Axion search goes deep underground:

θ-dependence of α-decay half-lives

Claudio Toni

based on the work w/
Carlo Broggini, Giuseppe Di Carlo and Luca Di Luzio
arxiv: 2404.18993, published on PLB

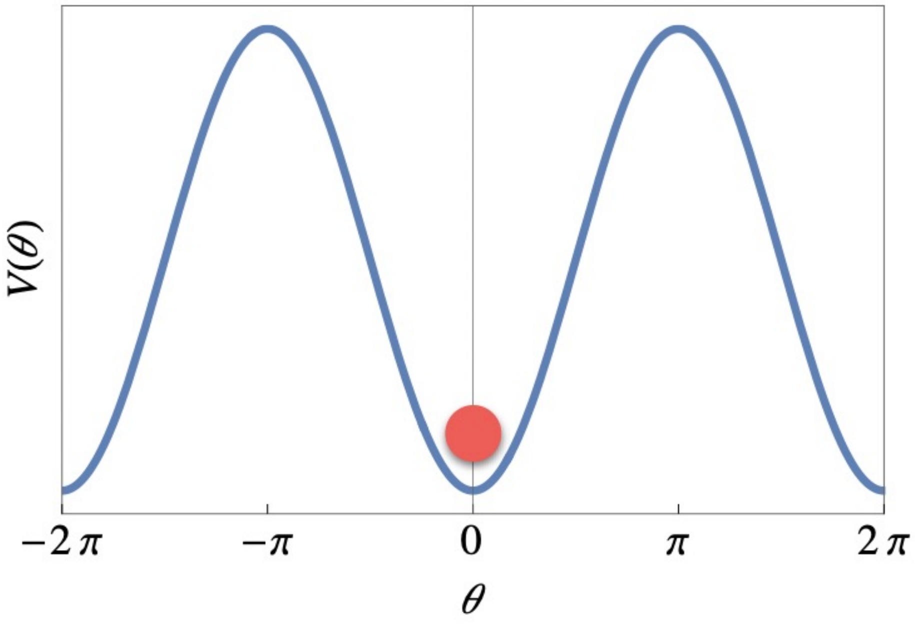
Istanbul, CA21106 2nd general meeting, 3 Sep. 2024

QCD Axion

- Axion potentially addresses the Strong CP problem $\mathcal{L}_\theta = \frac{g^2\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$ $|\theta| \lesssim 10^{-10}$

- θ promoted to a dynamical field: $\theta \to \frac{a}{f_a}$

- QCD potential relaxed *dynamically* to zero:

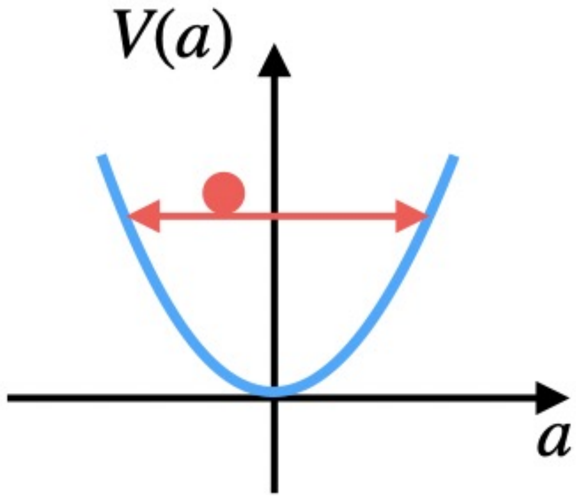


Oscillating axion DM

- An axion contribution to DM density is unavoidable so it is a natural DM candidate

- In a misalignment mechanism the DM axion field induces a time varying θ-term

Preskill, Wise, Wilczek '83,
Abbott, Sikivie '83,
Dine, Fischler '83



$$\theta \simeq \sqrt{\frac{2\rho_{DM}}{m_a^2 f_a^2}} \cos(\omega t + \vec{p}\cdot\vec{x} + \phi)$$

α-radioactivity and axion DM

➢ Search for time modulation of α-radioactivity from axion DM

Broggini, Di Carlo, Di Luzio, CT
arxiv:2006.12321

Lee, Meißner, Olive, Shifman, Vonk arxiv:2006.12321

$$\mathcal{L}_\theta = \frac{g^2\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

→ Non vanishing θ-term impacts nuclear physics

$$M_\pi^2(\theta) = M_\pi^2 \cos\frac{\theta}{2}\sqrt{1+\varepsilon^2\tan^2\frac{\theta}{2}}$$

For its impact anthropic context, see
Ubaldi arxiv:0811.1599

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→ Time modulation of radiative decays

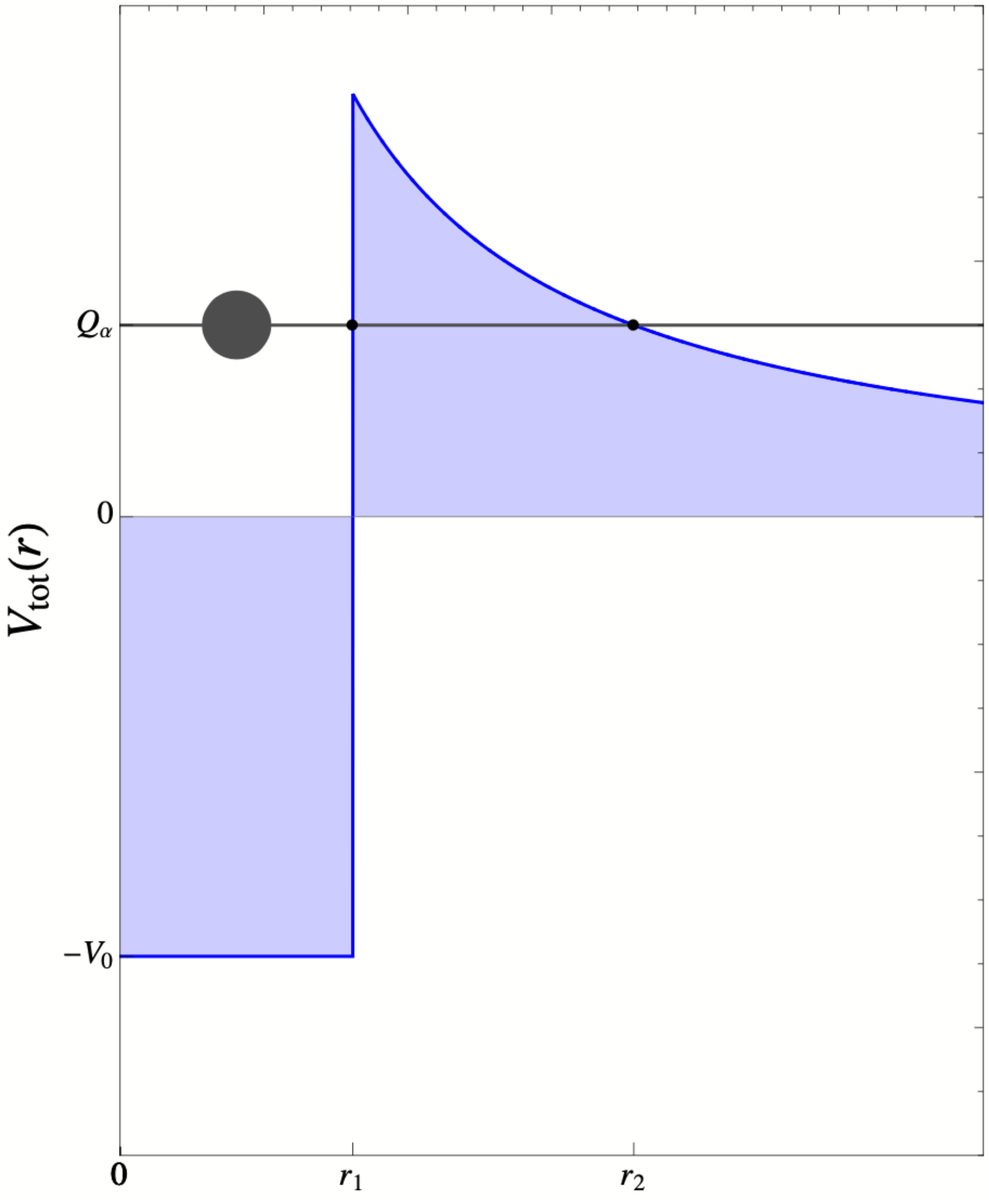
For a recent study of time modulation signals on β-decays, see
Zhang, Houston, Li arxiv:2303.09865

Theory of α-decay

Gamow theory of α-decay

$$T_{1/2} = \frac{\ln 2}{\nu_0} \exp(K)\,,$$

$$K = \frac{2}{\hbar} \int_{r_1}^{r_2} dr\ \sqrt{2\mu[V_{\rm tot}(r) - Q_\alpha]}$$



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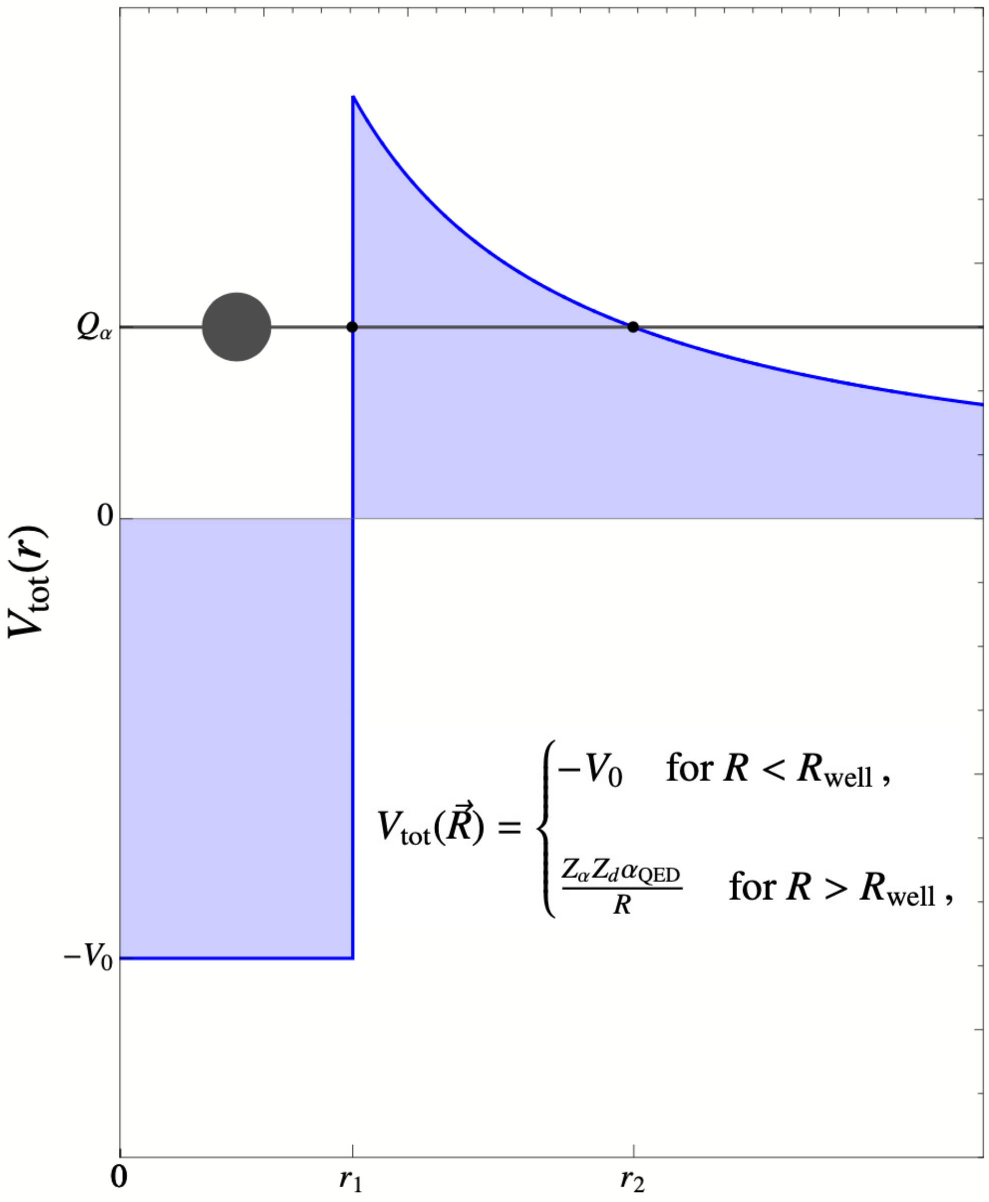

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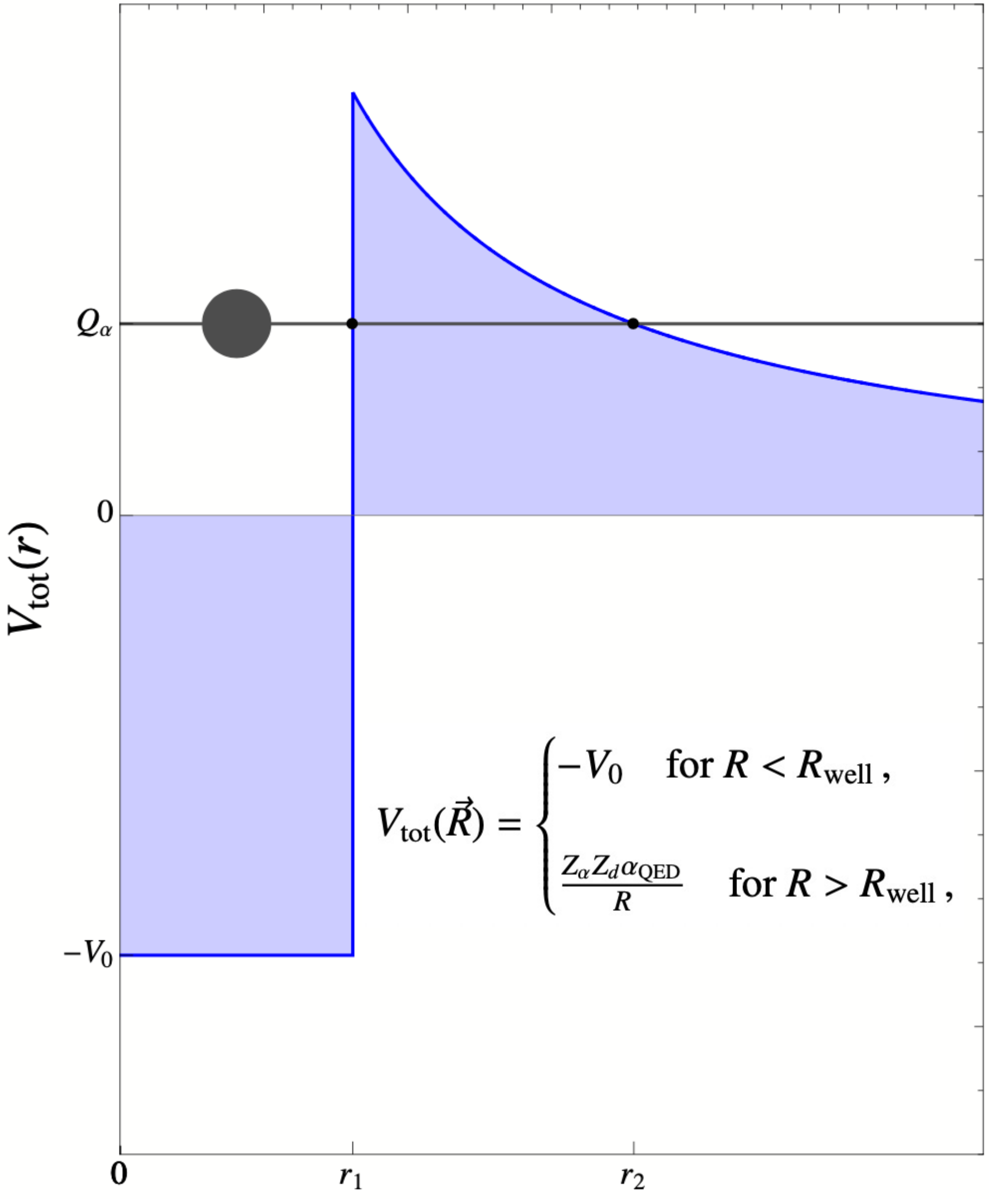
$$K = Z_\alpha Z_d \alpha_{\text{QED}} \left(\frac{8\mu}{Q_\alpha}\right)^{1/2} F\left(\frac{Q_\alpha R_{\text{well}}}{Z_\alpha Z_d \alpha_{\text{QED}}}\right),$$

with

$$F(x) = \arccos\sqrt{x} - \sqrt{x}\sqrt{(1-x)} \approx \frac{\pi}{2} - 2\sqrt{x} + \ldots,$$



Signal estimate

- Halftimes are highly sensible to the Q-value, i.e. the energy released in the decay

Question: how the θ-term impacts the Q?

$$Q_\alpha = \mathrm{BE}(A-4, Z-2) + \mathrm{BE}(4,2) - \mathrm{BE}(A,Z),$$

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- The θ-term changes the size of the scalar (attractive) and vector (repulsive) nuclear interaction that contributes to the BEs

$$H = G_S(\bar{N}N)(\bar{N}N) + G_V(\bar{N}\gamma_\mu N)(\bar{N}\gamma^\mu N),$$

$$\eta_S = \frac{G_S(\theta)}{G_S(\theta=0)}, \quad \eta_V = \frac{G_V(\theta)}{G_V(\theta=0)}.$$

Damour, Donoghue arxiv:0712.2968

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$$\eta_S(\theta) = 1.4 - 0.4\frac{M_\pi^2(\theta)}{M_\pi^2}$$

Damour, Donoghue arxiv:0712.2968

$$Q_\alpha(\theta) = Q_\alpha(\theta=0) - 97\ \mathrm{MeV}\,(\eta_S(\theta) - 1) \times ((A-4)^{2/3} + 4^{2/3} - A^{2/3}).$$

Exp. sensitivity

$$T_{1/2} = \frac{\ln 2}{\nu_0} \exp(K)$$

$$T_{1/2}(\theta) \approx T_{1/2}(0) + \mathring{T}_{1/2}(0)\theta^2$$

$$\mathring{f} \equiv df/d\theta^2$$

$$I(t) \equiv \frac{T^{-1}_{1/2}(\theta(t)) - \langle T^{-1}_{1/2} \rangle}{\langle T^{-1}_{1/2} \rangle}$$

$$\approx -\frac{1}{2}\frac{\mathring{T}_{1/2}(0)}{T_{1/2}(0)}\theta_0^2 \cos(2m_a t)$$

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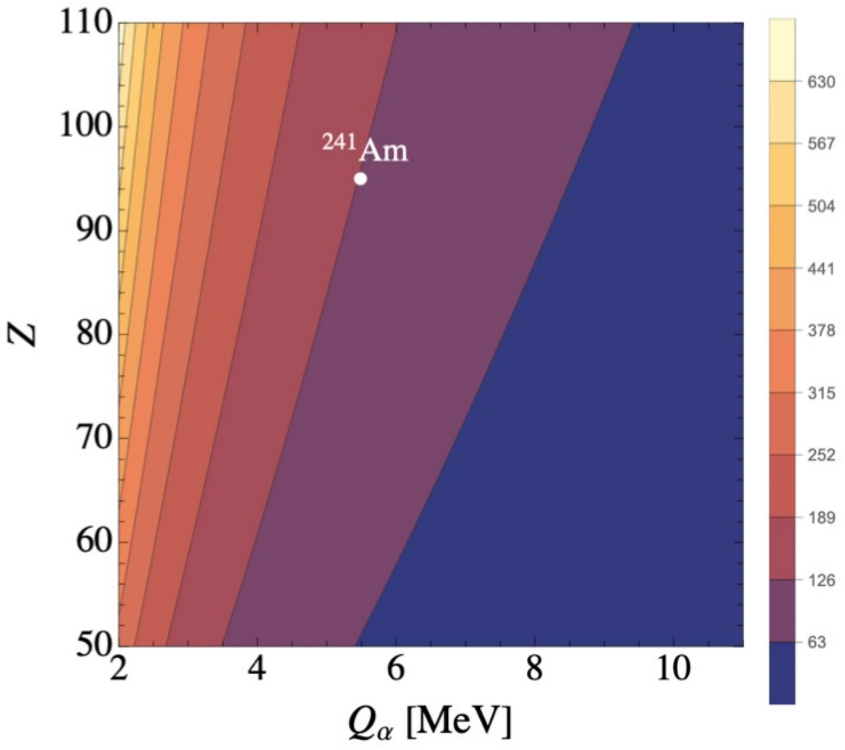

Figure A.3: Contours of $\mathring{T}_{1/2}(0)/T_{1/2}(0)$ in the (Q_α, Z) plane for $A = 241$. The case of ^{241}Am is indicated by a white dot.

$$\rightarrow \quad \frac{\mathring{T}_{1/2}(0)}{T_{1/2}(0)} \approx \mathring{K} \approx \frac{\partial K}{\partial Q_\alpha}\,\mathring{Q}_\alpha \approx 8.45\,(Z-2)\left[4^{2/3} - \frac{8}{3A^{1/3}}\right]\left(\frac{\rm MeV}{Q_\alpha}\right)^{3/2}$$

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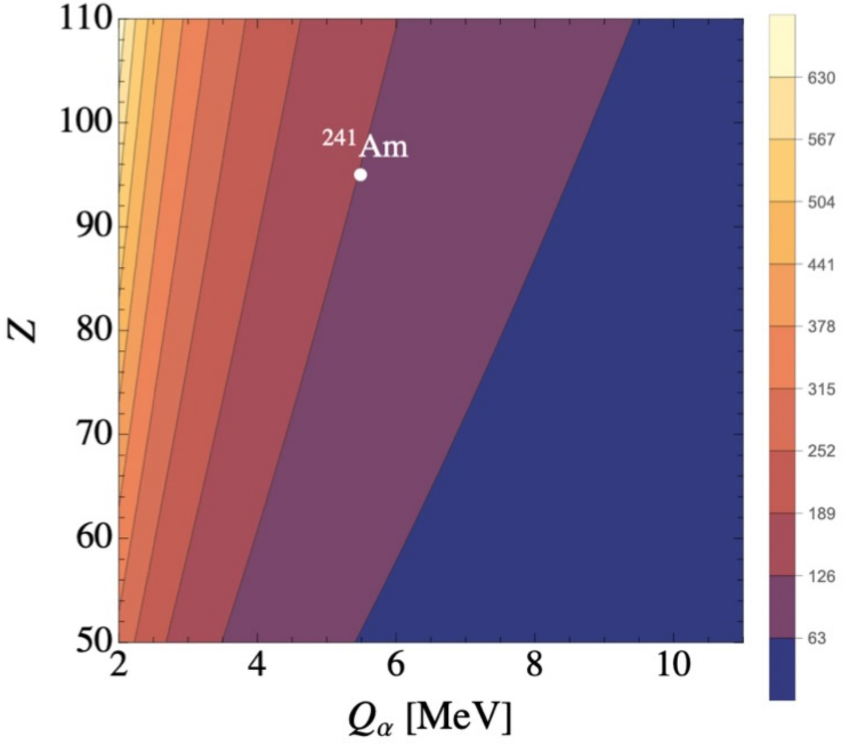

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≈ 125 (for Americium-241)

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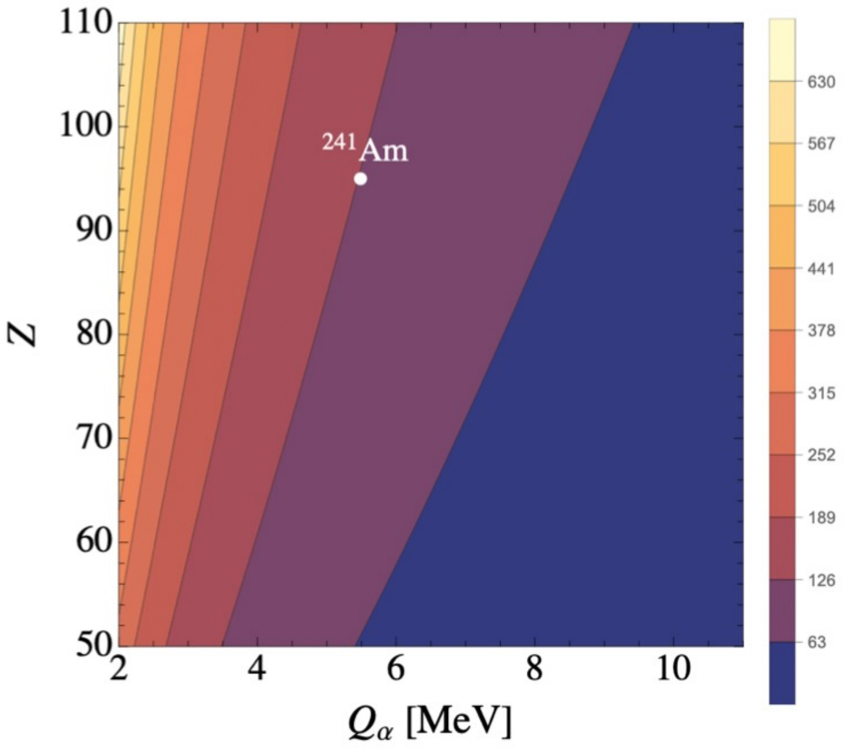
$$= -4.3\times 10^{-6}\cos(2m_a t)\left(\frac{\rho_{\rm DM}}{0.45\ {\rm GeV/cm^3}}\right)$$

$$\times\left(\frac{10^{-16}\ {\rm eV}}{m_a}\right)^2\left(\frac{10^8\ {\rm GeV}}{f_a}\right)^2,$$



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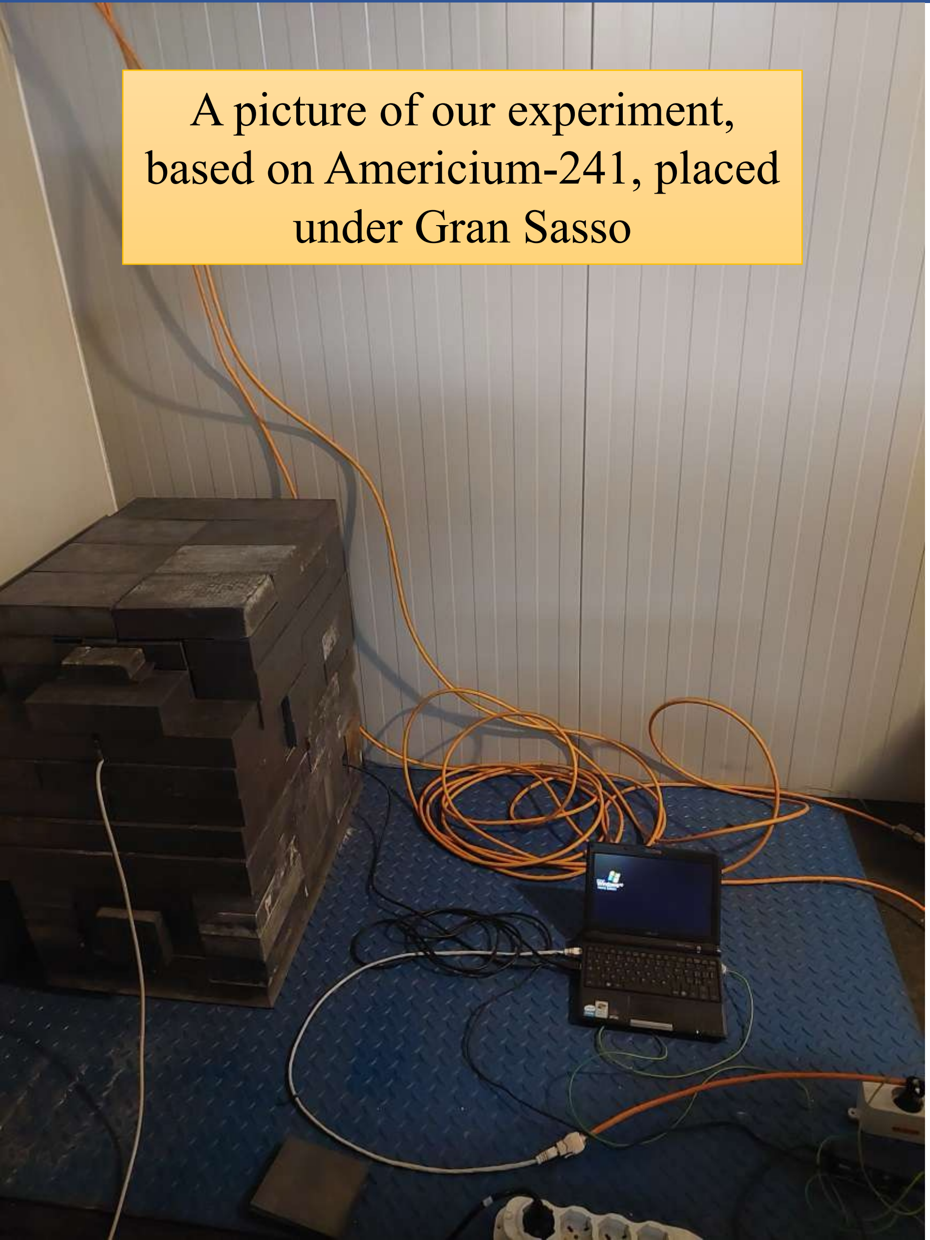

A picture of our experiment, based on Americium-241, placed under Gran Sasso

- A 3”x3” NaI crystal detects the gamma rays which are subproducts of the α-decays, primarily (85% of the time) at 59.5 keV
- The crystal is closed inside a cooper-lead shield

Similar studies have already been performed, see for example: Bellotti, Broggini, Di Carlo, Laubenstein, Menegazzo arxiv:1802.09373

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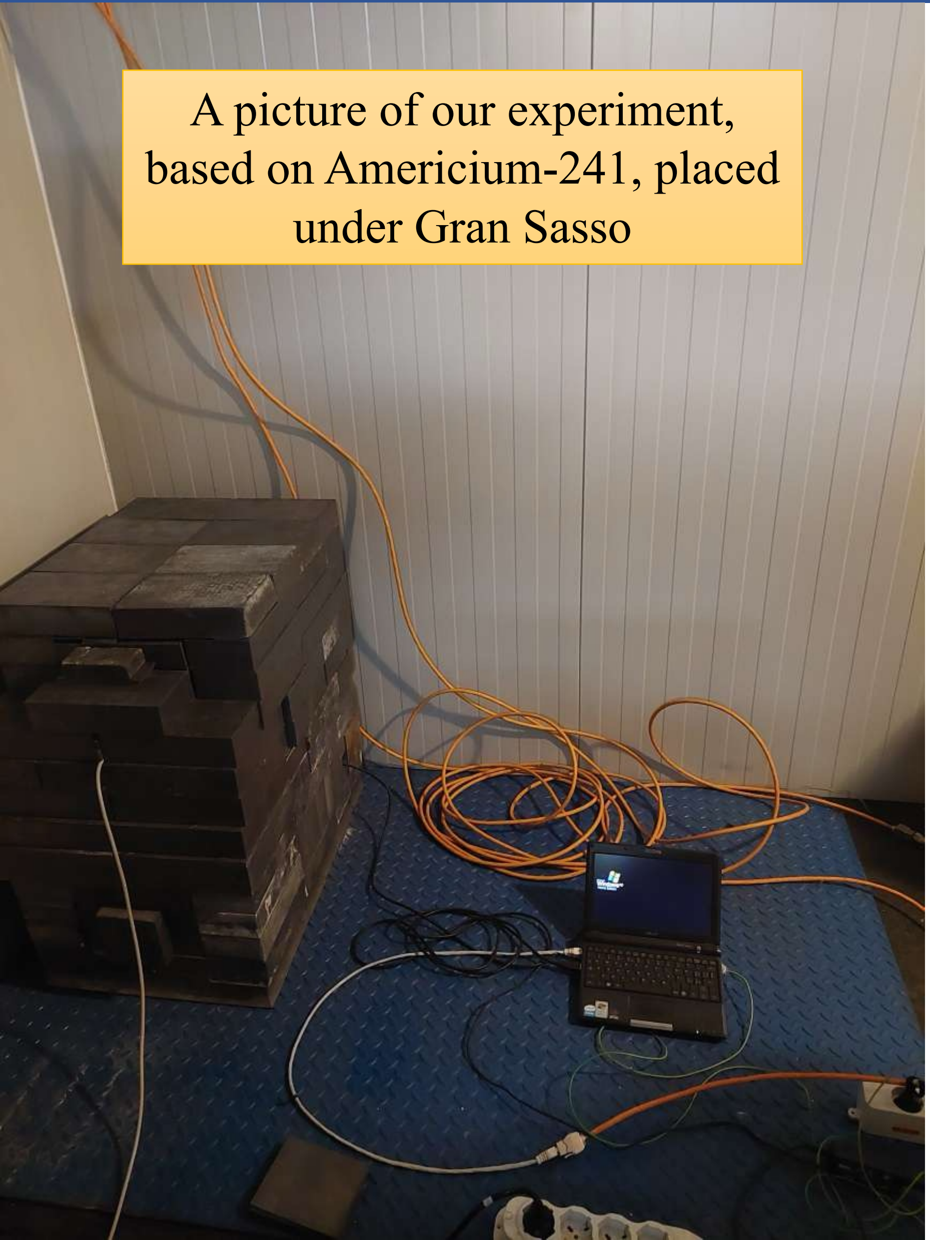

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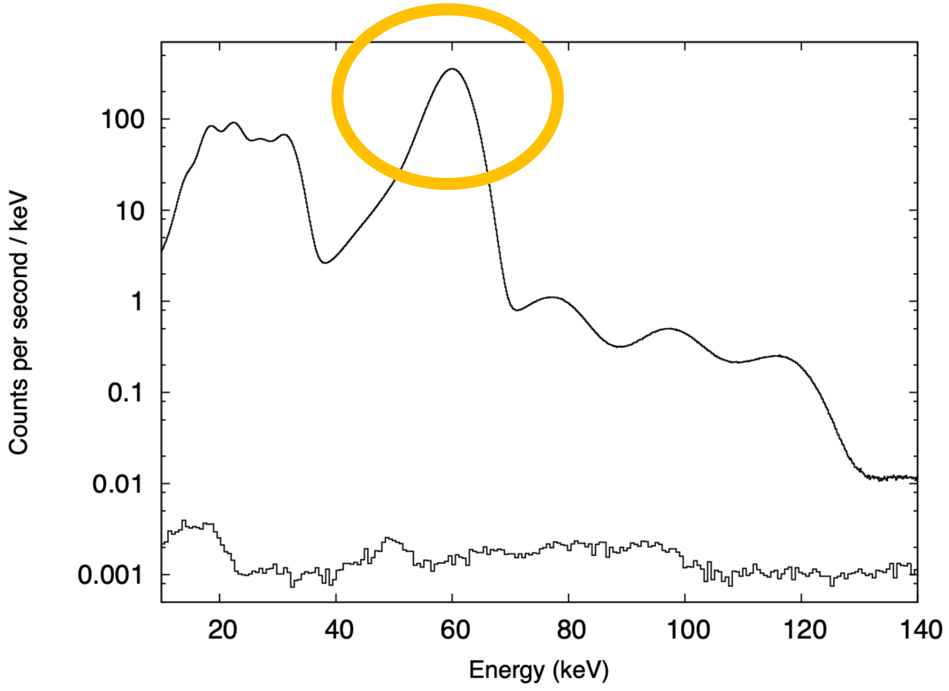

Figure 1: γ-spectrum (counts per second per keV) of the ^{241}Am source (upper curve) compared to the background (lower curve). The dominant contribution arises from the γ at 59.5 keV.

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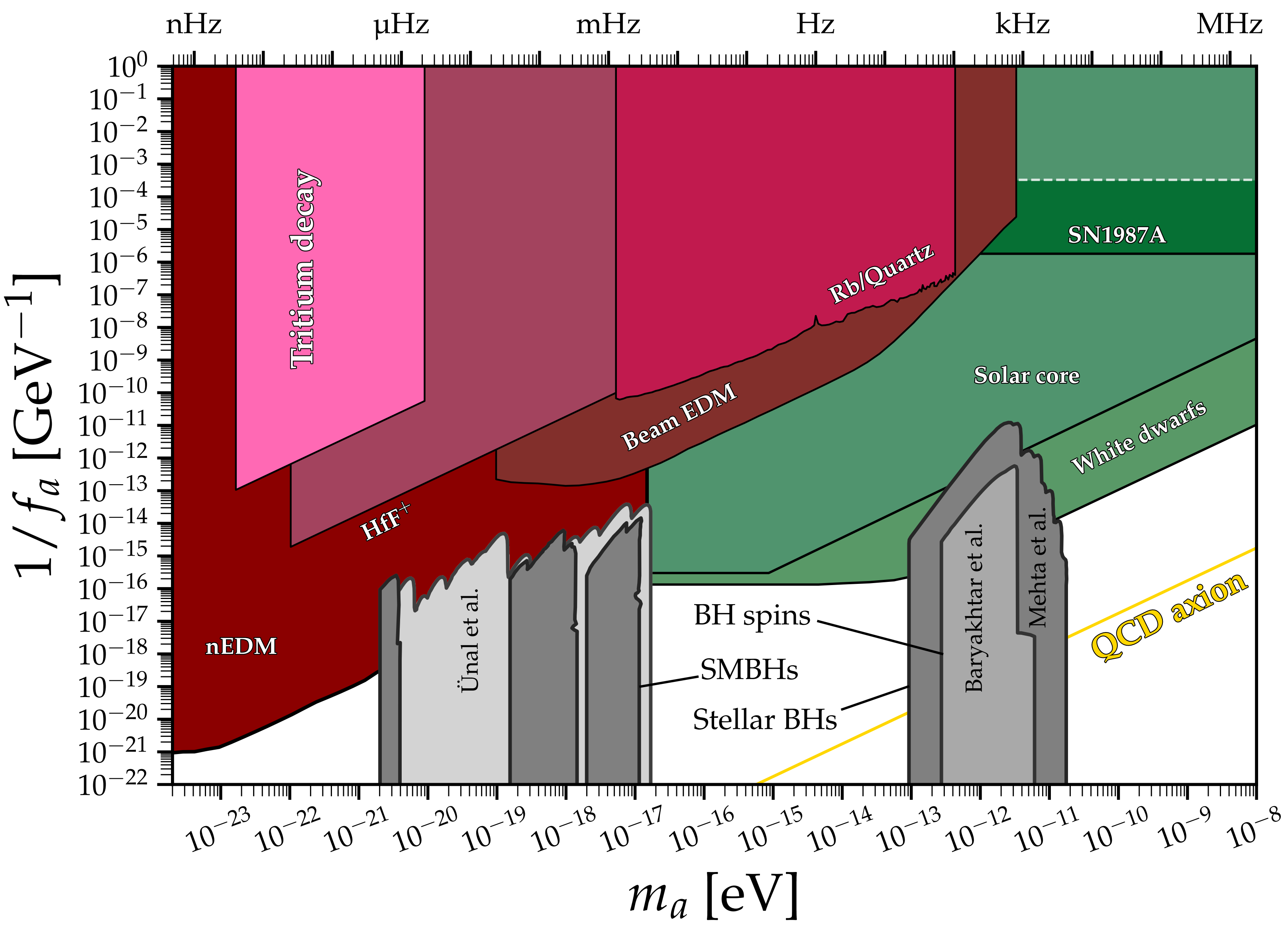
Exp. prospects

Prospect limits from measurements of Americium-241 α-decay



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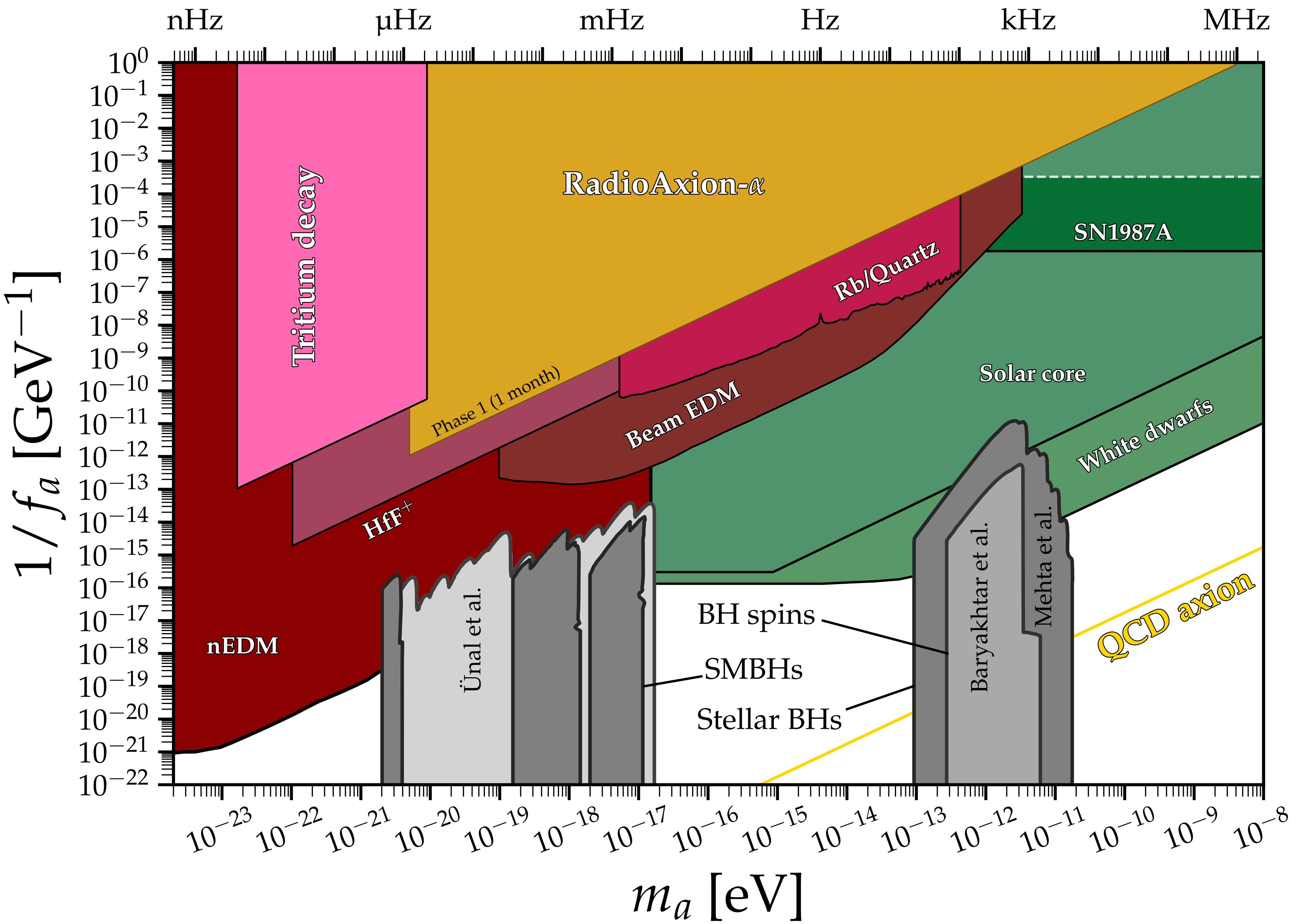
$$1\,\mu s < \Delta t < 10 \text{ days}$$

$$I_{\text{exp}} = 2 \times 10^{-5} \text{ at } 2\sigma$$



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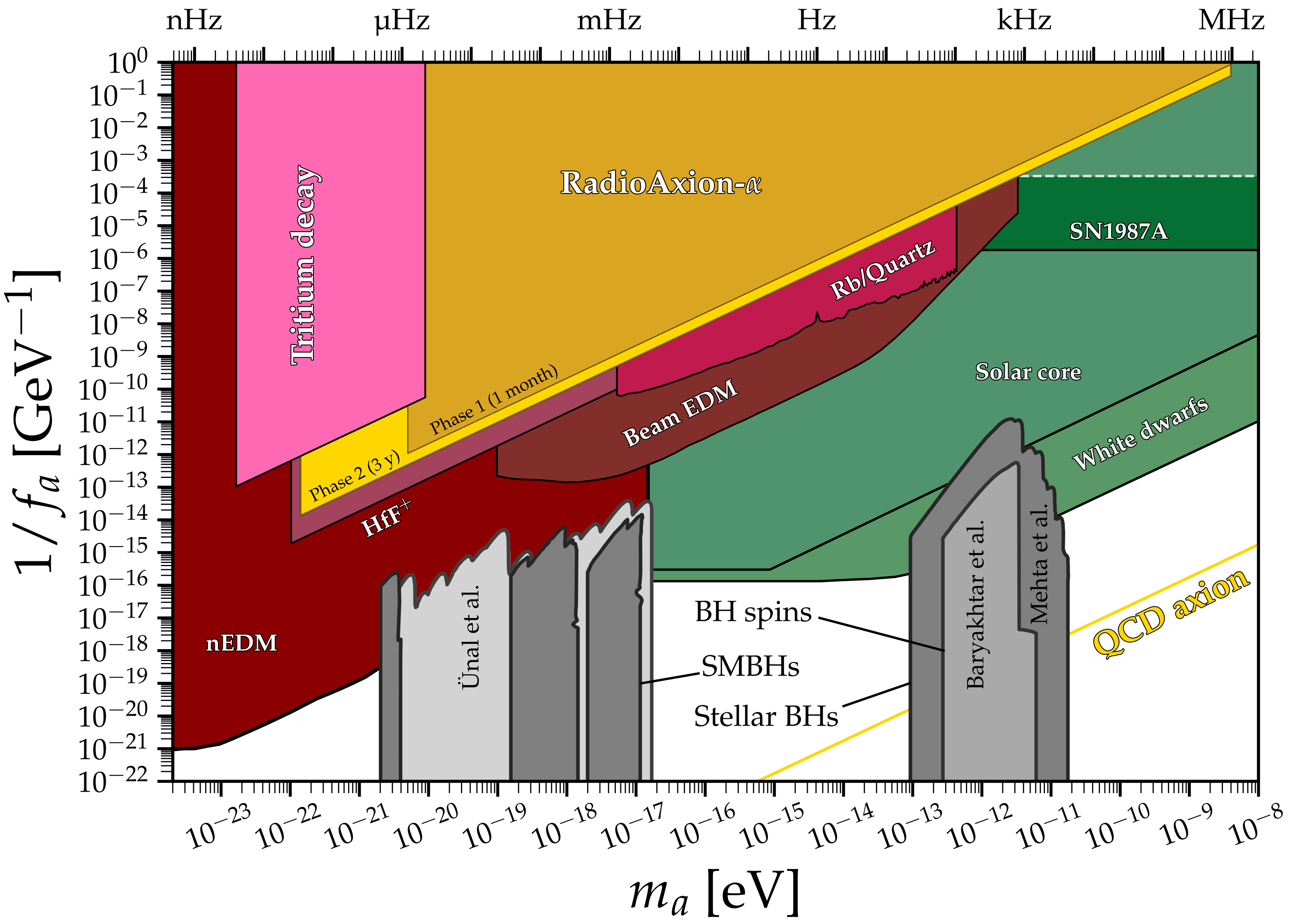
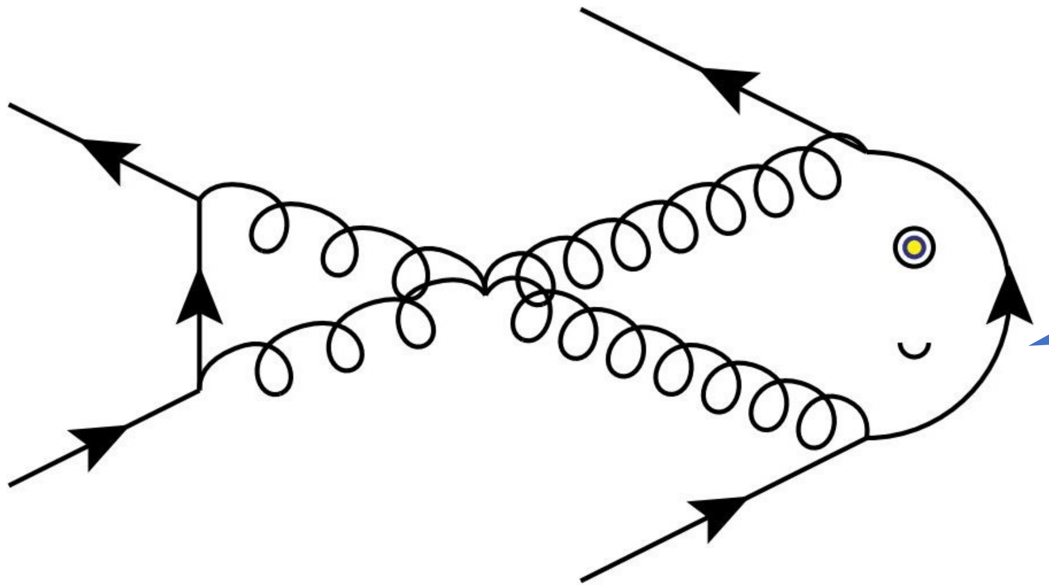
- Phase II, three years of data:

$$1\,\mu s < \Delta t < 1 \text{ yr}$$

$$I_{\text{exp}} = 4 \times 10^{-6} \text{ at } 2\sigma$$



The End



THANK YOU FOR THE ATTENTION!