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Characterization of massive axion emissivity from a core-collapse Supernova

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Outline

- Axions and ALPs nuclear interactions.
- Supernova (SN) explosion and neutrino emission.
- Massive Axion emission via NN Bremsstrahlung.
- Massive Axion emission via Pionic Compton processes.
- Cooling Bound on the axion-nucleon coupling.
- Axion Gravitational trapping.
- Conclusions.

Axions and Axion-like particles

- The QCD axion is a hypothetical particle postulated by Wilzcek and Weinberg in relation to the Peccei-Quinn mechanism *[Peccei & Quinn, Phys. Rev. Lett. 38 (1977)]* to solve the strong-CP problem of the QCD *[Weinberg, PRL 40 (1978); Wilzcek, Phys. Rev. Lett. 40 (1978)]* .

- Axion-like particles (ALPs) are novel particles which behave similarly to the QCD axion. They emerge in UV completions of the Standard Model.

- The QCD axion acquires a small mass as a consequence of the mixing with pions.

$$m_a f_a \approx f_\pi m_\pi$$

- For ALPs no relation between their mass and couplings.

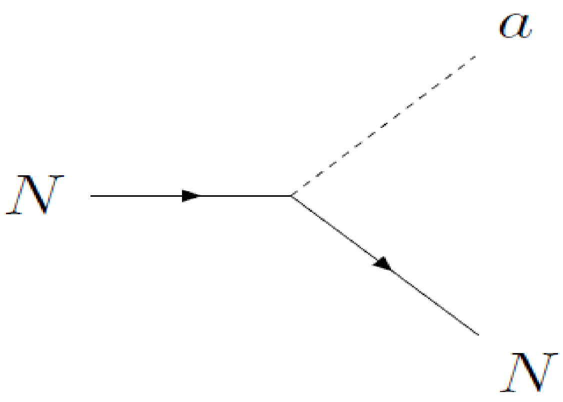
Axions and Axion-like particles

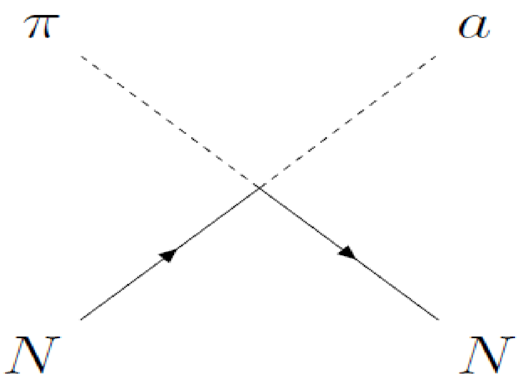
- Axions and ALPs could interact with all the Standard model particles.

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\alpha_s}{8\pi f_a} a \, \mathrm{Tr}\, G^{\mu\nu}\, \tilde{G}_{\mu\nu} + \frac{g_{a\psi}}{2\, m_\psi}\, \bar{\psi}\gamma_5\gamma_\mu\psi\partial^\mu a - \frac{1}{4} g_{a\gamma} a\, \tilde{F}^{\mu\nu} F_{\mu\nu}$$

- In this work we focus on their interaction with nuclear matter

$$\mathcal{L}_{nuc} = \sum_{i=p,n} \frac{g_{ai}}{2m_N}\, \bar{N}_i\gamma_\mu\gamma_5 N_i \partial^\mu a + \frac{g_{a\pi N}}{f_\pi}\partial^\mu a(i\pi^+\bar{p}\gamma_\mu n - i\pi^-\bar{n}\gamma_\mu p)$$

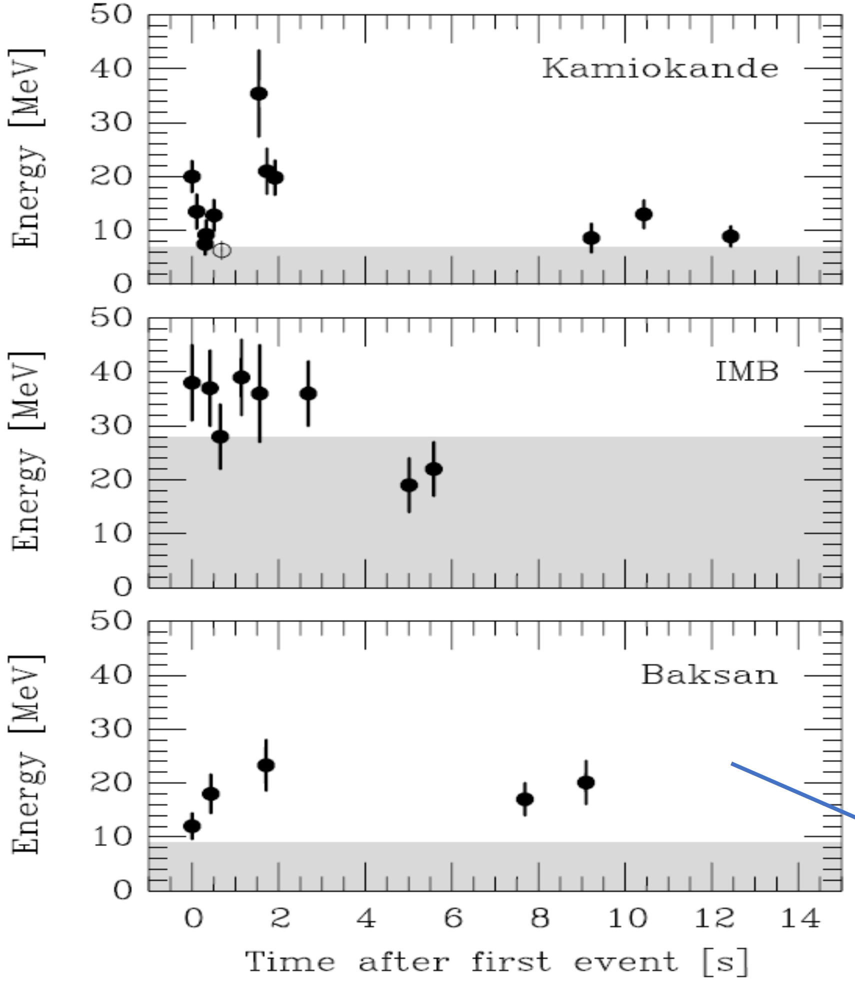




Supernova explosion and Neutrino emission

Core-collapse SN is the terminal phase of a massive star $[\mathrm{M} \geq 8\ M_{\odot}]$.

➢ Subsequent SN explosion and cooling of the remnant by neutrino emission.



The explosion of SN 1987A confirmed the prediction from the SN simulation.

- Duration of the burst ~ 10 s
- $\langle E_{\nu} \rangle \sim 15$ MeV
- $L_{\nu} \approx 10^{52}$ erg$/s$

Events from SN 1987A

Bounds on the axion-nucleon coupling

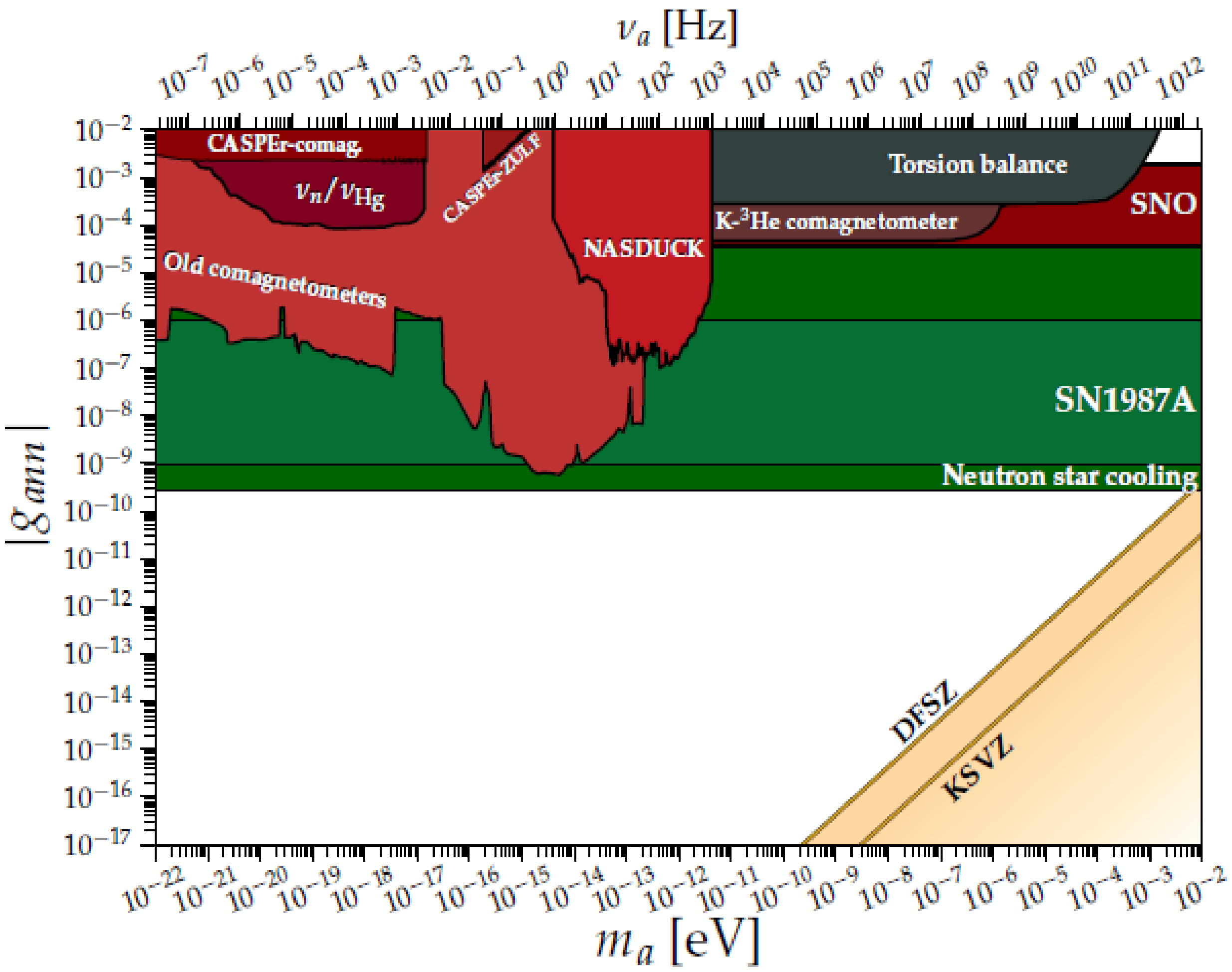
- Axion emission could represent an additional energy-loss channel during a SN explosion, which could shorten significantly the neutrino burst.
  ⟹ Cooling bound.

- From SN 1987A *[Carenza & al., JCAP 1010 (2019)]*:

$$g_{ap} < 1.2 \times 10^{-9}$$

- From Neutron Star cooling (Hess J1731-347) *[Beznogov, Phys. Rev. C 98.3 (2018)]* :

$$g_{an} < 2.8 \times 10^{-10}$$



[Payez, JCAP 02 (2020)]

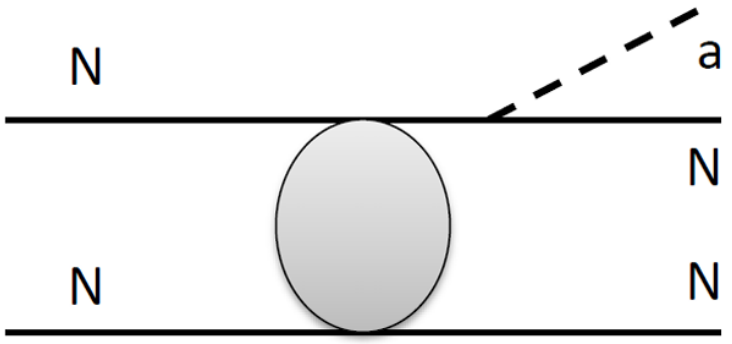
Aim of the work

- Extend the computation for axion emissivity via nuclear interaction to massive axions [$m_a \sim \mathcal{O}(10 - 100\ \mathrm{MeV})$], including all the effects due to the nuclear medium.
  - $T_{core} \sim 30\ \mathrm{MeV} \longrightarrow$ Boltzmann suppression $\sim e^{-\frac{m_a}{T}}$ for $m_a \sim \mathcal{O}(100\ \mathrm{MeV})$.
- Obtain a complete overview of axion emission via nuclear processes in a realistic SN model.
- Extract new bounds on g_{aN} in the whole range of masses studied.

Two main processes for axion production in a nuclear medium:
NN bremsstrahlung and pion conversions.

NN Bremsstrahlung

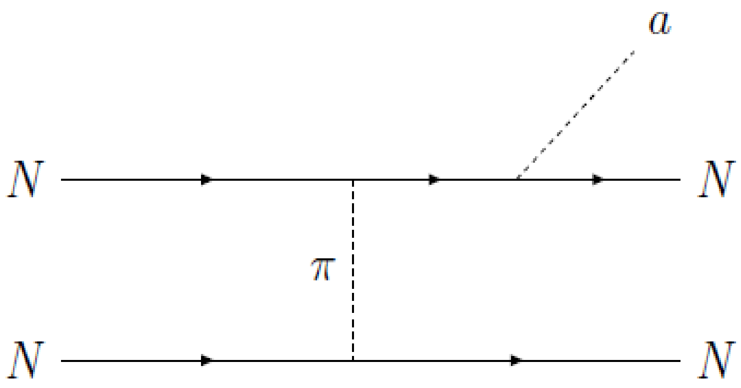
NN Bremsstrahlung is the emission of an axion after the scattering of two nucleons in a dense nuclear medium.



- First approach: «One Pion Exchange (OPE) approximation»
- In the massive case, the matrix element in OPE is given by *[Giannotti & Nesti, Phys. Rev. D 72 (2005)]*:

$$S \sum_{\text{spins}} |\mathcal{M}|^2 = \left(\frac{\boldsymbol{p}_a^2}{\omega_a^2}\right) |M_0|^2$$

Where $|M_0|^2$ is the matrix element in the massless case.

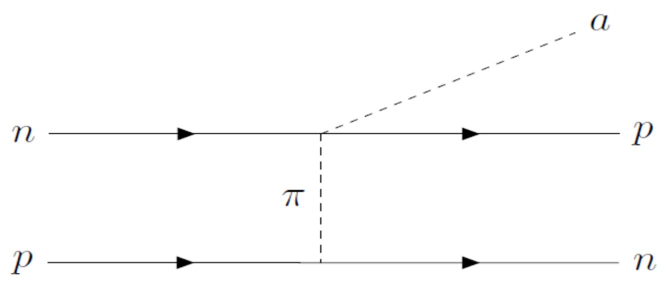


OPE Approximation

NN Bremsstrahlung

Corrections to the OPE approximation for the massless case *[Carenza et al., JCAP 10.10 (2019)]* :

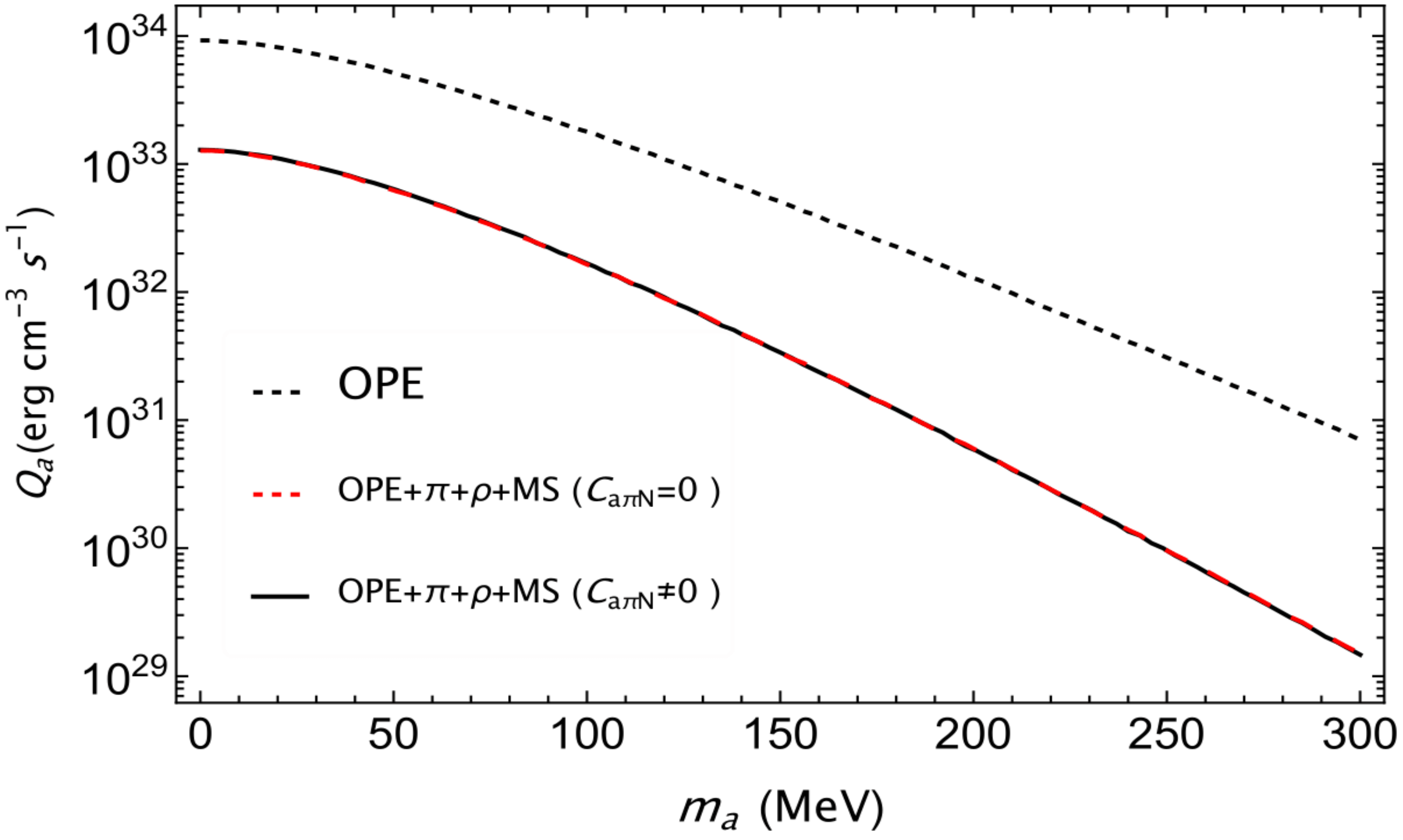
- Non zero Pion mass in the propagator $\longrightarrow$ $\dfrac{|\boldsymbol{k}|^2}{|\boldsymbol{k}|^2 + m_\pi^2}$
- Two pions exchange $\longrightarrow$ $\dfrac{|\boldsymbol{k}|^2}{|\boldsymbol{k}|^2 + m_\pi^2} \to \dfrac{|\boldsymbol{k}|^2}{|\boldsymbol{k}|^2 + m_\pi^2} - C_\rho \dfrac{|\boldsymbol{k}|^2}{|\boldsymbol{k}|^2 + m_\rho^2}$
- Nucleons multiple scattering $\longrightarrow$ $S_\sigma(\omega_a) = \dfrac{\Gamma_\sigma}{\omega_a} s(\omega_a) \to \dfrac{\Gamma_\sigma}{\omega_a + \Gamma^2} s(\omega_a)$
- Effective nucleon mass $\longrightarrow$ $m_N^* = m_N + \Sigma_S$
- Contact interaction contribution $\longrightarrow$



NN Bremsstrahlung

The extension to the massive case of the complete axion emission rate (emissivity) is given by:

$$Q_a^{NN} = \frac{g_a^2}{16\pi^2}\frac{n_B}{m_N^2}\int_{m_a}^{+\infty} d\omega_a \omega_a (\omega_a^2 - m_a^2)^{\frac{3}{2}} e^{-\frac{\omega_a}{T}} S_\sigma\left(\frac{\omega_a}{T}\right)$$

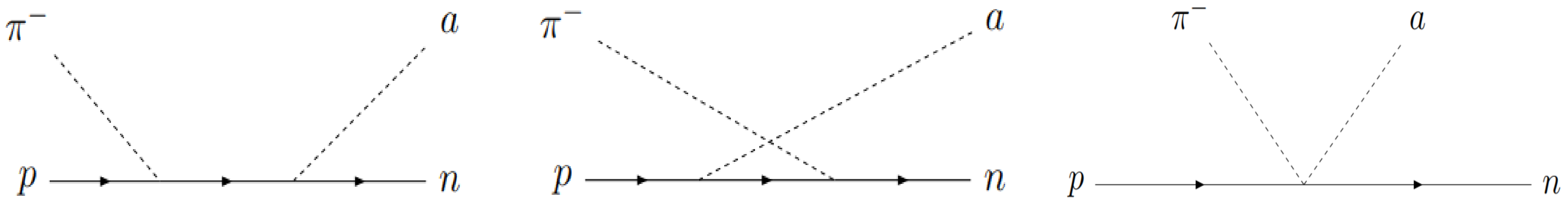


Pionic Compton processes

In this processes a pion is converted into an axion after the scattering on a nucleon.

- If the fraction of pions inside the SN core is high enough, pion conversions could become competitive with NN Bremsstrahlung *[Carenza et al., Phys. Rev. Lett. 126.7 (2021)]*.
- In *[Fore & Reddy, Phys. Rev. C 101.3 (2020)]* it has been proved that

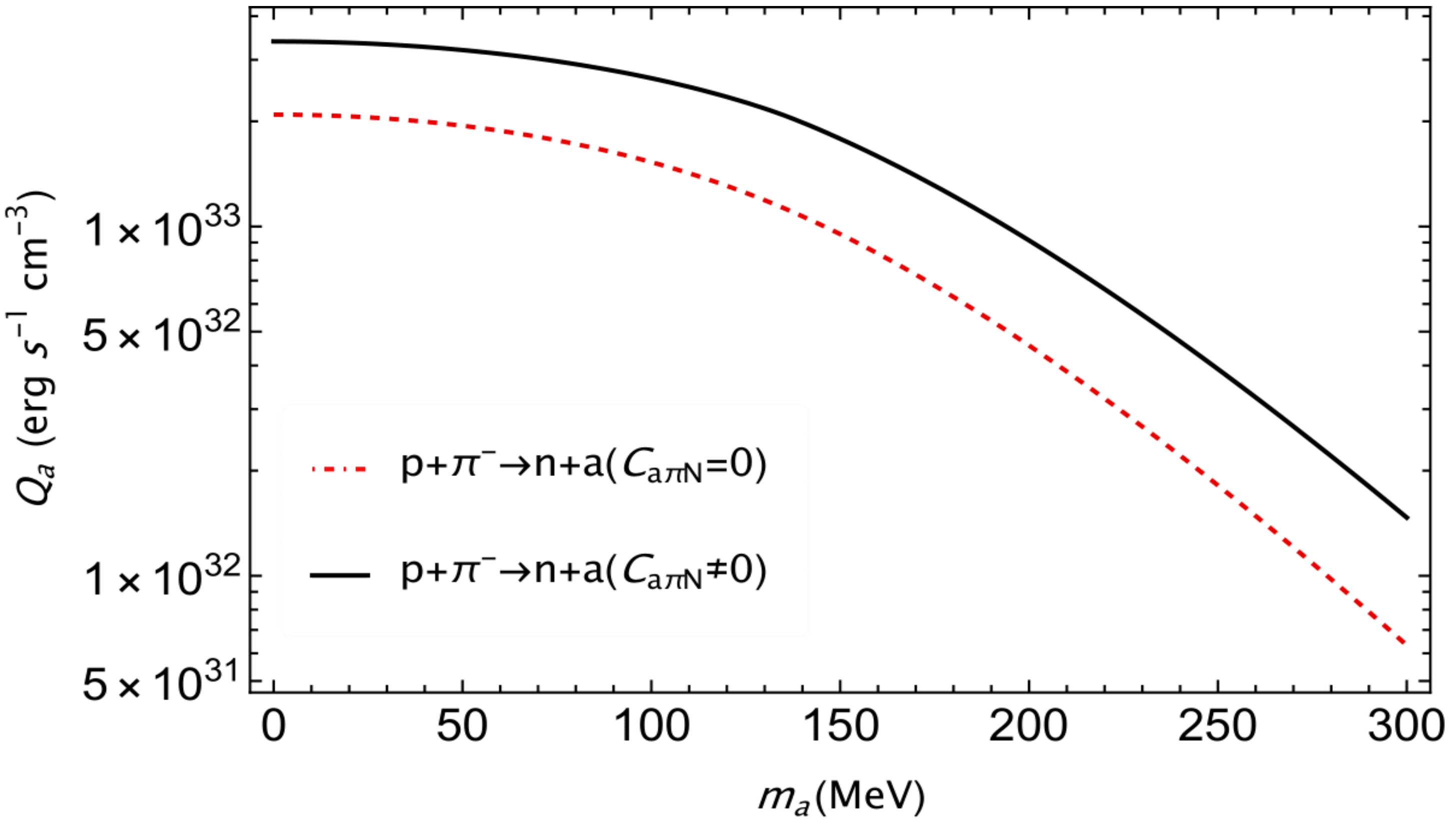
$$\frac{n_{\pi^0}}{n_{\pi^-}} \sim \frac{n_{\pi^+}}{n_{\pi^0}} \sim \frac{n_p}{n_n} = \mathcal{O}(0.1)$$



Pionic Compton processes

The complete expression for axion emissivity via Pionic Compton processes is:

$$Q_a^\pi = \frac{g_{aN}^2}{\sqrt{8}\pi^5}\left(\frac{g_A}{2f_\pi}\right)^2 \frac{T^{7.5}}{\sqrt{m_N}} \int_{\max[\frac{m_a}{T}, y_\pi]}^{+\infty} dx_a x_a \sqrt{x_a^2 - \frac{m_a^2}{T^2}} \sqrt{x_a^2 - y_\pi^2} \frac{C_a^{p\pi^-}}{e^{x_a - y_\pi} e^{-\widehat{\mu}_\pi} - 1} \int_0^{+\infty} dy\, y^2 \left(e^{y^2} e^{-\widehat{\mu}_\pi} + 1\right)^{-1} \left(e^{y^2} e^{-\widehat{\mu}_n} + 1\right)^{-1}$$

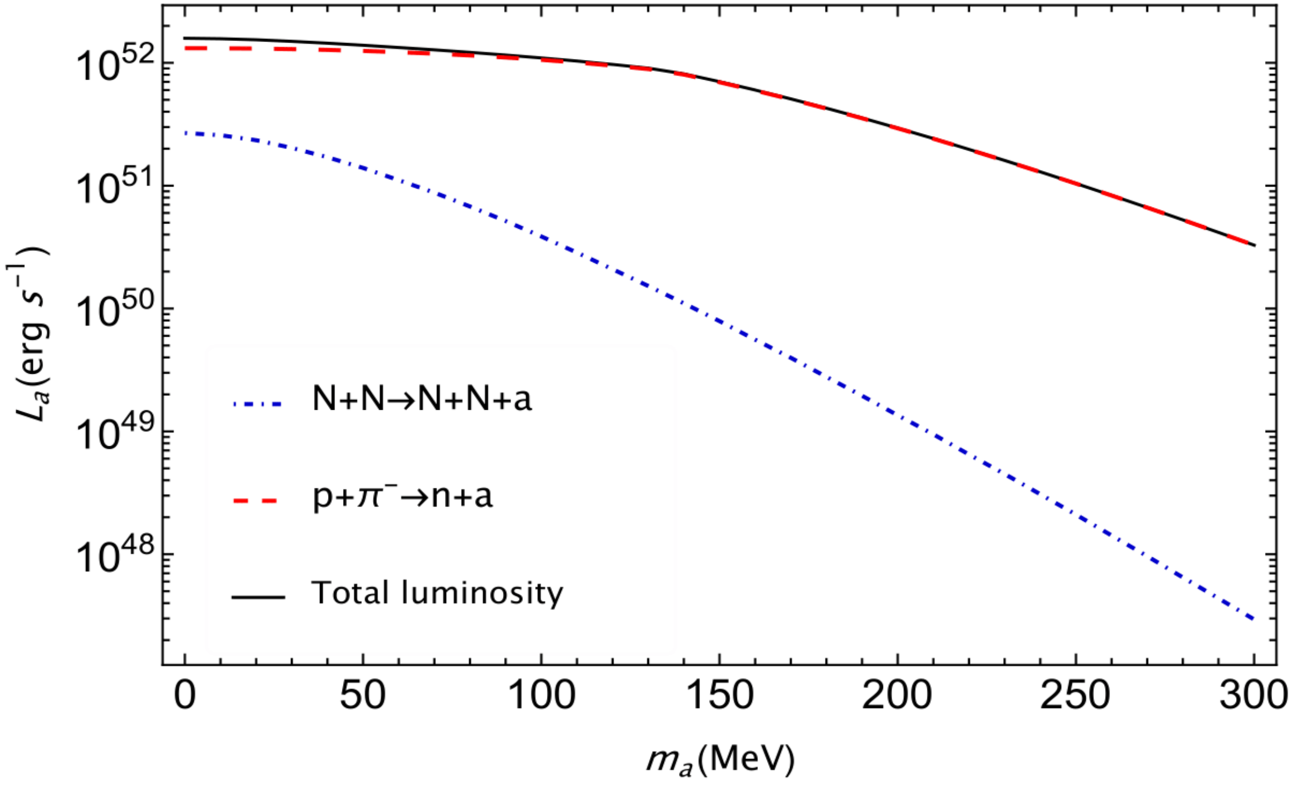


Axion luminosity

The energy emitted per unit time (luminosity) is obtained integrating emissivity over the SN model:

$$L_a = 4\pi \int_0^{r_{max}} \alpha^2\, Q_a(r)\, r^2\, dr$$

Lapse factor

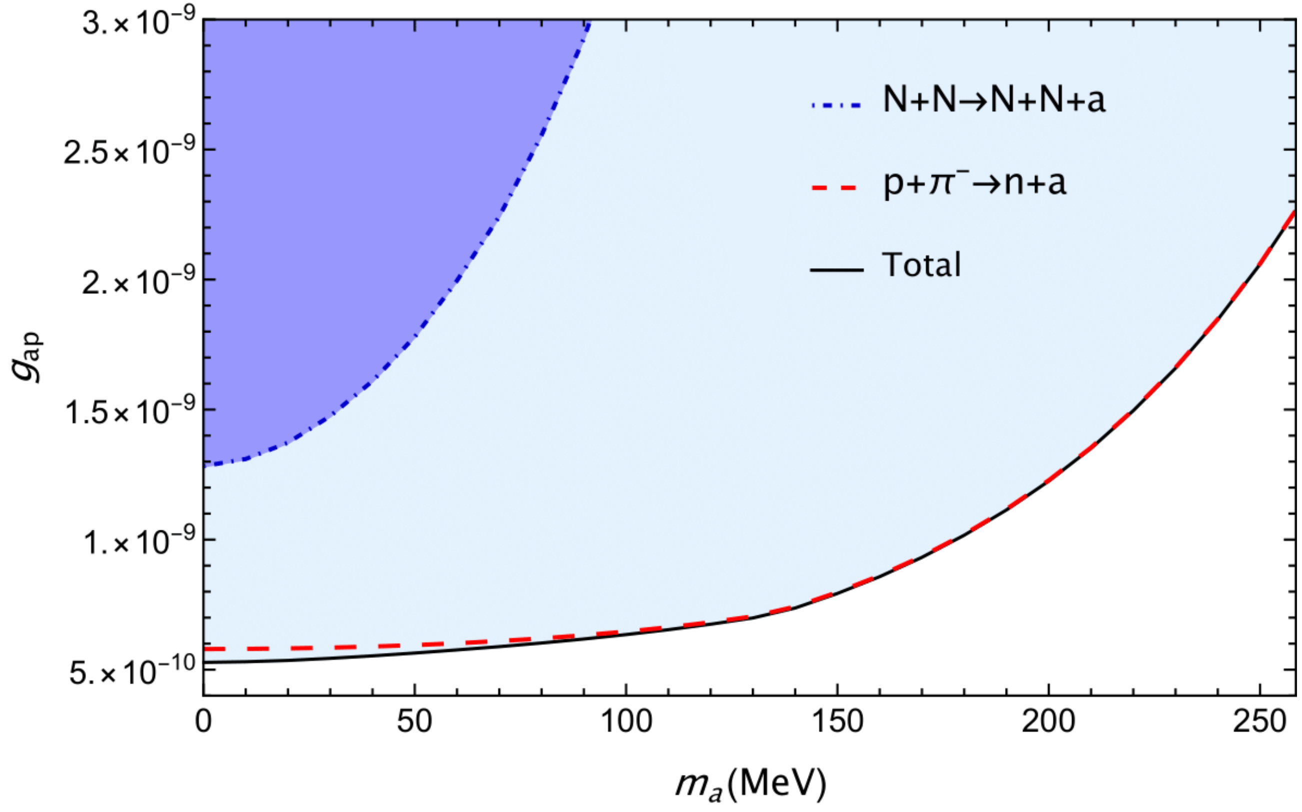


The cooling bound

Assuming that the neutrino burst observed from SN 1987A should not be shortened more than $\sim 1/2$ it is necessary that

$$L_a(\sim g_a^2) \lesssim L_\nu \approx 3 \times 10^{52}\ \mathrm{erg/s}$$

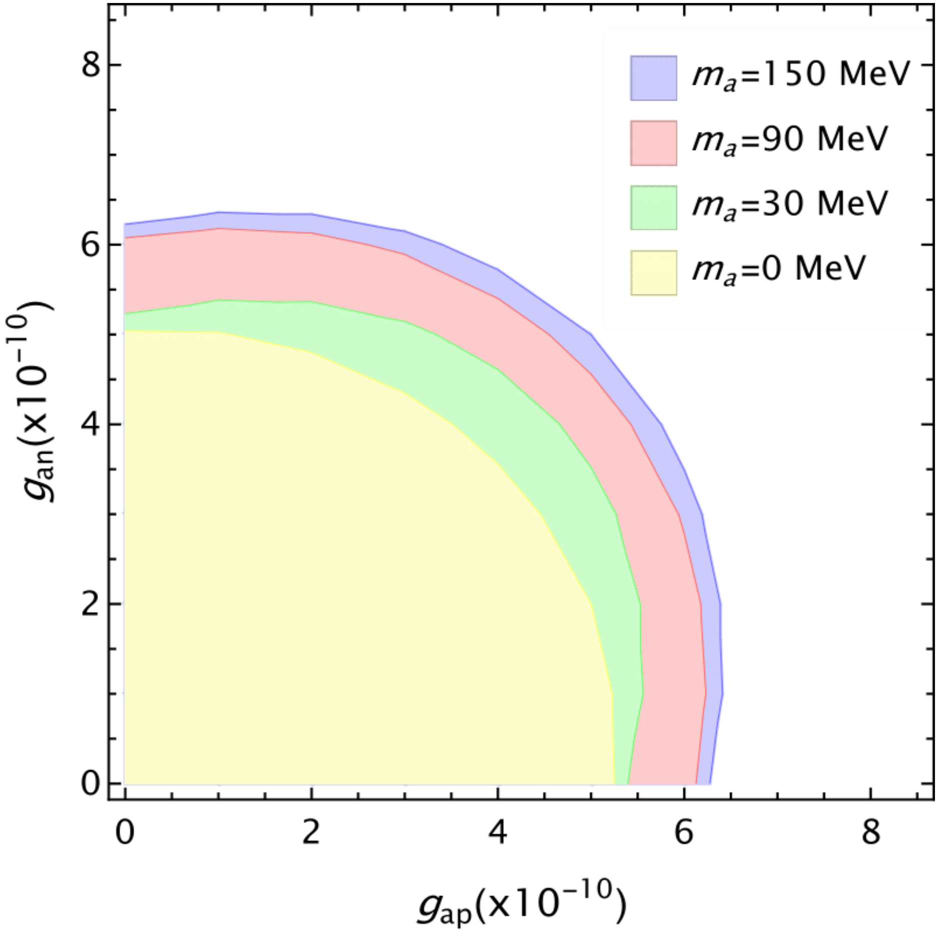
at $t = 1$ s *[Raffelt, Phys. Rept. 198 (1990)]*.



Comparison with previous bounds

Dependence on g_{an} and g_{ap} can be extracted from the following fitting formula:

$$L_a \simeq \epsilon \times \left(g_{an}^2 + b \times g_{ap}^2 + c \times g_{ap} g_{an} + d \times g_{a\pi N}\right) \mathrm{erg/cm^{-3}} \lesssim 3 \times 10^{52}\ \mathrm{erg/cm^{-3}}$$



In the massless case:

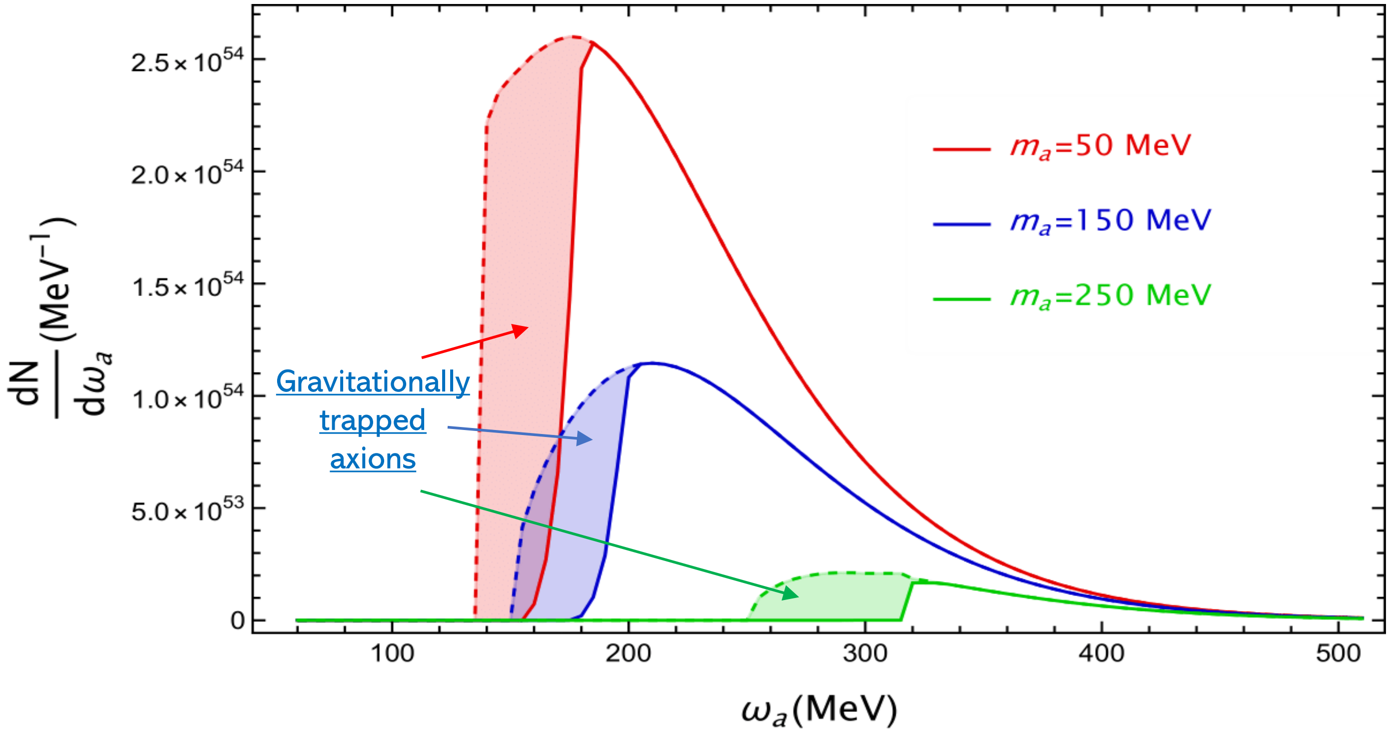
SN 1987A cooling		Updated Bound
$g_{ap} < 1.2 \times 10^{-9}$	$\Rightarrow$	$g_{ap} < 5 \times 10^{-10}$
Neutron Star cooling		New Bound
$g_{an} < 2.8 \times 10^{-10}$	$\Rightarrow$	$g_{an} < 2 \times 10^{-10}$

Gravitational trapping

Massive axions experience the strong gravitational effects due to the dense inner core. In order to be emitted they must have energy enough to overcome the gravitational potential:

$$\left(\frac{dN_a}{d\omega_a}\right)_{grav} = \frac{dN_a}{d\omega_a}\Theta\left(\omega_a - \frac{m_a}{\alpha}\right)$$

Where $\alpha = \sqrt{1-2M/R}$ is the lapse factor.



Gravitational trapping

- Let us assume that the trapped axion decay into photons.

$$a \to \gamma\gamma$$

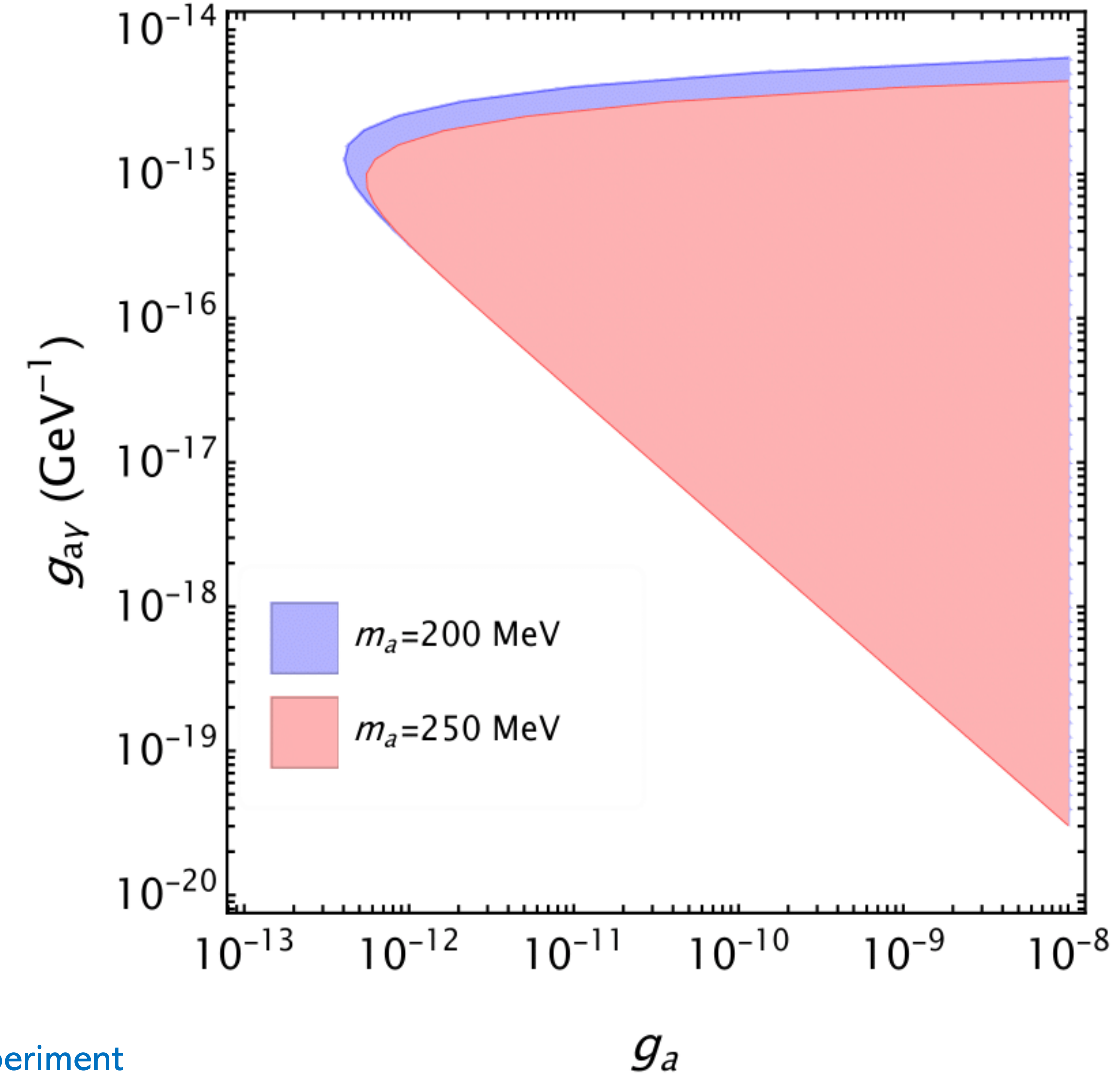
- This would give rise to an additional photon flux from a SN remnant

$$\frac{d\phi_\gamma}{dE_\gamma}(\sim g_a^2\,; \sim g_{a\gamma}^2) = \frac{1}{4\pi d^2}\, 2\left[\frac{dN_a(2E_\gamma)}{dE_\gamma}\right]_{trap} \Gamma_{a\gamma\gamma} e^{-\Gamma_{a\gamma\gamma} t}$$

- We can consider the SN remnant Cas A ($d \approx 3.4$ kpc, t$\approx$ 320 yrs). Since no photon flux has been observed from Cas A *[Hannestad & Raffelt, Phys. Rev. Lett. 88 (2002)]*:

$$\phi_{E>100\ \mathrm{MeV}} \lesssim 10^{-7}\ \mathrm{cm^{-2}\ s^{-1}}$$

Sensitivity of the EGRET experiment



Conclusions

- Inside the SN core ($T \sim 30 - 40\ \mathrm{MeV}$) massive axions could be copiously produced by means of Bremsstrahlung and pionic Compton-like processes.

- We extended the computation of the axion emission rates for these two processes to the case of massive axions.

- The energy-loss argument allowed us to constrain g_{aN} in the mass range $[0,300]\mathrm{MeV}$. In particular in the low mass limit we found $\mathrm{g_{ap}} \lesssim 5.2 \times 10^{-10}$, strengthening the previous bounds.

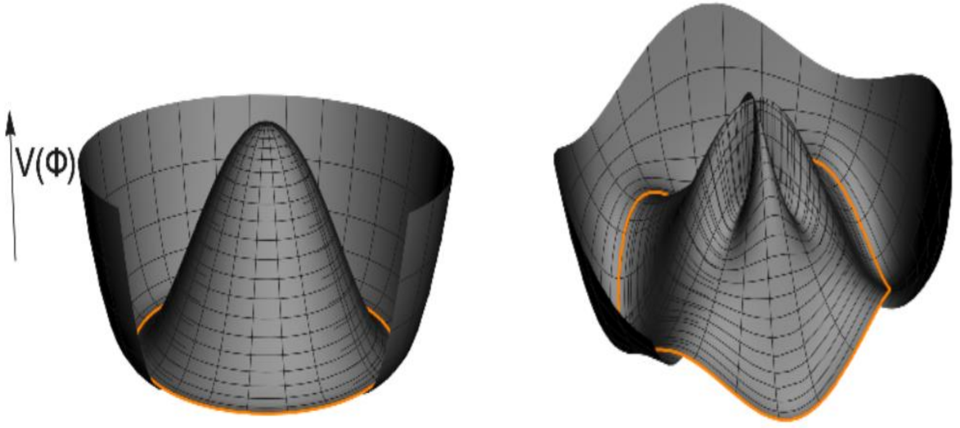
- Using gravitational trapping we also contrain the $g_{a\gamma}$- g_a axion parameter space.

THANK YOU FOR THE ATTENTION

The QCD axion

The *QCD axion* is a pseudoscalar particle postulated in relation to the Peccei-Quinn (PQ) mechanism to solve the *Strong-CP problem* in QCD.

→ PQ mechanism: the introduction of a global symmetry $U(1)_{\mathrm{PQ}}$ spontaneously broken at f_a and the Goldstone boson is the axion *[Peccei & Quinn, PRL 38 (1977)]*

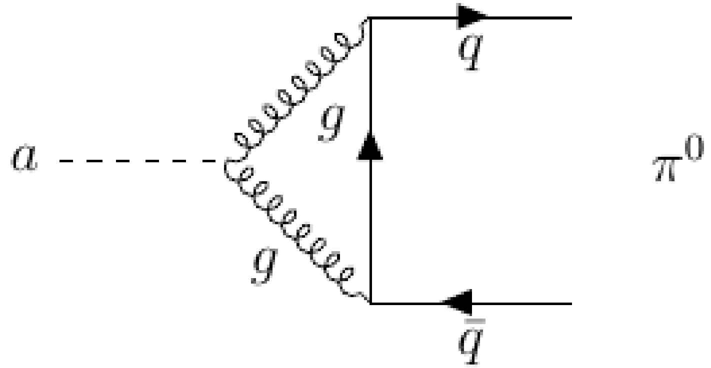


- Axion lagrangian:

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\alpha_s}{8\pi f_a} a \,\mathrm{Tr}\, G^{\mu\nu}\,\tilde{G}_{\mu\nu} + \frac{g_{a\psi}}{2\, m_\psi}\,\bar{\psi}\gamma_5\gamma_\mu\psi\partial^\mu a - \frac{1}{4} g_{a\gamma} a\,\tilde{F}^{\mu\nu}F_{\mu\nu}$$

- Axions acquire a small mass as a consequence of their mixing with pions

$$m_a\, f_a \approx m_\pi f_\pi$$



- The coupling constants depends on the energy scale f_a

Supernova explosion and Neutrino emission

Core-collapse SN is the terminal phase of a massive star $[\mathrm{M} \geq 8\ M_{\odot}]$.

- An initial gravitational collapse takes place.
- Shock-wave formation and propagation.
- Ejection of the outer layers of the star.
- Neutrino cooling.

About the 99% of the released energy ($\sim 10^{53}$ erg) is emitted by ν and $\bar{\nu}$ of all flavours.

Structure functions

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

$$s(x) = s_{nn}(x) + s_{pp}(x) + s_{np}(x)$$

$$\begin{aligned}
s_{nn}(x) =& \frac{1}{3} Y_n^2 C_{an}^2 (s_\mathbf{k} + s_\mathbf{l} + s_\mathbf{kl} - 3 s_{\mathbf{k}\cdot\mathbf{l}}) \\
s_{pp}(x) =& \frac{1}{3} Y_p^2 C_{ap}^2 (s_\mathbf{k} + s_\mathbf{l} + s_\mathbf{kl} - 3 s_{\mathbf{k}\cdot\mathbf{l}}) \\
s_{np}(x) =& \frac{4}{3} Y_n Y_p (C_+^2 + C_-^2) s_\mathbf{k} + \frac{4}{3} Y_n Y_p (4C_+^2 + 2C_-^2) s_\mathbf{l} + \\
& - \frac{8}{3} Y_n Y_p [(C_+^2 + C_-^2) s_\mathbf{kl} - (3C_+^2 - C_-^2) s_{\mathbf{k}\cdot\mathbf{l}}] \,.
\end{aligned}$$

$$s_\mathbf{k} = \int \frac{d\cos\delta}{2} \frac{d\phi}{2\pi} \frac{\sqrt{w}dw}{\frac{\sqrt{\pi}}{2}} \frac{dz}{2} du \left[\frac{\rho Y_1}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} \left[\frac{\rho Y_2}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} e^{u-\eta_3} e^{w-\eta_4} \sqrt{u(u-x)} [H_u^+ H_u^- H_v^+ H_v^- F_+^2]_{v=u-x} \tag{3.49}$$

$$s_\mathbf{l} = \int \frac{d\cos\delta}{2} \frac{d\phi}{2\pi} \frac{\sqrt{w}dw}{\frac{\sqrt{\pi}}{2}} \frac{dz}{2} du \left[\frac{\rho Y_1}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} \left[\frac{\rho Y_2}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} e^{u-\eta_3} e^{w-\eta_4} \sqrt{u(u-x)} [H_u^+ H_u^- H_v^+ H_v^- F_-^2]_{v=u-x} \tag{3.50}$$

$$s_\mathbf{kl} = \int \frac{d\cos\delta}{2} \frac{d\phi}{2\pi} \frac{\sqrt{w}dw}{\frac{\sqrt{\pi}}{2}} \frac{dz}{2} du \left[\frac{\rho Y_1}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} \left[\frac{\rho Y_2}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} e^{u-\eta_3} e^{w-\eta_4} \sqrt{u(u-x)} [H_u^+ H_u^- H_v^+ H_v^- F_+ F_-]_{v=u-x} \tag{3.51}$$

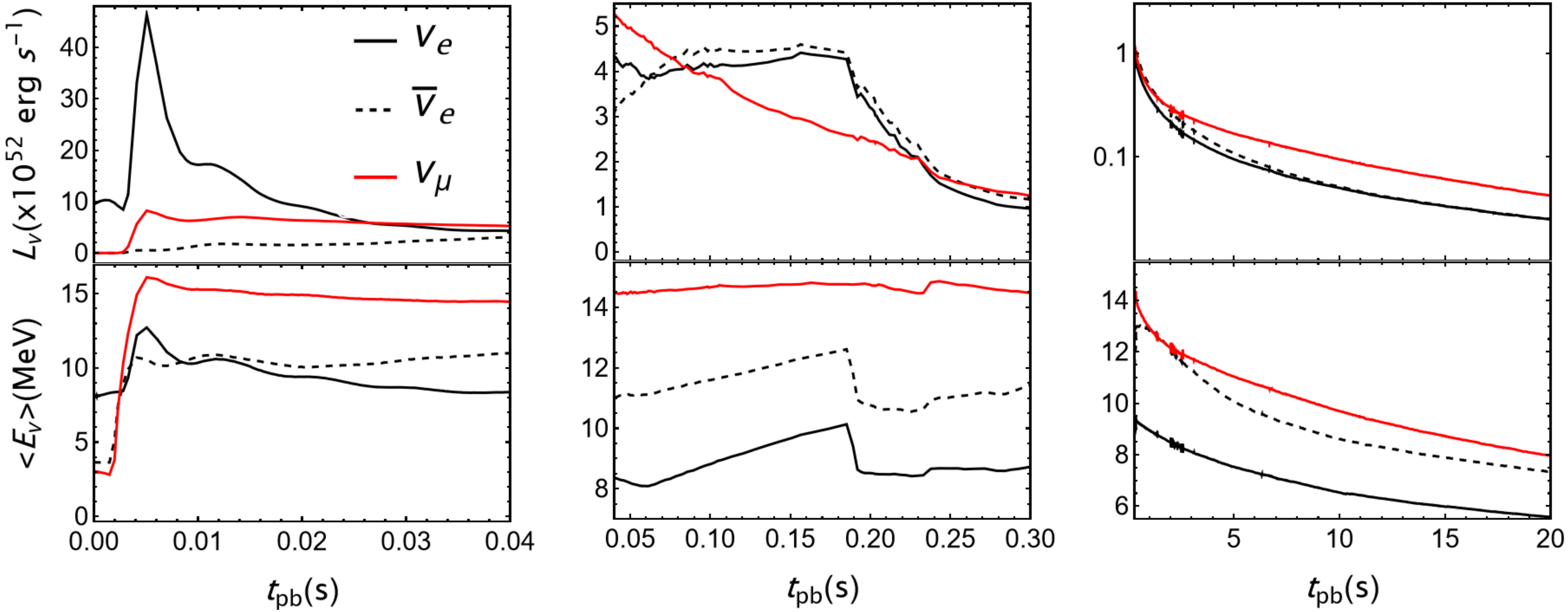
$$s_{\mathbf{k}\cdot\mathbf{l}} = \int \frac{d\cos\delta}{2} \frac{d\phi}{2\pi} \frac{\sqrt{w}dw}{\frac{\sqrt{\pi}}{2}} \frac{dz}{2} du \left[\frac{\rho Y_1}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} \left[\frac{\rho Y_2}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} e^{u-\eta_3} e^{w-\eta_4} \sqrt{u(u-x)} \left[H_u^+ H_u^- H_v^+ H_v^- F_+ F_- \frac{\xi}{3}\right]_{v=u-x} \tag{3.52}$$

Supernova Neutrinos

Neutronization burst
- Electron capture in the inner core

Accretion
- When shock stalls, ν powered by infalling matter

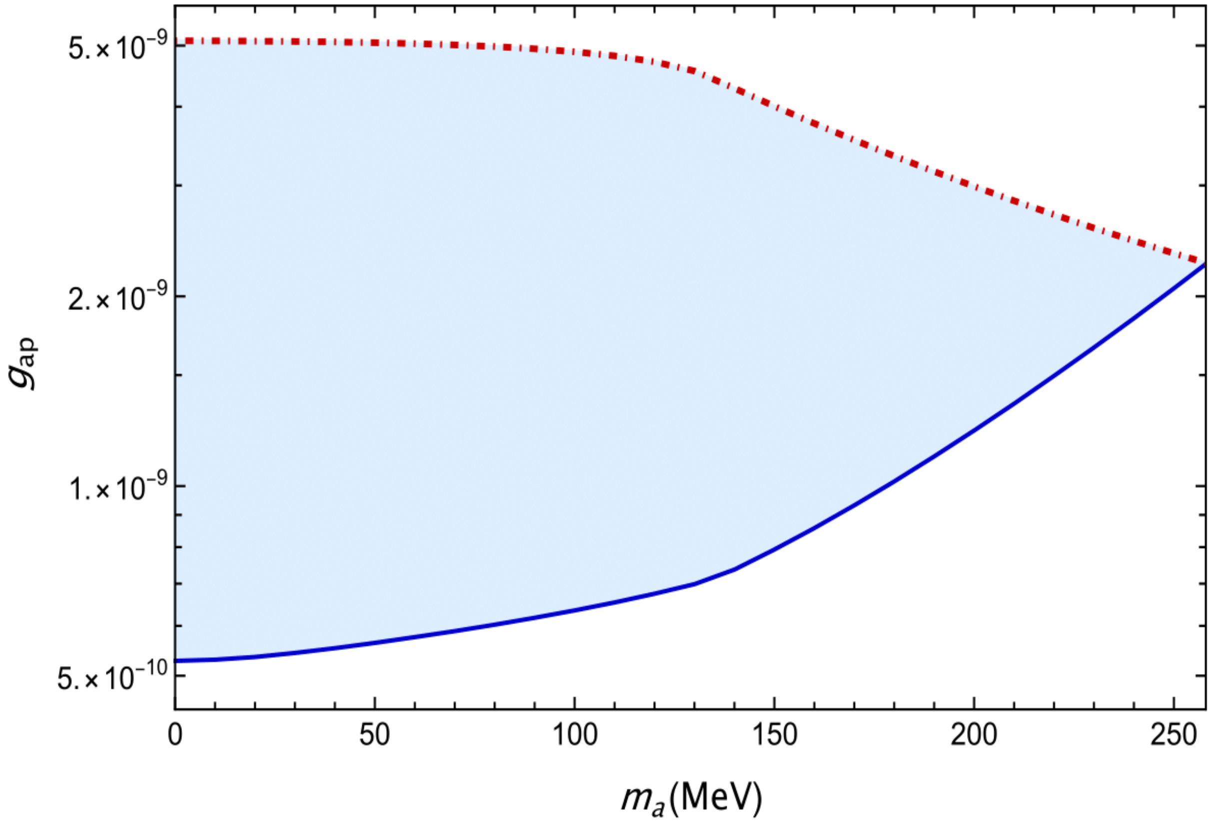
Cooling
- Cooling on ν diffusion time scale

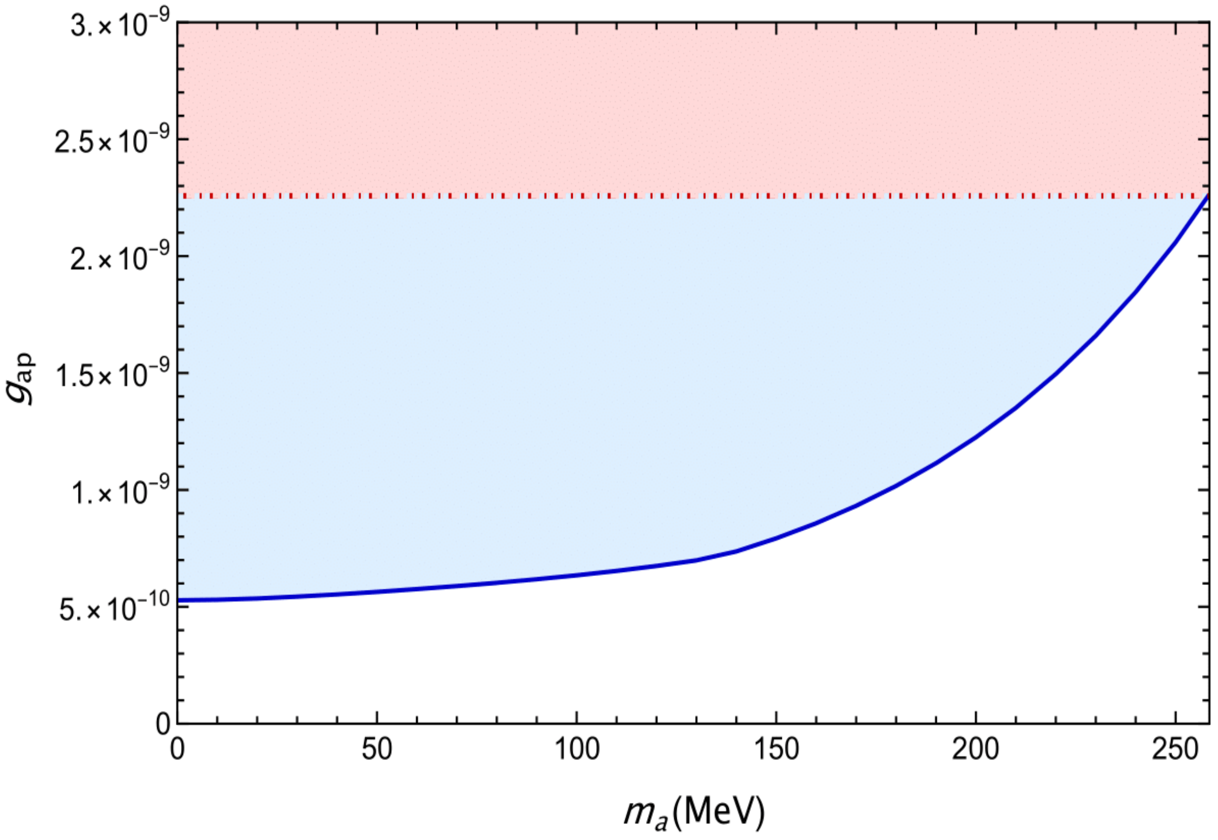


Estimation of the mean free path

$$Q_a = \int \omega_a \frac{d\mathcal{N}}{d\Pi_a} d\Pi_a \qquad \lambda_a^{-1} = \frac{1}{2|\mathbf{p}_a|} \frac{d\mathcal{N}}{d\Pi_a}$$

$$\lambda_a^{-1}(\omega_a) = \frac{g_a^2}{\sqrt{2}\pi^3} \left(\frac{g_A}{2f_\pi}\right)^2 \frac{T^{\frac{7}{2}}}{m_N^{\frac{1}{2}}} \sqrt{\frac{x_a^2 - y_\pi^2}{x_a^2 - \left(\frac{m_a}{T}\right)^2}} \frac{\mathcal{C}_a^{p\pi^-}}{e^{x_a - y_\pi} e^{-\hat{\mu}_\pi} - 1} \times \int_0^\infty dy y^2 \frac{1}{e^{y^2} e^{-\hat{\mu}_p} + 1} \frac{1}{e^{-y^2} e^{\hat{\mu}_n} + 1} .$$





Gravitational effects on axion emissivity

Gravitational effects lead to a shift of the axion energy and time intervals:

$$\omega_a \to \ \omega_a{}' = \alpha\omega_a \qquad\qquad dt \ \to dt' = \frac{t}{\alpha}$$

So the emissivity becomes:

$$Q'_\alpha = \int_{m_a}^{\infty} d\omega'_a\, \omega'_a \frac{dn}{d\omega'_a\, dt'} = \alpha^2 \int_{m'_a}^{\infty} d\omega'_a\, \omega'_a \frac{dn}{d\omega'_a\, dt'}$$

With:

$$m'_a = \frac{m_a}{\alpha} \simeq m_a\left(1 + \frac{M}{R}\right)$$

Axion couplings and contact term

$$C_{ap} = g_{ap}/g_a$$
$$C_{an} = g_{an}/g_a$$

$$C_{a\pi N} = \frac{C_{ap} - C_{an}}{\sqrt{2} g_A}$$

$$\mathcal{A}_{np} = (C_+^2 + C_-^2)(\frac{\mathbf{k}^2}{\mathbf{k}^2 + m_\pi^2})^2 + (4C_+^2 + 2C_-^2)(\frac{\mathbf{l}^2}{\mathbf{l}^2 + m_\pi^2})^2 + \\ - 2[(C_+^2 + C_-^2) - (3C_+^2 + C_-^2)\frac{\xi}{3}](\frac{\mathbf{k}^2}{\mathbf{k}^2 + m_\pi^2})(\frac{\mathbf{l}^2}{\mathbf{l}^2 + m_\pi^2}) + \\ + 3C_{a\pi n}^2 \frac{\mathbf{k}^2 \mathbf{p}_a^2}{(\mathbf{k}^2 + m_\pi^2)^2}$$

$$\mathcal{C}_a^{p\pi^-} = |\mathbf{p}_2|^2 \frac{|\mathbf{p}_a|^2}{\omega_a^2} \left[\frac{1}{2}(C_{ap}^2 + C_{an}^2) + \frac{1}{3} C_{ap} C_{an}\right] + \frac{C_{a\pi N}^2}{g_A^2} \omega_a^2$$