Center for Particle Cosmology at the University of Pennsylvania

Classical and Quantum Stability of Chameleon Theories

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w. Amol Upadhye, Junpu Wang, Wayne Hu, Lam Hui

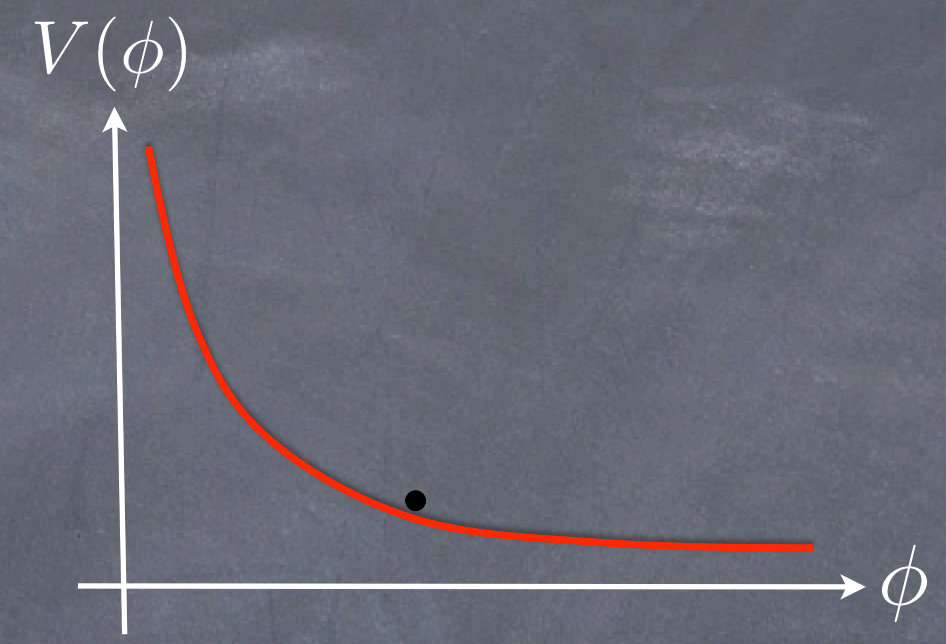
LEGES SINE MORIBUS VANAE

A Richer Dark Sector

- Dark energy candidates:

  Λ , quintessence...

  Ratra & Peebles (1988); Wetterich (1988); Caldwell, Dave & Steinhardt (1998)



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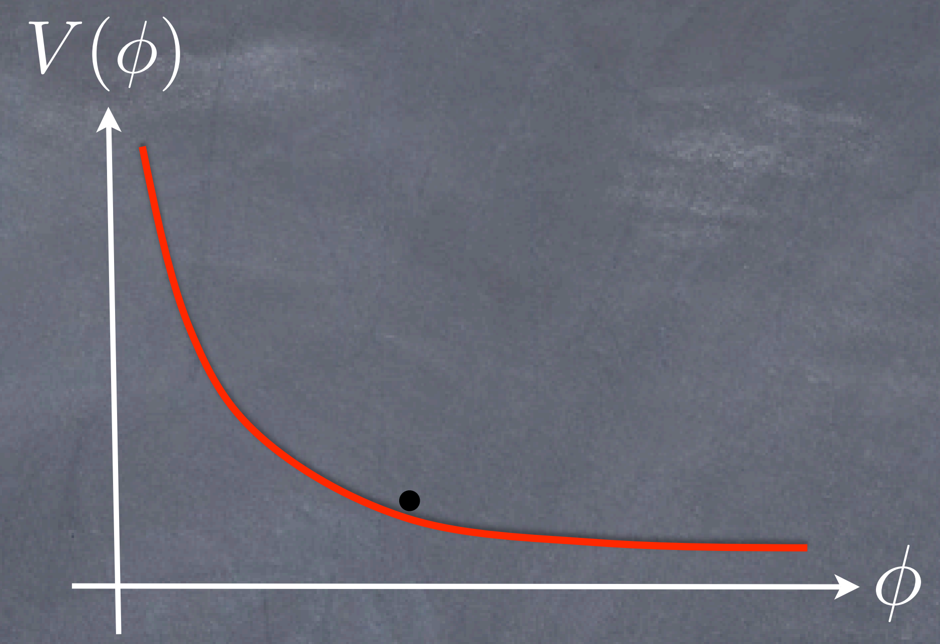

- Tantalizing prospect: dark sector includes new light fields (e.g. quintessence) that couple to both dark <u>and</u> baryonic matter.

Scalar fields can "hide" themselves from local exp'ts through screening mechanisms

$$\rho_{\rm here} \sim 10^{30} \rho_{\rm cosmos}$$

Large in a cosmological sense, but small in a particle physics sense

New Scale = New Physics?

$$\Lambda$$

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Λ

- To neutralize Λ to accuracy H_0^2, new degrees of freedom must be light:

$$m_\phi \lesssim H_0$$

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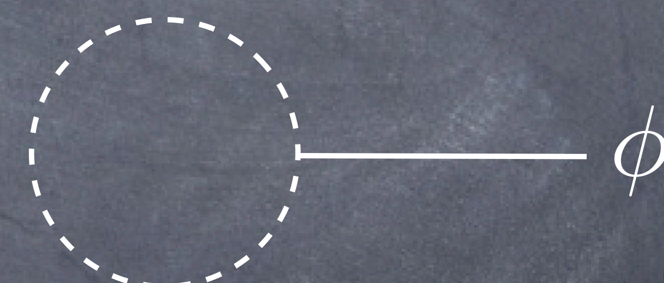

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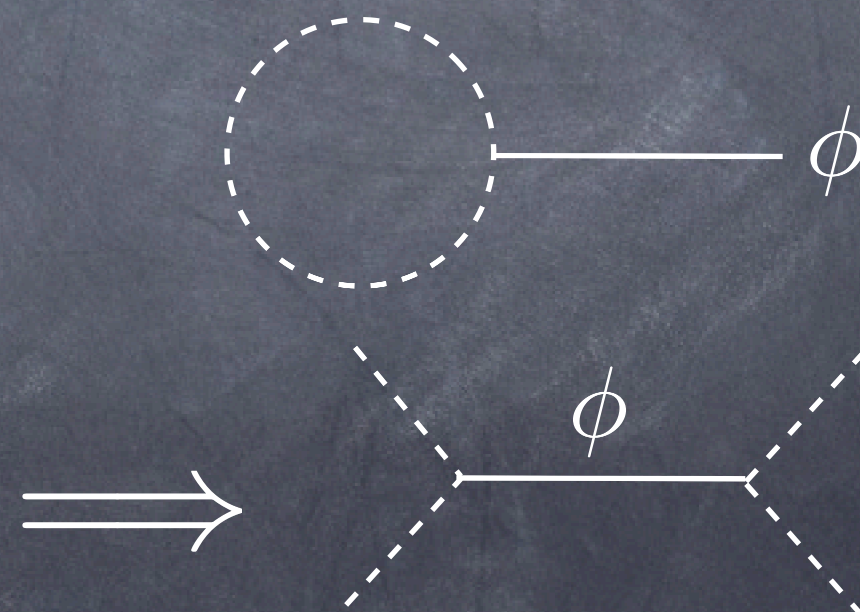

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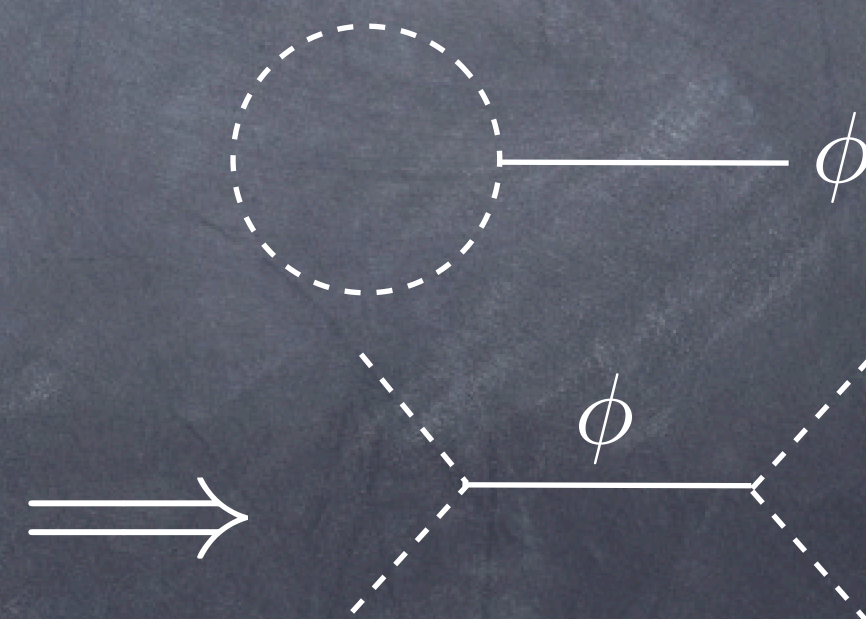
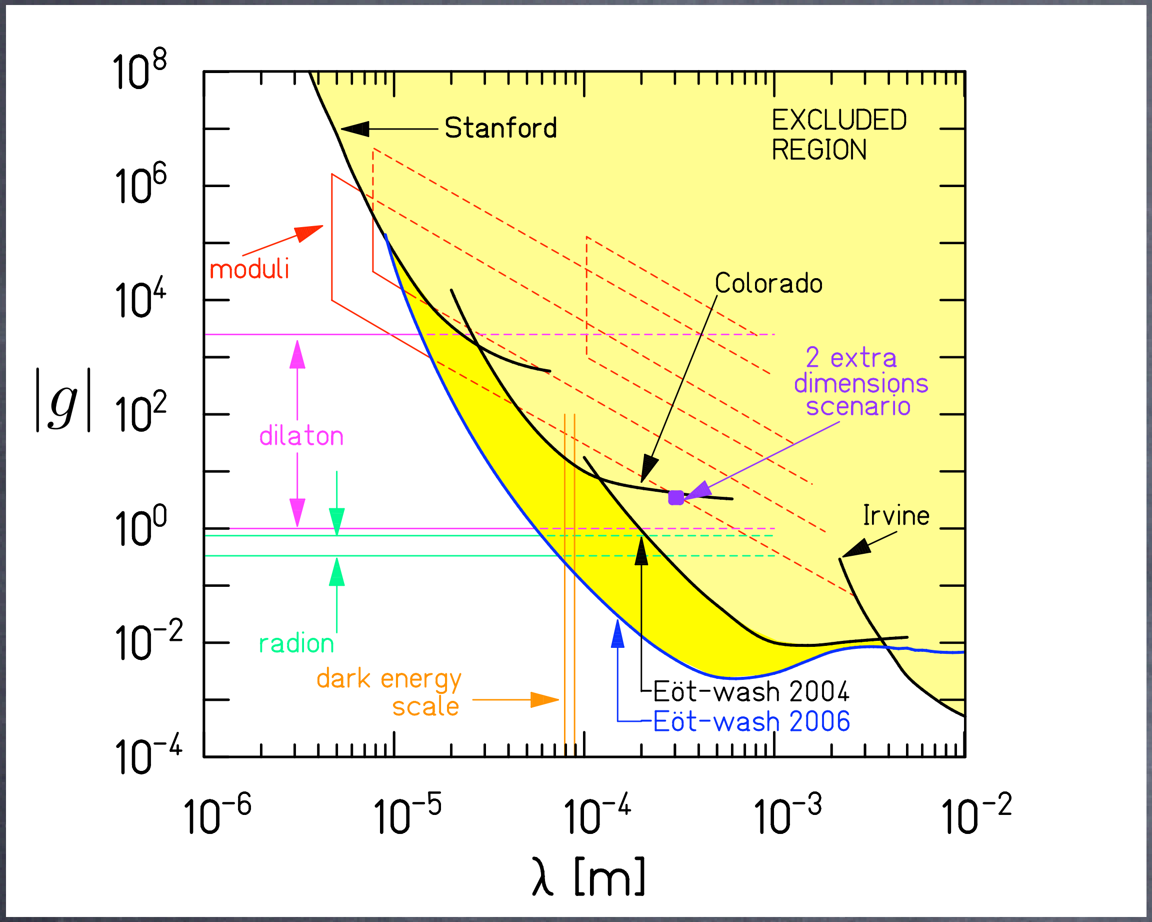
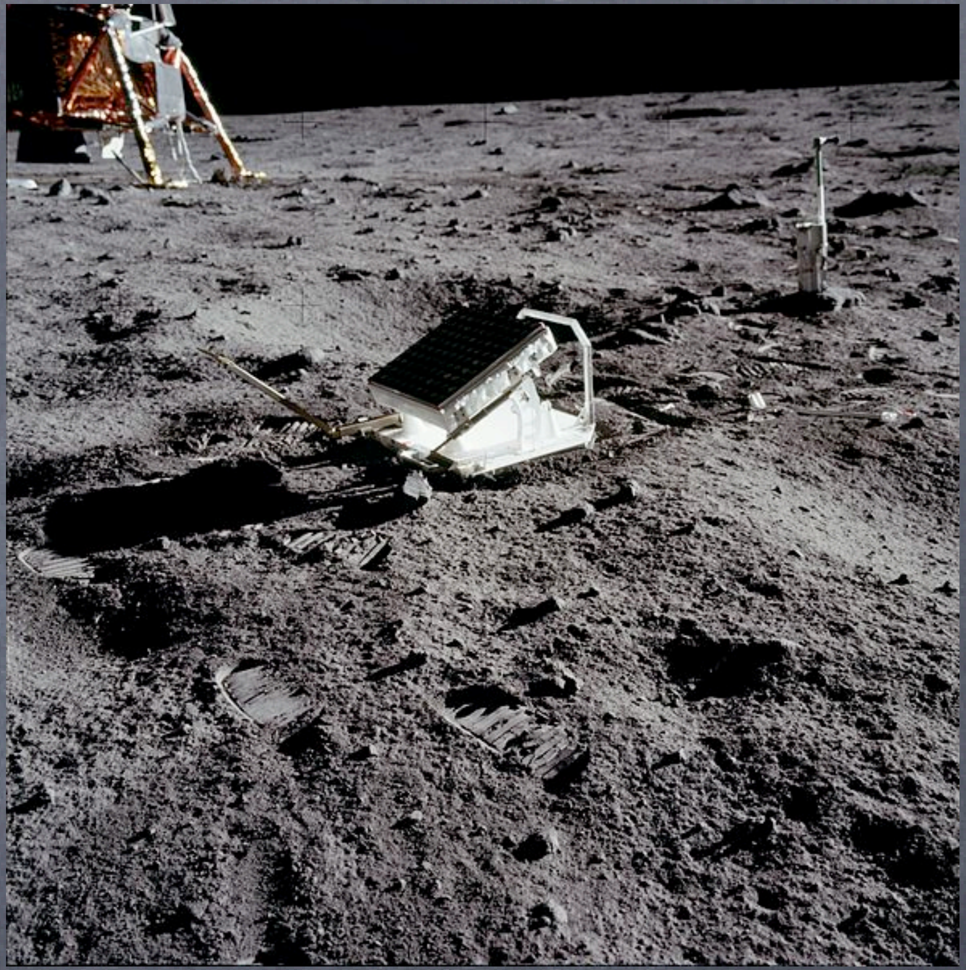


Must rely on screening mechanism for consistency with local tests of GR

Experimental Program

$$U(r) = -g \frac{M}{8\pi M_{\rm Pl}^2} \frac{e^{-r/\lambda}}{r}$$





Screening mechanisms have rich phenomenology for tests of GR:

- Forced us to rethink implications of existing data
- Inspired design of novel experimental tests

Screening Mechanisms

- Chameleon/symmetron/dilaton: $\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + A(\phi)T^\mu_\mu$

  Khoury & Weltman (2003); Brax et al. (2004);
  Hinterbichler & Khoury (2010); Brax et al. (2010)

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  Babichev, Deffayet & Ziour (200

  $|\partial^3\phi| \gg \Lambda^4$?

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Should we be worried?

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"The absence of evidence is <u>not</u> evidence of absence."

Chameleon Mechanism

Khoury & Weltman (2003); Gubser & Khoury (2004);
Brax, van de Bruck, Davis, Khoury and Weltman (2004);
Mota and Shaw (2006).

Consider scalar field ϕ with potential $V(\phi)$ and coupled to matter:

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + g\frac{\phi}{M_{\rm Pl}}T^{\mu}_{\mu}$$

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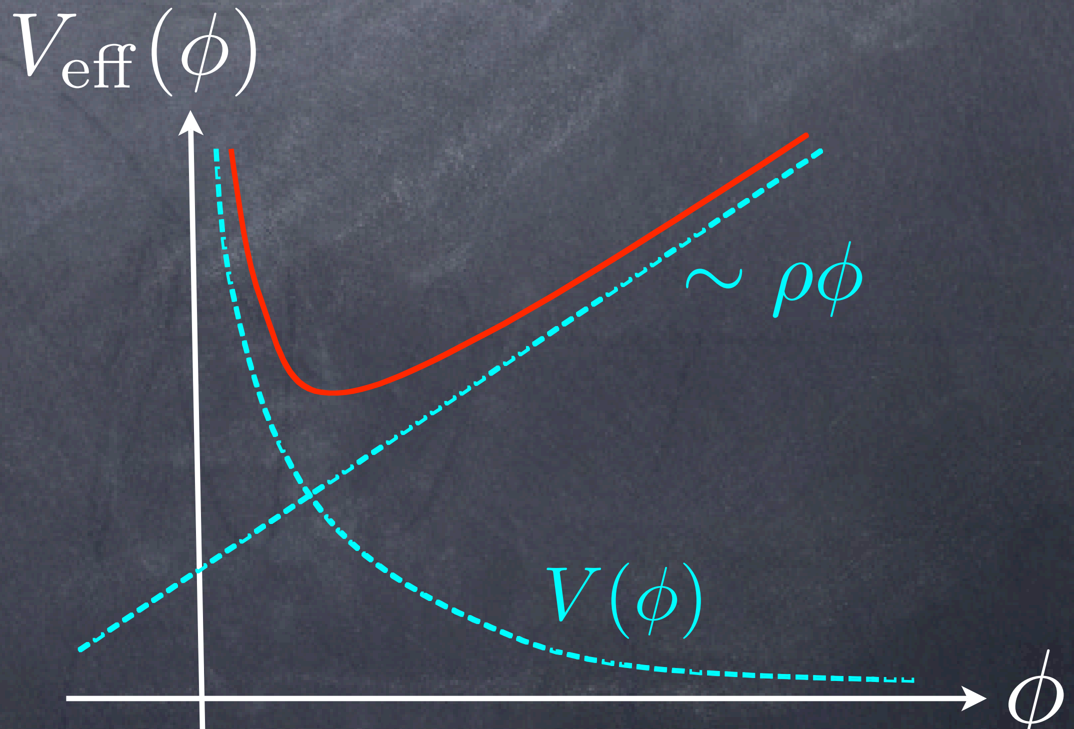
For non-relativistic matter, $T^{\mu}_{\mu} \approx -\rho$, hence

$$\nabla^2\phi = V_{,\phi} + \frac{g}{M_{\rm Pl}}\rho$$

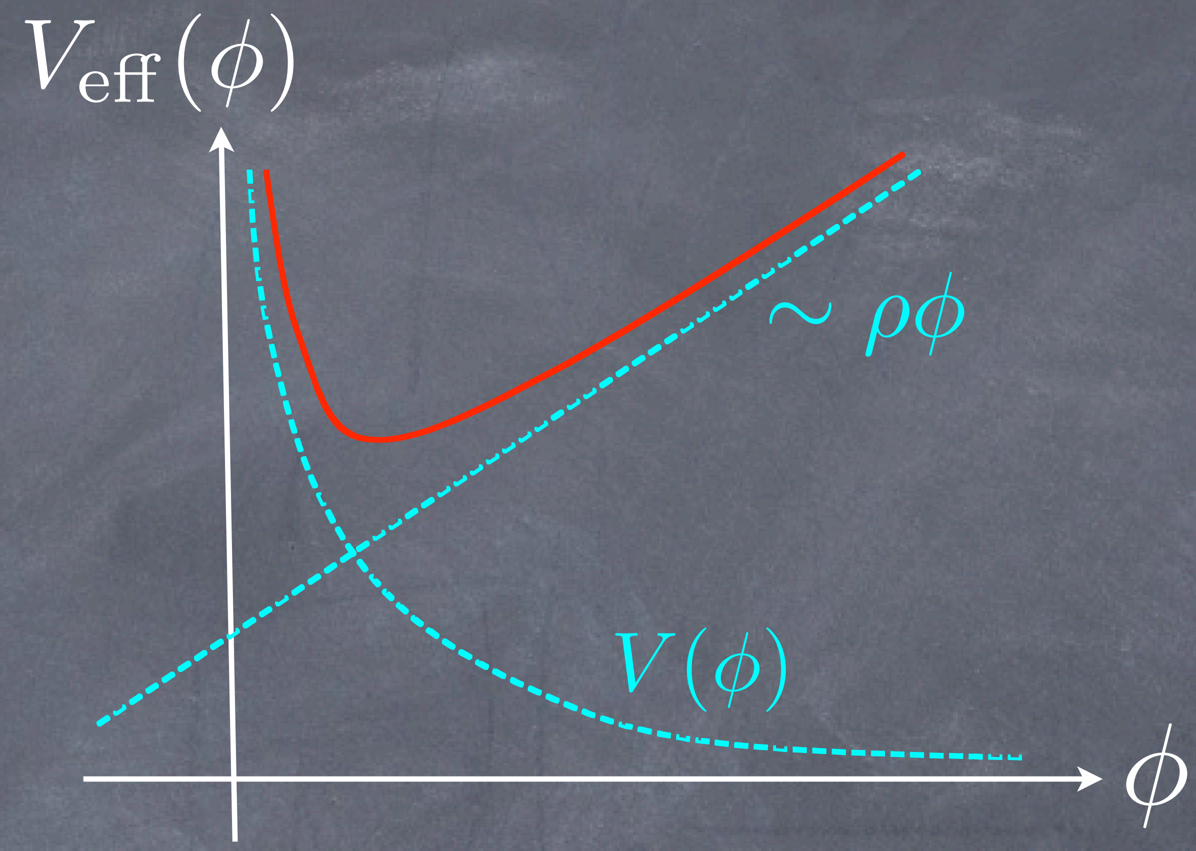
$$\Longrightarrow \quad \boxed{V_{\rm eff}(\phi) = V(\phi) + g\frac{\phi}{M_{\rm Pl}}\rho}$$



Density-dependent mass

$$V_{\text{eff}}(\phi) = V(\phi) + g\frac{\phi}{M_{\text{Pl}}}\rho$$

e.g. $V(\phi) = \dfrac{M^{4+n}}{\phi^n}$



Thus $m = m(\rho)$ increases with increasing density

Laboratory tests => set $m^{-1}(\rho_{\text{local}}) \lesssim \text{mm}$

Generally implies: $m^{-1}(\rho_{\text{cosmos}}) \lesssim \text{Mpc}$

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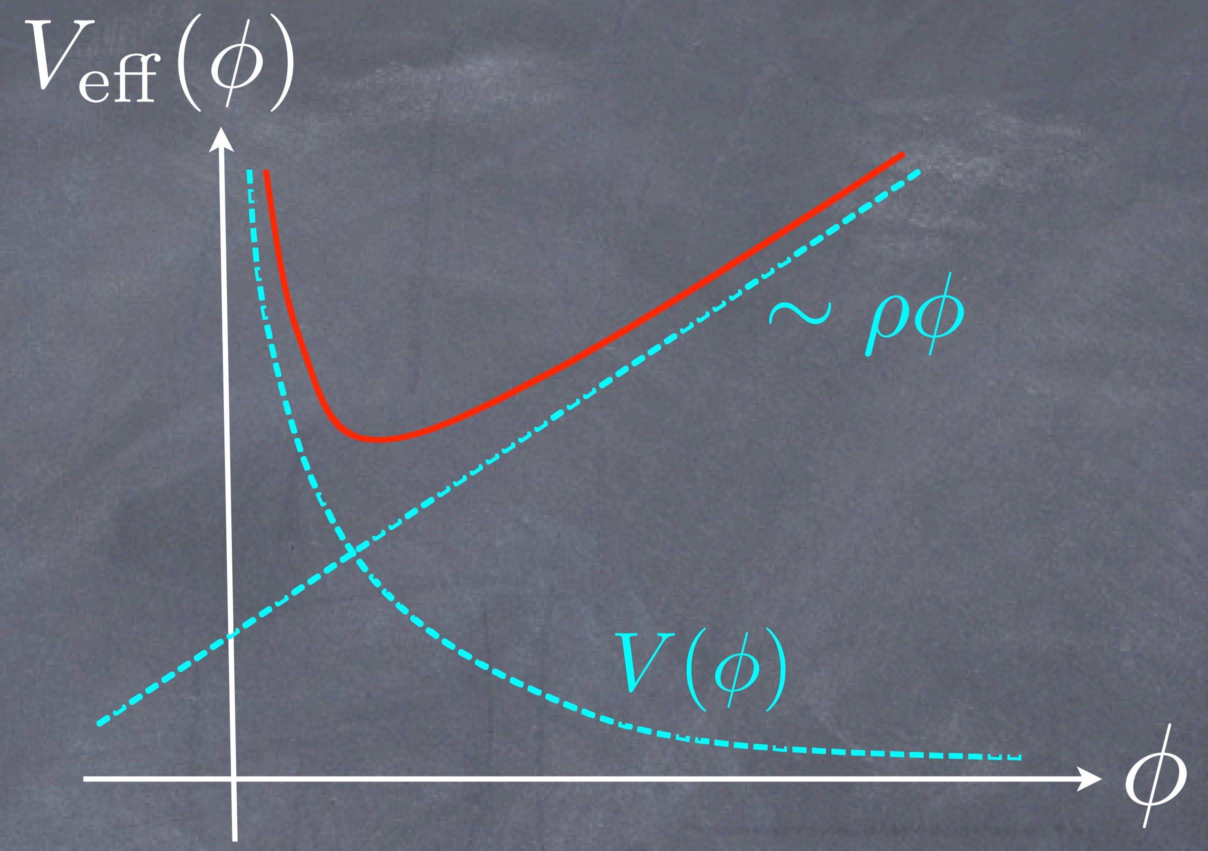

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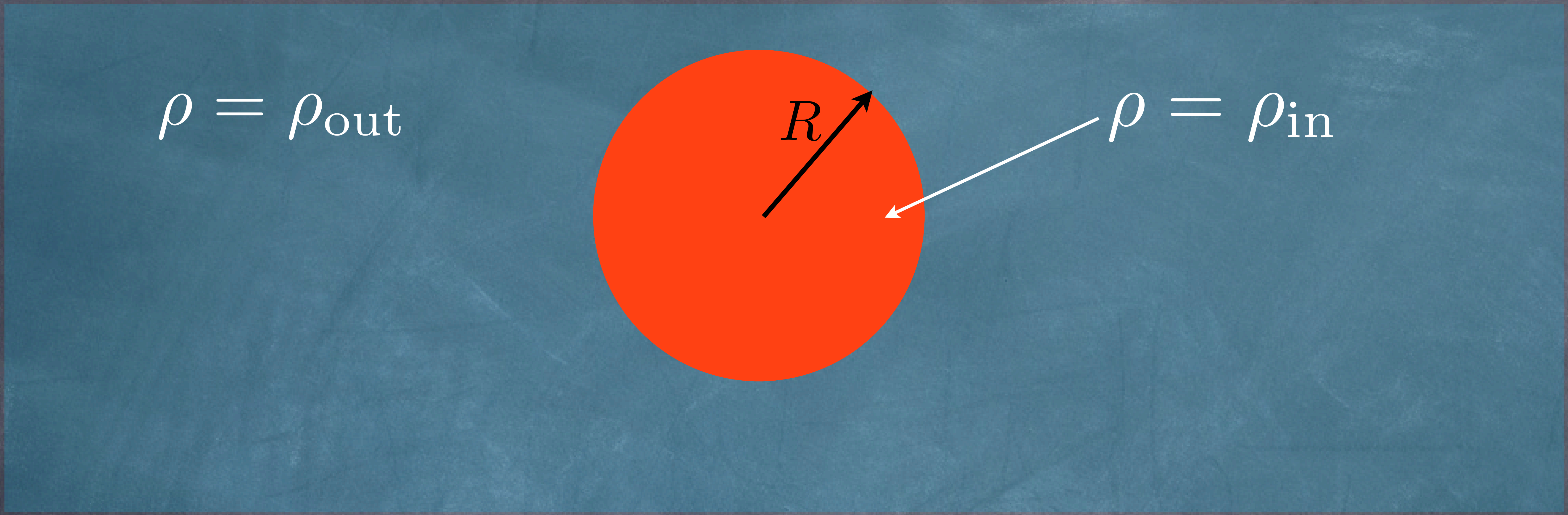
Generally implies: $m^{-1}(\rho_{\text{cosmos}}) \lesssim \text{Mpc}$

Meanwhile, $m^{-1}(\rho_{\text{solar system}}) \lesssim 10 - 10^4\ \text{AU}$

$\Longrightarrow$ ruled out by post-Newtonian tests?

Thin-shell screening



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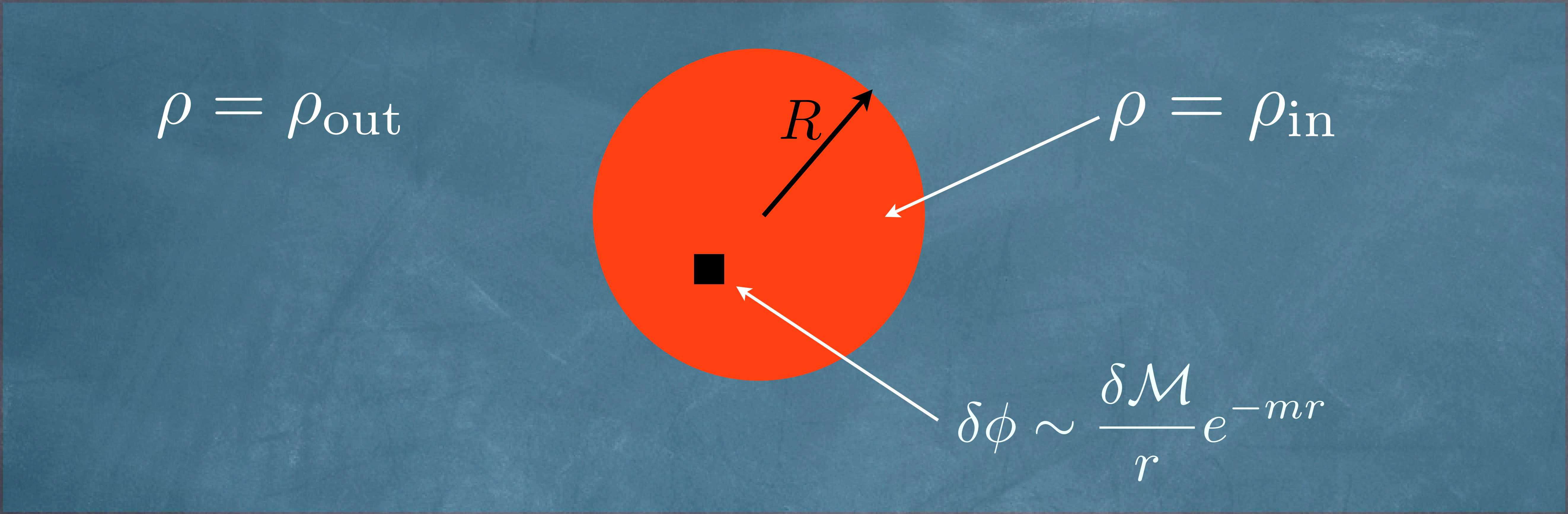

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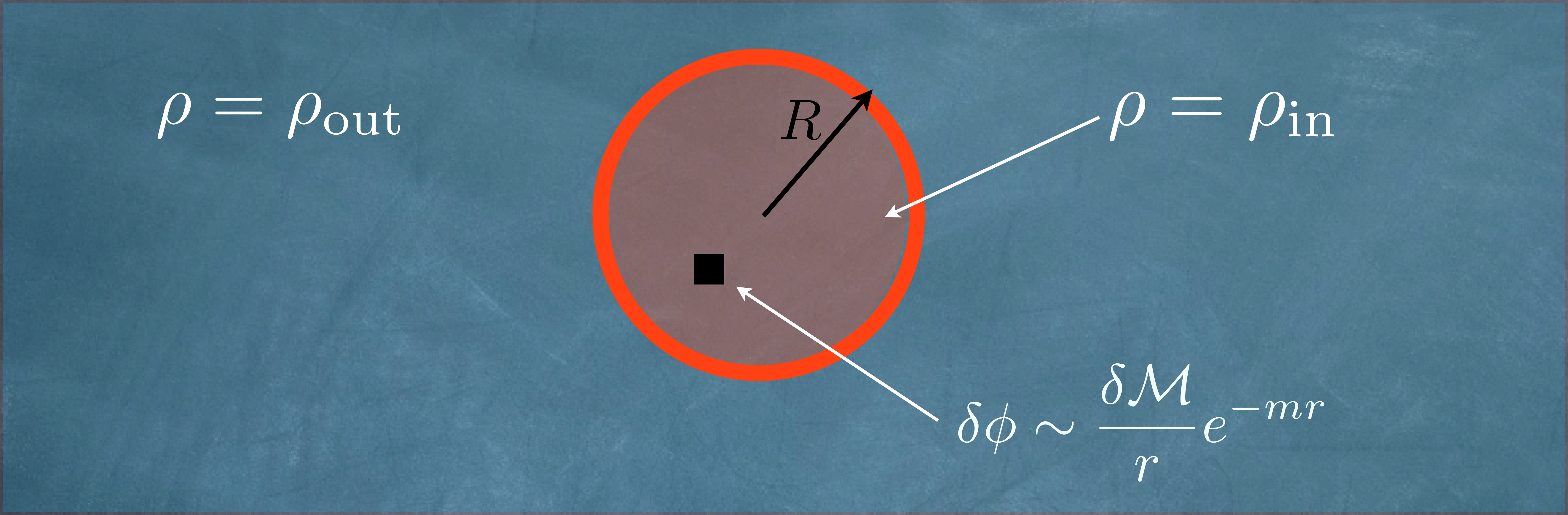

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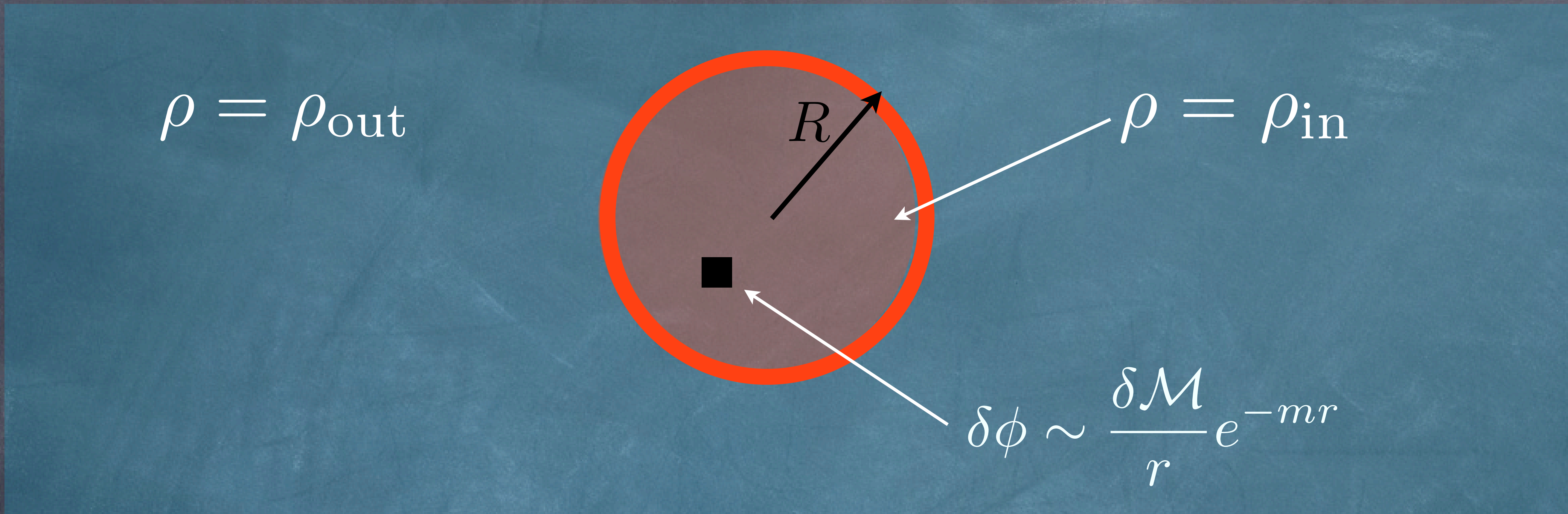

$$\Longrightarrow \quad \boxed{\phi(r > R) \sim \frac{\Delta R}{R} \times \frac{g\, G_{\rm N} M}{r}}$$

where $\dfrac{\Delta R}{R} = \dfrac{\phi_{\rm out} - \phi_{\rm in}}{6 g M_{\rm Pl} \Phi_{\rm N}} \ll 1 \quad \Longrightarrow$ thin-shell screening

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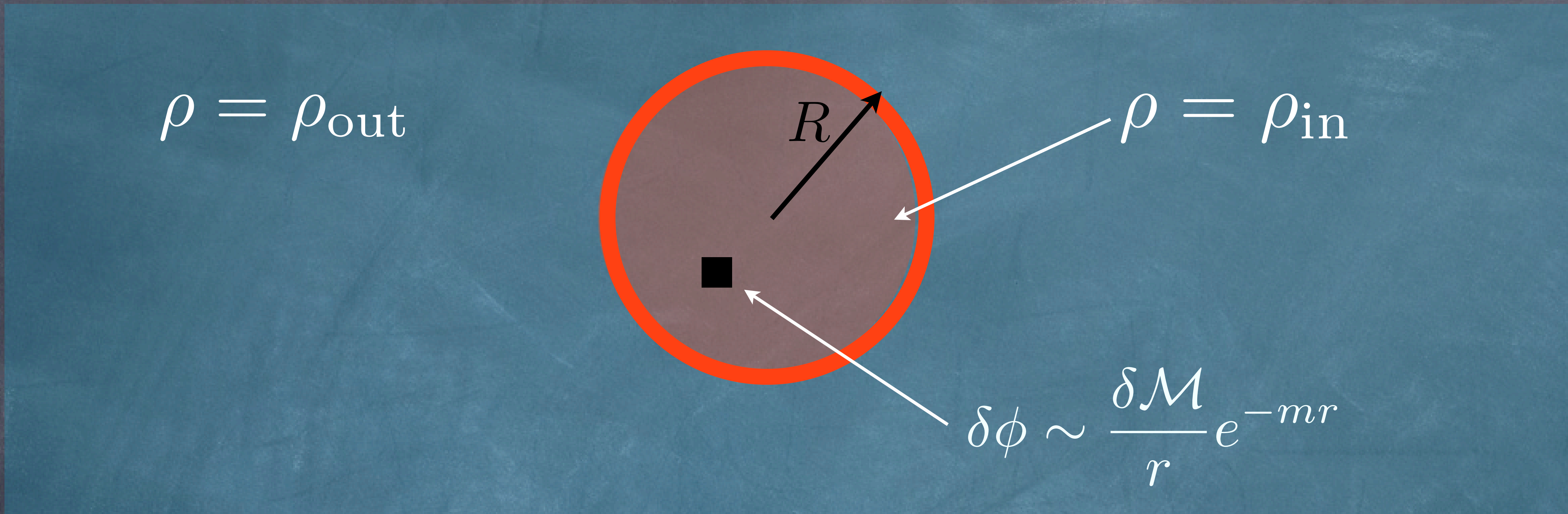

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But small objects $\Longrightarrow$ no thin-shell

Thin-shell condition depends on environment!

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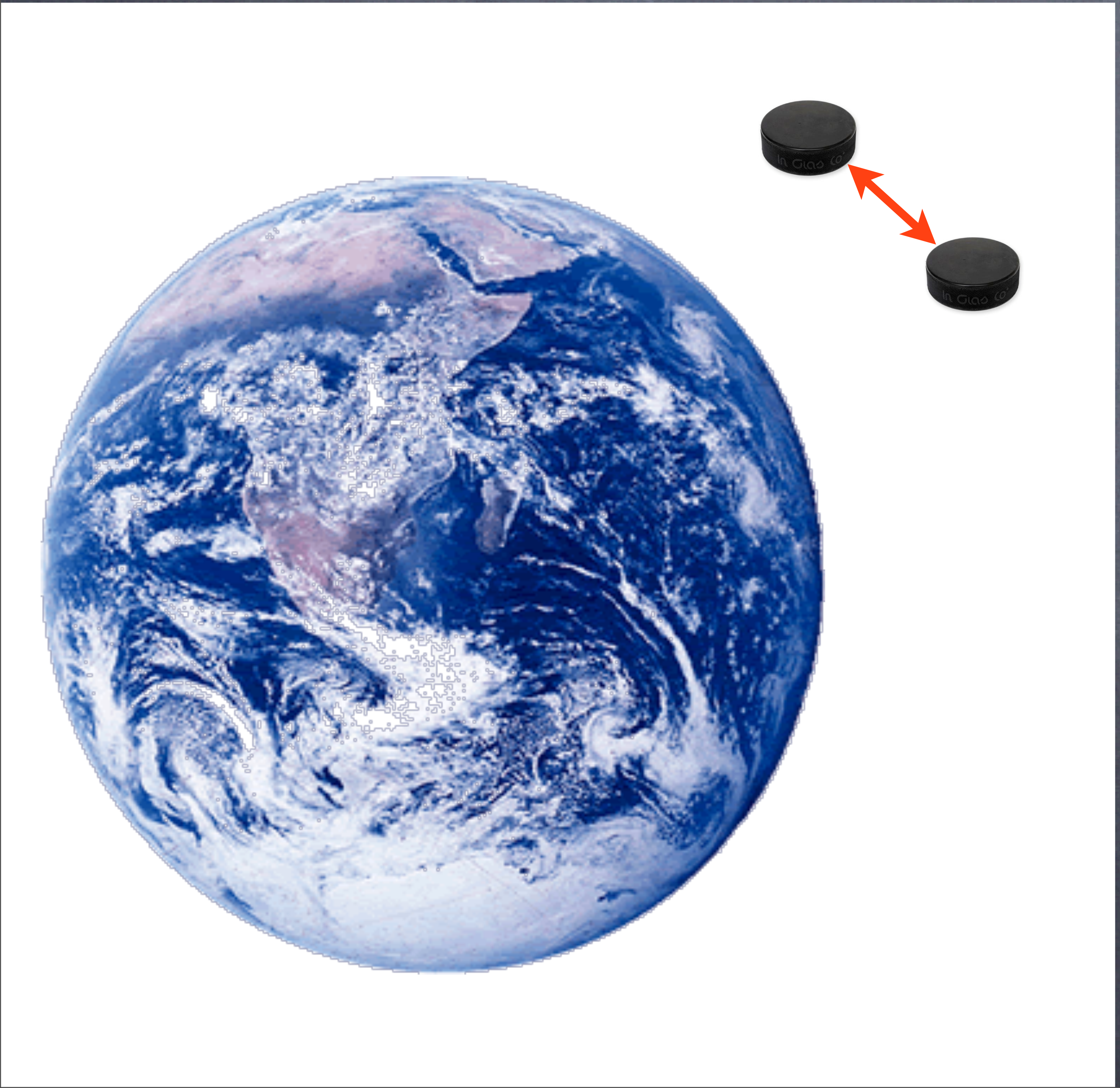

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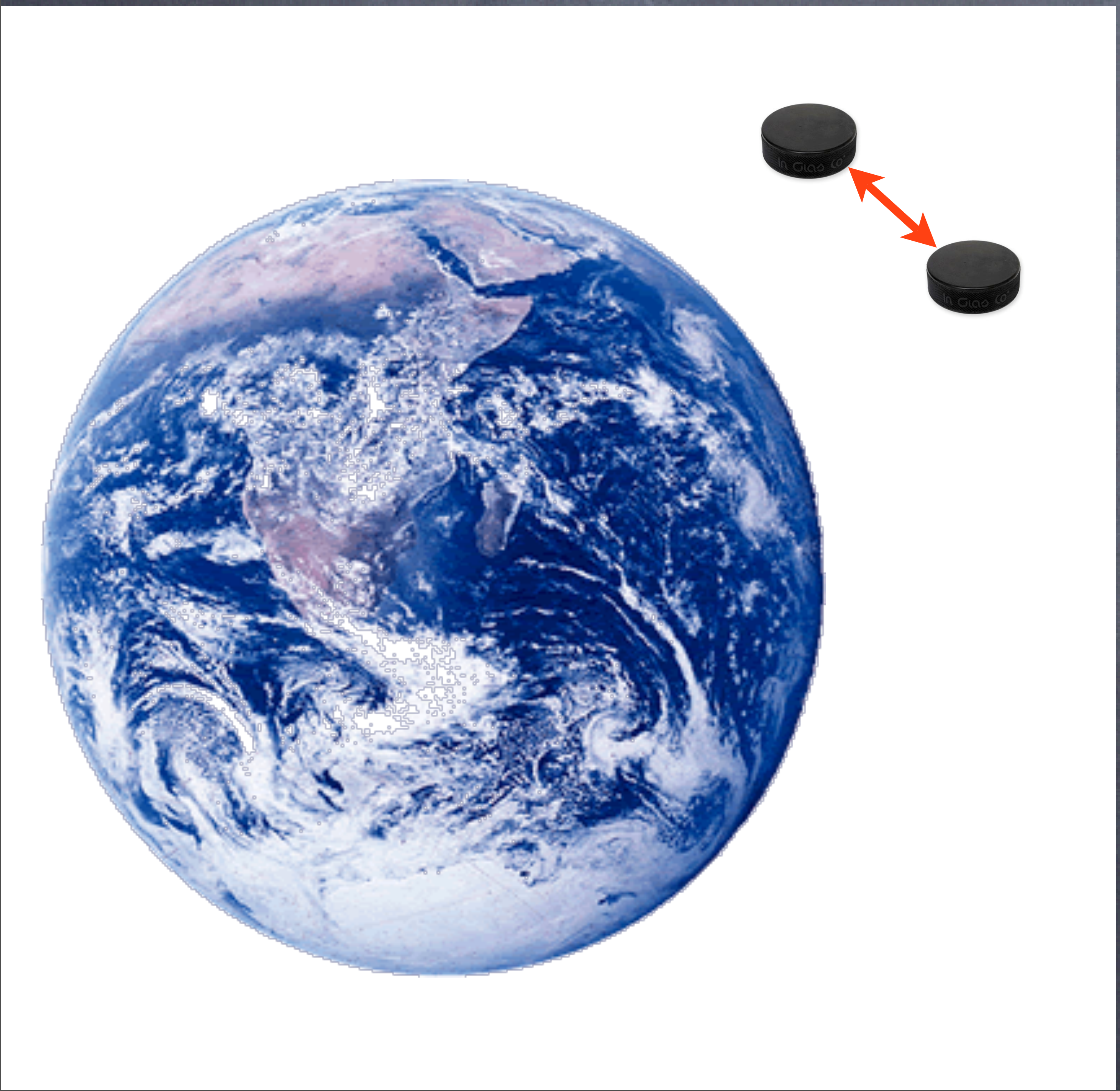


$$G_{\rm N}^{\rm eff} = G_{\rm N}(1+2g^2)$$

between small objects in space !

Smoking Guns

- Satellite Energy Exchange (SEE) Mission

$$\frac{\Delta G_{\mathrm{N}}}{G_{\mathrm{N}}} < 10^{-6}$$

$$\frac{\Delta G_{\mathrm{N}}}{G_{\mathrm{N}}} \sim \mathcal{O}(1)$$

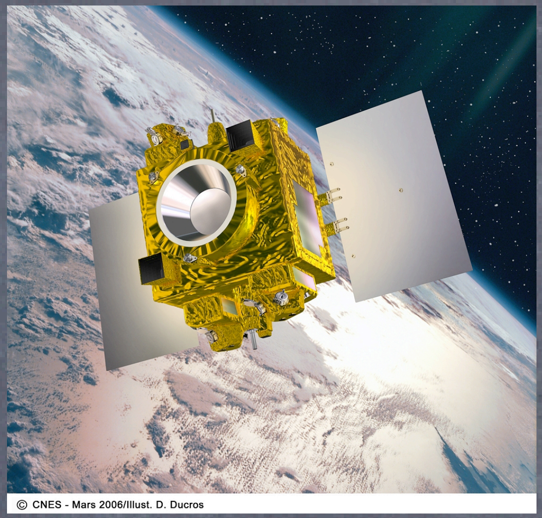
Smoking Guns

- Satellite Energy Exchange (SEE) Mission

$$\frac{\Delta G_{\rm N}}{G_{\rm N}} < 10^{-6}$$

- MICROSCOPE (2015)

$$\frac{\Delta a}{a} < 10^{-15}$$



- Satellite Test of the Equivalence Principle (STEP)

$$\frac{\Delta a}{a} < 10^{-18}$$

$$\downarrow$$

$$\frac{\Delta G_{\rm N}}{G_{\rm N}} \sim \mathcal{O}(1)$$

$$\frac{\Delta a}{a} > 10^{-13}$$

Symmetron Mechanism

K. Hinterbichler and J. Khoury, Phys. Rev. Lett. (2010); Olive and Pospelov (2008); Brax, van de Bruck, Davis and Shaw (2010).

Instead of $m(\rho)$, here coupling to matter depends on density.

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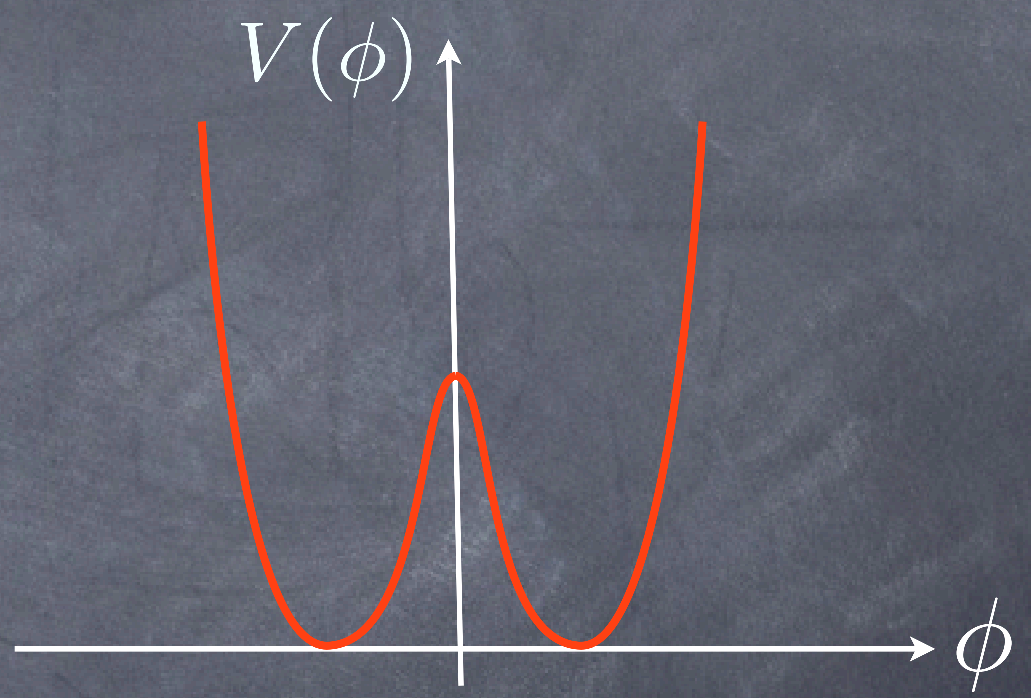
Potential is of the spontaneous-symmetry-breaking form:

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$



Most general renormalizable potential with $\phi \to -\phi$ symmetry.

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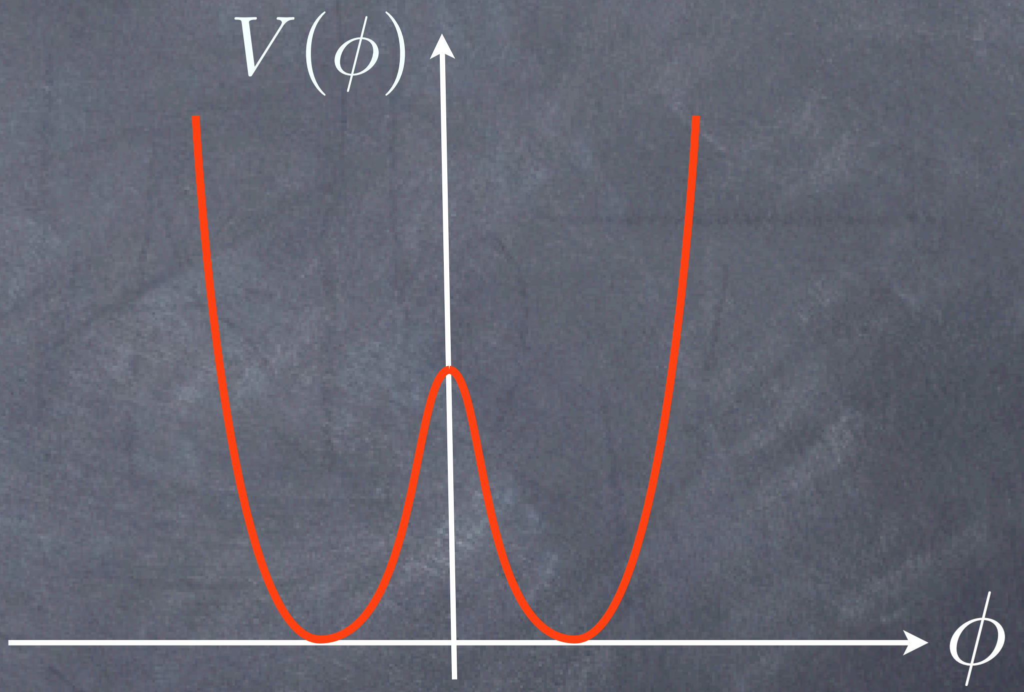


Most general renormalizable potential with $\phi \to -\phi$ symmetry.

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

$\therefore$ Whether symmetry is broken or not depends on local density

Density-dependent coupling

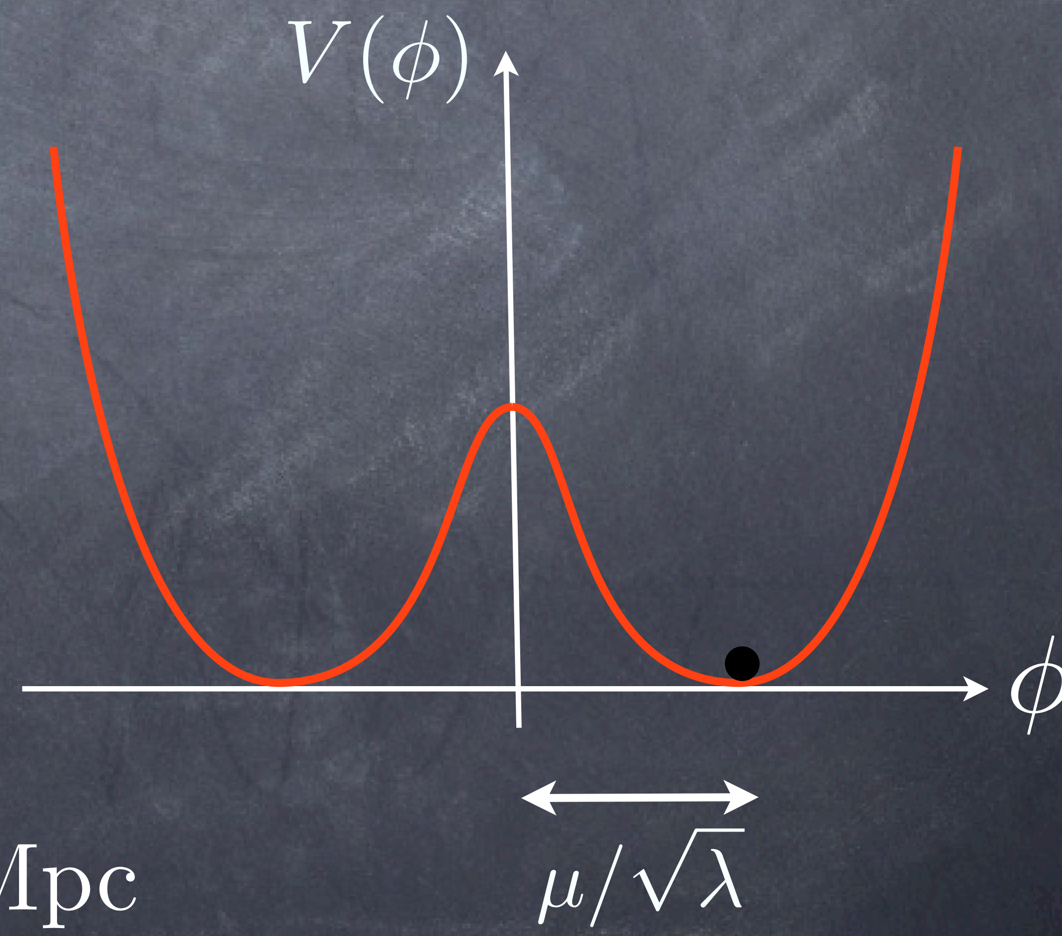
Perturbations $\delta\phi$ around local background value couple as:

$$\mathcal{L}_{\rm coupling} \sim \frac{\bar{\phi}}{M^2}\delta\phi\,\rho$$

- Symmetron decoupled in high-density regions (where $\bar{\phi} \simeq 0$)
- In voids, where symmetry is broken,

$$\mathcal{L}_{\rm coupling} \sim \frac{\mu}{\sqrt{\lambda}M^2}\delta\phi\,\rho \sim \frac{\delta\phi}{M_{\rm Pl}}\rho$$

gravitational strength



NOTE: Tests of gravity $\Longrightarrow$ $\mu^{-1} \sim {\rm Mpc}$

Inspiration...

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Symmetron Couch ($9500.00)

"NASA-style gravity reduction."

"Offers a unique multi-phase wave experience."

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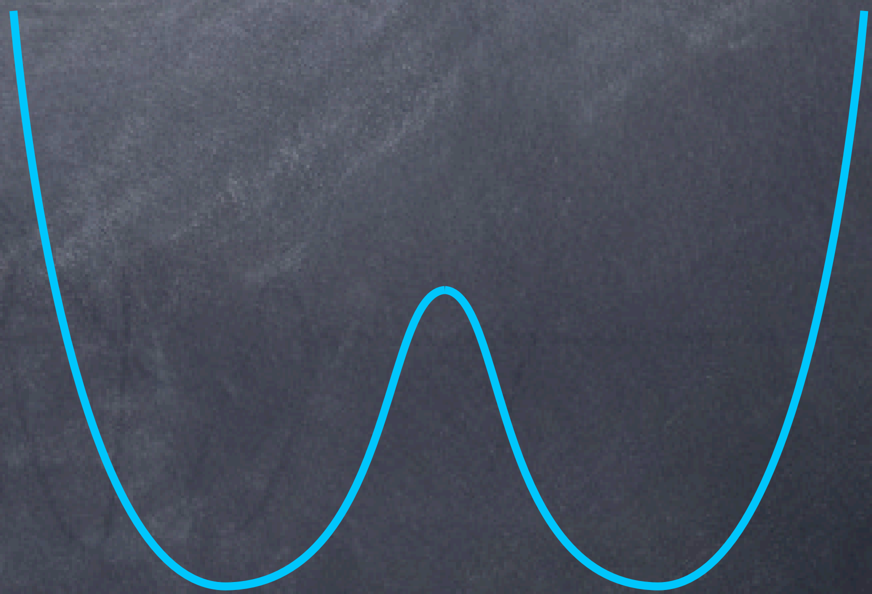
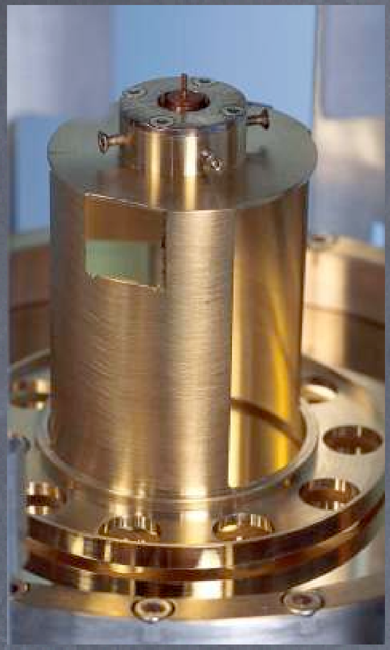
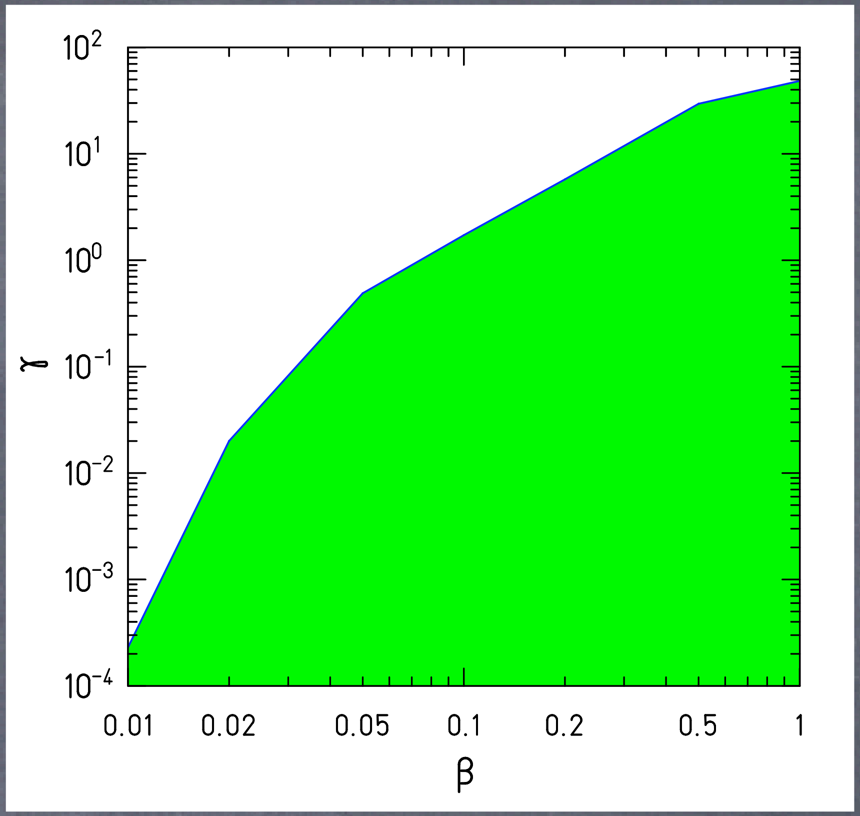


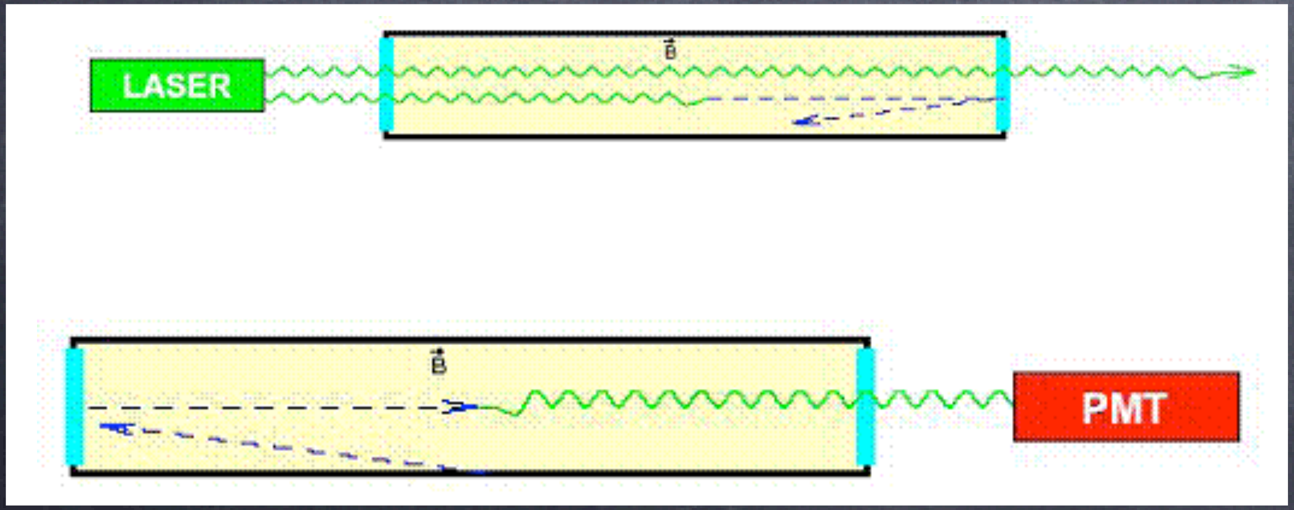
Chameleon Searches

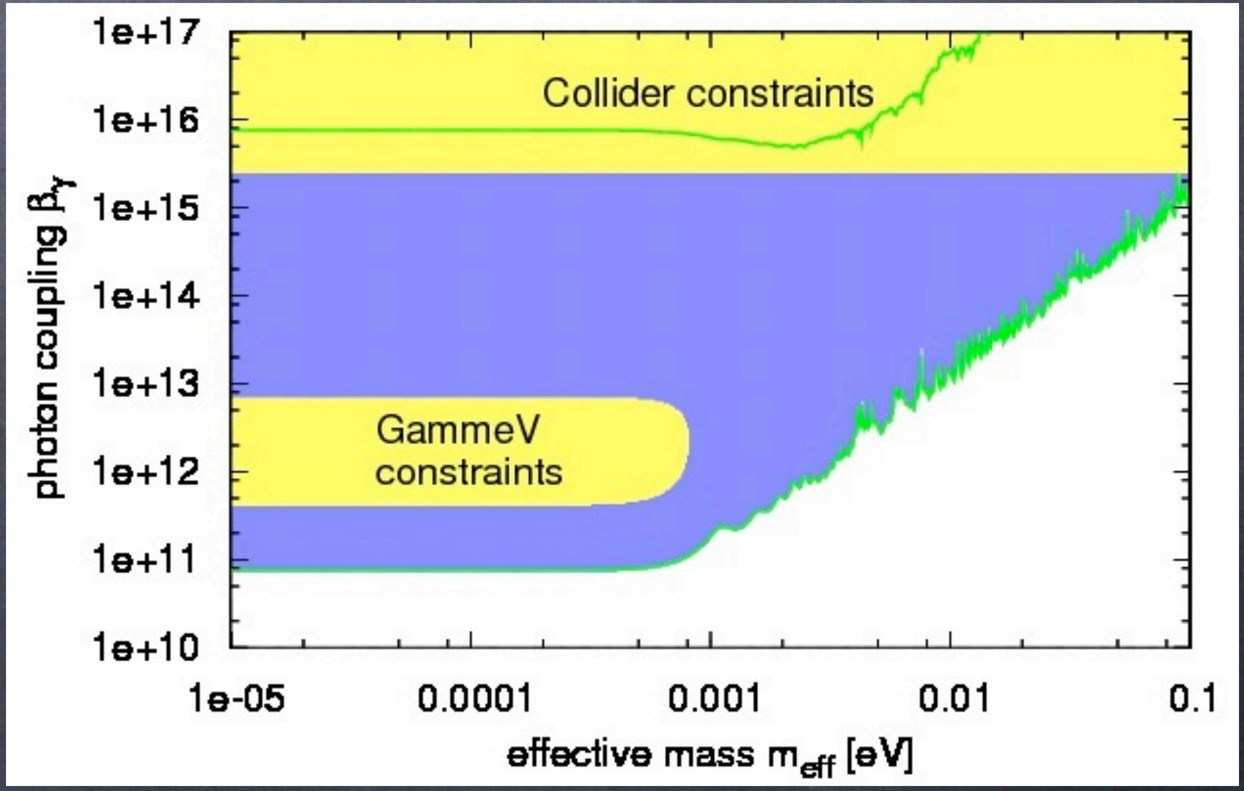
- Eot-Wash
  Adelberger et al.,
  Phys. Rev. Lett. (2008)





- CHameleon Afterglow SEarch (CHASE), Fermilab
  Chou et al., Phys. Rev. Lett. (2008,2010)

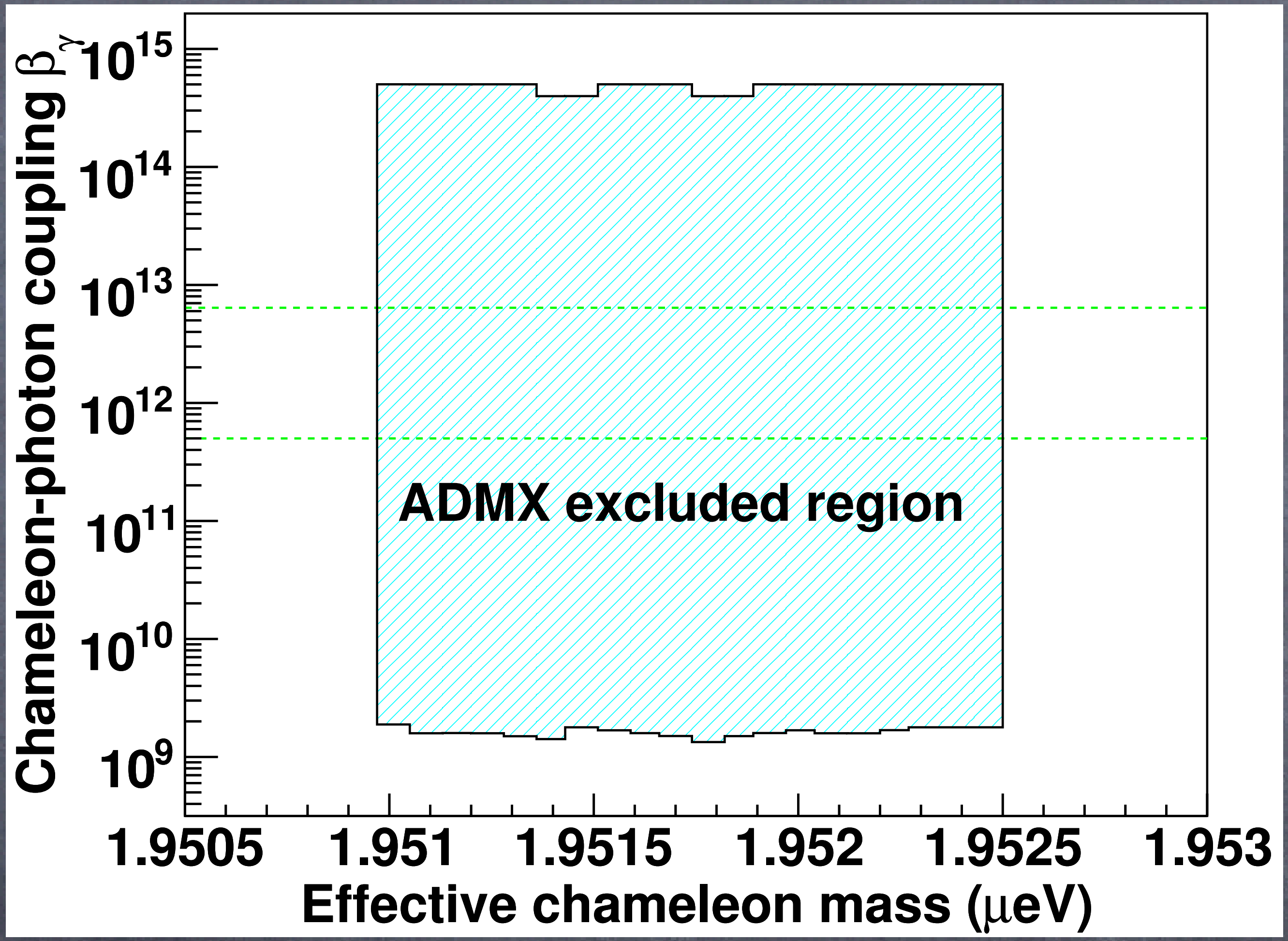




Chameleon Searches (cont'd)

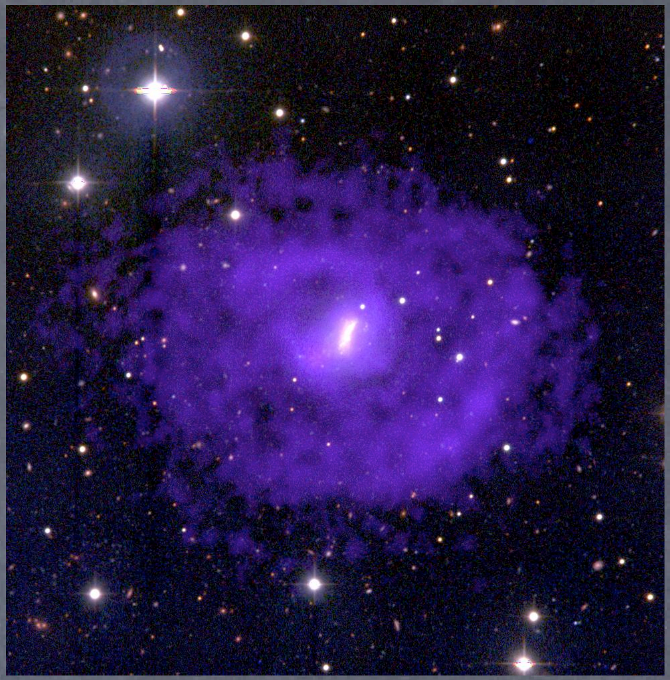
- Axion Dark Matter eXperiment (ADMX)

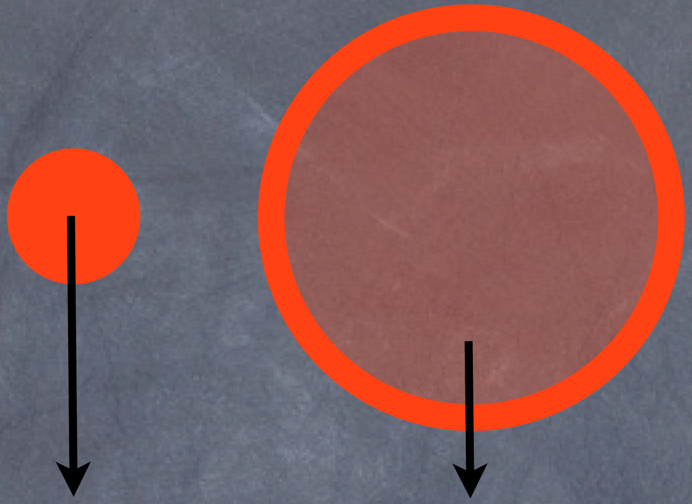
P. Sikivie & co., Phys. Rev. Lett. (2010)



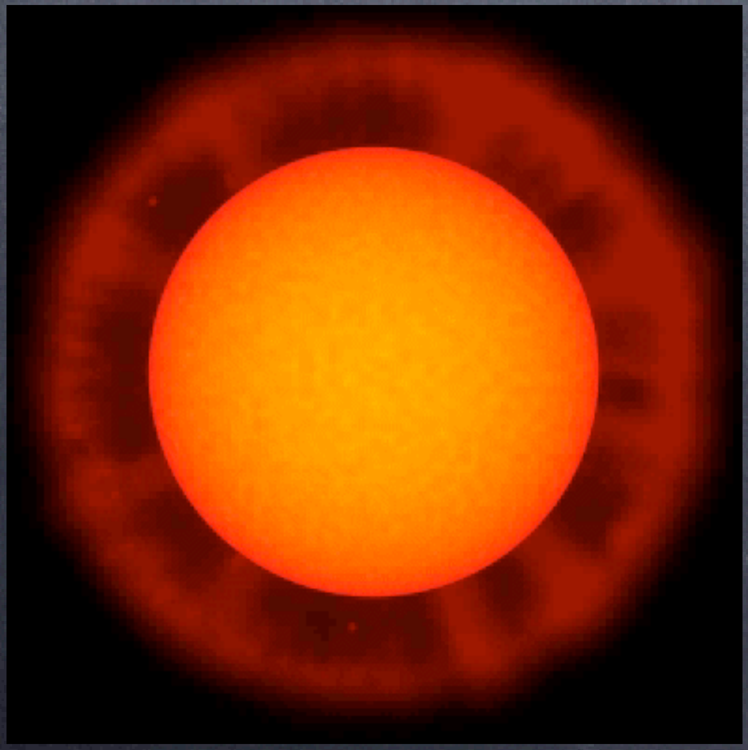
Astrophysical signatures

- Macroscopic violations of the Equivalence Principle Hui, Nicolis & Stubbs (2009); Jain & Vanderplas (2011)





- Modified stellar evolution



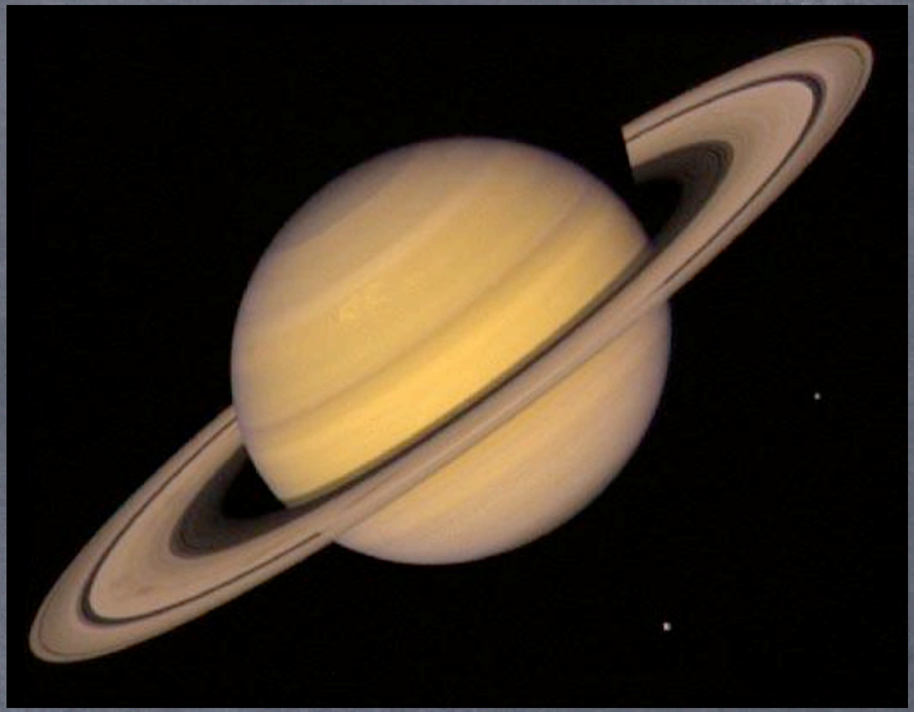
Chang & Hui (2010);
Davis, Lim, Sakstein & Shaw (2011);
Jain, Vikram & Sakstein (2012)

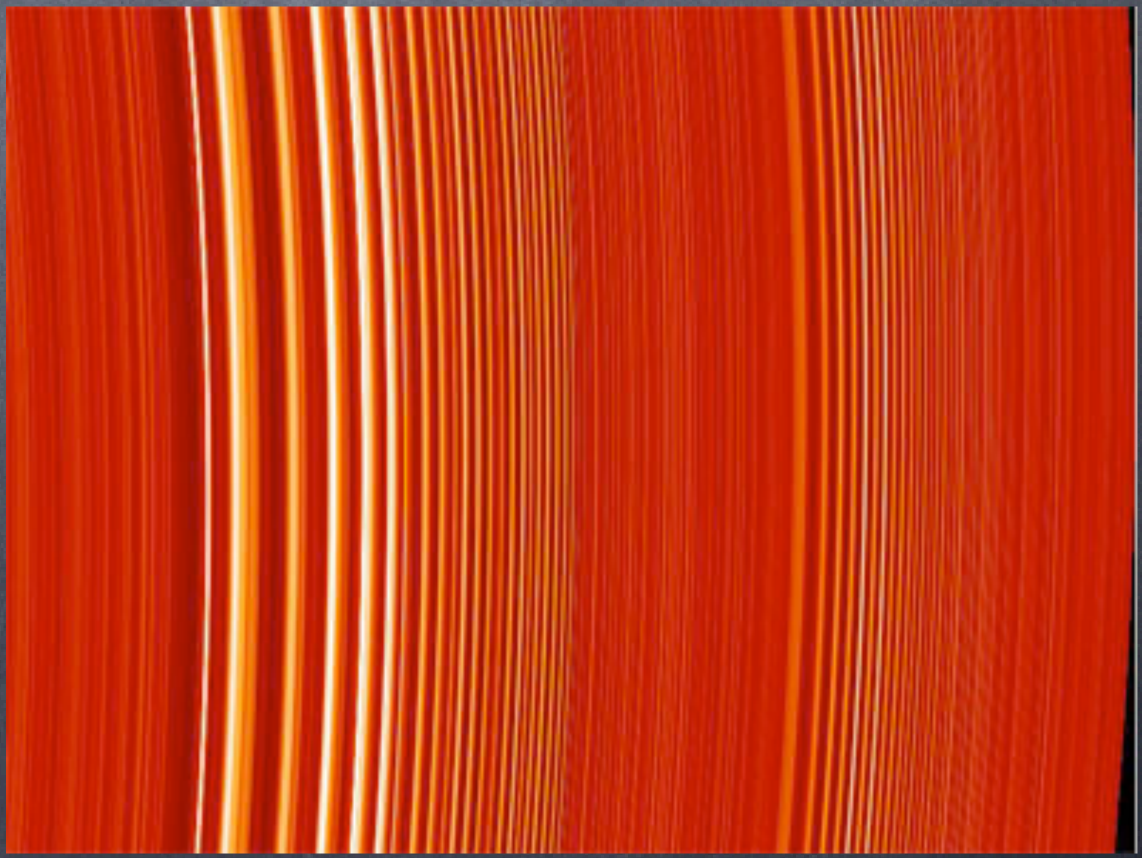
cf. Eugime Lim's talk

Astrophysical signatures (cont'd)

- Saturn's rings

Enhanced self-gravity due to chameleon should impact propagation of density waves.





$$v_g = \frac{\pi G_N \sigma_0}{\kappa}$$

$\sigma_0 \equiv$ surface density

$\kappa \equiv$ epicyclic frequency

Self-Acceleration?

Wang, Hui & J. Khoury, to appear

$$\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$$

"Jordan frame" ($\tilde{g}_{\mu\nu}$)

"Einstein frame" ($g_{\mu\nu}$)

Can cosmic acceleration result from $\Delta A \sim \mathcal{O}(1)$ even though Einstein-frame metric is NOT accelerating?

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Take chameleon with $A(\phi) = 1 + \dfrac{g\phi}{M_{\rm Pl}} + \ldots$

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- Screening condition: $\dfrac{\Delta R}{R} \approx \dfrac{\phi_0}{6 g M_{\rm Pl} \Phi_{\rm N}} < 1$

Milky Way potential $\Phi_{\rm N} \sim 10^{-6}$ $\Longrightarrow$ $\boxed{\phi_0 \lesssim 10^{-6} M_{\rm Pl}}$

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$$\therefore \quad \boxed{\Delta A \lesssim g \frac{\phi_0}{M_{\rm Pl}} \ll 1}$$

(NO self-acceleration)

The Mpc Barrier

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Cancellation must hold over last Hubble time:

$$\Delta\left(\frac{\mathrm{d}V}{\mathrm{d}\phi} + \frac{g}{M_{\rm Pl}}\rho\right) \sim H_0^2 M_{\rm Pl} \sim m_0^2 \Delta\phi$$

$$\Longrightarrow \quad \boxed{m_0 \sim H_0\sqrt{\frac{M_{\rm Pl}}{\Delta\phi}} > 10^3\ H_0}$$

Argument generalizes to very wide class of chameleon/symmetron theories, including many fields!

Quantum Stability

Upadhye, Hu & Khoury, 1204.3906 [hep-ph], to appear in Phys. Rev. Lett.

Focus on scalar loops: $$\Delta V_{1-\mathrm{loop}} = \frac{m_\phi^4(\phi)}{64\pi^2}\ln\left(\frac{m_\phi^2(\phi)}{\mu_0^2}\right)$$

$\Longrightarrow$ Tension: Need small m_ϕ to keep loop corrections under control, BUT chameleon mechanism relies on $m_\phi \uparrow$ with ρ

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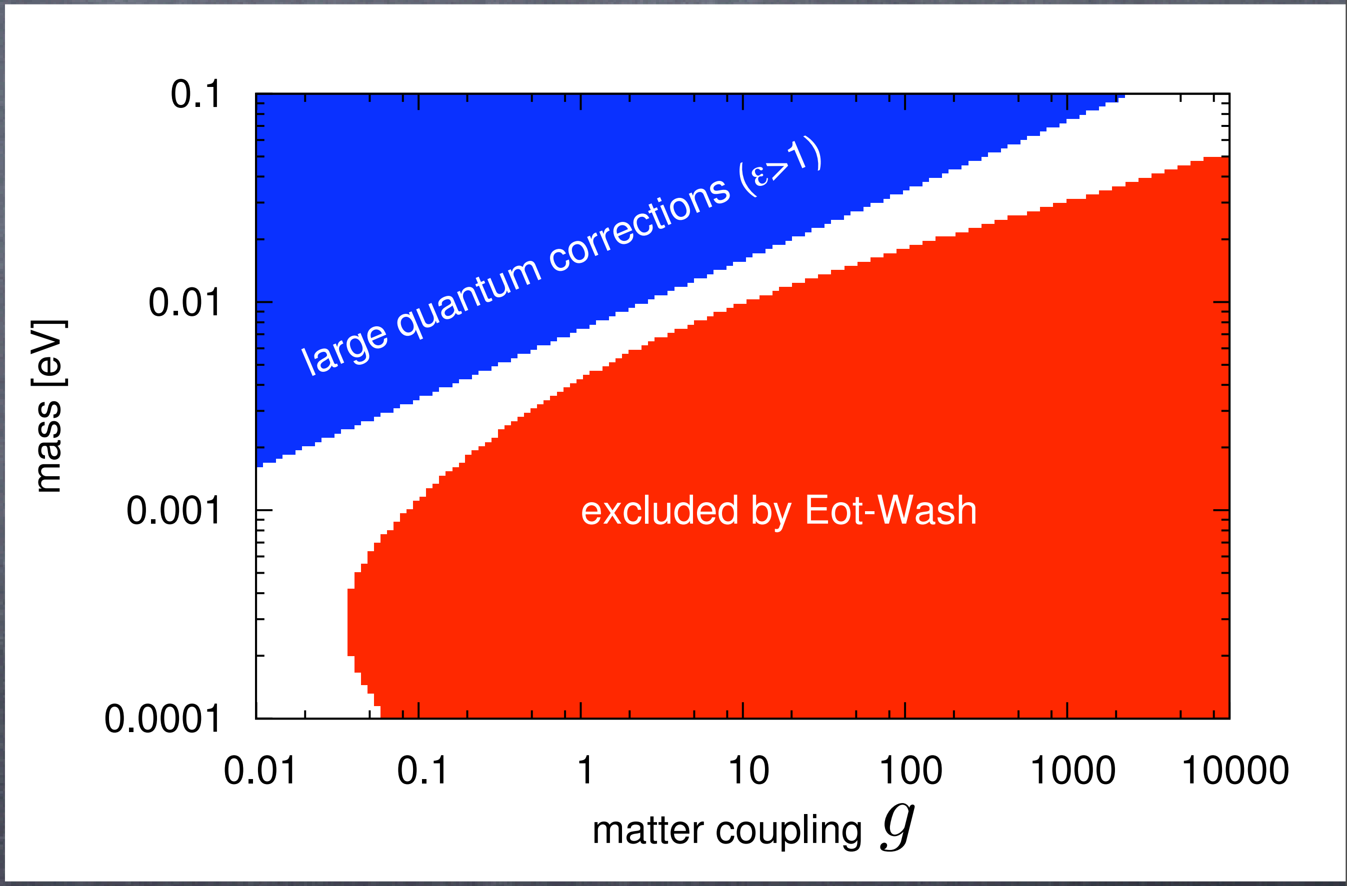
Using $V_{,\phi}(\phi_{\rm min}) = -\frac{g\rho}{M_{\rm Pl}}$ to relate $\phi_{\rm min}$ and ρ :

$$m_\phi^{-1} \gtrsim 27 \left(\frac{g\rho_{\rm lab}}{10\ {\rm g\,cm^{-3}}}\right)^{-1/3} \mu{\rm m}$$

(Model-independent)



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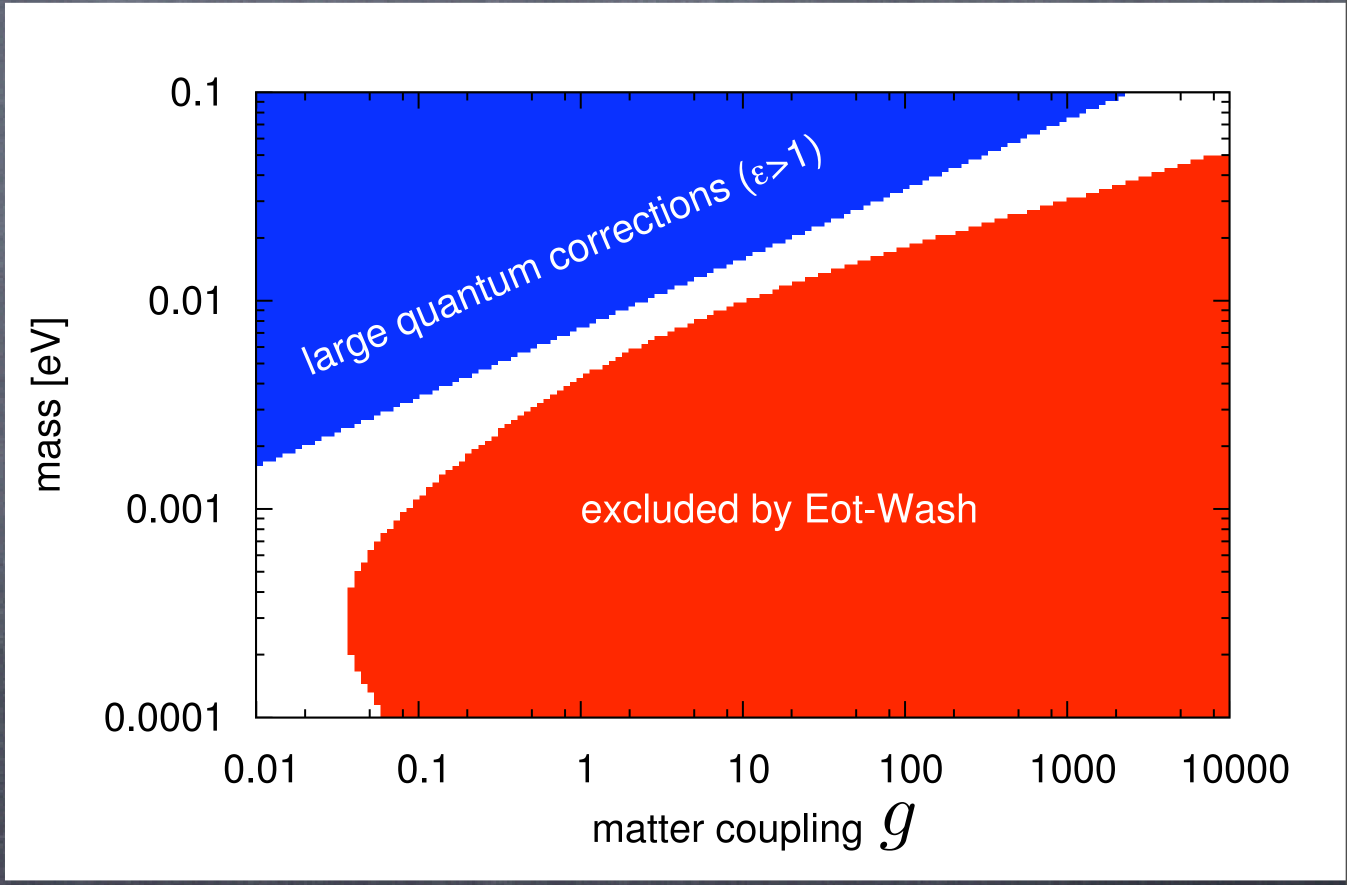
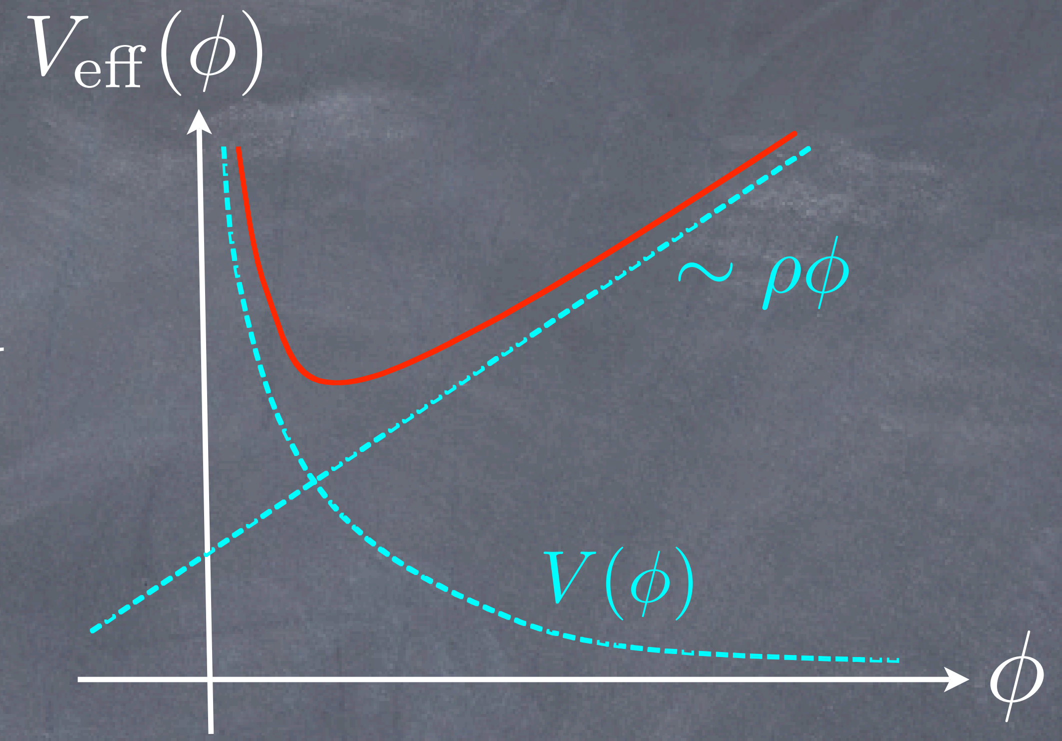


- Factor of ≈ 2 improvement in lab bounds on m_ϕ^{-1} would close the window around $g \sim 1$

Quantum Stability (cont'd)

Upadhye, Hu & Khoury, 1204.3906 [hep-ph]



$$V(\phi) = \frac{M^5}{\phi} \qquad M = 10^{-3}\ \mathrm{eV}$$

Expand around minimum:

$$V = \bar{V} + \ldots + \frac{\delta\phi^n}{\Lambda^{n-4}} + \ldots$$

where

$$\frac{\Lambda}{M} = \left(\frac{\bar{\phi}}{M}\right)^{\frac{n+1}{n-4}} = \left(\frac{M^2}{m^2}\right)^{\frac{n+1}{3(n-4)}} > \left(\frac{M^2}{m^2}\right)^{\frac{1}{3}}$$

- Cosmologically: $m \sim \mathrm{Mpc}^{-1} \Longrightarrow \Lambda \sim 10^5\ \mathrm{GeV}$
- Lab: $m \sim 10^{-3}\ \mathrm{eV} \Longrightarrow \Lambda \sim 10^{-3}\ \mathrm{eV}$

Conclusions

- If new forces are associated with dark sector, then some screening mechanism is required by local tests of gravity

- Chameleon and Symmetron mechanisms rely on density-dependent mass and coupling, respectively.

- Rich phenomenology for laboratory, solar-system and cosmological tests of gravity

Open questions

- UV completion? cf. Hinterbichler, J. Khoury, & Nastase, JHEP (2011)

- Symmetron topological defects?