Long-range axion forces and hadronic CP-violation

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arXiv: 2111.08040 [hep-ph]

Collaborators: Maxim Pospelov (U. Minnesota), Adam Ritz (U.Victoria)

E-ken Seminar @ Nagoya University

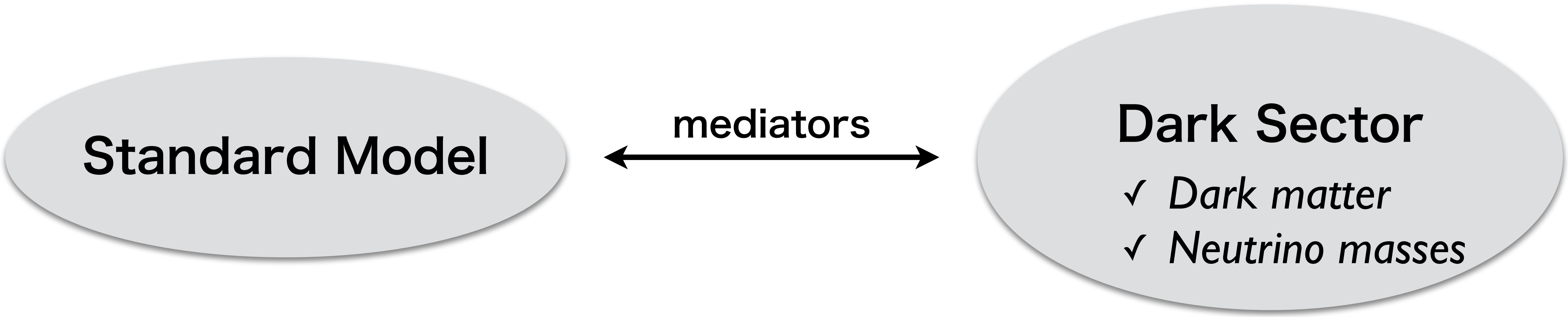
18/01/2022

ICCUB | Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA

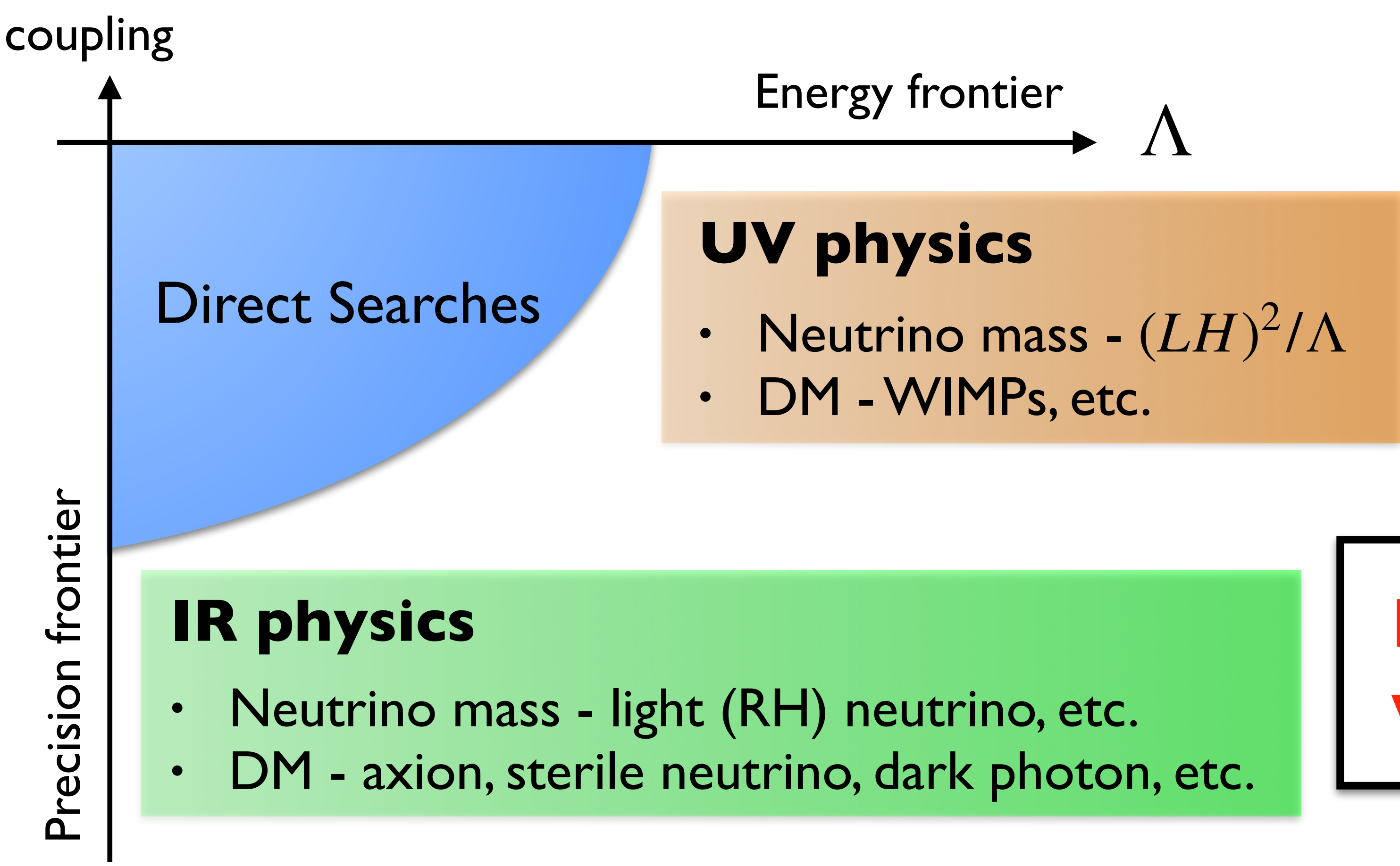
EXCELENCIA MARÍA DE MAEZTU 2020-2023

New physics in a dark sector

Empirical evidence for new physics (e.g. dark matter, neutrino mass) points to the existence of a dark sector, but not directly to its specific mass scale

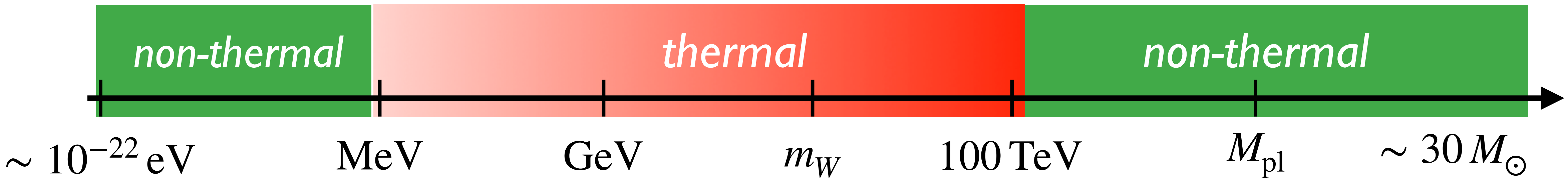


May contain light degrees of freedom, if sufficiently weakly coupled



Huge parameter space, so what guiding principle is there?

Cold Dark Matter Landscape



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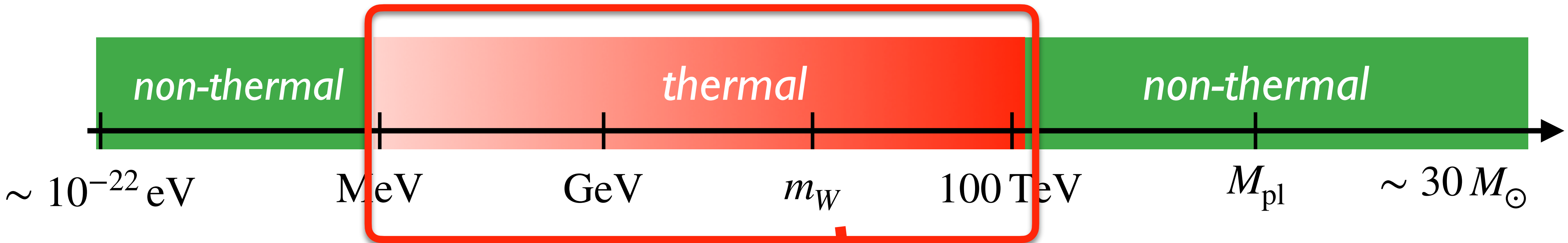
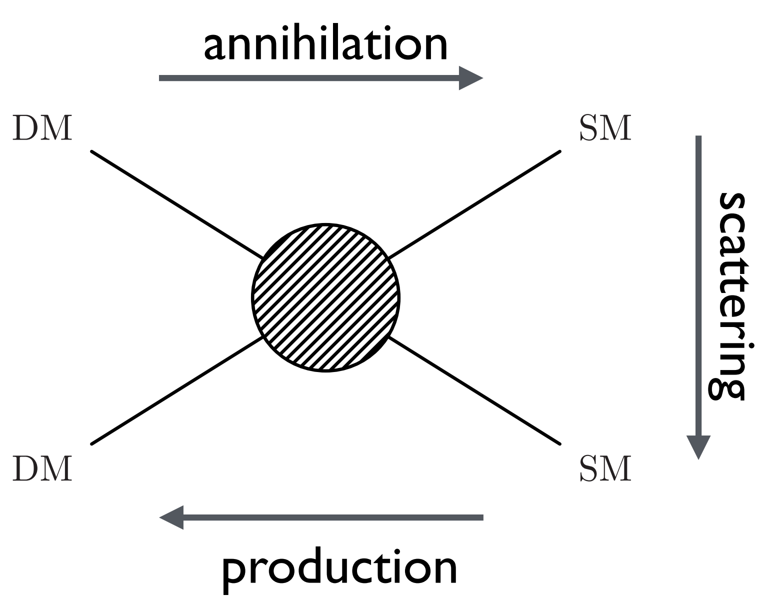
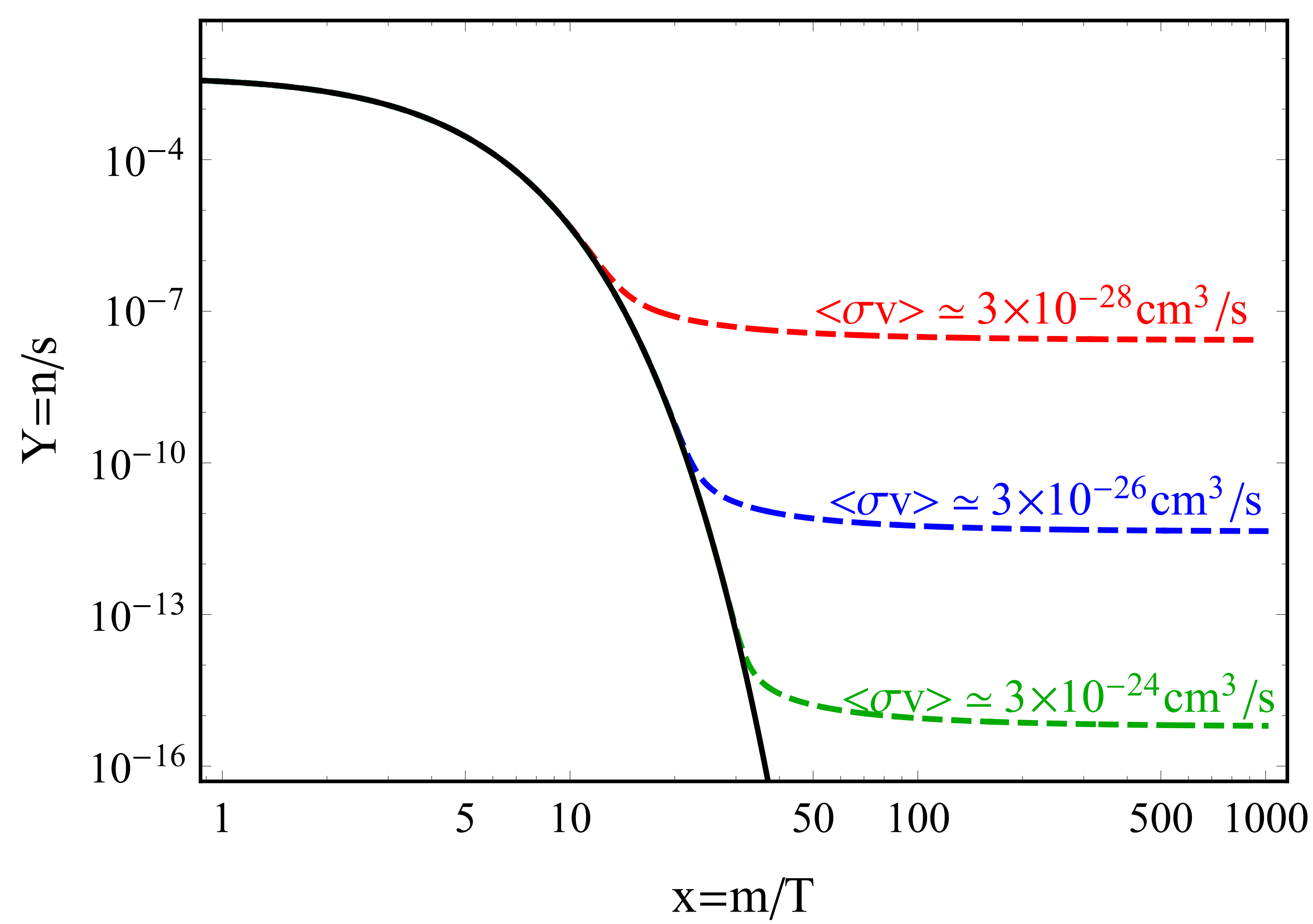


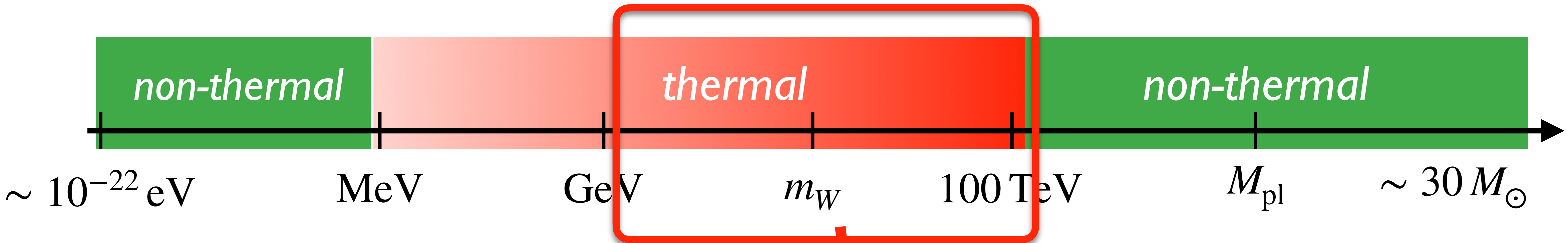
DM abundance at present is determined along with thermal evolution of the universe

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle\sigma_{\rm ann}v\rangle\left[n_{DM}^2 - (n_{DM}^{\rm eq})^2\right]$$





Cold Dark Matter Landscape



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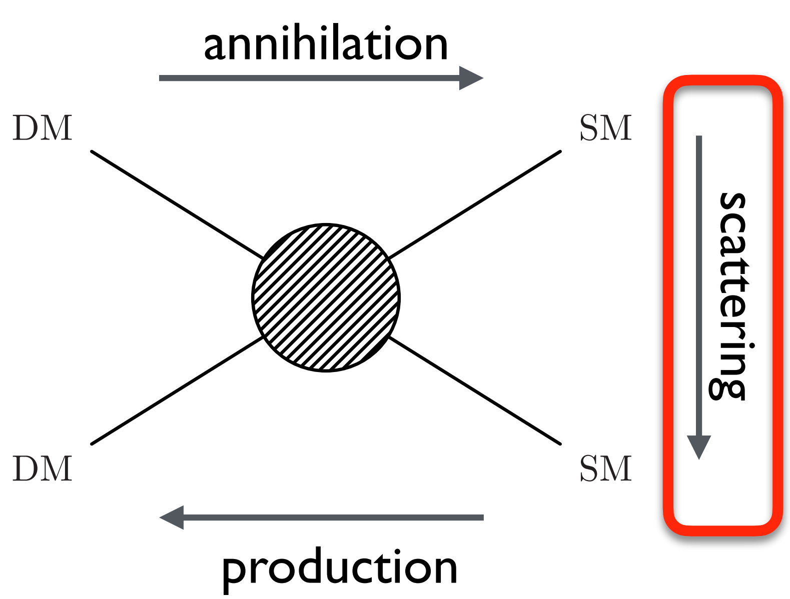
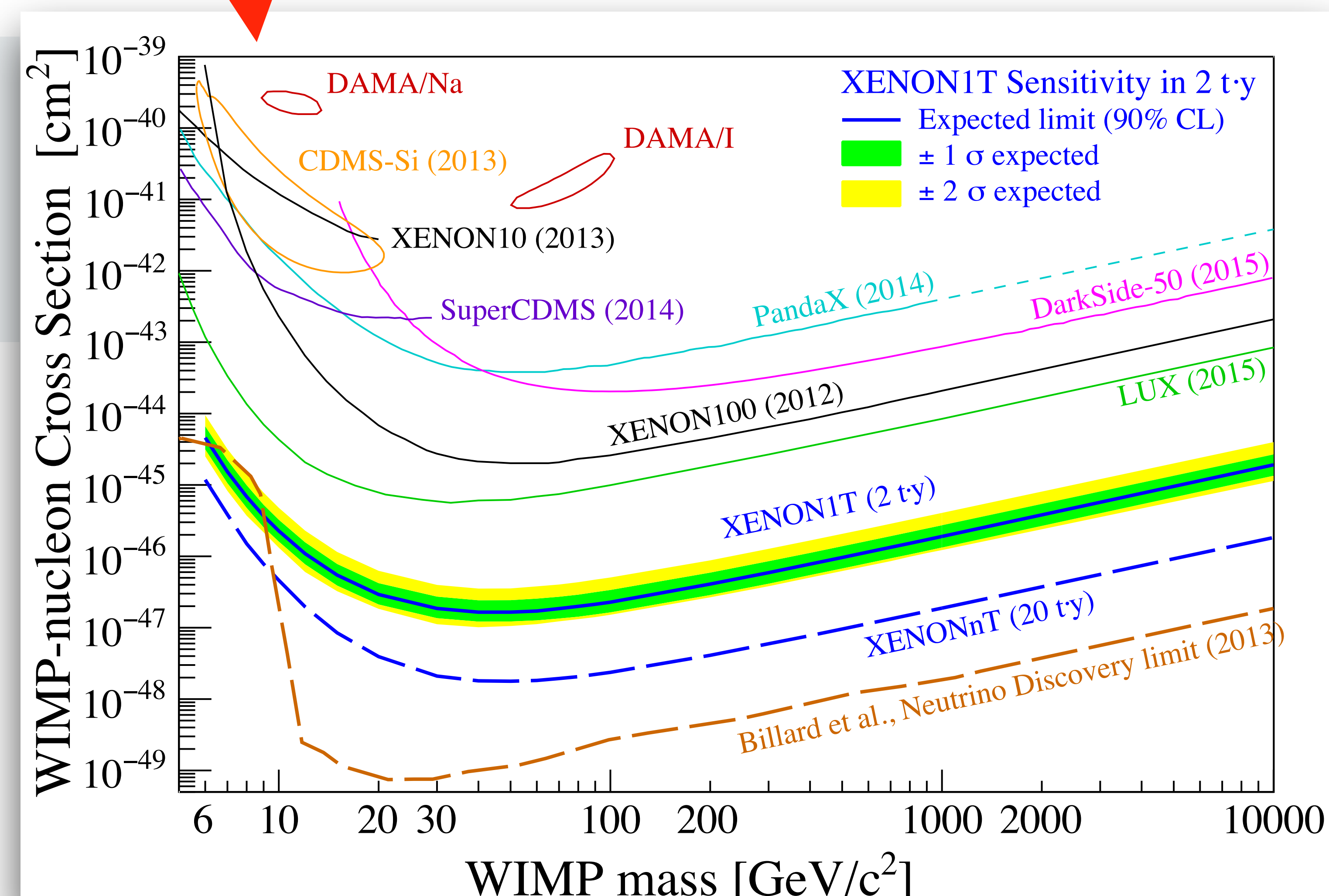
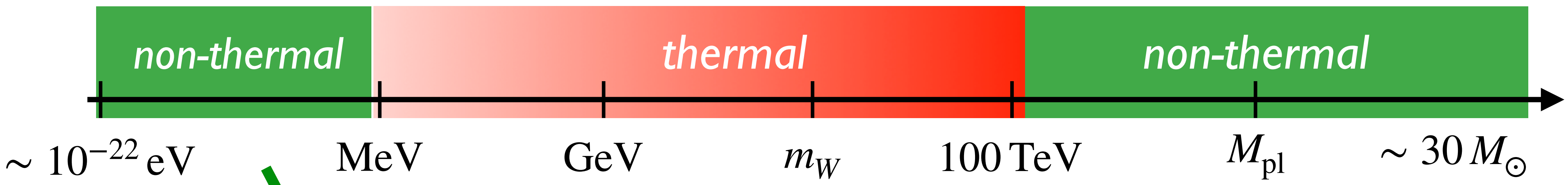
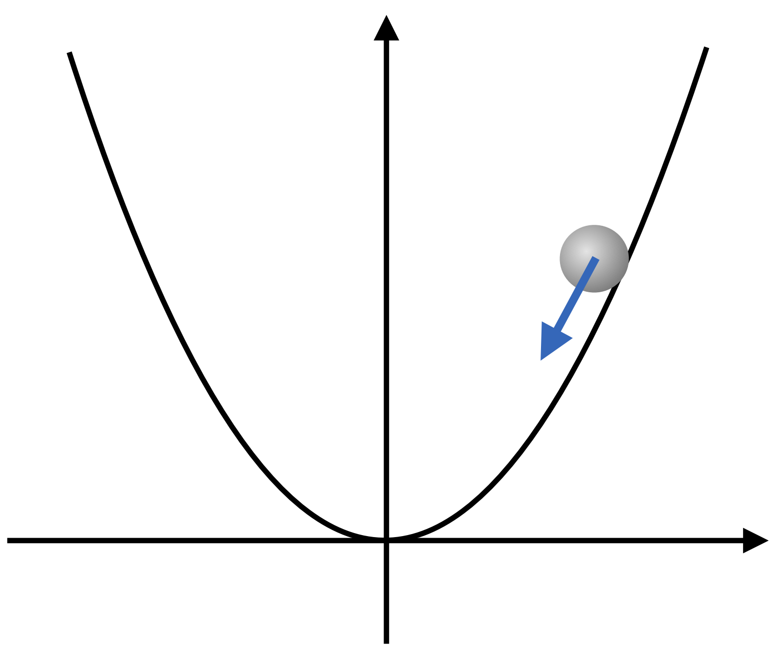




Cold Dark Matter Landscape



(ultra)light bosonic
dark matter



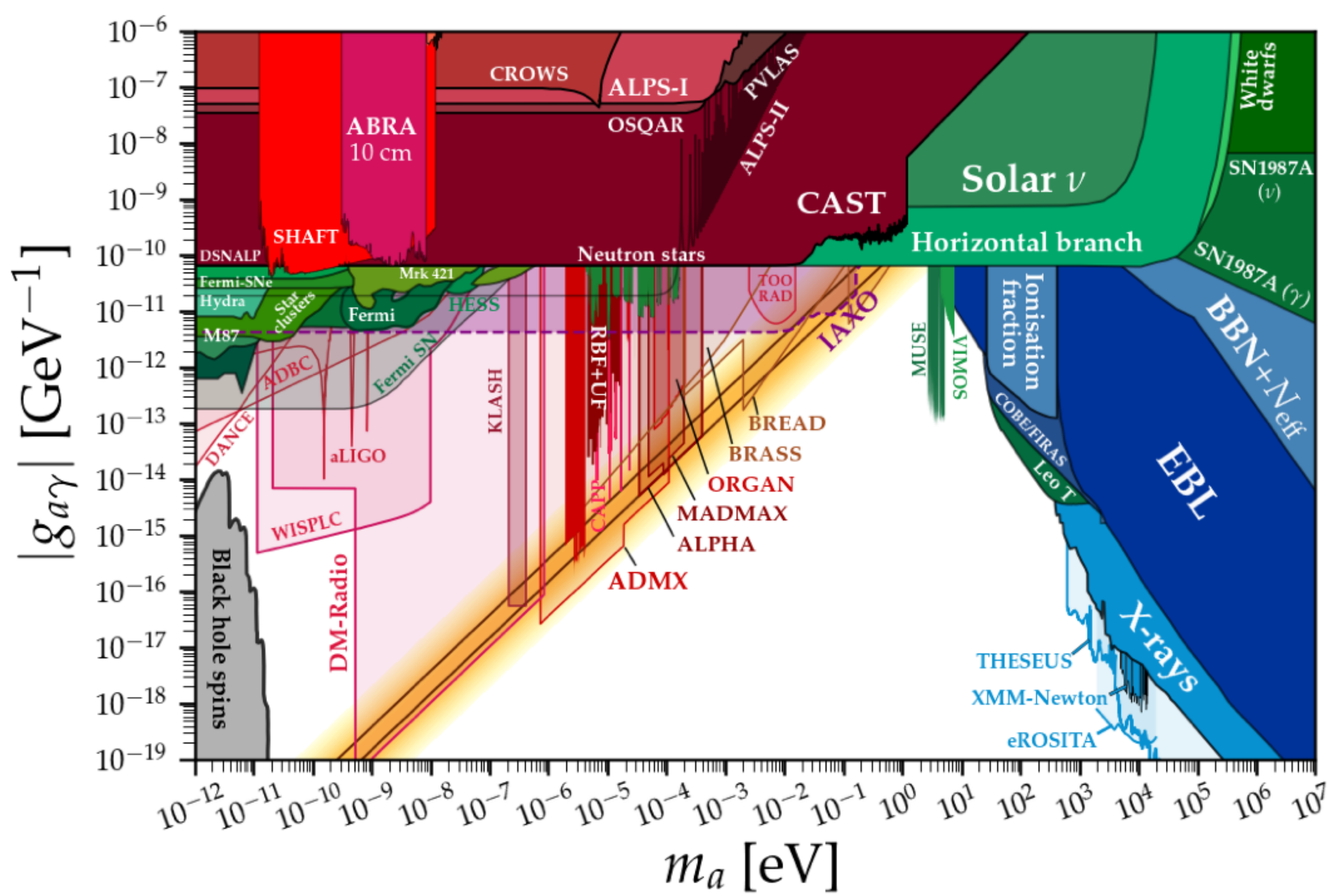


Figure from AxionLimits

Strong CP problem and axions

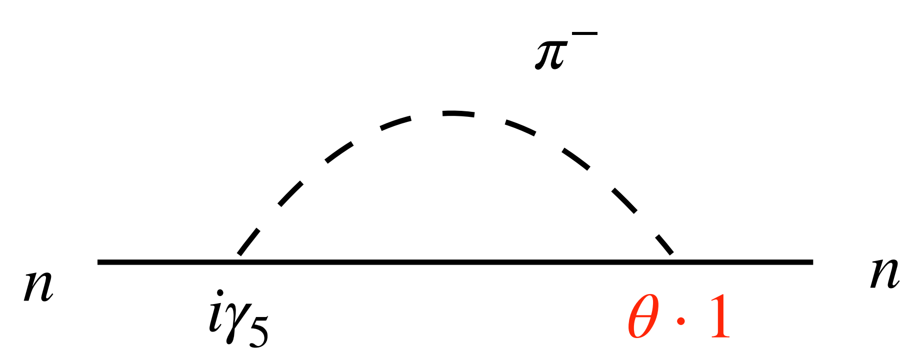
$$\mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \widetilde{G}^{\mu\nu}$$

- CP-violating effects are induced due to the QCD vacuum angle

$$\mathcal{L}_{m_q} = -m_u \bar{u}u - m_d \bar{d}d \rightarrow -m_u \bar{u}u - m_d \bar{d}d + \frac{1}{2} m_* \theta^2 \left(\frac{\bar{u}u + \bar{d}d}{2}\right) - \underline{m_* \theta (\bar{u} i\gamma_5 u + \bar{d} i \gamma_5 d)}$$

$$\boxed{q \rightarrow \exp\left(i \frac{m_*}{2m_q} \theta \gamma_5\right) q}$$

$$m_* = \left(\frac{1}{m_u} + \frac{1}{m_d} + \frac{1}{m_s}\right)^{-1} \simeq \frac{m_u m_d}{m_u + m_d}$$



$$\frac{d_n(\theta)}{e} \sim \frac{m_* \theta}{4\pi^2 F_\pi^2} \log \frac{4\pi F_\pi}{m_\pi} \sim 10^{-16} \theta \, \mathrm{cm}$$

$$\Rightarrow \quad |\theta| \lesssim 10^{-10} \qquad (|(d_n)_{\exp}| \lesssim 10^{-26} \, e\mathrm{cm})$$

- Solution: promote theta to a dynamical variable $\theta \rightarrow \theta + a/f_a$

$$\langle \theta + a/f_a \rangle = 0$$

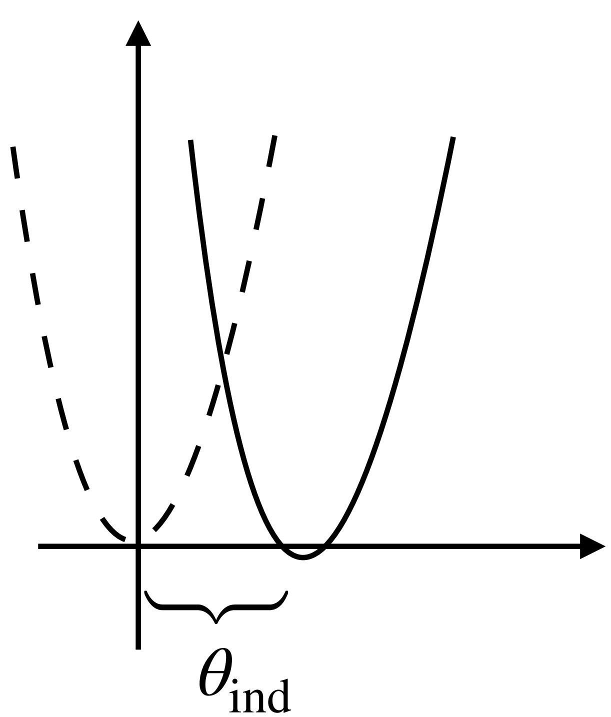
Peccei, Quinn (77)

Axions in the presence of extra CP-violation

- Let's imagine that CP-violating new physics at some high-energy scale will induce higher dimensional CP-odd operators at low scale

$$\mathcal{L}_{\rm CPV} = \Delta\theta(\delta_{\rm NP})\frac{\alpha_s}{8\pi}G\widetilde{G} - \sum_q \frac{i}{2}\widetilde{d}_q\bar{q}G\sigma\gamma_5 q + c_W(GG\widetilde{G}) + \cdots$$

- These CP-odd operators generate an additional axion potential and shift its minimum apart from $\theta = 0$ at the QCD vacuum:



$$\theta_{\rm ind} \propto \frac{\int d^4x T\langle 0|G\tilde{G}(0), \mathcal{O}_{\rm CPV}(x)|0\rangle}{\int d^4x T\langle 0|G\tilde{G}(0), G\tilde{G}(x)|0\rangle}$$

$\theta_{\rm ind}$ will regenerate EDMs and also induce novel axion-nucleon couplings

CP-violating axion-nucleon interaction

- θ_{ind} induces CP-odd axion couplings to nucleons

$$-m_u\bar{u}u - m_d\bar{d}d + \underline{\frac{1}{2}m_*\theta^2(\frac{\bar{u}u+\bar{d}d}{2})} - m_*\theta(\bar{u}i\gamma_5 u + \bar{d}i\gamma_5 d)$$

$$\theta = \theta_{\text{ind}} + \frac{a_{\text{ph}}}{f_a}$$

$$\frac{a_{\text{ph}}}{f_a} m_*\theta_{\text{ind}}\left(\frac{\bar{u}u+\bar{d}d}{2}\right) \longrightarrow \bar{g}_{aNN}\, a_{\text{ph}}\bar{N}N$$

CP-odd axion-nucleon coupling:

$$\bar{g}_{aNN} \simeq \frac{m_*\theta_{\text{ind}}}{f_a}\langle N|\bar{q}q|N\rangle$$

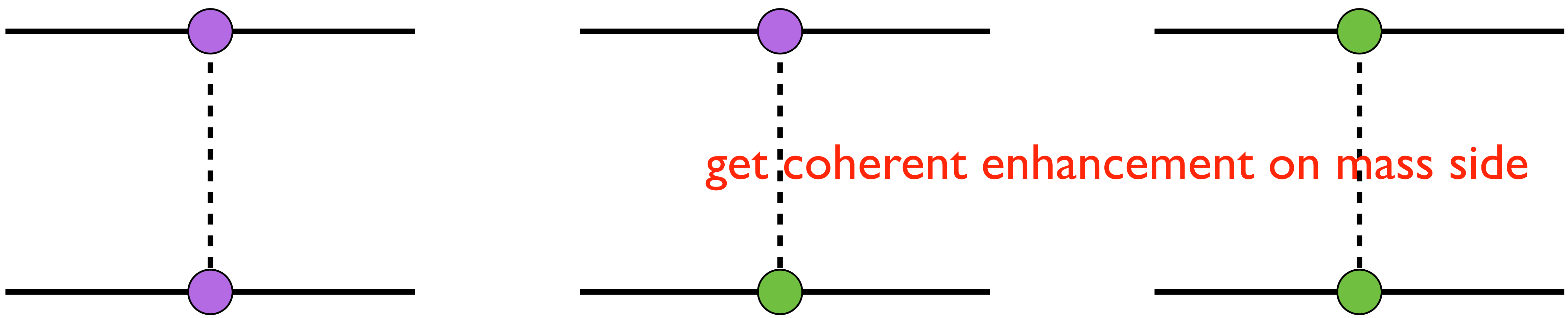
- Relative strength to the gravitational coupling:

$$\frac{\bar{g}_{aNN}}{g_{\text{grav},N}} \sim \frac{m_*\theta_{\text{ind}}/f_a}{m_N/M_{\text{pl}}} \simeq 10^{-3} \times \left(\frac{10^{10}\,\text{GeV}}{f_a}\right)\left(\frac{\theta_{\text{ind}}}{10^{-10}}\right)$$

Long-range axion forces

- Moody, Wilczek (1984), "New macroscopic forces?"

Spin-Spin | Spin-Mass | Mass-Mass



$$\frac{(g_p)^2}{m_1 m_2}\,\frac{(\vec{\sigma}_1\cdot\vec{q})(\vec{\sigma}_2\cdot\vec{q})}{\vec{q}^{\,2}+m_a^2}\qquad\qquad \frac{g_s\,g_p}{m_1}\,\frac{(\vec{\sigma}_1\cdot\vec{q})}{\vec{q}^{\,2}+m_a^2}\qquad\qquad \frac{(g_s)^2}{\vec{q}^{\,2}+m_a^2}$$

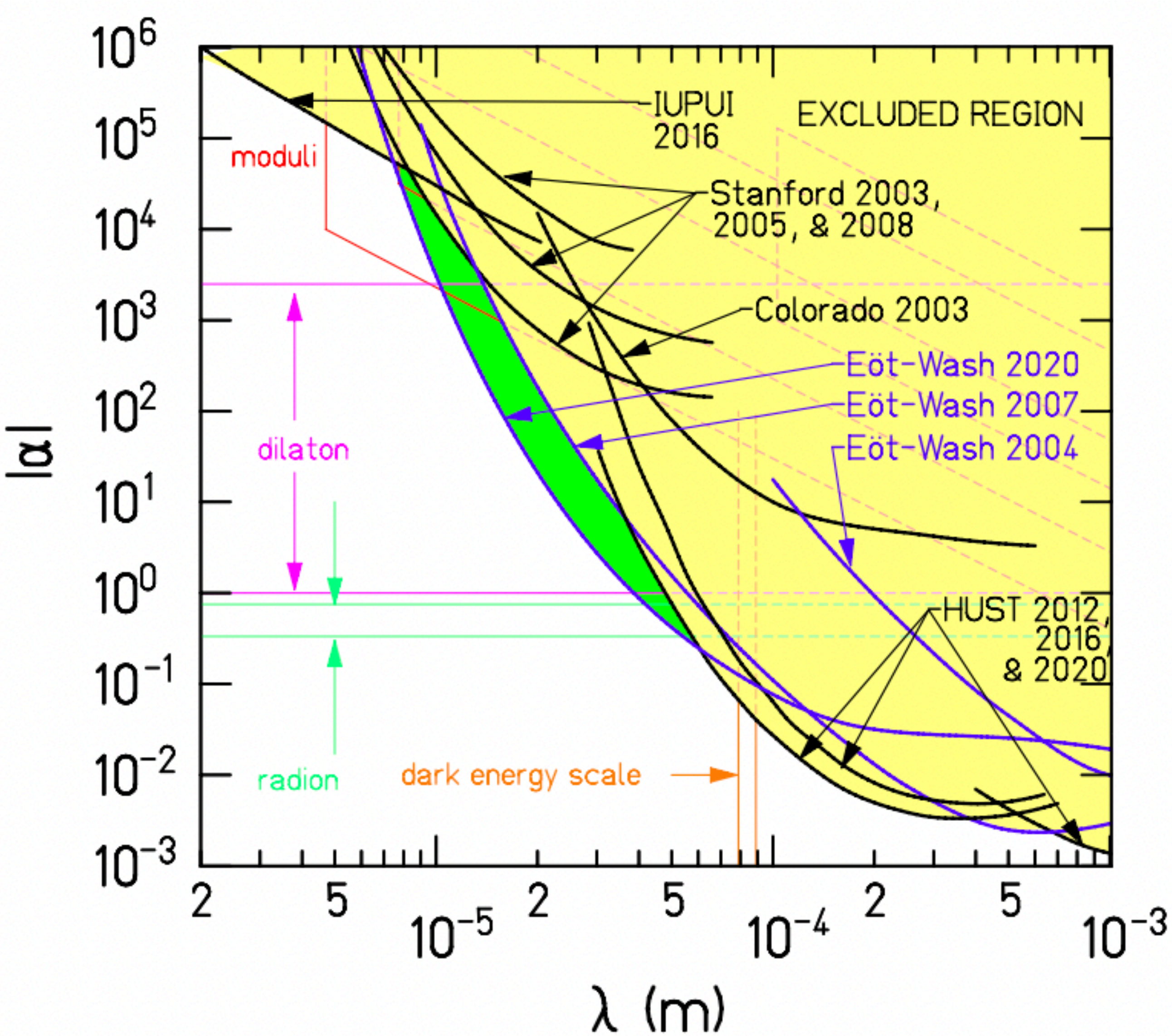
$m_a \sim \mu\mathrm{eV}$ corresponds to 20cm

- CP-even axion-nucleon coupling $g_p\, a\bar{N}i\gamma_5 N$
- CP-odd axion-nucleon coupling $g_s\, a\bar{N}N$

Detection of axion forces

■ Tests of the gravitational inverse-square law

Eöt-Wash group, U. Washington (2020)

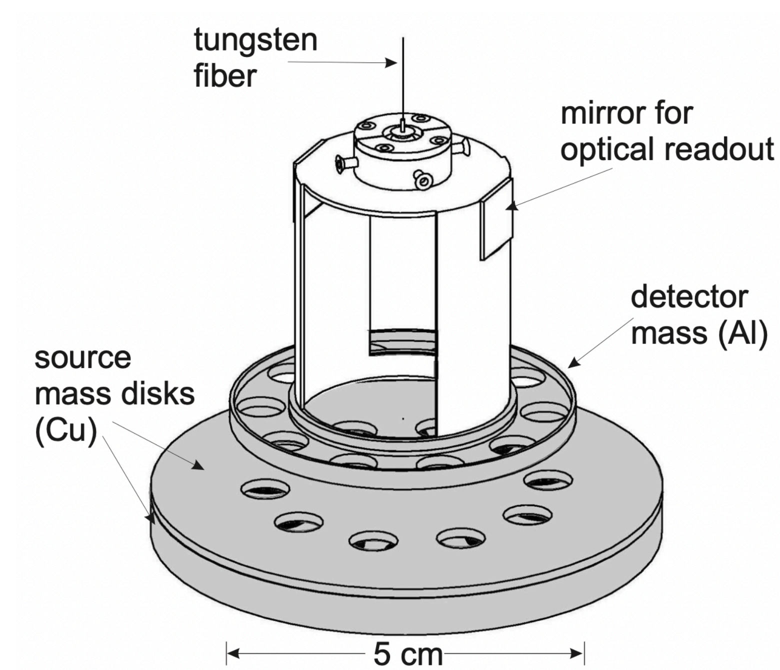


QCD axion predicts $\alpha \lesssim 10^{-3}$ with $\lambda \sim 10^{-4}\,\mathrm{m}$

- Mass-mass interaction creates the extra yukawa-type potential:

$$V(r) = -\frac{G_N m_1 m_2}{r}\left(1 + \alpha\, e^{-r/\lambda}\right)$$

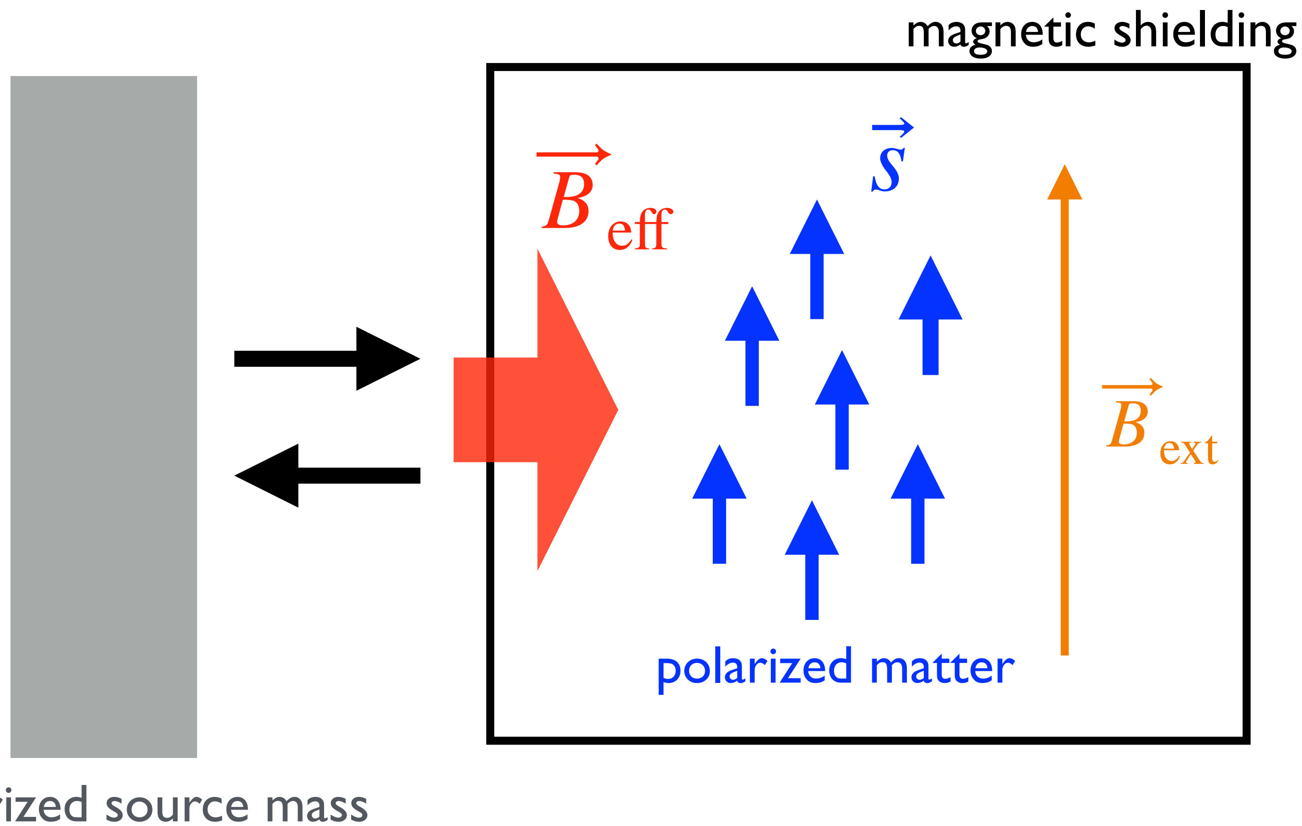
- This new potential can be probed with torsion oscillators



Searching for coherent mass-spin interaction using a resonant technique

$$V(\vec{r}) = \frac{g_s g_p}{8\pi m_f}\left(\frac{1}{r\lambda_a} + \frac{1}{r^2}\right) e^{-r/\lambda_a} (\vec{\sigma} \cdot \vec{r}) \equiv \vec{\mu} \cdot \vec{B}_{\mathrm{eff}}$$

- acts as an effective magnetic field
- but not couple to ordinary angular momentum
- not screened by magnetic shielding



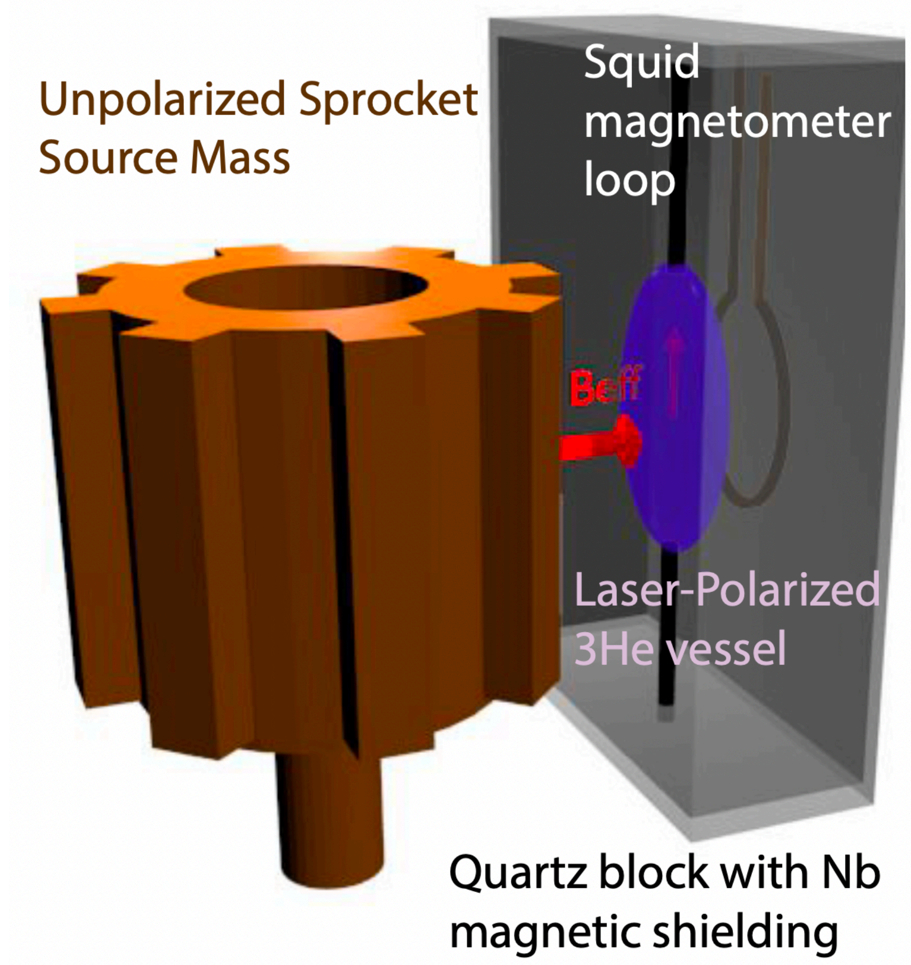
Periodically repeated moving-on and off will induce an NMR effect in the polarized medium in the absence of the actual oscillating magnetic field

Future long-range force experiments

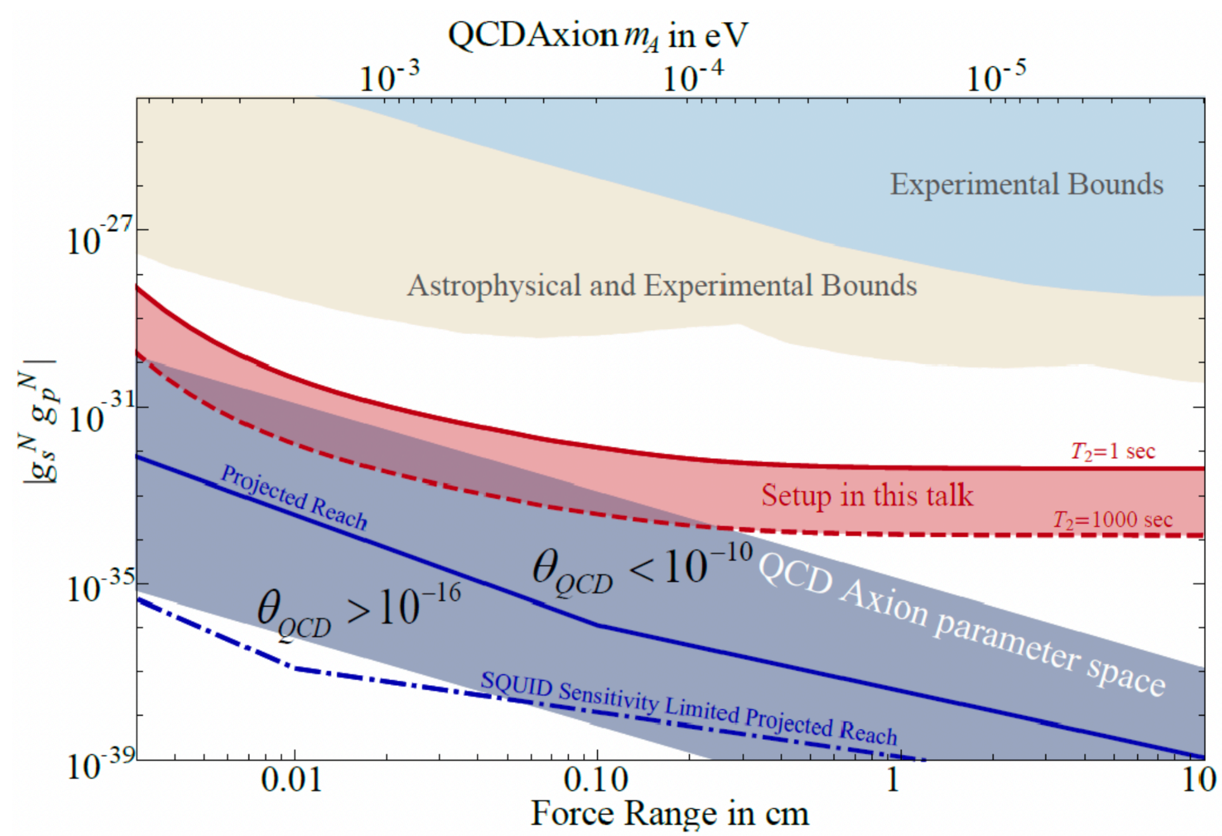
Resonant detection of axion mediated forces with Nuclear Magnetic Resonance

Asimina Arvanitaki[1], Andrew A. Geraci[2]
[1] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2L 2Y5, Canada and*
[2] *Department of Physics, University of Nevada, Reno, NV 89557, USA*
(Dated: March 7, 2014)

■ <u>ARIADNE (Northwestern U)</u>



- The NMR technique will improve the sensitivity by several orders of magnitude!
- Many challenges: miniaturization, vibration noises, magnetic gradients, magnetic shielding, etc.



Two topics today

It's good timing to revisit the CP-violating axion-nucleon couplings $\bar{g}_{aNN}$ from various CP-violating sources in the SM and beyond

- $\bar{g}_{aNN}$ from a generic CP violation in BSM models

  Revisit $\bar{g}_{aNN}$ from higher dimensional CP violating operators and update the value

- $\bar{g}_{aNN}$ from the CKM phase of the SM

  Revisit $\bar{g}_{aNN}$ due to the CKM phase, and give a more quantitative estimate than a classical estimate given by Georgi, Randall (1986)

Contents

- ☑ Introduction
- ☐ $\bar{g}_{aNN}$ from CP violation in BSM models
  1. quark CEDMs
  2. quark EDMs
- ☐ $\bar{g}_{aNN}$ from the CKM phase of the SM
- ☐ Summary

General remarks

- We are interested in non-derivative couplings of axions to nucleons $a\bar{N}N$ not derivative ones $(\partial^2 a)\bar{N}N$

- There are two couplings in general:

$$\mathcal{L} = -\bar{g}^{(0)}_{aNN}\, a\bar{N}N - \bar{g}^{(1)}_{aNN}\, a\bar{N}\tau^3 N \qquad\qquad N = (p, n)^T$$

  but we only keep the iso-singlet part $\bar{g}^{(0)}_{aNN}$ which leads to enhancement by the number of nucleons in nuclei. Simply drop the superscript (0).

- There are two contributions in general: (i) direct contribution, (ii) indirect contribution via a shift of the theta parameter $\theta_{\rm ind}$

  - axion potential: $V_a = \frac{1}{2} m_a^2 (a - f_a \theta_{\rm ind})^2$
  - physical axion: $a_{\rm ph} = a - \langle a \rangle;\ \theta = \frac{a}{f_a} = \theta_{\rm ind} + \frac{a_{\rm ph}}{f_a}$

$$\left.\begin{array}{l} V_a = \frac{1}{2} m_a^2 (a - f_a \theta_{\rm ind})^2 \\ a_{\rm ph} = a - \langle a \rangle;\ \theta = \frac{a}{f_a} = \theta_{\rm ind} + \frac{a_{\rm ph}}{f_a} \end{array}\right\} \longrightarrow \bar{g}_{aNN}\, a_{\rm ph} \bar{N}N$$

$\bar{g}_{aNN}$ from CP violation in BSM models

Extra CP-violation from new physics

- CP-odd higher dim. operators of our interest are

$$\mathcal{L}_{\mathrm{CEDM}} = -\sum_q \frac{i}{2} \tilde{d}_q \bar{q} G_{\mu\nu} \sigma^{\mu\nu} \gamma_5 q$$

$$\mathcal{L}_{\mathrm{EDM}} = -\sum_q \frac{i}{2} d_q \bar{q} F_{\mu\nu} \sigma^{\mu\nu} \gamma_5 q$$

For other sources, see e.g. Bertolini, Luzio, Nesti, 2006.12508

Step-by-step evaluation of $\bar{g}_{aNN}(\tilde{d}_q)$

1. Concentrate on the up and down quarks — Barbieri, Romanino, Strumia (96); Pospelov (98)

$$\mathcal{L}_4 = -m_u \bar{u}u - m_d \bar{d}d + \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$$\mathcal{L}_{\rm CEDM} = -\frac{i}{2}\tilde{d}_u \bar{u} G_{\mu\nu}\sigma^{\mu\nu}\gamma_5 u - \frac{i}{2}\tilde{d}_d \bar{d} G_{\mu\nu}\sigma^{\mu\nu}\gamma_5 d$$

2. Perform a chiral rotation to remove the $G\tilde{G}$ term

$$\boxed{u \to e^{i\frac{\theta_u}{2}\gamma_5}u, \quad d \to e^{i\frac{\theta_d}{2}\gamma_5}d\,; \quad \theta_q = \frac{m_*}{m_q}\theta \quad (\theta_u + \theta_d = \theta)}$$

$$\mathcal{L}_4 \to -m_u \bar{u}u - m_d \bar{d}d + \frac{1}{2}m_*\theta^2\left(\frac{\bar{u}u + \bar{d}d}{2}\right)$$
$$+\frac{1}{2}m_*\theta^2 \frac{m_d - m_u}{m_d + m_u}\left(\frac{\bar{u}u - \bar{d}d}{2}\right) - m_*\theta\left(\bar{u}i\gamma_5 u + \bar{d}i\gamma_5 d\right) + (\text{higher oders of } \theta)$$

$$\mathcal{L}_{\rm CEDM} \to \mathcal{L}_{\rm CEDM} + m_*\theta\left(\frac{\tilde{d}_u}{2m_u}\bar{u}G\sigma u + \frac{\tilde{d}_d}{2m_d}\bar{d}G\sigma d\right)$$

Step-by-step evaluation of $\bar{g}_{aNN}(\tilde{d}_q)$ (contd.)

3. Eliminate the π^0 tadpole by an additional chiral rotation

$$u \to e^{i\frac{\theta'_u}{2}\gamma_5}u, \quad d \to e^{i\frac{\theta'_d}{2}\gamma_5}d; \quad \theta'_u + \theta'_d = 0$$

$$\left\langle 0 \left| -\sum_q \frac{i}{2}\widetilde{d}_q \bar{q} G\sigma\gamma_5 q - \sum_q \theta'_q m_q \bar{q} i\gamma_5 q \right| \pi^0 \right\rangle = 0$$

$$\Rightarrow \quad \theta'_u = -\frac{\widetilde{d}_u - \widetilde{d}_d}{2(m_u + m_d)} \frac{\langle 0|\sum_q \bar{q}G\sigma q|0\rangle}{\langle 0|\sum_q \bar{q}q|0\rangle}$$

The resulting Lagrangian takes the form

$$\mathcal{L} = -\sum_q m_q \bar{q}q + \frac{1}{2}\theta^2 m_* \left(\frac{u\bar{u} + d\bar{d}}{2}\right) + \frac{1}{2}m_*\theta\left(\frac{\tilde{d}_u}{m_u}\bar{u}G\sigma u + \frac{\tilde{d}_d}{m_d}\bar{d}G\sigma d\right)$$
$$+ \frac{1}{2}m_*\theta^2 \frac{m_d - m_u}{m_d + m_u}\left(\frac{\bar{u}u - \bar{d}d}{2}\right) + m_*\theta\theta'_u\left(\frac{\bar{u}u - \bar{d}d}{2}\right) + \mathcal{L}_{\text{with }\gamma_5}$$

Step-by-step evaluation of $\bar{g}_{aNN}(\tilde{d}_q)$ (contd.)

4. Project on the iso-singlet part and find the minimum of theta

$$\mathcal{L}_{\text{iso-singlet}} = \frac{1}{2}\theta^2 m_* \left(\frac{u\bar{u} + d\bar{d}}{2}\right) + \frac{1}{2}m_*\theta\left(\sum_q \frac{\tilde{d}_q}{m_q}\right)\left(\frac{\bar{u}G\sigma u + \bar{d}G\sigma d}{2}\right)$$

$$\Rightarrow \quad \boxed{\theta_{\text{ind}} = -\frac{m_0^2}{2}\sum_q \frac{\tilde{d}_q}{m_q}} \qquad m_0^2 = \frac{\langle 0|\bar{q}G\sigma q|0\rangle}{\langle 0|\bar{q}q|0\rangle} \sim 0.8\,\text{GeV}^2$$

5. Expand $\theta = \theta_{\text{ind}} + a_{\text{ph}}/f_a$ and retain the linear terms in a_{ph}

$$\begin{aligned}\bar{g}_{aNN} \times f_a &= \left\langle N \left| \partial\mathcal{L}_{\text{iso-singlet}}/\partial\theta|_{\theta=\theta_{\text{ind}}} \right| N \right\rangle \\ &= \frac{1}{2}m_*\left(\frac{\tilde{d}_u}{m_u} + \frac{\tilde{d}_d}{m_d}\right)\left\langle N \left| \underbrace{\frac{\bar{u}G\sigma u + \bar{d}G\sigma d}{2}}_{\text{direct contribution from } \tilde{d}_q} - \underbrace{m_0^2\frac{u\bar{u} + d\bar{d}}{2}}_{\text{indirect contribution from } \theta_{\text{ind}}} \right| N \right\rangle\end{aligned}$$

6. Cross-check by replacing $|N\rangle \to |0\rangle$. The result gives the scalar tadpole, so should be vanishing.

Estimated size of $\bar{g}_{aNN}(\tilde{d}_q)$

- Let's see the numerical value of the estimated axion-nucleon coupling
- For the hadronic matrix elements, we use previous QCD sum rule evaluation

$$\langle N| \sum_q \frac{\bar{q}q}{2} - m_0^2 \frac{\bar{q}G\sigma q}{2} |N\rangle \simeq 0.6\,\mathrm{GeV}^2$$

Pospelov (2001)

$$\bar{g}_{aNN}(\tilde{d}_q) \simeq 1.5 \times 10^{-23} \left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right) \underline{\left(\frac{\sum_q \frac{m_* \tilde{d}_q}{m_q}}{10^{-26}\,\mathrm{cm}}\right)}$$

normalized by a quark-CEDM limit from the neutron and ^{199}Hg EDM constraints

CP-even coupling: $g_{aNN} \sim C_N \frac{m_N}{f_a}$

$$g_{aNN}\bar{g}_{aNN}(\tilde{d}_q)|_{\max} \sim 10^{-33} \left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right)^2$$

Within the reach of ARIADNE!

$\bar{g}_{aNN}$ from quark EDMs

$$\mathcal{L}_{\rm EDM} = -\sum_q \frac{i}{2} d_q \bar{q} F_{\mu\nu}\sigma^{\mu\nu}\gamma_5 q \longrightarrow \mathcal{L}_{\rm EDM} + \frac{m_* \theta}{2}\sum_q \frac{d_q}{m_q}\bar{q}F_{\mu\nu}\sigma^{\mu\nu} q$$

Under the chiral rotation
to remove the $G\tilde{G}$ term

- Magnetic susceptibility of the QCD vacuum:

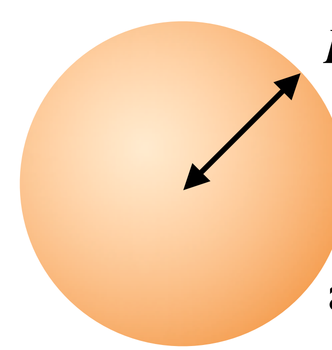
$$\langle \bar{q}\sigma_{\mu\nu} q\rangle_F \equiv F_{\mu\nu} \times \chi Q_q e \langle \bar{q} q\rangle \qquad \text{with} \qquad \chi = -\frac{3}{4\pi^2 F_\pi^2}$$

Vainshtein (2003)

- Axion coupling to the EM field strength:

$$\frac{a}{2f_a}\underline{(eF_{\mu\nu})^2} \times \chi \langle \bar{q} q\rangle \times \sum_q \frac{m_* Q_q d_q}{m_q e}$$

For a large nucleus, $\displaystyle\int d^3x (eF_{\mu\nu})^2 \simeq -\frac{48\pi}{5}\frac{(Z\alpha)^2}{R_N}$



$R_N \simeq 1.2\,\mathrm{fm} \times A^{1/3}$

nucleus (A, Z) with
a constant charge density

Numerical value of the EDM-induced $\bar{g}_{aNN}$

- Combining the pieces, we find an effective axion coupling *per nucleon*

$$\bar{g}_{aNN}^{\rm eff} \simeq \frac{1}{f_a}\frac{18(Z\alpha)^2\langle\bar{q}q\rangle}{5\pi A F_\pi^2 R_N}\sum_q \frac{m_* Q_q d_q}{m_q e}$$

$$\simeq 5\times 10^{-27}\left(\frac{10^{10}\,{\rm GeV}}{f_a}\right)\left(\frac{\sum_q \frac{m_* Q_q d_q}{m_q e}}{10^{-26}\,{\rm cm}}\right) \qquad (Z\simeq A/2=50)$$

- Much smaller value compared to the CEDM-induced one

$$\bar{g}_{aNN}(\widetilde{d}_q) \simeq 1.5\times 10^{-23}\left(\frac{10^{10}\,{\rm GeV}}{f_a}\right)\left(\frac{\sum_q \frac{m_* \widetilde{d}_q}{m_q}}{10^{-26}\,{\rm cm}}\right)$$

  - ✓ More important contribution via their operator mixing with CEDMs
  - ✓ The same could apply to dim-6 Weinberg operator

$\bar{g}_{aNN}$ from the CKM phase

$\bar{g}_{aNN}$ from the CKM phase δ of the SM

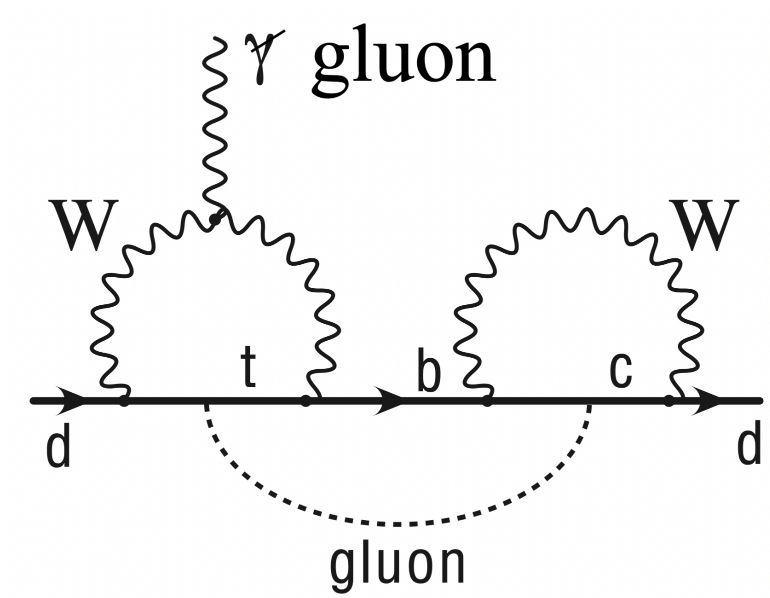
- Estimate on the naive dimensional analysis

$$\bar{g}_{aNN}(\delta)|_{\rm NDA} \sim \frac{m_*}{f_a} J G_F^2 F_\pi^4 \sim 10^{-31}\left(\frac{10^{10}\,{\rm GeV}}{f_a}\right)$$

Georgi, Randall (86)

$$J \sim 10^{-5} : \text{Jarlskog invariant}$$

- Short-distance contribution via quark CEDMs at perturbative three-loop orders



$$\frac{(\widetilde{d}_d)_{\rm SM}}{g_s} \sim \alpha_s \times J \times m_d G_F^2 m_c^2 \times (\text{loop factor})$$

$$\sim 10^{-34}\left(\frac{m_d}{10\,{\rm MeV}}\right)\,{\rm cm}$$

Czarnecki, Krause (97)

$$\bar{g}_{aNN}(\delta)|_{\text{short dist.}} \sim 10^{-31}\left(\frac{10^{10}\,{\rm GeV}}{f_a}\right)$$

Long-distance contributions?

- Suggested that long-distance effects dominate
  - ✓ EDMs of the neutron and nuclei
  - ✓ CP-violating coupling of pions to nucleons

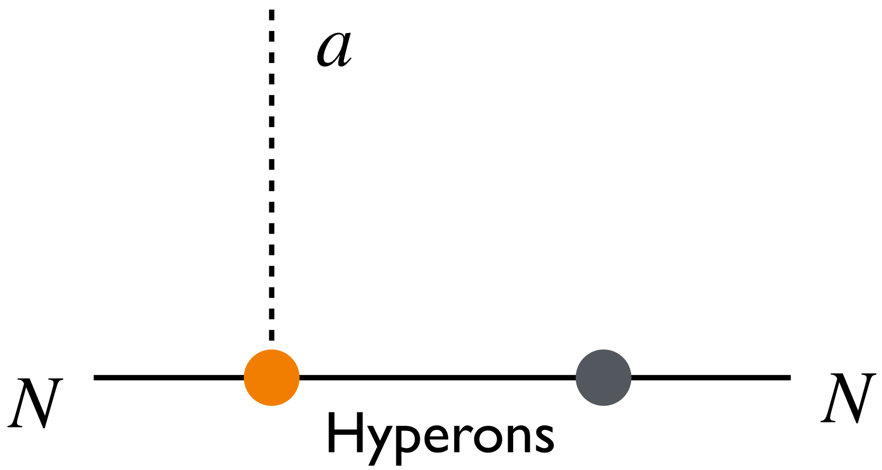
Khriplovich+(82), McKellar+(87), Donoghue+(87), Mannel+(12), Yamanaka+(15), etc.

- Natural question: does the same apply to the aNN coupling?

Baryon-pole contribution to $\bar{g}_{aNN}(\delta)$

- Consider aNN coupling via a combination of two non-leptonic $\Delta S = \pm 1$ transitions

SO, Pospelov, Ritz (2021)

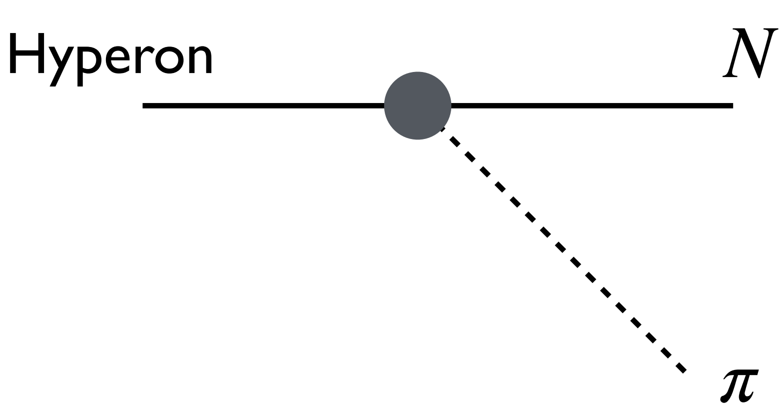


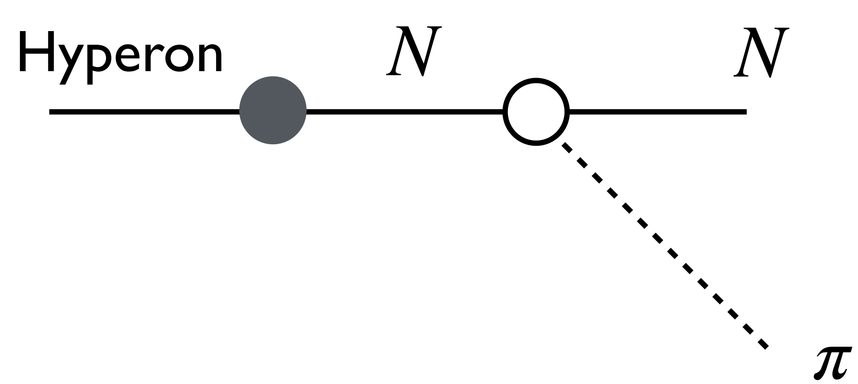
CP-odd a-N-Hyperon vertex

CP-even nucleon-hyperon transition

- $\Delta S = \pm 1$ weak vertices have been studied in hyperon decays, that allows a 'data-driven' analysis

Bijnens, Sonoda, Wise (85)





Strong QCD vertex

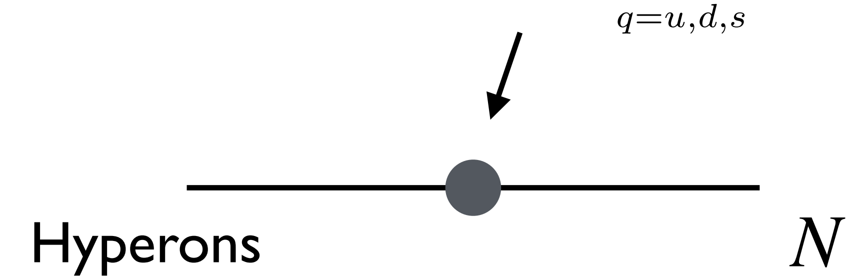
CP-even nucleon-hyperon transition

- CP-even $\Delta S = \pm 1$ weak vertices in the lowest order chiral perturbation:

Bijnens, Sonoda, Wise (85)

$$\mathcal{L}_{\text{chpt}}^{\Delta S=\pm 1} = -a_W \,\text{tr}\left(\bar{B}\{\xi^\dagger h \xi, B\}\right) - b_W \,\text{tr}\left(\bar{B}[\xi^\dagger h \xi, B]\right)$$
$$= -a_W \left(-\frac{1}{6}\bar{n}\left(\sqrt{6}\Lambda + 3\sqrt{2}\Sigma^0\right) + \bar{p}\Sigma^+\right)$$
$$- b_W \left(-\frac{1}{2}\bar{n}\left(\sqrt{6}\Lambda - \sqrt{2}\Sigma^0\right) - \bar{p}\Sigma^+\right) + \cdots$$

$$(\bar{s}_L \gamma_\mu u_L)(\bar{u}_L \gamma^\mu d_L)$$
$$(\bar{s}_L \gamma_\mu d_L)(\sum_{q=u,d,s} \bar{q}_R \gamma^\mu q_R)$$



$$h = (\lambda_6 + i\lambda_7)/2 \quad (\lambda_a : \text{Gell-Mann matrices})$$

$$\xi = \exp\left(\frac{iM}{F_\pi}\right) \qquad M : \text{octet meson matrix}, \;\; B : \text{octet baryon matrix}$$

- Fit of hyperon decays:

$$a_W = \tilde{a}_W \times \sqrt{2} G_F F_\pi m_{\pi^+}^2 ; \;\; b_W = \tilde{b}_W \times \sqrt{2} G_F F_\pi \underline{m_{\pi^+}^2}$$

$$\tilde{a}_W = 0.56 ; \;\; \tilde{b}_W = -1.42$$

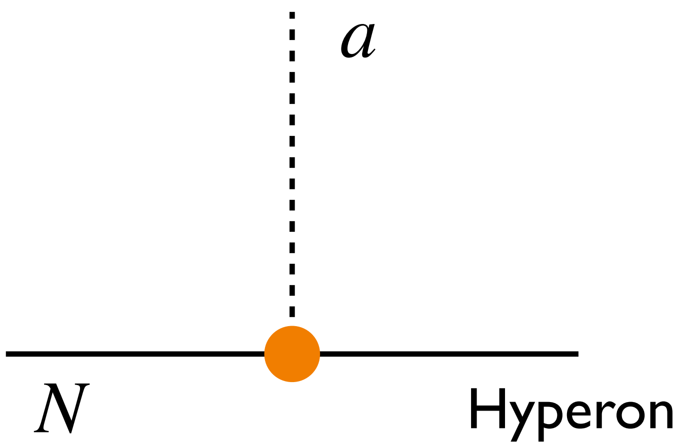
*just a number ~140MeV, not the theoretical parameter that is vanishing in the chiral limit

CP-violating axion-nucleon-hyperon vertex

- Need quark chirality-flipping to generate non-derivative $a\bar{B}B'$ couplings
  → s-d chromo-dipole operator as the primary CPV source

$$\mathcal{L}_{\rm CPV}^{\Delta S=\pm 1} = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \times C_{\rm dipole}\mathcal{O}_{\rm dipole}$$

$$\mathcal{O}_{\rm dipole} = \frac{1}{8\pi^2}\left[m_s \bar{s}G\sigma(1-\gamma_5)d + m_d \bar{s}G\sigma(1+\gamma_5)d\right]$$



- If axion dependence is included by a shift of quark mass $m_{s,d} \to m_{s,d} + i m_* \theta\gamma_5$ assuming the exact SU(3) flavor symmetry,

$$\mathcal{O}_{\rm dipole} \to \mathcal{O}_{\rm dipole} + \frac{1}{4\pi^2} m_* \theta\, \bar{s}G\sigma i\gamma_5 d$$

$\theta\,\bar{s}G\sigma d$ terms cancel out
→ no aBB' couplings

- Physical effects will appear as $\sim \theta\,\bar{s}G\sigma d \times (\mathrm{SU(3)\ breaking\ effects})$

CP-violating axion-nucleon-hyperon vertex

- Need quark chirality-flipping to generate non-derivative $a\bar{B}B'$ couplings
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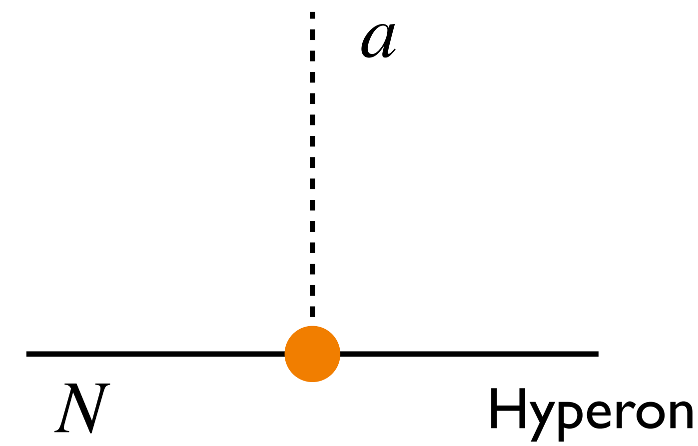


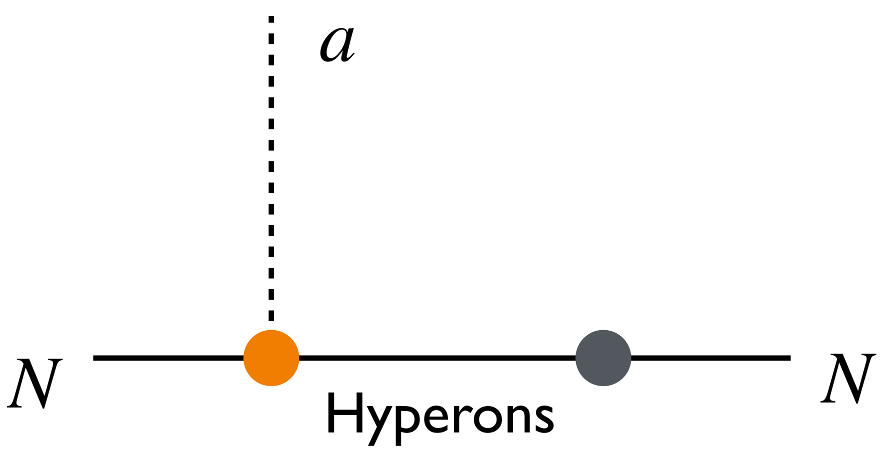
- Introduce κ to parametrize unspecified flavor SU(3) violating effects

$$\mathcal{L}_{\rm CPV}^{\Delta S=\pm 1} = \kappa\, m_* \theta \left(\bar{s}G\sigma d \underbrace{- m_0^2 \bar{s} d}_{\text{subtraction of kaon tadpole and axion-kaon mixing}} + h.c.\right) \times \underbrace{\frac{G_F}{\sqrt{2}} \frac{{\rm Im}(V_{td}V_{ts}^*)}{4\pi^2} \times (\text{loop function})}_{\equiv G_{\rm loop} = \frac{G_F}{\sqrt{2}} \times 3.3 \times 10^{-7}}$$

Numerical value of $\bar{g}_{aNN}(\delta)$

- Arrive at the following estimate

$$\mathcal{L}_{aNN} \sim \frac{a}{f_a} \times \kappa m_* G_F^2 F_\pi m_{\pi^+}^2 \times 3.3 \times 10^{-7} \times \langle N \left| \bar{q} G \sigma q - m_0^2 \bar{q} q \right| N \rangle$$
$$\times \left(\frac{\bar{n}n(-\tilde{b}_W/2 - \tilde{a}_W/6)}{m_n - m_\Lambda} + \frac{\bar{n}n(-\tilde{b}_W/2 + \tilde{a}_W)/2}{m_n - m_{\Sigma^0}} + \frac{\bar{p}p(-\tilde{b}_W + \tilde{a}_W)}{m_p - m_{\Sigma^+}} \right)$$



$$\bar{g}_{aNN}(\delta)|_{\text{long-dist}} \sim 1 \times 10^{-31} \left(\frac{10^{10}\,\text{GeV}}{f_a} \right) \times \kappa$$

NDA estimate (Georgi, Randall)

$$\bar{g}_{aNN}(\delta)|_{\text{NDA}} \sim 10^{-31} \left(\frac{10^{10}\,\text{GeV}}{f_a} \right)$$

Multi-nucleon contribution

- Meson exchange inside a large nucleus may generate a sizeable *equivalent* axion-nucleon coupling

$$\mathcal{L}_{4N} = -g_{4N}\, a(\bar{N}N)(\bar{N}N)$$

mean field approximation

$$\bar{N}N \sim \langle \bar{N}N \rangle \sim n_N \qquad\qquad n_N \simeq \frac{A}{\frac{4\pi}{3} R_N^3} \simeq (106\,\mathrm{MeV})^3$$

$$\mathcal{L}_{4N} \simeq -g_{4N} n_N\, a\bar{N}N \equiv \underline{-\bar{g}_{aNN}^{\mathrm{equiv}}}\, a\bar{N}N$$

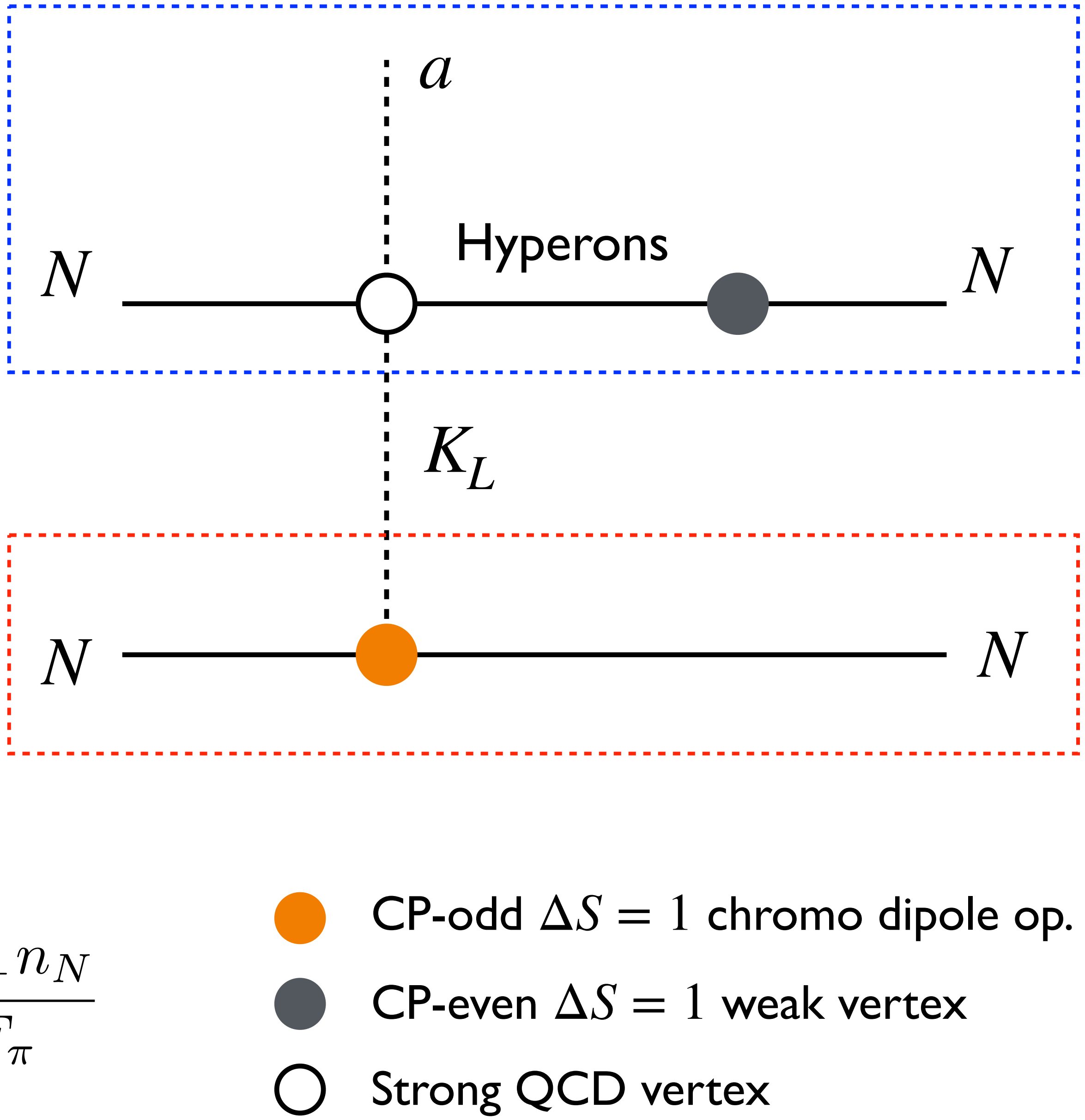
→ axion coupling *per nucleon*

$$\bar{g}_{aNN}^{\mathrm{equiv}} = g_{4N} n_N$$

Kaon exchange contribution

$$\mathcal{L}_{\mathrm{CPC},\,KNN} = \frac{m_* \theta K_L}{F_\pi}(2.0\bar{p}p + 2.8\bar{n}n) \times \frac{2\sqrt{2} G_F F_\pi m_{\pi^+}^2}{m_s}$$

$$\mathcal{L}_{\mathrm{CPV},\,KNN} = K_L(\bar{p}p + \bar{n}n) \times G_{\mathrm{loop}} \times \frac{m_s}{2F_\pi} \langle N \left| \bar{q} G \sigma q - m_0^2 \bar{q} q \right| N \rangle$$



$$\longrightarrow \quad \bar{g}_{aNN}^{\mathrm{equiv}}(\delta) \simeq 5 \times 10^{-7} \times \mathrm{GeV}^2 \times \frac{m_*}{f_a} \frac{G_F^2 m_{\pi^+}^2 n_N}{m_K^2 F_\pi}$$

$$g_{aNN}^{\mathrm{equiv}}(\delta) \simeq 2 \times 10^{-32} \left(\frac{10^{10}\,\mathrm{GeV}}{f_a} \right)$$

$$\bar{g}_{aNN}(\delta)|_{\mathrm{NDA}} \sim 10^{-31} \left(\frac{10^{10}\,\mathrm{GeV}}{f_a} \right)$$

Summary

- Axions and ALPs are attractive new particles
  - axions create macroscopic new forces between ordinary matter
  - CP-violating coherent mass-spin interaction can be probed using an NMR technique with oscillating source mass
- Revisit CP-violating axion-nucleon couplings from various CP-violating sources in the SM and beyond