Searching for Wavelike Dark Matter: The Theory

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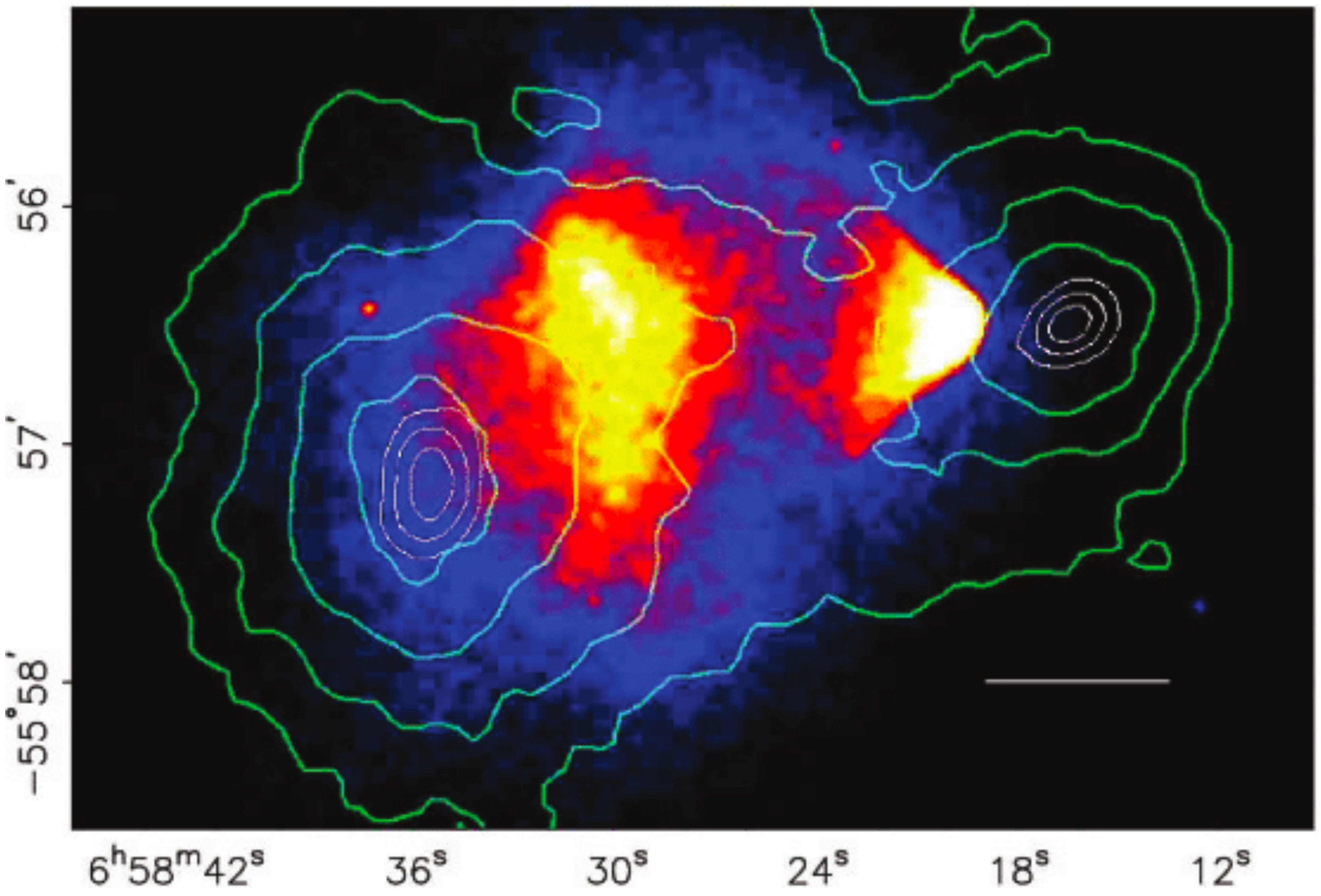
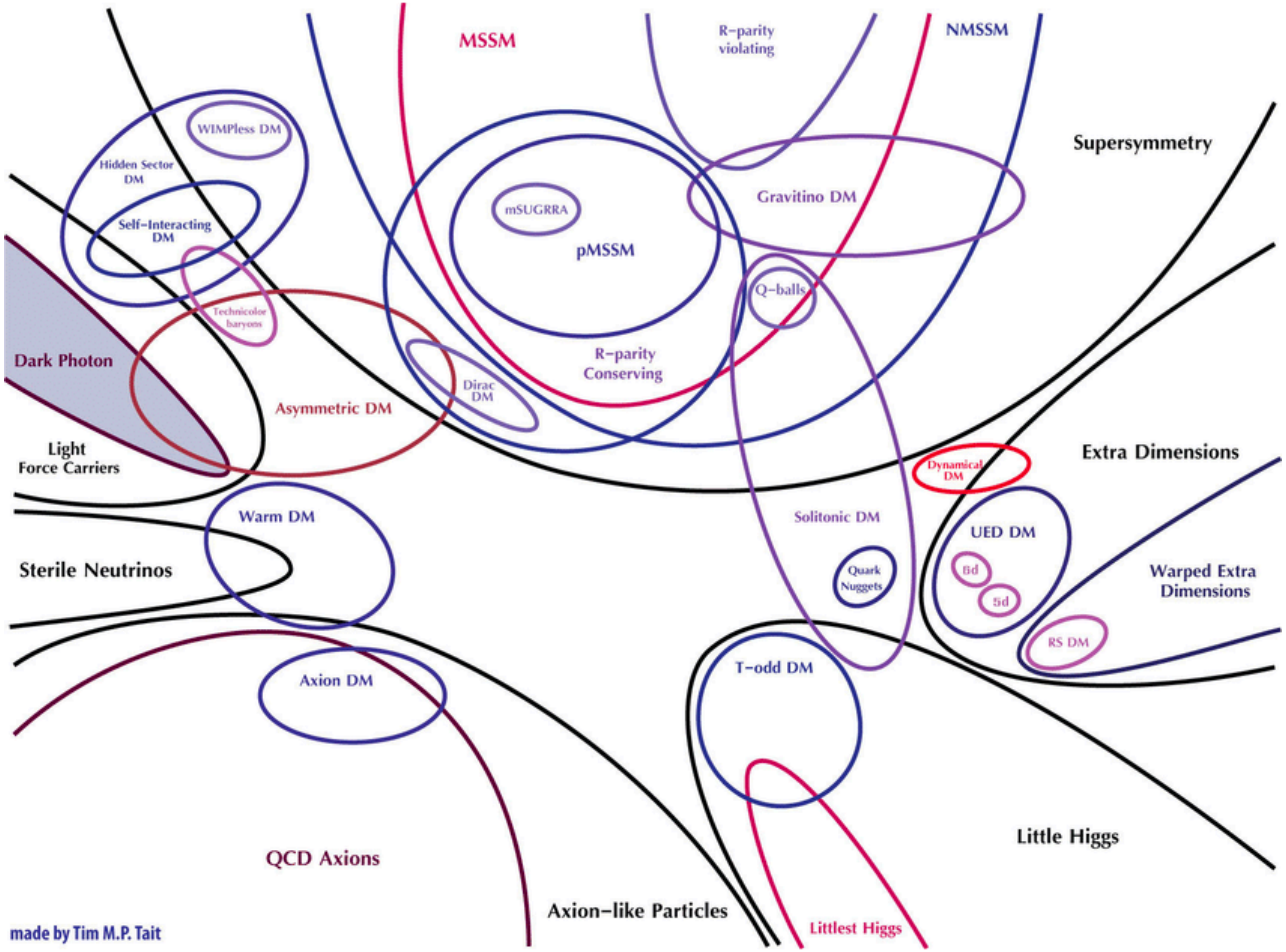
Dark Matter

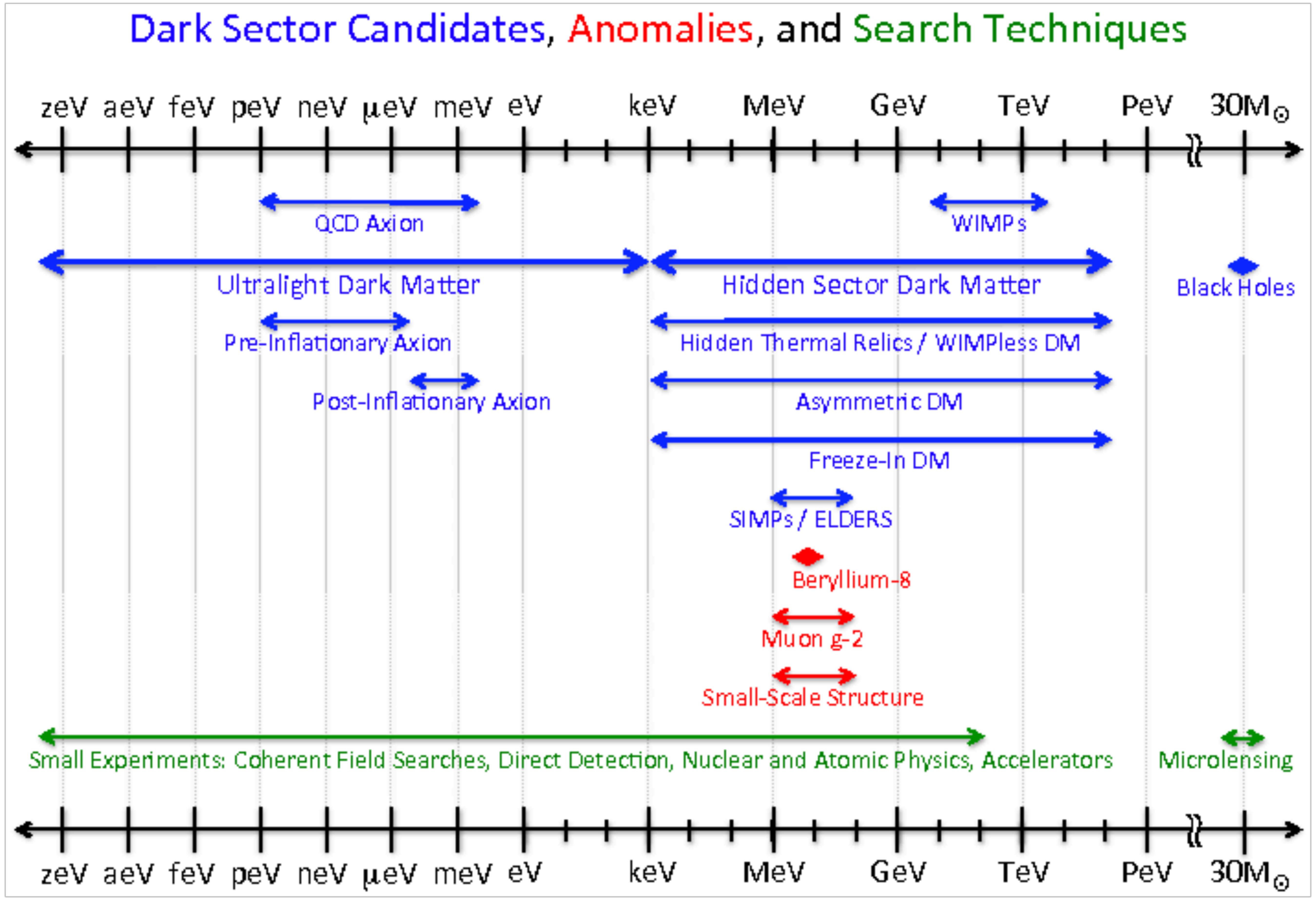
- Most (~85%) of the matter in the Universe is non-Baryonic
- Lacks electromagnetic or colour charges (probably)
- Modifications to gravity don't tend to work



Why Is Dark Matter So Hard to Solve?



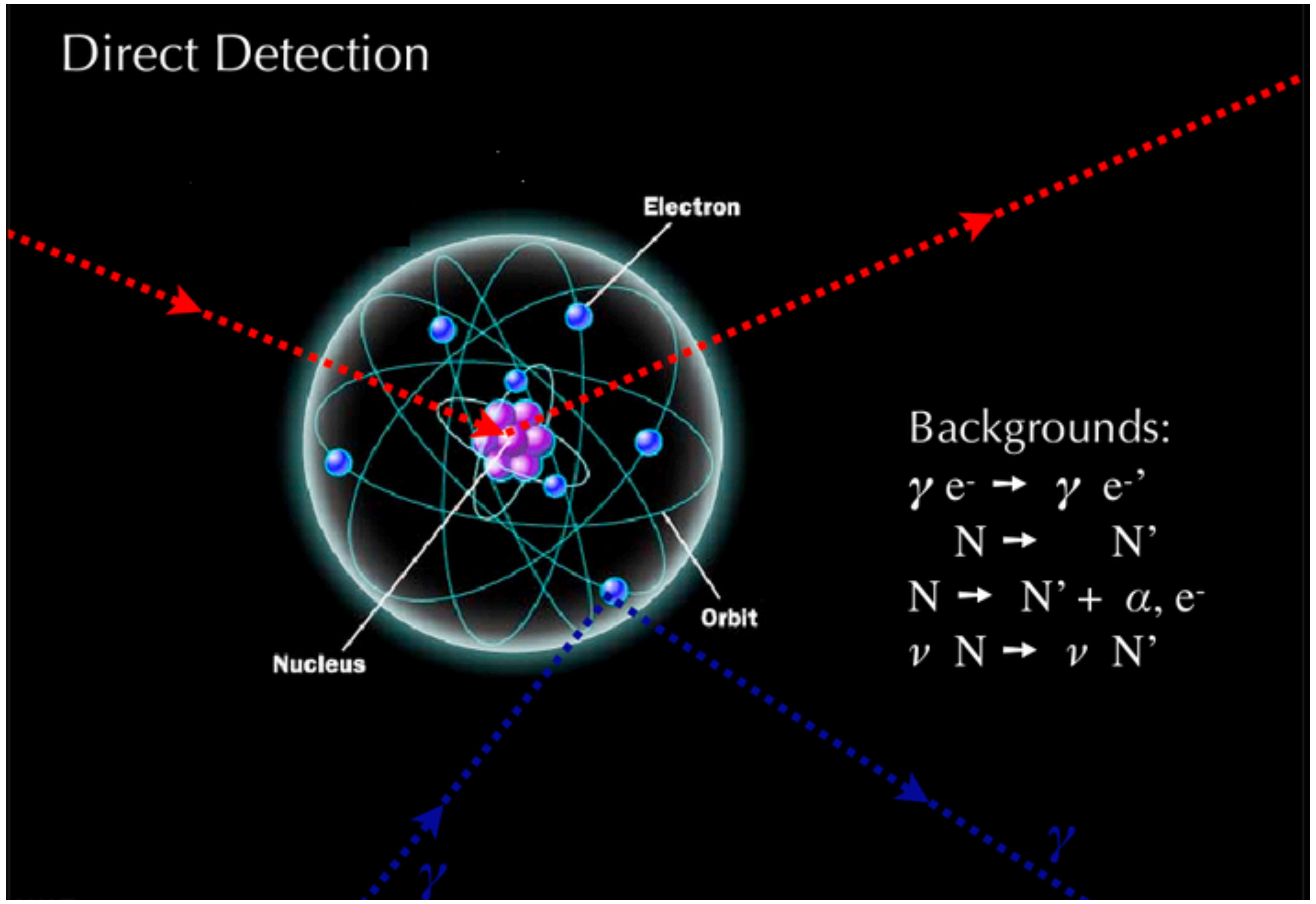
Why Is Dark Matter So Hard to Find?



Old Favourite: WIMP

The Problem With WIMPs

- No one has ever seen one!
- WIMP “miracle” relies on Weak force couplings… mostly ruled out
- SUSY not discovered at LHC



Wavelike Dark Matter

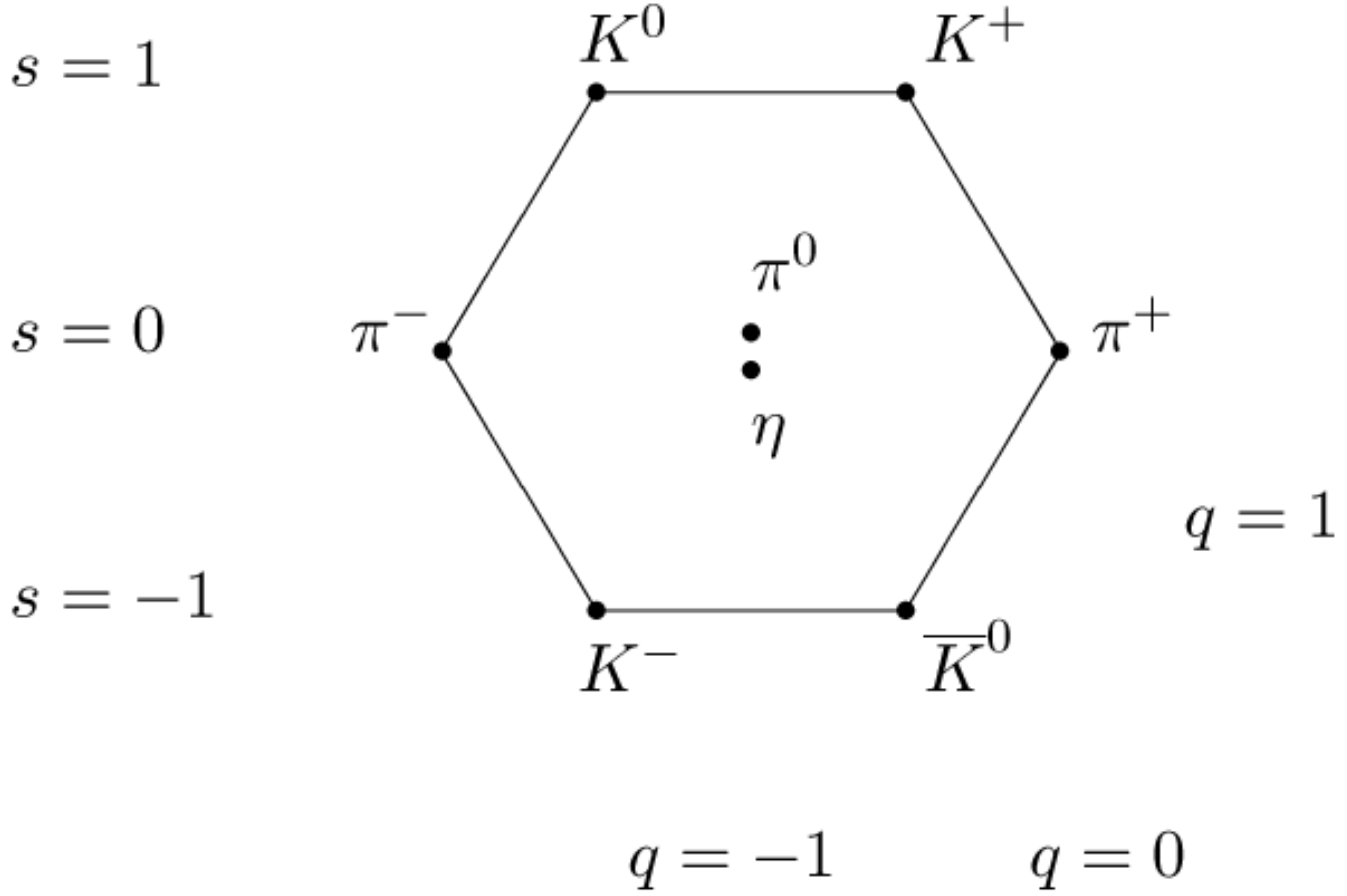
- Two classical limits of QFT: point particles and classical fields
- Wimps are an example of the first: heavy (~100 GeV) and low in number – direct detection looks for scatterings
- What about light dark matter, say below eV?
- Much higher occupation numbers (can be more than 10^{25}): usually treated as a classical field
- Totally different phenomenology

The U(1) Axial Problem

- The hadrons are arranged by symmetry structure
- Approximate symmetry due to low quark masses: independent rotations on the quarks

$$U(3)_R \times U(3)_L = U(3)_V \times U(3)_A$$

- The axial symmetries would be broken spontaneously by the quark condensate: 9 light peusdo-Goldstone Modes



The U(1) Axial Problem

- But we only see 8 light mesons!
- A nice argument by Weinberg says $m_{\eta'} < \sqrt{3} m_\pi$
- But $m_{\eta'} \sim 10 m_\pi$
- How can it be so heavy if its protected by a symmetry?

Meson	Mass
π^0	134 MeV
$\pi^\pm$	140 MeV
$K^\pm$	493 MeV
$K^0, \bar{K}^0$	498 MeV
η	549 MeV
η'	958 MeV

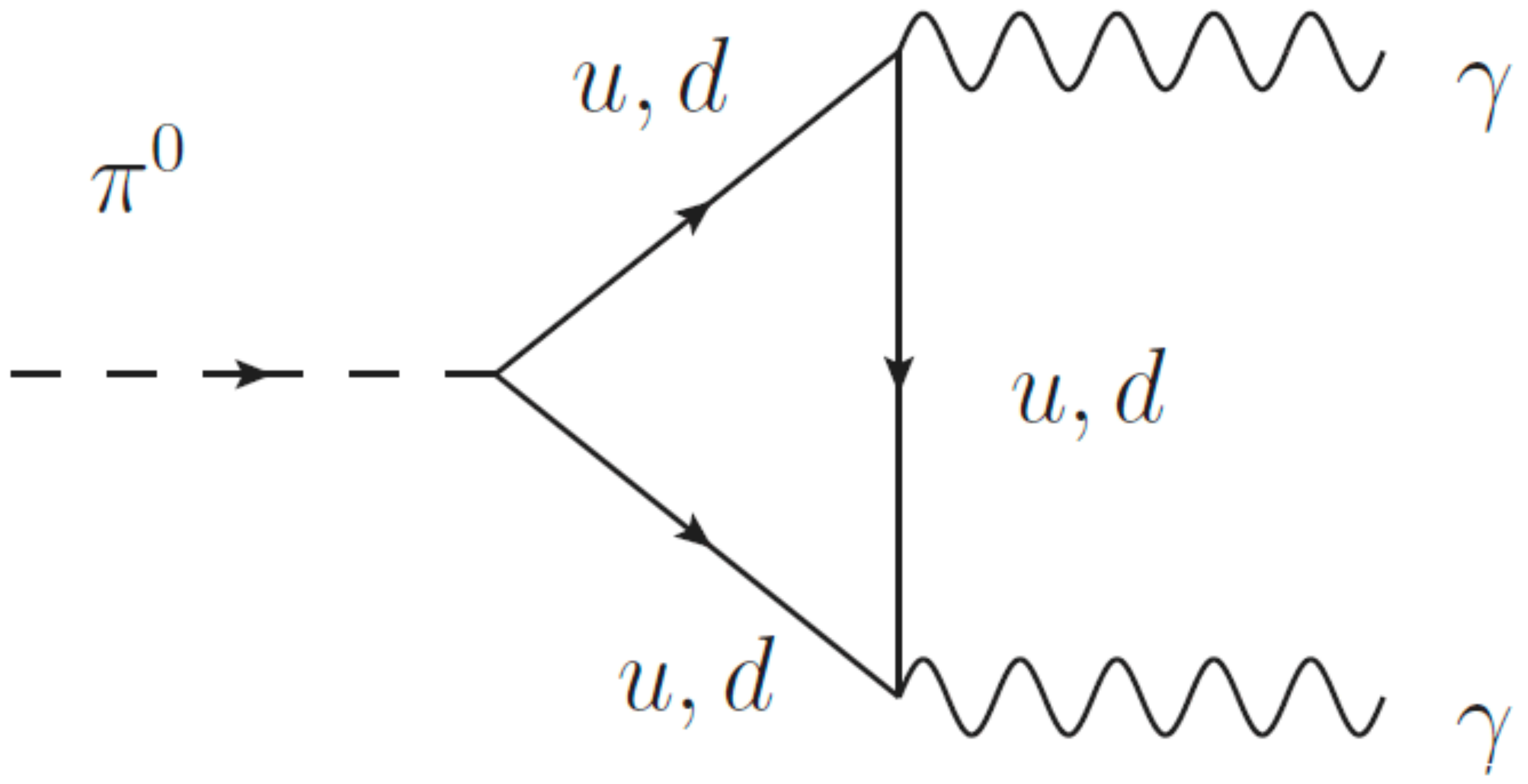
U(1) Axial Problem

- $U(3)_A$ is not a symmetry, $SU(3)_A$ is
- $U(1)_A$ is only a symmetry of the classical Lagrangian: the axial current isn't conserved

$$J^{\mu 5} = \bar{\psi}\gamma^{\mu}\gamma^{5}\psi$$

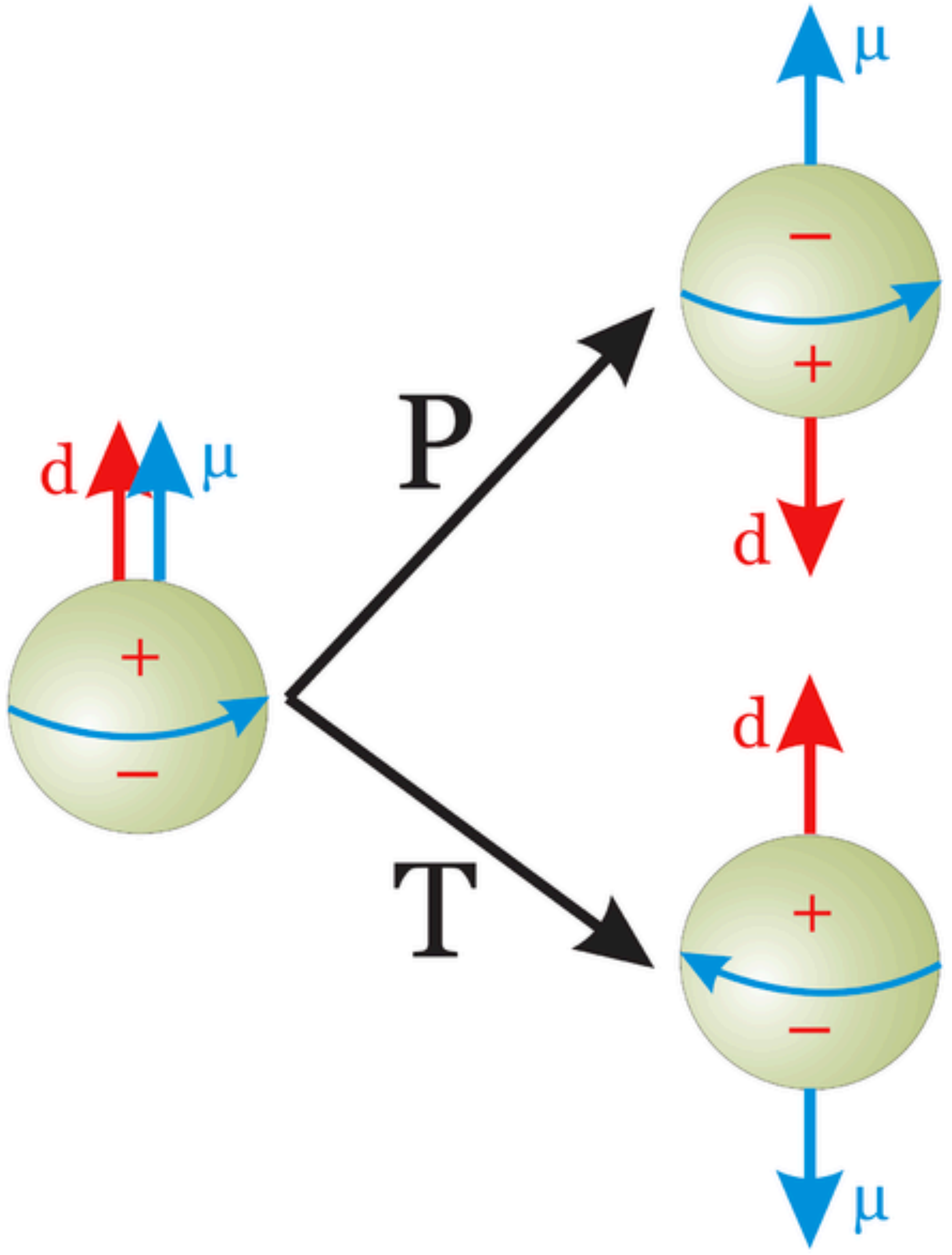
- Anomalously broken by a term proportional to a total derivative

$$\partial_{\mu}J^{\mu 5} \propto G\tilde{G}$$



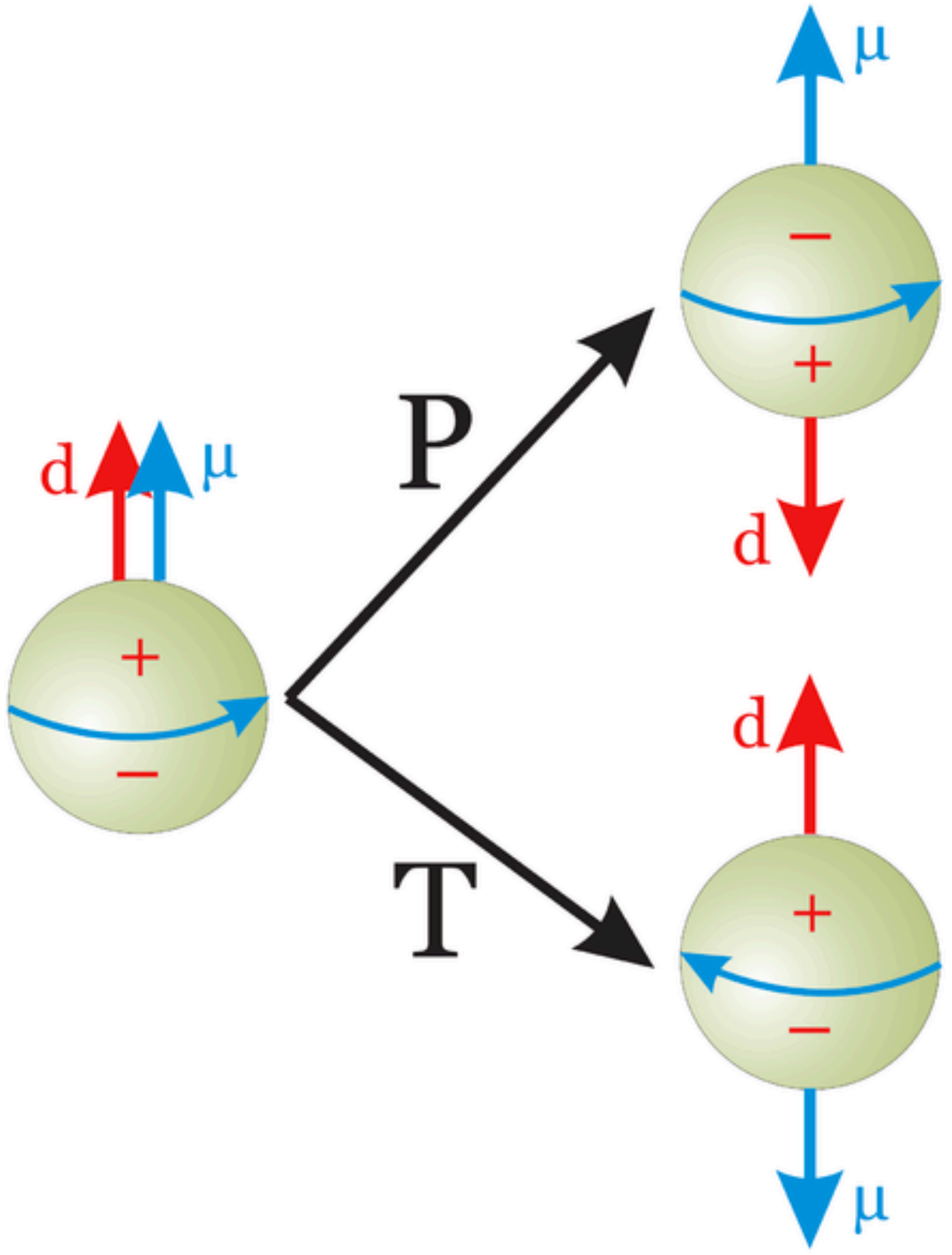
The Strong CP Problem

- Problem: now we can't just get rid of total derivatives
- What about the theta term? $$\theta \frac{g^2}{32\pi^2} G\widetilde{G}$$
- θ comes from some topological winding number
- This is like $E \cdot B$ for colour… violates P, CP (T)
- In principle can be $\theta \in [0,2\pi]$

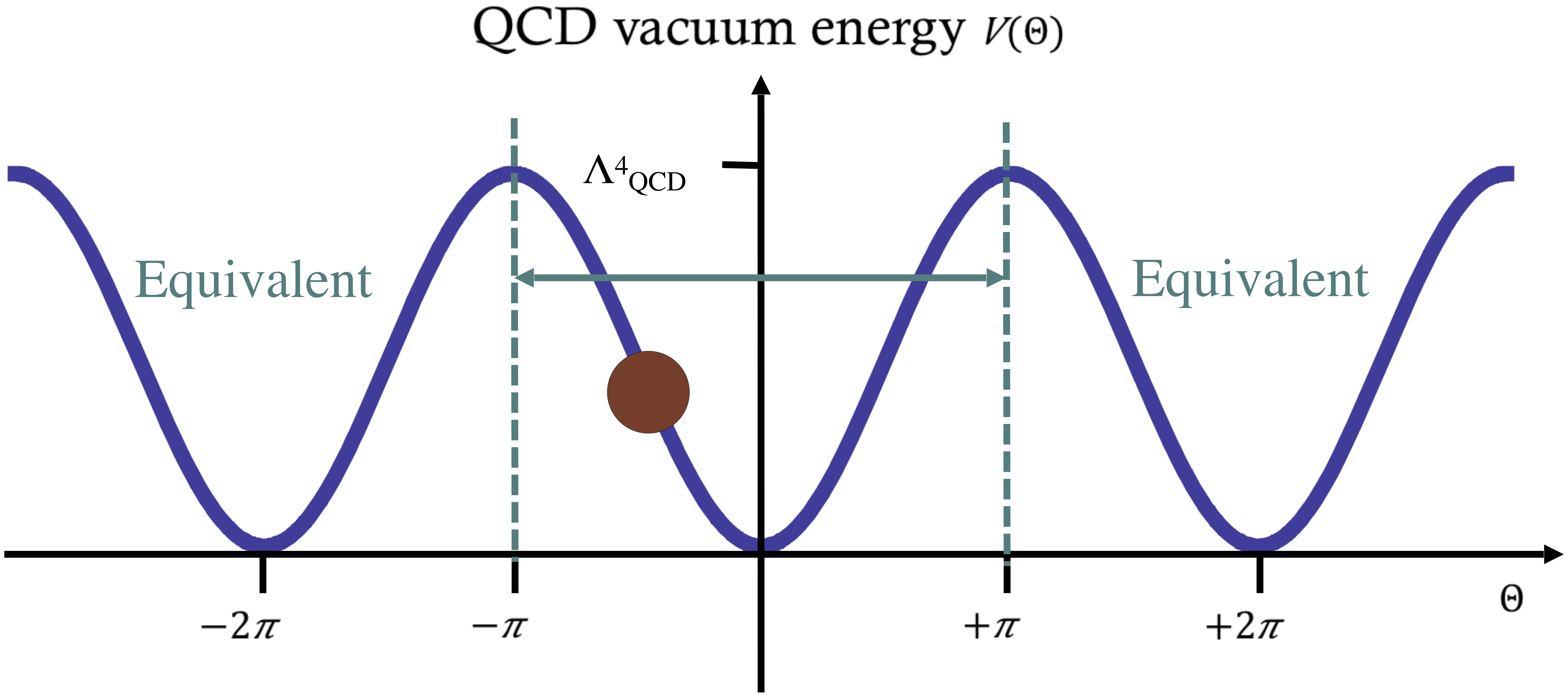


The Strong CP Problem

- Just go and measure it?
- Neutron electric dipole moment super sensitive
- $d_n = 2.4\theta \times 10^{-3}\mathrm{e\,fm}$
- Limit is $\theta \lesssim 10^{-10}$
- Why so small?



Strong CP problem



- θ=0 minimizes the vacuum energy, but θ is not a dynamical term

Solutions?

- Massless quark?
- Gives a new (chiral) axial symmetry, rephrasing the up quark θ unphysical
- $u_L \to e^{i\alpha/2}, u_R \to e^{-i\alpha/2}$ also makes $\theta \to \theta + \alpha$
- Mass ruins this, doesn't respect chiral rotations

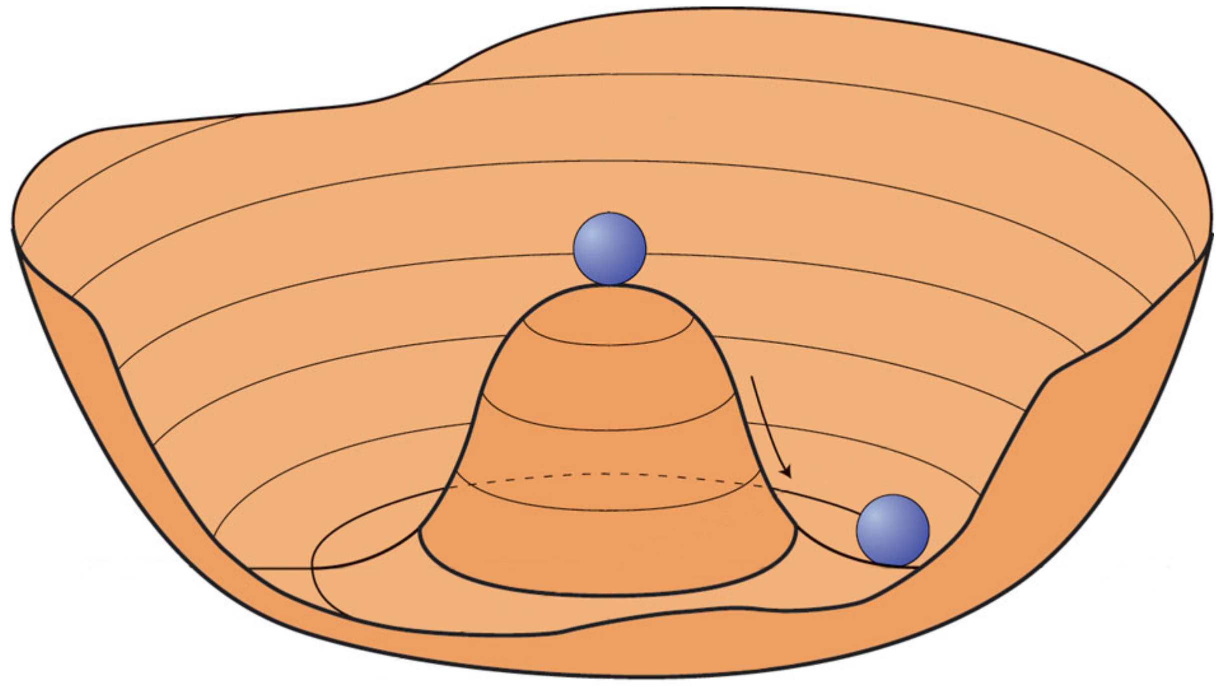
High Energy Picture

- What if we introduce new fields to make a U(1) chiral symmetry which is anomalous under QCD?
- Rotations under this new symmetry would similarly make θ unphysical
- Proposed by Peccei and Quinn, so called a PQ symmetry
- Needs new scalars (and maybe fermions) to make the symmetry

Low Energy Picture

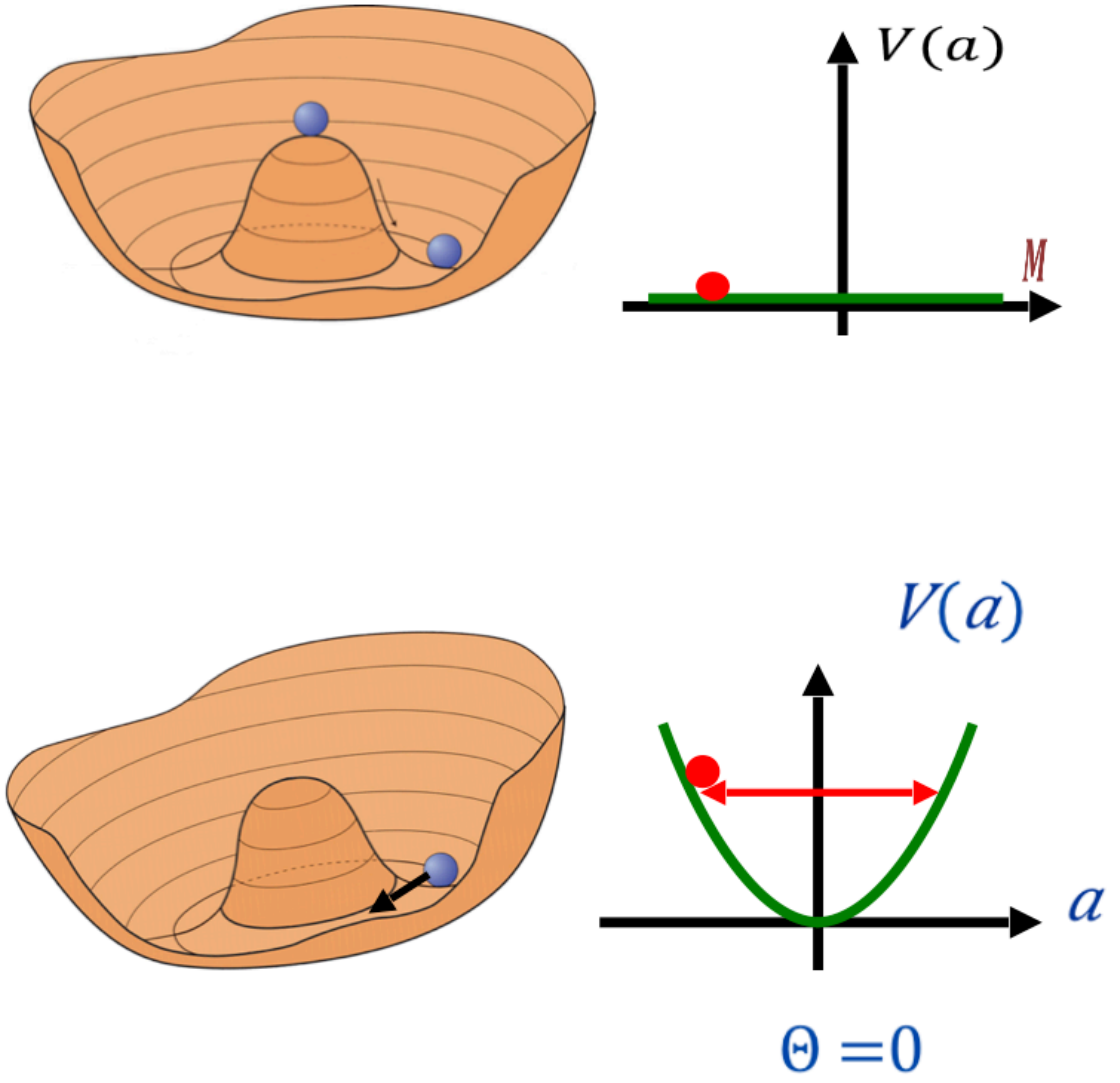
- The PQ symmetry is spontaneously broken at some scale f_a
- The "axion" is the angular degree of freedom: goldstone mode!
- This aspect was pointed out by Weinberg and Wilczek
- The radial part is very heavy, $m \sim f_a$
- Like all goldstone modes the couplings of the axion are all suppressed by f_a

$$\mathscr{L}_{\text{stand mod + axion}} = \ldots + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



Axions

- The shift symmetry is exact above the QCD scale (massless axion)
- At the QCD scale the potential tilts as the axion acquires a mass – axion rolls down to a CP conserving minimum
- Can be produced by misalignment or topological defects



DFSZ

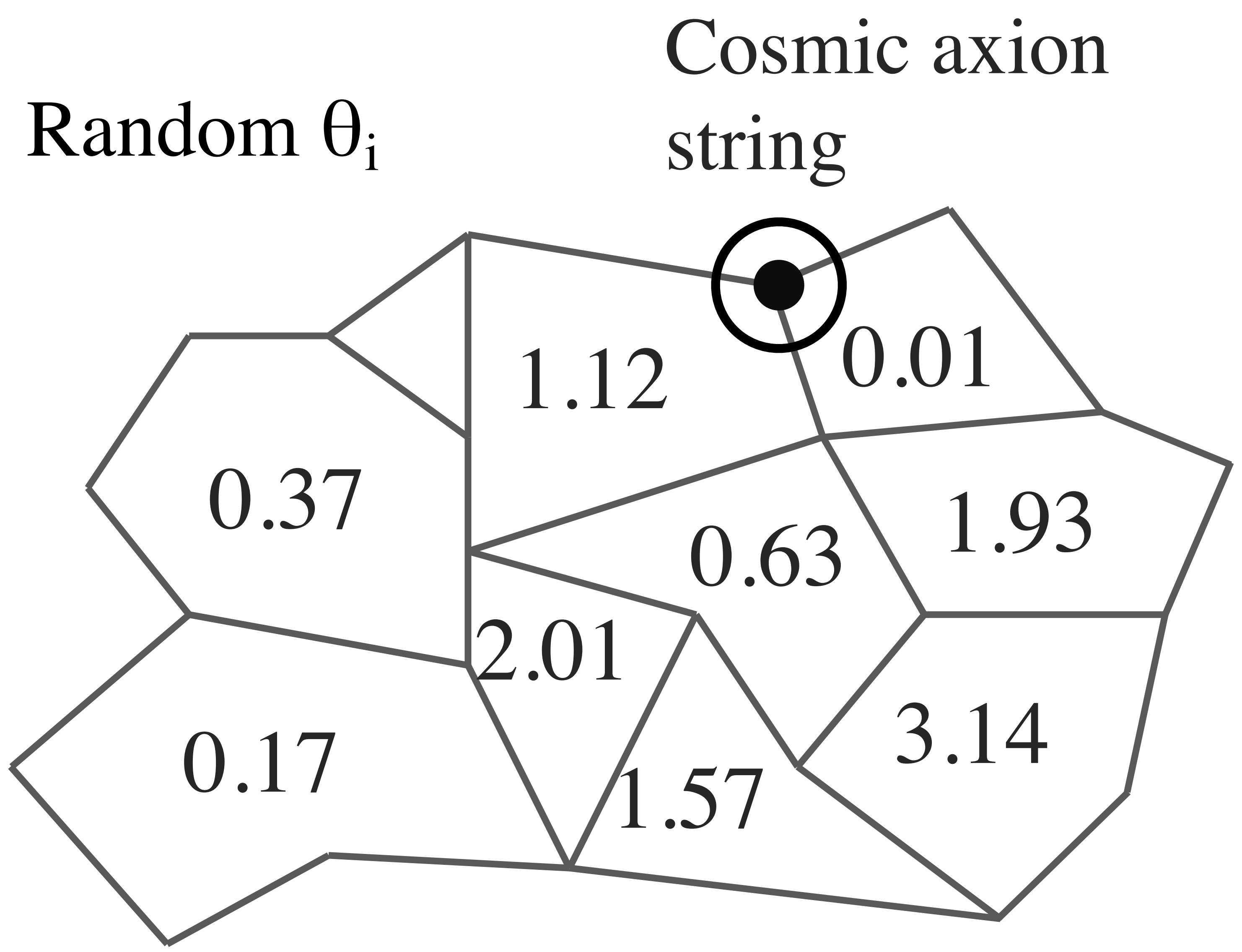
- Introduce a second Higgs and a SM scalar (which will make the axion)
- SM fermions have PQ charges
- 3 generations gives domain wall number 3
- Tree level axion-fermion couplings after symmetry breaking

KSVZ

- Similar singlet scalar, but no new Higgs
- Instead introduce new (heavy) coloured fermions
- Usually one, usually neutrally charged
- Domain wall number one
- No tree level couplings
- (“Hadronic” model)

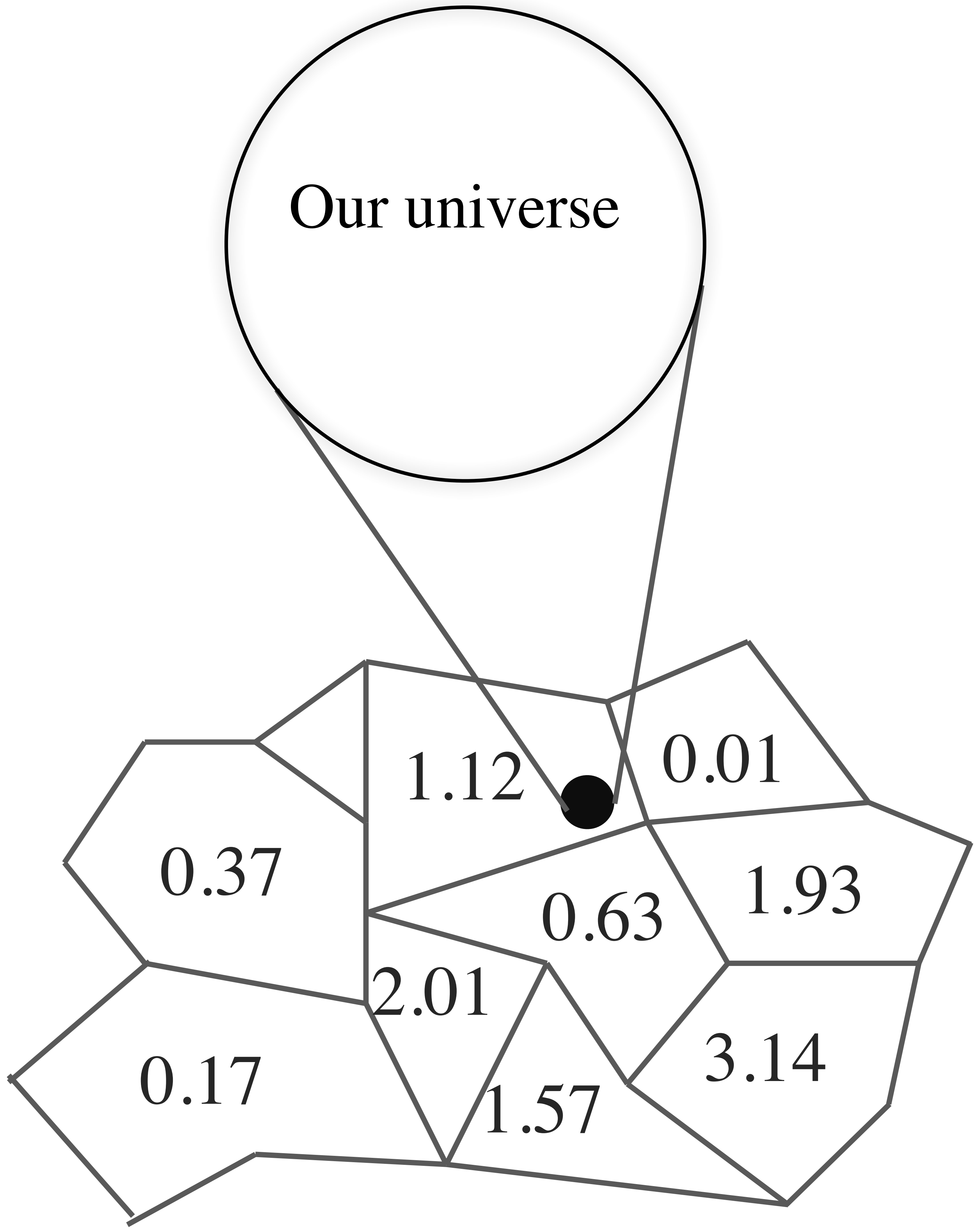
Axion DM: scenario 1

- Scenario 1: PQ broken after inflation
- θ_i has random values in every casual region, with the dark matter density determined by the average
- Topological defects such as strings and domain walls exist in the early universe



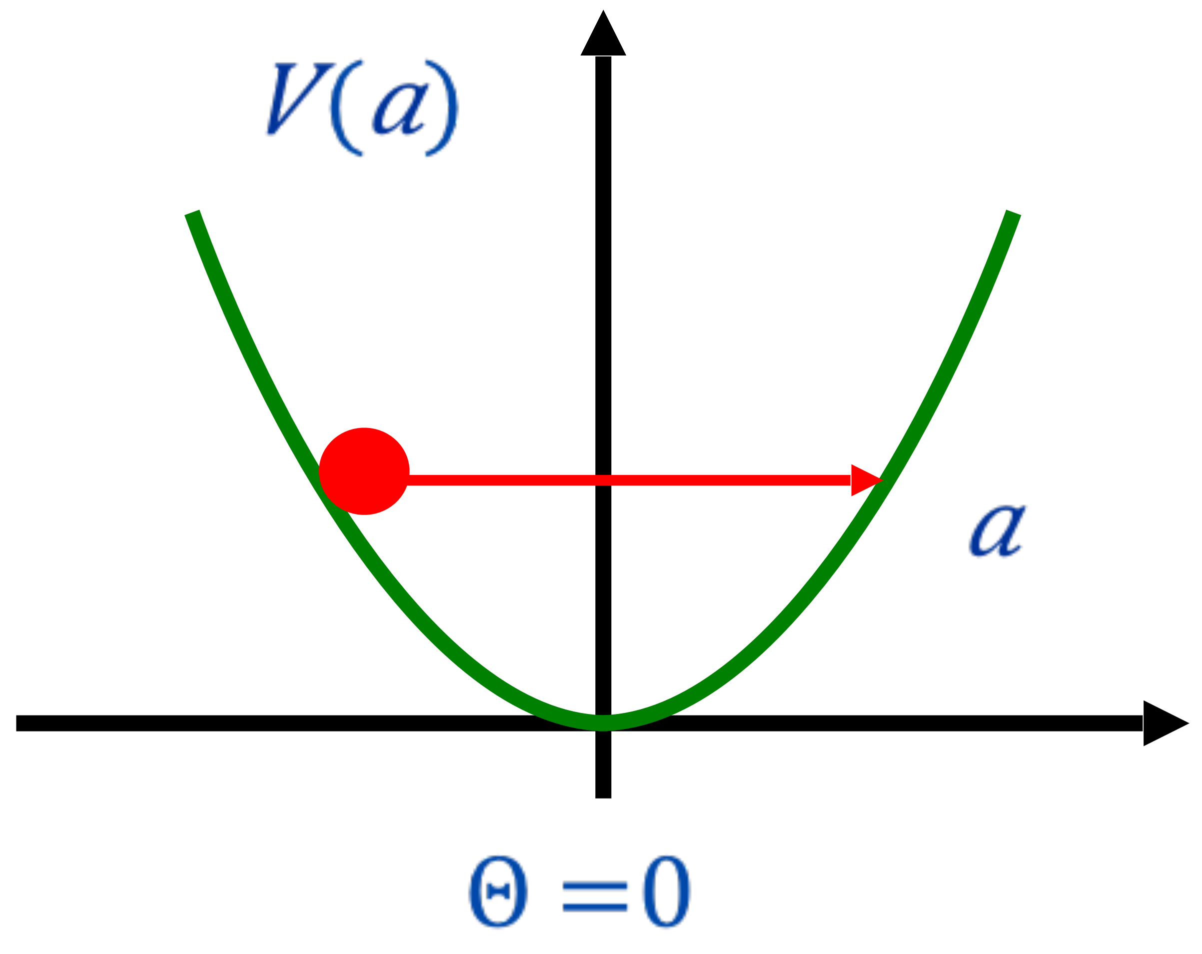
Axion DM: scenario 2

- Scenario 2: PQ broken before inflation
- θ_i has a single random value which determines the dark matter density
- No topological defects

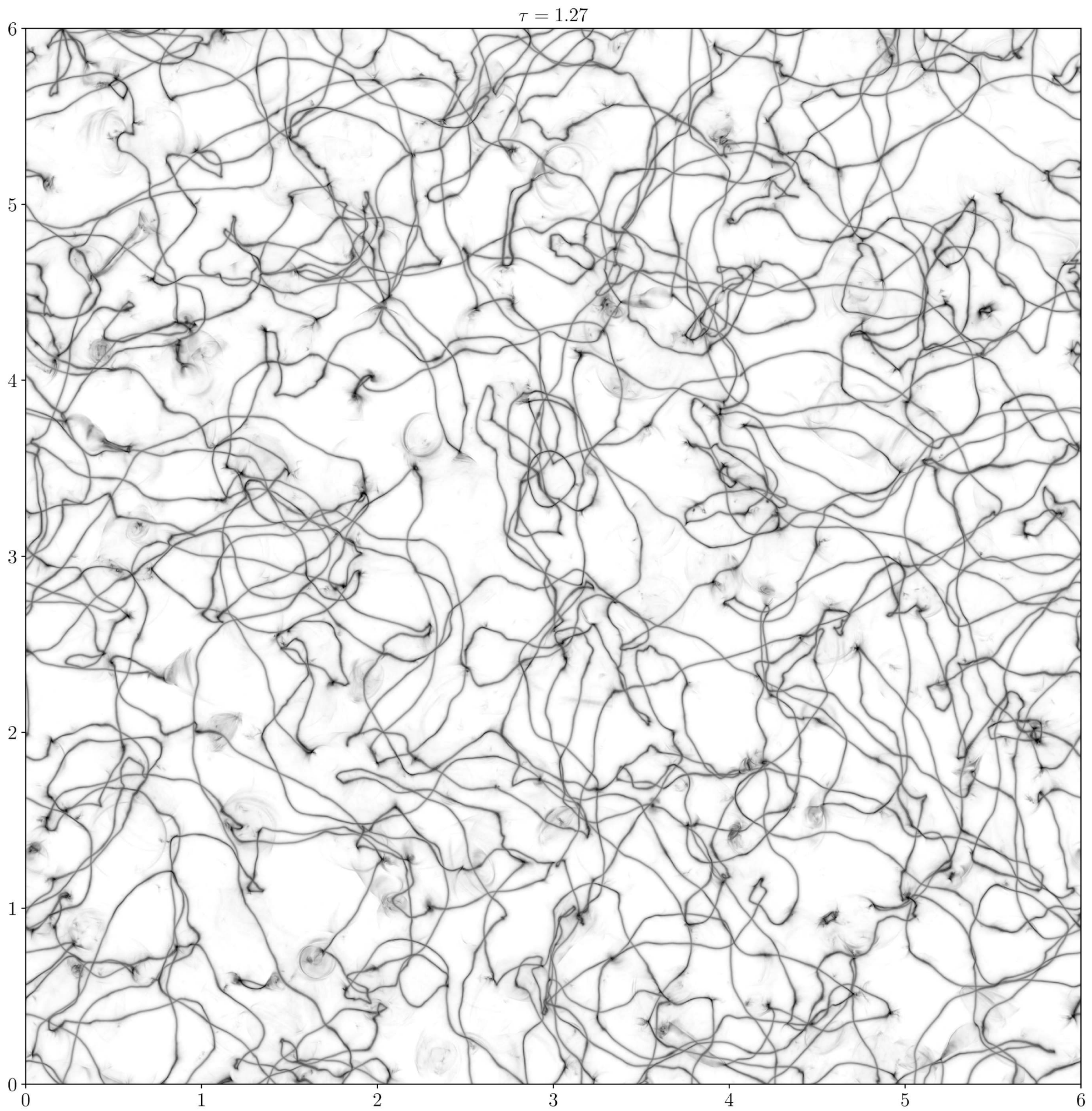


Axion production mechanisms

Vacuum Misalignment



Decay of topological defects



arXiv:1809.09241

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Axion production mechanisms

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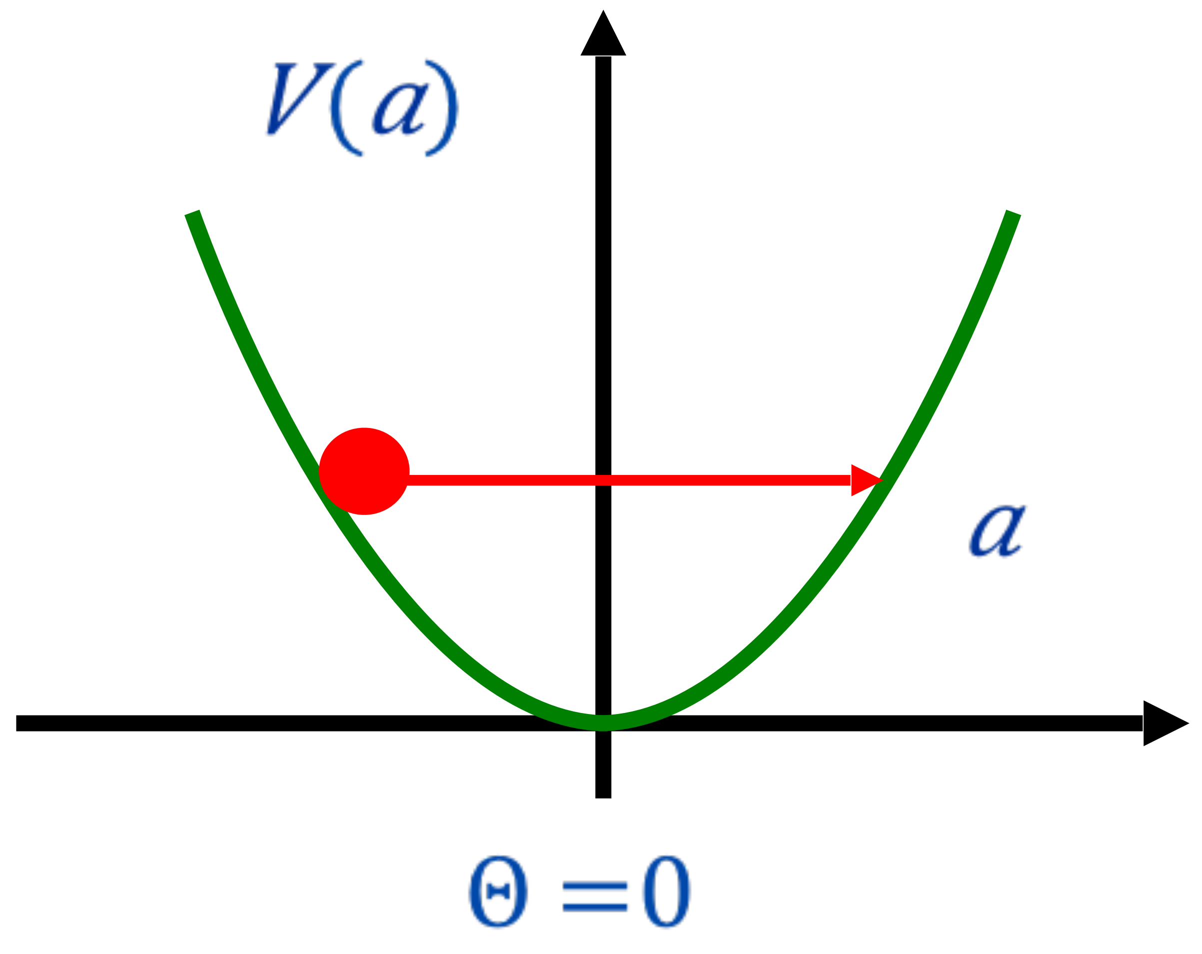

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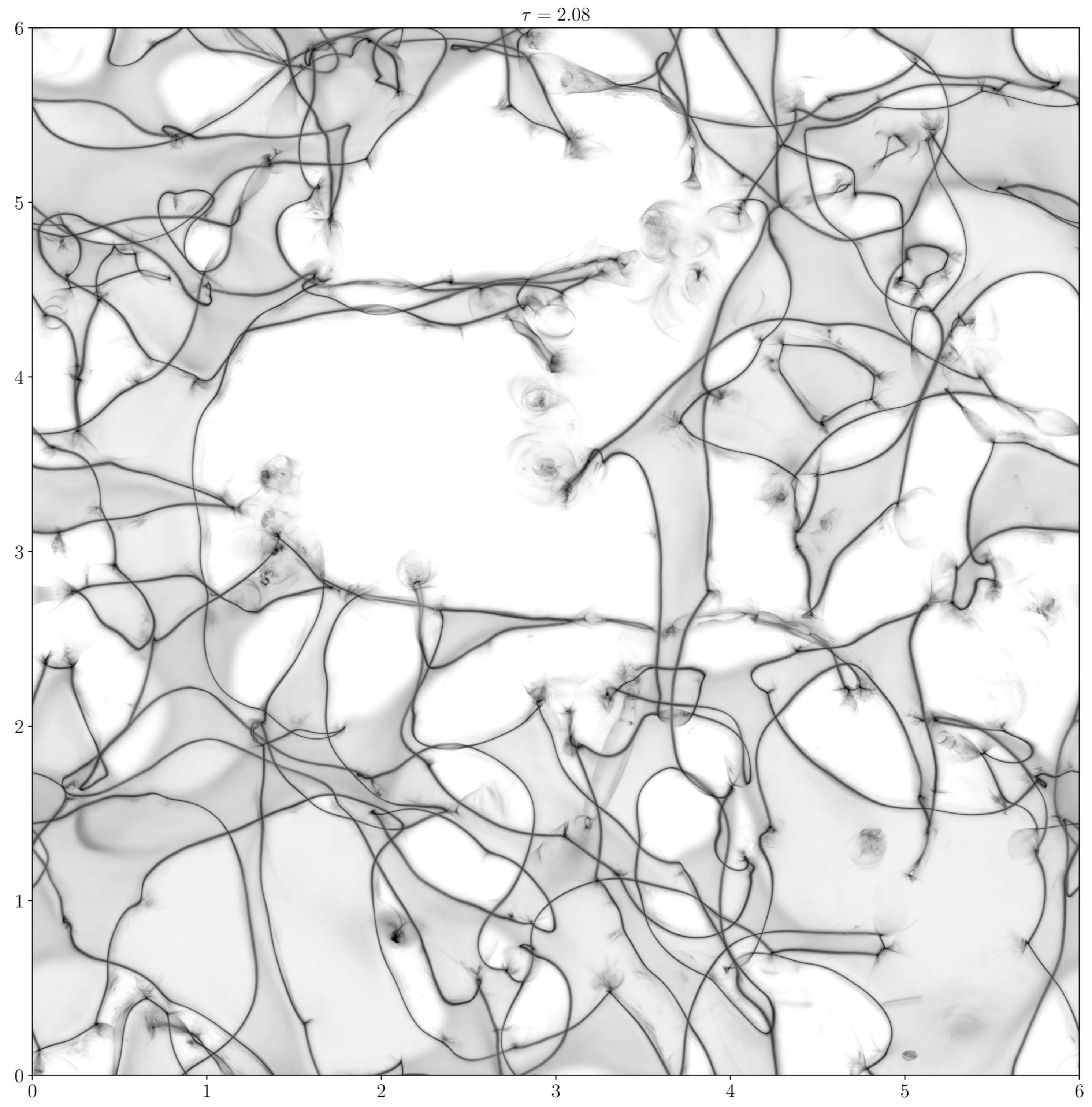

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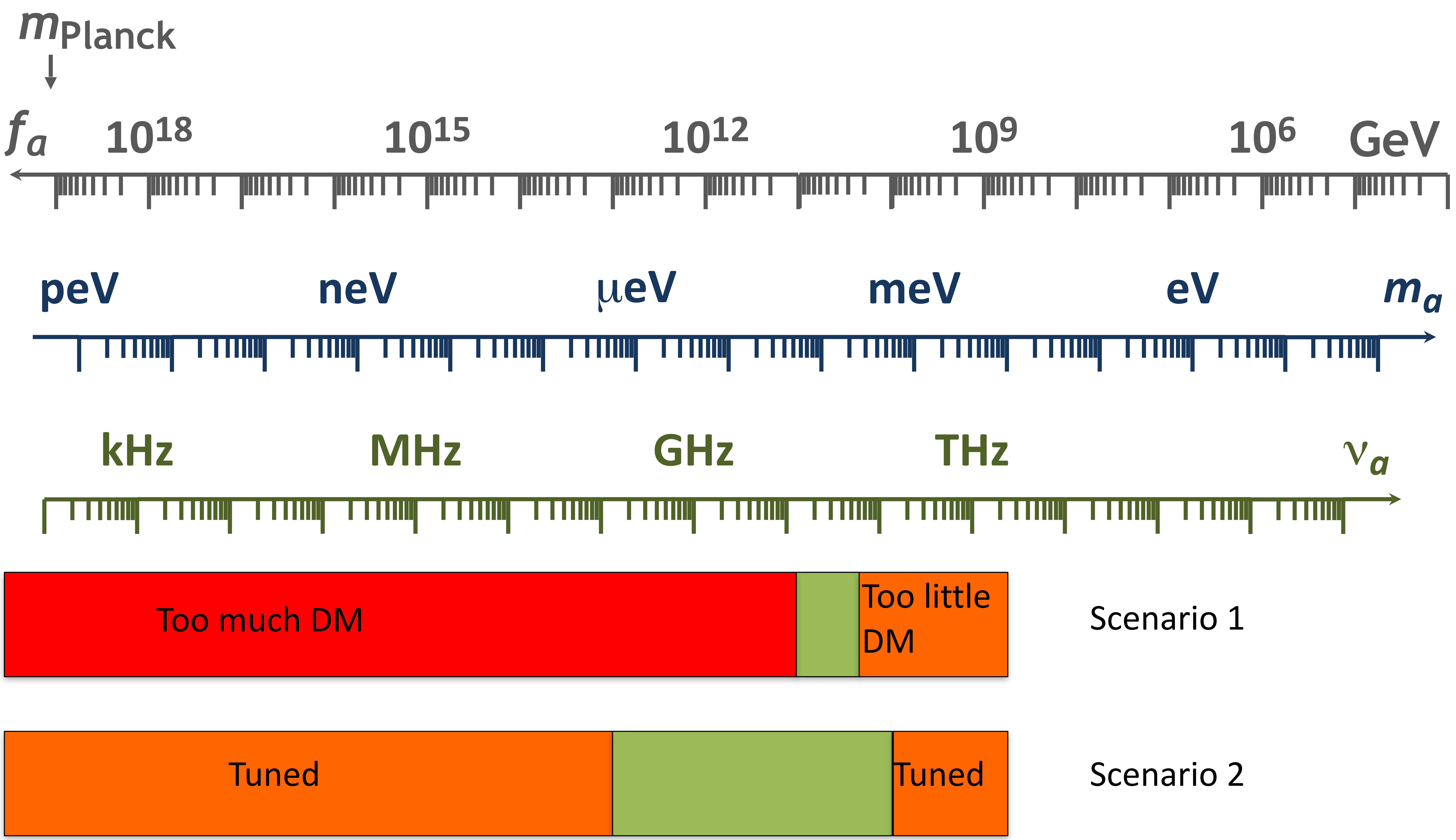

m_{Planck}
f_a 10^{18} 10^{15} 10^{12} 10^{9} 10^{6} GeV
peV neV μeV meV eV m_a
kHz MHz GHz THz ν_a
Too much DM
Too little DM
Scenario 1
Tuned
Tuned
Scenario 2

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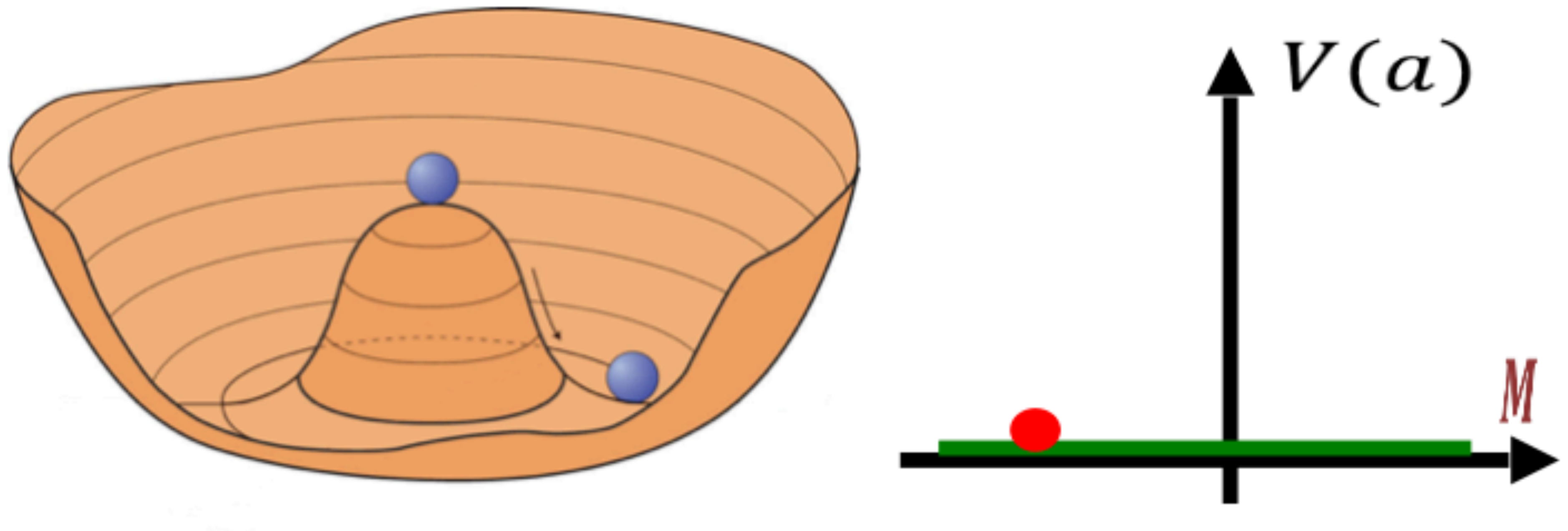
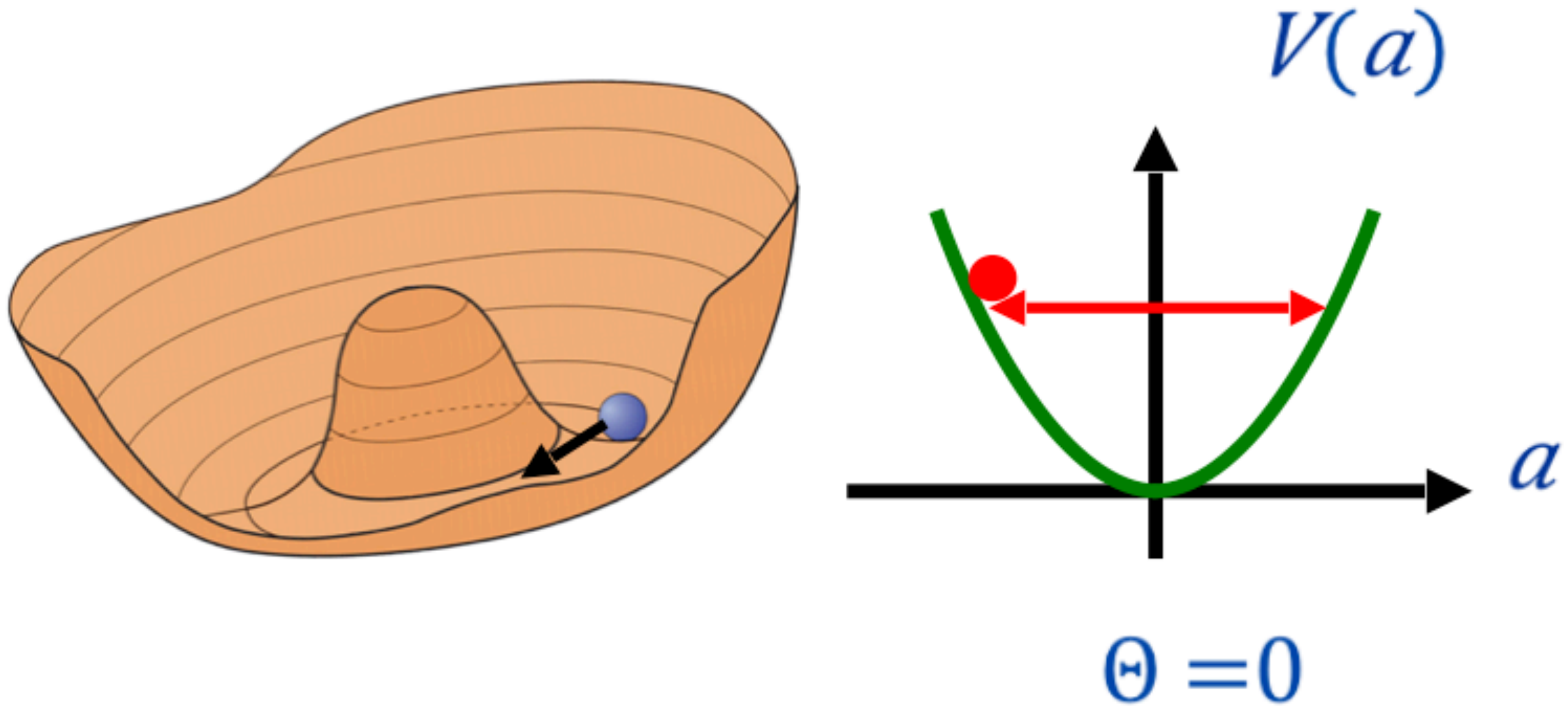
Axion-Like Particles

- General pseudo-scalar with a shift symmetry
- Does NOT solve Strong CP
- No fixed mass relation
- More general couplings
- Often comes from high energy theories





Axion-Like Particles

- Not just a cheap knockoff
- Can have stronger couplings!
- Can have lighter/heavier masses!
- Very useful in cosmology, for ULDM or CMB effects

Hidden/Dark Photons

- What about new vector particles?
- Introduce a new U(1) gauge boson

$$\mathcal{L} = -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{F}'_{\mu\nu}\tilde{F}'^{\mu\nu} + \boxed{\frac{\chi}{2}\tilde{F}_{\mu\nu}\tilde{F}'^{\mu\nu}}$$
$$+\frac{{m_X}^2}{2}\tilde{X}_\mu\tilde{X}^\mu + eJ^\mu\tilde{A}_\mu\,,$$

- Can have some small kinetic mixing with the photon (written here to lowest order)

Hidden/Dark Photons

- Easier to write it in the “interaction” basis

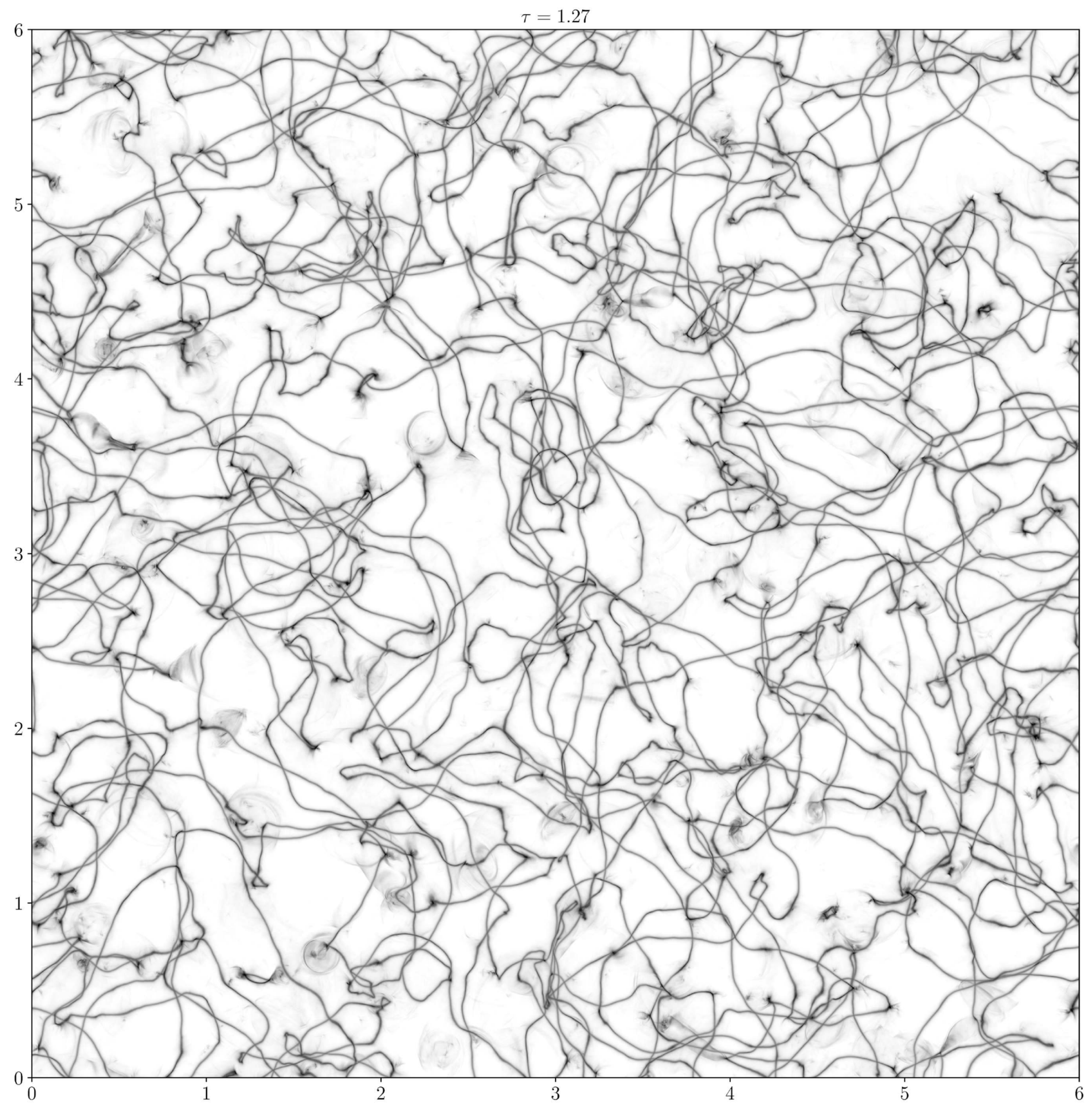
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + eJ^{\mu}_{\rm EM}A_{\mu} + \frac{m_X^2}{2}\left(X^{\mu}X_{\mu} + \boxed{2\chi X_{\mu}A^{\mu}}\right),$$

- Some differences if the mass comes from a Stueckelberg or Higgs mechanism

Hidden Photon Production

- Misalignment (can be before/after inflation)
- Quantum fluctuations during inflation
- Tachyonic instabilities
- Decay of topological defects like cosmic strings
- Rough estimates indicate polarisation should be unchanged over galactic timescales

$$\frac{\delta S}{S} \sim 4 \times 10^{-3} \left(\frac{v}{2 \times 10^{-3}}\right)^3 \frac{T}{13 \times 10^9\,\mathrm{yr}} \frac{8\,\mathrm{kpc}}{R},$$



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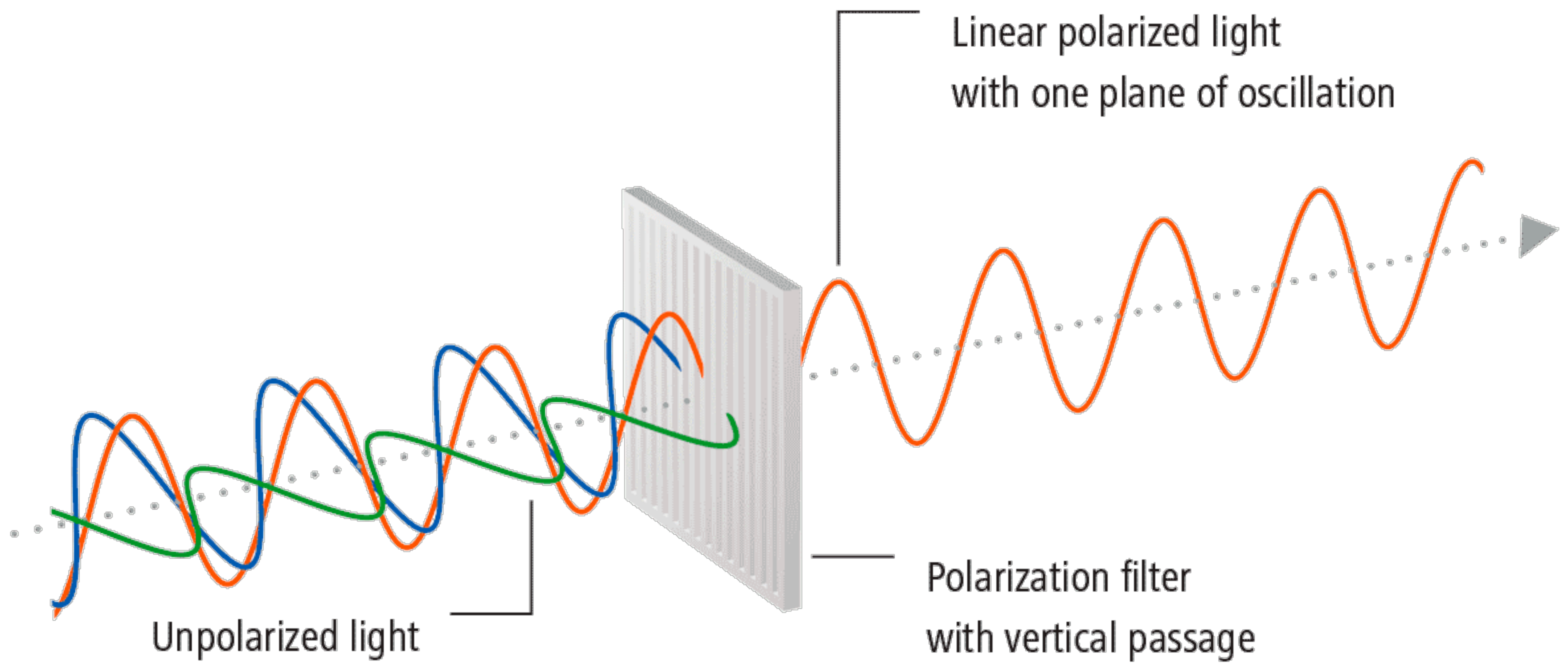
Hidden Photons vs ALPs

- Key difference: HP mixes in vacuum
- Key difference: HP has a polarisation!
- May be randomised or fixed depending on the production mechanism (or somewhere in-between)
- Structure formation may change this, but no detailed studies



Why Hidden Photons?

- Can appear in BSM theories
- Often axion searches are sensitive to HP
- “Easier” than axions
- Lots of other interesting ULDM!
- Scalars, B-L vectors…

Next time: Interactions