Cosmology of gravity theories beyond General Relativity

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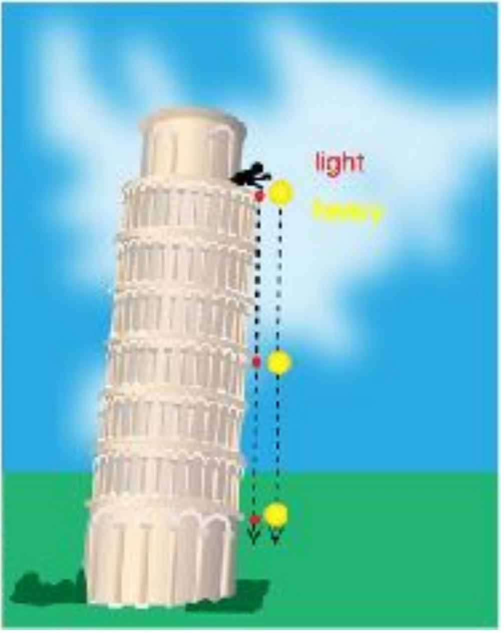
LECTURE 4

Cosmological test of the Equivalence Principle



Equivalence Principle

Inertial mass vs. Gravitational mass

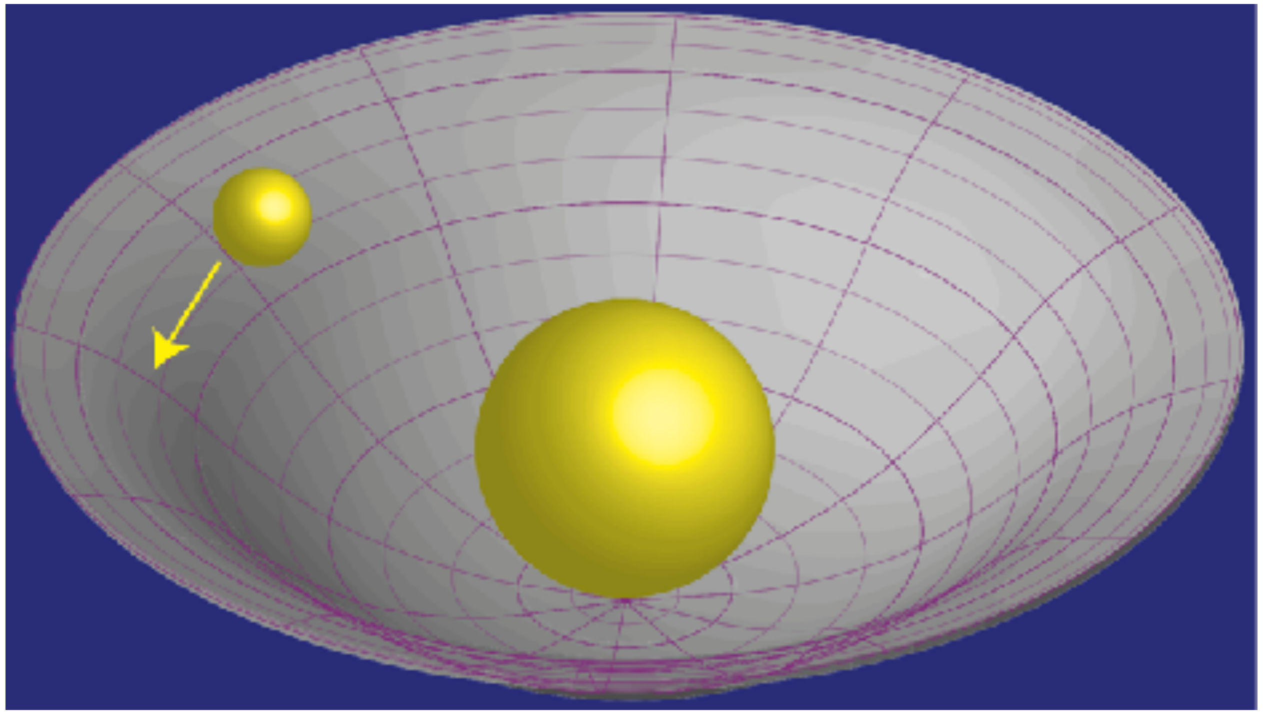
- **<u>Inertial Mass</u>** - The greater the mass, the greater force it takes to change its motion (acceleration)

$$F = \overset{\text{Inertial mass}}{m}a$$

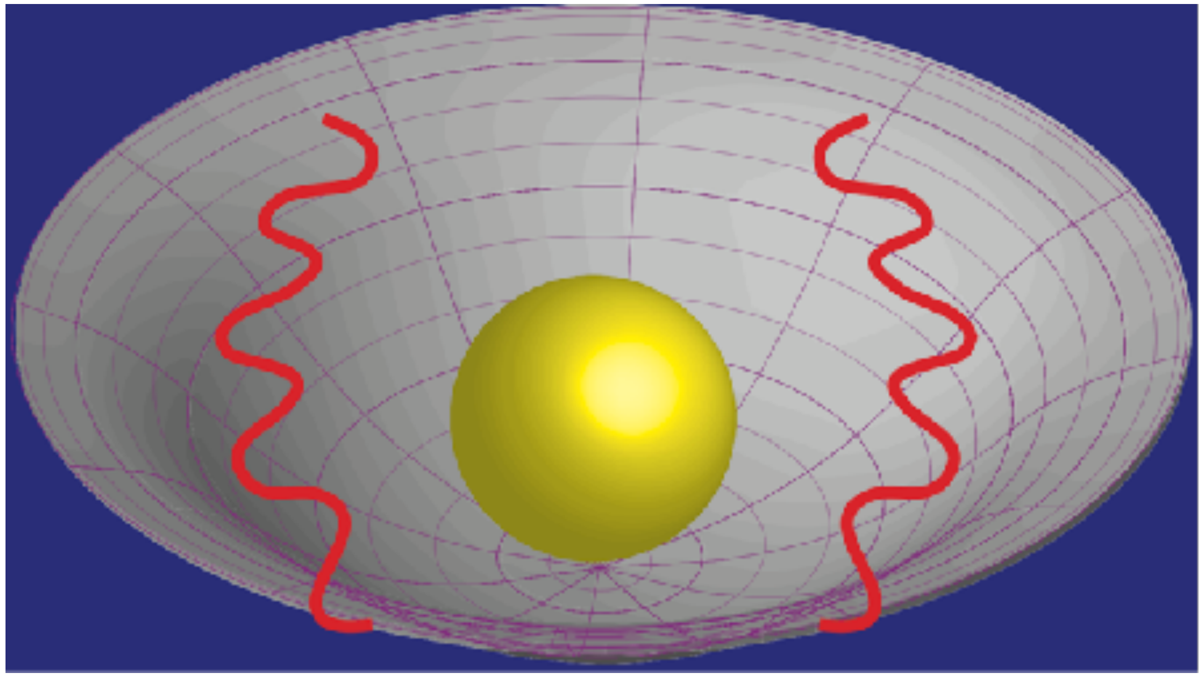
Equivalence principle: They are the same in GR!

Probing Mass / Curvature

Newtonian potential: $\Phi = \delta g_{00}/2g_{00}$ which non-relativistic particles feel



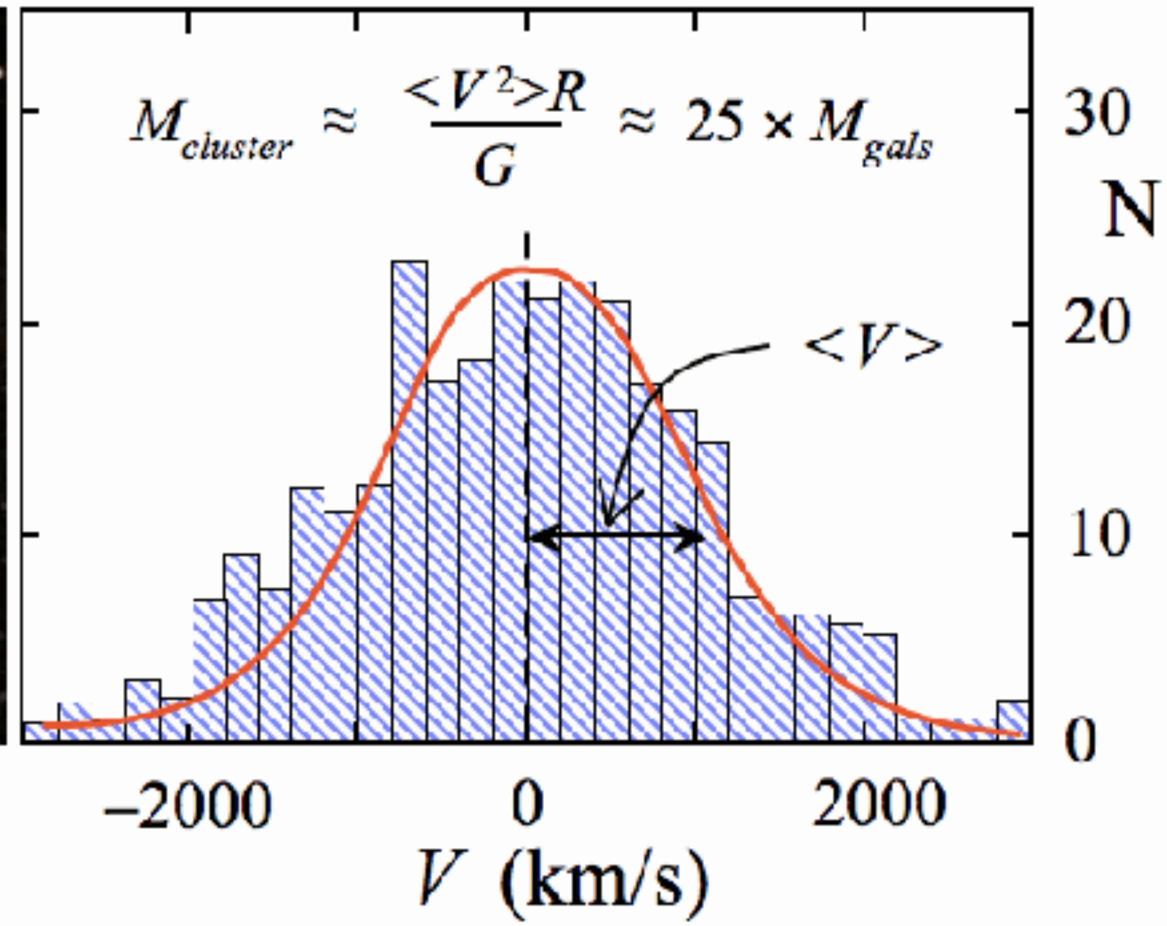
Space curvature: $\Psi = \delta g_{ij}/2g_{ij}$ which also deflects photons



Kinematical Mass (Inertial mass)

from velocity dispersions of galaxies

Coma cluster (central part)

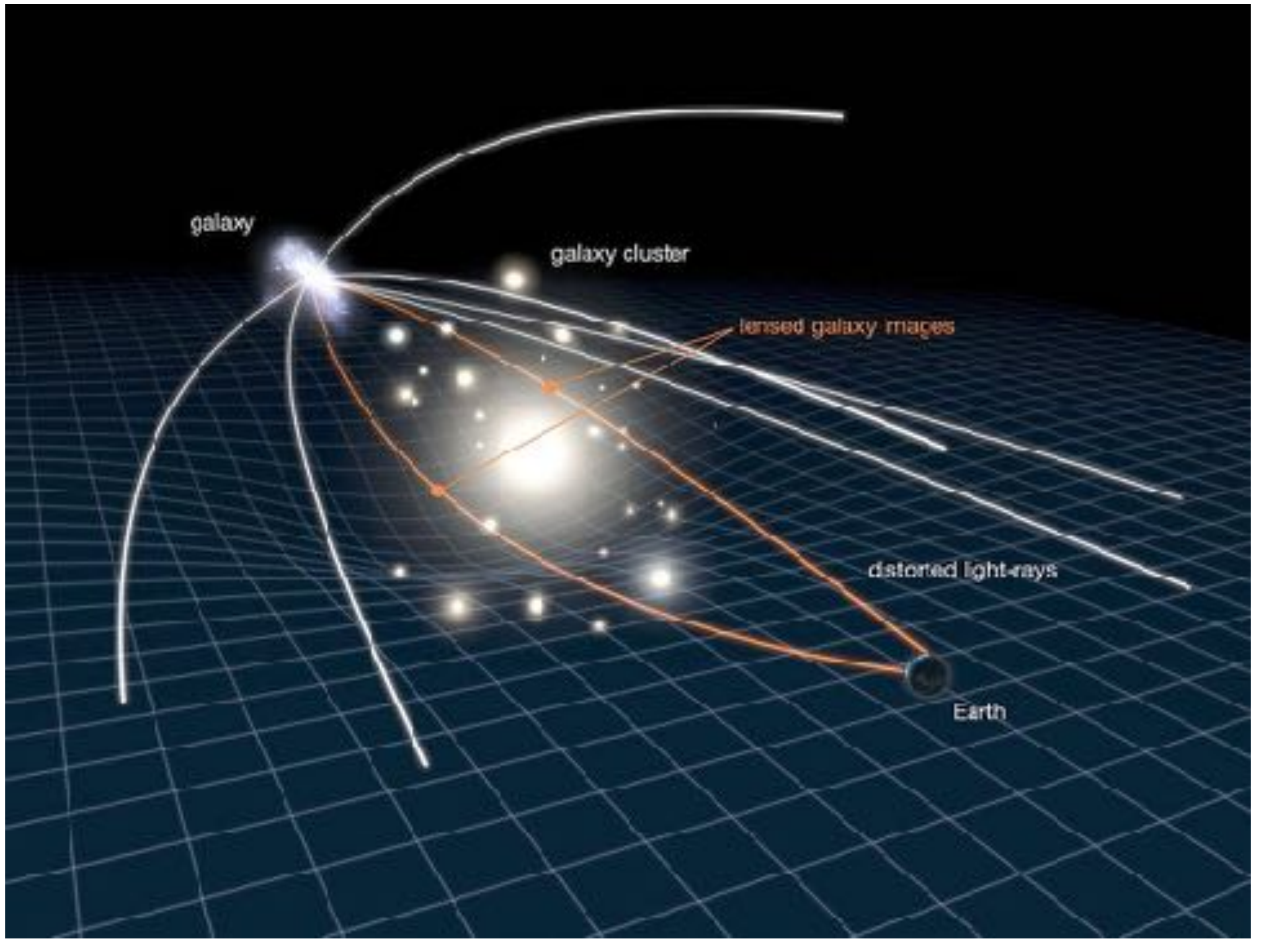


$$M_{kinematic} \frac{< V^2 >}{R} = F_N + \boxed{\mathbf{F}_\phi}$$

Modified Gravity <u>enhances</u> kinematical mass estimates for same velocity dispersion

Clusters Masses

Gravitational Mass: measured via lensing



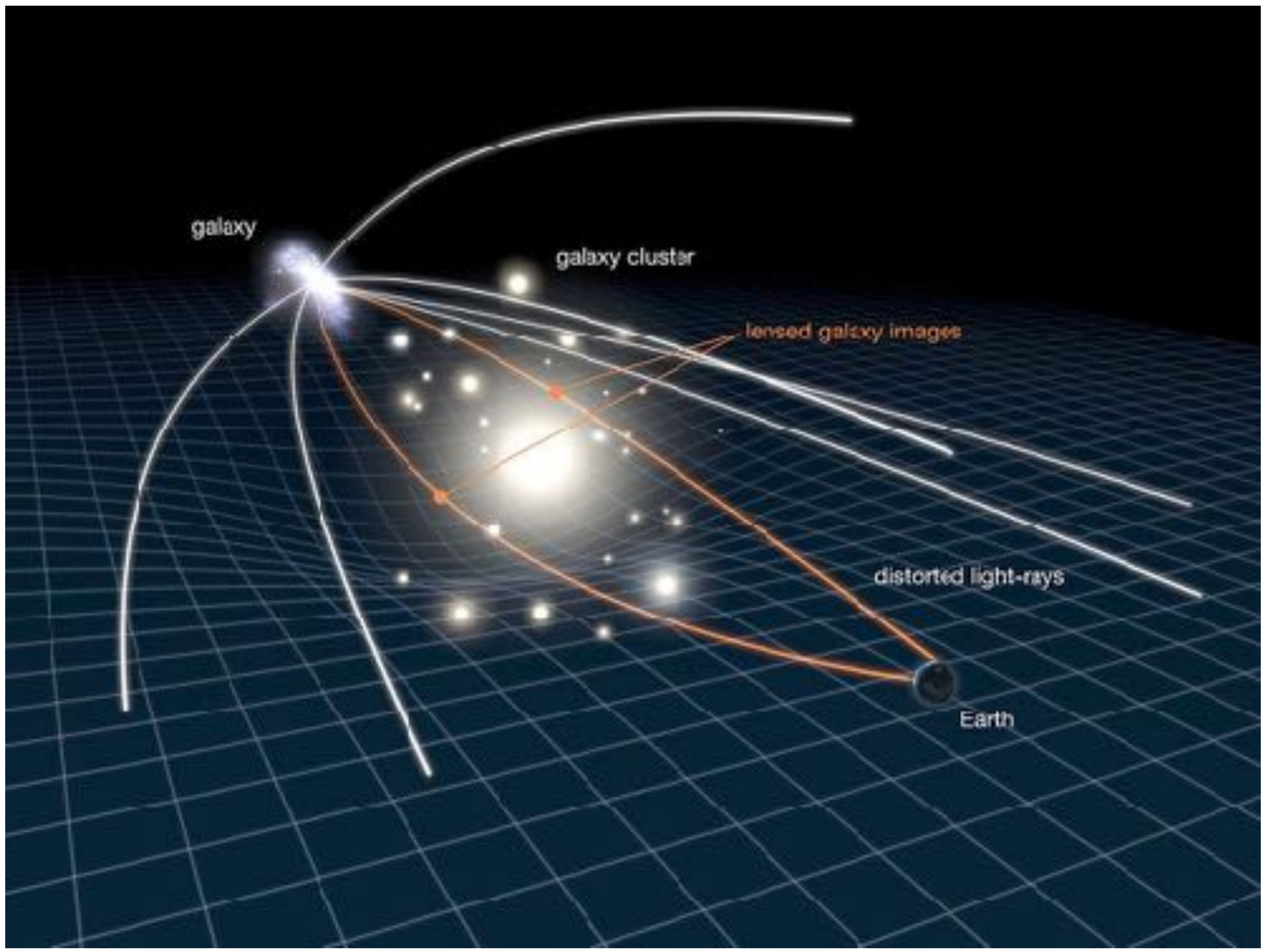
Conformal Invariance: null geodesic not affected by Modified Gravity

Lensing Mass in (conformal) Modified Gravity same as GR

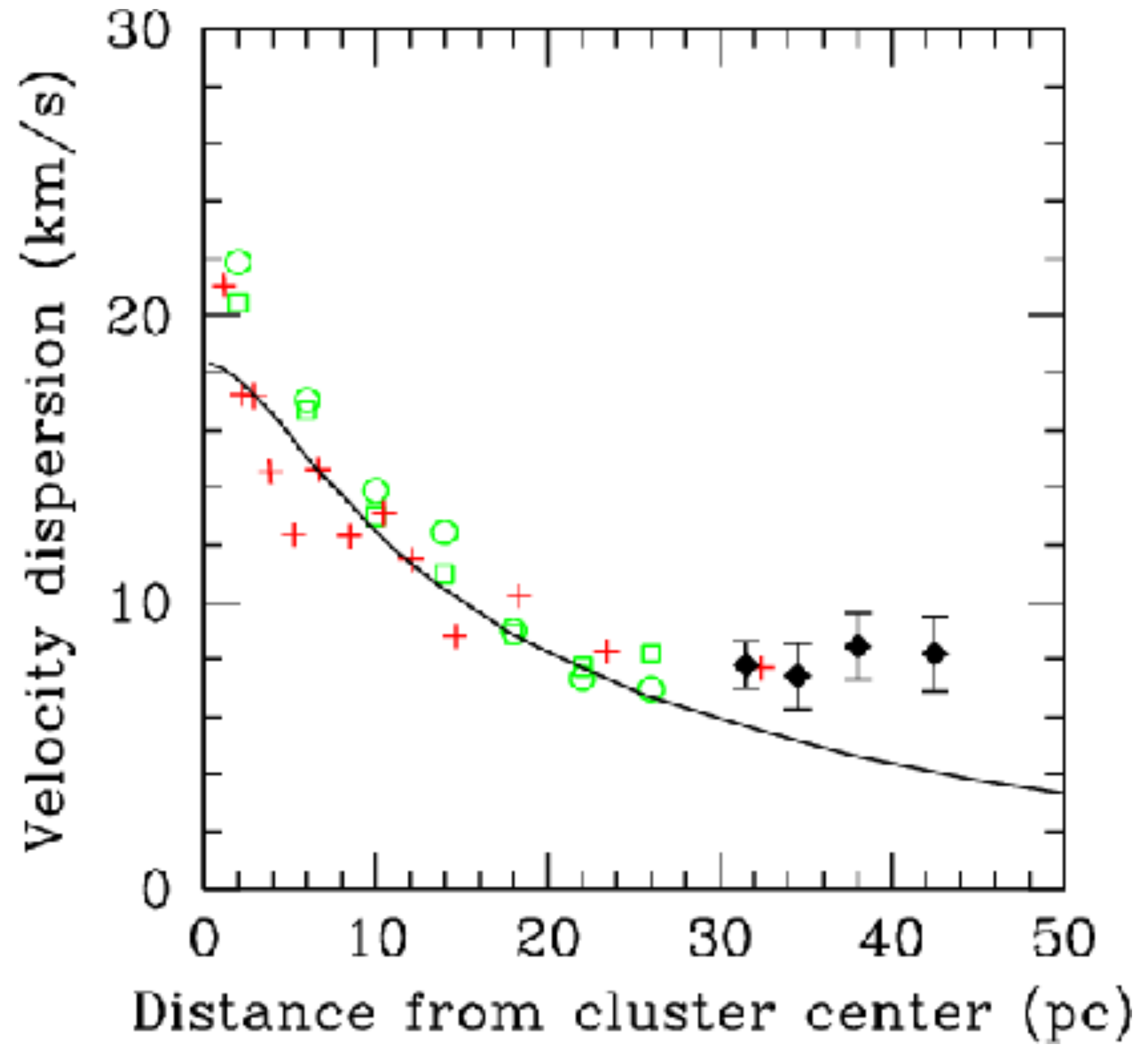
Smoking gun for Gravity beyond Einstein

Lensing Mass vs. Kinematic Mass

Lensing Mass same as in GR



Kinematic Mass depends on extra forces



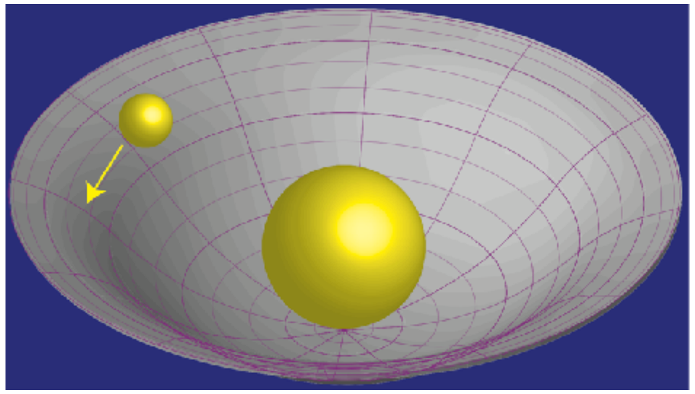
$$\Delta_M \equiv \frac{M_D}{M_L} - 1$$

Structure formation in GR

$$ds^2 = a^2(1+2\boxed{\Phi})d\eta^2 - (1-2\boxed{\Psi})d\vec{x}^2$$

Newtonian potential

Space curvature



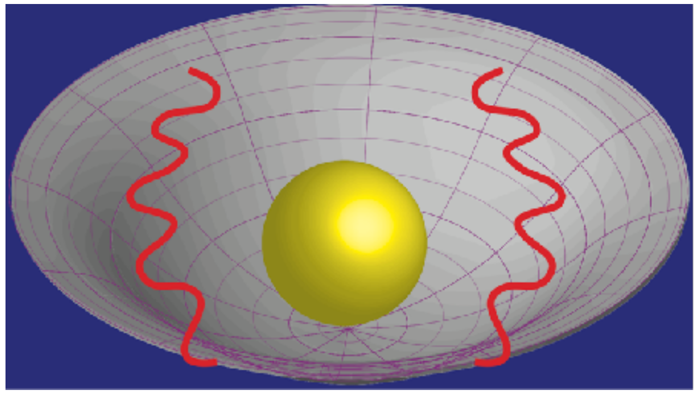
$$\Phi_N = \Phi$$

Responsible for "Newtonian force"
(dynamics of non-relativistic particles)

$$\nabla^2\Phi_+ = 4\pi G a^2 \delta\rho$$

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

Responsible for Lensing
(photons null geodesic)



Structure formation in f(R)

$$\delta R = -8\pi G\delta\rho - \frac{3\nabla^2\delta f_R}{a^2}$$

$$\nabla^2\Phi = \boxed{4\pi G a^2\delta\rho} + \boxed{\left(\frac{4\pi G a^2\delta\rho}{3} + \frac{a^2}{6}\delta R\right)}$$

$$= 4\pi G a^2\delta\rho_{\mathrm{eff}}$$

$$\nabla^2\Phi = \nabla^2\Phi_N - \frac{1}{2}\nabla^2 f_R$$

Responsible for particle dynamics

$$\nabla^2\Phi_+ = 4\pi G a^2\delta\rho$$

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

Responsible for Lensing
Same as in GR!

Structure formation in Symmetron

$$S=\int \mathrm{d}^4x\sqrt{-g}\left(\frac{M_{\mathrm{Pl}}^2}{2}R-\frac{1}{2}(\partial\phi)^2-V(\phi)\right)+S_{\mathrm{matter}}\left[A^2(\phi)g_{\mu\nu},\psi\right]$$

$$ds^2=a^2(\eta)\left[-d\eta^2(1+2\Phi)+(1-2\Psi)d\vec{x}^2\right]$$

Cassini: $\gamma-1=\frac{\Psi}{\Phi}-1\simeq-\frac{2\delta A(\phi)}{\Phi_N+\delta A(\phi)}\leq 10^{-5}$

$$\Phi\simeq\Phi_N+\delta A(\phi),$$

Responsible for particle dynamics

$$\Psi\simeq\Phi_N-\delta A(\phi),$$

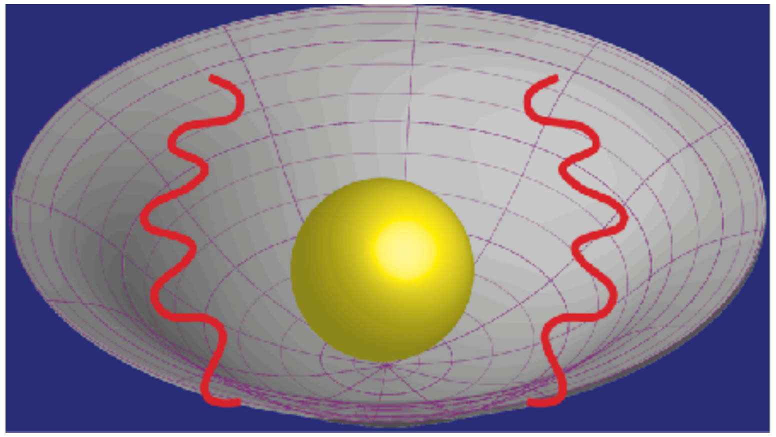
$$\Phi_+=\frac{\Phi+\Psi}{2}=\Phi_N$$

Responsible for Lensing
Same as in GR!

Lensing Mass - gravitational mass

"Real" mass of halo (dark matter and baryons)

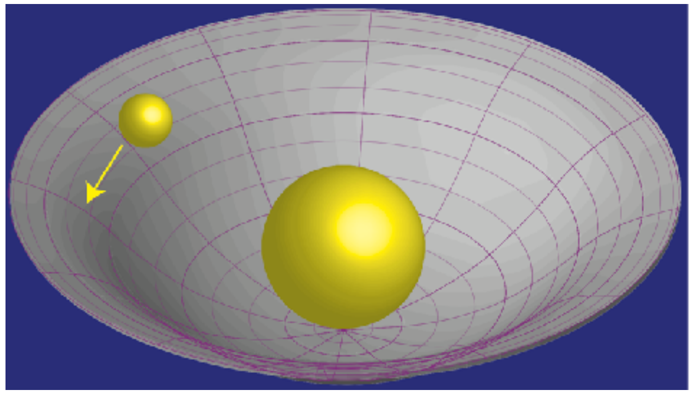
$$M_L \equiv \int a^2 \delta\rho dV$$



Dynamical Mass - inertial mass

mass contained within a radius r as inferred from the gravitational potential Φ

$$M_D \equiv \int a^2 \delta\rho_{\rm eff} dV$$



Mass Difference

Dependent of the environment

$$\boxed{\Delta_M \equiv M_D/M_L - 1 \;= \frac{d\Phi(r)/dr}{d\Phi_+(r)/dr} - 1}$$

$$\delta R = -8\pi G\delta\rho - \frac{3\nabla^2\delta f_R}{a^2}$$

$$\delta\rho_{\rm eff} = \frac{4}{3}\delta\rho + \frac{1}{24\pi G}\delta R$$

$$\cancel{\delta R = \ldots \frac{3\nabla^2 \delta f_R}{a^2}}$$

$$\delta\rho_{\rm eff} = \frac{4}{3}\delta\rho + \cancel{\frac{1}{24\pi G}}\delta R$$

In underdense environment

$$\cancel{\delta R = \ldots \frac{3\nabla^2 \delta f_R}{a^2}}$$

$$\delta\rho_{\rm eff} = \frac{4}{3}\delta\rho + \cancel{\frac{1}{2\ldots}}\delta R$$

In underdense environment

$$\Delta_M = 1/3$$

$$\delta R = -8\pi G \delta\rho - \frac{3\nabla^2 \delta f_R}{a^2}$$

$$\delta\rho_{\mathrm{eff}} = \frac{4}{3}\delta\rho + \frac{1}{24\pi G}\delta R$$

$$\delta R = -8\pi G \delta\rho - \cancel{\frac{3\nabla^2 \delta f_R}{a^2}}$$

$$\delta\rho_{\rm eff} = \frac{4}{3}\delta\rho + \frac{1}{24\pi G}\delta R = \delta\rho$$

In dense environment

$$\delta R = -8\pi G\delta\rho - \cancel{\frac{3\nabla^2\delta f_R}{a^2}}$$

$$\delta\rho_{\rm eff} = \frac{4}{3}\delta\rho + \frac{1}{24\pi G}\delta R = \delta\rho$$

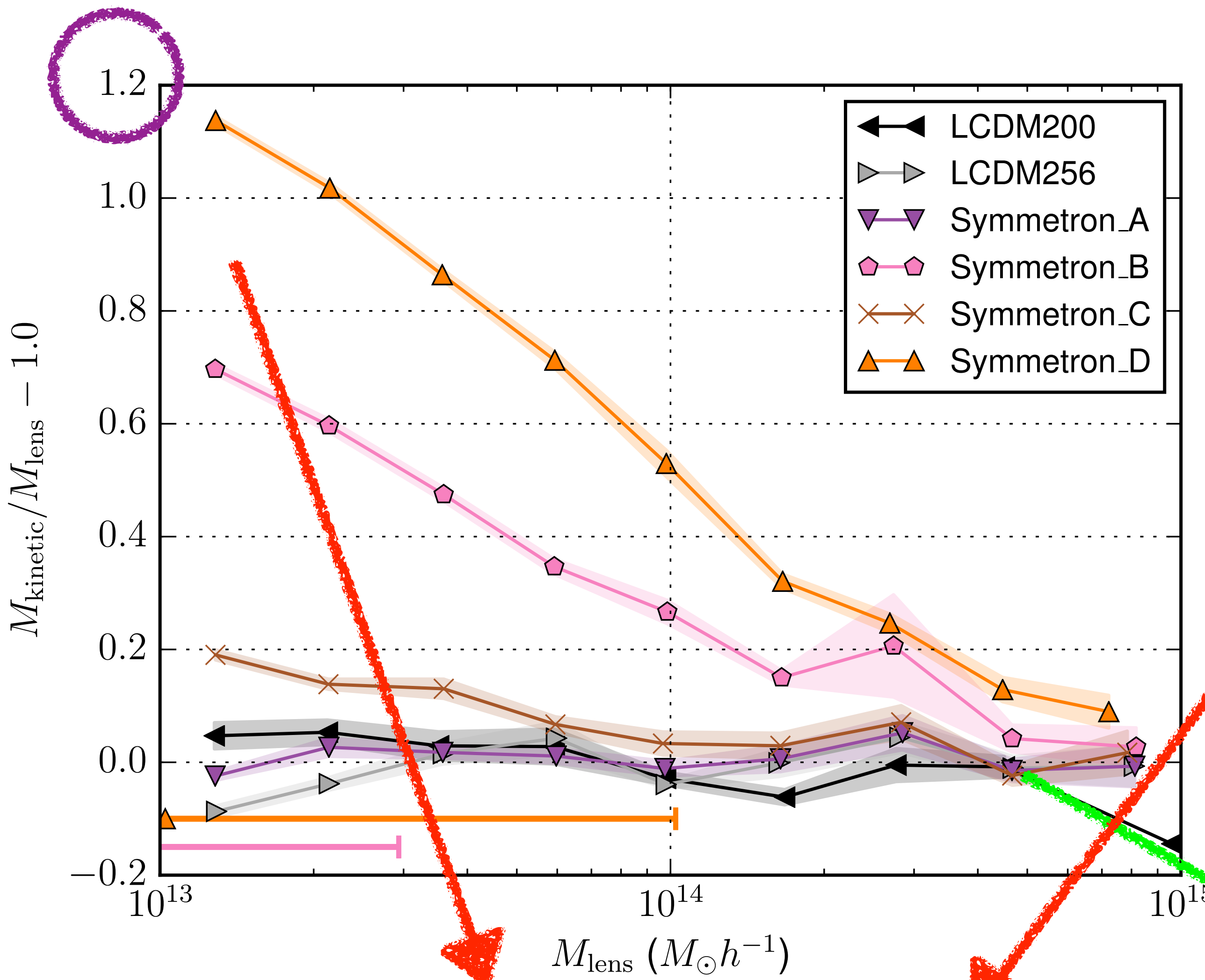
In dense environment

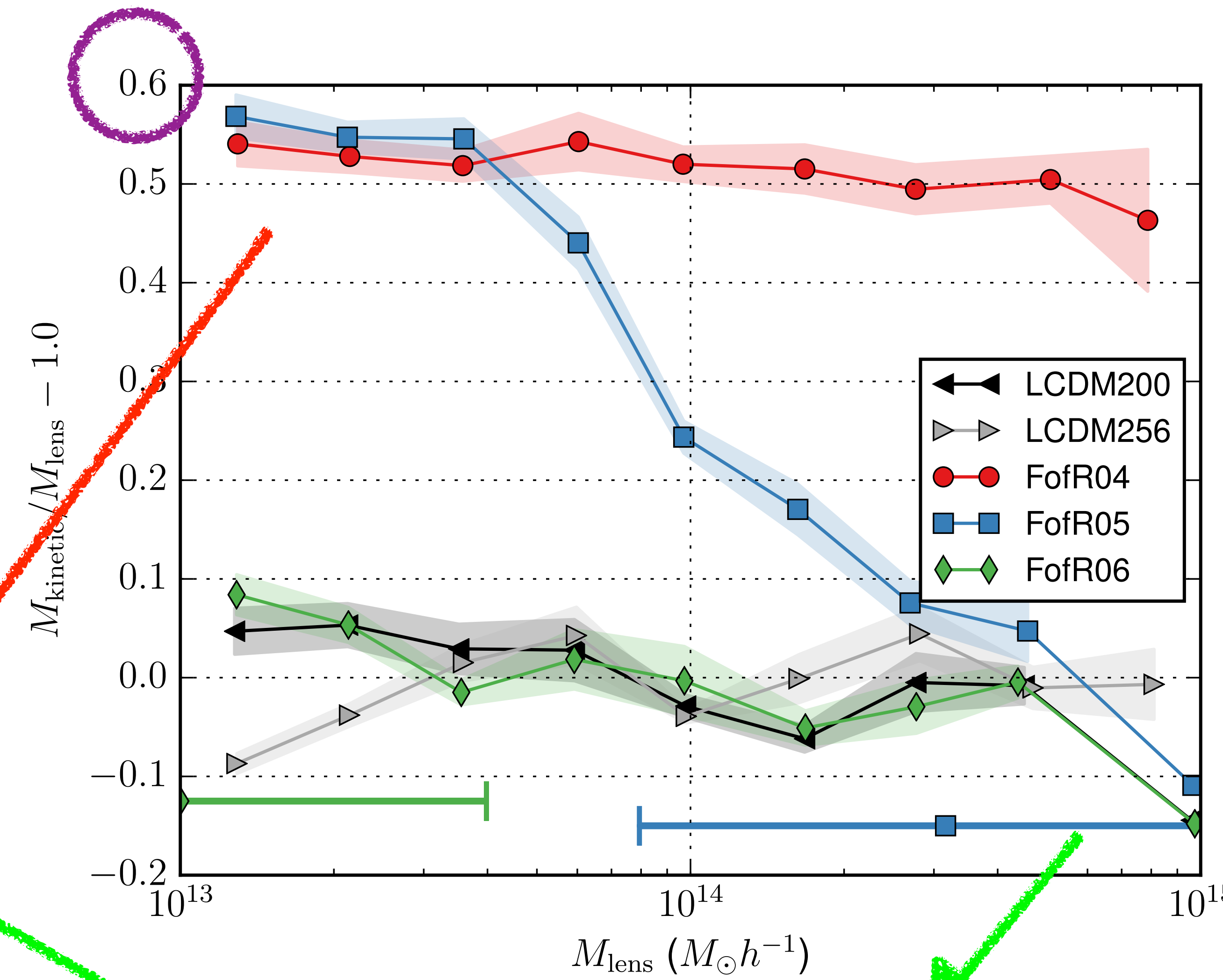
$$\Delta_M = 0$$

The halos are screened so that they cannot feel the enhancement of gravity!

Smoking gun for Screening Mechanisms

Lensing Mass vs. Kinematic Mass





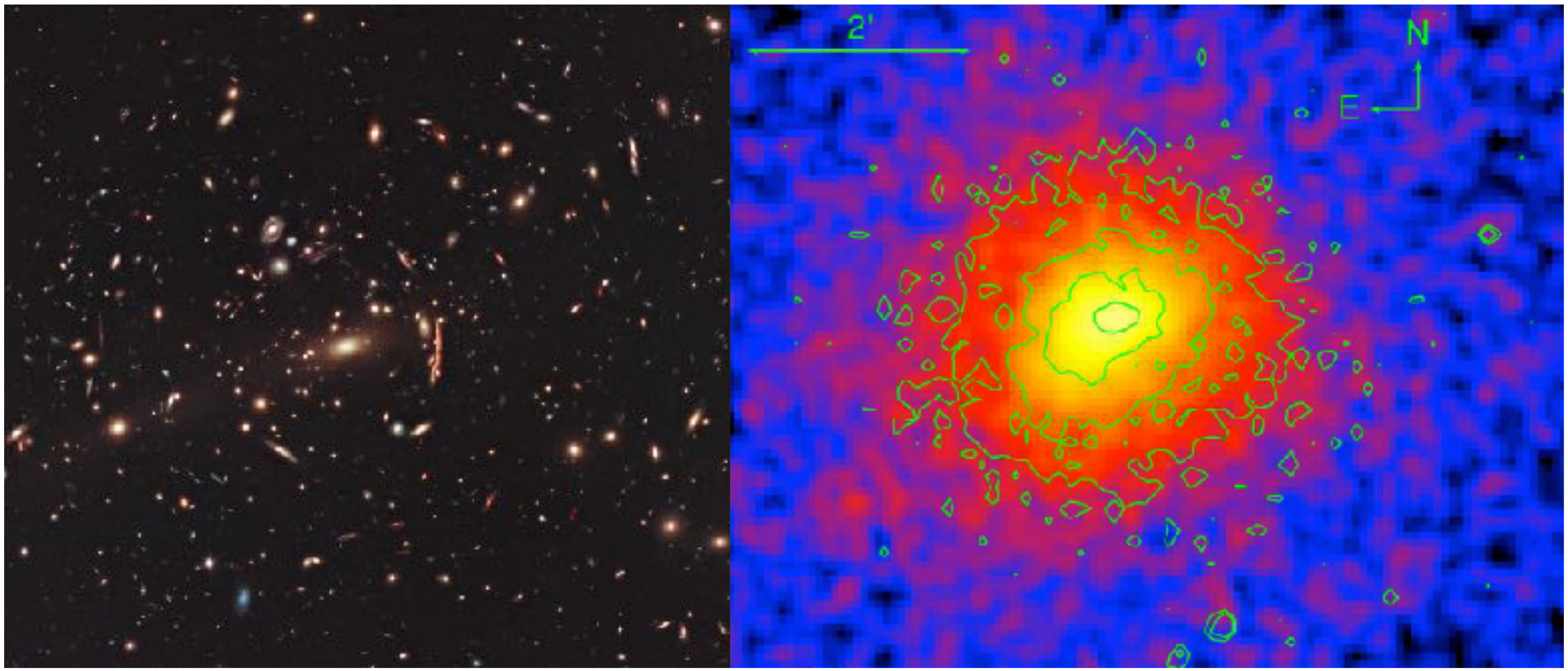
Small halos EP violation

Large halos no EP violation

Large deviations in spite of being undetected in Solar System, LSS, CMB, SNIa

Thermal Mass

from x-ray measurements of temperature and density profiles of intergalactic gas



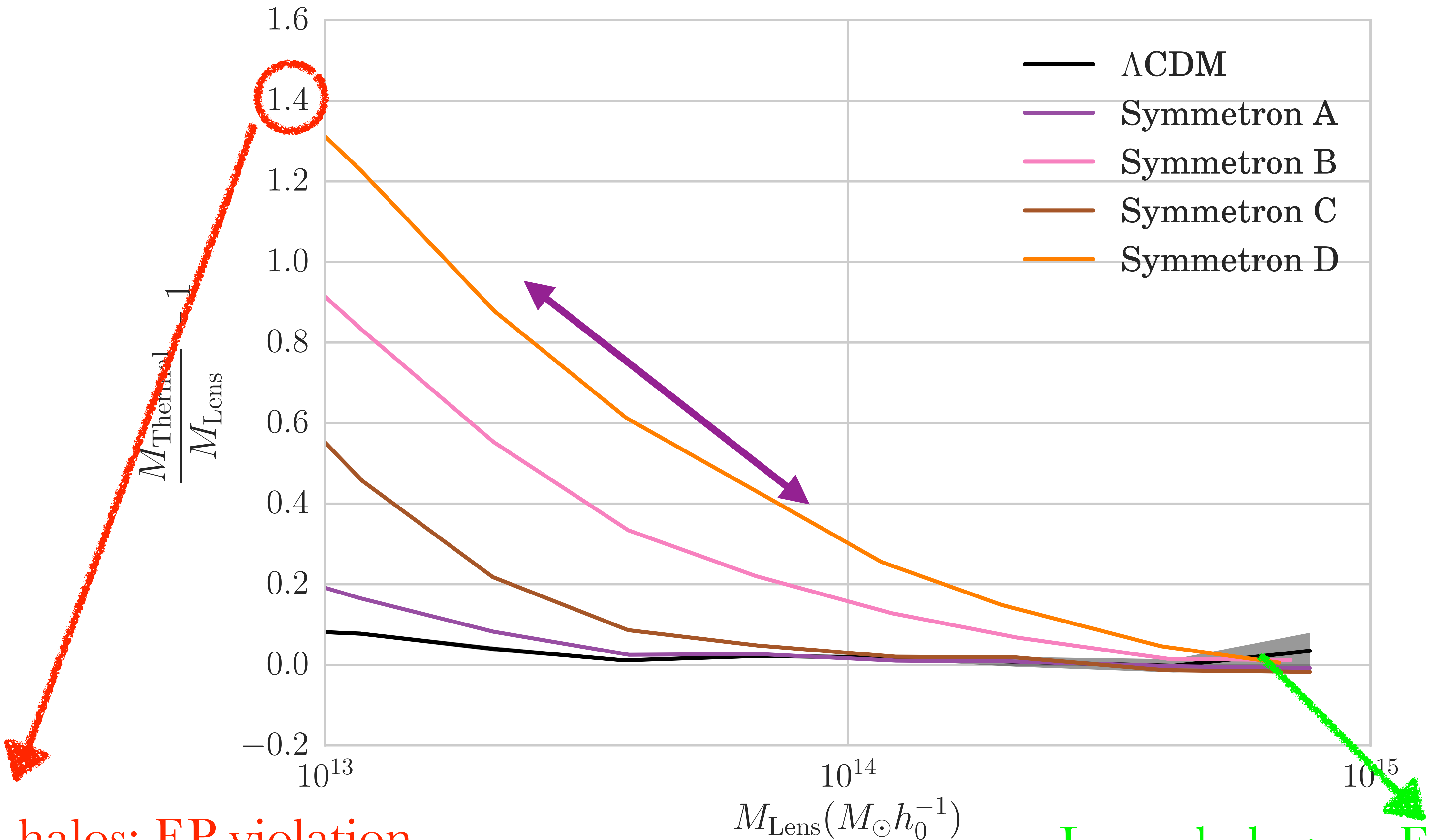
Mass holds hydrostatic equilibrium:

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2} + \boxed{F_\phi}$$

Thermal mass estimates in Modified Gravity differ from GR

Smoking gun for Modified Gravity

Lensing Mass vs. Thermal Mass



Small halos: EP violation

Large halos: no EP violation

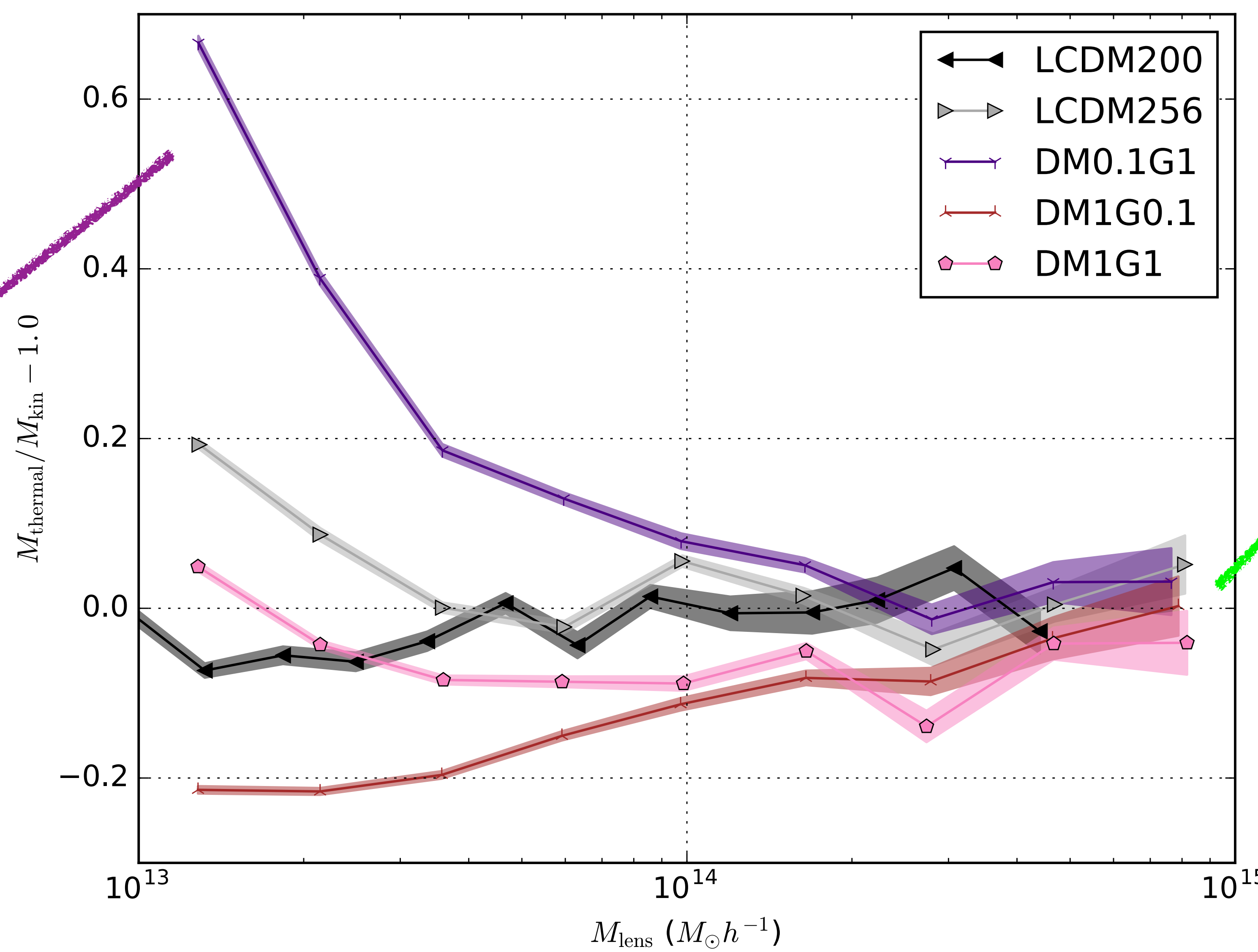
Large deviations in spite of being undetected in Solar System, LSS, CMB, SNIa, Black holes

Dark matter and baryons couple with same strength?

Kinematic Mass (inferred from halo velocities) traces coupling to dark matter

Thermal Mass (inferred from intergalactic gas) traces coupling to baryons

Large deviations small clusters



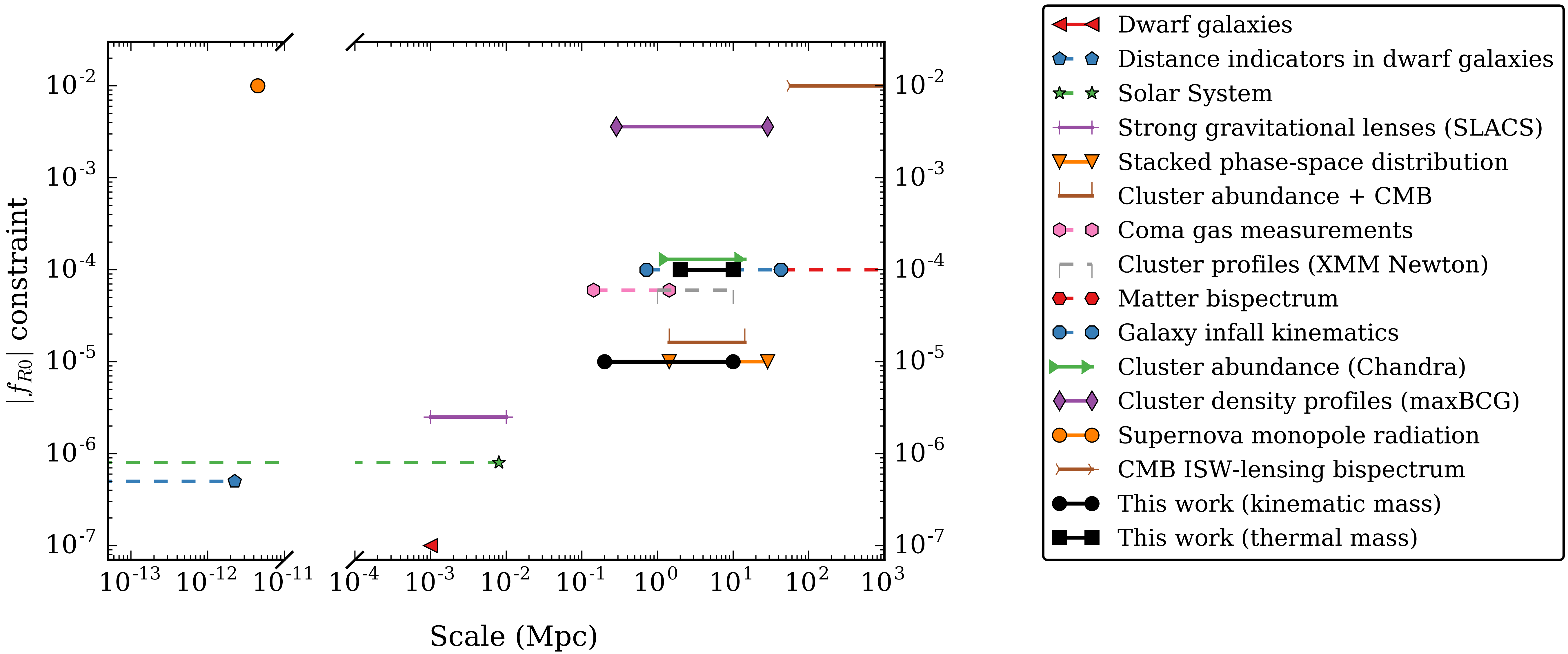
no deviations for large clusters

Differences between Kinematic and Thermal mass indicate non-universal couplings!

Hammami, DFM A&A

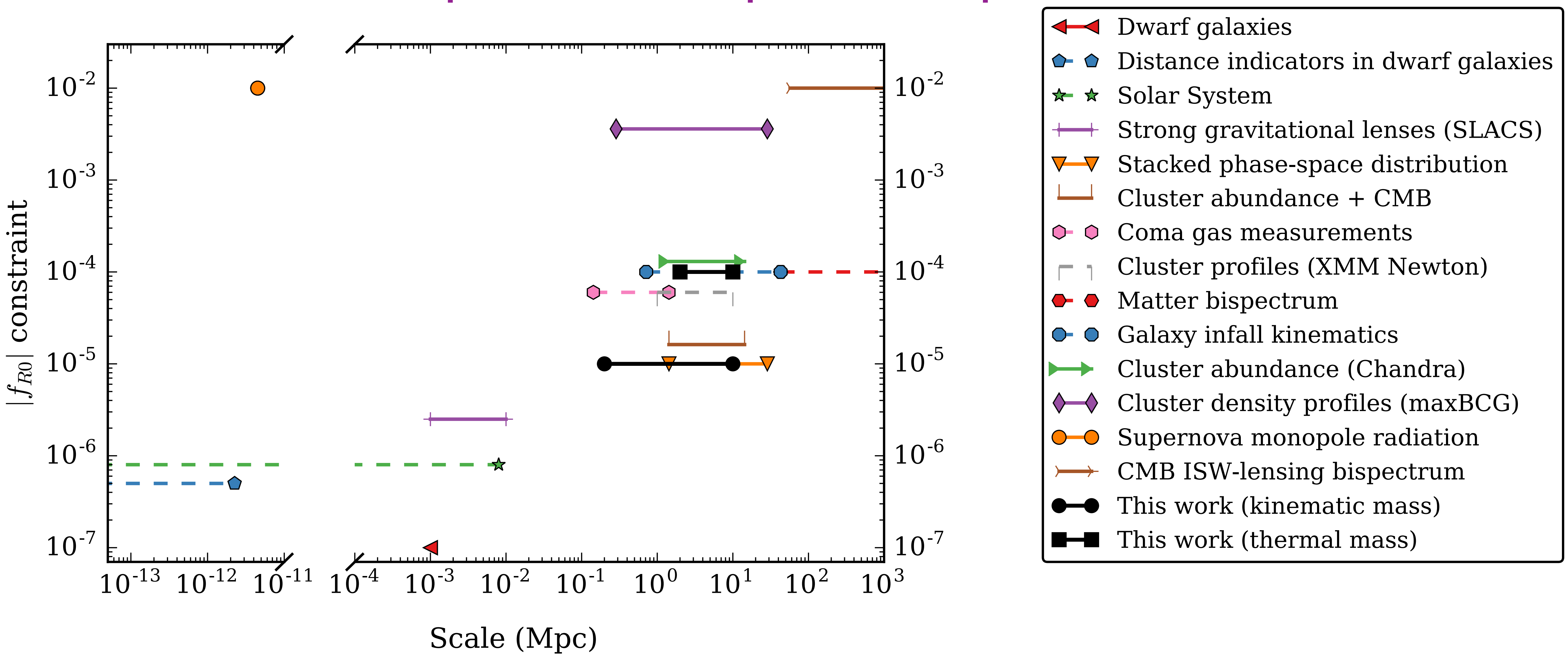
Observational Constraints

Gronke, DFM, Winther A&A



Observational Constraints

These constraints are however model- and parameter-specific dependent

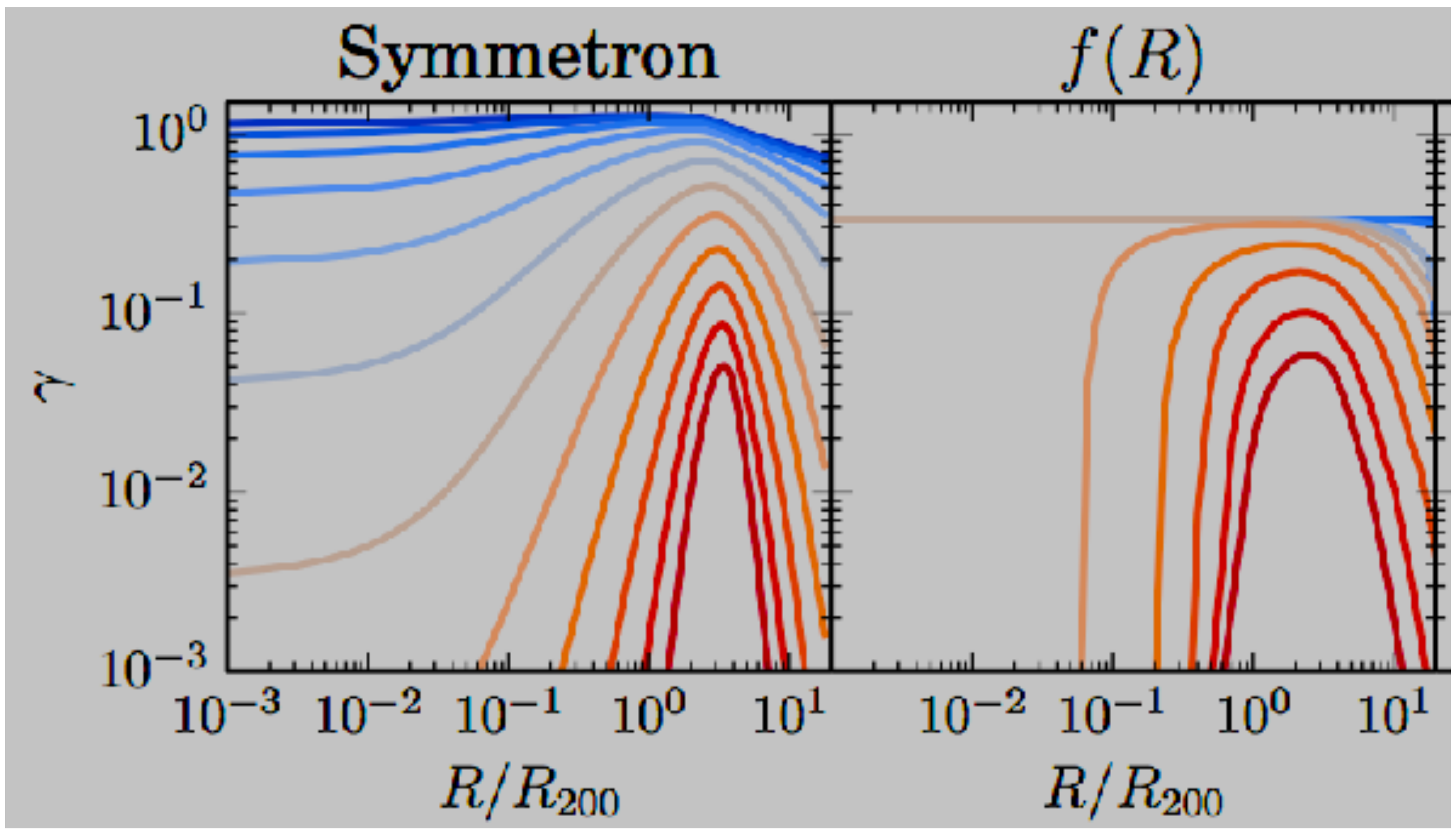


Is there a way to put constraints on screening mechanisms in general?

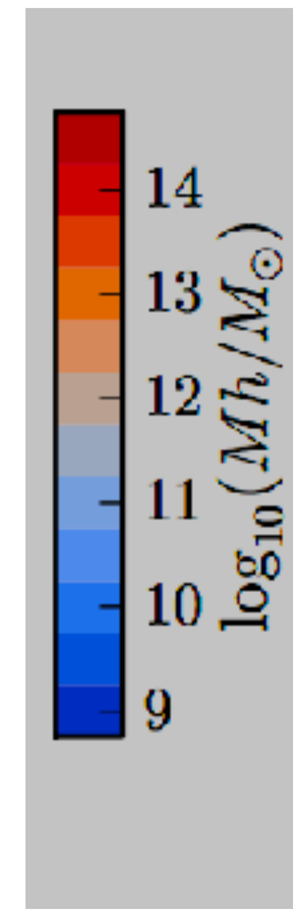
Gronke, DFM, Winther (2015)

What do screened modified gravity theories have in common?

enhancement of gravity



$$\gamma = \frac{G_{eff}}{G} - 1$$

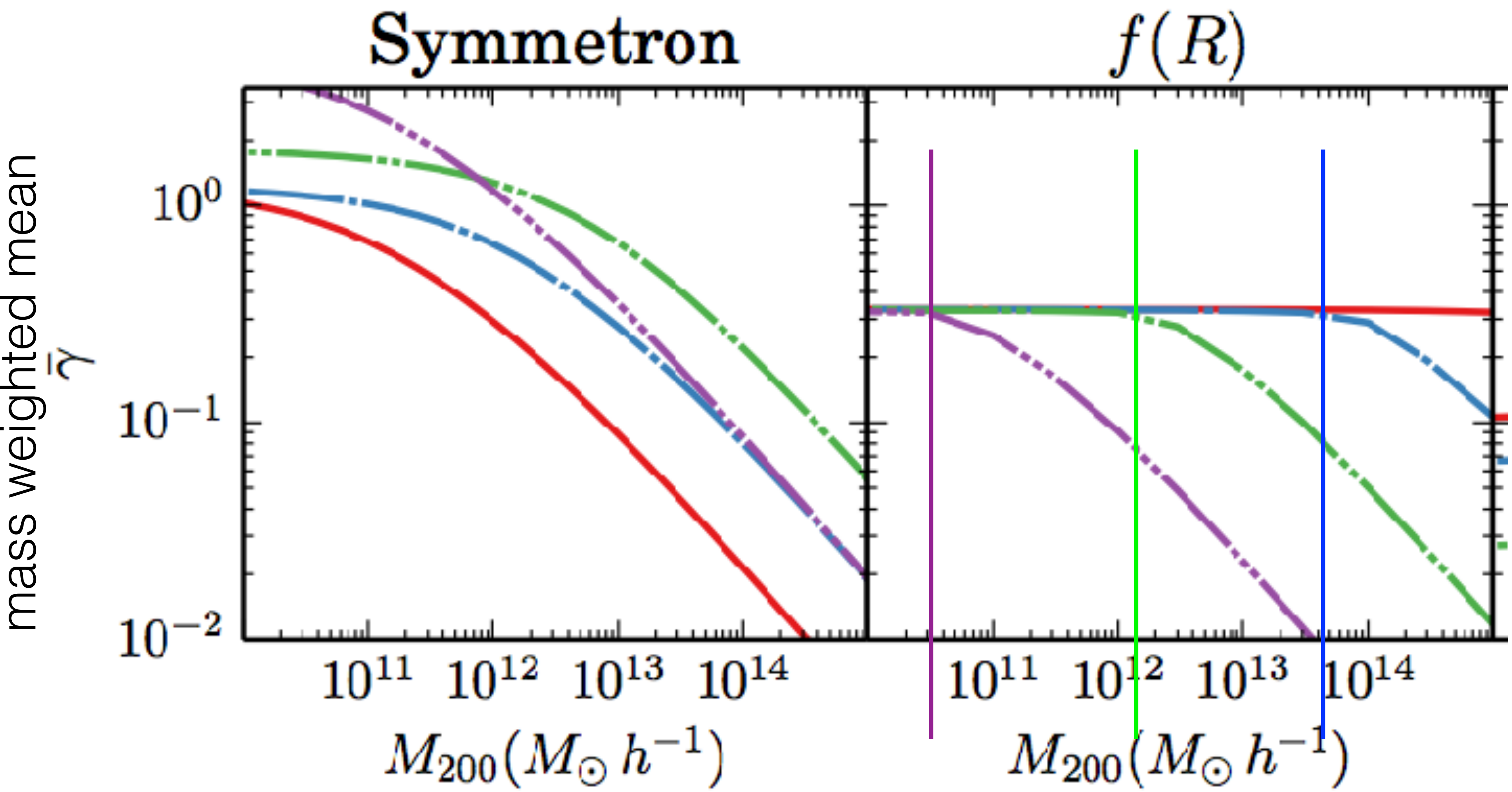


Screening

Symmetron	Chameleon
$V(\varphi)$	$V''(\varphi)$
coupling	*range*

Gronke, DFM, Winther (2015)

What do screened modified gravity theories have in common?



Screening

Symmetron	Chameleon
$V(\varphi)$	$V''(\varphi)$
coupling	*range*

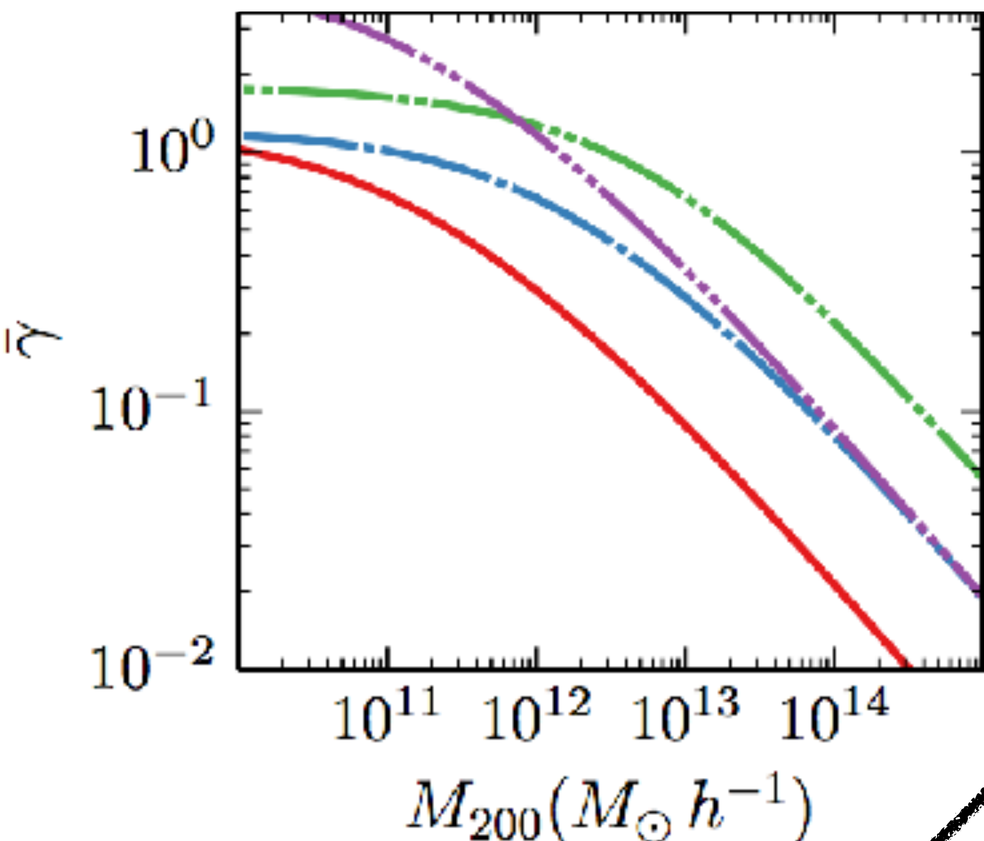
What do screened modified gravity theories have in common?

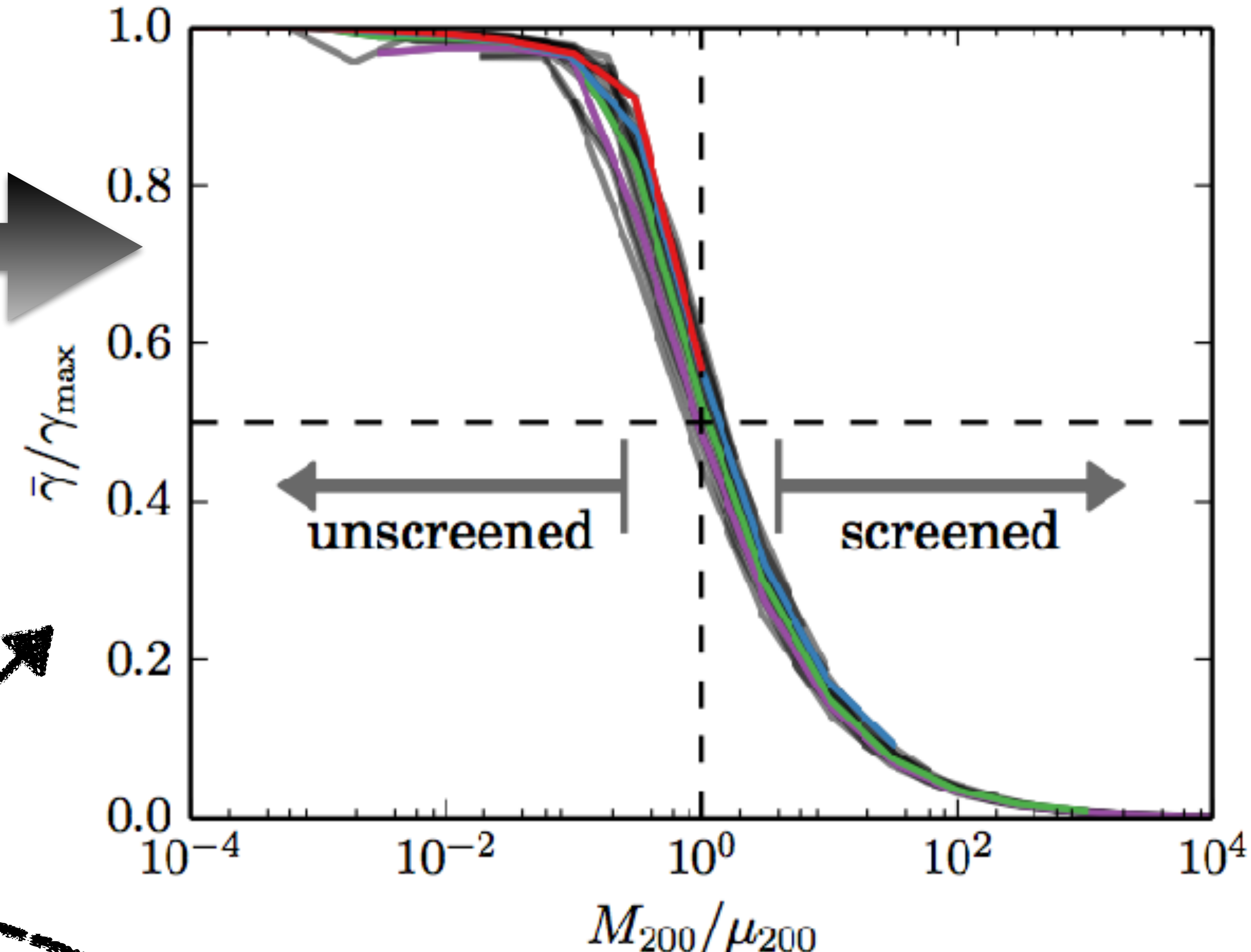
They…

…modify gravity. → maximum enhancement of gravity γ_{max} .

…possess a screening mechanism. → transition scale μ_{200} .

f(R) rescaling





maximum enhancement of gravity

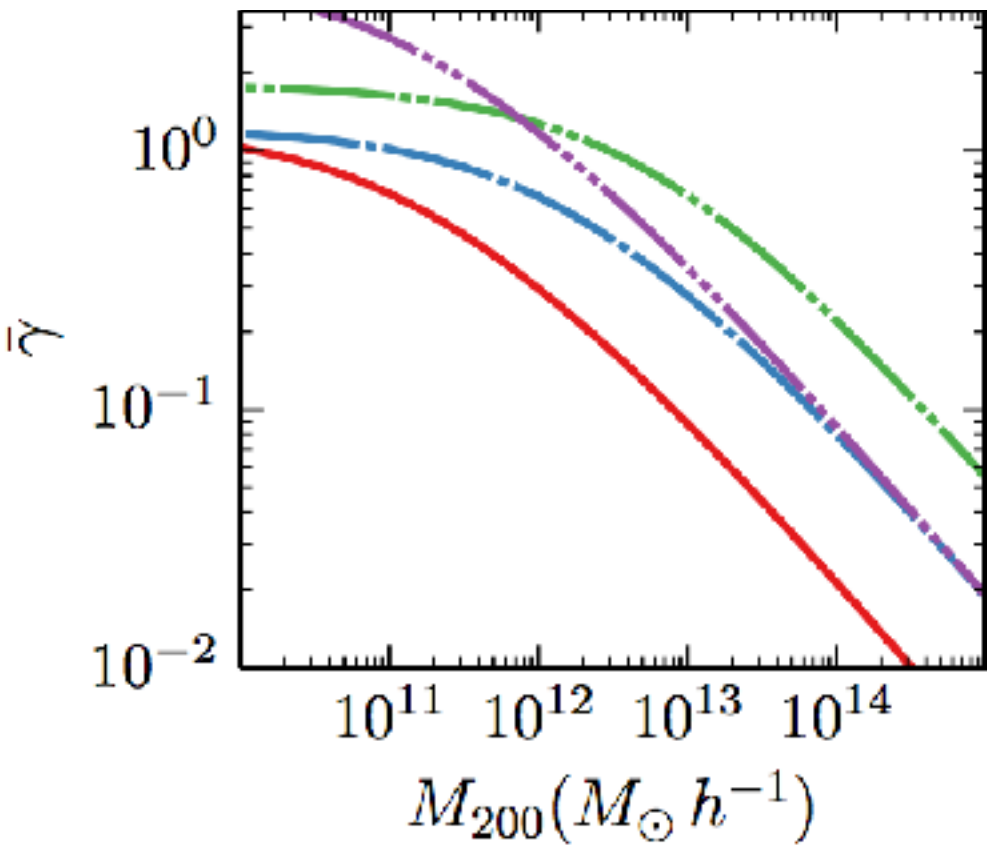
$$\gamma_{\rm max} = 2\beta^2 = \frac{1}{3}$$

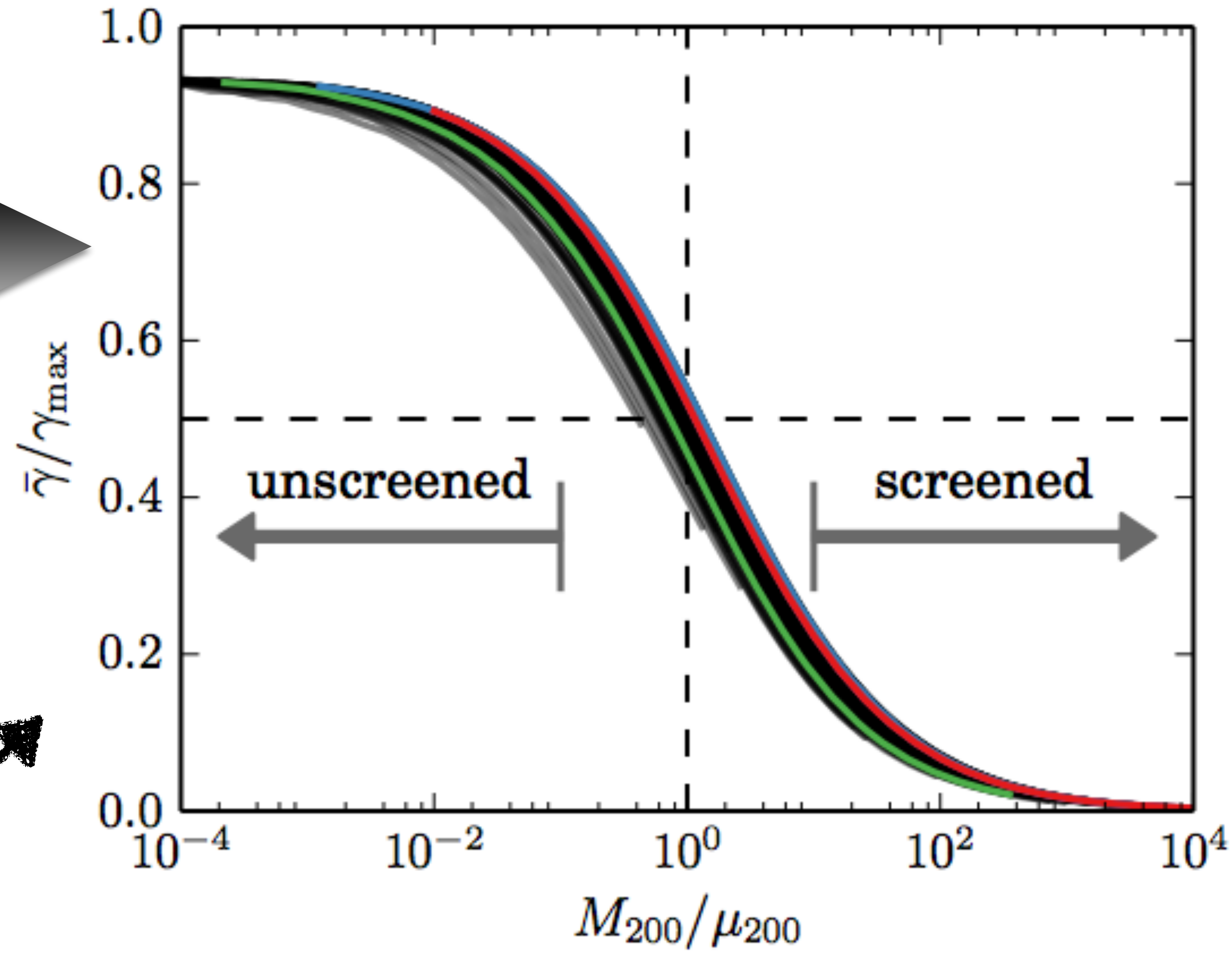
transition scale

$$\mu_{200}^{f(R)} = 10^{13} M_\odot h^{-1} \times \left(\frac{|f_{R0}|}{10^{-6}}\right)^{1.5}$$

Gronke, DFM, Winther (2015)

Symmetron rescaling





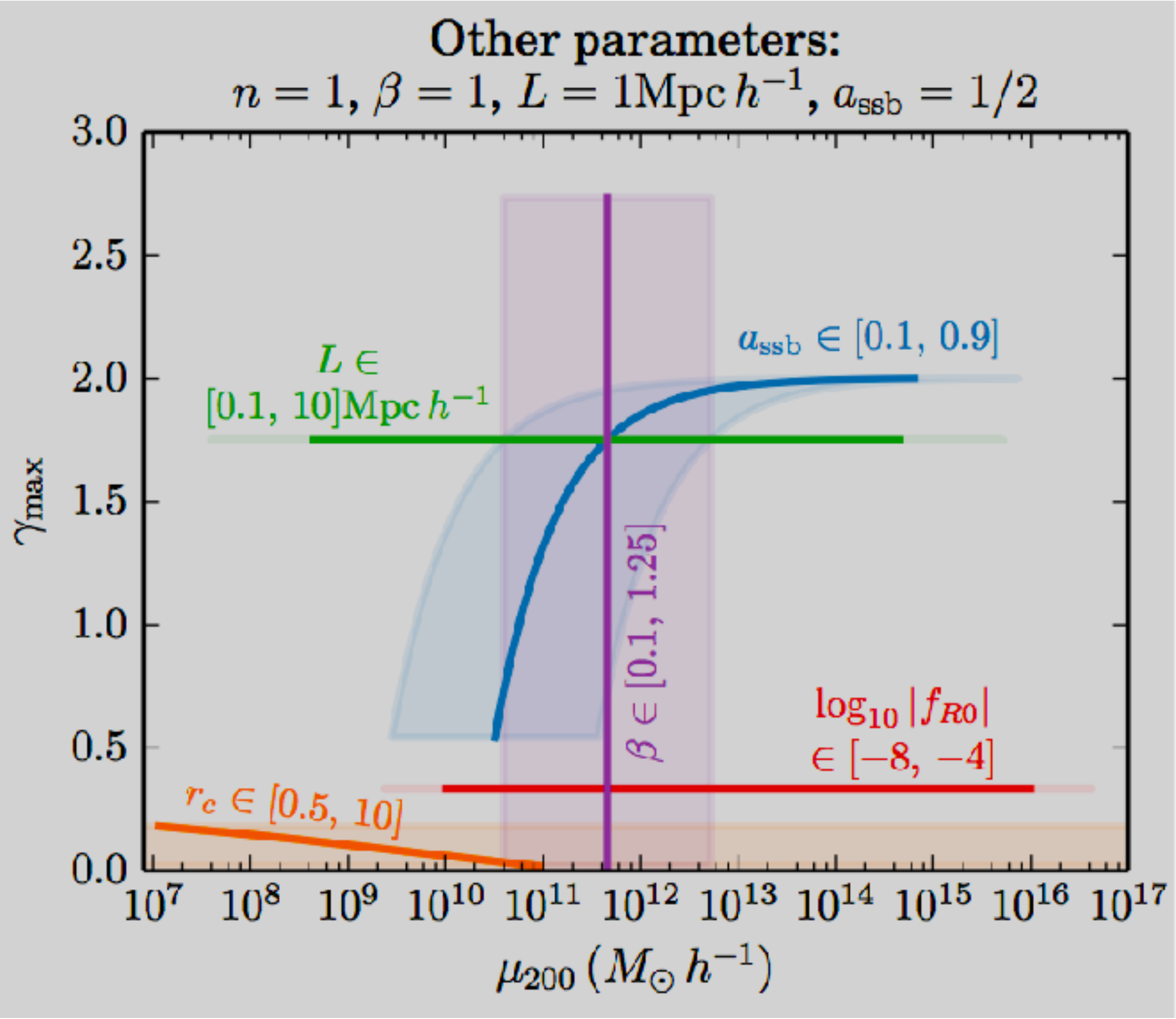
maximum
enhancement
of gravity

$$\gamma_{\max} = 2\beta^2 \left[1 - \left(\frac{a_{\rm ssb}}{a}\right)^3\right]$$

transition

$$\mu_{200}^{\rm Symmetron} = 2 \times 10^{10} M_\odot h^{-1} \times \left(\frac{L}{{\rm Mpc}\, h^{-1}}\right)^3 a_{\rm ssb}^{-4.5}$$

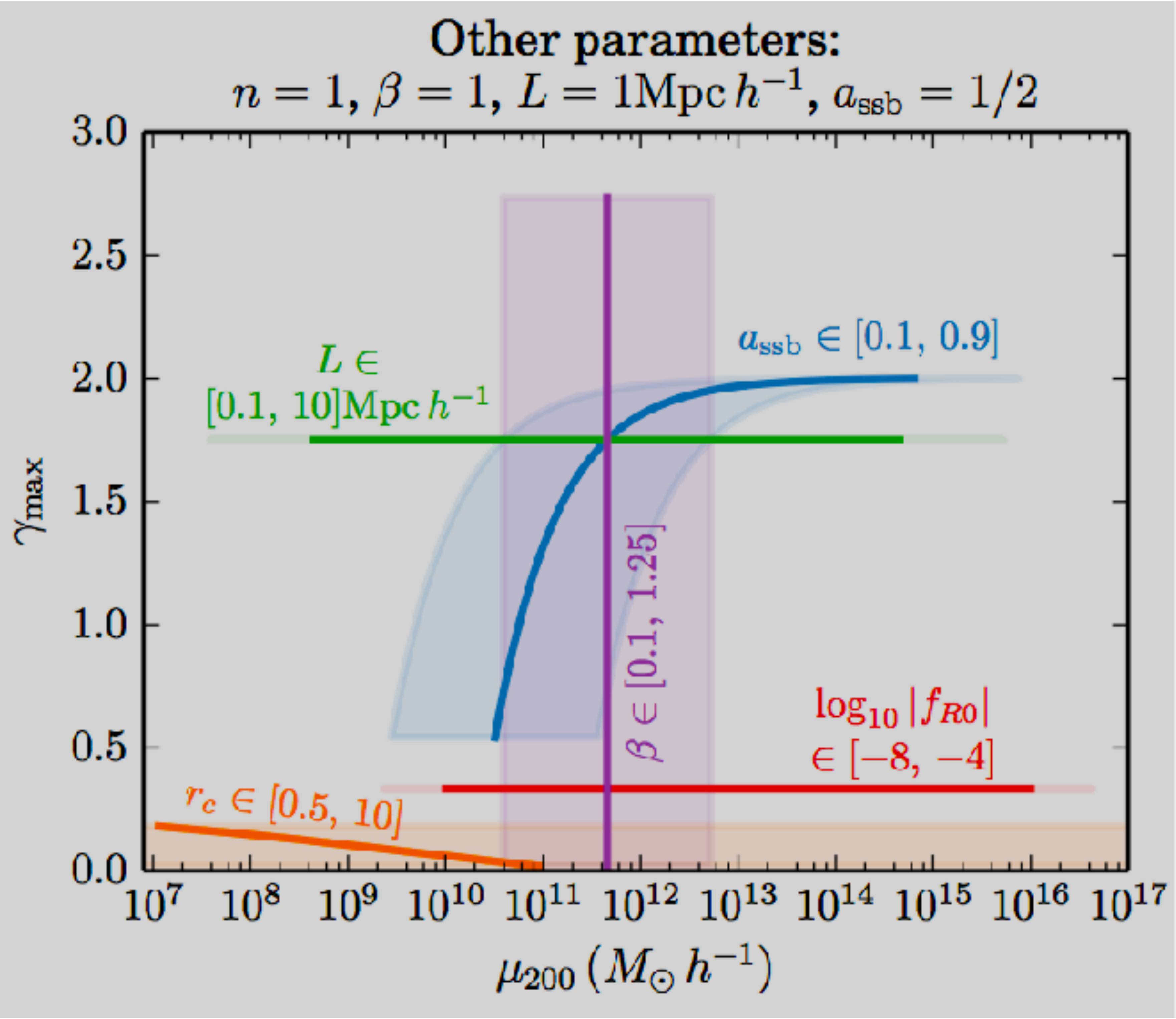
Parameterisation and specific model parameters



Universally characterisable by

- maximum enhancement of gravity $\gamma_{\max}$
- transition scale μ_{200}
- width of transition α.

Parameterisation and specific model parameters

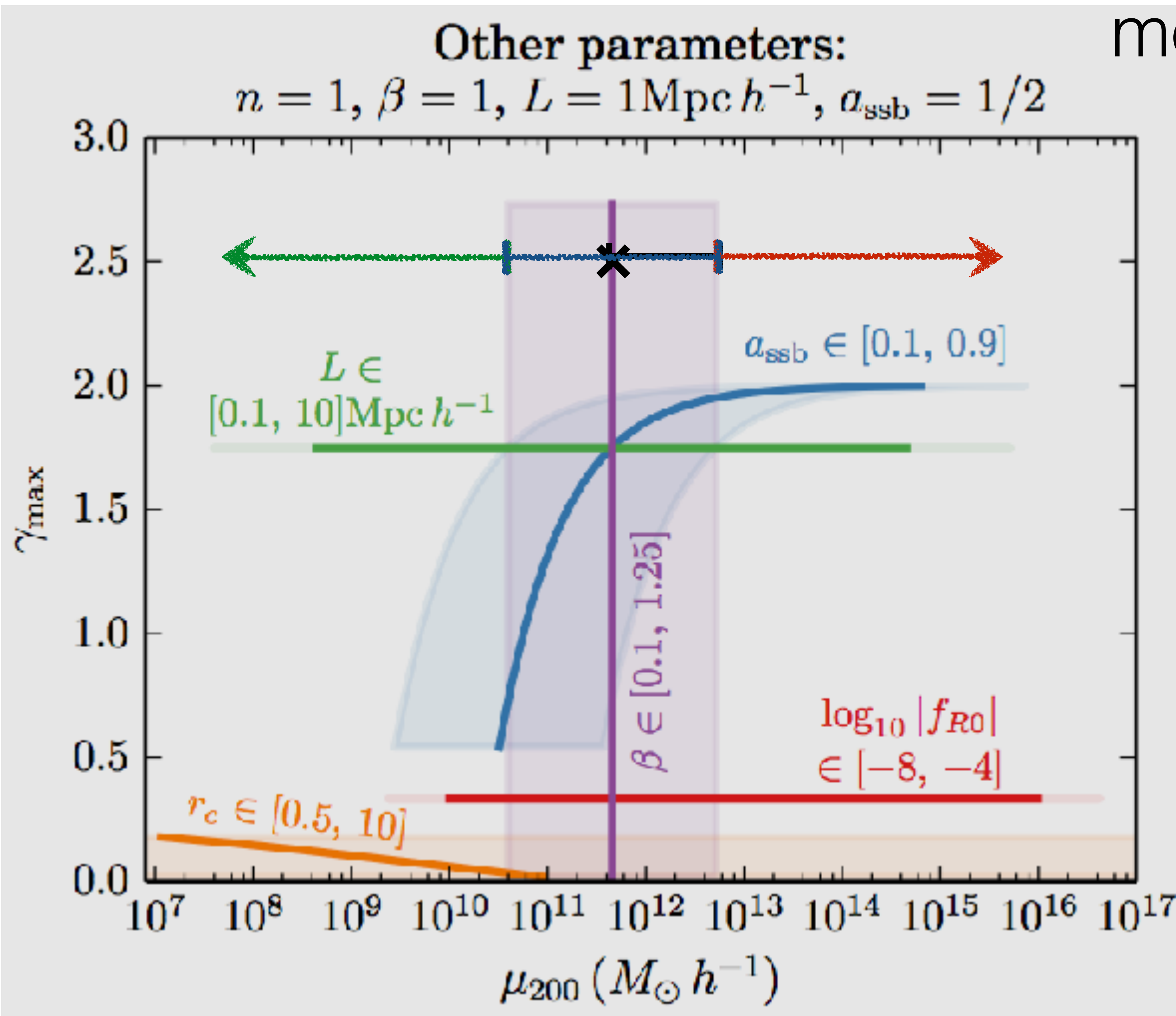


Symmetron reference

$$\beta = 1, L = 1M_{pc}h^{-1}, a_{ssb} = \frac{1}{2}$$

f(R) reference, n=1

Screened modified gravity rescaling



model parameters

↓

$\{\mu_{200},\ \bar{\gamma}_{\rm max}\}$ + width W

↓

3 regimes

- unscreened
- fully screened
- partially screened

Observational Constraints from Equivalent Principle violation