Dark energy fifth forces in torsion pendulum experiments
Outline

1. Cosmic acceleration
   - Deviations from cosmological constant
   - Matter couplings from modified gravity
   - Chameleon scalars and screening

2. Experimental probes
   - Eöt-Wash torsion pendulum experiment
   - Chameleons in Eöt-Wash

3. Quantum-stable chameleons
   - Chameleon models with small quantum corrections
   - Approximate Eöt-Wash constraints
   - Forecasts

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Dark energy fifth forces in torsion pendulum experiments
Dynamical explanations of the cosmic acceleration can differ from a cosmological constant in two ways: evolution and coupling.

### Dark energy evolves

### Dark energy couples

- Fifth forces
- New particle
- Screening mechanism:
  - Chameleon (mass)
  - Vainshtein (kinetic)

Constrain using:

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Types of dark energy

Dynamical explanations of the cosmic acceleration can differ from a cosmological constant in two ways: **evolution** and **coupling**.

**Dark energy evolves**
- $V(\phi)$
- $H(z)$ evolves with $\phi$
- Constrain using

**Dark energy couples**

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- New effects:
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Modified gravity and coupled scalar fields

The simplest modified gravity models reduce at low energies to 4-D matter-coupled scalar field theories.

Modified gravity

Effective scalar

New physics

New physics

Matter coupling, self-interaction $V(\phi)$

Matter coupling, non-canonical kinetic term

Matter coupling, photon (gauge field) coupling

A matter coupling implies a fifth force which must be screened.
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**Modified gravity**

- $f(R)$ gravity: action $S = \int \frac{d^4 x \sqrt{-g}}{16\pi G_N} f(R)$

**Effective scalar**

- Conformal transformation $\Rightarrow$ chameleon

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**Modified gravity**
- \( f(R) \) gravity: action
  \[ S = \int \frac{d^4x \sqrt{-g}}{16\pi G_N} f(R) \]
- DGP, etc.: non-compact extra dimension

**Effective scalar**
- Conformal transformation \( \Rightarrow \) chameleon
- Decoupling limit (weak gravity) \( \Rightarrow \) Galileon

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Modified gravity and coupled scalar fields

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Modified gravity
- $f(R)$ gravity: action $S = \int \frac{d^4x}{16\pi G_N} f(R)$
- DGP, etc.: non-compact extra dimension
- Kaluza-Klein, etc.: compact extra dimension

Effective scalar
- Conformal transformation $\Rightarrow$ chameleon
- Decoupling limit (weak gravity) $\Rightarrow$ Galileon
- Small extra dimension limit $\Rightarrow$ radion

New physics
- matter coupling, self-interaction $V(\phi)$
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A matter coupling implies a fifth force which must be screened.
Chameleon effect

\[ V_{\text{eff}}(\phi) = V(\phi) + \frac{\beta}{M_{\text{Pl}}} \left( -T^\mu_\mu \right) \phi \approx V(\phi) + \frac{\beta \rho}{M_{\text{Pl}}} \phi \]
Chamelecon effect

\[ V_{\text{eff}}(\phi) = V(\phi) + \frac{\beta}{M_{\text{Pl}}} (-T^\mu_{\mu}) \phi \approx V(\phi) + \frac{\beta \rho}{M_{\text{Pl}}} \phi \]

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

\[ V_{\text{eff}}(\phi) = V(\phi) + \frac{\beta}{M_{\text{Pl}}} (-T_{\mu}^{\mu}) \phi \approx V(\phi) + \frac{\beta \rho}{M_{\text{Pl}}} \phi \]

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

\[ (m_{\text{eff}}^2 = V'' \text{ is small}) \]
Chameleion effect

\[
V_{\text{eff}}(\phi) = V(\phi) + \frac{\beta}{M_{\text{Pl}}}(-T^\mu_\mu)\phi \approx V(\phi) + \frac{\beta \rho}{M_{\text{Pl}}} \phi
\]
$\phi^4$ chameleon field in Eöt-Wash pendulum

\[ x \text{ [mm]} \]
\[ z \text{ [mm]} \]
\[ \phi \text{ [mm}^{-1}\text{]} \]

AU, S. Gubser, J. Khoury, PRD 74 104024 (2006)
Adelberger, Heckel, Hoedl, Hoyle, Kapner, AU, PRL 98 131104 (2007)
Chameleons with small quantum corrections

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

AU, W. Hu, J. Khoury, PRL 109 041301 (2012)
1-D plane-parallel approximation to Eöt-Wash constraints

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

Next-generation Eöt-Wash: Forecasts


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Conclusions

1. Modified gravity could be responsible for the cosmic acceleration.
2. Scalar-mediated fifth forces from modified gravity must be screened in order to evade constraints from tests of gravity.
3. Chameleon-screened models with small quantum corrections and gravitation-strength couplings extend just beyond current experimental bounds in parameter space.
4. The next-generation Eöt-Wash torsion pendulum experiment will exclude a large range of quantum-stable chameleon models.