Neutrinos in Heavy Baryon Chiral Perturbation Theory

Neutrino production in Supernova

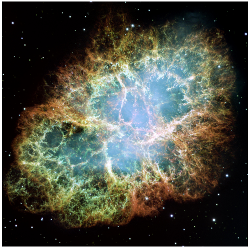
Sara Maggio

Technische Universität München

November 6, 2022

Table of contents

Motivation



Leading tool to probe the cosmic expansion; way to measure the Hubble constant; ”anthropically” relevant (O, F, Ne, Na, Mg, Al...).

Core-collapse SN [1].

What are we looking at? Why?

Fluxes and spectra of (SN) neutrinos are required for the understanding of [3]

- the explosion mechanism
- the birth of neutron star
- SN nucleosynthesis
- ...

Neutral current interactions → relevant contributions for the neutrino energy production behind the stalled shock wave

$$\nu \mathrm{N} \to \mathrm{N}\nu, \quad \nu\bar{\nu}\mathrm{NN} \leftrightarrow \mathrm{NN}, \quad \nu\mathrm{NN} \leftrightarrow \mathrm{NN}\nu \tag{1}$$

- $\nu \mathrm{N} \to \mathrm{N}\nu$ dominant opacity source for μ and τ neutrinos,
- $\nu\bar{\nu}\mathrm{NN} \leftrightarrow \mathrm{NN}$ relevant energy- and number-changing process,
- $\nu\mathrm{NN} \leftrightarrow \mathrm{NN}\nu$ more effective (by a factor of 10) for energy exchange [3].

Heavy baryon Chiral Perturbation Theory

1. QCD Lagrangian and chiral symmetry
2. UV Lagrangian after Electroweak symmetry breaking
3. implement this in the QCD Lagrangian with external fields
4. construction of the operators in Chiral Perturbation Theory
5. EOM elimination
6. Heavy Baryon Limit

QCD Lagrangian

QCD Lagrangian

$$\mathcal{L}_{\mathrm{QCD},0} = -\frac{1}{4}\mathrm{G}^{\mu\nu}\mathrm{G}_{\mu\nu} + \mathrm{i}\bar{\mathrm{q}}\not{\mathrm{D}}\mathrm{q}, \tag{2}$$

invariant under

$$\mathrm{SU(N_f)_L \times SU(N_f)_R \times U(1)_V \times U(1)_A} \tag{3}$$

breaking due to $\langle \bar{\mathrm{q}}_\mathrm{R} \mathrm{q}_\mathrm{L} \rangle$

$$\mathrm{SU(N_f)_L \times SU(N_f)_R \times U(1)_V \times U(1)_A \to SU(N_f)_V \times U(1)_V} \tag{4}$$

$\to$ Goldstone Bosons.

Chiral Lagrangian

- parametrization of the GBs for $N_f = 2$

$$U(\pi(x)) = e^{i\frac{\pi^a(x)\tau^a}{f_\pi}} \tag{5}$$

- mass term

$$\chi = 2B(s - ip), \tag{6}$$

- external vector and axial vector fields (isovector and isoscalar)

$$v_\mu^{(IV)}, \quad a_\mu^{(IV)}, \quad v_\mu^{(IS)}, \quad a_\mu^{(IS)} \tag{7}$$

How do we find them?

Heavy baryon Chiral Perturbation Theory

- UV Lagrangian after Electroweak symmetry breaking

$$\mathcal{L} = -\frac{e}{\sin\theta_W \cos\theta_W} Z_\mu \left[\bar{q}_i^L \gamma^\mu \frac{\tau^3}{2} q_i^L - \sin\theta_W^2 \left(\frac{2}{3} \bar{u}\gamma^\mu u - \frac{1}{3} \bar{d}\gamma^\mu d \right) \right] \tag{8}$$

- implement this in the QCD Lagrangian with external fields

$$\mathcal{L} = -\bar{q}(s - i\gamma_5 p)q + \left(\bar{q}\gamma^\mu\left(v_\mu + \frac{1}{3} v^s_\mu\right)q\right)_{q=(u,d)^T} + \left(\bar{q}\gamma^\mu(a_\mu + a^s_\mu)\gamma_5 q\right)_{q=(u} \tag{9}$$

Doing the matching we get the fields for the chiral Lagrangian, transforming as

$$l_\mu \rightarrow L l_\mu L^\dagger + iL\partial_\mu L^\dagger, \tag{10}$$

$$r_\mu \rightarrow R r_\mu R^\dagger + iR\partial_\mu R^\dagger, \tag{11}$$

to keep the invariance.

Construction of the operators in Chiral Perturbation Theory

- inclusion of the nucleons, $\mathcal{N} = (\mathrm{p}, \mathrm{n})^{\mathrm{T}}$

$$\mathrm{D}_\mu = \partial_\mu + \Gamma_\mu + \hat{\Gamma}_\mu, \tag{12}$$

$$\mathrm{D}_\mu \mathcal{N} \to \mathrm{K}(\mathrm{L}, \mathrm{R}, \mathrm{U}) \mathrm{D}_\mu \mathcal{N}, \tag{13}$$

- building blocks

$$\mathrm{u}_\mu, \quad \mathrm{u}'_\mu = \mathrm{K} \mathrm{u}_\mu \mathrm{K}^\dagger, \quad \langle \chi_+ \rangle, \quad \tilde{\chi}_+, \quad \langle \mathrm{F}^+_{\mu\nu} \rangle, \quad \tilde{\mathrm{F}}^+_{\mu\nu} \tag{14}$$

- parity and charge symmetry to find the most general form of the Lagrangian and the contact terms

- EOM elimination,
  Using the equation of motion at leading chiral order, $\not{D}\mathcal{N} \to \mathrm{i}m\mathcal{N}$, we can reduce the number of terms at a given chiral order, since the difference is one order higher, at $O(p^2)$ [4]

$$\mathbb{I}; \tag{15}$$

$$\gamma_5\gamma_\mu, D_\mu; \tag{16}$$

$$g_{\mu\nu}, \sigma_{\mu\nu}, \gamma_5\gamma_\mu D_\nu, D_{\mu\nu}; \tag{17}$$

- Heavy Baryon Limit

$$p^\mu = mv^\mu + l^\mu, \quad \text{with} \quad v \cdot l << m \tag{18}$$

  It is possible to separate the Nucleon field into an heavy and light component and integrate out the heavy one
- finite density nucleon propagator

$$iG(p) = \frac{i}{k^0 + i\epsilon} - 2\pi\delta(k^0)\Theta(p^0)\Theta(k_f - |\vec{k}|) + O(\frac{1}{m}) \tag{19}$$

$$\mathcal{L} = \mathcal{L}_{\pi} + \mathcal{L}_{\mathrm{NN}} + \mathcal{L}_{\mathrm{NNN}} + \mathcal{L}_{\pi\mathrm{N}} + \mathcal{L}_{\pi\mathrm{NN}}, \tag{20}$$

$$\mathcal{L}_{\pi}^{(2)} = \frac{1}{4} f_{\pi}^{2} \{[\nabla_{\mu} U^{\dagger} \nabla^{\mu} U + \chi^{\dagger} U + \chi U^{\dagger}]\} \tag{21}$$

$$\mathcal{L}_{\mathrm{NN}}^{(0)} = -\frac{1}{2} C_{S} (\bar{N}N)(\bar{N}N) + 2 C_{T} (\bar{N}SN) \cdot (\bar{N}SN) \tag{22}$$

$$\mathcal{L}_{\mathrm{NNN}}^{(0)} = -\frac{1}{2} \frac{c_{E}}{f_{\pi}^{4} \Lambda_{\chi}} (\bar{N}N)(\bar{N}\tau N) \cdot (\bar{N}\tau N) \tag{23}$$

$$\mathcal{L}_{\pi\mathrm{N}}^{(1)} = \bar{N}(iv \cdot D + g_{A} S \cdot u) N \tag{24}$$

$$\mathcal{L}_{\pi\mathrm{N}}^{(2)} = -\frac{1}{2m} \bar{N} \left(D^{2} + i g_{A} \{S \cdot D, v \cdot u\} \right) N + \sum_{i=1}^{7} \hat{c}_{i} \bar{N} \hat{O}_{i}^{(2)} N \tag{25}$$

$$\mathcal{L}_{\pi\mathrm{NN}}^{(1)} = \frac{c_{D}}{2 f_{\pi}^{2} \Lambda_{\chi}} (\bar{N}N)(\bar{N} S_{\mu} u^{\mu} N) \tag{26}$$

Antineutrino pair production

We can compute what we want!

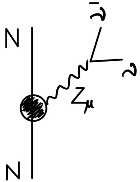
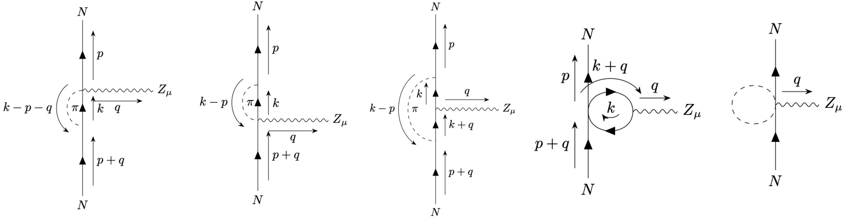


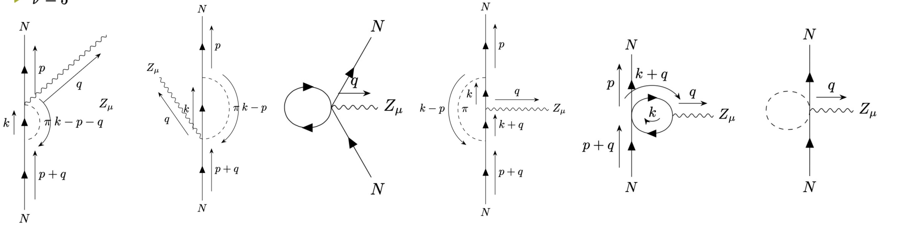
Figure: Neutrinos pair production process.

Example of diagrams

- $\nu = 2$



- $\nu = 3$



Some results

- Same cross section that we get at tree level with the 4 fermions effective Lagrangian.
- Vertex corrections:
  Tree level NNZ_μ: only two structure CSP[ϵ,σ] and SP[ϵ,v];
  NNZ_μ corrections at $\mathcal{O}(q^0)$: 6 structures: CSP[ϵ,σ], SP[ϵ,v], SP[ϵ, v]CSP[p, σ], CSP[ϵ, p] CSP[p, σ], CSP[p, $\epsilon\times\sigma$], CSP[p, ϵ];
  New structures at $\mathcal{O}(q^1)$ and so on;
  Computed also zero density corrections up to $\nu = 3$.
- Ongoing: understanding what we got for the NN$\rightarrow\nu\nu$ matrix element squared.

Finite density corrections for g_A

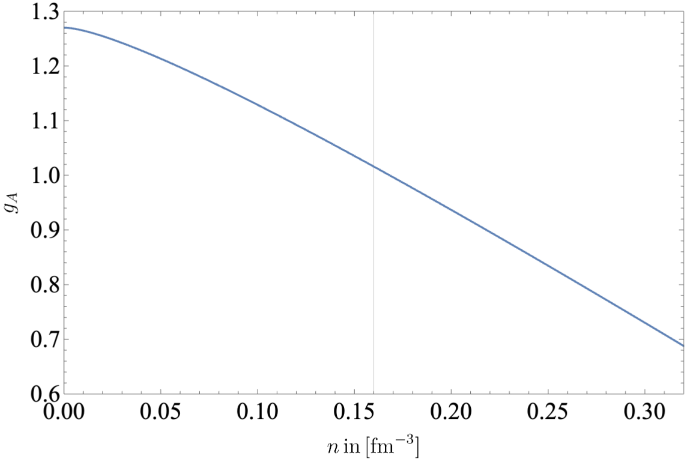


Figure: g_A coupling with finite density corrections.

Summary

- Neutrino-Nucleon scattering in high density environment
- systematically computed with HBChPT + density corrected nucleon propagator

$\rightarrow$

- matching with effective fermions interactions
- vertex corrections NNZ_μ
- scattering element $\mathrm{NN} \rightarrow \nu\nu$
- finite density corrections for $\mathrm{g_A}$

References

[1] Image Credit: NASA, ESA, J. Hester, A. Loll (ASU).
[2] T. Janka et al. Neutrino-driven explosion of a 20 solar-mass star in three dimensions enabled by strange-quark contributions to neutrino-nucleon scattering.
[3] G. Raffaelt et al. Supernova Neutrino Opacity from Nucleon-Nucleon Bremsstrahlung and Related Processes
[4] N. Fettes, U.-G. Meissner, M. Mojzis and S. Steininger, The Chiral effective pion nucleon Lagrangian of order p^4, Annals Phys. 283 (2000) 273 [arXiv:hep-ph/0001308].