The 5th KIAS Workshop on Cosmology and Structure Formation,
Nov. 2nd 2012

TESTING MODIFIED GRAVITY MODEL WITH CLUSTER OF GALAXIES

Kazuhiro Yamamoto
(Hiroshima Univ.)

My talk is based on

Ayumu Terukina & K.Y., arXiv:1203.6163, PRD, in press

Work in progress in collaboration with AyumuTerukina, K. Koyama, L. Lombriser, D. Bacon, R.C. Nichol

Contents

1. Introduction

Extended theory of gravity
higher dimensional theories
renormalizable theory of gravity

Modified gravity models

Alternative approach to explain the cosmic acceleration of the Universe

Observational cosmology plays an important roll of testing the consistency

CMB anisotropy, ISW effect, (today's talk by Dr. Hojjati,)
LSS of galaxies, redshift-space distortions

Cluster of galaxies as a probe of testing modified gravity models

F. Schmidt (10), Li & Hu (11), G.-B. Zhao, Li, Koyama (11),
L. Lombriser, et al. (2012a, 2012b), T-Y. Lam, et al. (12)
T. Narikawa & KY(12), ….

Variety of cluster observations

(see also the slides by Dr. Sepp, Dr. Tamura, Dr. Chon, Dr. Im, and Dr. Lee)

- Strong and Weak lensing
  Lensing potential ↔ (gravitational potential)
  -(curvature perturbation)

- Redshift measurement of galaxies
  (velocity of galaxies)^2 ↔ (gravitational potential)

- X-ray
  Intensity ↔ $n_e^2 T_e^{1/2}$ (electron density)^2 × (Temperature)$^{1/2}$

- Sunyaev-Zeldovich
  y-parameter ↔ $n_e T_e$ (electron density) × (Temperature)

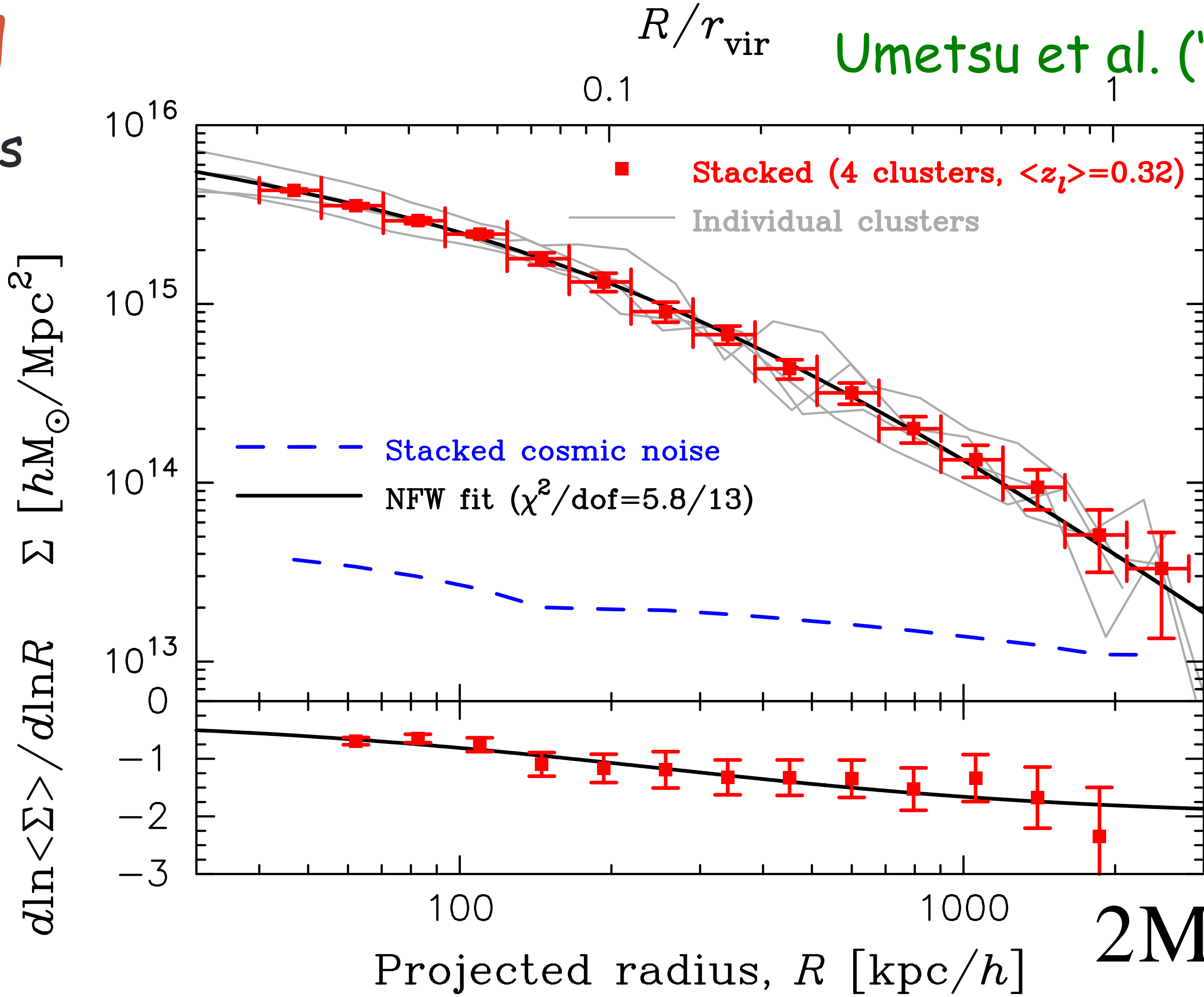
These observations in progress

Lensing

surface mass density

$$\Sigma_S = \int dz \rho$$

Umetsu et al. ('12)



2Mpc

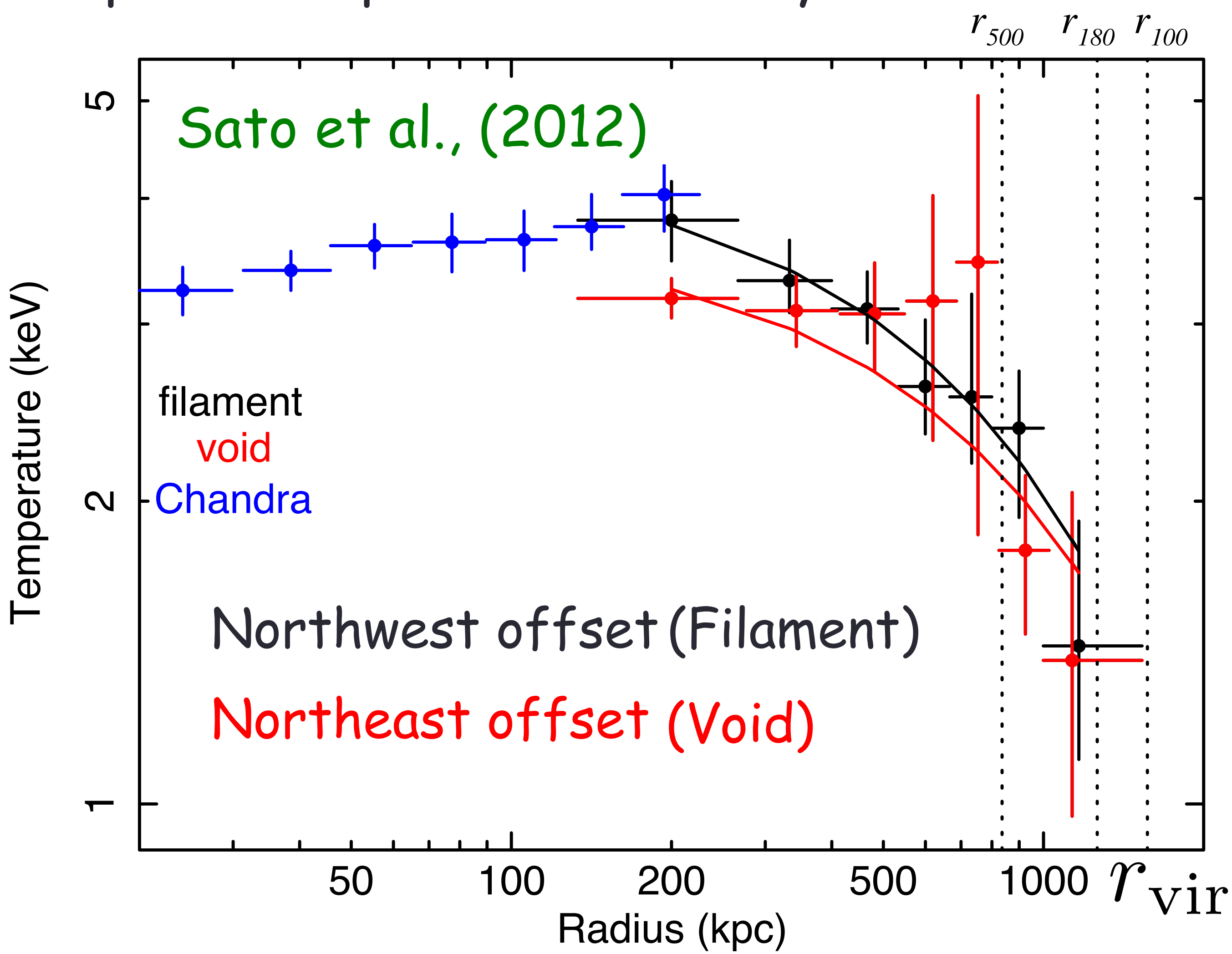
The NFW density profile fits the data out to the virial radius.

c.f. Oguri et al. ('12)

X-ray

c.f. Kawaharada et al. (2010)

temperature profile of the Hydra A cluster from Suzaku obs.

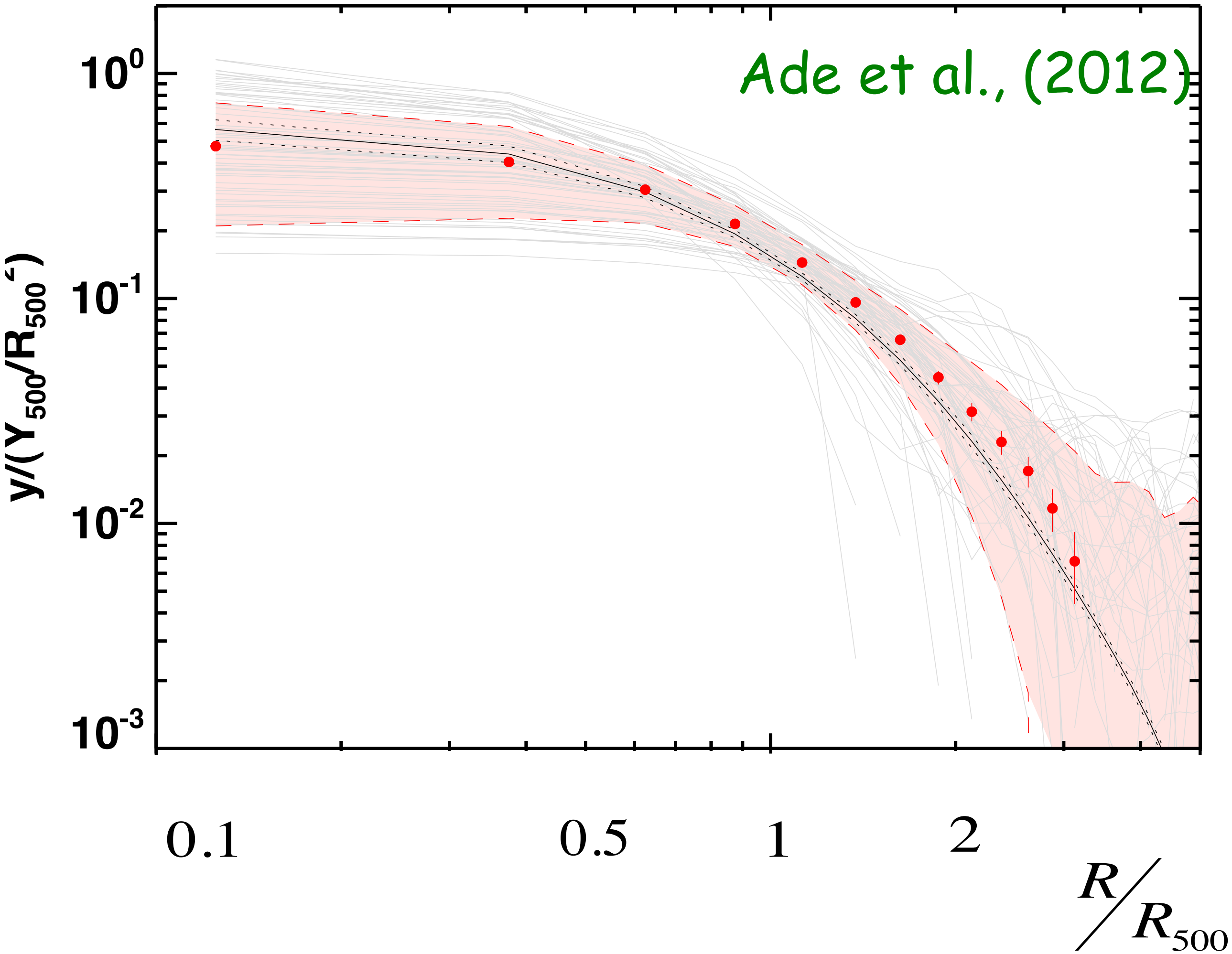


Hydra A cluster is medium-sized cluster located at a distance 230 Mpc.

Data out to the virial radius

Sunyaev-Zeldovich effect

y-parameter profile from 62 clusters measured by Planck satellite



Data out to
the virial radius

2. Chameleon gravity model – theoretical aspects

Modified gravity may explain the cosmic acceleration of the universe.

Modification of the general relativity introduces
additional degrees of freedom, which give rise to the fifth force.

In the chameleon gravity model, the chameleon scalar field is introduced.

(Example) - f(R) model

$$S = \int d^4\sqrt{-g}\left(\frac{R+f(R)}{16\pi G}\right) + S_m[\psi, g_{\mu\nu}]$$

$$\frac{\phi}{M_{\rm pl}} = \sqrt{\frac{3}{2}}\log(1+f'(R))$$

$$\widetilde{g}_{\mu\nu} = e^{\sqrt{\frac{2}{3}}\phi/M_{\rm pl}} g_{\mu\nu}$$

$$M_{\rm pl}^2 = \frac{1}{8\pi G} \quad \beta = \sqrt{\frac{1}{6}}$$

$$S = \int d^4\sqrt{-\widetilde{g}}\left(\frac{\widetilde{R}}{16\pi G} - (\widetilde{\partial}\phi)^2 - V(\phi)\right) + \underline{S_m[\psi, e^{-2\beta\phi/M_{\rm pl}}\widetilde{g}_{\mu\nu}]}$$

In this frame, the matter field is coupled with the scalar field

Chameleon gravity model (chameleon field ϕ)

Force on a matter = Gravitational force + Fifth force

$$\vec{F} = -\vec{\nabla}\left(\phi_G + \beta\frac{\phi}{M_{\rm pl}}\right)$$

Gravitational potential

$$\triangle\phi_G = 4\pi G\rho$$

ρ is the matter density.

Chameleon field obeys

$$\triangle\phi = V'(\phi) + \rho\frac{\beta}{M_{\rm pl}}e^{\beta\phi/M_{\rm pl}}$$

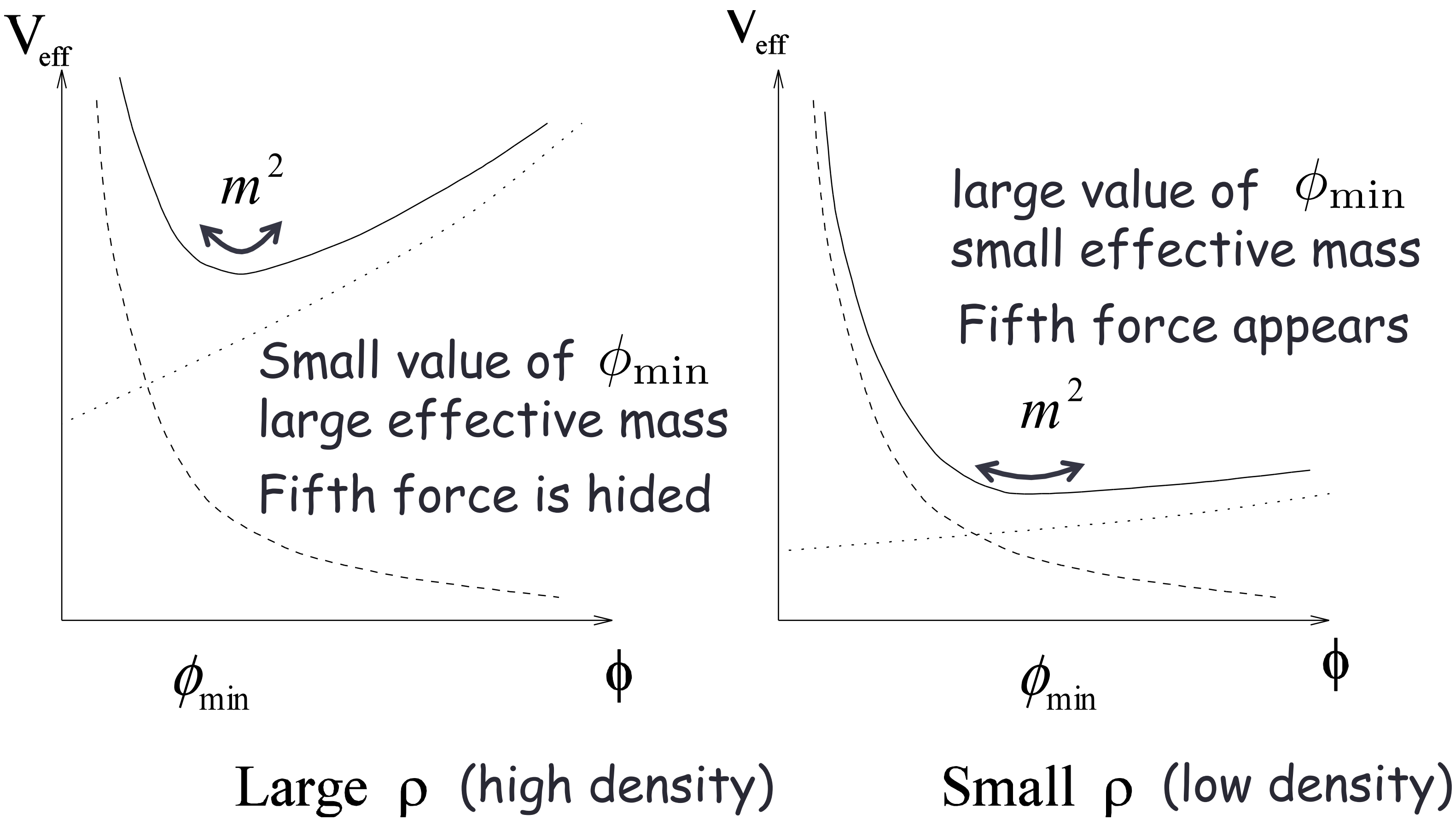
Fifth force is severely constrained
from the experiments in solar system

Due to the chameleon mechanism (Khoury & Weltman 04)

the chameleon field is hidden in the high density region

Chameleon field equation

$$\triangle\phi = V'_{\rm eff}(\phi) \qquad V_{\rm eff} = V(\phi) + \rho e^{\beta\phi/M_{\rm pl}} \qquad V(\phi) \propto \frac{1}{\phi^n}$$



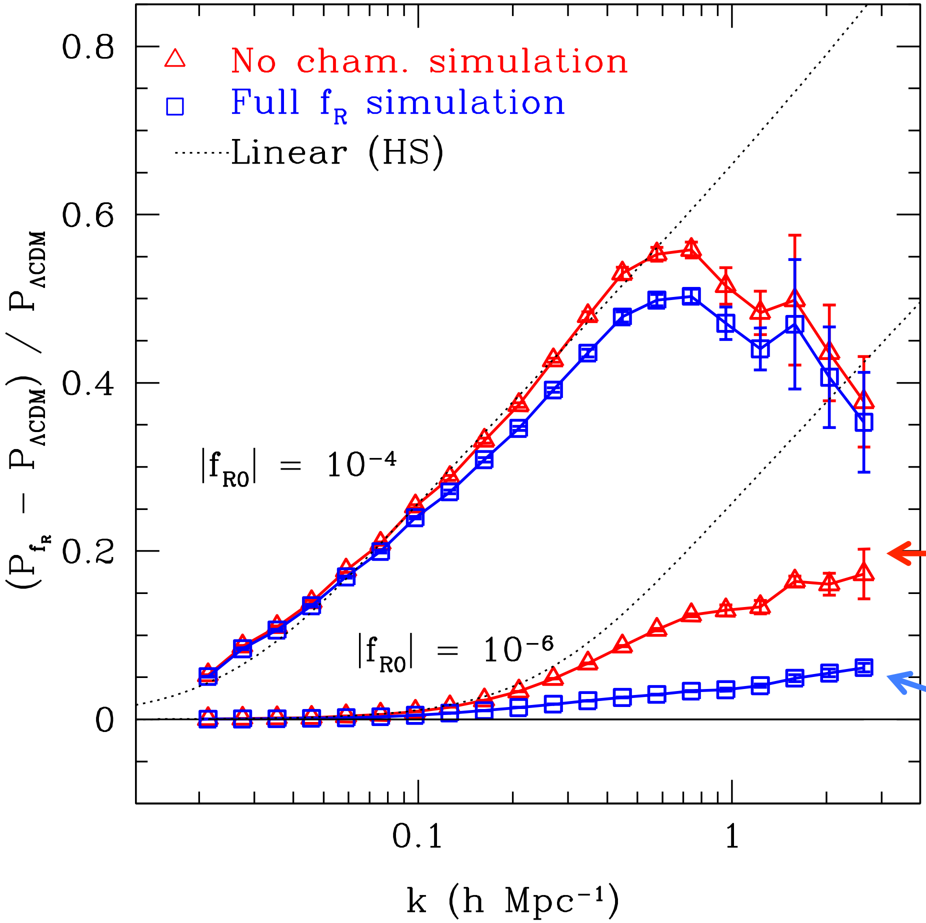
Chameleon mechanism: (Environment-dependent effect)

The chameleon field is hided in the high density region,
(The fifth force is hided)

f(R) model as the chameleon model

structure formation in an f(R) model

N-body simulation+ Solving the nonlinear chameleon field equation



Schmidt, et al (09)
Li & Barrow (11)
Zhao, Li, & Koyama (11)
Lombriser et al. (11,12)

Oyaizu, Lima, & Hu (08)

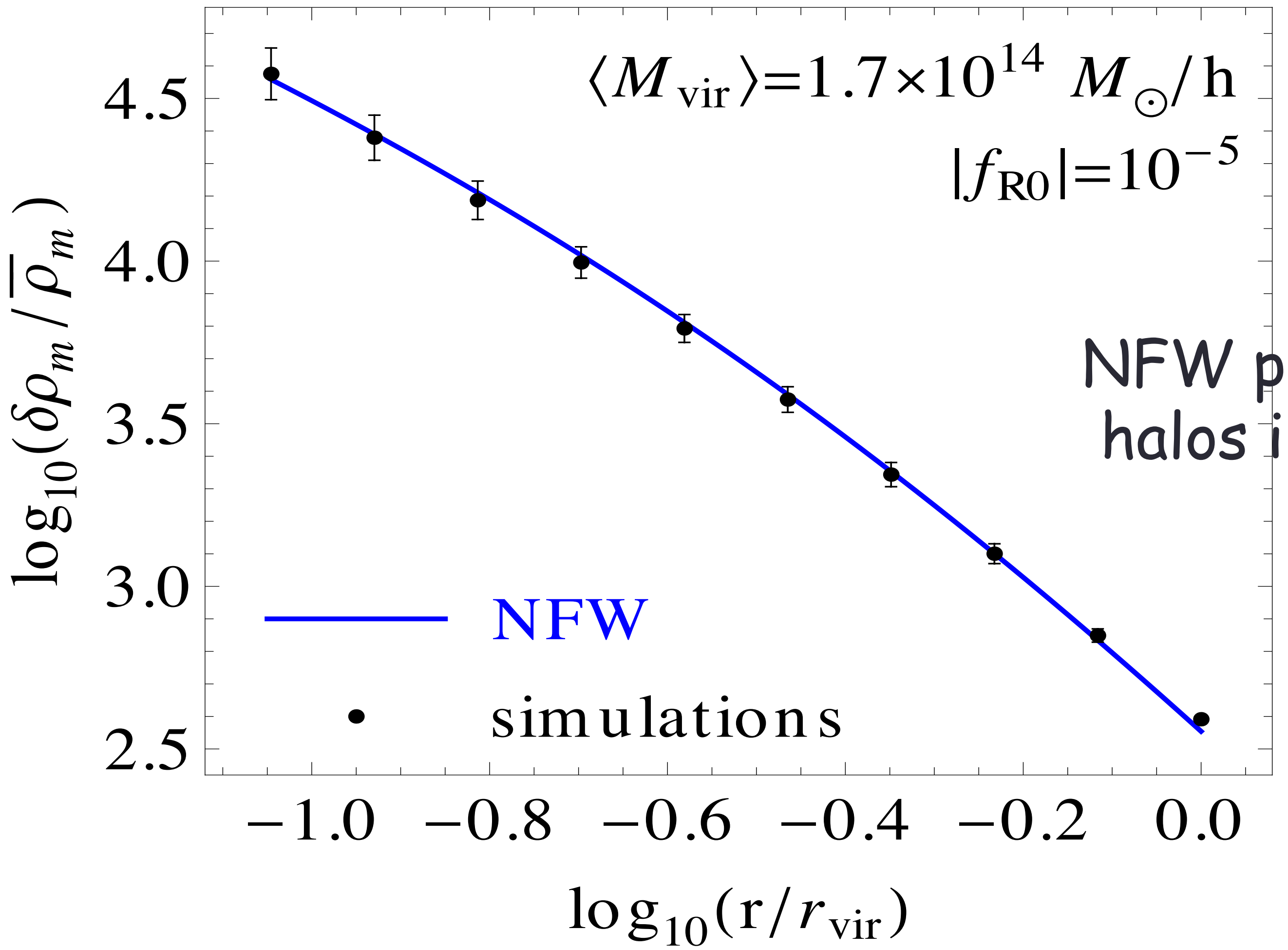
The fifth force enhances the amplitude of P(k)

The chameleon mechanism suppress the enhancement

halo structure in chameleon model in N-body simulation

Lombriser et al. (12)

Schmidt, et al (09)
Li & Barrow (11)
Zhao, Li, & Koyama (11)



NFW profile fits halos in an f(R) model

3. Gas distribution in a halo in chameleon gravity

Simple model (Makino, Suto, Sasaki '98)

- Hydrostatic equilibrium between the gas pressure gradient and the gravitational force and the fifth force

- Static and spherically symmetric matter distribution with generalized NFW density profile

$$\rho = \frac{\rho_s}{(r/r_s)(1+r/r_s)^b} \xrightarrow[b=2]{} \text{NFW profile}$$

Gravitational potential

$$\triangle \phi_G = 4\pi G \rho$$

$$\phi_G(x) = 4\pi G \rho_s r_s^2 \frac{(1+x)^{2-b}-1}{(b-2)(b-1)x}, \qquad x = \frac{r}{r_s}$$

Chameleon scalar field $\phi/M_{\rm pl} \ll 1$

$$\triangle\phi = V'(\phi) + \frac{\beta}{M_{\rm pl}}\rho \qquad V(\phi) = \frac{\Lambda^{n+4}}{\phi^n}$$

Analytic approach Pourhasan et al. ('12)

c.f. Lombriser et al. ('12)

Approximate solution

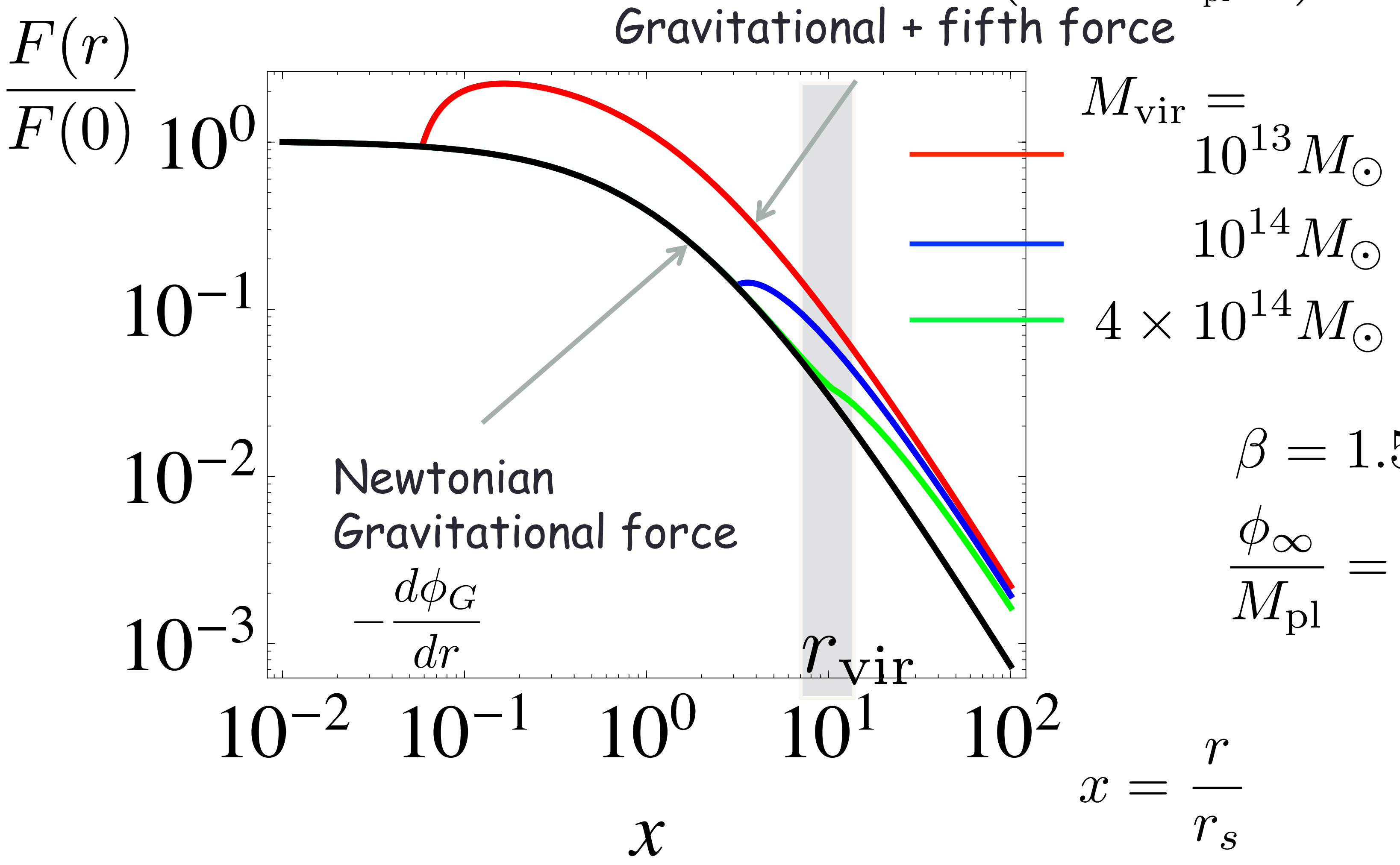
Asymptotic value at large radius

$$\phi(x) \cong \begin{cases} 0 \quad (x < x_c) & \text{(Interior region)} \\ \dfrac{\beta\rho_s r_s^2}{M_{\rm pl}} \dfrac{(1+x)^{2-b} - 1}{(b-2)(b-1)x} + \dfrac{C_1}{x} + \phi_\infty \quad (x > x_c) & \text{(Exterior region)} \end{cases}$$

Smooth matching condition at x_c

Gravitational force + fifth force

$$-\left(\frac{d\phi_G}{dr}+\frac{\beta}{M_{\rm pl}}\frac{d\phi}{dr}\right)$$



$$\beta = 1.5$$

$$\frac{\phi_\infty}{M_{\rm pl}} = 10^{-5}$$

$$x = \frac{r}{r_s}$$

The fifth force appears only in the outer region for large mass halo, but the effect enters inside of halo for smaller mass halo.

Gas density profile

Suto, Sasaki, Makino ('98)

Hydrostatic equilibrium

between the gas pressure gradient
and the combination of the gravitational force and the fifth force

$$\frac{dP_{\rm gas}}{dr} = -\rho_{\rm gas}\left(\frac{d\phi_G}{dr} + \beta\frac{d\phi}{dr}\right)$$

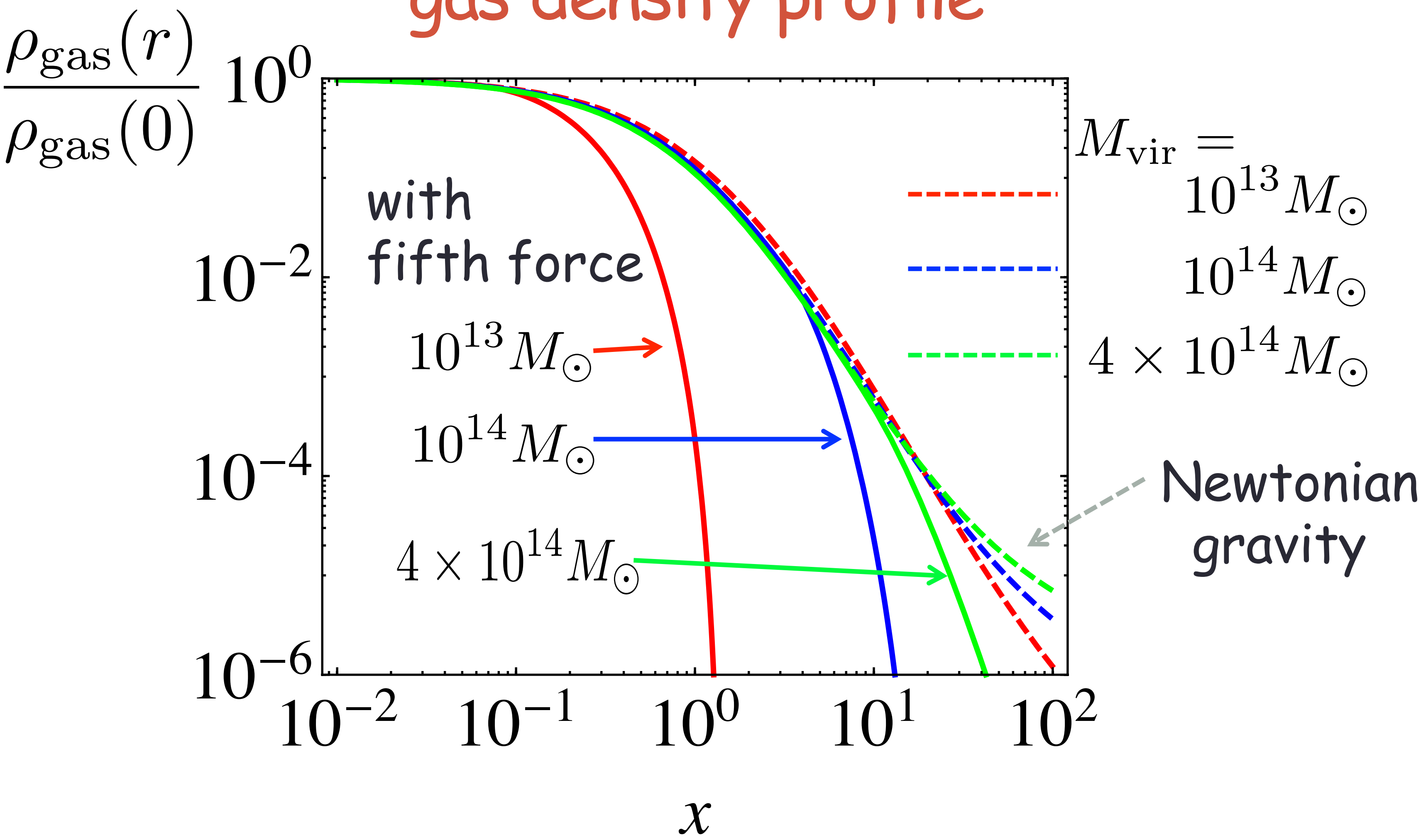
Polytropic equation of state

$$P_{\rm gas} \propto \rho_{\rm gas} T_{\rm gas} \propto \rho_{\rm gas}^{\gamma}$$

Analytic gas density profile Terukina and KY (2012)

$$\rho_{\rm gas}(x) = \rho_{\rm gas}(0)\left[1 - \frac{\mu m_p}{kT_{\rm gas}(0)}\left(\frac{\gamma-1}{\gamma}\right)\left\{\phi_G(x) - \phi_G(0) + \frac{\beta}{M_{\rm pl}}\phi(x) - \frac{\beta}{M_{\rm pl}}\phi(0)\right\}\right]$$

gas density profile



Sharp drop in the gas density, more significant for smaller mass halo.

⟺ Due to the Fifth force, larger pressure gradient is necessary.

Projected temperature profile

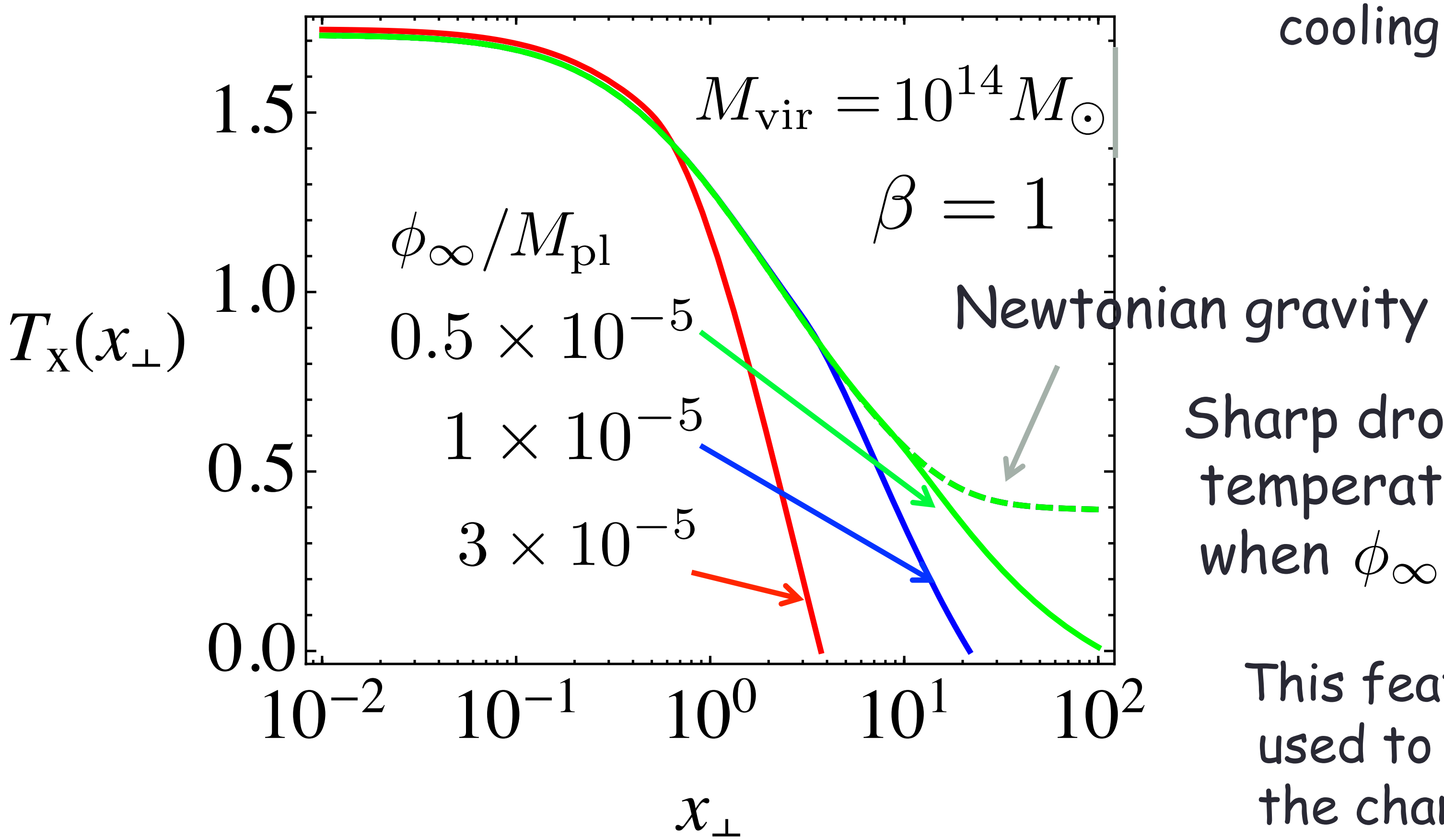
X-ray temperature
averaged over the line of sight

$$T_X(r_\perp) = \frac{\int dz \lambda_c \rho_{\rm gas}^2 T_{\rm gas}(\sqrt{r_\perp^2 + z^2})}{\int dz \lambda_c \rho_{\rm gas}^2}$$

emissivity $\propto \lambda_c \rho_{\rm gas}^2$

cooling function

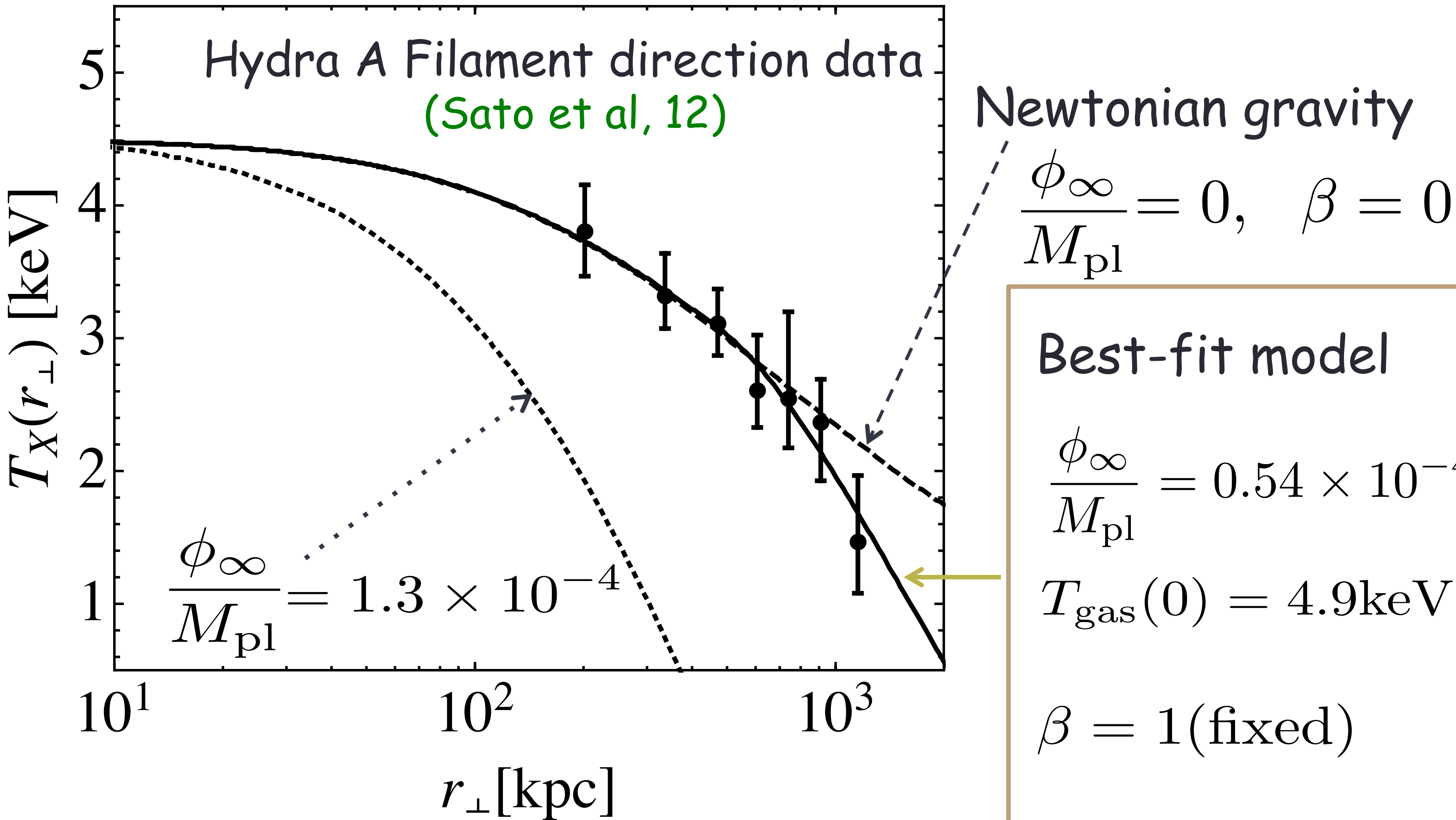
$\lambda_c \propto T_{\rm gas}^{1/2}$



Sharp drop in
temperature profile
when $\phi_\infty / M_{\rm pl}$ is large

This feature can be
used to constrain
the chameleon model

4.Comparison with the temperature profile of Hydra A cluster



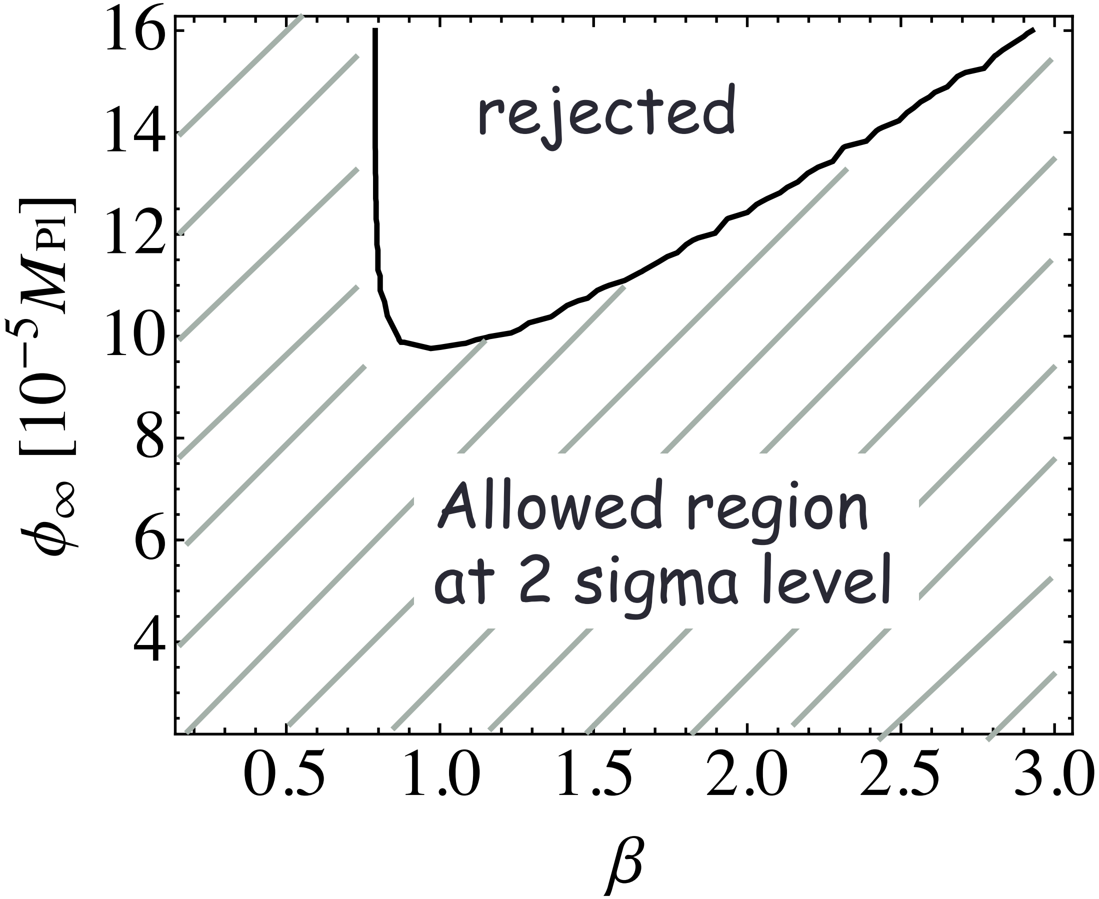
Best-fit model

$$\frac{\phi_\infty}{M_{\rm pl}} = 0.54 \times 10^{-4}$$

$$T_{\rm gas}(0) = 4.9 \mathrm{keV}$$

$$\beta = 1 (\text{fixed})$$

Constraint from the Hydra A cluster



varied

$M_{\rm vir}, T_{\rm gas}(0)$

fixed

$c = c(M_{\rm vir})$

$b = 2$

$\gamma = 1.2$

For $\beta = 1$, we have the upper limit $\dfrac{\phi_\infty}{M_{\rm pl}} < 10^{-4}$

Upper limit of $\phi_\infty / M_{\rm pl}$ for $\beta = 1$

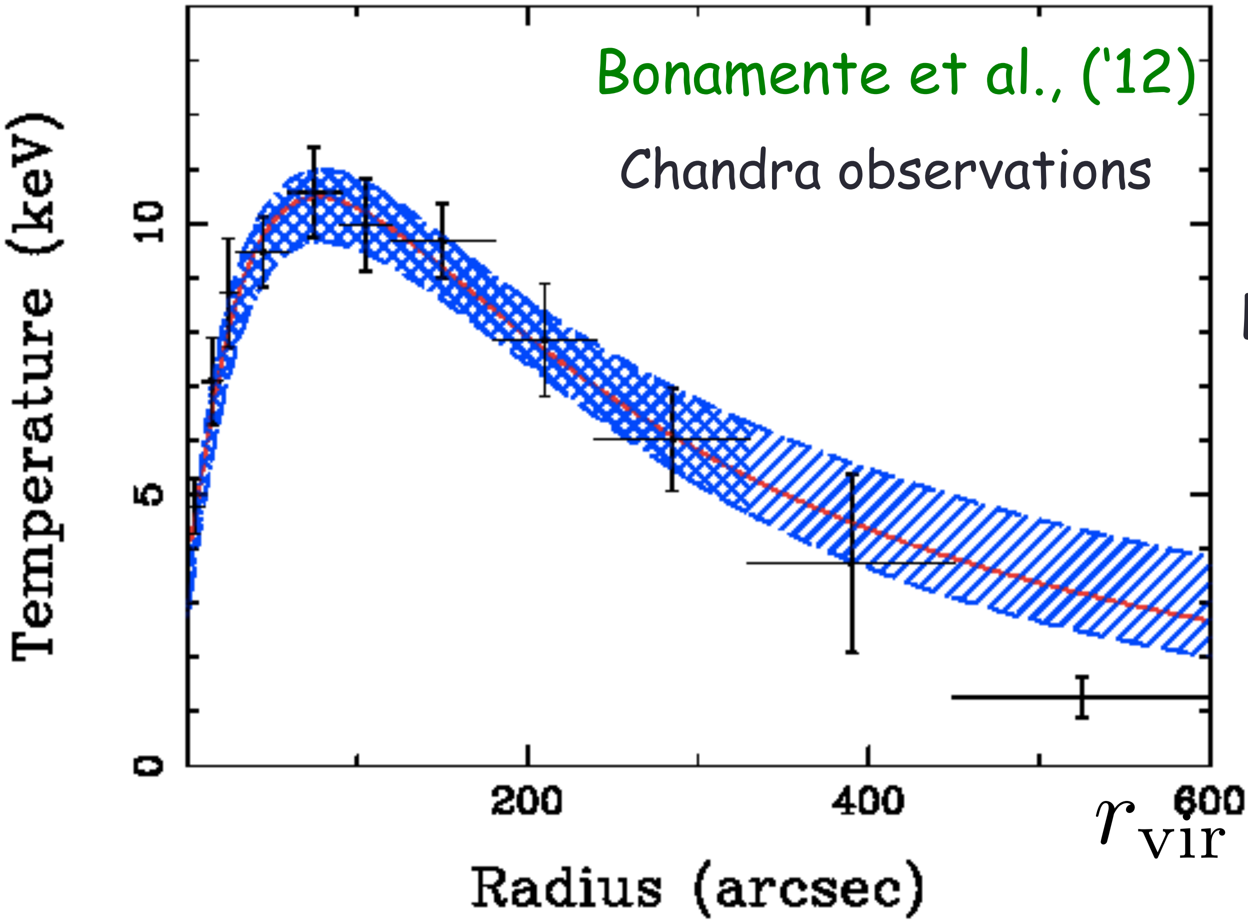
	Filament	Void
$b = 1.7$	1.4×10^{-4}	0.9×10^{-4}
$b = 2$	1.0×10^{-4}	0.8×10^{-4}
$b = 2.5$	0.8×10^{-4}	0.6×10^{-4}

$$\beta = 1 \qquad \frac{\phi_\infty}{M_{\rm pl}} \lesssim 10^{-4}$$

Abell 1835

Bright cluster located at z=0.253

undisturbed relaxed cluster



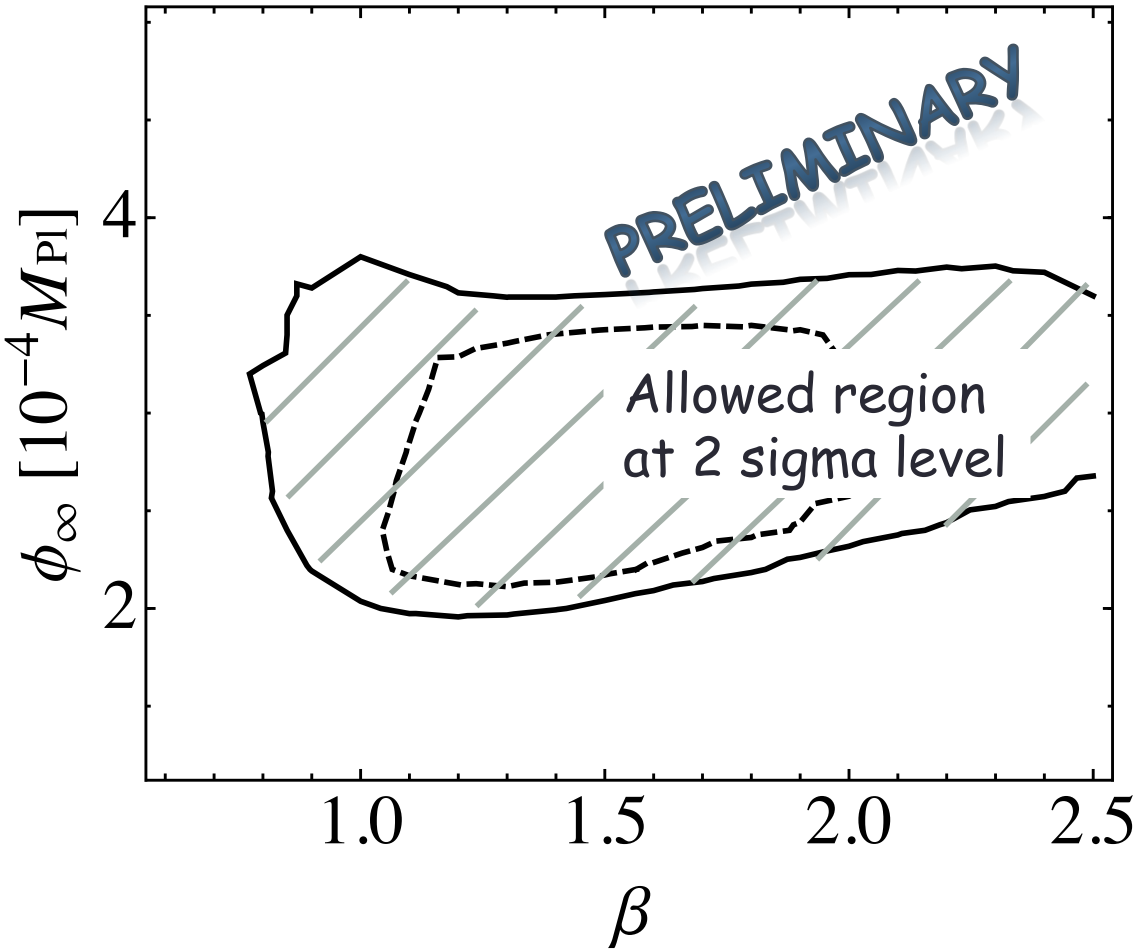
Corless et al., ('09)

Lensing mass

$$M_{200} = (6.7 \pm 2.2) \times 10^{12} M_\odot/h$$

Constraint from Abell 1835

Work in progress in collaboration with A. Terukina, D. Bacon, K. Koyama, L. Lombriser, R. C. Nichol

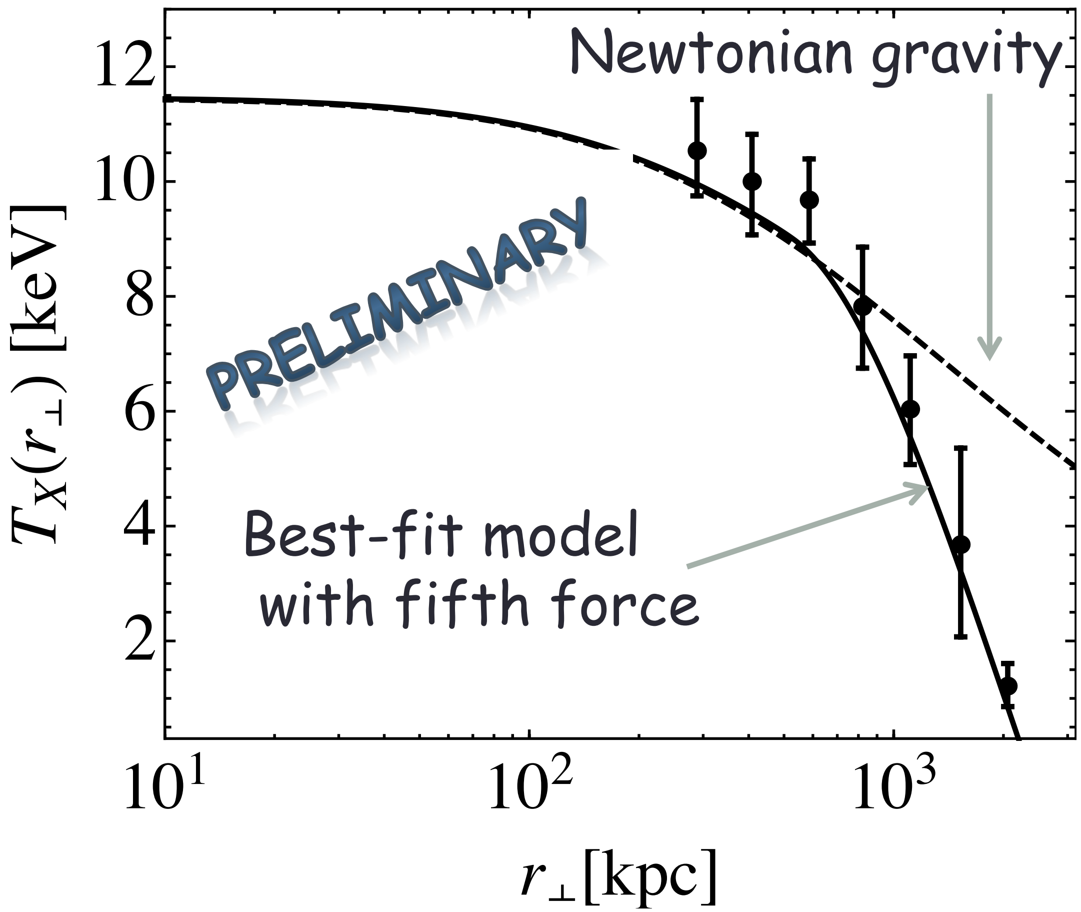


Chameleon gravity is favored than Newtonian gravity.

Newtonian gravity might not be consistent with the data.

Newtonian gravity + Hydrostatic equilibrium may not explain the temperature profile

Chameleon model better fits the data



Bonamente et al., ('12)
pointed out a sharp drop in the temperature profile.

Our conclusion is consistent.

What's the origin?

Astrophysical explanation

- Non-thermal pressure effect
- Projection effect
- Cold gas stream of not shock heated component
- observational bias
- gas clumping
- ………
- Fifth force effect

5.Summary and Conclusions

★Cluster of galaxy is useful for testing modified gravity model.

★Analytic formula for the gas distribution in the chameleon gravity model

- Hydrostatic equilibrium
- generalized NFW density profile

★The gas distribution becomes compact because a lager pressure gradient is necessary due to the additional chameleon fifth force.

★We obtained a useful constraint on the chameleon model by comparison with the observation of the Hydra A cluster.

★Preliminary, but the chameleon model better fits the data of Abell 1835.

★A sharp drop in temperature profile might be explained by the chameleon fifth force.