An Emergent Solution to the Strong CP Problem

(with Dark Matter!)

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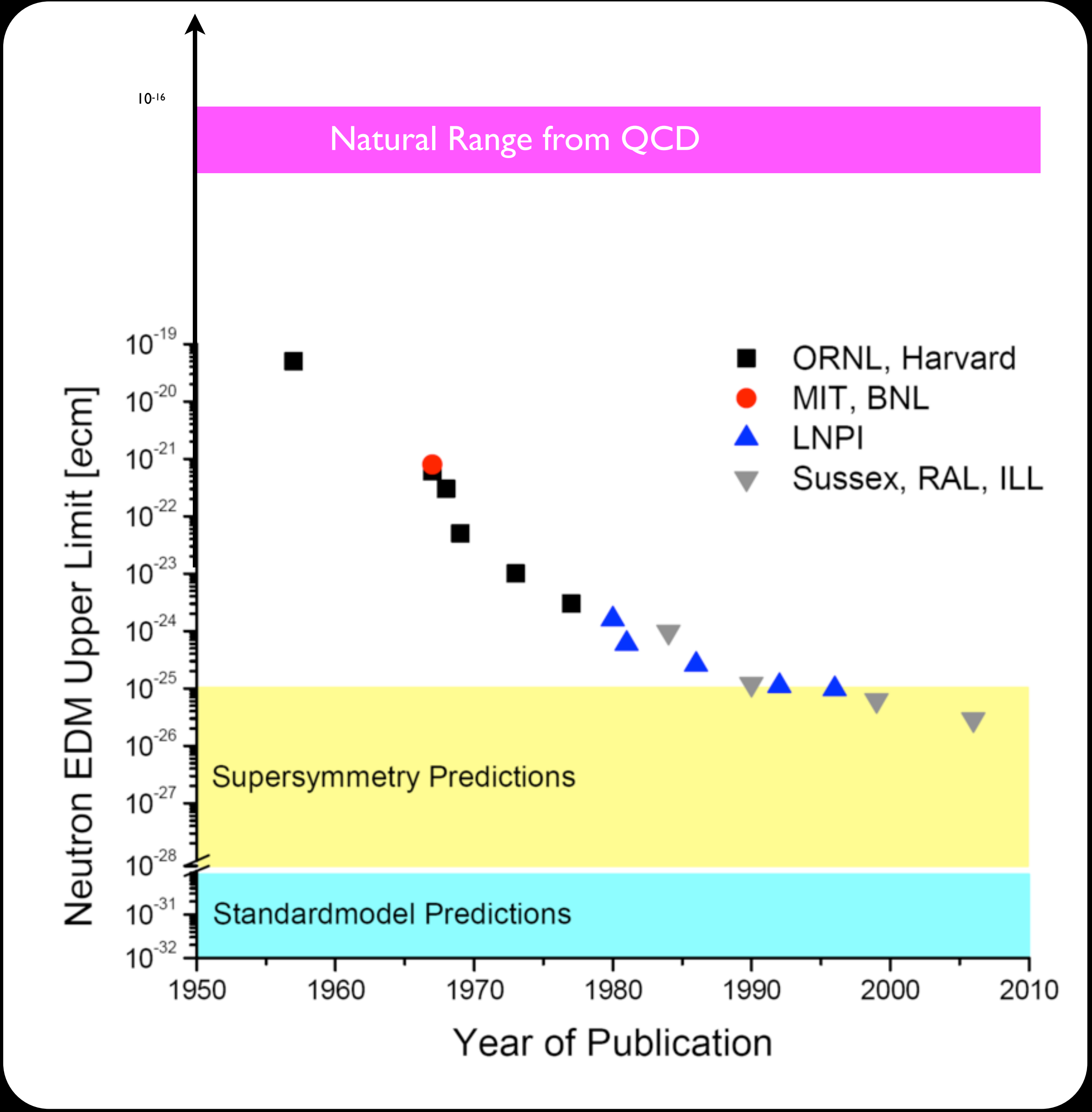
Could Dark Matter be the Solution to the Strong CP Problem?



The fact that the neutron EDM is consistent with zero is a strong indication that the strong force to very good approximation conserves CP.

$$\frac{\alpha_s}{8\pi}\ \bar{\theta}\ G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a$$

$$\bar{\theta} \lesssim 10^{-10}$$

This is the strong CP problem.

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

Yes.

The axion can both cancel theta-bar, and act as dark matter:

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

The dynamics of QCD itself drive the axion to a vacuum expectation value which cancels theta-bar.

An Emergent Solution?

- In this talk, I will explore a different type of approach to the PQ axion as a solution to the strong CP problem.
- Rather than the usual particle physics approach of introducing new fields with new dynamics which modify the properties of the vacuum (as e.g. embodied by the axion), I have in mind emergent physics from the particular non-vacuum state in which we happen to live.
- This is kind of like a condensed matter solution to a problem: its less about the dynamics of the vacuum, and more about the stuff that we happen to have around us where we do our measurements.
- 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

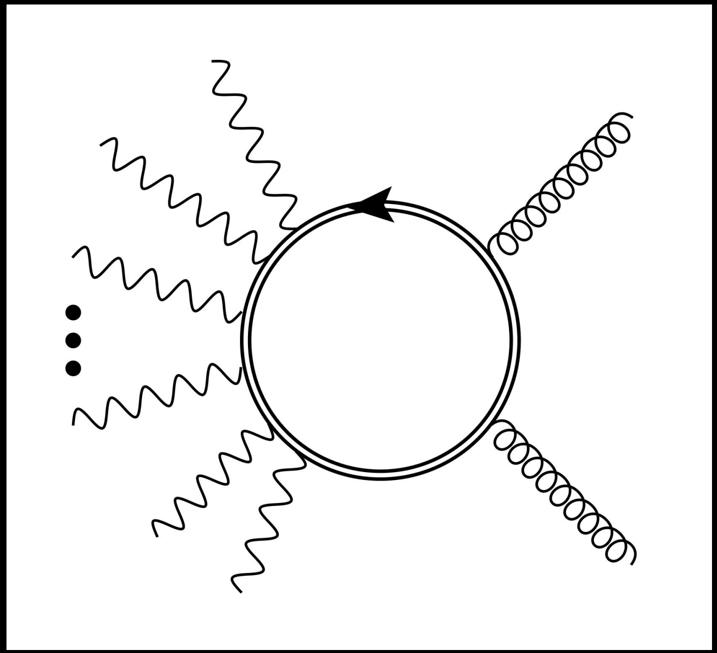
- Posit that DM is a spin-1 ultra-light boson (more on that later…)

- It couples to gluons:

Family of operators labeled by n

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

(Maybe from loops like these…)

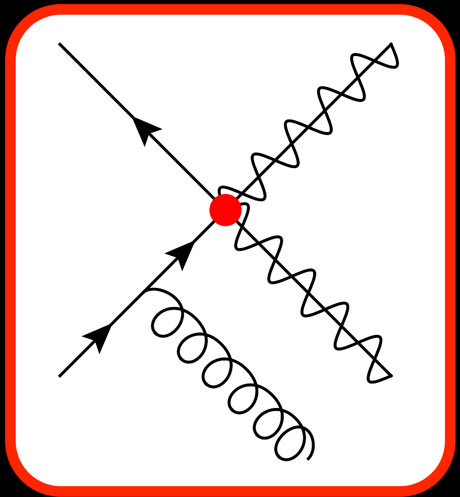


$$S^{\mu\nu\rho}[A] \equiv F^{\mu\nu}A^\rho - F^{\mu\rho}A^\nu$$

$\xrightarrow{\text{NR}}$ **Spin**

- Other operators involving spin could work.

- Presumably, $M_* \gtrsim$ TeV (monojets).



DM Galactic Dynamics

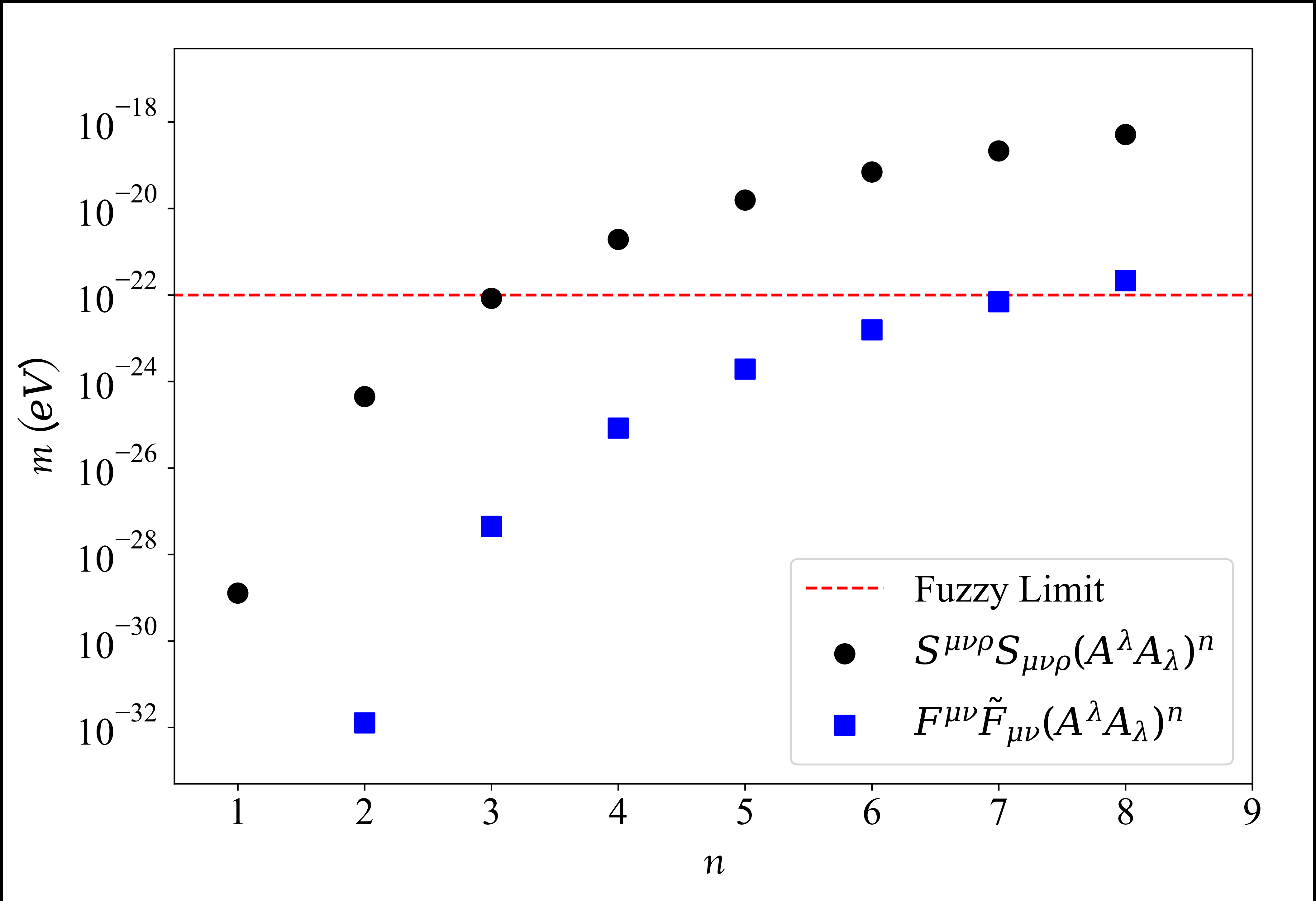
- The dark matter in the Galaxy feels a gravitational potential which tells it where to clump and how to move, determining the properties of the halo. Gravity (to very good approximation) doesn't care what the spin does.
- However, we have engineered an additional potential from QCD:

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

- This additional potential can be minimized by choosing the net polarization density of the field appropriately such that S^2 cancels theta bar.
- (But note that the spin density S^2 is bounded by the number density, n^2. To solve the strong CP problem locally on the Earth, the density needs to be large enough for us to completely cancel an O(1) $\overline{\theta}$.)

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

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



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 the local expectation of S, and thus spoil the solution of the strong CP problem. None of them look problematic.

  - E.g. 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

Typically way too small…

  - DM Spin - Earth Spin gravitational interactions

Phenomenology

- Dark matter can be produced via parametric resonance, though it requires some tuning to efficiently produce masses as small as we would like.

- Below the fuzzy limit, there are 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).

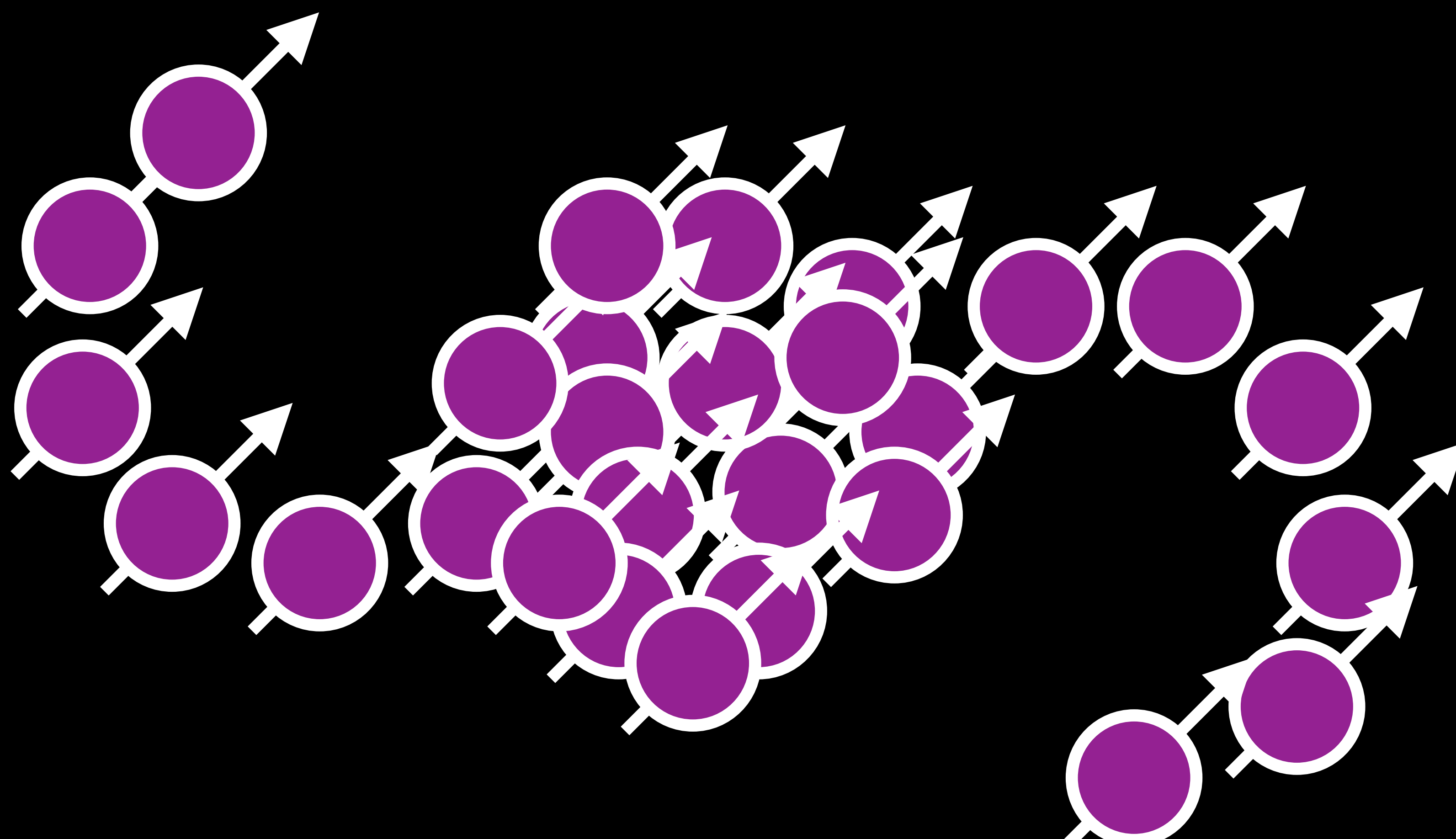
- Gravitational wave detectors put limits on fifth force: Eot-Wash constrains the size of the DM vector coupling to light quarks or electrons to be $< 10^{-23}$ in the mass range of interest. LISA will eventually improve limits for masses $> 10^{-18}$ eV.

- CP may be strongly violated in DM poor regions of the Universe (outskirts of galaxies, globular clusters). This might be visible in e.g. atomic spectra of distant stars.

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 that are amenable to emergent solutions?**

Thank You!



* To paraphrase a talk by Steve Martin at Pheno many years ago, “In summary, a 12 minute talk is itself a summary.”