Nonlinear Cosmological Probes of Screening Mechanisms in Modified Gravity

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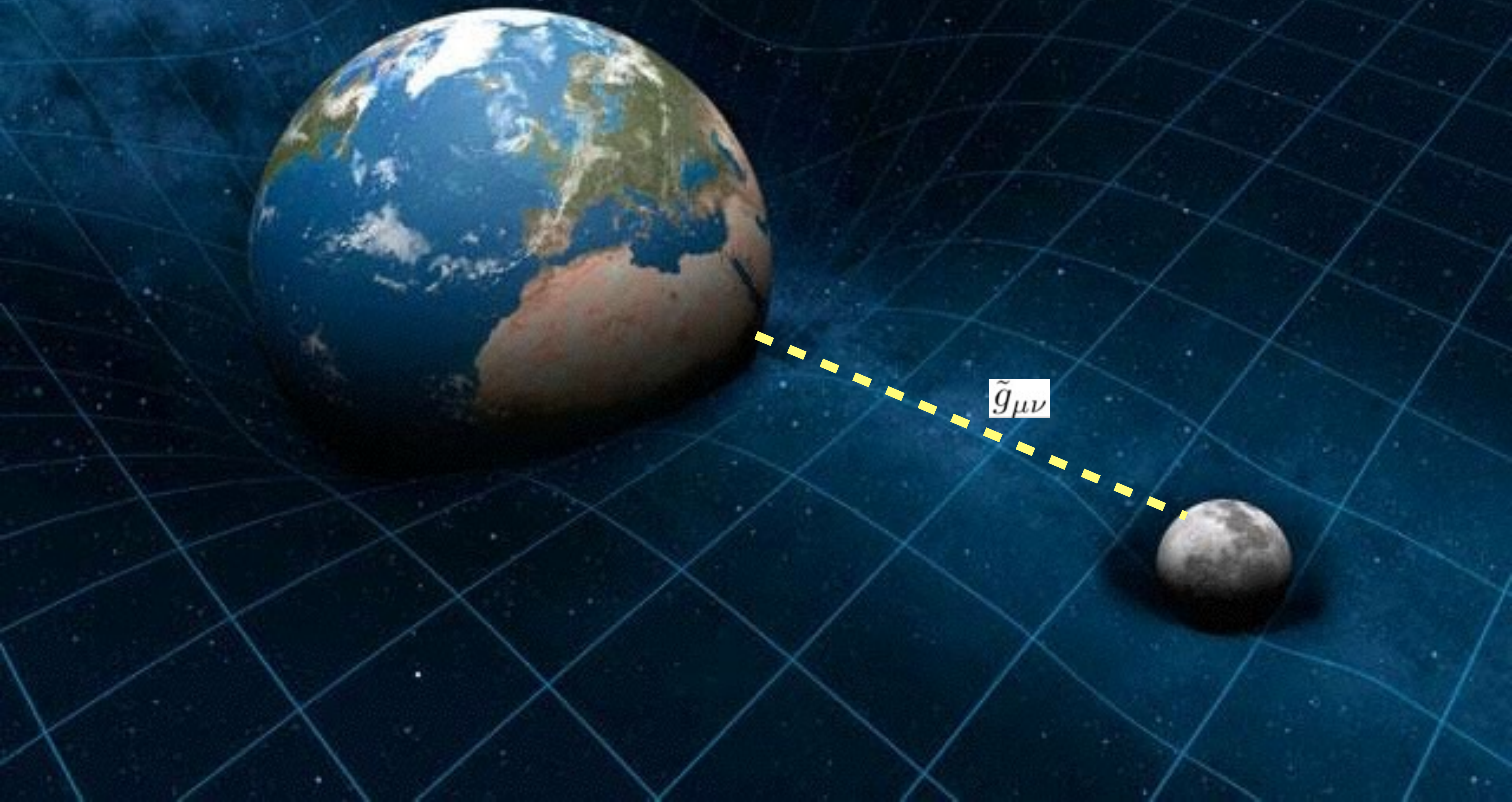
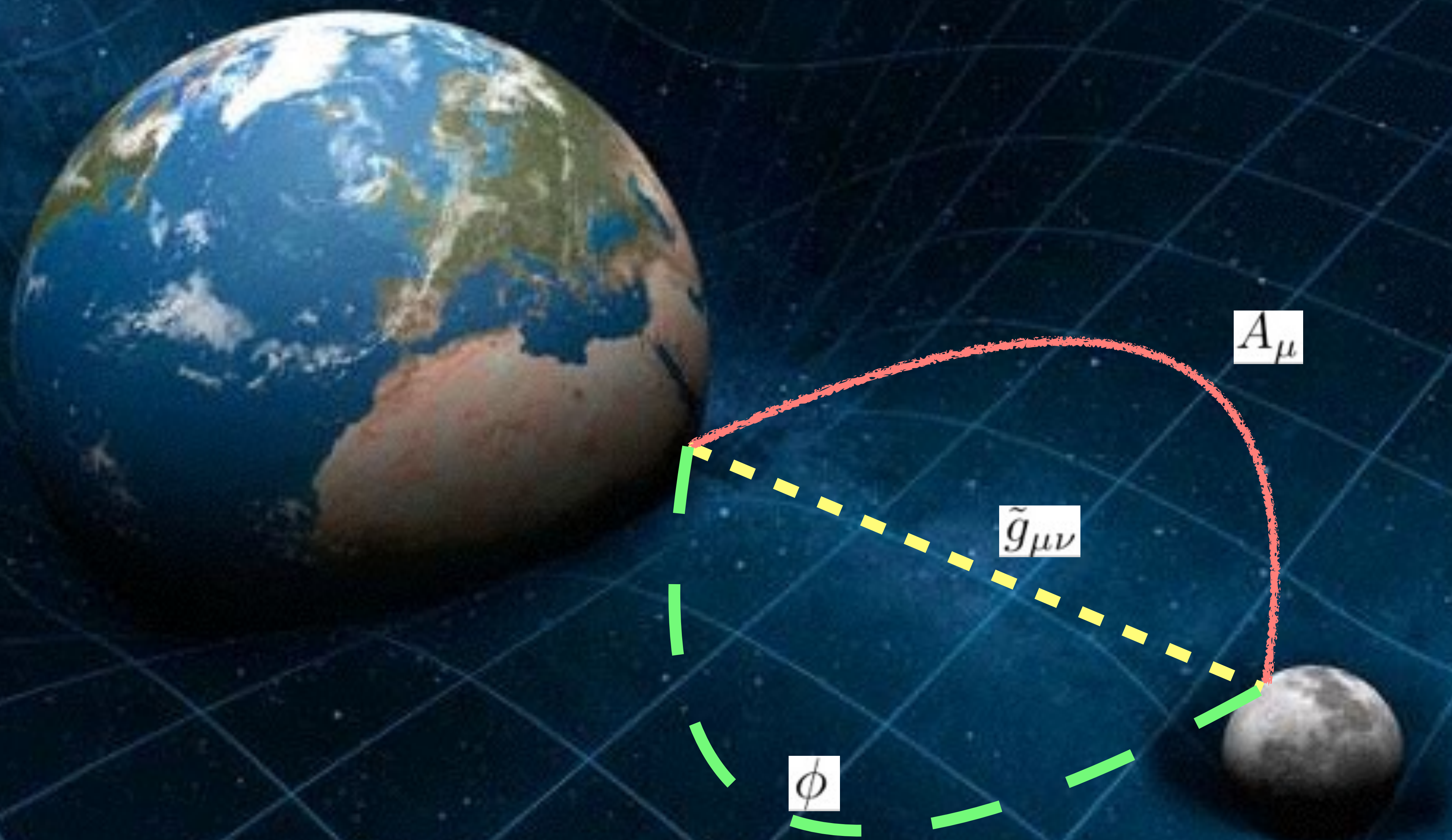
General Relativity: One field

- General Relativity is a theory where gravity is mediated by a tensor field $\tilde{g}_{\mu\nu}$



Modified Gravity: Extra degrees of freedom

- Gravity may be mediated by a tensor field $\tilde{g}_{\mu\nu}$, and/or a vector field A_μ , and/or a scalar field ϕ

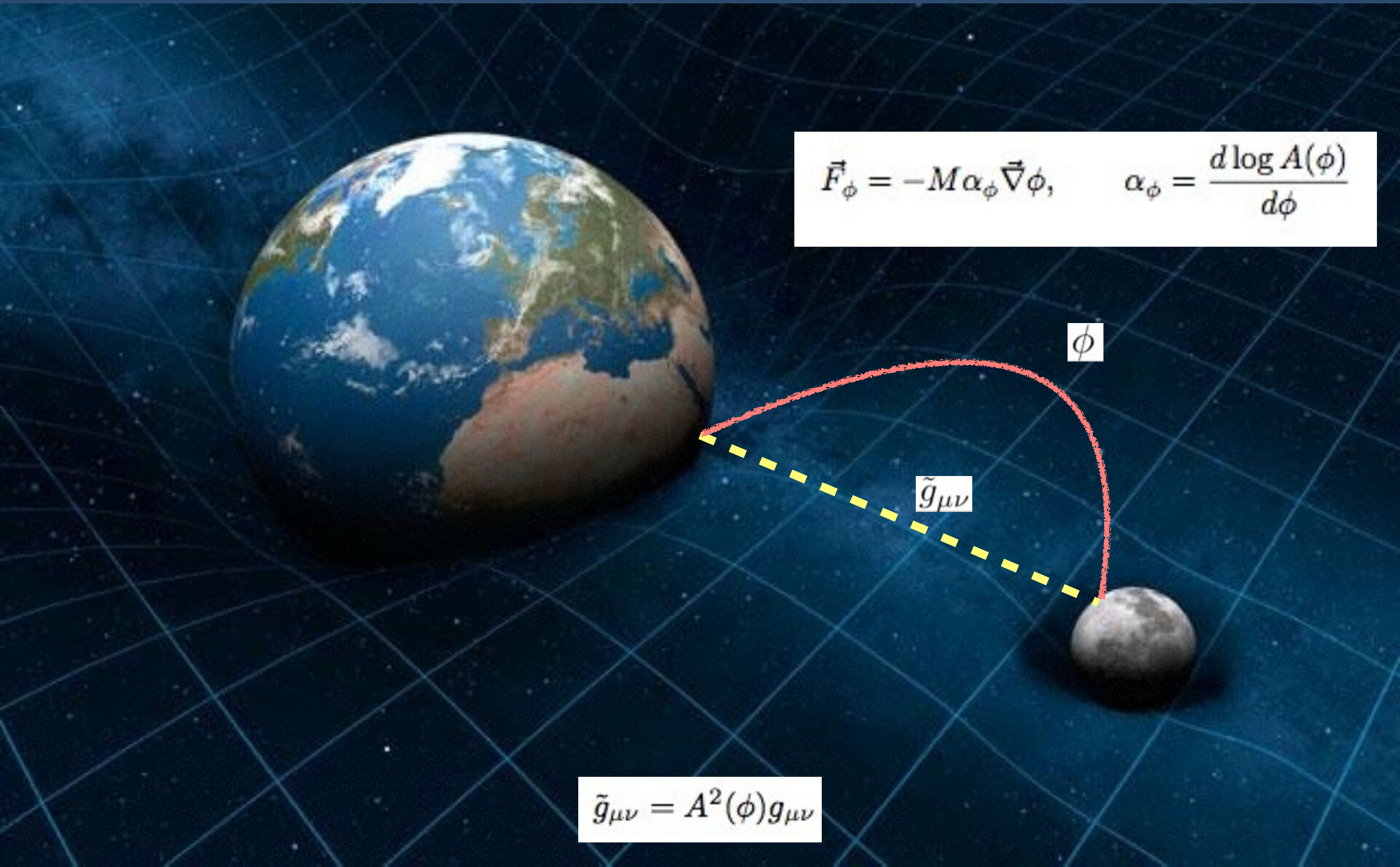


- Spacetime geometry may be a combination of all:

$$g_{\mu\nu} = e^{-2\phi}(\tilde{g}_{\mu\nu} + A_\mu A_\nu) - e^{2\phi} A_\mu A_\nu .$$

Scalar-Tensor Theories

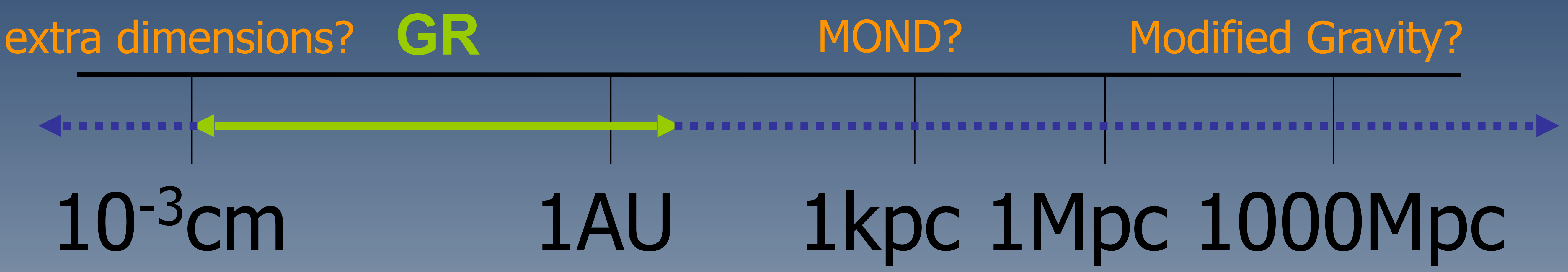
Extra scalar degree of freedom (fifth force)

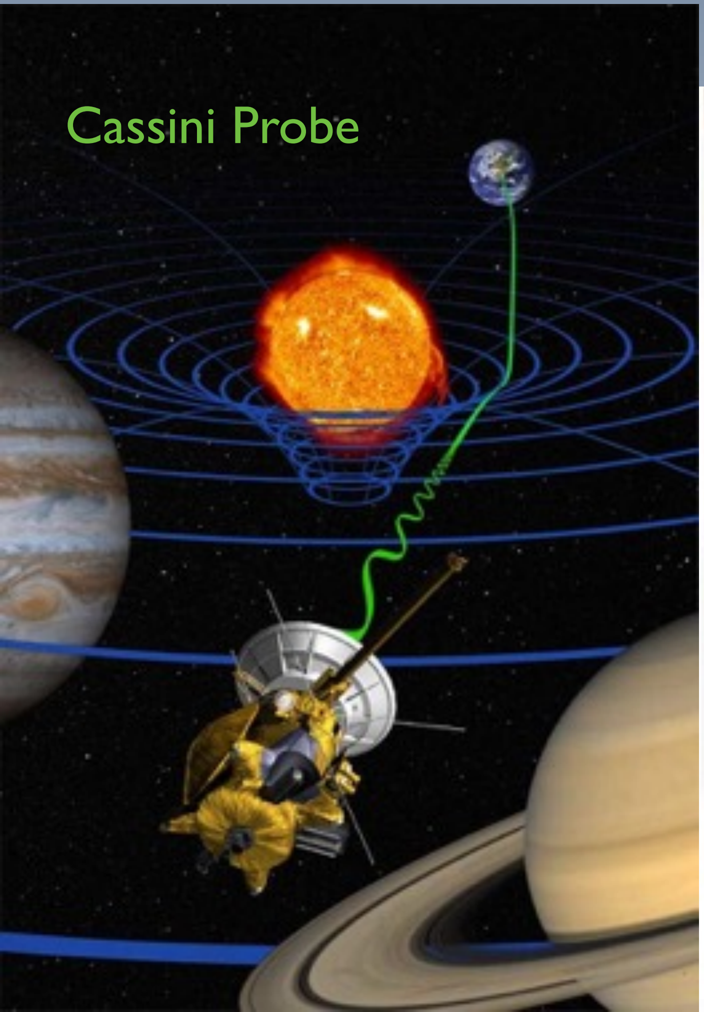


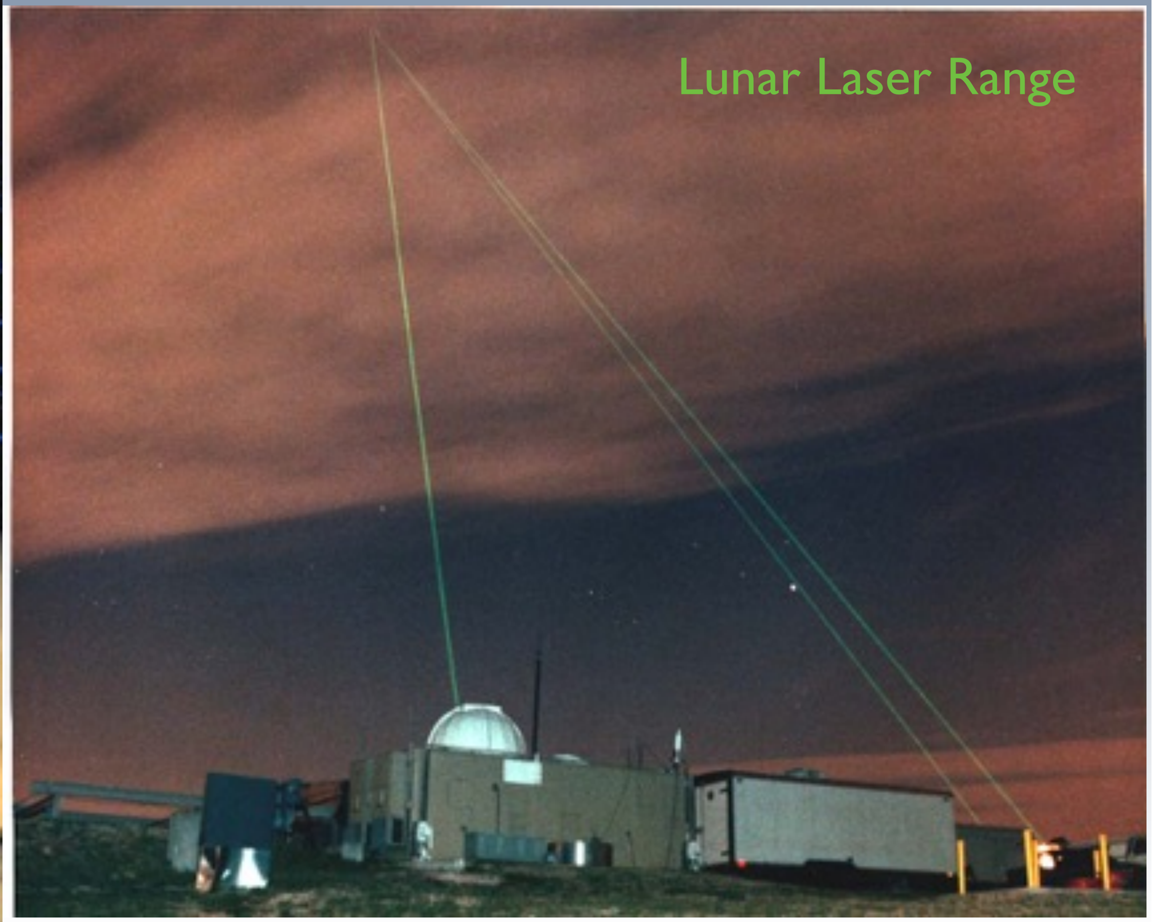
$$\vec{F}_\phi = -M\alpha_\phi \vec{\nabla}\phi, \qquad \alpha_\phi = \frac{d\log A(\phi)}{d\phi}$$

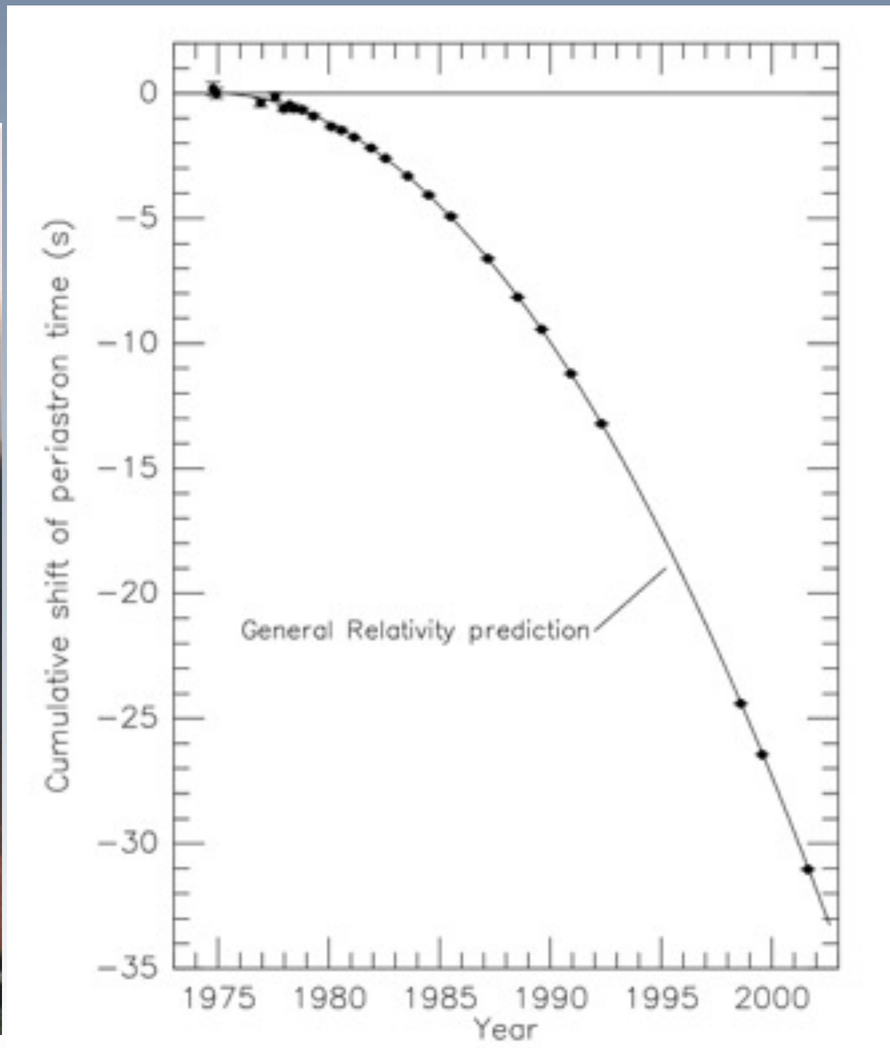
$$\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$$

Extremely tight constraints on Modified Gravity at *small scales and "strong" gravitational fields!*



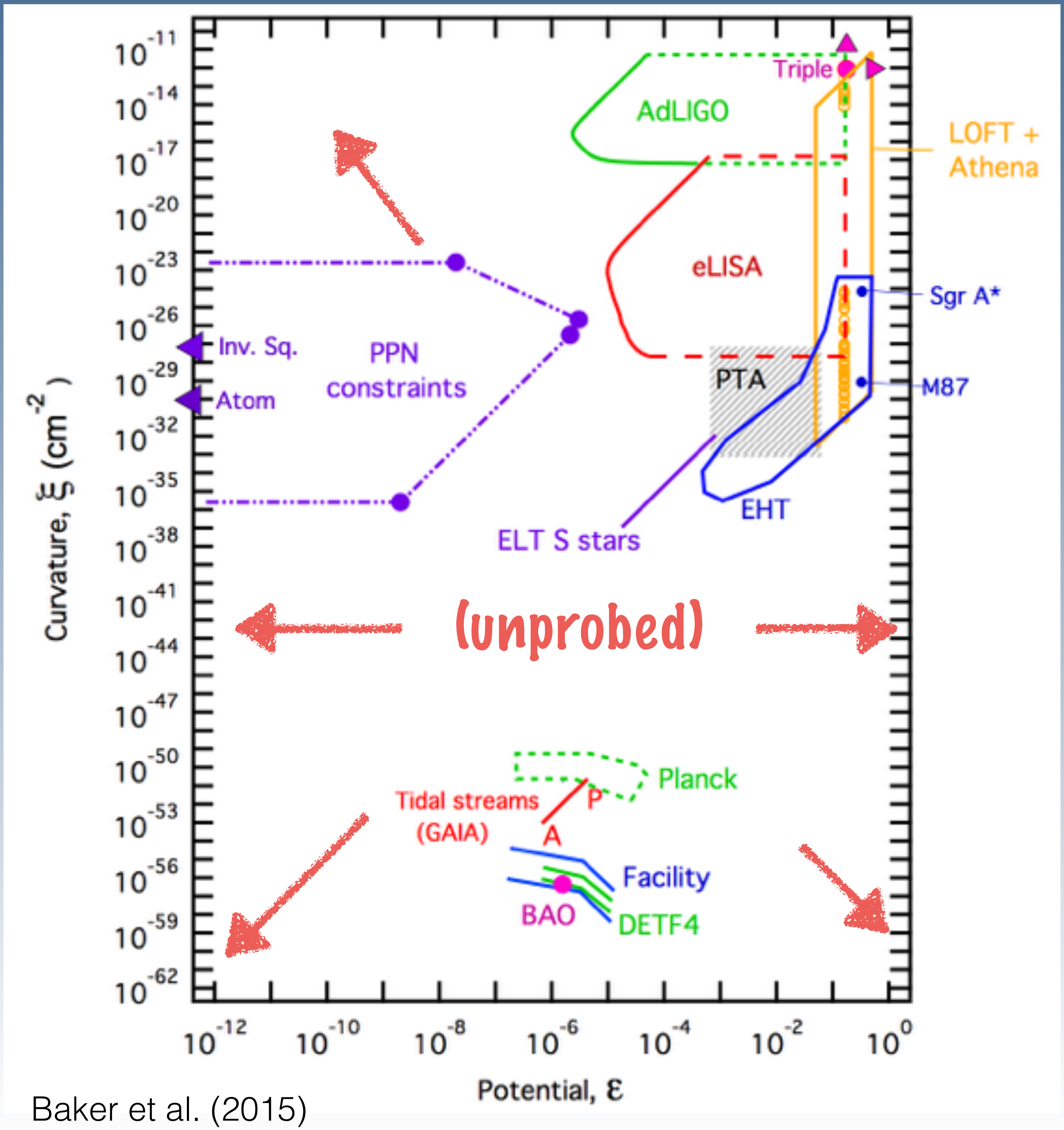






Extremely *loose* constraints on Modified Gravity at *large scales and "weak" gravitational fields!*

50 orders of magnitude!



Baker et al. (2015)

Modified Gravity as Dark Energy

$$\int dx^4 \sqrt{g}\left[f(R) + L_{matter}\right]$$

$$\int dx^4 \sqrt{g}\left(R + R^2 + R^3 + \ldots\right)$$

✓ f(R) models are simple

✓ easy to produce acceleration (first inflationary model)

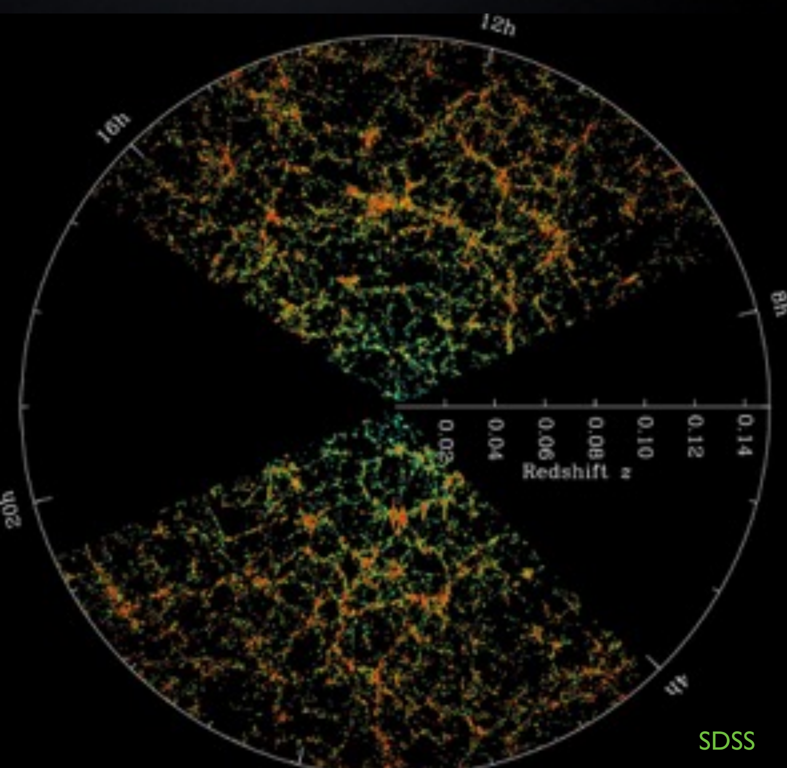
✓ high-energy corrections to gravity likely to introduce higher-order terms

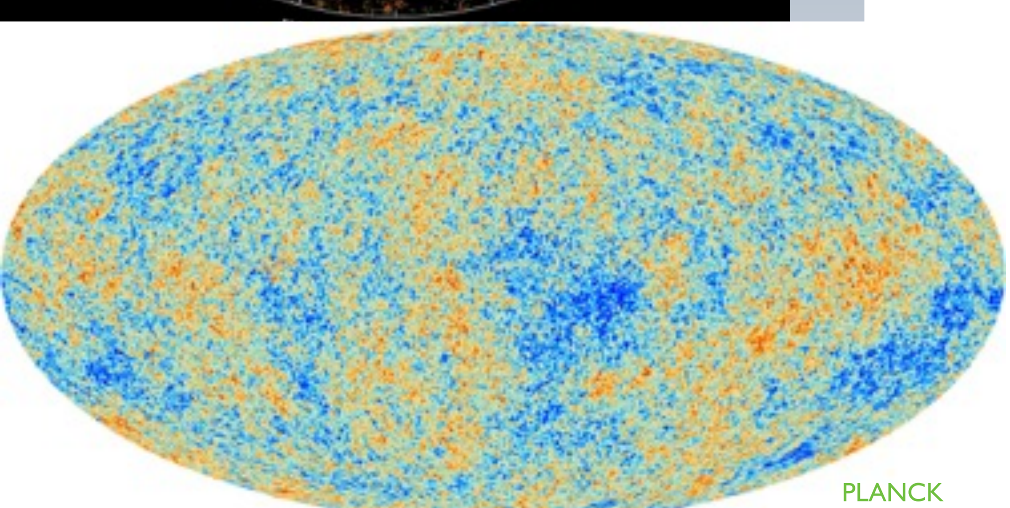
✓ particular case of scalar-tensor and extra-dimensional theory

$$\mathcal{L}_{ModGrav} = R - \alpha \frac{1}{R}$$

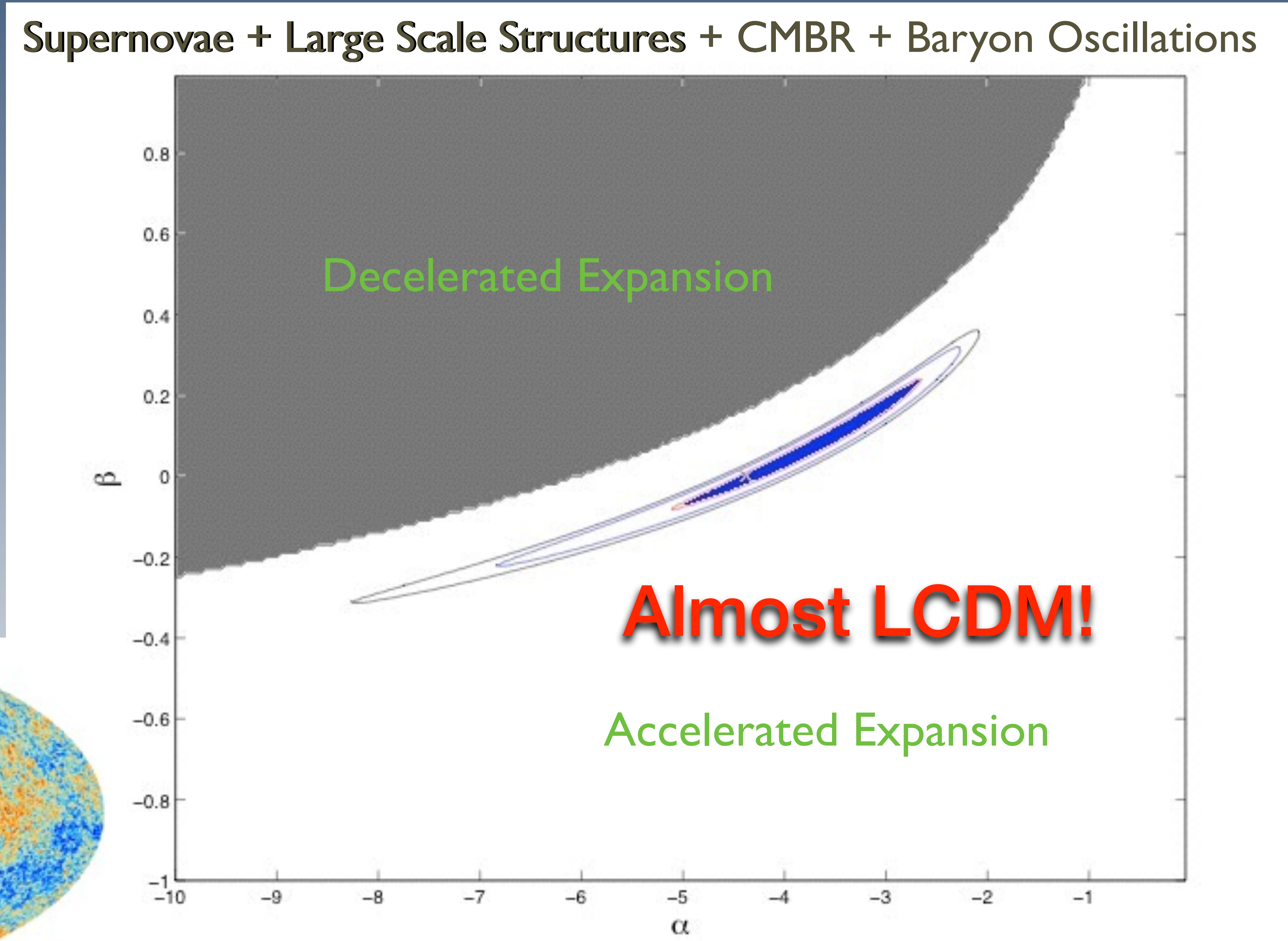
Negative Pressure!

Large Scale Structure Formation: deviations from GR must be small





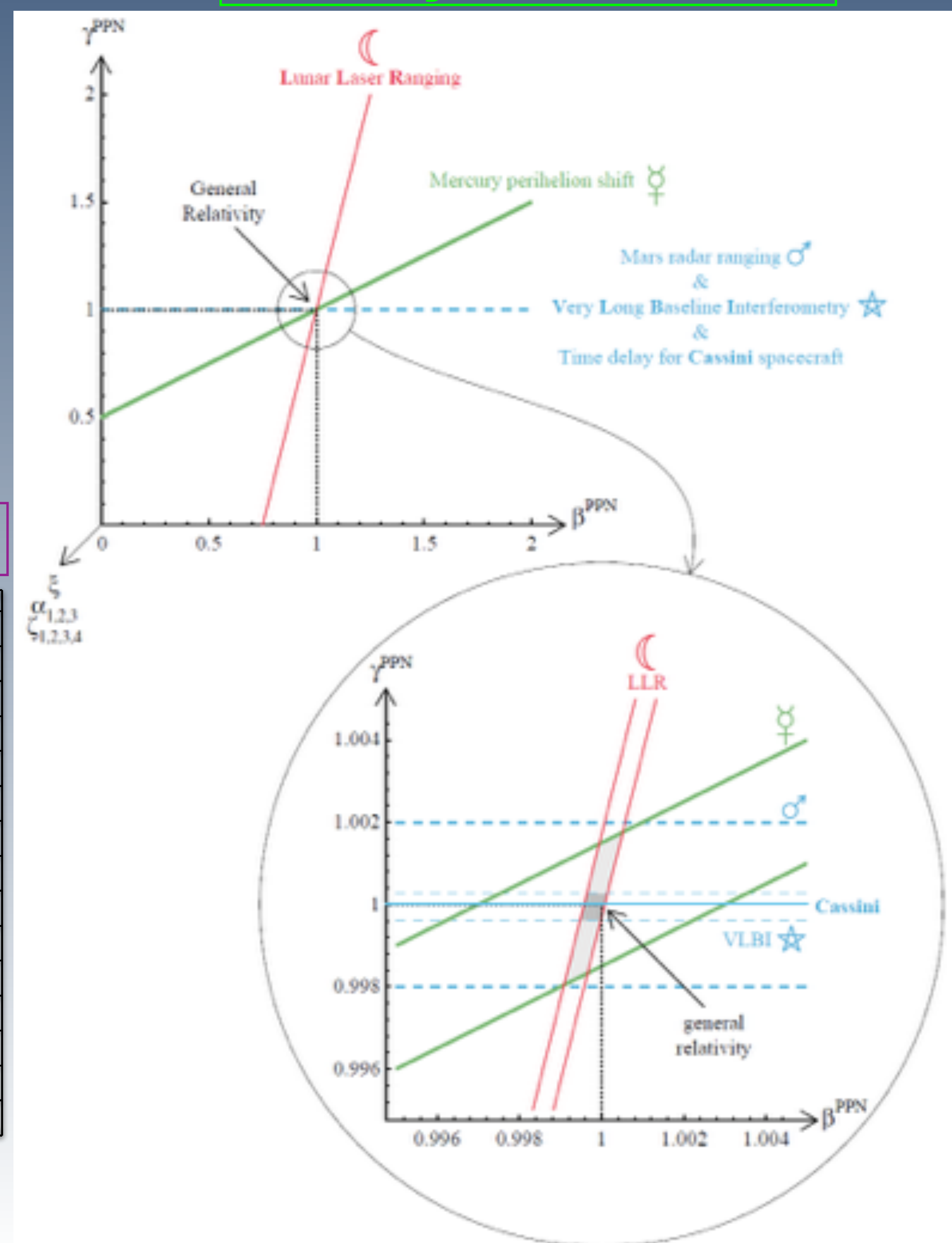
$$\mathcal{L}_{ModGrav} = R - \alpha R^{\beta}$$



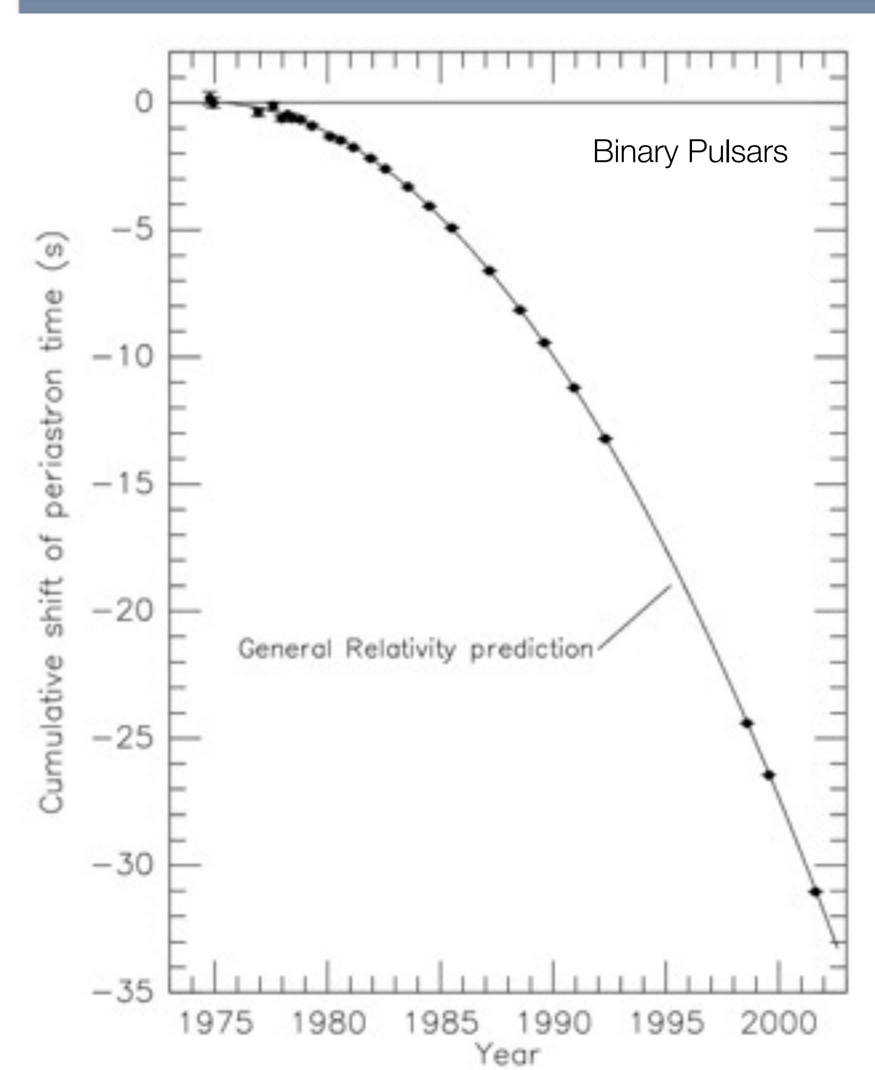
How to Modify Gravity and evade constraints?

Screening Mechanisms!

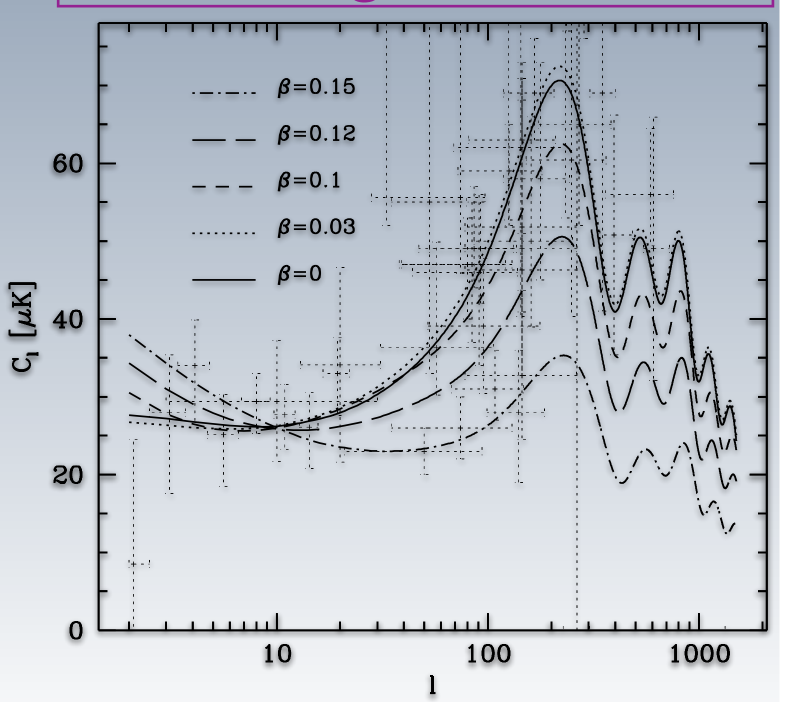
Solar System Bounds



Strong Field Bounds



Cosmological Bounds



Amendola PRD (1999)

Screening mechanisms key elements

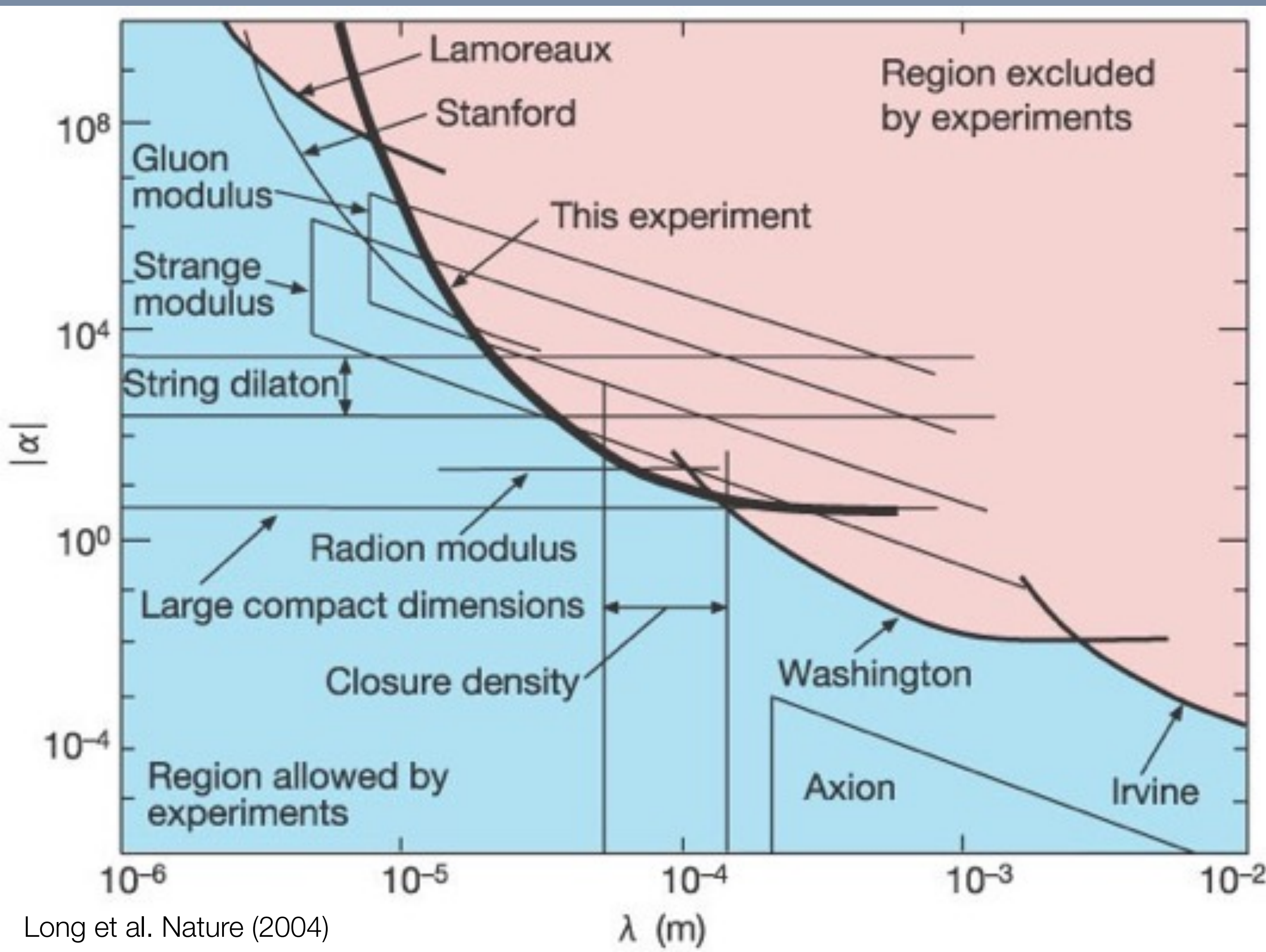
$$S = \int dx^4 \sqrt{-g} \left[\frac{R}{2} M_{\rm pl}^2 - \frac{1}{2}(\partial\phi)^2 - V(\phi) \right] + S_m(A^2(\phi) g_{\mu\nu}, \psi_i)$$

Scalar bosons produce Yukawa potential: $\Psi(r) = -\frac{GM}{r}(1 + \alpha e^{-r/\lambda})$

coupling

range

$$\alpha \sim \mathcal{O}(1) \Rightarrow \lambda \sim 0.1mm$$



Long et al. Nature (2004)

If extra scalar for gravity, then:
Either coupling becomes very small in Solar System
or…
the range becomes very short in Solar System

scale dependent coupling/range!

Range of Fifth Force on Scalar-Tensor Gravity

$$\Psi(r) = -\frac{GM}{r}(1+\alpha e^{-r/\lambda})$$

range

$$S = \int dx^4 \sqrt{-g}\left[\frac{R}{2}M_{\rm pl}^2 - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right] + S_m(A^2(\phi)g_{\mu\nu}, \psi_i)$$

$$\Box\varphi = \frac{dV_{\rm eff}}{d\varphi}$$

$$V_{eff}(\phi) = V + \rho e^{\alpha\phi/M_{pl}}$$

$$m_\phi = \sqrt{V''_{eff}(\phi_c)}$$

$$\lambda = \frac{\hbar}{mc}$$

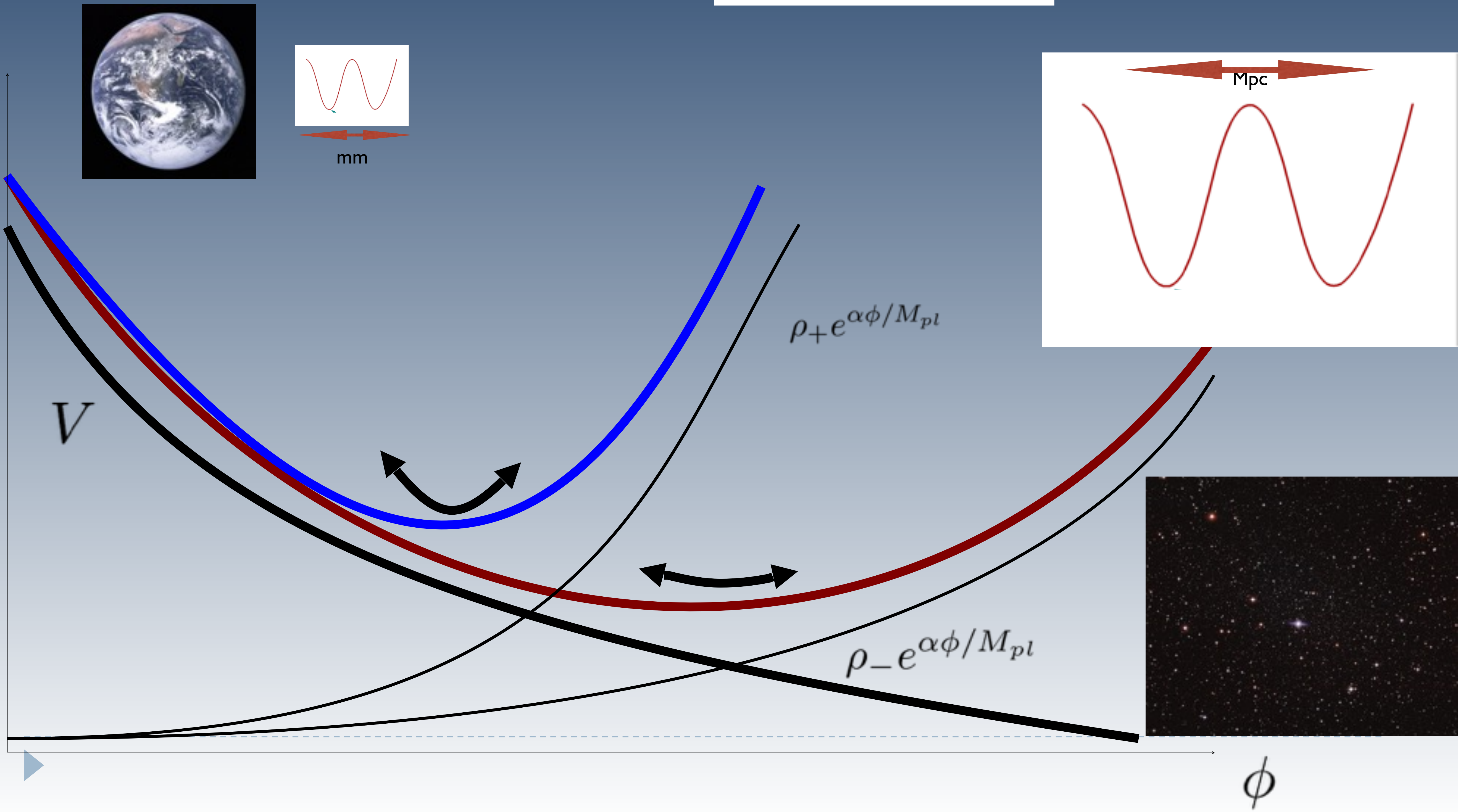
Chameleon Screening: range of fifth force depends on local density

$$S = \int dx^4 \sqrt{-g}\left[\frac{R}{2}M_{\rm pl}^2 - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right] + S_m(A^2(\phi)g_{\mu\nu}, \psi_i)$$

- Nonlinear mass/range

$$V_{eff}(\phi) = V + \rho e^{\alpha\phi/M_{pl}}$$

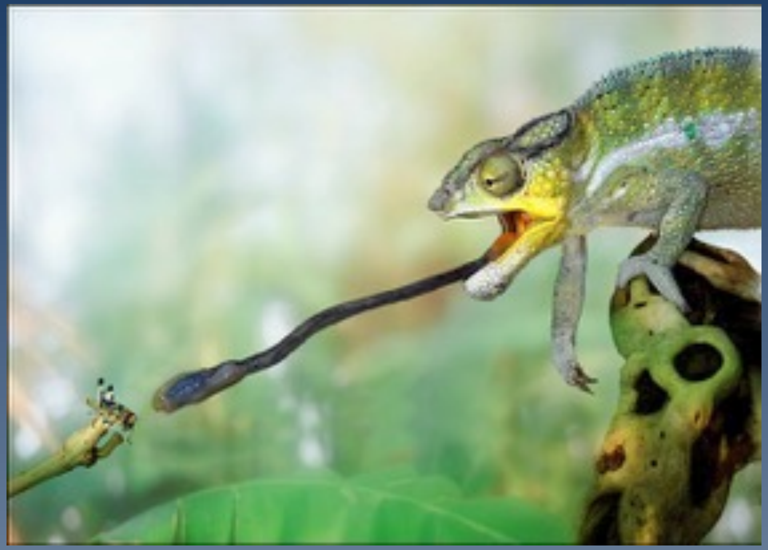
$$\lambda_{\rm Fifth} = \left(\frac{d^2 V_{\rm eff}}{d\varphi^2}\Big|_{\rm min}\right)^{-1/2}$$

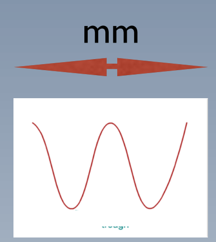


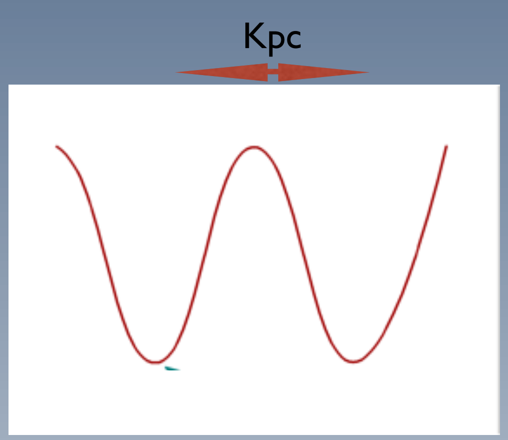
Chameleon mechanism

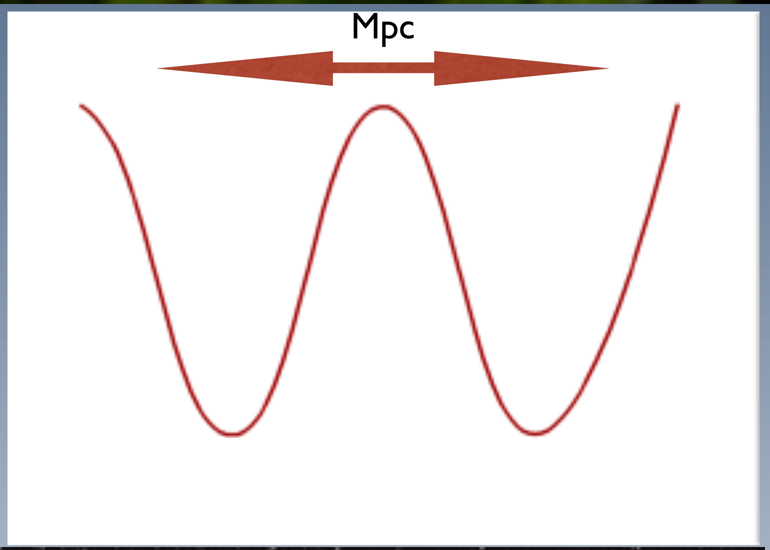
Range of dark force depends on local environment

(Khoury & Weltman 2004)









Symmetron Screening: coupling of fifth force depends on local density

$$S = \int dx^4 \sqrt{-g}\left[\frac{R}{2}M_{\rm pl}^2 - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right] + S_m(A^2(\phi)g_{\mu\nu}, \psi_i)$$

- Nonlinear coupling

$$\Psi(r) = -\frac{GM}{r}(1+\alpha e^{-r/\lambda})$$

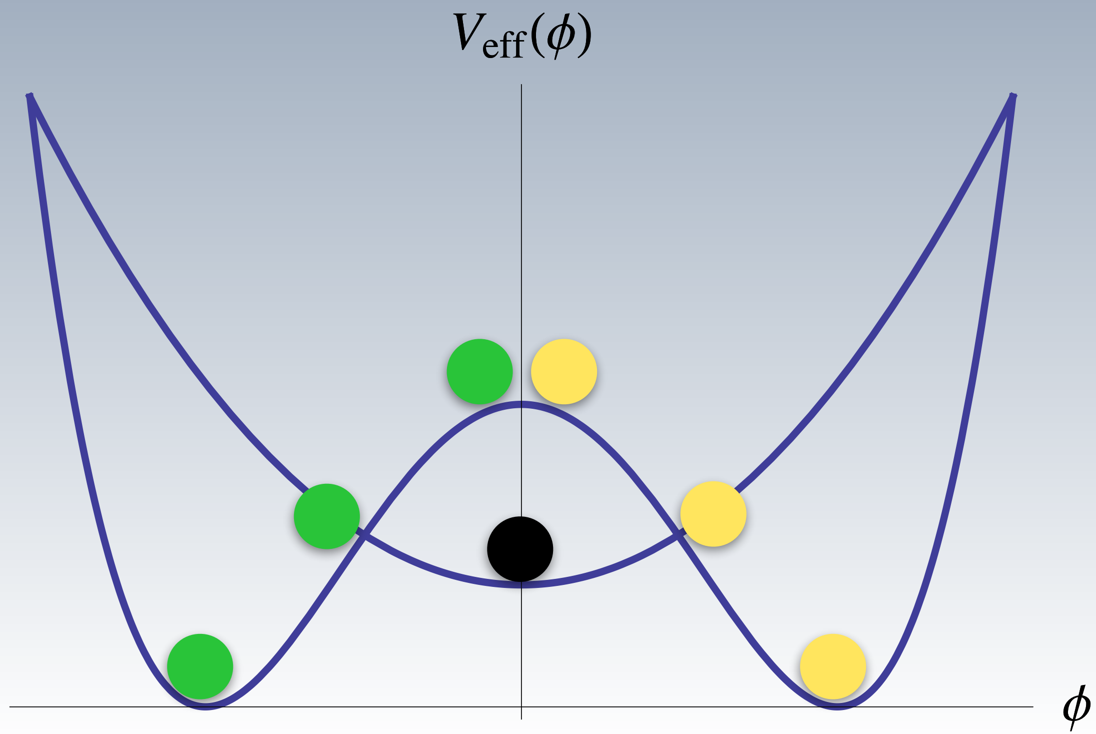
coupling

$$A(\phi) = 1 + \frac{1}{2M^2}\phi^2$$

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

No coupling!

$$A(\phi) = 1$$



coupled!

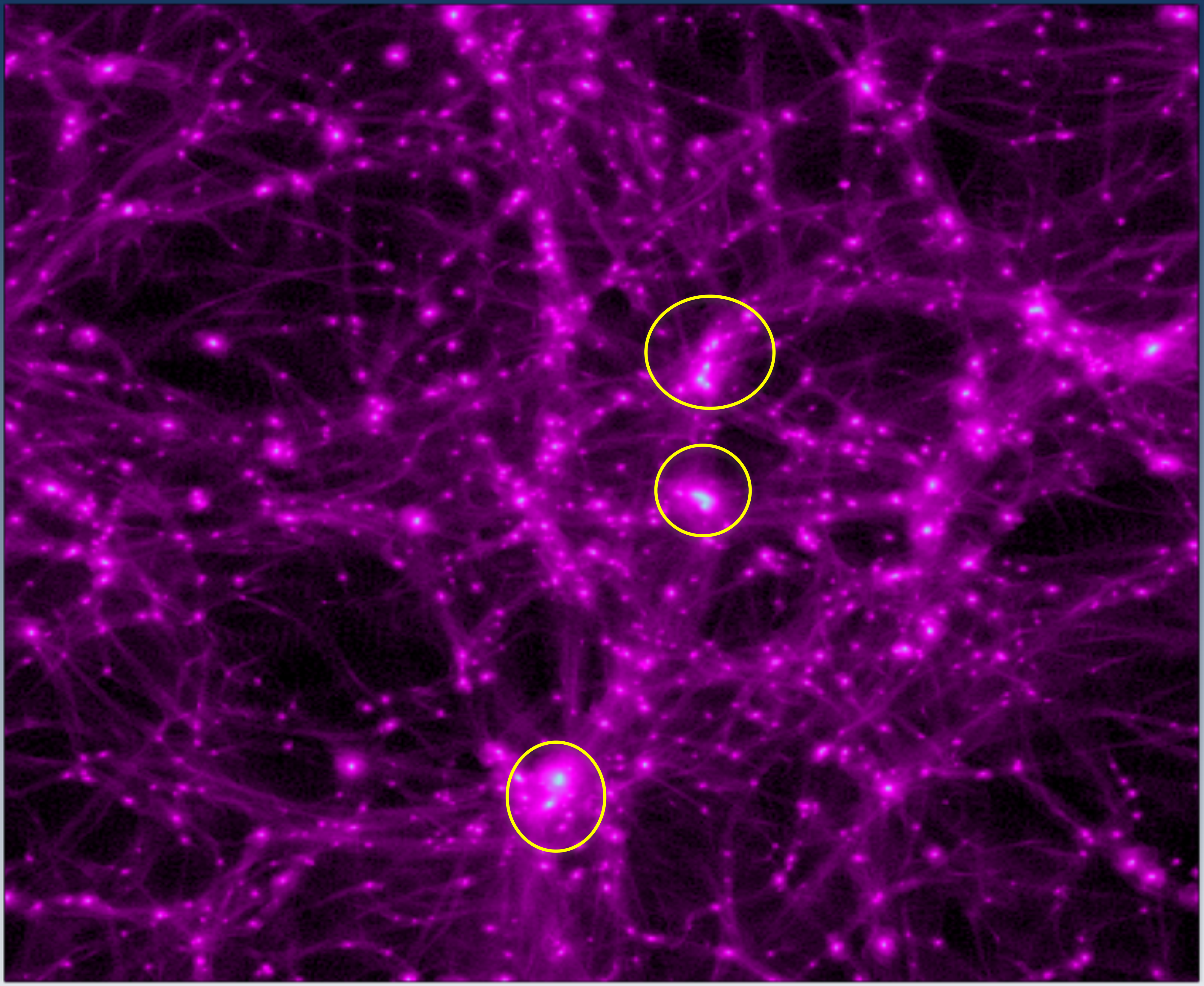
$$A(\phi) = 1 + \frac{1}{2M^2}\phi_{\rm vev}^2$$

Symmetron mechanism

Strength of dark force depends on local environment

(Hinterbicheler & Khoury 2010)

Structure formation probes deviations from GR



f(R)

Llinares, DFM & Winther, ApJ

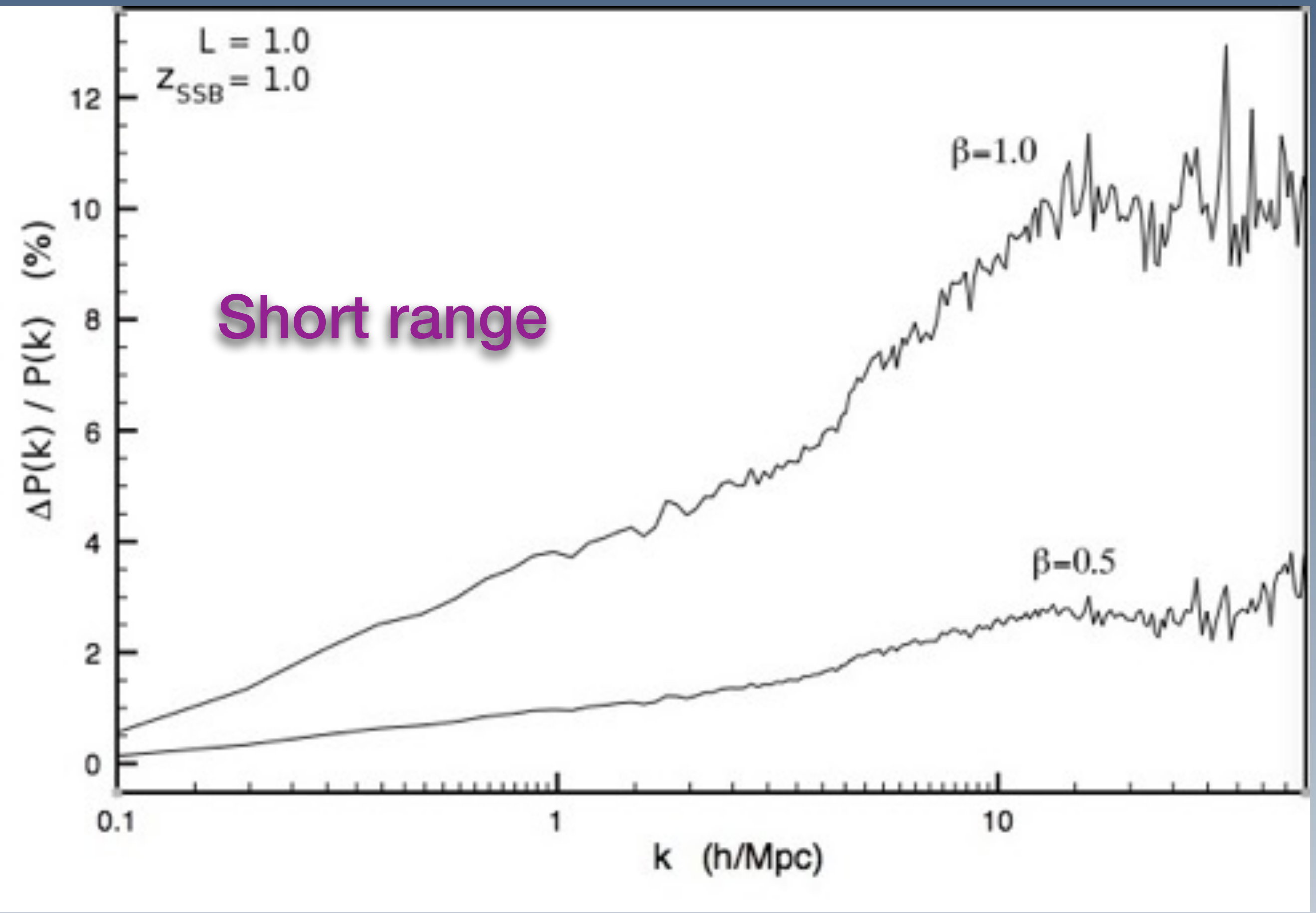
Structure formation dependence on coupling and range

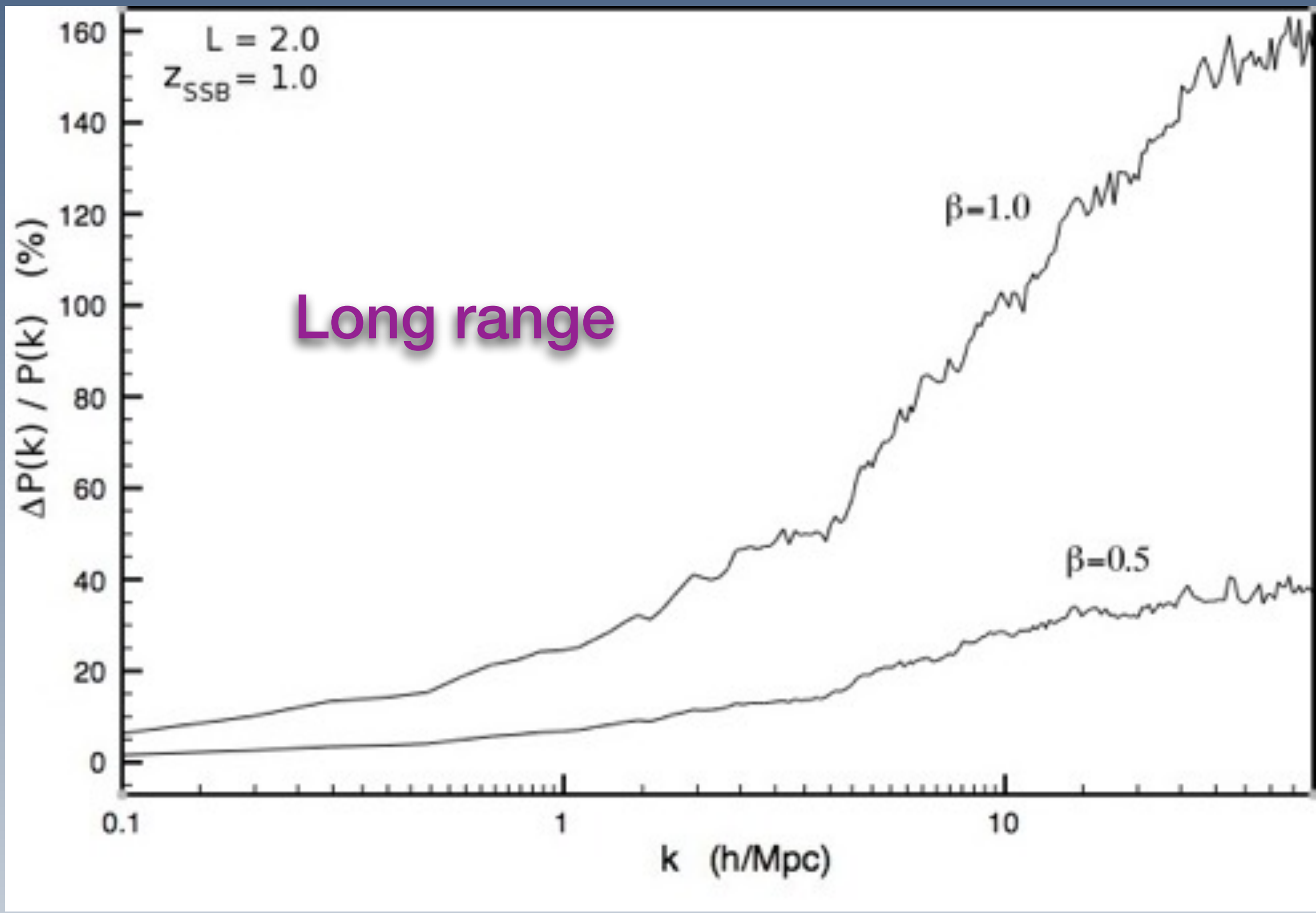
$$\frac{G_{\rm eff}(r)}{G} = 1 + 2\beta^2 e^{-r/\lambda_\phi}$$

$$\frac{G_{\rm eff}}{G} = \begin{cases} 1 & r \gg \lambda_\phi \\ 1 + 2\beta^2 & r \ll \lambda_\phi \end{cases}$$

Stronger coupling -> bigger deviations from LCDM

Larger range -> large scale deviations from LCDM



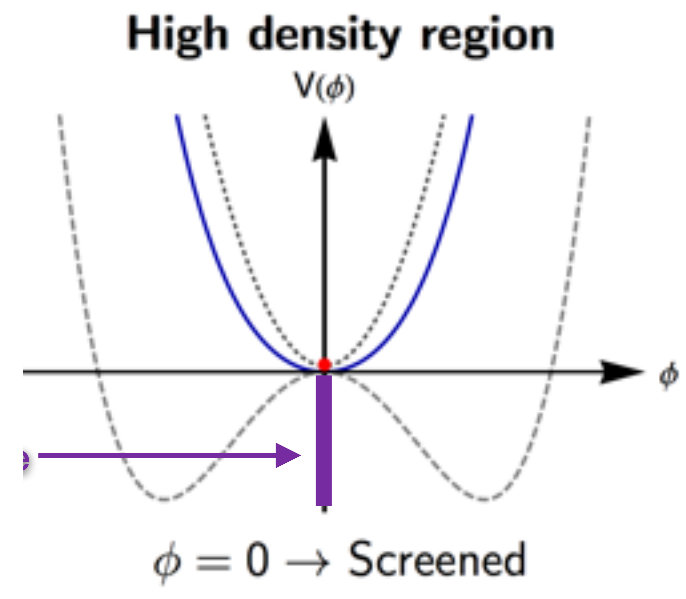


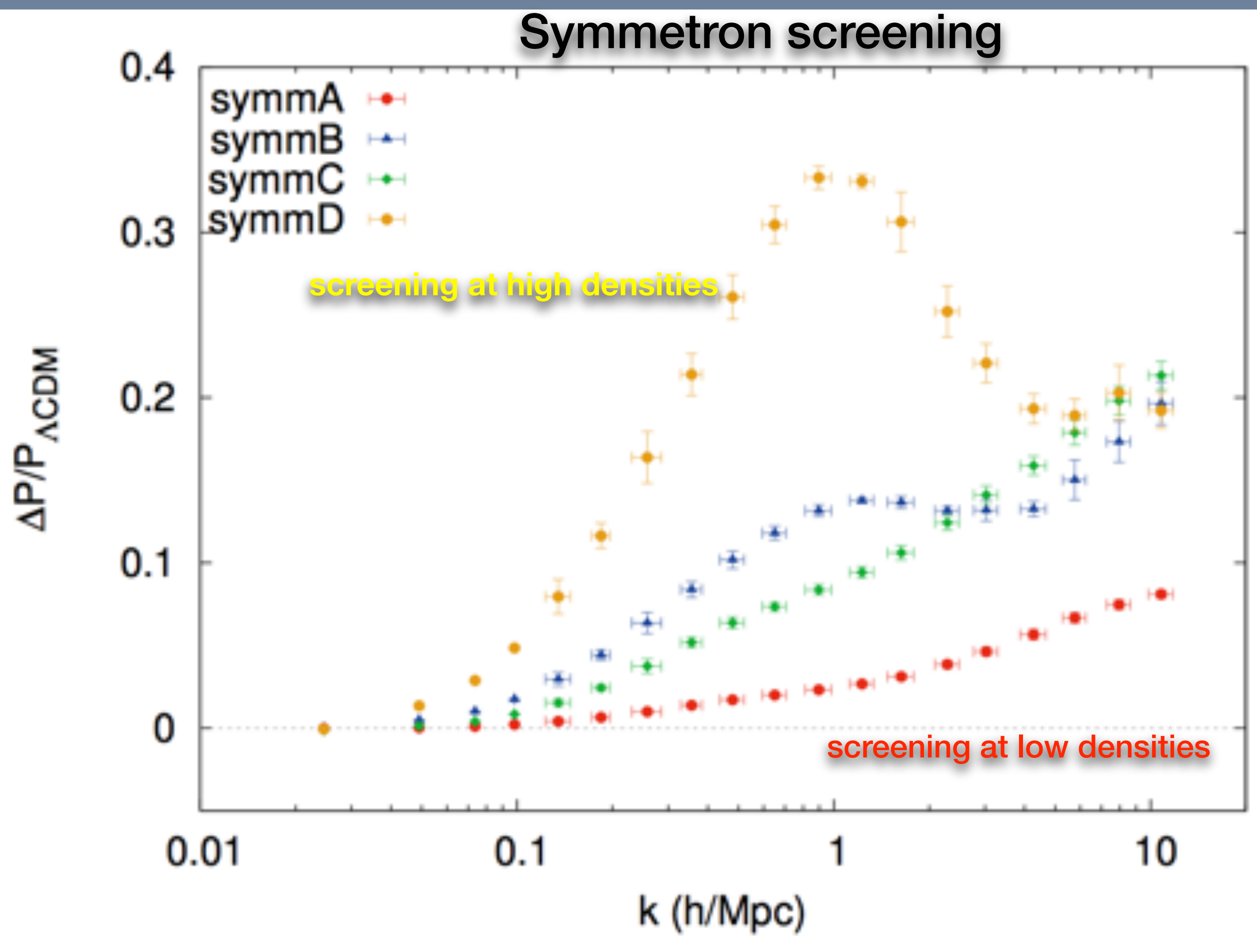
Scales larger than Compton wavelength: recovers GR

Llinares, DFM & Winther, ApJ

Structure formation dependence on the screening scale

$$\frac{G_{\rm eff}}{G} = 1$$

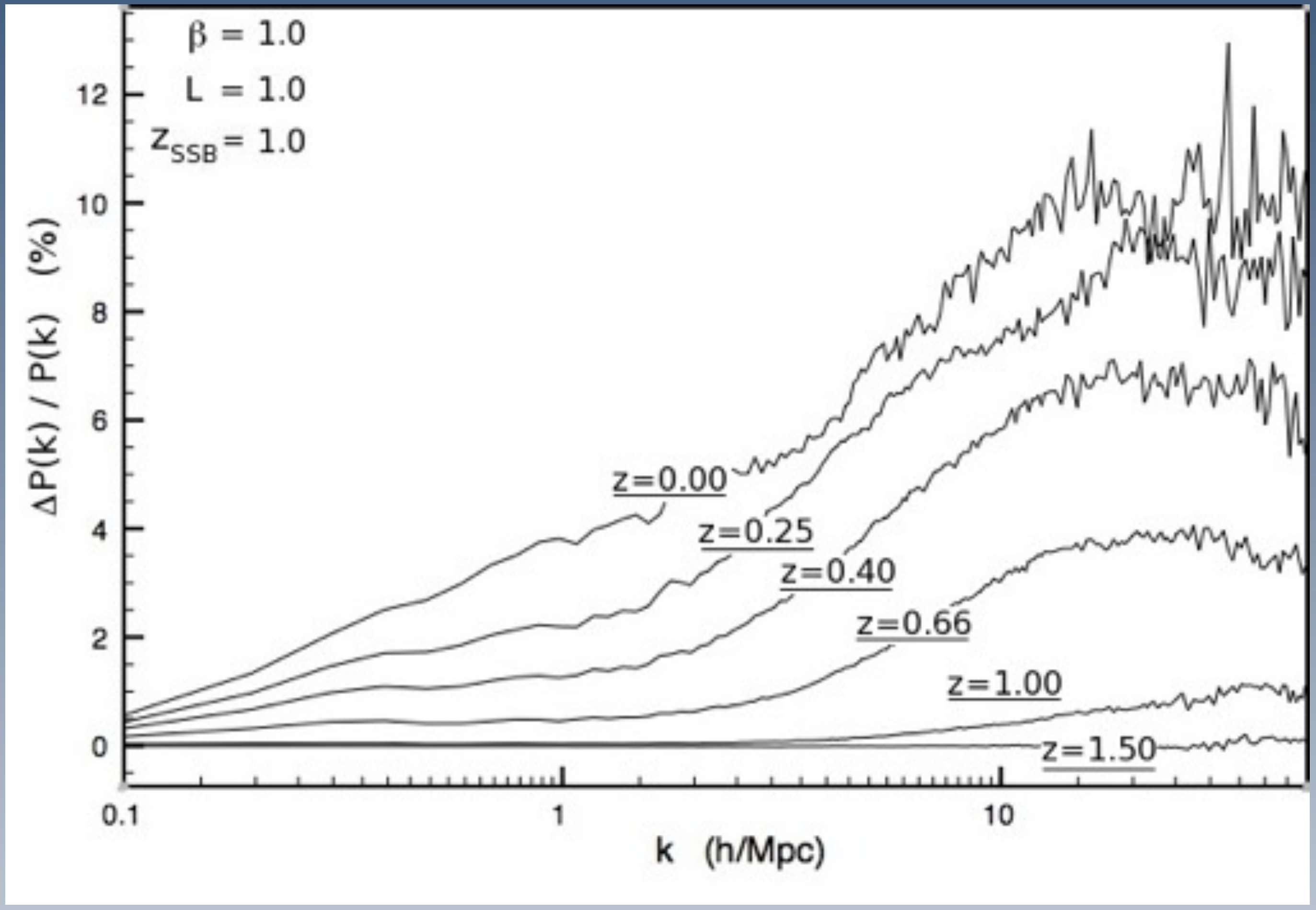




screening at high densities => deviations from GR easier to detect

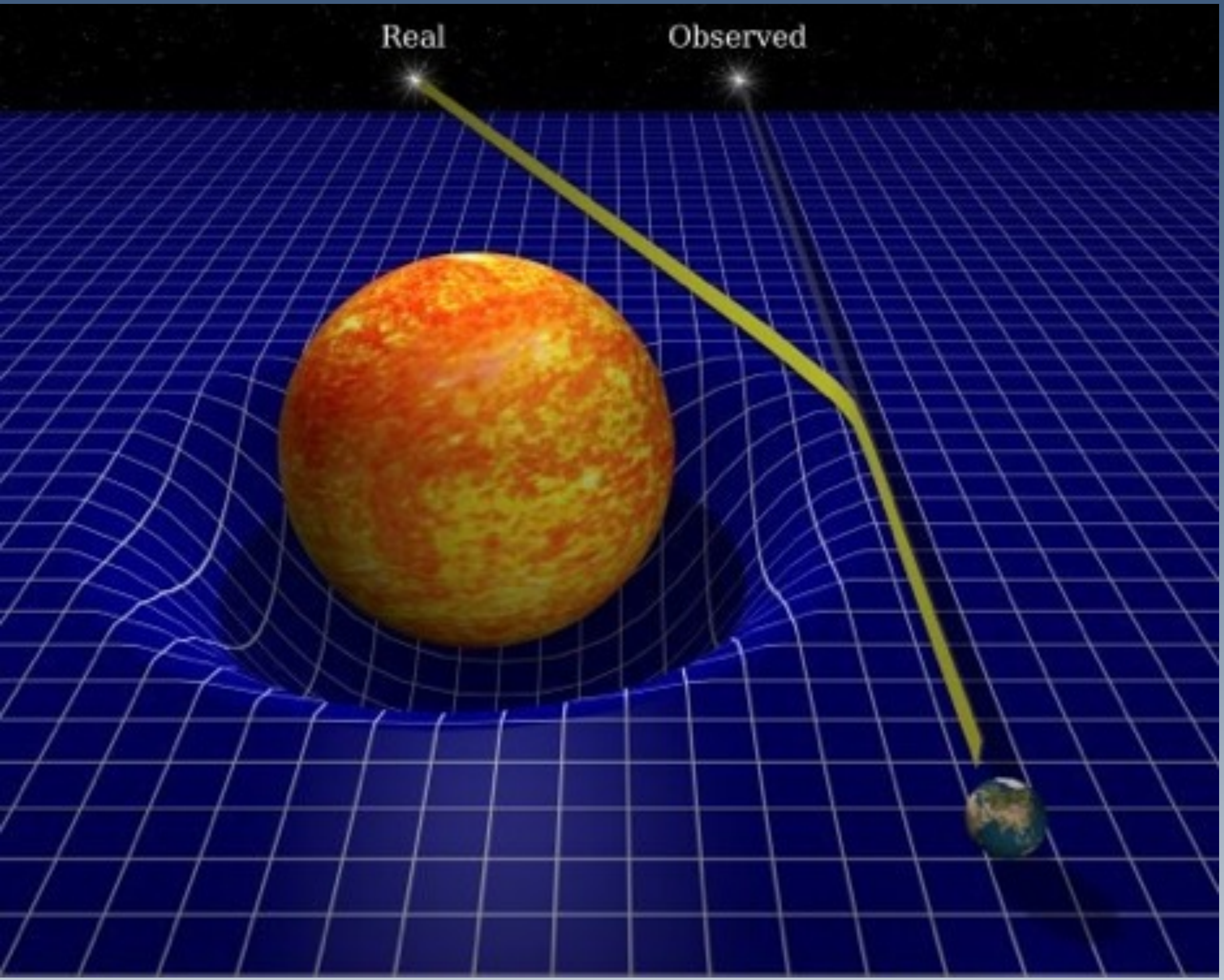
Gronke, Llinares, DFM, A&A

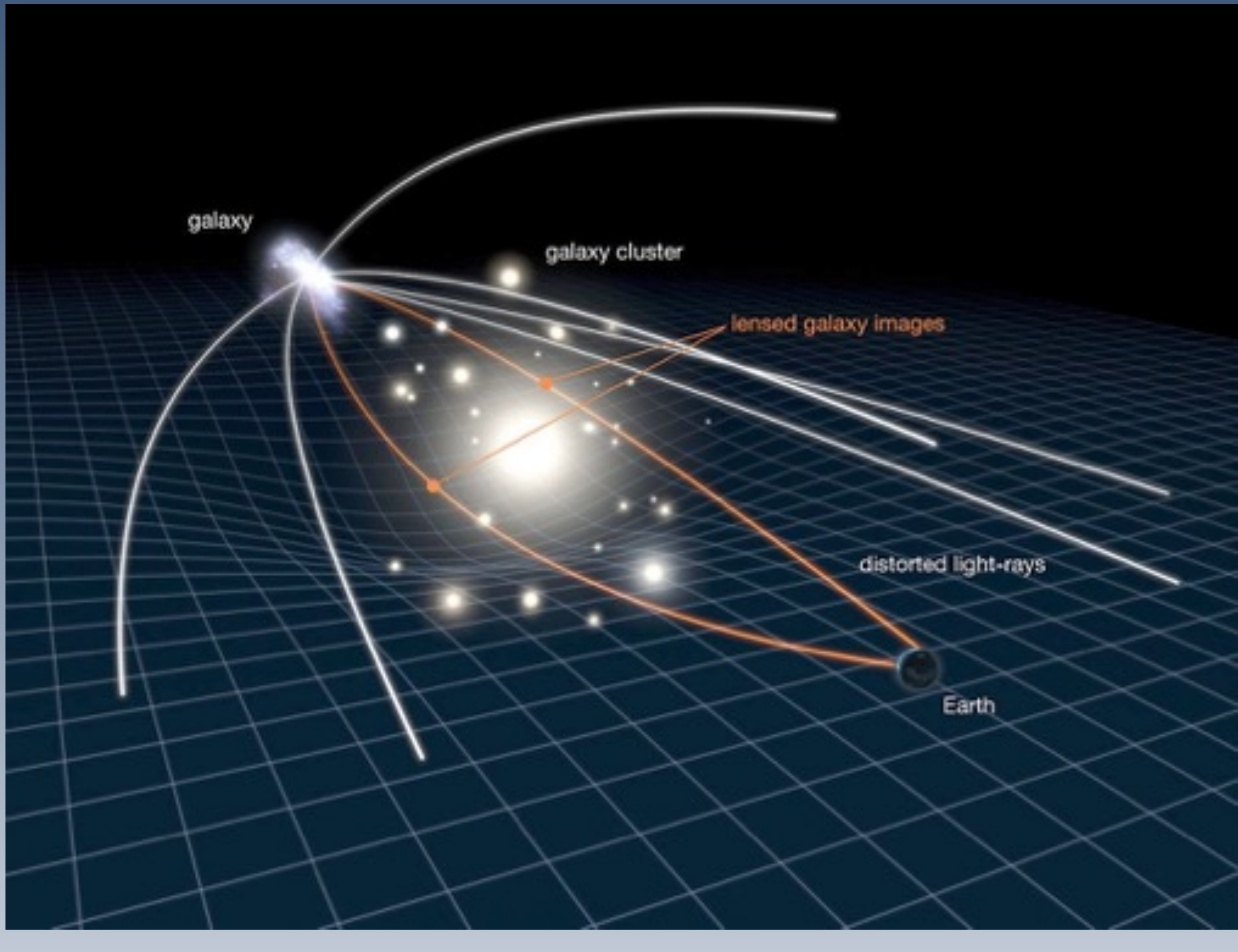
Global observables are not ideal to distinguish Modified Gravity theories with or without Screenings



How to Probe Screening Mechanisms?

Mass measured via gravitational lensing



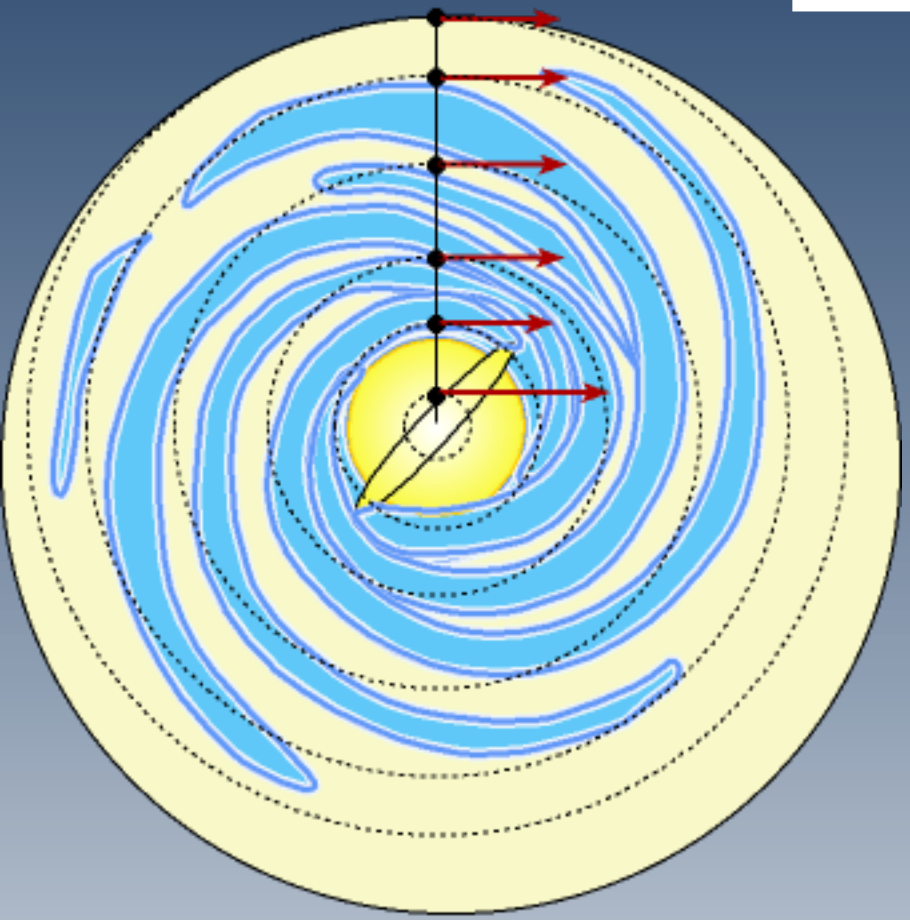


Conformal Invariance: photons not affected by Modified Gravity

Lensing Mass in (conformal) Modified Gravity same as GR

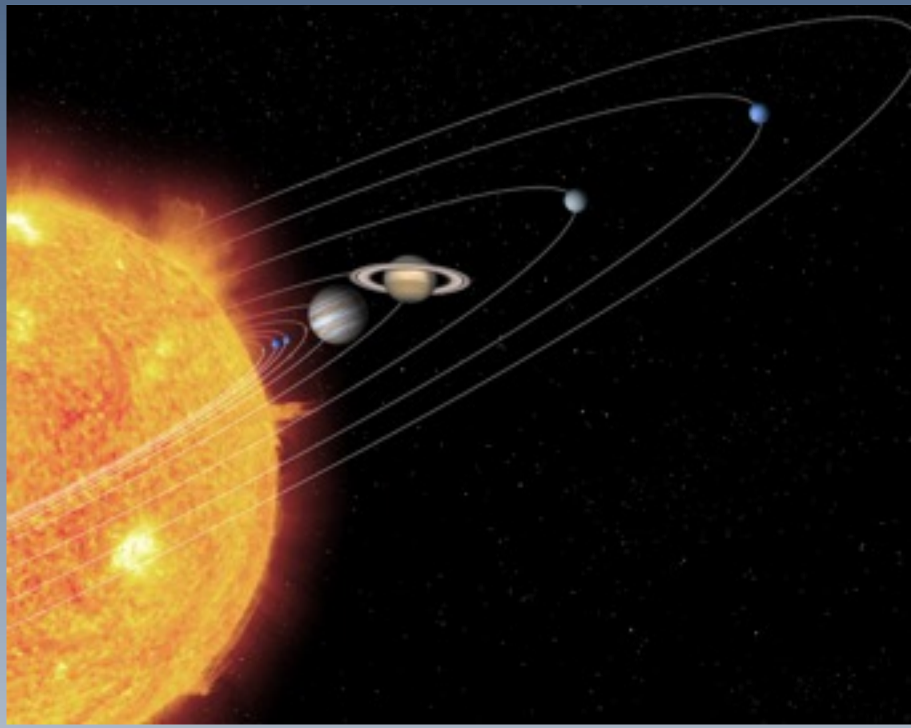
Mass measured via dynamics

$$M_{dyn}(r<R) \approx \frac{V_{rot}^2 R}{G} \quad M_\odot$$



The mass inside an orbit can be found using the size of the orbit and the orbital speed. The arrows show the speeds for certain points on the **rotation curve** for this galaxy.

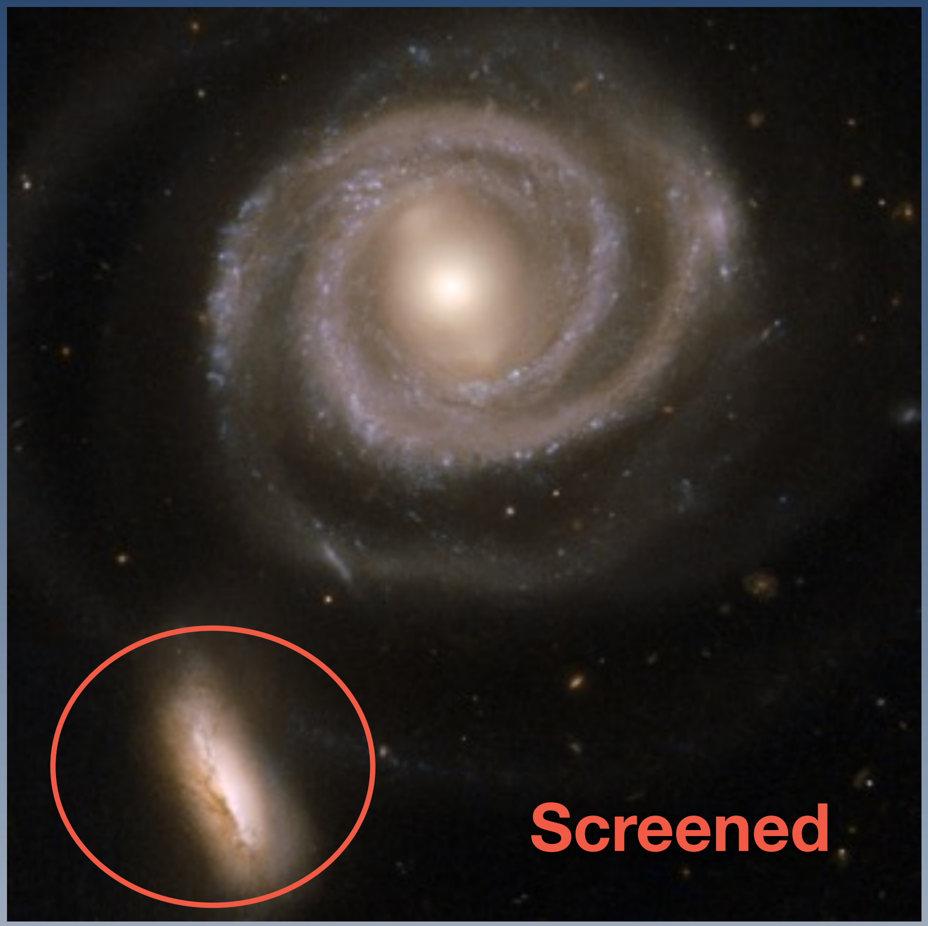
$$M_D = \frac{F_N + F_\phi}{a}$$

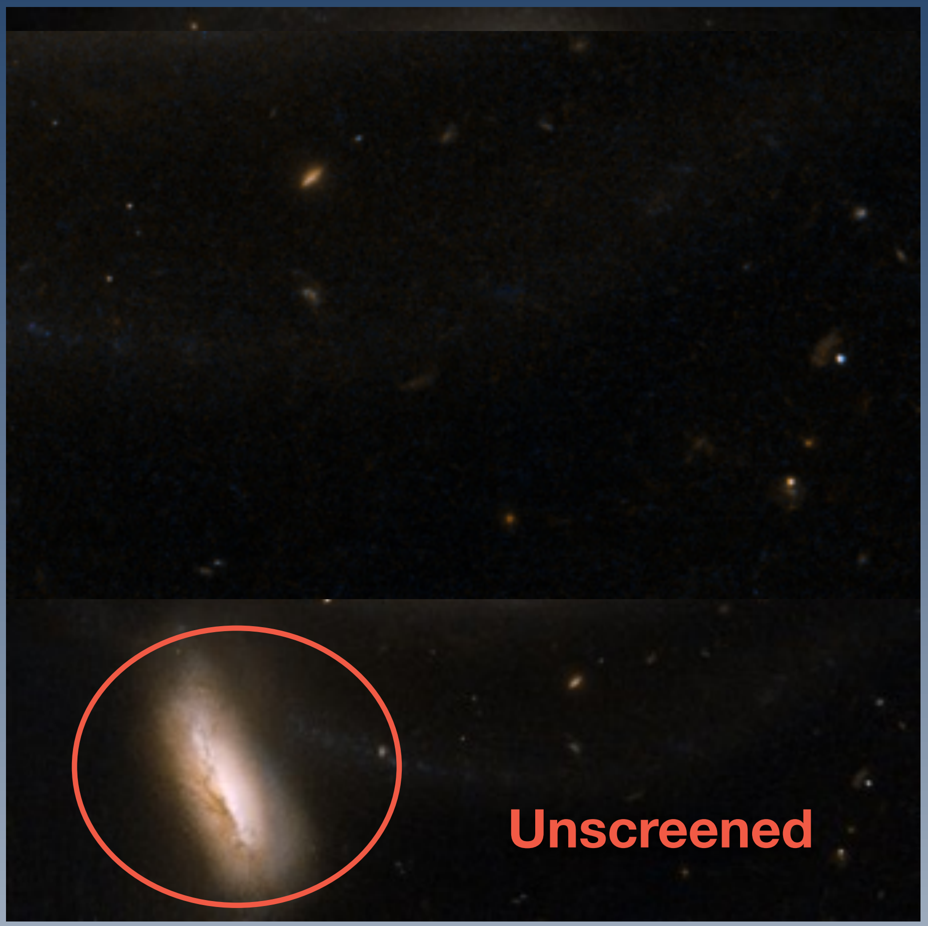


Modified Gravity enhances mass inferred via dynamical methods

Modified Gravity with Screening Mechanisms:

Dynamical mass depends on position in environment



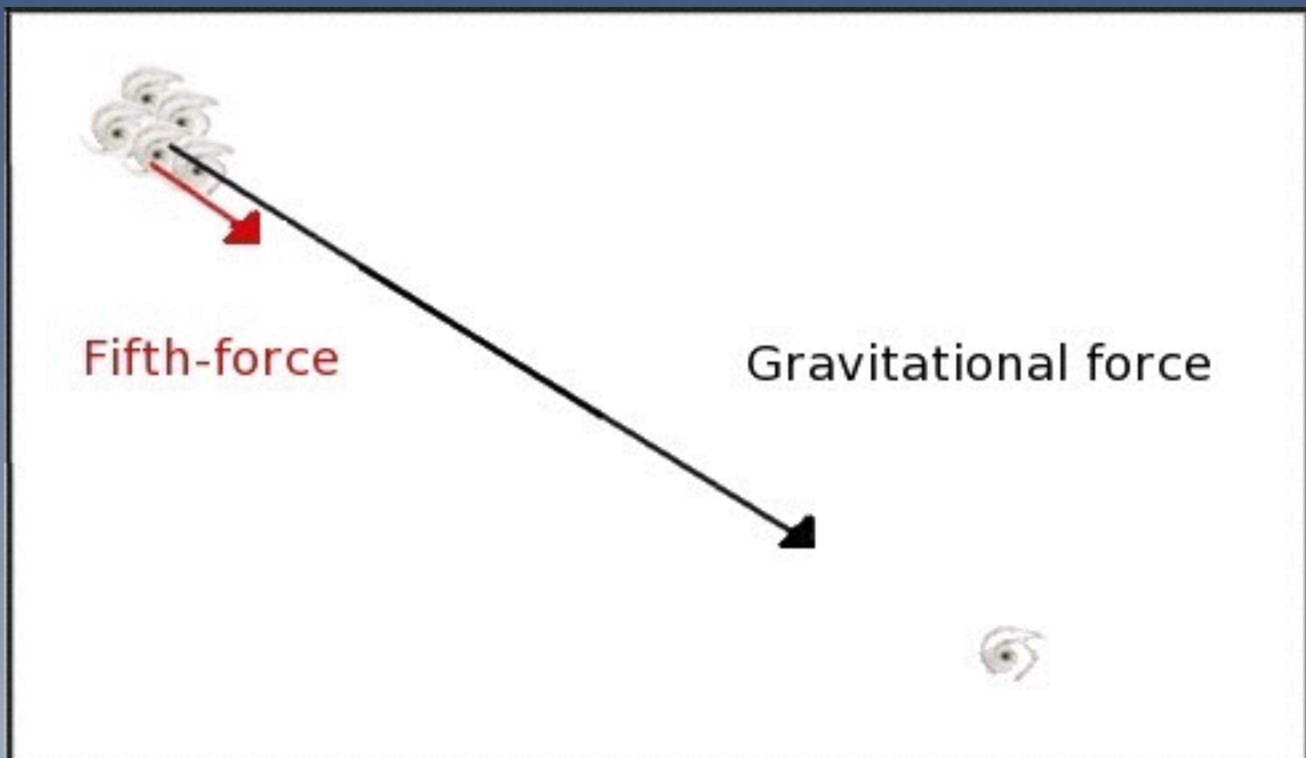


Dynamical mass is same in GR

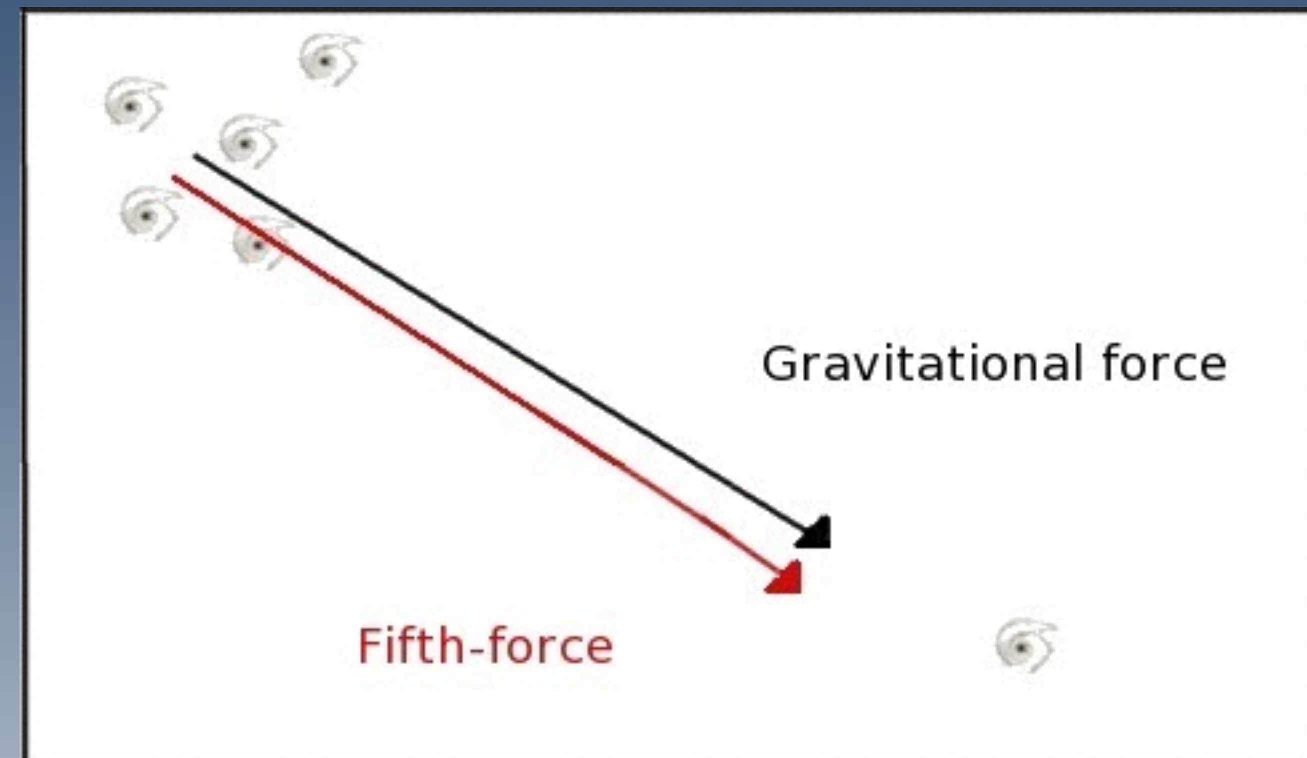
Dynamical mass differs from GR

Dynamical Mass depends on distance to high/low dense environment

Modified Gravity with Screening Mechanisms:
Dynamical Mass depends on size of cluster



Dynamical Mass same as in GR



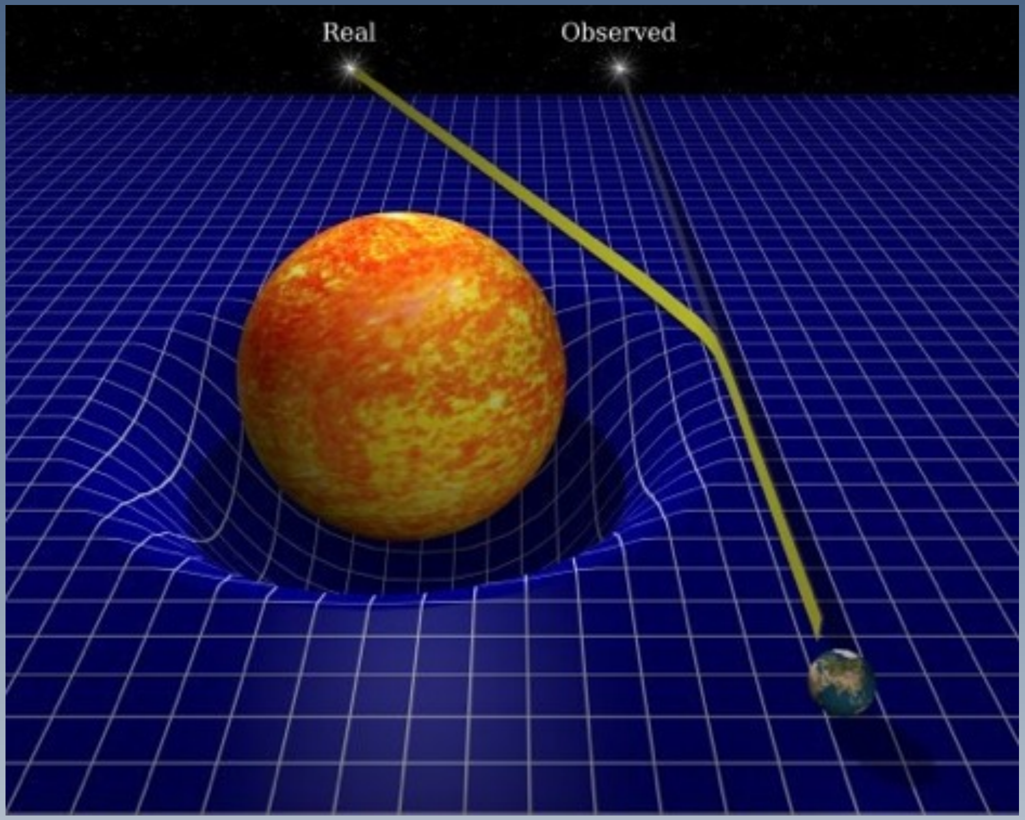
Dynamical Mass differs from GR

Dynamical Mass depends on size/density of cluster

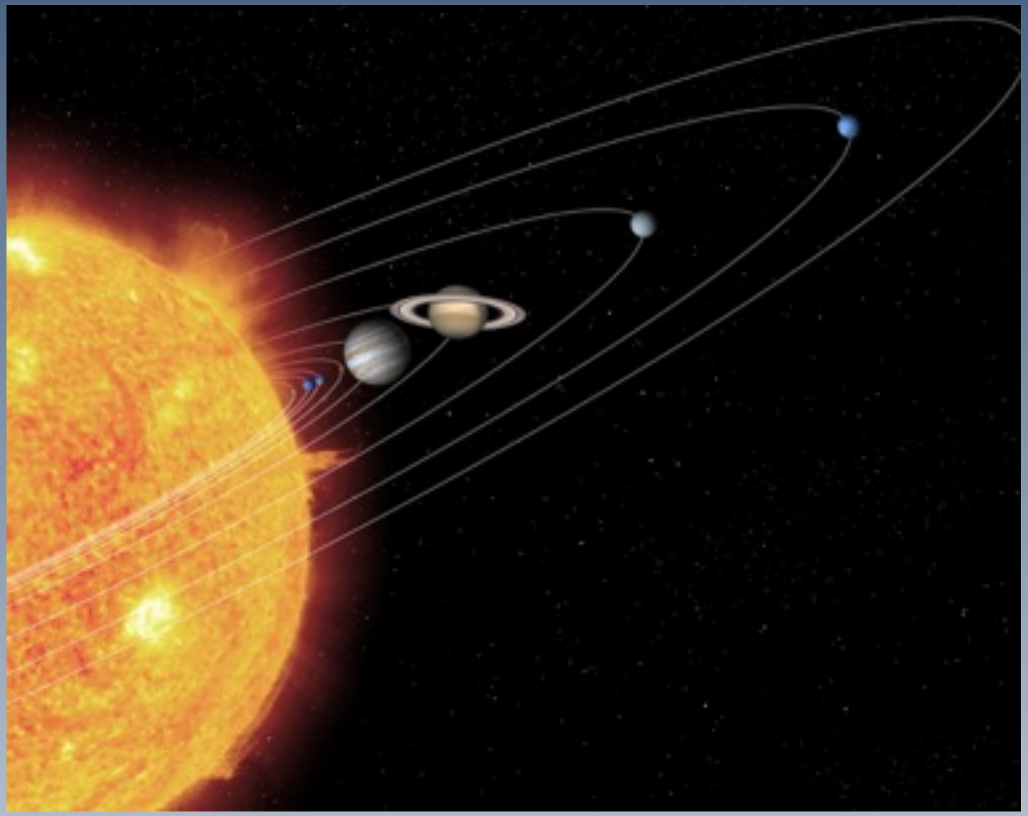
Smoking gun for Screening Mechanisms

Lensing Mass vs. Environmental dependent Dynamical Mass

Lensing Mass same as in GR



Dynamical Mass depends on environment



$$GR: \quad \Delta_M = 0$$

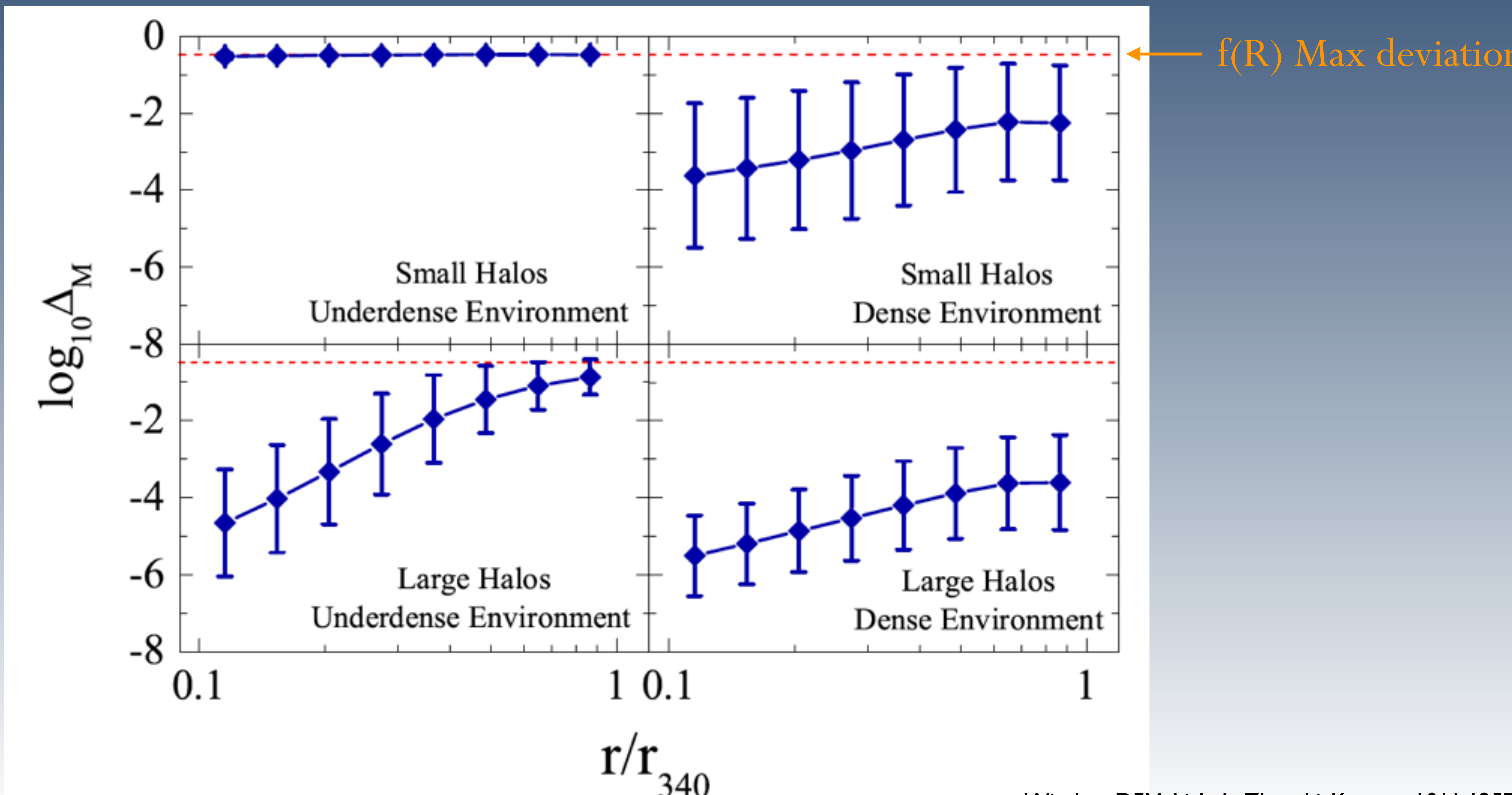
$$\Delta_M \equiv \frac{M_D}{M_L} - 1$$

$$F(R): \quad \Delta_M \in [0, \frac{1}{3}]$$

$$Chameleon/Symmetron: \quad \Delta_M \in [0, 2\beta^2]$$

dynamical vs. lensing masses of halos in clusters

$$\Delta_M \equiv \frac{M_D}{M_L} - 1$$



Winther, DFM, Li ApJ ; Zhao, Li, Koyama 1011.1257;

dynamical vs. lensing masses of halos in clusters

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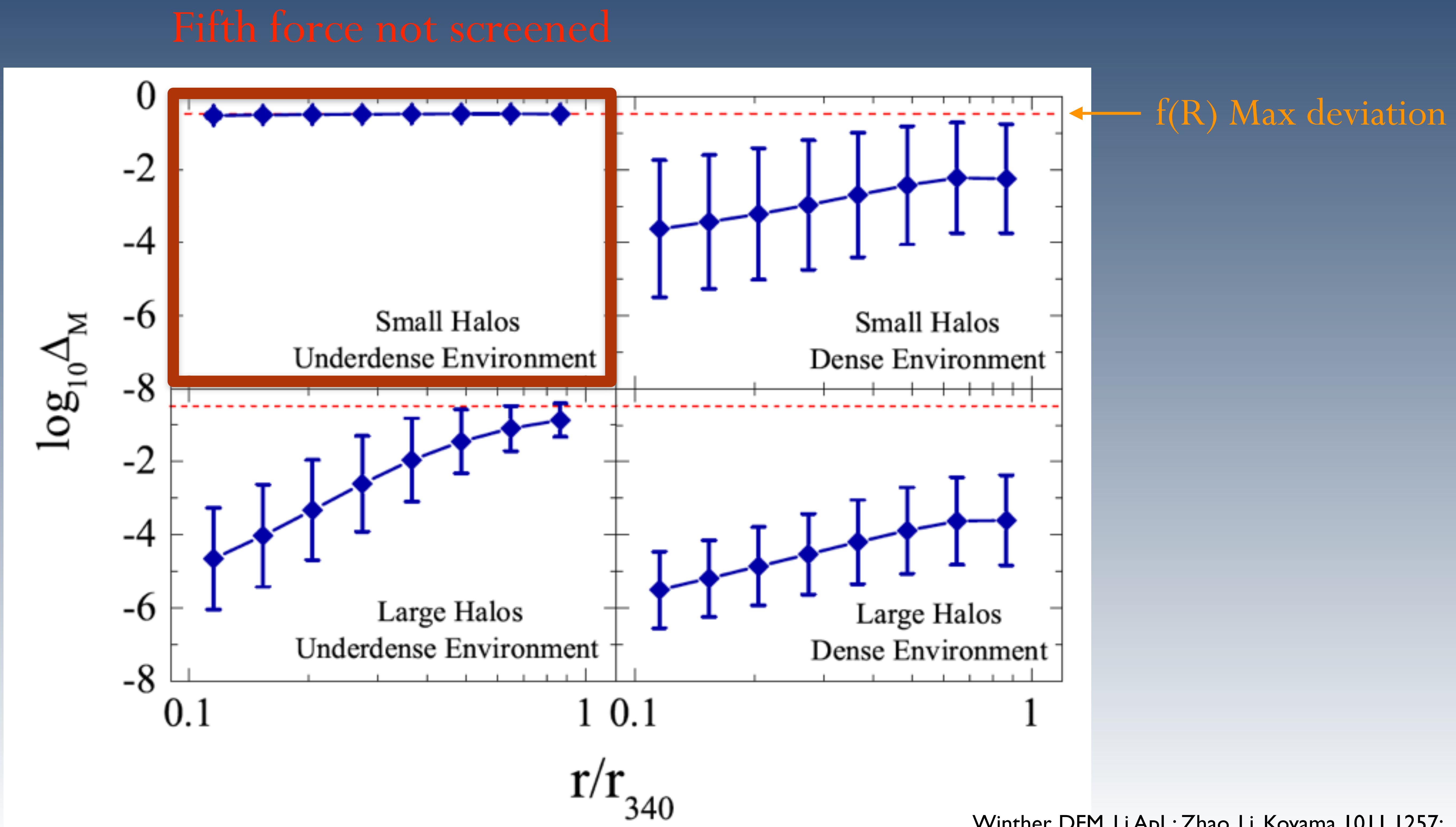

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dynamical vs. lensing masses of halos in clusters

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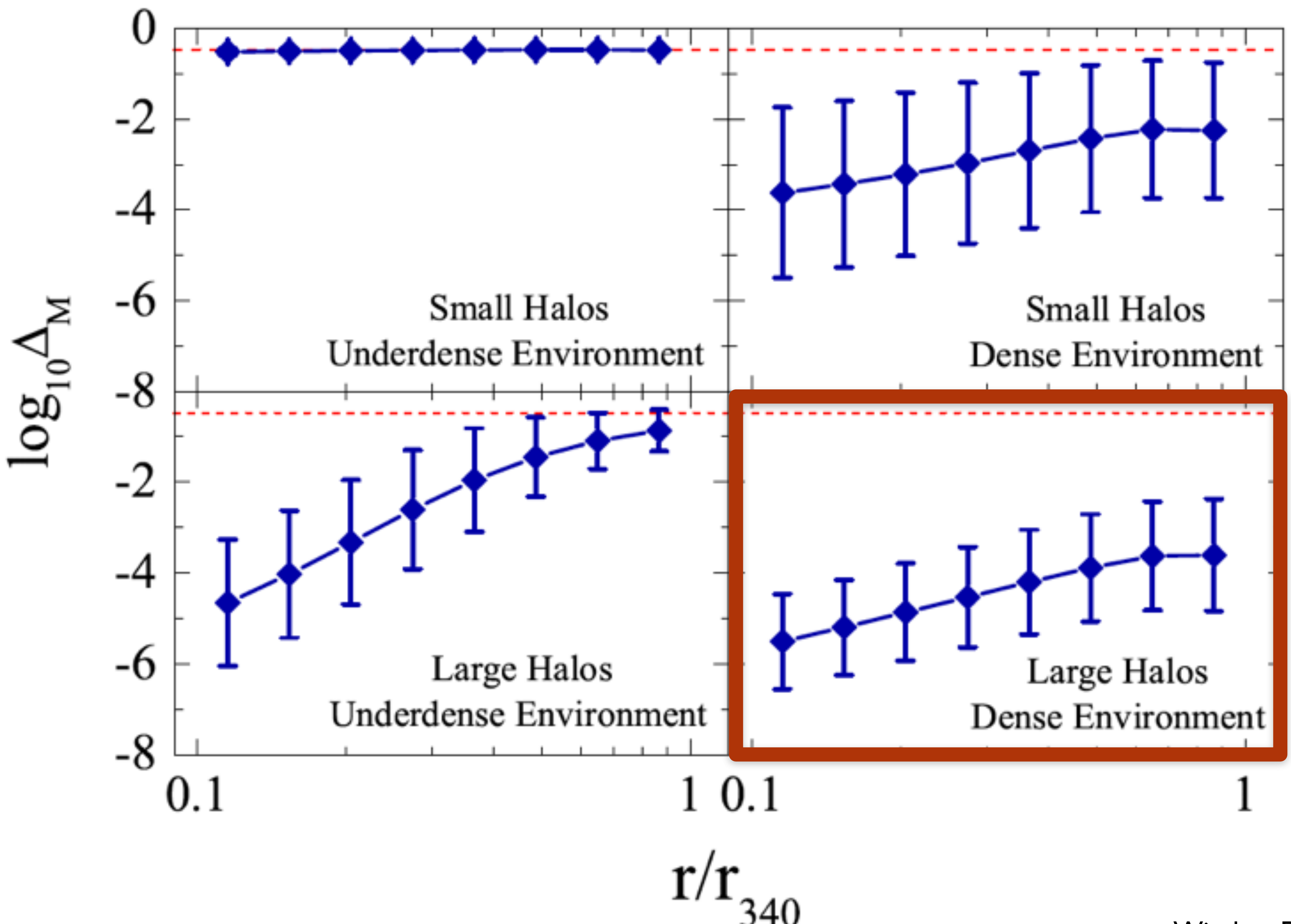


f(R) Max deviation

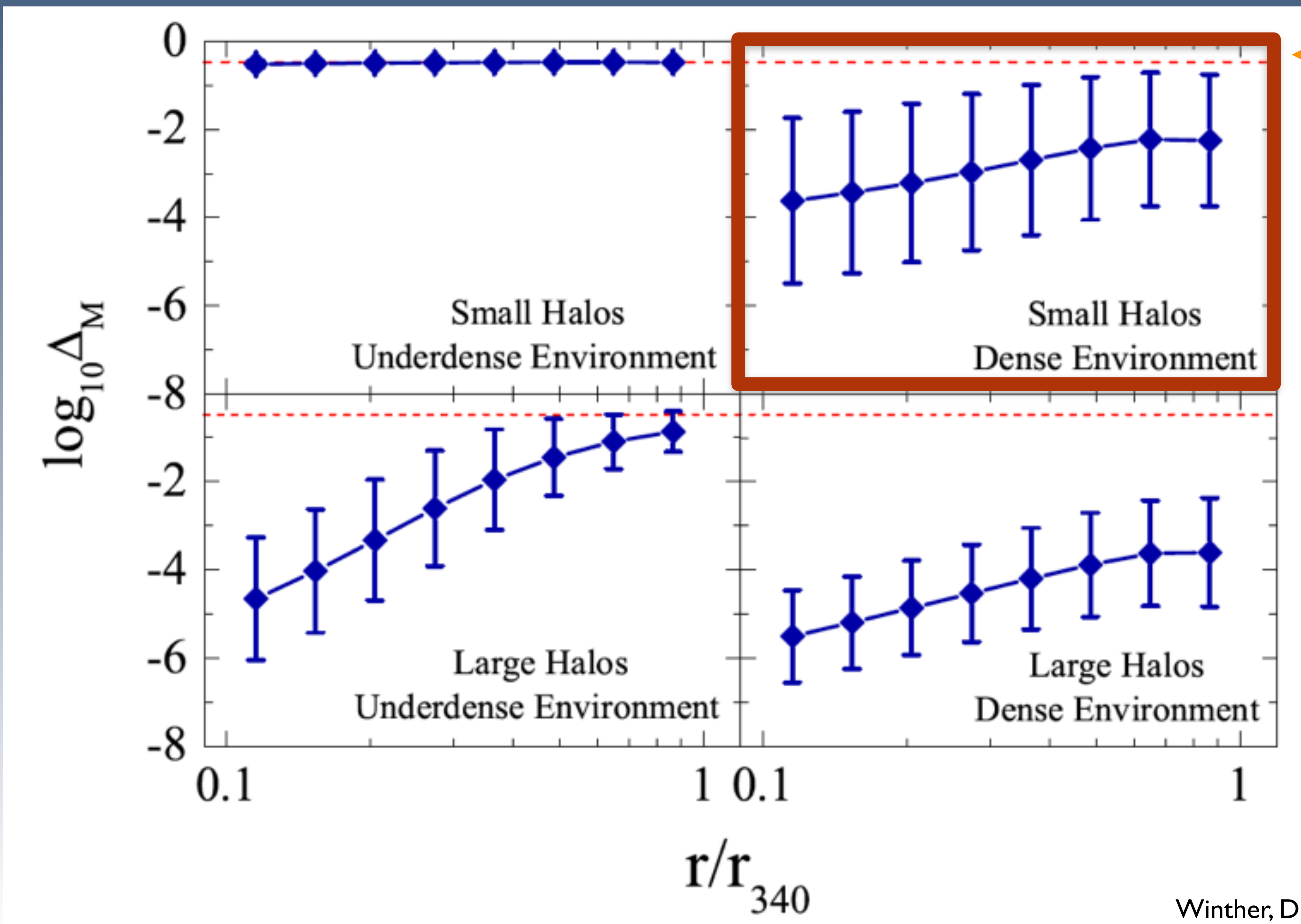
Max screening
Core screened

Winther, DFM, Li ApJ ; Zhao, Li, Koyama 1011.1257;

dynamical vs. lensing masses of halos in clusters

$$\Delta_M \equiv \frac{M_D}{M_L} - 1$$

Screened purely by environment

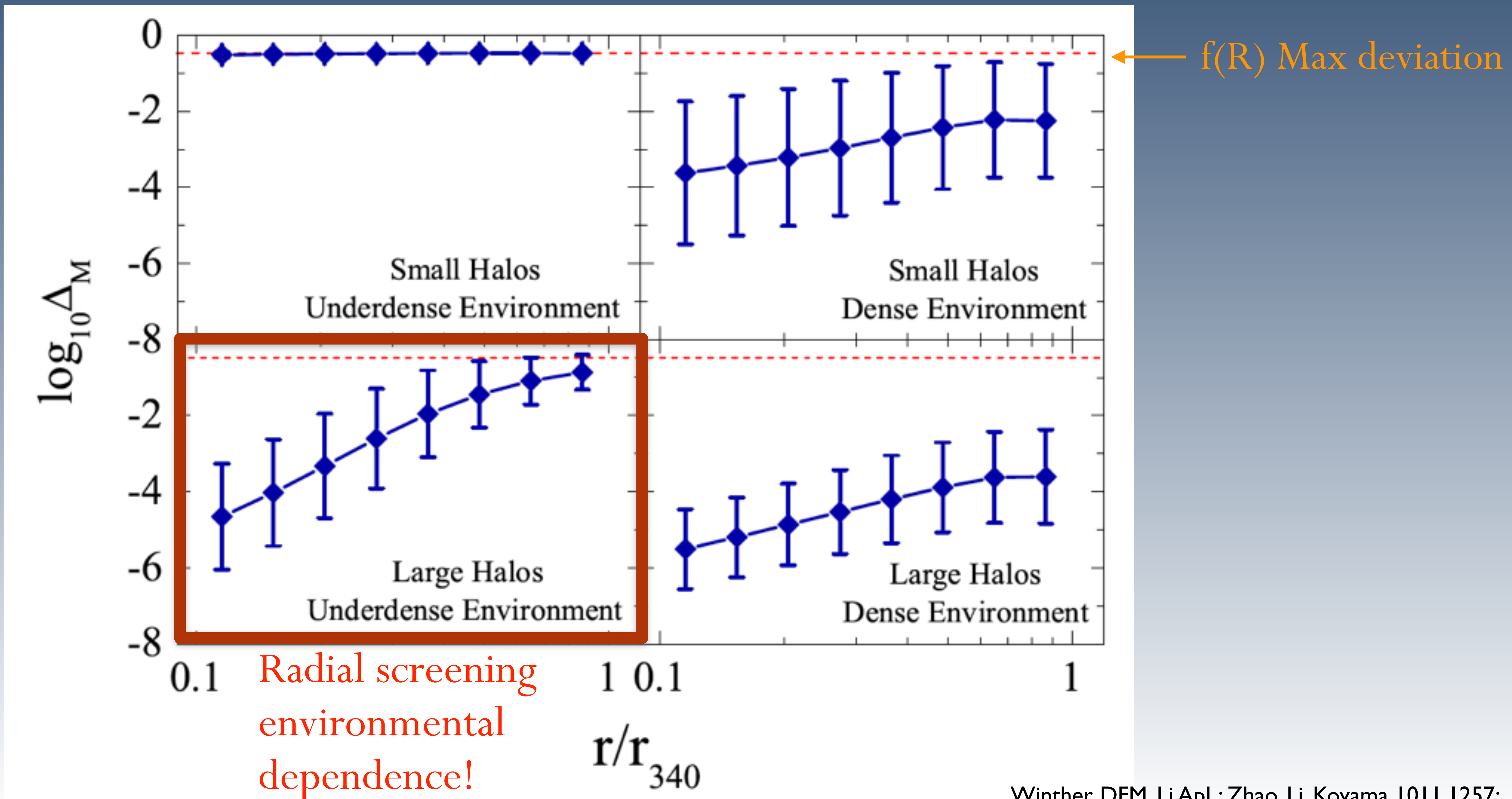


← f(R) Max deviation

Winther, DFM, Li ApJ ; Zhao, Li, Koyama 1011.1257;

dynamical vs. lensing masses of halos in clusters

$$\Delta_M \equiv \frac{M_D}{M_L} - 1$$



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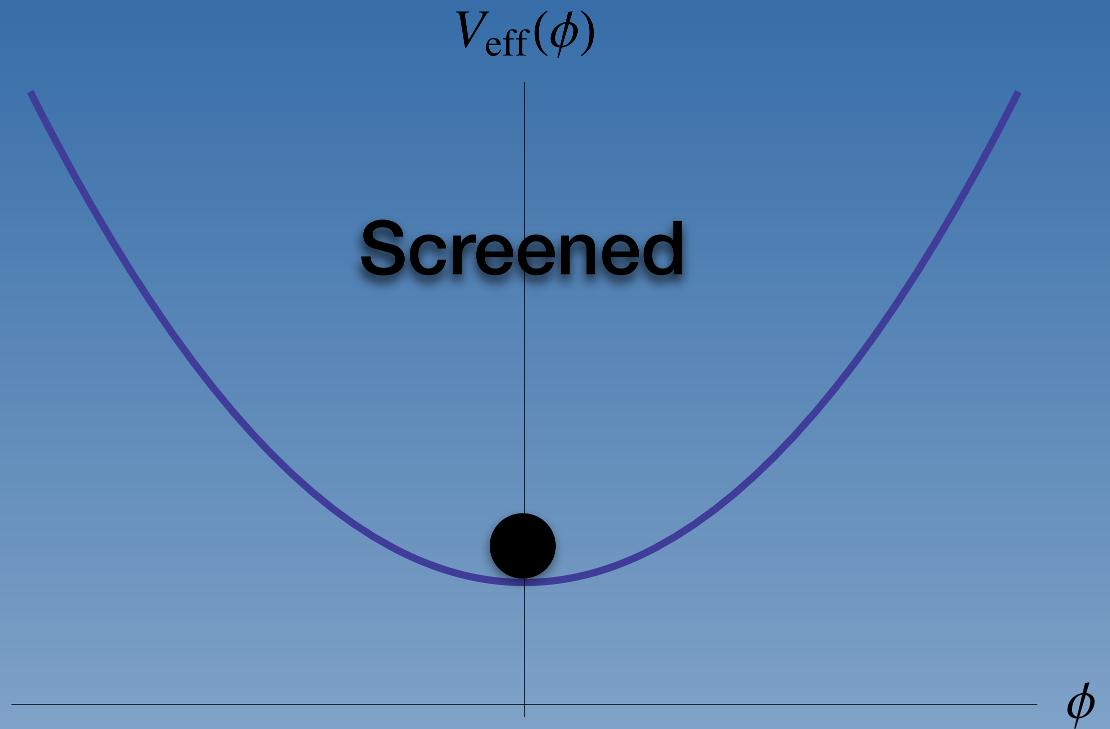
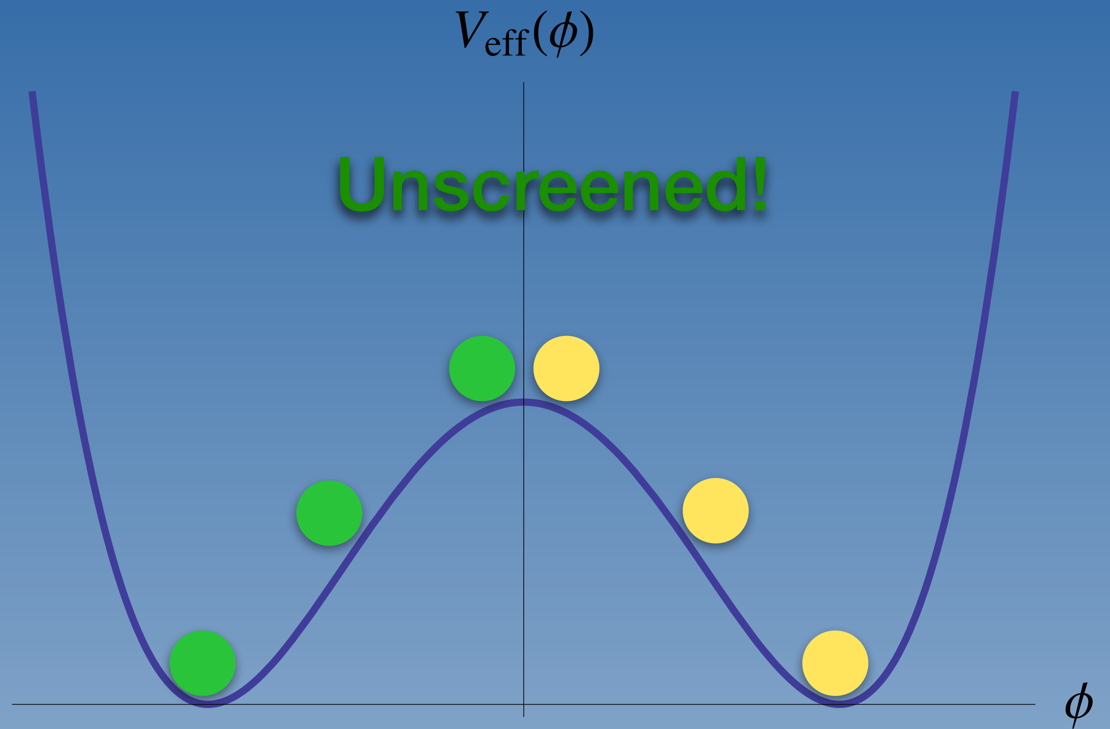
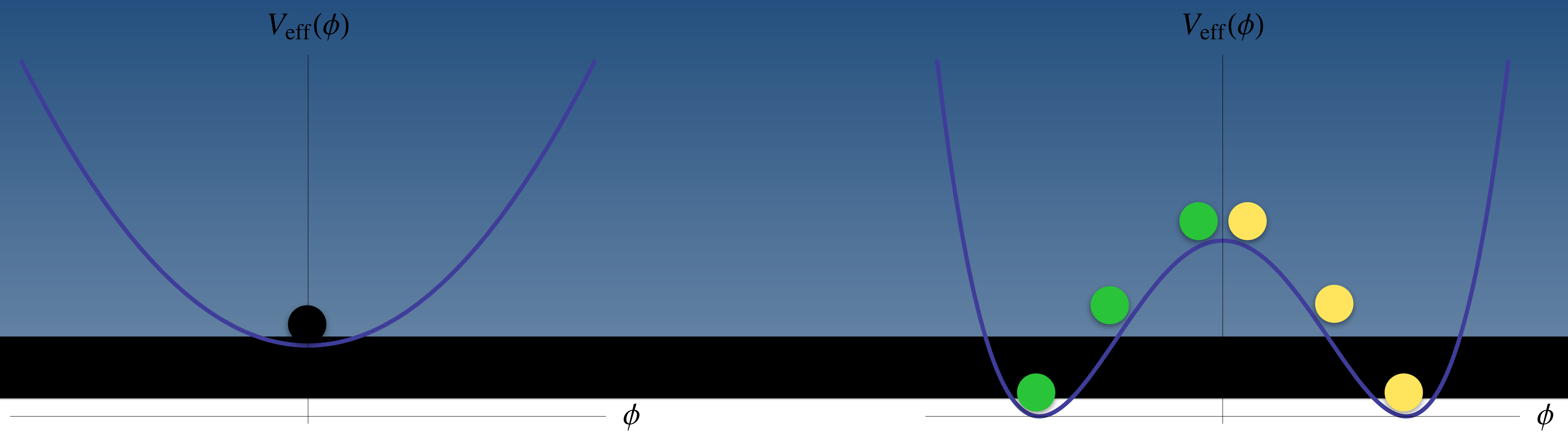
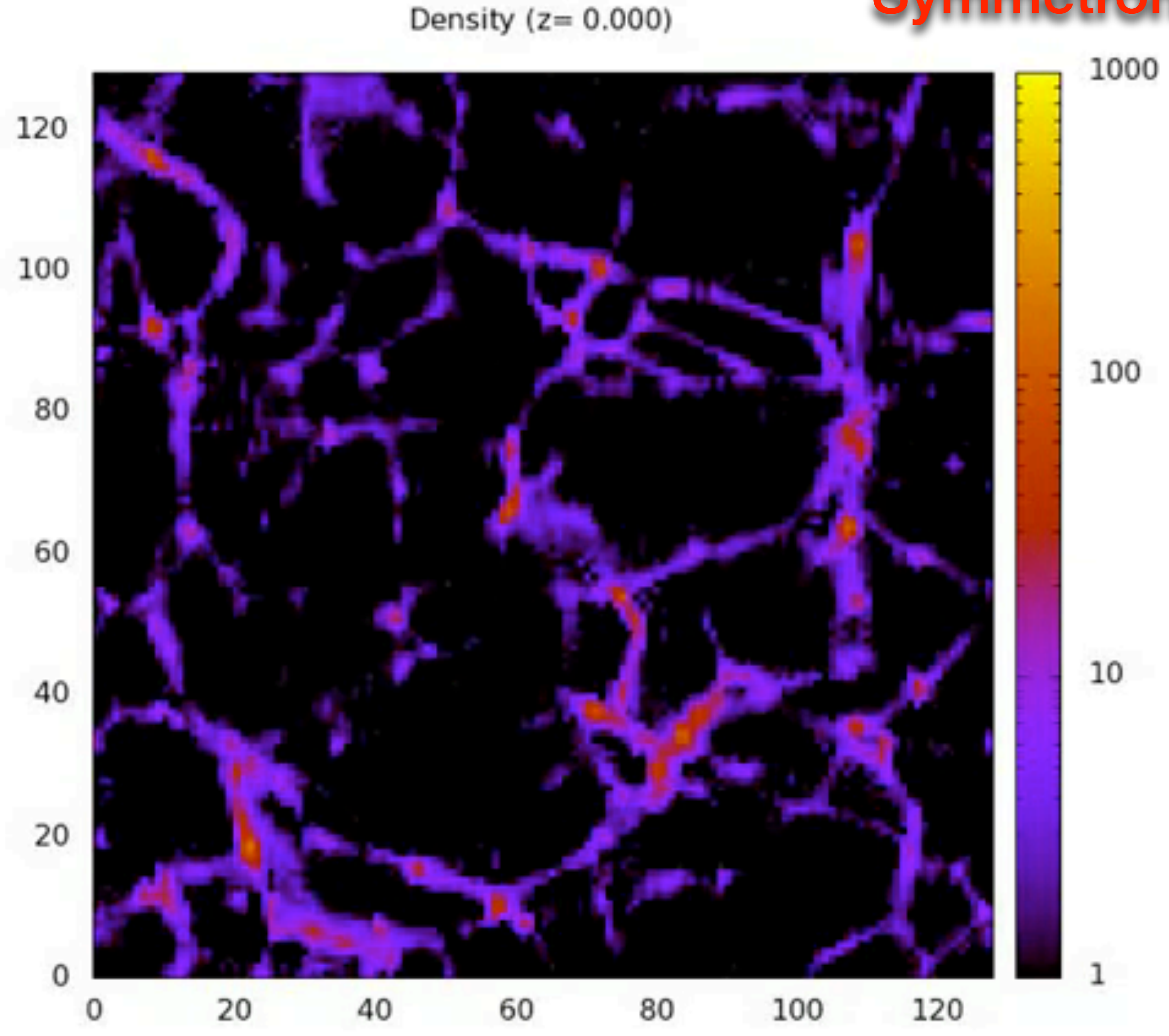


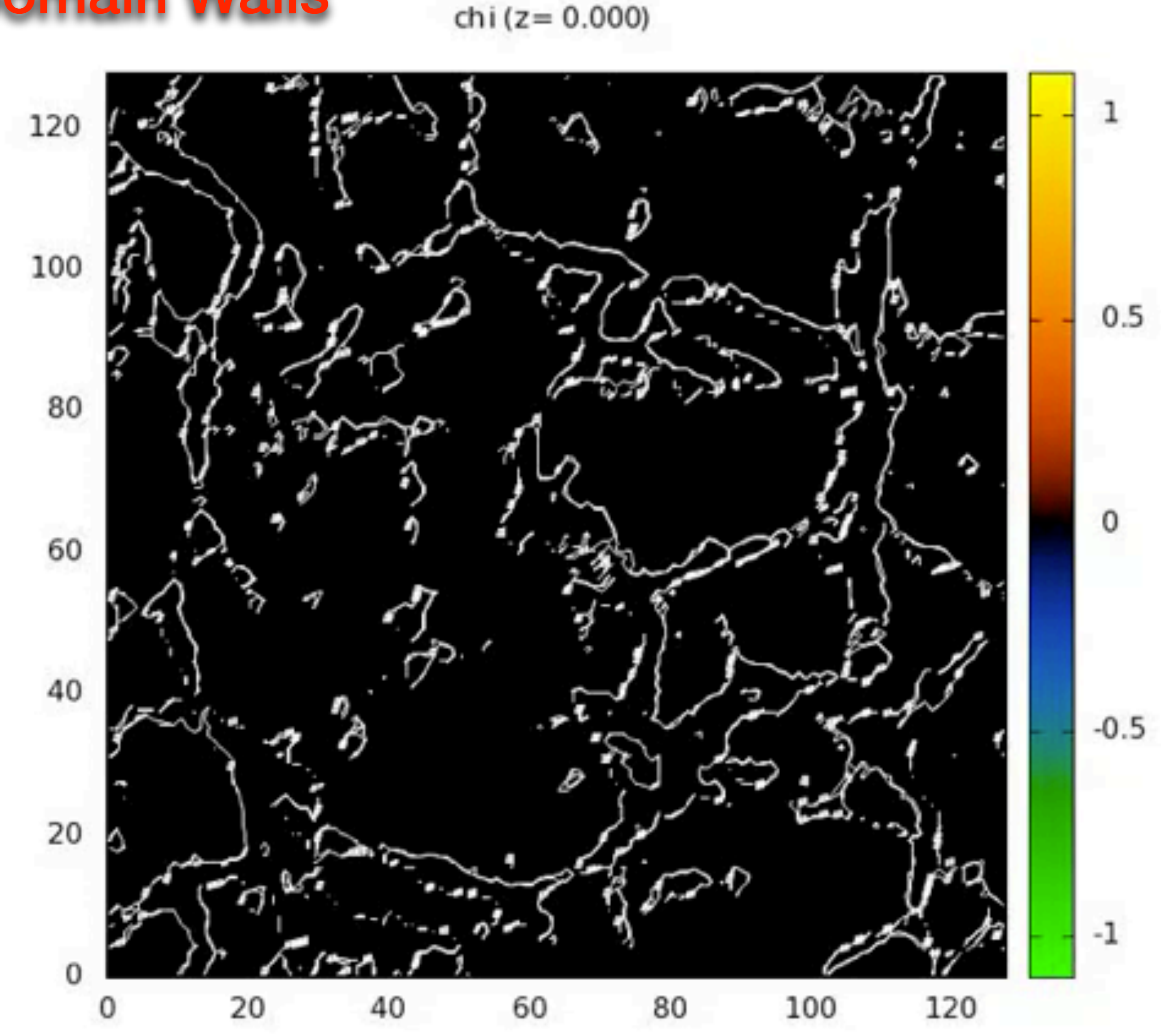


Symmetron Unique Feature



Symmetron Domain Walls



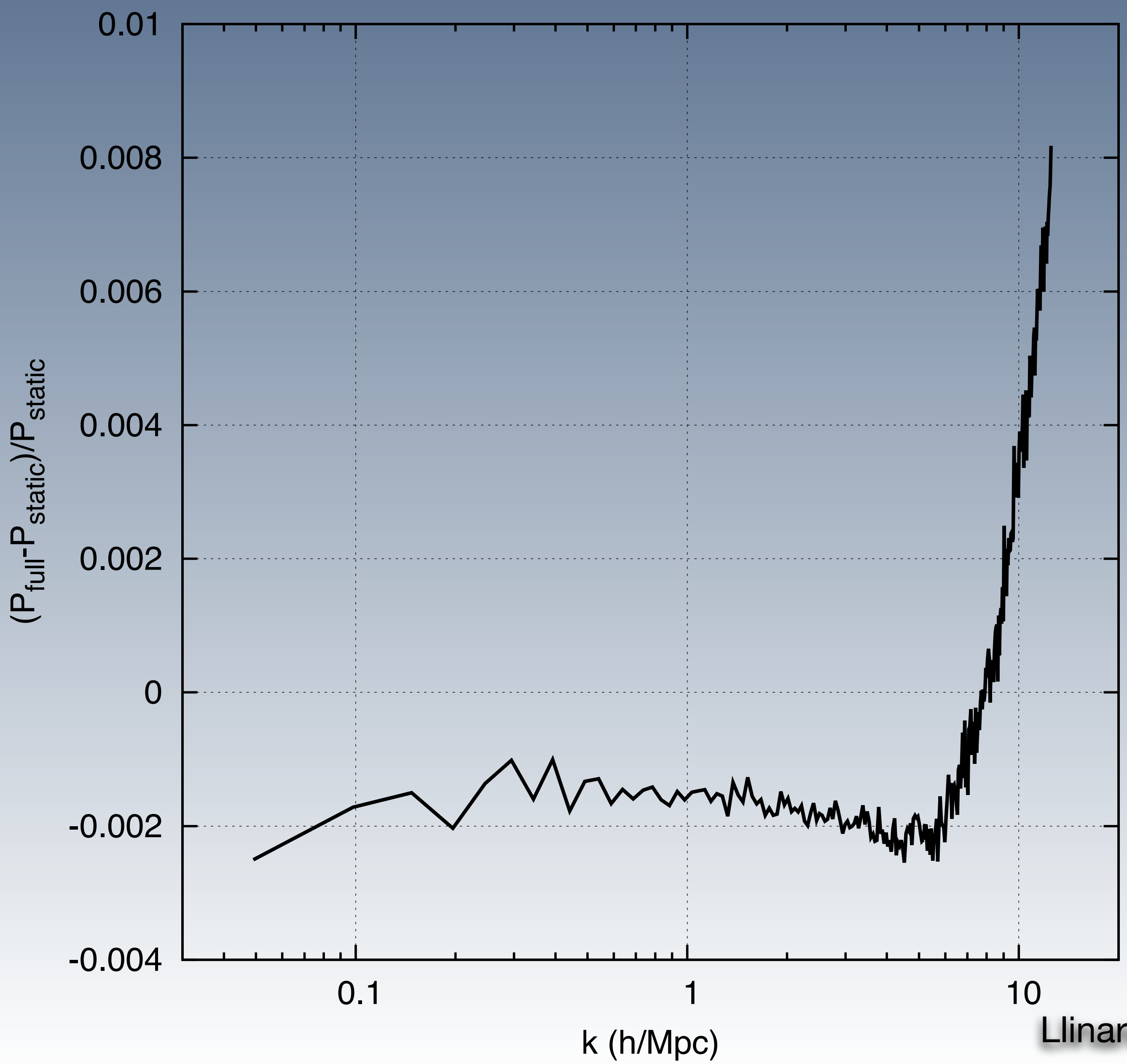


Llinares & DFM, PRL

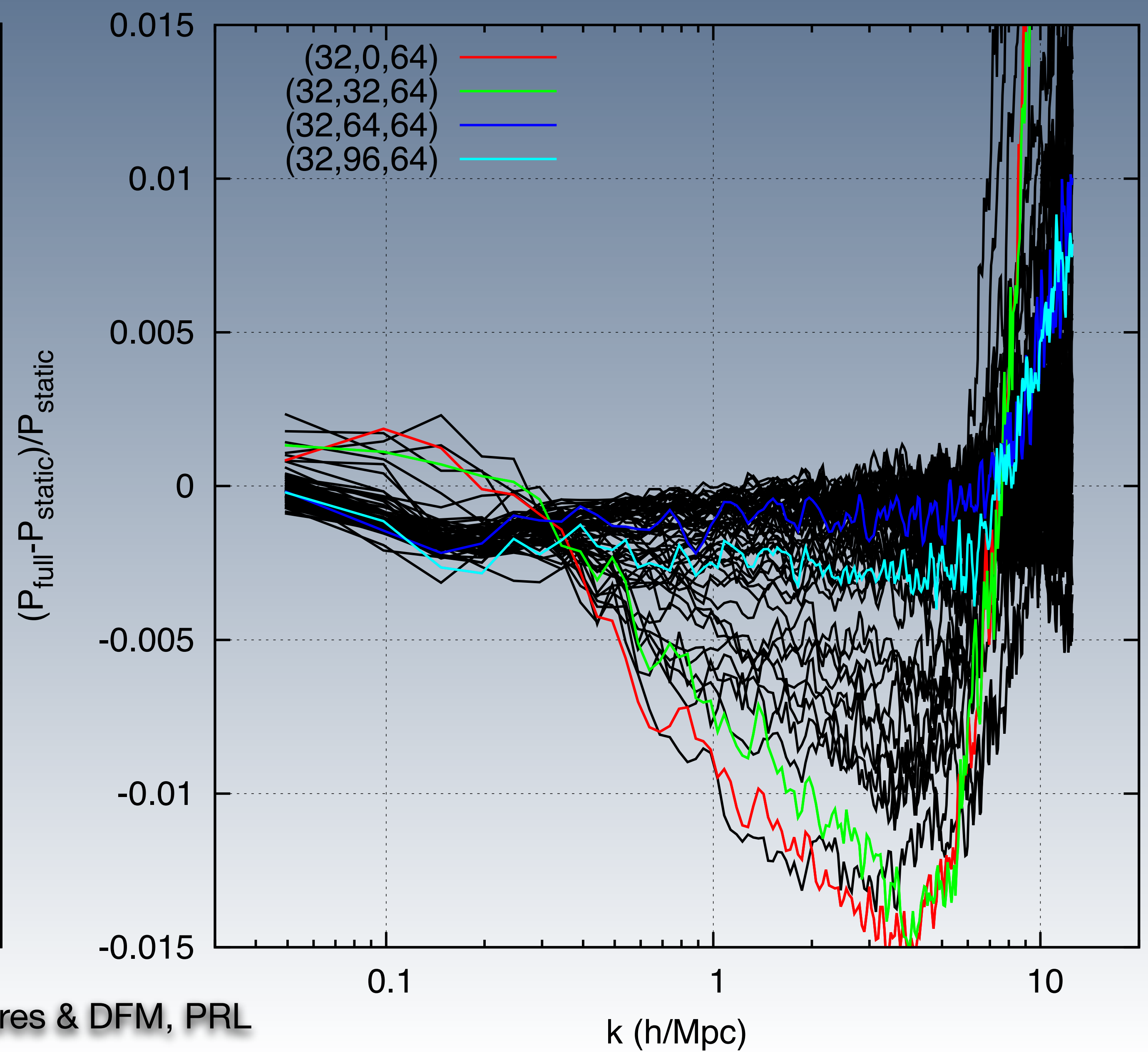
Probing Symmetron Unique Signature

Global Power Spectra deviates in 0.2%
Local Power Spectra deviates in 1%

Global Power Spectra



Local Power Spectra



Llinares & DFM, PRL

Summary: Probing Screened Modified Gravity

in laboratory

in the solar system

+ perfect to test EP violations, PPN, etc
+ Direct gravity experiments
- very limited time/space/energy scales
- only probes baryonic physics

at astrophysical scales

+ probe different Screening Mechanisms
- complicated non-linear/non-gravitational effects

at cosmological scales

+ unlimited scales
+ baryons, dark matter, dark energy
+ mostly linear processes
- Does not probe screening mechanisms