Center for Particle Cosmology at the University of Pennsylvania

Symmetron Fields: Screening Long-Range Forces Through Local Symmetry Restoration

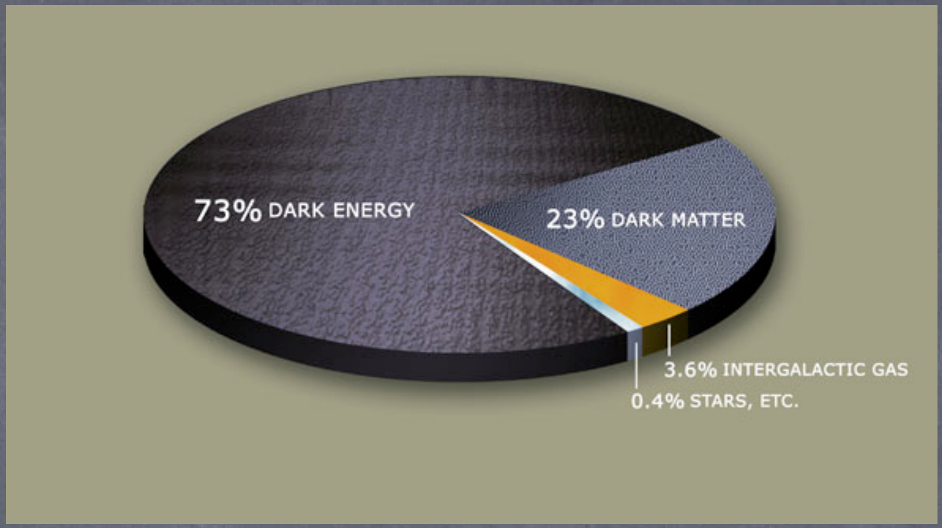
Justin Khoury (UPenn)

K. Hinterbichler and JK, hep-th/1001.4525
K. Hinterbichler, L. Hui and JK, in progress

Basic question: Is it possible for light, gravitationally-coupled scalars to exist while avoiding detection from local experiments?

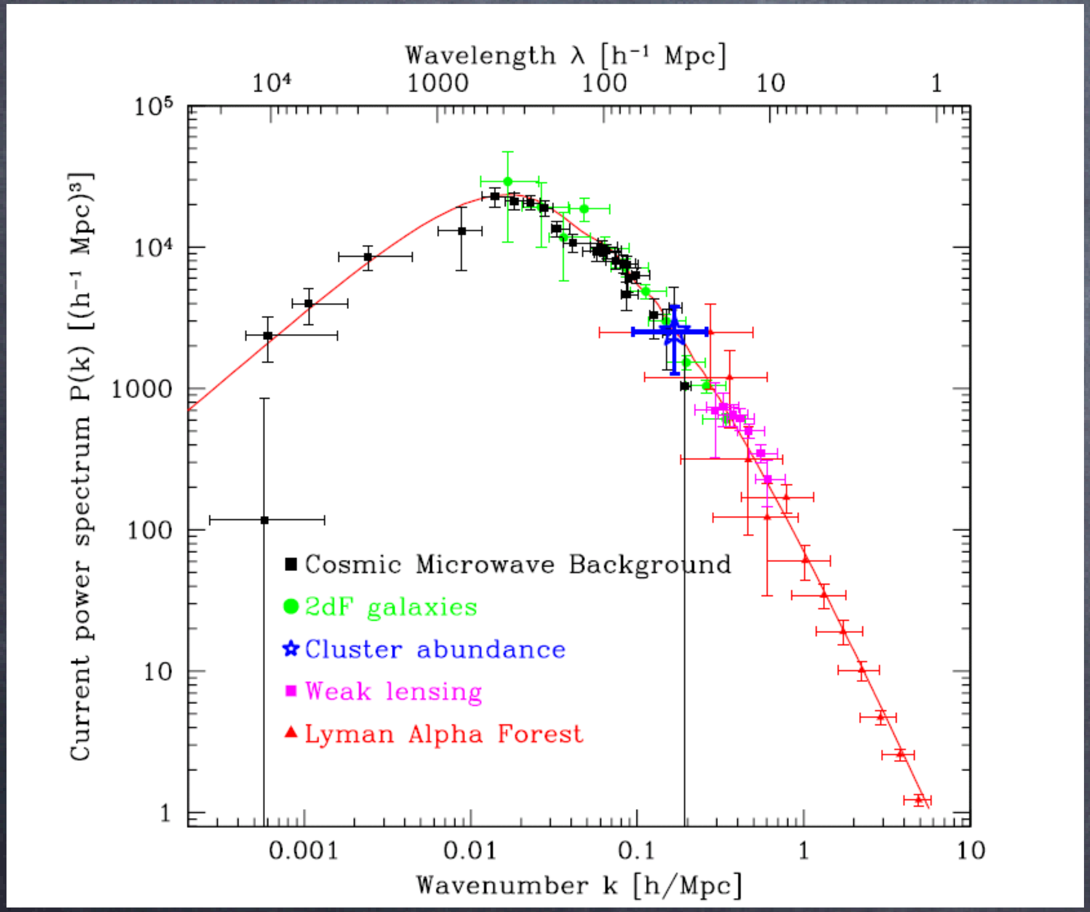
1. Cosmic Acceleration

- ΛCDM model remarkably predictive

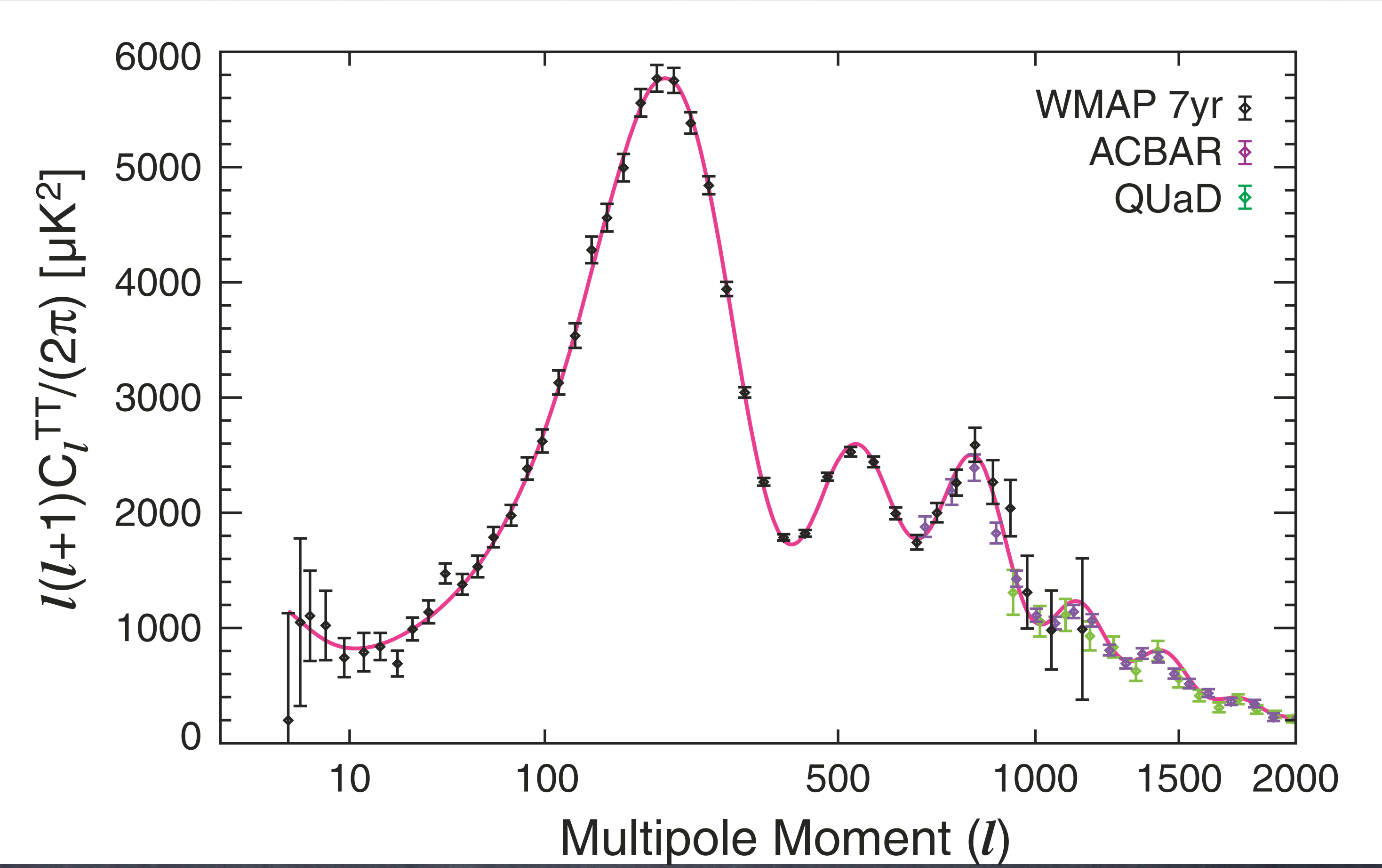


Λ → expansion history

Λ → growth of structure

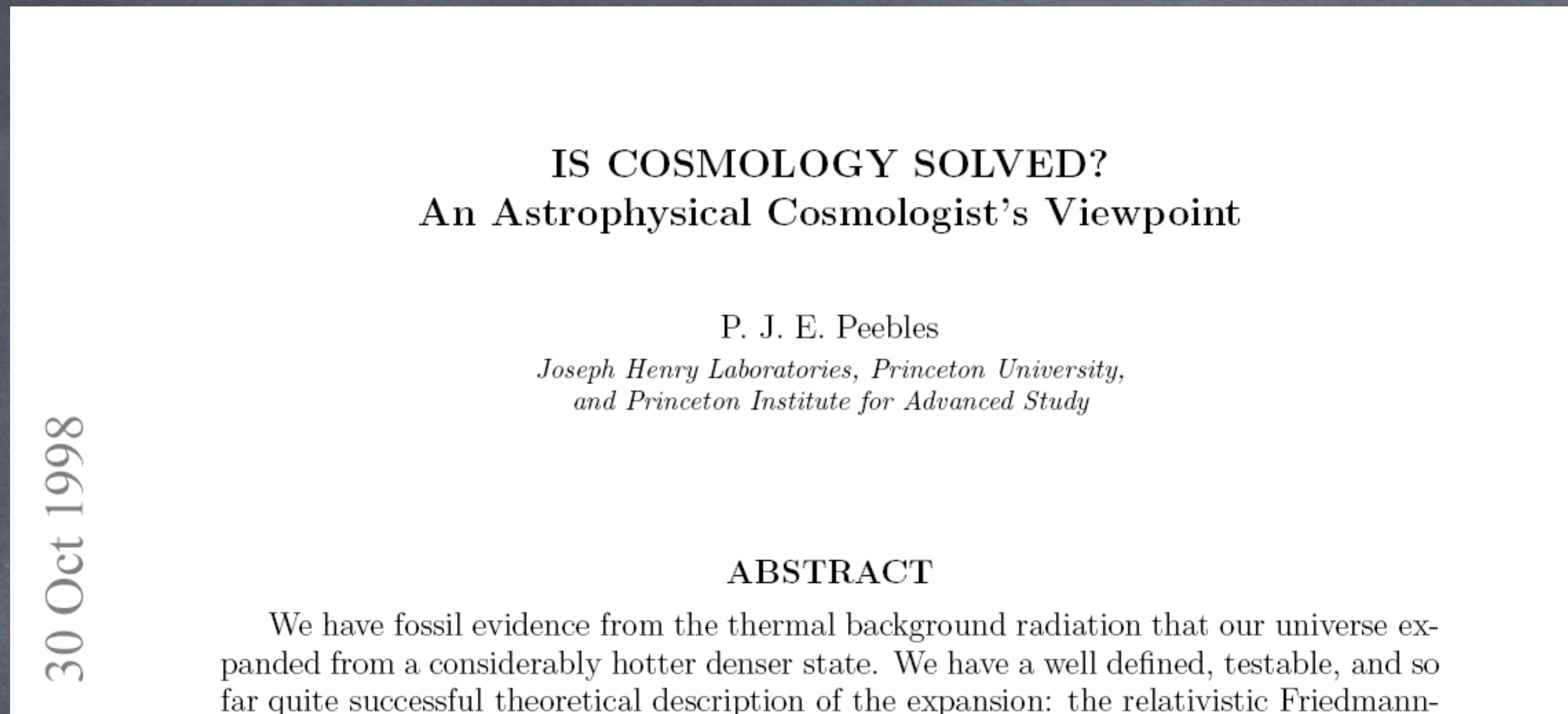


Zaldarriaga & Tegmark (2002)



Komatsu et al. (2010)

The end of cosmology?



IS COSMOLOGY SOLVED?
An Astrophysical Cosmologist's Viewpoint

P. J. E. Peebles

Joseph Henry Laboratories, Princeton University, and Princeton Institute for Advanced Study

30 Oct 1998

ABSTRACT

We have fossil evidence from the thermal background radiation that our universe expanded from a considerably hotter denser state. We have a well defined, testable, and so far quite successful theoretical description of the expansion: the relativistic Friedmann-

"Does ΛCDM signify completion of the fundamental physics that will be needed in the analysis of … future generations of observational cosmology? Or might we only have arrived at the simplest approximation we can get away with at the present level of evidence?"

Acceleration from New Degrees of Freedom

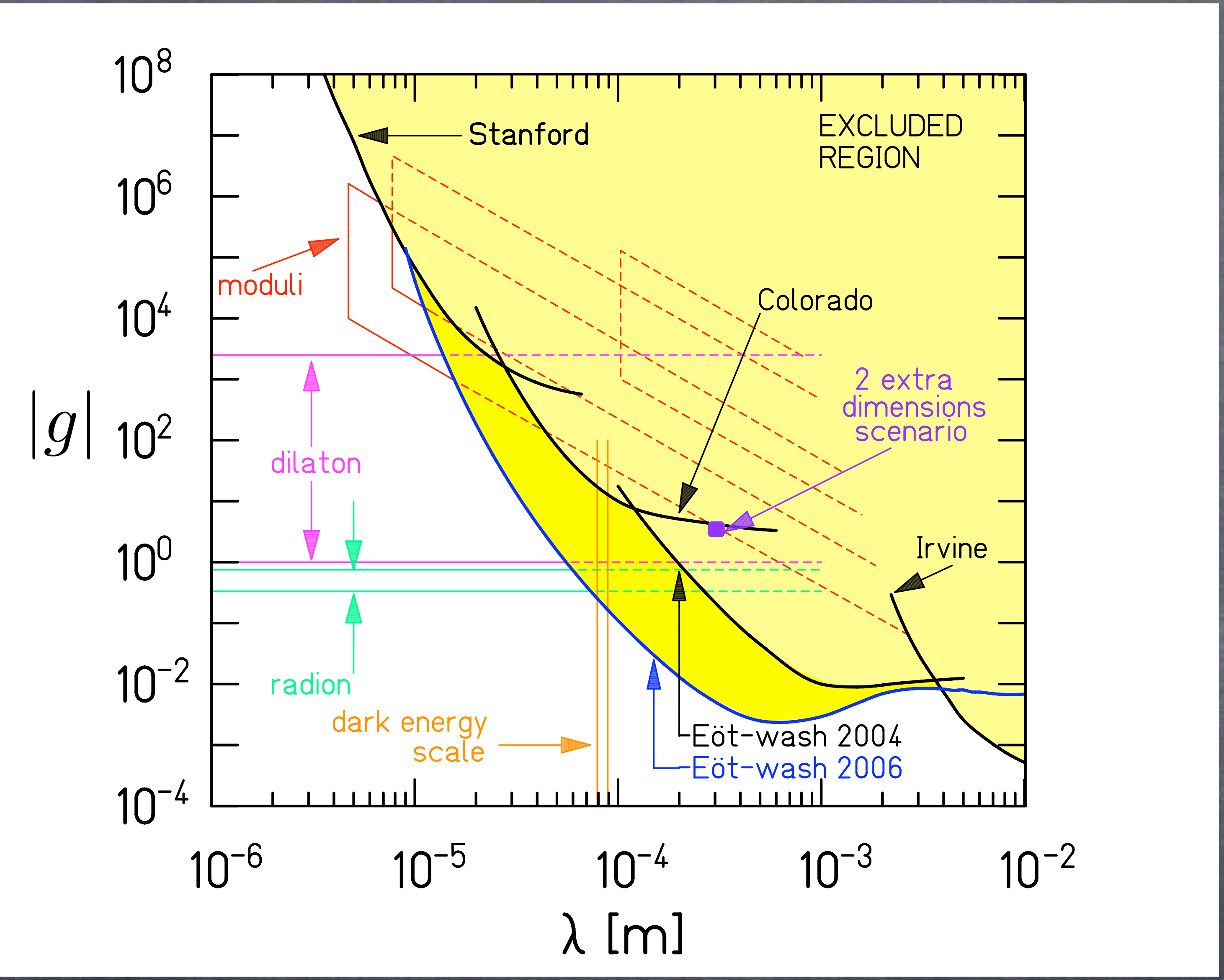
- If new degrees of freedom lead to O(1) deviations from GR on cosmological scales, then some screening mechanism is necessary to hide these degrees of freedom locally.

- Screening mechanisms are inherently non-linear and capitalize on

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

2. Experimental Program

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



Screening mechanisms invariably lead to small but potentially measurable effects in the solar system and/or in the lab

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

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

↑

chameleon

$$K(\rho)\,\nabla^2\phi + m^2\phi = \frac{g}{M_{\rm Pl}}\rho$$

↑

Vainshtein

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

symmetron

Chameleon Mechanism

JK & Weltman (2004); Gubser & JK, (2004)
Mota & Shaw (2007)

Make the mass of scalar field depend on local matter density

$$\mathcal{L} = \sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right] + \mathcal{L}_{\rm m}[\tilde{g}, \psi]$$

Matter fields ψ

Minimal coupling of ψ to metric $\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$

Scalar field equation of motion

$$\Box\phi - V_{,\phi} + A^3(\phi)A_{,\phi}\tilde{T} = 0$$

$$\tilde{T} = \tilde{T}_{\mu\nu}\tilde{g}^{\mu\nu}, \quad \tilde{T}_{\mu\nu} = -\frac{2}{\sqrt{-\tilde{g}}}\frac{\delta\mathcal{L}_{\rm m}}{\delta\tilde{g}^{\mu\nu}}, \qquad \tilde{\nabla}_\mu \tilde{T}^\mu_{\ \nu} = 0.$$

Around spherical body: spherical symmetry, static, flat space

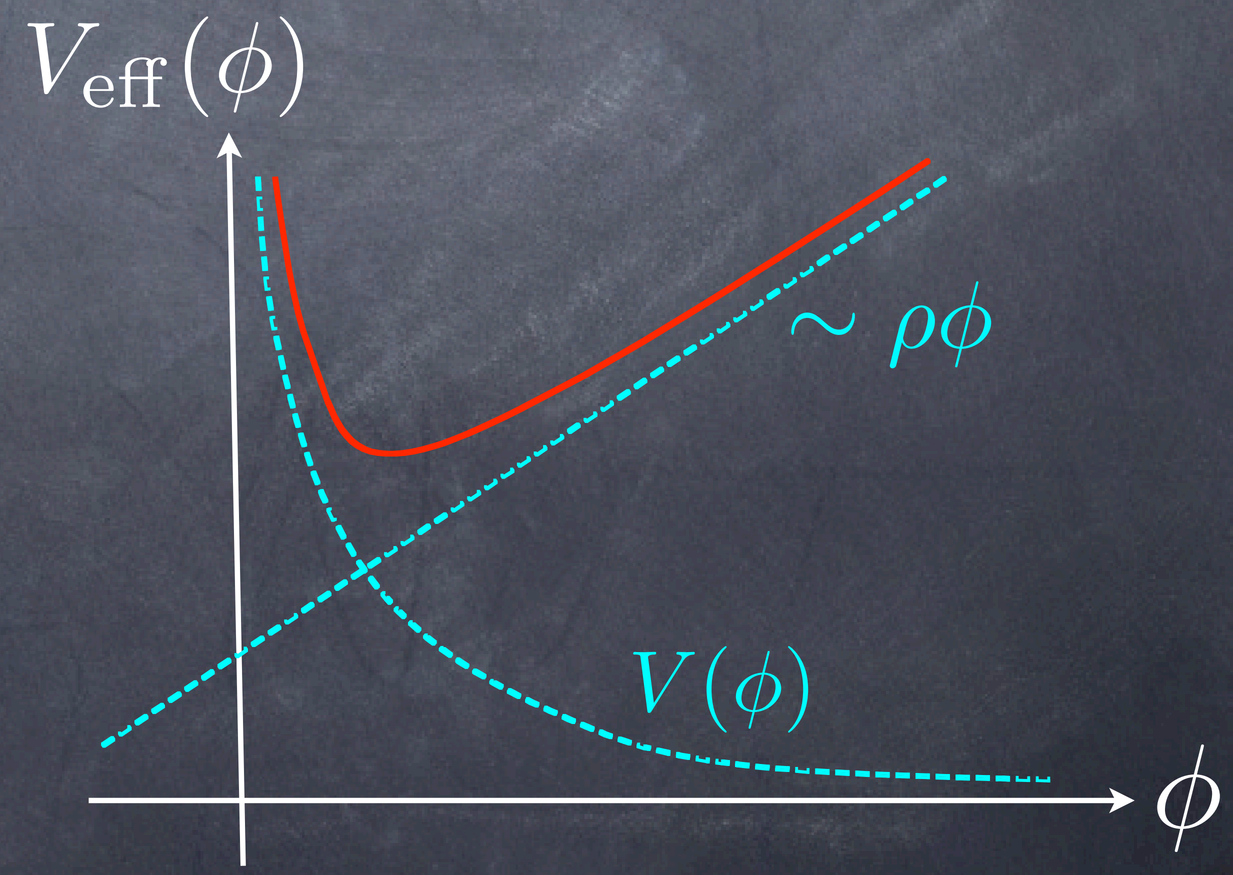
$$\frac{\mathrm{d}^2}{\mathrm{d}r^2}\phi + \frac{2}{r}\frac{\mathrm{d}}{\mathrm{d}r}\phi = V_{,\phi} + A_{,\phi}\rho$$

where $\rho = A^3\tilde{\rho}$ is density conserved in Einstein frame

$\Longrightarrow$ Scalar sees effective pot: $V_{\mathrm{eff}}(\phi) = V(\phi) + A(\phi)\rho$

With $A(\phi) = 1 + g\dfrac{\phi}{M_{\mathrm{Pl}}} + \ldots$, then

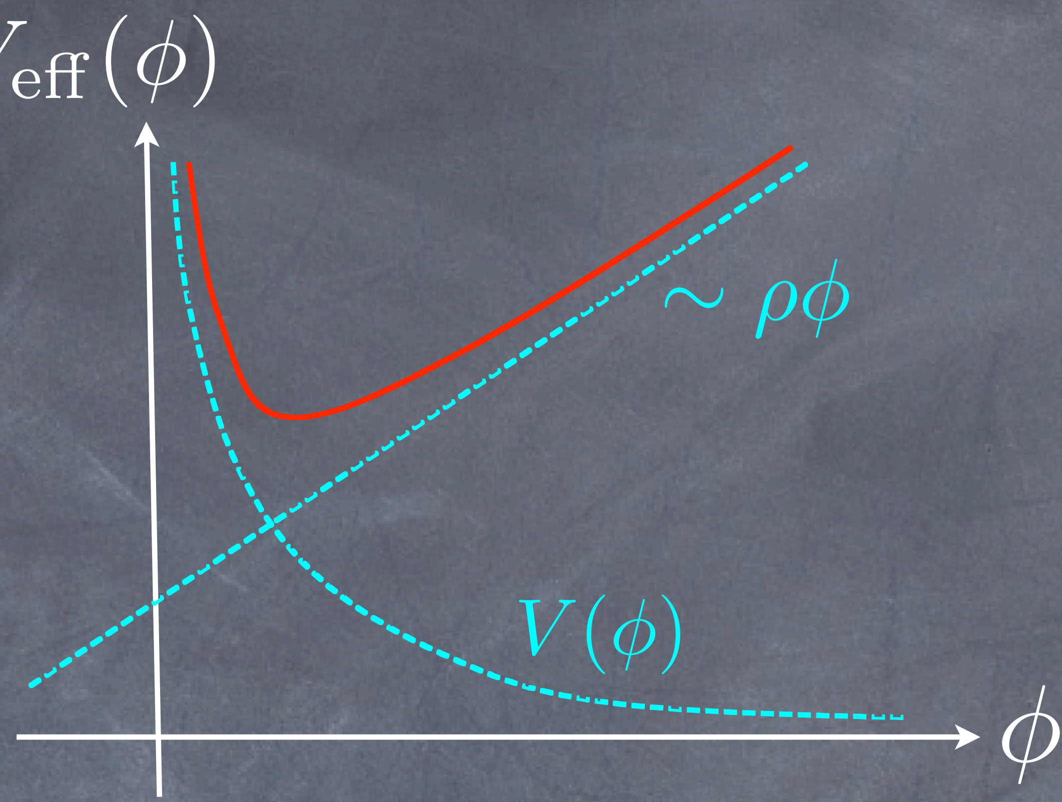
$$V_{\mathrm{eff}}(\phi) = V(\phi) + g\frac{\phi}{M_{\mathrm{Pl}}}\rho$$



e.g. $$V(\phi) = \frac{M^5}{\phi}$$

$$M = 10^{-3}\ \mathrm{eV}$$

Density-dependent mass



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

i.e. try to achieve $\dfrac{m(\rho_{\rm local})}{m(\rho_{\rm cosmo})} = \dfrac{\rm mm^{-1}}{H_0} \sim 10^{30}$,

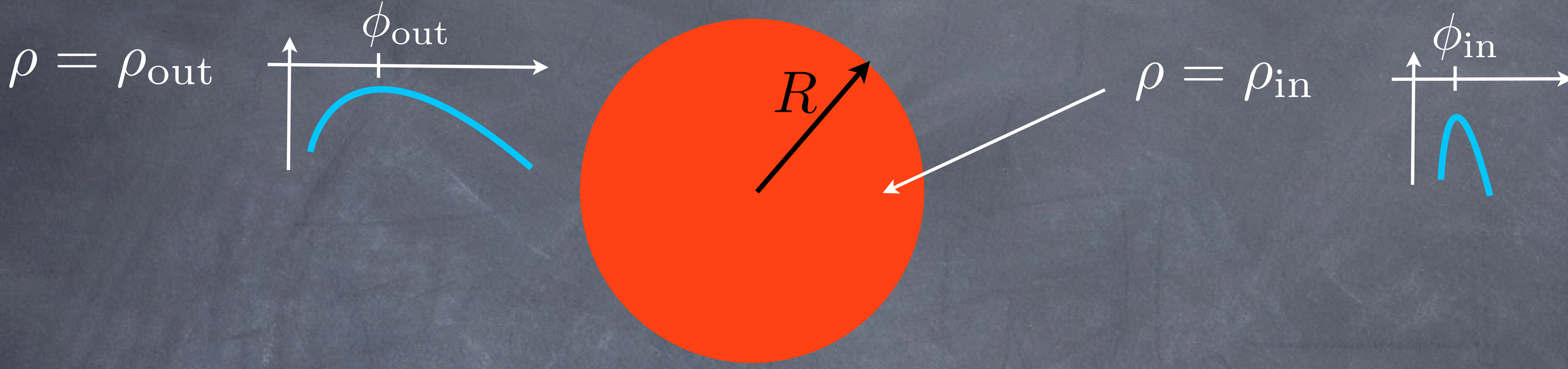
although in practice $m(\rho_{\rm cosmo}) \gtrsim {\rm Mpc}^{-1}$

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

$\Longrightarrow$ ruled out?

Thin-shell screening

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}r^2} + \frac{2}{r}\frac{\mathrm{d}\phi}{\mathrm{d}r} = \frac{\mathrm{d}V_{\mathrm{eff}}}{\mathrm{d}\phi}$$



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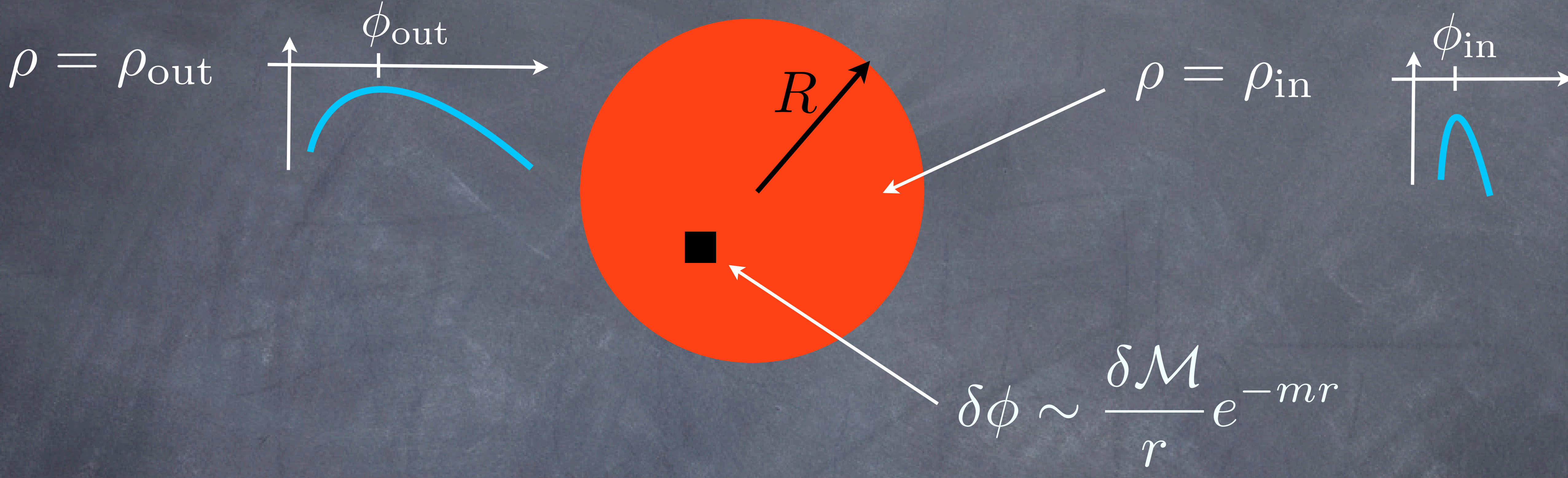

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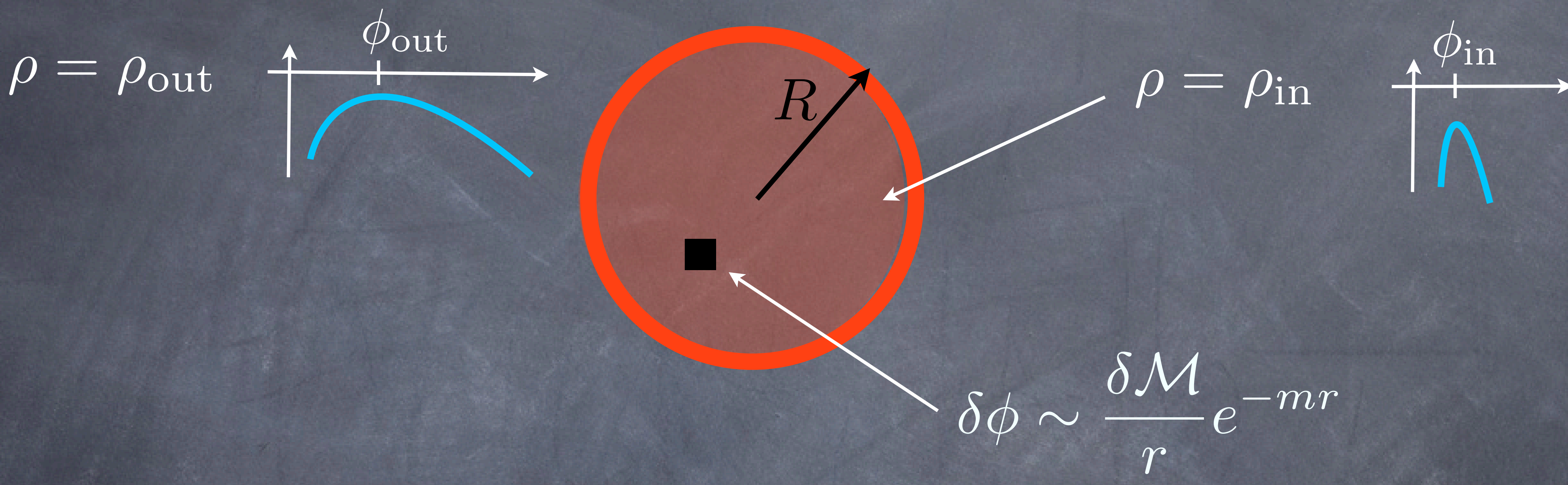

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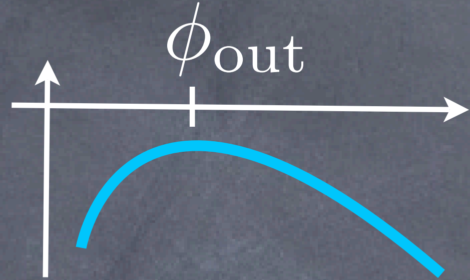
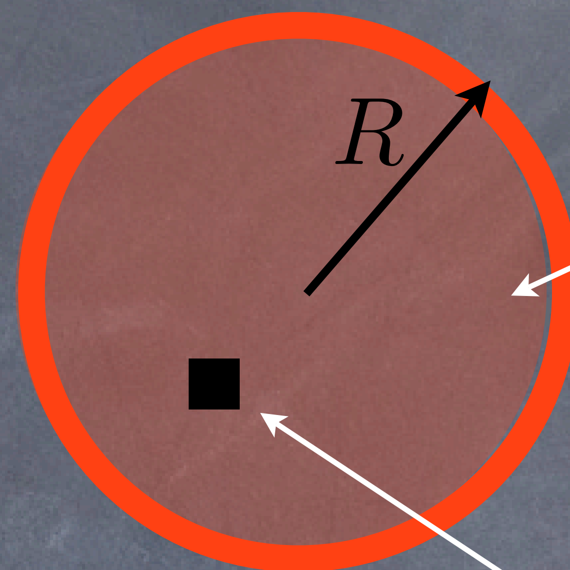
$\rho = \rho_{\rm out}$





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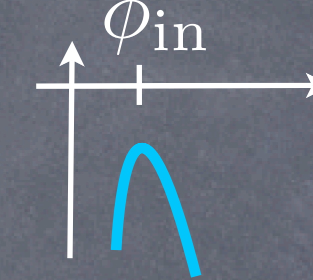

$$\delta\phi \sim \frac{\delta\mathcal{M}}{r} e^{-mr}$$

$$\Longrightarrow \quad \boxed{\phi(r > R) \sim \frac{\Delta R}{R}\frac{g}{M_{\rm Pl}^2}\frac{\mathcal{M}}{r}}$$

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

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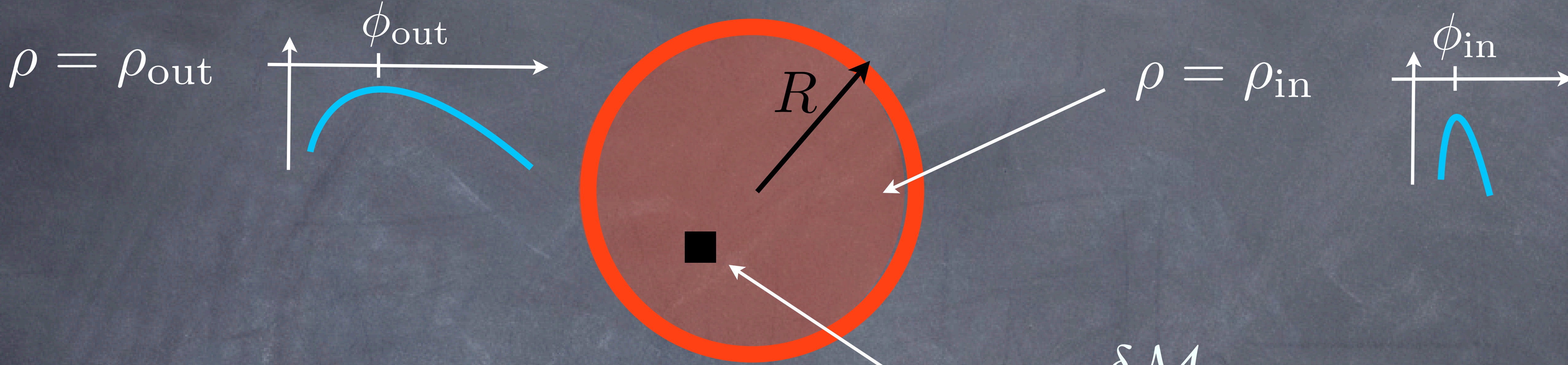

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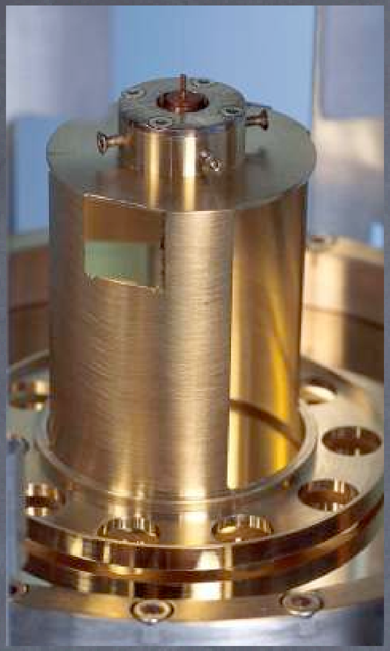
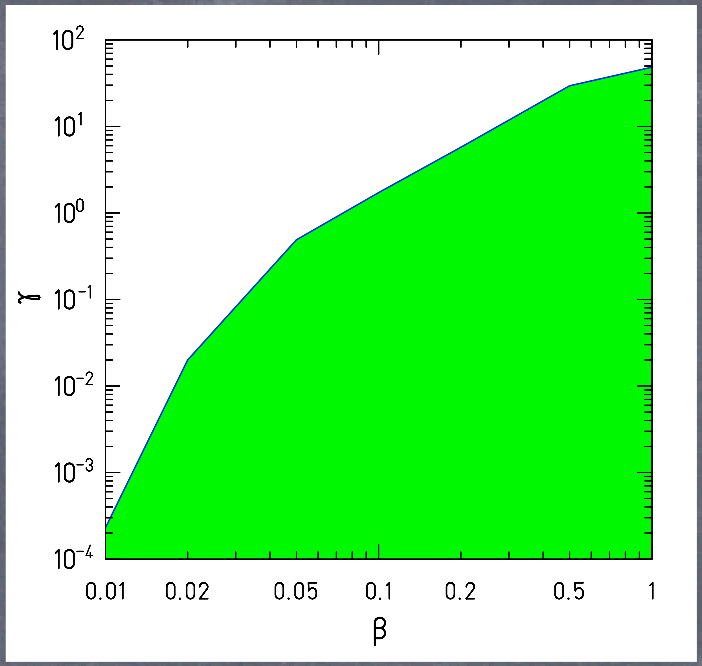
Note: screening condition depends on ρ_{out}!

Chameleon Tests

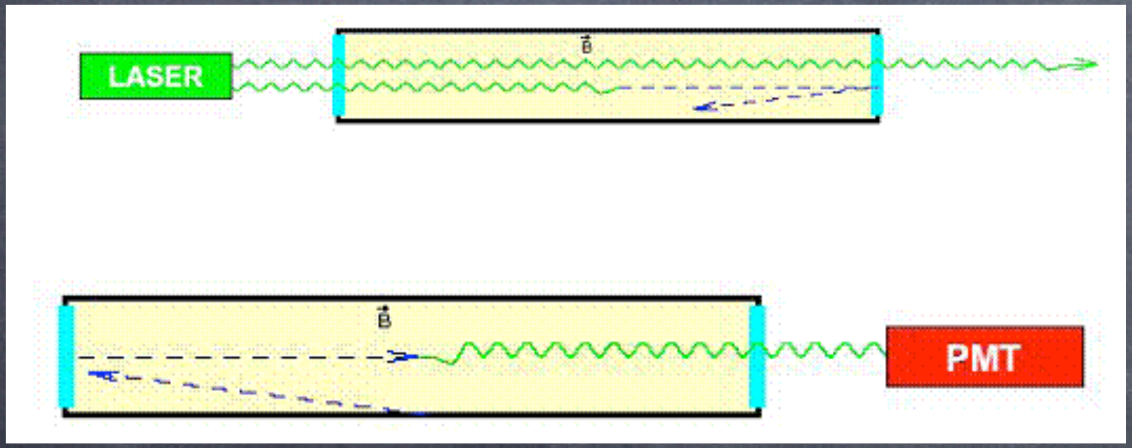
- Eot-Wash

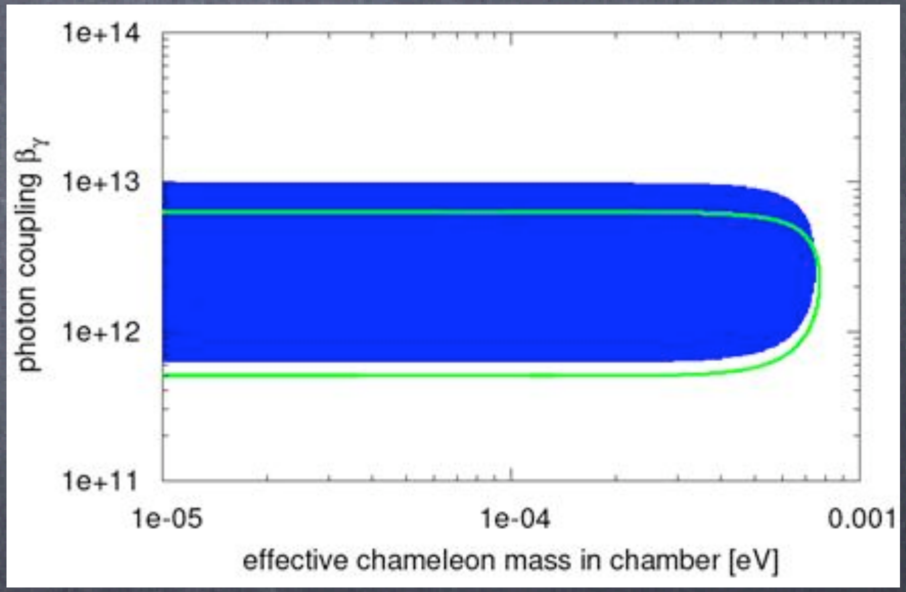
  Adelberger et al., Phys. Rev. Lett. (2008)





- GammeV, Fermilab   Chou et al., Phys. Rev. Lett. (2008)





- Astrophysical photon-chameleon mixing

  Burrage, Davis & Shaw, Phys. Rev. Lett. (2009)

Vainshtein Mechanism

Vainshtein (1972); Arkani-Hamed, Georgi, Schwartz (2003)
Deffayet, Dvali, Gabadadze & Vainshtein (2002);
Luty, Porrati & Rattazzi (2003); Nicolis & Rattazzi (2004)

4d effective theory in DGP: $$\mathcal{L}_\pi = 3(\partial\pi)^2\left(1+\frac{\nabla^2\pi}{3\Lambda^3}\right)+\frac{\pi}{M_{\rm Pl}}\rho$$

which enjoys Galilean symmetry: $\partial_\mu\pi \rightarrow \partial_\mu\pi + c_\mu$

$$3\nabla^2\pi + \frac{1}{\Lambda^3}\left[(\nabla^2\pi)^2 - (\partial_\mu\partial_\nu\pi)^2\right] = \frac{\rho}{2M_{\rm Pl}}$$

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$$3\nabla^2\pi+\frac{1}{\Lambda^3}\left[(\nabla^2\pi)^2-(\partial_\mu\partial_\nu\pi)^2\right]=\frac{\rho}{2M_{\rm Pl}}$$

Solution around point source of mass M:

$$\pi(r)=\begin{cases}\sim\Lambda^3R_V^{3/2}\sqrt{r}+const. & r\ll R_V\\ \sim\Lambda^3R_V^3\frac{1}{r} & r\gg R_V\end{cases}$$

Vainshtein radius:

$$R_V\equiv\frac{1}{\Lambda}\left(\frac{M}{M_{Pl}}\right)^{1/3}$$

5th force on a test particle, relative to gravity:

$$\frac{F_\pi}{F_{\rm Newton}}=\frac{\pi'(r)/M_{Pl}}{M/(M_{Pl}^2r^2)}=\begin{cases}\sim\left(\frac{r}{R_V}\right)^{3/2} & R\ll R_V\\ \sim 1 & R\gg R_V\end{cases}$$

Field generated on a background below Vainshtein radius of large object: $\pi = \pi_0 + \varphi\,, \qquad T = T_0 + \delta T$

$$\mathcal{L} = -3(\partial\varphi)^2 + \frac{2}{\Lambda^3}\left(\partial_\mu\partial_\nu\pi_0 - \eta_{\mu\nu}\Box\pi_0\right)\partial^\mu\varphi\partial^\nu\varphi$$
$$- \frac{1}{\Lambda^3}(\partial\varphi)^2\Box\varphi + \frac{1}{M_{\rm Pl}}\varphi\,\delta T$$

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$$\sim \left(\frac{R_{\rm V}}{r}\right)^{3/2} \gg 1$$

Kinetic term is enhanced, which means that, after canonical normalization, coupling to δT is suppressed. The non-linear coupling scale is also raised.

Other examples:

- Generalized Galileons
  Nicolis, Rattazzi and Trincherini (2009)
- k-Mouflage
  Babichev, Deffayet and Ziour (2009)

Symmetron Fields

K. Hinterbichler and JK, hep-th/1001.4525
See also Olive & Pospelov (2008); Pietroni (2005)

$$\mathcal{L} = \sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right] + \mathcal{L}_{\rm m}[\tilde{g},\psi]$$

where $$\tilde{g}_{\mu\nu} = \left(1 + \frac{\phi^2}{2M^2} + \mathcal{O}\left(\frac{\phi^4}{M^4}\right)\right)^2 g_{\mu\nu}$$

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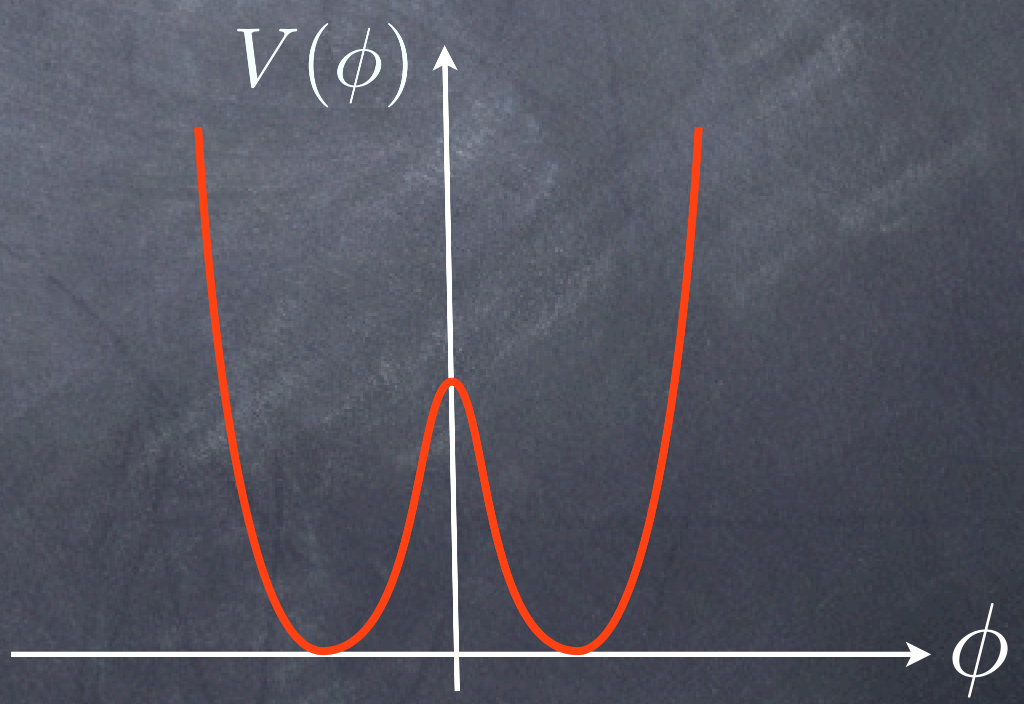
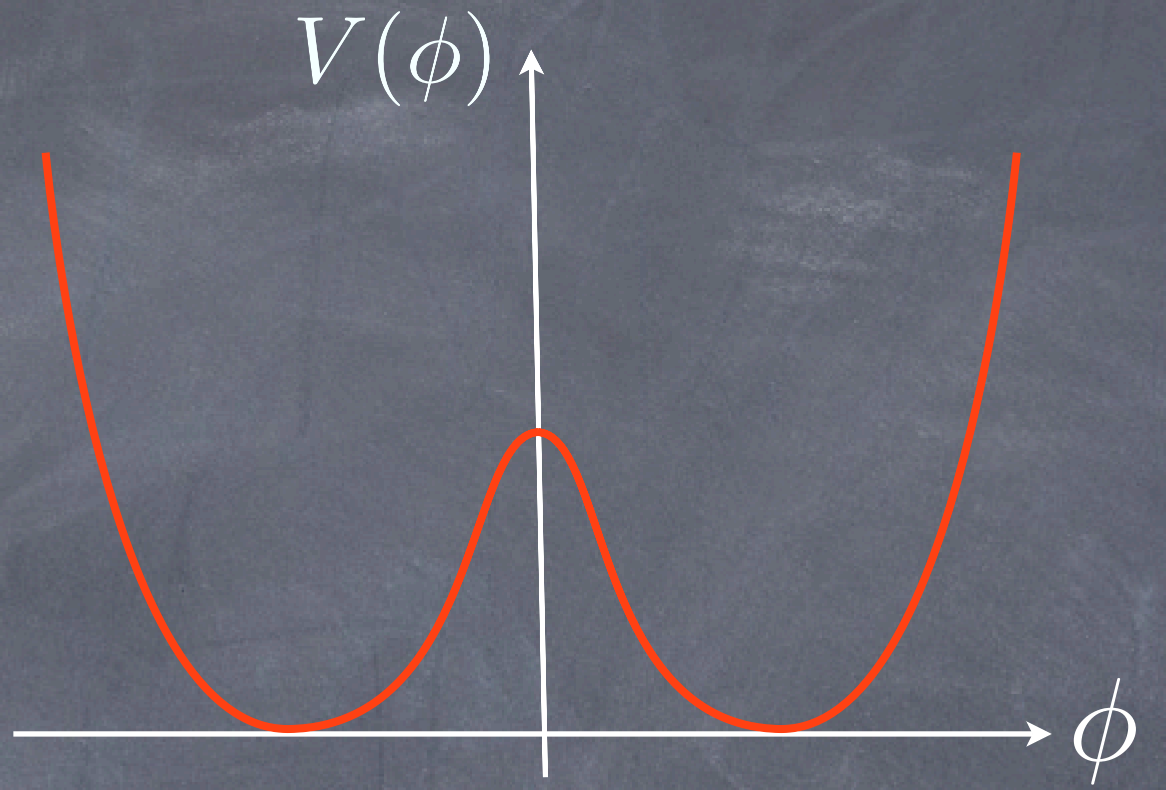
Potential is of the spontaneous-symmetry-breaking form:

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



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

Effective Potential

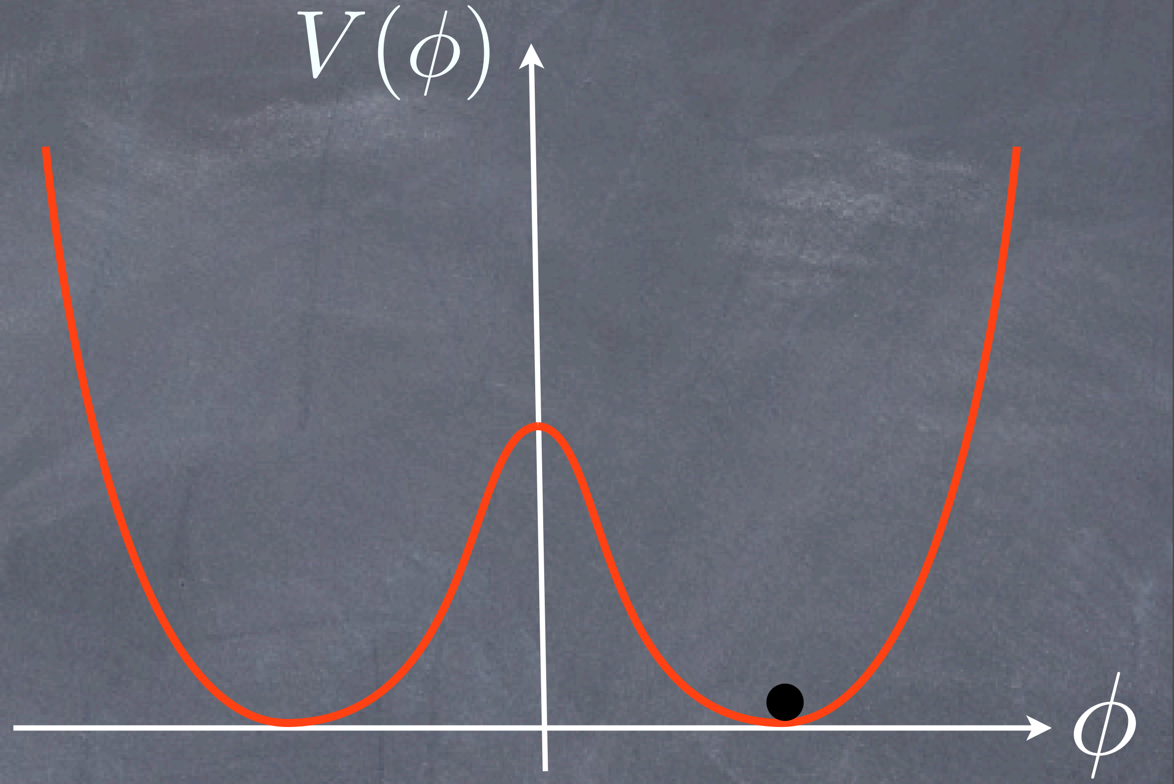


$$\nabla^2\phi = -\frac{\mathrm{d}V}{\mathrm{d}\phi} - \frac{\phi}{M^2}\rho$$

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

∴ Whether symmetry is broken or not depends on local density

Effective Potential



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

- Outside source, $\rho = 0$, symmetron acquires VEV and symmetry is spontaneously broken.

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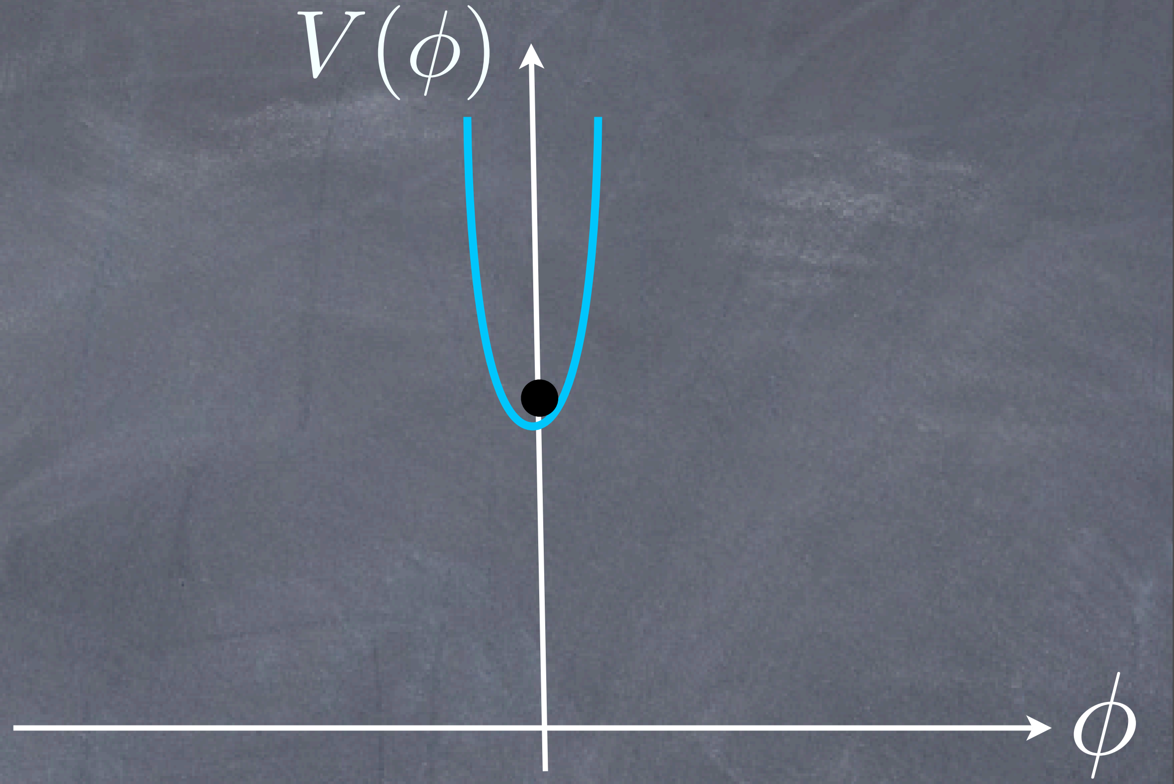

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$\therefore$ Whether symmetry is broken or not depends on local density

- Outside source, $\rho = 0$, symmetron acquires VEV and symmetry is spontaneously broken.
- Inside source, provided $\rho > \mu^2 M^2$, the symmetry is restored.

Effective Coupling

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

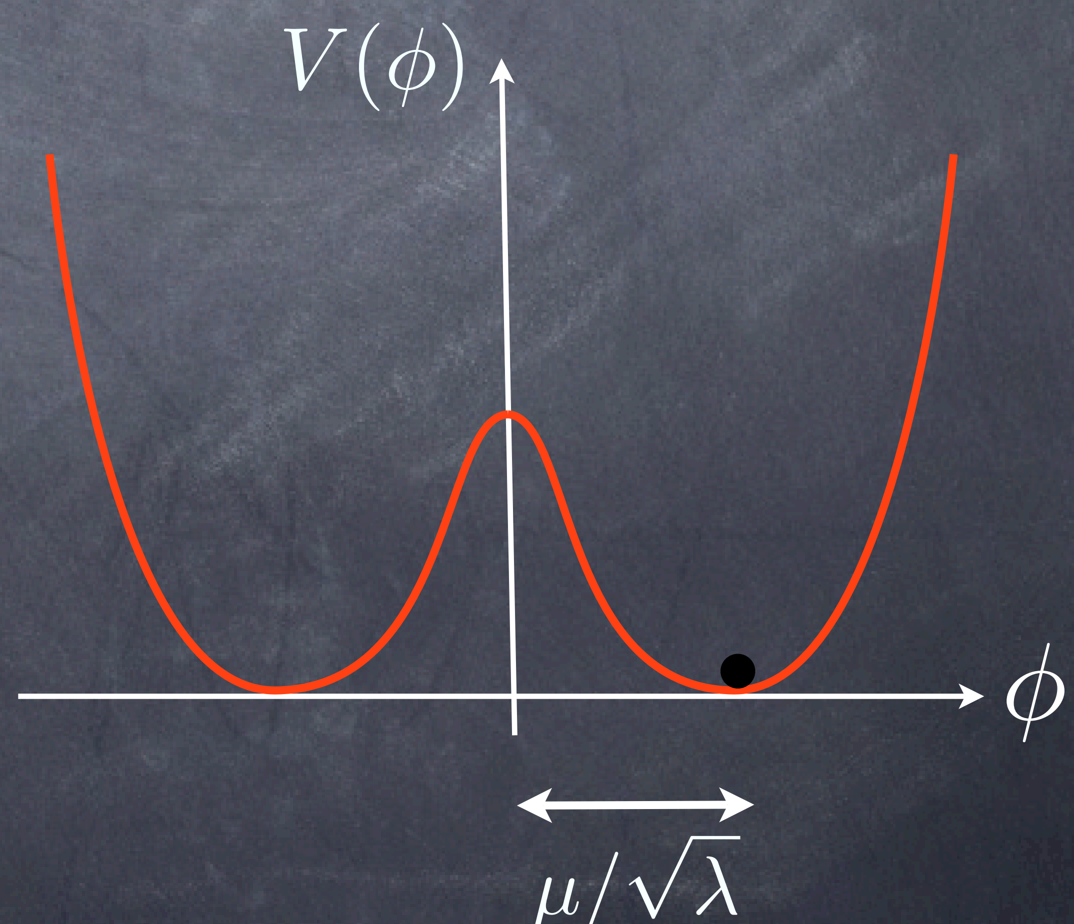
$$\mathcal{L}_{\rm coupling} \sim \frac{\bar{\phi}}{M^2}\delta\phi\,\rho$$

- Symmetron fluctns decouple in high-density regions
- In voids, where Z_2 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



Fixing Ideas

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

- Gravitational-strength symmetron-mediated force in vacuum

$$\phi_0 \equiv \frac{\mu}{\sqrt{\lambda}} \sim \frac{M^2}{M_{\text{Pl}}} \ll M$$

Hence field excursion is within validity of effective theory, i.e. can consistently neglect $\mathcal{O}(\phi^4/M^4)$ corrections to matter coupling.

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- Potential becomes tachyonic around current cosmic density

$$\mu^2 \sim \frac{H_0^2 M_{\rm Pl}^2}{M^2} \implies \lambda \sim \frac{M_{\rm Pl}^4 H_0^2}{M^6} \ll 1$$

Will see later that local tests of gravity constrain $M \lesssim 10^{-3} M_{\rm Pl}$

$$\implies m_0 = \sqrt{2}\mu \sim \frac{M_{\rm Pl}}{M} H_0 \sim {\rm Mpc}^{-1}$$

$\therefore$ Gravitational-strength, Mpc-range 5th force in voids.

Inspiration...

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Symmetron Couch ($9500.00)

"NASA-style gravity reduction."

"Offers a unique multi-phase wave experience."

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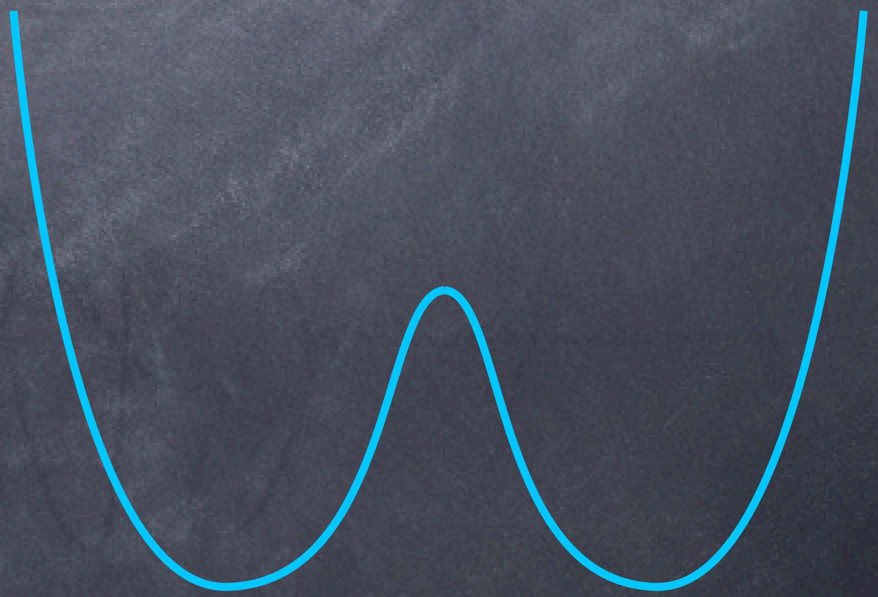
$\sim$



Fine Tuning and Quantum Corrections

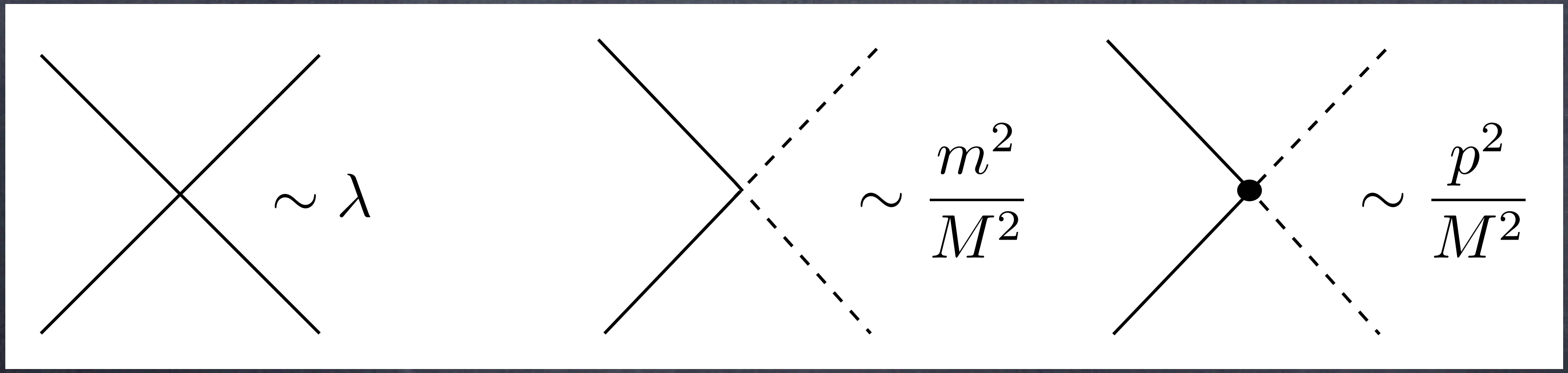
Consider scalar field ψ with mass m as fiducial matter field

$$\mathcal{L}_{\rm m}(\tilde{g}_{\mu\nu},\psi) = \sqrt{-\tilde{g}}\left(-\frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\psi\partial_\nu\psi - \frac{1}{2}m^2\psi^2\right) .$$

Effective field theory with cutoff M and Z_2 symmetry

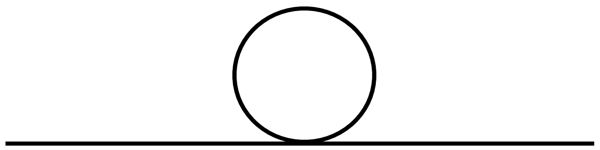
$$\begin{aligned}\mathcal{L} &= -\frac{1}{2}(\partial\phi)^2 + \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4 - \frac{1}{2}(\partial\psi)^2 - \frac{1}{2}m^2\psi^2 \\ &- \frac{\phi^2}{4M^2}(\partial\psi)^2 + \frac{m^2}{4M^2}\phi^2\psi^2 + \mathcal{O}(\phi^4/M^4)\end{aligned}$$

Calculate 1-loop corrections to potential. Vertices are

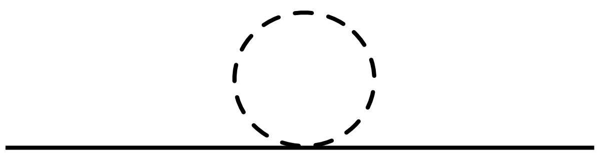


Quantum Corrections

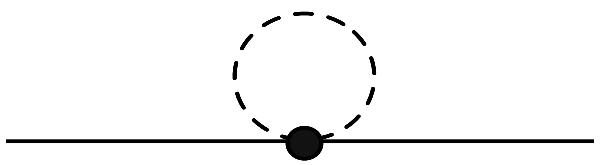
Corrections to the ϕ mass term:



$$\sim \lambda\Lambda^2 \sim \left(\frac{M_{Pl}}{M}\right)^2 \mu^2.$$

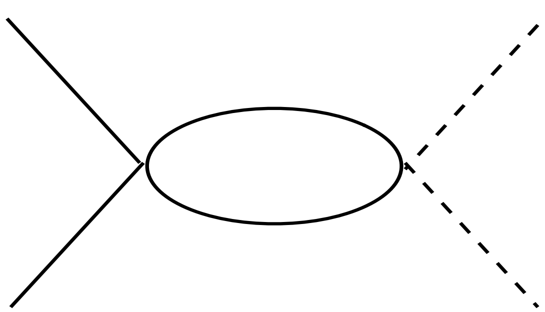


$$\sim \frac{m^2}{M^2}\Lambda^2 \sim m^2,$$



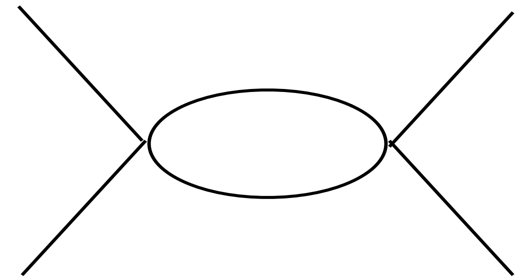
$$\sim \frac{1}{M^2}\Lambda^4 \sim M^2.$$

Corrections to the $\phi^2\psi^2$ interaction:

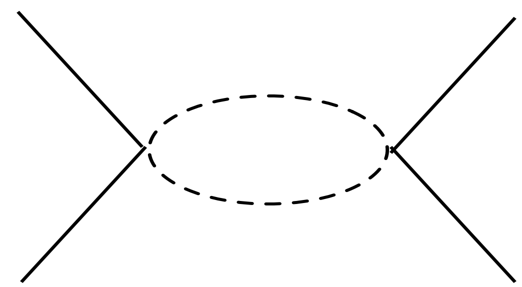


$$\sim \lambda\frac{m^2}{M^2}\log\Lambda.$$

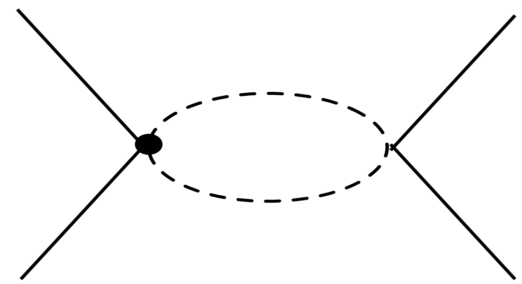
Corrections to the ϕ^4 interaction:



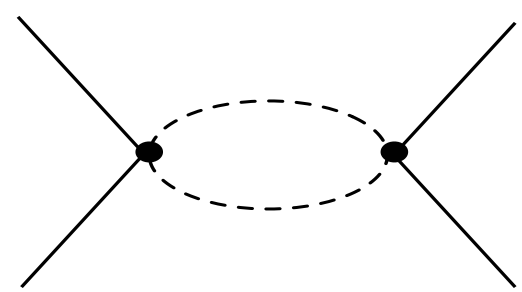
$$\sim \lambda^2\log\Lambda.$$



$$\sim \left(\frac{m}{M}\right)^4 \log\Lambda,$$



$$\sim \frac{m^2}{M^2}\frac{1}{M^2}\Lambda^2 \sim \left(\frac{m}{M}\right)^2,$$



$$\sim \frac{1}{M^4}\Lambda^4 \sim 1.$$

$\Longrightarrow$ No surprise: diagrams with matter loops are dangerous

But suppose work instead in Jordan frame:

$$\mathcal{L} = \sqrt{-\tilde{g}}\left\{\frac{M_{\rm Pl}^2}{2}\left(1-\frac{\phi^2}{M^2}\right)\tilde{R} - \frac{1}{2}\left[1-\left(1+6\frac{M_{\rm Pl}^2\phi^2}{M^4}\right)\right](\partial\phi)^2 + \frac{1}{2}\mu^2\phi^2 - \left(\frac{\lambda}{4}-\frac{\mu^2}{M^2}\right)\phi^4 + \frac{\lambda}{2M^2}\phi^6\right\} + \mathcal{L}_{\rm m}(\tilde{g}_{\mu\nu},\psi)$$

By general covariance, integrating out matter only generates diff inv functionals of the Jordan frame metric:

$$\int_\Lambda \mathcal{D}\psi e^{i\int {\rm d}^4x\mathcal{L}_{\rm m}(\tilde{g}_{\mu\nu},\psi)} \sim e^{i\int {\rm d}^4x\sqrt{-\tilde{g}}\left[\sim\left(\Lambda^4+\Lambda^2m^2+m^4\log\Lambda\right)+\left(\Lambda^2+m^2\log\Lambda\right)\tilde{R}+\ldots\right]}$$

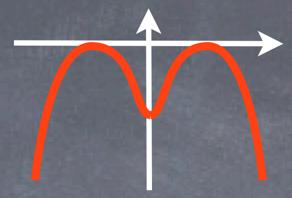
Jordan frame C.C. becomes Einstein frame potential:

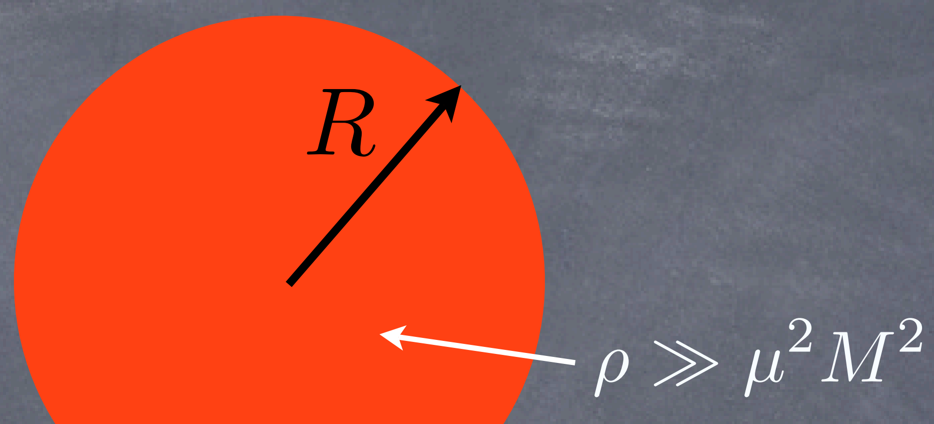
$$\begin{aligned}\mathcal{L}_{eff} \sim \sqrt{-\tilde{g}}\left(\Lambda^4+\Lambda^2m^2+m^4\log\Lambda\right) &= \sqrt{-g}\left(\Lambda^4+\Lambda^2m^2+m^4\log\Lambda\right)A(\phi)^4 \\ &= \sqrt{-g}\left(\Lambda^4+\Lambda^2m^2+m^4\log\Lambda\right)\left(1+2\frac{\phi^2}{M^2}+3\frac{\phi^4}{M^4}+\cdots\right).\end{aligned}$$

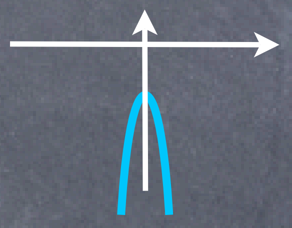
$\Longrightarrow$ All matter loops are taken care of by tuning of C.C.

Spherical Source

$\rho = 0$







$$\frac{\mathrm{d}^2\phi}{\mathrm{d}r^2} + \frac{2}{r}\frac{\mathrm{d}\phi}{\mathrm{d}r} = \frac{\mathrm{d}V_{\mathrm{eff}}}{\mathrm{d}\phi}$$

Describes a particle rolling on the "inverted potential" $-V_{\mathrm{eff}}(\phi)$, as a function of "time" r

Spherical Source

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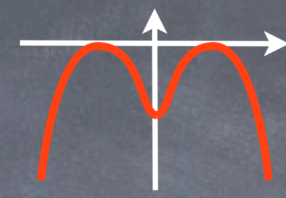
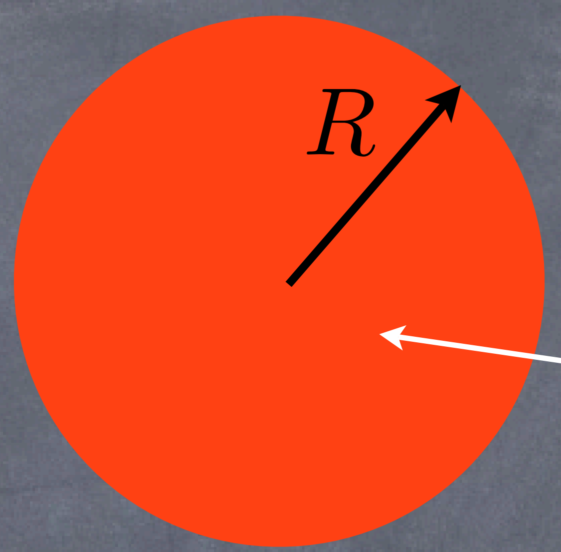
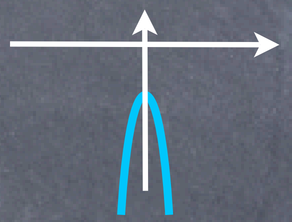




$\rho \gg \mu^2 M^2$



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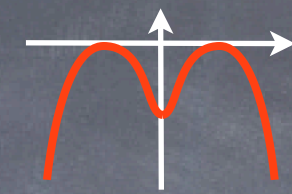

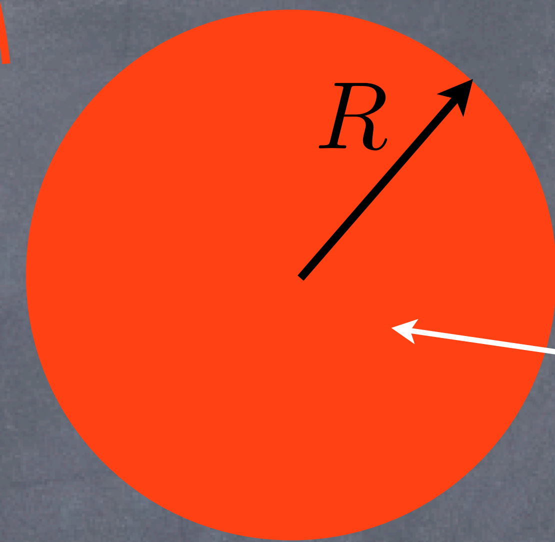

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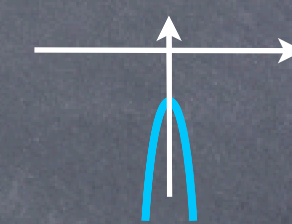

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Describes a particle rolling on the "inverted potential" $-V_{\mathrm{eff}}(\phi)$, as a function of "time" r

- Boundary conditions: $$\frac{\mathrm{d}}{\mathrm{d}r}\phi(0) = 0\,; \qquad \phi(r \to \infty) = \phi_0$$

- Solutions: $$\phi_{\mathrm{interior}}(r) = A\,\frac{R}{r}\sinh\left(r\sqrt{\frac{\rho}{M^2} - \mu^2}\right)$$

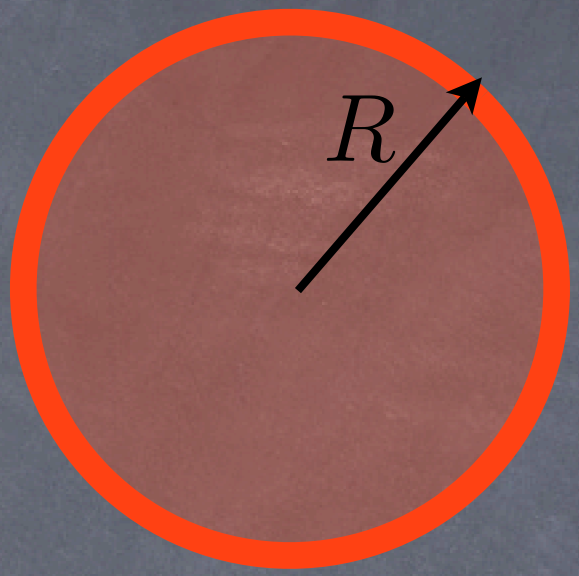
$$\phi_{\mathrm{exterior}}(r) = B\,\frac{R}{r}e^{-\sqrt{2}\mu r} + \phi_0$$

Fix A and B by matching ϕ and $\mathrm{d}\phi/\mathrm{d}r$ at the surface

Thin-Shell Screening Effect

Behavior of solution depends on

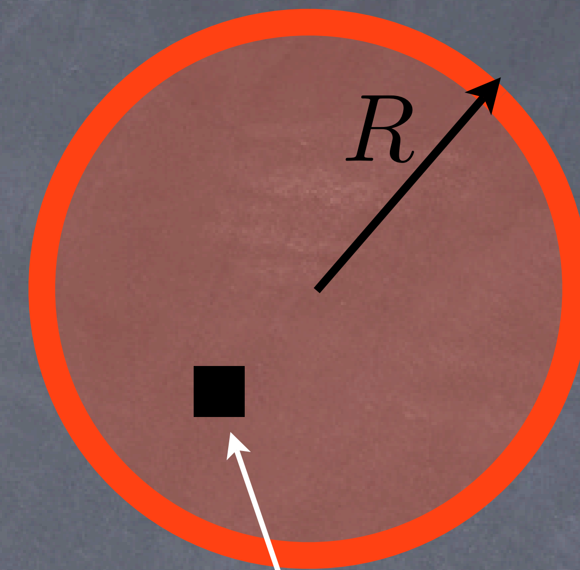
$$\alpha \equiv \frac{\rho R^2}{M^2} = 6\,\frac{M_{\rm Pl}^2}{M^2}\,\Phi_{\rm N}$$



- For sufficiently massive objects, such that $\alpha \gg 1$, solution is suppressed by thin-shell effect:

$$\phi_{\rm exterior}(r) \sim \frac{1}{\alpha}\,\frac{\mathcal{M}}{M_{\rm Pl}^2 r} + \phi_0$$

Thin-Shell Screening Effect



$$\delta\phi \sim \frac{\bar{\phi}}{M^2}\frac{\delta\mathcal{M}}{r}$$

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Why? Have $\phi_{\rm in}(r) = A\frac{R}{r}\sinh\left(\sqrt{\alpha}\frac{r}{R}\right)$, but field grows to at most $\phi_{\rm in}(R) \lesssim \phi_0$

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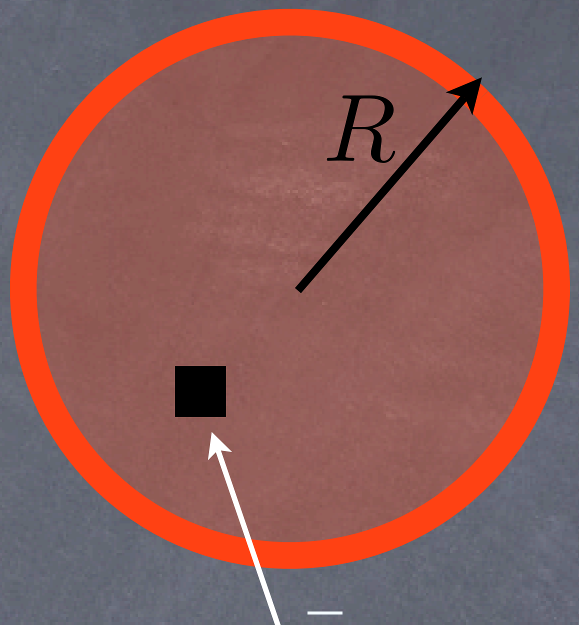

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- For small objects, $\alpha \ll 1$, we find $\phi \approx \phi_0$ everywhere

$$\Longrightarrow \quad \frac{F_\phi}{F_{\rm N}} \sim \mathcal{O}(1)$$

Constraints from Local Tests

Necessary (and sufficient) condition is that Milky Way has thin shell:

$$\alpha_{\rm G} = 6\frac{M_{\rm Pl}^2}{M^2}\Phi_{\rm G} \gtrsim 10$$

$$\Phi_{\rm G} \sim 10^{-6} \Longrightarrow \boxed{M \lesssim 10^{-3} M_{\rm Pl}}$$

But since $\mu \sim M_{\rm Pl} H_0 / M$, to get interesting cosmological effects we consider regime where this is barely satisfied, e.g. $\alpha_{\rm G} = 20$

$$\frac{\phi_{\rm G}}{M} \approx \frac{M}{M_{\rm Pl}} \frac{R_{\rm G}}{\sqrt{\alpha_{\rm G}} R_{\rm us}} \exp\left(-\frac{R_{\rm G} - R_{\rm us}}{R_{\rm G}} \sqrt{\alpha_{\rm G}} \right) \sim 10^{-5}$$

$\Longrightarrow$ Sun is screened, but Earth is <u>not</u>.

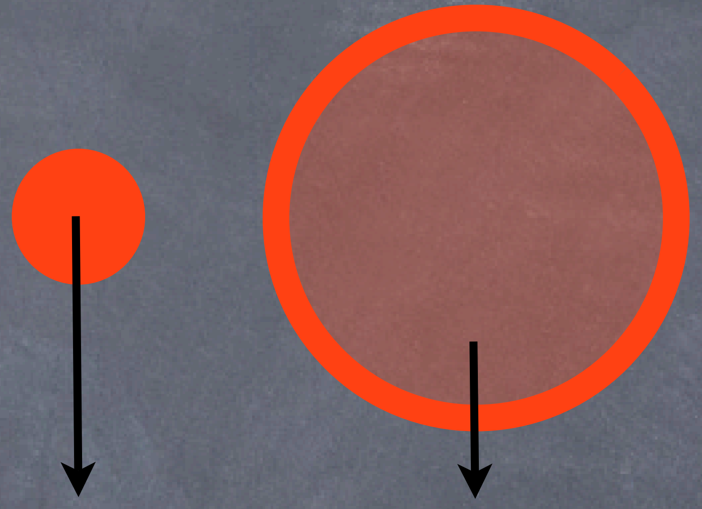
Constraints from Local Tests (continued)

Test	Effective parameter	Current bounds
Time delay/light deflection	$\lvert\gamma - 1\rvert \approx 10^{-5}$	$\lvert\gamma - 1\rvert \approx 10^{-5}$
Nordvedt effect	$\lvert\eta_{\rm N}\rvert \sim 10^{-4}$	$\lvert\eta_{\rm N}\rvert \sim 10^{-4}$
Mercury perihelion shift	$\lvert\gamma - 1\rvert \approx 4 \cdot 10^{-4}$	$\lvert\gamma - 1\rvert \approx 10^{-3}$
Binary pulsars	$\omega_{\rm BD}^{\rm eff} \gtrsim 10^6$	$\omega_{\rm BD}^{\rm eff} \gtrsim 10^3$

Macroscopic Violations of Equivalence Principle

Hui, Nicolis and Stubbs (2009)

Because of thin-shell screening, macroscopic objects fall with different acceleration in g-field



$$\vec{a} = -\vec{\nabla}\Phi + (1-\epsilon)\frac{\phi}{M^2}\vec{\nabla}\phi$$

- Unscreened objects ($\epsilon = 1$) follow geodesics in Jordan frame
- Screened objects ($\epsilon = 0$) do not.

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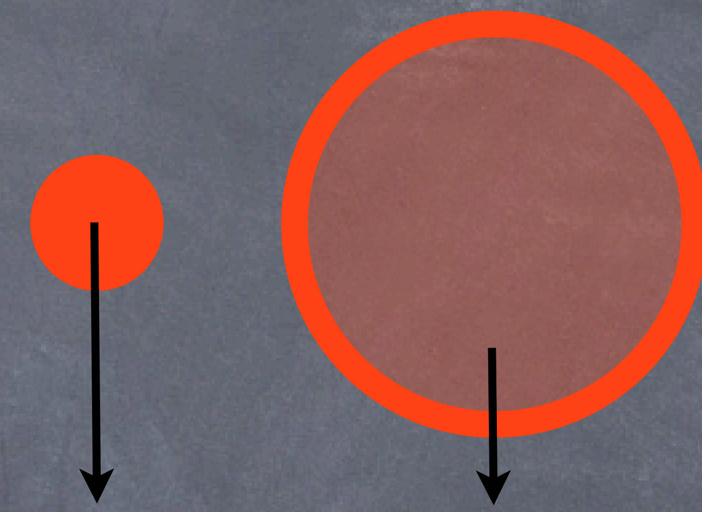

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- Unscreened objects ($\epsilon = 1$) follow geodesics in Jordan frame
- Screened objects ($\epsilon = 0$) do not.

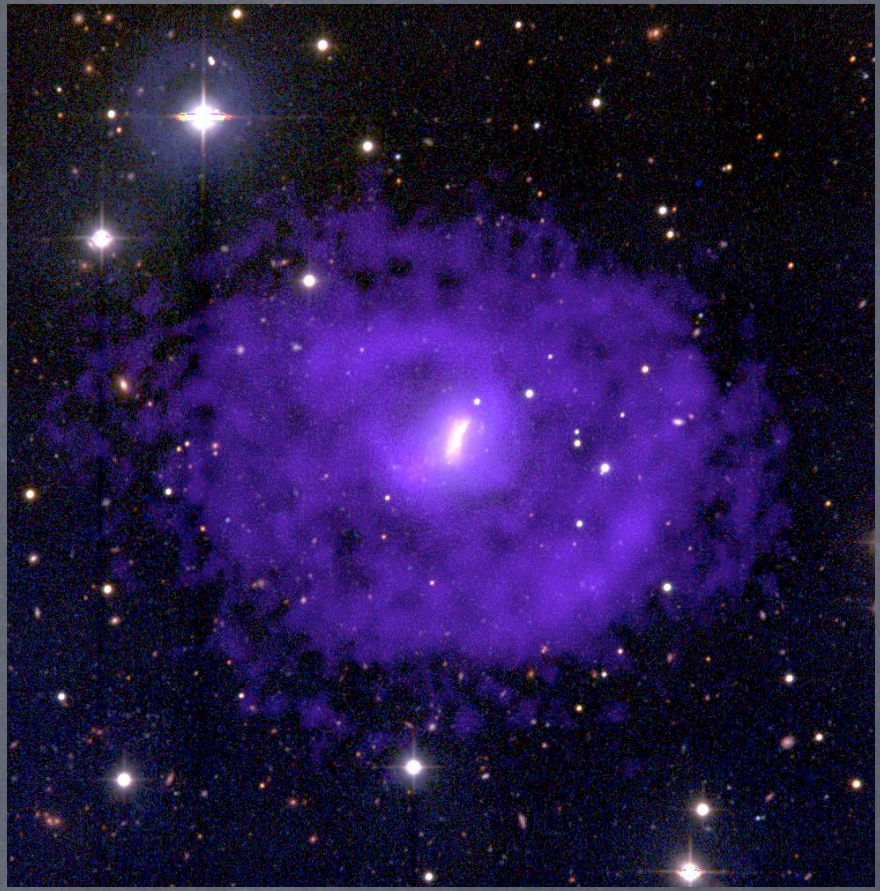
To maximize effect, look for

- large (~ Mpc) void regions, so that symmetry is broken and $\bar{\phi}/M^2 = 1/M_{\rm Pl}$

- look for unscreened objects (i.e. $\Phi < 10^{-7}$) in these voids

Various astrophysical signatures

Hui, Nicolis and Stubbs (2009)



- Look at dwarf galaxies in voids

- Stars are screened ($\Phi \sim 10^{-6}$), but hydrogen gas is unscreened. (Gas itself has only $\Phi \sim 10^{-11}$.)

- Should find systematic O(1) discrepancy in the mass estimates based on these two tracers.

NOTE: Effect also possible in chameleon theory but not generic. In the symmetron case, it is generic.

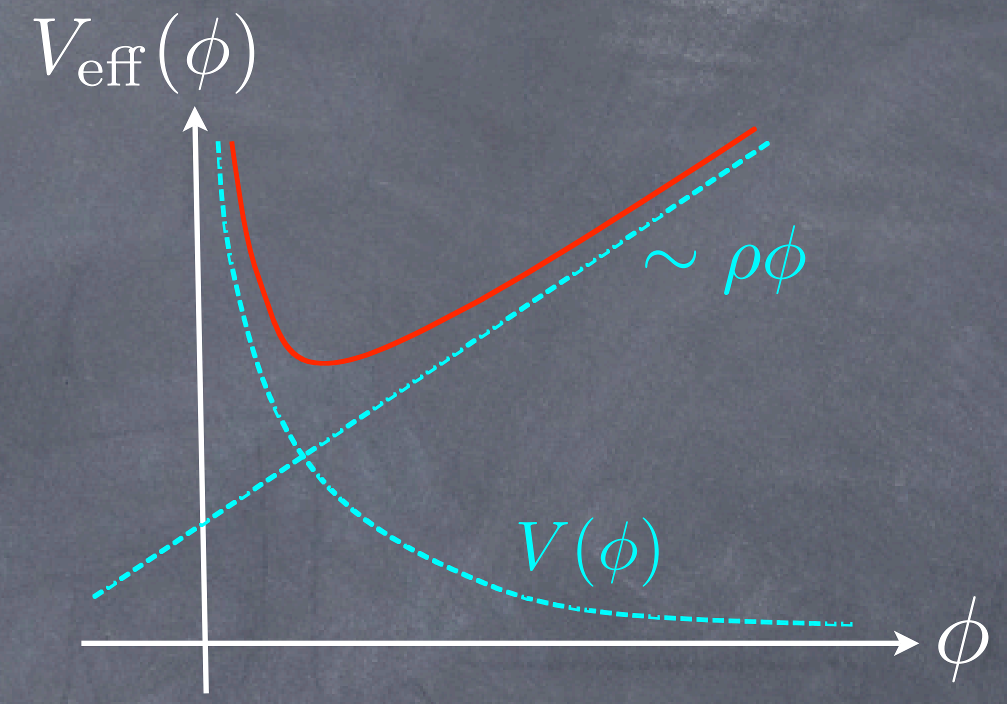
Distinguishable from Other Screening Mechanisms

Chameleon

- Potential is non-renormalizable,

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

- Tightest constraint comes from laboratory tests of gravity, and this results in tiny signals for solar system tests Khoury & Weltman (2003)



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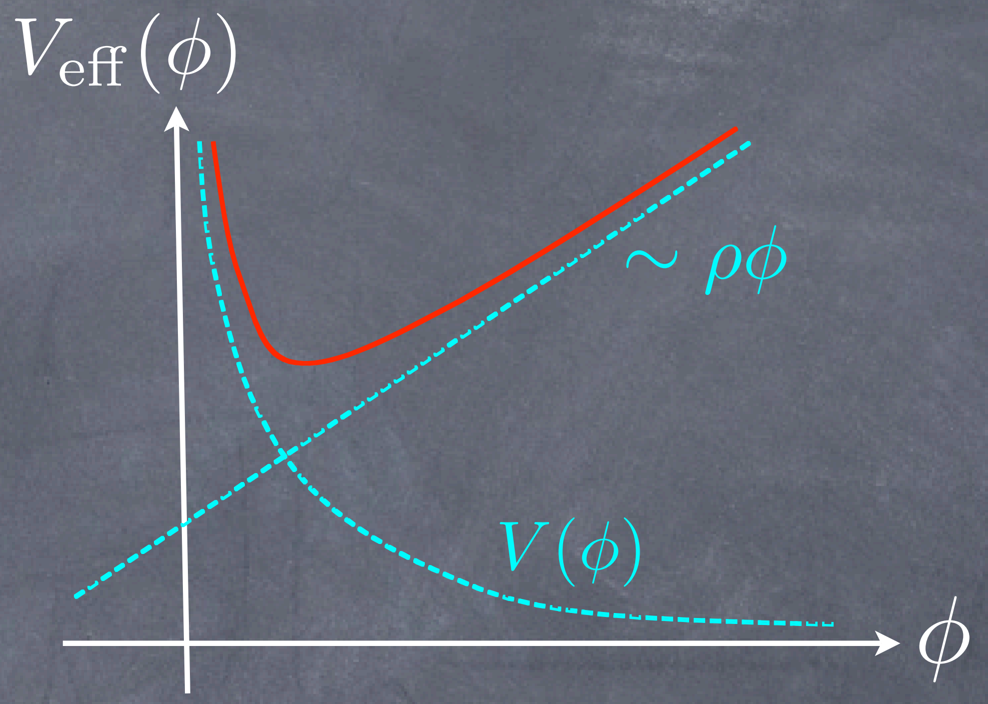

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Galileon

$$3\nabla^2\pi + \frac{1}{\Lambda_{\rm s}^3}\left[(\nabla^2\pi)^2 - (\partial_\mu\partial_\nu\pi)^2\right] = \frac{\rho}{2M_{\rm Pl}}$$

- Predicts LLR signal measurable by APOLLO, but insignificant time-delay/light deflection signals. Dvali, Gruzinov and Zaldarriaga (2002)

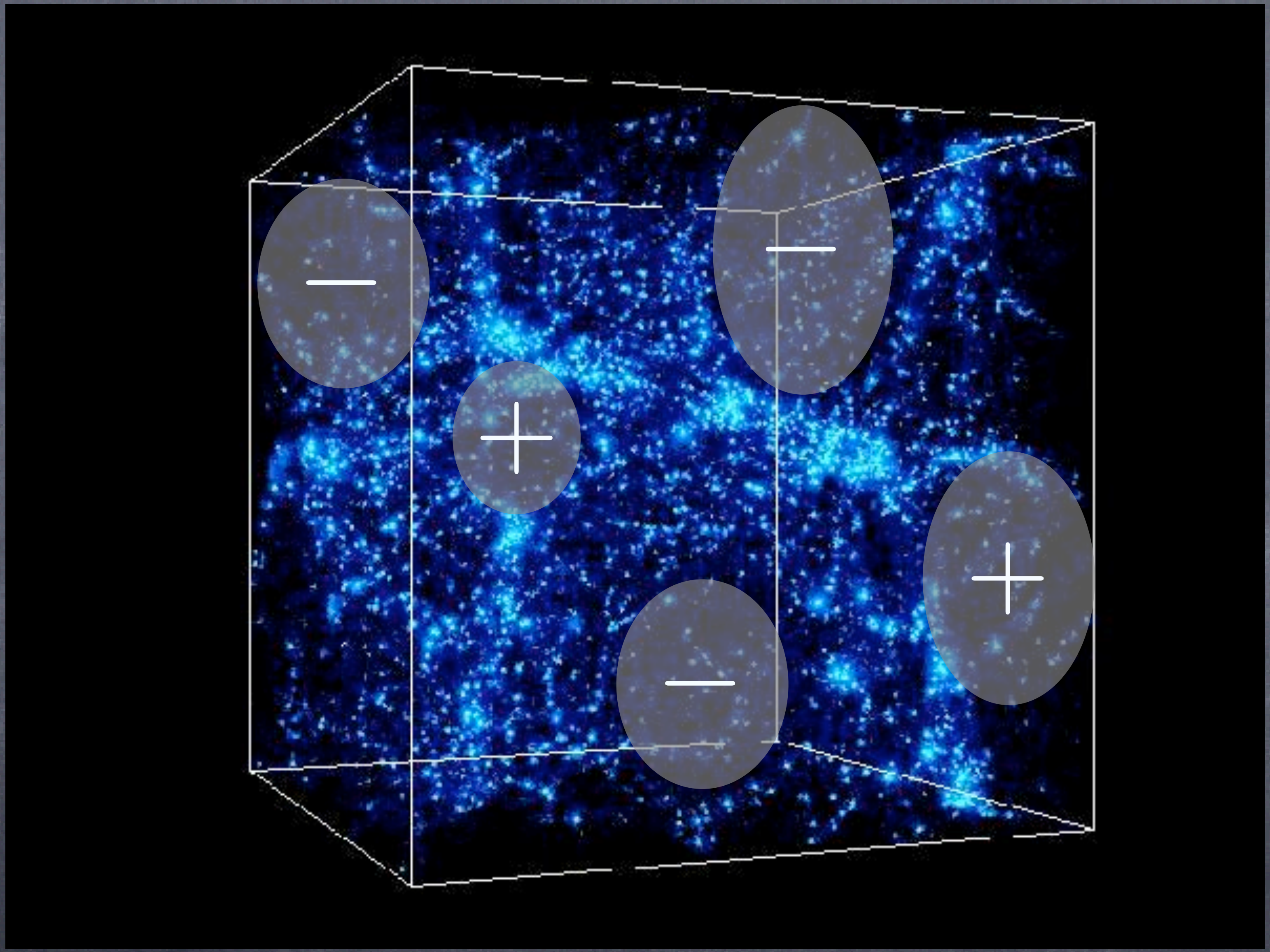
- No macroscopic violations of EP Hui, Nicolis and Stubbs (2009)

Avenues in progress...

1. Symmetron Defects

Hinterbichler, JK & Stojkovic

In void regions larger than $\mu^{-1} \approx \mathrm{Mpc}$, symmetron takes values $\phi = \pm\mu/\sqrt{\lambda}$

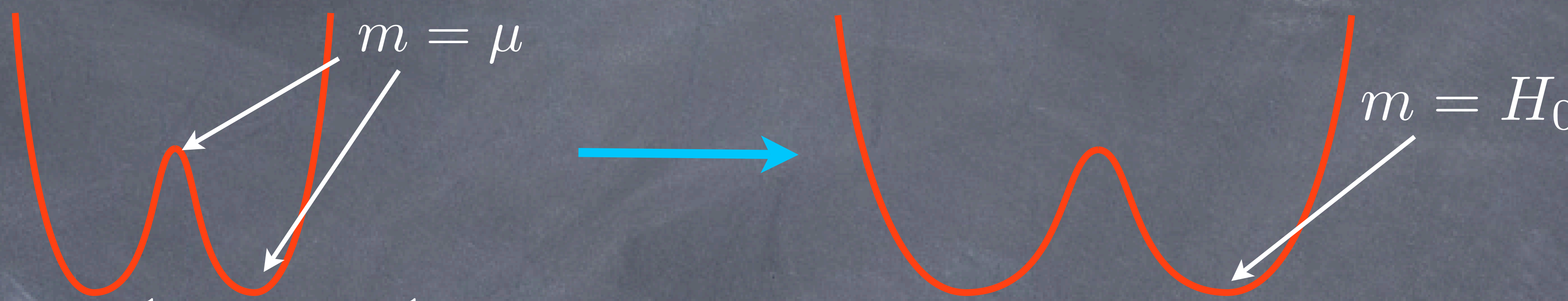


Multiple symmetrons $\Longrightarrow$ global strings, monopoles... ?

2. Cosmology

Hinterbichler, Hui & JK

* Hubble mass:



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

More general $V(\phi)$

e.g.

$$V(\phi) = H_0^2 M_{\rm Pl}^2 \left(e^{-\phi^2/M^2} + \frac{M}{M_{\rm Pl}} e^{\phi^2/M_{\rm Pl}^2} \right)$$

* Self-acceleration?

$$\tilde{g}_{\mu\nu} = \left(1 + \frac{\phi^2}{2M^2} + \mathcal{O}\left(\frac{\phi^4}{M^4}\right)\right)^2 g_{\mu\nu}$$

If no acceleration in Einstein frame, then can we have acceleration in Jordan frame because $\Delta\phi \sim M$?

3. Tantalizing Evidence?

Wyman & JK, to appear tomorrow

Large Scale Bulk Flows

- Local bulk flow within $50\, h^{-1}\mathrm{Mpc}$ is $407 \pm 81\ \mathrm{km/s}$

Watkins, Feldman & Hudson (2008)

- LCDM prediction is $\approx 180\ \mathrm{km/s}$

Find: $v < 240\ \mathrm{km/s}$

Bullet Cluster (1E0657-57)

- Requires $v_{\mathrm{infall}} \approx 3000\ \mathrm{km/s}$ at 5Mpc separation

Mastropietro & Burkett (2008)

- Probability in LCDM is between 3.3×10^{-11} and 3.6×10^{-9}

Lee & Komatsu (2010)

Find: 10^4 enhancement in prob.

Conclusions

- Symmetron offers a new screening mechanism
- Radiatively stable except for Λ and 10^{-3} mass tuning
- More natural than other screening mechanisms (normal looking effective theory, cutoff at the GUT scale)
- Solar-system deviations from GR just below current sensitivity levels, astrophysical signatures

Other consequences?

- Peculiar velocities, void phenomenon
- Topological defects