Binary Neutron Star Simulations: New Tools and Insights

Trevor Vincent

Committee

Prof. Harald Pfeiffer
Prof. Charles Dyer
Prof. Amar Vutha
Prof. John Sipe (convener)

PhD Internal Defense

Physics Department

University of Toronto

June 26, 2019

GW170817: Welcome to the Multi-messenger Era

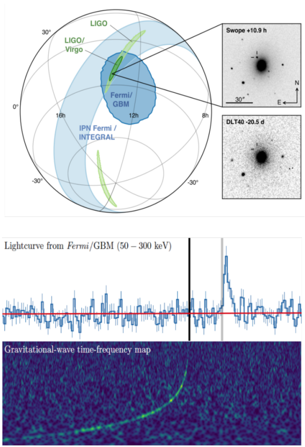
Event

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 $\to$ radio)
- neutrinos (none-found)
- r-process nuclei
- speed of gravity
- EOS constraints
- H_0 constraints

arXiv:1710.05833

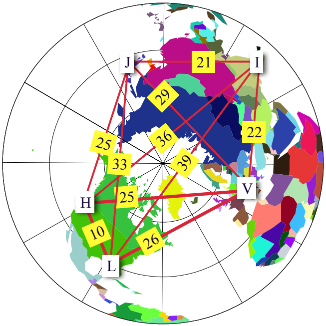


Next-Generation Gravitational Wave Astronomy

Detector network by $\approx$ 2026

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

[Sathyaprakash 2014]



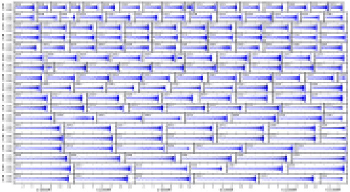
Expected NSNS Detection Rate

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

Numerical Relativity

- Numerical relativity is critical for the LIGO search pipeline and parameter estimation. LIGO uses SpEC for BBH.
- The Spectral Einstein Code (SpEC;black-holes.org) is a multi-domain spectral code for solving the Einstein field equations written primarily by Larry Kidder, Harald Pfeiffer and Mark Sheel.
- SpEC is now developed at 9 different universities which compose the SXS collaboration. The SXS collaboration just released a catalog of 2018 waveforms.

SXS
Simulating eXtreme Spacetimes



[arXiv:1904.04831]

Numerical Relativity: Two Problems

Problem 1

- Currently no code can handle multi-scales/microphysics required for all realistic simulations (10cm for MRI, 1-2000km for GW).
- Current Spectral codes have problems with discontinuities in EOS phase transitions.
- Supercomputers are becoming exascale in 2020 and SpEC doesn't scale very well.

Chapter 1

Develop a new code using new more powerful numerical techniques for problems in numerical realtivity.

Problem 2

- The gravitational network will be detecting 1-10 BNS per week.
- No large catalogs of BNS simulations with realistic microphysics to maximize science.

Chapter 2

Add to the ongoing effort by running and analyzing a set of BNS simulations with some of the most realistic microphysics available.

Chapter 1: Next generation Numerical Relativity

SpECTRE: A Task-based Discontinuous Galerkin Code for Relativistic Astrophysics

Lawrence E. Kidder[a], Scott E. Field[a,b], Francois Foucart[c], Erik Schnetter[d,e,f], Saul A. Teukolsky[a], Andy Bohn[a], Nils Deppe[a], Peter Diener[f,g], François Hébert[a], Jonas Lippuner[h], Jonah Miller[e,d], Christian D. Ott[h], Mark A. Scheel[h], Trevor Vincent[i,j]

[arXiv:1609.00098]

Science Goals

- GR-Radiation-MHD
- Realistic EOS
- BNS and Supernova

Computational Goals

- discontinuous Galerkin.
- Exascale.
- Open Source.

I was tasked with developing the elliptic solver for this code.

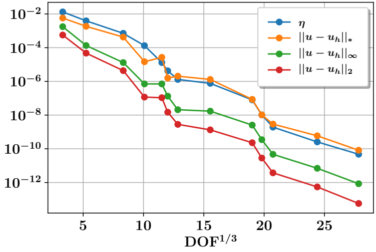
A new code for elliptic problems in NR

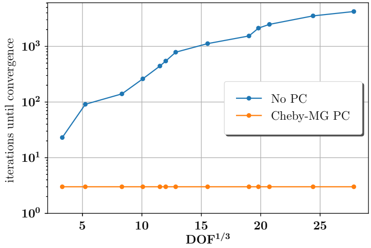
Location: github.com/trevor-vincent/d4est
Lines of C code: $\sim 100 - 200{,}000$
Discretization Method: Discontinous Galerkin
Adaptivity: hp-AMR driven by aposteriori estimator
Solver: Multigrid + Additive Schwarz
Scaling: 10k-100k cores currently

Test Problem 1: Single Non-smooth point

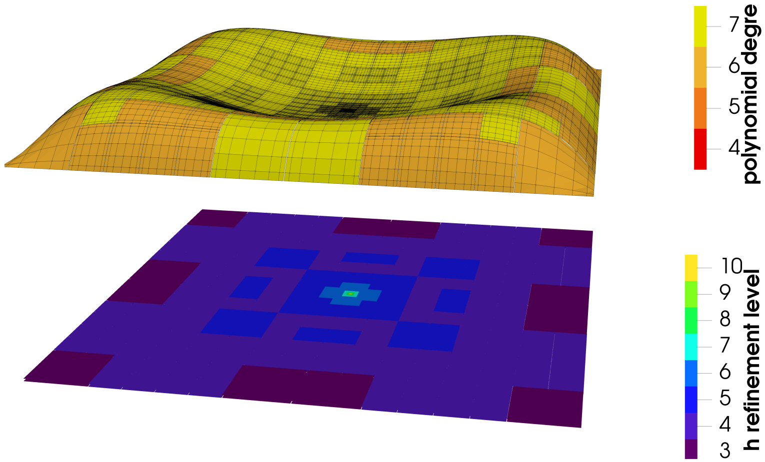
Test Problem Details

$$\nabla^2 u = f$$
$$\Omega = [0,1]^2$$
$$u = 0 \quad x \in \partial\Omega$$
$$u = x(1-x)y(1-y)\left[\left(x-\frac{1}{2}\right)^2 + \left(y-\frac{1}{2}\right)^2\right]^{3/2}.$$





Test Problem 1: Single Non-smooth point

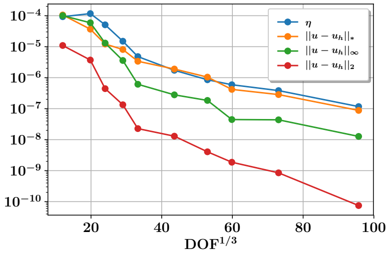


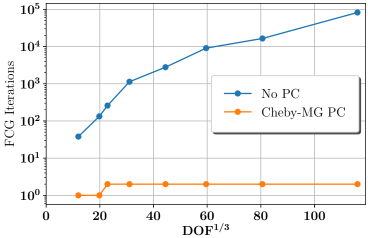
Test Problem 2: Constant Density Star

Test Problem Details

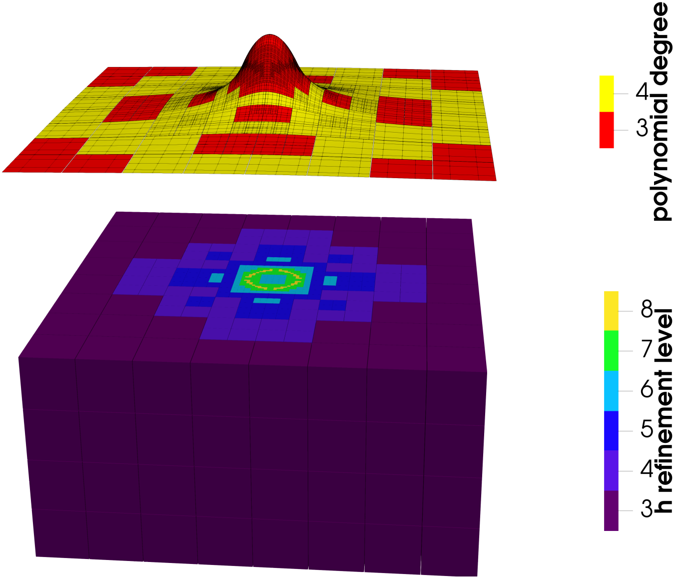
$$\nabla^2 \psi + 2\pi\rho\psi^5 = 0$$

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





Test Problem 2: Constant Density Star



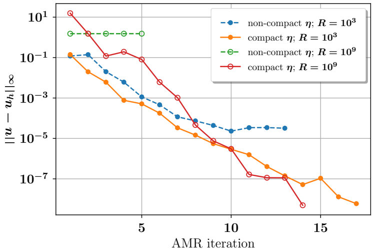
Test Problem 3: Cubed-spheres and Compactified grid

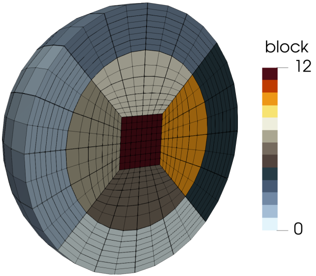
Lorentzian

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

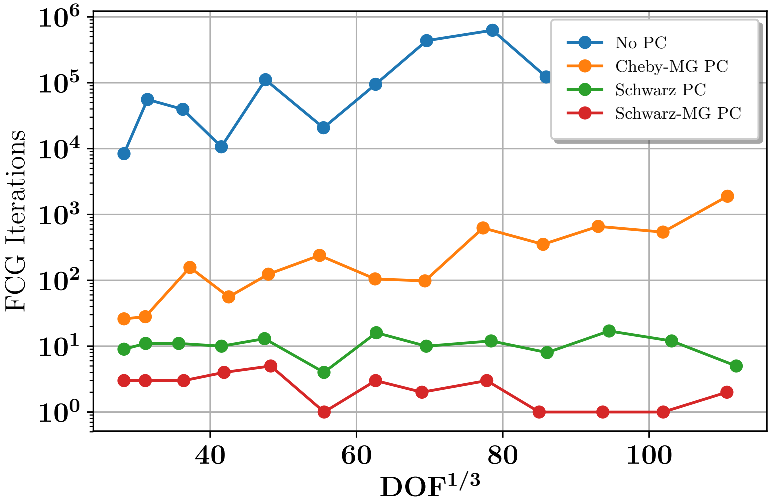
$$u = (1 + r^2)^{-1/2}$$

Mesh: Cubed Sphere with $R = 1000, 10^9$





Test Problem 3: Cubed-spheres and Compactified grid



Two Punctures: Old Code vs New Code

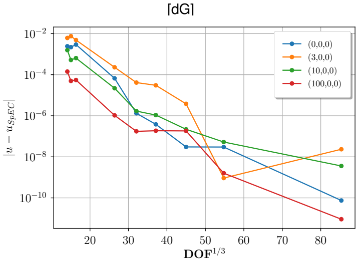
Equal Mass Binary Black Hole Initial Data

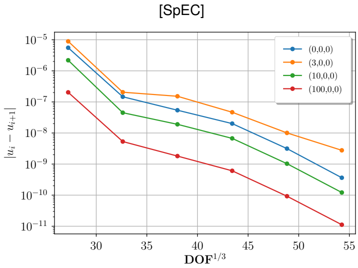
$$-\nabla^2 u = \frac{1}{8}\bar{A}^{ij}\bar{A}_{ij}\psi(u)^{-7}$$

$$u = 0 \qquad r = \infty$$

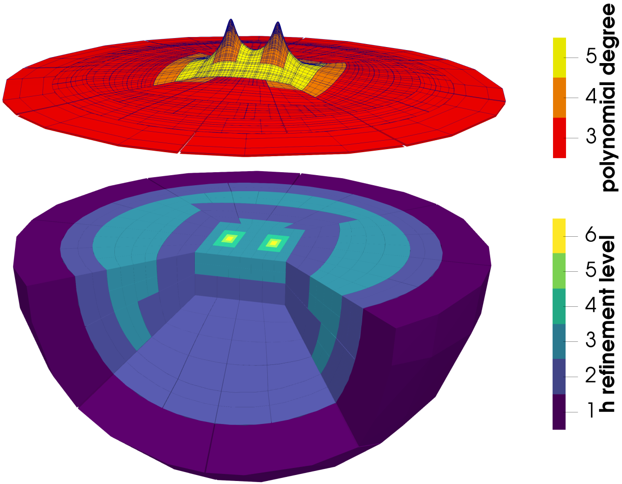
$$\vec{x}_{\pm} = (\pm 3, 0, 0) \qquad \vec{P}_{\pm} = (0, \pm .2, 0)$$

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



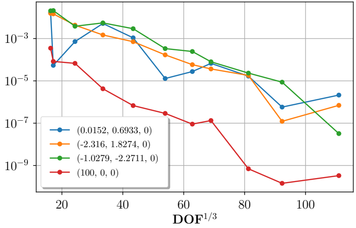


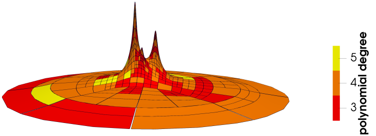
Two Punctures: Old Code vs New Code

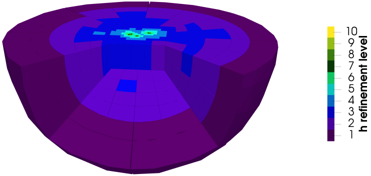


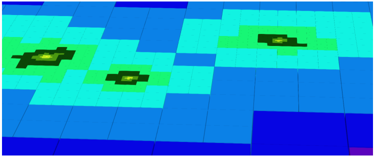
Random Three Punctures: New Code only

	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









Conclusions and Future work

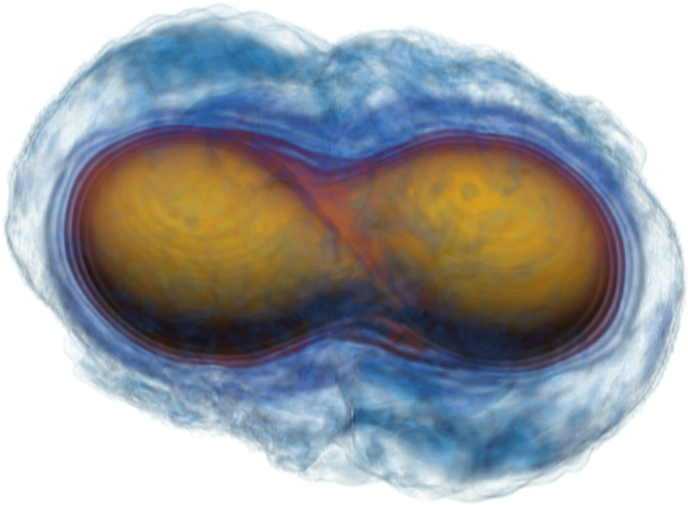
Conclusions:

- First dG code for elliptic problems in NR
- First dG scheme for curved, stretched nonconforming grids
- First demonstration of a Multigrid + Schwarz solver with dG on non-trivial grids
- dG appears to show excellent promise

Future work:

- Main paper detailing scheme/results uploaded to arXiv this week
- port into the task based parallel SpECTRe code - currently being done at the Albert Einstein Institute by Nils Fischer.
- Binary Neutron Star initial data

Chapter 2: Unequal Mass BNS w/ Neutrino Transport

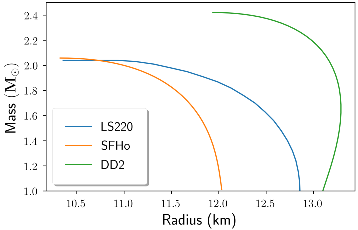


Merging DD2 $1.44M_{\odot} + 1.44M_{\odot}$ binary

Chapter 2: Unequal Mass BNS + Neutrino Transport

12 new simulations...

Model	EOS	M_1	M_2	q	C_1	C_2	$d_0(km)$	Collapse?
D144144	DD2	1.44	1.44	1.0	.161	.161	48.7	No
D12132	DD2	1.2	1.32	.91	.134	.147	48.7	No
D12144	DD2	1.2	1.44	.83	.134	.161	48.7	No
D12156	DD2	1.2	1.56	.77	.134	.173	48.7	No
L144144	LS220	1.44	1.44	1.0	.175	.175	44.3	$(\sim 2ms)$
L12132	LS220	1.2	1.32	.91	.146	.161	44.3	No
L12144	LS220	1.2	1.44	.83	.146	.175	44.1	No
L12156	LS220	1.2	1.56	.77	.146	.191	44.3	$(\sim 4.5ms)$
S144144	SFHO	1.44	1.44	1.0	.179	.179	44.3	$(\sim .5ms)$
S12132	SFHO	1.2	1.32	.91	.148	.163	44.3	No
S12144	SFHO	1.2	1.44	.83	.148	.179	44.3	No
S12156	SFHO	1.2	1.56	.77	.148	.195	44.3	$(\sim 1.4ms)$



Goal

Determine trends between source parameters and matter and neutrino emission.

Numerical Implementation

Using the SpEC Code, we solve:

Initial Data

$$\tilde{\nabla}^2\psi = \dots$$
$$\tilde{\nabla}^2(\bar{\alpha}\psi) = \dots$$
$$\mathcal{N}(\beta^i) = \dots$$
$$\mathcal{N}(\phi) = \dots$$

Fluid Evolution

$$\partial_t\rho_* = \dots$$
$$\partial_t\tau = \dots$$
$$\partial_t S_i = \dots$$
$$\partial_t\rho_* Y_e = \dots$$
$$P = EOS(\rho_0, Y_e, T)$$

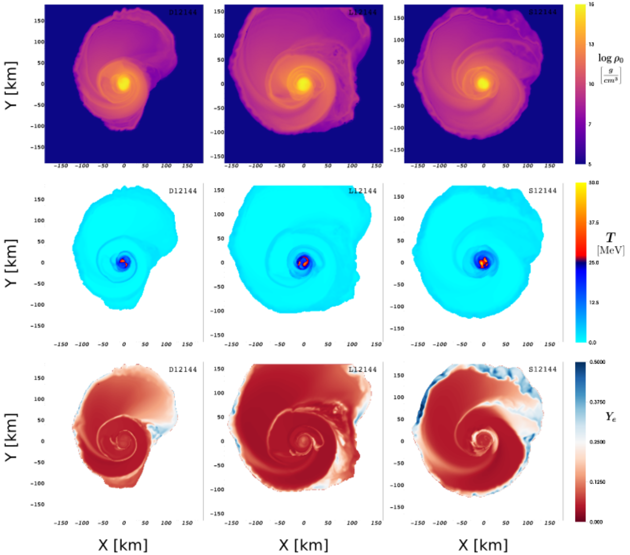
Spacetime Evolution

$$\partial_t g_{\alpha\beta} = \dots$$
$$\partial_t\Pi_{\alpha\beta} = \dots$$
$$\partial_t\Phi_{i\alpha\beta} = \dots$$
$$H_\alpha = \dots$$

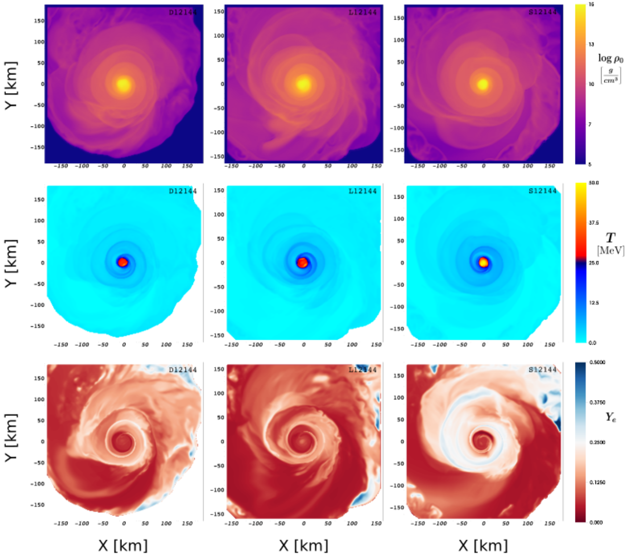
Neutrino Transport

$$\partial_t\sqrt{\gamma}E = \dots$$
$$\partial_t\sqrt{\gamma}F_i = \dots$$
$$\partial_t\sqrt{\gamma}N = \dots$$

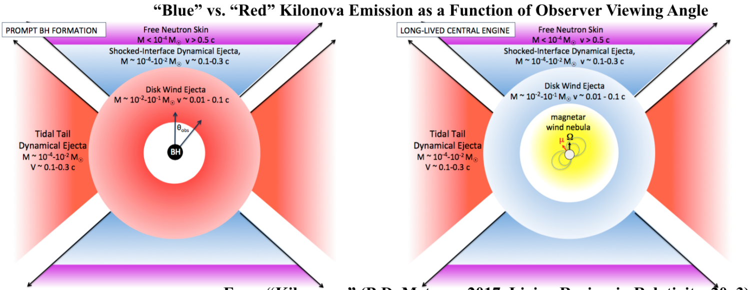
General Overview: 3ms



General Overview: 7.5ms



Ejecta Types



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

Soft EOS: More shock ejecta

Stiff EOS: More tidal tail ejecta

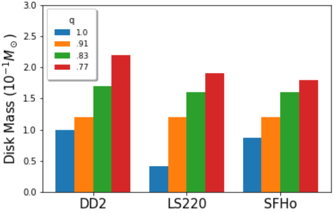
Dynamical Ejecta

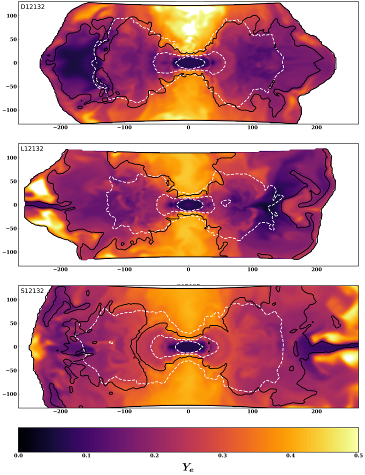
	Polar ($\theta < 30^\circ$)			Equatorial ($\theta > 30^\circ$)			Total		
model	$M_{ej}(10^{-2}M_\odot)$	$\langle Y_e \rangle$	$\langle v_\infty \rangle$	$M_{ej}(10^{-2}M_\odot)$	$\langle Y_e \rangle$	$\langle v_\infty \rangle$	$M_{ej}(10^{-2}M_\odot)$	$\langle Y_e \rangle$	$\langle v_\infty \rangle$
D12132	0.054	0.392	0.392	0.406	0.186	0.258	0.460	0.210	0.273
D12144	0.016	0.309	0.327	0.319	0.157	0.198	0.335	0.164	0.204
D12156	0.010	0.342	0.365	0.463	0.179	0.161	0.473	0.182	0.165
D144144	0.036	0.351	0.385	0.324	0.201	0.254	0.360	0.216	0.267
L12132	0.011	0.331	0.377	0.083	0.188	0.204	0.094	0.205	0.224
L12144	0.026	0.292	0.345	0.357	0.186	0.185	0.384	0.194	0.196
L12156	0.004	0.302	0.336	0.230	0.190	0.131	0.234	0.192	0.135
L144144	0.000	0.344	0.362	0.012	0.213	0.255	0.012	0.217	0.258
S12132	0.114	0.358	0.346	1.461	0.214	0.221	1.574	0.224	0.230
S12144	0.061	0.317	0.319	0.778	0.197	0.212	0.839	0.206	0.220
S12156	0.097	0.297	0.301	1.704	0.198	0.175	1.802	0.204	0.181
S144144	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

SFHo has the most ejecta
Collapse runs produce no ejecta
Ejecta is equatorial mostly

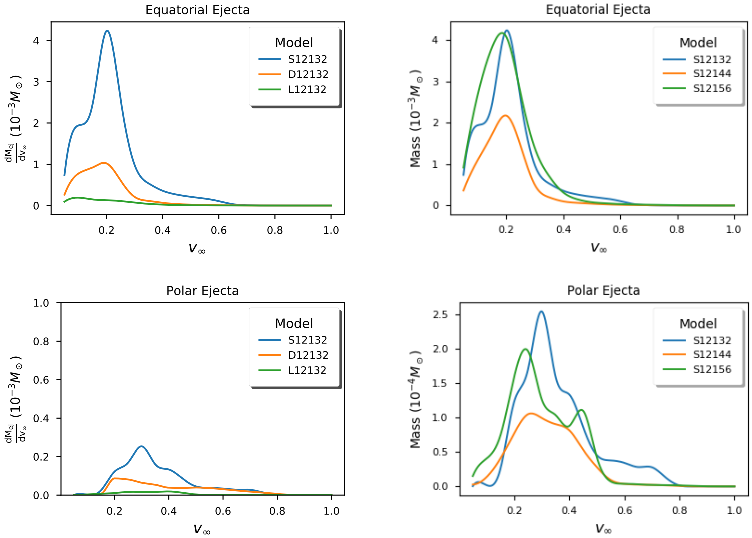
Secular Ejecta

- GW170817 $M_{ej} \sim 0.05 M_{\odot}$
- 40% of disk mass can get ejected [arXiv:1808.00461]

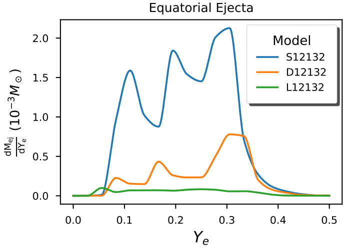


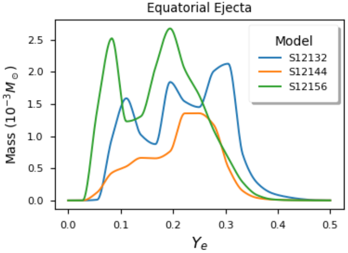


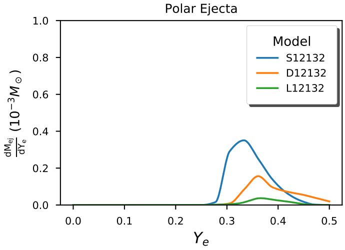
Velocity Distribution

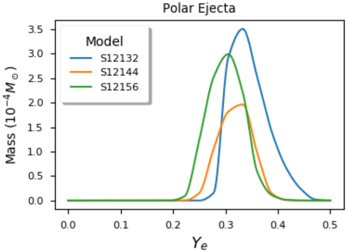


Y_e Distribution



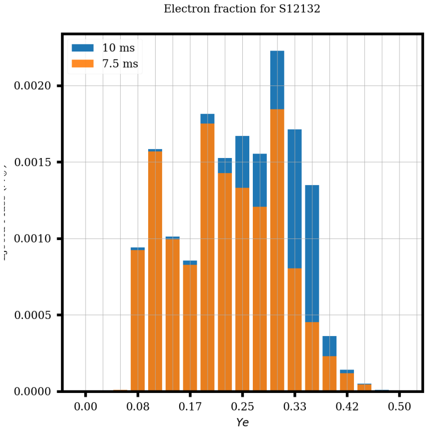






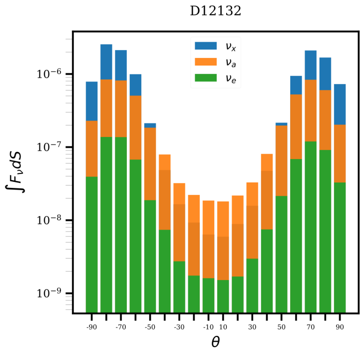
Y_e distributions shift over time

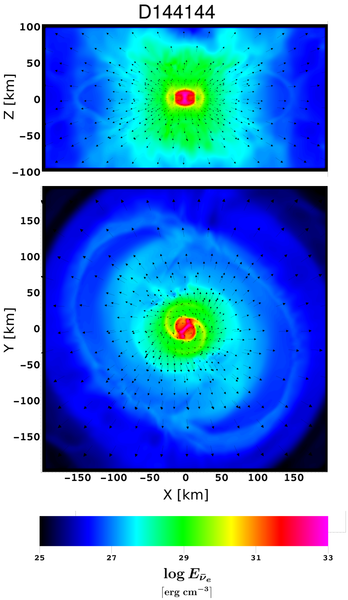
Neutrinos deposit net lepton number into the ejecta



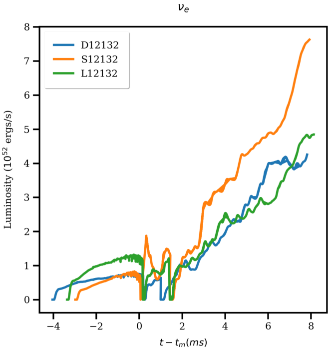
Neutrino Emission

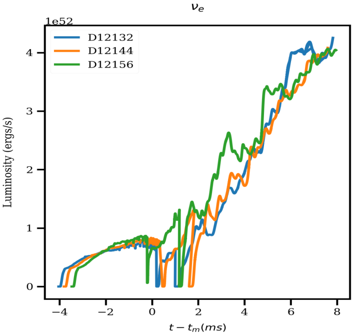
Largest concentration of neutrinos in polar regions, tail and disk.





Neutrino Emission





SFHo has largest luminosity
No Dependence on mass-ratio

Conclusions and Future work

Conclusions:

- Collapse models no ejecta, small disk mass
- Softest model has most ejecta $\sim .01 M_{\odot}$
- Broad Y_e distribution, mean 0.2 increasing over time
- Broad v_{∞} distribution, mean 0.2-0.3c decreasing with binary asymmetry
- Disk masses increase with binary-asymmetry and stiffness
- Neutrino emission dominated by SFHO, no dependence of emission/morphology on mass-ratio.

Future work:

- A subset already published in one paper [arXiv:1808.03836]
- Main paper outlining Chap. 2 results is being prepared for Phys. Rev D.
- Continue collapse runs, Tracers
- MHD/Spins/Different EOS/Neutrino improvements