A Theory Perspective: Particle Physics Beyond Colliders

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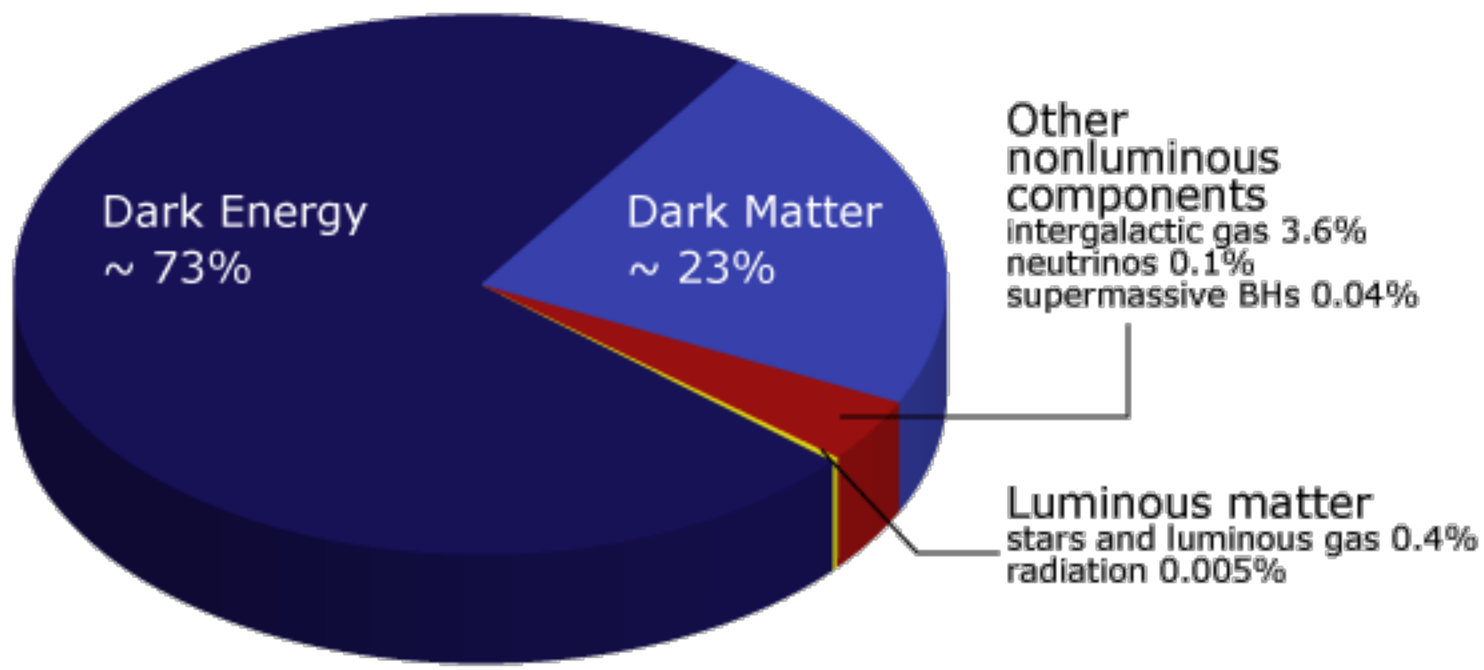
Perimeter Institute for Theoretical Physics

The Mystery of Dark Matter



Models of Dark Matter

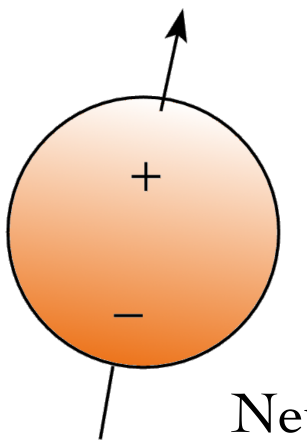
- What is it made out of?

- How is it produced?

- Does it have interactions other than gravitational?

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

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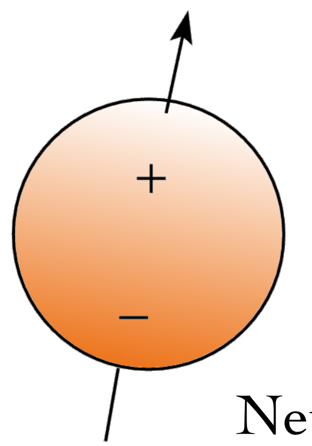

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Solution:
$\theta_s \sim a(x,t)$ is a dynamical field, an axion

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

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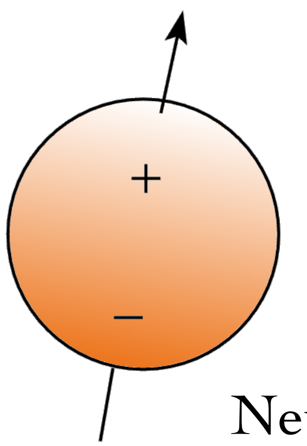

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f_a : axion decay constant

Mediates new forces and can be the dark matter

The String Axiverse

- Extra dimensions

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- Gauge fields

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- Extra dimensions

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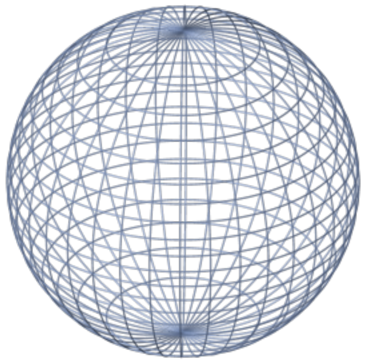
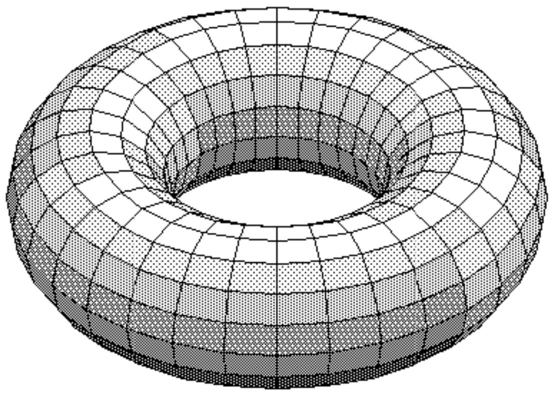
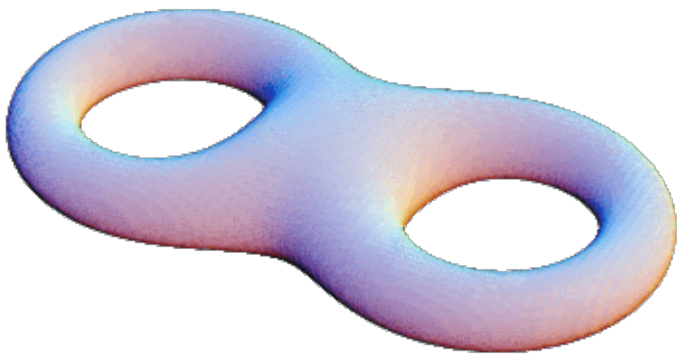
- Topology

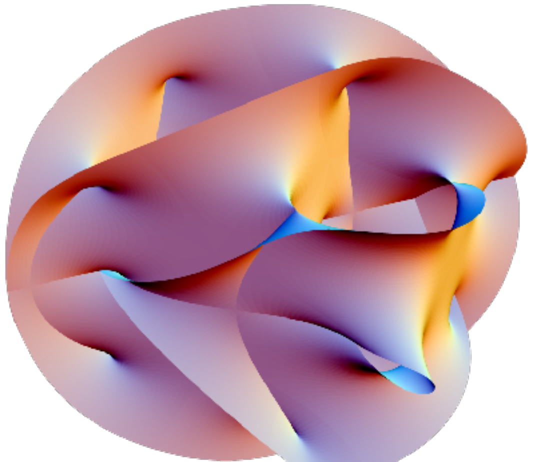




The String Axiverse

- Extra dimensions

- Gauge fields

- Topology



The String Axiverse

- Extra dimensions

- Gauge fields

- Topology

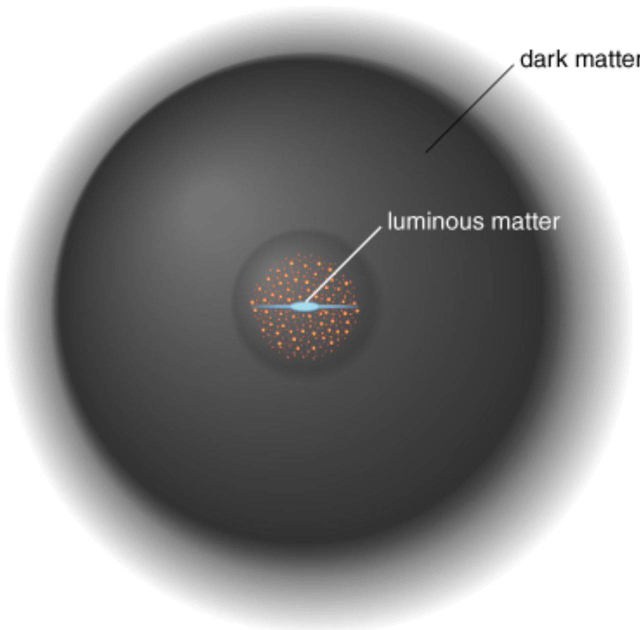
Give rise to a plenitude of massless particles in our Universe

A Plenitude of Massless Particles

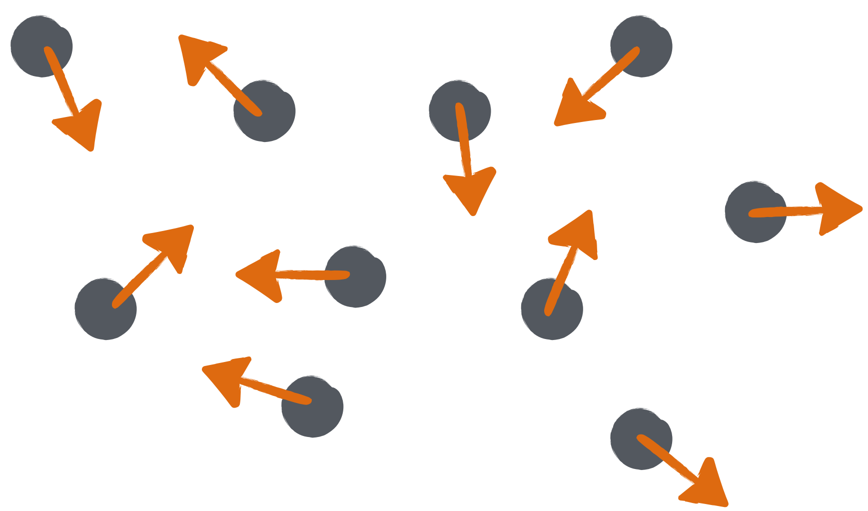
- Spin-0 non-trivial gauge field configurations: String Axiverse
- Spin-1 non-trivial gauge field configurations: String Photiverse
- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



Usually we think of …



like a WIMP

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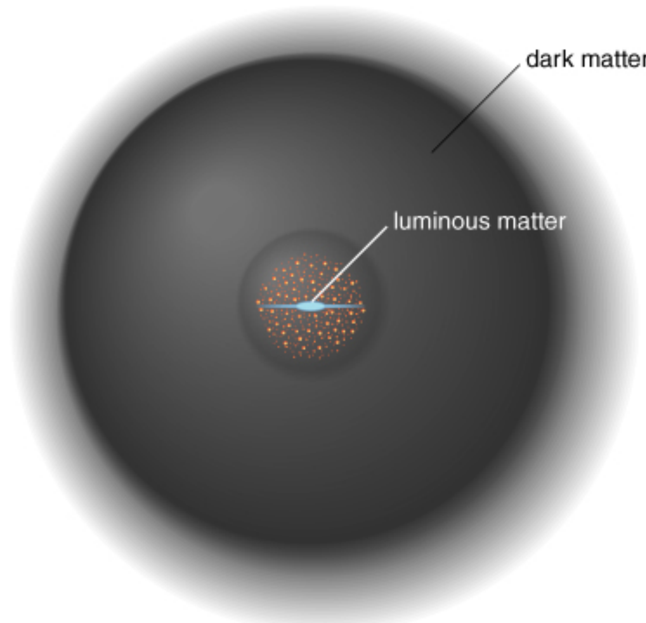

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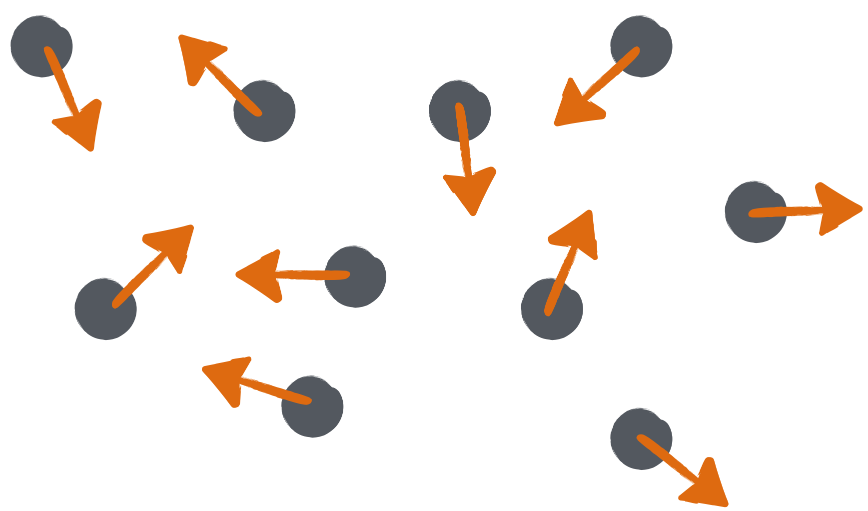
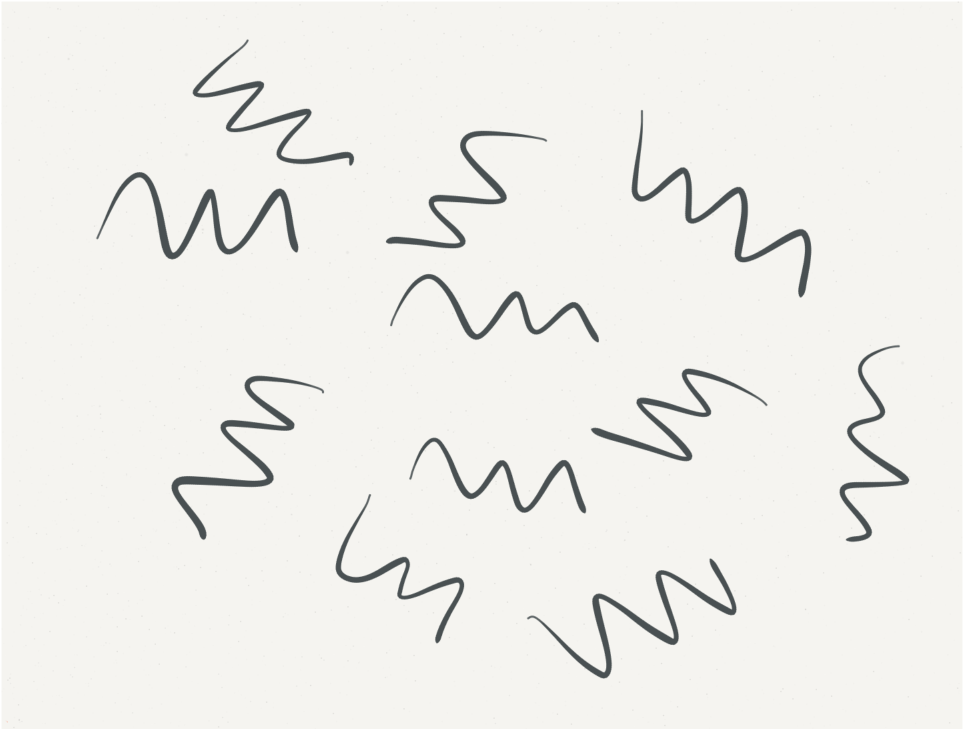


like a WIMP

instead of…



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

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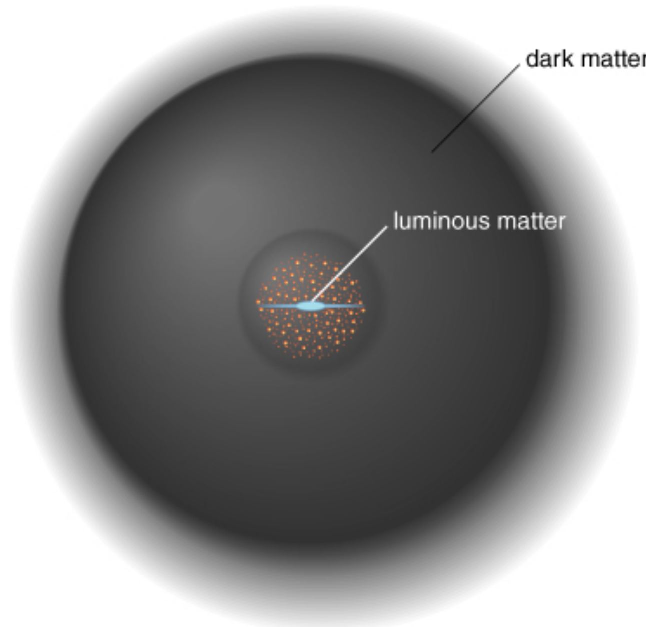

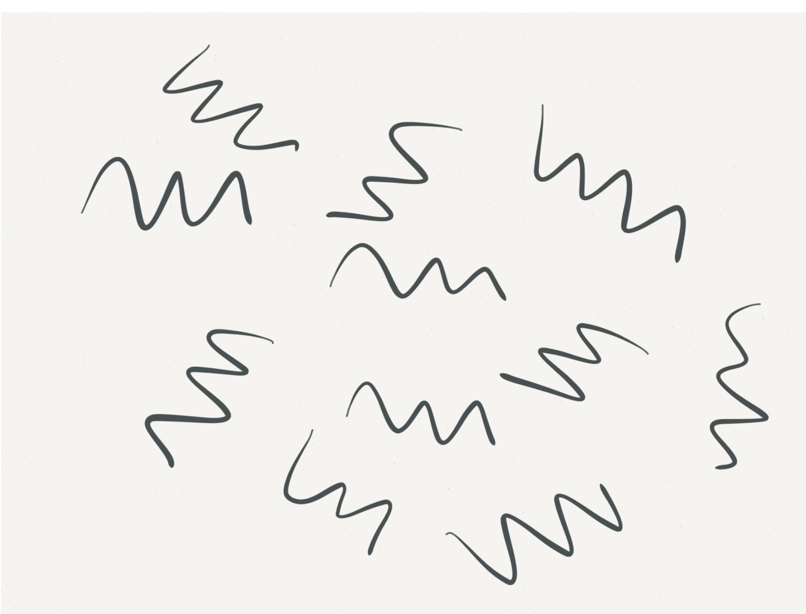

Decreasing DM Mass

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

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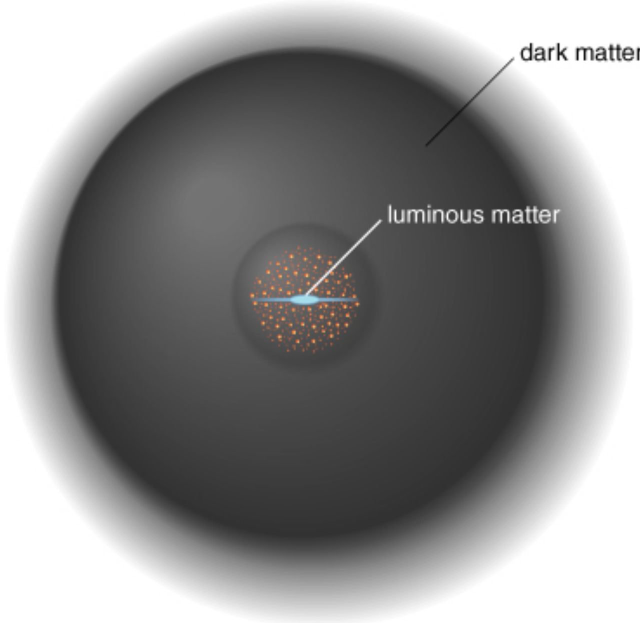
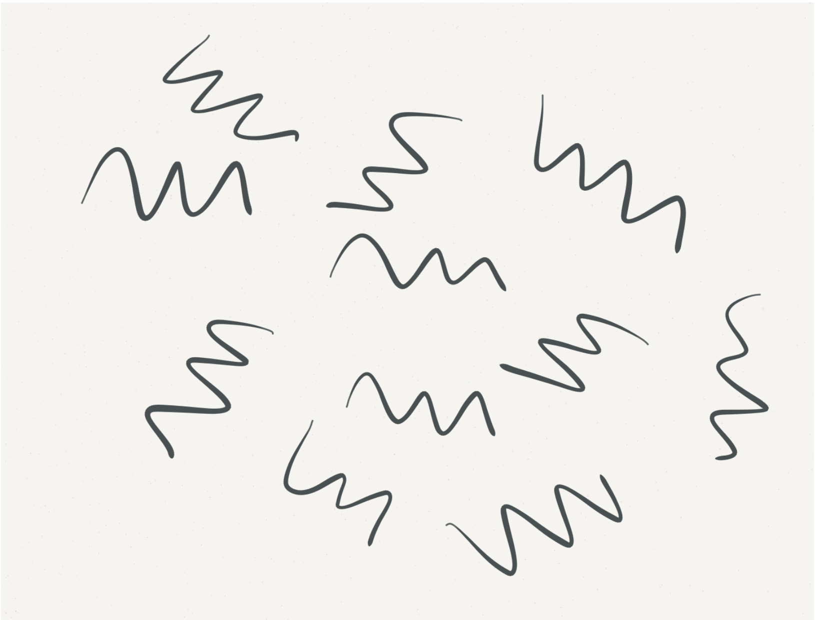




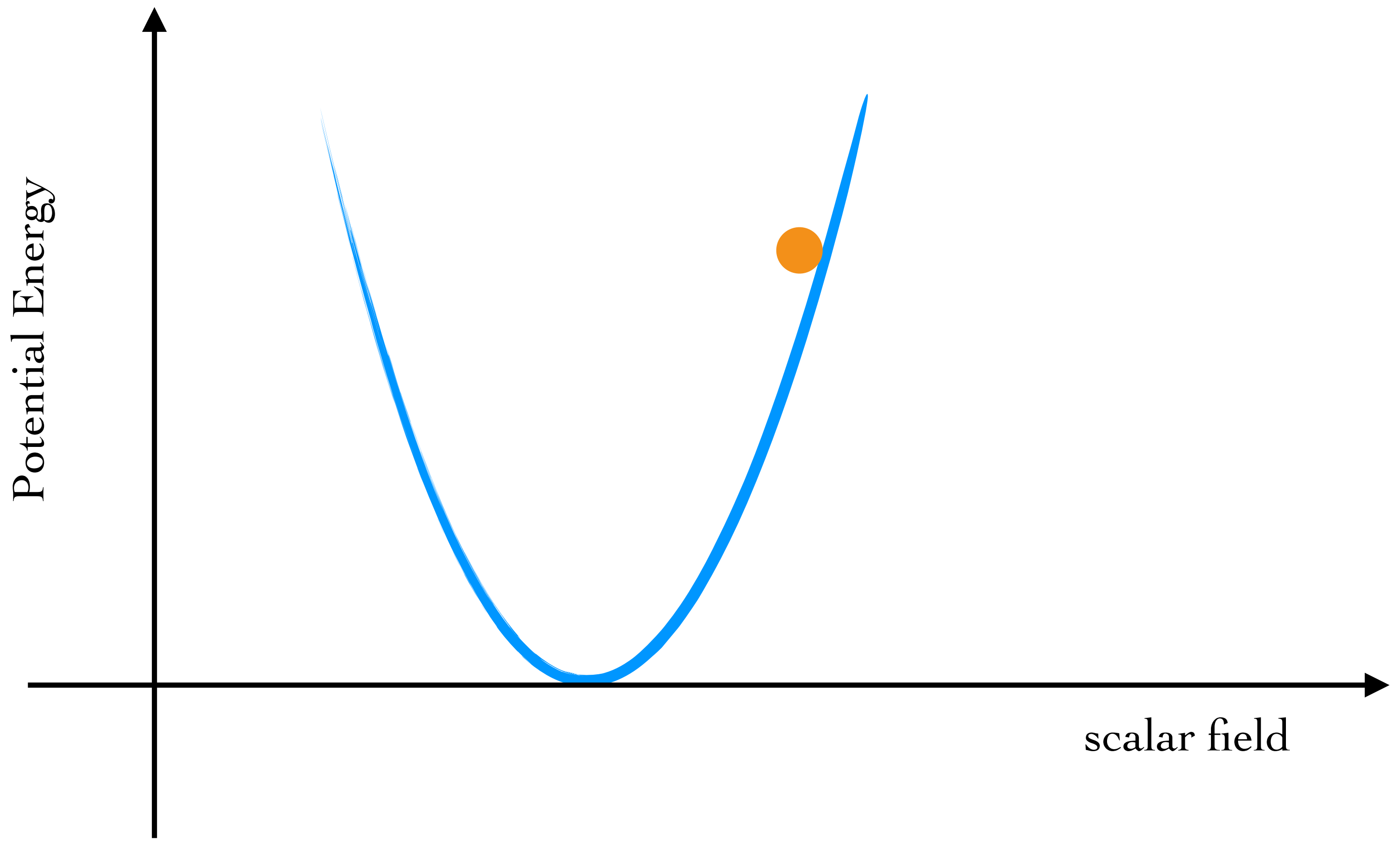
Decreasing DM Mass

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

Equivalent to a Scalar wave

Light Scalar Dark Matter

- Produced by the misalignment mechanism



Frozen when:
Hubble > m_ϕ

Initial conditions set by inflation

*The story changes slightly if DM is a dark photon

Light Scalar Dark Matter

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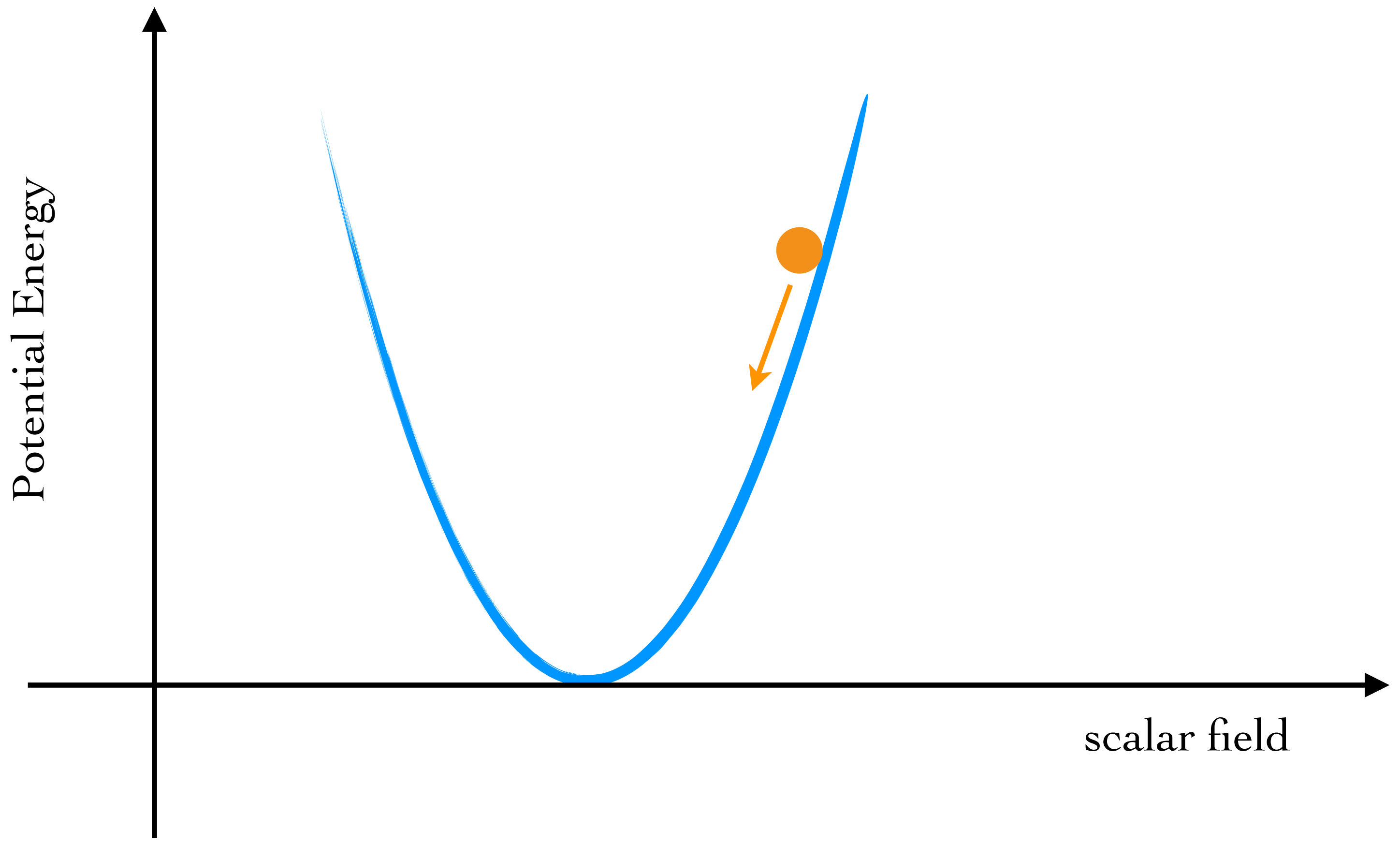


Frozen when:
Hubble > m_ϕ

Oscillates when:
Hubble < m_ϕ

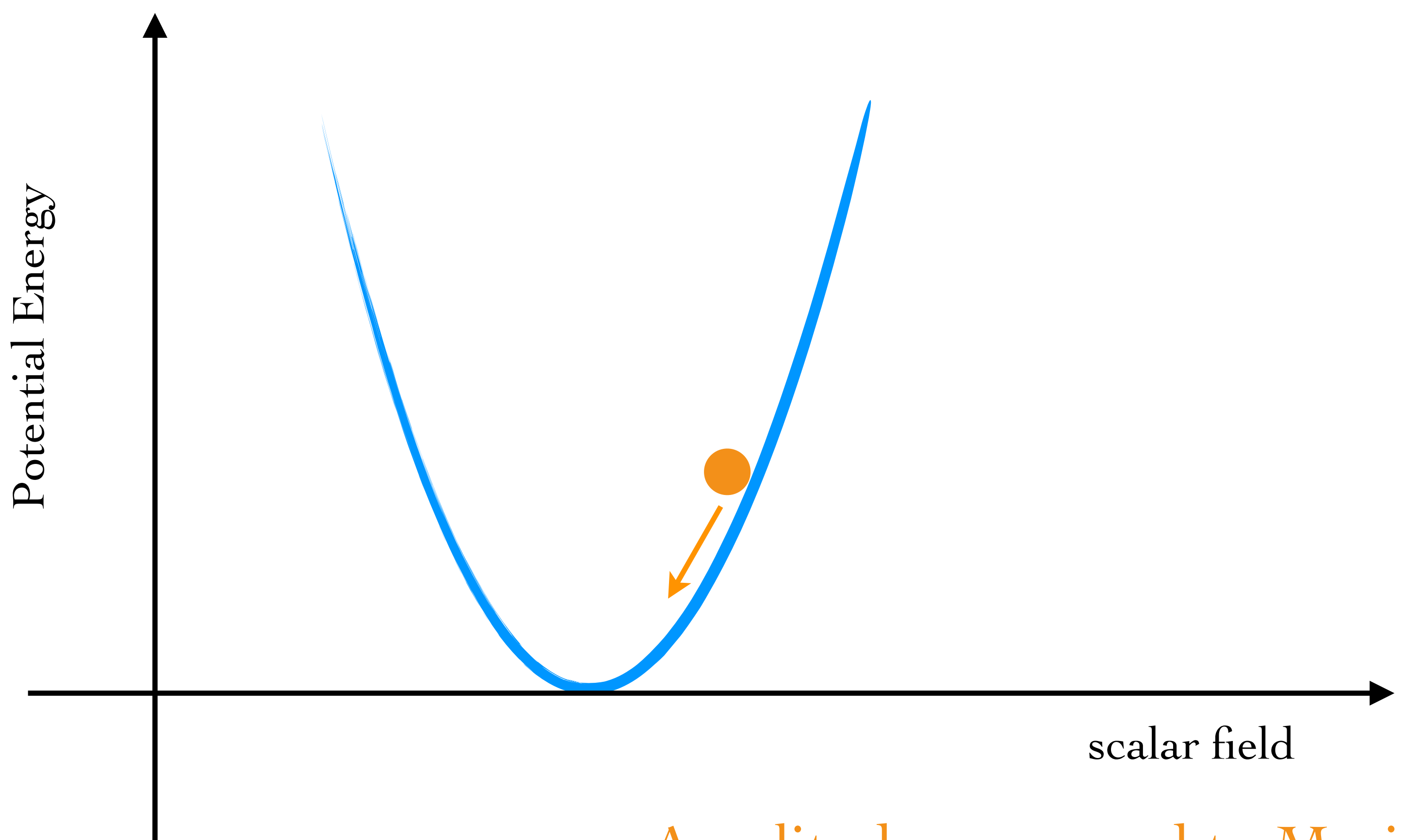
ρ_ϕ scales as a^{-3}
just like Dark Matter

Initial conditions set by inflation

*The story changes slightly if DM is a dark photon

Light Scalar Dark Matter Today

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



$m_\phi^{\ 2}\ \phi_o^2\ \cos^2(m_\phi\ t) \sim \rho_\phi$

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

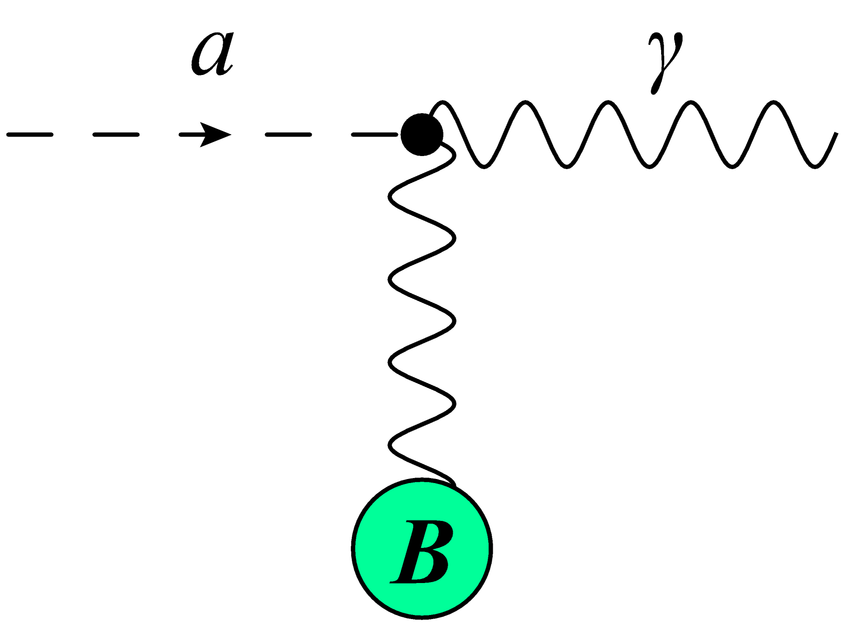
Amplitude compared to M_{Pl} in the galaxy:

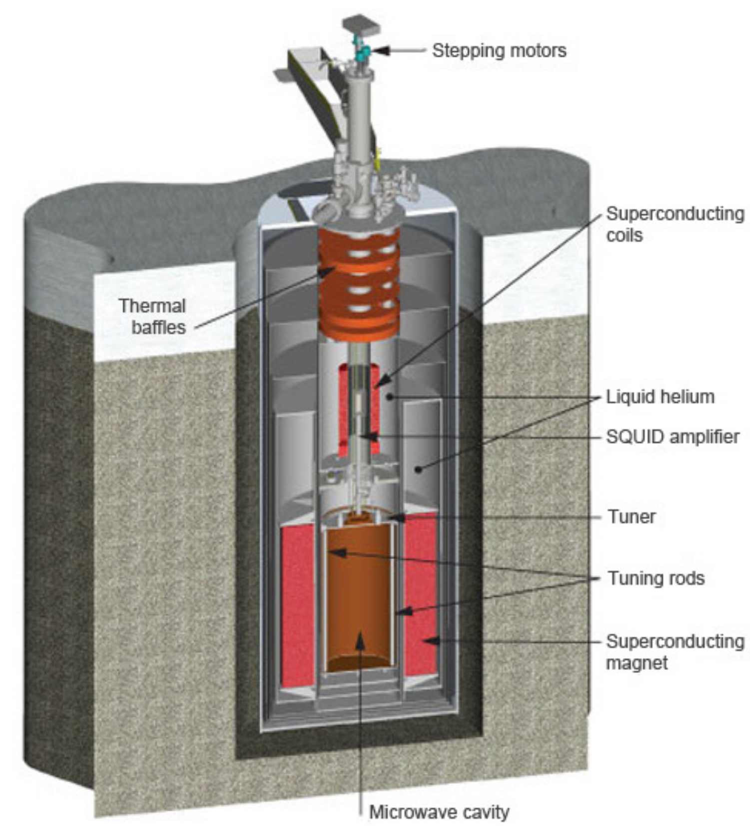
$$\kappa\phi_0 = \frac{\sqrt{8\pi\rho_\phi}}{m_\phi M_{\rm Pl}} = 6.4\cdot 10^{-13}\left(\frac{10^{-18}\,\mathrm{eV}}{m_\phi}\right)$$

Axion Dark Matter

Some examples

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

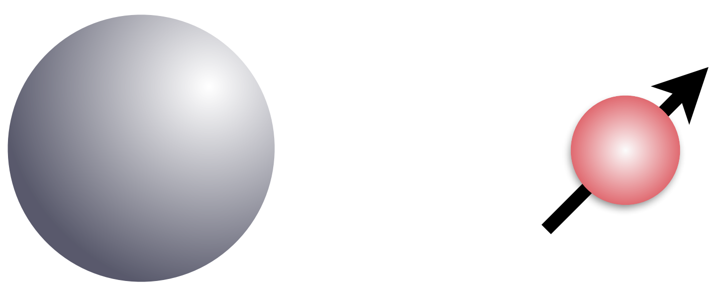


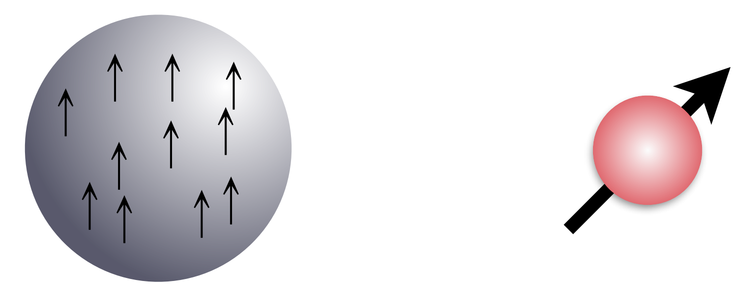


Cavity size = Axion size

Axion Dark Matter

Some examples





- Axion Force experiments (ex. ARIADNE)
- Axion Dark Matter experiments (ex. CASPEr)

Dark Photon Dark Matter

Some examples

- Detected if kinetically mixed with the photon

$$\mathcal{L} \supset \epsilon F_{EM} F_{DM}$$

- Detected like a photon (ex. DM Radio and ADMX)

DM electric field $\sim \sqrt{\rho_{DM}} \sim 50$ V/cm

Moduli Dark Matter

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

- Examples of couplings

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

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

Fundamental constants are not really constants

Oscillating Fundamental Constants

AA, J. Juang, K. Van Tilburg (2014)

From the local oscillation of Dark Matter

Ex. for the electron mass:

$$d_{m_e}\sqrt{\hbar c}\frac{\phi}{M_{Pl}}m_e c^2 e\bar{e}$$

$M_{pl} = 10^{18}$ GeV
reduced Planck scale in energy

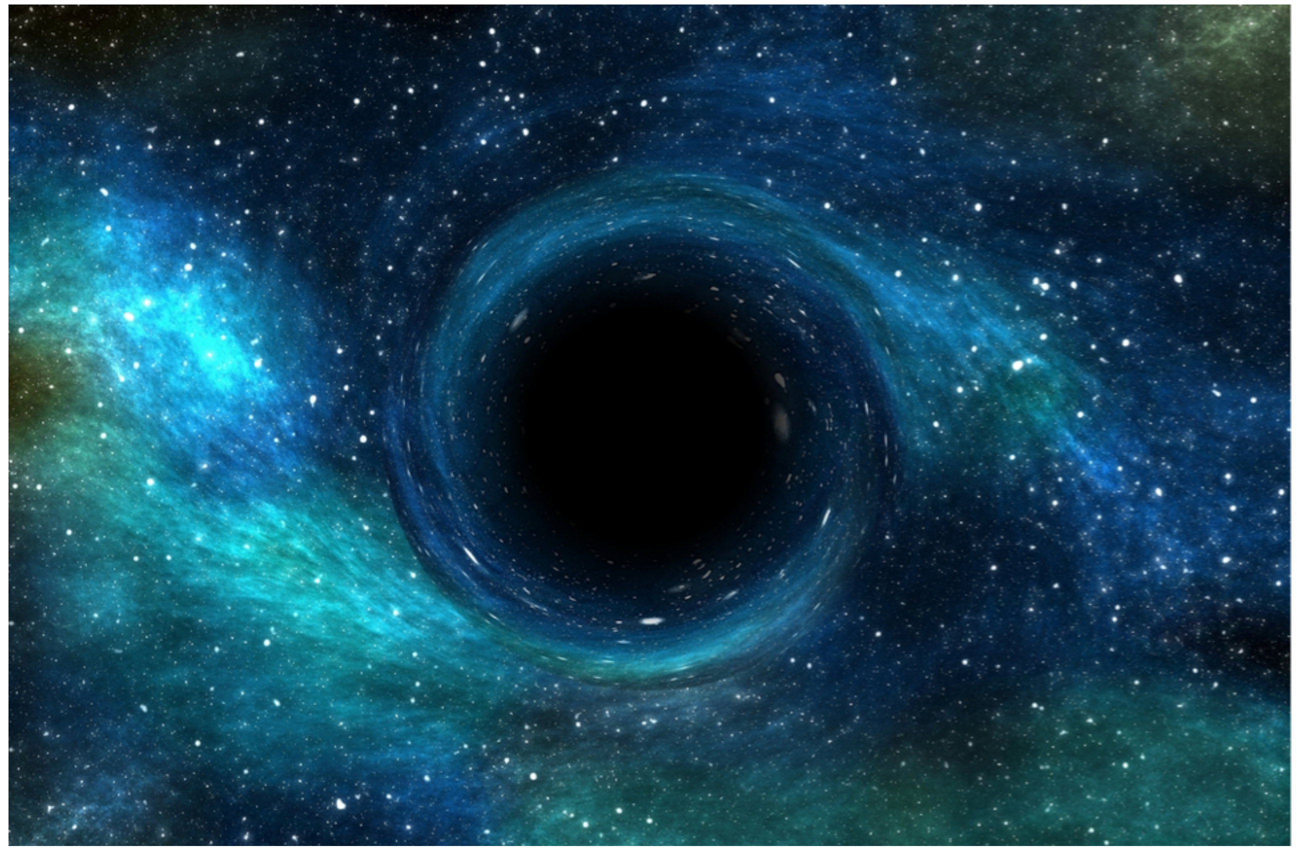
$$\frac{\delta m_e}{m_e} \approx \frac{d_{m_e}\phi_0}{M_{Pl}}\cos(\omega_{DM}t)$$

$$= 6.4 \times 10^{-13}\cos(\omega_{DM}t)\left(\frac{10^{-18}\ \text{eV}}{m_{DM}c^2}\right)\left(\frac{d_{m_e}}{1}\right)$$

d_{me} : coupling strength relative to gravity

Variation of atomic/nuclear transition frequencies at atomic clock experiments
Variation of the bohr radius excites acoustic modes at resonant mass GW detectors

Black Holes as Nature's Detectors

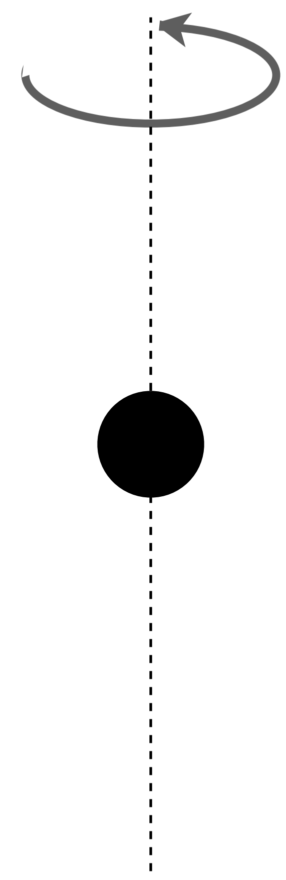


1 km -10 billion km

They can detect bosons of similar in size

Superradiance for a massive boson

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



Particle Compton Wavelength comparable to the size of the Black Hole

Superradiance for a massive boson

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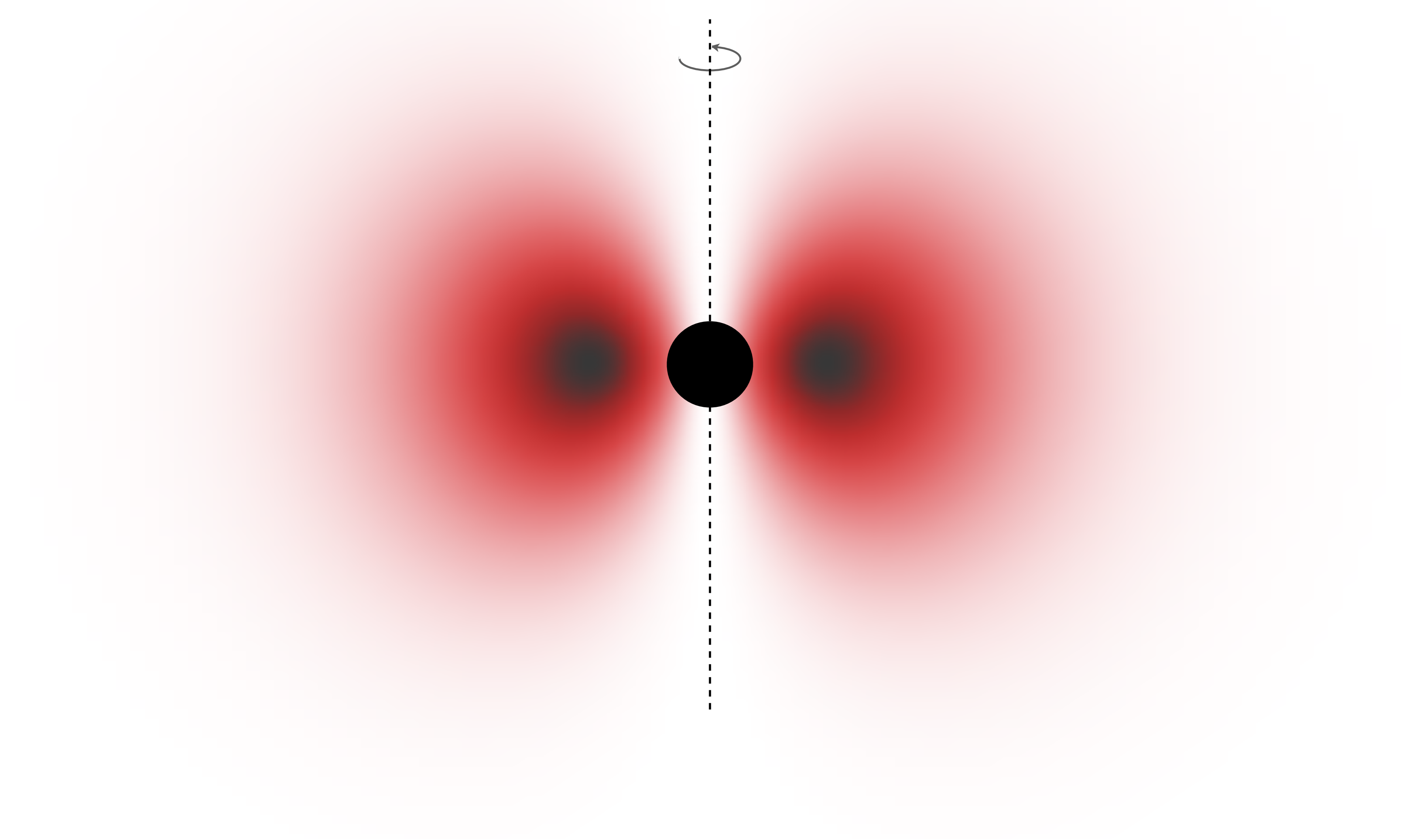
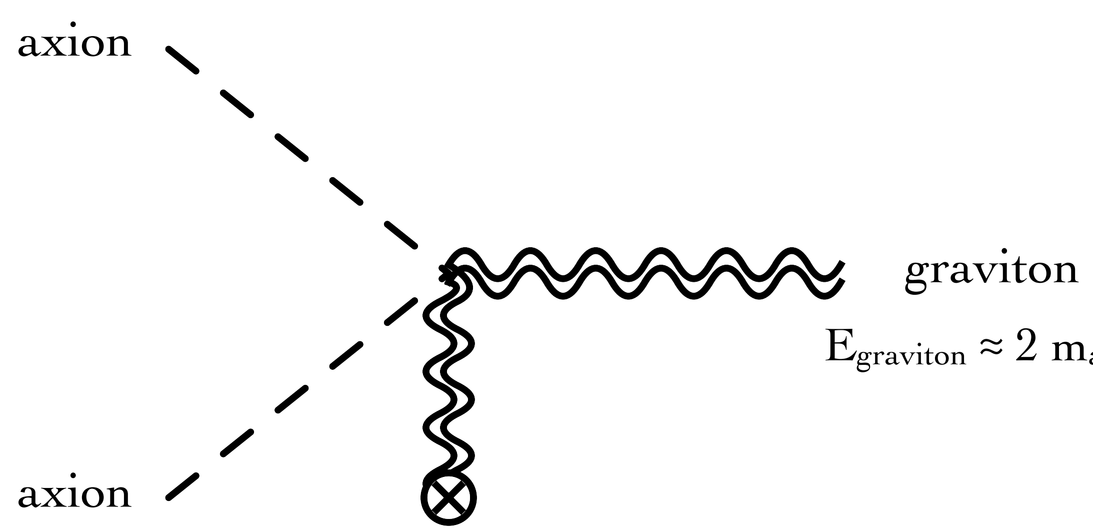


Particle Compton Wavelength comparable to the size of the Black Hole

Super-Radiance Signatures

GW annihilations



$$f \; = \; 10\,\mathrm{kHz} \times (\mu_a/10^{-11}\,\mathrm{eV})$$

$E_{\mathrm{graviton}} \approx 2\ m_{\mathrm{axion}}$ High frequency GWs

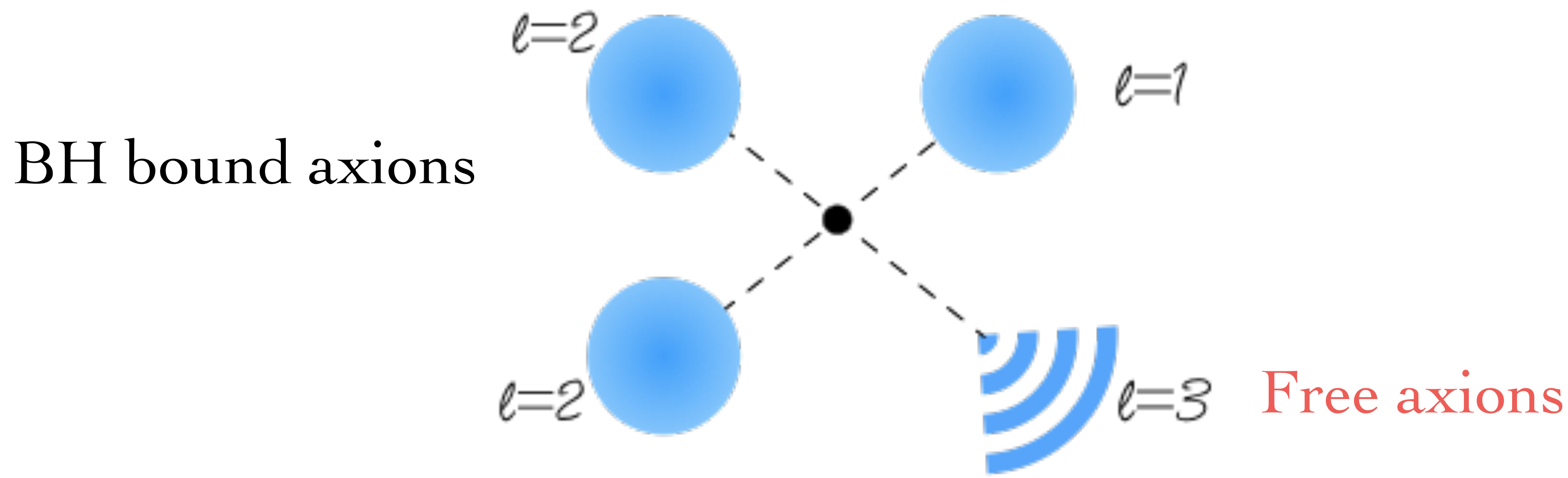
- Signal enhanced by the square of the occupation number of the state

$$h_{\mathrm{peak}} \simeq 10^{-22} \left(\frac{1\,\mathrm{kpc}}{r}\right) \left(\frac{\alpha/\ell}{0.5}\right)^{\frac{p}{2}} \frac{\alpha^{-\frac{1}{2}}}{\ell} \left(\frac{M}{10 M_\odot}\right)$$

- Signal duration determined by the annihilation rate (can last thousands of years)

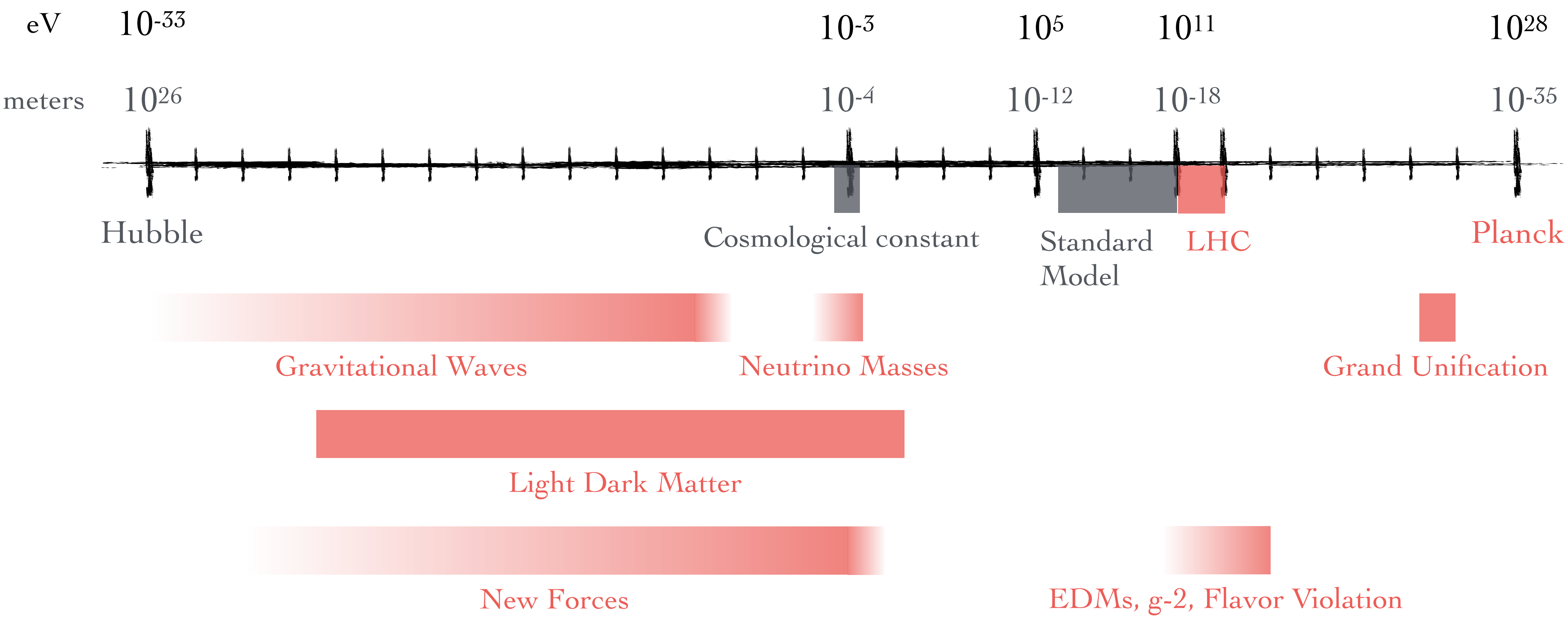
Superradiance Signatures

Scalar waves



- Axion self-interactions produce monochromatic scalar wave radiation
- Potentially detectable to table-top experiments looking for Dark Matter

The Scales in Our Universe



There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- Hamlet