Particle Physics with Table-Top Experiments

Asimina Arvanitaki
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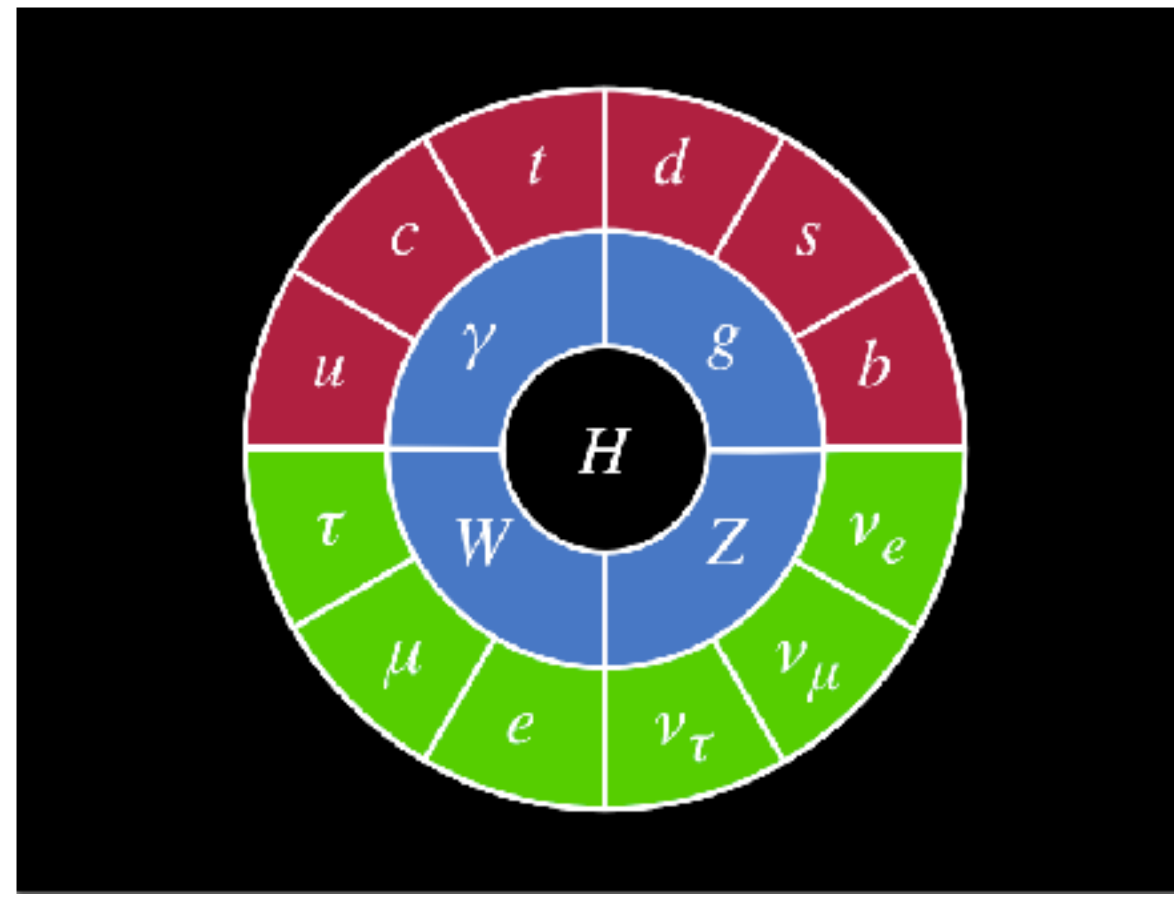
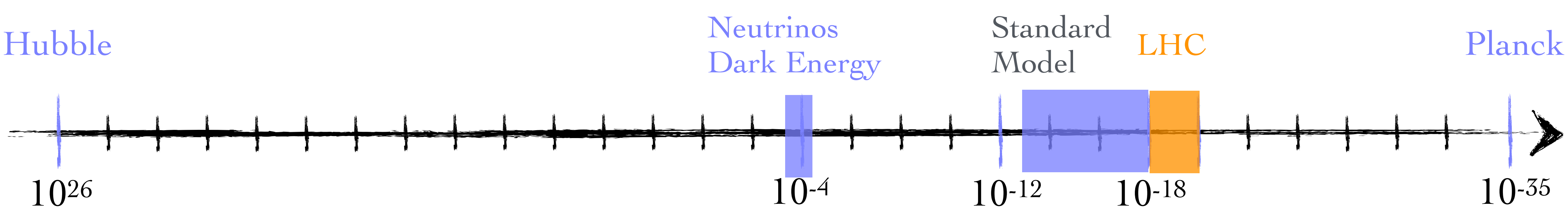
The Standard Model

$$\mathcal{L}_{SM} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\bar{\psi} + \bar{\psi}_i y_{ij} \psi_j \phi + |D_\mu \phi|^2 - V(\phi) + M_{pl}^2 R - \rho_{vacuum}$$



Contains ~20 particles and ~20 parameters

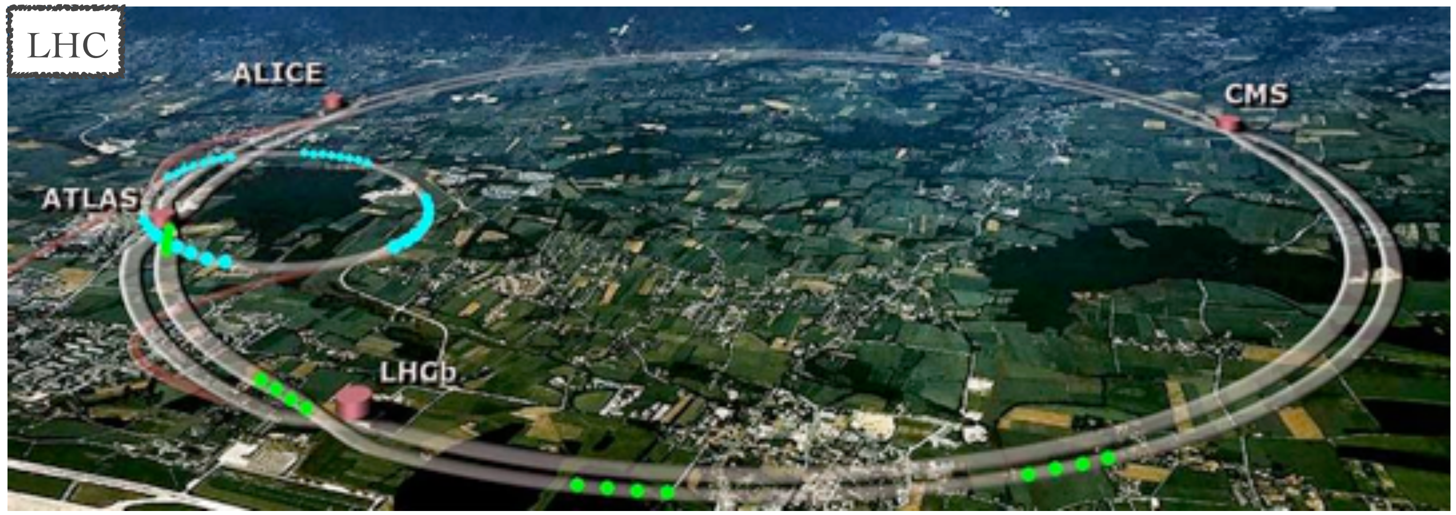
The Length Scales in the Universe



Scale in meters

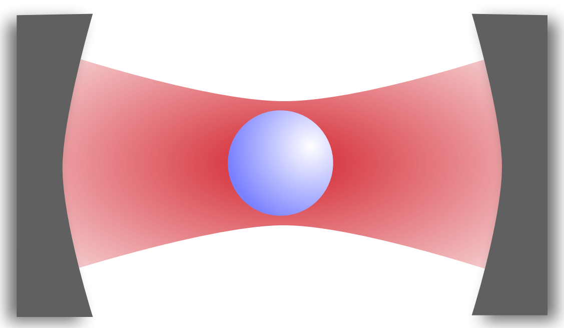
80% of the energy scale left to explore

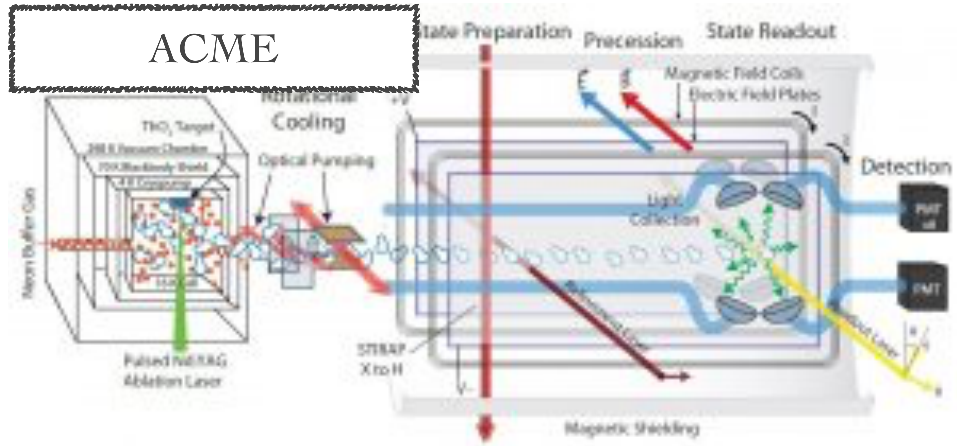
The High Energy Frontier



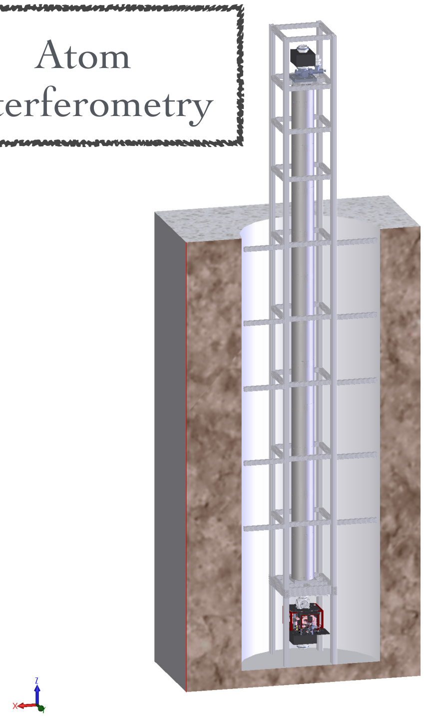
Opportunities at the Precision Frontier

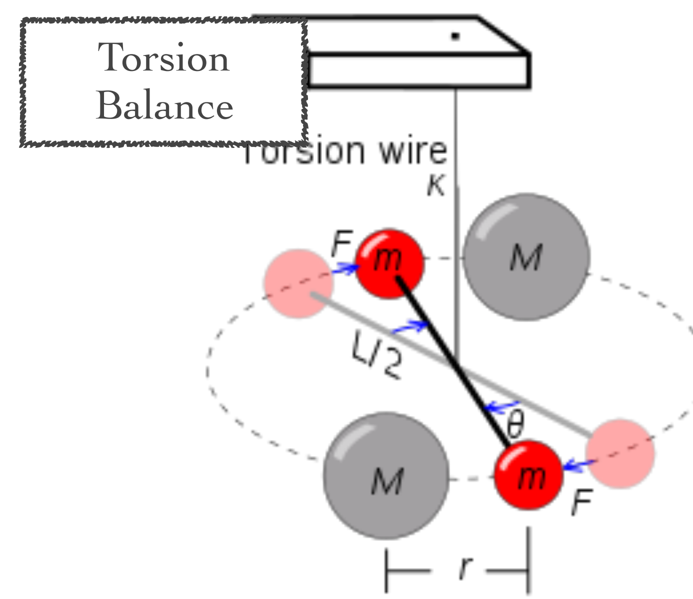
Optically Levitated Objects

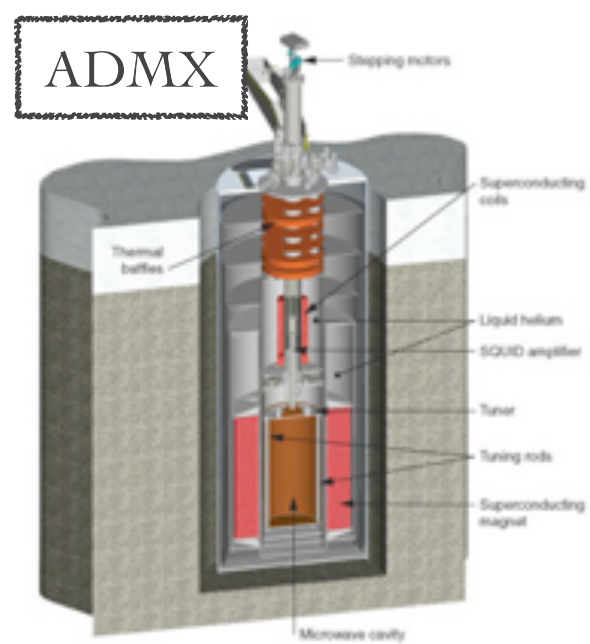




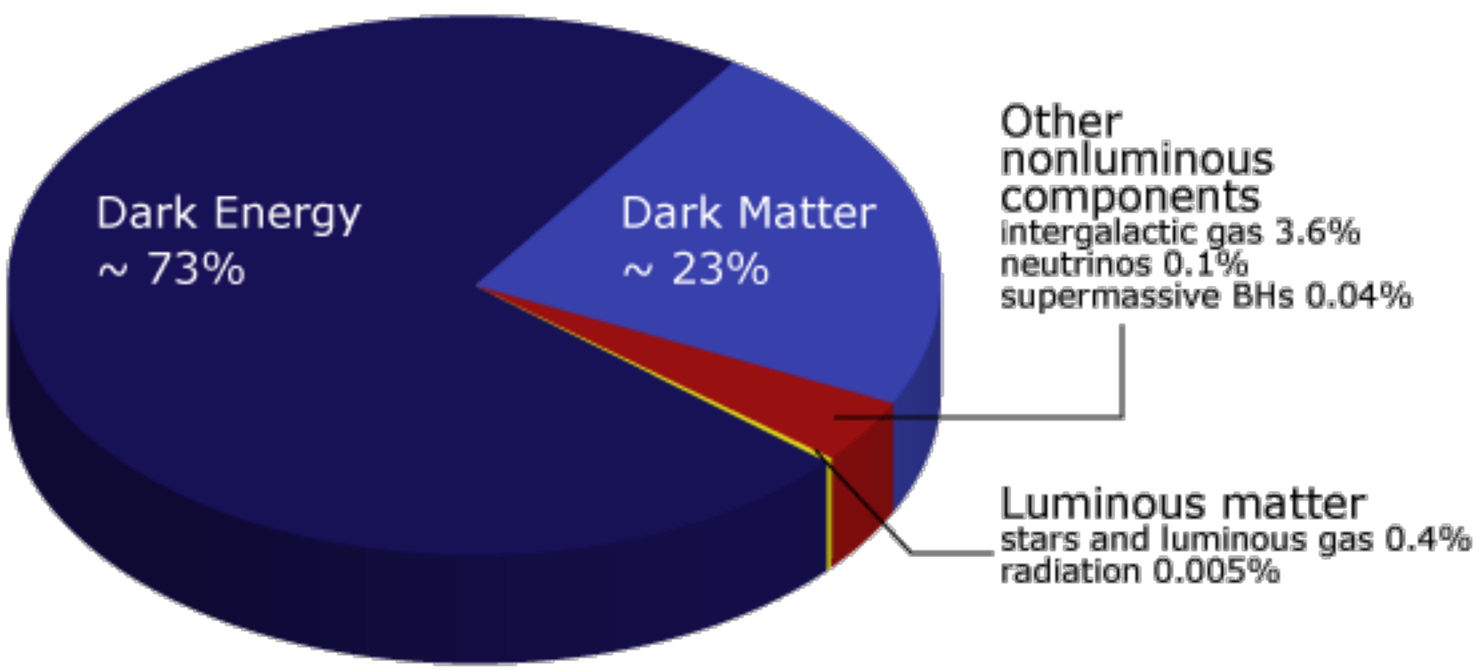
Atom Interferometry







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?

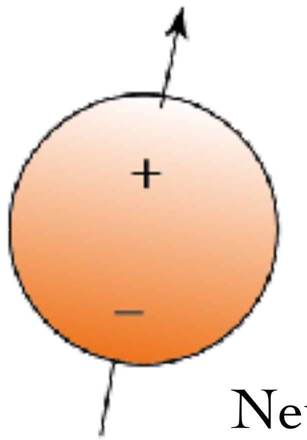
- Does it have interactions other than gravitational?

Outline

- Light Bosonic Dark Matter
- Atomic Clocks
- Molecules
- Black Holes

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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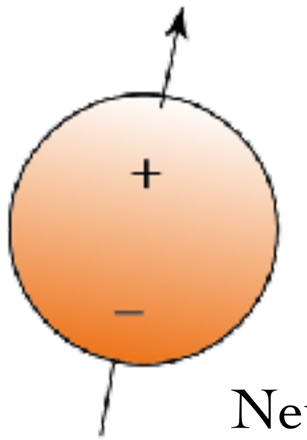

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Solution:
θ_s ~a(x,t) is a dynamical field, an axion

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

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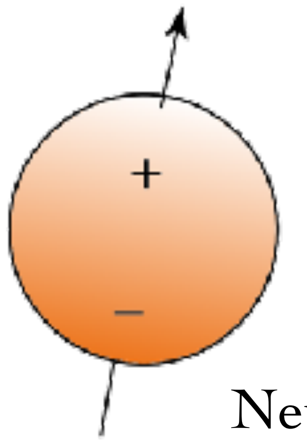

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f_a : axion decay constant

Mediates new forces and can be the dark matter

Elements of String Theory

- Extra dimensions

Elements of String Theory

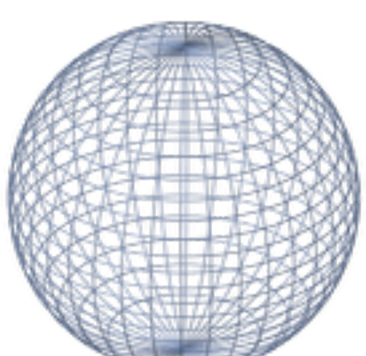
- Extra dimensions
- Gauge fields

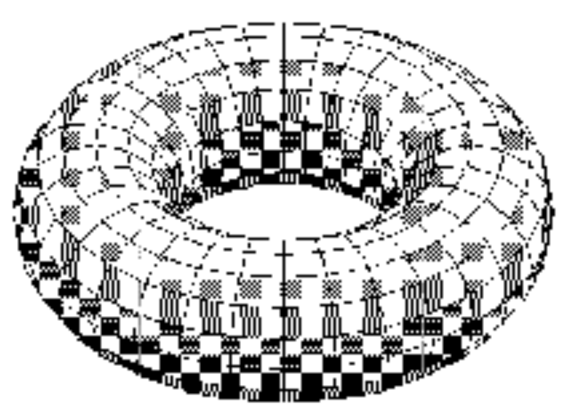
Elements of String Theory

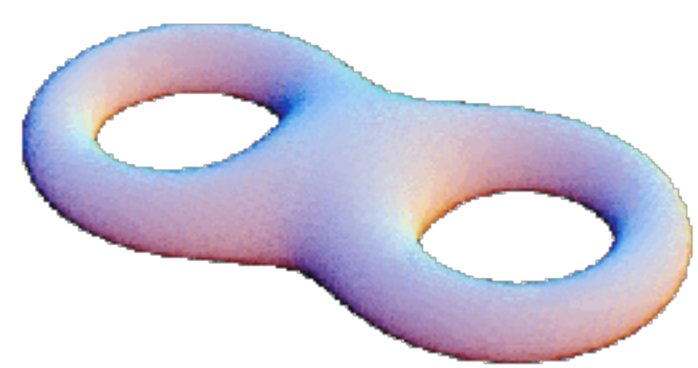
- Extra dimensions

- Gauge fields

- Topology





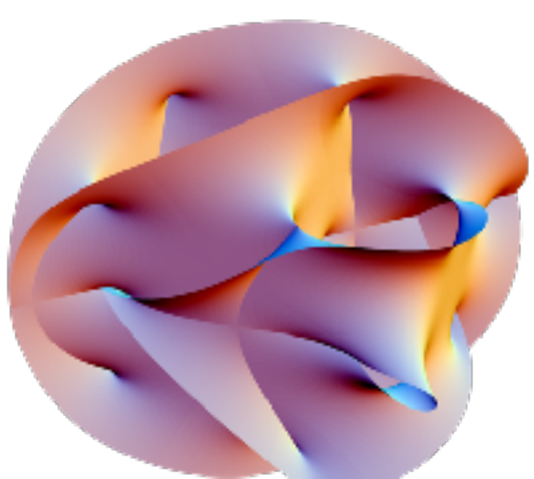


Elements of String Theory

- Extra dimensions

- Gauge fields

- Topology



Elements of String Theory

- Extra dimensions
- Gauge fields
- Topology

Give rise to a plenitude of Universes

Elements of String Theory

- Extra dimensions
- Gauge fields
- Topology

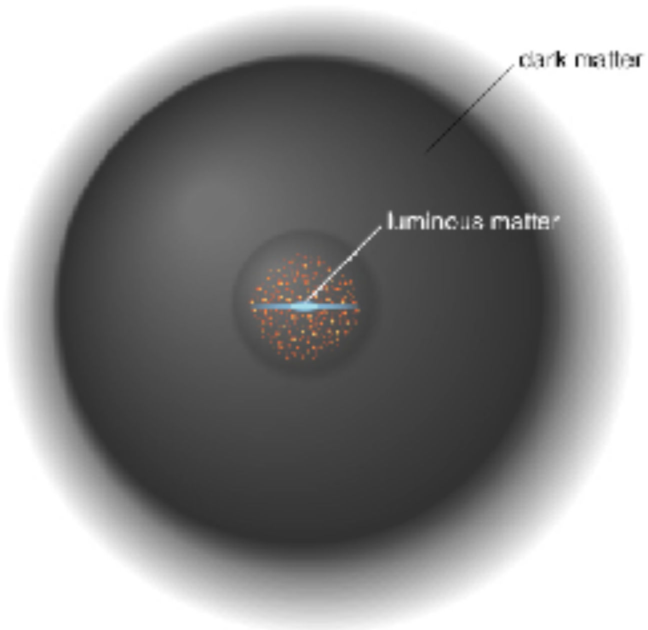
Give rise to a plenitude of massless particles in our Universe

A Plenitude of Massless Particles

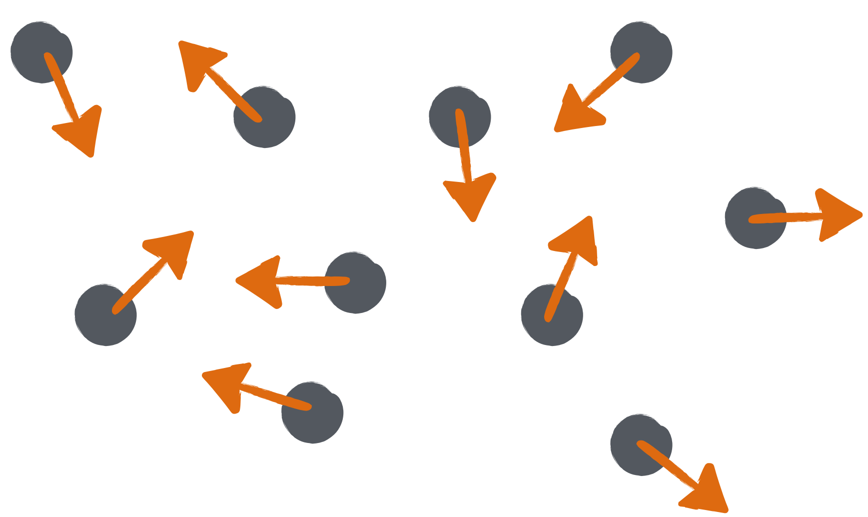
- Spin-0 non-trivial gauge field configurations: String Axiverse
- Spin-1 non-trivial gauge field configurations: String Photiverse
- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion

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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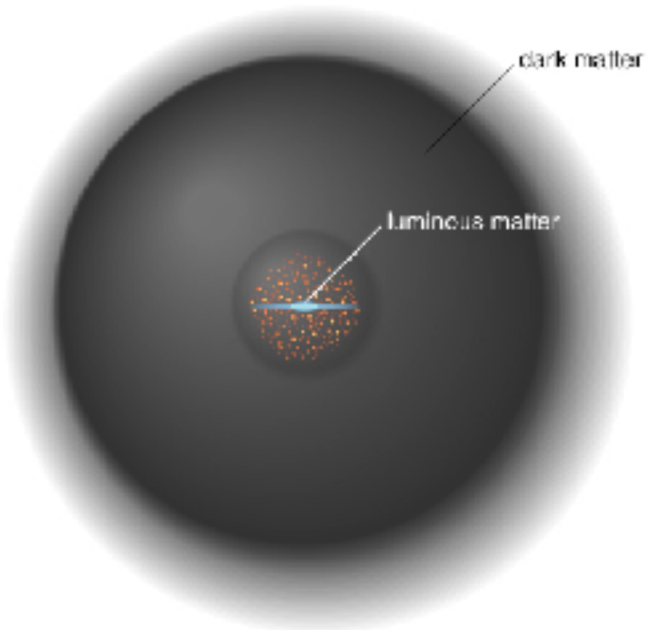

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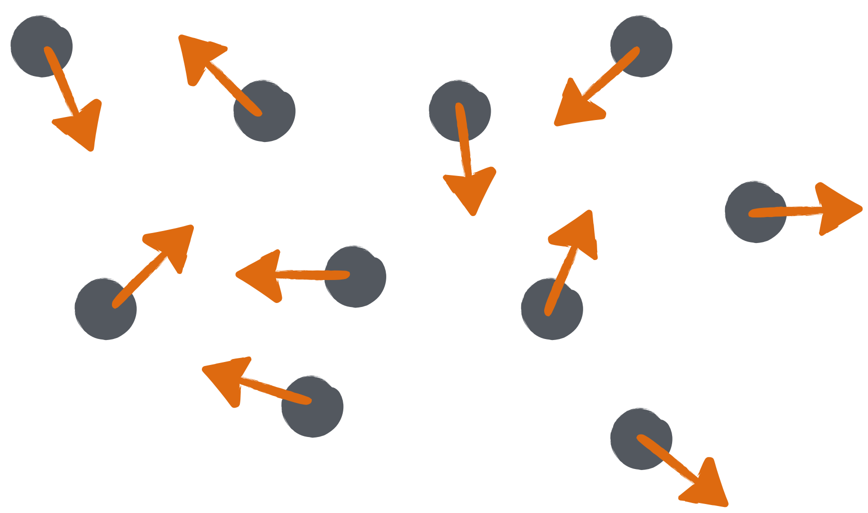
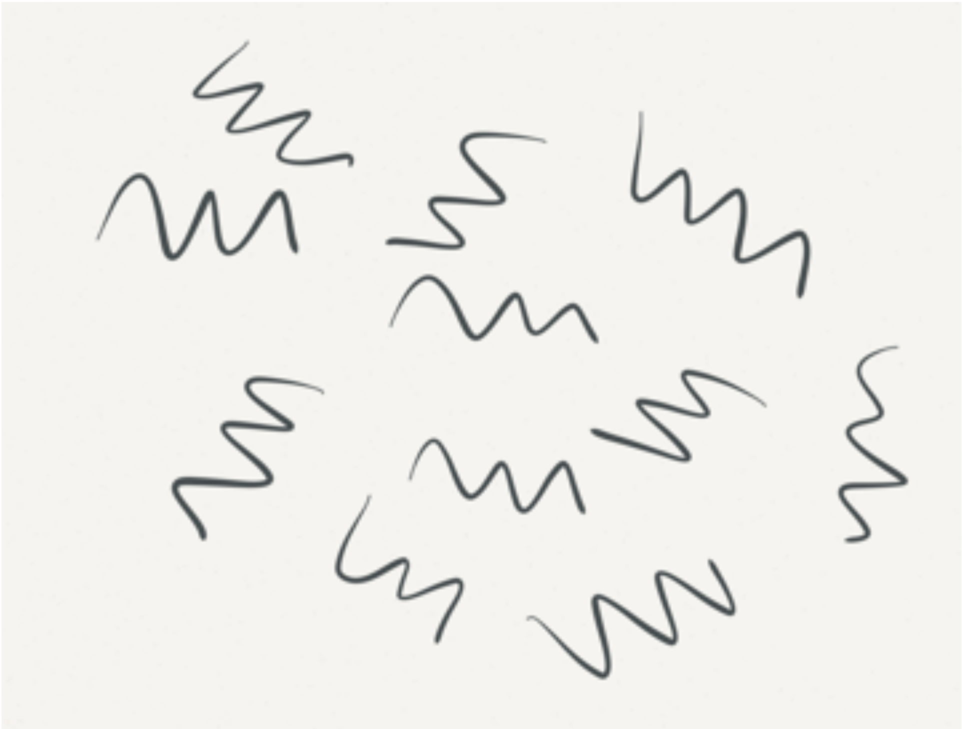


like a WIMP

instead of…



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

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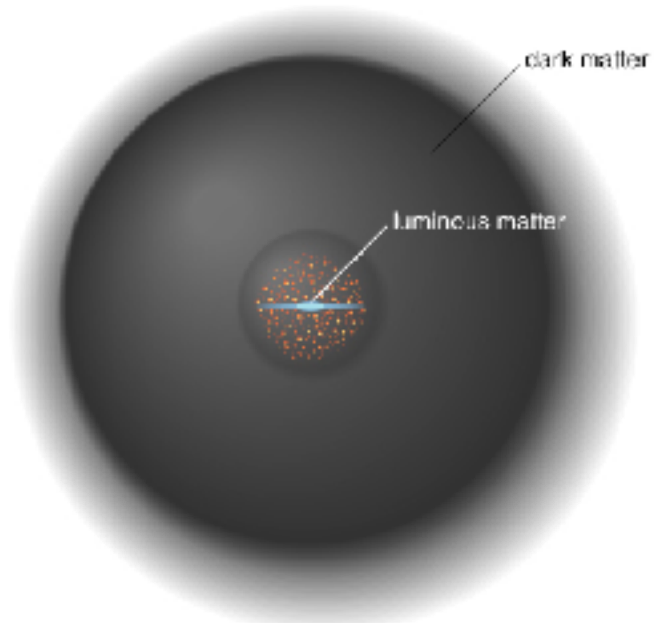

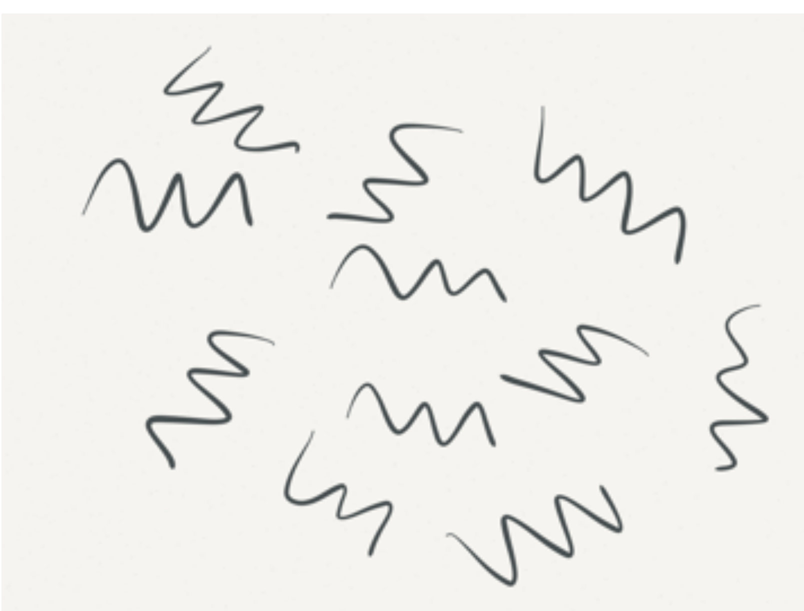

Decreasing DM Mass

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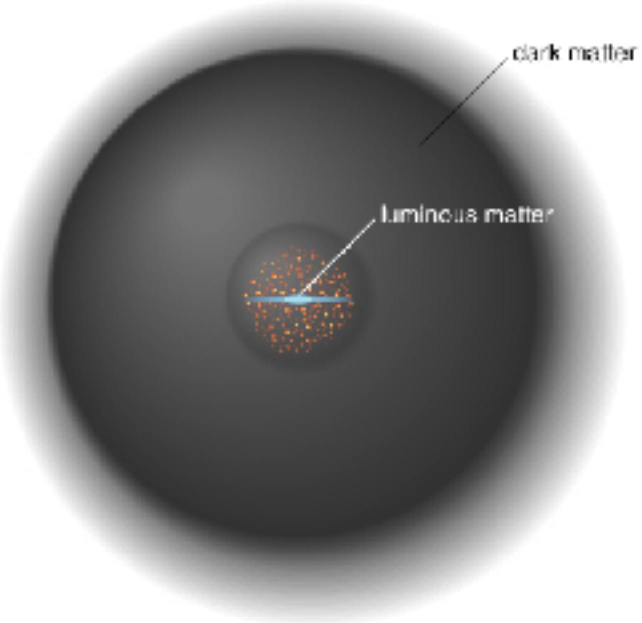
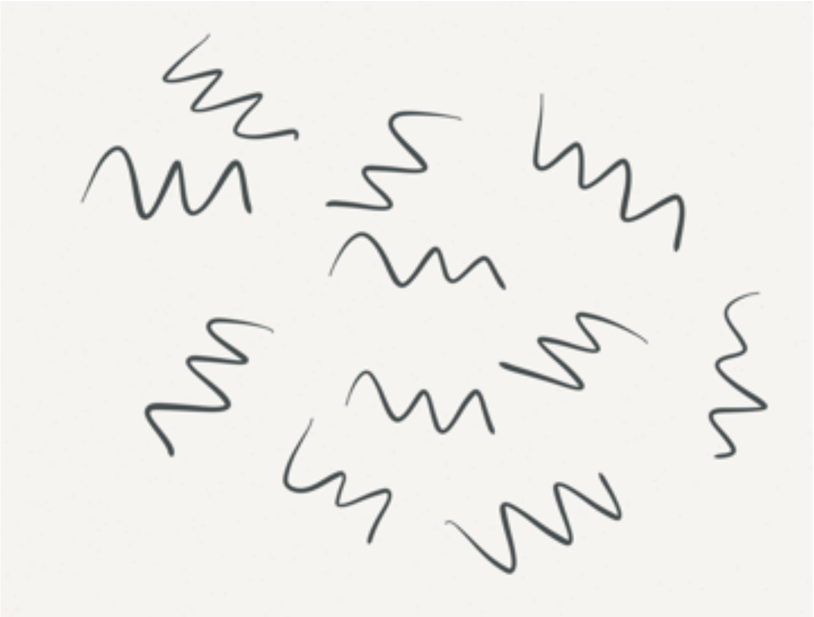




Decreasing DM Mass

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

Equivalent to a Scalar wave

Going from DM particles to a DM "wave"

When $n_{DM} > \frac{1}{\lambda_{DM}^3}$

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

we can talk about DM $\phi(x,t)$ 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

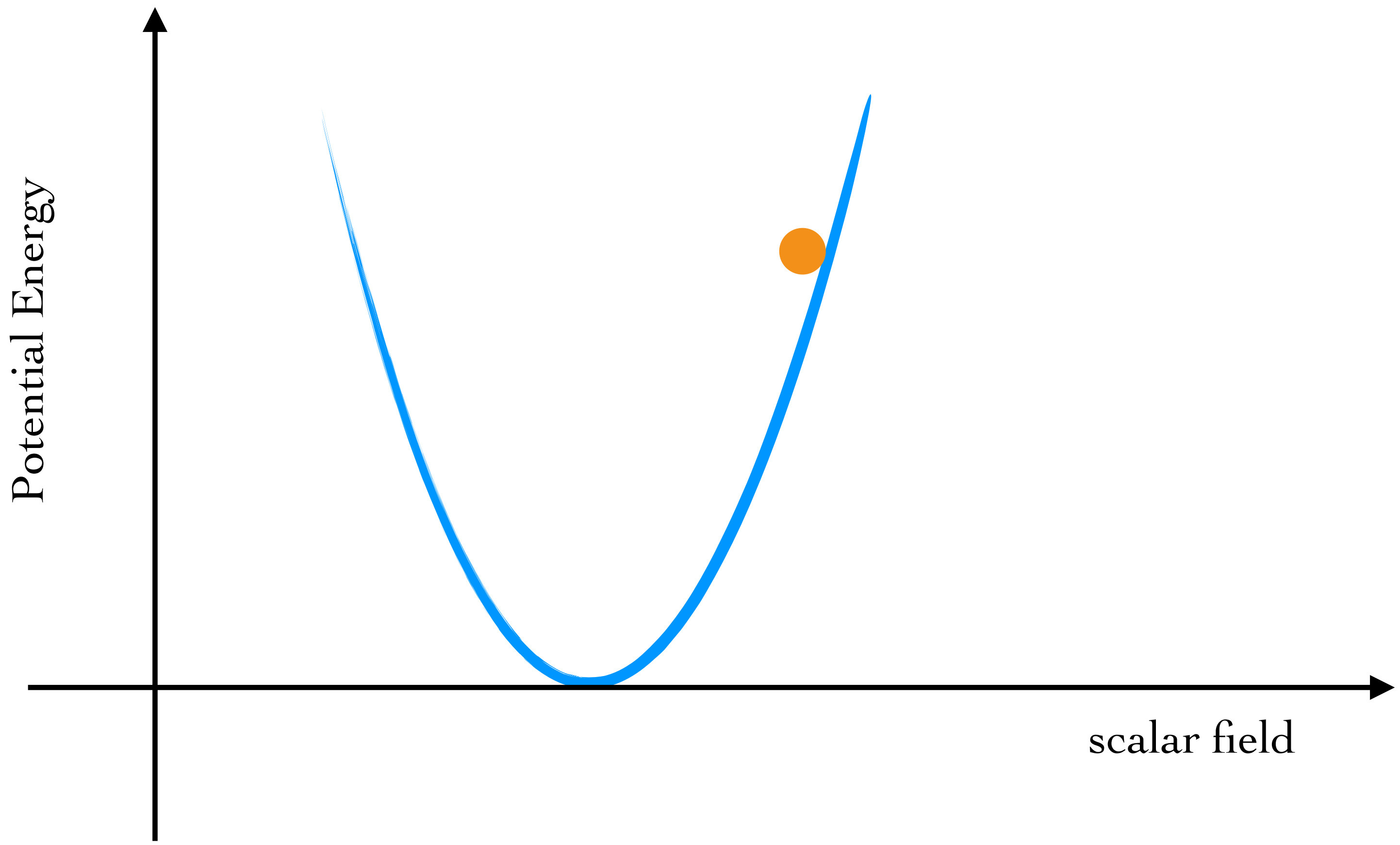
$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

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

Initial conditions set by inflation

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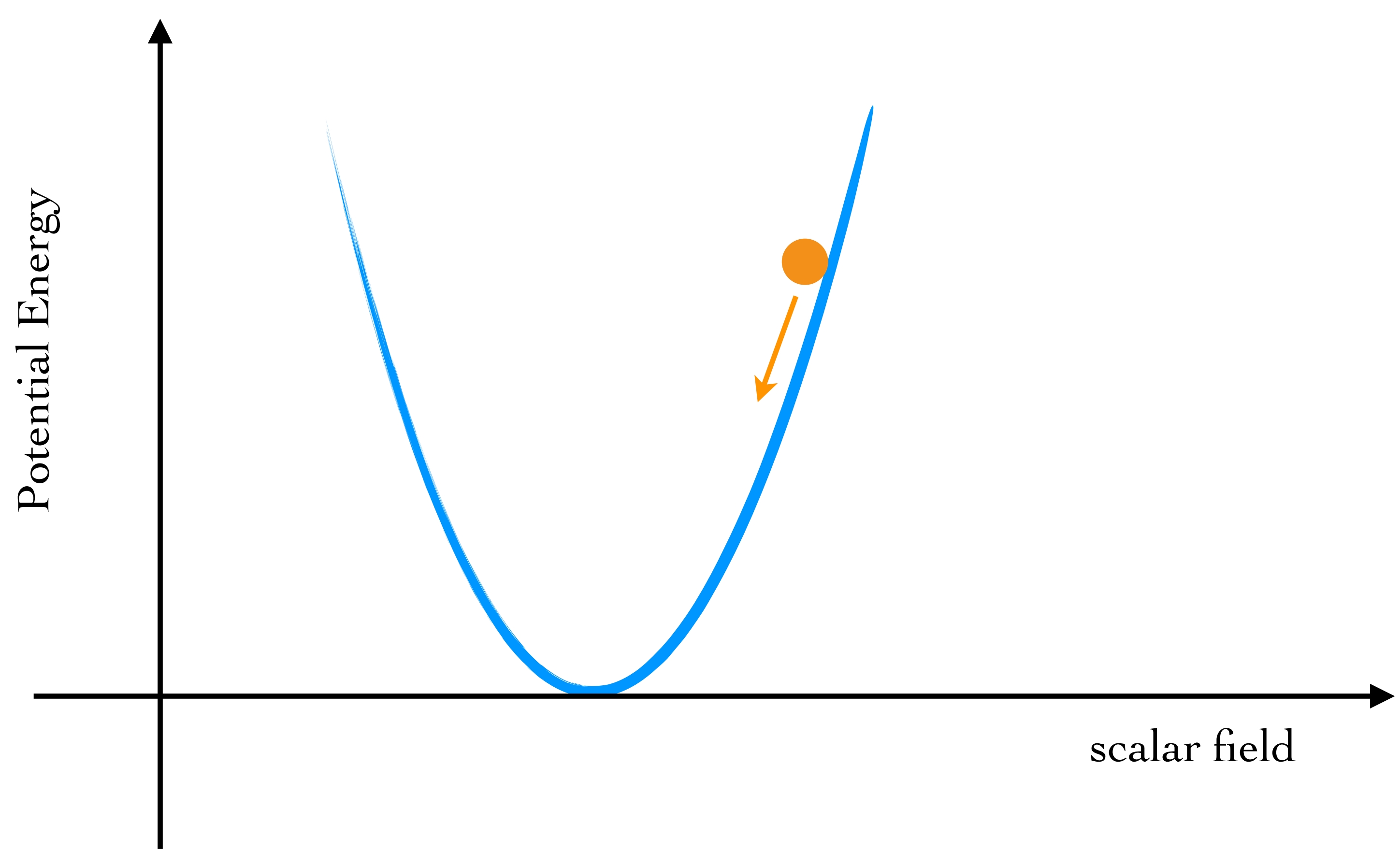


Frozen when:
Hubble > m_ϕ

Oscillates when:
Hubble < m_ϕ

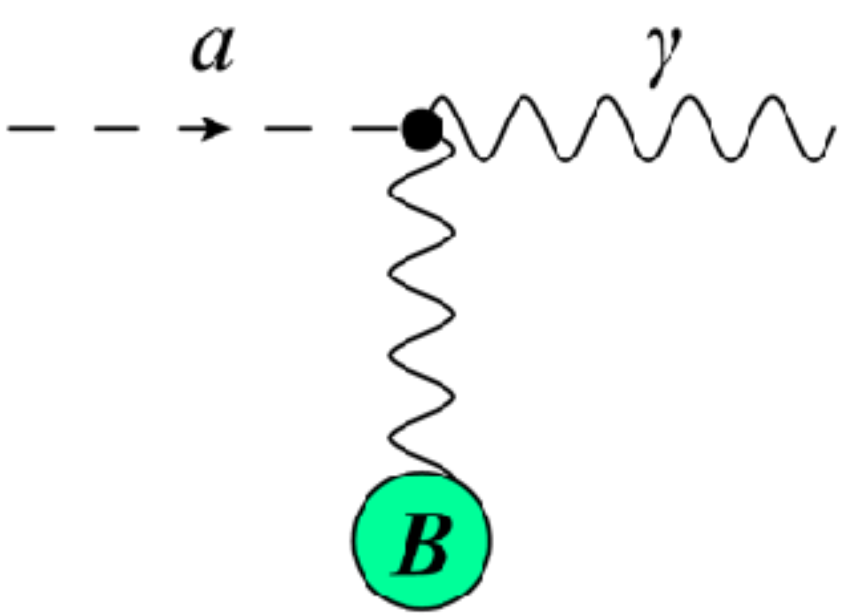
ρ_ϕ scales as a^{-3}
just like Dark Matter

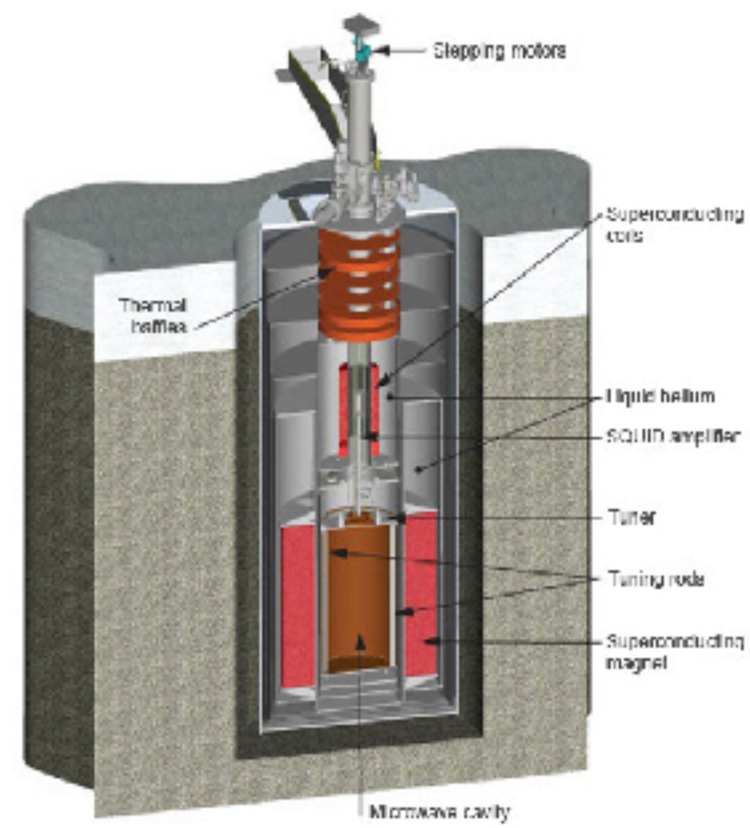
Initial conditions set by inflation

Axion Dark Matter

Some examples

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



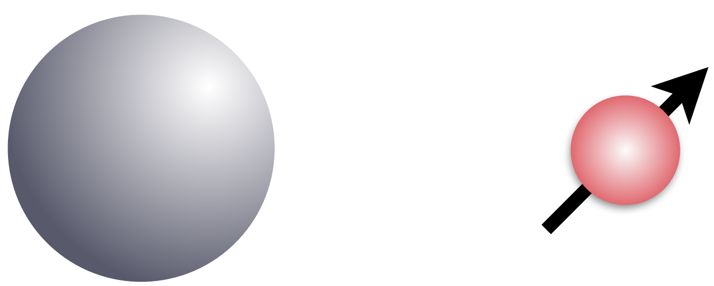


Cavity size = Axion size

Axion Dark Matter

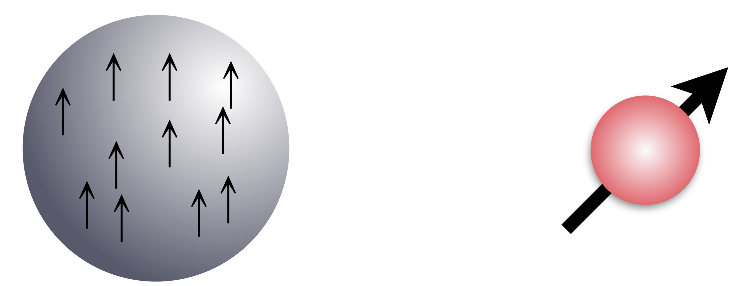
Some examples

Monopole-Dipole Interaction



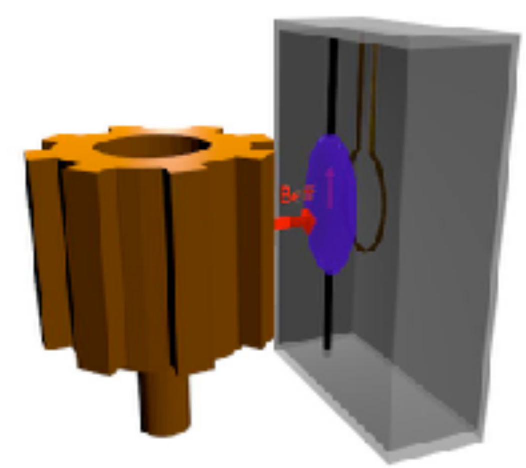
Mass with N nucleons   Spin

Dipole-Dipole Interaction



N spins   Spin

- Axion Force experiments and DM experiments



ARIADNE experiment

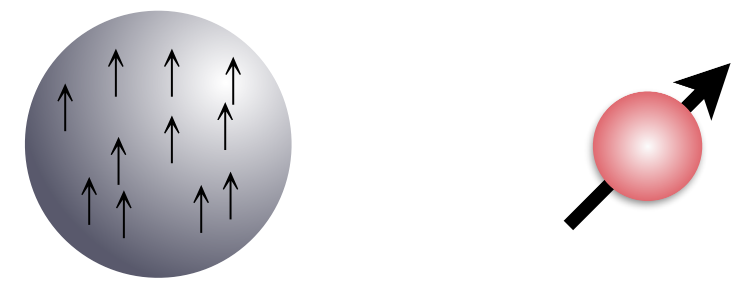
Axion Dark Matter

Some examples

Monopole-Dipole Interaction

Mass with N nucleons   Spin

Dipole-Dipole Interaction



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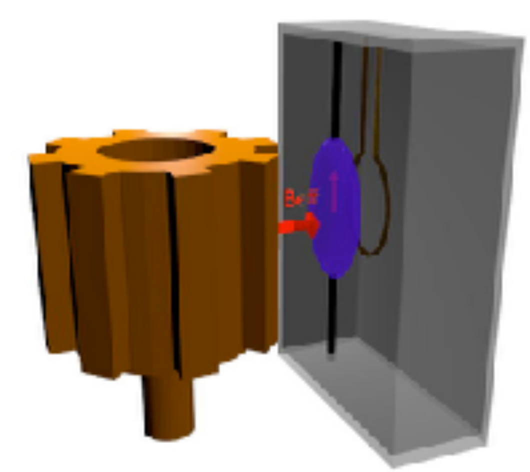


ARIADNE experiment

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 (ADMX)

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

Moduli Dark Matter

- Couple non-derivatively to the Standard Model (as well as 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

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

$$\Delta E_{\rm optical} \propto \alpha_{EM}^2 m_e \;\sim \text{eV}$$

- Hyperfine Splittings

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

- Nuclear Splittings

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

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

Atomic Clocks

- Kept tuned to an atomic energy level splitting

Current definition of a second:
the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom

- Have shown stability of 1 part in 10^{18}

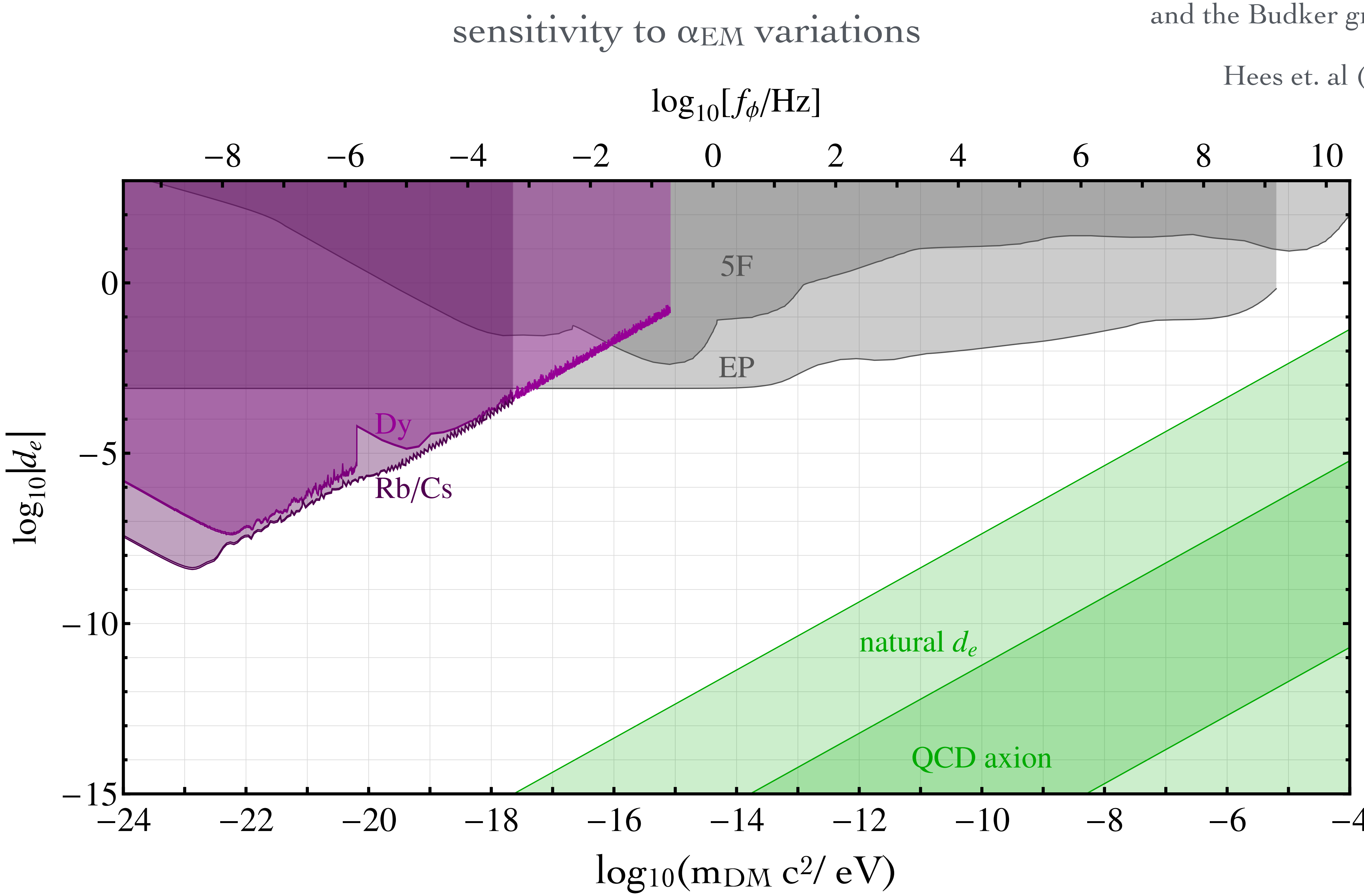
Compared to 1 part in 10^{13} expected by DM

- Have won several Nobel prizes in the past 20 years

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

The Sound of Dark Matter

with Ken Van Tilburg
and Savas Dimopoulos (2015)

Oscillating interatomic distances

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

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

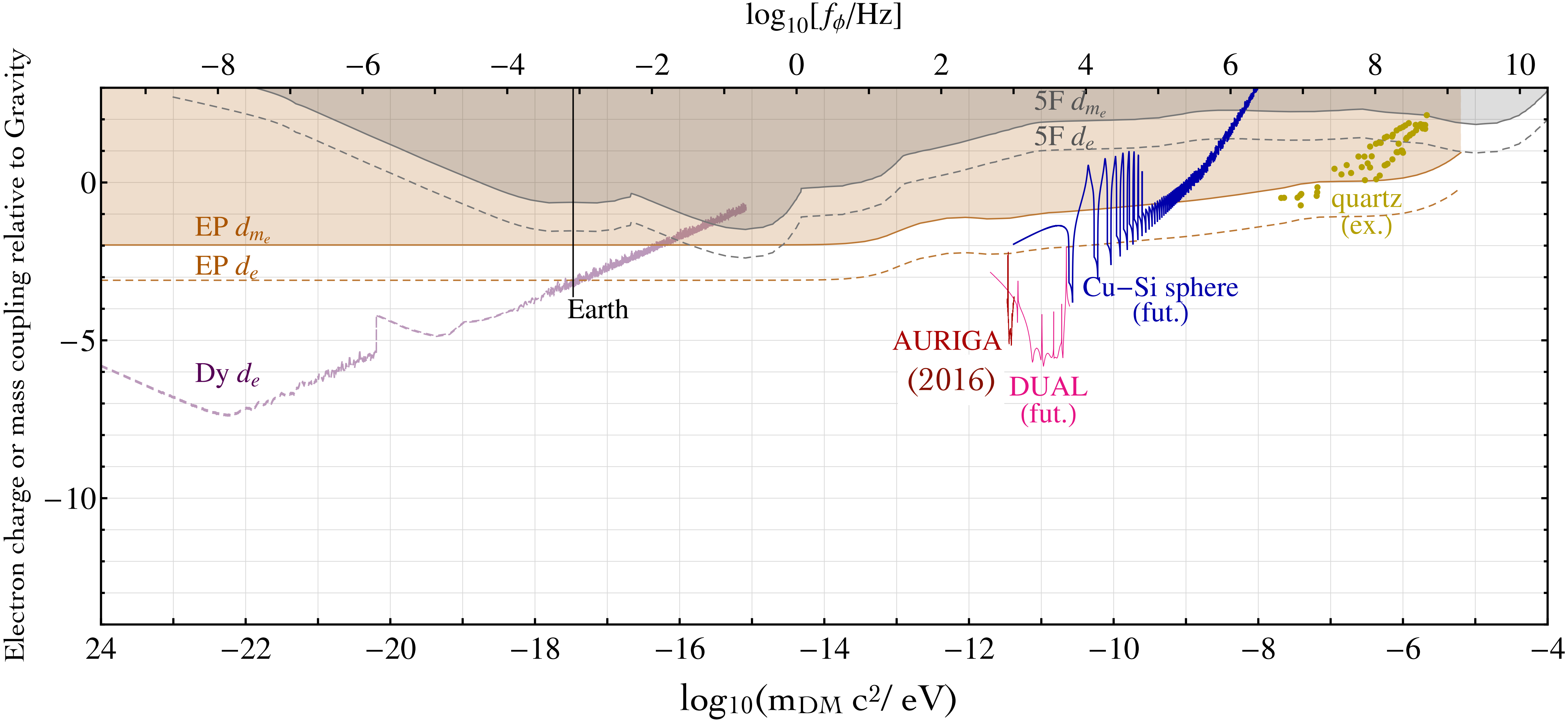
- The size of solids changes with DM
  - $L \sim N\ (\alpha\ m_e)^{-1}$

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

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

Need macroscopic objects to get a detectable signal

What can be done in the future?

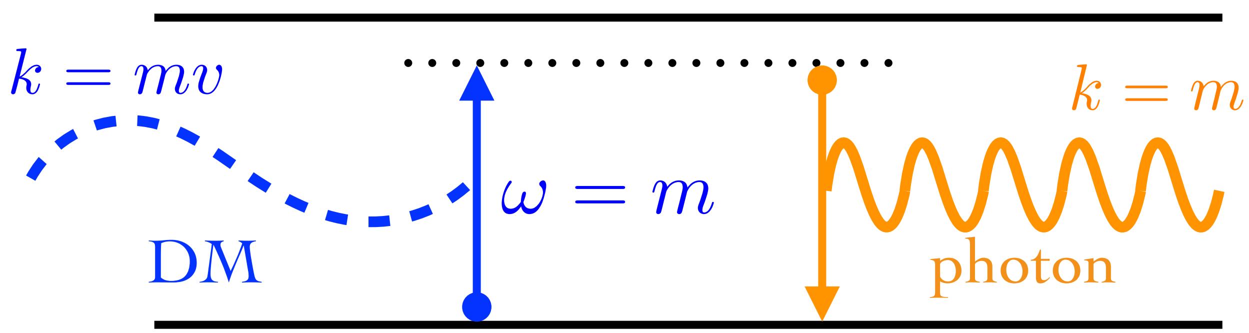


Resonant Absorption of Dark Matter

with Savas Dimopoulos and Ken Van Tilburg (2017)

Resonant Absorption of Dark Matter in Molecules

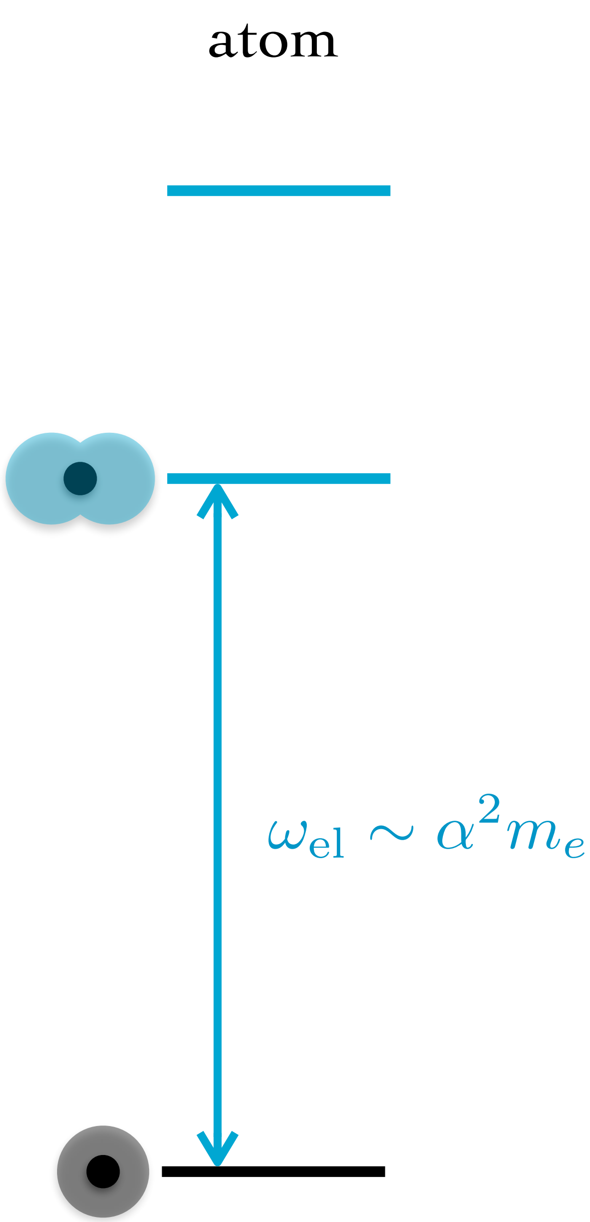
Resonant Absorption of Dark Matter in Molecules



$\Gamma_{abs} = N\, \Omega^2\, \tau$

N: number of molecules
Ω: Interaction energy between DM and molecule (ie Rabi frequency)
τ: Smallest of excitation lifetime, inter-molecule collisions, DM coherence time…

Why Molecules?



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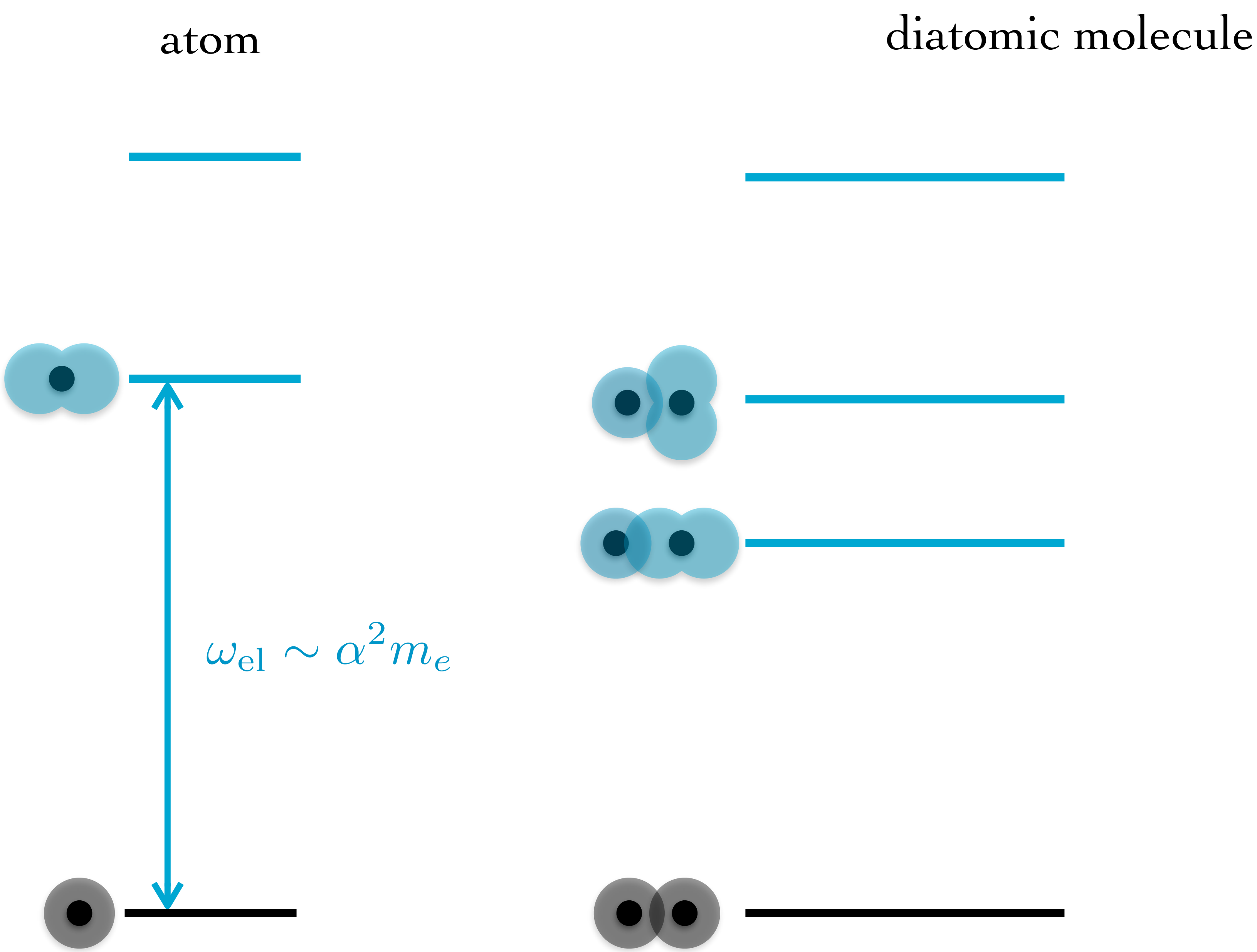

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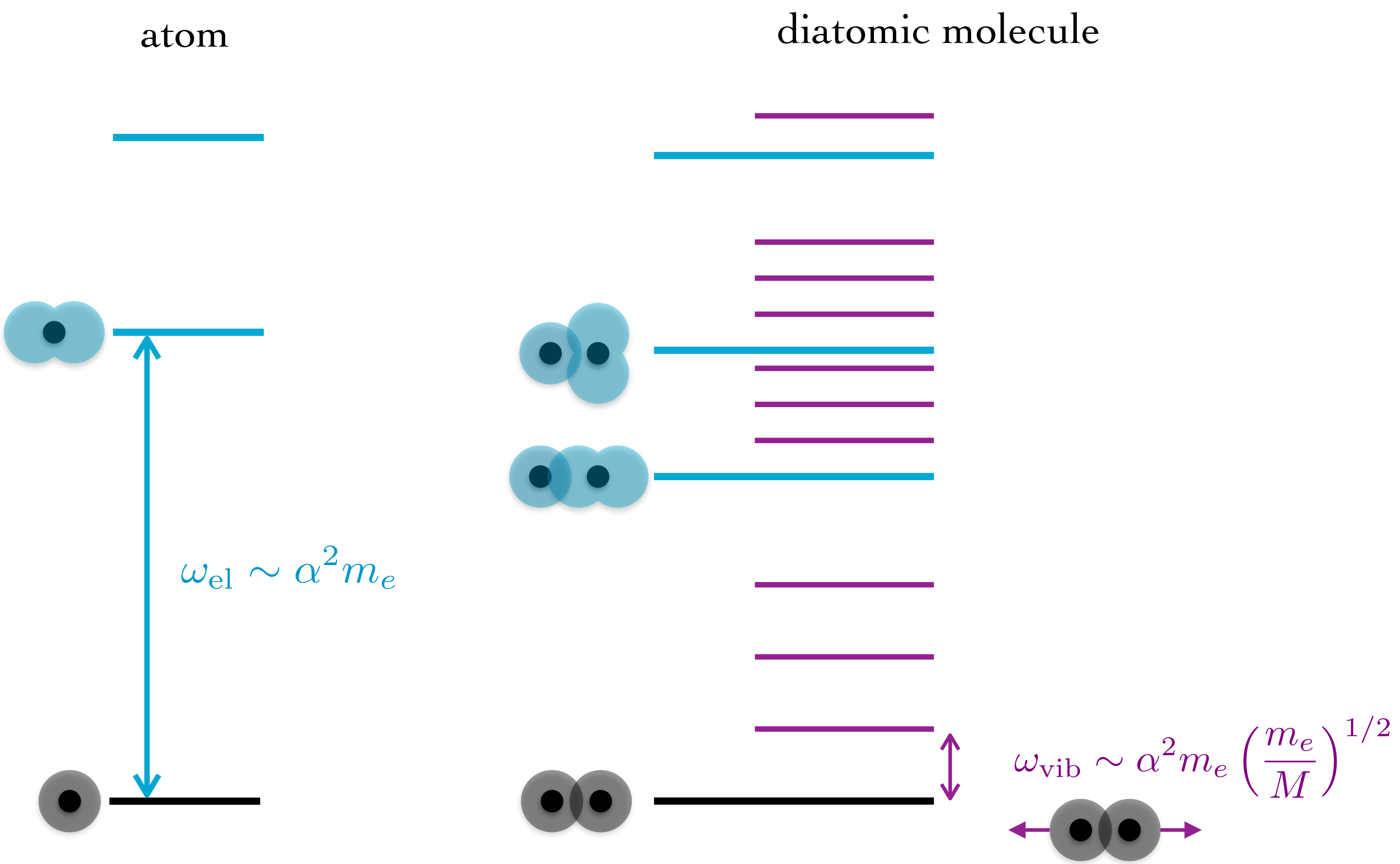

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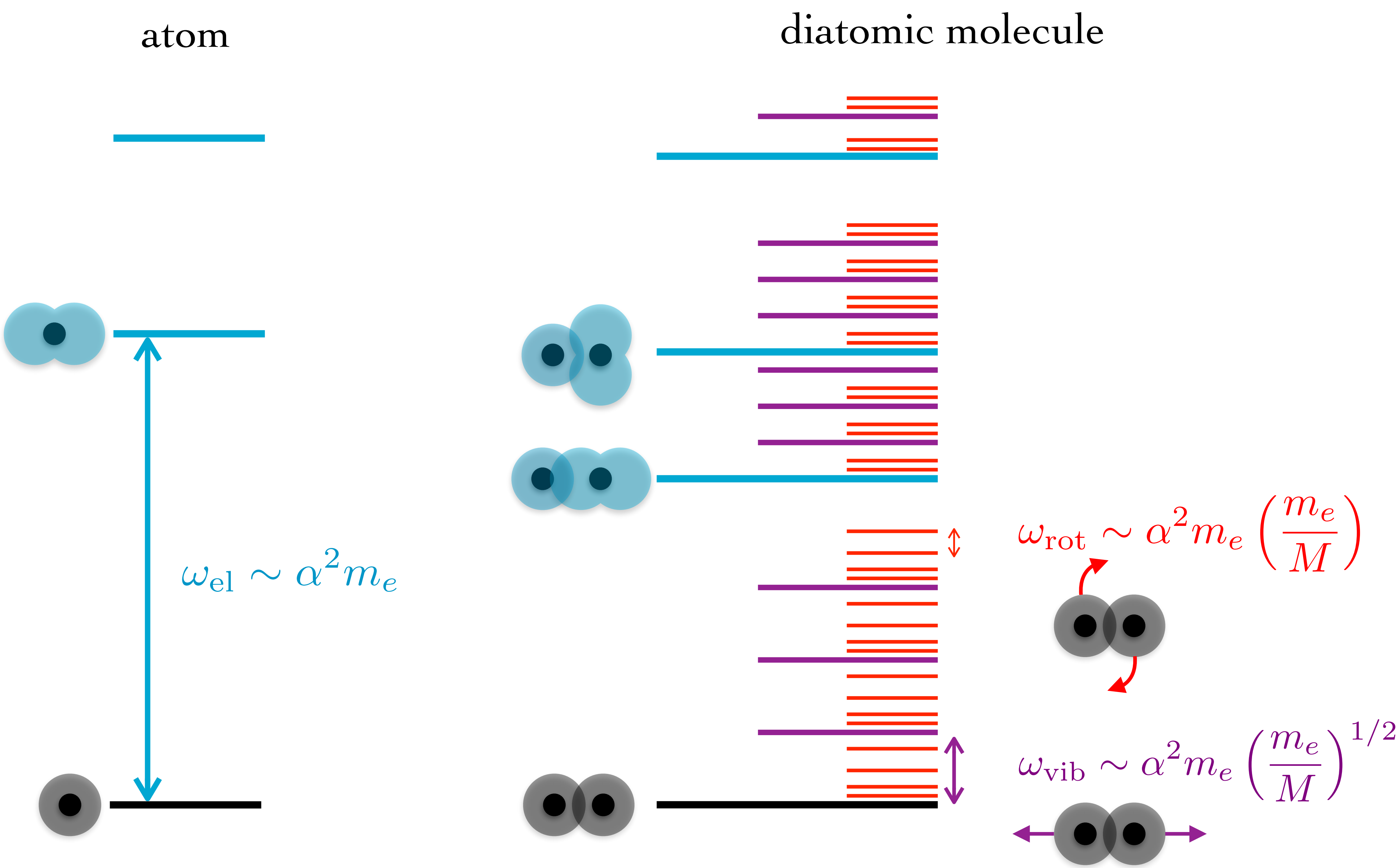

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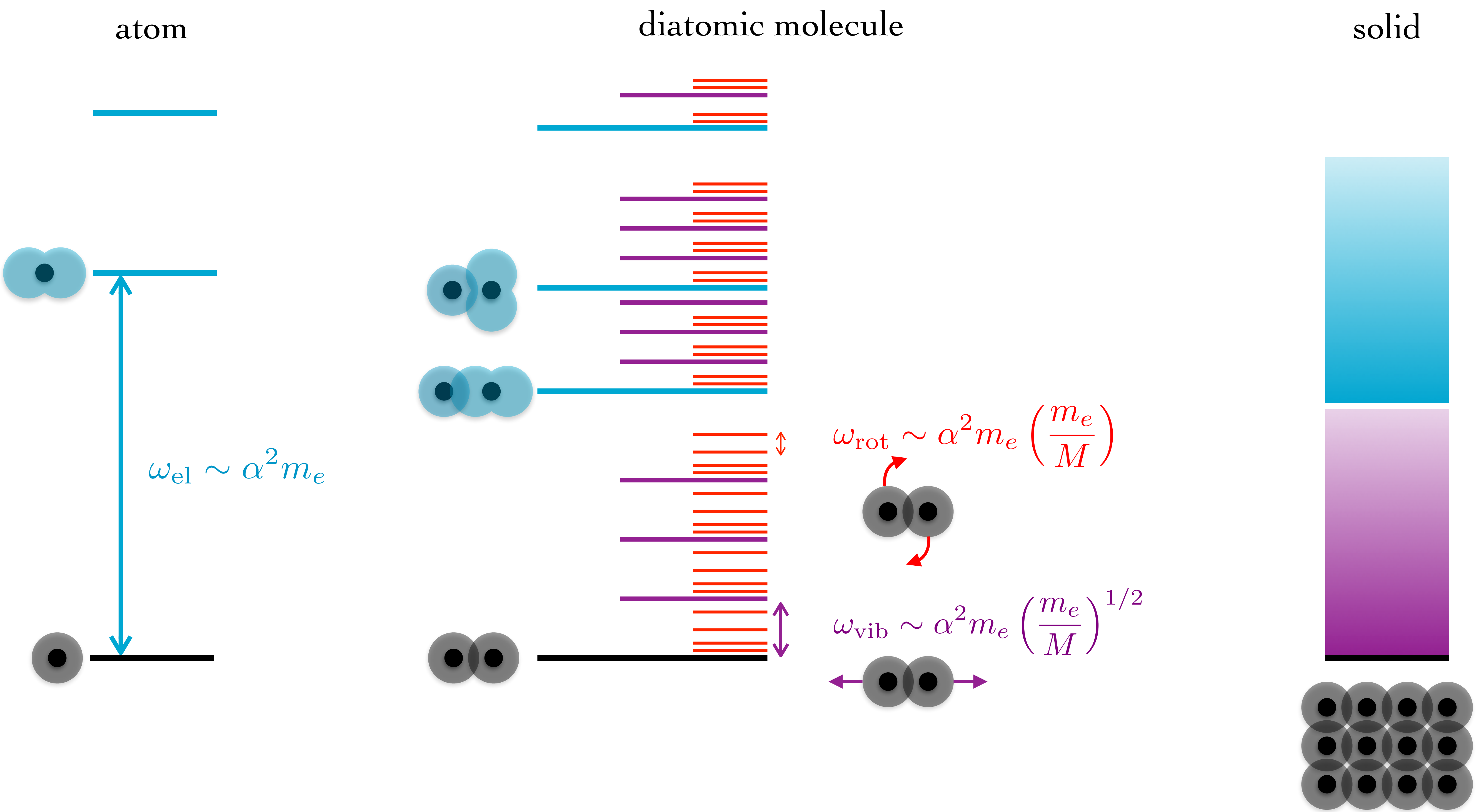
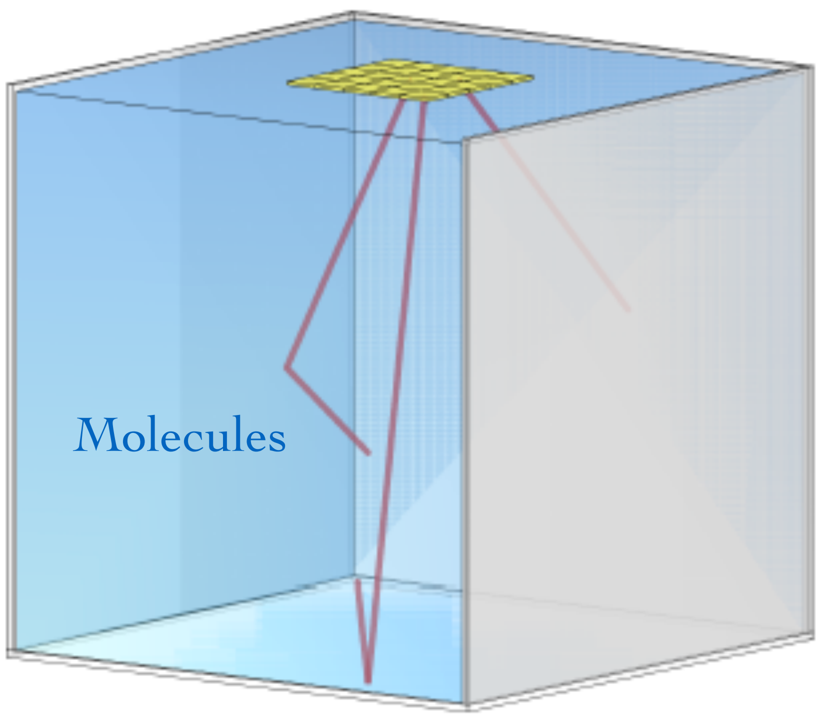


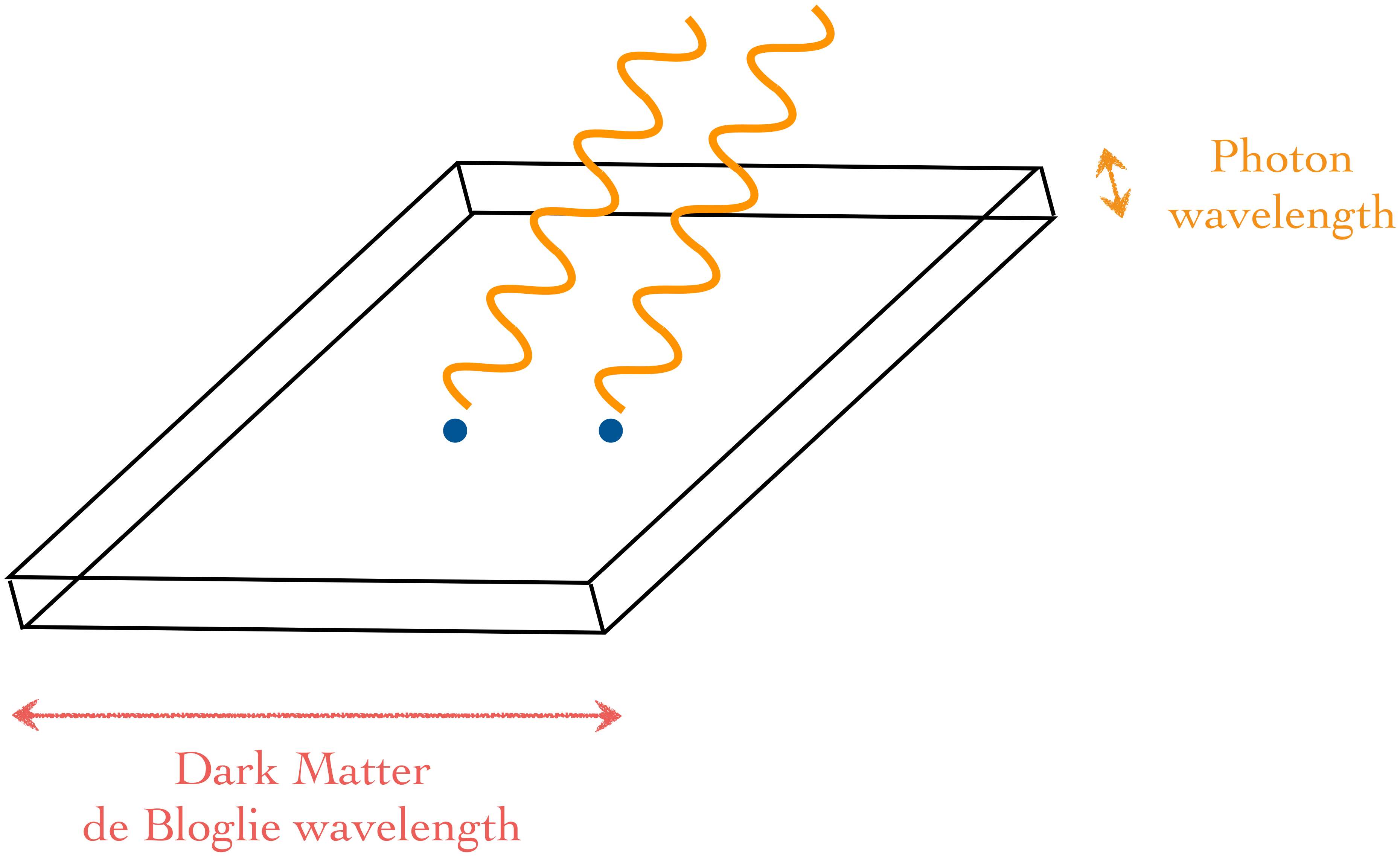
Molecules are a multi-mode resonator with well-understood spectrum

Proposed Set-ups



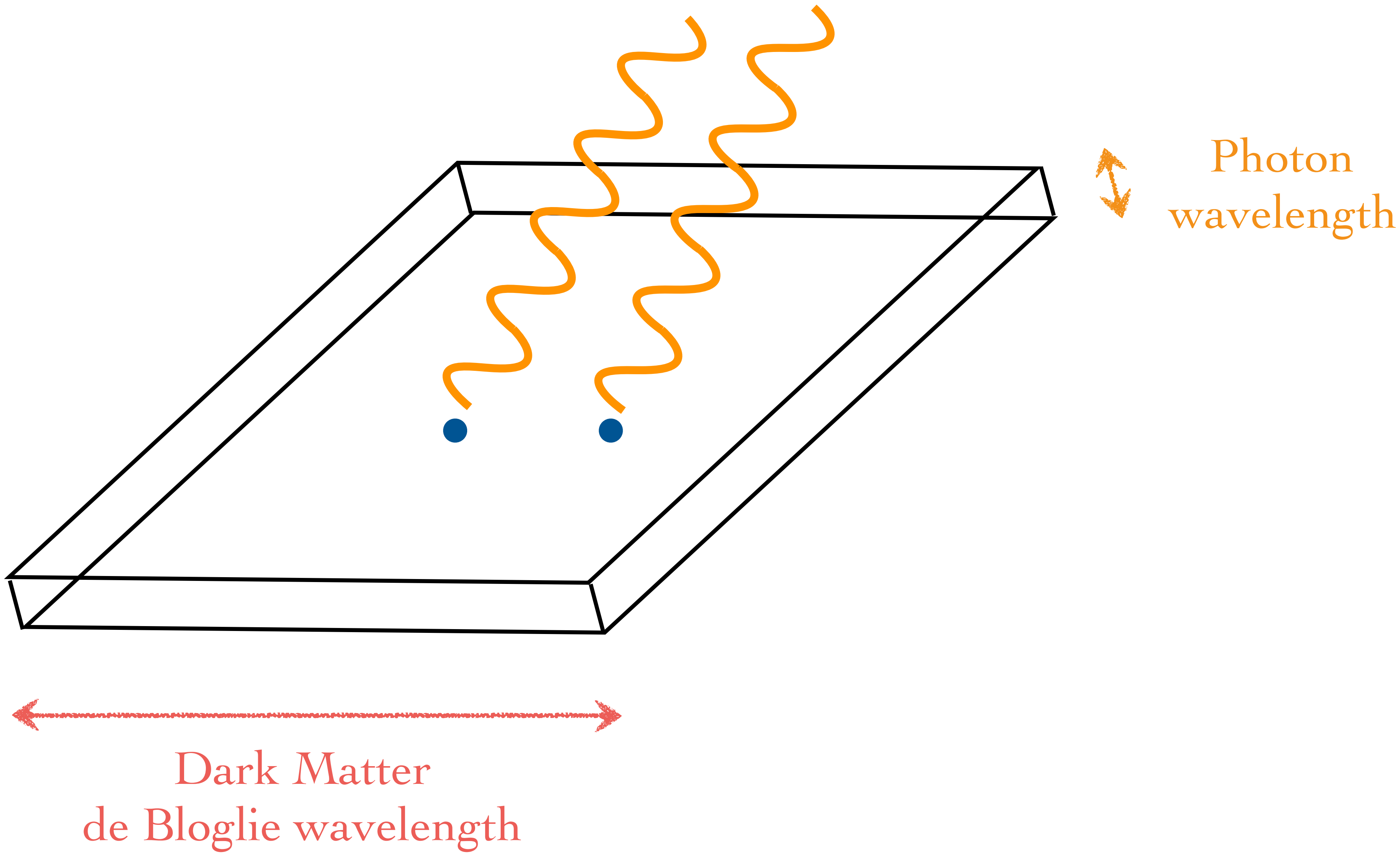
Bulk detector

Cooperative emission effects



Fluorecent photon interference produces interesting emission patterns

Cooperative emission effects



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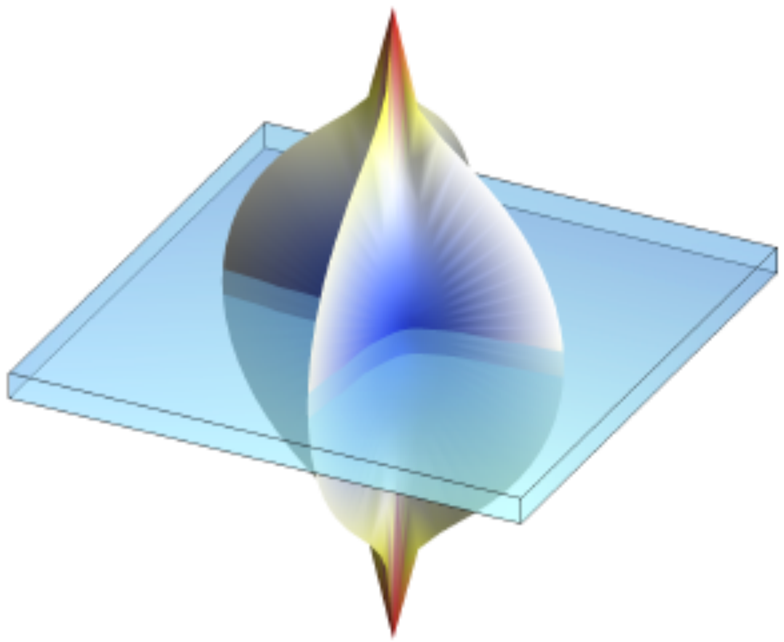
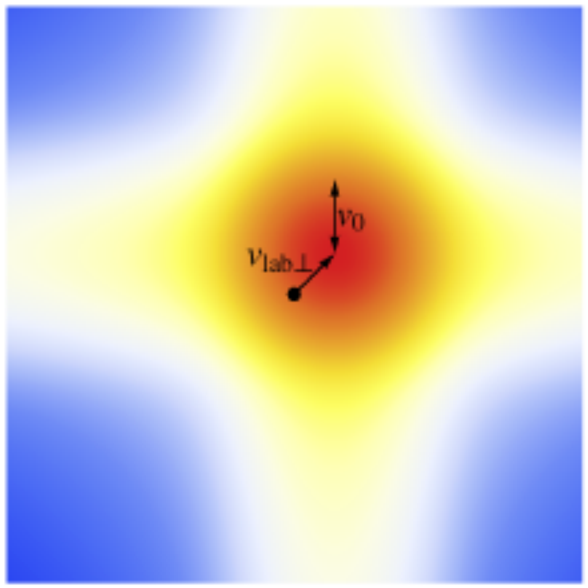
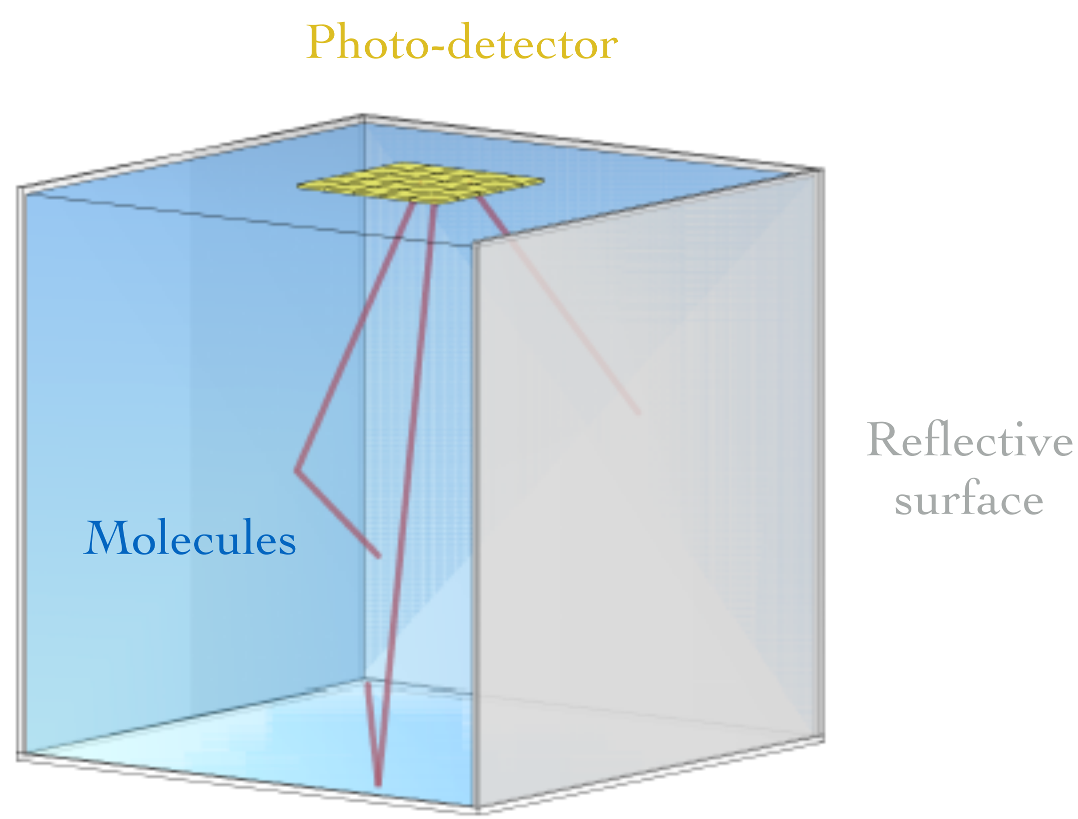


Fluorescent power emitted from a slab



Angular distribution of power close to the slab center

Proposed Set-ups



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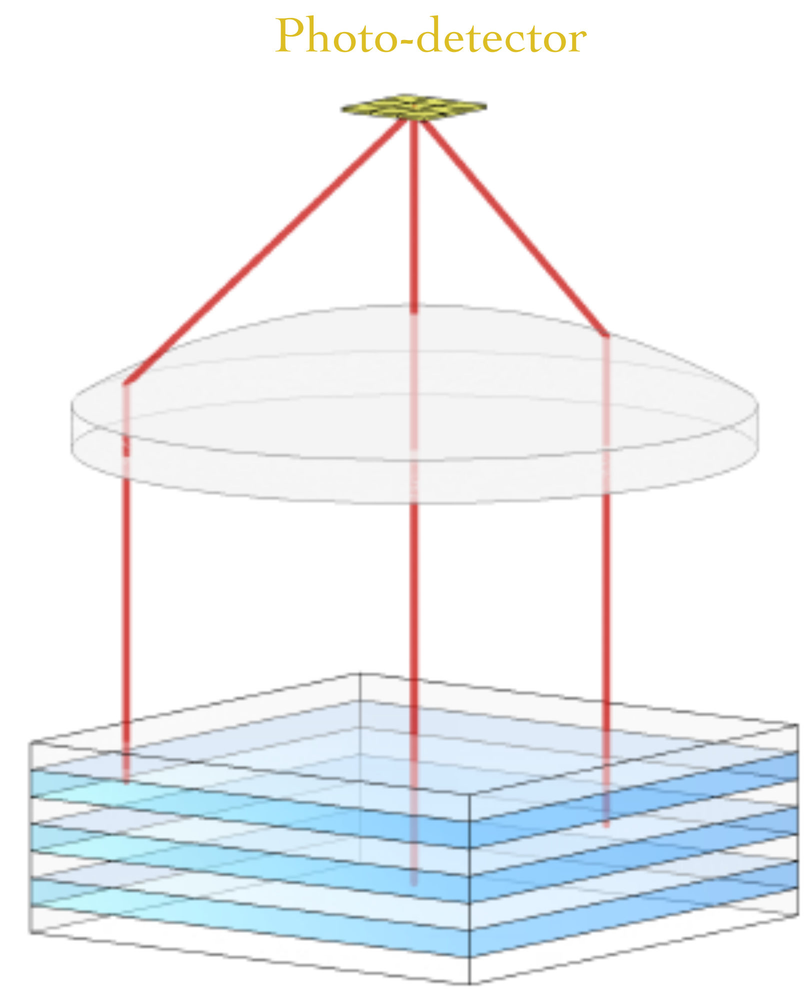
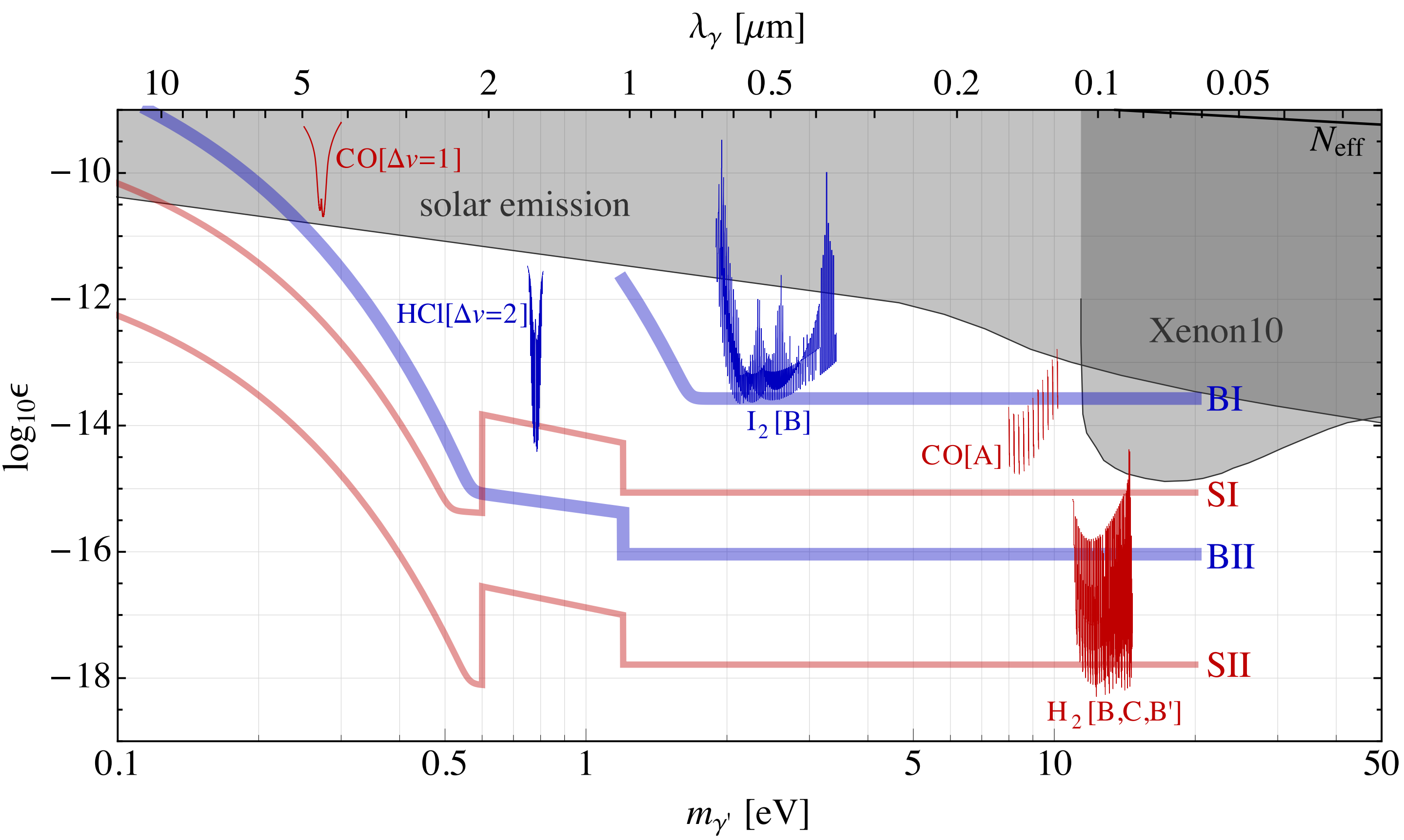


Shell detector

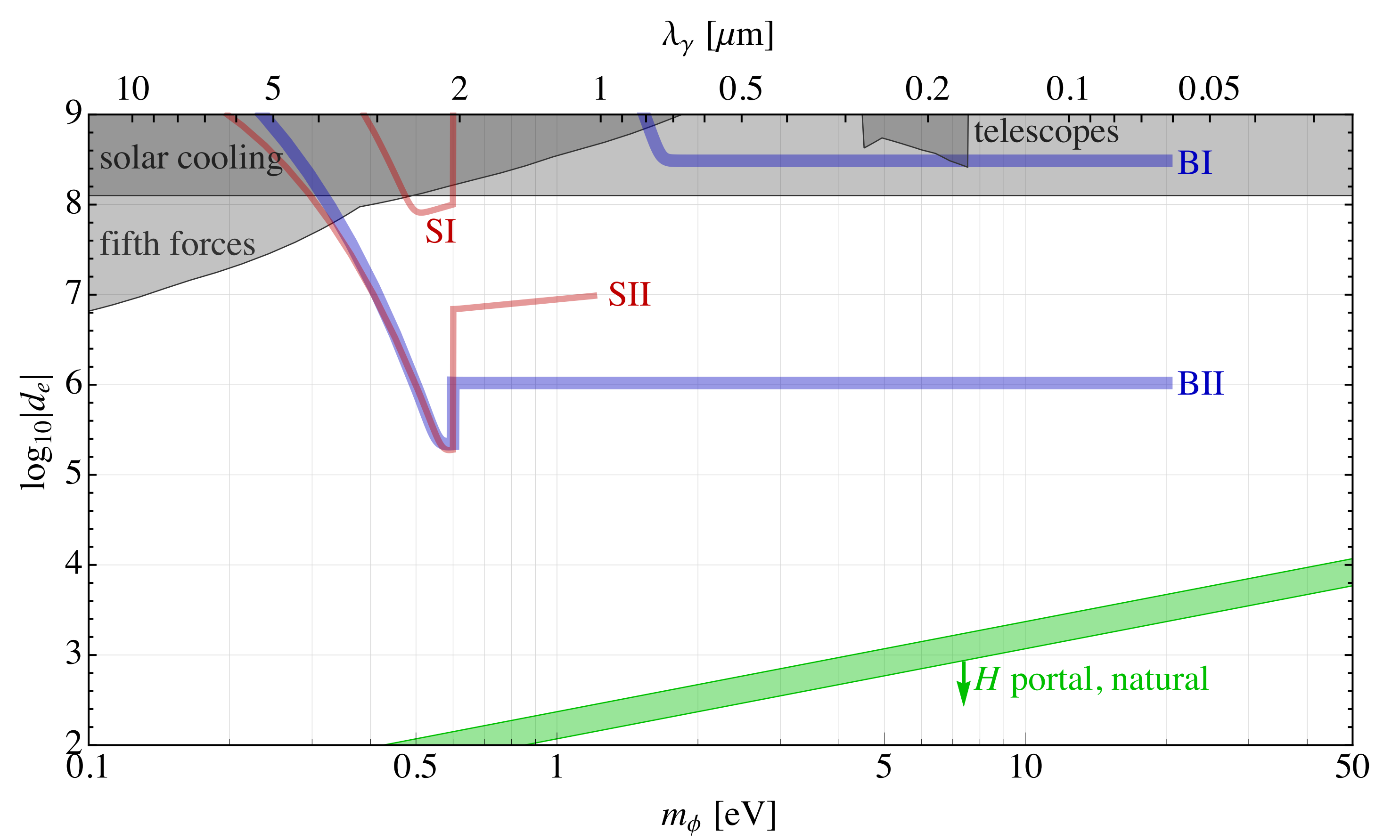
Alternating shells of gas filled and
empty containers of photon wavelength width

Sensitivity Plots
Some examples



Dark Photon Dark Matter

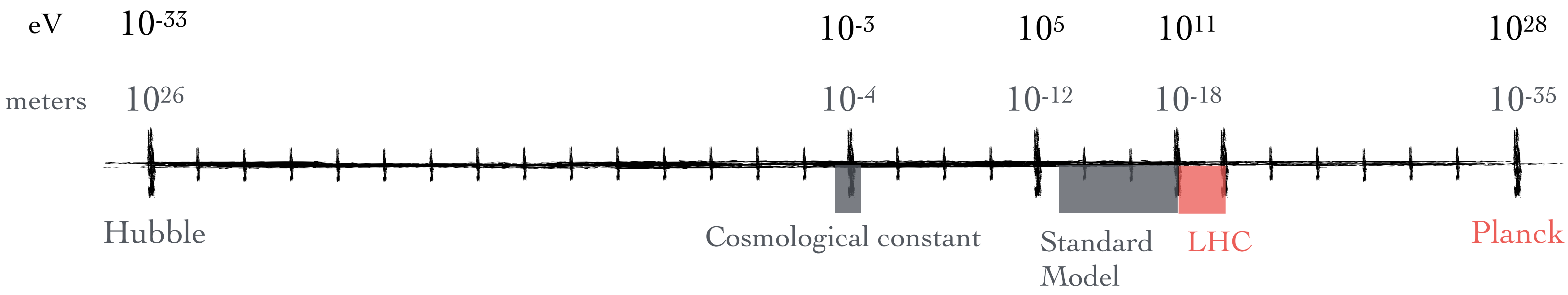
Electron charge modulus Dark Matter



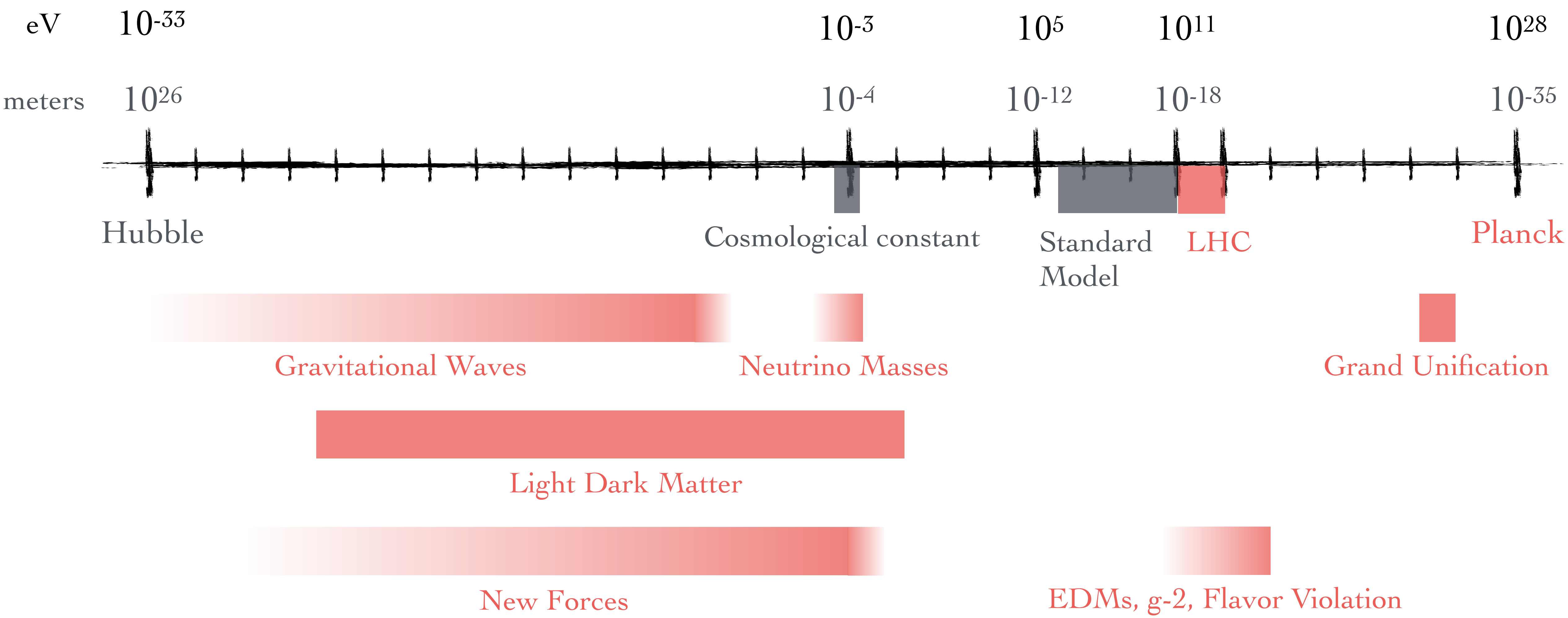
Advantages of Molecule based detector

- Sensitivity to many Dark Matter candidates
- Excellent Energy Resolution
- Tunable
- Background rejection
- Directional information for Dark Matter

The Scales in Our Universe

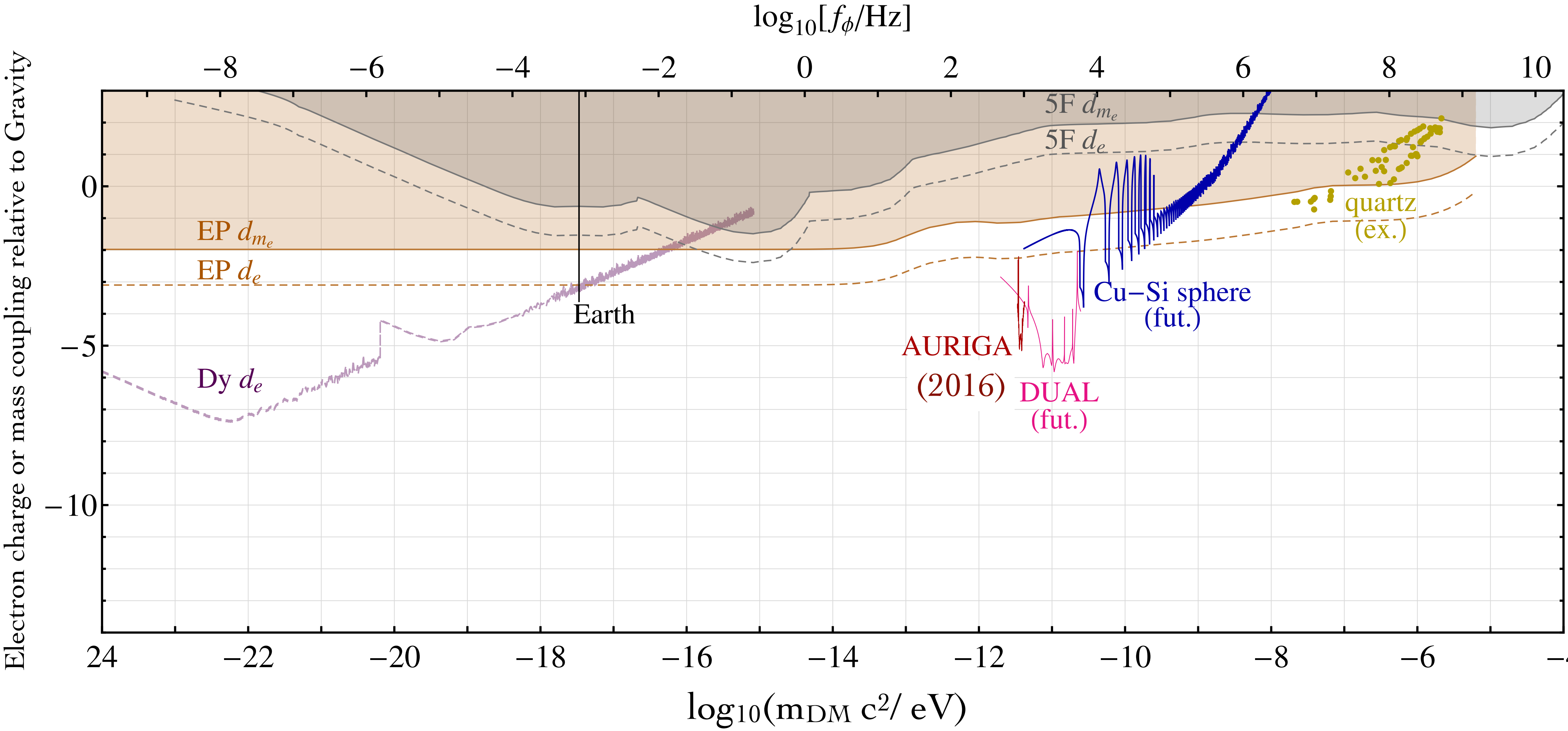


The Scales in Our Universe



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

What can be done in the future?

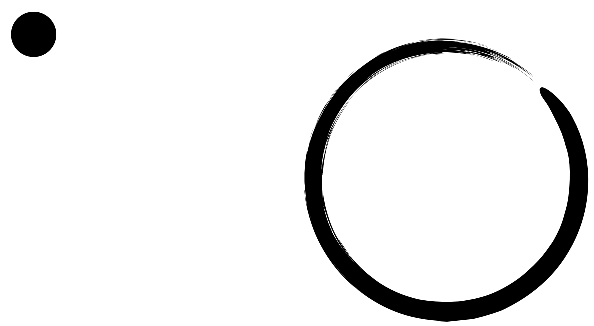


Black Holes as Nature's Detectors

1 km -10 billion km

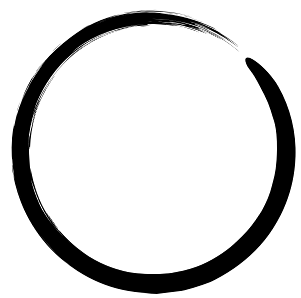
They can detect bosons of similar in size

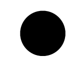
Super-Radiance Cartoon



Super-radiant scattering of a massive object

Super-Radiance Cartoon





Super-radiant scattering of a massive object

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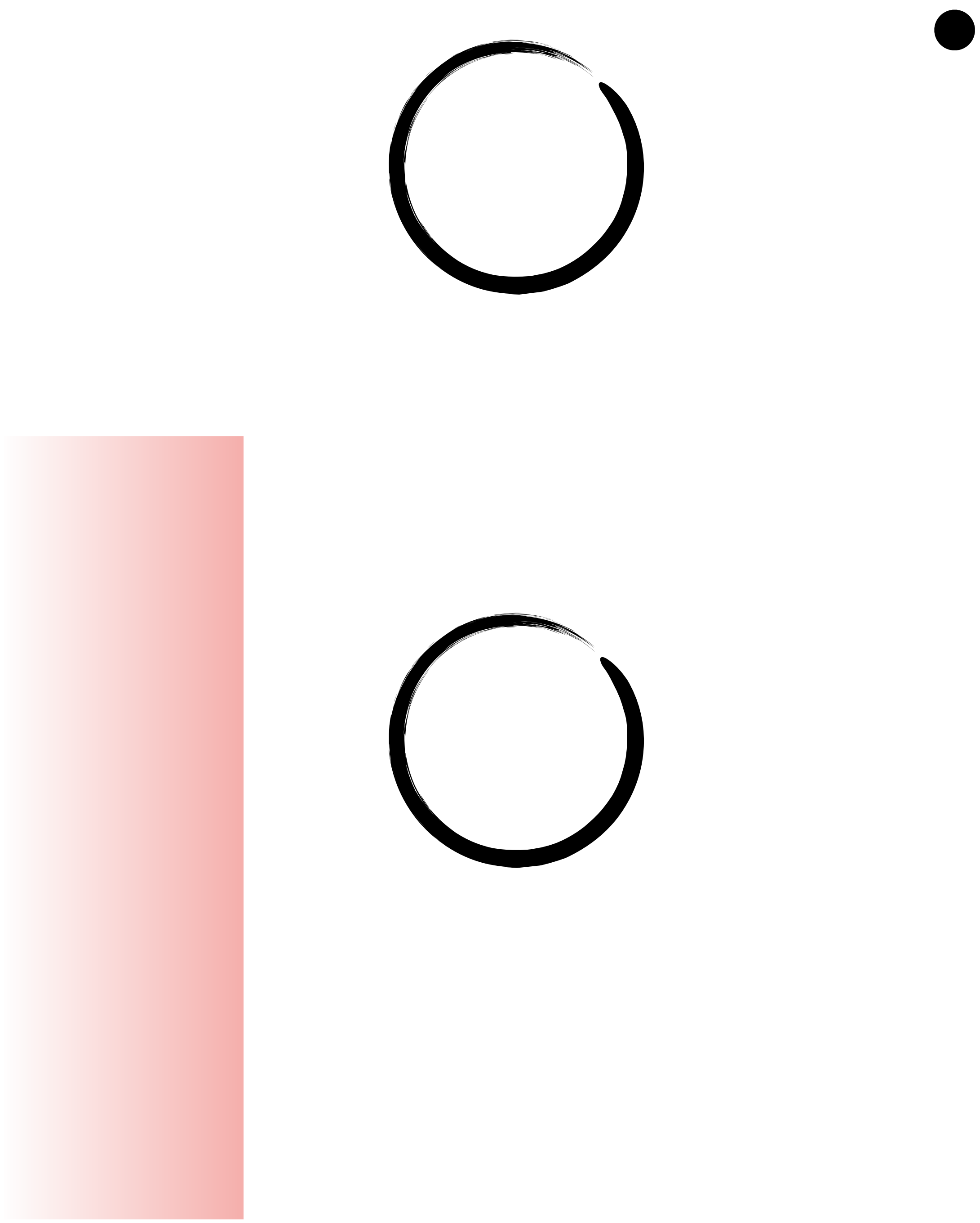


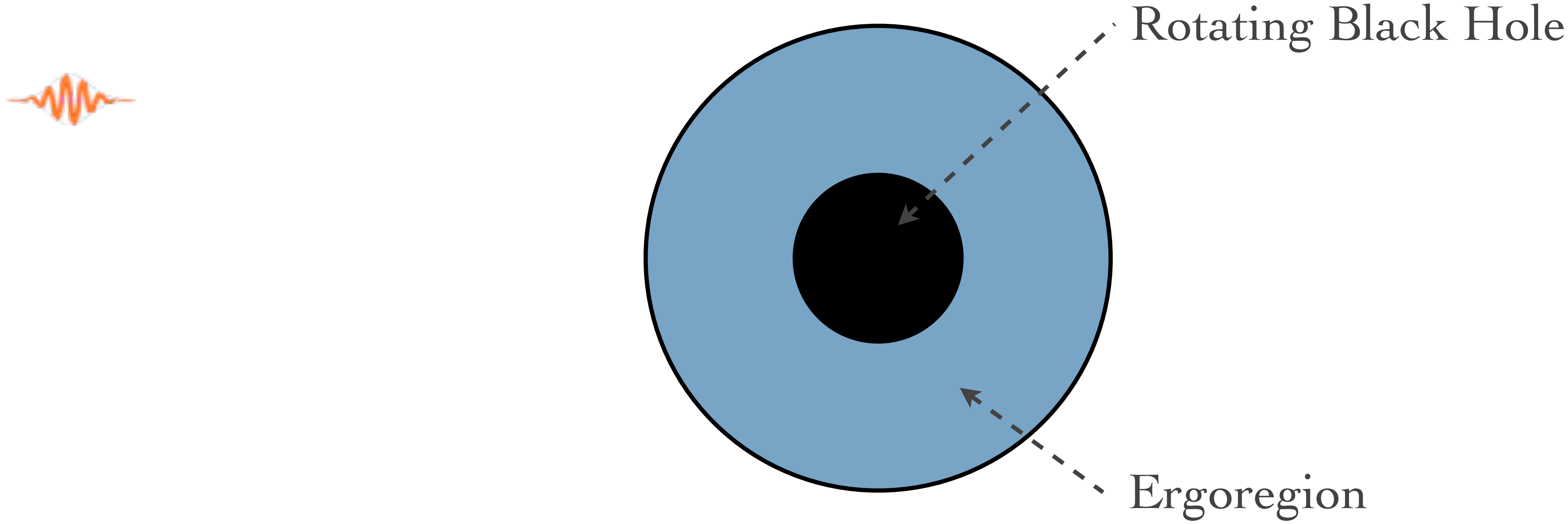
Super-radiant scattering of a wave

Super-Radiance Cartoon

Super-radiant scattering of a wave

Black Hole Superradiance

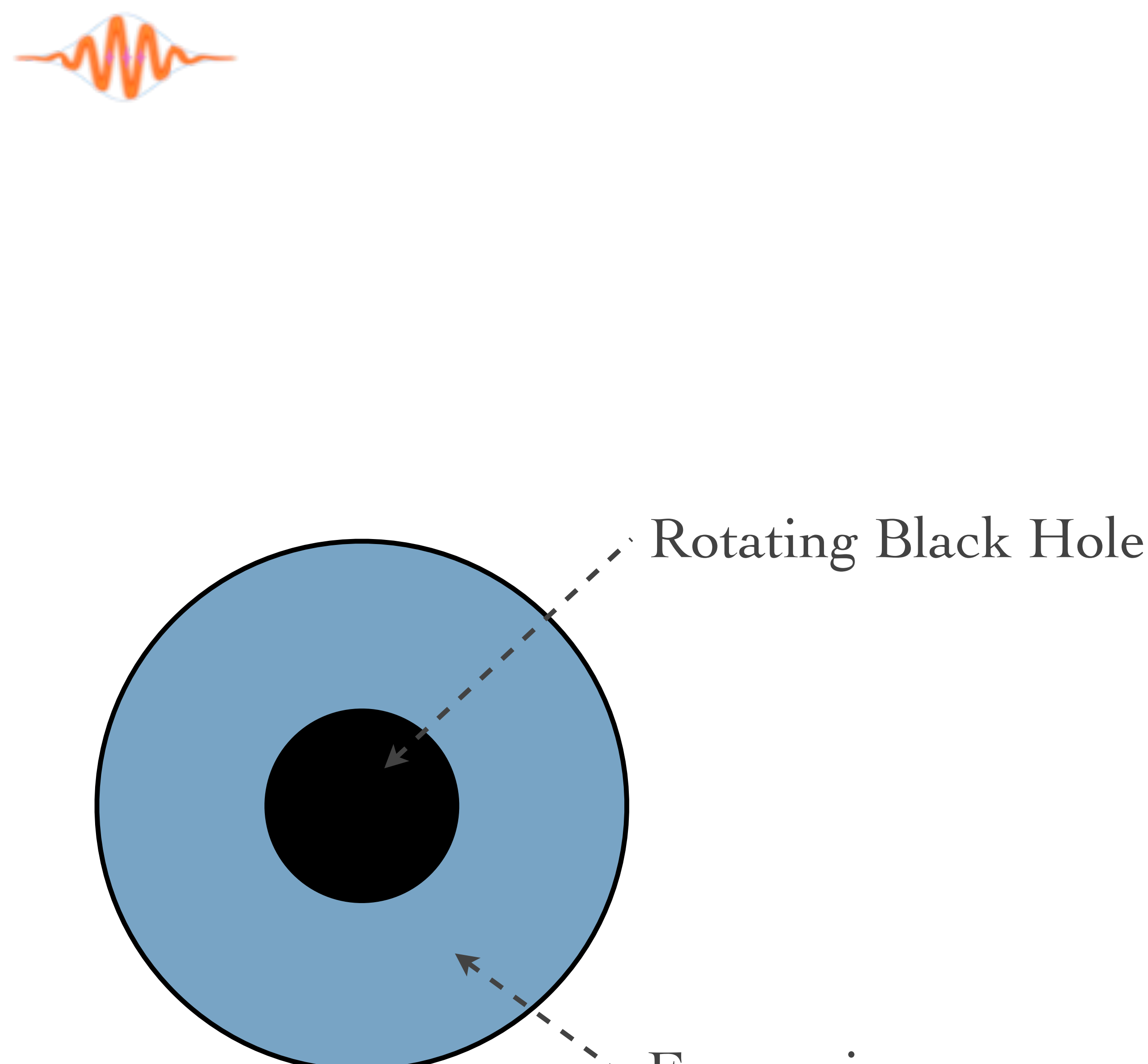
Penrose Process



Ergoregion: Region where even light has to be rotating

Black Hole Superradiance

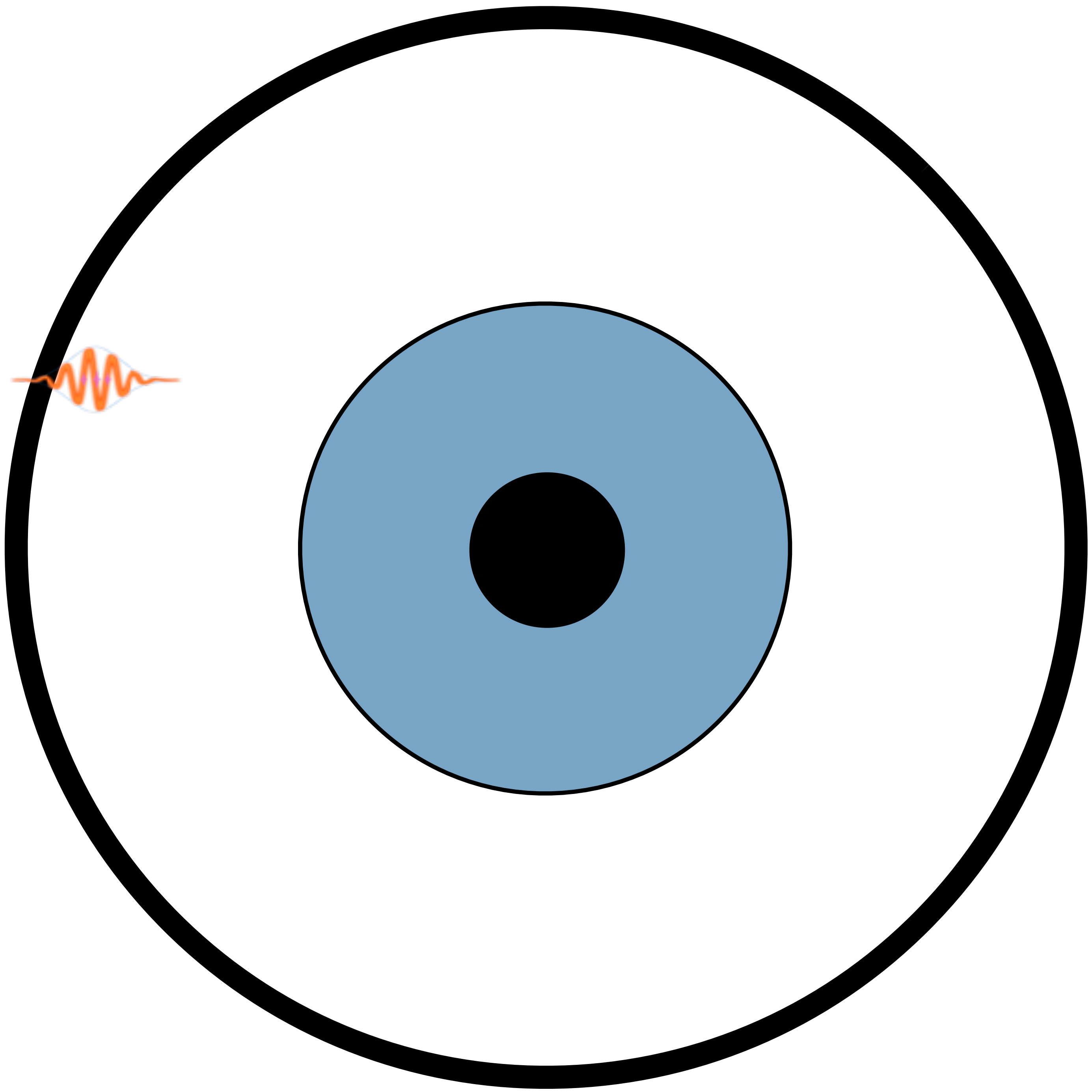
Penrose Process



Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

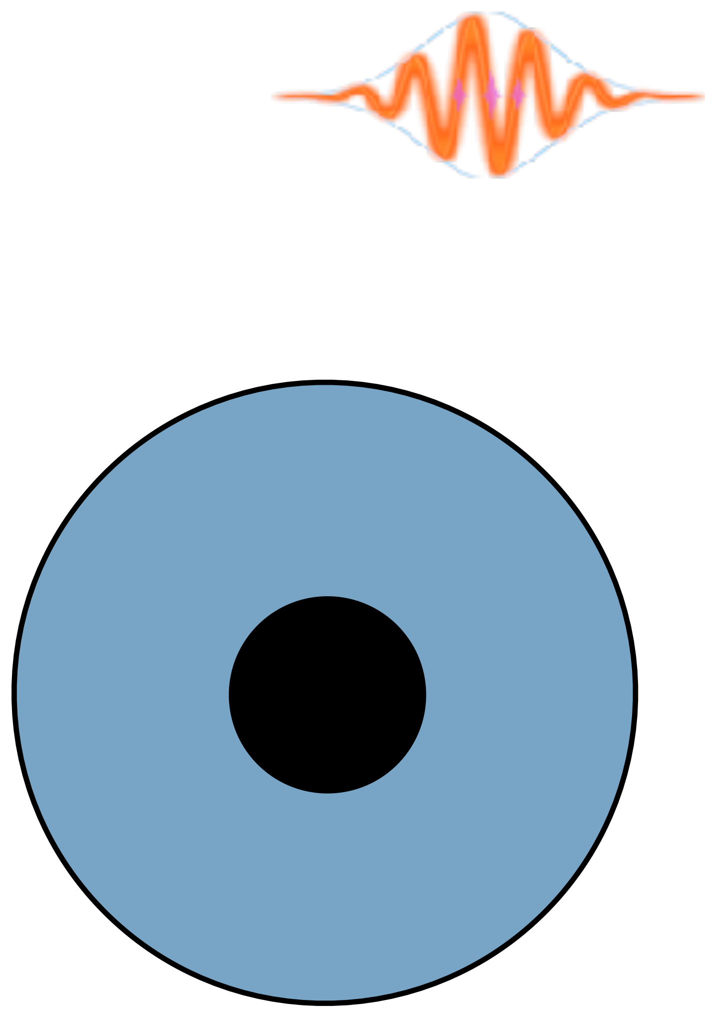
Press & Teukolsky 1972



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

Black Hole Bomb

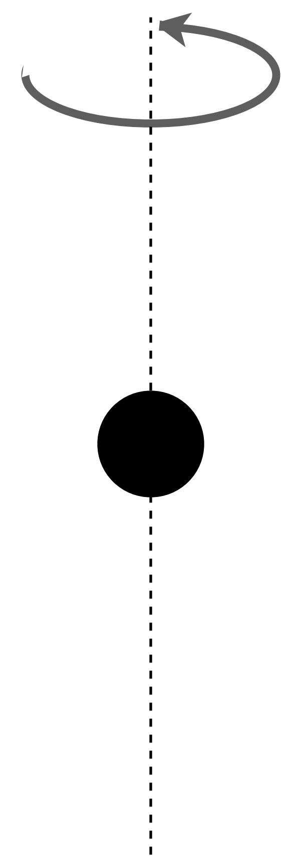
Press & Teukolsky 1972



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

Superradiance for a massive boson

Damour et al; Zouros & Eardley;
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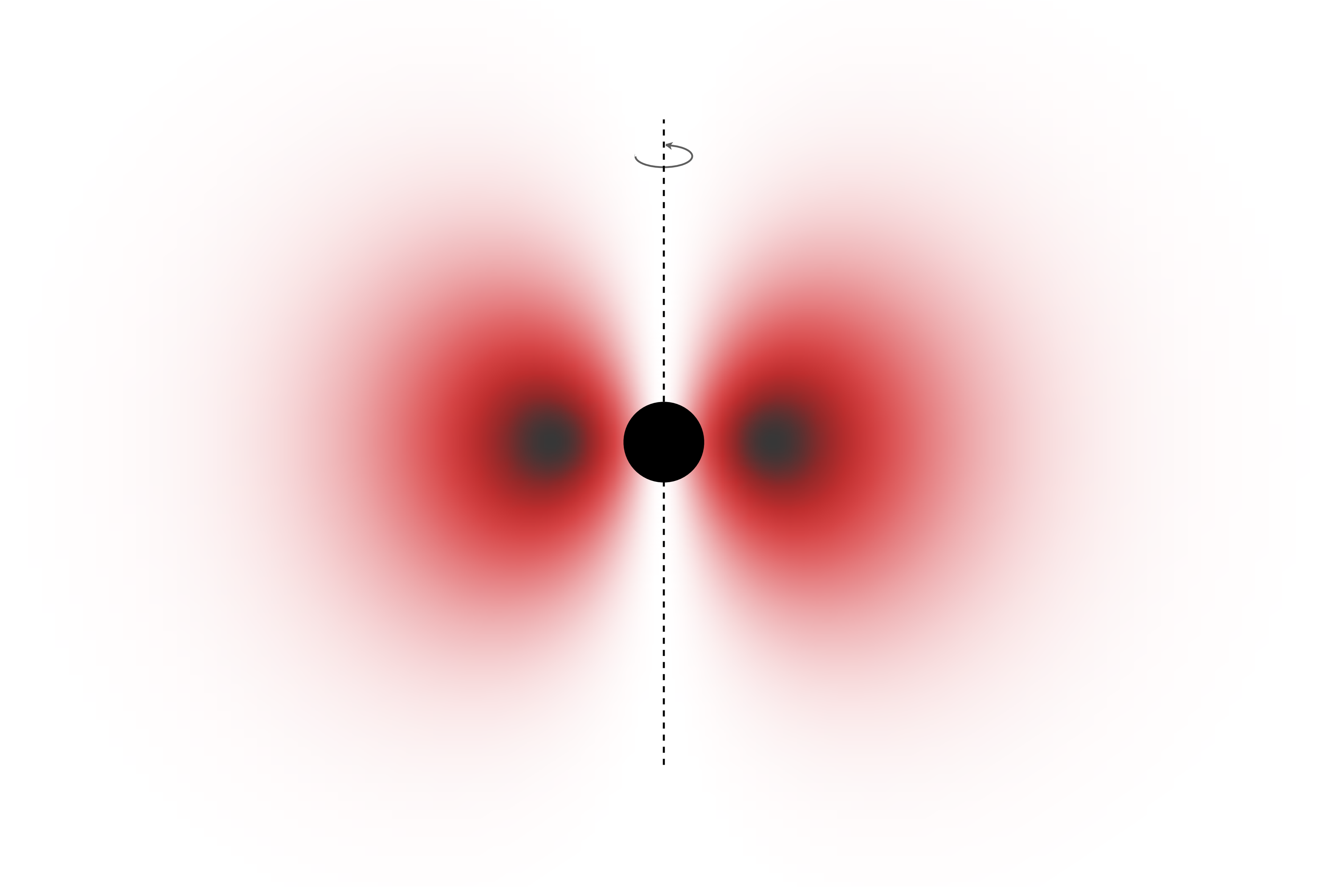
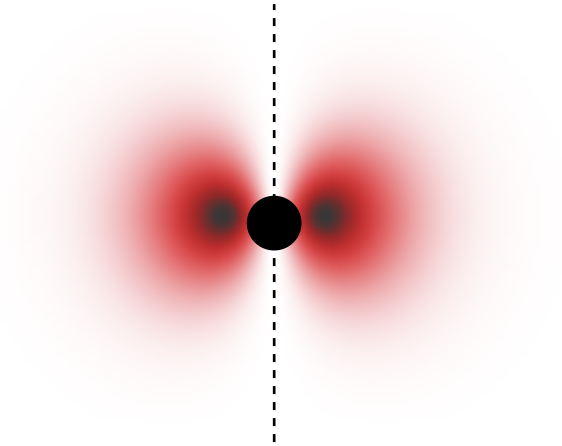


Particle Compton Wavelength comparable to the size of the Black Hole

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 $E_{\mathrm{binding}} = -\frac{\alpha^2 \mu_a}{2n^2}$

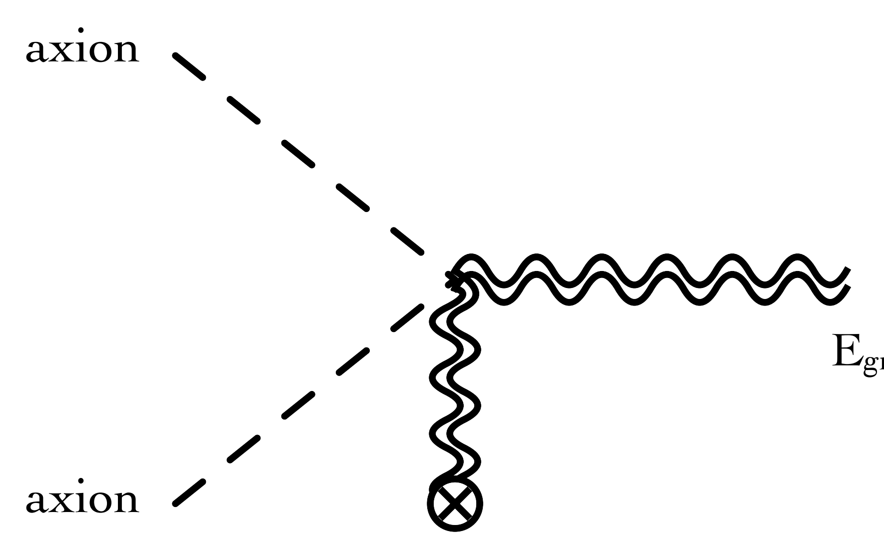
Main differences from hydrogen atom:

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

In-going Boundary Condition at Horizon

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

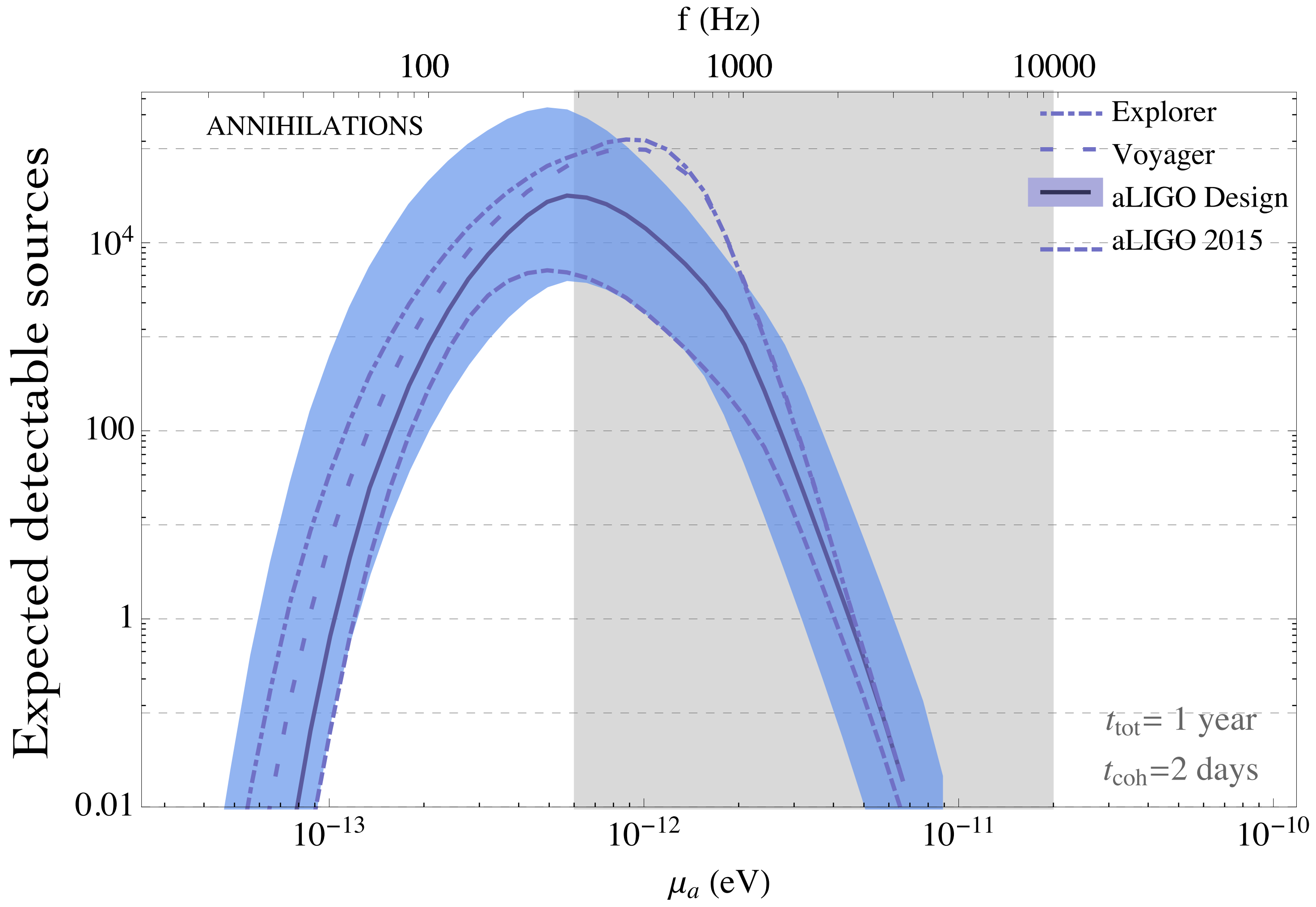
- Signal enhanced by the square of the occupation number of the state

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

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

Expected Events from Annihilations

- Large uncertainties coming from tails of BH mass distribution



Pessimistic: flat spin distribution and 0.1 BH/century

Realistic: 30% above spin of 0.8 and 0.4 BH/century

Optimistic: 90% above spin of 0.9 and 0.9 BH/century