Laboratory fifth force experiments probe dark energy

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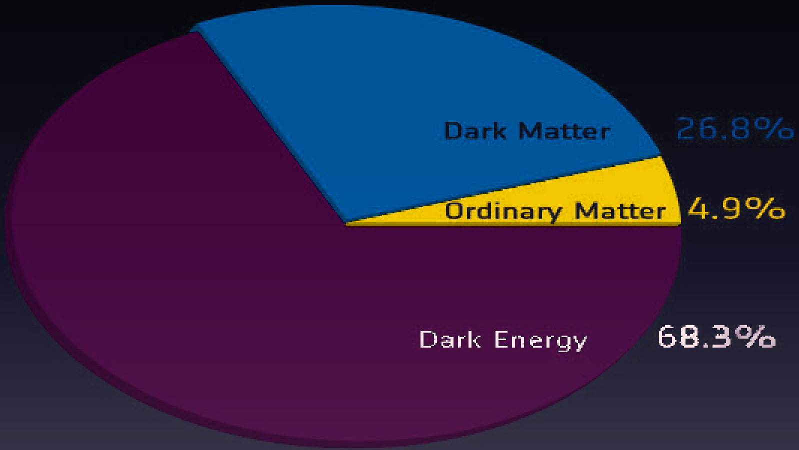
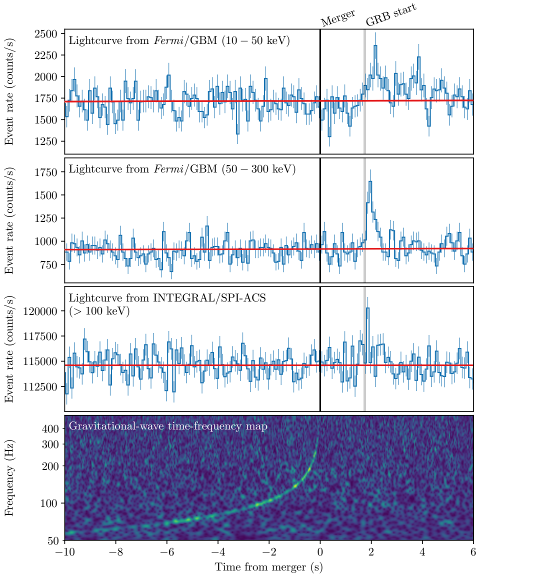
The greatest mystery in cosmology



2/3 of the effective energy density is a cosmological constant Λ, a “dark energy,” or some modification to gravity.

What does LIGO tell us?



Abbott, *et al.*, arXiv:1710.05834, Ap. J. (in prep)

LIGO, Virgo, Fermi, and INTEGRAL: $\Delta t = 1.74$ sec

$1\ \mathrm{Mpc}/c \approx 10^{14}$ sec, so:

$$\alpha_{GW} = \frac{c_{GW}^2 - c^2}{c^2} \lesssim \frac{\text{few seconds}}{40\ \mathrm{Mpc}/c} \sim 10^{-15}$$

Tuning?

- Δt from emission, escape?
- α_{GW} small only for $z < 0.01$?

What does LIGO tell us?

Most general scalar-tensor gravity with 2nd-order e.o.m.:

$$S = \int d^4x \sqrt{-g}\,[\mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_{\mathrm{M}}]$$

$$\mathcal{L}_2 = G_2 \qquad \mathcal{L}_3 = G_3 \Box\phi$$

$$\mathcal{L}_4 = G_{4,X}\left[(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi\right] + G_4 R$$

$$\mathcal{L}_5 = -\tfrac{1}{6}G_{5,X}\left[(\Box\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\phi\Box\phi + 2\nabla^\nu\nabla_\mu\phi\nabla^\alpha\nabla_\nu\nabla^\mu\nabla_\alpha\phi\right] + G_5 G_{\mu\nu}\nabla^\mu\nabla^\nu\phi$$

where the G_i are functions of ϕ and $X = -\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi$. Also, $G_{i,\phi}$ and $G_{i,X}$ are $\partial G_i/\partial\phi$ and $\partial G_i/\partial X$.

Velocity correction: $\alpha_{GW} \propto 2G_{4,X} - 2G_{5,\phi} - (\ddot{\phi} - \dot{\phi}H)G_{5,X}$

Baker, Bellini, Ferreira, Lagos, Noller, Sawicki, arXiv:1710.06394
Sakstein, Jain, arXiv:1710.05893

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$\alpha_{GW} = 0$, no tuning: What's left?

LIGO-preferred extensions to cosmological constant Λ:

Not-so-slow roll:

Conformal coupling $G_4(\phi)$ small to suppress $\partial G_N/\partial t$

- Quintessence:

  Wetterich 1988; Peebles, Ratra 1988

  $G_2 = X + V(\phi)$.

  $w = P/\rho = \frac{X-V}{X+V} \neq 1$ observed cosmologically

- Cubic Galileon:

  Nicolis, Rattazzi, Trincherini 2008

  $G_3 \propto X$, 5th force screened through kinetic term

Conformal coupling:

Rolling $\Delta\phi/M_{\rm Pl} \ll 1$ to suppress fifth force from $G_4(\phi)$

- Chameleons, $f(R)$ gravity:

  Khoury, Weltman 2004

  5th force screened through effective mass $m_{\rm eff} = V''$

- Symmetrons:

  Olive, Pospelov 2007; Hinterbichler, Khoury 2010

  G_2, G_4 invariant under $\phi \to -\phi$; 5th force screened through symmetry restoration

Screening of fifth forces

"Hide" 5$^{\mathrm{th}}$ forces in dense regions such as the Solar System. Consider small perturbations about a background: $\phi = \bar{\phi} + \delta\phi$:

$$\left[Z(\bar{\phi})\Box - m(\bar{\phi})^2\right]\delta\phi = \frac{1}{M_{\mathrm{Pl}}}\beta(\bar{\phi})\ \delta\rho$$

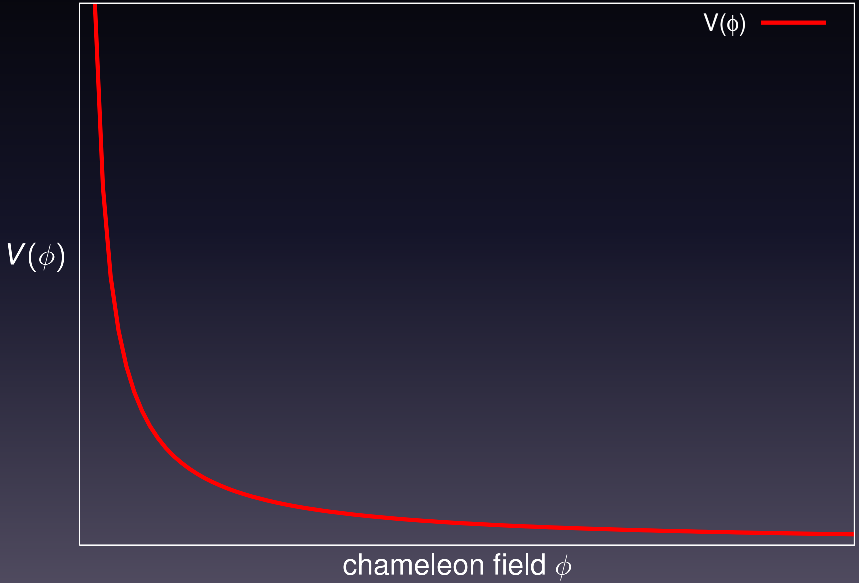
Chameleon screening: Increase m at high ρ.
e.g., $f(R)$ gravity. Reduces force range. Violates Equivalence Principle by making force density/geometry dependent.

Kinetic screening: Increase Z at high ρ.
e.g., Galileons. Deviations from Poisson's equation in high-density regions.

Dynamical coupling: Decrease β at high ρ.
e.g., symmetrons. Uncoupled phase at high densities.

Chameleon mechanism

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



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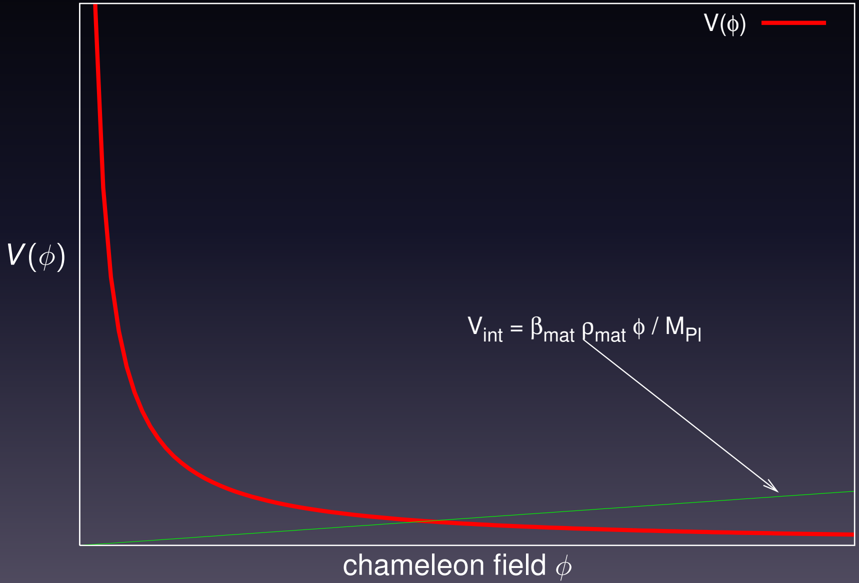

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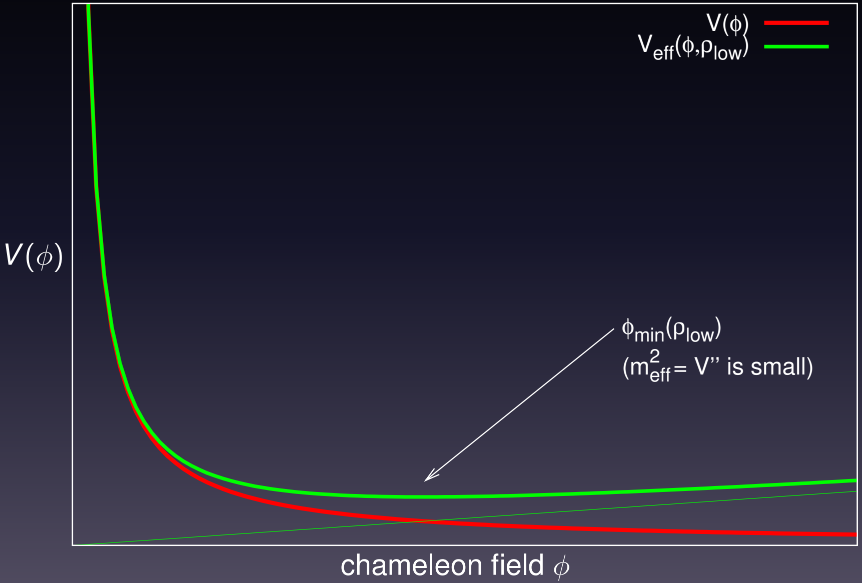

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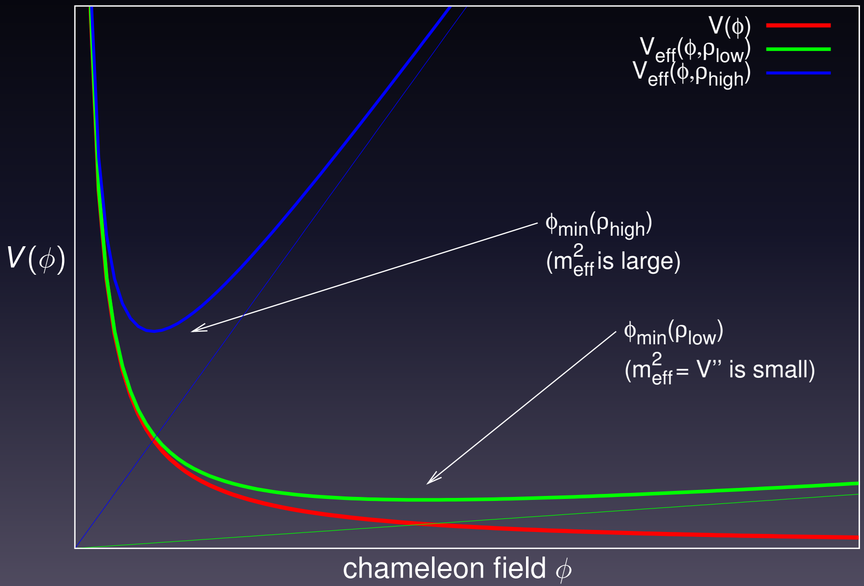
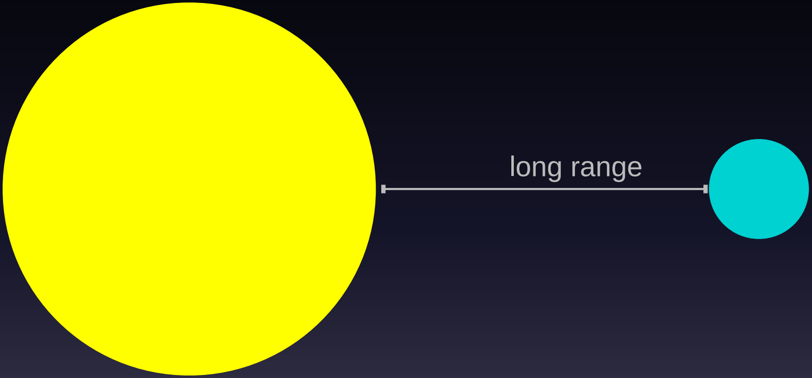


Effects of a large mass



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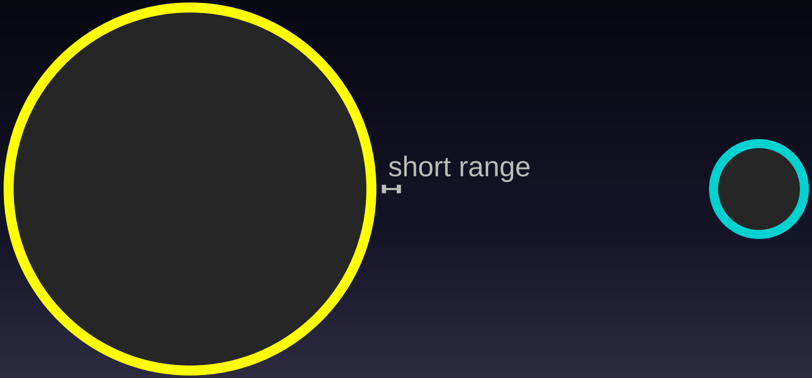
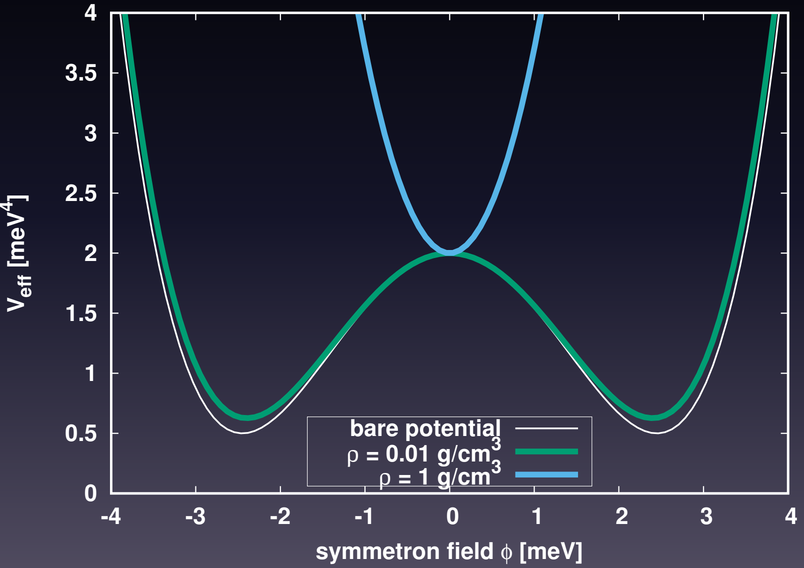


- Compton wavelength (force range) $\propto 1/m$
- Thin-shell effect: ϕ “sees” outer shell of thickness $\sim 1/m$.

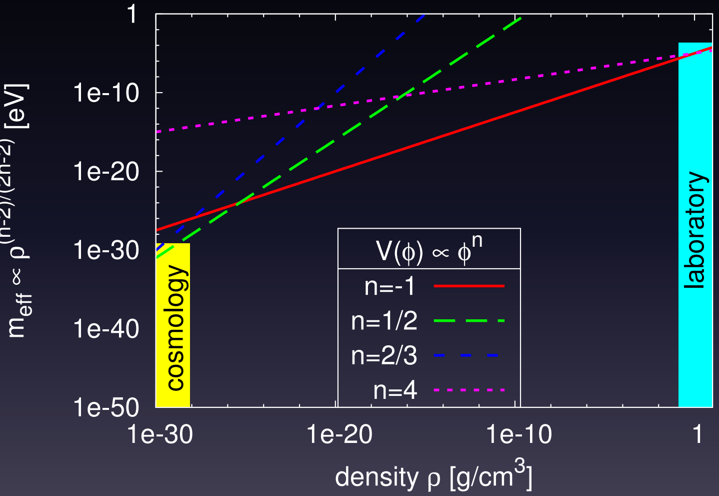
Symmetron screening

$$V_{\rm eff} = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4!}\phi^4$$



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 $n \lesssim -\frac{1}{2}$, $n > 2$)



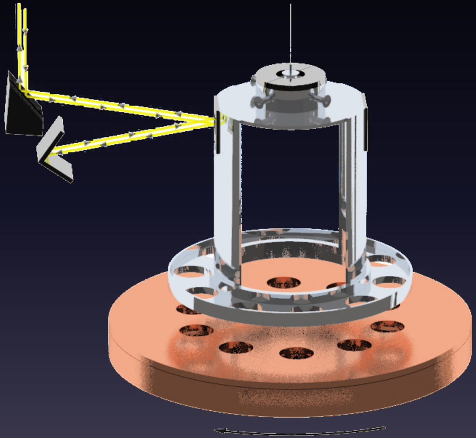
AU, PRD ***86****:102003(2012)[arXiv:1209.0211]*

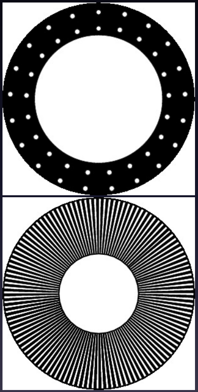
Finding hidden fifth forces in the lab

1. force with $m_{\rm eff}$ best detected using objects of size $1/m_{\rm eff}$
2. barrier between source and test masses weakens fifth force
3. chamber walls and surroundings contribute to screening
   - chameleons: consider effects of Earth, solar system, galaxy
   - symmetrons: no forces unless chamber radius $\gg \pi/\mu$

Fifth force tests using a torsion pendulum

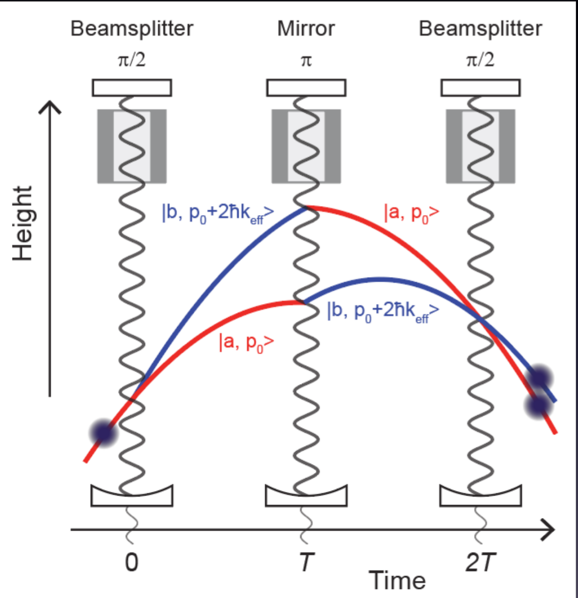
Eöt-Wash Experiment





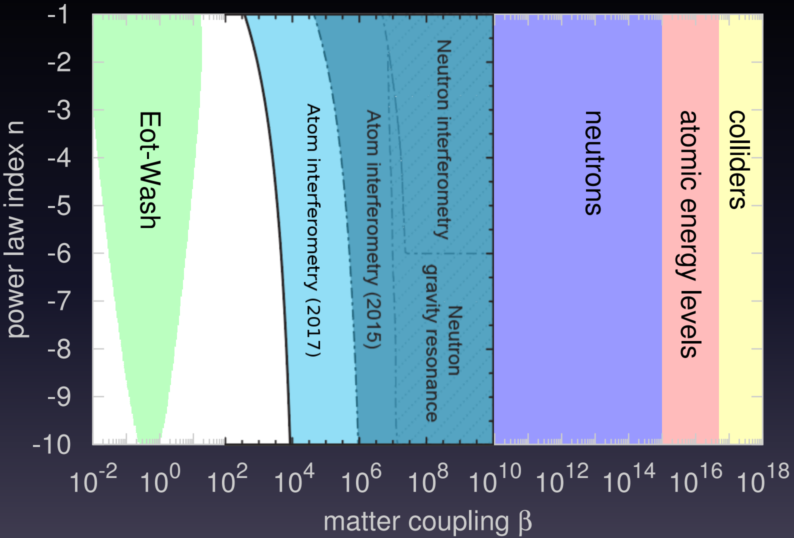
http://www.npl.washington.edu/eotwash

Fifth force tests using an atom interferometer



Jaffe,Haslinger,Xu,Hamilton,AU,Elder,Khoury,Müller, Nat. Phys. **13***:938(2017)[arXiv:1612.05171]*

Constraints on $V(\phi) = M_\Lambda^{4-n}\phi^n$ ($M_\Lambda = 2.4$ meV)



*AU, PRD **86**:102003(2012)[arXiv:1209.0211]*

*Adelberger,Heckel,Hoedl,Hoyle,Kapner,AU, PRL **98**:131104(2007)[arXiv:hep-ph/0611223]*

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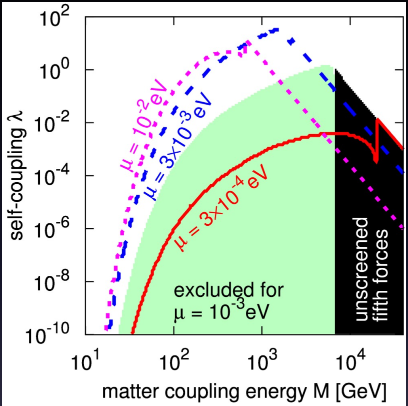
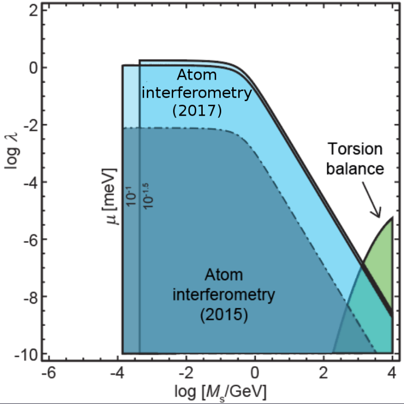
Constraints on symmetrons





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 $\lambda \sim 1$, $\mu \sim 10^{-3}$ eV (dark energy),

$M \sim 1$ TeV (beyond the Standard Model)

Interferometers extend constraints to lower μ, M

AU, PRL ***110****:031301(2013)[arXiv:1210.7804]*

Jaffe,Haslinger,Xu,Hamilton,AU,Elder,Khoury,Müller, Nat.Phys. ***13****:938(2017)[arXiv:1612.05171]*

Conclusions

1. Astrophysics suggests two extensions to Λ: rolling models and conformally-coupled models.
2. Chameleons and symmetrons are conformally-coupled models whose fifth forces are screened at high densities.
3. Laboratory experiments are close to the dark energy scale $(8\pi G_N/\Lambda)^{1/4} \approx 80~\mu$m and are the best ways to probe certain classes of chameleon and symmetron models.
4. Carefully-designed torsion pendulum experiments and atom interferometers have excluded orders of magnitude in parameter space.