Fundamental 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
The Low Energy Frontier

• In the Standard Model
  • Gravitons
  • Cosmic Neutrinos

• In String Theory
  • Axion(s)
  • Photons kinetically mixing with our photon
  • Dilaton, moduli, new dimensions
Opportunities to probe the low energy frontier

- Short Distance Tests of Gravity
- Extra Dimensions

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

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

- Axion Dark Matter Detection
- Axion Force Detection

NMR
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

- Dark Energy: ~73%
- Dark Matter: ~23%

Other nonluminous components:
- Intergalactic gas: 3.6%
- Neutrinos: 0.1%
- Supermassive BHs: 0.04%

Luminous matter:
- Stars and luminous gas: 0.4%
- Radiation: 0.005%
Properties of Dark Matter

- What is it?
- How is it produced?
- Does it have interactions other than gravitational?
What If It Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

Usually we think of …
What If It Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

Usually we think of …

instead of…
What If It Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

Decreasing DM Mass
What If It Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

Equivalent to a Scalar Wave

Frequency set by DM mass and Amplitude set by DM abundance
Theories of Light Scalars

- Moduli, Dilaton, Axions...

- Couples non-derivatively to the Standard Model

\[ \mathcal{L} \supset d_i \frac{\phi}{M_{Pl}} \mathcal{O}_{SM} \]

\[ \mathcal{O}_{SM} \equiv m_{e}e\bar{e}, m_{q}q\bar{q}, G_{s}^{2}, F_{EM}^{2}, \ldots \]
Constraints on Light Scalars

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

\[ F \sim \frac{(d_i Q_i)^2}{4\pi M_P^2} \frac{M_1 M_2}{r^2} e^{-m\phi r} \]

- Generates Equivalence Principle violation
Light Scalar Dark Matter

- Produced by the misalignment mechanism

Frozen when: Hubble > $m_\phi$
Light Scalar Dark Matter

- Produced by the misalignment mechanism

Frozen when: Hubble > $m_\phi$

Oscillates when: Hubble < $m_\phi$

$\rho_\phi$ scales as $a^{-3}$ just like Dark Matter

Initial conditions set by inflation
If $m_\phi < 1 \text{ eV}$, can still be thought of as a scalar field today

Potential Energy

$m_\phi^2 \phi_0^2 \cos^2 (m_\phi t) \sim \rho_\phi$

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

Amplitude compared to $M_{\text{Pl}}$ in the galaxy:

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

From the local oscillation of Dark Matter

Ex. for the electron mass:

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

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

Fractional variation set by square root of DM abundance

Need an extremely sensitive probe…
Light Scalar Dark Matter Detection

- Detecting Dark Matter with Atomic Clocks
- Detecting Dark Matter with Resonant-Mass Detectors
- ARIADNE
Keeping the DM time with Atomic Clocks

with Junwu Huang
and Ken Van Tilburg (2014)
Oscillating Atomic and Nuclear Energy Splittings

- Optical Splittings

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

- 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

\[ \Delta E \left( m_p, \alpha_s, \alpha_{EM} \right) \sim 1 \text{MeV} \]

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 an Atomic Clock Work?

Keep a laser tuned to a long-lived (> minutes) atomic transition.
How do you take the measurements?

- Observe two clocks every $\tau_{\text{cycling}}$

- Calculate ratio of frequencies taking into account:

$$f_A \propto \alpha_{EM}^{\xi_A+2} \left(\frac{m_e}{m_p}\right) \zeta_A$$

$$\frac{\delta f_A}{f_A} = (\xi_A + 2) \frac{\delta \alpha_{EM}}{\alpha_{EM}} + \zeta_A \frac{\delta m_e}{m_e} - \zeta_A \frac{\delta m_p}{m_p}$$

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

Atomic Clock DM searches are broadband searches
Table of atomic transitions used (or to be used)

\[
\frac{\delta f_A}{f_A} = (\xi_A + 2) \frac{\delta \alpha_{EM}}{\alpha_{EM}} + \zeta_A \frac{\delta m_e}{m_e} - \zeta_A \frac{\delta m_p}{m_p}
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Accidental cancellations in Dysprosium optical transitions are very sensitive to EM coupling variations
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Thorium nuclear transition cancellations increase sensitivity to EM coupling and quark mass coupling variations
Not measured yet…
What type of comparisons can we do?

- **Hyperfine to Optical transitions**
  - Sensitive to $m_e$, $m_q$, and $\alpha_s$ (less to $\alpha_{EM}$)

- **Optical to Optical transitions**
  - Sensitive to $\alpha_{EM}$

- **Nuclear to Optical transitions**
  - Sensitive to $m_e$, $\alpha_{EM}$, $m_q$, and $\alpha_s$
Hyperfine to Optical Transition Comparison

Current Sensitivity to $\alpha_s$ and $m_q$ variations

Experiments run for $10^6$ sec or ~ year
Optical to Optical Comparison

Current sensitivity to $\alpha_{EM}$ variations

![Graph showing sensitivity to $\alpha_{EM}$ variations](image)
The Dy isotope and Rb/Cs Clock Comparison

sensitivity to $\alpha_{EM}$ variations

$\log_{10}(f_\phi/\text{Hz})$

$\log_{10}(d_e)$

$\log_{10}(m_{DM}c^2/\text{eV})$

Analysis performed with existing data

Ken Van Tilburg
and the Budker group (2015)

Hees et. al (2016)
What are possible future improvements?

• Optical clock improvements by four orders of magnitude
  • Using more than one atom
  • Using entangled atoms

• The thorium clock under development:
  Nuclear-Optical Clock comparison
Nuclear to Optical Clock Comparison

Future Sensitivity of a $^{229}$Th clock with $10^{-15}/\text{Hz}^{-1/2}$ noise
Comparison of two spatially separated Sr clocks

Gravitational Wave interferometers such as aLIGO not sensitive enough due to laser noise
Keeping the DM time with Atomic Clocks

- Several orders of magnitude improvement possible now compared to 5th force and EP violation searches

- Nuclear clocks if ever built will give several orders of magnitude improvement in the reach
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
The simple harmonic oscillator

of mass $M$, resonant frequency $\omega$ and equilibrium length $L$

$$M \left[ \ddot{x} + \frac{\omega}{Q} \dot{x} + \omega^2 (x - L) \right] = F_{th} + F_{ext}$$

If the equilibrium size changes with time (with $D=x-L$):

$$L = L_o \left( 1 + \frac{\delta L}{L_o} \cos(m_\phi t) \right)$$

$$M \left[ \dddot{D} + \frac{\omega}{Q} \ddot{D} + \omega^2 D \right] \approx -M \ddot{L} + F_{th} + F_{ext}$$
The simple harmonic oscillator

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Driving force from change in the equilibrium position
The Simple Harmonic Oscillator

Dark Matter Driving Force:

\[ F_{DM} = -M \omega^2 L_o h \]

with

\[ h = - \left( \frac{\delta \alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e} \right) \]

Just like a scalar gravitational wave of same strain

Can use resonant-mass detectors to enhance and measure the acoustic waves produced the signal
Resonant-Mass Detectors

- In the 1960's: *The Weber Bar*

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

- Today: AURIGA, NAUTILUS, MiniGrail

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

- Resonant frequency set by size and speed of sound in the material
  - For sizes ~ 1 m resonant frequency of ~1 kHz

- Can take advantage of higher acoustic modes
  - Increases the bandwidth covered by a single device
Resonant-Mass Detectors

- Ultimate sensitivity limited by thermal noise

\[ h_{\text{min}} \sim \sqrt{\frac{4T}{MQ_n\omega_n^3 R^2 J_n^2}} \]

Improves with higher quality factor object size and (effective) mass

\( J_n \): mode overlap with DM signal —drops like \( n^{-2} \)

- Can cover frequencies from 1 kHz all the way to 100 MHz

- Need to worry about bandwidth coverage
The Sun and The Earth as Resonant-Mass Detectors

- Earth’s acoustic mode with frequency (20 min)$^{-1}$ and $Q \sim 7500$

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

- Sun’s acoustic modes with frequency $\sim 1$ mHz and $Q \sim 1000$

- Can potentially use other astrophysical objects

  Good only for setting bounds
What can be done with current resonant-mass detectors?

- **AURIGA**: Ten years of data taking available
- **Quartz**: Experiment by M. Tobar using $Q > 10^{10}$ piezoelectrics
- **Earth**: Using a single monopole seismic mode observed over several months
What can be done in the future?

Need to increase bandwidth

- Dual Mass detectors
- Xylophone
- Copper-Silicon alloy sphere: variations of few percent in sound speed between 4 — 100 K
  - Use temperature to scan resonant frequency
The scanning resonant-mass detector

- Use Fabry-Perot cavity to pick up displacement as small as $10^{-19} \text{ m/(Hz)}^{1/2}$

- Change operating temperature between 4-100 K at 2 mK increments

- Pick up ALL modes at once: continuous coverage above 10kHz
What can be done in the future?

- Probe even the theoretically biased regime of natural couplings and masses

Ex. \( \frac{\delta m_e}{m_e} < 10^{-20} \left( \frac{10 \text{ TeV}}{\Lambda} \right)^2 \)
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

Monopole Interaction
Mass with N nucleons

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

Dipole Interaction
N spins

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

\[
6 \times 10^{-27} \left( \frac{10^9 \text{ GeV}}{f_a} \right) \lesssim g_s \lesssim 10^{-21} \left( \frac{10^9 \text{ GeV}}{f_a} \right)
\]

From CP violation in the Standard Model

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

From CP violation allowed by experiment

Moody and Wilczek (1984)
Short Range Interactions of the Axion

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:

\[ \frac{g_p \mathbf{\bar{\nabla}} a}{m_f} \cdot \mathbf{\bar{\sigma}} \]

\[ \frac{\mathbf{\nabla} a}{\mu_f f_a} \cdot \mathbf{\bar{\mu}}_f \equiv \mathbf{B}_{eff} \cdot \mathbf{\bar{\mu}}_f \]

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

[Diagram of two particles with arrows indicating magnetic fields]
Precision Magnetometry

Nuclear Magnetic Resonance

Resonant transition:
Perturbation at the splitting frequency of the spins

Splitting set by B field
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

\[ \Delta E_{NMR} = \frac{g_p \vec{\nabla} a}{m_f} \cdot \vec{\sigma} \]

On resonance:

\[ \vec{M}(t) = n_{NMR} p \mu \Delta E_{NMR} t \sin \omega t \]

Signal grows till \( T_2 \)

p: polarized fraction, \( n_{NMR} \): density of spin in the detector, \( T_2 \): spin relaxation time
Detection Strategy

Just like a magnetic field

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ARIADNE:
Axion Resonant InterAction DetectioN Experiment

He-3 NMR sample with $T_2$ up to $\sim 1000$ sec
ARIADNE:
Axion Resonant InterAction DetectioN Experiment

$B_{\text{min}} \approx p^{-1} \sqrt{\frac{2\hbar b}{n_s \mu_3^{\text{He}} \gamma V T_2}} = 3 \times 10^{-19} \text{ T} \times$

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

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

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Axion Resonant InterAction DetectioN Experiment

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He-3 NMR sample with \( T_2 \) up to \( \sim 1000 \text{ sec} \)

\[ B_{\text{min}} = 10^{-16} \text{ T/(Hz)}^{1/2} \]
for SQUIDs
Experimental Setup

- 99 Hz Larmor precession frequency for $^3$He nuclei
- $2 \times 10^{21}$ / 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

PQ Axion $m_a$ in eV

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
Major systematics

• Magnetic field screening
  (requires less than $10^{-16} - 10^{-17} \text{T/(Hz)}^{1/2}$, ideally $10^{-19} - 10^{-20} \text{T/(Hz)}^{1/2}$)
  • Use superconducting shields
  • Additional advantages since it is an AC measurement

• Magnetic field gradients
  • Shape of the shield, shimming
  • Spin Echo techniques
Summary for Light Scalar Searches

Searches for Dark Matter

Electron charge or mass coupling relative to Gravity

Quark mass coupling relative to Gravity

Searches for Forces

Experimental Bounds

Astrophysical and Experimental Bounds

Projected Reach

Setup in this proposal $T_2=1000 \text{ sec}$

$T_2=1 \text{ sec}$

PQ Axion Parameter Space

$PQ$ Axion $m_a$ in eV

SQUID Sensitivity Limited Projected Reach

Force Range in cm

$|g_s N_g|$, $|g_p N_p|$
Summary

• Several orders of magnitude improvement in searches for scalar Dark Matter and the QCD axion

• Based on existing and well-established techniques

• There are several more possibilities

This is only scratching the surface…
Length Scales in the Universe

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