13:30-, Dec. 29, 2012

Testing modified gravity with cluster lensing

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Based on

TN & K. Yamamoto, JCAP 1205, 016 (2012) [arXiv:1201.4037];
TN, T. Kobayashi, D. Yamauchi & R. Saito, work in progress.

Outline

$\ddot{a} > 0$

- Introduction & Motivation
  - Cosmic Acceleration [Sami's talk]
  - Recent Progress of Modified Gravity [*]

    -Theoretical: Screening/General Framework[Kase's talk]

    -Observational: Galaxy Cluster Surveys
- Spherical Symmetric Configuration in General Modification (Horndeski's Theory)
- Cluster Lensing Signal in Modified Gravity
- Summary & Conclusion

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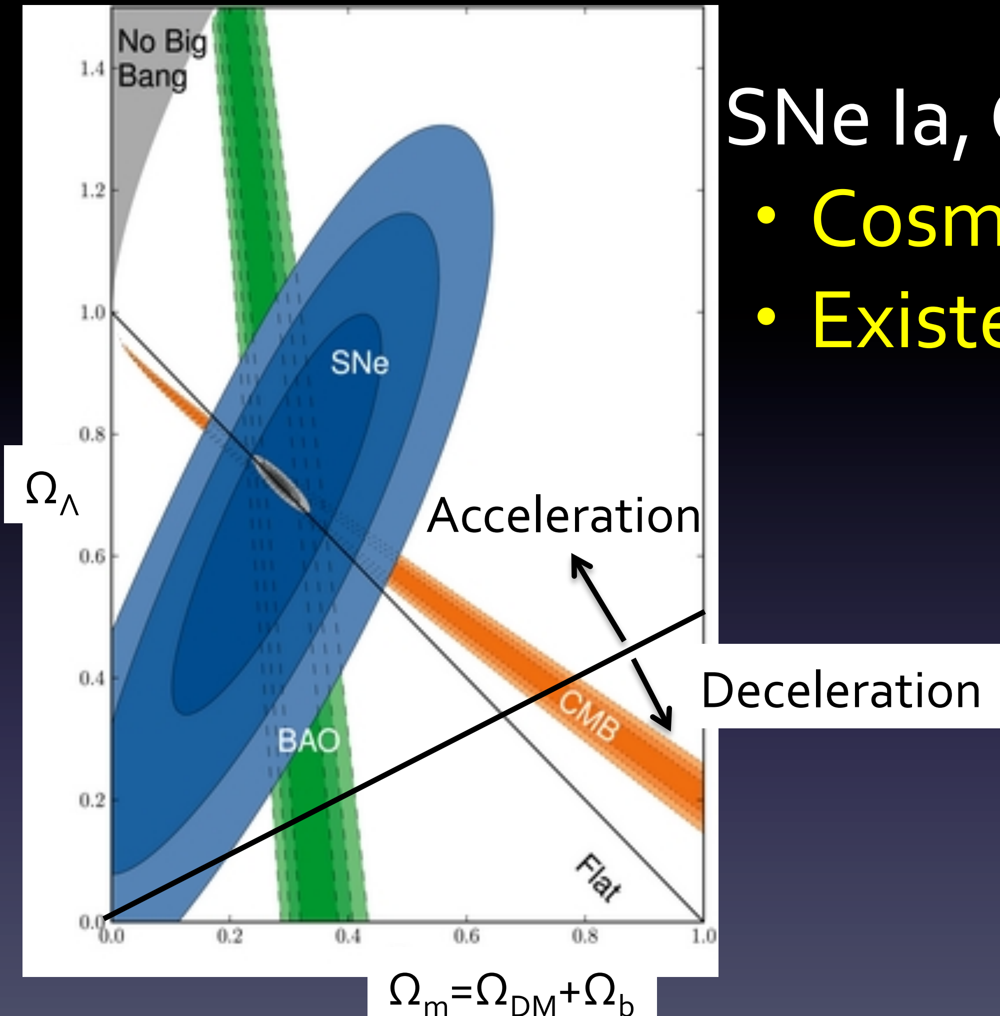
[*] X. Zhang; Bamba; Nojiri; Matsumoto; C.C. Lee; Saridakis; Ong; Wu; Ni; …

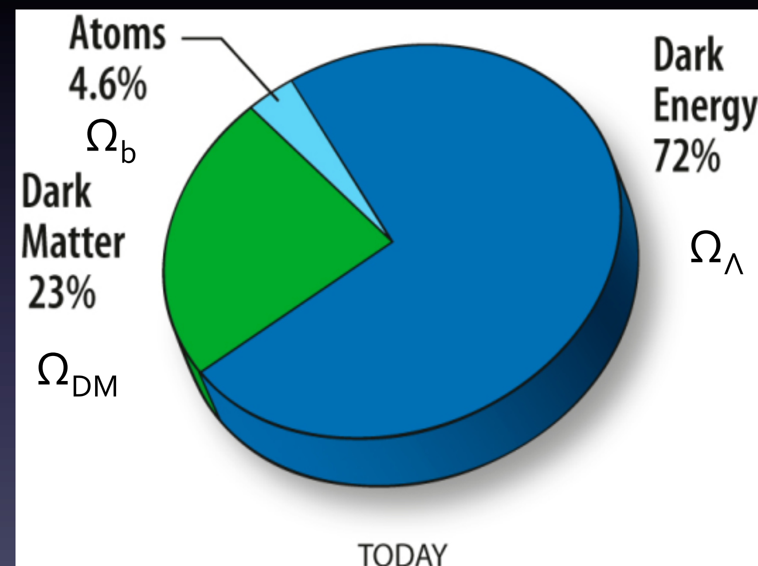
Evidence of Cosmic Acceleration



The Union2.1 compilation of 580 SNe
[Suzuki *et al.*(2012)]

SNe Ia, CMB, BAO are converging

- Cosmic acceleration
- Existence of Dark energy



[WMAP]

How to Explain Cosmic Acceleration

- Cosmological constant: w=-1

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \boxed{+ \Lambda g_{\mu\nu}} = \frac{1}{M_{\mathrm{Pl}}^2} T_{\mu\nu}$$

How to Explain Cosmic Acceleration

- Dark energy: w≠-1

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{1}{M_{\rm Pl}^2} T_{\mu\nu} + \boxed{\frac{1}{M_{\rm Pl}^2} T^{(\phi)}_{\mu\nu}}$$

How to Explain Cosmic Acceleration

- Cosmological constant: w=-1

- Dark energy: w≠-1

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R \boxed{+\Lambda g_{\mu\nu}} = \frac{1}{M_{\mathrm{Pl}}^2}T_{\mu\nu} \boxed{+\frac{1}{M_{\mathrm{Pl}}^2}T_{\mu\nu}^{(\phi)}}$$

- Modificatoin of gravity on cosmological scales

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \ ? = \frac{1}{M_{\mathrm{Pl}}^2}T_{\mu\nu}$$

The mystery of cosmic acceleration suggests that there is new gravitational physics on large scales.

Local Gravity Constraints

- In MG, an extra scalar field ϕ mediates fifth-force.

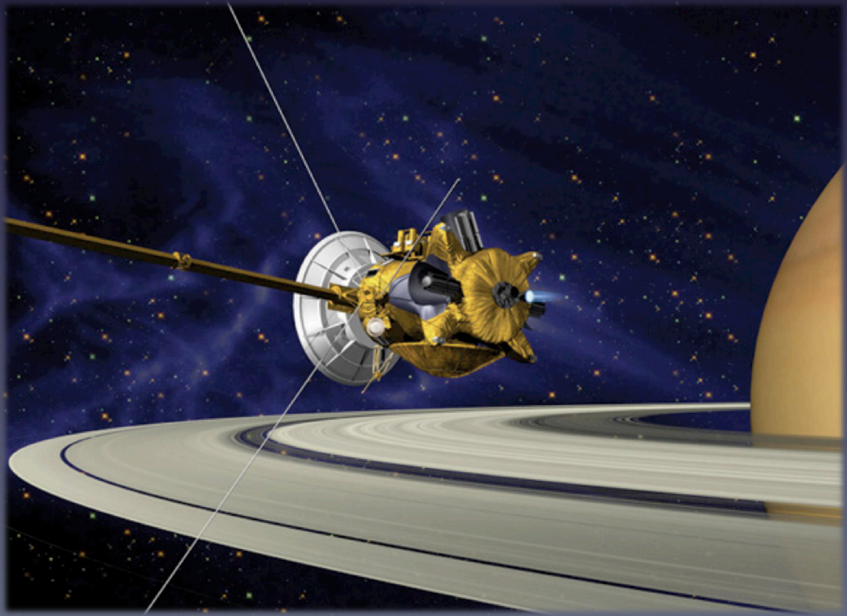
  $\rightarrow$deviation from GR on large-scales.

- Local gravity tests strongly constrain gravity.

- e.g. $\gamma_{PPN}-1=(2.1\pm2.3)\times10^{-5}$ by time-delay [Bertotti et al. (2003)]

- Screening mechanisms for ϕ are needed to evade local gravity constraints in modified gravity!

[Cassini spacecraft]

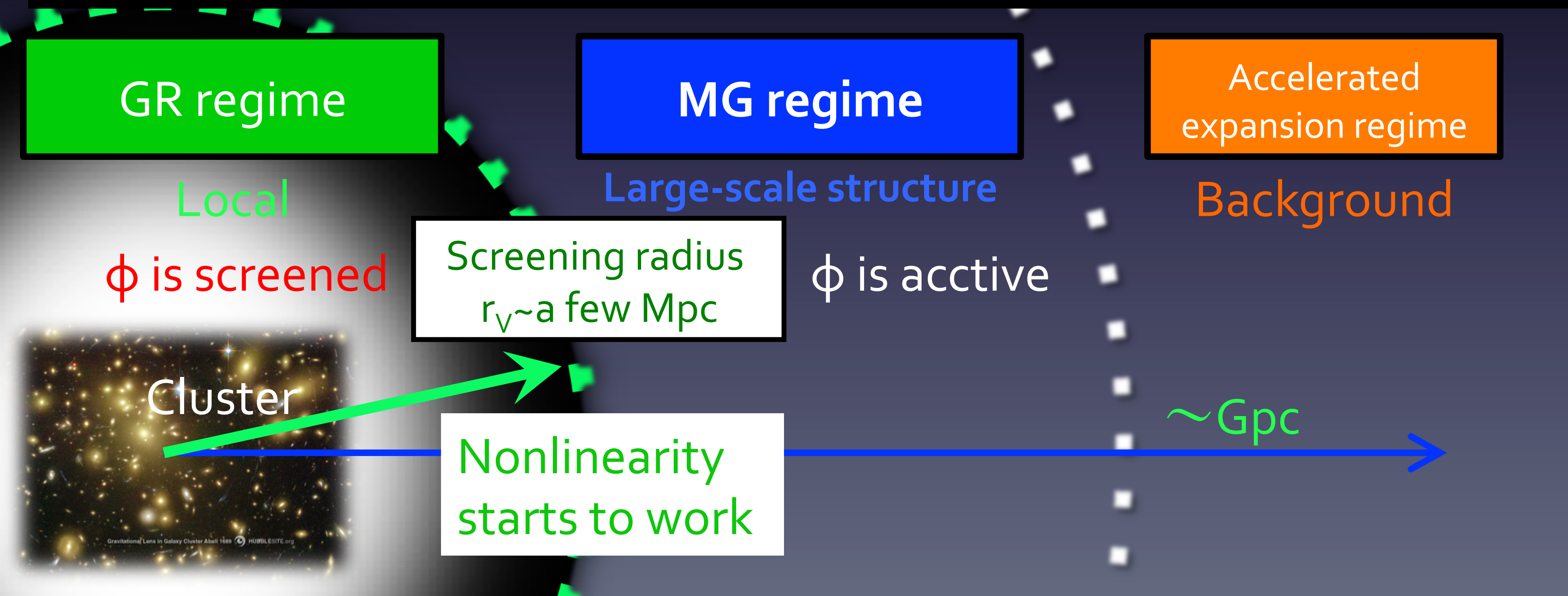


Modified Gravity

- Motivation: Cosmic acceleration
- Introduce an additional ϕ

{DGP, Galileon, Massive Gravity… } < General modification Horndeski's theory

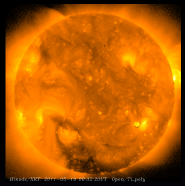
- This ϕ
  - cosmic accelerate,
  - mediate fifth force on large scales,
  - must be screened on small scales. [Vainshtein 1972]



Observational Tests of Modified Gravity

Especially Focus on Vainshtein Screening

Solar-system tests (time delay etc.)

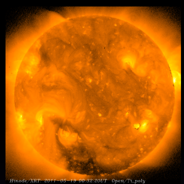


Galaxy (Lensing & Velocity dispersion)

Clusters of galaxies

Observational Tests of Modified Gravity

Especially Focus on Vainshtein Screening



Solar-system tests (time delay etc.)

Strict constraint

[Nicolis, Rattazzi & Trincherini (2009)]

Screening radius
r_V~kpc

Galaxy (Lensing & Velocity dispersion)

Strong constraint

r_V~Mpc

[Sjors & Mortsell (2012)]

Clusters of galaxies

r_V~10Mpc~r_{virial}

[Wyman (2011); TN & Yamamoto (2012)]

r_V~10Mpc that are very well measured by cluster surveys. Hence, it should be possible to discover or constrain this effect by cluster surveys.

Galaxy Cluster as a Probe of Modified Gravity

A variety of cluster observations

- X-ray
- Sunyaev-Zeldovich
- Gravitational lensing

Theor.> Lensing potential: $\triangle\Phi_+ \equiv \triangle(\Phi+\Psi)/2$

$\triangle\Phi_+ \propto r\phi'\phi''$ → deviation from GR at $r \sim r_V$

Obs.> Large amount of data for lensing profile will be provided by Subaru/Hyper Suprime-Cam (HSC).

Over a wide range of radius/ Small error of lensing profile data

Procedure

- Work in General framework (Horndeski's theory)
- Derive a condition that the Vainshtein screening work to study spherically symmetric configuration
- Demonstrate how an effect of ϕ appears on lensing signal $\triangle\Phi_+$ in the case that the Vainshtein screening works in modified gravity models
- Test modified gravity models by comparing some model predictions with cluster lensing data

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Top-down approach

→Construction a viable model/ getting its hint

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    -Observational: Galaxy Cluster Surveys

☑ Spherical Symmetric Configuration in General Modification (Horndeski's Theory)

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Galileon-type Modified Gravity

- Motivation: Decoupling limit of DGP braneworld model

$$\boxed{\mathcal{L}_{\rm int} \sim X\Box\phi}$$: 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
・Up to 2nd order derivatives in EOM
・Vainshtein screening 」

[DGP] Dvali, Gabadadze & Porrati 2000
[DLofDGP] Luty, Porrati, Rattazzi 2003; Nicolis, Rattazzi 2004
[Galileon] Nicolis, Rattazzi & Trincherini 2009

Vainshtein Screening in Cubic Galileon

$$\mathcal{L} = \mathcal{L}_{\rm GR} - X - \frac{1}{\Lambda^3} X \Box \phi + \mathcal{L}_m$$

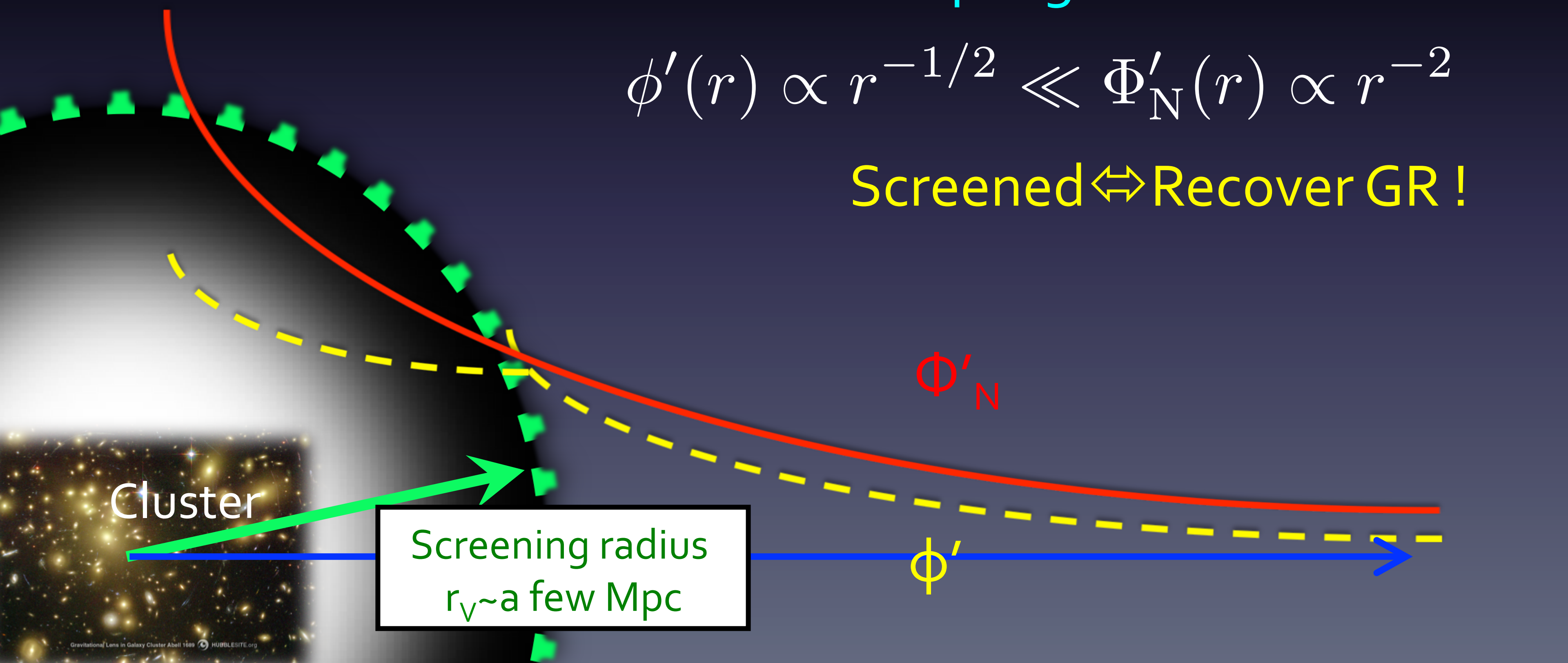
At $r \ll r_V$: Large kinetic term

⇔ Strong self-coupling

⇔ Weak coupling to matter

$$\phi'(r) \propto r^{-1/2} \ll \Phi'_{\rm N}(r) \propto r^{-2}$$

Screened ⇔ Recover GR !



Horndeski's Theory: General Modification in D=4 dim. Up to 2nd order derivatives in EOM

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

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

where $G_{iX} \equiv \partial G_i/\partial X$ 4 arbitrary functions of ϕ, X

[Horndeski 1974] is equivalent to the Generalized Galileon [Deffayet et al. 2011; Kobayashi, Yamaguchi, Yokoyama 2011]

Background Solution (Local Universe)

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

$$\phi = \phi_0 = \text{const}, \;\; X_0 = 0$$

Spherical symmetric perturbations produced by a nonrelativistic matter (Galaxy Cluster)

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

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

All the coefficients are evaluated at the background.

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])

Dimensionless parameters

Let us introduce six dimensionless parameters:
ξ, η, μ, α, ν, β

$$G_4 = \frac{M_{\rm Pl}^2}{2}, \quad G_{4\phi} = M_{\rm Pl}\xi,$$

$$K_X - 2G_{3\phi} = \eta,$$

$$-G_{3X} + 3G_{4\phi X} = \frac{\mu}{\Lambda^3},$$

$$G_{4X} - G_{5\phi} = \frac{M_{\rm Pl}}{\Lambda^3}\alpha,$$

$$G_{4XX} - \frac{2}{3}G_{5\phi X} = \frac{\nu}{\Lambda^6},$$

$$G_{5X} = -\frac{3M_{\rm Pl}}{\Lambda^6}\beta.$$

Quintic Scalar-Field Equation

Combining metric EOM and ϕEOM, we arrive at

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

where we define

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

both of which are dimensionless.

M(r) is the enclosed mass.

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

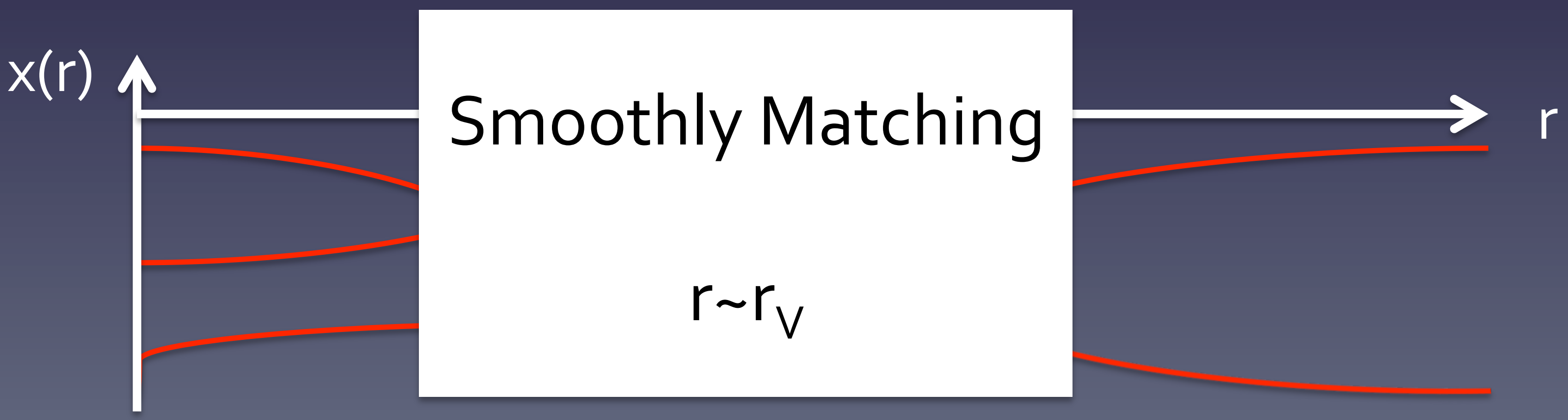
- Solve $x = \dfrac{1}{\Lambda^3}\dfrac{\varphi'}{r},\ \ A(r) = \dfrac{1}{M_{\rm Pl}\Lambda^3}\dfrac{M(r)}{8\pi r^3}$

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

$$+\left(\nu + 2\alpha^2 + 4\beta\xi\right)x^3 - 3\beta^2 x^5 = 0$$

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

- Derive a condition under which the two solutions are smoothly matched in an intermediate region.



Outer Solution: Asymptotically Flat

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

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

Inner Solution: Vainshtein

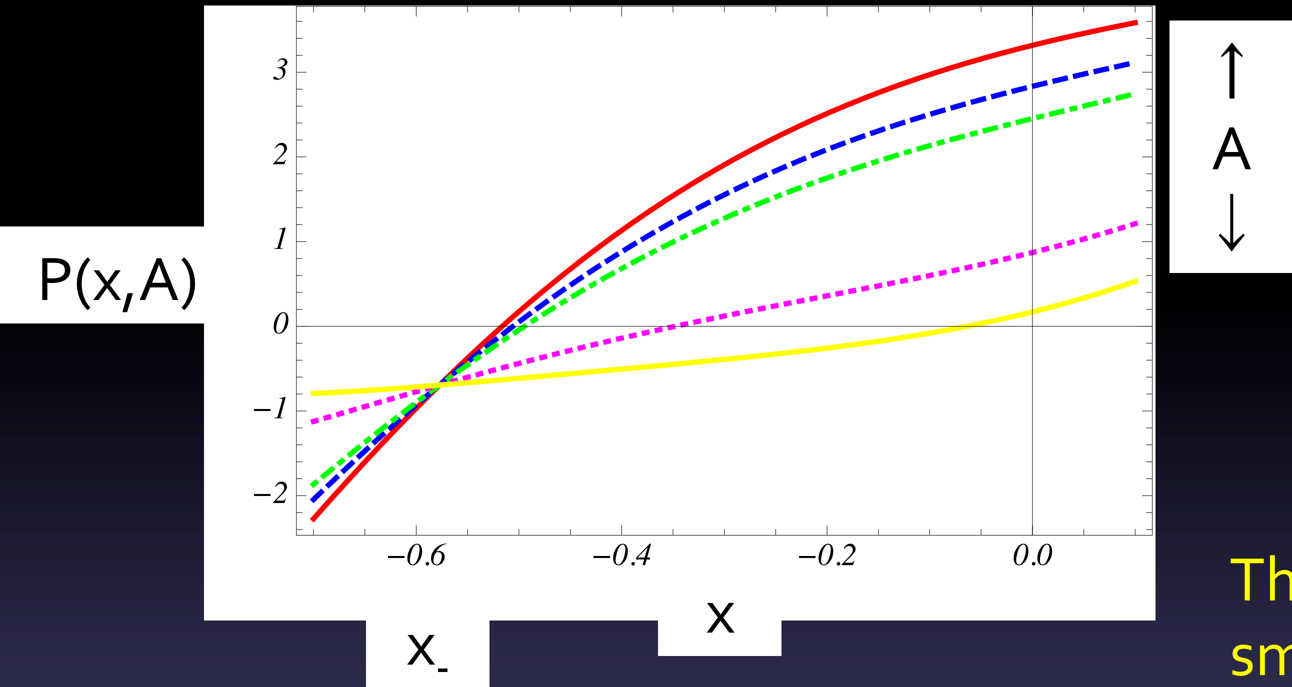
- In the inner region (A>>1), we have a solution (ξβ>0):

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

(P($x_{\pm}$) does not depend on A.)

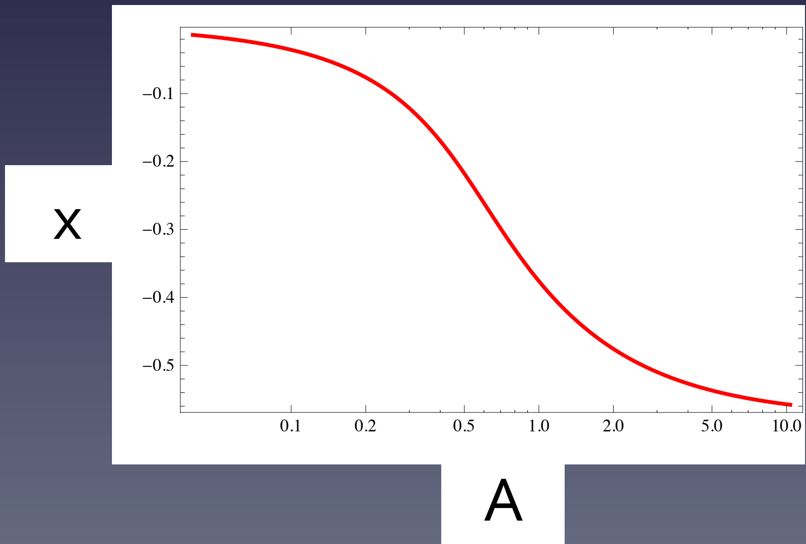
where $x = \frac{1}{\Lambda^3}\frac{\varphi'}{r}, \ A(r) = \frac{1}{M_{\rm Pl}\Lambda^3}\frac{M(r)}{8\pi r^3}$

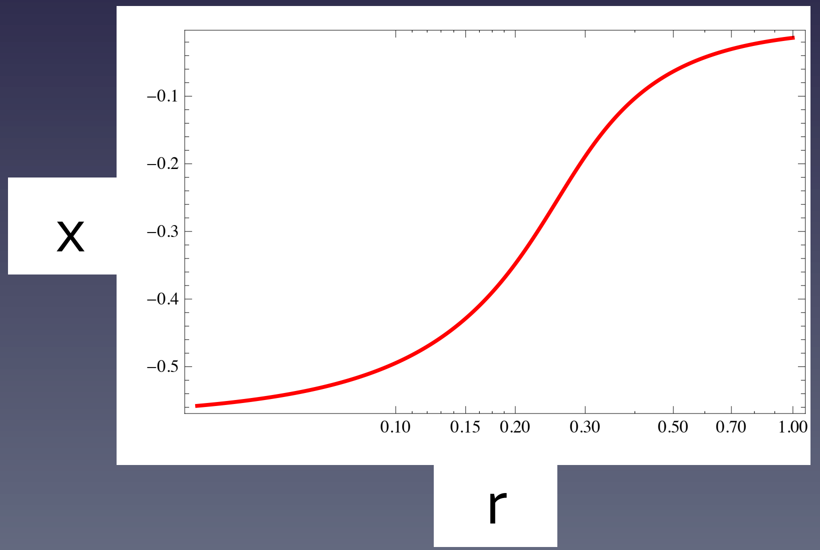
Smoothly Matching of Two Solutions



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

The two solutions are smoothly matched !





Parameters Corresponding to Decoupling Limit of Ghost-free Massive Gravity

$$\mathcal{L} = \mathcal{L}_{\mathrm{GR}} + m_g^2 h_{\mu\nu}^2 + \mathcal{O}(h_{\mu\nu}^3)$$

Massive Gravity = A sort of Galileon

[de Rham, Gabadadze & Tolley 2010]

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

Corresponding to

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

in Horndeski's theory.

$$G_{4X} - G_{5\phi} = \frac{M_{\rm Pl}}{\Lambda^3}\alpha, \ G_{5X} = -\frac{3M_{\rm Pl}}{\Lambda^6}\beta.$$

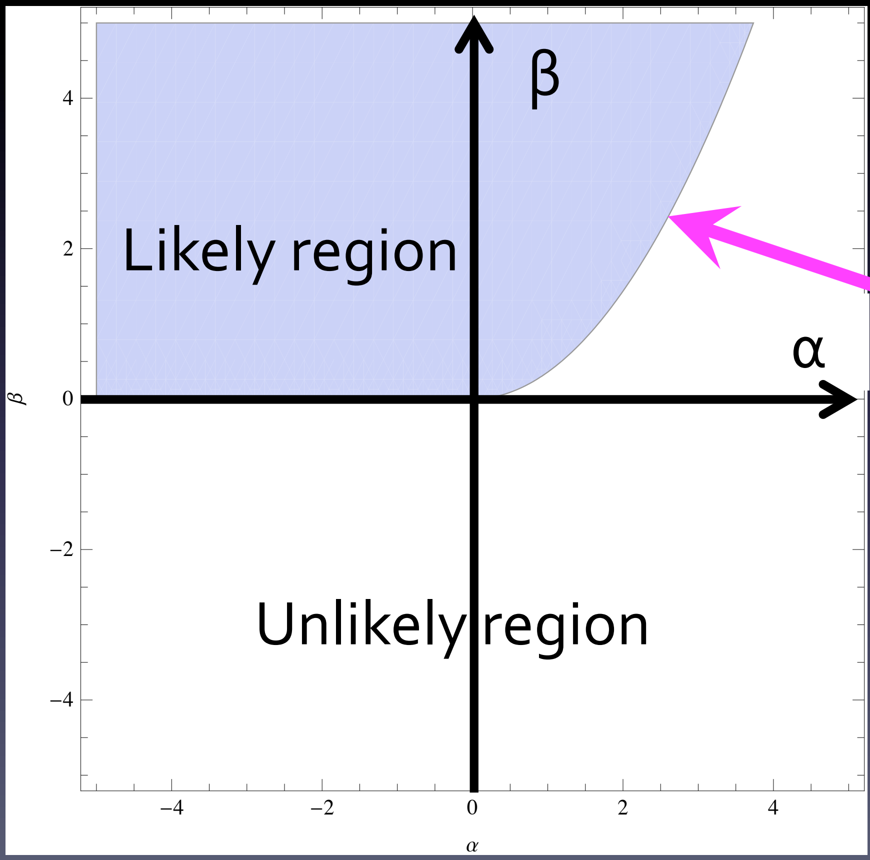
We found $\eta = \mu = \nu = 0, \ \xi = 1, \ \alpha \neq 0, \ \beta \neq 0$

(Proxy theory of massive gravity[de Rham & Heisenberg 2011])

The condition of smooth matching of the two solutions:

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

The region {α, β} which smoothly match the two solutions:



Boundary region where the solutions smoothly match.

Explore the observationally allowed region {α, β} with cluster lensing!

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Gravitational Lensing in Modified 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 $\Sigma_S(r_{perp}) \propto \kappa(r_{perp})$

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

where lensing potential in modified gravity:

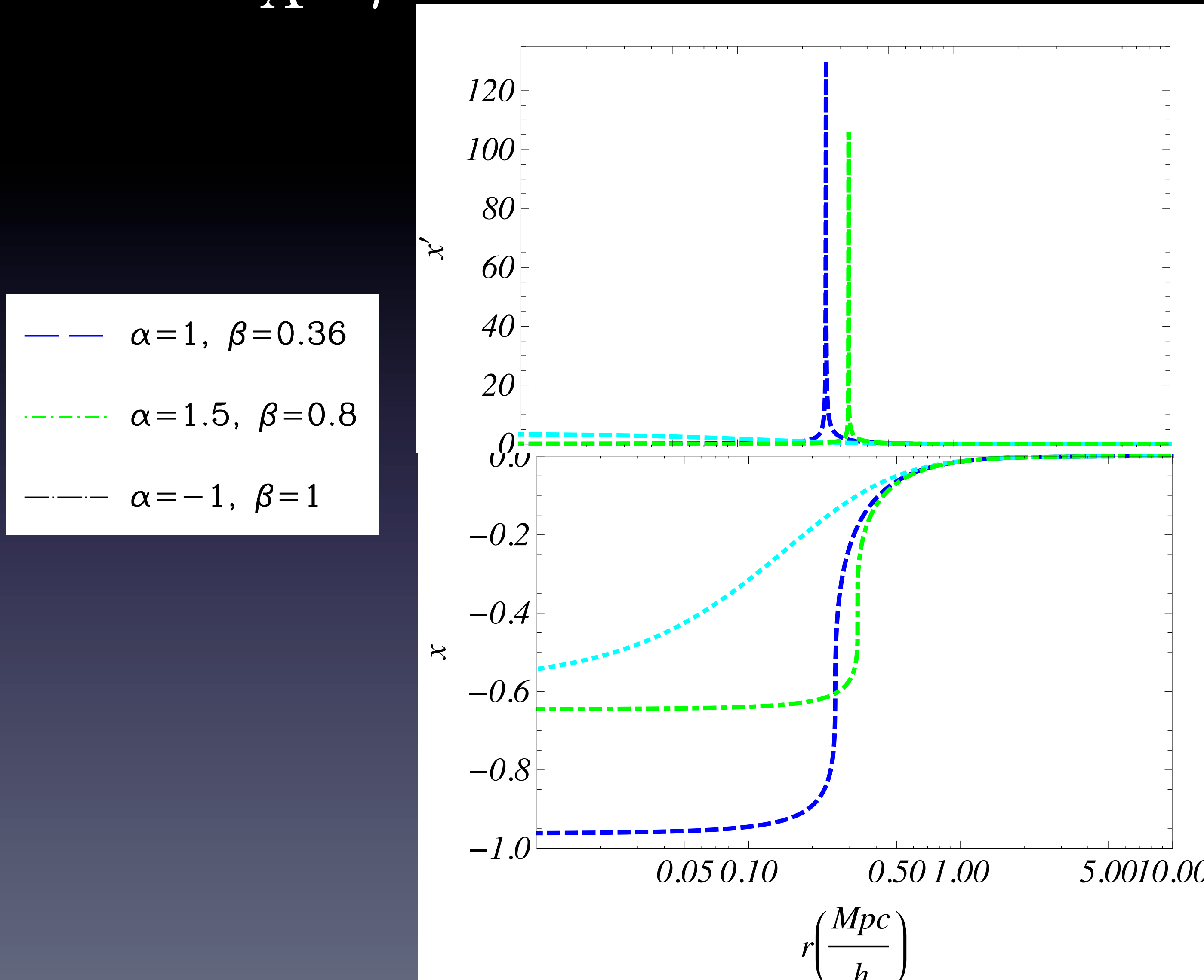
$$\triangle\Phi_+ = \frac{\Lambda^3}{M_{\rm Pl}} \frac{\left[\left(\alpha x^2 + 2\beta x^3 + 2A\right) r^3\right]'}{2r^2} \qquad \triangle\Phi_+ \propto r\phi'\phi''$$

assuming $\delta\rho(r)$ as NFW profile.

Scalar field in modified gravity:

$$x = \frac{1}{\Lambda^3}\frac{\varphi'}{r}$$

$\triangle\Phi_+ \propto r\phi'\phi''$

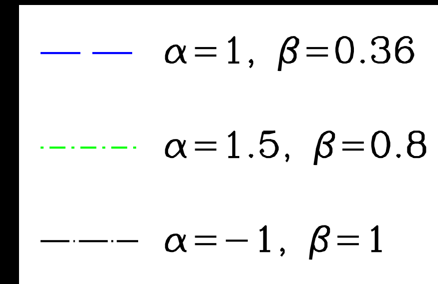


A dip appears.

Smoothly matching

Lensing potential in modified gravity:

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



$\triangle\Phi_{+} \propto r\phi'\phi''$

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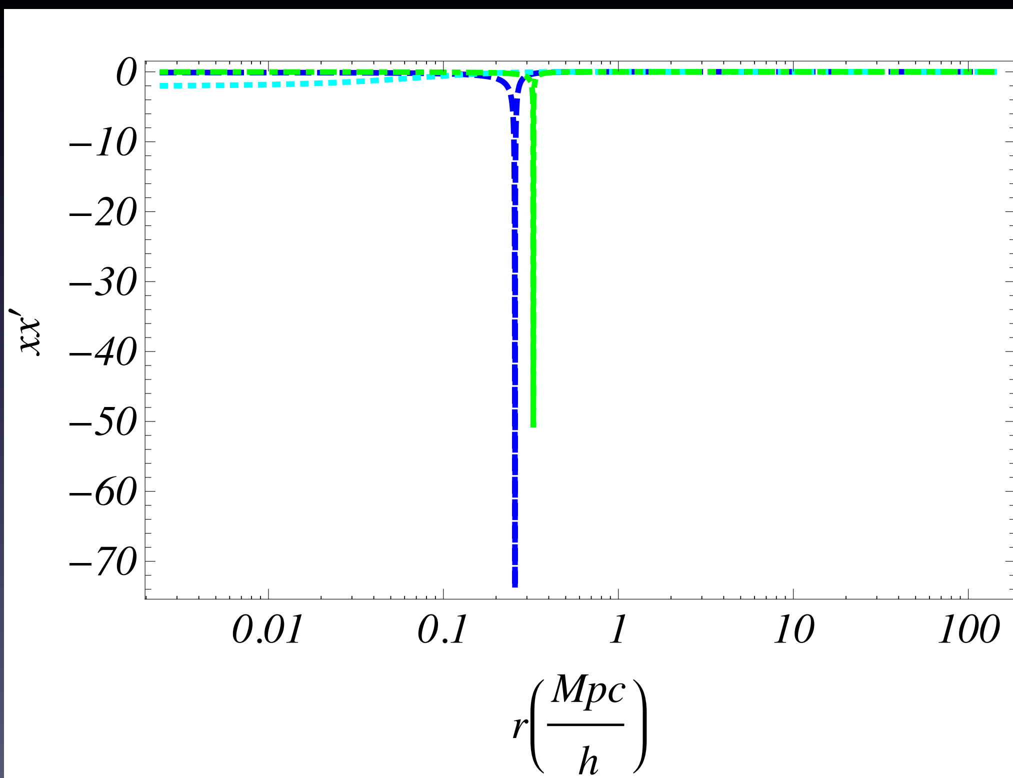
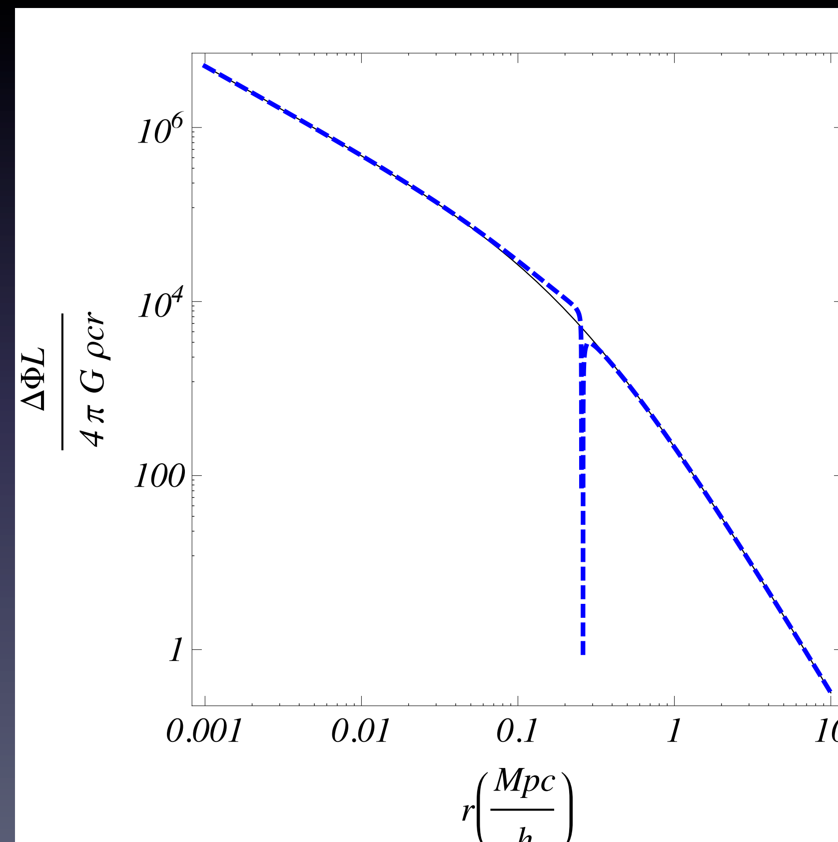
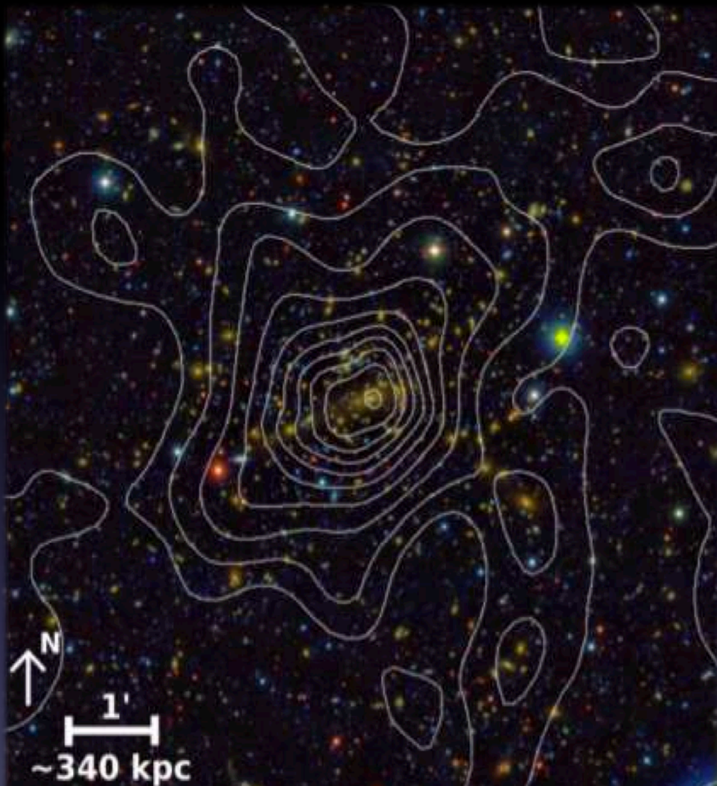


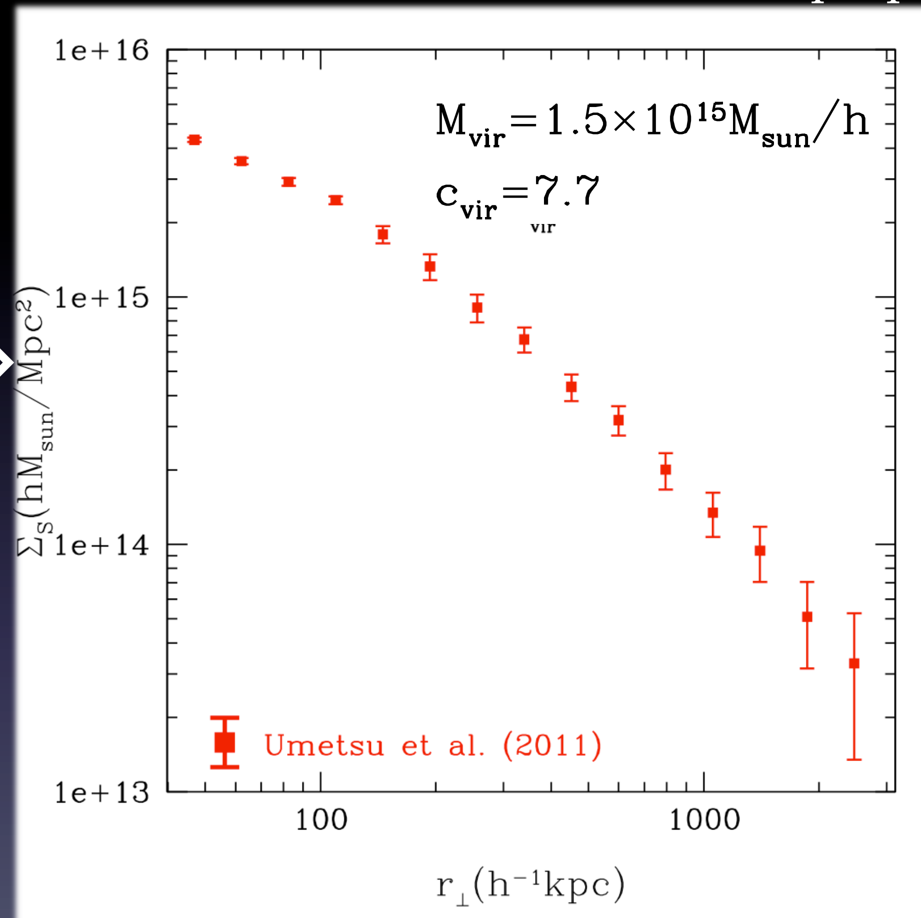


Lensing Potential of Galaxy Cluster

Mass map (shear)



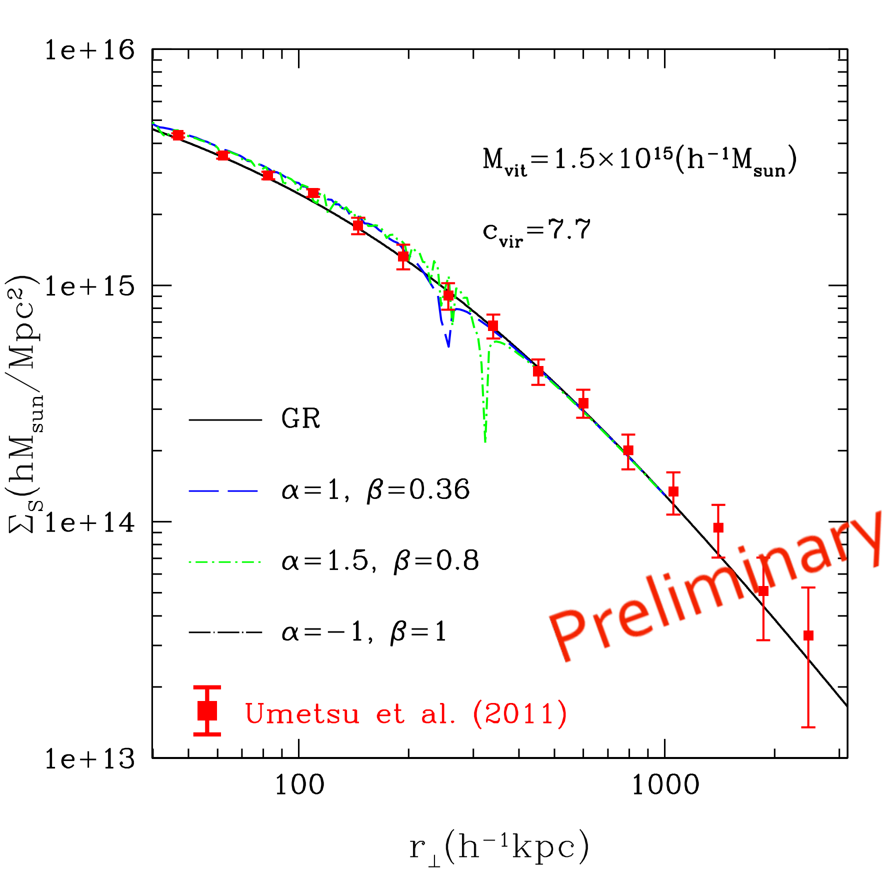
Surface mass density $\Sigma_S(r_{perp})$



Over a wide range of radius
Small error of the lensing profile data

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

Surface Mass Density in Modified Gravity



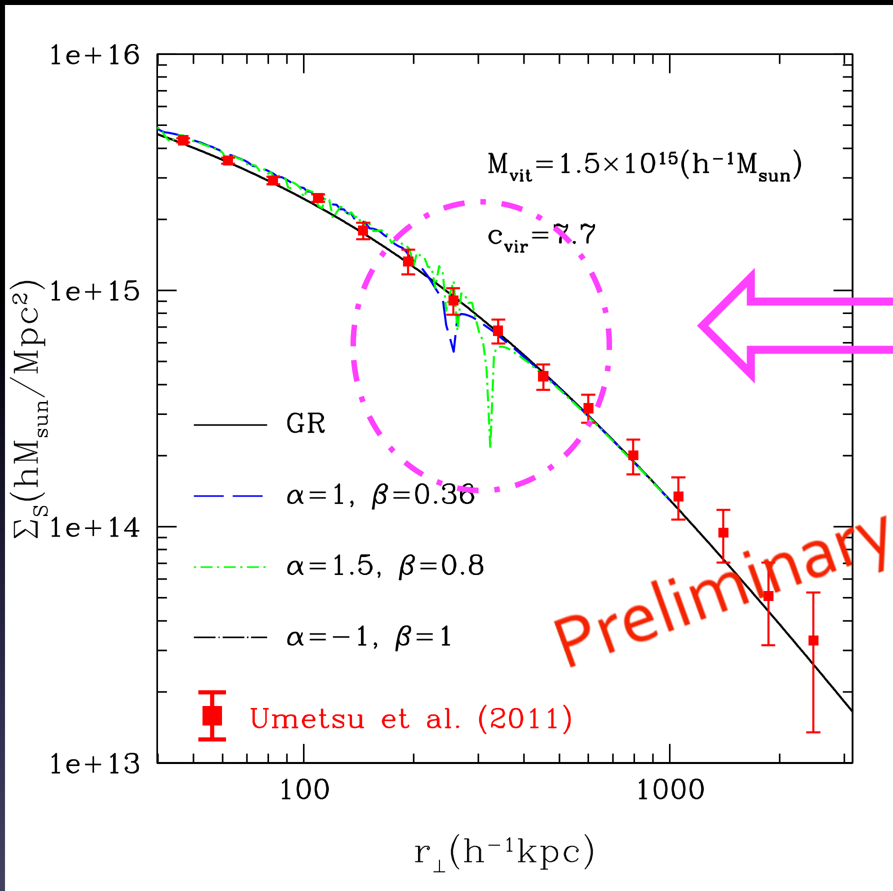
Parameters: $\{\alpha,\beta,\Lambda;\rho_s,r_s\}$

$(\Lambda^3=M_{Pl}/(0.01/H_0)^2,\ \rho_s,\ r_s$ fixed)

A dip appears at $r\sim r_V:=(r_s M_{Pl}/\Lambda^3)^{1/3}$ in a typical case.

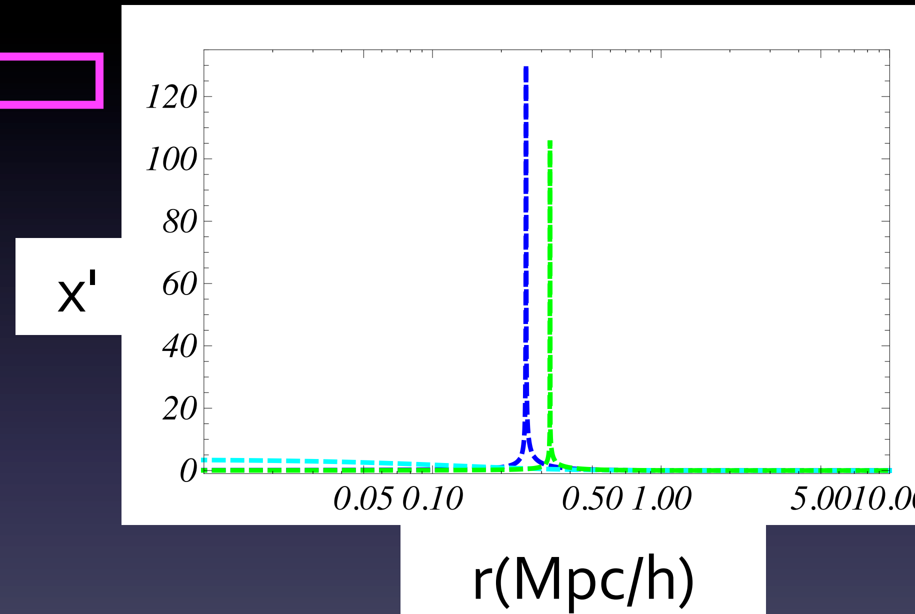
$\rightarrow$This allows us to put constraint.

Surface Mass Density in Modified Gravity



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

$(\Lambda^3=M_{Pl}/(0.01/H_0)^2,\ \rho_s,\ r_s$ fixed)



An origin of the dip: $x'(\Leftrightarrow\phi'')$

A dip appears at $r\sim r_V:=(r_sM_{Pl}/\Lambda^3)^{1/3}$ in a typical case.

$\rightarrow$This allows us to put constraint.

Summary & Conclusion

- Modified gravity by an ϕ
  - Motivation: Cosmic acceleration
  - With the screening mechanism
- We demonstrate how an effect of ϕ on $\triangle\Phi_+$ appears in General framework (Horndeski's theory). A dip appears!
- This allows us to put a constraint on modified gravity model with lensing profile of galaxy cluster.

Thank you for your attention