Model-independent constraints on the QCD axion from supernovae

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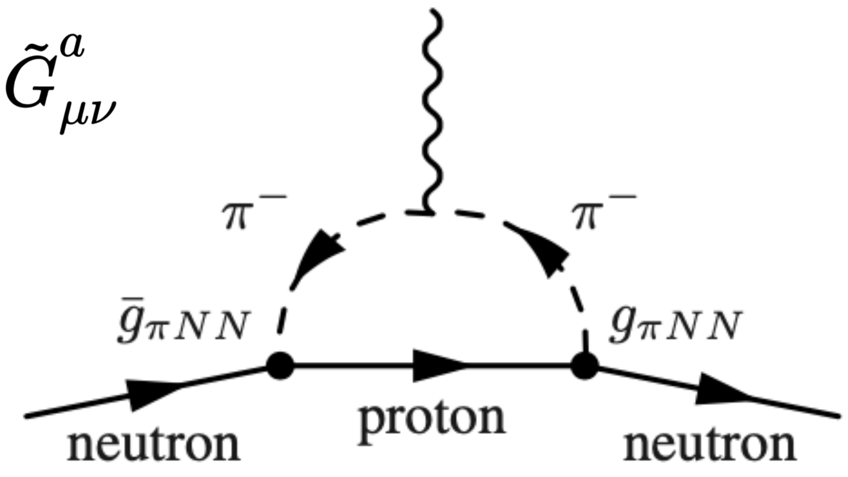
Why Axions?

CP violation in the strong sector

$$\mathcal{L}_{\rm QCD} = \sum_q \bar{q}\left(i\not{D} - m_q e^{i\theta_q}\right)q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

Predicts neutron EDM

$$\mathcal{L}_\chi \supset d_n \bar{n}\sigma^{\mu\nu}\gamma_5 n F_{\mu\nu}$$



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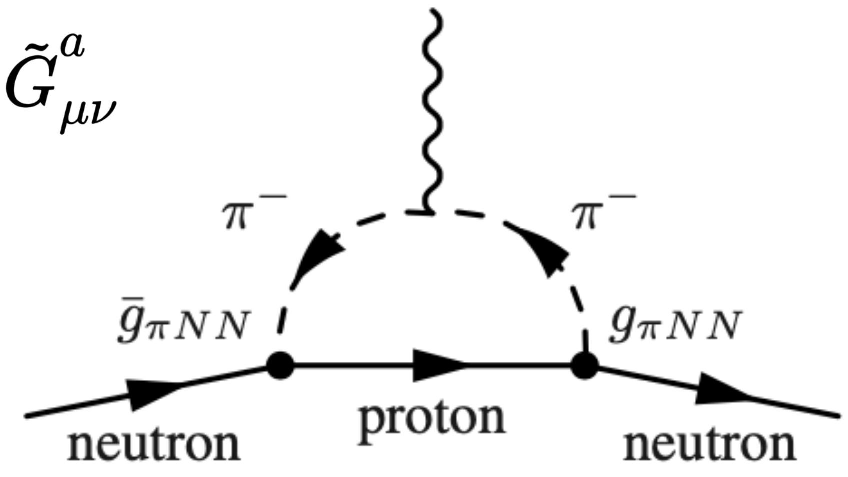

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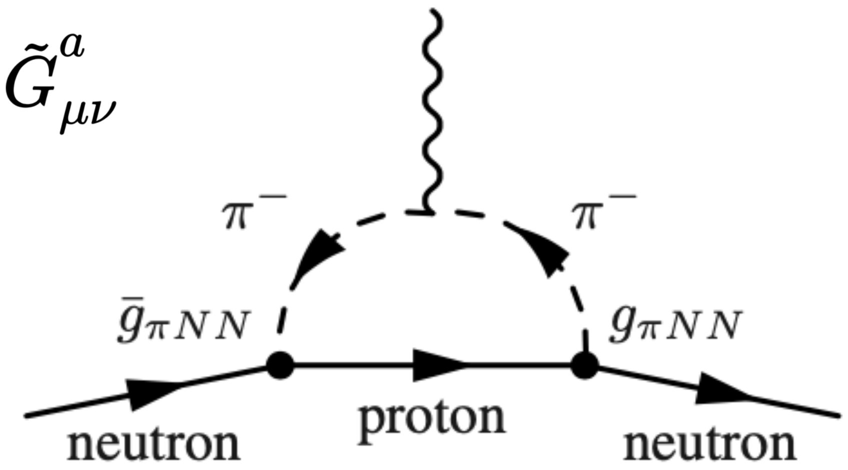

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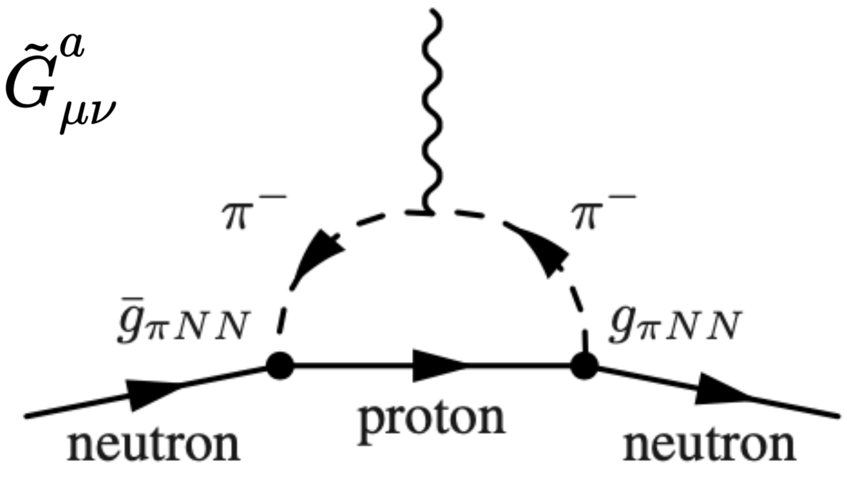

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Solution: QCD Axion

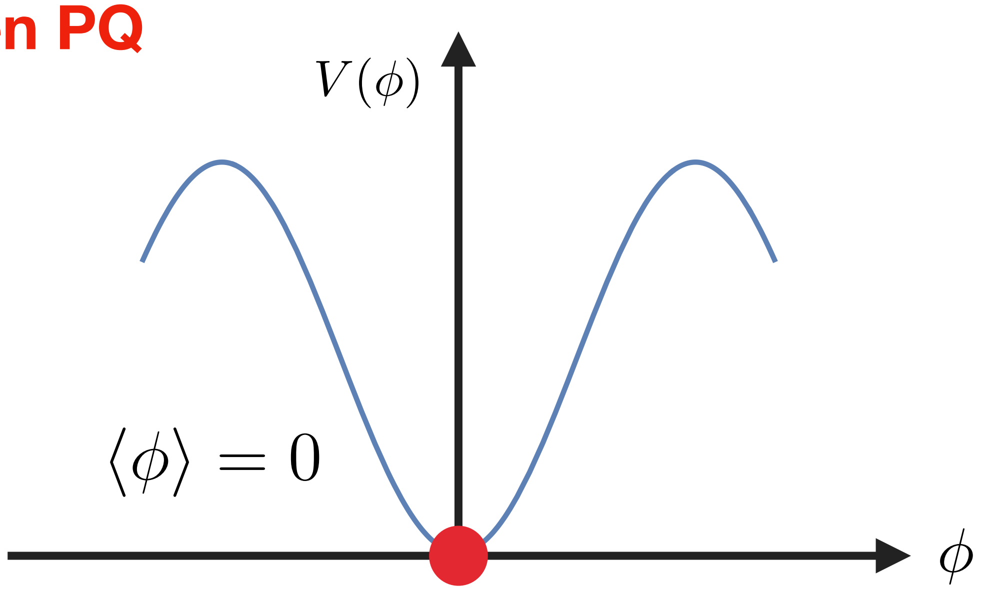
Spontaneously broken PQ symmetry at scale f

UV

$$\frac{g_s^2}{32\pi^2}\frac{\phi}{f}G\tilde{G}$$

IR

$$V(\phi) \simeq -\frac{m_\pi^2 f_\pi^2}{4}\left[\cos\left(\frac{\phi}{f}\right) - 1\right]$$



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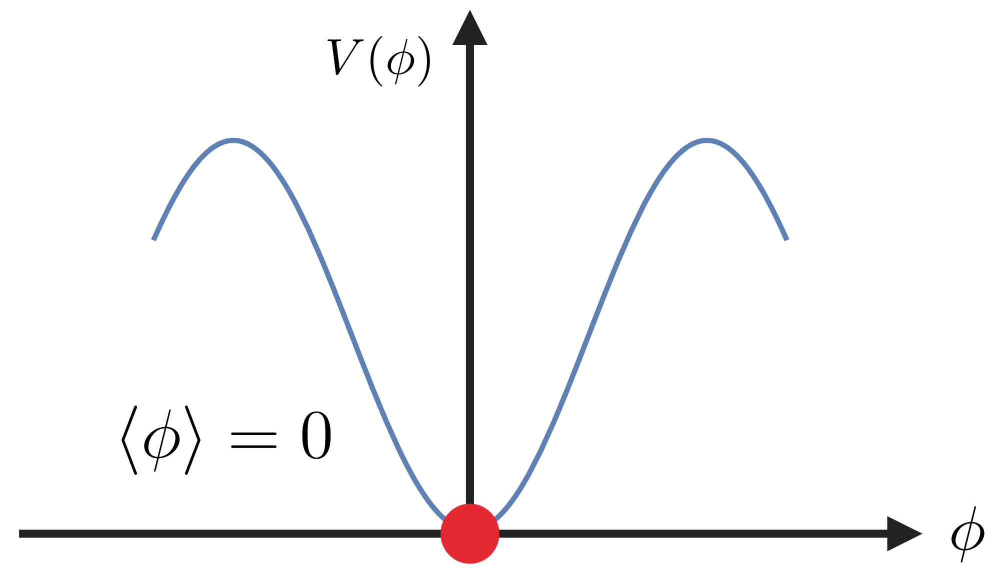

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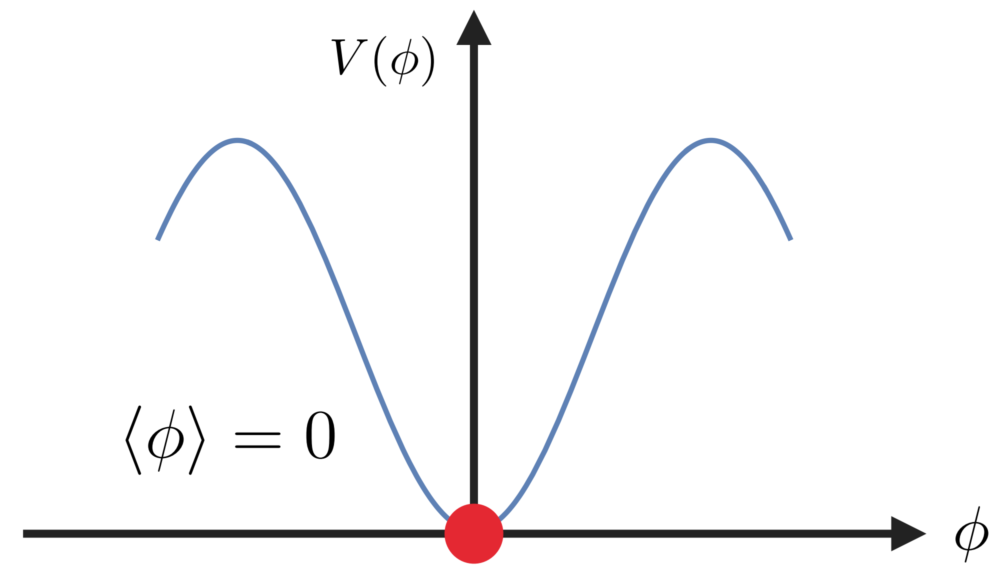


The QCD axion is very predictive

- Couplings to nucleons, photons, electrons,…
- Determined by the scale f
- Many ongoing experiments try to search for the (QCD) axion
- Strong bounds on f from SN and NS cooling

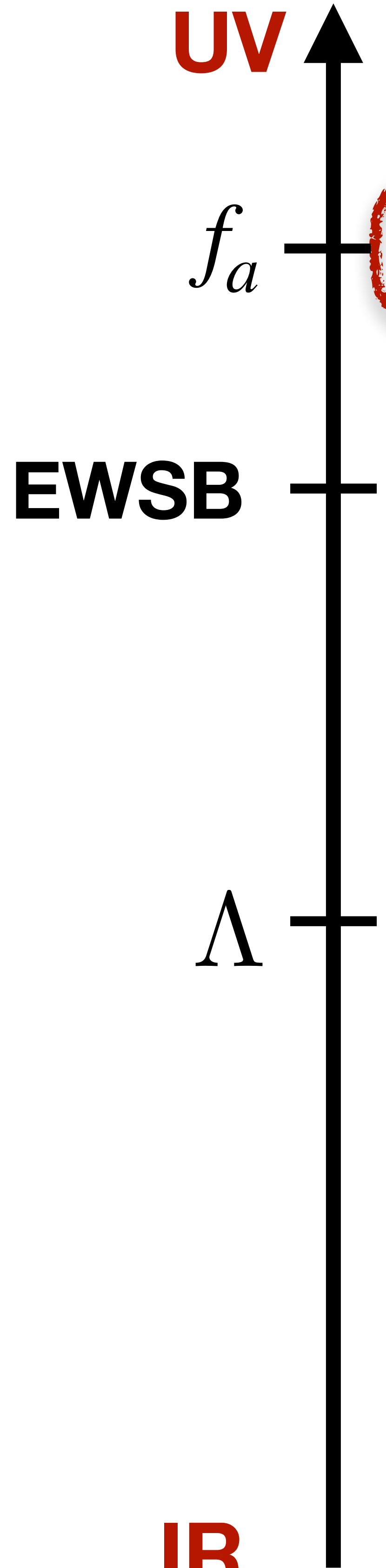
Outline

- Axion-nucleon couplings in Chiral Perturbation Theory

- Astrophysical axion bounds

- Model (in)dependence

From the UV to the IR



$\mathscr{L}_{\mathrm{UV}}$: **Model dependent UV Lagrangian**

Axial PQ symmetry $U(1)_{\mathrm{PQ}}$: spontaneously broken at the scale ~f_a

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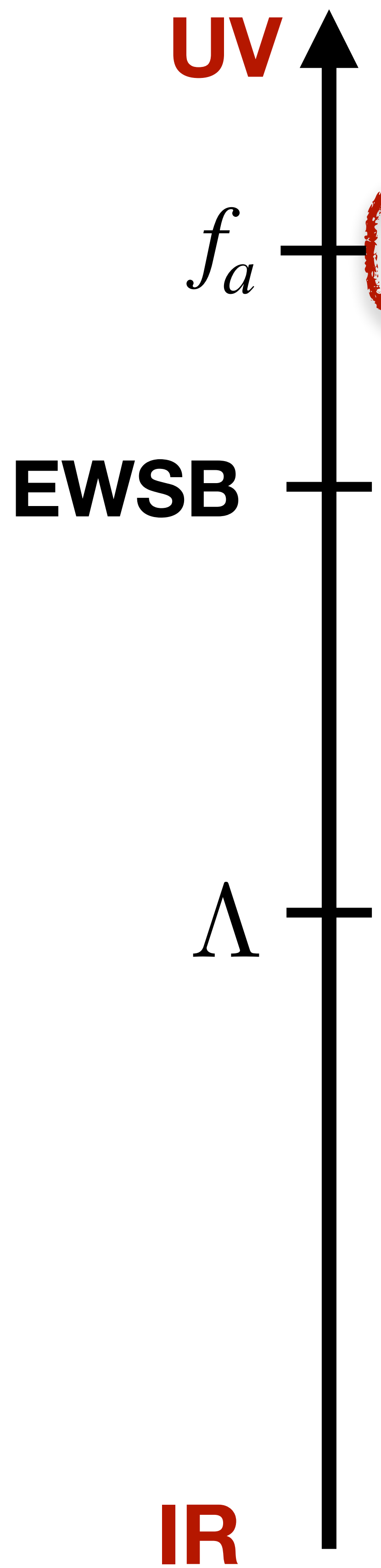

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axion

gluons

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Chiral SB

Λ

QCD confines and a chiral condensate develops

$$|\langle \bar{q}_L q_R \rangle| \equiv B f_\pi^2$$

Theory of Mesons and Baryons Valid for $p \lesssim \Lambda$

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Heavy baryon limit

$$p^\mu = m_N v^\mu + k^\mu \qquad \Psi(x) = e^{-i m_N v\cdot x}\left[N_v(x) + H_v(x)\right]$$

IR

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GG di Cortona et al. '15

Construct low energy EFT of NR nucleons, pions and the QCD axion

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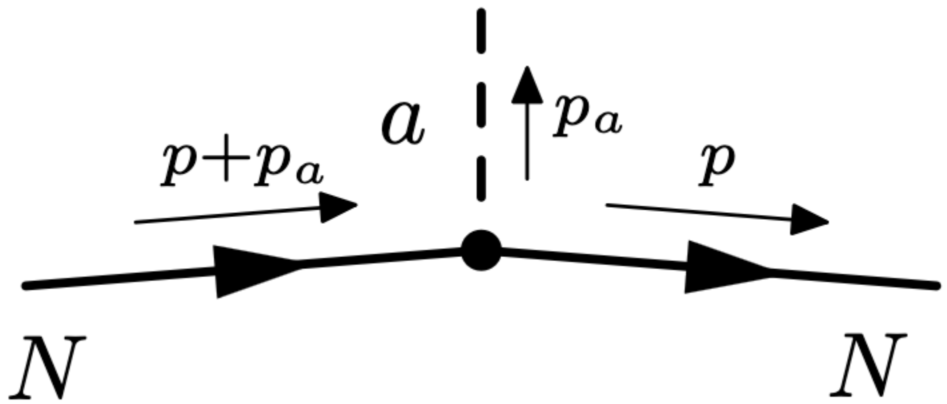

$$= \quad -\frac{1}{f_a} c_N S \cdot p_a$$

e.g. $c_p^{\mathrm{KSVZ}} = -0.47(3), \quad c_n^{\mathrm{KSVZ}} = +0.02(3)$

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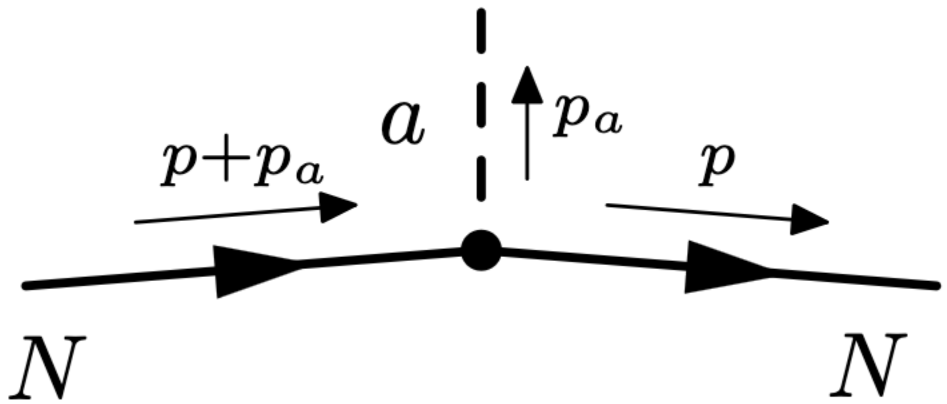

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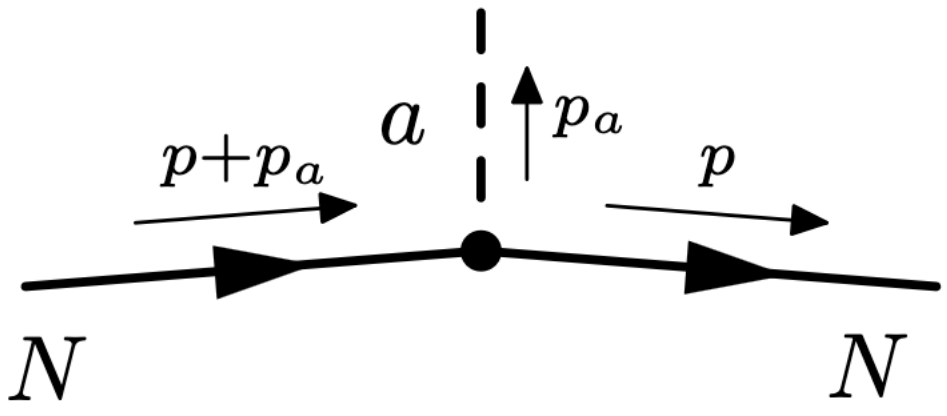

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Axion-nucleon coupling leads to strongest bound on the constant f_a from SN observation.

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2. **Model dependence of the QCD axion-nucleon coupling**

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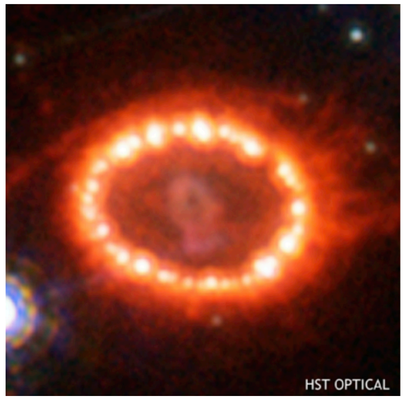

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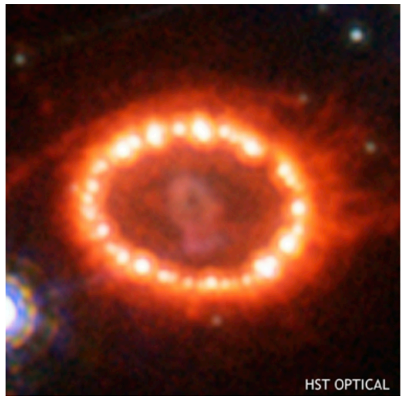

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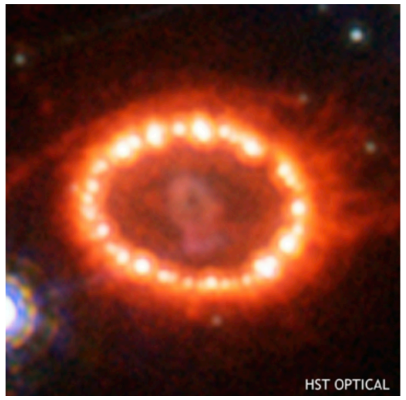

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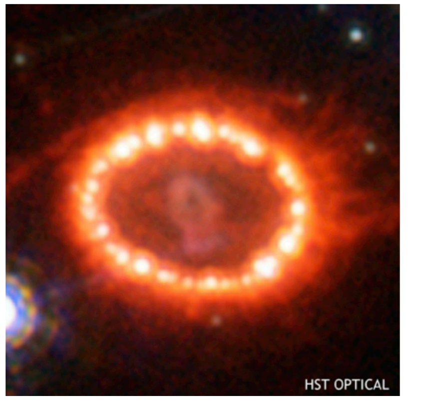

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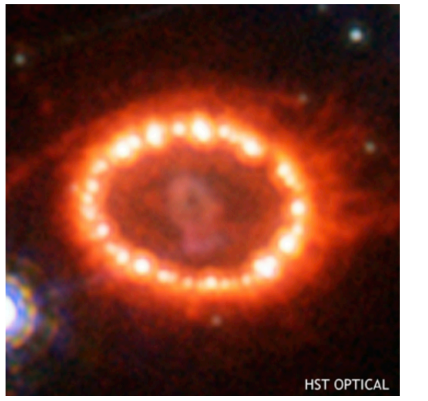

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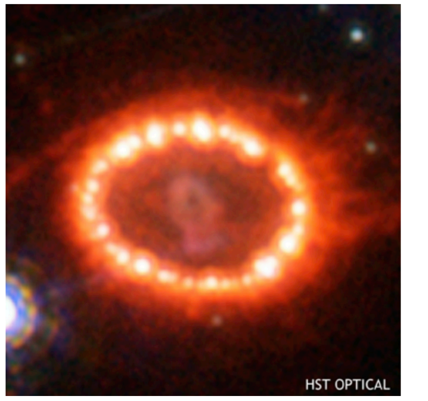

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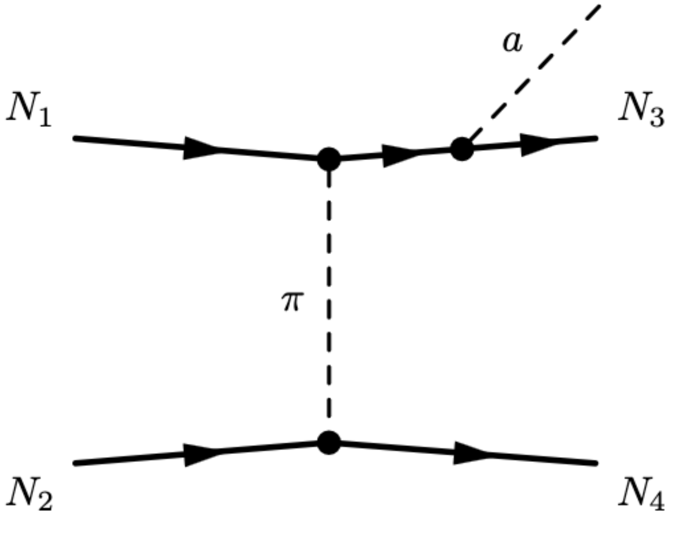
- For a QCD axion this constrains m_a and f_a



2. Model dependence of the QCD axion-nucleon coupling

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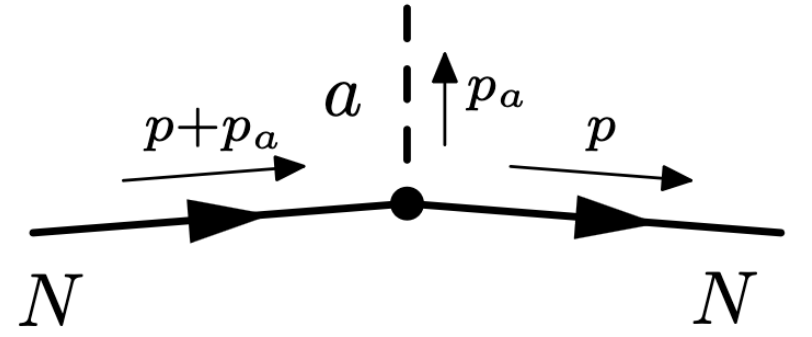

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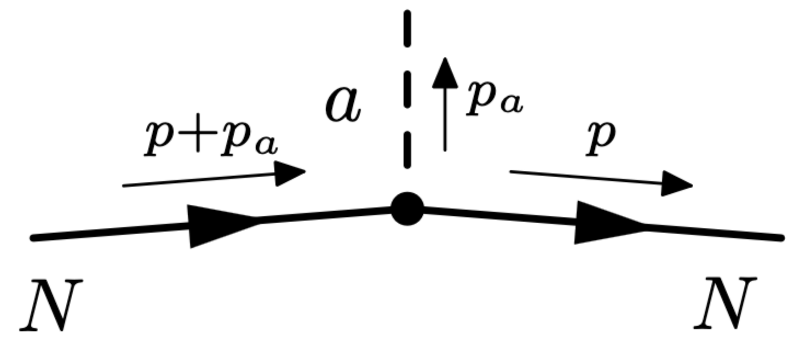

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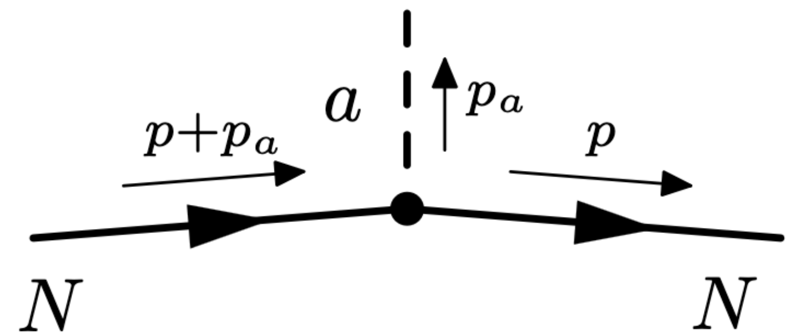

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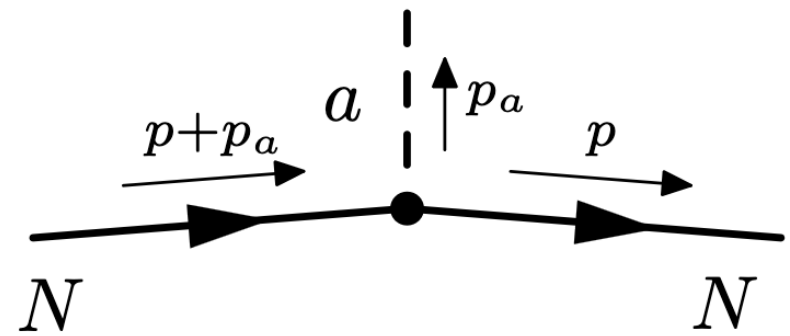

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What is left at NLO?

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LO: $\hat{\mathcal{L}}^{(1)}_{\pi N} = \bar{N}\left(iv \cdot D + g_A S \cdot u + g_0 S \cdot \hat{u}\right) N$

$$\hat{u}_\mu = c_{u+d}\left(\frac{\partial_\mu a}{f_a}\right)\mathbf{1} + \ldots$$

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NLO:

$$\begin{aligned}\hat{\mathcal{L}}^{(2)}_{\pi N} = \bar{N}\Bigg[&-\frac{1}{2m_N}\left(D^2 - (v\cdot D)^2 + ig_A\{S\cdot D, v\cdot u\} + ig_0\{S\cdot D, v\cdot \hat{u}\}\right)\\ &+ \hat{c}_1\langle\chi_+\rangle + \frac{\hat{c}_2}{2}(v\cdot u)^2 + \hat{c}_3(u\cdot u) + \frac{\hat{c}_4}{2} i\epsilon^{\mu\nu\rho\sigma}[u_\mu, u_\nu]v_\rho S_\sigma\\ &+ \hat{c}_5\widetilde{\chi}_+ + \frac{\hat{c}_8}{4}(v\cdot u)(v\cdot\hat{u}) + \hat{c}_9(u\cdot\hat{u})\Bigg]N,\end{aligned}$$

$$\mathcal{L}^{(2)}_{\pi NN} = \frac{c_D}{2f_\pi^2\Lambda_\chi}(\bar{N}N)\left(\bar{N}\,S\cdot u\,N\right) + \frac{\tilde{c}_D}{2f_\pi^2\Lambda_\chi}(\bar{N}N)\left(\bar{N}\,S\cdot\hat{u}\,N\right),$$

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$$+ \hat{c}_5\widetilde{\chi}_+ + \frac{\hat{c}_8}{4}(v\cdot u)(v\cdot\hat{u}) + \hat{c}_9(u\cdot\hat{u})\Bigg]N,$$

$$\mathcal{L}^{(2)}_{\pi NN} = \frac{c_D}{2f_\pi^2\Lambda_\chi}(\bar{N}N)(\bar{N}S\cdot u N) + \frac{\tilde{c}_D}{2f_\pi^2\Lambda_\chi}(\bar{N}N)(\bar{N}S\cdot\hat{u}N),$$

$$\chi = 2BM_a^\dagger \qquad M_a \equiv e^{\frac{ia(x)}{2f_a}Q_a} M_q e^{\frac{ia(x)}{2f_a}Q_a}$$

$$\chi_\pm = u^\dagger\chi u^\dagger \pm u\chi^\dagger u, \quad \widetilde{\chi}_\pm = \chi_\pm - \frac{1}{2}\langle\chi_\pm\rangle$$

2. Model dependence of the QCD axion-nucleon coupling

LO:

$$\hat{\mathcal{L}}^{(1)}_{\pi N} = \bar{N}\left(iv\cdot D + g_A S\cdot u + g_0 S\cdot \hat{u}\right)N \qquad \hat{u}_\mu = c_{u+d}\left(\frac{\partial_\mu a}{f_a}\right)\mathbb{1} + \ldots$$

$$u_\mu = -\left(\frac{\partial_\mu \pi^a}{f_\pi}\right)\tau^a + c_{u-d}\left(\frac{\partial_\mu a}{f_a}\right)\tau_3$$

NLO:

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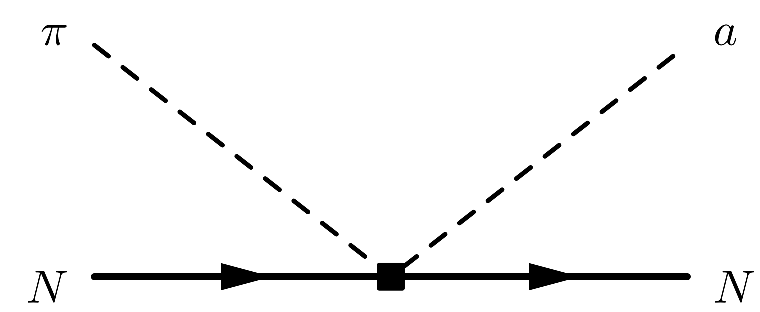
Which interactions does this give rise to?

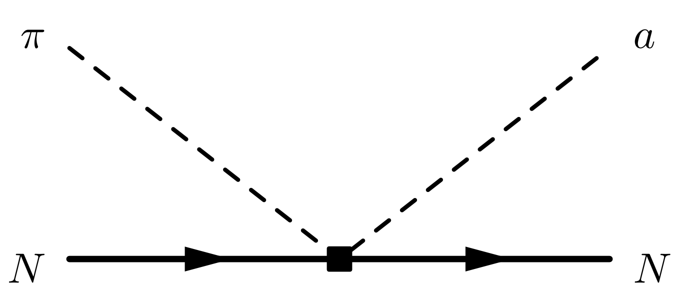
2. Model dependence of the QCD axion-nucleon coupling

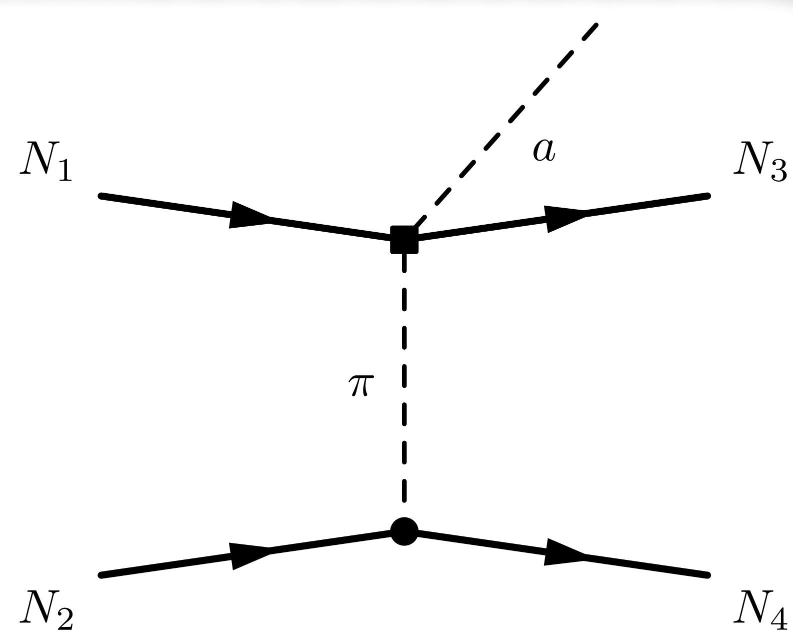
Isospin breaking term survives independent of the type of axion model

$$\mathcal{L}^{(2)}_{\pi N} \supset \hat{c}_5 \bar{N} \tilde{\chi}_+ N$$

with $\widetilde{\chi}_+ \supset -m_\pi^2 \frac{4z}{(1+z)^2} \left(\frac{\pi^a a}{f_\pi f_a} \right) \tau^a$







These diagrams dominate for the model independent SN bound

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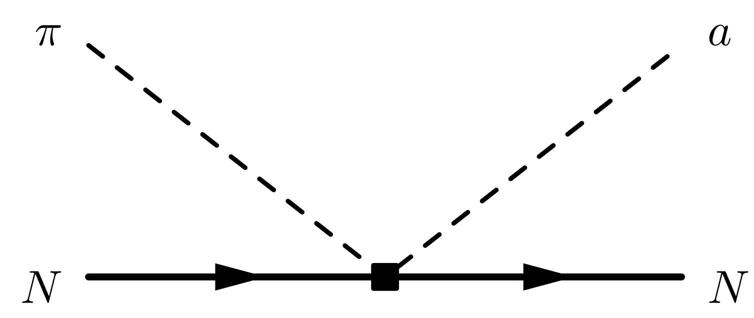

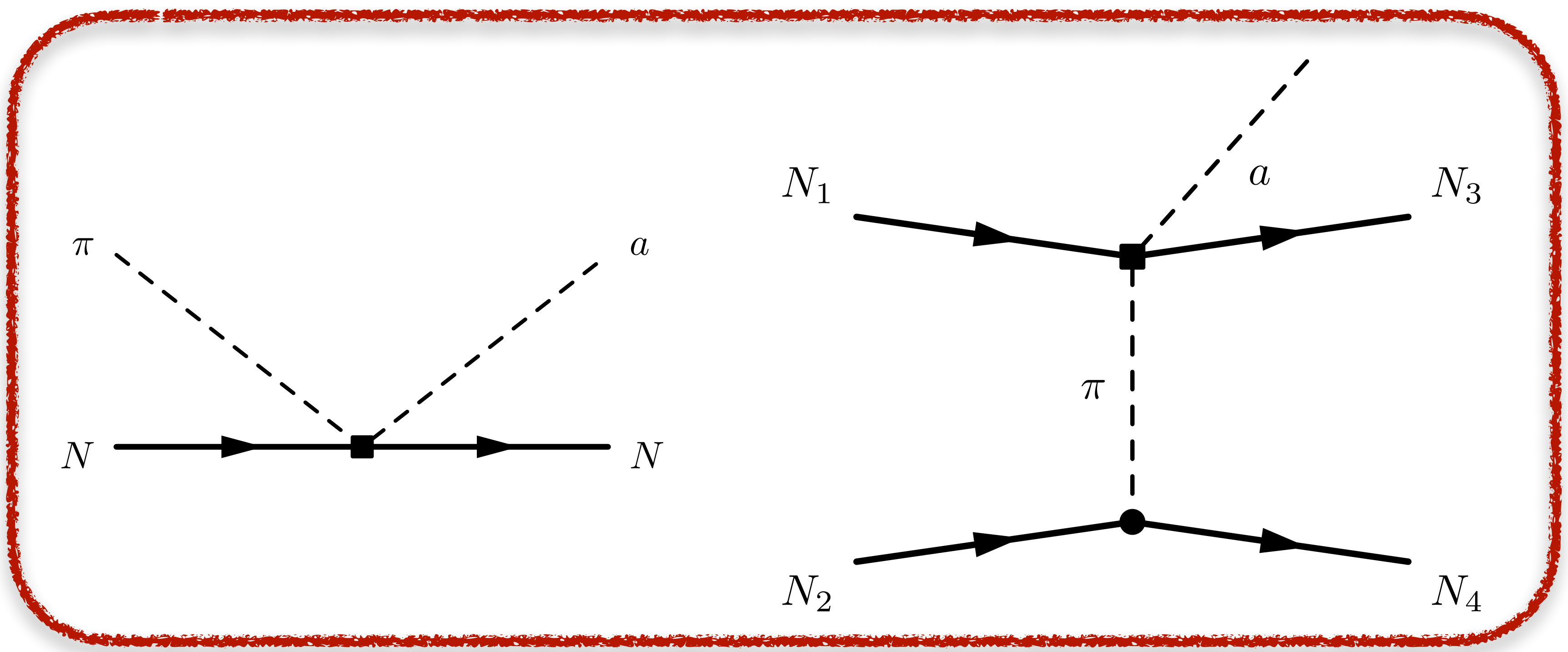

Leads to

$$f_a \gtrsim O(5) \times 10^7 \mathrm{GeV}$$

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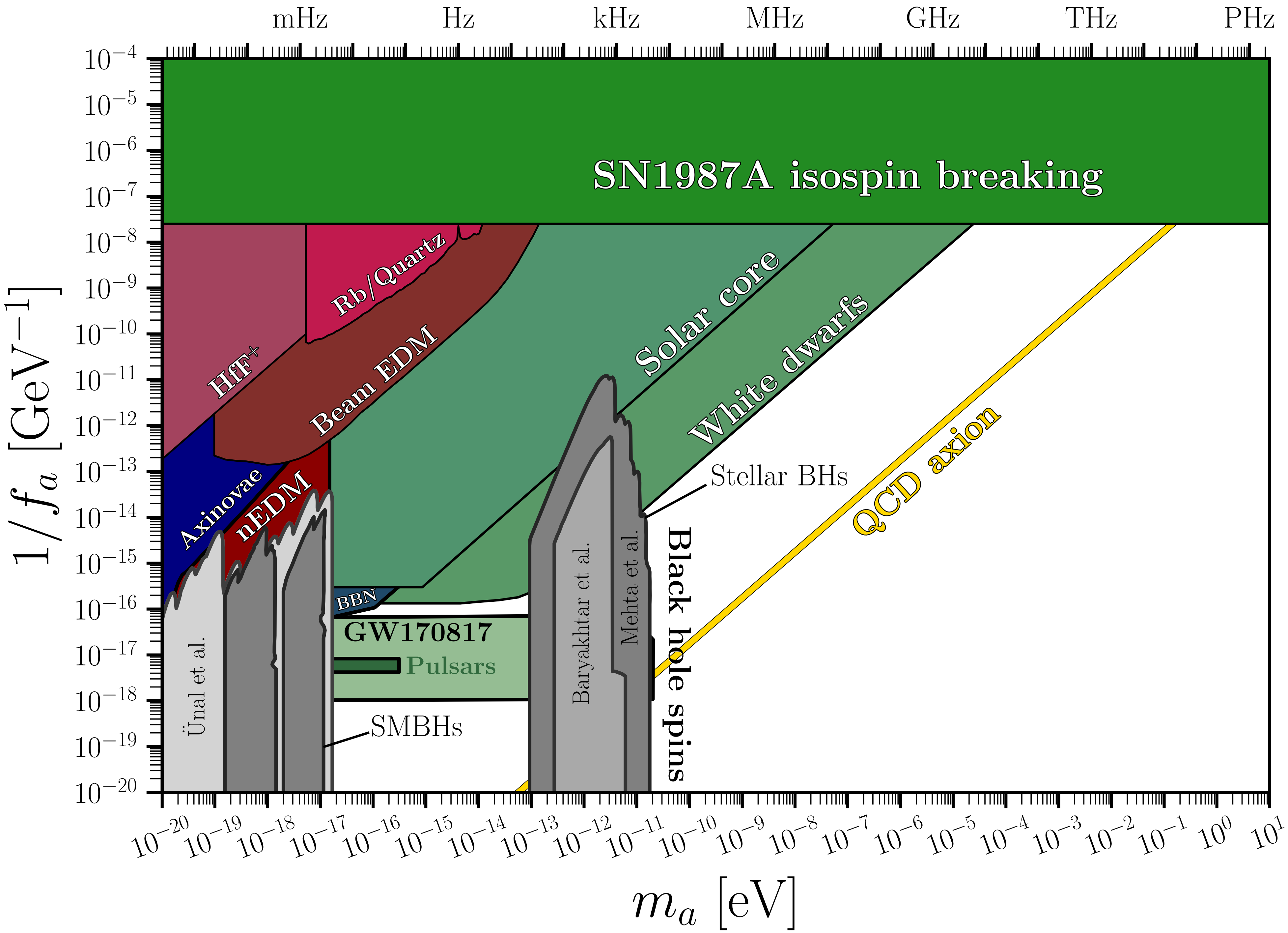
Bound on axion from SN1987A



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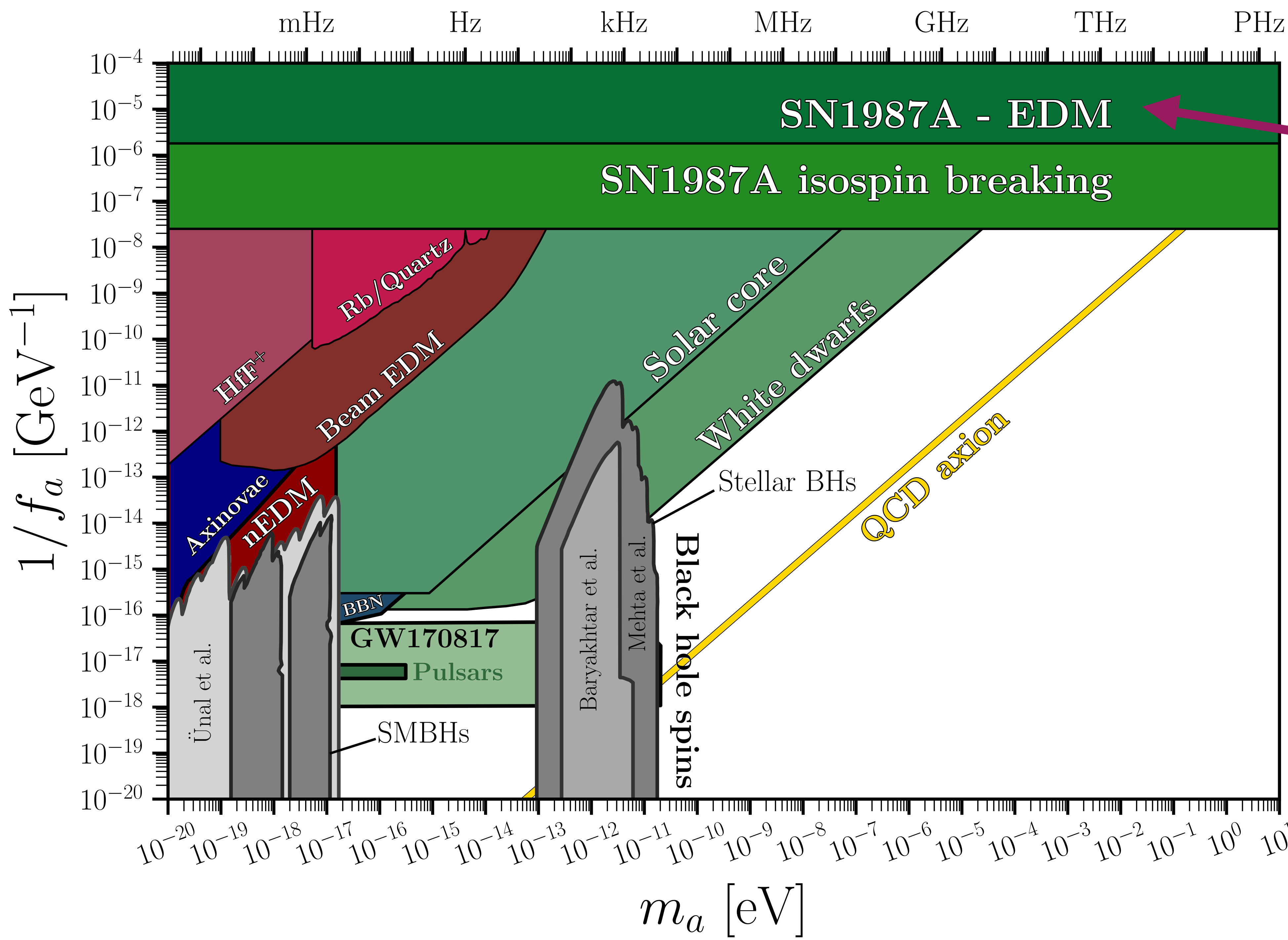

Current strongest bound in literature, see Lucente et al. '22

Summary and Conclusion

- Systematic study of model dependence of the axion nucleon interaction

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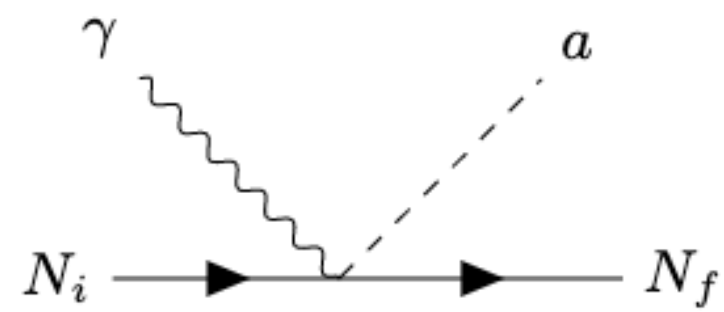
- Isospin breaking term in Lagrangian cannot be tuned away
- Leads to an order of magnitude stricter model-independent bound on f_a

Backup slides

Comparison with current literature

$$\mathcal{L}_a^{\mathrm{EDM}} = -\frac{i}{2} g_{d,N}\, a \bar{N} \gamma_5 \sigma_{\mu\nu} N F^{\mu\nu}$$



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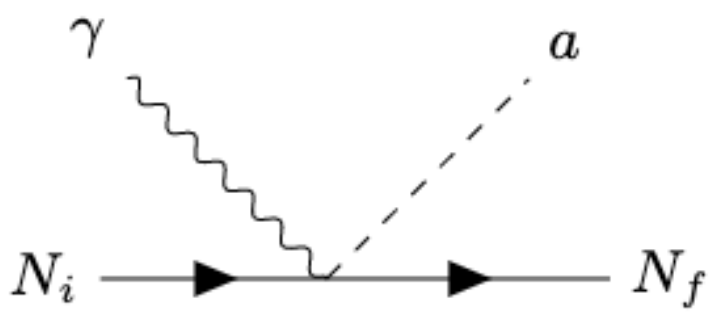

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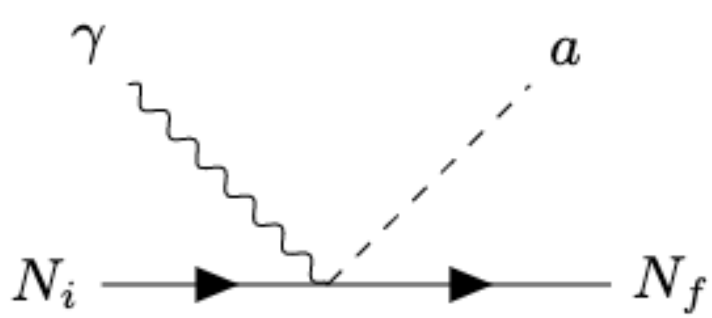

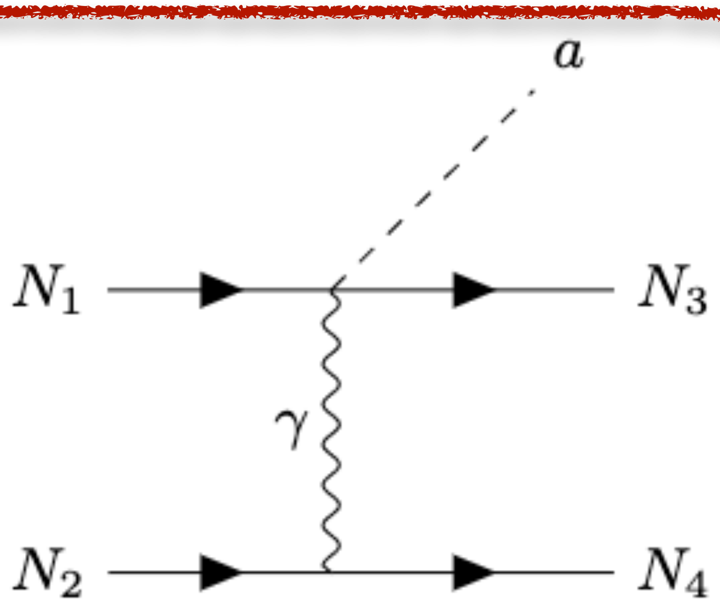

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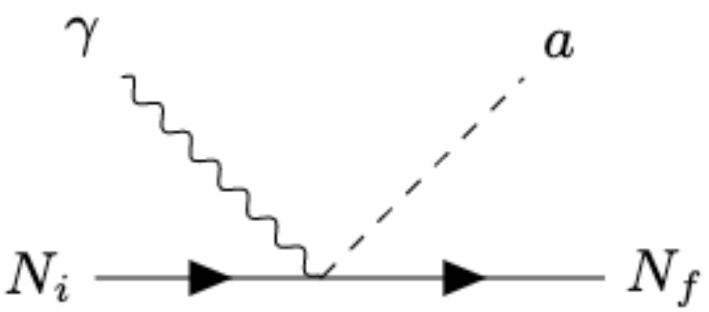

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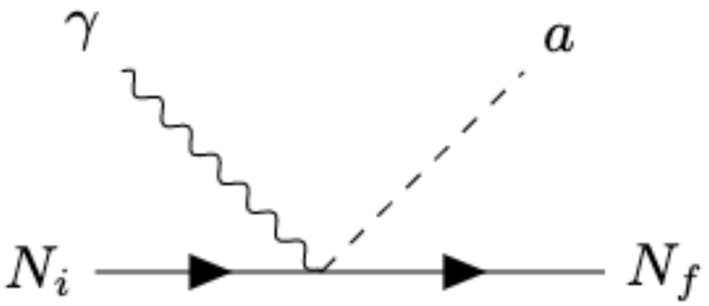

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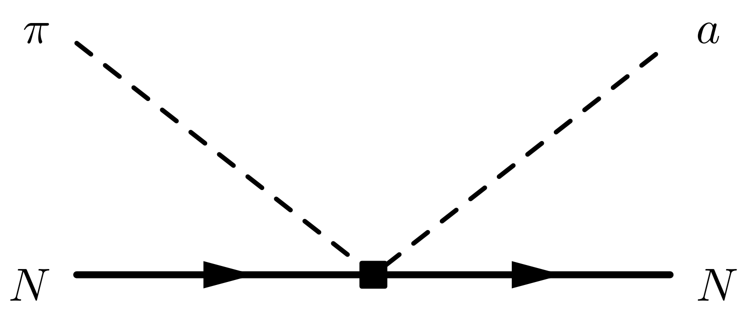

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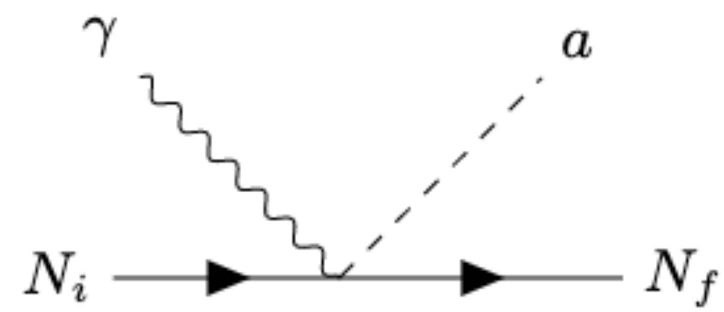

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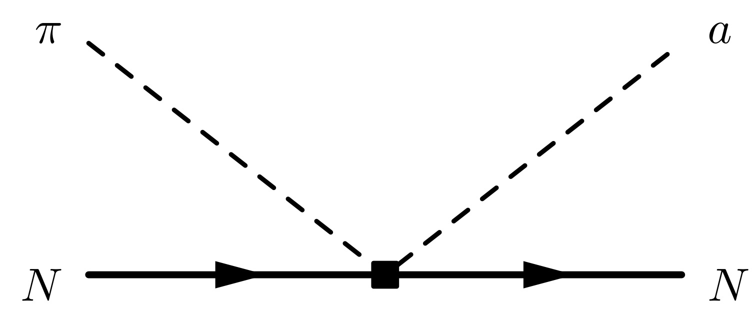
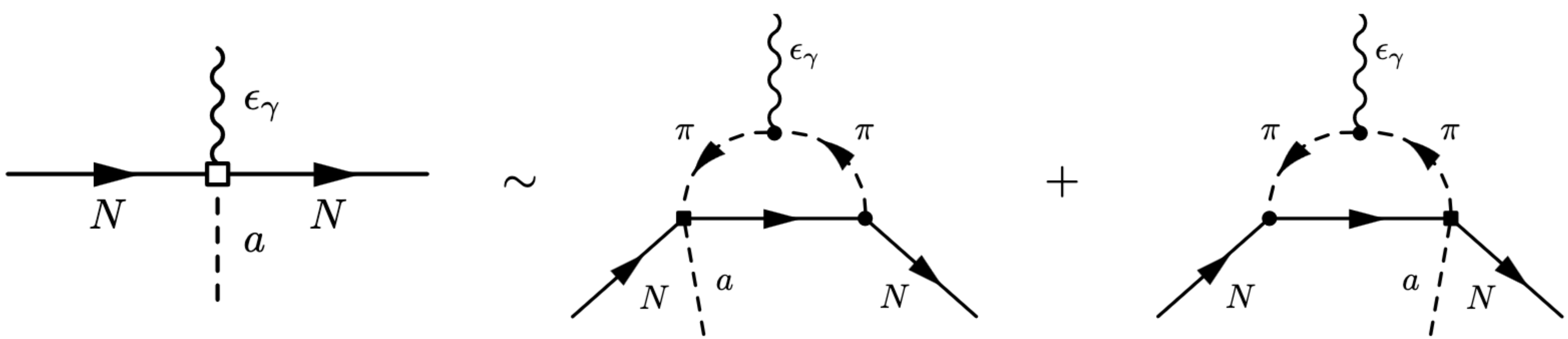




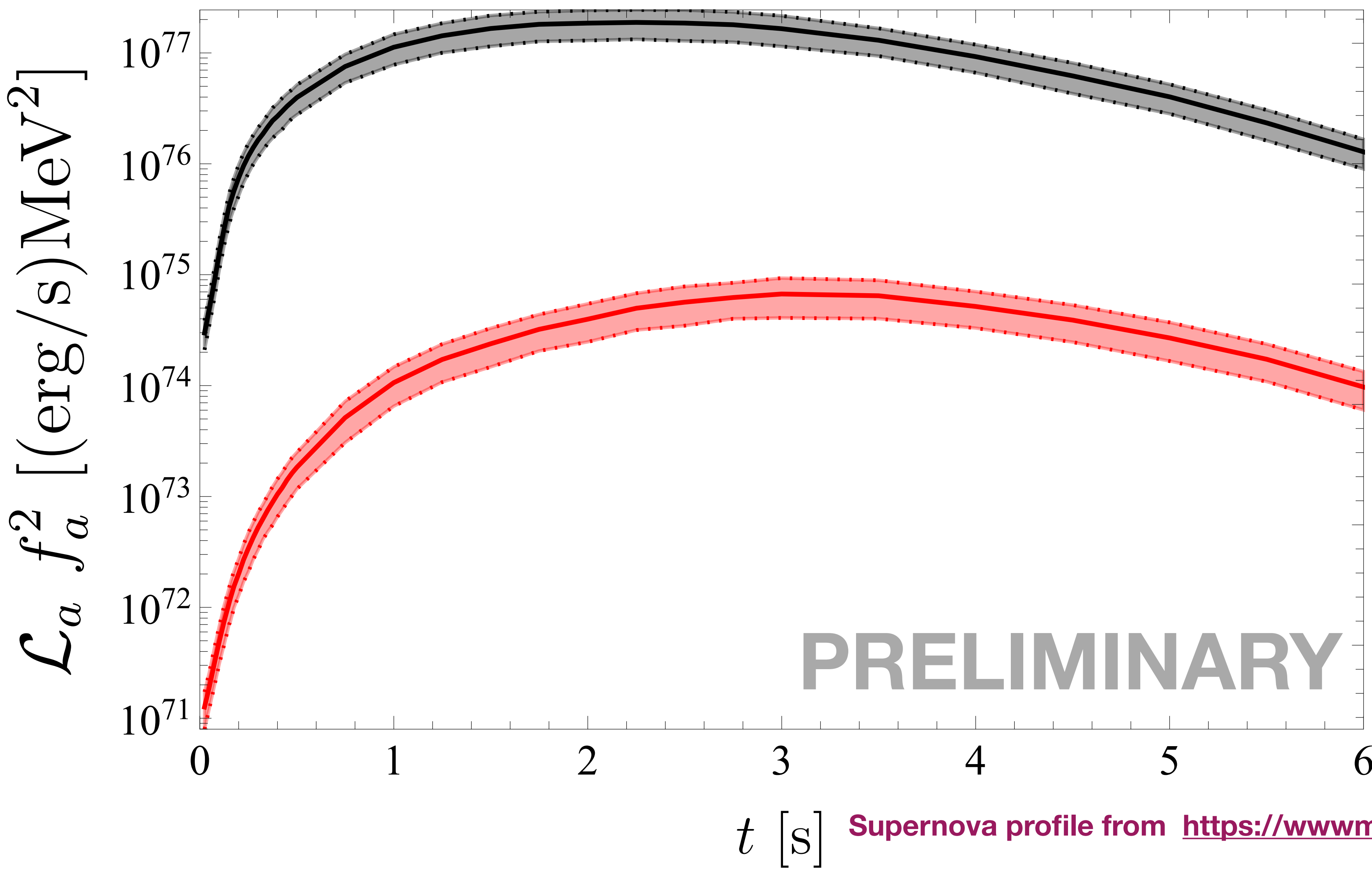
Astrophobic axions or a model-independent SN bound

di Luzio et al. '15

Models which try to 'tune away' axion nucleon interactions

Some aspects of 'astrophobic axion' survive at finite density, only subleading corrections

Model independent SN bound for all axions that solve strong CP problem



For current best bound see Lucente et al. '22

Supernova profile from https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/

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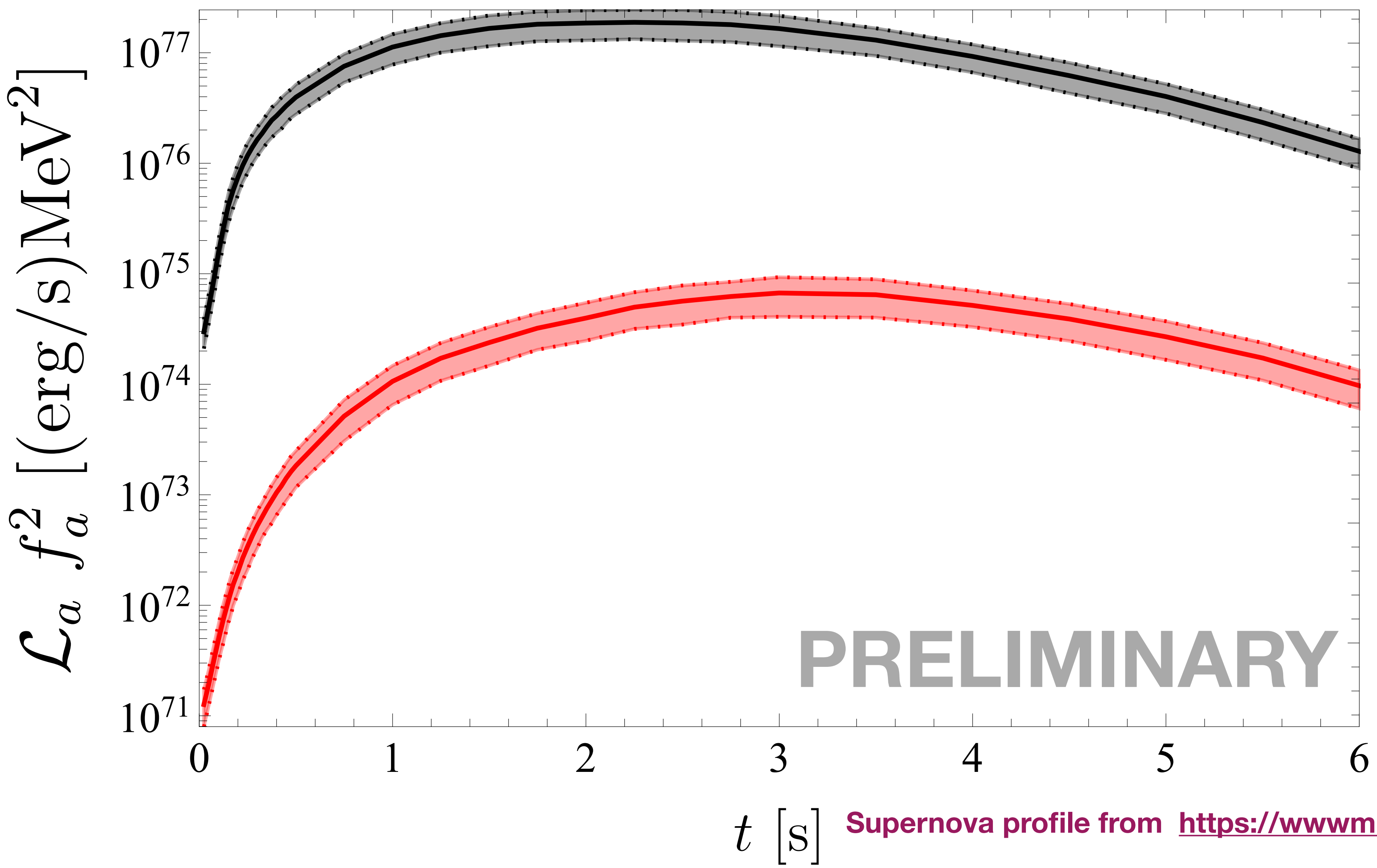

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