Predicting the Gravitational Wave Signatures of Core Collapse Supernovae: The Road Ahead

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What will it take?
- 3D, General Relativistic, Radiation Magnetohydrodynamics
- State of the Art Nuclear and Weak Interaction Physics
  - Neutrino Transport
  - Hydrodynamics
    - Instabilities (Convection, Neutron Fingers)
    - Rotation
  - Magnetic Fields
  - Strong Gravitational Field

We will not have THE waveforms any time soon.
- Only meaningful thing to discuss are steps toward this end.

Zwerger-Mueller-Dimmelmeier Catalogue
- How much can we capture with parameterized models?
- Not everything is parameterizable.

Next Steps:
- Investigate more thoroughly the limits of the ZMD catalogue.
- Increase model complexity.
Supernova Sources of Gravitational Waves

- Nonspherical Collapse
  - Inhomogeneities
  - Rotation
  - Magnetic Fields

- Instabilities
  - Bar Mode
  - Proto-Neutron Star Instabilities
    - Convection
    - Neutron Fingers
  - Neutrino-Driven Convection
  - Instability of Accretion Shock

- Anisotropic Neutrino Emission
Supernova Simulation Timeline

Year 1: 1D Models
Year 2: 2D Models
Year 3: 3D Models
Year 4: 2D Models
Year 5: 1D Models
Inner core mass determined by:
⇒ Neutrino Transport (Macrophysics)
⇒ Electron Capture (Microphysics)
Langanke and Martinez-Pinedo, NPA 673, 481 (2000)

**FFN:** Gamow-Teller strength at single parameterized energy.
Reality: GT strength distributed over many levels.

Electron capture rates can be orders of magnitude off.

+ Replace mean nucleus with ensemble.
Mean nucleus is fine for thermodynamics, but not weak interactions.
Near onset of collapse...

Near neutrino trapping...

Lack of Coverage
- Parameterized Models
- Hybrid Nuclear Model (RPA-like Computation; Langanke)

Hix (2002)
Inner core mass reduced as capture rate on nuclei increased.
Change explosion to dud?
⇒ Affect all postbounce GW predictions.

Parameterized Models.

Messer et al. (2002)
1D:

- Fully general relativistic.
- Boltzmann neutrino transport.
- Ensemble of nuclei.
- State of the art electron capture rates.

Inner core mass determined.

2D:

- We will have the machinery.
- Limited by precollapse models.

*There are no 2D precollapse models.*

- Work with Heger-Langer-Woosley models for now.

- Do bar modes exist (threshold $T/|W|$ reached)?
Ledoux Criterion *sans* Transport Effects:

\[
\left( \frac{\partial \rho}{\partial \ln Y_l} \right)_{s,P} \left( \frac{\partial \ln Y_l}{\partial r} \right) + \left( \frac{\partial \rho}{\partial \ln s} \right)_{Y_l,P} \left( \frac{\partial \ln s}{\partial r} \right) > 0
\]

*Negative entropy and lepton fraction gradients are destabilizing.*
Equations Governing Motion of Fluid Element:

\[
\dot{\theta}_s = \Sigma_s \theta_s - \Sigma_{Y_l} \theta_{Y_l} - \frac{d\tilde{s}}{dz} \theta
\]

\[
\dot{\theta}_{Y_l} = Y_s \theta_s - Y_{Y_l} \theta_{Y_l} - \frac{d\tilde{Y}_l}{dz} \theta
\]

\[
\ddot{\rho} = -g \left( \frac{\partial \rho}{\partial s} \right)_{p,Y_l} \theta_s - g \left( \frac{\partial \rho}{\partial Y_l} \right) \theta_{Y_l}
\]

Solutions:

\[
Ae^{\alpha_1 t} + Be^{\alpha_2 t} + Ce^{\alpha_3 t}
\]

\[
Ae^{\alpha_1 t} + Be^{(\alpha_2 + i\beta) t} + Ce^{(\alpha_2 - i\beta) t}
\]

\[
\alpha_i = f(s, Y_l, \alpha_s, \alpha_{Y_l}, \Sigma_s, Y_{Y_l}, \frac{d\tilde{s}}{dz}, \frac{d\tilde{Y}_l}{dz})
\]

Bruenn and Dineva (1996)

\[\text{N.B. Wilson does not “get” neutron fingers when Lattimer-Swesty EoS is used.}\]
Mezzacappa et al. (1998a)


⇒ New 2D models will shed light here.
⇒ Need state of the art neutrino opacities consistent with EoS!
The simulations concentrating on the convective processes inside the proto-neutron star have been performed neglecting effects due to neutrinos entirely...the convective velocities seen in our simulations are so high that convective mixing is probably faster than neutrino diffusion.

Neutrino transport sets the scale of the gain region, where neutrino-driven convection occurs.

Mezzacappa et al. (1998b)

- More difficult to assess.
- Depends on explosion/failure.
- New 2D models a step forward.

Neutrino transport sets the scale of the gain region, where neutrino-driven convection occurs.
Accretion Shock *Stability*: A New Twist?

Blondin, Mezzacappa, DeMarino (2002)
Accretion Shock Instability

- Independent of initial perturbation.
  - Independent of unknown inhomogeneities in precollapse models.
- Present in 2D/3D.
- Similar outcomes: \( l=1,2 \) modes dominate.
- Axisymmetry broken!

- What will happen when rotation is added?
- What will happen when neutrino cooling is added?
  - Seems to be present in parameterized 2D explosion models reported in Janka and Mueller (1996).
  - Inadequate gridding in other 2D simulations to see it.
Instability delayed for:
- softer equations of state (mimic cooling),
- decreased postshock volume.

SAS Instability
Help initiate explosion?
Occur after explosion initiated?
Not at all?
Bruenn, DeNisco, and Mezzacappa (2001)
Things that can be done now:

- Better assess strengths/weaknesses of ZMD catalogue.
- Consider 3D parameterized models with rotation and convection.
- Compute GW emissions from 2D/3D SAS instability.

In the next few months, 1D models will assess the impact of improved weak interaction physics on inner core size/collapse and bounce physics.

- Relevant for supernova mechanism.
- Relevant for gravitational wave emission.

2D Models (Newtonian)

“Better” determine GW emission from:

- PNS Convection
- Neutrino Driven Convection
- Axisymmetric Core Collapse (limited by precollapse models)

2D MHD Polytropic Collapse
3D Models (Newtonian)
  Begin 1 year from now.
  Increasing realism relative to 2D simulations.
  Assess existence of f-modes (limited by precollapse models).

GR?
  Conformally Flat Approach (Short-ish Term)
  Coupled Einstein Equations (Long Term)

B Fields?
  All in good time.

Not-So-Ordinary Supernovae? (the “H” word)
SN1998bw: 30 FOE, 0.5 Solar Masses of Nickel, 40 Solar Mass Progenitor
SN2002ap: 4-10 FOE, 0.07 Solar Masses of Nickel, 20-25 Solar Mass Progenitor
  Modeling challenges.
  Continuum of possibilities from “ordinary” supernovae to hypernovae?

Hypernovae: Broad spectral features, high ejecta velocities.
  Very energetic Type Ic supernovae.
  Collapsars? (Macfadyen and Woosley 1999)
  “Ordinary” Type Ic Models vs. Collapsar Models