TOWARD COMPUTING THE GRAVITATIONAL WAVE SIGNATURES OF CORE COLLAPSE SUPERNOVAE

with Konstantin Yakunin (FAU), Pedro Marronetti (FAU), and the ORNL-FAU-NCSU CHIMERA team
• Core Bounce: Requires realistic (3D) GR electron-neutrino transport.
  1D: Liebendoerfer et al. 2001. PRD 63, 103004.

• PNS Instabilities: Require realistic 3D GR multiflavor neutrino transport.
  1. Prompt convection.
  2. PNS convection.

• Neutrino-Driven Convection and SASI: Require realistic 3D explosion models.
Simulation Building Blocks

- "RbR-Plus" MGFLD Neutrino Transport
  - $O(\nu/c)$, GR time dilation and redshift, GR aberration (in flux limiter)

- 2D PPM Hydrodynamics
  - GR time dilation, effective gravitational potential, adaptive radial grid

- 2D Effective (GR) Gravitational Potential

- Nuclear (Alpha) Network
  - 14 alpha nuclei between helium and zinc

- Lattimer-Swesty EOS
  - 180 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)

- Neutrino Emissivities/Opacities
  - "Standard" + Elastic Scattering on Nucleons
    + Nucleon–Nucleon Bremsstrahlung

“Ray-by-Ray-Plus” Approximation

- Solve set of 1D transport problems.
- Ignore differences in lateral fluxes.
- Include lateral advection in trapped region.


CHIMERA
Shock begins to move outward dramatically owing to the development of the SASI.

Explosion energy becomes positive at ~350 ms after bounce.

Continues to grow as SASI funnels feed stellar matter to deeper layers.
2D MODELS: GRAVITATIONAL WAVE SIGNATURES

Yakunin et al. 2010, Class. Quant. Grav. 27, 194005
• Bounce
• Prompt Convection
• Early Shock Deceleration

• Lower-Frequency Envelope: SASI-Induced Shock Excursions
• Higher-Frequency Variations: Impingement of Downflows on PNS from Neutrino-Driven Convection and SASI (+ PNS Convection).

• Rise: Prolate Explosion
ANATOMY OF A GRAVITATIONAL WAVE SIGNAL

Gravitational Wave Signal (S15 LS EoS 256x256)

A\(_{20}\) (cm)

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<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
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<th>70</th>
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</tbody>
</table>

Shock Deceleration

Prompt Convection

Explosion
Neutrino-Driven Convection
Post-Shock SASI Flows

PNS Convection/SASI-Induced PNS Flows

Yakunin et al. 2010, *Class. Quant. Grav.* 27, 194005
2D MODELS: GRAVITATIONAL WAVE ENERGY EMMITED

\[ E_{GW} \times 10^{-8} M_{\odot} c^2 \]

\[ \text{time from bounce (ms)} \]

Yakunin et al. 2010, *Class. Quant. Grav.* 27, 194005
Prediction from parameterized model.

Yakunin et al. 2010, Class. Quant. Grav. 27, 194005
What can we expect from 3D?

Blondin, Mezzacappa, and DeMarino 2003 *ApJ* 584, 971

Blondin and Mezzacappa 2007 *Nature* 445, 58
Simulation Building Blocks

- **“RbR-Plus” MGFLD Neutrino Transport**
  - O(v/c), GR time dilation and redshift, GR aberration (in flux limiter)

- **3D PPM Hydrodynamics**
  - GR time dilation, effective gravitational potential, adaptive radial grid

- **3D Effective Gravitational Potential**

- **Nuclear (Alpha) Network**
  - 14 alpha nuclei between helium and zinc

- **Lattimer-Swesty EOS**
  - 220 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)

- **Neutrino Emissivities/Opacities**
  - “Standard” + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung

Resolution

512 X 128 X 256

⇒ 32,768 processors

~ 2000 hours

~ 65 M processor-hours
Gravitational wave signatures, including the explosion phase, for a range of stellar progenitors have been computed \textit{in non-parameterized models}.

A more complete gravitational wave “template” has emerged from this work.

The models predict signatures that should be detectable by Advanced LIGO for a Galactic event.

Fundamental limitation of the work reported here: The imposition of axisymmetry – i.e., it’s 2D.

$\ast$ \textit{3D simulations are ongoing}.

Other model improvements completed or underway:

- Replacement of GR approximation with BSSN.
- Replacement of RbR approximation with full GR transport.
These are exciting times for core collapse supernova modeling and their GW emission detection:

- We are rapidly approaching the point where more realistic predictions of gravitational wave emissions from core collapse supernovae are possible.
- There is an emerging consensus from the ORNL-FAU-NCSU and MPA teams:

  Both teams demonstrate neutrino-driven explosions over a range of stellar progenitors.

  *A significant step forward in supernova theory, and one with important ramifications for gravitational wave prediction.*

- Several of our ongoing 3D models will likely be completed before Advanced LIGO is operative.
- ~10 simulations within a few years is possible.
Multi-institution, multi-investigator, multi-disciplinary effort.

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Applied Math/CS Collaborators
- Closures, Solvers: Hauck, D’Azevedo
- Data Management: Klasky and collaborators
- Networking: Beck, Rao, and collaborators
- Visualization: Ahern, Ma, Meredith, Pugmire, Toedte
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