$n - \alpha$ neutrino pair bremsstrahlung processes in supernovae

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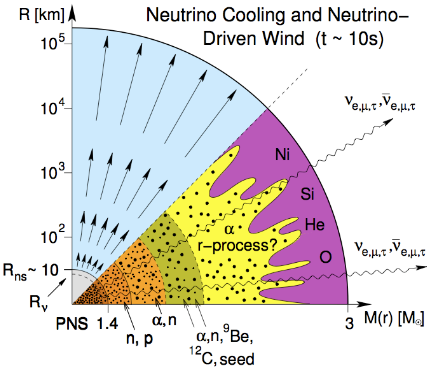
July 26, 2013

(in progress with Sonia Bacca and Achim Schwenk)

Type II supernovae

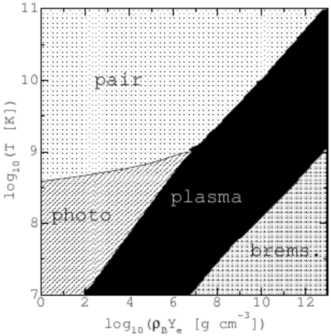


- Neutrino production and scattering processes determine the initial spectra. Oscillations then modify it *Fuller, Duan, Raffelt, Carlson, Chen, ...*
- Neutrinos may also play a role in the revival of the stalled shock *Colgate, White (1960), Wilson (1985)*

ν near the proto-neutron star

- Most of the gravitational energy $\sim 3 \times 10^{53}$ergs taken away by the neutrinos
- This is a robust prediction of supernova theory and the neutrino spectrum is an important observable
- Immediately after the collapse neutrinos come from a thin region near the surface of the proto-neutron star – the neutrino sphere

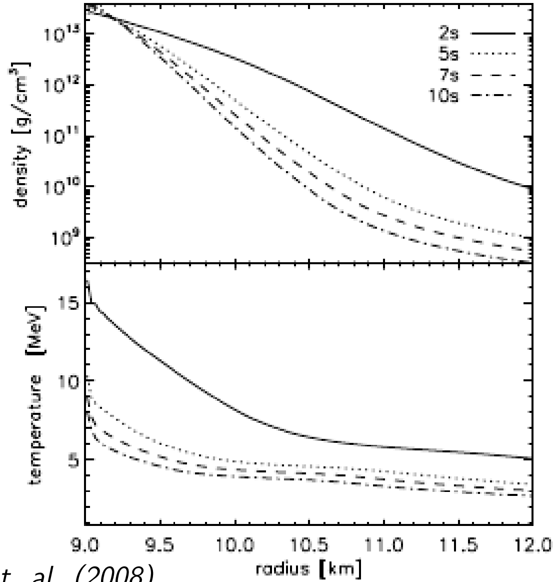
Neutrino production processes



- Pair $e^+ + e^- \to \nu + \bar{\nu}$
- Photo $e^\pm + \gamma^* \to e^\pm + \nu + \bar{\nu}$
- Plasma $\gamma^* \to \nu + \bar{\nu}$
- Brems $(n, p) \to (n, p) + \nu + \bar{\nu}$

- *Prakash et. al. (Review 2004)*

Temperature versus r

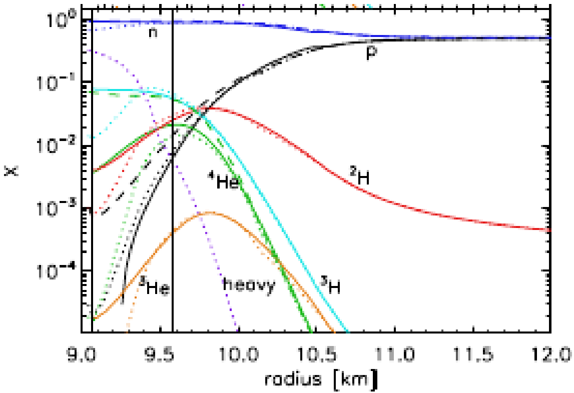


Arcones et. al. (2008)

Effects of nuclei on neutrinos

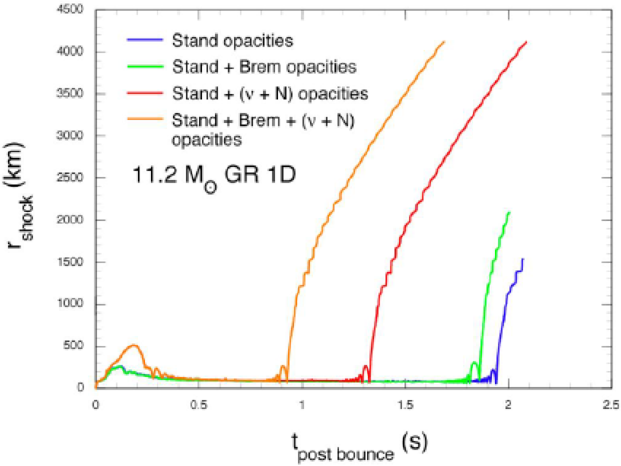
- We are looking at processes just after collapse. The temperature $\lesssim 15$MeV
- For the propagation through the crust, the relevant distance is $9-12$km from the centre
- In this region, there are light nuclei like deuteron, triton, and helium. We focus on Helium

Nuclei near the neutrinosphere



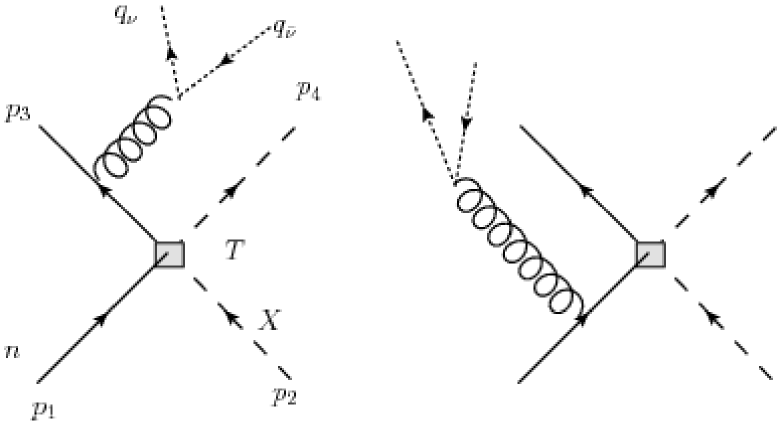
(Arcones et. al.)

Effects



(A. Mezzacappa (2007))

$\nu\bar{\nu}$ bremsstrahlung production



Bremsstrahlung matrix element

- The matrix element is given by

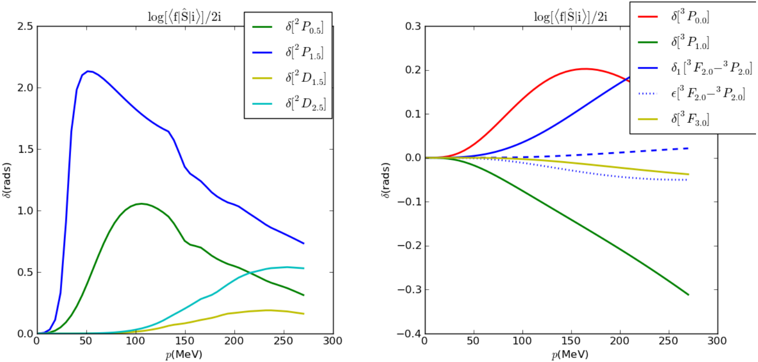
$$i\mathcal{M} = \frac{iG_F}{\sqrt{2}}\frac{C_A}{q^0} l^i \chi_4^\dagger [\sigma^i, T(k)]\chi_2$$

- Proportional to the commutator of the T matrix with the Pauli matrices
- The T matrix can be obtained from the phase shifts for different angular momentum phase shifts

$$T(\sigma', p'; \sigma, p) \sim \sum_{j,l,m_j,m_l,m} Y_{lm'}(\hat{p}') Y_{lm'}(\hat{p})$$

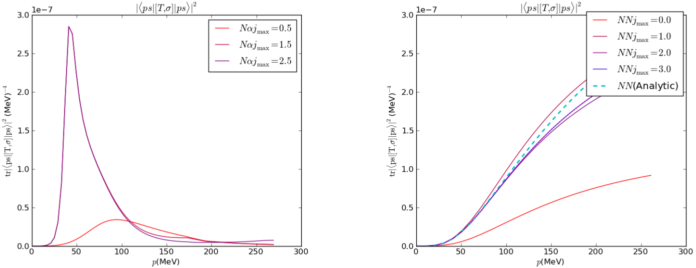
$$c((s, m_s')(l, m_l')|(jm_j)ls) c((s, m_s)(l, m_l)|(jm_j)ls) \frac{-1}{2\pi i}(e^{2i\delta_{l,j}(E)} - 1)$$

A comparison of the phase shifts



- Below threshold from *Arndt and Roper*
- Above threshold from *Amos et. al.*
- A prominent $p_{3/2}$ resonance at $\sim$ 0.9MeV leads to large phase shifts for $n\alpha$

Comparing $|[T(k), \sigma^i]|^2$

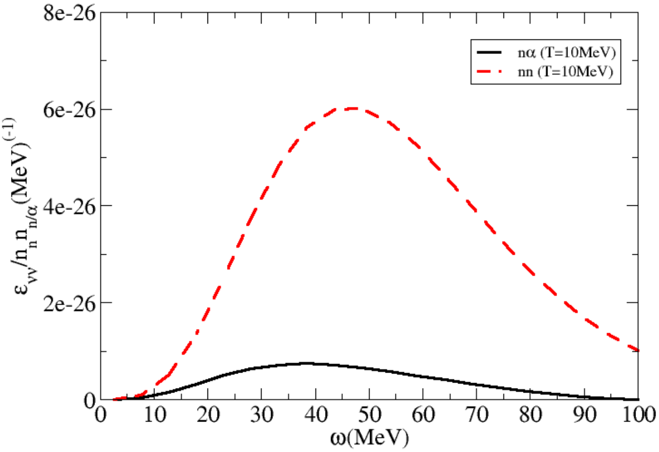


- Comparing $n\alpha$ and OPE
- Take p_i to be in the $\hat{z}$ direction and p_f in the $(1/2, 1/2, 1/\sqrt{2})$ direction
- Convergence as a function of j is good

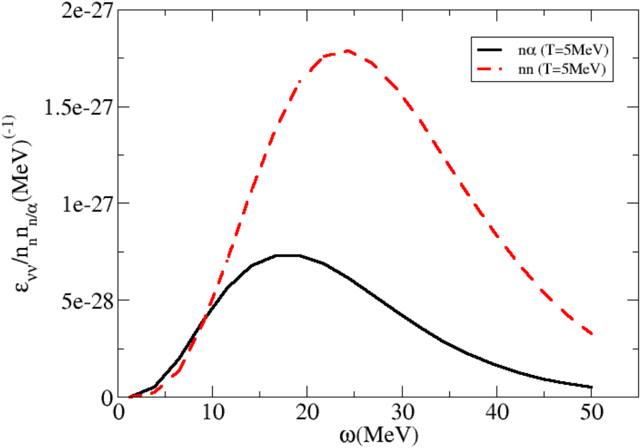
Bremsstrahlung contribution, comparing *nn* and $n\alpha$

- At low momenta, $n - \alpha$ scattering matrix is comparable or larger than $n - n$ scattering from one pion exchange
- On the other hand the density of α is a factor of $50 - 100$ smaller than n
- $$\epsilon_{\nu\bar{\nu}} \sim \int \Pi d^3p_i d^3q_j \frac{1}{e^{-e_1+\mu}+1}\frac{1}{e^{-e_2+\mu}+1}\frac{1}{e^{e_3-\mu}+1}\frac{1}{e^{e_4-\mu}+1} |M|^2\delta(p^\mu)(q^0_\nu + q^0_{\bar{\nu}})$$
- Near the neutrino sphere, the Boltzmann limit may be sufficient *Bacca et. al. (2012)*

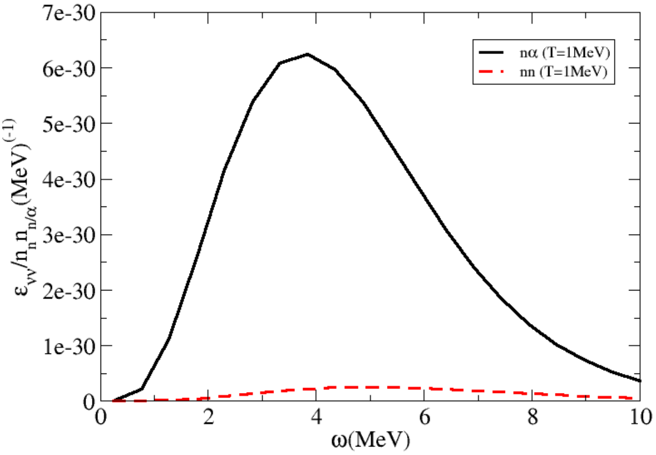
A comparison of the emissivities



A comparison of the emissivities



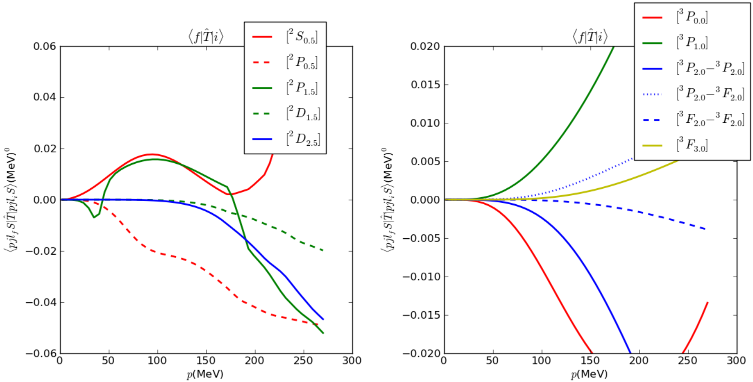
A comparison of the emissivities



Conclusions

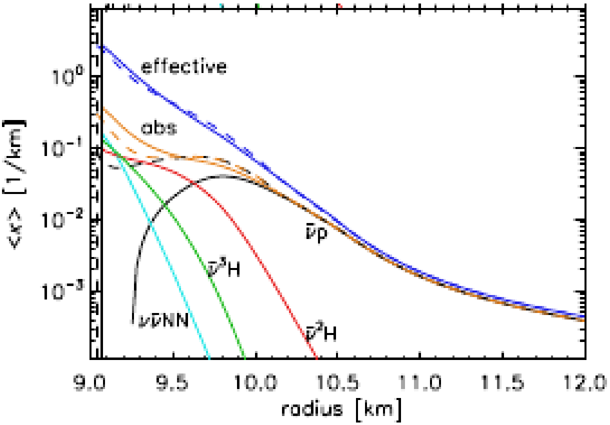
- At low temperatures, *n*α, $\nu\bar{\nu}$ bremsstrahlung can compete with *nn* bremsstrahlung
-
  - Can it affect the $\nu_{\mu,\tau}$ spectrum or $\bar{\nu}$ spectrum at low momenta?
  - Can it affect the dynamical evolution of the neutron star?

A comparison of the $T(^{2S+1}(L_f, L_i)_j)$ matrix



- A prominent $p_{3/2}$ resonance at $\sim$ 0.9MeV leads to large phase shifts for $n\alpha$

Effect on the neutrinosphere



(Arcones et. al.)