15$^{\text{th}}$ Patras workshop on axions, WIMPs and WISPs

Freiburg, 3$^{\text{rd}}$ - 7$^{\text{th}}$ June 2019

Improved axion emissivity from a supernova and the SN1987A bound

Based on a work in progress in collaboration with

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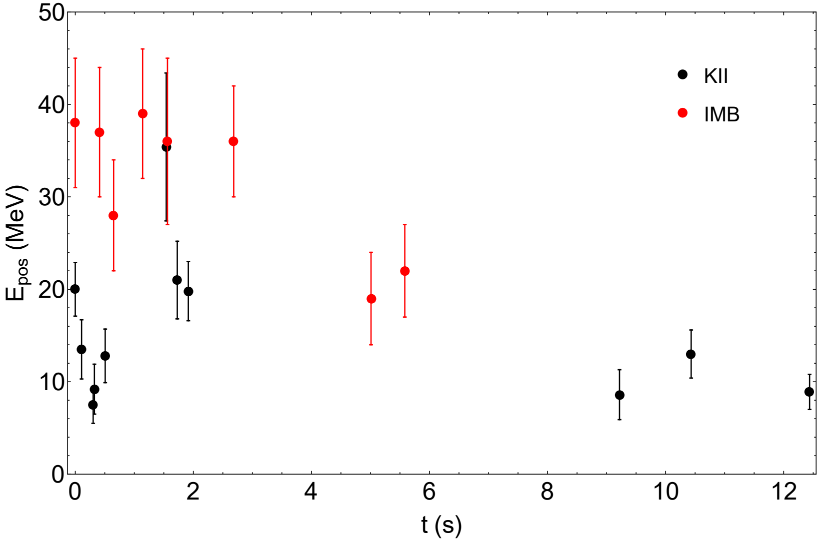
Outline

- Introduction to SN1987A
- Axion emissivity beyond One-Pion-Exchange (OPE)
- Revisiting the SN axion bound
- Conclusions

SN1987A: neutrino signal

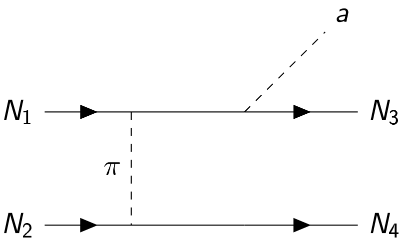
$\sim 10^{53}$ erg emitted as neutrinos with energy $\sim O(15\,\mathrm{MeV})$ in $\sim 10\,\mathrm{s}$



Axion production in SNe

M. S. Turner, Phys. Rev. Lett. **60** (1988)

SN axions are produced by nucleon-axion bremsstrahlung



in the One Pion Exchange (OPE) approximation and neglecting the pion mass, the matrix element is

$$S \times \sum |\mathcal{M}|^2 = \frac{64}{3} g_a^2 m_N^2 \left(\frac{f}{m_\pi} \right)^4$$

The energy-loss rate in OPE

R. P. Brinkmann *et al.*, Phys. Rev. D **38** (1988)

The axion emissivity is

$$Q_a = \int \prod_{i=1}^{4} \frac{d^3\mathbf{p}_i}{(2\pi)^3 2m_N} \frac{d\omega_a}{(2\pi)^3 2\omega_a} S \times |\mathcal{M}|^2$$
$$(2\pi)^4 \delta^4(P_f - P_i) f_1 f_2 (1 - f_3)(1 - f_4)$$

and then

$$Q_a^{(0)} = 64 g_a^2 \left(\frac{f}{m_\pi} \right)^4 m_N^{5/2} T^{13/2} \times F(\bar{\xi}, \hat{\mu}_n, \hat{\mu}_p)$$

where F depends on the nucleons degeneracy parameters

Beyond the OPE approximation

- Non-zero pion mass in the propagator$\rightarrow$ $\sqrt{3m_N T} \sim m_\pi$
- Two-pions exchange$\rightarrow$ Important around $2\mathrm{fm} \simeq 1.5{m_\pi}^{-1}$
- Effective nucleon mass$\rightarrow$ $m_N^*(\rho)$
- Multiple nucleon scatterings$\rightarrow$ Nucleon spin fluctuations

Non-zero pion mass in the propagator

G. Raffelt *et al.*, Phys. Rev. D **52**, 1780 (1995)

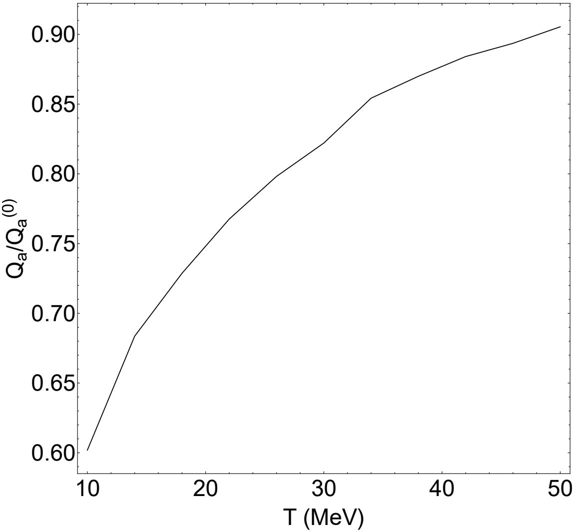
The pion propagator is

$$\frac{|\mathbf{k}|^2}{|\mathbf{k}|^2 + m_\pi^2}$$

And the matrix element can be written as

$$S \times \sum |\mathcal{M}|^2 = \frac{64}{3} g_a^2 m_N^2 \left(\frac{f}{m_\pi}\right)^4 (\mathcal{A}_{nn} + \mathcal{A}_{pp} + 4\mathcal{A}_{np})$$

where $\mathcal{A}_{NN}$ contains the pion propagator



$Q_a/Q_a^{(0)}$ with pion mass correction in function of T

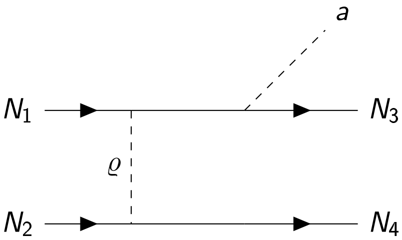
Two-pions exchange

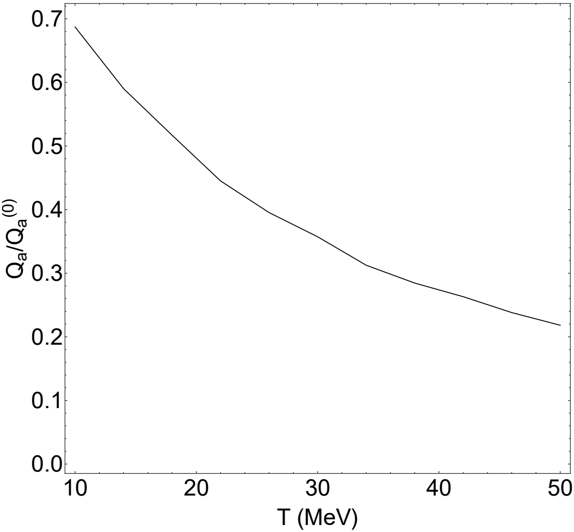
T. E. O. Ericson *et al.*, Phys. Lett. B **219** (1989)

The two-pions exchange can be modelled as an exchange of a ϱ meson

$$\frac{|\mathbf{k}|^2}{|\mathbf{k}|^2 + m_\pi^2} \to \frac{|\mathbf{k}|^2}{|\mathbf{k}|^2 + m_\pi^2} - C_\varrho \frac{|\mathbf{k}|^2}{|\mathbf{k}|^2 + m_\varrho^2}$$

where $m_\varrho = 770\,\mathrm{MeV}$ and $C_\varrho = 1.67$



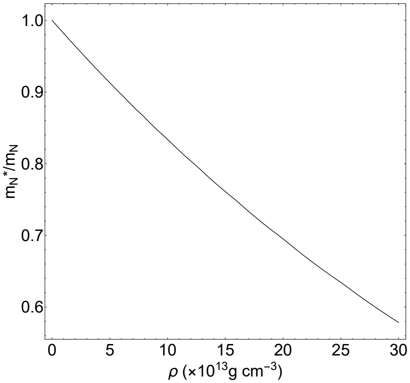


$Q_a/Q_a^{(0)}$ with ϱ mass correction in function of T

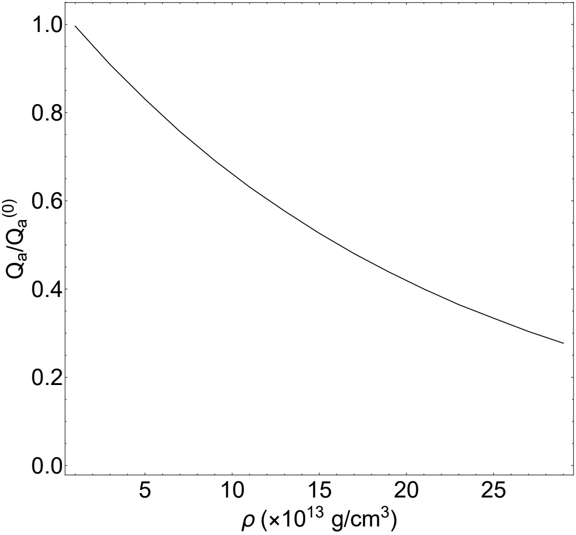
Effective nucleon mass

T. Fischer *et al.*, Phys. Rev. D **94** 085012 (2016)

Interactions in a high density enviroment lead to a variable effective nucleon mass



Ratio of effective nucleon mass m_N^* with respect to the vacuum value m_N as a function of ρ



$Q_a/Q_a^{(0)}$ including the effective nucleon mass m_N^* in function of the density ρ

Multiple nucleon scatterings

G. Raffelt *et al.*, Phys. Rev. D **52**, 1780 (1995)

The axion emissivity can be written as

$$Q_a = \frac{n_B}{2\pi^2}\frac{g_a^2}{m_N^2}\int d\omega_a\,\omega_a^4 e^{-\omega_a/T} S_\sigma(\omega_a)$$

where $S_\sigma(\omega_a)$ is the structure function and

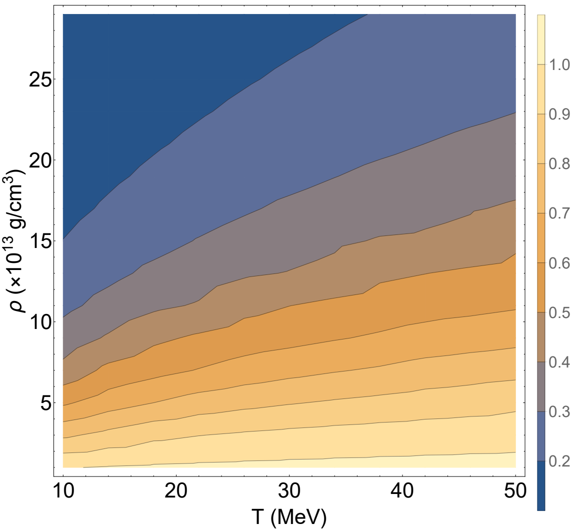
$$S_\sigma(\omega_a) = \frac{4}{3n_B}\int dt\, e^{i\omega_a t}\langle \mathbf{s_k}(t)\cdot \mathbf{s_{-k}}(0)\rangle$$

For interacting nucleons

$$S_\sigma(\omega_a) = \frac{\Gamma_\sigma}{\omega_a^2+\Gamma^2} s\left(\frac{\omega_a}{T}\right)$$

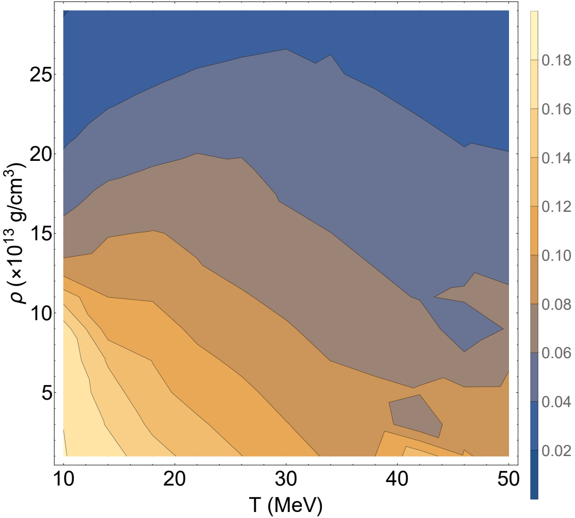
where the spin fluctuation rate is

$$\Gamma_\sigma = 4\pi^{-1.5}\rho\left(\frac{f}{m_\pi}\right)^4 T^{0.5} m_N^{0.5}$$



$Q_a/Q_a^{(0)}$ including multiple nucleon scatterings

OPE vs Beyond OPE



$Q_a/Q_a^{(0)}$ including all the corrections

The SN axion bound

G. Raffelt, Lect. Notes Phys. **741** (2008) 51

The SN1987A neutrino burst lasted $\sim 10\,\mathrm{s}$, then

$$L_\mathrm{a} < 2 \times 10^{52}\,\mathrm{erg\,s^{-1}}$$

The axion luminosity for our model at $t = 1\,\mathrm{s}$ is

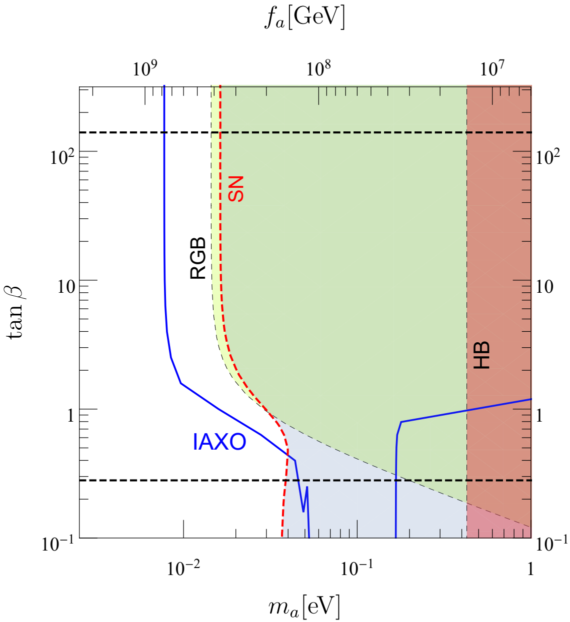
$$L_\mathrm{a,OPE+MS} = 4.2 \times 10^{70} g_a^2 \left(C_n^2 + 0.35\,C_p^2 + 0.02\,C_n C_p\right) \mathrm{erg\,s^{-1}}$$
$$L_\mathrm{a,corr.+MS} = 1.6 \times 10^{70} g_a^2 \left(C_n^2 + 0.36\,C_p^2 + 0.04\,C_n C_p\right) \mathrm{erg\,s^{-1}}$$

KSVZ axion bound

Bounds on axion couplings and mass for KVSZ model in our SN model at $t_{\rm pb} = 1$ s

$C_{ap} = -0.47$; $C_{an} = 0$	g_{ap} $(\times 10^{-10})$	m_a (meV)	$f_a(\times 10^8$ GeV)
OPE	20	12	5.0
OPE+MS	25	15	4.0
OPE+corr. (no MS)	39	23	2.6
OPE+corr.+MS	40	24	2.5

DFSZ axion bound



Conclusions

- We performed an updated study of axion emissivity from a SN
- Including the corrections the mass bound is $m_a \sim 20 - 40\,\text{meV}$ depending on the axion model
- The next step is to include the corrections in self-consistent SN simulations

THANKS FOR YOUR ATTENTION