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Gravitational waves from rotational supernova core collapse: New relativistic simulations

- Motivation
- Model
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- Summary

Work done at the MPA Garching
in collaboration with E. Müller and J.A. Font-Roda.

Gravitational Waves from Core Collapse Supernovæ

Problem with observing a core collapse supernova:

We only see optical light emission (light curve) of the explosion (hours after collapse – envelope optically thick).

But: Gravitational waves are a direct means of observation of stellar core collapse.

Some of the new gravitational wave detectors are already taking data.

Challenge: Such a burst signal is very complex!
⇒ We need realistic prediction of the signal from relativistic numerical simulations!

Our contribution:

The first *relativistic* simulation of rotational core collapse to a neutron star.

Physical Model

Physical model of a core collapse supernova:

- Massive star develops an iron core ($M_{\text{core}} \approx 1.5 M_{\odot}$), which then collapses ($T_{\text{collapse}} \approx 100$ ms).
- At supernuclear density, neutron star forms (EoS of matter stiffens $\Rightarrow$ bounce).
- Shock wave propagates through stellar envelope and disrupts rest of the star (visible explosion).

During the various evolution stages, core collapse involves many aspects of physics.

$\Rightarrow$ Numerical simulations are very complicated, many approximations necessary.

And not even all the physics is known: Supernuclear EoS, rotation rate and profile of iron core, ...

Measurement of the signal waveform will reveal new physics!

Max Planck Institute for Astrophysics, Garching

Assumptions about the Model

To reduce the complexity of the problem, we assume

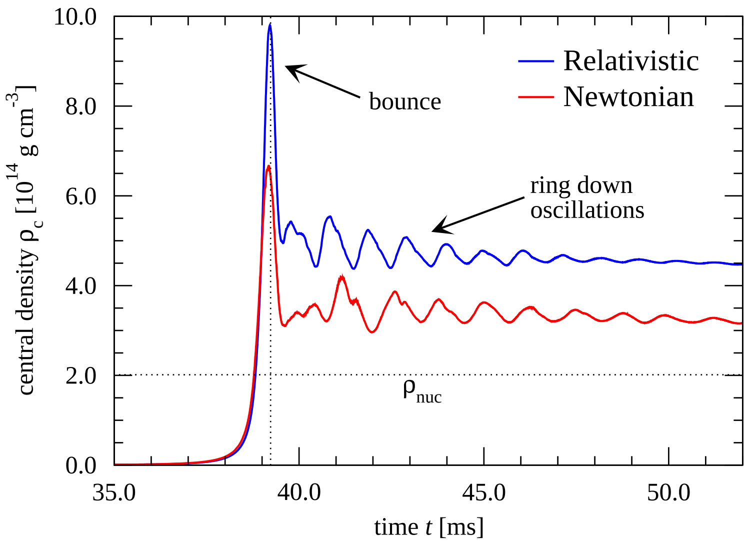
- axisymmetry and equatorial symmetry,
- rotating $\gamma = 4/3$ polytropes in equilibrium as initial models,
  with central density $\rho_{\mathrm{c\,ini}} = 10^{10}$ gm cm^{-3},
  radius $R_{\mathrm{core}} \approx 1\,500$ km, and
  various rotation profiles and rotation rates,
- simplified ideal fluid equation of state, $P(\rho, \epsilon) = P_{\mathrm{poly}} + P_{\mathrm{th}}$ (neglect complicated microphysics),
- constrained system of the Einstein equations (assume conformal flatness for the three-metric).

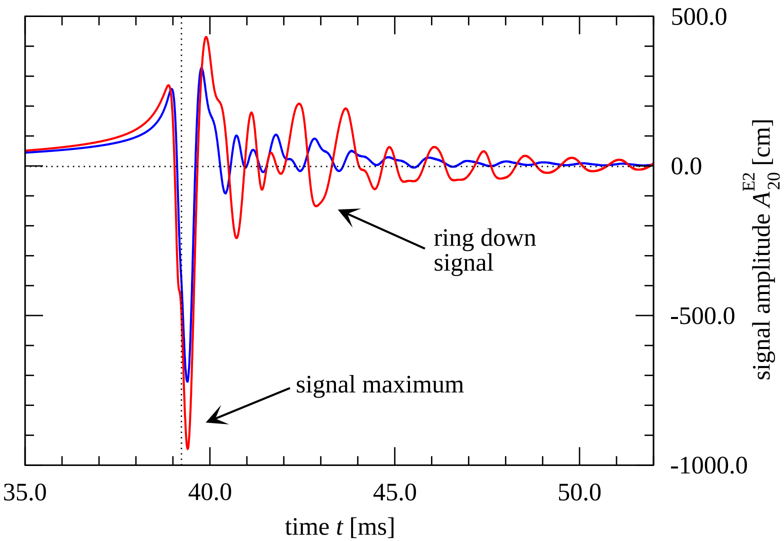
Goals

- Extend research on Newtonian rotational core collapse by Zwerger and Müller to GR.
- Obtain more realistic waveforms as “wave templates” for interferometer data analysis.
- Have a versatile 2D GR hydro code for comparison with future simulations.

Regular Collapse

Model A: Slow, almost uniform rotation, fast collapse (≈ 40 ms), soft supernuclear EoS.





- Deep dive into potential, high supernuclear densities, single bounce, subsequent ring down.
- GR simulation: Higher central density and signal frequency, but *lower* signal amplitude.

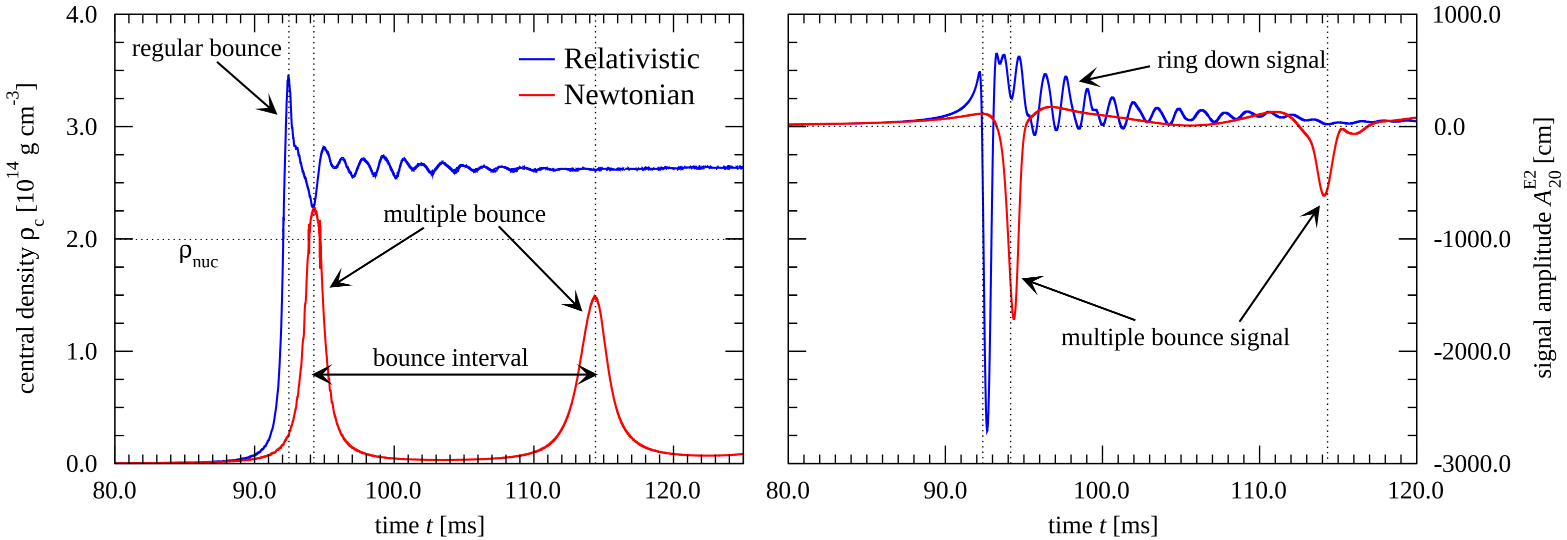
  Explanation: GW signal is determined by accelation of *extended* mass distribution:

$$A_{20}^{E2} = \ddot{Q} \propto \frac{d^2}{dt^2} \int dV \rho \boxed{r^2}. \quad \leftarrow \text{ weight factor!}$$

  In relativistic gravity core is more compact. ⇒ Gravitational waves can have smaller amplitude!

Change of Collapse Dynamics

Model B: Slow, almost uniform rotation, slow collapse (≈ 90 ms).

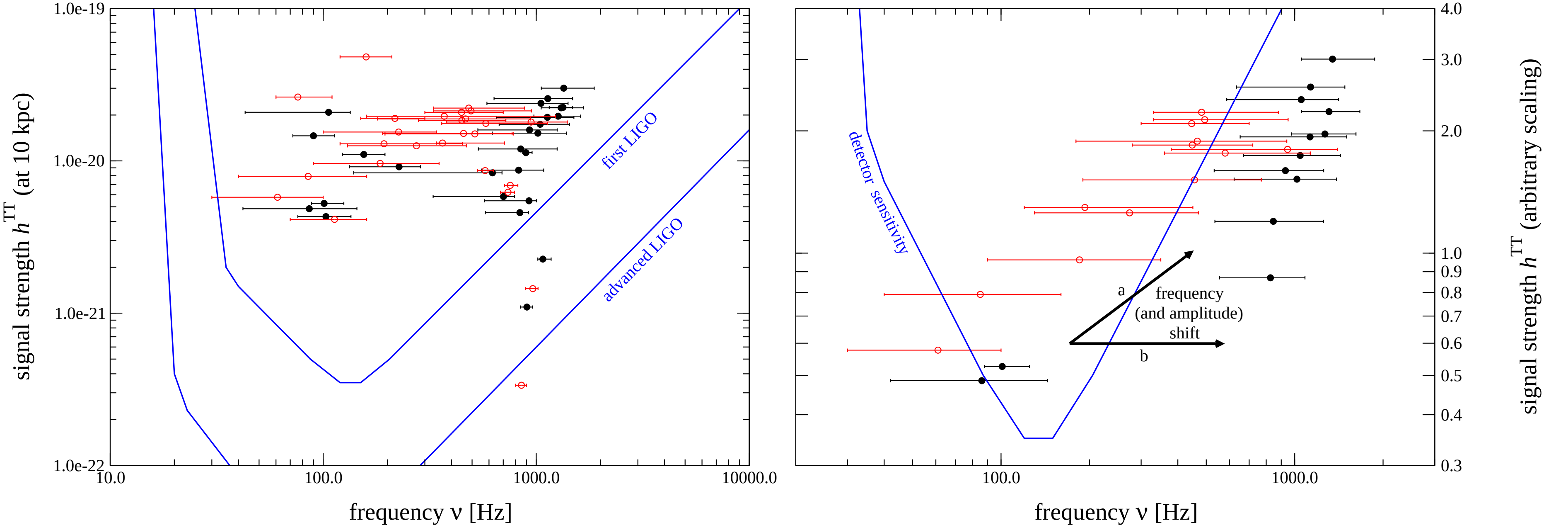


- Rotation increases strongly during collapse (angular momentum conservation!).
- Newtonian: Nuclear density hardly reached, multiple centrifugal bounce with re-expansion.
- GR: Nuclear density easily reached, regular single bounce.
- Relativistic simulations show multiple bounces only for a few extreme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

Strong *qualitative* difference in the collapse dynamics and thus in the signal form.

Gravitational Wave Signals

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

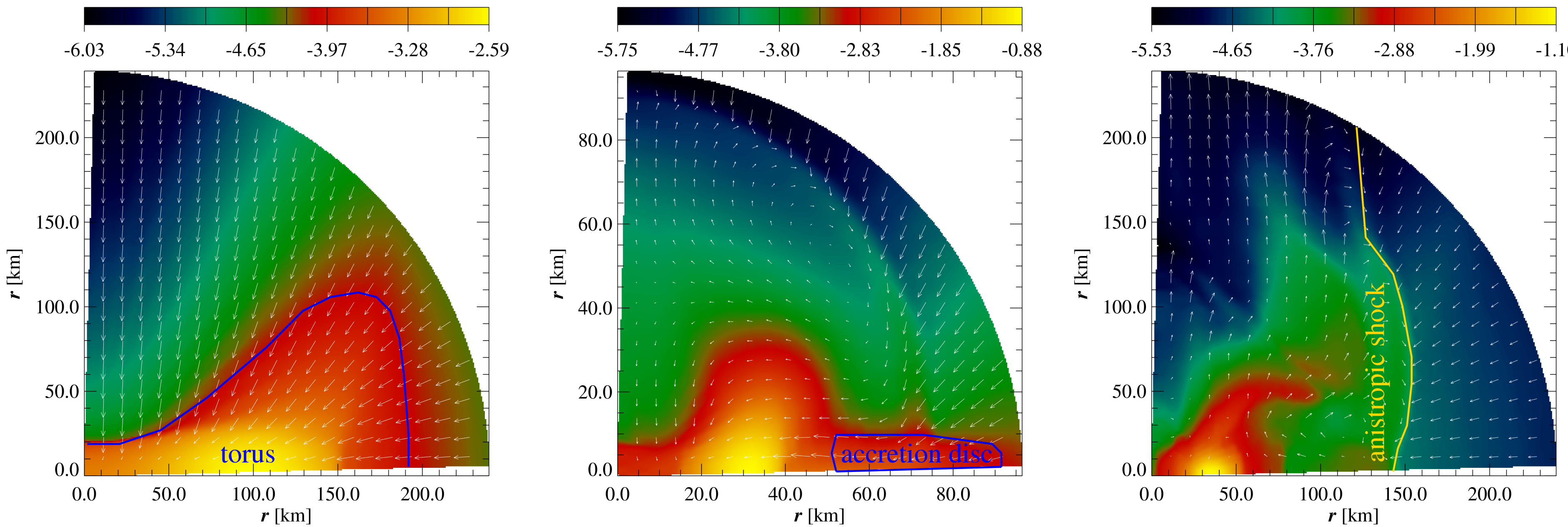


- **Spread of the 26 models does not change much. ⇒ Signal of a galactic supernova detectable.**
- **On average: Amplitude ⟶, Frequency ↗.**

If close to detection threshold: Signal could fall out of the sensitivity window!

Rapidly Rotating Models

Model C: Fast and extremely differential rotation, rapid collapse (≈ 30 ms).



- Initial model has toroidal density shape; torus becomes more pronounced during contraction.
- Proto-neutron star is surrounded by a disc-like structure, which is accreted.
- Bar instabilities are likely to develop on dynamical timescale.
- After bounce, a strongly anisotropic shock front forms.

Summary

These are the first gravitational wave templates obtained by simulations of rotational supernova core collapse in *general relativity*.

Our simulations show:

- Central densities are significantly higher than in Newtonian simulations.
- Many previous multiple bounce models collapse to supernuclear densities in relativity.
- On average, the signal amplitude does not change, but the signal frequency increases; we still have $h^{\mathrm{TT}} \approx 10^{-23} \cdot 10\ \mathrm{Mpc}/R$ for axisymmetric supernova core collapse.
- Relativistic effects increase rotation rate; many models could develop triaxial instabilities.
- Our wave templates replace the Zwerger catalogue; we will make them publicly available.

Validity of the Conformal Flatness Condition (CFC)

Assuming conformal flatness for the three-metric is sufficiently accurate for

- not very nonspherical matter distributions
  (fulfilled very good in core collapse – compare to rotating dust disks, Schäfer and Kley), and
- if the energy of gravitational wave emission can be neglected
  (no significant gravitational radiation backreaction on the dynamics – $E_{\mathrm{gw}} \lesssim 10^{-7} E_{\mathrm{tot}}$!).

Facts and results from accuracy tests for the CFC approximation:

- CFC makes no explicit assumptions about the time-dependence of spacetime.
- CFC metric solves the ADM constraints.
- Evolution equations for γ_{ij} are only slightly violated.
- Evolution equations for K_{ij} are violated stronger
  (K_{ij} are a particular combination of metric components – they are never used in our approach).
- We can maintain long-term stability for rotating neutron stars.
- Even for strongly deformed rotating neutron stars, CFC is a fair approximation.