The Principle of Plenitude

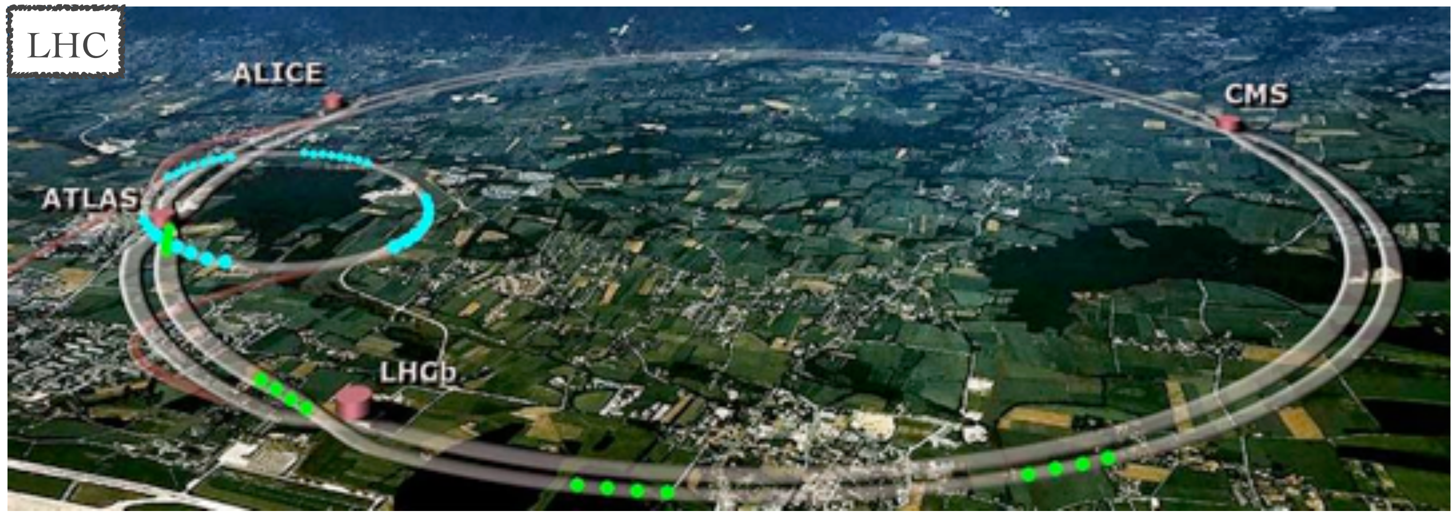
Asimina Arvanitaki
Perimeter Institute

Plenitude

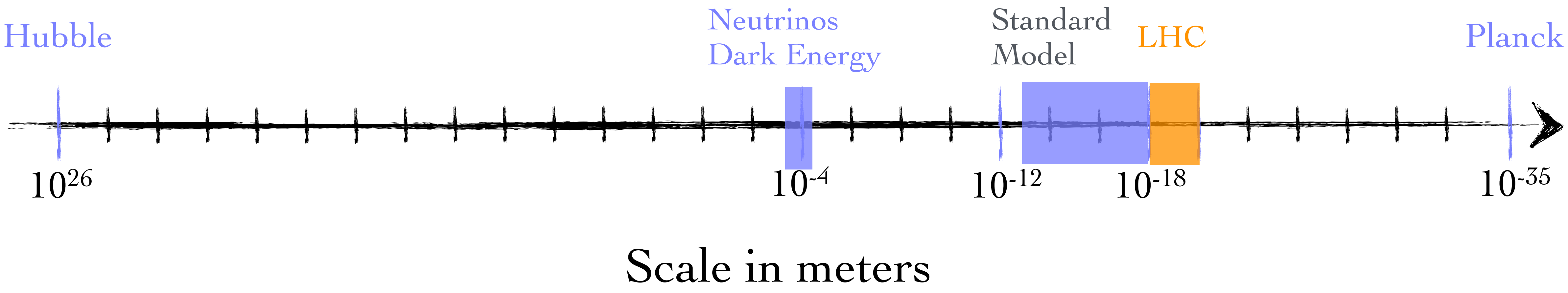
Gottfried Wilhelm Leibniz

" 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



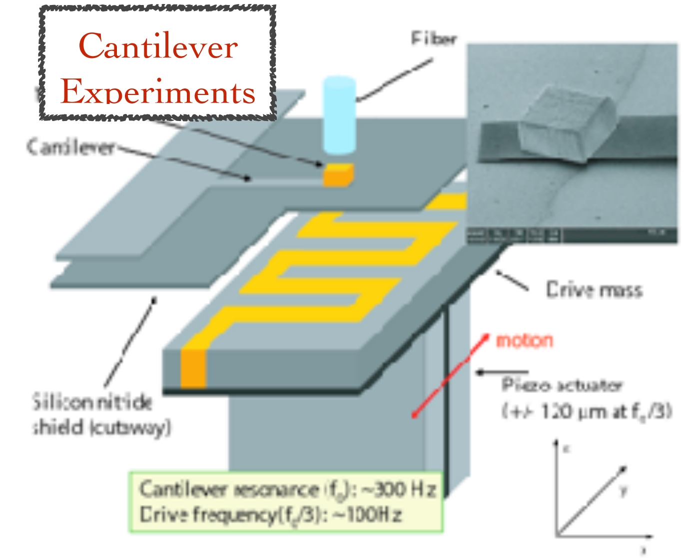
The Length Scales in the Universe



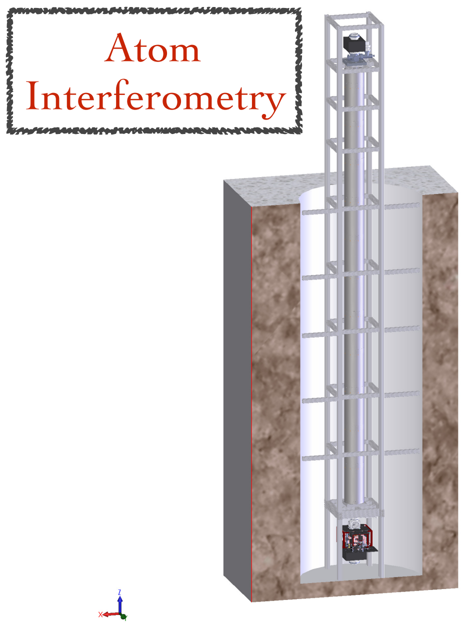
80% of the energy scale left to explore

Opportunities to probe the low energy frontier

- Short Distance Tests of Gravity
- Extra Dimensions



Dimopoulos, Kapitulnik (1997)

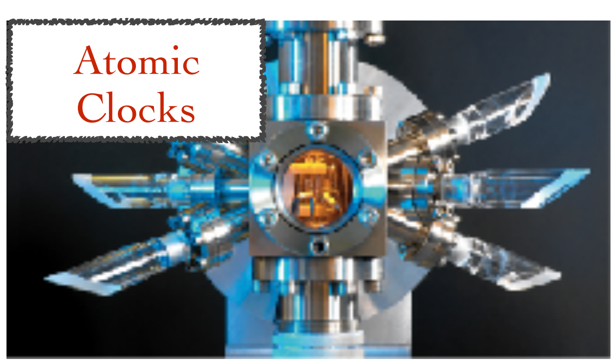


- Tests of Gravity
- Gravitational Wave detection at low frequencies
- Tests of Atom Neutrality at 30 decimals

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

- Axion Dark Matter Detection
- Axion Force Detection

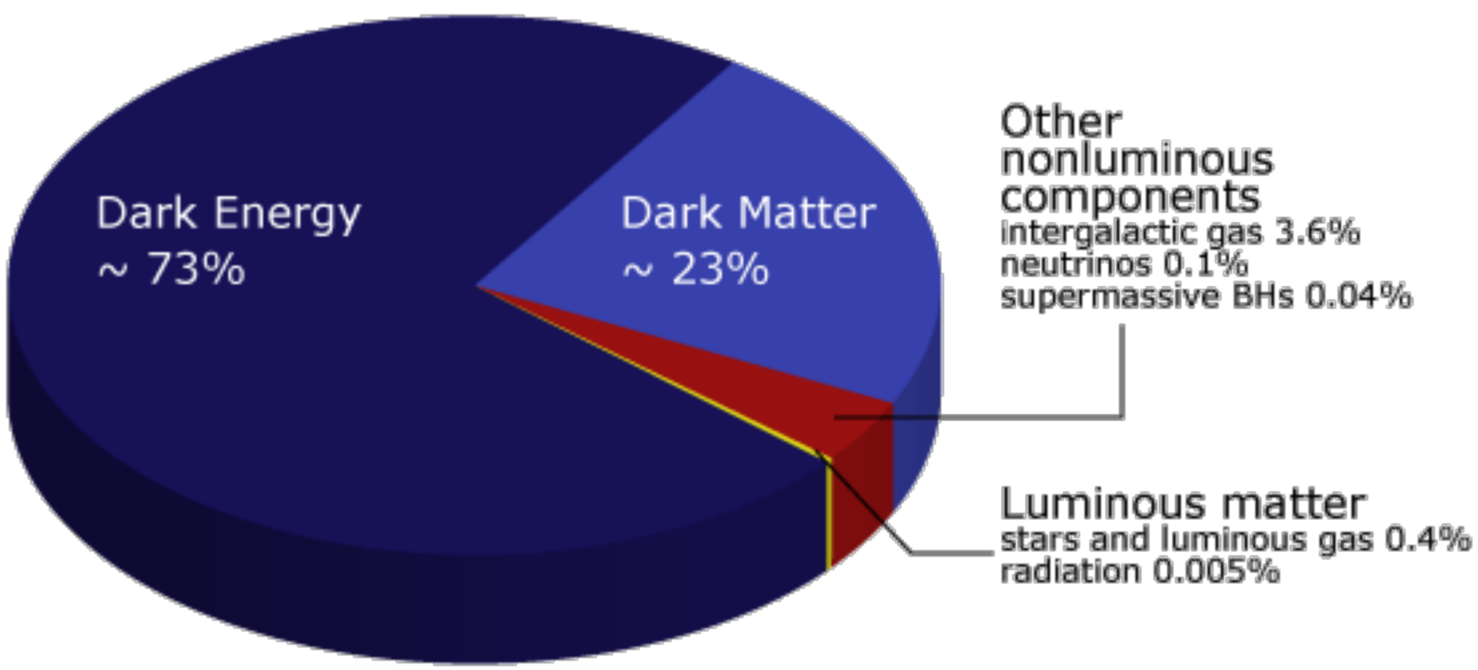
Graham et. al. (2012)
AA, Geraci (2014)



- Setting the Time Standard
- Dilaton Dark Matter Detection

AA, Huang, Van Tilburg (2014)

The Mystery of Dark Matter

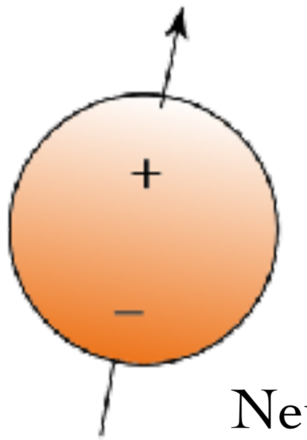


Models of Dark Matter

- What is it made out of?
- 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: $\theta_s < 10^{-10}$

Why is the Electric Dipole Moment of the Neutron Small?

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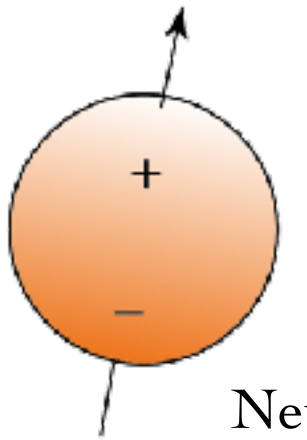


Neutron EDM

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

EDM ~ e fm θ_s

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

Solution:

$\theta_s \propto a(x,t)$ 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

Elements of String Theory

- Extra dimensions

Elements of String Theory

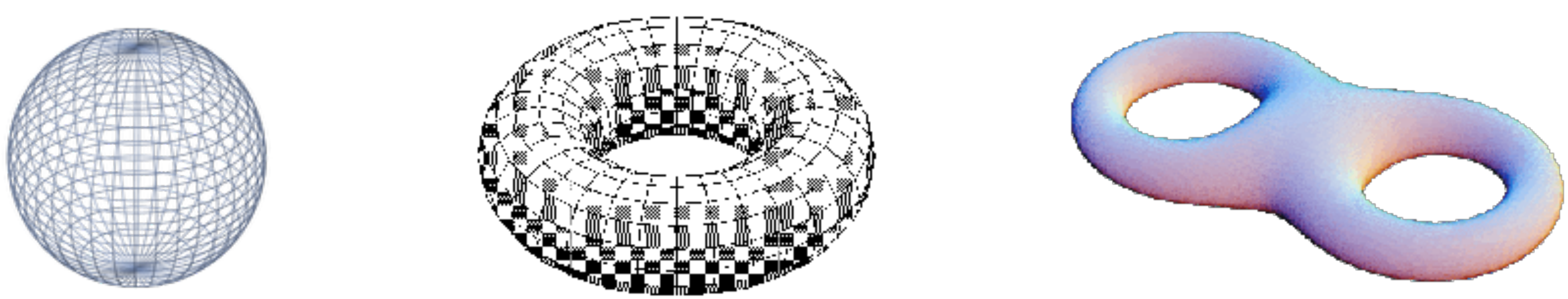
- Extra dimensions
- Gauge fields

Elements of String Theory

- Extra dimensions

- Gauge fields

- Topology

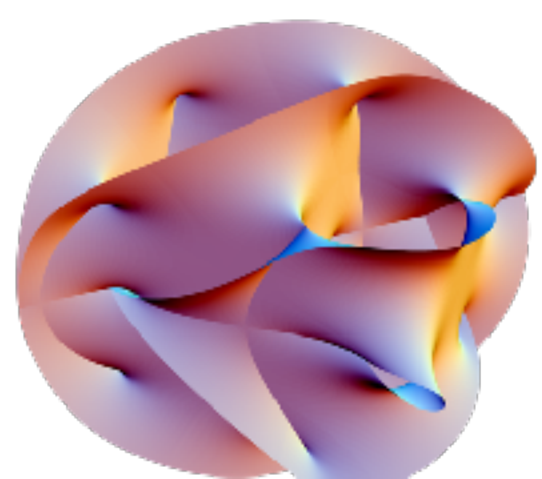


Elements of String Theory

- 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

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

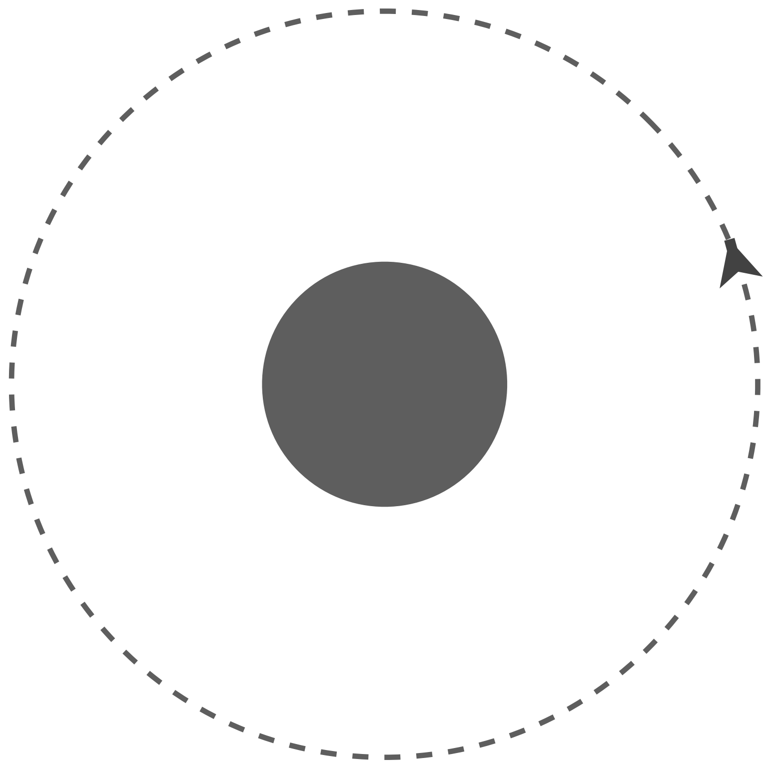
$$\vec{B} = 0$$

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

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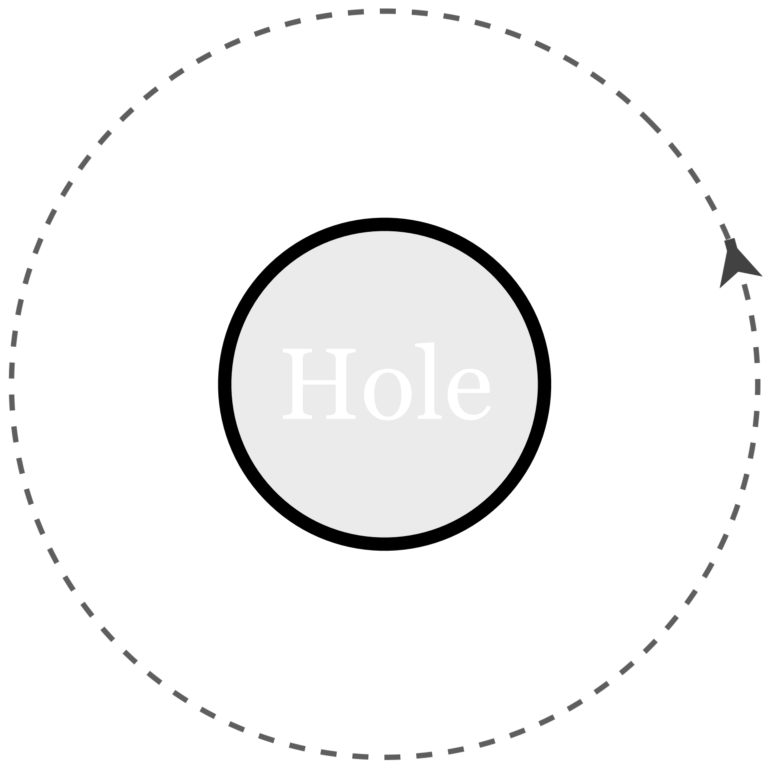


Taking an electron around the solenoid

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

while

$$\vec{B} = 0$$

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

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

Properties of Plenitude of Particles from String Theory

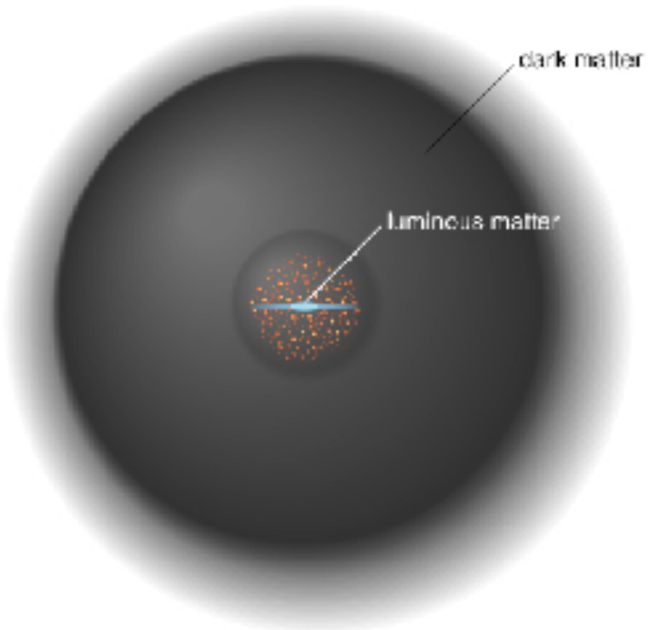
- They couple very weakly to the Standard Model

- They can be extremely light

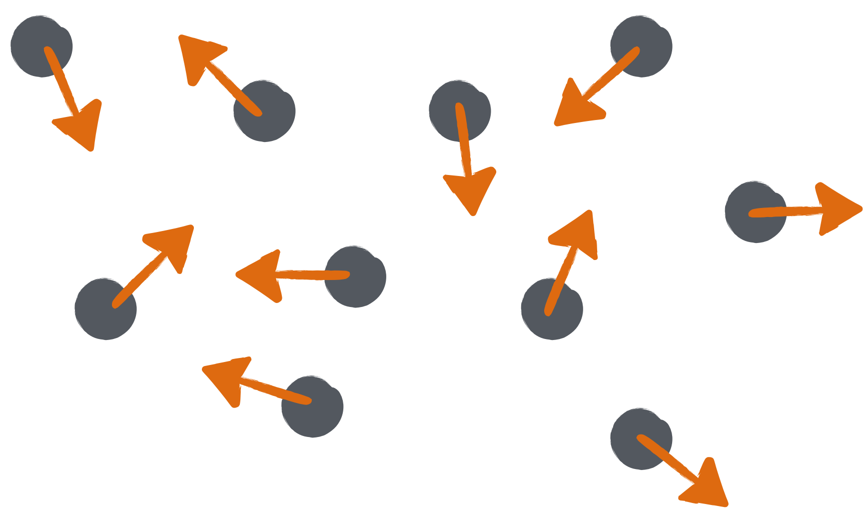
- Constrained if the coupling is large enough by astrophysics, BBN, CMB…

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



Usually we think of ...



like a WIMP

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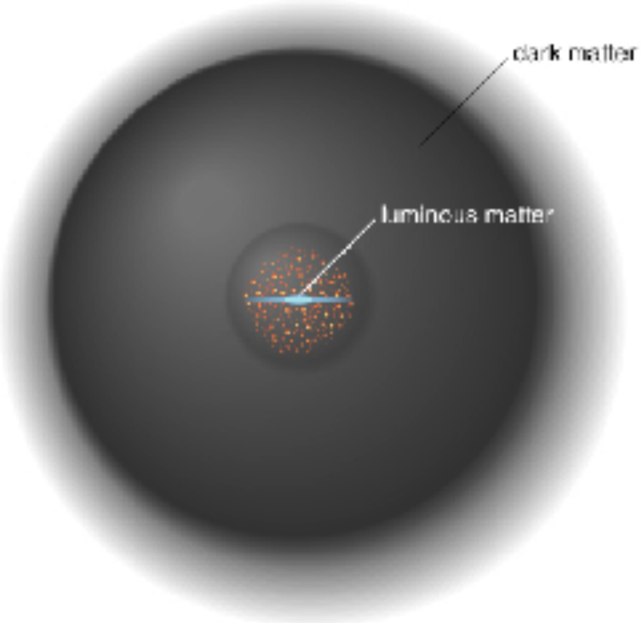

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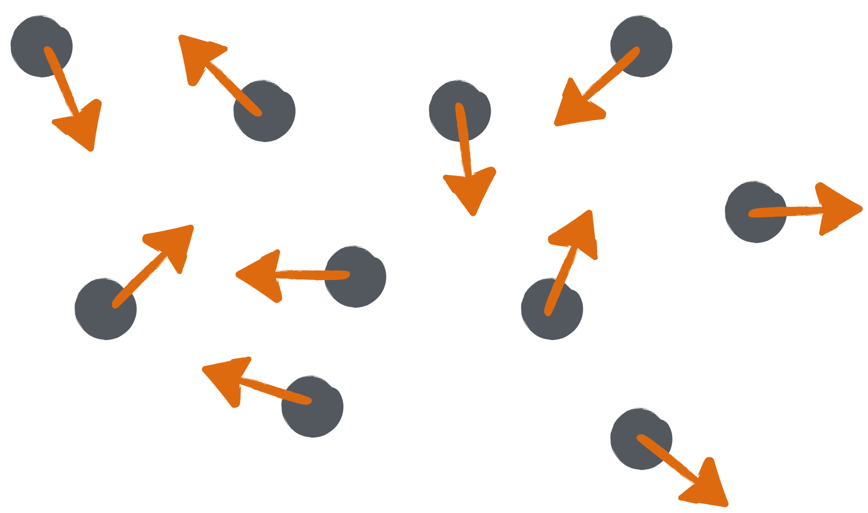
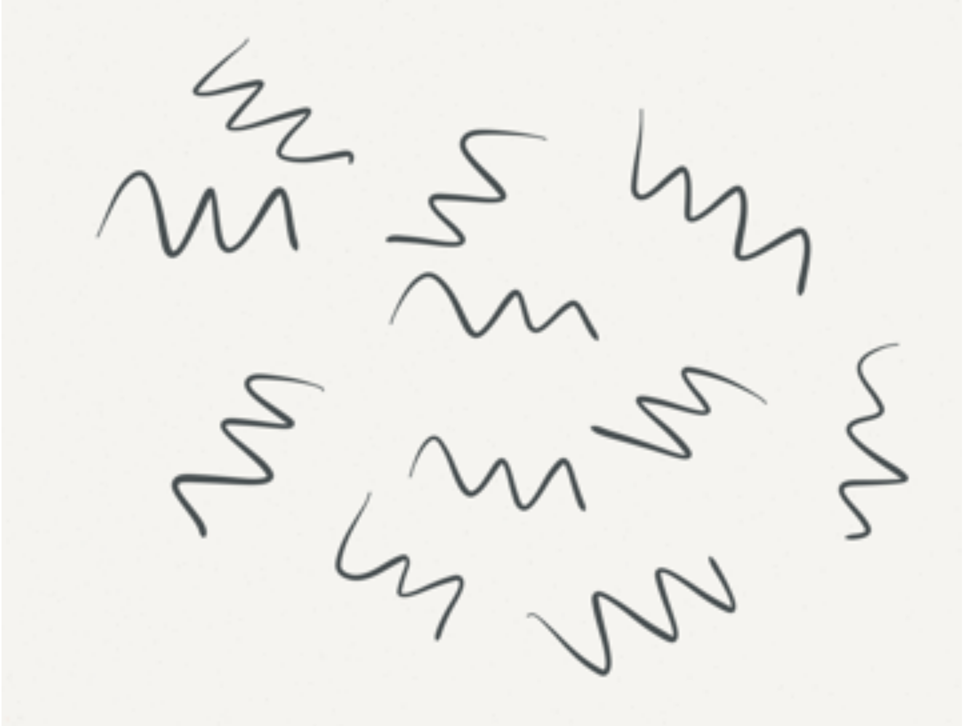


like a WIMP

instead of…



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

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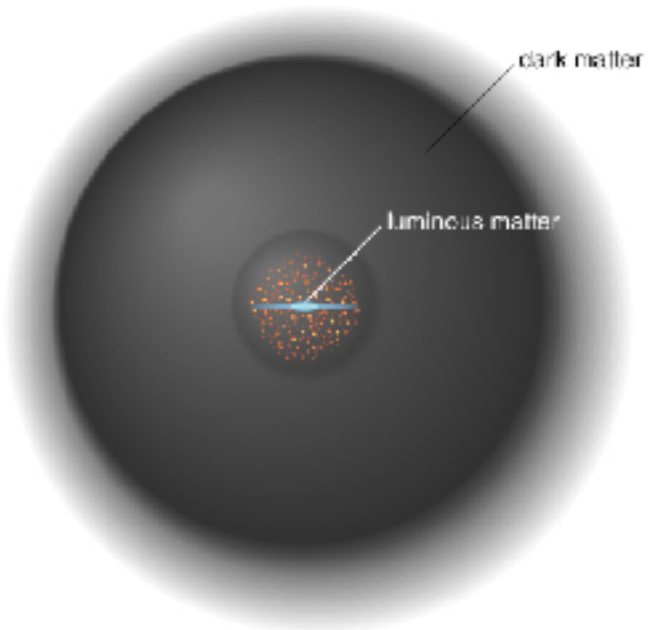
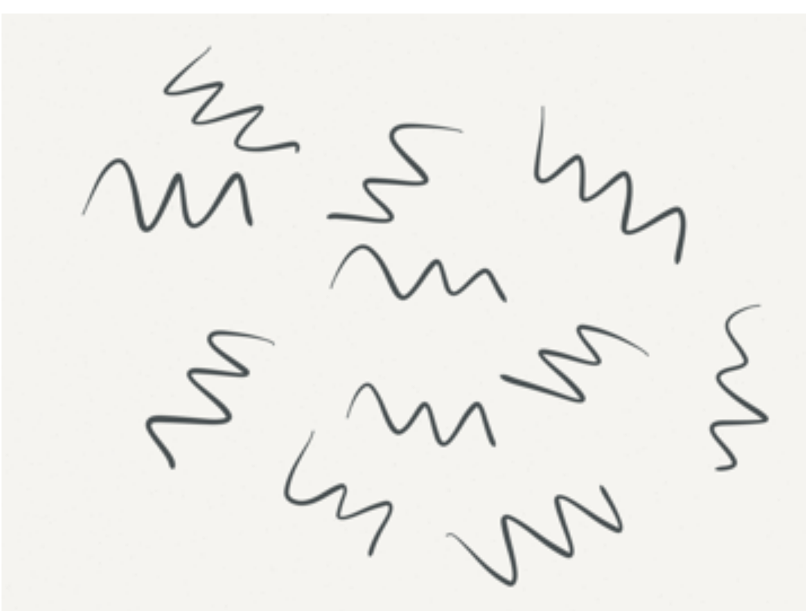
Dark Matter Particles in the Galaxy





Decreasing DM Mass

What If DM Is a Boson and Very Light?

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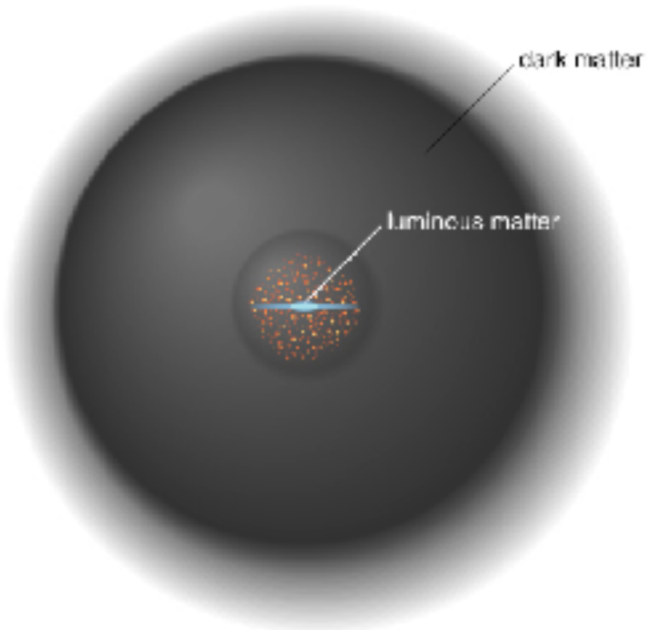

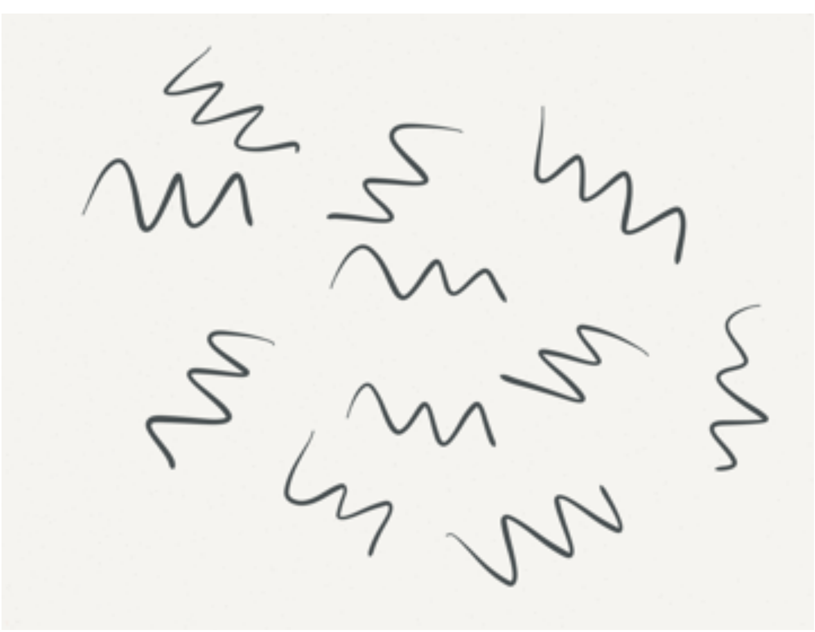

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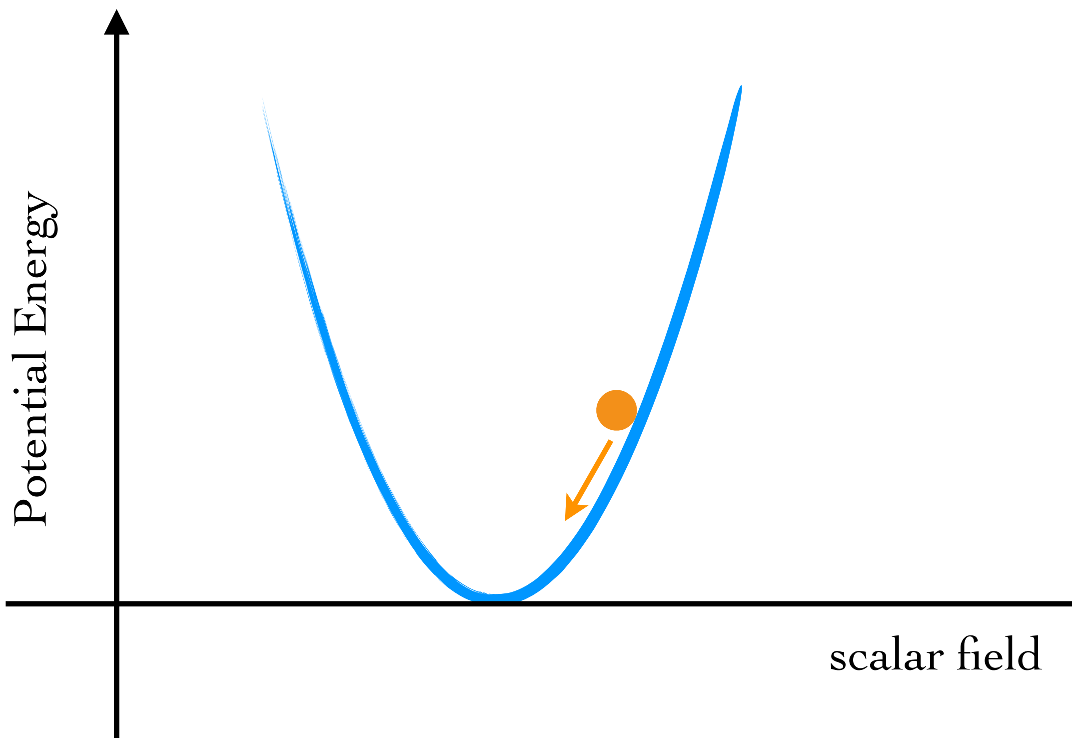


Equivalent to a Scalar Wave

Going from DM particles to a DM "wave"

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

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

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

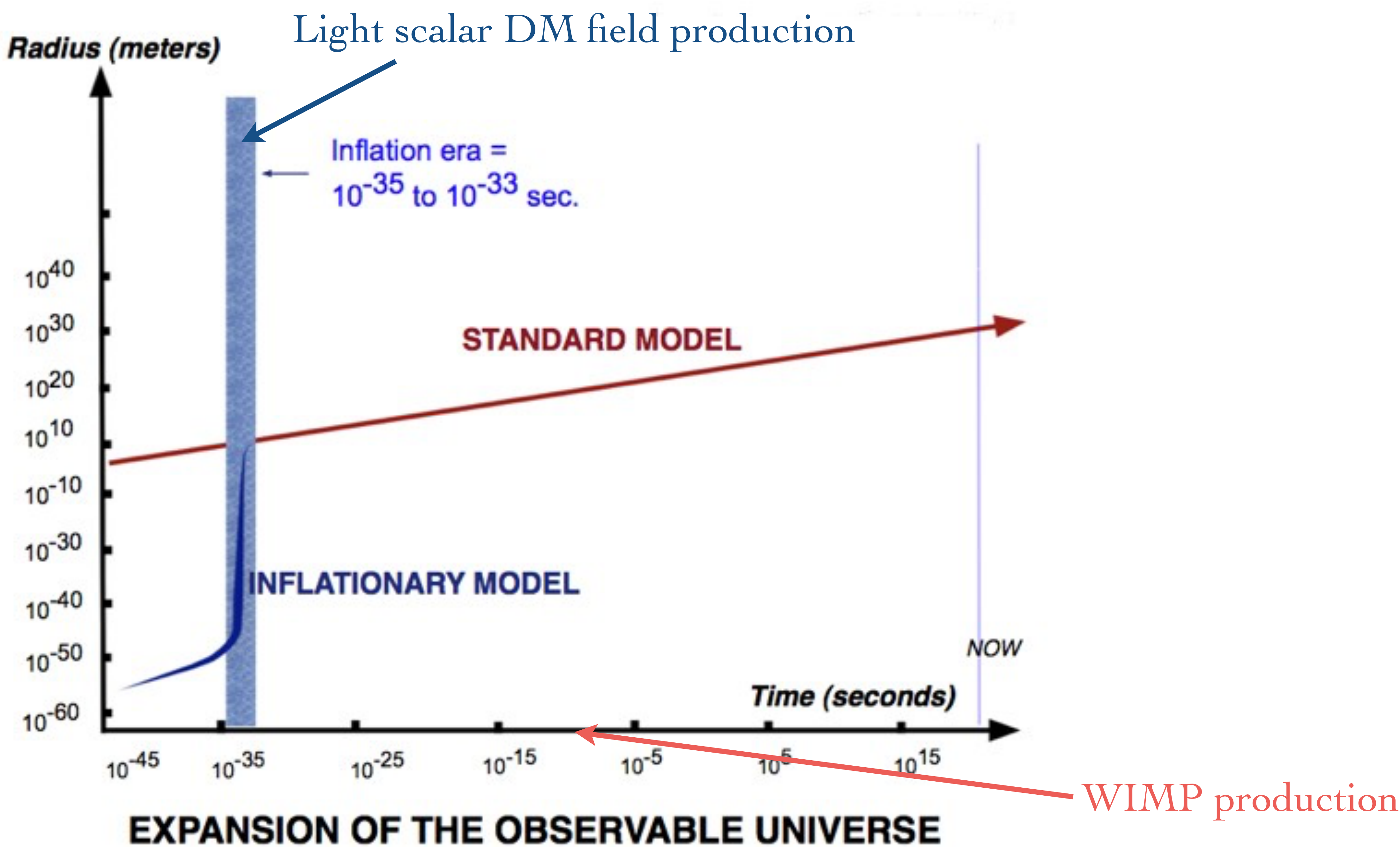
$$\omega_{DM} \approx \frac{m_{DM} c^2}{\hbar}$$

and finite coherence

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

Scalar DM field Production Mechanism

- The "misalignment mechanism" during inflation

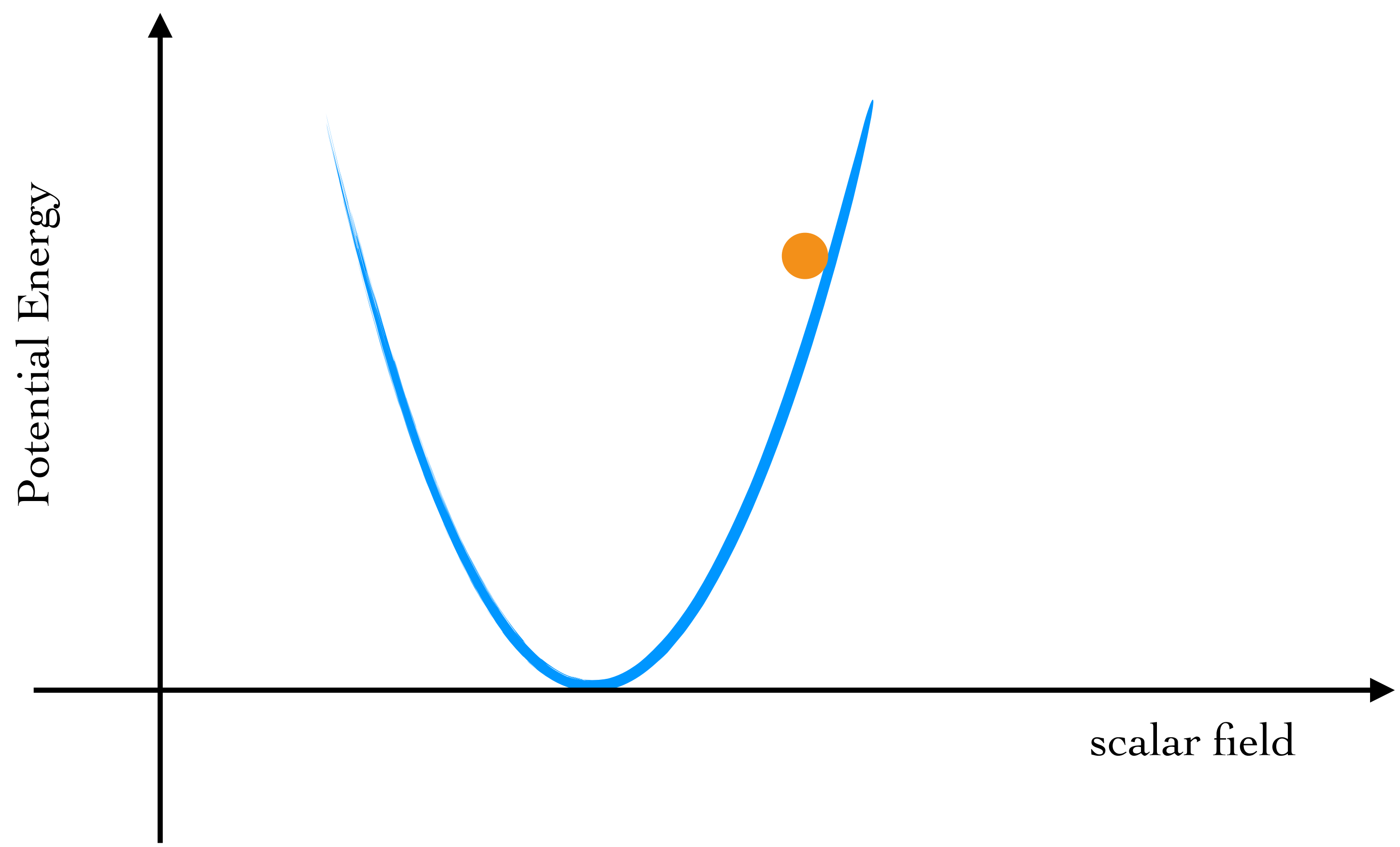


Light Scalar Dark Matter

- 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

*The story changes slightly if DM is a dark photon

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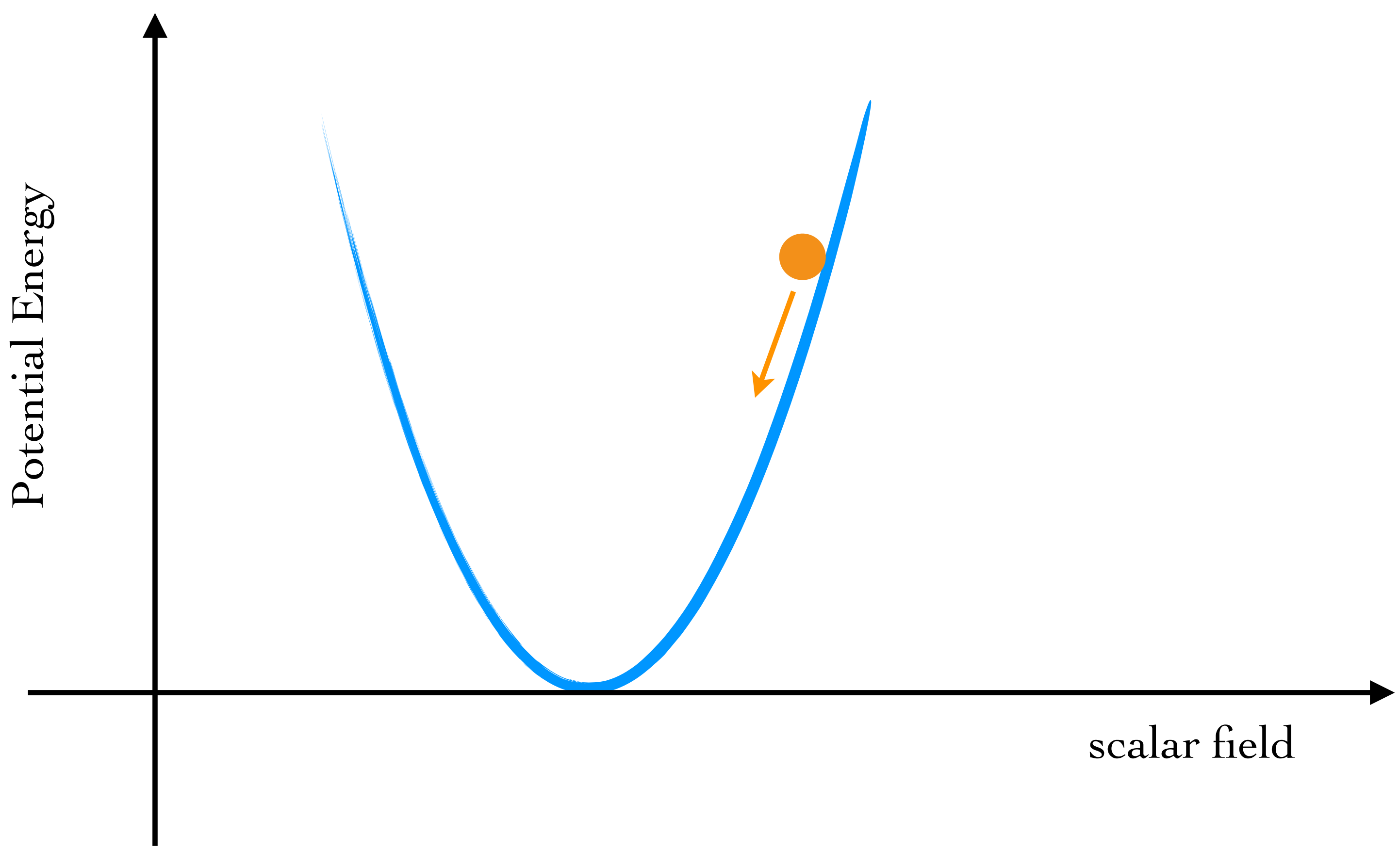


Frozen when:
Hubble > m_ϕ

Oscillates when:
Hubble < m_ϕ

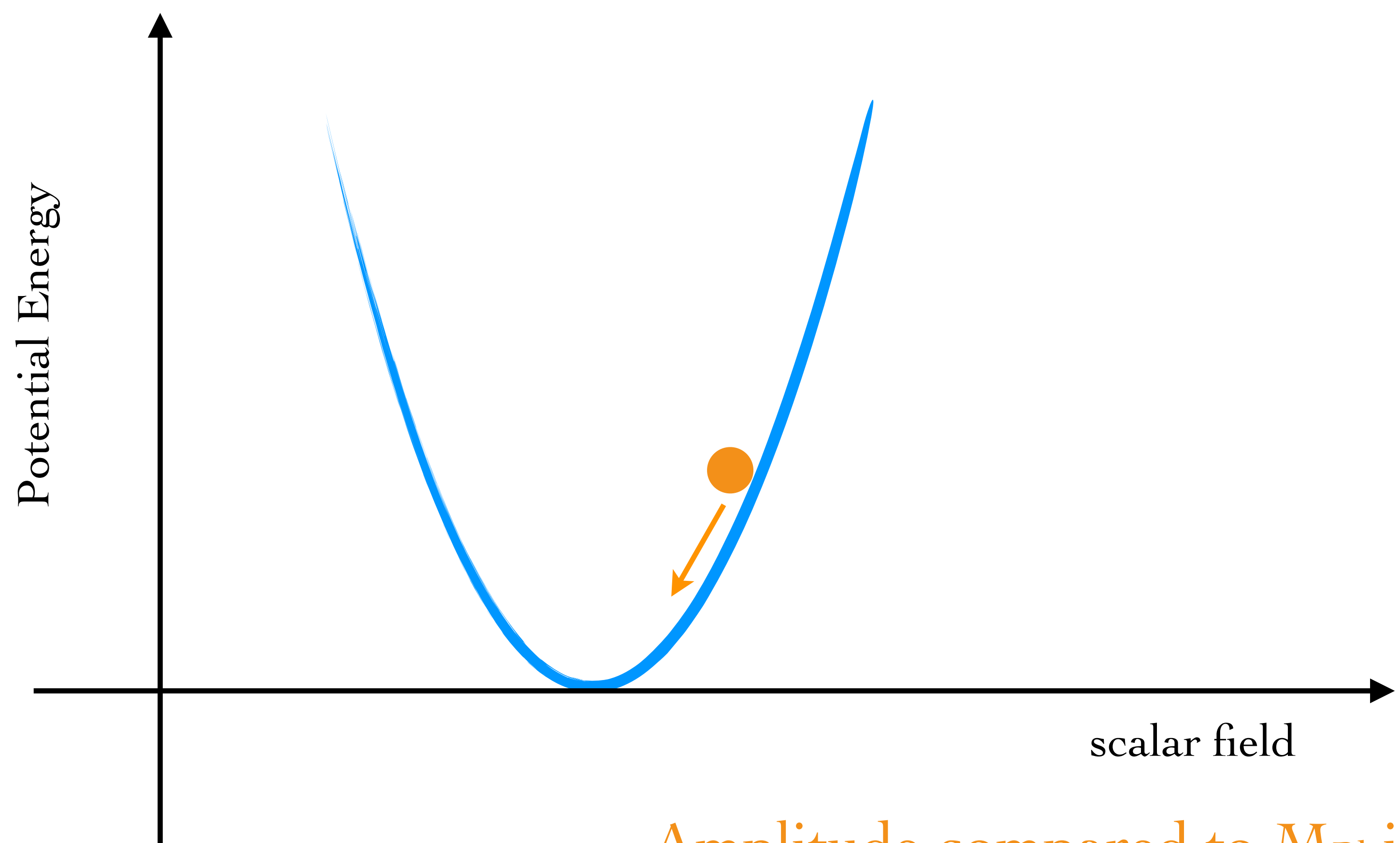
ρ_ϕ scales as a^{-3}
just like Dark Matter

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:

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

Moduli Dark Matter

- Moduli set values of measured fundamental constants

- Examples of couplings

$$d_{m_e} \frac{\phi}{M_{Pl}} m_e e\bar{e}$$

Fundamental constants are not really constants

Oscillating Fundamental Constants

From the local oscillation of Dark Matter

Ex. for the electron mass:

$$d_{m_e} \frac{\phi}{M_{Pl}} m_e e \bar{e}$$

$$\frac{\delta m_e}{m_e} \approx \frac{d_{m_e} \phi_o}{M_{Pl}} \cos(m_\phi t)$$

$$= 6 \times 10^{-13} \cos(m_\phi t) \frac{10^{-18}\ \text{eV}}{m_\phi} \frac{d_{m_e}}{1}$$

Fractional variation set by square root of DM abundance

Need an extremely sensitive probe

Other properties of light scalars

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

$$F \sim \frac{(d_i Q_i)^2}{4\pi M_{Pl}^2} \frac{M_1 M_2}{r^2} e^{-m_\phi r}$$

  - Generates Equivalence Principle violation

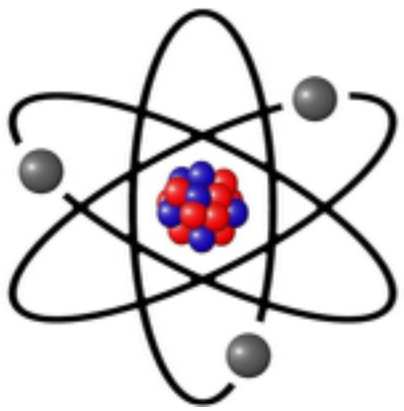
Light Scalar Dark Matter Detection

- Detecting Dark Matter with Atomic Clocks
- Detecting Dark Matter with Resonant-Mass Detectors
- ARIADNE
- Black Hole Superradiance

Keeping the DM time with Atomic Clocks

with Junwu Huang
and Ken Van Tilburg (2014)

Oscillating Atomic and Nuclear Energy Splittings



- 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

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

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

Oscillating Atomic and Nuclear Energy Splittings

- Optical Splittings

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

- 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

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?

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

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}

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

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

Number of times the observation is repeated

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

How do you take the measurements?

- Observe two clocks every $\tau_{cycling}$ to remove systematics

- Calculate ratio of frequencies which depends on Dark Matter

- Take Fourier transform to look for oscillations with period longer than $\tau_{cycling}$

Atomic Clock DM searches are broadband searches

What type of comparisons can we do?

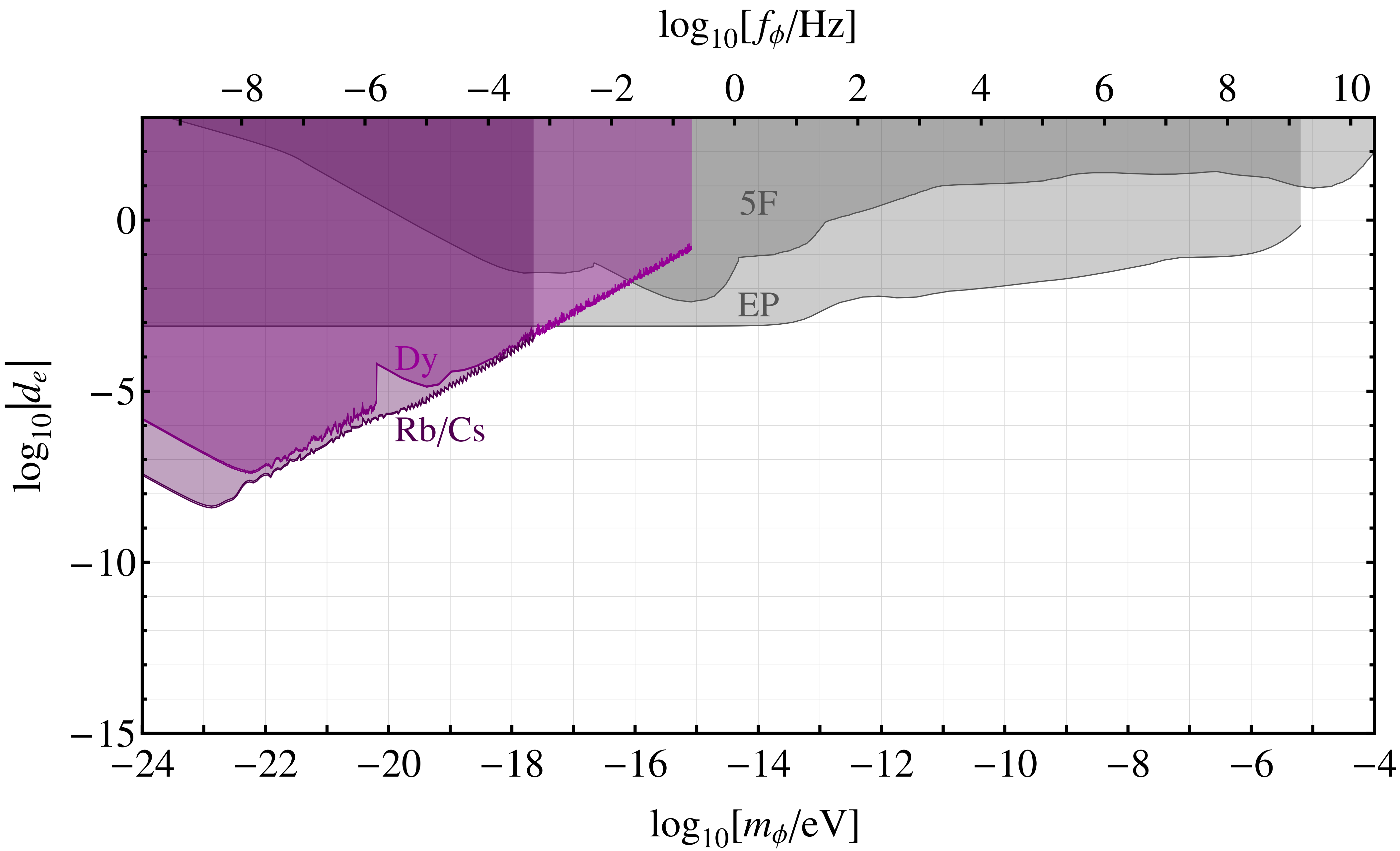
- Hyperfine to Optical transitions
  - Sensitive to m_e, m_q, and α_s (less to α_{EM})
- Optical to Optical transitions
  - Sensitive to α_{EM}
- Nuclear to Optical transitions
  - Sensitive to m_e, α_{EM}, m_q, and α_s

The Dy isotope and Rb/Cs Clock Comparison

Ken Van Tilburg
and the Budker group (2015)

Hees et. al (2016)

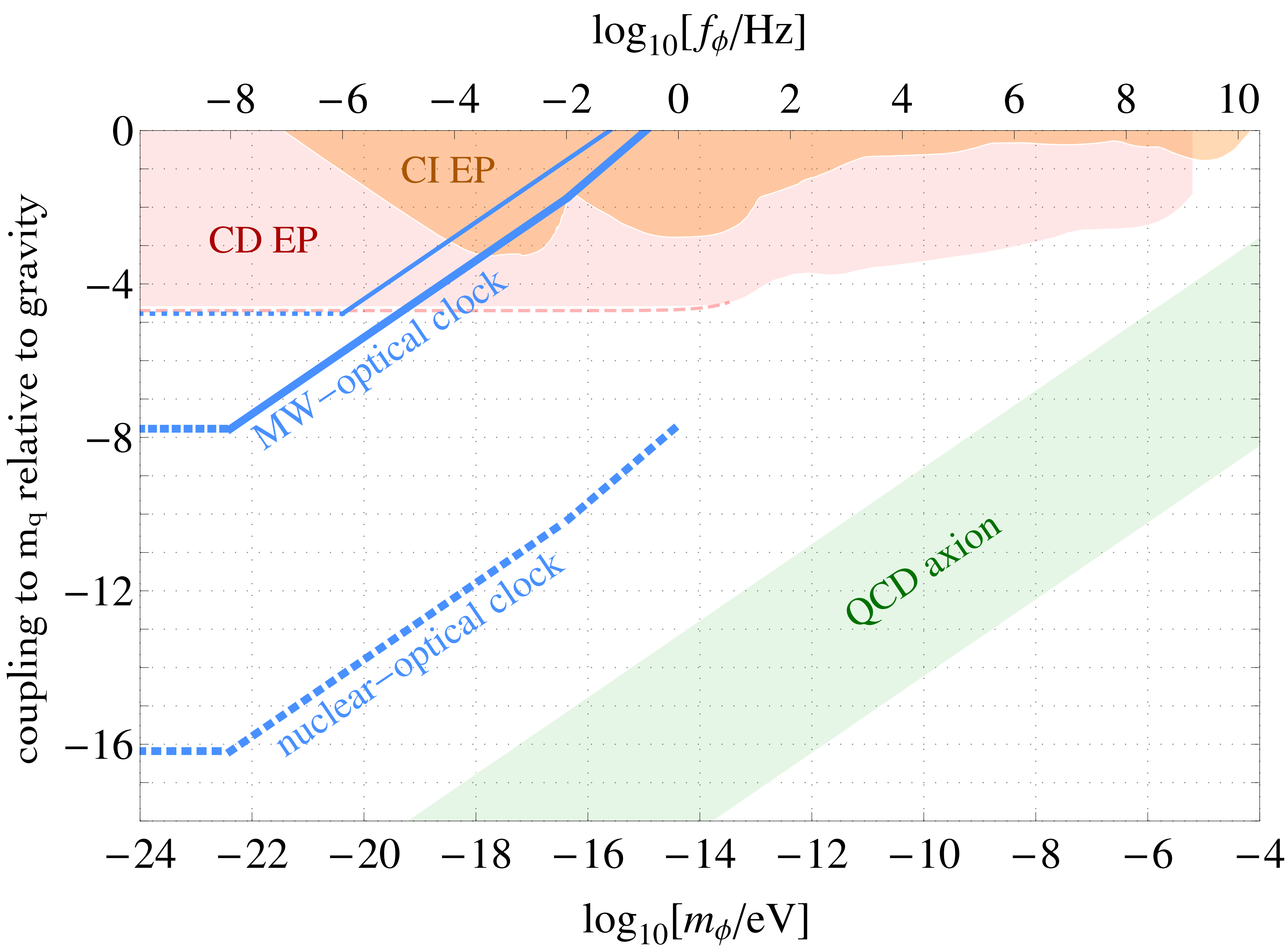
sensitivity to α_{EM} variations



Analysis performed with existing data

Nuclear to Optical Clock Comparison

Future Sensitivity of a ^{229}Th clock with $10^{-15}/\mathrm{Hz}^{-1/2}$ noise



The Sound of Dark Matter

with Ken Van Tilburg
and Savas Dimopoulos (2015)

Oscillating interatomic distances

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

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

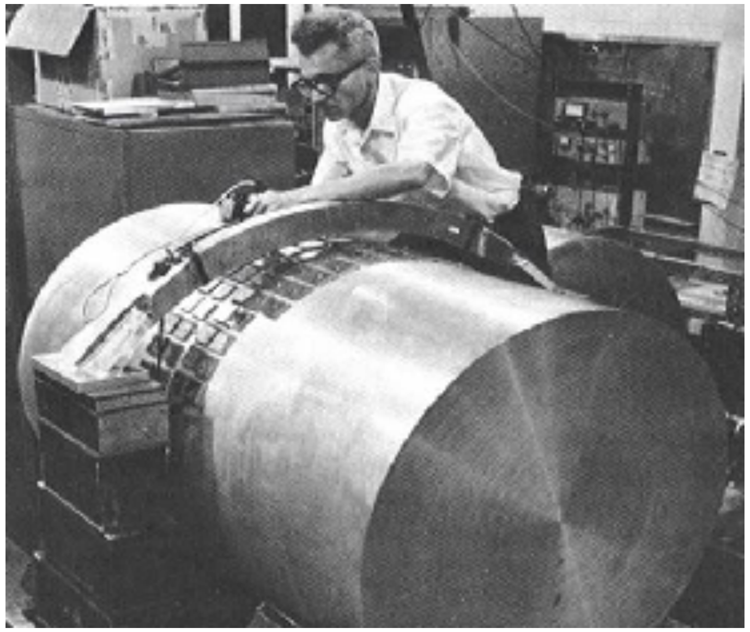
- The size of solids changes with DM
  - $L \sim N\, (\alpha\, m_e)^{-1}$

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

Need macroscopic objects to get a detectable signal

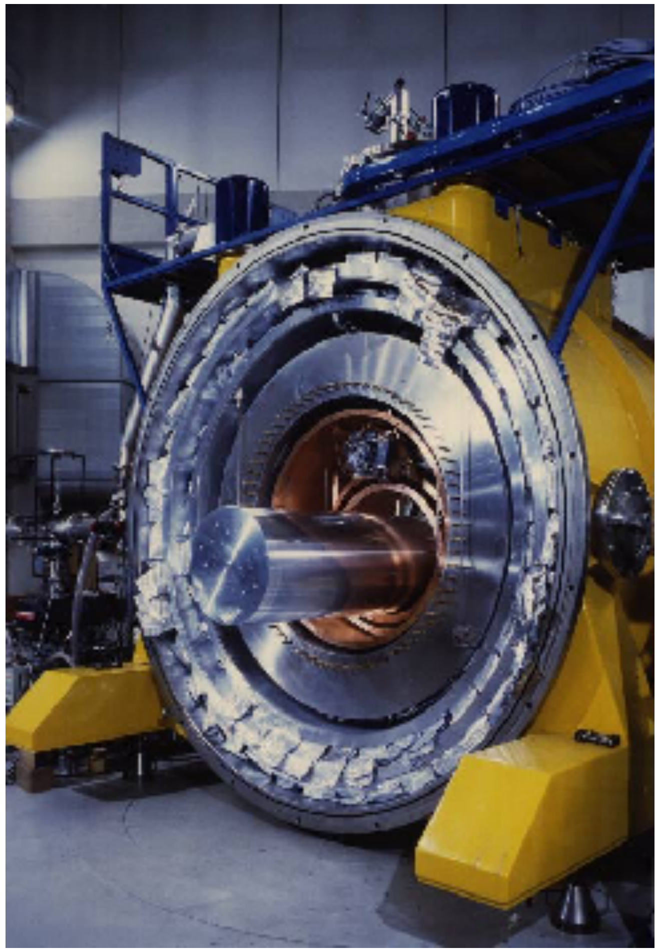
Resonant-Mass Detectors

- In the 1960's: The Weber Bar

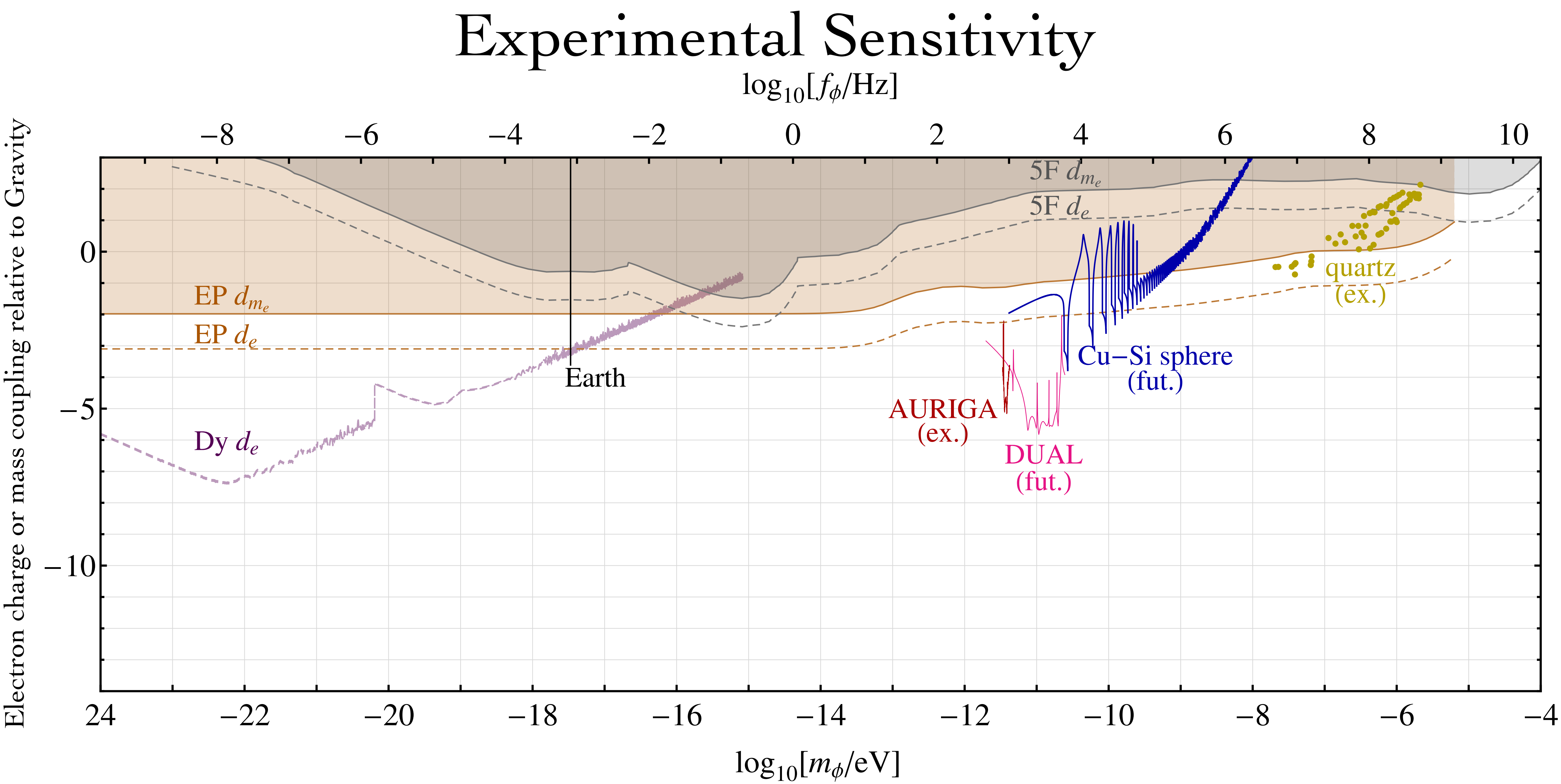


Strain sensitivity $h \sim 10^{-17}$

- Today: AURIGA, NAUTILUS, MiniGrail



Strain sensitivity $h \sim 10^{-23}$

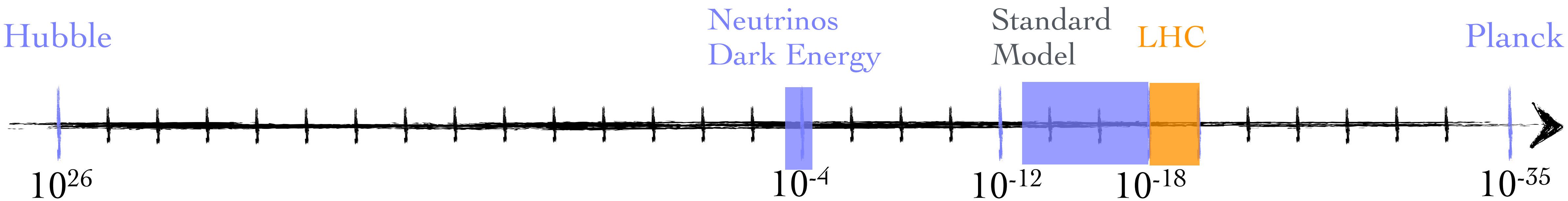

Experimental Sensitivity
log10[fϕ/Hz]
−8
−6
−4
−2
0
2
4
6
8
10
5F dme
5F de
EP dme
EP de
Earth
Dy de
quartz
(ex.)
Cu−Si sphere
(fut.)
AURIGA
(ex.)
DUAL
(fut.)
0
−5
−10
Electron charge or mass coupling relative to Gravity
24
−22
−20
−18
−16
−14
−12
−10
−8
−6
−4
log10[mϕ/eV]

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."

Length Scales in the Universe



Scale in m

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

Back up

ARIADNE:

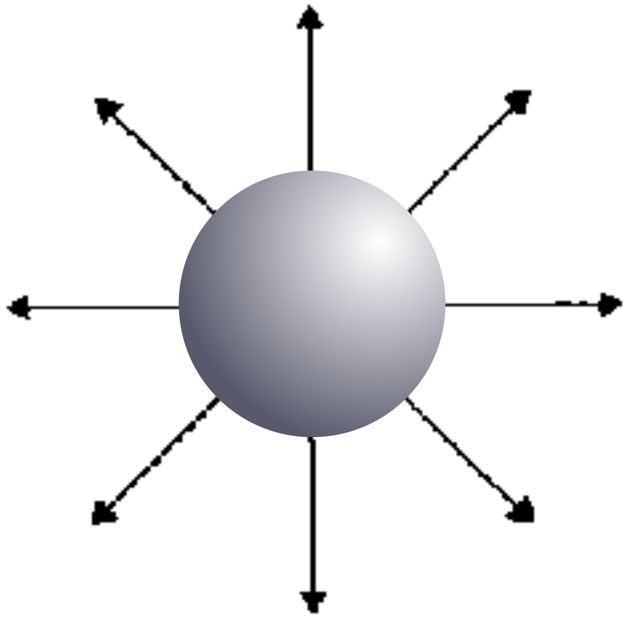
Axion Resonant InterAction DetectioN Experiment

with Andrew Geraci (2014)

and A. Kapitulnik, Chen-Yu Liu,J. Long, Y. Semertzidis, M. Snow (to be built)

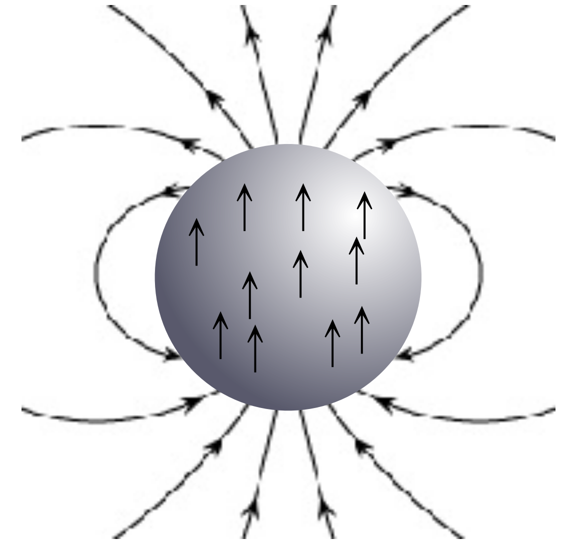
Short Range Interactions of the Axion

Moody and Wilczek (1984)



Monopole Interaction

Mass with N nucleons



Dipole Interaction

N spins

$$a(r) \approx \frac{g_s N}{4\pi} \frac{e^{-m_a r}}{r}$$

$$a(r) \approx \frac{g_p N}{4\pi m_f} \frac{e^{-m_a r}}{r^2} (\vec{\sigma} \cdot \hat{r})$$

$$\boxed{6 \times 10^{-27} \left(\frac{10^9 \; GeV}{f_a} \right)} \lesssim g_s \lesssim \boxed{10^{-21} \left(\frac{10^9 \; GeV}{f_a} \right)}$$

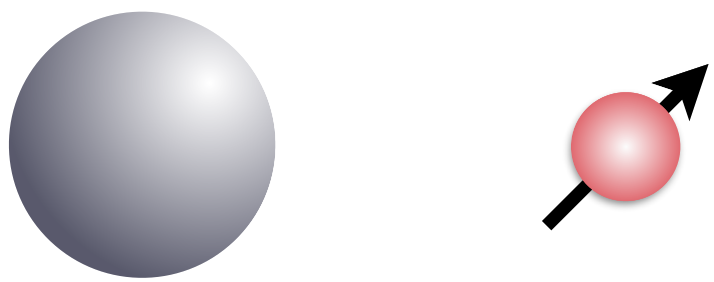
From CP violation in the Standard Model

From CP violation allowed by experiment

$$g_p \approx 10^{-9} \left(\frac{m_f}{1 \text{ GeV}} \right) \left(\frac{10^9 \text{ GeV}}{f_a} \right)$$

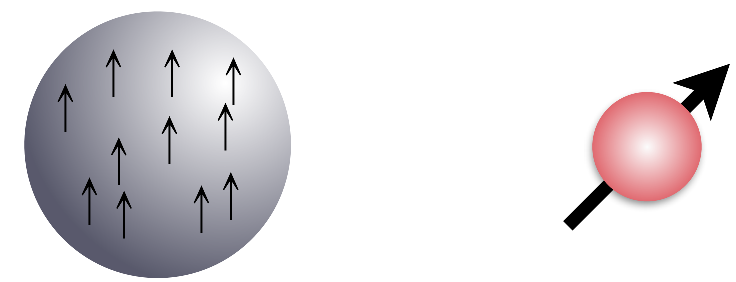
Short Range Interactions of the Axion

Monopole-Dipole Interaction



Mass with N nucleons   Spin

Dipole-Dipole Interaction



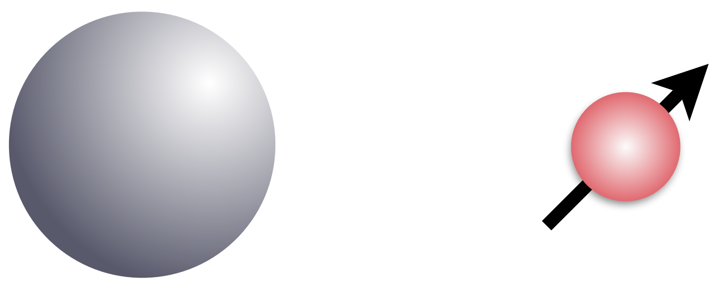
N spins   Spin

Interaction energy:

$$\frac{g_p \vec{\nabla} a}{m_f} \cdot \vec{\sigma}$$

Short Range Interactions of the Axion

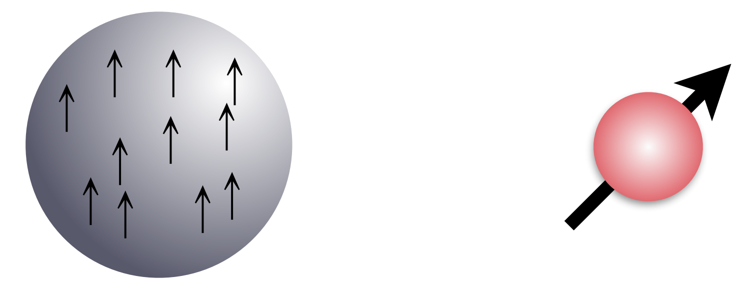
Monopole-Dipole Interaction



Mass with N nucleons

Spin

Dipole-Dipole Interaction



N spins

Spin

Interaction energy:

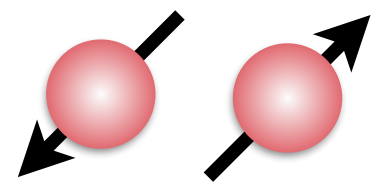
$$\frac{g_p \vec{\nabla} a}{m_f} \cdot \vec{\sigma} \qquad \frac{\vec{\nabla} a}{\mu_f f_a} \cdot \vec{\mu_f} \equiv \vec{B}_{eff} \cdot \vec{\mu_f}$$

Just like a magnetic field

- B_{eff} is 2000 times bigger for nucleons than it is for electrons
- B_{eff} cannot be screened

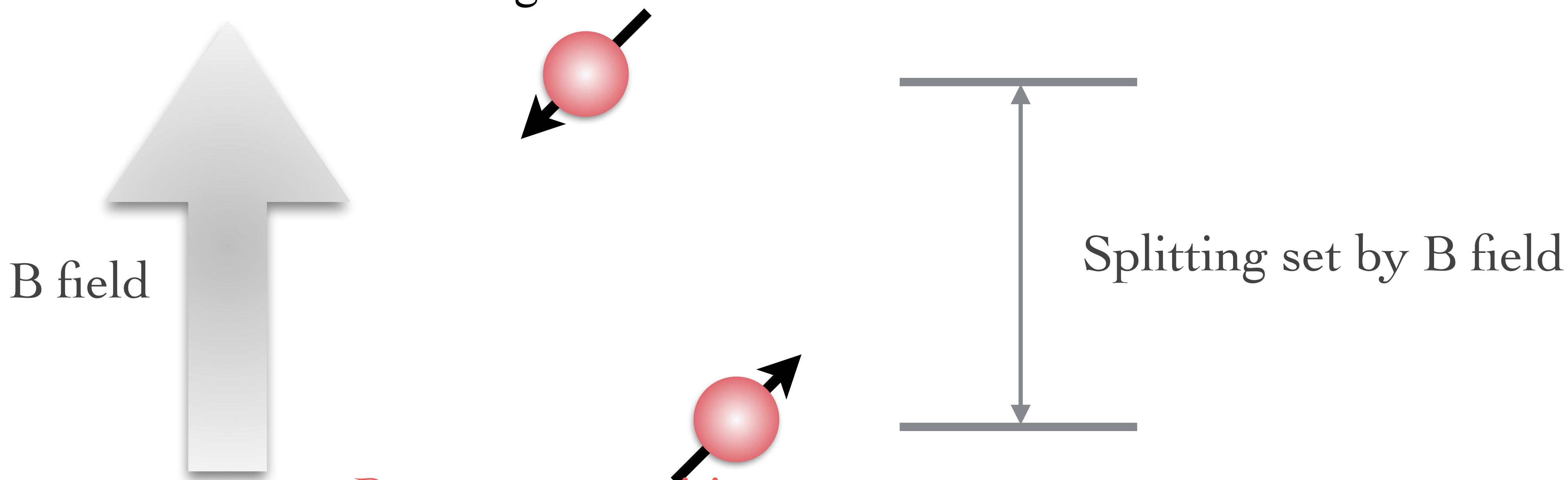
Precision Magnetometry

Nuclear Magnetic Resonance



Precision Magnetometry

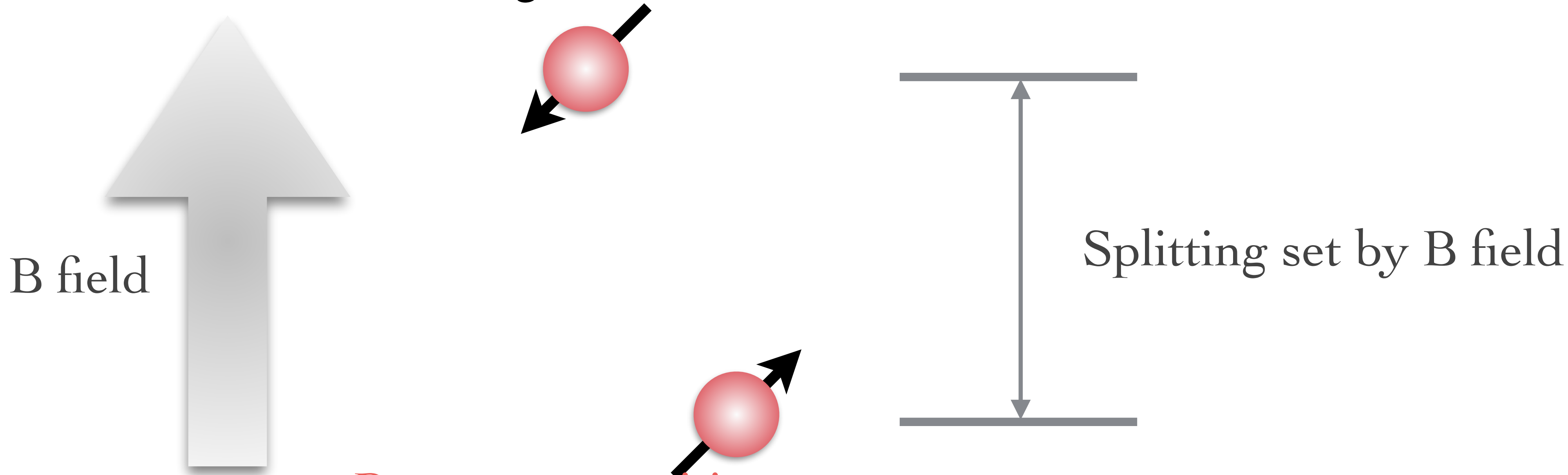
Nuclear Magnetic Resonance



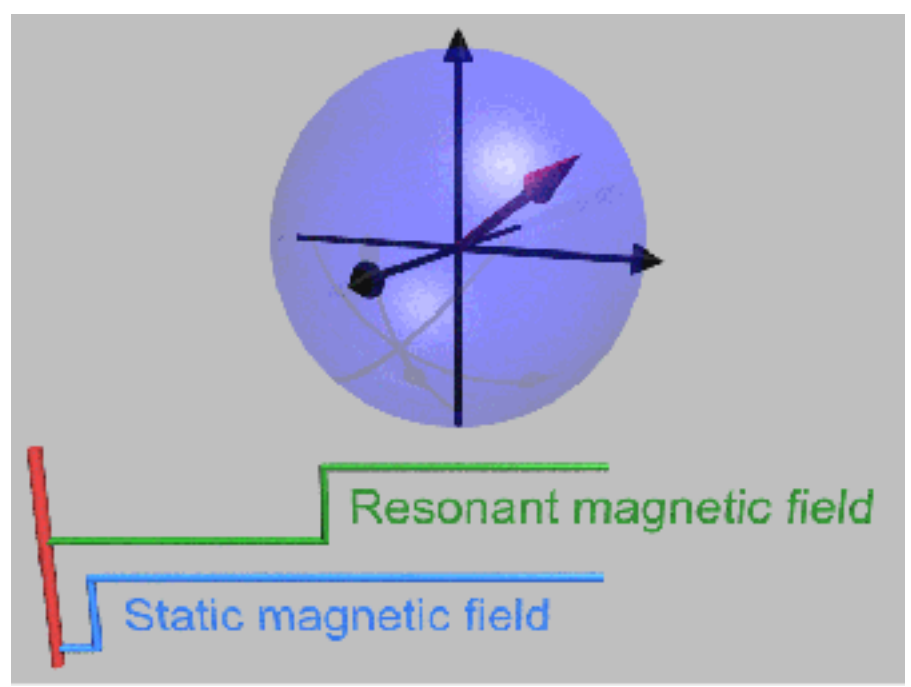
Resonant transition:
Perturbation at the splitting frequency of the spins

Precision Magnetometry

Nuclear Magnetic Resonance



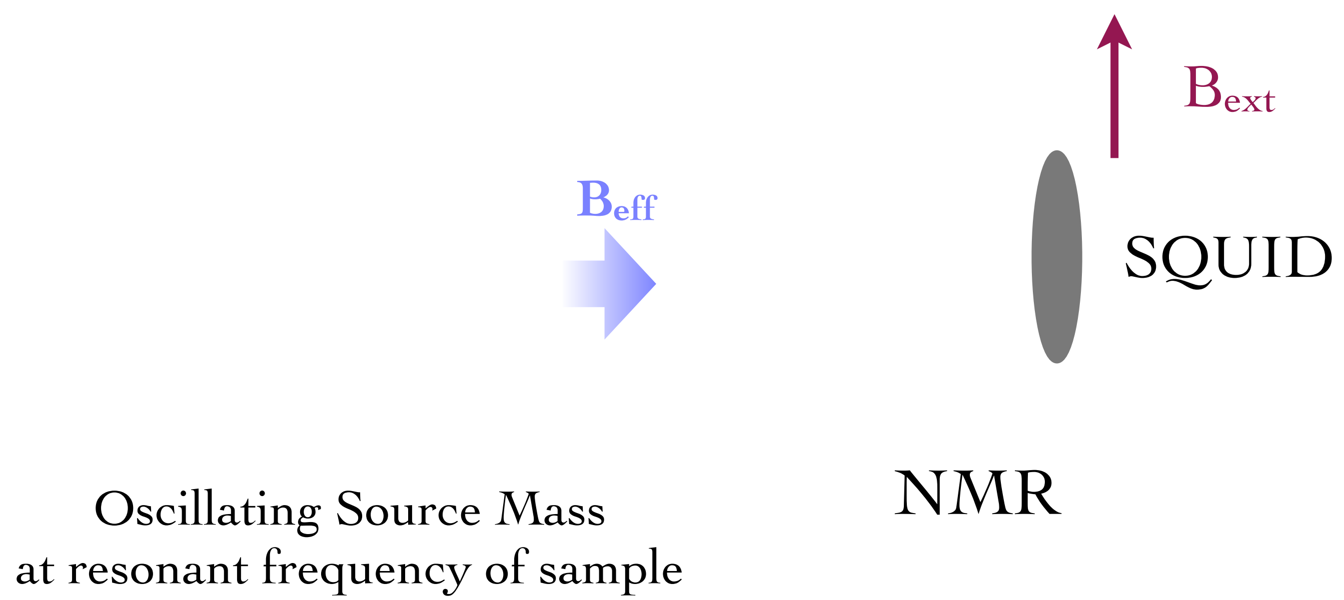
Resonant transition:
Perturbation at the splitting frequency of the spins



In the classical picture: Spins precessing around the perturbing magnetic field

Detection Strategy

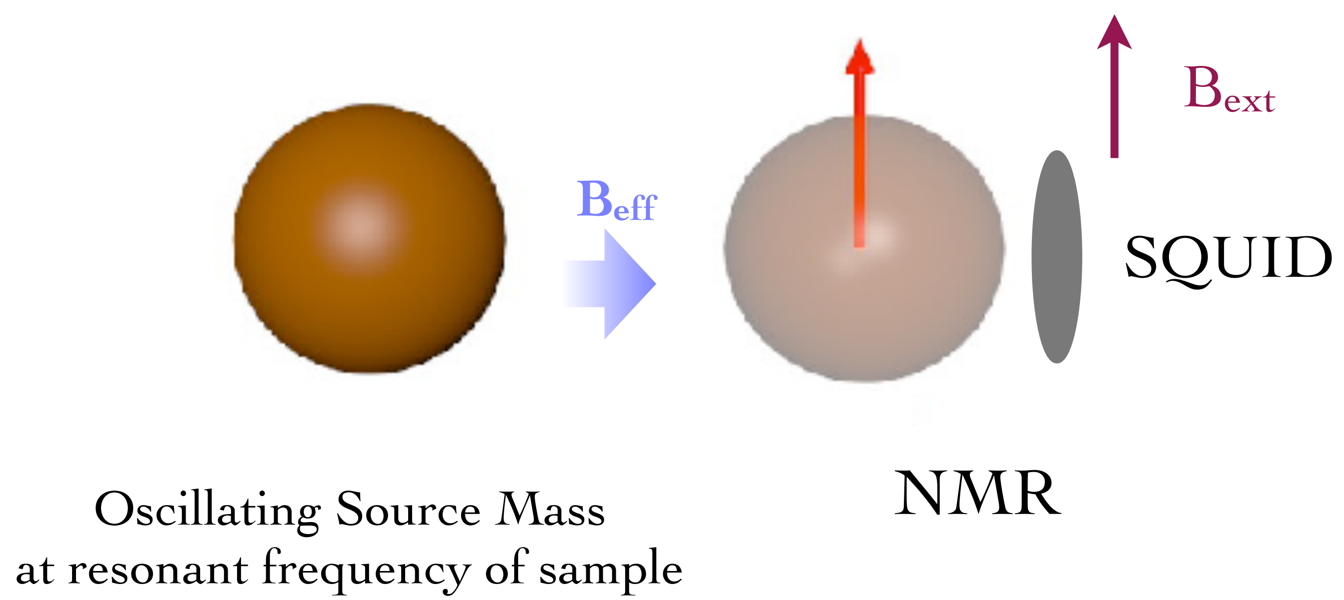
Just like a magnetic field



Signal grows with polarized spin density n_{NMR} and coherence time of NMR sample T_2

Detection Strategy

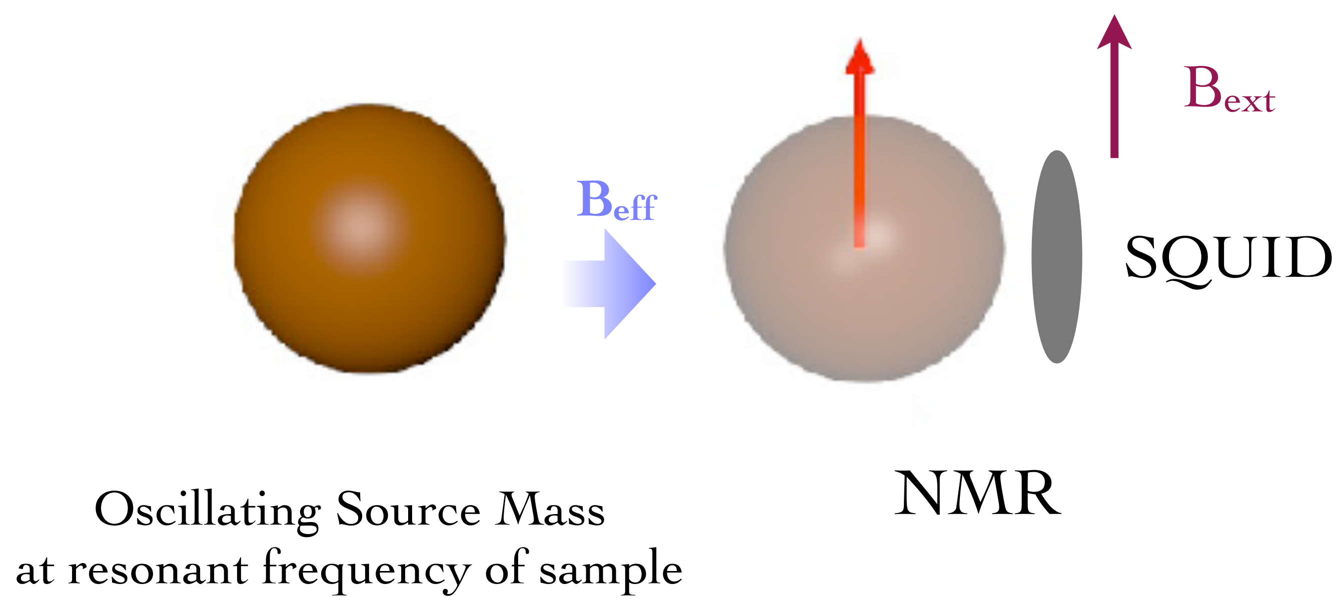
Just like a magnetic field



Signal grows with polarized spin density n_{NMR} and coherence time of NMR sample T_2

Detection Strategy

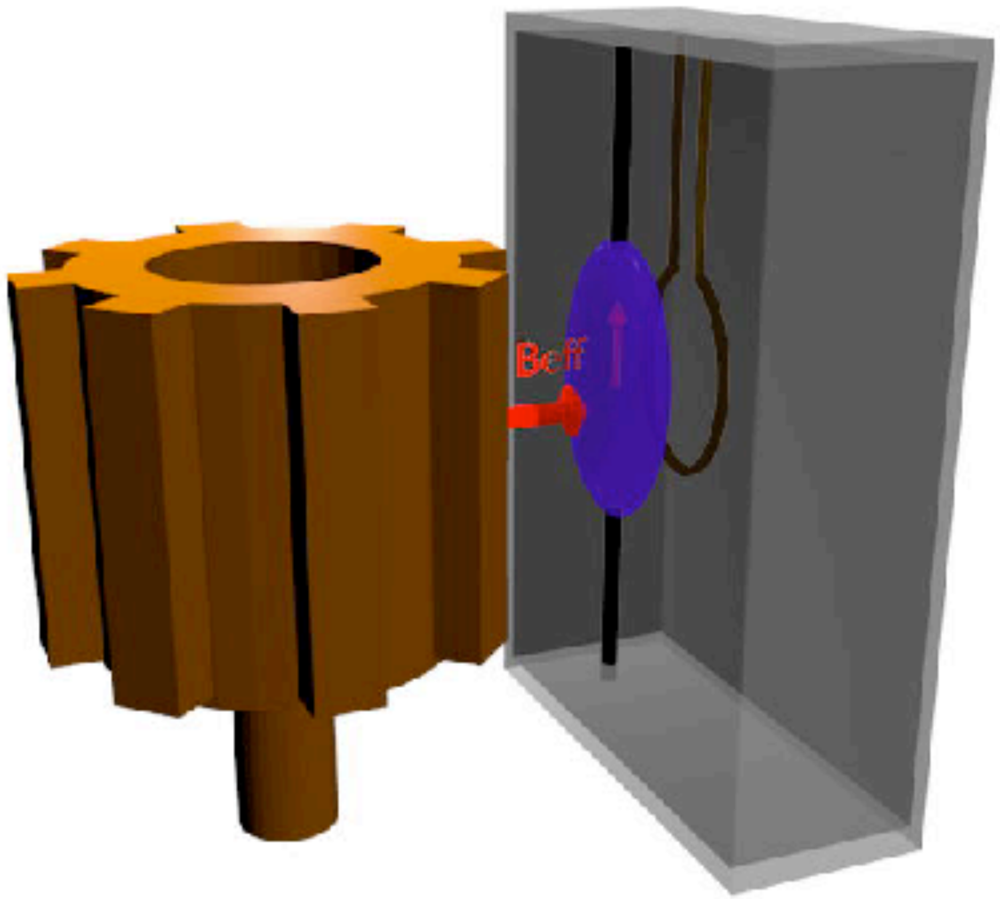
Just like a magnetic field



Signal grows with polarized spin density n_{NMR} and coherence time of NMR sample T_2

ARIADNE:

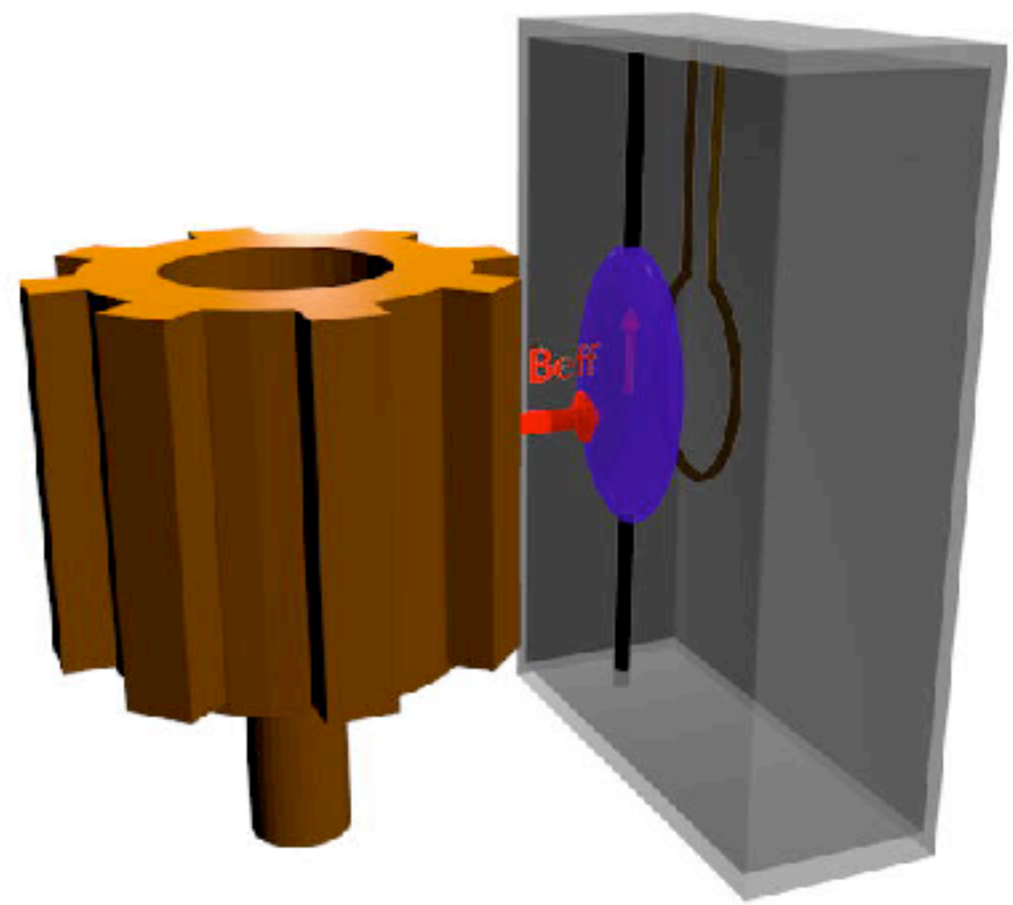
Axion Resonant InterAction DetectioN Experiment



He-3 NMR sample with
T_2 up to ~1000 sec

ARIADNE:

Axion Resonant InterAction DetectioN Experiment



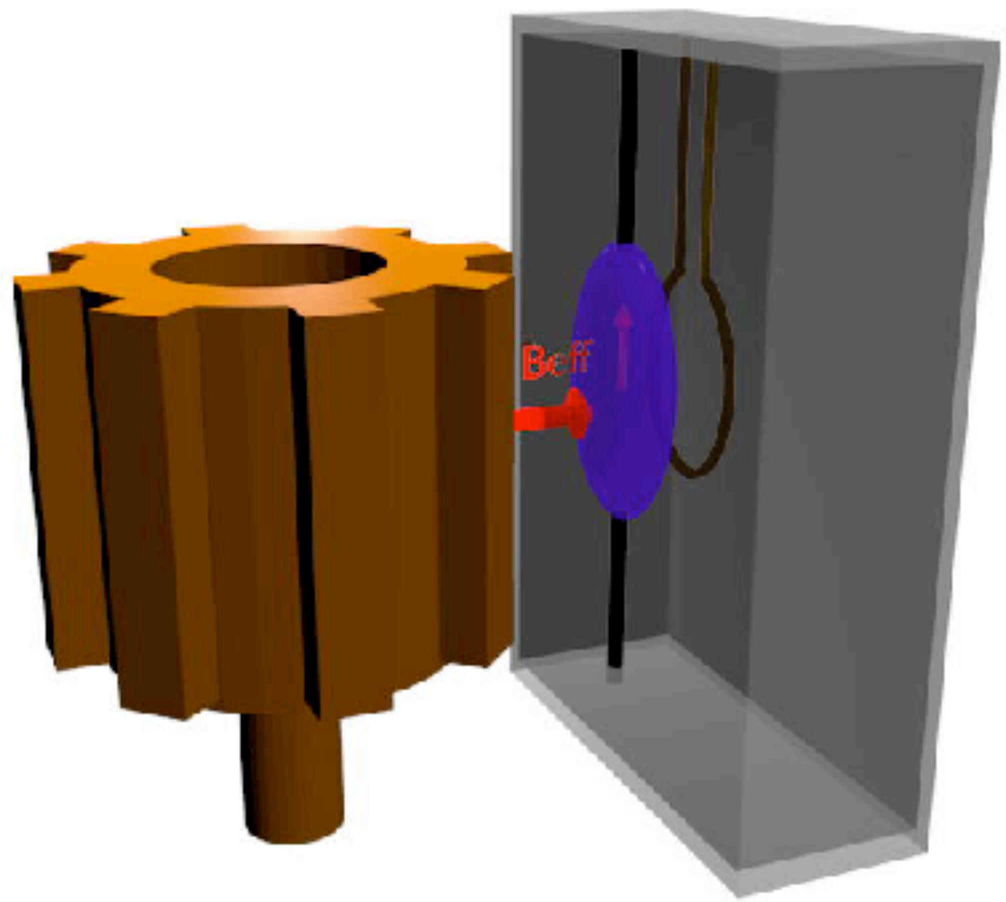
He-3 NMR sample with T_2 up to ~1000 sec

$$B_{\text{min}} \approx p^{-1}\sqrt{\frac{2\hbar b}{n_s \mu_{^3\text{He}} \gamma V T_2}} = 3 \times 10^{-19}\ \text{T} \times$$
$$\left(\frac{1}{p}\right)\sqrt{\left(\frac{b}{1\ \text{Hz}}\right)\left(\frac{1\ \text{mm}^3}{V}\right)\left(\frac{10^{21}\ \text{cm}^{-3}}{n_s}\right)\left(\frac{1000\ \text{s}}{T_2}\right)}$$

$B_{min} = 10^{-16}$ T/(Hz)$^{1/2}$
for SQUIDs

ARIADNE:

Axion Resonant InterAction DetectioN Experiment



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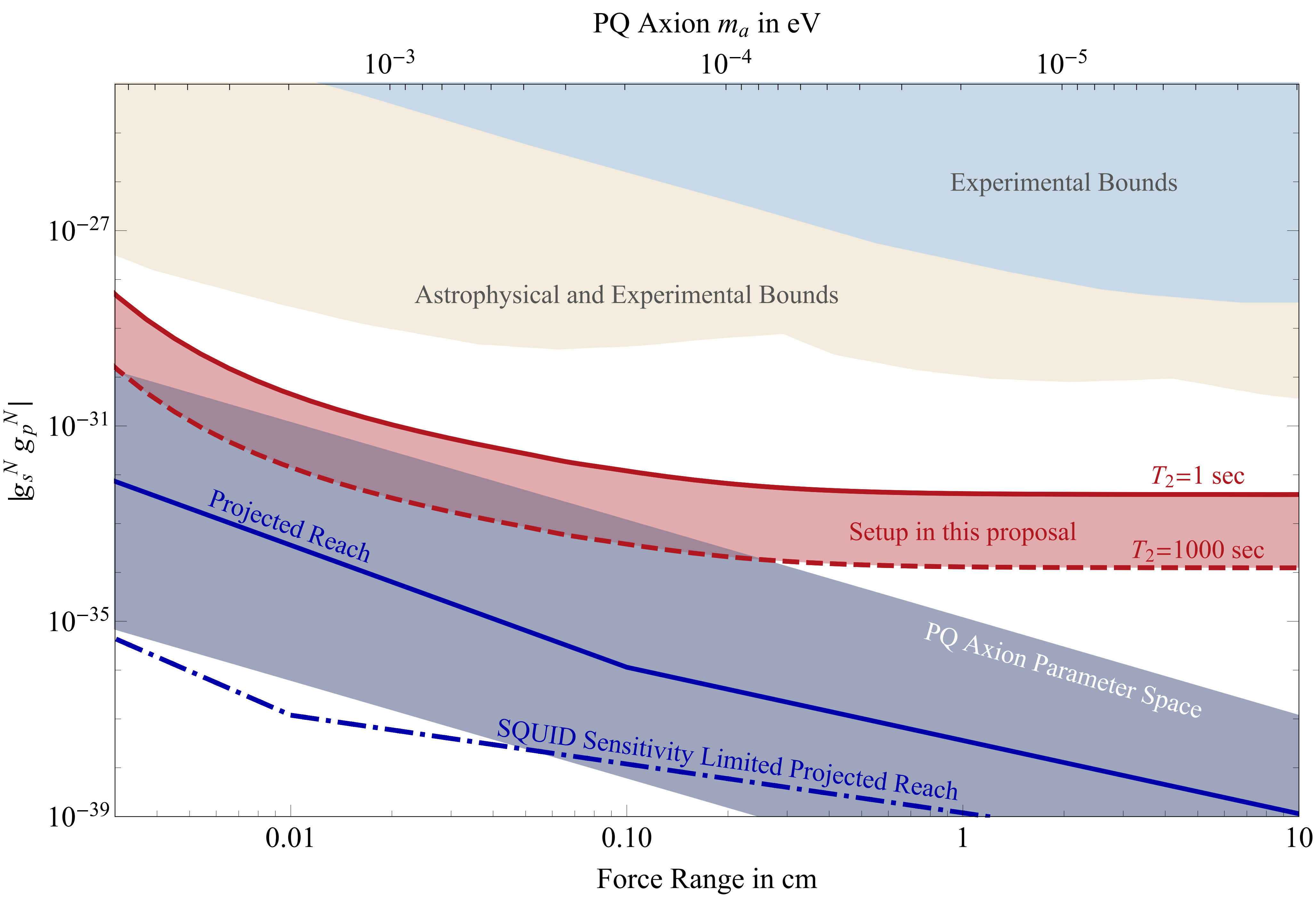
$B_{min} = 10^{-16}$ T/(Hz)$^{1/2}$ for SQUIDs

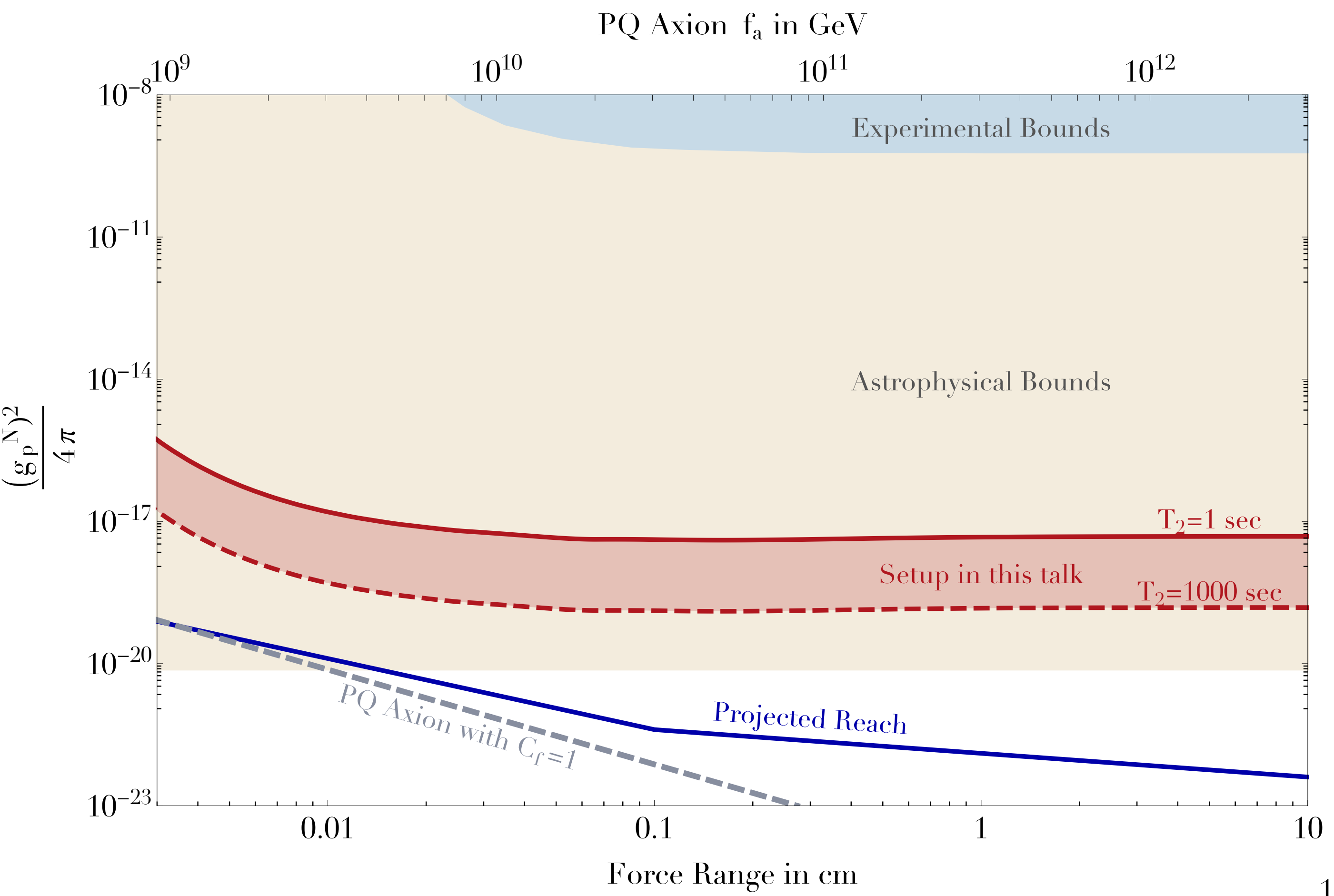
Monopole-Dipole Interaction Reach

Unpolarized Source Mass with 10^6 sec integration



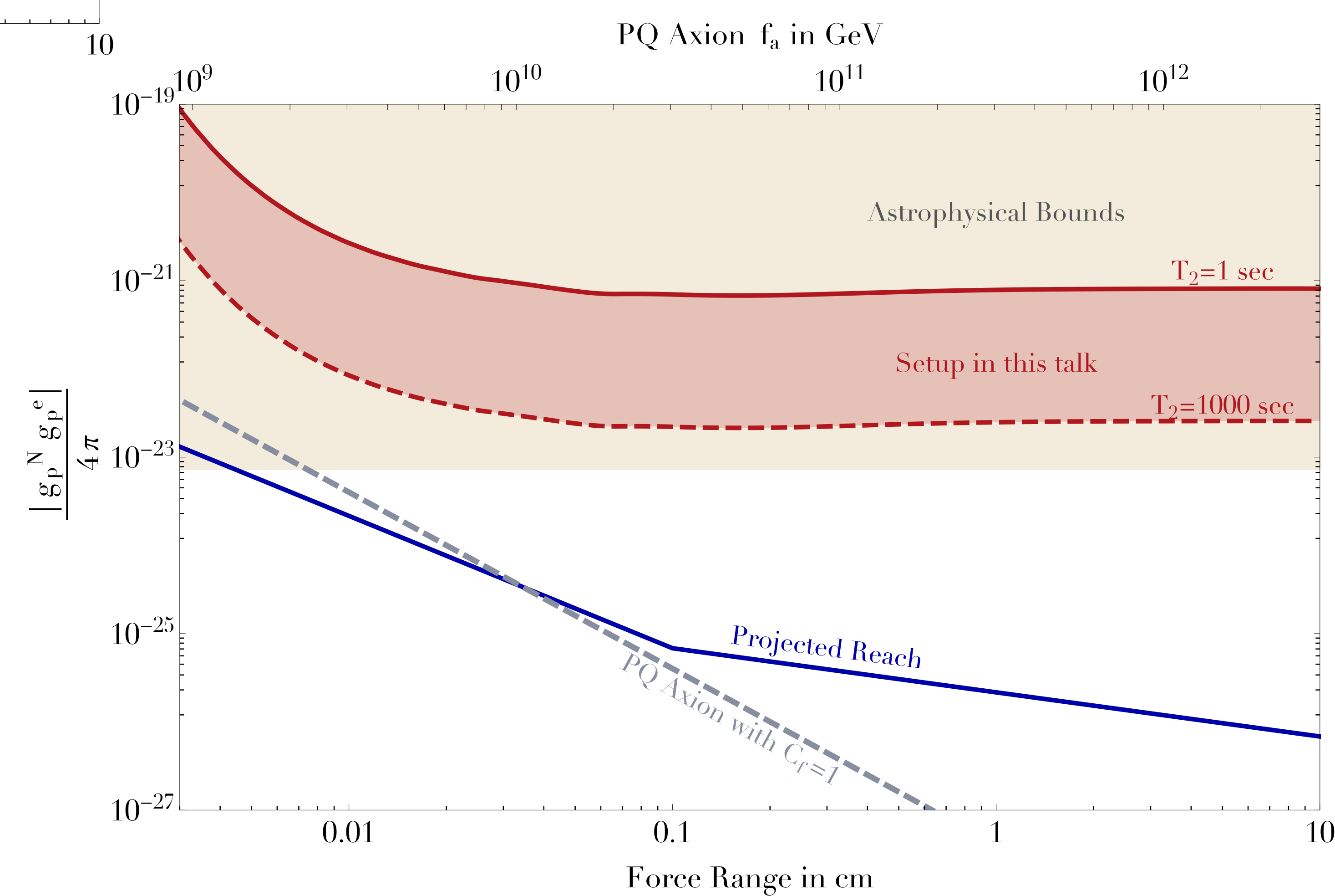
Projected Reach with increase of polarized spin density
and larger NMR sample volume

Dipole-Dipole Interaction Reach



Nuclear Spin Polarized Source Mass
with 10^6 sec integration

Electron Spin Polarized Source Mass
with 10^6 sec integration



Black Holes as Particle Detectors

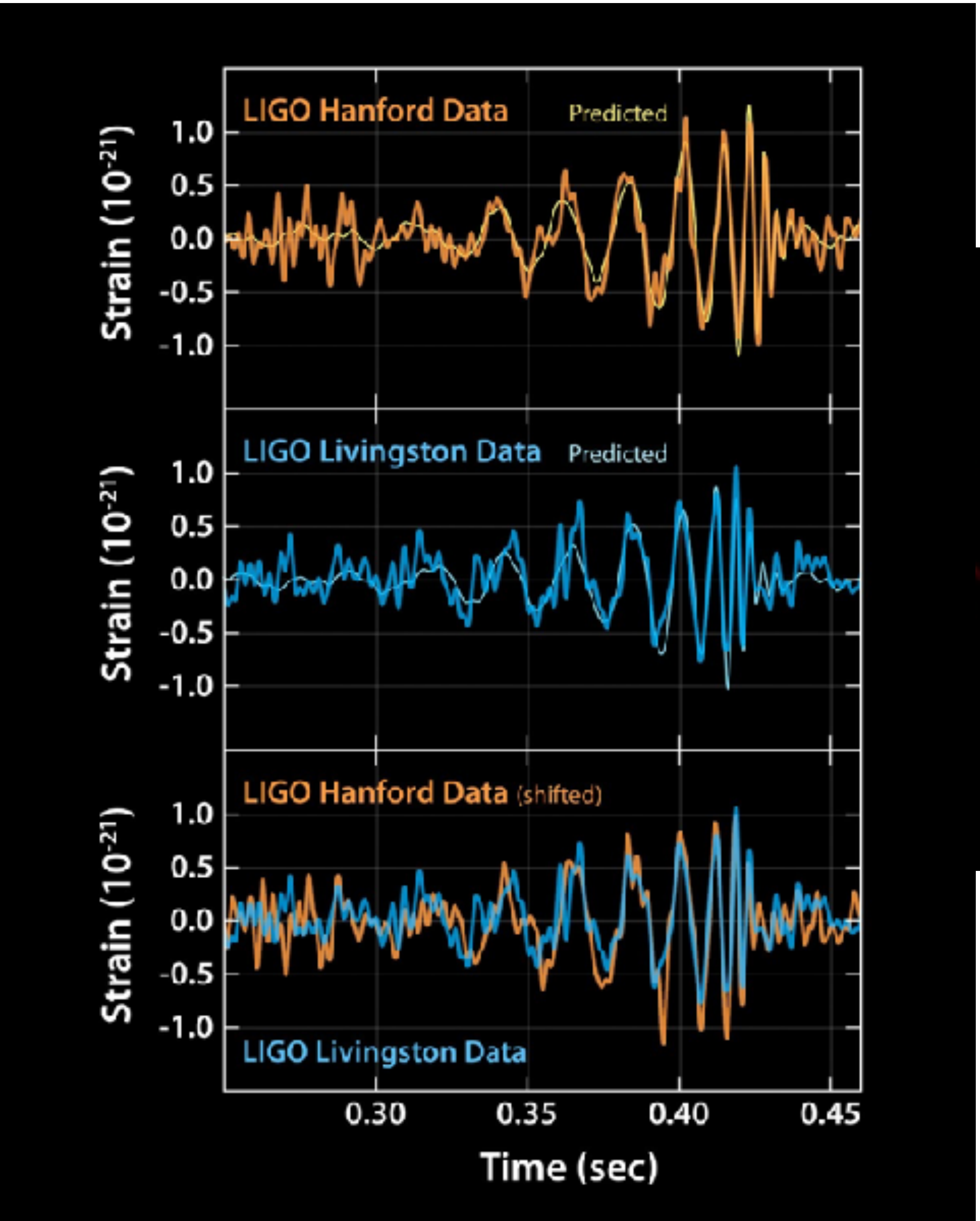
with
Dimopoulos, Dubovsky, Kaloper, March-Russell (2009)
Dubovsky(2010)
Baryakhtar, Huang (2014)
Baryakhtar, Dimopoulos, Dubovsky, Lasenby (2016)

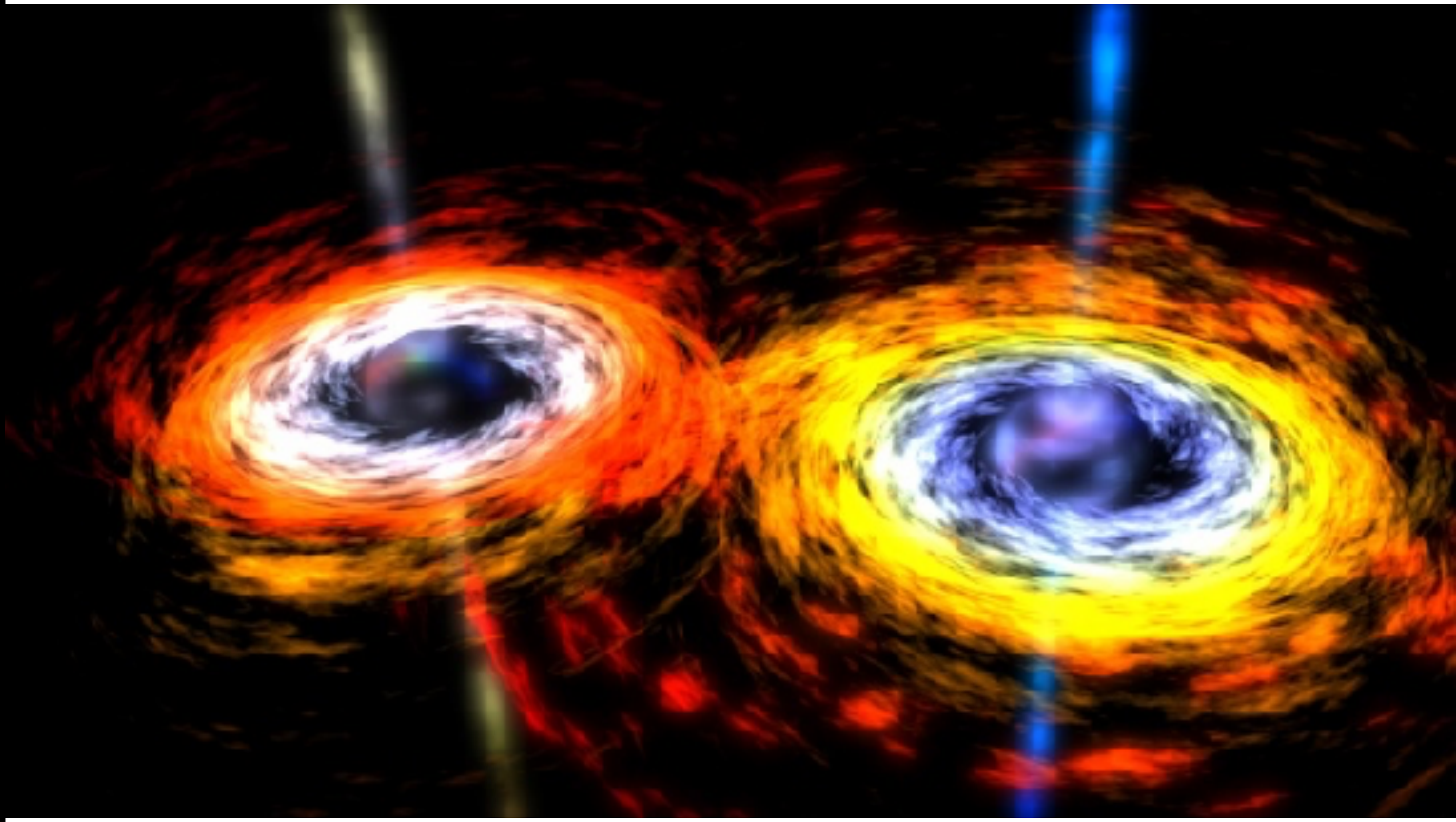
Black Holes as Nature's Detectors

1 km -10 billion km

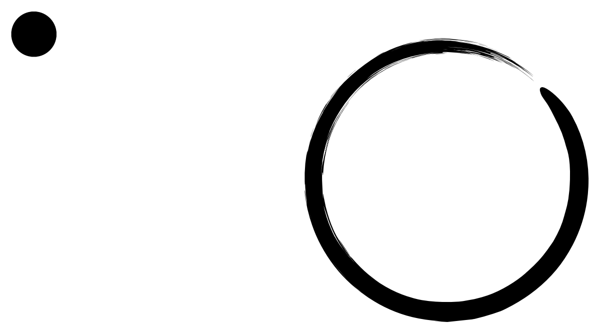
They can detect bosons of similar in size

September 14, 2015



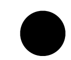


Super-Radiance Cartoon



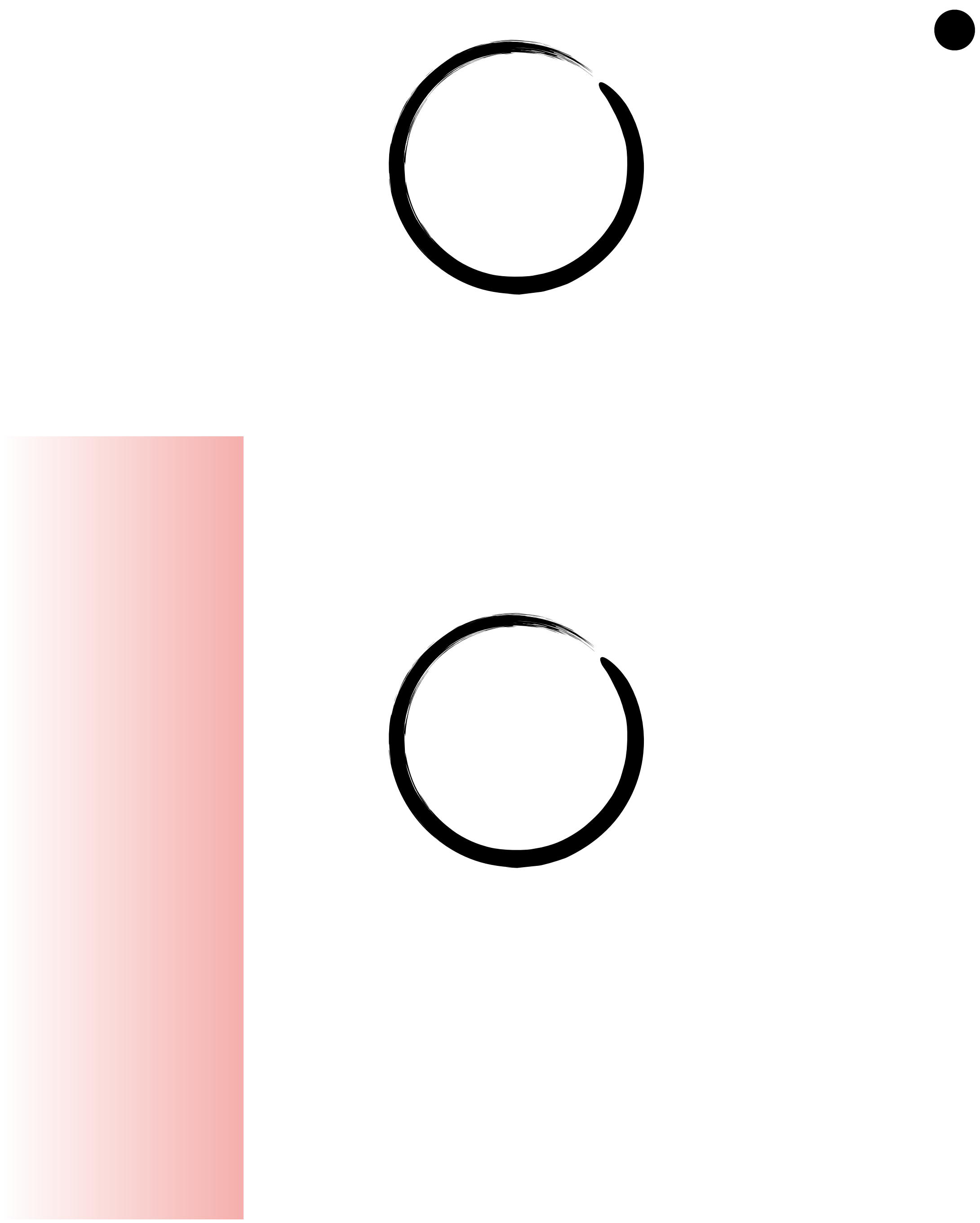
Super-radiant scattering of a massive object

Super-Radiance Cartoon



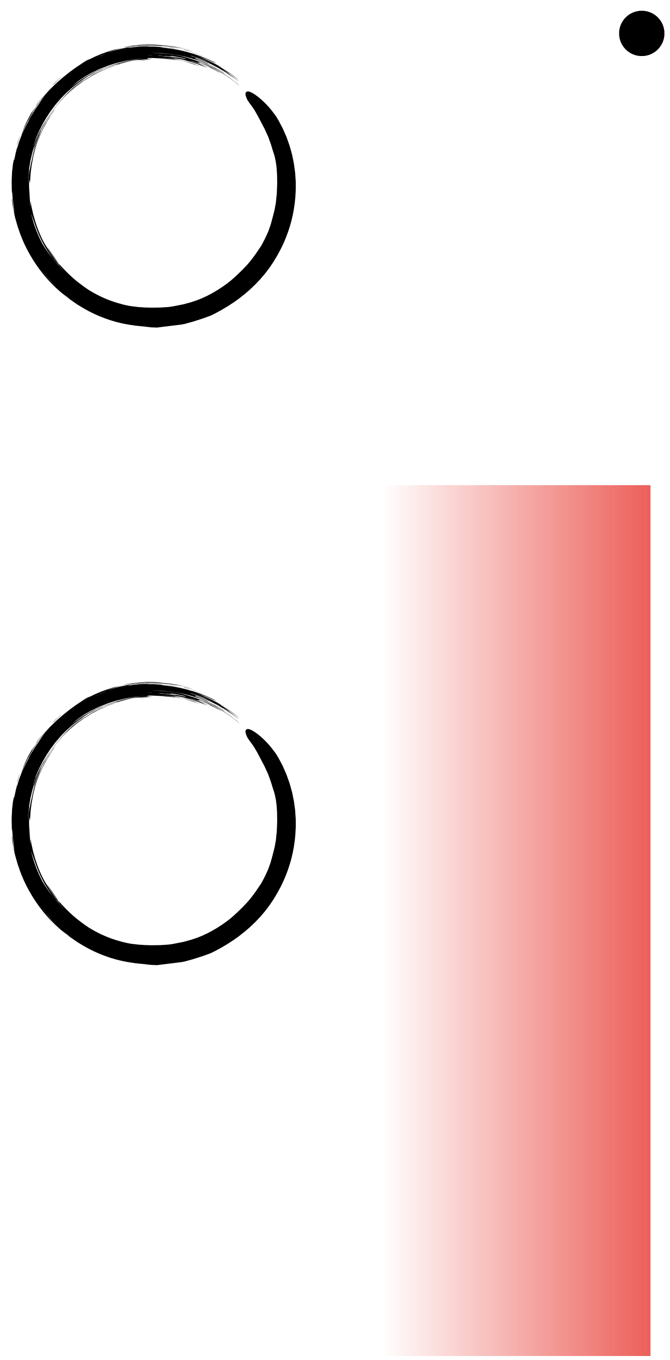
Super-radiant scattering of a massive object

Super-Radiance Cartoon



Super-radiant scattering of a wave

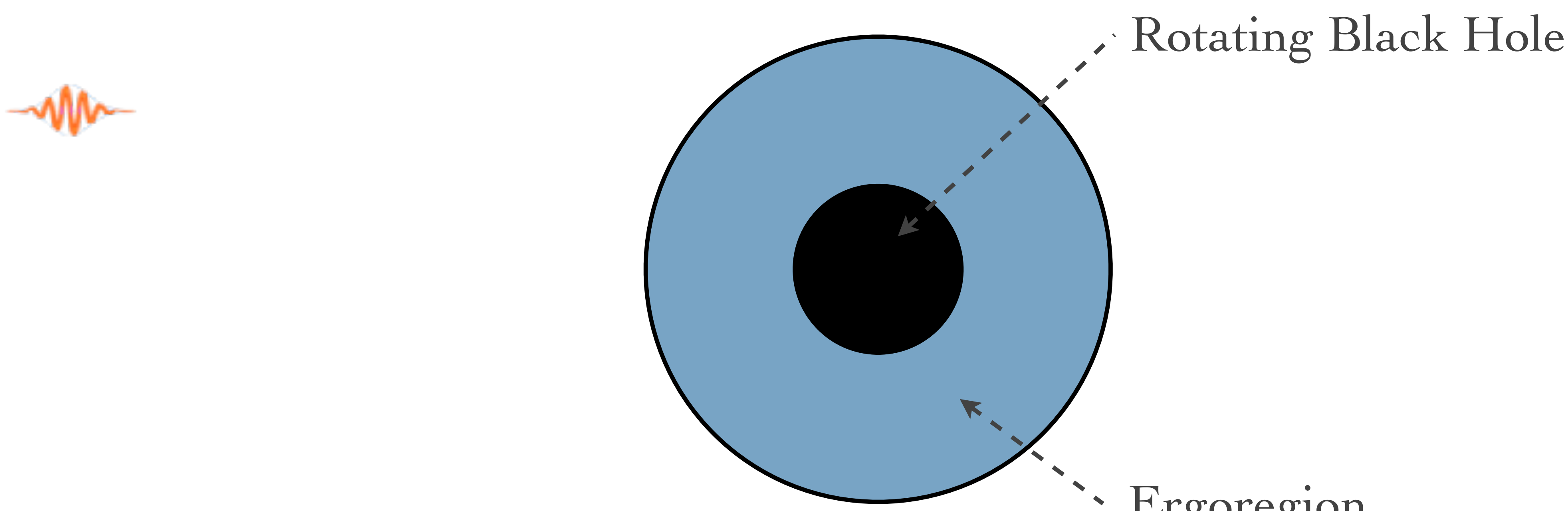
Super-Radiance Cartoon



Super-radiant scattering of a wave

Black Hole Superradiance

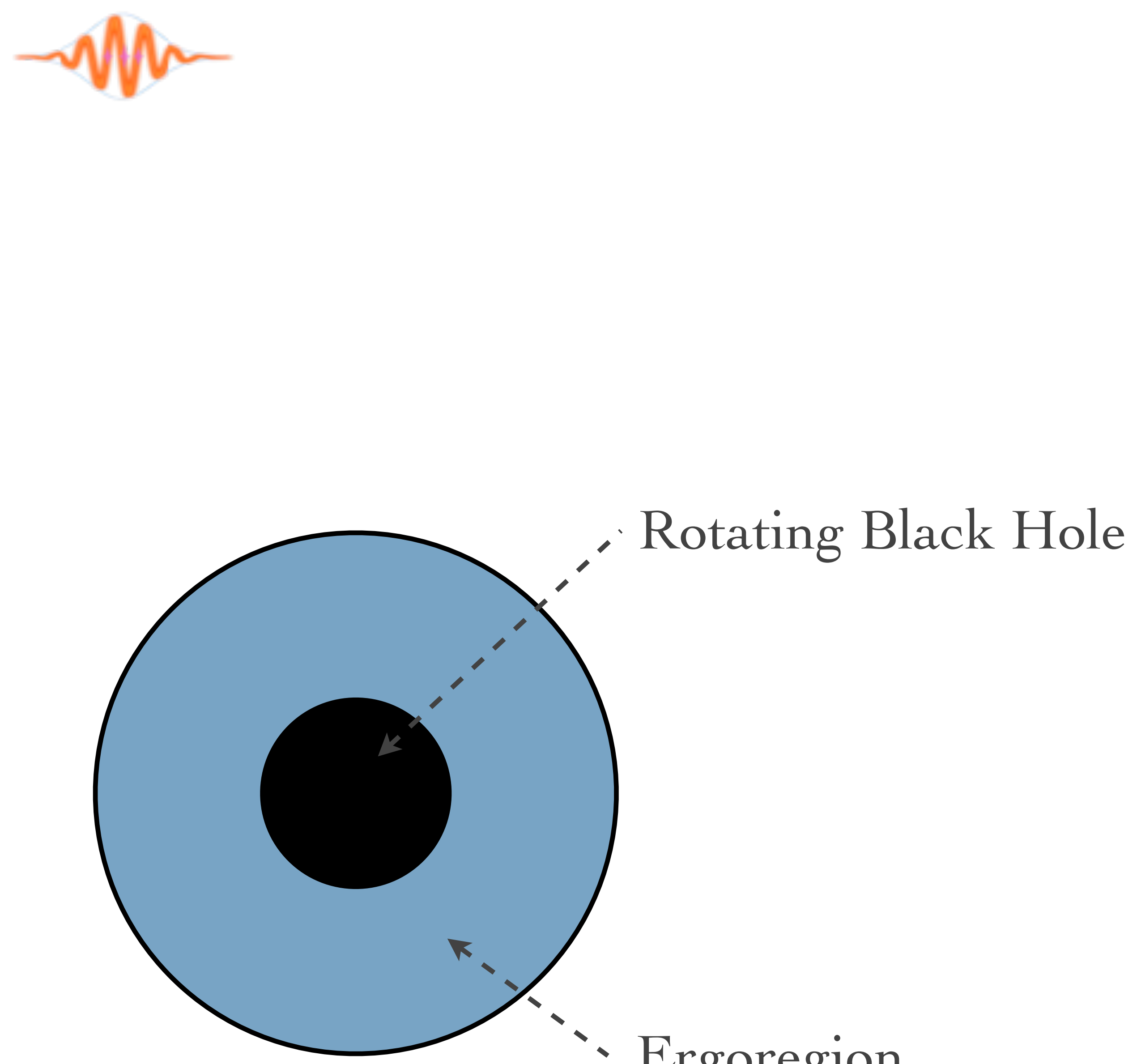
Penrose Process



Ergoregion: Region where even light has to be rotating

Black Hole Superradiance

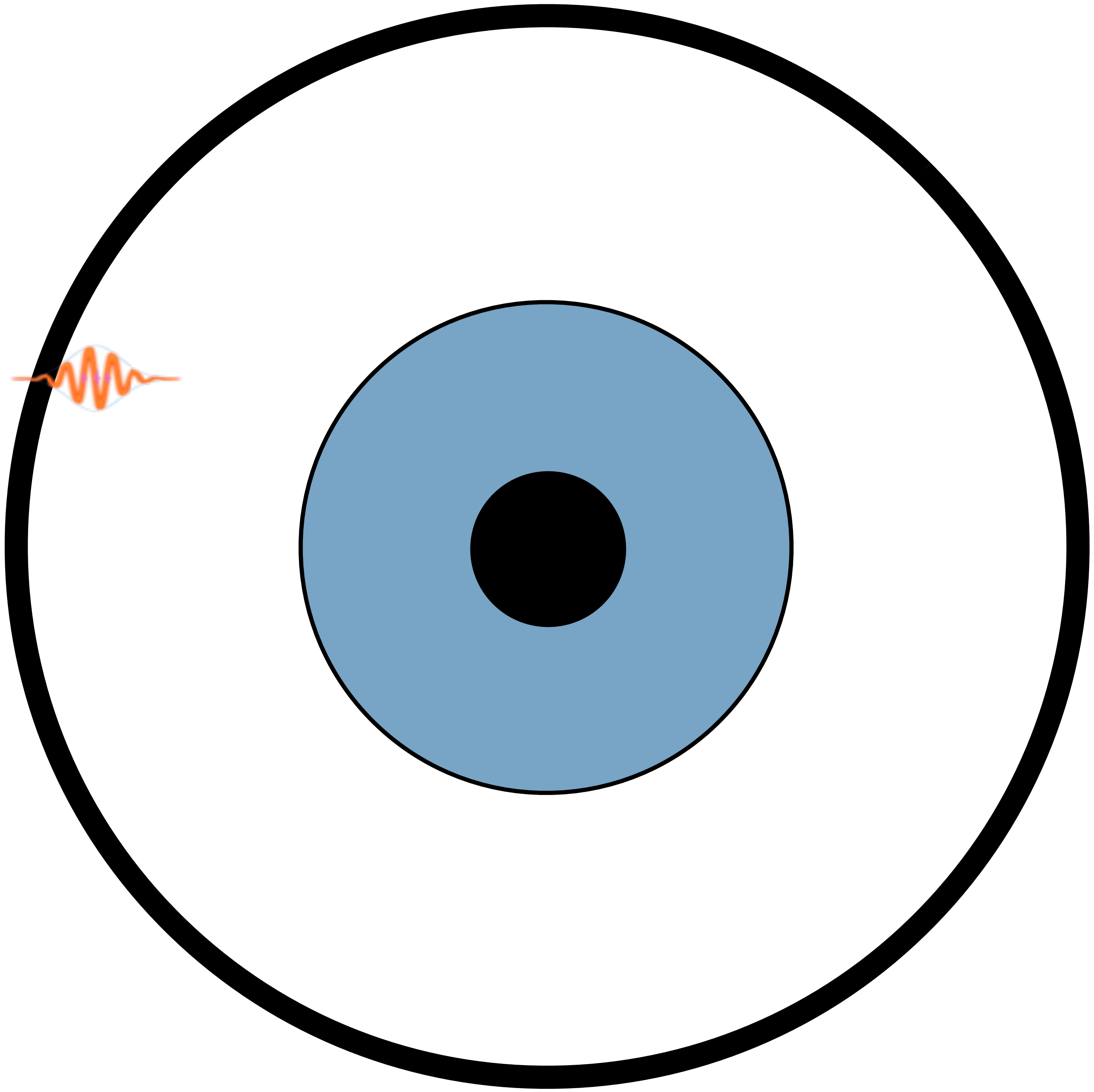
Penrose Process



Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

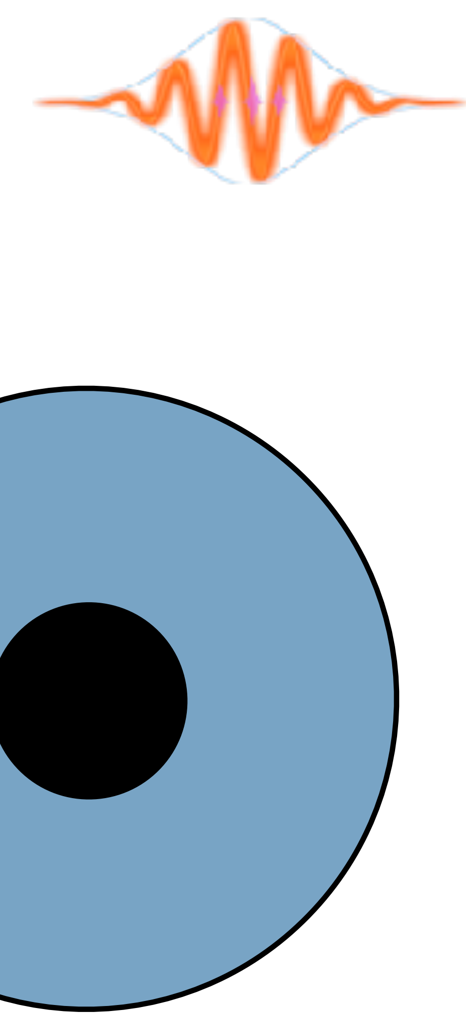
Press & Teukolsky 1972



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

Black Hole Bomb

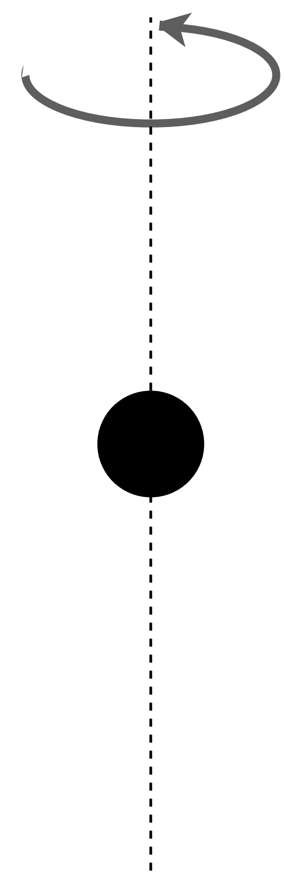
Press & Teukolsky 1972



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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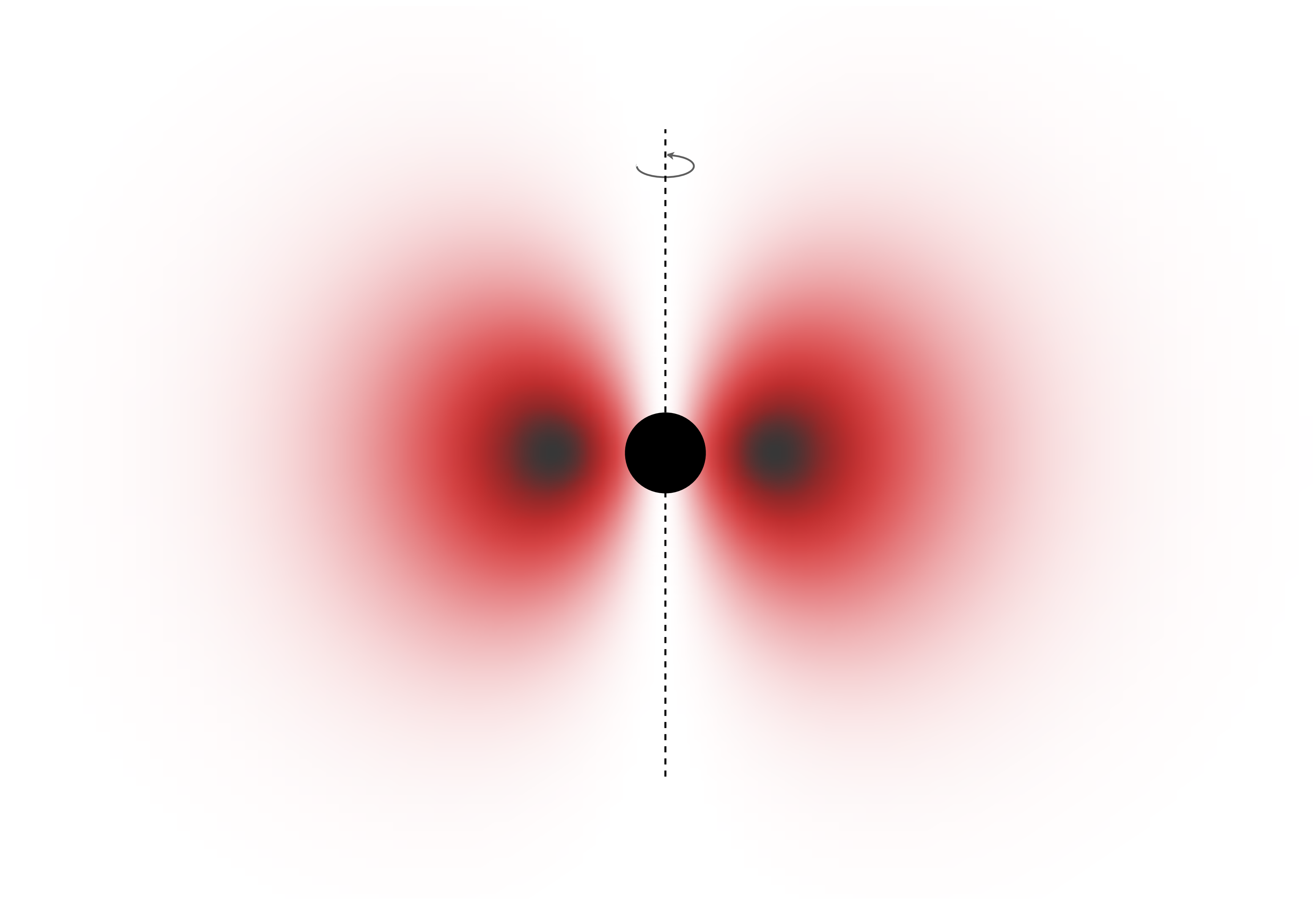
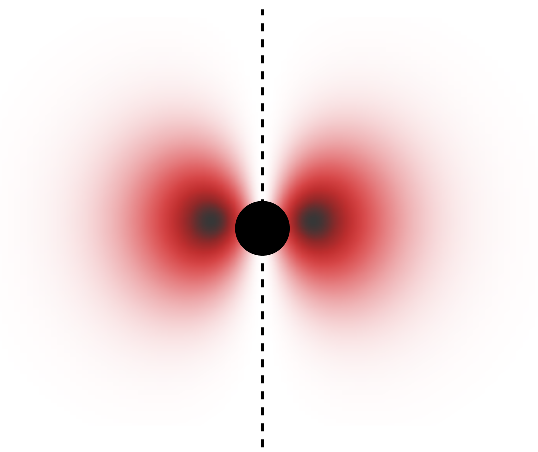


Particle Compton Wavelength comparable to the size of the Black Hole

Gravitational Atom in the Sky

The gravitational Hydrogen Atom



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

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

Main differences from hydrogen atom:

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

In-going Boundary Condition at Horizon

Key Points About Superradiance

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

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

Superradiance Parametrics

Superradiance Condition

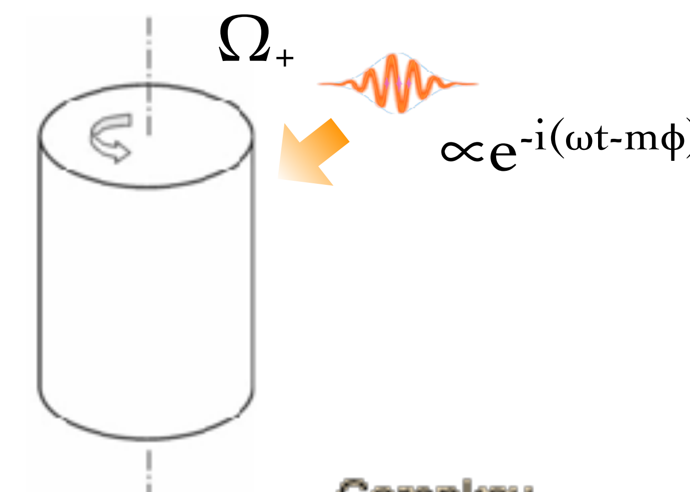
$$\omega_{\rm axion} < m\ \Omega_+$$

m : magnetic quantum number

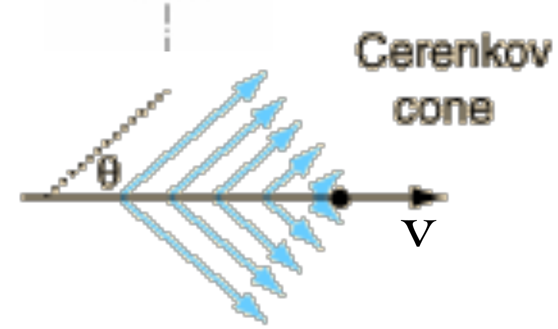
Ω_+ : angular velocity of the BH

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 $R_g\ \mu_a >> 1$,

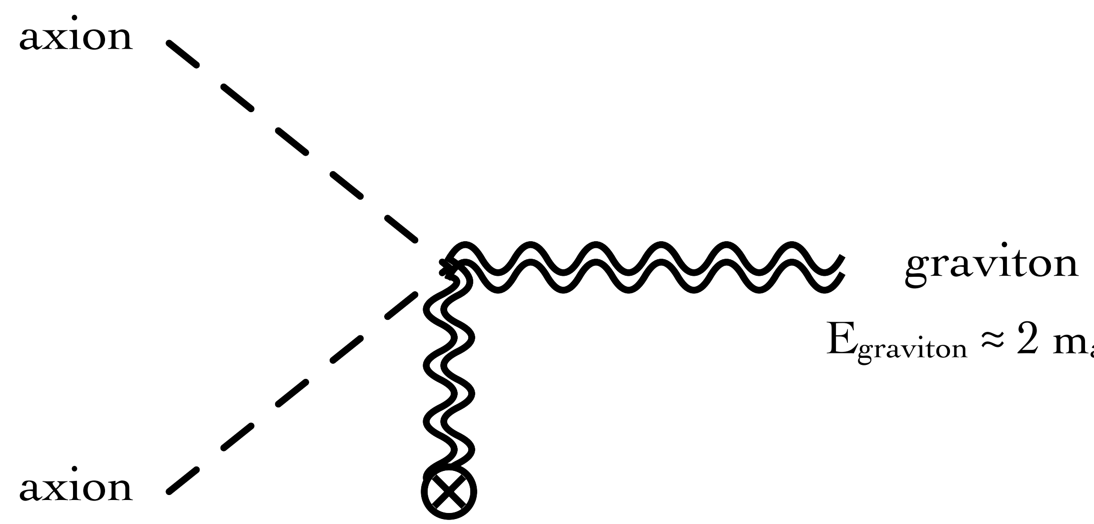
$$\tau_{sr} = 10^7 e^{3.7(\mu_a R_g)} R_g$$

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

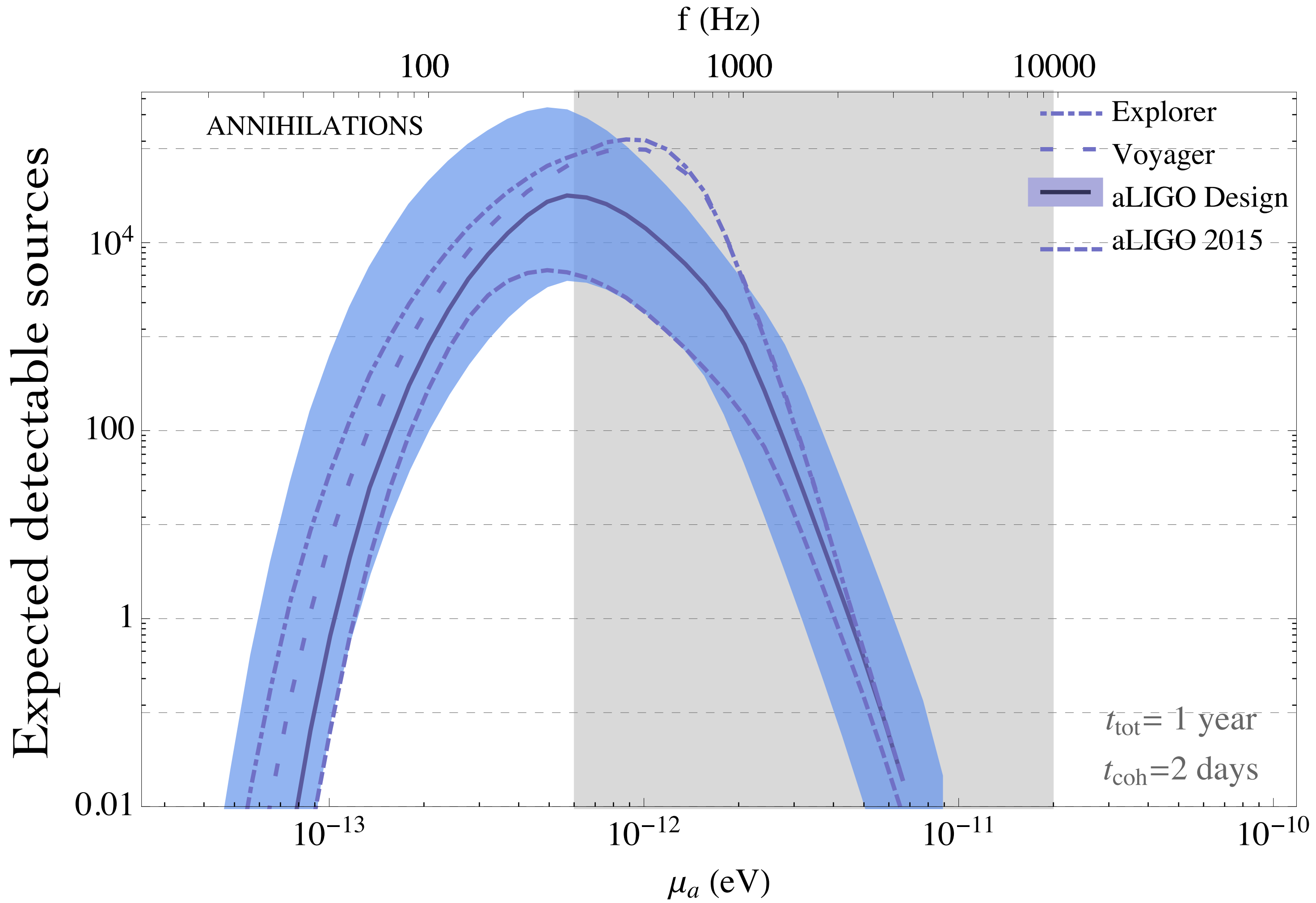
- Signal enhanced by the square of the occupation number of the state

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

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

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

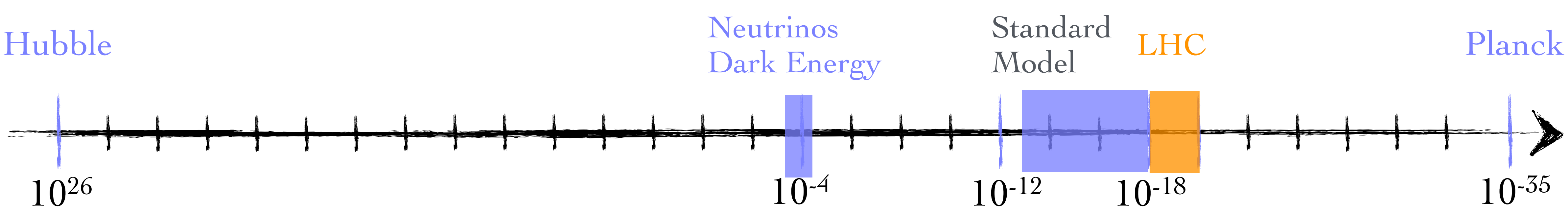
Optimistic: 90% above spin of 0.9 and 0.9 BH/century

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."

Length Scales in the Universe



Scale in m

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