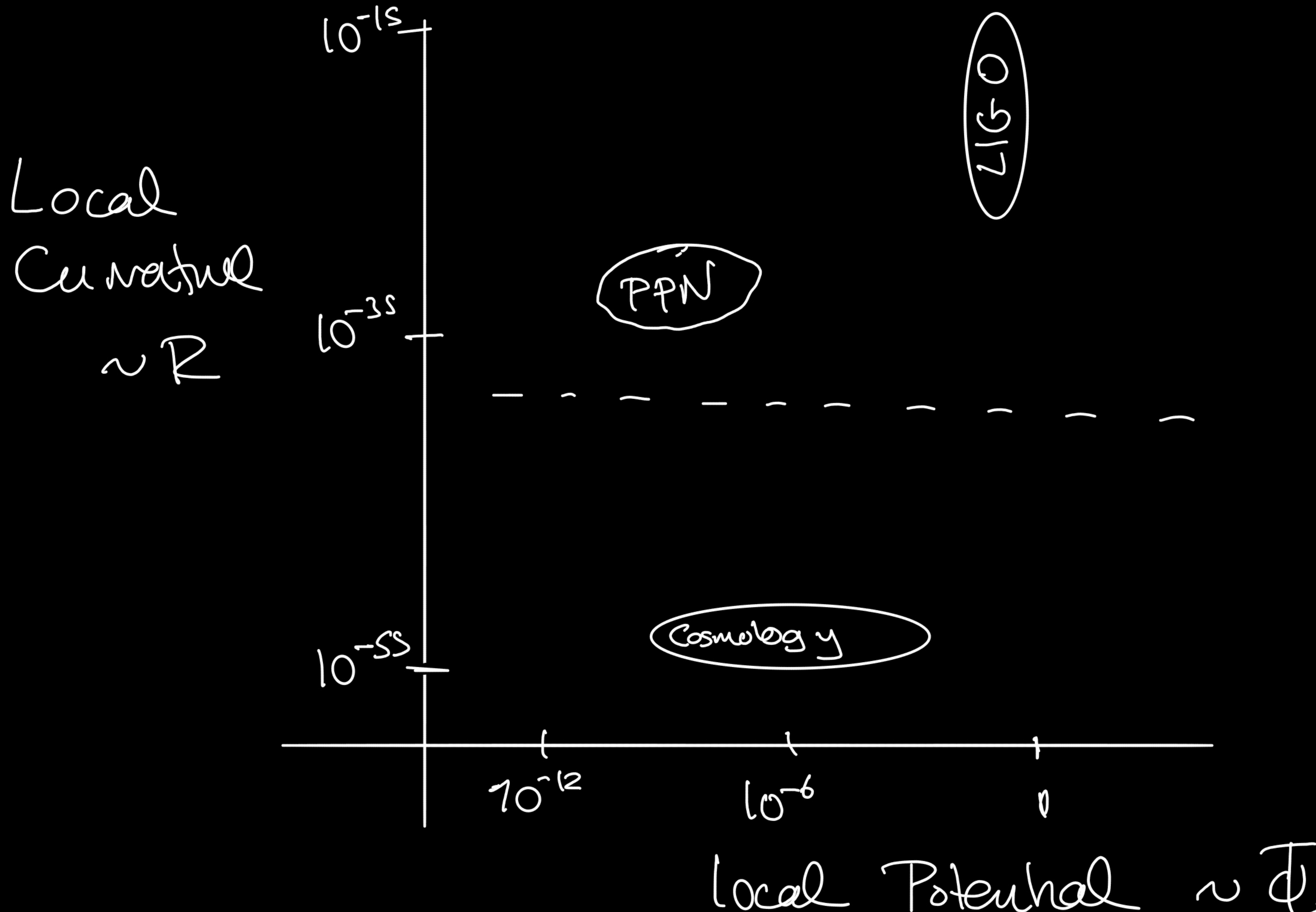
Fifth Forces and Gravitational Screening



See Baker et al, ApJ 802, 63, 2015

Fifth Force

Yukawa force : $\Phi_S = \frac{g^2}{4\pi} \frac{M}{r} e^{-m_\phi r}$

Φ_S is small if : $g^2 \to 0$

or

$m_\phi \to \infty$ (very short range)

Fifth Force

Einstein frame: geodesics on $\tilde{g}_{\alpha\beta} = \Psi(\phi) g_{\alpha\beta}$

i.e $\dfrac{d^2 x^\mu}{d\lambda^2} + \tilde{\Gamma}^\mu{}_{\alpha\beta} \dfrac{dx^\alpha}{d\lambda} \dfrac{dx^\beta}{d\lambda} = 0$

Minkowski

Taylor expand: $\Psi(\phi) \sim 1 + \alpha\phi$

Recall that $\tilde{\Gamma} \sim \tilde{g}^{-1} \partial \tilde{g}$ and $\partial_\gamma \tilde{g}_{\alpha\beta} = \partial_\gamma \left[(1+\alpha\phi)\eta_{\alpha\beta} \right] = \alpha \partial_\gamma \phi \, \eta_{\alpha\beta}$

Then: $a^\mu = -3\alpha U^\mu U^\nu \partial_\nu \phi - \alpha \partial^\mu \phi$ $\quad \left(U^\mu = \dfrac{dx^\mu}{d\lambda} \right)$

If static, spherically symmetric

$a_r = -\alpha \partial_r \phi$ (i.e $\vec{F} \sim -\vec{\nabla}\phi$)

Fifth Force

What does ϕ look like?

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + \mathcal{L}_m\left(\text{matter},\ (1+\alpha\phi)\,g_{\mu\nu}\right)$$

E.o.m.

$$\Box\phi - m_\phi^2\phi + \frac{1}{\sqrt{g}}\frac{\delta\mathcal{L}_m}{\delta g^{\mu\nu}}(-\alpha\, g^{\mu\nu}) = 0$$

which gives

EM Tensor

$$\Box\phi - m_\phi^2\phi + \frac{\alpha}{2}T^\mu{}_\mu$$

Assume static, spherical symmetry : $T^\mu{}_\mu = -\rho(r)$

Take $\rho(r) = M_c\,\delta^3(r)$ and regular solution $\phi = \frac{A}{r}e^{-m_\phi r}$

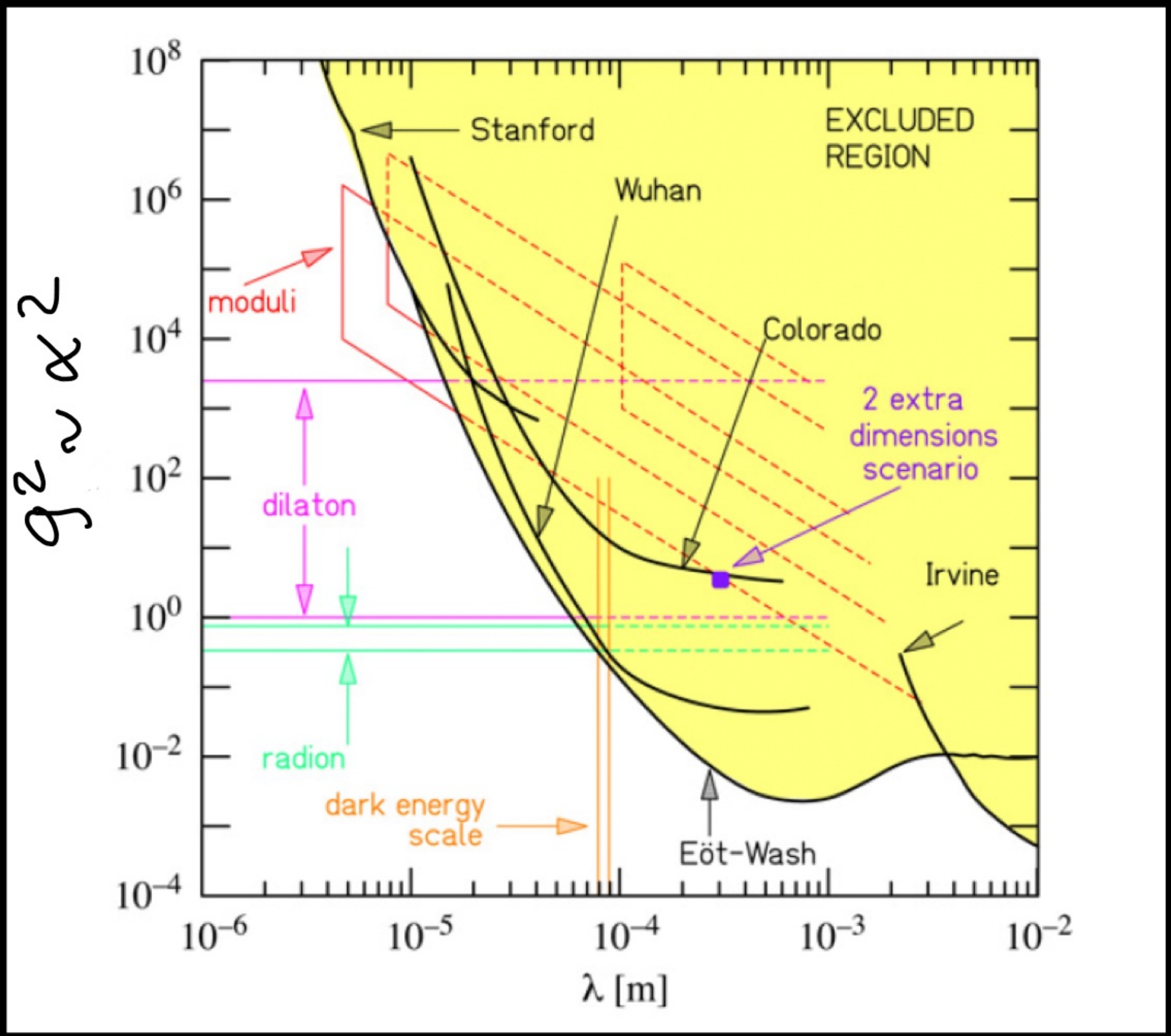
Solve to get

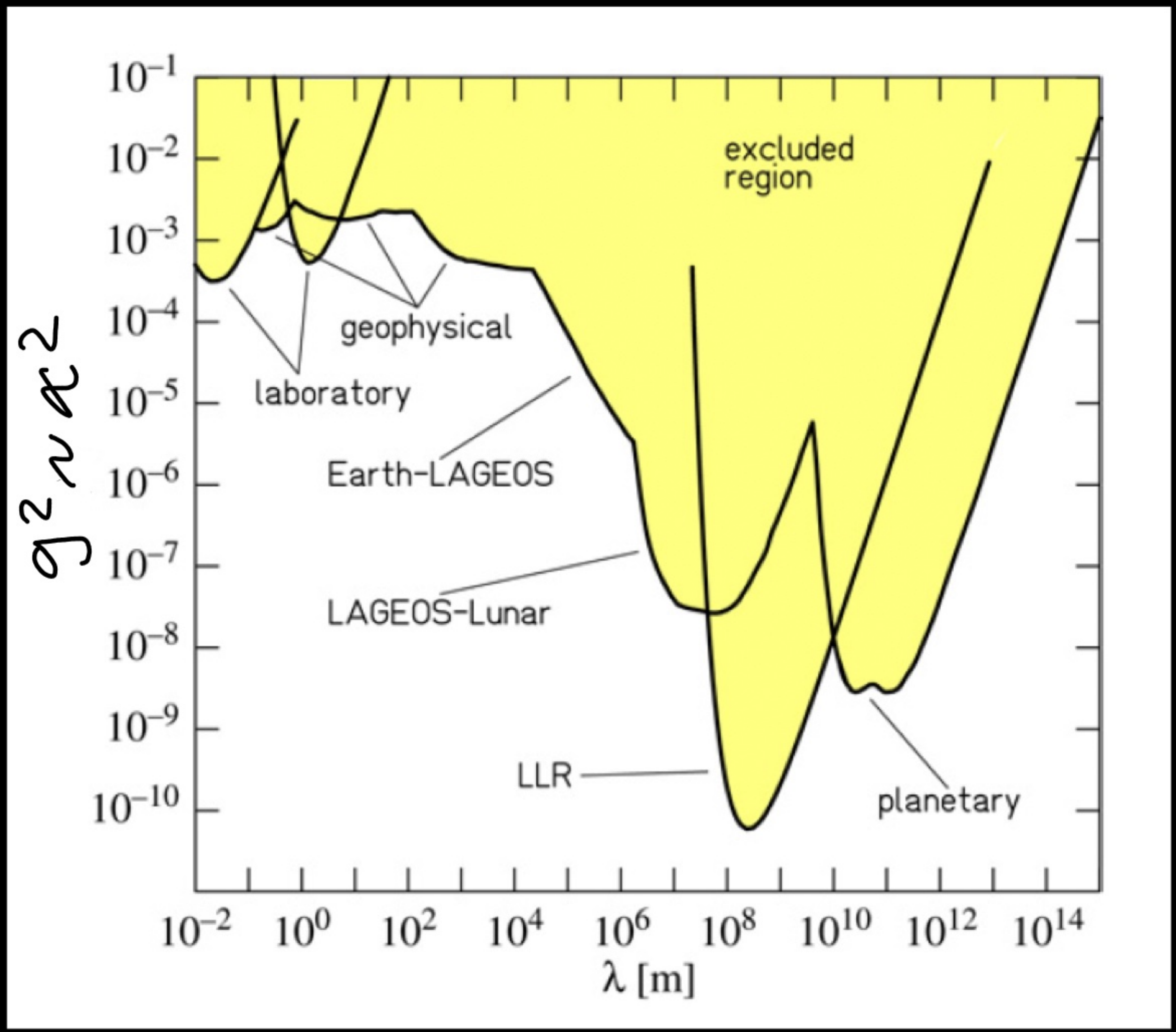
$$A = -\frac{\alpha M_c}{8\pi}$$

$$\boxed{\text{Force}: \quad F_r = \partial_r\phi = -\frac{\alpha^2 M_c}{8\pi r^2}(1+m_\phi r)\,e^{-m_\phi r}}$$

Fifth Force

$$\Phi_s = \frac{g^2}{4\pi}\frac{M}{r}e^{-m_\phi r}$$





range : $\lambda \sim \frac{1}{m_\phi}$.

Adelberger et al
Prog P. N. Physics
62, 102 (2009)

Gravitational Screening

Idea: the 'environment' affects the strength or range of the fifth force.

Note: This is not an 'add-on', it is an inherent part of many theories.

Gravitational Screening : Chameleons.

Action in Einstein Frame Khoury & Weltman, PRD 69, 044026, 2004

$$S = \int d^4x \sqrt{-g}\left[\frac{M_{Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right] + \int d^4x\, \mathcal{L}_m(\text{matt}, \tilde{g}_{\alpha\beta})$$

Recall : $\tilde{g}_{\alpha\beta} = \Psi(\phi)\, g_{\alpha\beta}$ pick $\Psi(\phi) = (1+\alpha\phi) \equiv \left(1+\frac{2\phi}{M}\right)$

Redo calculation:

E.O.M: $\Box\phi - V'(\phi) + \frac{1}{M}\left(1+\frac{2\phi}{M}\right)\underbrace{T^\mu{}_\mu}_{= -\rho} = 0$

For small ϕ

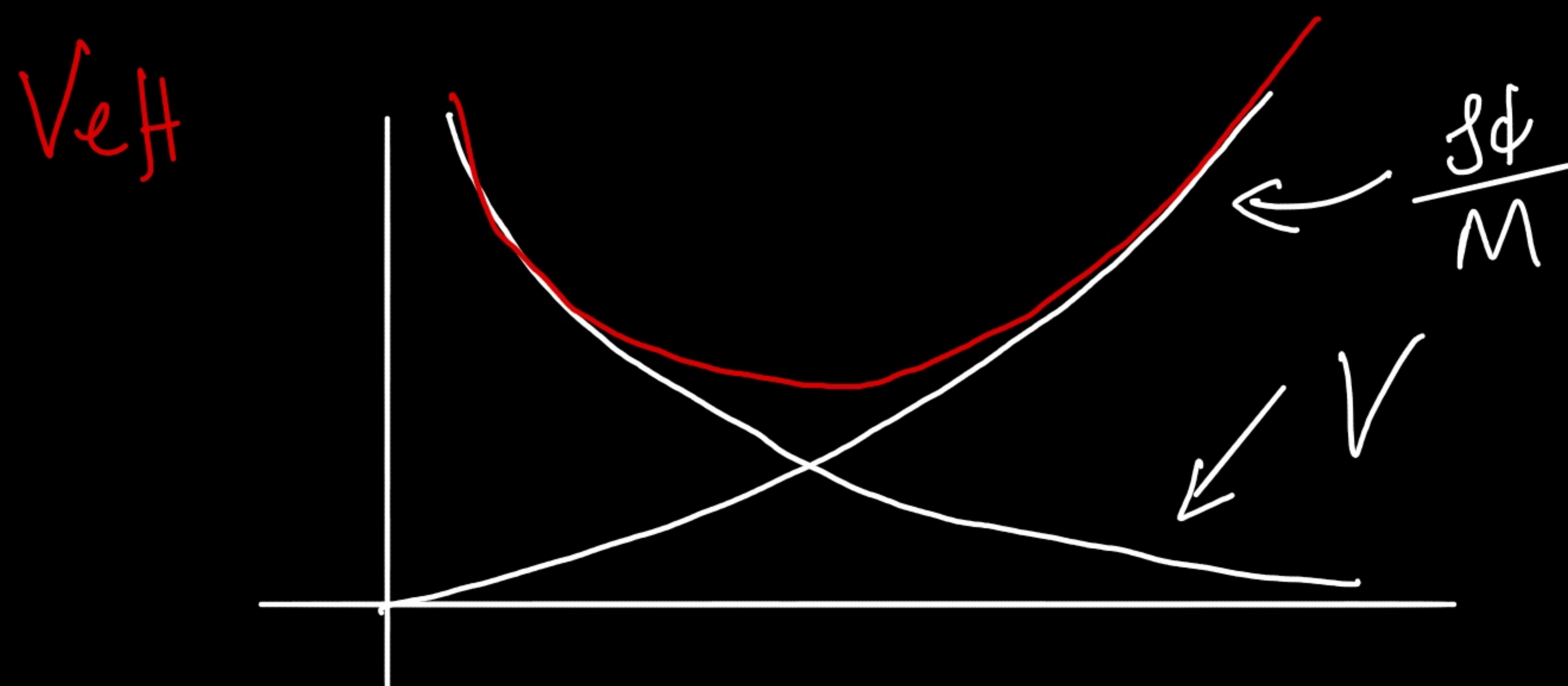
$$\Box\phi \simeq V' + \frac{\rho}{M} = V_{eff}'(\phi)$$

So $\boxed{V_{eff}(\phi) = V(\phi) + \frac{\rho\phi}{M}}$

Gravitational Screening : Chameleons.

$$V_{eff} = V(\phi) + \frac{\rho\phi}{M}$$

Assme: $V(\phi) = \Lambda^{4-n}\phi^{n} \qquad (n<0)$

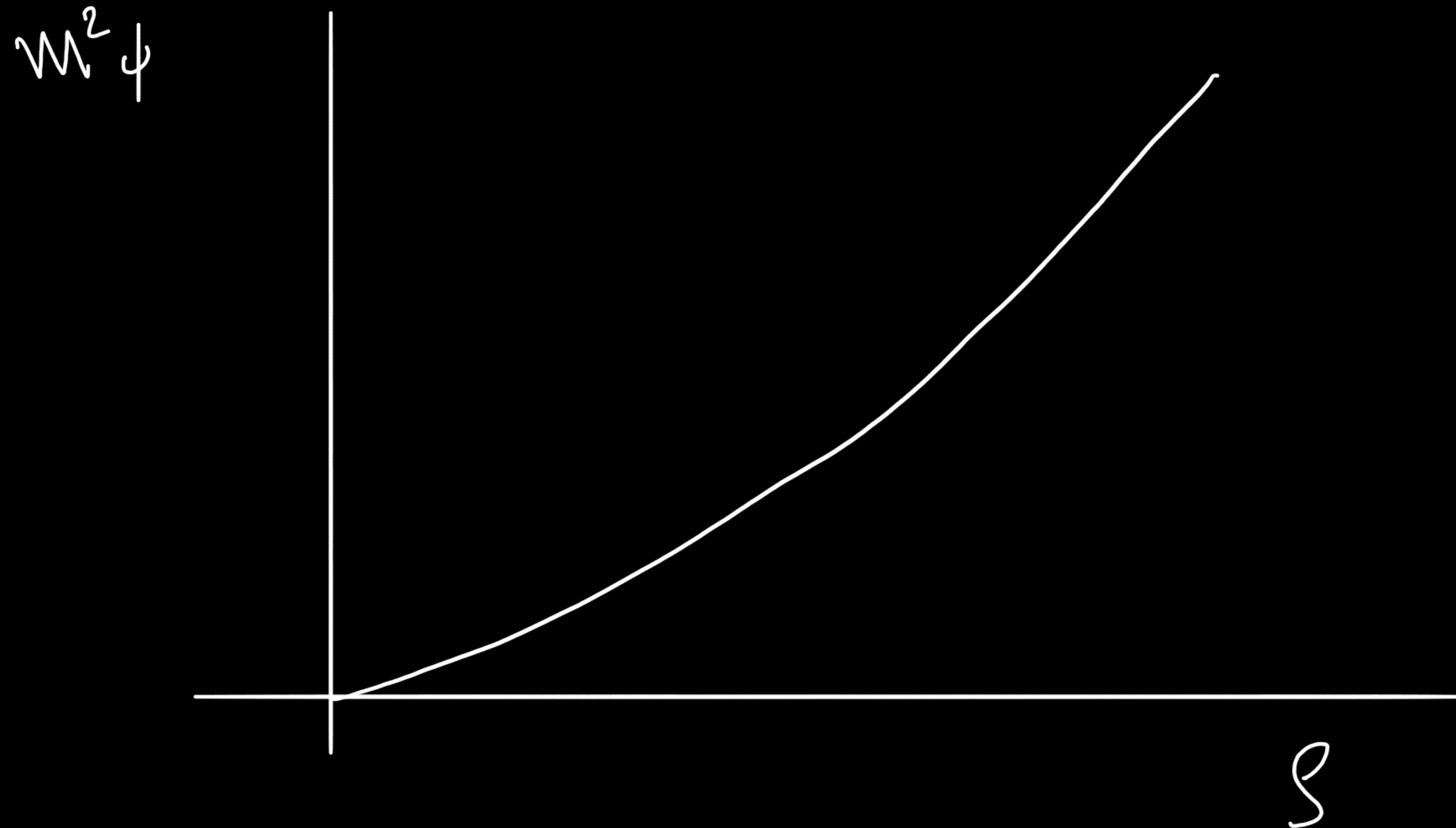


$$\phi_{min} = -\frac{\rho}{nM\Lambda^{4-n}}$$

Look at fluctuations around this background

$$m_\phi^2 = V'_{eff} = n(n-1)\Lambda^{4-n}\left(-\frac{\rho}{nM\Lambda^{4-n}}\right)^{\left(\frac{n-2}{n-1}\right)}$$

Gravitational Screening : Chameleons.

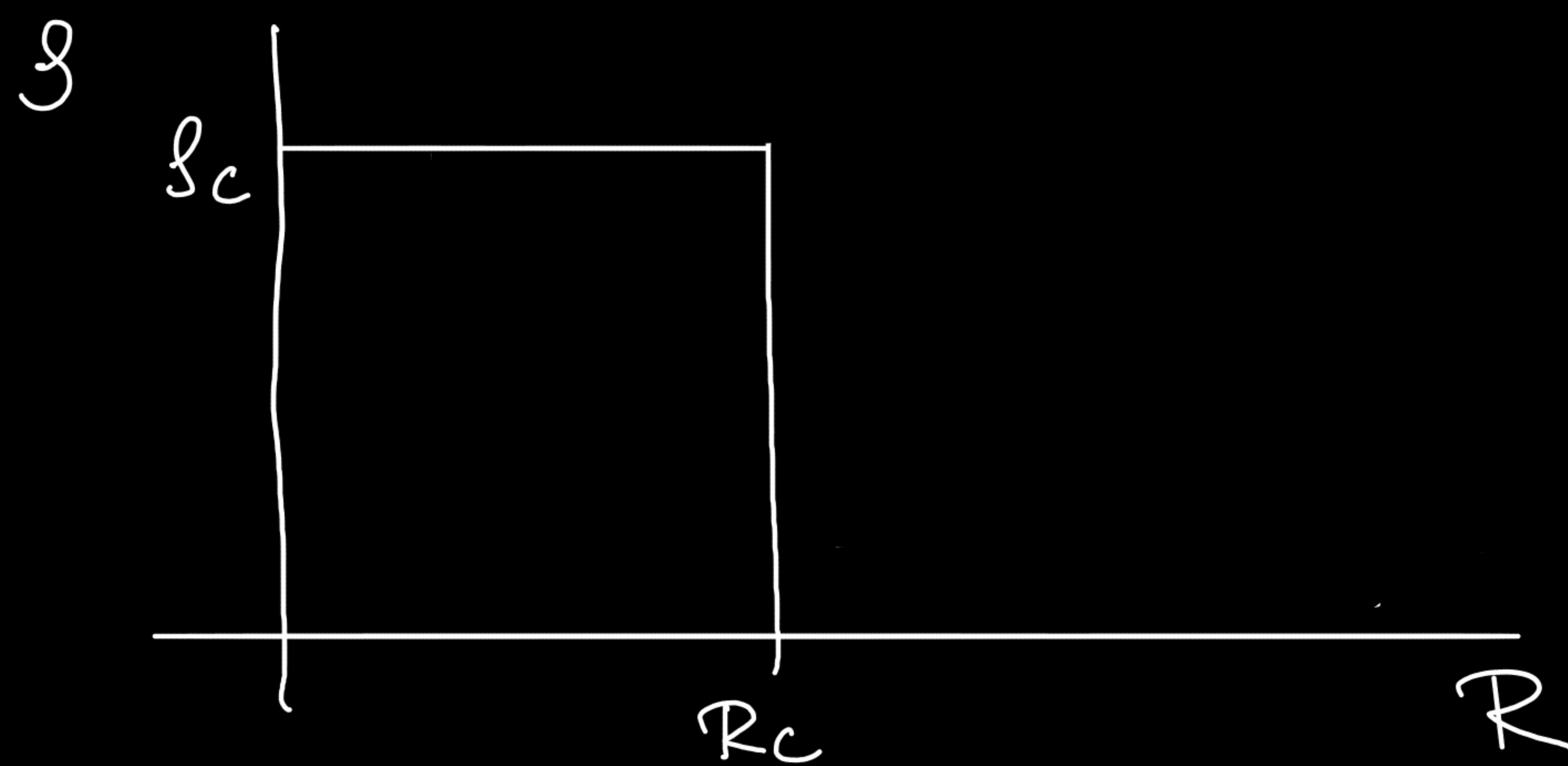


i.e $m^2_\phi(\rho) \to$ the range of 5th force depends on ρ!

High $\rho \Longrightarrow$ large $m^2_\phi \Longrightarrow$ short range $\Longrightarrow$ supressed!

Gravitational Screening : Chameleons.

Build a solution



$r > R_c$: Far away, ϕ_∞ set $\rho_\infty \longrightarrow m_\infty^2 = V''_{eff}(\phi_\infty)$

Regular solution: $\phi = \phi_\infty + \frac{A}{r} e^{-m_\infty r}$

Small object: ϕ will be a small perturbation around ϕ_∞. The effective potential $V_{eff} \sim \frac{\rho_c \phi}{M}$ density of small object

Gravitational Screening : Chameleons.

Small object (continued)

Solution

$$\phi = \begin{cases} \phi_\infty - \dfrac{M_c}{4\pi M R_c}\left(2 - \dfrac{r^2}{R_c^2}\right) & 0 < r < R_c \\[2ex] \phi_\infty - \dfrac{M_c}{4\pi M r}\, e^{-m_\infty (r - R_c)} & r > R_c \end{cases}$$

If $m_\infty r \ll 1$

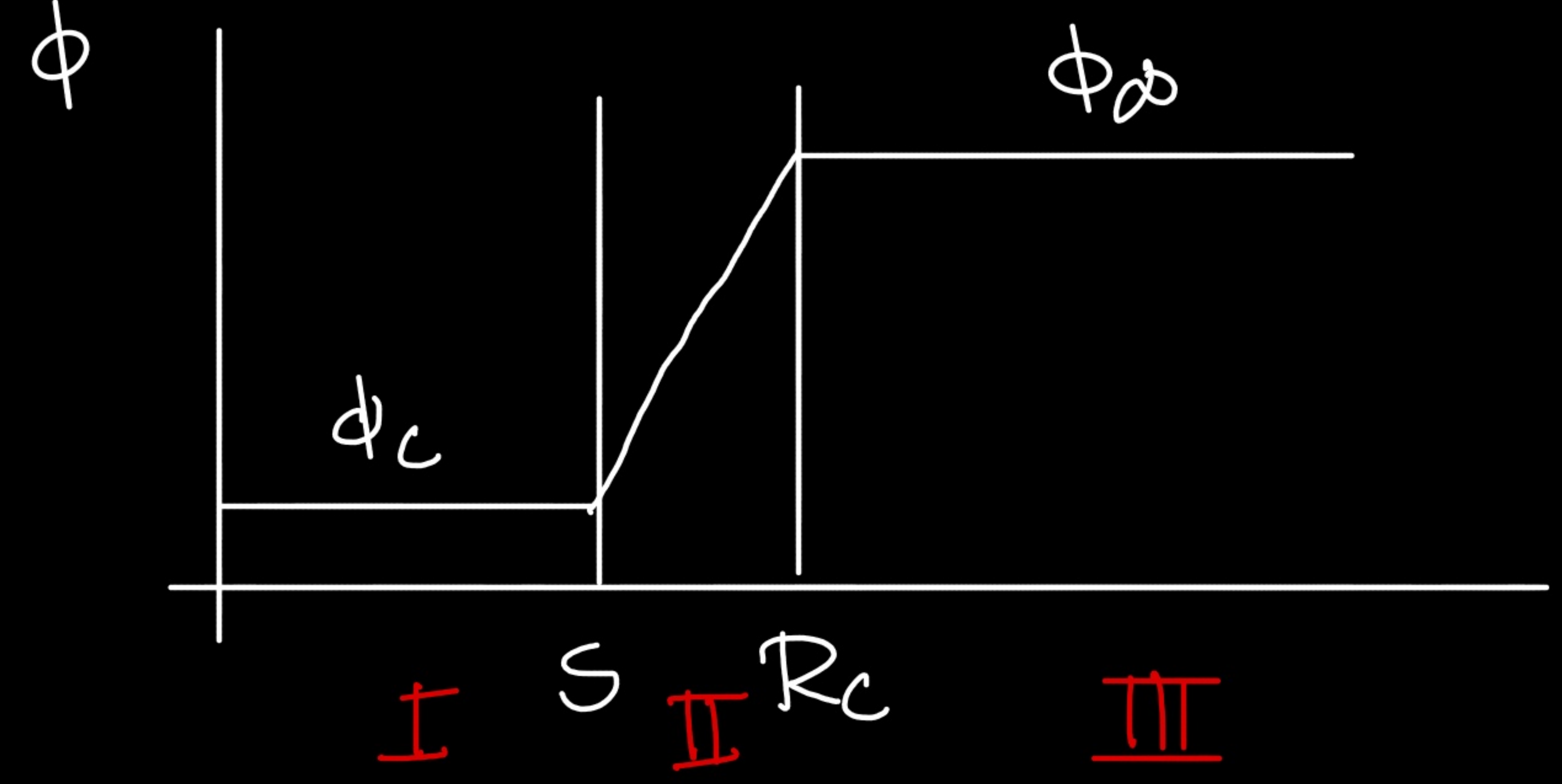
$$|F| = \frac{M_c}{4\pi M^2 r^2} \sim \text{Newtonian.}$$

Density has no effect $\rightarrow$ there is a Newtonian like Fifth force.

Gravitational Screening : Chameleons.

Large Object / High Density

Can't expand around ϕ_∞ but $\phi_c(\rho_c)$



Solution

$$\phi = \begin{cases} \phi_c & \mathrm{I} \\ \dfrac{\rho_c r^2}{6M} + \dfrac{C}{r} + D & \mathrm{II} \\ \phi_\infty + \dfrac{A}{r} e^{-m_\infty r} & \mathrm{III} \end{cases}$$

Need to match A, C, D and $\underline{\underline{S}}$.

Gravitational Screening : Chameleons.

Large Object / High Density (continued)

Solve to find: $\dfrac{R_c - S}{R_c} \ll 1 \implies$ Thin shell

$$\frac{F_\phi}{F_N} = \frac{\frac{\phi_\infty}{M}}{\frac{GM_c}{R_c}} \ll 1 \implies$$ 5th force is supressed.

So near heavy objects / dense objects we have that

Fifth Force is screened!

Gravitational Screening : Chameleons.

In practice :

- in dense objects we don't see fifth force

  e.g : in our Galaxy, in clusters

- near dense objects we don't see, they don't feel fifth force

  e.g: stars, compact objects.

- Diffuse material will feel fifth force

  e.g: gas, dark matter halo

- Empty regions of space will enhance fifth force

  e.g: voids.

Gravitational Screening : Vainshtein.

Coupling to matter is supressed

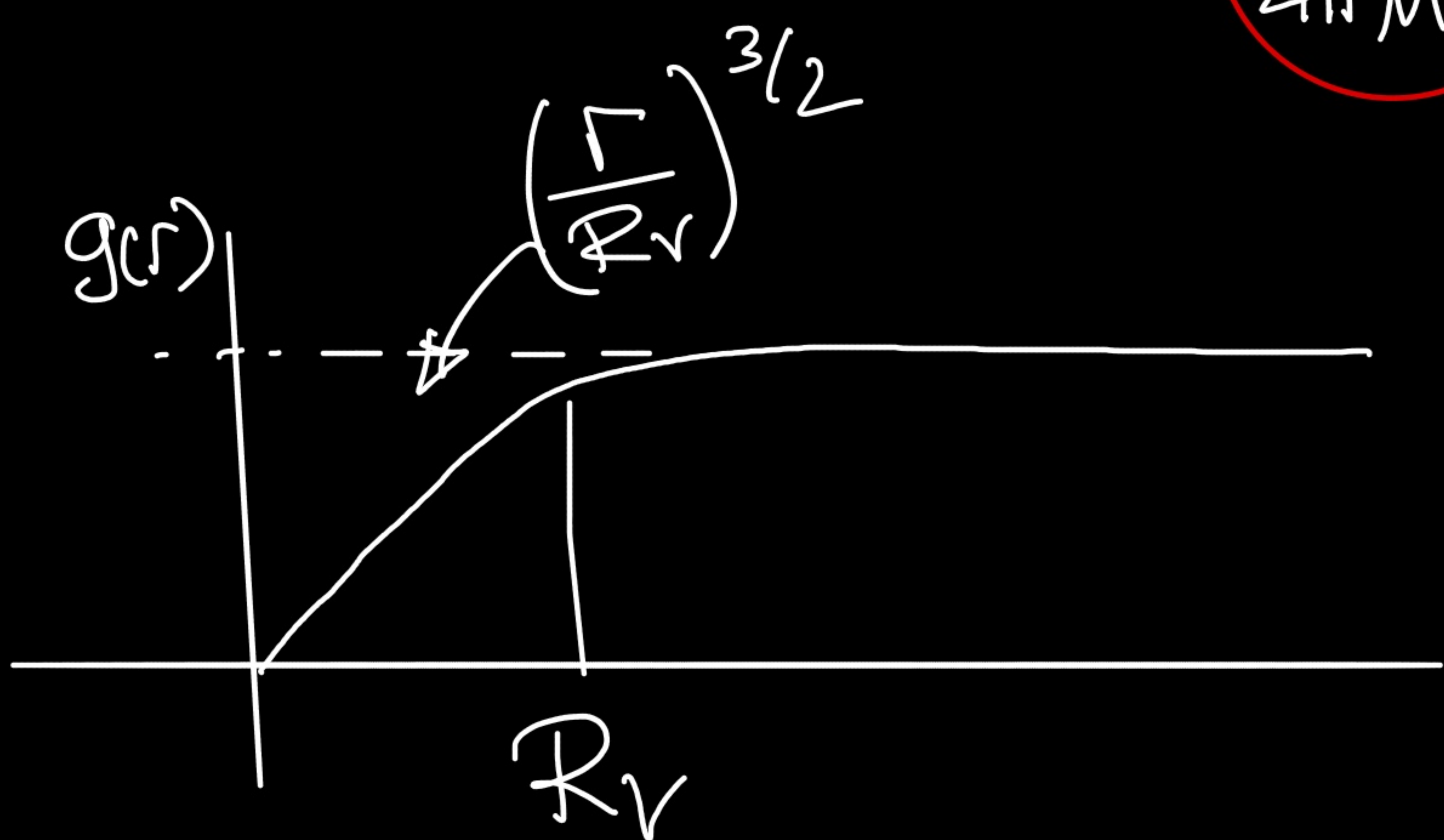
Babichev & Deffayet
CQG, 30, 184001 (2013)

Eg: Galileon

$$\mathcal{L} = (\partial\phi)^2 + \frac{c_3}{\Lambda^3}\Box\phi\,(\partial\phi)^2 + \frac{\phi}{M}T^{\mu}{}_{\mu}$$

Newtonian force

Solve, assume $\partial_r\phi(r) = \frac{M_c}{4\pi M r^2}\, g(r)$



Vainshtein Radius

$$R_V = \frac{1}{\Lambda}\left(\frac{c_3 M_c}{4\pi M}\right)^{1/3}$$

Depends on M_c!

Inside R_V, force is supressed.

Summary

- Extra fields generally lead to fifth forces
- Fifth forces are well constrained in certain regimes
- Natural mechanisms to supress them → Screening
- Chameleon screening → environment/density
- Vainshtein screening → size of object.