Laser Probes of the Dark Sector

Jason H. Steffen
Fermilab Center for Particle Astrophysics
Northwestern University

Jefferson Lab
September 2012
Outline

• The Dark Sector

• GammeV – a dark matter search

• CHASE – a test of chameleon dark energy

• Holometer – a search for new gravitation phenomena

• Future endeavors for electromagnetic probes of the dark sector
The Dark Sector

dark matter, dark energy, gravity
Dark Matter WIMPs

A non-relativistic particle with a Weak-scale cross section naturally produces the observed amount of dark matter.
Dark Matter WIMPs

A non-relativistic particle with a Weak-scale cross section naturally produces the observed amount of dark matter.

Who is looking for WIMP dark matter?
Dark Matter WIMPs

A non-relativistic particle with a Weak-scale cross section naturally produces the observed amount of dark matter.

Who is looking for WIMP dark matter?

Who isn't looking for WIMP dark matter?
Axions, the other dark matter
Axions, the other dark matter

The QCD Lagrangian has this

\[ \mathcal{L} = -\frac{1}{4} \text{tr} F_{\mu\nu} F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2} \text{tr} F_{\mu\nu} \tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta\gamma_5})\psi \]

which should be of order unity.

This would give the neutron an electric dipole moment.

Measurements indicate that \(\theta\) must be less than \(\sim 10^{-10}\).

This discrepancy is known as the “strong CP problem”.
Axions, the other dark matter

Peccei-Quinn ('77), Wilczek ('78), Weinberg ('78) proposed a solution:

\[ \mathcal{L}_{\text{int}} = -\frac{1}{4} \frac{\phi}{M} F_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{\phi}{M} (\vec{E} \cdot \vec{B}) \]

Pseudoscalar coupling to two photons.

The coupling constant and mass depend upon the mass and coupling constant of the pion:

\[ (f_a m_a = f_\pi m_\pi) \]

String theories also predict a variety of scalar or pseudoscalar axion-like particles.
Axions, the other dark matter

If axions are the dark matter, they would live here.
Numerology

Dark Energy: $\Lambda = (2 \text{ meV})^4$

Neutrino Masses: 

\[
\begin{align*}
(\Delta m_{21})^2 &= (9 \text{ meV})^2 \\
(\Delta m_{32})^2 &= (50 \text{ meV})^2
\end{align*}
\]

Weak Scale See Saw: $\text{meV} \sim \text{TeV}^2/M_{\text{Planck}}$
Numerology

Dark Energy: \[\Lambda = (2 \text{ meV})^4\]

Neutrino Masses: 
\[\left(\Delta m_{21}\right)^2 = (9 \text{ meV})^2\]
\[\left(\Delta m_{32}\right)^2 = (50 \text{ meV})^2\]

Weak Scale See Saw: \[\text{meV} \sim \text{TeV}^2/M_{\text{Planck}}\]

hc \sim 1\text{meV mm}
Numerology

Dark Energy: \[ \Lambda = (2 \text{ meV})^4 \]

Neutrino Masses: \[
(\Delta m_{21}^2) = (9 \text{ meV})^2 \\
(\Delta m_{32}^2) = (50 \text{ meV})^2
\]

Weak Scale See Saw: meV ~ TeV\(^2/M_{\text{Planck}}\)

hc ~ 1meV mm

\[ \Delta m^2 \frac{L}{E} \sim \text{meV}^2 \text{ m/eV} \]
Numerology

Dark Energy: \( \Lambda = (2 \text{ meV})^4 \)

Neutrino Masses: 
\( (\Delta m_{21}^2)^2 = (9 \text{ meV})^2 \)
\( (\Delta m_{32}^2)^2 = (50 \text{ meV})^2 \)

Weak Scale See Saw: \( \text{meV} \sim \text{TeV}^2/M_{\text{Planck}} \)

\( hc \sim 1\text{meV}\text{mm} \)

\( \Delta m^2 L/E \sim \text{meV}^2 \text{ m/eV} \)
Dark Energy: $\Lambda = (2 \text{ meV})^4$

Neutrino Masses: $(\Delta m_{21}^2)^2 = (9 \text{ meV})^2$
$(\Delta m_{32}^2)^2 = (50 \text{ meV})^2$

Weak Scale See Saw: $\text{meV} \sim \text{TeV}^2/M_{\text{Planck}}$

$hc \sim 1\text{meV mm}$

$\Delta m^2 L/E \sim \text{meV}^2 \text{m/eV}$

Optical Photons
Laser searches for axion-like particles
GammeV search for axion-like particles
GammeV search for axion-like particles
Dark Energy

Situation somewhat similar to axions.

The vacuum should have some energy density,

$$E_{\text{ground}} = \frac{1}{2} \hbar \omega$$

for each “smallest” box.
**Dark Energy**

Situation somewhat similar to axions.

The vacuum should have some energy density,

\[ E_{\text{ground}} = \frac{1}{2} \hbar \omega \]

for each “smallest” box.

\[ \Lambda_{\text{theory}} = \frac{E_{\text{ground}}}{\ell_P^3} \sim M_P^4 \sim 10^{124} \text{ meV}^4 \]
Dark Energy

Situation somewhat similar to axions.

The vacuum should have some energy density,

\[ E_{\text{ground}} = \frac{1}{2} \hbar \omega \]  

for each “smallest” box.

\[ \Lambda_{\text{theory}} = \frac{E_{\text{ground}}}{\ell_P^3} \sim M_P^4 \sim 10^{124} \text{ meV}^4 \]

\[ \Lambda_{\text{experiment}} = 2 \text{ meV}^4 \]
Dark Energy

Situation somewhat similar to axions.

The vacuum should have some energy density,

\[ E_{\text{ground}} = \frac{1}{2} \hbar \omega \]  
for each "smallest" box.

\[ \Lambda_{\text{theory}} = \frac{E_{\text{ground}}}{\ell_P^3} \sim M_P^4 \sim 10^{124} \text{ meV}^4 \]

\[ \Lambda_{\text{experiment}} = 2 \text{ meV}^4 \]

Slight discrepancy
Dark Energy

Situation somewhat similar to axions.

The vacuum should have some energy density,

$$E_{\text{ground}} = \frac{1}{2} \hbar \omega$$

for each “smallest” box.

$$\Lambda_{\text{theory}} = \frac{E_{\text{ground}}}{\ell_P^3} \sim M_P^4 \sim 10^{124} \text{ meV}^4$$

$$\Lambda_{\text{experiment}} = 2 \text{ meV}^4$$

Ask Santa Claus to force vacuum contribution to zero and add a new particle that will supply the measured energy density.
Physicists Toolkit

Experimentalist

Theorist
Physicists Toolkit

Experimentalist

If something should move but it doesn't...

Theorist
Physicists Toolkit

Experimentalist

If something should move but it doesn't...

If something moves but it shouldn't...

Theorist
Physicists Toolkit

**Experimentalist**

If something should move but it doesn't...

**Theorist**

If something moves but it shouldn't...

(anthropic principle)

If something moves but it shouldn't...

**Sum, ergo ita est.**
Physicists Toolkit

**Experimentalist**

If something should move but it doesn't...

**Theorist**

If something moves but it shouldn't...

(anthropic principle)

\( \Phi \)

(scalar field)

\( \text{Sum, ergo ita est.} \)
Experimental Evidence for Scalar Fields
Experimental Evidence for Scalar Fields

\[ V = -\frac{GM}{r} \left( 1 + \alpha \frac{e^{-r/\lambda}}{r} \right) \]
How do you hide a scalar field?

\[ \nabla^2 \phi + m^2 \phi = \frac{g}{M_{\text{Pl}}} \rho \]

\[ K(\rho) \nabla^2 \phi + m^2 \phi = \frac{g}{M_{\text{Pl}}} \rho \]

\[ \nabla^2 \phi + m^2 \phi = \frac{g(\rho)}{M_{\text{Pl}}} \rho \]

\[ \nabla^2 \phi + M^2(\rho) \phi = \frac{g}{M_{\text{Pl}}} \rho \]

Vainshtein

Symmetron

Chameleon

Slides stolen from Justin Khoury
The Chameleon Effect

\[ S = \int d^4x \sqrt{-g} \left[ \frac{R}{16\pi G} - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{1}{4} e^{\frac{\beta_1 \phi}{M_{Pl}}} F_{\mu \nu} F^{\mu \nu} + \mathcal{L}_m \left( e^{\frac{2 \beta_m \phi}{M_{Pl}}} g_{\mu \nu}, \psi_m^{(i)} \right) \right] \]

chameleon potential

photon coupling

matter coupling

Sketch of chameleon mechanism: Low Density Background

Sketch of chameleon mechanism: High Density Background

Effective minimum \( \phi = \phi_c(\rho) \)

Mass of \( \phi \) near \( \phi_c \) is small because \( V_{\text{eff}} \) is quite flat near \( \phi_c \)

Mass of \( \phi \) near \( \phi_v \) is large because \( V_{\text{eff}} \) is quite steep near \( \phi_v \)

Mota & Shaw 2007
We consider potentials of the form

\[ V(\phi) = M^4 \exp(\phi^N/M^N) \approx M^4 \left(1 + \frac{\phi^N}{M^N}\right) \]

- \( M \) is the dark energy scale, \( 2.4 \times 10^{-3} \text{eV} \)

In bulk matter density, \( m_{\text{eff}} \) scales as

\[ m_{\text{eff}} = \frac{(N-2)}{(2N-2)} \]

- \( = (N-2)/(2N-2) \)
- \( = 1/3 \) for \( \phi^4 \) theory, \( = 3/4 \) for \( 1/\phi \) model
Quantum Measurement: Walls

Quantum Measurement: Windows
a) production: Stream photons through the magnetic field region via glass windows. Any chameleon particles produced will be trapped in the chamber.

b) afterglow: Turn off the photon source, and wait for chameleon particles to convert back into detectable photons, which emerge through the windows.
Expected Signal

The figure shows the expected signal over time, with different lines representing different values of $\beta_\gamma$ and two sets of lines, solid and dotted, corresponding to different values of $m_{\text{eff}}$.

- Solid lines: $m_{\text{eff}} = 1 \times 10^{-4} \text{eV}$
- Dotted lines: $m_{\text{eff}} = 5 \times 10^{-4} \text{eV}$

The observation period is highlighted in yellow, indicating a specific time range of interest.
Constraints from GammeV

![Graph showing constraints from GammeV on effective chameleon mass in chamber and photon coupling. The graph distinguishes between Pseudoscalar and Scalar models.](image-url)
Constraints from GammeV

- Transition and B field
- Magnetic field length
- Detector systematic uncertainty
- Vacuum system design

Diagram:
- Effective chameleon mass in chamber [eV]
- Photon coupling $\beta_\gamma$
- Pseudoscalar and Scalar regions
- Power Law Models: $\phi^4$, $\phi^6$, $\phi^8$, $\text{Exp}[^{2/\phi^2}]$, $\text{Exp}[^{\Lambda/\phi}]$
CHASE Schematic
Lowering the magnetic field allows us to probe larger photon couplings and to eliminate some systematic effects.
Orange Glow

![Graph showing rate (Hz) over time (sec)]
Orange Glow

\[ \Gamma_{\text{preferred}}(t) = \Gamma_1 e^{-\gamma_1 t} + \frac{\Gamma_2 e^{-\gamma_2 t}}{1 - \xi e^{-\gamma_2}} + C \]

Steffen et al. (2012)
CHASE Science Data

Excess Rate (Hz) vs. $\log_{10} t$ (sec)

- Scalar
- Pseudoscalar
95% Confidence Level

Constraints from CHASE

- Collider constraints
- GammaV constraints
- Scalar
- Pseudoscalar

Effective mass $m_{\text{eff}}$ [eV]

Power Law Models
- $\phi^4$
- $\phi^6$
- $\phi^8$

Dark Energy Models
- $\exp[\Lambda^2/\phi^2]$
- $\exp[\Lambda/\phi]$
Constraints from CHASE

95% Confidence Level

Collider constraints

GammaV constraints

scalar
pseudoscalar

30,000 TeV

Power Law Models
- $\phi^4$
- $\phi^6$
- $\phi^8$

Dark Energy Models
- $\text{Exp}[\Lambda^2/\phi^2]$
- $\text{Exp}[\Lambda/\phi]$
Model Dependent Results

95% Confidence Level

Collider constraints

\[ g_\gamma = \beta_\gamma / M_{Pl} [\text{GeV}^{-1}] \]

\[ \beta_\gamma \]

\[ \beta_m \]

\[ n=-1 \]
\[ n=-2 \]
\[ n=-4 \]
\[ n=4, \lambda=10^{-2} \]
\[ n=4, \lambda=10^{-4} \]

Power Law Models

\[ \phi^4 \]
\[ \phi^6 \]
\[ \phi^8 \]

Dark Energy Models

\[ \text{Exp}[\Lambda/\phi] \]
\[ \text{Exp}[\Lambda^2/\phi^2] \]
Model Dependent Results

95% Confidence Level

Collider constraints

\( g_\gamma = \frac{\beta_\gamma}{M_{Pl}} [\text{GeV}^{-1}] \)

\( n = -1 \)
\( n = -2 \)
\( n = -4 \)
\( n = 4, \lambda = 10^{-2} \)
\( n = 4, \lambda = 10^{-4} \)

Power Law Models

\( \phi^4 \)
\( \phi^6 \)
\( \phi^8 \)

Dark Energy Models

\( \text{Exp}[\Lambda^2/\phi^2] \)
\( \text{Exp}[\Lambda/\phi] \)
The Intensity Frontier:
1 Mega Watt 100 GeV proton beam \( \sim 10^{14} \) protons/second
More Numerology

The Intensity Frontier:
1 Mega Watt 100 GeV proton beam $\sim 10^{14}$ protons/second
1 Watt eV photon beam $\sim 10^{19}$ photons/second
More Numerology

The Intensity Frontier:
- 1 Mega Watt 100 GeV proton beam \( \sim 10^{14} \) protons/second
- 1 Watt eV photon beam \( \sim 10^{19} \) photons/second

Add a resonating cavity...
- Increase power by a factor of 100 to 100,000
- Power recycle for a factor of 10 to 100
The Intensity Frontier:
   1 Mega Watt 100 GeV proton beam $\sim 10^{14}$ protons/second
   1 Watt eV photon beam $\sim 10^{19}$ photons/second

Add a resonating cavity...
   Increase power by a factor of 100 to 100,000
   Power recycle for a factor of 10 to 100

Use an interferometer...
   Angular sensitivity $\sim 10^{-12}$ radians
   Differential length sensitivity $\sim 10^{-19}$ meters
The Intensity Frontier

Working group on
Hidden Sector Photons, Axions, and WISPs
The Intensity Frontier

New Light, Weakly Coupled Particles
Laser Test of Gravity: The Holometer

Bold idea from black hole physics: the world is a hologram

“This is what we found out about Nature’s book keeping system: the data can be written onto a surface, and the pen with which the data are written has a finite size.”

-Gerard ‘t Hooft

Everything is written on 2D surfaces moving at the speed of light

Are there experimental consequences of this idea?
Laser Test of Gravity: The Holometer

Suppose that there is an information bound at the Planck scale – Planck-sized bits on a null surface (light sheet).

Displacement noise is equivalent to the size of the diffraction spot:

$$\Delta x^2 = l_p L$$
Laser Test of Gravity: The Holometer

Michelson interferometer

Events contributing to interferometer signal

On worldlines of beamsplitter and two end mirrors

Measurement is coherent, nonlocal in space and time, includes position in two directions
Laser Test of Gravity: The Holometer

Top view of diamonds for one interferometer

(a)

“T” configuration
No overlap of diamonds from end mirrors
No signal correlations

(b) “L” configuration
Highly entangled diamonds
Highly correlated signals

(c)
Laser Test of Gravity: The Holometer
Laser Test of Gravity: The Holometer
Final Slide of Numerology

$$\sqrt{\frac{\ell_P}{H_0}} \simeq \frac{1}{2} \text{ mm (4 meV)}$$
Where we go from here?
Where to go: Paraphoton Search

Signatures of a Hidden Cosmic Microwave Background

Joerg Jaeckel, Javier Redondo, and Andreas Ringwald

1 Institute for Particle Physics and Phenomenology, Durham University, Durham DH1 3LE, United Kingdom
2 Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany

(Received 23 May 2008; published 26 September 2008)

The Case for Dark Radiation

Maria Archidiacono, Erminia Calabrese, and Alessandro Melchiorri

a Physics Department and INFN, Università di Roma “La Sapienza”, Ple Aldo Moro 2, 00185, Rome, Italy
Where to go: Paraphoton Search
Where to go: Paraphoton Search
Where to go: Axion Search
Enhance production of axions with this cavity

Reconverted photons resonantly drive this cavity

Where to go: Axion Search
Where to go: Axion Search

Enhance production of axions with this cavity

Reconverted photons resonantly drive this cavity
Where to go: Cavity Axion Search

Tevatron Dipole

RF Cavities
Where to go: Cavity Axion Search

- Tevatron Dipole
- RF Cavities
Where to go: Cavity Axion Search
Conclusions

- 96% of the universe lives in the dark sector

- Laser probes of the dark sector cover a wide variety of physics
  - Axions and axion-like particles may be dark matter constituents
  - Dark energy models with weak couplings to photons
  - The Holometer probes the fundamental nature of spacetime

- A wide variety of future experiments are being conceived
  - The Holometer (now partly constructed)
  - Resonant regeneration axion search
  - Low-mass (meV) paraphotons from the Sun
  - Axion haloscope using Tevatron dipole magnets

- Recent workshop on experimental tests of dark energy
  - Sizeable to-do list – perhaps reconvene in 18-24 months

- Recent workshop on the intensity frontier
  - Working group dedicated to topics discussed in this presentation
Science Data

- 16 total science runs, 8 for each laser polarization

- Nominal Run
  - Fill the cavity for 10 minutes
  - Observe afterglow for 14 minutes
  - One measurement for each magnetic field

- Extended Run (for 5.0 Tesla magnetic field)
  - Fill cavity for 5 hours
  - Observe afterglow for 45 minutes
  - Repeat this measurement

- Shutter cycle is ~15 seconds on and ~15 seconds off

- 15 minute calibration run before and after each science run
Photons and Chameleon Dark Energy

• equations of motion: \[ \partial_{\mu} \left( e^{\frac{2}{M_{Pl}} F_{\mu\nu}} \right) = 0 \]
  - the other two of Maxwell's equations stay the same

• plane wave perturbations about background fields (assuming \( \mathbf{B} = B_0 \hat{x} \))
  - \[ \left( -\frac{\partial^2}{\partial t^2} - \vec{k}^2 \right) \Psi_\phi = m_{\text{eff}}^2 \Psi_\phi + \frac{\beta_{\gamma} k B_0}{M_{Pl}} \hat{x} \cdot \vec{\Psi}_\gamma \]
  - \[ \left( -\frac{\partial^2}{\partial t^2} - \vec{k}^2 \right) \vec{\Psi}_\gamma = \frac{\beta_{\gamma} k B_0}{M_{Pl}} \hat{k} \times (\hat{x} \times \hat{k}) \psi_\phi \]

• example: \( \phi \quad \gamma \) oscillations in relativistic case
  - \[ P_{\gamma \leftrightarrow \phi} = |\vec{\Psi}_\gamma \cdot \Psi_\gamma^*| = \frac{4k^2 \beta_{\gamma}^2 B_0^2}{m_{\text{eff}}^2 M_{Pl}^2} \sin^2 \left( \frac{m_{\text{eff}}^2 t}{4k} \right) |\hat{k} \times (\hat{x} \times \hat{k})|^2 \]
  - photon production rate: \[ \Gamma = \frac{P_{\gamma \leftrightarrow \phi}(t_M)}{t_M} \]