The Principle of Plenitude

Asimina Arvanitaki
Perimeter Institute

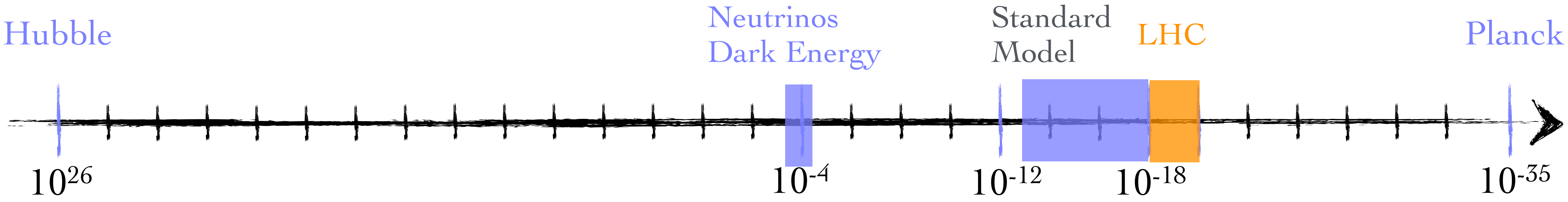
Plenitude

Gottfried Wilhelm Leibniz

" This best of all possible worlds will contain all possibilities, with our finite experience of eternity giving no reason to dispute nature's perfection."

The High Energy Frontier

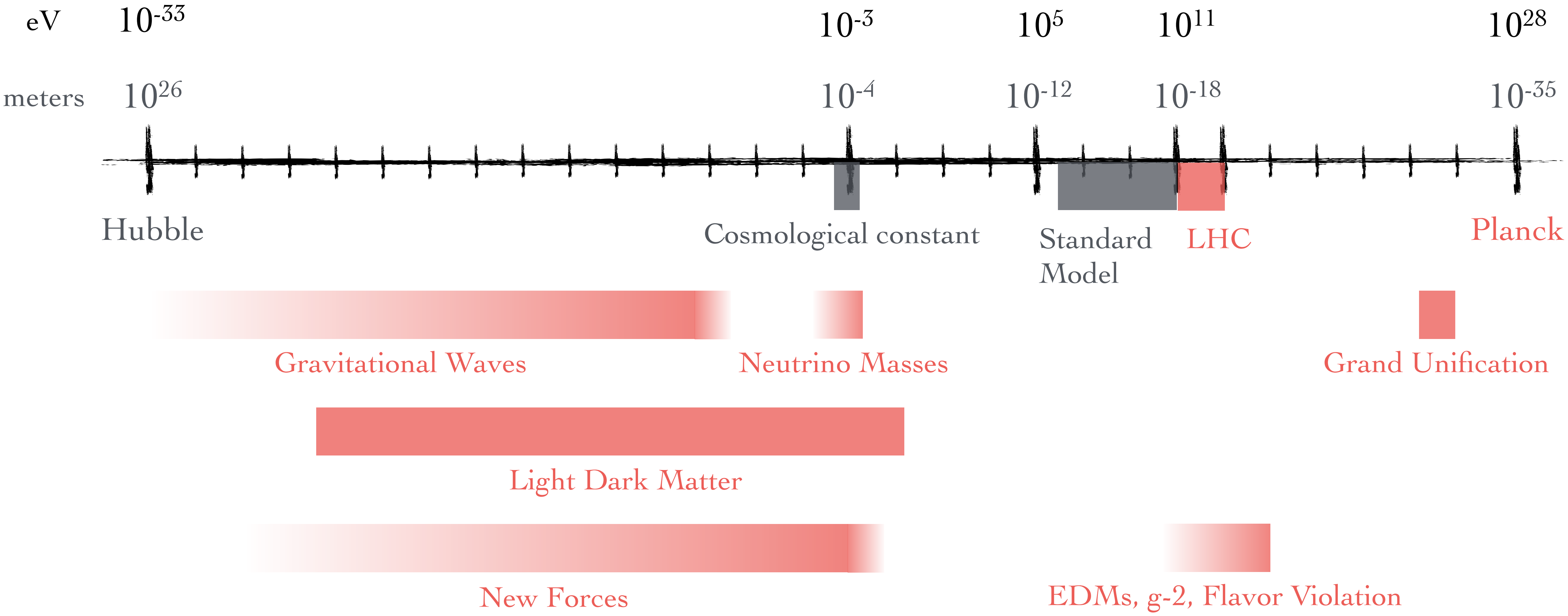
Particle Physics — Precision vs Energy Frontier



Scale in meters

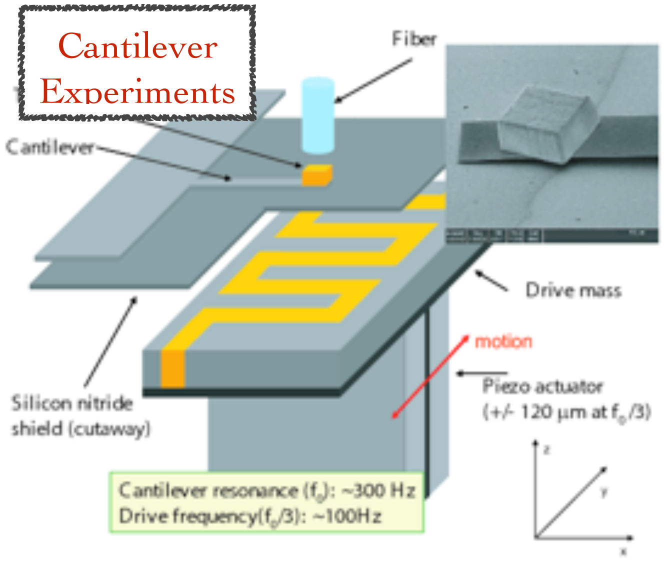
80% of scales unexplored

The Scales in Our Universe



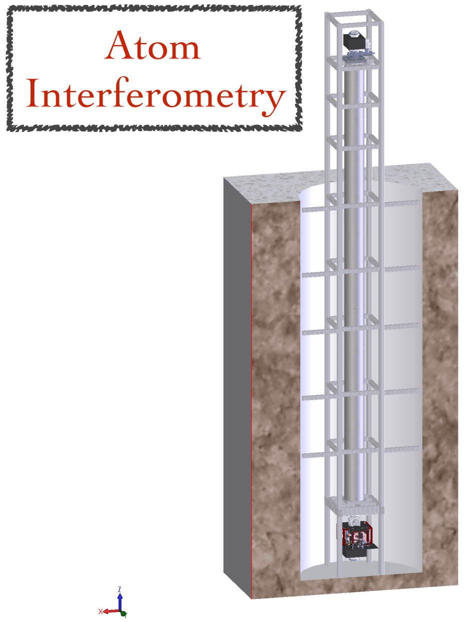
There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
\- Hamlet

Opportunities to probe the low energy frontier



- Short Distance Tests of Gravity
- Extra Dimensions

Dimopoulos, Kapitulnik (1997)

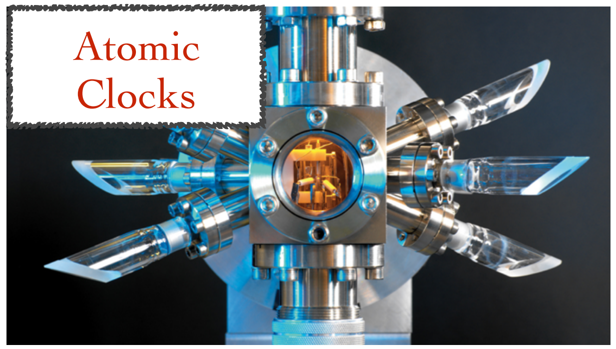


- Tests of Gravity
- Gravitational Wave detection at low frequencies
- Tests of Atom Neutrality at 30 decimals

Dimopoulos, Geraci (2003)
Dimopoulos, Kasevich et. al.(2006-2008)

- Axion Dark Matter Detection
- Axion Force Detection

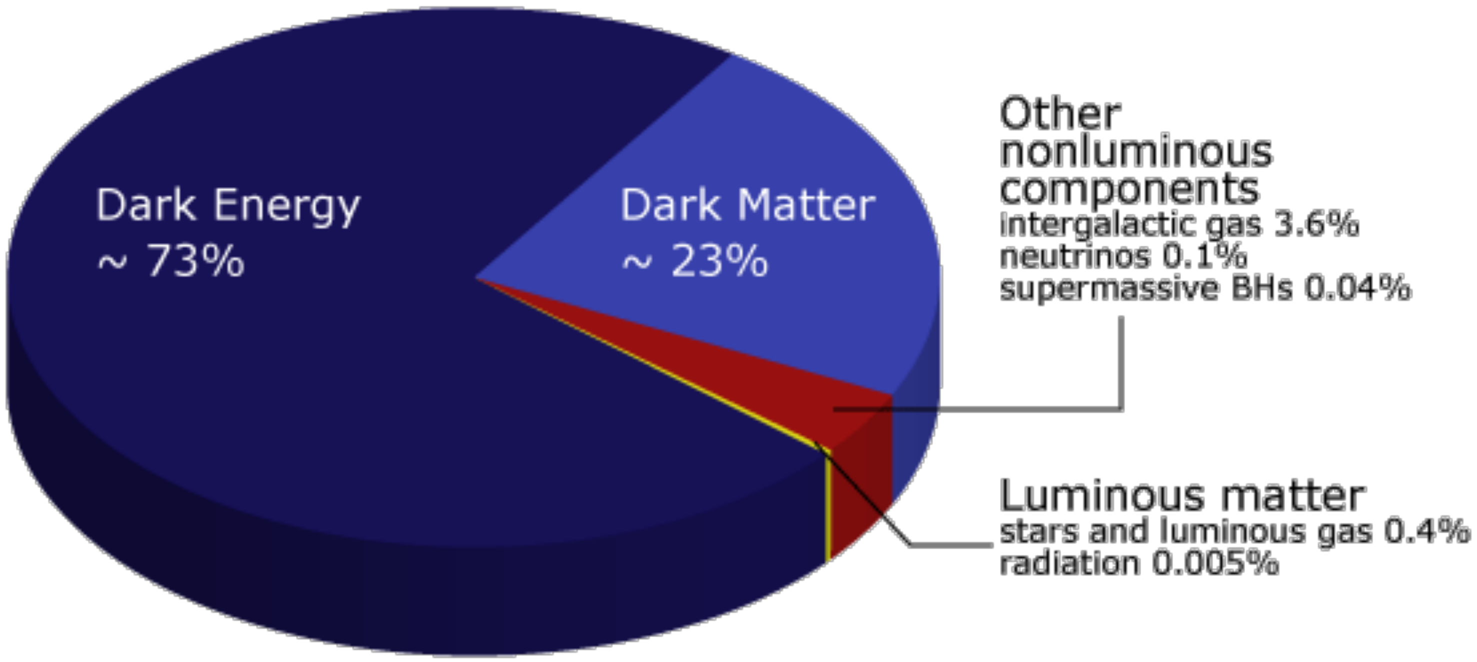
Graham et. al. (2012)
AA, Geraci (2014)



- Setting the Time Standard
- Dilaton Dark Matter Detection

AA, Huang, Van Tilburg (2014)

The Mystery of Dark Matter



Models of Dark Matter

- What is it made out of?

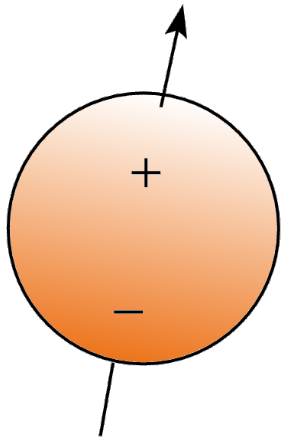
  Anything from 10^{-22} eV to 10^{70} eV in mass

- 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 Electric Dipole Moment
~ e fm θ_{QCD}

$$L_{\text{SM}} \supset \frac{g_s^2}{32\pi^2}\theta_{\text{QCD}} G^a \tilde{G}^a$$

Experimental bound: $\theta_{QCD} < 10^{-10}$

Solution:
θ_{QCD} is a dynamical field, an axion

Weinberg(1978) and Wilczek (1978)
Peccei and Quinn (1977)

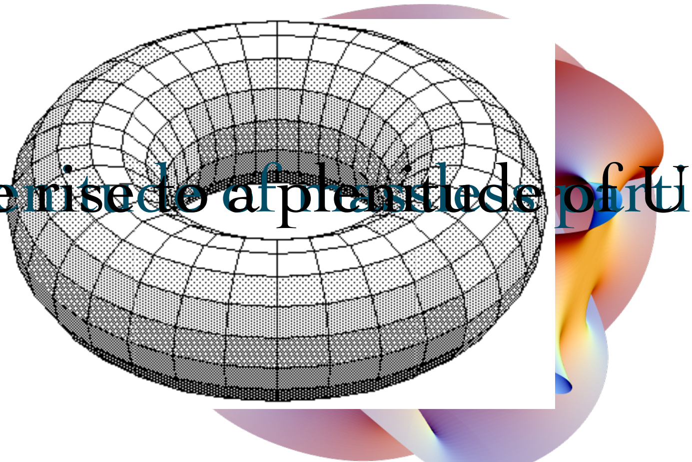
Axion mass from QCD:

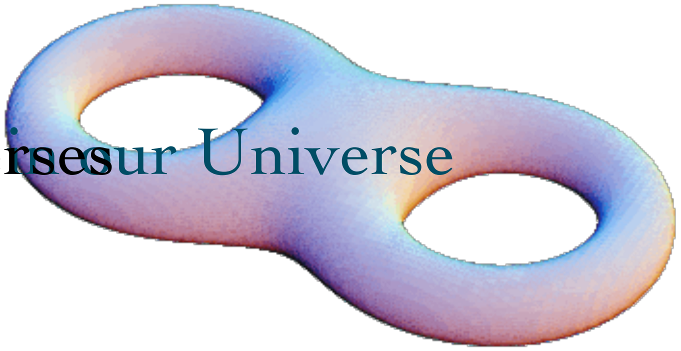
$$\mu_a \sim 6 \times 10^{-11}\ \text{eV}\ \frac{10^{17}\ \text{GeV}}{f_a} \sim (3\ \text{km})^{-1}\ \frac{10^{17}\ \text{GeV}}{\text{f}_\text{a}}$$

f_a : axion decay constant

Elements of String Theory

- Extra dimensions





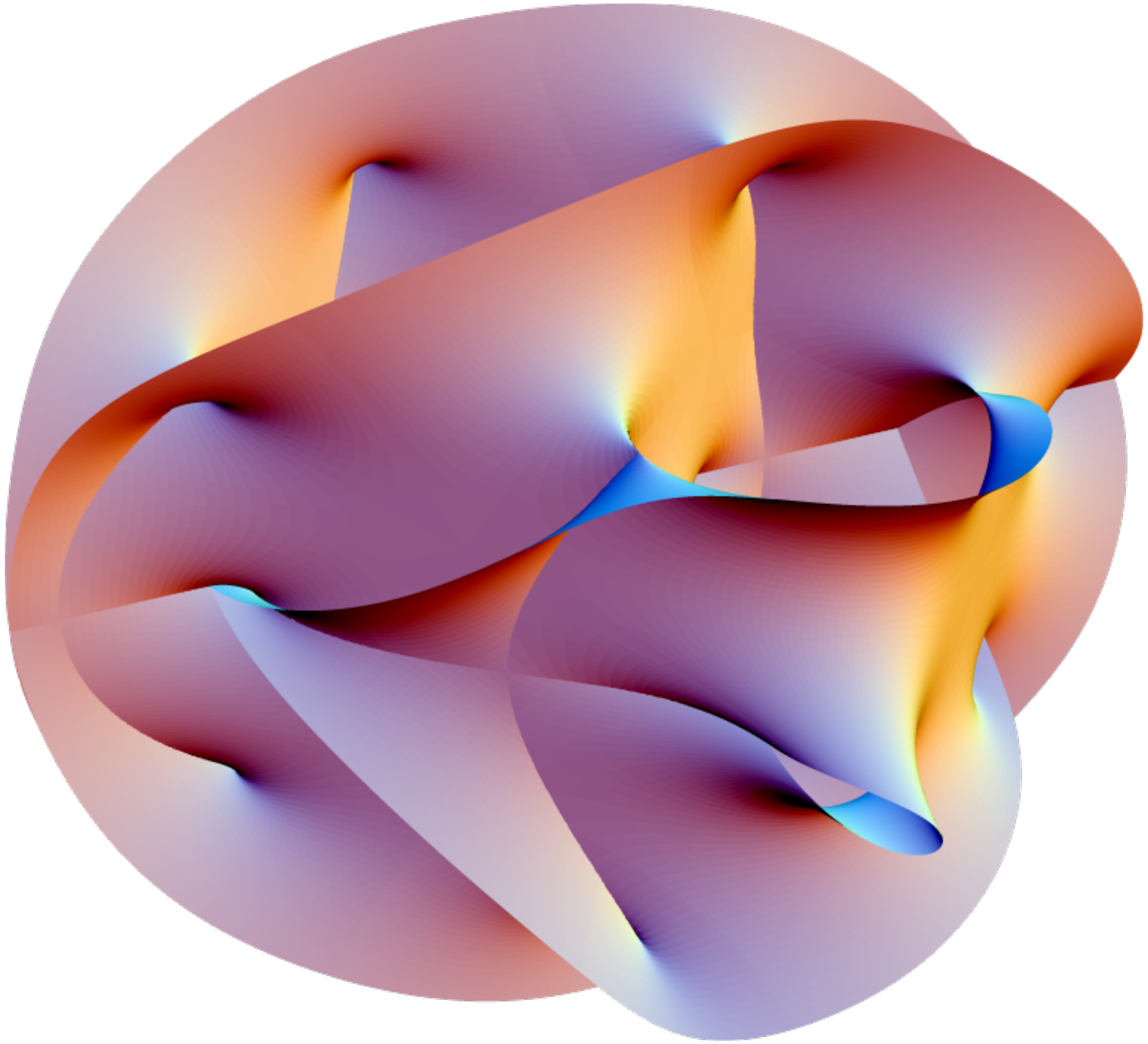
Give rise to a plenitude of particles in our Universe

Give rise to a plenitude of Universes

A Plenitude of Massless Particles

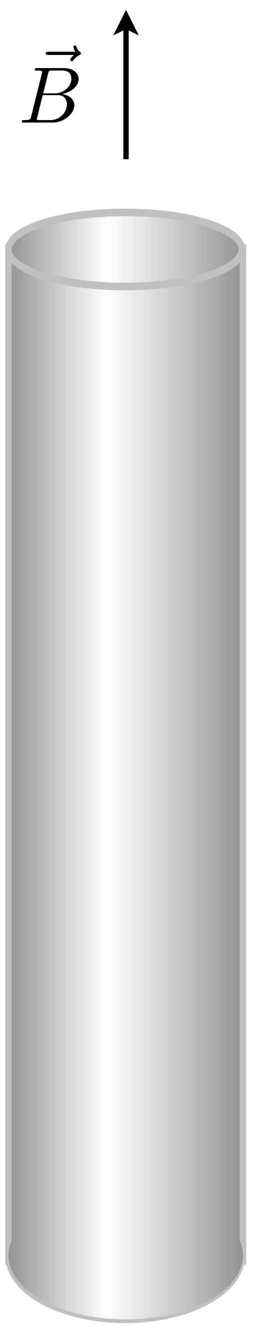
Compactification naturally gives rise to massless particles

In the presence of non-trivial topology,
non-trivial gauge field configurations can carry no energy,
resulting in 4D massless particles



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

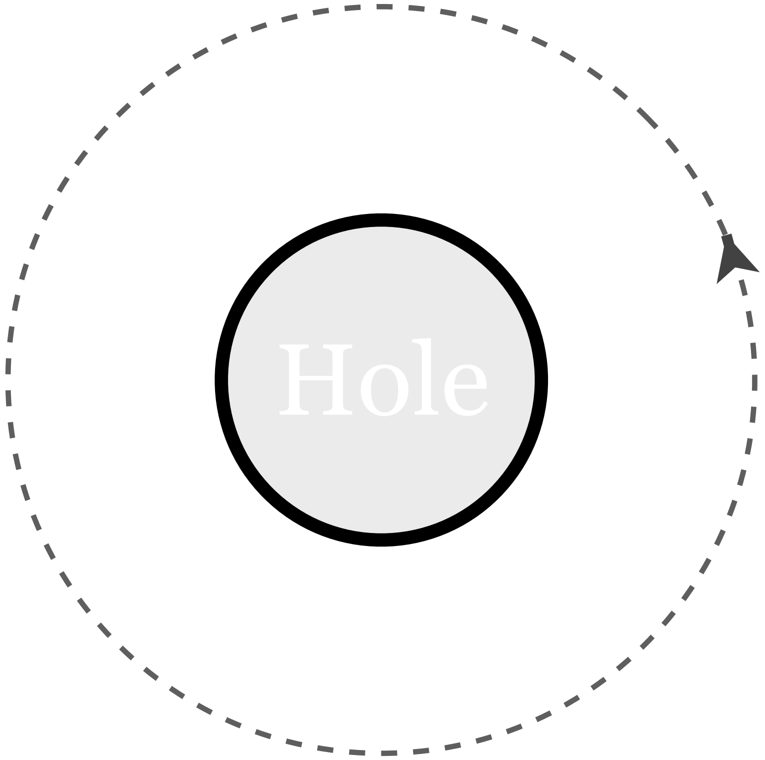
$$\vec{B} = 0$$

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 gauge configuration far away carries no energy

Non-trivial topology:

“Blocking out.” the core still leaves a non-trivial gauge, but no mass

A Plenitude of Massless Particles

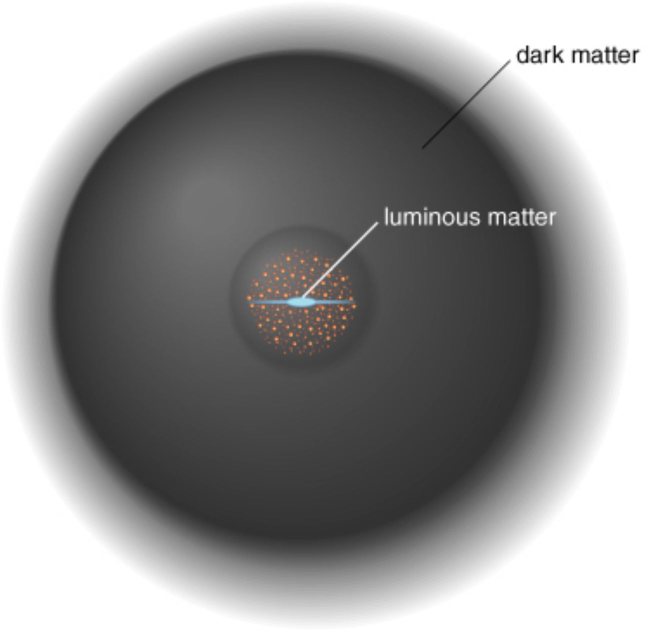
- Spin-0 non-trivial gauge field configurations: String Axiverse
- Spin-1 non-trivial gauge field configurations: String Photiverse
- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion

Properties of Plenitude of Particles from String Theory

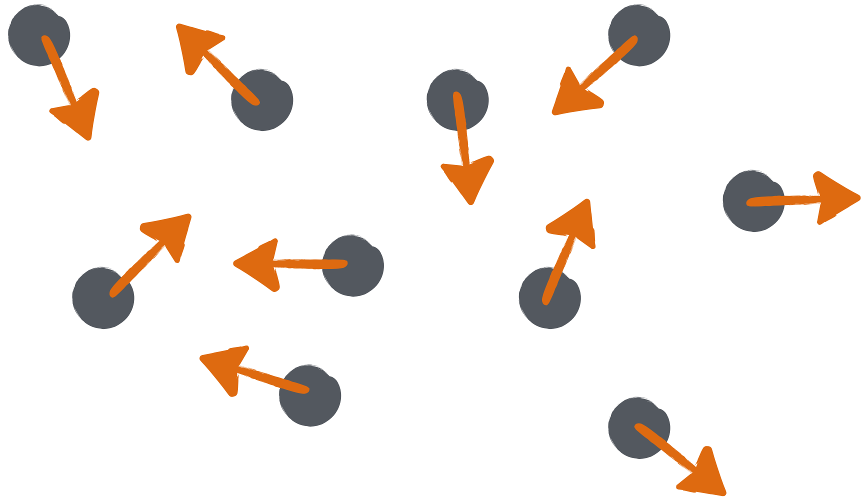
- They couple very weakly to the Standard Model
- They can be extremely light
- Constrained if the coupling is large enough by astrophysics, BBN, CMB…

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

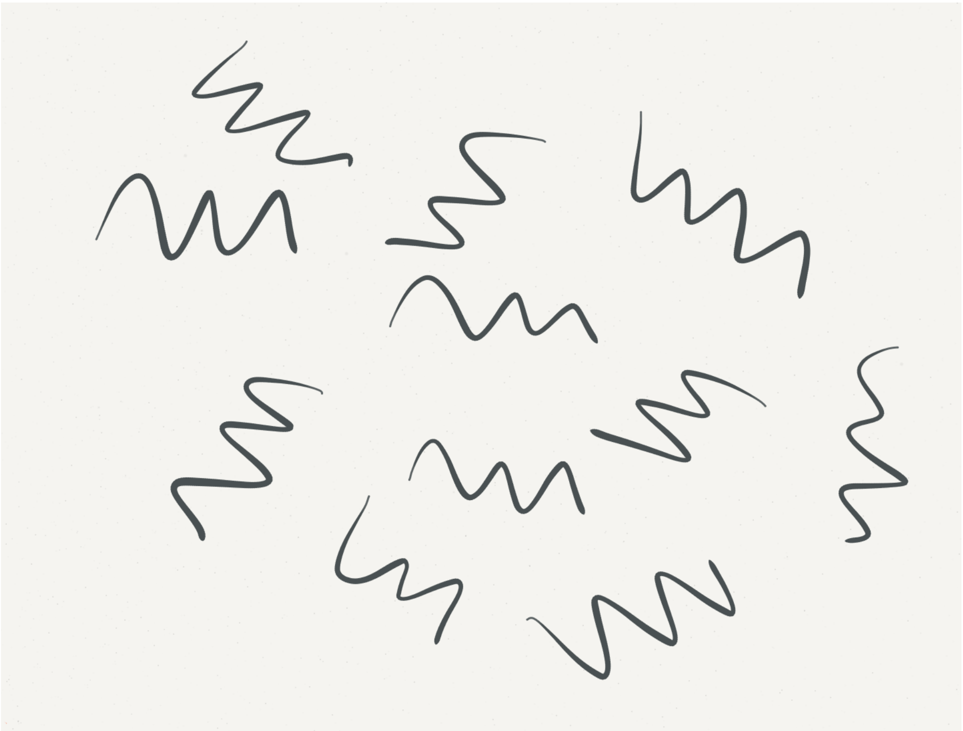


Usually we think of …



like a WIMP

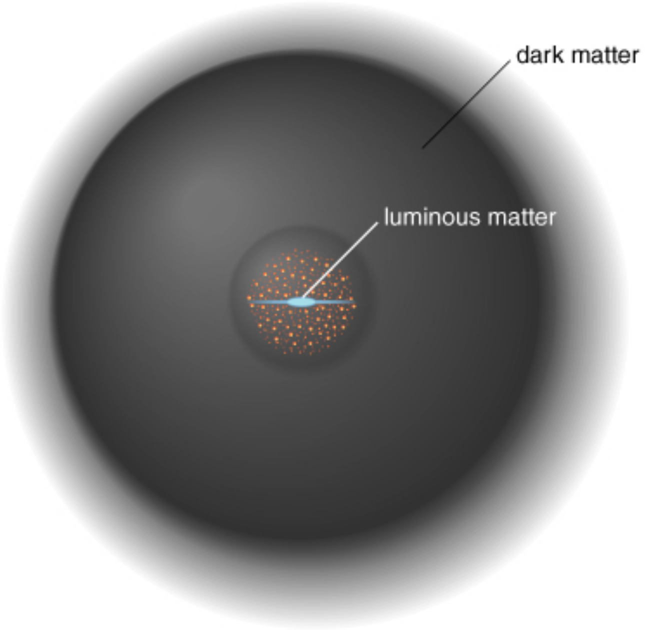
instead of…

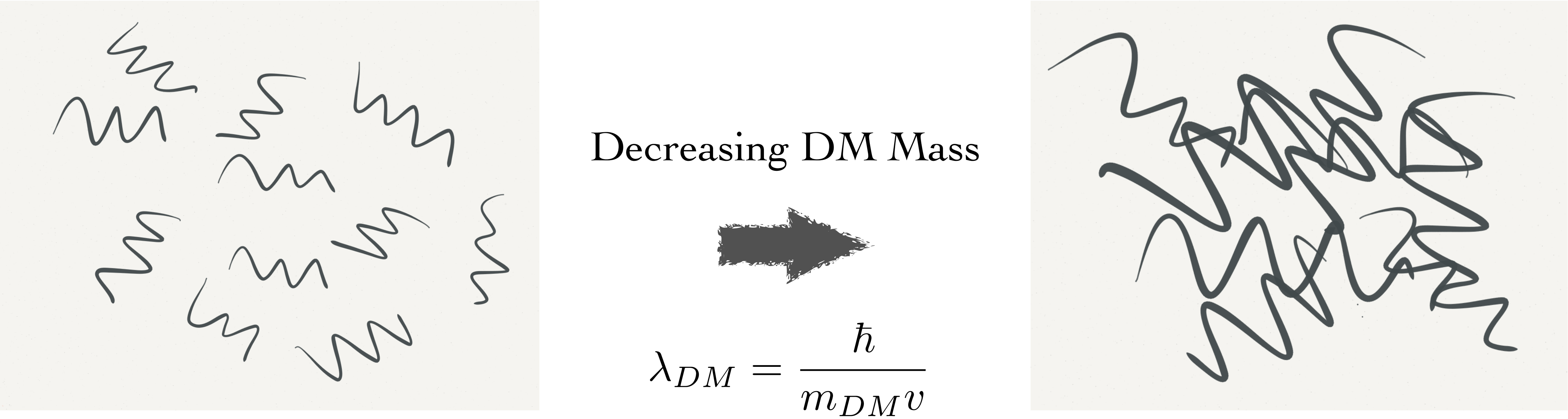


$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy





Decreasing DM Mass

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

Equivalent to a Scalar wave

Going from DM particles to a DM "wave"

$$\text{When } n_{DM} > \frac{1}{\lambda^3_{DM}}$$

In our galaxy this happens when $m_{DM} < 1$ eV/c^2

we can talk about DM ϕ(x,t) and locally

$$\phi(t) \approx \phi_0 \cos \omega_{DM} t$$

with amplitude

$$\phi_0 \propto \frac{\sqrt{\text{DM density}}}{\text{DM mass}}$$

with frequency

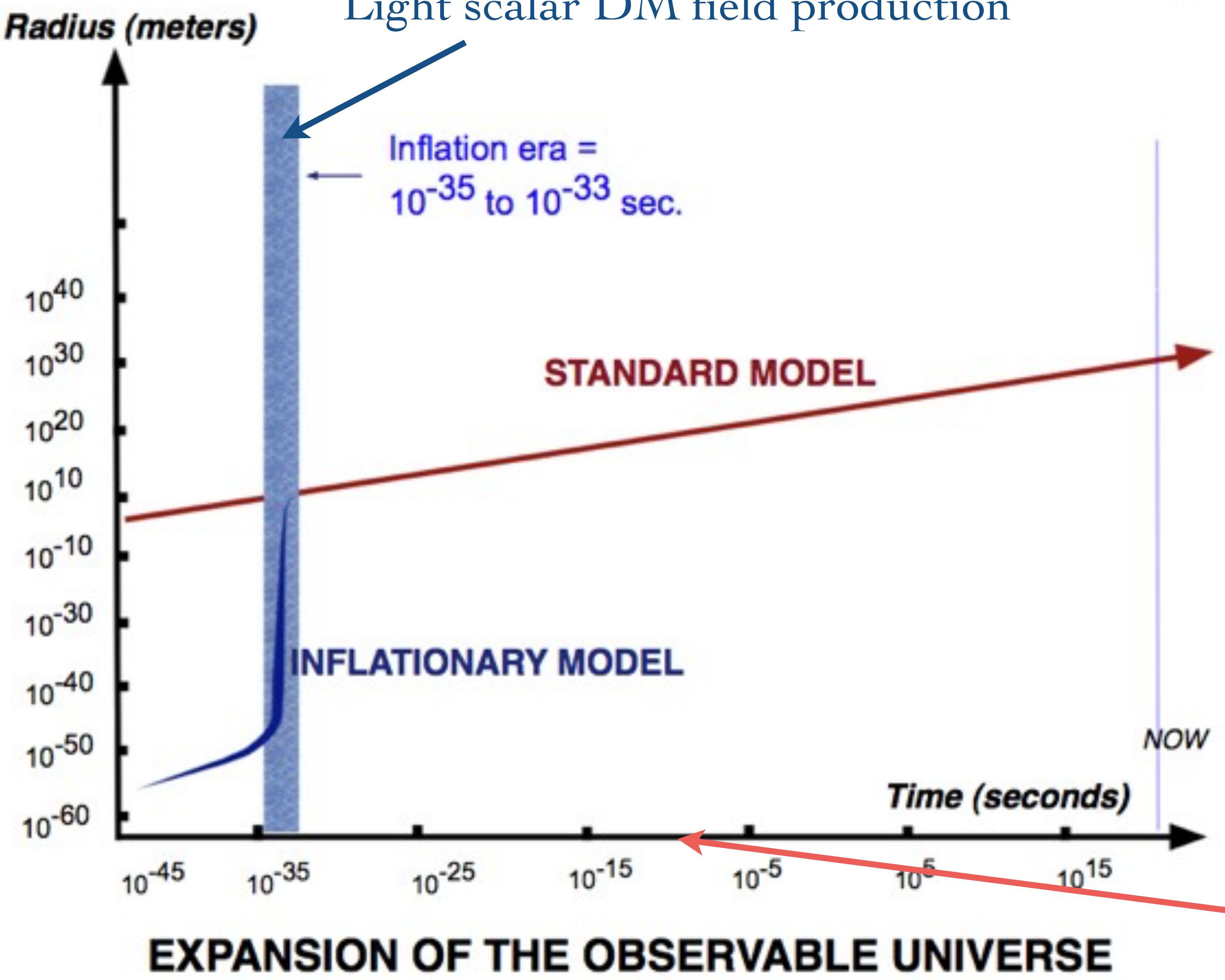
$$\omega_{DM} \approx \frac{m_{DM} c^2}{\hbar}$$

and finite coherence

$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

Scalar DM field Production Mechanism

- The “misalignment mechanism” during inflation



Light scalar DM field production

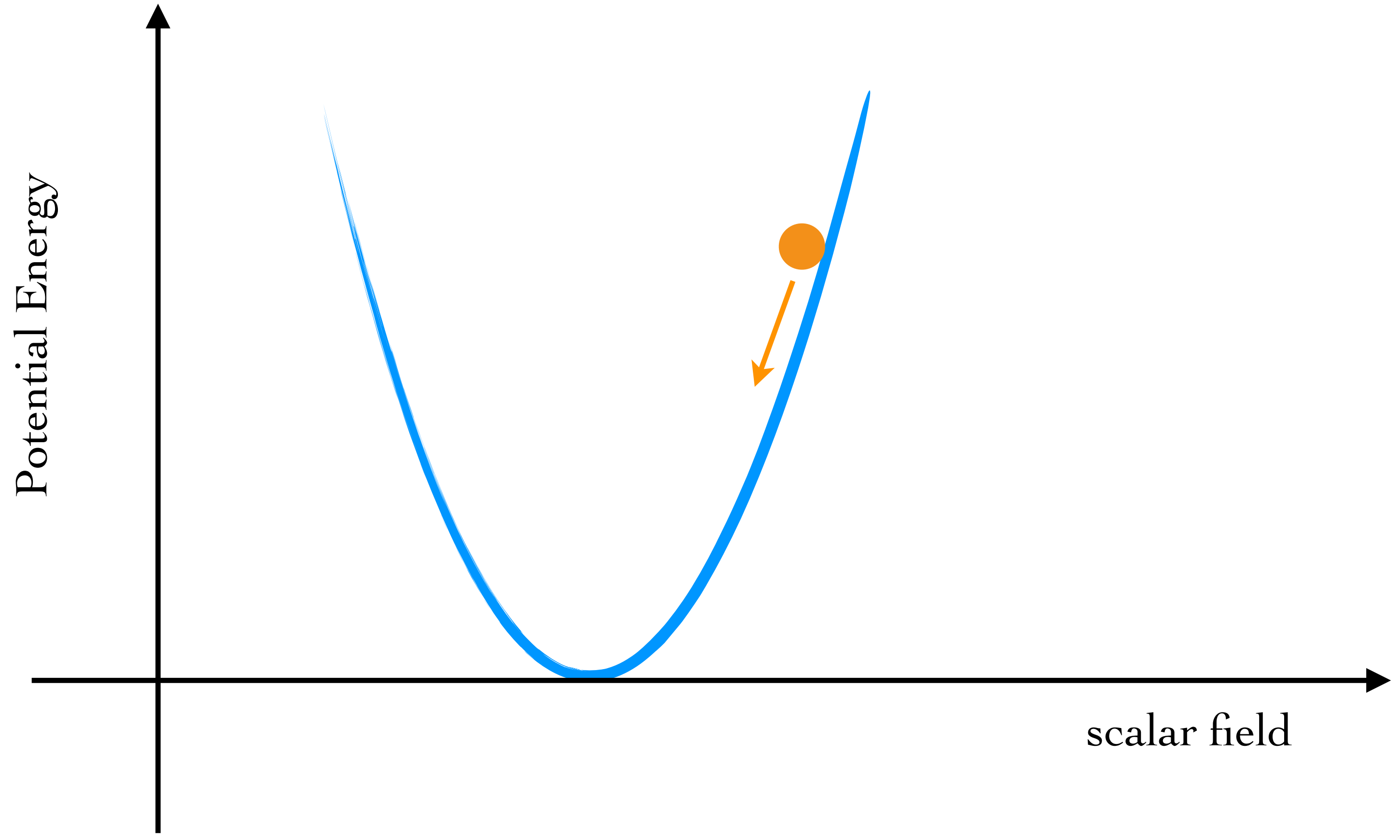
WIMP production

Light Scalar Dark Matter

- Just like a harmonic oscillator

$$\ddot{\phi} + 3\ H\ \dot{\phi} + m_\phi^2 \phi = 0$$

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



Frozen when:
Hubble > m_ϕ

Oscillates when:
Hubble < m_ϕ

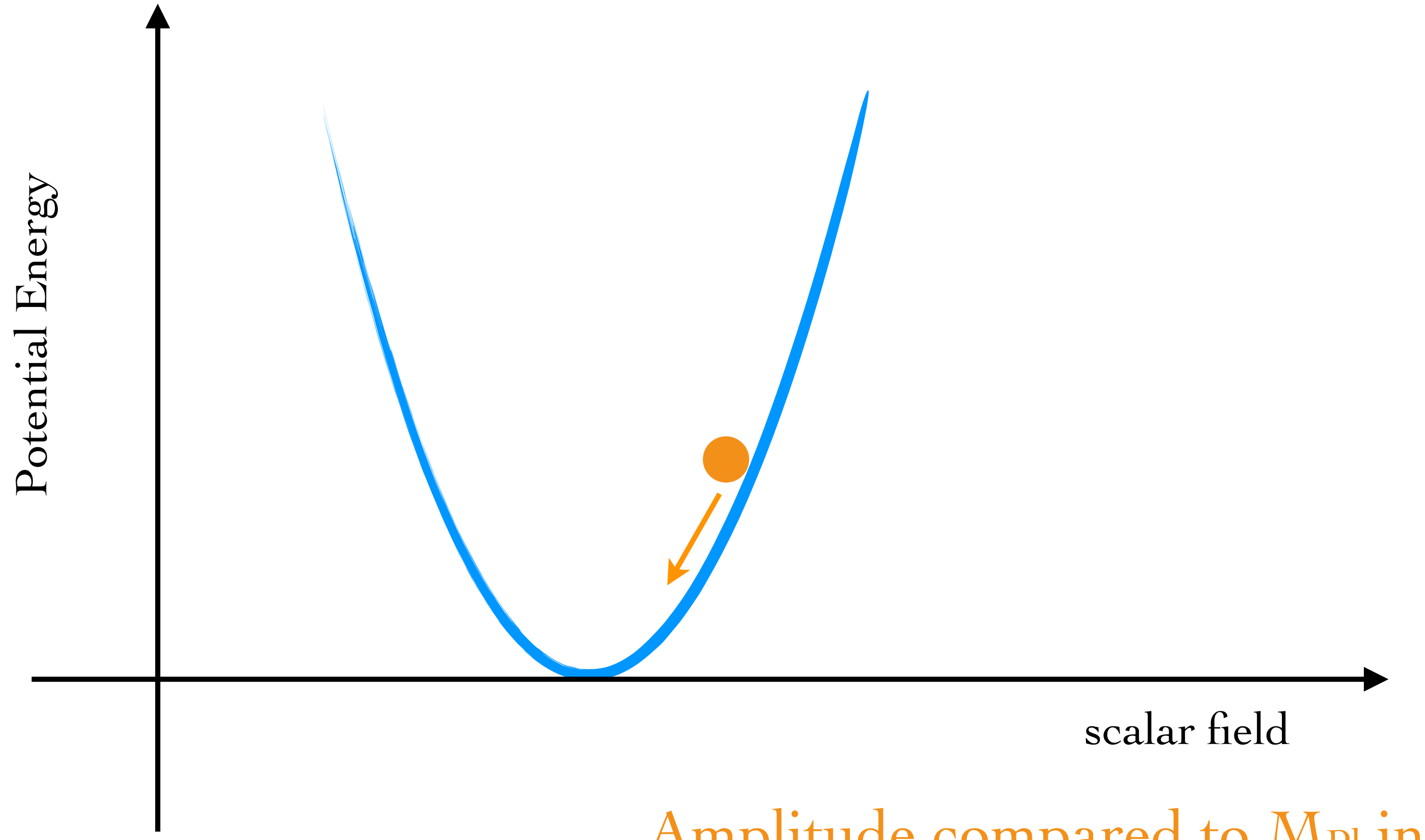
ρ_ϕ scales as a^{-3}
just like Dark Matter

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:

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

Scalar Dark Matter and Isocurvature Fluctuations

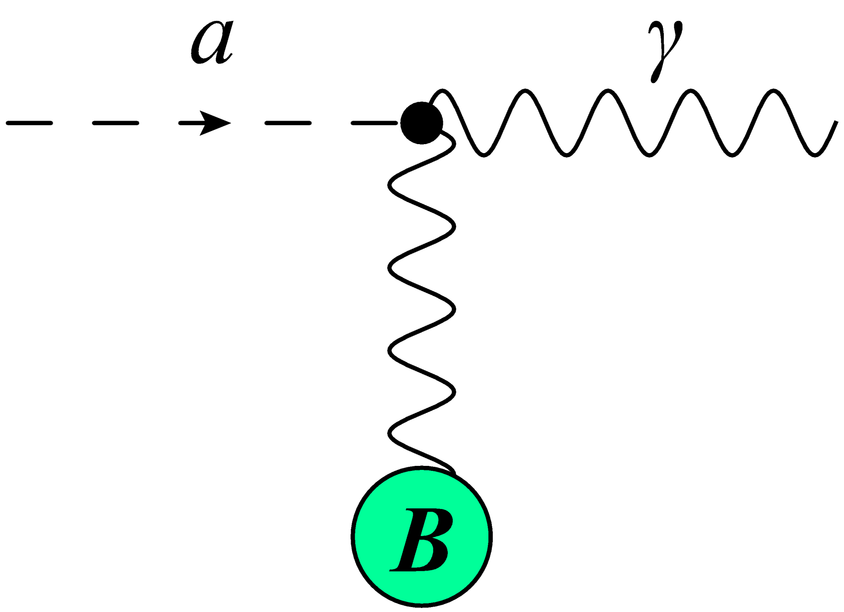
During Inflation

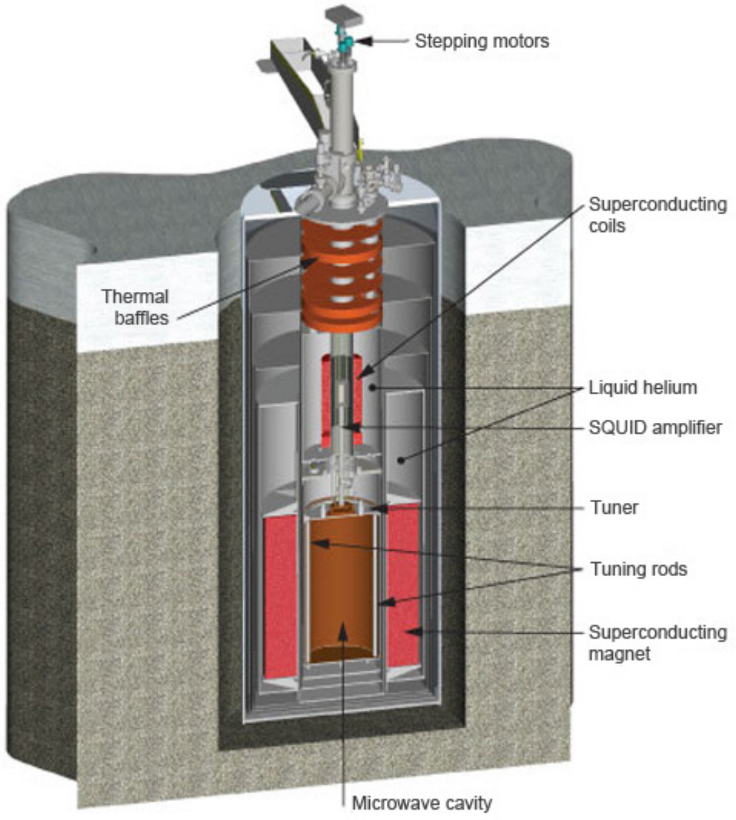
- $\delta\phi_{\text{quantum}} \sim$ Hubble
- Scalar Dark Matter carries its own fluctuation spectrum
- A discovery of tensor modes excludes large part of the parameter space

Axion Dark Matter

Some examples

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





Cavity size = Axion size

Axion Dark Matter

Some examples

Monopole-Dipole Interaction

Dipole-Dipole Interaction

- Axion Force experiments (ex. ARIADNE) and DM 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 $\sim \sqrt{\rho_{DM}}$ ~ 50 V/cm

Moduli Dark Matter

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

- Examples of couplings

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

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

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

Fractional variation set by square root of DM abundance

Need an extremely sensitive probe…

Ultra-light Scalar Dark Matter

- Mediates new interactions in matter
  - Generates a fifth force in matter

  - Generates Equivalence Principle violation

Keeping the DM time with Atomic Clocks

with Junwu Huang
and Ken Van Tilburg (2014)

Oscillating Atomic and Nuclear Energy Splittings due to Dark Matter

- Optical Splittings

$$\Delta E_{\mathrm{optical}} \propto \alpha_{EM}^2 m_e \sim \mathrm{eV}$$

- Hyperfine Splittings

$$\Delta E_{\mathrm{hyperfine}} \propto \Delta E_{\mathrm{optical}} \alpha_{EM}^2 \left(\frac{m_e}{m_p}\right) \sim 10^{-6}\ \mathrm{eV}$$

- Nuclear Splittings

$$\Delta E\ (m_p, \alpha_s, \alpha_{EM}) \sim 1\ \mathrm{MeV}$$

DM appears as a signature in atomic (or nuclear) clocks

How does and Atomic Clock Work?

Keep a laser tuned to a long-lived (> minutes) atomic transition

How well can I measure the frequency of the laser when tuned to the atom?

From the uncertainty principle ~ 10^{-16}

$$\frac{\delta f}{f} \sim \frac{\Gamma_{\text{atom}}}{f}\frac{1}{\sqrt{N_{\text{atoms}}}}\sqrt{\frac{\tau_{\text{cycling}}}{t_{\text{experiment}}}}$$

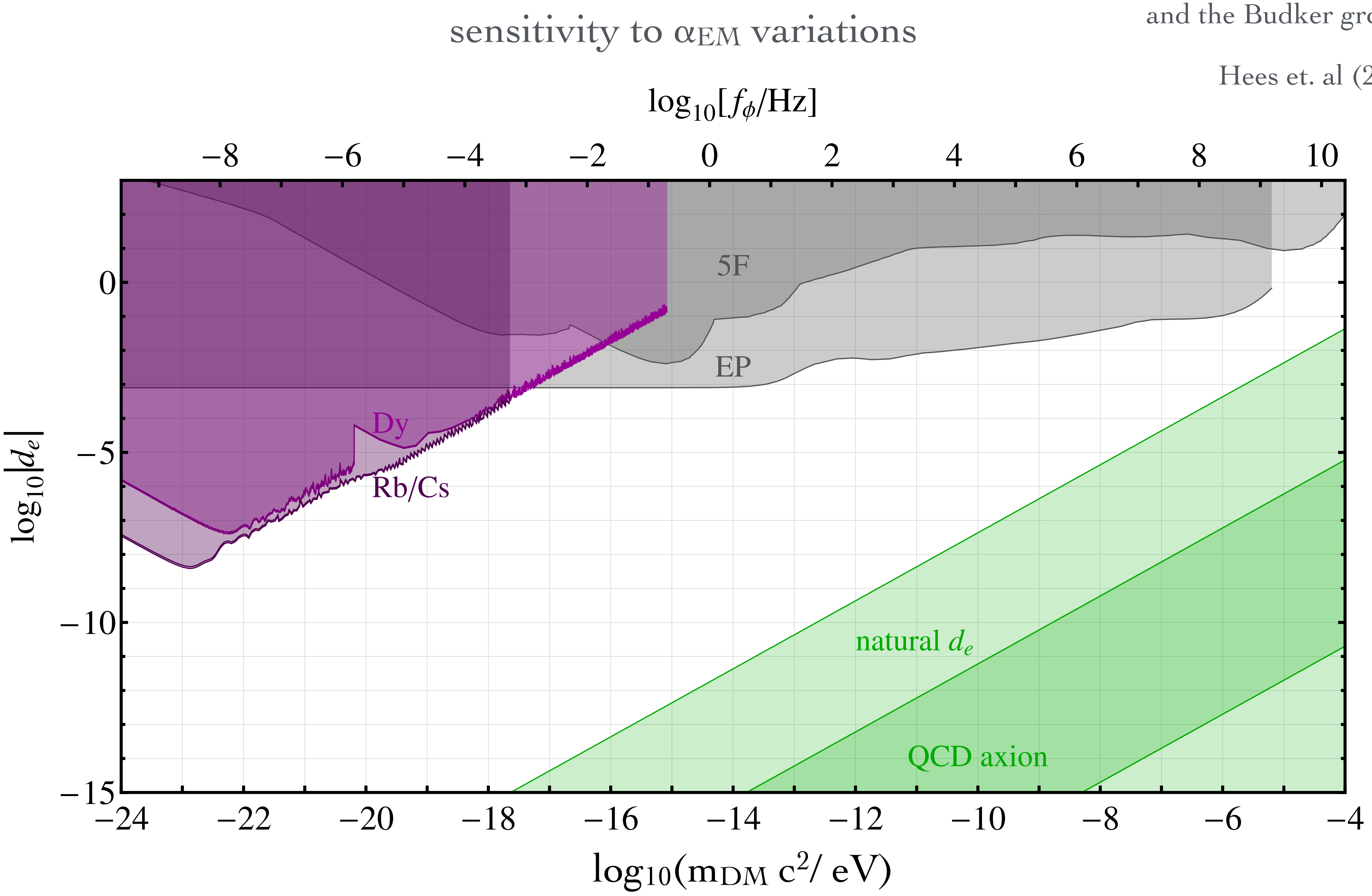
Number of times the observation is repeated

τ_{cycling} time that it takes to do one measurement (of order the atomic lifetime)

The Dy isotope and Rb/Cs Clock Comparison

Ken Van Tilburg
and the Budker group (2015)

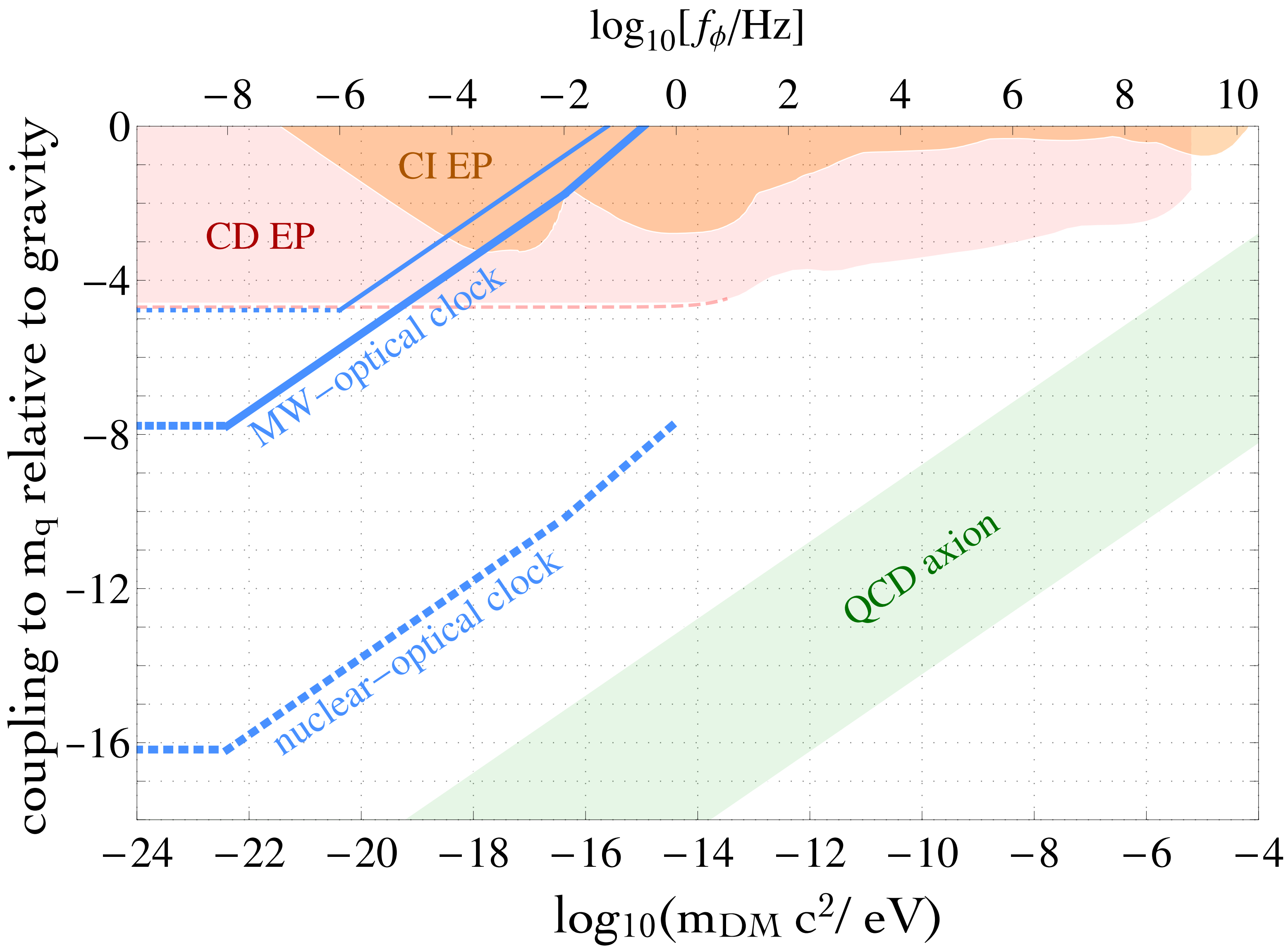
Hees et. al (2016)



Analysis performed with existing data

Nuclear to Optical Clock Comparison

Future Sensitivity of a ^{229}Th clock



The Sound of Dark Matter

with Ken Van Tilburg
and Savas Dimopoulos (2015)

Oscillating interatomic distances

- The Bohr radius changes with DM
  - $r_B \sim (\alpha\, m_e)^{-1}$

$$\frac{\delta r_B}{r_B} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

- The size of solids changes with DM
  - $L \sim N\, (\alpha\, m_e)^{-1}$

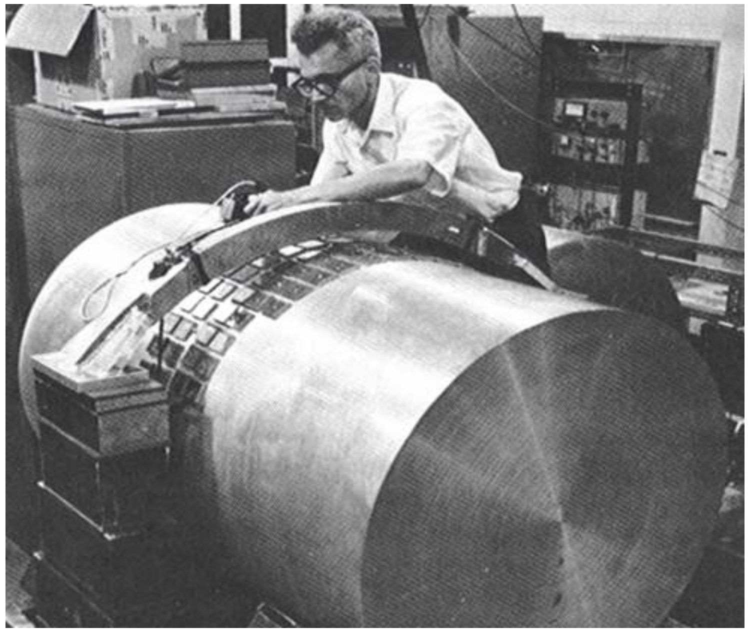
$$\frac{\delta L}{L} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

For a single atom $\delta r_B \sim 10^{-30}$ m

Need macroscopic objects to get a detectable signal

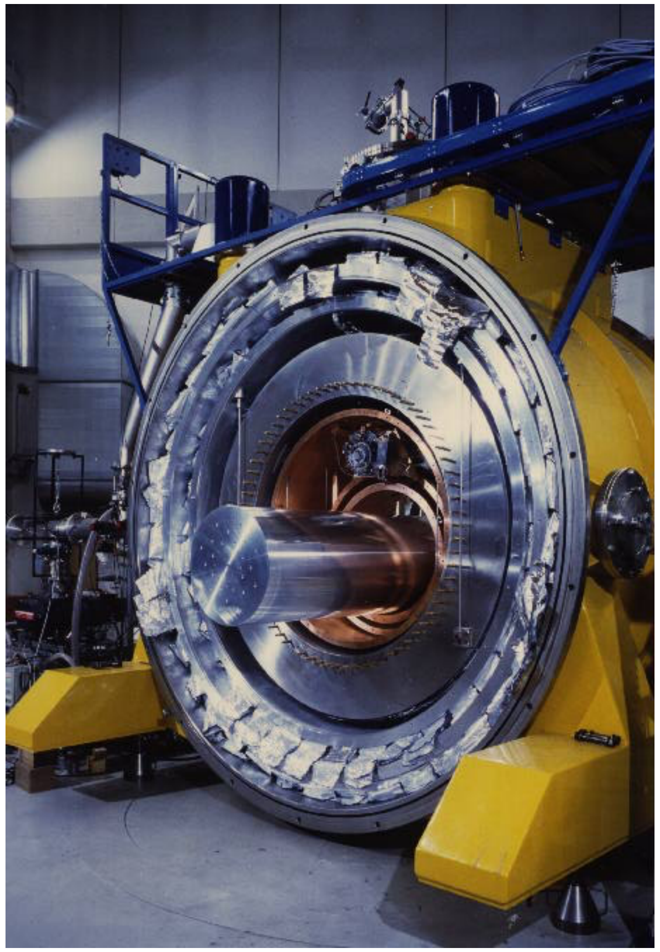
Resonant-Mass Detectors

- In the 1960's: The Weber Bar



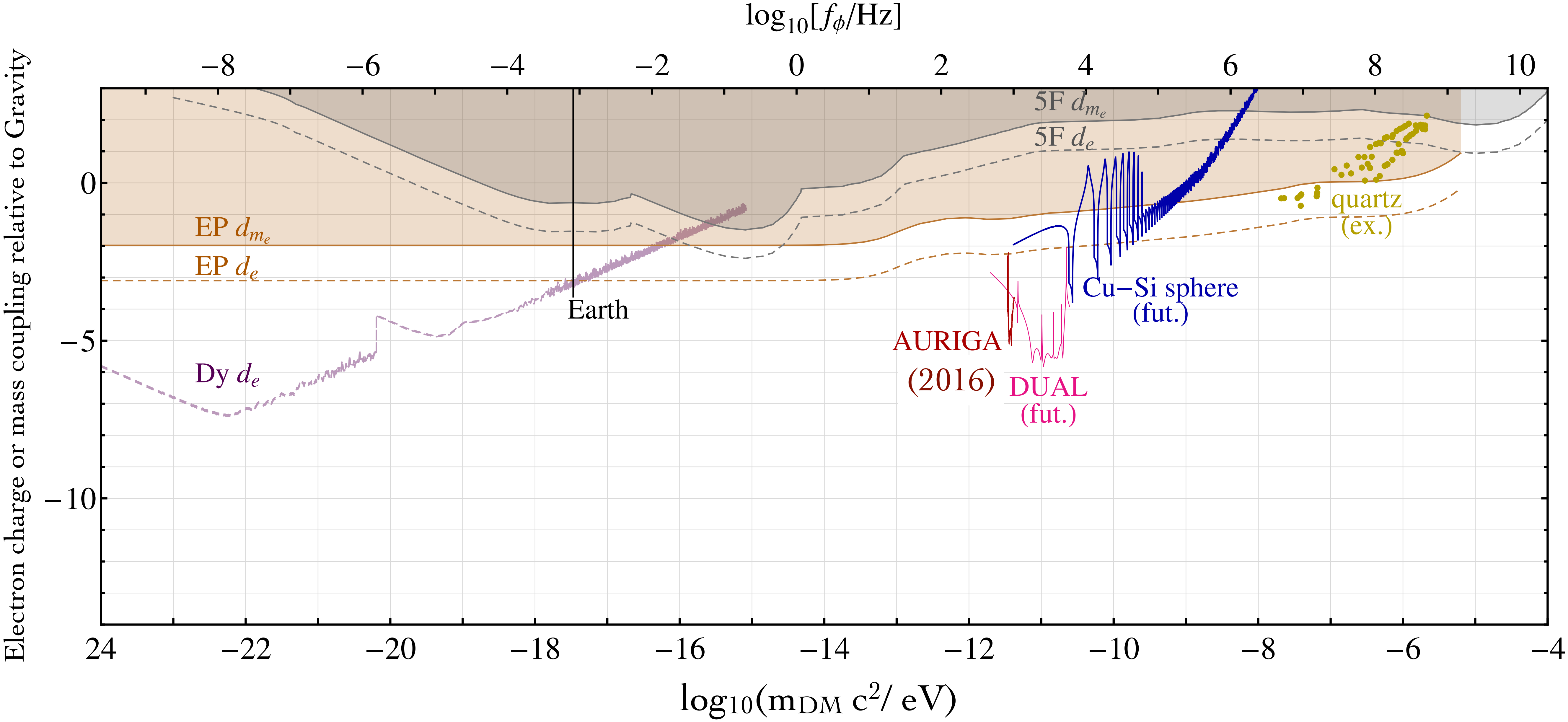
Fractional length variation $\delta L/L \sim 10^{-17}$

- Today: AURIGA, NAUTILUS, MiniGrail

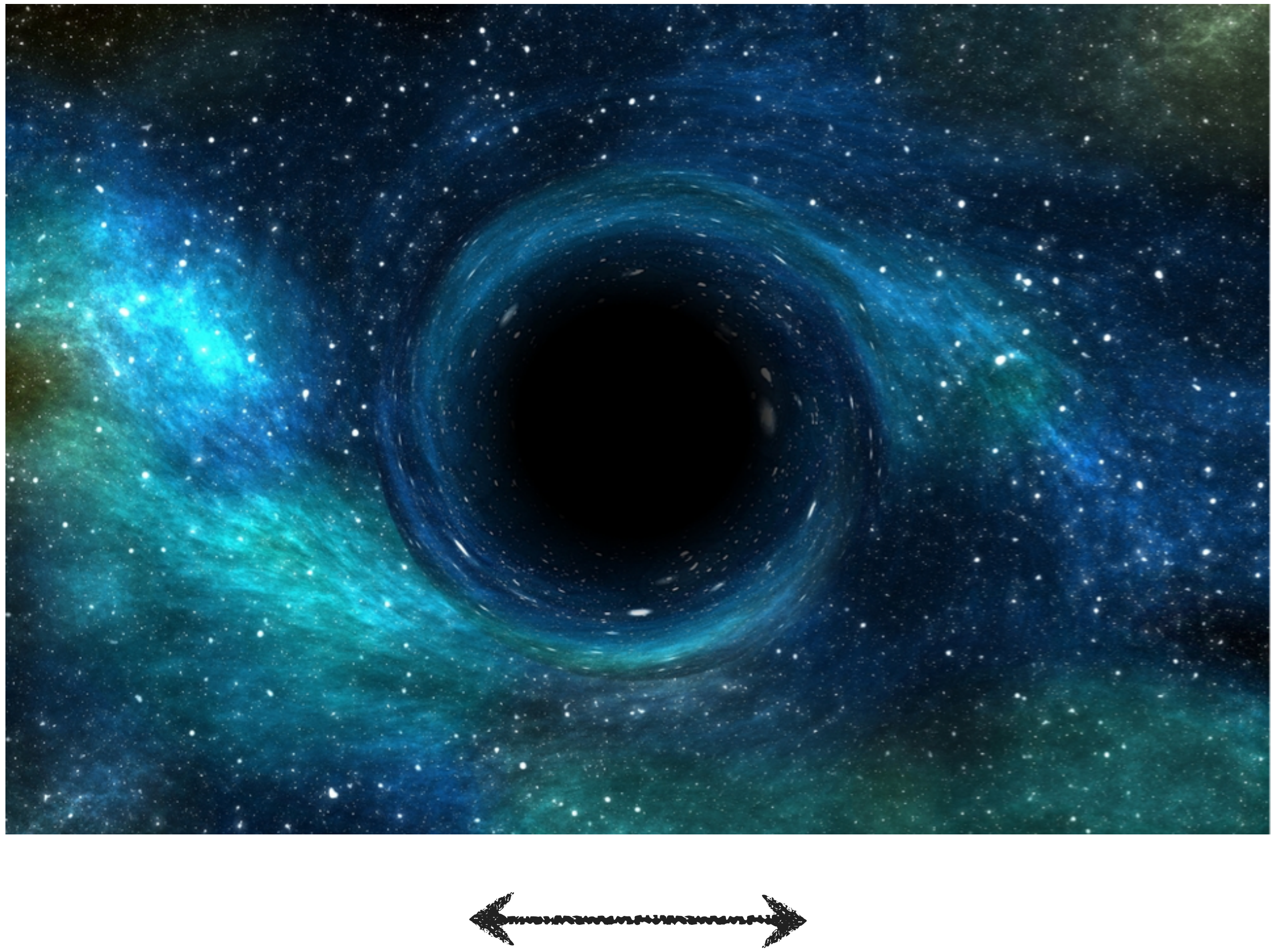


Fractional length variation $\delta L/L \sim 10^{-23}$

What can be done in the future?



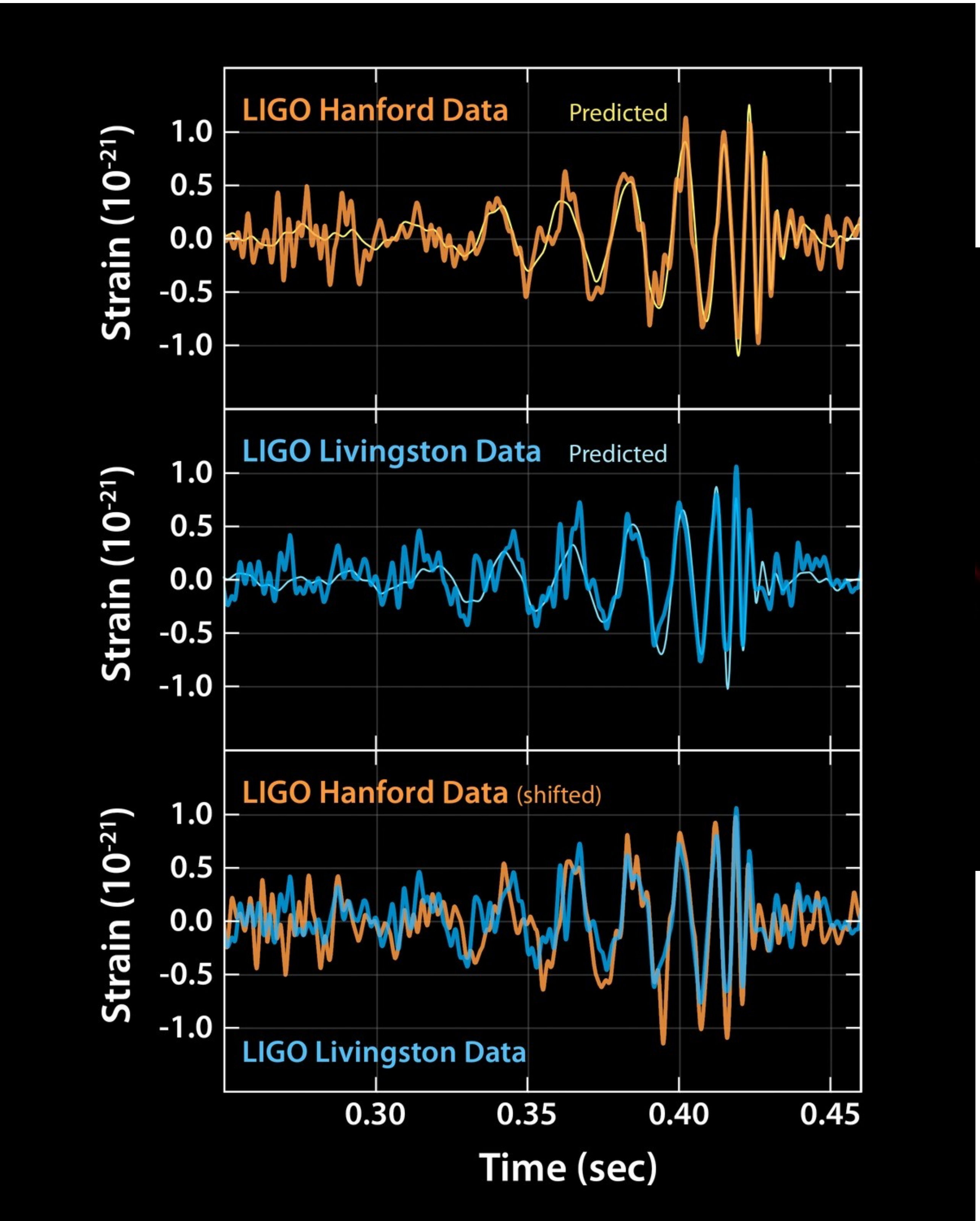
Black Holes as Nature's Detectors

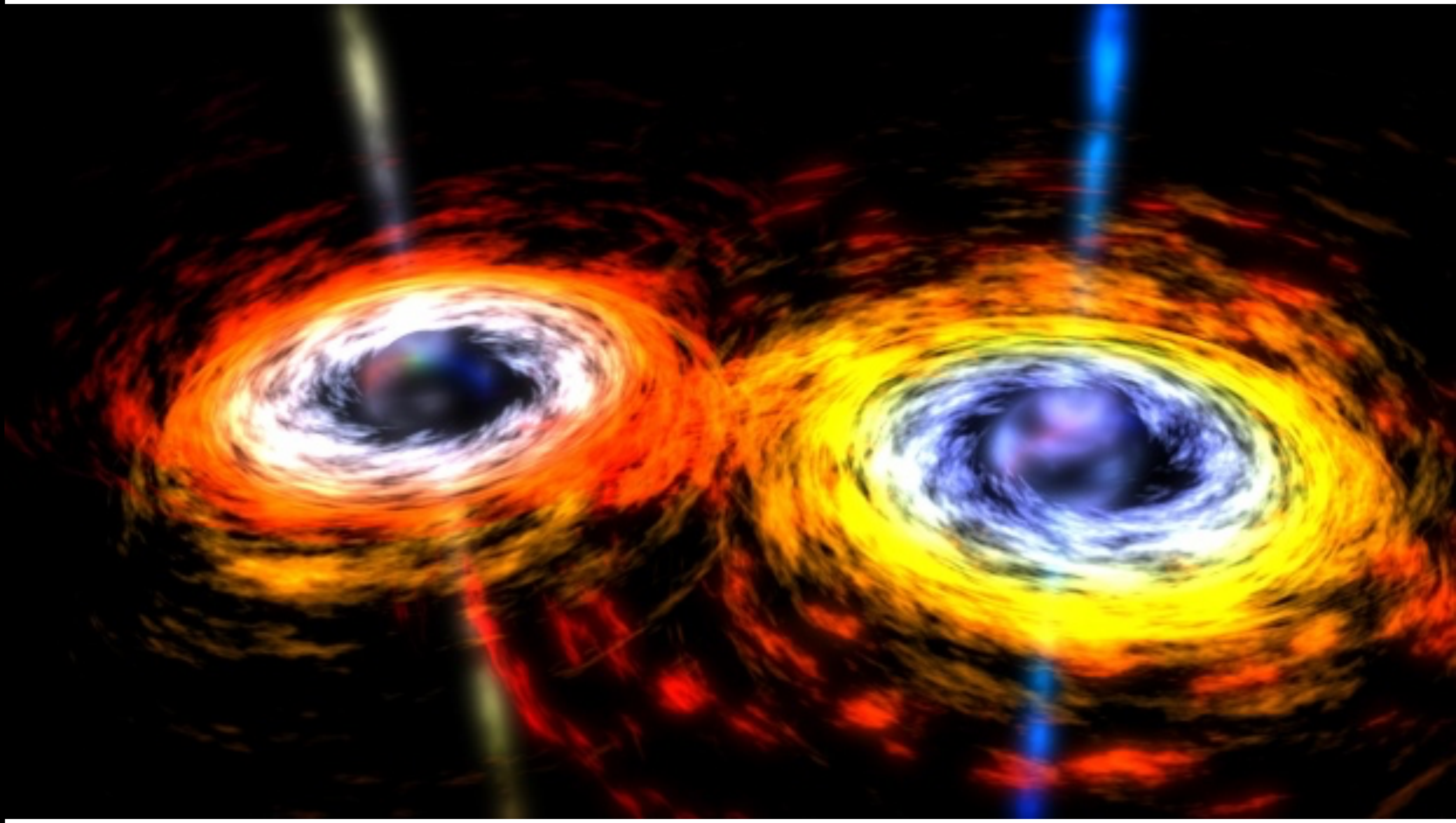


1 km -10 billion km

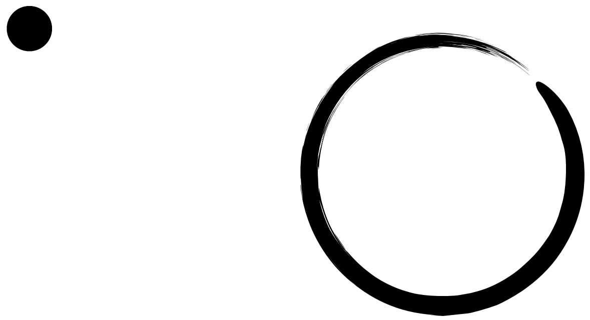
They can detect bosons of similar in size

September 14, 2015

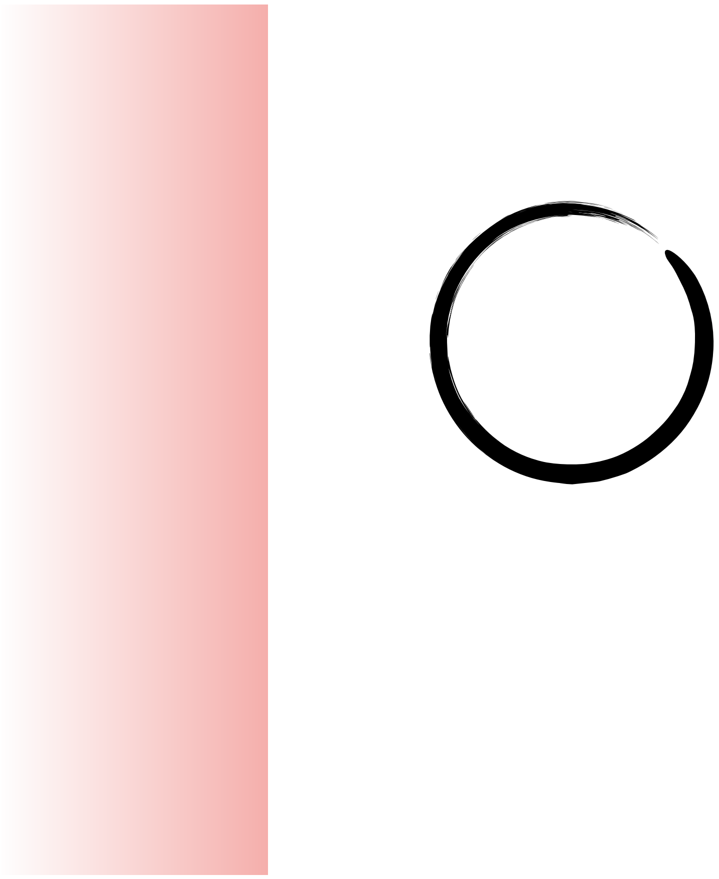




Super-Radiance Cartoon



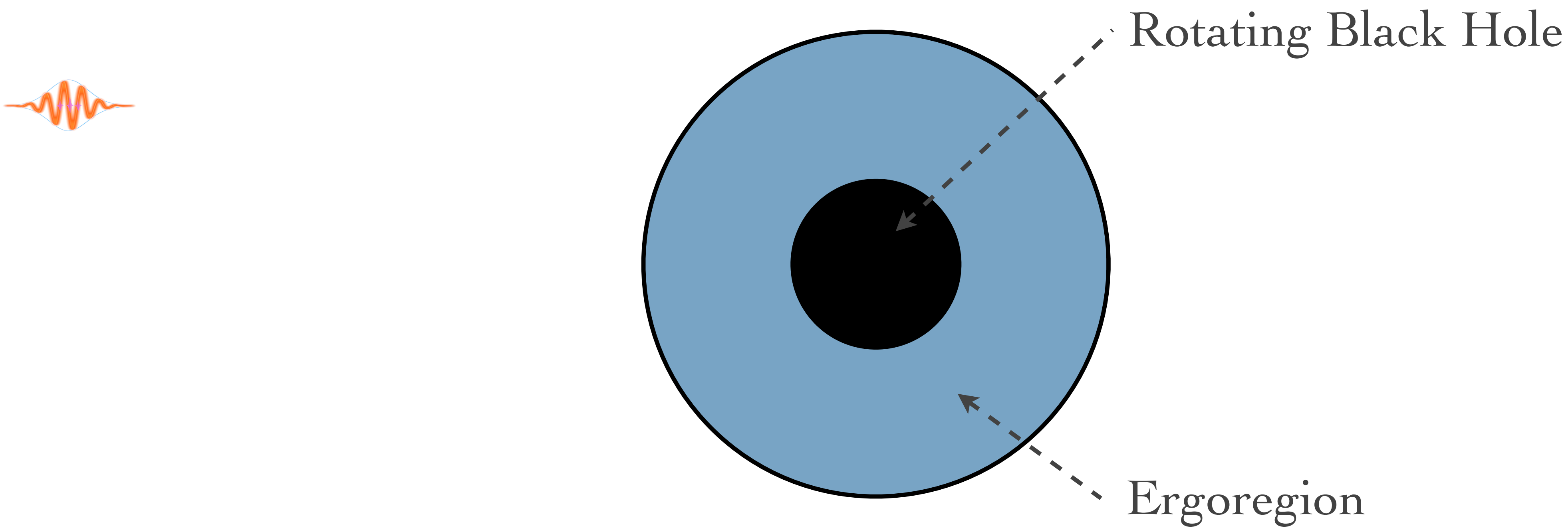
Super-radiant scattering of a massive object



Super-radiant scattering of a wave

Black Hole Superradiance

Penrose Process

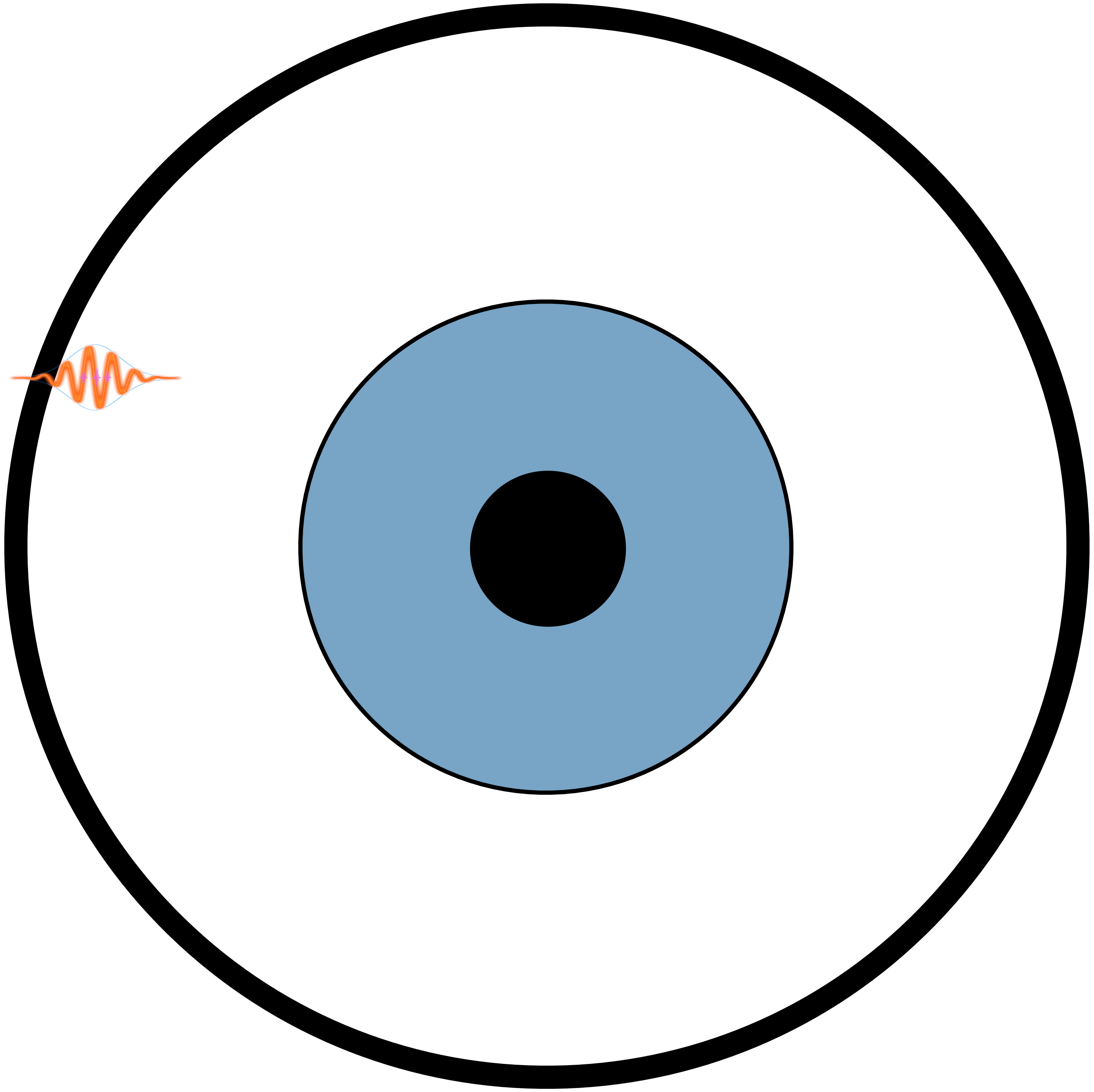


Extracts angular momentum and mass from a spinning black hole

Ergoregion: Region where even light has to be rotating

Black Hole Bomb

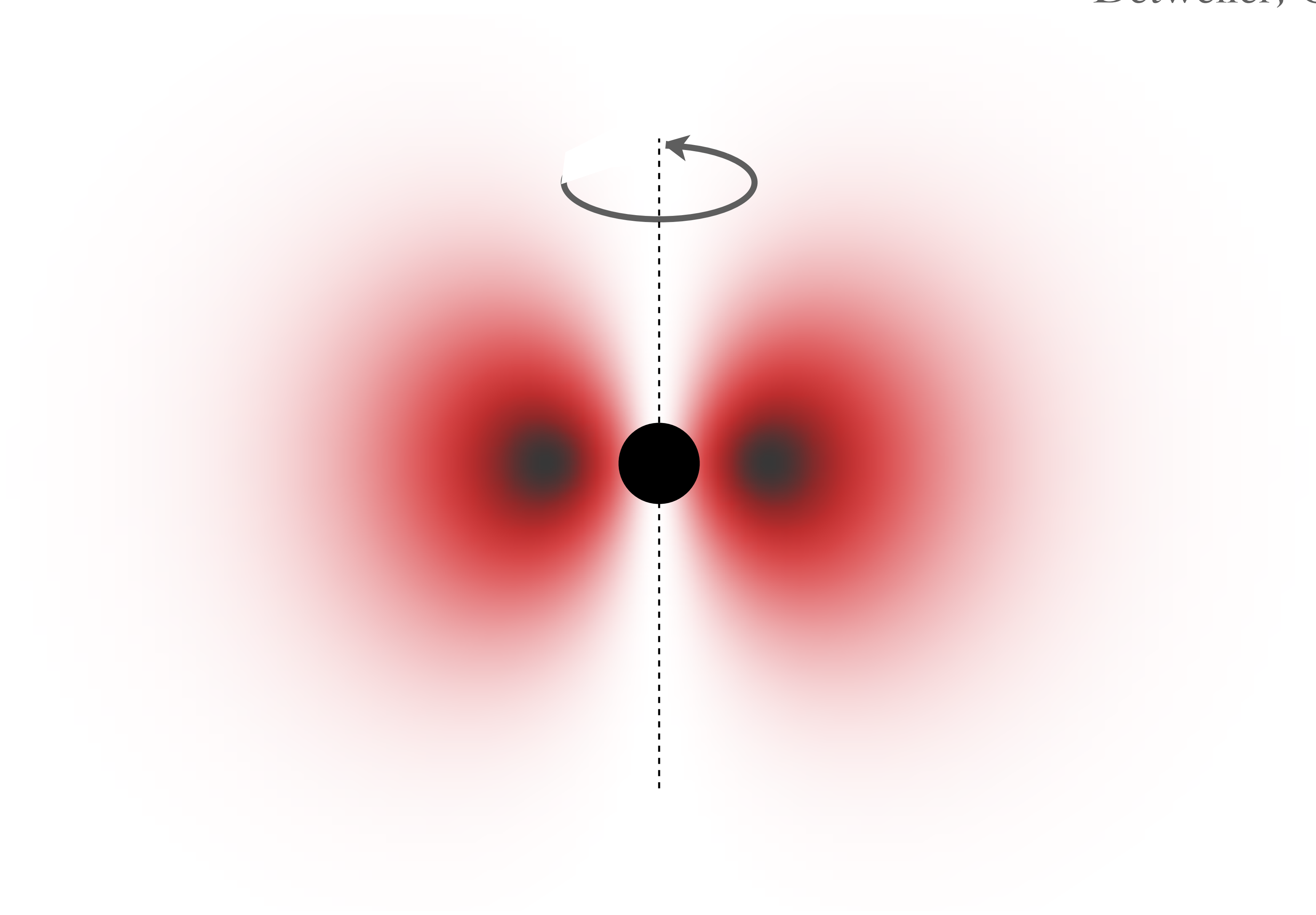
Press & Teukolsky 1972



Photons reflected back and forth from the black hole
and through the ergoregion

Superradiance for a massive boson

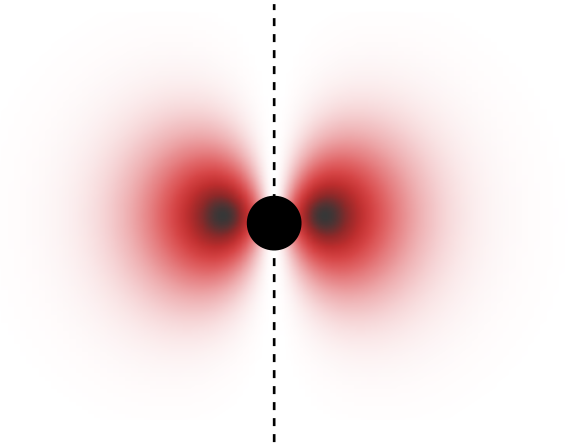
Damour et al; Zouros & Eardley;
Detweiler; Gaina (1970s)



Particle Compton Wavelength comparable to the size of the Black Hole

Gravitational Atom in the Sky

The gravitational Hydrogen Atom



Fine-structure constant: $\alpha = G_{\mathrm{N}} M_{\mathrm{BH}} \mu_a = R_g \mu_a$

Principal (n), orbital (l), and magnetic (m) quantum number for each level $E_{\text{binding}} = -\dfrac{\alpha^2 \mu_a}{2n^2}$

Main differences from hydrogen atom:

Levels occupied by bosons - occupation number >10^{77}

In-going Boundary Condition at Horizon

Key Points About Superradiance

- For light axions(weak coupling) equation identical to Hydrogen atom

- Boundary conditions different:
    - Regular at the origin → Ingoing (BH is absorber)
    - Hermitian → Non-hermitian

Superradiance Parametrics

Superradiance Condition

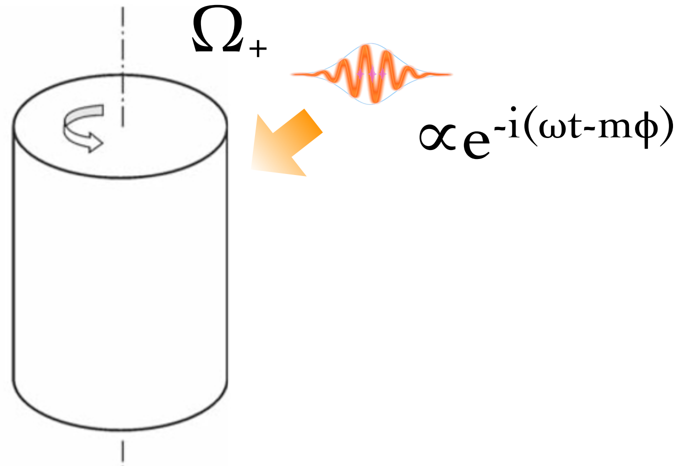
$$\omega_{\text{axion}} < m\ \Omega_{+}$$

m : magnetic quantum number

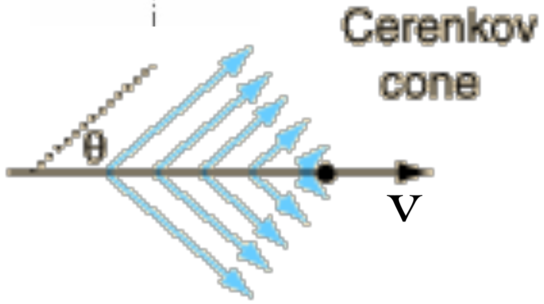
Ω_{+} : angular velocity of the BH

Universal Phenomenon:

Superluminal rotational motion of a conducting cylinder



Superluminal linear motion - Cherenkov radiation $1/n(\omega) < v$



Condition can be extracted from requiring that $dA_{BH} > 0$

Superradiance Parametrics

Superradiance Rate

$\tau_{sr} \sim 0.6 \times 10^{7} R_g$ for $R_g \mu_a \sim 0.4$

As short as 100 sec vs $\tau_{accretion} \sim 10^{8}$ years

When $R_g \mu_a >> 1$,

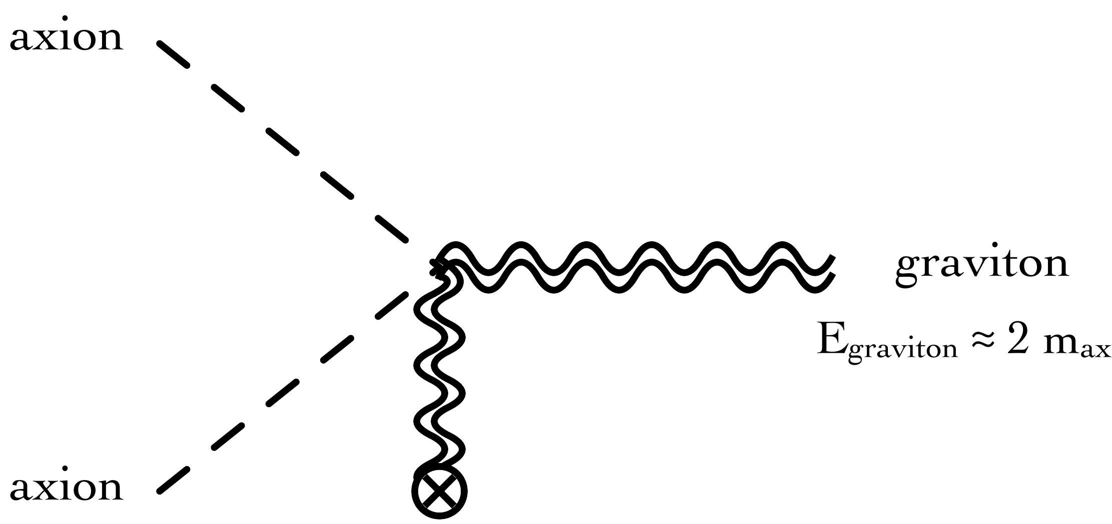
$$\tau_{sr} = 10^7 e^{3.7(\mu_a R_g)} R_g$$

When $R_g \mu_a << 1$

$$\tau_{sr} = \left(\frac{24}{a}\right)(\mu_a R_g)^{-9} R_g$$

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)

Plenitude


Gottfried Wilhelm Leibniz

“ This best of all possible worlds will contain all possibilities, with our finite experience of eternity giving no reason to dispute nature's perfection.”