New 2D/3D CHIMERA Simulations of Core Collapse Supernovae

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IPMU - Focus Week on Messengers of Supernova Explosions, November 17-21
Core Collapse Supernova Energetics

- Photons $\sim 10^{49}$ ergs
- Ejecta Kinetic energy $\sim 10^{50} - 10^{52}$ ergs
- Neutrinos $\sim 3 \times 10^{53}$ ergs
Core Collapse Supernova Asymmetries

Polarization
- Core collapse SN are polarized at ~1% level
- Degree of polarization increases with decreasing envelope mass
- Degree of polarization generally increases after optical maximum

- Outward mixing of Ni in SN1987A & Cas A
- Axisymmetric ejecta of SN1987A
- Early Emission of x-rays and gamma-rays from SN1987A
The Core Collapse Supernova Mechanism: A Computational Challenge

- Inherently multi-dimensional
- Variety of complex physical processes that need to be accurately modeled
- Extremely nonlinear with many feedbacks
- Explosions are marginal
Core-Collapse Supernova Mechanisms

Magnetic Field Mechanism
- Shibata Liu, Shapiro, & Stephens, Phys. Rev. D 74, 104026 (2D MHD, High res)

Acoustic Mechanism

Neutrino Transport Mechanism
- Bruenn, Dirk, Mezzacappa, Hayes, Blondin, Hix, Messer, SciDAC 2006 (2D ray-by-ray plus)
Magnetic Field Mechanism

- Taps free energy of differential rotation
  
  \[ T_{\text{rot}} = 4 \left( \frac{\kappa J}{0.3} \right) \left( \frac{M}{1.4 M_\odot} \right) \left( \frac{R}{10 \text{ km}} \right)^2 \left( \frac{P_{\text{rot}}}{2 \text{ ms}} \right)^{-2} \ B \quad 1 \ B = 10^{51} \text{ ergs} \]

- Predicted rotational rates of newly formed neutron stars
  
  3 - 15 ms (Heger, Woosley & Spruit, 2005)

- Extrapolated periods of newly formed pulsars
  
  - Crab: 21 ms
  - PSR J0537-6910 10 ms
  - PSR B0540-69 39 ms
  - PSR B1509-58 20 ms

- Problem: Need rapid rotation (not observed or predicted)
Anisotropic accretion onto inner core over time excites core g-modes

Core eigenmodes (mainly $L = 1$) grow to large amplitudes and radiate sound

Sound pulses steepen into shocks and deposit energy and momentum in the shocked mantle powering an explosion

Problem: Occurs late (many hundreds of milliseconds to seconds post bounce), and only one group has seen it
The Neutrino Transport Mechanism

\[ \nu_e + n \rightarrow p + e^- \\
\nu_e + p \rightarrow n + e^+ \]

Matter Flow

Neutrino flow

Shock

Gain Radius

Cooling

Heating

Protoneutron Star

Spheres
Current State-of-the-Art Neutrino Transport Supernova Modeling

**1D**
- Fully GR
- Boltzmann neutrino transport
- Sophisticated weak interaction physics

**2D**
- Ray-by-Ray-Plus Neutrino Transport
  - Post-Newtonian spherical gravity with Newtonian nonspherical components
  - MGFLD or variable Eddington neutrino transport
  - Sophisticated weak interaction physics
- Fully 2D MGFLD, SN Neutrino Transport
  - Newtonian gravity
  - In-group weak interaction physics

**3D**
- Hydrodynamic or Magnetohydrodynamic only
- Smooth particle hydro with grey transport
- Ray-by-Ray-Plus (as 2D above)
CHIMERA Code
1D, 2D, and 3D

Hydrodynamics
Nuclear Reactions
Equation of State
Gravity Solver
Neutrino Transport
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Hydrodynamics

- Lagrangian PPM with Remap implementation of a Godunov scheme
- Newtonian spectral Poisson solver with effective GR radial potential
- Spherical polar grid
- Moving radial grid option during infall, sliding adaptive below shock after shock generation
Nuclear Network

- $^4\text{He}$, $^{12}\text{C}$, $^{16}\text{O}$, $^{20}\text{Ne}$, $^{24}\text{Mg}$, $^{28}\text{Si}$, $^{32}\text{S}$, $^{36}\text{Ar}$, $^{40}\text{Ca}$, $^{44}\text{Ti}$, $^{48}\text{Cr}$, $^{52}\text{Fe}$, $^{56}\text{Ni}$, $^{60}\text{Zn}$

- n, p, Fe-like tracers

- Advection of material into and out of NSE

- Flashing and freeze-out of zones
Neutrino Transport

- Multigroup, flux-limited diffusion tuned to Boltzmann transport
- Ray-by-ray plus approximation
- Full flavor implicit solve
- All $O(v/c)$ velocity corrections, red shift and time dilation effects included
Neutrino Interactions

Emission and Absorption of $\nu_e$'s
$$e^- + p, A(Z, N) \rightleftharpoons \nu_e + p, A(Z - 1, N + 1)$$

Emission and Absorption of $\bar{\nu}_e$'s
$$e^+ + n, A(Z, N) \rightleftharpoons \bar{\nu}_e + p, A(Z + 1, N - 1)$$

Neutrino-Electron, Neutrino-Positron Scattering
$$\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau} + e^-, e^+ \rightleftharpoons \nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau} + e^-, e^+$$

Neutrino Scattering on Nucleons and Nuclei
$$\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau} + n, p, A \rightleftharpoons \nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau} + n, p, A$$

Electron-Positron Pair Annihilation
$$e^- + e^+ \rightleftharpoons \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$

Nucleon-Nucleon Bremsstrahlung
$$N + N \rightleftharpoons N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$

Neutrino-Neutrino Scattering
$$\nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} \rightleftharpoons \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$
CHIMERA vs Agile-Boltztran
Supernova Connections

Nucleosynthesis

Neutrino Signatures

Supernovae

Neutron Stars

Black Holes

Gravitational Waves
4000 - 8000 Lagrangian tracer particles in each model (Lee & Hix)

- Records thermodynamic state and spectral neutrino history along its trajectory
- Each tracer particle can be post-processed by a full nuclear network
Progenitor Series

- A suite of progenitor masses (12, 15, 20, and 25 M☉) (Woosley and Heger, 2007 PhR) (ongoing)
- Progenitors of given mass evolved with different equations of state (planned)
- Progenitors of given mass evolved by different groups (planned)
- Progenitors of given mass with different
Progenitor Structure

Progenitor $\rho$ vs enclosed mass

Density [g cm$^{-3}$]

Enclosed Mass [M$_{\odot}$]

- Woosley-Heger 12
- Woosley-Heger 15
- Woosley-Heger 20
- Woosley-Heger 25

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2D Model Grid and EOS

- 256 nonuniformly spaced radial zones out to 2000 km
- 256 evenly spaced angular zones from 0 to 180 degrees
- Lattimer-Swesty EOS for NSE; 17 nuclei network coupled for non-NSE; electron-positron-photon EOS everywhere
- 4 neutrino flavors, 20 energy zones from 4 to 400 MEV for each flavor
Lagrangian and Shock Trajectories

Mean Nuclear Mass Number

Radius (km)

Elapsed Time (sec)

Ni, p

Si

Ne, Mg

He

Ni

n, p

<2

2–5

5–18

18–28

28–40

>40
Explosion Energy vs Grid Resolution

Explosion Energy vs Time from Bounce

- **Woosley-Heger 15 256x256**
- **Woosley-Heger 15 512x256**

**Time from Bounce [s]**

**Explosion Energy [10^{51} ergs]**

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Explosion Energy vs Initial MS Mass

Explosion Energy vs Time from Bounce

- Blue: Woosley-Heger 12
- Green: Woosley-Heger 15
- Red: Woosley-Heger 20
- Purple: Woosley-Heger 25

Explosion Energy [10^{51} \text{ ergs}]

Time from Bounce [s]
Why Are We Getting Explosions?

- Dimensional Effects:
  - Convection driven by neutrino heating
  - SASI (Standing Accretion Shock Instability)
  - Improved neutrino rates
  - Energy deposition by nuclear reactions
Dimensional Effects on Shock Propagation

20 M$_\odot$ Woosley-Heger

Shock Radius [km]

Min/Max/Mean Shock Radius 2D

Time from Bounce [s]
15 $M_\odot$ Heger

- Shock Radius 1D
- Min/Mean/Max Shock Radius 2D

Shock Radius [km]

Time from Bounce [s]
Dimensional Effects on Neutrino Luminosities

![Graph showing neutrino luminosity over time from bounce for a 20 M_☉ Woosley-Heger explosion.](image)

- **ν_e**
- **ν_x**
- **ν_e**
- **ν_x**

Time from Bounce [s]

ν Luminosity [10^{51} ergs s^{-1}]

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Dimensional Effects on Neutrino rms Energies

20 M$_\odot$ Woosley-Heger

$\nu\varepsilon_{\text{rms}}$ [MeV]

Time from Bounce [s]

$\nu_e$, $\bar{\nu}_e$, $\nu_x$, $\bar{\nu}_x$

1D, 2D
15 M☉ Woosley-Heger

\[ \nu_\text{rms} [\text{MeV}] \]

\[ \nu_\text{e} \]

\[ \nu_\text{x} \]

\[ \nu_\text{x} \]

1D

2D

Time from Bounce [s]
Role of the SASI

Mode

15 $M_\odot$ Woosley-Heger

SASI Mode Power

Time from bounce [s]
Neutrinospheres

Heating

Cooling

Protoneutron Star

$\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$, $\bar{\nu}_\tau$, $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$, $\bar{\nu}_\tau$
1D Supernova Simulations

![Graph showing the rate of energy deposition as a function of density, labeled as S11.2, 63 ms post bounce. The graph includes various processes such as electron-positron scattering, electron capture, and bremsstrahlung.](image-url)
\( \nu\text{-}p \text{ Process} \)

- Inclusion of neutrino interactions during nucleosynthesis opens up a new chain of nuclear reactions
  - Fröhlich, Martínez-Pinedo, Liebendörfer, Thielemann, Bravo, Hix, Langake, Zinner, PRL, 96, 142502, 2006

- Neutrino absorption on proton rich material creates residual neutron abundance \( \bar{\nu}_e + p \rightarrow n + e^+ \)

- Neutron captures on proton-rich seeds bypasses the \( ^{64}\text{Ge} \) bottleneck
Example $v$-p Process
3D 15 M\(_0\) Model Simulation

- 304 nonuniformly spaced radial zones out to 2000 km
- 78 evenly spaced angular zones from 0 to 180 degrees
- 156 evenly spaced azimuthal zones from 0 to 360 degrees
- 4 neutrino flavors, 20 energy zones from 4 to 400 MEV for each flavor
- Requires 11,552 processors
Comparison of Shock Trajectories

15 M\(_{\odot}\) Heger

- Shock Radius 1D
- Min/Mean/Max Shock Radius 2D
- Min/Mean/Max Shock Radius 3D

Shock Radius [km]

Time from Bounce [s]
2D simulations with spectral neutrino transport exhibit explosions for each of the Woosley-Heger 12, 15, 20, & 25 solar mass models. 3D simulation in progress.

The explosion energy may be directly correlated with the mass of the progenitor.

However, comparisons of the 2D simulations with other groups have yet to show a convergence of results.
Investigate the observables of the exploding models---nucleosynthesis, neutrino and gravitational wave signatures, neutron star masses and kick velocities

- Use a singularity-free grid
- Incorporate magnetic fields
The End

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