Charged current interactions of muon neutrinos in supernova

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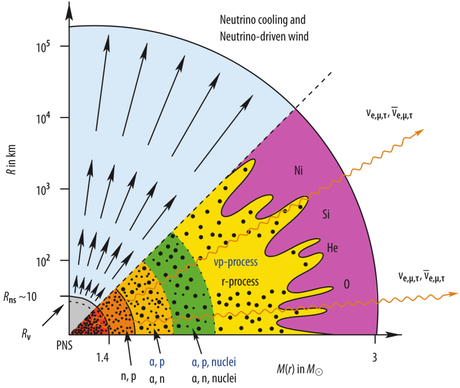
Neutrinos in core collapse supernova

A core collapse supernova releases 99% of it's energy, up to 10^{53} *erg* in neutrinos. Hence they affect the evolution of the supernova and the protoneutron star in multiple ways:

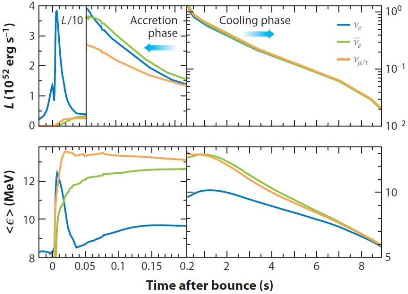
- Neutron to proton ratio for nucleosynthesis
- Matter ejection in neutrino driven wind
- Cooling and deleptonization



H.Th.Janka et al.,Phys.Rep.442(2007)38-74

Role of μ and τ flavor neutrinos

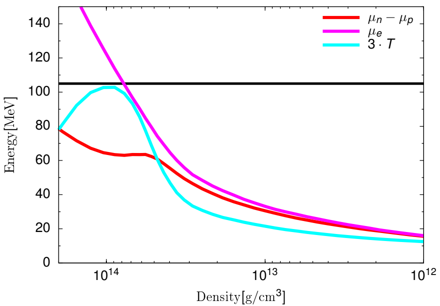
- ν_μ and ν_τ transport energy from core of PNS ($> 50\%$)
- Charged current interactions are assumed to be negligible
- Emission from higher density than ν_e
- Current CC-SN simulations treat ν_μ, ν_τ as a single type ν_x
- Production of ν_x - $\bar{\nu}_x$ pairs only
- Spectral differences between ν_x and $\bar{\nu}_x$ could arise from neutral current scattering with electrons and neutrons



Hüdepohl et al., PRL 104,251101(2010)

Charged current interactions for μ-flavor

- Charged current reactions suppressed by large Q values: m_μ, m_τ
- In the core of PNS μ_e and $\mu_n - \mu_p$ are of the order of m_μ
- Production of μ^+ and τ always suppressed



$18M_\odot$-modell from T.Fischer et al.,(2010) A&A 517 A80

$\Rightarrow$ Charged current reactions could be a significant opacity source for ν_μ.
This could induce spectral differences between ν_μ and other ν_x (potentially interesting for oscillations).

Charged current interactions for μ-flavor

Charged current weak reactions for μ-type neutrinos:

- $\nu_\mu + n \rightarrow p + \mu^-$ nucleonic absorption
- $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$ purely leptonic, difficult kinematics
- $\nu_\mu + \bar{\nu}_e + e^- \rightarrow \mu^-$ inverse muon decay
- $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$ production of muons without ν_μ

Concept of neutrinosphere

The neutrinosphere R_{sp} is the radius where emitted neutrinos become free streaming. It is defined via the optical depth τ:

$$\tau\left(R_{sp}\right) = \int_{R_{sp}}^{\infty} \frac{1}{\lambda_{tot}\left(r\right)} \mathrm{d}r = \frac{2}{3}$$

- Scattering sphere R_{Scat}: All opacities contribute equally

$$\frac{1}{\lambda_{tot}} = \sum \left(\frac{1}{\lambda_{scatt}} + \frac{1}{\lambda_{abs}} \right)$$

Raffelt, APJ 561(2001)840-914

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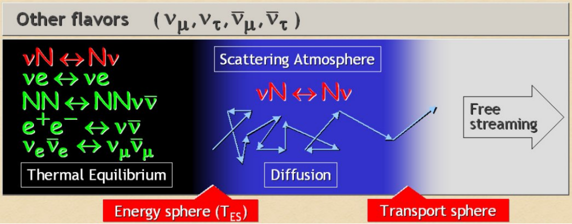
- Energy sphere R_{Eff}: Last energy exchange

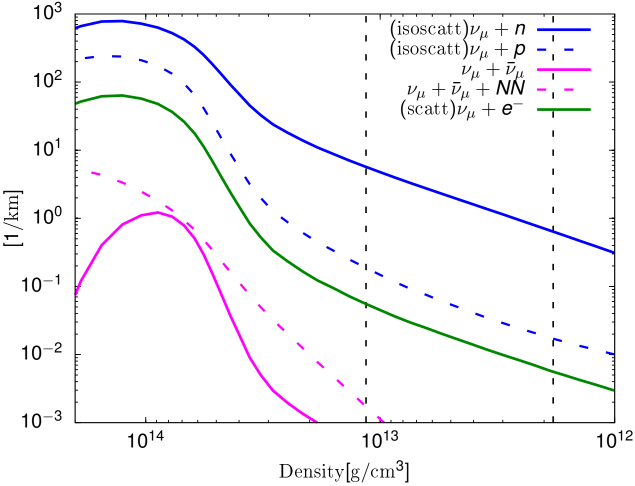
$$\frac{1}{\lambda_{tot}} = \sqrt{\sum \frac{1}{\lambda_{abs}}} \cdot \sqrt{\sum \left(\frac{1}{\lambda_{scatt}} + \frac{1}{\lambda_{abs}}\right)}$$



Raffelt, APJ 561(2001)840-914

Mean free path and neutrino sphere

Inverse mean free path for ν_μ at 722 ms postbounce



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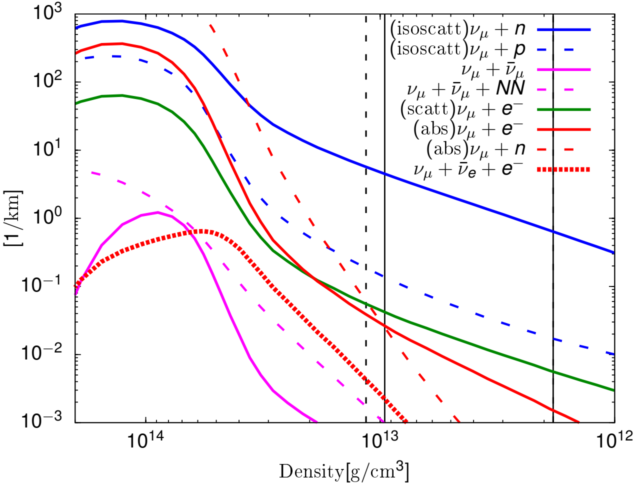
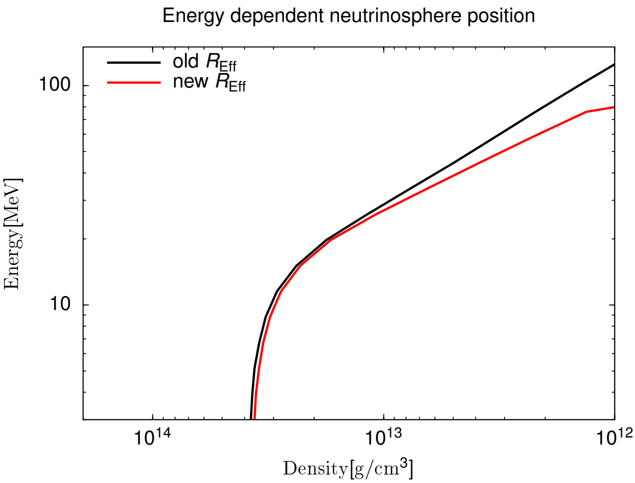


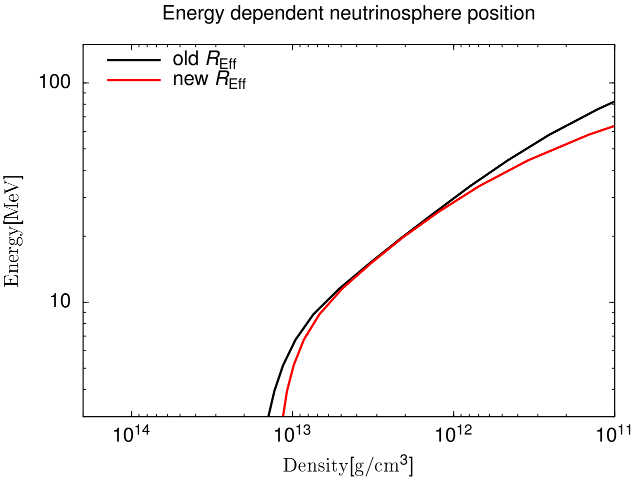
Mean free path and neutrino sphere

Energy dependent R_{Eff} for ν_μ at 722 ms postbounce



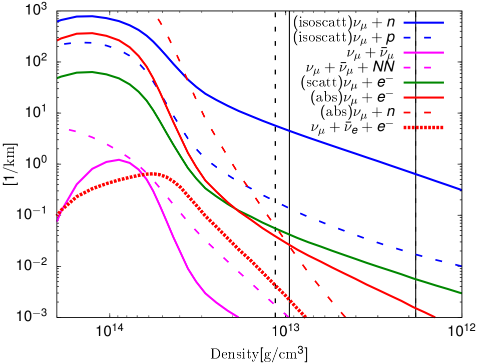
Mean free path and neutrino sphere

Energy dependent R_{Eff} for ν_μ at 168 ms postbounce



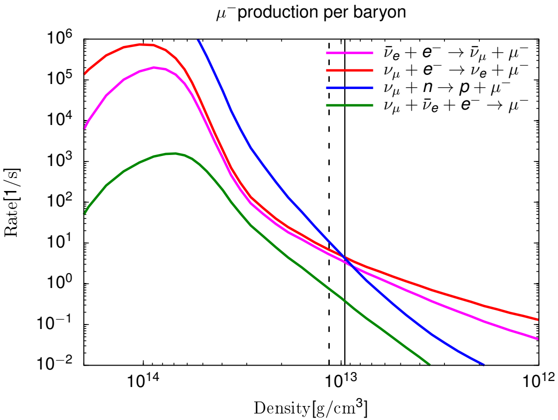
Mean free path and neutrino sphere

- Energy sphere shifted.
- $\Delta T \simeq 200 - 300 keV$
- Scattering sphere not affected



Muonic reactions are significant at the region of ν_μ decoupling.
This will cause a difference to the spectrum of $\bar{\nu}_\mu$.
All these reactions will produce muons, but how fast is the timescale of muon production?

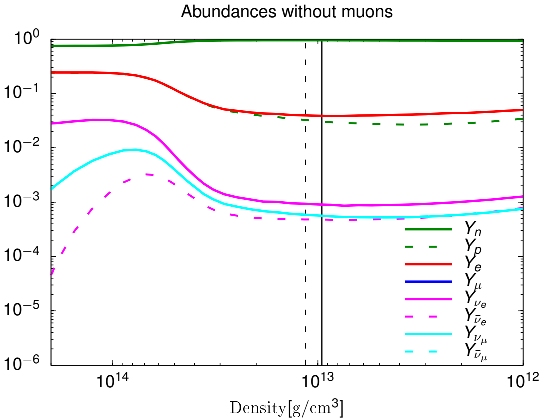
Muon production



Timescale for μ production faster than dynamical timescale
$\Rightarrow$ muons are in chemical equilibrium.

muon abundance in early PNS

New composition including muons. Net muon number must be zero inside effective ν_μ-sphere.



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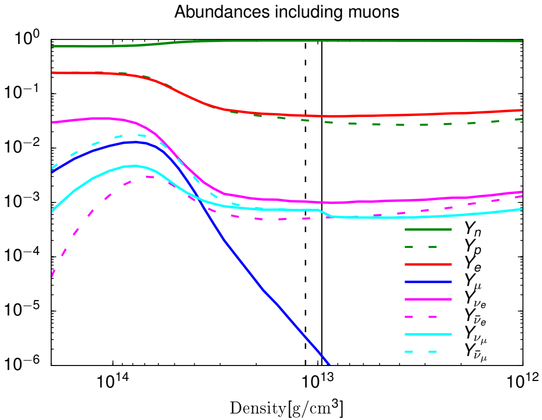
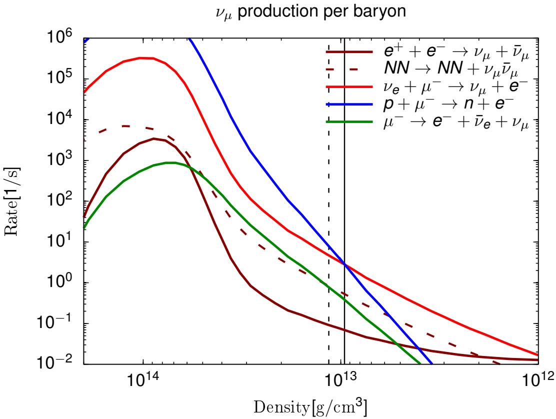


Production of ν_μ

ν_μ must be produced by pair process in the first place. This has to happen fast enough.



Summary and Outlook

- We have calculated charged-current reactions for ν_μ in supernova.
- At densities $\gtrsim 10^{13}$ g cm^{-3} they become one of the dominating sources of ν_μ opacity, manifested by an outward shift of the energy neutrinosphere.
- We expect that the spectrum of emitted ν_μ will be different from $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$. This should lead to a production of net muon number in the PNS core.
- Further, we find muons reach equilibrium in very short timescales.
- PNS deleptonization timescale could be affected.
- Possibile impact in collective neutrino oscillations.