The Dark Sector

dark matter, dark energy, gravity

Number Abundance Relative to Hydrogen

$\Omega_{Bh^2}$ $\Omega_\Lambda$

He-4, D, He-3, Li-7

No Big Bang
Supernovae
CMB
Expands forever
Recollapses eventually
Clusters
Flat, open, closed
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:

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

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:

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

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
Axions, the other dark matter

If axions are the dark matter, they would live here.
Laser searches for axion-like particles
GammeV search for axion-like particles
GammeV search for axion-like particles
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: \( \text{meV} \sim \text{TeV}^2/M_{\text{Planck}} \)
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$hc \sim 1\text{meV mm}$
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$\Delta m^2 \ L/\ E \sim \text{meV}^2 \ m/eV$
Dark Energy: $\Lambda = (2 \text{ meV})^4$

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$\Delta m^2 L/E \sim \text{meV}^2 \text{m/eV}$
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Weak Scale See Saw: \( \text{meV} \sim \text{TeV}^2/\text{M}_{\text{Planck}} \)

\( h\epsilon \sim 1\,\text{meV mm} \)

\( \Delta m^2 \, L/E \sim \text{meV}^2 \, \text{m/eV} \)

Optical Photons
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.

$$\Lambda_{\text{theory}} = \frac{E_{\text{ground}}}{\ell_P^3} \sim M_P^4 \sim 10^{124} \text{ meV}^4$$
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$$\Lambda_{\text{experiment}} = 2 \text{ meV}^4$$

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

Experimentalist

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

Theorist

If something moves but it shouldn't...
Physicists Toolkit

**Experimentalist**
- If something should move but it doesn't...

**Theorist**
- If something moves but it shouldn't...

*(anthropic principle)*
- Sum, ergo ita est.
- If something moves but it shouldn't...
Physicists Toolkit

**Experimentalist**

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

![](WD-40.png)

If something moves but it shouldn't...

**Theorist**

Φ

(sum, ergo ita est.

(anthropic principle)

If something moves but it shouldn't...

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

(Scalar field)
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?

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

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

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

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

Vainshtein

symmetron

chameleons

Slides stolen from Justin Khoury
The Chameleon Effect

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

- **Chameleon potential**
- **Photon coupling**
- **Matter coupling**

Sketch of chameleon mechanism: Low Density Background

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

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

Sketch of chameleon mechanism: High Density Background

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

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

\[ V(\phi) \sim \phi^{-4} \]

\[ - \rho \frac{\partial (\beta\phi / M_{Pl})}{\partial \phi} \]

\[ V_{\text{eff}}(\phi) \]

Mota & Shaw 2007
We consider potentials of the form

$$V(\phi) = M_\Lambda^4 \exp(\phi^N/M_\Lambda^N) \approx M_\Lambda^4 (1 + \phi^N/M_\Lambda^N)$$

- $M_\Lambda$ is the dark energy scale, $2.4 \times 10^{-3}$ eV

In bulk matter density $\rho$, $m_{\text{eff}}$ scales as $\rho^\eta$

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

Quantum Measurement: Windows

- density $\rho$
- background $\phi_0$
- $\phi_0 + \delta\phi$
- photon

$x [m_{\text{eff}}^{-1}]$
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

\[ m_{\text{eff}} = 1 \times 10^{-4} \text{eV} \]

solid lines: \( m_{\text{eff}} = 1 \times 10^{-4} \text{eV} \)

dotted lines: \( m_{\text{eff}} = 5 \times 10^{-4} \text{eV} \)
Constraints from GammeV

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

Transition and B field

Detector systematic uncertainty

Magnetic field length

Vacuum system design

Power Law Models

Dark Energy Models
Lowering the magnetic field allows us to probe larger photon couplings and to eliminate some systematic effects.
CHASE Science Data

Excess Rate (Hz)

Scalar

Pseudoscalar

Log_{10}t (sec)
Constraints from CHASE

95% Confidence Level

Collider constraints

GammaMeV constraints

scalar
pseudoscalar

Power Law Models

Dark Energy Models

$\eta$

$0$ $1$
Constraints from CHASE

95% Confidence Level

Collider constraints

Photon coupling $\beta_\gamma$

GammaV constraints

Scalar pseudoscalar

30,000 TeV
Model Dependent Results

95% Confidence Level

Collider constraints

$\eta$

Power Law Models

$\phi^4 \phi^6 \phi^8$

Exp[$\Lambda^2/\phi^2$]

Dark Energy Models

Exp[$\Lambda/\phi$]
Model Dependent Results

95% Confidence Level

Collider constraints

Power Law Models

Dark Energy Models

\eta

\phi^4 \phi^6 \phi^8 \exp[\Lambda^2/\phi^2] \exp[\Lambda/\phi]
More Numerology

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
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
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

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

FUNDAMENTAL PHYSICS AT THE INTENSITY FRONTIER

November 30–December 2, 2011
Rockville, MD | www.intensityfrontier.org

Working group on
Hidden Sector Photons, Axions, and WISPs
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

(a) Top view of diamonds for one interferometer

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

(c) “T” configuration
   - No overlap of diamonds from end mirrors
   - No signal correlations
Laser Test of Gravity: The Holometer
Laser Test of Gravity: The Holometer
Final Slide of Numerology

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

Signatures of a Hidden Cosmic Microwave Background

Joerg Jaeckel,1 Javier Redondo,2 and Andreas Ringwald3

1Institute for Particle Physics and Phenomenology, Durham University, Durham DH1 3LE, United Kingdom
2Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany
3(Received 23 May 2008; published 26 September 2008)

The Case for Dark Radiation

Maria Archidiacono4, Erminia Calabrese5, and Alessandro Melchiorri1

4Physics 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

Matched Fabry-Perots

Photon Detectors

Laser

Io
Where to go: Axion Search

Enhance production of axions with this cavity

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

Enhance production of axions with this cavity

Reconverted photons resonantly drive this cavity

![Diagram of axion search setup with labels for Laser, IO, Magnet, Matched Fabry-Perots, and Photon Detectors.]

![Graph showing mass vs. g (GeV^-1) with various curves and axes labeled Mass (eV) and g (GeV^-1).]
Where to go: Cavity Axion Search

Tevatron Dipole

RF Cavities
Where to go: Cavity Axion Search

Tevatron Dipole

RF Cavities

Axion
Where to go: Cavity Axion Search

Tevatron Dipole

RF Cavities

Axion
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
- Recent workshop on experimental tests of dark energy
  - Sizeable to-do list – perhaps reconvene in 18-24 months
- Pending workshop on the intensity frontier
  - Working group dedicated to topics discussed in this presentation
Chameleon Dark Energy

Equation of state parameter from chameleon dark energy (current limits ~0.1).

Variation in fine structure constant from chameleon dark energy (current limits 1e-6)
Conversion Rate

• The conversion process
  - chameleons measured at window
  - $\phi-\gamma$ superposition propagates in some direction $k$ through magnetic field, with $\gamma$ amplitude growing with time
  - particle bounces from walls, with partial reduction in photon amplitude due to nonzero absorption probability
  - particle measured again at opposite window

• Afterglow and decay rates
  - Afterglow: $\Gamma_{\text{aft}} = \frac{1}{4\pi} \int d^2k \frac{P_{\gamma-\phi}(k, t(k))}{t(k)} \times P(\text{detection})$
  - Decay: $\Gamma_{\text{dec},\gamma} = \frac{1}{4\pi} \int d^2k \frac{P_{\gamma-\phi}(k, t(k)) + P(\text{absorption})}{t(k)}$
Orange Glow

- Appears in the red and orange part of the spectrum not in the green where a chameleon signal is expected

- Independent of the magnetic field and laser polarization unlike a chameleon signal

- Temperature dependence, also unlike a chameleon signal

![Graph showing temperature dependence of rate at t=5 sec]
Orange Glow

- A few components are seen, only one remains after ~100 seconds
- Data before 120 seconds are ignored
- Orange glow and uncertainty are estimated via Monte Carlo assuming a single exponential and subtracted
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
Dark Matter WIMPs

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

Among other things, supersymmetry:
- solves the hierarchy problem
- unifies the coupling constants of the forces
- provides a dark matter candidate (the neutralino)
Photons and Chameleon Dark Energy

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

- plane wave perturbations about background fields (assuming \( \mathbf{B} = \mathbf{B}_0 \hat{x} \))
  - \( \left( -\frac{\partial^2}{\partial t^2} - k^2 \right) \psi_\phi = m_{\text{eff}}^2 \psi_\phi + \frac{\beta_\gamma k B_0}{M_{Pl}} \hat{x} \cdot \tilde{\psi}_\gamma \)
  - \( \left( -\frac{\partial^2}{\partial t^2} - k^2 \right) \tilde{\psi}_\gamma = \frac{\beta_\gamma k B_0}{M_{Pl}} \hat{k} \times (\hat{x} \times \hat{k}) \psi_\phi \)

- example: \( \phi \rightarrow \gamma \) oscillations in relativistic case
  - \( P_{\gamma \rightarrow \phi} = \tilde{\psi}_\gamma \cdot \tilde{\psi}_\gamma^* = \frac{4k^2 \beta_\gamma^2 B_0^2}{m_{\text{eff}}^4 M_{Pl}^2} \sin^2 \left( \frac{m_{\text{eff}}^2 t}{4k} \right) |\hat{k} \times (\hat{x} \times \hat{k})|^2 \)
  - photon production rate: \[ \Gamma = \frac{P_{\gamma \rightarrow \phi}(t_M)}{t_M} \]
What if...
What if...
Expected Signal
Expected Signal

Solid lines: $\xi_{\text{ref}} = 0$

Dotted lines: $\xi_{\text{ref}} = \pi/3$
CHASE Review

- Take data with two different laser polarizations to search for scalar and pseudoscalar chameleons
- Take data with seven different magnetic field strengths to probe a variety of photon couplings
- Three different partitions allow us to probe a larger range of chameleon masses
- PMT dark rate measured during science run using shutter-closed data
- Calibration data taken before and after (or between) each chameleon science run, excess is subtracted
- Characterized orange glow independently and subtracted it
Example of Raw Science Data

Blue = shutter open
Red = shutter closed

Dark rate and detector systematic variations measured using shutter-closed data.
Laser Test of Gravity: The Holometer

The graph shows a log-log plot comparing atomic clocks and interferometers with holographic noise. The horizontal axis represents the logarithm of the length or time interval in meters, while the vertical axis represents the logarithm of the differential length or time in meters. The points labeled GEO600, LIGO, and LISA are plotted on the graph, indicating their performance in terms of precision compared to the other mentioned technologies.