A theory perspective on ultra-light bosons

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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?

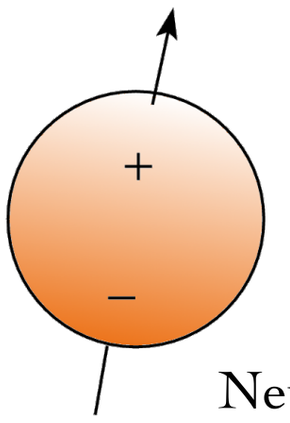
- Bottom-Up approach: They provide a consistent theoretical framework for BSM physics
  to be contrasted with chameleons or modifications of QM

- 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:

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

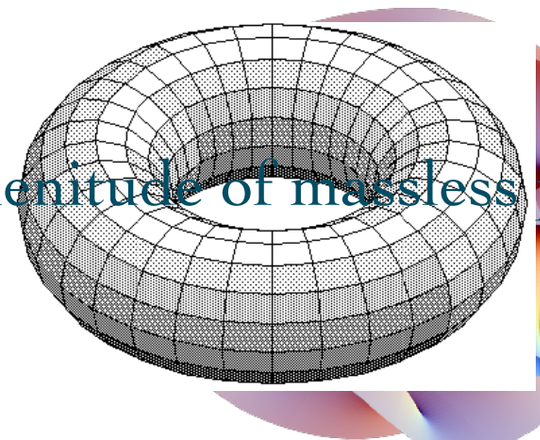
f_a : axion decay constant

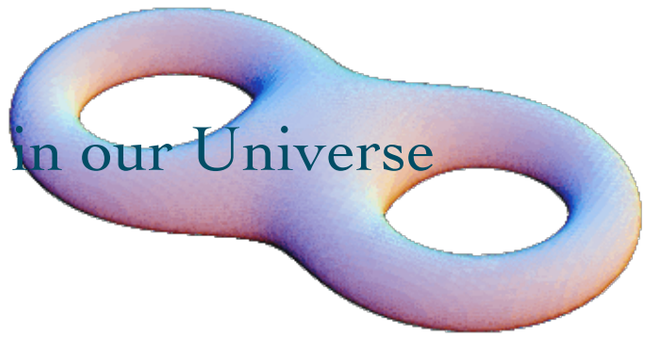
Mediates new forces and can be the dark matter

String Axiverse

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

- Extra dimensions





Give rise to a plenitude of massless particles in our Universe

Non-trivial gauge configurations

The Aharonov-Bohm Effect

Solenoid

Taking an electron around the solenoid

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

while

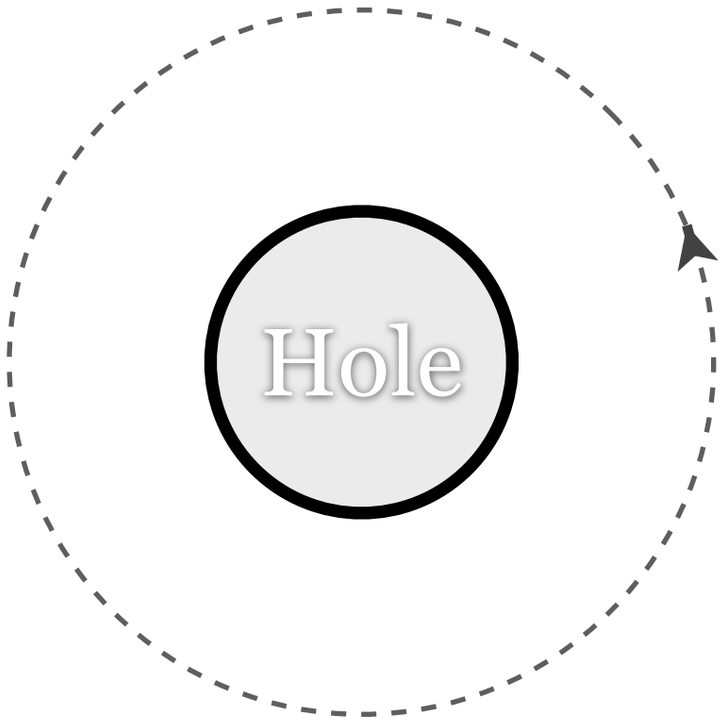
$$\vec{B} = 0$$

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

A Plenitude of (Almost) Massless Particles

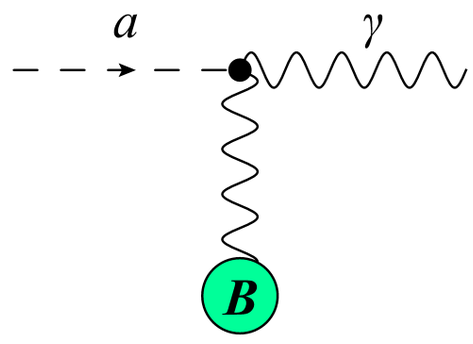
- Spin-0 non-trivial gauge field configurations: String Axiverse

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

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

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

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

- 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

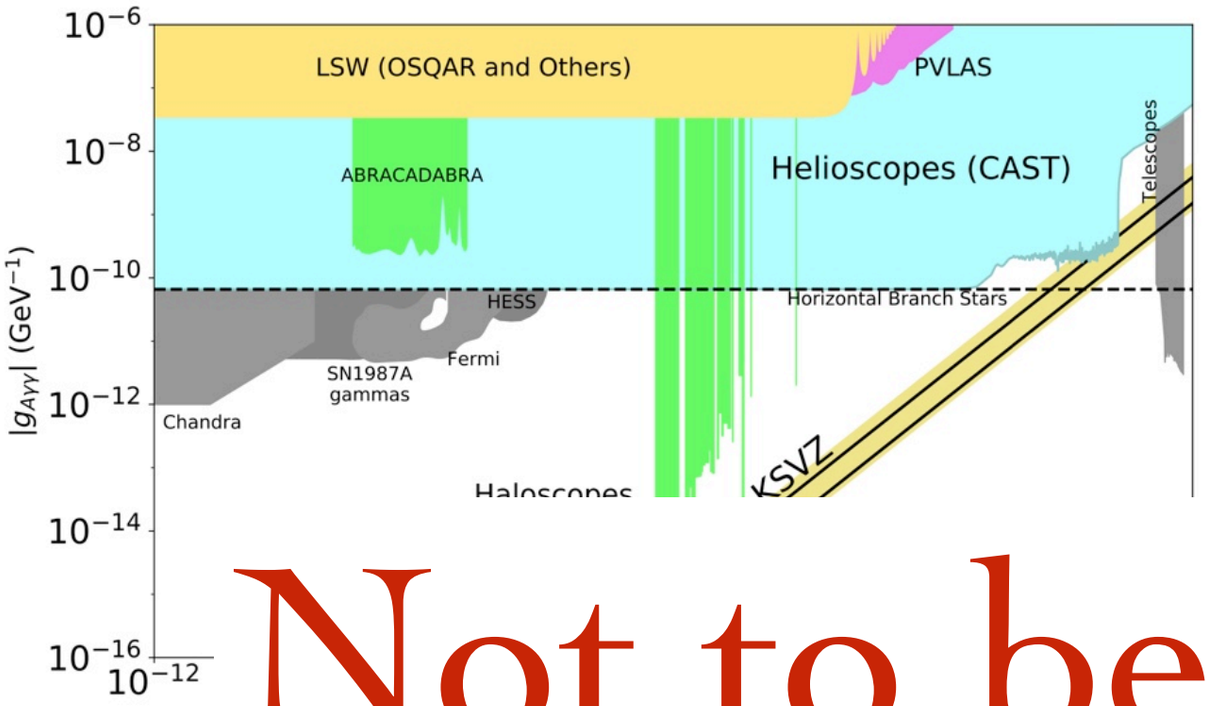
$$\mathcal{L} = \mathcal{L}_{SM} + \sqrt{\hbar c}\frac{\phi}{\Lambda}\mathcal{O}_{SM}$$

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

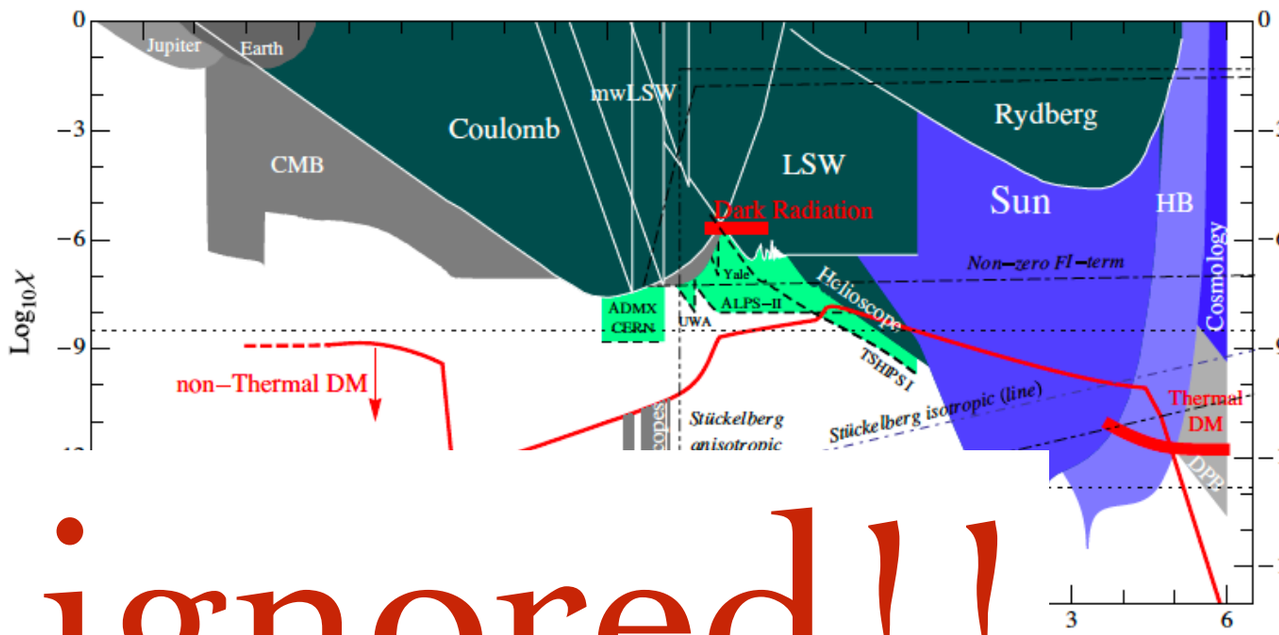
Current astrophysical and laboratory constraints

Not an exhaustive list

Axion-photon coupling

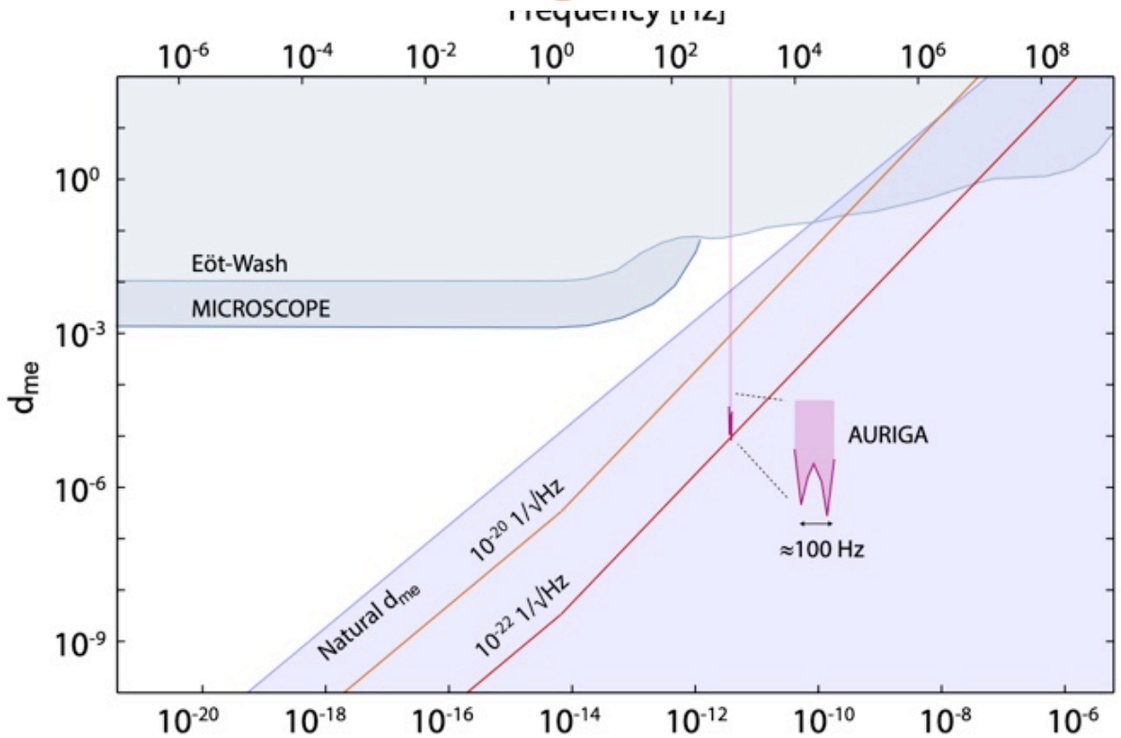


Dark photon constraints



Not to be ignored!!

Electron mass modulus

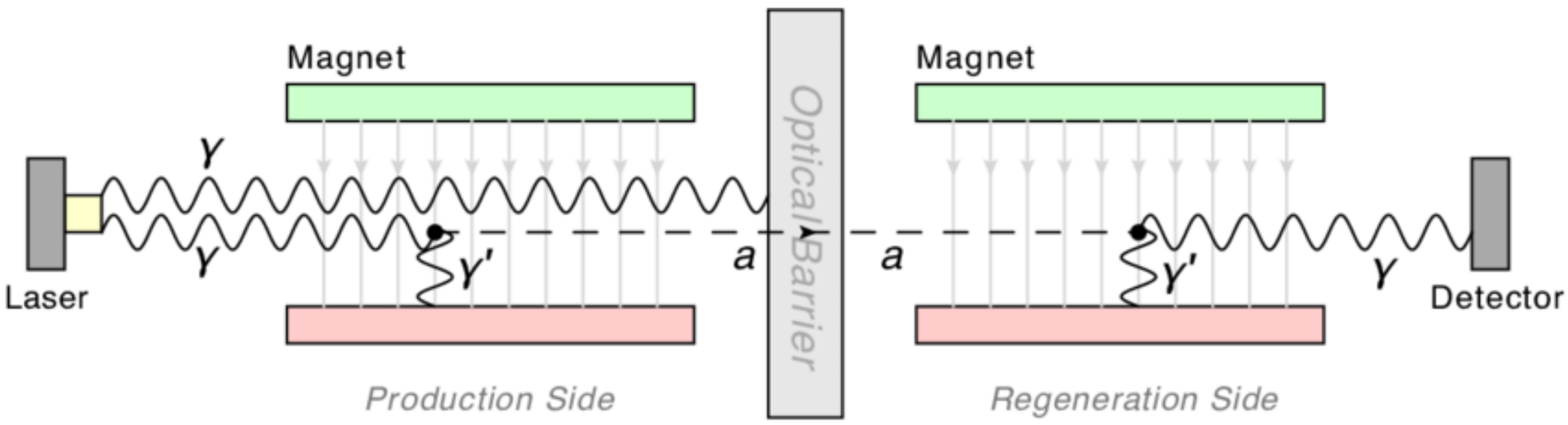


Outline

- 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

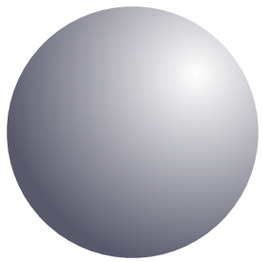
Light shining through wall experiments



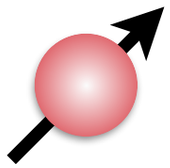
Axion signatures independent of cosmology

Searches for long range forces

Monopole-Dipole Interaction



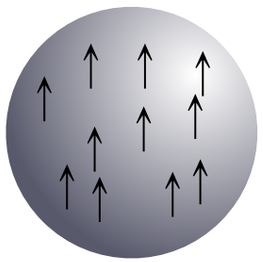
Mass with N nucleons



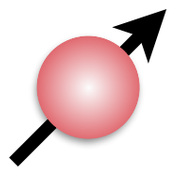
Spin

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

Dipole-Dipole Interaction



N spins

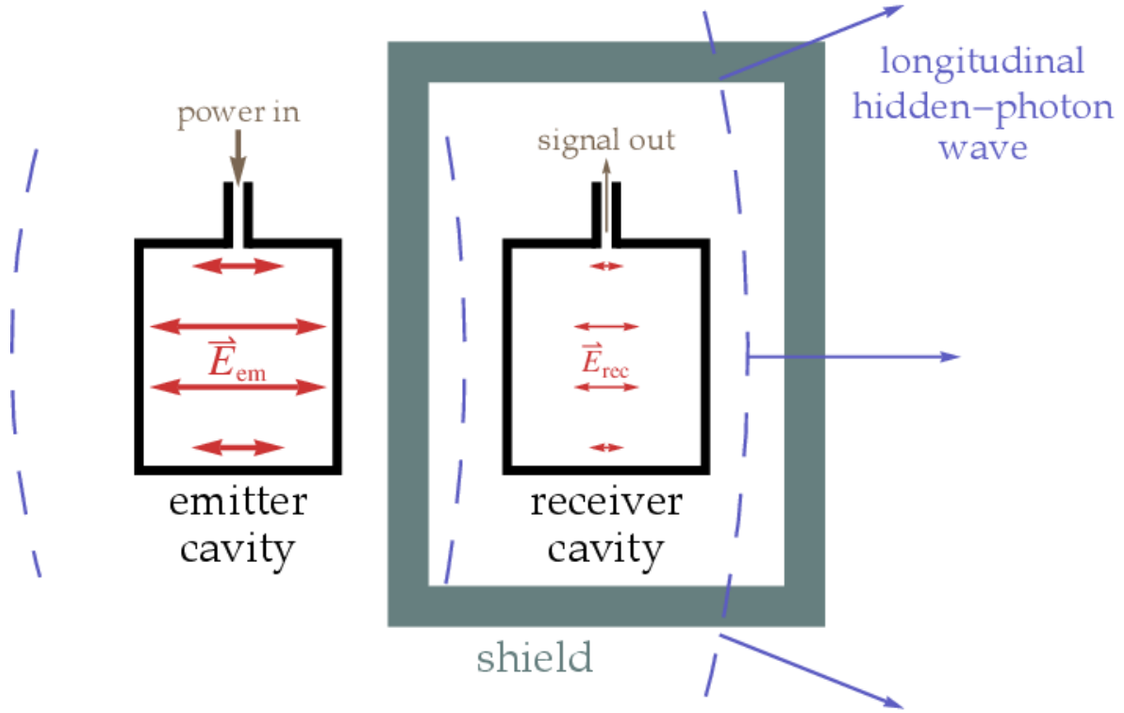


Spin

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

Cosmology-independent dark photon signatures

- Coupled cavity searches



- Short range modifications of Coulomb's law

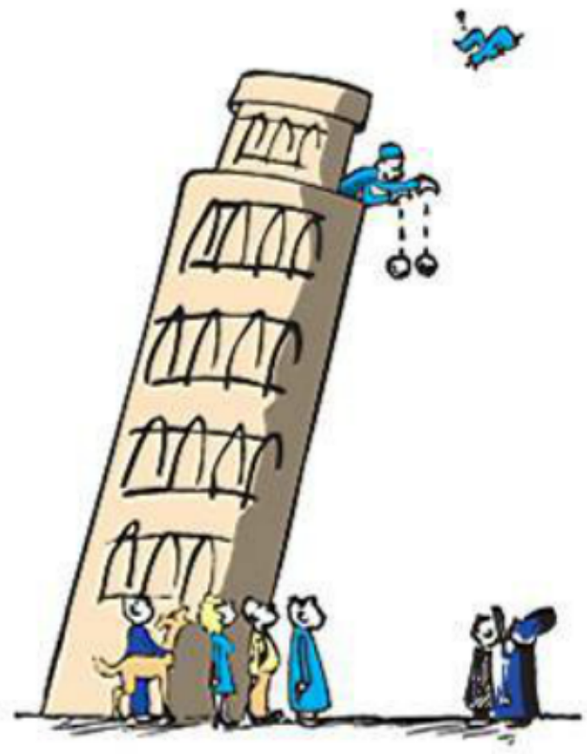
Cosmology-independent moduli signatures

Modifications of Newton's Law

- Fifth-force searches

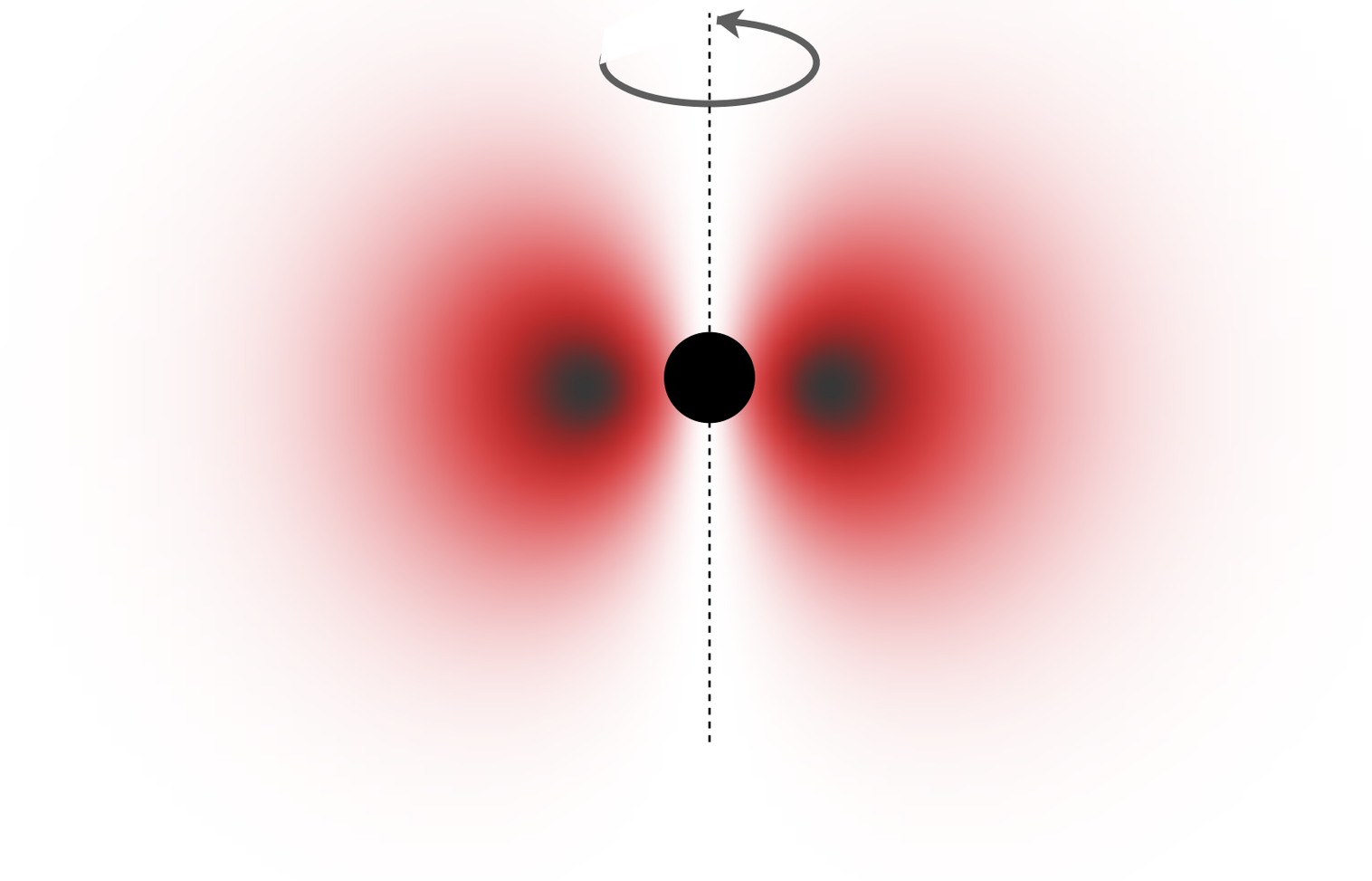
$$V(r) \sim \frac{1}{r} e^{-m_\phi r}$$

- Equivalence principle violation searches



Cosmology-independent signatures of all bosons

Black hole super-radiance



Particle Compton Wavelength comparable to the size of the Black Hole

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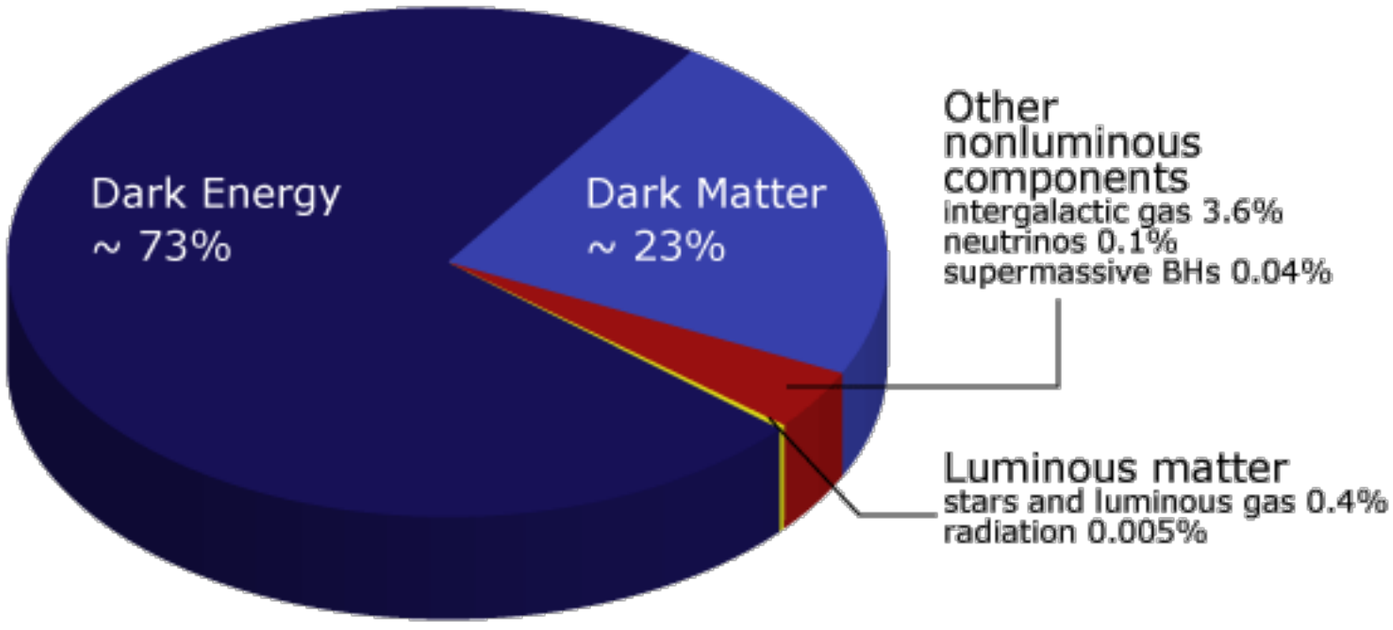
- The non-Dark Matter signatures of ultra-light boson fields
- Ultra-light boson DM

The Mystery of Dark Matter



Ultra-light bosons as DM

- Self-consistent DM production mechanism
  - Misalignment for scalars ($m_{DM} > 10^{-22}\ eV$) and inflationary production for dark photons ($m_{DM} > 10^{-5}\ eV$)

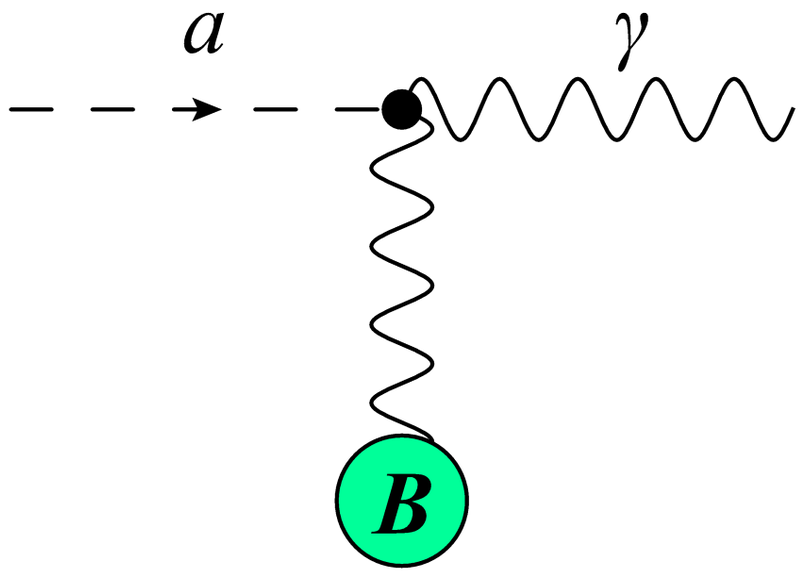
- Large array of possible experimental probes

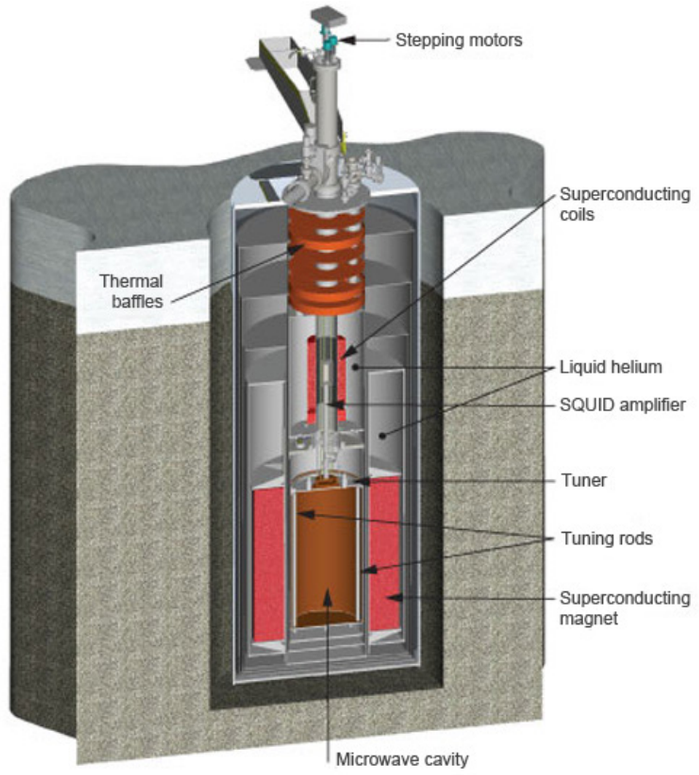
- All experiments are absorption experiments
  - Ultra-light DM is not necessarily stable

Axion Dark Matter

Some examples

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

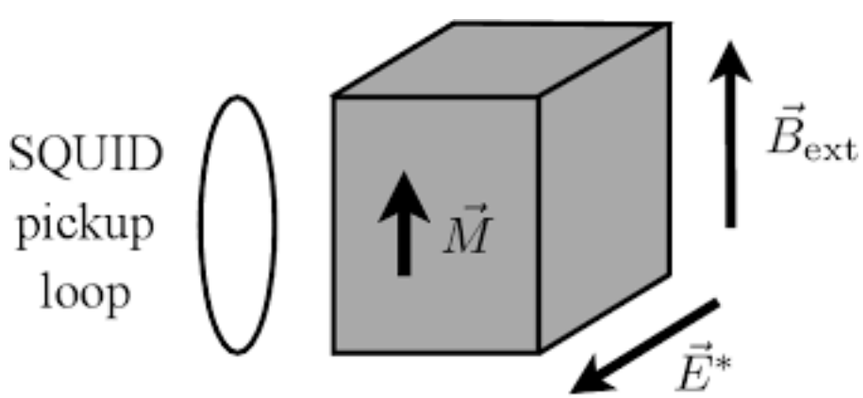




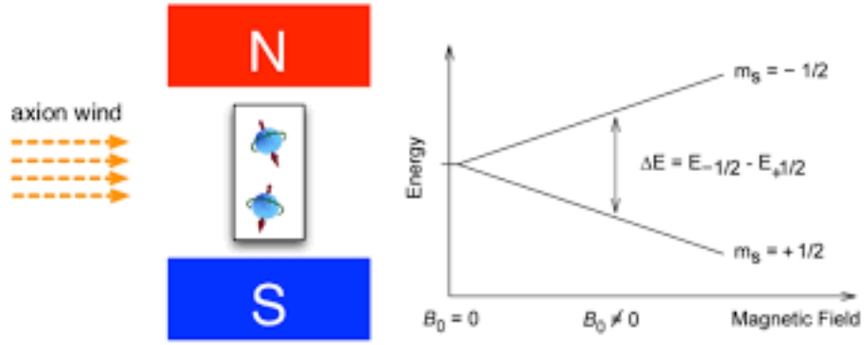
Cavity size = Axion size

Axion Dark Matter

- Spin precession experiments



EDM coupling of the axion

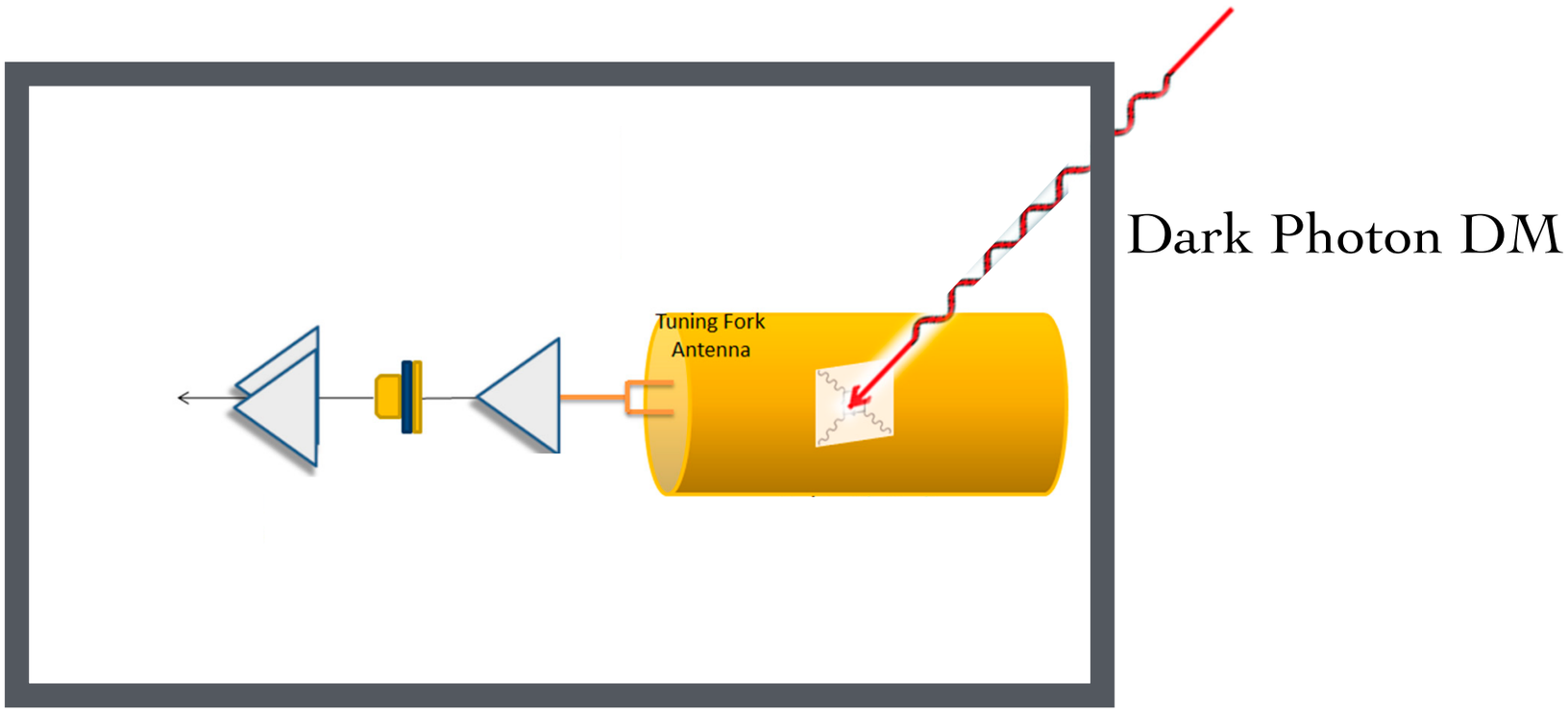


Spin coupling of the axion
axion wind

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

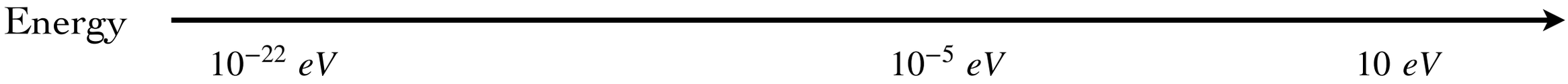
Summary

- There is good motivation behind the possible presence of ultra-light bosons

- They can be probed across a wide-variety of energy scales, even through their gravitational coupling alone

- They are excellent Dark Matter candidates

Signatures summary



Cosmology-independent observables

All: New Forces and EPV

Dark photons axions(+ magnetic field): Light shining through wall and coupled cavity

All: BH superradiance

Dark Matter search observables

Spin-0 DM range

Spin-1 DM range

Axions: Spin precession and axion wind experiments

Dark photons axions(+ magnetic field): LRC circuit and resonant cavities

Moduli: Atomic clock and atom interferometry

Resonant-mass

All: Atomic and molecular absorption

Questions for discussion

- Is this list exhaustive?
- What about other theories of DM?
- Can you ignore astrophysical constraints? No
- How much do the searches depend on the structure of DM?
- What about fermions?