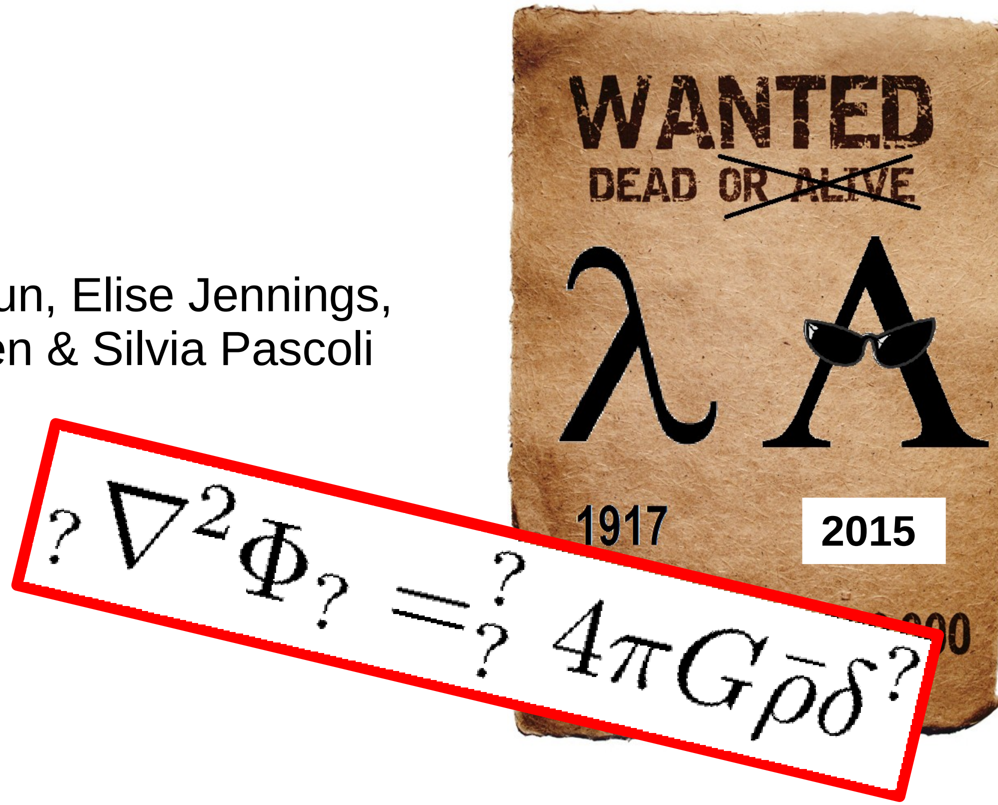
Lensing in modified lensing potentials

Alex Barreira
ICC&IPPP, Durham University, UK.

with Carlton M. Baugh, Marius Cautun, Elise Jennings, Lindsay King, Baojiu Li, Julian Merten & Silvia Pascoli



invisibles
neutrinos, dark matter & dark energy physics

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

ICC

Durham University

IP3

Theoretical and Observational Progress on Large-scale Structure of the Universe

Thursday, 23th July 2015, Garching, Germany

In modified gravity cosmologies

1) The Universe can expand at different rates

$$H^2 = H_0^2 \left[\Omega_{r0} a^{-4} + \Omega_{m0} a^{-3} + \Omega_{\rm de}(a)\right]$$

Not a constant !

In modified gravity cosmologies

1) The Universe can expand at different rates

$$H^2 = H_0^2\left[\Omega_{r0}a^{-4} + \Omega_{m0}a^{-3} + \Omega_{\rm de}(a)\right]$$

Not a constant !

2) The gravitational force law is modified.

$$\nabla^2\Phi = 4\pi G\bar{\rho}_m\delta + \text{Something else}$$

$$\Phi = \Phi_{\rm dyn} = \Phi_{\rm len}$$

In modified gravity cosmologies

1) The Universe can expand at different rates

$$H^2 = H_0^2 \left[\Omega_{r0} a^{-4} + \Omega_{m0} a^{-3} + \Omega_{\rm de}(a)\right]$$

Not a constant !

2) The gravitational force law is modified.

$$\nabla^2 \Phi = 4\pi G \bar{\rho}_m \delta + \text{Something else}$$

$$\Phi = \Phi_{\rm dyn} = \Phi_{\rm len}$$

Key to this talk: lensing potential is directly modified !

Galileon as a working case

- ***Cubic Galileon*** $S=\int \mathrm{d}^4x\sqrt{g}\left[\frac{R}{16\pi G}+\mathcal{L}_m+\nabla^\mu\varphi\nabla_\mu\varphi\left(\frac{c_2}{2}+\frac{c_3}{2\mathcal{M}^3}\Box\varphi\right)\right]$

Nicolis et al. (2009); Defayet et al. (2009)

Galileon as a working case

- ***Cubic Galileon*** $S = \int \mathrm{d}^4x\sqrt{g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \nabla^\mu\varphi\nabla_\mu\varphi\left(\frac{c_2}{2} + \frac{c_3}{2\mathcal{M}^3}\Box\varphi\right)\right]$

Nicolis et al. (2009); Defayet et al. (2009)

Time and density dependent gravitational strength

Normal gravity **Fifth force term**

$$\nabla^2\Phi = 4\pi G\bar{\rho}_m\delta + f(a)\nabla^2\varphi(a,\delta)$$

$$= 4\pi G_{\rm eff}(a,\delta)\bar{\rho}_m\delta$$

Galileon as a working case

- ***Cubic Galileon*** $S=\int d^4x\sqrt{g}\left[\frac{R}{16\pi G}+\mathcal{L}_m+\nabla^\mu\varphi\nabla_\mu\varphi\left(\frac{c_2}{2}+\frac{c_3}{2\mathcal{M}^3}\Box\varphi\right)\right]$

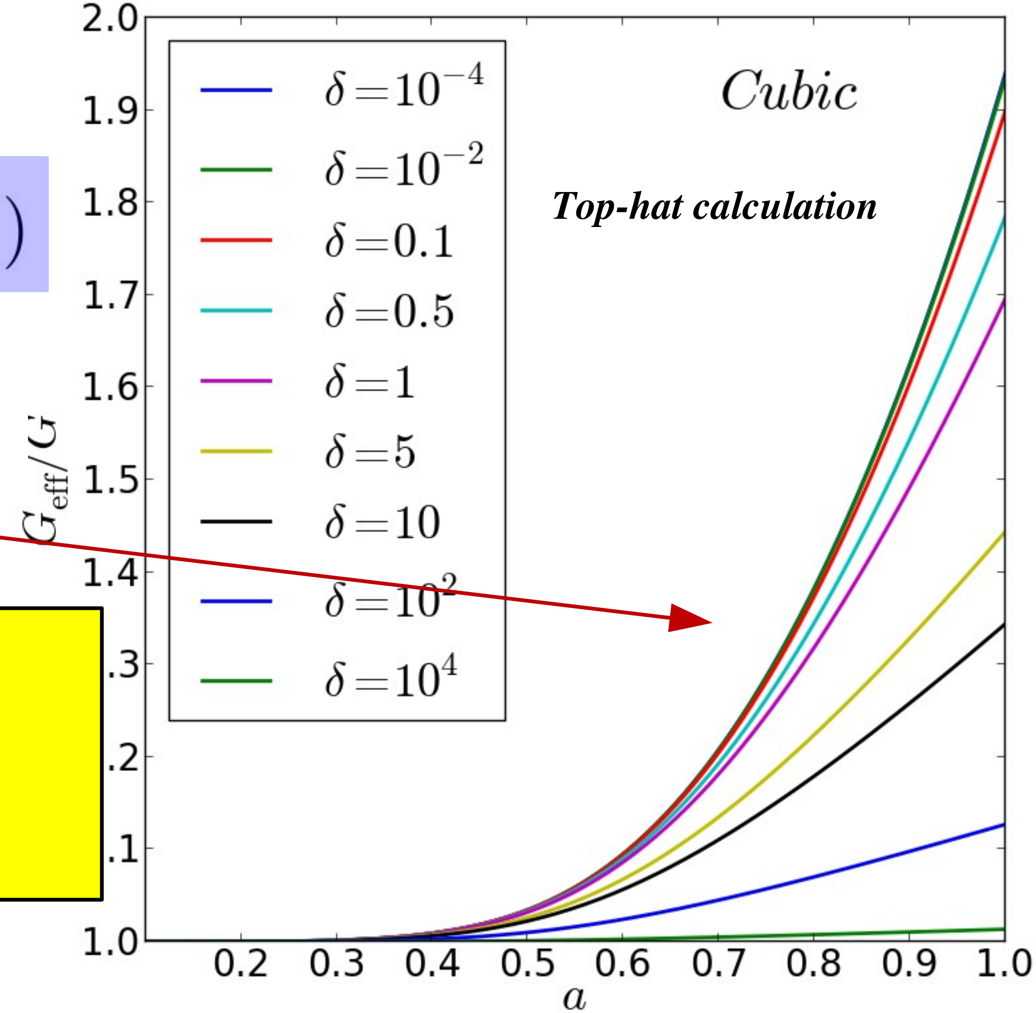
Nicolis et al. (2009); Defayet et al. (2009)

Time and density dependent gravitational strength

Normal gravity / Fifth force term

$$\nabla^2\Phi = 4\pi G\bar{\rho}_m\delta + f(a)\nabla^2\varphi(a,\delta)$$

$$= 4\pi G_{\rm eff}(a,\delta)\bar{\rho}_m\delta$$



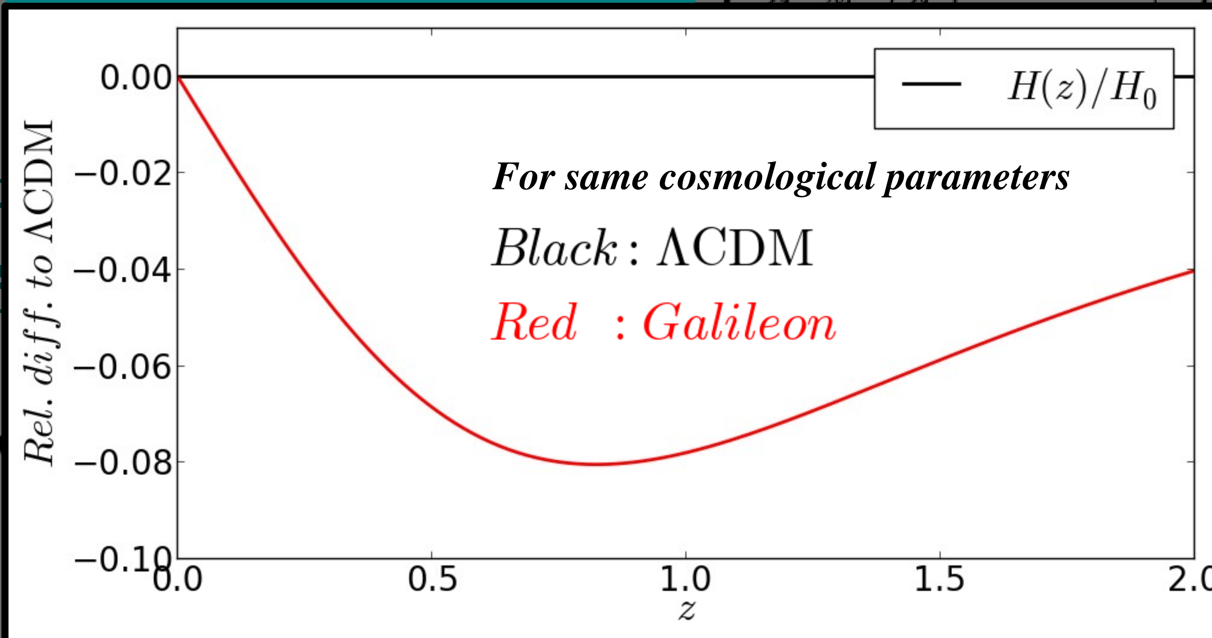
Vainshtein screening:
Enhancement gets suppressed when density contrast is high

Galileon as a working case

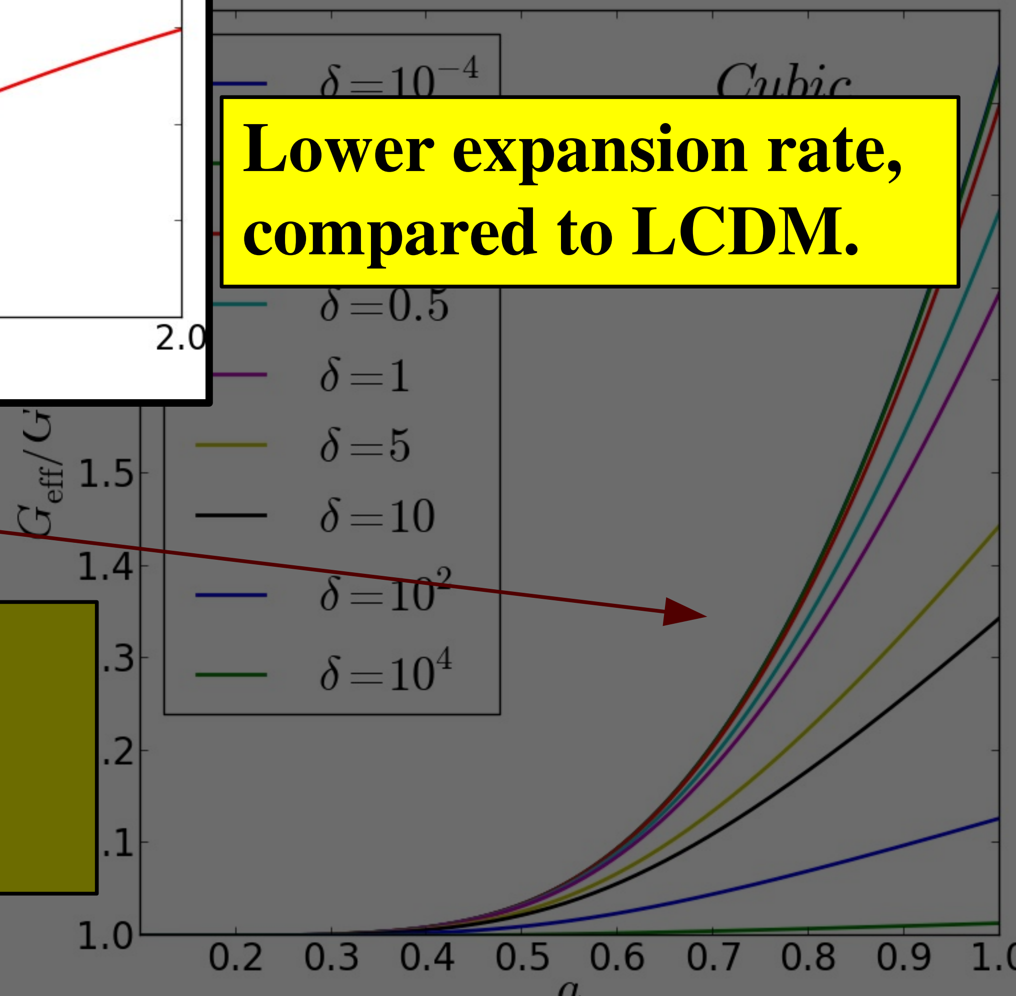
Hubble expansion rate

$$\int d^4x \sqrt{-g}\left[\frac{R}{\ldots} + \mathcal{L}_m + \nabla^\mu\varphi\nabla_\mu\varphi\left(\frac{c_2}{2} + \frac{c_3}{2\mathcal{M}^3}\Box\varphi\right)\right]$$

…colis et al. (2009); Defayet et al. (2009)



$$= 4\pi G_{\rm eff}(a,\delta)\bar{\rho}_m\delta$$



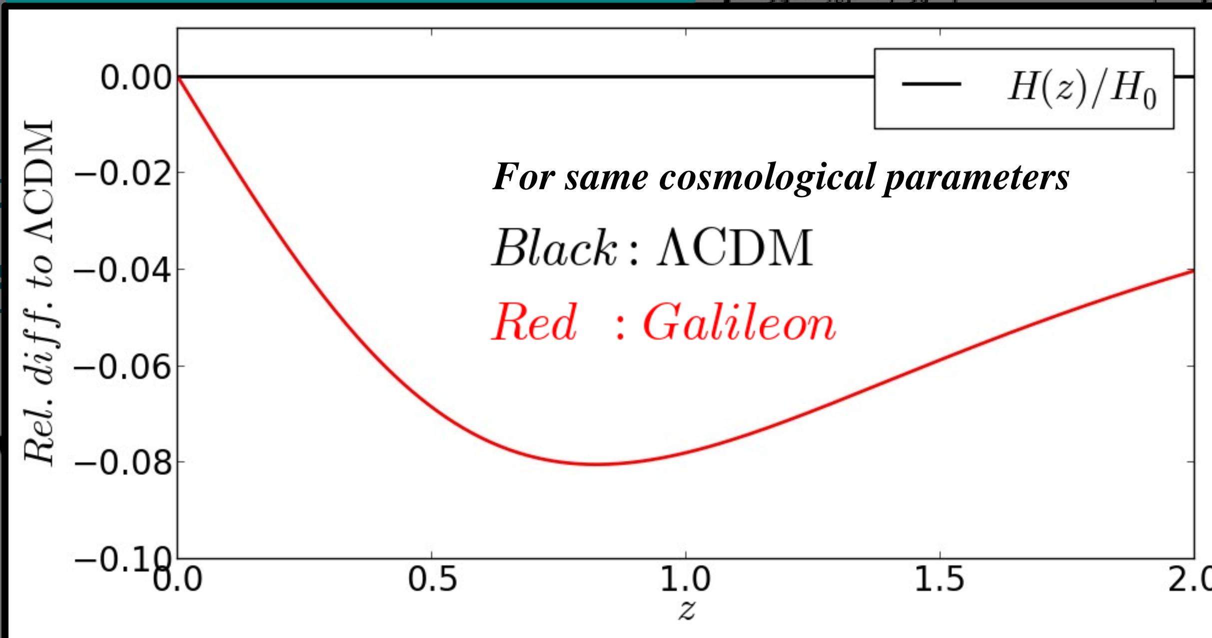
Lower expansion rate, compared to LCDM.

Vainshtein screening:

Enhancement gets suppressed when density contrast is high

Galileon as a working case

Hubble expansion rate



...colis et al. (2009); Defayet et al. (2009)

Lower expansion rate, compared to LCDM.

Observational constraints

Fits CMB temperature, CMB lensing and BAO !

Nice !

Barreira et al (2014); arXiv:1406.0485

Tensions with sign of the ISW effect !

Not Nice !

Outline

1) **Lensing by clusters**

Barreira et al ; arXiv:1505.03468

2) **Lensing by voids**

Barreira et al ; arXiv:1505.05809

Lensing by clusters

Methodology

1) ***Lensing convergence profiles*** from non-parametric reconstructions of the lensing potential for 19 CLASH galaxy clusters.

Merten et al. (2015) ApJ 806, 4

$$z_{\text{clusters}} \sim [0.2,\ 0.9]$$
$$z^{\text{eff}}_{\text{sources}} \sim [0.9,\ 1.5]$$

2) Fit the ***NFW lensing signal*** computed in the modified gravity cosmologies.

3) How ***sensitive*** are the constraints on *M200* and *c200* on the ***assumed theory of gravity*** ?

Methodology

1) ***Lensing convergence profiles*** from non-parametric

survey galaxy clusters.

$z_{\rm clusters} \sim [0.2,\ 0.9]$

$z^{\rm eff}_{\rm sources} \sim [0.9,\ 1.5]$

Careful about model-dependent analysis !!

2) Fit the ***NFW lensing signal*** computed in the modified gravity cosmologies.

3) How ***sensitive*** are the constraints on *M200* and *c200* on the ***assumed theory of gravity*** ?

Methodology

Careful about model-dependent analysis !!

$z_{\mathrm{clusters}} \sim [0.2,\ 0.9]$

<u>1) Careful about LCDM angular diameter distances in the data analysis.</u>

Tractable by scaling these distances, but need to do it !

2) Fit the ***<u>NFW lensing signal</u>*** computed in the modified gravity cosmologies.

3) How ***<u>sensitive</u>*** are the constraints on *M200* and *c200* on the ***<u>assumed theory of gravity</u>*** ?

Methodology

Careful about model-dependent analysis !!

$z_{\rm clusters} \sim [0.2,\ 0.9]$

<u>1) Careful about **LCDM angular diameter distances** in the data analysis.</u>

Tractable by scaling these distances, but need to do it !

*2) <u>Careful about using **GR in parametrized mass modelling!**</u>*

CLASH analysis being used here is nonparametric, so we're good !

3) How ***<u>sensitive</u>*** are the constraints on *M200* and *c200* on the ***<u>assumed theory of gravity</u>*** ?

Methodology

Careful about model-dependent analysis !!

$z_{\rm clusters} \sim [0.2,\ 0.9]$

1) Careful about LCDM angular diameter distances in the data analysis.

Tractable by scaling these distances, but need to do it !

al computed
logies.

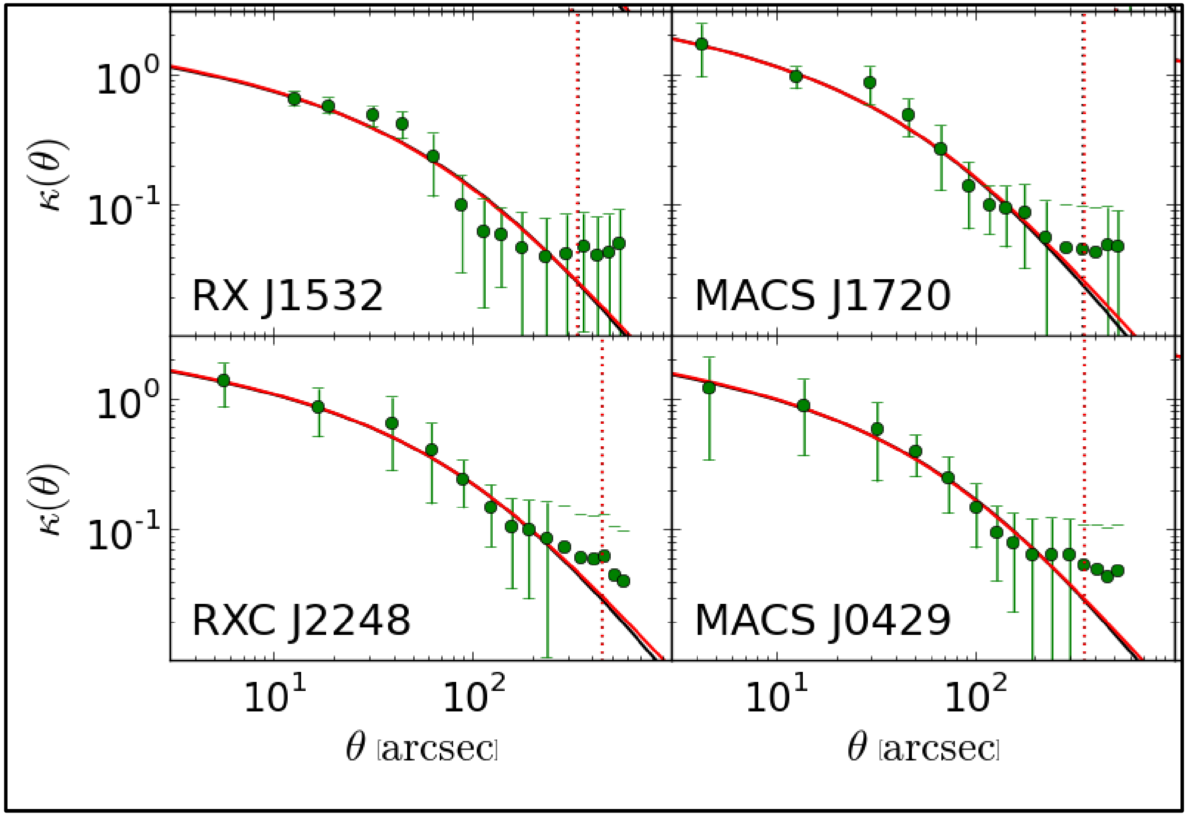
2) Careful about using GR in parametrized mass modelling!

CLASH analysis being used here is nonparametric, so we're good !

If working with modified gravity remember: photons do not trace mass, they trace potentials !

Cluster lensing masses

Lensing profiles for 4 CLASH clusters

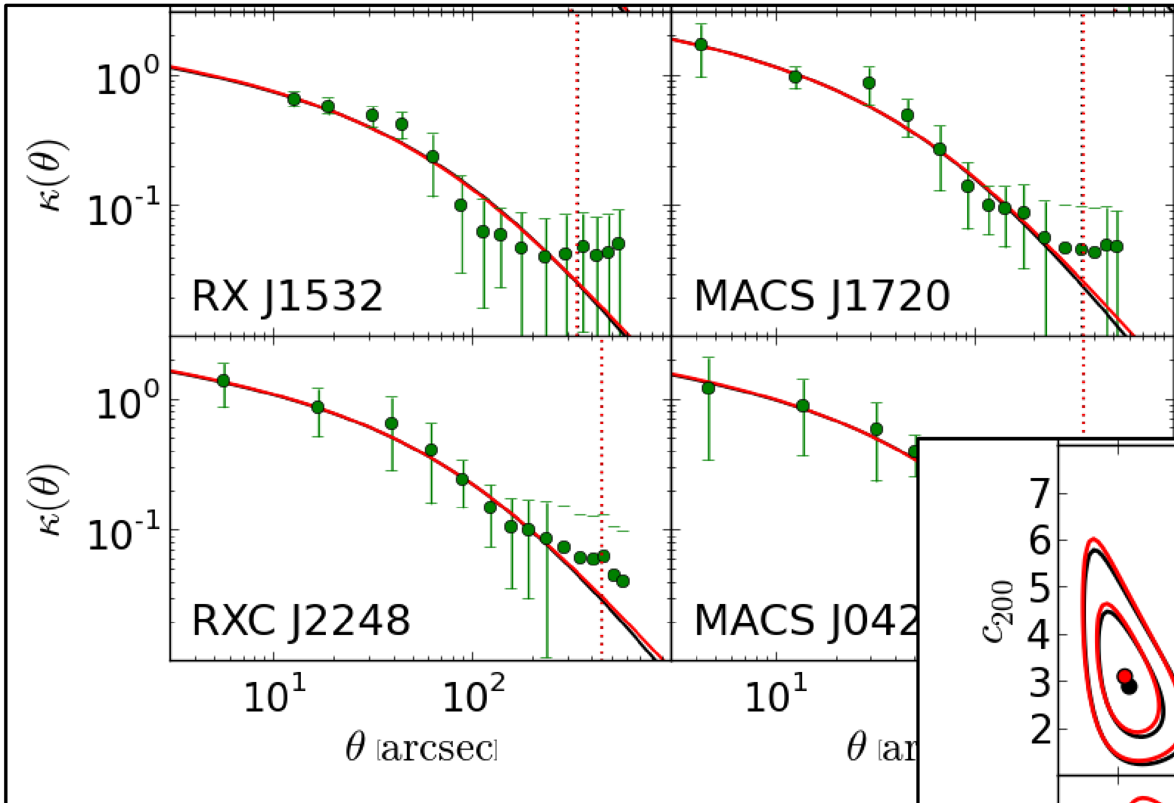


$Black : \Lambda\mathrm{CDM}$

$Red \;\; : Galileon$

Cluster lensing masses

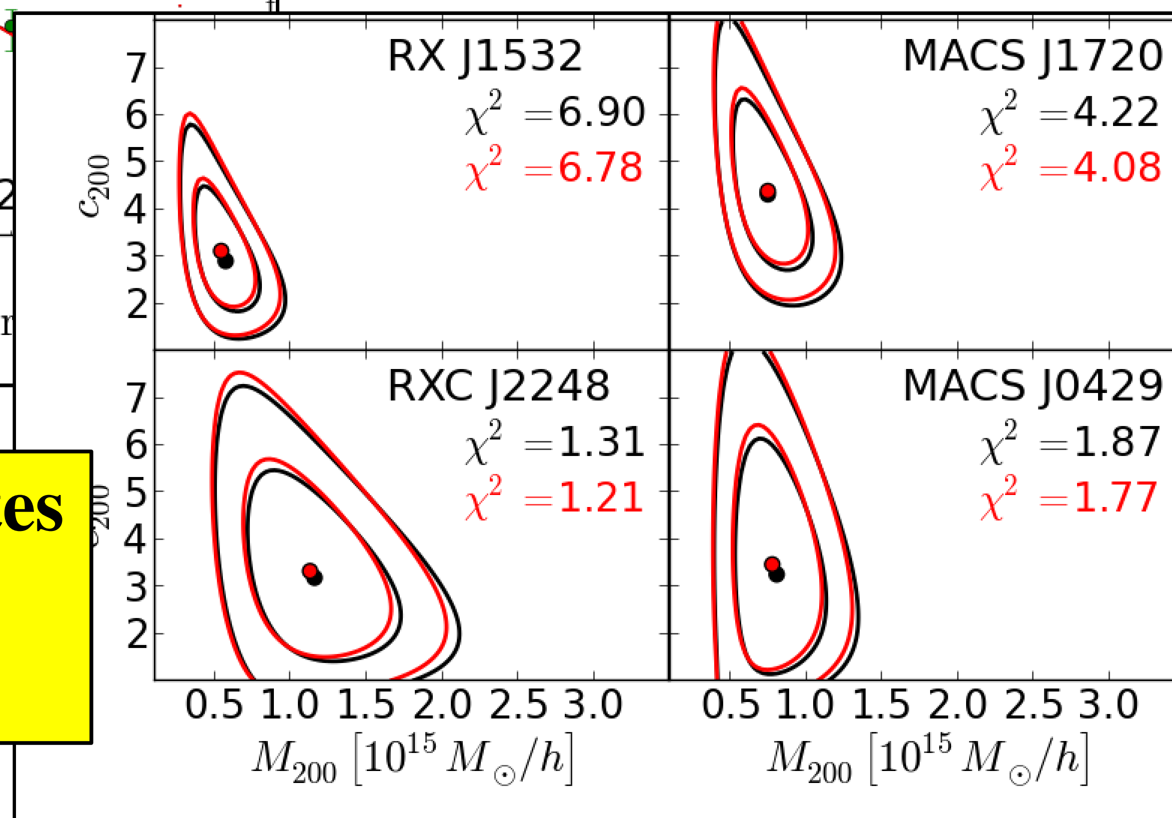
Lensing profiles for 4 CLASH clusters



$Black : \Lambda\mathrm{CDM}$

$Red : Galileon$

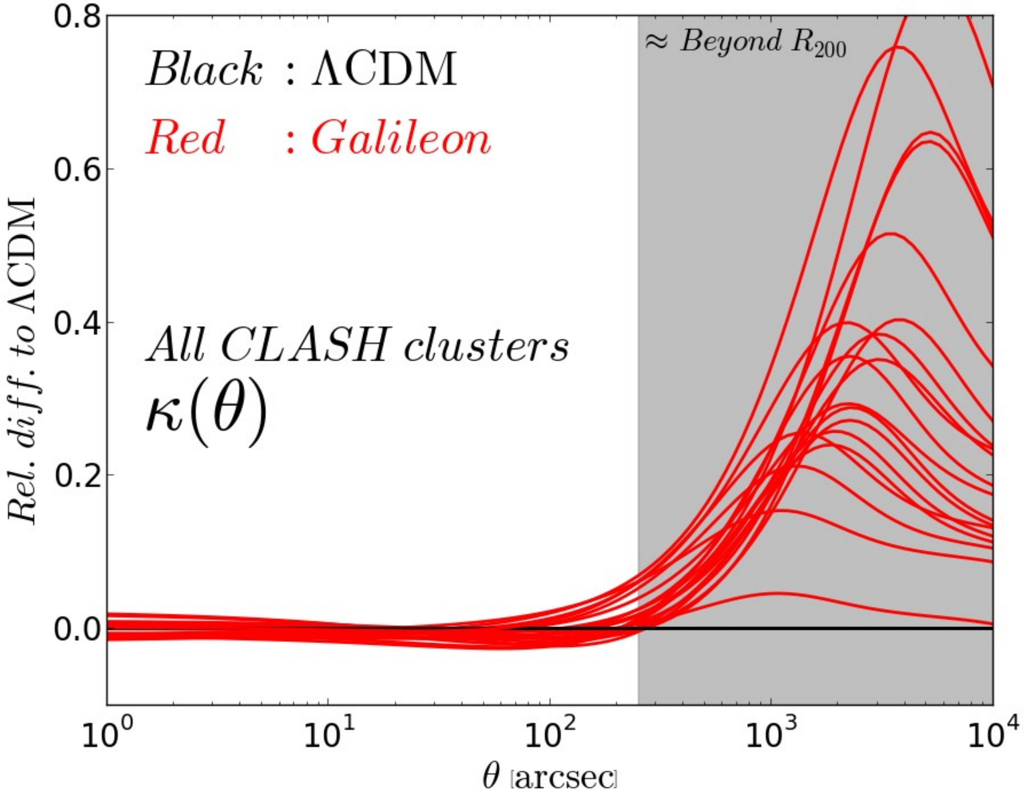
c-M contours for 4 CLASH clusters.



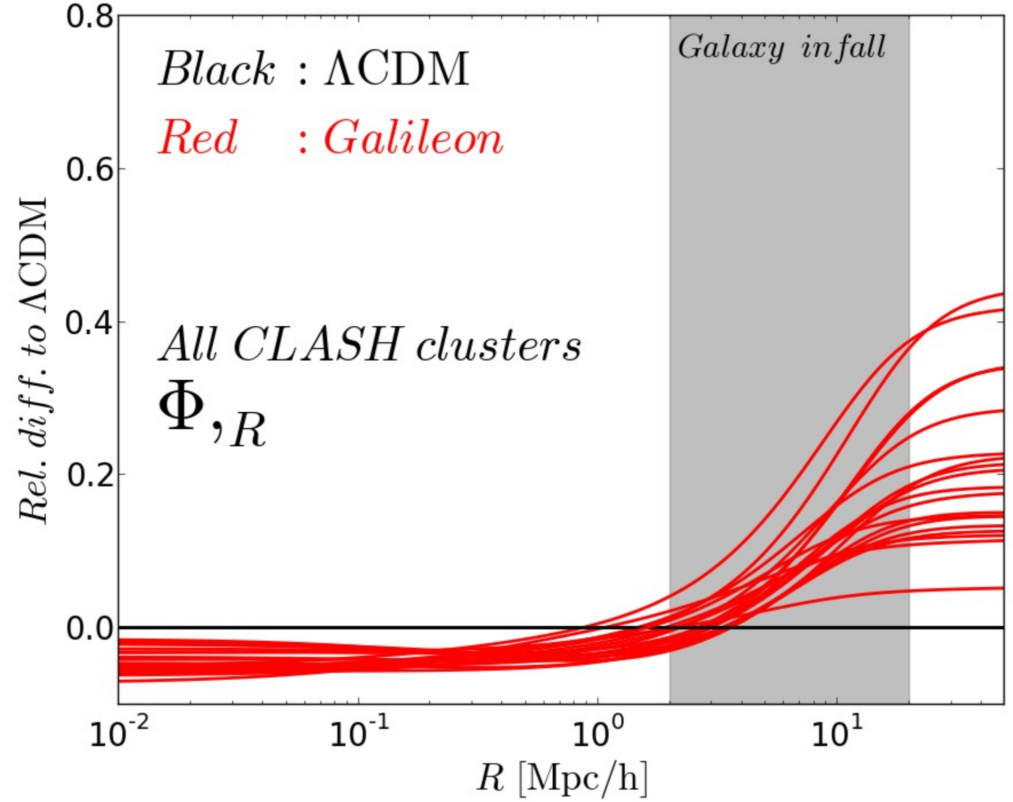
Mass/concentration estimates virtually the same in the 2 theories of gravity !

Cluster lensing profiles

Lensing Convergence

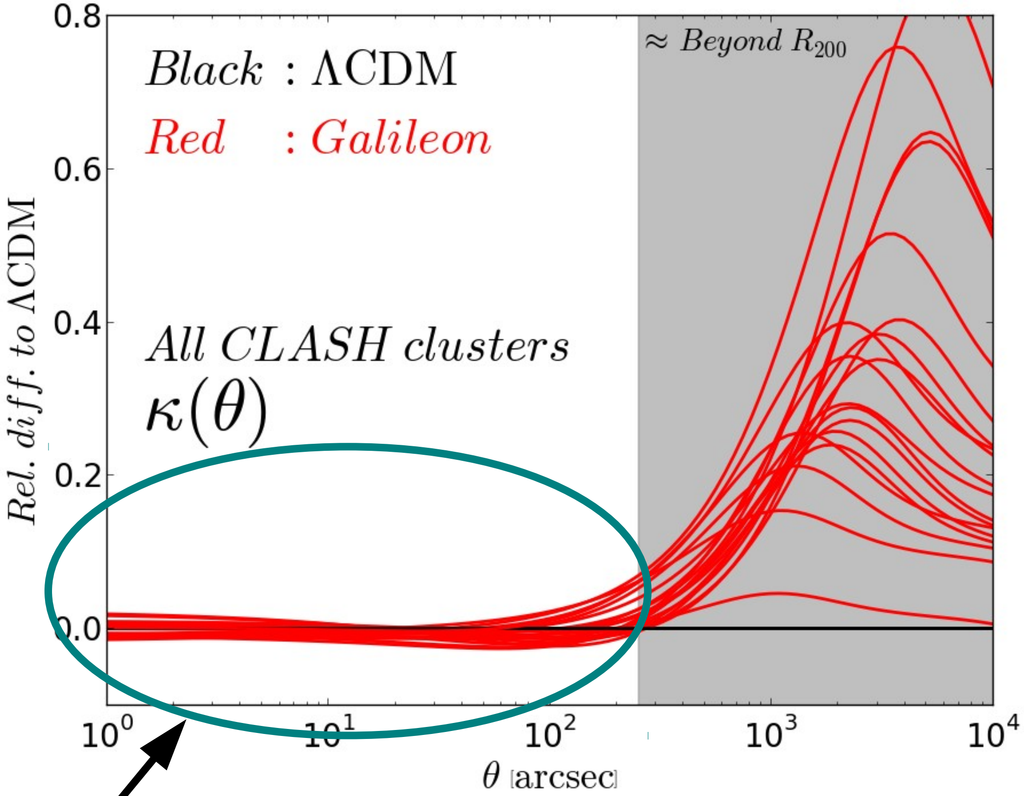


Force

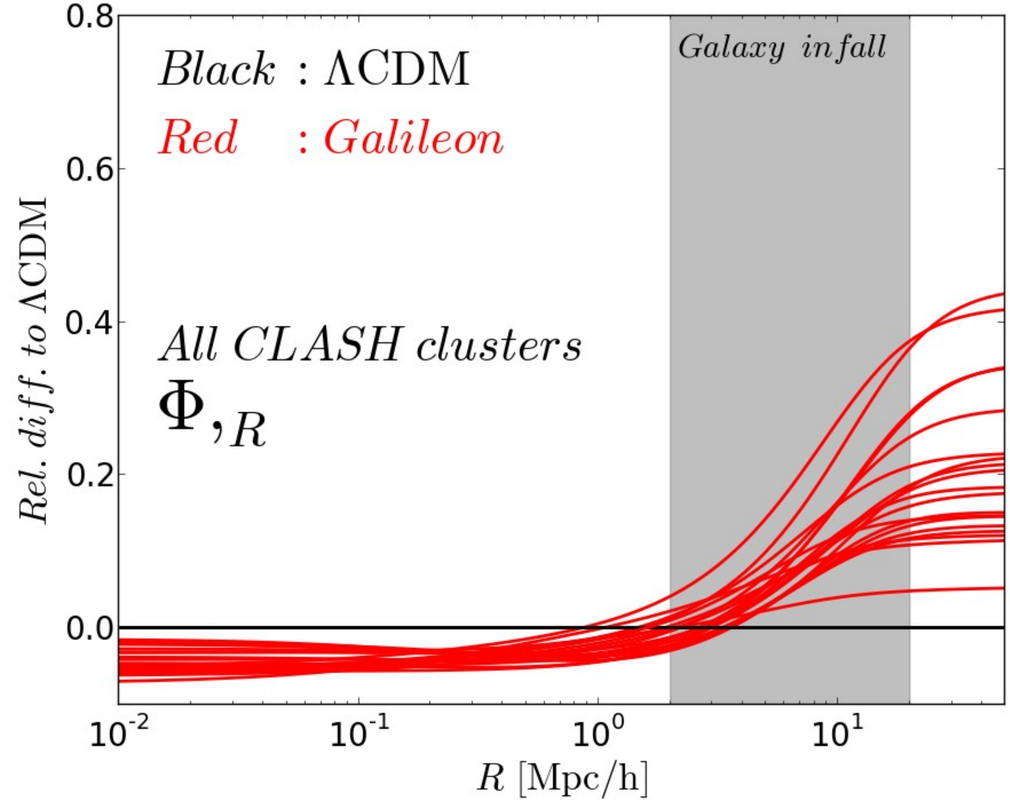


Cluster lensing profiles

Lensing Convergence



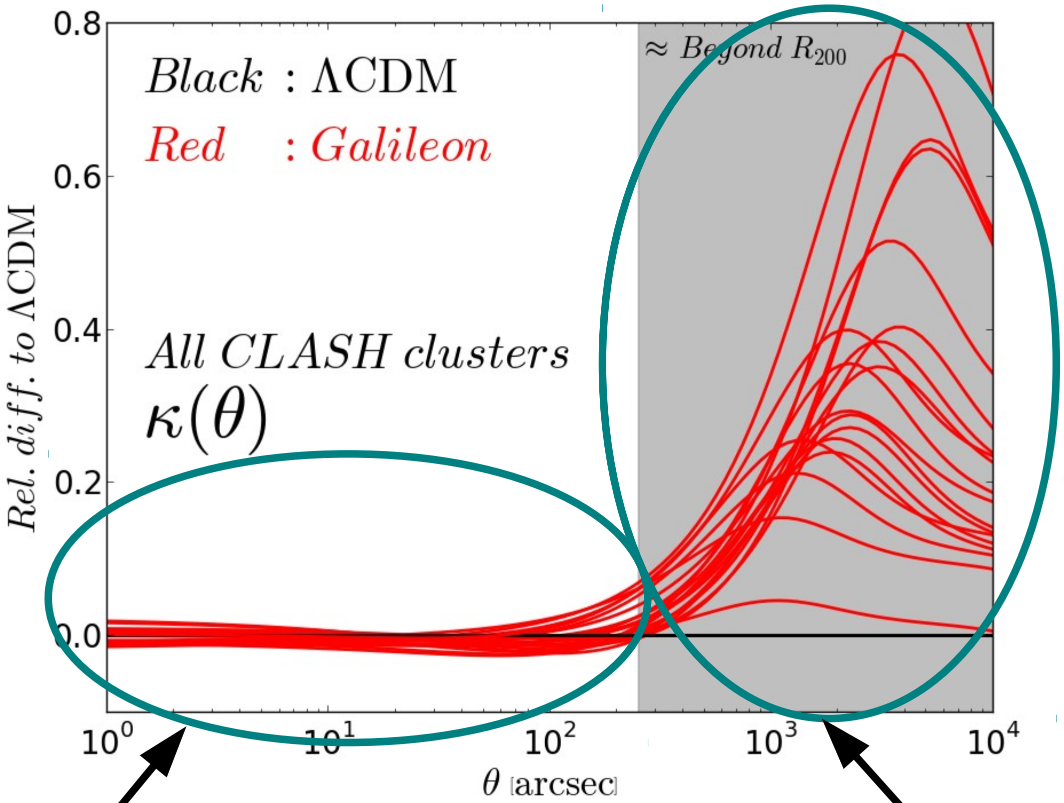
Force



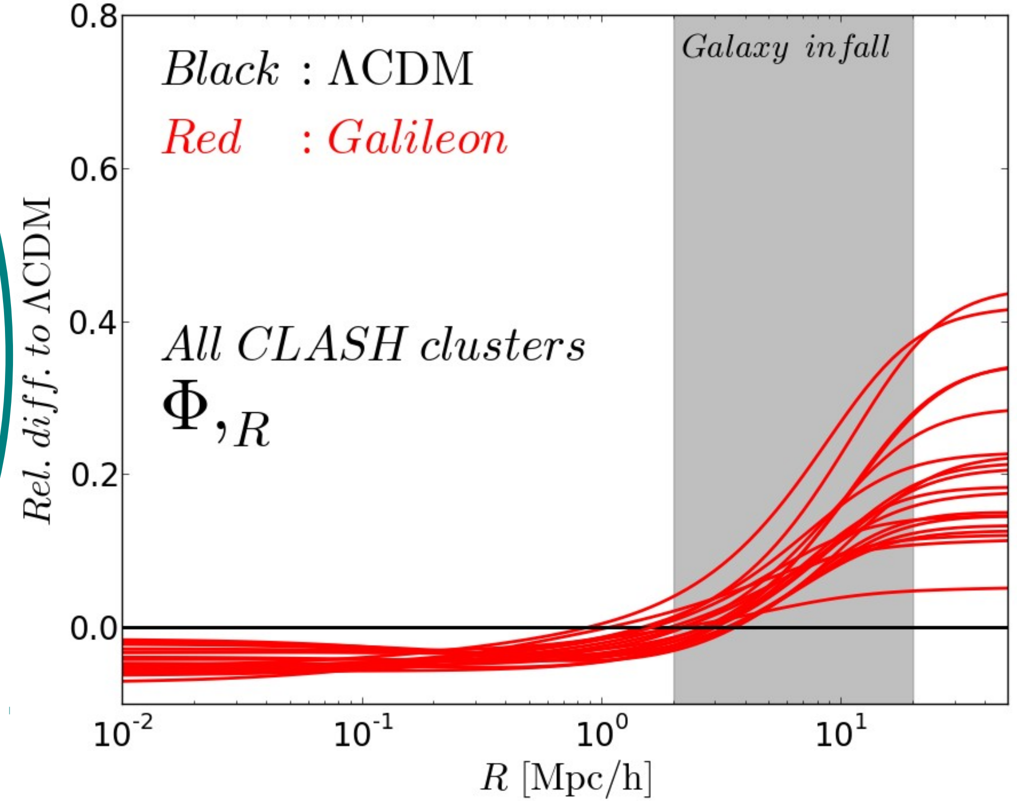
Screening is very efficient at R < R200 → lensing masses unchanged !

Cluster lensing profiles

Lensing Convergence



Force

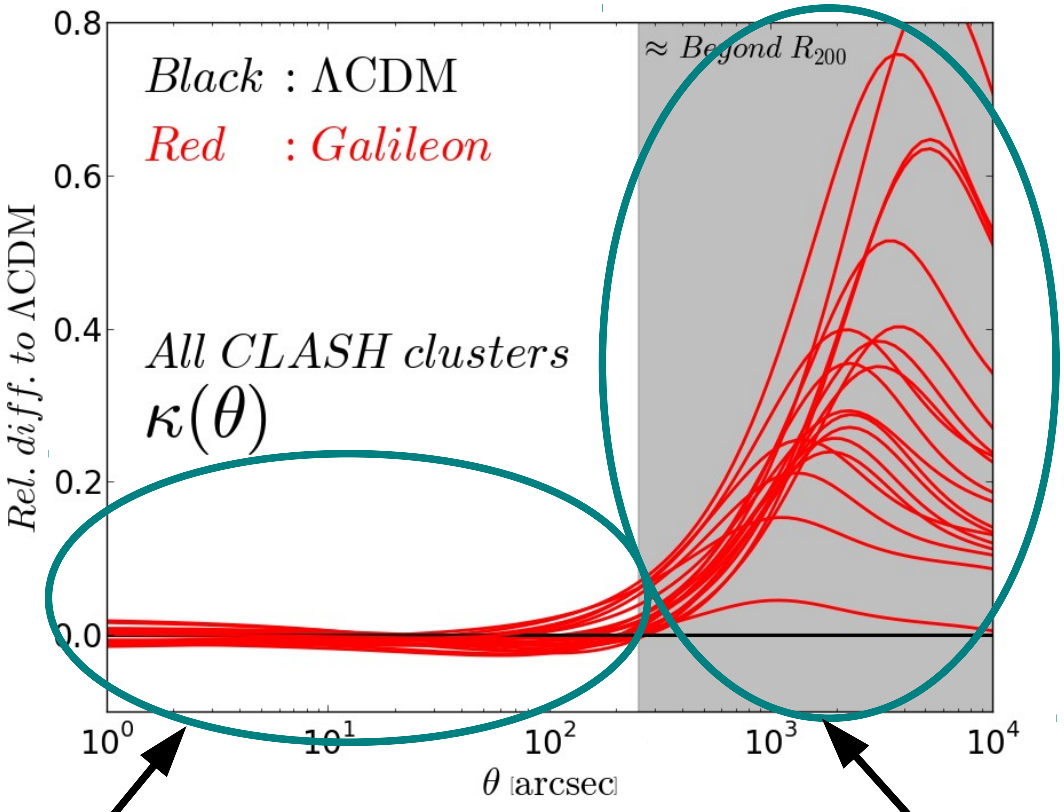


Screening is very efficient at R < R200 → lensing masses unchanged !

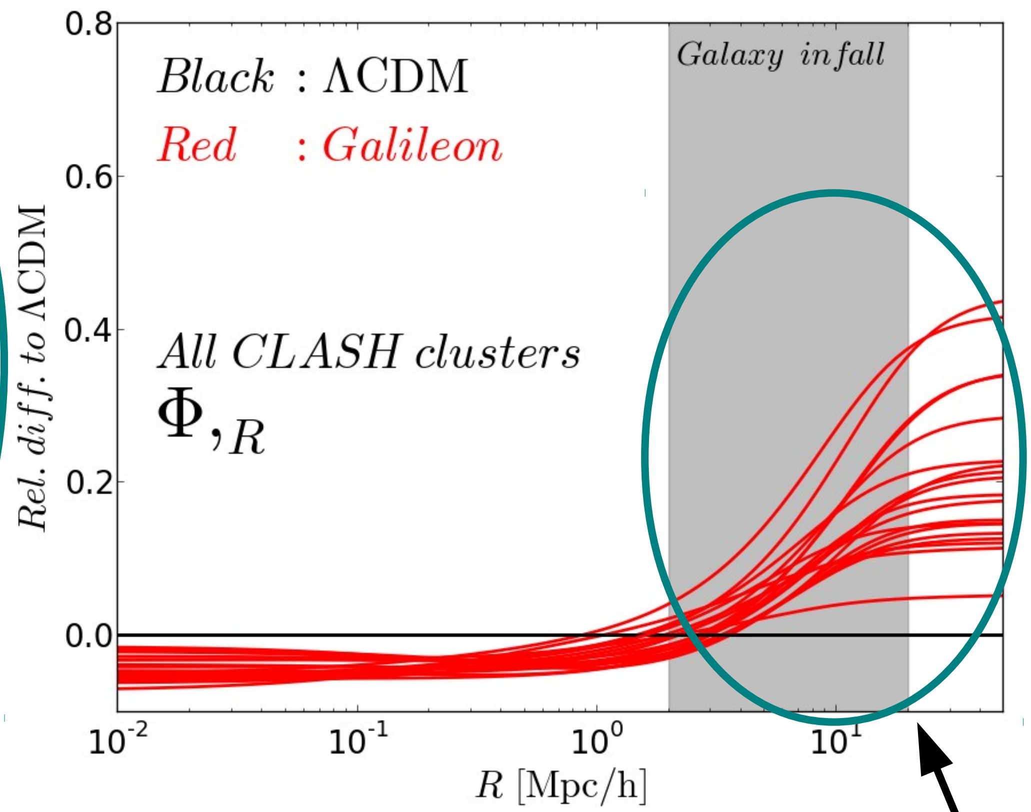
Large effects at R > R200, potentially probed with galaxy-galaxy lensing: Wyman(2011), Park&Wyman(2014).

Cluster lensing profiles

Lensing Convergence



Force



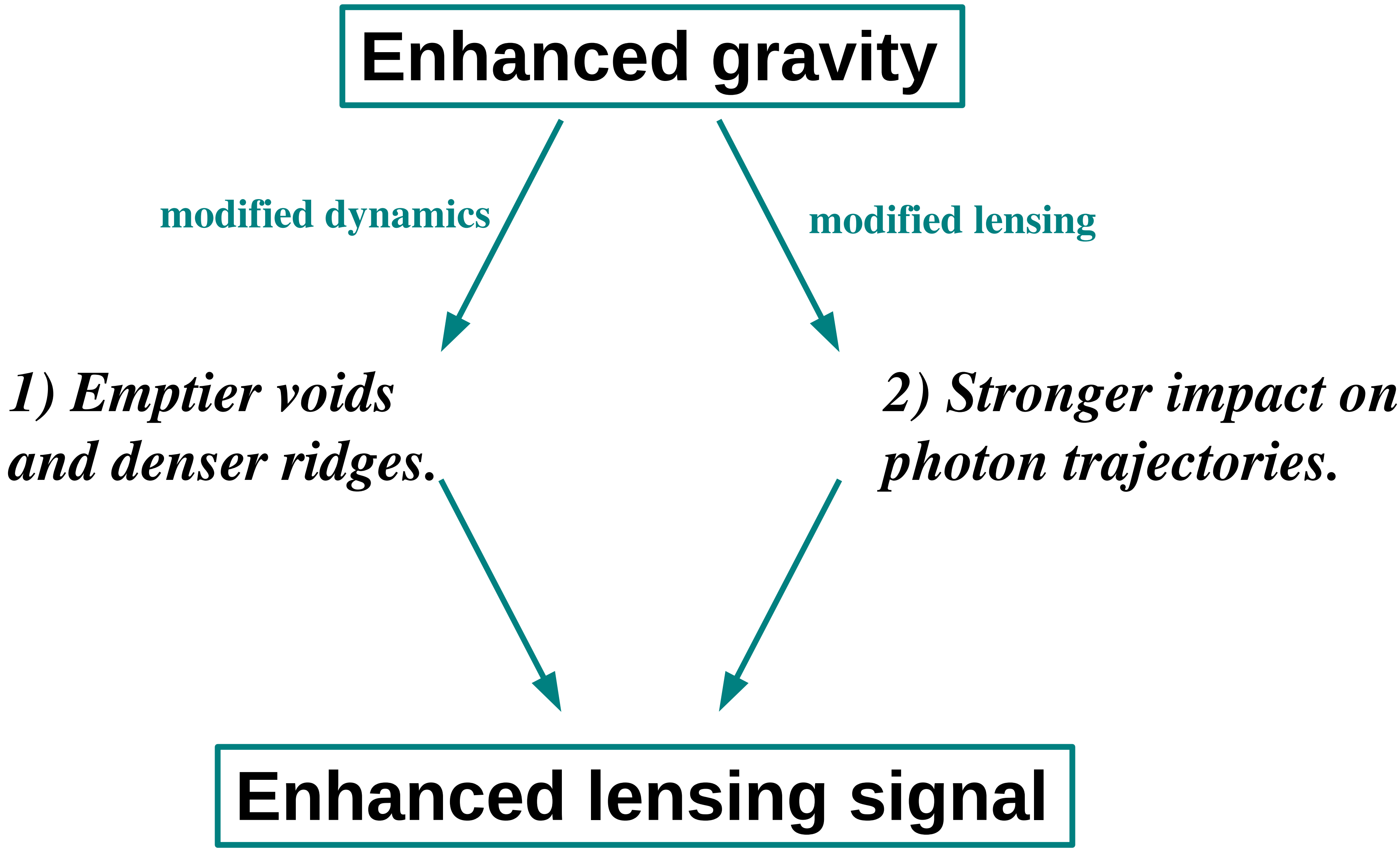
Screening is very efficient at R < R200 → lensing masses unchanged !

Large effects at R > R200, potentially probed with galaxy-galaxy lensing: Wyman(2011), Park&Wyman(2014).

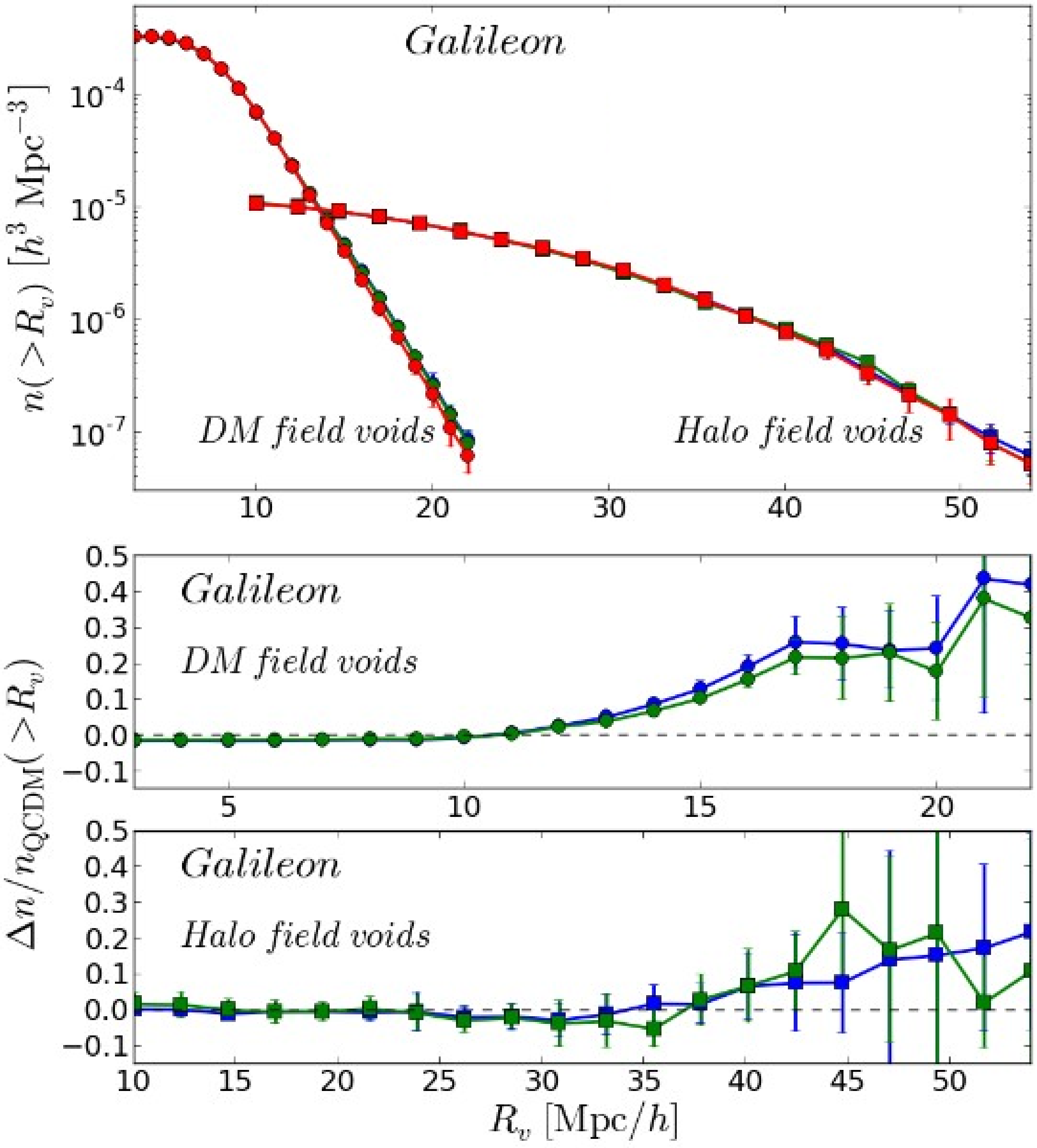
For R > R200, infall galaxy dynamics should be affected as well: Lam et al(2012), Zu et al(2013)

Lensing by voids

Line of reasoning



Void abundances



$L_{\mathrm{box}} = 400\mathrm{Mpc}/h, \quad N_p = 512^3$

ECOSMOG code, Watershed void finder

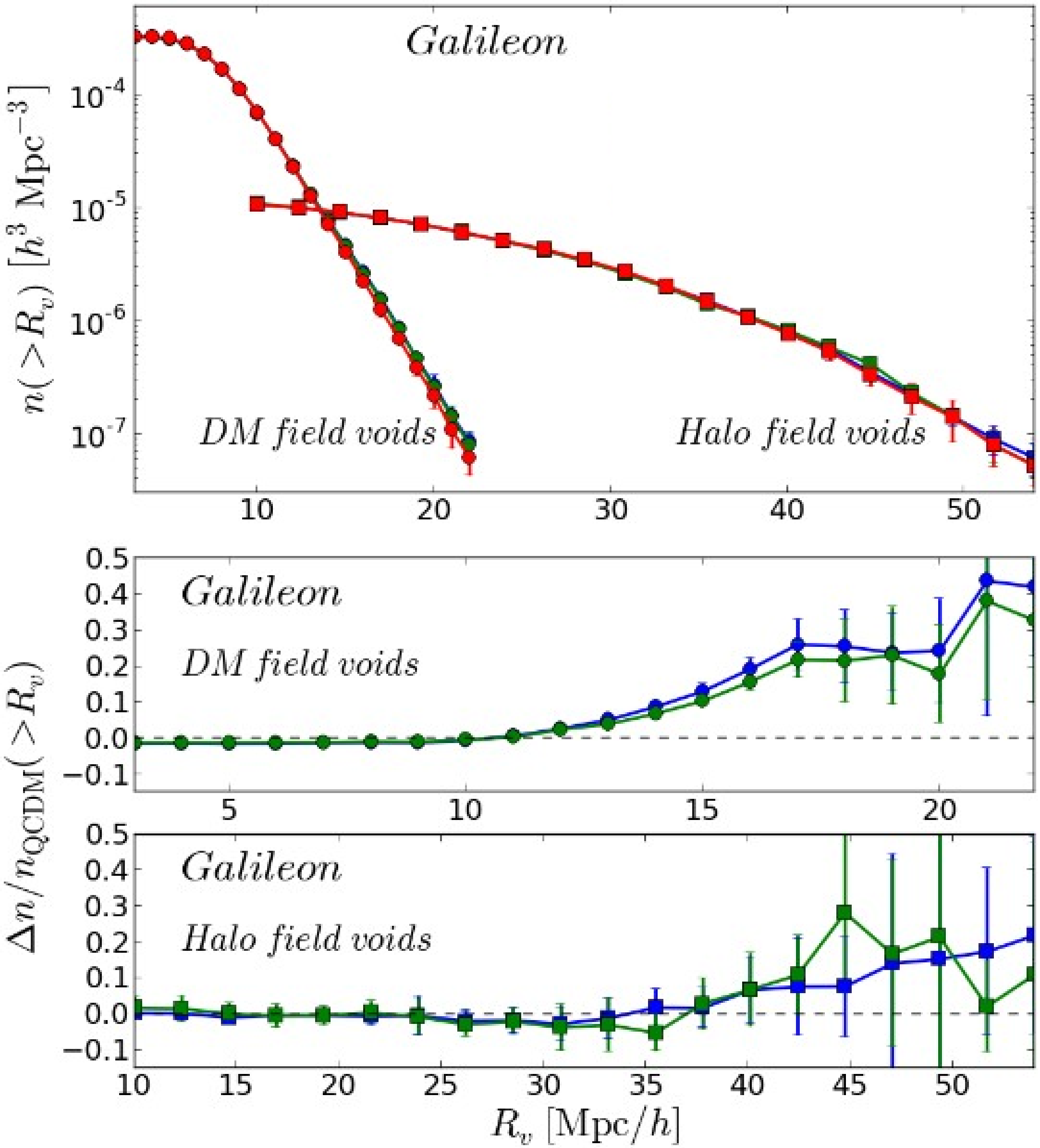
Li et al(2012) **Platen et al(2007)**

Blue : *Full* — **Force with screening**

Green : *Linear* — **Force with screening artificially suppressed**

Red : QCDM — **GR**

Void abundances



$L_{\mathrm{box}} = 400\mathrm{Mpc}/h, \quad N_p = 512^3$

ECOSMOG code, Watershed void finder

Li et al(2012) **Platen et al(2007)**

Blue : *Full* — **Force with screening**

Green : *Linear* — **Force with screening artificially suppressed**

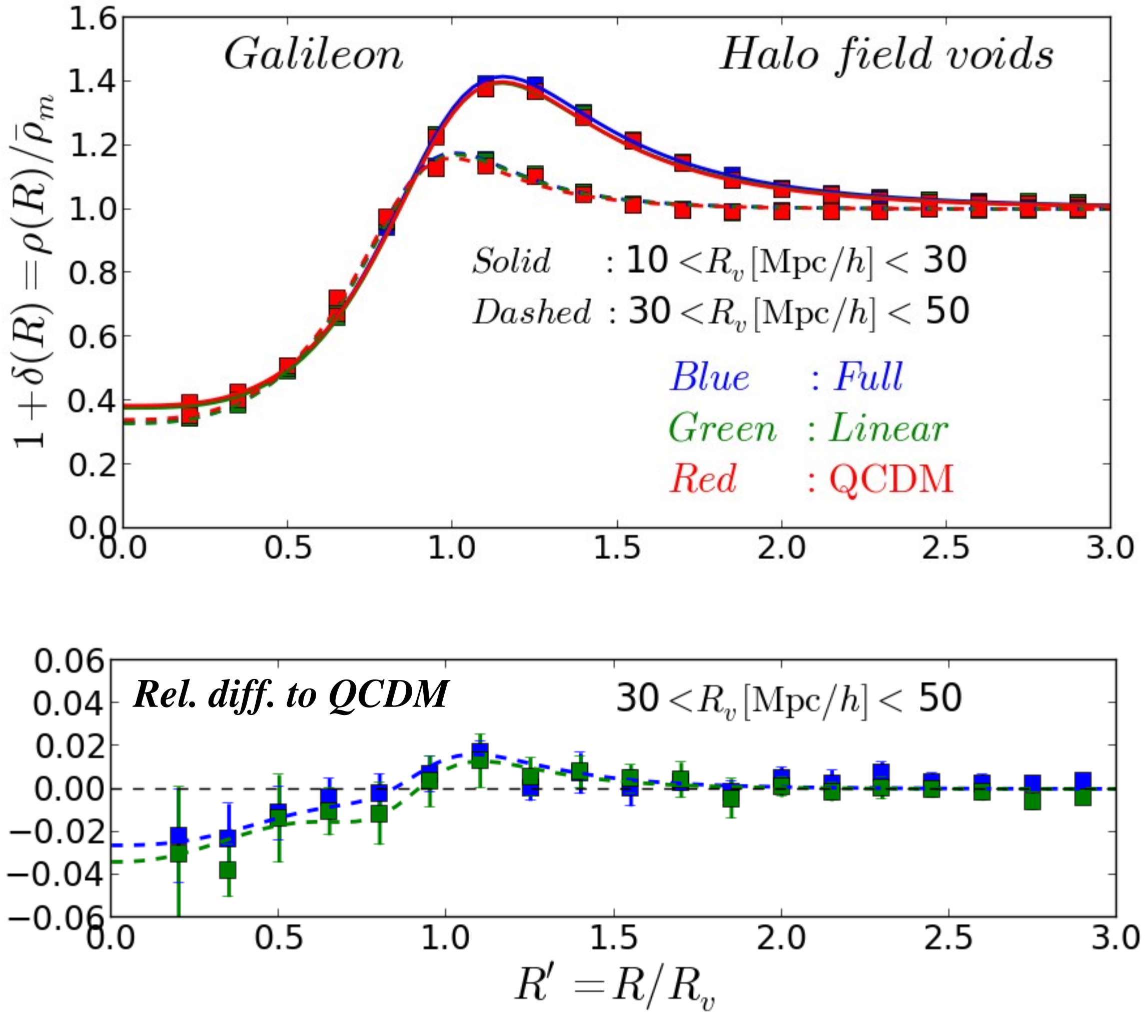
Red : QCDM — **GR**

Larger number of large voids.

Full and Linear predictions are very similar: **screening is weak** when it comes to voids !

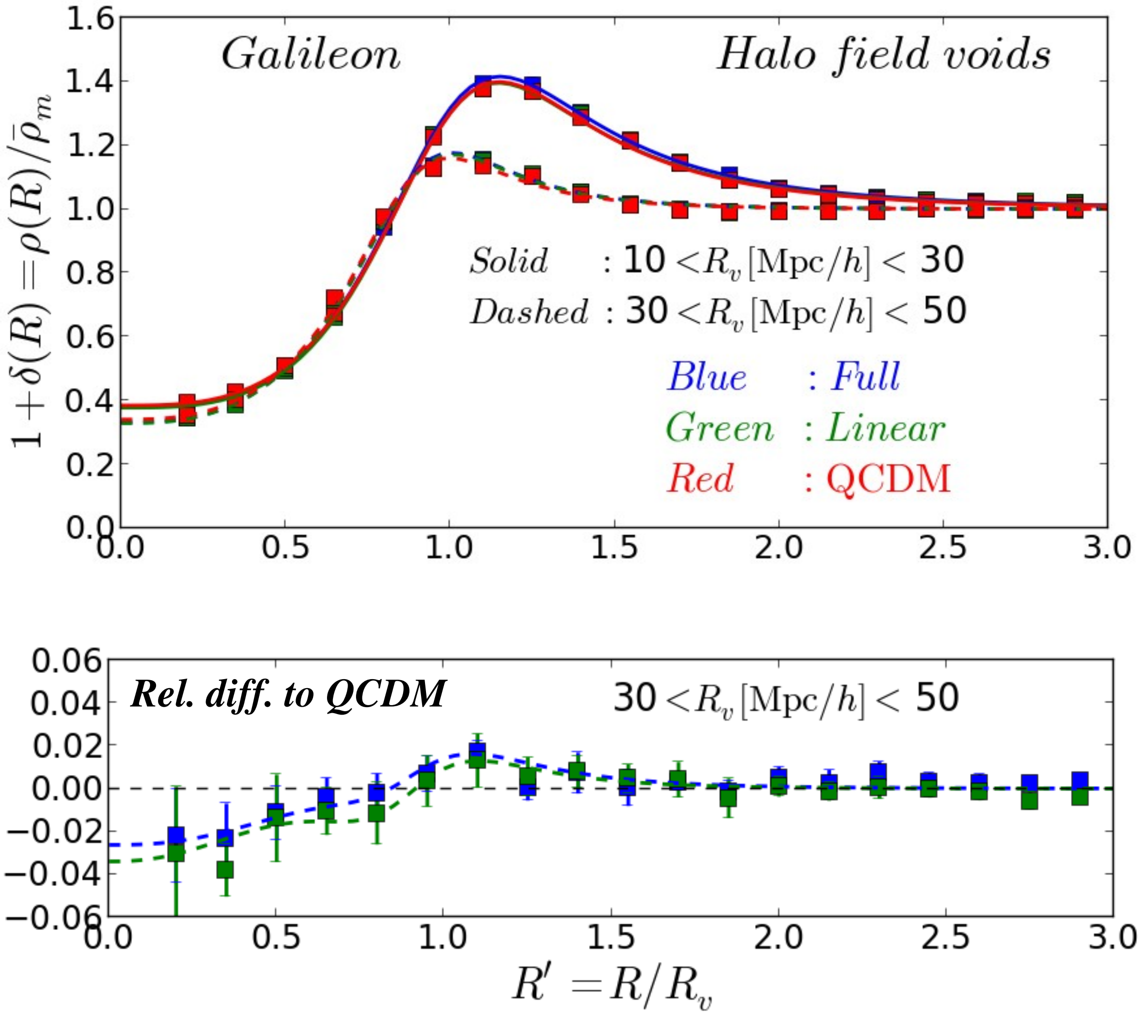
Void density profiles

DM density of halo field voids



Void density profiles

DM density of halo field voids



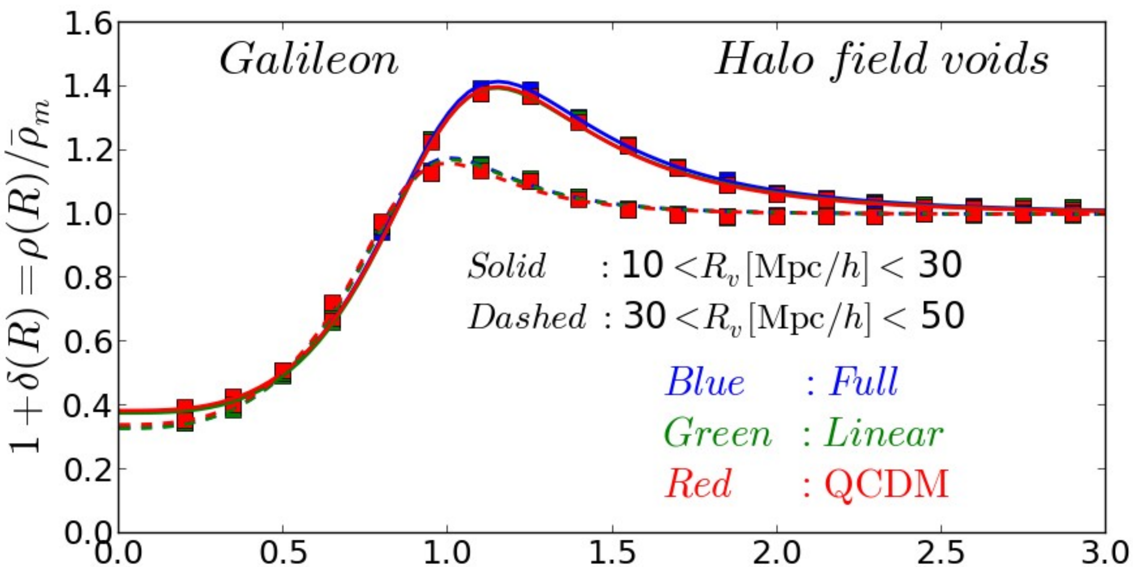
Watershed void profiles well fit by

$$\delta(R' = R/R_v) = \delta_v \frac{1-(R'/s_1)^\alpha}{1+(R'/s_2)^\beta}$$

Will use it to compute **lensing analytically.**

Void density profiles

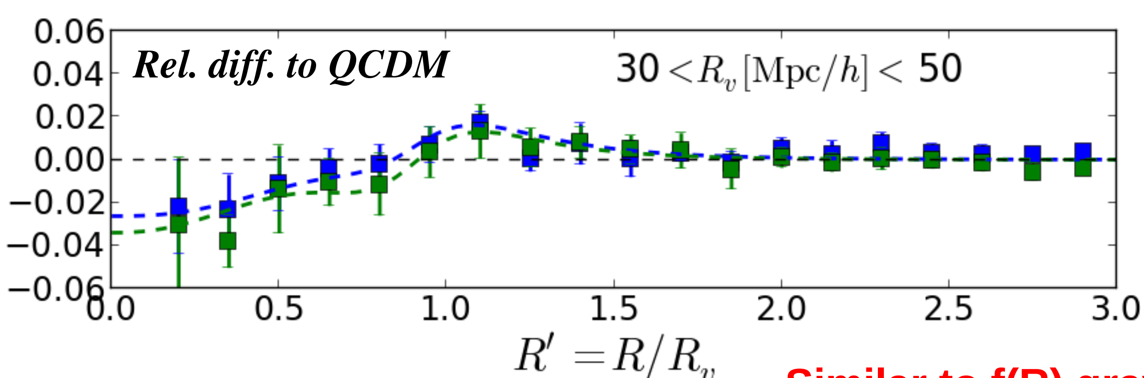
DM density of halo field voids



Watershed void profiles well fit by

$$\delta(R' = R/R_v) = \delta_v \frac{1-(R'/s_1)^\alpha}{1+(R'/s_2)^\beta}$$

Will use it to compute **lensing analytically.**



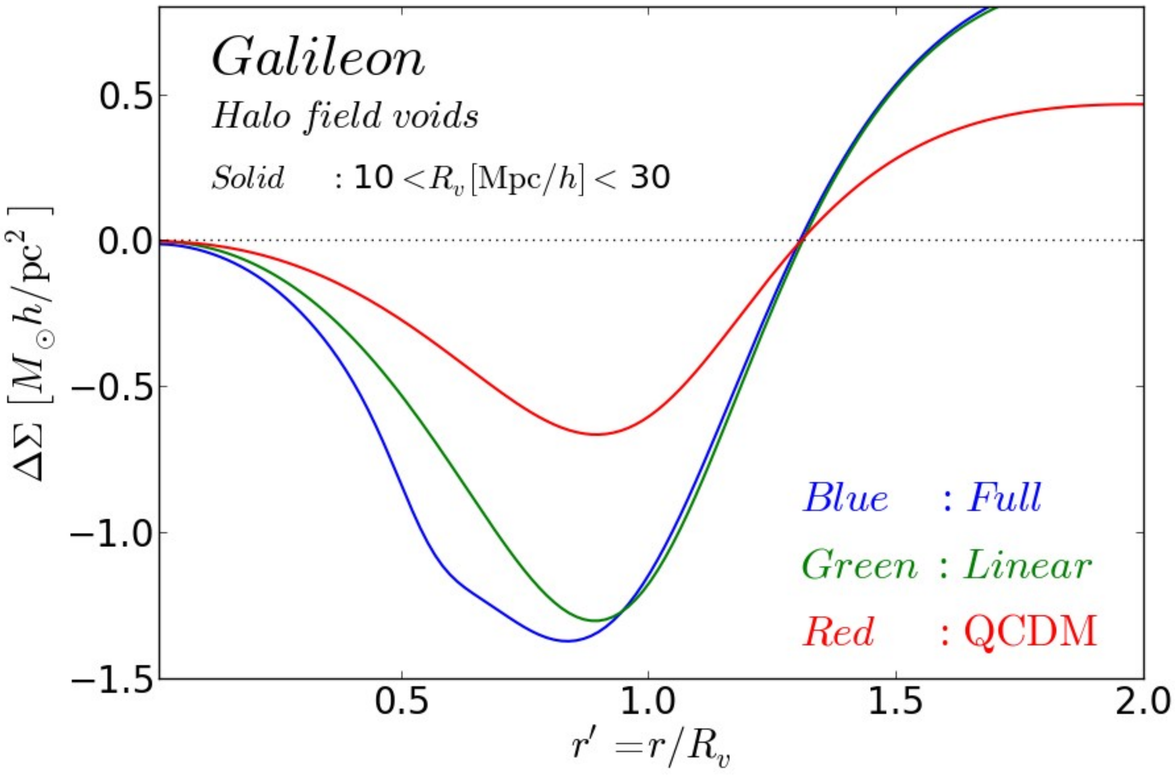
Voids emptier inside/denser at ridge – few % effect only !

Screening effects are weak.

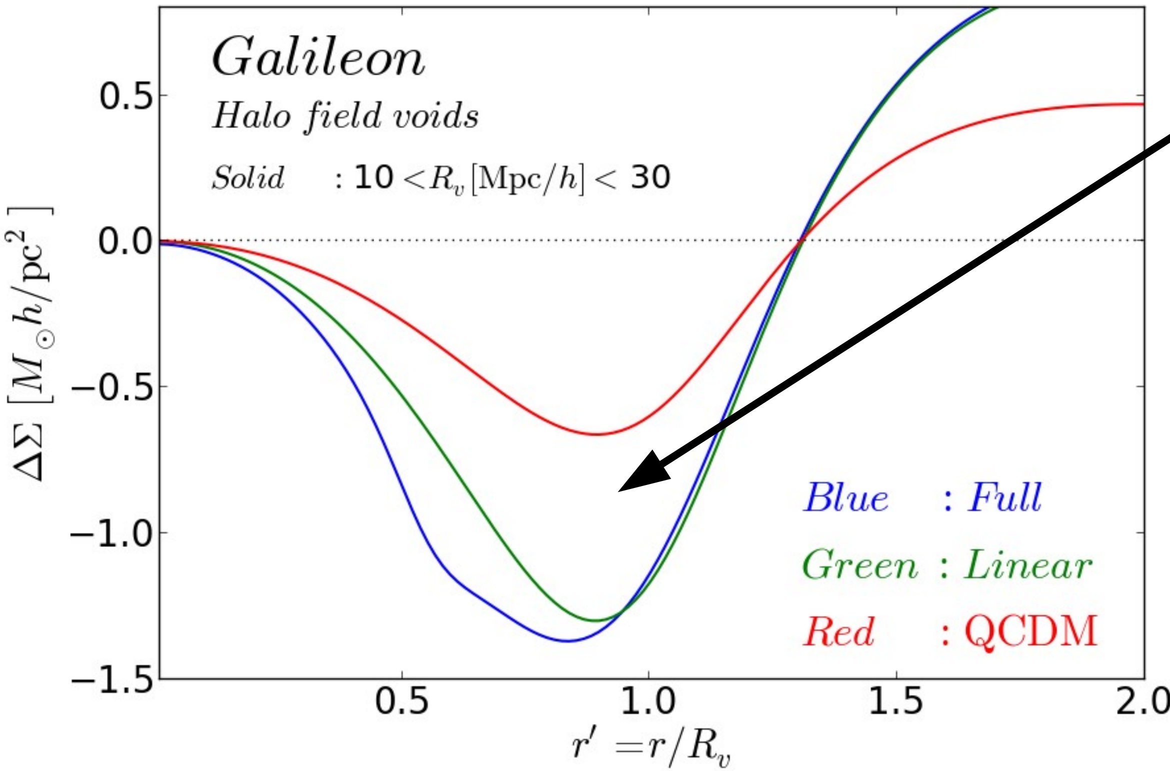
Similar to f(R) gravity

Cai et al. (2014) arXiv:1410.1510

Void lensing

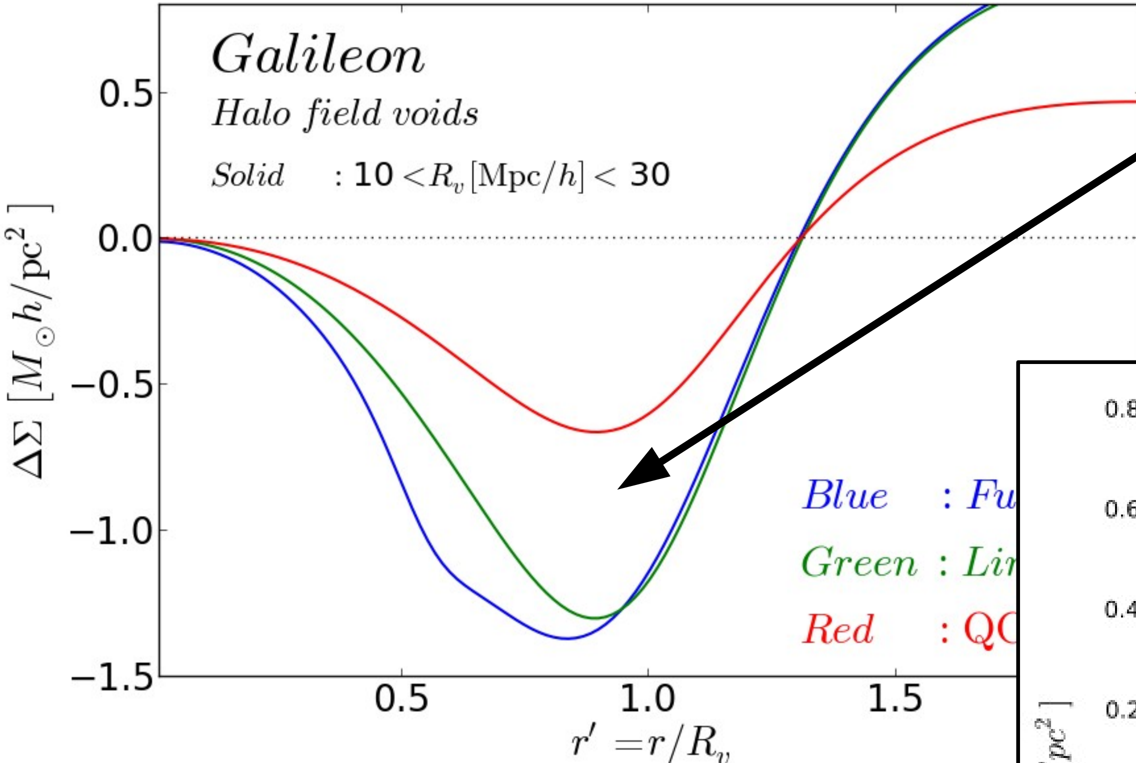


Void lensing

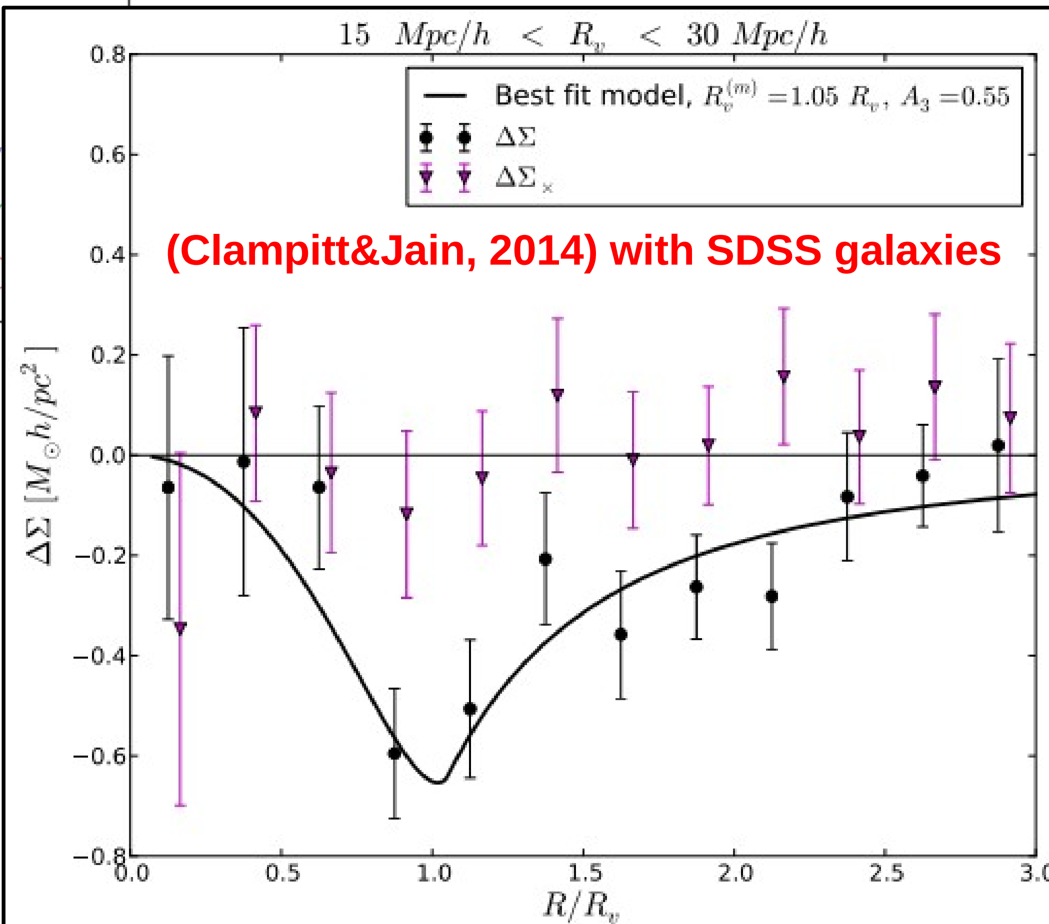


Lensing signal gets **<u>enhanced by ~ factor of 2</u>**, compared to GR.

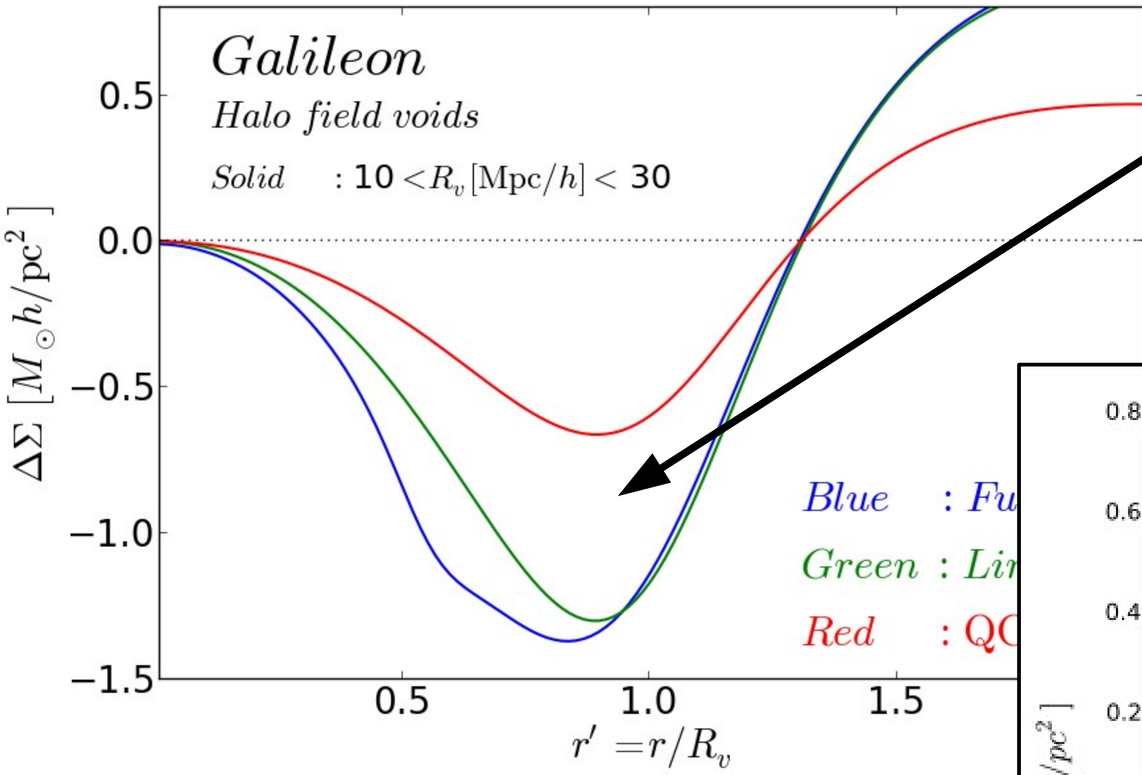
Void lensing



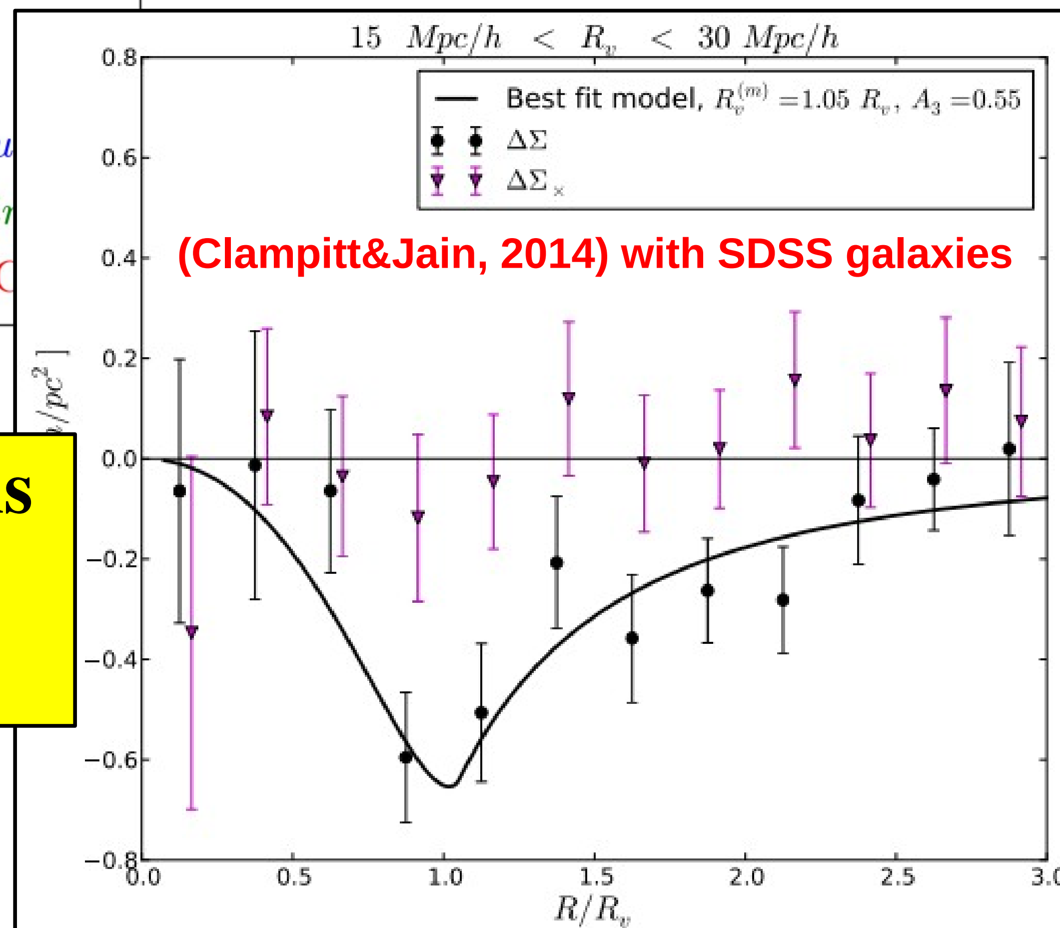
Lensing signal gets **enhanced by ~ factor of 2**, compared to GR.



Void lensing



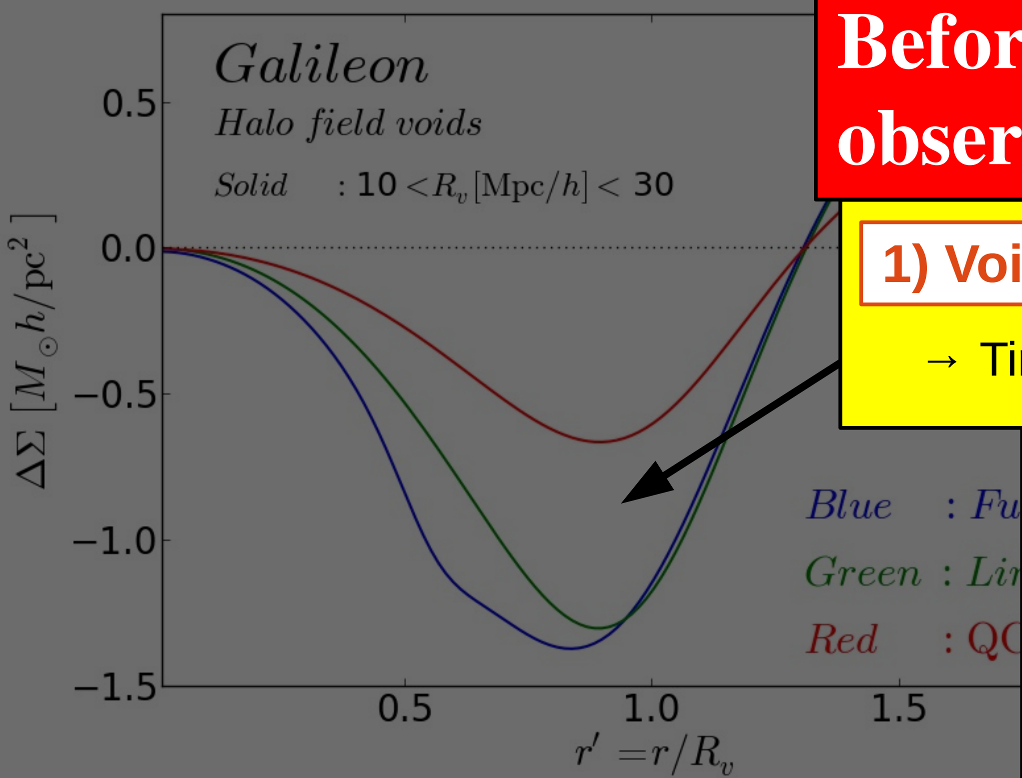
Lensing signal gets **enhanced by ~ factor of 2**, compared to GR.



The strength of the signal opens good prospects to use voids to test gravity.

Some data exists already:
[1] - Melchior et al, 2014 using SDSS
[2] - Clampitt&Jain, 2014 using SDSS
[3] - Gruen et al. 2015 using DES

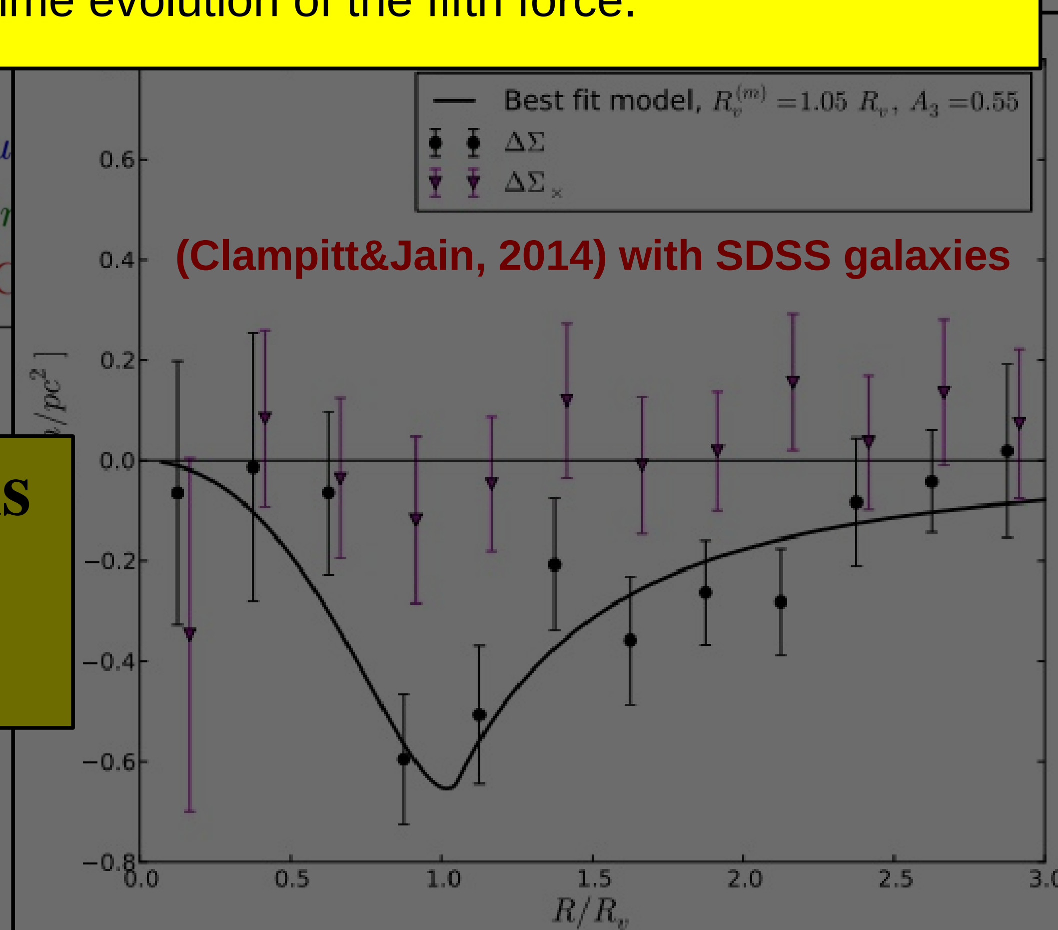
Void lensing



Before rigorously comparing to observations:

1) Void/source redshift distribution

→ Time evolution of the fifth force.



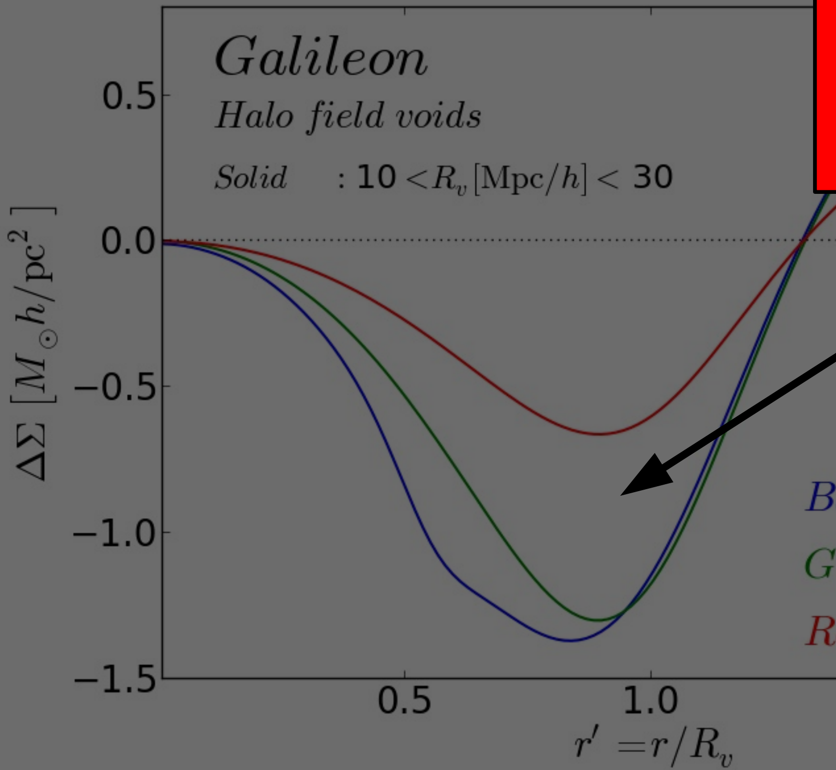
(Clampitt&Jain, 2014) with SDSS galaxies

The strength of the signal opens good prospects to use voids to test gravity.

Some data exists already:

[1] - Melchior et al, 2014 using SDSS
[2] - Clampitt&Jain, 2014 using SDSS
[3] - Gruen et al. 2015 using DES

Void lensing



Before rigorously comparing to observations:

1) Void/source redshift distribution

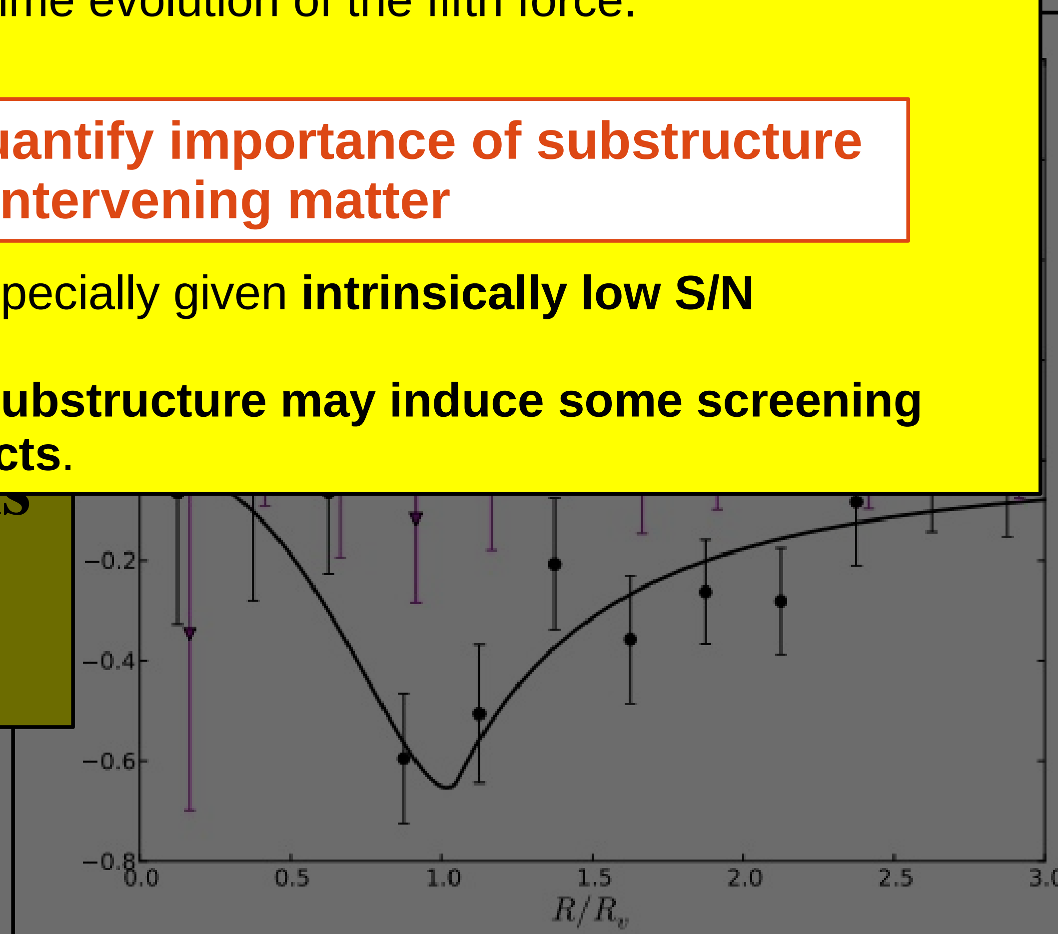
→ Time evolution of the fifth force.

2) Quantify importance of substructure and intervening matter

→ Specially given **intrinsically low S/N**

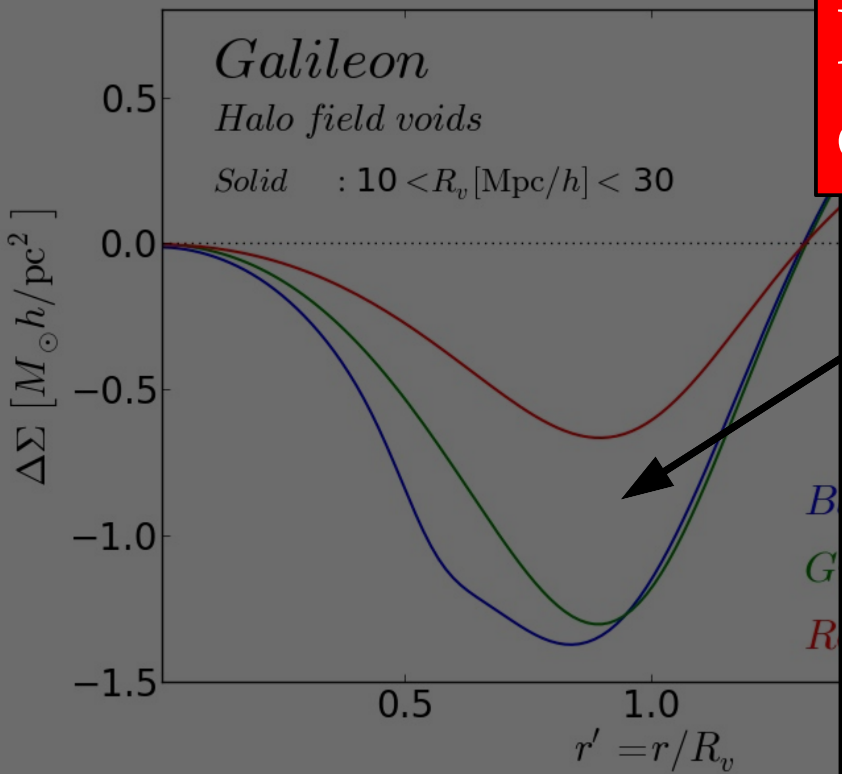
→ **Substructure may induce some screening effects**.

The strength of the signal opens good prospects to use voids to test gravity.



Some data exists already:
[1] - Melchior et al, 2014 using SDSS
[2] - Clampitt&Jain, 2014 using SDSS
[3] - Gruen et al. 2015 using DES

Void lensing



Before rigorously comparing to observations:

1) Void/source redshift distribution

→ Time evolution of the fifth force.

2) Quantify importance of substructure and intervening matter

→ Specially given **intrinsically low S/N**

→ **Substructure may induce some screening effects**.

3) Void characterization

→ **Void finder (watershed, sph. und., troughs), sizes, tracer bias, abundance …**

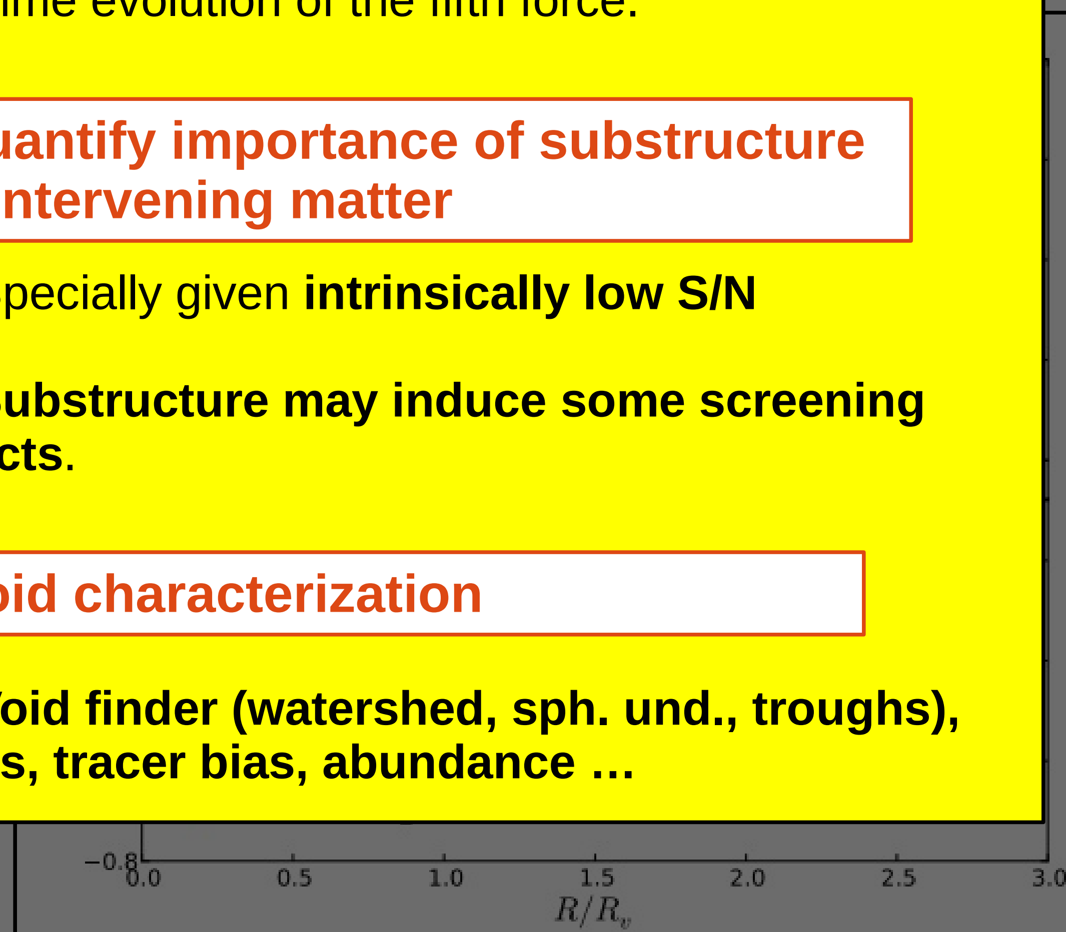
The strength of the signal … good prospects to use void… test gravity.

Some data exists already:

[1] - Melchior et al, 2014 using SDSS

[2] - Clampitt&Jain, 2014 using SDSS

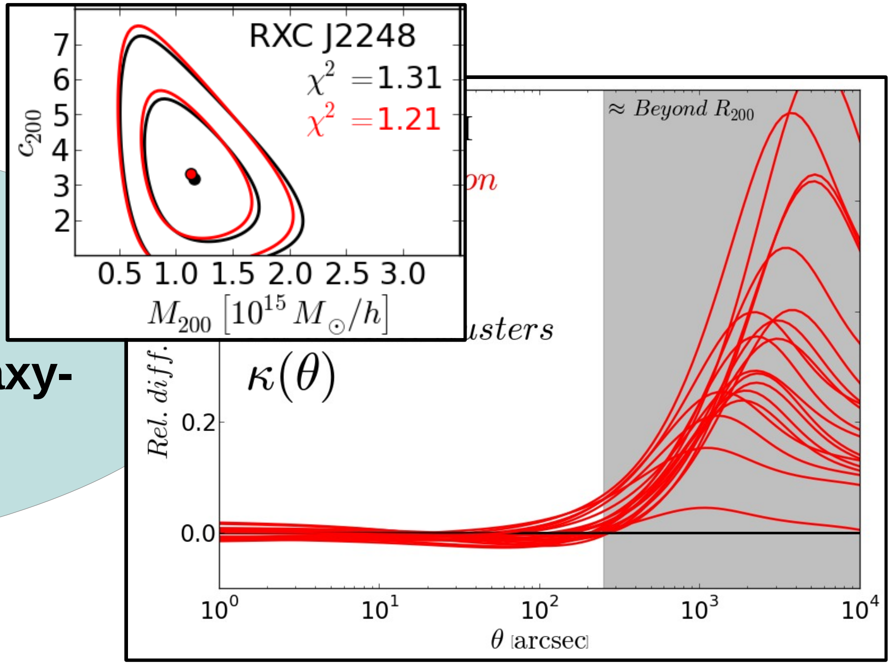
[3] - Gruen et al. 2015 using DES



To take home …

1) Cluster lensing

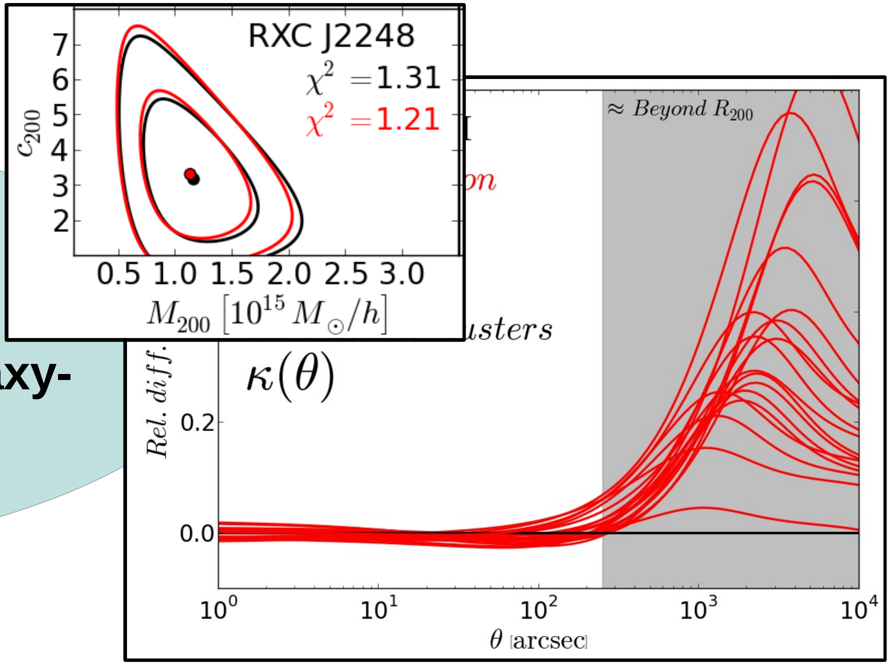
- **Mass estimates based on data for R<R200 are unchanged due to screening efficiency.**
- **Larger effects at R>R200 may be probed via galaxy-galaxy and/or galaxy infall dynamics.**



To take home …

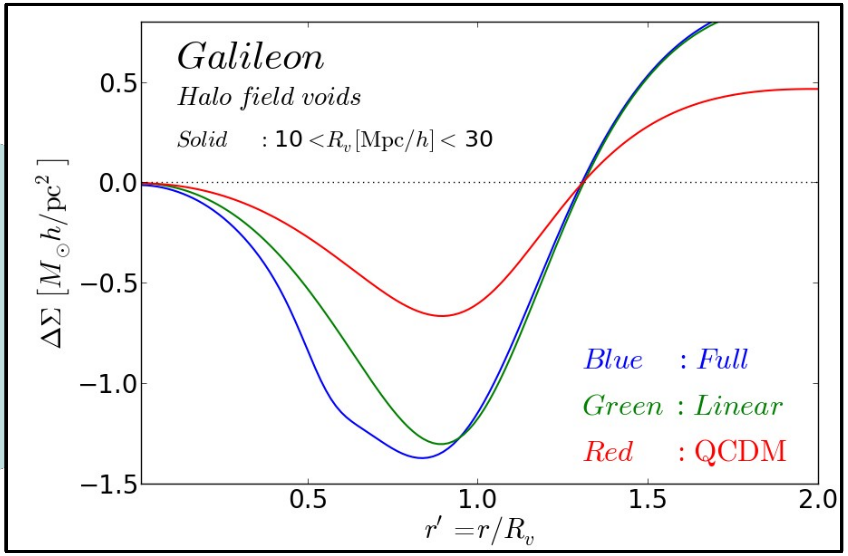
1) Cluster lensing

- **Mass estimates based on data for R<R200 are unchanged due to screening efficiency.**
- **Larger effects at R>R200 may be probed via galaxy-galaxy and/or galaxy infall dynamics.**



2) Void lensing

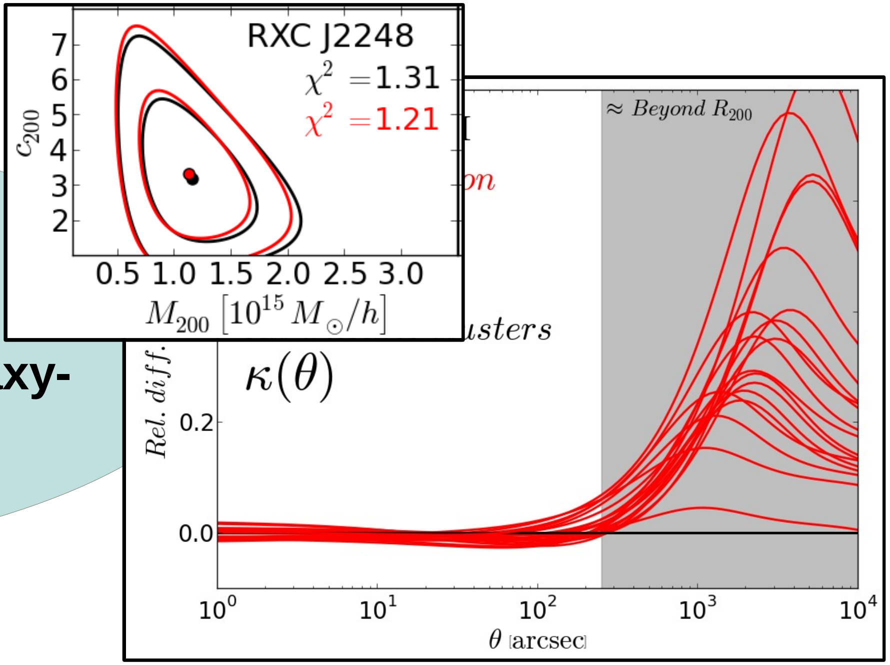
- **The suppression effects of the screening are weak in voids !**
- **Lensing signal can be boosted by ~100%, so should investigate better the merit of lensing by voids to test gravity !**



To take home …

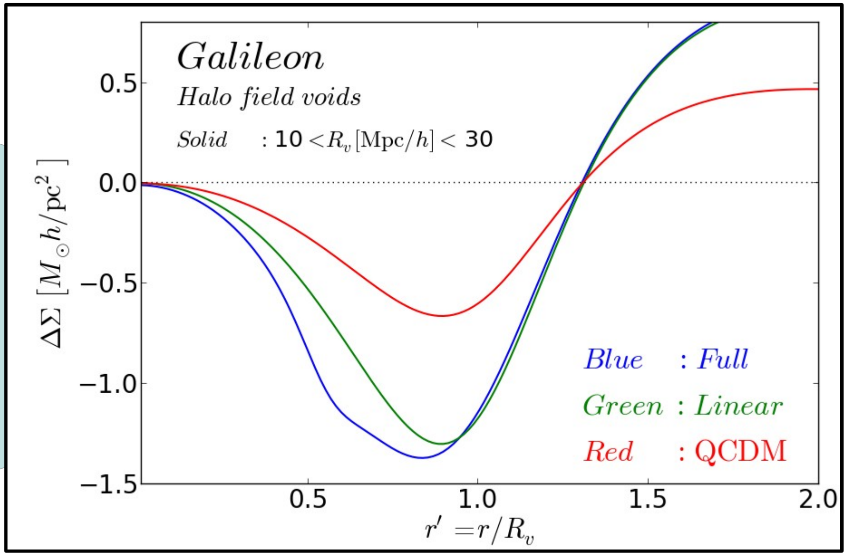
1) Cluster lensing

- **Mass estimates based on data for R<R200 are unchanged due to screening efficiency.**
- **Larger effects at R>R200 may be probed via galaxy-galaxy and/or galaxy infall dynamics.**



2) Void lensing

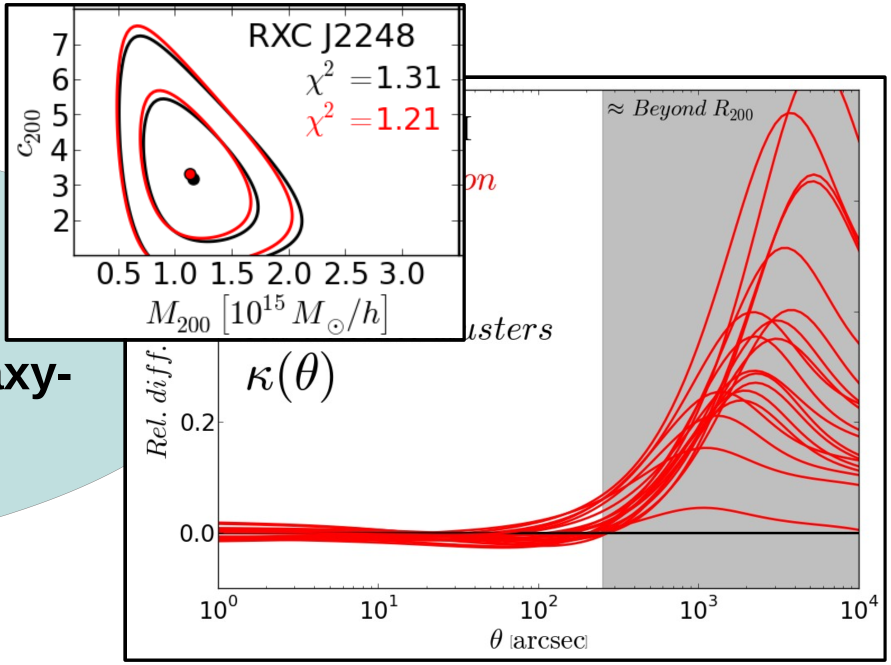
- **The suppression effects of the screening are weak in voids !**
- **Lensing signal can be boosted by ~100%, so should investigate better the merit of lensing by voids to test gravity !**



To take home …

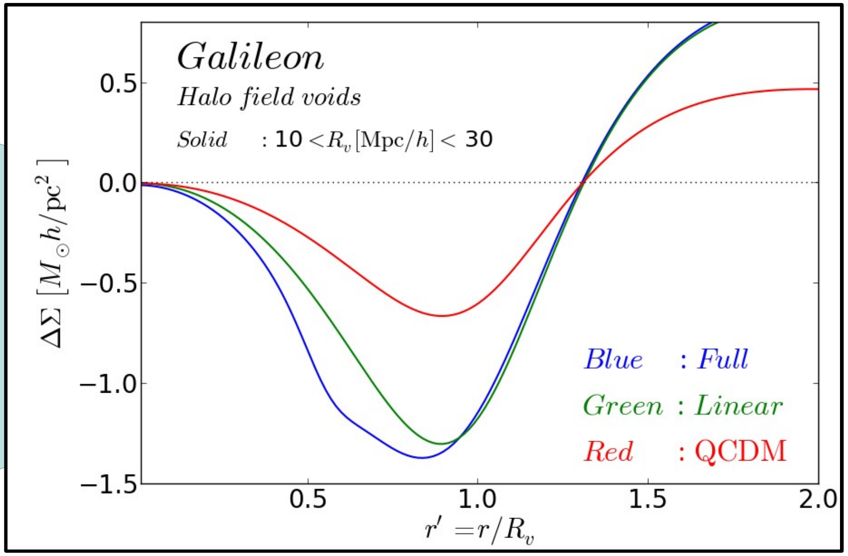
1) Cluster lensing

- **Mass estimates based on data for R<R200 are unchanged due to screening efficiency.**
- **Larger effects at R>R200 may be probed via galaxy-galaxy and/or galaxy infall dynamics.**



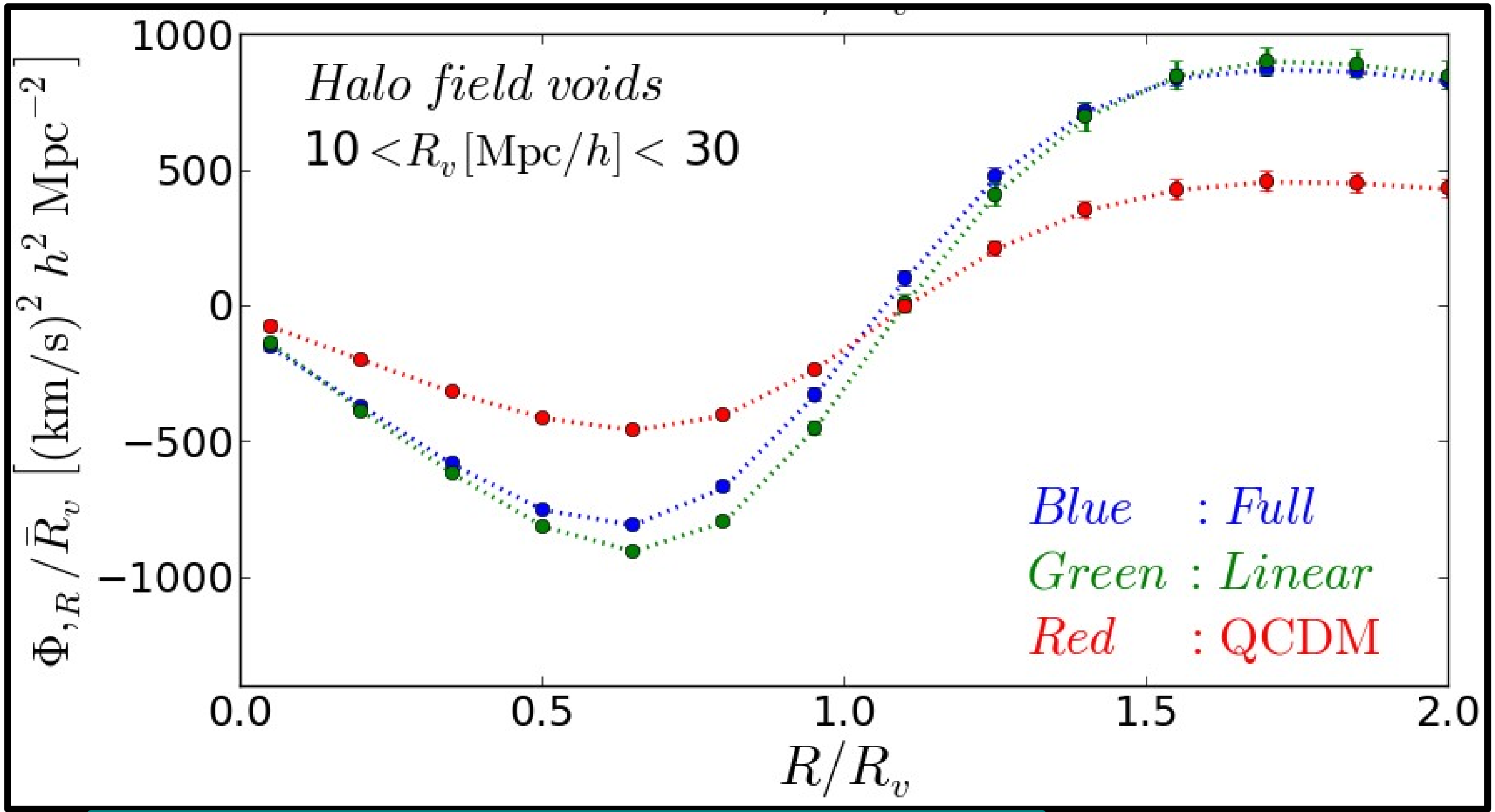
2) Void lensing

- **The suppression effects of the screening are weak in voids !**
- **Lensing signal can be boosted by ~100%, so should investigate better the merit of lensing by voids to test gravity !**



. . . .

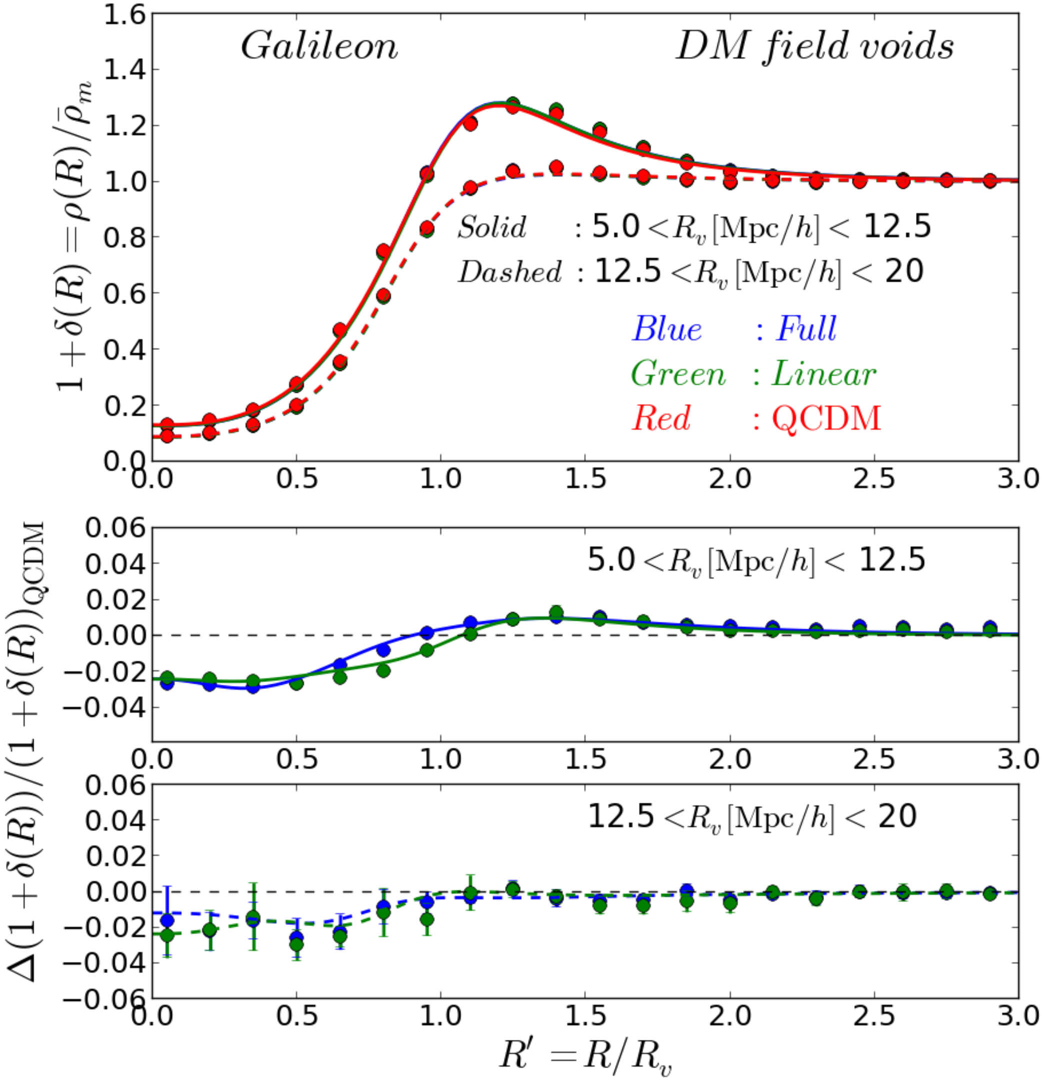
Force profiles



Although weak, there is still some screening by haloes near the edge of the voids !

Void density profiles

DM as void tracers



Haloes as void tracers