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"Testing gravity with galaxy cluster"

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Testing gravity with galaxy cluster

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Outline

- Modified gravity
- Screening mechanism
- Cluster lensing
- Summary

Based on
TN, Yamamoto, JCAP (2012)
TN, Kobayashi, Yamauchi, Saito, work in progress

Modified Gravity

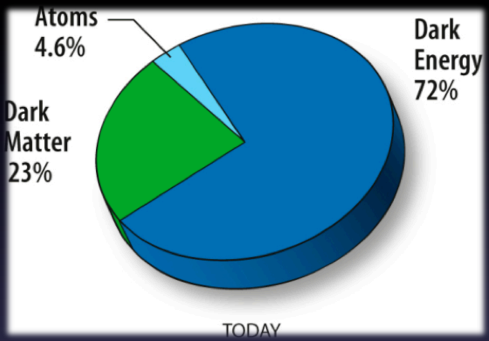
- Motivation: Discovery of current cosmic acceleration

[Riess, Schmidt et al. '98, Perlmutter et al. '99]

$\ddot{a} > 0$

→Breakdown of GR at large-scales？

- As an alternative to dark energy



[WMAP]

- Modified gravity with extra fields ϕ

Scalar-tensor gravity, f(R) gravity, DGP model,

Galileon model, Decoupling-limit of Ghost-free massive gravity, etc.

[Mukohyama-san's talk]

Local Gravity Constraints

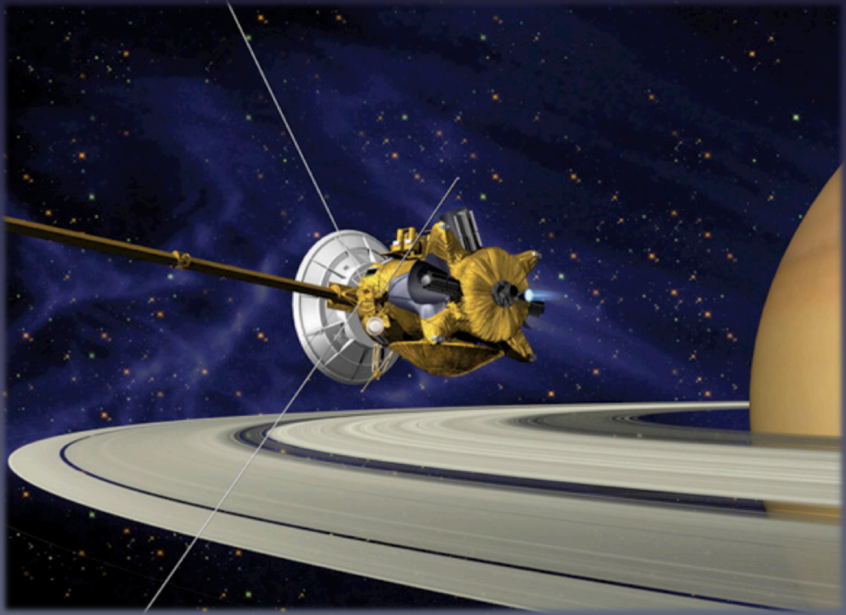
- In MG, new d.o.f. ϕ mediates fifth-force.

$\rightarrow$deviation from GR on large-scales.

- However, local gravity constraints are strong:
  - e.g. $\gamma_{PPN}-1=(2.1\pm2.3)\times10^{-5}$ by time-delay [Bertotti et al. '03]
- MG need to evade local gravity tests with

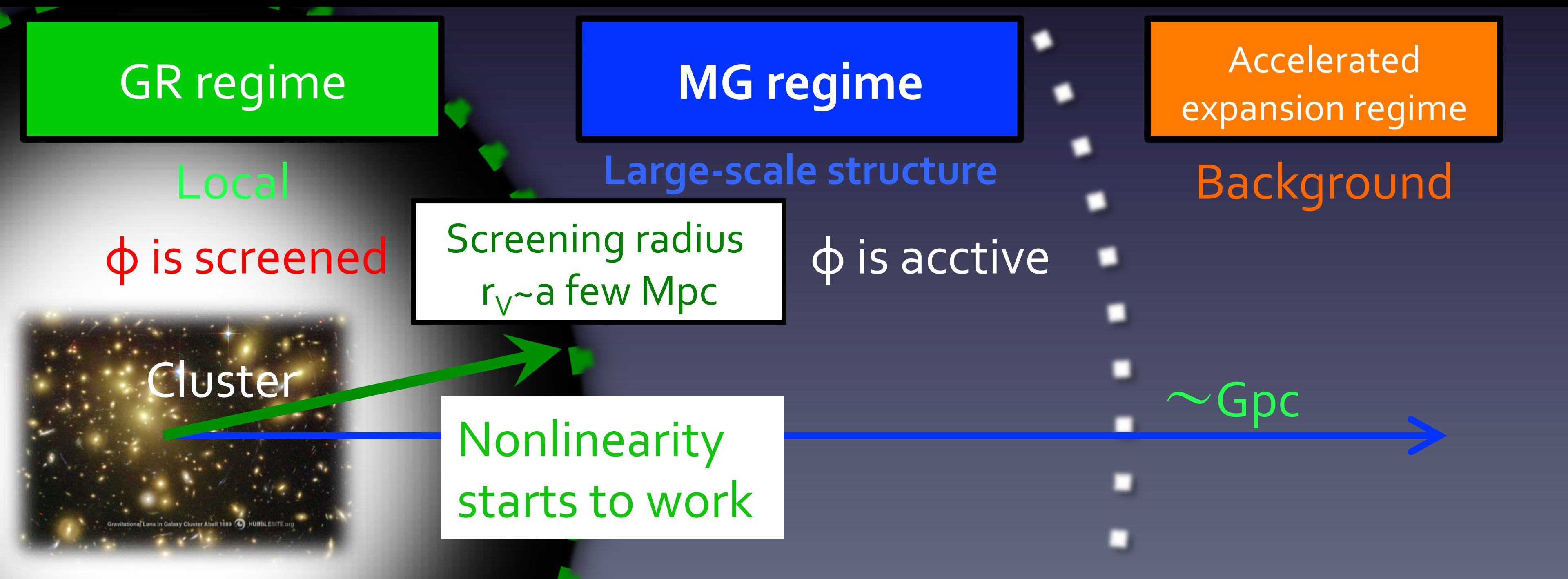
screening mechanisms!

[Cassini spacecraft]



Screening Mechanisms of ϕ in Local Region

- Kinetic type: Vainshtein mechanism [Vainshtein '72]
  - Large kinetic term ⇔ weak coupling: Galileon-type
- Potential type: Chameleon mechanism, Symmetron [Khoury & Weltman '04, Hinterbichler & Khoury '10]
  - Large curvature of potential ⇔ massive scalar field m_ϕ



Observational Test of Modified Gravity

- Whether the screening mechanism works completely or not around high-density regions ?
- Gravitational lensing of galaxy clusters may be useful to test modified gravity
- Key: lensing potential $\triangle\Phi_+ \equiv \triangle(\Phi + \Psi)/2$

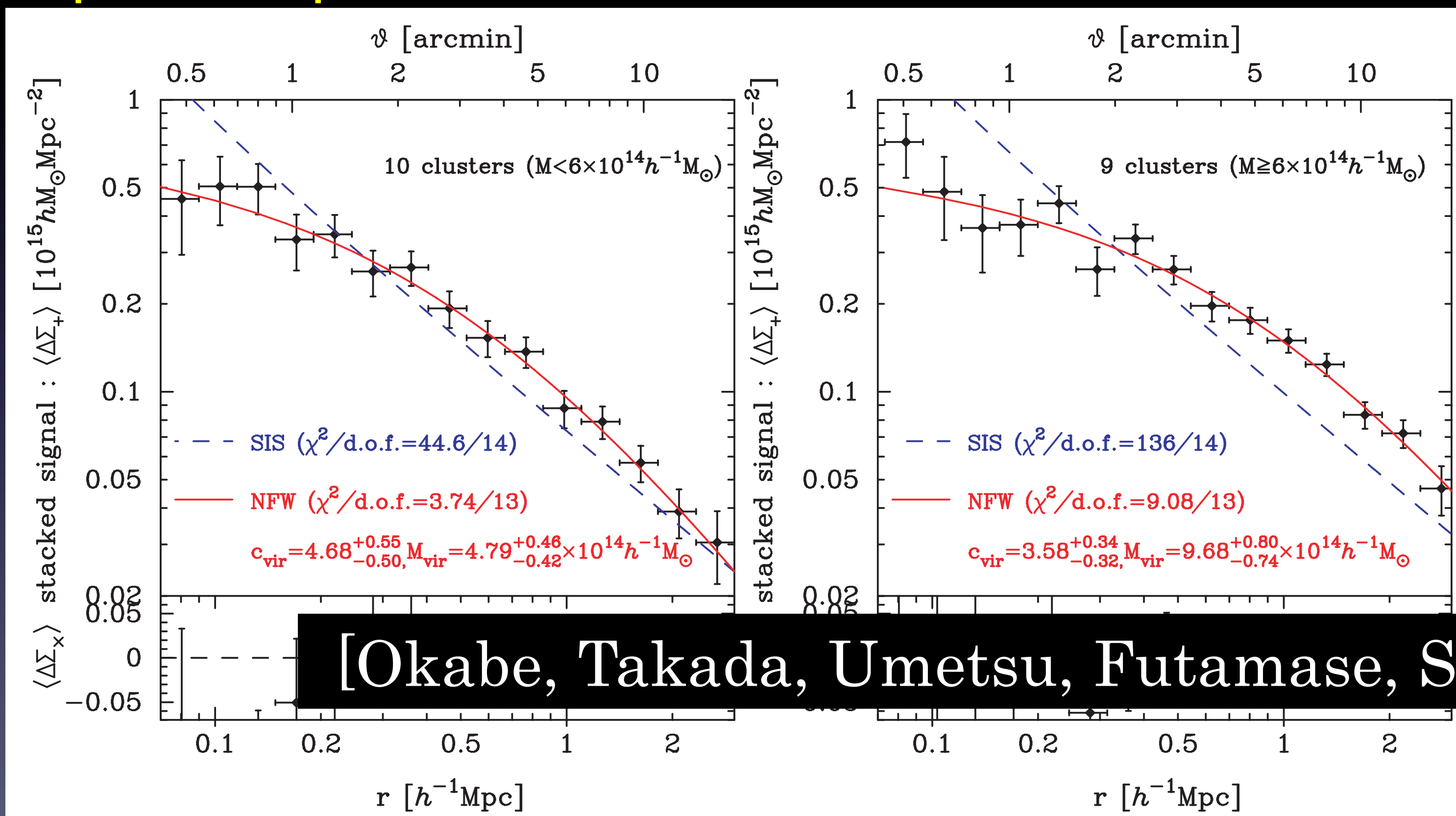
[TN, Yamamoto, '12]

- Large amount of data of cluster lensing will be provided by Hyper Suprime-Camera (HSC) [Takada-san's talk]

Stacked Cluster Lensing Analysis

The average distortion profile [Itoh-san's talk]

- is less sensitive to individual substructures/asphericity
- helps to improve the S/N



[Okabe, Takada, Umetsu, Futamase, Smith '10]

- may be also useful to test modified gravity

Galileon-type Modified Gravity

- Motivation: decoupling limit of DGP model

$$\mathcal{L}_{\rm int} \sim X\Box\phi$$: higher-derivative term

where ϕ : scalar field, $X \equiv -\frac{1}{2}(\partial\phi)^2$

enjoy Galileon shift symmetry: $\partial_\mu\phi \to \partial_\mu\phi + c_\mu$

→ 「 • Cosmic acceleration

• 2nd order EOM

• Vainshtein mechanism 」

[DLofDGP] Luty, Porrati & Rattazzi '03, Nicolis & Rattazzi '04

Vainshtein Mechanism in Simple Model

$$\mathcal{L}_\phi = 3\phi\Box\phi - \frac{2}{\Lambda^3}(\partial\phi)^2\Box\phi + \frac{2}{M_{\rm Pl}}\phi T$$

ϕEOM

$$3\Box\phi + \frac{1}{\Lambda^3}\left((\Box\phi)^2 - (\partial_\mu\partial_\nu\phi)^2\right) = -\frac{1}{M_{\rm Pl}}T$$

At $r \ll r_V$: Large kinetic term ⇔ Weak coupling to matter

$$\phi'(r) \sim \left(\frac{M}{2M_{\rm Pl}}\frac{\Lambda^3}{r}\right)^{1/2} \ll \partial_r \Phi_{\rm N}$$ ←screened !

where Vainshtein radius: $r_V \equiv (M/M_{\rm Pl})\Lambda^{-1}$

[Luty, Porrati & Rattazzi ‘03, Nicolis & Rattazzi ‘04]

The Most General Second-Order Scalar-Tensor Theory [Horndesky '74]

$$S = \int d^4x \sqrt{-g}[\mathcal{L} + \mathcal{L}_m]$$

assume matter do not directly couple to ϕ

$$\mathcal{L} = K(\phi, X) - G_3(\phi, X)\Box\phi$$
$$+ G_4(\phi, X)R + G_{4X} \times (\text{field derivatives})$$
$$+ G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi$$
$$- \frac{1}{6}G_{5X} \times (\text{field derivatives})$$

where $G_{iX} \equiv \partial G_i / \partial X$

4 arbitrary functions of ϕ, X

is equivalent to the generalized galileon

[Deffayet et al. '11, Kobayashi, Yamaguchi , Yokoyama '11]

Background solution

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu$$

$$\phi = \phi_0 = \mathrm{const}, \;\; X = 0$$

Inorder to admit this solution, we require that

$$K(\phi_0, 0) = 0, \;\; K_\phi(\phi_0, 0) = 0$$

Spherical symmetric perturbations produced by a nonrelativistic matter

$$ds^2 = -[1 + 2\Phi(r)]dt^2 + [1 - 2\Psi(r)]\delta_{ij} dx^i dx^j$$

$$\phi = \phi_0 + \varphi(r)$$

All the coefficients are evaluated at the background.

We will ignore the mass term $K_{\phi\phi}$.

Static-Spherically Symmetric Configurations

Metric EOM:

$$\frac{M_{\rm Pl}^2}{2}\frac{(r^2\Psi')'}{r^2} - M_{\rm Pl}\xi\frac{(r^2\varphi')'}{2r^2} - \frac{M_{\rm Pl}}{\Lambda^3}\alpha\frac{[r(\varphi')^2]'}{2r^2} - \frac{3M_{\rm Pl}}{\Lambda^6}\beta\frac{[(\varphi')^3]'}{6r^2} = -\frac{1}{4}T_t{}^t$$

$$M_{\rm Pl}^2(\Psi' - \Phi') - 2M_{\rm Pl}\xi\varphi' - \frac{M_{\rm Pl}}{\Lambda^3}\alpha\frac{(\varphi')^2}{r} = 0$$

ϕEOM:

$$\eta\frac{(r^2\varphi')'}{r^2} - 2\frac{\mu}{\Lambda^3}\frac{[r(\varphi')^2]'}{r^2} + 2M_{\rm Pl}\xi\frac{[r^2(2\Psi-\Phi)']'}{r^2} + 4\frac{M_{\rm Pl}}{\Lambda^3}\alpha\frac{[r\varphi'(\Psi'-\Phi')]'}{r^2} +$$
$$2\frac{\nu}{\Lambda^6}\frac{[(\varphi')^3]'}{r^2} - \frac{6M_{\rm Pl}}{\Lambda^6}\beta\frac{[(\varphi')^2\Phi']'}{r^2} = 0$$

where six dimensionless parameters:

ξ, η, μ, α, ν, β are functions of K_X, $G_{3\phi}$, G_{3X}, G_{4X}, $G_{5\phi}$,….

(cf. Vainshtein mechanism under considering background evolution [Kimura, Kobayashi, Yamamoto '12])

Quintic Scalar-Field Equation

We arrive at

$$P(x, A) := \xi A(r) + \left(\frac{\eta}{2} + 3\xi^2\right) x + \left[\mu + 6\alpha\xi - 3\beta A(r)\right] x^2$$
$$+ \left(\nu + 2\alpha^2 + 4\beta\xi\right) x^3 - 3\beta^2 x^5 = 0$$

where we define

$$x = \frac{1}{\Lambda^3}\frac{\varphi'}{r}, \; A(r) = \frac{1}{M_{\mathrm{Pl}}\Lambda^3}\frac{M(r)}{8\pi r^3}$$

which are dimensionless.

M(r) is the enclosed mass.

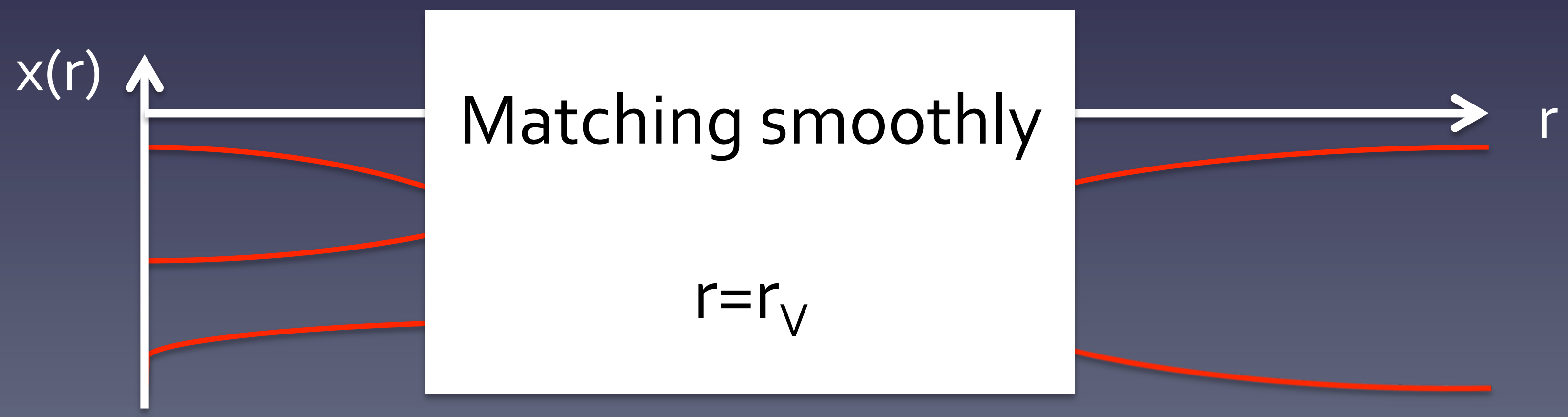
Scalar-Field Equation [cf. Sbisa, Niz, Koyama, Tasinato '12]

We solve $x = \frac{1}{\Lambda^3}\frac{\varphi'}{r}, \ A(r) = \frac{1}{M_{\rm Pl}\Lambda^3}\frac{M(r)}{8\pi r^3}$

$$P(x, A) := \xi A(r) + \left(\frac{\eta}{2} + 3\xi^2\right)x + \left[\mu + 6\alpha\xi - 3\beta A(r)\right]x^2$$
$$+ \left(\nu + 2\alpha^2 + 4\beta\xi\right)x^3 - 3\beta^2 x^5 = 0$$

for the inner region (A>>1) and the outer region (A<<1).

We then derive the conditions under which the two solutions are matched smoothly in an intermediate region.



Outer Solution: Asymptotically Flat

・ In the outer region (A<<1), there is always a decaying solution,

$$x \approx x_{\rm f} := -\frac{2\xi A(r)}{\eta + 6\xi^2}$$

which is obtained by neglecting the nonlinear terms in P(x,A)=0.

The other solutions do not correspond to an asymptotically flat spacetime.

Inner Solution: Vainshtein

- In the inner region (A>>1), P=0 reduces to

$$P(x, A) \approx \xi A - 3\beta A x^2 - 3\beta^2 x^5 \approx 0$$

We have a solution (ξβ>0):

$$x \approx x_{\pm} := \pm\sqrt{\frac{\xi}{3\beta}} = \mathrm{const}$$

(P(x-,A) does not depend on A.)

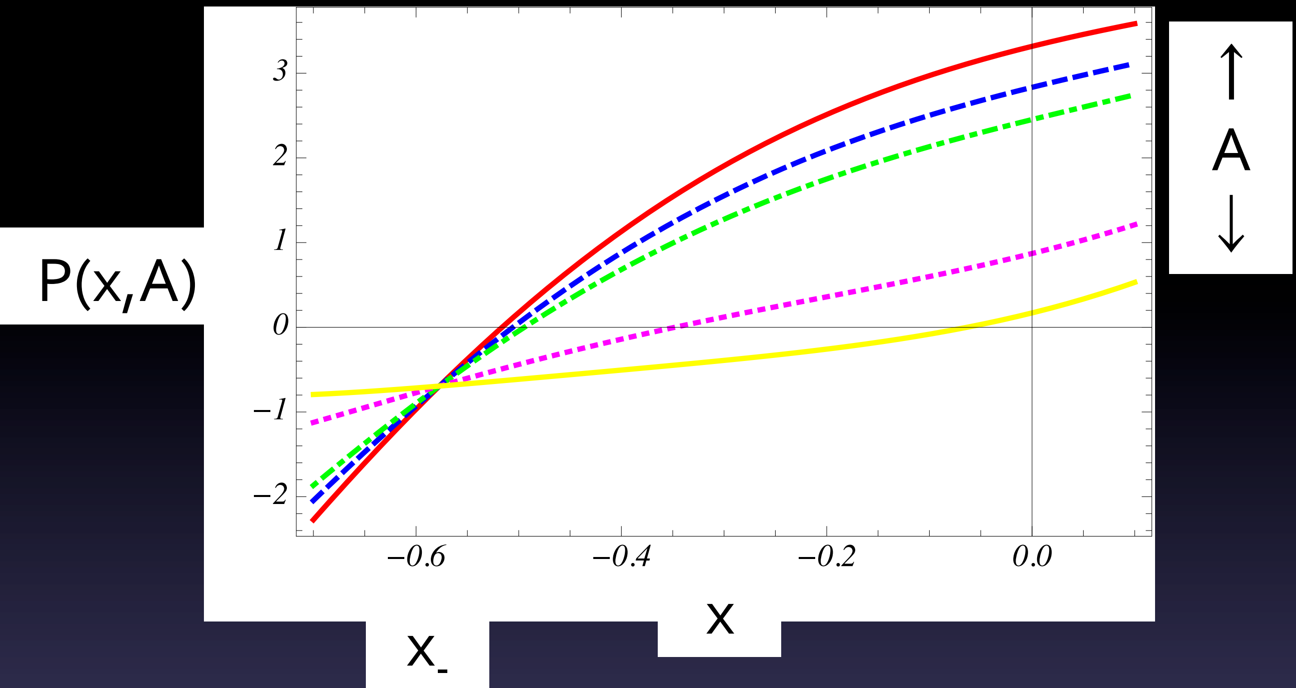
For this solution, we have Newtonian behavior:

$$\Psi'/r \simeq \Phi'/r \propto A$$

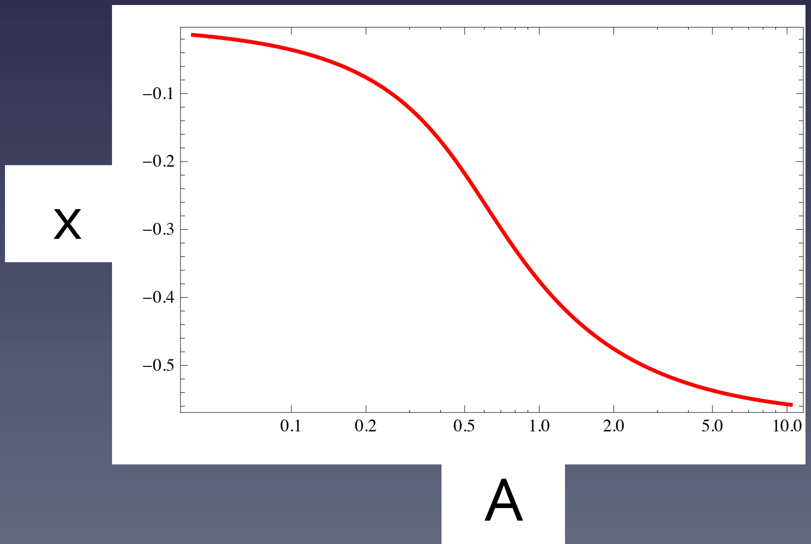
This is therefore the Vainshtein solution.

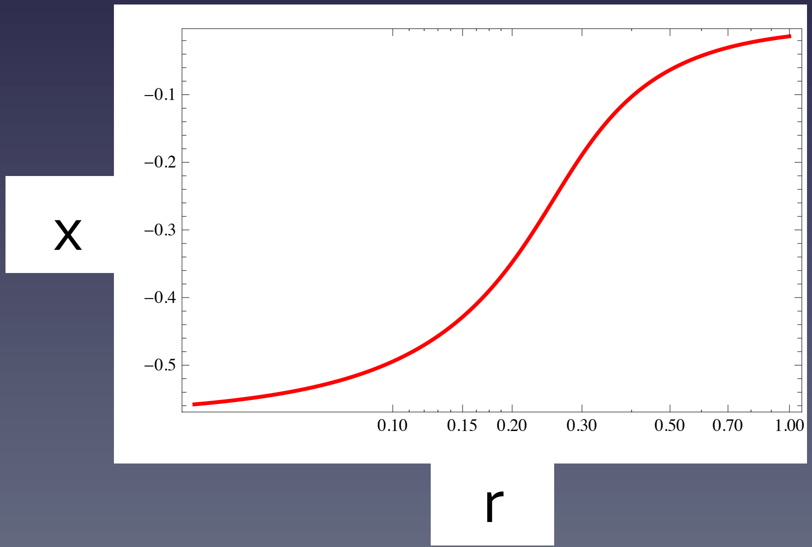
For simplicity we focus on the case of ξ>0.

Matching of Two Solutions



In this case, P(x)=0 has a single real root in (x-,0) for any A>0.





Decoupling Limit of Massive Gravity

[de Rham, Heisenberg '11]

Decoupling limit: $M_{pl} \to \infty$, $m_g \to 0$, $\Lambda^3 = M_{pl} m_g^2$ =fixed.

The corresponds to

$$\mathcal{E}^{\alpha\beta}_{\mu\nu} H_{\alpha\beta}$$

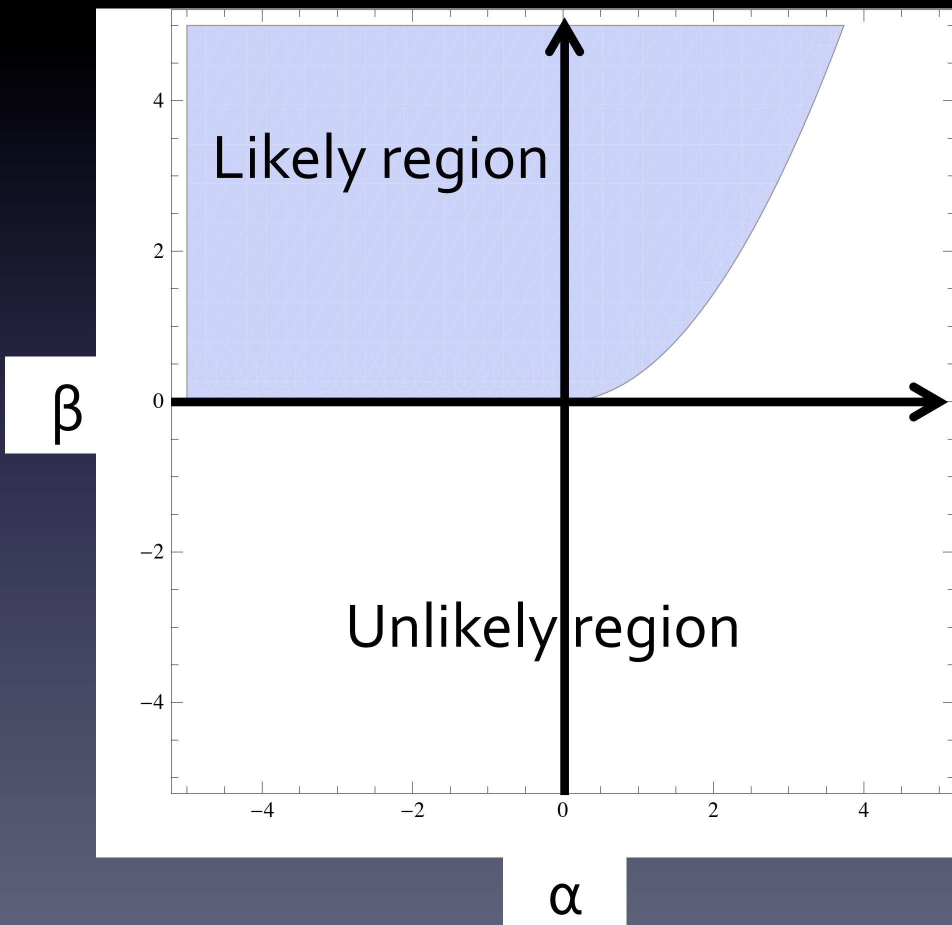
$$K = 0 = G_3,\ G_4 = \frac{M_{\rm pl}^2}{2} + M_{\rm Pl}\phi + \frac{M_{\rm Pl}}{\Lambda^3}\alpha X,\ G_5 = -3\frac{M_{\rm Pl}}{\Lambda^6}\beta X$$

One finds

$$\eta = \mu = \nu = 0,\ \xi = 1,\ \alpha \neq 0,\ \beta \neq 0$$

The condition of smooth matching of the two solutions:

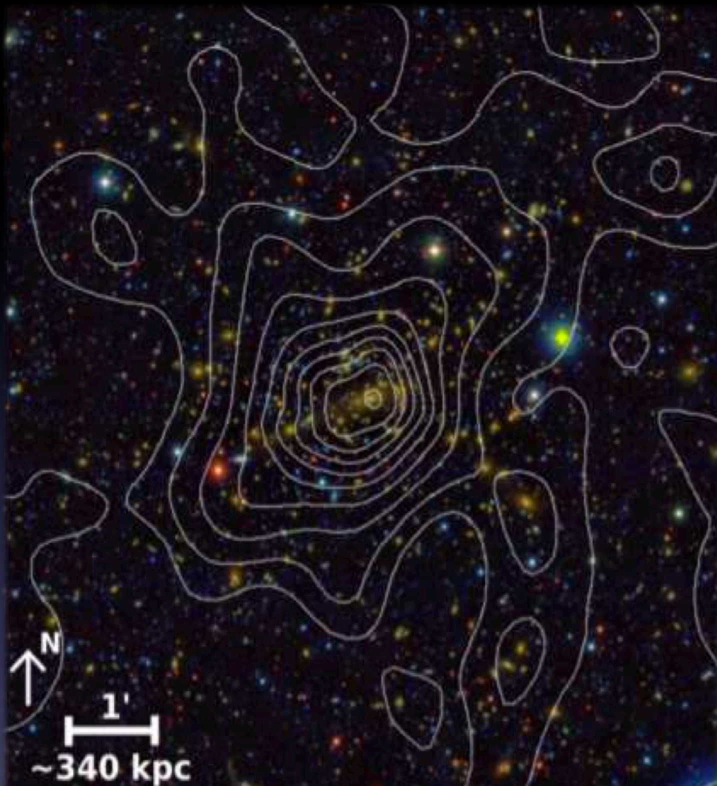
$$\alpha < 0 \text{ or } \frac{\sqrt{\beta}}{\alpha} \geq \sqrt{\frac{5+\sqrt{13}}{24}} \sim 0.6$$



Explore the observationally allowed region with cluster lensing.

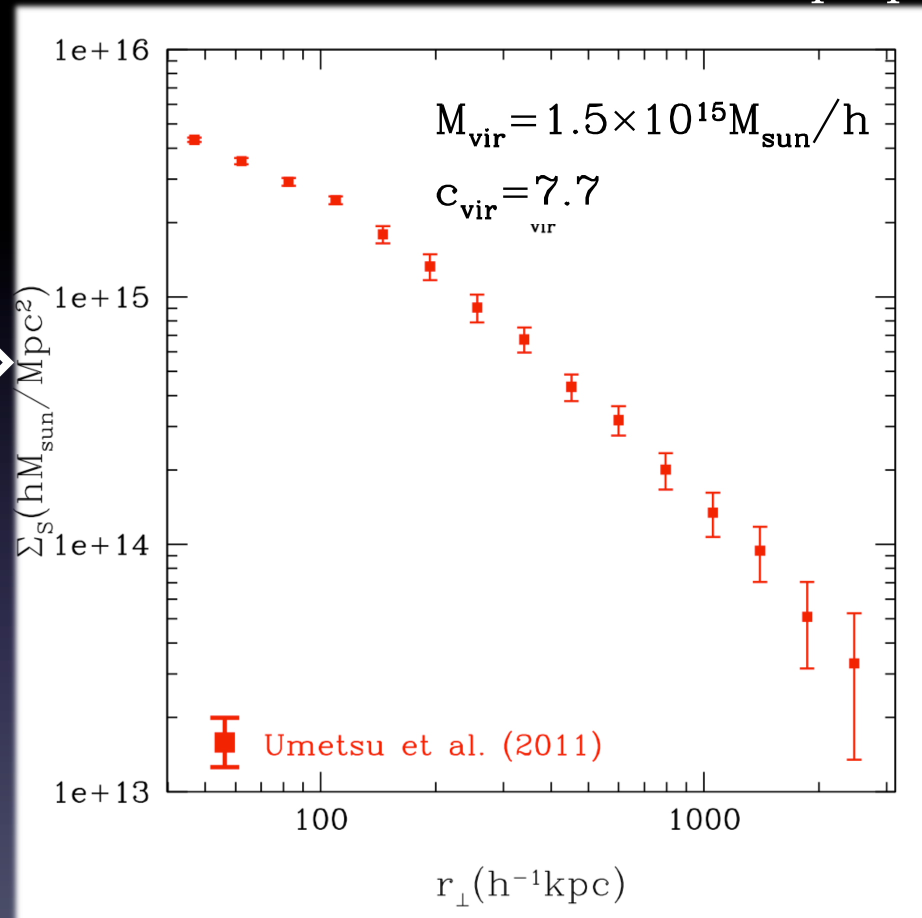
Cluster Lensing

Mass map (shear)



[Bartelmann's talk]

Surface mass density $\Sigma_S(r_{perp})$



[Umetsu et al. '11,
cf. Oguri et al. '12]

Gravitational Lensing in Massive Gravity

- Geodesic equation

$$\frac{d^2}{d\chi^2}(\chi\theta^i) = 2\Phi_{+,i}, \quad i = 1, 2 \qquad \Phi_+ \equiv (\Phi + \Psi)/2$$

- Surface mass density $\Sigma_S(r_{perp}) \propto \kappa(r_{perp})$

$\Phi_+ \equiv (\Phi + \Psi)/2$

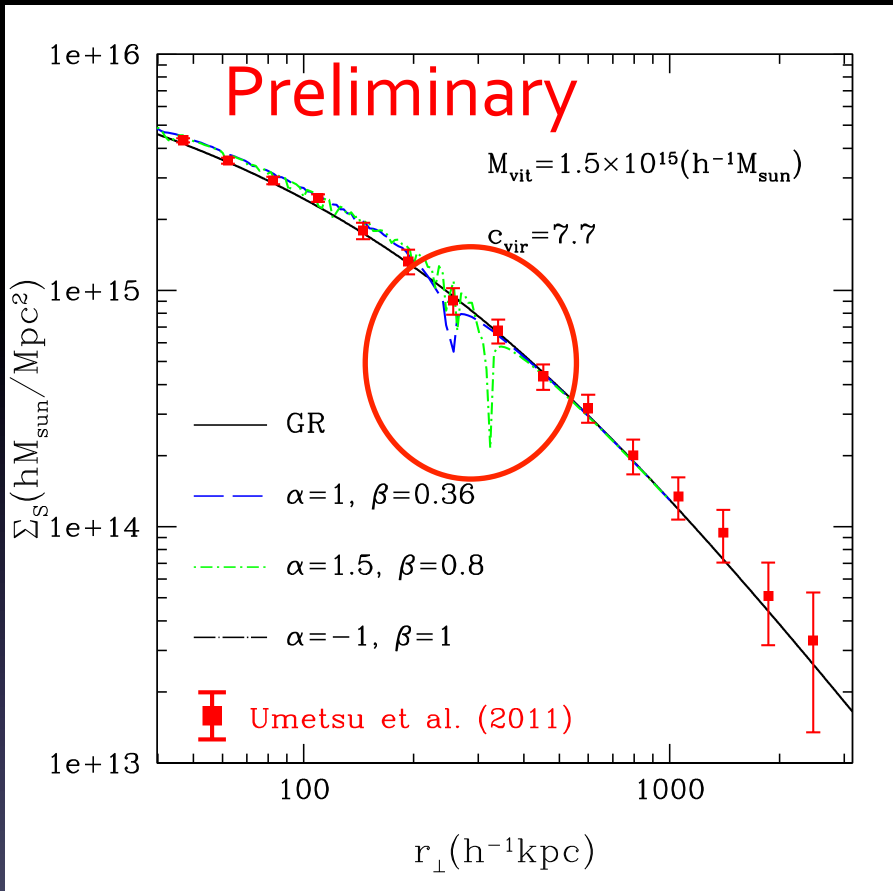
$$\Sigma_S \propto \int_0^\infty dZ \triangle^{(2D)} \Phi_+ \qquad r = \sqrt{r_\perp^2 + Z^2}$$

where lensing potential in massive gravity:

$$\triangle\Phi_+ = \frac{\Lambda^3}{M_{\rm Pl}} \frac{\left[\left(\alpha x^2 + 2\beta x^3 + 2A\right) r^3\right]'}{2r^2}$$

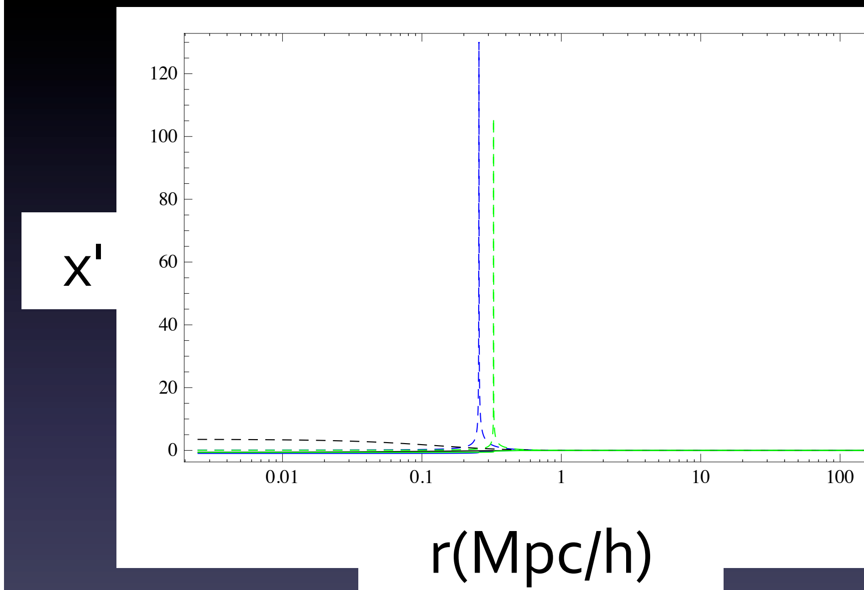
Assume $\delta\rho(r)$ as NFW profile: $\rho(r) = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$

Surface Mass Density in Massive Gravity



Parameters: $\{\alpha,\beta,\Lambda;\rho_s,r_s\}$

($\Lambda=0.01/H_0$, ρ_s, r_s fixed)



Origin of dip: x′(<=>ϕ″)

Dip appears at $r\sim r_V:=(r_s M_{Pl}/\Lambda^3)^{1/3}$

→allows us to put constraint

Summary

・Static-spherically symmetric solutions of ϕEOM in the context of Horndeski's theory.

・We explore the possibility of testing modified gravity exhibiting the Vainshtein mechanism against observation of cluster lensing.

・Key effects on cluster lensing Σ_S is that x'(<=>ϕ'') can substantially be large at the transition from screened to unscreened regions.

→This allows us to put observational constraints on modified gravity.

Thank you for your attention