TESTING MODIFIED GRAVITY WITH HALO DENSITY PROFILES

Tatsuya Narikawa

HIROSHIMA UNIVERSITY

Based on
TN & K.Yamamoto
[arXiv: 1201.4037]

AGENDA

1. *INTRODUCTION*
2. *FORMULATIONS*
3. *CONSTRAINTS*
4. *Summary*

2012 Asia Pacific School/Workshop on Cosmology and Gravitation
@YITP, 3/1-4 2012

GENERAL DESCRIPTION OF MODIFIED GRAVITY

Cosmic Accelerate

Modified Gravity

General Relativity

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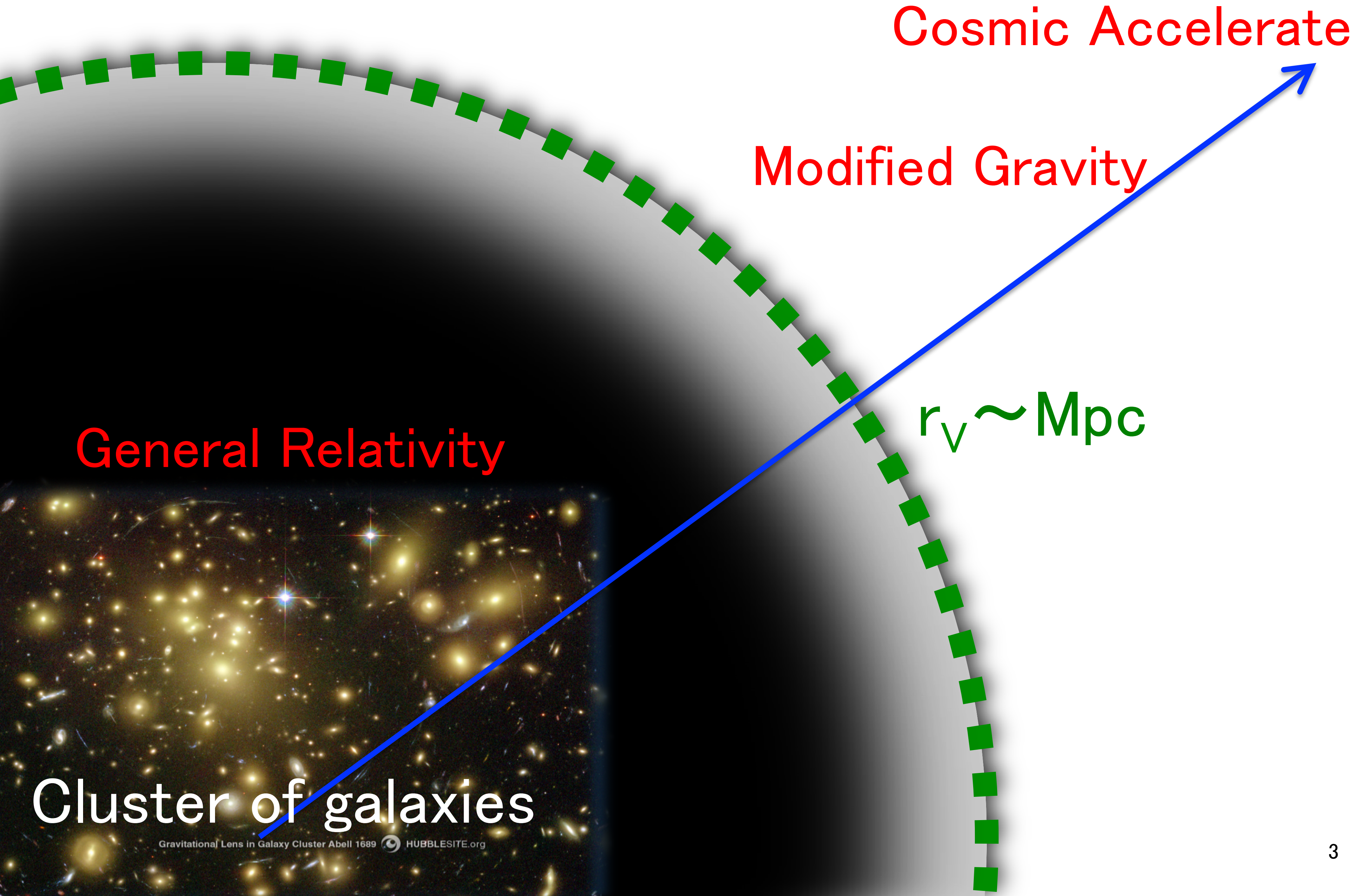

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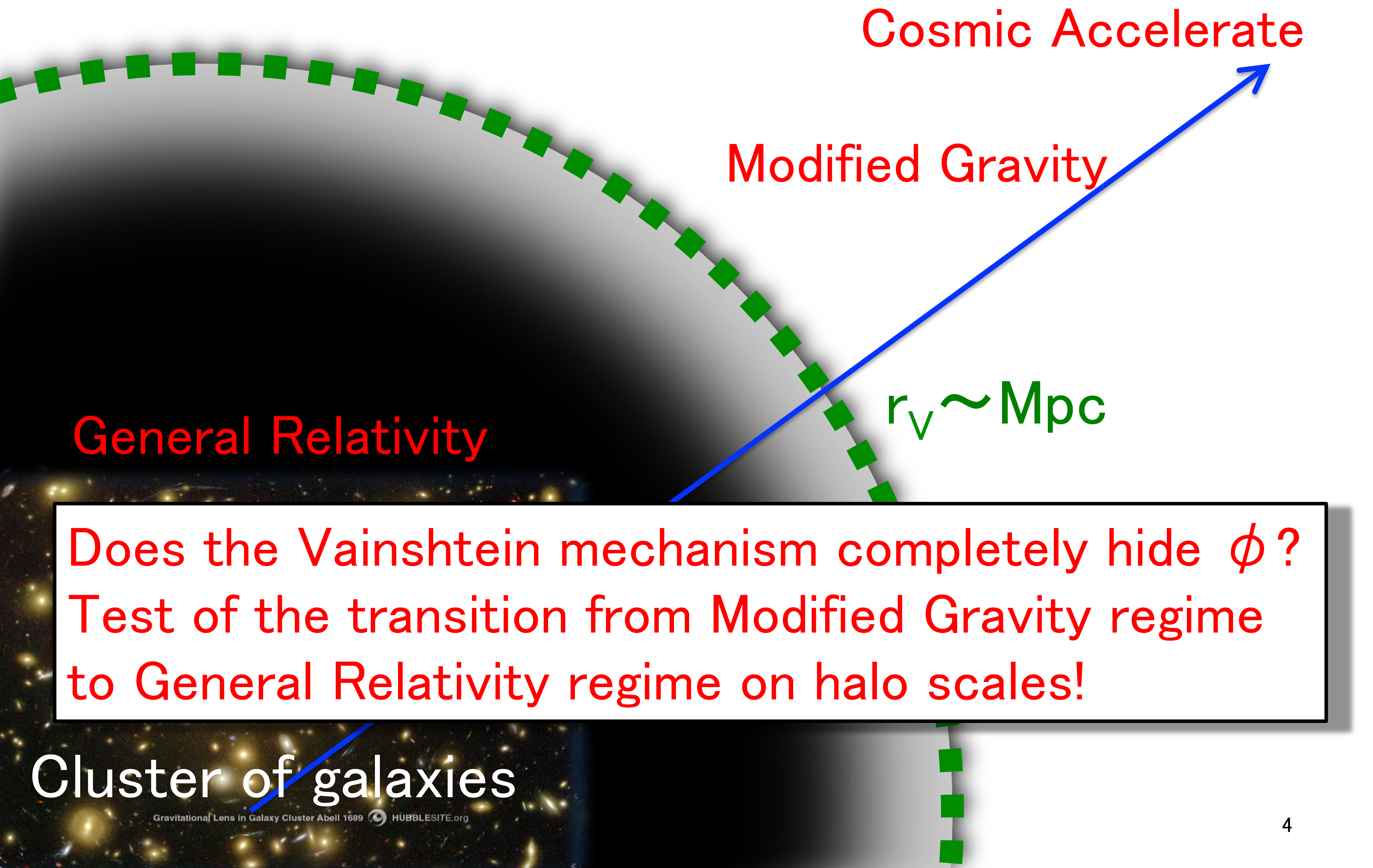

Does the Vainshtein mechanism completely hide ϕ?
Test of the transition from Modified Gravity regime to General Relativity regime on halo scales!

GALILEON-LIKE MODEL
EQUIPPED WITH VAINSHTEIN MECHANISM

$$\mathcal{L} = \frac{1}{2}F(\phi)R + K(\phi, X) - \boxed{G(\phi, X)\Box\phi}$$

Including Original Galileon:

$$X \equiv -\frac{1}{2}(\partial\phi)^2$$

$$\boxed{\mathcal{L}_{\mathrm{int}} \propto (\partial\phi)^2\Box\phi}$$

Self-interaction term leads interesting features.

- Cosmic acceleration
- Second-order field EOM
- Vainshtein mechanism

PERTURBATIONS FOR GRAVITY AND SCALAR FIELD

Newtonian gauge

$$ds^2 = -(1 + 2\Psi)dt^2 + a(t)^2(1 + 2\Phi)dx^2$$

$$\phi(t, x) = \phi(t)(1 + \varphi(x))$$

Perturbation equations on cluster's scales

$$\frac{\triangle}{a^2}\Phi = -4\pi G\delta\rho + \xi\frac{\triangle}{a^2}\varphi$$

(00)

$$\Phi + \Psi = -\alpha\varphi$$

Traceless

$$\frac{\triangle}{a^2}\varphi + \lambda^2\left(\frac{\varphi_{,ij}}{a^2}\frac{\varphi^{,ij}}{a^2} - \left(\frac{\triangle}{a^2}\varphi\right)^2\right) = -4\pi G\zeta\delta\rho$$

ϕ EOM

$\alpha, \xi, \zeta, \lambda$ are determined by the background evolution.

PERTURBATION EQUATION

In spherically symmetric case,

$$\frac{d\Psi}{dr} = \frac{GM(r)}{r^2} - \frac{(\alpha+\xi)r}{4\lambda^2}\left(1-\sqrt{1+\frac{8G\lambda^2\zeta M(r)}{r^3}}\right)$$

Enclosed mass:

$$M(r) = 4\pi\int_0^r dr' r'^2 \underline{\delta\rho(r')}$$

Assuming the same halo profile as that in GR

VAINSHTEIN MECHANISM

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$r \gg r_V$ $\frac{d\Psi}{dr} \simeq \frac{G_{\rm eff}M(r)}{r^2}$ Gravitational force is modified.

where $G_{\rm eff} = G\left(1+(\alpha+\xi)\zeta\right)$

How can we detect the transition from Modified Gravity regime to General Relativity regime ?

[KANATA @Hiroshima by TN]

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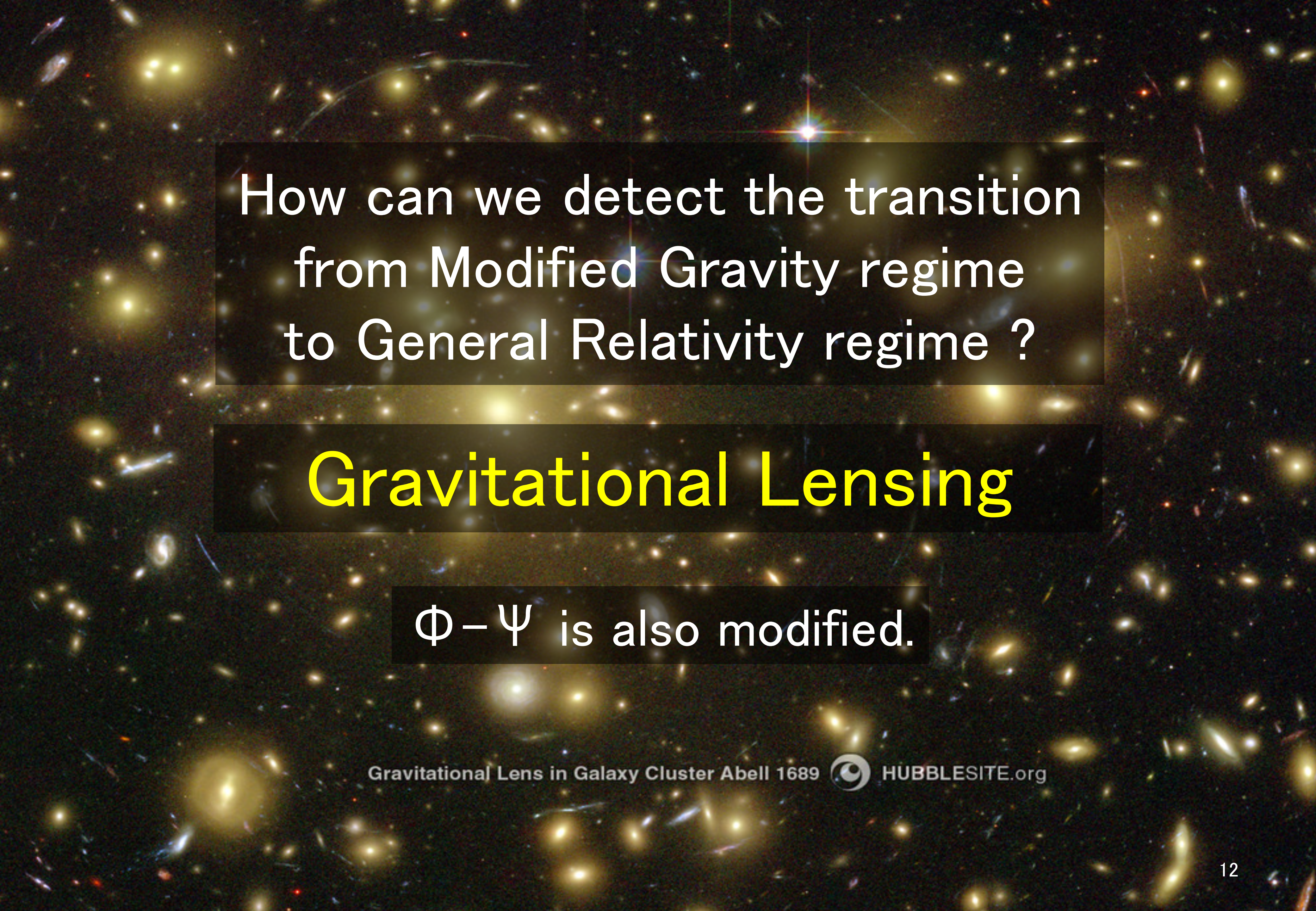
Gravitational Lensing

$\Phi - \Psi$ is also modified.



USING THE THIN-LENS APPROXIMATION,

Convergence which describes magnification

$$\kappa \simeq \frac{(\chi_S - \chi_L)\chi_L}{\chi_S} \int_0^{\chi_S} d\chi' \triangle^{(2D)} \left(\frac{\Psi - \Phi}{2} \right)$$

In modified gravity,

Lensing potential

$$\frac{\triangle}{a^2} \left(\frac{\Psi - \Phi}{2} \right) = 4\pi G \delta\rho - \frac{\alpha + 2\xi}{2} \frac{\triangle}{a^2} \varphi$$

$$\kappa \simeq \frac{(\chi_S - \chi_L)\chi_L}{\chi_S} \int_0^{\chi_S} d\chi' \left[4\pi G \rho(r') - \frac{\alpha + 2\xi}{2} \frac{\triangle}{a_L^2} \varphi \right] a_L^2$$

OBSERVED SURFACE MASS DENSITY

$$\Sigma_S \equiv \Sigma_{\rm cr}\kappa$$

$$\Sigma_S(r_\perp) = \int_0^{\chi_S} dZ \left[\rho(r) - \frac{\alpha + 2\xi}{8\pi G}\frac{\triangle}{a_L^2}\varphi\right]$$

Introduction of the spatial coordinate:

$$r = \sqrt{r_\perp^2 + Z^2}$$

$$r_\perp = a_L \chi_L \theta \qquad\qquad Z = a_L(\chi - \chi_L)$$

whose origin is located at the center of the lens object.

PARAMETRIZATION OF MODIFIED GRAVITY

$$\mu = \frac{(\alpha + 2\xi)\zeta}{2} \qquad \epsilon = \sqrt{H_0^2 \lambda^2 \zeta}$$

$$\Sigma_S(r_\perp) = \int_0^{\chi_S} dZ \left[\rho(r) - \frac{\mu}{4\pi G \zeta} \frac{\triangle}{a_L^2} \varphi \right]$$

$$\frac{d\varphi}{dr} = \frac{H_0^2 \zeta r}{4\epsilon^2} \left(1 - \sqrt{1 + \frac{8G\epsilon^2 M(r)}{H_0^2 r^3}} \right)$$

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Physical meaning of μ

$$r \to \infty \qquad \frac{\triangle}{a^2}\left(\frac{\Psi - \Phi}{2}\right) \simeq 4\pi G_{\mathrm{eff}} \delta\rho$$

Effective G $\quad G_{\mathrm{eff}} \simeq G(1 + \mu)$

$$\Sigma_S \simeq 2\int_0^\infty dZ \rho(r)[1 + \mu]$$

PARAMETRIZATION OF MODIFIED GRAVITY

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Vainshtein radius

$$r_V \equiv [8G\lambda^2\zeta M_{\rm vir}]^{1/3} = \left[\frac{8G\epsilon^2 M_{\rm vir}}{H_o^2}\right]^{1/3}$$

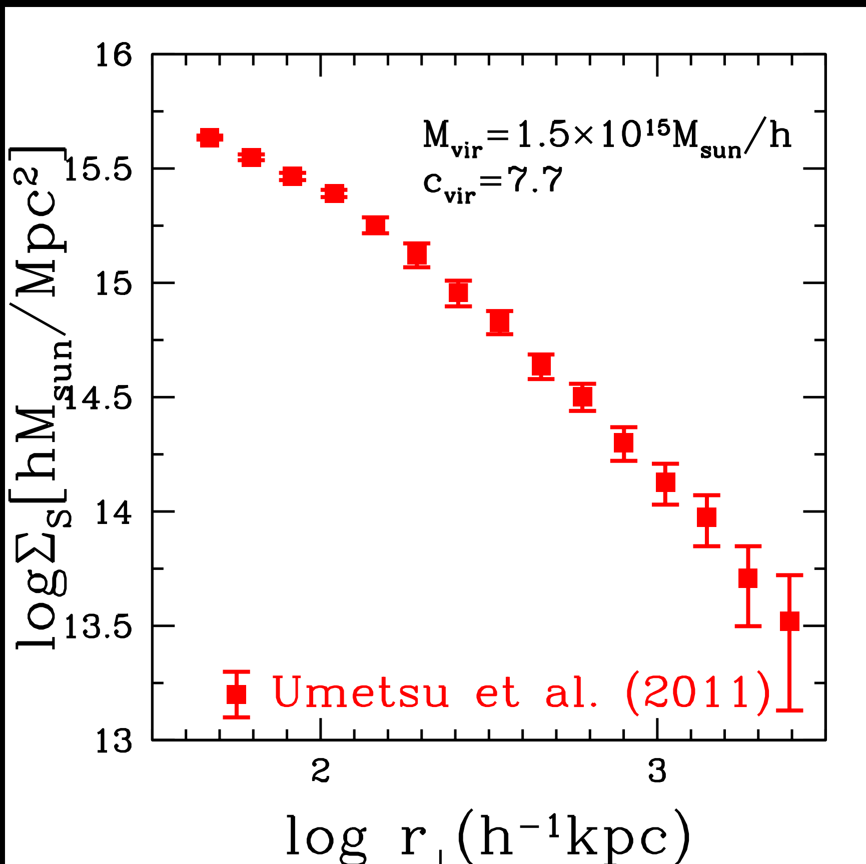
$$r_V \simeq 10 \left(\frac{M_{\rm vir}}{10^{15} M_{\rm sun}}\right)^{1/3} \epsilon^{2/3} h^{-1}{\rm Mpc}$$

In the limit $\mu \to 0$ or $\varepsilon \to \infty$,

Newtonian gravity is reproduced on all scales.

CONSTRAINTS ON MODIFIED GRAVITY WITH HALO DENSITY PROFILES OBSERVED THROUGH LENSING [TN & Yamamoto, arXiv:1201.4037]

Surface mass density

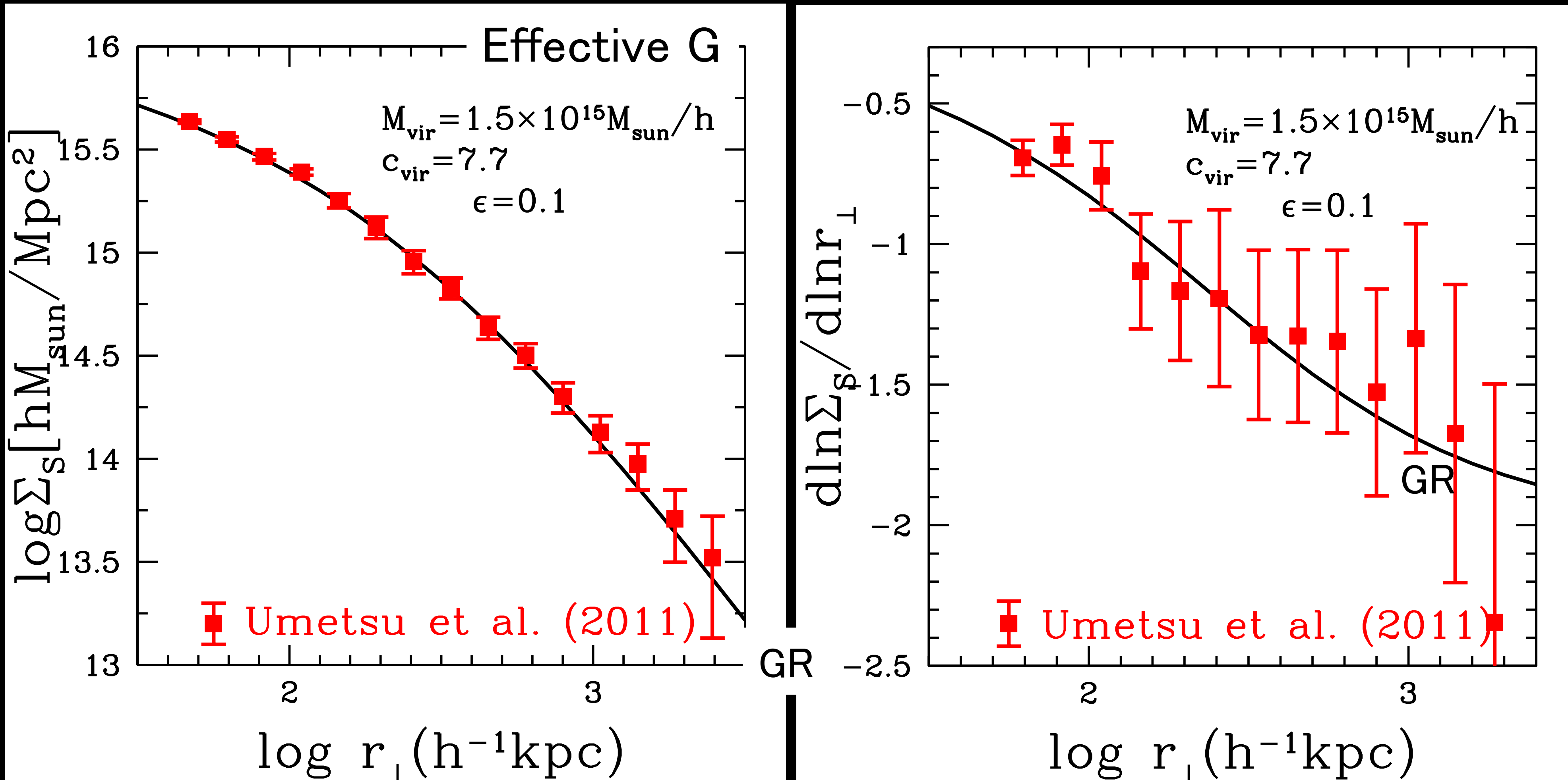


Σ_S measured through gravitational lensing. [Umetsu et al. (2011), Oguri et al. (2012)]

Over a wide range of radius

Small error of the stacked data

EFFECTS OF μ ON Σ_S AND $d\ln\Sigma_S/d\ln r$



As radii becomes large, the amplitude of Σ_S is enhanced for positive μ, while it is suppressed for negative μ.

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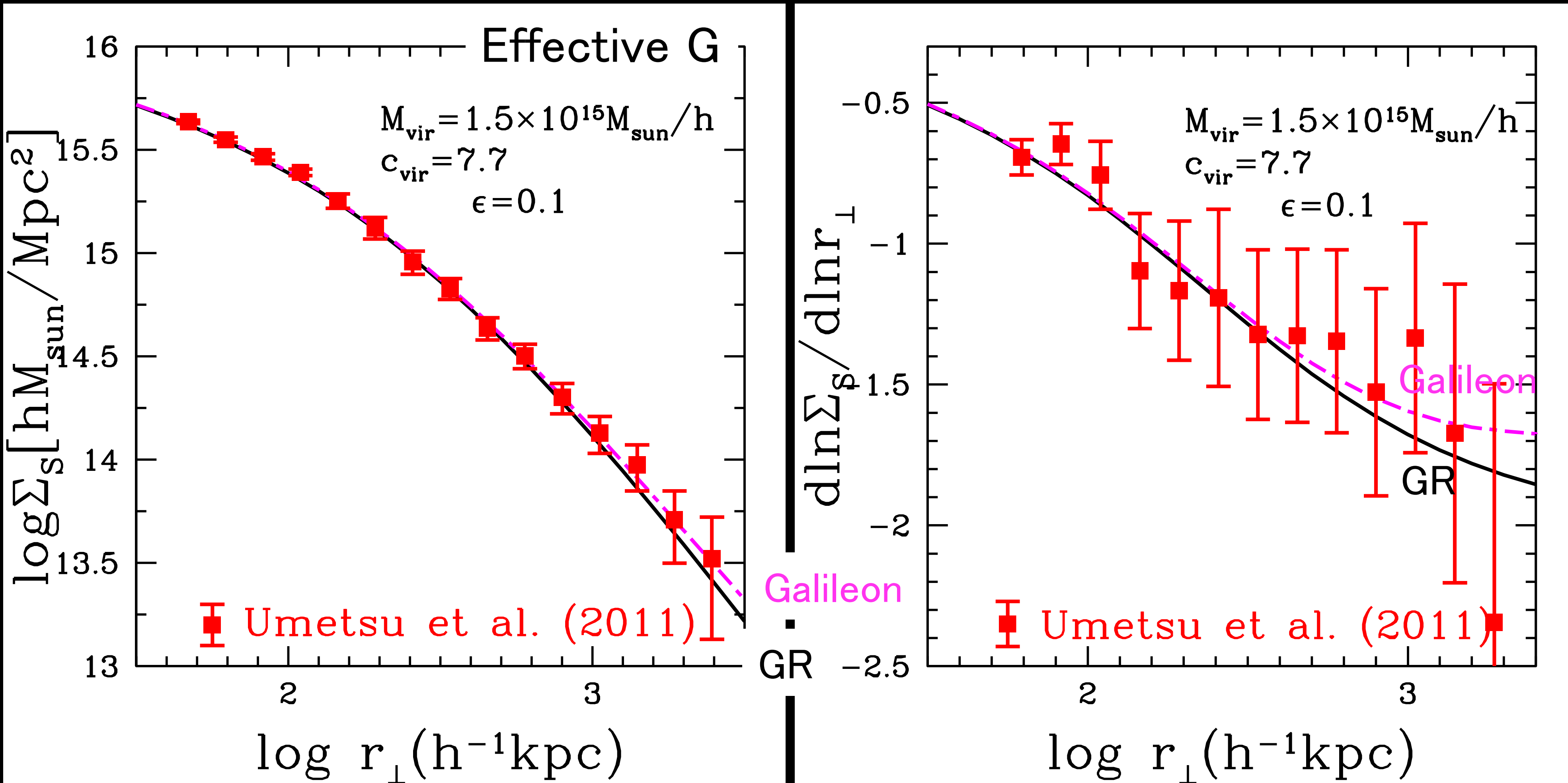

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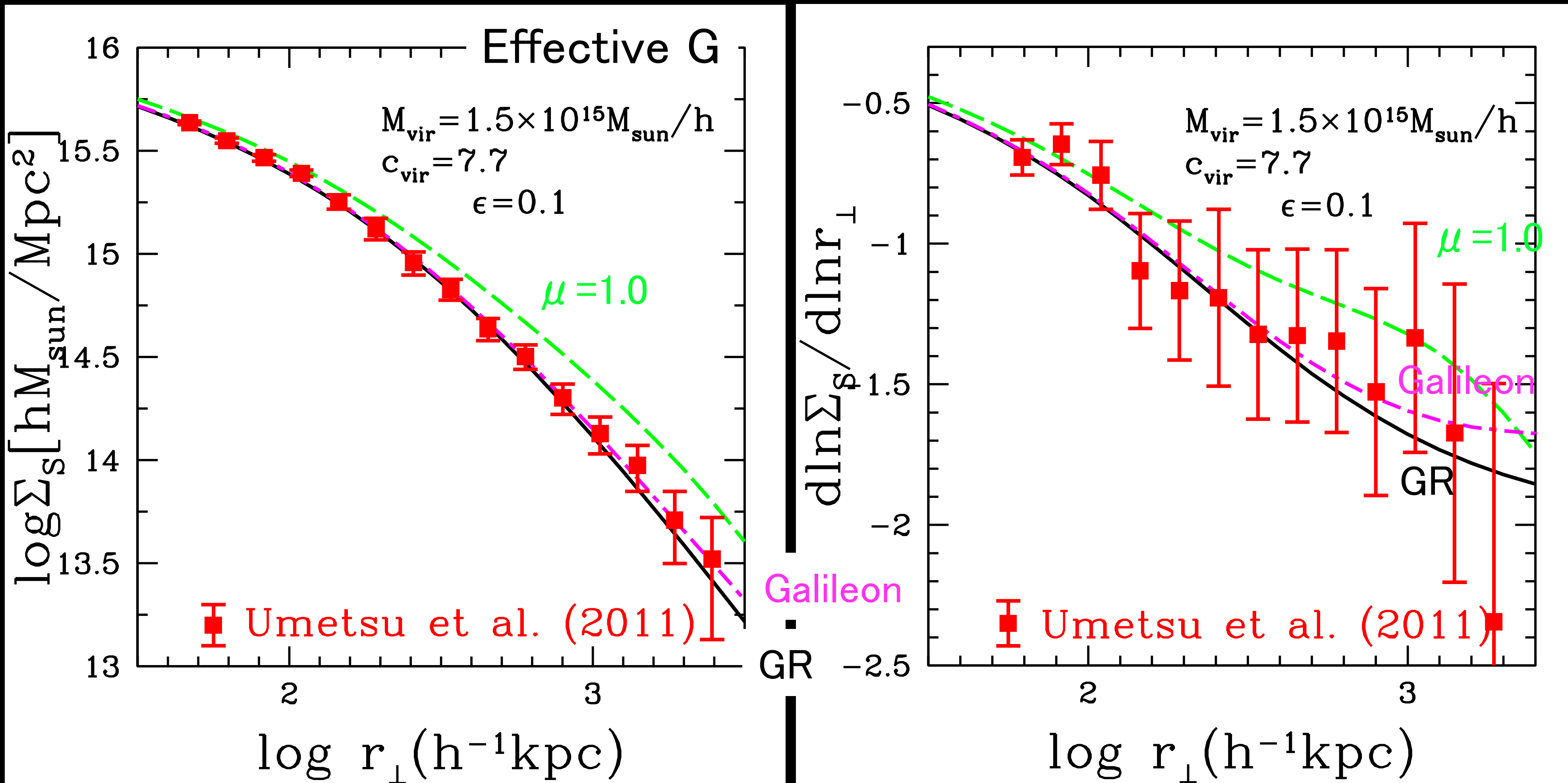

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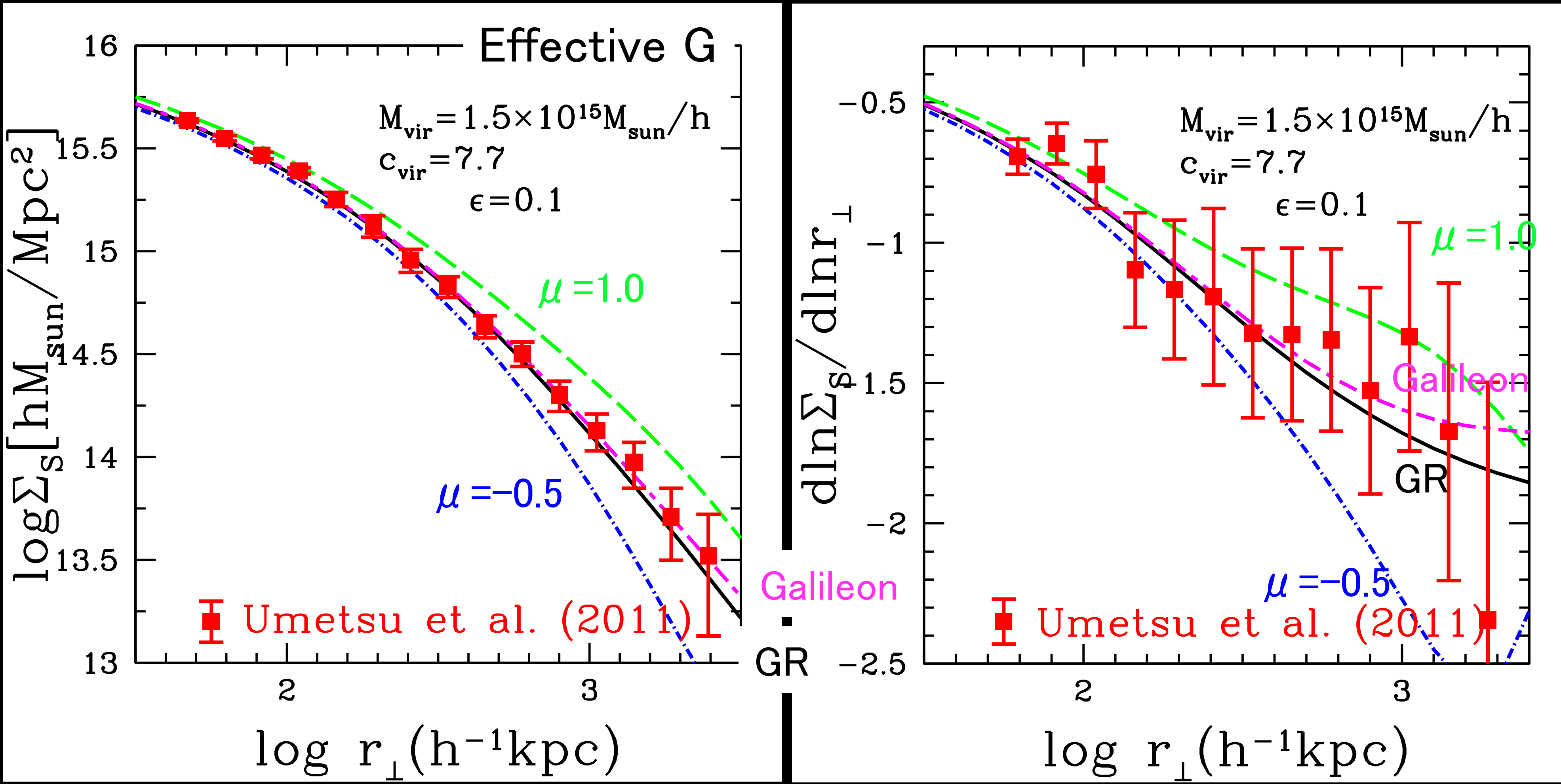

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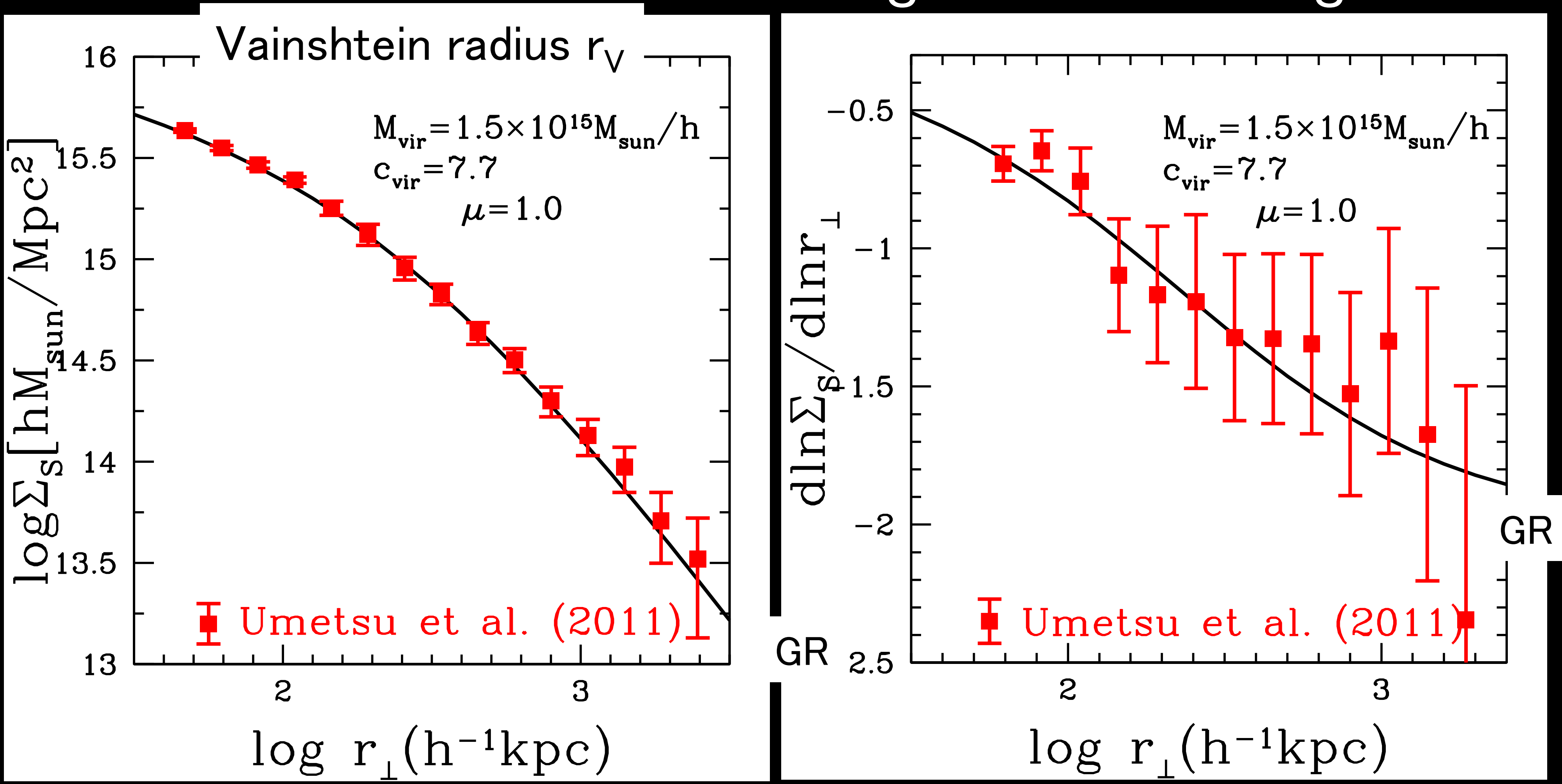
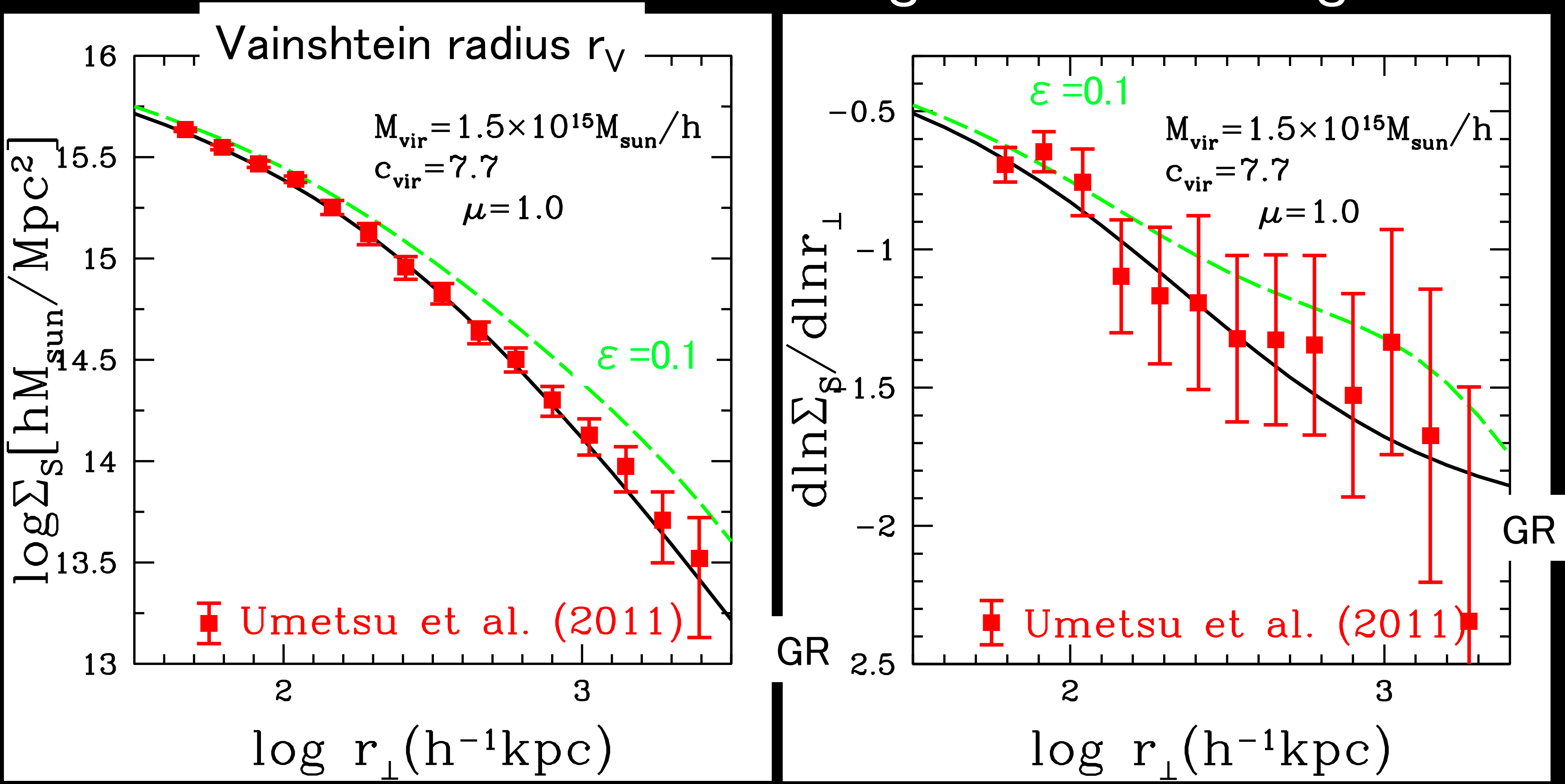
EFFECTS OF ε ON Σ_S AND $d\ln\Sigma_S/d\ln r$



Σ_S deviates from GR even at small radii for small ε, while Σ_S does from GR only at large radii for large ε.

EFFECTS OF ε ON Σ_S AND $d\ln\Sigma_S/d\ln r$



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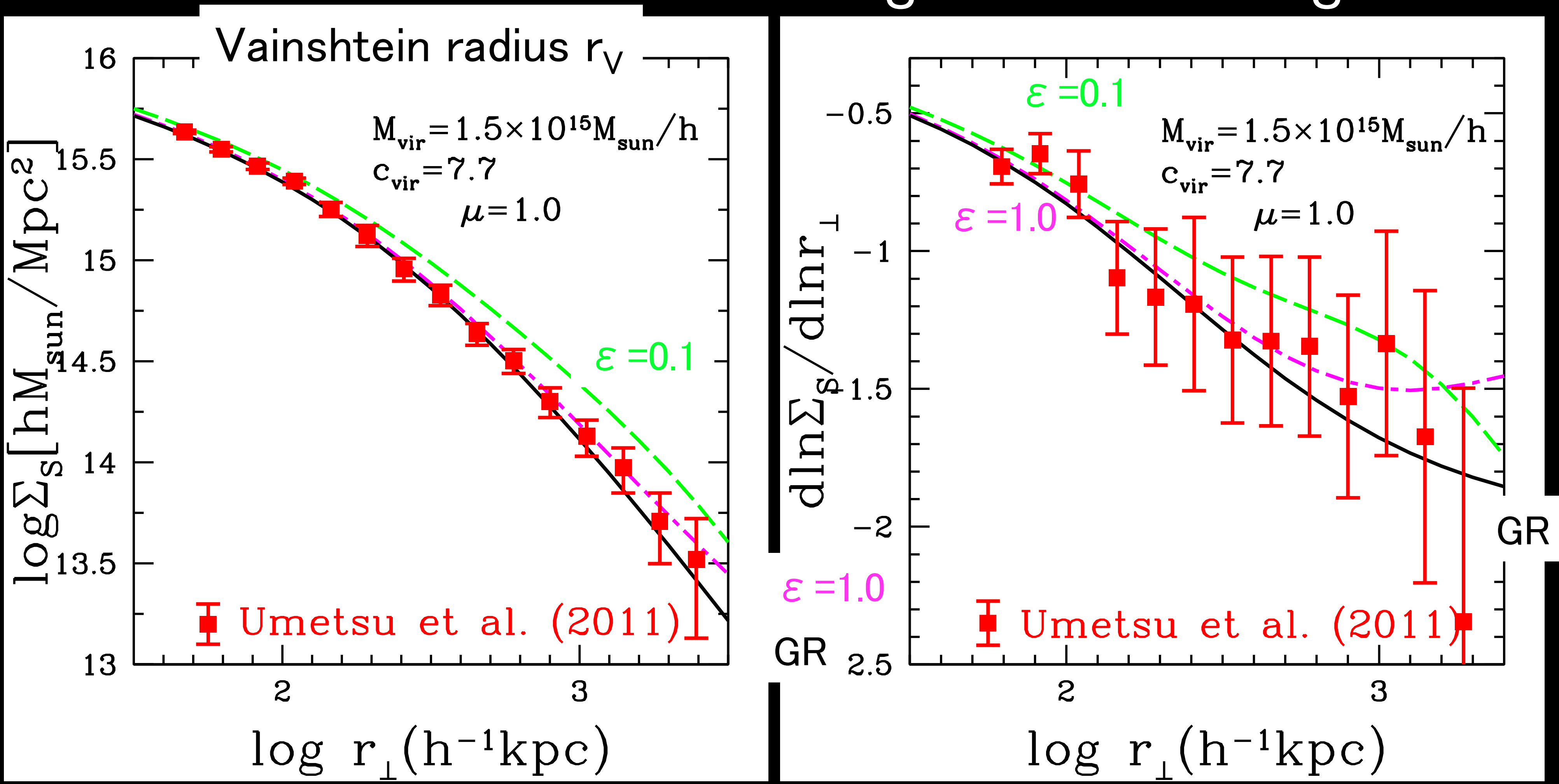

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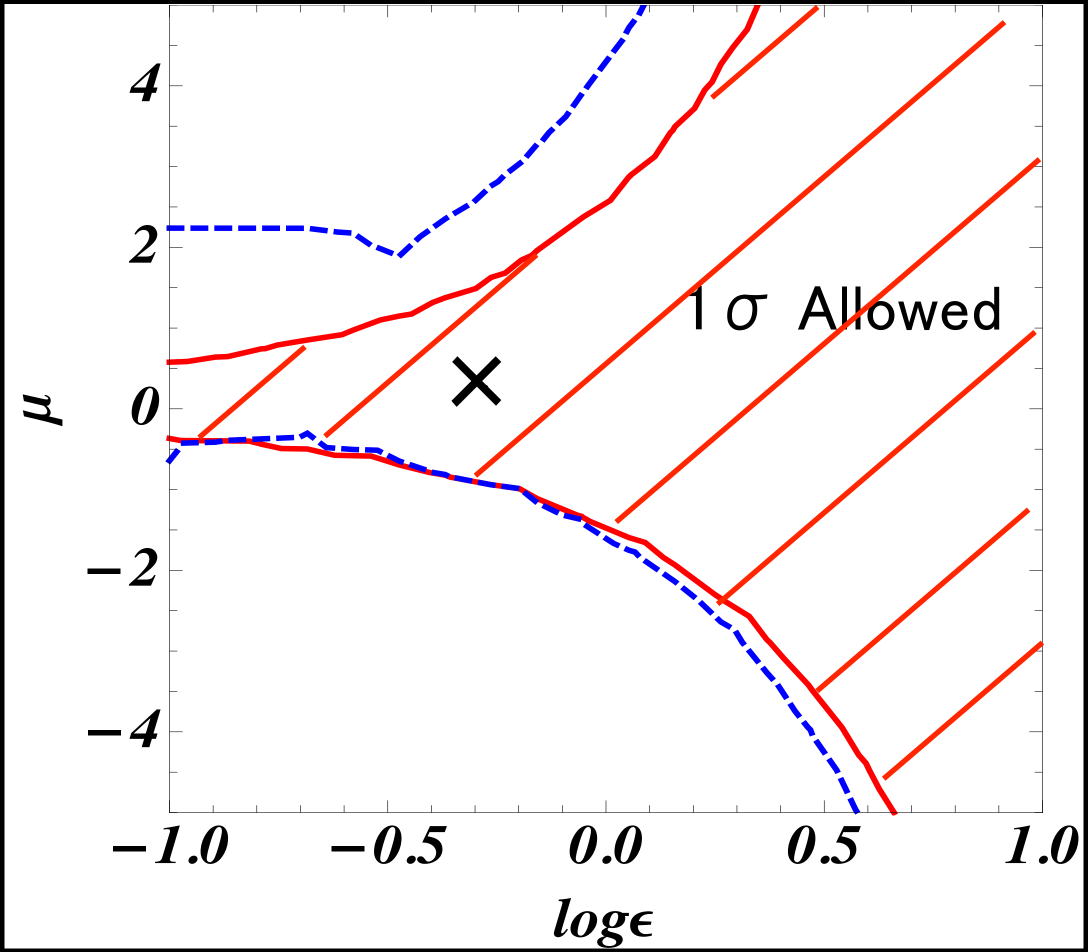
CONSTRAINTS ON $\mu-\varepsilon$ FOR NFW WITH Σ_S

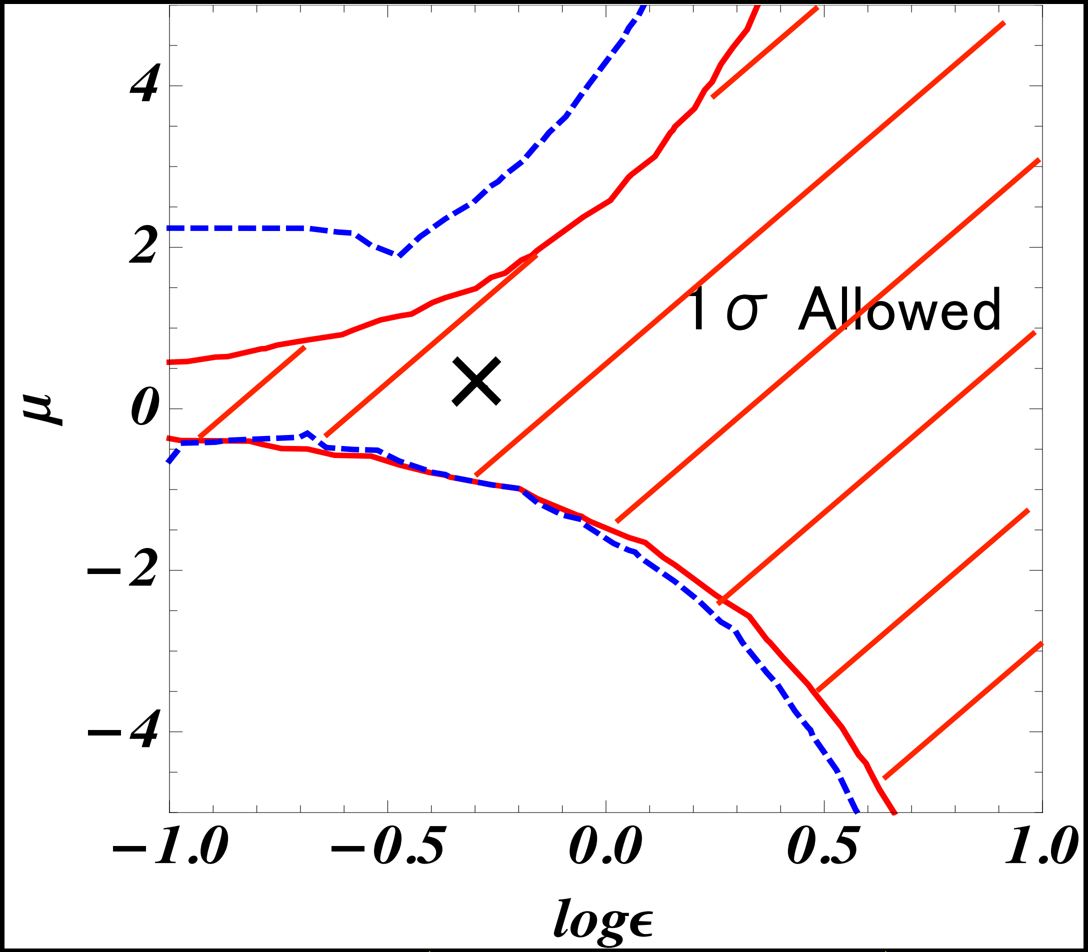


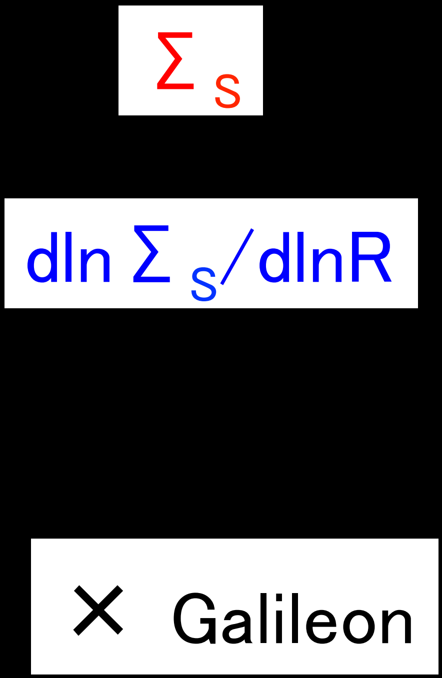
Σ_S

$d\ln\Sigma_S/d\ln R$

× Galileon

CONSTRAINTS ON $\mu-\varepsilon$ FOR NFW WITH Σ_S





Newtonian gravity (μ=0 or ε>>1) is favored.

Original Galileon model is allowed.

Better constraints on μ for small r_V (small ε)

SUMMARY & CONCLUSION

The transition from MG regime to GR regime

- How to appear it on halo ?
- Constraints on it characterizing by μ and ε .

A unique test with $\Phi-\Psi$ at cluster's scales

The original Galileon model is not excluded.

But our method provides us with a unique chance to test the gravity theory on halo scales with cluster surveys, Subaru/HSC, CLASH and LoCuSS.

Thank you for your attention !!

THE COEFFICIENTS IN PERTURBATION EQUATIONS

Gravitational constant: $G \equiv 1/(8\pi F(\phi))$

$$\alpha = \frac{F_\phi}{F}\phi, \qquad \xi = \frac{2XG_X - F_\phi}{2F}\phi, \qquad \zeta = \frac{2(A_1 + A_2)H}{\beta\dot{\phi}\phi}, \qquad \lambda^2 = \frac{B_0 H \phi}{\beta X \dot{\phi}},$$

$$\beta = -\left(A_0 + A_2\frac{F_\phi\dot{\phi}}{FH} + (A_1 + A_2)\frac{A_2}{F}\right)\frac{2H^2}{\dot{\phi}^2}.$$

$$A_0 = \frac{\dot{\Theta}}{H^2} + \frac{\Theta}{H} - F - 2\frac{F_\phi\dot{\phi}}{H} - \frac{\mathcal{E} + \mathcal{P}}{2H^2},$$

$$A_1 = \frac{F_\phi\dot{\phi}}{H}, \qquad A_2 = F - \frac{\Theta}{H}, \qquad B_0 = \frac{\dot{\phi}^3 G_X}{2H},$$

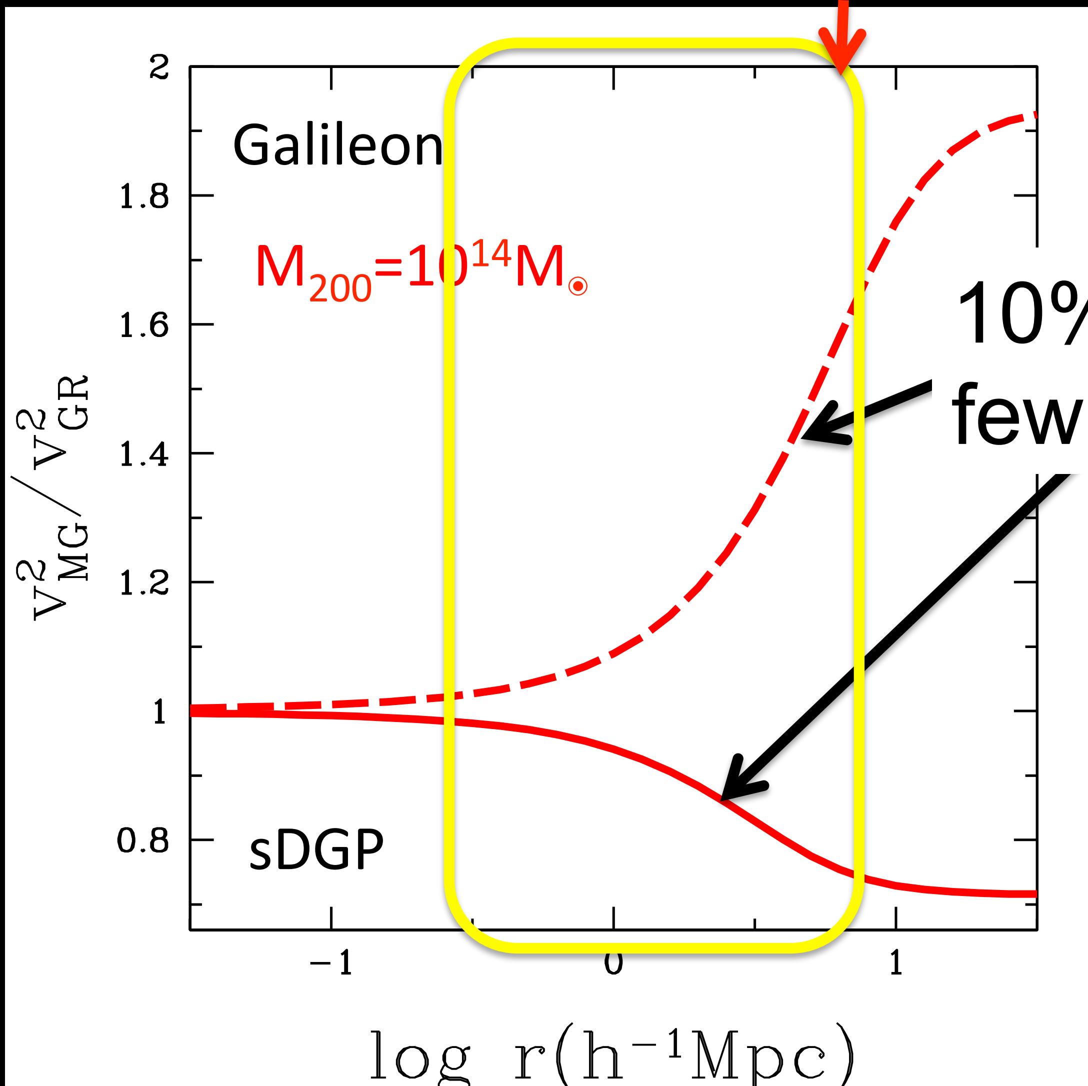
$$\mathcal{E} = 2XK_X - K + 6HX\dot{\phi}G_X - 2XG_\phi - 3H^2F - 3H\dot{\phi}F_\phi,$$

$$\mathcal{P} = K - 2X(G_\phi + \ddot{\phi}G_X) + (3H^2 + 2\dot{H})F + (\ddot{\phi} + 2H\dot{\phi})F_\phi + 2XF_{\phi\phi},$$

$$\Theta = -X\dot{\phi}G_X + HF + \dot{\phi}F_\phi/2$$

CIRCULAR SPEED FOR NFW NORMALIZED BY v_{GR}^2

Vainshtein mechanism does not completely hide effect of modification of gravity in cluster's scales.



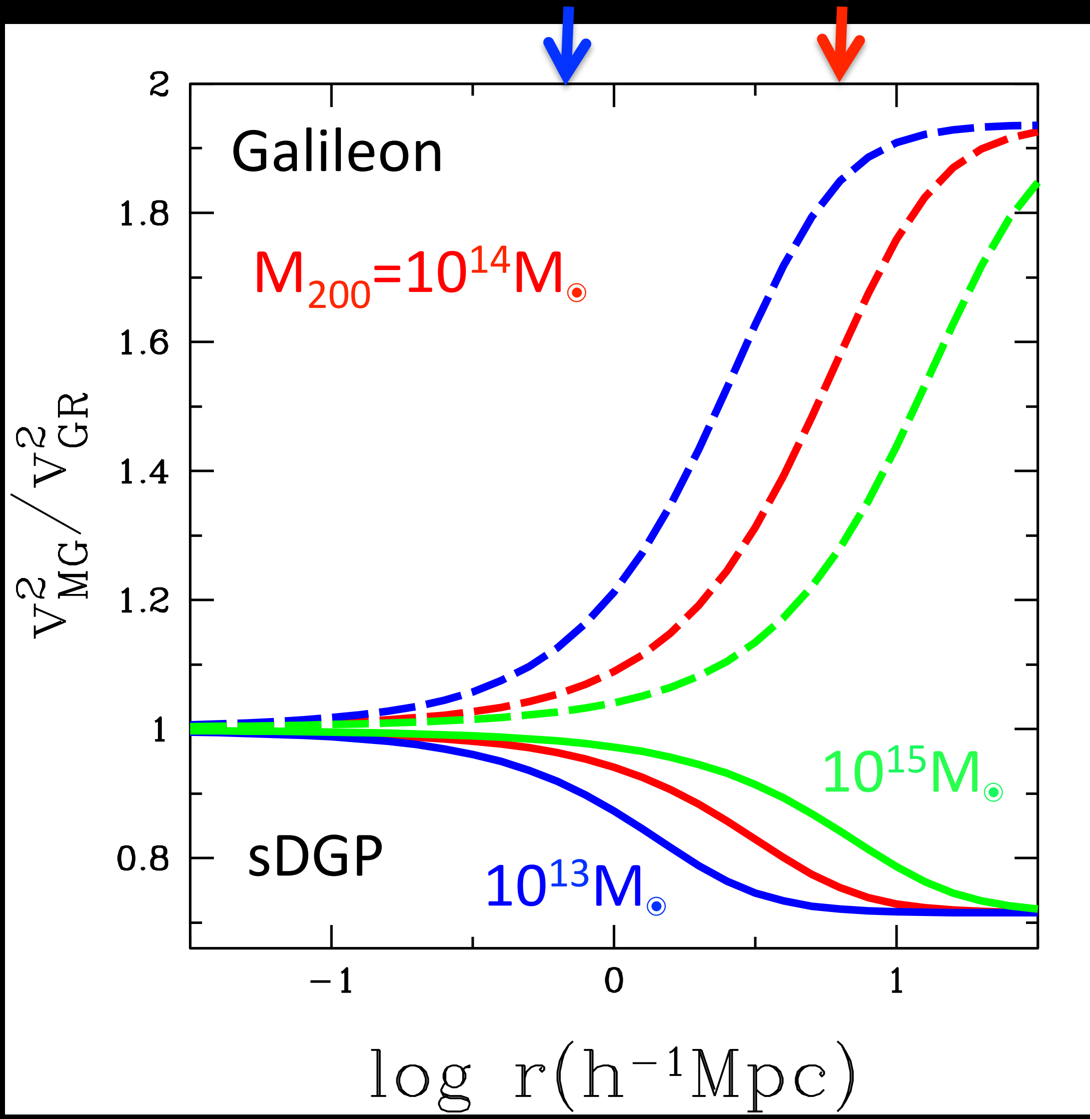
[TN,Kimura,Yano,Yamamoto,2011 (arXiv: 1108.2346)]

10% level deviation at a few Mpc (cluster's scales)

This makes the effect potentially observable.

CIRCULAR SPEED FOR NFW NORMALIZED BY v_{GR}^2

$$v^2(r) = r\frac{d\Psi}{dr}$$



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Conclusion depends on cluster's virial mass.