The Current Theoretical Status of Axions

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What are axions?

Classical

Simple solution to a simple problem

Quantum

Simple solution to a subtle problem

Only one or two parameters

Can naturally be Dark Matter

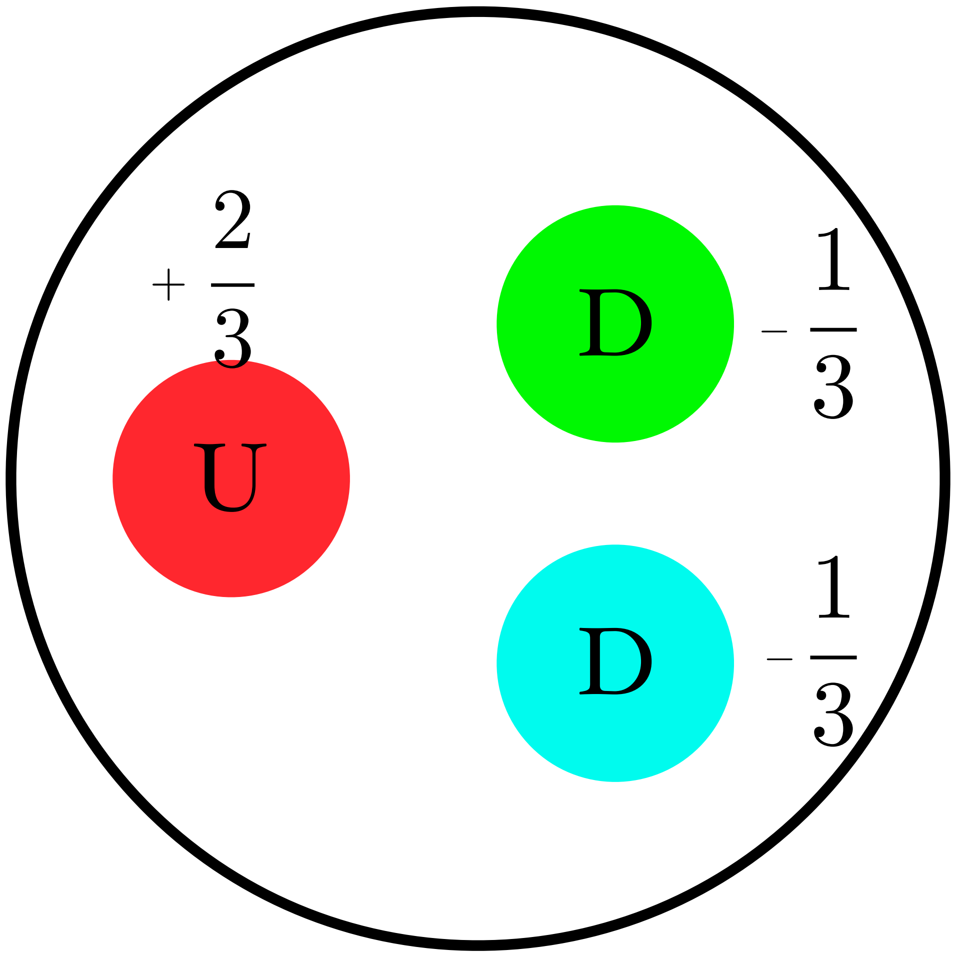
(Wrong) Classical Strong CP Problem

Draw a neutron

Neutron contains an up quark and two down quarks

(Wrong) Classical Strong CP Problem

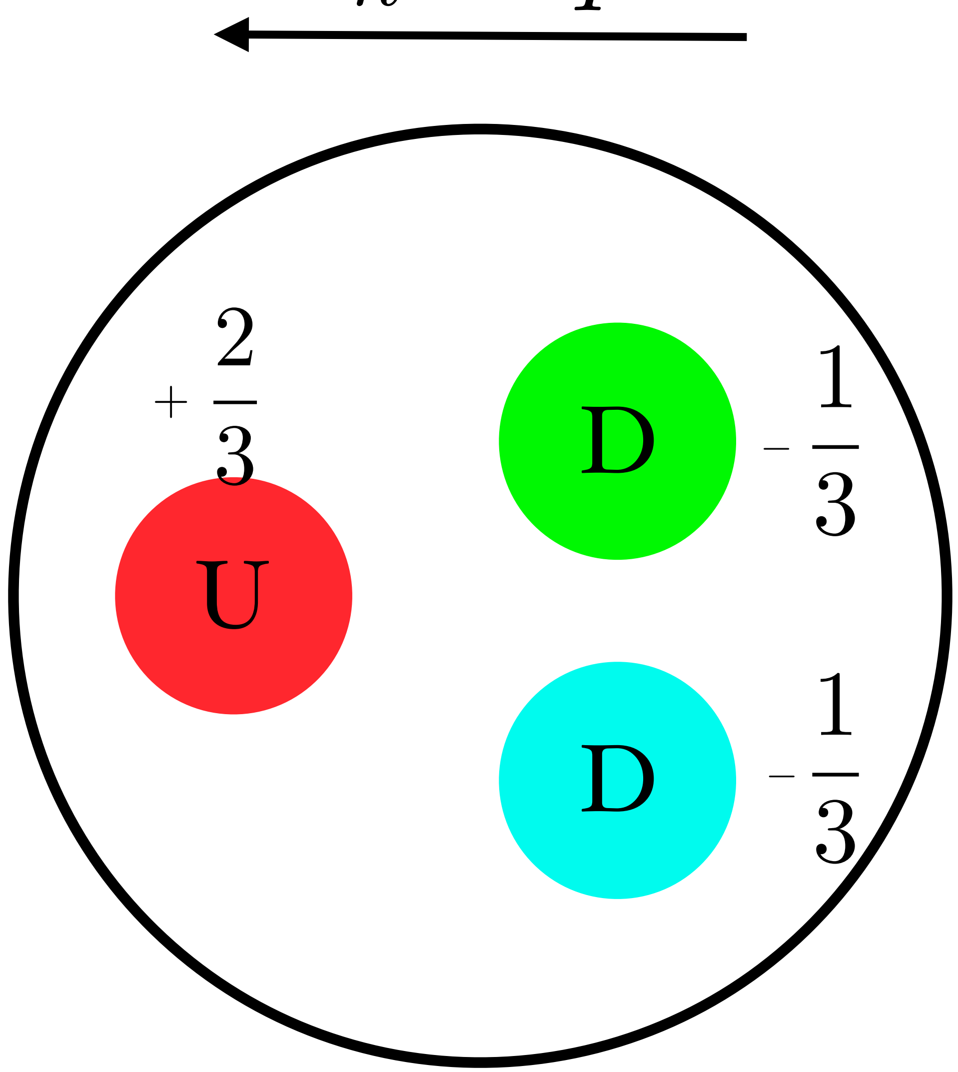
Neutron contains an up quark and two down quarks



(Wrong) Classical Strong CP Problem

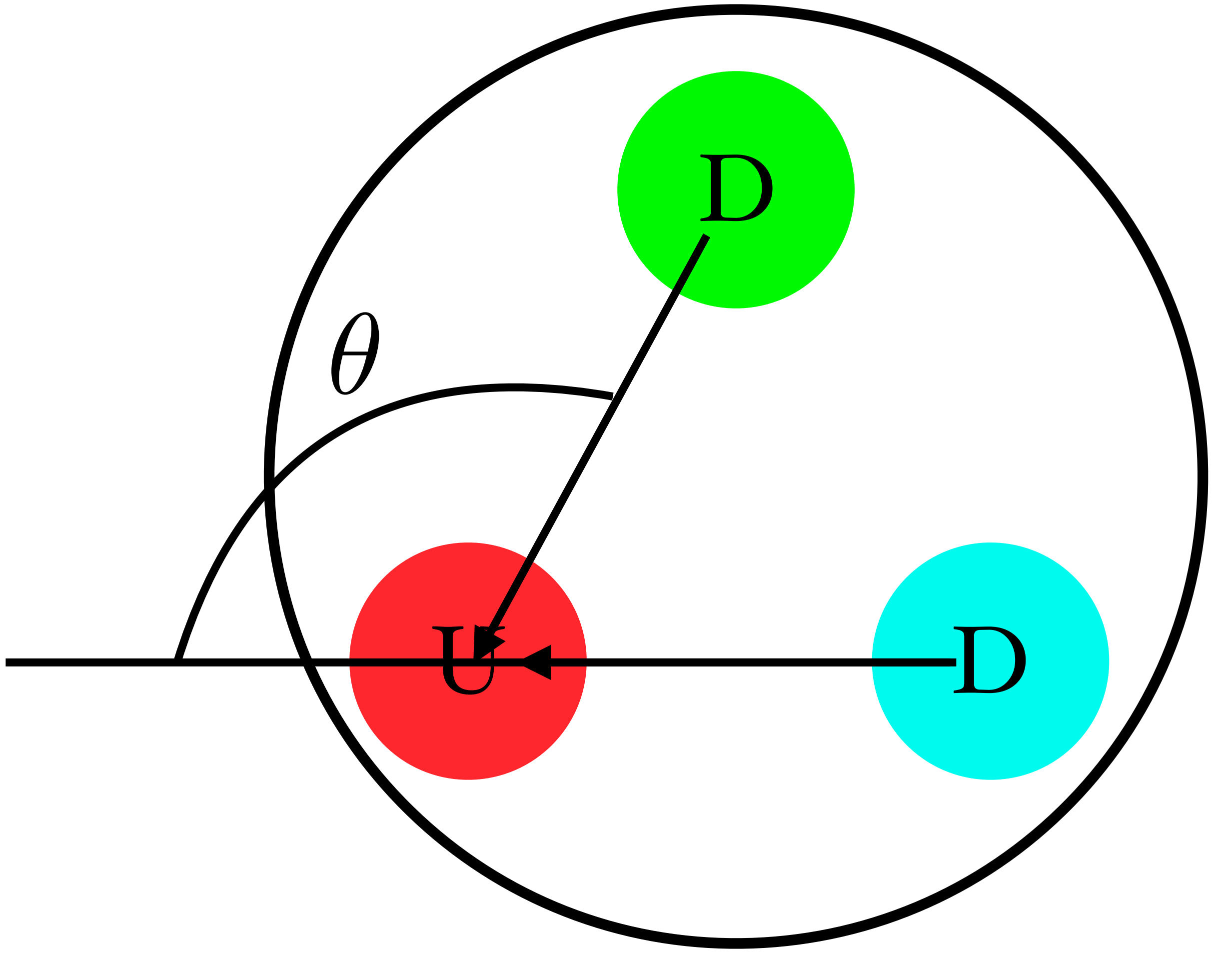
Calculate electric dipole moment

$$d_n = qx$$



(Wrong) Classical Strong CP Problem

$$
\begin{aligned}
|d_n| &\approx ex\sqrt{1-\cos\theta} \\
&\approx 10^{-14}\, e\,\sqrt{1-\cos\theta}\ \mathrm{cm}
\end{aligned}
$$

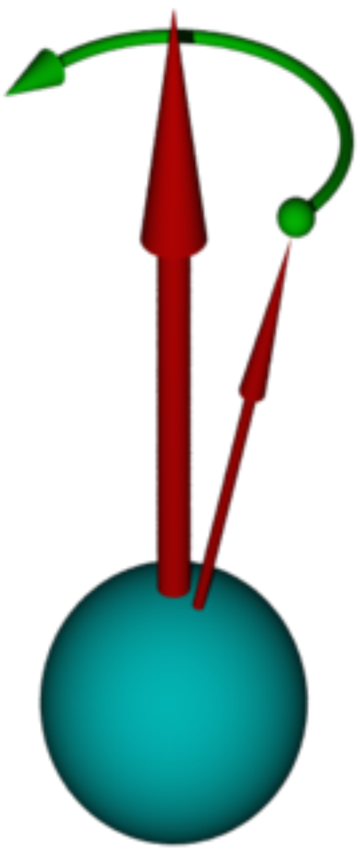


(Wrong) Classical Strong CP Problem

Measurement via Larmor frequency

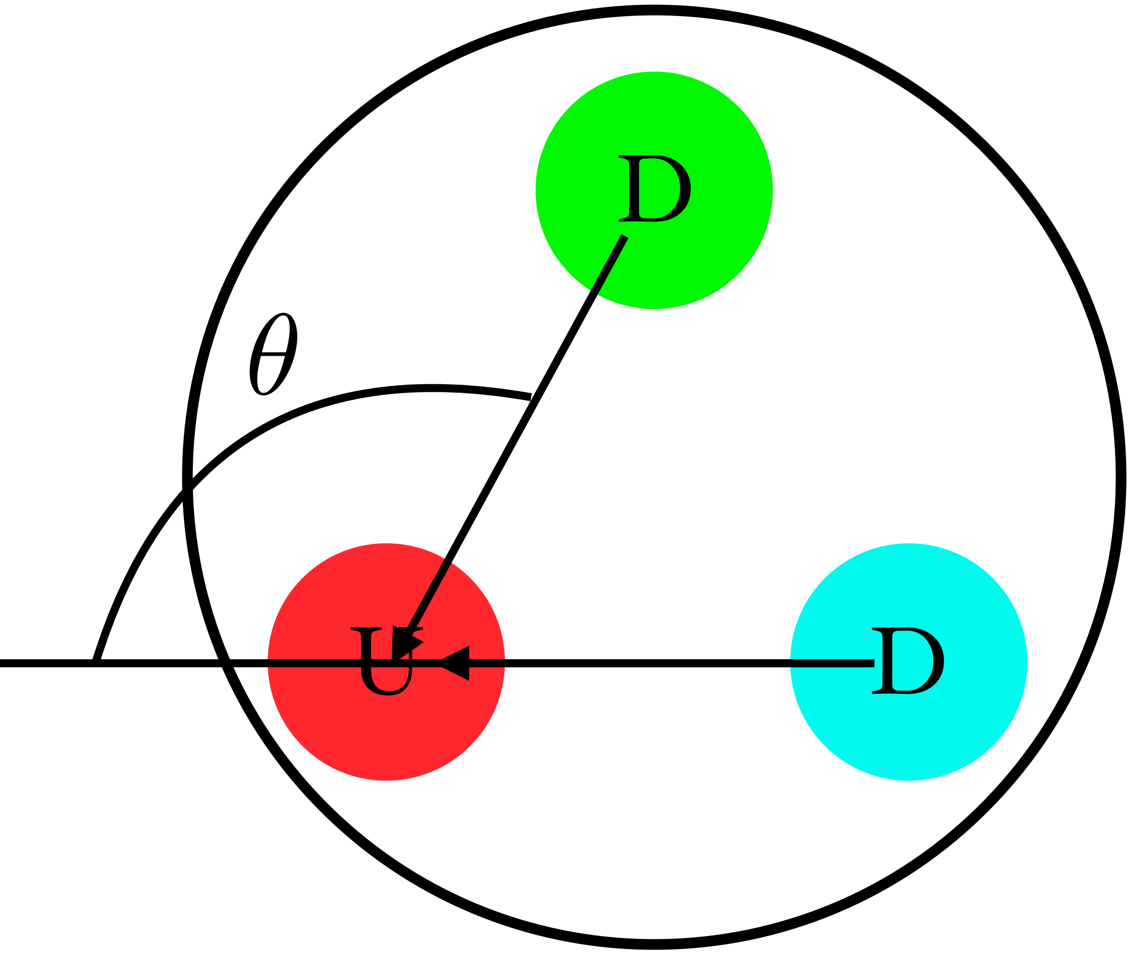
$$h\nu_{\uparrow\uparrow} = |2\mu_n B + 2d_n E|$$

$$h\nu_{\uparrow\downarrow} = |2\mu_n B - 2d_n E|$$



Measure number of spin up versus spin down neutrons for parallel and anti-parallel electric and magnetic fields

eDM estimate



Estimate

$$|d_n| \approx ex\sqrt{1-\cos\theta}$$
$$\approx 10^{-14}\, e\,\sqrt{1-\cos\theta}\ \mathrm{cm}$$

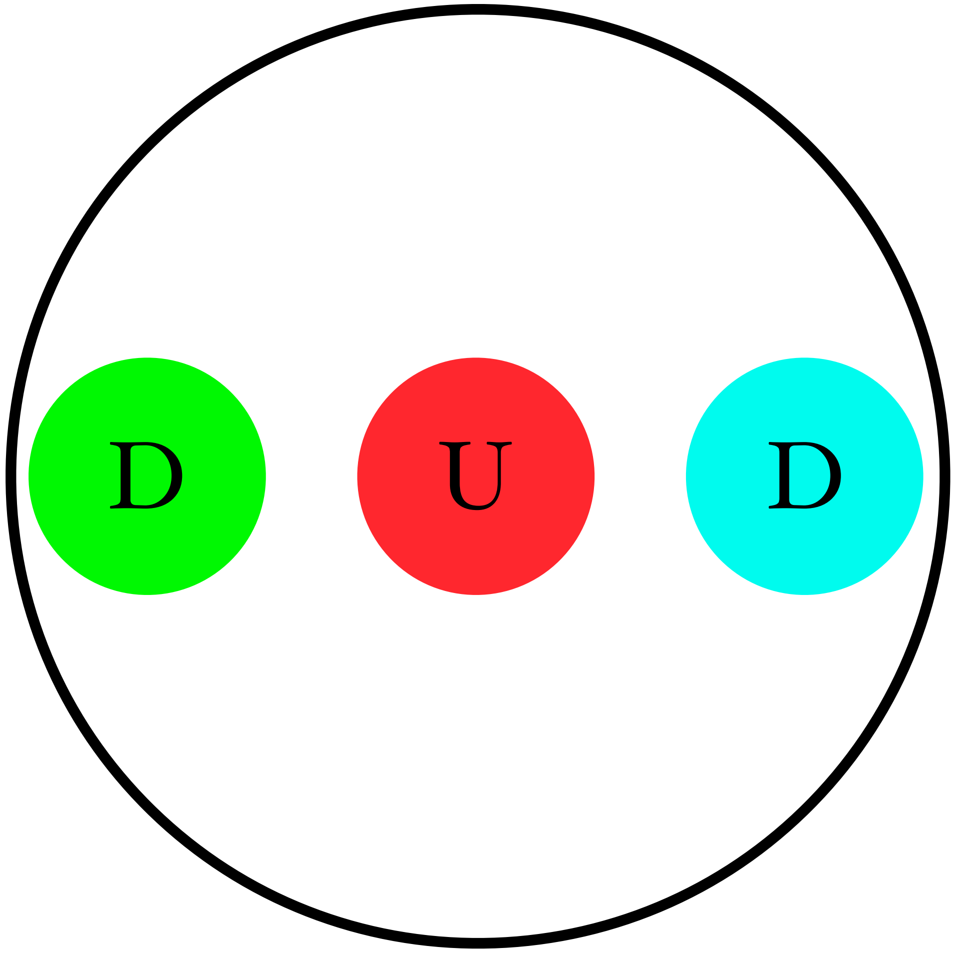
Measurement

$$|d_n| < 2.9 \times 10^{-26}\, e\,\mathrm{cm}$$

Baker et. al. hep-ex/0602020 :
Institut Laue-Langevin, Grenoble

(Wrong) Classical Strong CP Problem

Aka why does everyone draw the neutron wrong?



$$\theta < 10^{-12}$$

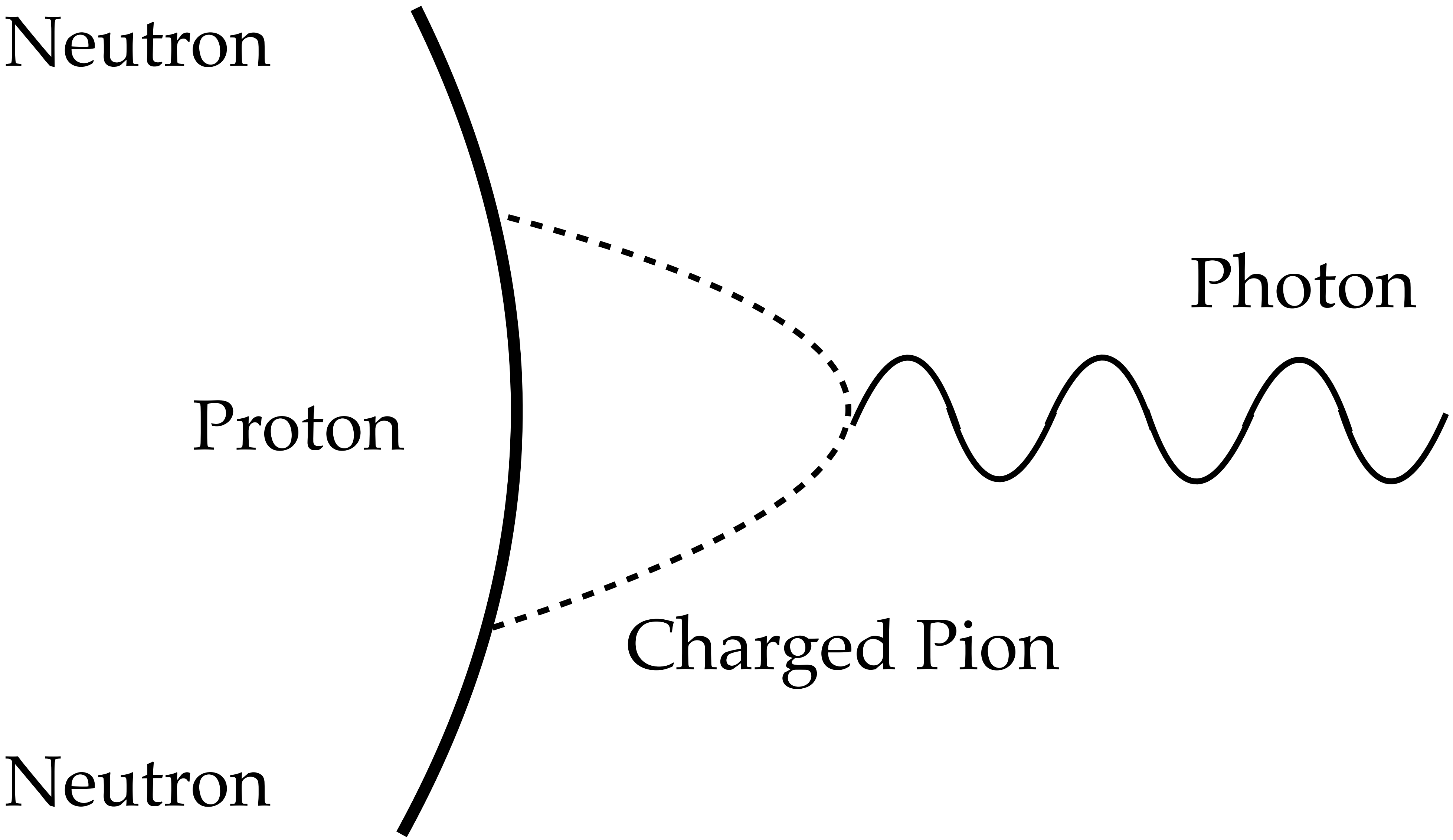
4D Quantum Strong CP problem

Theory of QCD

$$\frac{g^2}{32\pi^2}\theta G_{\mu\nu}\tilde{G}^{\mu\nu} + m_u e^{i\theta_u} u^c u + m_d e^{i\theta_d} d^c d$$

Use Chiral Perturbation theory to calculate neutron eDM

4D Quantum Strong CP problem



$$|d_n| = 3.2 \times 10^{-16}(\theta + \theta_u + \theta_d)\, e\, \mathrm{cm}$$

4D Quantum Strong CP problem

$$|d_n| < 2.9 \times 10^{-26}\, e\, \mathrm{cm}$$

$$\bar{\theta} \equiv \theta + \theta_u + \theta_d < 10^{-10}$$

QFT formulation of the Strong CP problem

Simple Solutions

Four simple solutions to this simple problem

1. Universe is Left-Right symmetric
2. Universe is Time reversal invariant
3. Massless up quark
4. Axions

Simple Solutions

Four simple solutions to this simple problem

1. ~~Universe is Left-Right symmetric~~
2. ~~Universe is Time reversal invariant~~
3. ~~Massless up quark~~
4. Axions

Weak interactions

Kaon oscillations

Lattice

Parity is Under-Rated

Before diving into Axions

The simplest parity based solutions to the strong CP problem are as simple as the QCD axion

Gets very messy very quickly though

S. M. Barr, D. Chang, and G. Senjanovic, Phys.Rev.Lett. 67, 2765 (1991)

(Wrong) Classical Axion

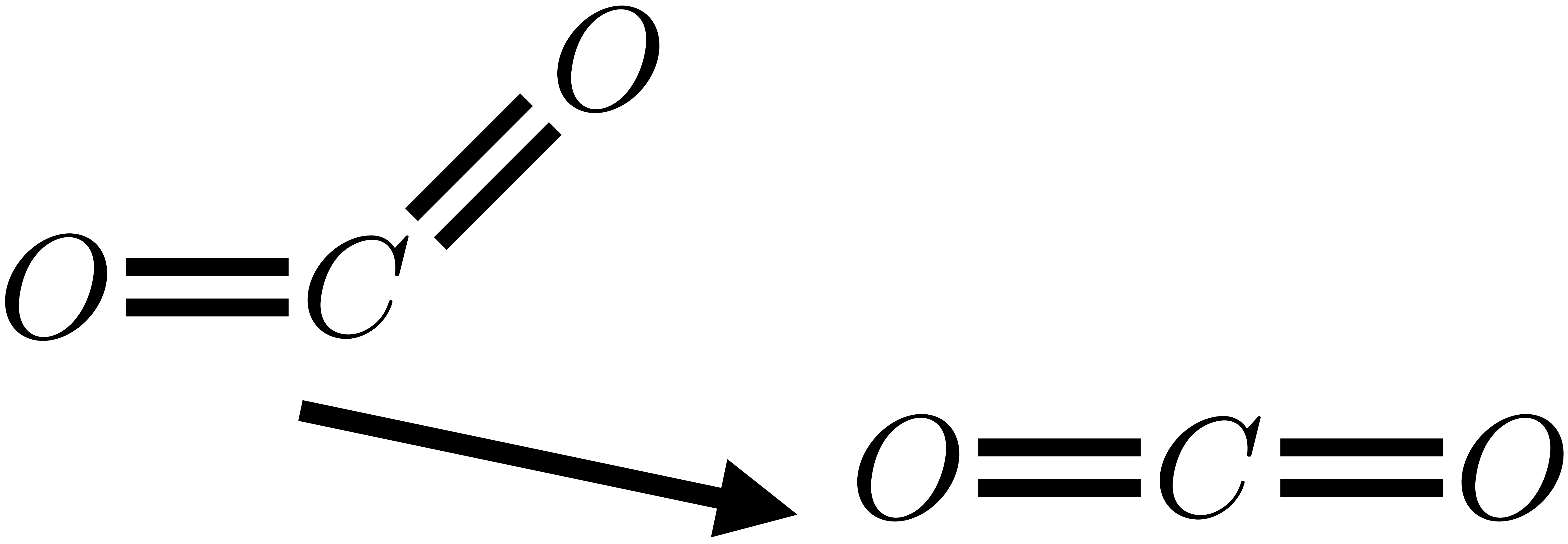
CO_2 also has a zero dipole moment

$$O = C = O$$

$$\delta_- \qquad \delta_+ \qquad \delta_-$$

Why is the dipole moment zero?

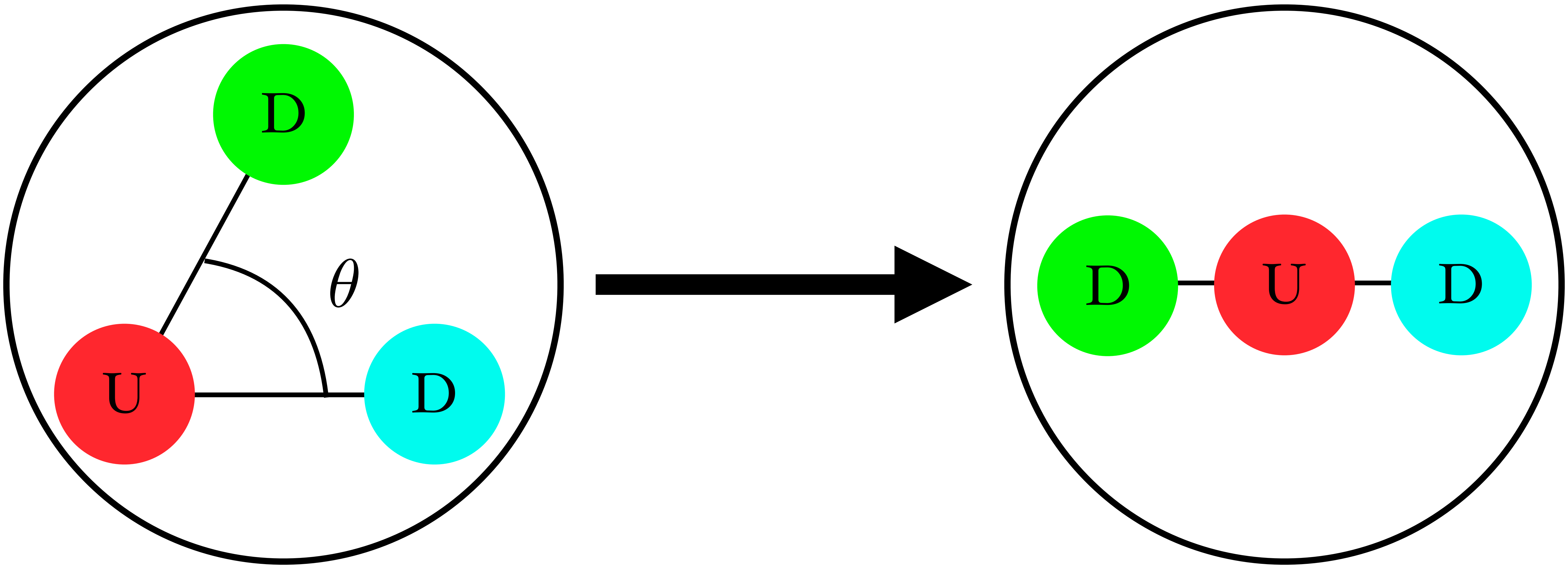
(Wrong) Classical Axion



Angle relaxes itself to zero!

(Wrong) Classical Axion

Plausible that if angle were dynamical maybe it would relax itself to a symmetric state



Quantum Axion

$$\frac{g^2}{32\pi^2}\theta G_{\mu\nu}\tilde{G}^{\mu\nu} \to \frac{g^2}{32\pi^2}\left(\theta - \frac{a}{f_a}\right)G_{\mu\nu}\tilde{G}^{\mu\nu}$$

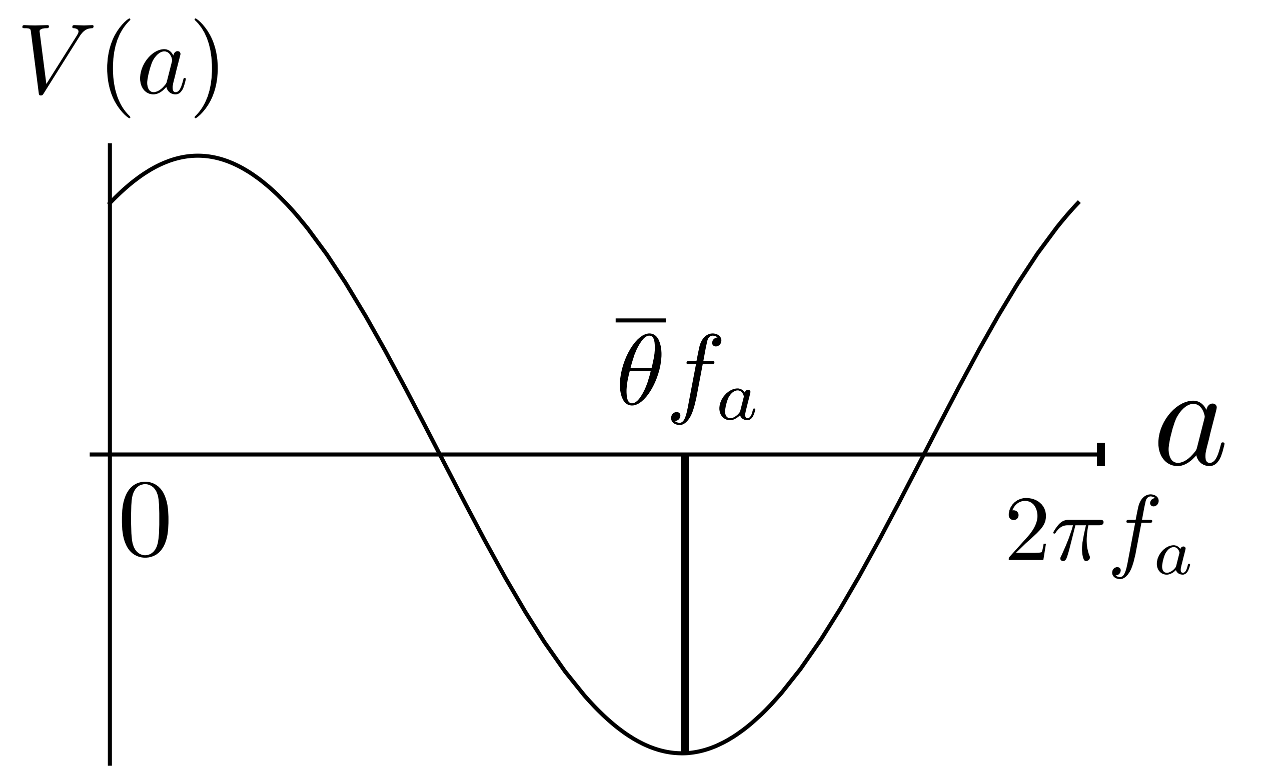
Introduce a field whose sole purpose is to make the angle dynamical

Quantum Axion

$$V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\bar\theta - a/f_a}{2}\right)}$$

Axion dynamically sets the neutron EDM to 0

$$|d_n| = 3.2 \times 10^{-16}\,(\bar\theta - \langle\frac{a}{f_a}\rangle)\,e\,\mathrm{cm}$$



The Axion

Problem

Why does everyone draw the neutron wrong?
Why is the neutron electric dipole moment small?

Simple solution

Make angle dynamical

The Axion

Such a simple theory, what is there to do theory-wise?

1. Axion theory has a weakness - Quality problem
2. Expand the parameter space of the invisible axion
3. Axion DM abundance
4. Axion Strings
5. Axion probes of quantization of electric charge

Quality Problem

In order to solve the Strong CP problem axion needs to ONLY modulate ϑ. Anything else changes the location of the minimum

There is NO symmetry that can force the axion to just modulate ϑ and do nothing else

Anomalous symmetries such as $U(1)_{PQ}$ are not symmetries

Quality Problem

Broadly speaking there are 3 classes of solutions

Quality Problem

Broadly speaking there are 3 classes of solutions

1. $U(1)_{PQ}$ is an accidental symmetry much like baryon number in the SM
   A. Composite Axions
   B. Z_N symmetry

Quality Problem

Broadly speaking there are 3 classes of solutions

2. Increase the size of the axion potential
   A. Heavy axion - discrete symmetries/UV instantons
   B. Multiple axions

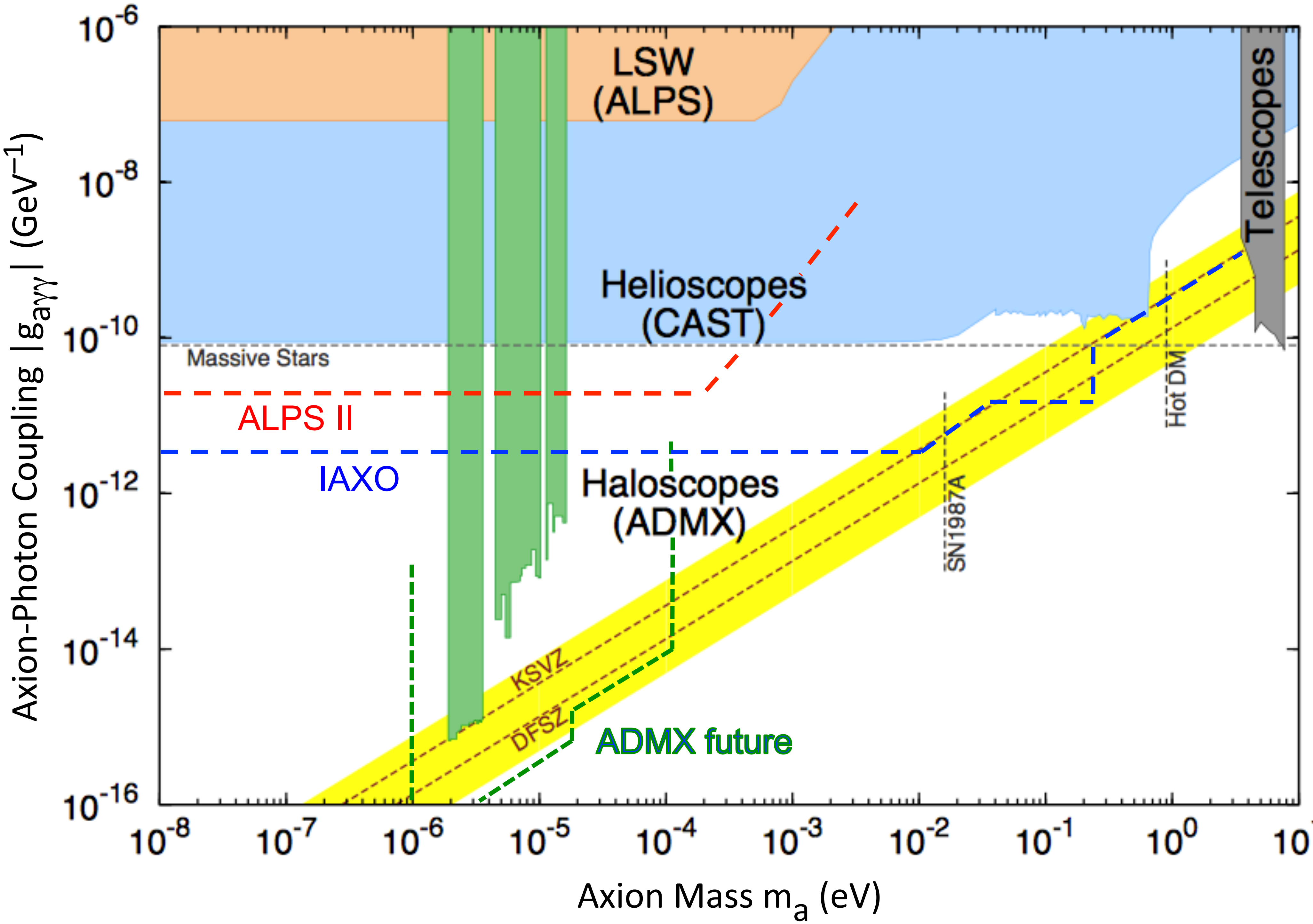
Quality Problem

Broadly speaking there are 3 classes of solutions

3. Extra Dimensions
   A. $U(1)_{PQ}$ is made into a gauge symmetry - takes the log of the problem
   B. Extra dimensional instantons

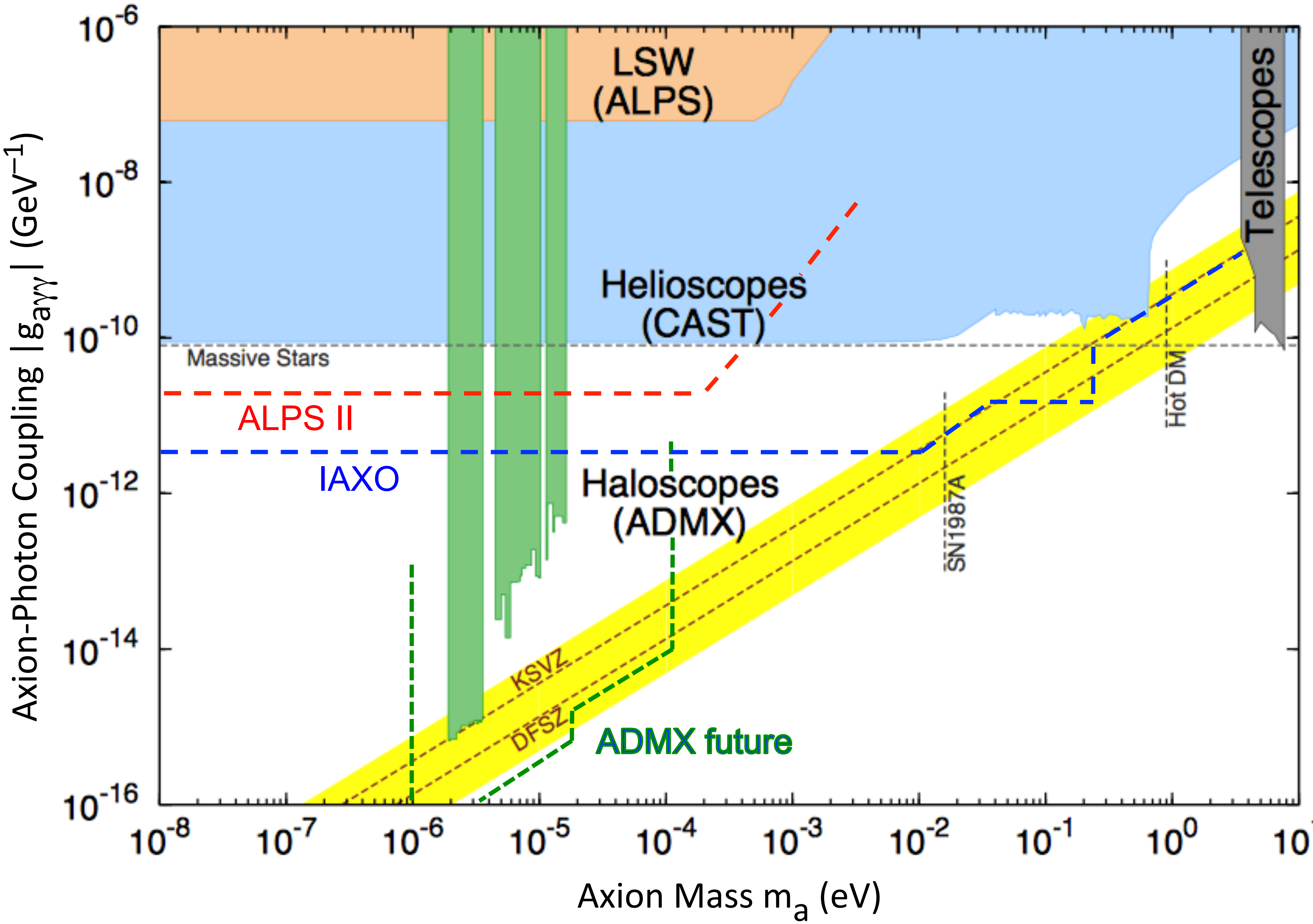
Extending the parameter space

KSVZ : Simplest 1 parameter axion model



Extending the parameter space

Lots of parameter space off of the QCD axion line



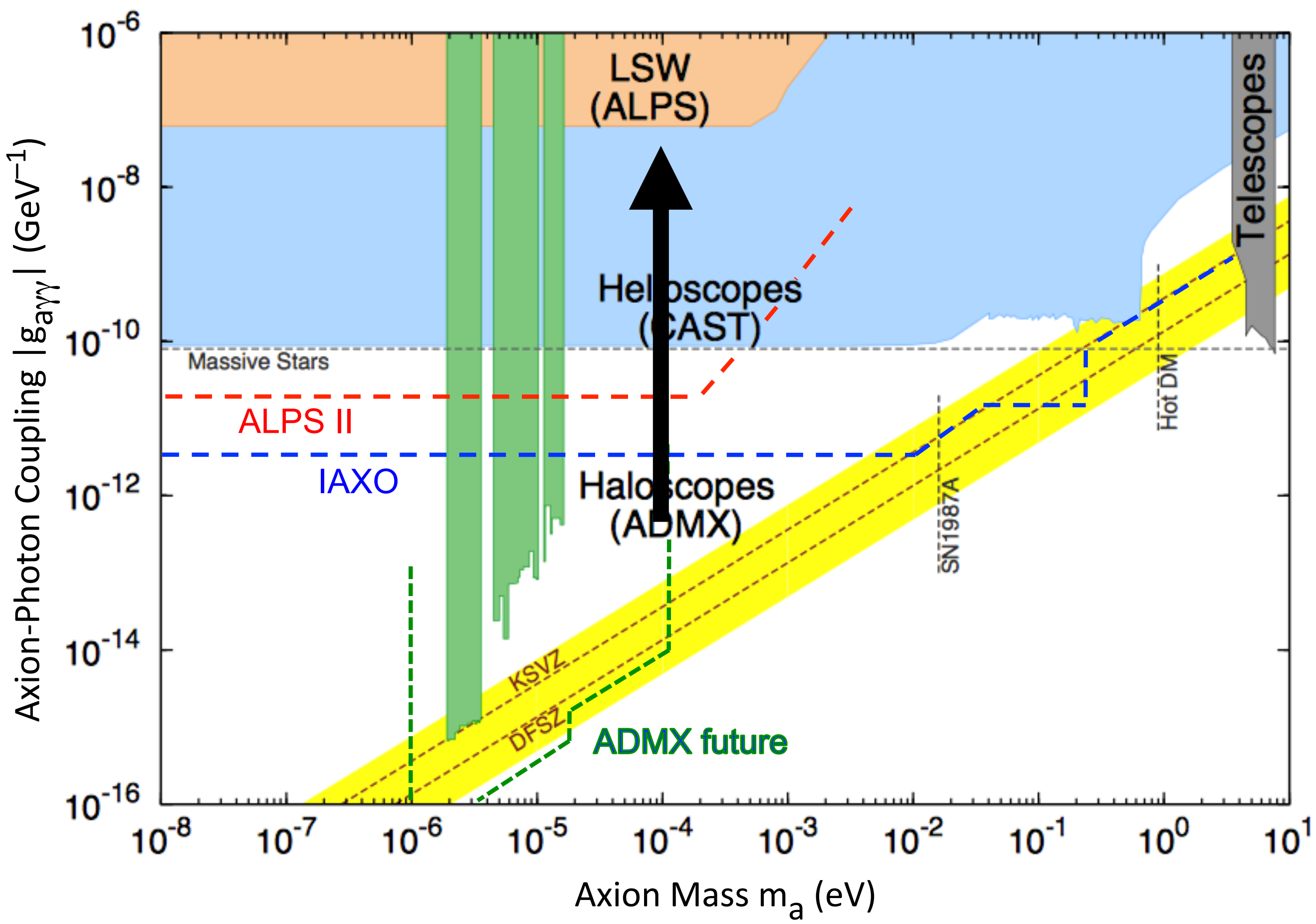
Span all of parameter space

Extend model of the axion so that you can cover all of the parameter space

Two approaches : change mass of the axion and change the coupling of the axion

Photon/Spin Couplings

More Strongly coupled



Large charge

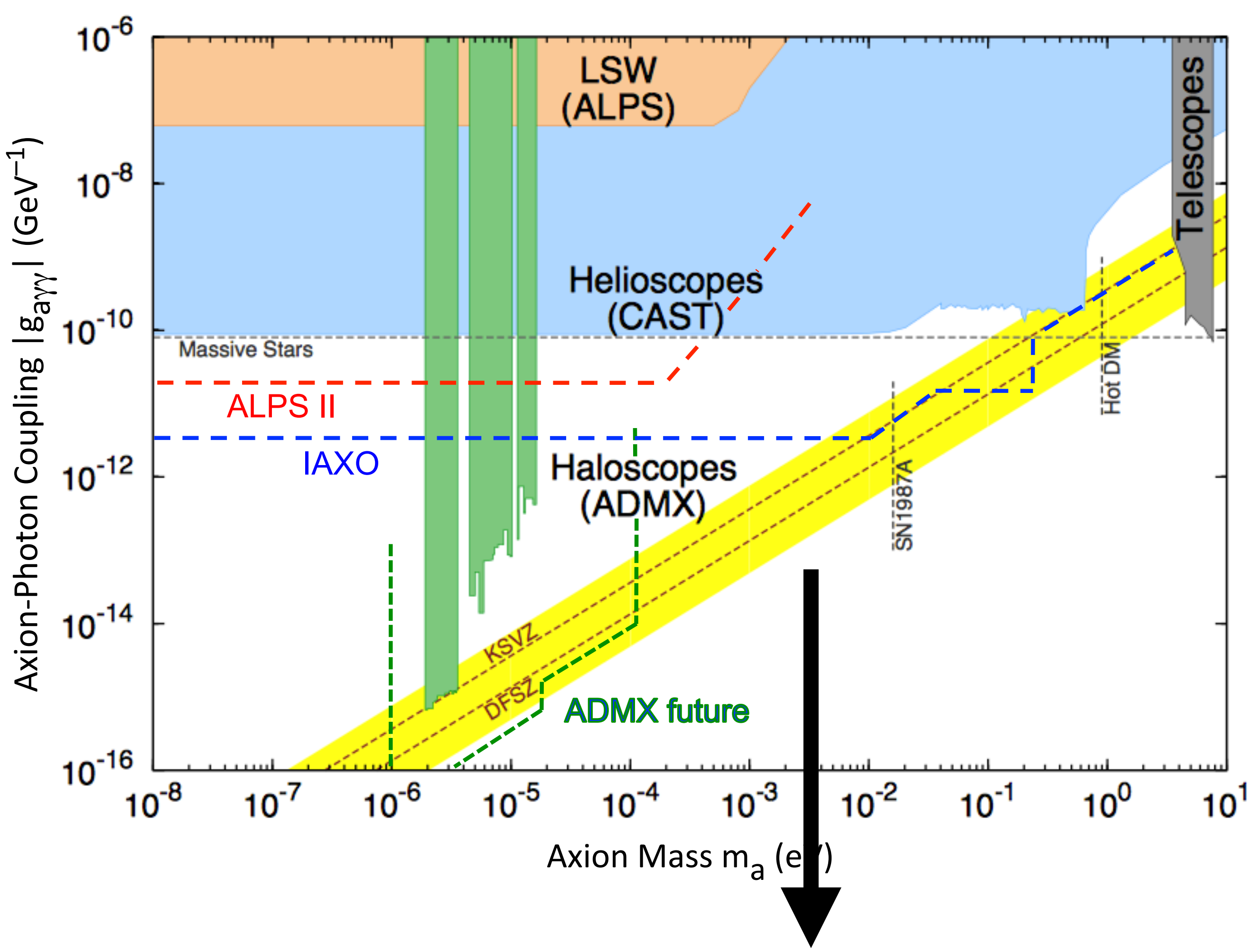
Clockwork

Mass mixing with ALPS

Kinetic mixing with ALPS

Photon/Spin Couplings

More weakly coupled



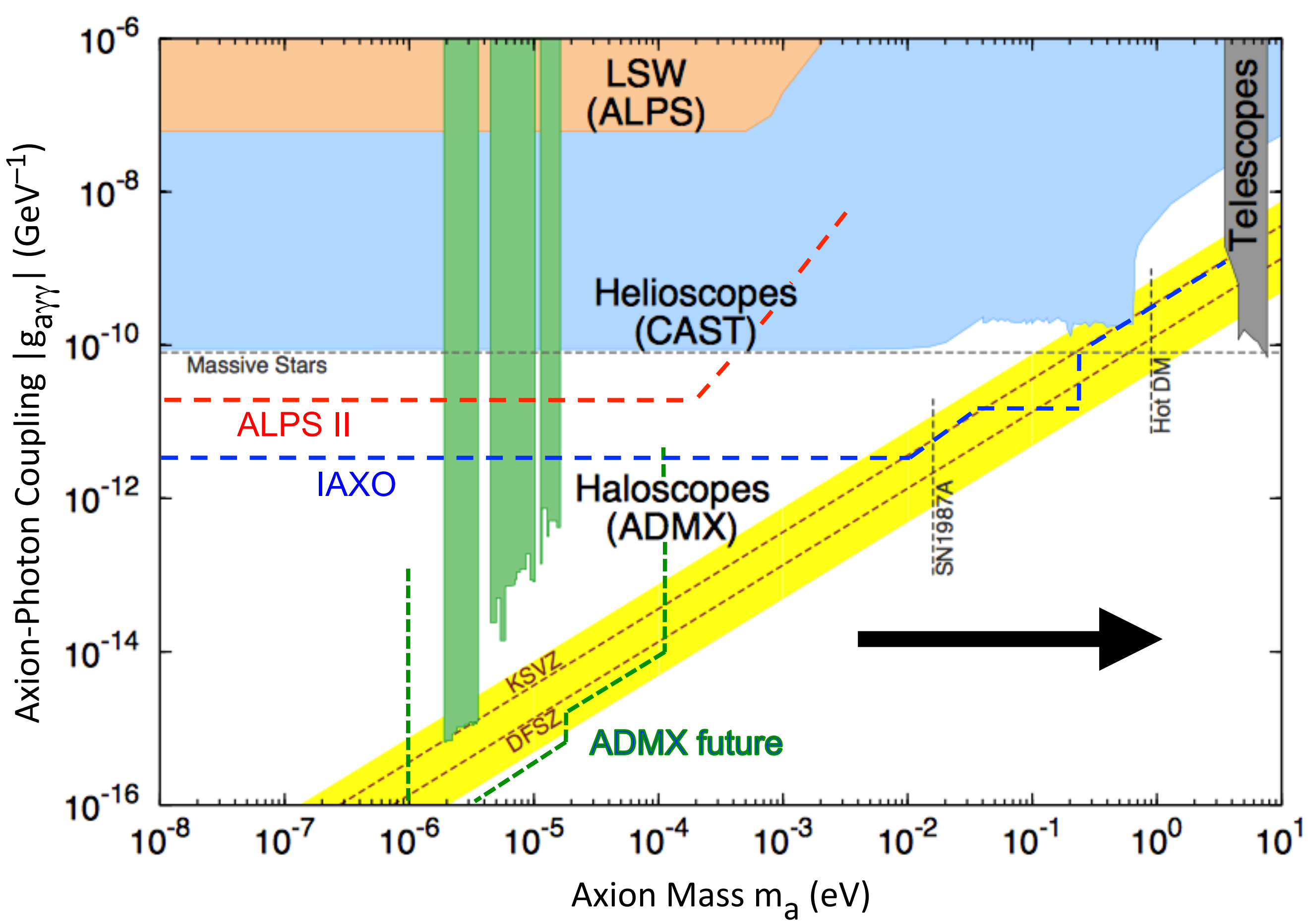
% level accidental cancelation for GUTs

Fine-Tuning

Opportunity for anyone with good ideas!

Mass

Heavier axions



Mirror worlds

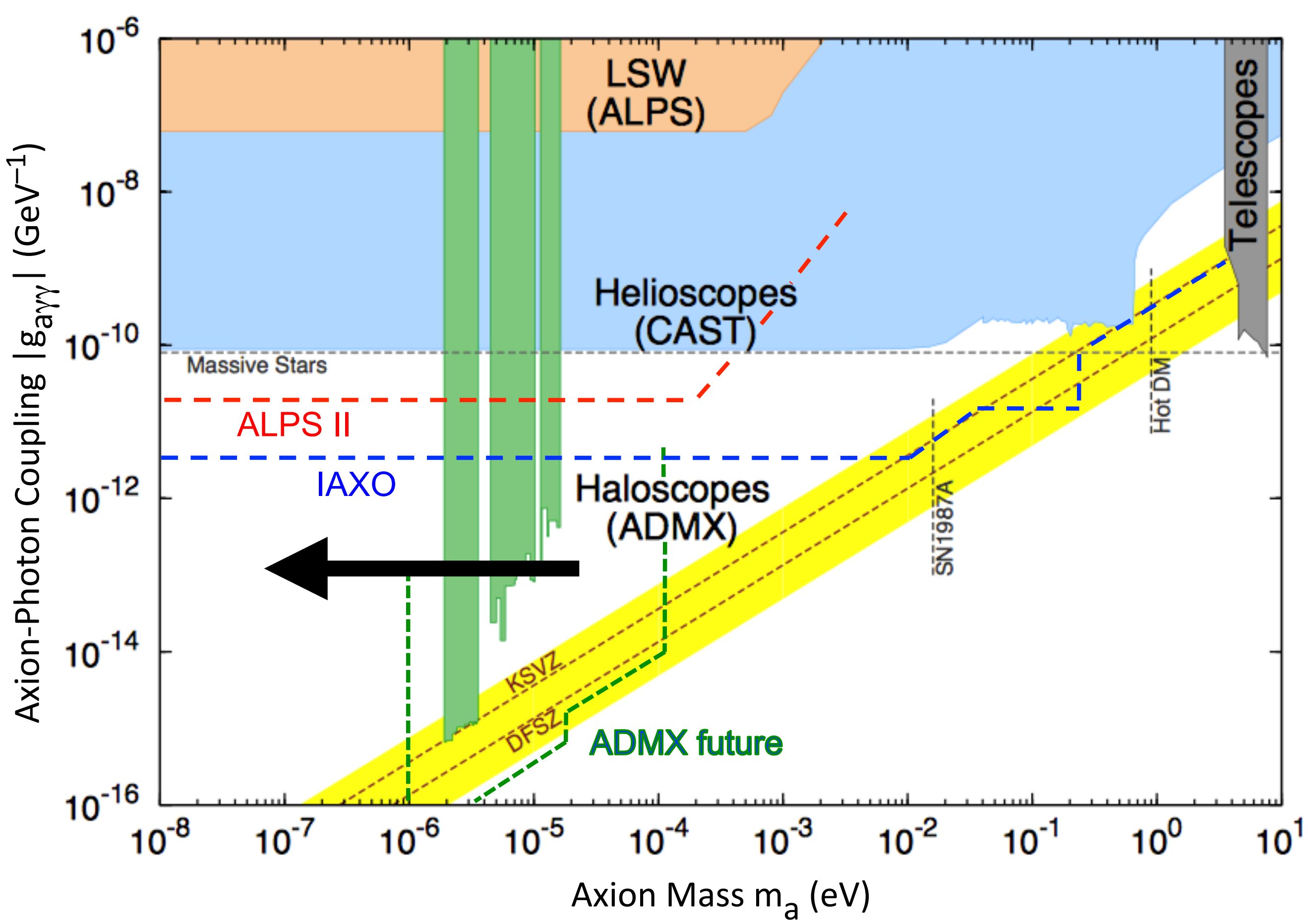
Discrete symmetries

UV instantons

Multiple Axions

Mass

Lighter axions



Discrete symmetries

Another opportunity for anyone with good ideas!

Span all of parameter space

Many models make the QCD axion more strongly coupled and heavier

Only 1-2 models make the QCD axion more weakly coupled and lighter

Great opportunity

Axion DM

Axion DM can easily be all of DM

1. Misalignment
   A. Multiple axions, Magnetic fields, Affleck-Dine, Inflation, Time dependent potentials, …
2. Topological Defects
3. Thermal production
4. Dark photons
5. …

m >> μeV : Oversaturated

m << μeV : Only misalignment

Great opportunity

Axion Strings

Axion Strings are woefully under explored theoretically

1. Superconducting
2. Large cross section with gluons/photons in the early universe
3. Scaling behavior/Emission of axions (Numerical)
4. Interesting GW/CMB/Polarization signals
5. …?

Lots of opportunities!

Quantization of electric charge

Axion couplings are connected to the quantization of electric charge

Unique opportunity to prove that E+M is U(1) not R

Fine structure constant

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

Axion periodicity

Quantization of electric charge

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

$$\mathcal{A} = \mathbb{Z}e_{\rm min}^2$$

Value of the anomaly informs us about the quantization of electric charge

Would be extremely interesting if something could be done with this fact

Conclusion

Axions are a simple solution to a simple problem

Theoretical progress in a few directions

Quality problem

Smaller masses

Expanding parameter space

Weaker couplings

Very Light Axions

Axion DM abundance

Axion strings

Needs more exploration

Quantization of charge