Title: Particle Physics Beyond Colliders

Date: Oct 03, 2018 02:00 PM

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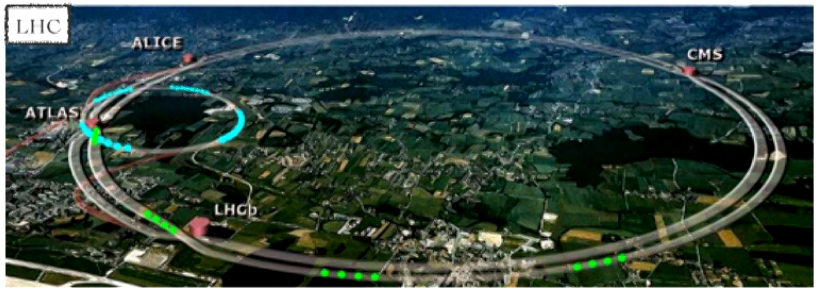
Abstract: <p>Recently there have been several proposals of low-energy precision experiments that can search for new particles, new forces, and the Dark Matter of the Universe in a way that is complementary to collider searches. In this talk, I will present some examples involving atomic clocks, nuclear magnetic resonance, and astrophysical black holes accessible to LIGO.</p>

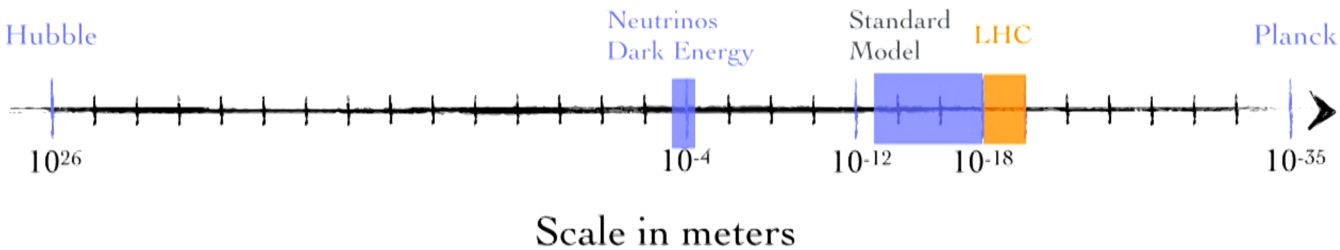
Particle Physics Beyond Colliders

Asimina Arvanitaki
Perimeter Institute

The High Energy Frontier



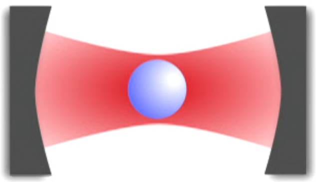
The Length Scales in the Universe



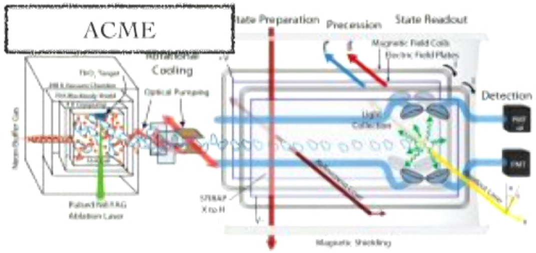
80% of the energy scale left to explore

Opportunities at the Precision Frontier

Optically Levitated Objects



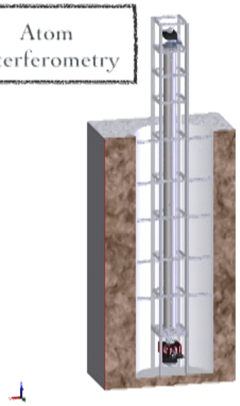
ACME



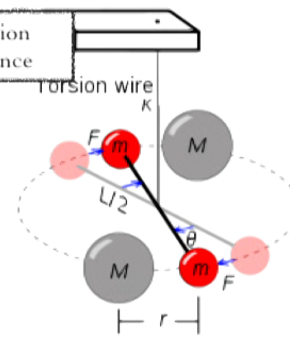
NMR

LIGO

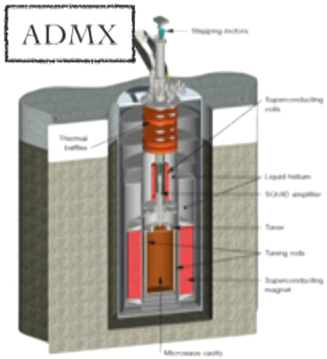
Atom Interferometry



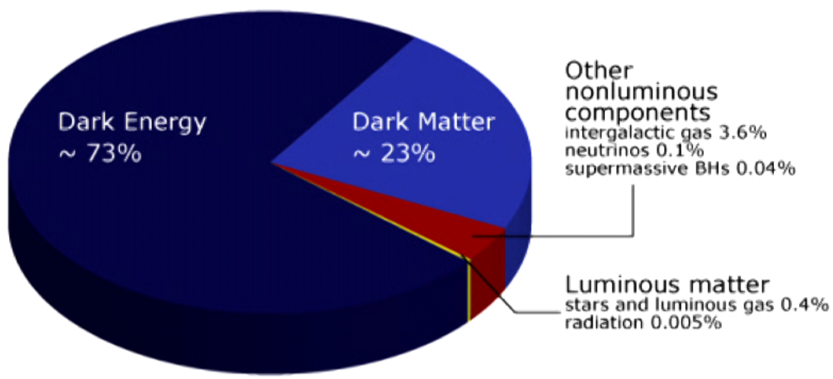
Torsion Balance



ADMX



The Mystery of Dark Matter



Models of Dark Matter

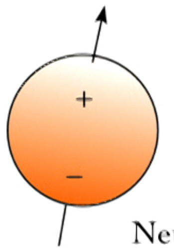
- What is it made out of?
- How is it produced?
- Does it have interactions other than gravitational?

Outline

- Light Bosonic Dark Matter
- Atomic Clocks
- ARIADNE
- Black Hole Superradiance

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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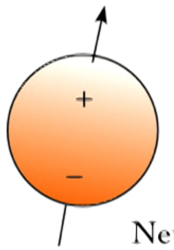

Neutron
EDM

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

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:

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

f_a : axion decay constant

Elements of String Theory

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

- Extra dimensions

Elements of String Theory

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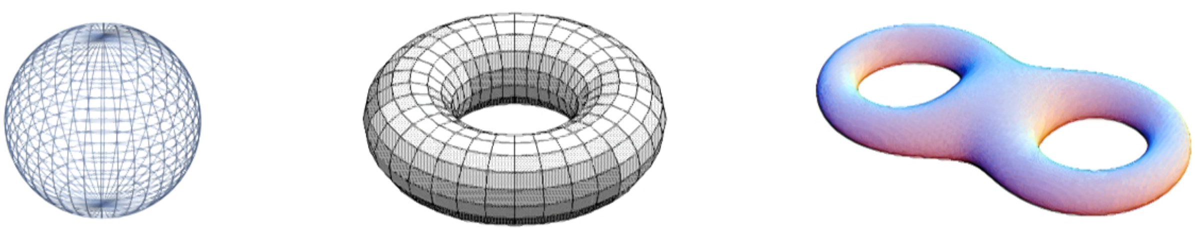
- Extra dimensions

- Gauge fields

- Topology



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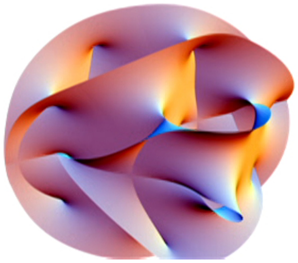


Elements of String Theory

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

- 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

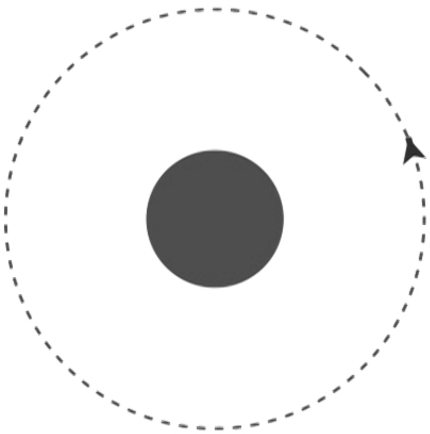
$$\vec{B} = 0$$

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

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

while

$$\vec{B} = 0$$

Energy stored only inside the solenoid

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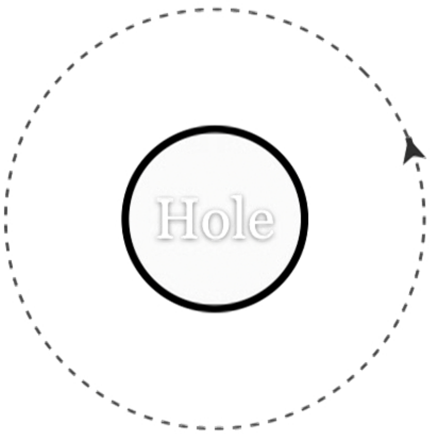


Taking an electron around the solenoid

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

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

String Axion mass and the QCD axion

$$\text{Particle Mass} \sim \frac{M_{\text{Planck}}^2 e^{-S/2}}{f_a}$$

Requirements on string theory for QCD axion
to solve the strong CP problem

$\theta_{QCD} < 10^{-10}$

String corrections < $10^{-10} \times$ QCD

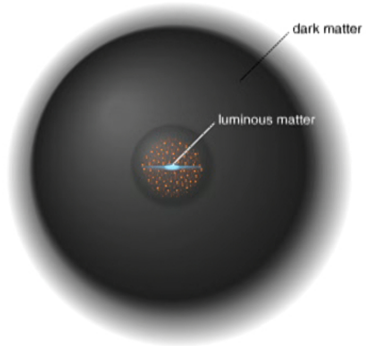
$M_{Planck}^4 \; e^{-S} < 10^{-10} \times m_\pi^2 f_\pi^2$

$S \gtrsim 200$ $\quad\quad$ $S \sim 2\pi / \alpha$

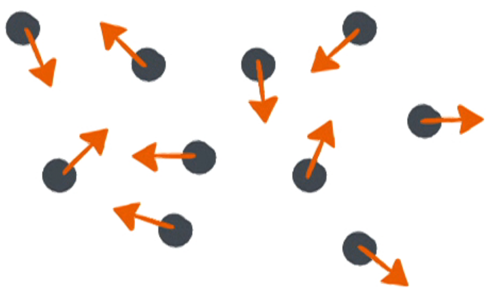
The QCD axion should not be special
There could be **many** light axions

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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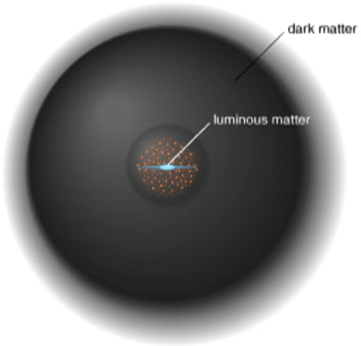

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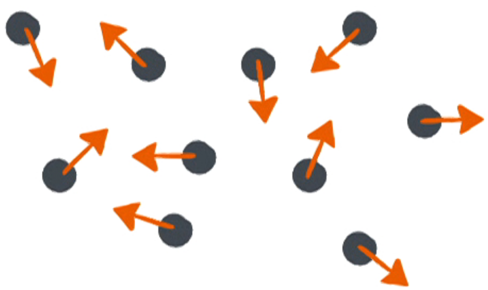
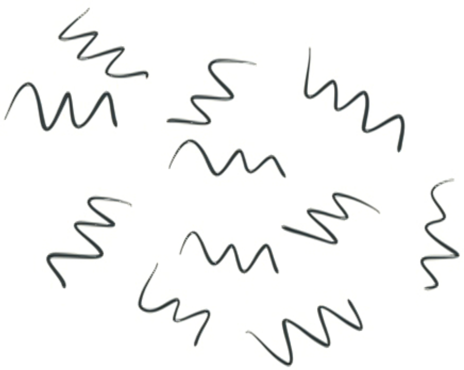


like a WIMP

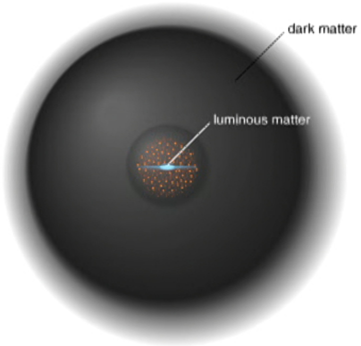
instead of…

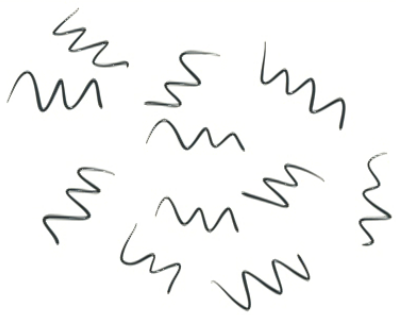


$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

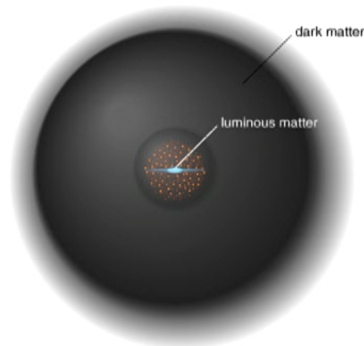


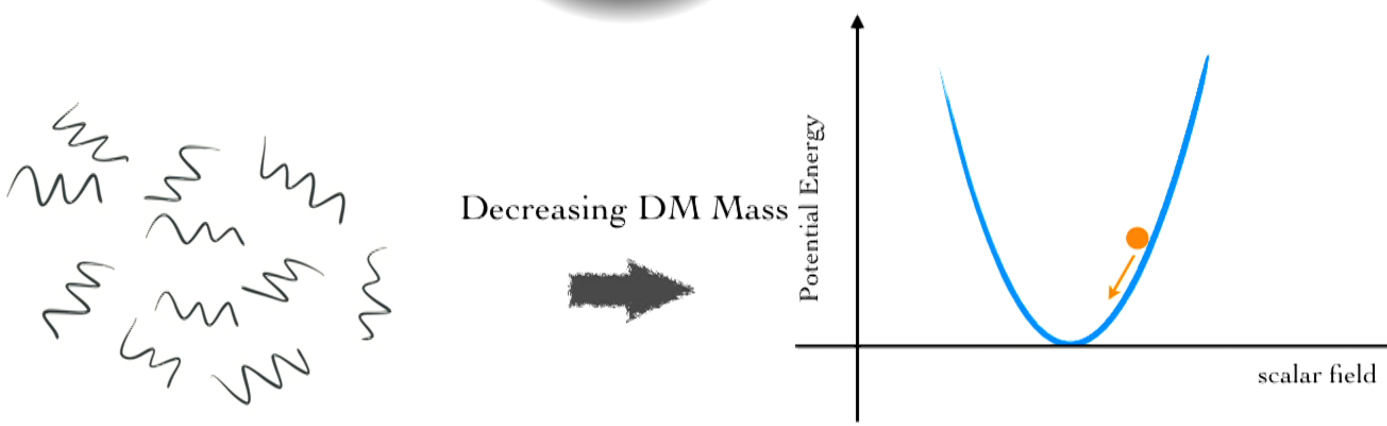


Decreasing DM Mass

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy





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 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

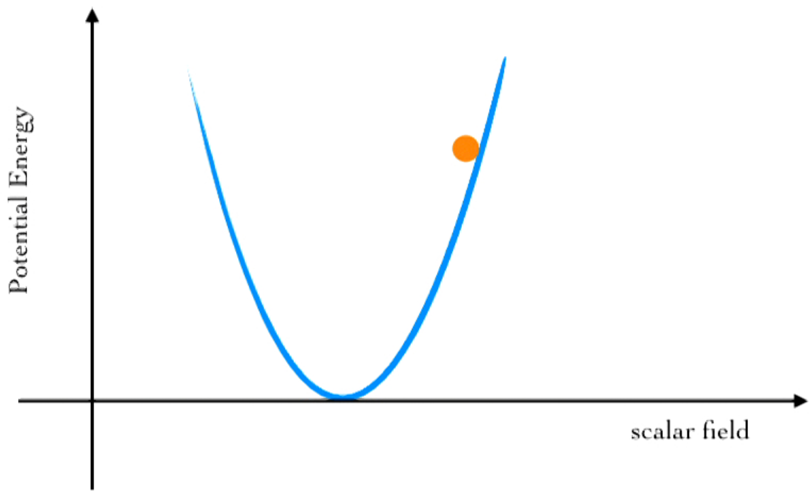
$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

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

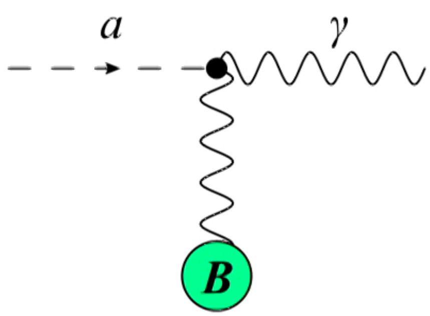
*The story changes slightly if DM is a dark photon

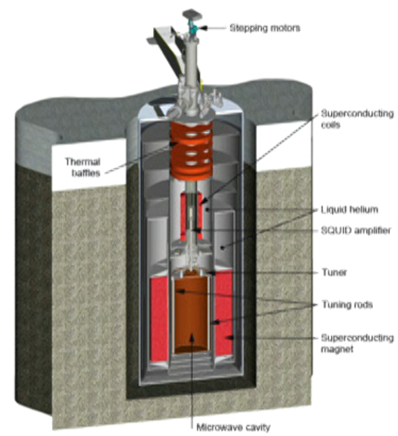
Axion Dark Matter

Some examples

- Axion-to-photon conversion in EM cavities (ex. ADMX)

$$\frac{a(x,t)}{f_a}\vec{E}\cdot\vec{B}$$

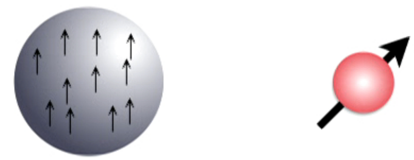




- At large wavelengths, axion detected via LC circuits (ex. ABRACADABRA and DM Radio)

Axion Dark Matter

Some examples



- Axion Force experiments (ex. ARIADNE) and DM experiments (ex. Casper)

Dark Photon Dark Matter

Some examples

- Detected if kinetically mixed with the photon

$$\mathcal{L} \supset \epsilon(\vec{E}_{EM}\vec{E}_{DM} + \vec{B}_{EM}\vec{B}_{DM})$$

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

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

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:

$$d_{m_e} \frac{\phi}{M_P l} m_e e \bar{e}$$

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

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

Fractional variation set by square root of DM abundance

Need an extremely sensitive probe

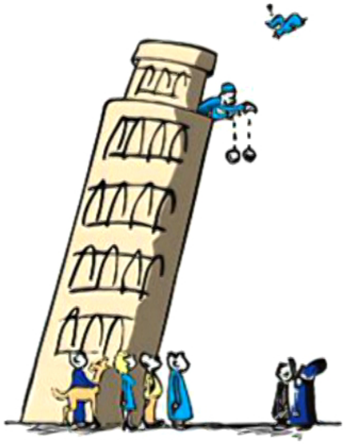
Other properties of light scalars

- Mediates new interactions in matter

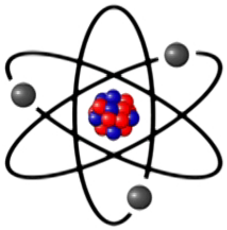
  - Generates a fifth force in matter

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

  - Generates Equivalence Principle violation



Oscillating Atomic and Nuclear Energy Splittings



- Optical Splittings

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

- Hyperfine Splittings

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

- 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}

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

How does and Atomic Clock Work?

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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?

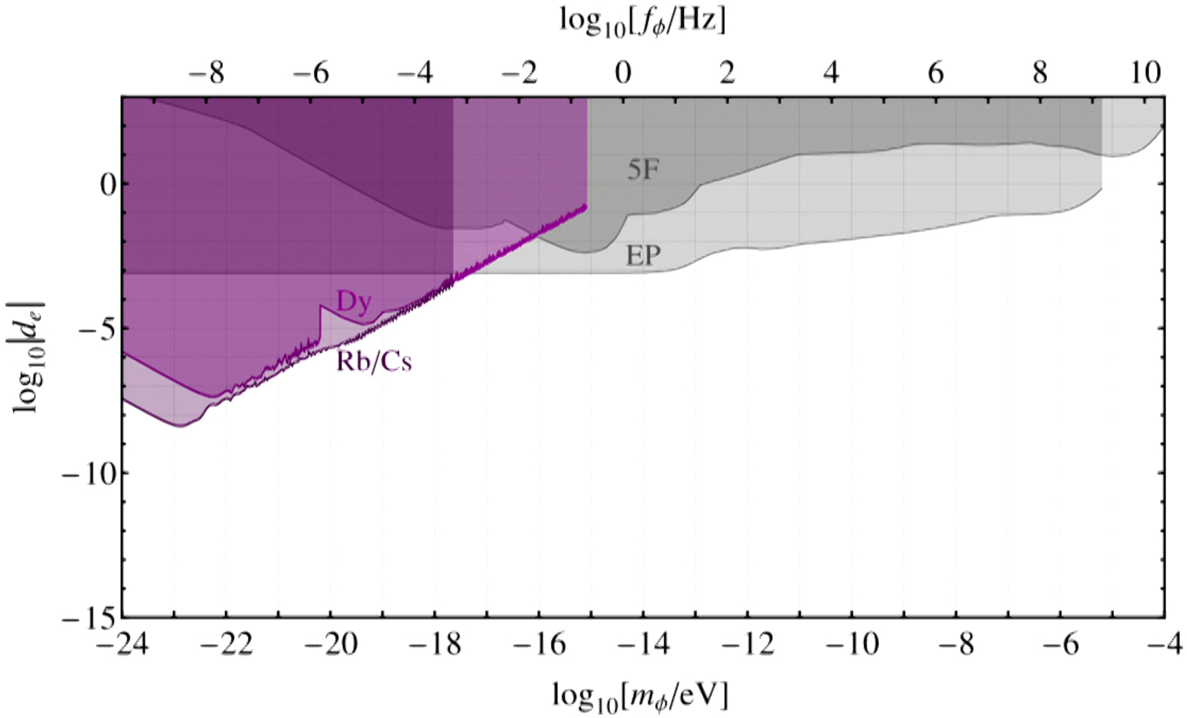
- Hyperfine to Optical transitions
  - Sensitive to m_e, m_q, and α_s (less to α_{EM})
- Optical to Optical transitions
  - Sensitive to α_{EM}
- Nuclear to Optical transitions
  - Sensitive to m_e, α_{EM}, m_q, and α_s

The Dy isotope and Rb/Cs Clock Comparison

Ken Van Tilburg
and the Budker group (2015)

Hees et. al (2016)

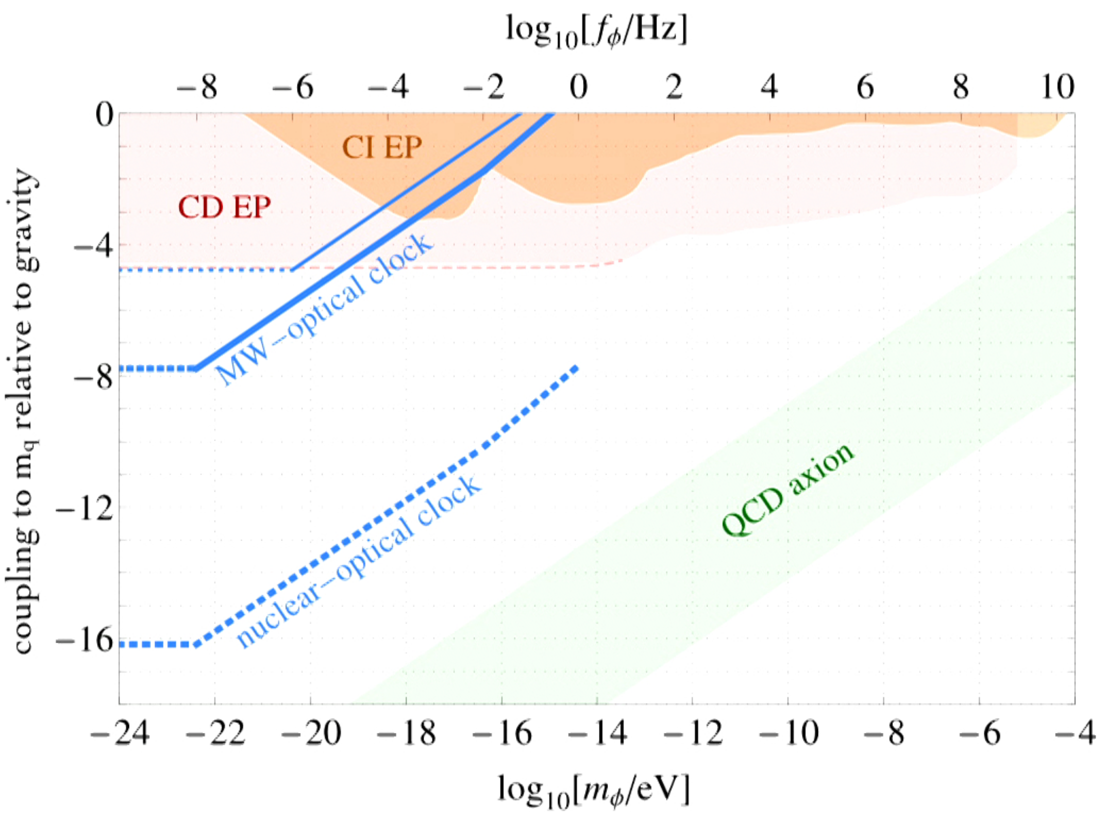
sensitivity to α_{EM} variations



Analysis performed with existing data

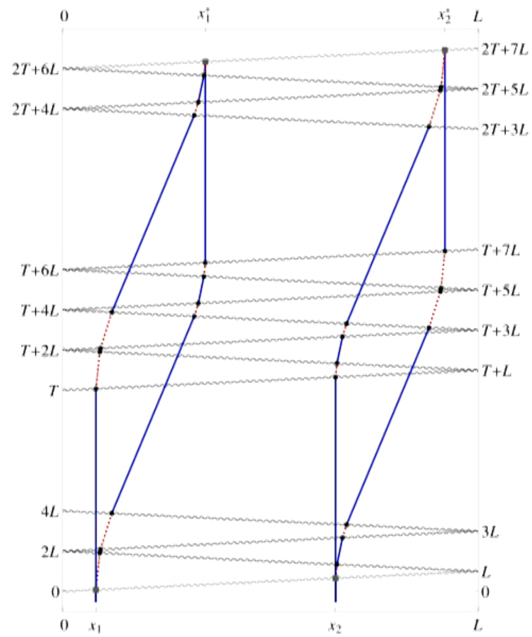
Nuclear to Optical Clock Comparison

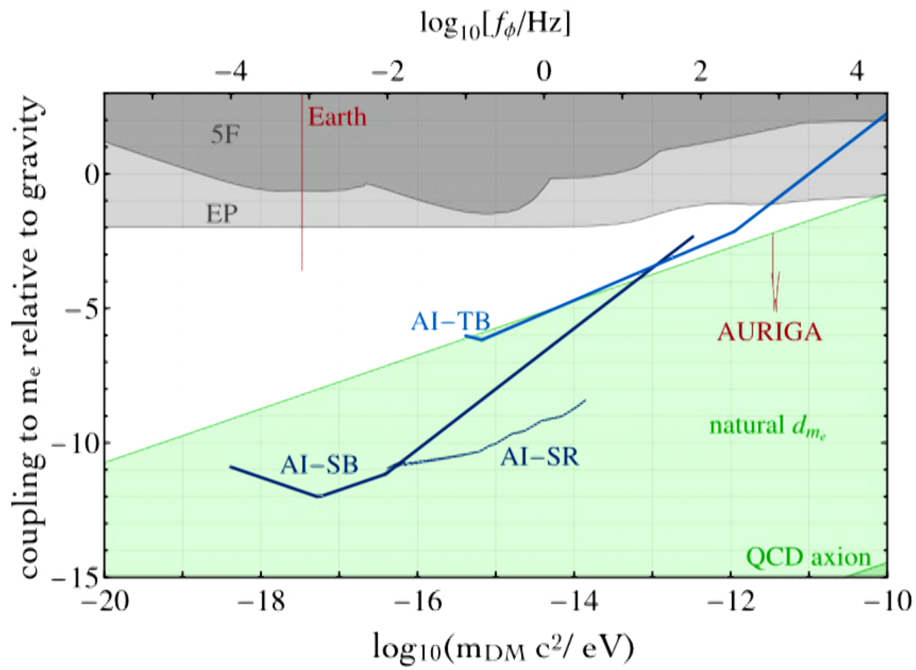
Future Sensitivity of a ^{229}Th clock with 10^{-15}/Hz$^{-1/2}$ noise



Comparison of two spatially separated Sr clocks

with Peter Graham, Jason Hogan,
Surjeet Rajendran and Ken Van Tilburg(2016)





Gravitational Wave interferometers such as aLIGO not sensitive enough due to laser noise

ARIADNE:

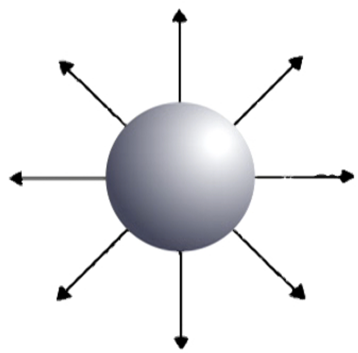
Axion Resonant InterAction DetectioN Experiment

with Andrew Geraci (2014)

and A. Kapitulnik, Chen-Yu Liu,J. Long, Y. Semertzidis, M. Snow
(under construction)

Short Range Interactions of the Axion

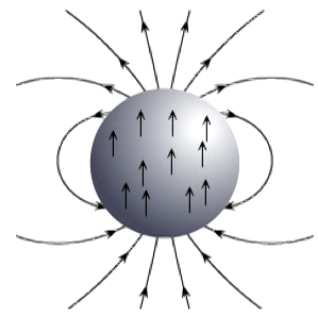
Moody and Wilczek (1984)



Monopole Interaction

Mass with N nucleons

$$\vec{B}_{axion} \approx \frac{g_s N}{4\pi}\frac{\hat{r}}{r^2}e^{-m_a r}$$



Dipole Interaction

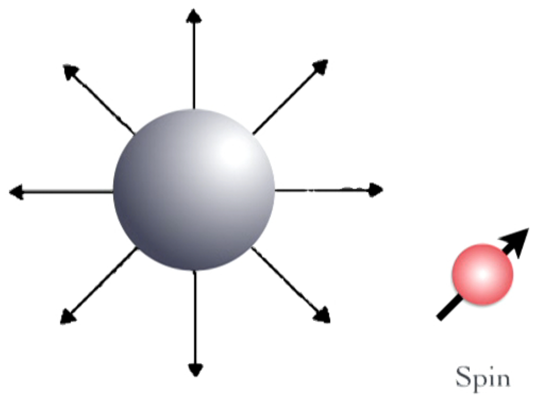
N spins

$$\vec{B}_{axion} \approx \frac{g_p N}{4\pi}\left(3\frac{(\vec{\sigma}\cdot\hat{r})\hat{r}}{r^3} - \frac{\vec{\sigma}}{r^3}\right)e^{-m_a r}$$

*For theorists: $\vec{\nabla} a \equiv \vec{B}_{axion}$

Short Range Interactions of the Axion

Moody and Wilczek (1984)



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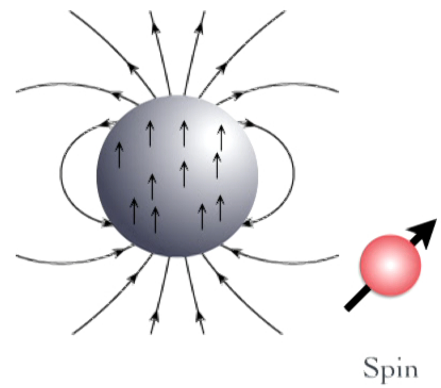


Dipole Interaction

N spins

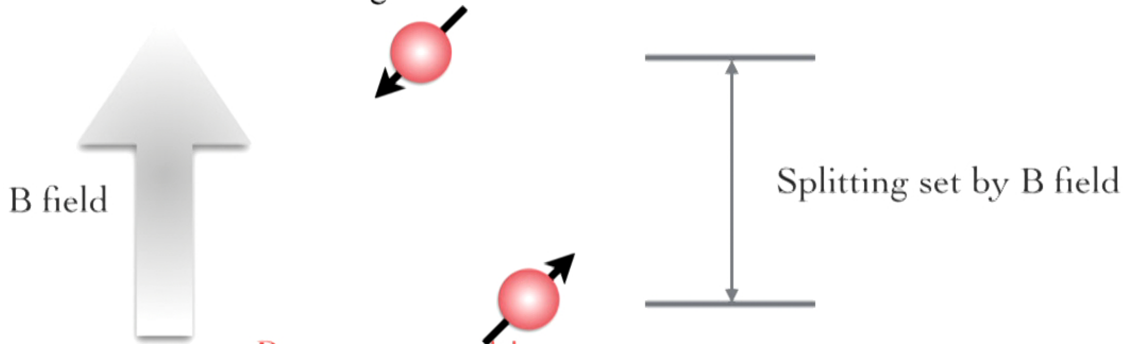
Interaction between mass and spin, just like a magnetic field:

$$B_{eff} \quad \boxed{g_p \vec{B}_{axion}} \cdot \frac{\vec{\sigma}}{m_f}$$

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

Precision Magnetometry

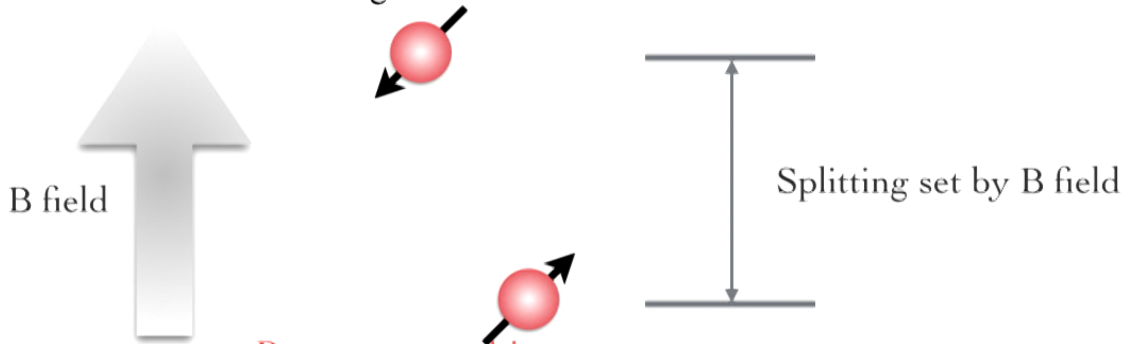
Nuclear Magnetic Resonance



Resonant transition:
Perturbation at the splitting frequency of the spins

Precision Magnetometry

Nuclear Magnetic Resonance



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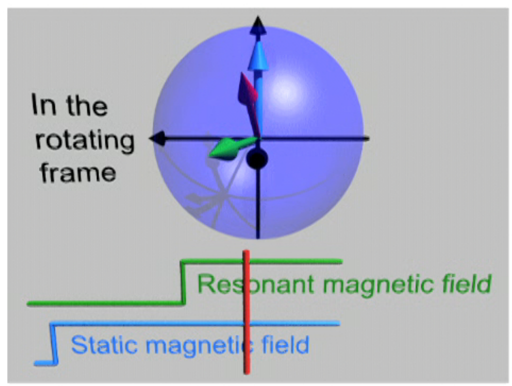
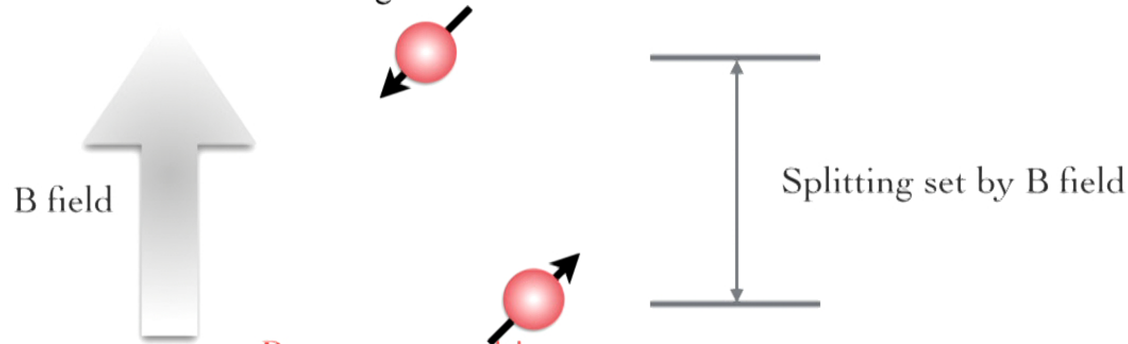


In the classical picture: Spins precessing around the perturbing magnetic field

Precision Magnetometry

Nuclear Magnetic Resonance



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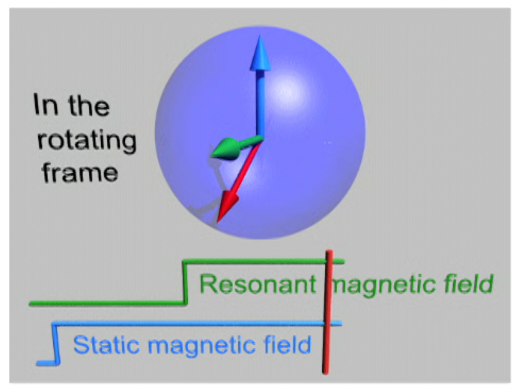

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Precision Magnetometry

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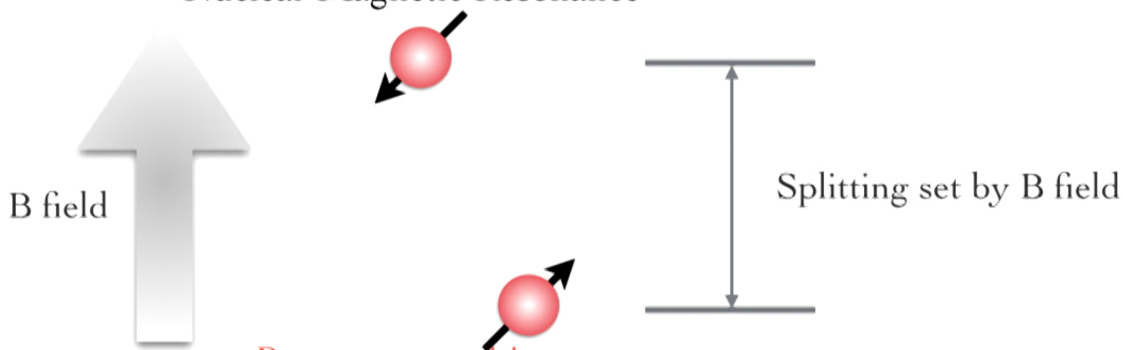
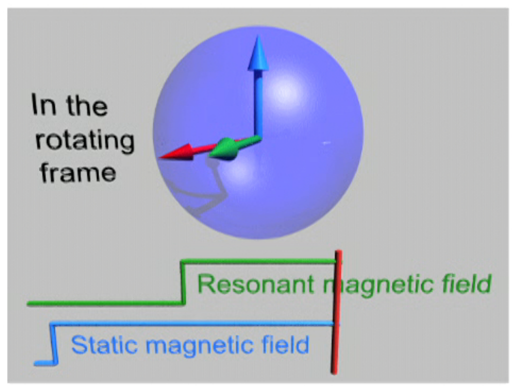


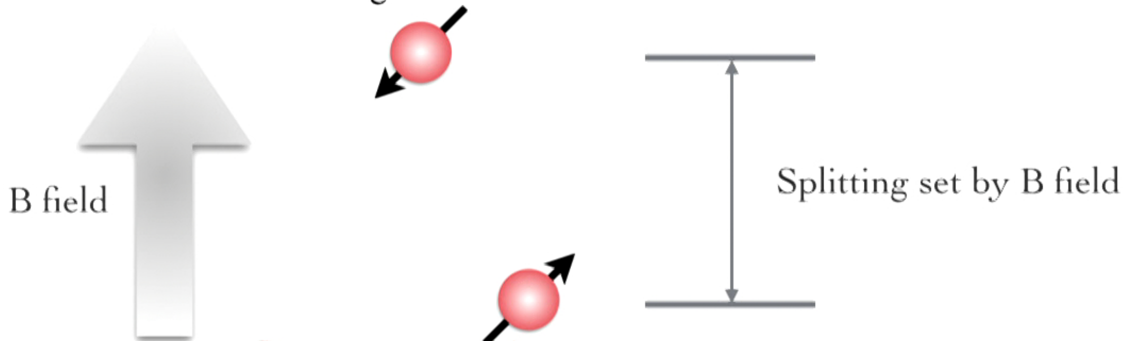
Resonant transition:
Perturbation at the splitting frequency of the spins



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

Precision Magnetometry

Nuclear Magnetic Resonance



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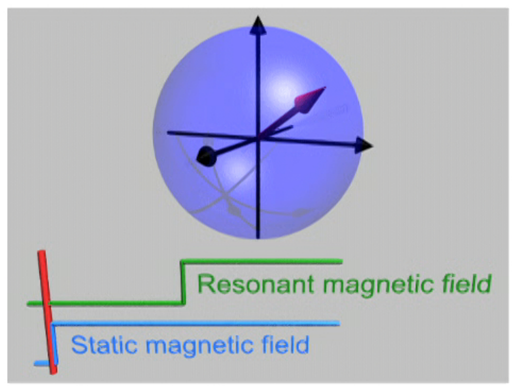

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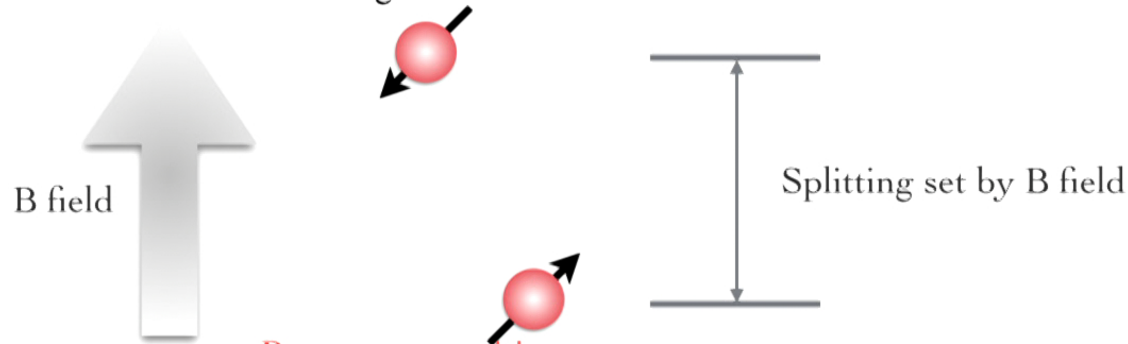

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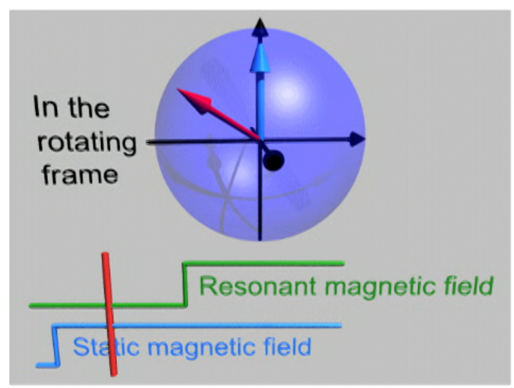

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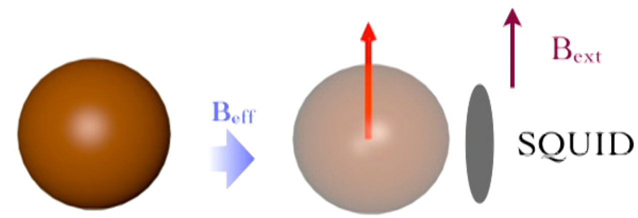
Detection Strategy

Just like a magnetic field



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

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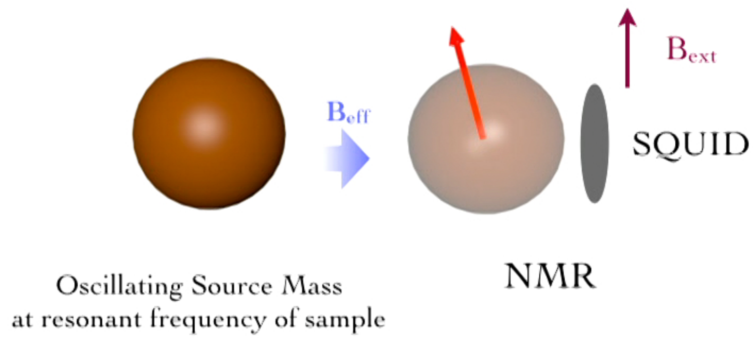

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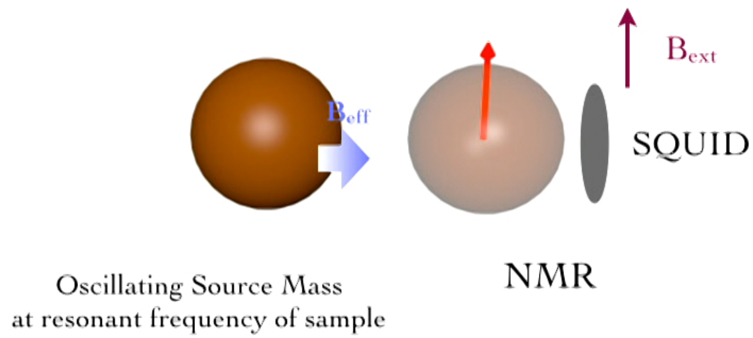

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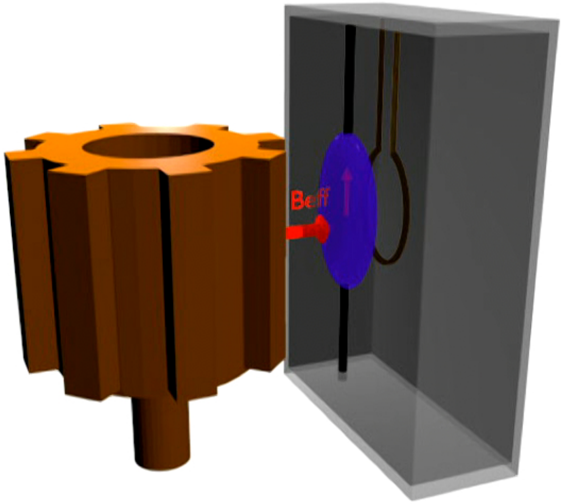
ARIADNE:

Axion Resonant InterAction DetectioN Experiment



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

$$B_{\min} \approx p^{-1}\sqrt{\frac{2\hbar b}{n_s \mu_{^3\mathrm{He}} \gamma V T_2}} = 3\times 10^{-19}\ \mathrm{T} \times$$

$$\left(\frac{1}{p}\right)\sqrt{\left(\frac{b}{1\ \mathrm{Hz}}\right)\left(\frac{1\ \mathrm{mm}^3}{V}\right)\left(\frac{10^{21}\ \mathrm{cm}^{-3}}{n_s}\right)\left(\frac{1000\ \mathrm{s}}{T_2}\right)}$$

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

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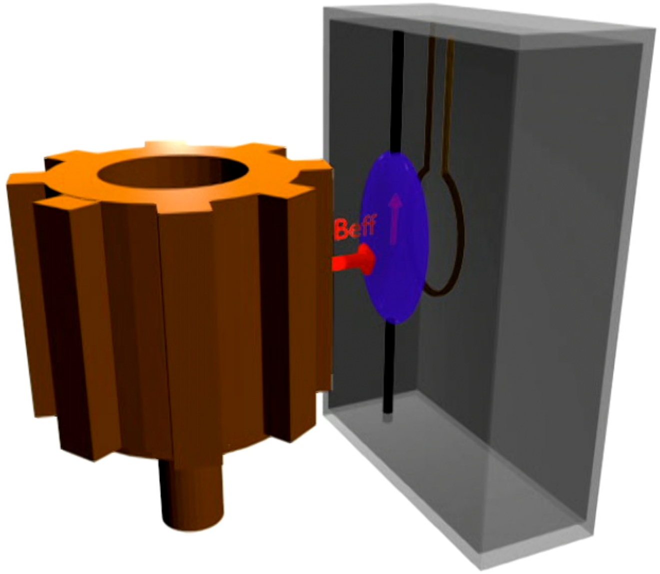

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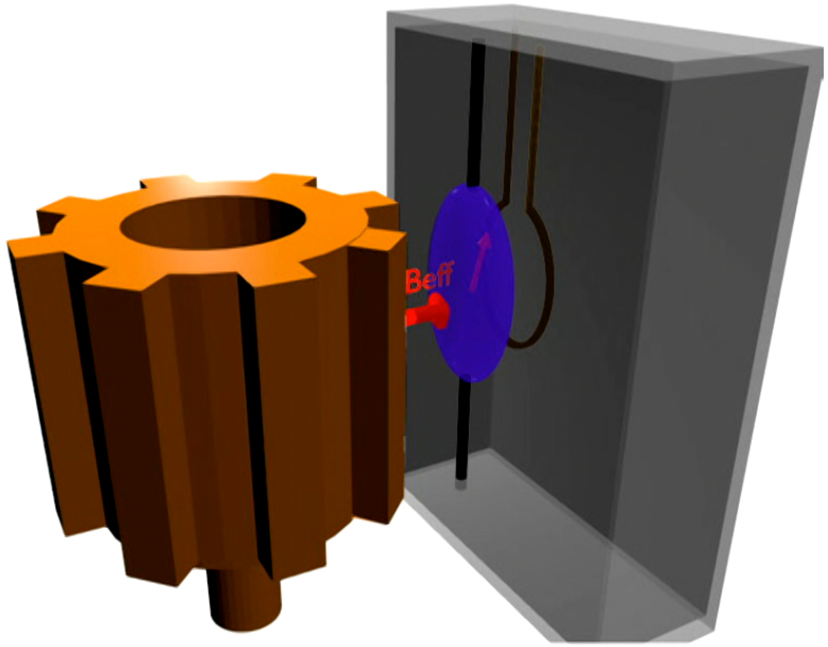

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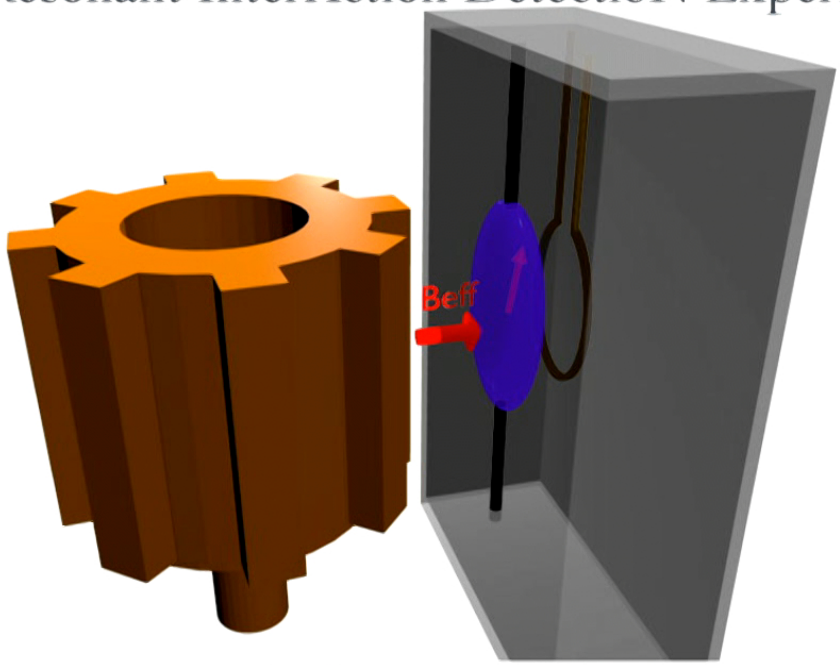

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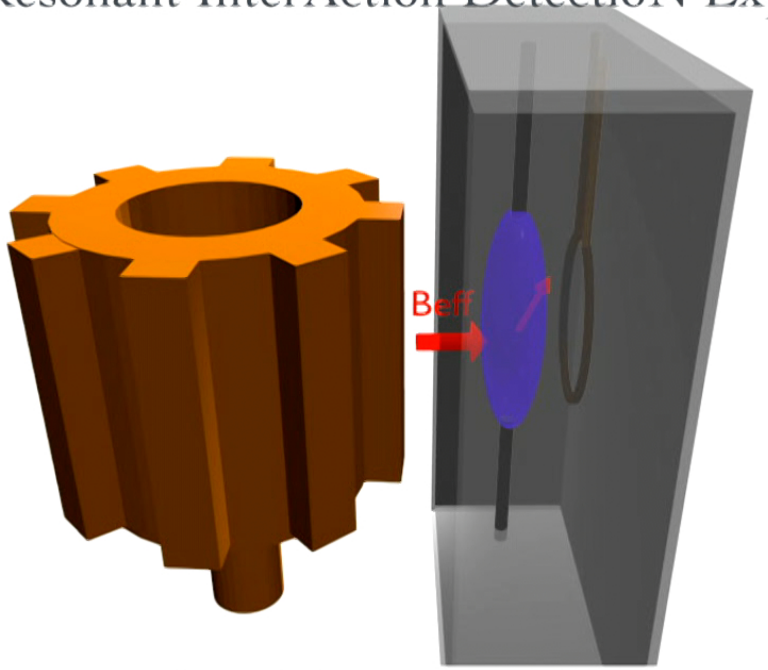

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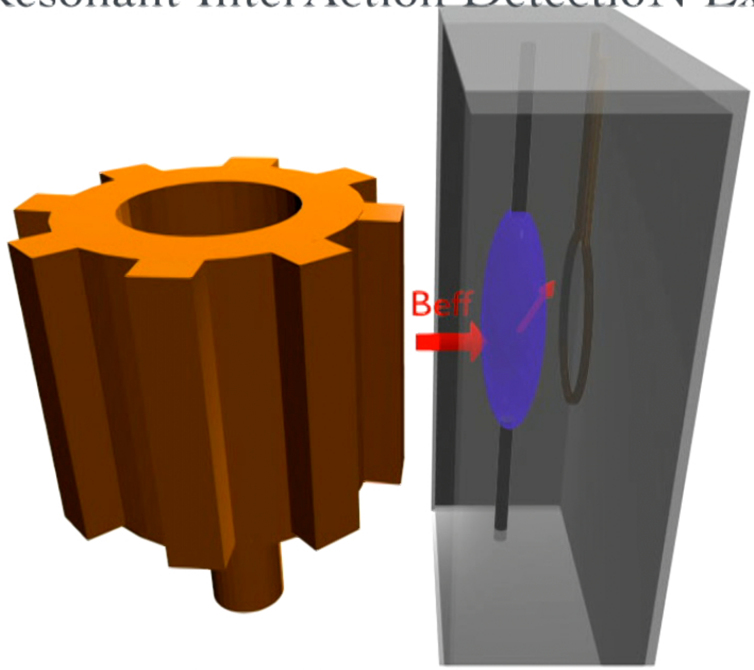

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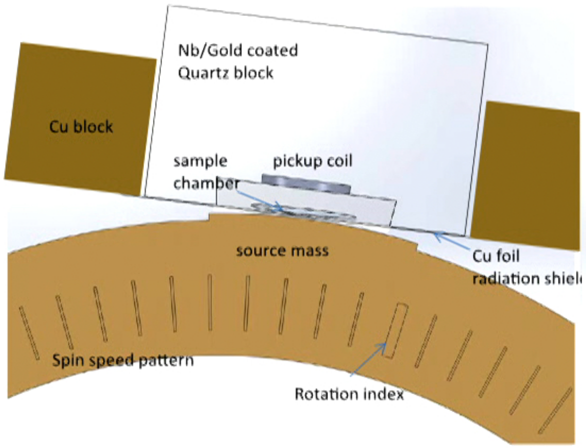
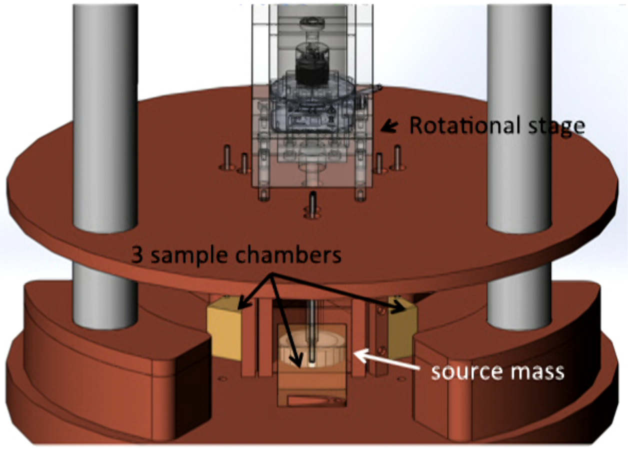
Experimental Setup

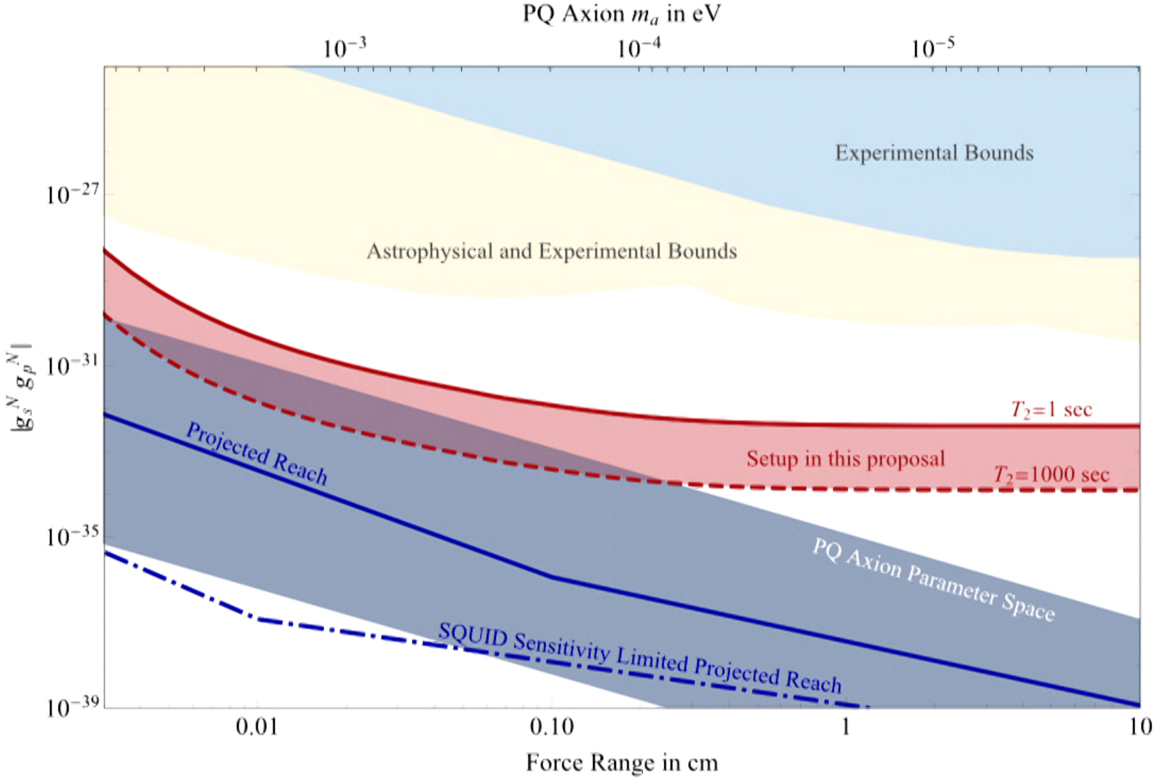




- 99 Hz Larmor precession frequency for ^{3}He nuclei
- $2\text{x}10^{21}$ / cc ^{3}He polarized spin density
- 10 mm x 3 mm x 150 μm NMR sample size
- Tungsten (or nuclear - electron spin polarized He or Fe) source mass

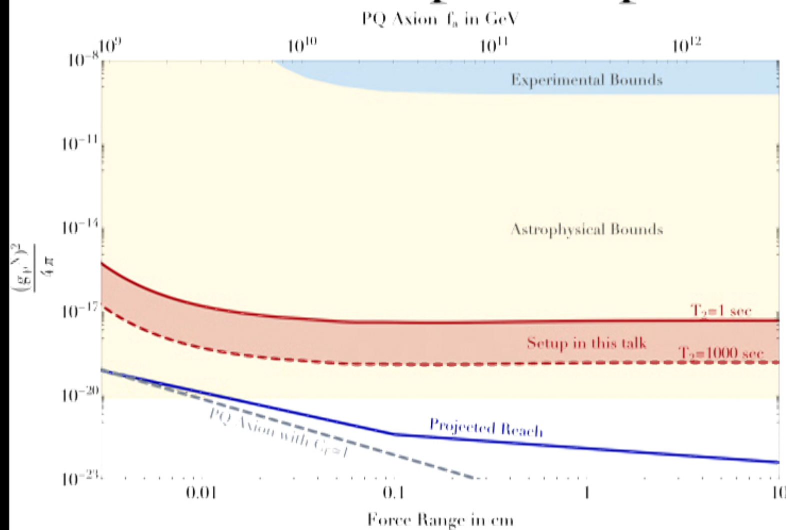
Monopole-Dipole Interaction Reach

Unpolarized Source Mass with 10^6 sec integration



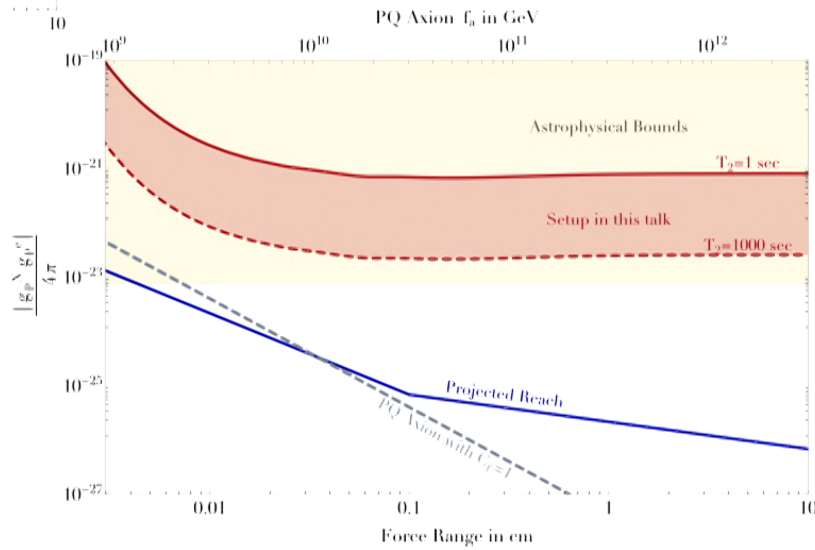
Projected Reach with increase of polarized spin density
and larger NMR sample volume

Dipole-Dipole Interaction Reach



Nuclear Spin Polarized Source Mass
with 10^6 sec integration

Electron Spin Polarized Source Mass
with 10^6 sec integration



Experimental Backgrounds/Challenges

Systematic Effect/Noise source	Background Level	Notes
Magnetic gradients	3×10^{-6} T/m	Limits T_2 to ~ 100 s
		Possible to improve w/shield geometry
Vibration of mass	10^{-22} T	For 10 μm mass wobble at ω_{rot}
External vibrations	5×10^{-20} T/$\sqrt{\mathrm{Hz}}$	For 1 μm sample vibration (100 Hz)
Patch Effect	$10^{-21}(\frac{V_{\mathrm{patch}}}{0.1\mathrm{V}})^2$ T	Can reduce with V applied to Cu foil
Flux noise in squid loop	2×10^{-20} T/$\sqrt{\mathrm{Hz}}$	Assuming $1\mu\Phi_0/\sqrt{\mathrm{Hz}}$
Trapped flux noise in shield	$7 \times 10^{-20} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$	Assuming 10 cm^{-2} flux density
Johnson noise	$10^{-20}(\frac{10^8}{f})$T/$\sqrt{\mathrm{Hz}}$	f is SC shield factor (100 Hz)
Barnett Effect	$10^{-22}(\frac{10^8}{f})$ T	Can be used for calibration above 10 K
Magnetic Impurities in Mass	$10^{-25} - 10^{-17}(\frac{\eta}{1\mathrm{ppm}})(\frac{10^8}{f})$ T	η is impurity fraction (see text)
Mass Magnetic Susceptibility	$10^{-22}(\frac{10^8}{f})$ T	Assuming background field is 10^{-10} T
		Background field can be larger if $f > 10^8$

Table 1: Table of estimated systematic error and noise sources, as discussed in the text. The projected sensitivity of the device is $3 \times 10^{-19}(\frac{1000\mathrm{s}}{T_2})$ T/$\sqrt{\mathrm{Hz}}$

A. Geraci et al., arXiv.1710.05413

Current Status

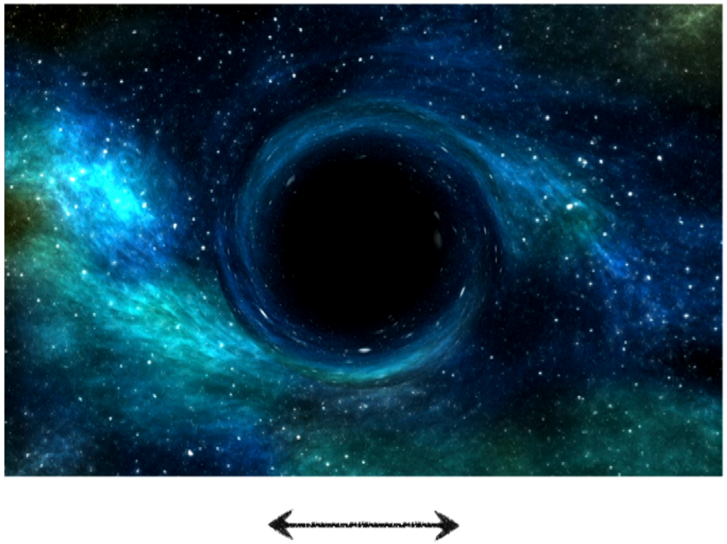
- Source mass and rotation platform being tested at Northwestern University
- Nb shielding tested at Stanford/CAPP
- He-3 sample and cryostat tested in Indiana
- Experiment to be put together in January

How do we look for Dark Matter if it only couples through gravity?

Black Holes as Particle Detectors

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

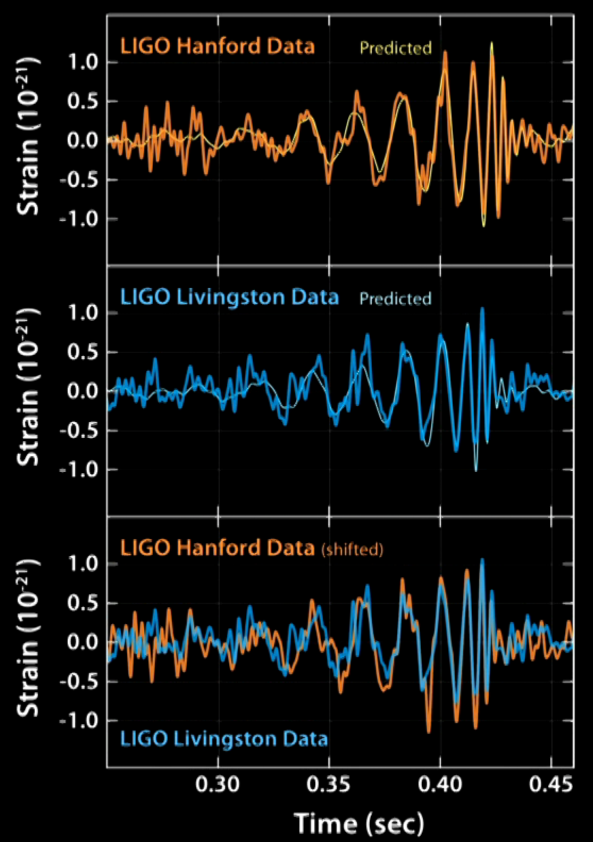
Black Holes as Nature's Detectors

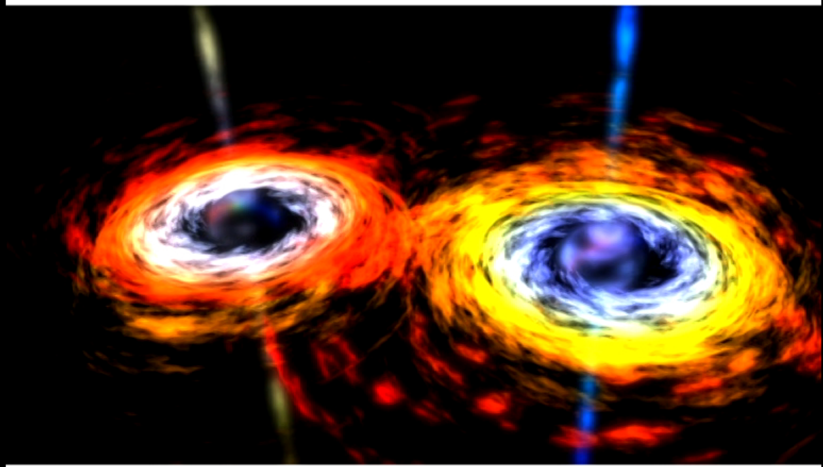


1 km -10 billion km

They can detect bosons of similar in size

September 14, 2015

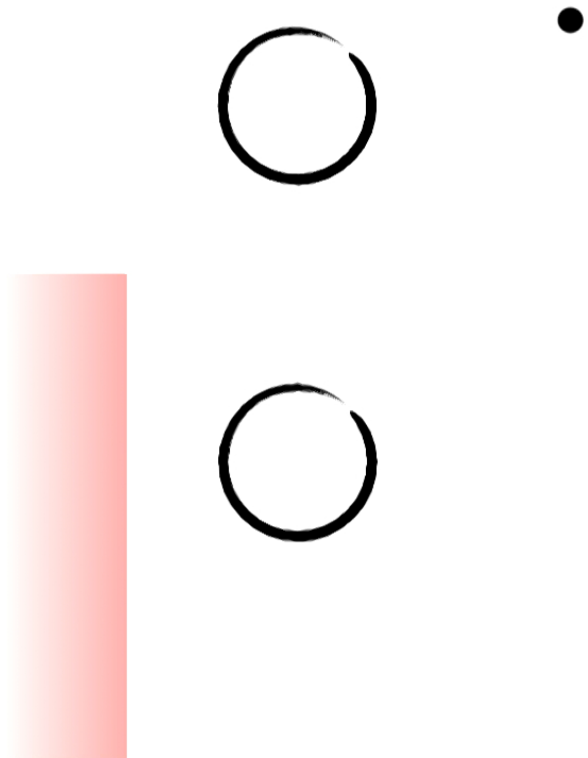




Super-Radiance Cartoon

Super-radiant scattering of a massive object

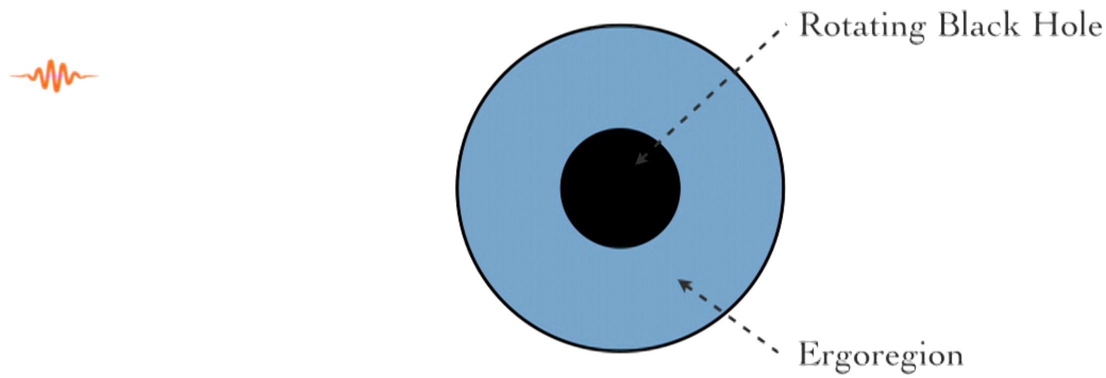
Super-Radiance Cartoon



Super-radiant scattering of a wave

Black Hole Superradiance

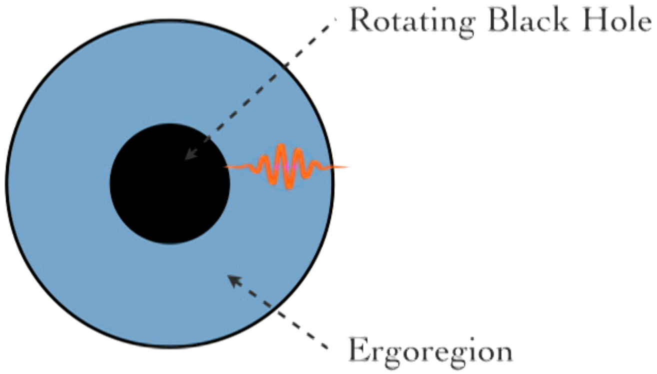
Penrose Process



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 Superradiance

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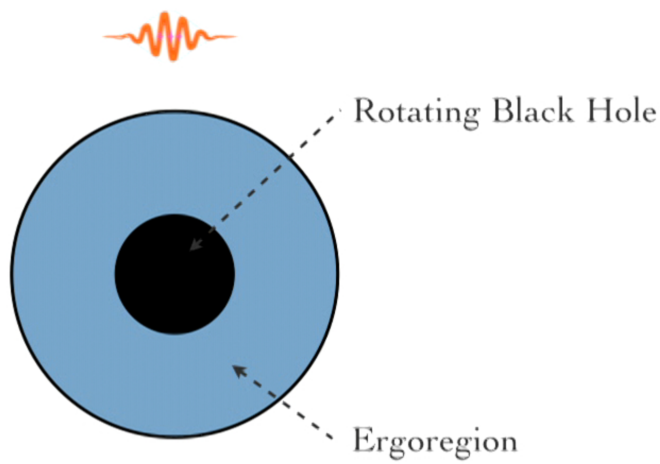

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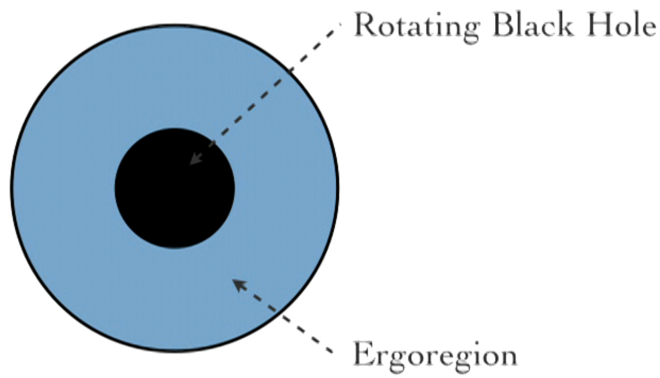
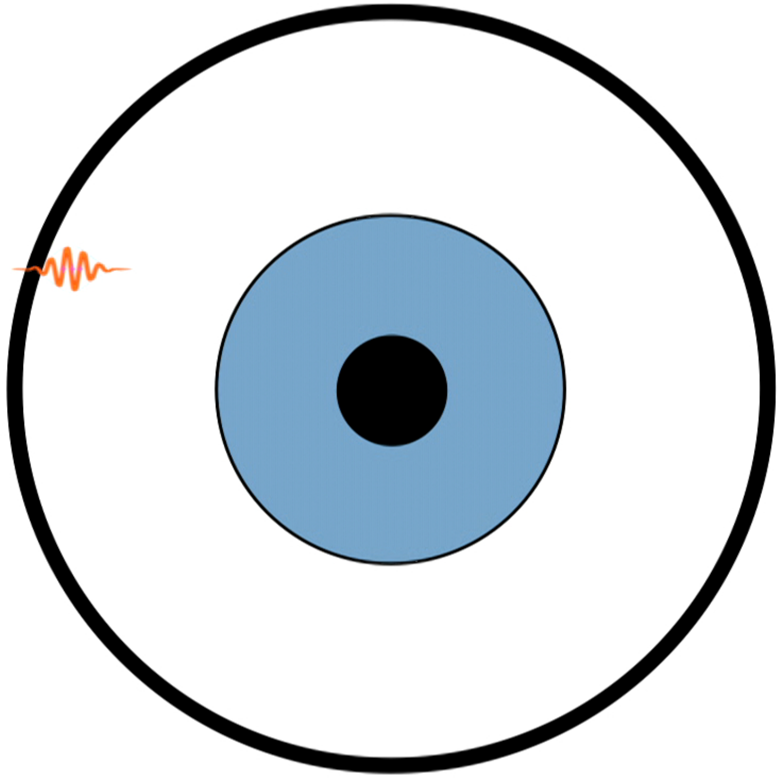


Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

Press & Teukolsky 1972



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

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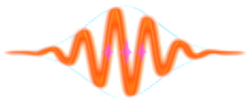

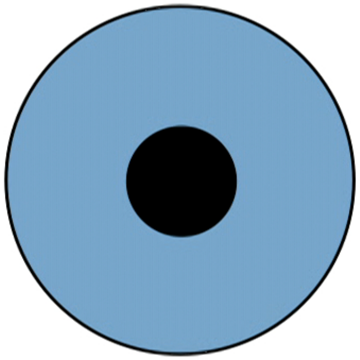

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Superradiance for a massive boson

Damour et al; Zouros & Eardley;
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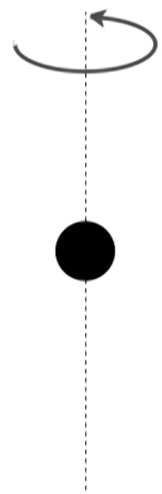

Particle Compton Wavelength comparable to the size of the Black Hole

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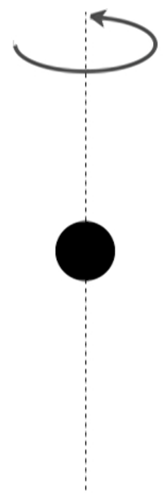

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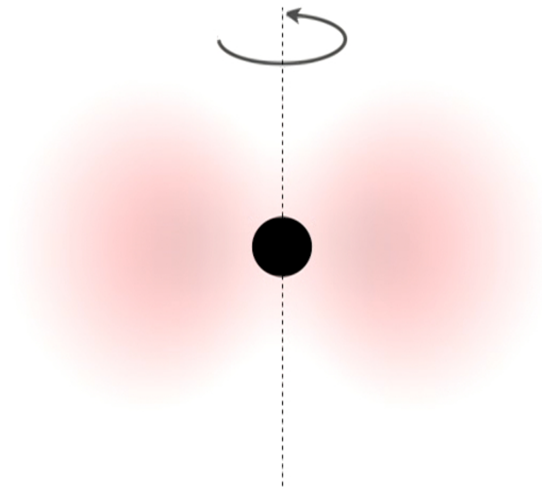

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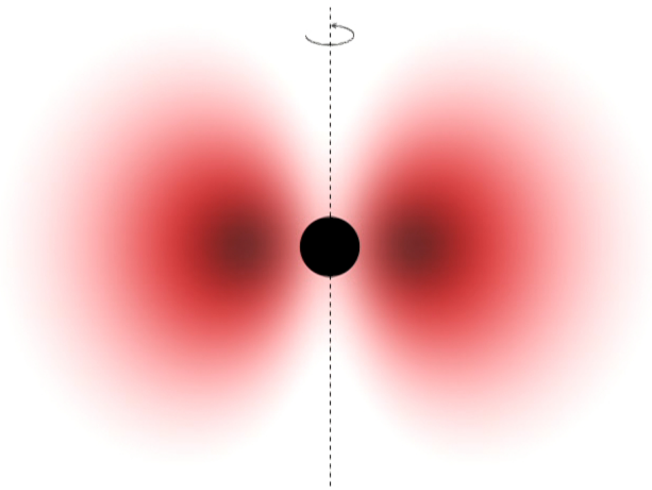

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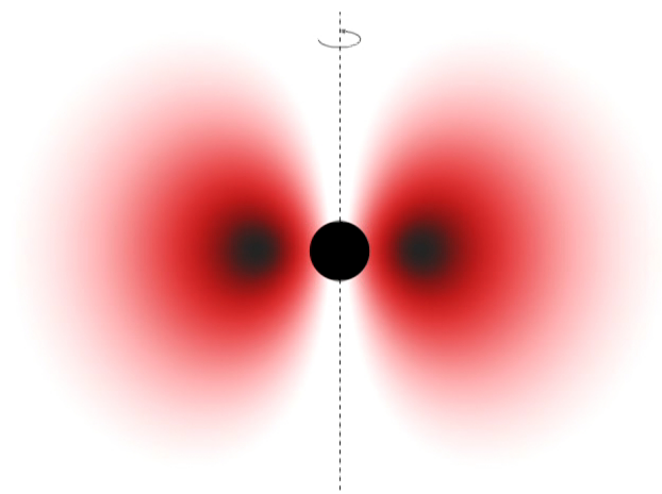
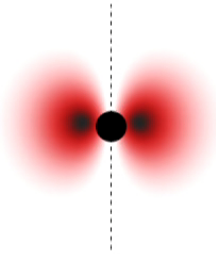


Particle Compton Wavelength comparable to the size of the Black Hole

Gravitational Atom in the Sky

The gravitational Hydrogen Atom



Fine-structure constant: $\alpha = G_N M_{BH} \mu_a = R_g \mu_a$

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

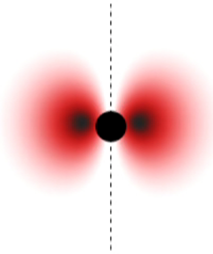
Main differences from hydrogen atom:

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

In-going Boundary Condition at Horizon

Gravitational Atom in the Sky

The gravitational Hydrogen Atom



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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 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 $R_g\ \mu_a >> 1$,

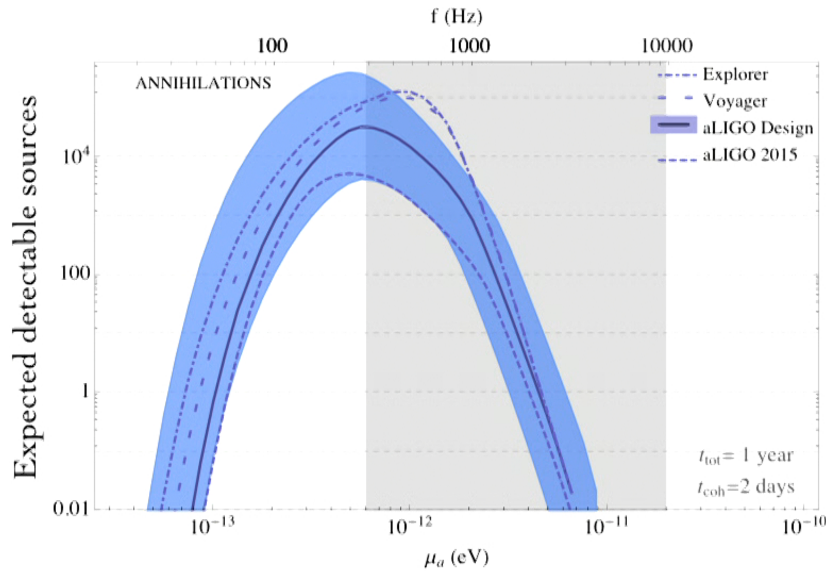
$$\tau_{sr} = 10^7 e^{3.7(\mu_a R_g)} R_g$$

When $R_g\ \mu_a << 1$

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

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

More on superradiance

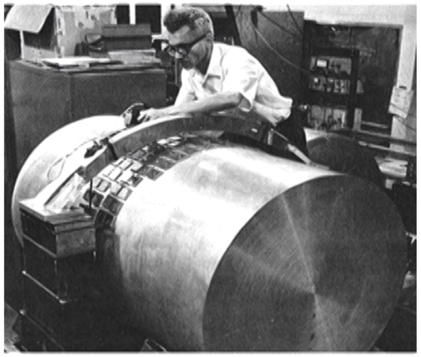
- Vector particle superradiance
  (ex. see work by Baryakhtar, and Lasenby, as well as East)

- Effects of self-interactions and interactions with the environment
  (ex. ongoing by Huang, Baryakhtar and East as well as Baryakhtar, Galanis, Lasenby, Thompson)

- The Event Horizon Telescope

- …

New opportunities at the precision frontier



Weber bar detectors for moduli DM searches

with Dimopoulos and Van Tilburg (2016)

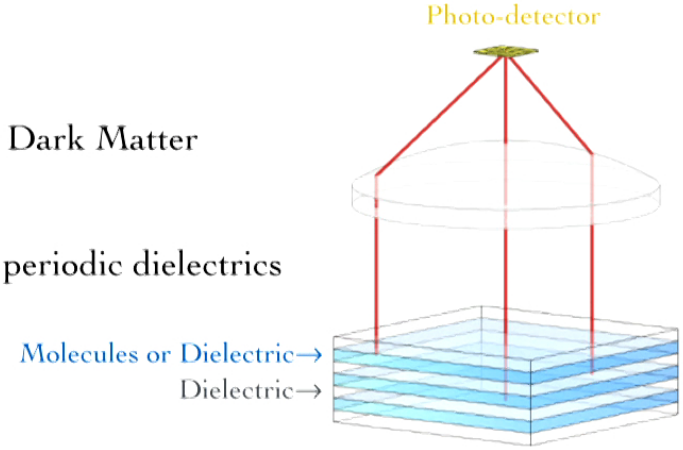
Resonant excitation of molecules by Dark Matter

with Dimopoulos and Van Tilburg (2017)

or

Conversion of Dark Matter to photons in periodic dielectrics

Baryakhtar, Huang, and Lasenby (2018)



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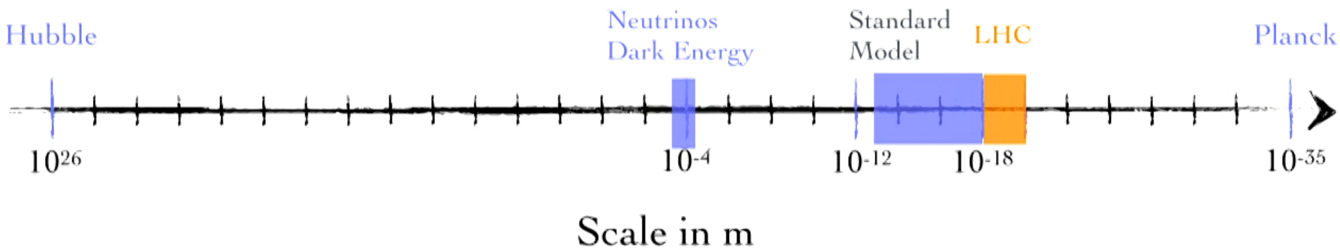

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- Hamlet