Center for Particle Cosmology at the University of Pennsylvania

Screening Dark Energy

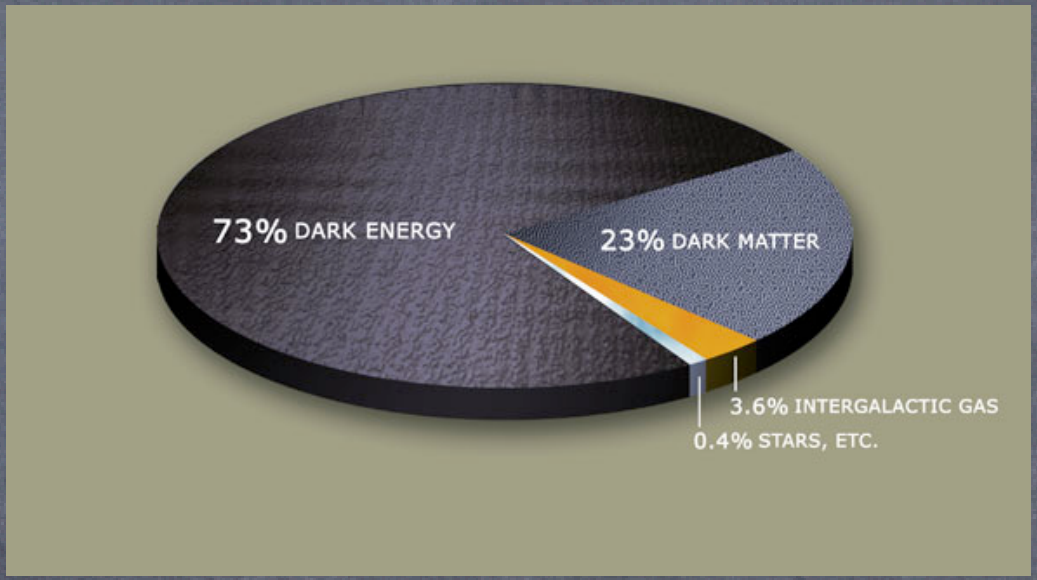
Justin Khoury (UPenn)

K. Hinterbichler & J. Khoury, Phys. Rev. Lett. 104, 231301 (2010)

B. Jain & J. Khoury, Annals Phys. 325, 1479 (2010)

A. Levy, A. Matas, K. Hinterbichler and J. Khoury, in progress

The Era of Precision Uncertainty



$$\Omega_b h^2 = 0.02260 \pm 0.053\,; \qquad \Omega_c h^2 = 0.1123 \pm 0.0035\,;$$
$$\Omega_\Lambda = 0.728 \pm 0.016 \qquad n_s = 0.963 \pm 0.012\,;$$
$$\tau = 0.087 \pm 0.014\,; \qquad \Delta^2_{\mathcal{R}} = (2.441 \pm 0.090) \times 10^{-9}$$

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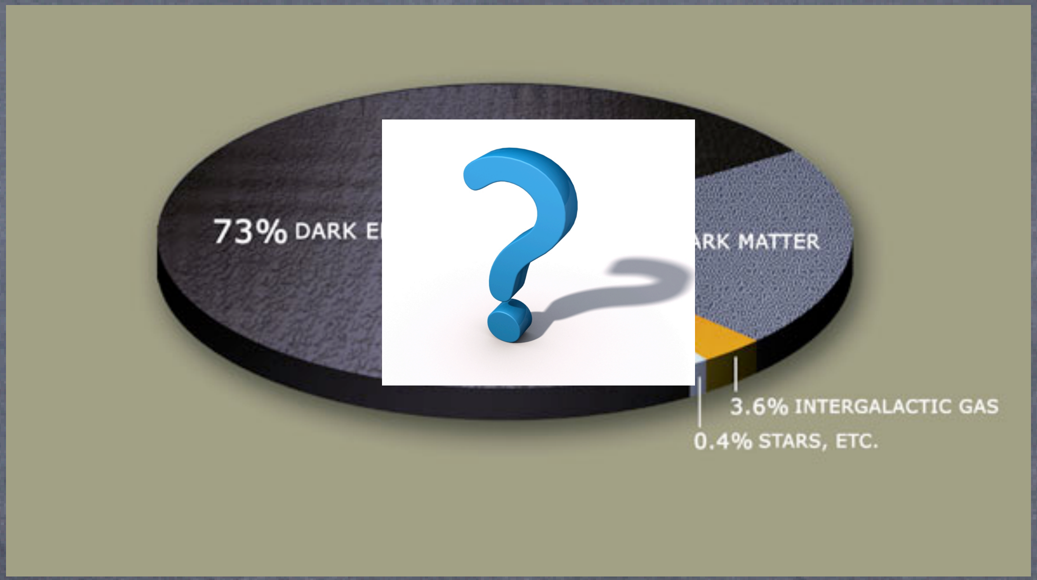

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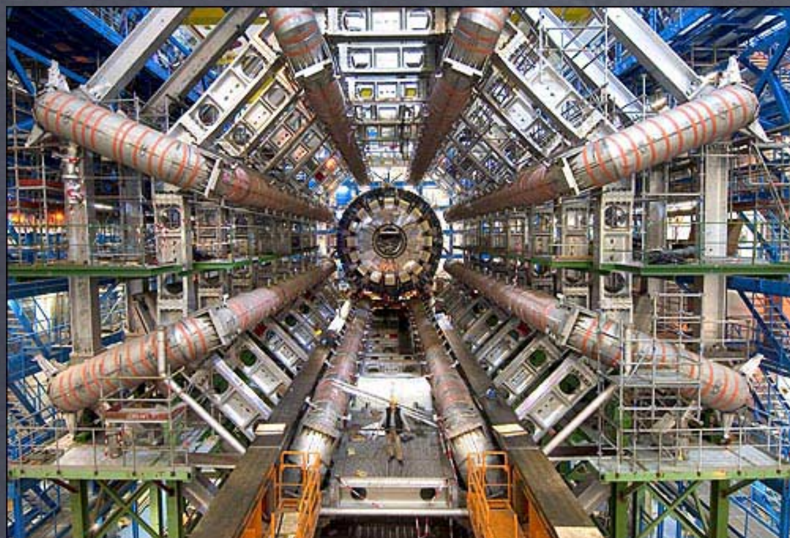

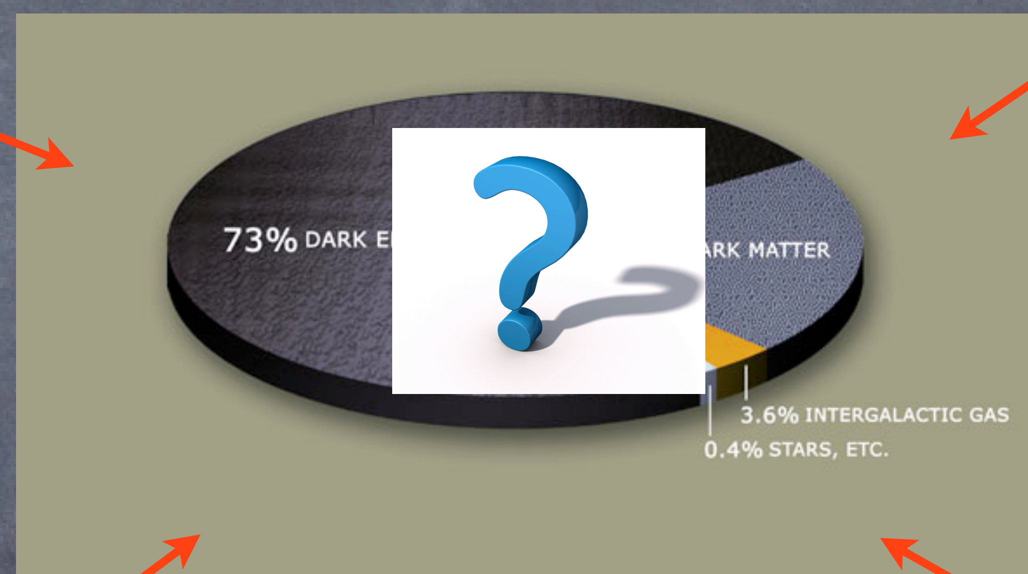

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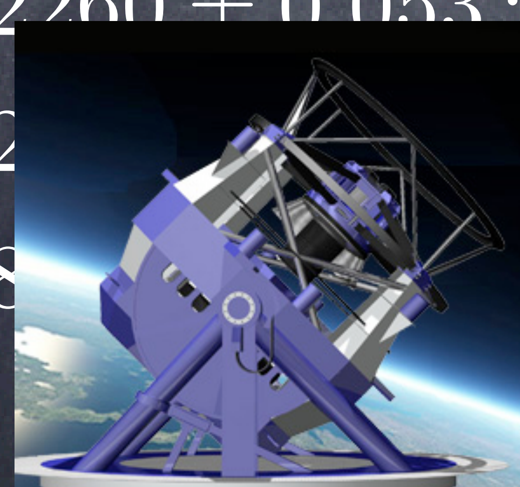

The end of cosmology?

30 Oct 1998

IS COSMOLOGY SOLVED?
An Astrophysical Cosmologist's Viewpoint

P. J. E. Peebles
Joseph Henry Laboratories, Princeton University,
and Princeton Institute for Advanced Study

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

Said differently...

...will convergence to ΛCDM continue?

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Or are we in for a BIG surprise?

Cosmologist

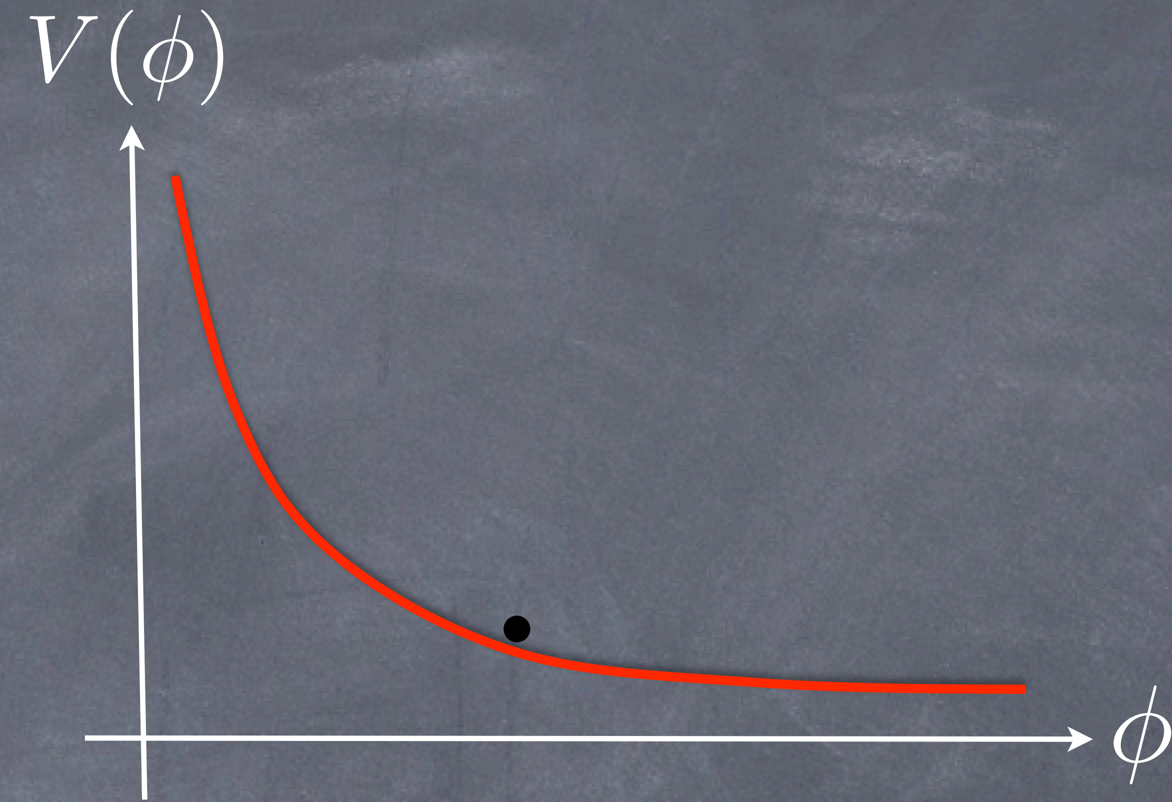
Mother Nature

A Richer Dark Sector

- Dark energy candidates:

Λ , quintessence...

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



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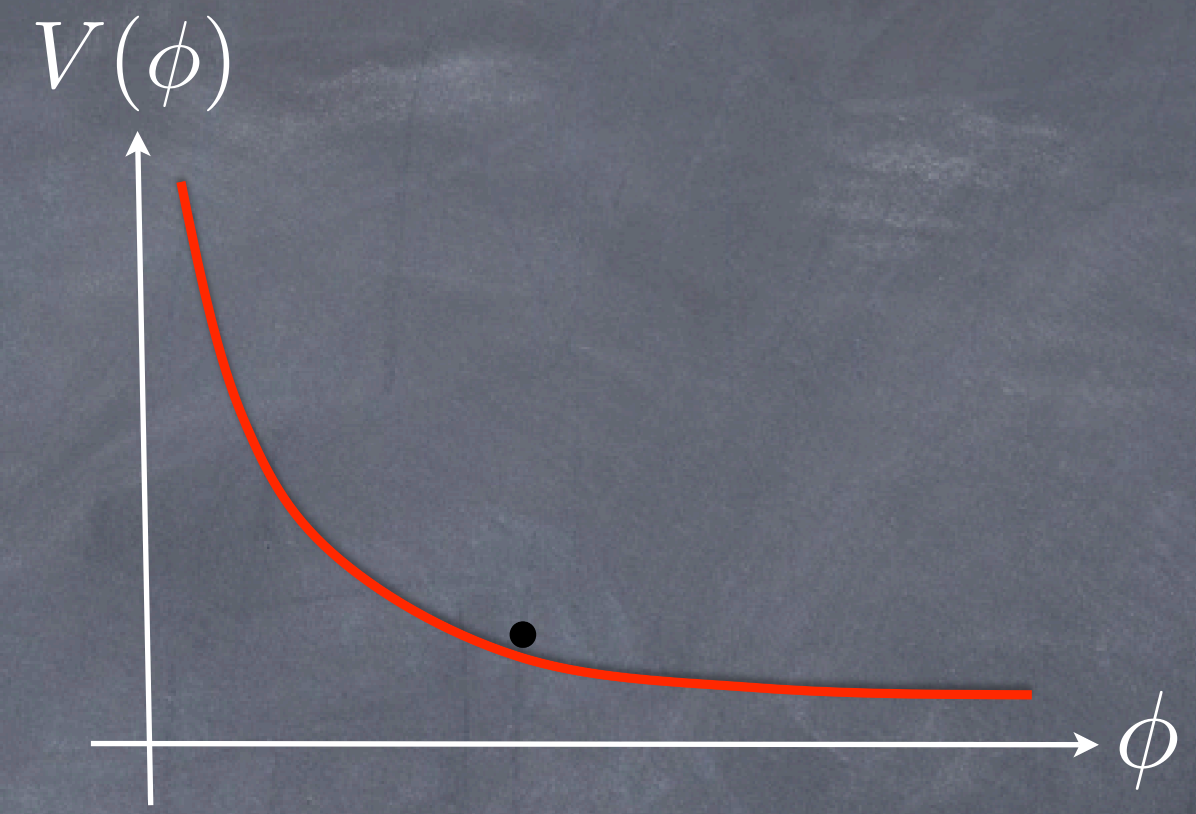

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  $\Longrightarrow$ ruled out?

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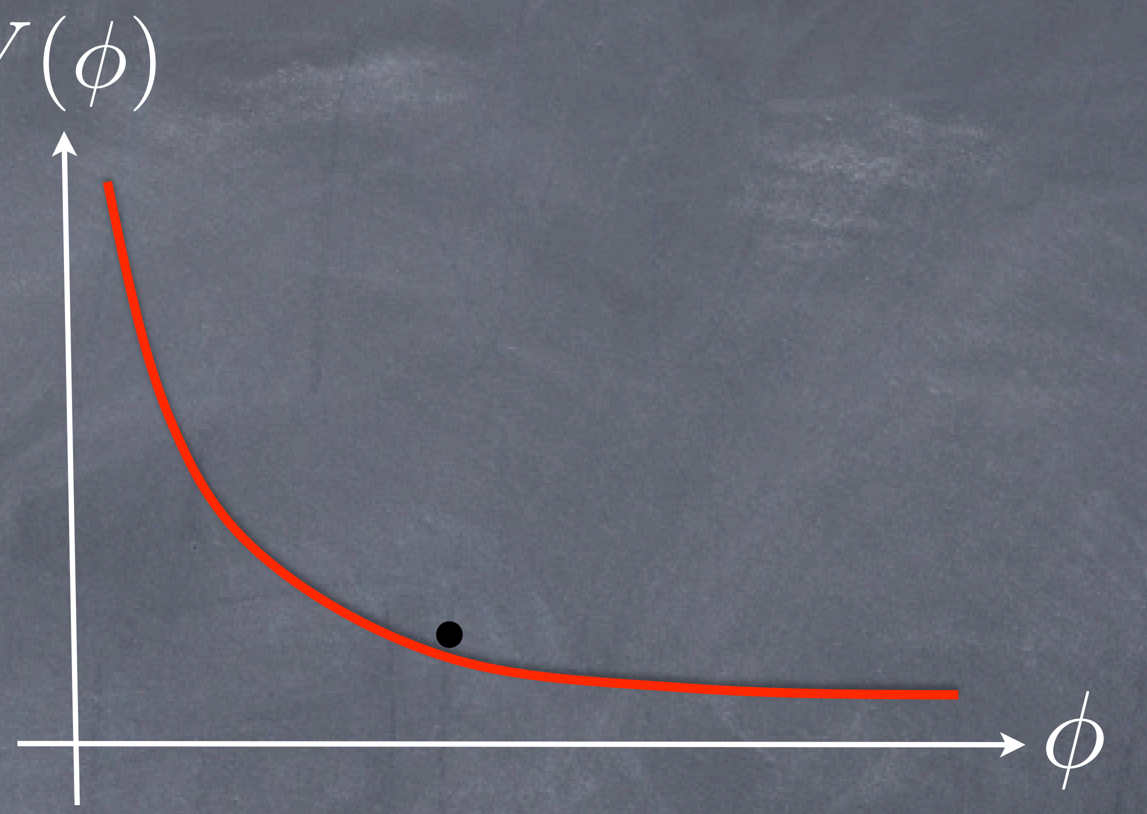

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$$\Longrightarrow \quad \text{ruled out?}$$

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

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

New Scale = New Physics?

$$\Lambda$$

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

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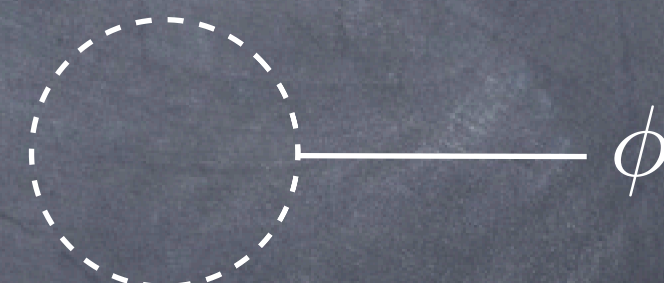

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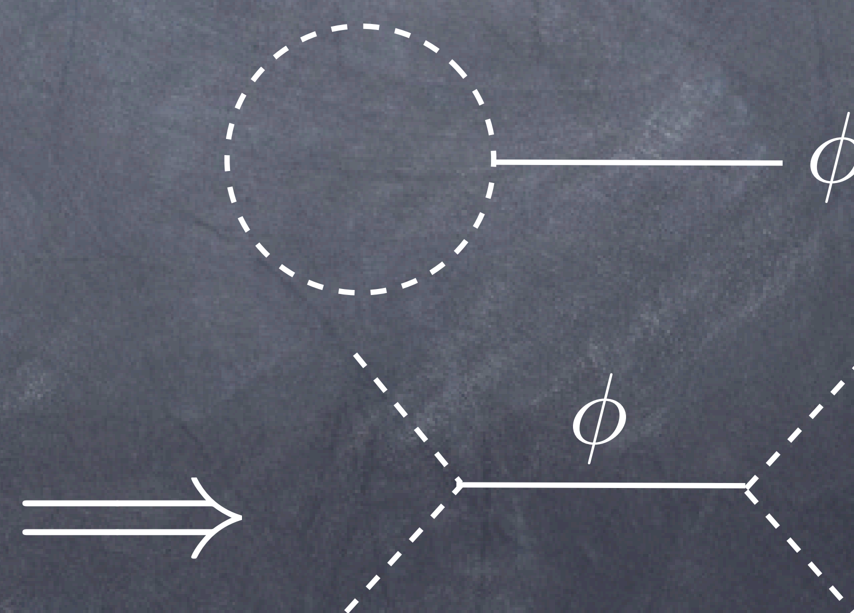

5th force

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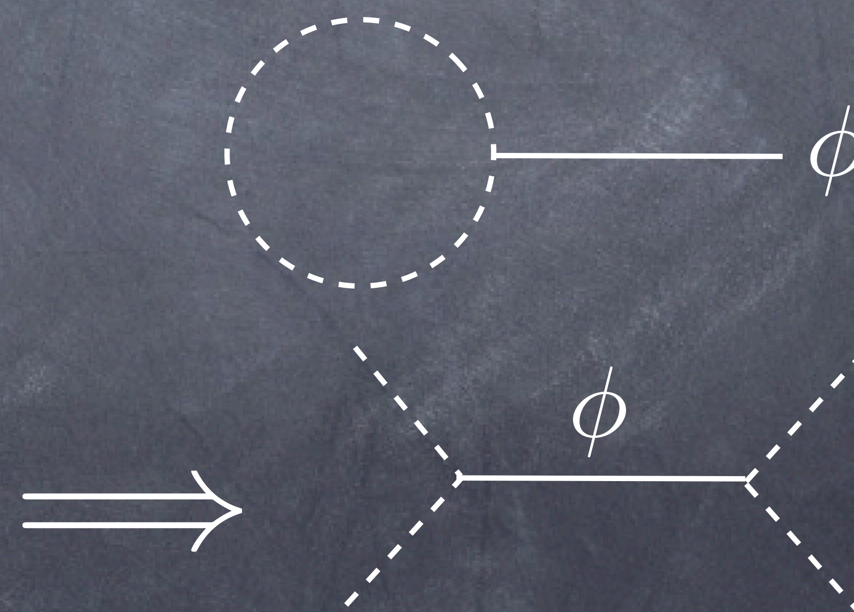
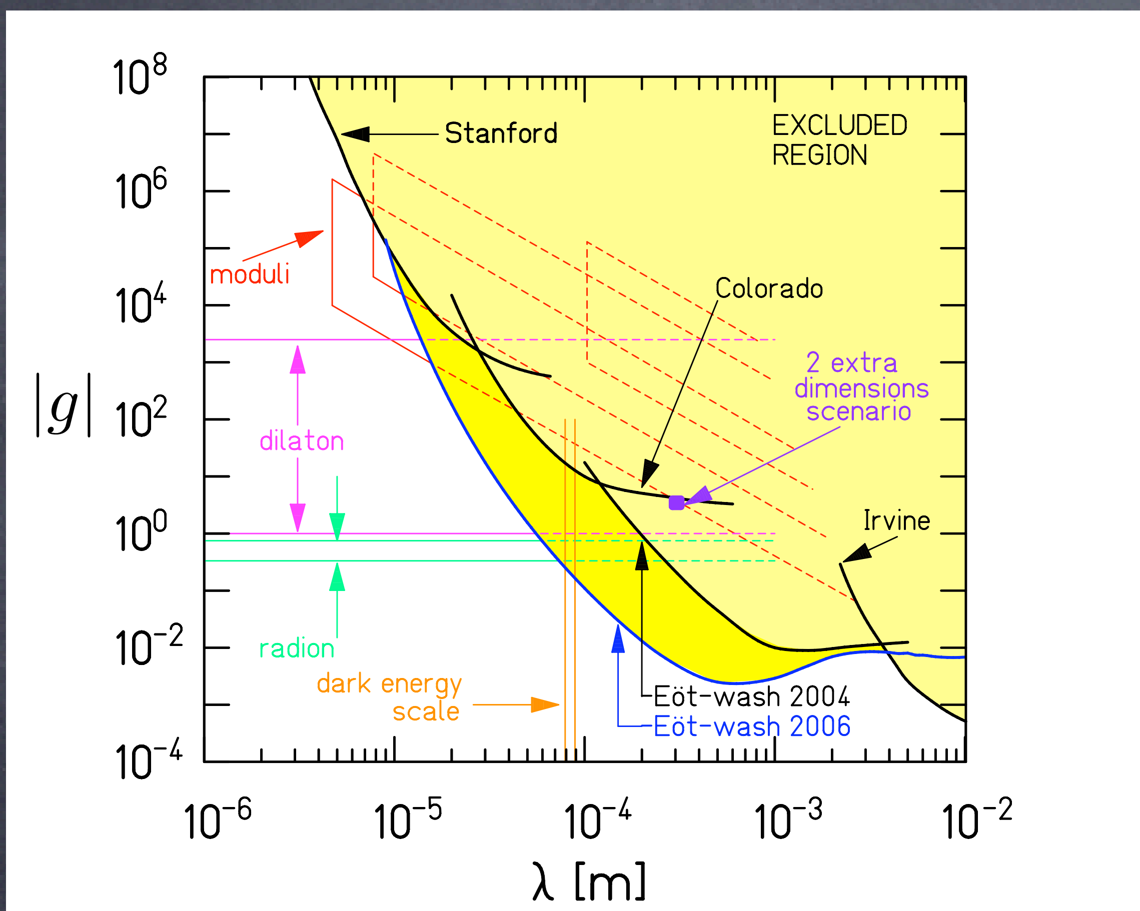


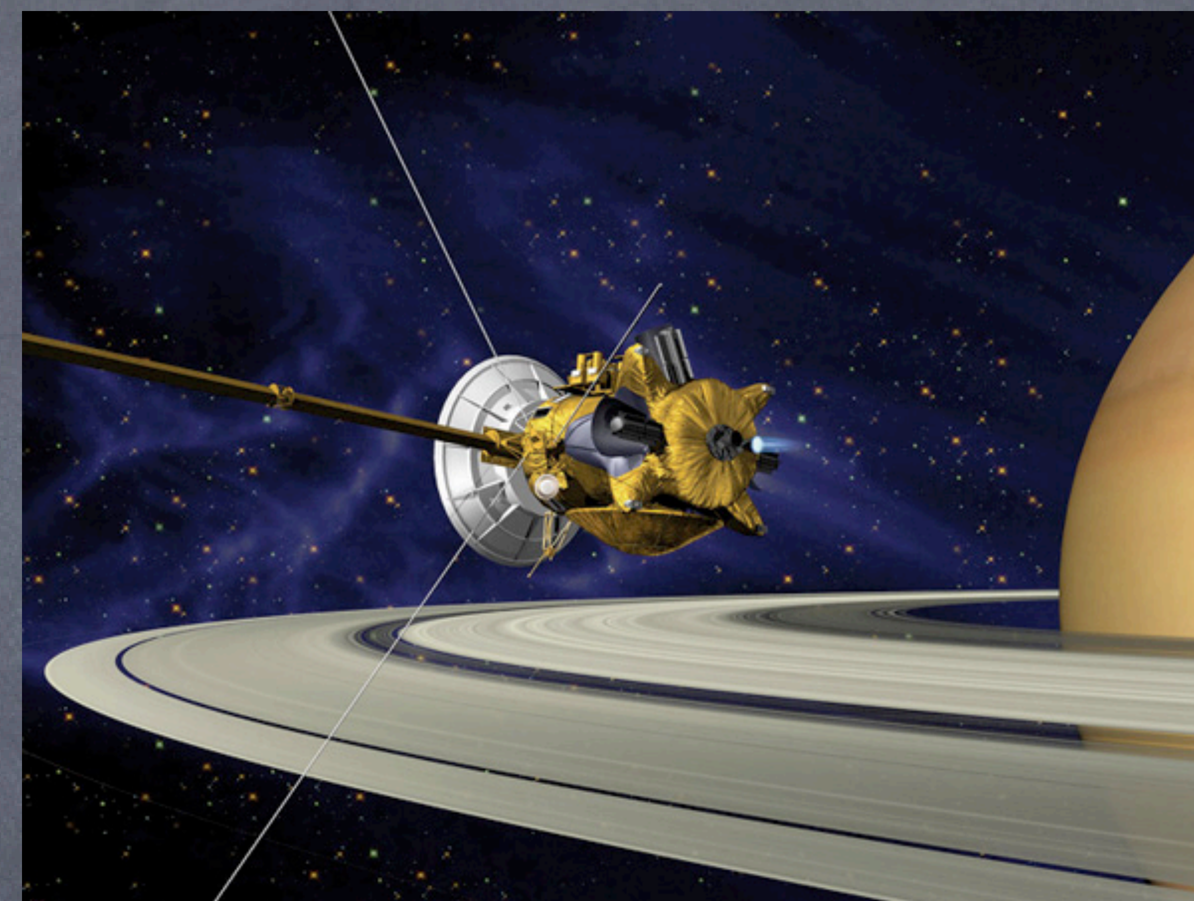
5th force

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

Experimental Program

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





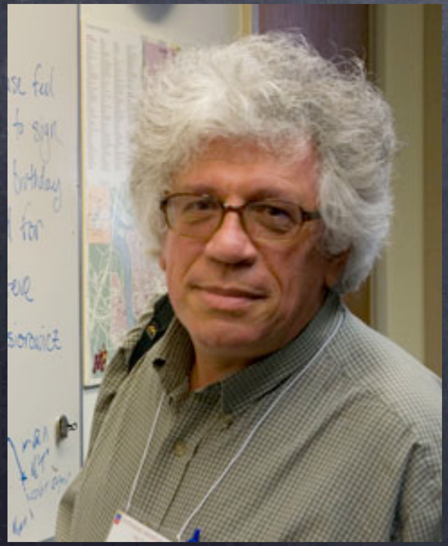
Screening mechanisms invariably lead to small but potentially measurable effects in the solar system and/or in the lab

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

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

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

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



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

symmetron

Chameleon Mechanism

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

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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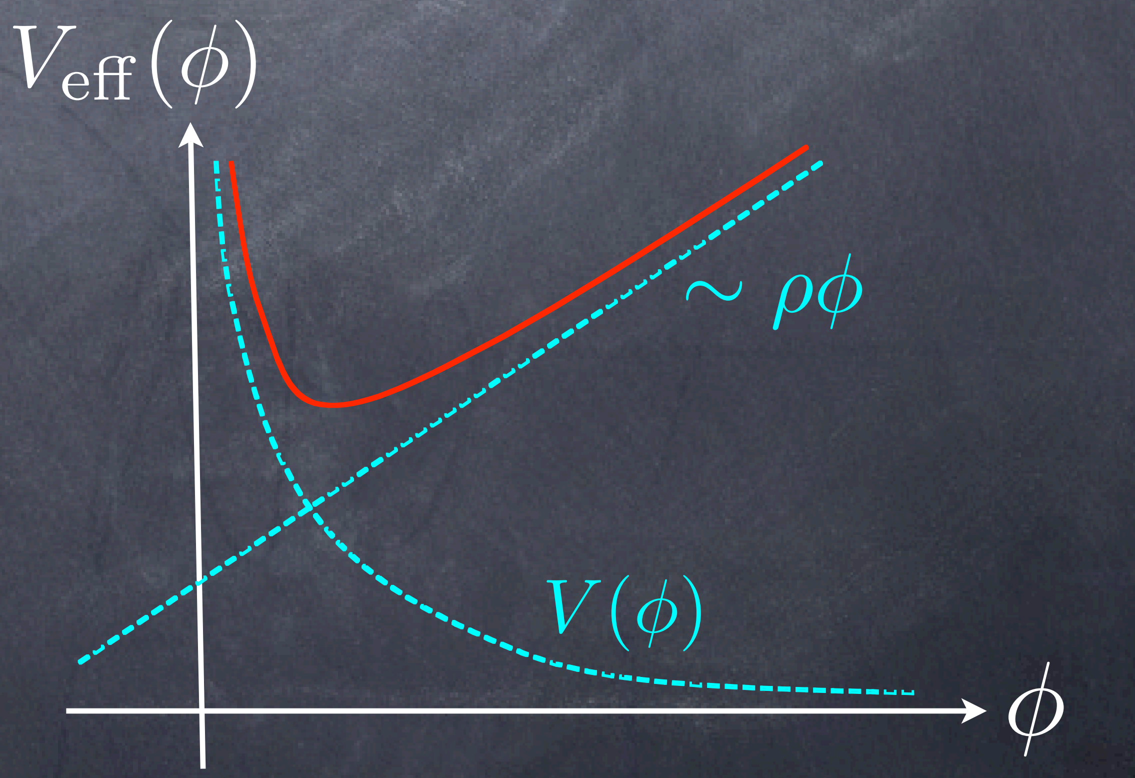
where T^μ_μ is stress tensor of all matter (Baryonic and Dark)

For non-relativistic matter, $T^\mu_\mu \approx -\rho$, hence

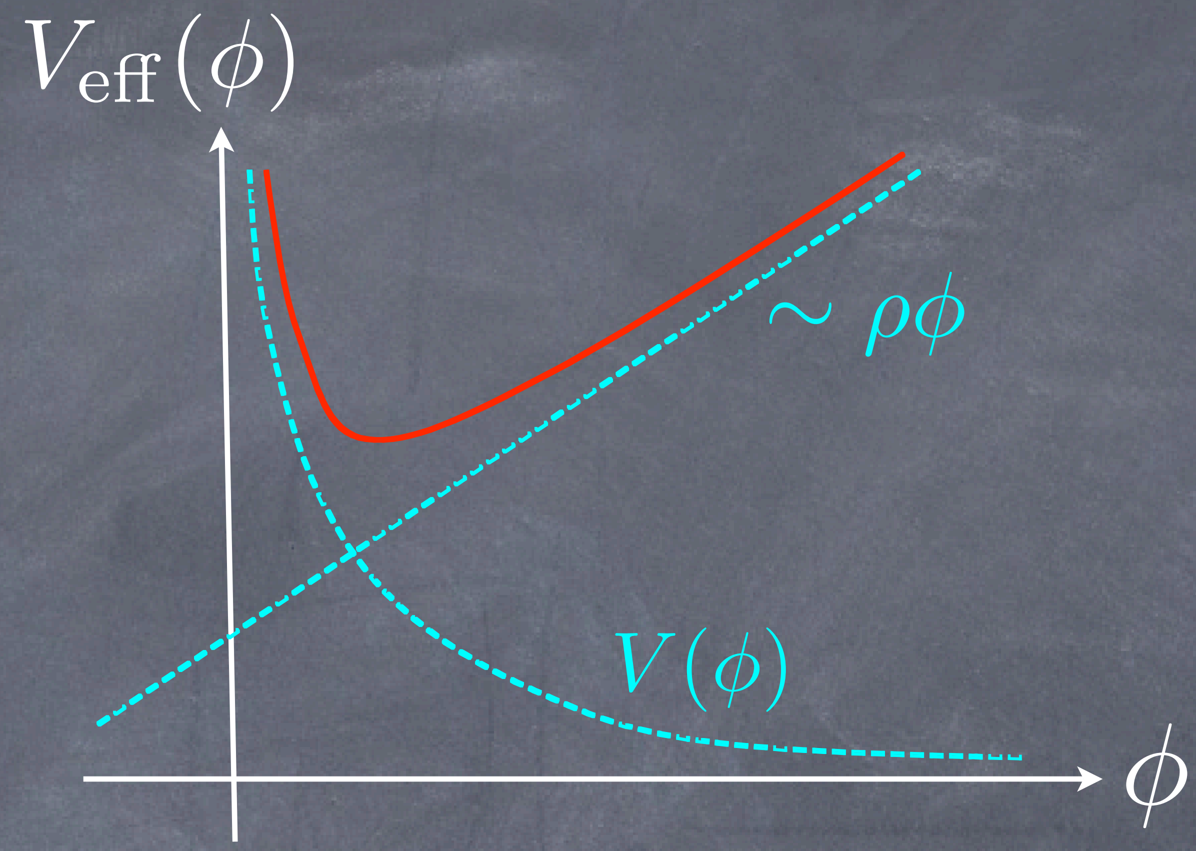
$$\nabla^2\phi = V_{,\phi} + \frac{g}{M_{\rm Pl}}\rho$$

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



Density-dependent mass

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



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

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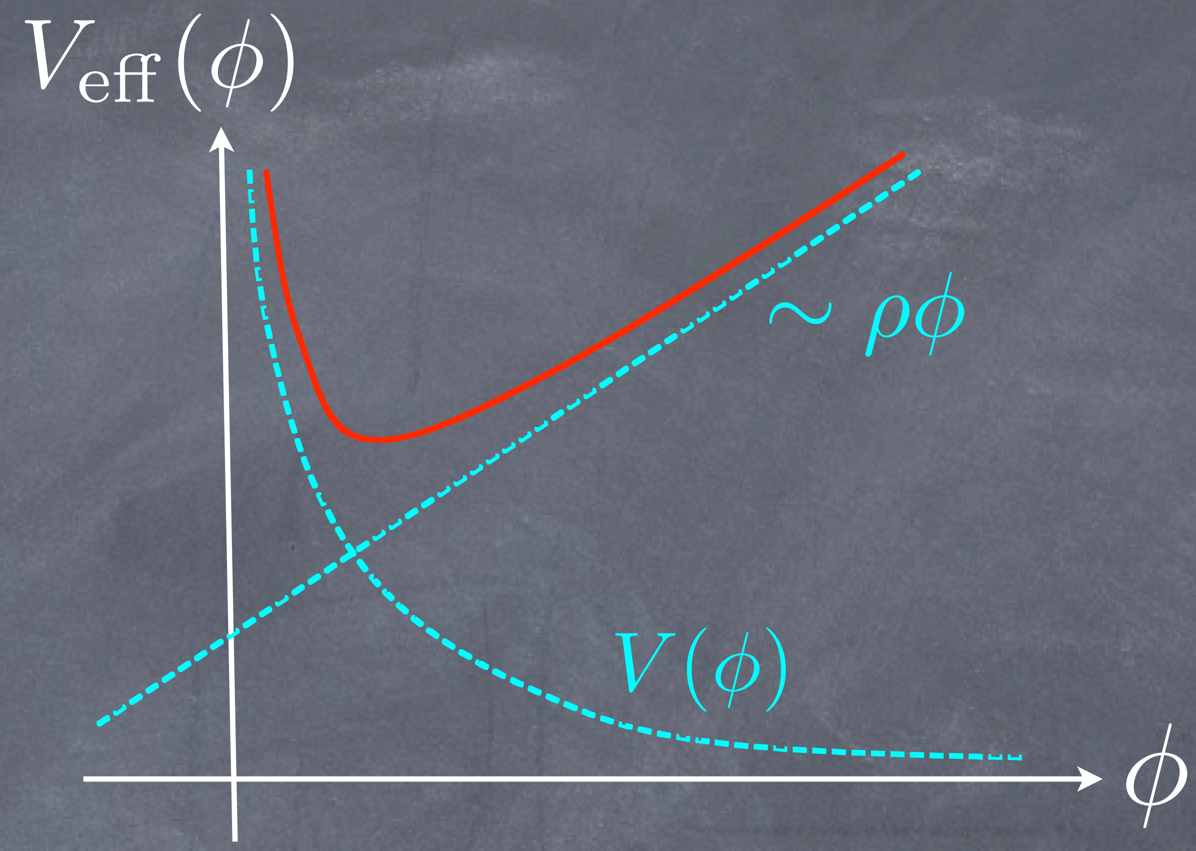

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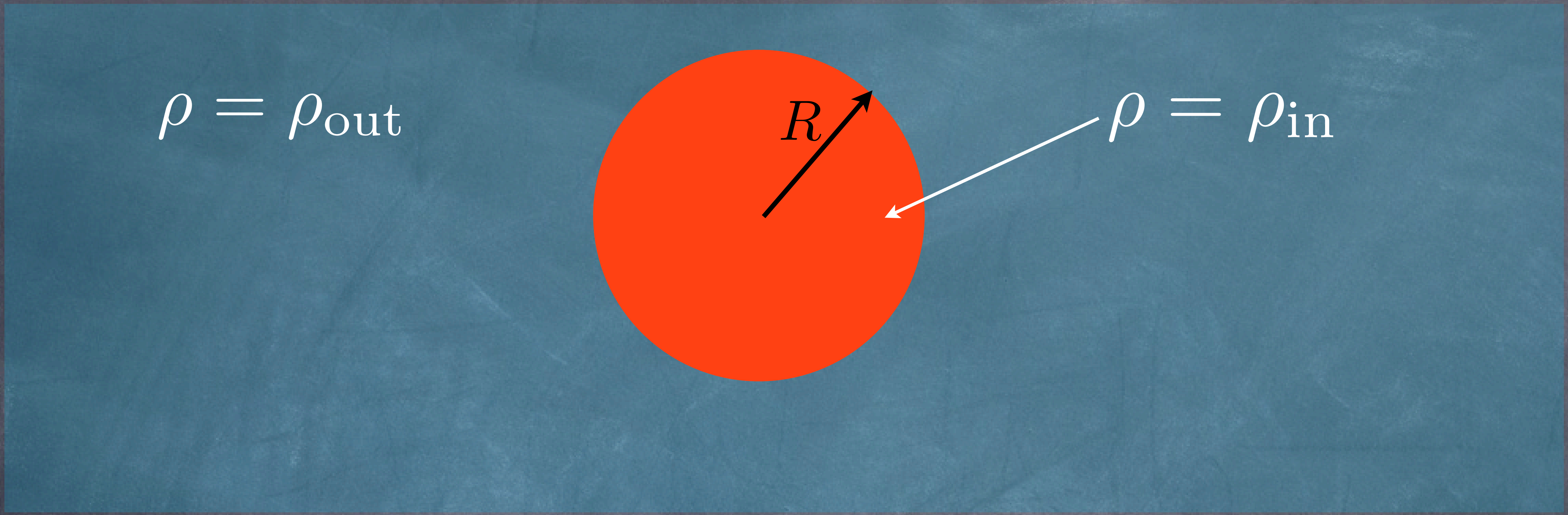
Laboratory tests => set $m^{-1}(\rho_{\rm local}) \lesssim {\rm mm}$

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

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

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

Thin-shell screening



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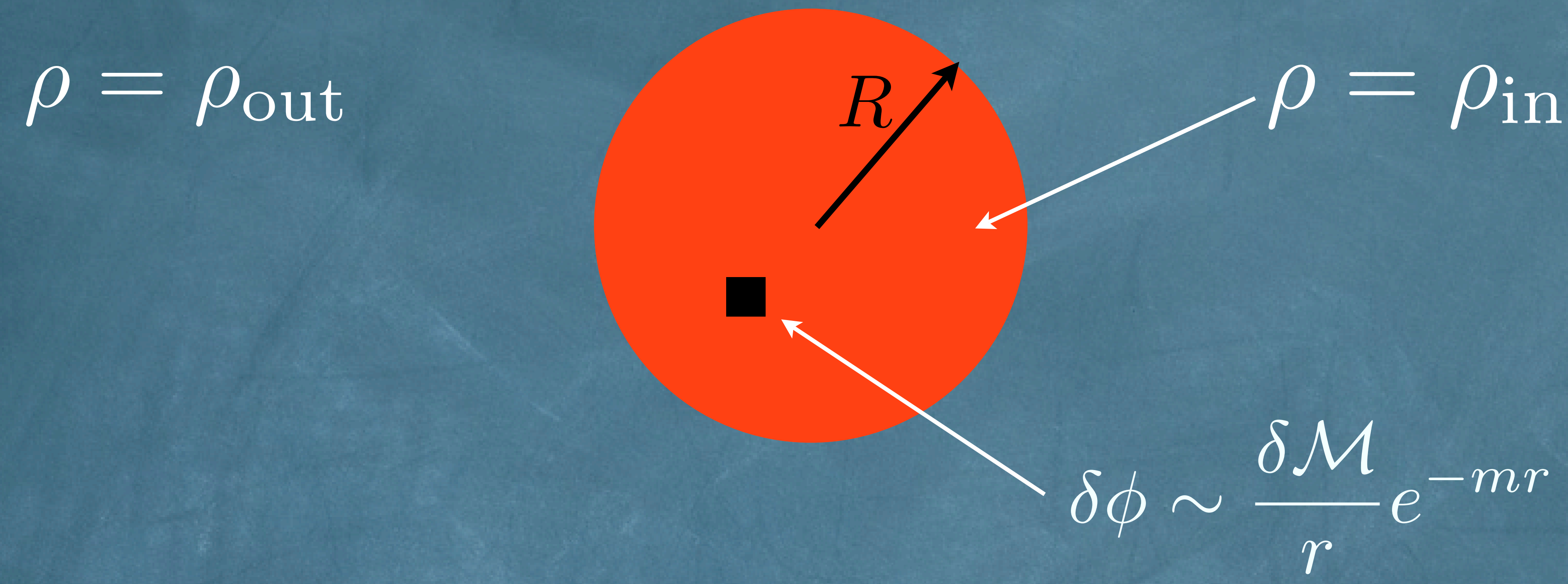

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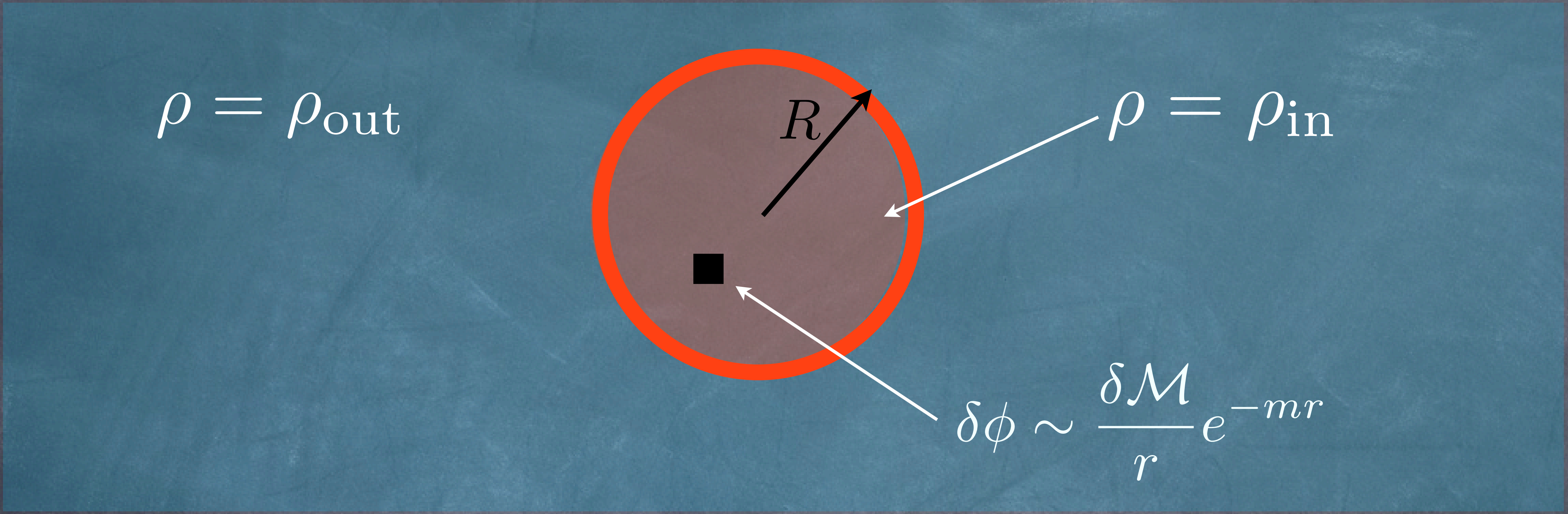

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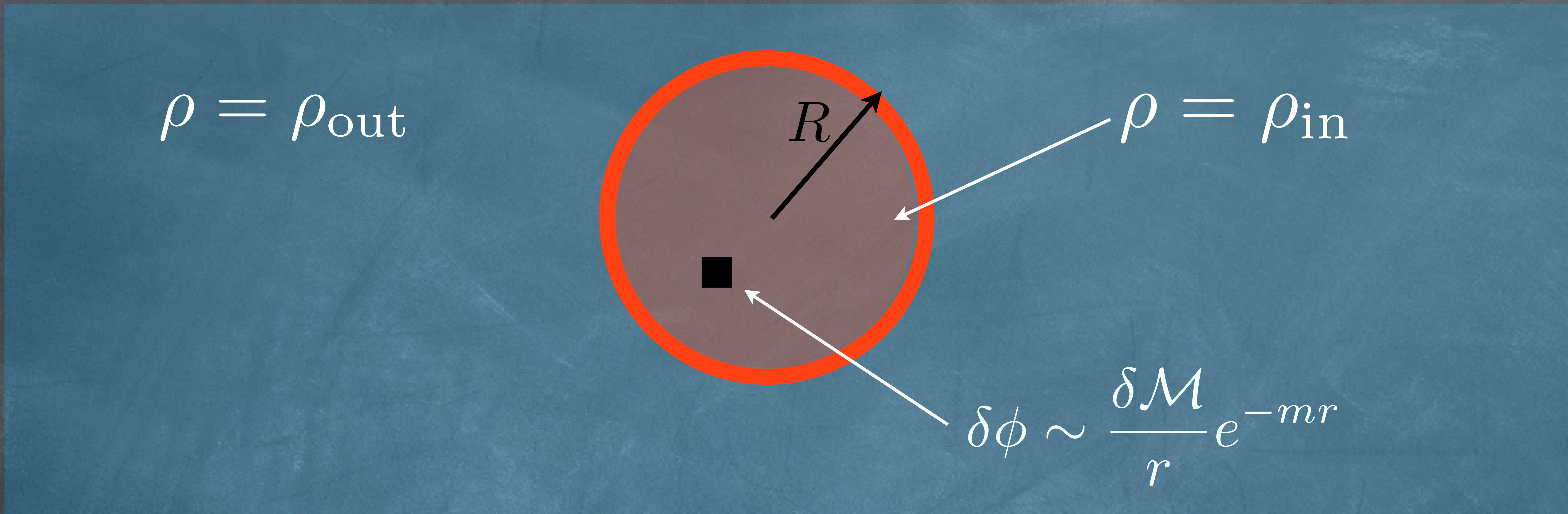

$$\Longrightarrow \quad \boxed{\phi(r > R) \sim \frac{\Delta R}{R} \times \frac{g\, G_{\rm N} M}{r}}$$

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

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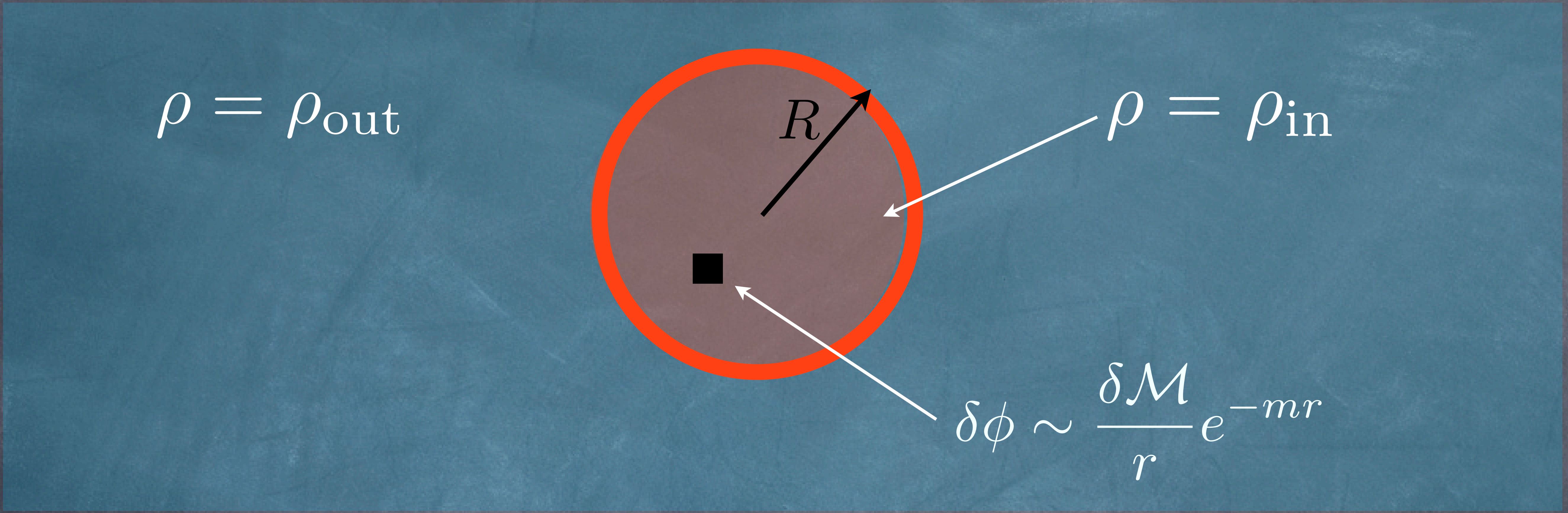

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But small objects $\Longrightarrow$ no thin-shell

Thin-shell condition depends on environment!

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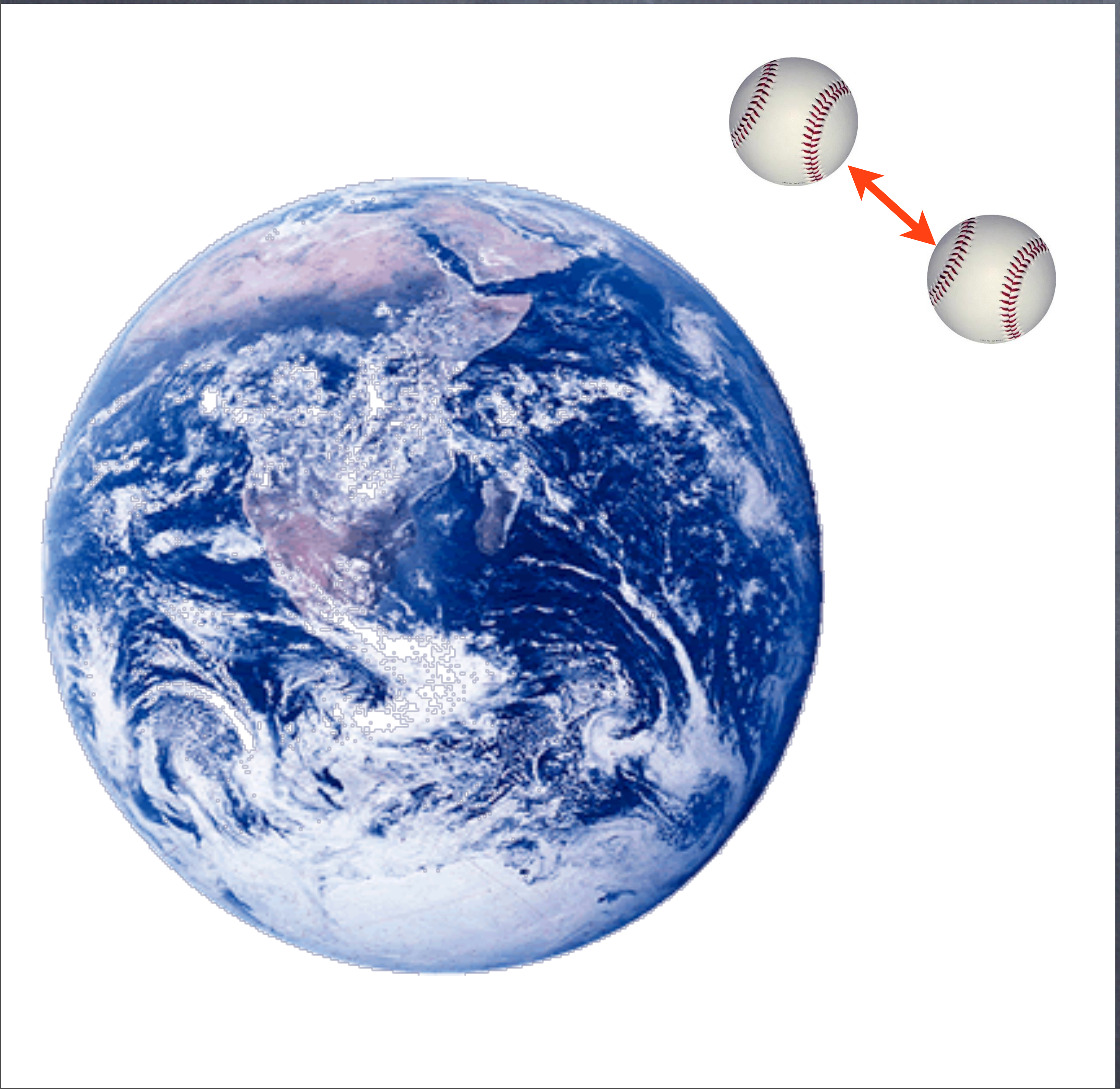

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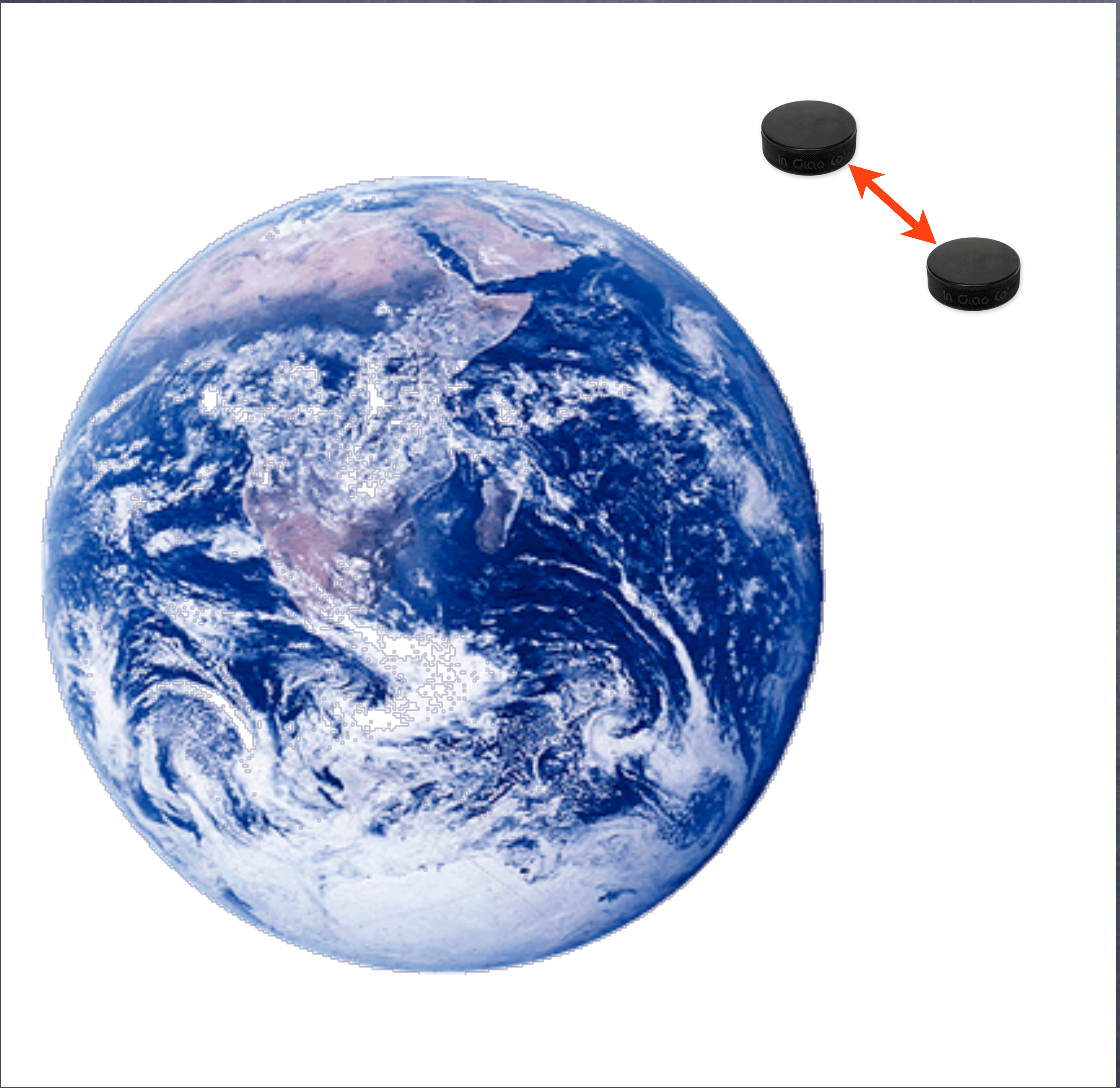

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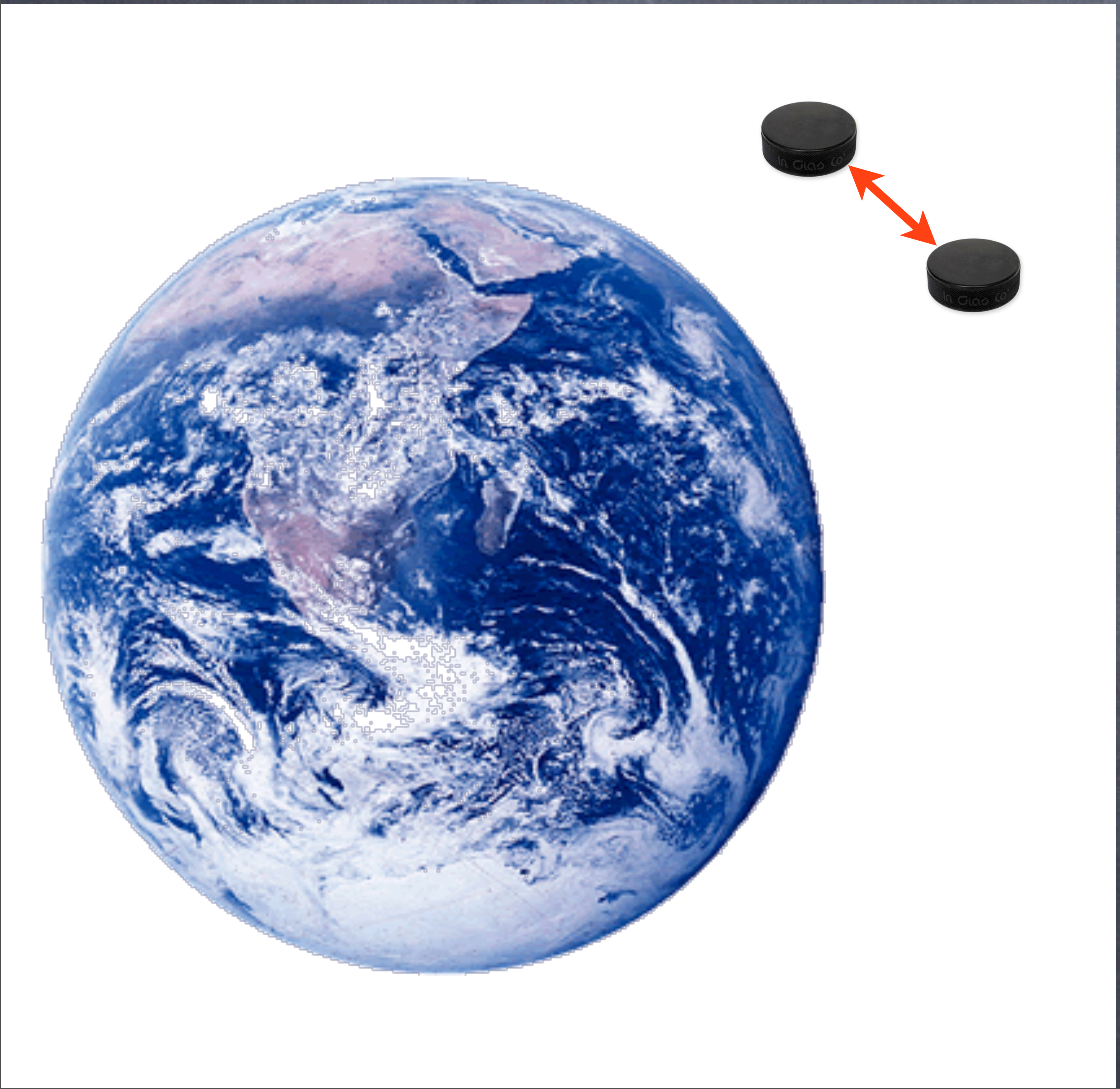

$$G_{\rm N}^{\rm eff} = G_{\rm N}(1+2g^2)$$

between small objects in space !

Smoking Guns

- Satellite Test of the Equivalence Principle (STEP)

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

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

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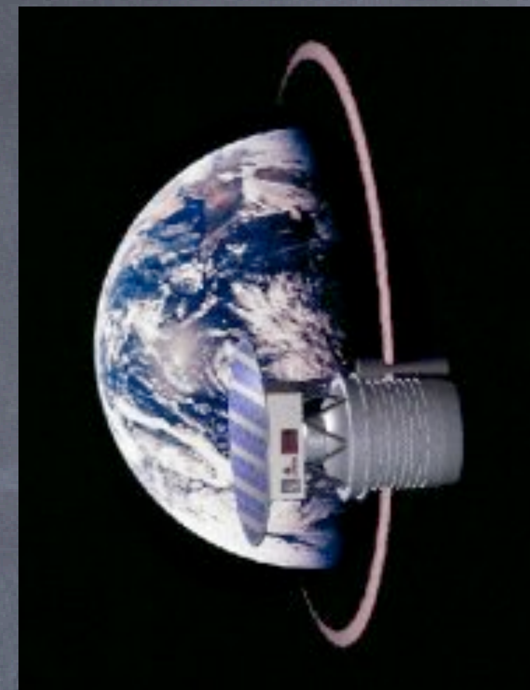
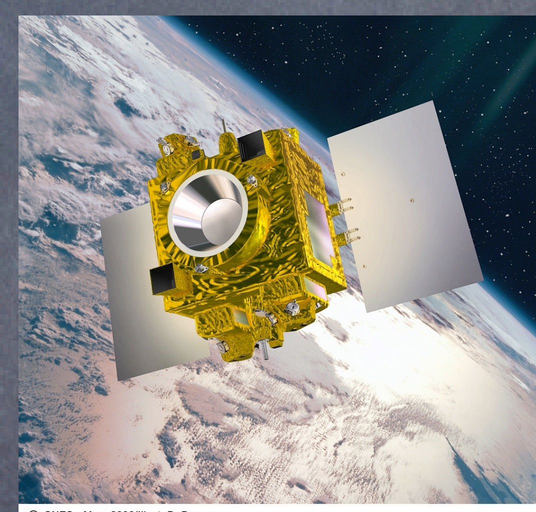
$$\frac{\Delta a}{a} < 10^{-18}$$



- MICROSCOPE (2012)

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



- Galileo Galilei (???)

$$\frac{\Delta a}{a} < 10^{-17}$$

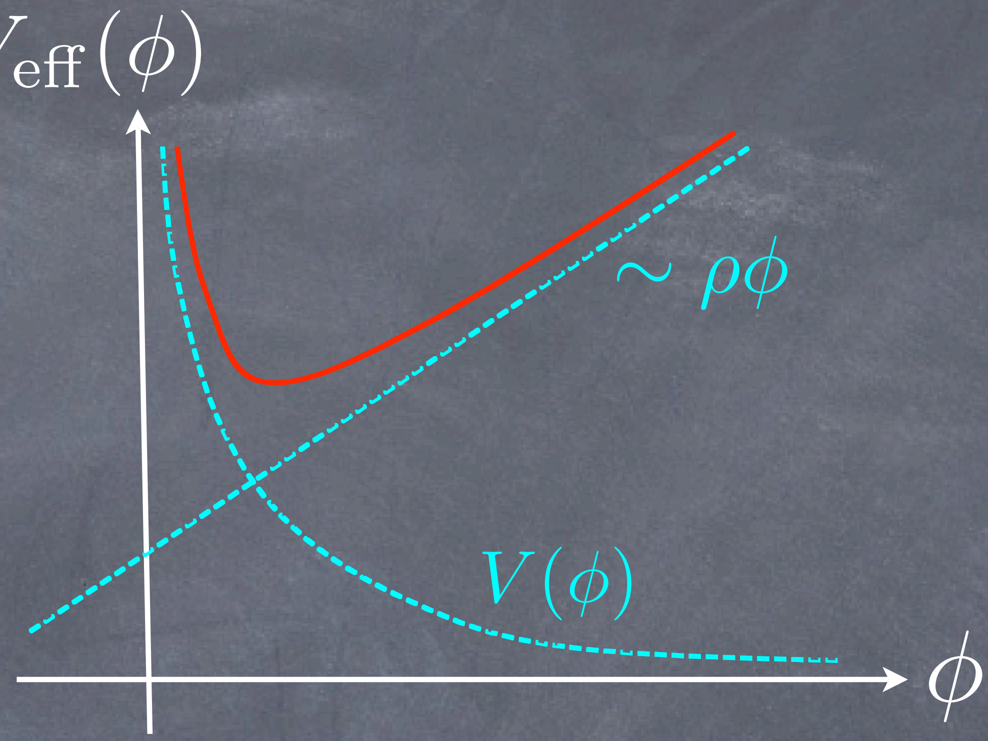
$$\frac{\Delta G_{\rm N}}{G_{\rm N}} \sim \mathcal{O}(1)$$

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

Strong coupling?

J. Khoury, A. Upadhye & W. Hu, to appear

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



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

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:

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

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Field redefinitions: $g_{\mu\nu} = \frac{{\rm d}f}{{\rm d}\psi}\tilde{g}_{\mu\nu}$; $\phi = -\sqrt{\frac{3}{2}}M_{\rm Pl}\log\frac{{\rm d}f}{{\rm d}\psi}$

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

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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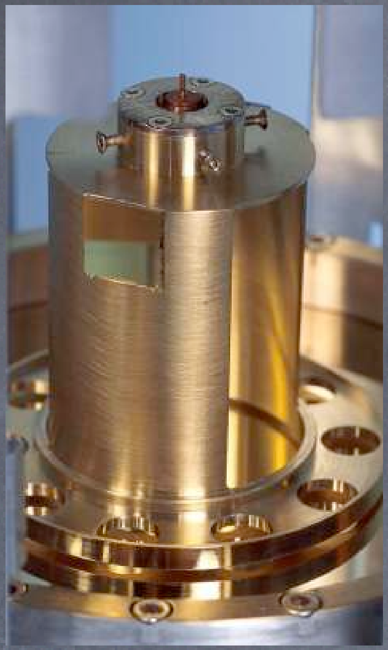
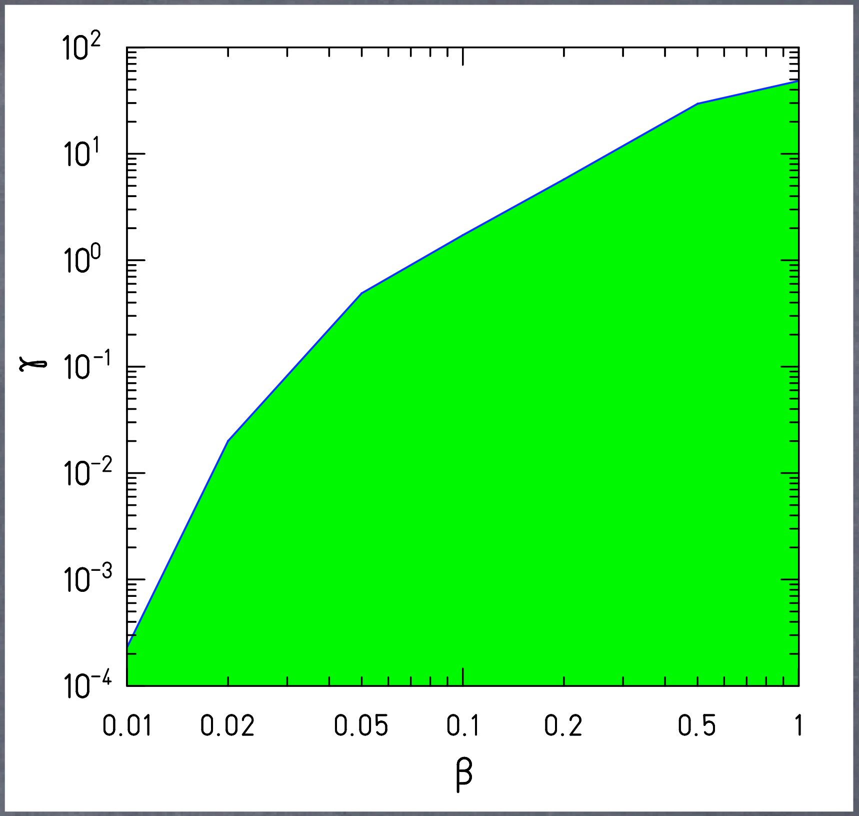
Chameleon Searches

- Eot-Wash

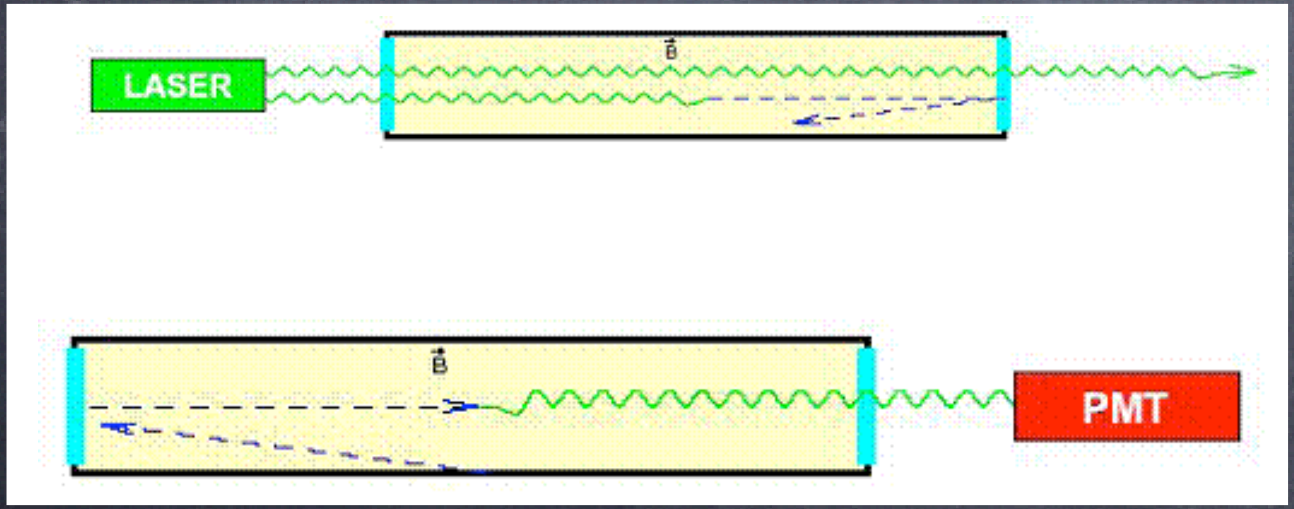
  Adelberger et al.,
  Phys. Rev. Lett. (2008)

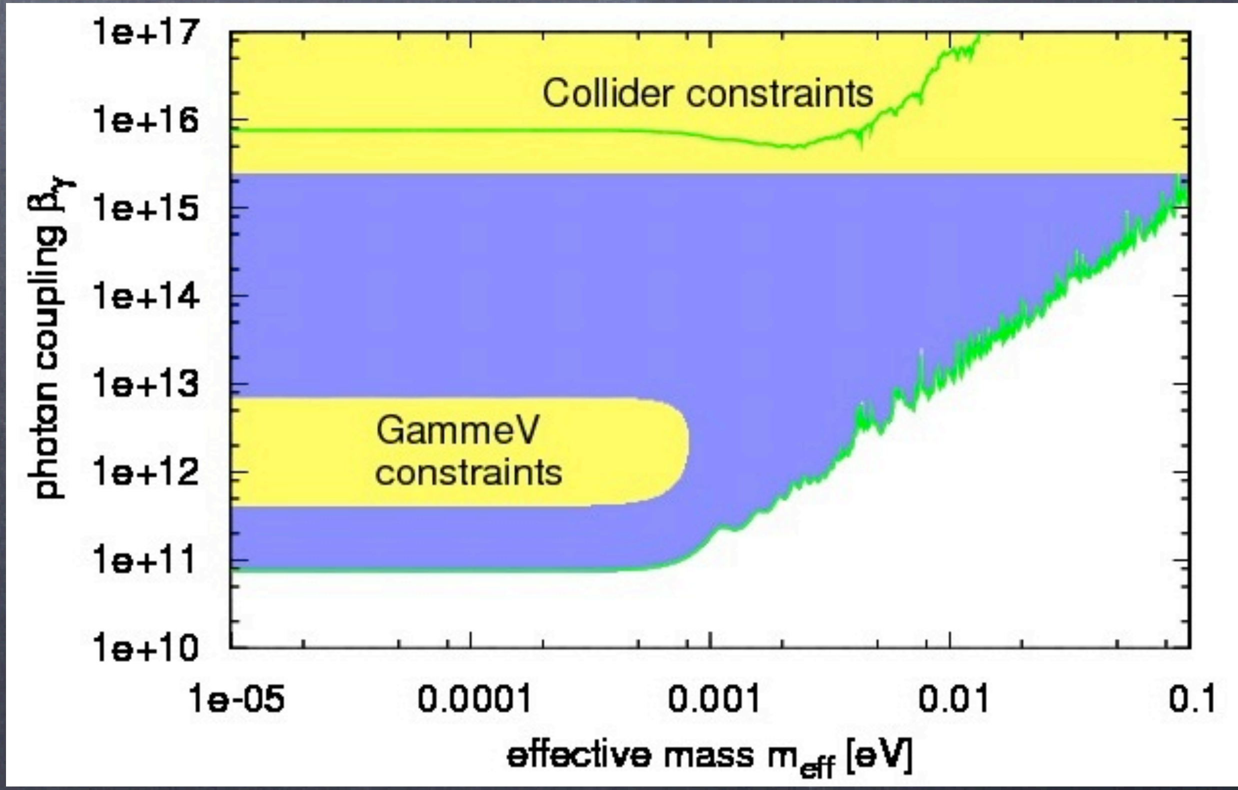




- CHameleon Afterglow SEarch (CHASE), Fermilab

  Chou et al., Phys. Rev. Lett. (2008,2010)

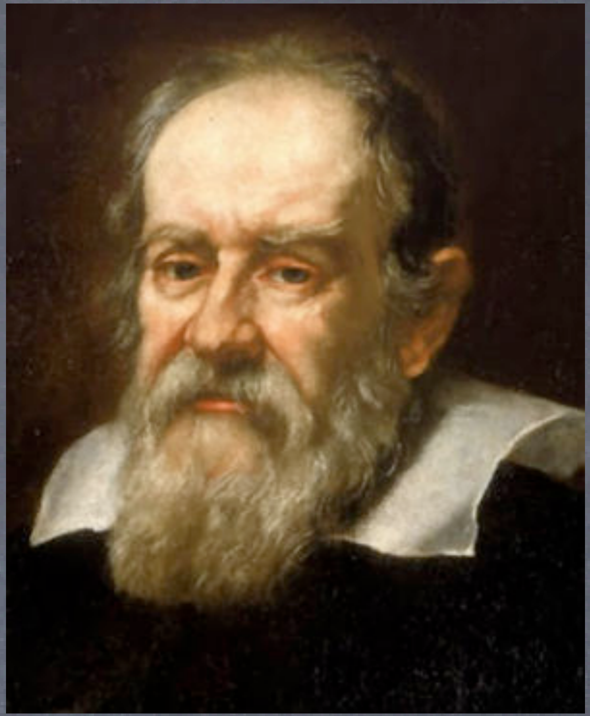




See also ADMX expt

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

Vainshtein/Galileon Mechanism



Vainshtein (1972); Deffayet, Dvali, Gabadadze & Vainshtein (2002); Luty, Porrati & Rattazzi (2003); Nicolis & Rattazzi (2004)

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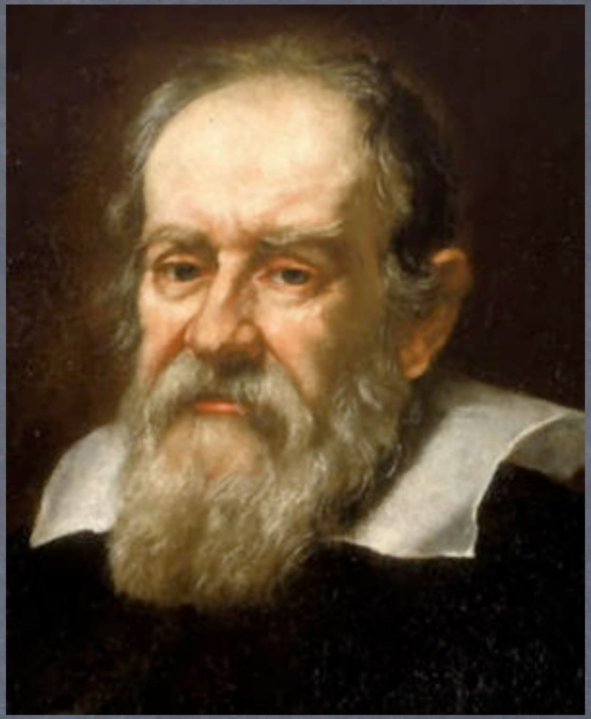

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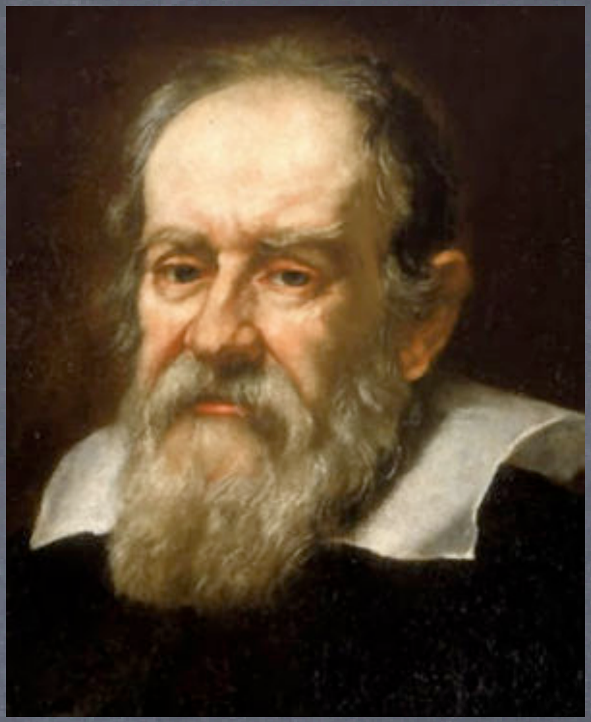

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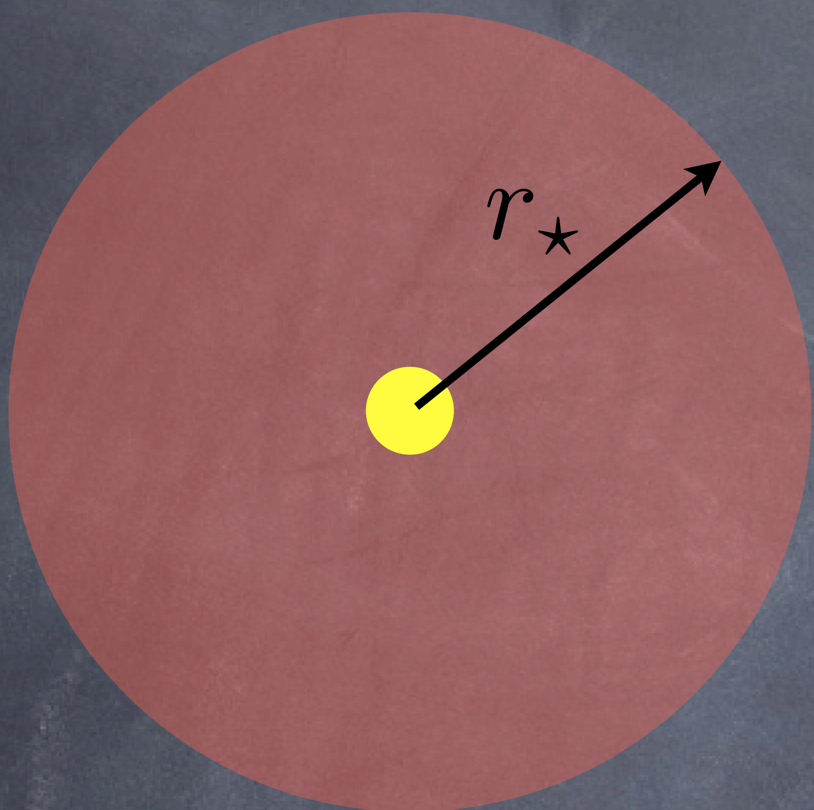
Enjoys "Galilean" symmetry: $\phi \to \phi + c + b_\mu x^\mu$

Leads to 2nd order eqns of motion:

$$\Box\phi + \frac{L^2}{3\sqrt{6}M_{\rm Pl}}\left[(\Box\phi)^2 - (\partial_\mu\partial_\nu\phi)^2\right] = \frac{T^\mu_\mu}{\sqrt{6}M_{\rm Pl}}$$

For a spherically-symmetric source,

$$\nabla^2\phi + \frac{L^2}{3\sqrt{6}M_{\rm Pl}}\left[(\nabla^2\phi)^2 - (\nabla_i\nabla_j\phi)^2\right] = \frac{\rho}{\sqrt{6}M_{\rm Pl}}$$



$$\phi \sim \frac{r_{\rm Sch}}{r}$$
$$r \gg r_\star$$

where

$$r_\star = \left(r_{\rm Sch}L^2\right)^{1/3}$$

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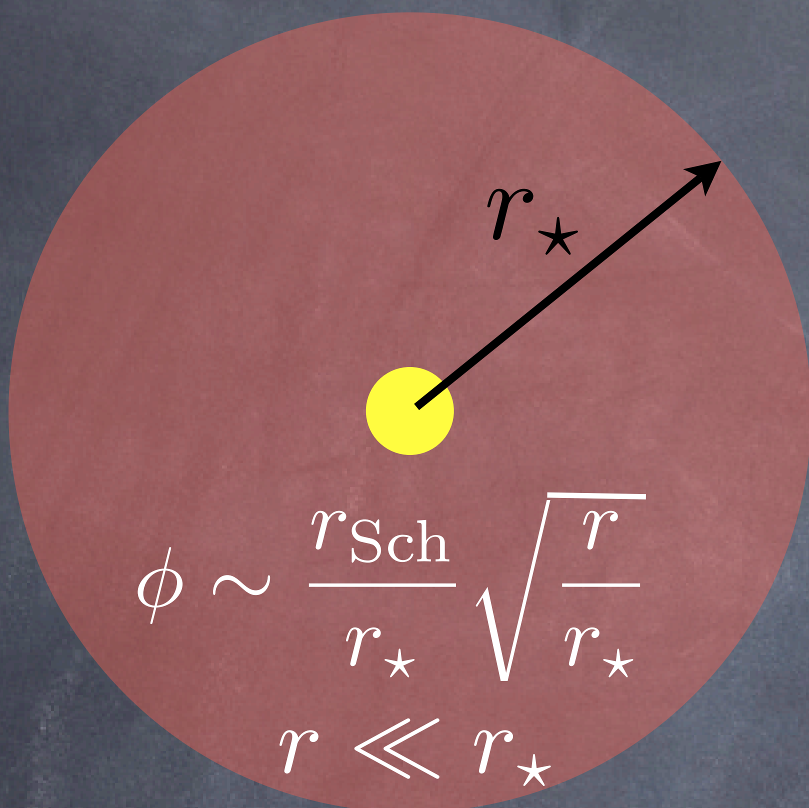

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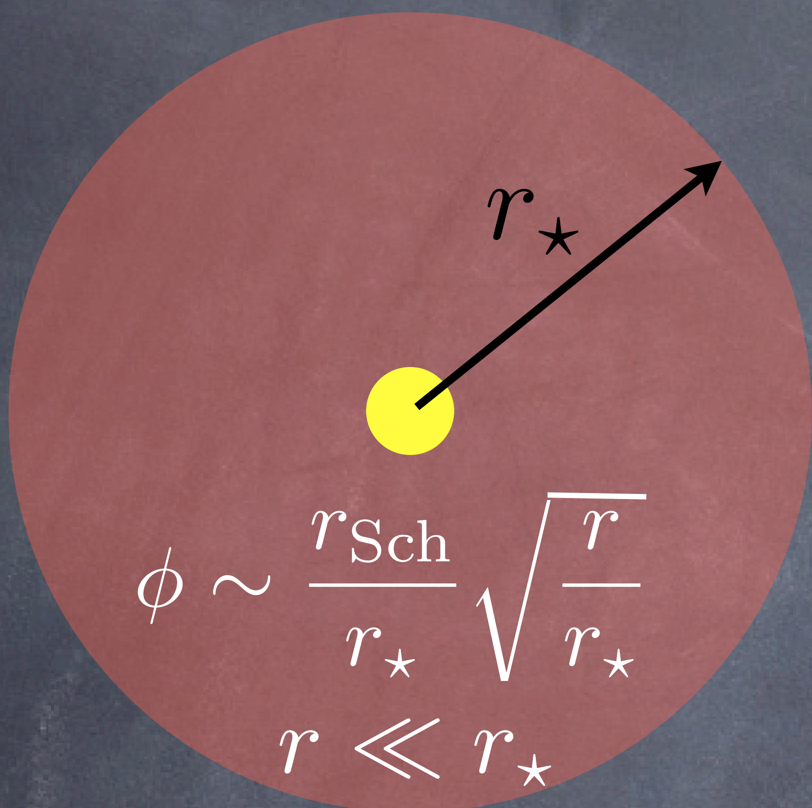

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e.g. $L = 3000 \text{ Mpc}$

$$\Longrightarrow \quad \begin{aligned} r_\star|_\odot &\simeq 0.1 \text{ kpc} \\ r_\star|_{\rm gal} &\simeq \text{Mpc} \\ r_\star|_{\rm clus} &\simeq 10 \text{ Mpc} \end{aligned}$$

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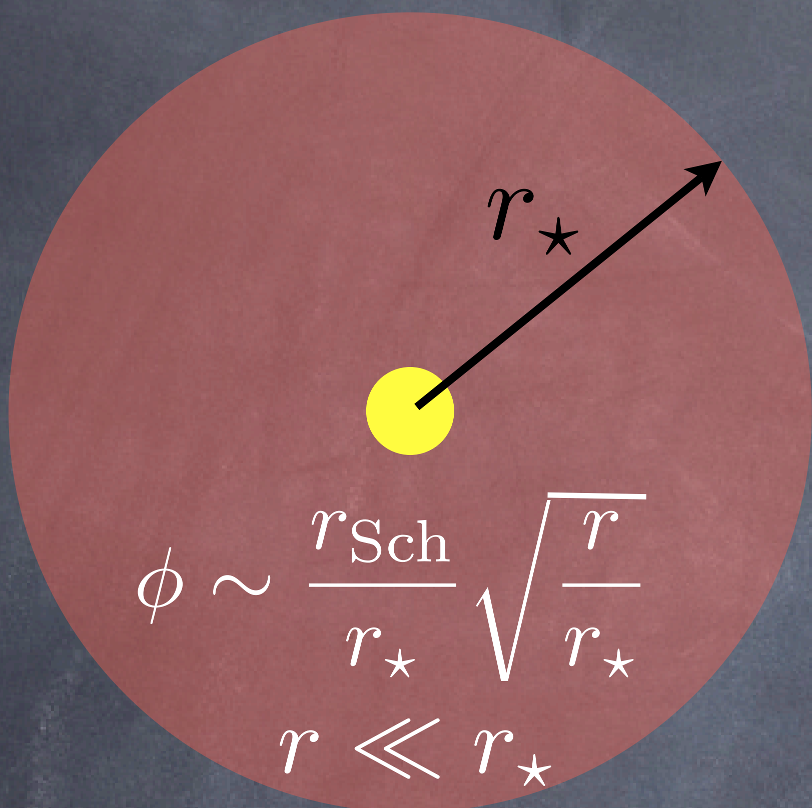

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For $r \gg r_\star$, gravity enhanced: $G_{\rm N}^{\rm eff} = G_{\rm N}\left(1 + \frac{1}{3}\right)$

Note: Deviations from GR are largest on scales $\gtrsim 1 - 10\ {\rm Mpc}$

Kinetic screening:

Consider perturbations $\phi = \bar{\phi}(r) + \delta\phi$

$$\mathcal{L}_{\rm pert} = -\frac{1}{2}(\partial\delta\phi)^2\left(1+\frac{L^2}{M_{\rm Pl}}\bar{\phi}''(r)\right) - \frac{L^2}{6\sqrt{6}M_{\rm Pl}}(\partial\delta\phi)^2\Box\delta\phi + \frac{\delta\phi}{\sqrt{6}M_{\rm Pl}}\delta T$$

Kinetic screening:

Consider perturbations $\phi = \bar{\phi}(r) + \delta\phi$

$$\sim \left(\frac{r_\star}{r}\right)^{3/2} \gg 1$$

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The non-linear coupling scale is also raised.

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Lunar Laser Ranging:

Dvali, Gruzinov and Zaldarriaga (2002)

$$\frac{\delta\Phi_{\rm N}}{\Phi_{\rm N}} \sim \left(\frac{r}{r_\star}\right)^{3/2} \simeq 10^{-12}$$

Symmetron Mechanism

K. Hinterbichler and J. Khoury, Phys. Rev. Lett. (2010)

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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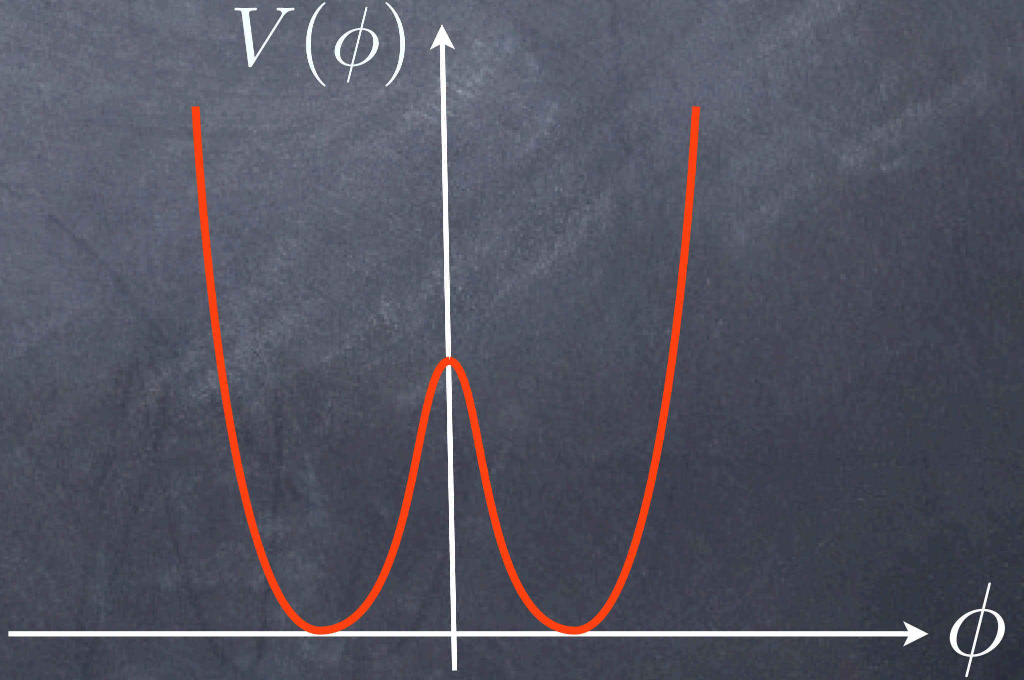
where T^μ_μ is stress tensor of all matter (Baryonic and Dark)

Potential is of the spontaneous-symmetry-breaking form:

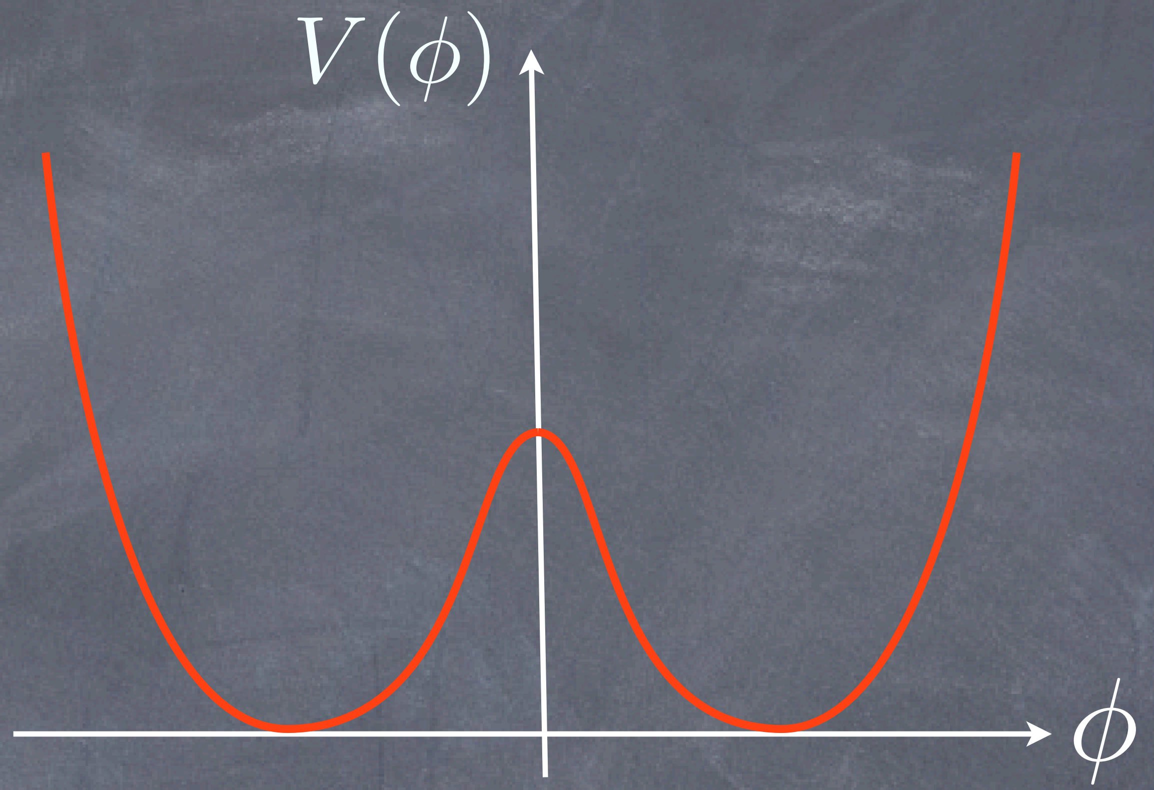
$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

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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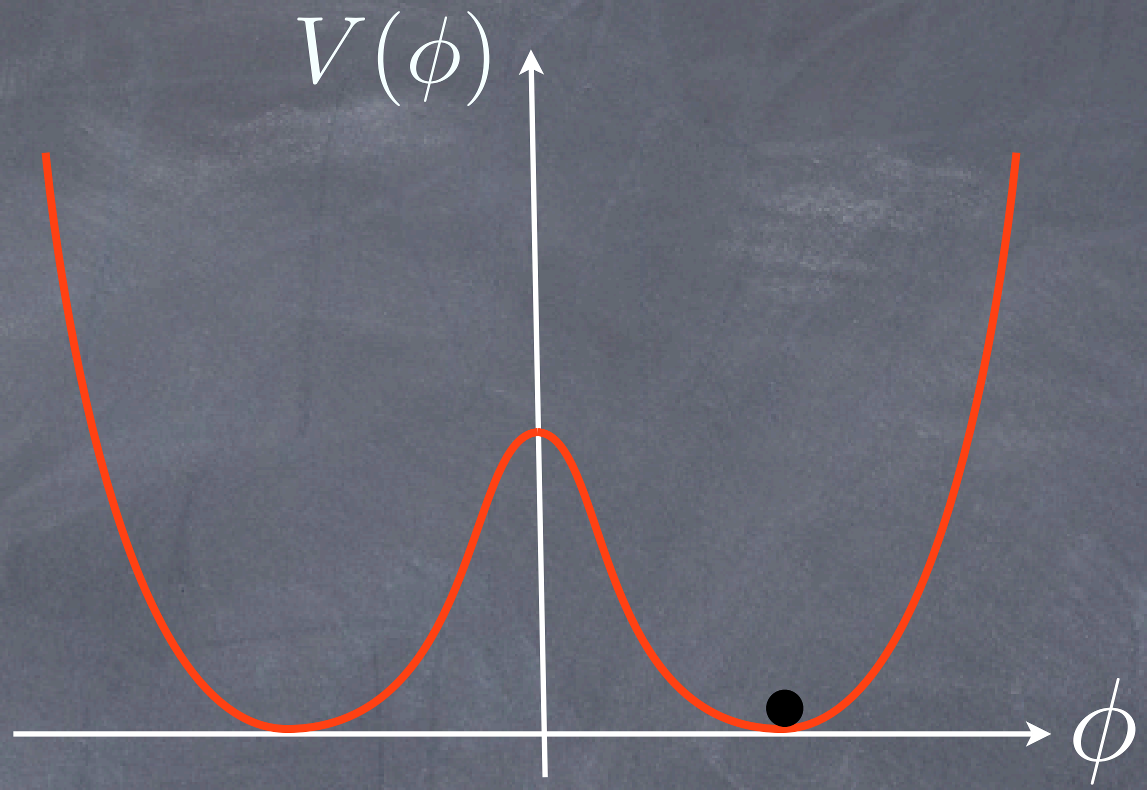
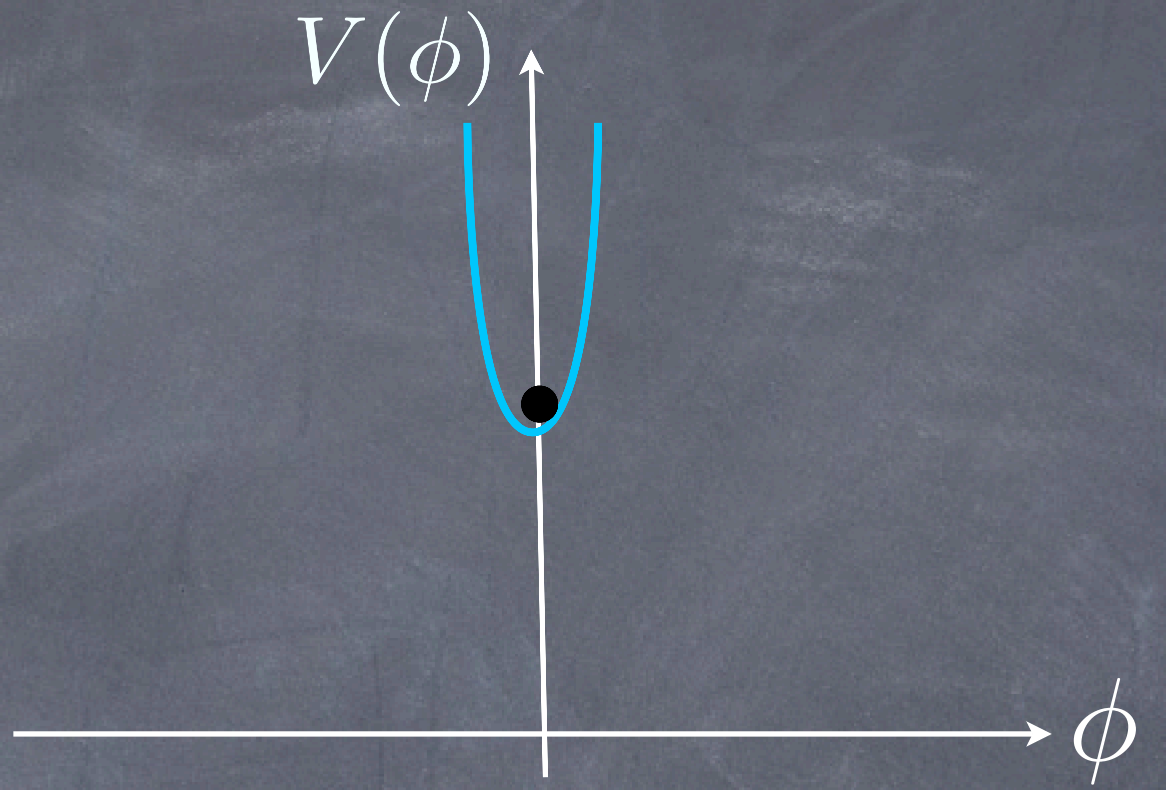


$\therefore$ Whether symmetry is broken or not depends on local density

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

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.

- Inside source, provided $\rho > \mu^2 M^2$, the symmetry is restored.

Effective Coupling

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

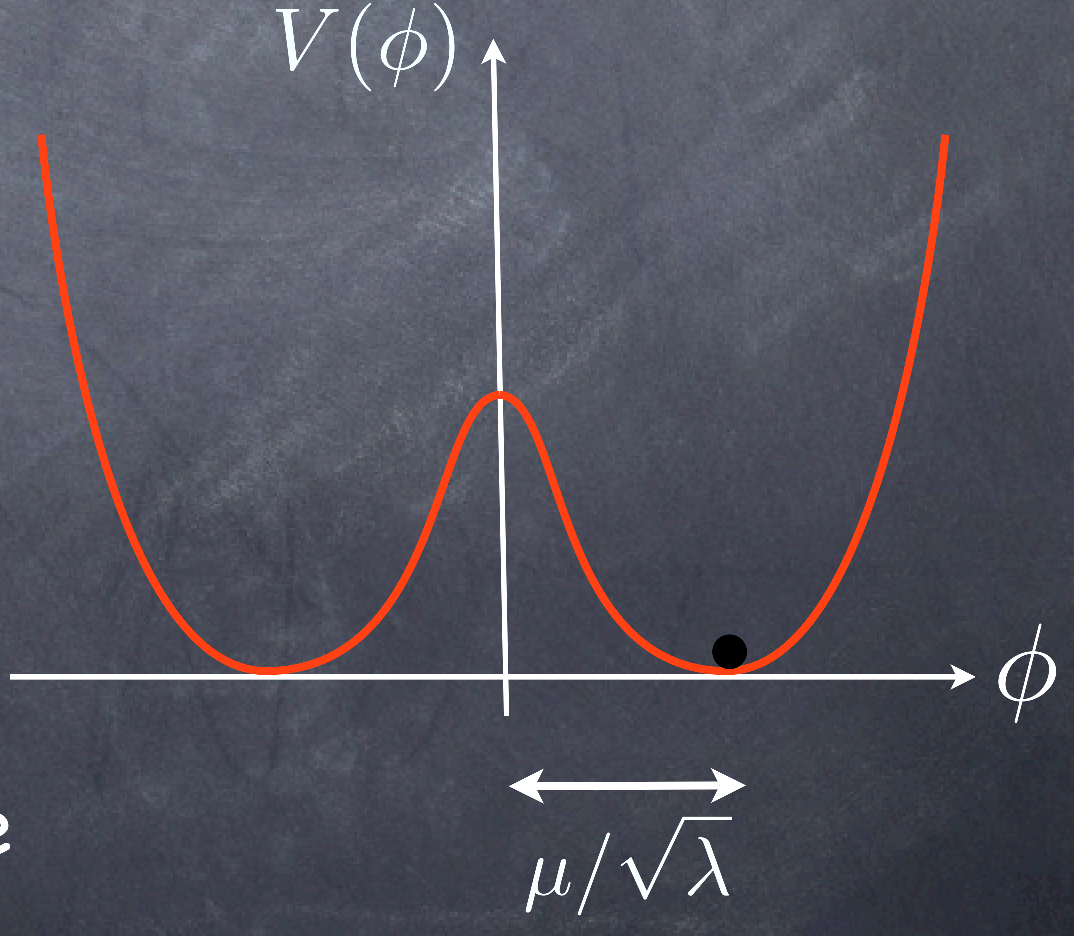
$$\mathcal{L}_{\rm coupling} \sim \frac{\bar{\phi}}{M^2}\delta\phi\,\rho$$

- 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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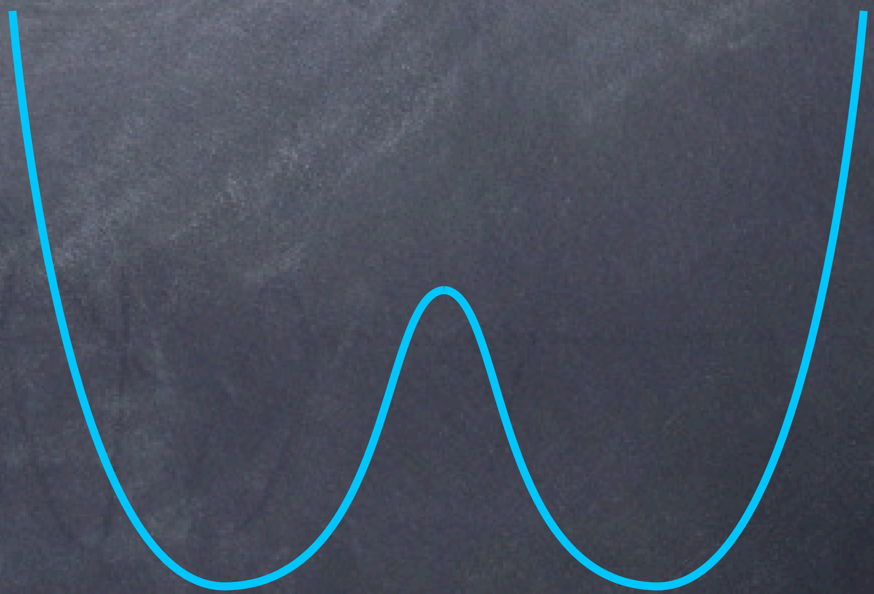
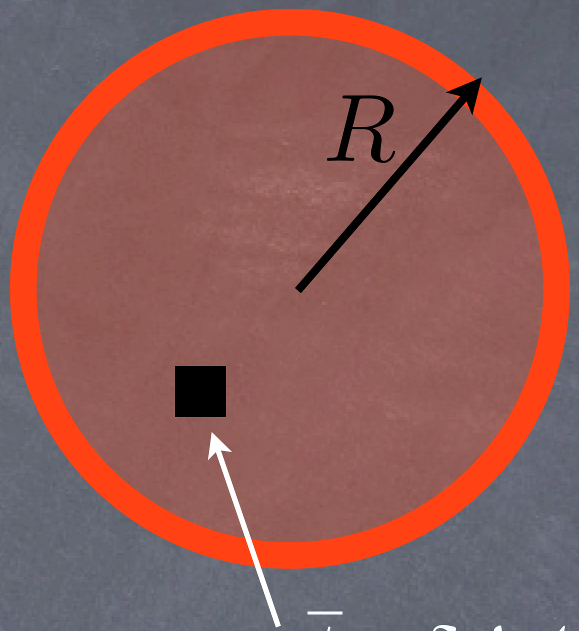


Thin-Shell Screening Effect



Behavior of solution depends on

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

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

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

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

- 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

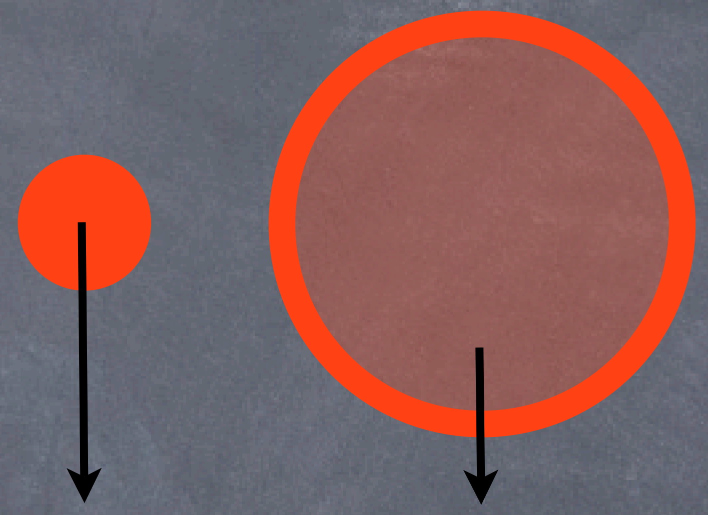
Test	Effective parameter	Current bounds
Time delay/light deflection	$\|\gamma - 1\| \approx 10^{-5}$	$\|\gamma - 1\| \approx 10^{-5}$
Nordvedt effect	$\|\eta_{\rm N}\| \sim 10^{-4}$	$\|\eta_{\rm N}\| \sim 10^{-4}$
Mercury perihelion shift	$\|\gamma - 1\| \approx 4 \cdot 10^{-4}$	$\|\gamma - 1\| \approx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

Observational Tests

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



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

- Unscreened objects ($\epsilon = 1$) feel gravity + symmetron forces
- Screened objects ($\epsilon = 0$) only feel gravity

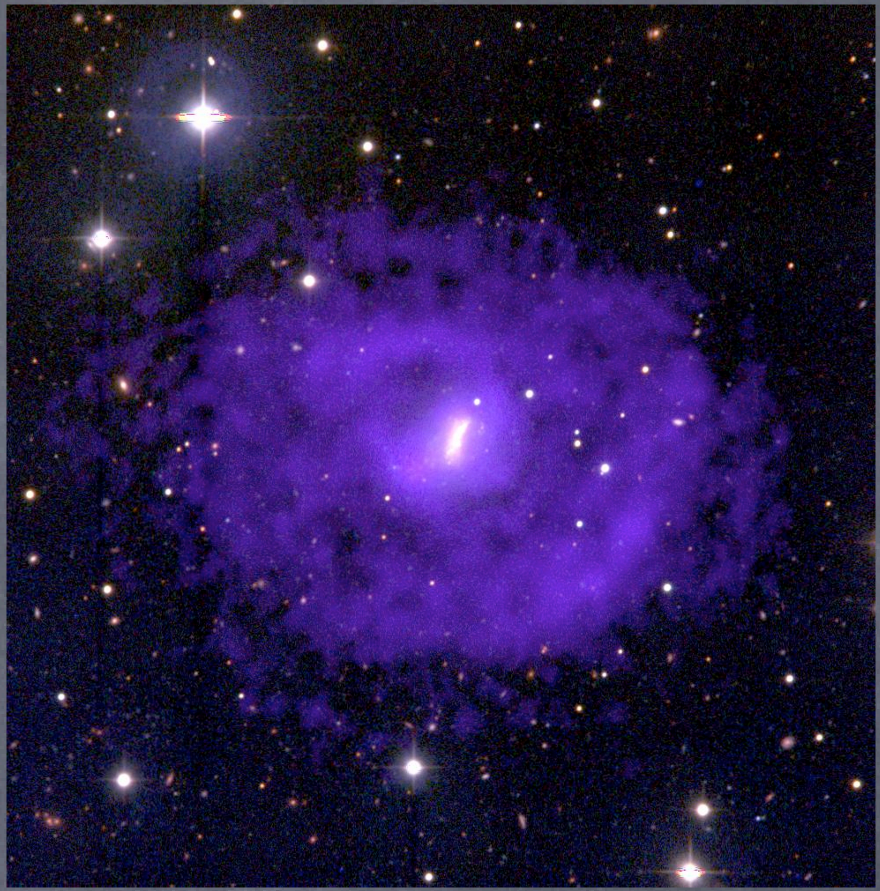
To maximize effect, look for

- 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

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: Applies to chameleons and symmetrons, but not galileons.

The Mpc barrier

Wang, Hui & J. Khoury, to appear

Chameleons/Symmetrons: $$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + A(\phi)T^{\mu}_{\mu}$$

Can we ever obtain $m_0 \sim H_0$? NO: Mpc is the best you can do.

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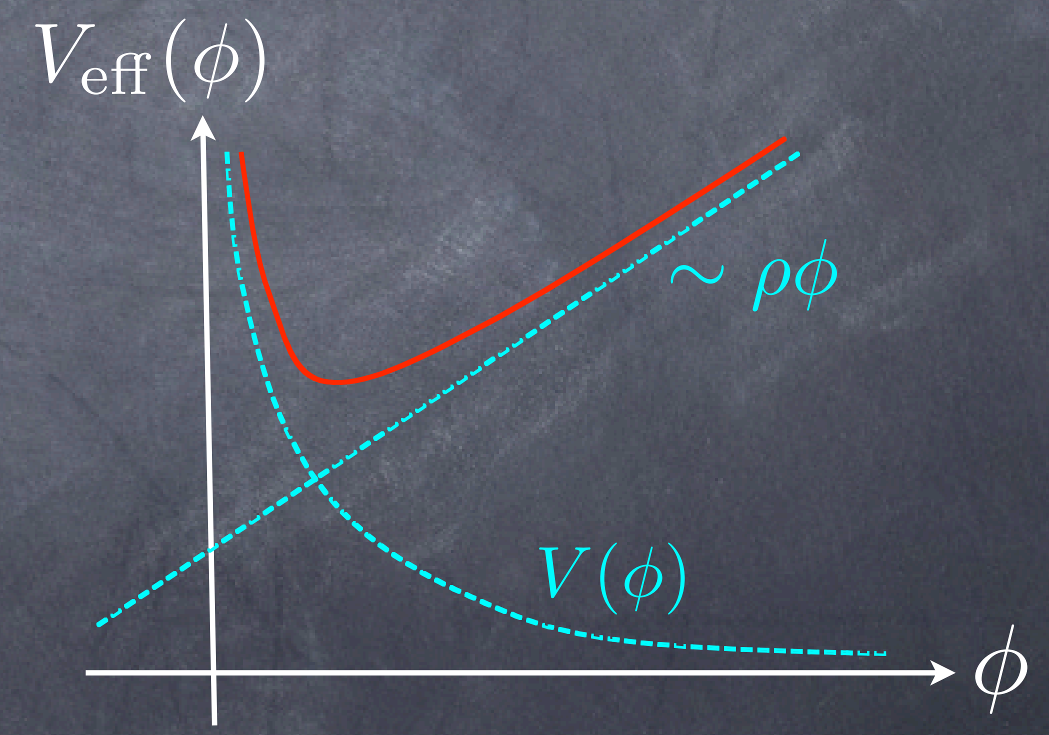
Proof: Take chameleon with $A(\phi) \simeq 1 + g\frac{\phi}{M_{\rm Pl}}$



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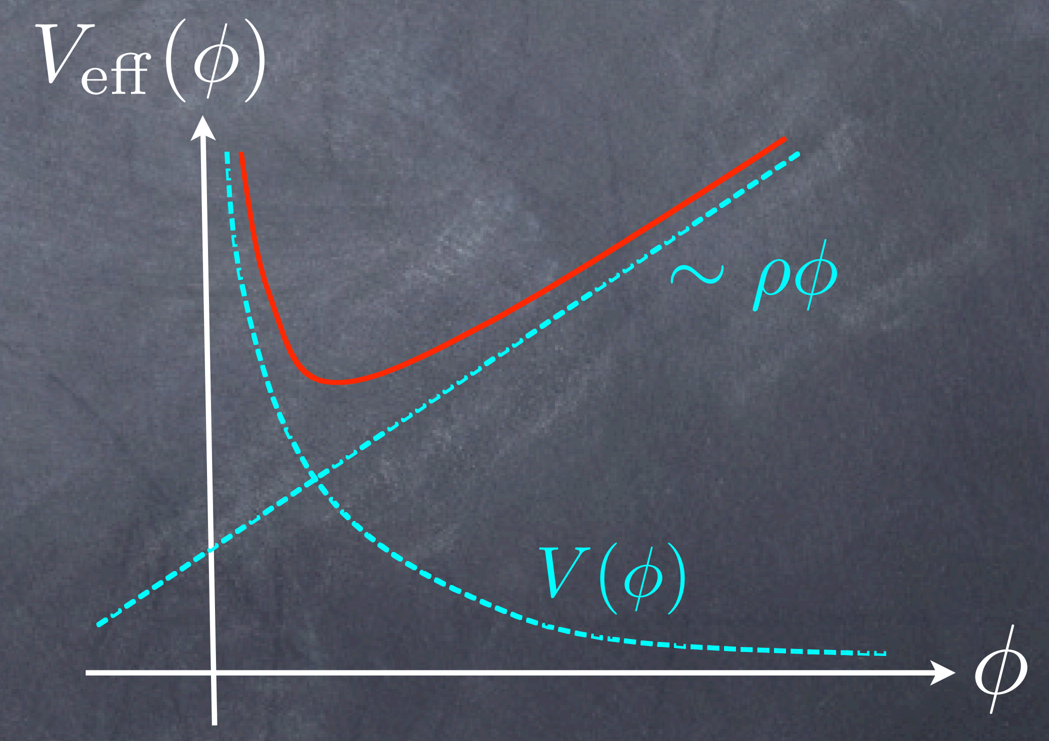
Proof: Take chameleon with $A(\phi) \simeq 1 + g\frac{\phi}{M_{\rm Pl}}$

- Screening condition:

$$\frac{\Delta R}{R} \approx \frac{\phi_0}{6gM_{\rm Pl}\Phi_{\rm N}} < 1$$



Milky Way has $\Phi_{\rm N} \sim 10^{-6}$

$$\Longrightarrow \quad \boxed{\phi_0 \lesssim 10^{-6} M_{\rm Pl}}$$

- Cosmological evolution:

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\mathrm{d}V}{\mathrm{d}\phi} - \frac{g}{M_{\mathrm{Pl}}}\rho$$

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$\therefore$ Pretty large force!

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$\therefore$ Pretty large force!

Hence $\mathrm{d}V/\mathrm{d}\phi$ & $g\rho/M_{\rm Pl}$ must cancel to good accuracy

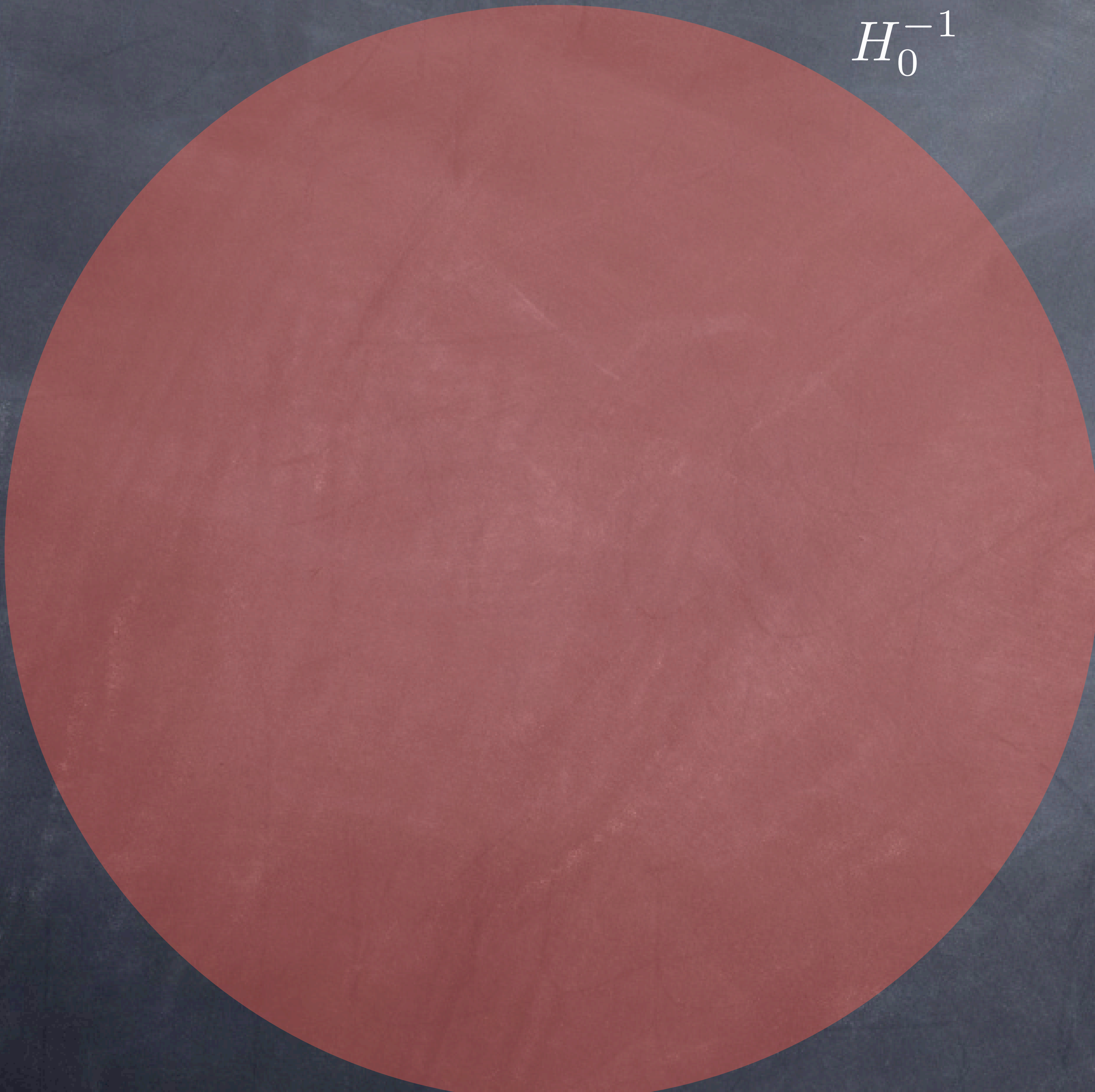
Cancellation must hold over last Hubble time:

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

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

Argument generalizes to arbitrary chameleon/symmetron theories

The Mpc divide



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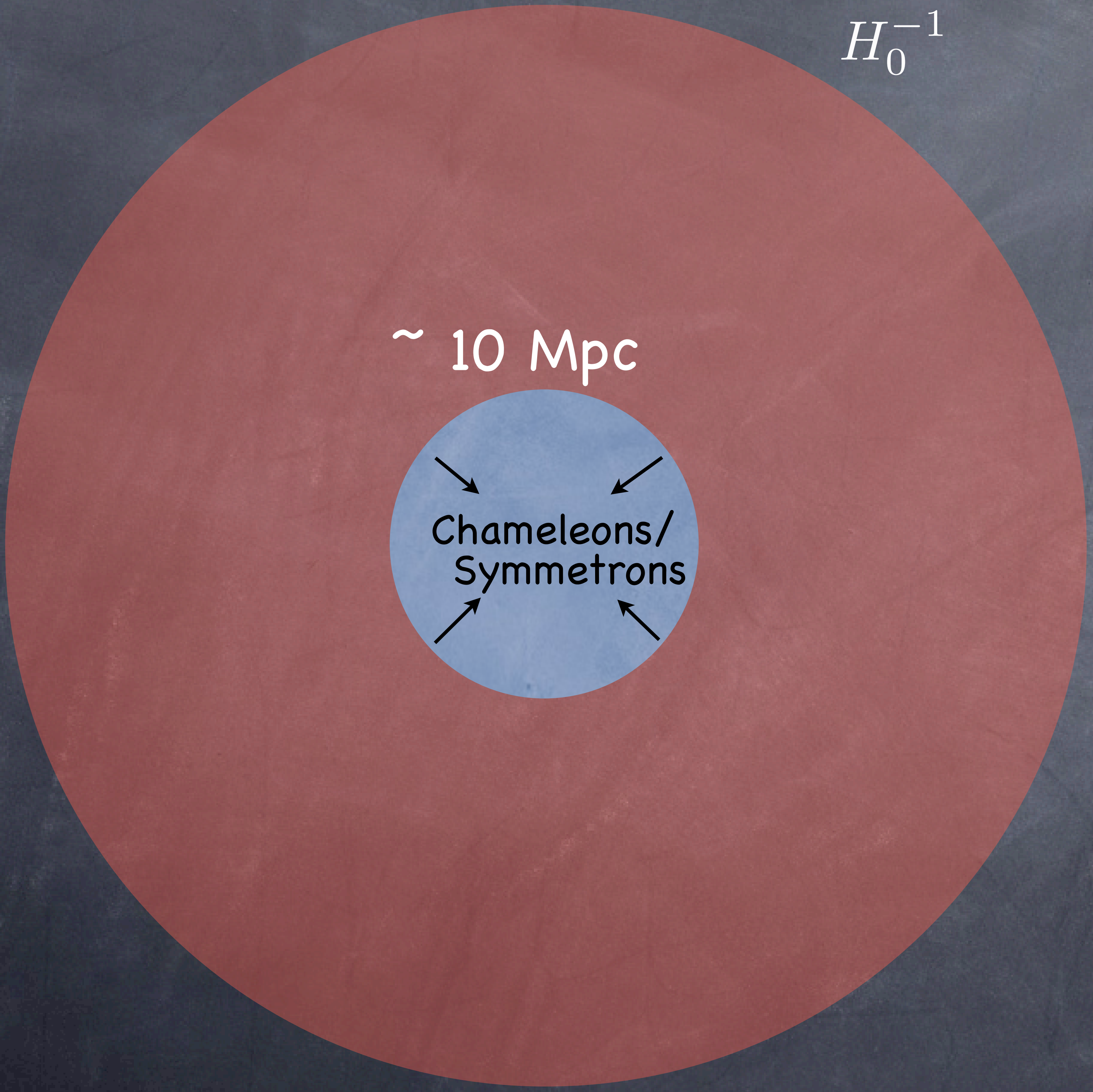

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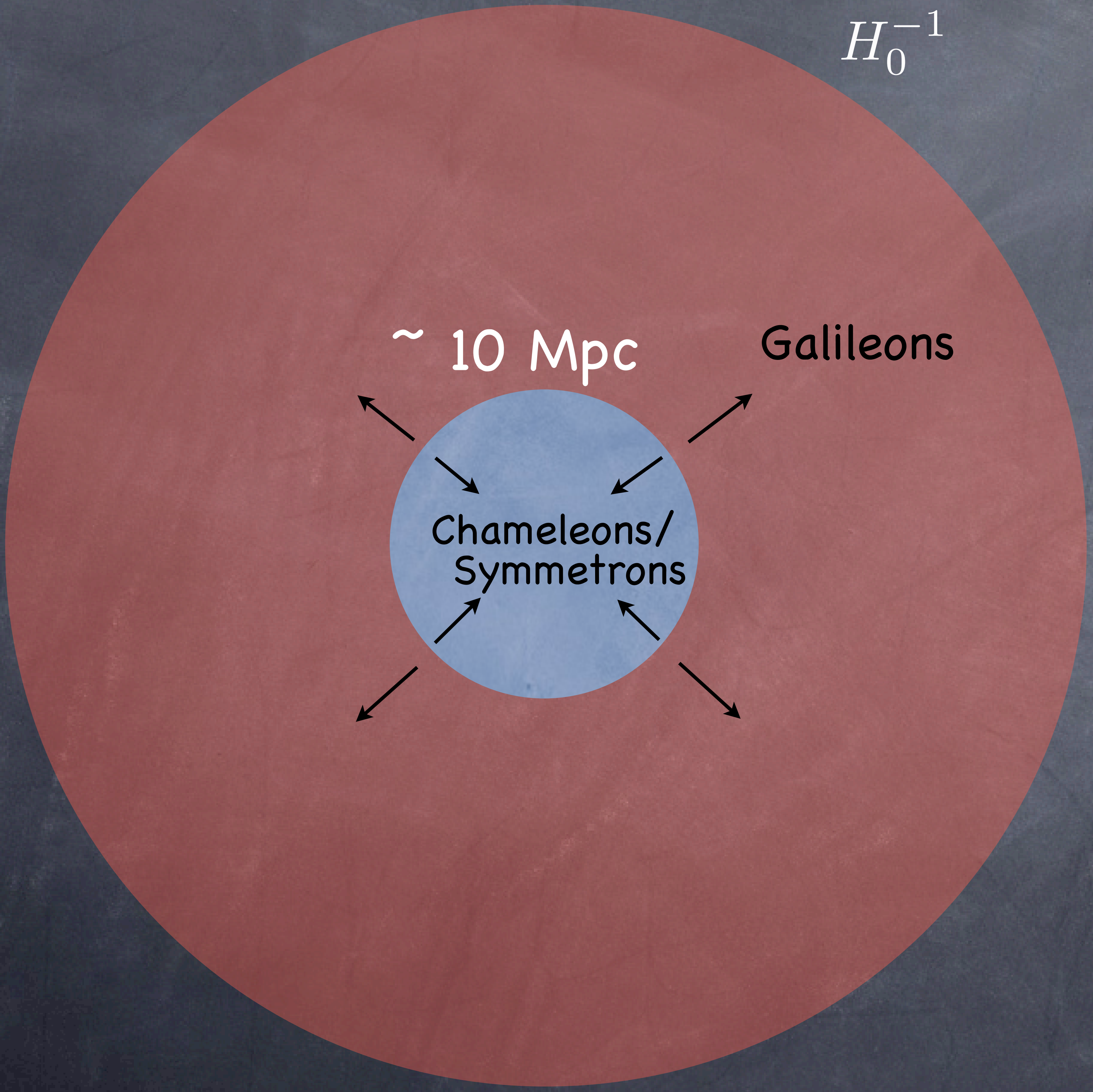

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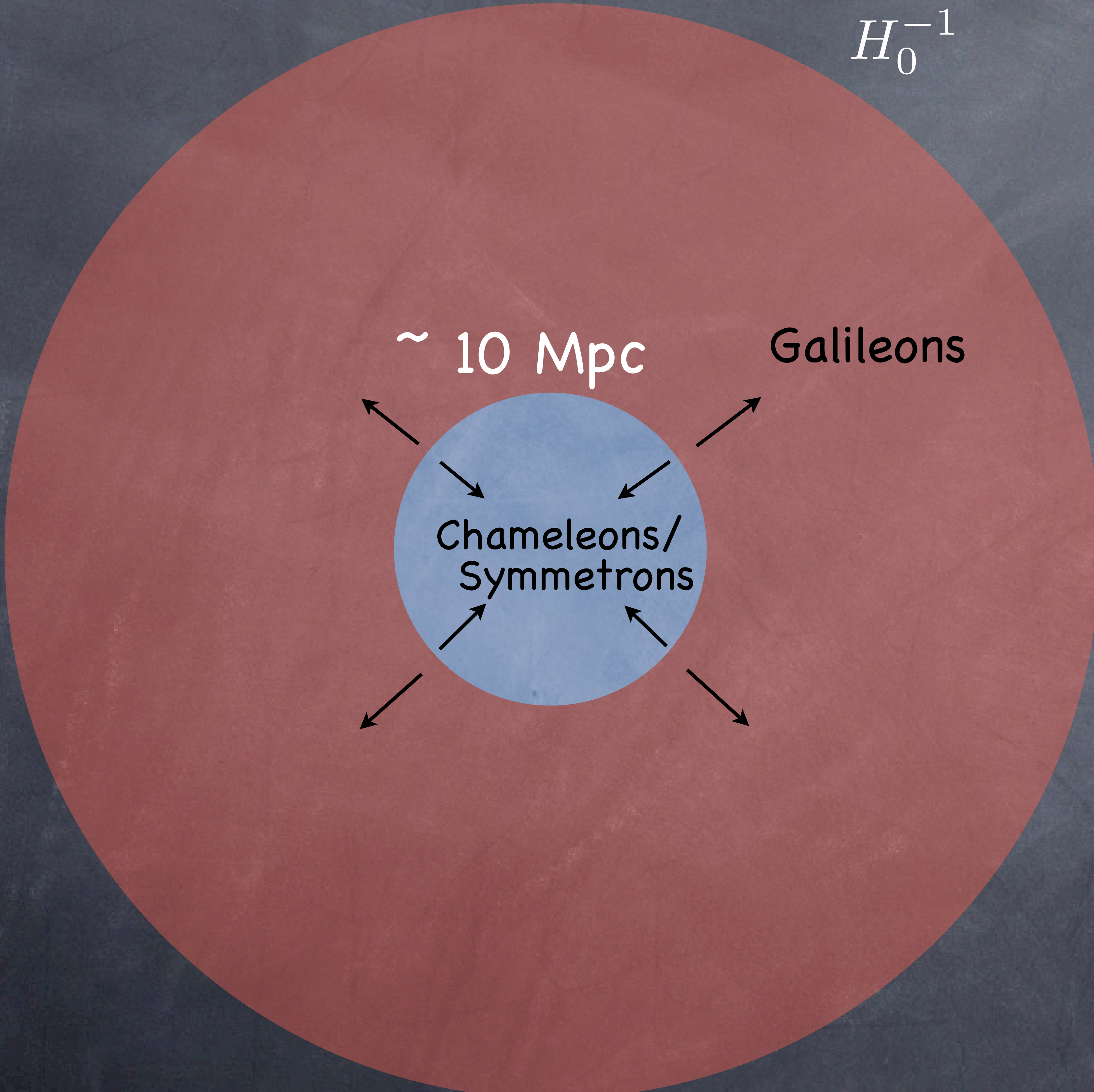
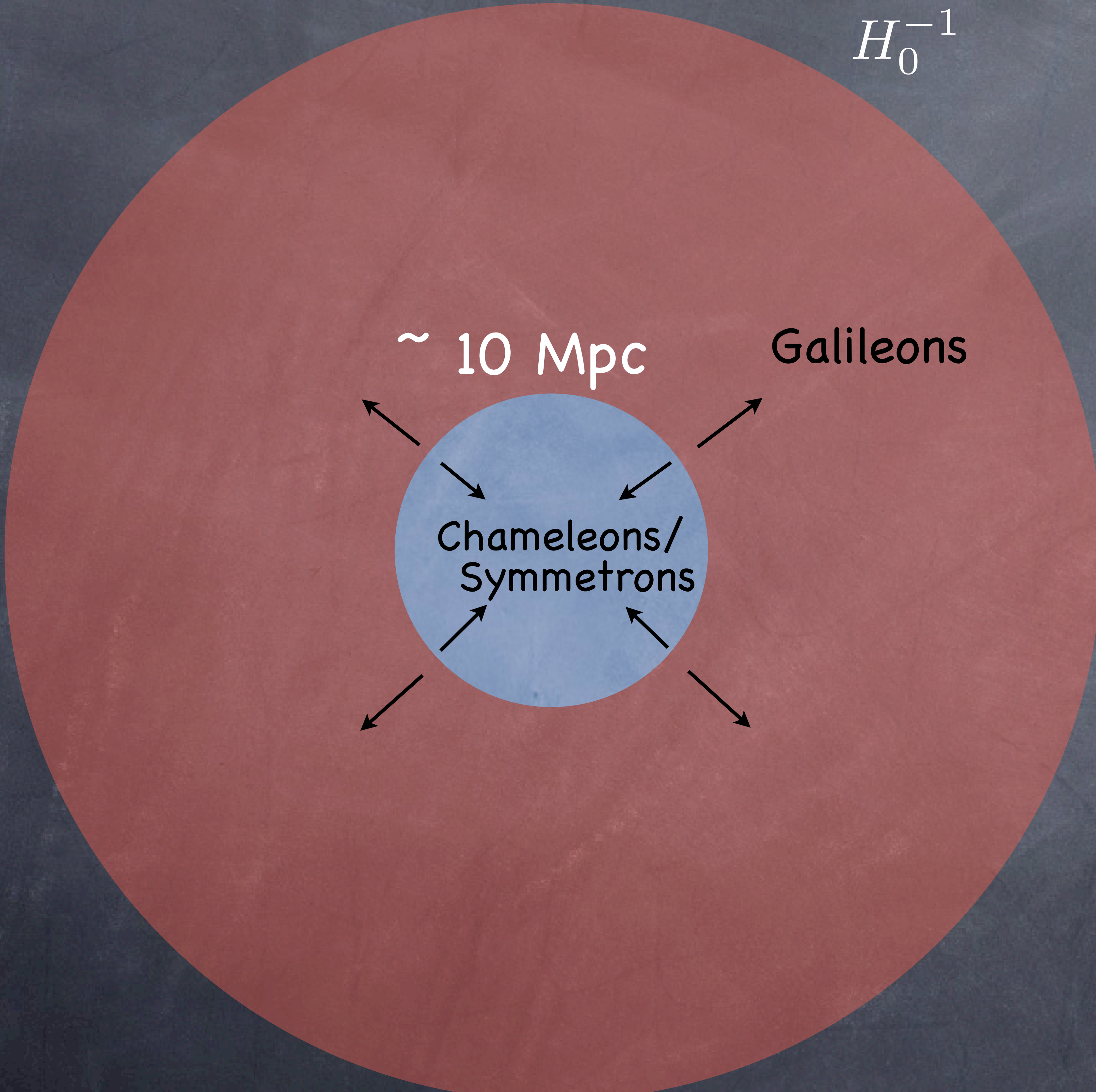


- Galileons (DGP):
  Lombriser et al. (2009)

$$L > 9000 \text{ Mpc}$$

The Mpc divide



- Galileons (DGP):
  Lombriser et al. (2009)

$$L > 9000 \text{ Mpc}$$

- Chameleons/f(R):
  Ferraro et al. (2010)

$$m_0^{-1} < 10 - 100 \text{ Mpc}$$

Tantalizing Hints?

Wyman & J. Khoury, PRD (2010)
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)
Farrar & Rosen (2007)

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

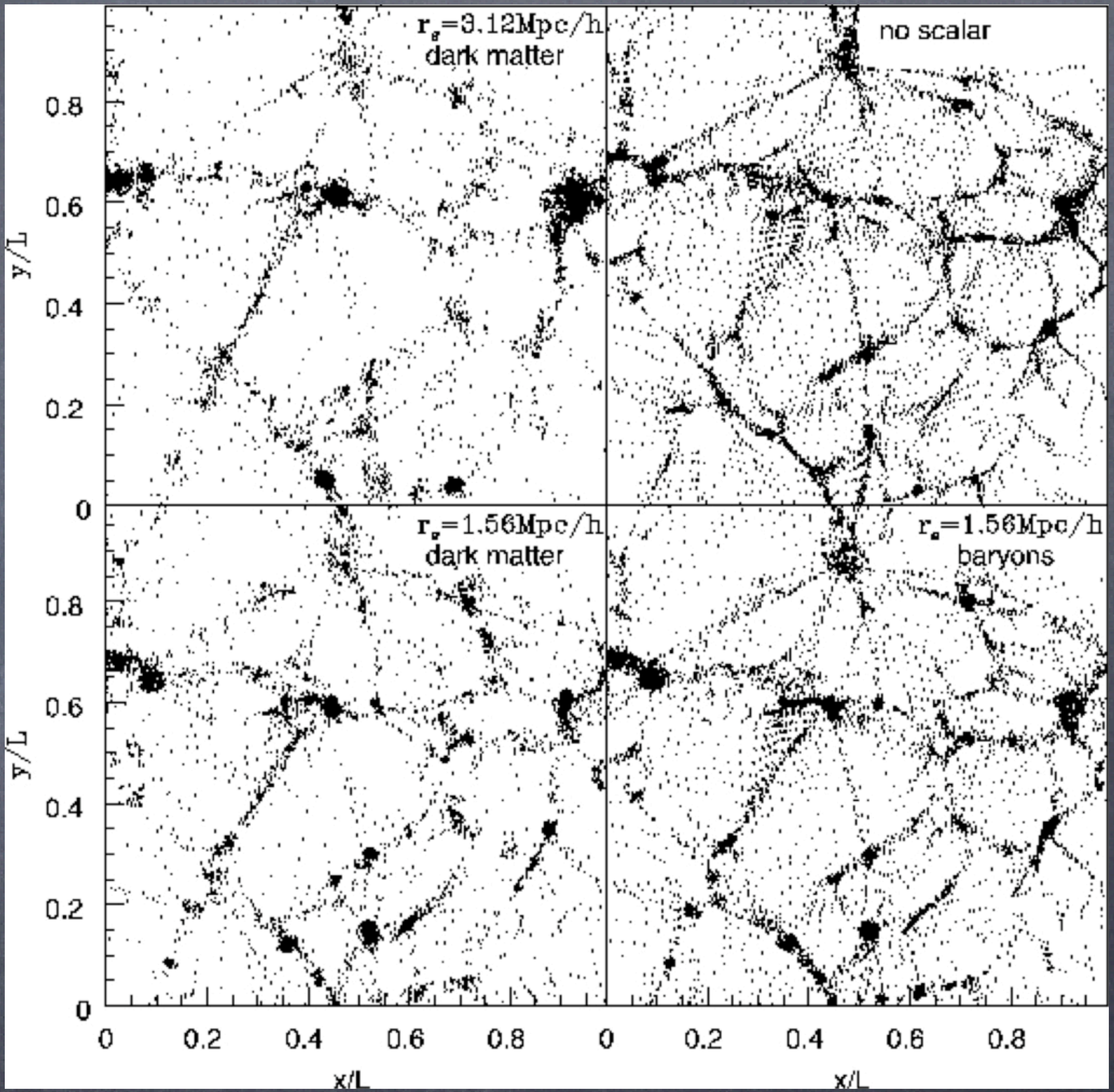
Between DM only!!!

* 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 circumvents Kesden-Kamionkowski because Milky Way is screened.

Thank you!