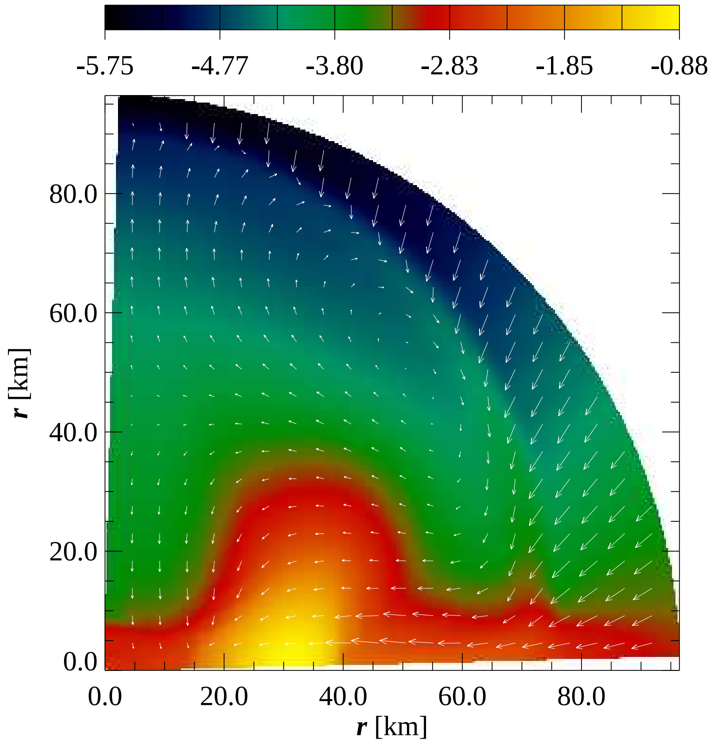




Harald Dimmelmeier


# Gravitational Waves from Supernova Core Collapse:

# Present Status and Future Developments

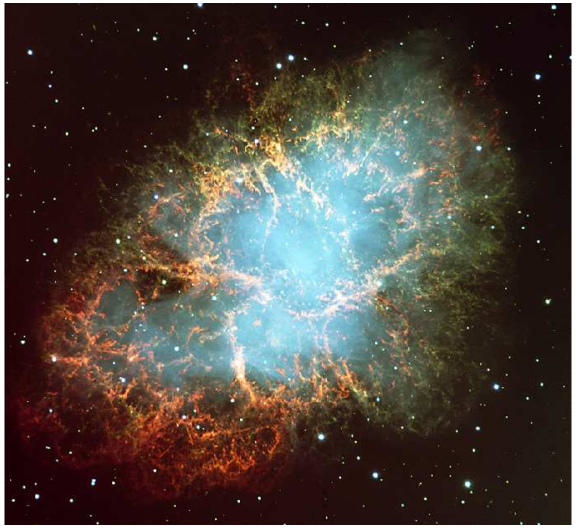
Dimmelmeier, Font, Müller, ***Astrophys. J. Lett.***, **560, L163–L166 (2001), astro-ph/0103088**

Dimmelmeier, Font, Müller, ***Astron. Astrophys.***, **388, 917–935 (2002), astro-ph/0204288**

Dimmelmeier, Font, Müller, ***Astron. Astrophys.***, **393, 523–542 (2002), astro-ph/0204289**

`http://www.mpa-garching.mpg.de/Hydro/RGRAV/`

## Why is GR Crucial for Simulations of Supernova Core Collapse?



Still today:
Split of simulations of core collapse into ones with

- elaborate microphysics in Newtonian gravity, or
- crude microphysics in relativistic gravity.

Strategy:

Unification to 3d simulation with state-of-the-art microphysics in relatistic gravity.

Benefits will include

- consistent treatment of all important physical aspects,
- better modeling of objects with strong gravity (black hole formation, GRBs),
- more natural extraction of gravitational wave signals (beyond quadrupole formula).

## Why are Gravitational Waves from Supernovæ so Interesting?

First step:

Use numerical simulations to obtain templates (essential for detection in interferometers).

After positive detection: Use detected signal to

- infer about uncertain physics
  (put constraints onto rotation rate/profile, supernuclear EoS, degree of convection, influence of magnetic field, . . . ), and
- subsequently refine numerical models.

This will give mutual boost to both observation and theory (just as in conventional astrophysics and astronomy).

How to hide ignorance of various aspects of physics: Parametrize problem!

## What are the Mechanisms for Wave Emission during Core Collapse?

There are various mechanisms for generating gravitational waves in a core collapse:

- Regular Type II supernova core collapse:

  At supernuclear density, EoS of matter stiffens
  $\Rightarrow$ core bounce, hot proto-neutron star forms.

  $\longrightarrow$ Gravitational wave burst from core bounce (our work)

  Neutrinos deposit energy behind stalled shock and revive it (delayed explosion mechanism).

  $\longrightarrow$ Gravitational waves from convection

  Proto-neutron star may develop bar mode instabilities.

  $\longrightarrow$ Gravitational waves from rotating proto-neutron star

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## What are the Mechanisms for Wave Emission during Core Collapse?

There are various mechanisms for generating gravitational waves in a core collapse:

- Core collapse of very massive star, instantaneous or delayed collapse to black hole (GRB model):

  Black hole either immediately forms, or for delayed formation, accretes matter.

  $\longrightarrow$ $\boxed{\text{Gravitational waves from matter accretion and ring down}}$

  Black hole may be surrounded by matter torus.

  $\longrightarrow$ $\boxed{\text{Gravitational waves from oscillations of torus}}$

## What have been Major Recent Developments in Numerical Relativity?

**Early attempts** to simulate **relativistic core collapse** we hindered by

- **computational limitations**, and particularly
- **numerical problems and difficulties**
  (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**
  (hyperbolic formulation, Bona–Masso, BSSN, constrained evolution, Z4).
- Various **approximation approaches of metric** equations.

## What is the Current State of the Art in Relativistic Core Collapse?

These breakthroughs have given boost to simulations of supernova core collapse (particularly in relativistic gravity):

- 2d Cartesian Cartoon method with rotation (Shibata).
- 3d Cartesian with BSSN and HRSC or conventional hydrodynamics (Cactus–Whisky, Shibata, . . . ).
- 2d characteristic light cone approach with simple EoS and without rotation (Siebel et al.).
- 3d SPH with spherical relativistic gravity (Fryer and Heger).
- 2d Newtonian hydrodynamics with tabulated EoS (Ott et al.).
- 2d Newtonian hydrodynamics with sophisticated EoS and neutrino transport (MPA).
- 2d rotational core collapse in relativistic gravity with CFC approximation (Dimmelmeier et al.).

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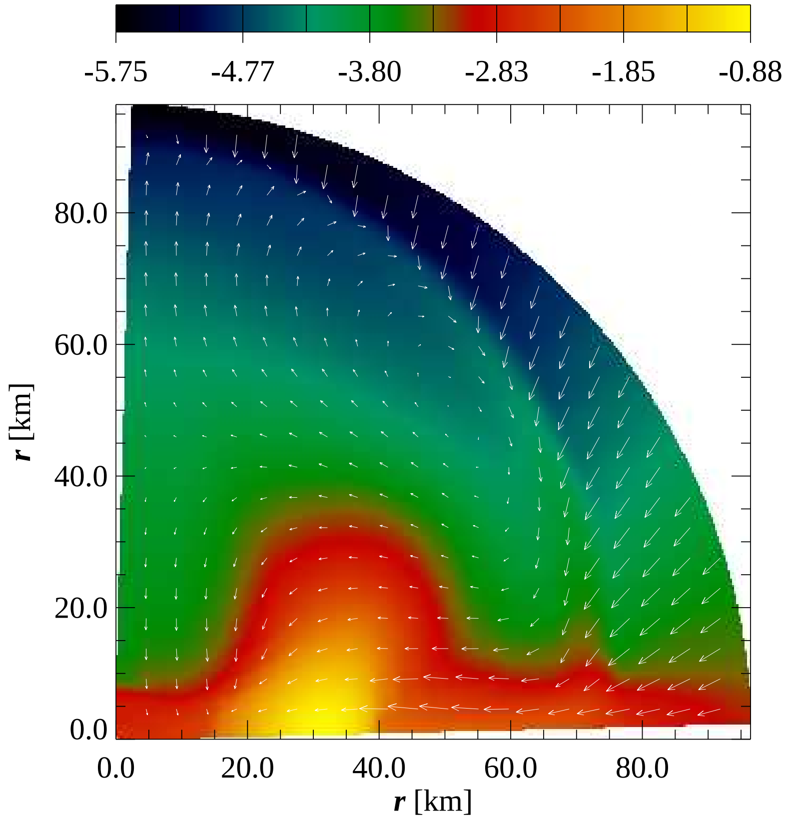
## What is our Contribution to this?

**We have performed relativistic simulations of rotational core collapse in axisymmetry.**

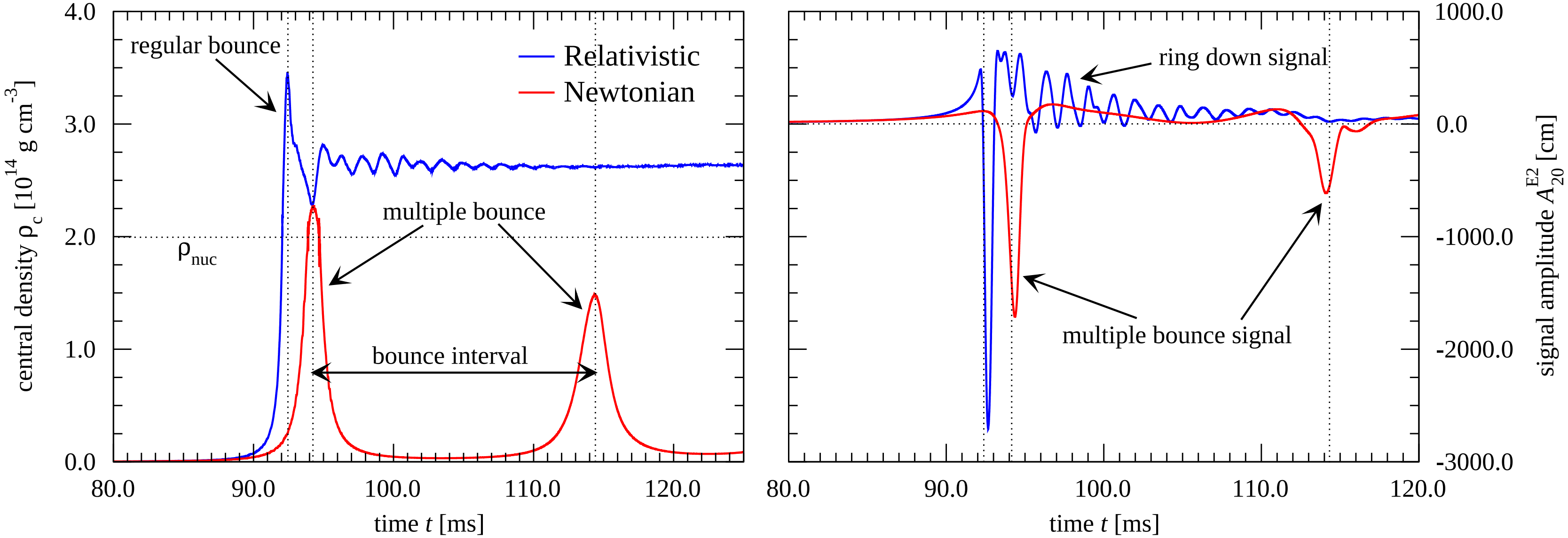



For simplicity, we assume

- rotating $\gamma = 4/3$ polytropes as initial models (various rotation states),
- simplified ideal fluid hybrid equation of state (neglect complicated microphysics),
- constrained system of metric equations (assume conformal flatness for 3-metric),
- quadrupole formula for wave extraction.

## Can Relativistic Gravity make the Collapse Dynamics change?

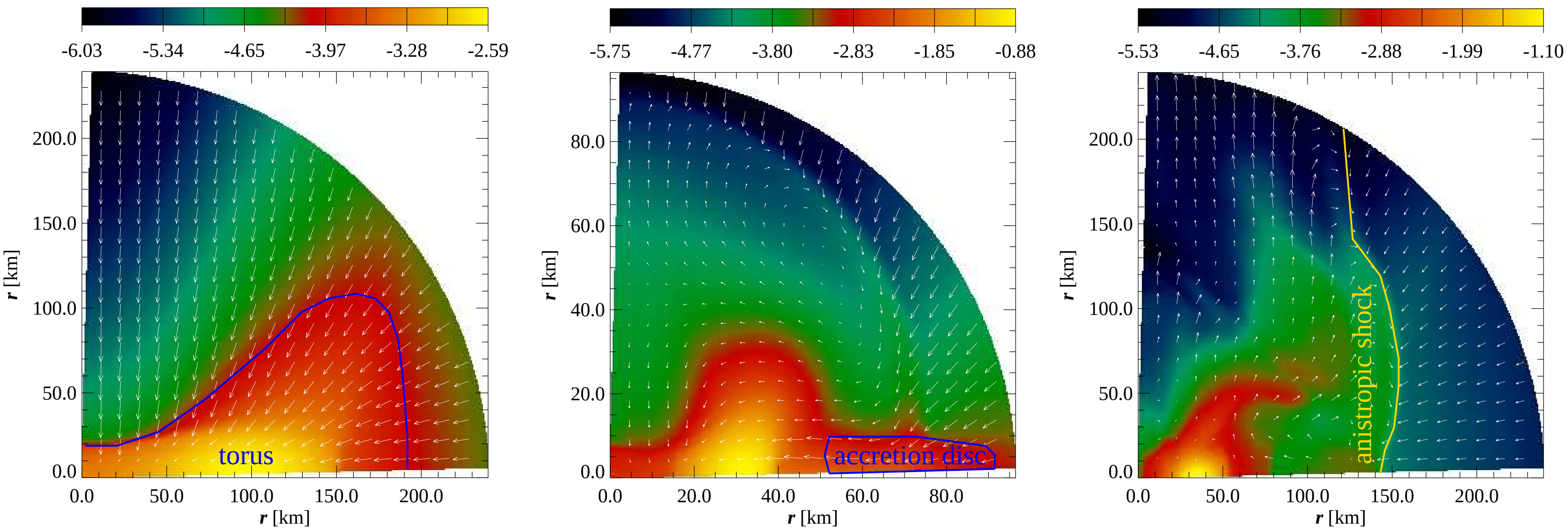
**Many Newtonian models show multiple bounces. In GR, collapse dynamics can change.**




- **Newtonian: Nuclear density hardly reached, multiple centrifugal bounces.**
- **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.**

# What Behavior do Rapidly Rotating Models exhibit?

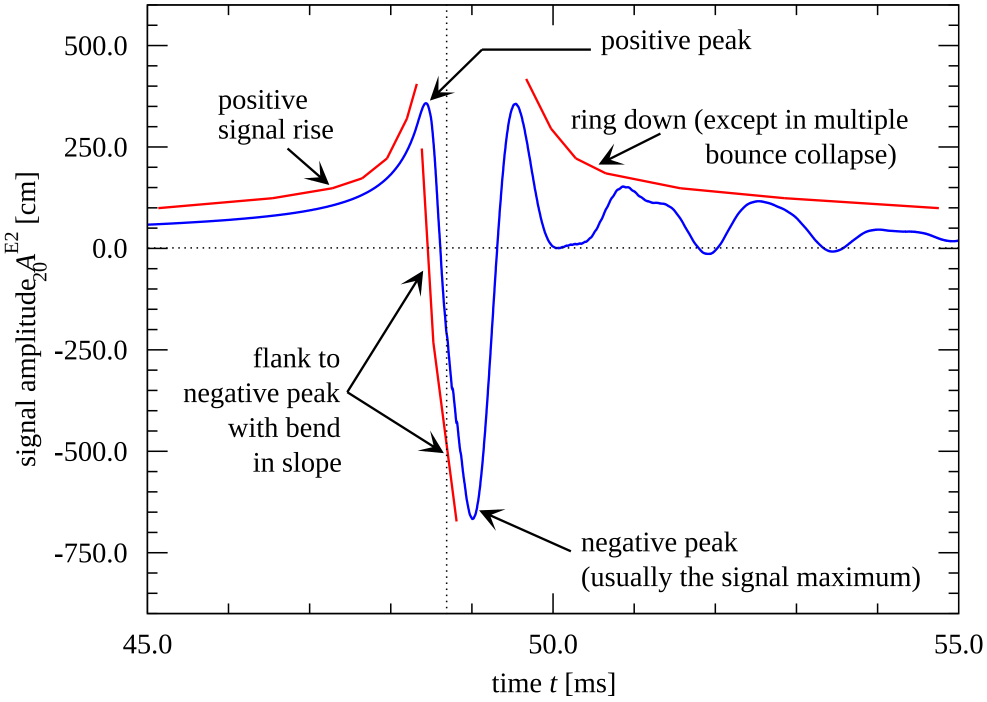



- Initial model has toroidal density shape; contraction enhances toroidal form.
- Proto-neutron star is surrounded by short-lived accretion disc.
- After bounce, strongly anisotropic shock front forms.
- Bar mode instability with a characteristic signal can develop on dynamical timescale (particularly with differential rotation and in GR); for this need 3d code!

## 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.

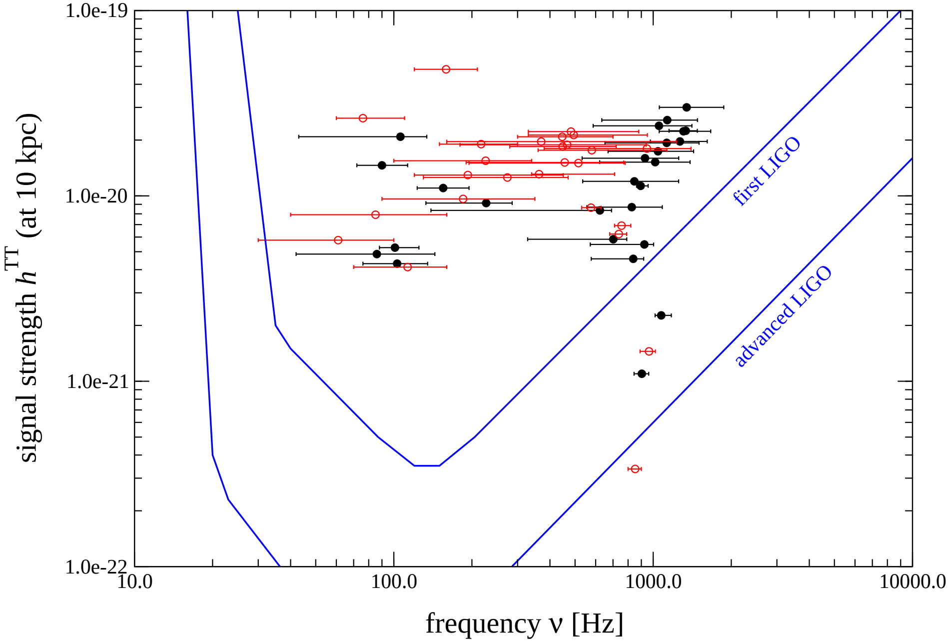
We present our waveform catalogue at

www.mpa-garching.mpg.de/Hydro/RGRAV/.

Conversely, in detected signal, features allow for conclusions about core collapse physics.

## 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 galactic supernova detectable.**
- **On average: Amplitude $h^{\mathrm{TT}} \approx 10^{-23} \cdot 10$ Mpc$/R$, frequency doubles to $\nu \approx 1000$ Hz.**

**Increase of frequency: Signals get closer to high-frequency sensitivity limit!**

## What is the Current Status of our Work and Where do we go?

Ongoing and planned developments of our axisymmetric code:

- Extract oscillation frequencies of rotating neutron stars
  (José A. Font, Nick Stergioulas).
- Include CFC+ for better approximation of spacetime metric
  (Pablo Cerda, Guillaume Faye).
- Implement spectral methods for calculating metric using LORENE
  (Jérôme Novak).

  Current solver methods:

  - Discretrized multi-dimensional Newton–Raphson iteration
    (robust, much too slow for 3d).
  - Integral conventional Poisson solver iteration
    (fast, slow/no convergence in 2d/3d).
  - Integral Poisson solver iteration using LORENE's spectral methods
    (fast, intrinsically 3d, rapid convergence, very accurate, compactified grid).

## What is the Current Status of our Work and Where do we go?

**Ongoing and planned developments of our axisymmetric code:**

- **Extend code to 3d, and investigate dynamic development of bar instability.**
- **Parallelize code for shared memory architectures using OpenMP.**
- **Investigate problem of degeneracy of metric equations for strongly gravitating systems.**
- **Use code for simulating critical spacetimes with non-/generic initial data (José M. Martín García).**
- **Add more realistic microphysics (Lattimer–Swesty, neutrinos), check signal robustness.**
- **Simulate spherical and rotational black hole formation until formation of horizon.**
- **Assess quality of CFC by comparing to core collapse simulations with Cactus–Whisky (Christian Ott, Ian Hawke).**

## What are the Future Directions of this Research Field?

In next few years,

- breakthroughs in numerical relativity (new formulations of field equations) and
- increasing computer power (massive parallel computing)

will pave way to more sophisticated simulations.

In next years, we expect following developments:

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

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

An interesting road lies ahead!