Center for Particle Cosmology at the University of Pennsylvania

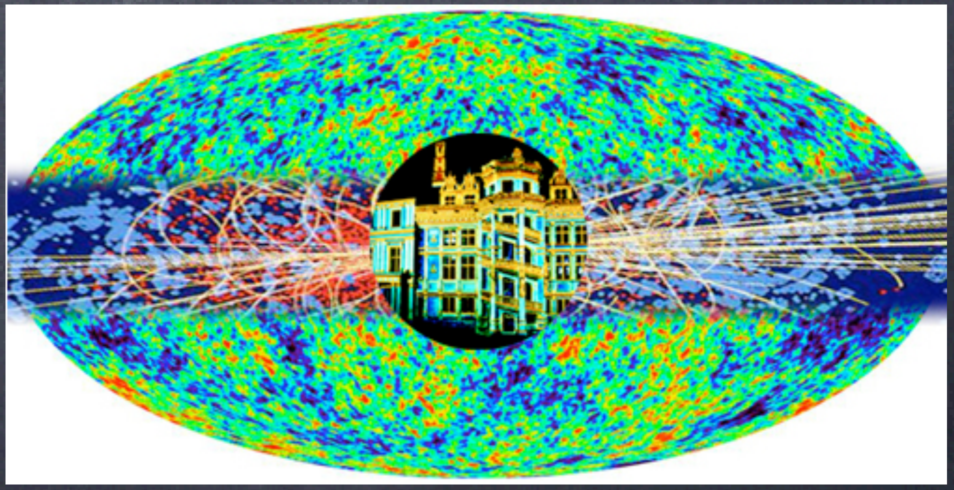
Gravity on the Largest Scales and Cosmic Acceleration

Justin Khoury (UPenn)

K. Hinterbichler & J. Khoury, Phys. Rev. Lett. 104, 231301 (2010) [arXiv:1001.4525 [hep-th]]

J. Khoury & A. Weltman, Phys. Rev. Lett. 93, 171104 (2004); Phys. Rev. D 69, 044026 (2004)

22nd Rencontres de Blois
July 20, 2010



Cosmology at the Rencontres...

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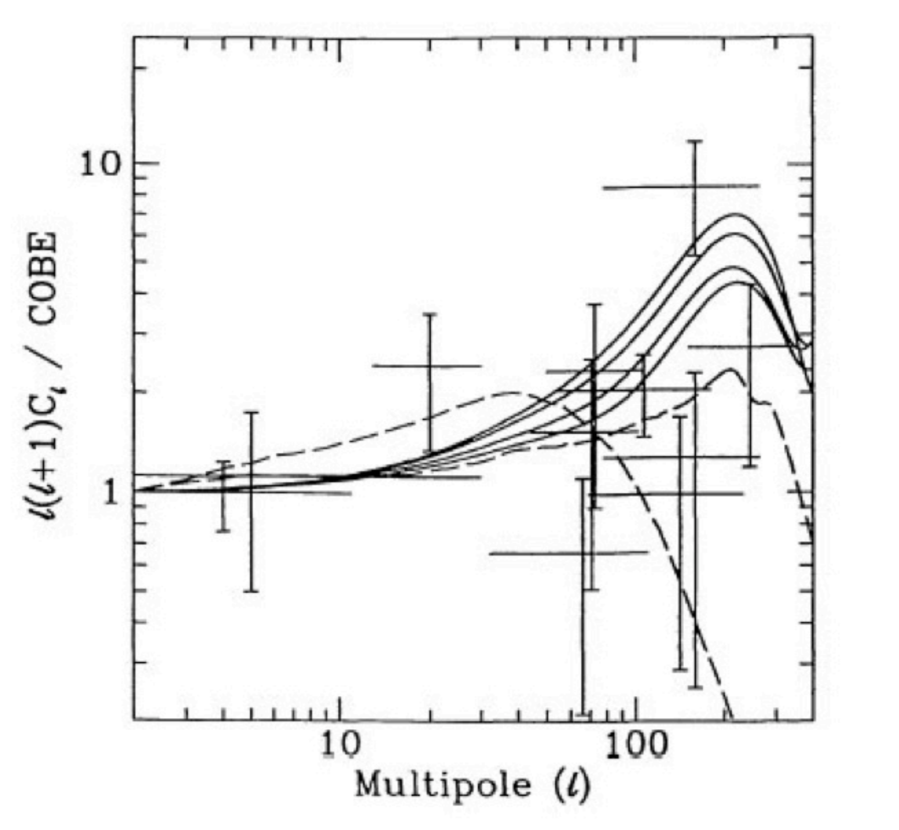

8th Rencontres (1996)

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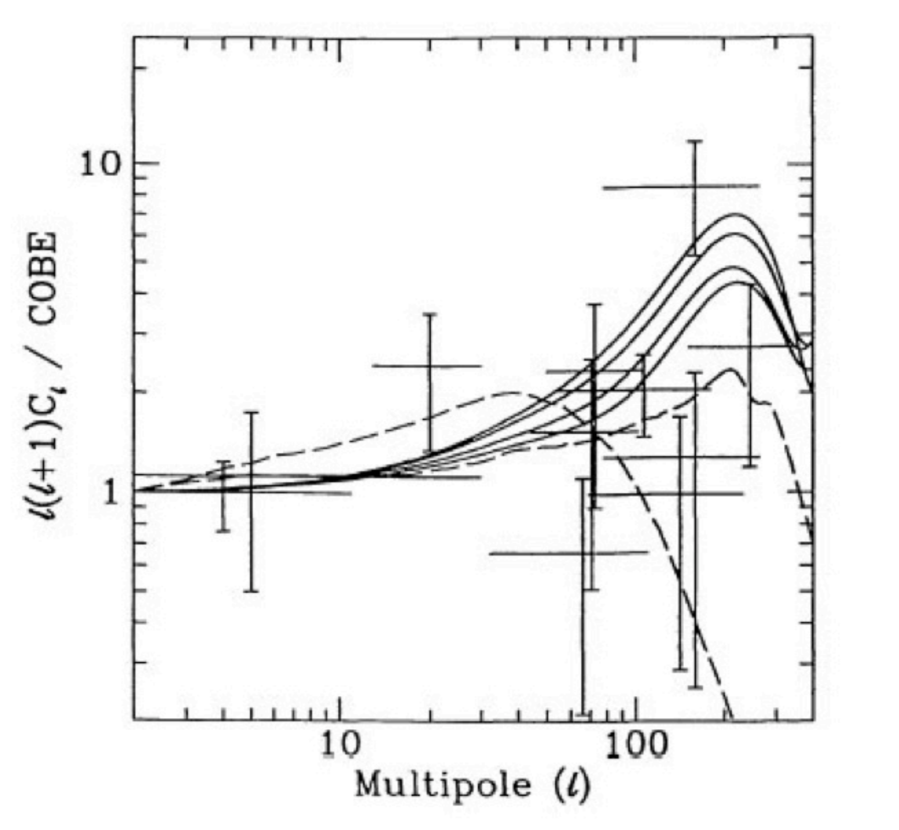

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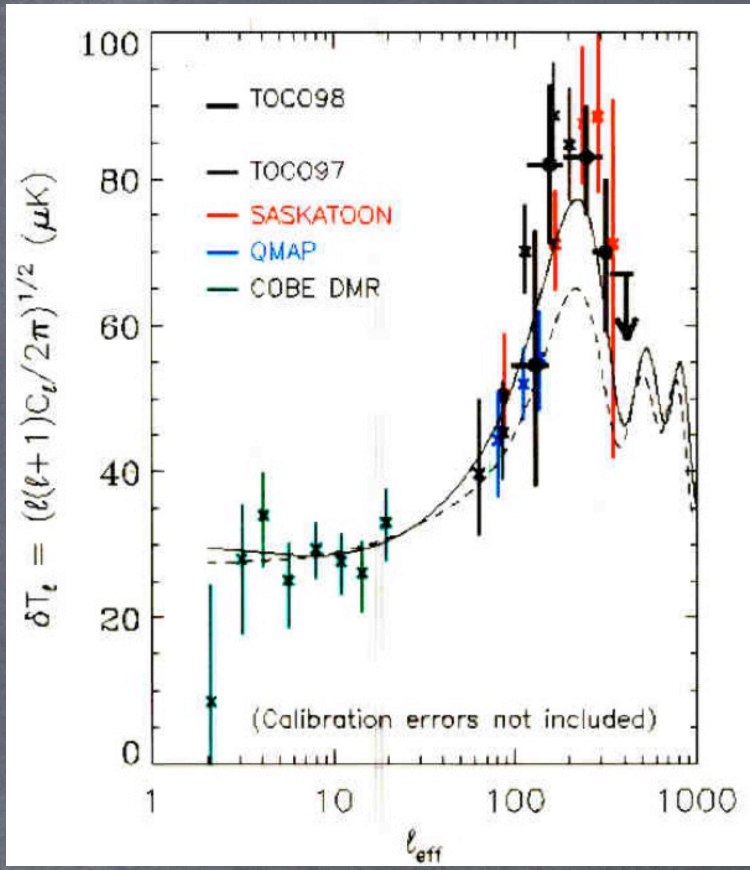

11th Rencontres (1999), F. Bouchet

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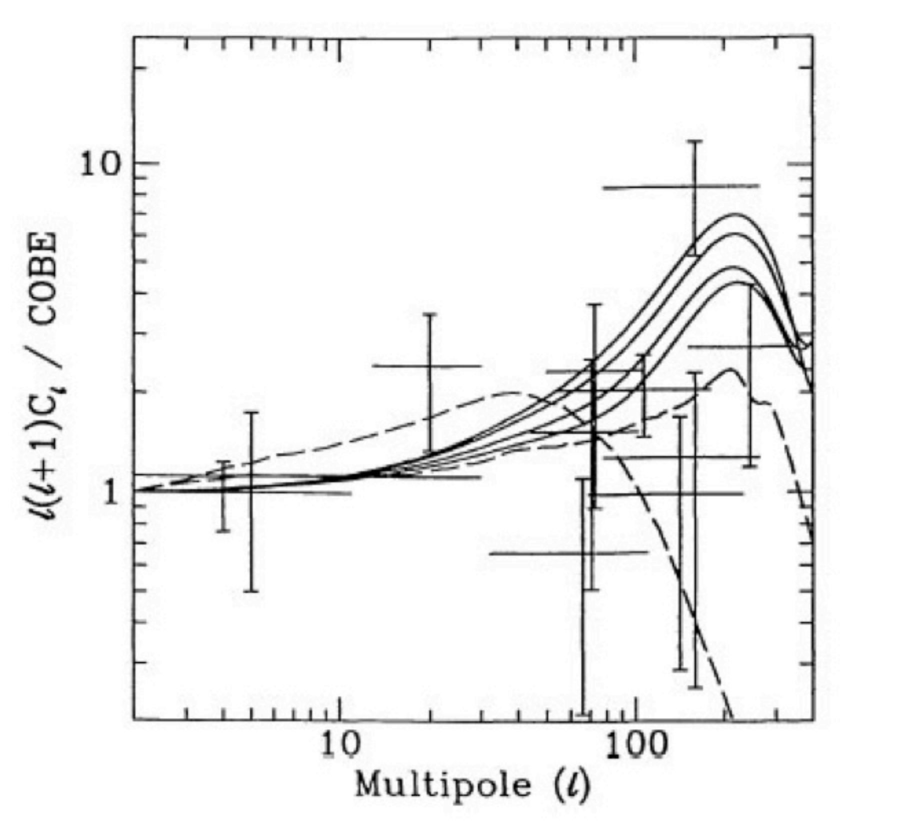

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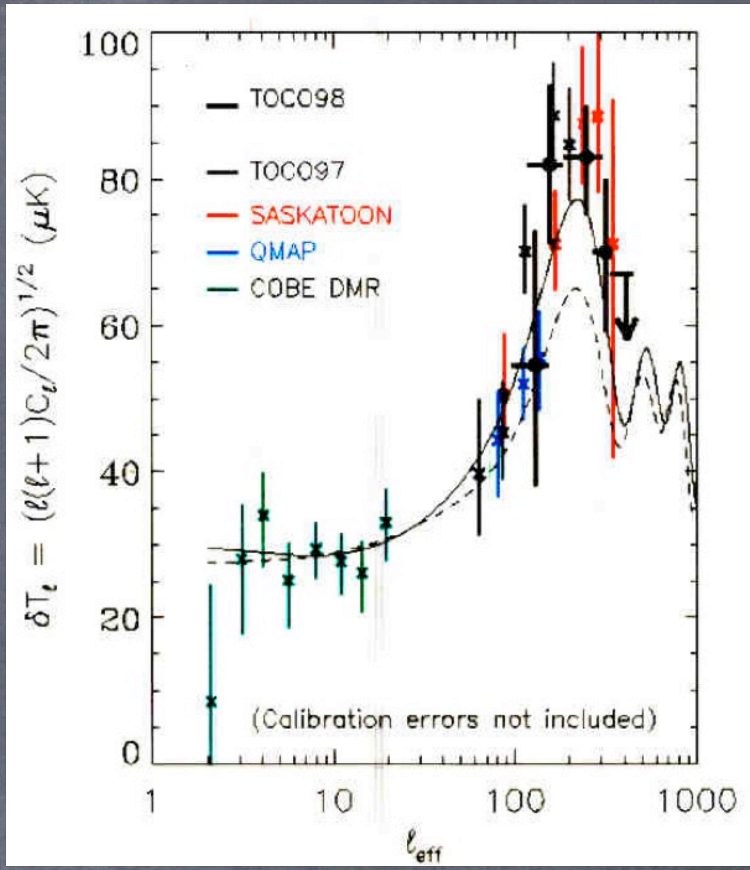

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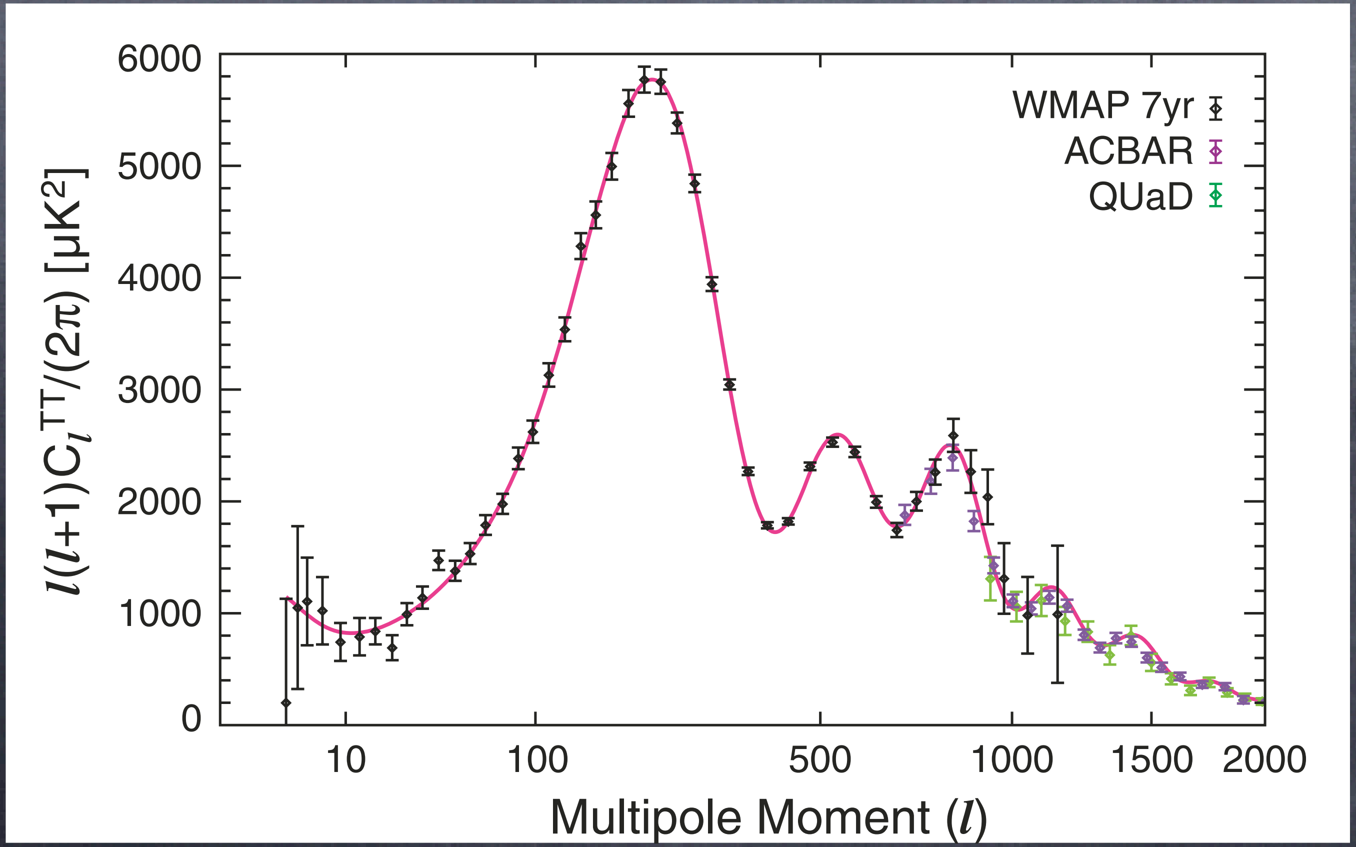
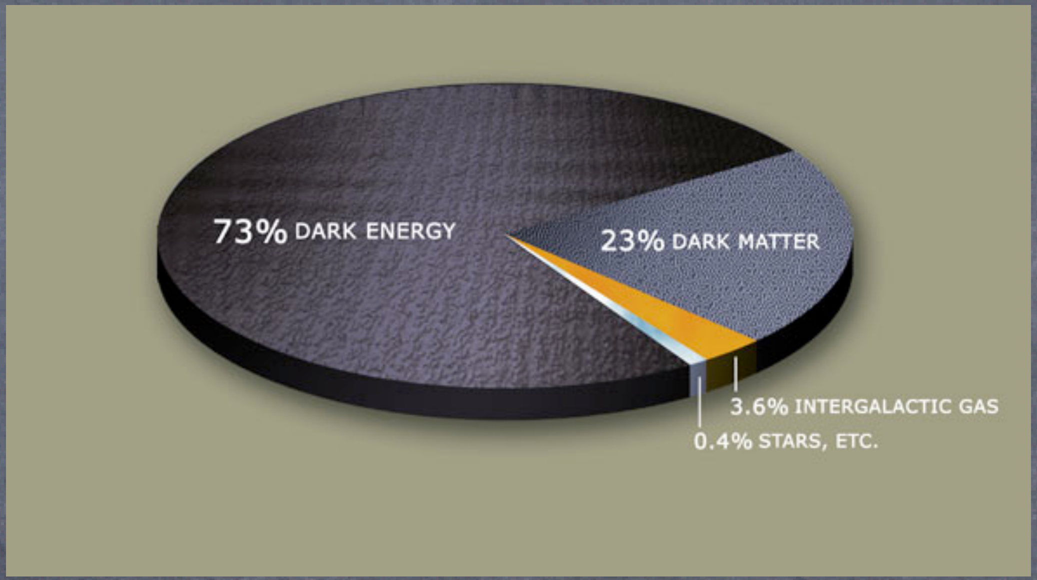


22nd Rencontres (2010)

The Era of Precise Unknowns



$$\Omega_{\mathrm{b}} h^2 = 0.02260 \pm 0.053\,; \qquad \Omega_{\mathrm{c}} h^2 = 0.1123 \pm 0.0035\,;$$
$$\Omega_{\Lambda} = 0.728 \pm 0.016 \qquad n_s = 0.963 \pm 0.012\,;$$
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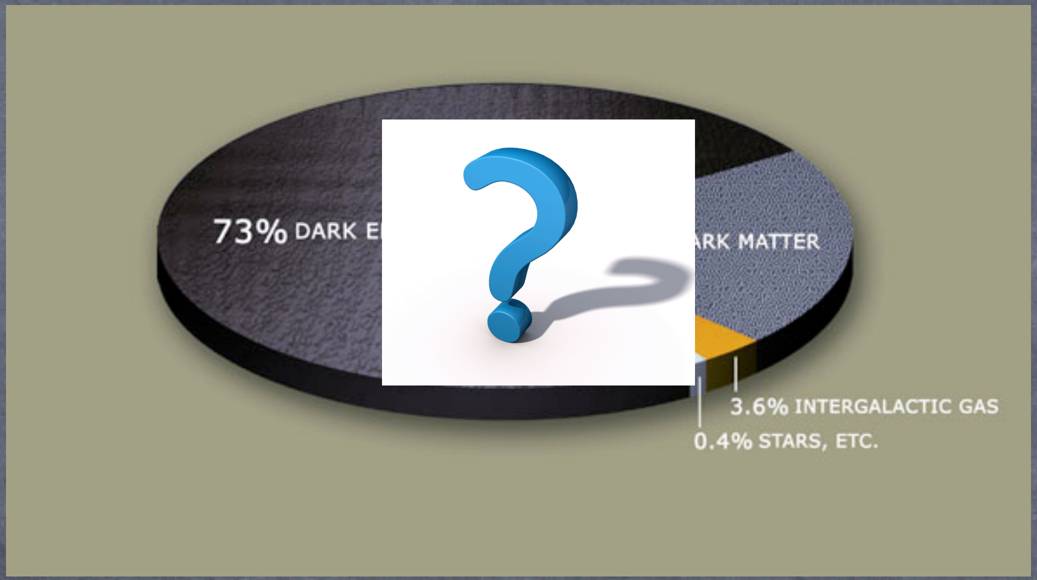

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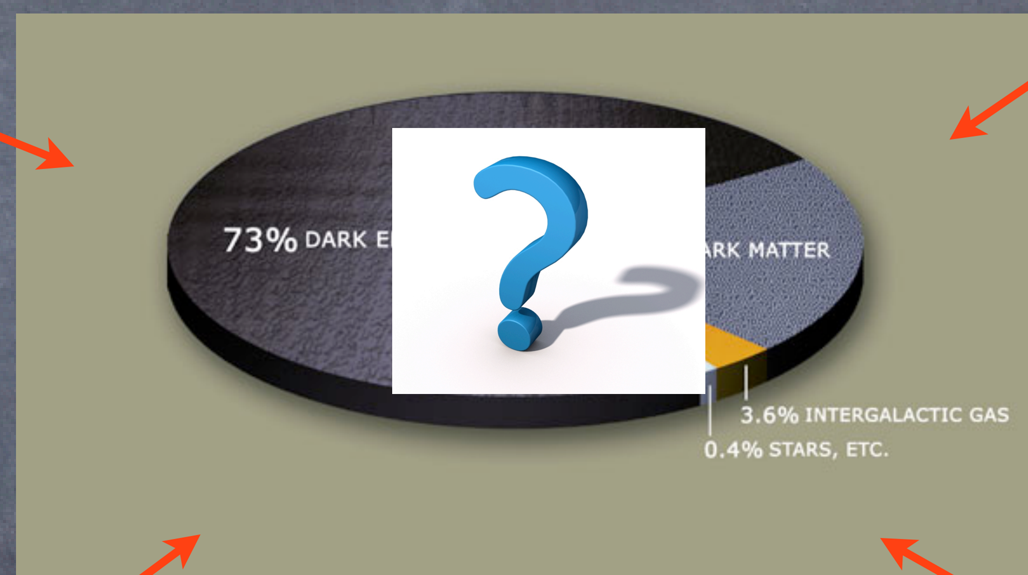

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The end of cosmology?

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?"

- Prof. P. J. E. Peebles

Already a surprise: Dark energy is coming to dominate the energy budget much more quickly than anticipated...

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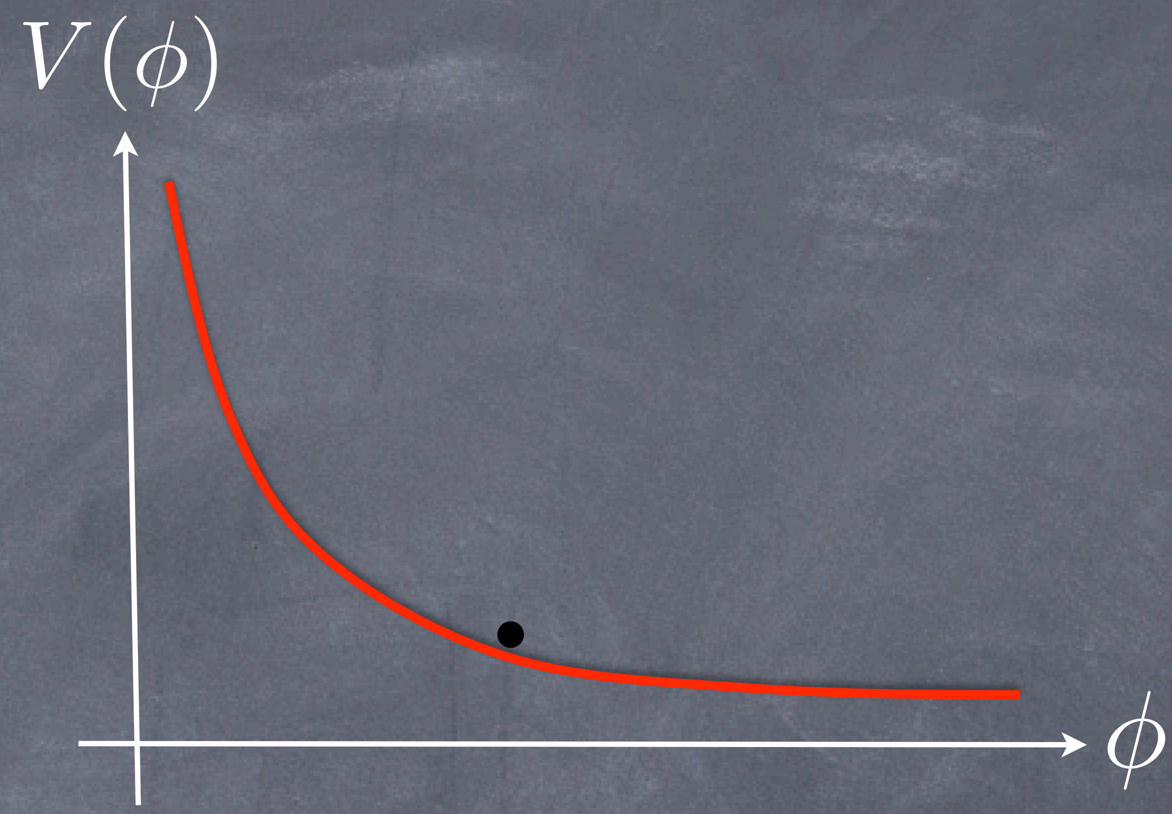
WMAP 1st-year $\Omega_\Lambda = 0.71$

WMAP 3-year $\Omega_\Lambda = 0.716$

WMAP 5-year $\Omega_\Lambda = 0.742$

$$\vdots$$

A Richer Dark Sector



- Dark energy candidates:

  Λ, quintessence...

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

- Tantalizing prospect: quintessence (or any other light field) couples to both dark and baryonic matter.

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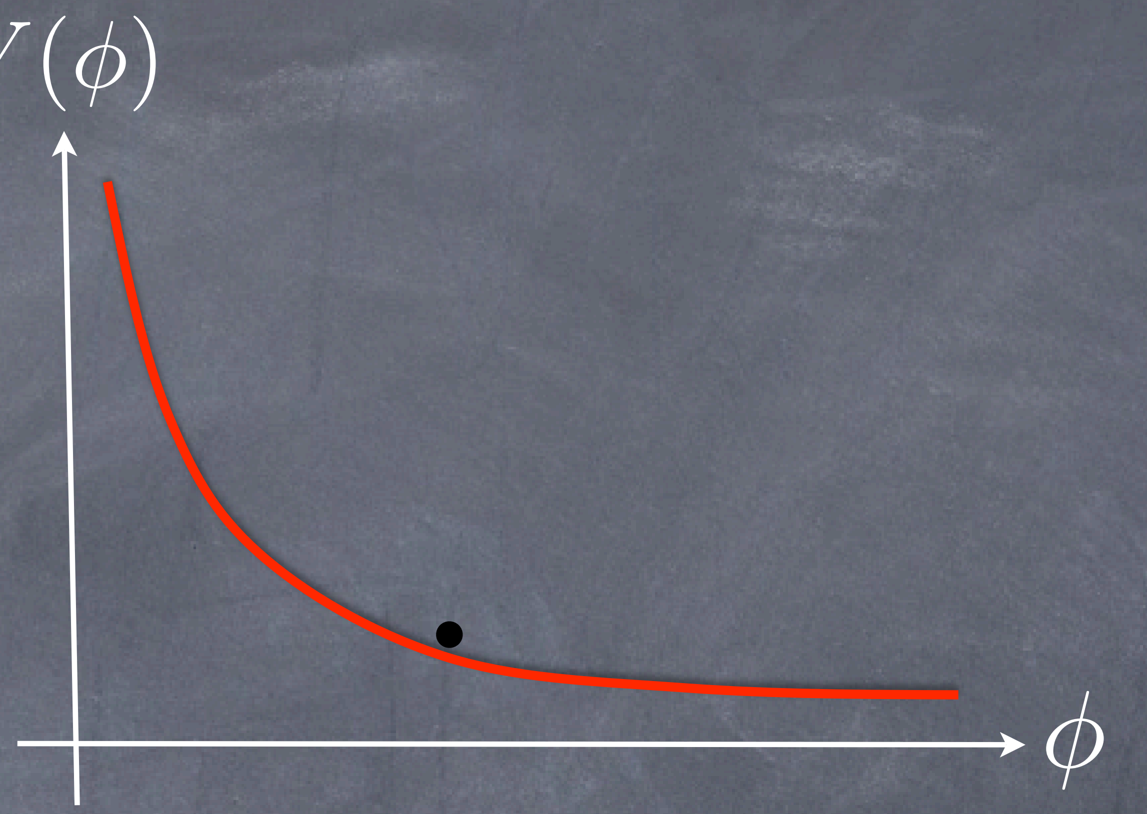

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Not so fast. Scalar fields can "hide" themselves from local experiments through screening mechanisms

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

3 ways of hiding scalar fields...

$$\nabla^2\phi + m^2\phi = -\frac{g}{M_{\rm Pl}} T^\mu_\mu$$

3 ways of hiding scalar fields...

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

3 ways of hiding scalar fields...

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

chameleon

3 ways of hiding scalar fields...

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

↑

Vainshtein

3 ways of hiding scalar fields...

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

↑

symmetron

Chameleon Mechanism

J. Khoury & Weltman, Phys. Rev. Lett. (2004);
Gubser & J. Khoury, (2004)

(At play in f(R) theories. Carroll, Duvvuri, Trodden & Turner (2004))

Consider scalar field ϕ with potential $V(\phi)$ and conformally-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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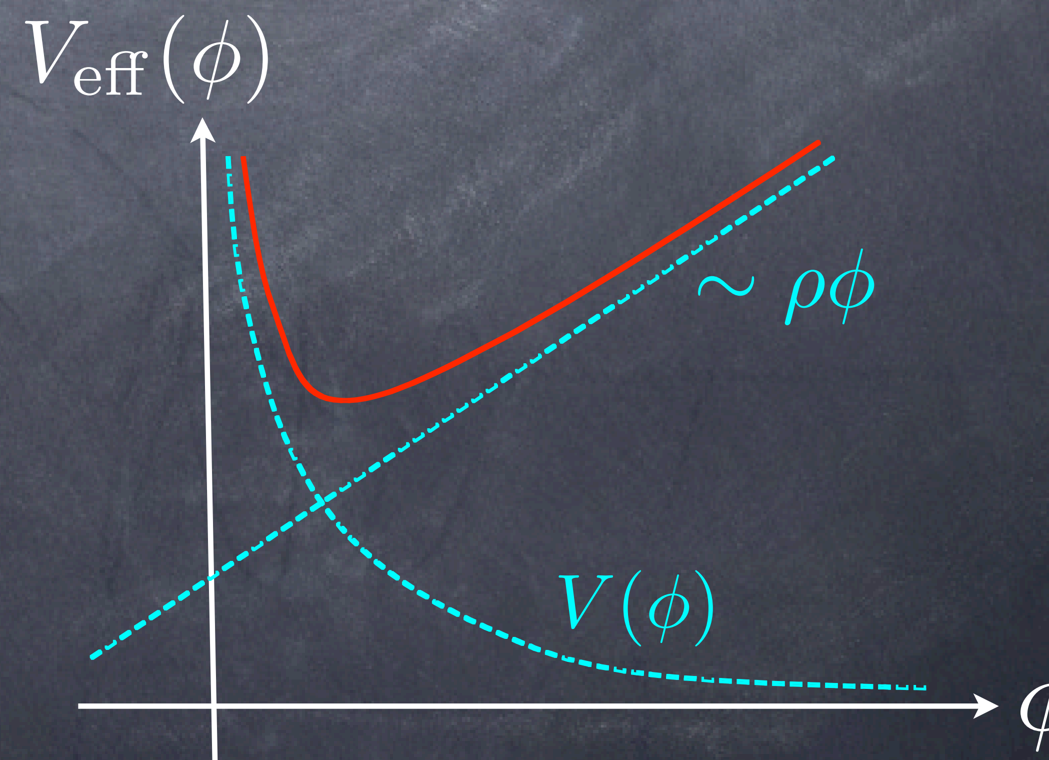
For non-relativistic matter, $T^\mu_\mu \approx -\rho$, hence

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

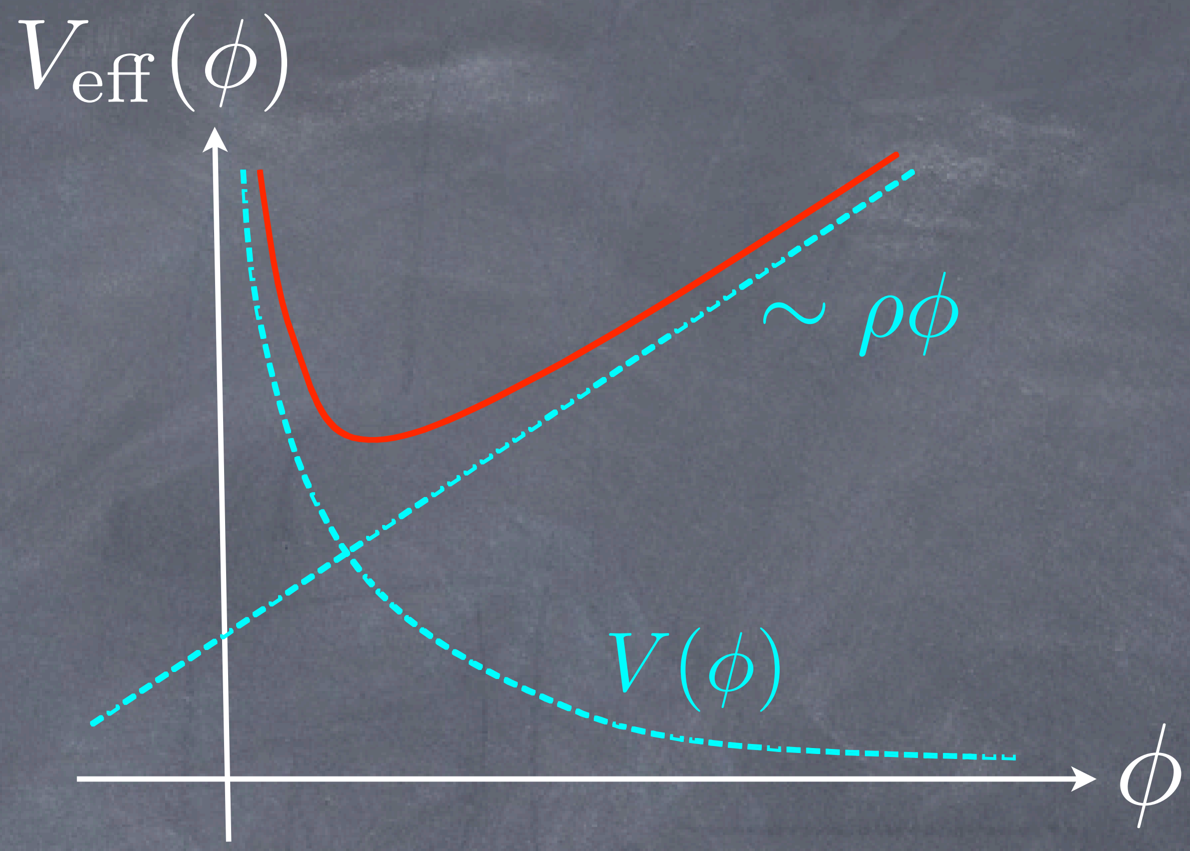
$$\Longrightarrow \quad V_{\rm eff}(\phi) = V(\phi) + g\frac{\phi}{M_{\rm Pl}}\rho$$



Density-dependent mass

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

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



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

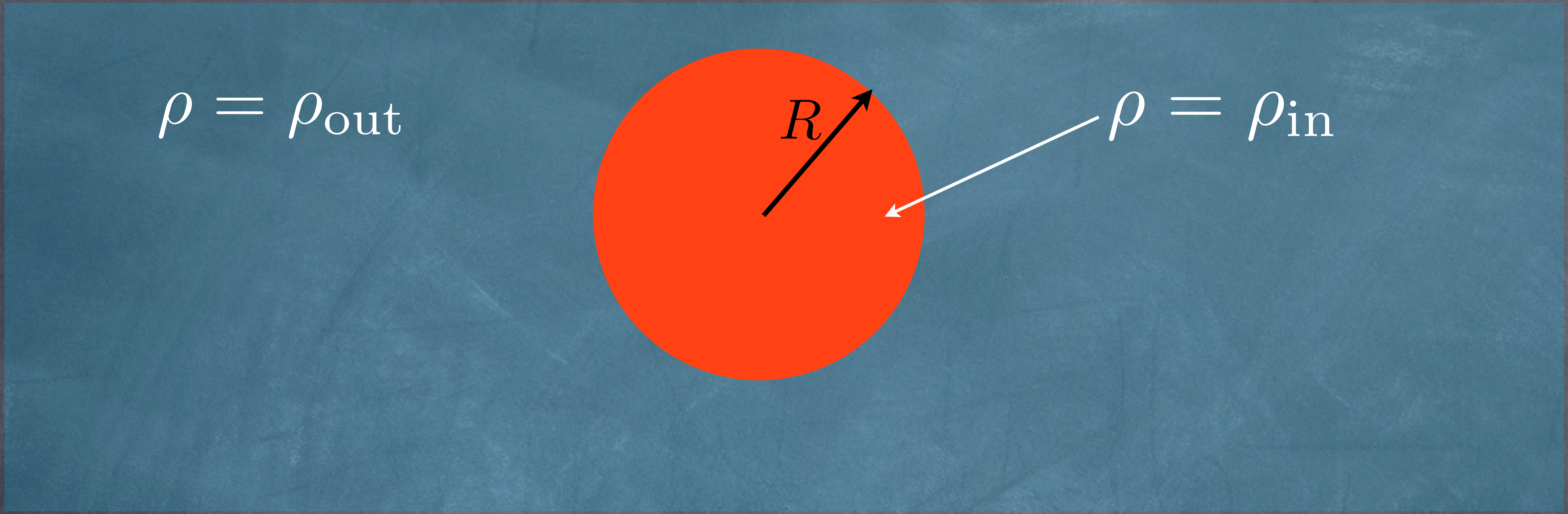
Laboratory tests => set $m^{-1}(\rho_{\rm local}) \lesssim {\rm mm}$

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

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

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

Thin-shell screening



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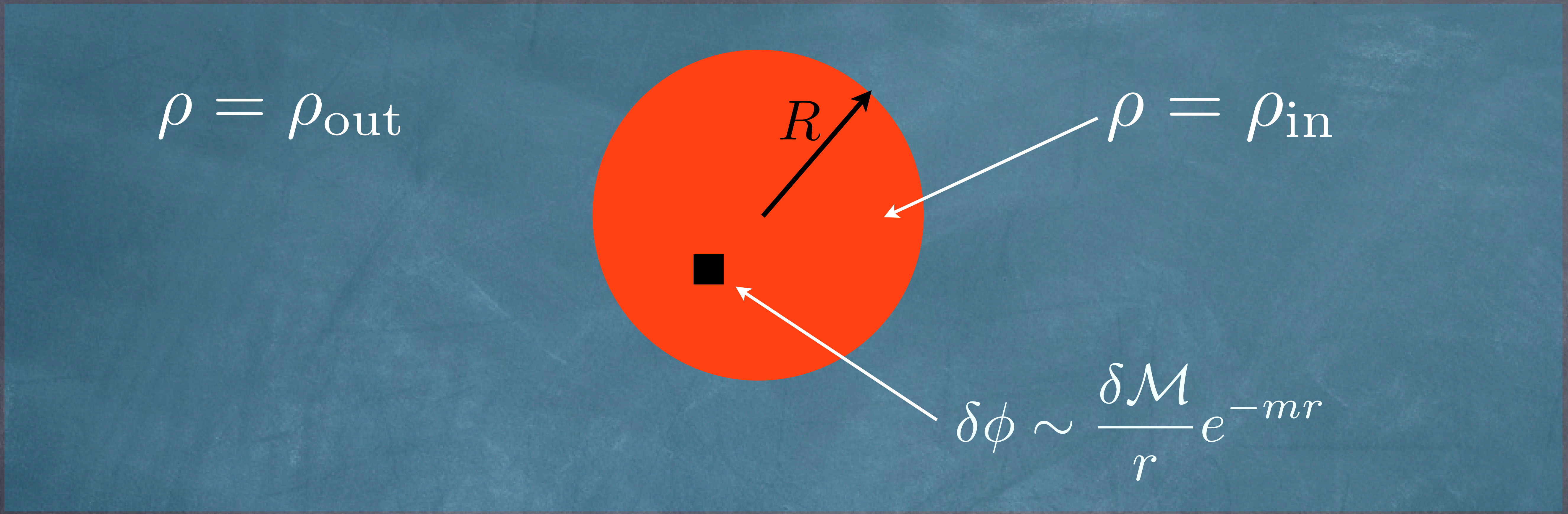

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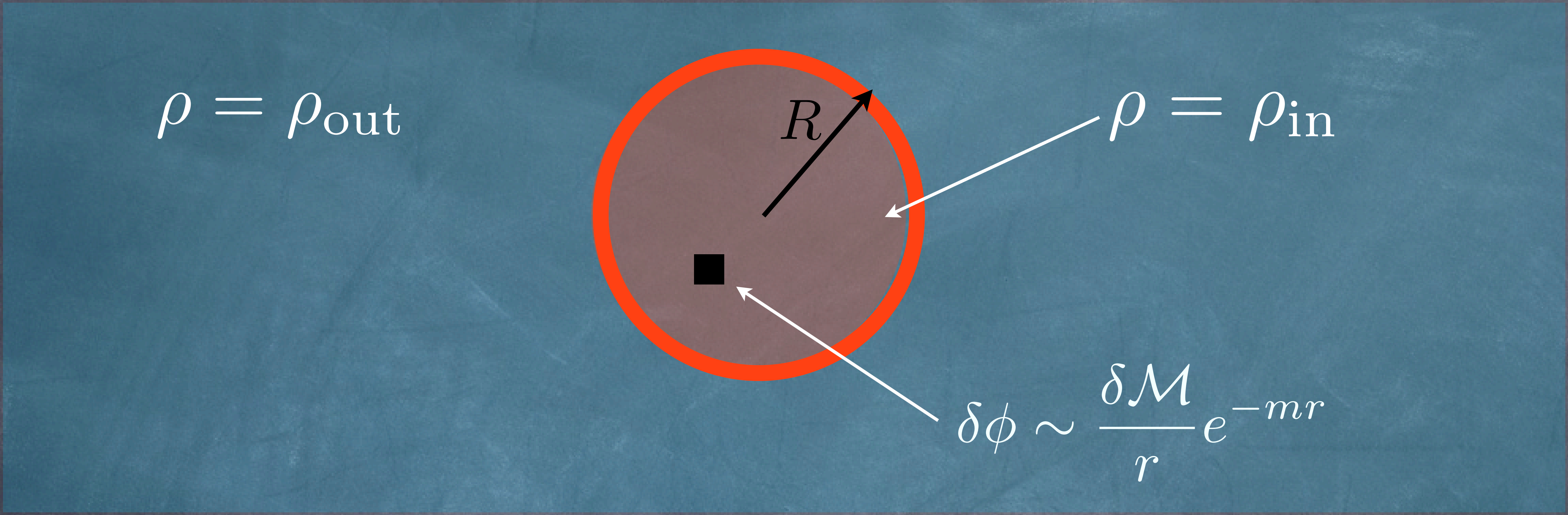
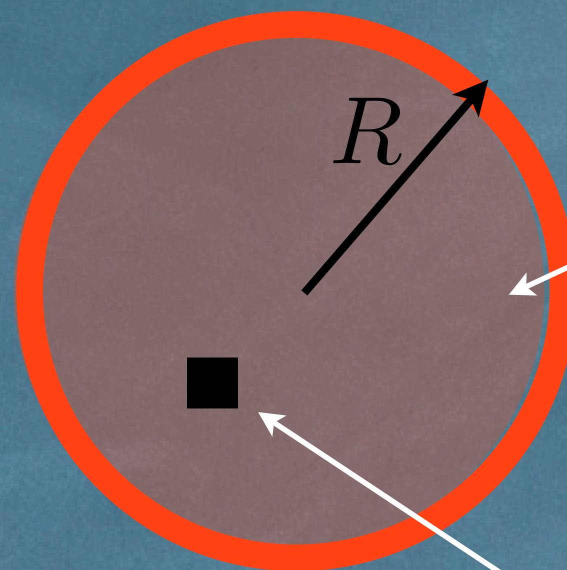


Thin-shell screening

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



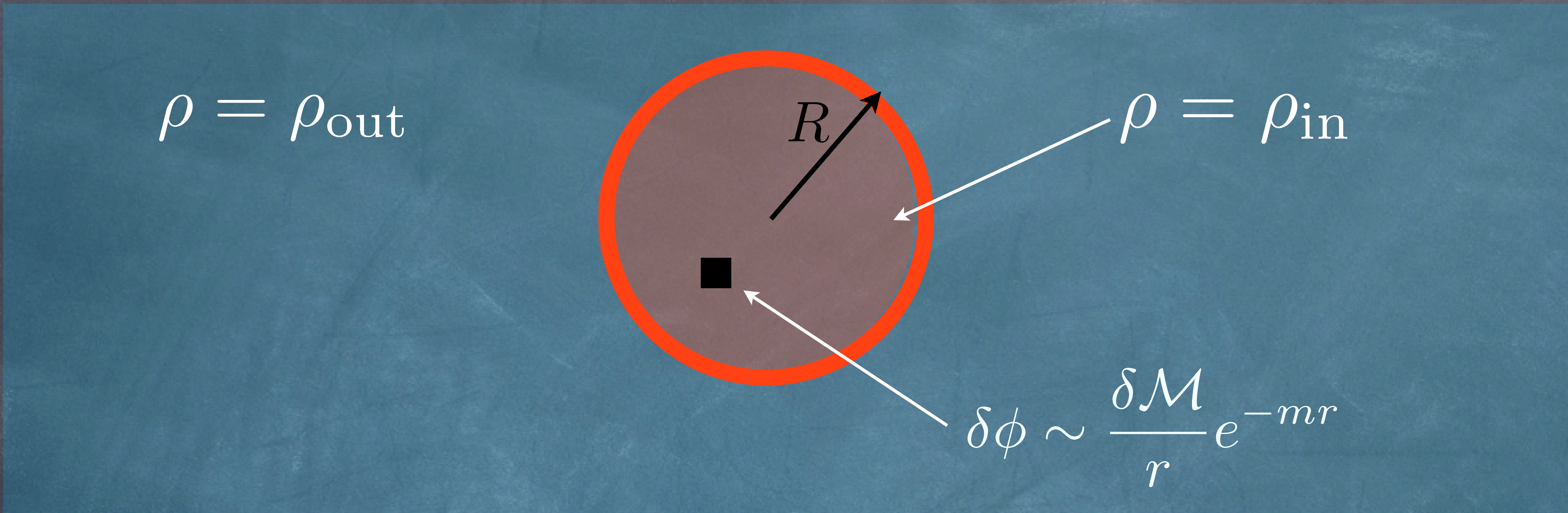
$\rho = \rho_{\rm in}$

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

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

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

Thin-shell screening



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

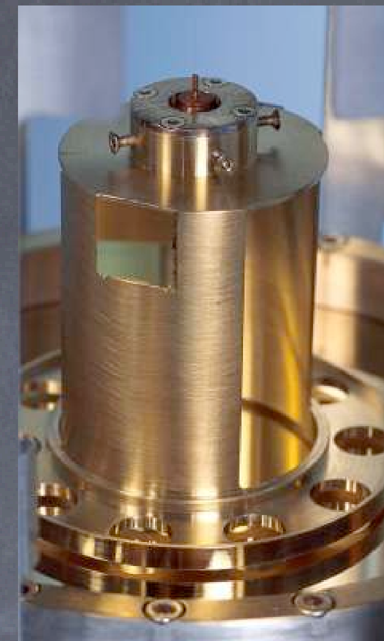
But small objects $\Longrightarrow$ no thin-shell

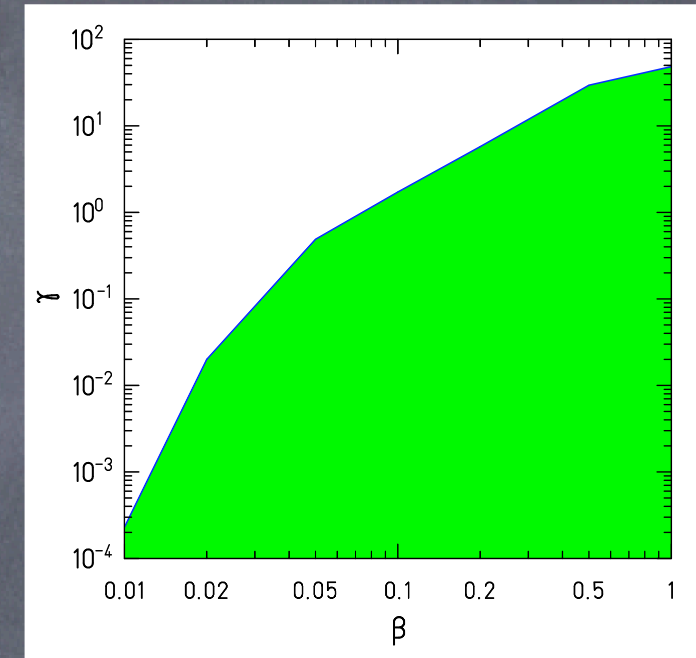
$\Longrightarrow G_{\rm N}^{\rm eff} = G_{\rm N}(1 + 2g^2)$ in space !

Chameleon Searches

- Eot-Wash

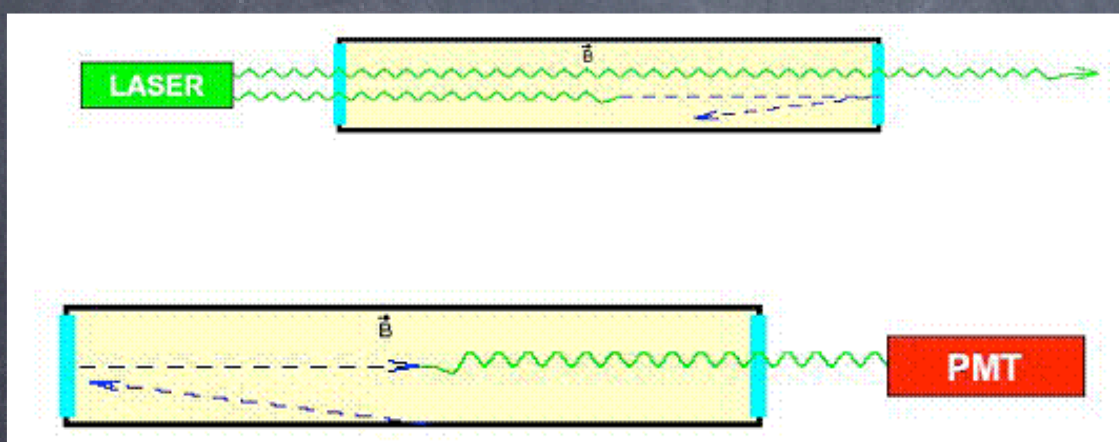
  Adelberger et al.,
  Phys. Rev. Lett. (2008)

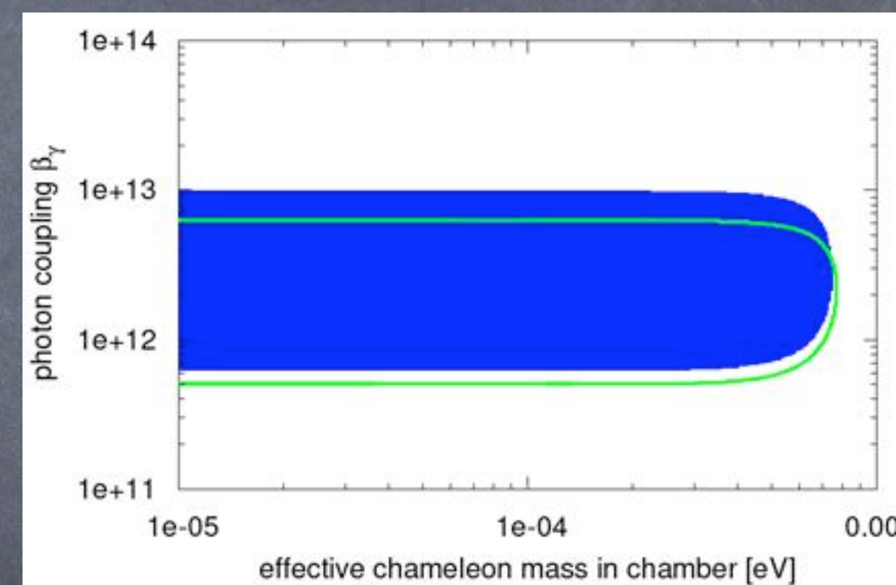




- GammeV, Fermilab

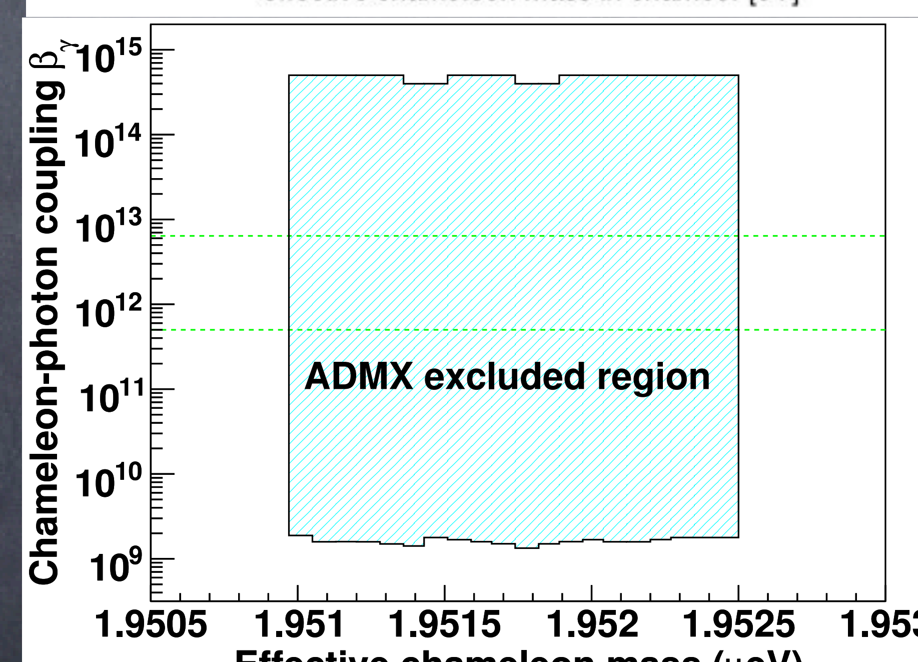
  Chou et al., Phys. Rev. Lett. (2008)





- ADMX

  P. Sikivie & co., arXiv:1004.5160



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: $\partial_\mu\pi \to \partial_\mu\pi + c_\mu$

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

Solution around point source of mass M:

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

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:

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

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

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

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

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 J. Khoury, Phys. Rev. Lett. (2010)
See also Olive & Pospelov (2008); Pietroni (2005)

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

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + \frac{\phi^2}{2M^2}T^\mu_\mu$$

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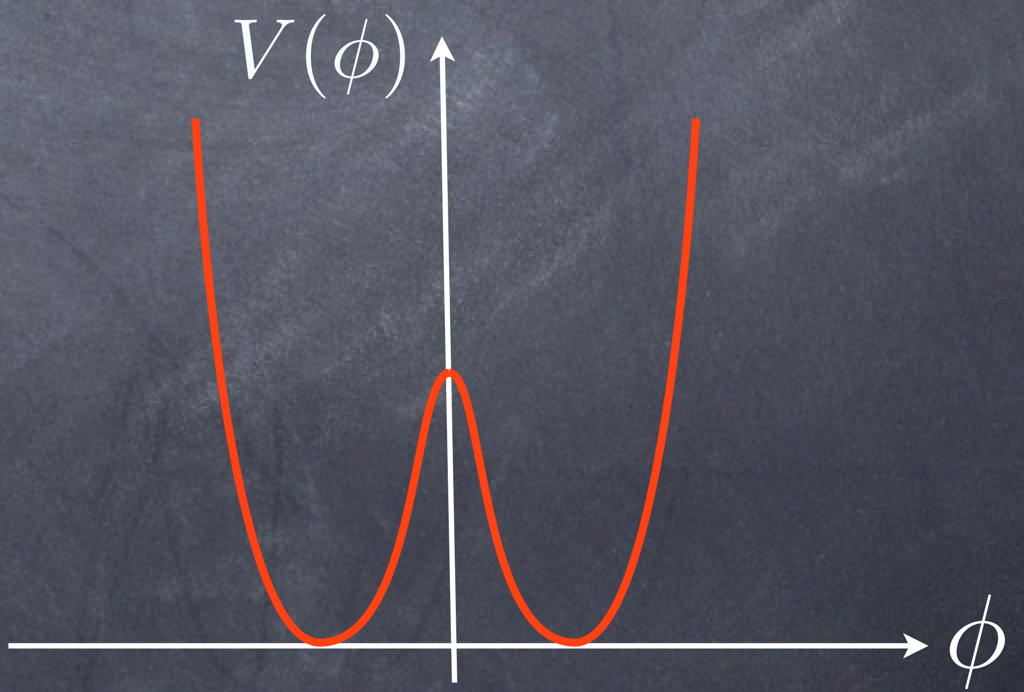
Potential is of the spontaneous-symmetry-breaking form:

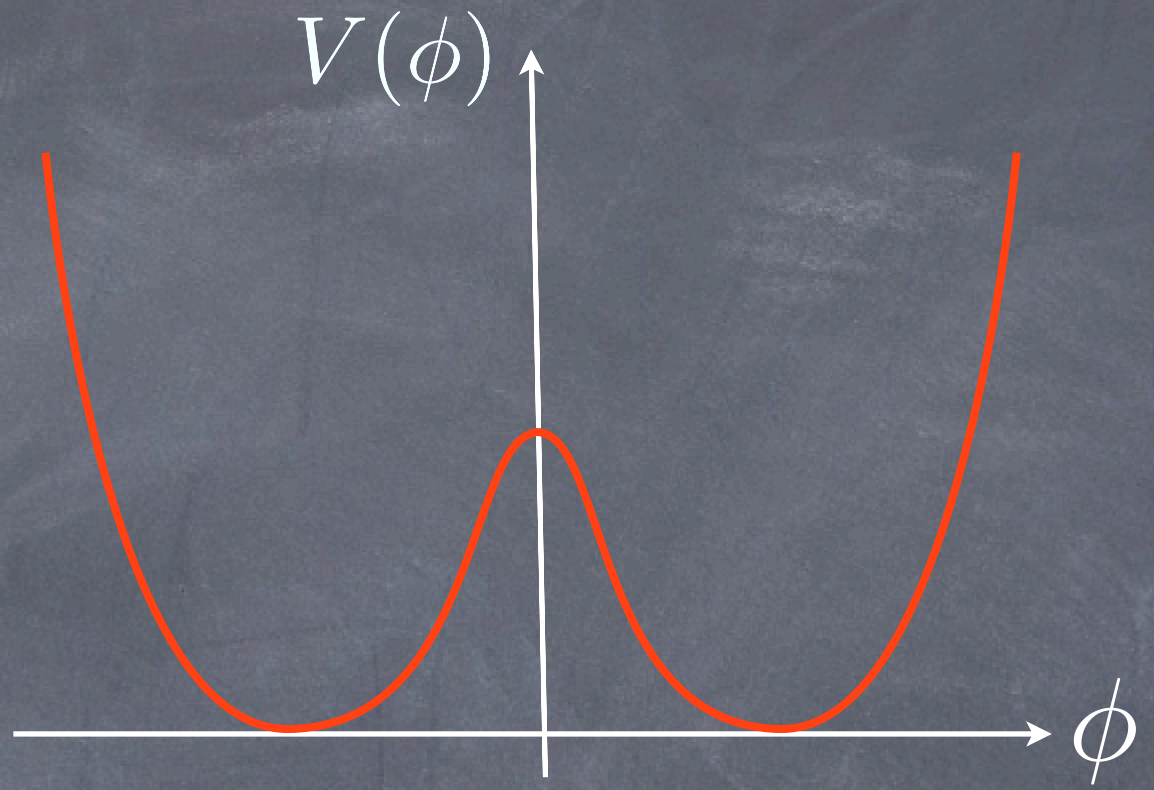
$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

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



Effective Potential

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



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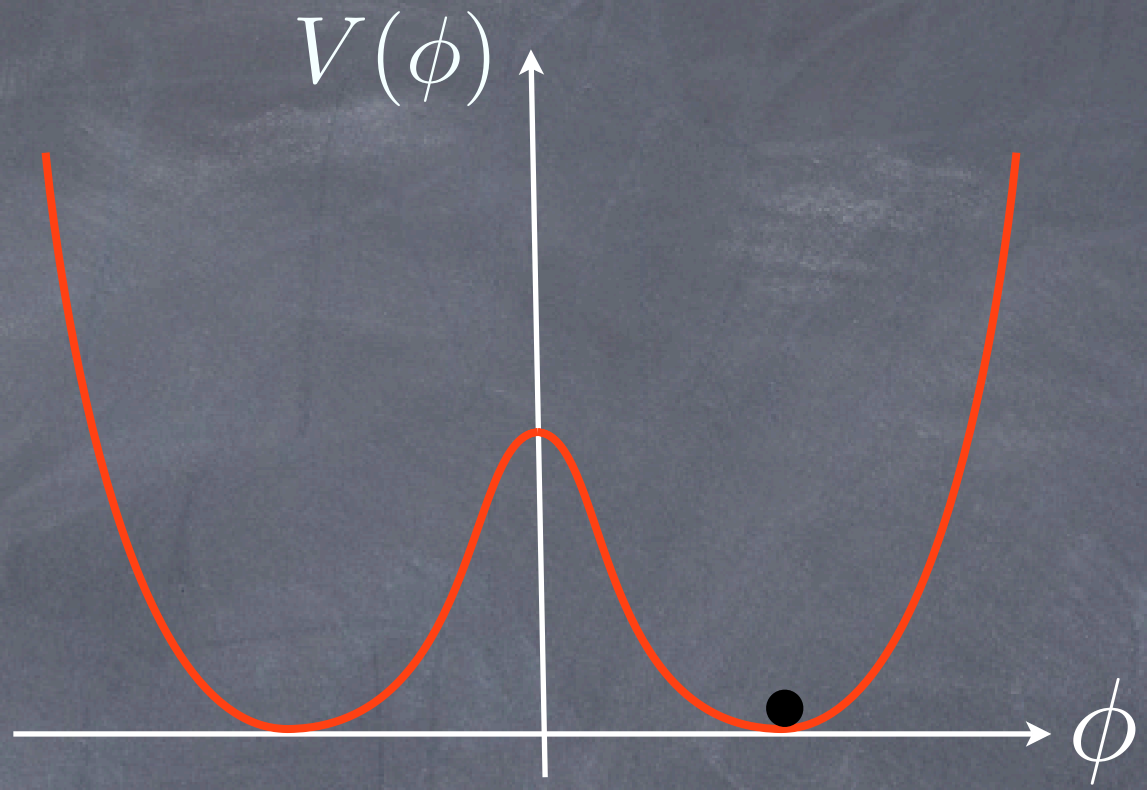

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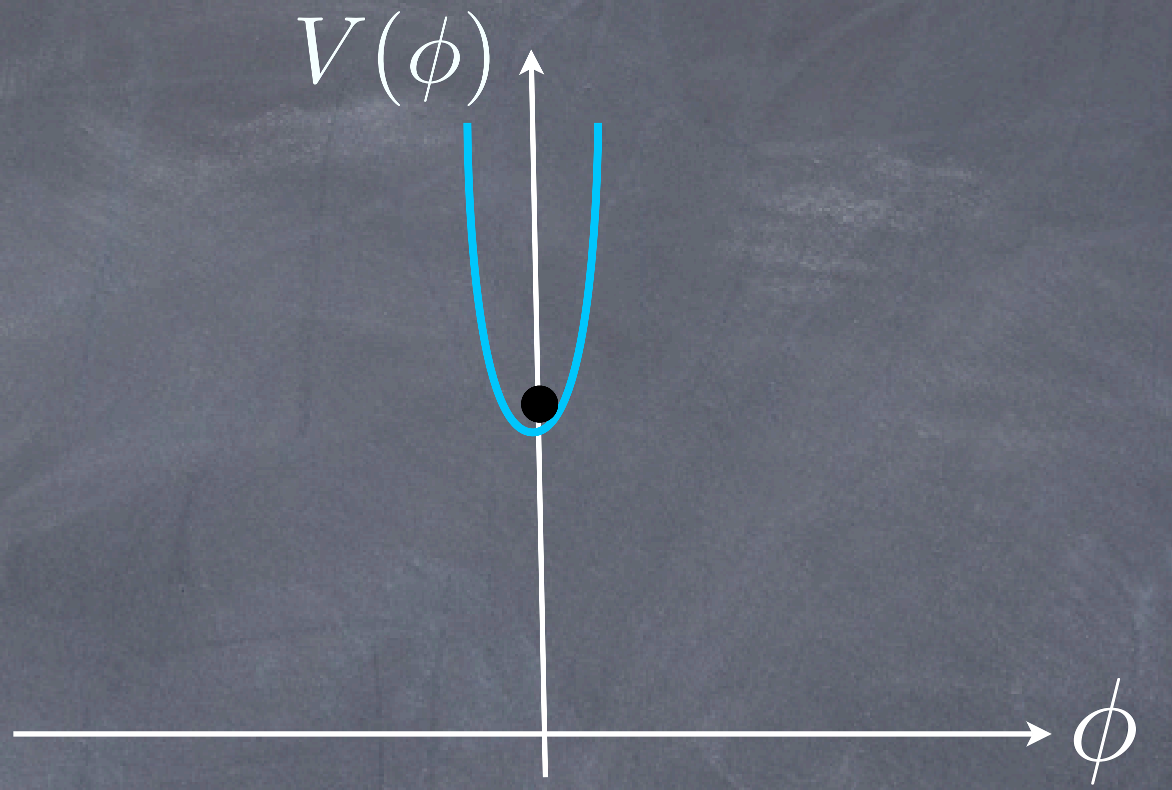

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$\therefore$ Whether symmetry is broken or not depends on local density

- 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

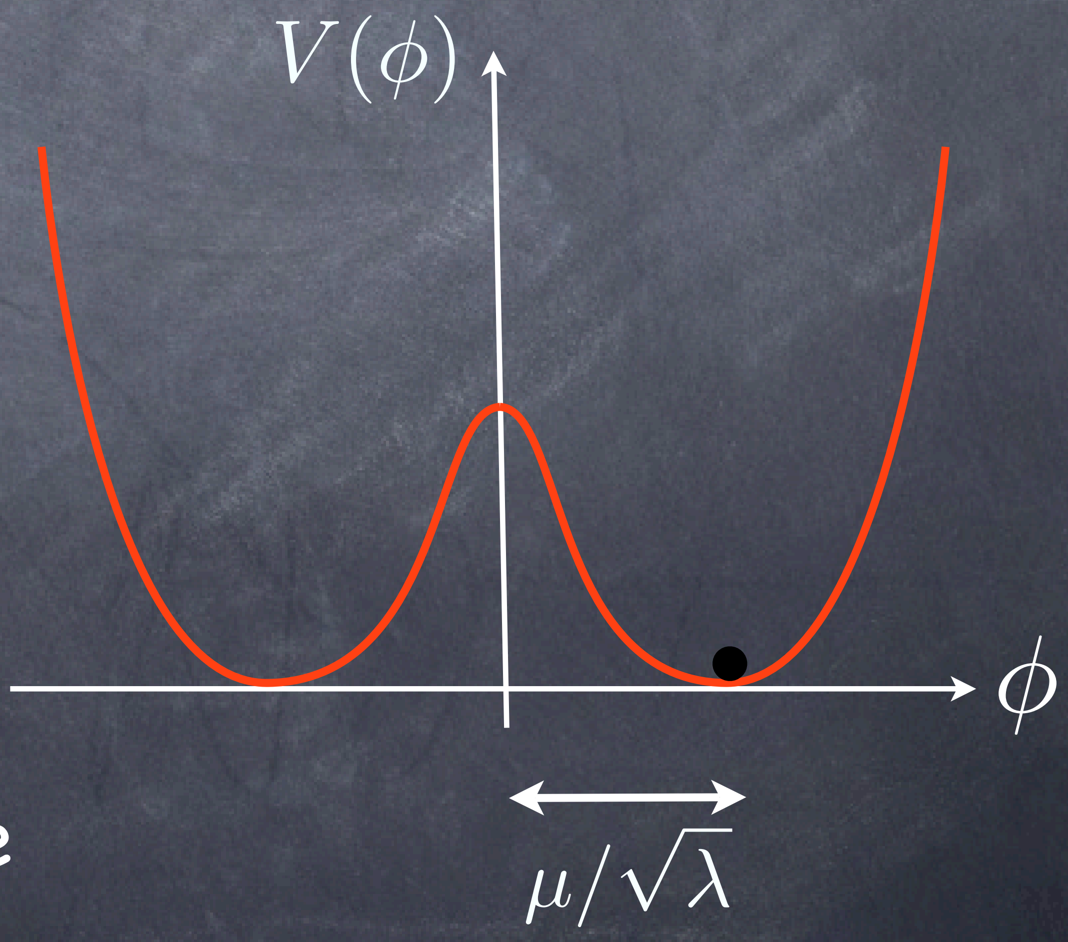
Perturbations $\delta\phi$ around local background value couple as:

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

- 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



$\therefore$ 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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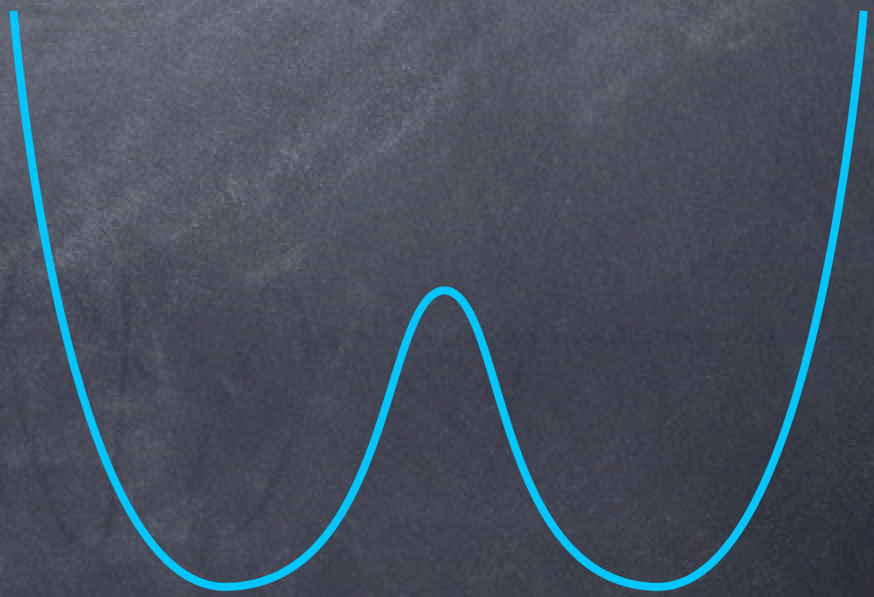
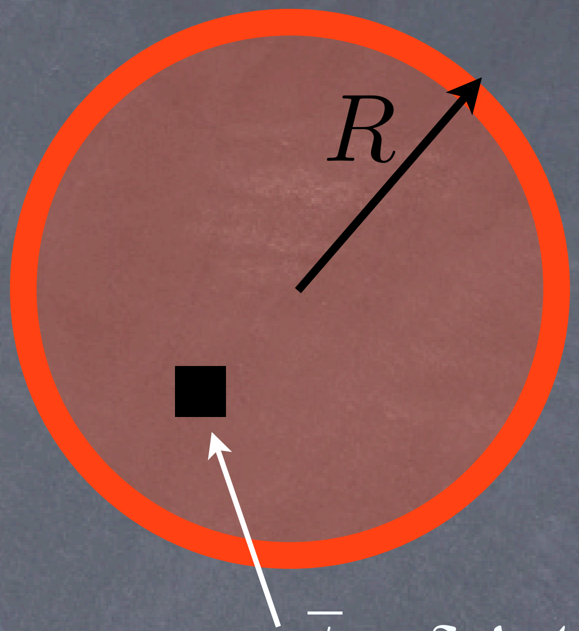


Thin-Shell Screening Effect

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:

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

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

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

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

Parameter Constraints

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4 + \frac{\phi^2}{2M^2}T^\mu_\mu$$

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

$$\alpha_{\rm G} = 6\frac{M_{\rm Pl}^2}{M^2}\Phi_{\rm G} \gtrsim 1$$

$$\Phi_{\rm G} \sim 10^{-6}$$

$$\Longrightarrow \quad \boxed{M \lesssim 10^{-3} M_{\rm Pl}}$$

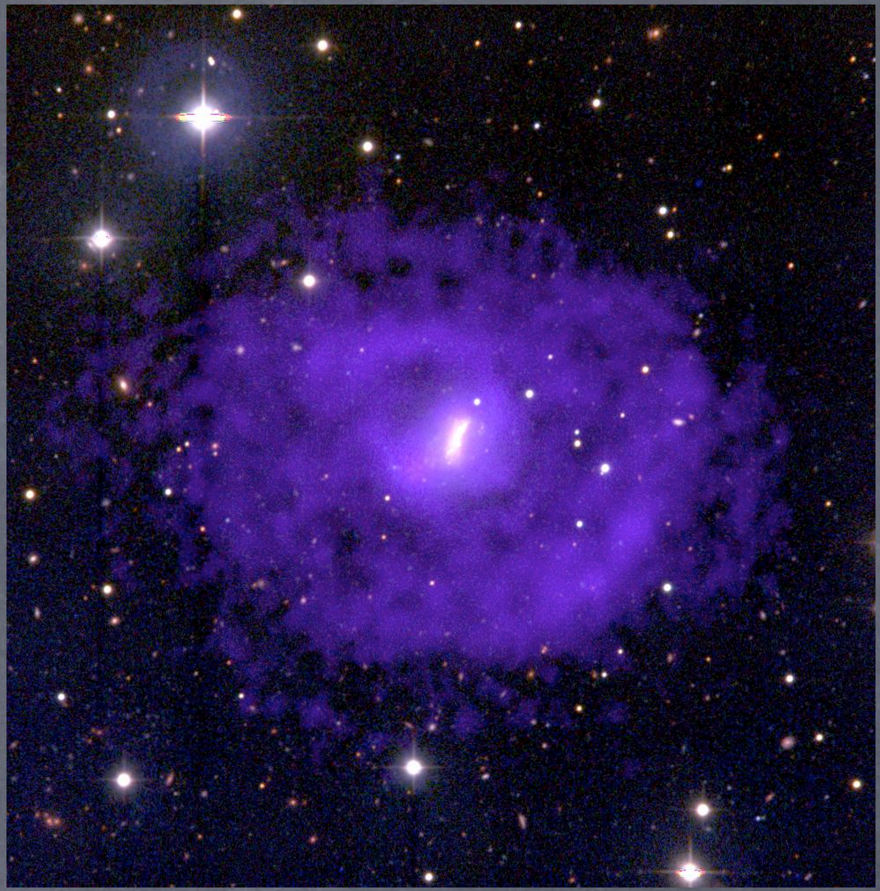
$$\Longrightarrow \quad \mu \sim \frac{M_{\rm Pl}}{M}H_0 \gtrsim {\rm Mpc}^{-1} \qquad \lambda \sim \frac{M_{\rm Pl}^4 H_0^2}{M^6} \gtrsim 10^{-100}$$

Predictions for Tests of Gravity

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	$\lvert\eta_{\mathrm{N}}\rvert \sim 10^{-4}$	$\lvert\eta_{\mathrm{N}}\rvert \sim 10^{-4}$
Mercury perihelion shift	$\lvert\gamma - 1\rvert \approx 4 \cdot 10^{-4}$	$\lvert\gamma - 1\rvert \approx 10^{-3}$
Binary pulsars	$\omega_{\mathrm{BD}}^{\mathrm{eff}} \gtrsim 10^{6}$	$\omega_{\mathrm{BD}}^{\mathrm{eff}} \gtrsim 10^{3}$

Astrophysical signatures

Khoury and Weltman (2004)
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.

Tantalizing Hints?

Wyman & J. Khoury, astro-ph/1004.2046
Lima, Wyman & J. Khoury, in progress

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

ii) 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)

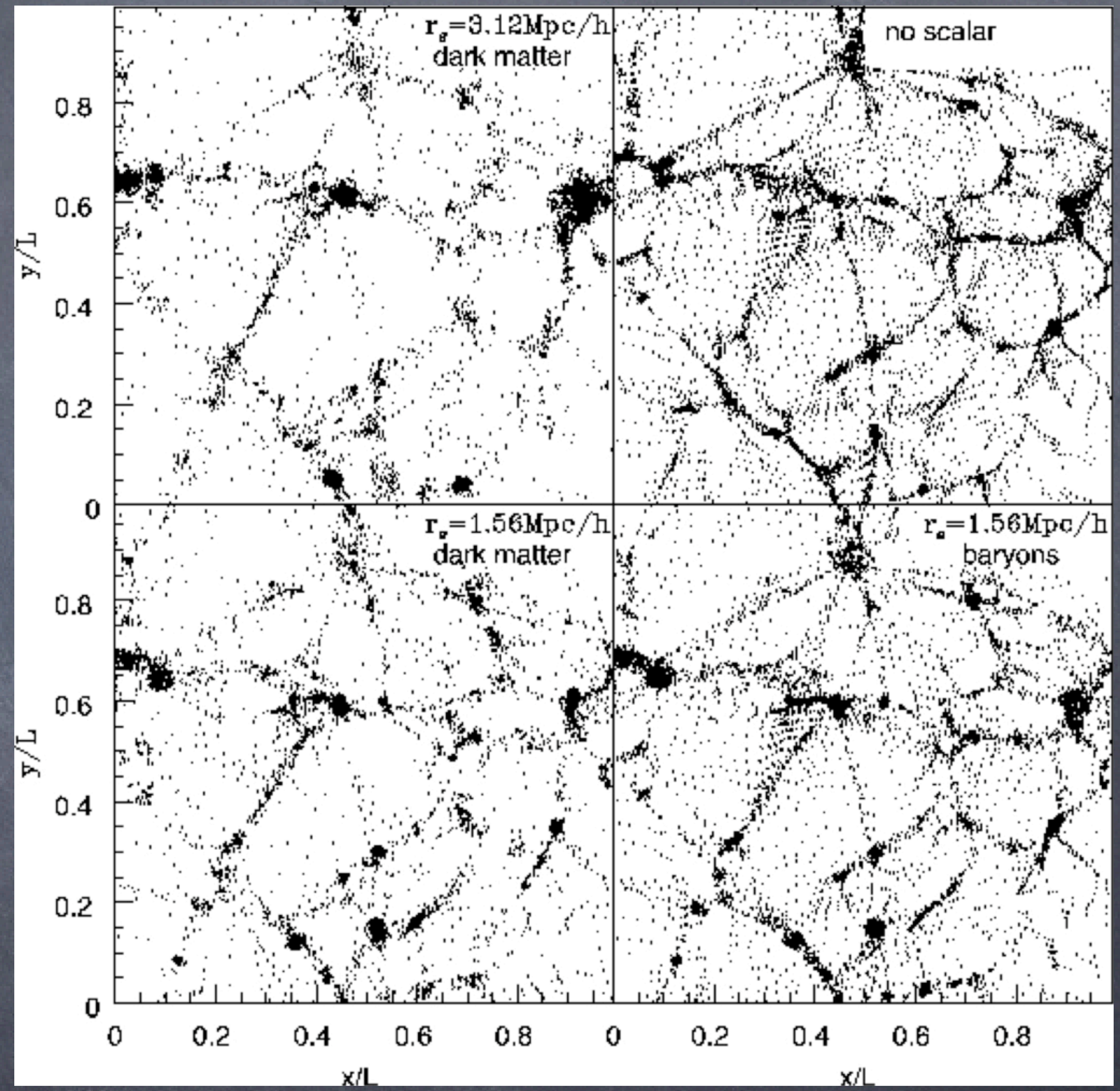
Find: 10^4 enhancement in prob.

iii) Void phenomenon

Peebles, astro-ph/0712.2757
Nusser, Gubser & Peebles, PRD (2005)

$$V(r) = -\frac{\beta G m^2}{r} e^{-r/r_s}$$

with $\beta \sim \mathcal{O}(1)\ ; \quad r_s \sim \mathrm{Mpc}$



* However, Yukawa force is tightly constrained on galactic scales:

$$\beta < 0.1$$

Kesden & Kamionkowski, PRL (2007)

(See, however, Peebles et al. (2009).)

But screening mechanism helps...

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

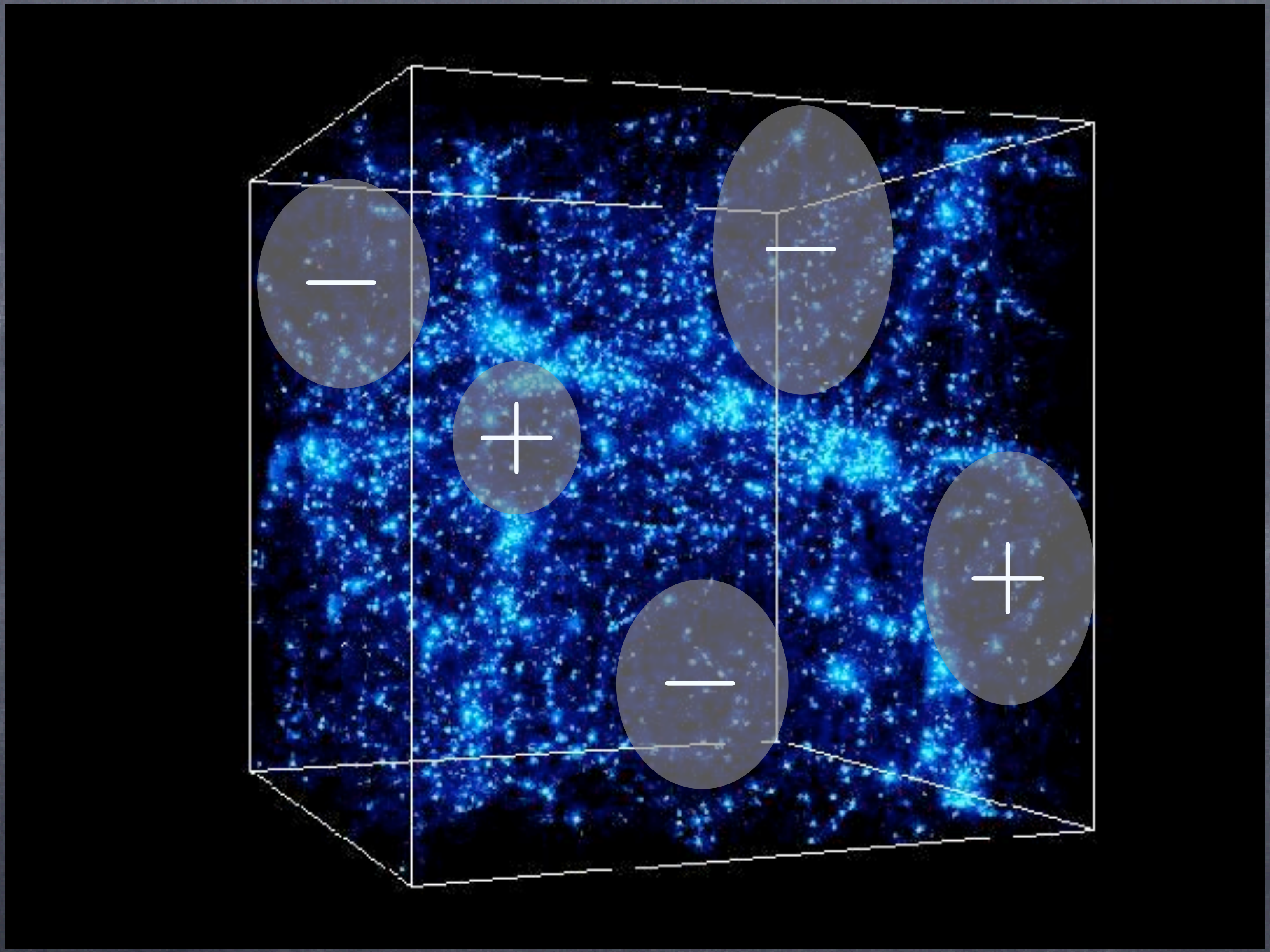
Cosmological consequences?

- Peculiar velocities, high-velocity mergers, void phenomenon
- Topological defects

1. Symmetron Defects

Hinterbichler, Hui & Khoury, in progress

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

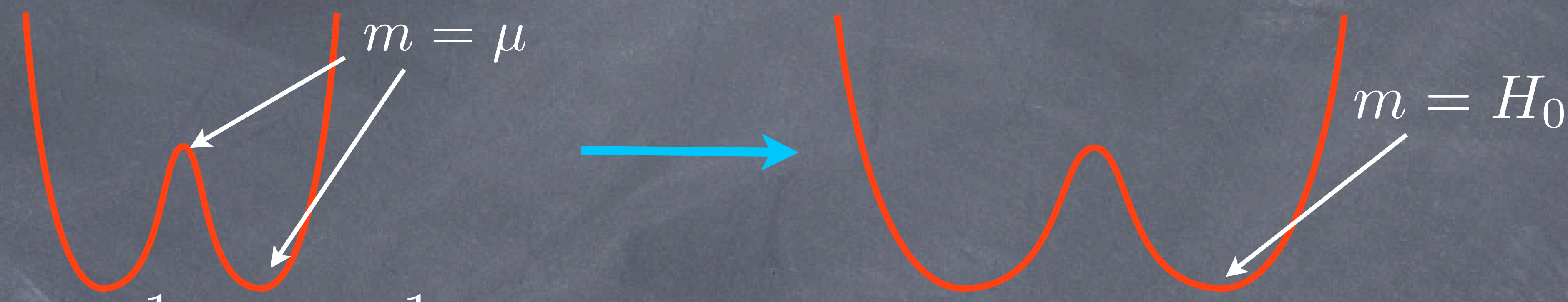


Multiple symmetrons $\Longrightarrow$ global strings, monopoles... ?

2. Cosmology

Levy, Matas, Hinterbichler, Hui & Khoury, in progress

* 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 $\Delta\phi \sim M$?

Fixing Ideas

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

- Gravitational-strength symmetron-mediated force in vacuum

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

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

$$\mu^2 \sim \frac{H_0^2 M_{\text{Pl}}^2}{M^2} \quad \Longrightarrow \quad \lambda \sim \frac{M_{\text{Pl}}^4 H_0^2}{M^6} \ll 1$$

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

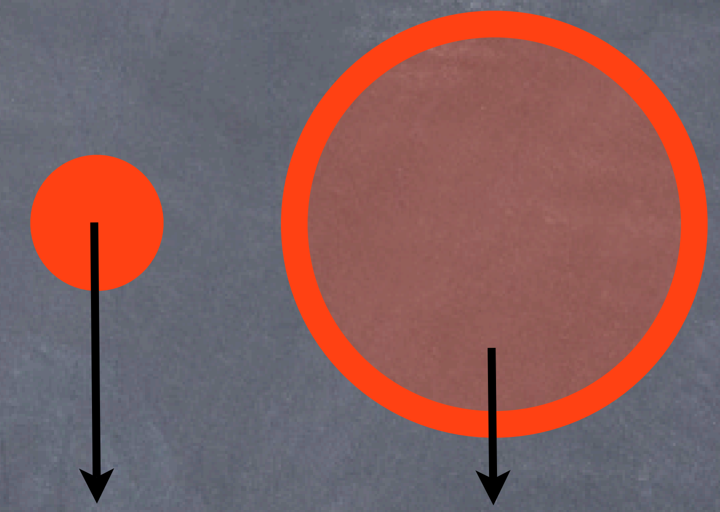
$$\Longrightarrow \quad m_0 = \sqrt{2}\mu \sim \frac{M_{\text{Pl}}}{M} H_0 \sim \text{Mpc}^{-1}$$

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

Macroscopic Violations of Equivalence Principle

Khoury & Weltman (2003); 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.

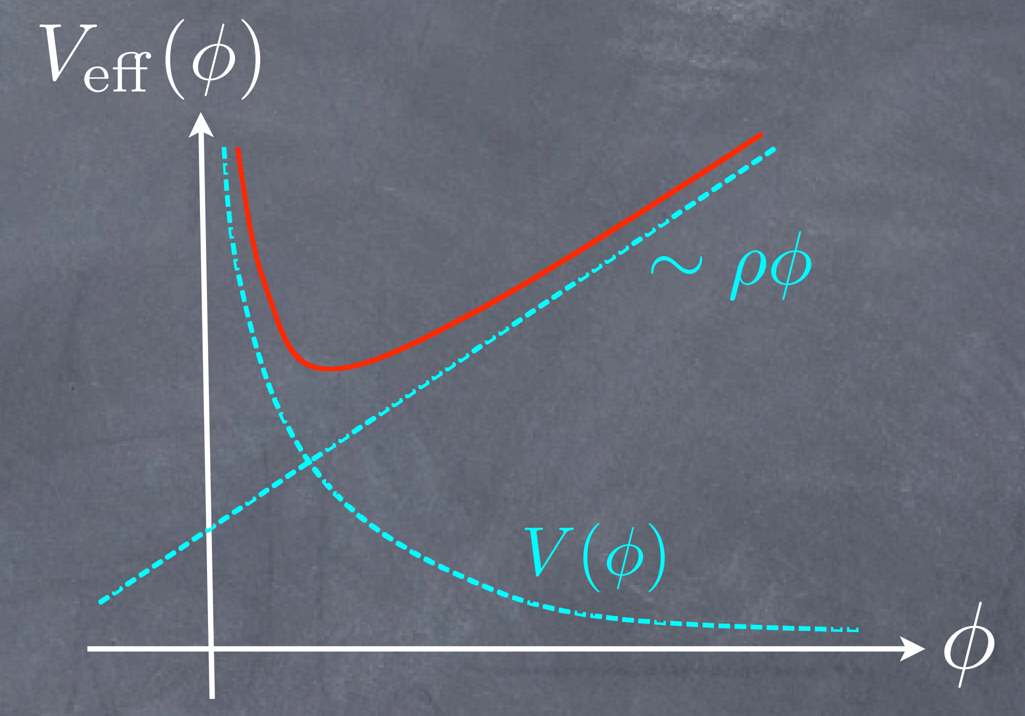
To maximize effect, look for

- 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

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)

Galileon

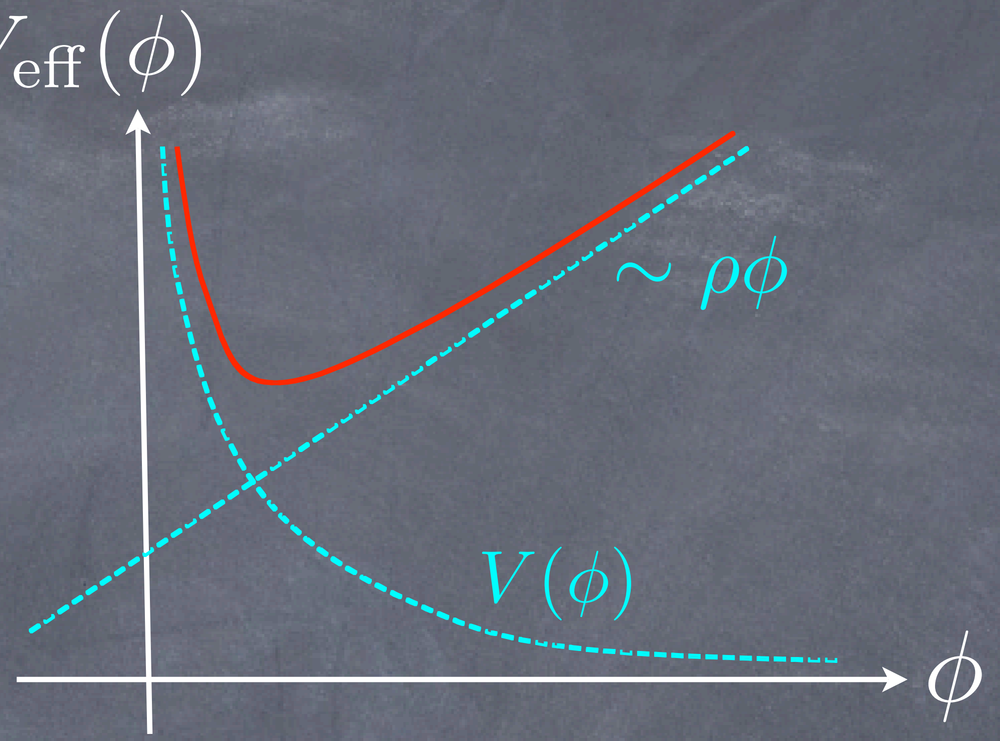
$$3\nabla^2\pi + \frac{1}{\Lambda_{\rm s}^3}\left[(\nabla^2\pi)^2 - (\partial_\mu\partial_\nu\pi)^2\right] = \frac{\rho}{2M_{\rm Pl}}$$

- 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)

Strong coupling?

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



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

Relation to f(R) gravity

Carroll, Duvvuri, Trodden & Turner (2004);
Capozziello, Carloni & Troisi (2004)

$$S = \frac{M_{\rm Pl}^2}{2}\int {\rm d}^4x\sqrt{-\tilde{g}}f(\tilde{R}) + S_{\rm matter}[\tilde{g}_{\mu\nu}]$$

Special case of chameleon theories:

$$S = \frac{M_{\rm Pl}^2}{2}\int {\rm d}^4x\sqrt{-\tilde{g}}\left\{f(\psi) + \frac{{\rm d}f}{{\rm d}\psi}(\tilde{R}-\psi)\right\} + S_{\rm matter}[\tilde{g}_{\mu\nu}]$$

Varying wrt to ψ $\Longrightarrow$ $\psi = \tilde{R}$

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$$\Longrightarrow S = \int {\rm d}^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm matter}\left[g_{\mu\nu}e^{\sqrt{2/3}\phi/M_{\rm Pl}}\right]$$

where $V = \frac{M_{\rm Pl}^2\left(\psi\frac{{\rm d}f}{{\rm d}\psi} - f\right)}{2\left(\frac{{\rm d}f}{{\rm d}\psi}\right)^2}$.

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