Journée GPhys 2015

Institut d'Astrophysique de Paris

Relativistic Rotating Stars With Hot Matter

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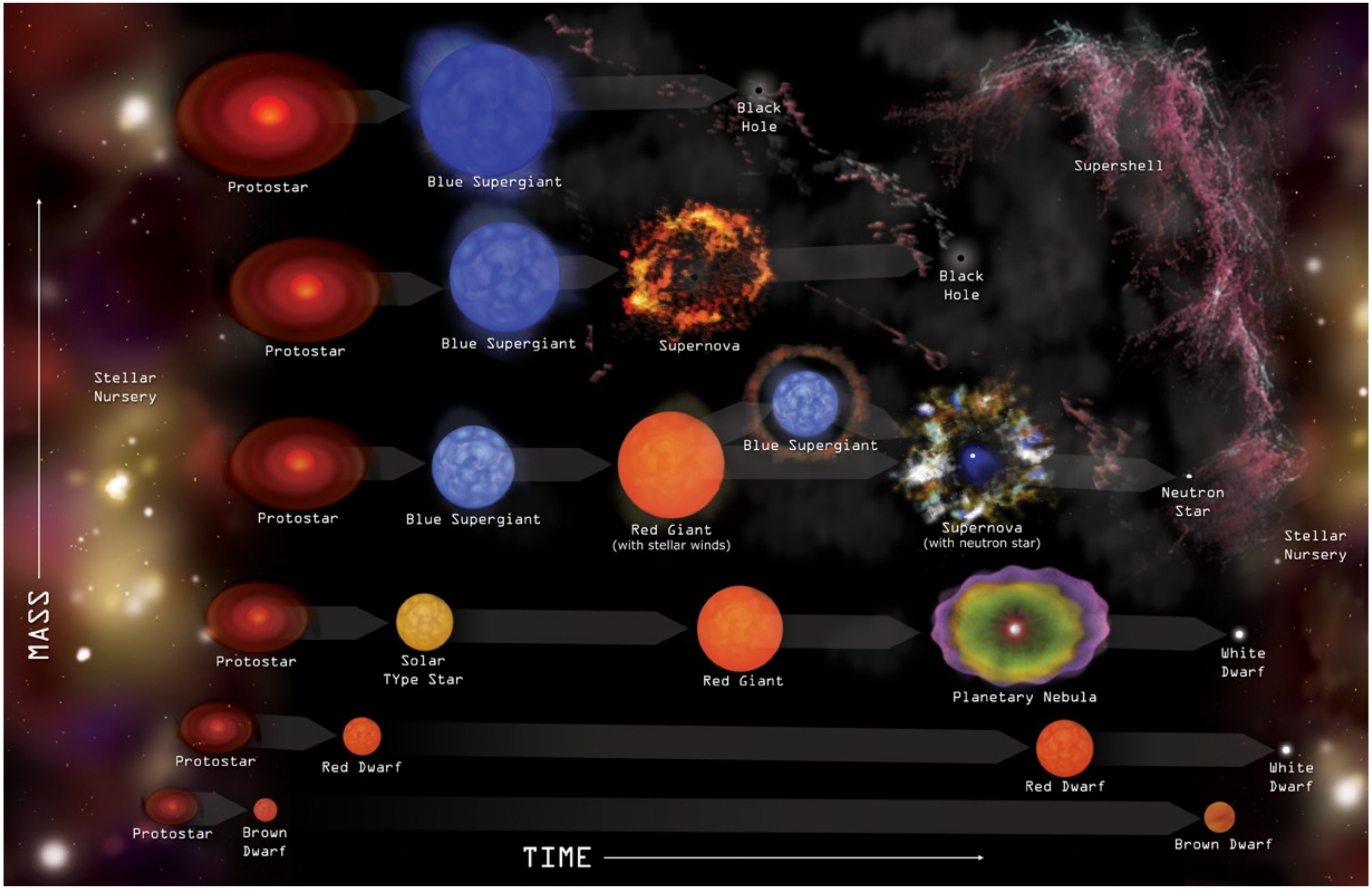
How do Massive Stars Die?

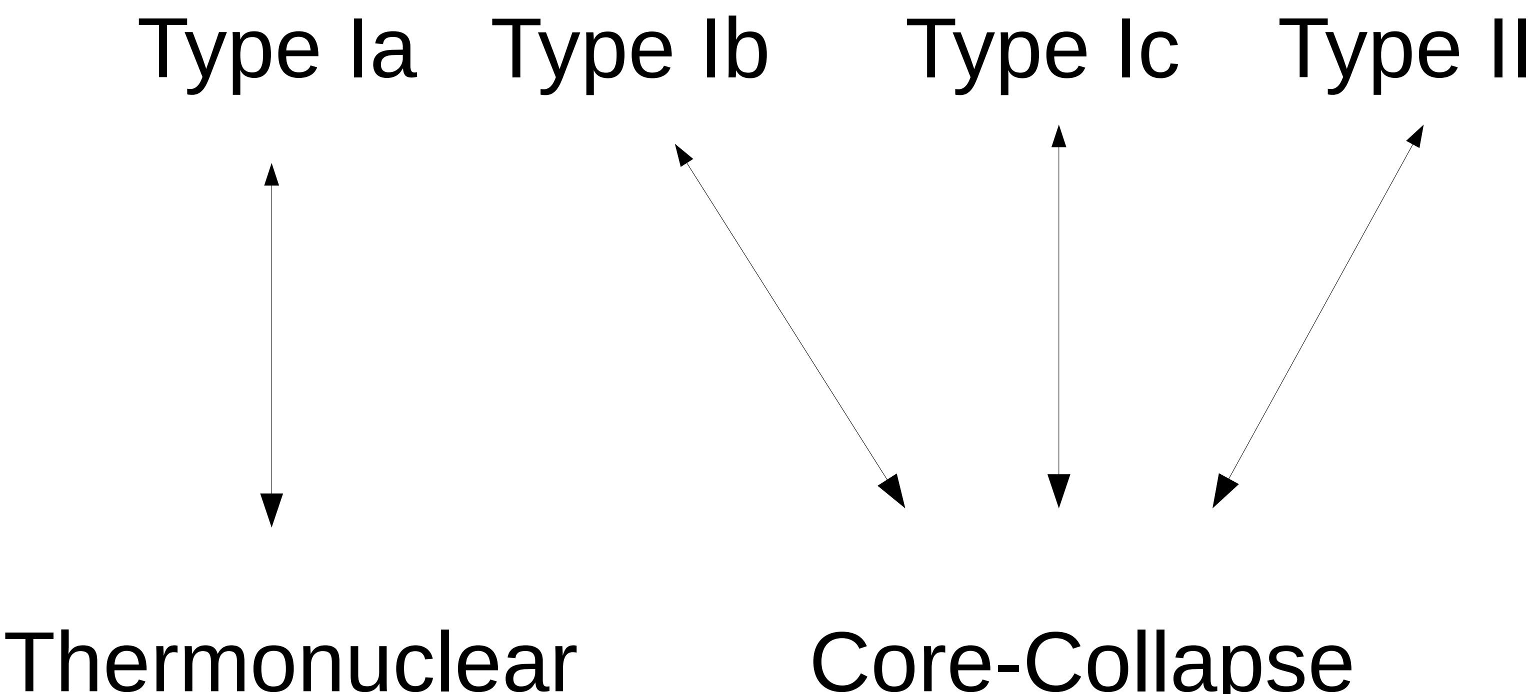
- The final fate of star evolution



Chandra

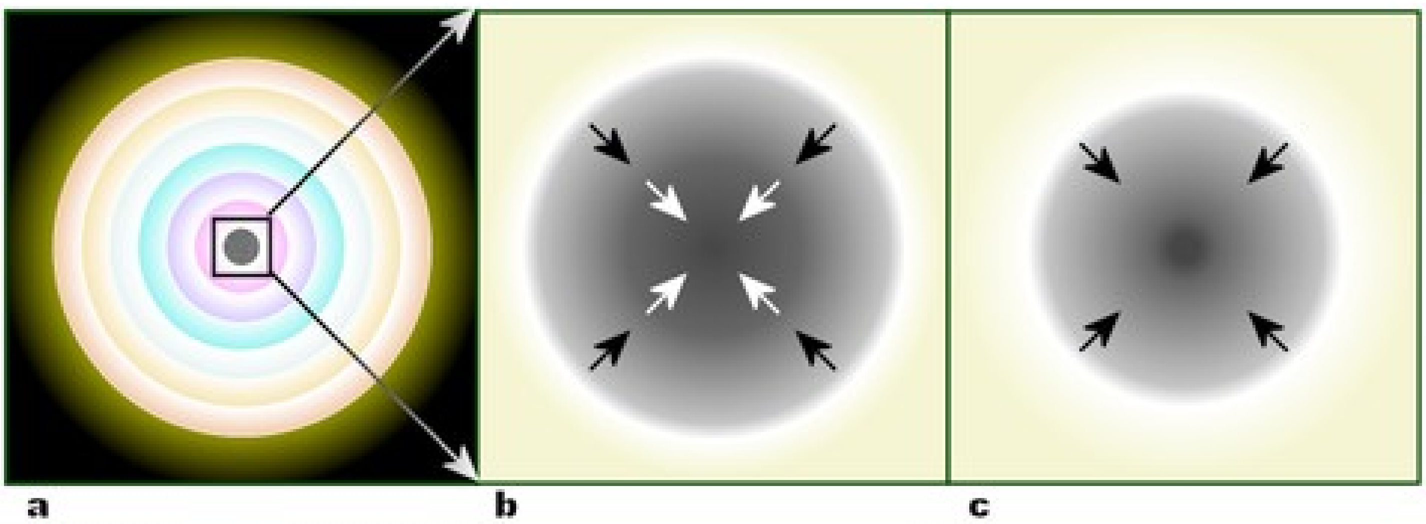
How do Massive Stars Die?

- Which supernovae?



Core-Collapse

- The gravitational collapse of the iron core



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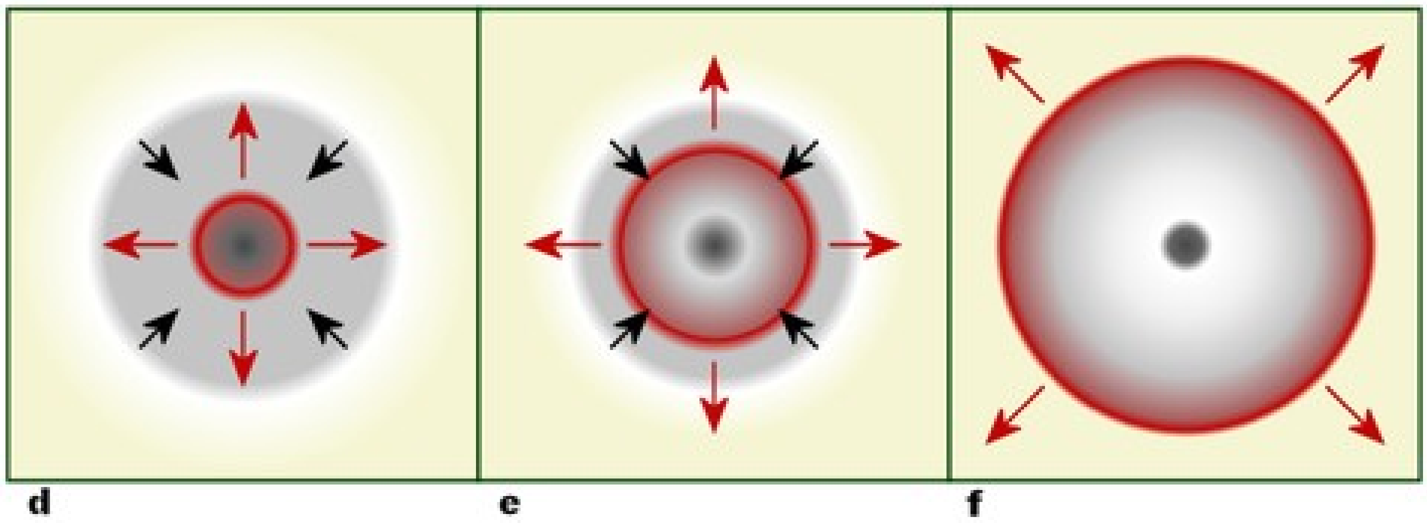
Core-Collapse

- The consequences of the core-collapse



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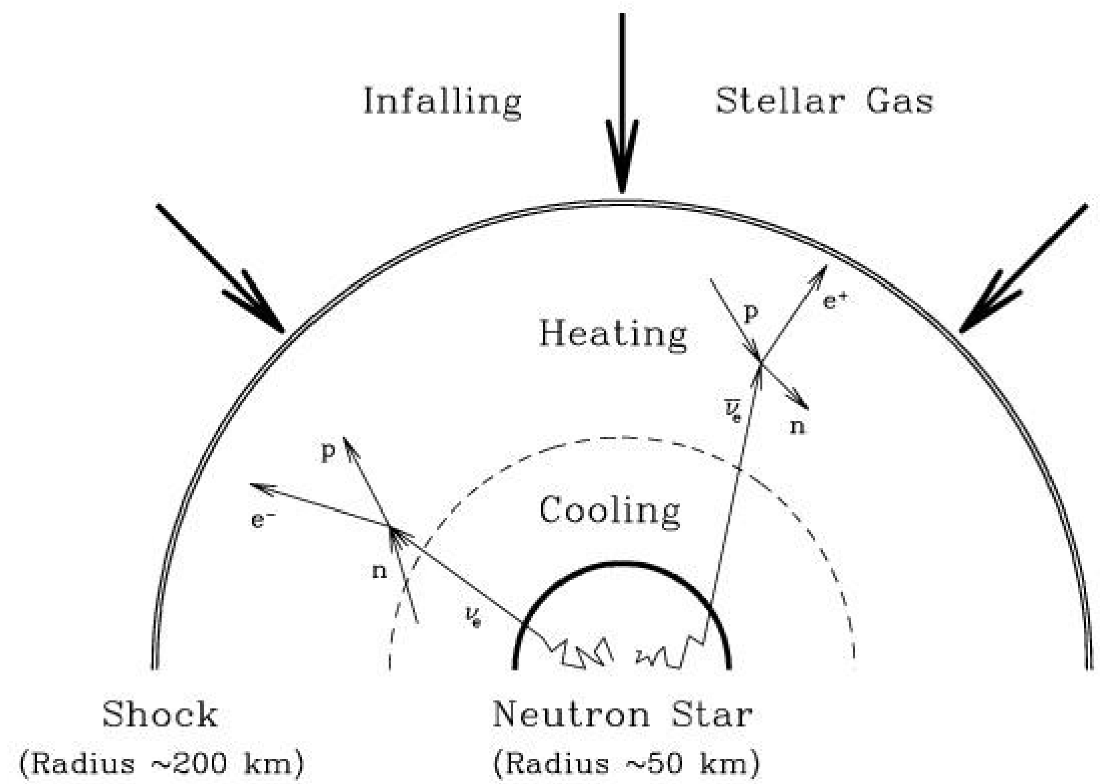
Core Collapse

- The neutrino driven mechanism

Explosion mechanisms

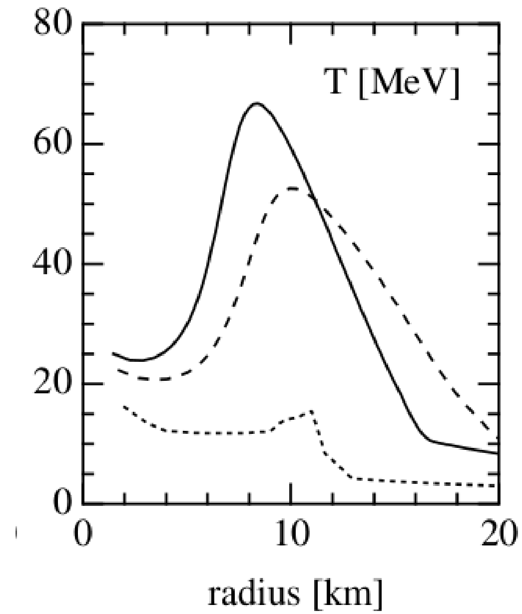
- The neutrino heating
- Hydrodynamical instabilities
 (Sasi, convection)
- Magnetorotational instabilities
- ...



H. T. Janka

Finite Temperature in Compact Stars

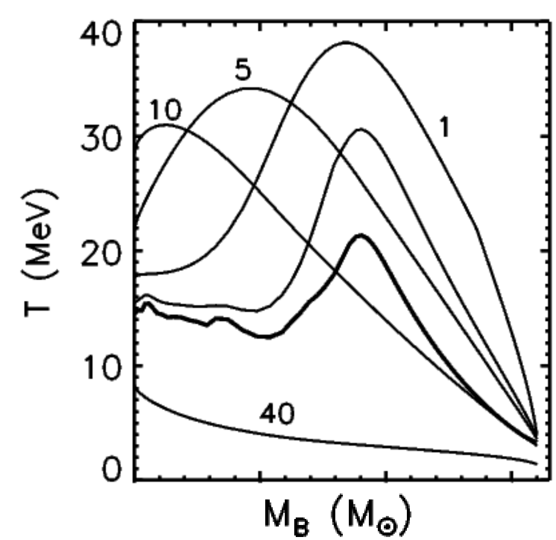
- Core-Collapse Supernovae
  - T ~ 50 - 100 MeV



Fischer (2009)

- Neutron Star Mergers
  - T ~ 80 MeV

- Proto-Neutron Stars
  - T ~ 50 MeV



Ferrari et al (2003)

10 MeV ≈ 1.16 x 10^{11} K

Finite Temperature in Compact Stars

- Core-Collapse Supernovae

  - Temperature effects included since many years in dynamical simulations

- Neutron Star Mergers

  - Kaplan et al (2014), Bauswein et al (2012), Abdikamalov et al (2013), Sekiguchi et al (2011) …

- Proto-Neutron Stars

  - Martinon et al (2014), Villain et al (2004), Pons et al (1999), Goussard et al (1998, 1997) ...

Finite Temperature in Compact Stars

- Finding a general solution for the equilibrium equations of stationary axisymetric spacetimes with finite temperature is difficult. Typical strategies are:

- Effective barotropic EoS

Goussard et al (97,98), ...

$$p = p(n_b, T(n_b), Y_e(n_b, T(n_b)))$$

- Using perturbative approximation methods for the metric

Martinon et al (2014)

Our model for hot stars

- General relativistic, stationary axisymmetric solutions of rotating stars

- Perfect fluid

Energy-momentum tensor → $T^{\mu\nu} = (p + \varepsilon) u^\mu u^\nu + p\, g^{\mu\nu}$

- Temperature (or entropy) dependent EoS's

$$p := p(n_b, s_b)$$

$$\varepsilon := \varepsilon(n_b, s_b)$$

Spacetime Solution

- Stationary axisymmetric spacetimes

Two killing vector fields:

$\partial_t,\ \partial_\phi$

We use a conformal 3-metric, defined as:

$\tilde{\gamma}_{ij} := \Psi^{-4}\gamma_{ij}$

- Dirac Gauge

(Bonazzola et al, 2004)

(Lin and Novak, 2006)

$\mathcal{D}_j h^{ij} = 0,$

$h^{ij} := \tilde{\gamma}^{ij} - f^{ij}$

- Maximal slicing condition

$K = 0$

Star equilibrium

- Equilibrium equations (for rigid rotation)

$$\nabla_\mu T^{\mu\nu} = 0$$

Defining the pseudo-log enthalpy field as

$$H = \ln\left(\frac{\varepsilon + p}{m_b n_b}\right),$$

With the help of the 1st law of thermodynamics, the equilibrium equations read

$$\partial_i \left(H + \nu - \ln\Gamma\right) = T e^{-H} \partial_i s_b, \qquad i = r, \theta$$

Goussard et al, 97

Star equilibrium

- Equilibrium equations (for rigid rotation)

$$\partial_i \left(H + \nu - \ln \Gamma\right) = T e^{-H} \partial_i s_b, \qquad i = r, \theta$$

No first integral in general! First integral for the barotropic EoS $H(n_b)$.

Star equilibrium

- Equilibrium equations (for rigid rotation)

$$\partial_i \left(H + \nu - \ln \Gamma\right) = Te^{-H} \partial_i s_b, \qquad i = r, \theta$$

Instead of solving an analytical first integral, we propose the following scheme

$$H = -\nu + \ln \Gamma + \int_0^{r_s} Te^{-H} \partial_r s_b \, dr'$$

$$\Delta_{\theta\phi} s_b = \left(\partial^\theta + \frac{1}{\tan \theta}\right) \frac{\partial_\theta (Te^{-H})}{\partial_r (Te^{-H})} \partial_r s_b$$

Where the monopolar part of the s_b has to be specified, whereas the higher multipoles are determined by the equilibrium solver

Results

- To test the code, we use the relativistic ideal gas EoS:

$$p(H, s_b) = k\, n_b(H, s_b)^\gamma e^{(\gamma-1)s_b}$$

$$\varepsilon(H, s_b) = \frac{k}{\gamma - 1} n_b(H, s_b)^\gamma e^{(\gamma-1)s_b} + m_b n_b(H, s_b)$$

$$T(H) = m_b \frac{\gamma - 1}{\gamma\, k_b} \left(e^H - 1\right)$$

$$n_b(H, s_b) = \left(m_b \frac{\gamma - 1}{\gamma\, k} \left(e^H - 1\right)\right)^{\frac{1}{\gamma-1}} e^{-s_b}$$

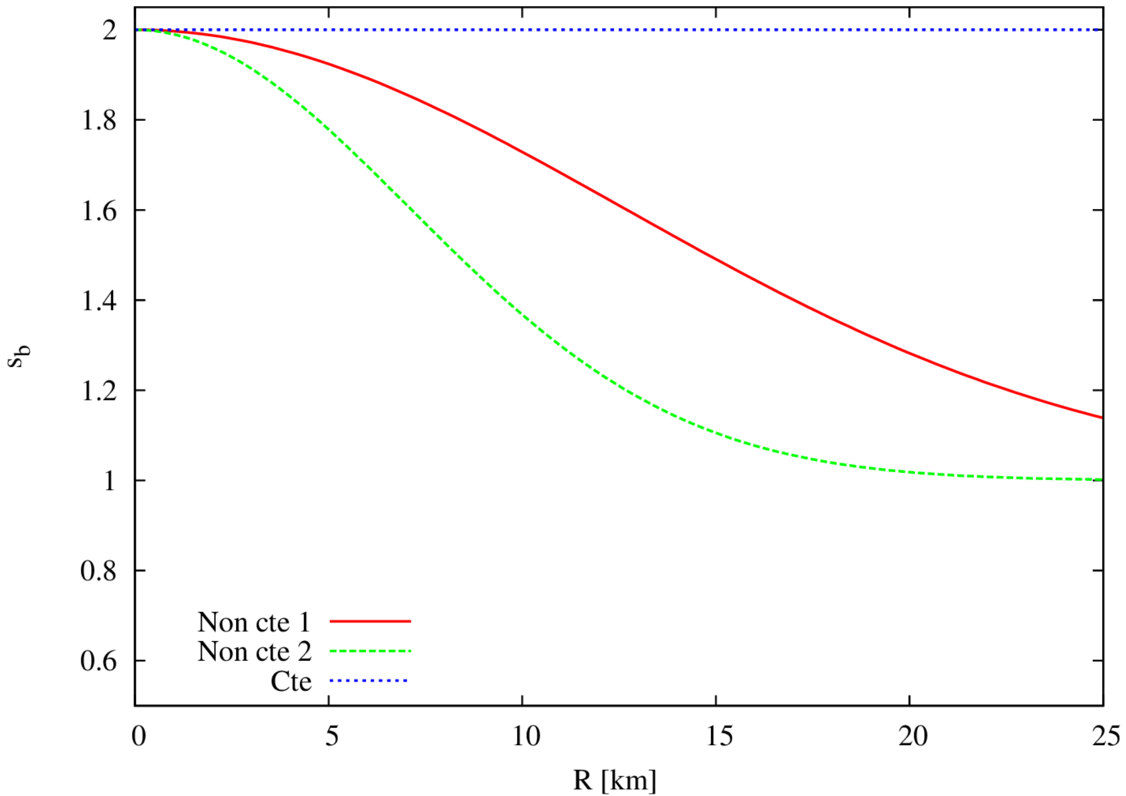
with $\gamma = 2$ and $k = 0.026\, \rho_{nuc}\, c^2 / n_{nuc}$

Results

- We will consider three different entropy per baryon profiles

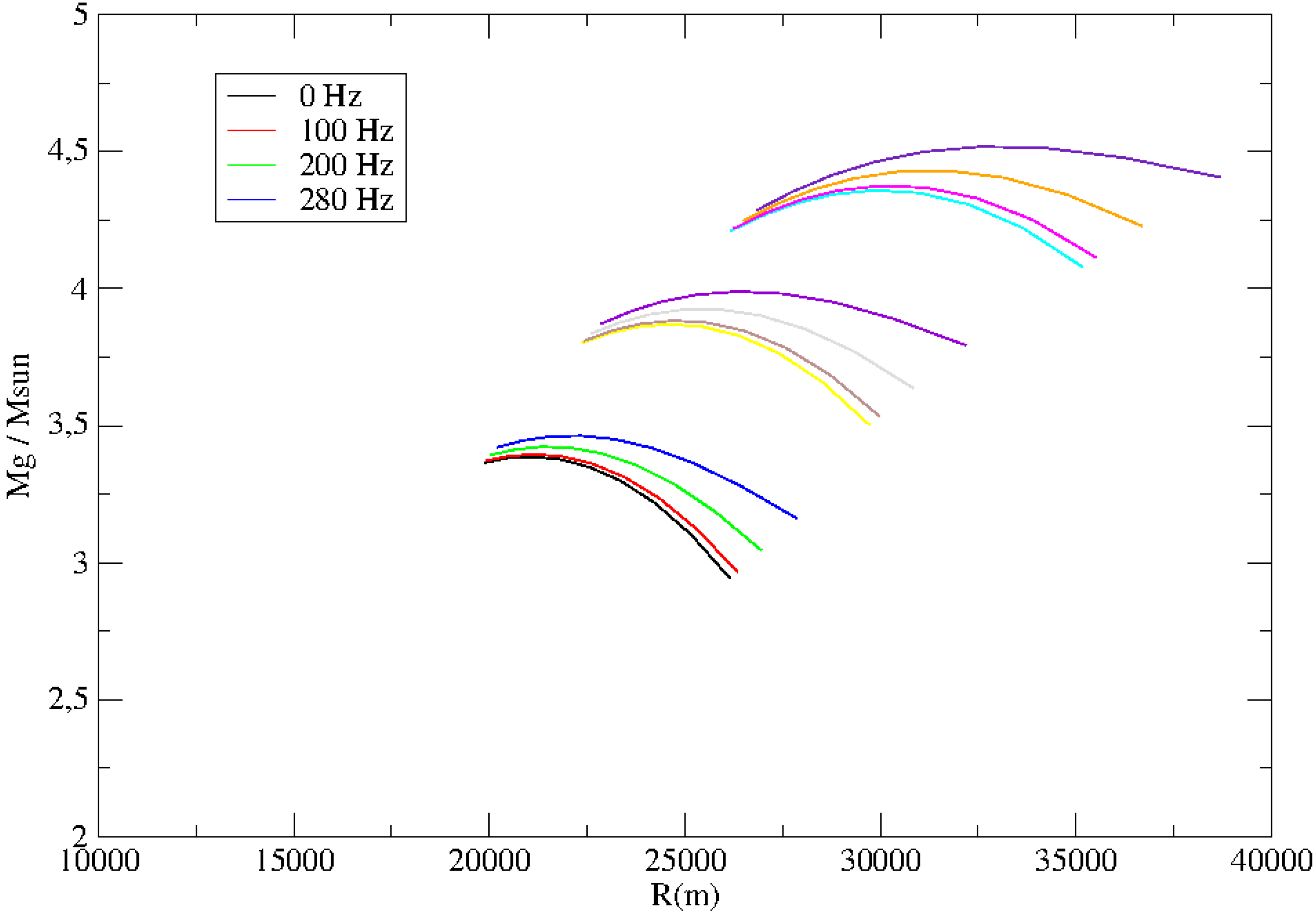
non cte 1 → $s_b = 1 + e^{-\frac{r^2}{10^{2.5}}}$

non cte 2 → $s_b = 1 + e^{-\frac{r^2}{10^2}}$



Results

- Mass/Radius profiles



Results

Constant sb profile

Rot = 373.5 Hz

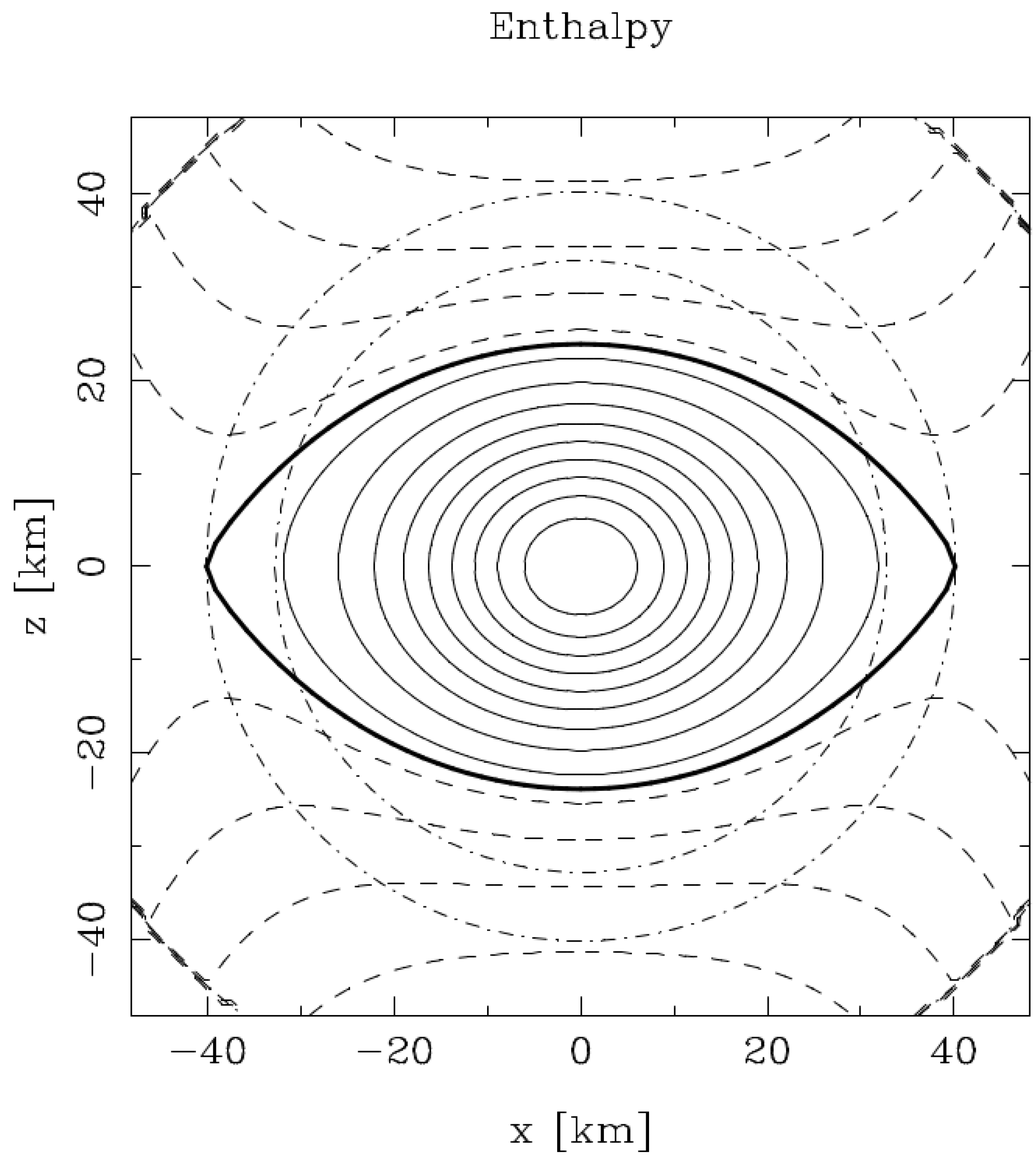
Central H = 0.3 c^2

Equatorial r = 60.21 Km

Gravitational M = 4.83 M_{sol}

Rpole/Req = 0.39

GRV2 = -8.84 e-6
GRV3 = -1.04 e-5



Results

Non constant s_b profile 2

Rot = 310 Hz

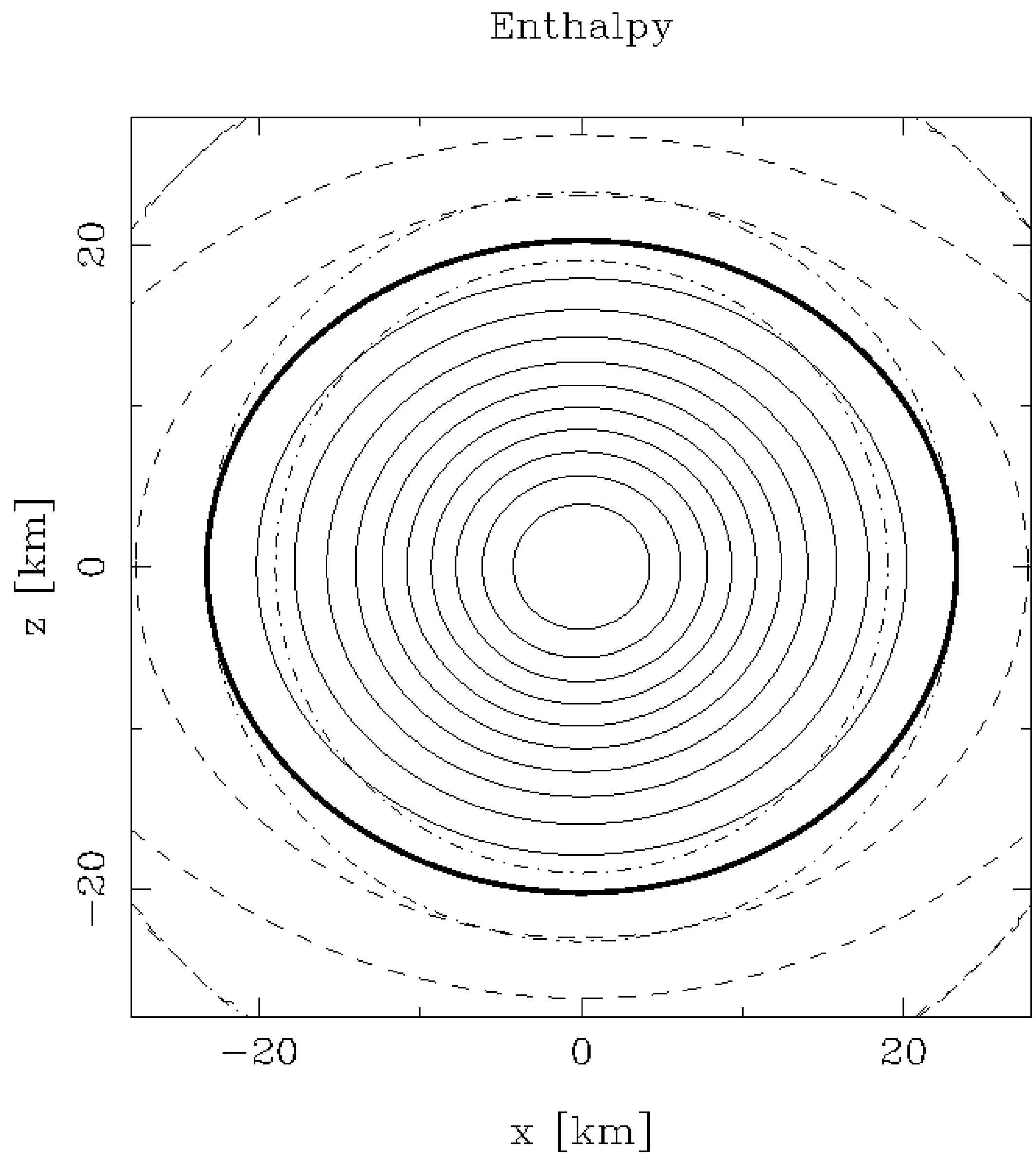
Central H = 0.3 c^2

Equatorial r = 32.19.21 Km

Gravitational M = 3.79 M_{sol}

Rpole/Req = 0.86

GRV2 = 3.12 e-6
GRV3 = 5.94 e-7



Conclusions and future perspectives

- We propose a numerical scheme to consistently make use of not necessarily barotropic EoS capable of modeling appropriately the finite temperature effects on a stationary axisymmetric star, using general entropy profiles
- Having in mind the use of realistic EoS's, we intend to extend the code for EoS's with electron fraction as a third parameter
- We plan to use this for developing quasi-stationary models of proto-neutron stars

Thank You!