# An Emergent Solution to the Strong CP Problem

## (with Dark Matter!)


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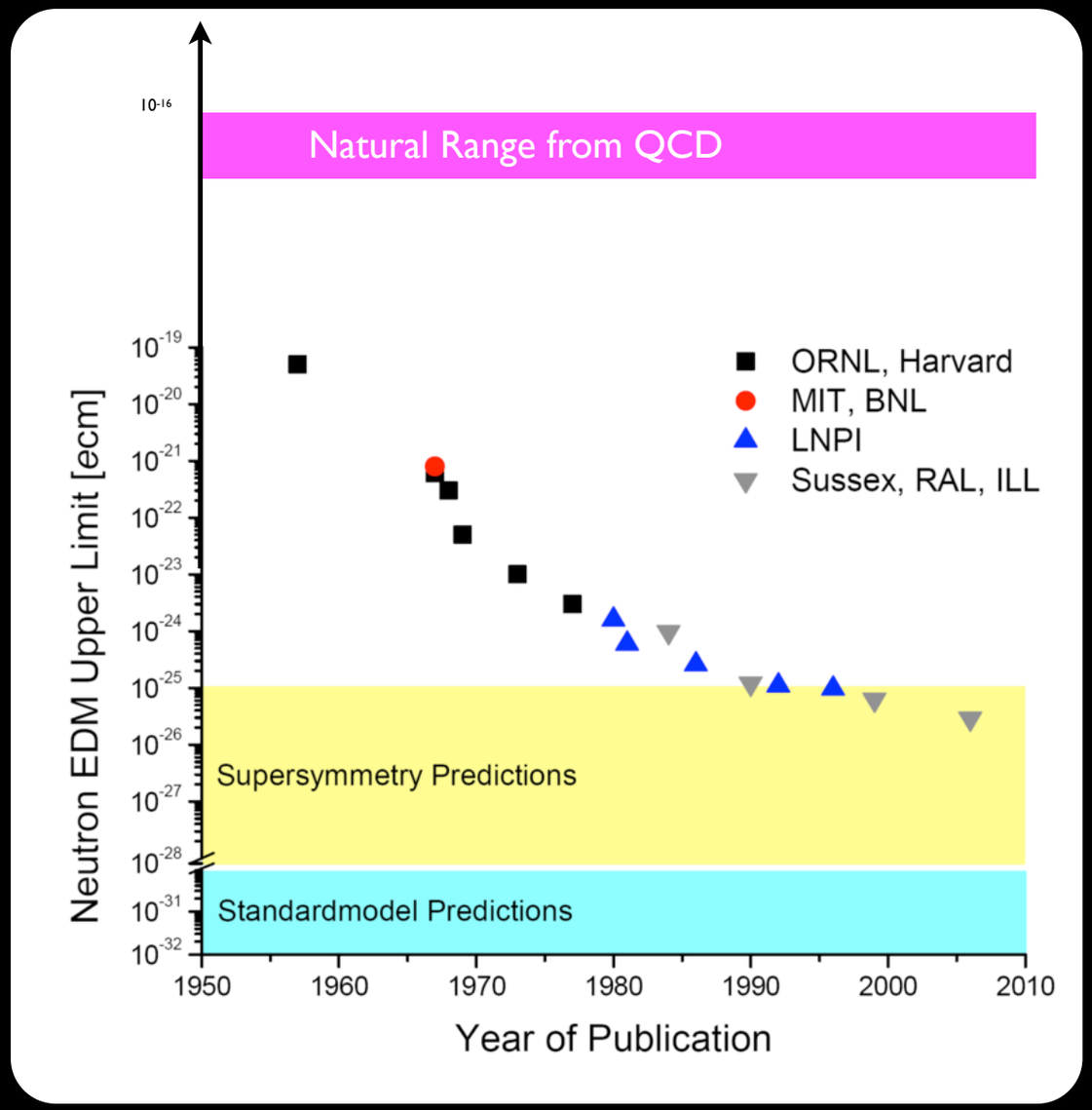
# Could Dark Matter be the Solution to the Strong CP Problem?



# Could Dark Matter be the Solution to the Strong CP Problem?

**Yes, Axion:**

$$\frac{a(x)}{f_a}\, G_a^{\mu\nu}\widetilde{G}^a_{\mu\nu}. \longrightarrow -\Lambda^4 \cos\left(a/f_a - \overline{\theta}\right)$$

# An Emergent Solution?

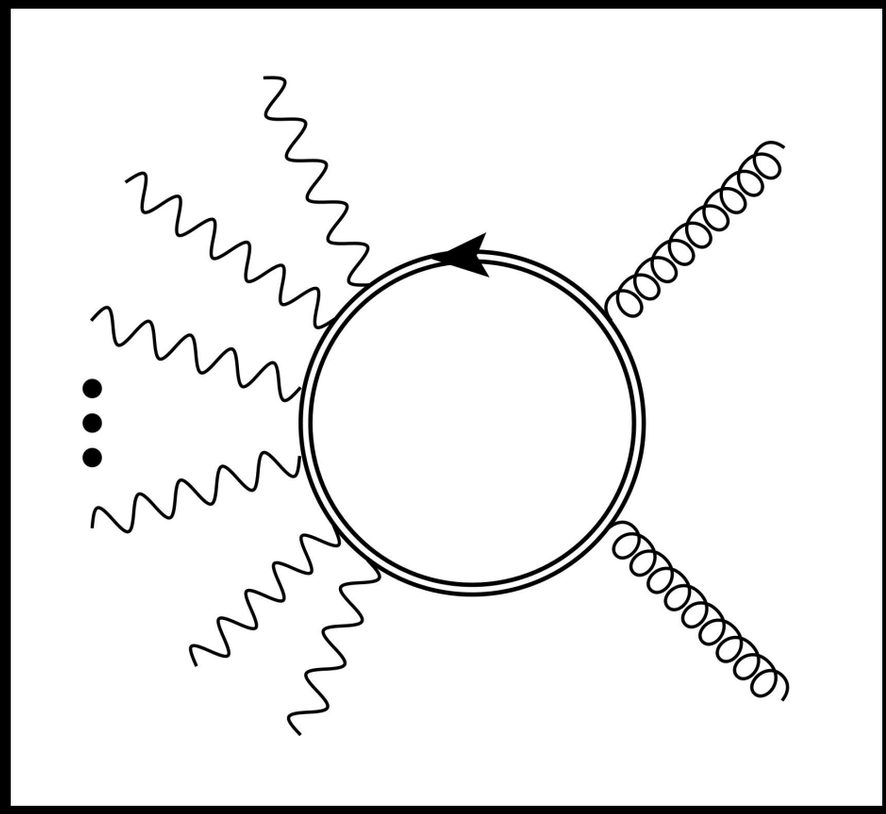
- I'd like to explore a different type of approach.
- Rather than the usual particle physics approach of introducing new fields with new dynamics which modify the properties of the vacuum, I have in mind emergent physics from the non-vacuum state we live in.
- This is kind of like a condensed matter solution to a problem.
- In this case, I imagine that the dark matter spin cancels theta bar. There is no fundamental axion field, though there is a spin-wave excitation of the DM medium that is axion-like.

# Dark Matter

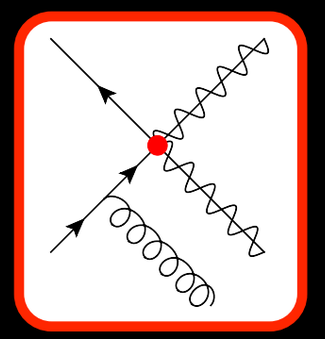
- Spin -1 ultra-light boson (more on that later…)
- Couples to gluons:

$$\frac{\alpha_s}{16\pi}\frac{1}{M_*^{(6+2n)}}\; S^{\mu\nu\rho}S_{\mu\nu\rho}\,(A^\alpha A_\alpha)^n\;\; G^a_{\sigma\lambda}\widetilde{G}^{\sigma\lambda}_a$$

$$S^{\mu\nu\rho}[A] \equiv F^{\mu\nu}A^\rho - F^{\mu\rho}A^\nu \xrightarrow{\text{NR}} \textbf{Spin}$$



- Other operators involving spin could work.
- $M_* \sim$ TeV (monojets)



# Strong CP

- The dark matter in the Galaxy feels a gravitational potential which tells it how to clump and how to move.  It doesn't care what the spin does.

- It feels an additional potential from QCD:

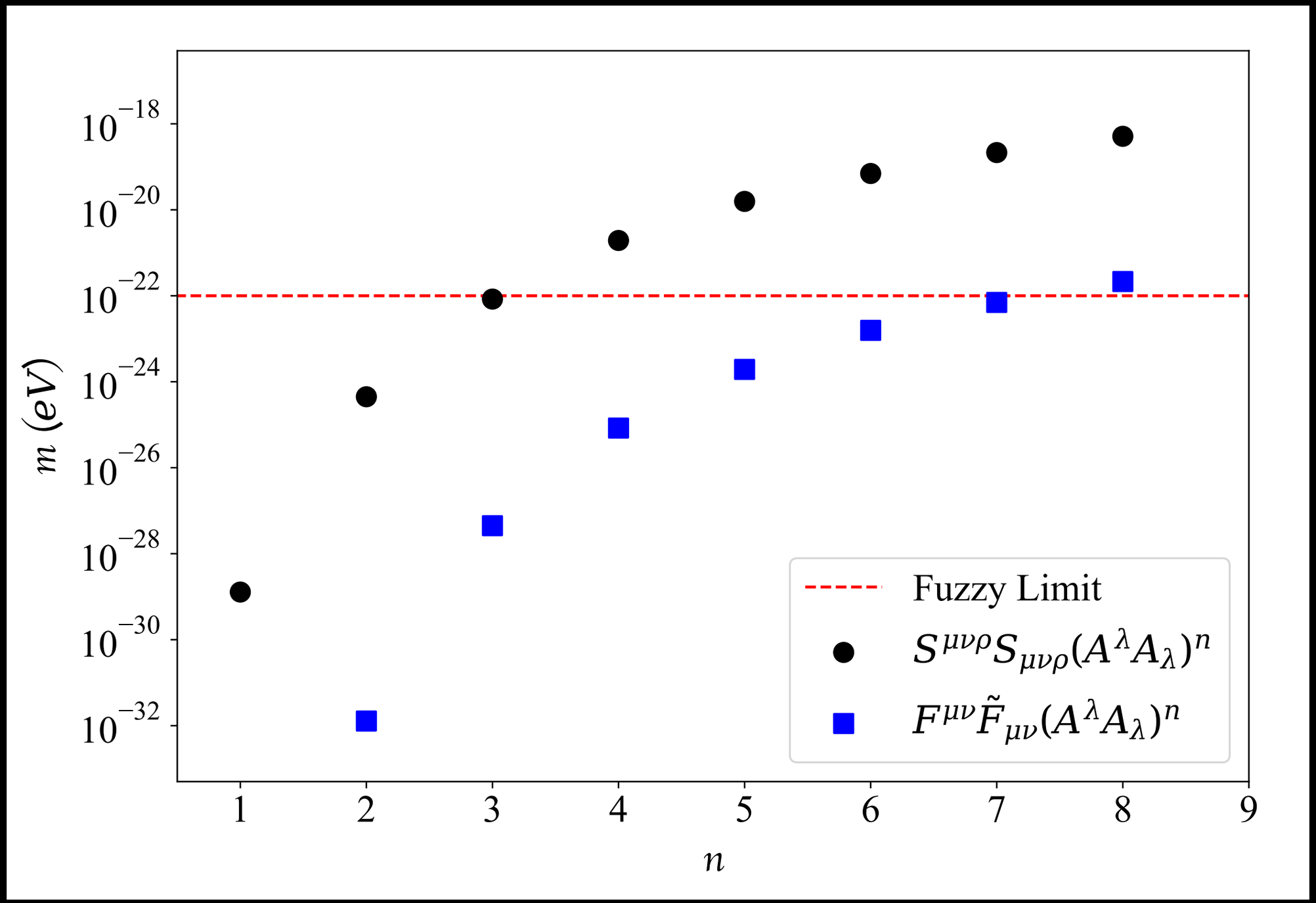
$$\frac{\alpha_s}{16\pi}\frac{1}{M_*^{(6+2n)}}\; S^{\mu\nu\rho}S_{\mu\nu\rho}\left(A^\alpha A_\alpha\right)^n\; G^a_{\sigma\lambda}\widetilde{G}^{\sigma\lambda}_a \longrightarrow -\Lambda^4\cos\left(\frac{S^{\mu\nu\rho}S_{\mu\nu\rho}\left(A^2\right)^n}{M_*^{(6+2n)}}-\overline{\theta}\right)$$

- This additional potential can be minimized by choosing the net polarization density of the field appropriately such that $S^2$ cancels theta bar.

- The spin density $S^2$ is bounded by the number density $n^2$.

$$\frac{s^2 m^2 \mathcal{A}^{(4+2n)}}{M_*^{(6+2n)}} \sim s^2 \frac{\rho^{(2+n)}}{M_*^{(6+2n)} m^{(2+2n)}}$$

$$m \lesssim \left( \frac{\rho_\odot^{(2+n)}}{M_*^{(6+2n)}} \right)^{\frac{1}{2+2n}}$$




**The presence of operators with lower n is not problematic: they just don't give a large enough contribution to cancel an O(1) theta bar.**

# Perturbations

- We checked a bunch of things which could distort S, and thus spoil the solution of the strong CP problem.  None look problematic.

  - Higher dimensional operators

**e.g.** $\frac{a_p}{16\pi^2}\frac{1}{M_*^{(8+2p)}}\left(S^{\mu\nu\rho}S_{\mu\nu\rho}\right)^2\left(A_\lambda A^\lambda\right)^p$ ⟶ **p < n+5**

- Dark matter magnetic dipole moment

- DM Spin - Earth Spin gravitational interactions

# Phenomenology

- Dark matter can be produced via parametric resonance.

- Below the fuzzy limit, constraints from e.g. the shapes of galaxies.

- Structure formation is weird, because of QCD contributions to the vacuum energy which vary with position. (However, for n>6 and masses less than $10^{-20}$ eV, nothing would have happened yet).

- Gravitational wave detectors put limits on fifth force: Eot-Wash constrains the size of the DM coupling to the SM to be $< 10^{-23}$ in the mass range of interest. LISA will eventually improve limits for masses $> 10^{-18}$ eV.

- CP may be strongly violated in DM poor regions of the Universe (outskirts of galaxies, globular clusters).

# Open Questions

- Locally varying contributions to the vacuum energy?
  - Tied up with a solution to the CC problem?
- Structure formation?
  - Some kind of Quintessence?
- Probes of distant CP violation?
- What about the axion-like spin-wave state?
- **Are there other fundamental problems amenable to emergent solutions?**

# Thank You!