Probing the general axion-nucleon-nucleon interaction in water Cherenkov experiments

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Theory motivation

Among low-mass particles,
the QCD axion is especially well-motivated

- solves, by a symmetry, the question why the strong force does not violate CP
- provides an excellent Dark Matter candidate
- ...

Axion-quark interaction

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Dense and hot enough astro-objects may radiate a large quantity of axions

How to constrain axions

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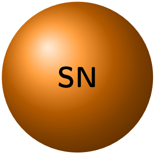
Supernova Axion Emission

First generation: [Ericson, Mathiot, 1989 ; Carenza et al, 2019 ; Carenza et al, 2020 ; Lella et al, 2022 ; Caputo, Raffelt, 2024]

With strange matter: [Cavan-Piton et al, PRL, 2024]

Axion emission from SNe



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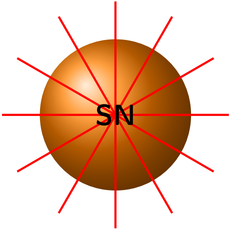

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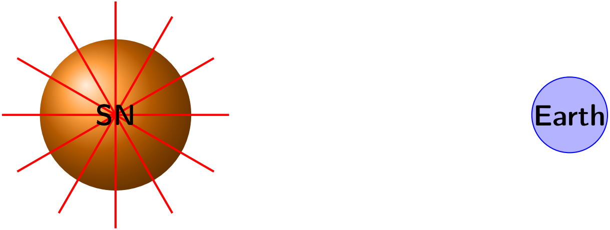

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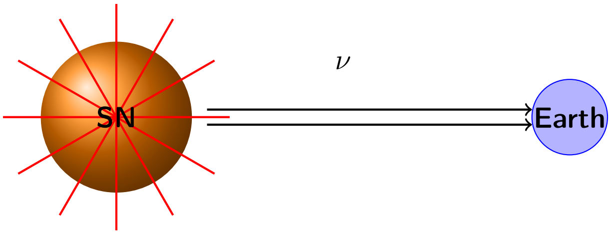

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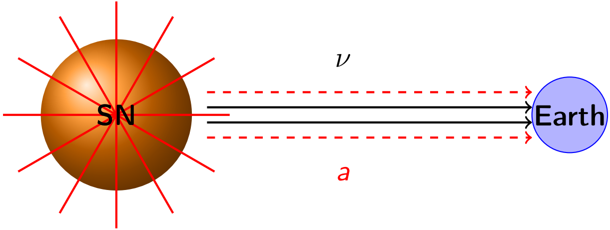

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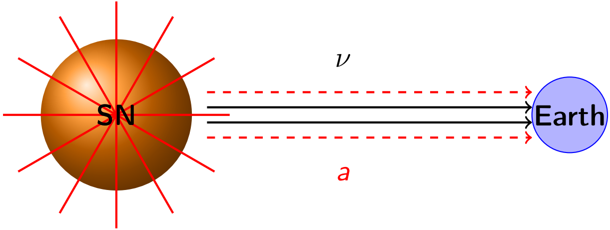

Axions reaching Earth could leave traces in Cherenkov facilities (like neutrinos)

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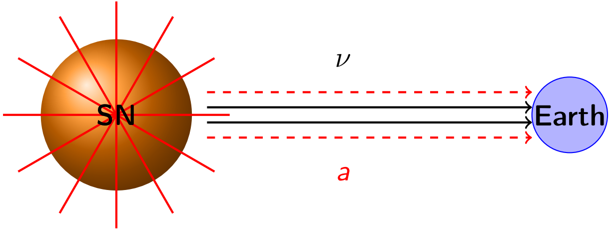

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Steps :

Axion emission spectrum calculation	Calculation of detectable particle spectrum in Cherenkov facilities
$\frac{dN_a}{dE_a}$	$\frac{dN_i}{dE_i} = \frac{N_{target}}{4\pi d^2_{SN-Earth}} \int \frac{d\sigma}{dE_i} \frac{dN_a}{dE_a} dE_a$

Axion emission :

pion-nucleon scattering:

$$\pi + N \rightarrow N' + a \quad (E_a \sim 240 \pm 80\ \mathrm{MeV})$$

nucleon-nucleon scattering:

$$N_1 + N_2 \rightarrow N_3 + N_4 + a \quad (E_a \sim 60 \pm 50\ \mathrm{MeV})$$

Processes in the litterature

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Axion reception :

Interaction with oxygen:

$$a + {}^{16}O \to {}^{16}O^* \to \begin{cases} {}^{16}O + \gamma \\ {}^{15}O + n + \gamma \\ {}^{15}N + p + \gamma \end{cases} \quad (E_a \sim \mathcal{O}(10 \ \mathrm{MeV}))$$

Interaction with free proton:

$$ap \to p\gamma$$

through the nucleon electric
dipole moment (EDM) portal interaction

Processes study

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Our conclusions must be proved robust w.r.t. the modeling of:

- **axion-matter interactions:**
  we address this question within a consistent EFT approach
- **SN-core equation of state (EoS) and thermodynamics:**
  we consider different EoS and also vary the thermodynamic parameters

Axion-hadron interaction

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$$\mathcal{L}_{axion-quark} = \frac{\partial_\mu a}{f_a} \bar{q} \left(k_R \gamma_R^\mu + k_L \gamma_L^\mu \right) q$$

low $\downarrow$ *energy*

$$\mathcal{L}_{axion-hadron} = \frac{\partial_\mu a}{f_a} \left(x_R^b(k_R) J_R^{\mu,b}(U; B) + x_L^b(k_L) J_L^{\mu,b}(U; B) \right)$$

$x_R^b(k_R)$, $x_L^b(k_L)$: axion-hadron couplings parametrized in terms of the fundamental k-couplings

U: meson-octet field

B: baryon-octet field

axion-hadron interactions and their couplings fixed by global symmetries (i.e. as Noether currents)

Axion-matter couplings

In the first generation, all axion-matter couplings can be expressed in terms of the axion-nucleon-nucleon couplings C_{aNN} ($N \in \{p; n\}$)

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KSVZ :

$$C_{app} = -0.452(28) \text{ and } C_{ann} = 0.012(28)$$

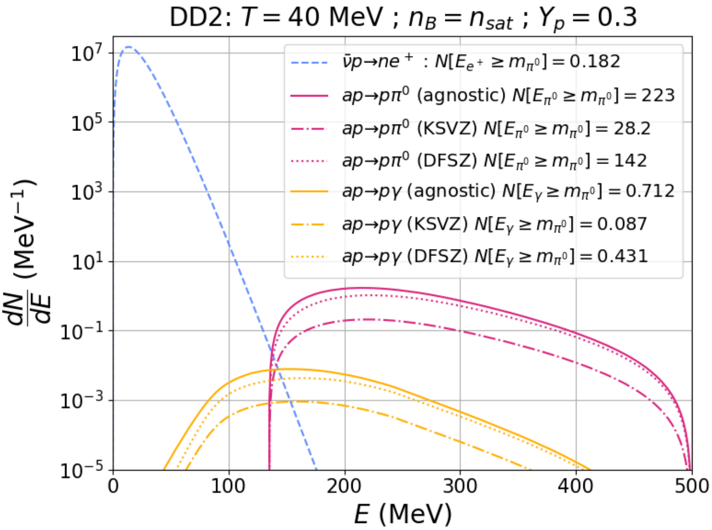
DFSZ :

$$C_{app} = -0.169(30) - 0.430(15)\sin^2(\beta),$$
$$C_{ann} = -0.123(30) + 0.406(15)\sin^2(\beta)$$
$$\text{with } \tan(\beta) \in [0.25; 170]$$

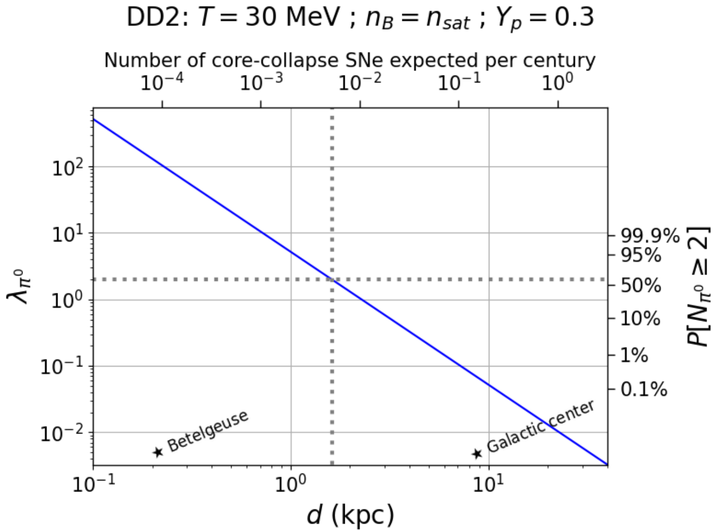
"Agnostic":

C_{aNN} are only constrained by data (NSs or SNe)

Results



Hyper-Kamiokande ($M_{det} = 374$ kton), Betelgeuse ($d = 0.2$ kpc)



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Conclusion

- SNe are excellent probes of fundamental physics, in particular of well-motivated SM extensions.
- The process $ap \to p\pi^0$ is a promising candidate.

Thanks !