銀河団から探る修正重力
-Exploring Modified Gravity with Clusters of Galaxies-

成川達也 Tatsuya Narikawa

Osaka University Theoretical Astrophysics (Osaka University)

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Self-introduction

成川達也 Tatsuya Narikawa

Osaka University Theoretical Astrophysics, PD

（受入：田越秀行）

新学術領域「重力波天体の多様な観測による宇宙物理学の新展開」（領域代表：中村卓史）

- A04班 「多様な観測に連携する重力波探索データ解析の研究」（研究代表：神田展行）

My Research on ``Modified Gravity in Clusters of Galaxies":

Narikawa, Kimura, Yano, & Yamamoto, 1108.2346.

Narikawa & Yamamoto, 1201.4037.

Narikawa, Kobayashi, Yamauchi, & Saito, 1302.2311.

Summary

Impact of clusters of galaxies on modified gravity:
clusters of galaxies are also useful to test modified gravity.

There are not any requirement of modifying gravity from observations of clusters of Galaxies.

Modified gravity by an additional scalar ϕ is motivated by late-time cosmic acceleration.

How is cluster modified by modifying gravity?

Adding a scalar ϕ motivated by cosmic acceleration
$\rightarrow$ modifying gravitational field Φ on outskirts of cluster

Useful observables of clusters to test modified gravity

1. Radial profiles ($\Phi_{lens}(r_p)$, $T_X(r_p)$, $\Delta T_{SZ}(r_p)$)
2. Cluster abundance (mass function: dn/dlnM)

3. Galaxy infall kinematics into cluster [Takada-san's talk]

4. Gravitational redshifts of galaxies in clusters ($z_{gr}=\Delta\Phi/c^2$)
5. Cosmic mach number ($M(r)=\sqrt{\langle V^2(r)\rangle}/\sqrt{\langle\sigma^2(r)\rangle}$)
6. Scaling relation (σ^2-M in MG)
7. Most massive object
8. Environmental dependence (dwarf galaxy in void)

Main topics of this talk

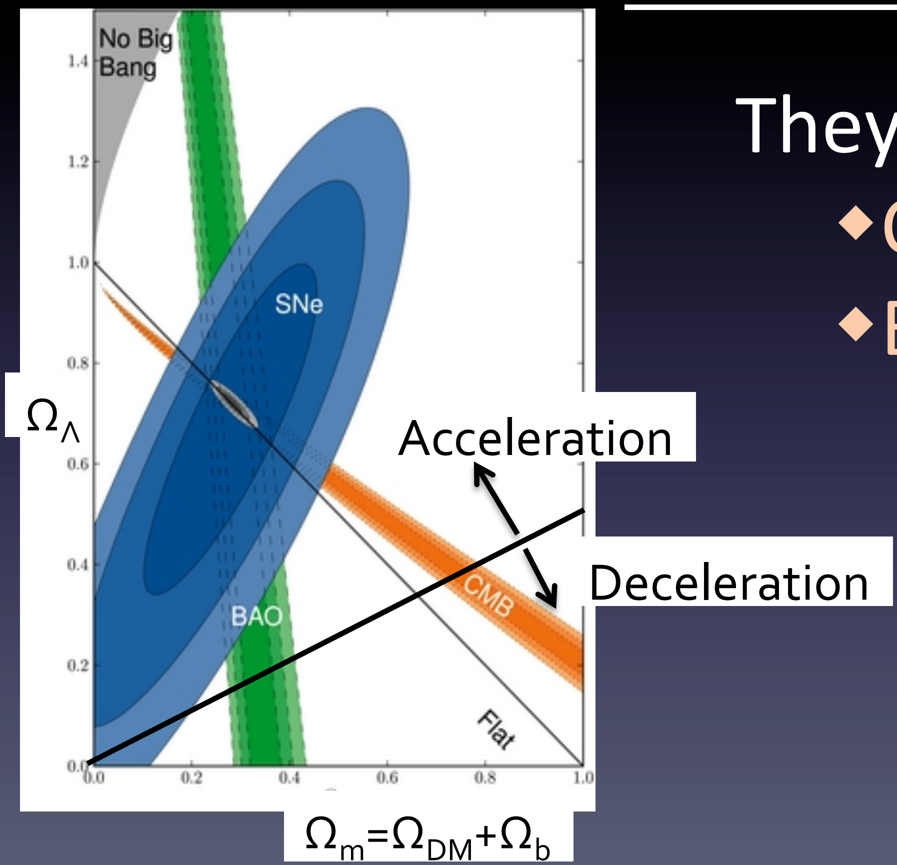
1. Modified gravity with screening mechanism

2. Exploring modified gravity with clusters of galaxies

1. Modified gravity with screening mechanism

Why modify GR ?

Late time accelerated expansion of the Universe

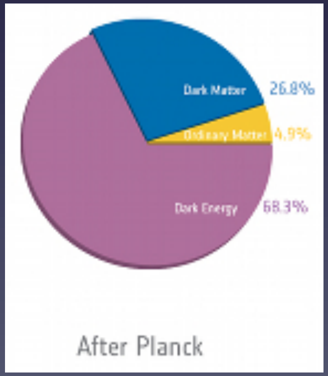


<u>Combination of SNe, CMB & BAO</u>

They are converging

- Cosmic acceleration
- Existence of Dark Energy

$H_0 \sim 10^{-33}$eV



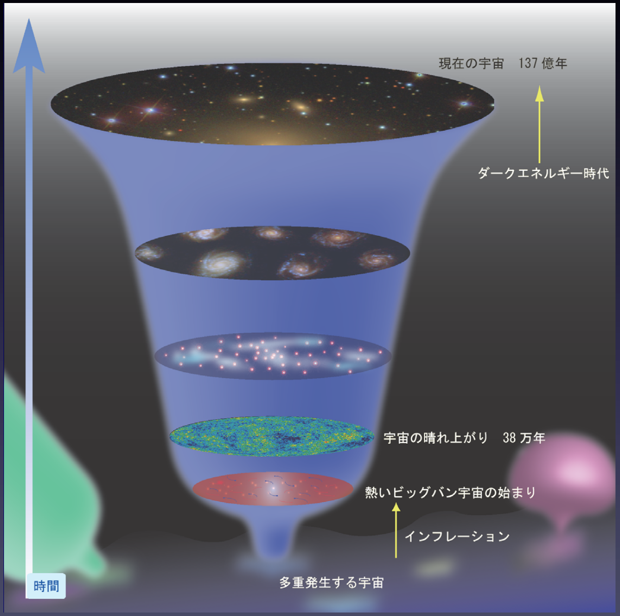
[Suzuki *et al.*, 1105.3470]

Why modify GR ?

Mystery of dark energy

⇕

Signs of the breakdown of GR on cosmological scales ?



[M. Nakashima (RESCEU)]

Modified gravity as an alternative to Dark energy

Additional ϕ is added to cosmic accelerate

The effects of the additional ϕ is hidden by the screening mechanism in the vicinity of a matter source.

$\rightarrow$ recover GR and pass solar-system tests

Cosmic acceleration (1)

Einstein equation

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

Planck mass: $\mathrm{M_{Pl}}^{-2} = 8\pi\mathrm{G}$

Light speed: $\mathrm{c}=1$

Cosmic acceleration (1)

Einstein equation

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

Background solution: homogeneous & isotropy

$$ds^2 = -dt^2 + a^2(t) d\vec{x}^2$$

Field equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$ >0 $\rightarrow$ acceleration

ρ : energy density, p: pressure

Cosmic acceleration (2)

- Cosmological constant Λ : standard model
- Dark energy: negative pressure

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

Cosmic acceleration (2)

- Cosmological constant Λ : standard model
- Dark energy: negative pressure

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

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- Modified gravity: adding a scalar ϕ

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

Tests of gravity: Solar-system bounds on Parameterized Post-Newtonian parameters

γ: g_{ij} component

$$g_{ij} = (1 + 2\gamma U)\delta_{ij}$$

β: g_{00} component

$$g_{00} = -1 + 2U - 2\beta U^2$$

Weak field:

$$\epsilon := \frac{2GM}{Rc^2} \ll 1$$

[Will,gr-qc/0510072]

Parameter	Effect	Limit	Remarks
$\gamma - 1$	time delay	2.3×10^{-5}	Cassini tracking
	light deflection	4×10^{-4}	VLBI
$\beta - 1$	perihelion shift	3×10^{-3}	$J_2 = 10^{-7}$ from helioseismology
	Nordtvedt effect	2.3×10^{-4}	$\eta_{\mathrm{N}} = 4\beta - \gamma - 3$ assumed

Local gravity constraints are stringent.

Einstein's GR is valid when gravity is weak.

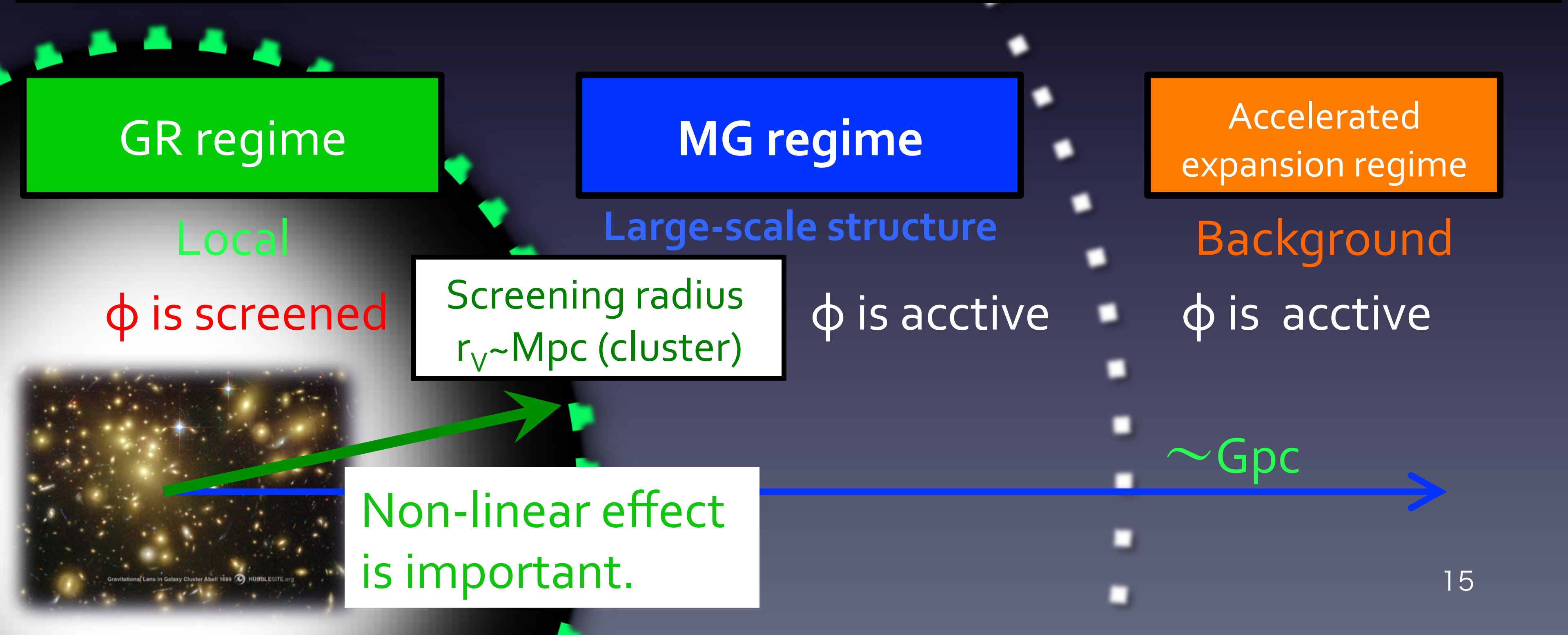
General description of Modified Gravity

Screening Mechanisms:

- Kinetic type: Vainshtein mechanism [Vainshtein, 1972]

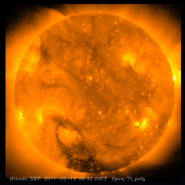
Additional d.o.f is effectively weakly coupled to matter

- Cf. Potential type: Chameleon mechanism [Khoury & Weltman, 0309411]



Typical values of Vainshtein screening radius

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 might be possible to discover or constrain this effect by cluster surveys.

Gravitational action

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

Dark matter + baryon

- Cosmological constant

$$\mathcal{L} = \frac{M_{\rm Pl}^2}{2}[R - 2\Lambda]$$

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

[DGP] Dvali, Gabadadze, Porrati '00
[DLofDGP] Luty, Porrati, Rattazzi '03, Nicolis, Rattazzi '04

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$\rightarrow$ 「 • 2nd-order field equations

• Cosmic acceleration

• Vainshtein screening mechanism 」

[DGP] Dvali, Gabadadze, Porrati '00
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Vainshtein Mechanism in Simple Model

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

[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

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

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

Vainshtein Mechanism in Simple Model

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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 $r \ll r_V$:

Nonlinear kinetic term becomes large⇔decoupling to matter

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

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

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

Vainshtein mechanism in general scalar-tensor theory and massive gravity

[TN, Kobayashi, Yamauchi, & Saito, 1302.2311]

- Work in General framework (Horndeski's theory)
- Derive a screening condition to study static, 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
- Testing modified gravity models by comparing some model predictions with cluster lensing data

The most general scalar-tensor theory with 2nd-order field eqs.

$$\mathcal{L} = K(\phi, X) - G_3(\phi, X)\Box\phi$$
$$+G_4(\phi, X)R + G_{4X}[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2]$$
$$+G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5X}[(\Box\phi)^3$$
$$-3\Box\phi(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3]$$

$$X \equiv -\frac{1}{2}(\partial\phi)^2 \qquad G_{iX} \equiv \partial G_i/\partial X$$

[Horndeski (1974), Deffayet, Gao, Steer, & Zahariade (2011), Kobayashi, Yamaguchi & Yokoyama (2011)]

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, 1111.6749])

Dimensionless parameters

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

$$
\begin{aligned}
G_4 = \frac{M_{\rm Pl}^2}{2}, \quad G_{4\phi} = M_{\rm Pl}\xi, \\
K_X - 2G_{3\phi} = \eta, \\
-G_{3X} + 3G_{4\phi X} = \frac{\mu}{\Lambda^3}, \\
G_{4X} - G_{5\phi} = \frac{M_{\rm Pl}}{\Lambda^3}\alpha, \\
G_{4XX} - \frac{2}{3}G_{5\phi X} = \frac{\nu}{\Lambda^6}, \\
G_{5X} = -\frac{3M_{\rm Pl}}{\Lambda^6}\beta.
\end{aligned}
$$

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

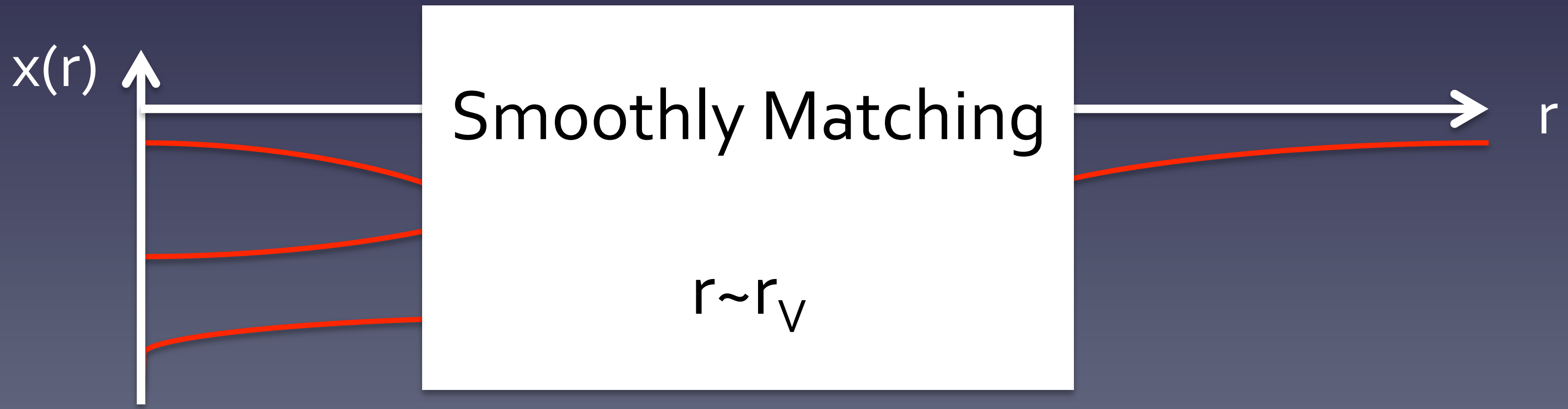
$$x=\frac{1}{\Lambda^3}\frac{\varphi'}{r},\ \ A(r)=\frac{1}{M_{\rm Pl}\Lambda^3}\frac{M(r)}{8\pi r^3}$$

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

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

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 where A(r)<<1: Asymptotically flat

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

Decaying solution in 1/r

Inner Solution where A(r)>>1: Vainshtein screening

$$\boxed{x \approx x_- := -\sqrt{\frac{\xi}{3\beta}} = \text{const.}}$$

We have the Newtonian behavior:

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

As a relavant example, decoupling limit of massive gravity

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

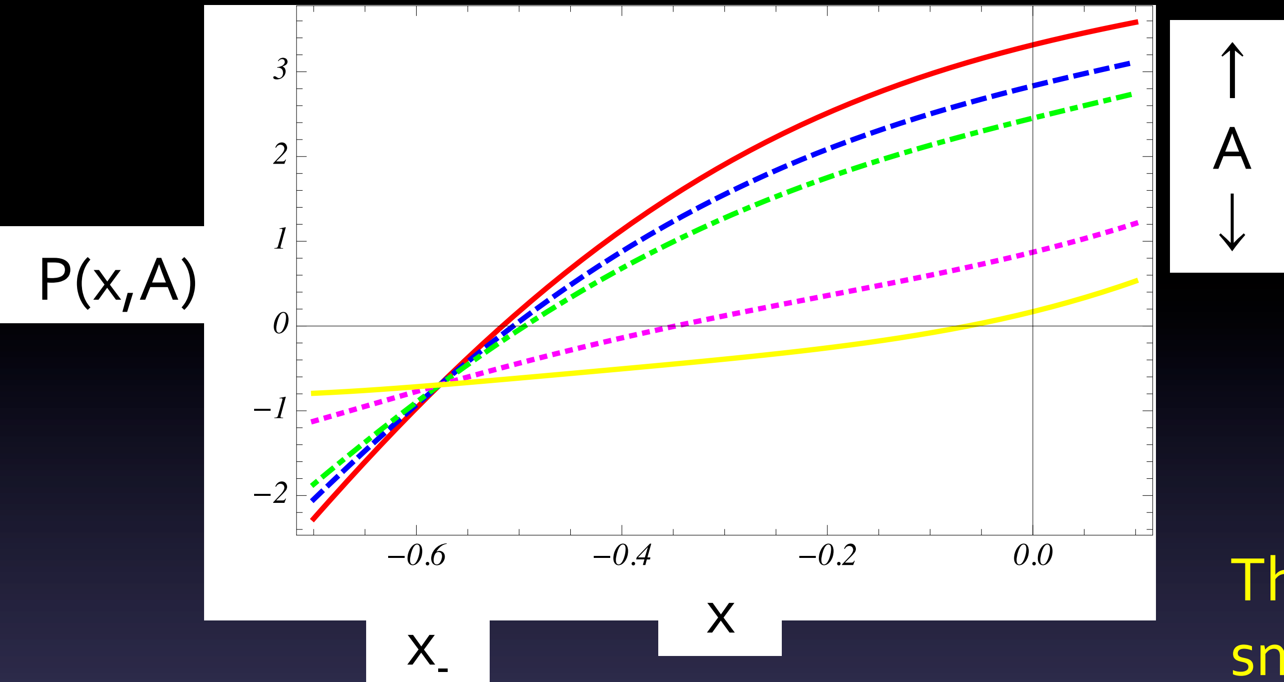
$$\eta = \mu = \nu = 0,\ \xi = 1,\ \alpha \neq 0,\ \beta \neq 0$$

The condition of smooth matching of the two solutions:

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

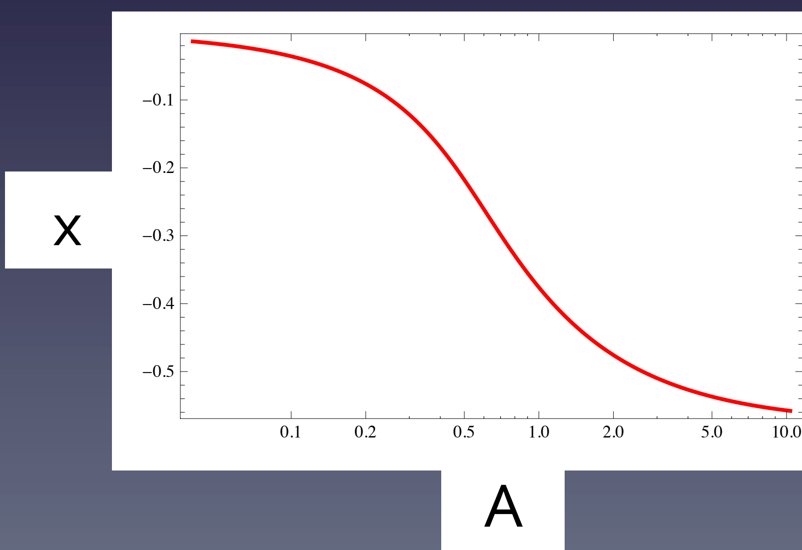
[Sbisa et al. 1204.1193; TN et al., 1302.2311]

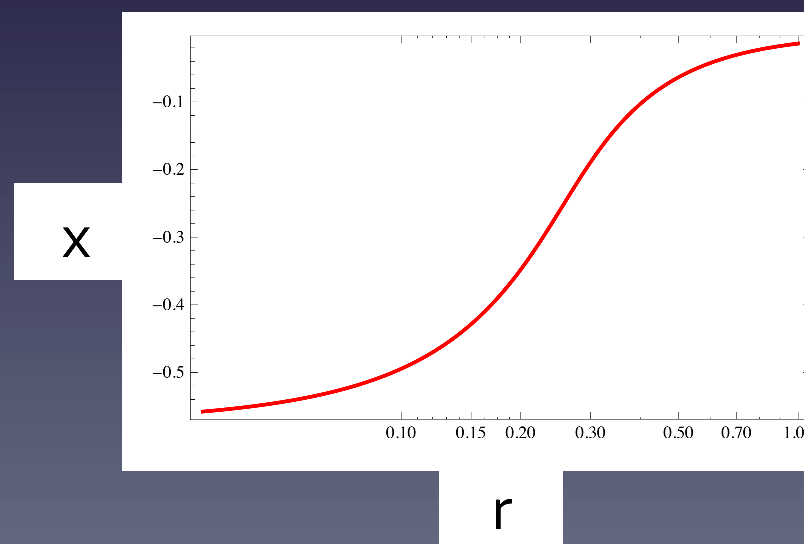
Smoothly Matching of Two Solutions



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

The two solutions are smoothly matched !



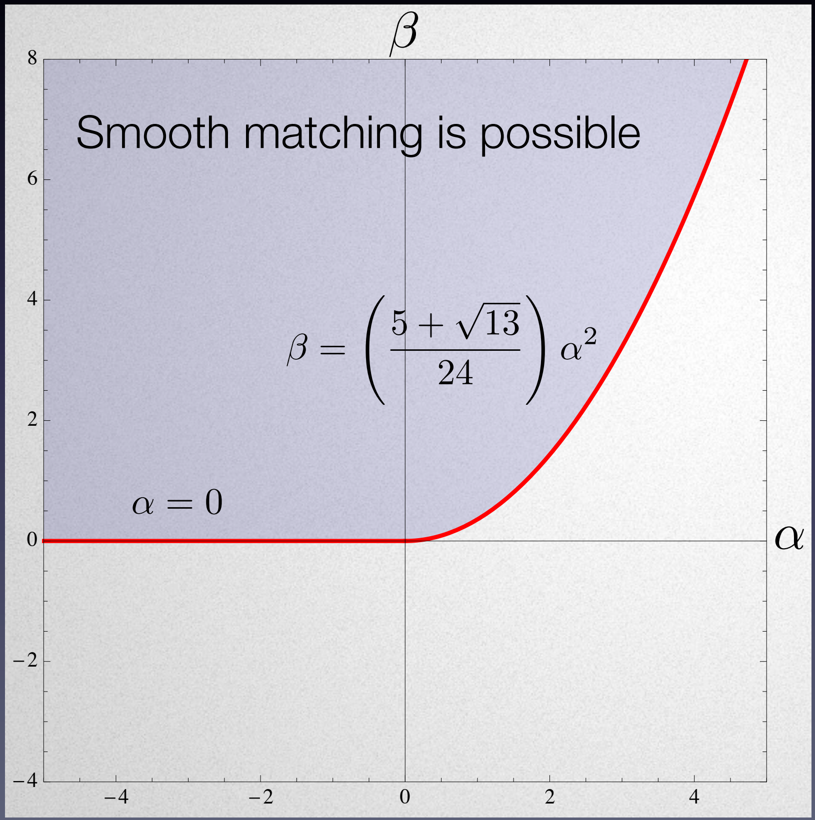


The condition of smooth matching of the two solutions:

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

in the case of massive gravity.

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



Explore the observationally allowed region {α, β} with clusters of galaxies.

2. Exploring modified gravity with clusters of galaxies

How is cluster modified by modifying gravity?

Adding a scalar ϕ motivated by cosmic acceleration
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Useful observables of clusters to test modified gravity

1. Radial profiles ($\Phi_{lens}(r_p)$, $T_X(r_p)$, $\Delta T_{SZ}(r_p)$)
2. Cluster abundance (mass function: dn/dlnM)
3. Galaxy infall kinematics into cluster [Takada-san's talk]
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5. Cosmic mach number ($M(r)=\sqrt{\langle V^2(r)\rangle}/\sqrt{\langle\sigma^2(r)\rangle}$)
6. Scaling relation (σ^2-M in MG)
7. Most massive object
8. Environmental dependence (dwarf galaxy in void)

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 $\Sigma_S(r_{perp}) \propto \kappa(r_{perp})$

$$\kappa = \int_0^{\chi_S} d\chi \frac{(\chi_S - \chi)\chi}{\chi_S} \Delta_\perp \Phi_+$$

where lensing potential in modified gravity:

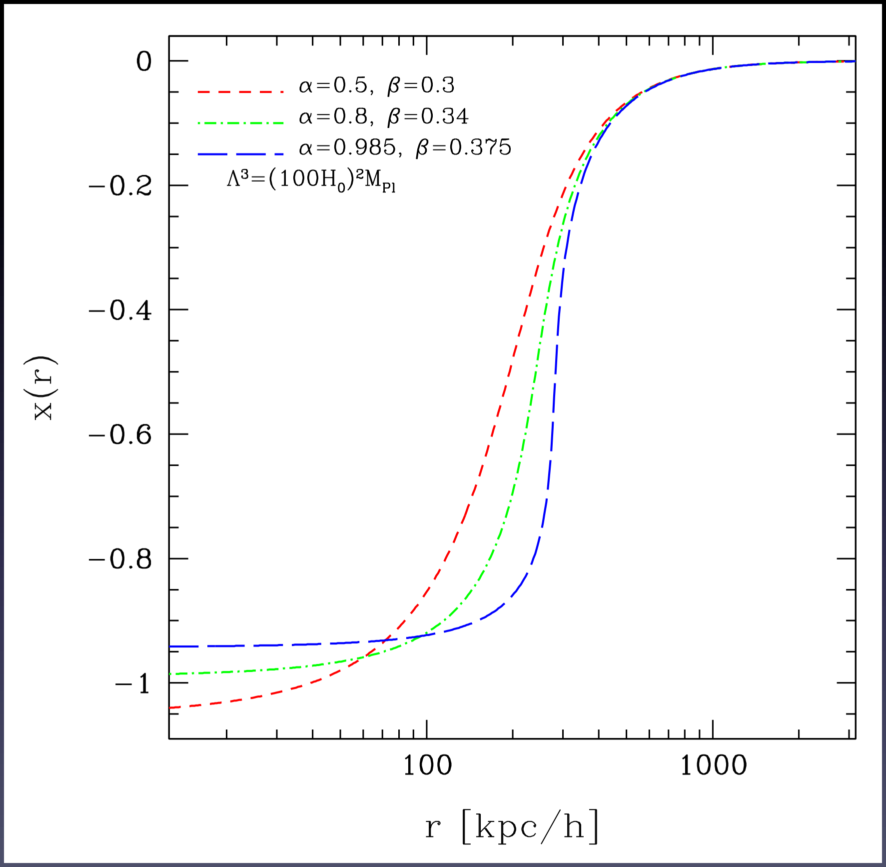
$$\triangle\Phi_+ = \frac{\Lambda^3}{M_{Pl}} \frac{\left[\left(\alpha x^2 + 2\beta x^3 + 2A\right) r^3\right]'}{2r^2} \qquad \triangle\Phi_+ \propto r\phi'\phi''$$

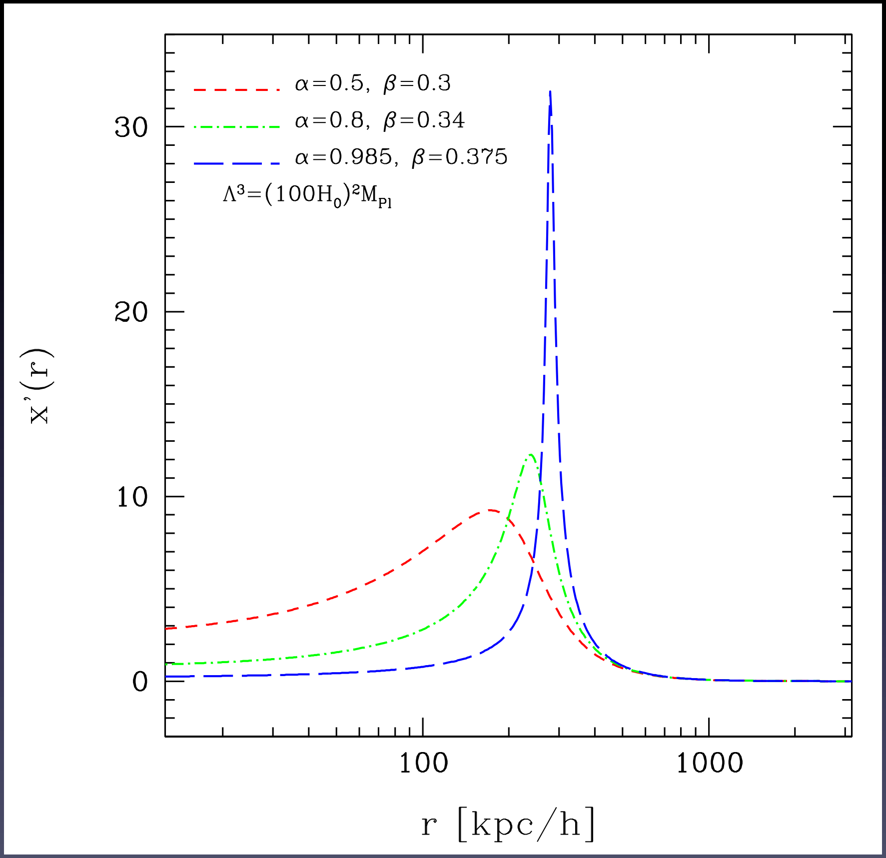
assuming $\delta\rho(r)$ as NFW profile.

x′(r) can be large at transition from screened to unscreened regions

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

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



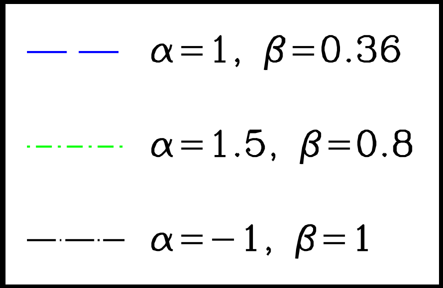


Smoothly matching

A dip appears.

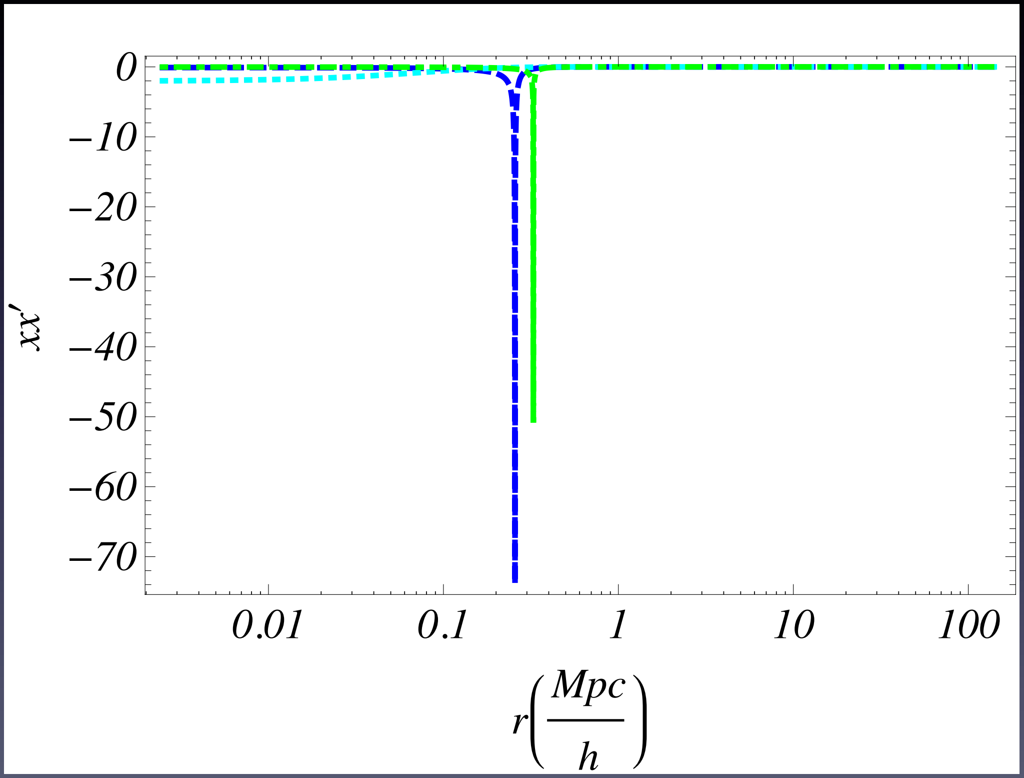
Lensing potential in modified gravity:

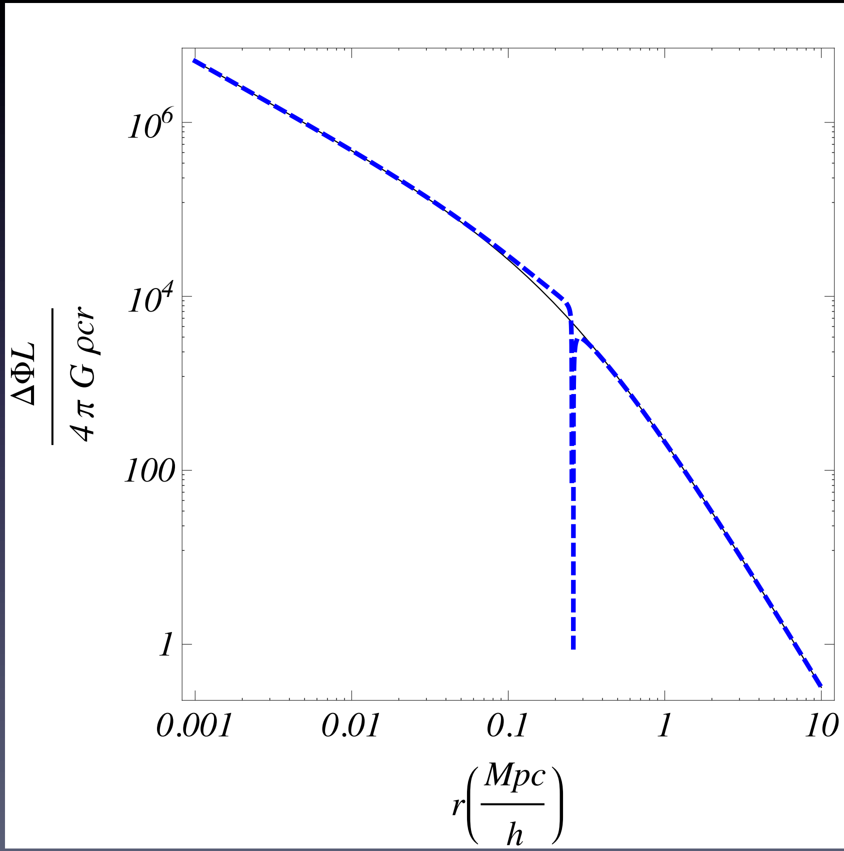
$$\triangle\Phi_+ = \frac{\Lambda^3}{M_{\rm Pl}} \frac{\left[\left(\alpha x^2 + 2\beta x^3 + 2A\right) r^3\right]'}{2r^2}$$



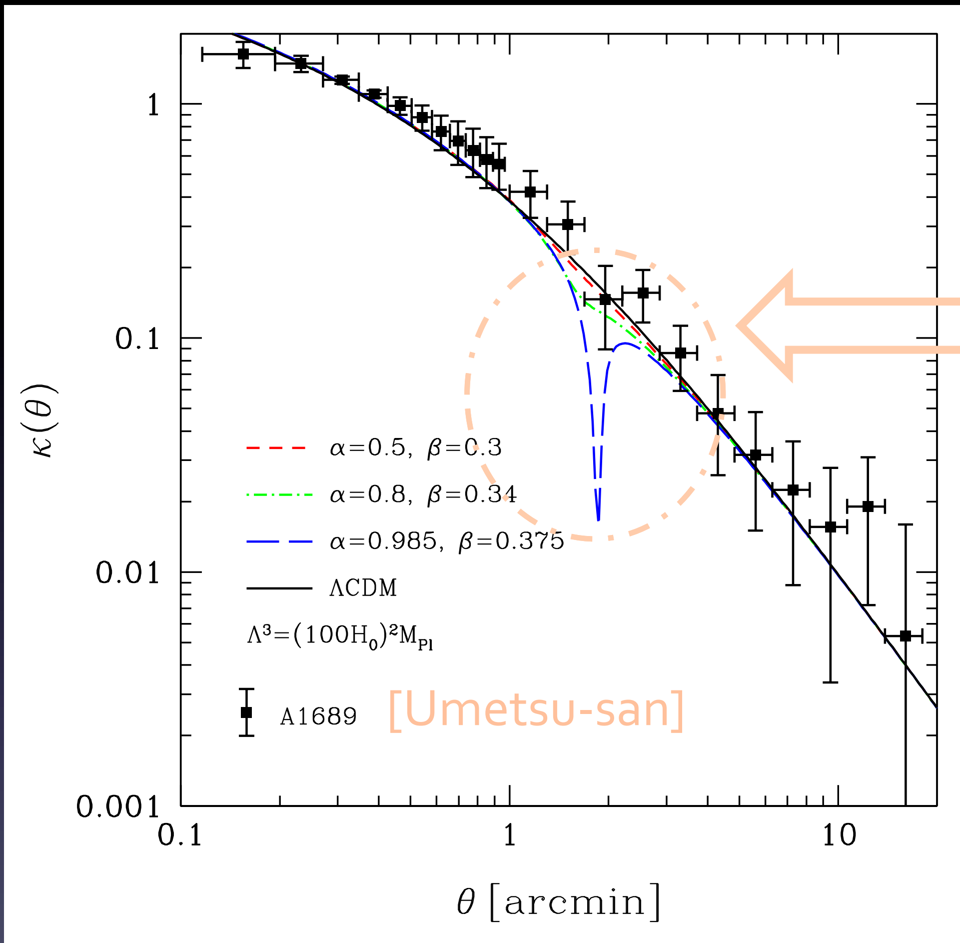
$\triangle\Phi_+ \propto r\phi'\phi''$

A dip appears.



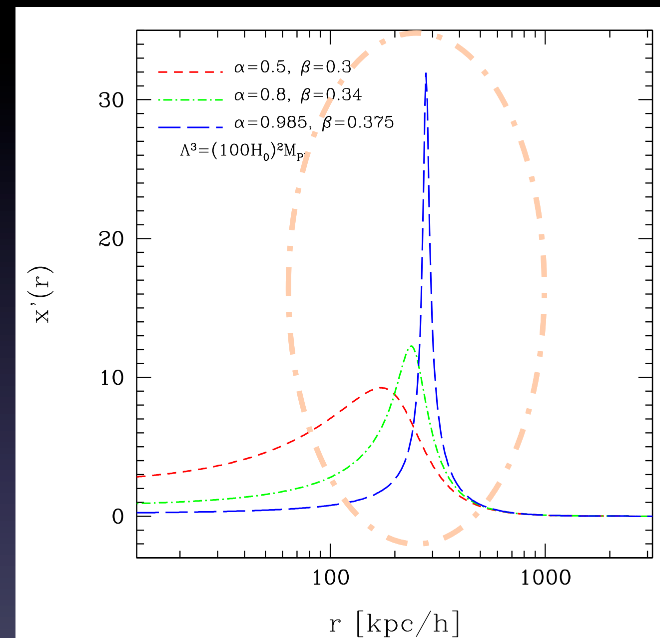


Surface Mass Density in Modified Gravity



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

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



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

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

→This allows us to put constraint.

Short Summary

★Modified gravity by ϕ

☆Motivation: Cosmic acceleration

☆Mechanisms to recover GR play a crucial role.

★Need to solve non-linear ϕ’s equation.

☆Screened conditions are clarified.

★A challenge for theoretical predictions

☆Cluster lensing: A dip appears!

★Need to find the best places to detect deviations from GR.

☆Application to testing gravity w/ another cluster observables

Summary

Impact of clusters of galaxies on modified gravity:
clusters of galaxies are also useful to test modified gravity.

There are not any requirement of modifying gravity from observations of clusters of Galaxies.

Modified gravity by an additional scalar ϕ is motivated by late-time cosmic acceleration.

Thank you for your attention

Appendix

Hydrostatic Mass + Chameleon

- 静水圧平衡

$$\rho_{\rm gas}^{-1}\frac{dP_{\rm gas}}{dr} = -\frac{GM(<r)}{r^2} - \frac{\beta}{M_{\rm Pl}}\frac{d\phi}{dr}$$

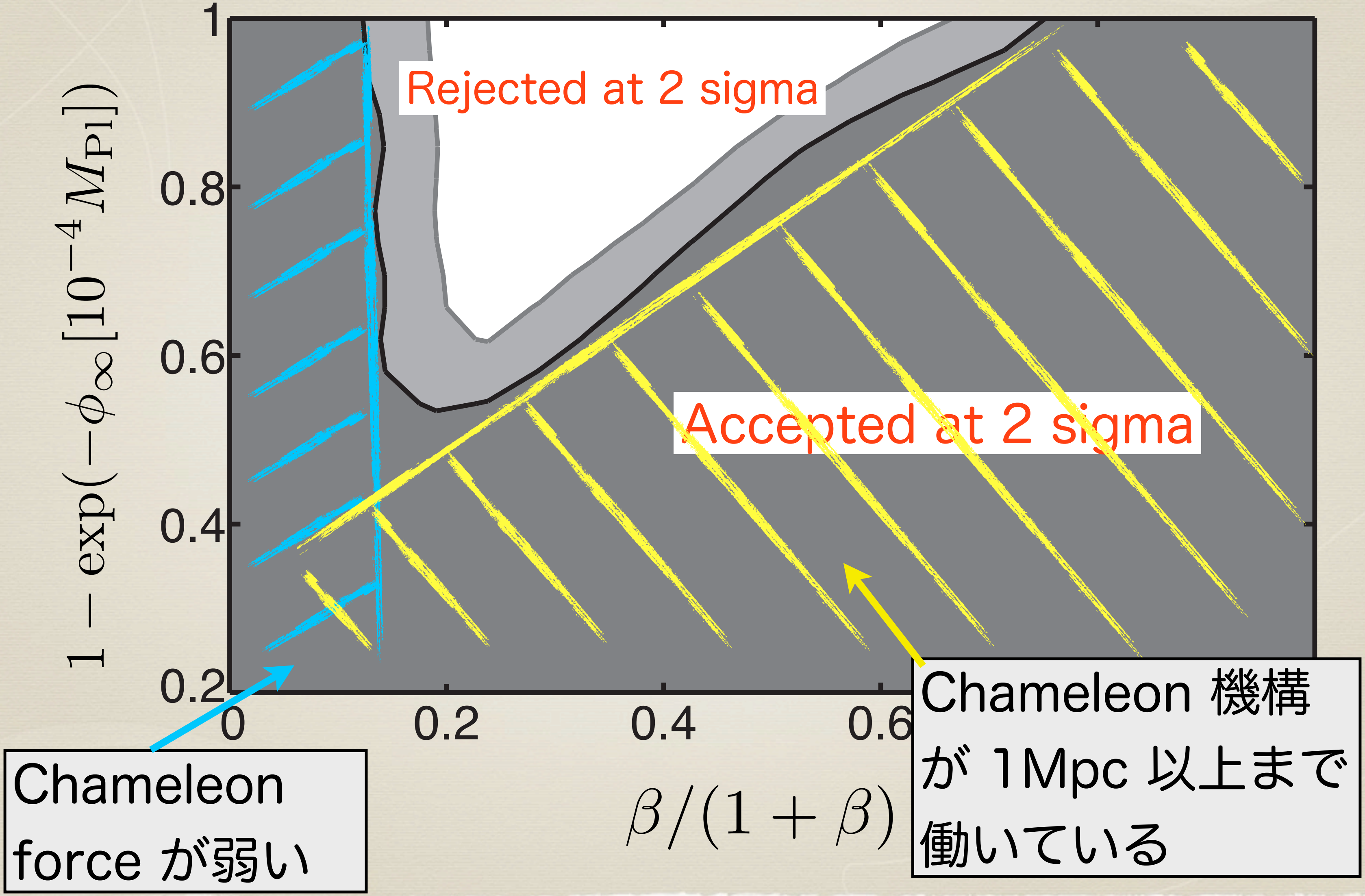
gravitational force

chameleon force

- Hydrostatic Mass

$$M_{\rm HE}(<r) = M_{\rm gas}(r) + M_\phi(r)$$

モデルパラメータに対する制限 (MCMC)



まとめ

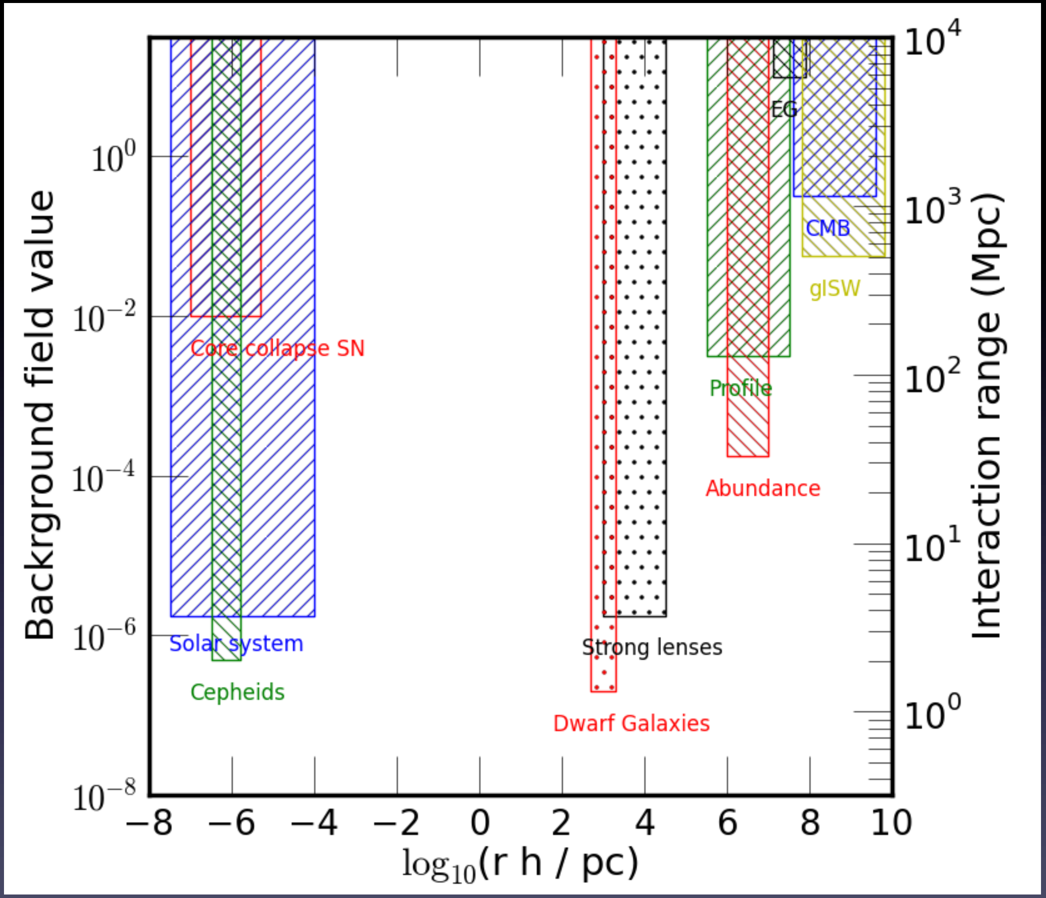
* かみのけ座銀河団の多波長観測を用いて、以下の3つの結果を得た。

1. かみのけ座銀河団において、静水圧平衡は重力レンズの誤差の範囲で成立している。

2. Chameleon force が存在すると、Hydrostatic mass は小さく見積もることになる。

3. ガス分布の理論予想と観測を比較することで、Chameleon 重力模型のモデルパラメータに対して有用な制限を得ることができた。
viable f(R) 模型に対しては　$|f_{R0}| \lesssim 0.6 \times 10^{-4}$

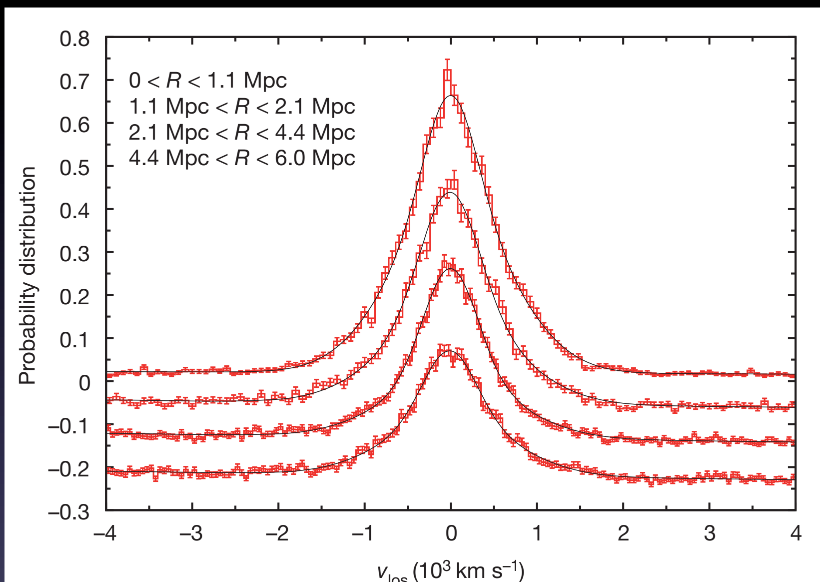
Current constraints on f(R) gravity

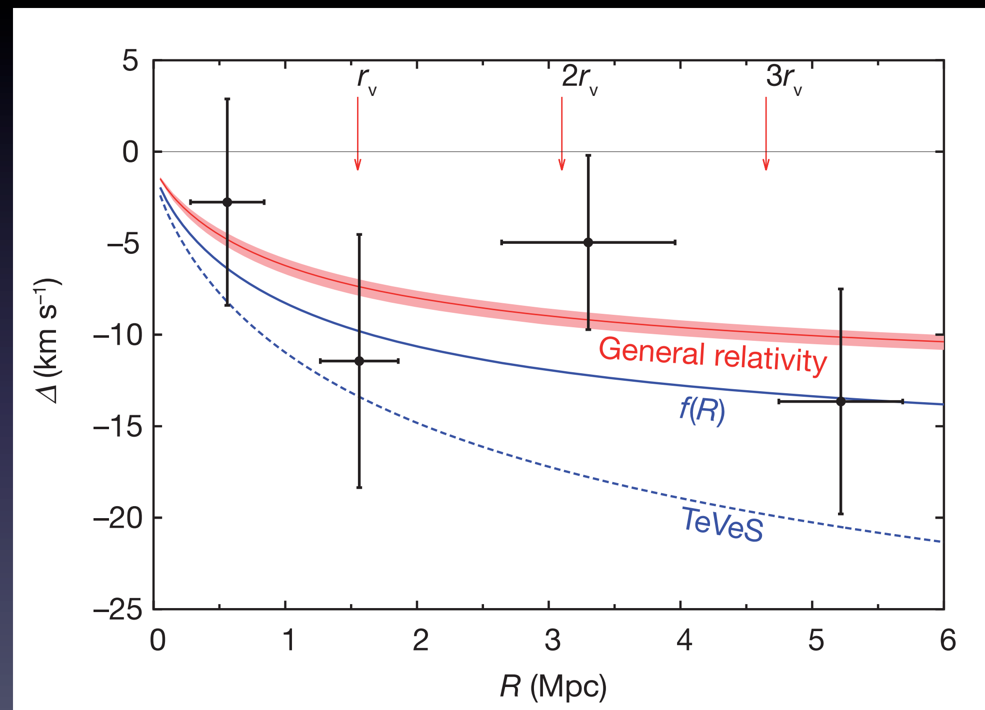


$|f_{R0}| < 3.5 \times 10^{-3}$ at the 1D-marginalized 95%

Constraints on Gravity with Gravitational Redshift from galaxy clusters

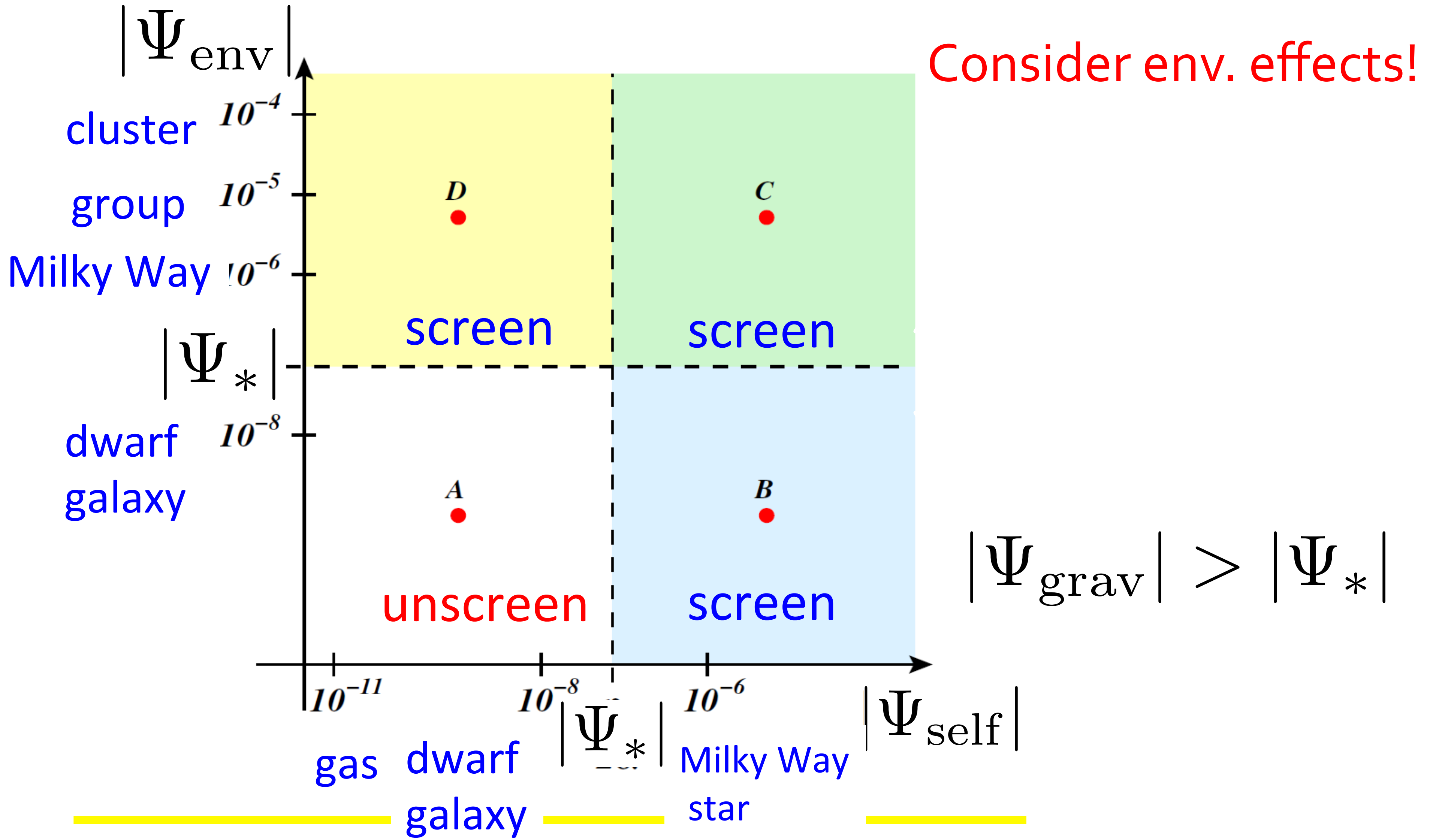
[Wojtak et al. (2011)]





Constraints on Gravity on intermediate scales is Still Weak.

Screening Depends on $\Psi_{\text{environment}}$!



[Hui, Nicolis & Stubbs (2009)]

Dwarf galaxies in voids

- ***Davis et al.'12***: Unscreened stars can be more luminous and ephemeral than their screened doppelgangers.
- ***Jain & VanderPlas '11***: F_ϕ acts on the DM and HI gas disk, but not non the stellar disk ←self-screening of MS stars.

1. A displacement of the stellar disk from HI disk.
2. Warping of the stellar disk along the direction of the external force.
3. Enhancement of the rotation curve measured from the HI gas compared to that the stellar disk.
4. Assymetry in the rotation curve of the stellar disk.