Binary Neutron Star Simulations: New Tools and Insights

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GW170817: Welcome to the Multi-messenger Era

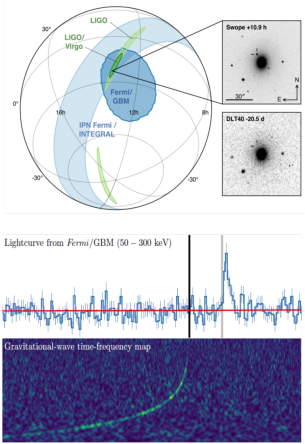
Event

Object: BNS
Total mass: $2.74 M_\odot$
Distance: 40 Mpc
GW Radiation: $0.025 M_\odot$
GW Duration: 100 s
Galaxy: NGC-4993

Science

- short gamma ray burst
- kilonova (optical $\rightarrow$ radio)
- neutrinos (none-found)
- r-process nuclei
- speed of gravity
- EOS constraints
- H_0 constraints

arXiv:1710.05833

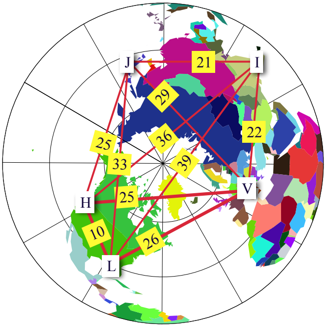


Next-Generation Gravitational Wave Astronomy

Detector network by $\approx$ 2026

- LIGO A+ (Washington State)
- LIGO A+ (Louisiana)
- aVIRGO (Italy)
- GEO-HF (Germany)
- KAGRA (Japan)
- LIGO-India

[Sathyaprakash 2014]



Expected NSNS Detection Rate

More than 10+ NSNS mergers detected per **week**

Numerical Relativity

Detector network by $\approx$ 2026

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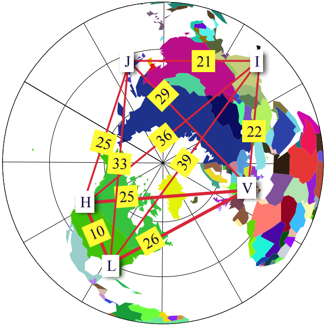

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Solving Non-linear Elliptic Equations

Code Overview

Discontinuous Galerkin: Model Problem

Test Problem 1: Single Non-smooth point

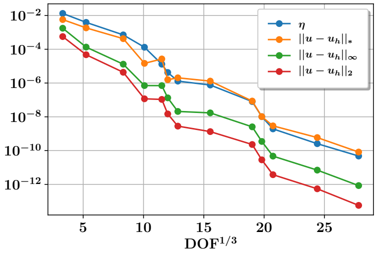
Test Problem Details

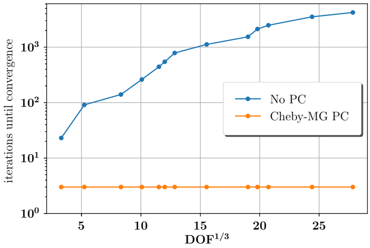
$$\nabla^2 u = f$$

$$\Omega = [0,1]^2$$

$$u = 0 \quad x \in \partial\Omega$$

$$u = x(1-x)y(1-y)\left[\left(x-\frac{1}{2}\right)^2 + \left(y-\frac{1}{2}\right)^2\right]^{3/2}.$$





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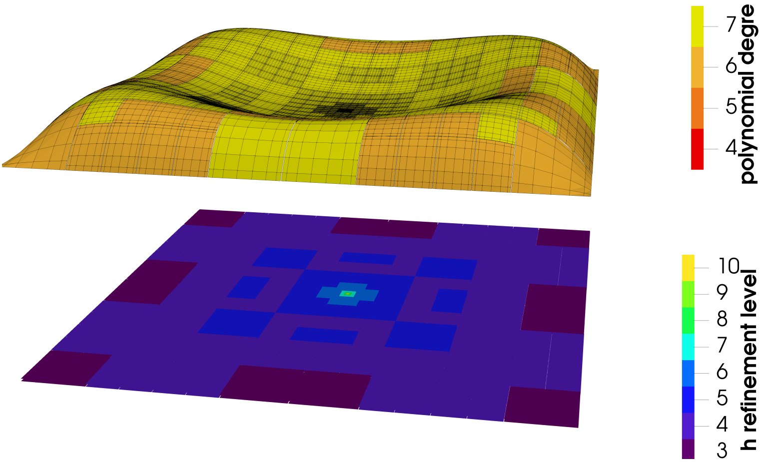
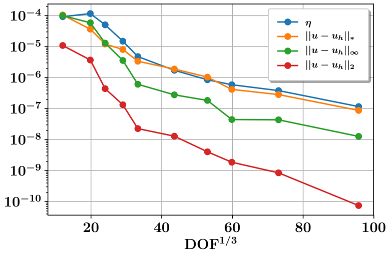


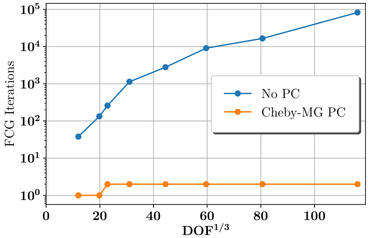
Test Problem 2: Constant Density Star

Test Problem Details

$$\nabla^2\psi + 2\pi\rho\psi^5 = 0$$

$$\rho = \begin{cases} \rho_0 & r \leq r_0 \\ 0 & r > r_0, \end{cases}$$





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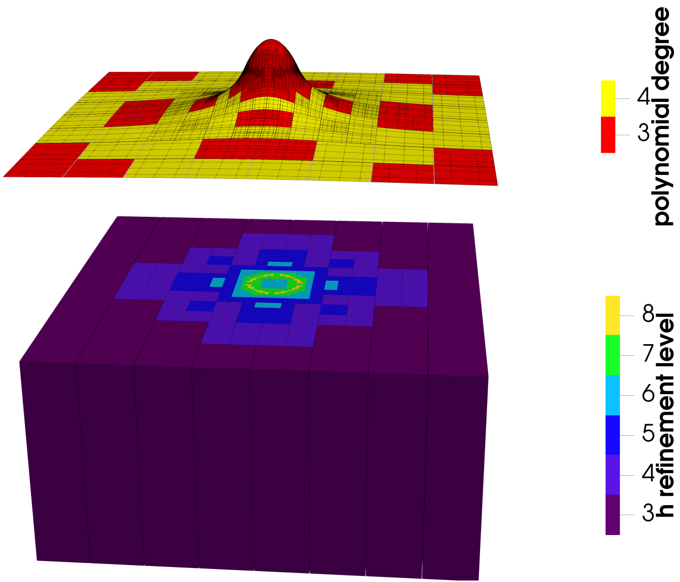


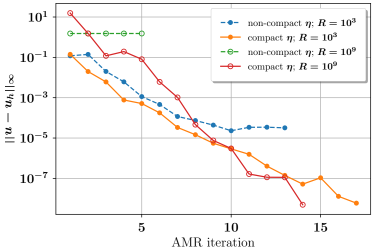
Test Problem 3: Cubed-spheres and Compactified grid

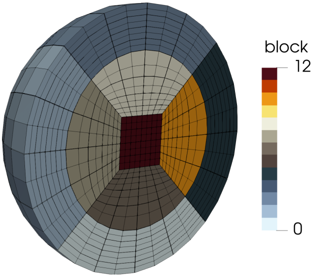
Lorentzian

$$-\nabla^2 u = f$$

$$u =$$

Mesh: Cubed Sphere with $R = 1000$





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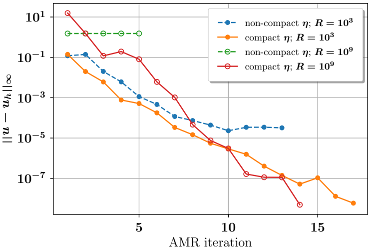
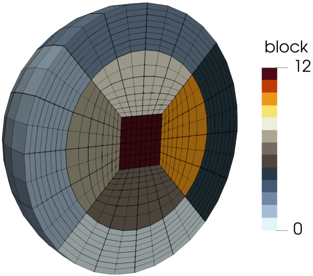




Two Punctures: Old Code vs New Code

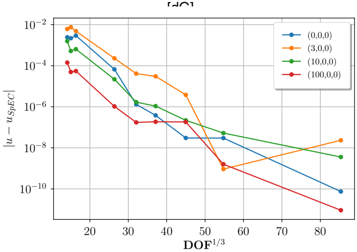
Equal Mass Binary Black Hole Initial Data

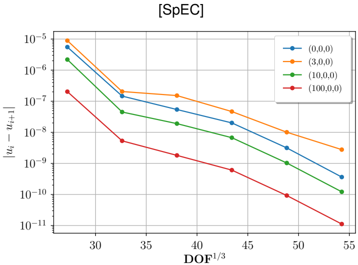
$$-\nabla^2 u = \frac{1}{8}\bar{A}^{ij}\bar{A}_{ij}\psi^{-7}$$

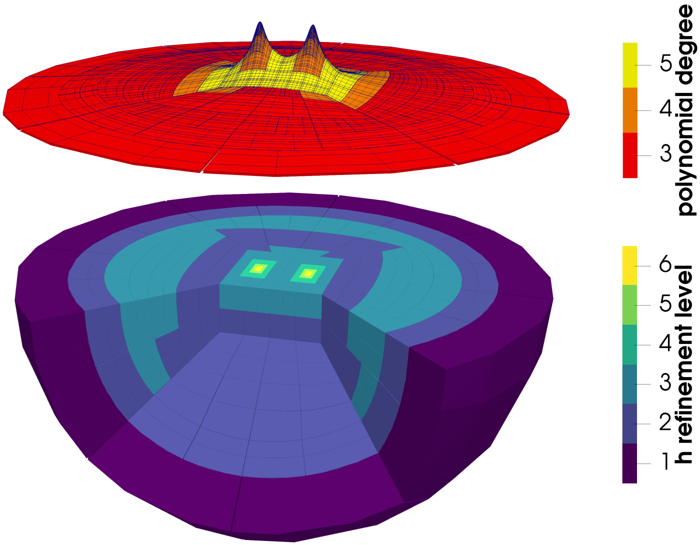
$$u = 0 \quad r = \infty$$

$$\vec{x}_\pm = (\pm 3, 0, 0) \quad \vec{P}_\pm = (0, \pm .2, 0)$$

Mesh: Cubed Sphere with $R = 10^{11}$

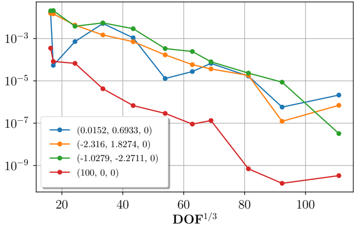


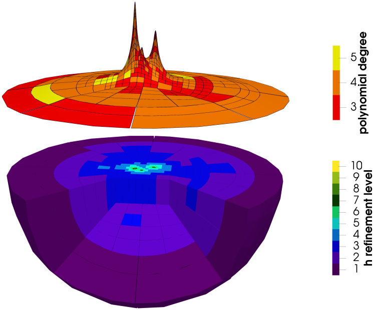


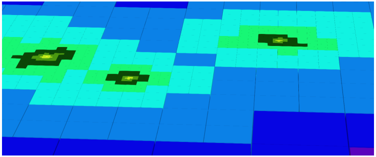

polynomial degree
5
4
3
h refinement level
6
5
4
3
2
1

Random Three Punctures: New Code only

	Puncture 1	Puncture 2	Puncture 3
m	0.2691	0.4063	0.3245
x	0.0152	-2.316	-1.0279
y	-0.6933	1.8274	-2.2711
P_x	0.0585	-0.0284	0.1640
P_y	0.0082	-0.1497	0.0515
S_z	-0.0134	-0.0332	-0.0708







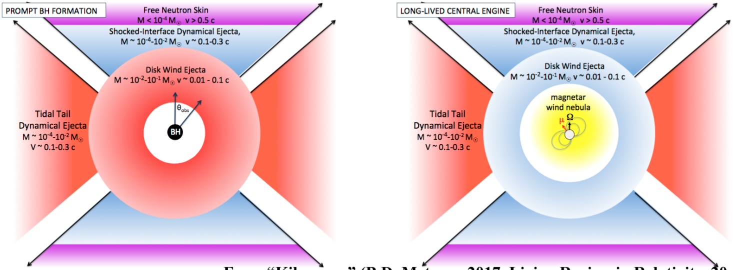
Future work

Unequal Mass Binary Neutron Star Simulations

General Relativistic Radiation-Hydrodynamics

Ejecta Types

“Blue” vs. “Red” Kilonova Emission as a Function of Observer Viewing Angle



From “Kilonovae” (B.D. Metzger, 2017, Living Review in Relativity, 20, 3)

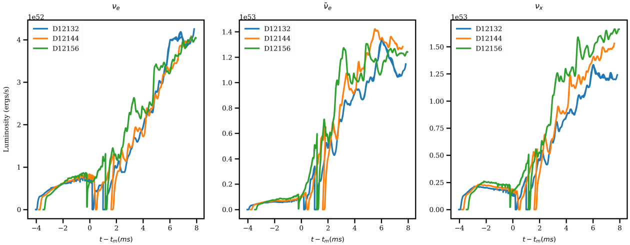
Dynamical Ejecta

Secular Ejecta

Velocity and Electron Fraction

Neutrino Irradiation

Neutrino Emission



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