Observational signatures of non-GR theories gravity in cosmology

Alex Barreira

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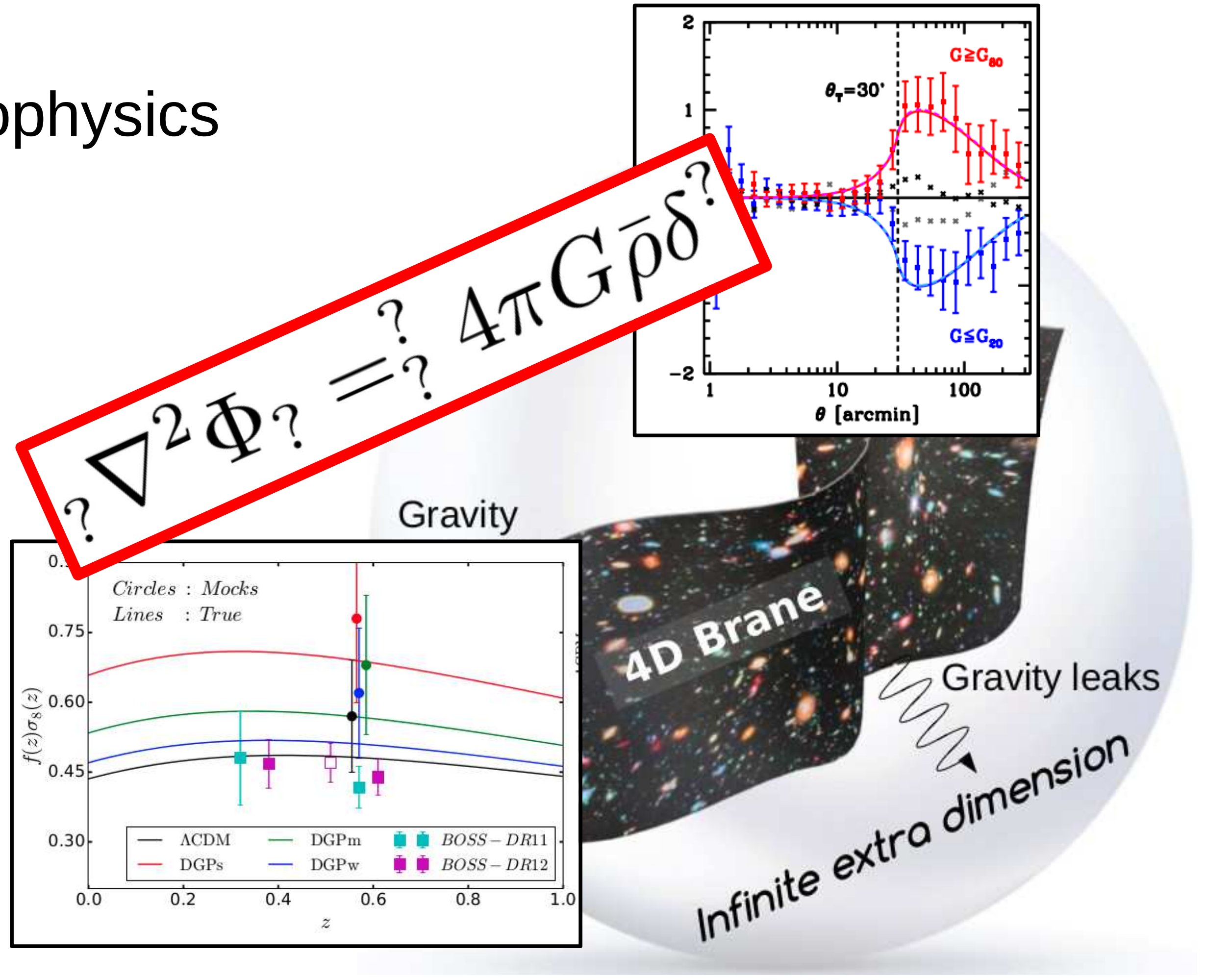

HIP - Cosmology Seminar

Why modified gravity ?

1) Extend tests of gravity onto cosmological scales

- The study of alternatives to GR tells us about what to look for in the data.

2) Cosmic acceleration

- The "dark energy" may simply be a breakdown of GR on large scales.

3) GR is not a quantum theory

- Not unreasonable to suspect that a theory that fixes GR on quantum scales, may also differ from it on cosmological ones.

What is modified gravity?

Beyond General Relativity …

1) The Universe can expand at different rates.

2) The gravitational force law is modified

What is modified gravity?

Beyond General Relativity …

1) The Universe can expand at different rates.

2) The gravitational force law is modified, but cannot in the Solar System !

A primer on screening

Modified Poisson Eq.

$$\frac{\nabla^2\Phi}{\nabla^2\Phi_{GR}} = 1 + \frac{\nabla^2\varphi}{\nabla^2\Phi_{GR}}$$

"Standard" Poisson Eq.

$$\nabla^2\Phi_{GR} = 4\pi G\rho$$

A primer on screening

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Scalar field Eq. (Vainshtein type)

$$\left[\nabla^2\varphi\right]^2 + \nabla^2\varphi = \rho$$

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Low density

$$\text{If } \rho \ll 1 \longrightarrow \nabla^2\varphi \sim \rho$$

$$\frac{\nabla^2\Phi}{\nabla^2\Phi_{GR}} = 1 + \mathcal{O}(1)$$

Order unity corrections.

A primer on screening

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$$\left[\nabla^2\varphi\right]^2 + \nabla^2\varphi = \rho$$

Low density

$$\text{If } \rho \ll 1 \longrightarrow \nabla^2\varphi \sim \rho$$

High density

$$\text{If } \rho \gg 1 \longrightarrow \nabla^2\varphi \sim \sqrt{\rho}$$

$$\frac{\nabla^2\Phi}{\nabla^2\Phi_{GR}} = 1 + \mathcal{O}(1)$$

Order unity corrections.

$$\frac{\nabla^2\Phi}{\nabla^2\Phi_{GR}} = 1 + \frac{1}{\sqrt{\rho}} \approx 1$$

Recover standard GR .

Welcome to the jungle

$$S=\int \mathrm{d}^4x\sqrt{g}\left[\frac{R}{16\pi G}+\mathcal{L}_m+\frac{\Lambda}{8\pi G}\right]$$

$$S=\int \mathrm{d}^4x\sqrt{g}\left[\frac{R}{16\pi G}+\mathcal{L}_m+f(R)\right]$$

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Welcome to the jungle

GR curvature term

$$S = \int \mathrm{d}^4x\sqrt{g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \frac{\Lambda}{8\pi G}\right]$$

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GR curvature term

Particle physics and DM

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Stuff that accelerates

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$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \text{Your more or less motivated model}\right]$$

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The DGP model:
Our working model for this talk

$$S=\int d^4x\sqrt{g}\left[\frac{R}{16\pi G}+\mathcal{L}_m\right]+\int d^5x^{(5)}\left[\frac{R^{(5)}}{16\pi G^{(5)}}\right]$$

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Our toy model today: nDGP

Action of the Dvali-Gabadadze-Porrati model (hep-th/0005016)

$$S = \int \mathrm{d}^4x\sqrt{g}\left[\frac{R}{16\pi G} + \mathcal{L}_m \quad\right] + \int \mathrm{d}^5x^{(5)}\left[\frac{R^{(5)}}{16\pi G^{(5)}}\right]$$

- Matter and radiation are confined to a 4D brane (our spacetime) of a 5D bulk
- Gravity "leaks" from the brane to the bulk.

Crossover scale

$$r_c = \frac{1}{2}\frac{G^{(5)}}{G}$$

→ *Measure of the scales on the brane above which gravity becomes 5-dimensional.*

Our toy model today: nDGP

Modified dynamical potential

$$\Psi = \Psi^{\rm GR} + \varphi/2$$

"Fifth force potential" governed by

Equation of motion of the additional scalar field

$$\nabla^2\varphi + \frac{r_c^2}{3\beta(a)a^2}\left[\left(\nabla^2\varphi - (\nabla_i\nabla_j\varphi)^2\right)\right] = \frac{8\pi G}{3\beta(a)}a^2\delta\rho_m$$

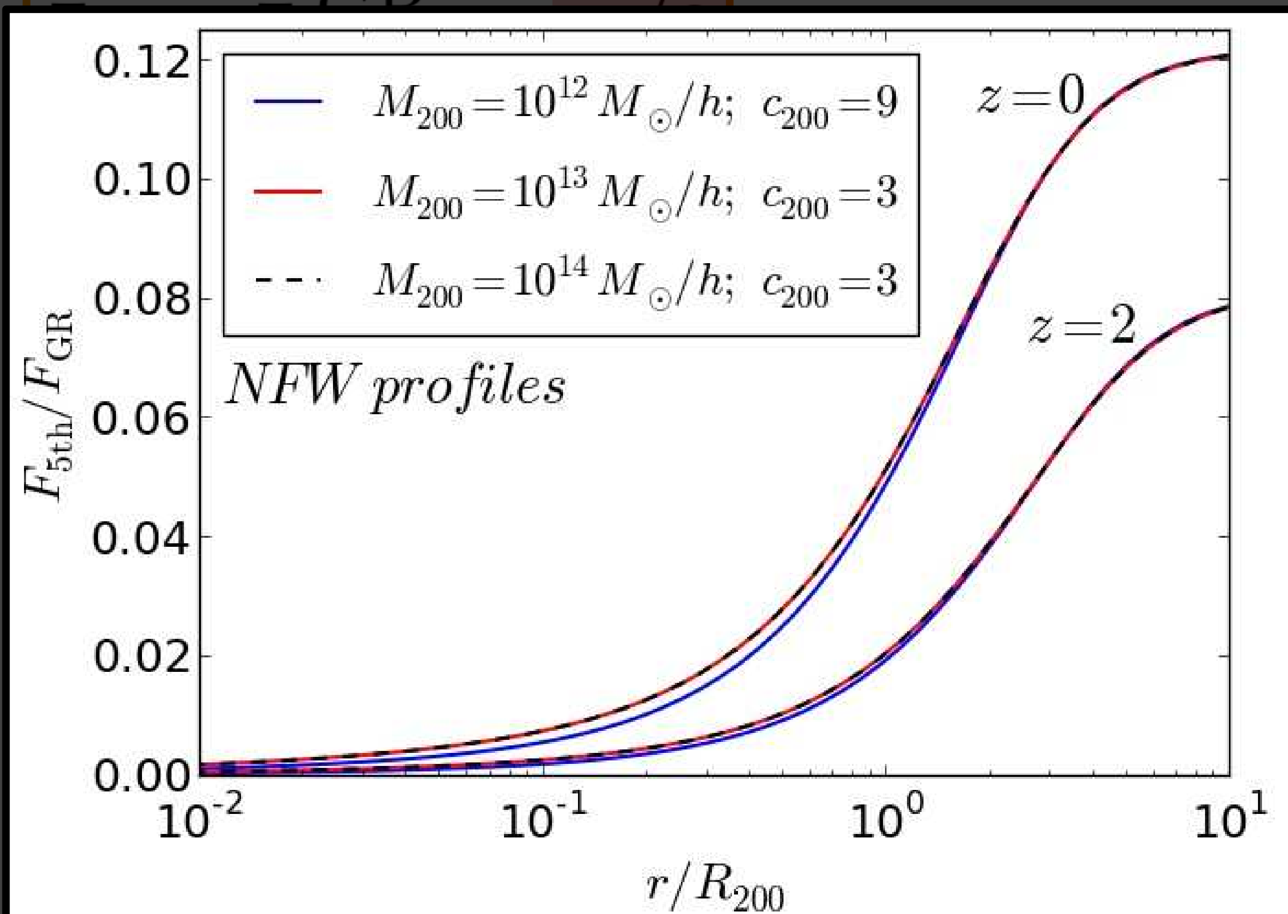
$$\beta(a) = 1 + 2Hr_c\left(1 + \frac{\dot{H}(a)}{3H^2(a)}\right)$$

Hubble expansion rate: will tune it to yield exactly LCDM, but this is not necessary!

$$H(a) = H_0\sqrt{\Omega_{m0}a^{-3} + \Omega_{\rm de}(a) + \Omega_{rc}} + \sqrt{\Omega_{rc}}$$

Our toy model today: nDGP

Fifth to normal force ratio profiles



ned by

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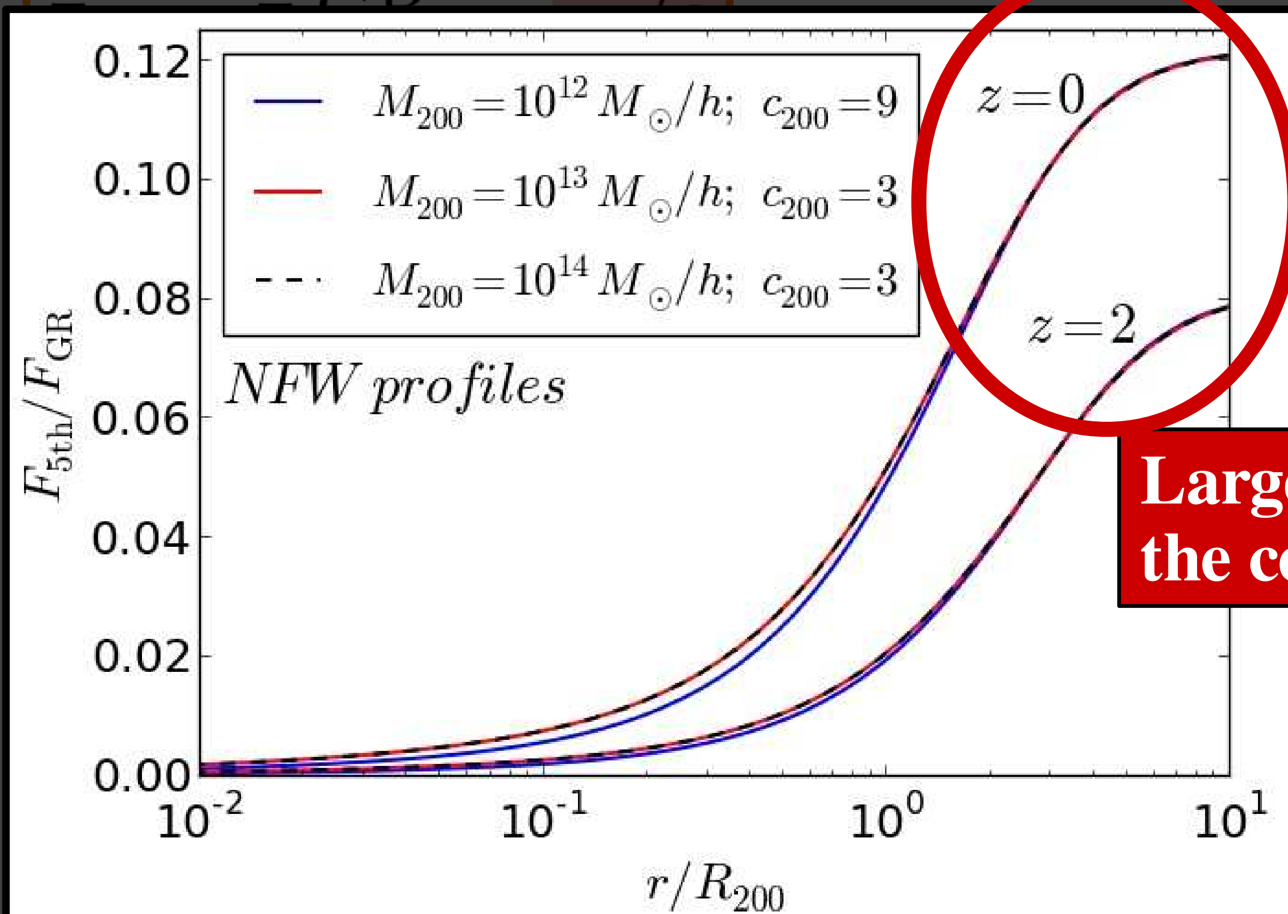

Large fifth force far from the center (lower density).

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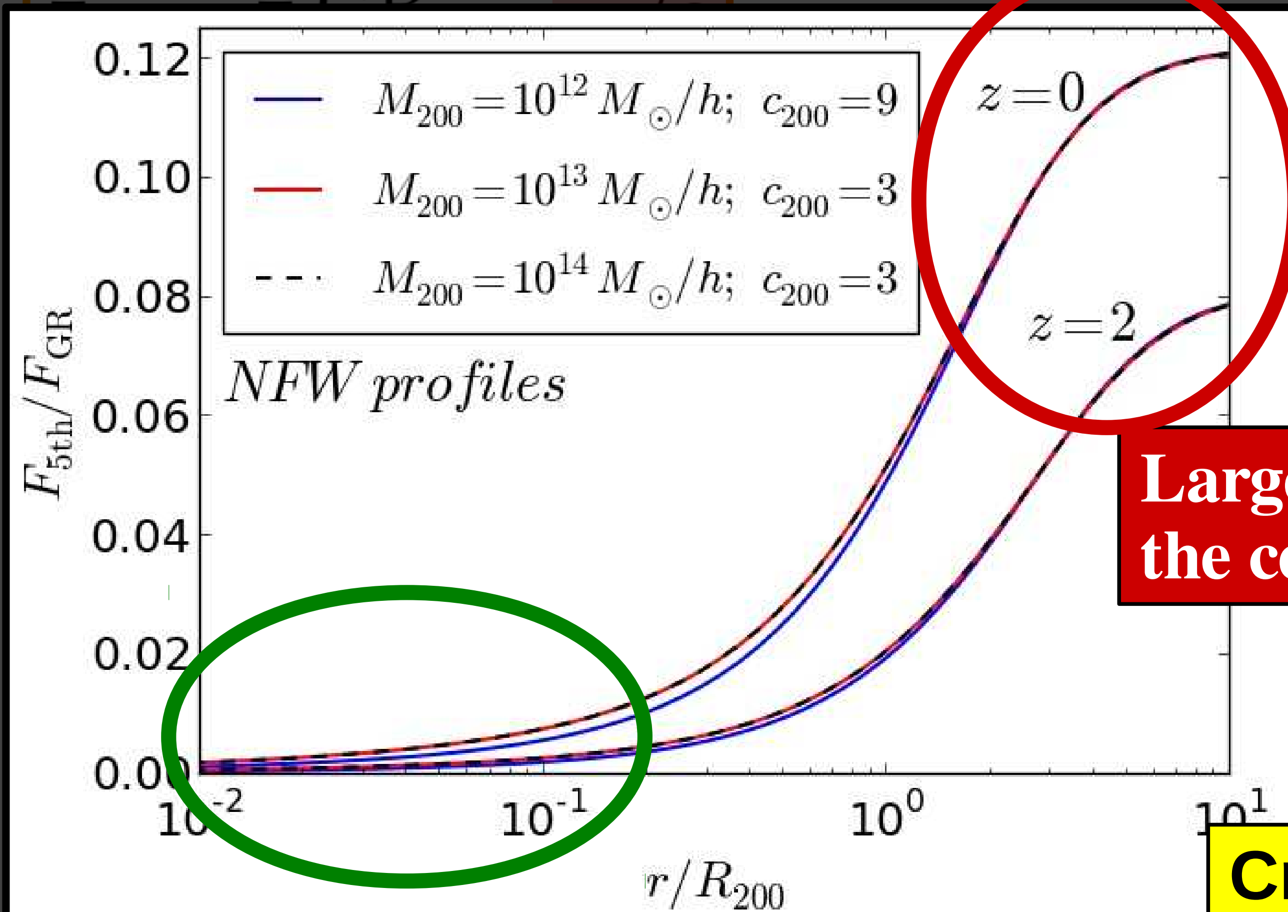

...ned by

$$\beta(a) = 1 + 2Hr_c\left(1 + \frac{H(a)}{3H^2(a)}\right)$$

Large fifth force far from the center (lower density).

Fifth force is suppressed close to the center (higher density).

Crucial for Solar System tests.

...ssary!

$$H(a) = \ldots + \Omega_{rc} + \sqrt{\Omega_{rc}}$$

In the rest of this talk …

1) Validating estimates of the growth rate of structure in modified gravity.

Barreira, Sánchez & Schmidt

Phys. Rev. D (2016)

arXiv:1605.03965

In the quest for ever precise measurements in cosmology, are we giving accuracy away ?

2) Lensing by galaxy troughs in modified gravity.

Barreira, Bose, Li, Llinares

JCAP02(2017)031

arXiv:1605.08436

Can we find evidence of screening by comparing the lensing signal from over- and underdense regions?

Validating estimates of the growth rate of structure in modified gravity.

Barreira, Sánchez & Schmidt

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In the quest for ever precise measurements in cosmology, are we giving accuracy away ?

The growth rate of structure

What we observe

What is "easy" to predict

Galaxy clustering in redshift space

Linear matter power spectrum

The growth rate of structure

What we observe

Galaxy clustering in redshift space

Insert favourite model of:

- → **Galaxy bias**
- → **RSD**
- → **Mode-coupling**

What is "easy" to predict

Linear matter power spectrum

Contains $f\sigma_8, \sigma_v, b_1, \ldots$

$$f = \frac{\mathrm{d}\ln\ \delta(a)}{\mathrm{d}\ln\ a}$$

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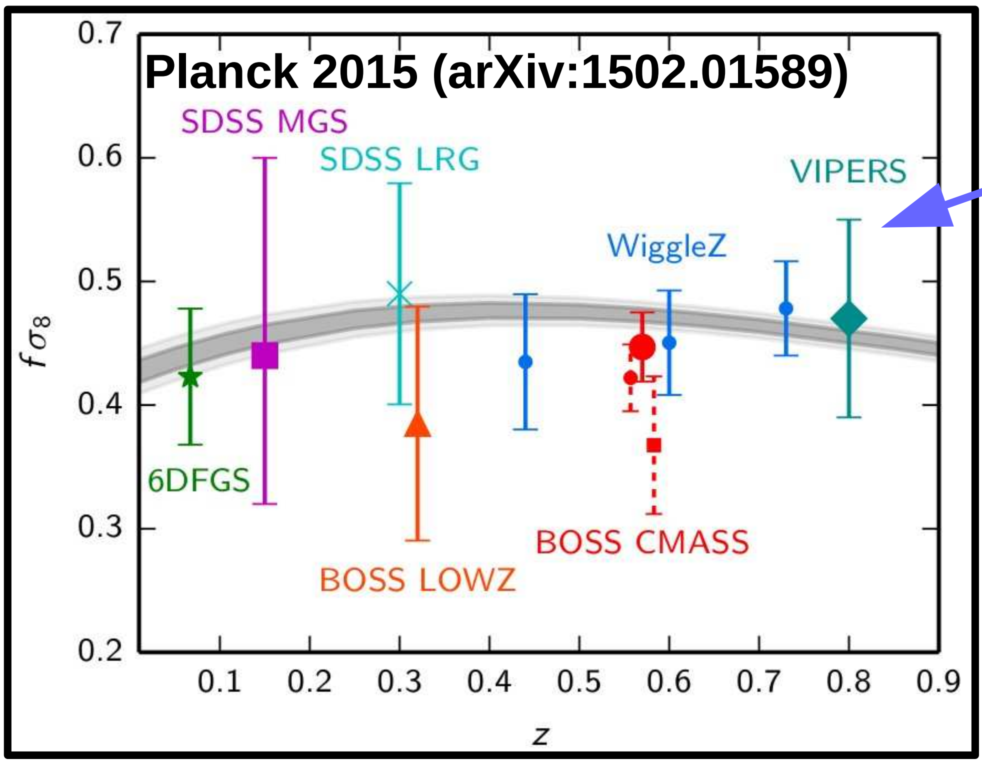


Powerful way to test gravity .. but ..

measurements rely on consistency between data modeling and theory.

Validate them using mock galaxy catalogues.

Step by step

1) Construct galaxy mock catalogues out of N-body simulations of both GR and DGP gravity.

2) Analyse the mocks with observational pipelines, as if analysing real data.

3) Check whether returned values of the growth rate are consistent with the cosmology of the simulations.

Yes ?

Can use measurements to test the desired theories.

No ?

Measurements are biased! Cannot use to test the theories.

Step by step

1) Construct galaxy mock catalogues with N-body simulations of both GR and DGP gravity

→ *This exercise has been standard practice for GR, but not modified gravity!*

...onal
pipelines, as if analysing real data

3) ...
co...

→ *Constraints on modified gravity have been placed ignoring that the data could be biased.*

Yes ?

No ?

Can use measurements to test the desired theories.

Measurements are biased! Cannot use to test the theories.

Modified gravity simulations

Equation of motion of the additional scalar field

$$\nabla^2\varphi + \frac{r_c^2}{3\beta(a)a^2}\left[\left(\nabla^2\varphi - (\nabla_i\nabla_j\varphi)^2\right)\right] = \frac{8\pi G}{3\beta(a)}a^2\delta\rho_m$$

1. **Discretize on AMR grid;**
2. **Iterate to find the scalar field at every AMR cell;**
3. **Construct total potential;**
4. **Standard N-body code with modified potential until next time step.**

$$\Psi = \Psi^{\mathrm{GR}} + \varphi/2$$

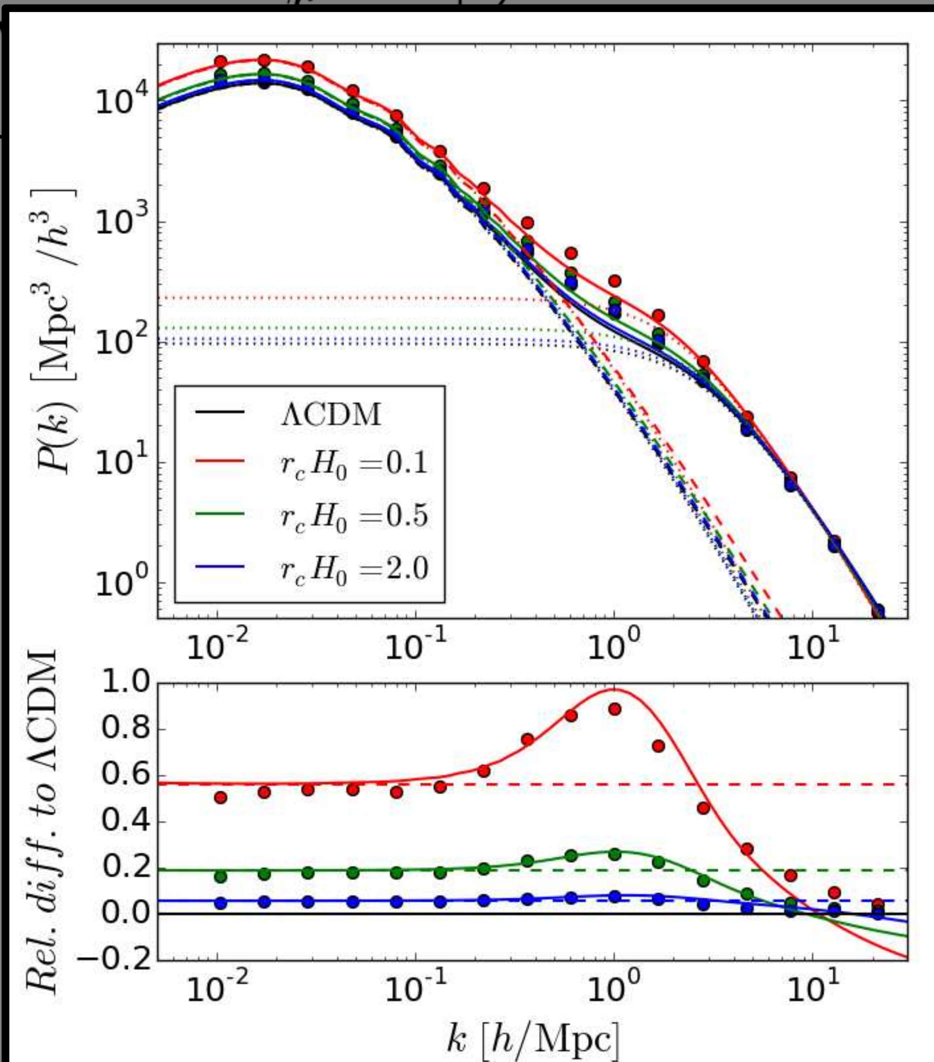
ECOSMOG code **:**

Baojiu Li et al
arXiv:1110.1379
arXiv:1303.0008

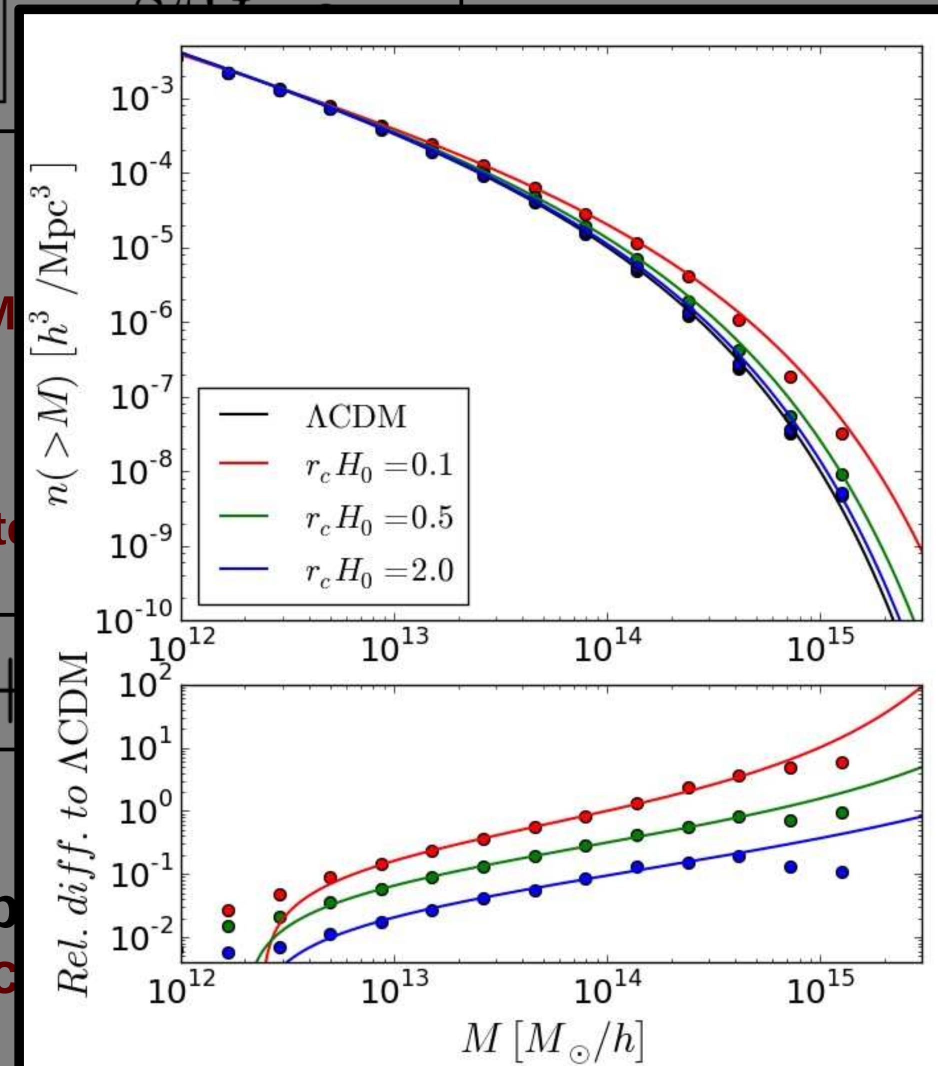
- **Modified gravity N-body code comparison project: Winther et al arXiv 1506.06384. All codes compared check out!**

Modified gravity simulations

Matter power spectrum



Halo mass function



Modified gravity simulations

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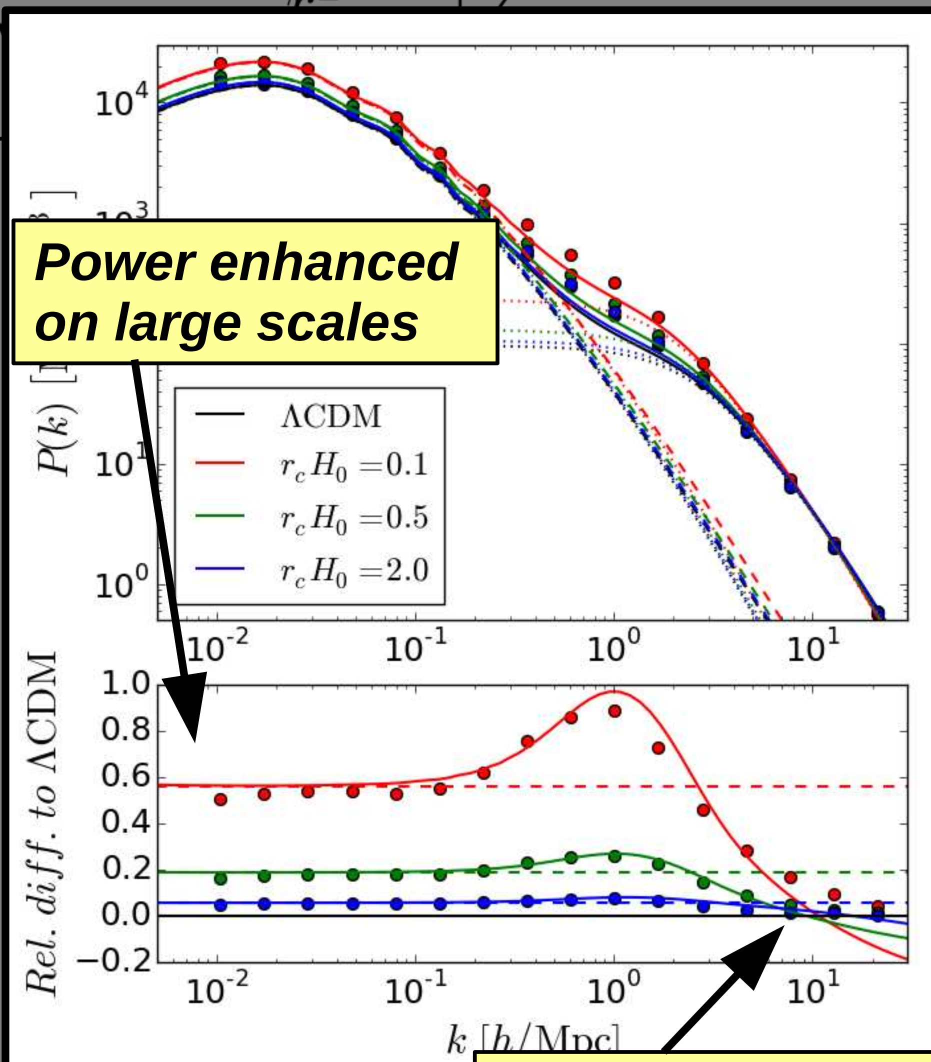
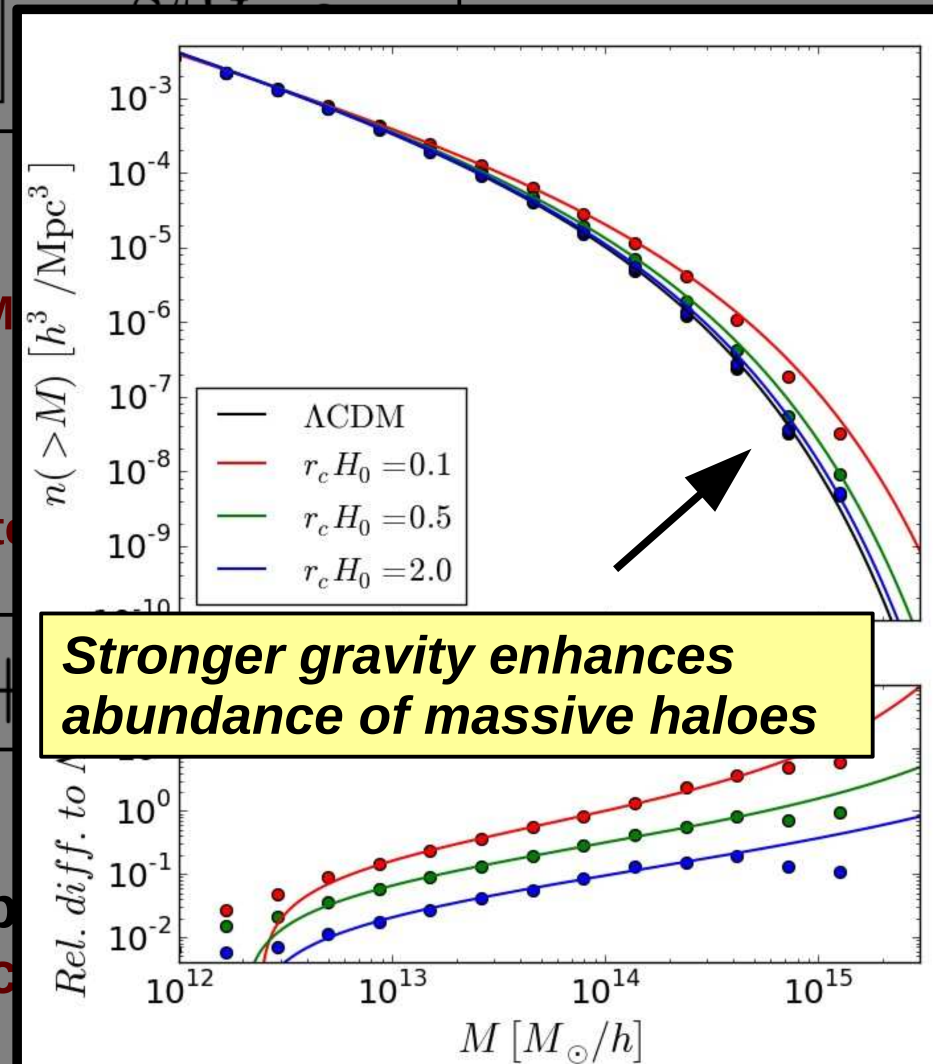


Screening effects on small scales

Halo mass function



Halo occupation distribution (HOD)

(i) *Parametrize the number of galaxies that live in haloes of a given mass;*

$$N_{\rm galaxies}(M) = N_{\rm central} + N_{\rm satellite}$$

$$N_{\rm central} = \frac{\Theta(M - M_{\rm min})}{2}\left[1 + {\rm erf}\left(\frac{\log_{10}M - \log_{10}M_{\rm min}}{\sigma_{\log_{10}M}}\right)\right]$$

$$N_{\rm satellite} = N_{\rm central}\left(\frac{M - M_0}{M_1'}\right)^{\alpha}$$

(ii) *Assign galaxies to each halo by sampling from the HOD distribution;*

Centrals → position and velocity of the halo center
Satellites → position and velocity of randomly chosen halo particles

(iii) *Tune the HOD parameters to match desired galaxy sample.*

Halo occupation distribution (HOD)

*Match the **BOSS CMASS sample (z = 0.57)** in terms of*

(i) galaxy number density;
(ii) angle-averaged galaxy power spectrum

...pes of a given mass;

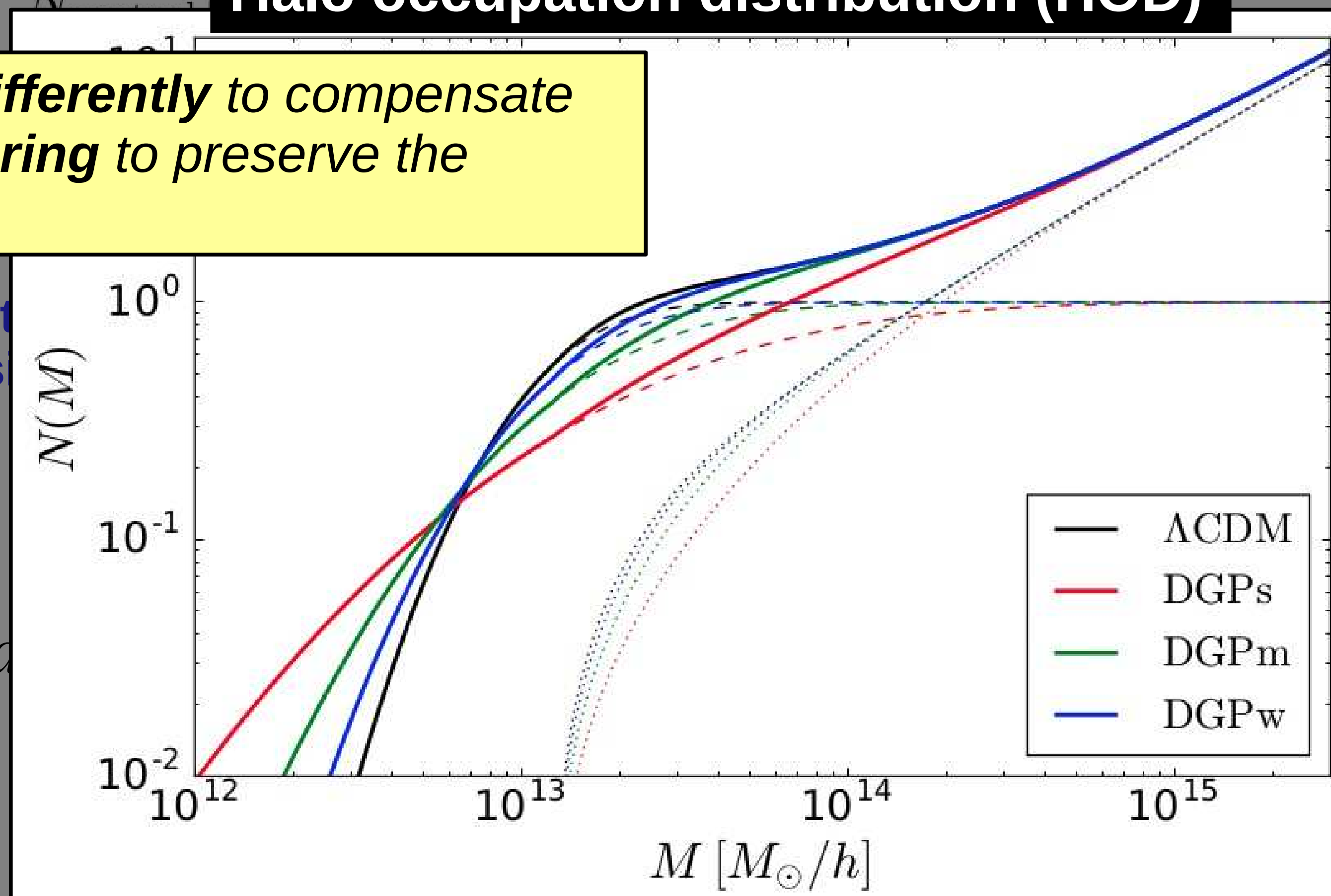
$$N_{\rm central} = \frac{\ \ }{2}\left[1+{\rm erf}\left(\frac{\ \ -\log_{10}M_{\rm min}}{\sigma_{\log_{10}M}}\right)\right]$$

$$N_{\rm satellite} = N$$

*Galaxies **populate halos differently** to compensate the changes on **halo clustering** to preserve the **galaxy clustering.***

Centrals → posit
Satellites → pos

***(iii)** Tune the HOD para*



“Observing” the mocks

What we observe

Galaxy clustering in redshift space

↔

Insert favourite model of:

- → Galaxy bias
- → RSD
- → Mode-coupling

↔

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Clustering wedges (Sánchez et al 2013, 2014, 2016)

$$\xi_{\mu_1}^{\mu_2}(s) = \frac{1}{\mu_2 - \mu_1} \int_{\mu_1}^{\mu_2} \xi(s,\mu)\,\mathrm{d}\mu$$

s = galaxy pair separation

μ = cosine angle of pair with LOS

Redshift space galaxy 2-point correlation function.

$$\xi_{\perp} \;::\; \mu_1 = 0 \;,\; \mu_2 = 0.5$$

$$\xi_{||} \;::\; \mu_1 = 0.5 \;,\; \mu_2 = 1$$

Measured directly from the mocks.

“Observing” the mocks

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↔ **Linear matter power spectrum**

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Galaxy bias

$$\delta_g = b_1\delta + \frac{b_2}{2}\delta^2 + \gamma_2\mathcal{G}_2(\bar{\Phi}_v) + \gamma_3^- \left[\mathcal{G}_2(\bar{\Phi}) - \mathcal{G}_2(\bar{\Phi}_v)\right]$$

Redshift space distortions

$$W_\infty(\lambda) = \frac{1}{\sqrt{1-\lambda^2 a_{\rm vir}^2}} \exp\left[\frac{\lambda^2\sigma_v^2}{1-\lambda^2 a_{\rm vir}^2}\right]$$

$$P_g^z(k,\mu) = W_\infty(ifk\mu)\sum_{i=1}^{3} P_{\rm novir}^{(i)}(k,\mu)$$

$$P_{\rm novir}^{(1)}(k,\mu) = P_g(k) + 2f\mu^2 P_{g\theta}(k) + f^2\mu^4 P_\theta(k)$$

Mode-coupling

$$P_{\rm NL}(k) = P_{\rm lin}(k)G(k)^2 + P_{\rm MC}(k)$$

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Key to know here:

1) *Exactly as used in real data analysis (Sánchez et al 2016);*

2) *Constructed to be valid only in GR!*

3) *Can the free nuisance parameters of the model “absorb” modified gravity and **leave fsigma8 unbiased?***

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Galaxy bias

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Redshift space dist

P_g

Mo

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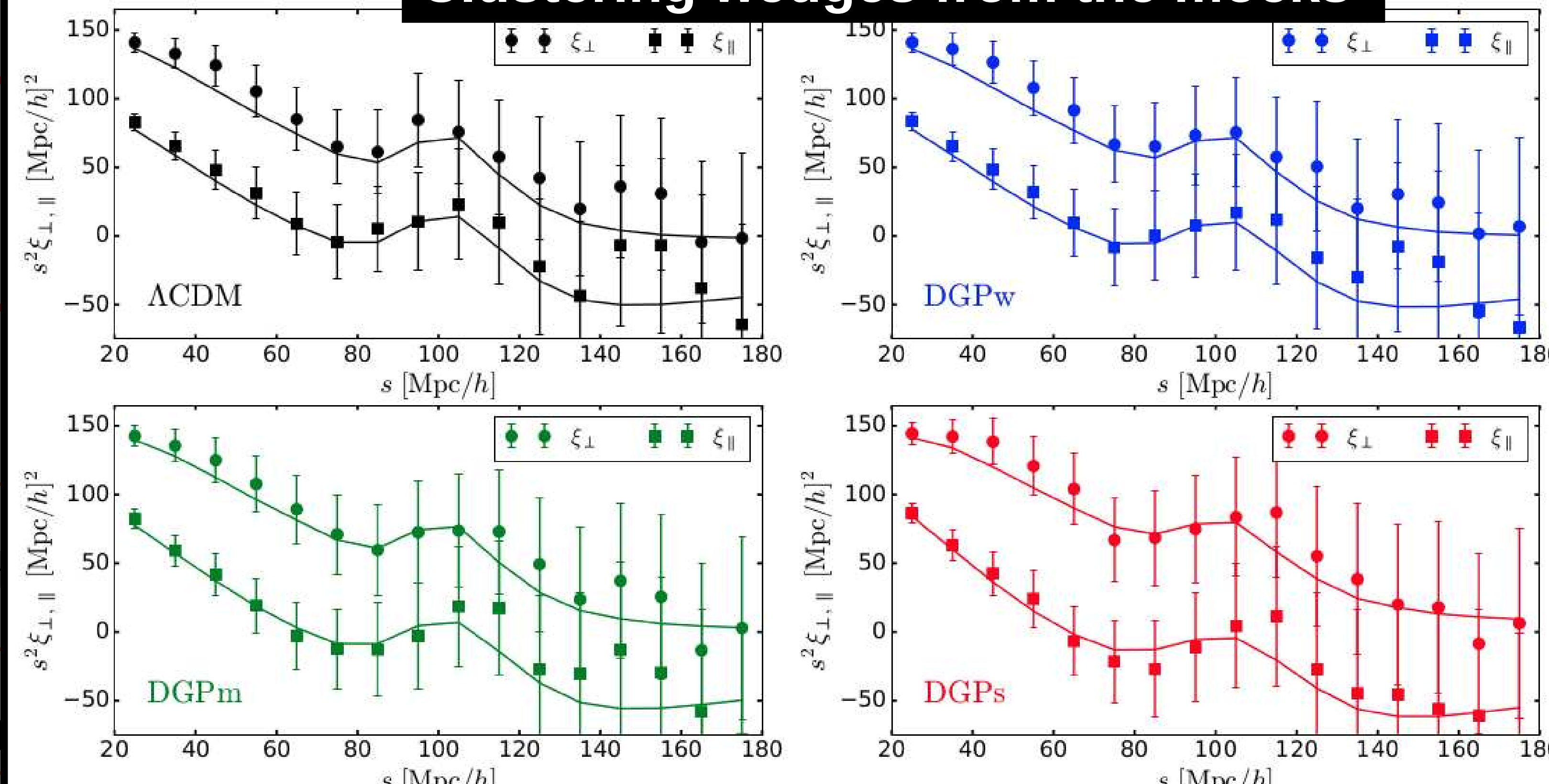
Clustering wedges from the mocks



Symbols : mock measurements

Lines : Bias-RSD-Nonlinear model

Note that s > 20 Mpc/h .

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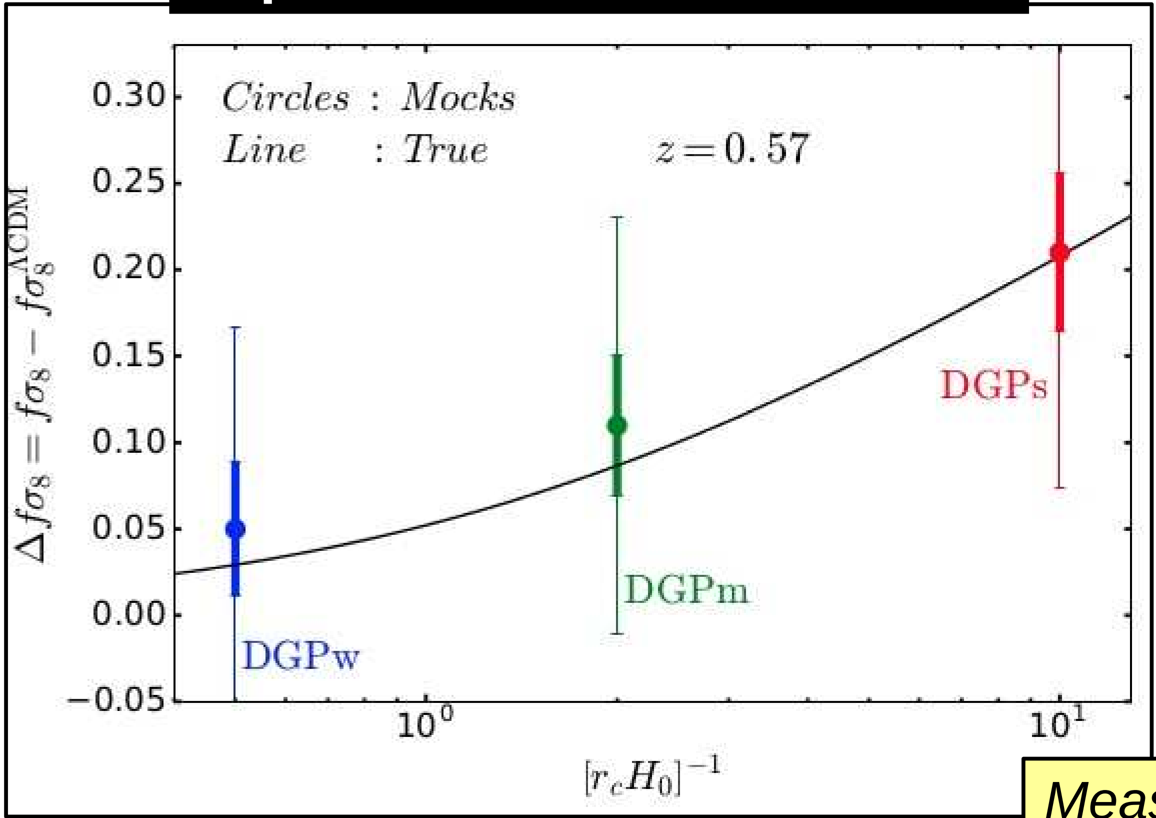
Growth rate from the mocks

Expected difference to LCDM

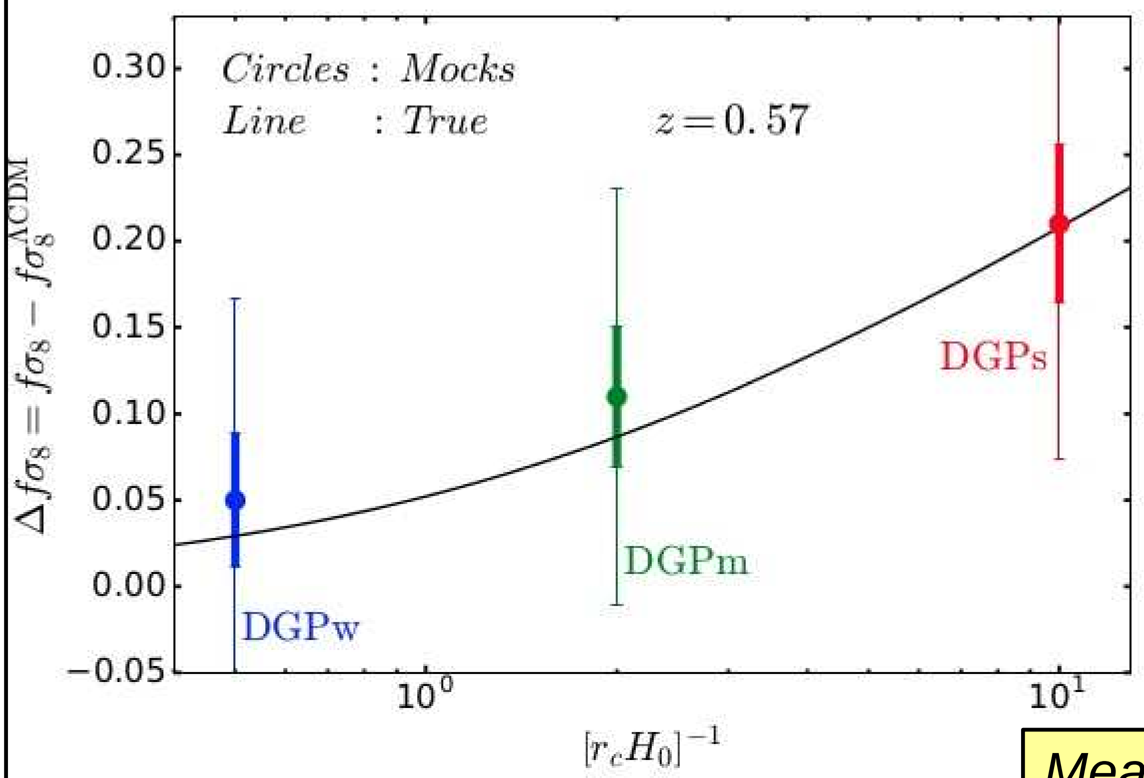


Measurements from the mocks ***recover the expected difference*** *to LCDM.*

No evidence for a biased performance in the DGP model !

Growth rate from the mocks

Expected difference to LCDM



Measurements from the mocks ***recover the expected difference*** *to LCDM.*

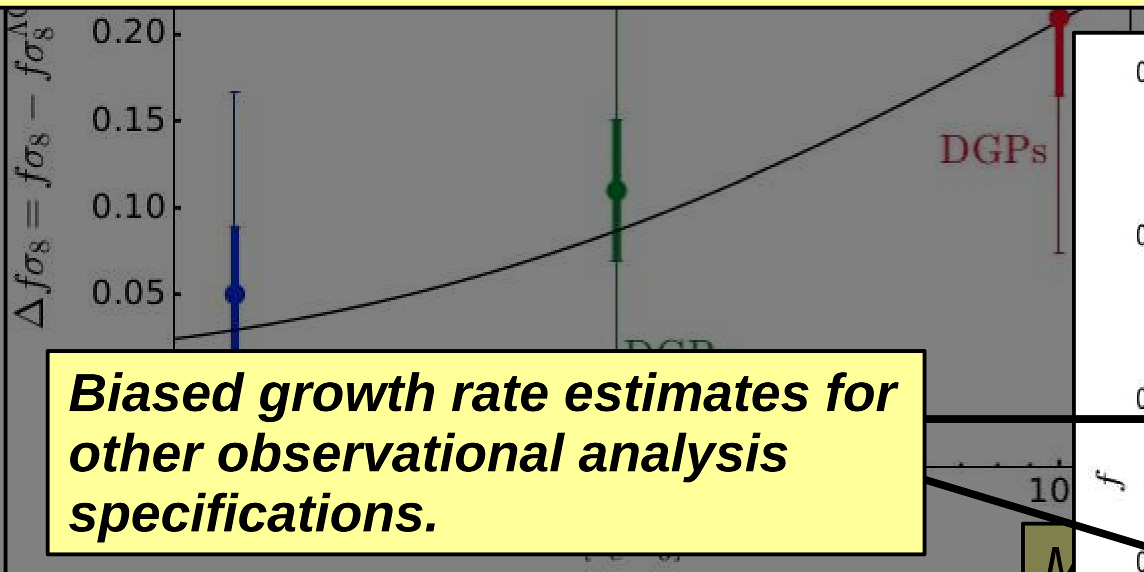
No evidence for a biased performance in the DGP model !

Growth rate from the mocks

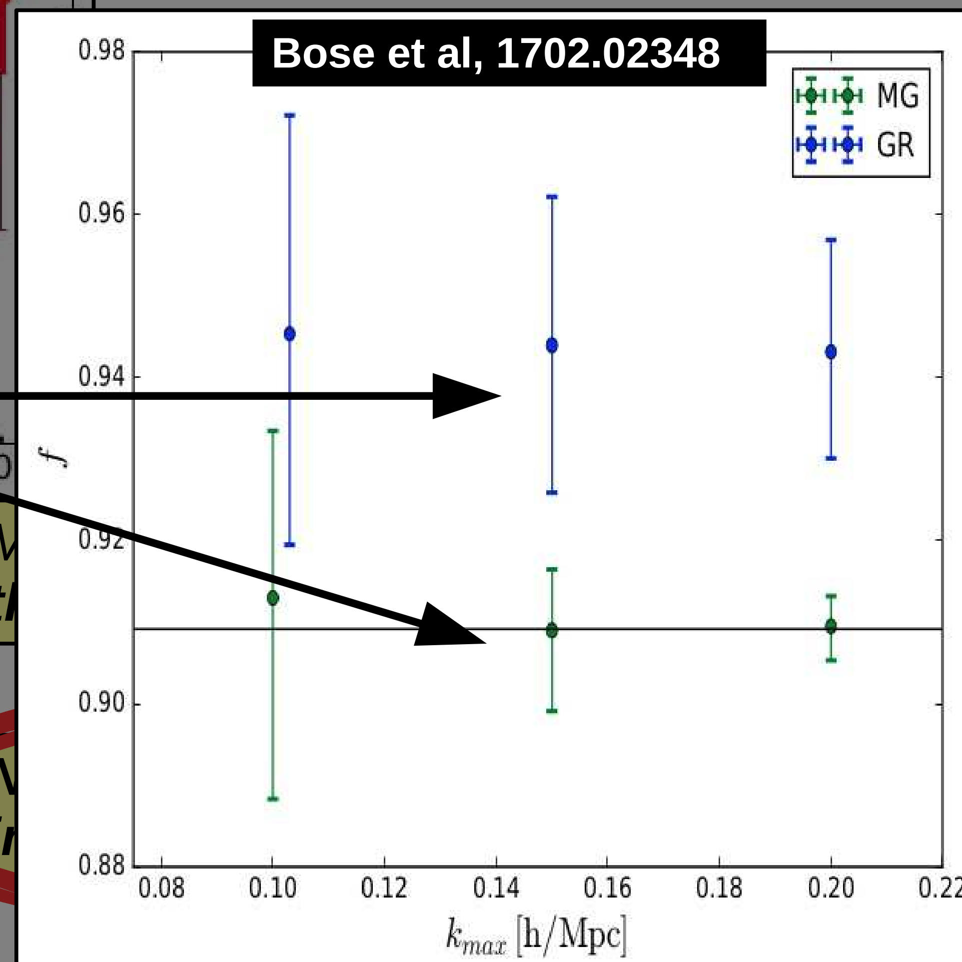
But this is not necessarily the case for all (i) gravity models,(ii) range of scales,; (iii) galaxy samples etc.

[1] Bose et al, 1702.02348

[2] Taruya et al, 1309.6783



Biased growth rate estimates for other observational analysis specifications.



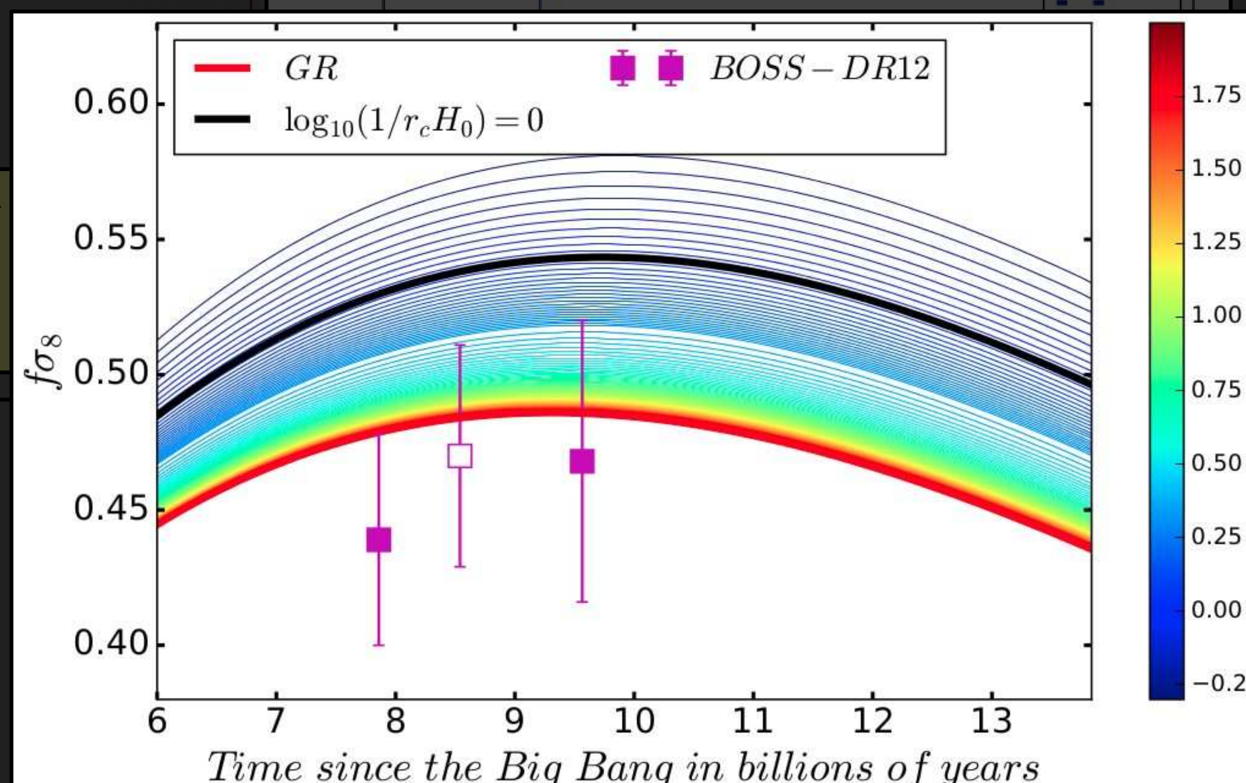
Growth rate from the mocks

But this is not necessarily the case for all (i) gravity

***Unbiased performance** of the clustering wedges model in DGP then permits **using results from real data** to constrain DGP gravity.*

$$[r_c H_0]^{-1} < 0.97 \ (2\sigma)$$

Bose et al, 1702.02348



Biased growth rate estimates other observational analysis specifications.

Lensing by galaxy troughs in modified gravity.

Barreira, Bose, Li, Llinares

JCAP02(2017)031

arXiv:1605.08436

Can we find evidence of screening by comparing the lensing signal from over- and underdense regions?

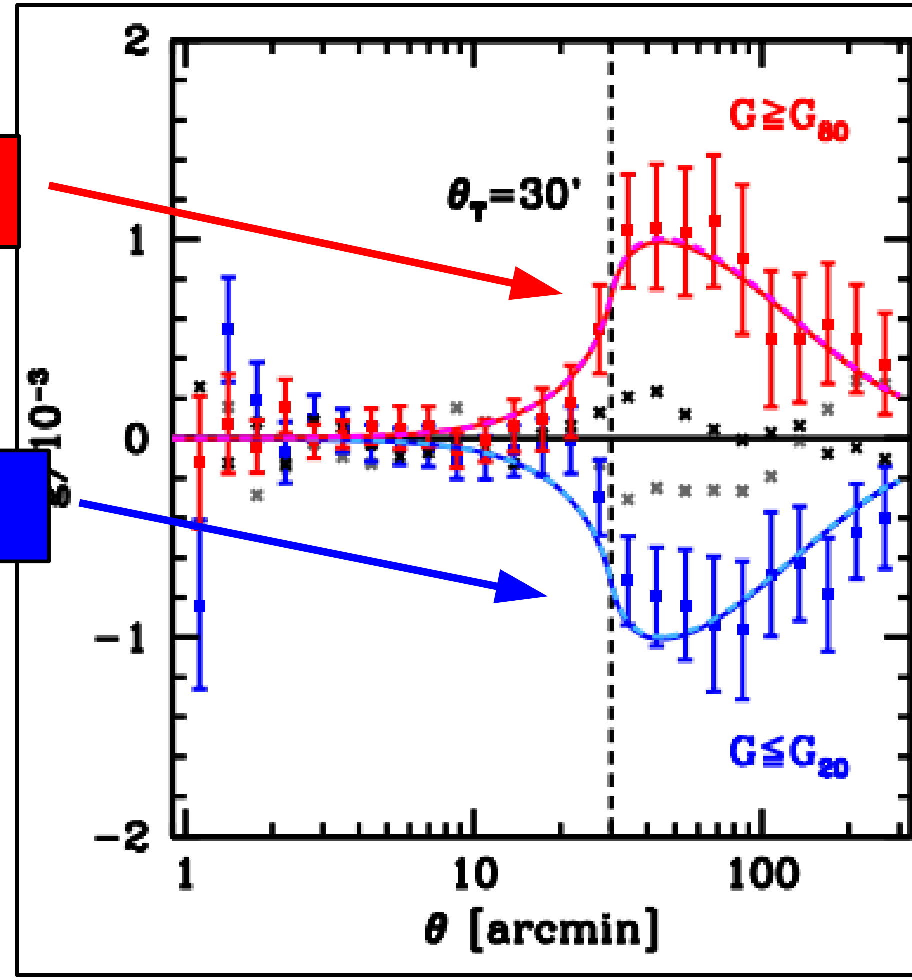
Motivation

Weak lensing by galaxy troughs in DES data

Gruen et al, arXiv:1507.05090

Lensing around overdense LOS

Lensing around underdense LOS



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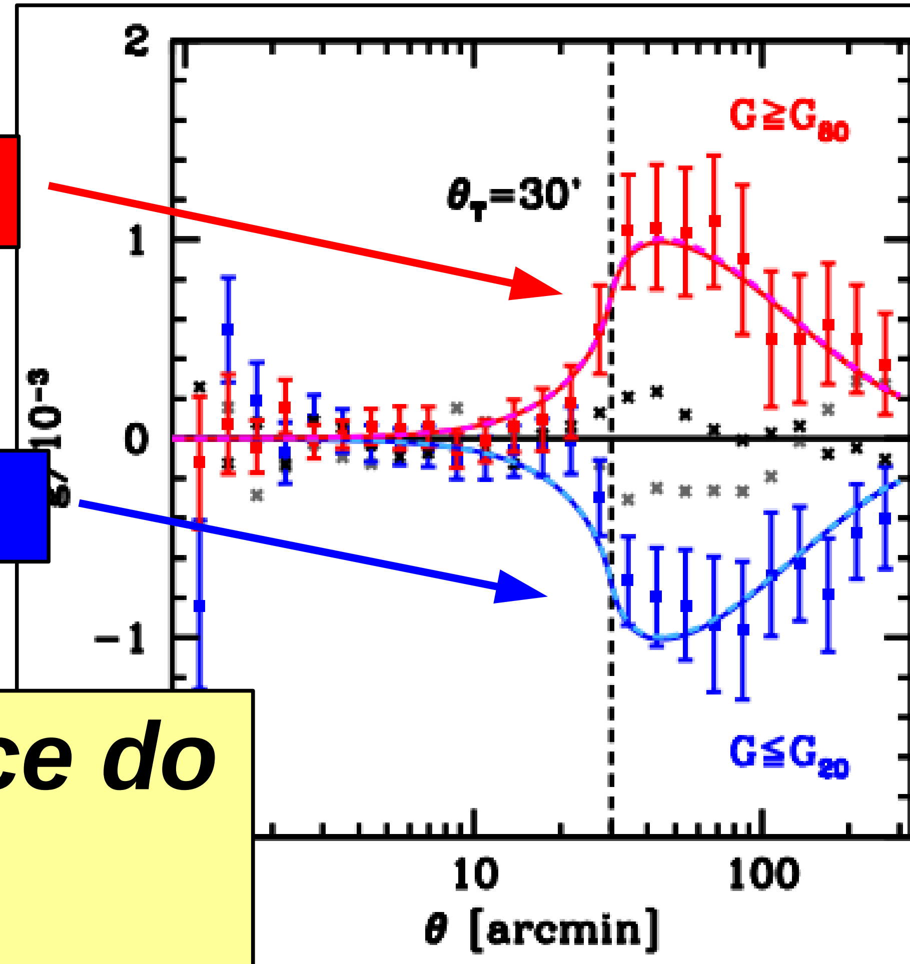


What does the fifth force do this lensing signal?

Does the screening discriminate between underdense/overdense LOS?

A variant of the DGP model

Modified dynamical potential

$$\Psi = \Psi^{\rm GR} + \varphi/2$$

$$\Phi_{\rm len} = \Phi^{\rm GR}_{\rm len}$$

In the nDGP model, the lensing potential is the same as in GR (for fixed mass)

$$\Phi_{\rm len} = \Phi^{\rm GR}_{\rm len} + \varphi/2$$

Introduce a phenomenological variant "nDGPlens" that directly modifies lensing.

Take parameter bordeline consistent with growth rate constraints

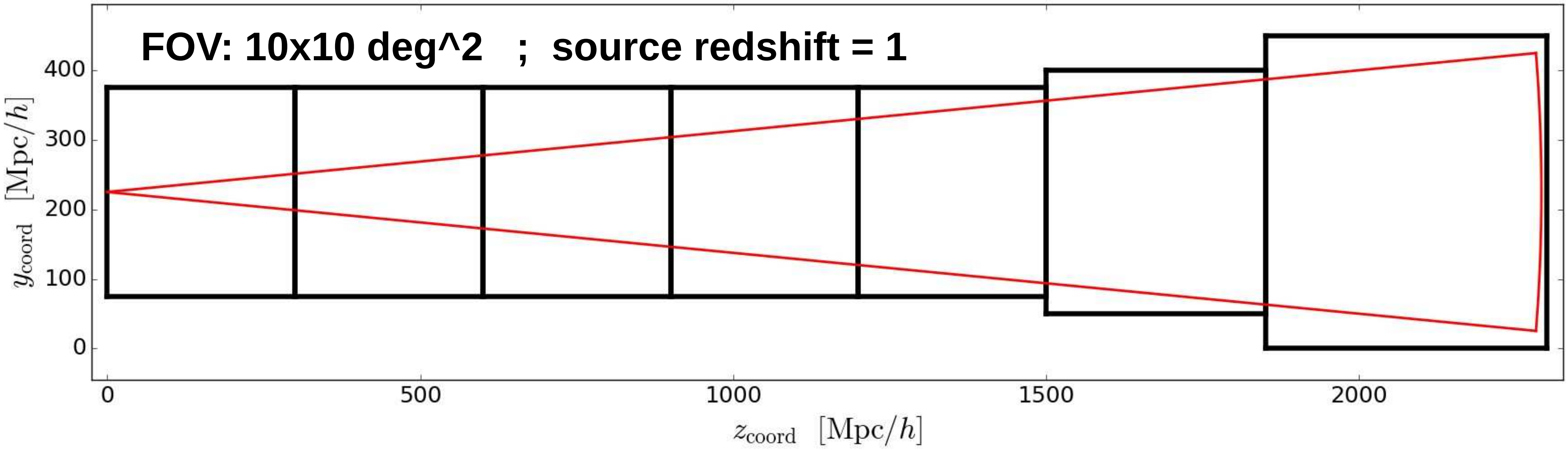
$$r_c H_0 = 1$$

Lensing simulations : Ray-Ramses

Ray-Ramses : Lensing on the fly with the N-body simulations

Barreira, Llinares, Bose and Li
arXiv:1601.02012

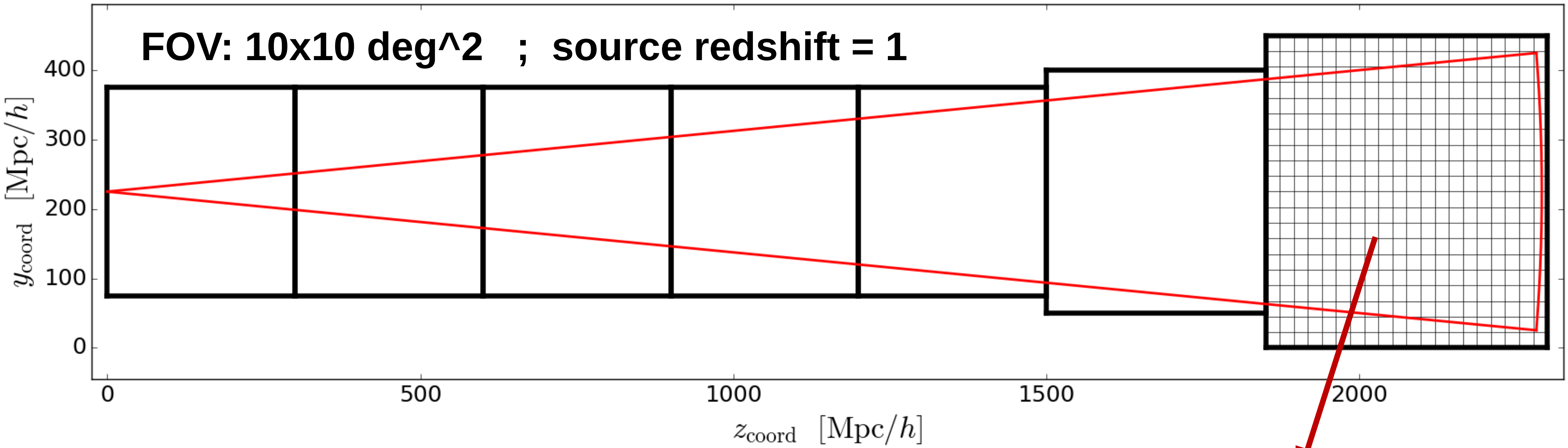
Lensing simulations : Ray-Ramses



Evaluate the lensing convergence integral on the fly with the N-body simulations.

$$\kappa = \frac{1}{c^2}\int_0^{\chi_s} \frac{\chi\left(\chi_s - \chi\right)}{\chi_s}\nabla^2_{2D}\Phi_{\rm len}\,{\rm d}\chi$$

Lensing simulations : Ray-Ramses



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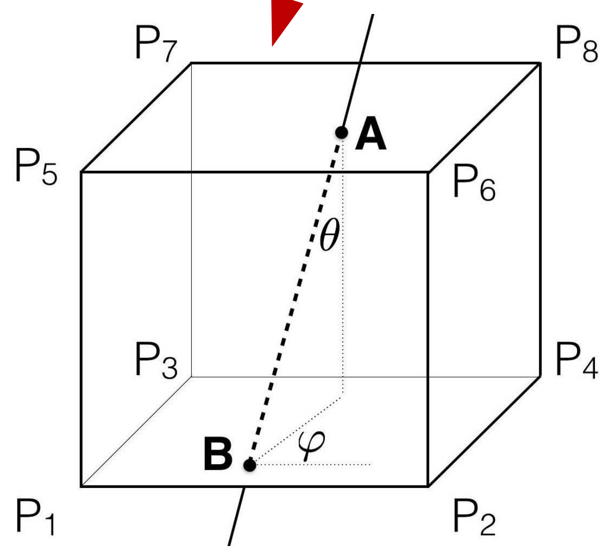
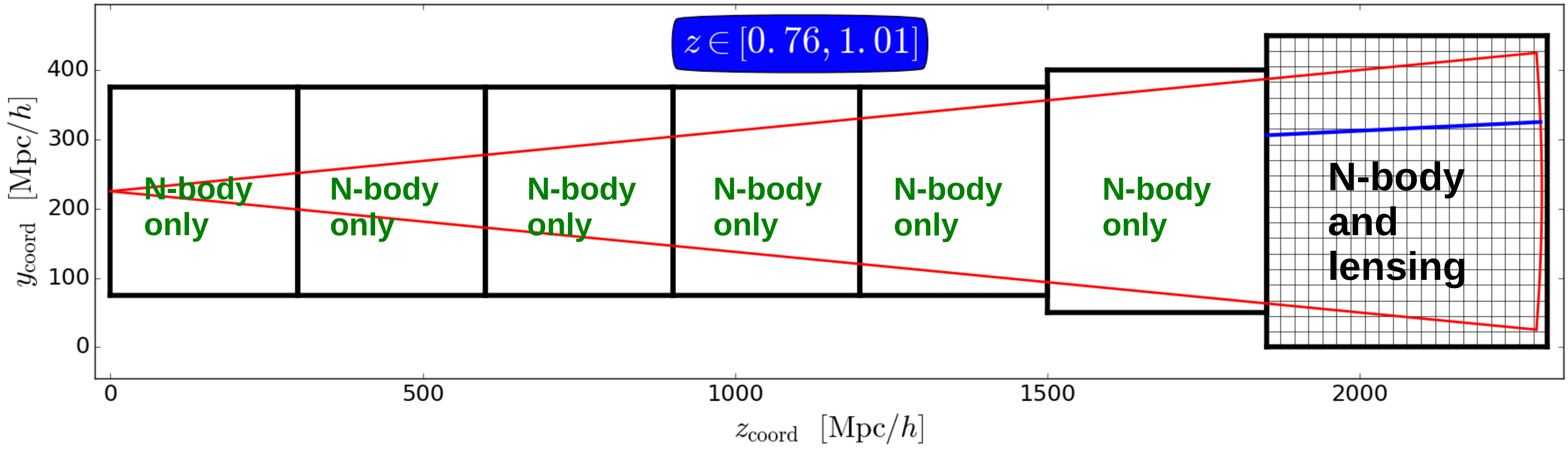


Split it into the contribution from each AMR cell crossed by the rays.

$$\kappa = \sum_{\mathrm{cells}} \kappa_{\mathrm{cell}}$$

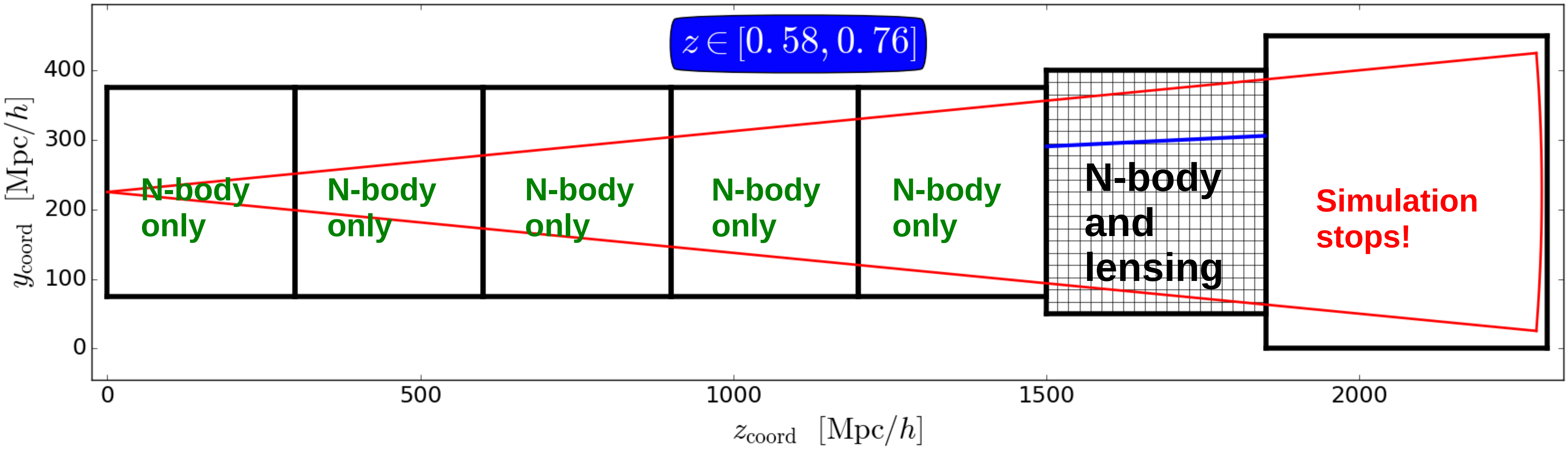
Computed analytically from potential values on the AMR cells.

Lensing simulations : Ray-Ramses



- **All boxes simulate structure formation, but only do ray integrations during the redshift range associated with their position in the tile.**
- **Use different initial conditions to avoid repetition of structures.**

Lensing simulations : Ray-Ramses



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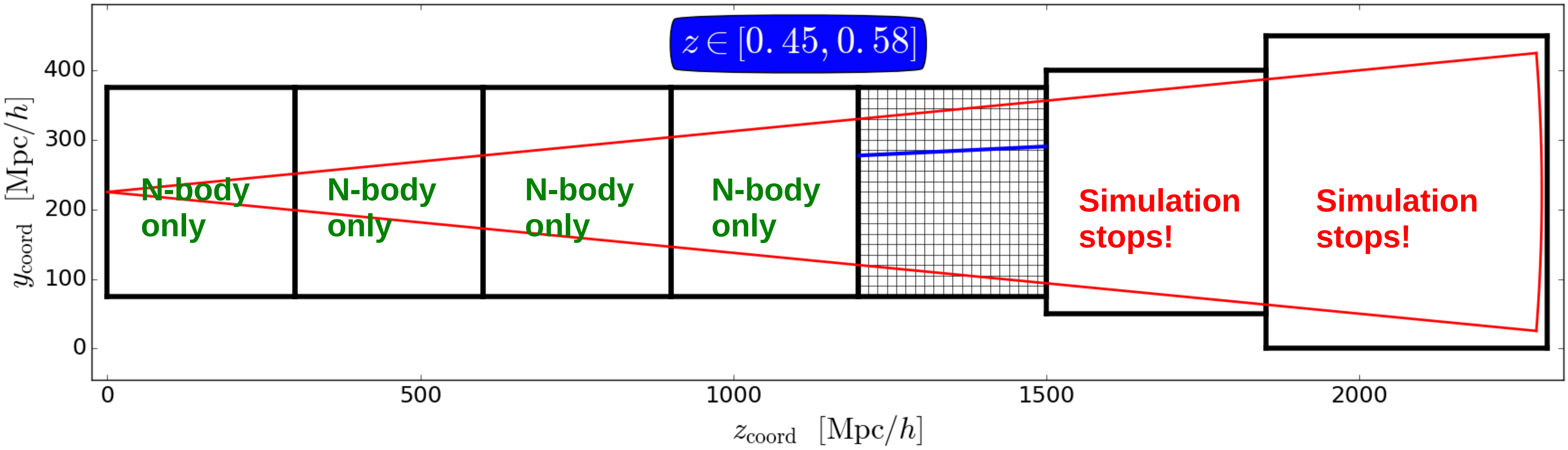

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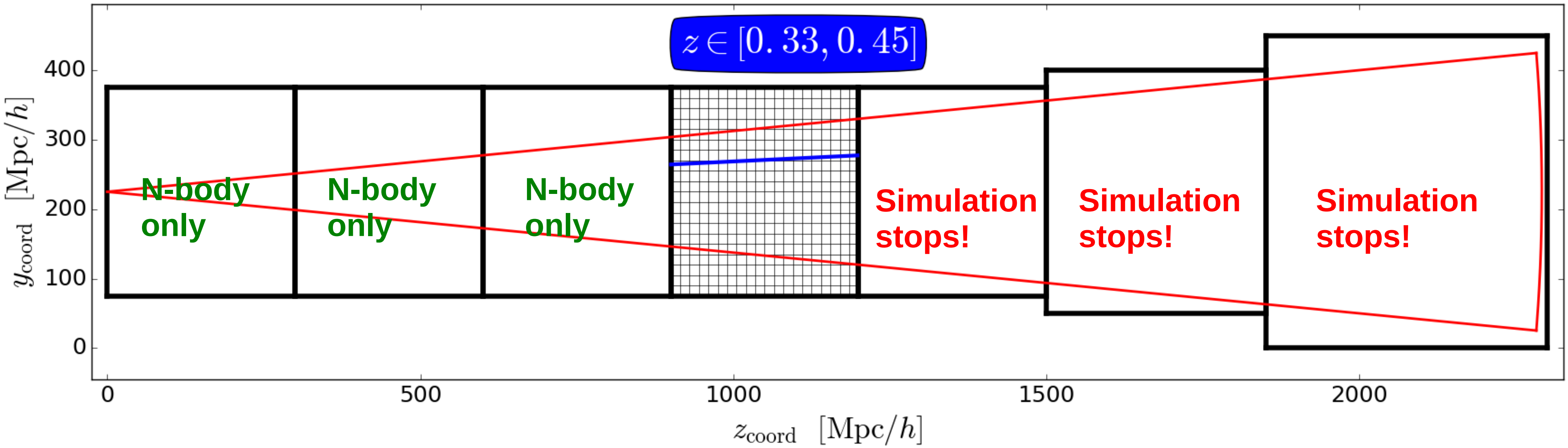

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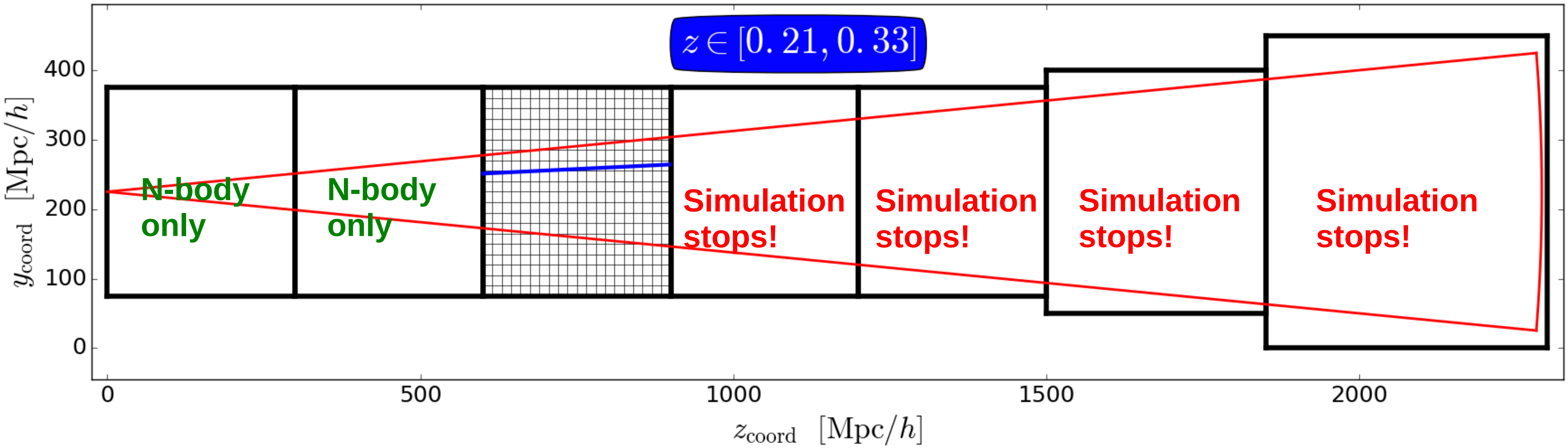

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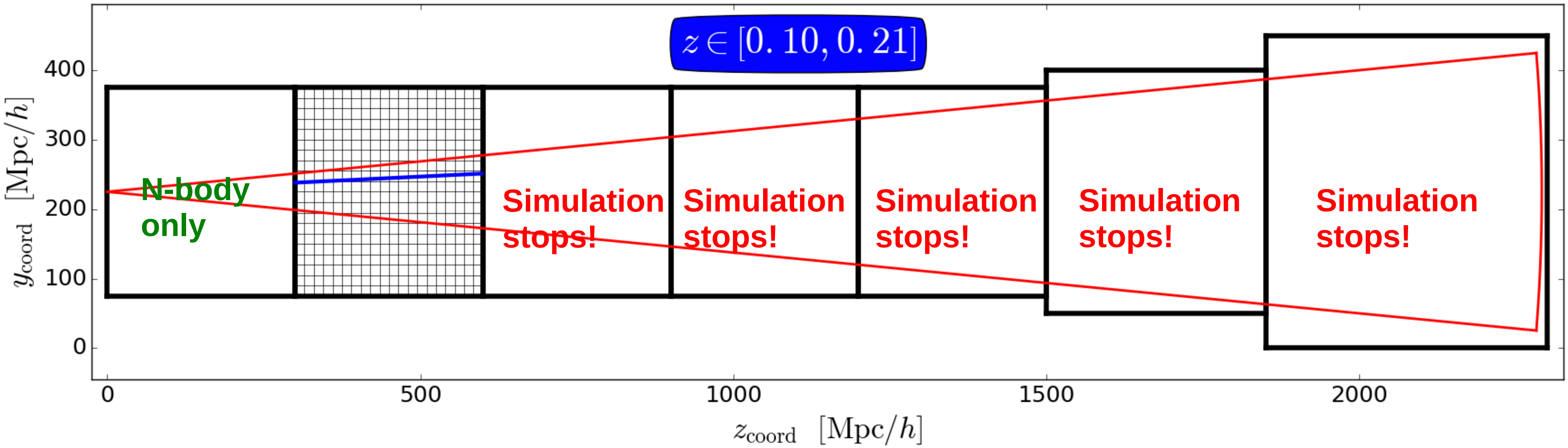

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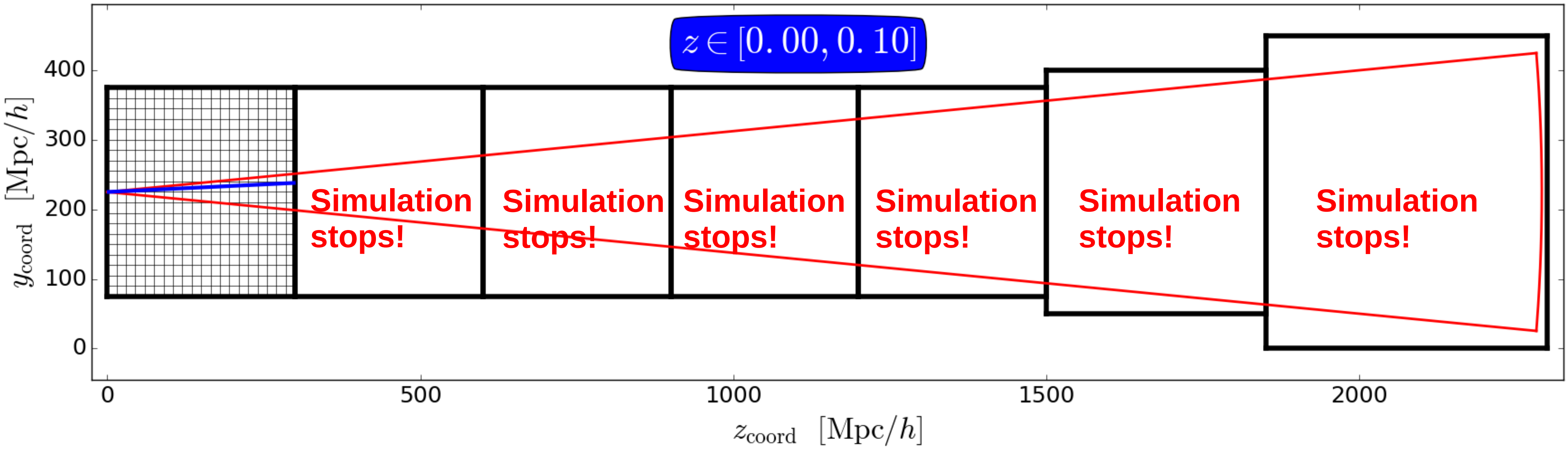

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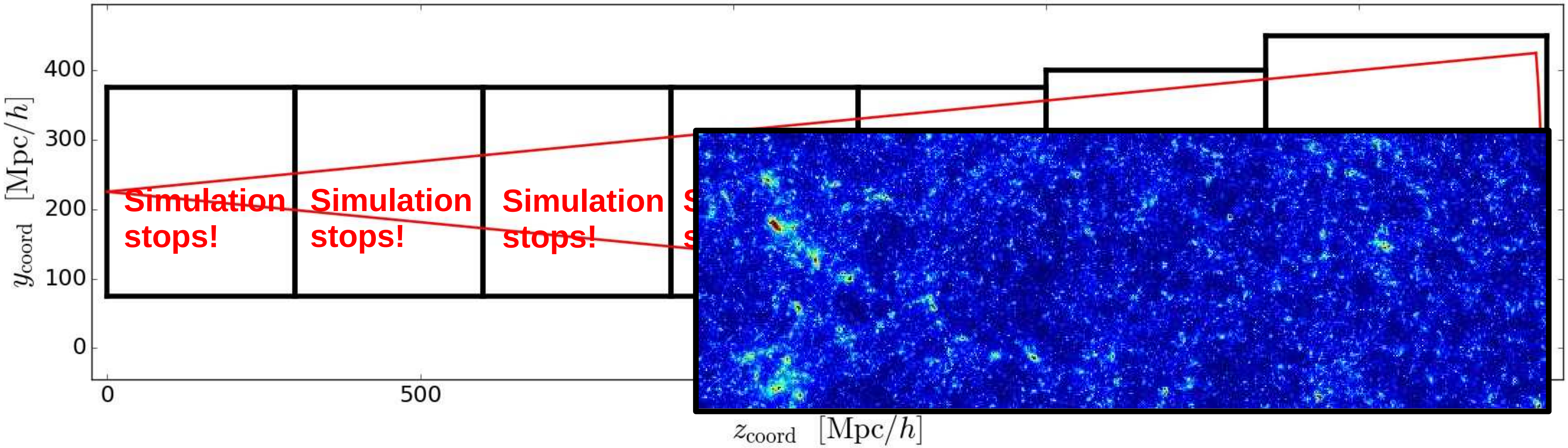
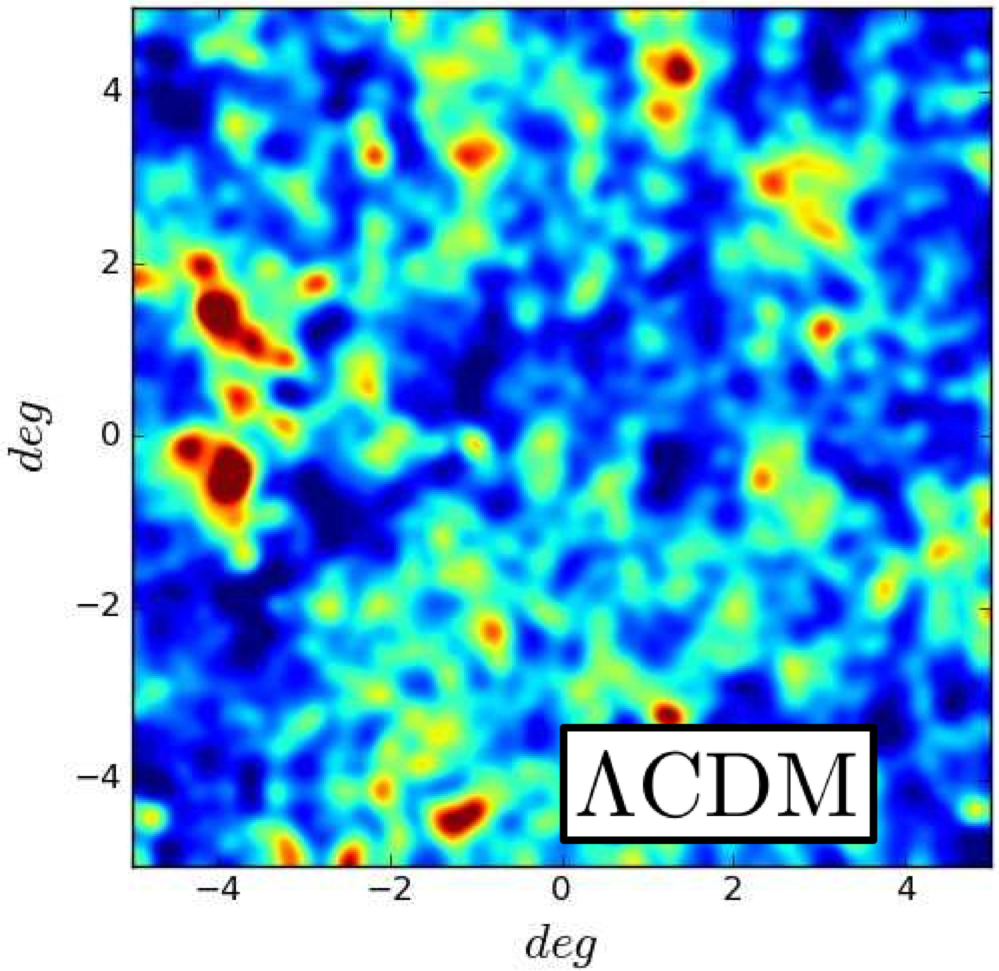


- **All boxes simulate structure formation, but only do ray integrations during the redshift range associated with their position in the tile.**

- **Use different initial conditions to avoid repetition of structures.**

- **Total lensing signal is the sum of the contribution from each box. <u>Beware of 1st order Born approximation:</u> unperturbed photon trajectories.**

Build some intuition …



$\Lambda\mathrm{CDM}$

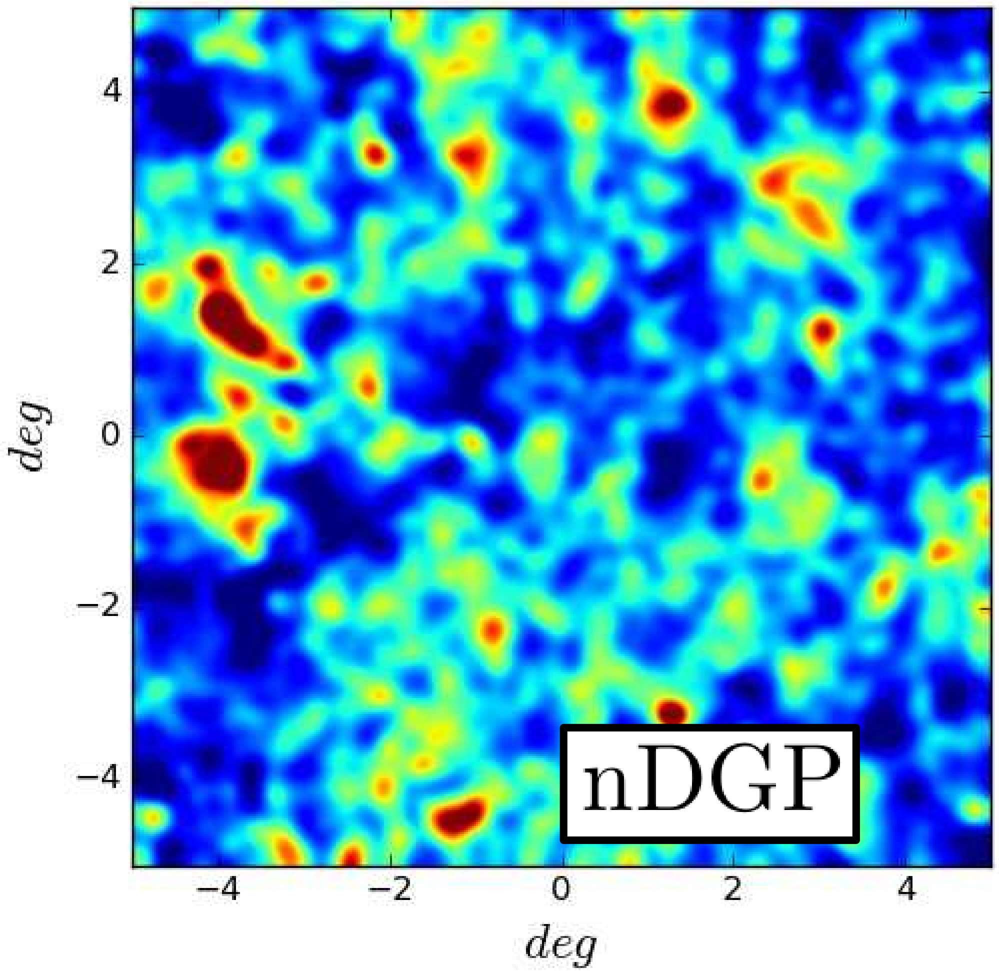
Lensing modified because of modified *dynamical* potential (different LSS).

nDGP

Lensing modified because of modified *lensing* potential (same LSS).

$\mathrm{nDGP}_{\mathrm{lens}}$

Build some intuition …



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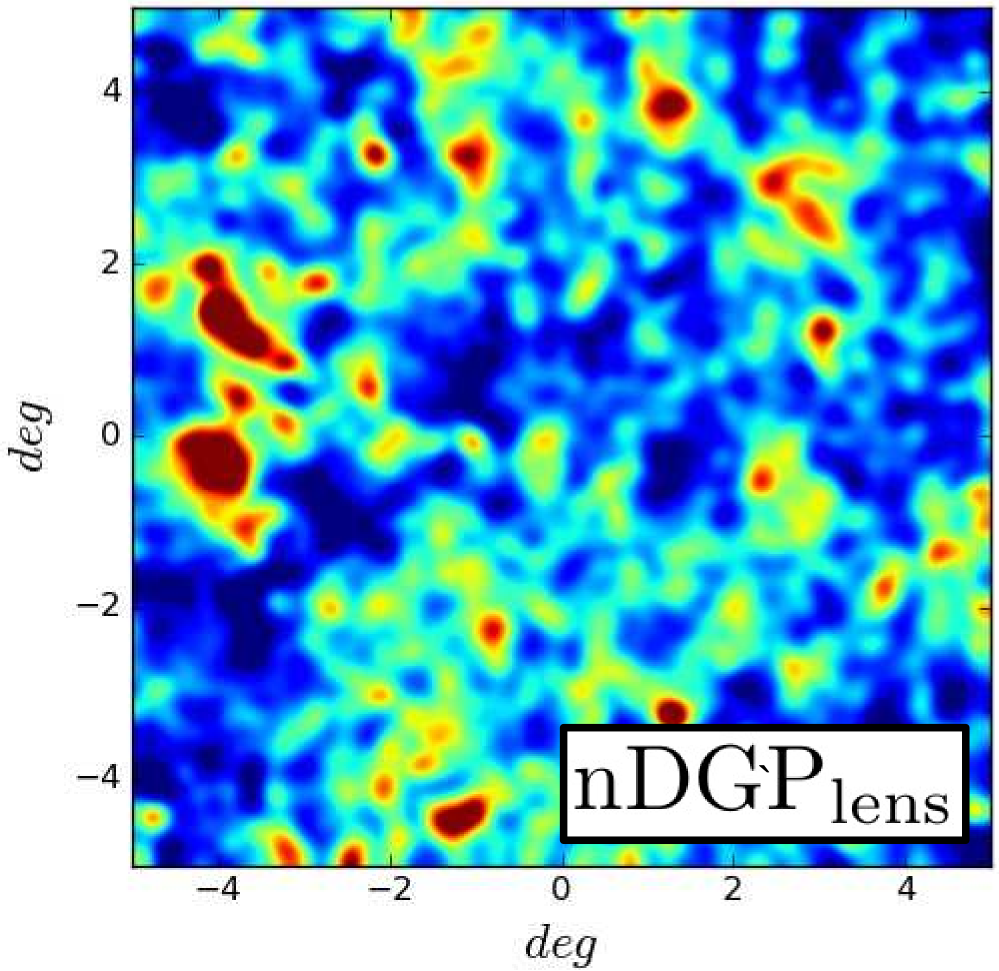

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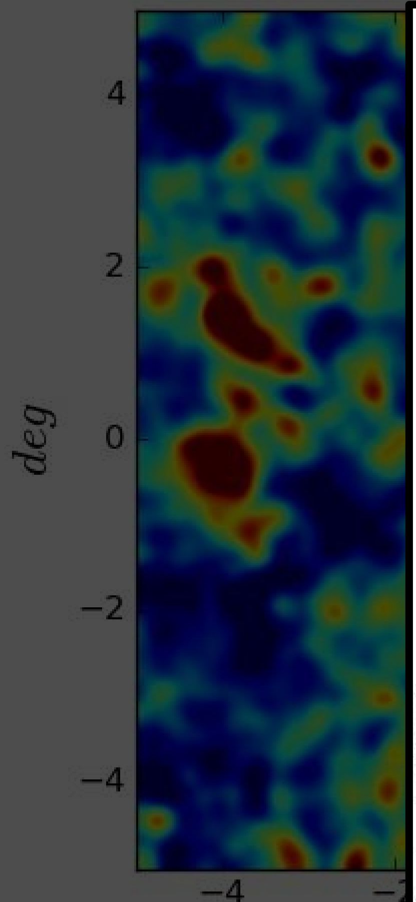
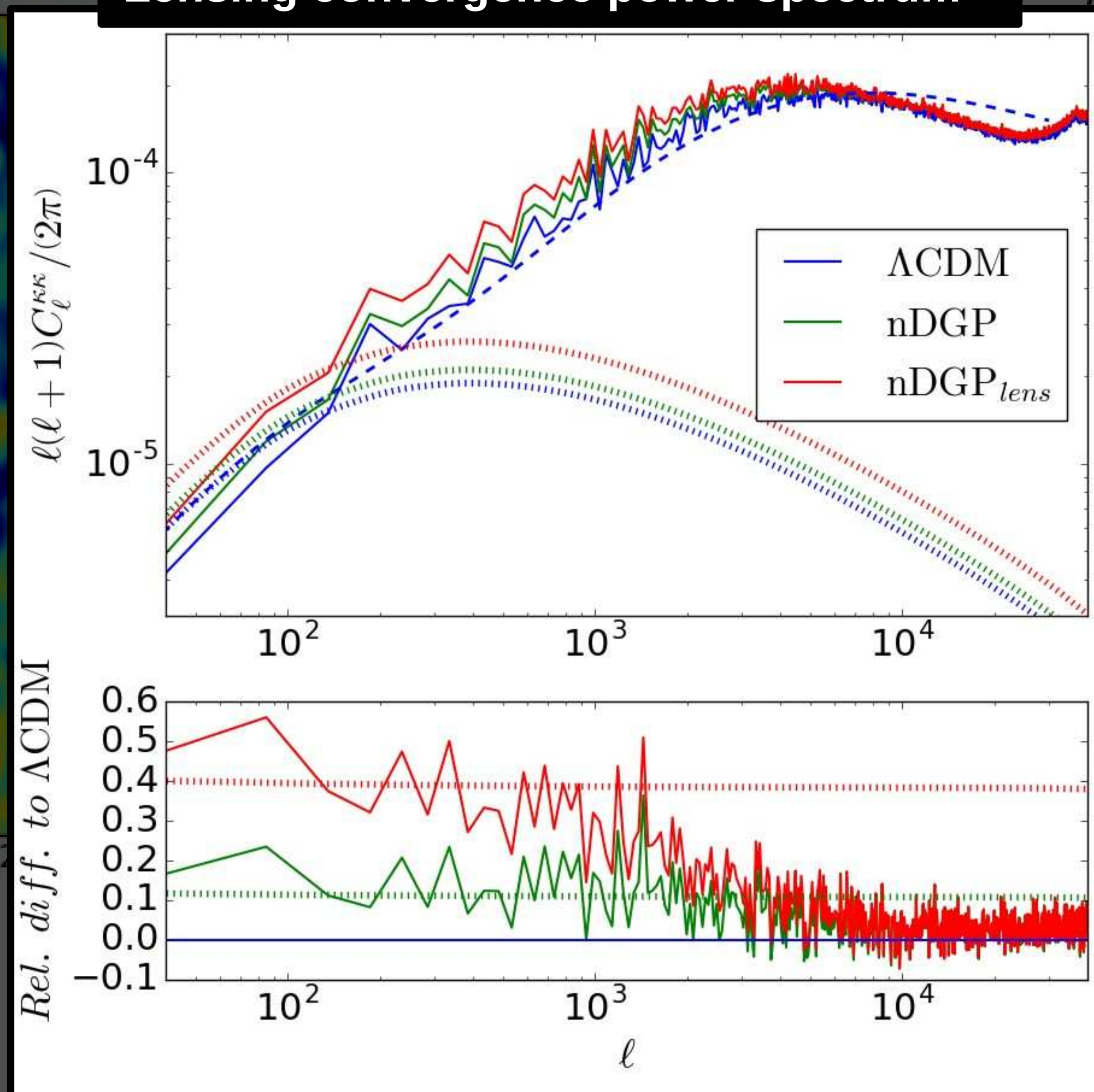


Lensing convergence power spectrum



ΛCDM

because of
cal potential

nDGP

because of
potential

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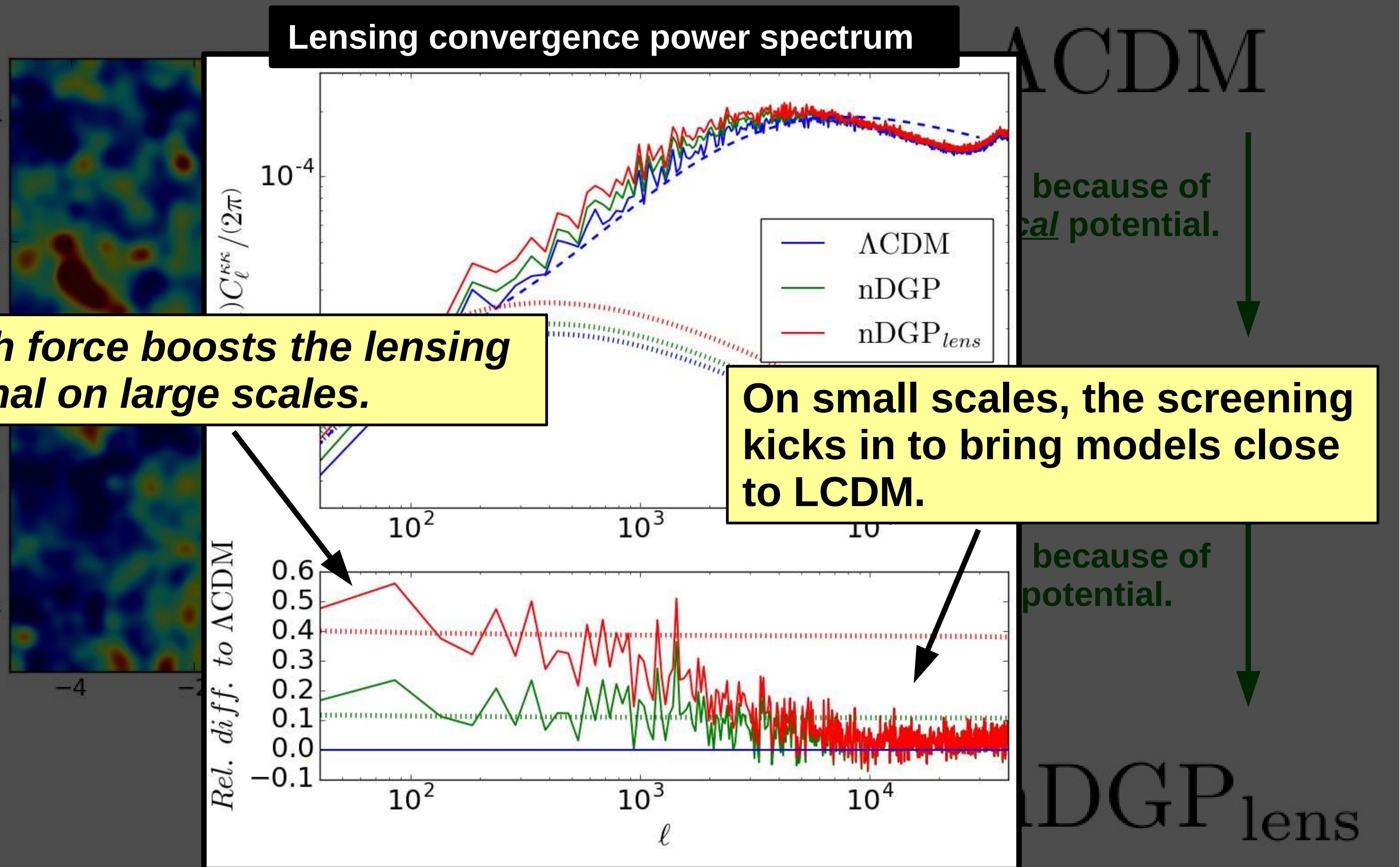
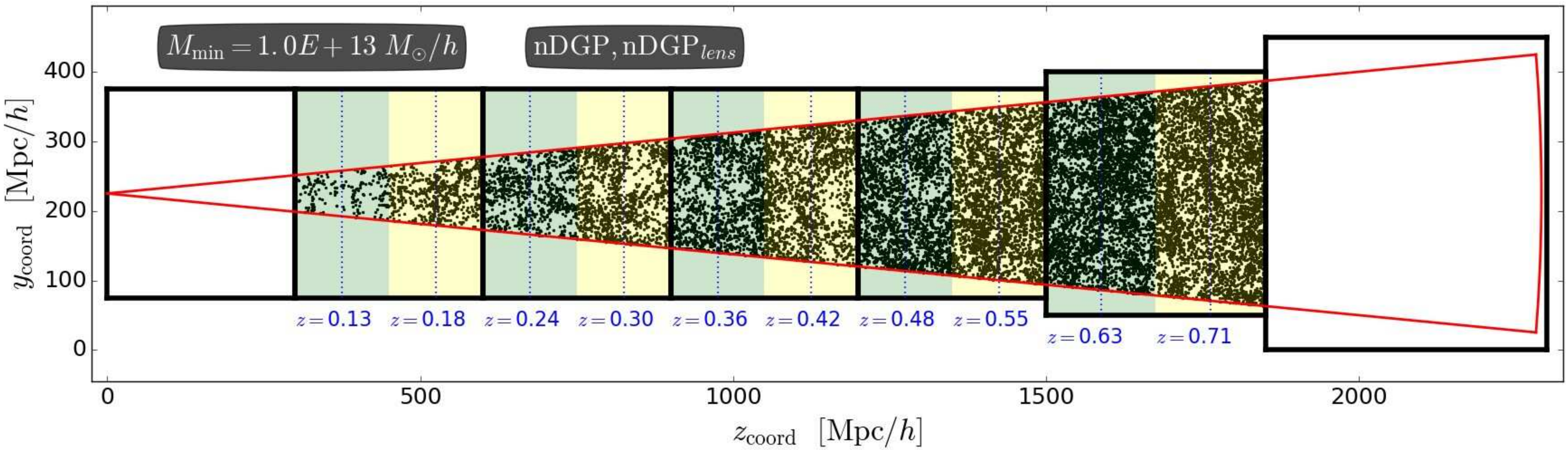
Build some intuition …



Fifth force boosts the lensing signal on large scales.

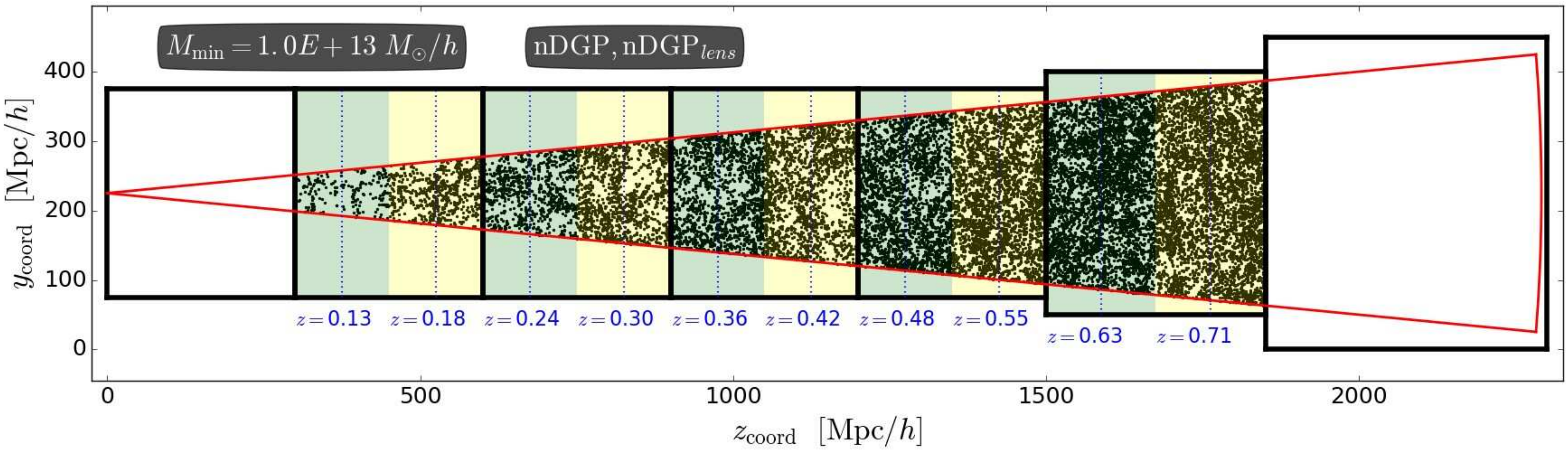
On small scales, the screening kicks in to bring models close to LCDM.

LOS identification



- **Construct a "pseudo" halo lightcone using two output times per box.**

LOS identification



- **Construct a “pseudo” halo lightcone using two output times per box.**

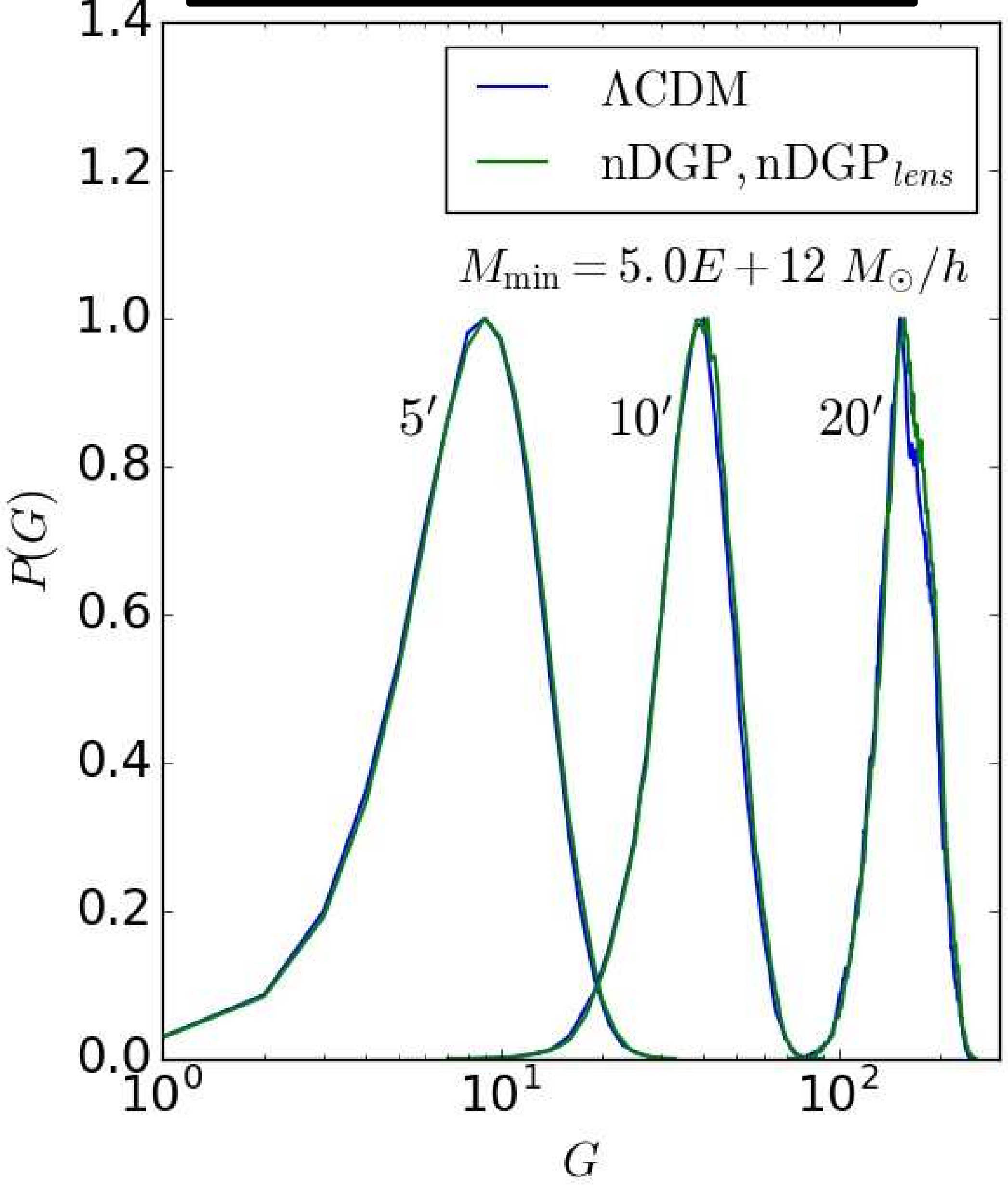
The *G* field : projected halo number counts within some aperture.

$$G(\vec{\theta}) = \sum_{i=1}^{N_{\rm halo}} W_{\rm sel,i}\left(\theta_T, z_l, z_u, M_{\rm min}\right)$$

$$W_{\rm sel,i} = \begin{cases} 1, & |\vec{\theta} - \vec{\theta}_i| \leq \theta_T, z_i \in [z_l, z_u], M_i \geq M_{\rm min} \\ 0, & \text{otherwise} \end{cases}$$

LOS identification

Halo count G distribution



Halo-underdense LOS
→ lower 20% quantile

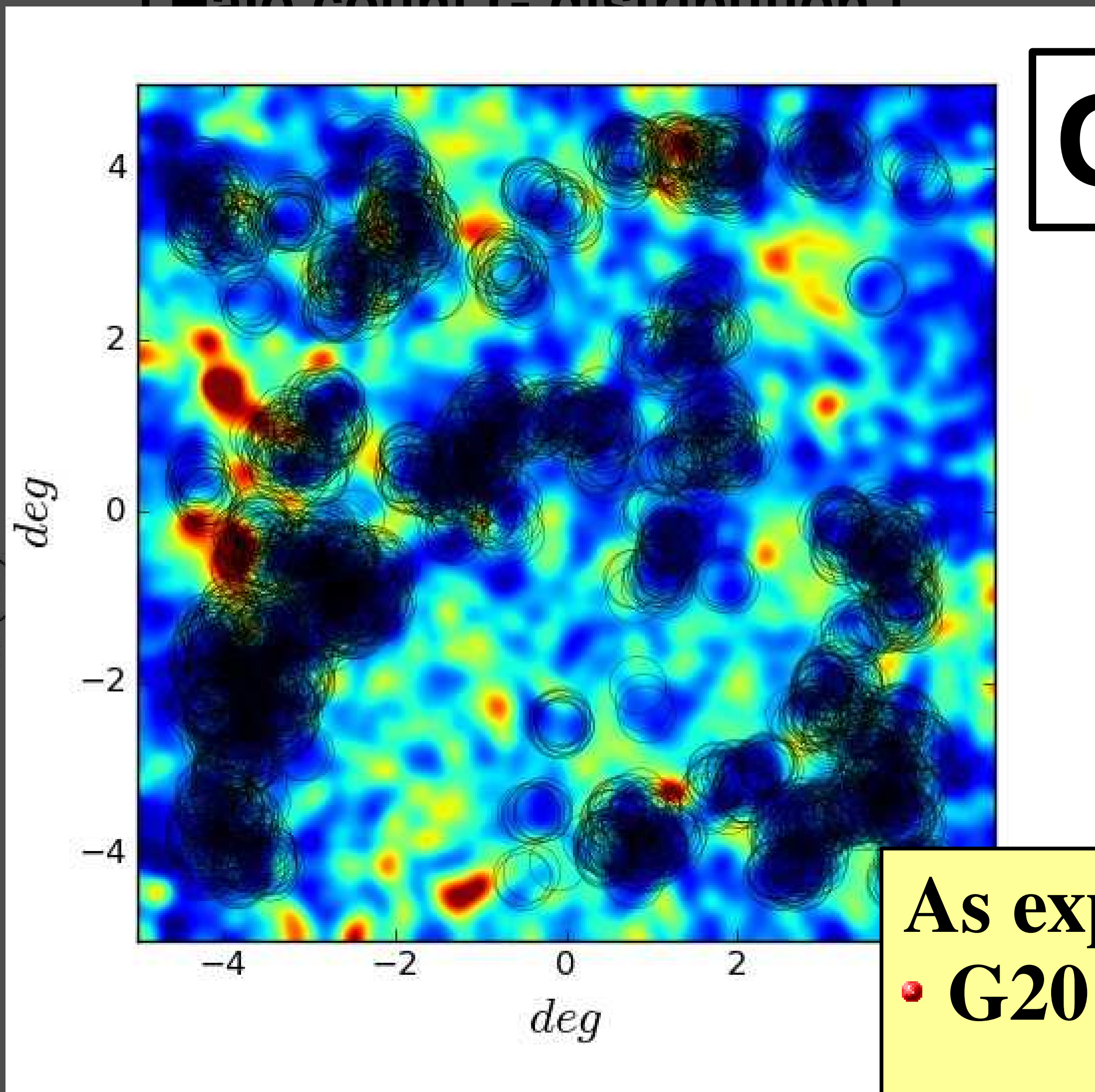
Call them G20

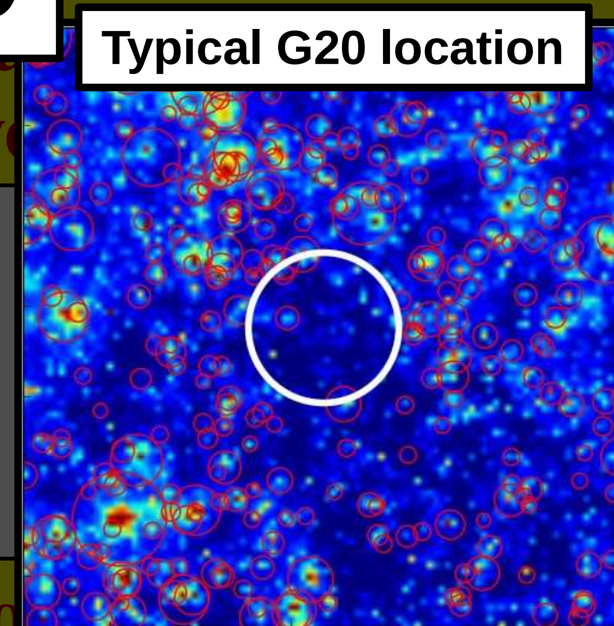
Halo-overdense LOS
→ upper 20% quantile

Call them G80

LOS identification

G20

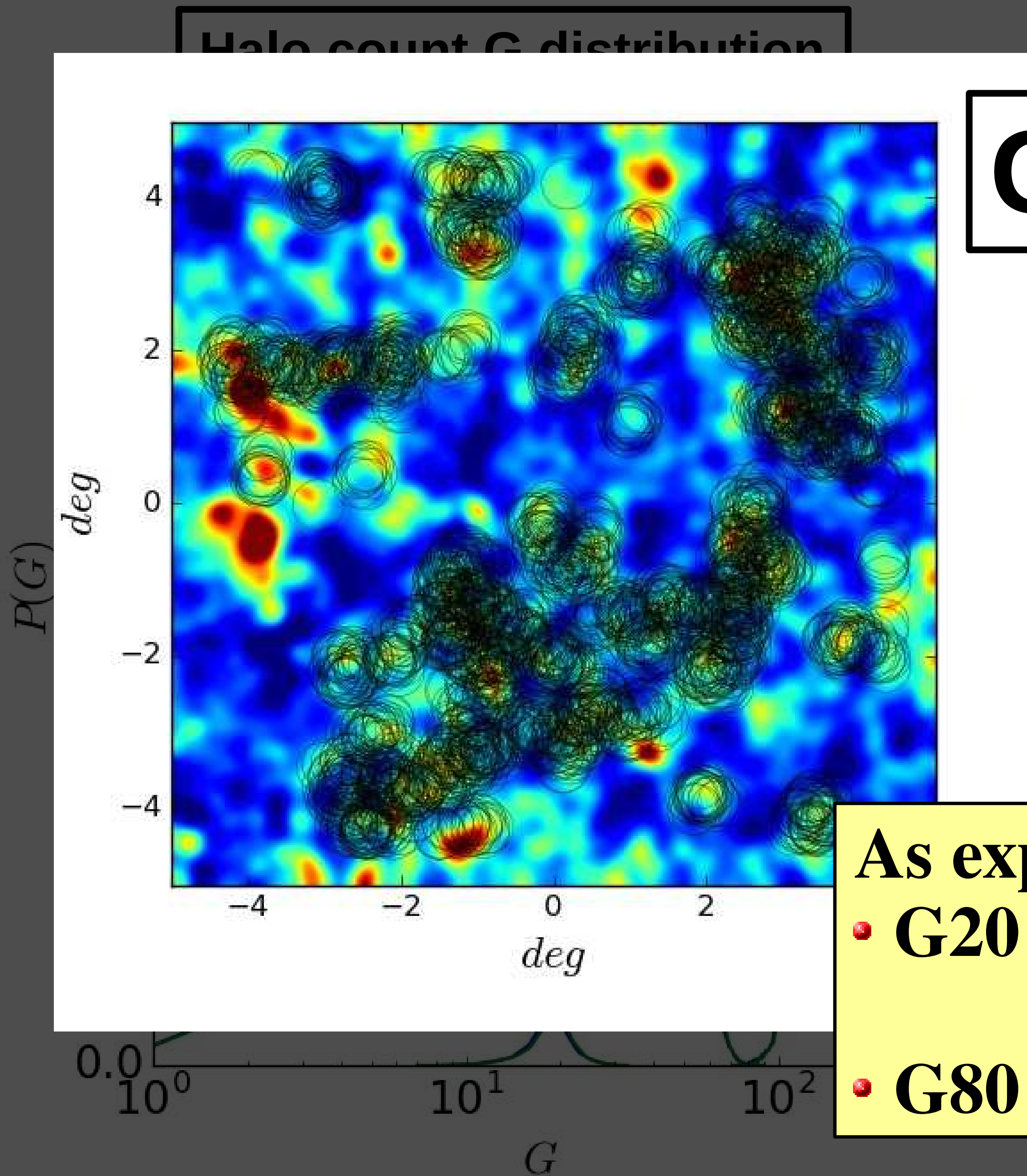




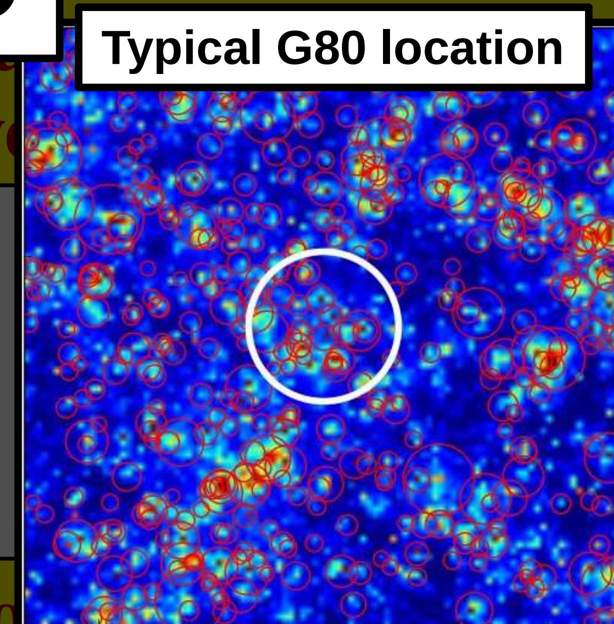
As expected:

- **G20 trace lower convergence;**
- **G80 trace higher convergence.**

LOS identification



G80



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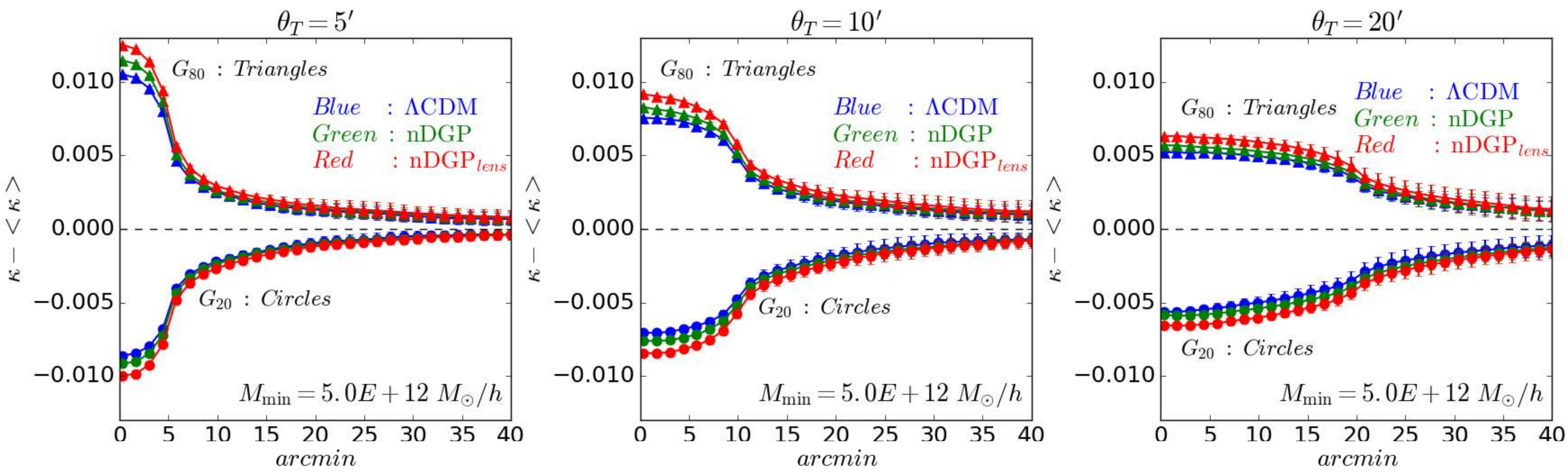
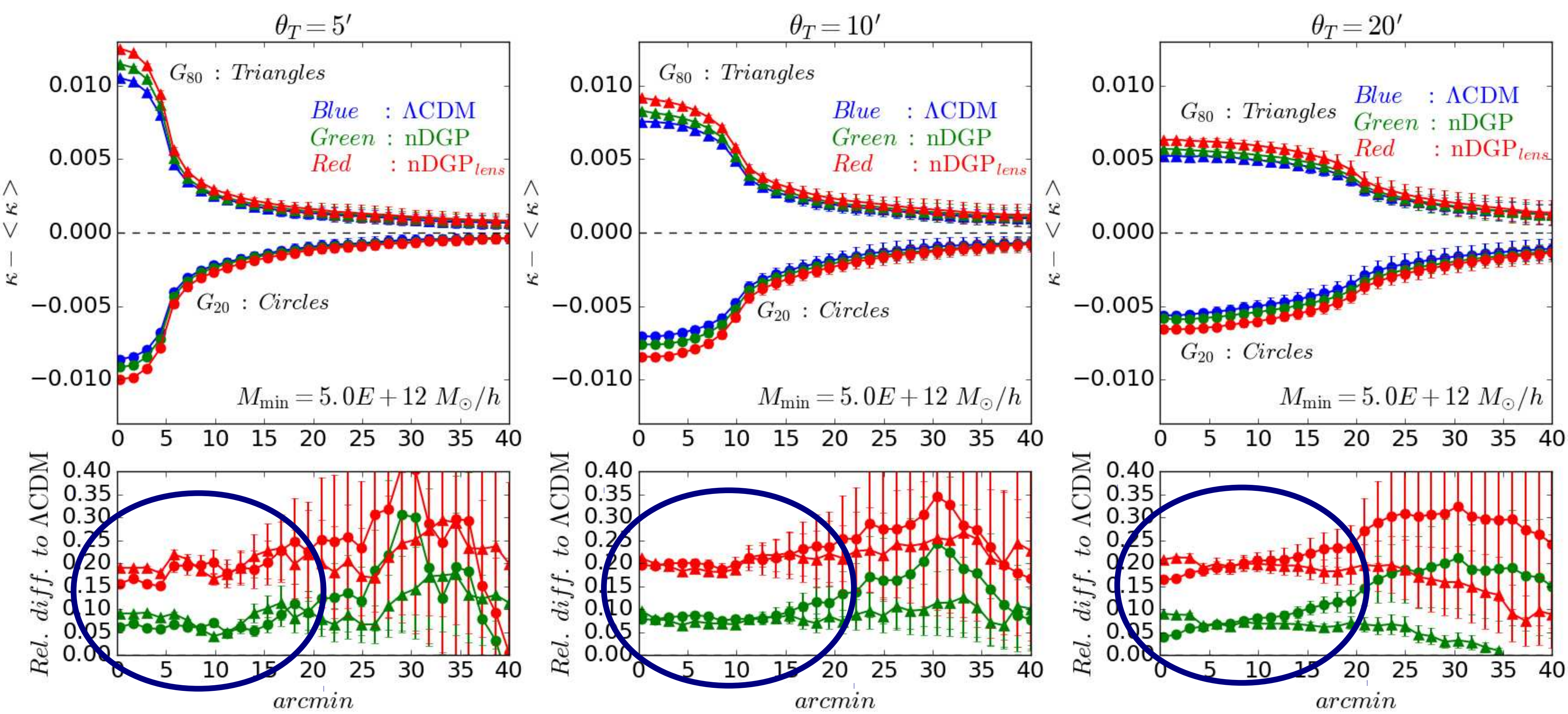
Convergence profiles



M_halo > 5e12 Msun/h
0.1 < z_halo < 0.76

Convergence profiles

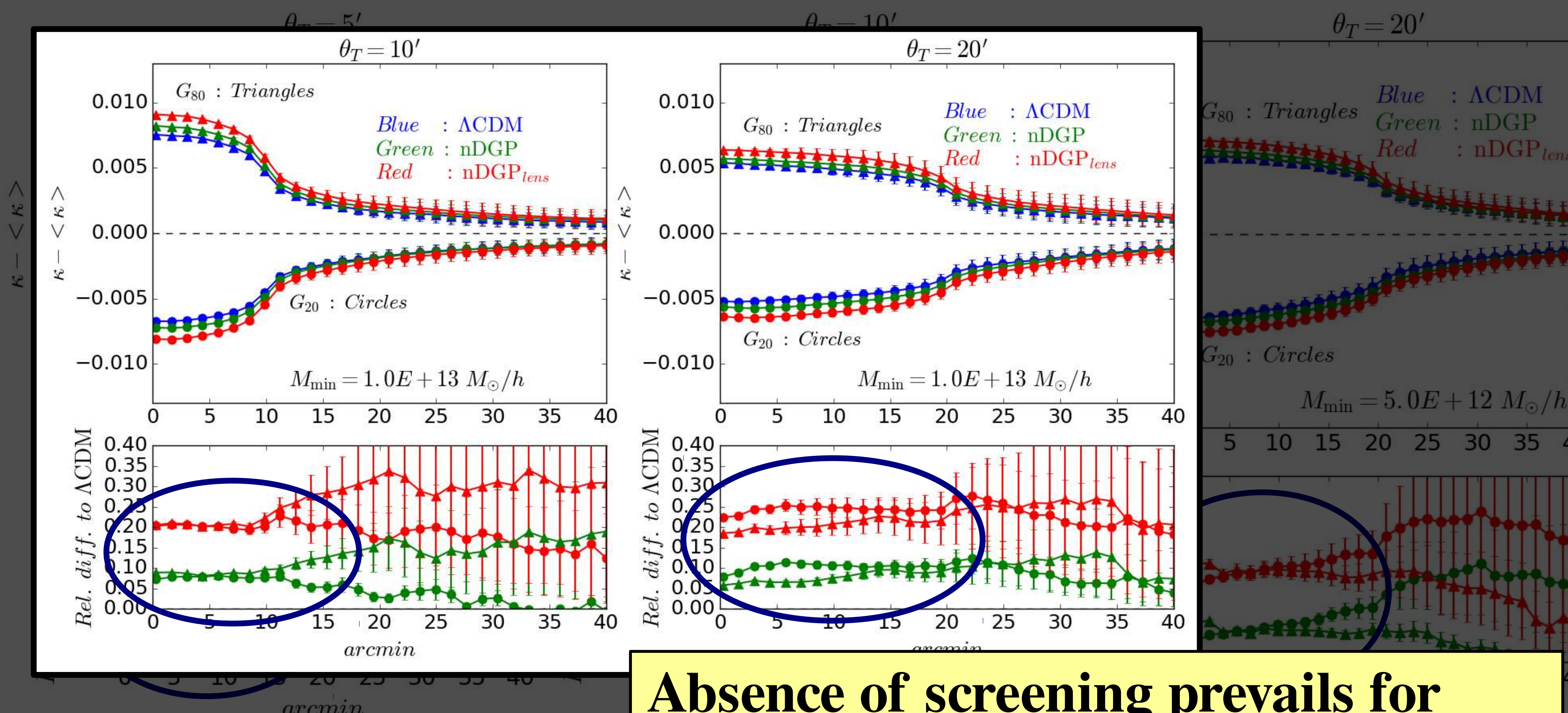


Fifth force has the same impact on G20/G80 LOS, despite them probing low/high density regions.

M_halo > 5e12 Msun/h
0.1 < z_halo < 0.76

No evidence for screening effects !!

Convergence profiles



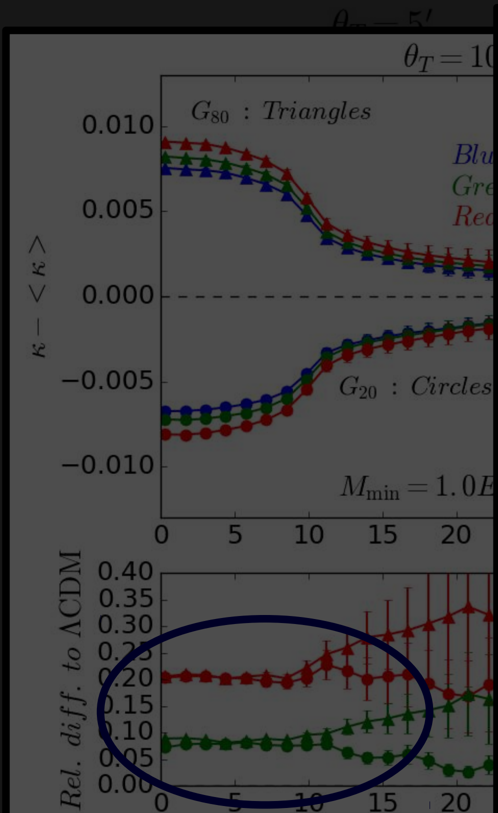
Absence of screening prevails for other minimum halo mass choices.

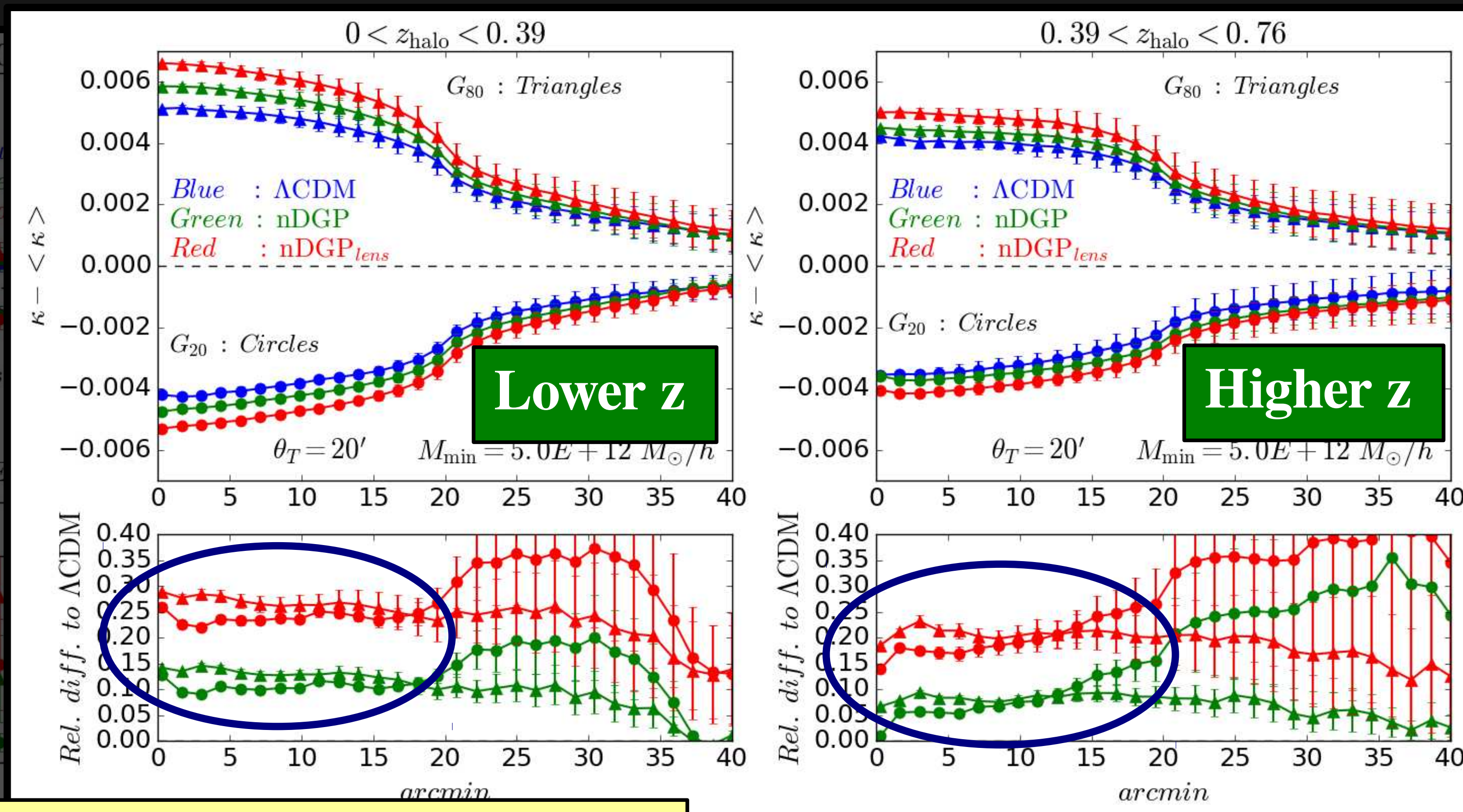
Fifth force has the same im... them probing low/high density regions.

No evidence for screening effects !!

M_halo > 1e13 Msun/h
0.1 < z_halo < 0.76

Convergence profiles





Absence of screening also for other halo redshift binning.

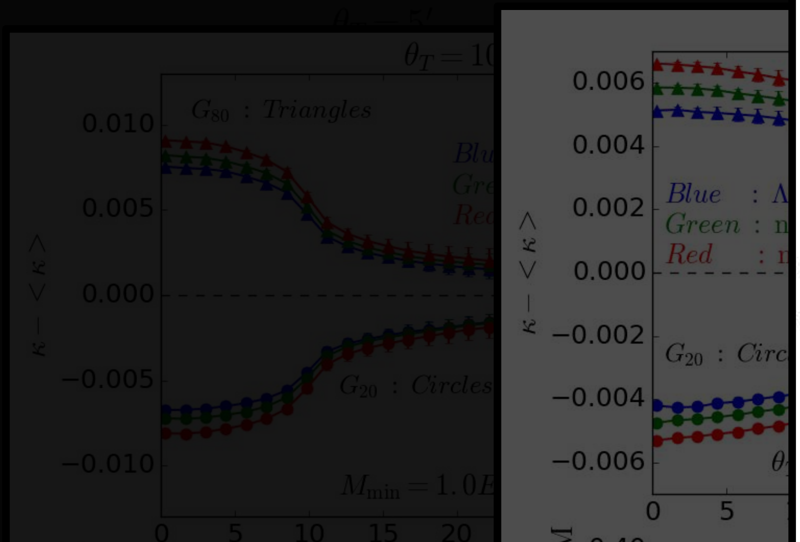
creening prevails for
um halo mass choices.

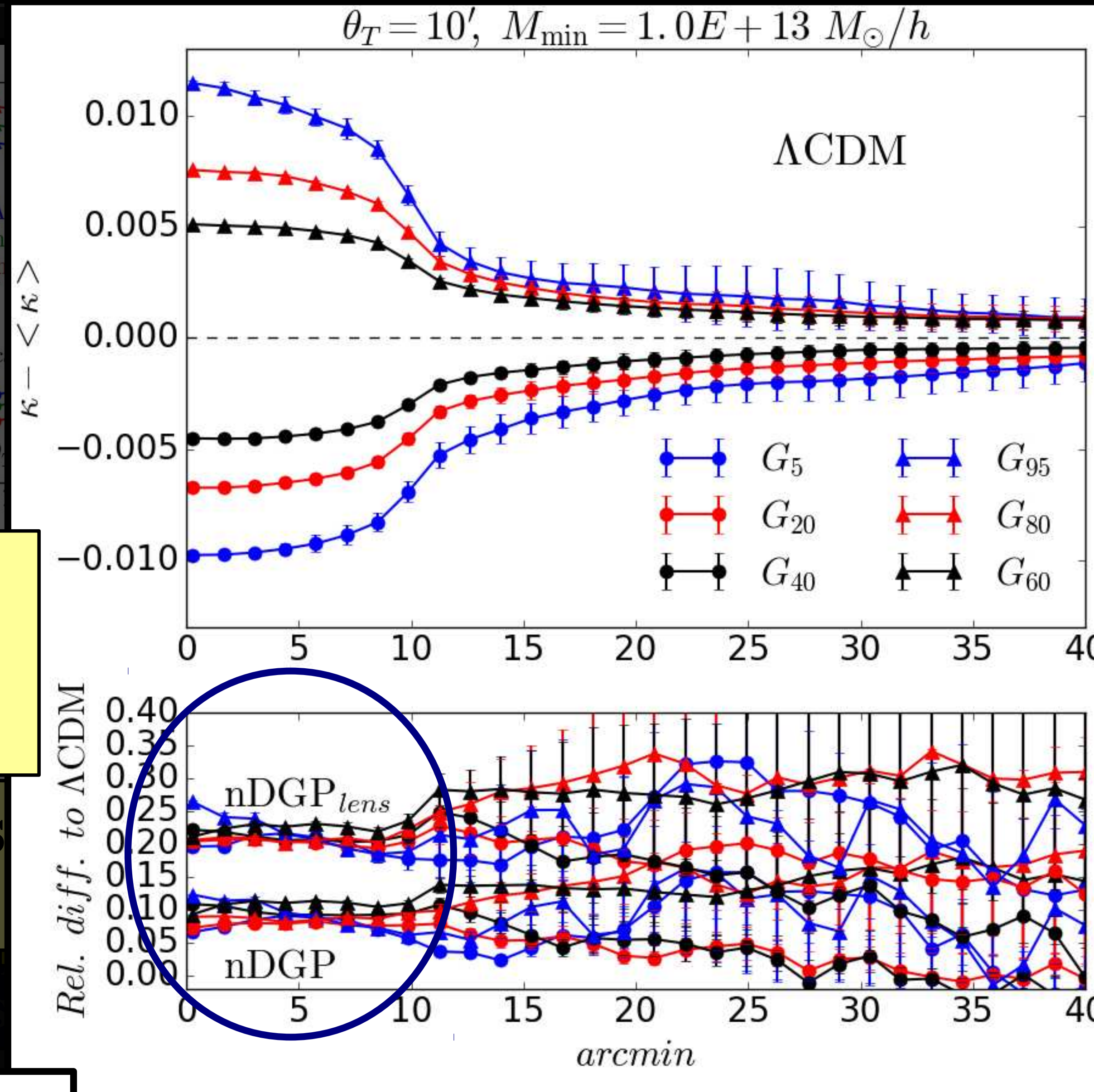
them probing low/high density regions.

No evidence for screening effects !!

M_halo > 5e12 Msun/h
Two redshift bins

Convergence profiles





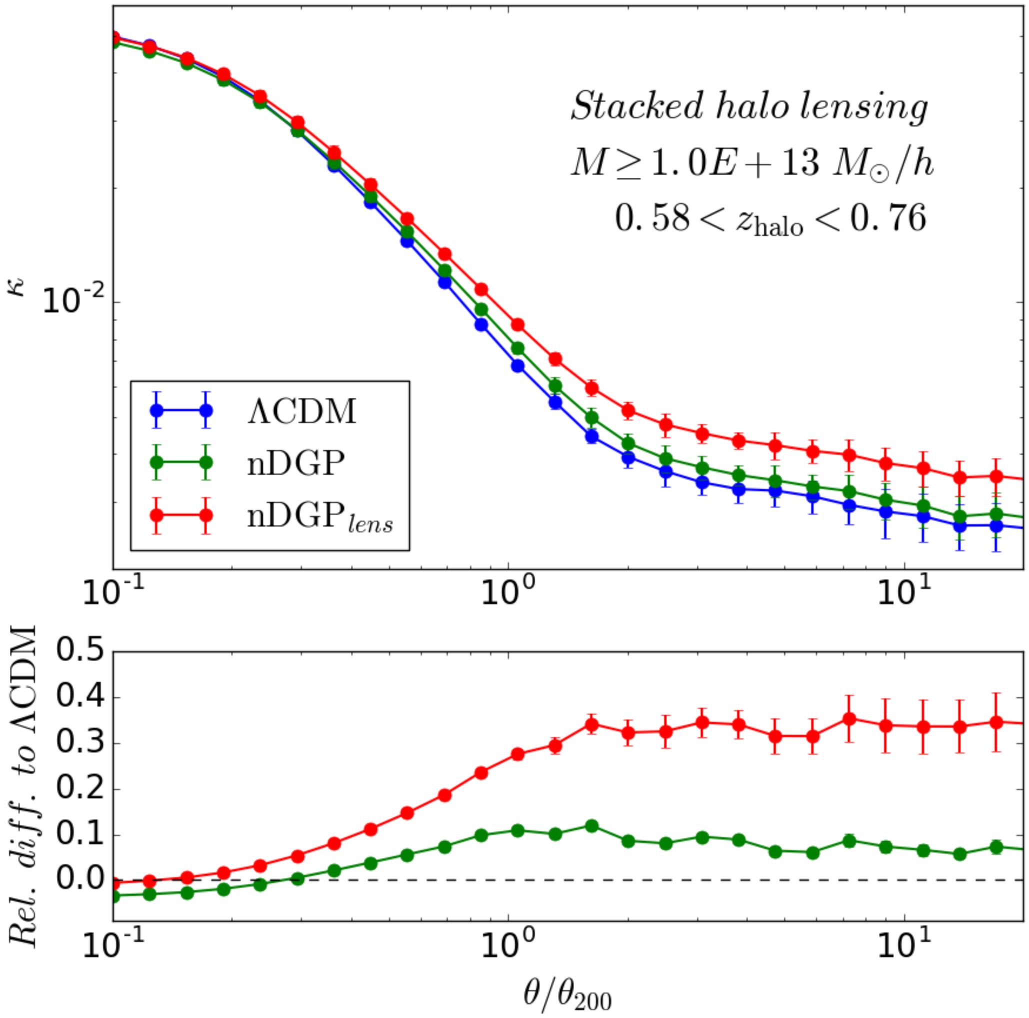
Fifth force effects are of the same size for other quantile choices.

Absence of screening als halo redshift binning.

M_halo > 1e13 Msun/h
Different quantiles

Screening with halo lensing

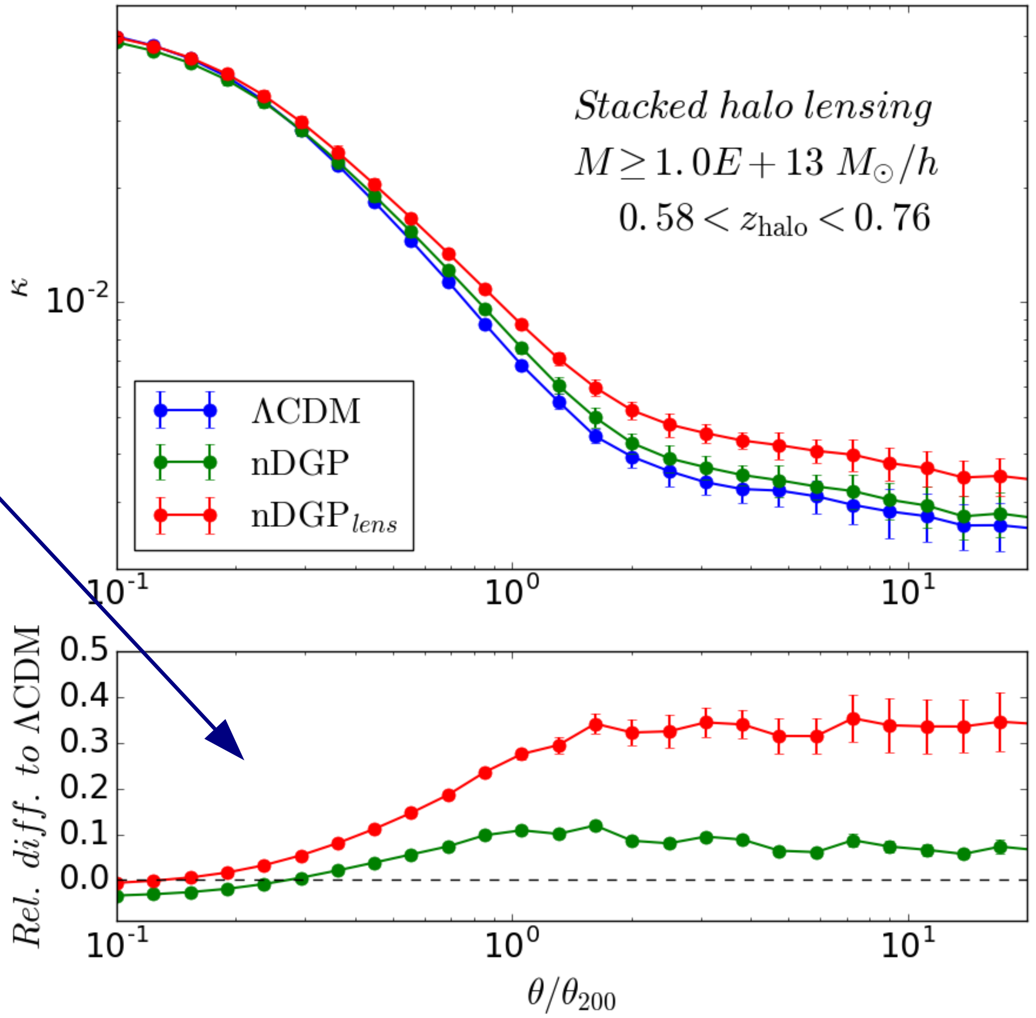
Stacked halo lensing



Screening with halo lensing

Stacked halo lensing

Evidence for screening in stacked halo lensing though.



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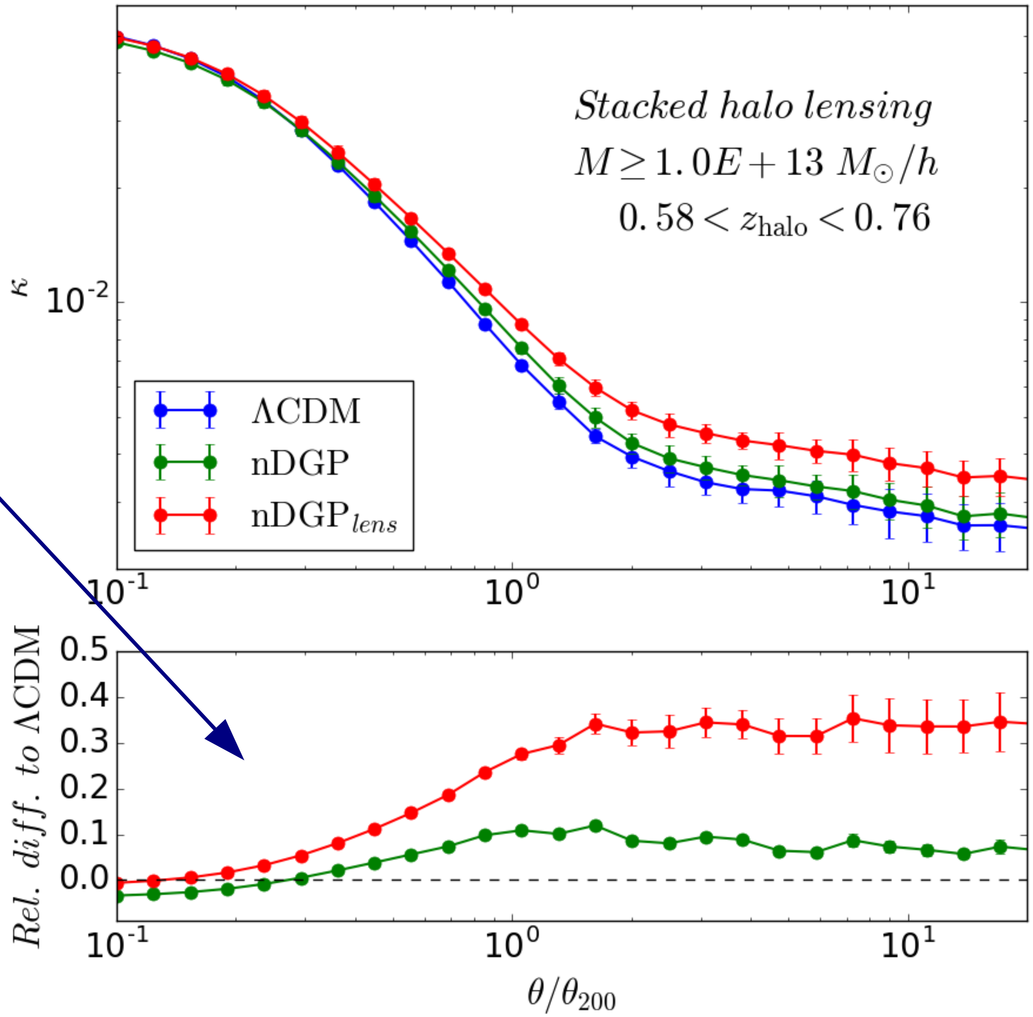
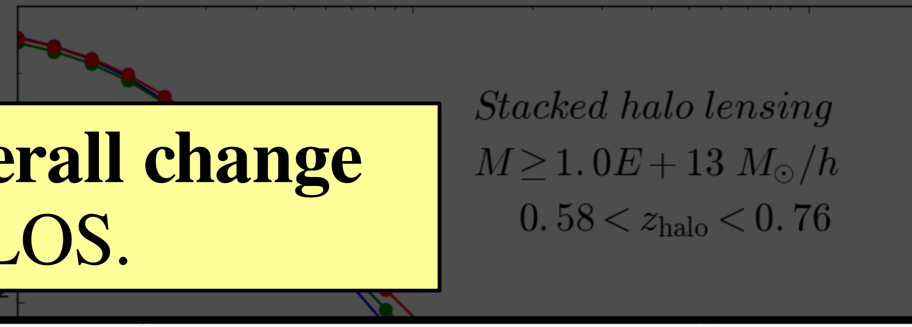


Overall conclusion:

- **Lensing around G80 LOS is dominated by the mass between haloes, not inside.**
- **G80 LOS are overdense, just not enough to “trigger screening”.**

Shear profiles



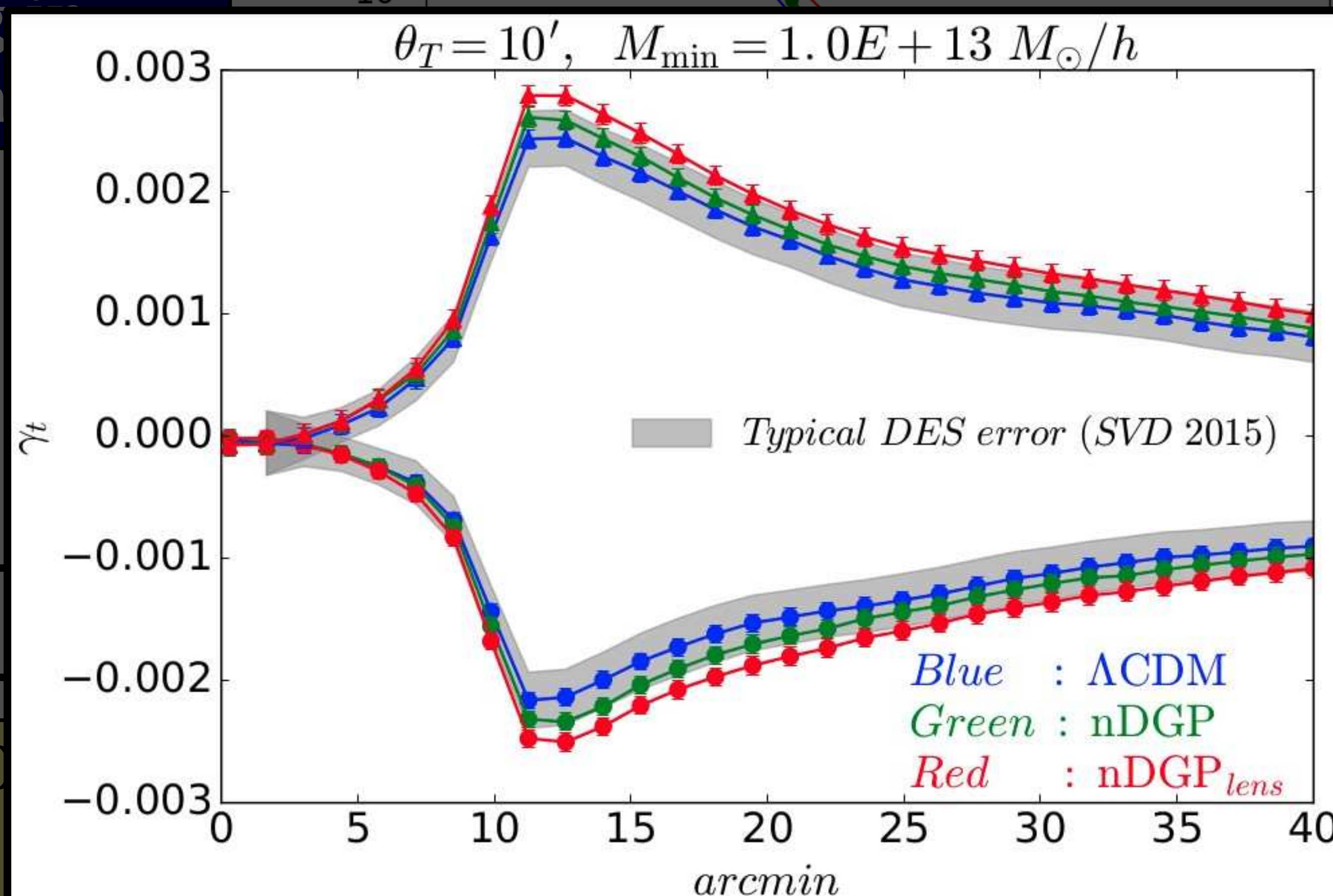
Main observational signature is an **overall change in amplitude** of both G20 and G80 LOS.

Evidence for screening in … stacked halo lensing th…

Lensing shear: "amount of tangential distortion"

$$\gamma_t(r) = \bar{\kappa}(<r) - \kappa(r)$$

$$\bar{\kappa} = \frac{1}{r^2}\int_0^r \mathrm{d}r' \kappa(r')$$



- **Lensing around G80 LO… inside.**
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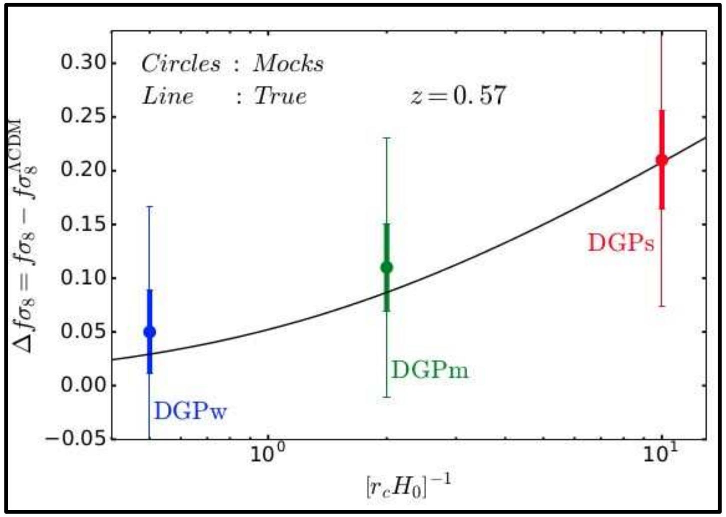
Summary

1) Validating estimates of the growth rate of structure.



Clustering wedges model used on BOSS DR12 data ***is compatible with DGP-like cosmologies.***

But this is not necessarily the case for all (i) gravity models,(ii) range of scales, etc.

Always ensure compatibility between theory and data analysis !

Summary

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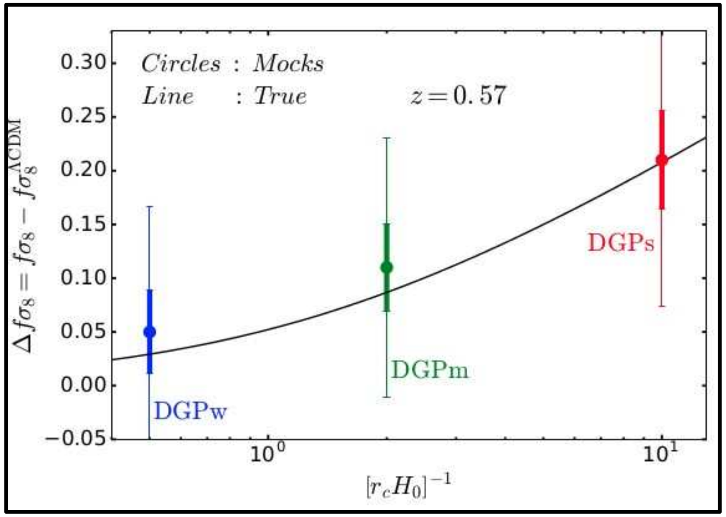

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Always ensure compatibility between theory and data analysis !

2) Weak lensing by troughs in DGP

Fifth force impacts under/overdense LOS in the same way → ***no evidence of striking screening signatures!***

Constant boost *in the amplitude is the main observational signature.*