Gravitational waves from proto-neutron star evolution

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Supernovae (SNe)

- $8\,\mathrm{M}_\odot \lesssim M_\star \lesssim 25\,\mathrm{M}_\odot \rightarrow$ neutron star (NS);
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- Fe core supported by electrons Fermi pressure;
- when $M_{\mathrm{core}} > M_{\mathrm{Ch}} = 1.44\,\mathrm{M}_\odot \to$ core collapse;
- increasing density $\to$ nucleons Fermi pressure $n_{\mathrm{B}} \simeq n_0$;
- outer-core bounce $\to$ shock wave;

Proto-neutron star (PNS)

PNSs are the SN contracting cores:

- very early evolution (PHASE I): core bounce $\div \sim 0.2\,\mathrm{s}$:
  - fully relativistic, highly dynamical codes;
  - mass accretion;
  - PNS contraction $150\,\mathrm{km} \to 30\,\mathrm{km}$;
  - high-temperature PNS envelope;
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  - beta equilibrium;
  - deleptonization stage (heating of the inner core);
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- minutes: birth of a mature neutron star (neutrino transparent).

We are interested in the gravitational wave emission (from rotation or stellar oscillations) of the PNS in PHASE II.

PNS evolution: general facts

- in a "cold" NS the EoS is barotropic: $P \to (n_{\rm B}, \epsilon, \ldots)$
- in a PNS the $T \simeq 40\,\mathrm{MeV} \gtrsim E_{\rm F} \simeq 10\,\mathrm{MeV}$ and therefore the EoS is non-barotropic $(s, Y_L, P) \to (n_{\rm B}, \epsilon, T, Y_\nu, \ldots)$

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- PNS structure from general relativistic TOV equations (spherical metric) with a given finite-temperature EoS $\epsilon(s, Y_L, P)$;
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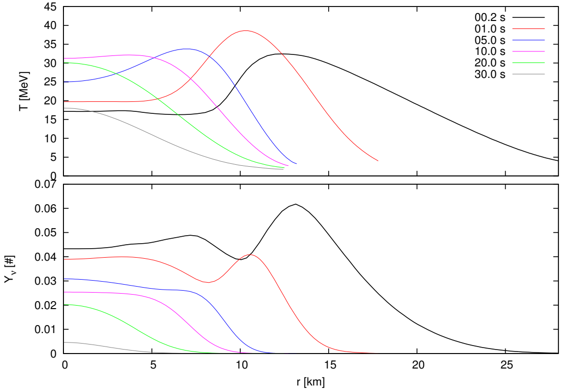
- neutrino diffusion coefficients depend on the neutrino cross sections (and therefore on the EoS...);
- For now, only mean-field EoSs have been used (e.g., GM3 Glendenning & Moszkowski, "Reconciliation of Neutron-Star Masses and Binding of the Λ in Hypernuclei", PRL **67**:2414–2417 [1991]).

PNS evolution: our code

Our code reproduces the results of Pons, Reddy, Prakash, Lattimer & Miralles, "Evolution of proto-neutron stars", ApJ **513**:780–804 [1999]:



- low T core;
- high T envelope;
- trapped ν;
- inner core heating;
- cooling;
- deleptonization.

Figure: PNS evolution, GM3 EoS (our code).

Effective inclusion of rotation: the procedure

We have extended the work of Villain, Pons, Cerdá-Durán & Gourgoulhon, "Evolutionary sequences of rotating protoneutron stars", A&A **418**:283–294 [2004]:

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First, evolve the non-rotating star:

- fix the total baryon mass M_b;
- the finite-temperature EoS is $\epsilon(s, Y_L, P)$;
- the (non-rotating) evolution gives $s(t, a)$, $Y_L(t, a)$.

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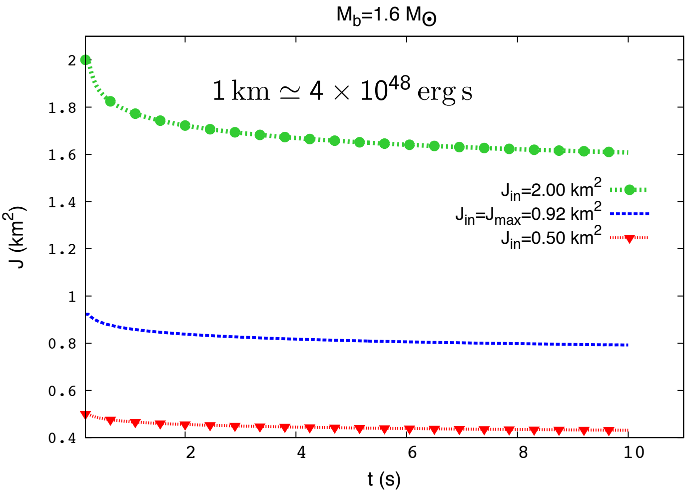
To effectively include the rotation:

1. fix an initial angular momentum $J_{in} = J(t = 0)$;
2. "effective" EoS at time t: $\epsilon'_t(a, P) = \epsilon(s(t, a), Y_L(t, a), P)$;
3. using ϵ'_t, solve Hartle-Torne (structure equations of a slowly rigidly rotating PNS) at time t with fixed M_b and $J(t)$;
4. determine $J(t + \mathrm{d}t)$ using the Epstein formula;
5. $t \to t + \mathrm{d}t$, back to point 2.

Effective inclusion of rotation: results



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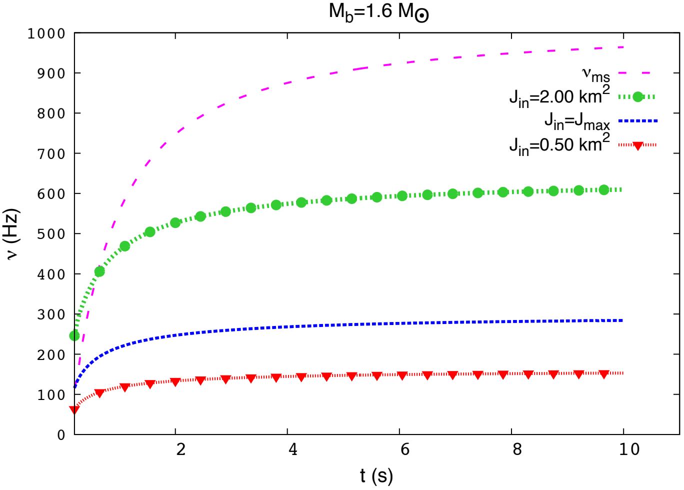

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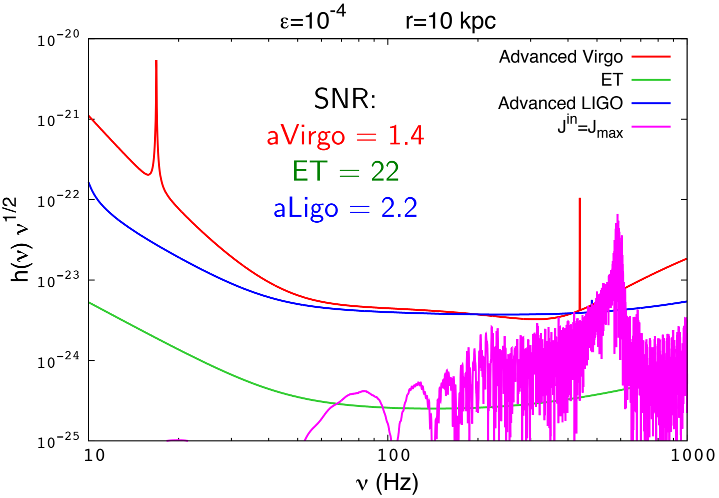

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EoS dependence: general facts

- previous PNS evolution studies used relativistic mean-field EoSs; we want to use a general EoS, e.g. a nuclear many-body theory EoS (Lovato & Benhar, "An effective interaction from Argonne-Urbana nuclear forces", in preparation);

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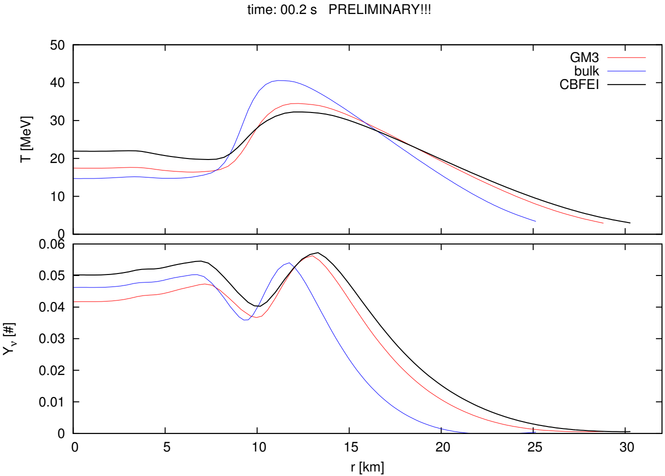
- from the free energy per baryon $f(T, n_b, Y_p)$ you can obtain all the other thermodynamical quantities with derivatives!
- we want to obtain the EoS from the fit of the interacting part of the baryon free energy

$$
\begin{aligned}
f_{\mathrm{EoS}}(T, n_b, Y_p) &= f_{\mathrm{free\,gas}}(T, n_b, Y_p) + f_{\mathrm{I}}(T, n_b, Y_p), \\
f_{\mathrm{I}}(T, n_b, Y_p) &= 4Y_p(1-Y_p) f_{\mathrm{SNM}}(T, n_b) \\
&\quad + (1-2Y_p)^2 f_{\mathrm{PNM}}(T, n_b), \\
f_{*\mathrm{NM}}(T, n_b) &= \text{polynomial in } T \text{ and } n_b,
\end{aligned}
$$

that is similar to how the bulk nuclear matter has been treated in Lattimer & Swesty, "A generalized equation of state for hot, dense matter", Nucl.Phys.A **535**:331 [1991].

EoS dependence: results (preliminary!)



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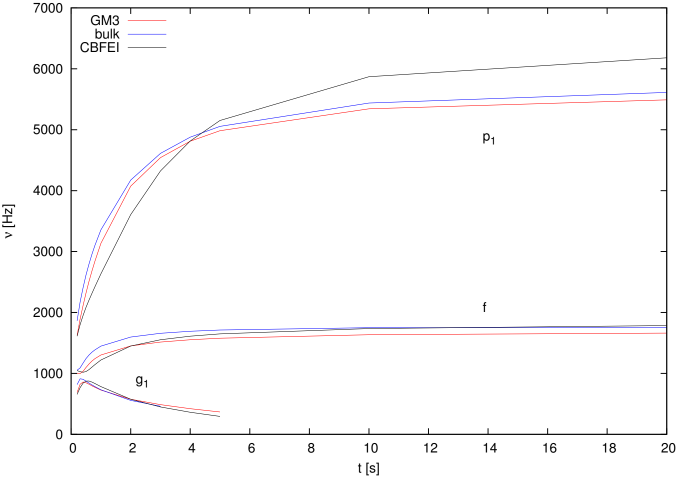

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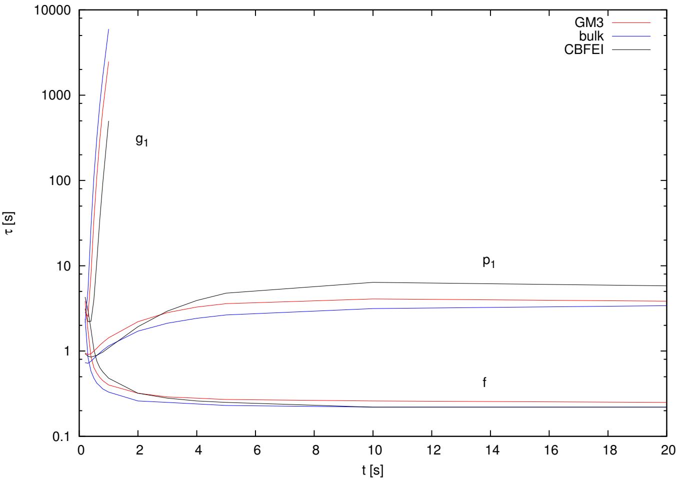

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Conclusions

Done:

- new PNS evolution code;
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Outlooks:

- convection (mixing length theory);
- accretion;
- evolution in 1+1.5D (consistent inclusion of rotation).