High-intensity searches for dark energy and modified gravity

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Cosmic acceleration

Evolution with time

Coupling to known particles

The Energy Frontier
The Intensity Frontier
The Cosmic Frontier

Origin of Mass
Neutrino Physics
Proton Decay
Cosmic Particles

Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model

Matter/Anti-matter Asymmetry
Dark Matter
Dark Energy

Cosmic acceleration
Amol Upadhye
High-intensity searches for dark energy and modified gravity
Introduction

- Motivation: DE scale $M_{\Lambda} = 2.4 \times 10^{-3}$ eV
- Dark energy: a phenomenological tool box
- Example: Chameleon screening

Fifth forces

- Quantum-stable chameleons
- Eöt-Wash constraints and forecasts
- Neutron experiments

New particles

- Production through photon coupling
- GammeV-CHASE afterglow experiment
- Upcoming experiments
## Coupled dark energy from modified gravity

A phenomenological toolbox:

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<td>DGP, etc.: non-compact extra dimension</td>
<td>Decoupling limit (weak gravity) $\Rightarrow$ Galileon</td>
<td>matter coupling, non-canonical kinetic term</td>
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At low energies, dark energy can have a matter coupling, whose fifth force must be screened locally. Dark energy can also have a photon coupling, allowing the production of dark energy particles.
Chameleon mechanism

effective potential: \( V_{\text{eff}}(\phi, \rho) = V(\phi) + \frac{\beta \rho \phi}{M_{\text{Pl}}} \)
Chameleon mechanism

effective potential: \( V_{\text{eff}}(\phi, \rho) = V(\phi) + \beta \rho \phi / M_{\text{Pl}} \)

\[
V_{\text{int}} = \beta_{\text{mat}} \rho_{\text{mat}} \phi / M_{\text{Pl}}
\]
Chameleons mechanism

effective potential: \( V_{\text{eff}}(\phi, \rho) = V(\phi) + \beta \rho \phi / M_{\text{Pl}} \)

\( \phi_{\text{min}}(\rho_{\text{low}}) \)

\( m_{\text{eff}}^2 = V'' \) is small
Chameleon mechanism

effective potential: \( V_{\text{eff}}(\phi, \rho) = V(\phi) + \frac{\beta \rho \phi}{M_{\text{Pl}}} \)
At which scale should we probe each model?

$$V(\phi) \propto \phi^n + \text{const.} \Rightarrow m_{\text{eff}} \propto \rho^{\frac{n-2}{2n-2}}$$ (use lab for $$n \lesssim -\frac{1}{2}, n > 2$$)
Part II: Fifth forces
Laboratory benchmark: “quantum-stable” chameleons

\[
\Delta V_{1-\text{loop}}(\phi) = \frac{m_{\text{eff}}(\phi)^4}{64\pi^2} \log \left( \frac{m_{\text{eff}}(\phi)^2}{\mu^2} \right) < V_{\text{tree}}
\]

\[
\Rightarrow m_{\text{eff}} \leq \left( \frac{48\pi^2 \beta^2 \rho^2}{M_{\text{Pl}}^2} \right)^{1/6} = 0.0073 \left( \frac{\beta \rho}{10g/cm^3} \right)^{1/6} \text{eV}
\]

\[\text{mass } m_\phi(\rho_{\text{lab}}) \text{ [eV]}\]

\[\text{matter coupling } \beta\]

\[\text{excluded by Eot-Wash}\]

\[\text{large quantum corrections}\]

Fifth-force tests using a torsion pendulum

Eöt-Wash Experiment

http://www.npl.washington.edu/eotwash
Eötvös constraints on chameleons

\[ V(\phi) = \frac{\lambda}{4!} \phi^4 \]

\[ \lambda \begin{array}{ccccccc}
0.001 & 0.01 & 0.1 & 1 & 10 & 100 & 1000 \\
\end{array} \]

\[ \beta \begin{array}{ccccccc}
10^{-6} & 10^{-5} & 10^{-4} & 10^{-3} & 10^{-2} & 10^{-1} & 100 \\
\end{array} \]

linear

Eötvös

1Dpp approx.

large quantum corrections


Next-generation Eöt-Wash: chameleon forecasts

\[ V(\phi) = \frac{\lambda}{4!} \phi^4 \]

\[ V(\phi) = \gamma M_\Lambda^5 / \phi \]

\[ V(\phi) = M_\Lambda^{4-n} \phi^n \]

Symmetron effective potential: \[ V_{\text{eff}} = \frac{1}{2} \left( \frac{\rho}{M^2} - \mu^2 \right) \phi^2 + \frac{\lambda}{4!} \phi^4 \]

Eöt-Wash probes \( \lambda \sim 1, \mu \sim 10^{-3} \text{ eV} \) (dark energy),

\( M \sim 1 \text{ TeV} \) (beyond the Standard Model)

Neutrons in a gravitational field

\[
\left(-\frac{\hbar^2}{2m_N} \frac{d^2}{dz^2} + m_N \Psi + \frac{\beta m m_N}{M_{Pl}} \phi \right) |N\rangle = E |N\rangle
\]

- \(\Psi(z) = gz\) is gravitational field
- \(\phi(z)\) is chameleon field (nonlinear in \(z\))
- energy levels \(E\) of bouncing neutrons quantized (\(\Delta E \sim 1\) peV)

\[P. \ Brax\ and\ G.\ Pignol,\ PRL \]
Neutron interferometry

Constraints from neutron interferometry:
- split neutron beam into two
- sent one beam through vacuum chamber with scalar “bubble”, other beam through chamber containing phase-neutral gas
- climbing out of scalar potential well slows down beam passing through vacuum chamber \( \Rightarrow \) phase shift

Brax, Pignol, Roulier (2013)
[arXiv:1306.6536]

W. M. Snow, AU, et al., NIST proposal
Part III: Dark energy particles
How dark is dark energy? Searches for photon couplings

**Oscillation**: Photon coupling term \(\frac{\beta\gamma}{4M_{Pl}} F_{\mu\nu} F^{\mu\nu} \phi \Rightarrow \) dark energy particles produced from photons in magnetic field

**Containment**: Dark energy particles reflect from matter. Windows perform quantum measurements.
An afterglow experiment has two phases:

(a) Production phase: photons streamed through $\tilde{B}_0$ region; some oscillate into chameleons

(b) Afterglow phase: chameleons slowly oscillate back into photons, escaping chamber

Systematics:
- adiabatic evolution
- emission from vacuum materials
- diffuse reflection
- scattering from atoms
- effects of chamber geometry

CHASE (CHameleon Afterglow SEarch)

Vacuum chamber

B field region

Lens
Shutter
PMT

1.61m  6.0m  1.74m  0.64m  0.1m

2.54cm  3.175cm  0.25cm

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Expected afterglow signal

\[ \text{afterglow rate [sec}^{-1}] \]

\[ \text{time [sec]} \]

\[ \text{observation period} \]

\[ \beta_\gamma = 1 \times 10^{11} \]

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Expected afterglow signal

\[ \text{afterglow rate [sec}^{-1}\text{]} \]

\[ \text{time [sec]} \]

\[ 0.2 \text{ T} \]
\[ 0.45 \text{ T} \]
\[ 2.2 \text{ T} \]
\[ 5.0 \text{ T} \]

observation period \[ \beta_\gamma = 3 \times 10^{11} \]
Expected afterglow signal

\[ \text{afterglow rate [sec}^{-1}] \]

\[ \text{time [sec]} \]

\[ 0.05 T \quad 0.09 T \quad 0.2 T \quad 0.45 T \quad 1.0 T \quad 2.2 T \quad 5.0 T \]

\[ \text{observation period} \quad \beta \gamma = 1 \times 10^{12} \]
Expected afterglow signal

\[
\beta_\gamma = 3 \times 10^{12}
\]

\begin{align*}
\text{afterglow rate} & [\sec^{-1}] \\
\text{time} & [\sec]
\end{align*}

-observation period

-0.05 T
-0.09 T
-0.2 T
-0.45 T
-1.0 T
-2.2 T
-5.0 T
Expected afterglow signal

![Graph showing the expected afterglow signal with time in seconds and afterglow rate in sec\(^{-1}\). The graph includes observation periods for different time intervals marked as $T$. The time intervals are marked as $0.05 T$, $0.09 T$, $0.2 T$, $0.45 T$, $1.0 T$, $2.2 T$, and $5.0 T$. The observation period is marked with a shaded region and the parameter $\beta_\gamma = 1 \times 10^{13}$ is shown.](image-url)
Expected afterglow signal

![Graph showing afterglow rate over time for different observation periods. The graph includes lines for observation periods of 0.05T, 0.09T, 0.2T, 0.45T, 1.0T, 2.2T, and 5.0T. The y-axis represents afterglow rate in sec\(^{-1}\), and the x-axis represents time in sec. The observation period is highlighted in yellow.]
Expected afterglow signal

- Plot showing the afterglow rate versus time for different observation periods.
- Observation period marked with $\beta_\gamma = 10^{14}$.

Graph parameters:
- Y-axis: afterglow rate [sec$^{-1}$]
- X-axis: time [sec]

Legend:
- $5.0 \times 10^2$ T
- $2.2 \times 10^2$ T
- $1.0 \times 10^2$ T
- $0.45 \times 10^2$ T
- $0.2 \times 10^2$ T
- $0.09 \times 10^2$ T
- $0.05 \times 10^2$ T
Expected afterglow signal

\[ \text{afterglow rate [sec}^{-1}] \]

\[ \text{time [sec]} \]

\( 0.05 \, T \)
\( 0.09 \, T \)
\( 0.2 \, T \)
\( 0.45 \, T \)
\( 1.0 \, T \)
\( 2.2 \, T \)
\( 5.0 \, T \)

observation period \( \beta_\gamma = 3 \times 10^{14} \)
Expected afterglow signal

- Afterglow rate [sec$^{-1}$]
- Time [sec]

- Observation period
- $\beta_\gamma = 1e15$

- $5.0 \, T$
- $2.2 \, T$
- $1.0 \, T$
- $0.45 \, T$
- $0.2 \, T$
- $0.09 \, T$
- $0.05 \, T$
Expected afterglow signal

\[ \beta_{\gamma}=3\times10^{15} \]

\[ \text{afterglow rate} \quad [\text{sec}^{-1}] \]

\[ \text{time} \quad [\text{sec}] \]

Observation period

- 5.0 T
- 2.2 T
- 1.0 T
- 0.45 T
- 0.2 T
- 0.09 T
- 0.05 T
Expected afterglow signal

![Graph showing afterglow rates vs time with observation period highlighted.]

- Time [sec]: -1500 to 3000
- Afterglow rate [sec\(^{-1}\)]: 0.01 to 1e+12
- Observation period: \(\beta_\gamma = 1e16\)

- Time intervals:
  - 0.05 T
  - 0.09 T
  - 0.2 T
  - 0.45 T
  - 1.0 T
  - 2.2 T
  - 5.0 T
Chameleons in CHASE: a thorough study

Adiabatic transition suppresses oscillation

- \( \tilde{B}(z) \) transition distance \( \gg \) oscillation length \( 4\pi E/\Delta m^2 \)
  \( \Rightarrow \) adiabatic transition \( \Rightarrow \) no chameleon production

- internal measurement (window) mitigates this effect

No internal measurement

One measurement

---

“Orange glow:” a transient systematic photon flux

CHASE constraints on $V(\phi) = M_\Lambda^4(1 + M_\Lambda/\phi)$


Experiment: Steffen, AU, Baumbaugh, Chou, Mazur, Tomlin, Weltman,
Chameleon fragmentation?

Chameleon particles can interact to produce a greater number of lower-energy chameleon particles.

*P. Brax and AU (2013, in prep.)*
Cavity afterglow experiments

http://www.phys.washington.edu/groups/admx/cavity.html

Procedure:

1. source excites EM mode
2. turn off source; EM modes decay
3. EM modes regenerated from chameleon
4. adjust tuning rods for sensitivity to different mass range
ADMX constraints on photon-coupled chameleons

Chameleons from the Sun

- $\sim$ keV photons oscillate into chameleons inside Sun
- chameleon particles reach Earth
- helioscope magnet regenerates photons for detection
Helioscope forecasts

Solar chameleon spectrum peaked at 600 eV. 
Forecast constraints. 


Increase collecting area using an X-ray mirror. 

Conclusions

1. The physics responsible for the cosmic acceleration may differ from a cosmological constant by evolving with time or by coupling to known particles. Couplings imply fifth forces.

2. Laboratory and cosmological experiments are complementary; they probe models whose masses scale differently with density.

3. The Eöt-Wash torsion pendulum experiment will be able to exclude chameleon models with gravitation-strength couplings and small quantum corrections, as well as symmetron models with TeV-scale couplings. Neutron experiments can exclude chameleons and symmetrons with larger couplings.

4. The CHASE afterglow experiment has excluded a range of light photon-coupled dark energy models. Upcoming afterglow and helioscope experiments promise to improve these constraints over the next few years.
Symmetron mechanism

effective potential: \( V_{\text{eff}}(\phi, \rho) = \frac{1}{2} \left( \frac{\rho}{M^2} - \mu^2 \right) \phi^2 + \frac{\lambda}{4!} \phi^4 \)
At which scale should we probe symmetrons?

Fifth forces are predicted for $\rho_m > \mu^2 M^2 > \rho_v$ at distances $\gtrsim 1/\mu$. 

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<th>$\mu$ [GeV]</th>
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<td>$1e^{-40}$</td>
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Photons coupled to chameleon dark energy

The time-dependent equation of motion is $\Box \phi = V'_{\text{eff}}$.

Equations of motion ($V_{\phi\gamma} = \frac{\beta_{\gamma}}{4M_{\text{Pl}}} F^{\mu\nu} F_{\mu\nu} \phi$ with $\beta \phi \ll M_{\text{Pl}}$):

- $\partial_\mu \left[ \left( 1 + \frac{\beta_{\gamma} \phi}{M_{\text{Pl}}} \right) F^{\mu\nu} \right] = 0$

- $\Box \phi = V'(\phi) + \frac{\beta_m}{M_{\text{Pl}}} \rho_{\text{mat}} + \frac{\beta_{\gamma}}{4M_{\text{Pl}}} F_{\mu\nu} F^{\mu\nu}$

Plane wave perturbations about background $\phi_0$ and $\vec{B}_0 = B_0 \hat{x}$ (Raffelt and Stodolsky 1988; AU, Steffen, and Weltman 2010):

- $\left( -\frac{\partial^2}{\partial t^2} - \vec{k}^2 \right) \psi_\phi = m^2_{\text{eff}} \psi_\phi + \frac{\beta_{\gamma} k B_0}{M_{\text{Pl}}} \hat{x} \cdot \vec{\psi}_\gamma$

- $\left( -\frac{\partial^2}{\partial t^2} - \vec{k}^2 \right) \vec{\psi}_\gamma = \omega_{\text{P}}^2 \vec{\psi}_\gamma + \frac{\beta_{\gamma} k B_0}{M_{\text{Pl}}} \hat{k} \times (\hat{x} \times \hat{k}) \psi_\phi$

$\phi \rightarrow \gamma$ oscillation (low-mass, $\vec{k} \perp \vec{B}_0$): $P_{\gamma \leftrightarrow \phi} \approx \frac{\beta_{\gamma}^2 B_0^2 L^2}{4M_{\text{Pl}}^2}$