Weak nuclear interactions in Core-Collapse supernovae

Accouting for the full nuclei distribution

Outline

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Interactions and model

Interactions studied:

- **Neutrino-nucleus elastic scattering**: $\nu + X \rightarrow \nu + X$ $(\nu = \nu_e, \bar{\nu_e}, \nu')$
- **Electron-capture**: ${}^{A}_{Z}X + e^- \rightarrow {}^{A}_{Z-1}X' + \nu_e$

Hypotheses:

- All reactions in thermodynamic equilibrium except for weak interactions
- The neutrino gas follows a fermi-dirac distribution with effective potential μ_e^{eff} ("Leakage scheme")
- Assumes nuclei distribution is equivalent to average nucleus $a_{heavy} = \langle A \rangle$, $z_{heavy} = \langle Z \rangle$. (=SNA, Single Nucleus Approximation)

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Questions

- How important is the impact on interactions strength?
- How important is the impact on supernova simulations ? (Y_e, L_ν)...

Program structure

- An external program computes electron-capture rates and scattering cross-sections for each $(T, n_b, Y_e, \mu_{nu}^{eff})$ of the phase-space.
  - Input: CompOSE tables (including nuclei distribution)
  - Output: HDF5 format tables containing capture rates λ_{ec} and scattering cross-sections σ
- CoCoNuT imports these tables and use quadrilinear interpolation to recover σ's and λ_{ec} (neutrino scattering on the nucleus - cross-sections used to be calculated on the fly)

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Cross-section expression

Same as employed in [2].

$$\sigma(A,Z) = \frac{\sigma_0 A^2 \epsilon_\nu^2}{m_e} Y_X n_b \frac{F_5(\mu_\nu/T)}{F_3(\mu_\nu/T)} \tag{1}$$

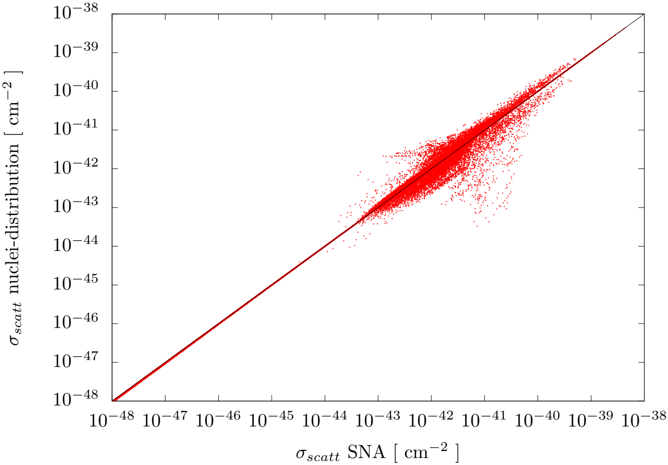
$$\times \left[(C_A - C_V) + (2 - C_A - C_V) \frac{2Z - A}{A} \right]^2 \tag{2}$$

$$\times \frac{f(r_X^2 \epsilon_\nu^2)}{1 + \exp(-\epsilon_\nu/T)} \tag{3}$$

$\Longrightarrow$ SNA $\rightarrow \sum_{A,Z}$

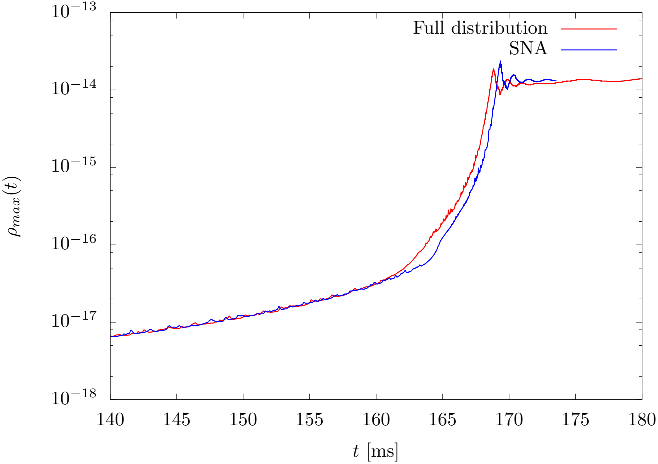
$\sigma_{scattering}$

0.01 MeV $< T <$ 5 MeV, $10^{-8}\mathrm{fm}^{-3} < n_b < 10^{-2}\mathrm{fm}^{-3}$, $Y_e > 0.1$



Impact on supernova

$M = 40 M_\odot$



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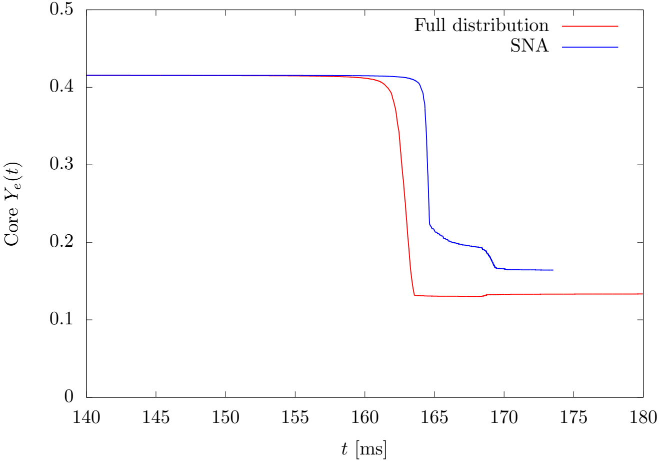

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Rate expression

Previously used Bruenn 1985[1]

- proton capture ($p + e^- \to n + \nu_e$): unchanged
- nucleus capture: B. Peres used Bruenn expr. with shell blocking effect:

$$
\begin{aligned}
\lambda(A,Z) = {} & \frac{7G_F^2}{\pi^2} Y_X |V_{ud}|^2 g_A^2 \\
& \times \mathcal{N}(Z,N) \\
& \times \int E^2 (E+Q)^2 \sqrt{1 - \frac{m_e^2}{(E+Q)^2}} \\
& \times \quad S(E+Q,\mu_e)(1 - S(E,\mu_\nu))\,\mathrm{d}E
\end{aligned}
$$

$\Longrightarrow$ Shell effect shown to be removed at high densities
$\Longrightarrow$ SNA $\to \sum_{A,Z}$

Rate expression

$\Longrightarrow$ full expression too expensive to compute.
Instead: Parametrization by Langake et al.

$$\lambda = \frac{\beta \ln 2}{K} \left(\frac{T}{m_e} \right)^5 \Big(F_4(\eta) - 2\chi F_3(\eta) + \chi^2 F_2(\eta) \Big) \tag{4}$$

$(\chi = (Q - \Delta E)/T,\ \eta = \chi + \mu_e/T,\ F_i(t) = \int_0^{+\infty} \frac{x^i dx}{1 + \exp(x - t)})$.
$\Longrightarrow$ Problem: doesn't account for ν blocking. Suggested param alternative:

$$\lambda = \frac{\beta \ln 2}{K} \left(\frac{T}{m_e} \right)^5 \int_0^{\infty} \tag{5}$$

Outline

Next

- Electron capture: test parametrization relevance
- Electron capture: impact on collapse simulations
- Compute L_ν

References I

[1] S. W. Bruenn. Stellar core collapse - Numerical model and infall epoch. *Astr.J*, 58:771–841, August 1985.

[2] Bruno Peres. Transport de neutrinos dans les supernovas gravitationnelles. page 1 vol. (207 p.), 2013. Thèse de doctorat dirigée par Novak, Jérôme et Oertel, Micaela Astronomie et astrophysique Observatoire de Paris 2013.

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a_{heavy}/z_{heavy} problem

$0.01 \text{ MeV} < T < 5 \text{ MeV}$, $10^{-8}\mathrm{fm}^{-3} < n_b < 10^{-2}\mathrm{fm}^{-3}$, $Y_e > 0.1$