Neutrino interactions with supernova matter

A. Bartl, M. Voskresenskaya, C. J. Pethick, and A. Schwenk

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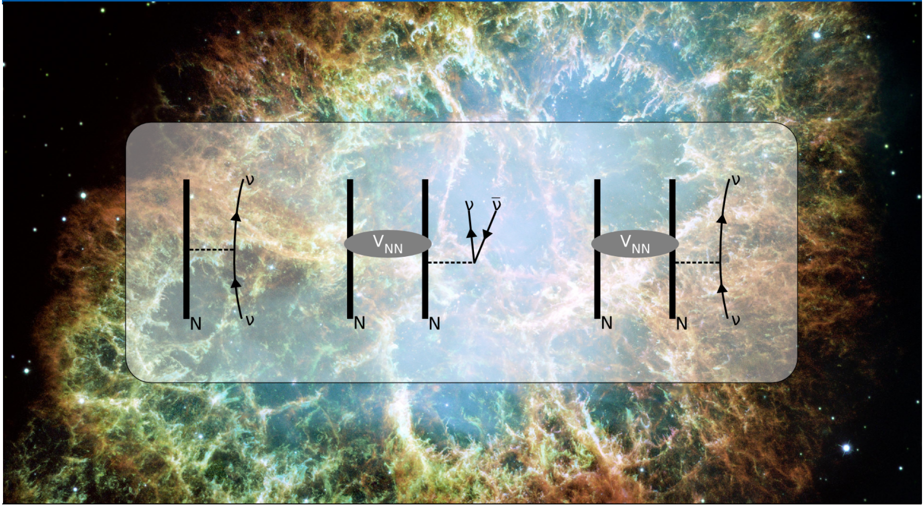

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Interaction rates in mixtures of protons and neutrons

Energy transfer in neutrino scattering

Conclusion

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Introduction:

Neutral-current neutrino processes

$$\nu e^{\pm} \longleftrightarrow \nu e^{\pm}$$

$$\nu\bar{\nu} \longleftrightarrow e^{+}e^{-}$$

$$\nu_x\bar{\nu}_x \longleftrightarrow \nu_e\bar{\nu}_e$$

$$\nu N \longleftrightarrow \nu N$$

$$\nu NN \longleftrightarrow \nu NN$$

$$\nu\bar{\nu} NN \longleftrightarrow NN$$

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Neutral-current neutrino processes

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Introduction:

Neutral-current neutrino processes

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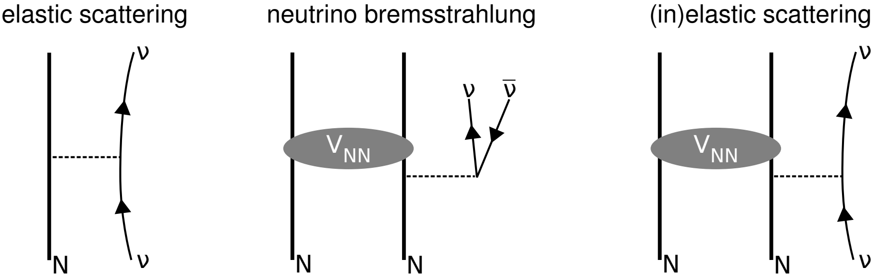


based on Raffelt (1996)

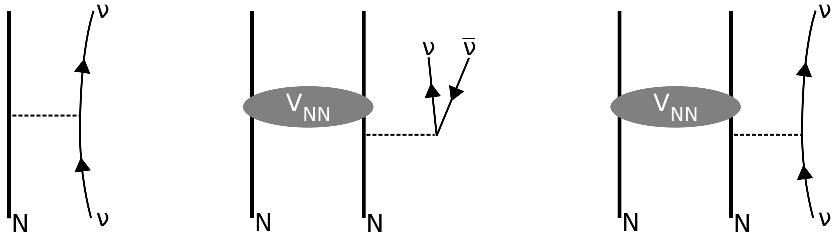
Differential cross section:

$$\frac{d^2\sigma}{d\cos\theta\, d\omega} = \frac{G_F^2 E_\nu^2}{4\pi^2}\left((3-\cos\theta)S_A(\omega,\mathbf{q}) + (1+\cos\theta)S_V(\omega,\mathbf{q})\right)$$

Introduction:

Neutral-current neutrino processes

elastic scattering | neutrino bremsstrahlung | (in)elastic scattering



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Differential cross section:

$$\frac{d^2\sigma}{d\cos\theta\, d\omega} = \frac{G_F^2 E_\nu^2}{4\pi^2}(3 - \cos\theta) S_A(\omega,\mathbf{q})$$

- relevant for bremsstrahlung and inelastic scattering at low energies

Introduction:
Rates in simulations

NN interaction rates described by Hannestad & Raffelt (HR) Hannestad & Raffelt, ApJ (1998)

- One-pion-exchange (OPE) interaction in Born approximation
- Long-wavelength limit ($\mathbf{q} \rightarrow 0$)
- NN interactions approximated by nn only
  $\Rightarrow$ no central terms, no Y_e dependence
- no correlations

Introduction:
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Goal of this work: Go beyond this

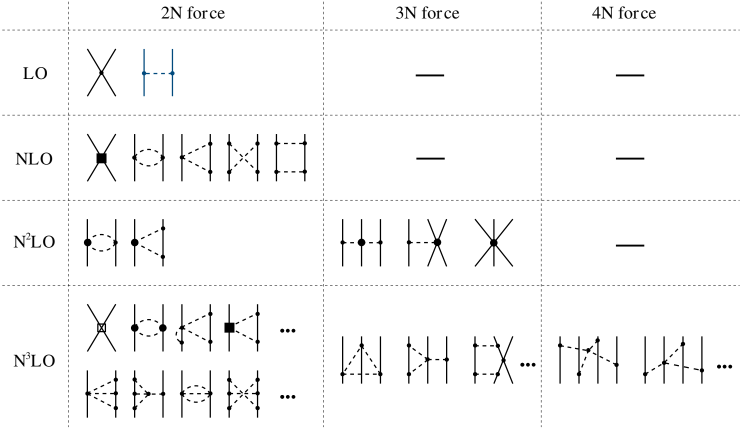
- generalize to mixtures
- include recoil effects together with NN interactions
- use modern nuclear interactions, consistent with EOS ($\to$ chiral EFT)
  Lykasov et al., PRC (2008), Bacca et al., PRC (2009) and ApJ (2012)

Introduction:
Chiral effective field theory

Weinberg, PLB (1990) and Nucl Phys B (1991), Entem and Machleidt, PRC (2003), Epelbaum et al., Nucl Phys A (2005)

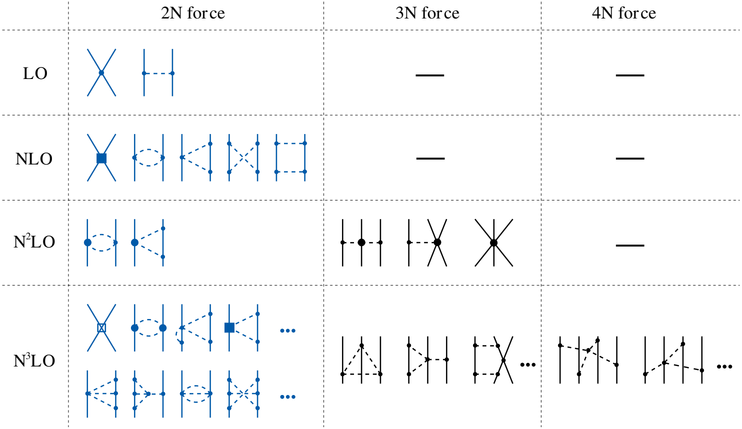
- Calculations with elementary degrees of freedom in QCD cumbersome
- Idea: Instead use relevant degrees of freedom at energy scale in question
- For $Q \lesssim m_\pi \approx 140\,\text{MeV}$: nucleons and pions
- Systematic expansion in terms of momentum
- Provides uncertainties stemming from truncation
- Long-range parts: pion exchanges
  Short-range parts: contact terms with couplings fitted to experiment
- Including 3N forces, remarkably good results when applied to medium-mass nuclei Otsuka et al., PRL (2010), Holt et al., JPhG (2012), Roth et al., PRL (2012), Hagen et al., PRL (2012), Gallant et al., PRL (2012), Hergert et al., PRC (2013), Wienholtz et al., Nature (2013), Holt et al., PRC (2014), Hergert et al., PRC (2014), ...

Introduction:
Chiral effective field theory



Epelbaum, arXiv:1001.3229

Introduction:
Chiral effective field theory



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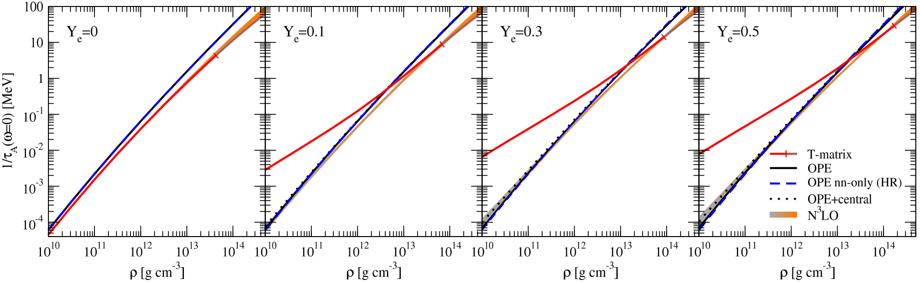
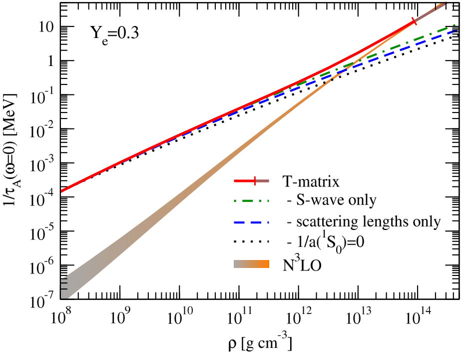
Interaction rates in mixtures of protons and neutrons:
Relaxation rate



- $T = 3\,\rho_{11}^{1/3}$ MeV
- in pure neutron matter, T-matrix and chiral N^{3}LO results agree
- resonant enhancement of T-matrix rates due to large NN scattering length in mixtures

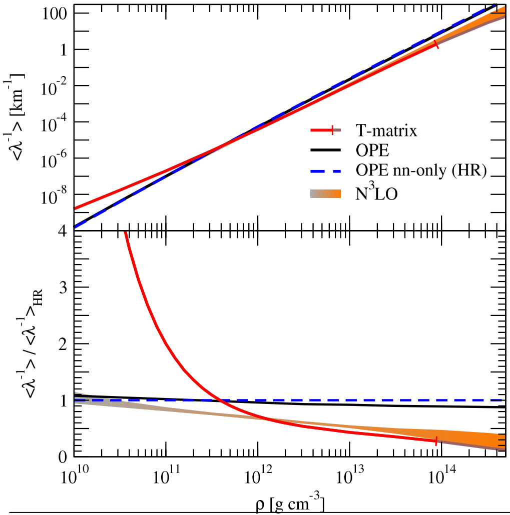
Bartl et al., PRL (2014)

Interaction rates in mixtures of protons and neutrons:
Resonant Enhancement



Interaction rates in mixtures of protons and neutrons:

Inverse mean-free path



- inverse mfp against pair absorption: $\langle \lambda^{-1} \rangle \propto \int_0^\infty d\omega\, \omega^5\, e^{-\omega/T} S_A(\omega)$
- discrepancy between OPE and T-matrix results reduced, but remains sizeable
- factor of ~2 difference between OPE and chiral N^3LO/T-matrix results around the neutrinosphere

Bartl et al., PRL (2014)

Interaction rates in mixtures of protons and neutrons:

Comparison to actual HR results

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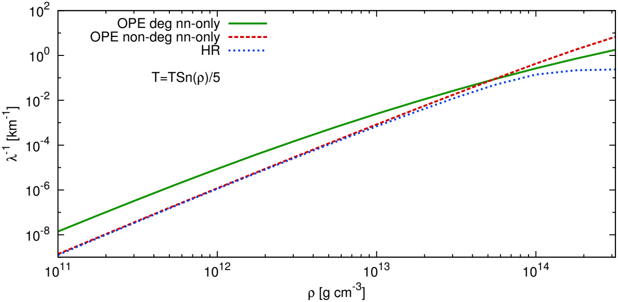
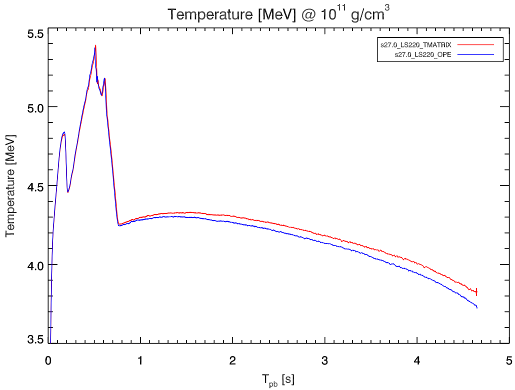
- OPE nn-only: our degenerate/non-degenerate formalism with HR-like assumptions (OPE, $Y_e = 0$) Lykasov et al., PRC (2008), Bacca et al., PRC (2009), Bartl et al., PRL (2014)
- HR: Fitted expressions derived in Hannestad & Raffelt, ApJ (1998)



- our formalism does not reproduce HR exactly; however, HR exhibits strange behavior at least at very degenerate conditions

Interaction rates in mixtures of protons and neutrons:
Astrophysical impact



- 27 $M_\odot$ star with a (T-matrix / OPEnn) correction factor to HR rates, simulated by R. Bollig and T. Janka
- T-matrix rate: slightly less cooling at late times

Astrophysical impact

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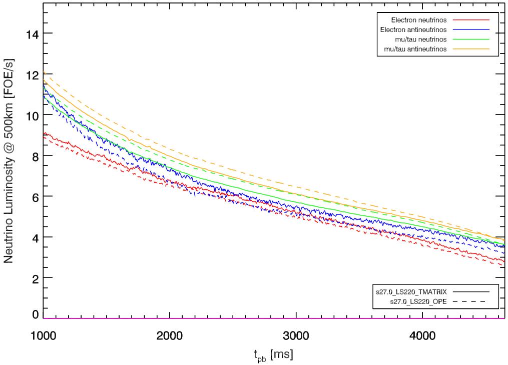
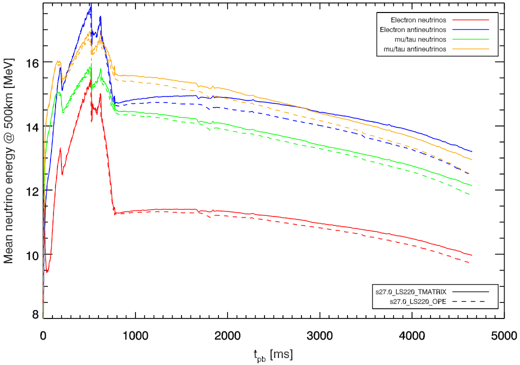


- 27 $M_\odot$ star with a (T-matrix / OPEnn) correction factor to HR rates, simulated by R. Bollig and T. Janka
- T-matrix rate: reduced luminosity of μ and τ (anti-)neutrinos, increased electron (anti-)neutrino luminosity

Interaction rates in mixtures of protons and neutrons:

Astrophysical impact



- 27 $M_\odot$ star with a (T-matrix / OPEnn) correction factor to HR rates, simulated by R. Bollig and T. Janka
- large local differences, small global changes
- T-matrix rate: slower neutron-star cooling, small Y_e reduction

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Energy transfer in neutrino scattering:

Formalism

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- root-mean-square energy transfer per collision

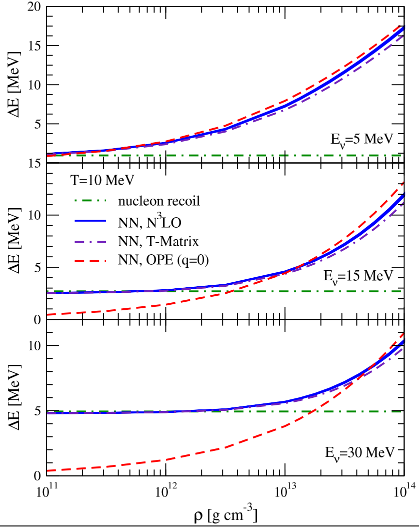
$$\Delta E = \sqrt{\frac{\langle (E - E')^2 \rangle}{\langle (E - E')^0 \rangle}}$$

- energy-exchange moments

$$\langle (E_\nu - E_{\nu'})^n \rangle = \int \frac{d^3 p_{\nu'}}{(2\pi)^3} (E_\nu - E_{\nu'})^n \, \Gamma(\omega, \mathbf{q})$$

- obtain an approximate expression for the non-degenerate structure factor at finite $\mathbf{q}$
- nn-only (for now)

Energy transfer in neutrino scattering:
Results



- OPE (q = 0) conceptionally similar to HR approach
- other NN lines include recoil
- N^{3}LO band spanned by EM 500, EGM 450/700 and EGM 450/700 potentials
- recoil dominates at small densities

Energy transfer in neutrino scattering:
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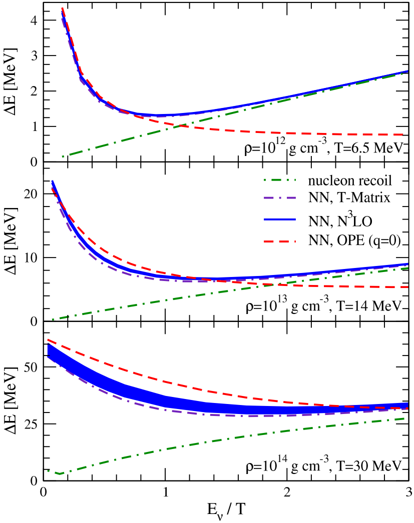

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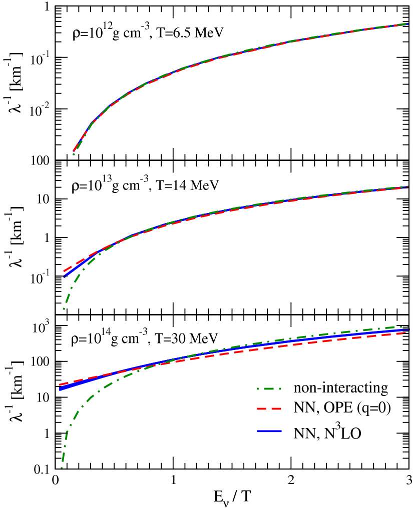

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- full **q** dependence not important for mean-free path

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Conclusion

- Goal: Better calculations of neutrino-matter interaction rates
- Formalism for supernova conditions (non-deg, $Y_e > 0$) in place

- N^3LO results differ significantly from OPE/HR results
- At low densities in mixtures, T-matrix calculations show important role of large scattering lengths

- Nucleon recoil can be included in NN scattering rate $\Rightarrow$ combined treatment of $N\nu \leftrightarrow N\nu$ and $NN\nu \leftrightarrow NN\nu$ scattering
- Energy transfer dominated by NN scattering at high ρ and T and low E_ν/T

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