Ultralight Dark Matter and the Precision Frontier

Peter Graham
Stanford
Direct Detection

Divide direct detection into two regimes:

DM mass: 

$10^{-22}$ eV

dwarf galaxy size

$10^{19}$ GeV

black holes
Direct Detection

Divide direct detection into two regimes:

DM mass: $10^{-22}$ eV (dwarf galaxy size) to $10^{19}$ GeV

$\rho_{\text{DM}} \approx 0.3 \frac{\text{GeV}}{\text{cm}^3} \approx (0.04 \text{ eV})^4 \quad \Rightarrow \text{high phase space density if} \quad m \lesssim 10 \text{ eV}$
Direct Detection

Divide direct detection into two regimes:

DM mass:  
- $10^{-22}$ eV dwarfgalaxy size
- $10$ eV axion
- $100$ GeV WIMP
- $10^{19}$ GeV black holes

$$\rho_{DM} \approx 0.3 \frac{\text{GeV}}{\text{cm}^3} \approx (0.04 \text{ eV})^4 \ \Rightarrow \text{high phase space density if} \quad m \lesssim 10 \text{ eV}$$
Direct Detection

Divide direct detection into two regimes:

DM mass:

- $10^{-22} \text{ eV}$: dwarf galaxy size
- $10 \text{ eV}$: field-like (e.g. axion)
- $100 \text{ GeV}$: WIMP
- $10^{19} \text{ GeV}$: particle-like (e.g. WIMP)

\[ \rho_{DM} \approx 0.3 \frac{\text{GeV}}{\text{cm}^3} \approx (0.04 \text{ eV})^4 \quad \Rightarrow \text{high phase space density if } m \lesssim 10 \text{ eV} \]

- field-like (e.g. axion)
- new, precision detectors required
- particle-like (e.g. WIMP)
- particle detectors best

black holes
Direct Detection

Divide direct detection into two regimes:

DM mass:

- \(10^{-22} \text{ eV}\) for dwarf galaxy size
- \(10 \text{ eV}\)
- \(100 \text{ GeV}\) for WIMP
- \(10^{19} \text{ GeV}\) for black holes

\[ \rho_{DM} \approx 0.3 \frac{\text{GeV}}{\text{cm}^3} \approx (0.04 \text{ eV})^4 \] high phase space density if \( m \lesssim 10 \text{ eV} \)

- Field-like (e.g. axion) requires new, precision detectors
- Detect coherent effects of entire field (like gravitational wave detector)

- Particle-like (e.g. WIMP) best
- Search for single, hard particle scattering
Direct Detection

Divide direct detection into two regimes:

DM mass: 10^{-22} \text{ eV}

dwarf galaxy size

10 eV

100 GeV

10^{19} \text{ GeV}

\rho_{\text{DM}} \approx 0.3 \frac{\text{GeV}}{\text{cm}^3} \approx (0.04 \text{ eV})^4 \rightarrow \text{high phase space density if } m \lesssim 10 \text{ eV}

field-like (e.g. axion)

new, precision detectors required

Detect coherent effects of entire field (like gravitational wave detector)

Frequency range accessible!

particle-like (e.g. WIMP)

particle detectors best

Search for single, hard particle scattering
“Field” Dark Matter

DM at long deBroglie wavelength useful to picture as a “coherent” field:
“Field” Dark Matter

DM at long deBroglie wavelength useful to picture as a “coherent” field:

particle DM
“Field” Dark Matter

DM at long deBroglie wavelength useful to picture as a “coherent” field:

signal frequency = DM mass = \( m \)

spread by DM kinetic energy \( \sim m v^2 \)

galactic virial velocity \( v \sim 10^{-3} \) \( \Rightarrow \) line width \( \sim 10^{-6} m \)

\( \Rightarrow \) coherence time, \( Q \sim 10^6 \) periods
New High Precision Experiments for DM

Caveat: I will only describe a few ideas (that I’ve been involved in), but there are many more new experiments, this is a rapidly evolving area!
DM Radio

with

Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Surjeet Rajendran
Yue Zhao

+ collaborating with Tony Tyson + Mani Tripathi’s groups (Davis)
DM Radio Experiment

Widely tunable, lumped element EM resonator
- low dissipation/low noise resonator Q ~ $10^6$
- high precision magnetometry/amplifiers (SQUIDs)
DM Radio Experiment

Widely tunable, lumped element EM resonator
- low dissipation/low noise resonator $Q \sim 10^6$
- high precision magnetometry/amplifiers (SQUIDs)

Pathfinder: 4 K  300 cm³  under construction, initial results ~ 2018

start with hidden photon detection, later add B field for axion detection

see Arran Phipps’s talk here
DM Radio

galactic virial velocity $\sim 10^{-3}$ $\Rightarrow$ dark matter signal width $\sim 10^{-6} f$

must scan frequencies to find dark matter
DM Radio

galactic virial velocity $\sim 10^{-3}$ → dark matter signal width $\sim 10^{-6} f$

must scan frequencies to find dark matter

optimal experiment:

- make highest resonator Q possible, even above $10^6$
- take analysis bandwidth (step size) much broader than resonator and dark matter bandwidth:

can enhance sensitivity by orders of magnitude
Ultralight DM Direct Detection

DM mass: $10^{-22}$ eV, $10^{-18}$ eV, $10^{-14}$ eV, $10^{-10}$ eV, $10^{-6}$ eV, $10^{-2}$ eV

Frequency: $10^{-8}$ Hz, $10^{-4}$ Hz, 1 Hz, $10^4$ Hz, $10^8$ Hz, $10^{12}$ Hz
Ultralight DM Direct Detection

DM mass: $10^{-22}$ eV, $10^{-18}$ eV, $10^{-14}$ eV, $10^{-10}$ eV, $10^{-6}$ eV, $10^{-2}$ eV

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E&M and DM Radio
Ultralight DM Direct Detection

- DM mass: $10^{-22}$ eV
- $10^{-18}$ Hz
- $10^{-14}$ Hz
- $10^{-10}$ Hz
- $10^{-6}$ Hz
- $10^{-2}$ Hz

E&M
DM Radio
also: cavities, dielectrics…
see talks by C. Boutan, J. Yoo, A. Millar
Cosmic Axion Spin Precession Experiment (CASPER)

with

Dmitry Budker
Micah Ledbetter
Surjeet Rajendran
Alex Sushkov

Axion solution to strong CP problem:
make nucleon EDM dynamical instead of a fundamental constant
dependent on background axion field
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make nucleon EDM dynamical instead of a fundamental constant
dependent on background axion field

→ axion DM causes oscillatory nuclear EDM

using this nuclear coupling completely changes axion detection
this QCD coupling is only axion coupling not derivative-suppressed at low mass

generally light bosonic DM causes oscillating fundamental “constants”
Cosmic Axion Spin Precession Experiment (CASPER)

search for oscillating nuclear EDM
Cosmic Axion Spin Precession Experiment (CASPER)

search for oscillating nuclear EDM

Applied EM fields cause NMR-style resonance
SQUID measures resulting transverse magnetization
Cosmic Axion Spin Precession Experiment (CASPER)

search for oscillating nuclear EDM

Applied EM fields cause NMR-style resonance
SQUID measures resulting transverse magnetization

Only known way to reach QCD axion at lowest masses $\sim$ kHz - MHz
Cosmic Axion Spin Precession Experiment (CASPEr)

search for oscillating nuclear EDM

Applied EM fields cause NMR-style resonance
SQUID measures resulting transverse magnetization

Only known way to reach QCD axion at lowest masses ~ kHz - MHz

under construction at Mainz and BU

Sensitivity comes from:
• NMR technology
• high precision magnetometry
Ultralight DM Direct Detection

DM mass:

\begin{align*}
10^{-22} \text{ eV} & & 10^{-18} \text{ eV} & & 10^{-14} \text{ eV} & & 10^{-10} \text{ eV} \ & & 10^{-6} \text{ eV} & & 10^{-2} \text{ eV} \\
10^{-8} \text{ Hz} & & 10^{-4} \text{ Hz} & & 1 \text{ Hz} & & 10^4 \text{ Hz} & & 10^8 \text{ Hz} & & 10^{12} \text{ Hz} \\
\end{align*}

\[ \text{E&M} \]

DM Radio
Ultralight DM Direct Detection

DM mass:

- $10^{-22}$ eV
- $10^{-18}$ eV
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Frequencies:

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- $10^{12}$ Hz

Techniques:

- E&M
- DM Radio
- NMR
- CASPEr
Axion DM Effects

Spin coupling: \((\partial_\mu a) \bar{\psi} \gamma^\mu \gamma_5 \psi \rightarrow H \ni \nabla a \cdot \vec{\sigma}_N\)

Axion DM field gradient torques electron and nucleon spins oscillates with axion frequency proportional to axion momentum ("wind")
Axion DM Effects

spin coupling: \((\partial_{\mu} a) \bar{\psi} \gamma^\mu \gamma_5 \psi \rightarrow H \propto \nabla a \cdot \vec{\sigma}_N\)

Axion DM field gradient torques electron and nucleon spins oscillates with axion frequency proportional to axion momentum ("wind")

Scalar coupling: \(a H^\dagger H\) e.g. change electron mass

Axion DM field gradient can exert a force oscillatory and violates equivalence principle

Same effects allow searches for hidden photons
Force/Torque from Dark Matter


New oscillatory force/torque from dark matter
Equivalence principle violating

New Direct Detection Experiments:
Force/Torque from Dark Matter


New oscillatory force/torque from dark matter
Equivalence principle violating

New Direct Detection Experiments:

Torsion Balances
scalar balance for force
spin-polarized for torque

Eot-Wash analysis underway
Force/Torque from Dark Matter


New oscillatory force/torque from dark matter
Equivalence principle violating

New Direct Detection Experiments:

Torsion Balances
scalar balance for force
spin-polarized for torque

Atomic Interferometers (Clocks)
split + recombine atom wavefunction
measure atom spin and acceleration

Eot-Wash analysis underway
In construction Kasevich/Hogan groups
Force/Torque from Dark Matter


New oscillatory force/torque from dark matter
Equivalence principle violating

New Direct Detection Experiments:

Torsion Balances
scalar balance for force
spin-polarized for torque

Atomic Interferometers (Clocks)
split + recombine atom wavefunction
measure atom spin and acceleration

Pulsar Timing Arrays
measure relative acceleration of earth and pulsar

Eot-Wash analysis underway
In construction Kasevich/Hogan groups
ultralight DM and gravitational wave detection similar!
MAGIS-100 Proposal at Fermilab

- MINOS, MINERνA, and NOνA experiments use the NuMI beam
- 100 meter access shaft
- Atom DM detector (small scale project)
- 100 m atom interferometer drop tower
- Detect dark matter through oscillatory force/torque
- Demonstrator for future gravitational wave detector
Gravitational Wave Detection with Atom Interferometry

GRG 43 (2011) arXiv:1009.2702
Gravitational Spectrum

Gravitational waves open a new window to the universe

Every new EM band opened has revealed unexpected discoveries,

Advanced LIGO can only detect GW’s > 10 Hz ➜ How look at lower spectrum?

New detectors?
Gravitational Wave Detection

Gravitation Wave Detector

inertial test masses

baseline

good clock
Gravitational Wave Detection

Gravitation Wave Detector

LIGO

inertial test masses

mirrors

baseline

laser

good clock

second arm
Gravitational Wave Detection

Gravitation Wave Detector

- inertial test masses
- baseline
- good clock

LIGO

- mirrors
- laser
- second arm

Atom Interferometry

- atoms
- laser
- atoms
Gravitational Wave Detection

Gravitation Wave Detector

- inertial test masses
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- good clock

LIGO

- mirrors
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- second arm

Atom Interferometry

- atoms
- laser
- atoms

Atom Interferometers
Atom Interferometry for Gravitational Waves

Future detectors (terrestrial + satellite) could access mid-frequency band:

for example this band allows:

• observe new sources
• localize and predict BH and NS binary mergers for other telescopes to observe
• good measurement of BH spins

with Sunghoon Jung
Ultralight DM Direct Detection

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Methods: E&M, DM Radio, NMR, CASPEr
Ultralight DM Direct Detection

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Methods:

- torsion balances
- Eot-Wash
- atom interferometry
- MAGIS
- atomic magnetometers
- Romalis and Trahms groups
- E&M
- DM Radio
- NMR
- CASPEr
Ultralight DM Direct Detection

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- NMR
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- Romalis and Trahms groups

E&M

DM Radio

these + many more new experiments (and ideas) will hopefully cover entire mass range for ultralight DM!
Summary

Precision measurement is a powerful tool for particle physics and cosmology
e.g. combination of several experiments will cover QCD axion dark matter fully

Light dark matter (axions) and gravitational wave detection similar:
detect coherent effects of entire field, not single particles

- EM resonators
- laser interferometry
- atom interferometry (clocks)
- NMR
- high-precision magnetometry (SQUIDs, atomic systems)
- torsion pendulums
- optically-levitated dielectric spheres
- ...

Many more possibilities we haven’t thought of yet…
Backup Slides
current technology already allows many new searches, and will improve by orders of magnitude
Possibilities for Light Dark Matter

Effective field theory ➔ only a few possible couplings to us 
either scalar or vector, four types of experiments:

light DM

Possibilities for Light Dark Matter

Effective field theory → only a few possible couplings to us either scalar or vector, four types of experiments:

- **E&M - drive currents**
  \[ a \, F \, \tilde{F} \]

- **QCD - change nuclear properties**
  \[ a \, G \, \tilde{G} \]

- **spin - cause precession**
  \[ (\partial_\mu a) \psi \gamma^\mu \gamma_5 \psi \]

- **scalar - new force/SM properties**
  \[ aH^\dagger H \]

Possibilities for Light Dark Matter

Effective field theory → only a few possible couplings to us either scalar or vector, four types of experiments:

- E&M - drive currents
  \[ a \, F \, \tilde{F} \]
- QCD - change nuclear properties
  \[ a \, G \, \tilde{G} \]
- spin - cause precession
  \[ (\partial_\mu a) \psi \gamma^\mu \gamma_5 \psi \]
- scalar - new force/SM properties
  \[ a \, H^\dagger \, H \]

current axion searches e.g. ADMX

light DM

Possibilities for Light Dark Matter

Effective field theory → only a few possible couplings to us either scalar or vector, four types of experiments:

**E&M - drive currents**
\[ \alpha F \tilde{F} \]

current axion searches
e.g. ADMX

**QCD - change nuclear properties**
\[ \alpha G \tilde{G} \]
e.g. aids axion detection

**spin - cause precession**
\[ (\partial_\mu a) \psi \gamma^\mu \gamma_5 \psi \]

**scalar - new force/SM properties**
\[ \alpha H^\dagger H \]

Can cover all these possibilities

DM Radio Sensitivity to Hidden Photons

coupling to E&M
we found hidden photon DM is produced by inflation, and in this frequency range

PWG, Mardon, Rajendran PRD 93 (2016)

a discovery allows measurement of DM power spectrum:
verify quantum fluctuation production
and measure scale of inflation
Axion Limits on \( \frac{\alpha}{f_a} G \tilde{G} \)

\[ g_d = \frac{d_N}{\alpha} \]

\[ d_N = -\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} \]
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Gravitational Wave Detection with Atom Interferometry

with

Savas Dimopoulos
Jason Hogan
Mark Kasevich
Surjeet Rajendran

GRG 43 (2011) arXiv:1009.2702
Recent Experimental Results
(Kasevich and Hogan groups)

Stanford Test Facility

Macroscopic splitting of atomic wavefunction: