Gravitational Waves from Supernova Core Collapse

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The Last Decade and Future Directions
Gravitational Waves from Supernova Core Collapse

Motivation

What happens in a Supernova Explosion?

Physical model of a core collapse supernova:

- Massive progenitor star \((M_{\text{progenitor}} \approx 10 - 30 M_\odot)\) develops core of iron group nuclei.
- When core exceeds Chandrasekhar mass \((M_{\text{core}} \approx 1.5 M_\odot)\), it collapses \((T_{\text{collapse}} \approx 100 \text{ ms})\).
- At supernuclear density, EoS of matter stiffens ⇒ bounce, hot proto-neutron star forms.

→ Gravitational waves from core bounce.

- Hydrodynamic shock propagates outward, stalls at \(R_{\text{stall}} \approx 300 \text{ km}\).
- Proto-neutron star cools and shrinks, energy is released by neutrino emission \((T_\nu \approx 1 \text{ s})\).
- Neutrinos deposit energy behind stalled shock and revive it (delayed explosion mechanism).

→ Gravitational waves from neutrino boiling and reheating.

- Shock propagates through stellar envelope, disrupts rest of star (visible explosion).
- Neutron star may develop triaxial instabilities.

→ Gravitational waves from rotating/oscillating neutron star.
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Motivation

Why are Gravitational Waves from Supernovae so interesting?

Conventional means of observing supernovae:

- **Optical light** emission:
  Hours after actual collapse; emitted from stellar surface; no direct information about collapse engine.

- **Neutrinos** from core bounce:
  Directly from engine region; flux decays like $1/r^2$; extremely low detectability (for SN 1987A: only $\sim 10$ neutrinos detected).

Gravitational waves can **directly probe collapse mechanism**!
With $1/r$, fall-off behavior is superior to neutrinos.

**Measurement of signal waveform will reveal new physics!**

Gravitational waves will put **constraints on rotation states** of iron core and neutron star, supernuclear **EoS**, degree of **convection**, ...
Can Convection yield a Detectable Signal?

Convection can develop in:
- boiling proto-neutron star,
- reheated post-shock region,
- outer stellar envelope.

First two mechanisms produce gravitational waves with signal strength comparable to bounce signal (results from Müller and Janka, 1997).
What happens if a Black Hole forms?

For large core mass or soft supernuclear EoS, a black hole can form instantaneously or delayed (due to fall-back of matter).

Gravitational radiation emitted by

- black-hole quasi-normal mode ringing,
- accretion of matter onto black hole, or
- oscillation of matter around black hole (Zanotti et al., 2003).
What Signals can we expect from the Rotating Neutron Star?

Development of triaxial instabilities

- in proto-neutron stars (dynamical and secular), or
- in old neutron stars (r-mode instability, ...)

are another important source of gravitational waves.

Signal amplitudes can be comparable to bounce signals.

These processes yield quasi-periodic signals, which reveal information about supernuclear EoS.

Such simulations can only be done in 3d codes (e.g. Newtonian results by Rampp et al., 1998).
What are the Source Simulation Challenges?

Simulations of core collapse face many challenges:

- Physical complexity:
  
  Many and complicated aspects of physics involved (some physics like supernuclear EoS uncertain). Initial conditions from stellar evolution (like rotation state of iron core) not well known. (Full or approximated) general relativistic gravity needed.

- Numerical difficulties:

  Many different time and length scales (comoving coordinates, FMR, AMR). Multidimensional treatment needed (rotation, convection, magnetic fields, ...).
  Solution of Boltzmann transport equations for consistent treatment of neutrinos.

Numerical simulations are very complicated, many approximations necessary.
What is the Current State of the Art in Relativistic Core Collapse?

Early attempts to simulate relativistic core collapse were hindered by

- computational limitations, and particularly
- numerical problems (nonconservative hydrodynamics, axis problems, instability of ADM equations).

Major breakthroughs in both aspects. New mathematical and numerical formulations:

- HRSC schemes exploiting hyperbolic hydrodynamics.
- Reformulation of ADM equations by Baumgarte, Shapiro, Shibata, and Nakamura (BSSN).
- Various approximation approaches of metric equations.

This has given boost to simulations of supernova core collapse, which utilize very different approaches:

- 2d Cartesian Cartoon method with rotation (Shibata).
- 3d Cartesian with BSSN and HRSC or conventional hydrodynamics (AEI CACTUS/WHISKY code, Shibata, Baumgarte, Shapiro).
- 3d SPH with spherical gravity (Fryer and Heger).
- 3d hydrodynamics with NewtonPlus gravity (Mezzacappa at al.).
- Multidim. hydrodynamics with (modified) Newtonian gravity (Burrows et al., Janka et al.).
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Our Work

What is our Contribution to this?

We have developed a relativistic hydro code for simulating rotational core collapse.


What Simplifications do we make?

To reduce complexity, we assume

- **axisymmetry** and equatorial symmetry,
- **rotating** $\gamma = 4/3$ polytropes in equilibrium as initial models,
  with $\rho_{cini} = 10^{10}$ gm cm$^{-3}$, $R_{\text{core}} \approx 1500$ km, and various rotation profiles and rates,
- **simplified ideal fluid equation of state**, $P(\rho, \epsilon) = P_{\text{poly}} + P_{\text{th}}$ (neglect complicated microphysics),
- **constrained system of Einstein’s equations** (assume conformal flatness for spatial 3-metric – CFC).
Can Relativistic Gravity make the Collapse Dynamics change?

Many Newtonian simulations show multiple core bounces. In relativity, collapse dynamics can change.

- Rotation increases strongly during collapse (angular momentum conservation!).
- Newtonian: Nuclear density hardly reached, multiple centrifugal bounce with re-expansion.
- GR: Nuclear density easily reached, regular single bounce.
- Relativistic simulations show multiple bounces only for few models.

**Strong qualitative** difference in collapse dynamics and thus in signal form.
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What are the Typical Features of a Gravitational Wave Signal?

Most waveform share common features. This is important for filters in data analysis!

Example: Signal from regular core collapse with single bounce.

Goal: Estimate
- robustness of signal, and
- dependence on model parameters.

We present our waveform catalogue at
http://www.mpa-garching.mpg.de/Hydro/RGRAV/.

Our “wave templates” are used in data analysis of VIRGO and GEO.

Conversely, in a detected signal, these features allow for conclusions about physics of core collapse.
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Results

Where in the Sensivity Diagram are our Models located?

Influence of relativistic effects on signals: Investigate amplitude–frequency diagram.

- Spread of models does not change much. $\Rightarrow$ Signal of a galactic supernova detectable.
- On average: Amplitude remains at $h^{TT} \approx 10^{-23} \cdot 10 \text{ Mpc}/R$, frequency doubles to $\nu \approx 1000 \text{ Hz}$.

If close to detection threshold: Signal could leave sensitivity window in relativistic gravity!
What Behavior do Rapidly Rotating Models exhibit?

- Initial model has toroidal density shape; torus becomes more pronounced during contraction.
- Proto-neutron star is surrounded by short-lived accretion disc.
- After bounce, a strongly anisotropic shock front forms.
- Bar instability could develop on dynamical timescale; this will produce a characteristic signal.
What are the Future Directions of this Research Field?

Roadmap for next few years includes:

- Extension of relativistic 2d codes to 3d, including fixed or adaptive mesh refinement.
- Better simulations of black hole formation (extending work of Stark and Piran, and Shibata).
- Inclusion of microphysics/relativistic gravity into relativistic/supernova codes.
- More consistent and realistic rotating initial models.

Increasing detector sensitivity: Consider additional mechanisms for wave generation in core collapse.

Ultimately: Now separate branches of

- numerical relativity (dominated by vacuum solutions), and
- classical astrophysical hydrodynamics (focused on microphysics and explosion mechanism)

will be reunified.
What are the Future Directions of our Work?

Further developments of our axisymmetric code:

- Extract oscillation frequencies of rotating neutron stars (equilibrium and collapse simulations; Font and Stergioulas).
- Include more accurate approximation of spacetime metric (CFC Plus; Cerdá and Font).
- Use spectral methods in Lorene for calculating metric (more accurate and faster; Novak).
- Extend code to 3d, and investigate dynamic development of bar instability.
- Add more realistic microphysics and check robustness of signal.
- Further explore parameter space in response to data analysis requests (Chassande-Mottin).

Ongoing other projects:

- Assess quality of CFC approximation by comparison to fully relativistic simulations.
- Use Cactus code to simulate axisymmetric and fully 3d core collapse (Hawke and Ott).
- Compare our results to new realistic Newtonian simulations.