

Universal predictions of screened modified gravity in galaxy cluster

David F. Mota



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Mass of clusters

***inferred via lensing, kinematics and thermal observations
are different!***

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Scalar-Tensor Theories

with Chameleon or Symmetron screening mechanisms

$$\vec{F}_\phi = -M\alpha_\phi\vec{\nabla}\phi, \quad \alpha_\phi = \frac{d \log A(\phi)}{d\phi}$$



ϕ

$\tilde{g}_{\mu\nu}$



$$\tilde{g}_{\mu\nu} = A^2(\phi)g_{\mu\nu}$$

Chameleon $f(R)$ -gravity

Hu & Sawicki (2007)

$$f(\tilde{R}) = -m^2 \frac{c_1(\tilde{R}/m^2)^n}{1 + c_2(\tilde{R}/m^2)^n} \approx -16\pi G\rho_\Lambda - \frac{f_{R0}}{n} \frac{\tilde{R}_0^{n+1}}{\tilde{R}^n}$$

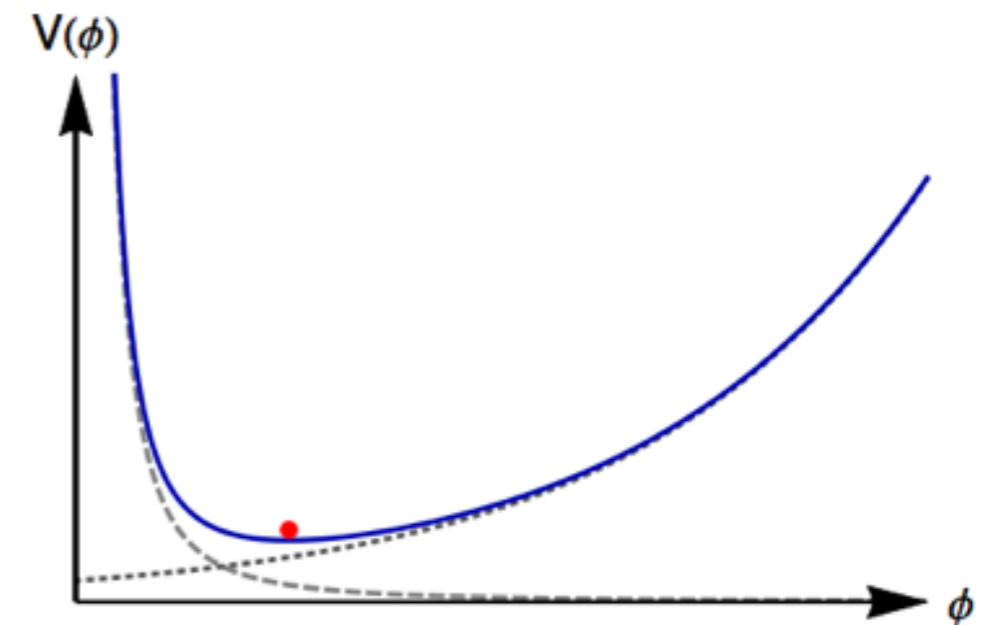
- Effective potential (Einstein frame)

$$V_{\text{eff}} = V(\phi) + \left(e^{\beta\phi/M_{\text{Pl}}} - 1\right) \rho \approx V(\phi) + \frac{\beta\phi}{M_{\text{Pl}}} \rho$$

- Free parameters

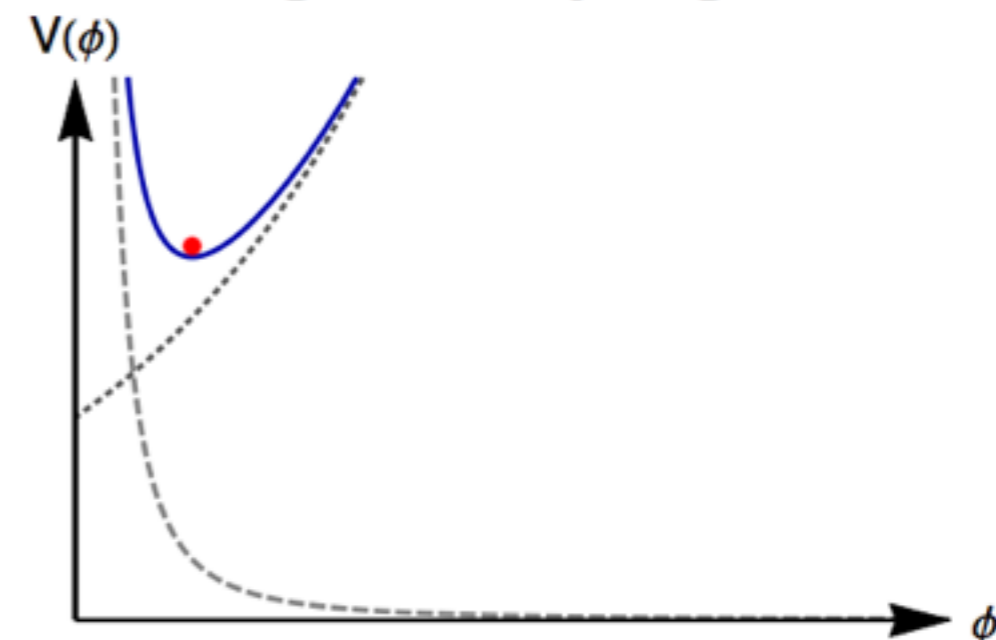
$$f_{R0}, n$$

Low density region



$V''(\phi) \ll 1 \rightarrow$ Unscreened

High density region



$V''(\phi) \gg 1 \rightarrow$ Screened

The Symmetron

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} - \frac{1}{2}(\partial\varphi)^2 - V(\varphi) \right] + S_m(\tilde{g}_{\mu\nu}, \psi)$$

- Effective potential

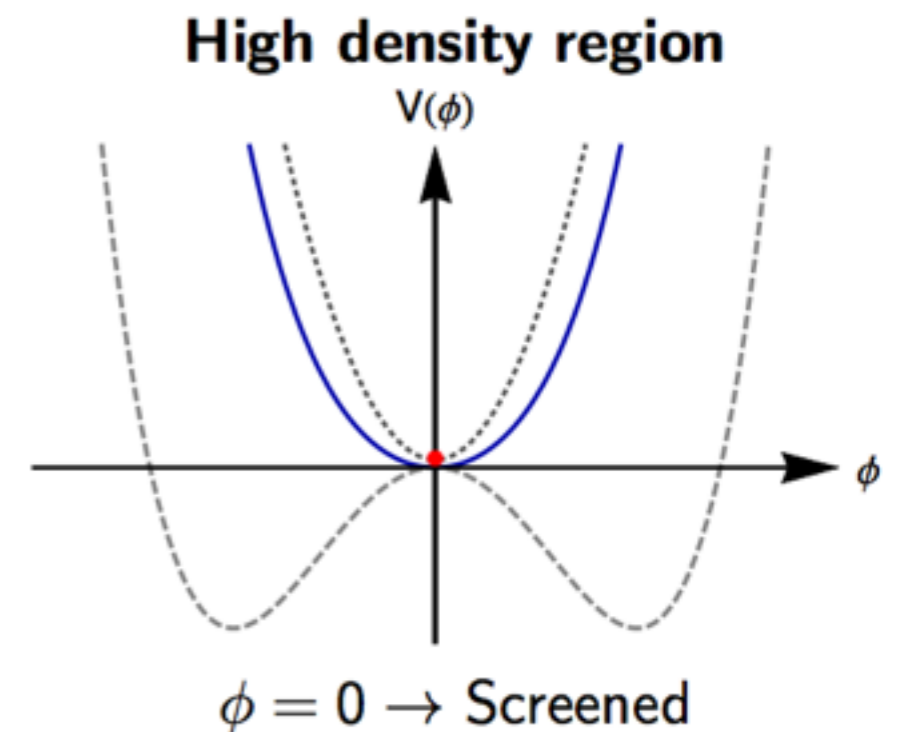
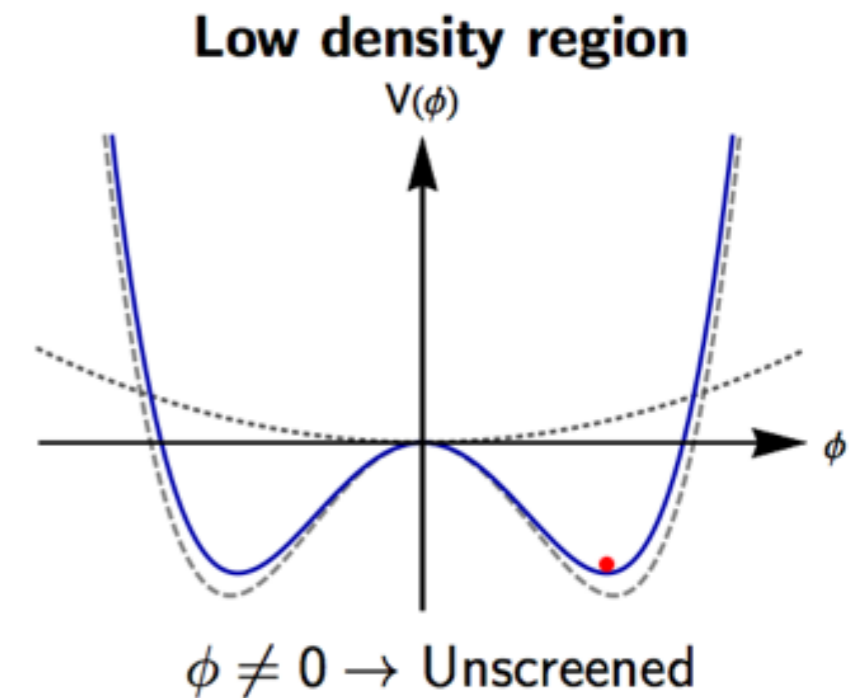
$$V_{\text{eff}} = \frac{1}{2} \left(\frac{\rho_m}{M^2} - \mu^2 \right) \varphi^2 + \frac{1}{4} \varphi^4$$

- Free parameters

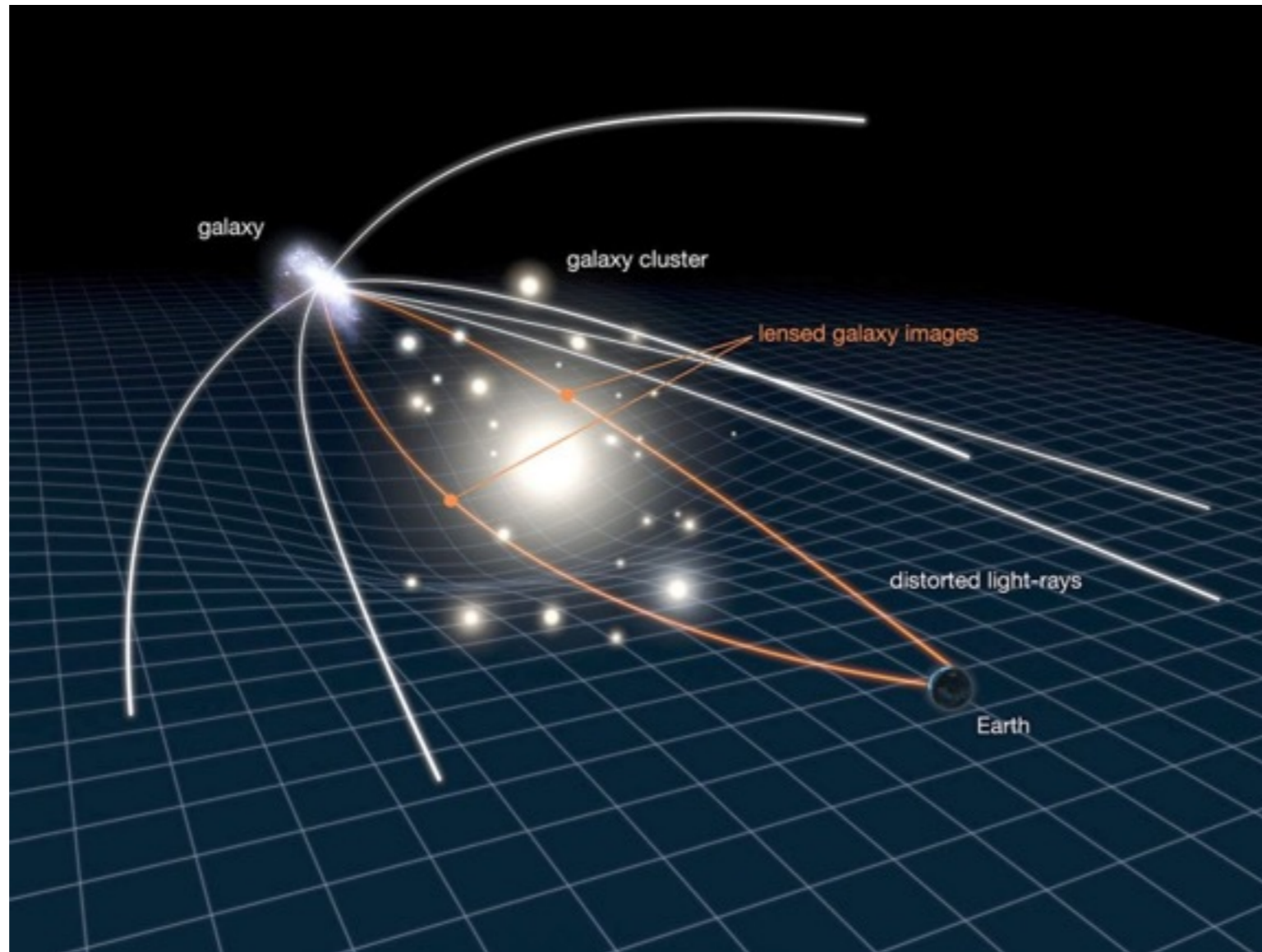
- Range $L = \frac{1}{\sqrt{2}\mu}$,

- Symmetry breaking $a_{\text{ssb}}^3 = \frac{\Omega_{m0}\rho_{c0}}{\mu^2 M^2}$,

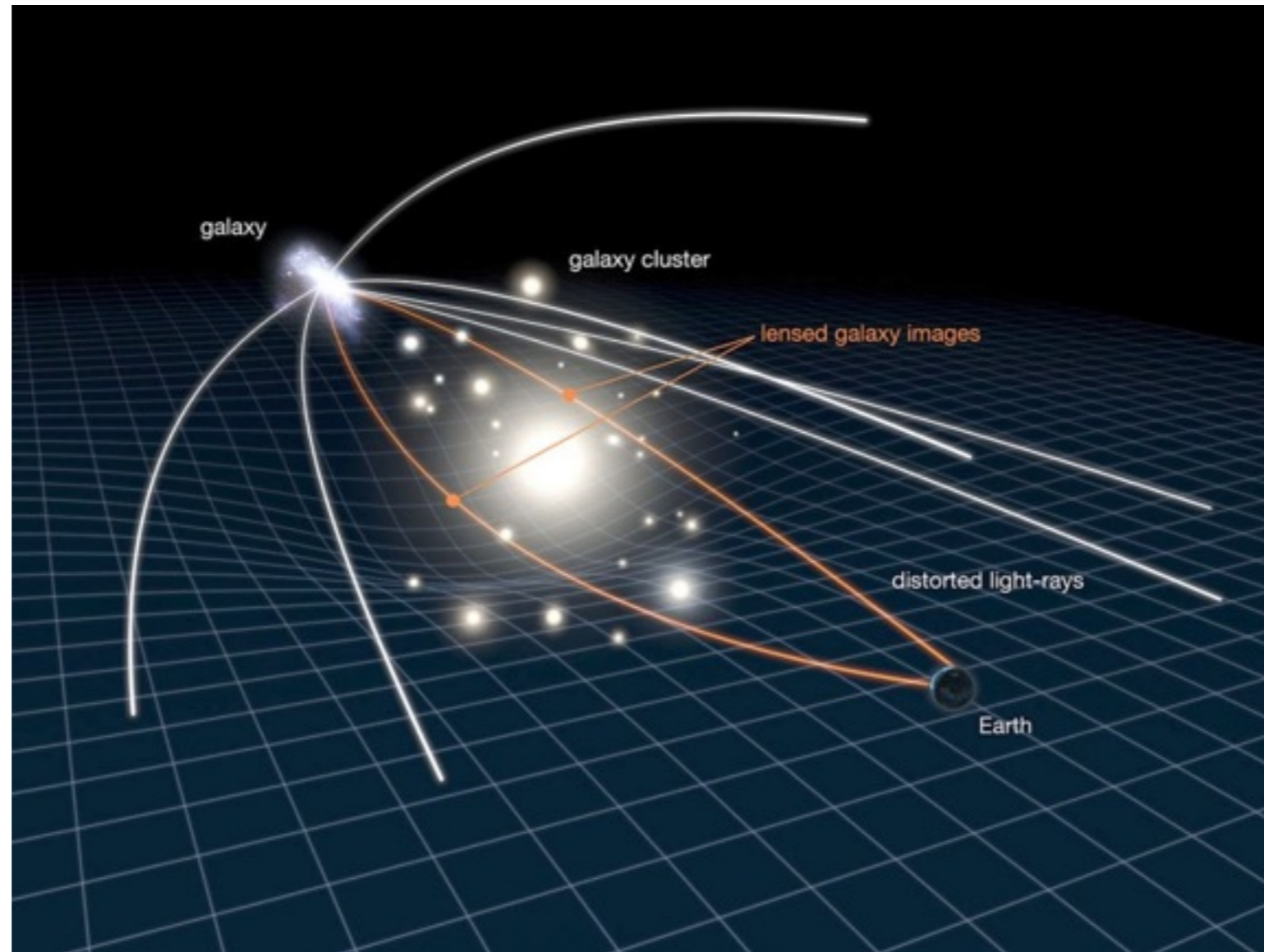
- Coupling strength $\beta = \frac{\mu M_{\text{Pl}}}{M^2 \sqrt{\lambda}}$.



Lensing Mass measured via gravitational lensing

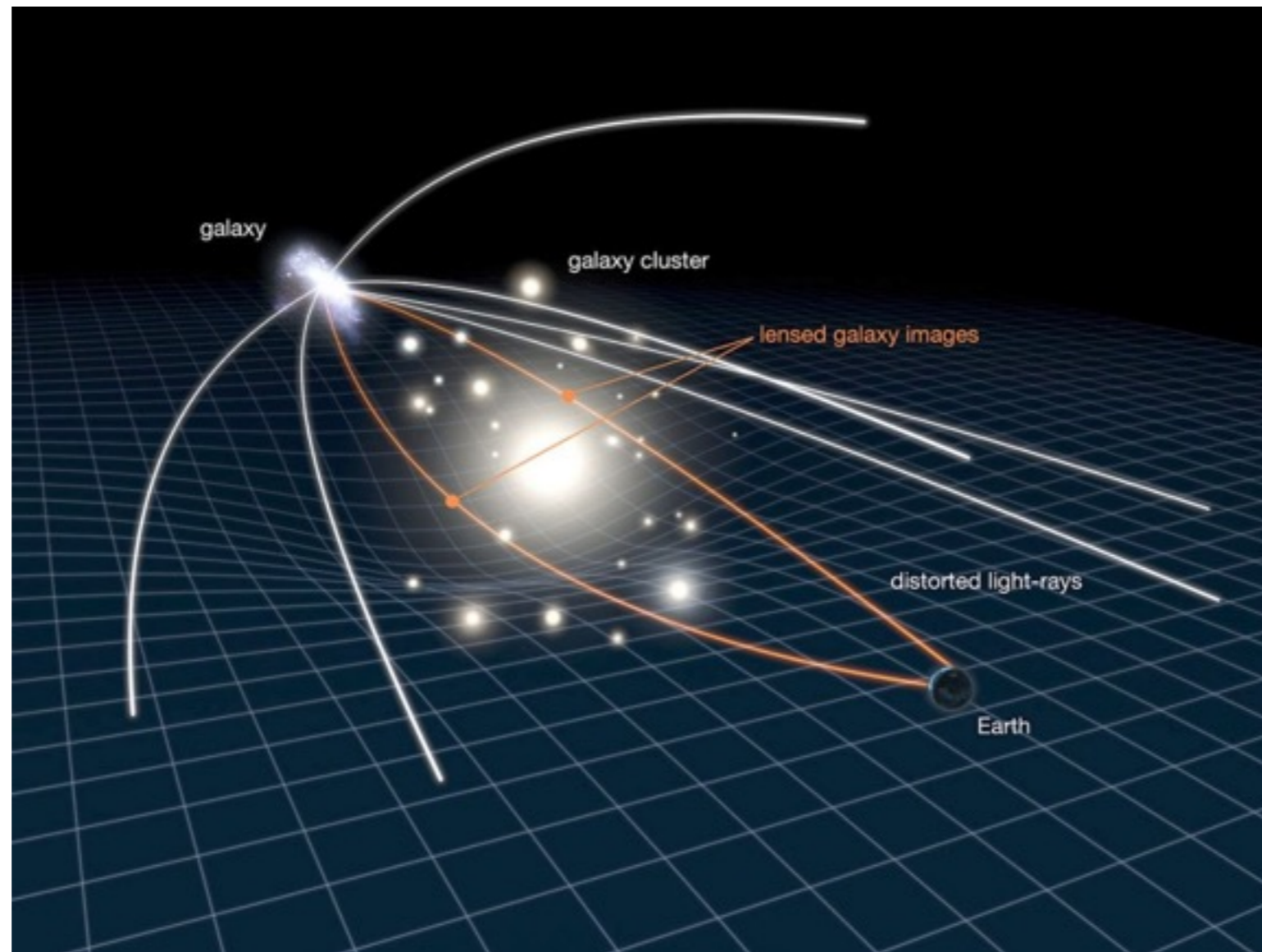


Lensing Mass measured via gravitational lensing



Conformal Invariance: photons not affected by Modified Gravity

Lensing Mass measured via gravitational lensing



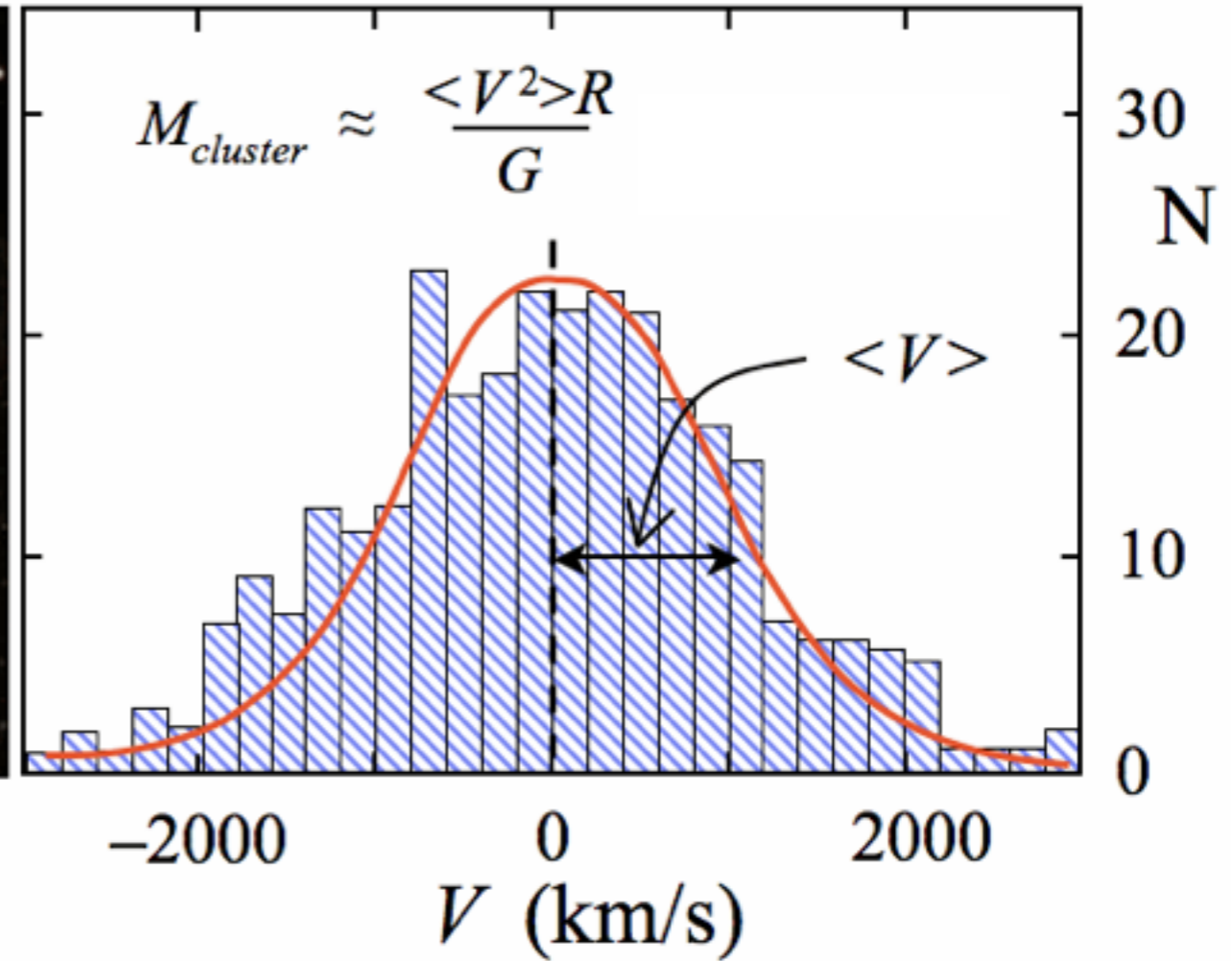
Conformal Invariance: photons not affected by Modified Gravity

Lensing Mass in (conformal) Modified Gravity same as GR

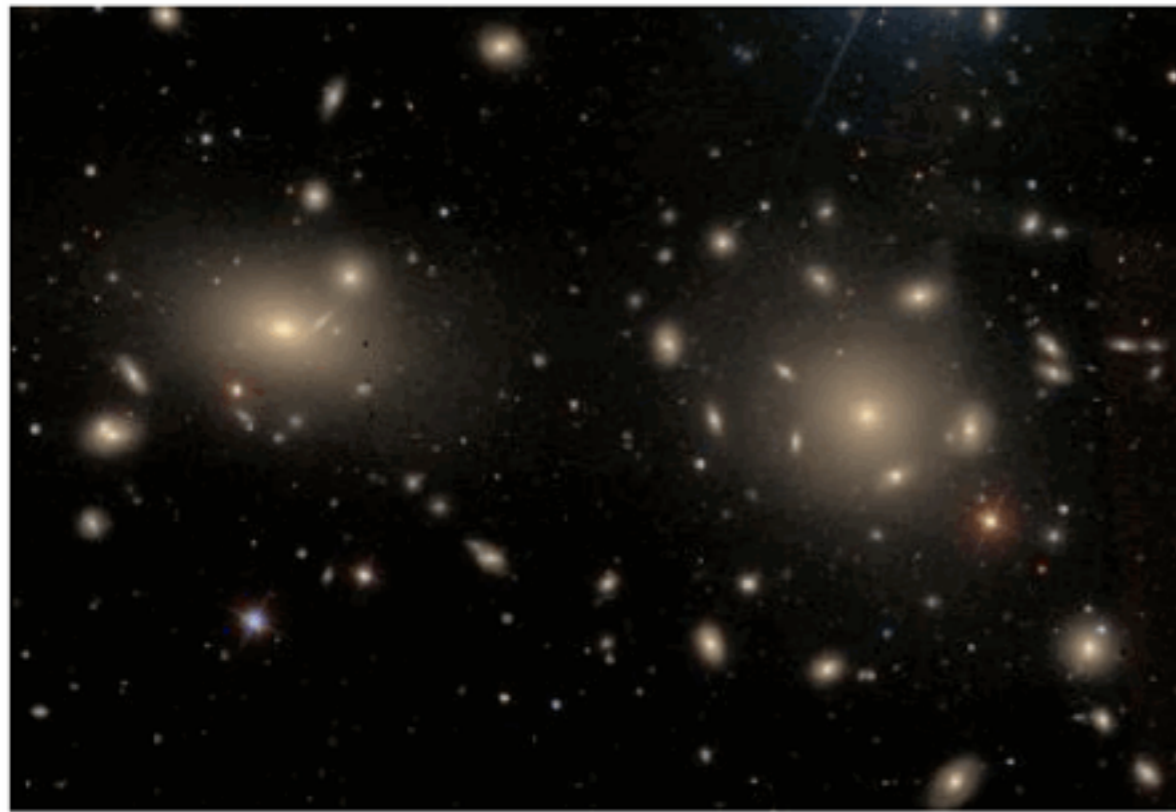
Kinematical Mass: from velocity dispersions



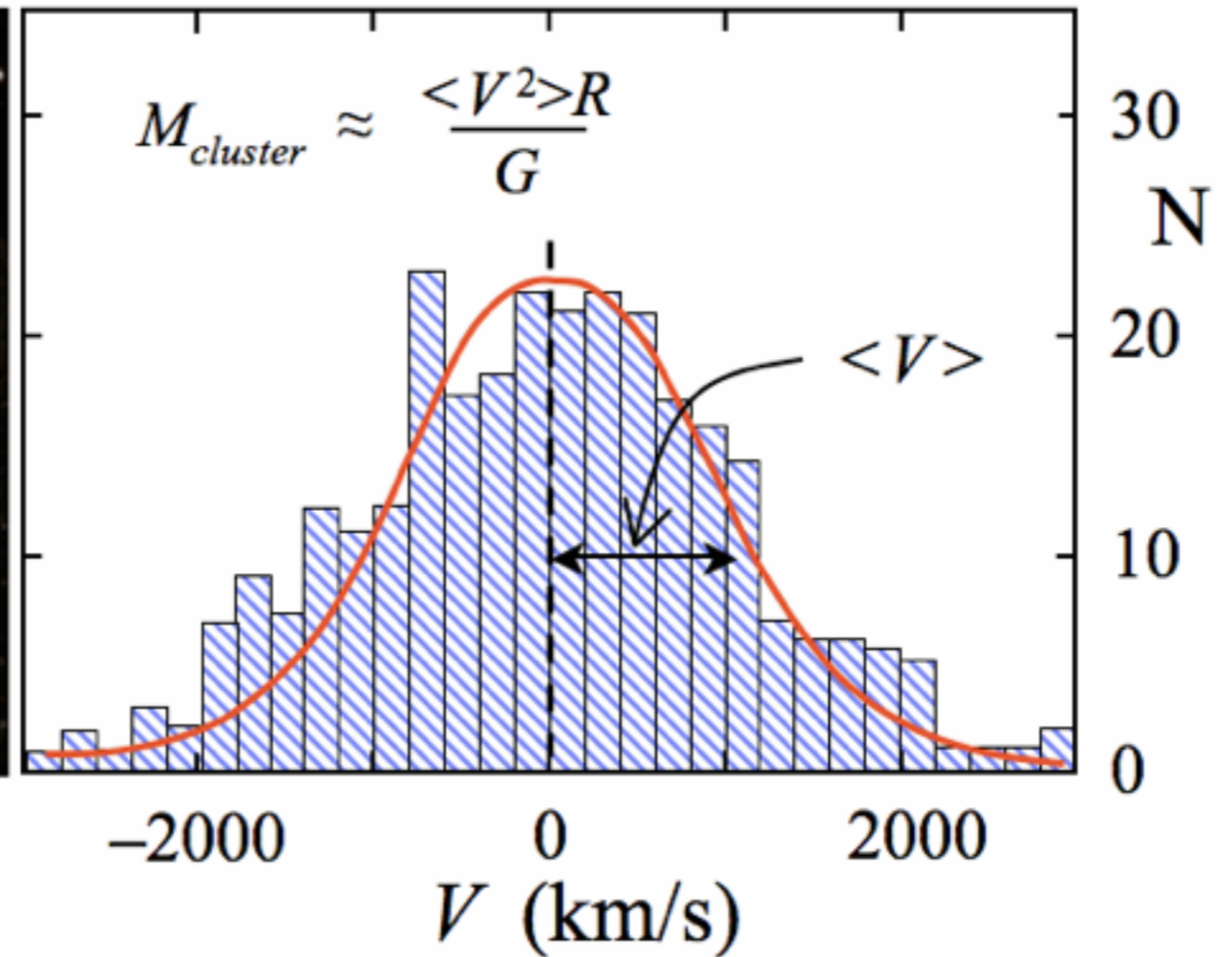
Coma cluster (central part)



Kinematical Mass: from velocity dispersions



Coma cluster (central part)

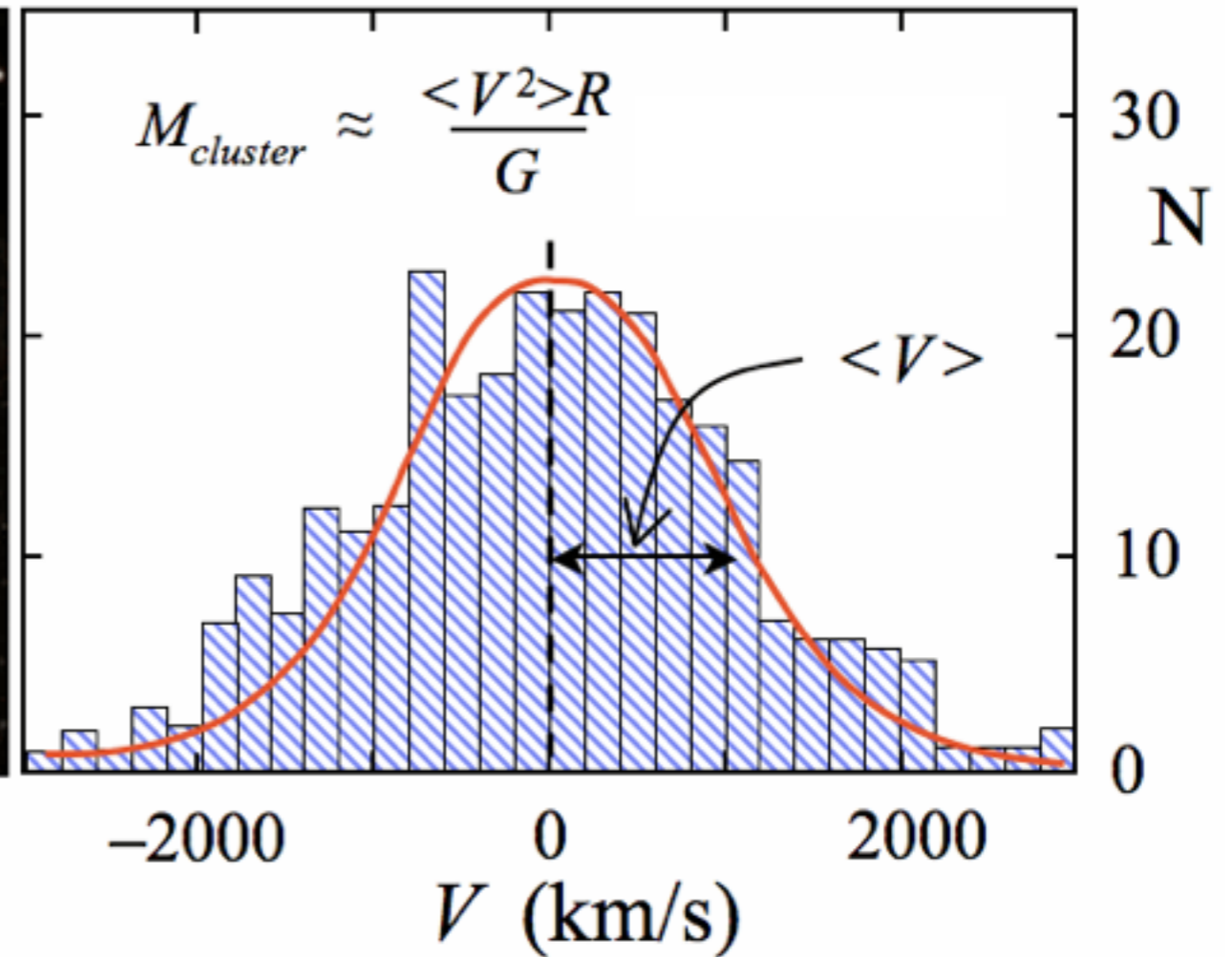


$$M_{kinematic} \frac{\langle V^2 \rangle}{R} = F_N$$

Kinematical Mass: from velocity dispersions



Coma cluster (central part)

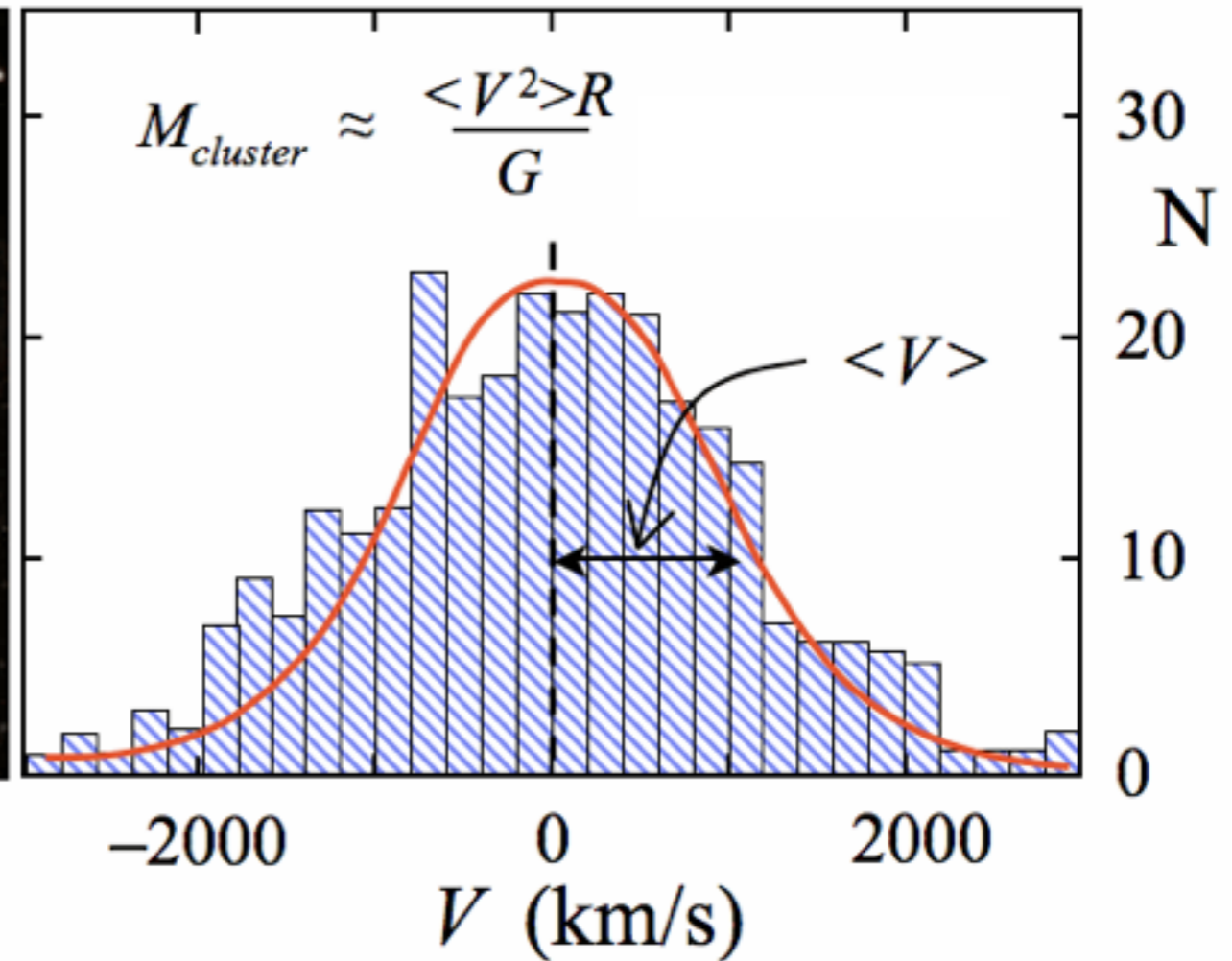


$$M_{kinematic} \frac{\langle V^2 \rangle}{R} = F_N + \mathbf{F}_\phi$$

Kinematical Mass: from velocity dispersions



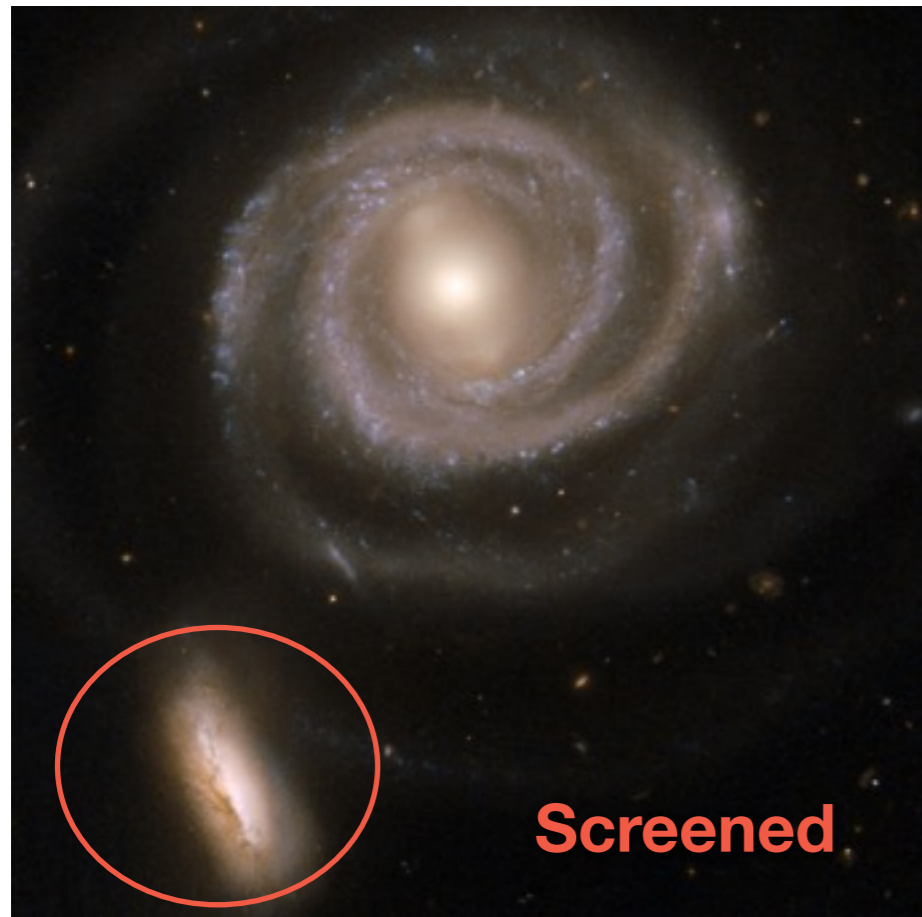
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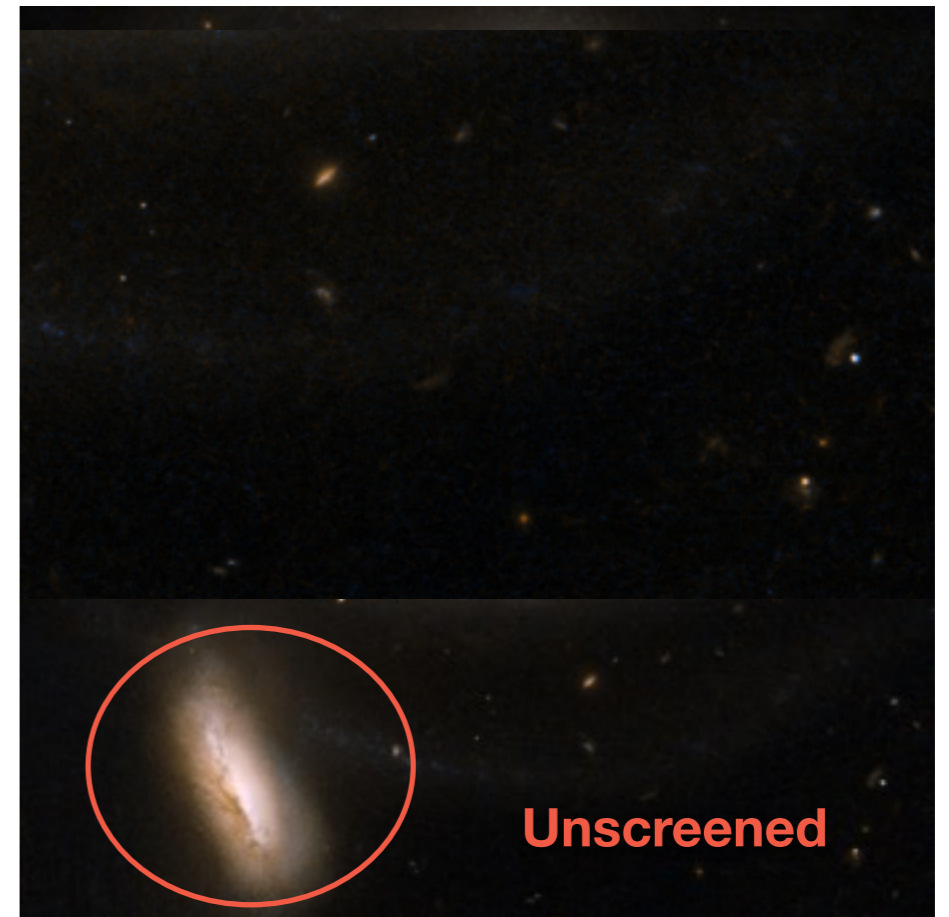
$$M_{kinematic} \frac{\langle V^2 \rangle}{R} = F_N + \mathbf{F}_\phi$$

Modified Gravity enhances kinematical mass

Modified Gravity with Screening Mechanisms: Fifth force depends on environmental density

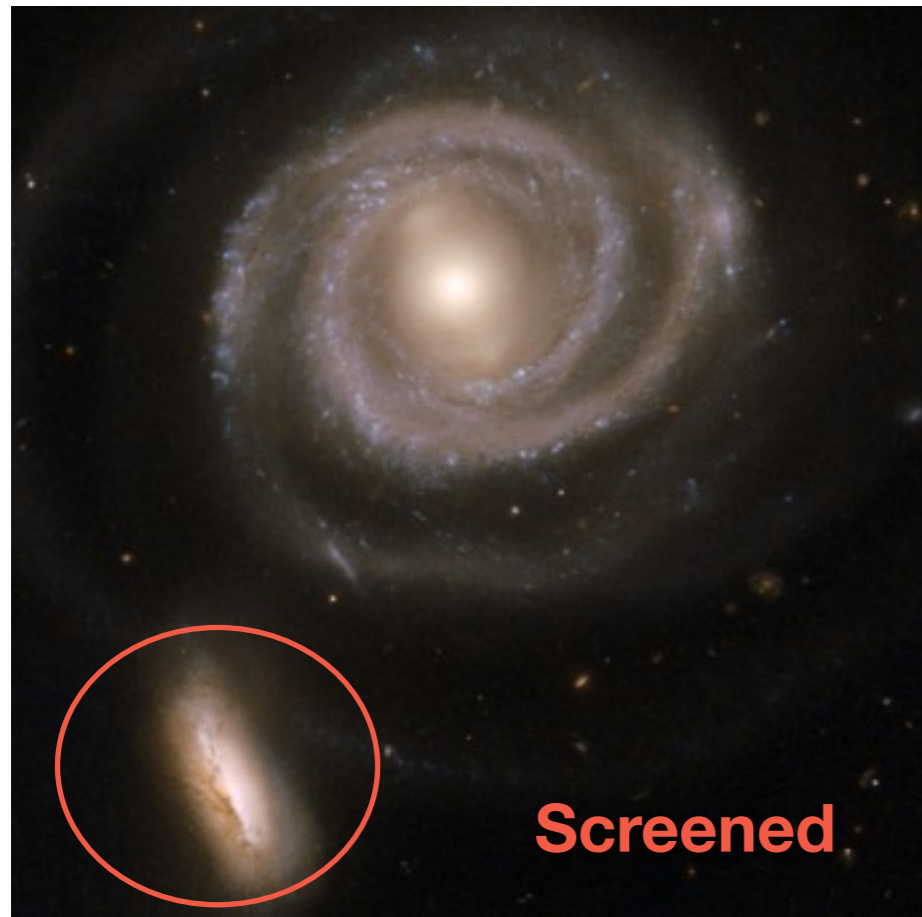


Kinematic mass is same in GR

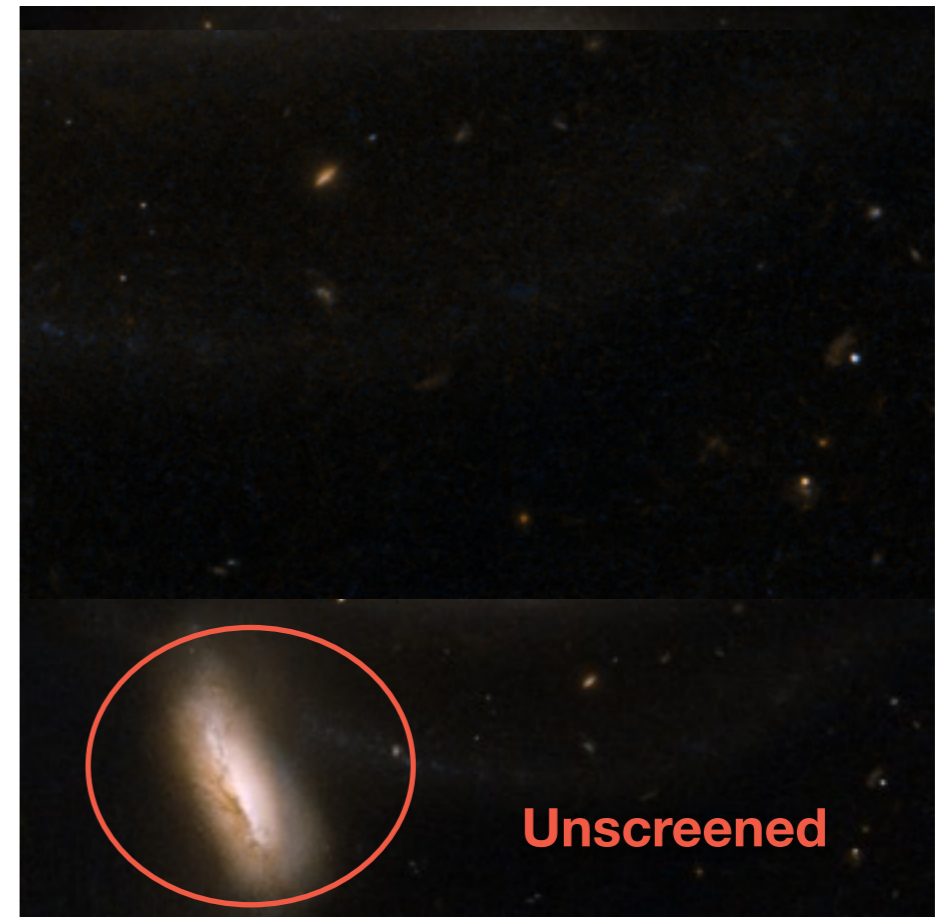


Kinematic mass differs from GR

Modified Gravity with Screening Mechanisms: Fifth force depends on environmental density



Kinematic mass is same in GR



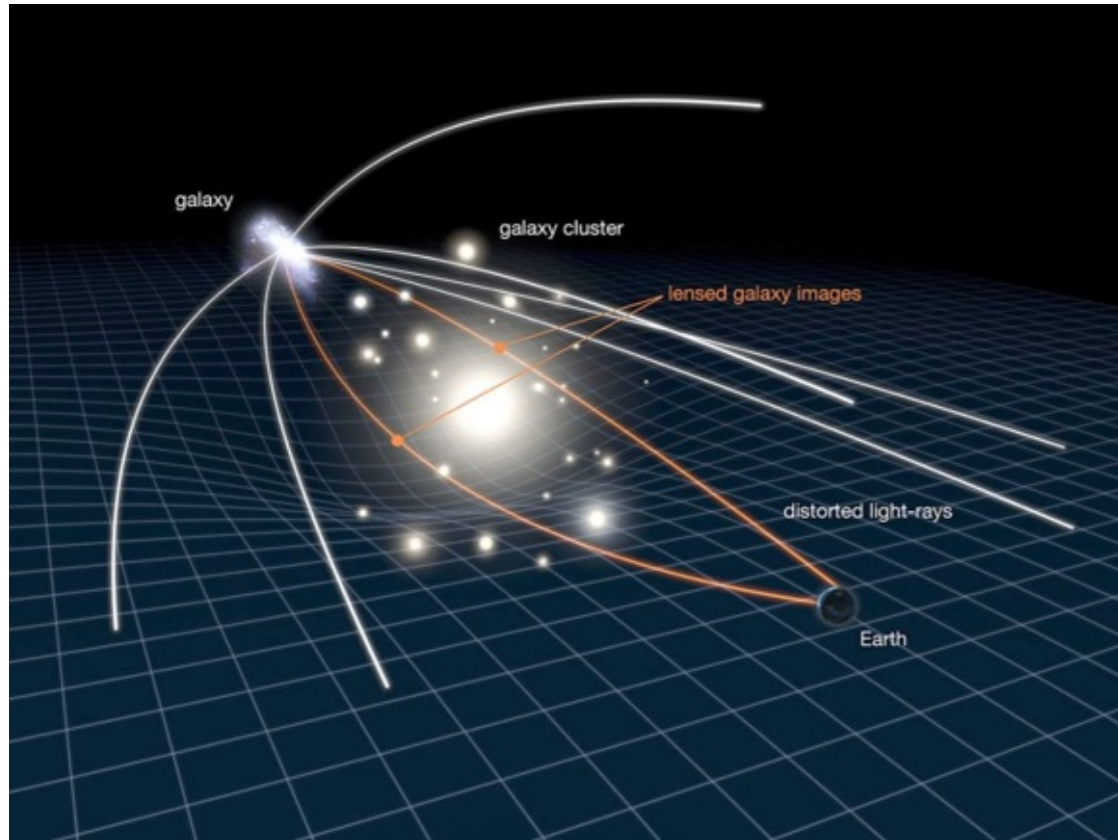
Kinematic mass differs from GR

Kinematic Mass depends on location in a high/low dense environment (size of cluster)

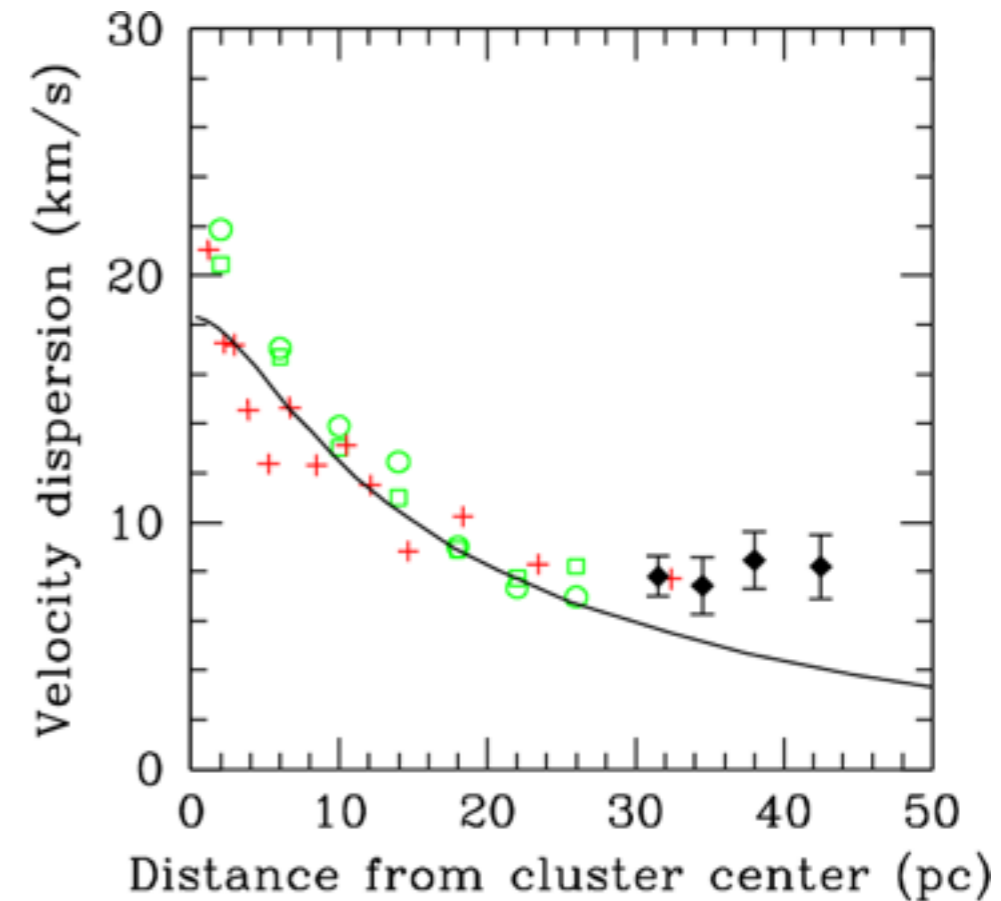
Smoking gun for Screening Mechanisms

Lensing Mass vs. Environmental dependent Kinematic Mass

Lensing Mass same as in GR



Kinematic Mass depends on environment

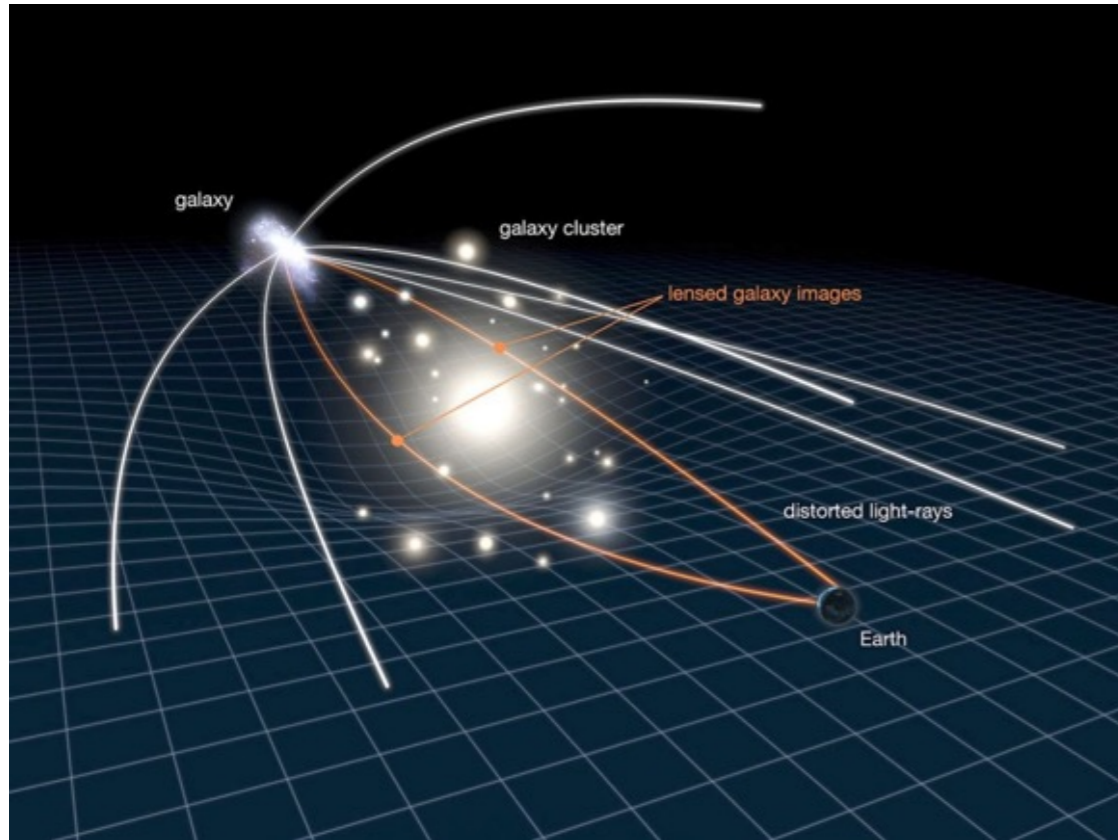


$$\Delta_M \equiv \frac{M_D}{M_L} - 1$$

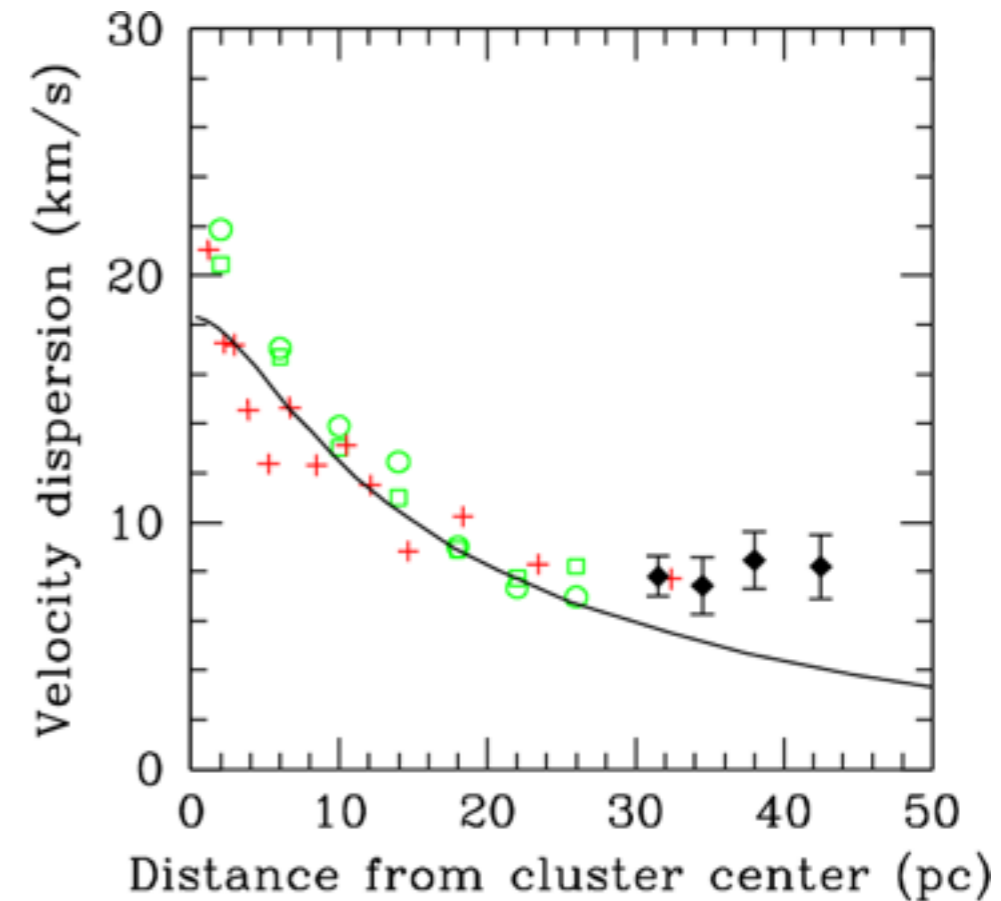
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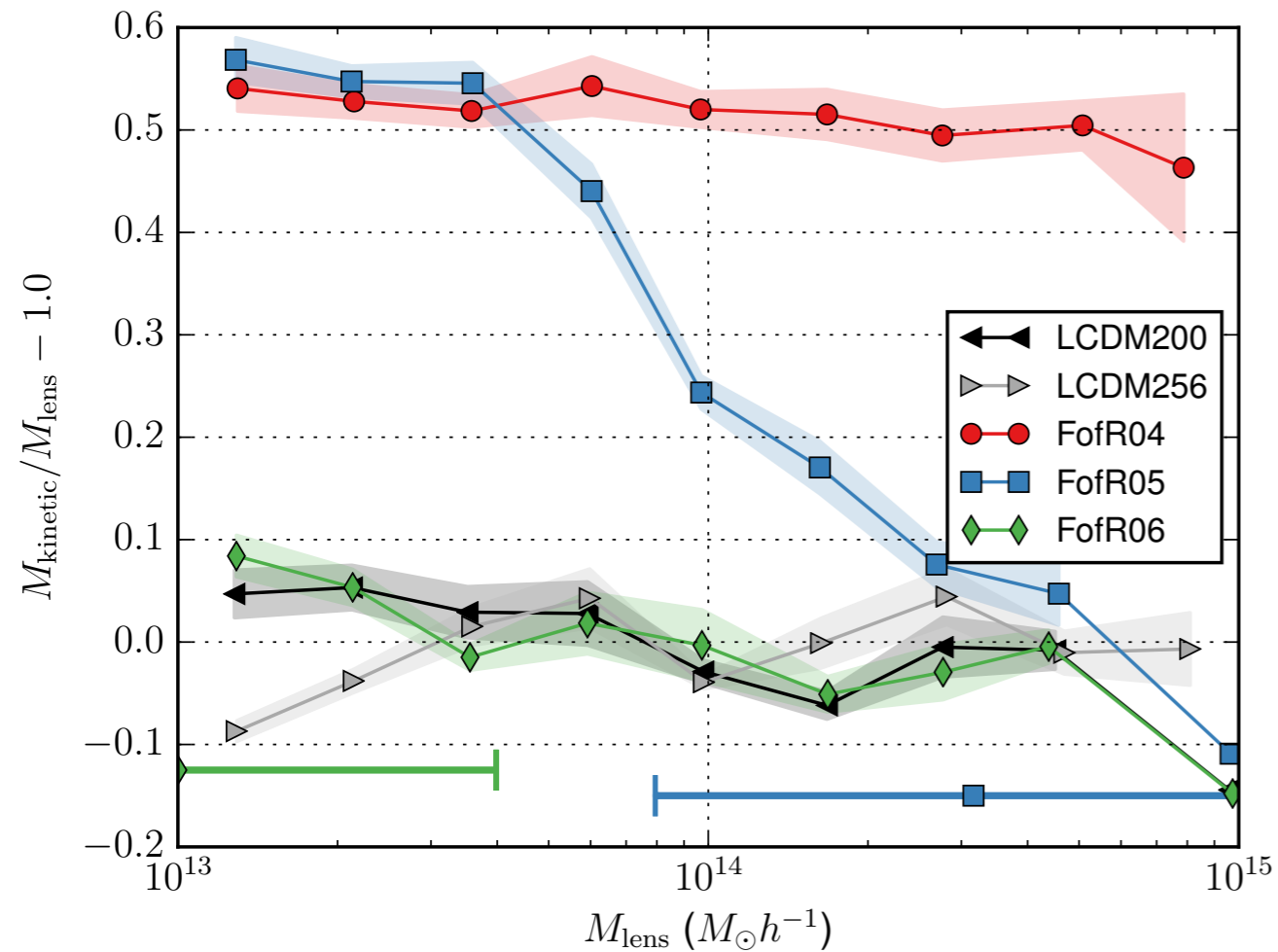
$$GR : \Delta_M = 0$$

$$F(R) : \Delta_M \in [0, \frac{1}{3}]$$

$$Chameleon/Symmetron : \Delta_M \in [0, 2\beta^2]$$

Smoking gun for Screening Mechanisms

Lensing Mass vs. Kinematic Mass



fofr4~24 Mpc

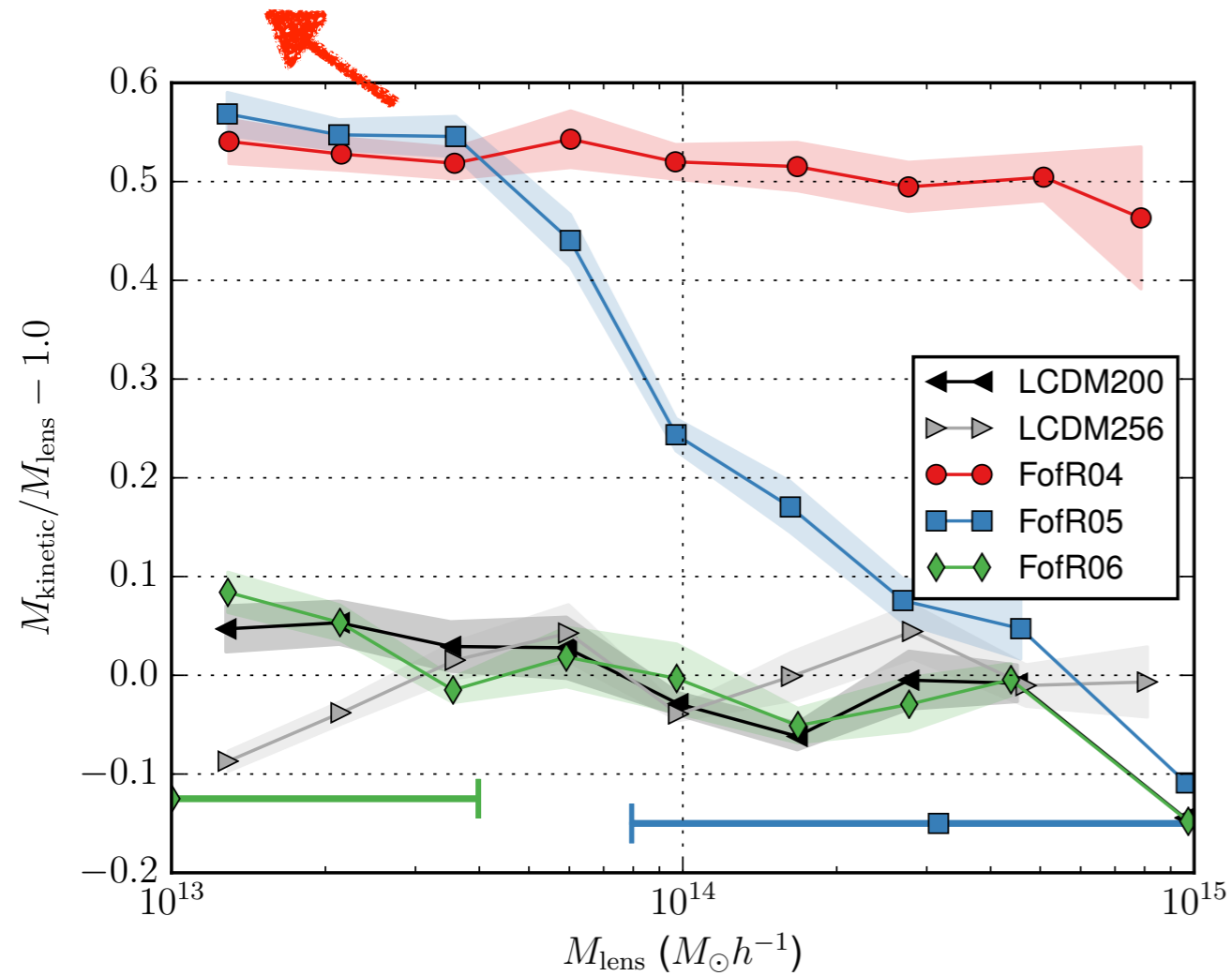
fofr5~7 Mpc

fofr6~2 Mpc

Smoking gun for Screening Mechanisms

Lensing Mass vs. Kinematic Mass

Unscreened Modified Gravity



fofr4~24 Mpc

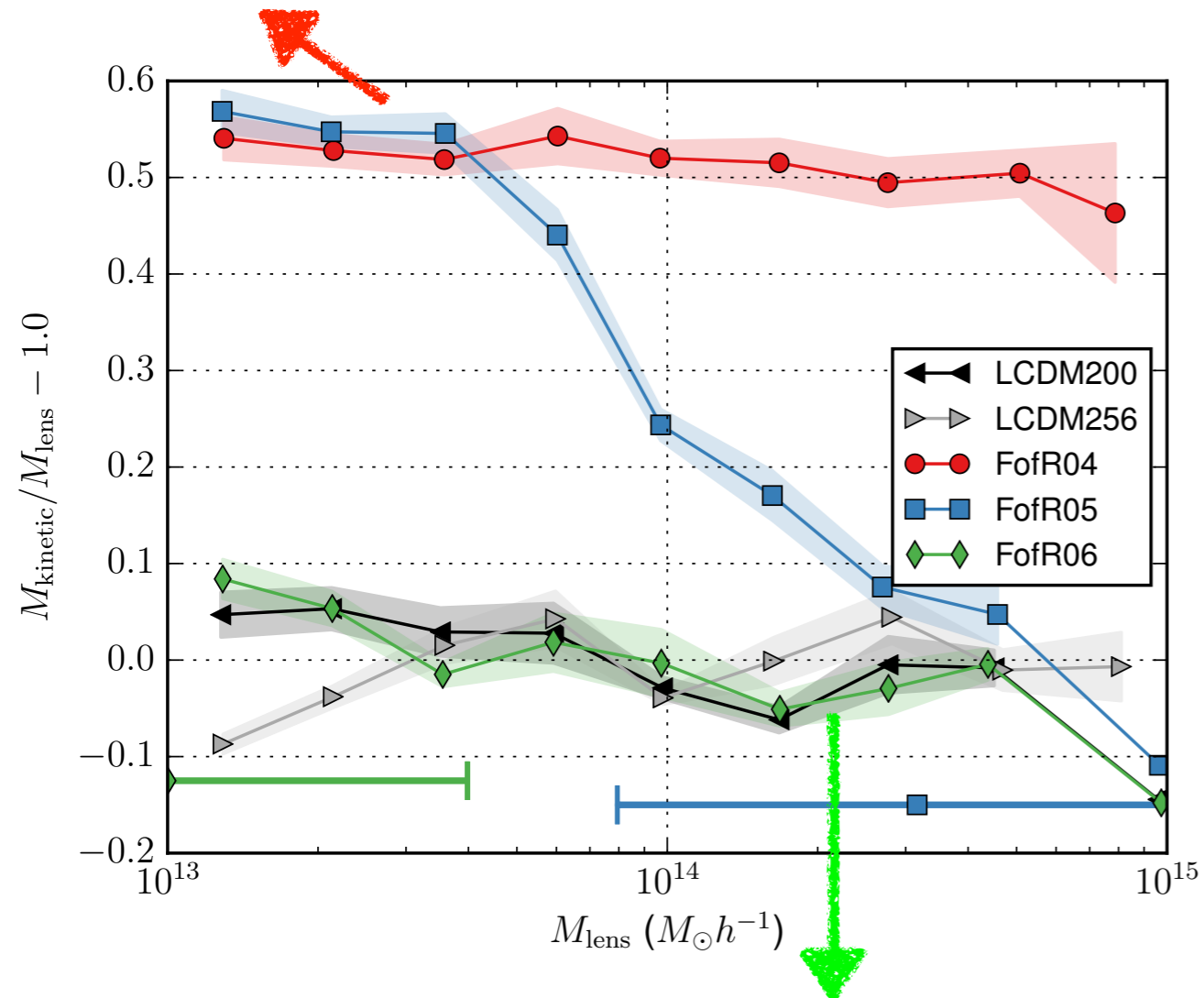
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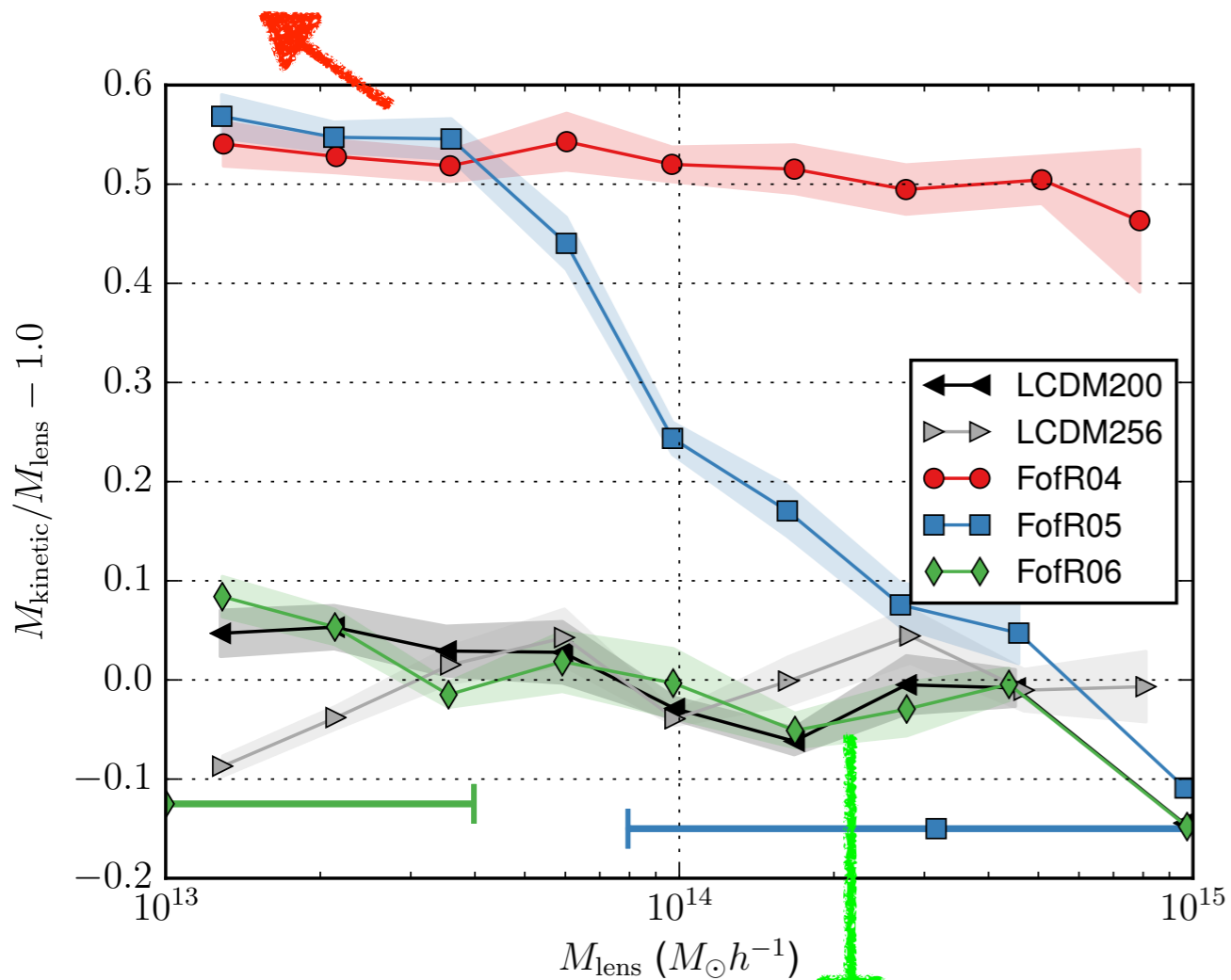
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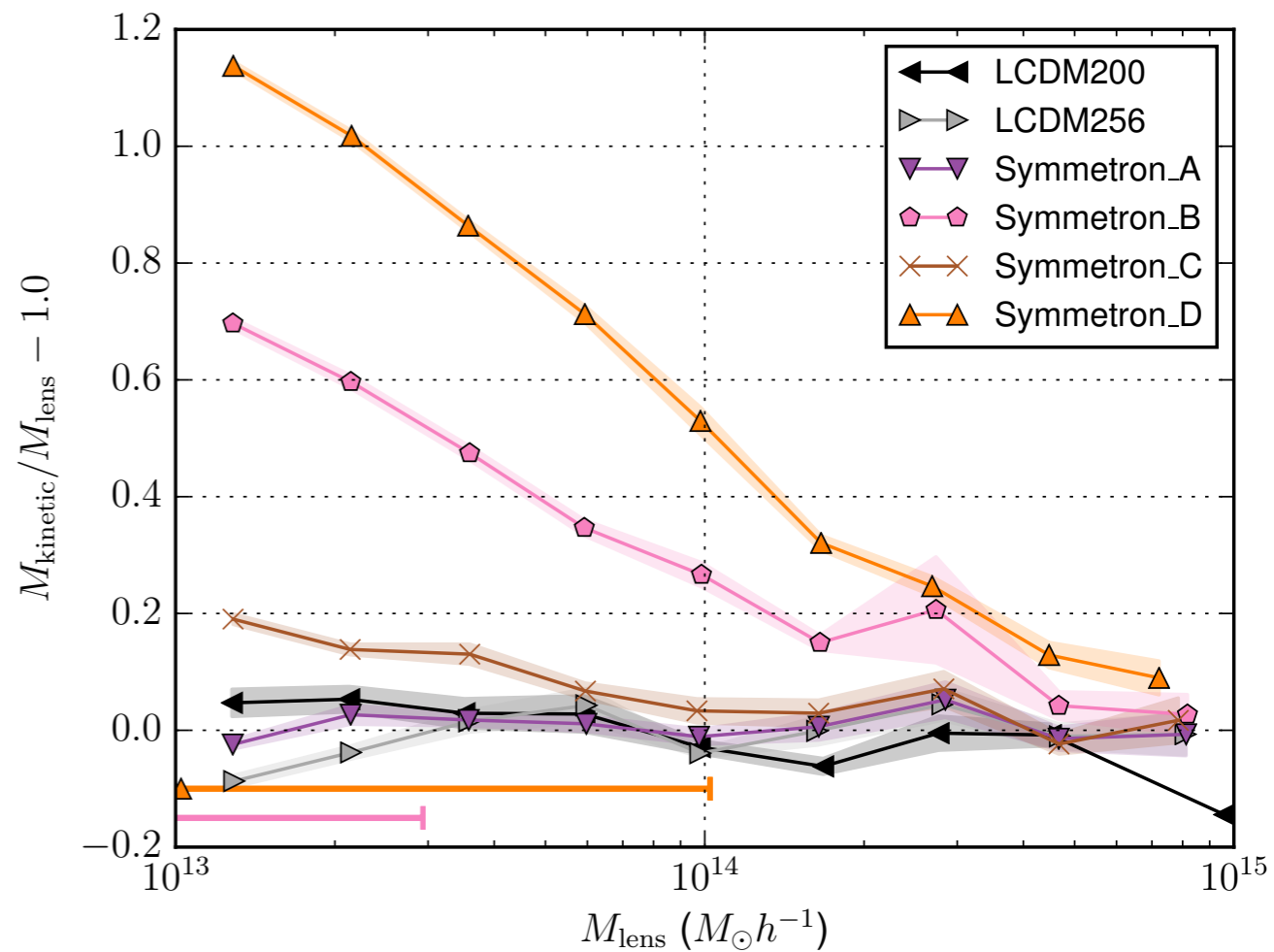


Screened Modified Gravity

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fofr5~7 Mpc

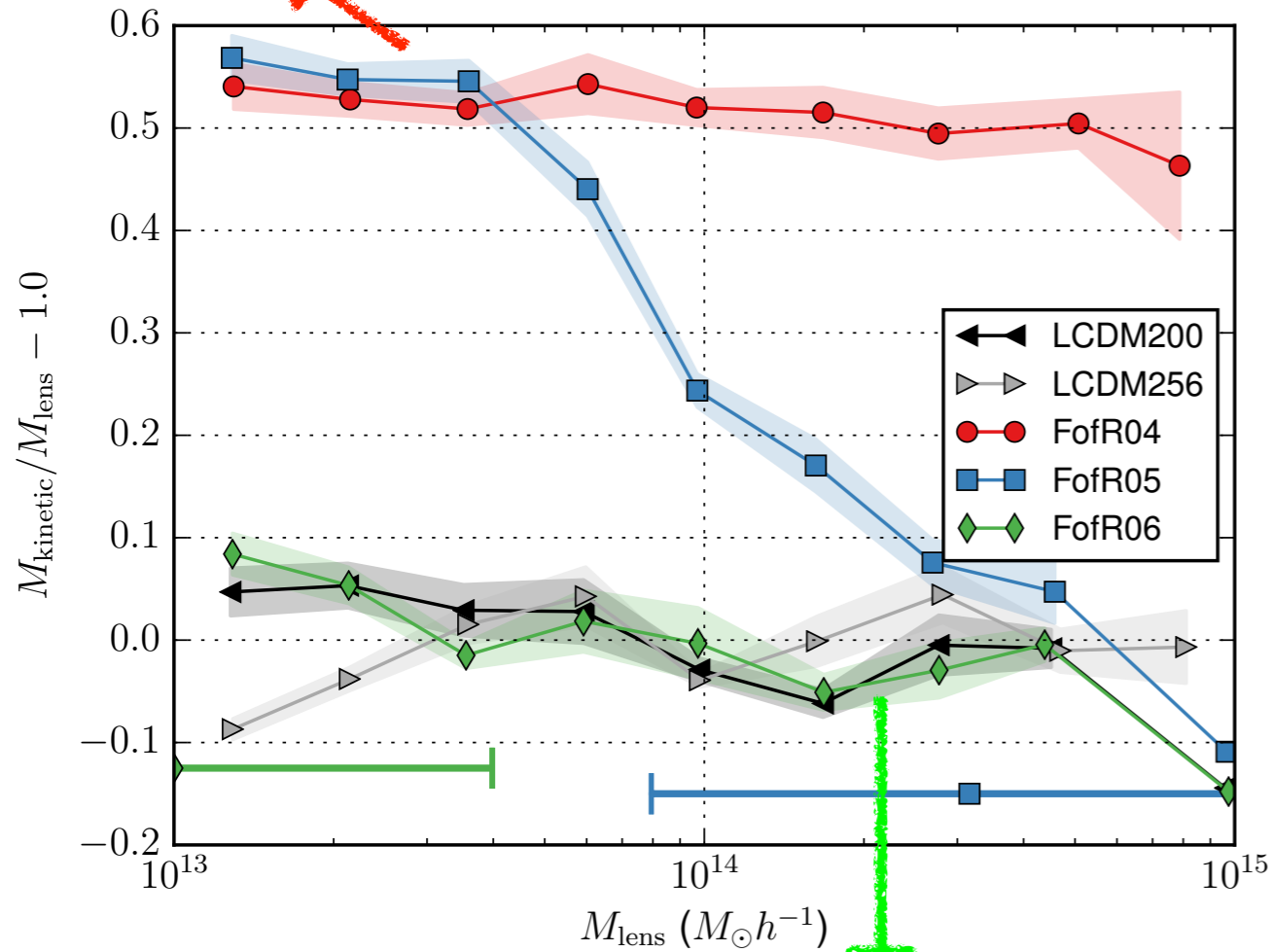
fofr6~2 Mpc



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Lensing Mass vs. Kinematic Mass

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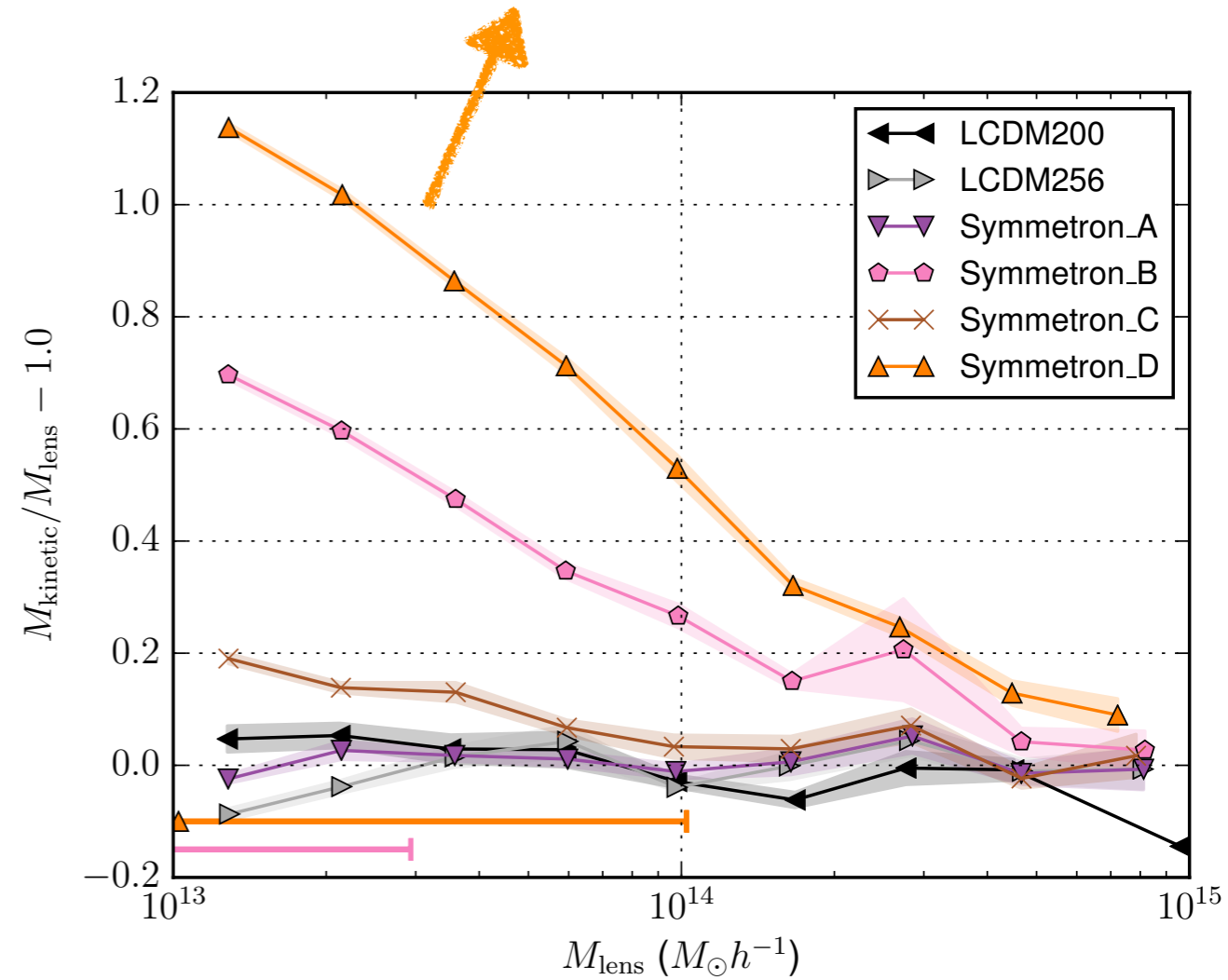
Screened Modified Gravity

fofr4~24 Mpc

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fofr6~2 Mpc

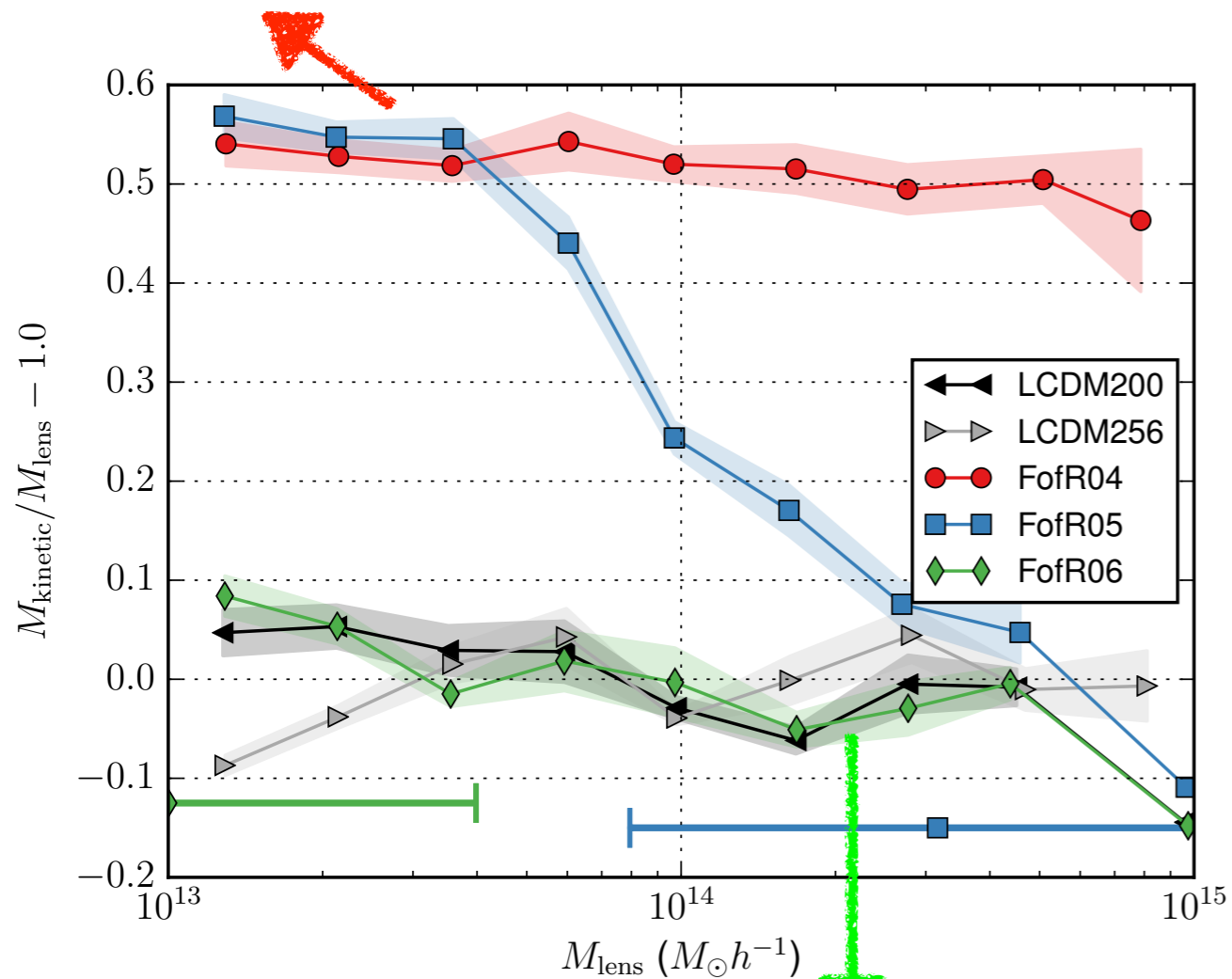
Large coupling/small scale screening



Smoking gun for Screening Mechanisms

Lensing Mass vs. Kinematic Mass

Unscreened Modified Gravity



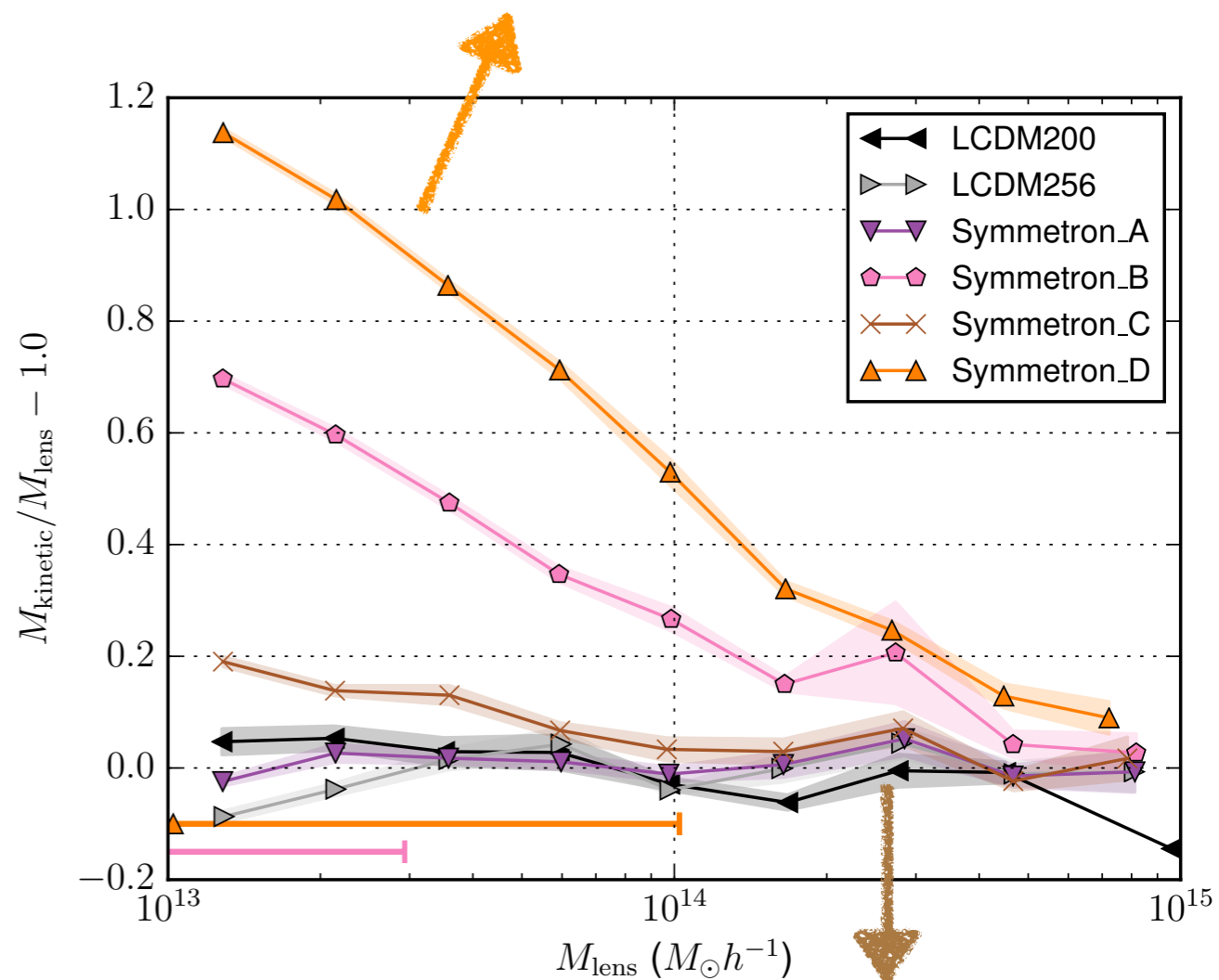
Screened Modified Gravity

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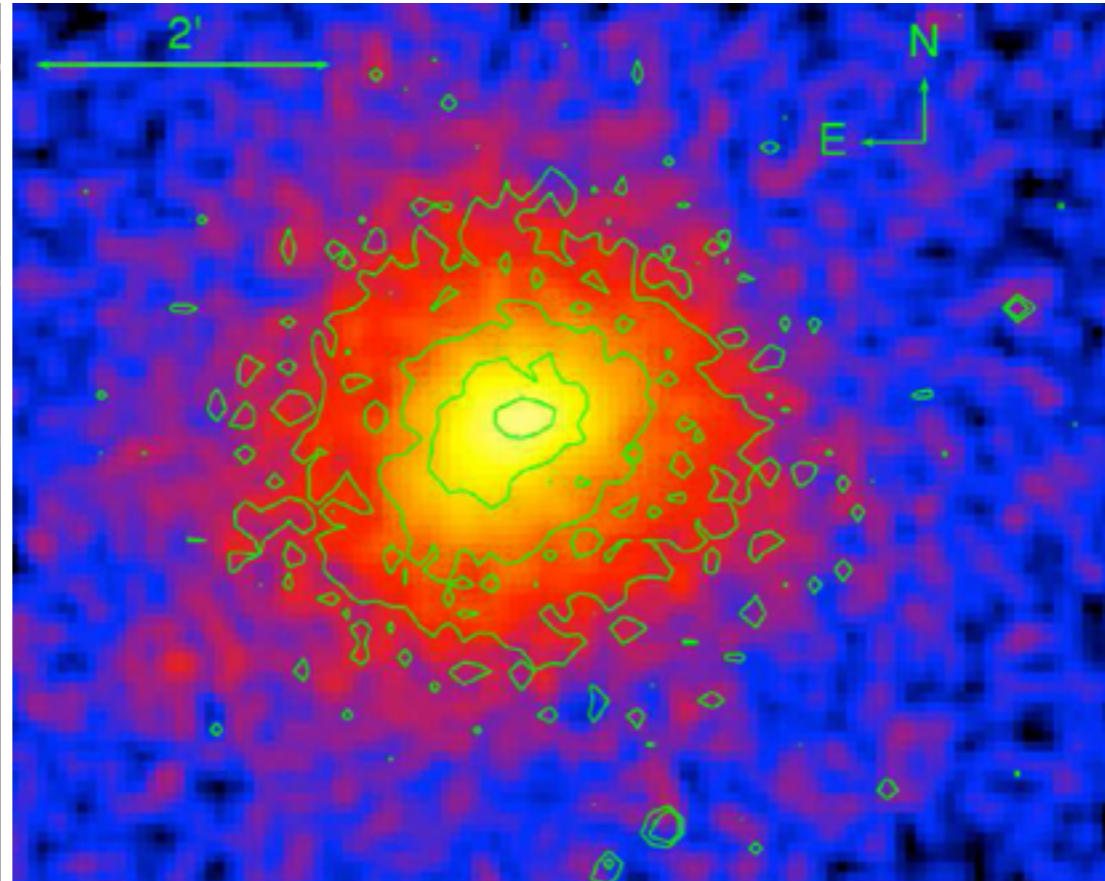
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small coupling/large scale screening

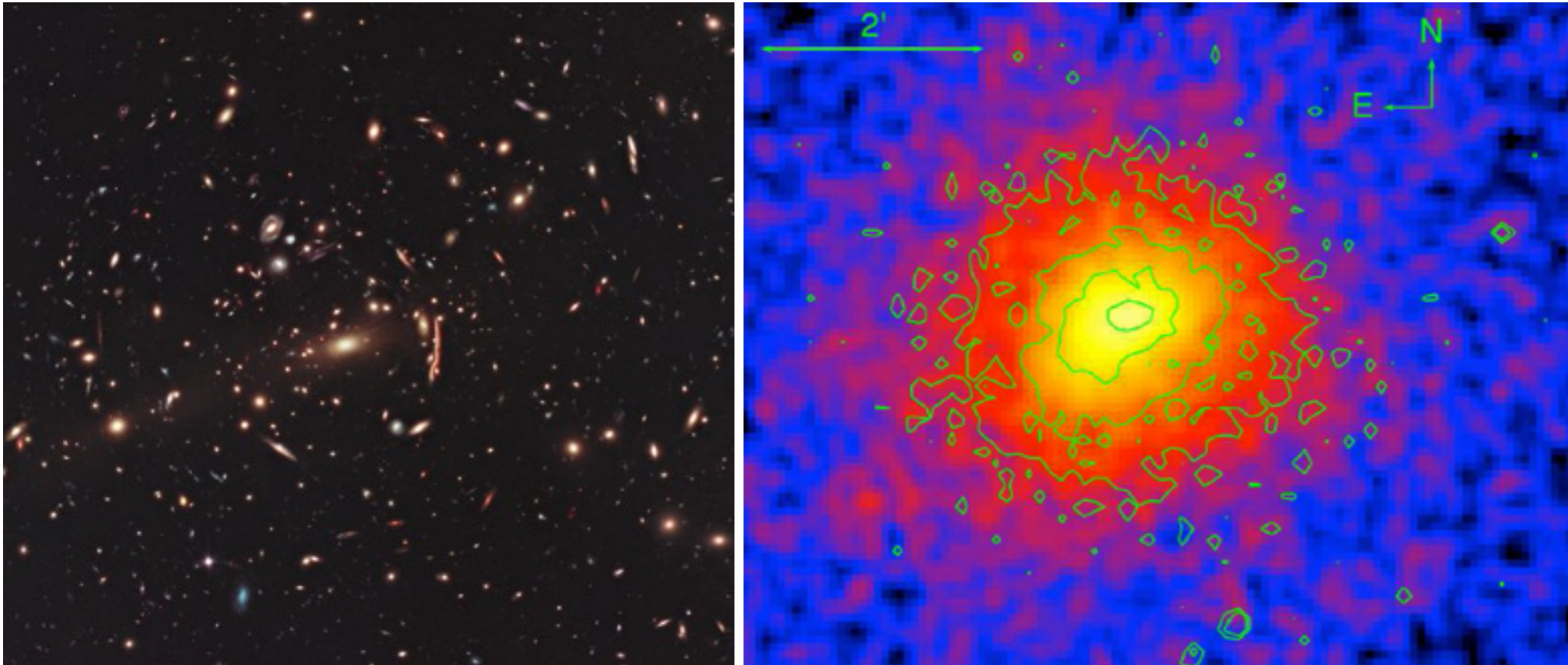
Thermal Mass: from x-ray measurements of temperature and density profiles of baryons

Umetsu et al., ApJ 755, 56 (2012)



Thermal Mass: from x-ray measurements of temperature and density profiles of baryons

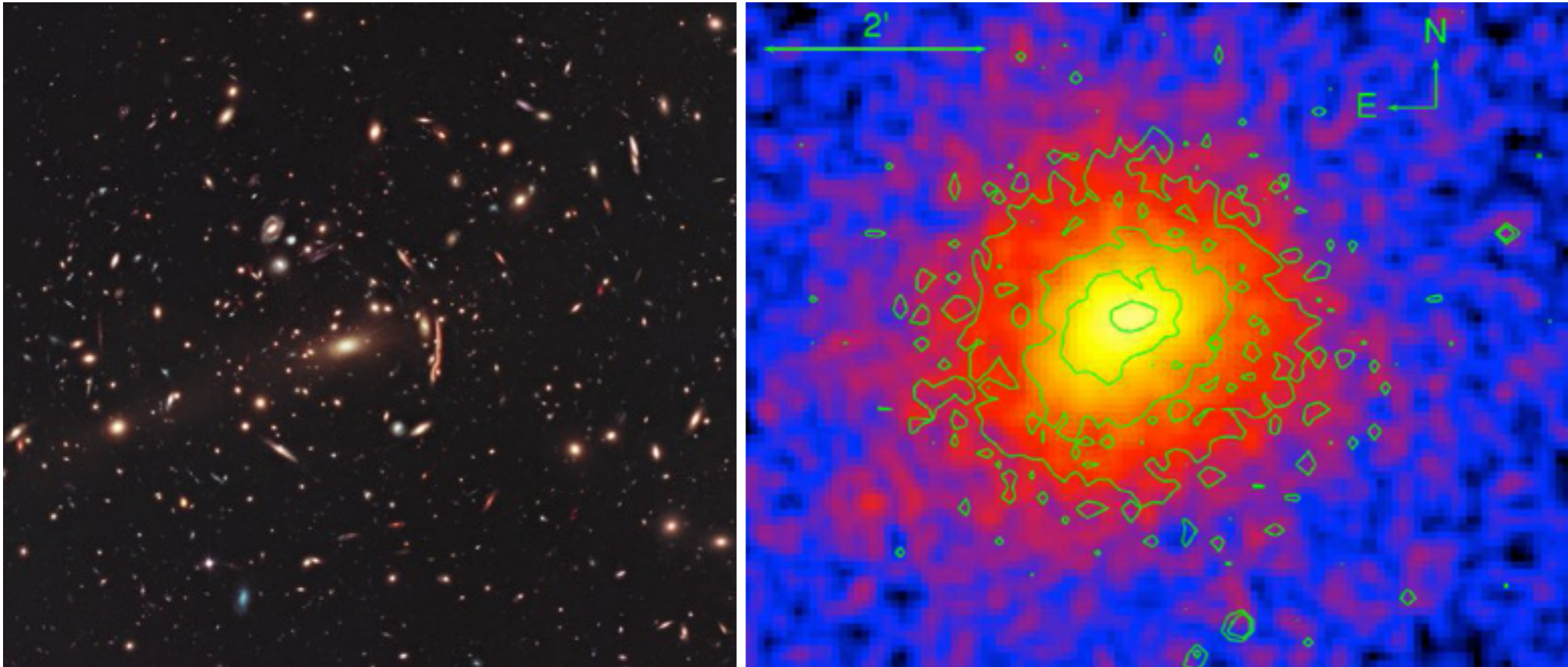
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Mass holds hydrostatic equilibrium: $\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$

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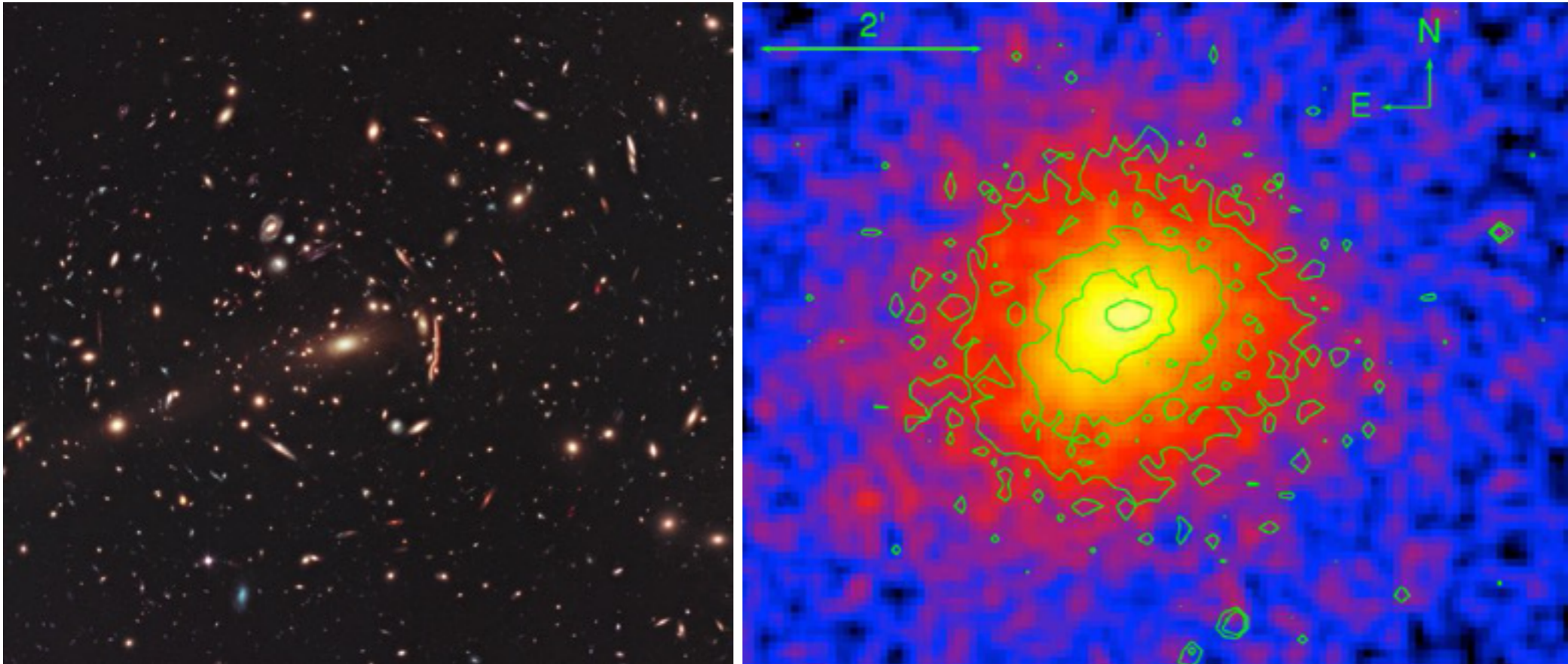
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Mass holds hydrostatic equilibrium: $\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2} + F_\phi$

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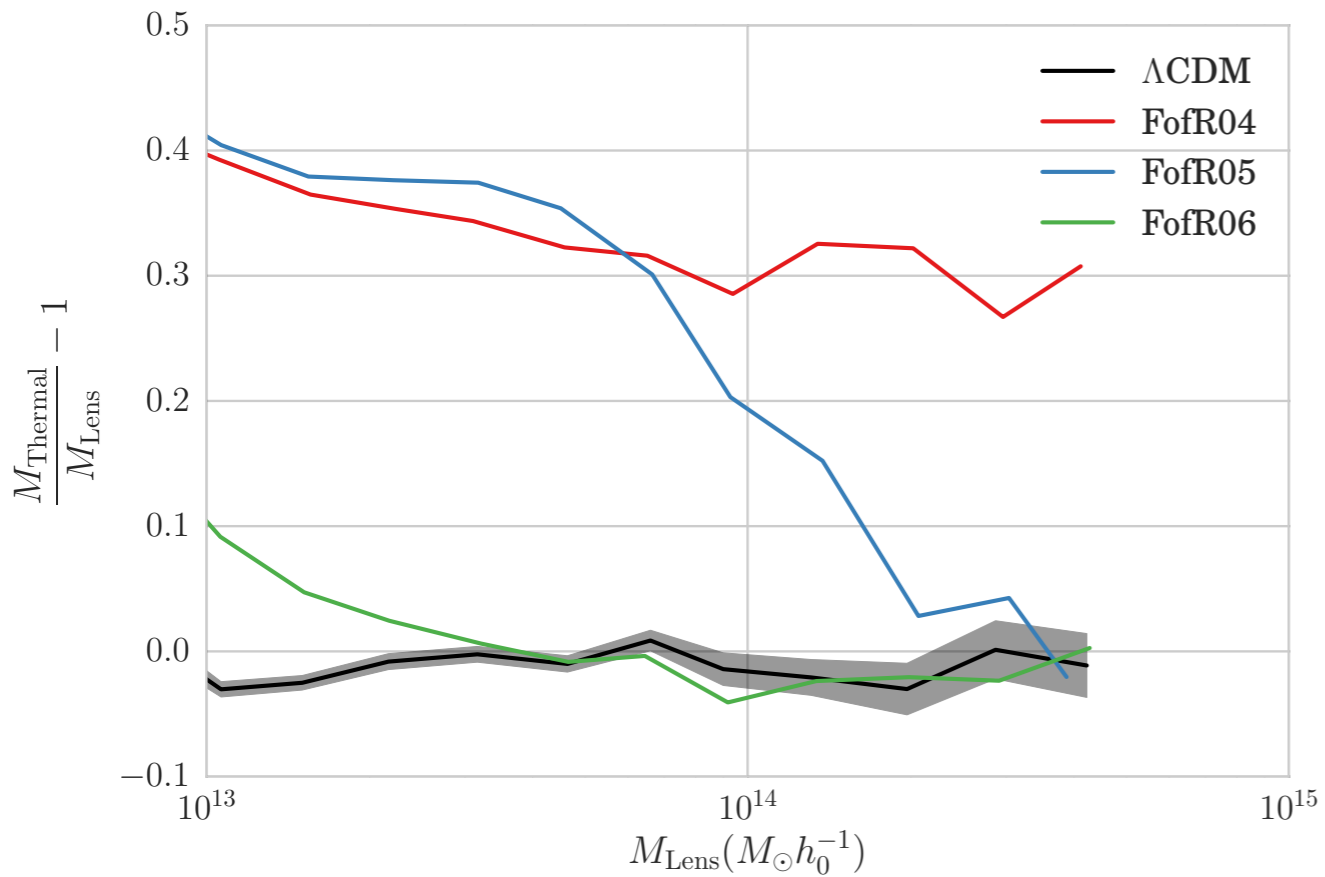


Mass holds hydrostatic equilibrium: $\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2} + F_\phi$

Thermal mass in Modified Gravity depends on the fifth force (which is environmental dependent!)

Smoking gun for Screening Mechanisms

Lensing Mass vs. Environmental dependent Thermal Mass



fofr4~24 Mpc

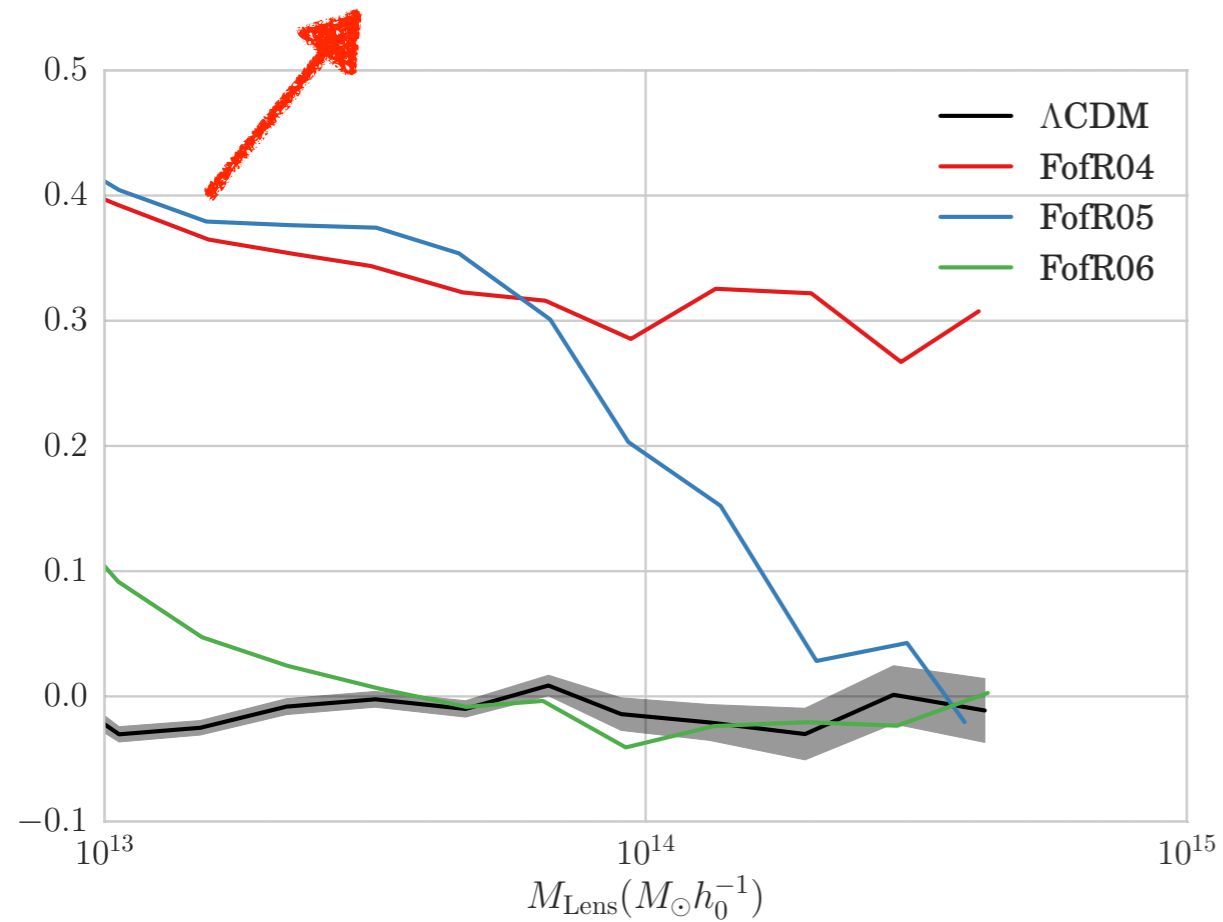
fofr5~7 Mpc

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Smoking gun for Screening Mechanisms

Lensing Mass vs. Environmental dependent Thermal Mass

Unscreened Modified Gravity



fofr4~24 Mpc

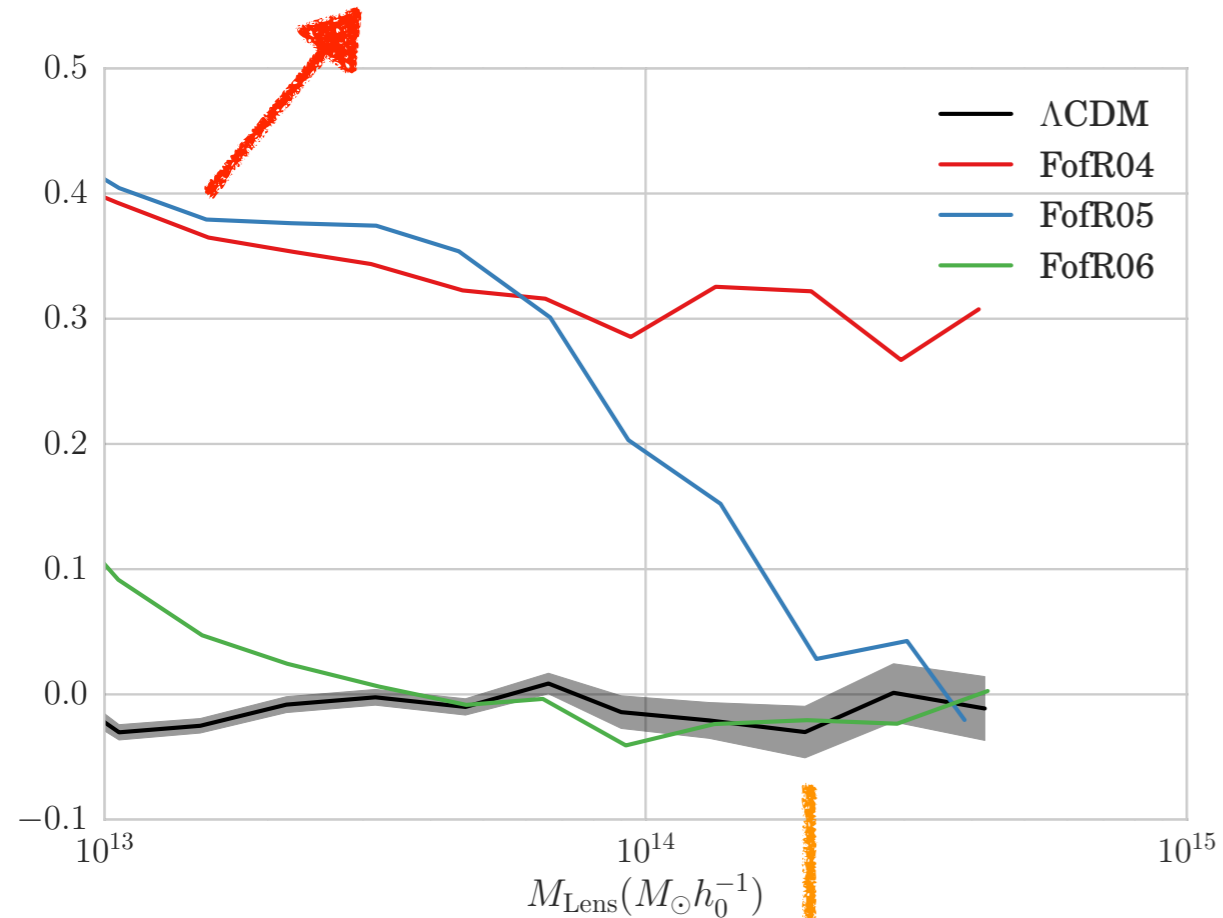
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Screened Modified Gravity

fofr4 ~ 24 Mpc

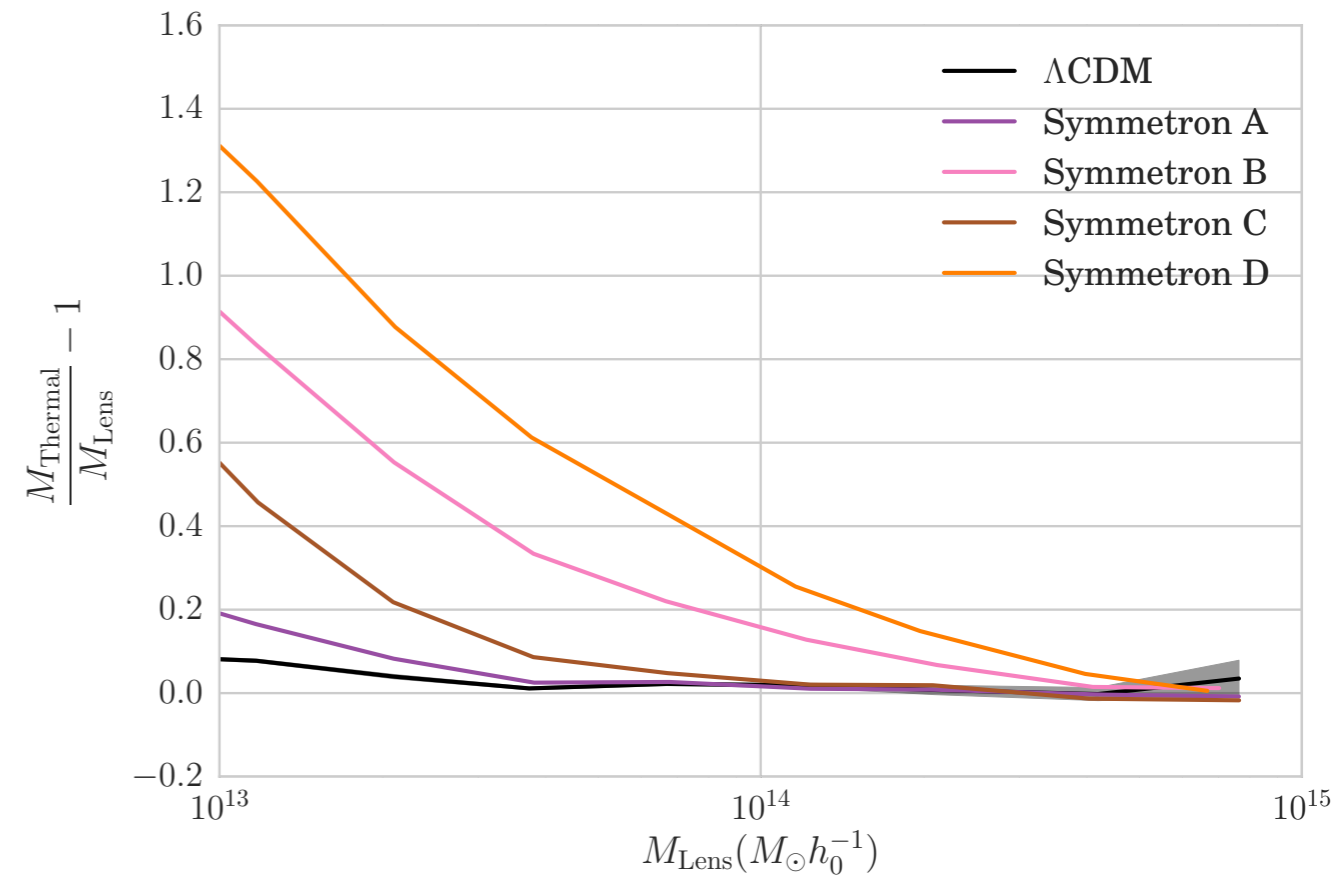
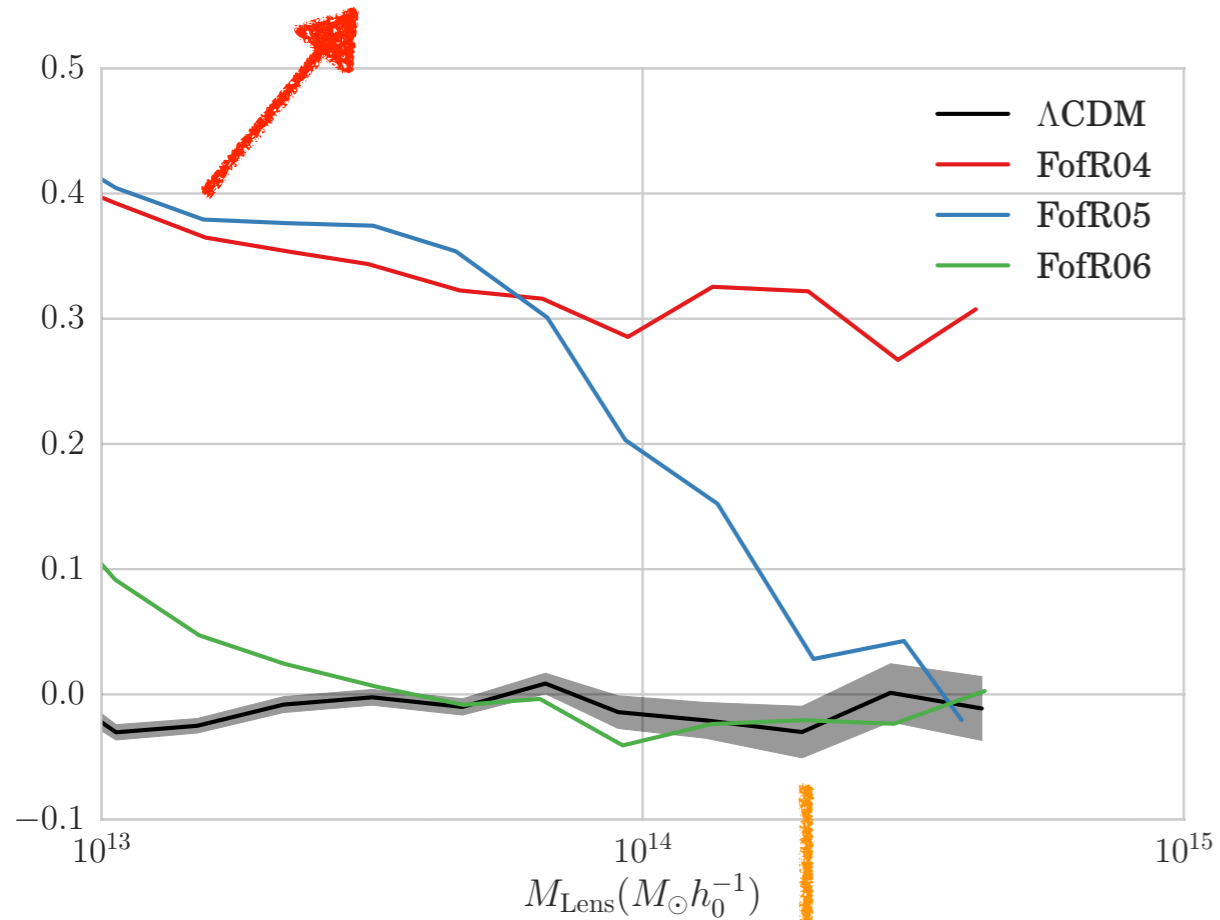
fofr5 ~ 7 Mpc

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Smoking gun for Screening Mechanisms

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Unscreened Modified Gravity



Screened Modified Gravity

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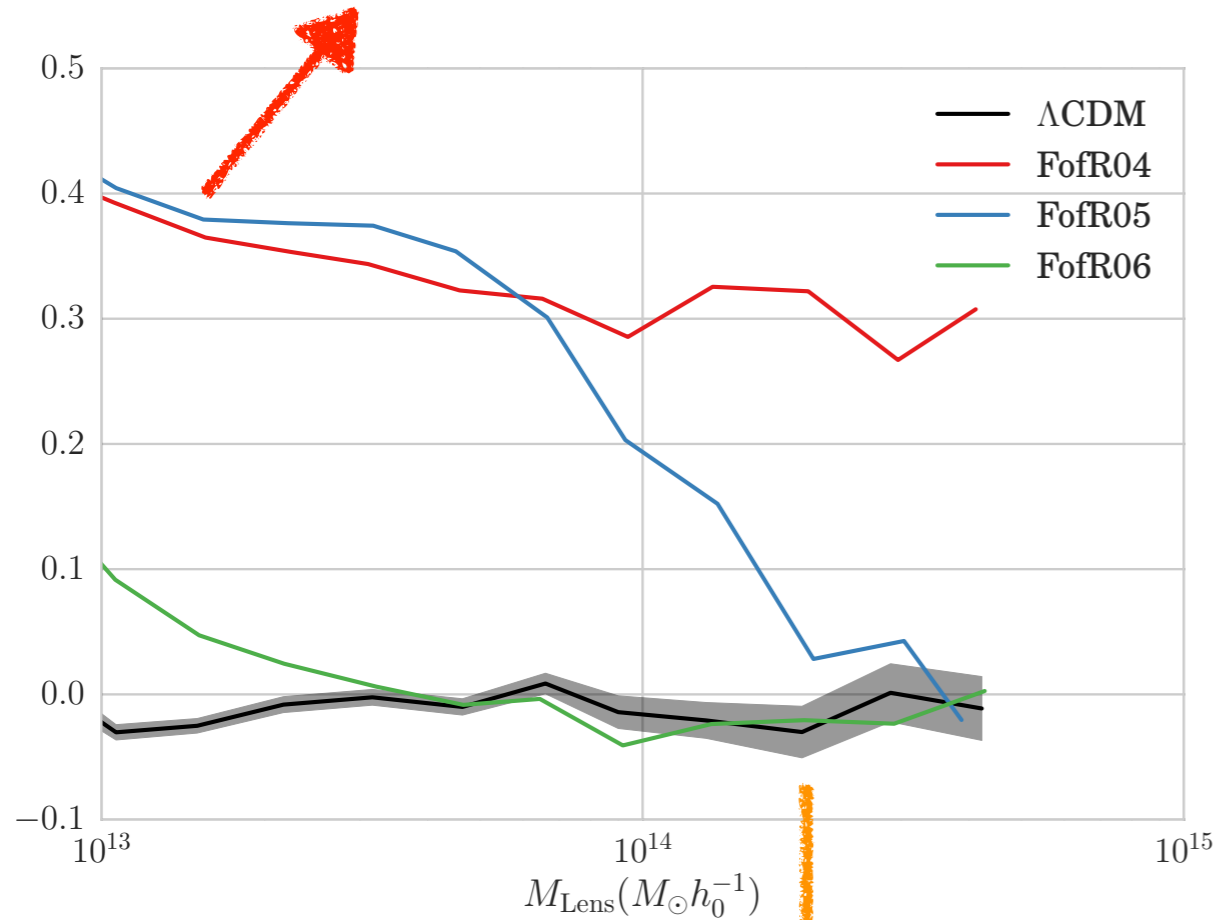
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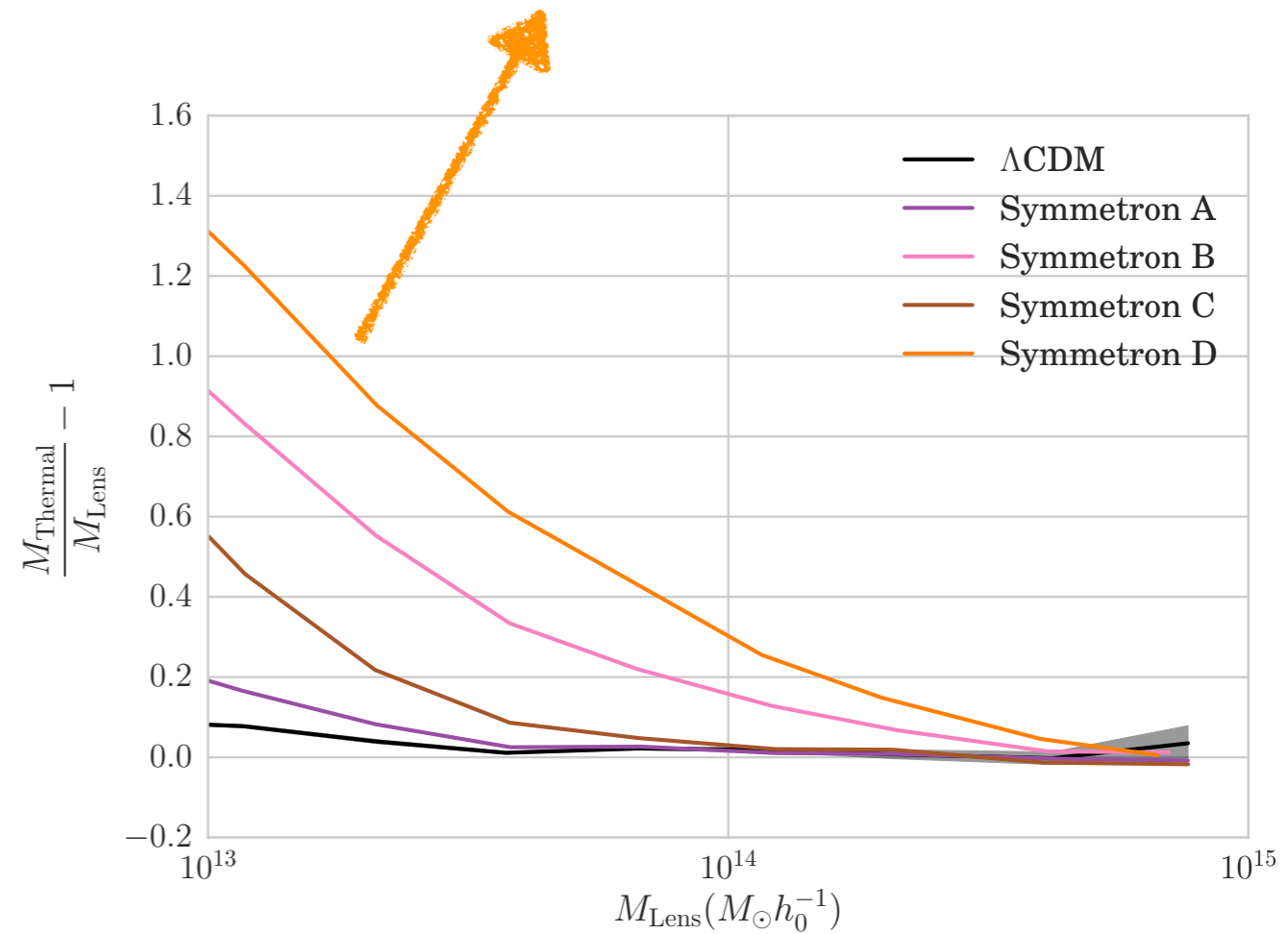
Smoking gun for Screening Mechanisms

Lensing Mass vs. Environmental dependent Thermal Mass

Unscreened Modified Gravity



Large coupling / small scale screening



Screened Modified Gravity

fofr4 ~ 24 Mpc

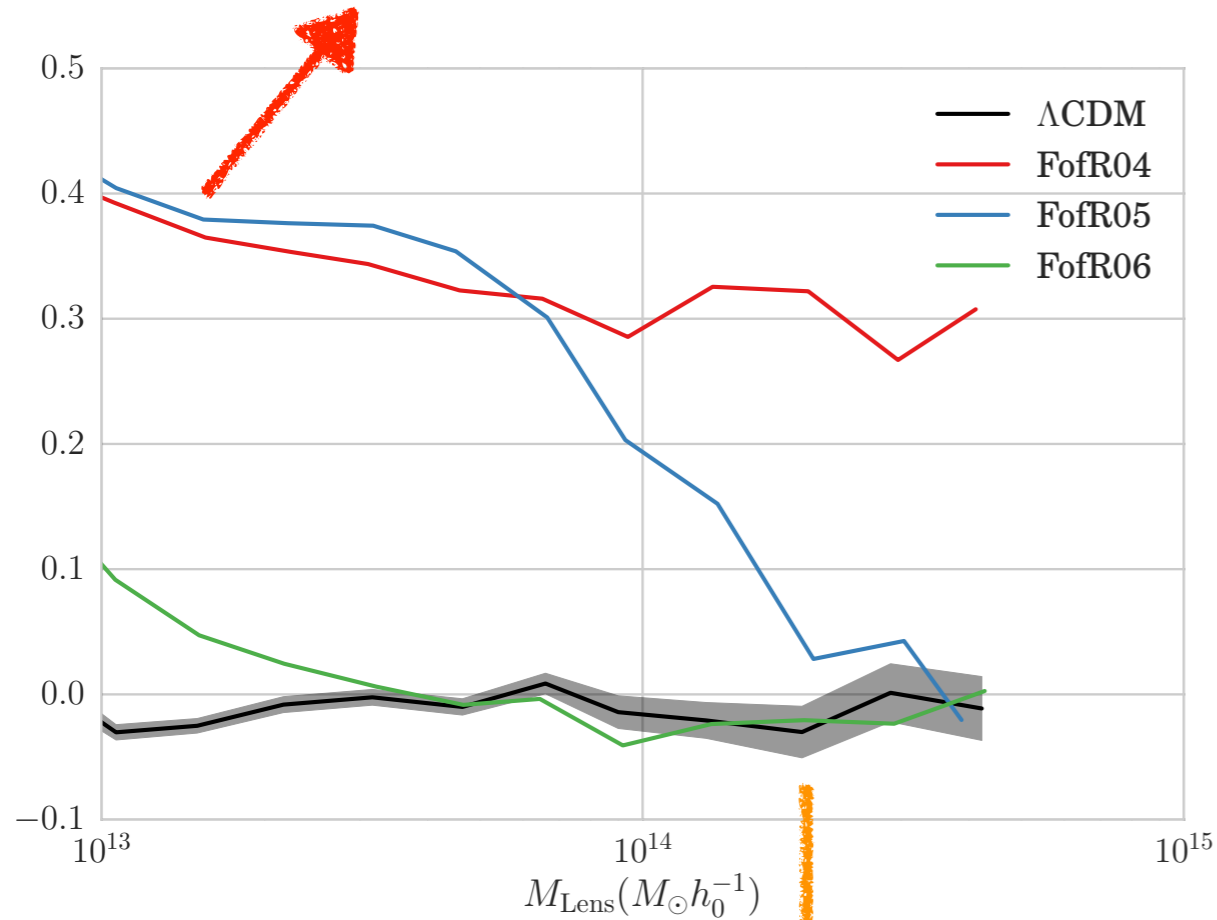
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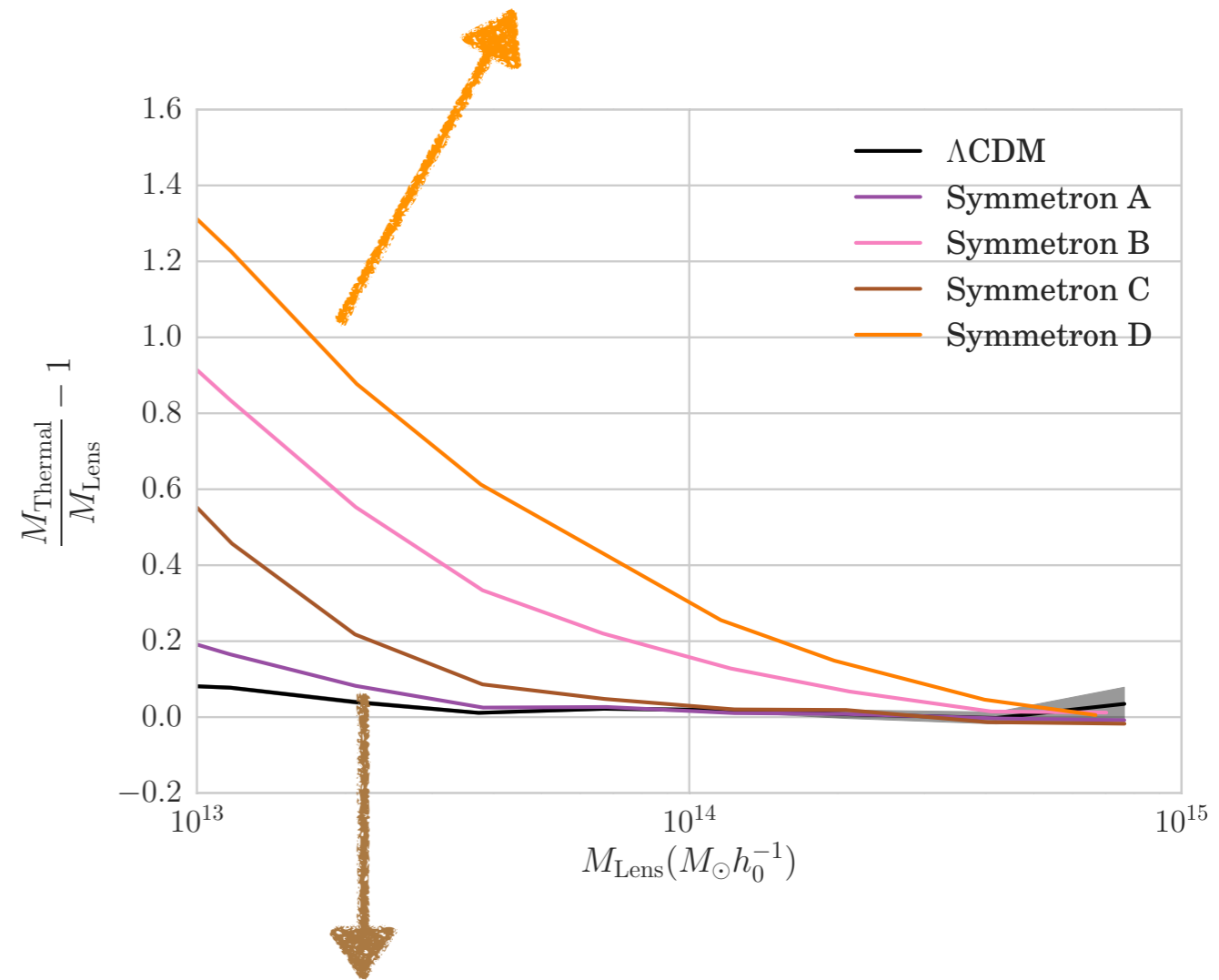
Screened Modified Gravity

fofr4 ~ 24 Mpc

fofr5 ~ 7 Mpc

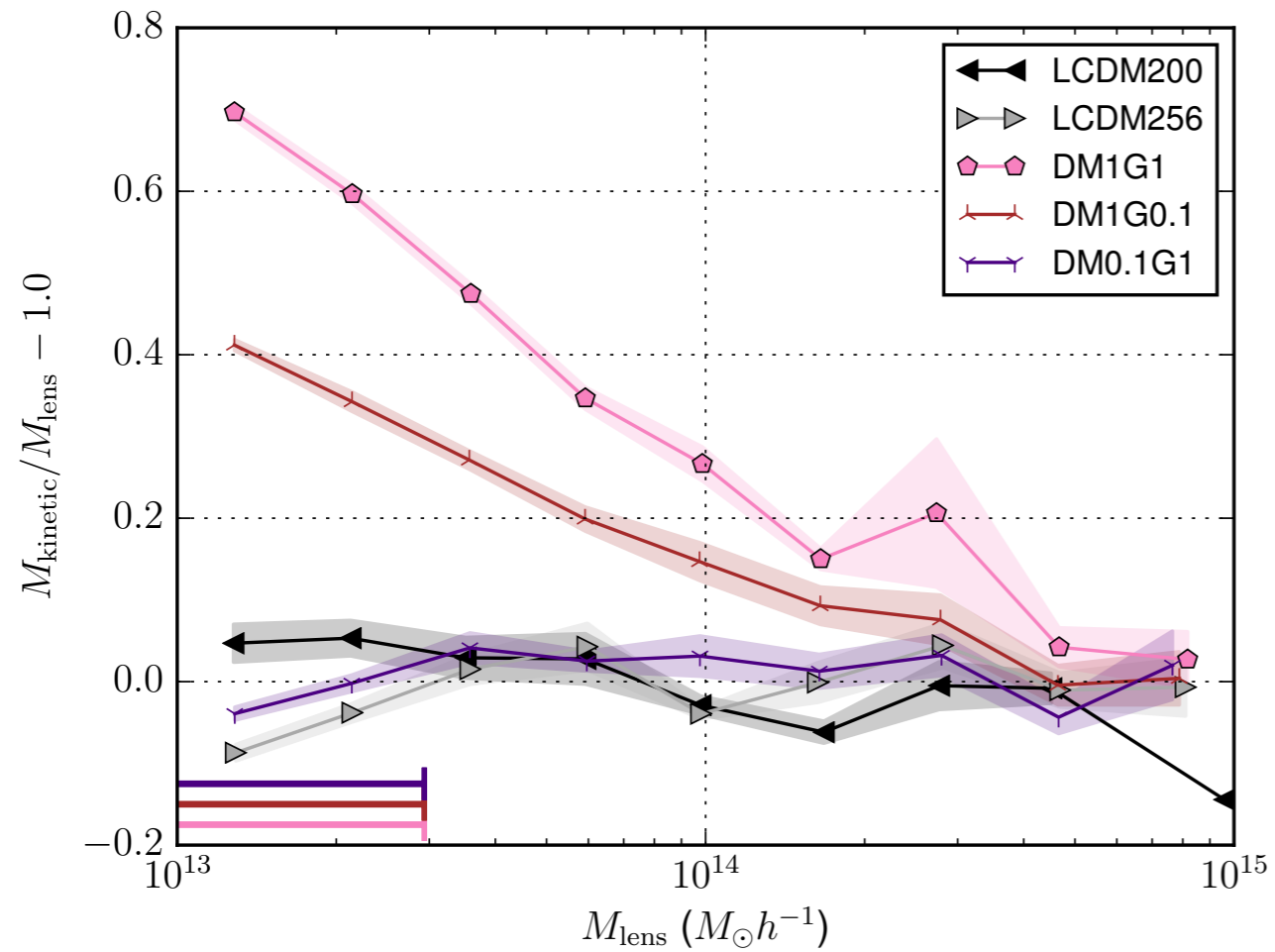
fofr6 ~ 2 Mpc

Large coupling / small scale screening



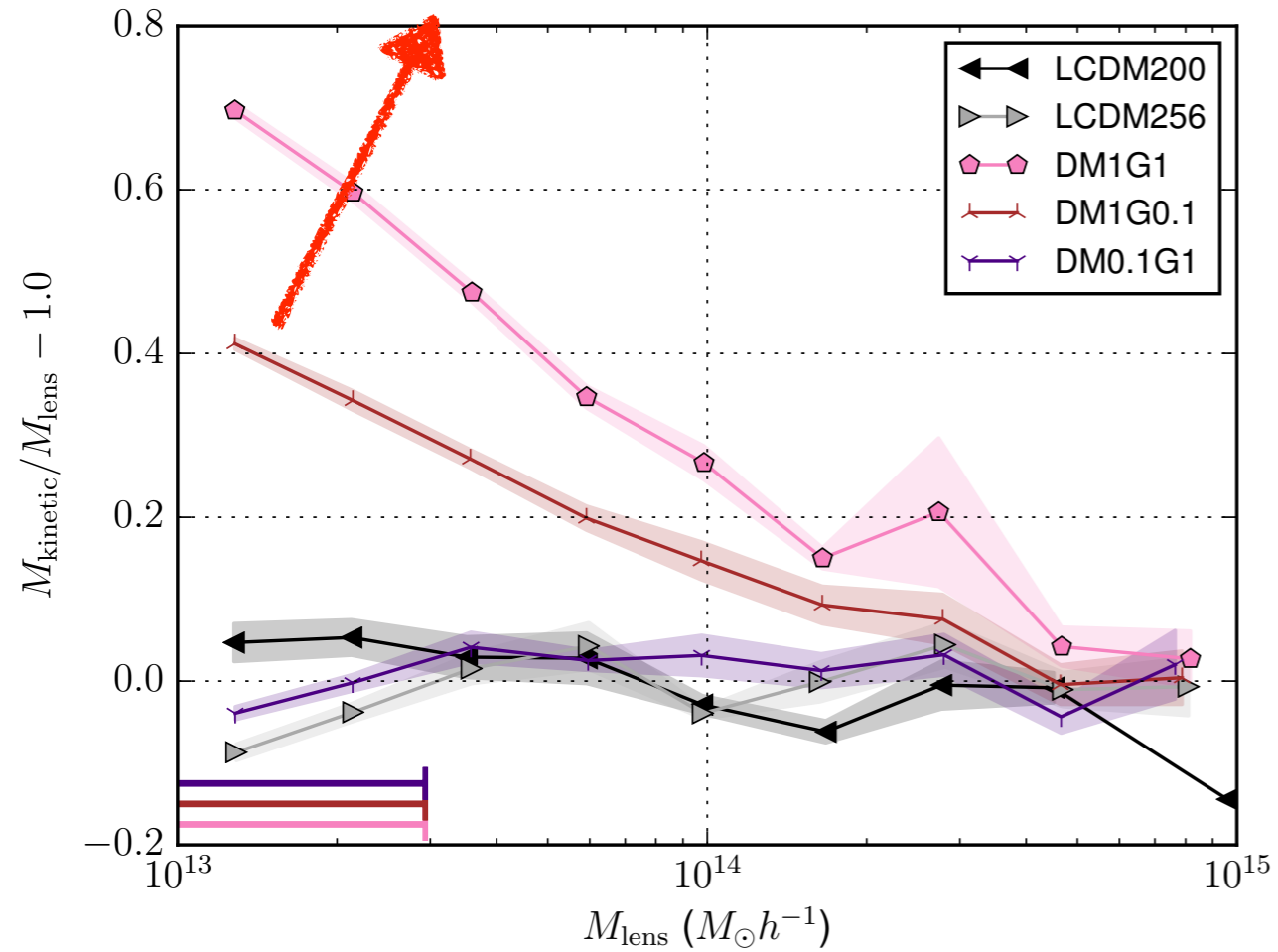
small coupling / large scale screening

Thermal + Lense+Kinematic Mass Probe for non-universal couplings



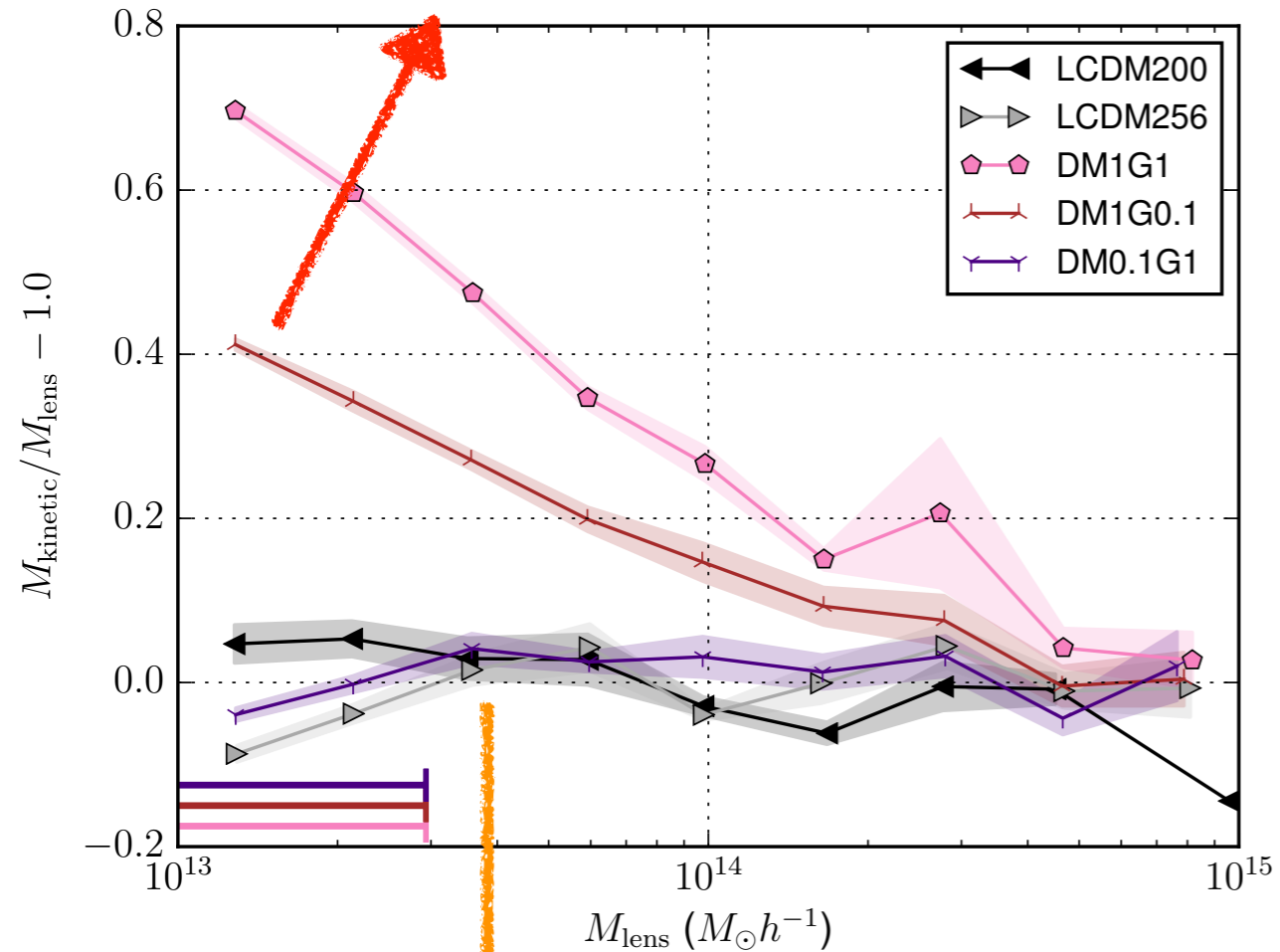
Thermal + Lense+Kinematic Mass Probe for non-universal couplings

Kinematic mass strongly
affected by coupling to DM



Thermal + Lense+Kinematic Mass Probe for non-universal couplings

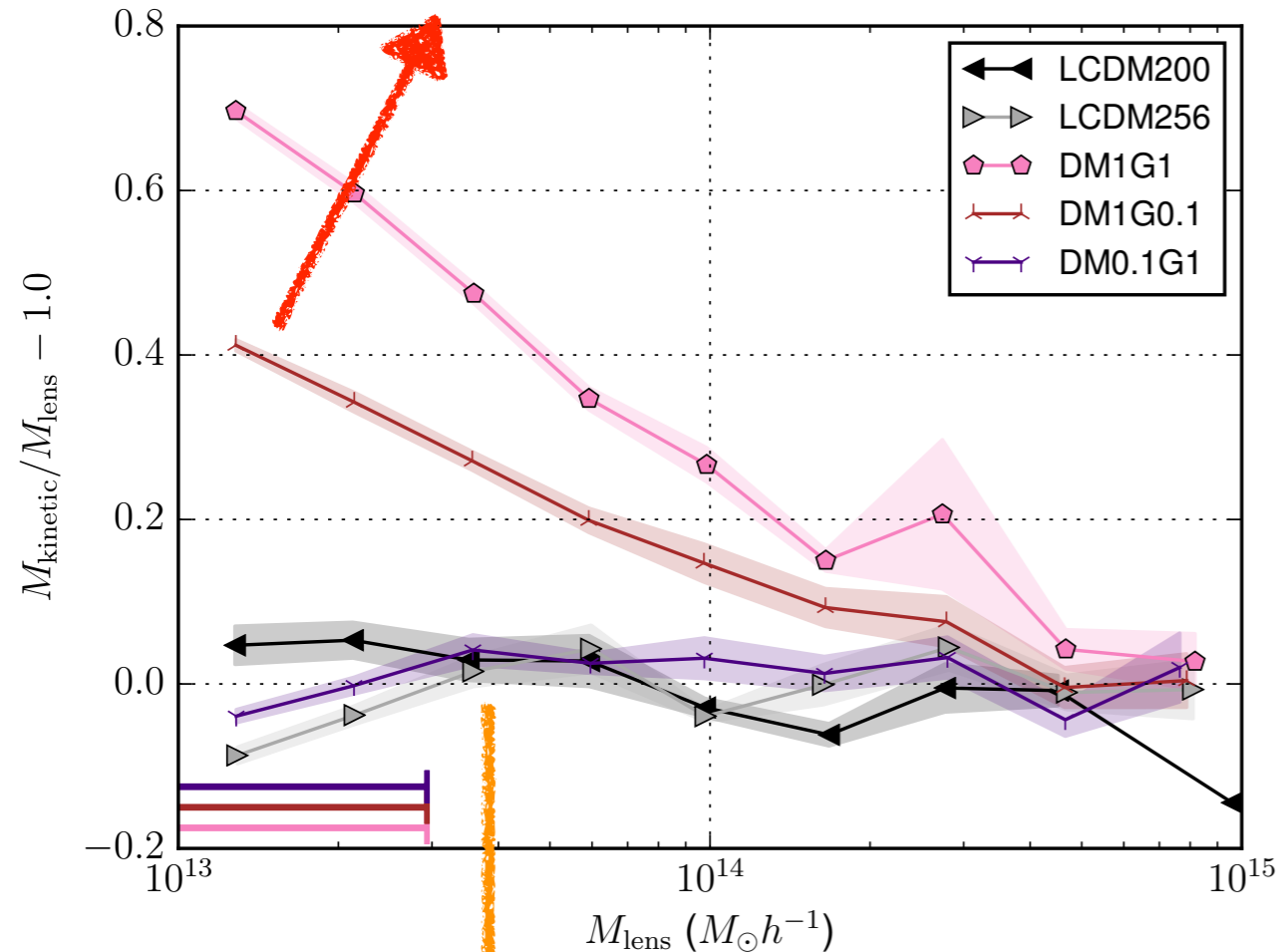
Kinematic mass strongly
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Kinematic mass weakly affected
by coupling to baryons

Thermal + Lense+Kinematic Mass Probe for non-universal couplings

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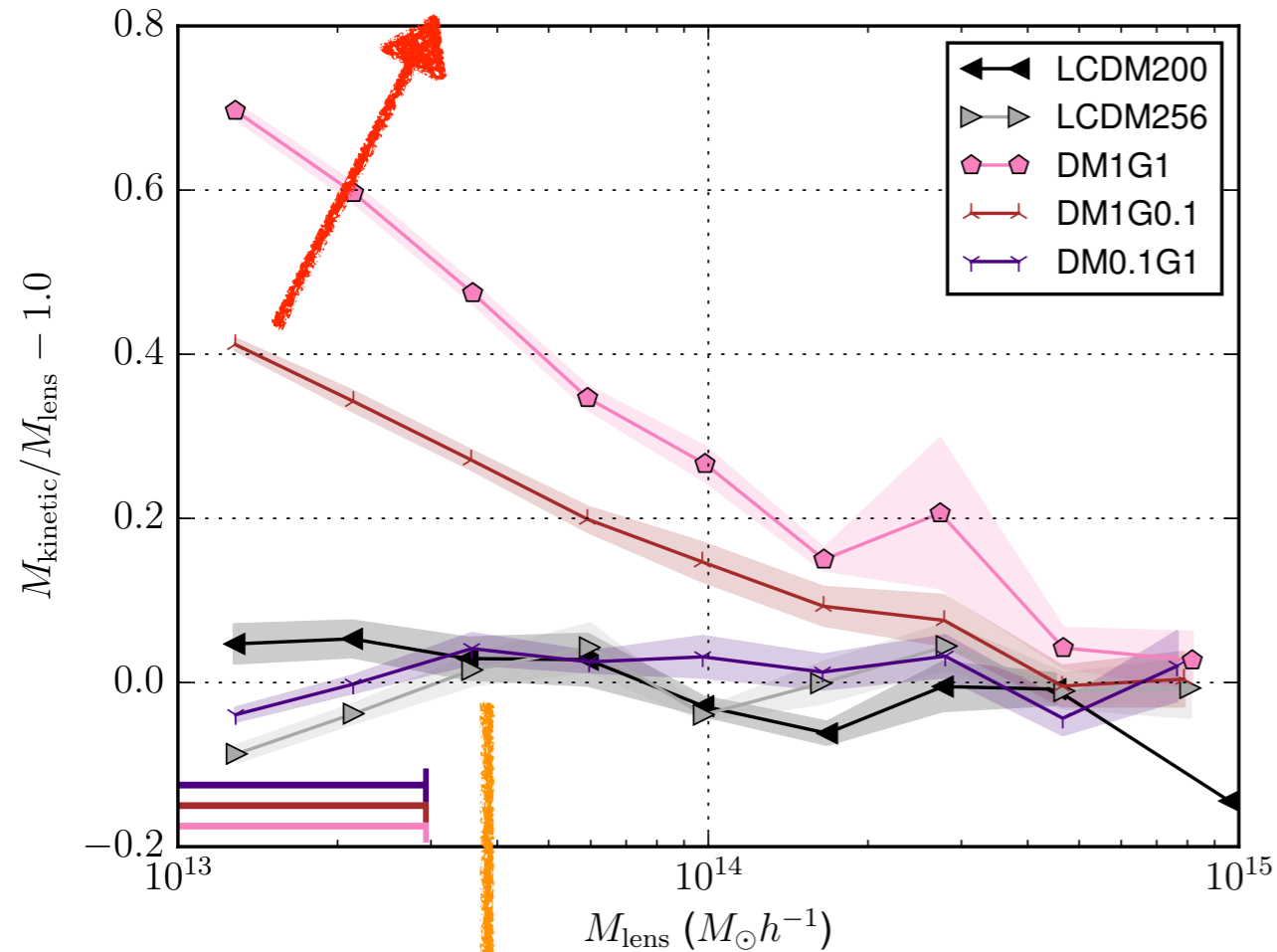


Kinematic mass weakly affected
by coupling to baryons

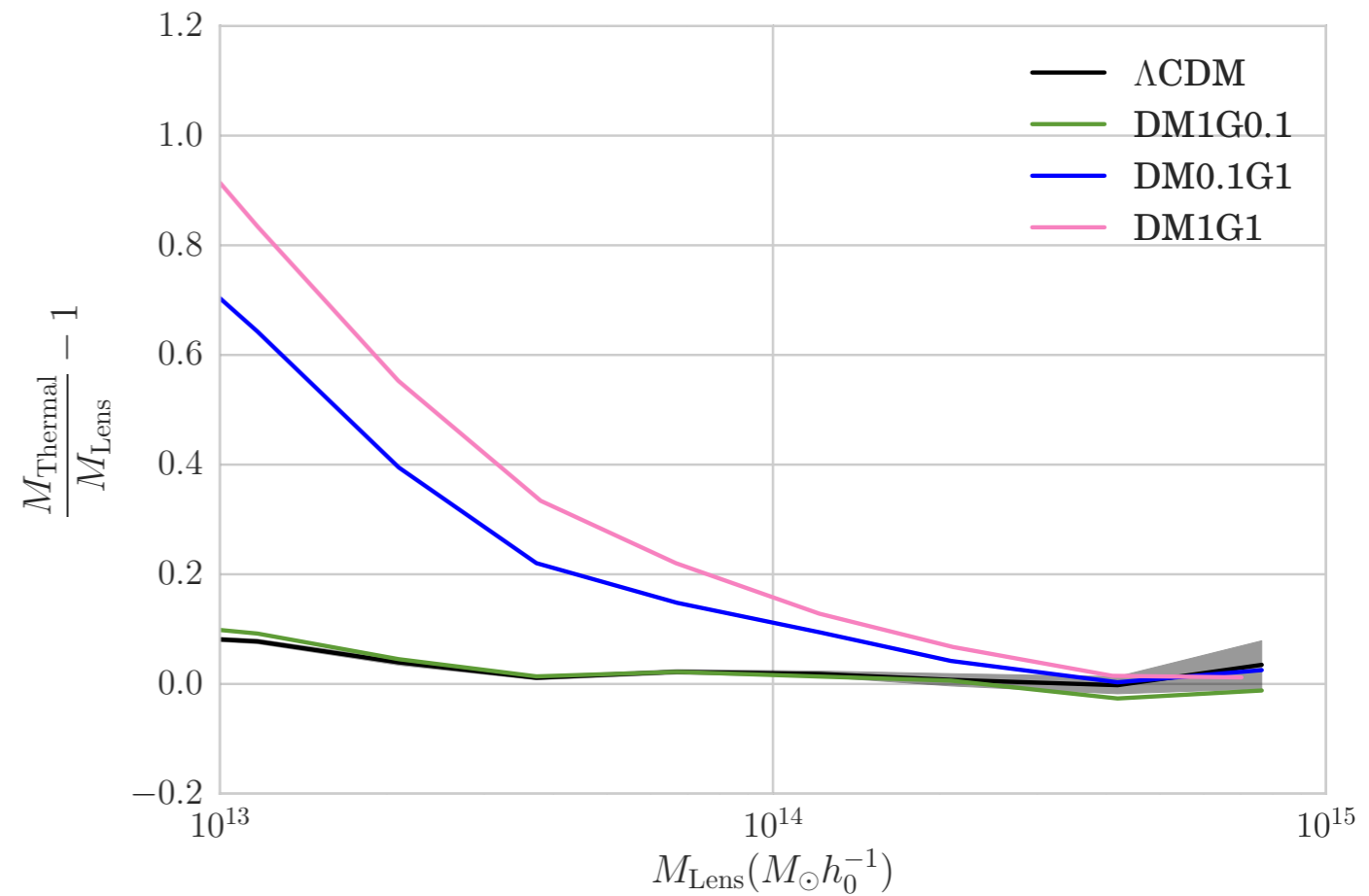
Kinematic Mass probes couplings to dark matter

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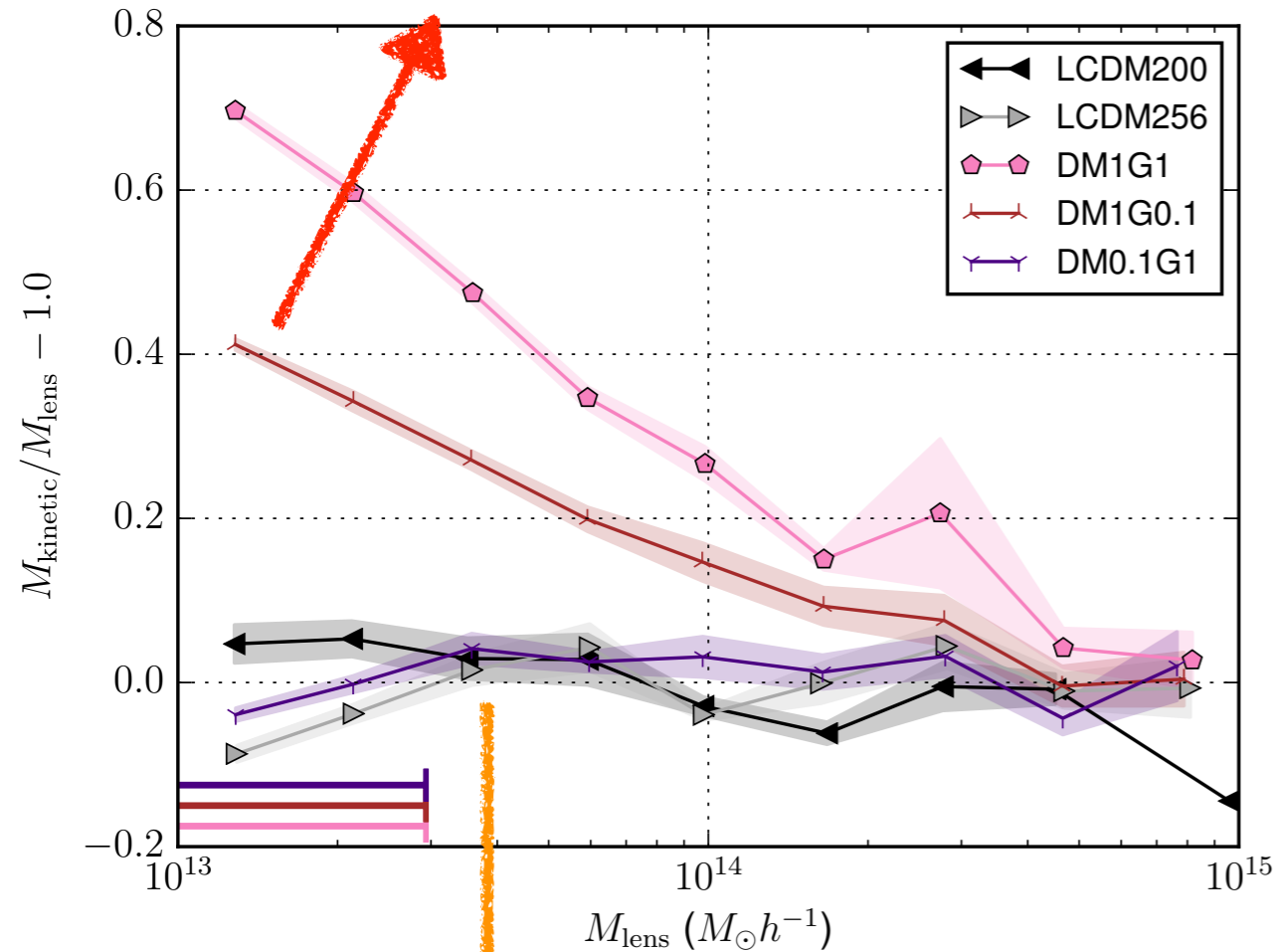
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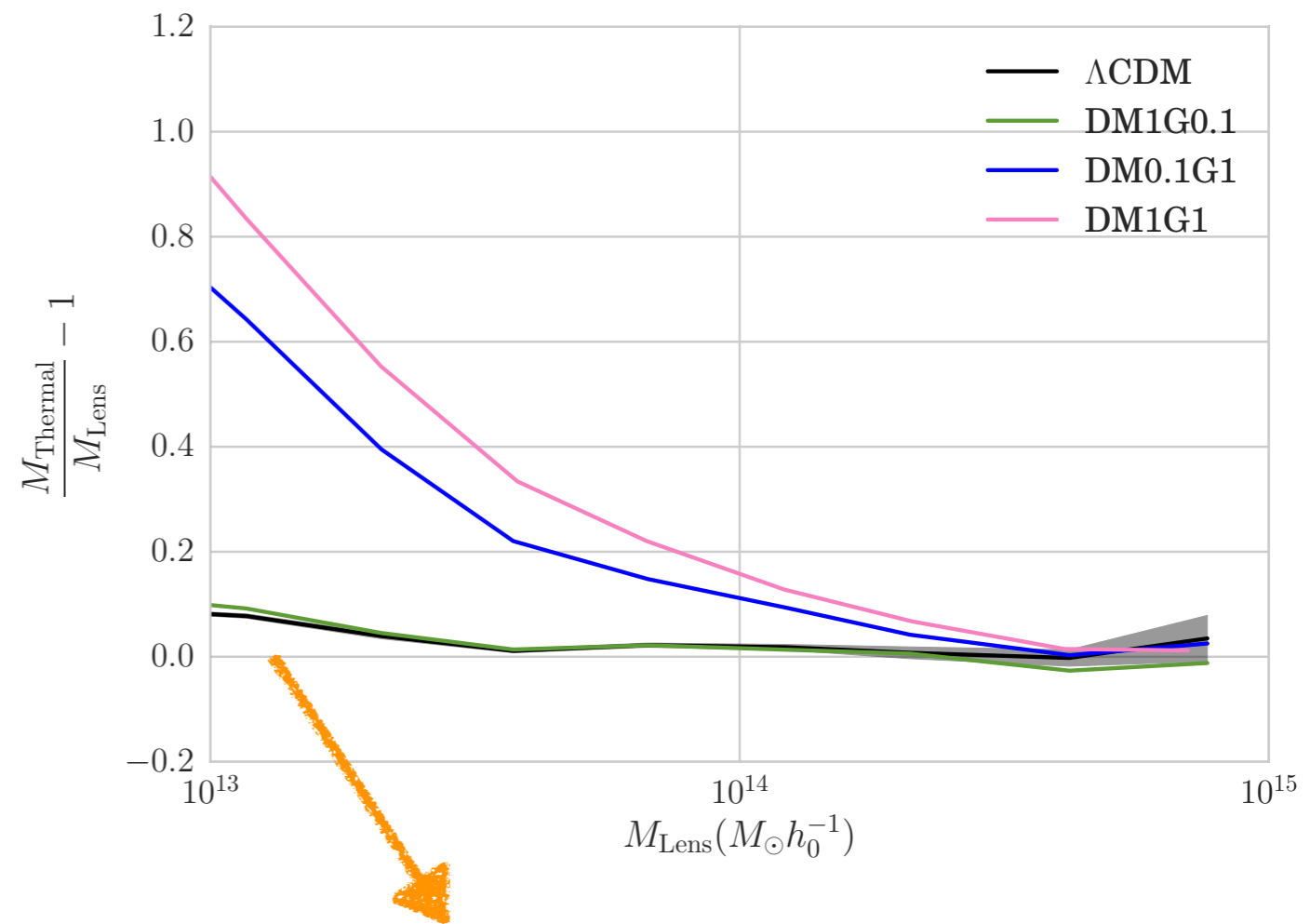
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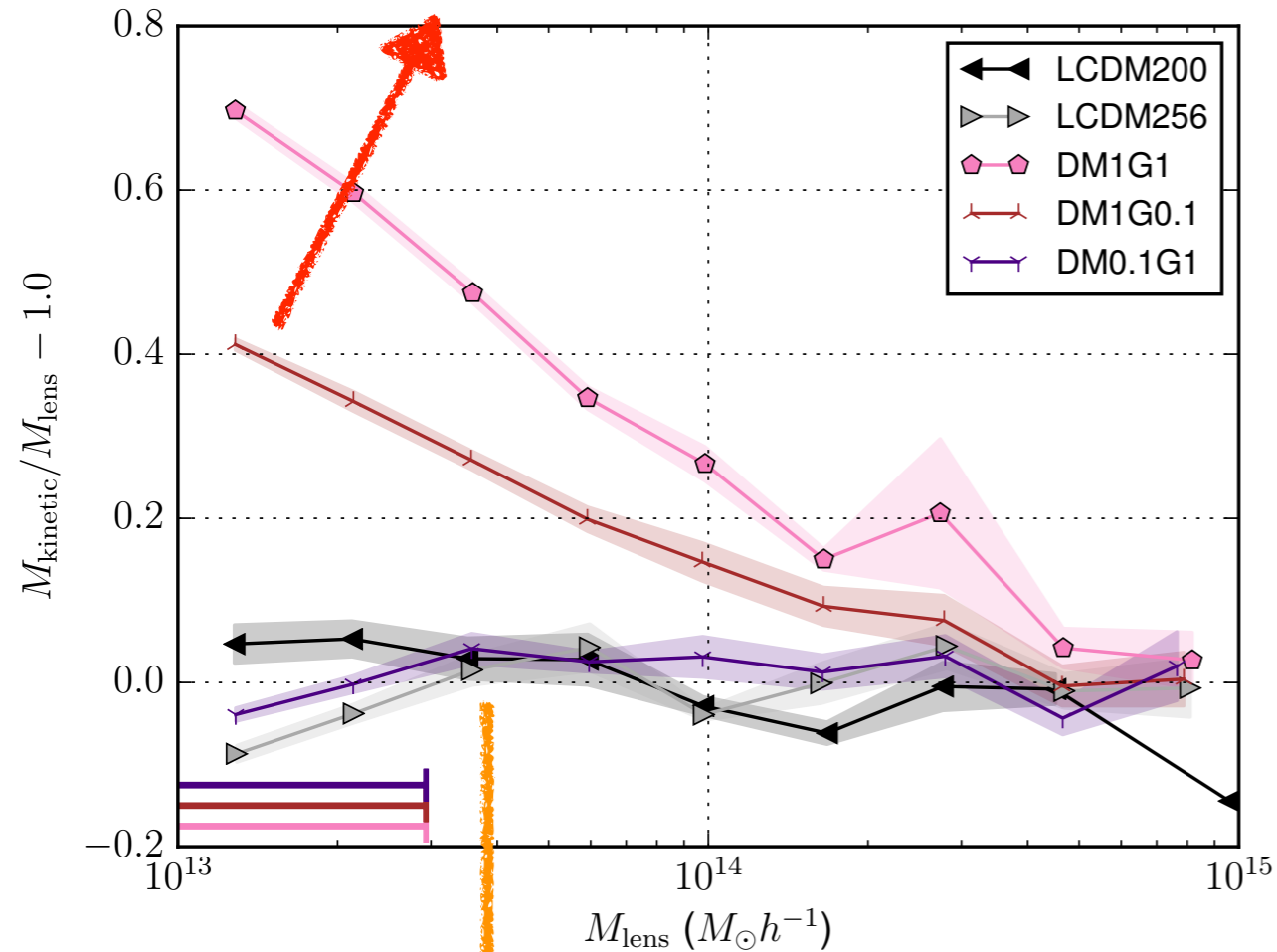
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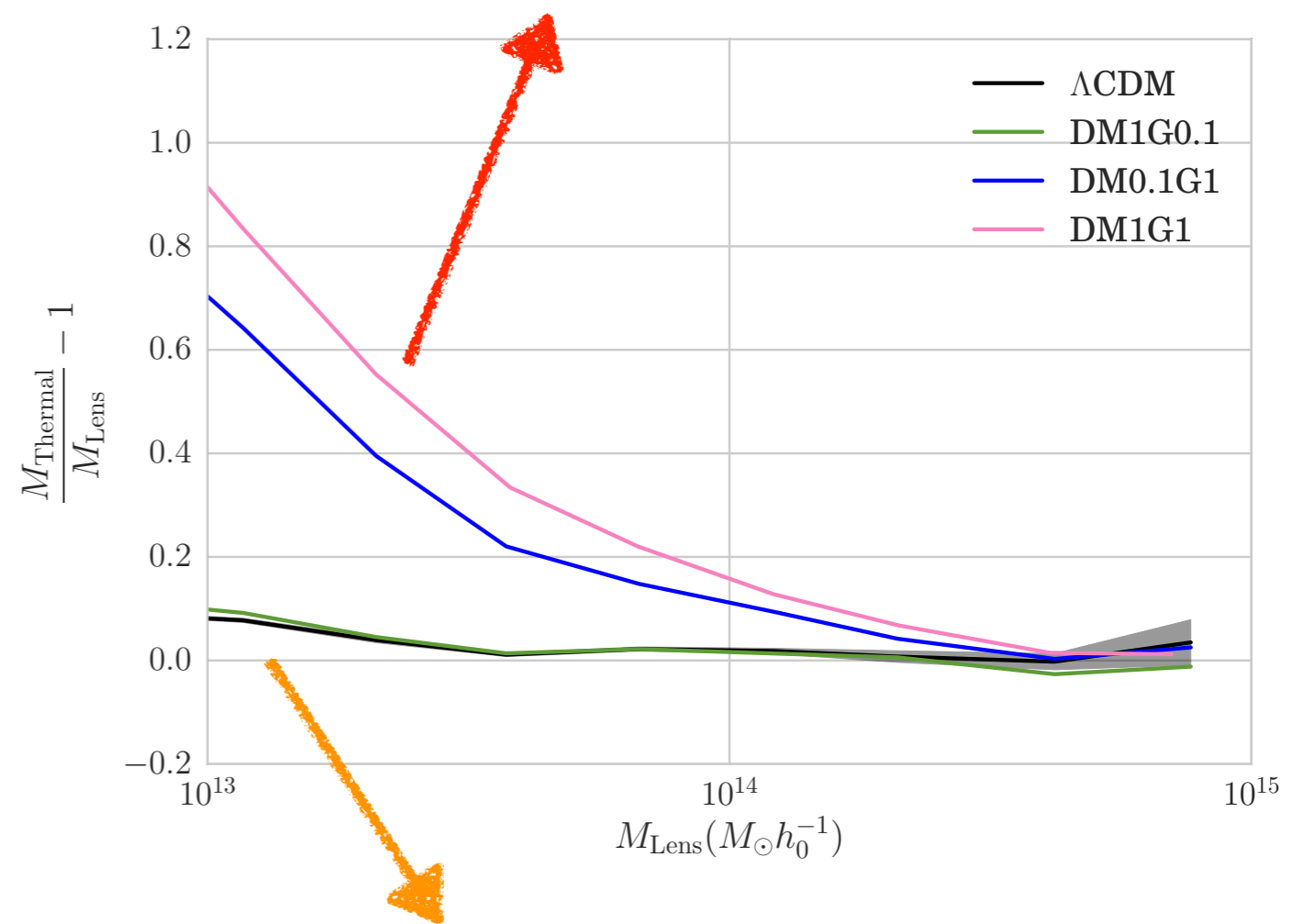
Probe for non-universal couplings

Kinematic mass strongly affected by coupling to DM

Thermal mass strongly affected by coupling to baryons



Kinematic mass weakly affected by coupling to baryons



Thermal mass weakly affected by coupling to dark matter

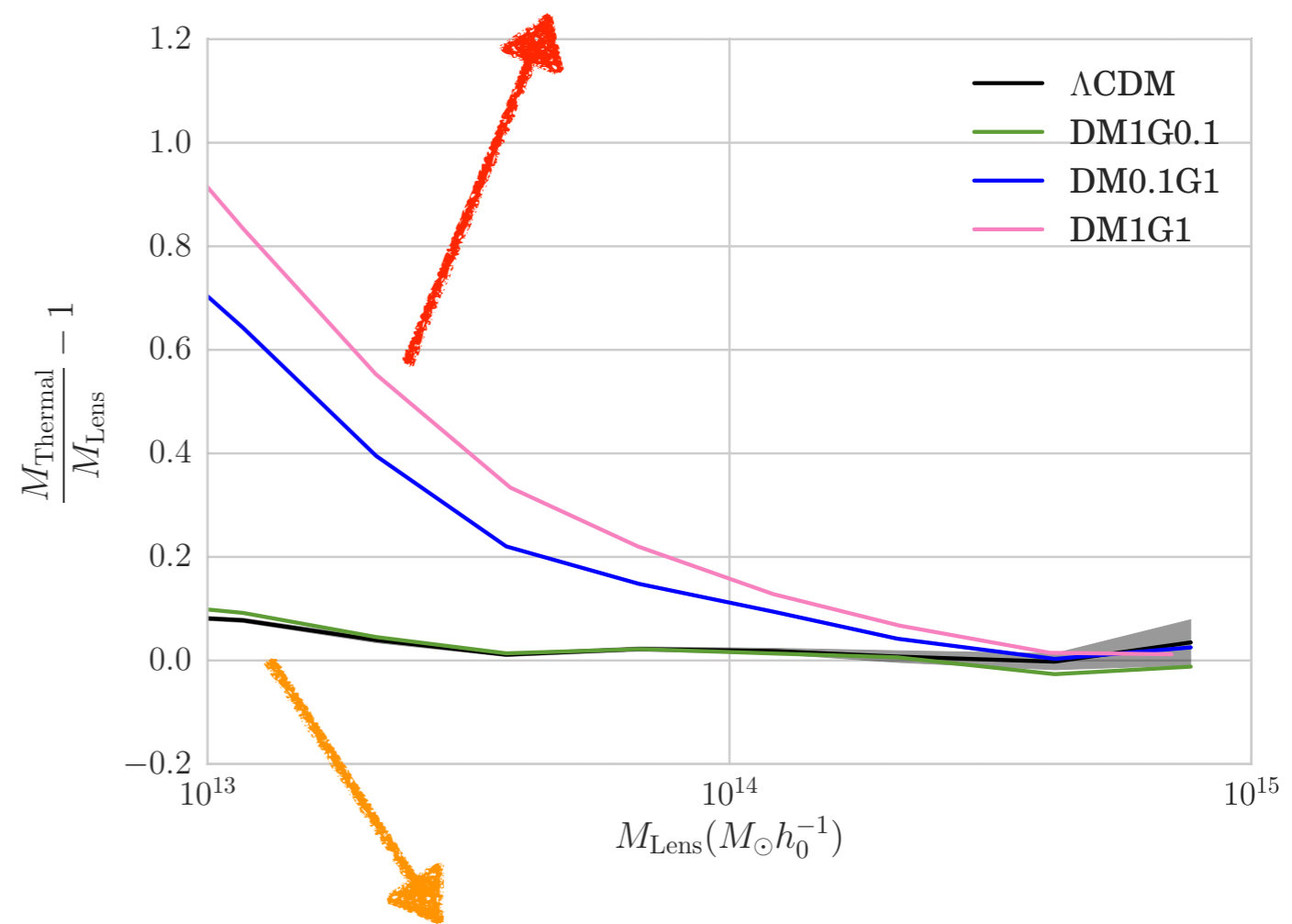
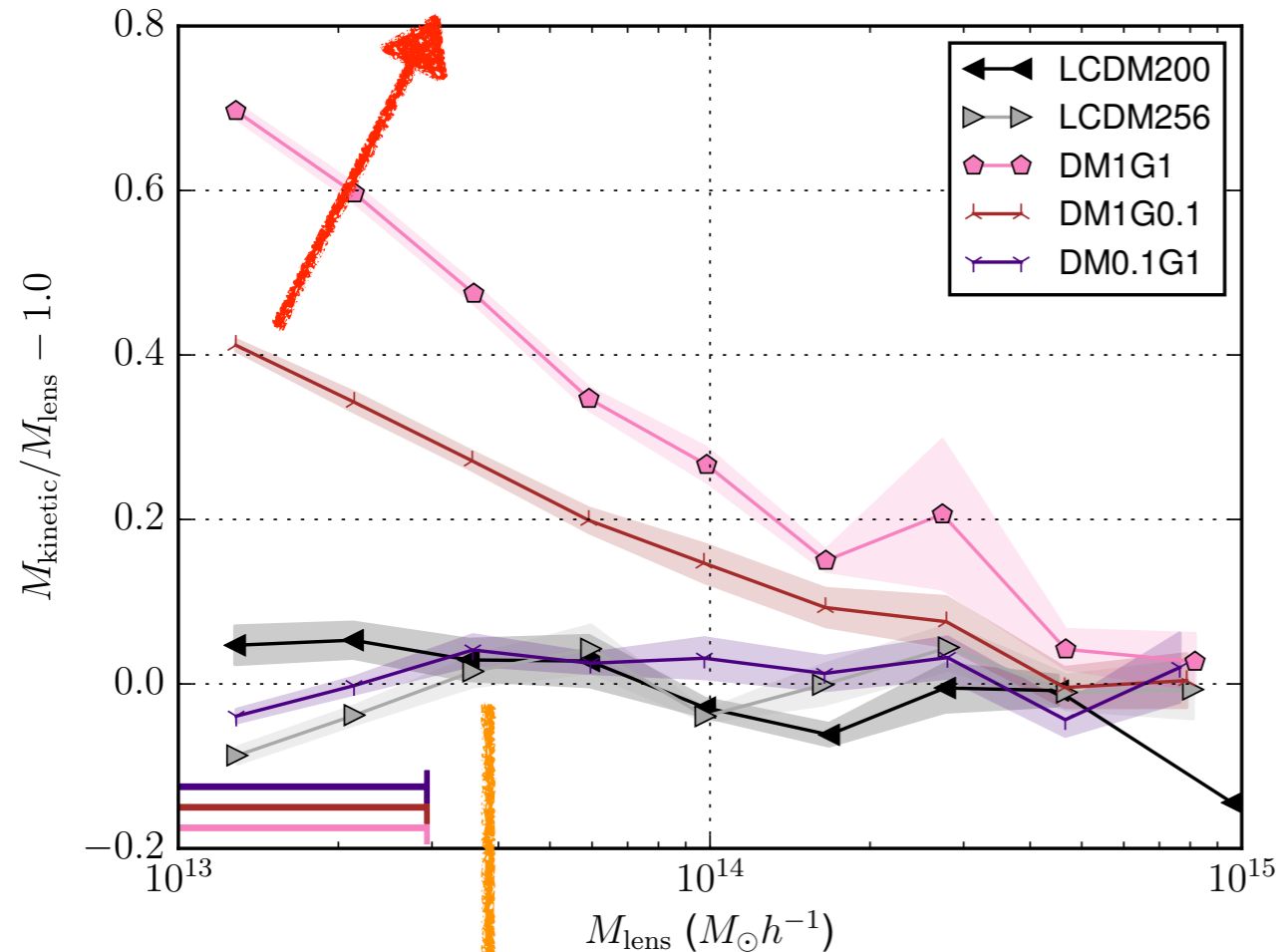
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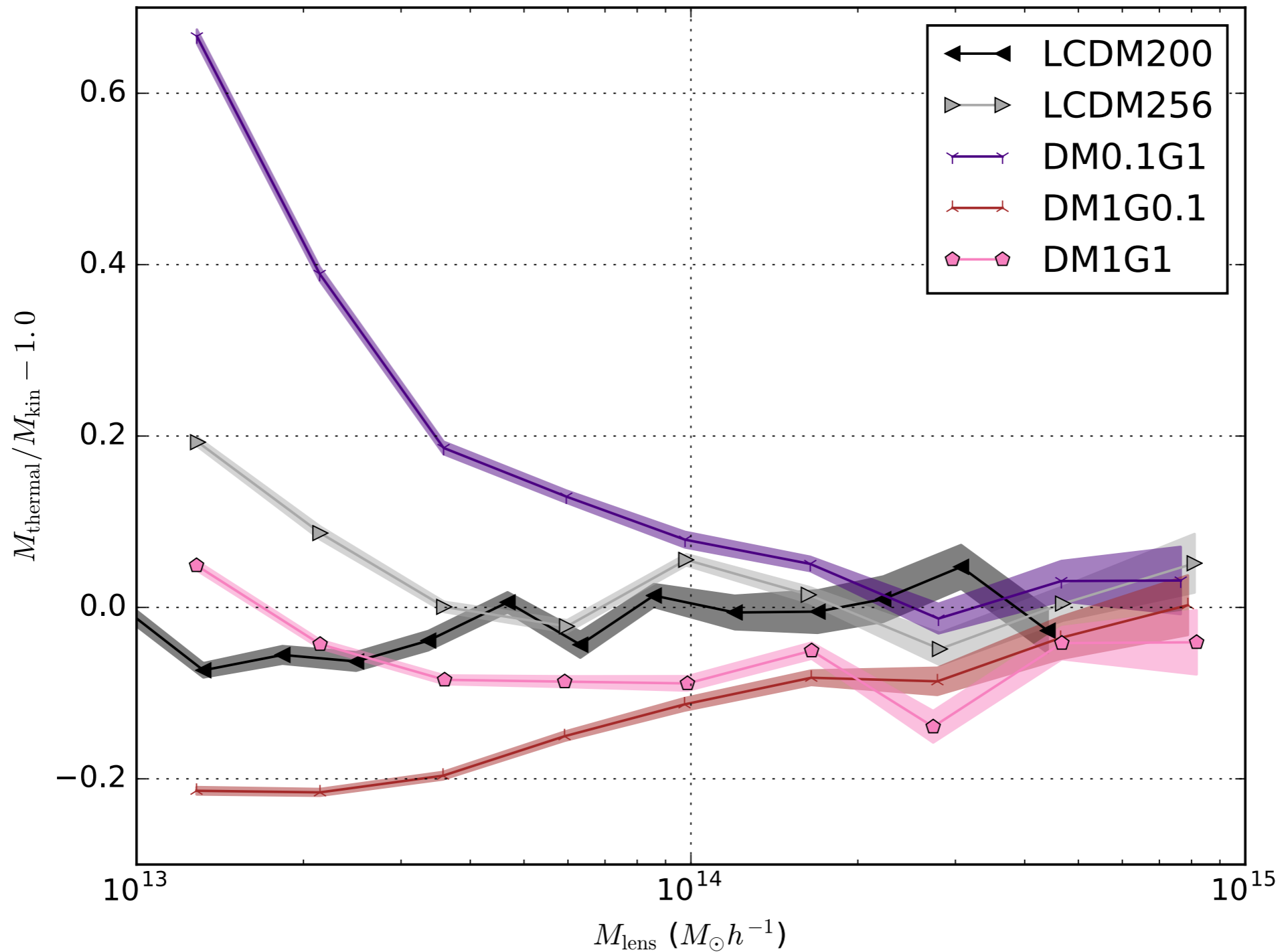
Kinematic mass weakly affected by coupling to baryons

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Kinematic Mass probes couplings to dark matter

Thermal Mass probes couplings to baryons

Probing for non-universal couplings



Summary

- ▶ The measured mass of galaxy clusters can probe equivalence principle violations
 - ▶ In screened modified gravity the mass inferred via lensing differs from the mass inferred via kinematical methods and thermal methods
 - ▶ The differences between the observed masses are environmental dependent
- ▶ Non-universally coupled models can be differentiated by combining lensing, kinematic and thermal mass
 - ▶ Lensing mass probes gravity
 - ▶ Kinematic mass probes coupling to dark matter
 - ▶ Thermal mass probes coupling to baryons