Ultra-light bosons beyond the Standard Model

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Outline

- The origins of ultra-light boson fields
- Cosmology-independent signatures of ultra-light boson fields
- Ultra-light boson Dark Matter

Why ultra-light bosons?

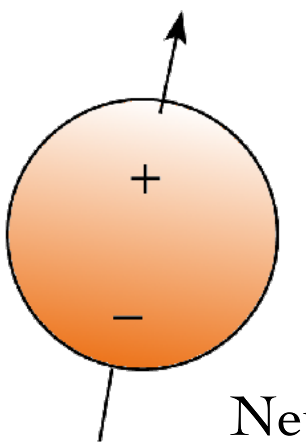
- Bottom-Up approach: They provide a consistent theoretical framework for BSM physics

- Top-Down approach: They appear as byproducts in many BSM theories, like those trying to explain the flavor problem

- In this talk: My point of view of what constitutes an excellent top-down approach

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron EDM

$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm θ_s

Experimental bound: $\theta_s < 10^{-10}$

Solution:

θ_s ~a(x,t) is a dynamical field, an axion

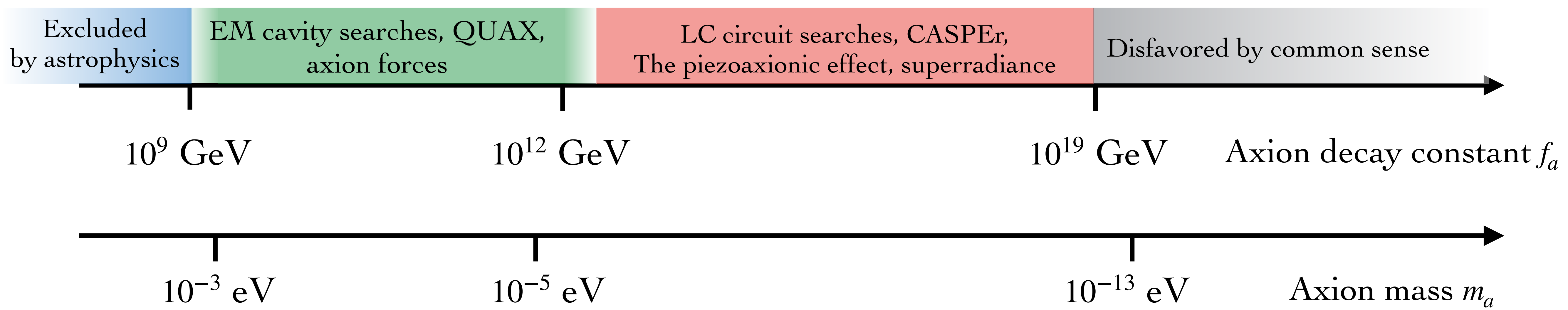
Axion mass from QCD:

$$\mu_a \sim 6 \times 10^{-11}\ \mathrm{eV}\ \frac{10^{17}\ \mathrm{GeV}}{f_a} \sim (3\ \mathrm{km})^{-1}\ \frac{10^{17}\ \mathrm{GeV}}{\mathrm{f_a}}$$

f_a : axion decay constant

Mediates new forces and can be the dark matter

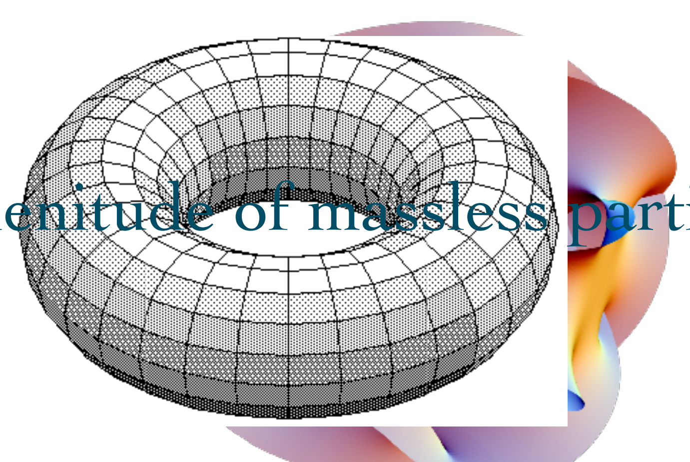
Parameter Space of the QCD axion

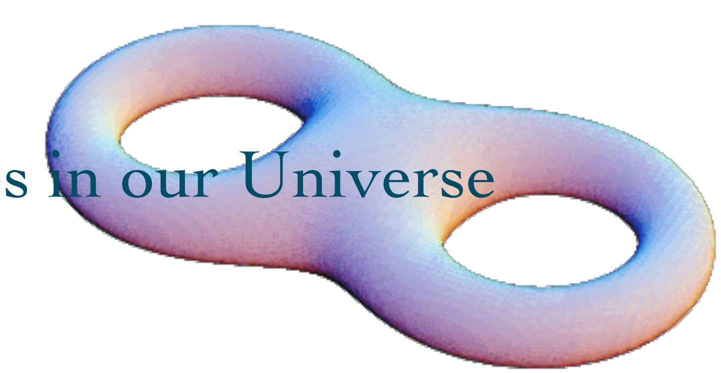


A Plenitude of Particles from String Theory

- Extra dimensions

Give rise to a plenitude of massless particles in our Universe





A Plenitude of (Almost*) Massless Particles

- Spin-0 non-trivial gauge field configurations: String Axiverse

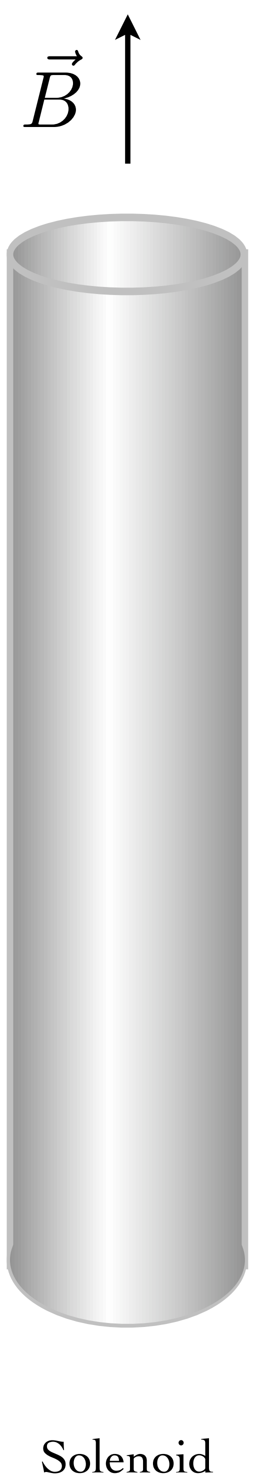
- Spin-1 non-trivial gauge field configurations: String Photiverse

AA, Craig, Dimopoulos, Dubovsky, March-Russell (2009)

- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion

Non-trivial gauge configurations

The Aharonov-Bohm Effect



Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

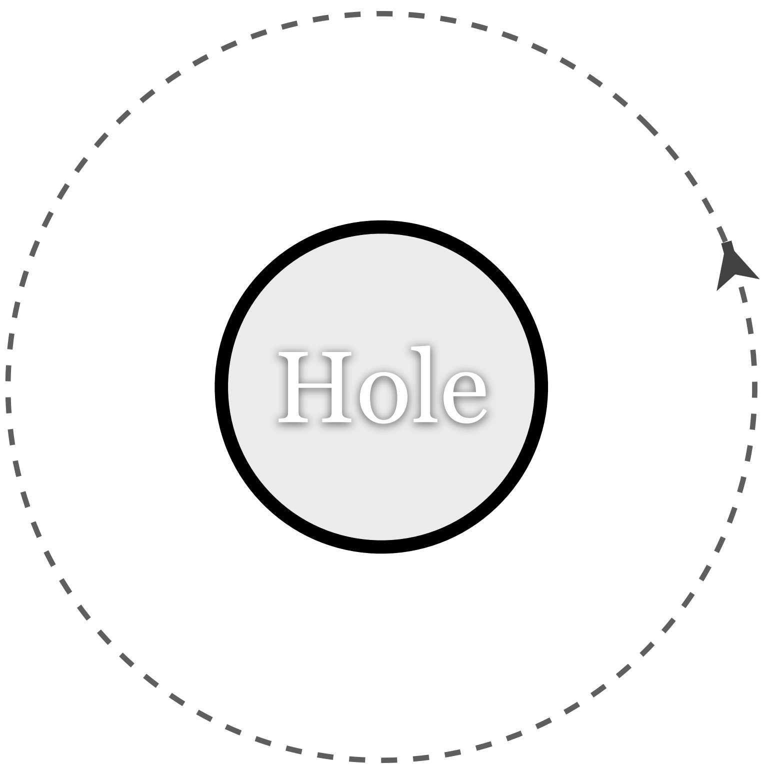
$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Non-trivial gauge configurations

The Aharonov-Bohm Effect



Taking an electron around the solenoid

$$e\int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial topology:

"Blocking out" the core still leaves a non-trivial gauge, but no mass

Non-trivial gauge configuration far away carries no energy

String Axion mass and the QCD axion

AA, Dimopoulos, Dubovsky, March-Russell, and Kaloper (2009)

$$\text{Particle Mass} \sim \frac{M_{\text{Planck}}^2 e^{-S/2}}{f_a}$$

Kallosh et. al. (1995)

Requirements on string theory for QCD axion
to solve the strong CP problem

$\theta_{QCD} < 10^{-10}$

String corrections $< 10^{-10} \times$ QCD

$M_{\text{Planck}}^4 \; e^{-S} < 10^{-10} \times m_\pi^2 f_\pi^2$

Svrcek, Witten (2006)

$S \gtrsim 200$

$S \sim 2\pi / \alpha$

The QCD axion should not be special

There could be **many** light axions

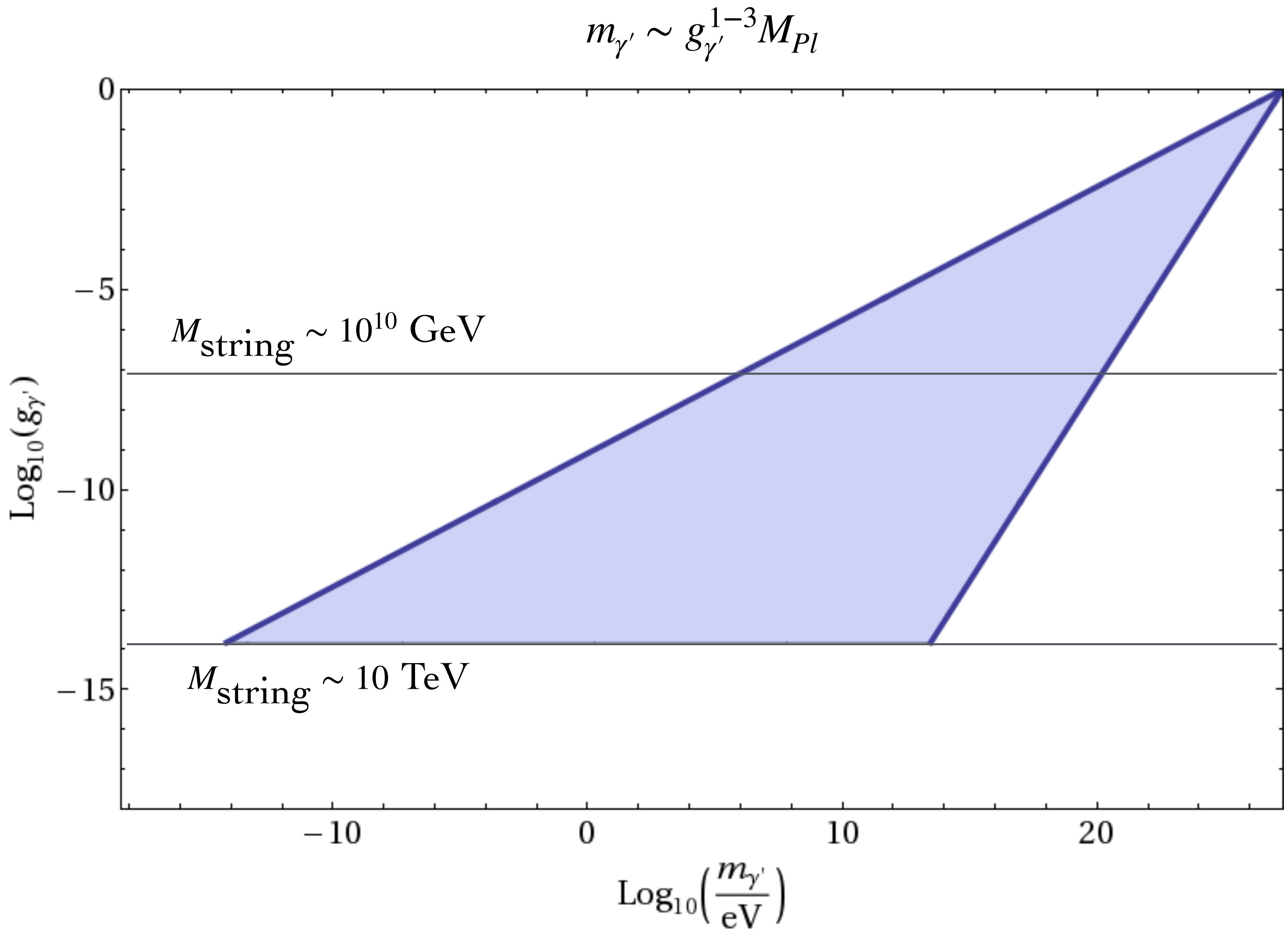
The String Photiverse

- Mass generated from fluxes

- Seem to require large volume compactifications

The String Photiverse

AA, S. Dimopoulos, G. Villadoro (2014-unpublished)



Expected range of dark photon masses in large volume compactifications

Moduli, the dilaton, Radion

- They are not protected by *any* symmetry
  - Natural value for the mass $\geq$ meV

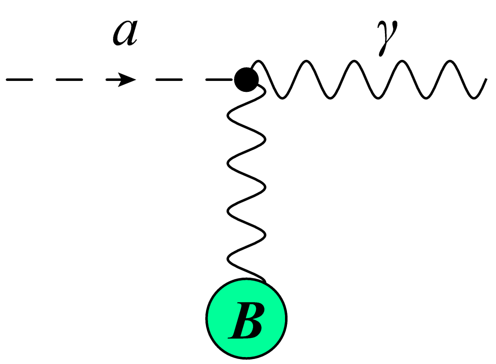
Damour, Polyakov (1994)
Dimopoulos, Giudice (1996)

- They determine the size of extra dimensions, fluxes, fundamental constants
  - Could the mass be associated with the tuning for the cosmological constant?

AA, S. Dimopoulos, V. Gorbenko, J. Huang, K. Van Tilburg (2016)

Axion Couplings

- Axion-photon mixing in a background field



- Axion have an EDM-like coupling to nucleons (in particular for the QCD axion)

- Axion spin coupling to leptons or nucleons $\frac{\nabla a}{f_a} \cdot \sigma$

- Scalar coupling to nucleons in the presence of CP violation (in particular for the QCD axion)

Dark Photon Couplings

- Couples through mixing with the ordinary photon

$$\epsilon(\overrightarrow{E'} \cdot \overrightarrow{E} + \overrightarrow{B'} \cdot \overrightarrow{B})$$

- Dark photon decouples as its mass goes to zero

Moduli, dilatons and other scalars

- Couple non-derivatively to the Standard Model (as well axions with CP violation)

- Examples of couplings

$$\mathcal{L} = \mathcal{L}_{SM} + \sqrt{\hbar c}\frac{\phi}{\Lambda}\mathcal{O}_{SM}$$

$$\mathcal{O}_{SM} \equiv m_e e\bar{e},\ m_q q\bar{q},\ G_s^2,\ F_{EM}^2, ...$$

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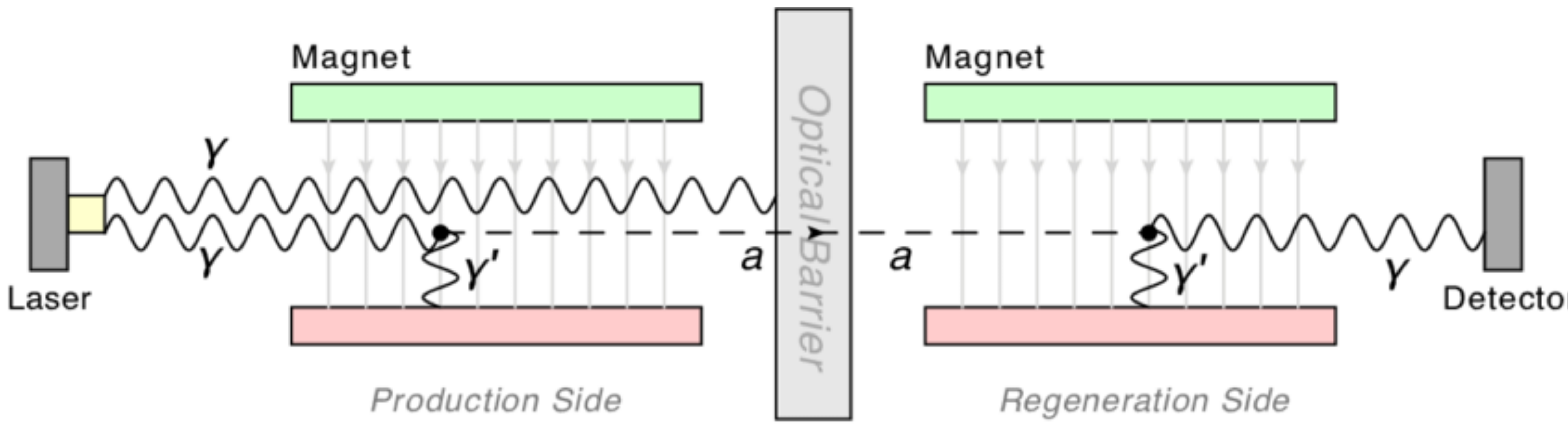
- The origins of ultra-light boson fields
- The non-Dark Matter signatures of ultra-light boson fields
- Ultra-light boson DM

Axion signatures independent of cosmology

Light shining through wall experiments



Photon-to-axion conversion in astrophysical environments with magnetic fields

Axion signatures independent of cosmology

Searches for long range forces

Monopole-Dipole Interaction

Mass with N nucleons
or nuclear spin-polarized piezoelectric

Spin

$$V(r) \sim \frac{1}{r^2} e^{-m_\phi r}$$

Dipole-Dipole Interaction

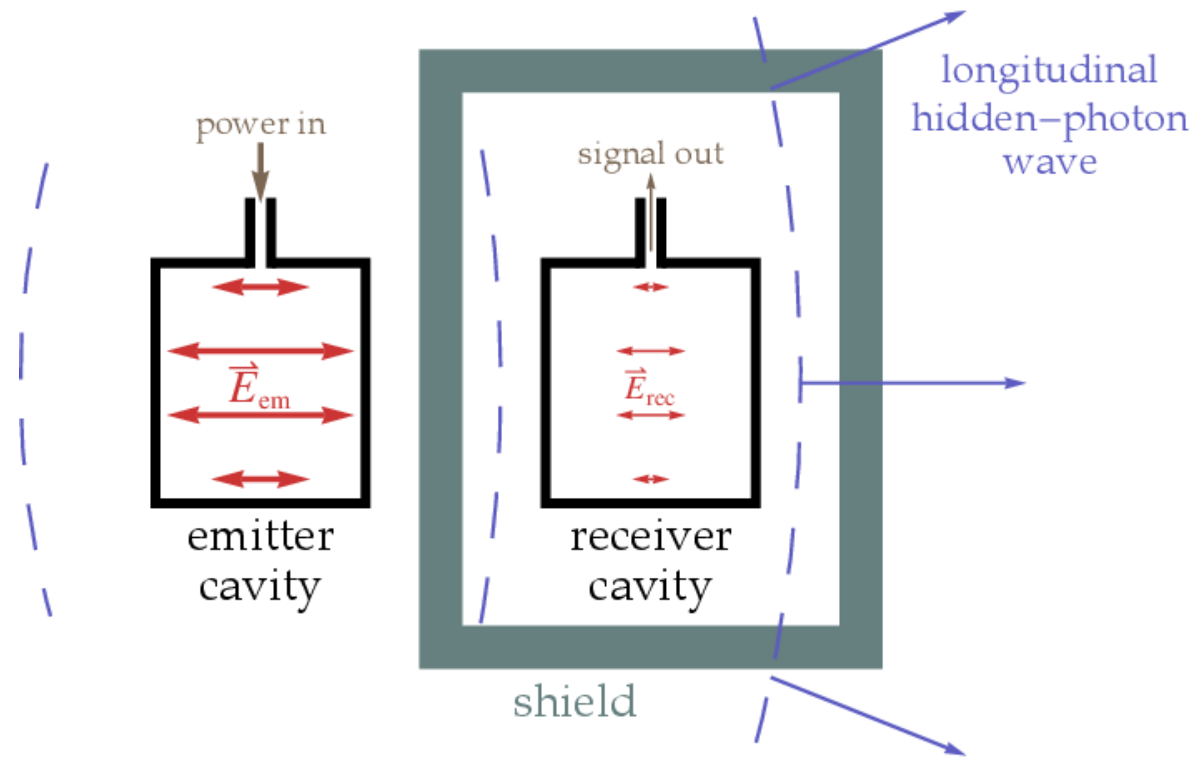
N spins

Spin

$$V(r) \sim \frac{1}{r^3} e^{-m_\phi r}$$

Cosmology-independent dark photon signatures

- Coupled cavity searches



- Short range modifications of Coulomb's law

Cosmology-independent moduli signatures

Modifications of Newton's Law

- Fifth-force searches, and short-range modifications of gravity

$$V(r) \sim \frac{1}{r} e^{-m_\phi r}$$

- Equivalence principle violation searches

Production in stars and other astrophysical environments

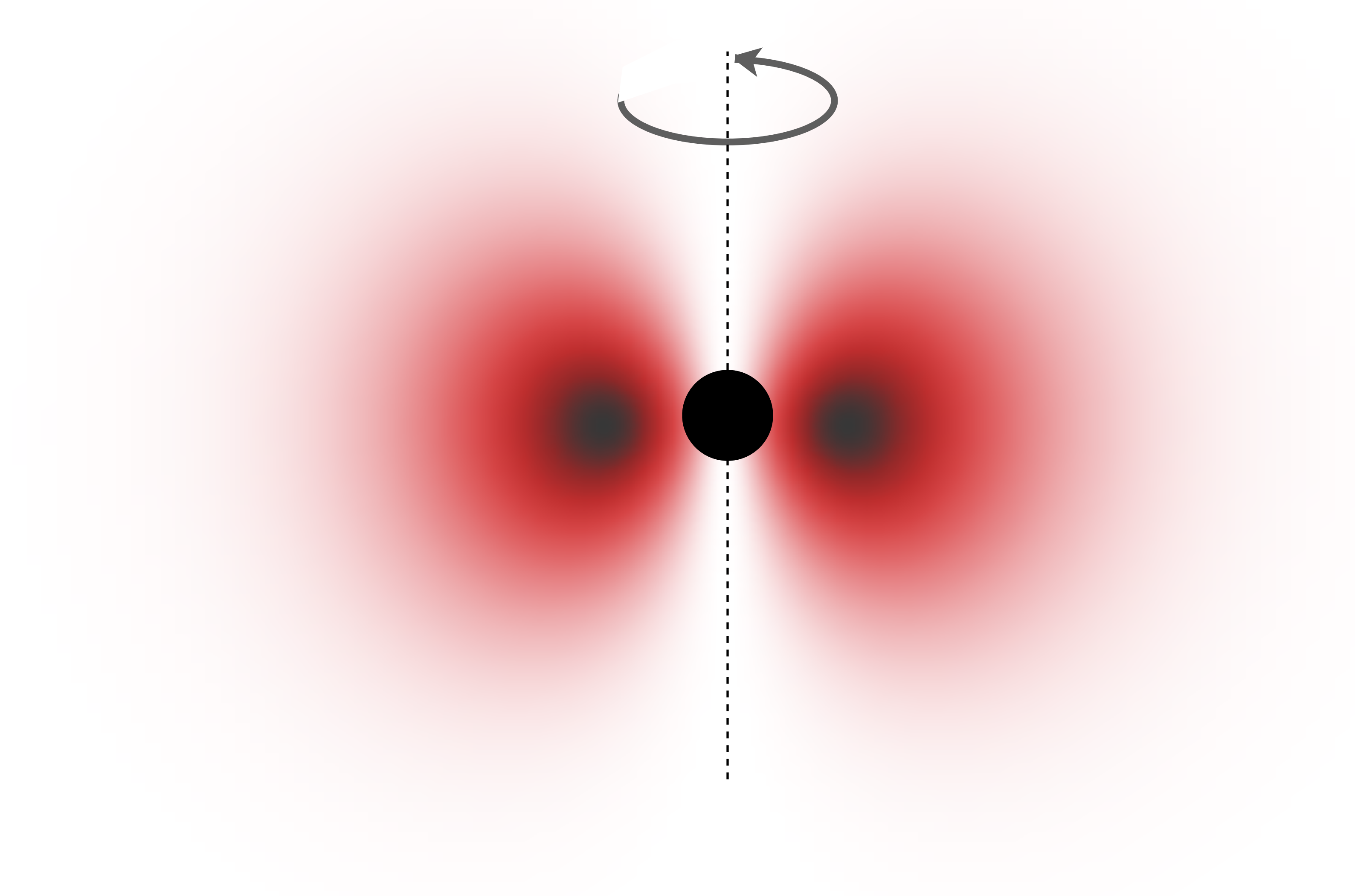
- Stellar cooling/heating
- Supernovae 1987a
- Provide in some cases the most stringent constraints on these particles

Cosmology-independent signatures of all bosons

AA, Dimopoulos, Dubovsky, March-Russell, and Kaloper (2009)

Black hole superradiance

Damour et al; Zouros & Eardley;
Detweiler; Gaina (1970s)



Particle Compton Wavelength comparable to the size of the Black Hole

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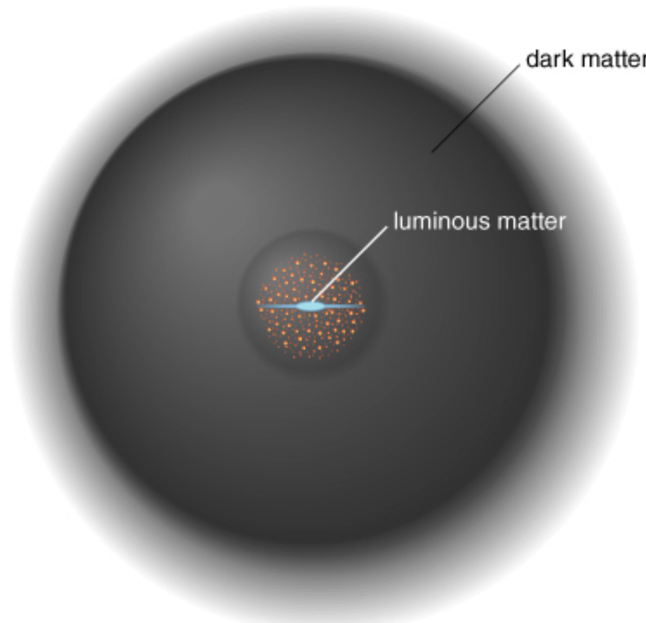
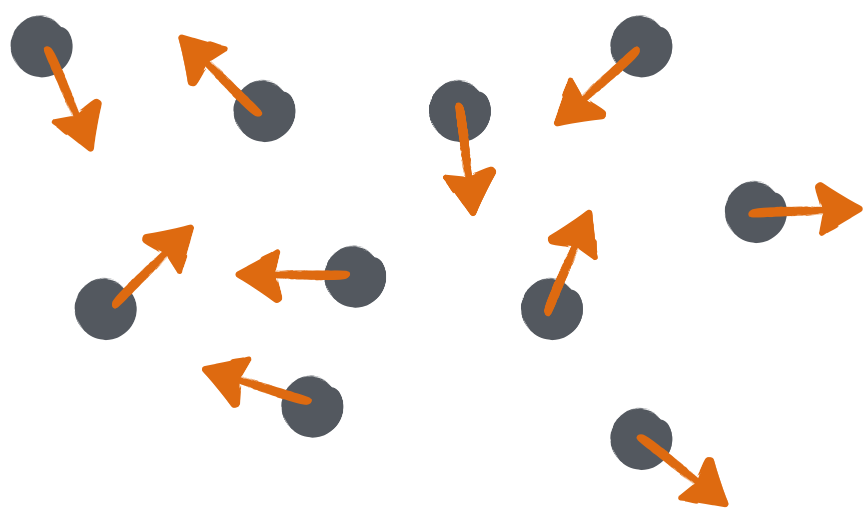
- Ultra-light boson DM

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

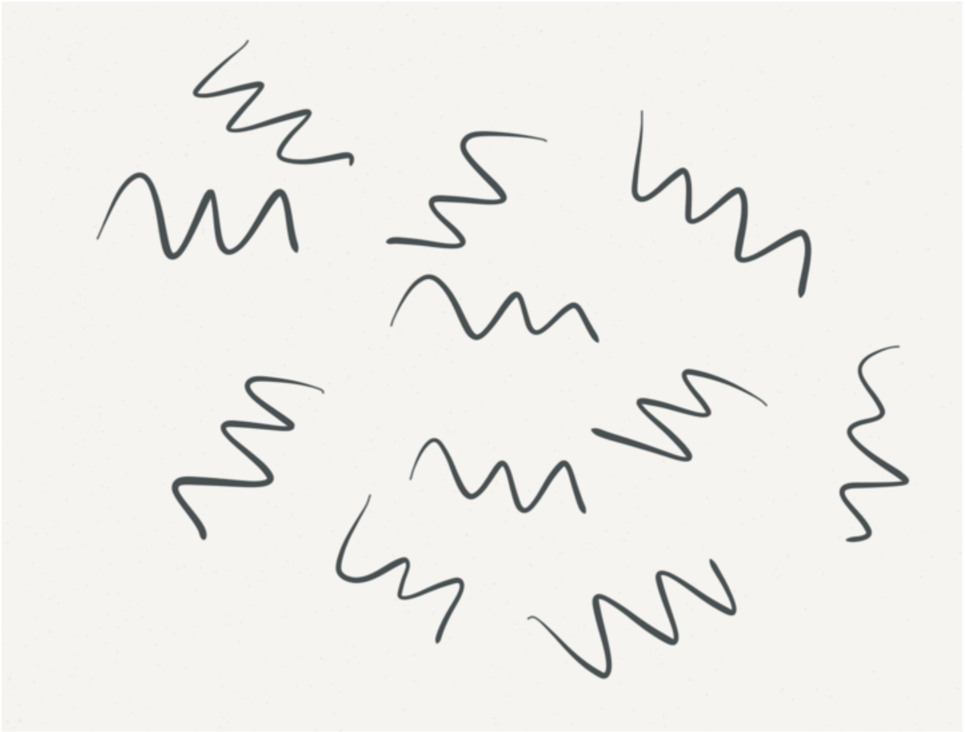


Usually we think of …



like a WIMP

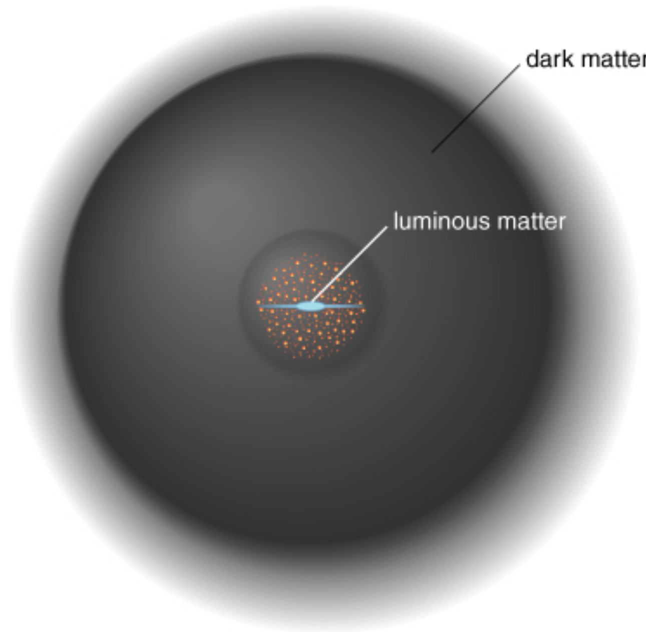
instead of…

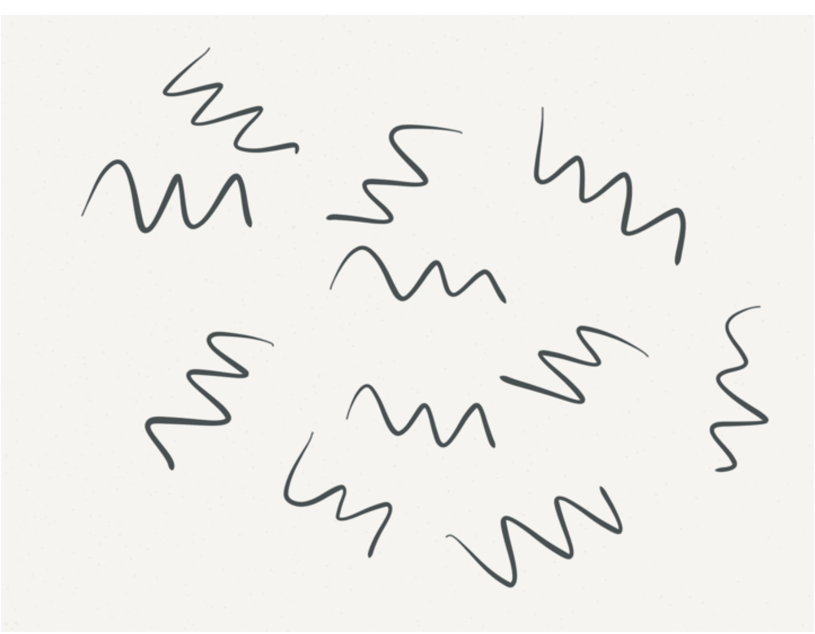


$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

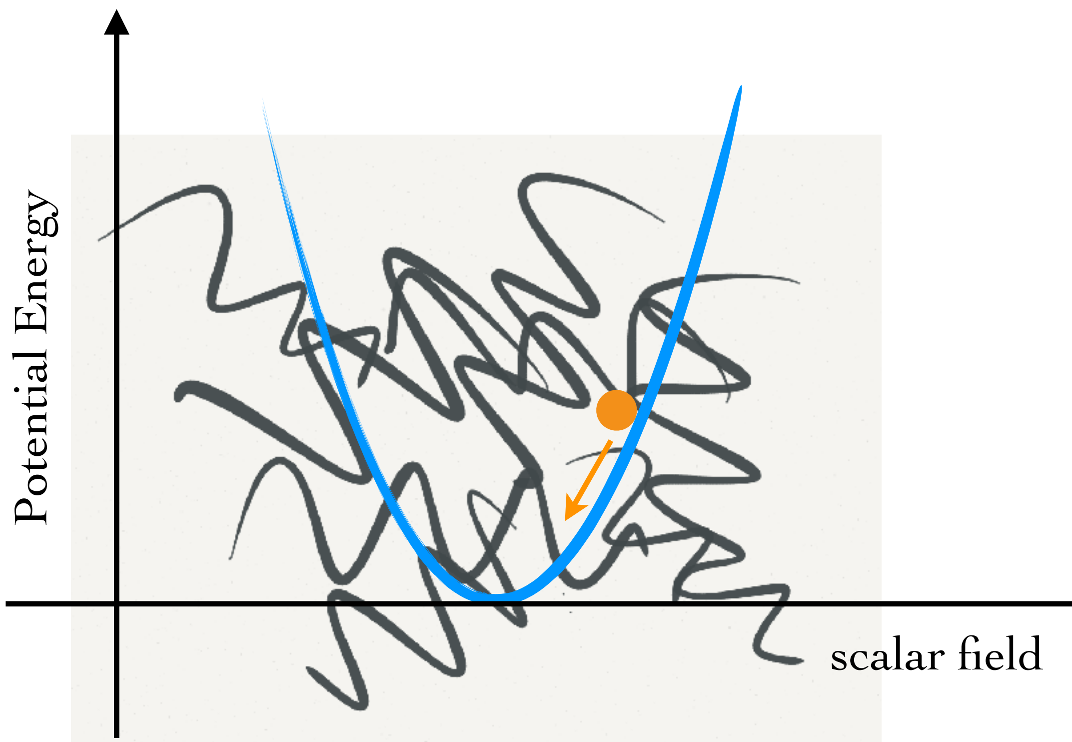
What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy





Decreasing DM Mass



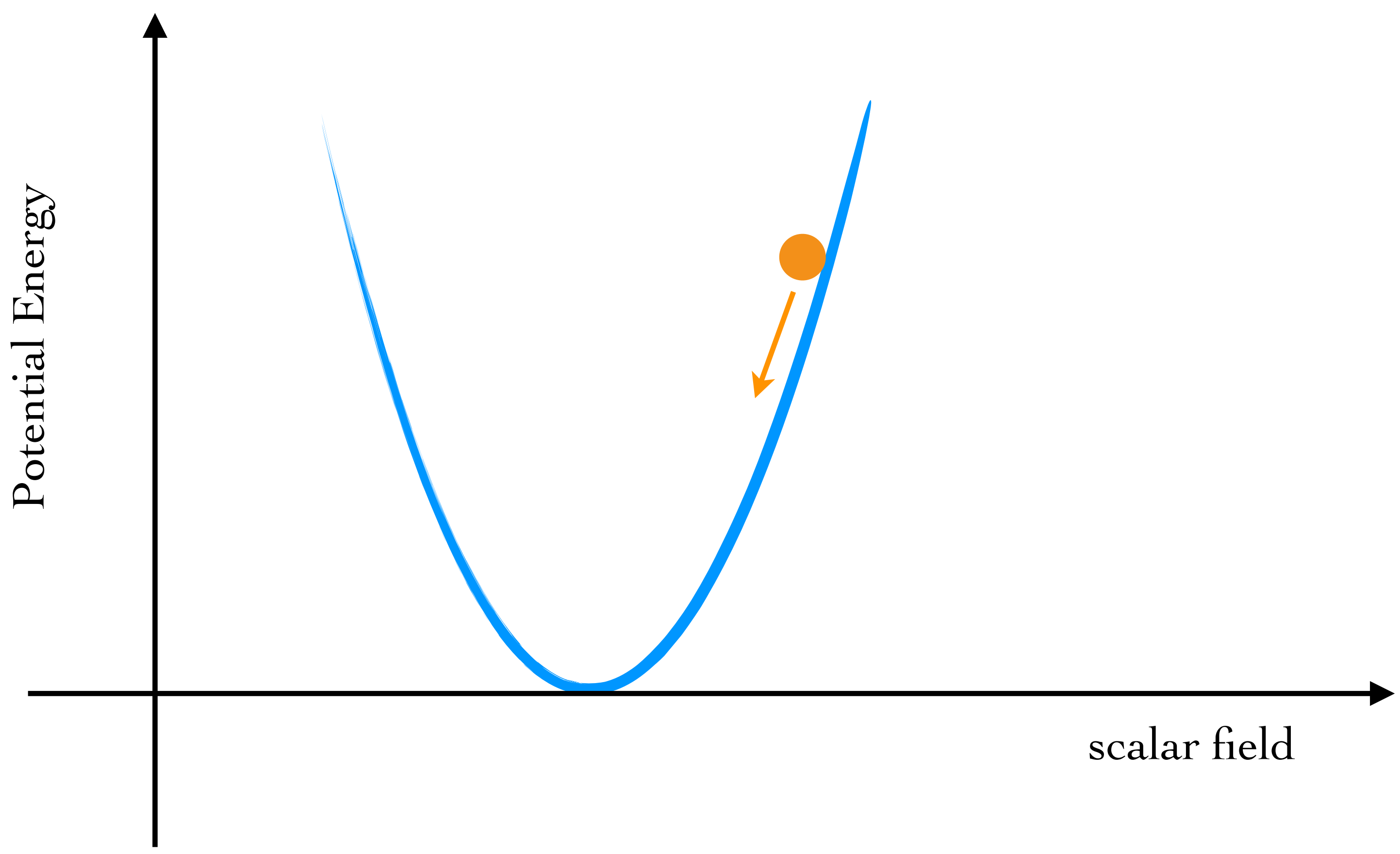
Equivalent to a Scalar Wave

Light Scalar Dark Matter

- Just like a harmonic oscillator

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

$$\ddot{x} + \gamma\,\dot{x} + \omega^2 x = 0$$



Frozen when:
Hubble > m_a

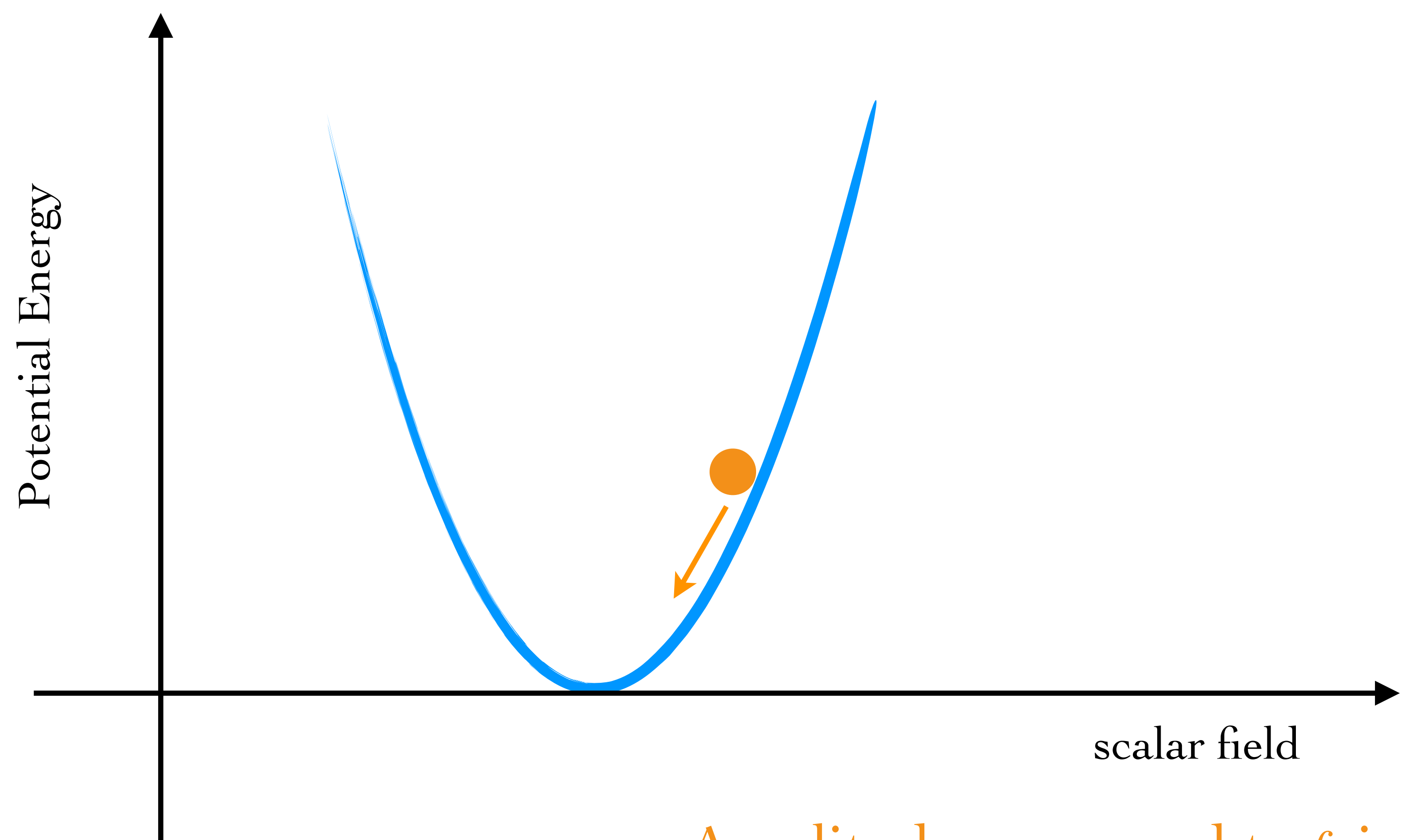
Oscillates when:
Hubble < m_a

ρ_a scales as a^{-3}
just like Dark Matter

Initial conditions set by inflation

Light Scalar Dark Matter Today

- If $m_\phi < 1$ eV, can still be thought of as a scalar field today



$m_a{}^2\, a_o{}^2\ \cos^2(m_a t) \sim \rho_a$

Coherent for $\upsilon_{vir}{}^{-2} \sim 10^6$ periods

Amplitude compared to f_a in the galaxy:

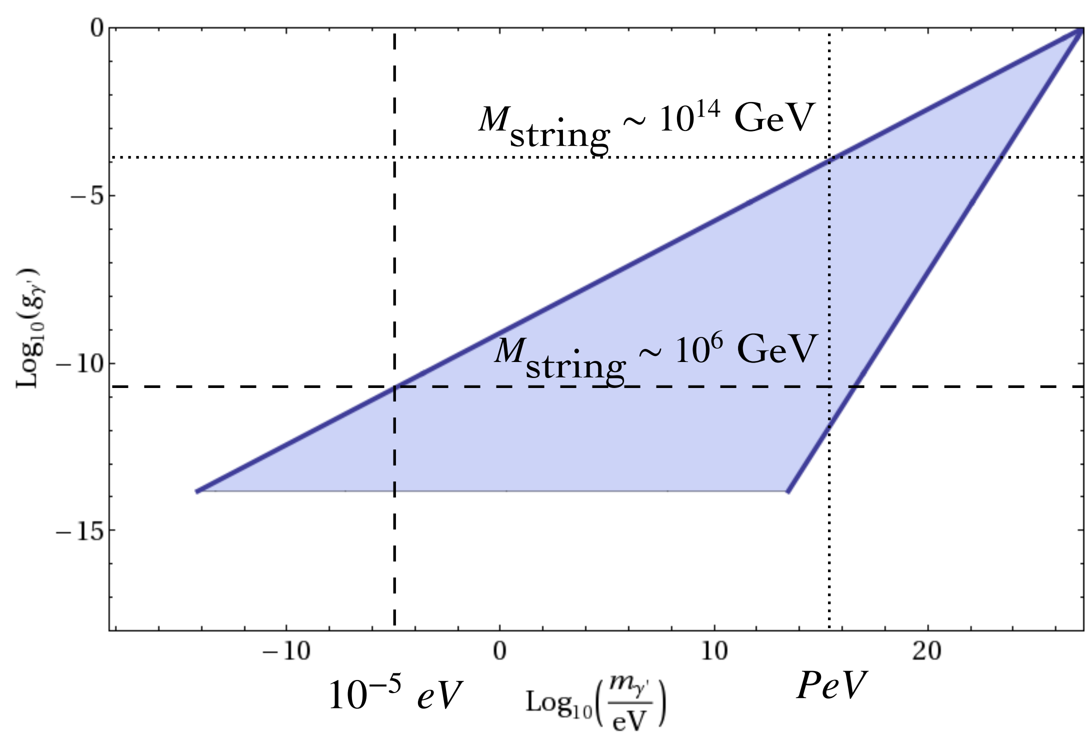
$\frac{a}{f_a} \equiv \bar{\theta} = 4 \times 10^{-19}$ for the QCD axion

Inflationary production of dark photon DM

- Fluctuations of a Stuckelberg spin-1 field during inflation
  - $m_{DM} \approx 10^{-5}\ eV \left(\frac{10^{14}\ GeV}{H_I} \right)^4$

Graham, Mardon, Rajendran (2015)

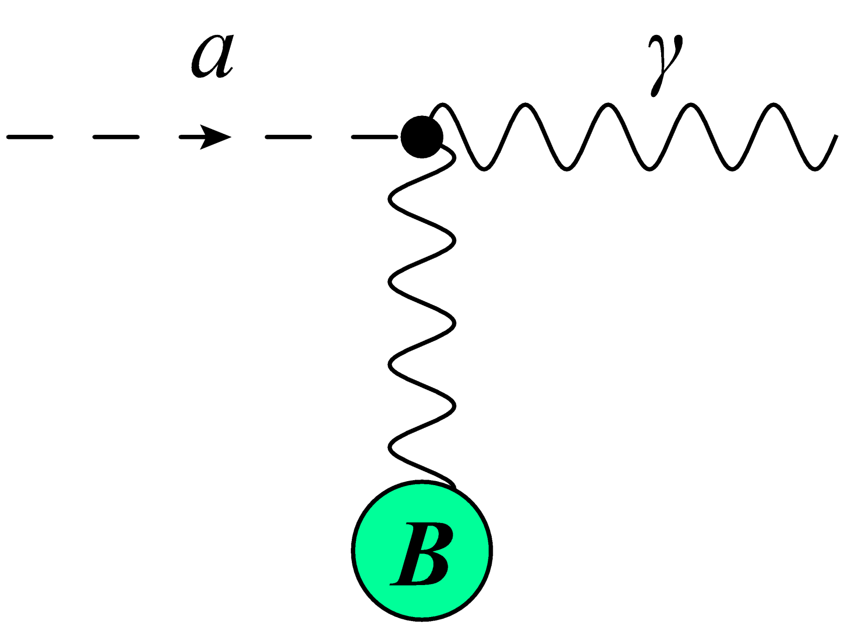
- Not clear how this can be reconciled with the string picture
  - Light dark photons require low cutoffs

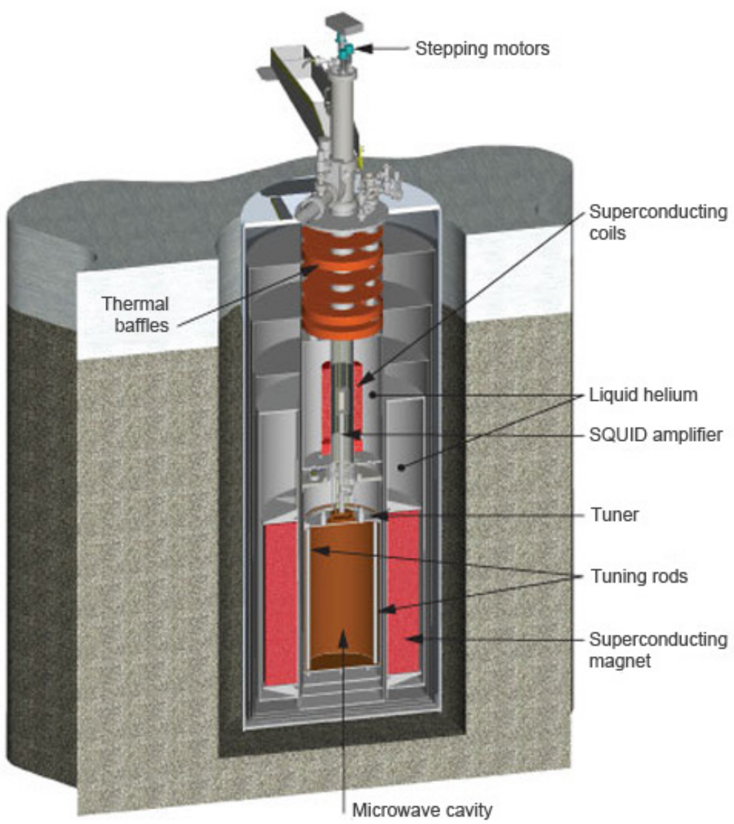


Axion Dark Matter

Some examples

- Axion-to-photon conversion (ex. ADMX)



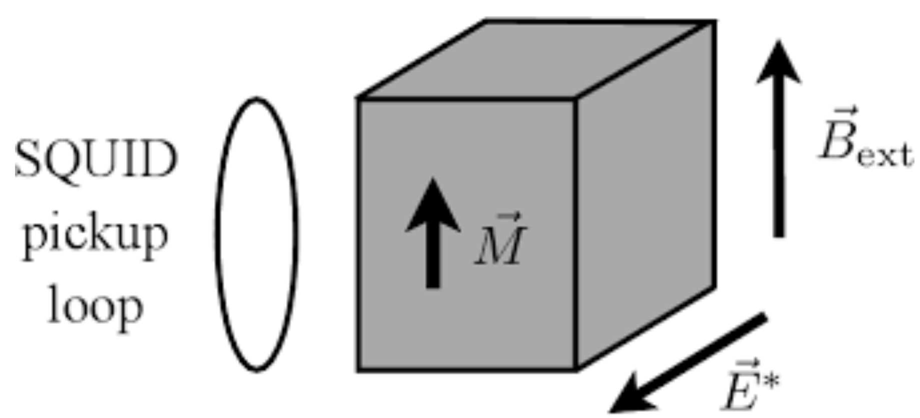


Cavity size = Axion size

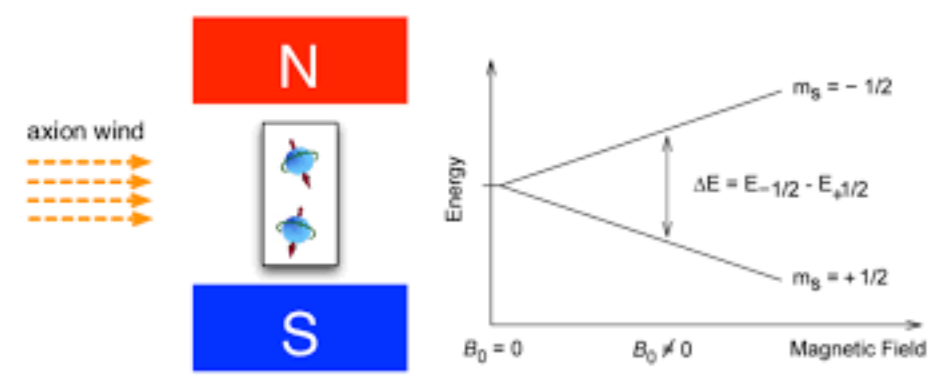
- Changes the dispersion relation of polarized light

Axion Dark Matter

- Spin precession experiments

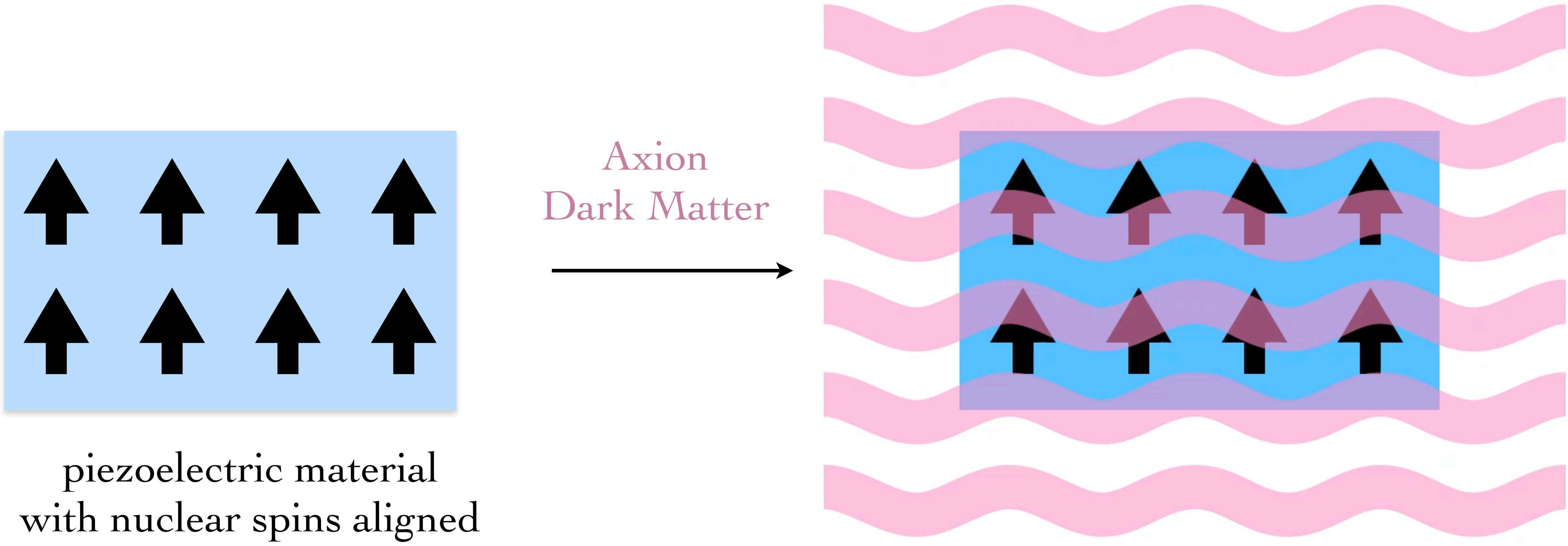


EDM coupling of the axion



Spin coupling of the axion
axion wind

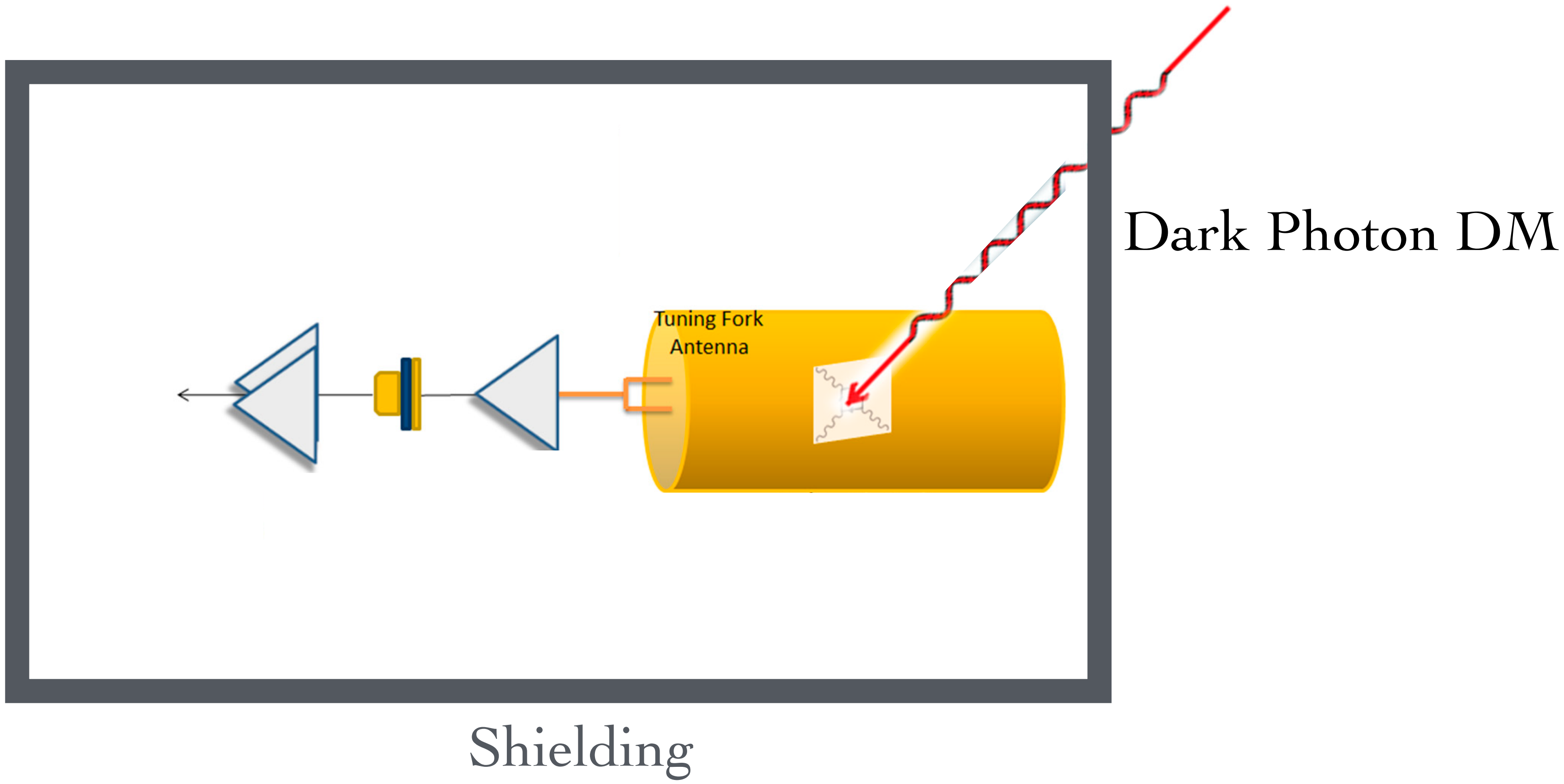
The Piezoaxionic Effect



Dark Photon Dark Matter

Couples similarly to a photon

$$|\vec{E}'| \sim 50\ \frac{V}{cm}$$

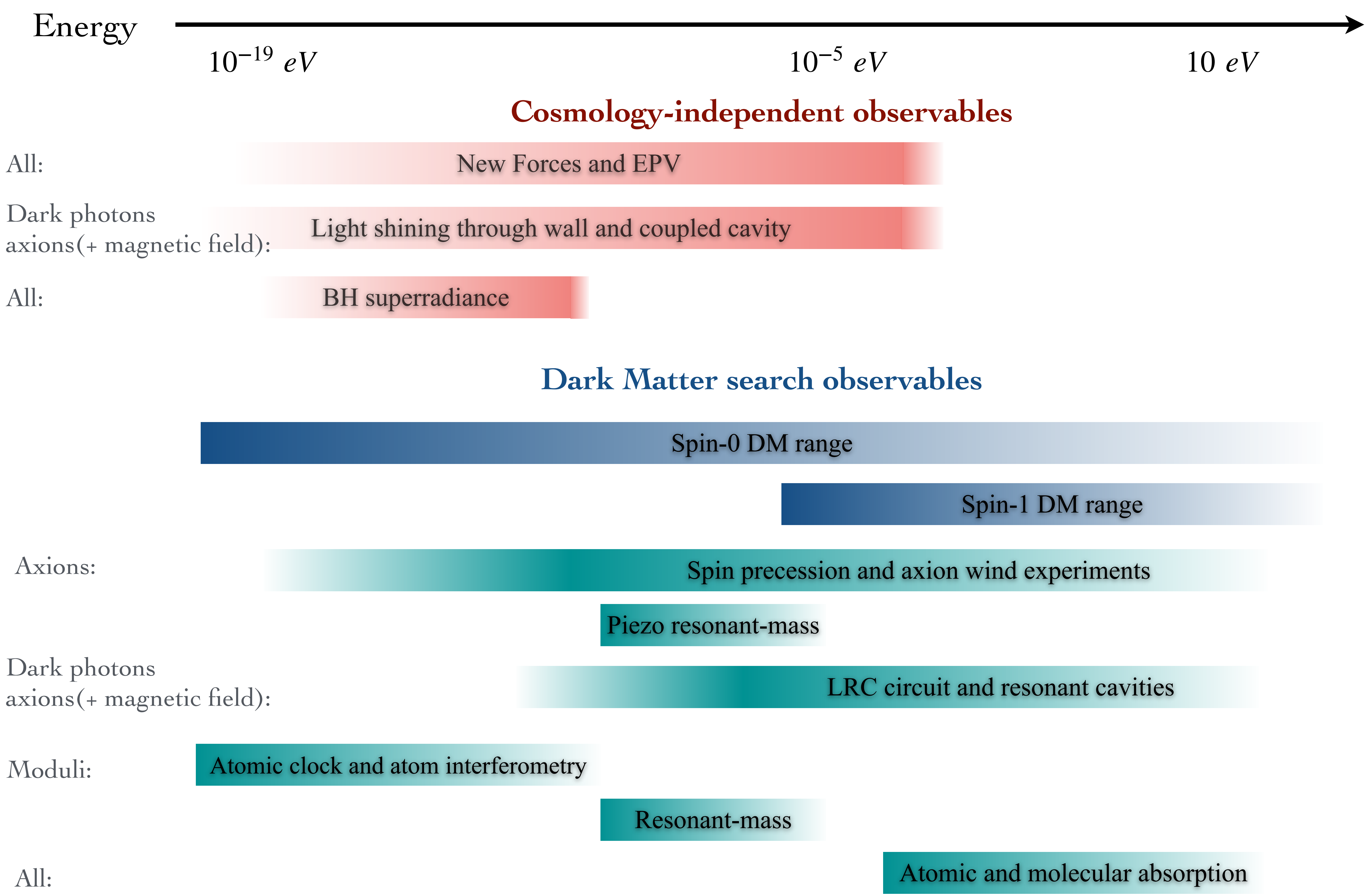


Moduli Dark Matter

Causes variation of fundamental constants

- Makes the energy splitting of atoms and nuclei oscillate in time
  - Atomic clocks and atom interferometry searches
- Makes the size of atoms change in time
  - Resonant mass detectors and oscillator searches

Signatures summary



Theory evaluation summary

	Grade
QCD axion	A(+): well-defined range, solves the CP problem, excellent DM candidate
Axions	A-: easy to make light in string theory, finite number of couplings, excellent DM candidate
Dark Photons	B(+): can be lightish, but there may be issues with DM production
Moduli, Dilaton, Radion	B(±): well-defined DM production mechanism, but there is a (perhaps justified) tuning