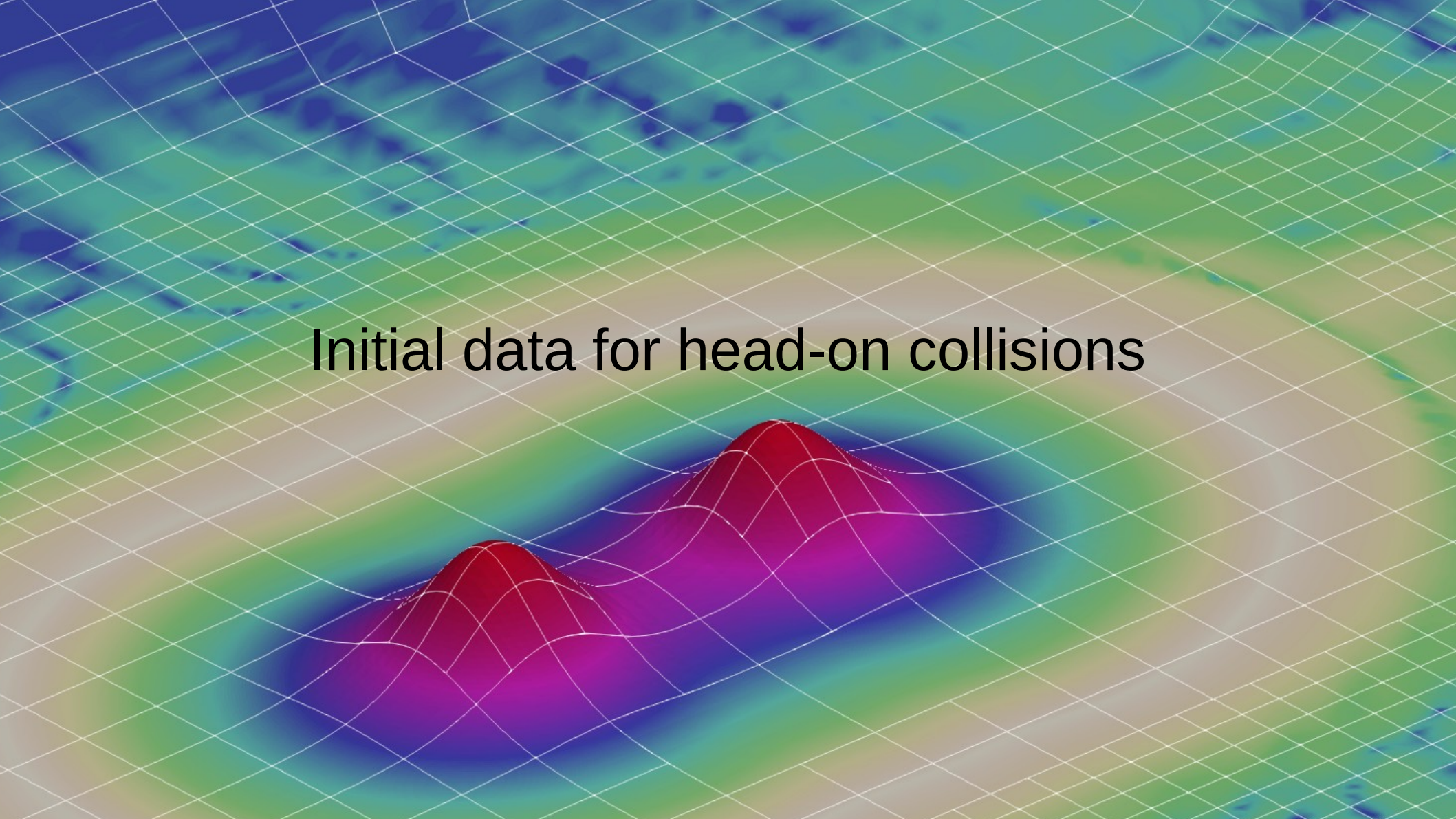$$G_{\mu\nu} = 8\pi T_{\mu\nu} \qquad \Box\phi = \phi\frac{dV(|\phi|^2)}{d|\phi|^2}$$
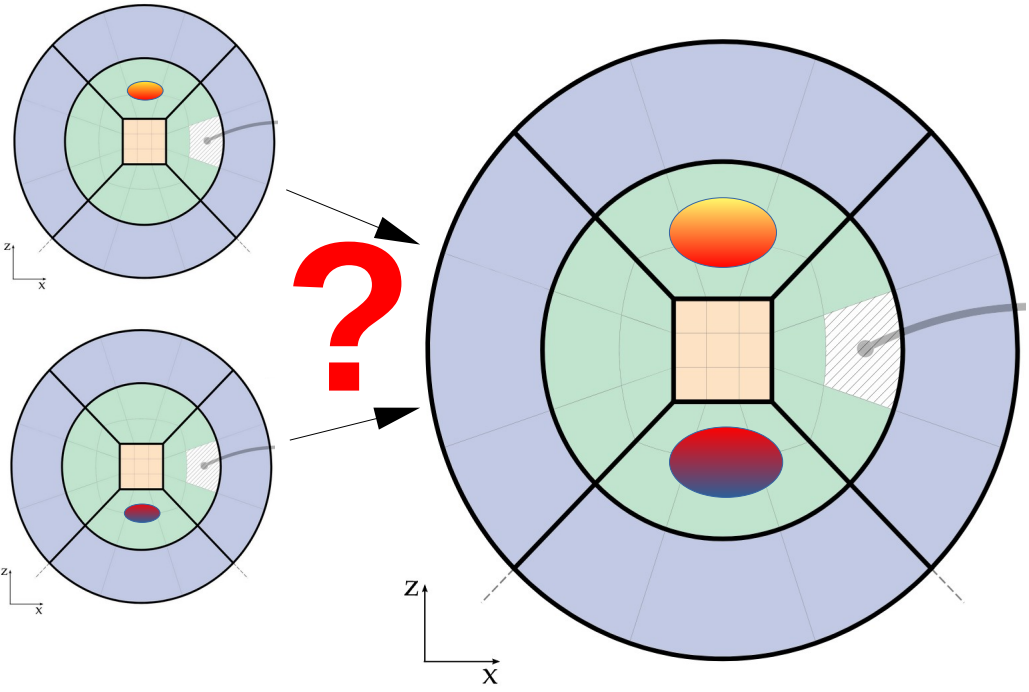
$$V(|\phi|^2) = |\phi|^2$$
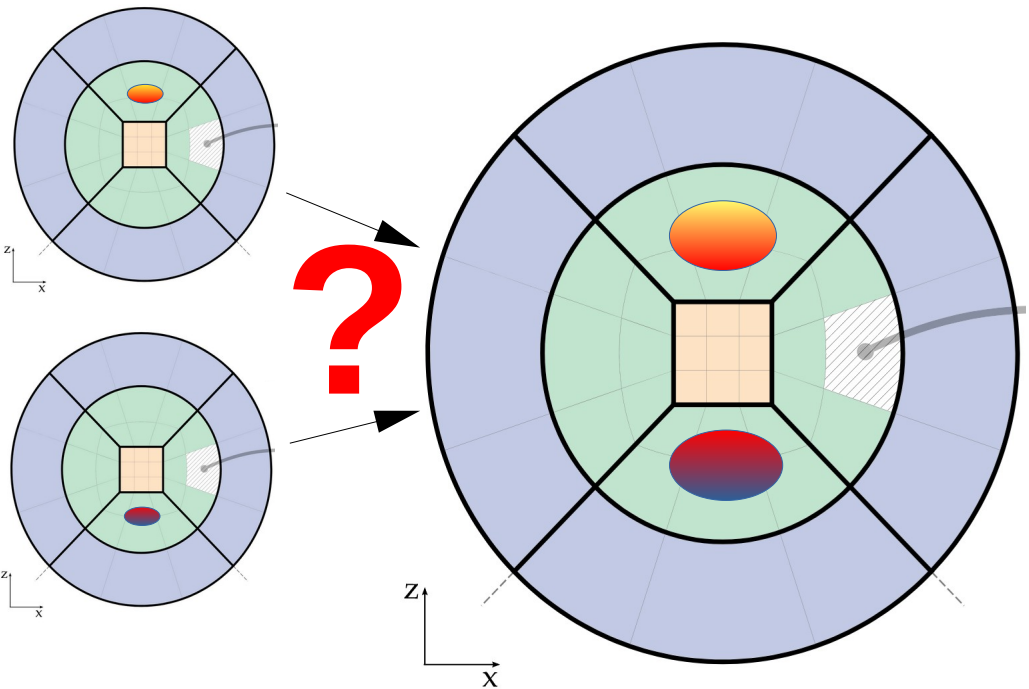


Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), 2021

Initial data for head-on collisions

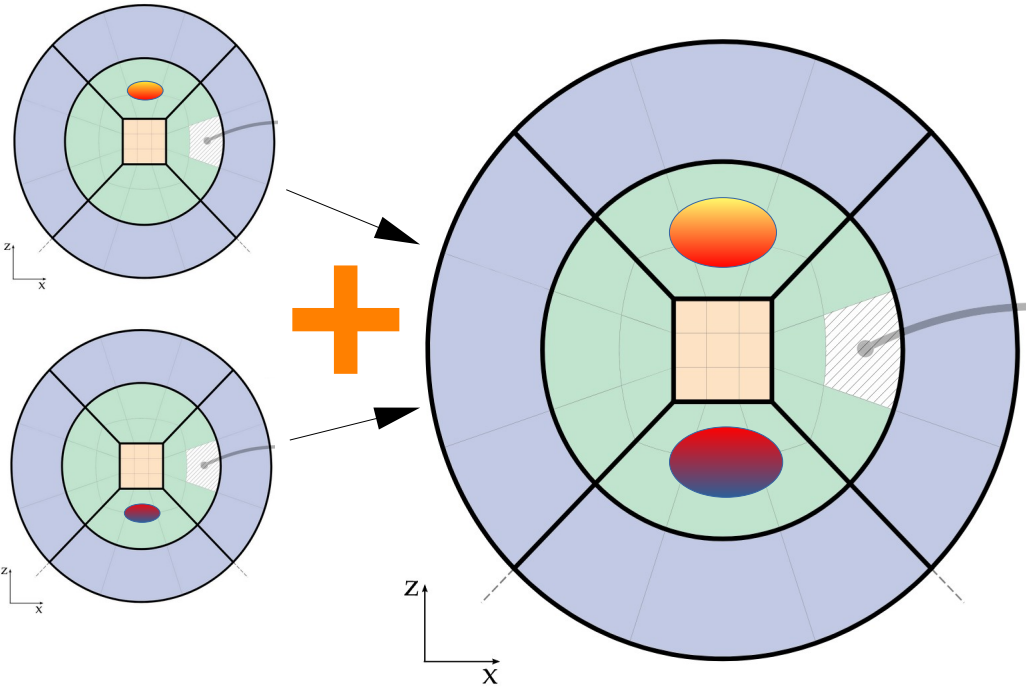Boson star head-on collisions
Florian Atteneder

$$^3R + K^2 - K_{ij}K^{ij} = 16\pi\rho$$
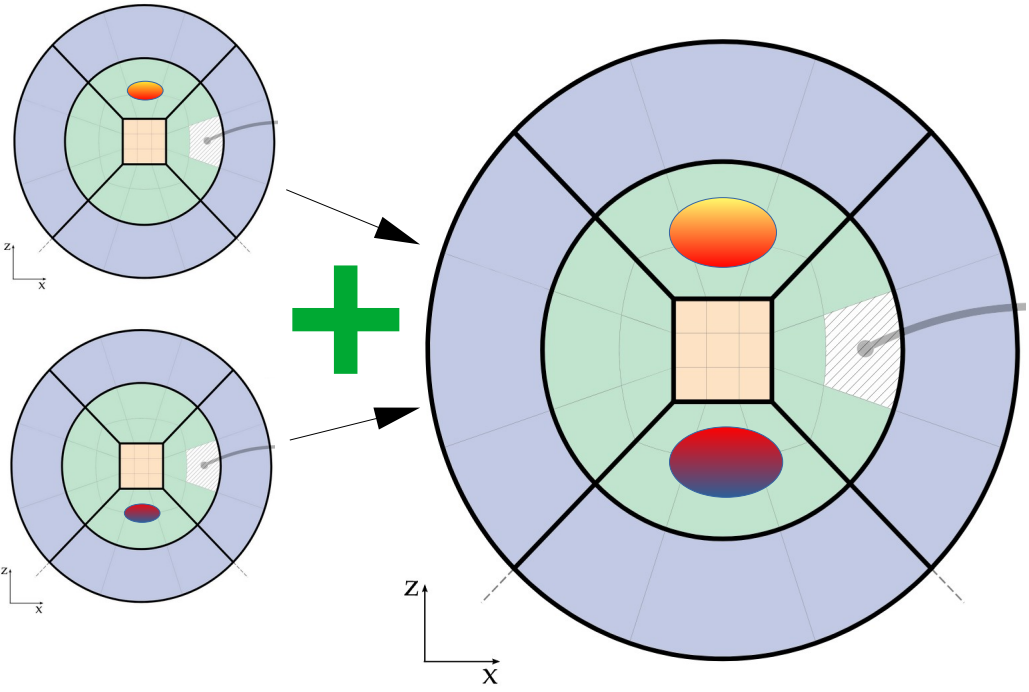$$D_j(K^{ij} - \gamma^{ij}K) = 8\pi S^i$$

Most of current literature uses
**superpositioned data**

Palenzuela et al. 2007; Palenzuela, Lehner, Liebling, 2008; Bezares, Palenzuela, 2017; Palenzuela, 2018; ...

- Simple to construct

- Accepting non-zero constraint violations

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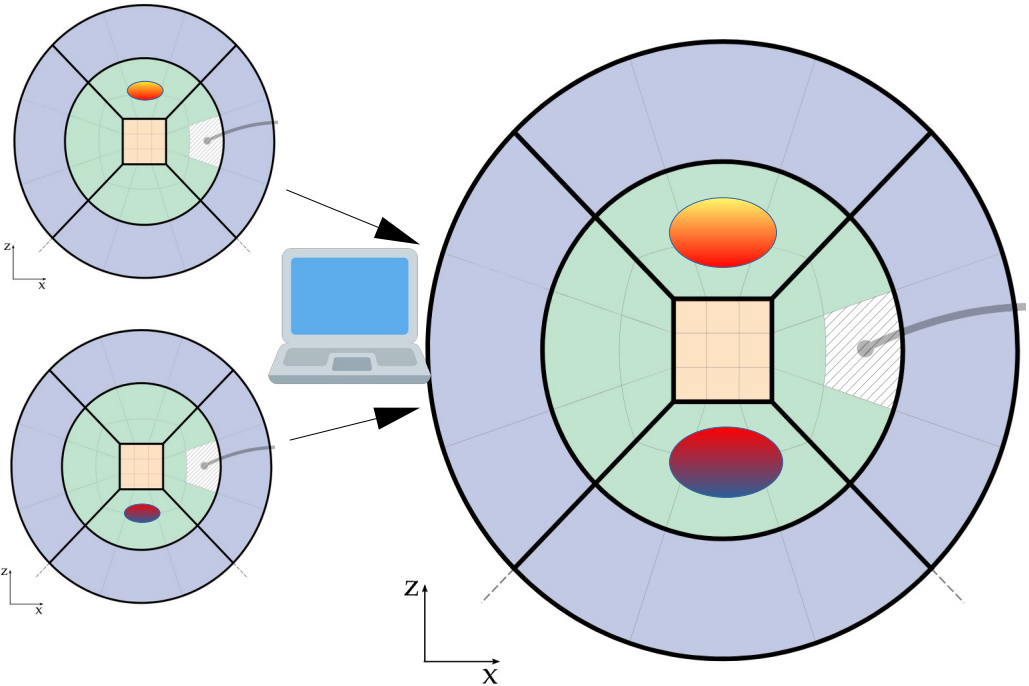
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# Improved superposition

Helfer et al. 2022; Croft et al. 2023; Evstafyeva et al. 2023;

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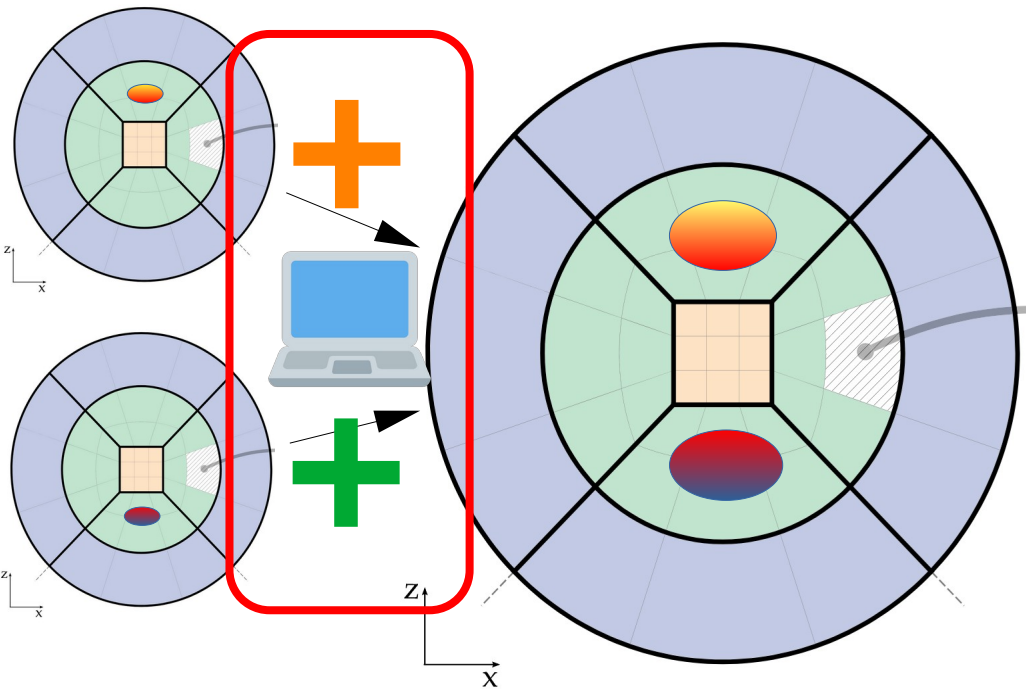
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# Constraint solved data

Siemonsen, East, 2023; Dietrich, Ossokine, Clough, 2018

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## Does it matter?

## Constraint solved data

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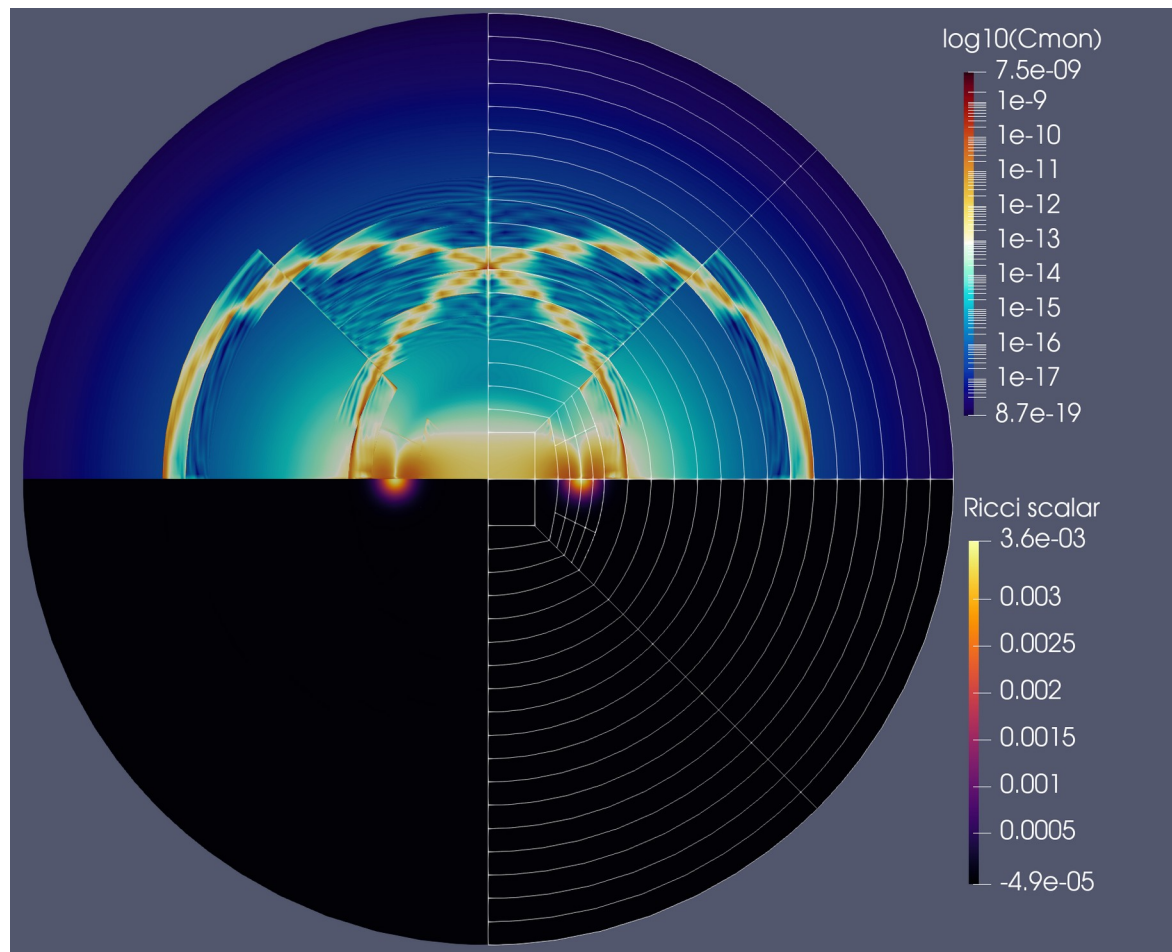$$D_j(K^{ij} - \gamma^{ij}K) = 8\pi S^i$$

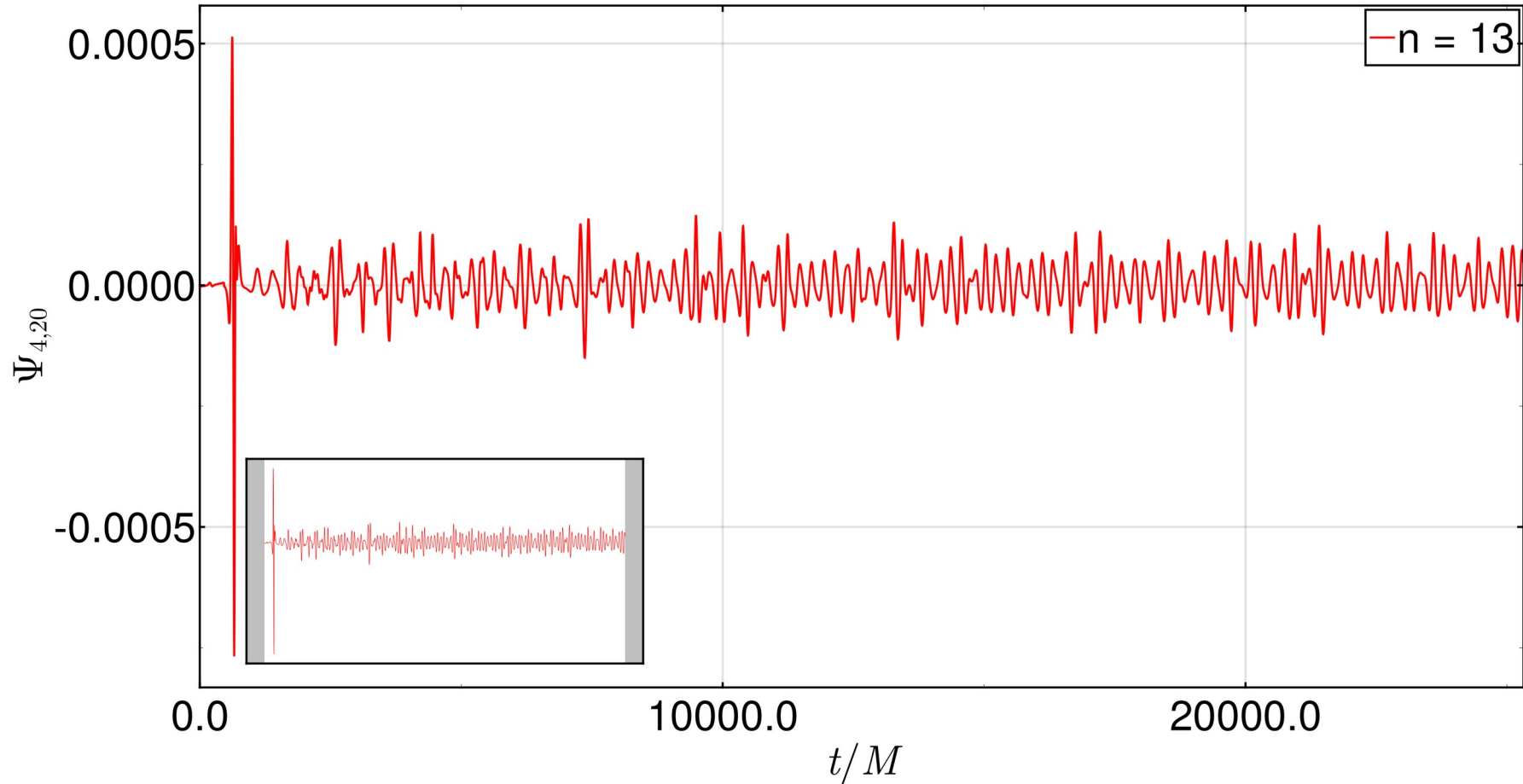# First results: stable and convergent evolutions
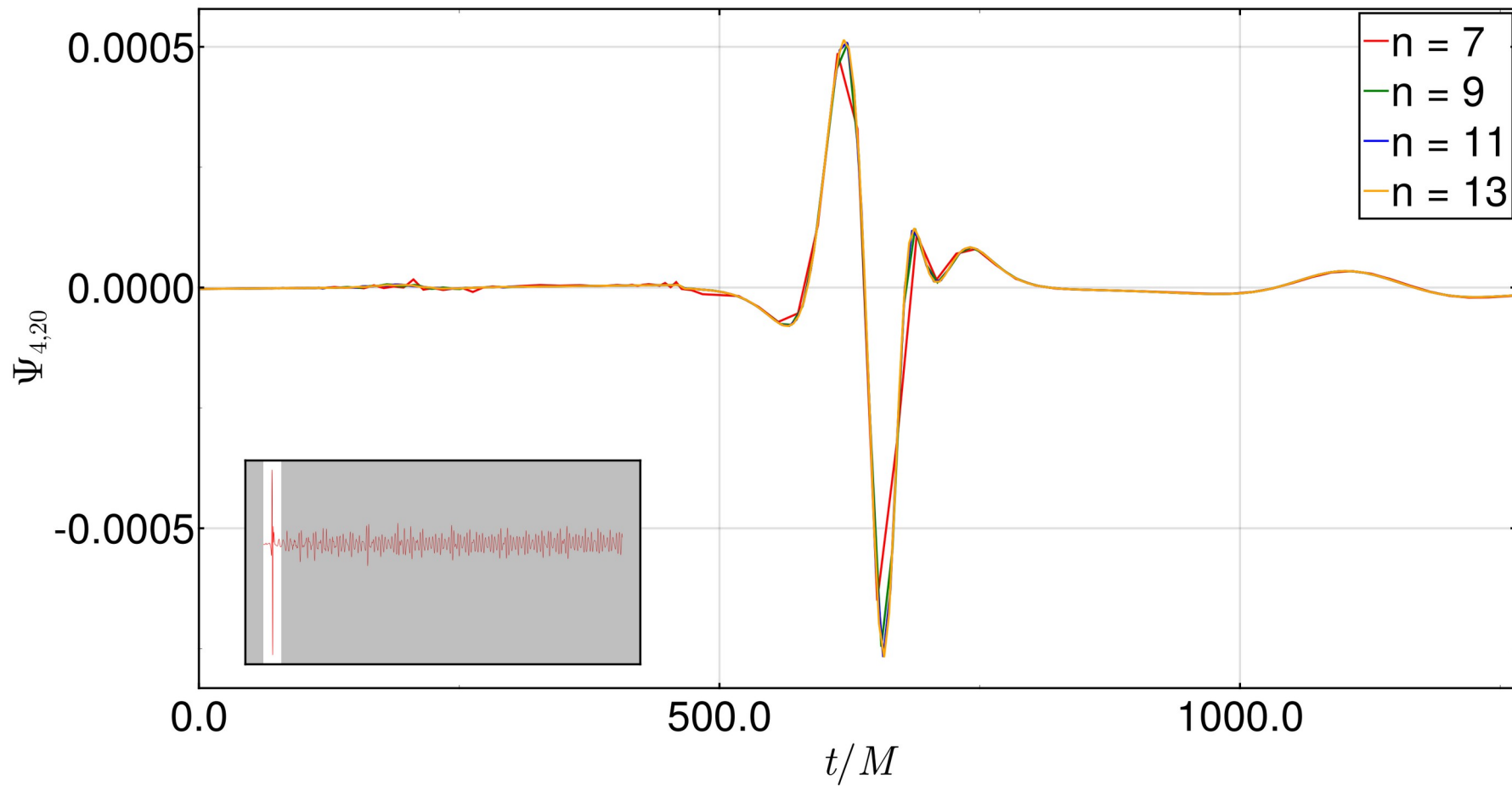
(no actual comparison yet)

# Setup

- Code: bamps

- Evolution with generalized harmonic gauge formulation

- Gauge source function from Deppe et al. 2019

- Constraint preserving boundary conditons

- Initial data

  - Equal mass BS head-on

  - Cartoon method + reflection symmetry

  - Total mass M = 0.79

  - Initial separation d = 100 M

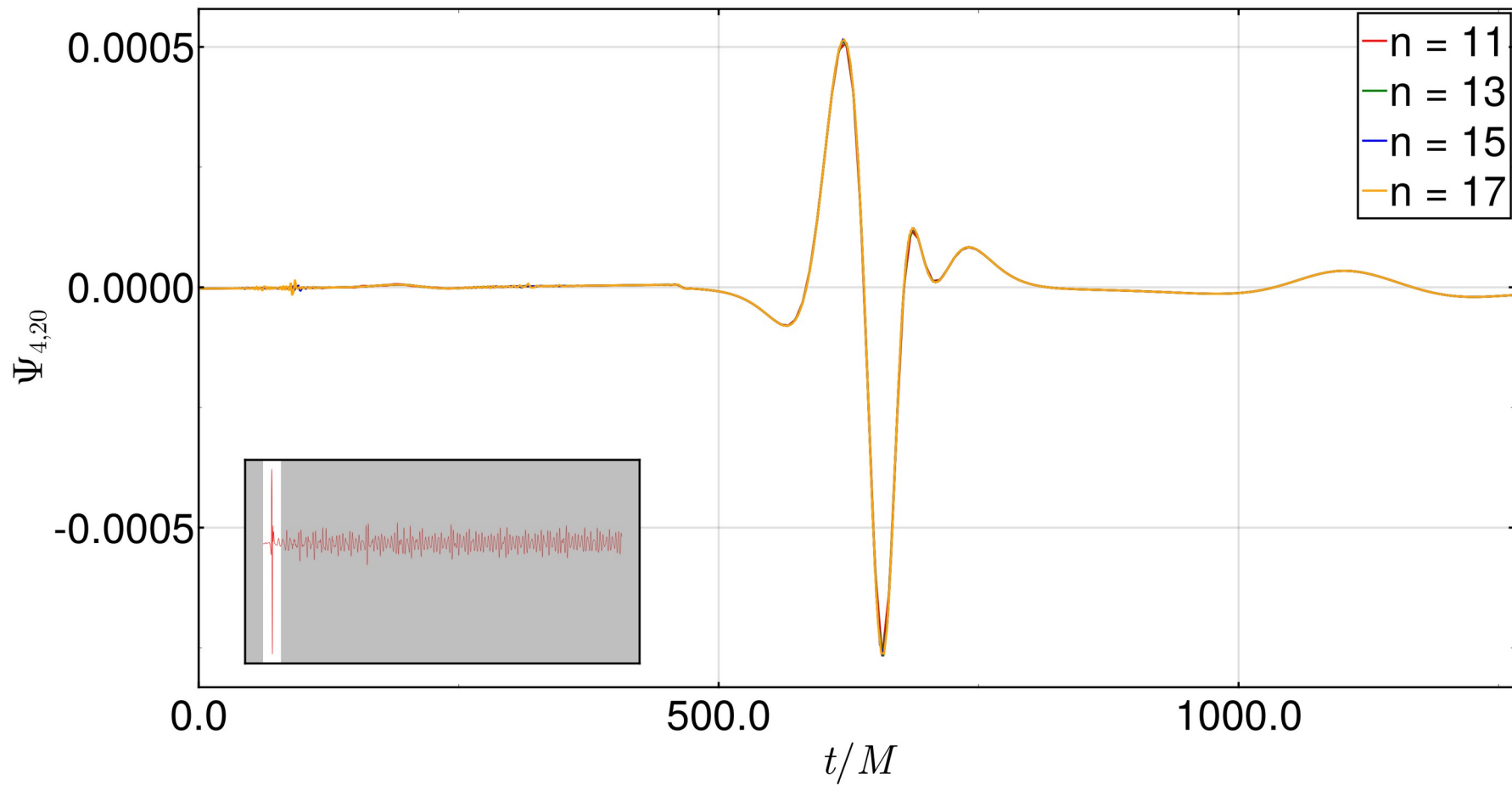  **+** Improved superposition

    a la Helfer et al. 2022

Boson star head-on collisions
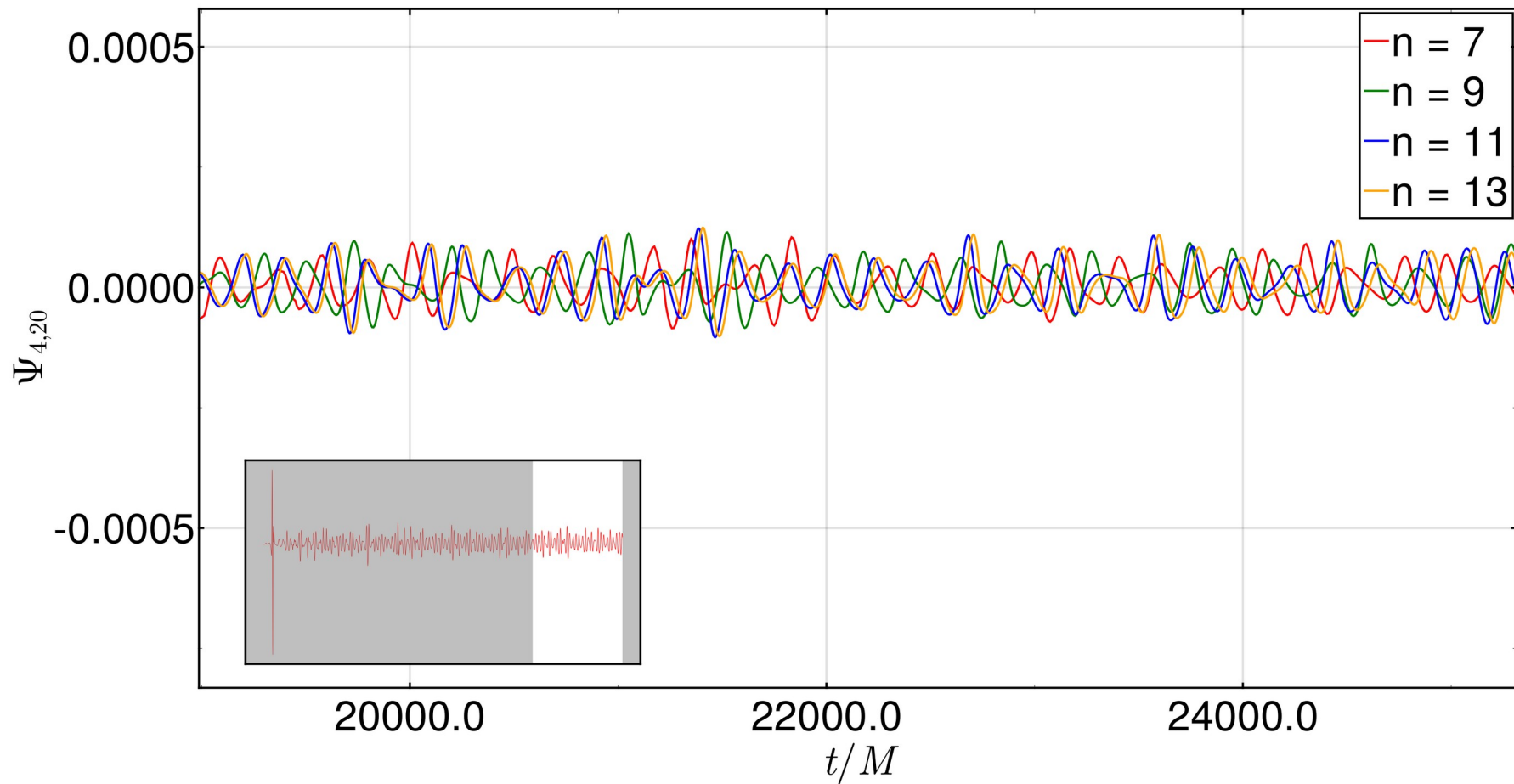Florian Atteneder

# Convergence - GWs
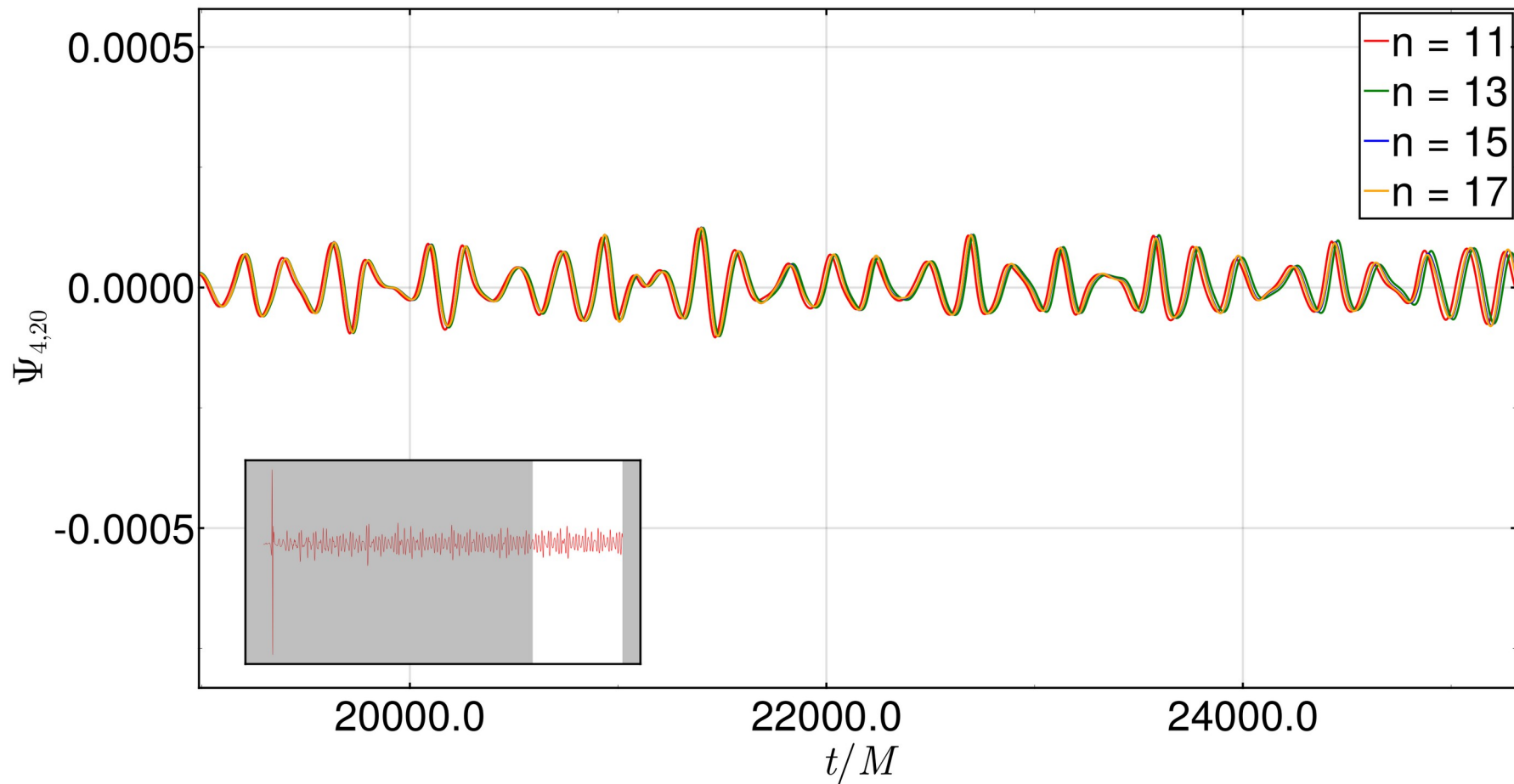
# Convergence - GWs

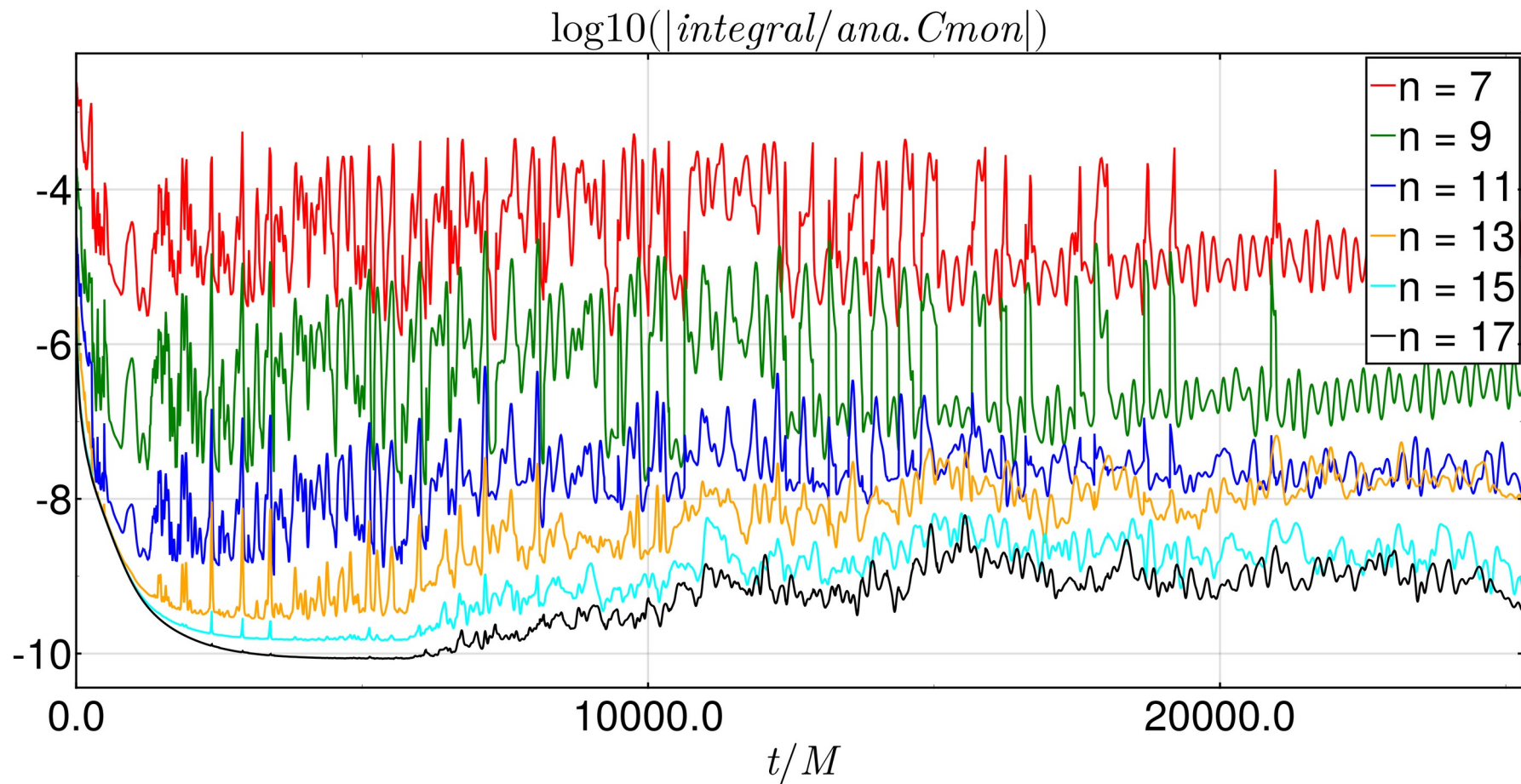# Convergence - GWs

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# Summary

- BS ≡ soliton-like solutions to Einstein-Klein-Gordon equations

- Superposition vs. constraint solved – does it matter?

- bamps can do stable & convergent BS head-ons

## Thank you

# Convergence - Constraints



$$\log10(|integral/ana.Cmon|)$$

Legend:
- n = 7
- n = 9
- n = 11
- n = 13
- n = 15
- n = 17

x-axis: $t/M$

# Future directions

- Binary BS systems
  - Phenomenology
  - Unequal masses
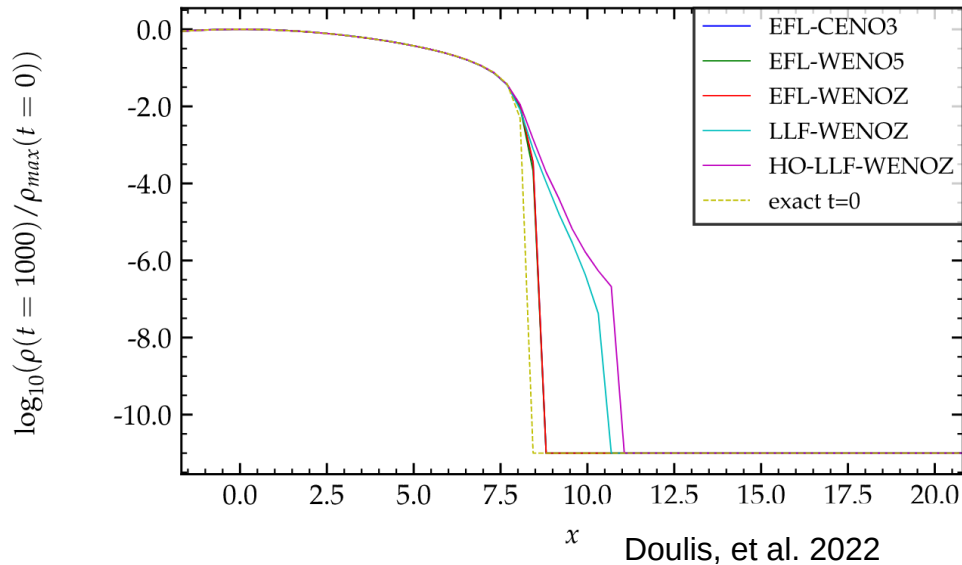  - BS – anti-BS or BS – BS+$\delta$     $\phi(r,t) = A(r)e^{\pm i(\omega t + \delta)}$
  - Rotating remnants    Siemonsen, East, 2023
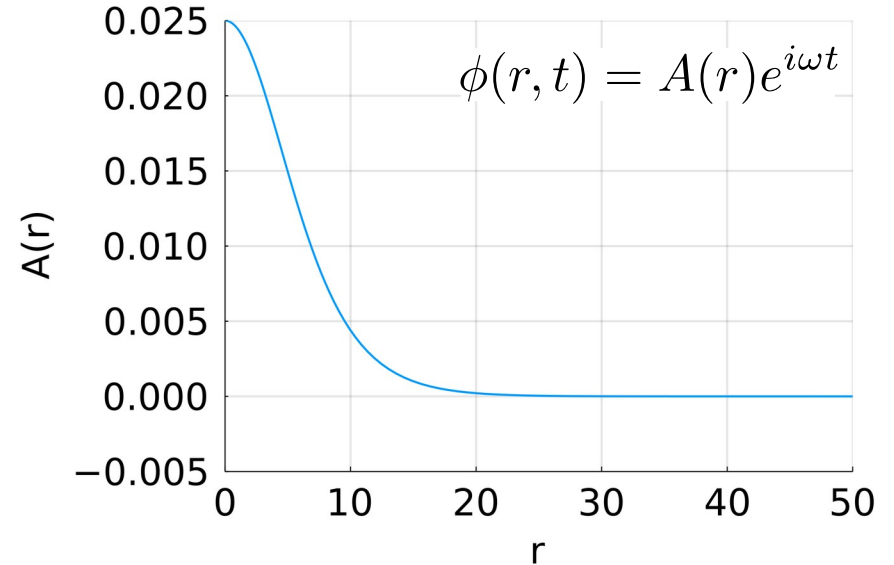
- Far future: BSs in massive scalar-tensor theory

# Why study boson stars?

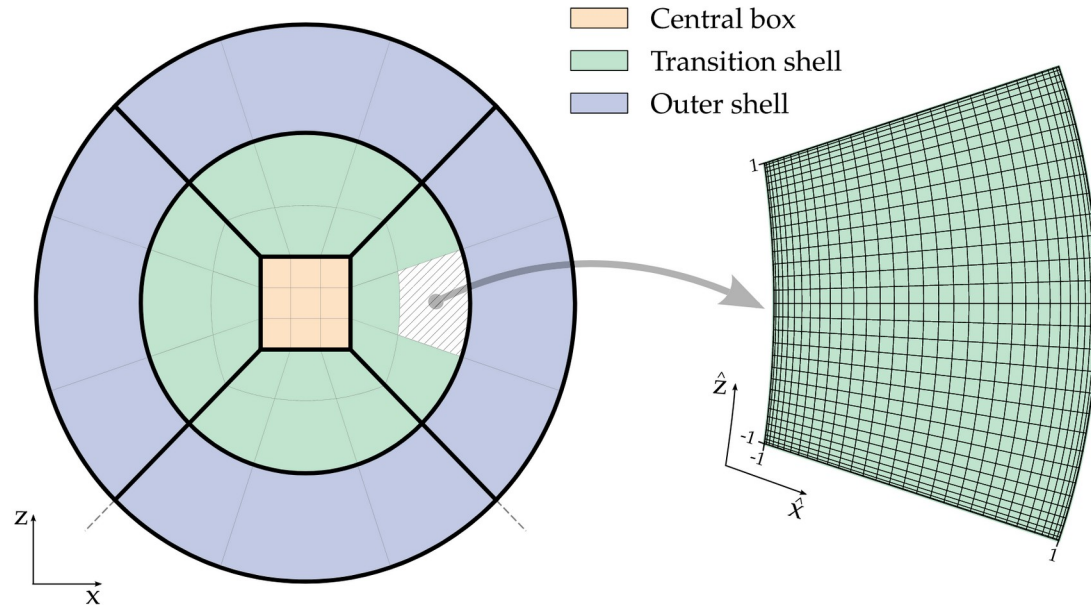- *Believed to be simpler* to evolve than BHs and NSs.

Neutron star



Doulis, et al. 2022

Boson star



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

# bamps code

- Pseudospectral approximation in space

- Explicit stepping in time

- h- and p- aware AMR

- MPI parallelization

- Successfully used for critical collapse simulations



Central box
Transition shell
Outer shell

Boson star head-on collisions
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# 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

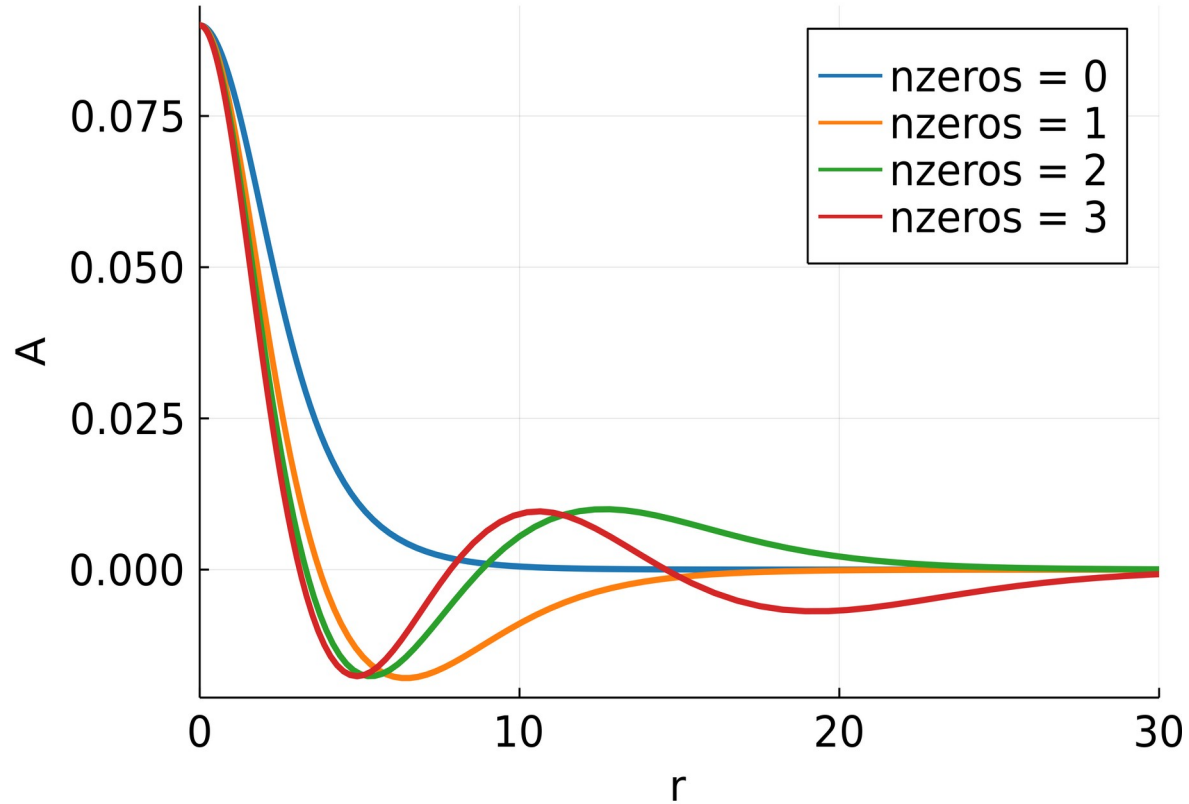$$r \to \infty \qquad g_{\mu\nu} \to \eta_{\mu\nu}, \qquad\qquad r \to 0 \qquad g_{\mu\nu} \text{ regular},$$

$$r \to \infty \qquad |\phi| \to 0, \qquad\qquad r \to 0 \qquad |\phi| \to |\phi_0|.$$
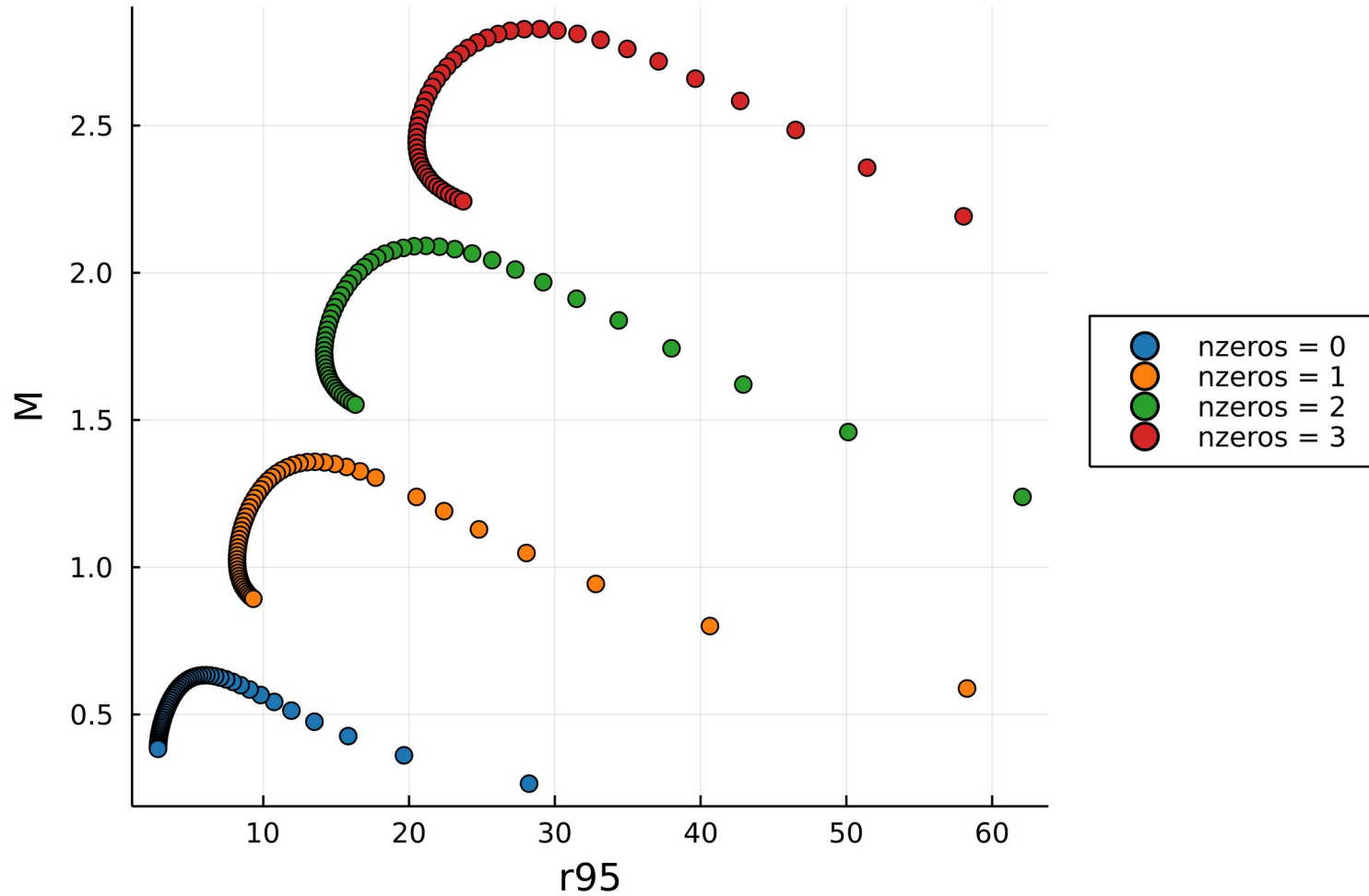
# Degeneracy of BSs

- Stationary Ansatz

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

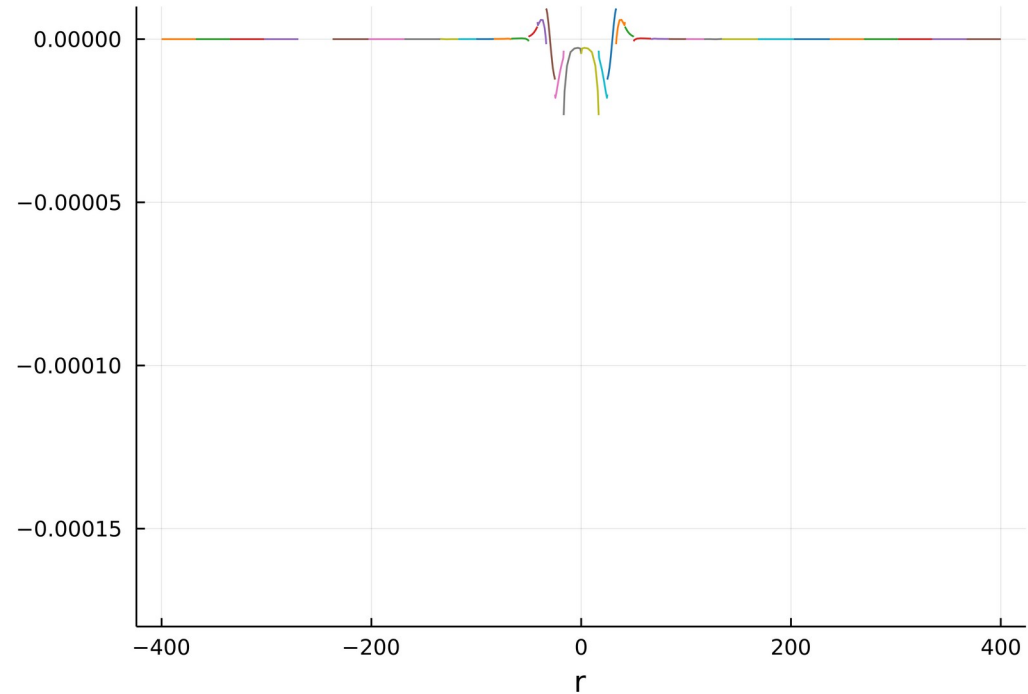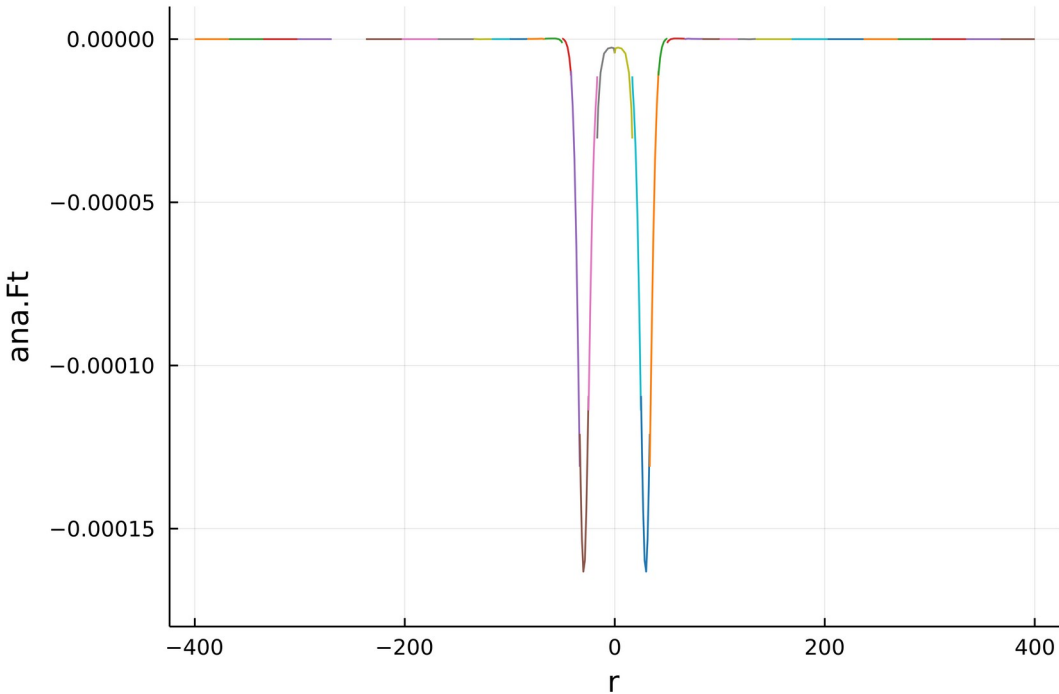- We obtain family of solutions for $|\phi_0|$ with different $\omega$

Boson star head-on collisions
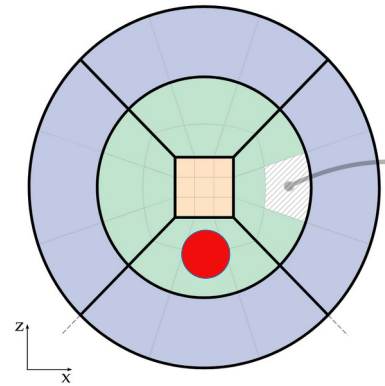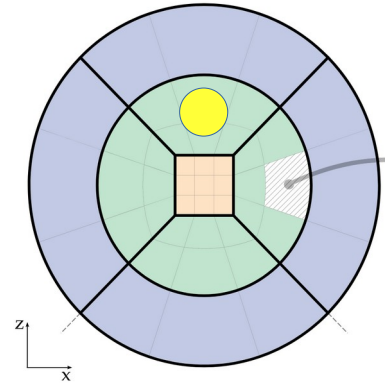Florian Atteneder

# Compactness

# Effects of constraint violations
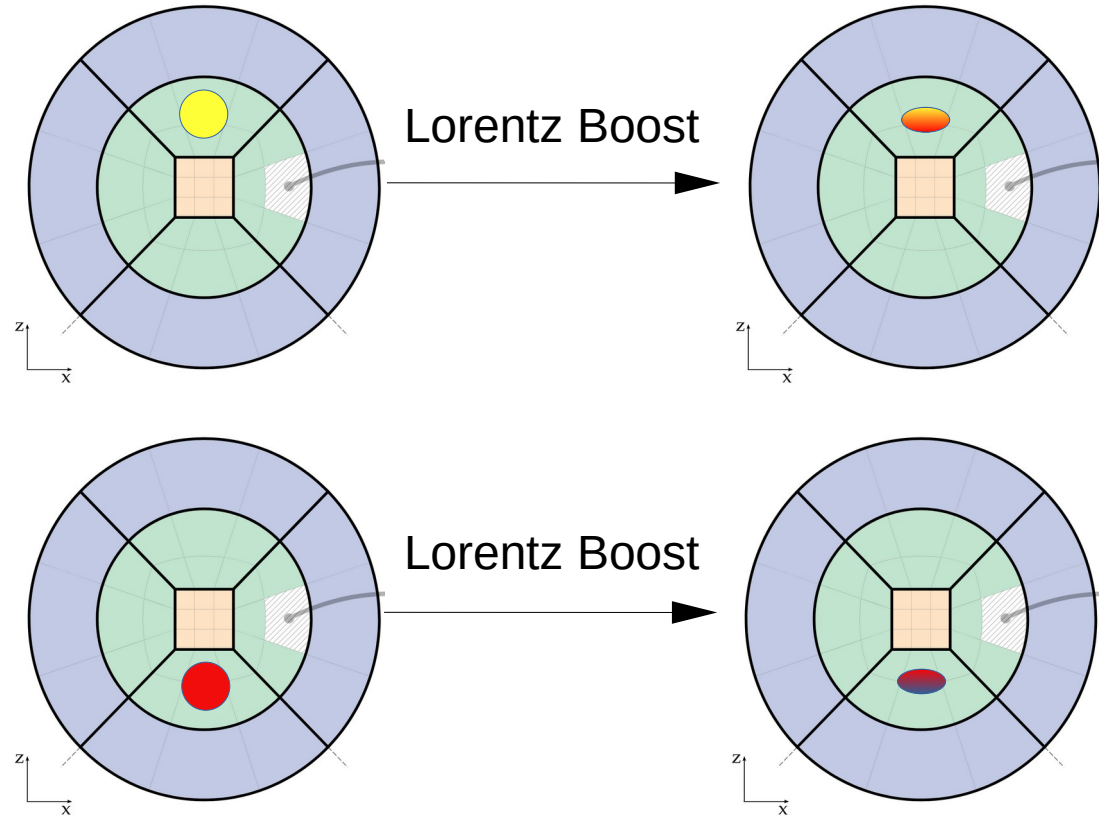
$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \delta_{ij}$$

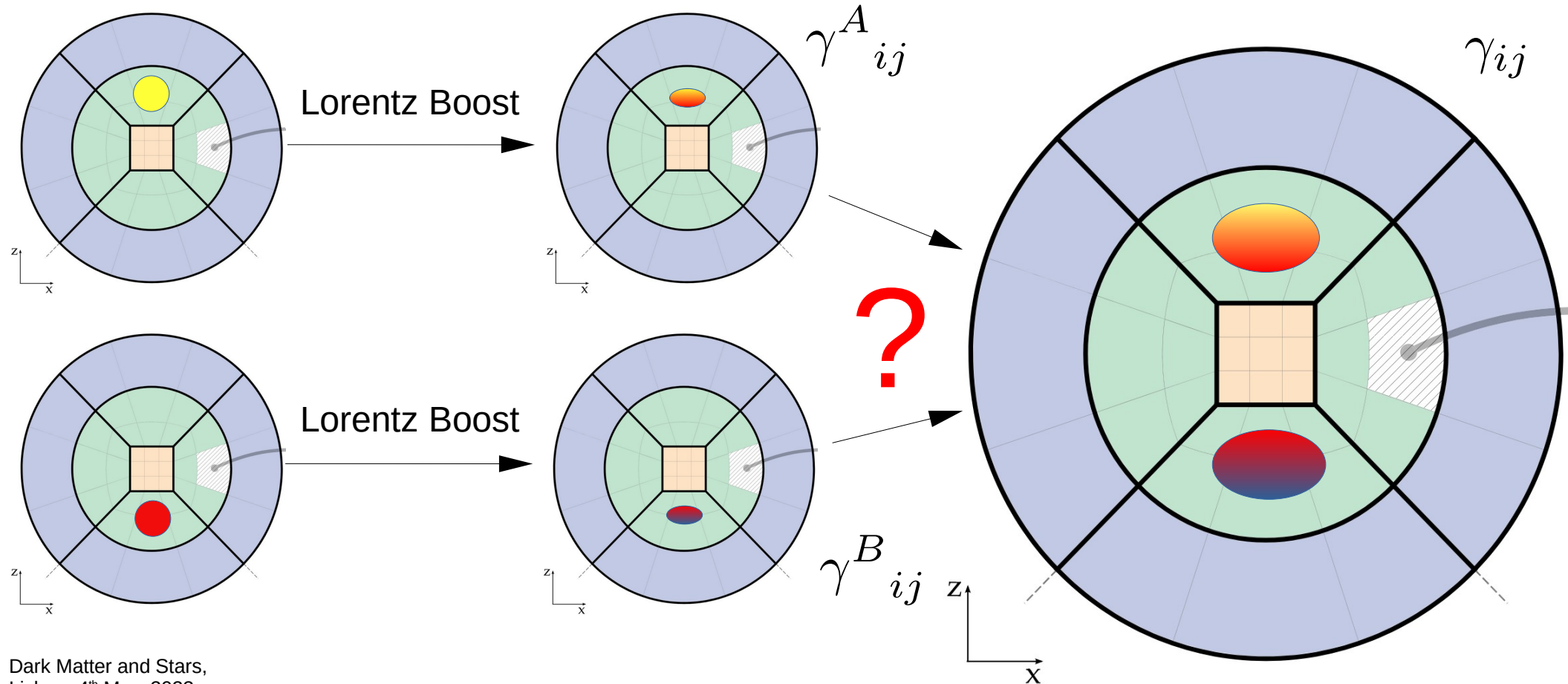$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \gamma_{ij}^A(x^B)$$

# Superposition of isolated stars

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Lorentz Boost

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# Superposition of isolated stars



Lorentz Boost

Lorentz Boost

$\gamma^A_{\ ij}$

$\gamma^B_{\ ij}$

$\gamma_{ij}$

?

Dark Matter and Stars,
Lisbon, 4th May, 2023

# Superposition of isolated stars

(Most of) current literature

"Naive" superposition

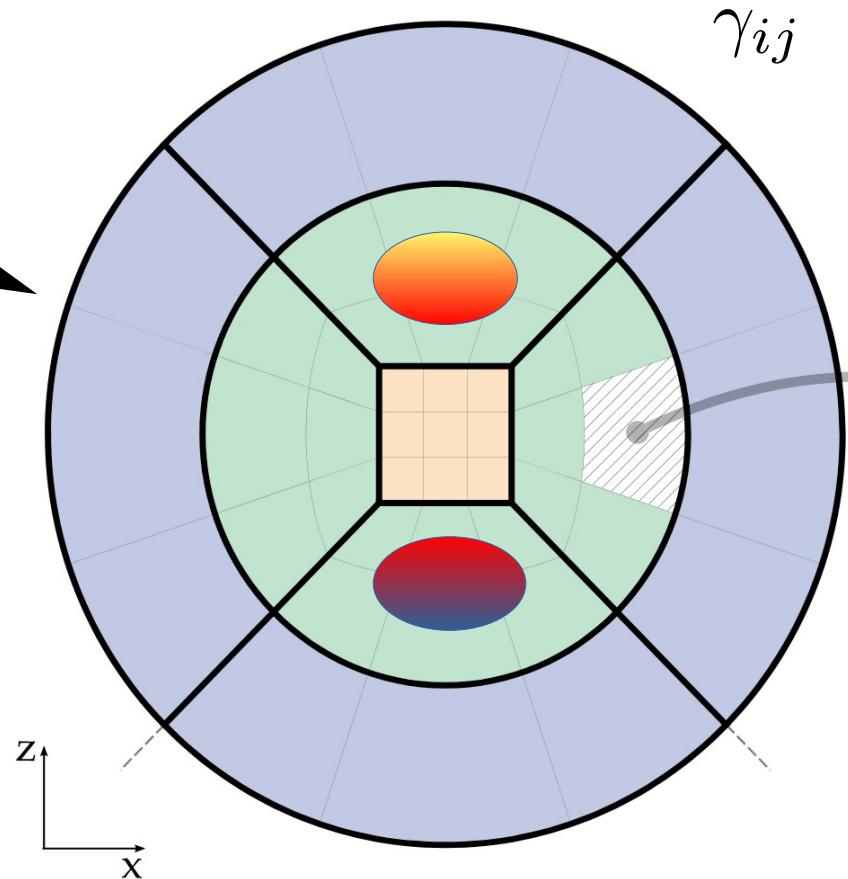$$\gamma_{ij} = \gamma_{ij}^A + \gamma_{ij}^B - \delta_{ij}$$

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Improved superposition

Helfer et al. 2022

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

$\gamma_{ij}$