The quest for Dark Energy when theories meet simulations

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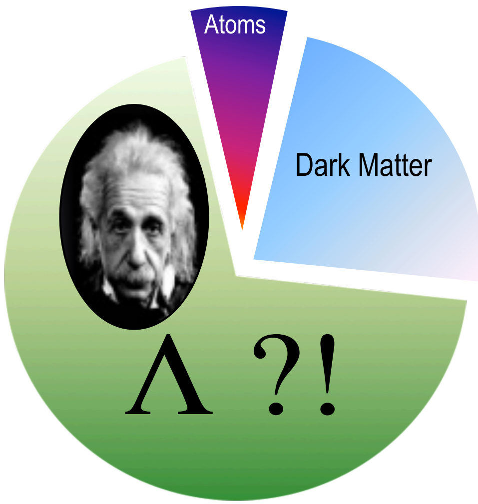
Universe is Accelerating

$$G_{\mu\nu} = \frac{1}{M_p^2}\widetilde{T}_{\mu\nu}$$

$$\widetilde{G}_{\mu\nu} = \frac{1}{M_p^2}T_{\mu\nu}$$



Modified Gravity
e.g. Chameleon, Symmetron, Dilaton, Braneworld, etc

Indistinguishable at the background level
Need to study the structure growth to break the degeneracy

Make Universe accelerate by tweaking RHS

$$G_{\mu\nu} = \frac{1}{M_p^2}\widetilde{T}_{\mu\nu}$$

DARK ENERGY

w=p/ρ<0

- Cosmological Constant (w=-1)
- Quintessence (w>-1)
- Phantom (w<-1)
- Quintom (w crosses -1)

Model-independent reconstruction of w

Crittenden, Pogosian, GBZ (2009)
Crittenden, GBZ, Pogosian, Samushia, Zhang (2012)

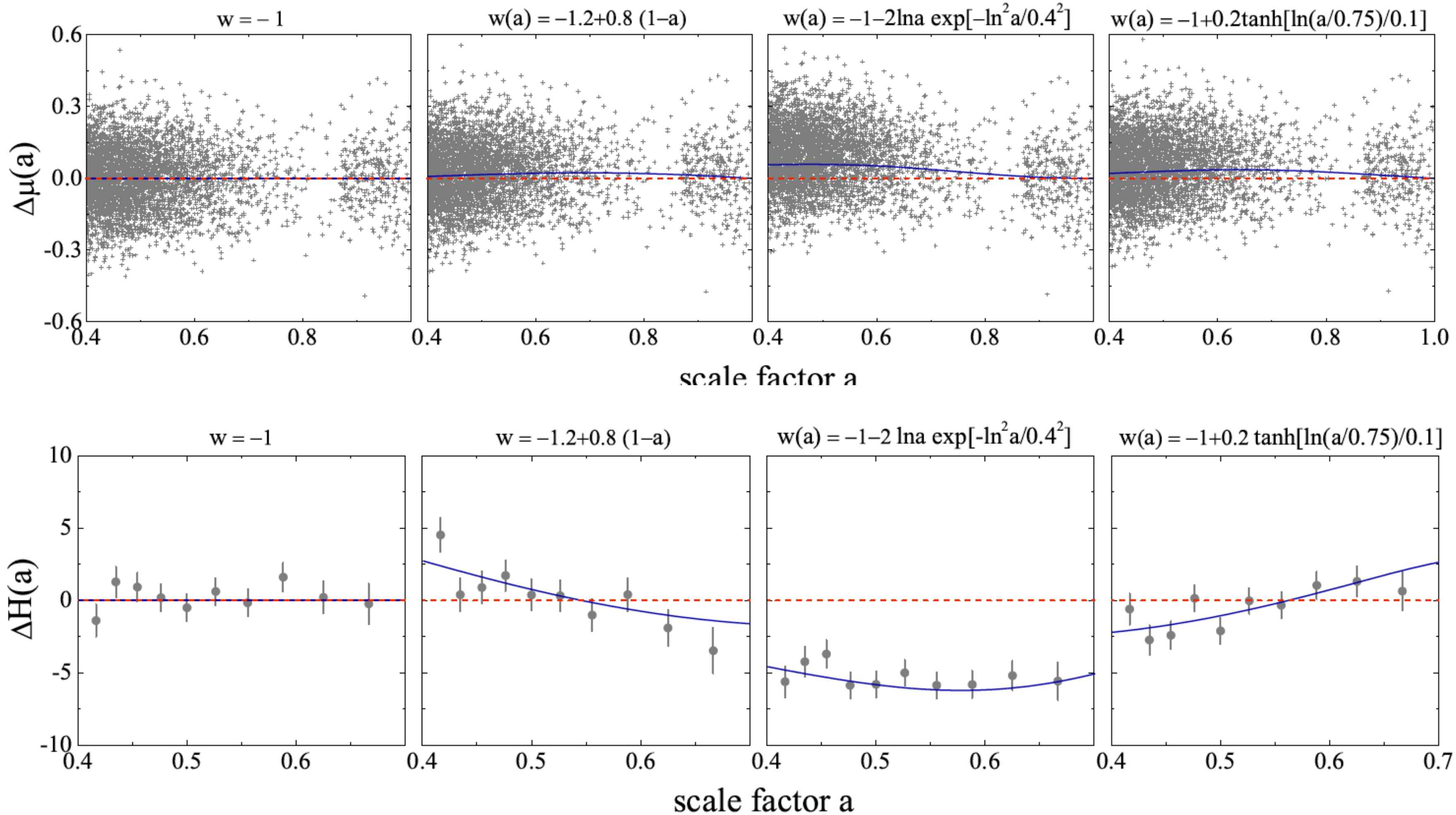
$$\xi_w(|a-a'|) \equiv \langle [w(a)-w^{\rm fid}(a)][w(a')-w^{\rm fid}(a')] \rangle$$

$$w_i = \frac{1}{\Delta}\int_{a_i}^{a_i+\Delta} da\, w(a)$$

$$C_{ij} \equiv \langle \delta w_i \delta w_j \rangle = \frac{1}{\Delta^2}\int_{a_i}^{a_i+\Delta} da \int_{a_j}^{a_j+\Delta} da' \xi_w(|a-a'|)$$

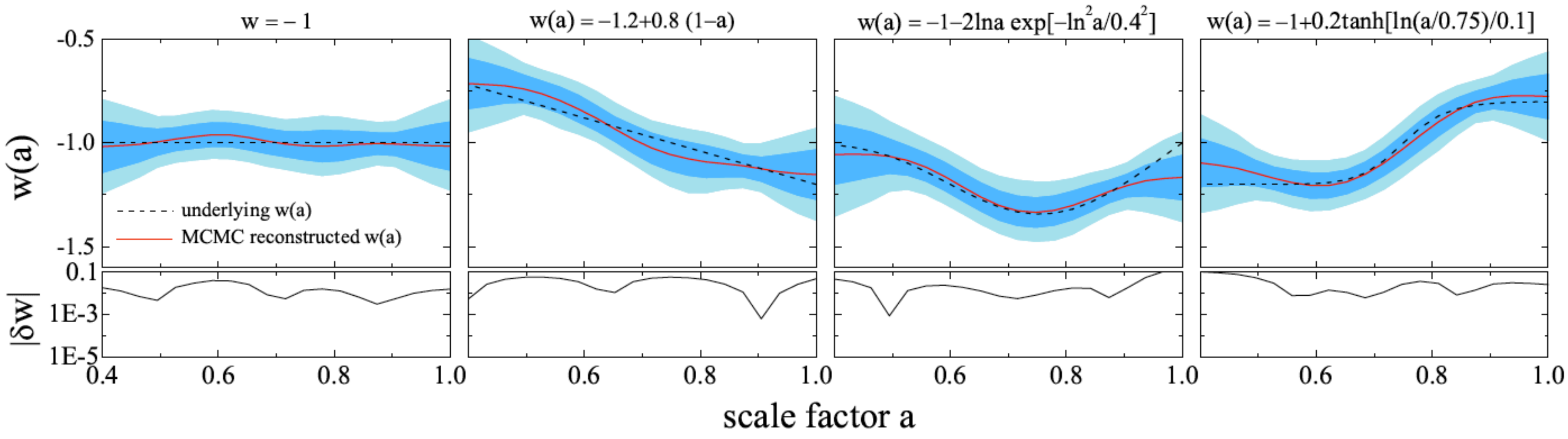
$$\chi^2_{\rm prior} = -2\ln \mathcal{P}_{\rm prior} = (\mathbf{w}-\mathbf{w}^{\rm fid})^T \mathbf{C}^{-1} (\mathbf{w}-\mathbf{w}^{\rm fid})$$

Hide w(z) models in the mock data



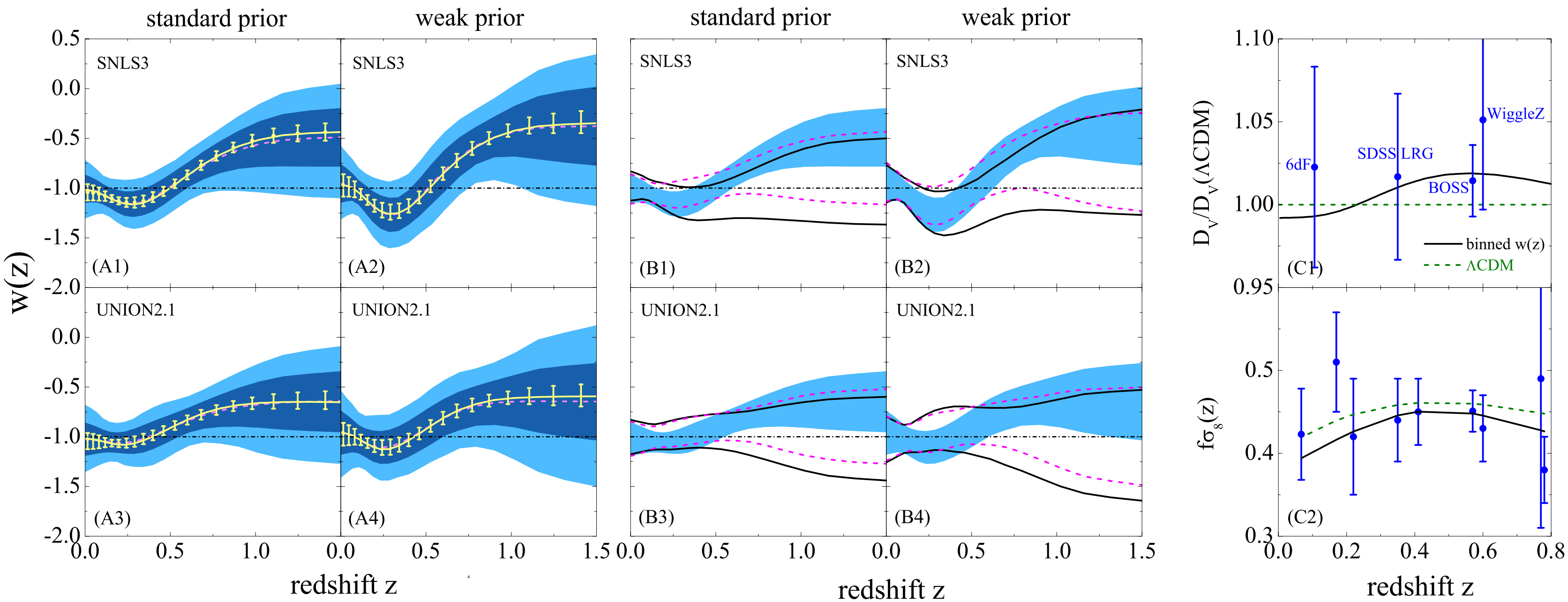
w reconstructed successfully

Crittenden, GBZ, Pogosian, Samushia, Zhang(2012)



Result using the latest data (WMAP7+SNLS3(Union2.1)+BOSS BAO, RSD)

GBZ, Robert Crittenden, Levon Pogosian, Xinmin Zhang, to appear soon



Make Universe accelerate by tweaking LHS

$$\widetilde{G}_{\mu\nu} = \frac{1}{M_p^2} T_{\mu\nu}$$

MODIFIED GRAVITY

- chameleon, symmetron, dilaton
- DGP
- Massive gravity

Fighting against gravity: A painful happiness!!

Testing GR on linear scales

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

$$\nabla_\mu T^{\mu\nu} = 0 \quad \Longrightarrow \quad \begin{aligned} \Phi' &= \frac{1}{3}\left(\delta' + \frac{k}{aH}v\right) \\ \Psi &= \frac{aH}{k}(v' + v) \end{aligned}$$

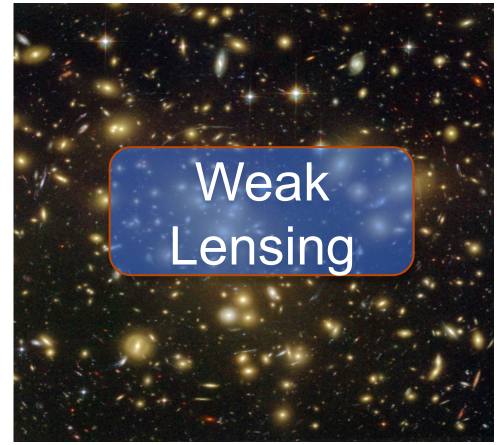
General Relativity

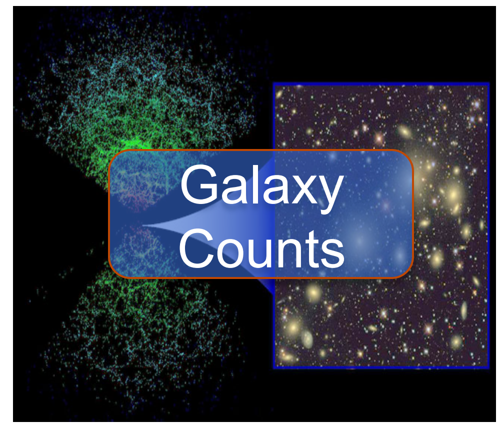
Modified Gravity

$$\Longrightarrow \quad \begin{aligned} k^2\Phi &= -\mu(a,k)4\pi G a^2 \rho\delta \\ \frac{\Phi}{\Psi} &= \gamma(a,k) \end{aligned}$$

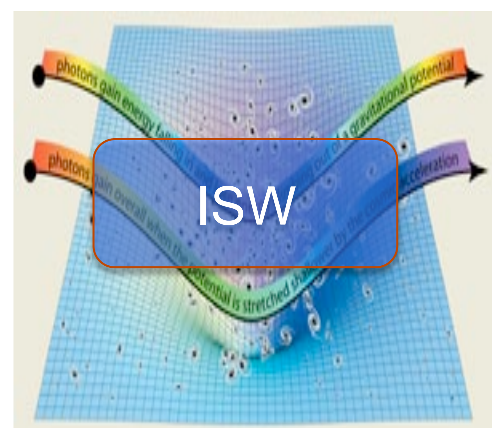
MGCAMB

μ(a,k), γ(a,k)
cosmo. param.

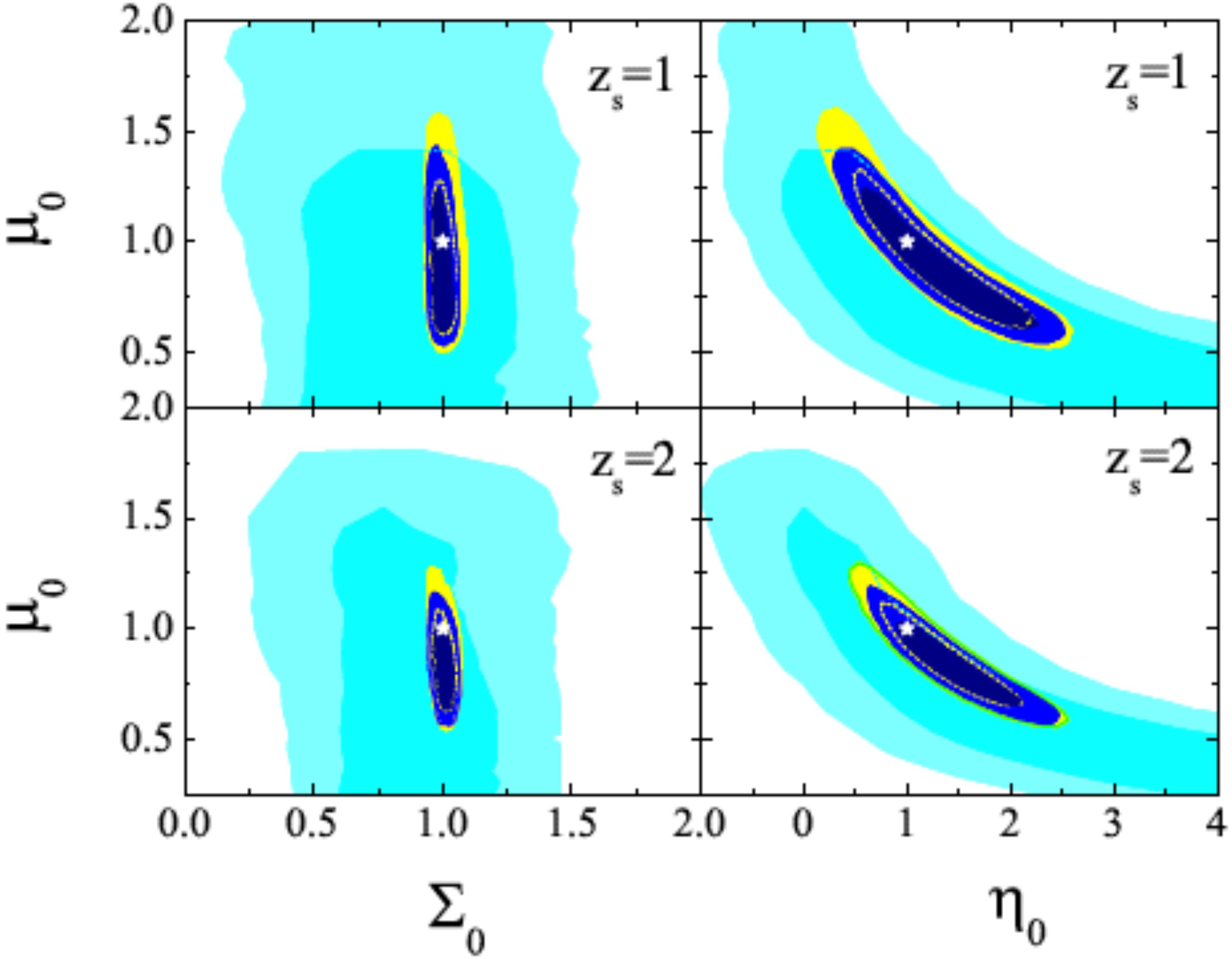




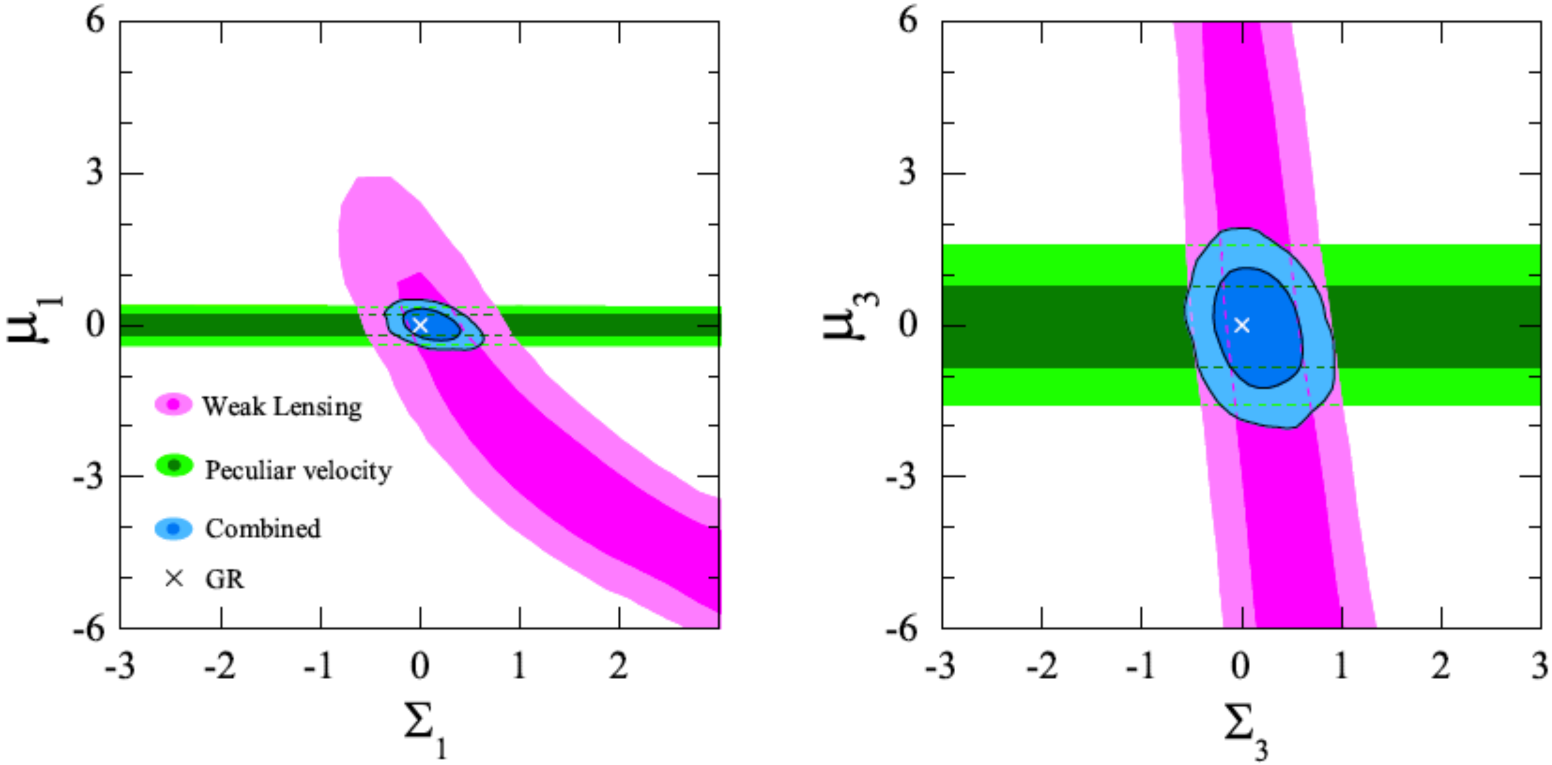
http://www.sfu.ca/~aha25/MGCAMB.html



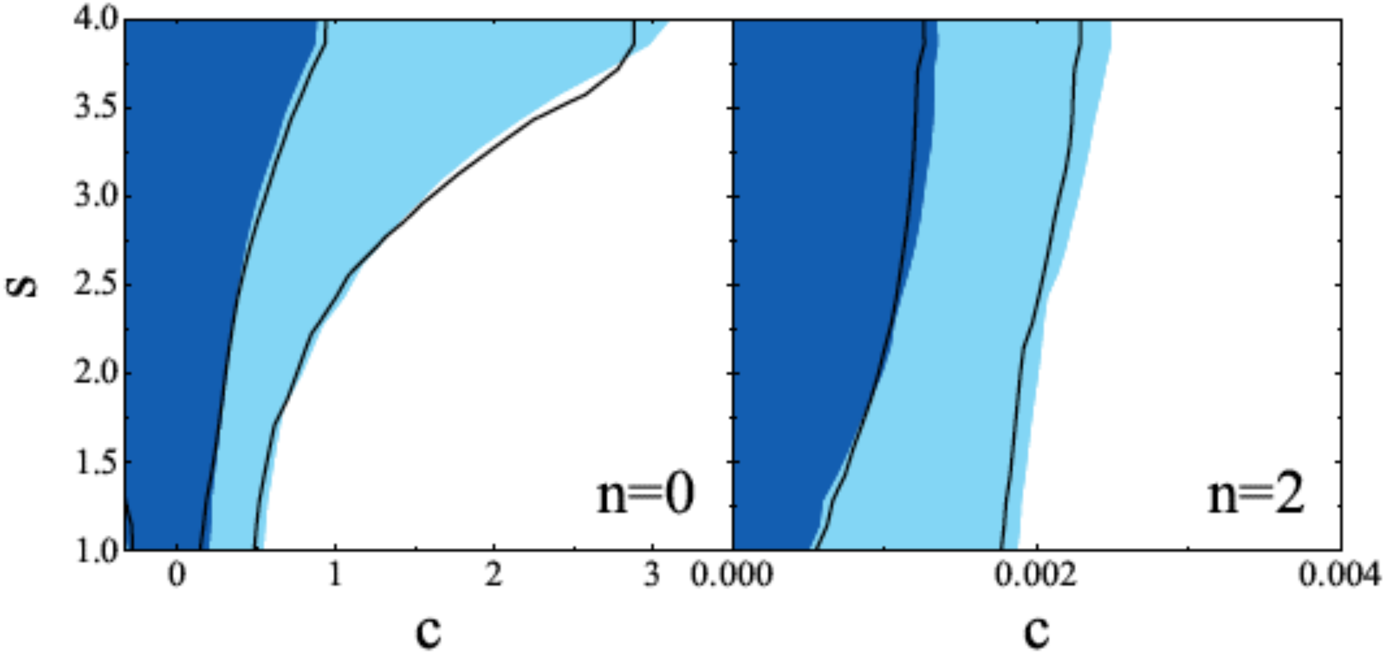
GBZ, Giannantonio, Pogosian, Silvestri, Bacon, Koyama, Nichol, Song
1003.0001, PRD, 2010



Song, GBZ, Bacon, Koyama, Nichol, Pogosian
1011.2106, PRD, 2011

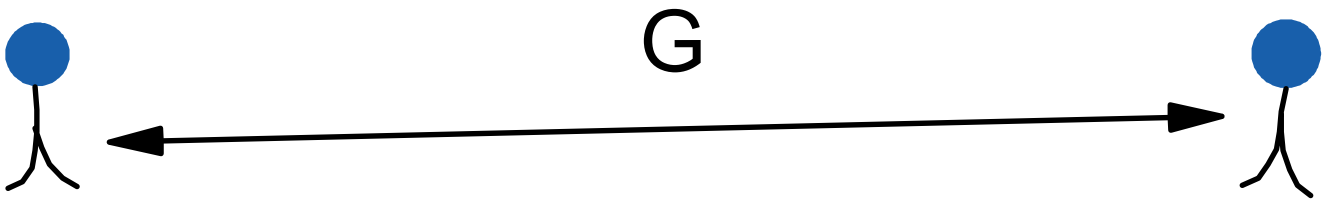


GBZ, Li, Linder, Koyama, Bacon, Zhang
1109.1846, PRD, 2012

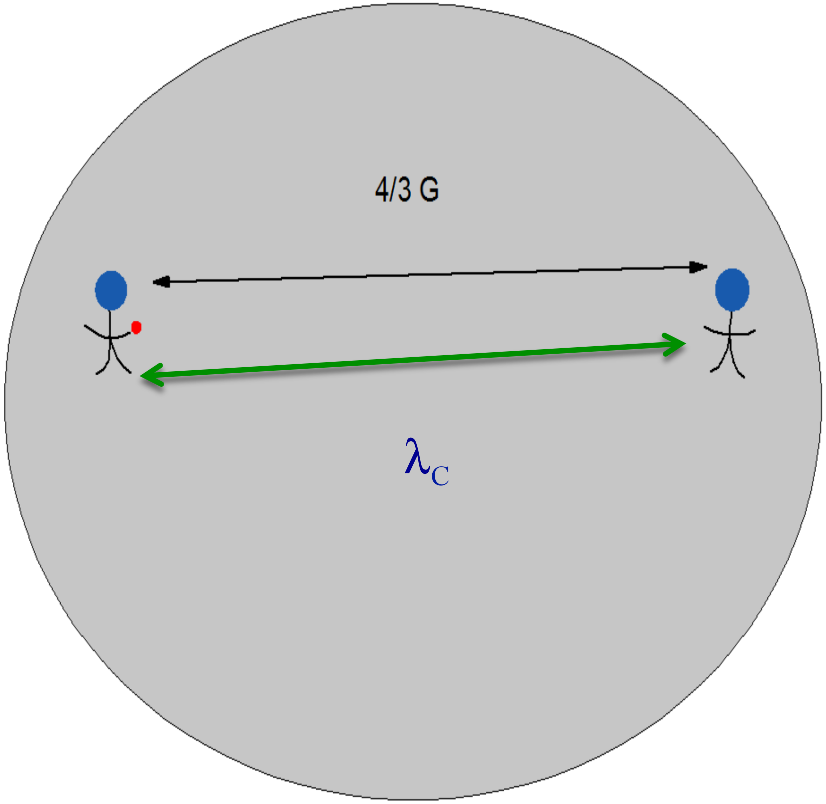


Testing GR on nonlinear scales?
Simulation is needed!

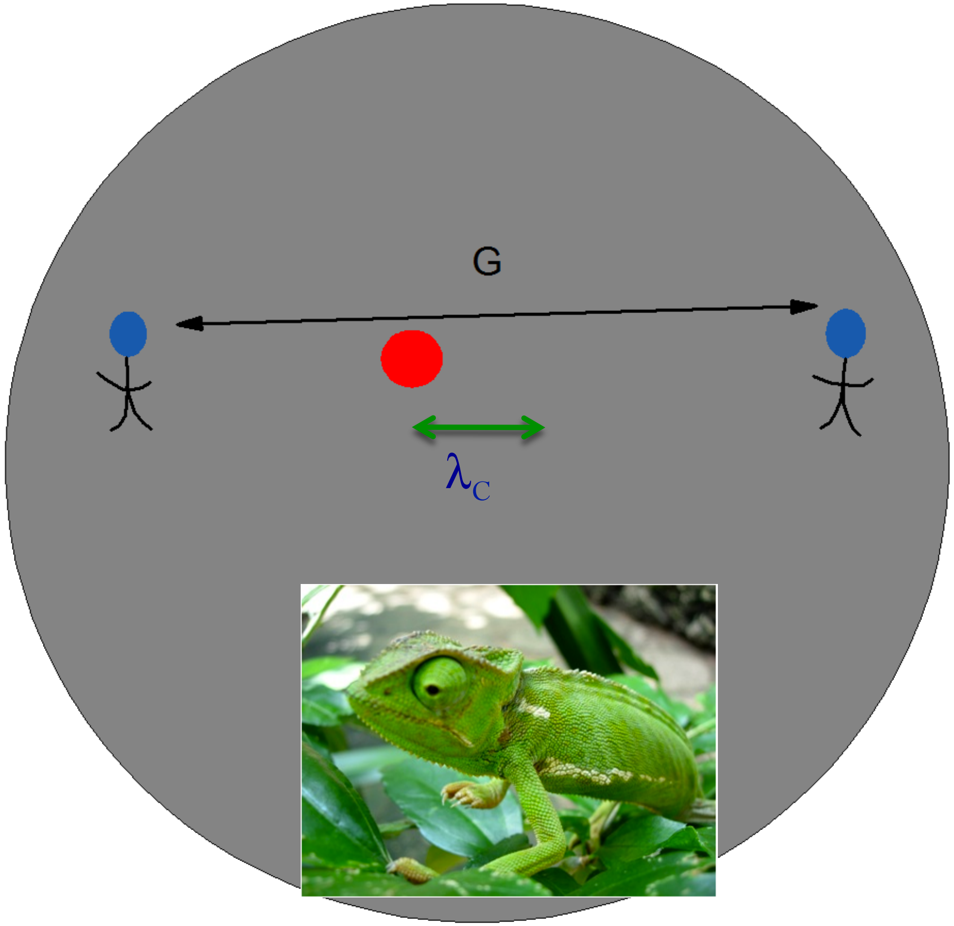
In GR



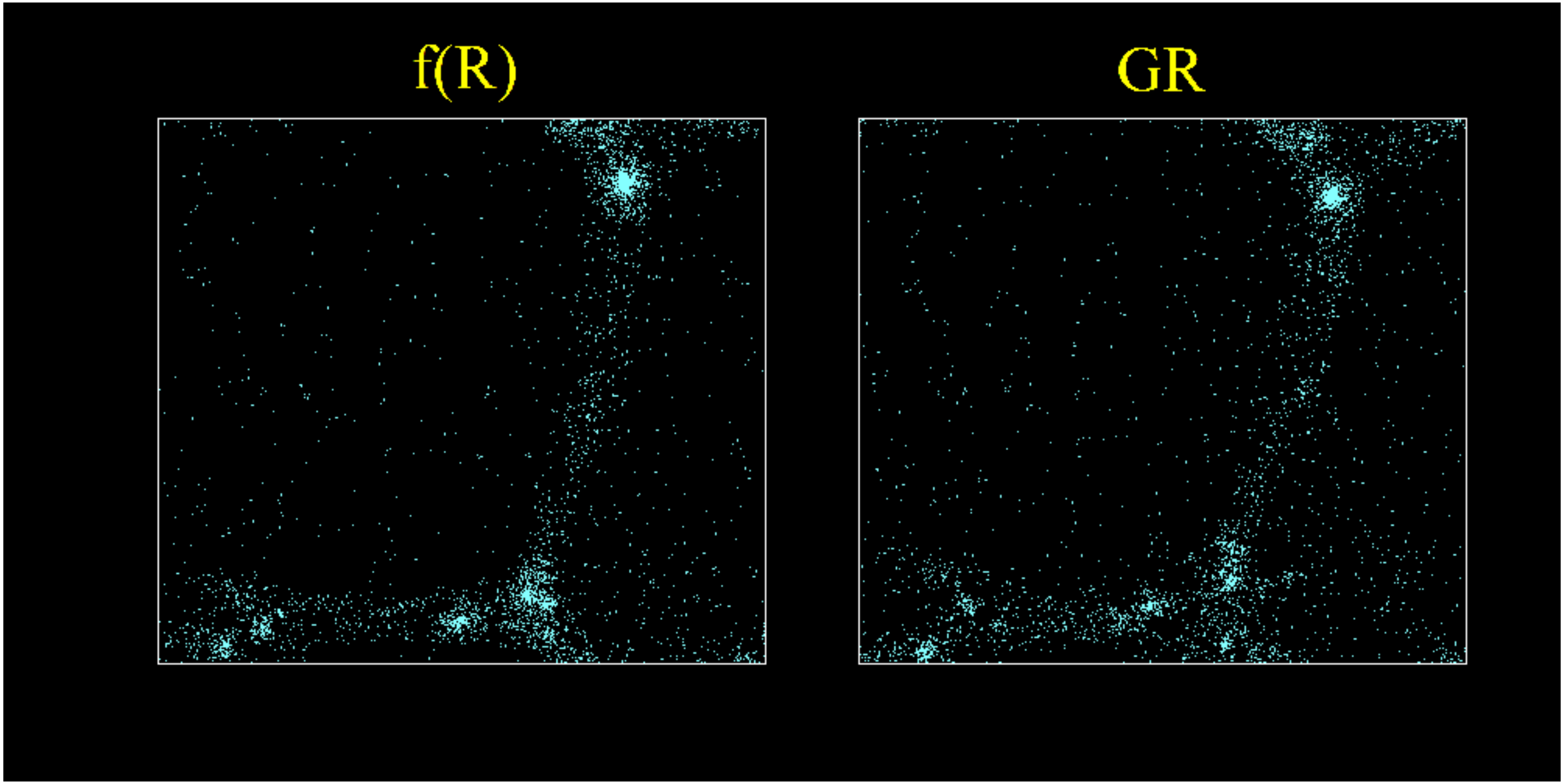
In f(R)



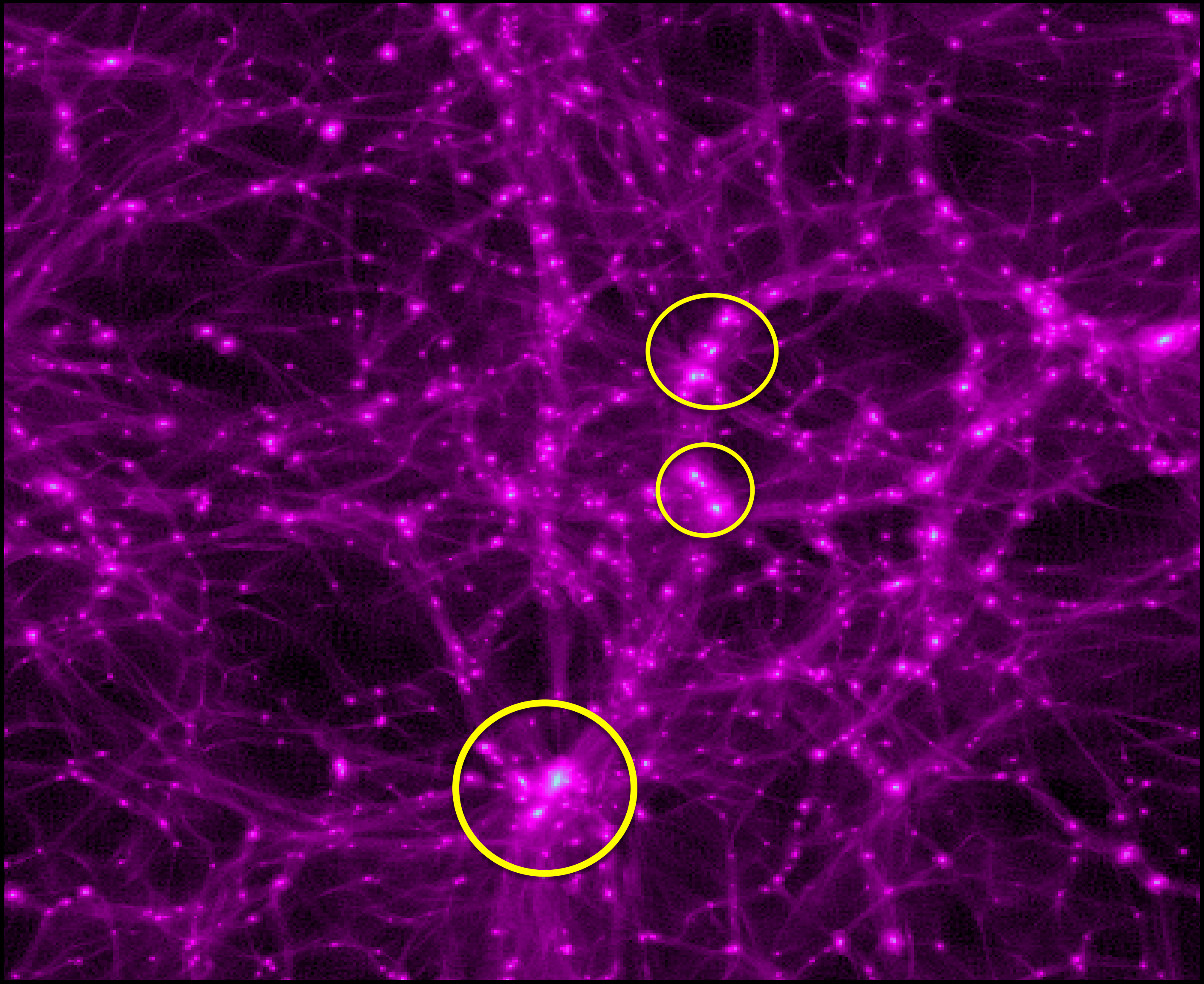
In very dense regions



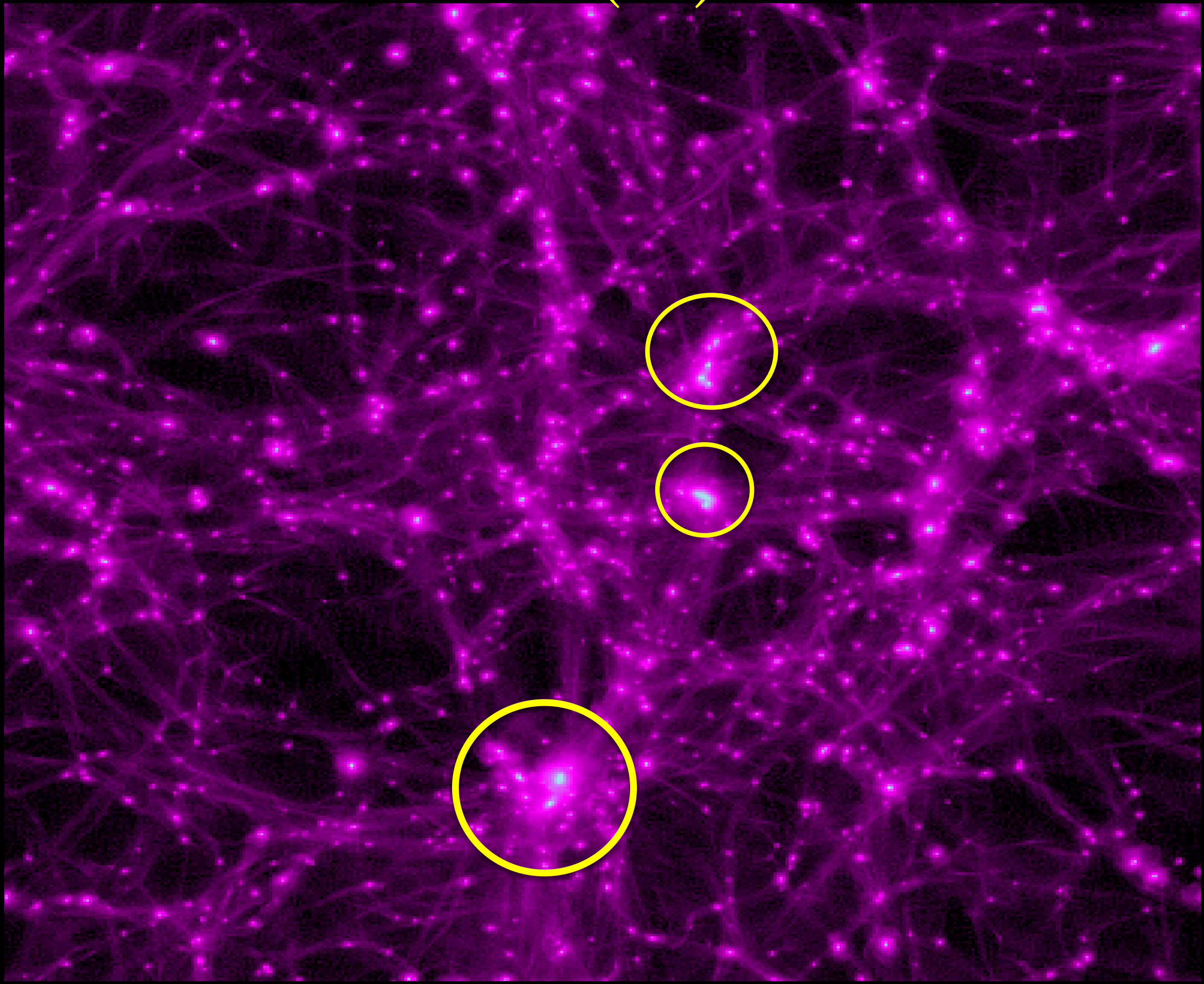
Get some sense…



GR



f(R)



Structure formation in GR

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

$$\begin{aligned}\delta R &= -8\pi G\delta\rho \\ \nabla^2\Phi &= 4\pi G a^2 \delta\rho\end{aligned}$$

Structure formation in f(R)

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

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

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

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

Dynamical Mass

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

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

Dynamical Mass

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

$$\nabla^2 \Phi = 4\pi G a^2 \delta\rho_{\rm eff}$$

Spherical symmetry

$$\Longrightarrow \quad M_D(r) = r^2 \frac{d\Phi}{dr}$$

Lensing Mass

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

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

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

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

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

Spherical symmetry

$$M_L(r) = r^2 \frac{d\Phi_+}{dr}$$

Mass Difference

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

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

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

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

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

In underdense environment

$\delta R =$ [illegible] $3\nabla^2$ [illegible] f_R / [illegible]

$\delta\rho_{\rm eff} = \frac{4}{3}\delta\rho + \frac{1}{2\ldots}$ [illegible] δR

In underdense environment

$$\Delta_M = 1/3$$

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

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

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

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

In dense environment

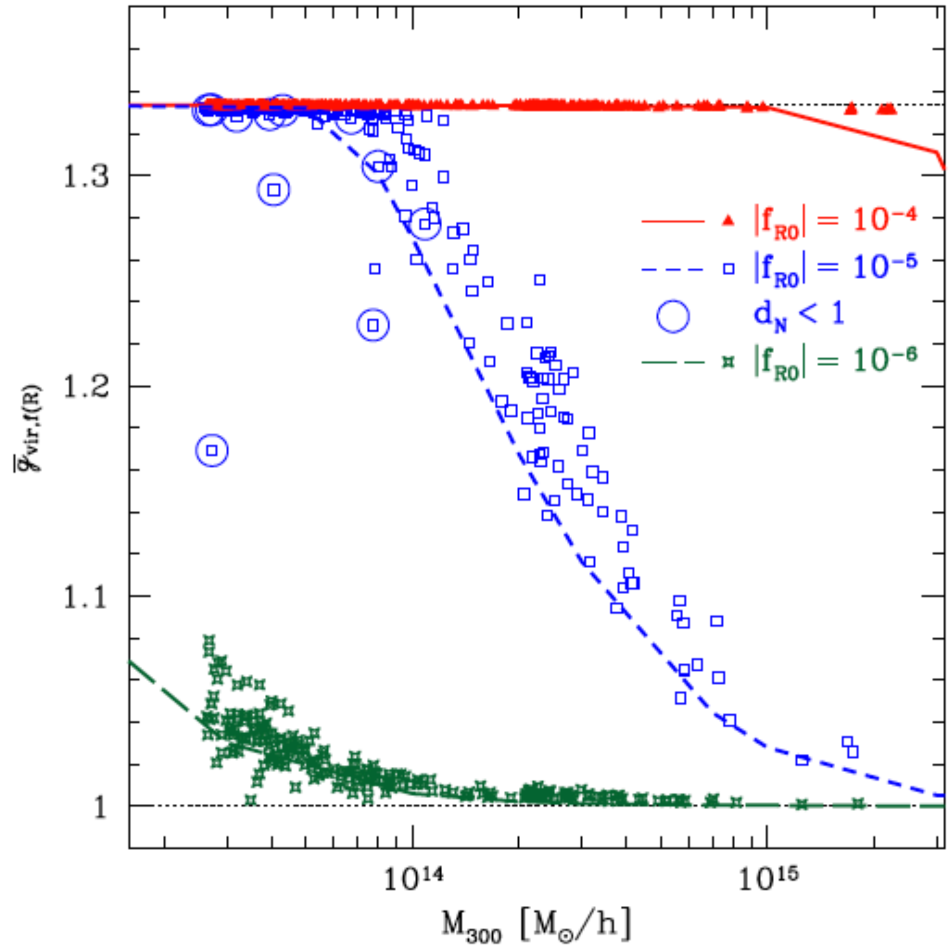
$$\delta R = -8\pi G \delta\rho - \frac{3\nabla^2 \delta f_R}{a^2}$$

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

In dense environment

$$\Delta_M = 0$$

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



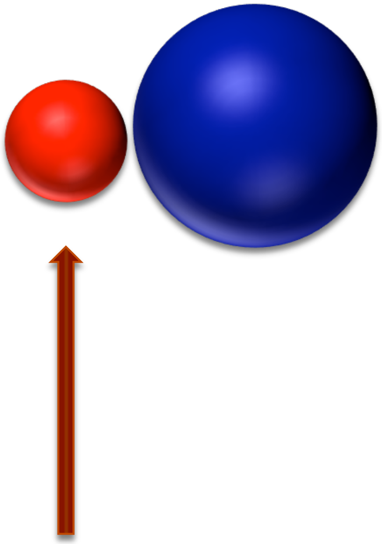
Fabian Schmidt, 1003.0409, PRD 2010

To see the pure environmental effect, we need a new environment indicator which is uncorrelated with halo mass

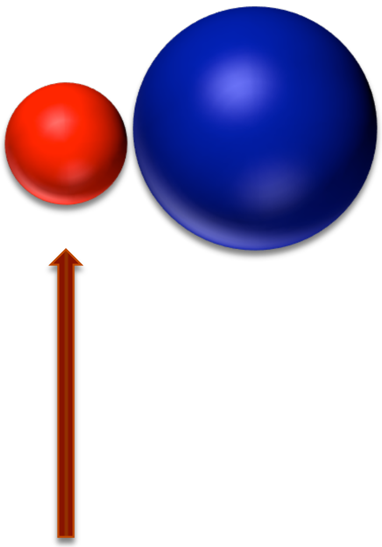
The three-dimensional distance to the Nth nearest neighbour with a viral mass that is at least *f times that of the halo* under consideration, divided by the virial radius of the *Nth nearest* neighbour:

$$D_{N,f} = \frac{r_{N(M_{\mathrm{ngb}} \geqslant f \cdot M_{\mathrm{halo}})}}{R_{\mathrm{vir,\,ngb}}},$$

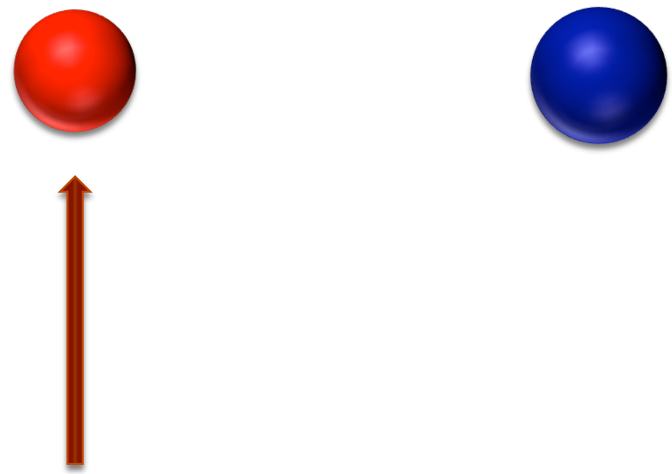
Haas et al., 1103. 0547



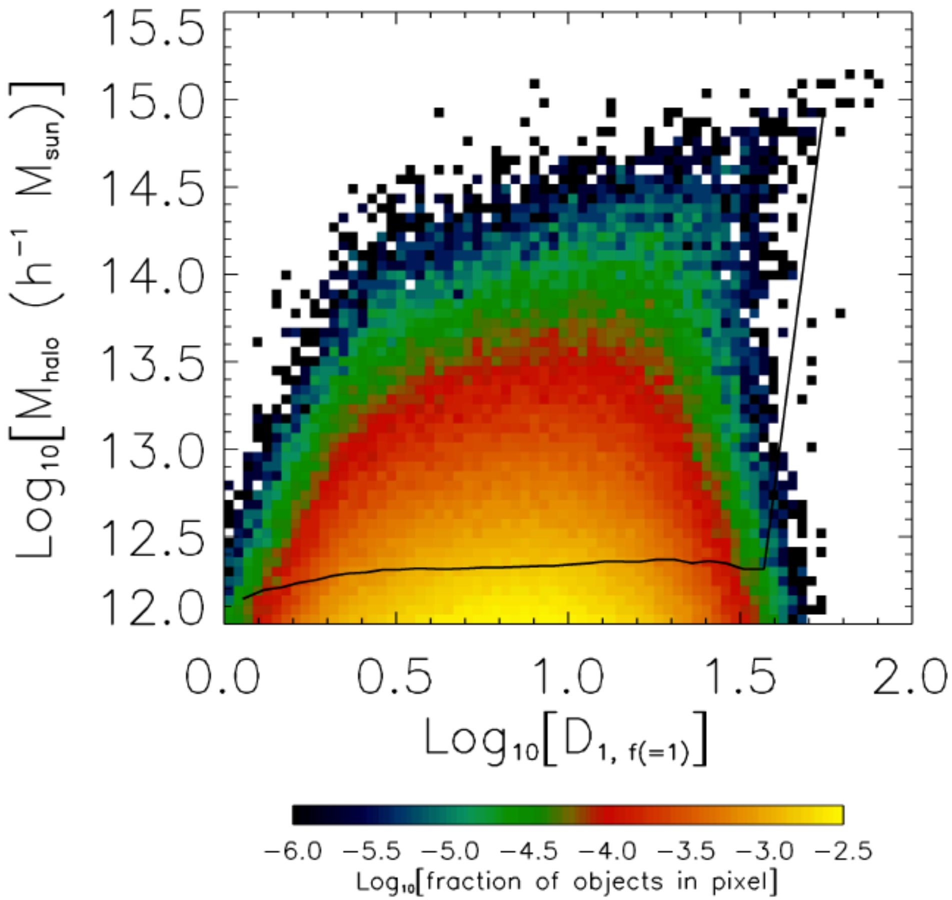
Small D
Affected by the local environment



Small D
Affected by the local environment

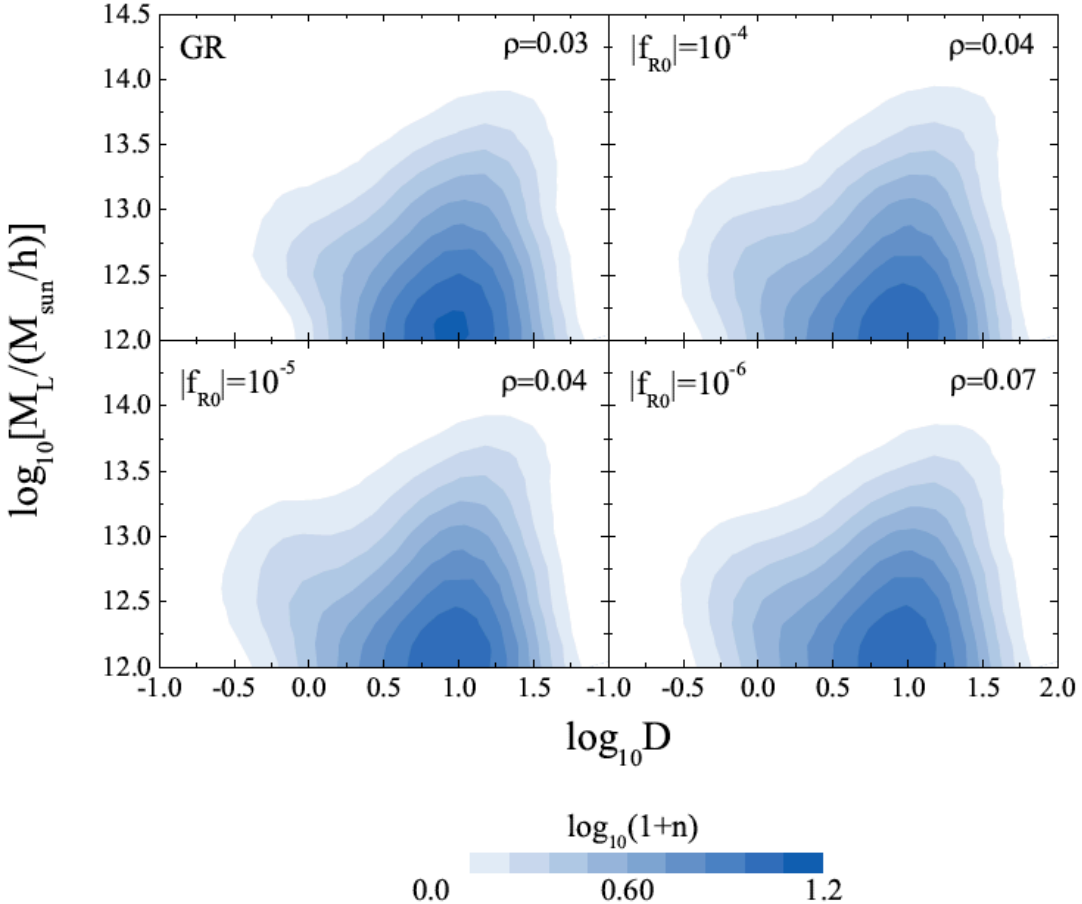


Large D
Affecting the local environment

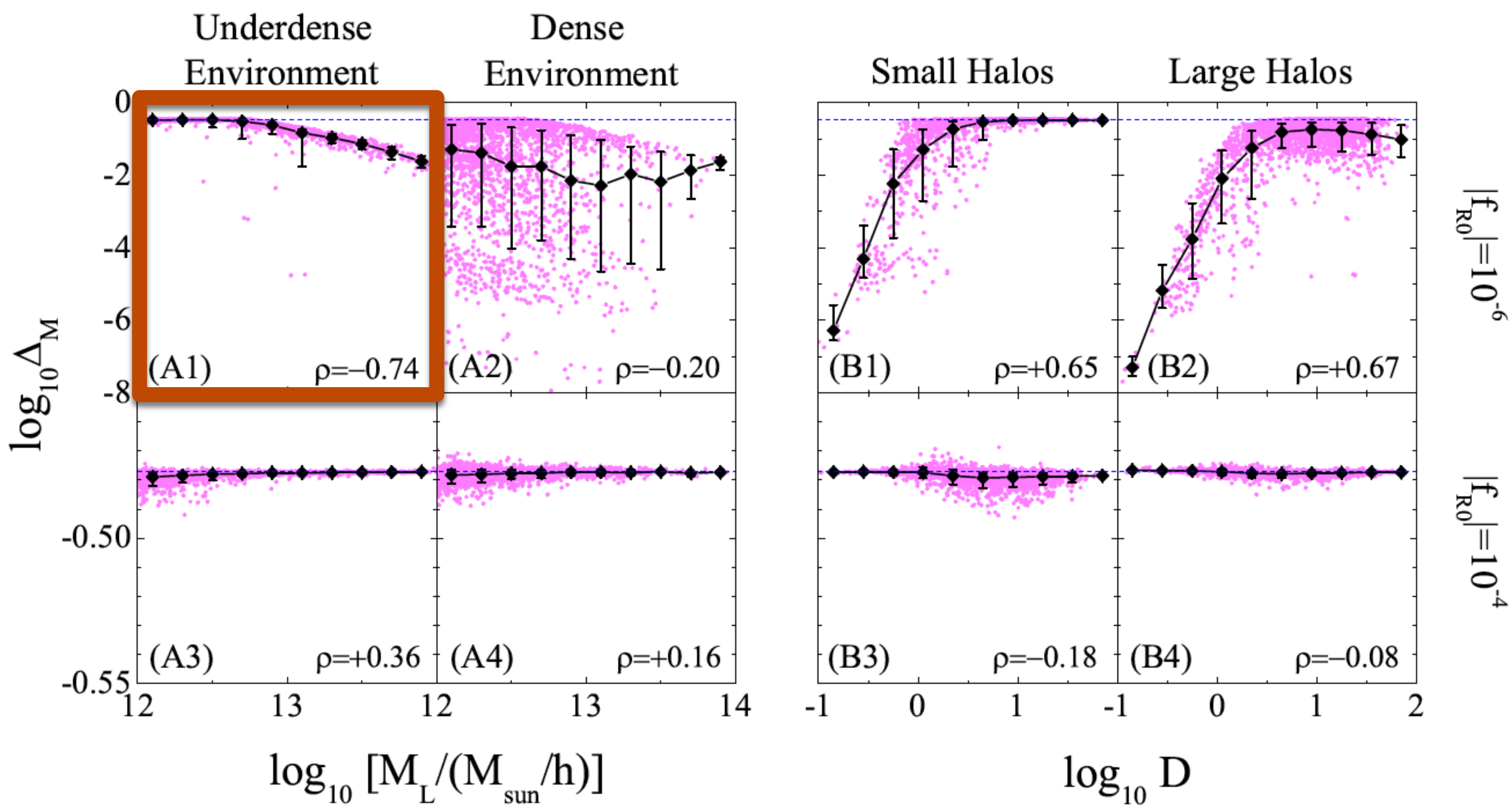


GR analysis, Haas et al., 1103. 0547

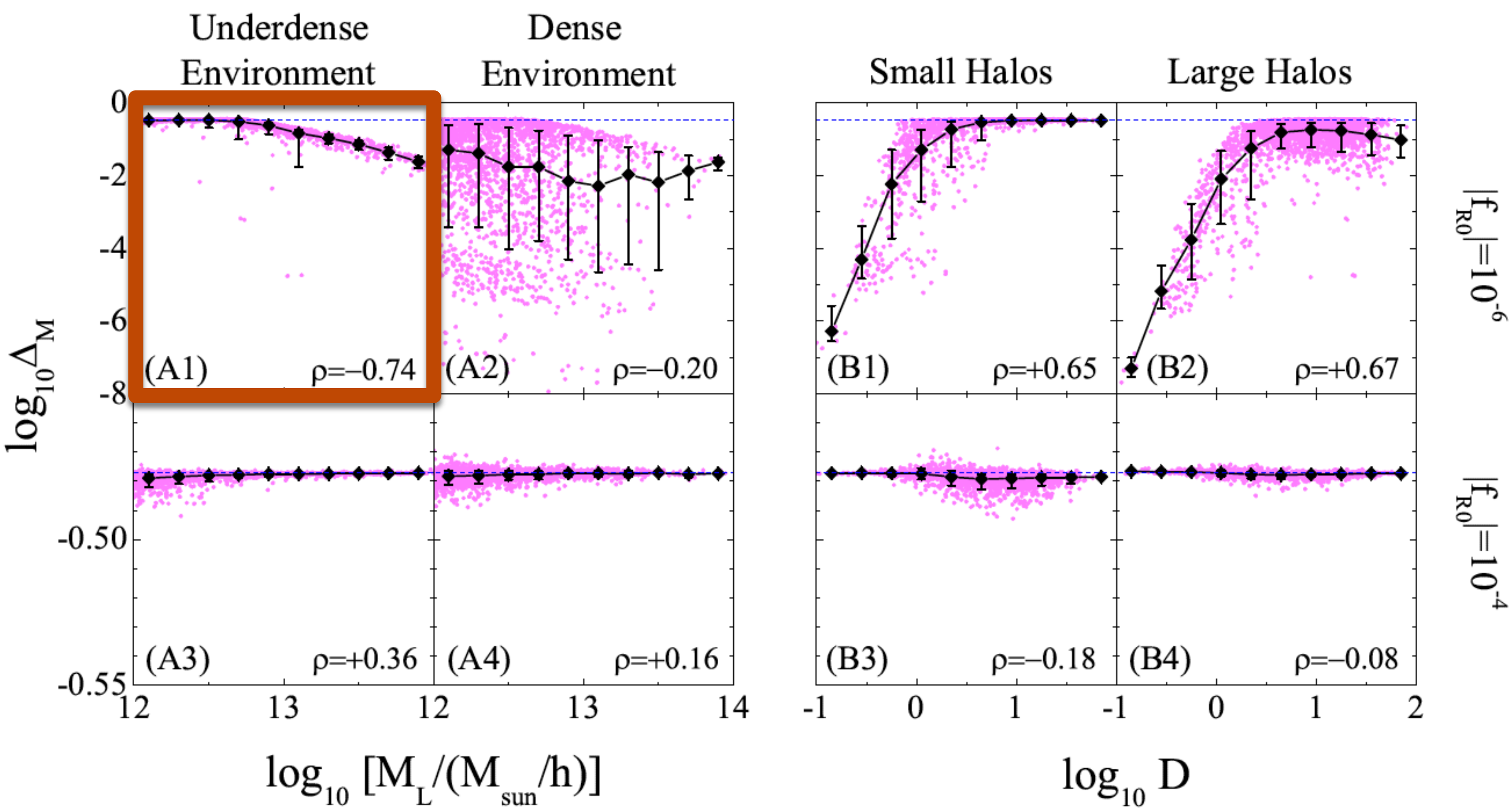
D is a clean indicator for the local environment!

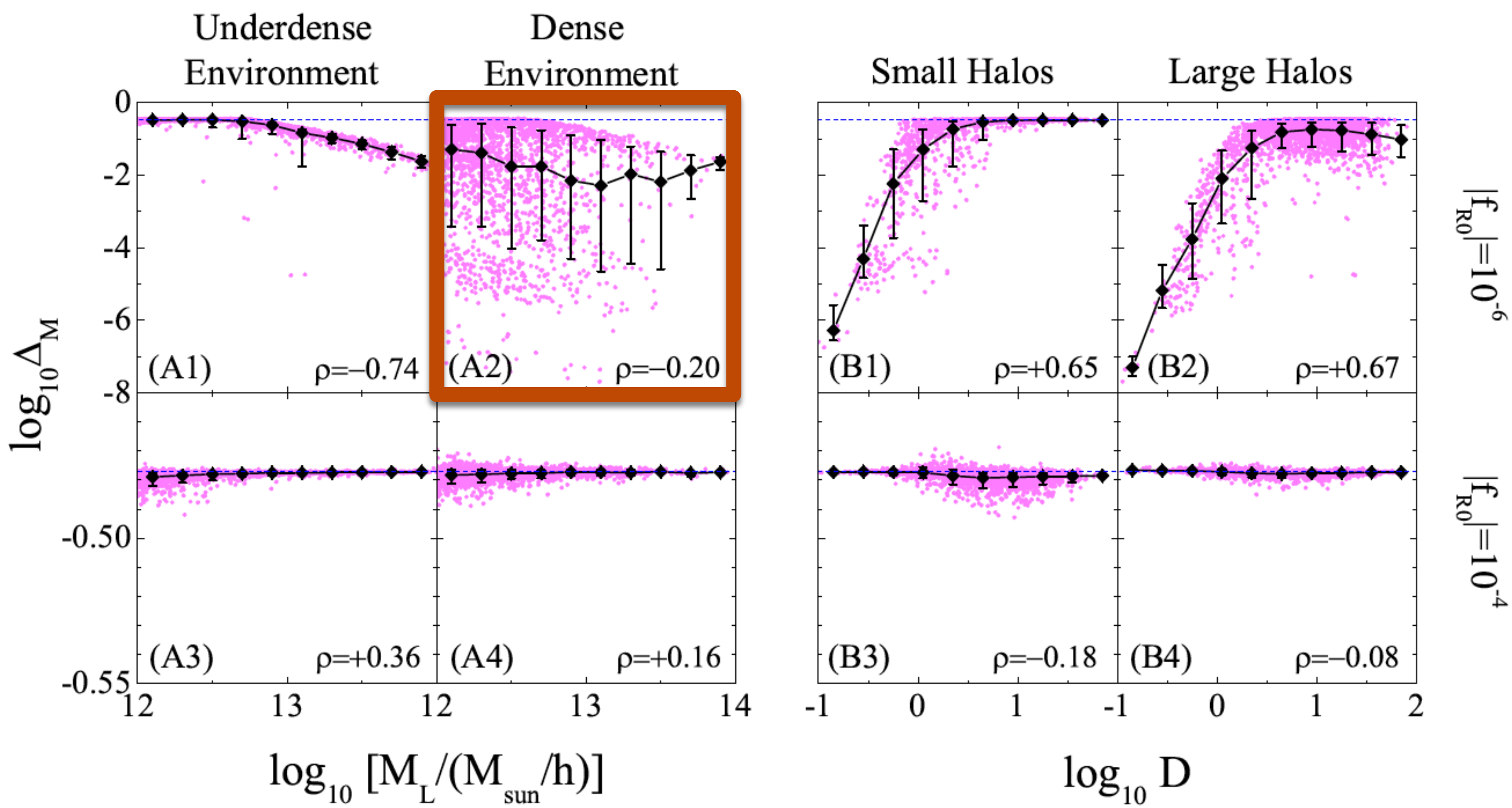


f(R) analysis, 1105.0922
GBZ, Baojiu Li, Kazuya Koyama (PRL 2011)

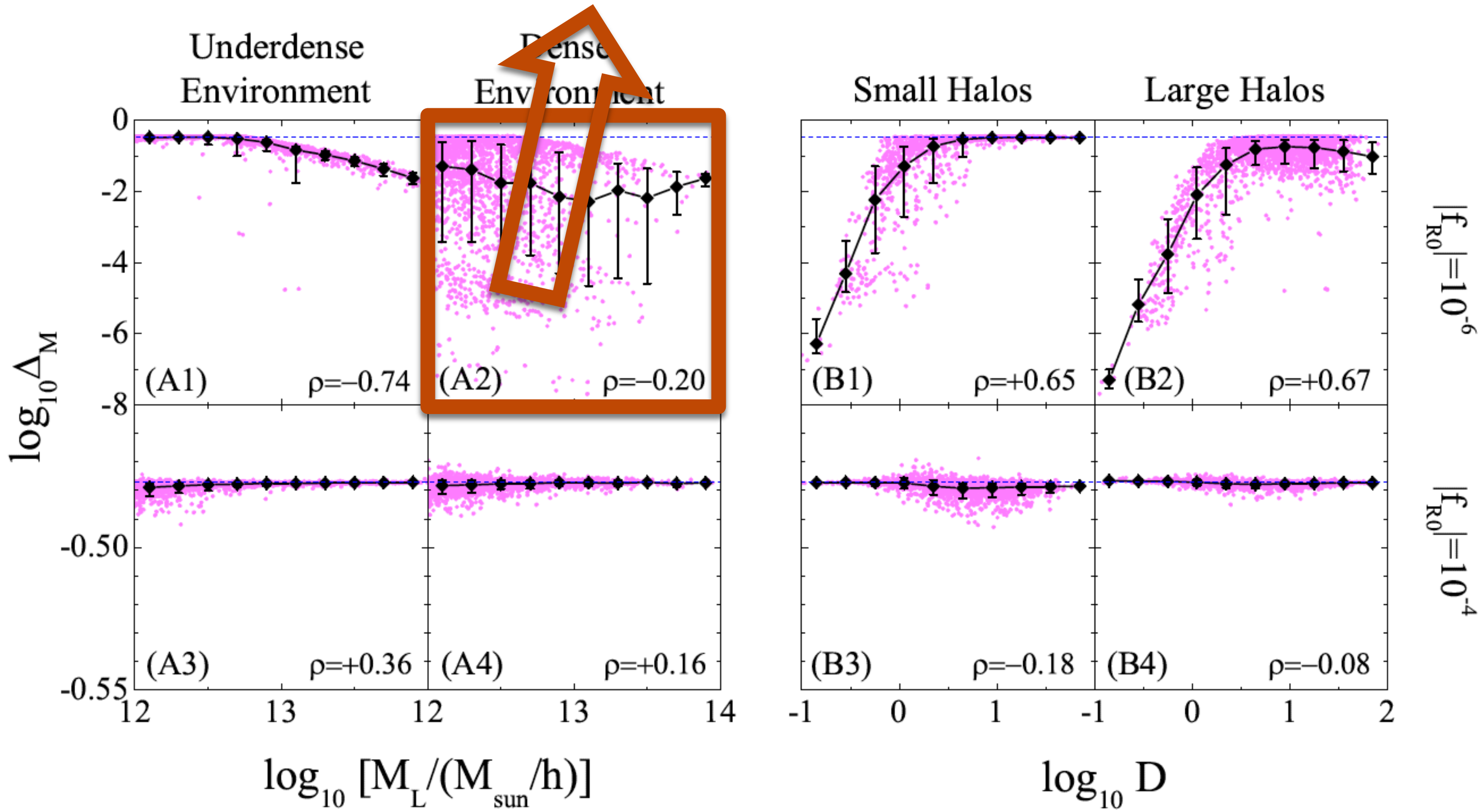

Underdense Environment
Dense Environment
Small Halos
Large Halos
(A1) ρ=−0.74
(A2) ρ=−0.20
(B1) ρ=+0.65
(B2) ρ=+0.67
(A3) ρ=+0.36
(A4) ρ=+0.16
(B3) ρ=−0.18
(B4) ρ=−0.08
$\log_{10}\Delta_M$
$\log_{10}[M_L/(M_{sun}/h)]$
$\log_{10} D$
$|f_{R0}|=10^{-6}$
$|f_{R0}|=10^{-4}$

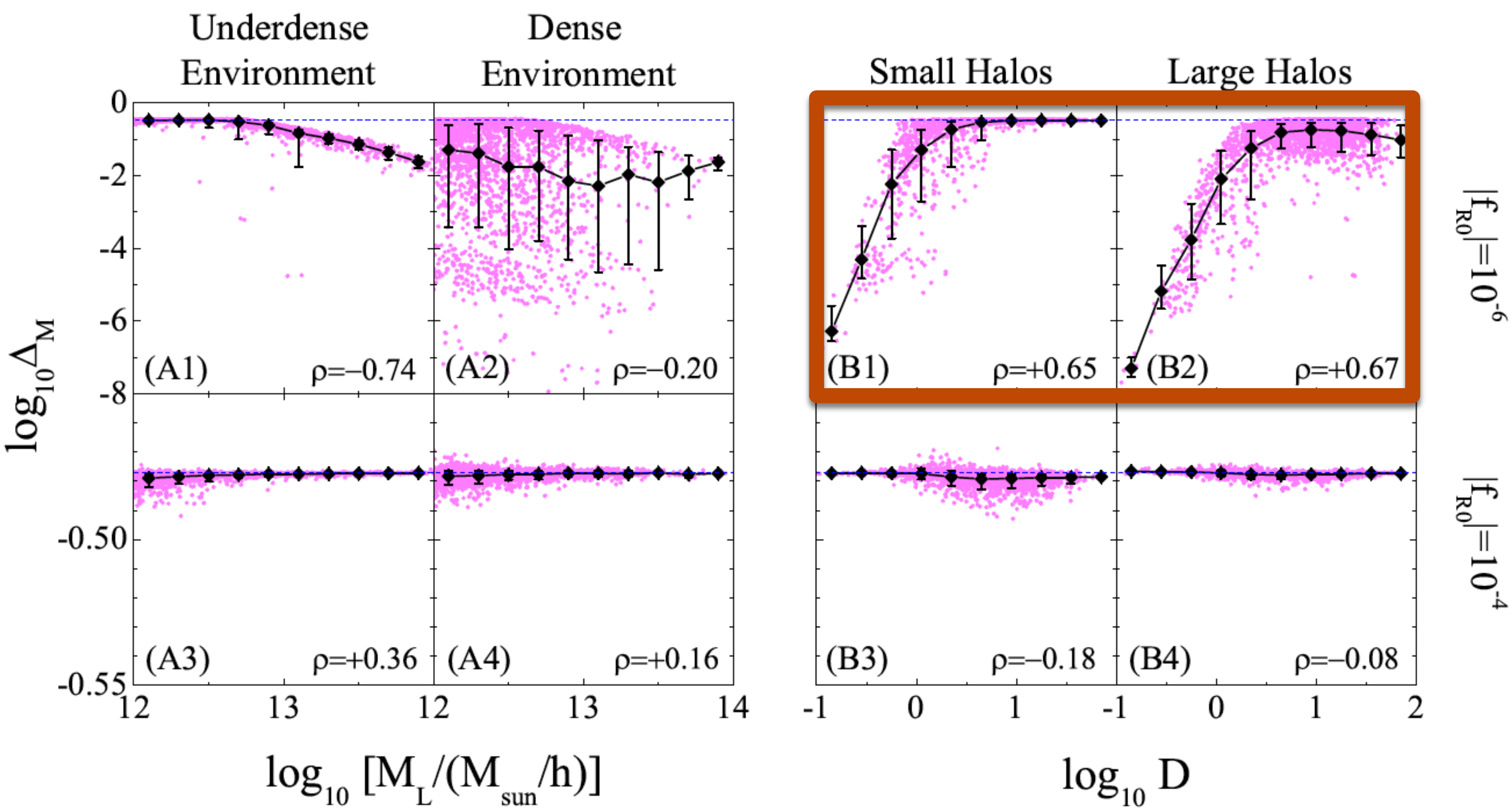
Clean mass dependence!




Underdense Environment
Dense Environment
Small Halos
Large Halos
0
-2
-4
-6
-8
-0.50
-0.55
(A1)
ρ=−0.74
(A2)
ρ=−0.20
(B1)
ρ=+0.65
(B2)
ρ=+0.67
(A3)
ρ=+0.36
(A4)
ρ=+0.16
(B3)
ρ=−0.18
(B4)
ρ=−0.08
12
13
12
13
14
-1
0
1
-1
0
1
2
$\log_{10}\Delta_M$
$\log_{10}[M_L/(M_{sun}/h)]$
$\log_{10} D$
$|f_{R0}|=10^{-6}$
$|f_{R0}|=10^{-4}$

Large scatter shows the environmental effect!!





Underdense Environment
Dense Environment
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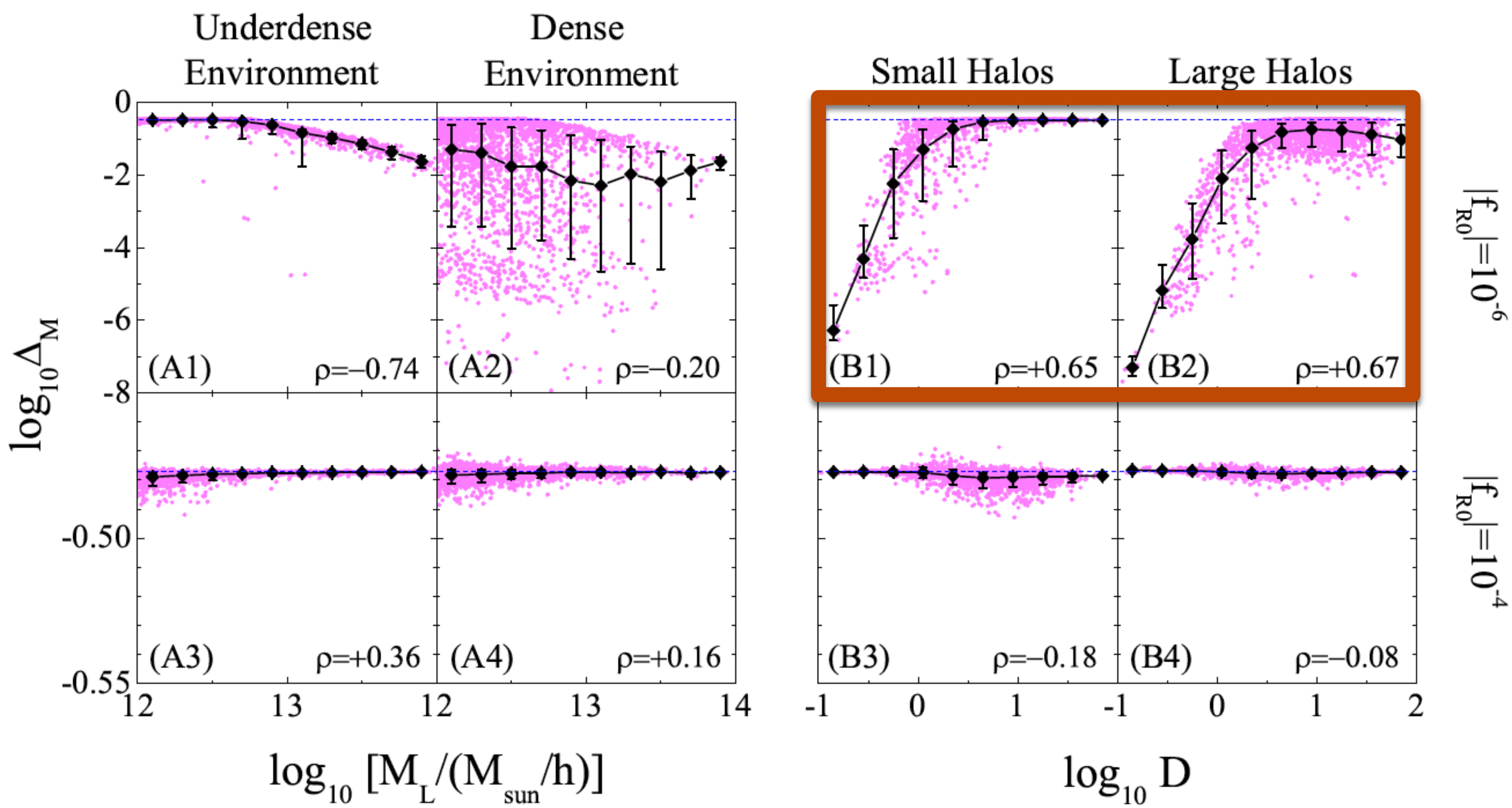
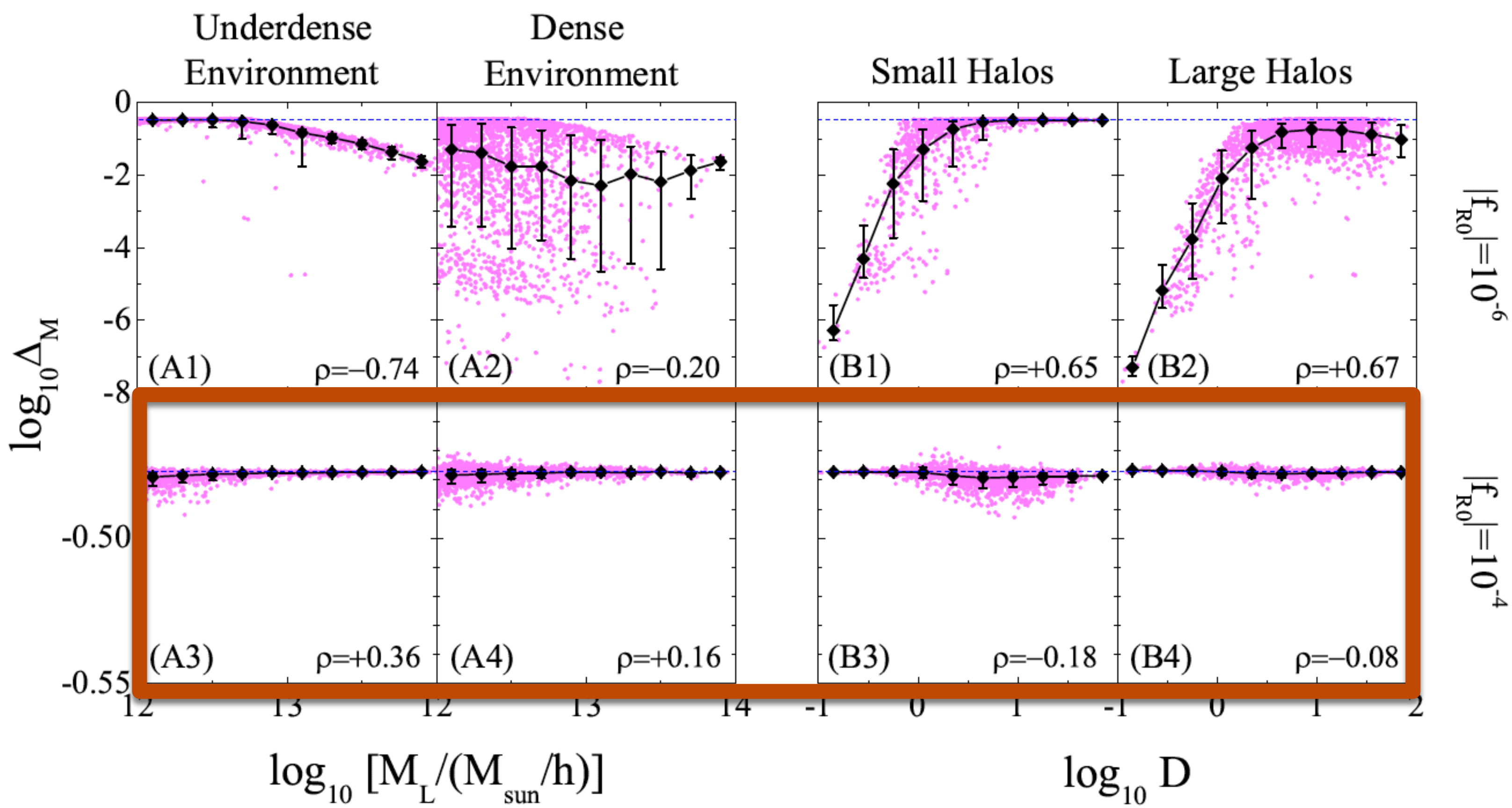
$|f_{R0}|=10^{-6}$
$|f_{R0}|=10^{-4}$
$\log_{10}[M_L/(M_{sun}/h)]$
$\log_{10} D$

Apparent environmental dependence!!





Underdense Environment
Dense Environment
Small Halos
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12
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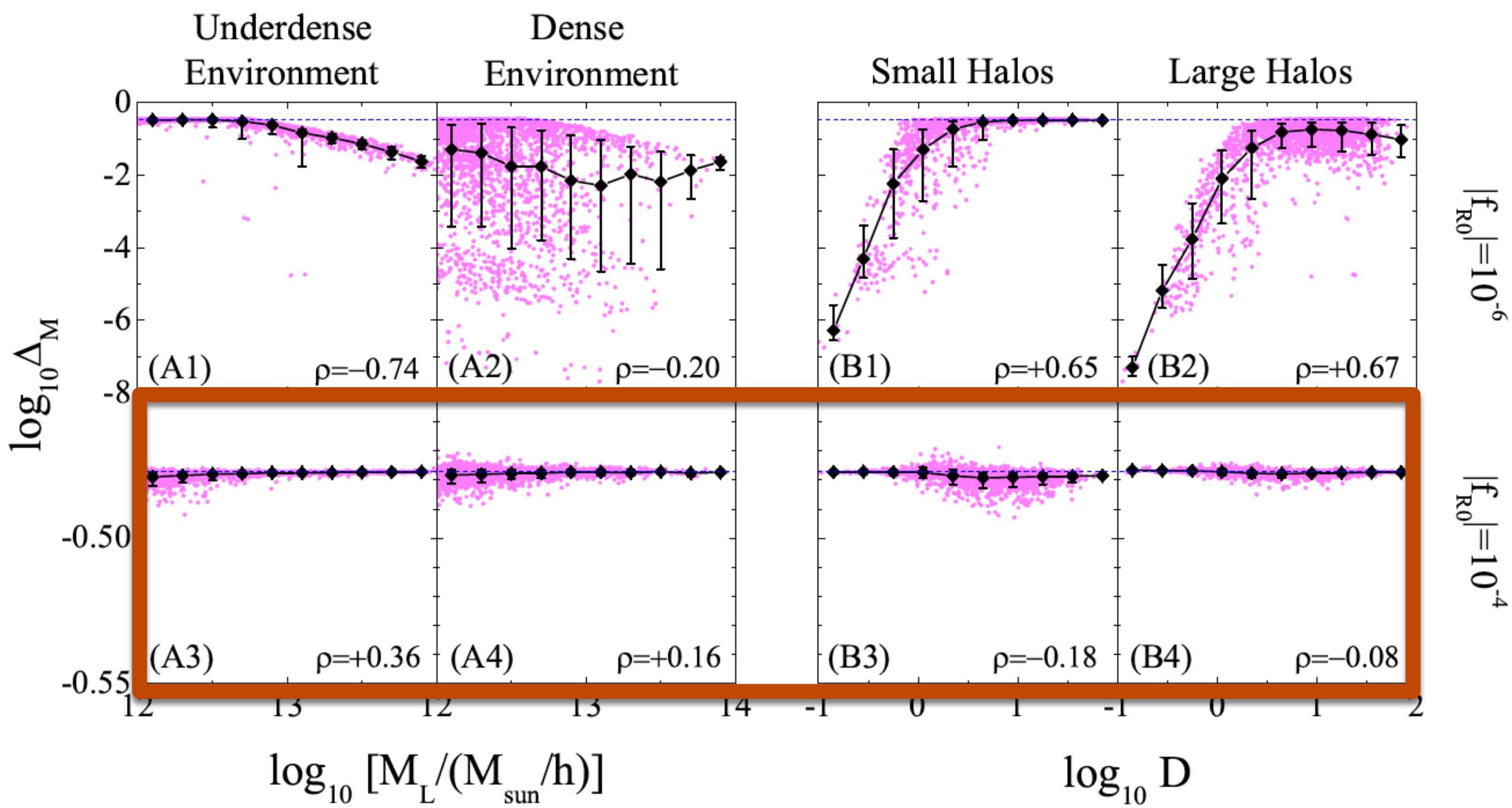
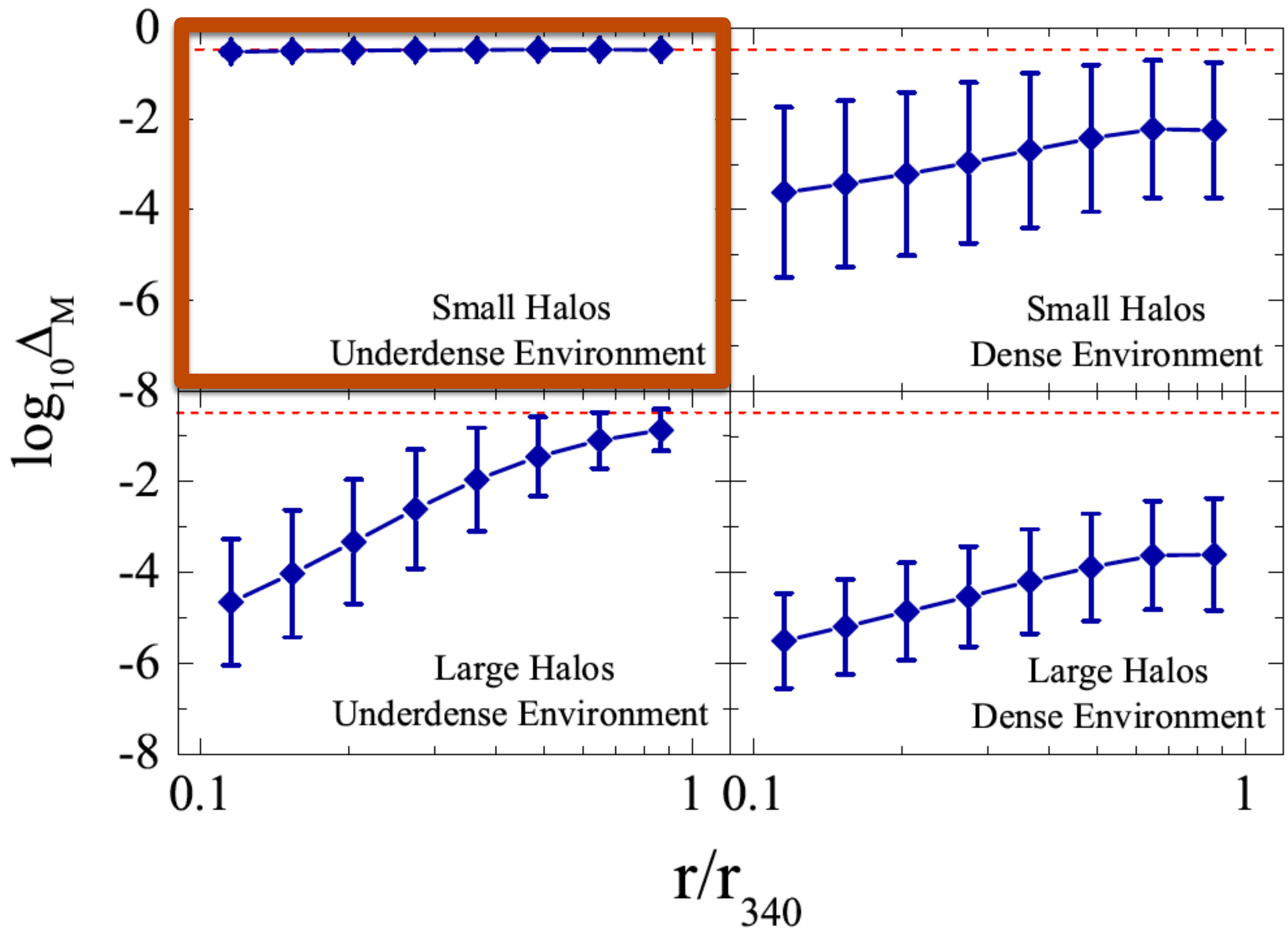
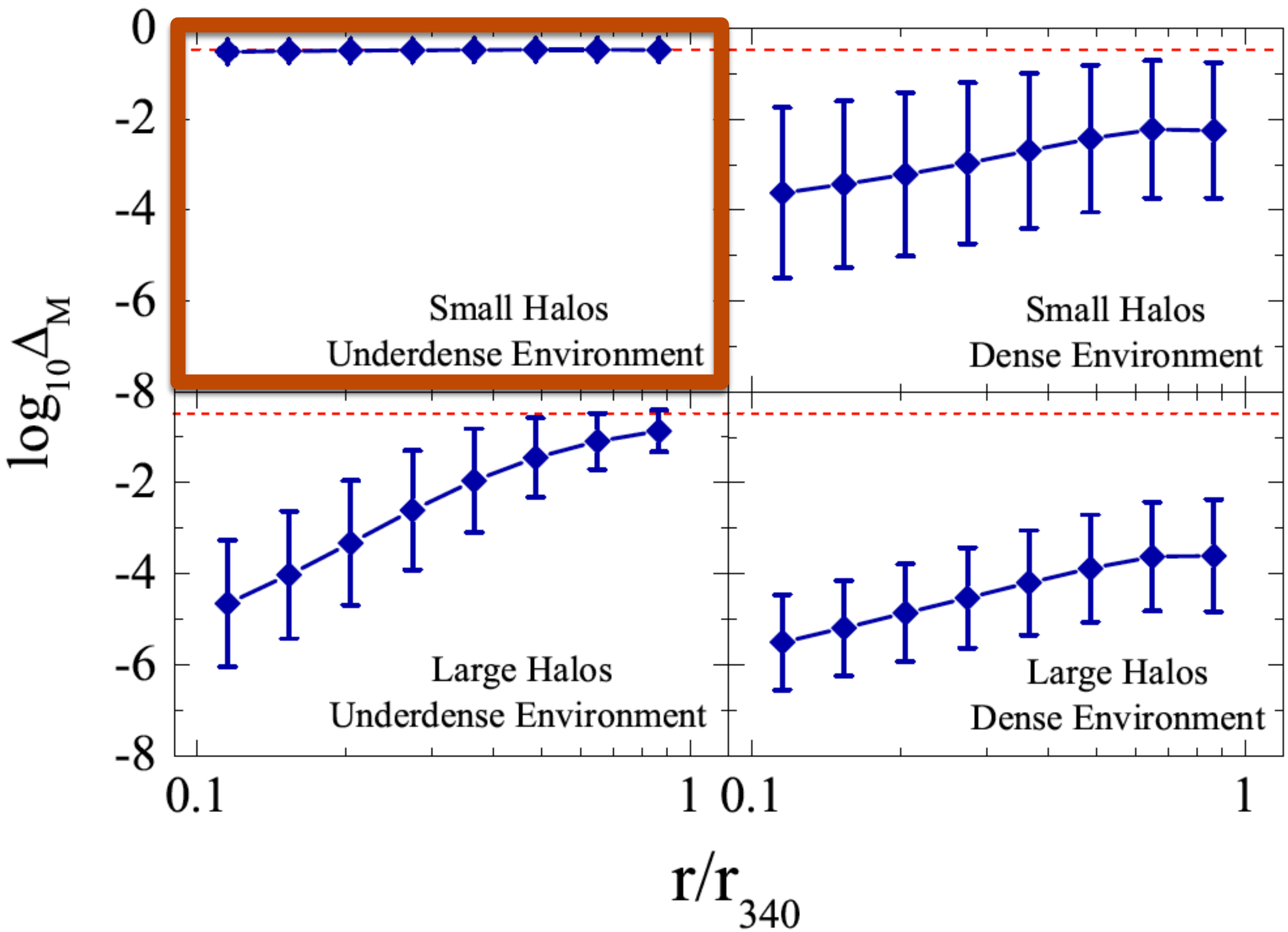
$\log_{10}[M_L/(M_{sun}/h)]$
$\log_{10} D$

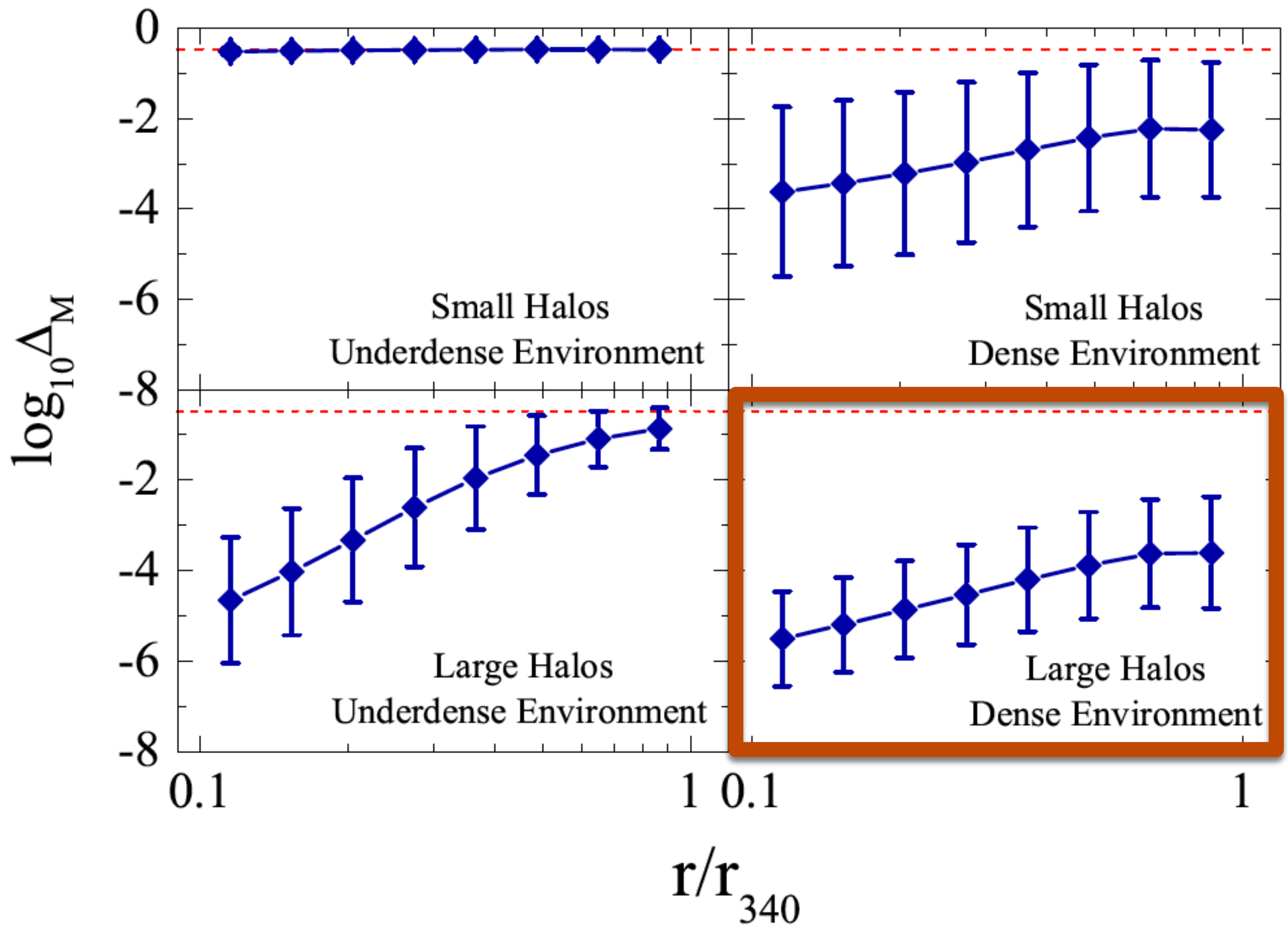


No screening at all!!


0
-2
-4
-6
-8
-2
-4
-6
-8
$\log_{10}\Delta_M$
Small Halos
Underdense Environment
Small Halos
Dense Environment
Large Halos
Underdense Environment
Large Halos
Dense Environment
0.1
1
0.1
1
r/r_{340}

No screening!





0
-2
-4
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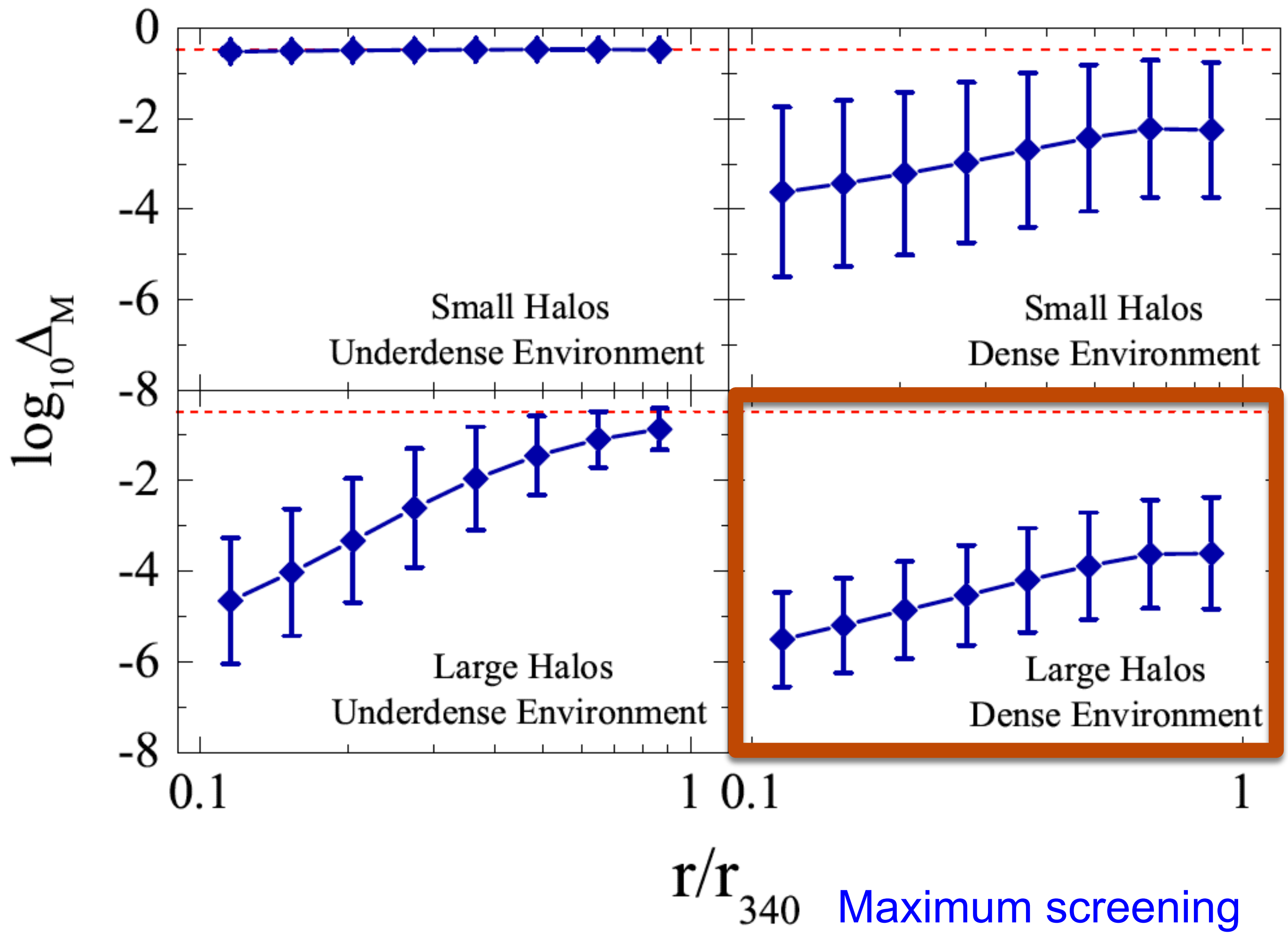
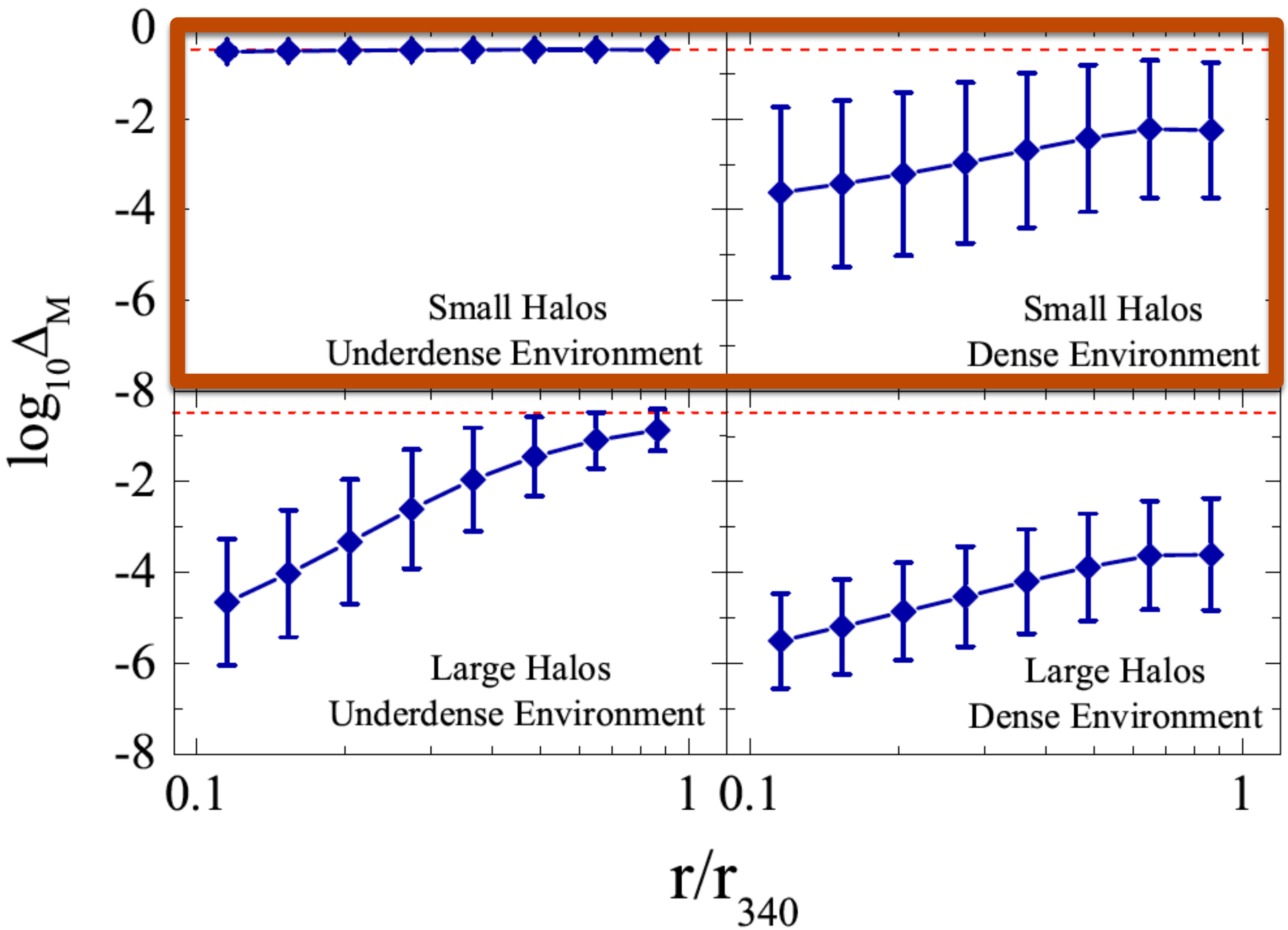
log10ΔM
Small Halos
Underdense Environment
Small Halos
Dense Environment
Large Halos
Underdense Environment
Large Halos
Dense Environment
0.1
1
r/r340



Maximum screening
Core is better screened



0
-2
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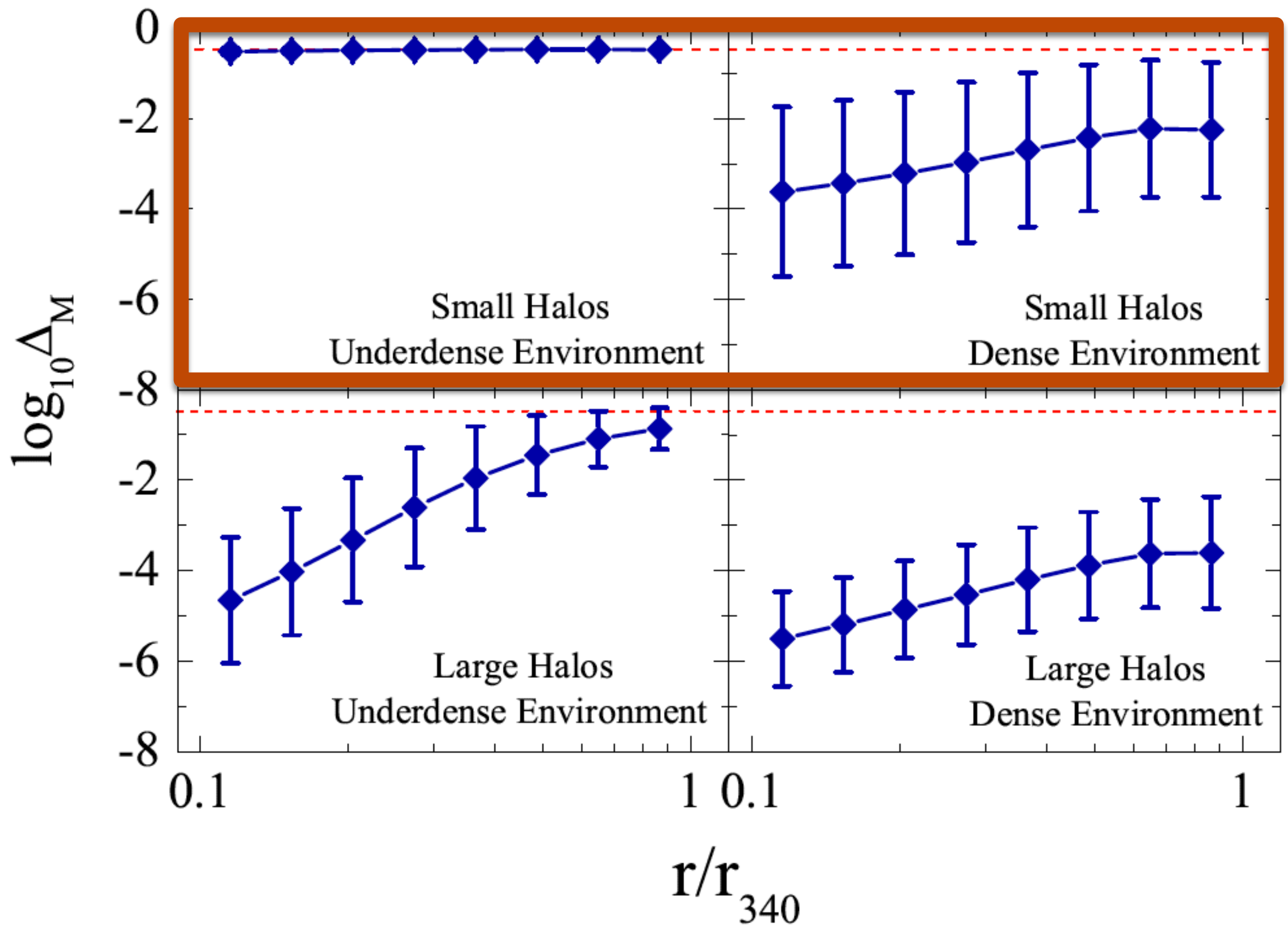
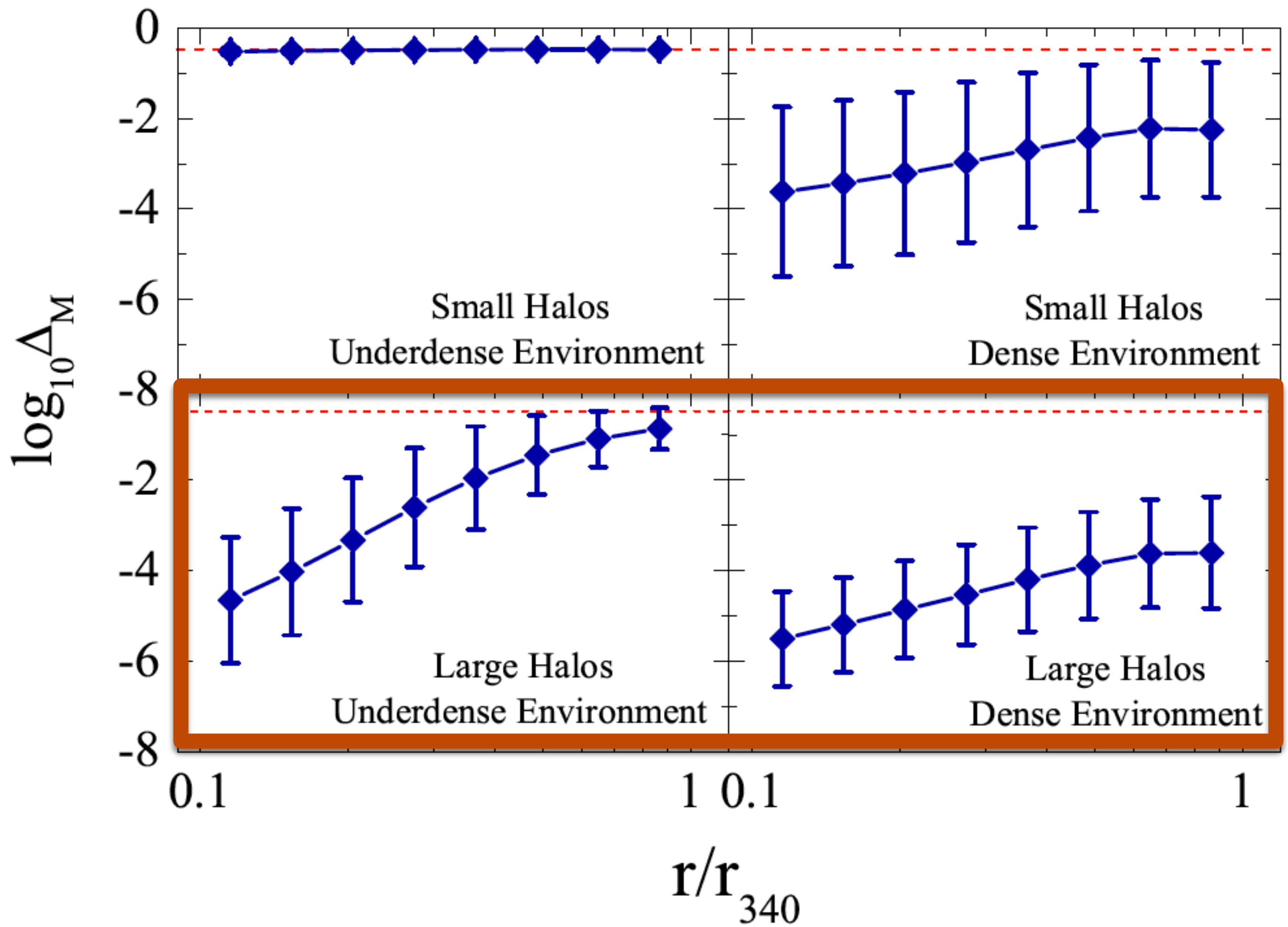
-8
$\log_{10}\Delta_M$
Small Halos
Underdense Environment
Small Halos
Dense Environment
Large Halos
Underdense Environment
Large Halos
Dense Environment
0.1
1
0.1
1
r/r_{340}

Screened purely by environment





0
-2
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$\log_{10}\Delta_M$
Small Halos
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Dense Environment
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0.1
1
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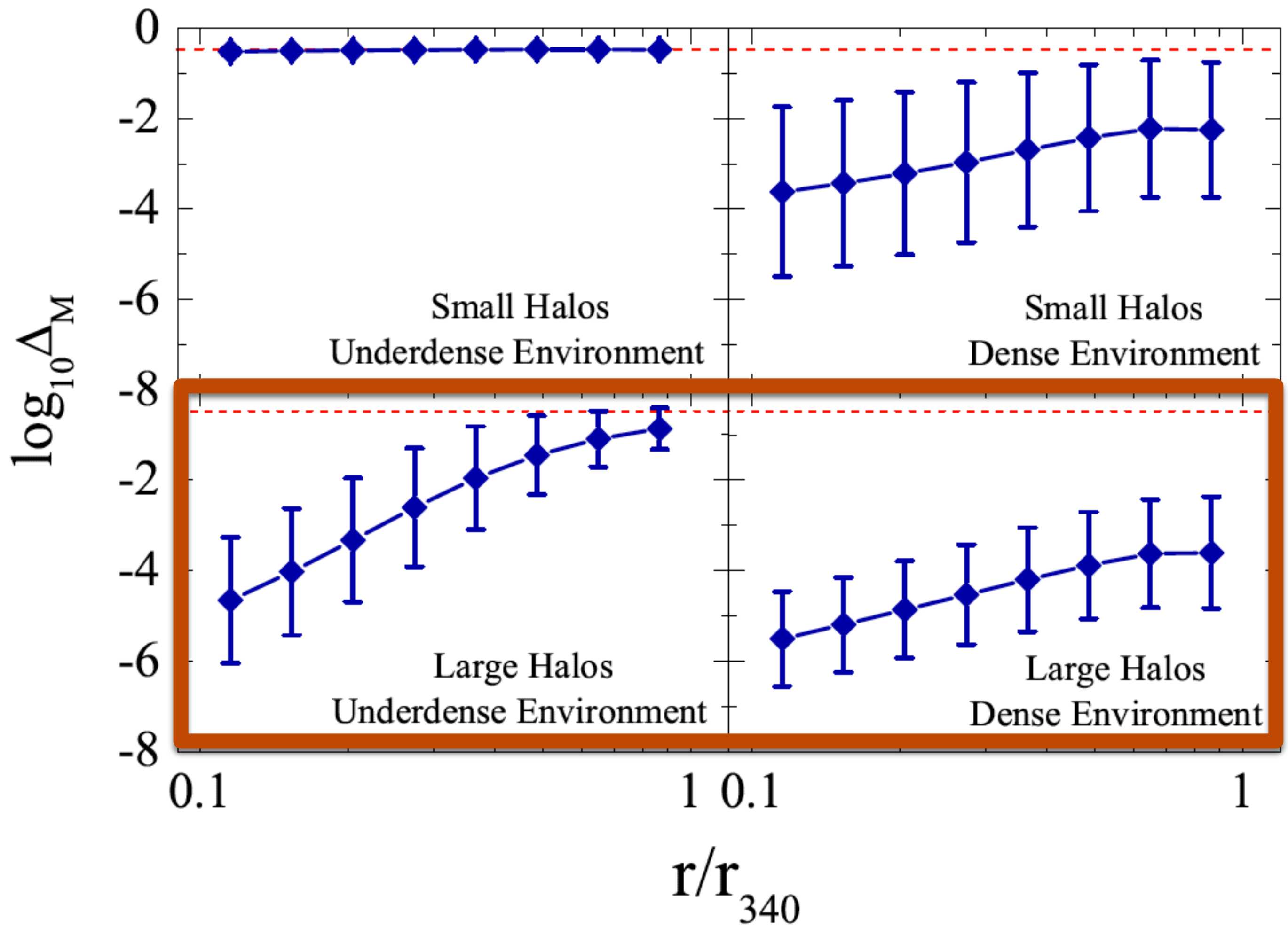
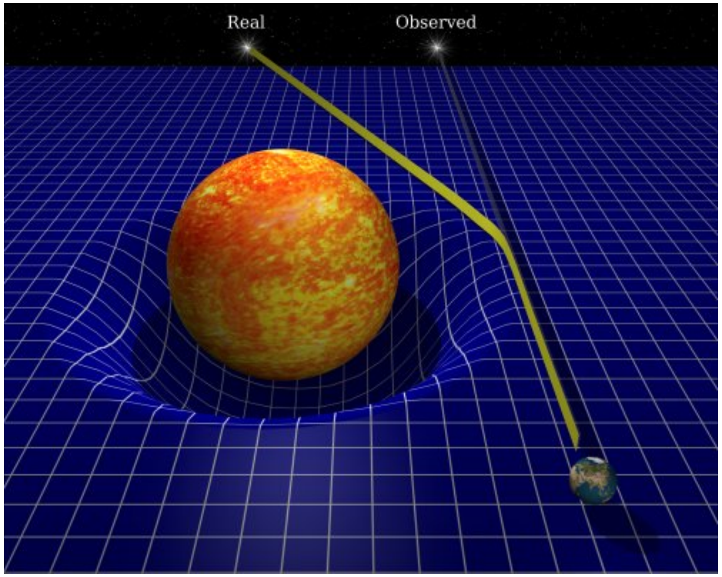
1
r/r_{340}



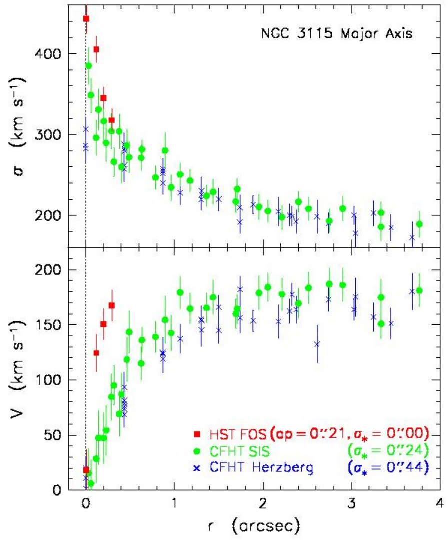
Screening on the edge shows environmental dependence!

Observationally…

Lensing Mass



Dynamical Mass



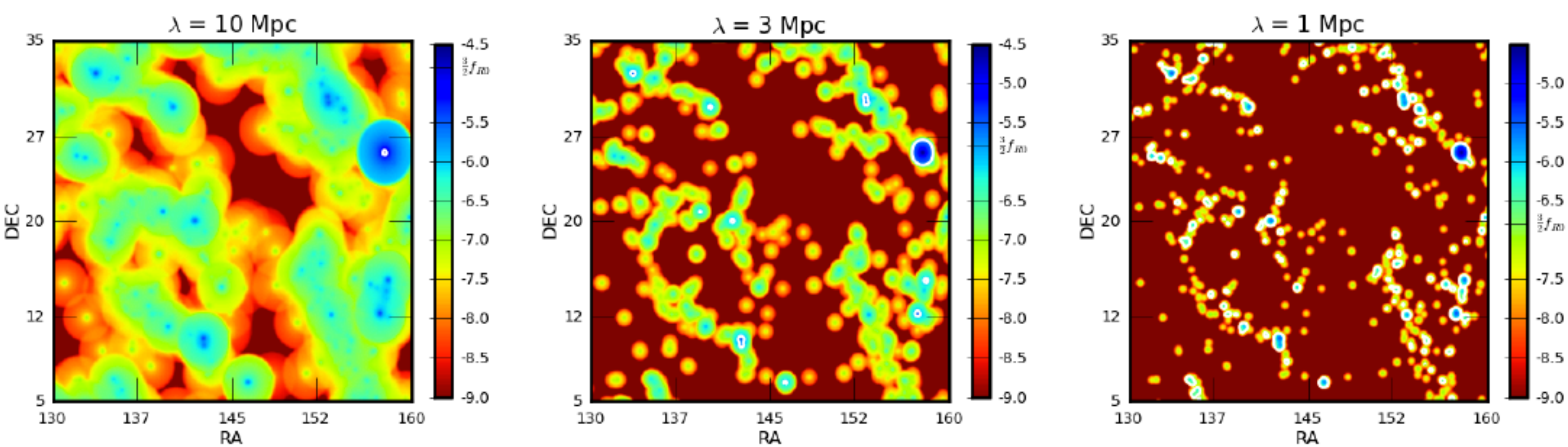
- Measure lensing and dynamical mass for each halo;
- Divide the sample using D;
- Compare!

- Measure lensing and dynamical mass for each halo;
- Divide the sample using D;
- Compare!

Applying to BOSS data…

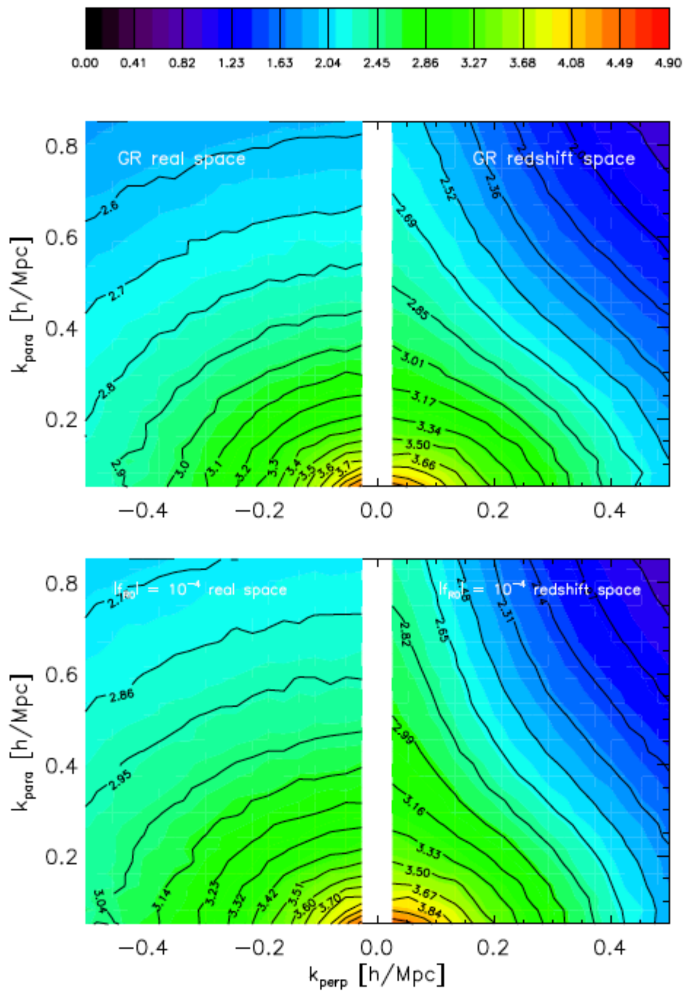
Screening map in the SDSS region

Cabre, Vikram, GBZ, Jain, Koyama
1204.6046



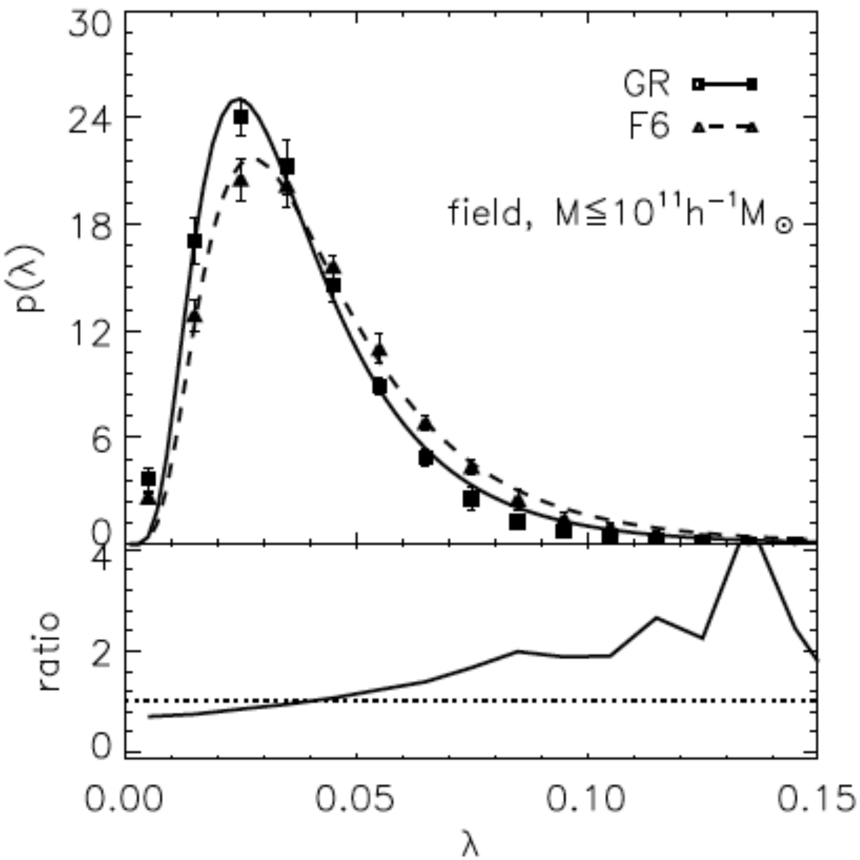
RSD measurement

Jennings, Baugh, Li, Zhao, Koyama
1205.2698 see Elise's talk



A new GR test using the spin of halos

Lee, GBZ, Li, Koyama
1204.6608



Summary and Outlook

- A 2σ detection of w deviating from -1
- GR so far so good
- N-body simulations for MG provide a platform for the GR tests on nonlinear scales using the upcoming data of BOSS, eBOSS, BigBOSS, Euclid, LSST, KDUST, TMT?