What can be learned from a proto-neutron star's mass and radius ?

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1) Introduction

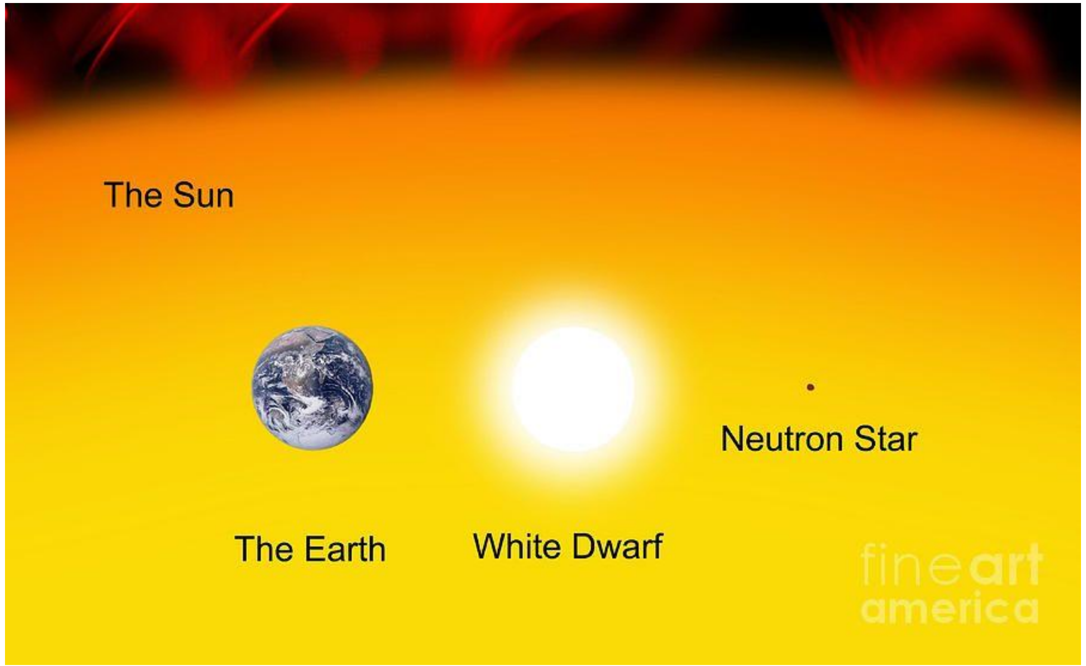
1.1) What is a Neutron Star ?

- Very dense stars → supranuclear density

- Large fraction of neutrons

- $M \sim 1{,}4 M_*$ and $R \sim 10$ km $\sim 10^{-5} R_*$
→ most compact stars known in the Universe

- The observation of NS offers a unique opportunity to test our understanding of matter at high densities:
  - no experimental data
  - strongly coupled



1.2) Neutron star structure and Equation of state

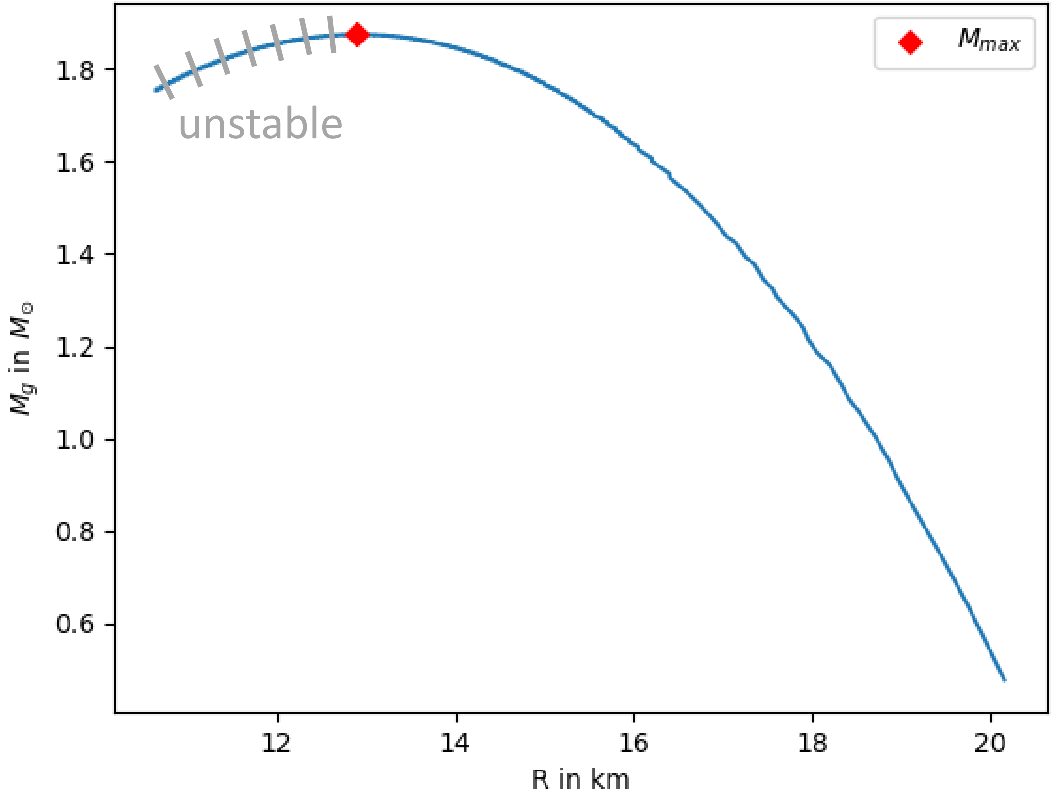
- *here:* structure = distribution of energy and pressure

- Determined by the Einstein Equations of GR
  → (Tolman-Oppenheimer-Volkov) TOV system

$$\frac{dm}{dr} = \frac{4\pi}{c^2} r^2 \varepsilon \,,$$

$$\frac{dP}{dr} = -\frac{G\varepsilon m}{r^2 c^2}\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi P r^3}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1} .$$

- Closed by an EoS, $P = P(\varepsilon)$



M-R diagram for a polytropic EoS

M-R diagram

- Curve $M_g(R)$, parametrized by the central ε

- EoS ↔ M-R diagrams
  → constraints on the EoS from M&R

1.3) The formation of a neutron star and gravitational wave emission

- NS formed as remnants of CCSN of massive stars $(M > 10M_*)$

- An iron core forms, stabilized against gravity by the pressure of degenerate electrons

- **Gravitational instability** initiated by electron captures
  $e + p \rightarrow n + \nu_e$,
  $e + (A, Z) \rightarrow (A, Z-1) + \nu_e$.

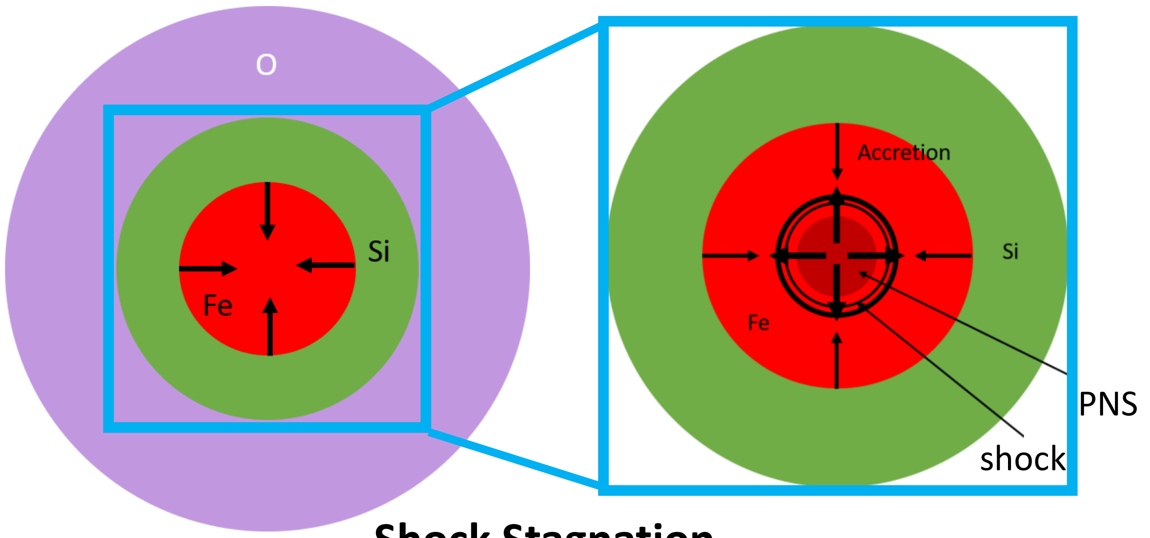
- The implosion stops due to the short-range N-N repulsive interaction → new stable state = PNS embryo

- The inner core **bounces back** → propagating shock

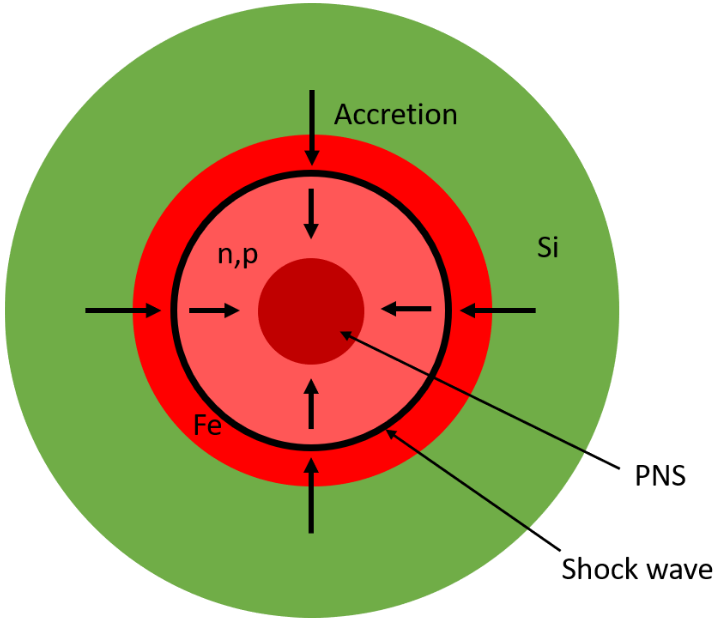
- As it propagates, the post-shock pressure diminishes → **shock stagnation**

- Shock revival (ν absorption, …) → **supernova explosion**

Collapse & Bounce of the Stellar Core

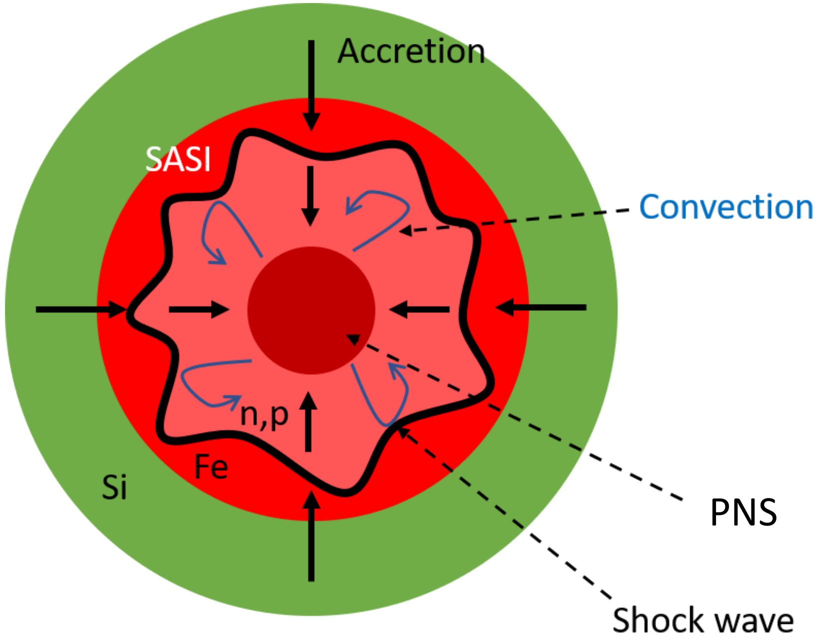


Shock Stagnation



Gravitational Wave Emission during a CCSN

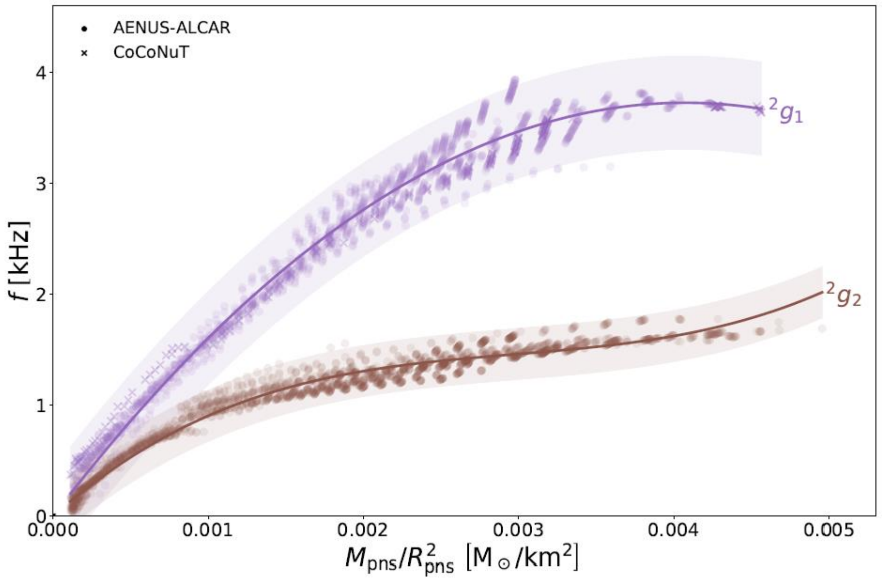
- Shock-core system subject to non-radial fluid instabilities
  →break spherical symmetry
  →GW signal



- GW spectrum studied for several CCSN simulations by [Torres-Forné et al.], from the analysis of PNS oscillations.

- The frequency of the modes depends on the general properties of the PNS such as its M&R.

- Frequency of the dominant g-modes can be directly related to M/R^2



https://arxiv.org/abs/1902.10048

Can the measurement of the mass and radius of a PNS in a CCSN put constraints on the EoS of *cold* NS ?

1.4) Structure of a PNS

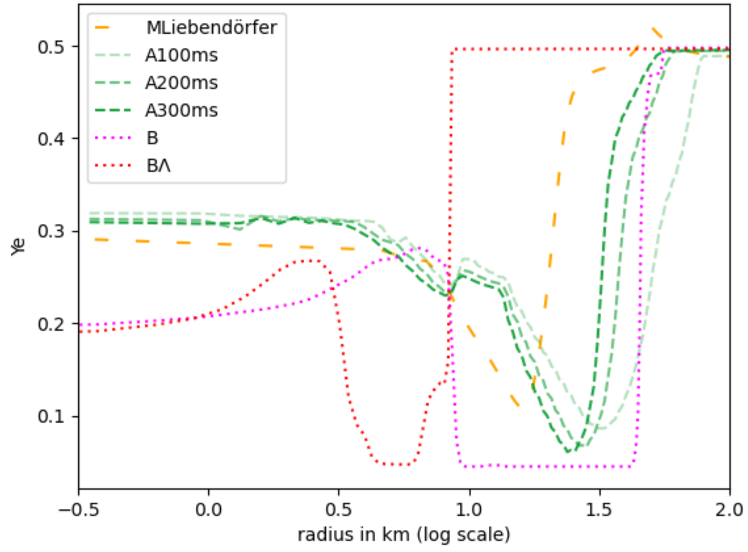
- Structure of a PNS still determined by the TOV system (quasi-static)

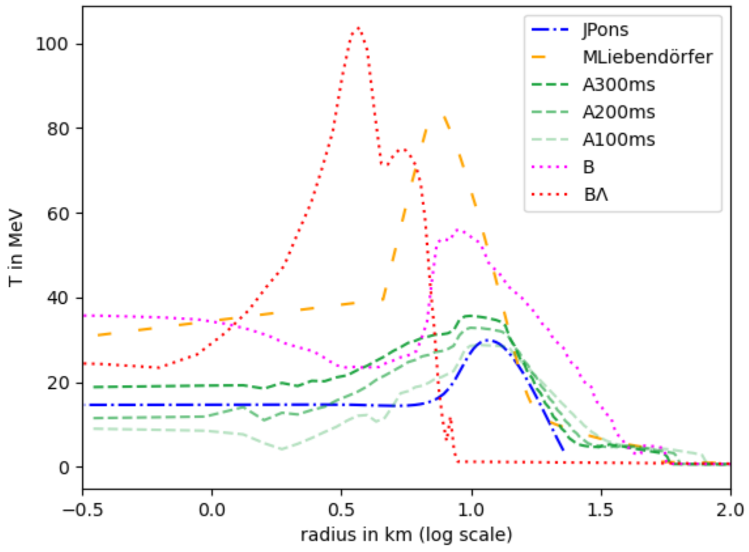
$$\frac{dm}{dr} = \frac{4\pi}{c^2} r^2 \varepsilon \, ,$$
$$\frac{dP}{dr} = -\frac{G\varepsilon m}{r^2 c^2}\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi P r^3}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1} .$$

- Still closed by an EoS $P = P(\varepsilon)$, but the EoS depends on:
  - -The temperature T
  - -The electron fraction $Y_e = \frac{n_{electron}}{n_{baryon}}$
  - → written $P = P(\varepsilon, T, Y_e)$ (3D EoS).

- Profiles $T(r)$ and $Y_e(r)$ necessary to integrate the TOV

- High variability of the profiles
  → should be taken into account when investigating PNS structures





Ye(r) (top) and T(r) (bottom) profiles from CCSN simulations

2) Methods and Results

2.1) Parametrization of the profiles

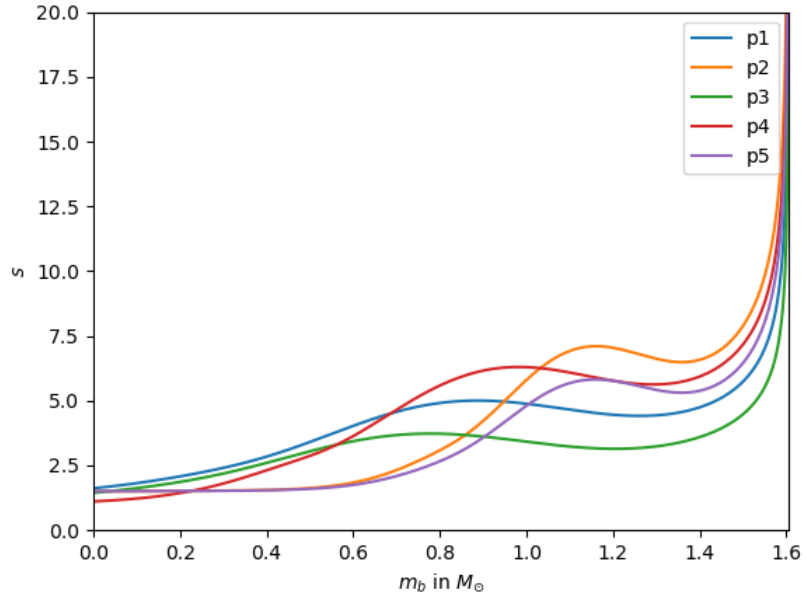
❖ Need to have an idea of the ensemble of possible PNS structures that could arise in a CCSN

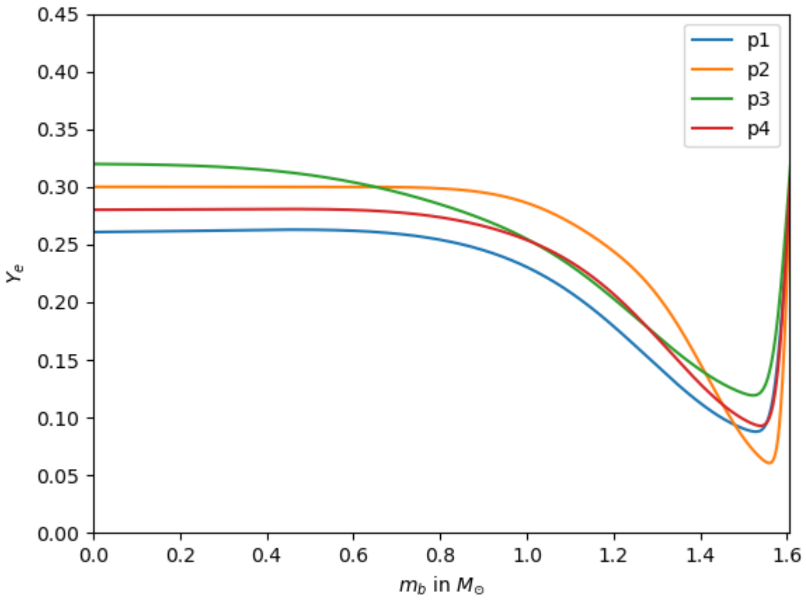
❖ <u>Method:</u>

- Build parametrized profiles for T and Y_e at the bounce
- Simulate the PNS evolution during $\sim$1 s after the bounce
- For several post-bounce times, and for various EoS, derive the PNS structure

❖ Instead of $T(r)$ and $Y_e(r)$, it is more convenient to parametrize $s(m_b)$ and $Y_e(m_b)$.

❖ 5 parametrizations for the initial profiles, for each of 3 initial baryon masses $M_b = 1.6\ M_*, 1.8\ M_*, 2\ M_*$.



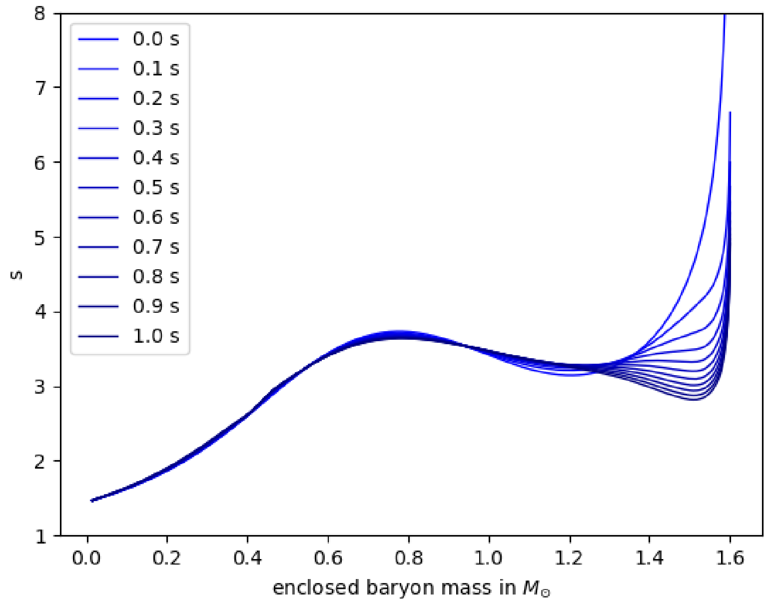


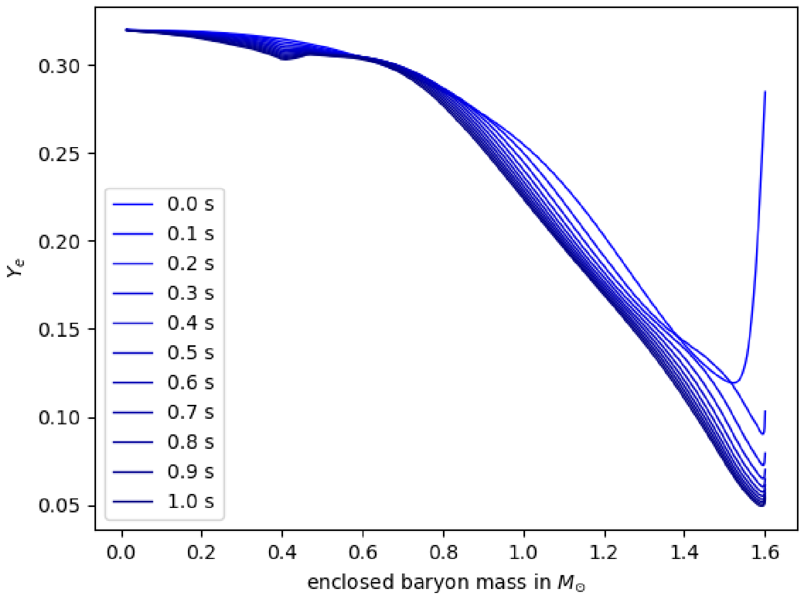
2.2) PNS evolution

❖ Next step: simulate the evolution of a PNS.
→ evolution code developed by A. Pascal (A. Pascal et al. ; in preparation).

❖ The evolution depends on the EoS, that has been chosen among four : HSDD2, SLY4, SFHO and SRO(APR).

❖ We produce profiles every 0.1s after the bounce.





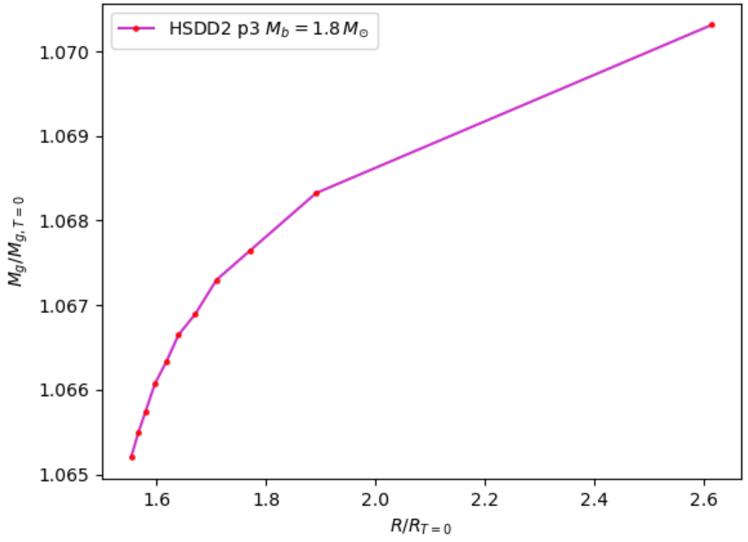
Results: Constraints on the EoS of cold NS ?

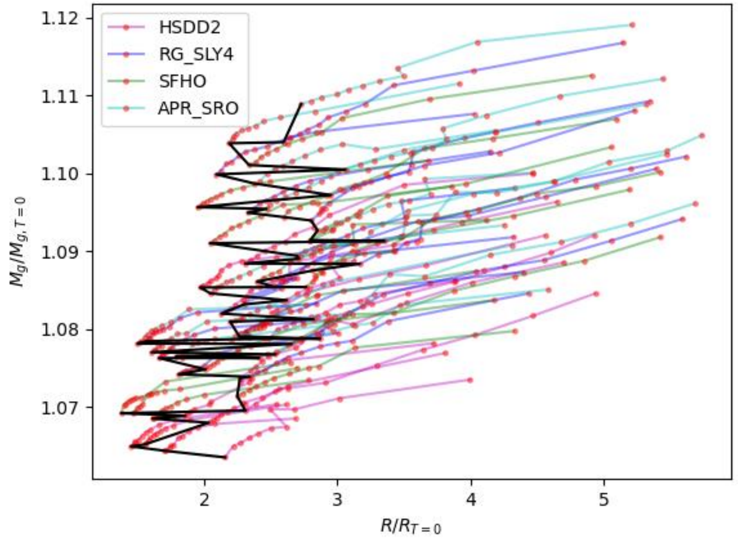
❖ Need to measure the cold NS M&R
→ Can we put constraints on the cold NS M&R from the observation of the PNS M&R ?

❖ For each evolved profile, derive the PNS structure from the TOV

❖ After 1 s, M is larger by about 6-10% and R by about 40-200% compared with the cold configuration.

❖ The measure of R cannot be used to constrain the cold NS radius
→ Neither can M/R^2





Conclusion

- New method to investigate the structure of PNS newly born in a CCSN, taking into account our ignorance of the profiles of entropy and electron fraction inside the star.
- Used this method to determine whether the observation of the M&R of PNS in CCSN would be able to put constraints on the EoS of cold NS
- M : upper bound quite close to the value for the cold NS
- R : much less reliable
- In particular, the measure of M/R^2 of a PNS proposed by (Torres-Forné et al.) is not expected to give a reliable estimate of the same quantity in the cold configuration.
- Other question: constraints on the 3D EoS of the observed PNS ?