A systematic approach to axion production at finite density

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Konstantin Springmann

In collaboration with **Michael Stadlbauer (TUM,MPP)**, **Stefan Stelzl (EPFL)** and **Andreas Weiler (TUM)**

Based on

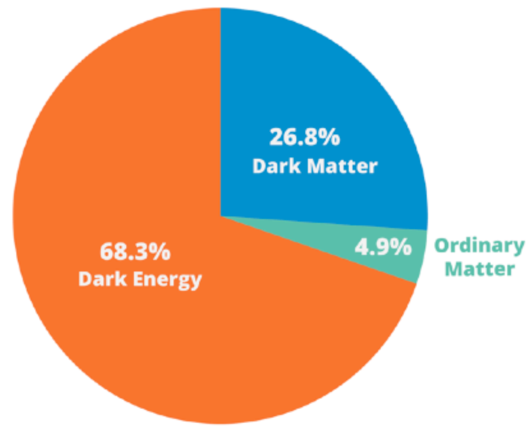
2410.10945, and 2410.19902

Also 2003.04903
with **Reuven Balkin (UCSC)** and **Javi Serra (IFT)**

SN 1987A as seen from James Webb

Why Axions?

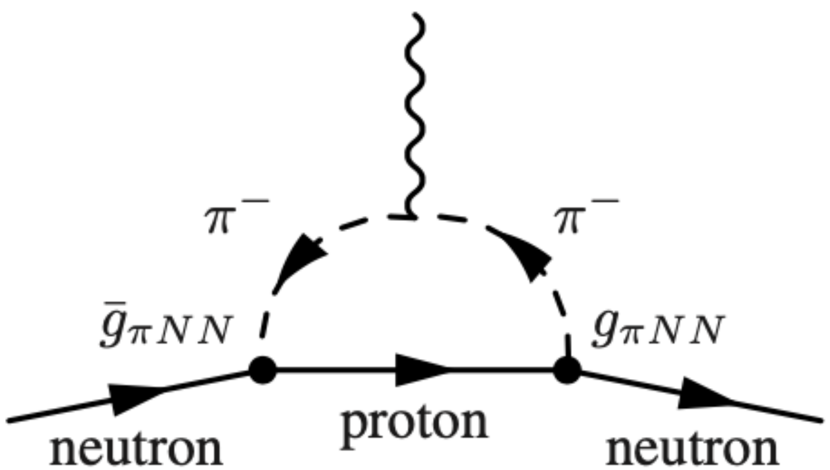
- **Can be DM**



- **Solves Strong CP Problem** $|\bar{\theta}| \lesssim 10^{-10}$

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

nEDM $$d_n \approx \frac{e|\bar{\theta}|m_\pi^2}{m_n^3} \approx 10^{-16}|\bar{\theta}|e \text{ cm}$$



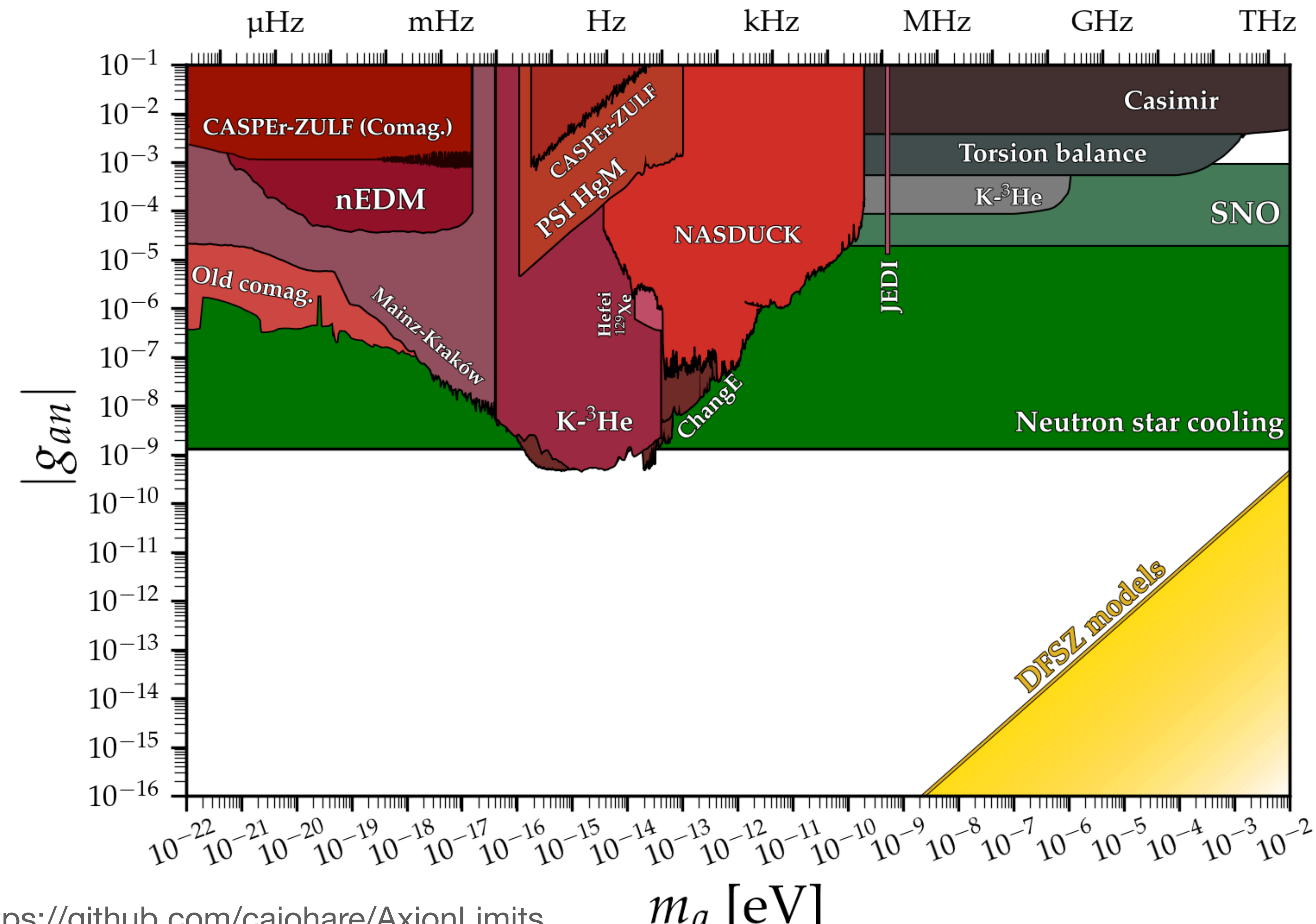
Crewther, Vecchia, Veneziano, Witten ('79)

Axion-Neutron coupling

Some of the strongest bounds from SN and NS cooling

$$g_{an} = c_n \frac{m_n}{f_a}$$

For recent astro bounds see e.g. Mirizzi et al. ’19 (SN), Buschmann et al. (NS) ‘21



https://github.com/cajohare/AxionLimits

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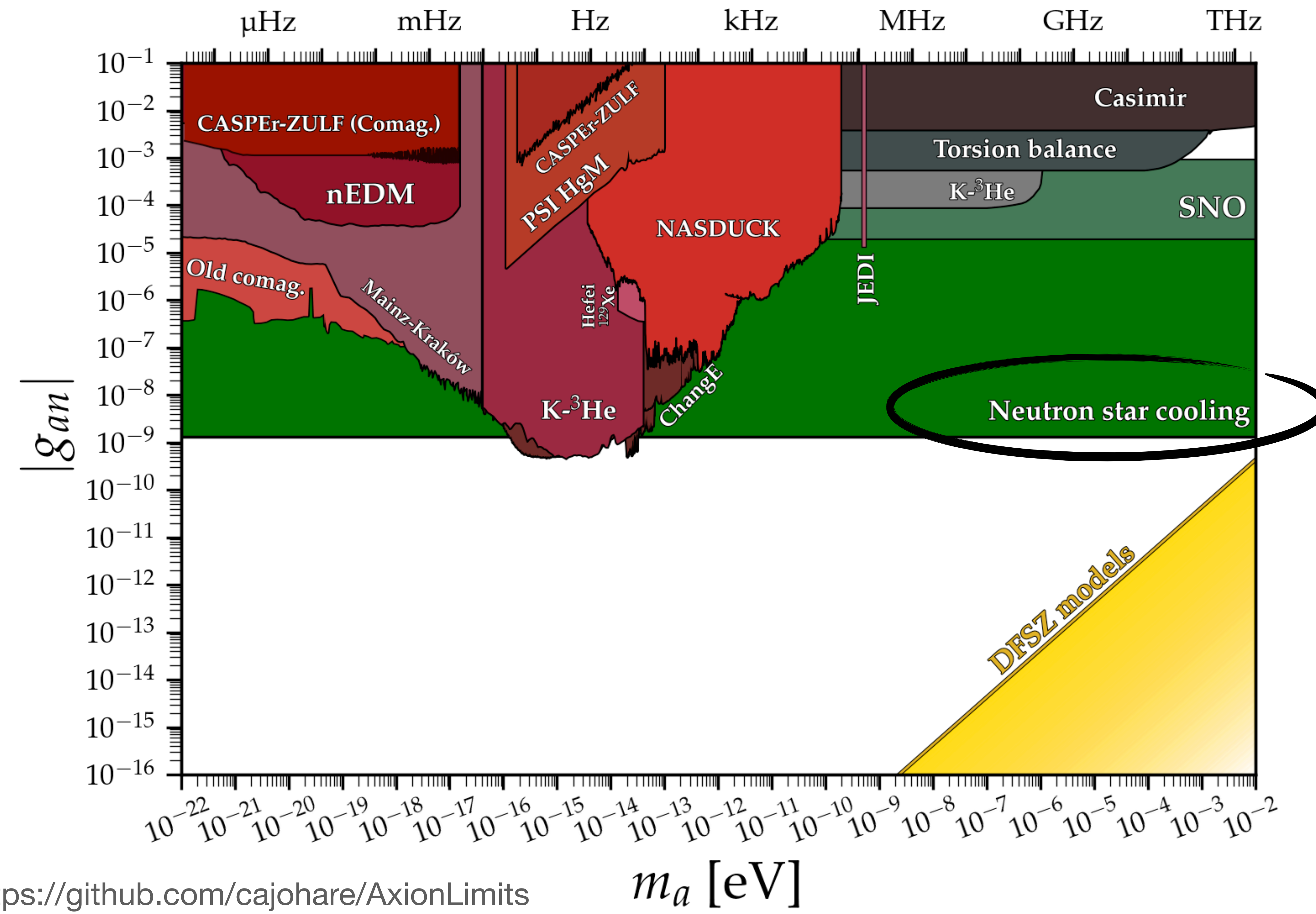

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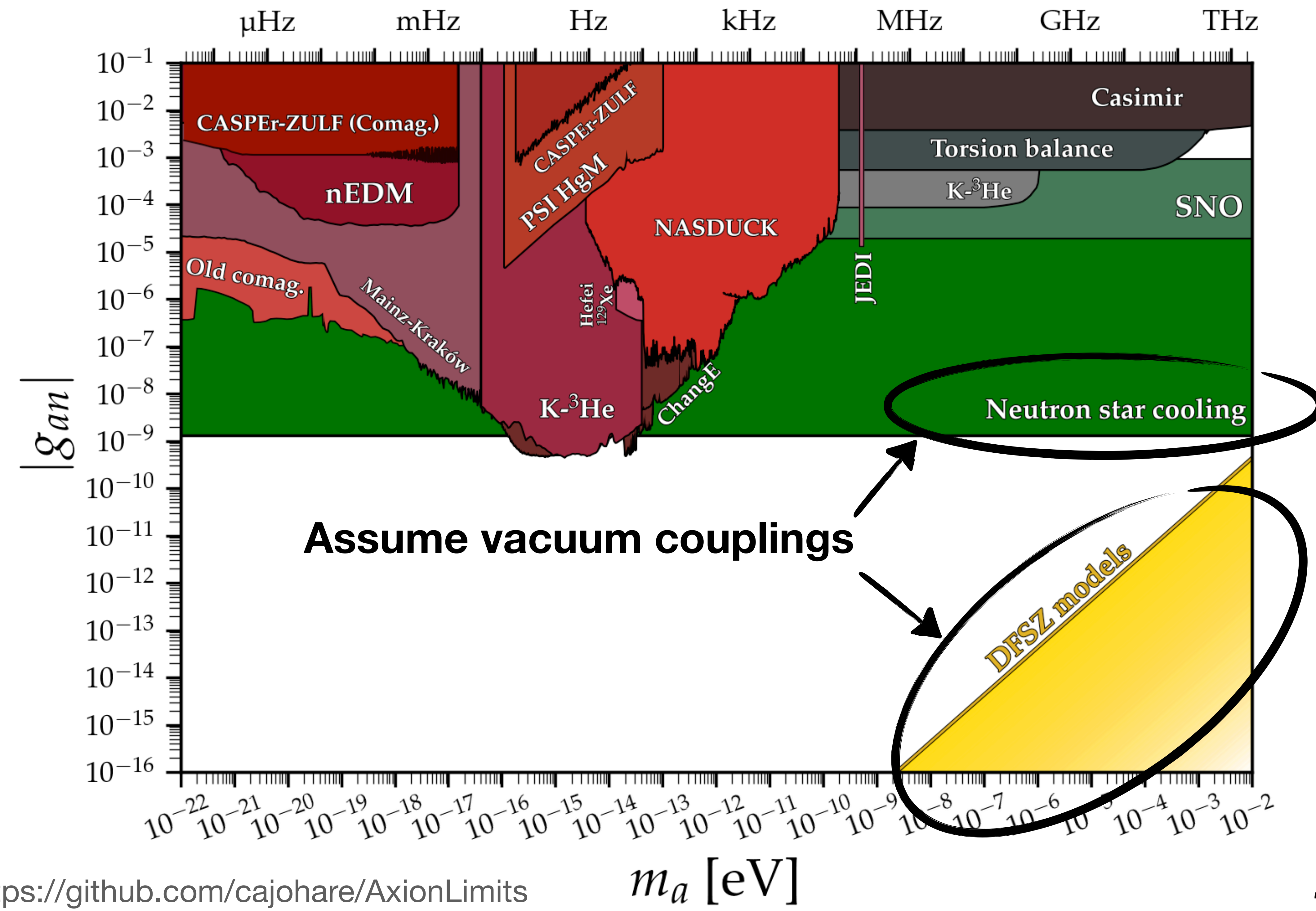

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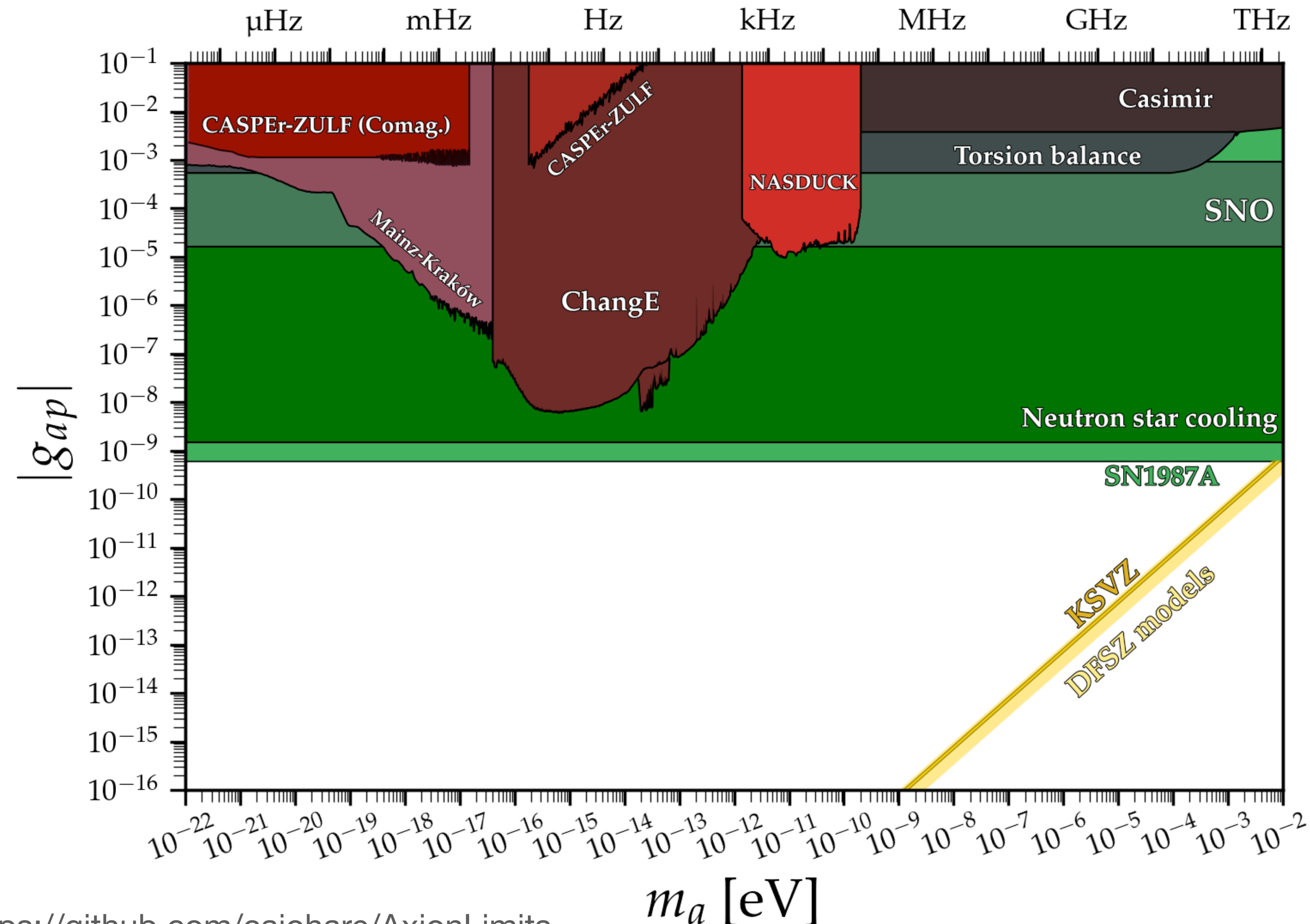

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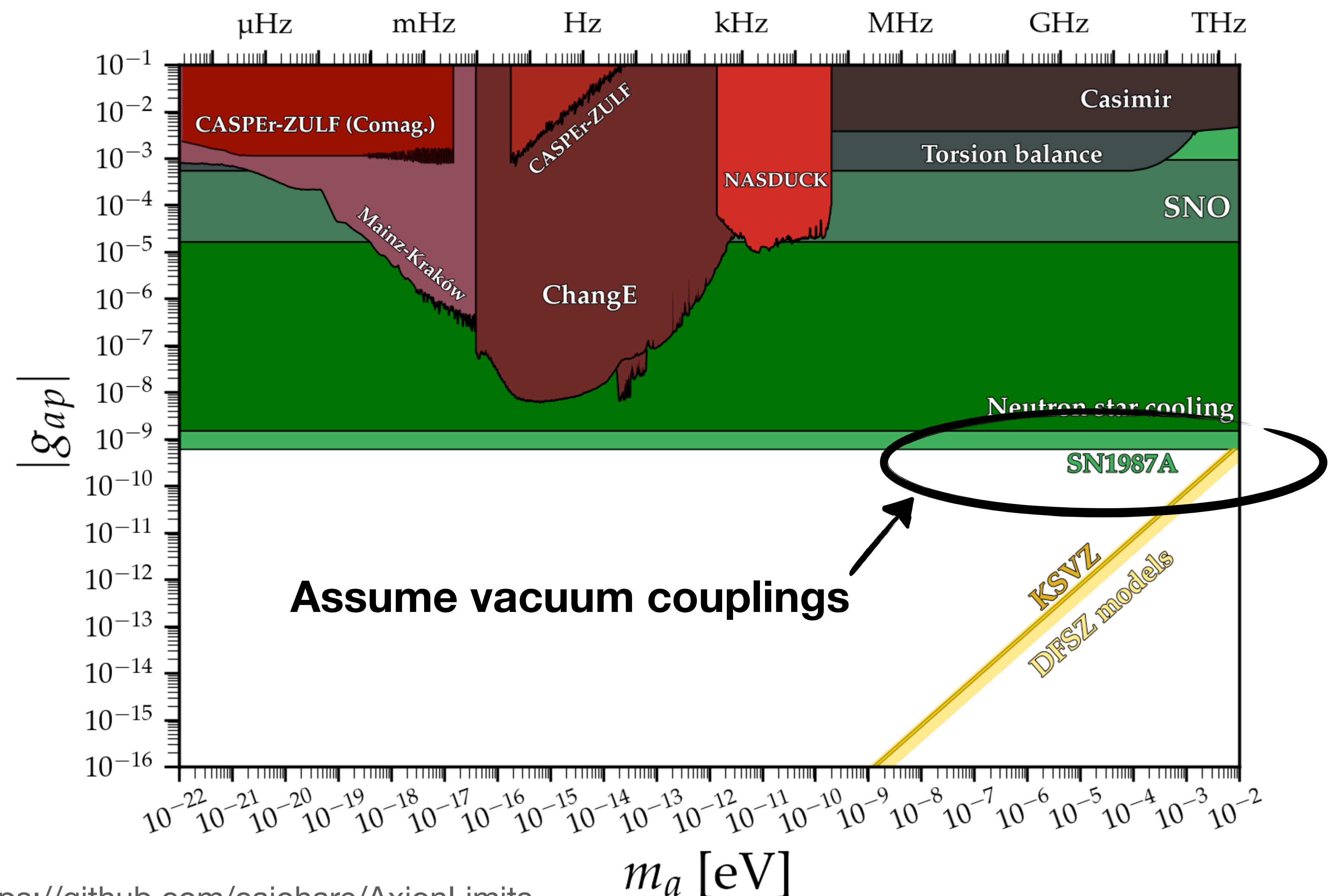

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Axion properties are highly susceptible to matter effects

Potential changes

Couplings to matter change

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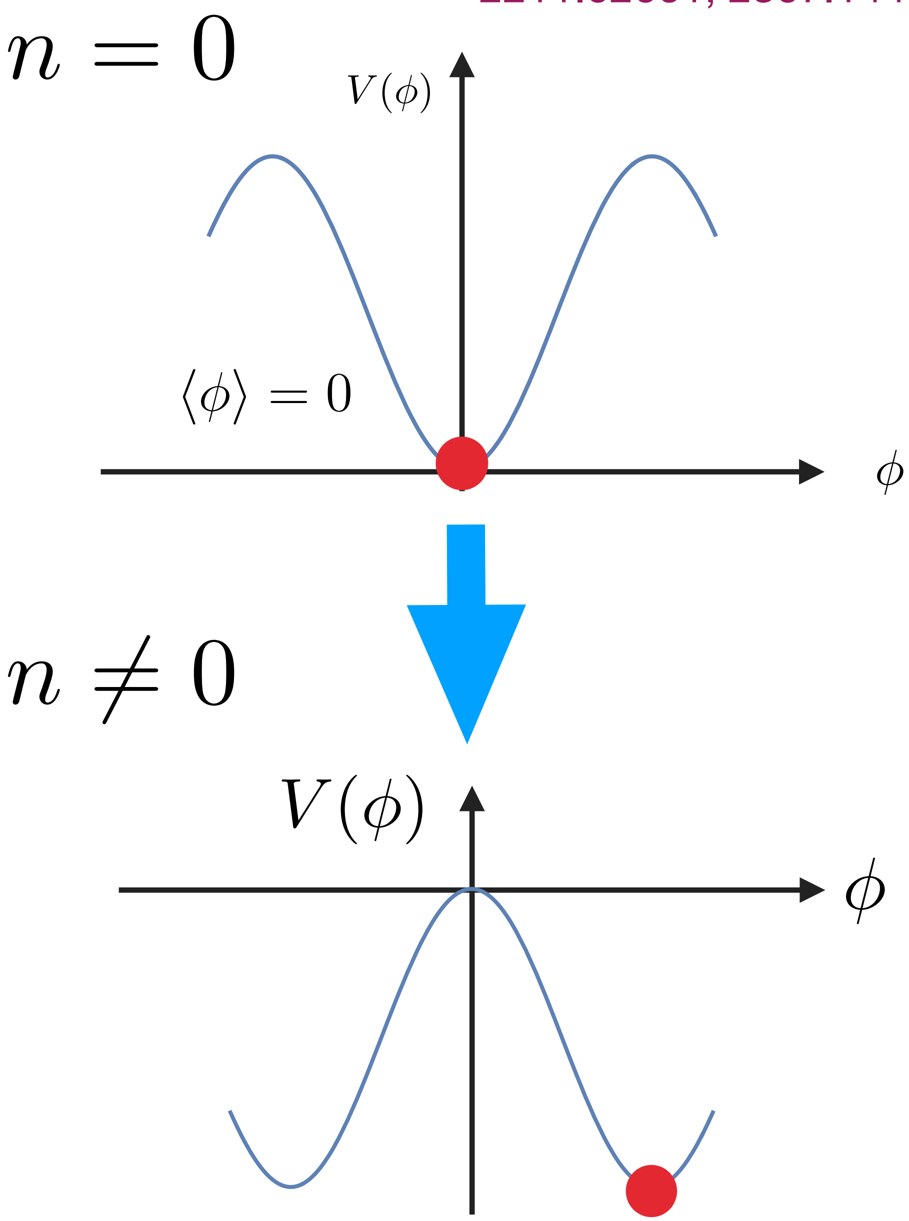
2211.02661, 2307.14418, 2408.07740



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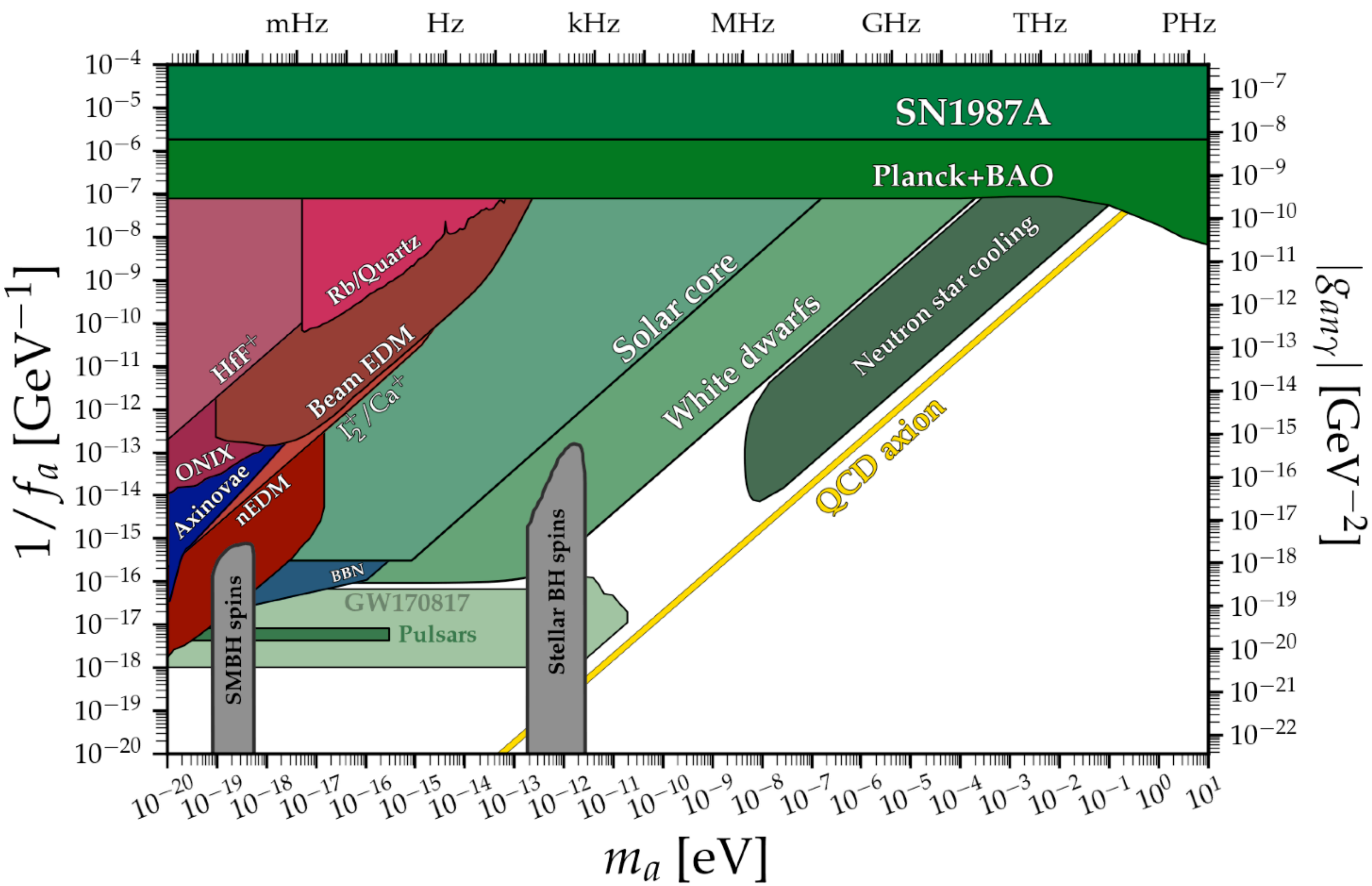

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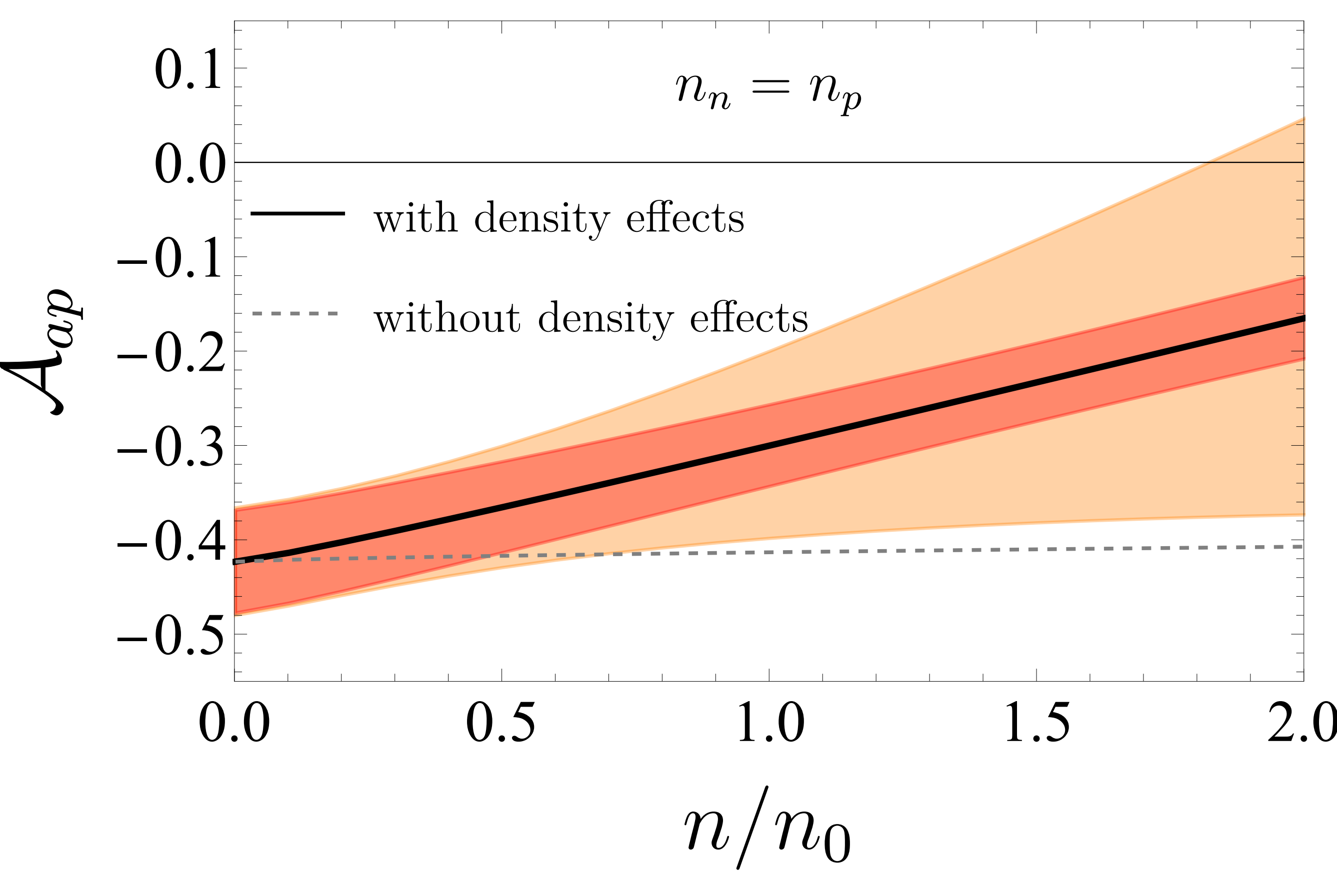
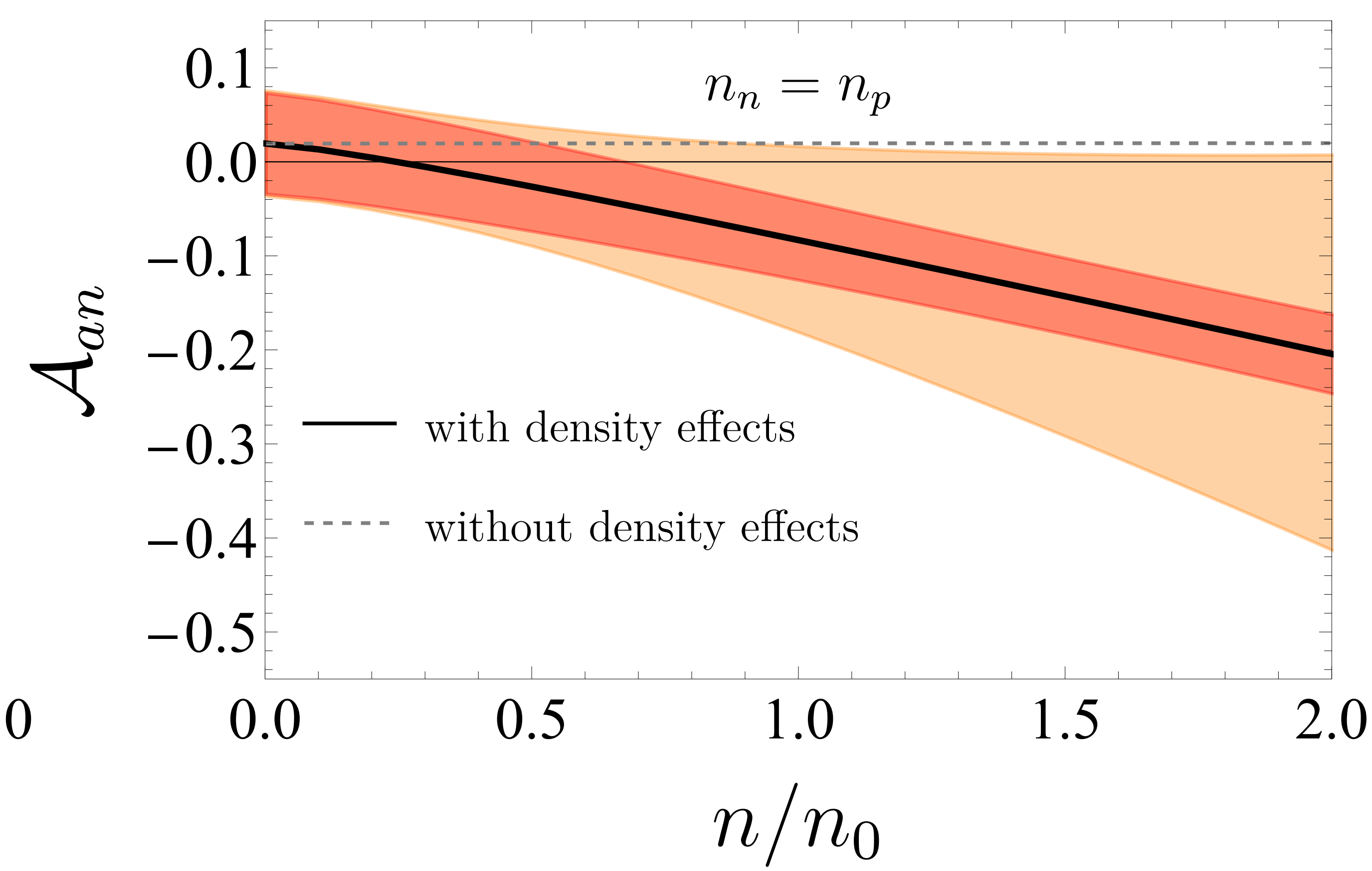
Proton **Neutron**





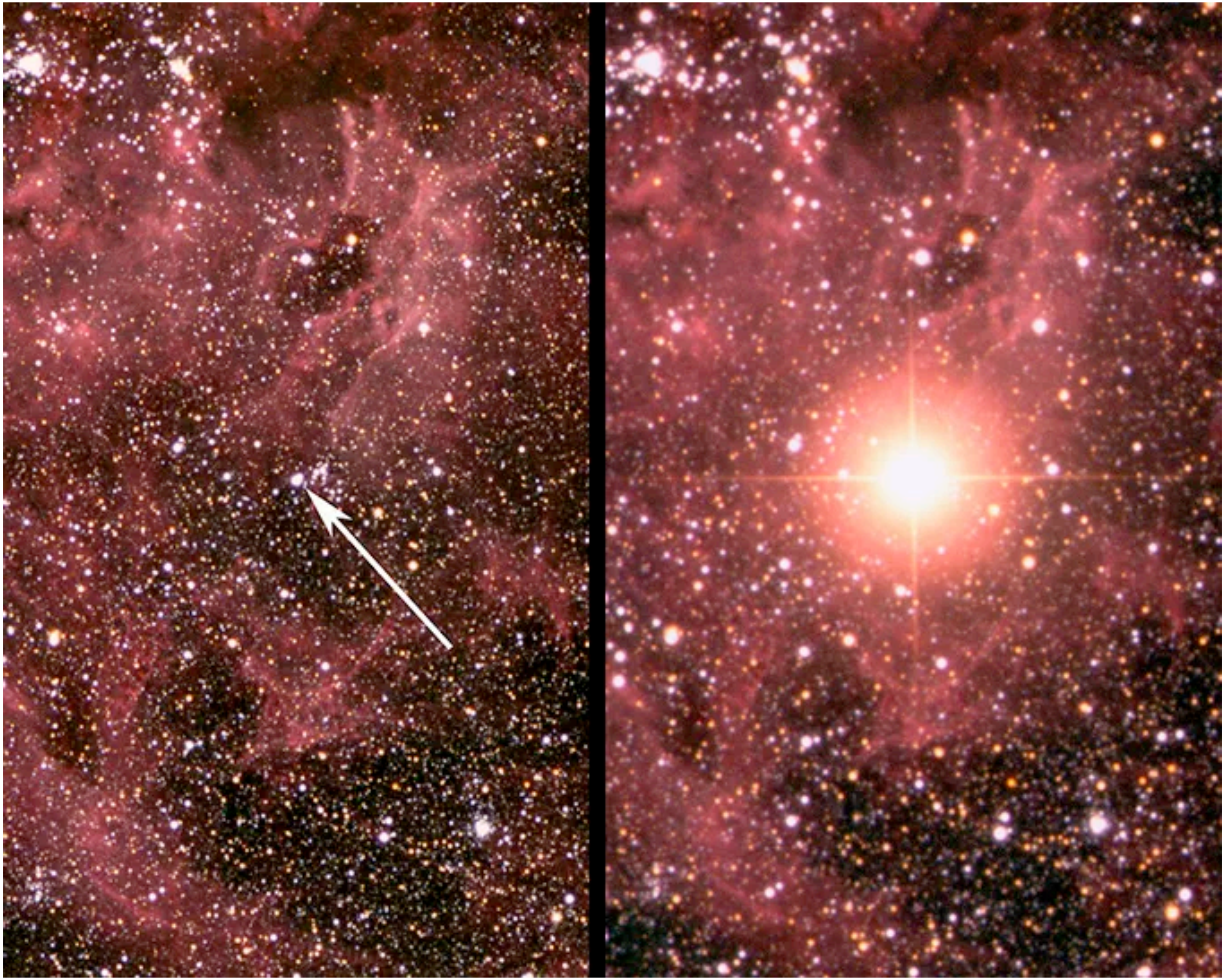
Results for KSVZ-type QCD axion

Outline

- Supernova bound on the QCD axion
- Axion EFTs
- Couplings in vacuum and finite density
- Supernova bound revisited
- Astrophobic axions

Bound from SN 1987A

Have observed a core-collapse (type II) SN in 1987 in the Large Magellanic Cloud



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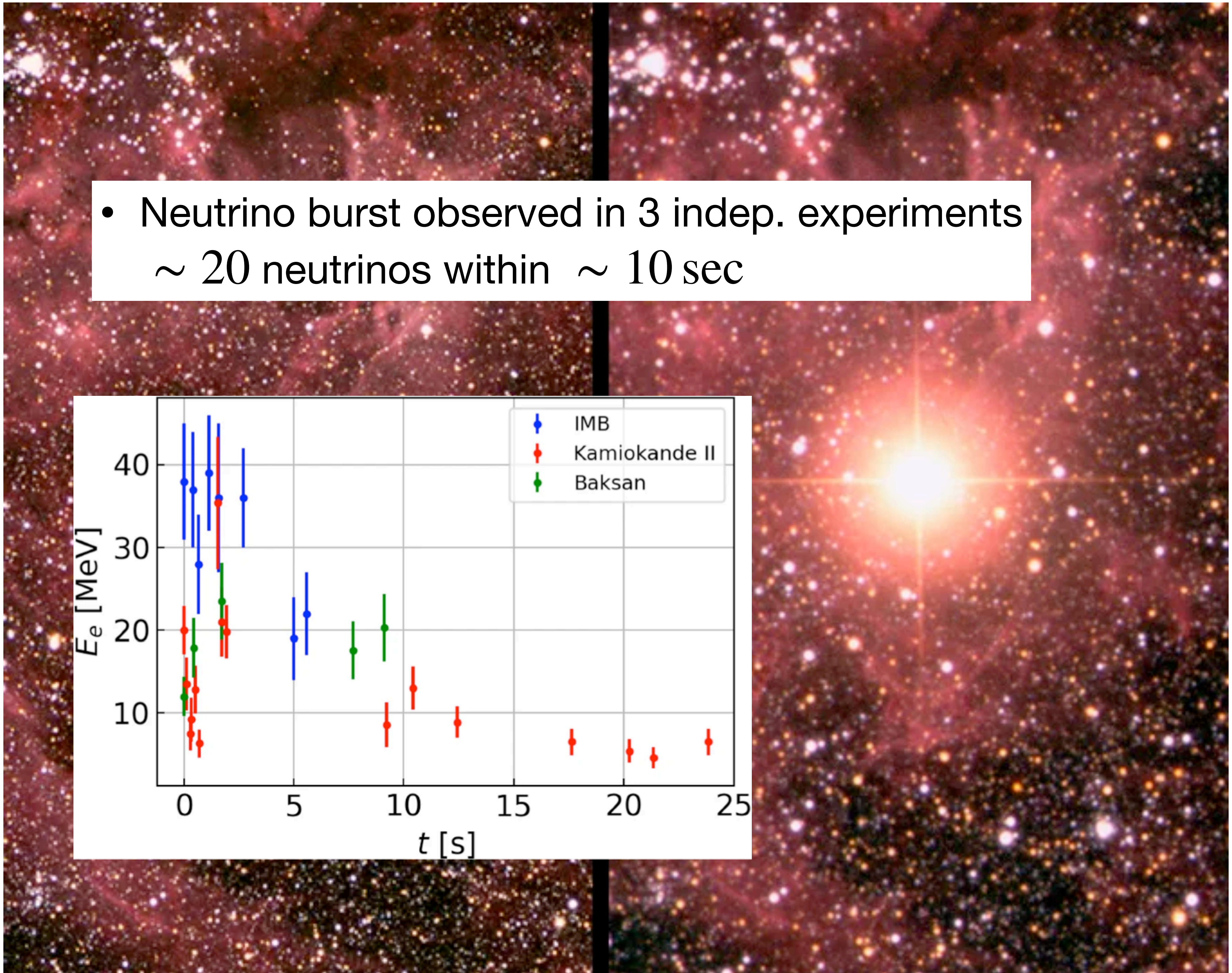
- Neutrino burst observed in 3 indep. experiments
  ~ 20 neutrinos within $\sim 10\,\mathrm{sec}$



Bound from SN 1987A

- If new lightly coupled particle gets produced, it could shorten the duration of the neutrino signal

Raffelt criterion: $$L_{\rm new} \lesssim L_\nu(t=1{\rm s}) \simeq 3\times 10^{52}{\rm erg\,s^{-1}}$$

Raffelt, Lect.Notes Phys. 741 (2008) 51-71

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- Uncertainty in SN **dynamics** and **axion production**

Bar, Blum, D'Amico ('19)

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- For Q…

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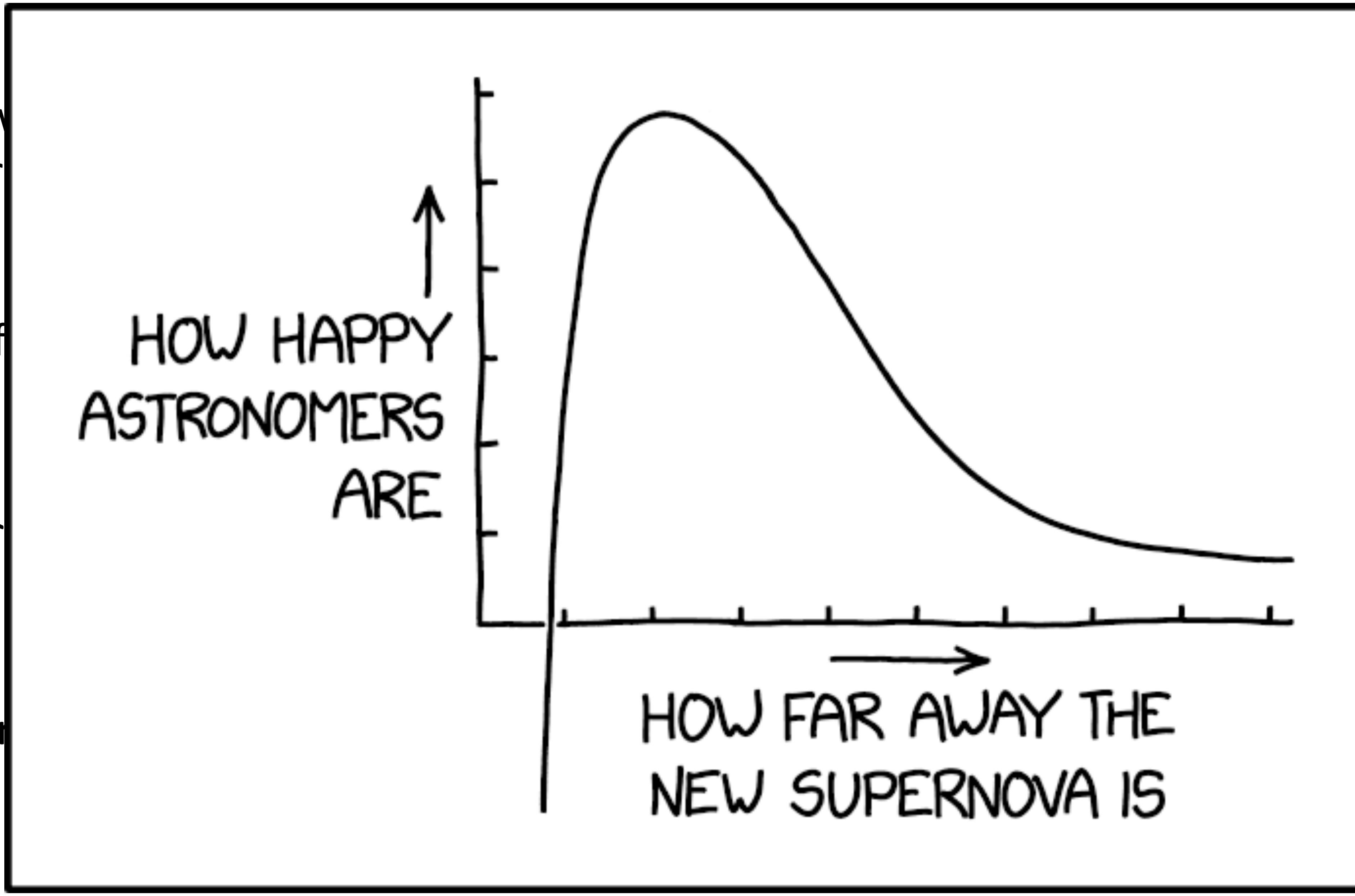

https://xkcd.com/2878

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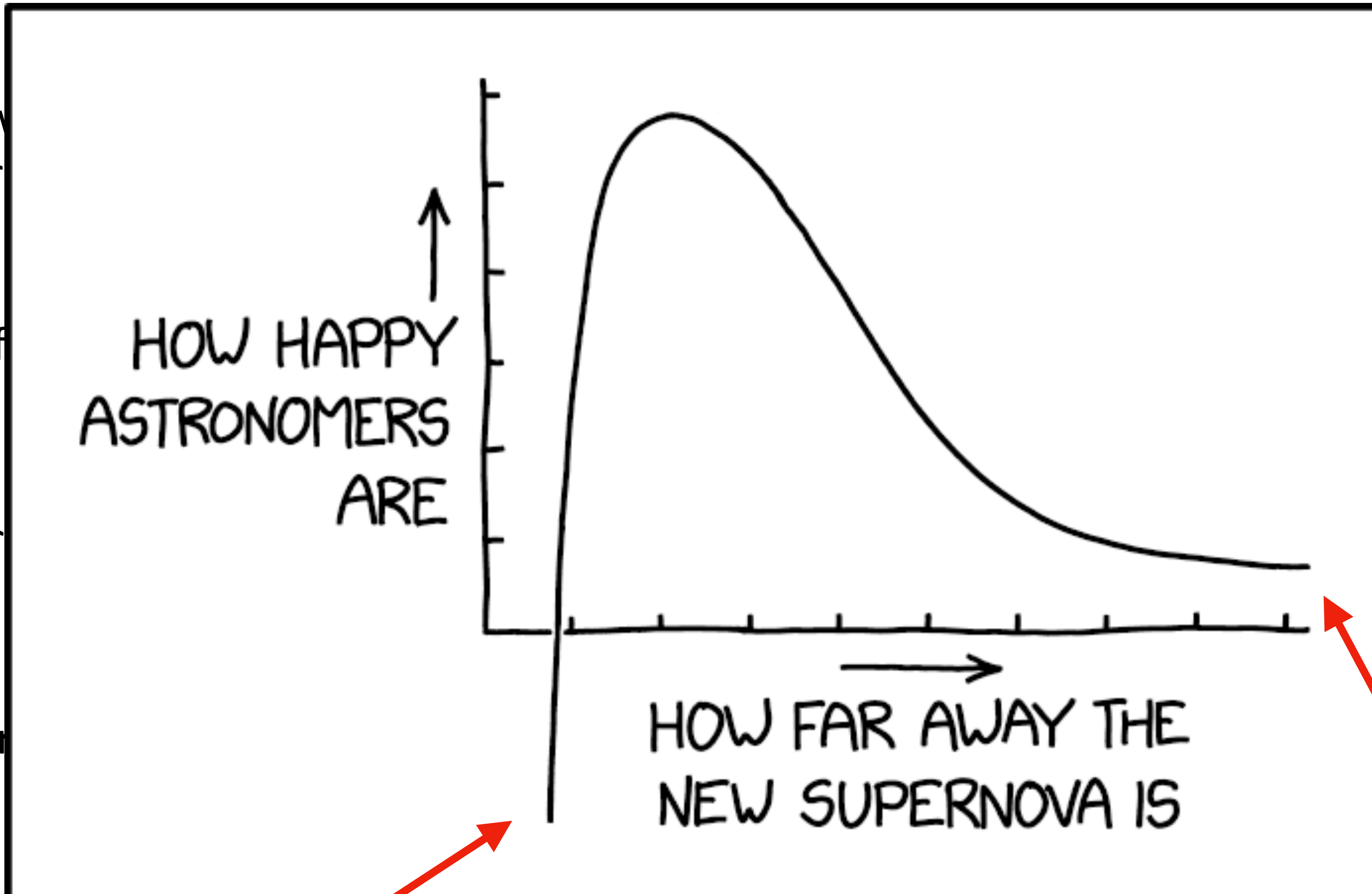

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Actually dead

Bored to death

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Focus on this

- Uncertainty in SN dynamics and **axion production**

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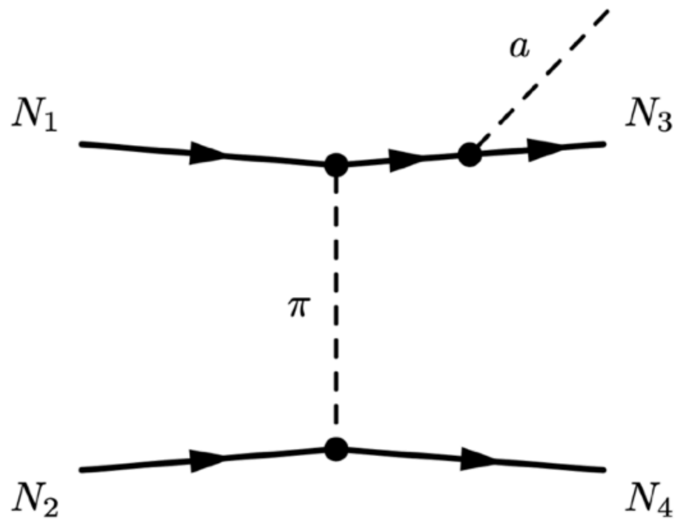
- Axions dominantly produced via Bremsstrahlung



Corrections to Bremsstrahlung

What has been done? Included corrections **phenomenologically**

- Multiply rate by fudge factors: $\Gamma_a = \Gamma_a^{\rm tree} \gamma_f \gamma_p \gamma_h$ Chang, Essig, McDermott ('18)

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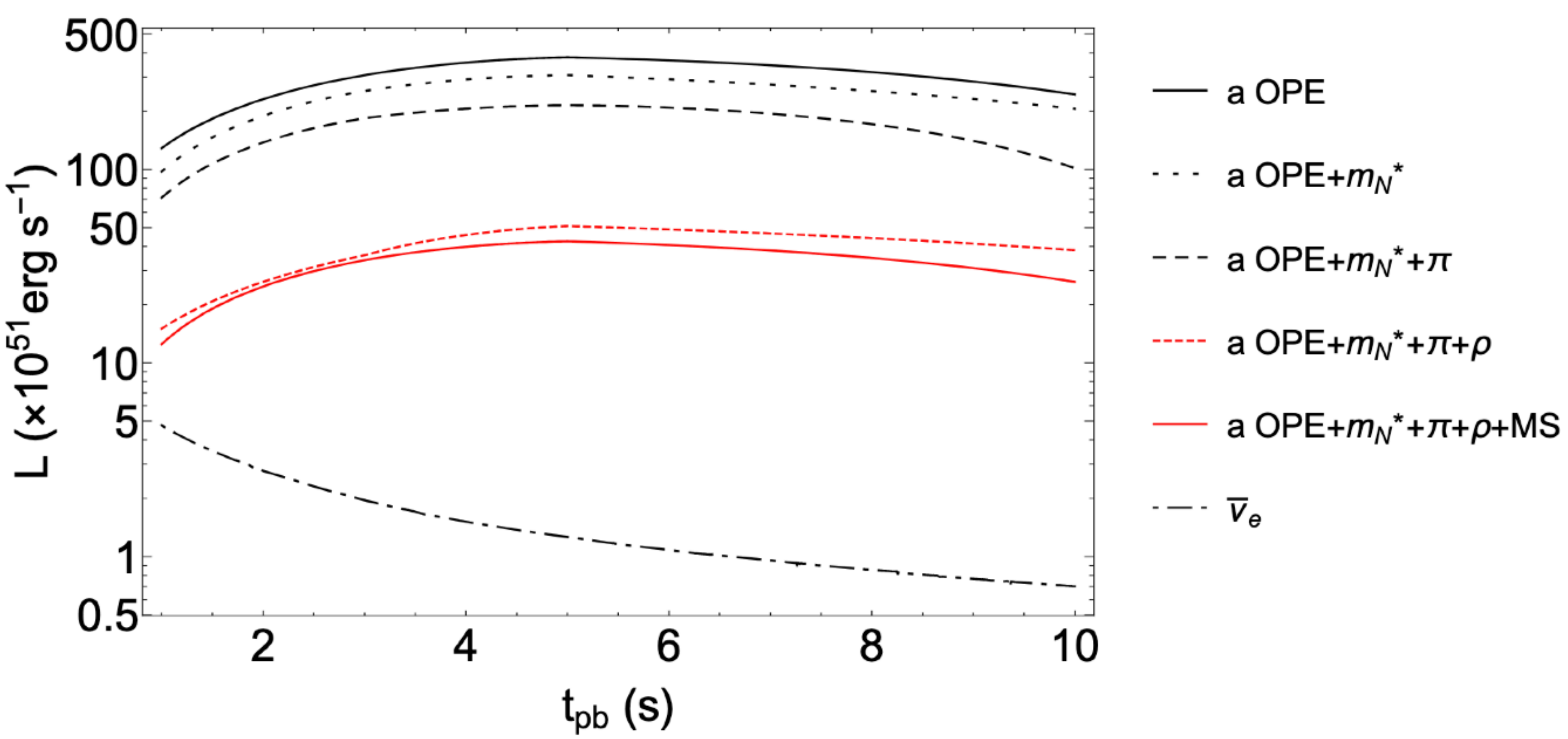

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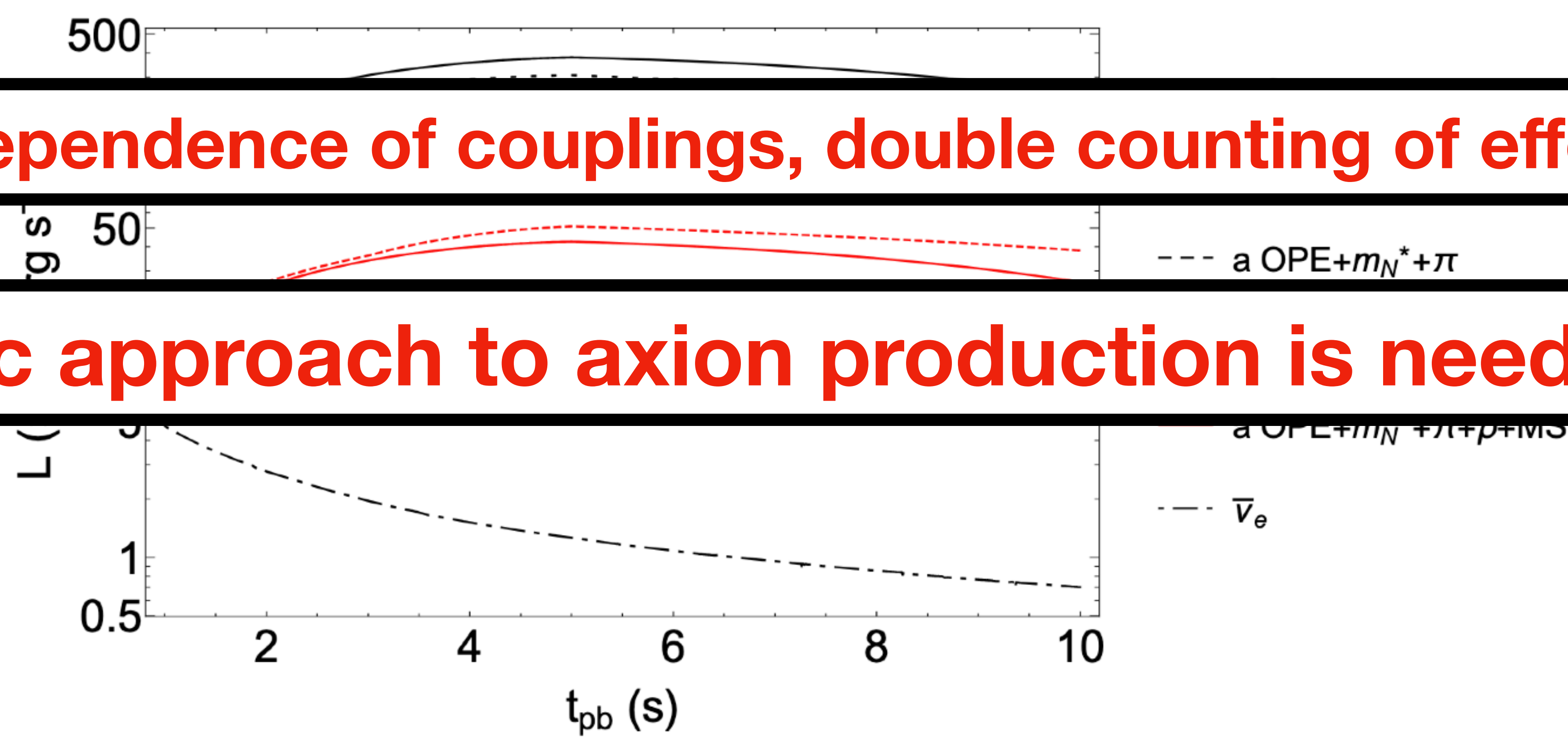

No density dependence of couplings, double counting of effects

Systematic approach to axion production is needed

Axion-Nucleon coupling

- Axion-Nucleon coupling

$$\mathcal{L} \supset \frac{1}{f_a} \bar{N} c_N S \cdot \partial a N, \quad N = (p, n)^T \qquad N_f = 2$$

$$c_N = G_A c_{u-d} \tau^3 + G_0 c_{u+d} \mathbf{1}$$

Villadoro et.al. 15’

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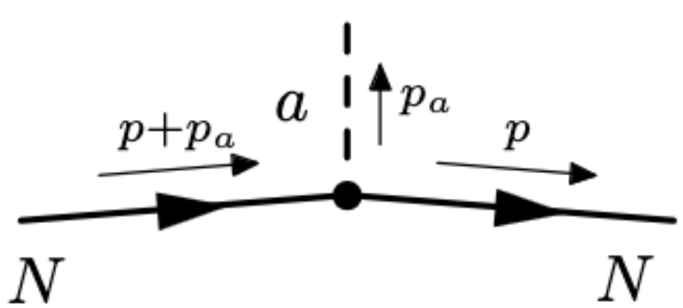

$$= \quad -\frac{1}{f_a} c_N S \cdot p_a .$$

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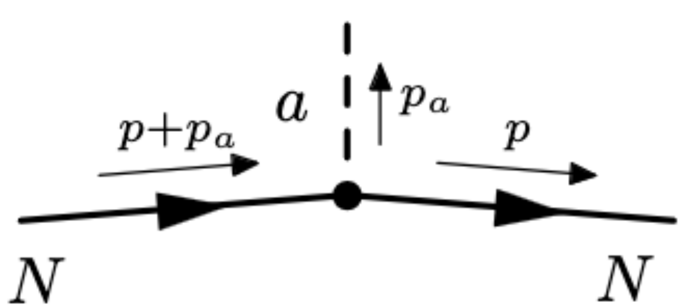

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- KSVZ axion $c_p^{\mathrm{KSVZ}} = -0.47(3), \quad c_n^{\mathrm{KSVZ}} = +0.02(3)$

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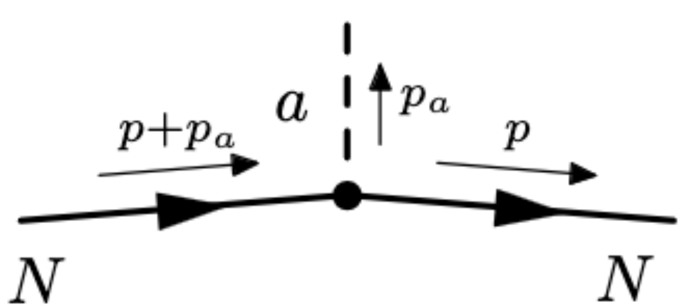

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Compatible with zero due to accidental cancellation

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Is this EFT valid in astrophysical environments?

This Hubble Space Telescope image shows Supernova 1987A within the Large Magellanic Cloud

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Not really…

- Typical momenta $k_F \simeq (3\pi^2 n_0)^{1/3} \simeq 260\,\mathrm{MeV}$ $n_0 \simeq 0.16\,\mathrm{fm}^{-3}$

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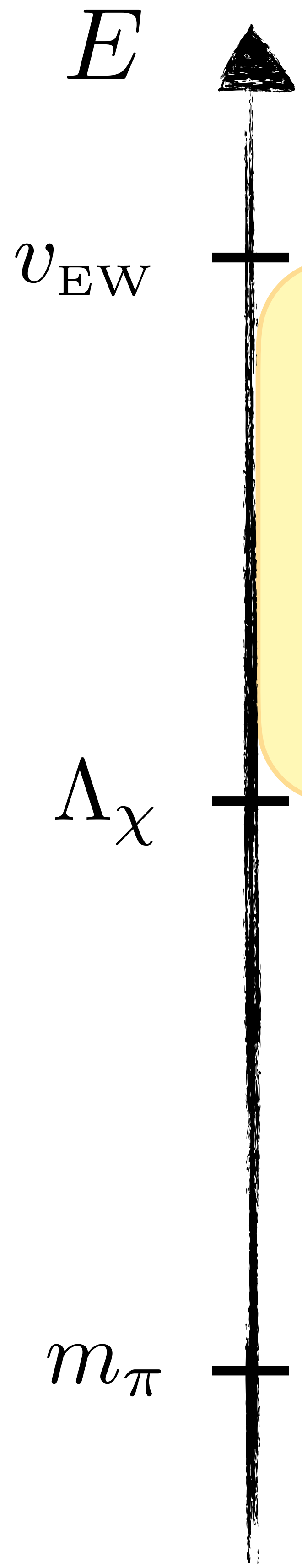
Need to construct EFT of pions and nuclons!

Axion EFTs



KSVZ axion $c_q^0 = 0$

After chiral quark rotation

$$\mathcal{L} \supset \bar{q} M_a q + \frac{\partial_\mu a}{f_a} \bar{q} \gamma^\mu \gamma_5 \left(c_q^0 - [Q_a]_q \right) q$$

$$M_a = e^{\frac{ia}{f_a} Q_a} M_q \qquad\qquad Q_a \equiv M_q^{-1} / \mathrm{Tr}(M_q^{-1})$$

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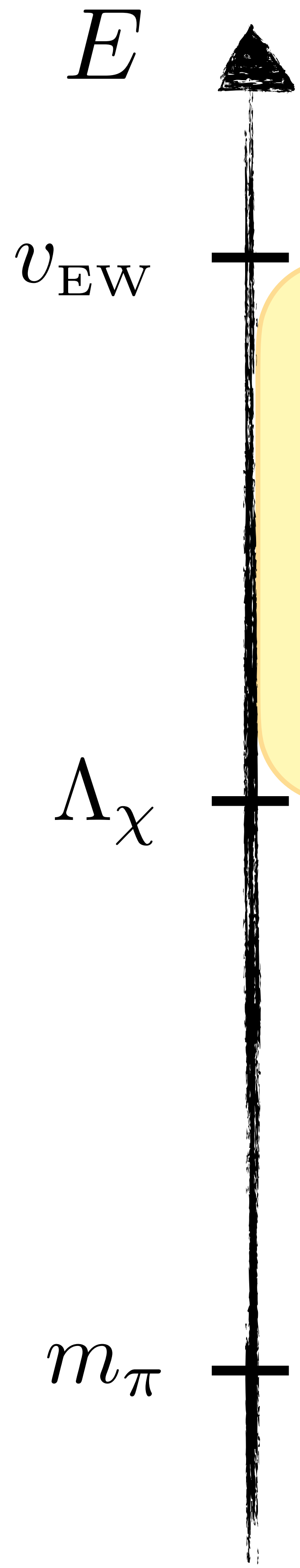

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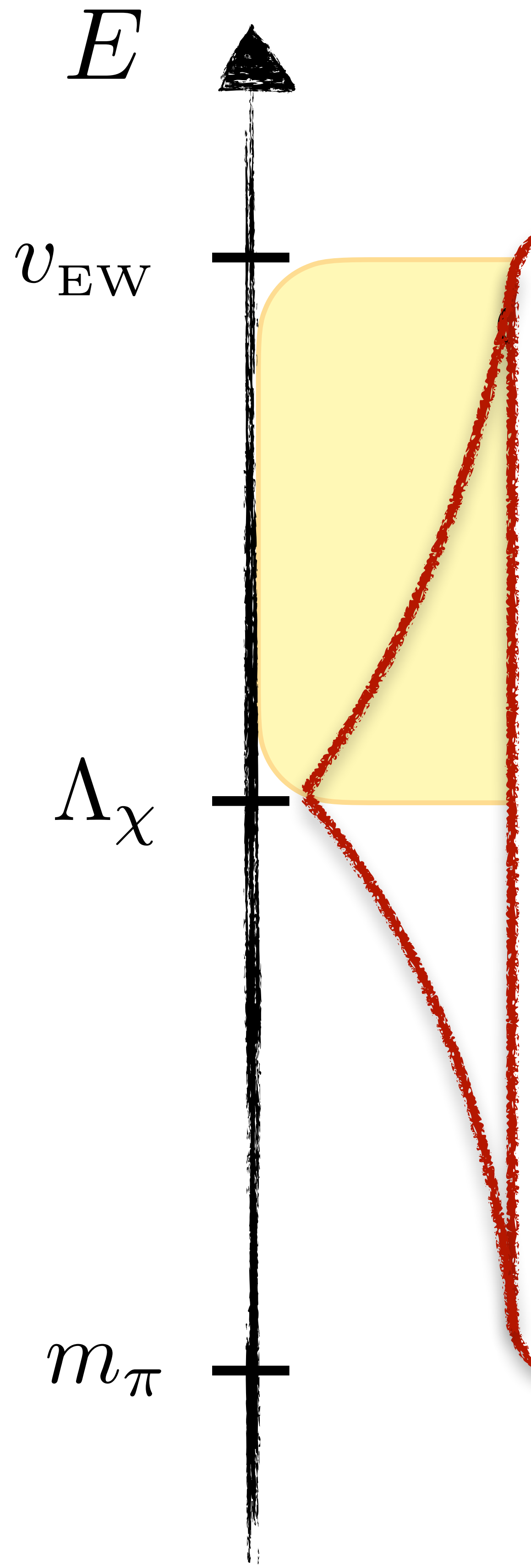

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$$G_\chi = U(2)_L \times U(2)_R \to U(2)$$

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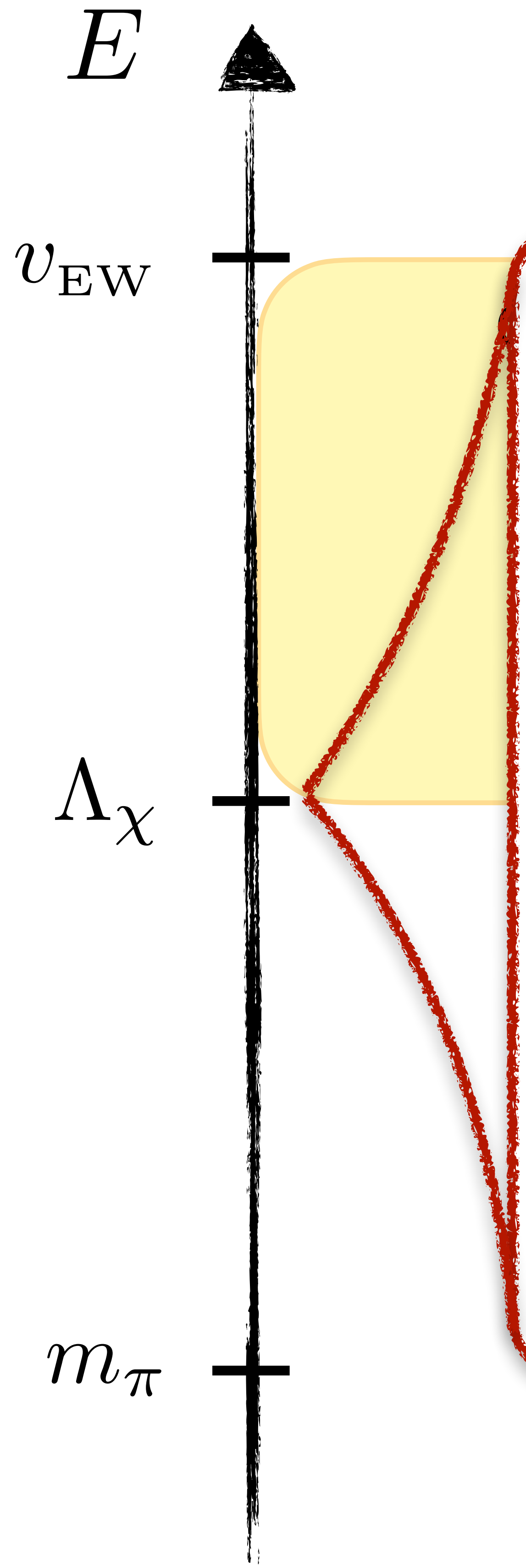
  Chiral Perturbation Theory: spurion analysis

Weinberg ('79)
Gasser, Leutwyler ('85)

Axion EFTs



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

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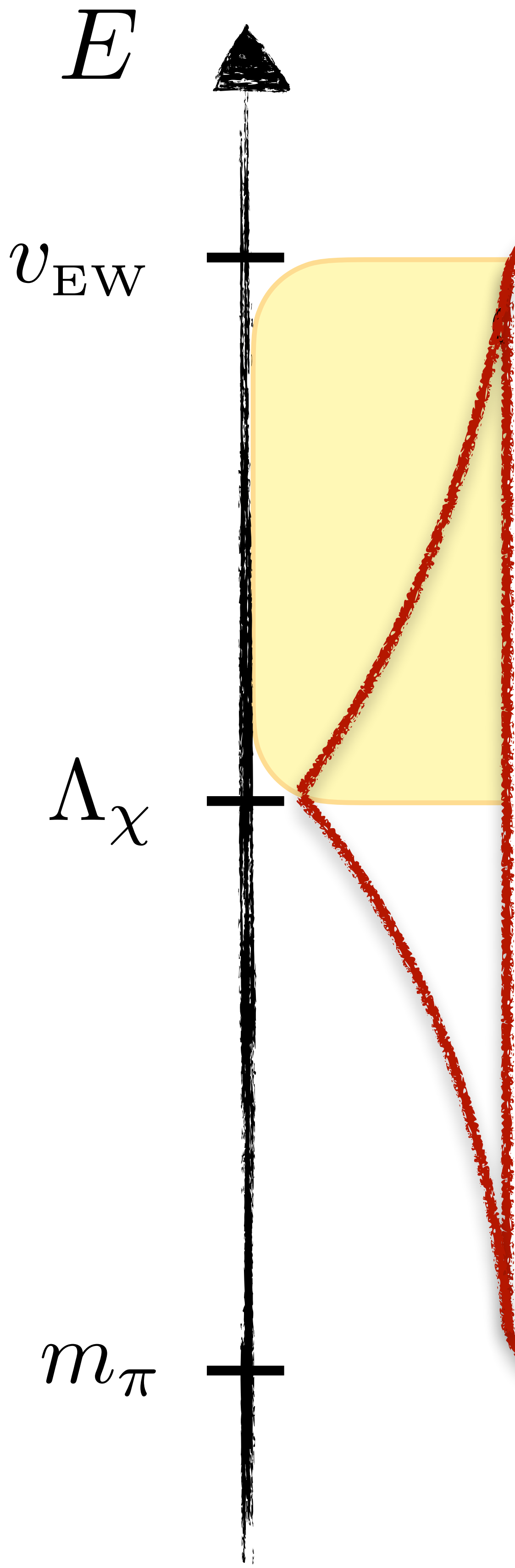

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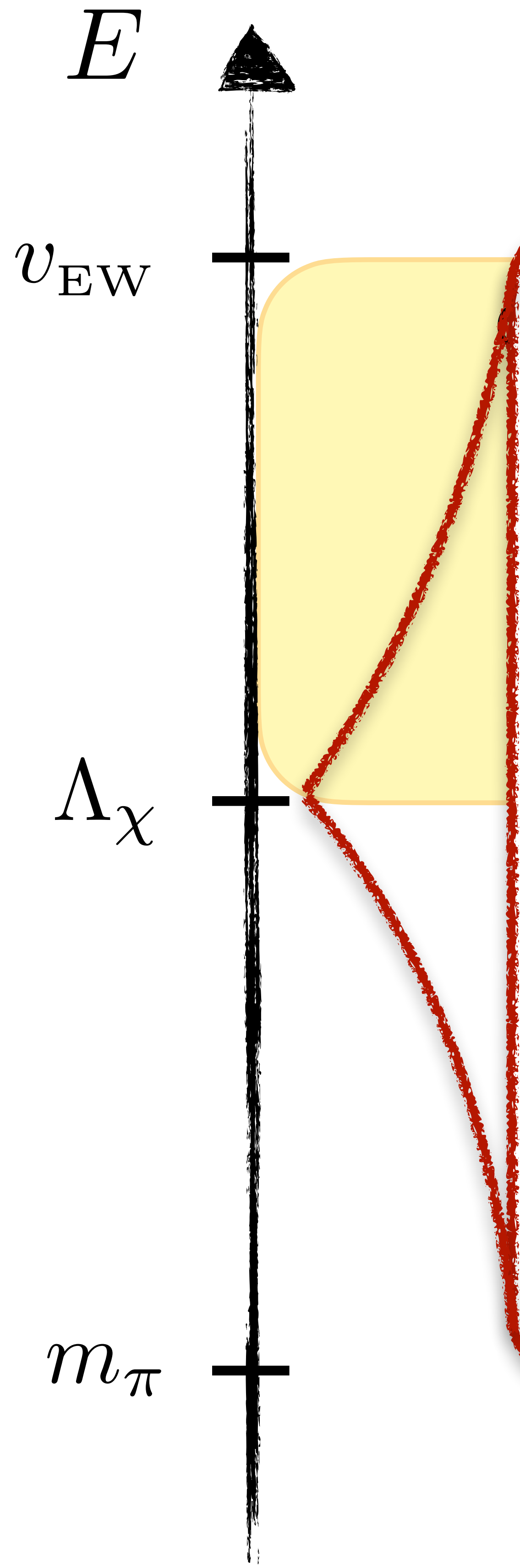

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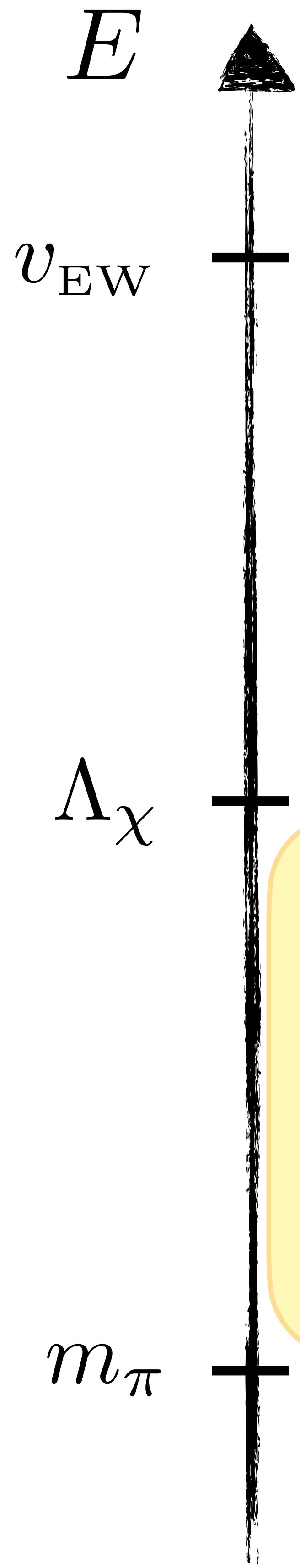
$1\,\mathrm{GeV}$ $\quad$ $1\,\mathrm{GeV}$ $\quad$ Resonances, e.g. $\Delta(1232)$

$\Lambda_\chi \sim (300-750)\,\mathrm{MeV}$

Axion EFTs



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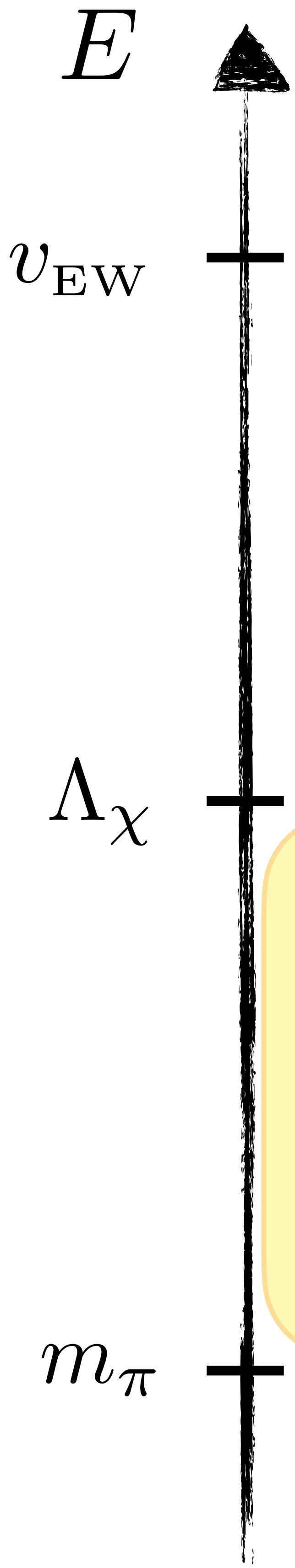
LO: $$\mathcal{L}_{\pi\pi}^{(2)} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[\nabla^\mu U(\nabla_\mu U)^\dagger + (\chi U^\dagger + \mathrm{h.c.})\right]$$

$$U = e^{i\pi^a\tau^a/f_\pi} \qquad \chi = 2BM_a$$

Axion EFTs



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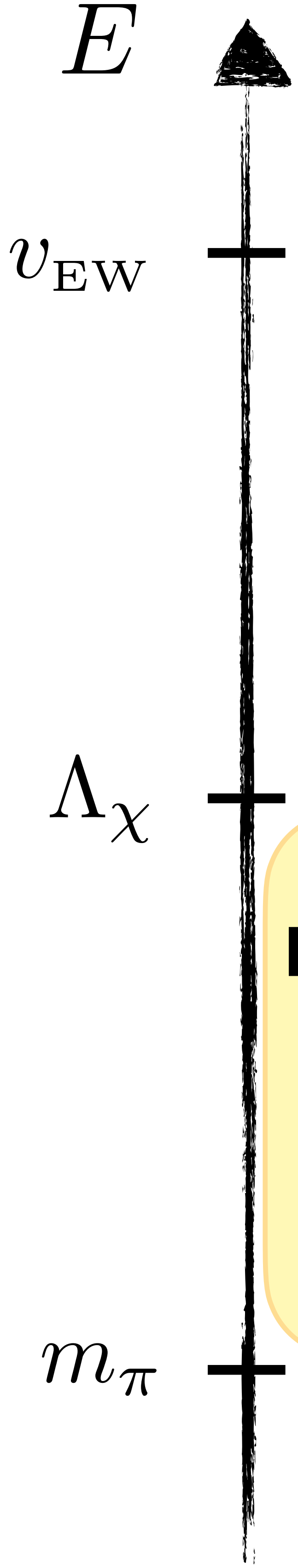
LO: $$\hat{\mathcal{L}}^{(1)}_{\pi N} = \bar{N}\left(iv\cdot D + g_A S\cdot u + g_0 S\cdot\hat{u}\right) N$$

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

Axion EFTs



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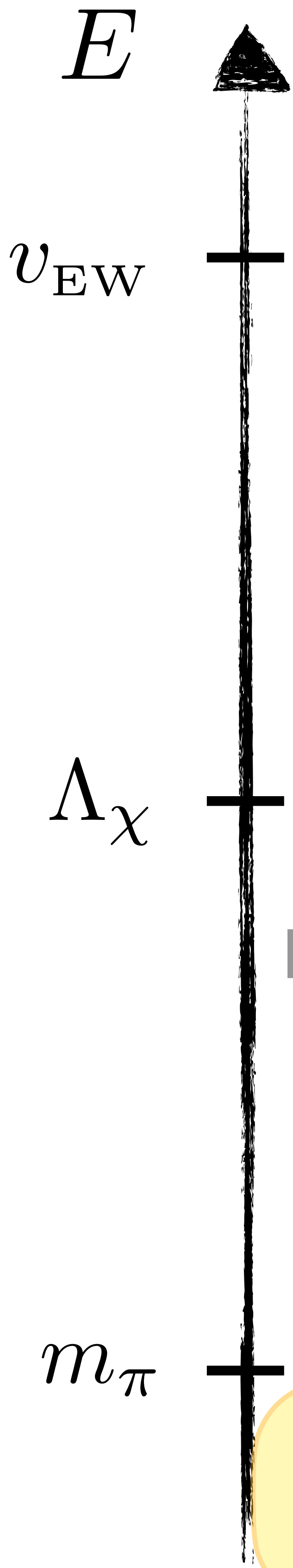
NLO:

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

Axion EFTs



Can be mapped to QCD Lagrangian with external sources

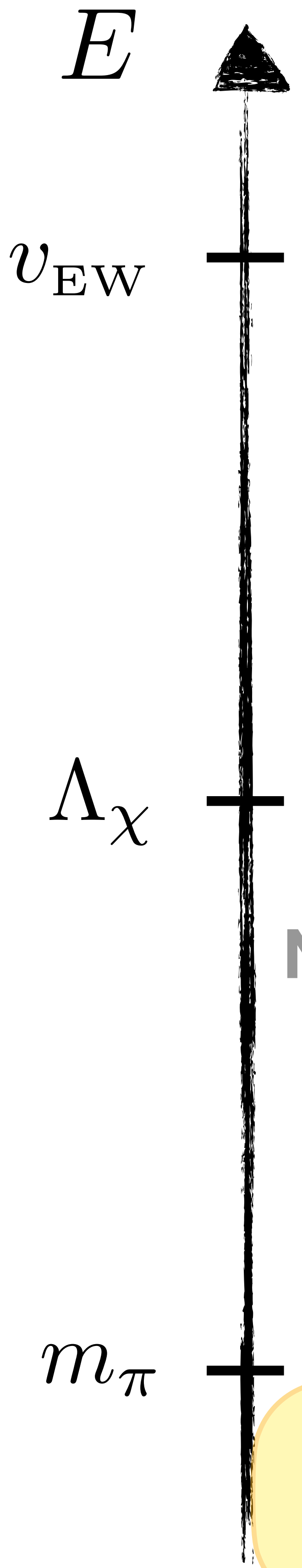
$$\mathcal{L} \supset -\bar{q}\left(s - i\gamma_5 p\right) q + \bar{q}\gamma^\mu\gamma_5\left(a_\mu + a_\mu^s\right) q$$

$$s = \mathrm{Re}\, M_a \qquad p = -\mathrm{Im}\, M_a \qquad a_\mu = c_{u+d}\frac{\partial_\mu a}{2f_a}\tau^3 \qquad a_\mu^s = c_{u-d}\frac{\partial_\mu a}{2f_a}$$

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

Integrate out pions: theory of baryons and axion

Axion EFTs



Can be mapped to QCD Lagrangian with external sources

$$\mathcal{L} \supset -\bar{q}\left(s - i\gamma_5 p\right) q + \bar{q}\gamma^\mu\gamma_5\left(a_\mu + a_\mu^s\right) q$$

$$s = \mathrm{Re}\, M_a \qquad p = -\mathrm{Im}\, M_a \qquad a_\mu = c_{u+d}\frac{\partial_\mu a}{2f_a}\tau^3 \qquad a_\mu^s = c_{u-d}\frac{\partial_\mu a}{2f_a}$$

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

Match constants $\quad G_A = g_A - \dfrac{g_A^3 m_\pi^2}{16\pi^2 f_\pi^2} + 4m_\pi^2\bar{d}_{16} + \dfrac{g_A m_\pi^3}{6\pi f_\pi^2}(2\hat{c}_4 - \hat{c}_3)$

Axion EFTs

E

v_{EW}

Can be mapped to QCD Lagrangian with external sources

$$\mathcal{L} \supset -\bar{q}\left(s - i\gamma_5 p\right) q + \bar{q}\gamma^\mu\gamma_5\left(a_\mu + a_\mu^s\right) q$$

$$s = \mathrm{Re}\, M_a \qquad p = -\mathrm{Im}\, M_a \qquad a_\mu = c_{u+d}\frac{\partial_\mu a}{2f_a}\tau^3 \qquad a_\mu^s = c_{u-d}\frac{\partial_\mu a}{2f_a}$$

Λ_χ

NLO:

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

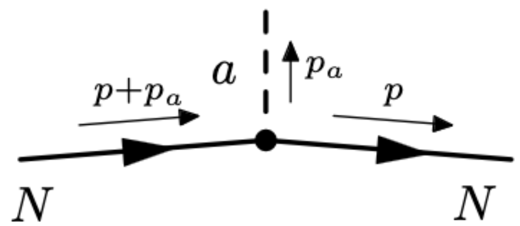
m_π

$$\mathcal{L}_{aN} = \bar{N}\left[iv\cdot\partial + \frac{S\cdot\partial a}{f_a}\left(G_A c_{u-d}\tau^3 + G_0 c_{u+d}\mathbf{1}\right) + \sigma\left\langle \mathrm{Re}\left(M_a\right)\right\rangle + \dots\right] N$$

Axion-Nuclon Coupling: Loop corrections

Corrections to the coupling can be calculated systematically in $\left(\frac{p}{4\pi f_\pi}\right)^\nu$

LO:



Axion-Nuclon Coupling: Loop corrections

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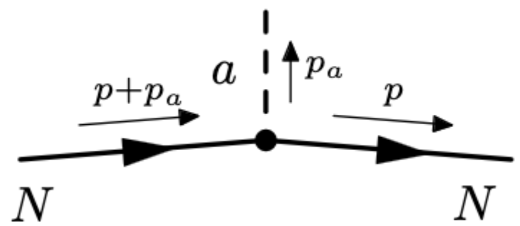
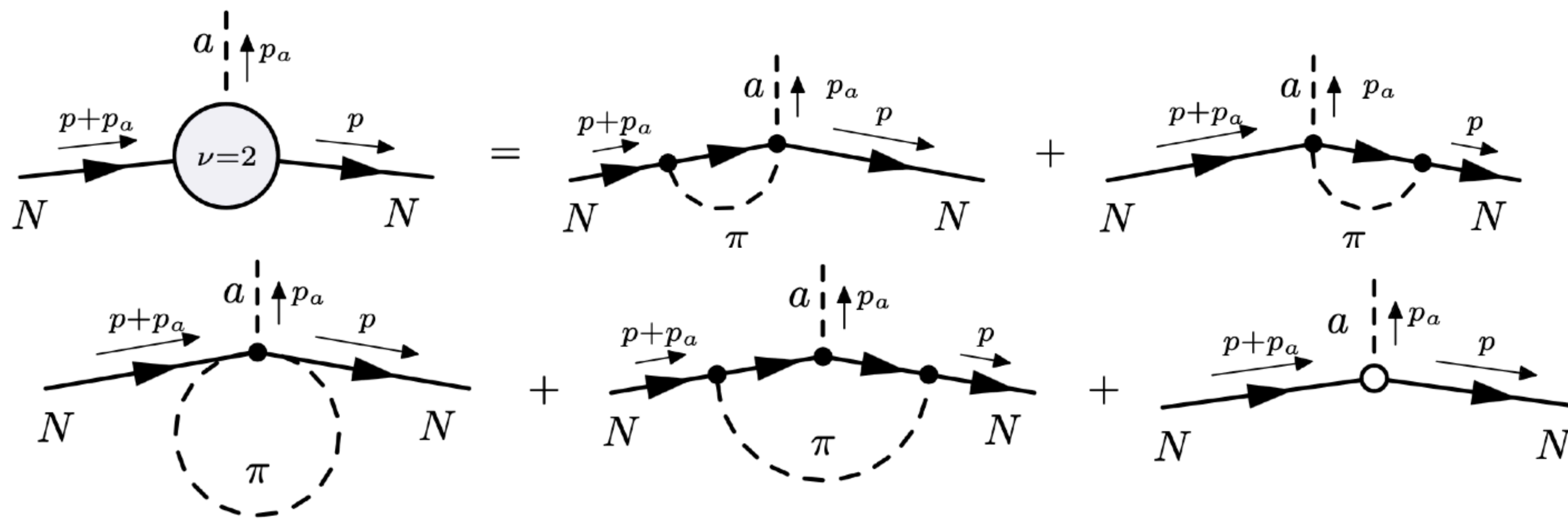


NLO:

$$\left(\frac{p}{4\pi f_\pi}\right)^2$$

Vonk, Guo, Meißner (2000)



Axion-Nuclon Coupling: Loop corrections

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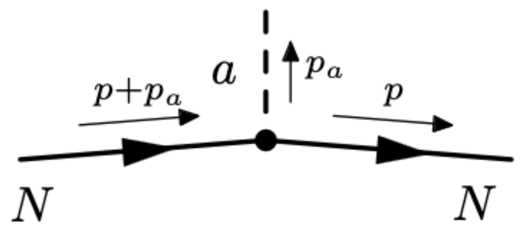

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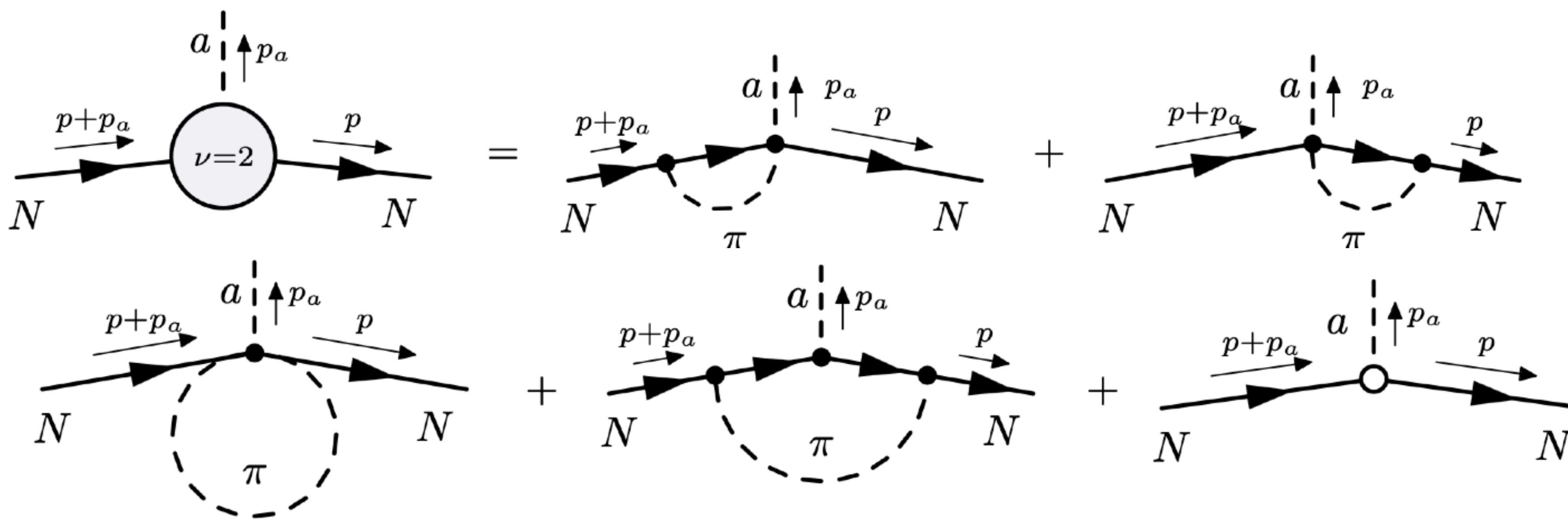


NNLO:

Naively suppressed by $\left(\frac{p}{4\pi f_\pi}\right)^3$

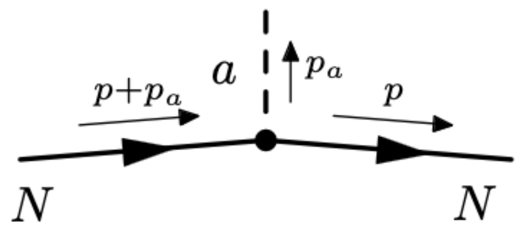
But low-lying $\Delta(1232)$ resonance enhances contribution $\left(\frac{p}{4\pi f_\pi}\right)^2 \left(\frac{p}{\Lambda_\chi}\right)$

$\Lambda_\chi \sim (300 - 750)\,\mathrm{MeV}$

Axion-Nuclon Coupling: Loop corrections

Corrections to the coupling can be calculated systematically in $\left(\frac{p}{4\pi f_\pi}\right)^\nu$

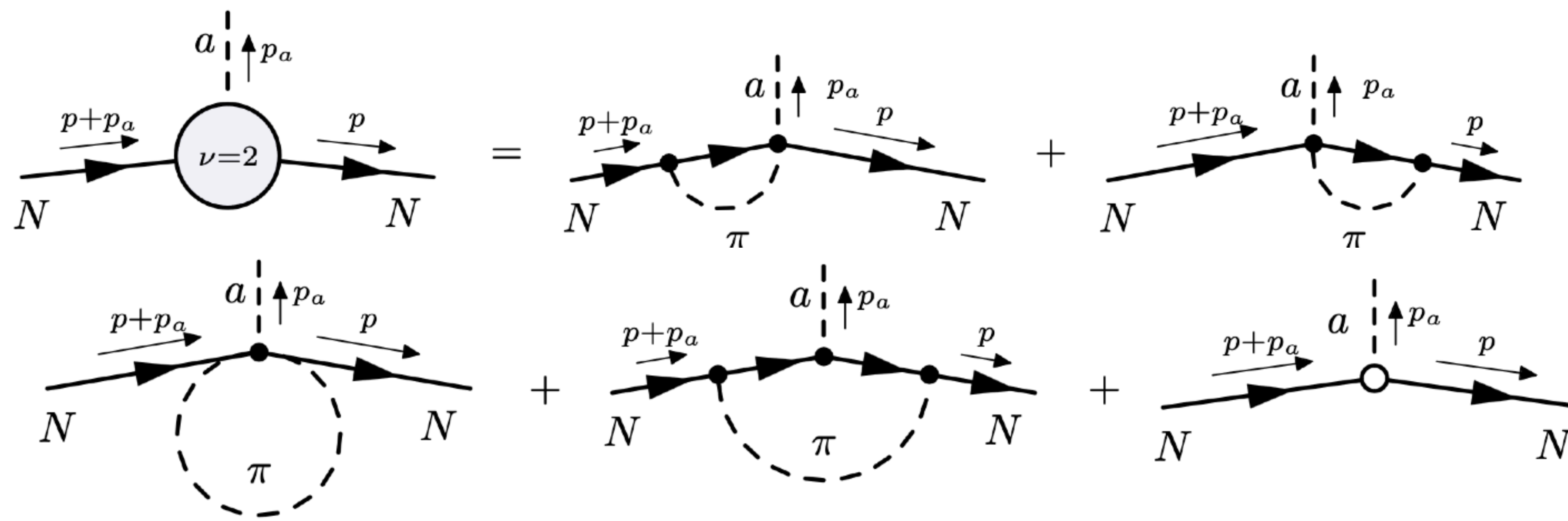
LO:



NLO:

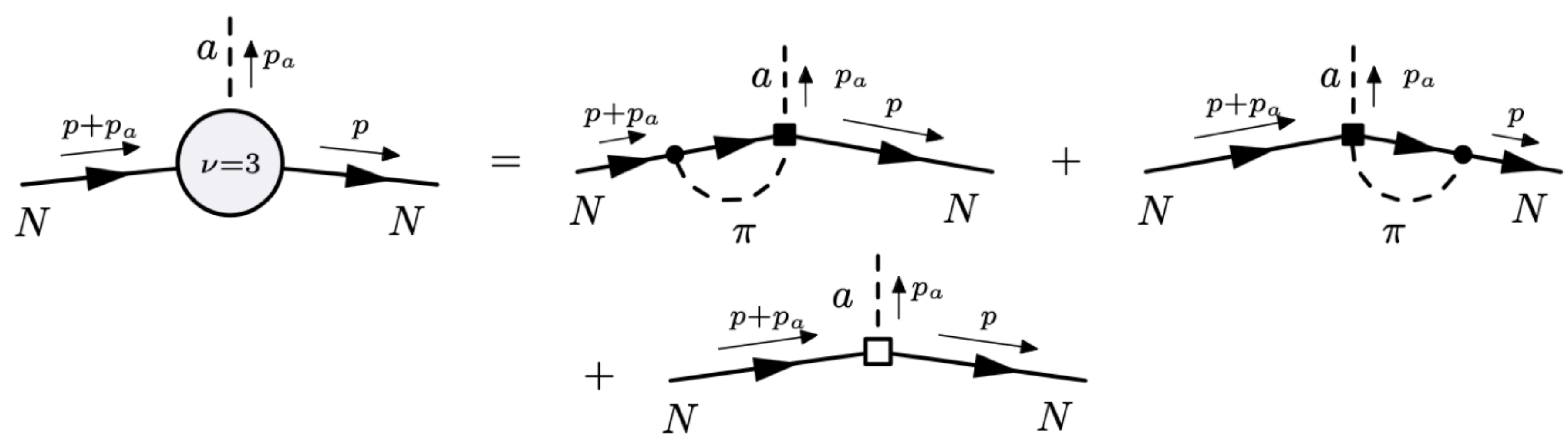
$$\left(\frac{p}{4\pi f_\pi}\right)^2$$

Vonk, Guo, Meißner (2000)



NNLO:

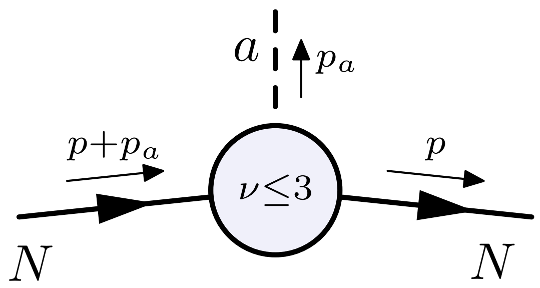
$$\left(\frac{p}{4\pi f_\pi}\right)^2 \left(\frac{p}{\Lambda_\chi}\right)$$



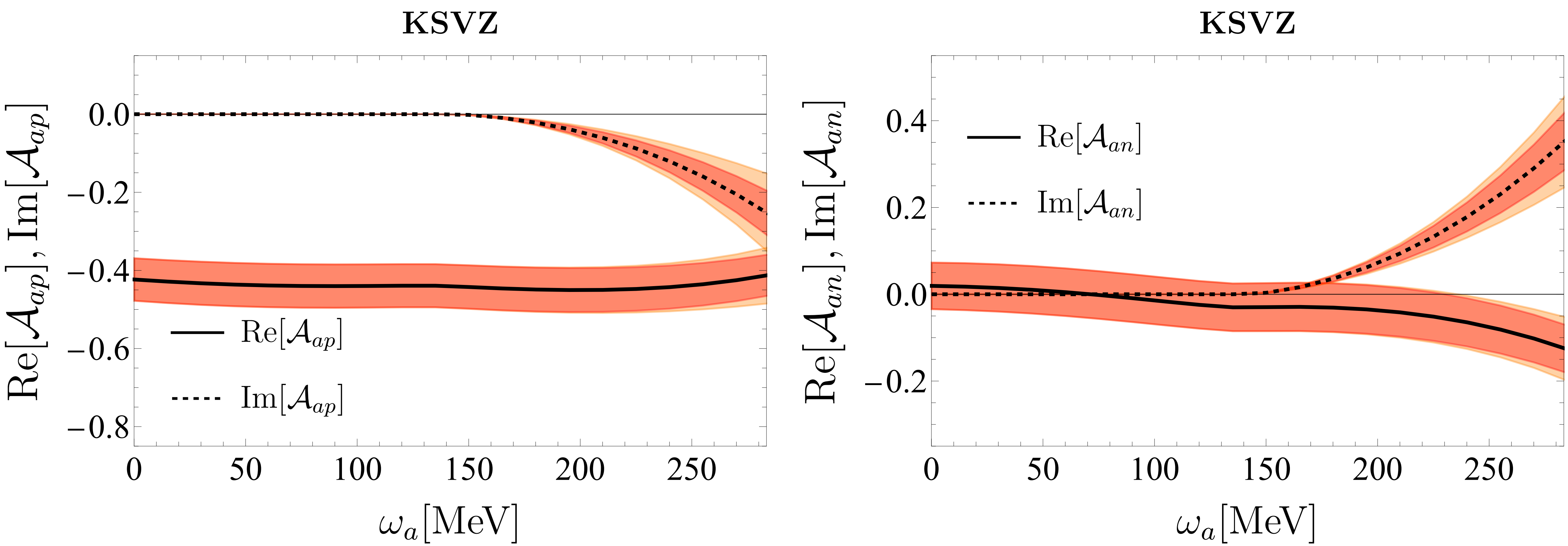
$$\Lambda_\chi \sim (300 - 750)\,\text{MeV}$$

Axion-Nuclon Coupling: Loop corrections

Coupling depends on the axion energy! Can be written as



$$= -\frac{1}{f_a}\mathcal{A}^{\nu\leq3}(\omega_a)\,S\cdot p_a - \frac{1}{f_a}\mathcal{B}^{\nu\leq3}(\omega_a)\,S\cdot p$$



Axion-Nuclon Coupling: Loop corrections

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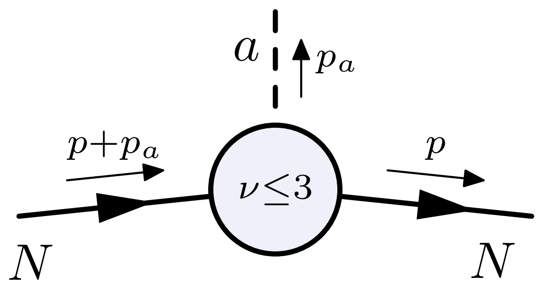

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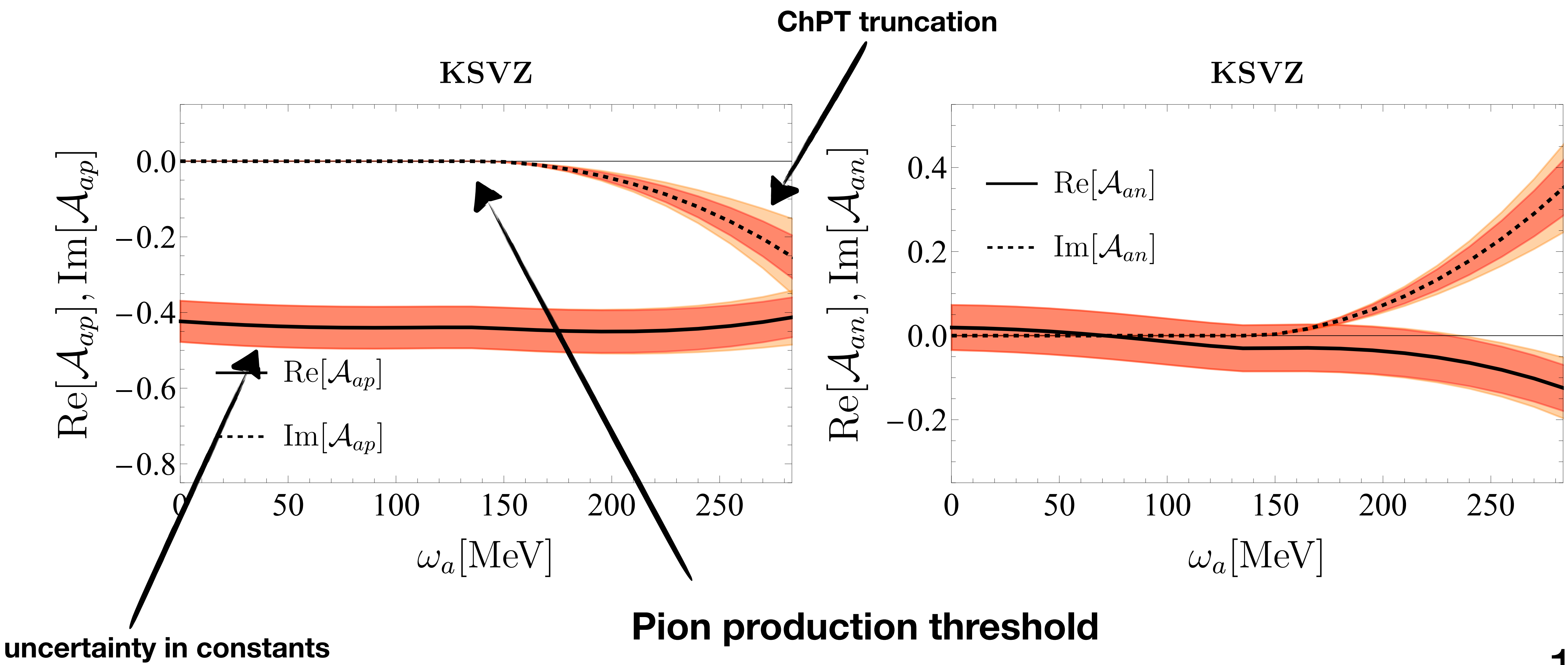
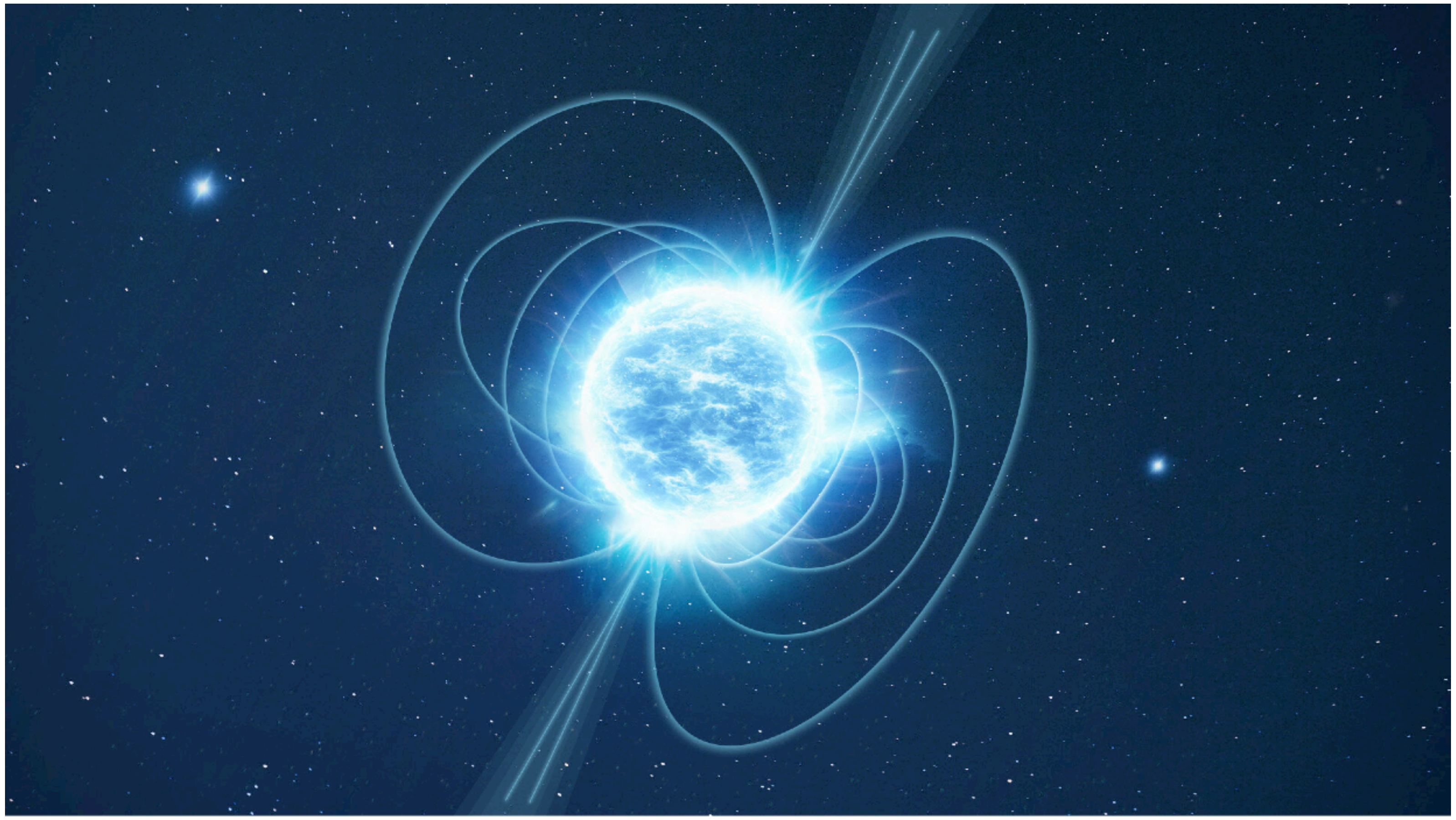


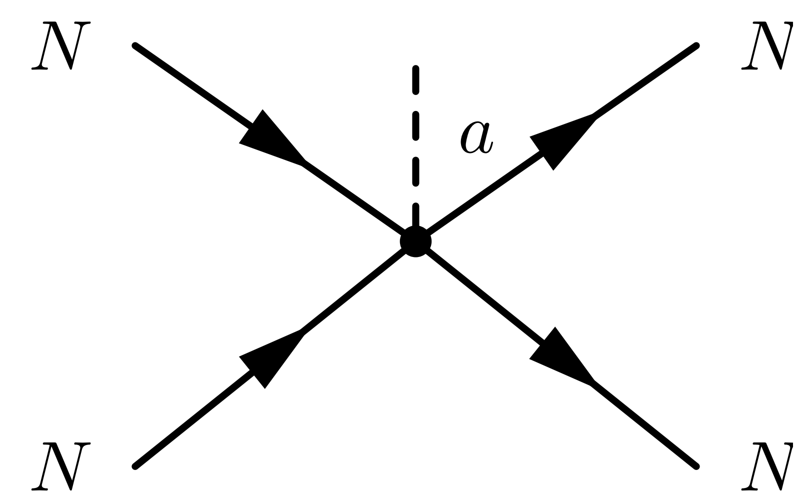
How does a density background change these couplings?



Axion-Nuclon Coupling: Finite density

- **Schematic example:**

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



Axion-Nuclon Coupling: Finite density

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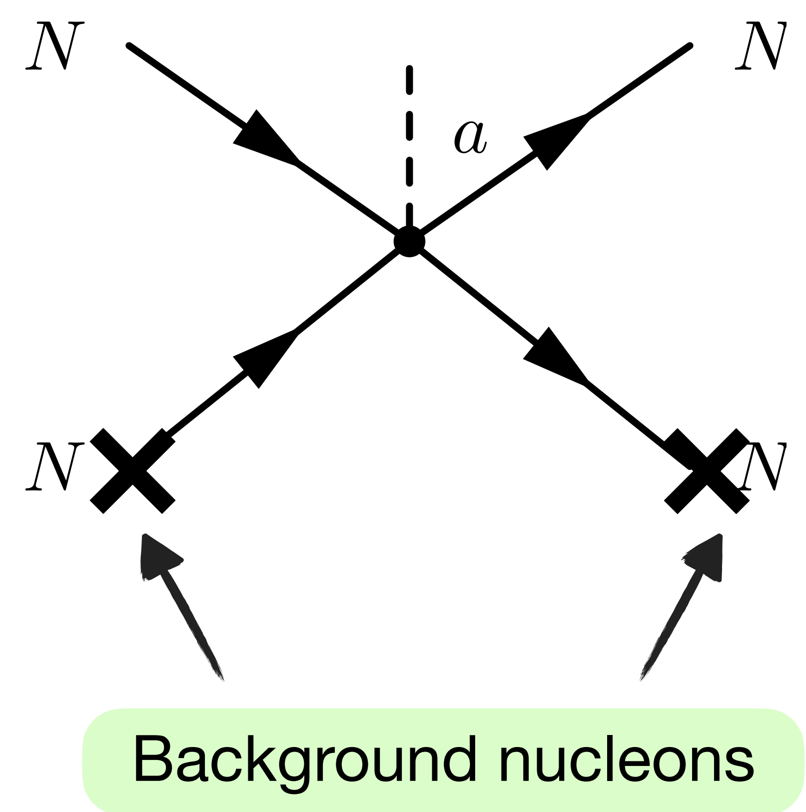


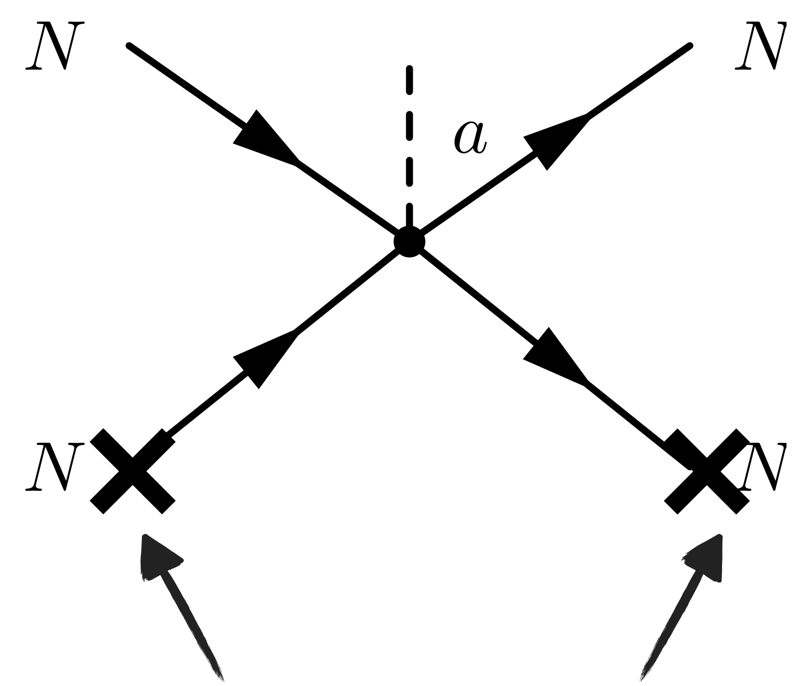
Axion-Nuclon Coupling: Finite density

- **Schematic example:**

$$\mathcal{L}^{(2)}_{\pi NN} = \frac{c_D}{2 f_\pi^2 \Lambda_\chi} (\bar{N}N)(\bar{N}S \cdot uN)$$

$$\langle \bar{N}N \rangle = n$$

Number density



Background nucleons

- **Gives contribution to coupling:** $\sim \dfrac{k_f^3}{(4\pi f_\pi)^2 \Lambda_\chi}$

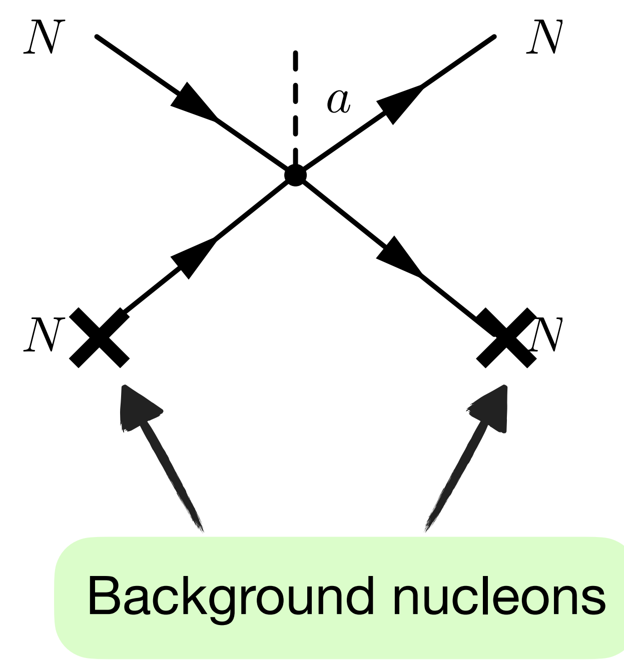
Axion-Nuclon Coupling: Finite density

- **Schematic example:**

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

$$\langle \bar{N} N \rangle = n$$

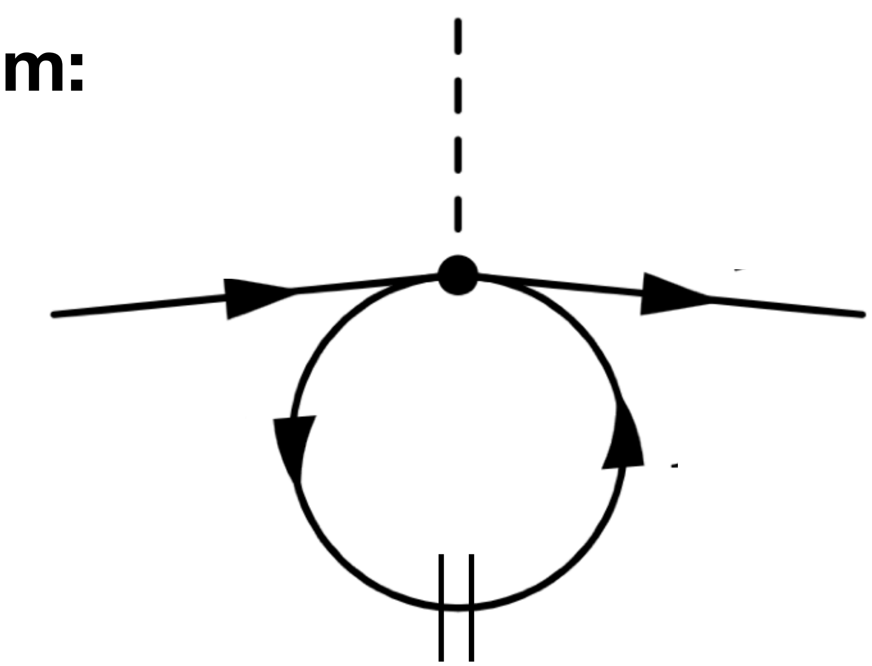
Number density



- **Systematically via QFT in Real-Time Formalism:**

Nucleon propagator at finite density

$$iG(k) = \frac{i}{k^0 + i\epsilon} - 2\pi\delta(k^0)\theta(k_f - |\vec{k}|)$$



Furnstahl, Serot ('91)
Ghosh, Grossman, Tangarife, Zu, Yu ('22)

Axion-Nuclon Coupling: Finite density

- **Schematic example:**

$$\mathcal{L}^{(2)}_{\pi NN} = \frac{c_D}{2f_\pi^2\Lambda_\chi}(\bar{N}N)(\bar{N}S\cdot uN)$$

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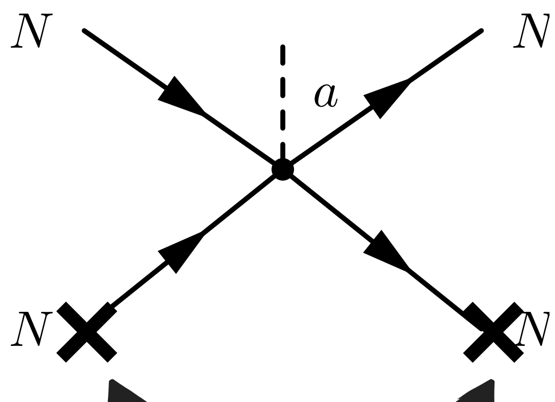
Number density



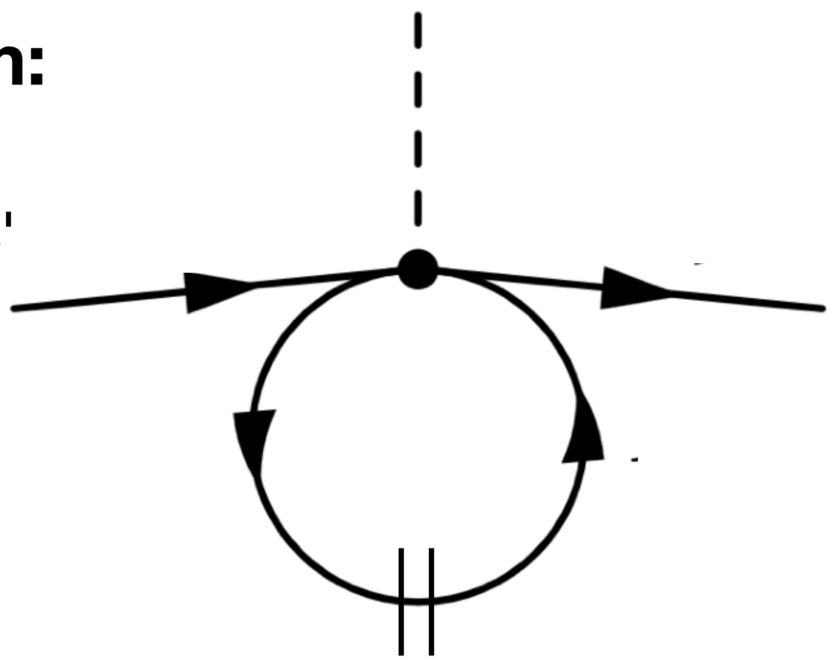
- **Systematically via QFT in Real-Time Formalism:**

Nucleon propagator at finite density

Filled 'Fermi sea'

$$iG(k) = \frac{i}{k^0 + i\epsilon} - 2\pi\delta(k^0)\theta(k_f - |\vec{k}|)$$

NR fermion propagator

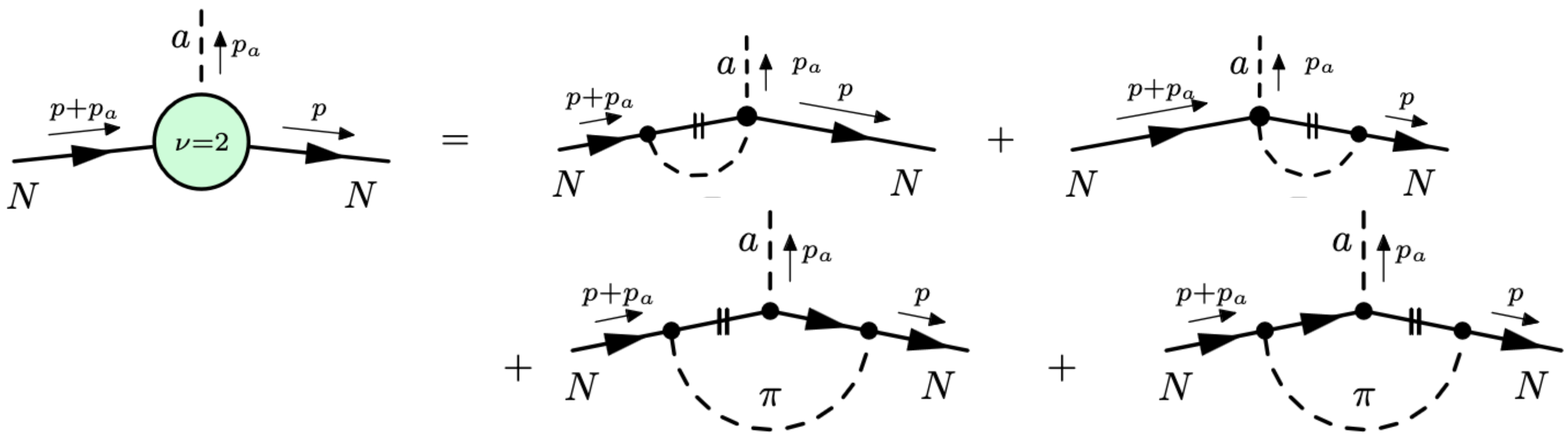


Furnstahl, Serot ('91)
Ghosh, Grossman, Tangarife, Zu, Yu ('22)

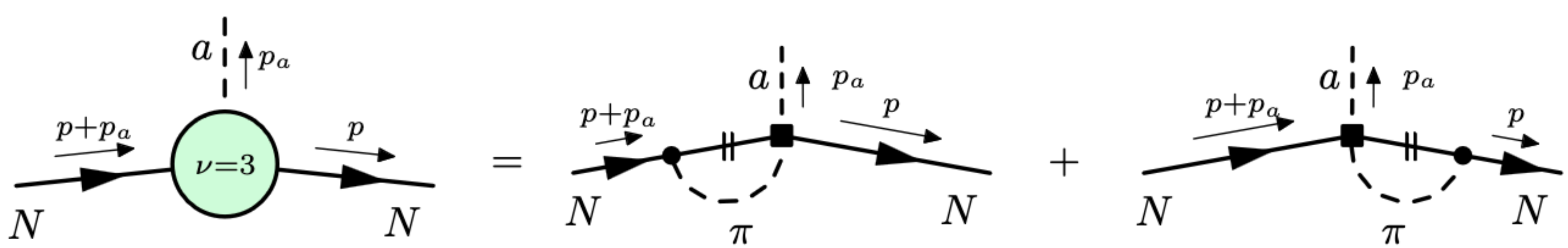
Axion-Nuclon Coupling: Finite density

Get corrections systematically $\left(\frac{p}{4\pi f_\pi}\right)^\nu \to \left(\frac{k_f}{4\pi f_\pi}\right)^\nu$

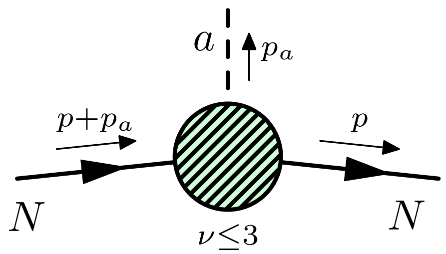
$$\left(\frac{k_f}{4\pi f_\pi}\right)^2$$



$$\left(\frac{k_f}{4\pi f_\pi}\right)^2 \left(\frac{k_f}{\Lambda_\chi}\right)$$

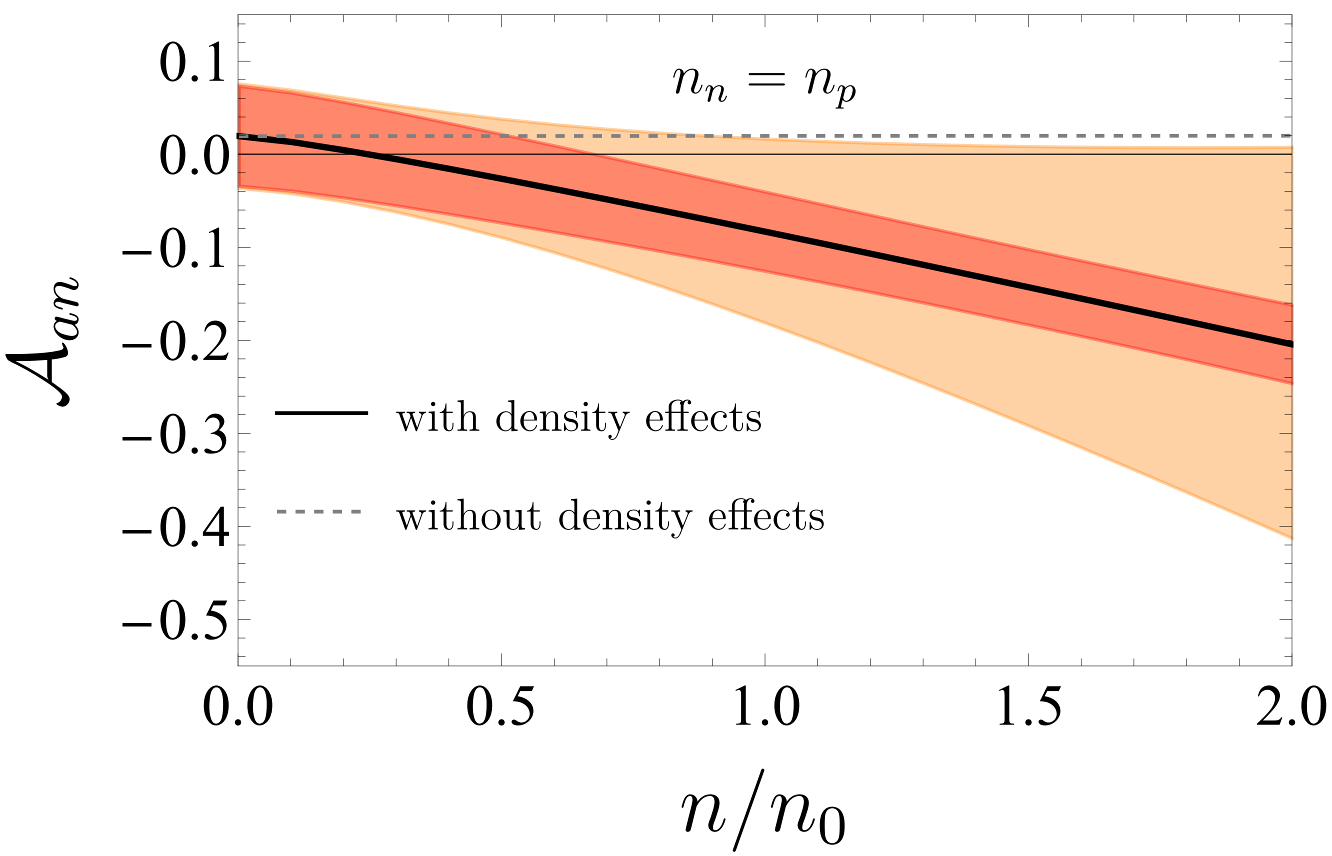


Axion-Nuclon Coupling: Finite density

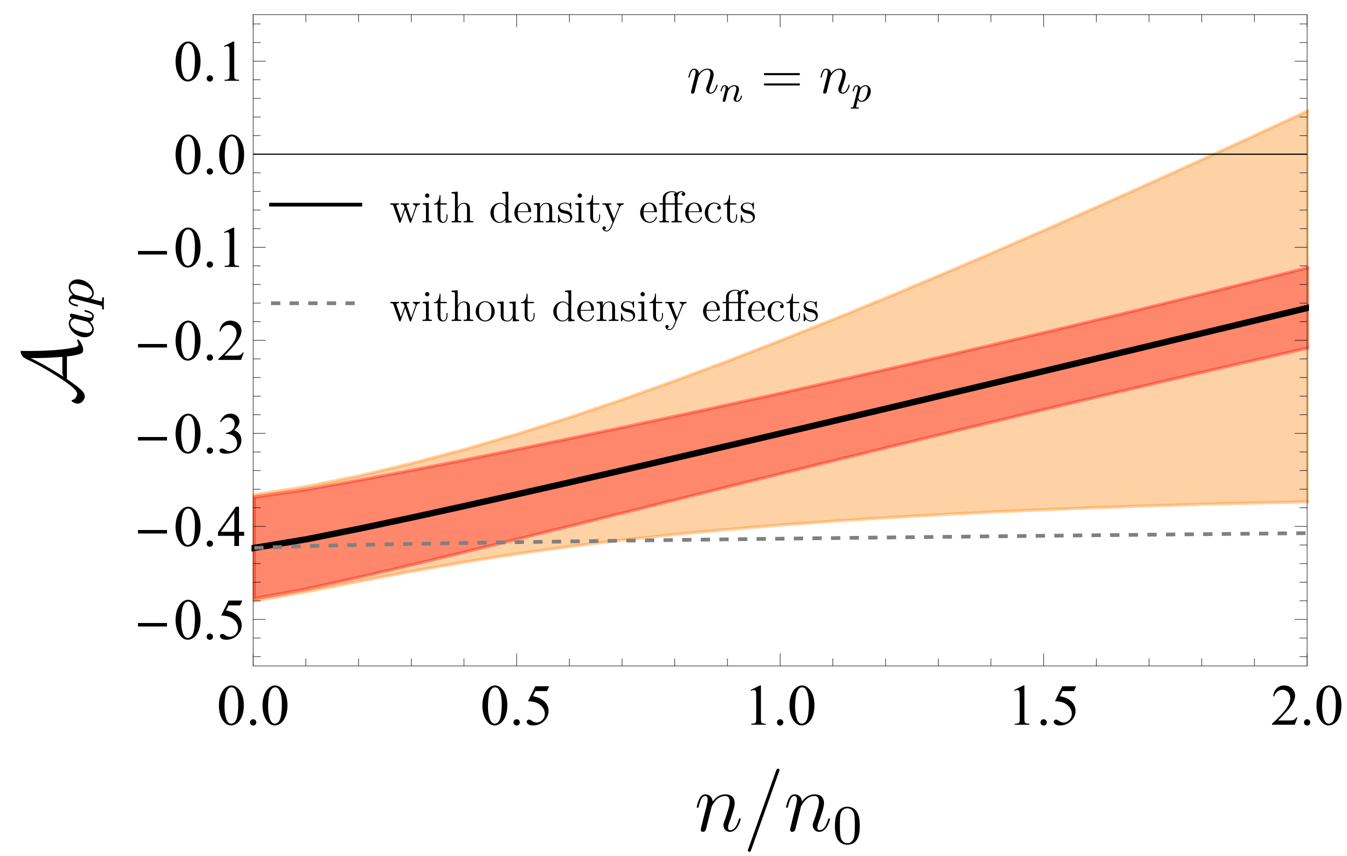


$$= -\frac{1}{f_a}\mathcal{A}^{\nu\leq 3}(k_f, p_a)\, S\cdot p_a - \frac{1}{f_a}\mathcal{B}^{\nu\leq 3}(k_f, p_a)\, S\cdot p$$

Neutron



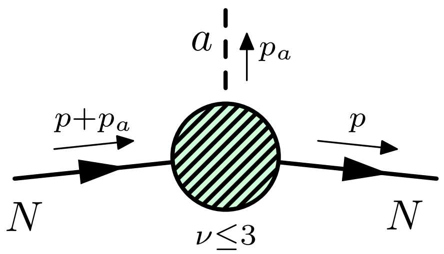
Proton



At finite density $\mathcal{A}_{an}^{\mathrm{KSVZ}}(n_0) = -0.1(4)(9)$

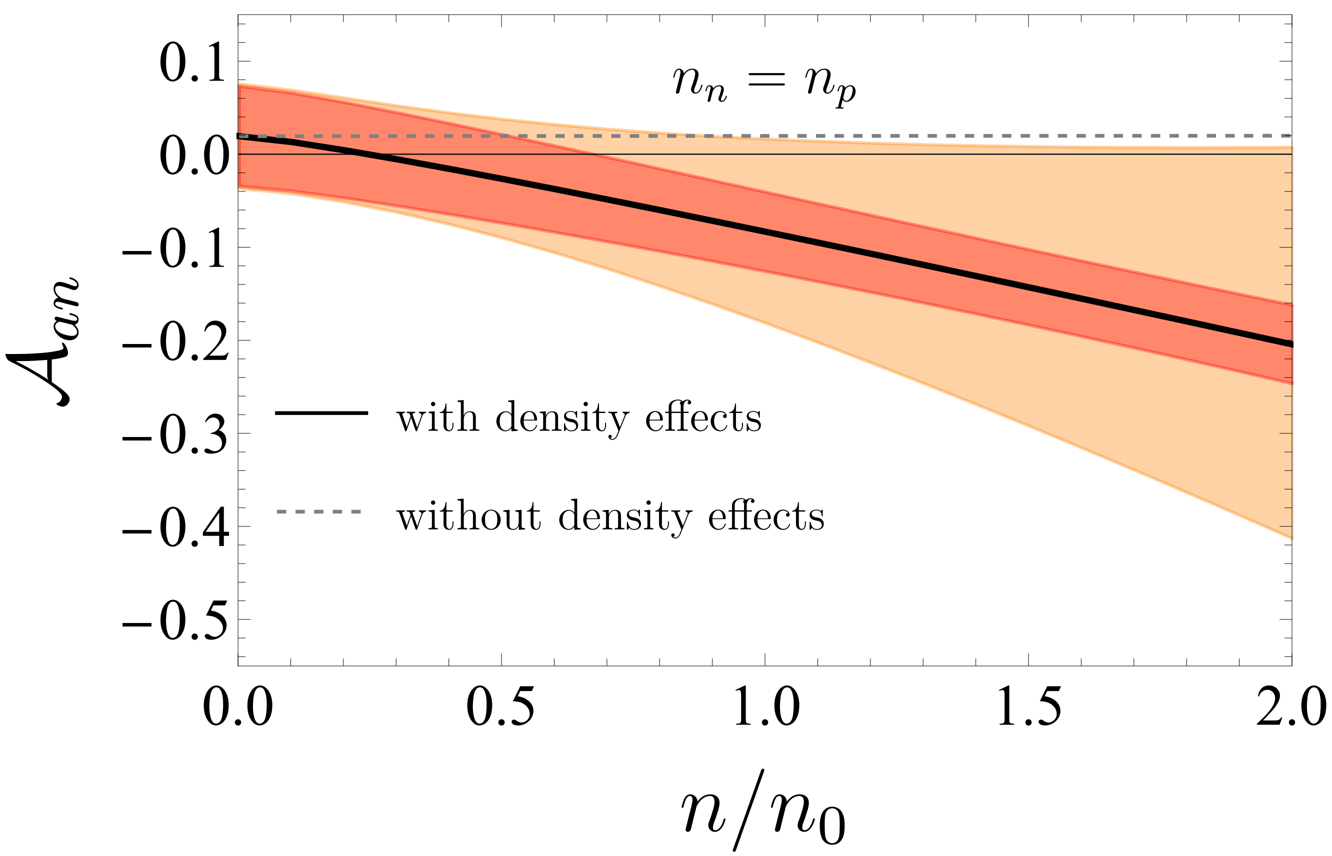
vs. vacuum $\mathcal{A}_{an}^{\mathrm{KSVZ}}(0) = 0.02(5)$

Axion-Nuclon Coupling: Finite density

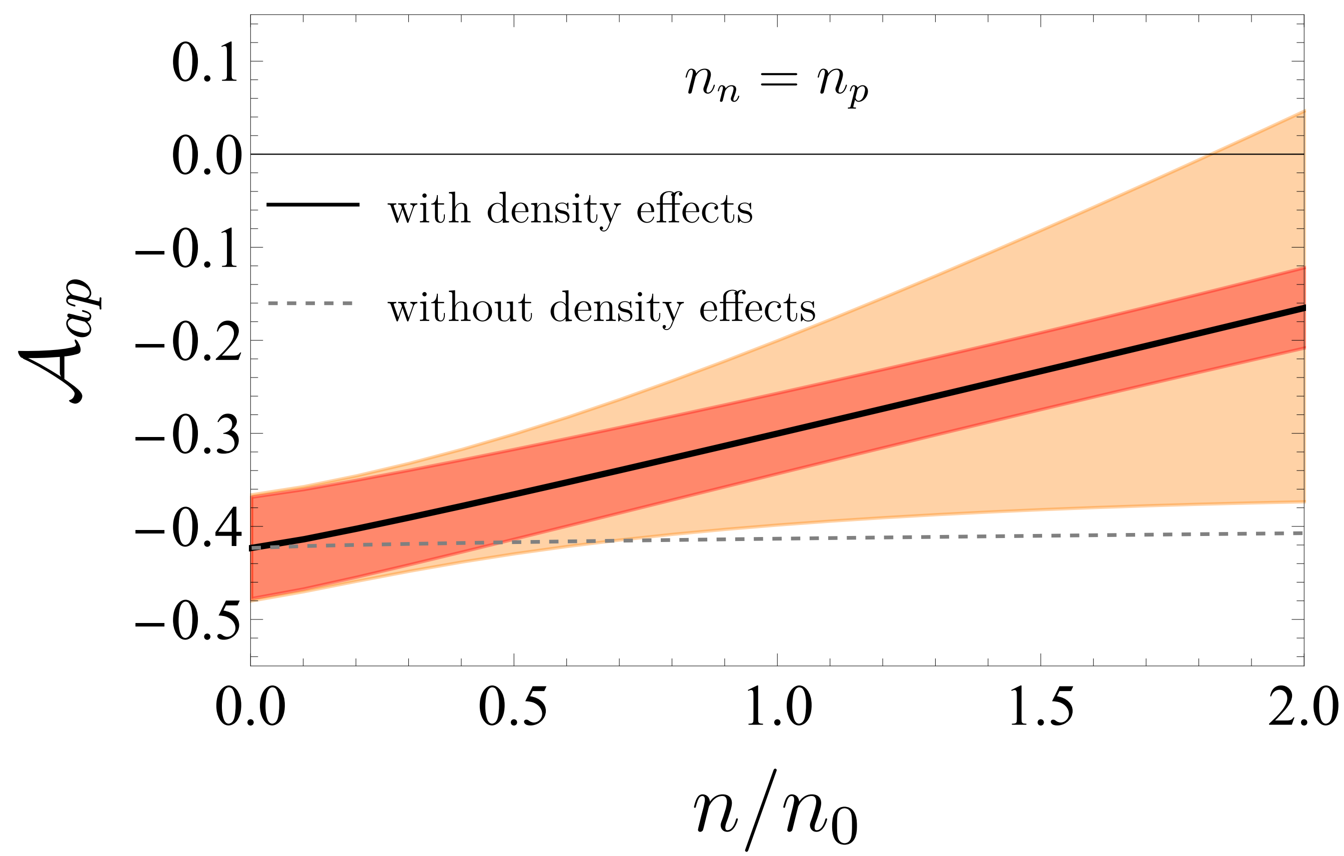


$$= -\frac{1}{f_a}\mathcal{A}^{\nu\leq 3}(k_f,p_a)\,S\cdot p_a - \frac{1}{f_a}\mathcal{B}^{\nu\leq 3}(k_f,p_a)\,S\cdot p$$

Neutron



Proton

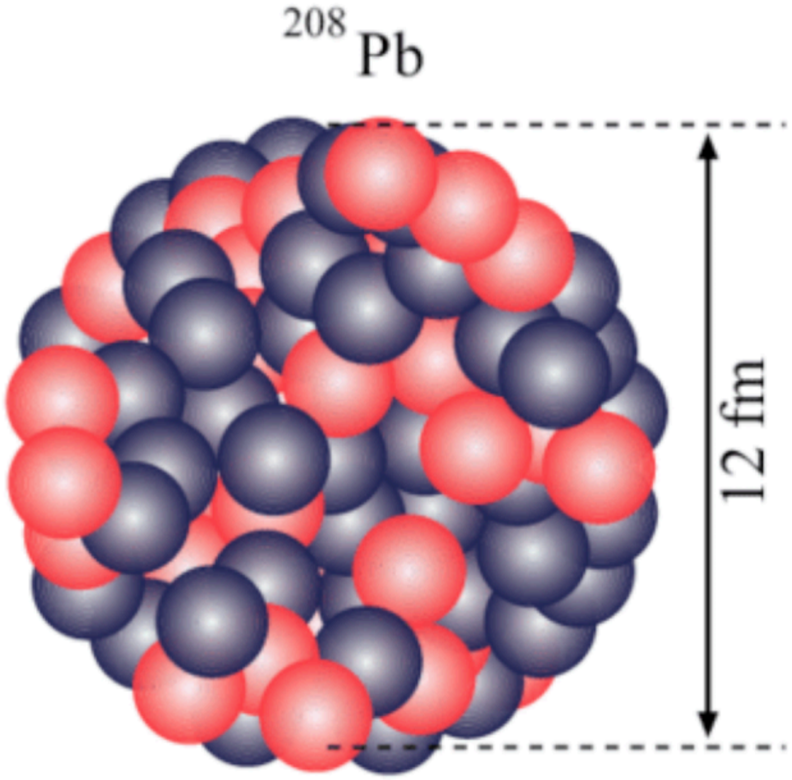


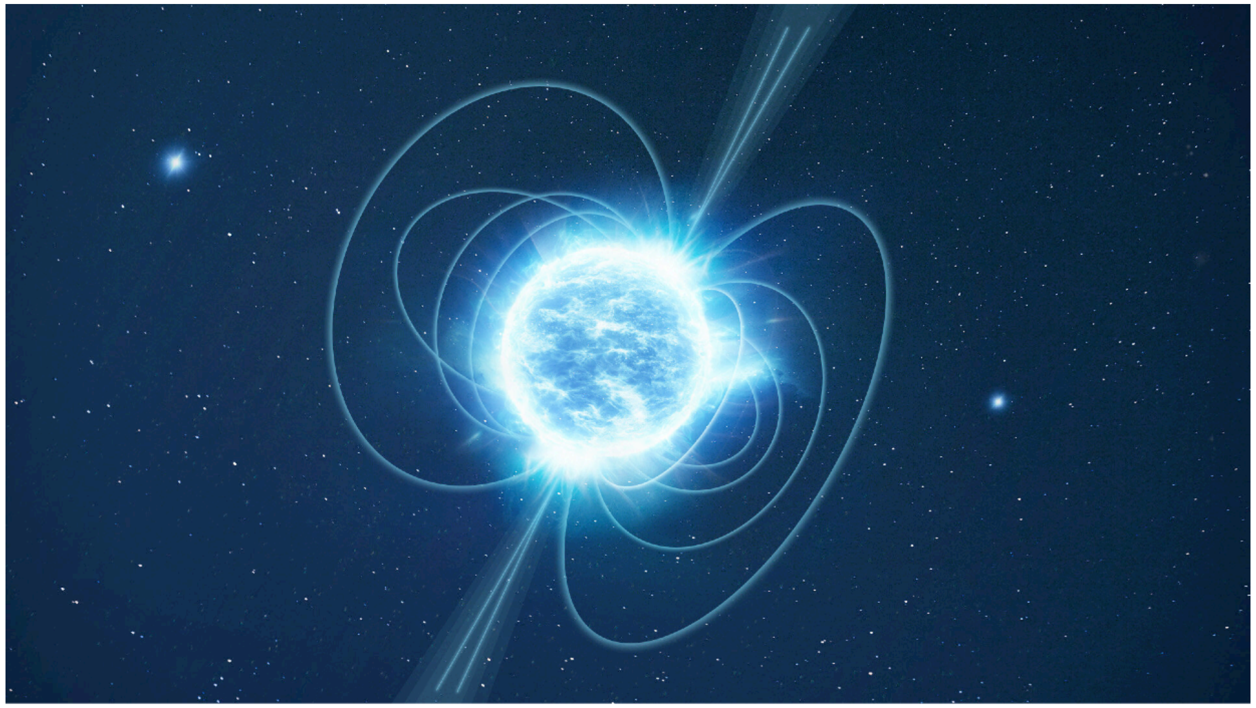
At finite density $\mathcal{A}_{an}^{\mathrm{KSVZ}}(n_0) = -0.1(4)(9)$

vs. vacuum $\mathcal{A}_{an}^{\mathrm{KSVZ}}(0) = 0.02(5)$

Accidental cancellation is lifted!

Implications for phenomenology





Supernova bound revisited

- Axion Luminosity

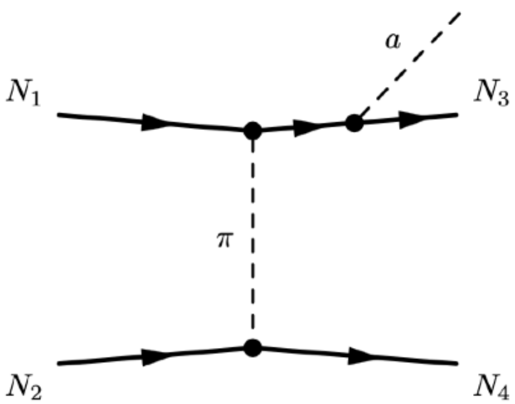
$$L_a = \int dr 4\pi r^2 \dot{\epsilon}_a(r)$$

With emissivity

$$\dot{\varepsilon}_a = \int \prod_{i=1}^{4} d\Pi_i d\Pi_a (2\pi)^4 S|\mathcal{M}|^2 \delta^{(4)} \left(\sum_i p_i - p_a\right) E_a f_1 f_2 \left(1 - f_3\right) \left(1 - f_4\right)$$

- Typically 1 pion exchange at tree level + pheno corrections

Chang, Essig, McDermott ('18) Carenza, Fischer, Giannotti, Guo, Martinez-Pinedo, Mirizzi ('19)

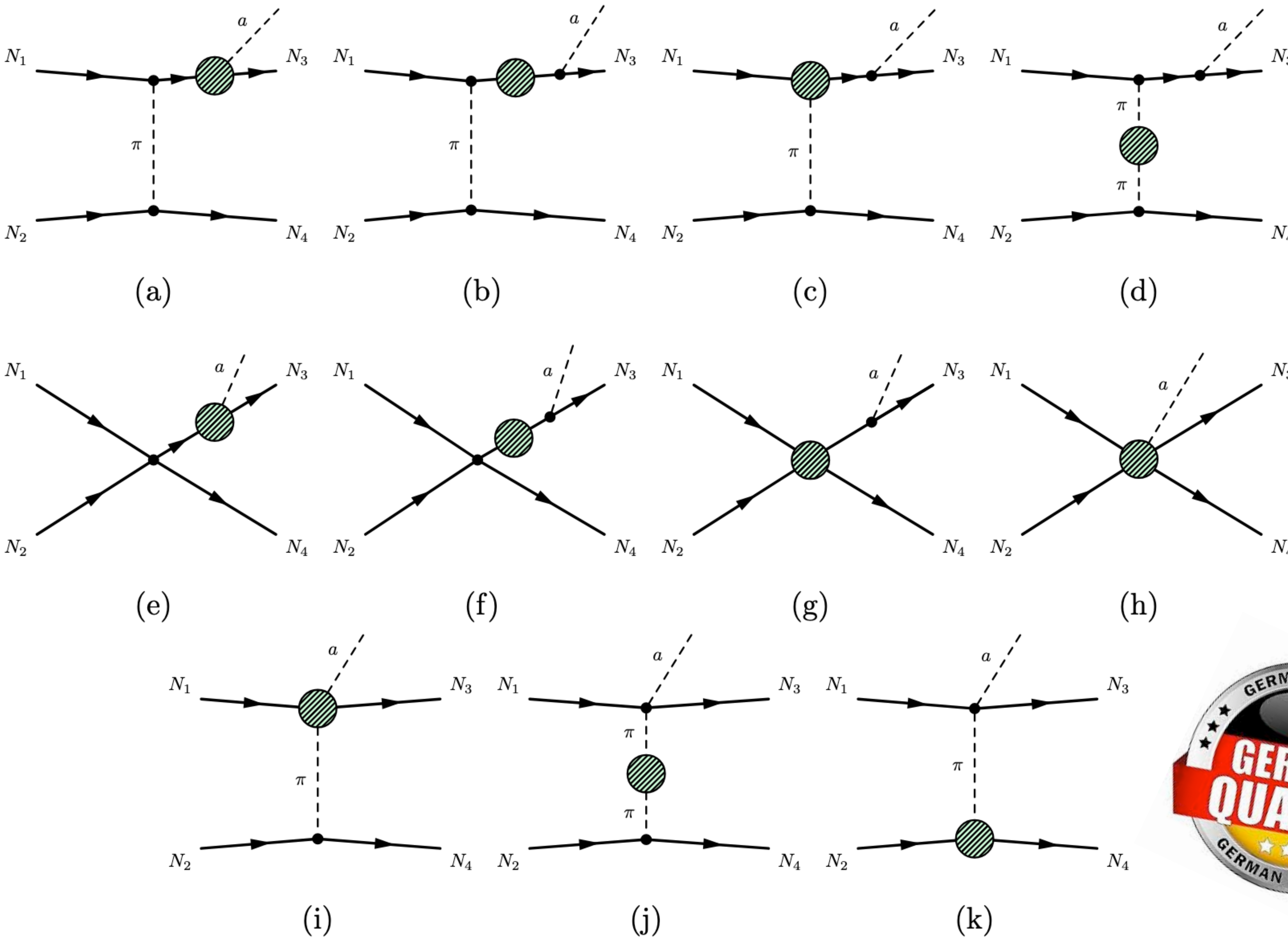


- **Outlined all relevant corrections diagramatically up to NNLO in chiral expansion**

Allows to systematically account for all effects from first principles!

Supernova bound revisited

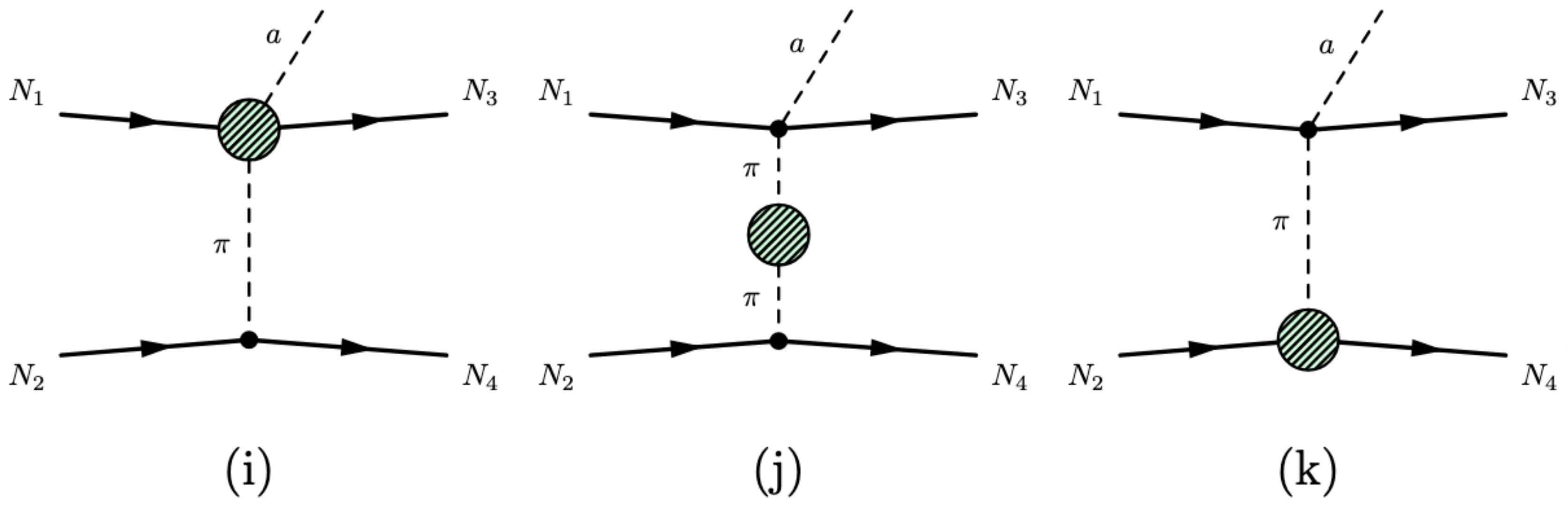
Relevant diagrams up to NLO



Supernova bound revisited

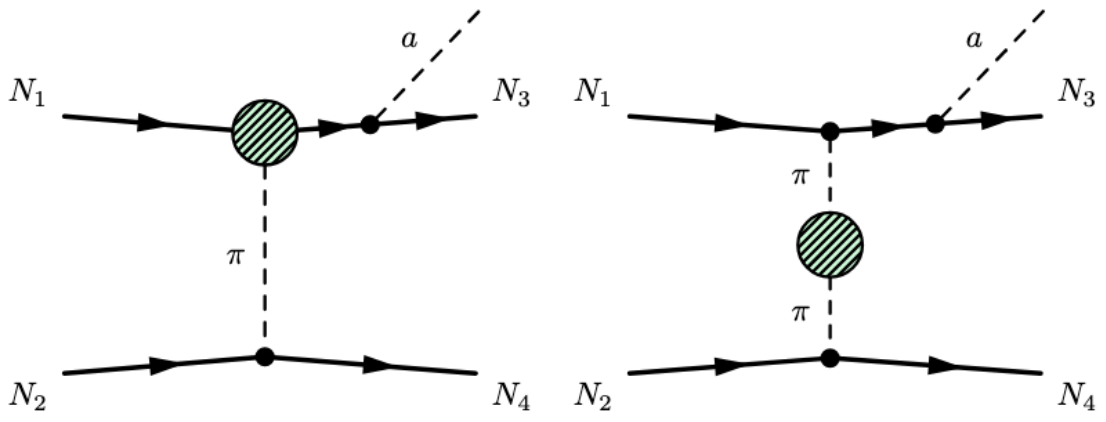
These are typically suppressed by $v \cdot k \simeq \dfrac{k^2}{2m_N}$

Choi, Kim, Seong, Shin ('21)



Supernova bound revisited

Neglected



(c) (d)

Modification of nuclear interaction:

- Fudge factor γ_p

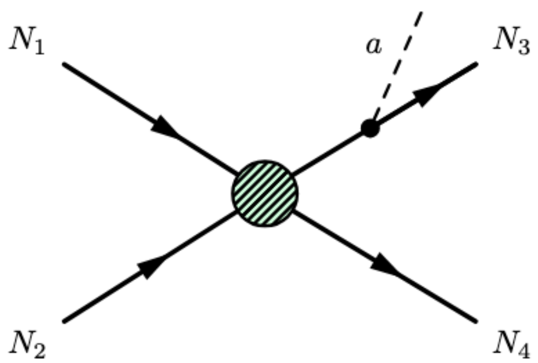
  Chang, Essig, McDermott ('18)

- Phenomenologically modelled

  Ericson, T., & Mathiot, J.-F. 1989, Phys. Lett. B, 219, 507

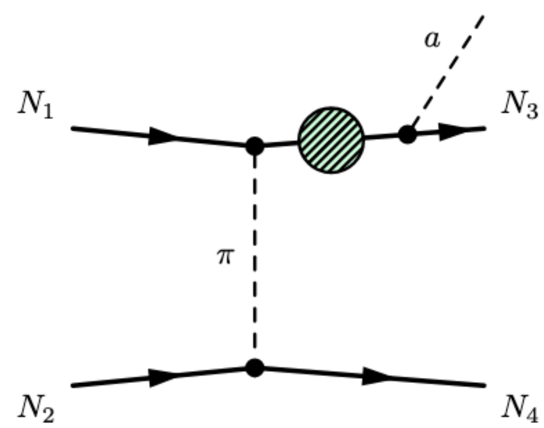
  Hannestad, Raffelt *Astrophys.J.* 507 (1998) 339-352

  Carenza, Fischer, Giannotti, Guo, Martinez-Pinedo, Mirizzi ('19)

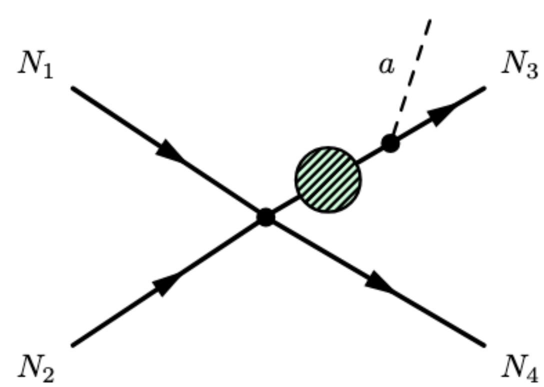


(g)

Supernova bound revisited



(b)



(f)

Modelled as nucleon re-scatterings

- Fudge factor γ_h

  Raffelt, Seckel ('88)

  Chang, Essig, McDermott ('18)

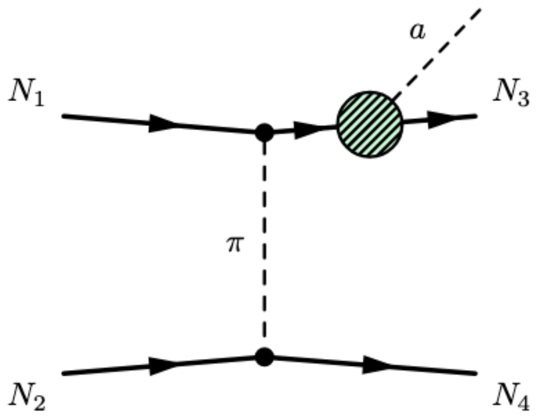
- Phenomenologically

  Raffelt, Seckel ('88)

  Carenza, Fischer, Giannotti, Guo, Martinez-Pinedo, Mirizzi ('19)

Neglected

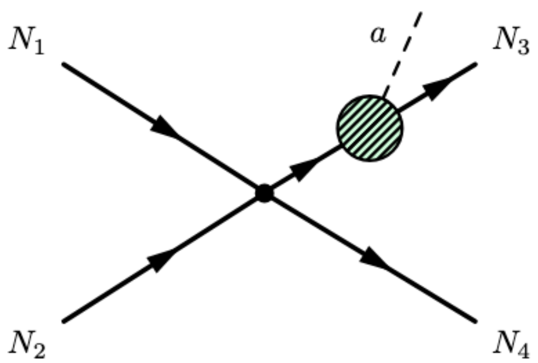
Supernova bound revisited



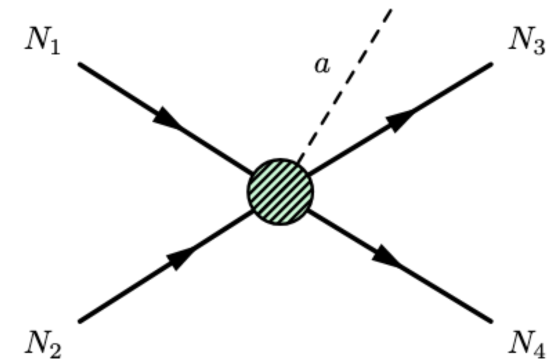
(a)

Outlined for the first time

KS, Stadlbauer, Stelzl, Weiler ('24)

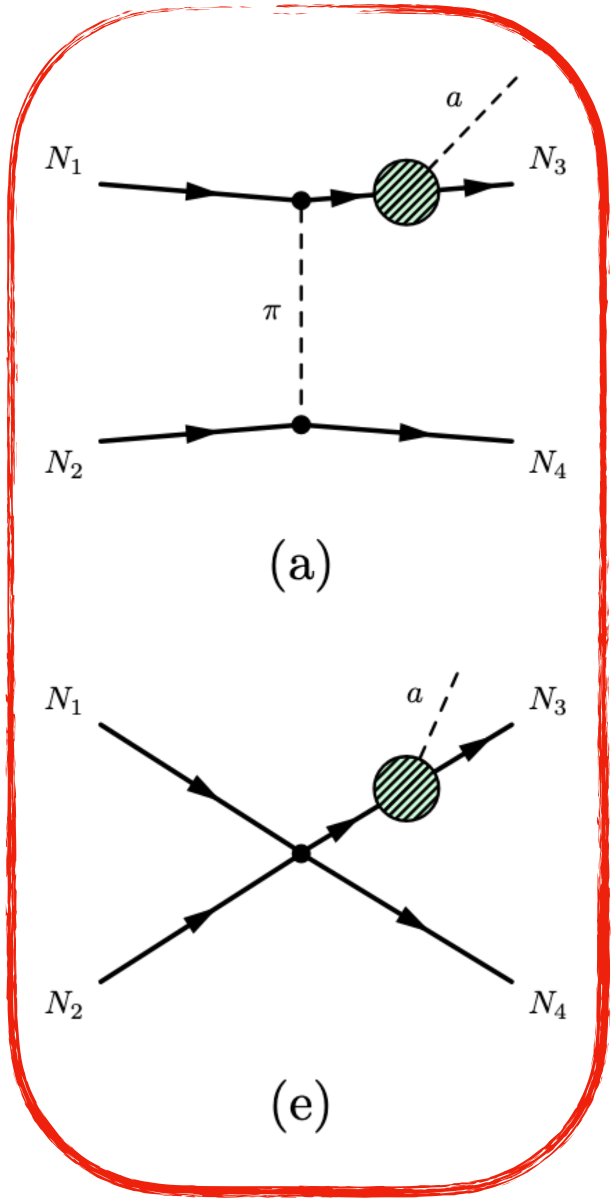


(e)



(h)

Supernova bound revisited



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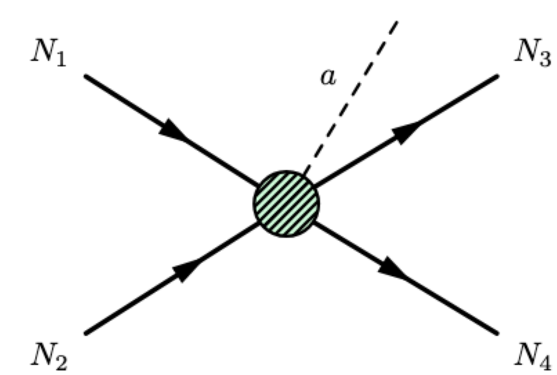
Modified couplings



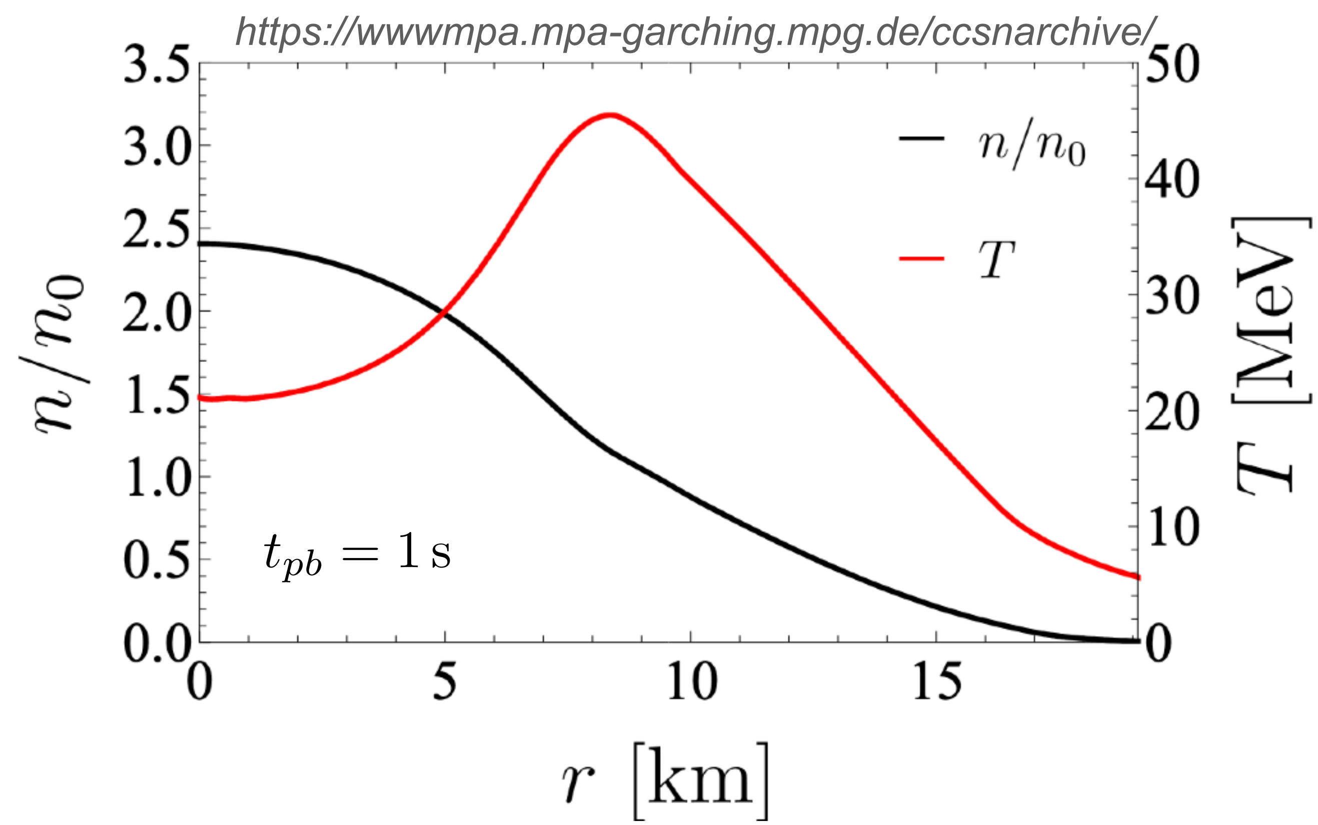
(h)

Focus on these for now.. but:

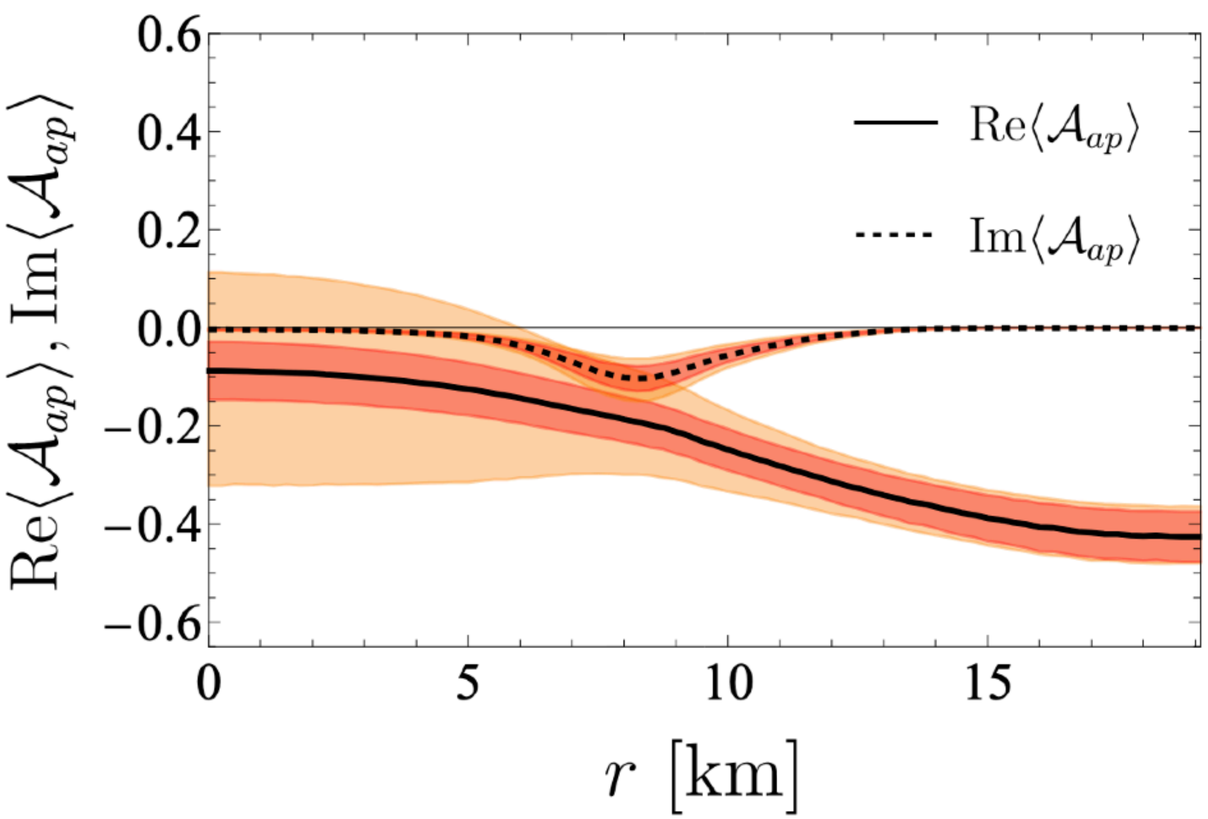
Fully systematic evaluation should take into account all diagrams up to given order

Supernova bound revisited

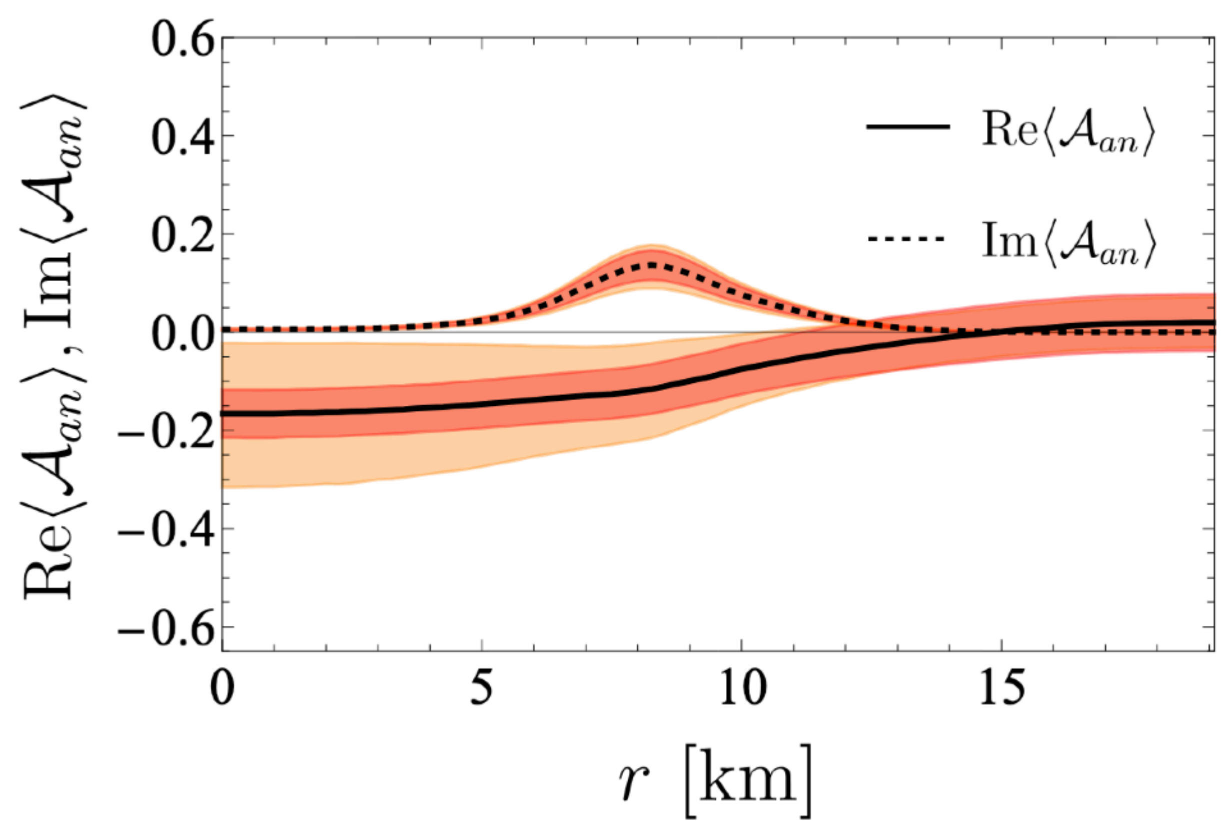
KSVZ axion couplings in a SN:



Proton



Neutron

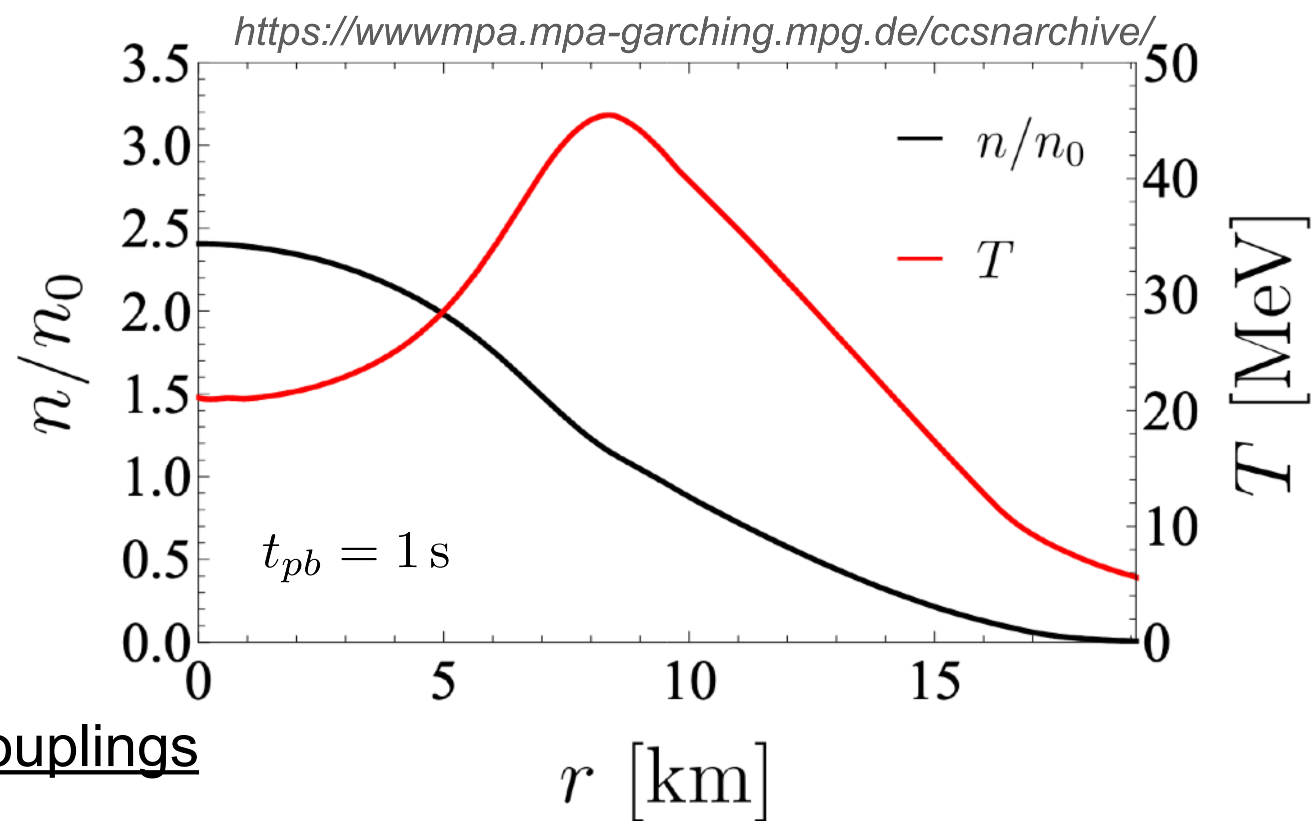


Supernova bound revisited

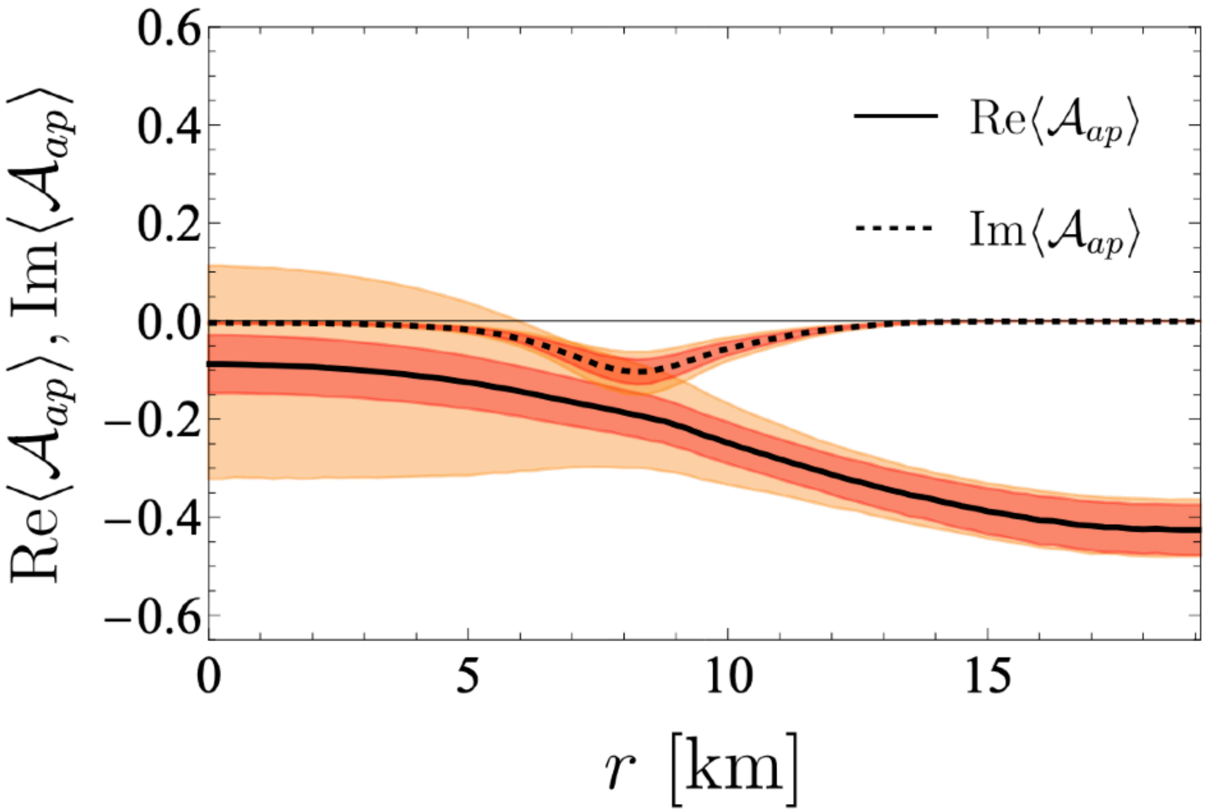
KSVZ axion couplings in a SN:

Available on GitHub

https://github.com/michael-stadlbauer/Axion-Couplings



Proton



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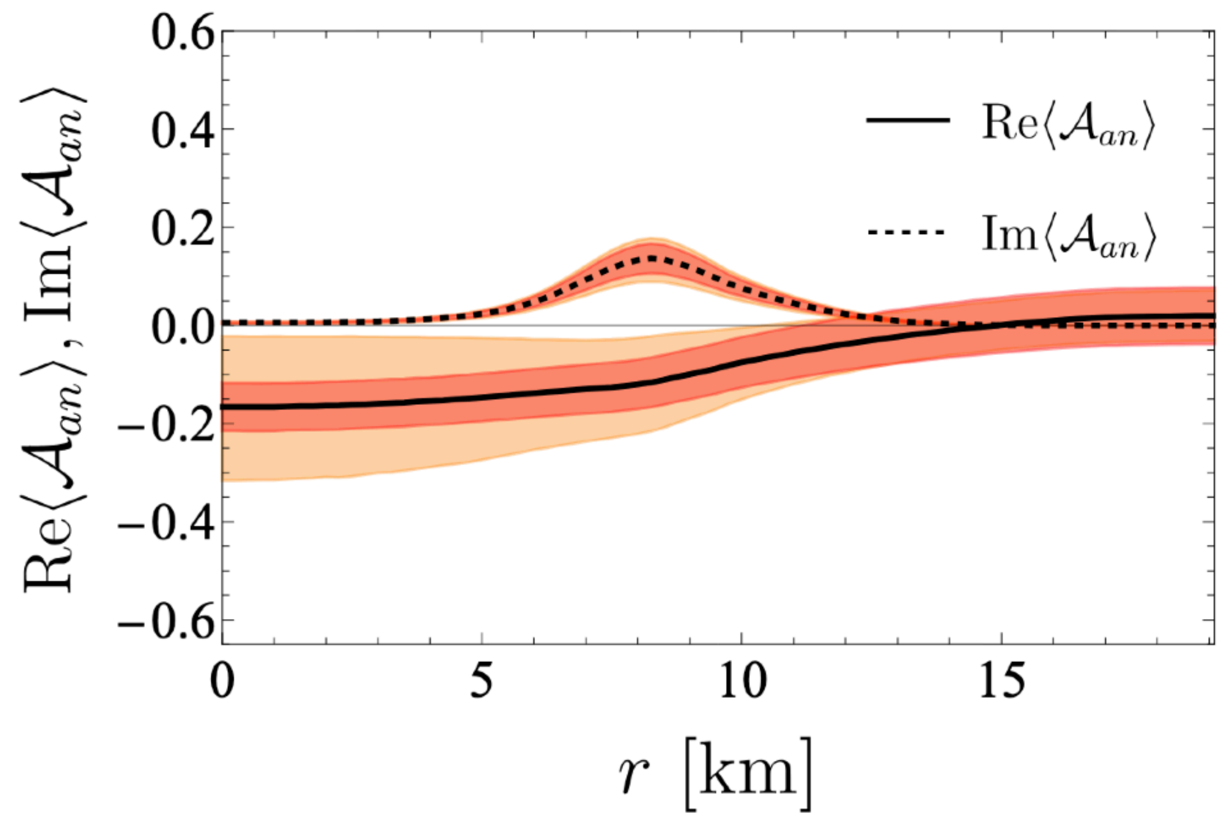
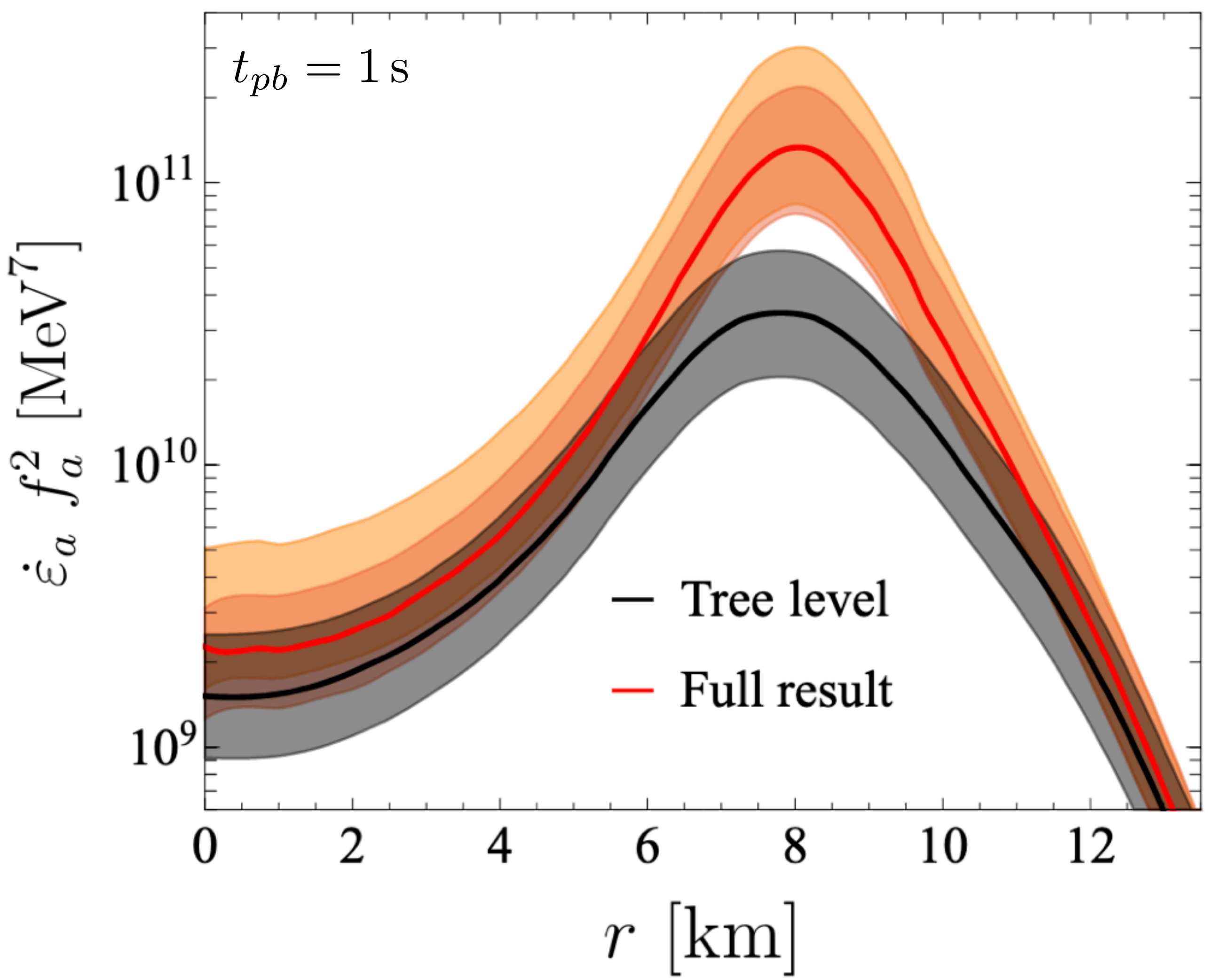


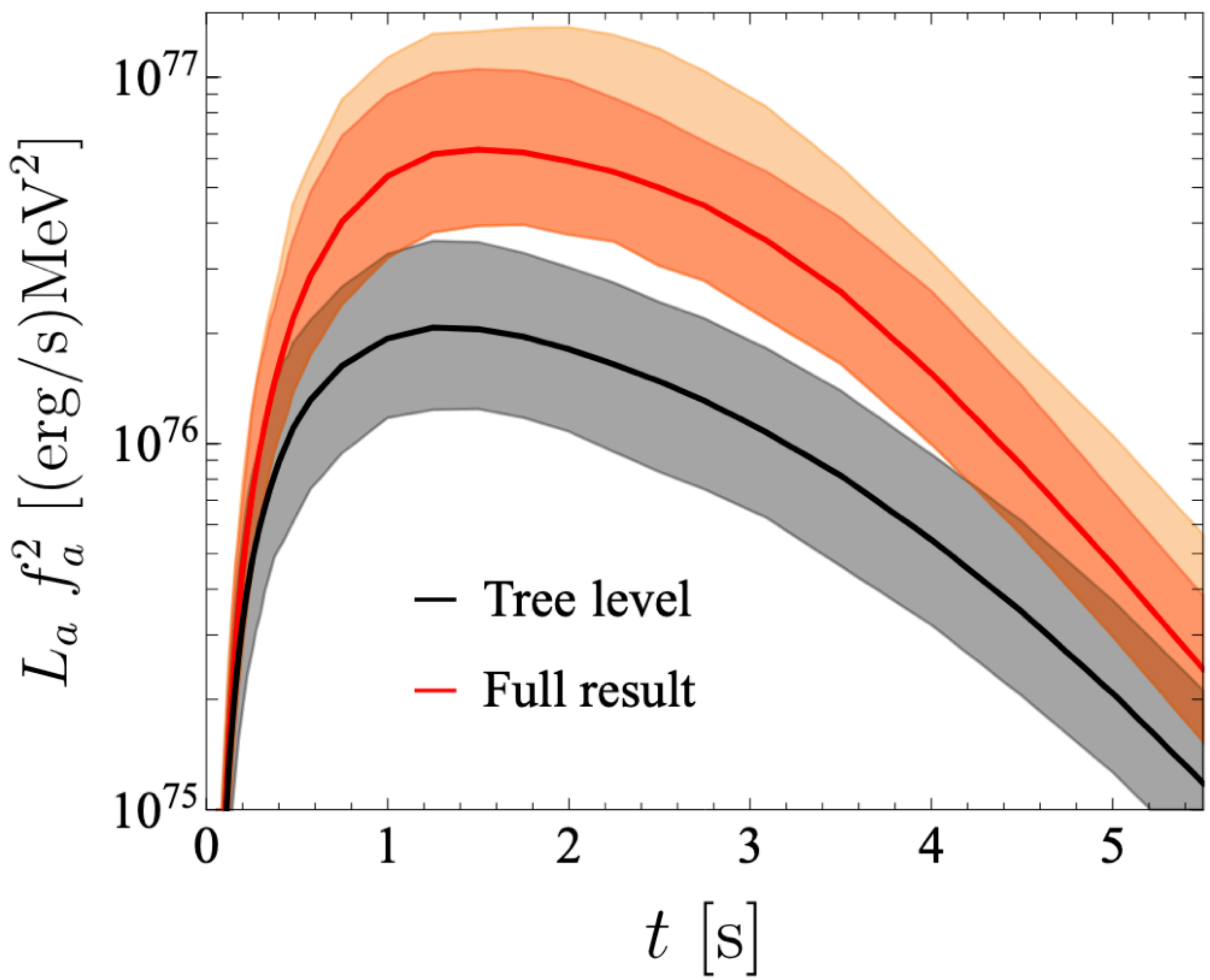
Supernova bound revisited

KSVZ axion

Emissivity



Luminosity



Supernova bound revisited

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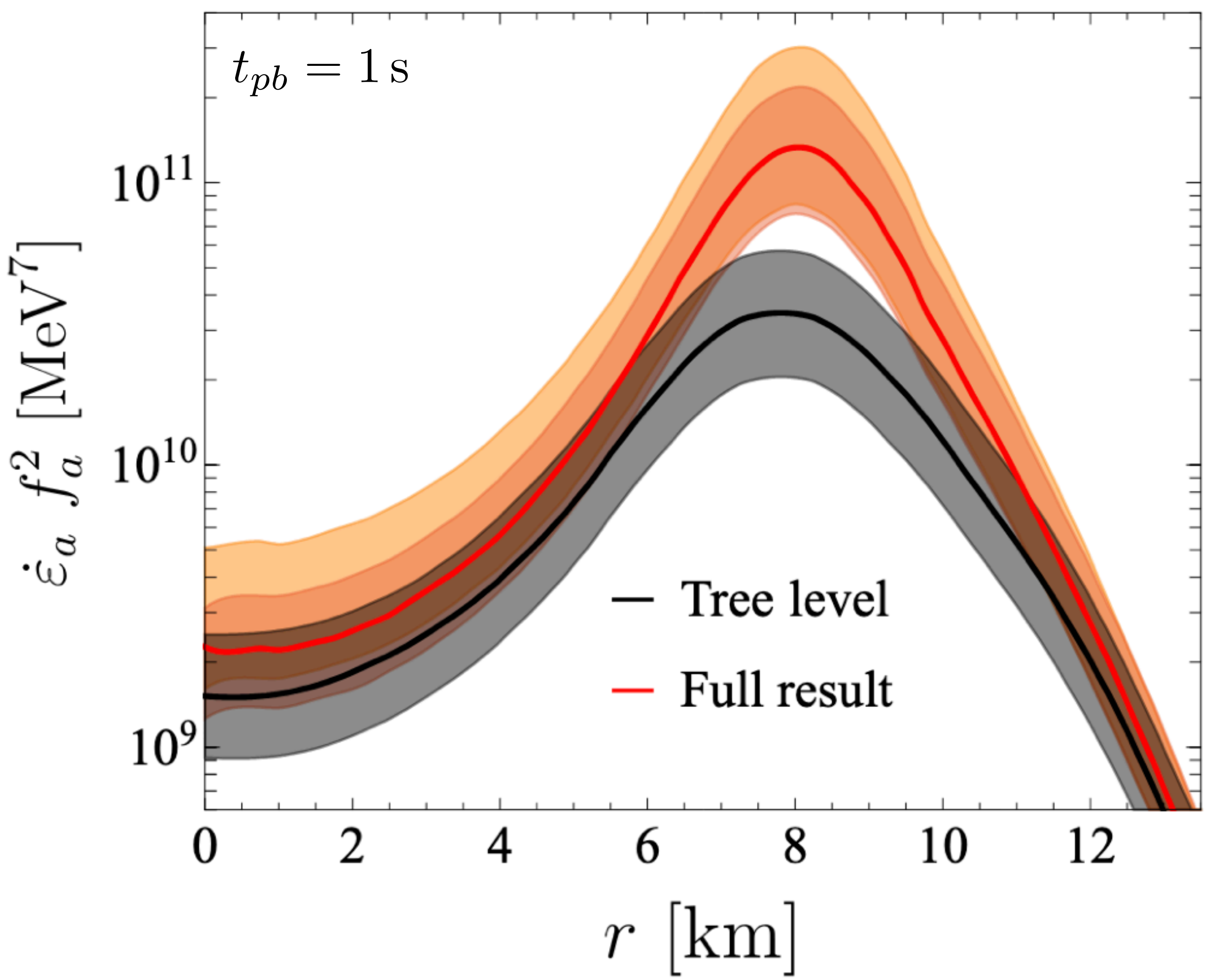
<u>**Emissivity**</u>



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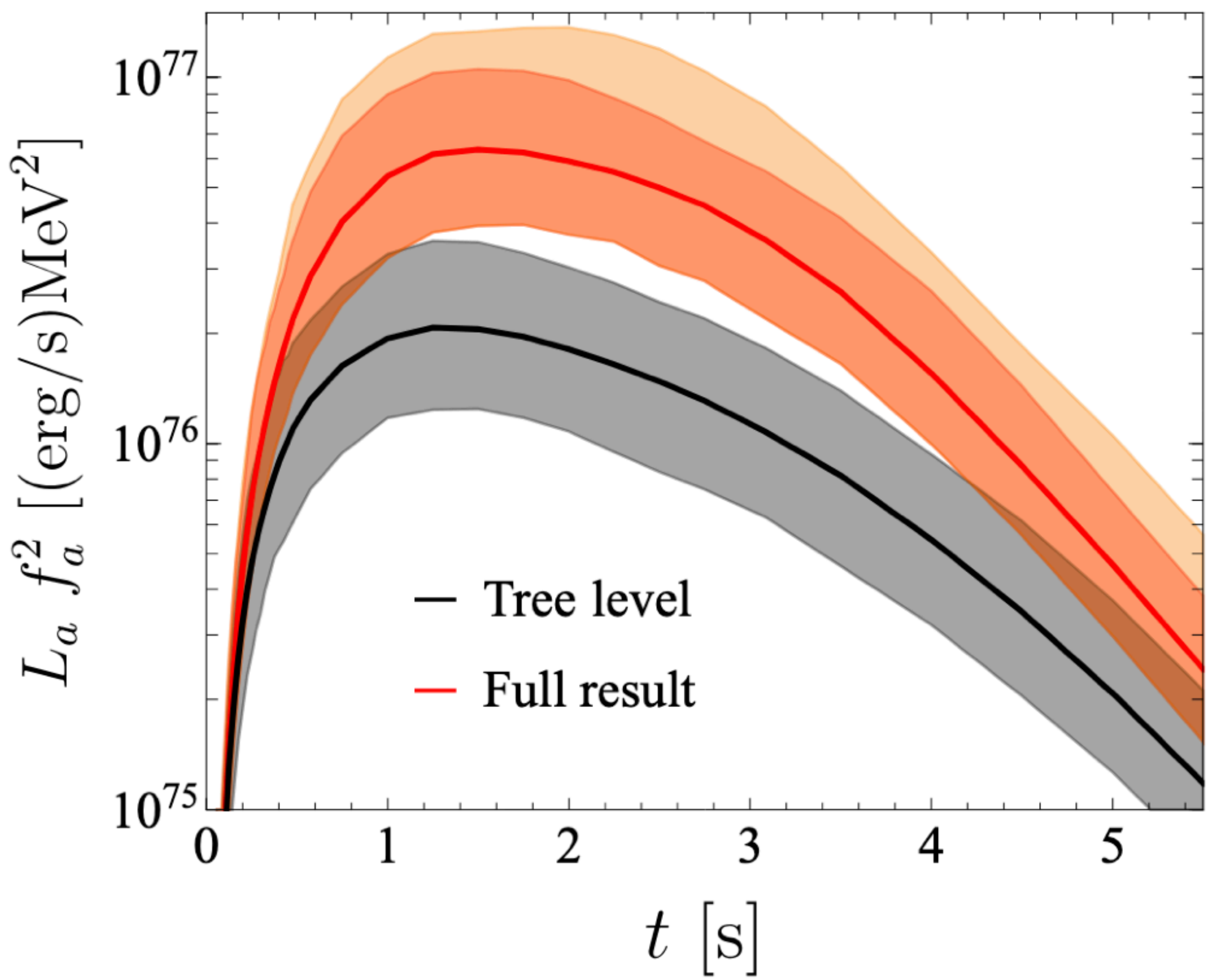

Tree level: $f_a \gtrsim 6.1^{+1.7}_{-1.4} \times 10^8\,\mathrm{GeV}, \quad m_a \lesssim 9.8^{+3.0}_{-2.2}\,\mathrm{meV}.$

Vertex corrections: $f_a \gtrsim 1.0^{+0.5}_{-0.2} \times 10^9\,\mathrm{GeV}, \quad m_a \lesssim 5.9^{+1.8}_{-2.0}\,\mathrm{meV}.$

Astrophobic axions

Derivative axion-nucleon couplings are **model-dependent**

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$$c_N = G_A c_{u-d} \tau^3 + G_0 c_{u+d} \mathbf{1}$$

$$c_{u-d} = c_u^0 - c_d^0 - \frac{1}{2}\frac{1-z}{1+z}$$

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$$c_{u+d} = c_{u-d} \simeq 0$$

DiLuzio, Mescia, Nardi, Panci, Ziegler ('17)

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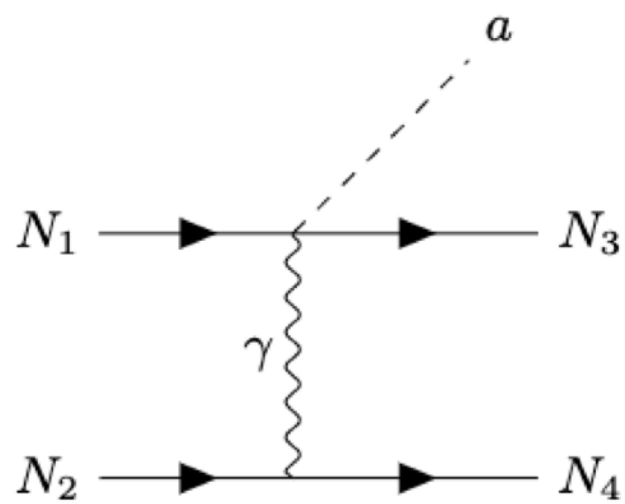
- Still want to solve CP problem so at least $aG\tilde{G}$ which induces nEDM

$$\mathcal{L}_a^{\rm EDM} = -\frac{i}{2}\frac{C_{aN\gamma}}{m_N}\frac{a}{f_a}\bar{N}\gamma_5\sigma_{\mu\nu}NF^{\mu\nu}$$



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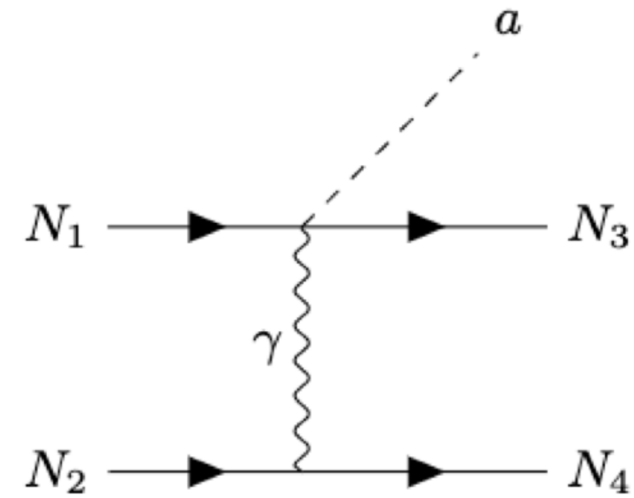

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EDM induced at 1-loop:

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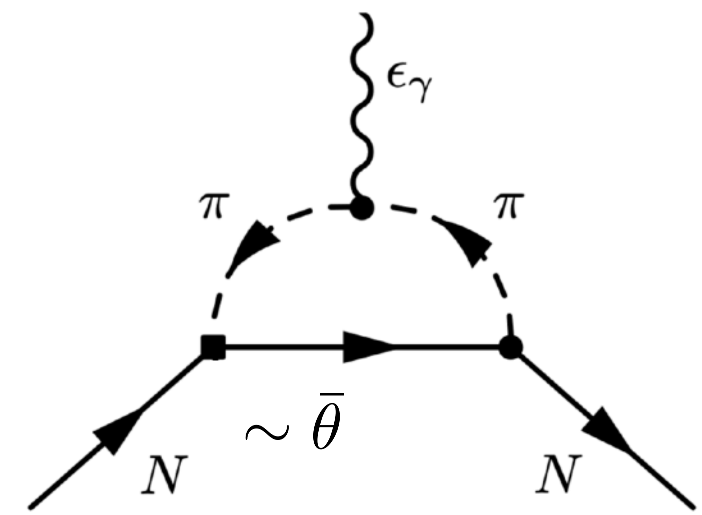
Schwartz, QFT



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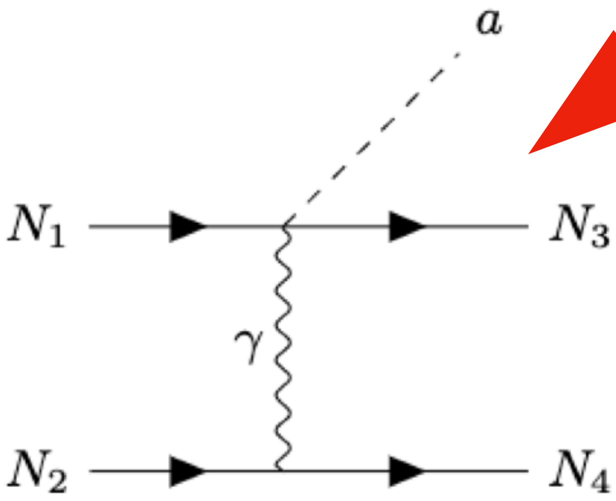

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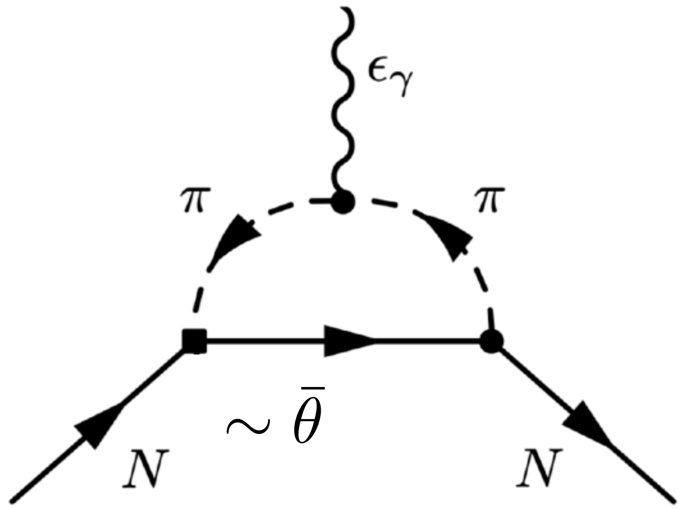

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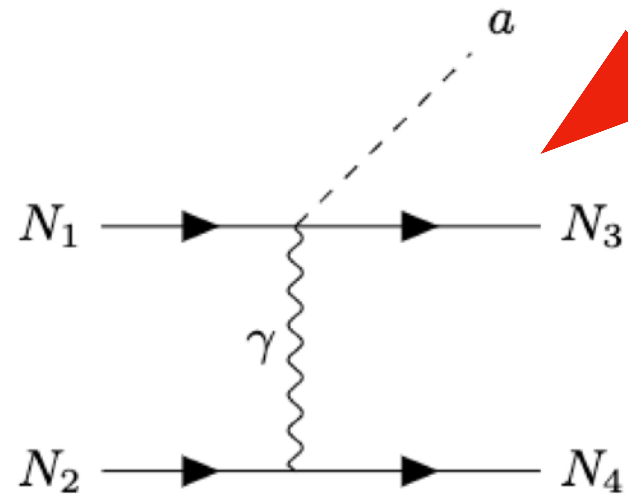

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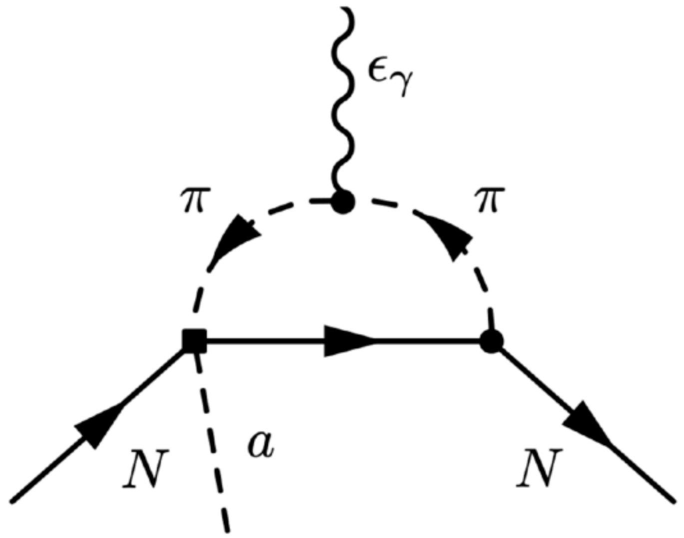

- Due to systematic approach, can identify (ir)relevant operator

$$\mathcal{L}_{\pi N}^{(2)} \supset -\hat{c}_5 m_\pi^2 \frac{4z}{(1+z)^2}\bar{N}\left(\frac{\pi^a a}{f_\pi f_a}\right)\tau^a N$$

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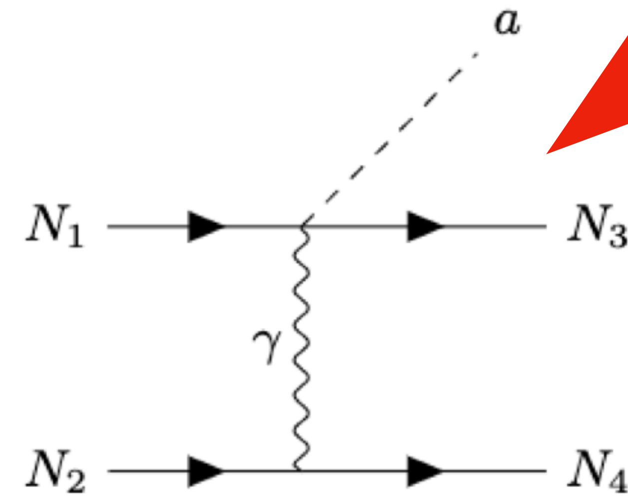

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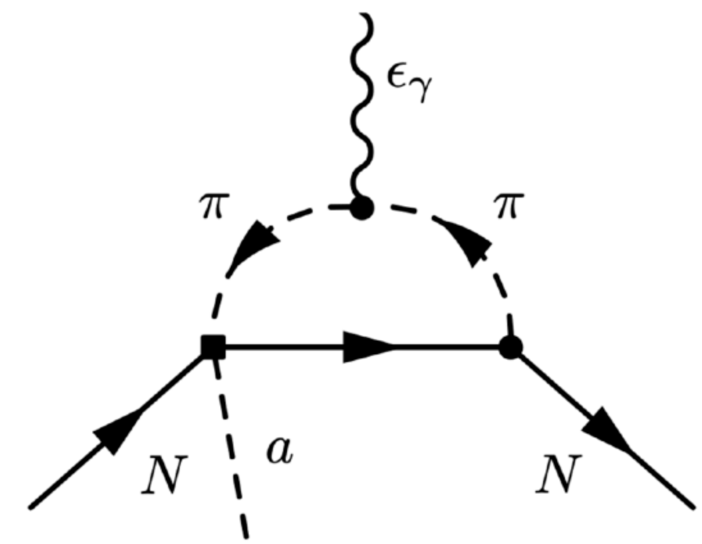

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- NLO, shift-symmetry breaking, isospin-breaking
- Size of EDM operator can be determined

$$\frac{C_{aN\gamma}}{m_N} \sim \frac{m_\pi^2}{(4\pi f_\pi)^2}\hat{c}_5$$

Crewther, Vecchia, Veneziano, Witten ('79)

Astrophobic axions

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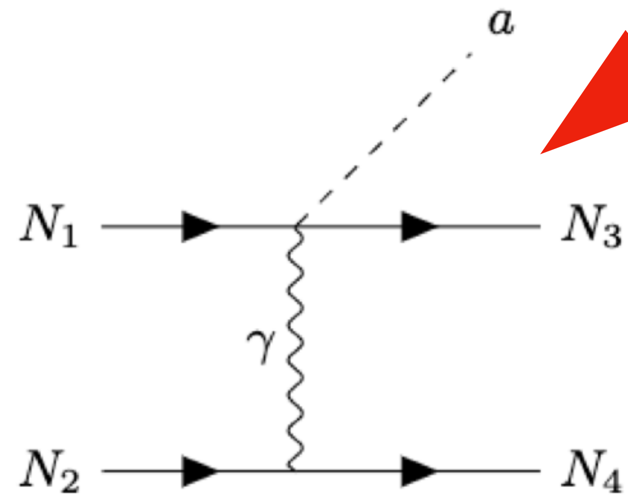

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1 tree-level diagram

- Due to systematic approach, can identify (ir)relevant operator

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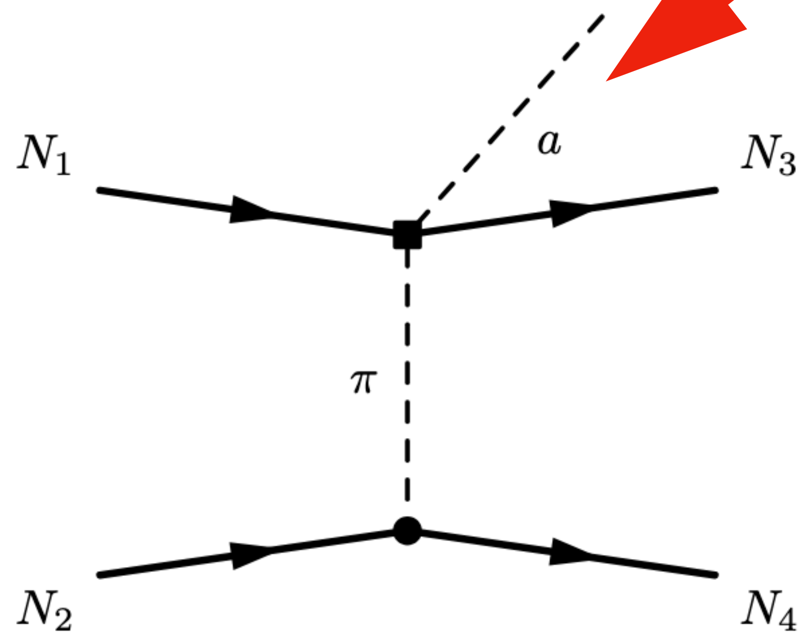
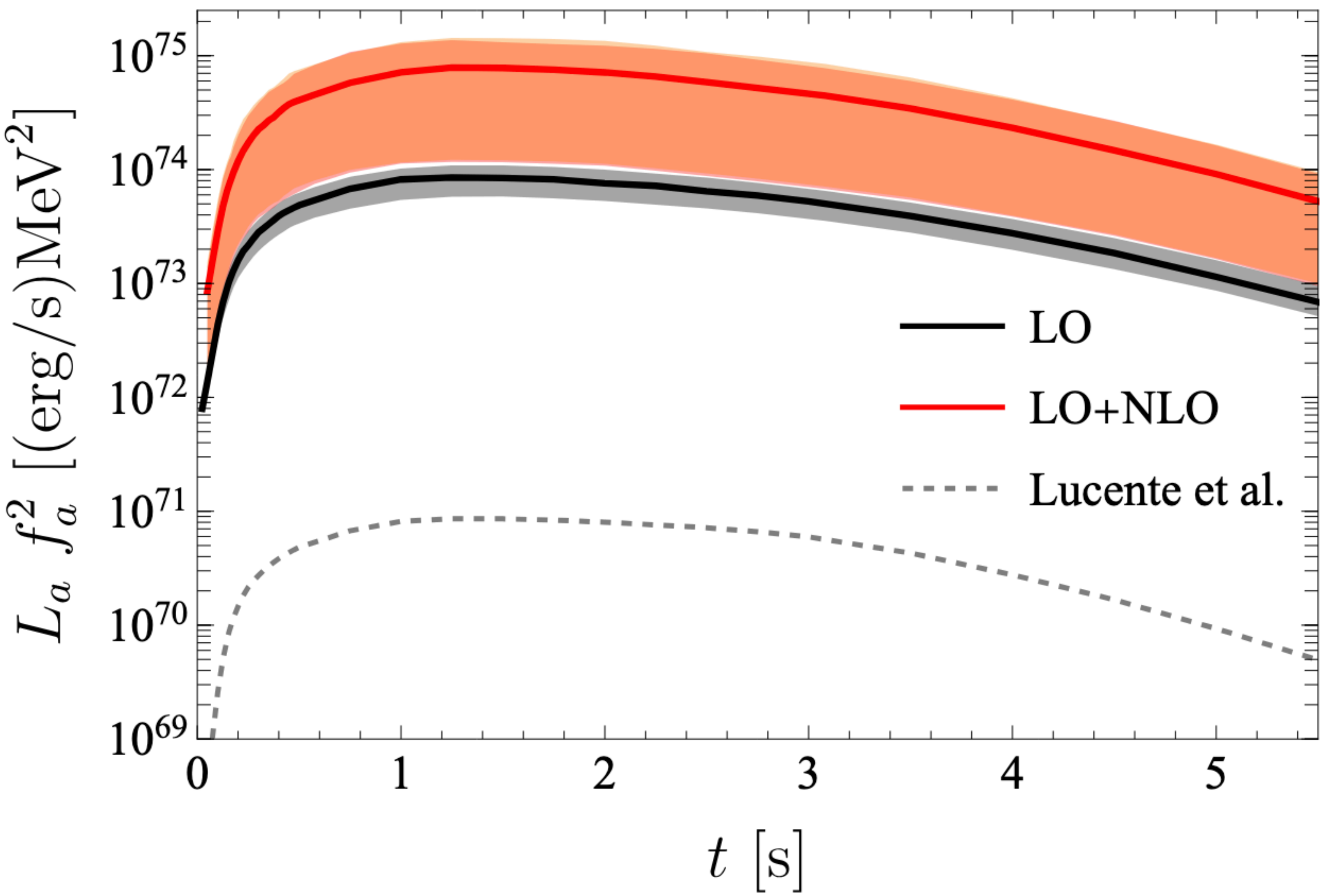
- Induces a **tree-level** diagram



Astrophobic axions

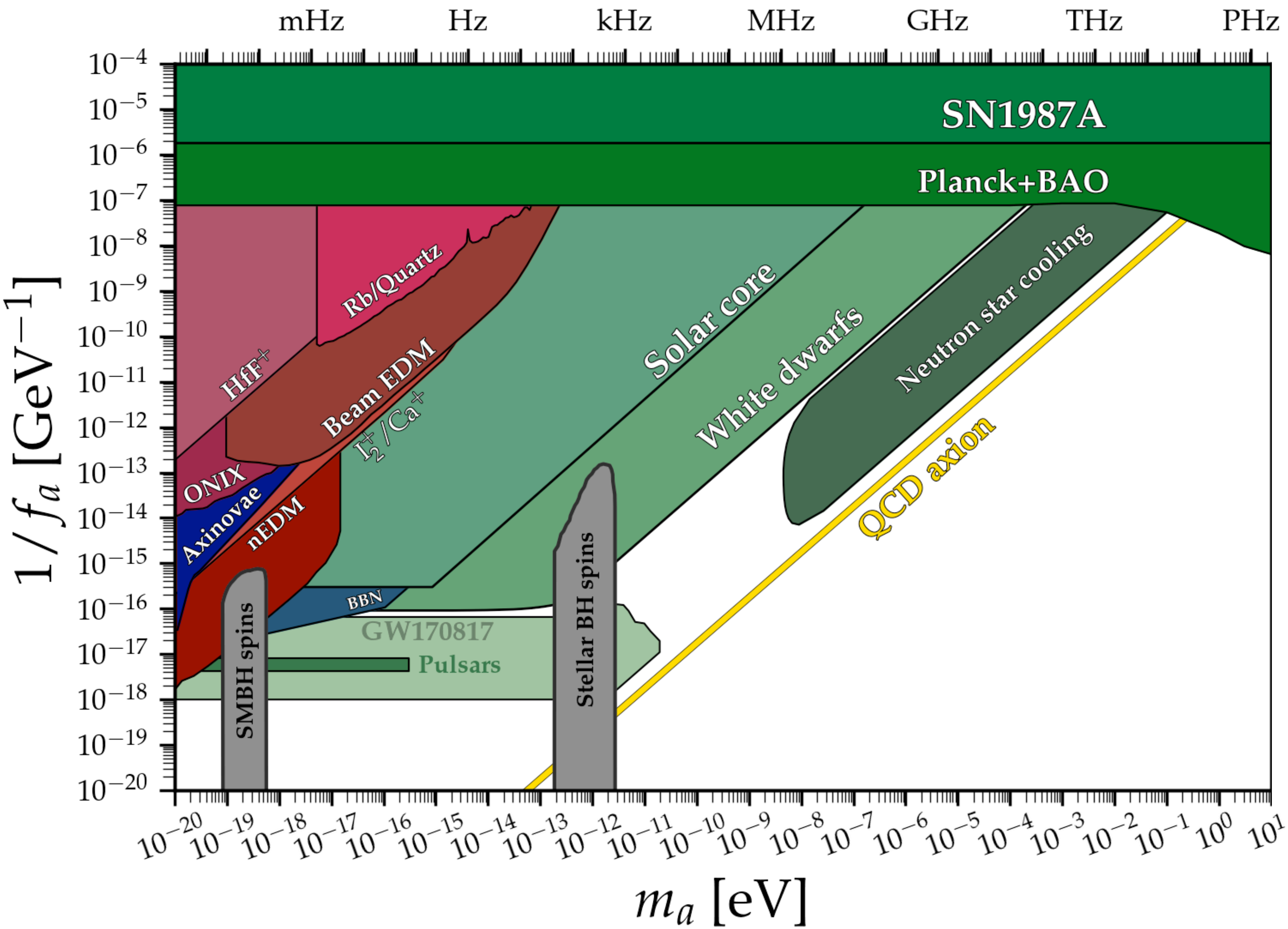
- Loose the loop-suppression compared to EDM operator

$$L_a^{\text{tree},\hat{c}_5} \simeq (4\pi)^4 L_a^{\text{EDM}} \simeq 10^4 L_a^{\text{EDM}}$$



Strong universal bound on QCD axions: $f_a > 1.1^{+0.4}_{-0.6} \times 10^8\,\text{GeV}, \quad (68\%\ \text{C.L.})$

Astrophobic axions



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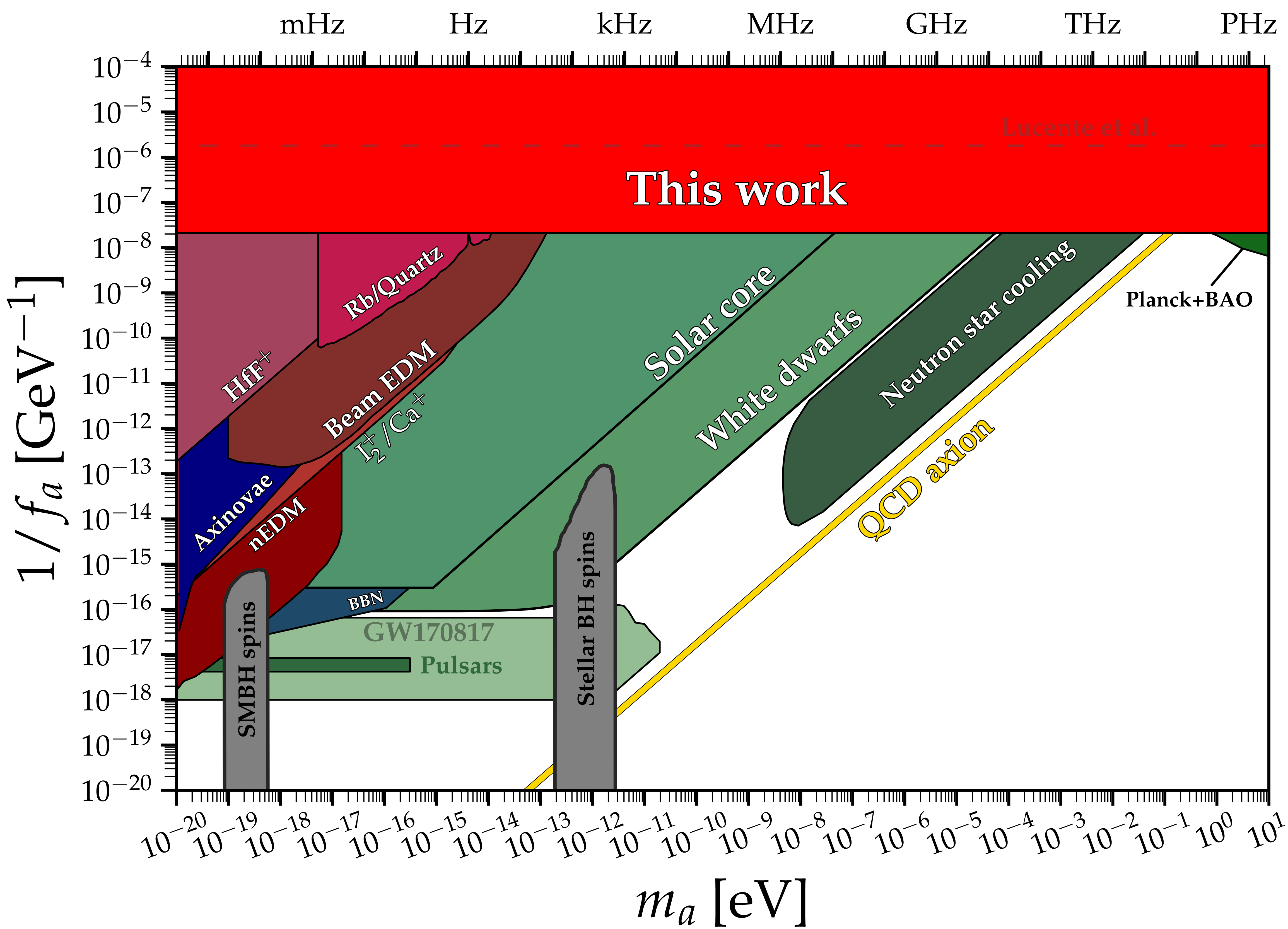

Neutron Star Cooling

High densities inside NS of $n \sim O(\mathrm{few}) n_0$

ChPT expansion breaks down at these densities!

No way to consistently calculate the axion couplings

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High densities inside NS of $n \sim O(\mathrm{few}) n_0$

ChPT expansion breaks down at these densities!

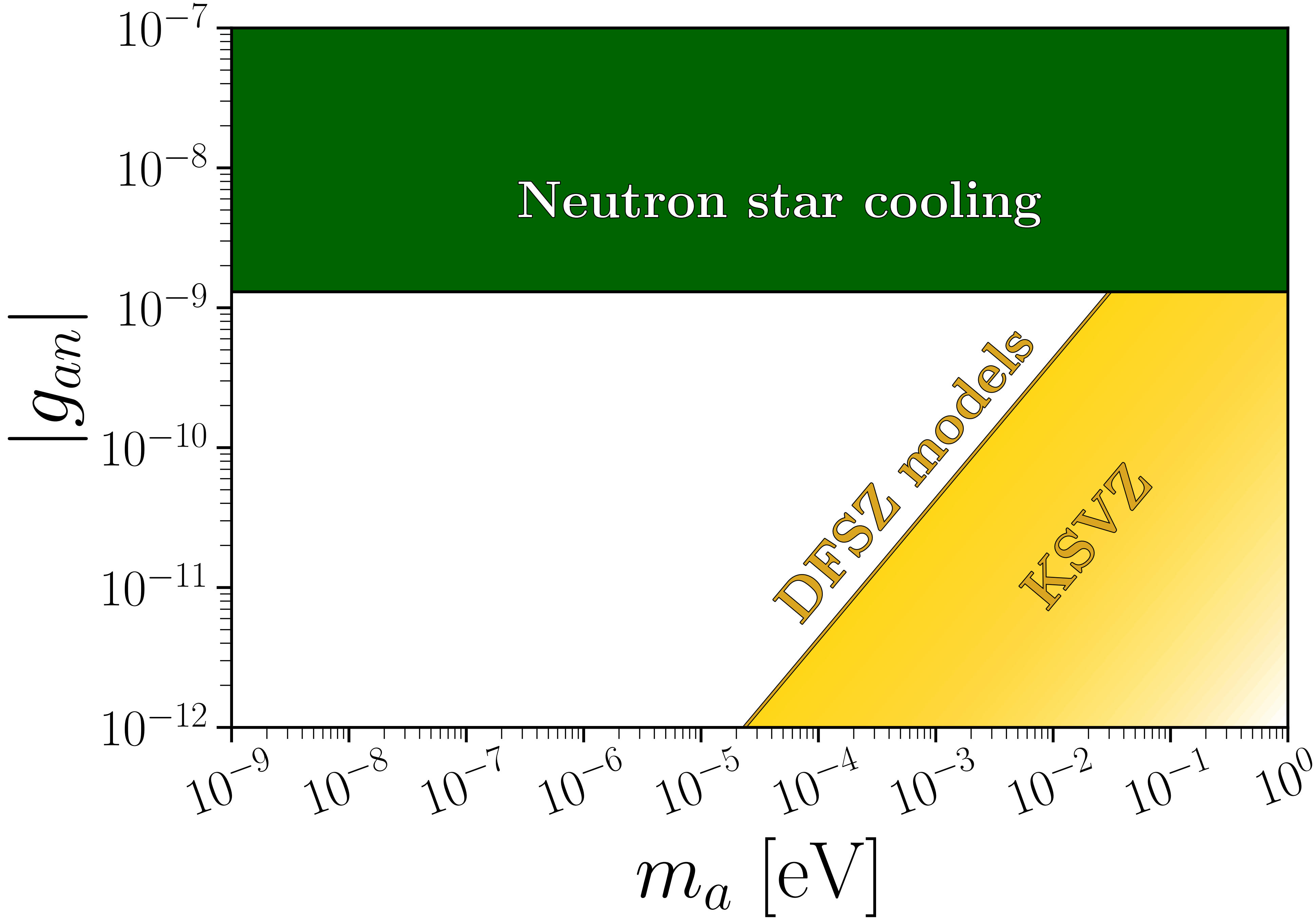
No way to consistently calculate the axion couplings

But also no reason for some to be small…

No distinction between models possible, only order of magnitude estimates

e.g. $|c_N| \sim O(0.3) \pm 0.3$

Neutron Star Cooling



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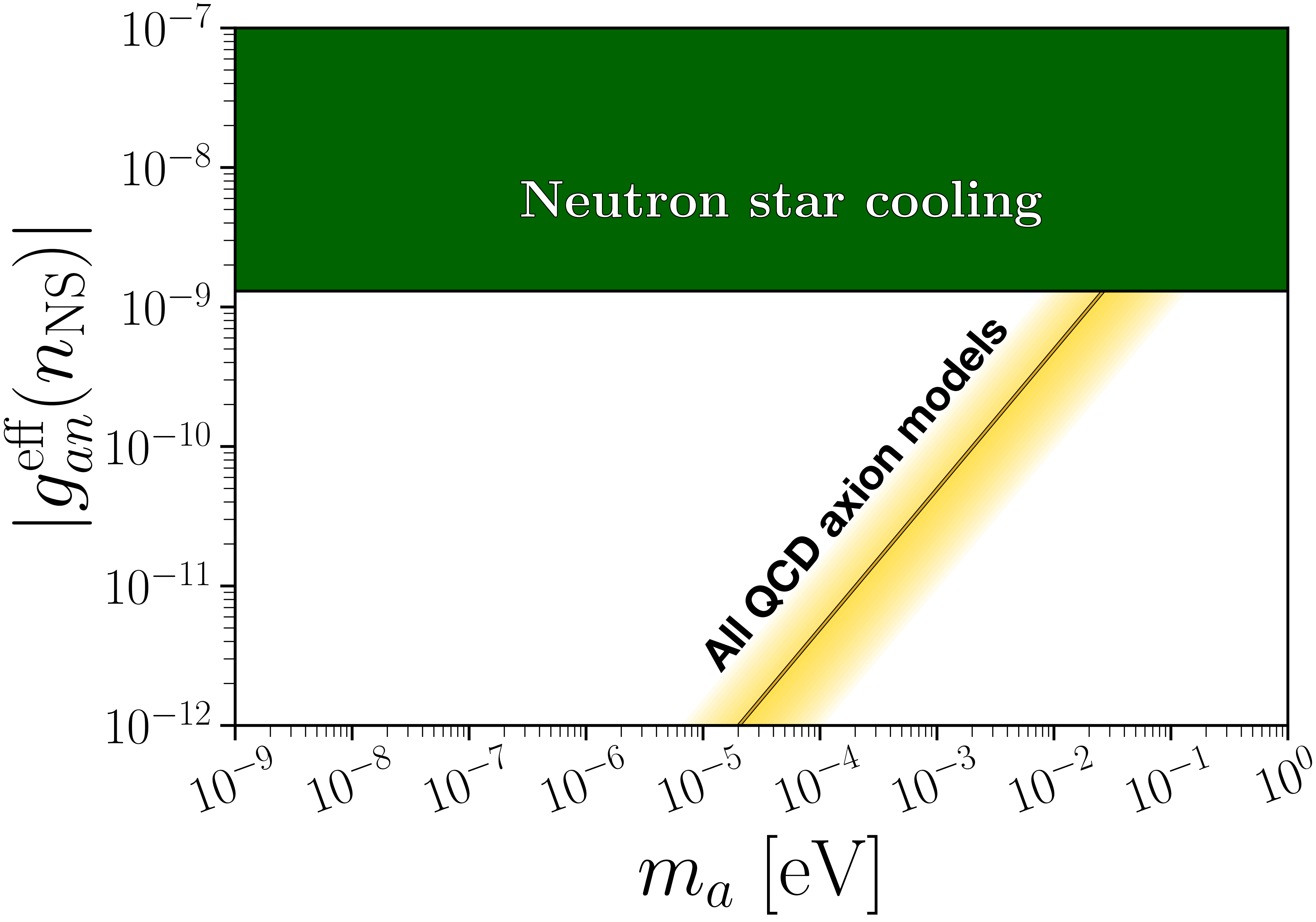
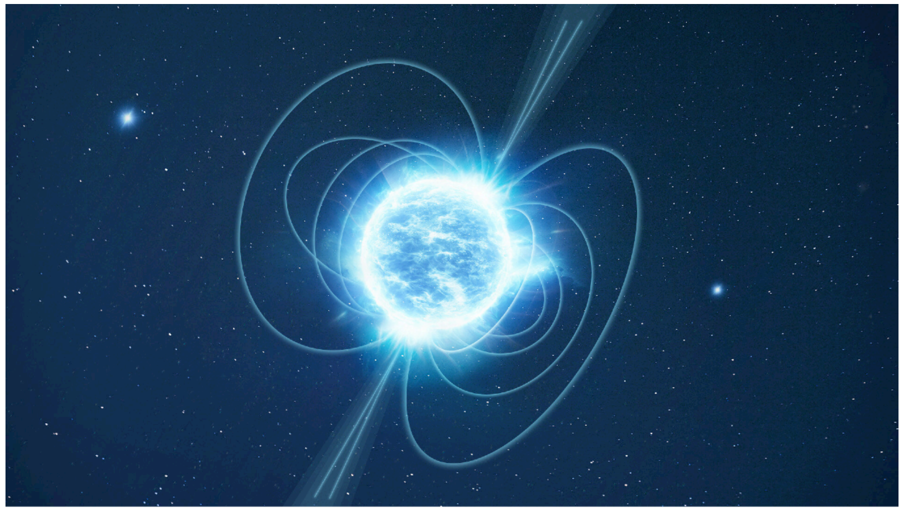
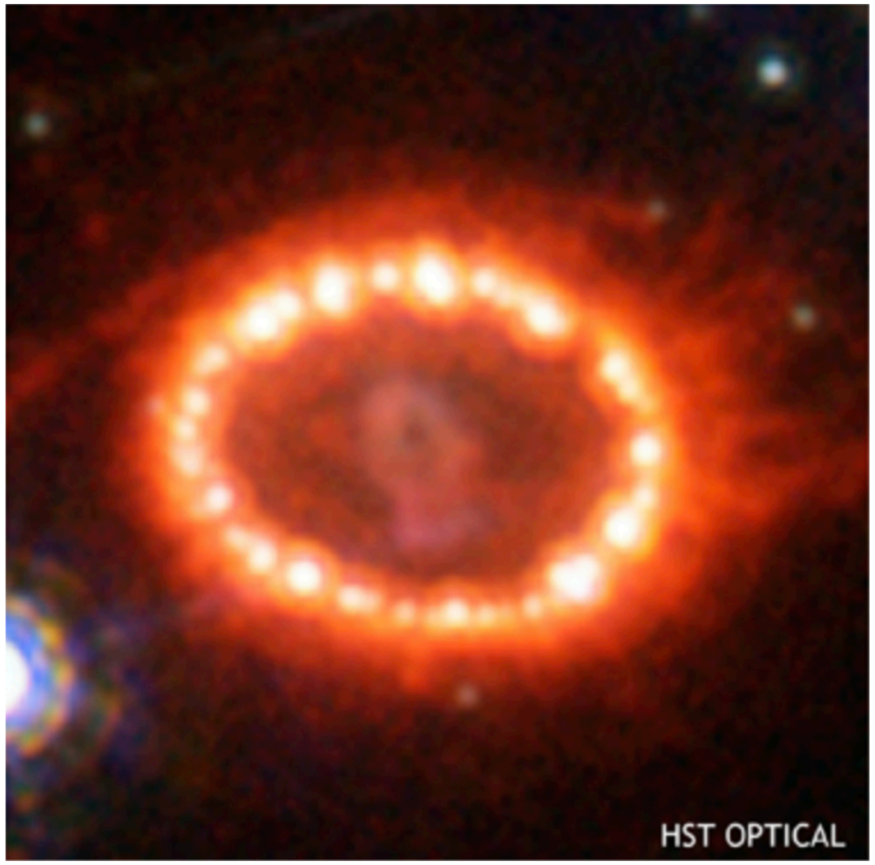


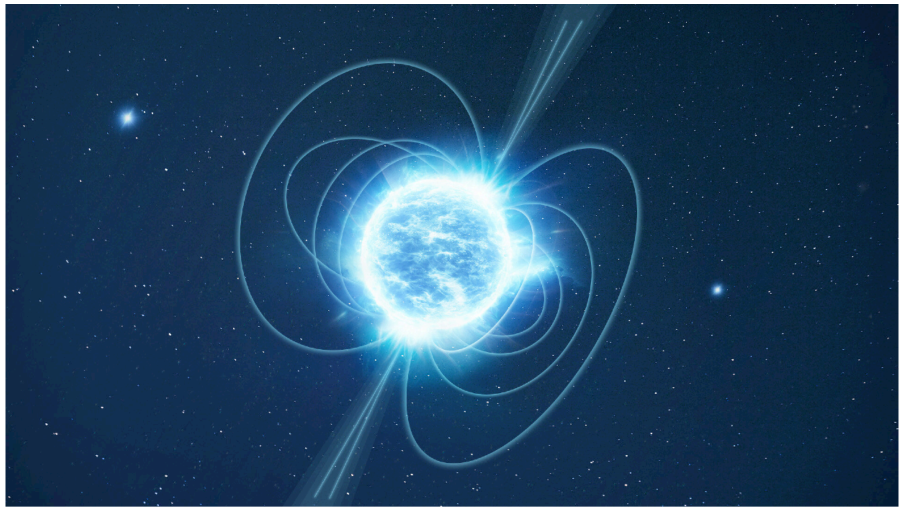
Break down of EFT, hard to distinguish models

Conclusions



- QCD axion couplings are density dependent!
- Systematic calculation of axion couplings within ChPT
- Significant changes of supernova bound
- Large uncertainty at high densities





Thank you!