# Testing Gravity with the Stacked Phase-space around Galaxy Clusters

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## Texas Symposium 2013

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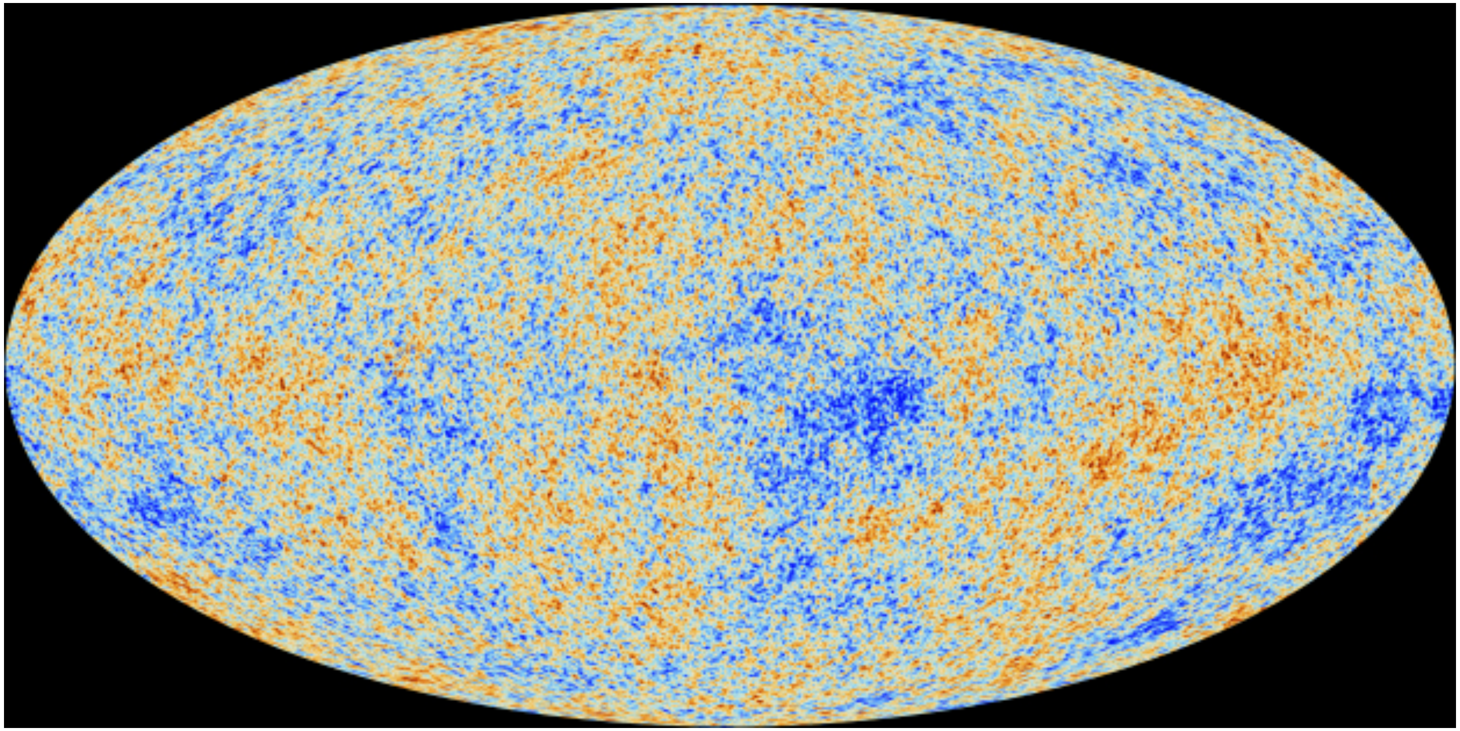
1. PRL, 2012, 109, 051301
2. PRD, 2013, 88, 023012

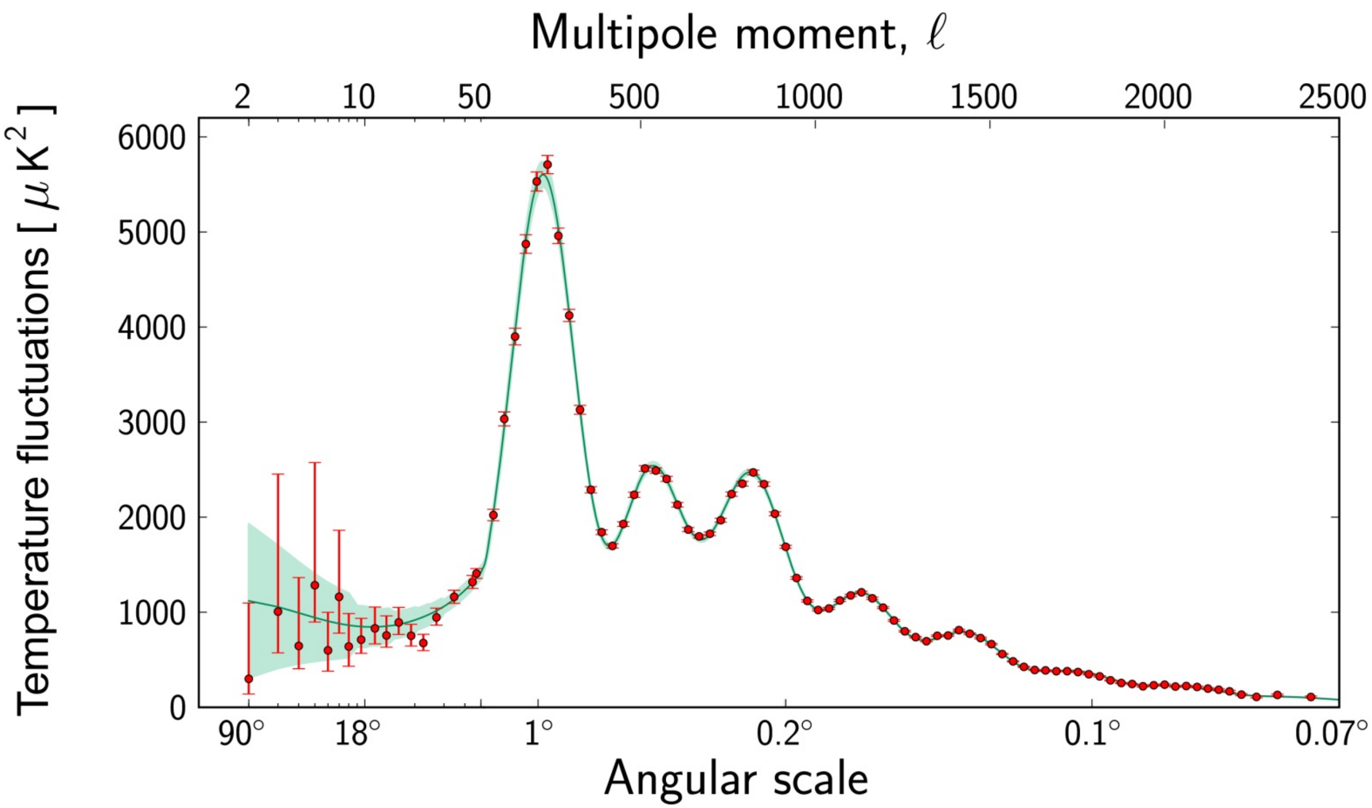
Max Planck Institute
for Astrophysics

# A glimpse of the early Universe



Planck Collaboration

# Initial fluctuations – Gaussian statistics

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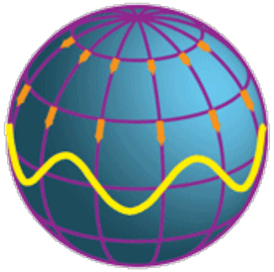
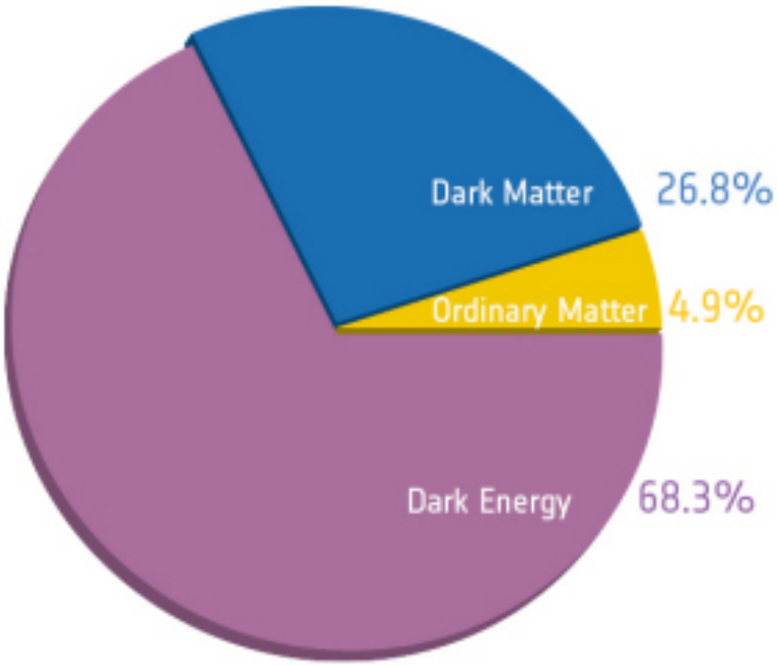
# Late-time cosmic acceleration

* Our Universe is expanding – with increasing speed
* Supernova 1a
* Baryon Acoustic Oscillation



# LCDM: Lambda and CDM

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Standard Concordance Cosmology:

5% ordinary matter

27% cold dark matter

68% dark energy

Late-time cosmic acceleration

# Everything seems fine

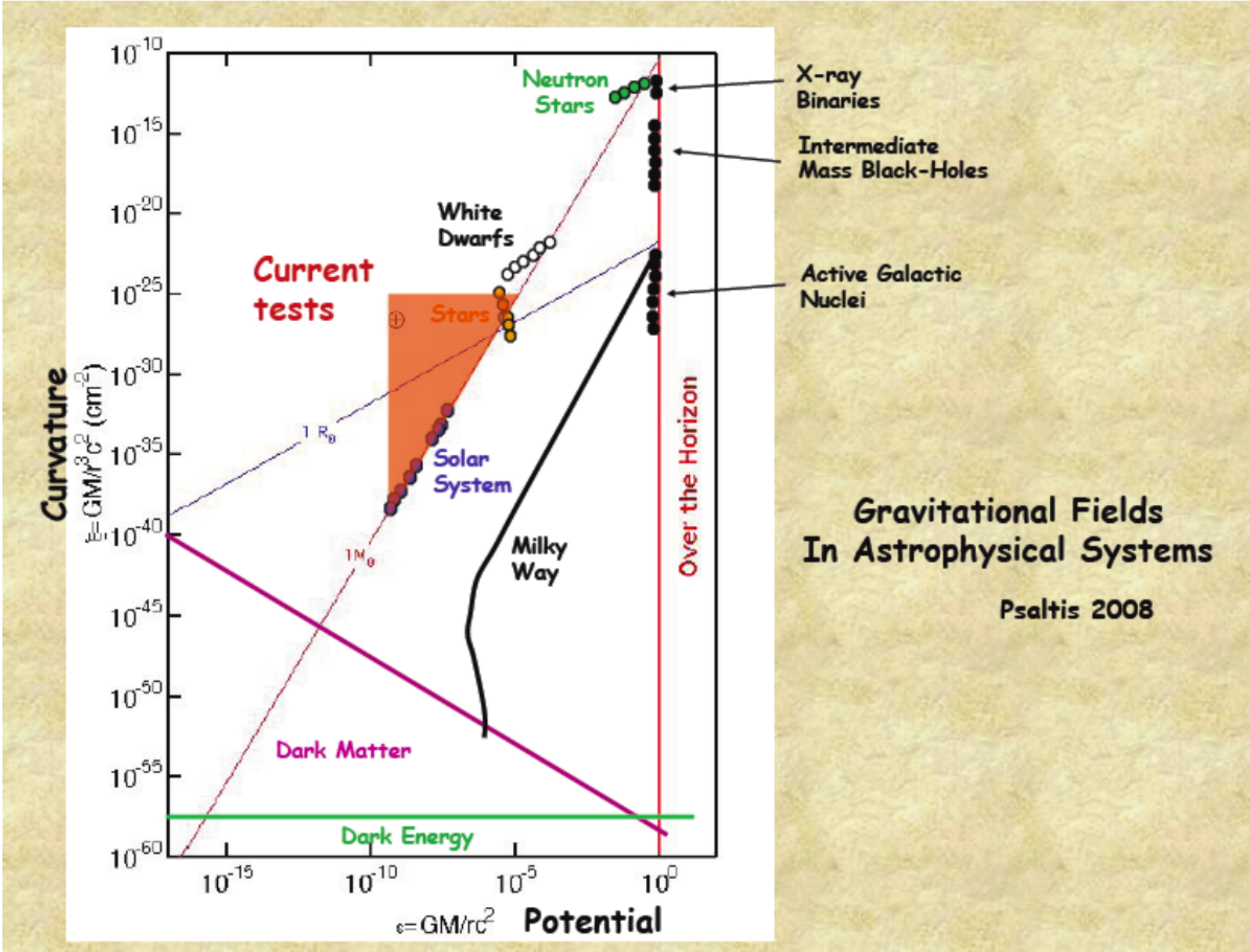
BUT

- What are the dark components?
- Theoretical prediction of vacuum energy $10^{120}$ larger than the observed value

# How about modifying the gravity model to something other than GR?

GR is very well-tested

- Solar system test (precession of perihelion of Mercury)
- Gravitational lensing by the Sun
- Binary pulsars
- Lunar ranging experiment
- Eötvös experiment




Slide taken (stolen) from Ferreira’s talk

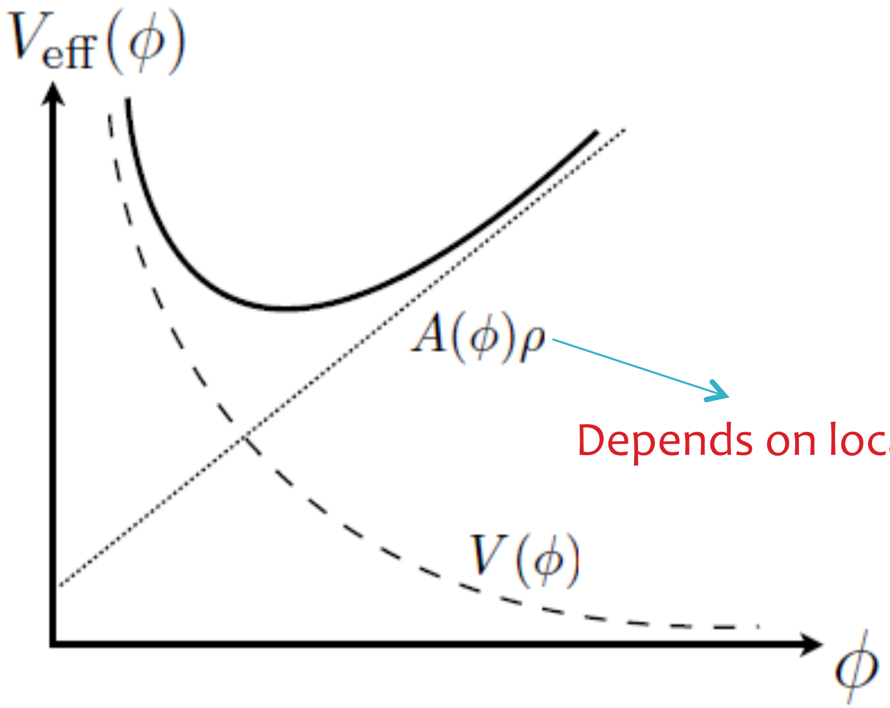
Modifying gravity on cosmological scales, but keep everything GR otherwise

1. Mimic the cosmic expansion history WITHOUT $\Lambda$
2. Restore to GR in high density regimes

# Coupling scalar field with chameleon mechanism

- Additional scalar field $\Phi$ that couples with matter content
- Scalar field having a potential $V(\Phi)$
- Effective potential for the scalar field depends on environment

# Chameleon mechanism




Depends on local density

Jain & Khoury (2010)

# f(R) Models

Modify the Einstein Hilbert Action by adding a f(R) piece – R is the Ricci scalar – it is a subclass of the chameleon model.

One popular choice of the f(R) form is Hu & Sawicki (2007)

$$f(R) = -2\Lambda \frac{R}{R+\mu^2} \approx -2\Lambda - f_{R0}\frac{R_0^2}{R} \quad \text{for } R \gg \mu^2$$

$$f_{R0} = -2\Lambda \mu^2 / R_0^2$$

Current constraint (Lombriser et al. 2011): $|f_{R0}| \leq 2\times 10^{-4}$

# Model Specification

$$\mathcal{L}=1/2\ [\mathcal{R}/8\pi G-\nabla^{a}\nabla_{a}\phi]+V(\phi)-A(\phi)\mathcal{L}_{DM}+\mathcal{L}_{s}$$

$$A(\phi)=\exp(\gamma\sqrt{8\pi G}\,\phi)$$

$$V(\phi)=\Lambda/[1-\exp(-\sqrt{8\pi G}\,\phi)]^{\alpha}$$

This model is equivalent to popular f(R) model, in which the Einstein-Hilbert action contains an additional f(R) piece to the original R.

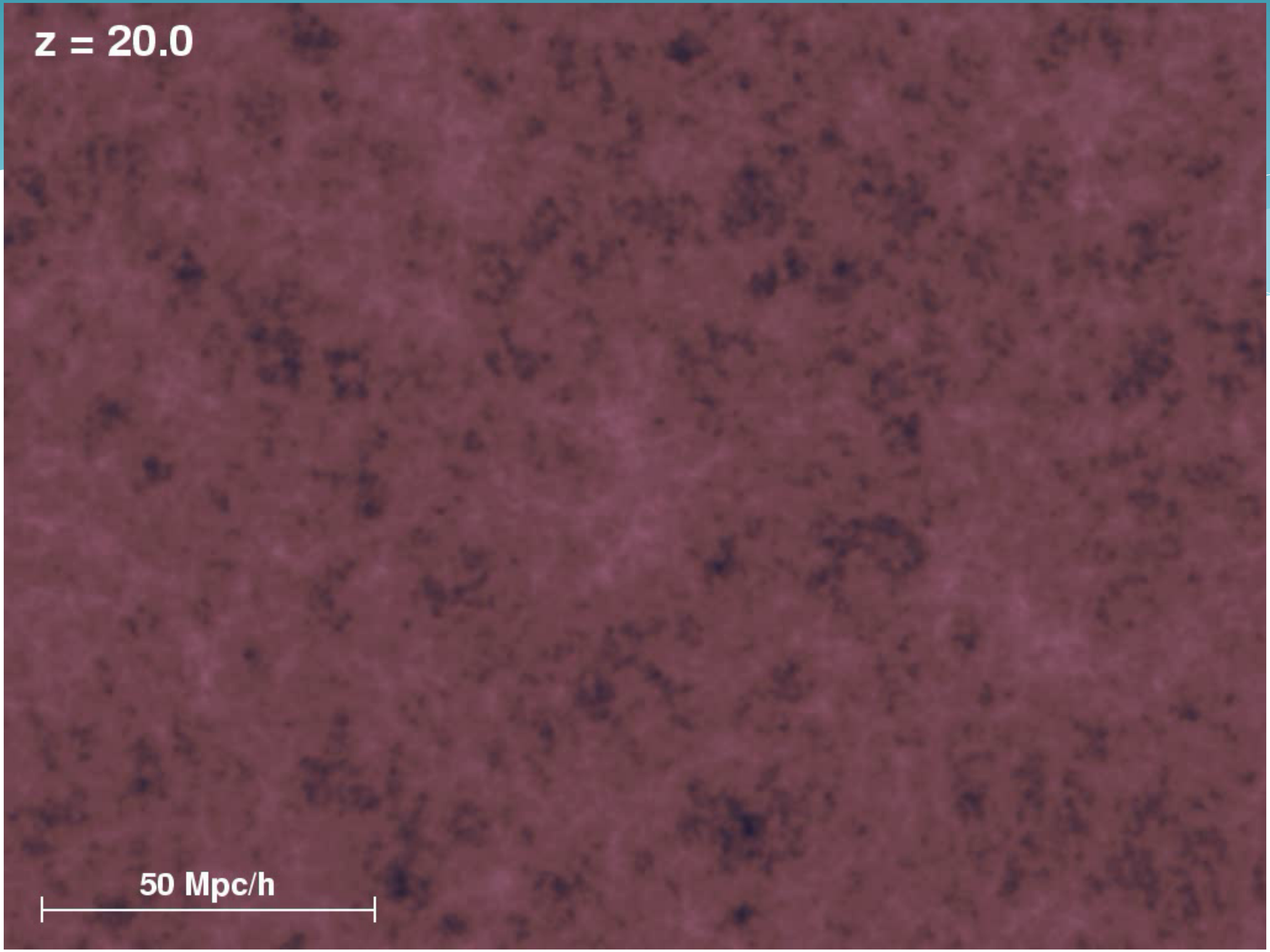
# MG signatures in LSS

* Abundance/Clustering of rare objects (halos/voids)

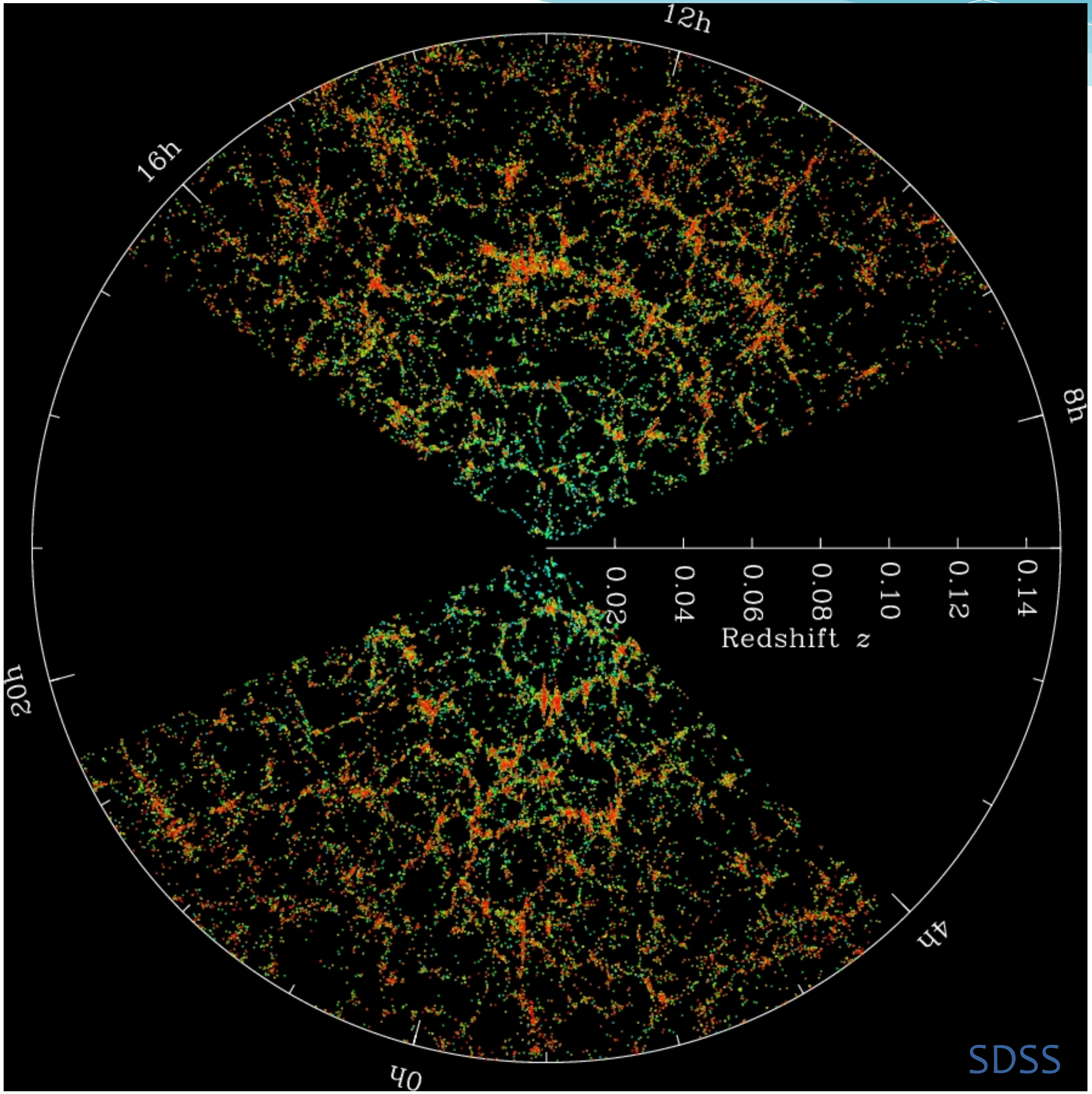
  see Li & TYL (2012) and TYL & Li (2012) for halos
  Clampitt, Cai & Li (2013) and TYL et al. (in prep) for voids

* Gravitational lensing mass vs dynamical mass

# Formation of Structure in 30s

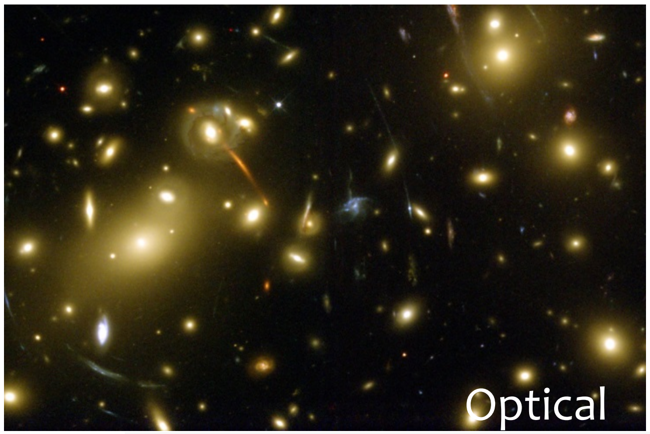


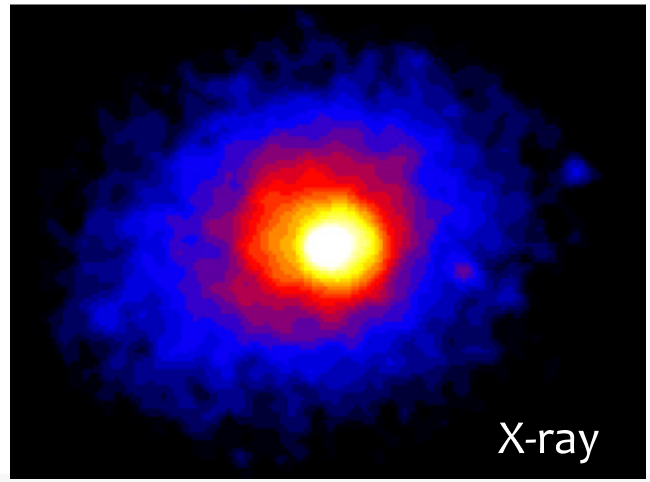
# Late-time Universe

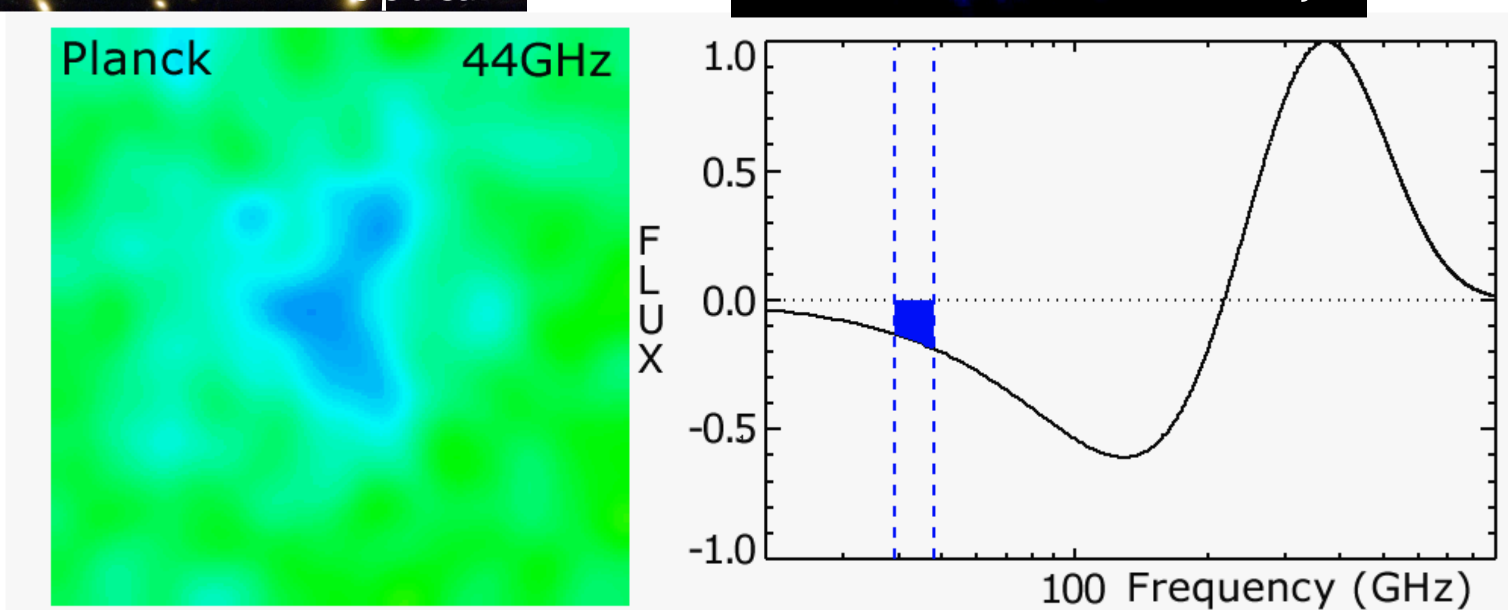


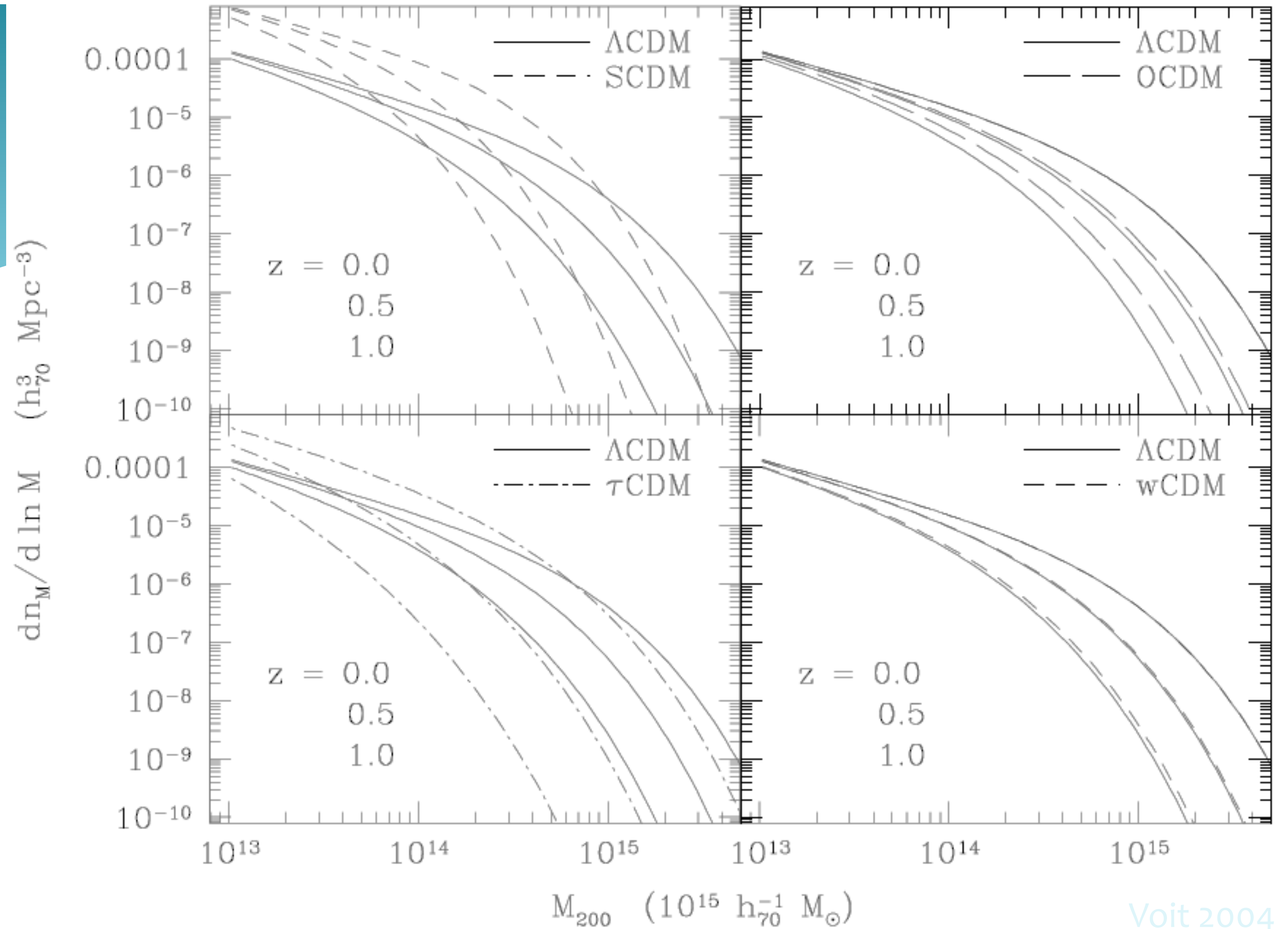
# Part 1: Abundance of Rare Objects

- Abundance & clustering of massive clusters are sensitive probes for cosmology
- Detections: optical; x-ray; Sunyaev-Zeldovich; gravitational lensing



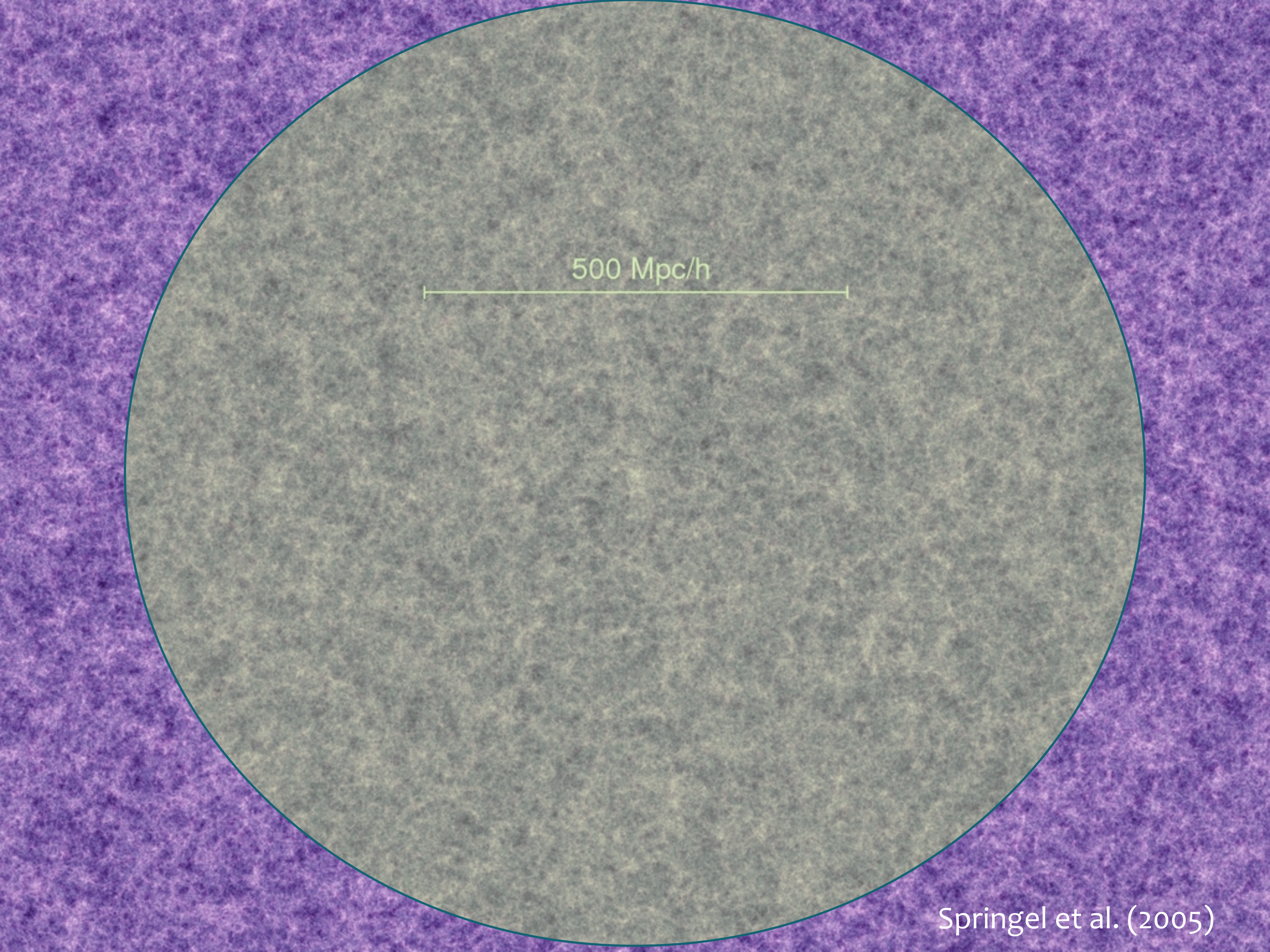



Halo Mass Function: Number density of halos in various mass bins

# Excursion Set Approach

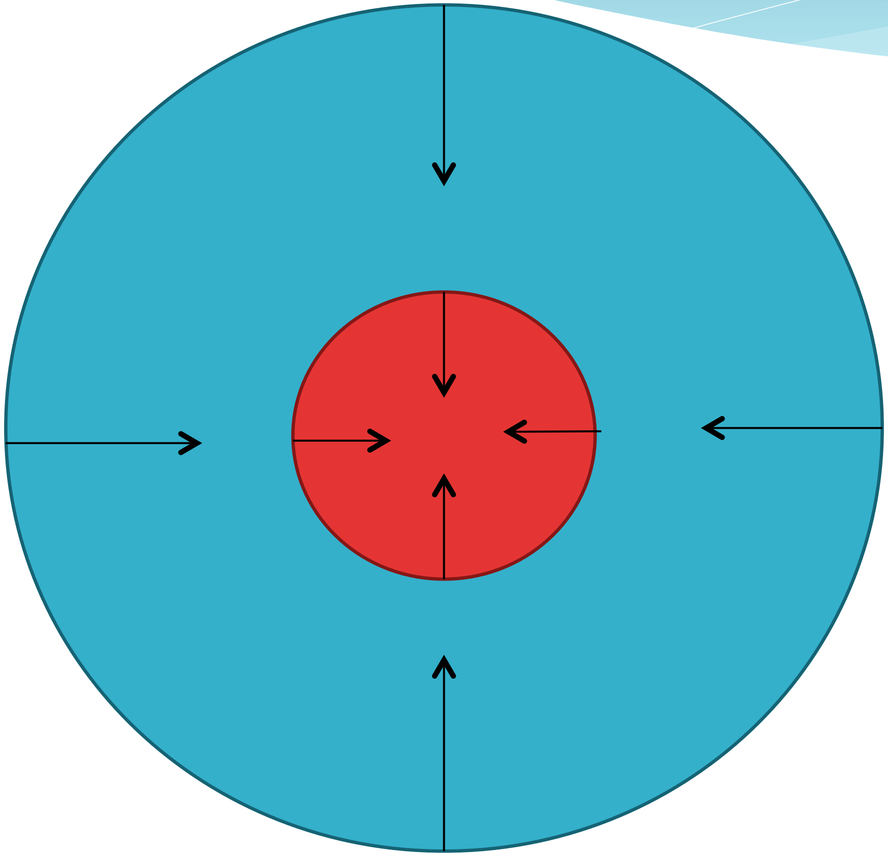
* Halos form at regions where the initial density contrast is sufficiently high.
* Count regions where the density contrast exceeds the critical value in the initial condition.
* Start from large scale, gradually decrease the smoothing scale until the density contrast exceeds the critical value.

Definition: $M/\rho V = \Delta = 1 + \delta$

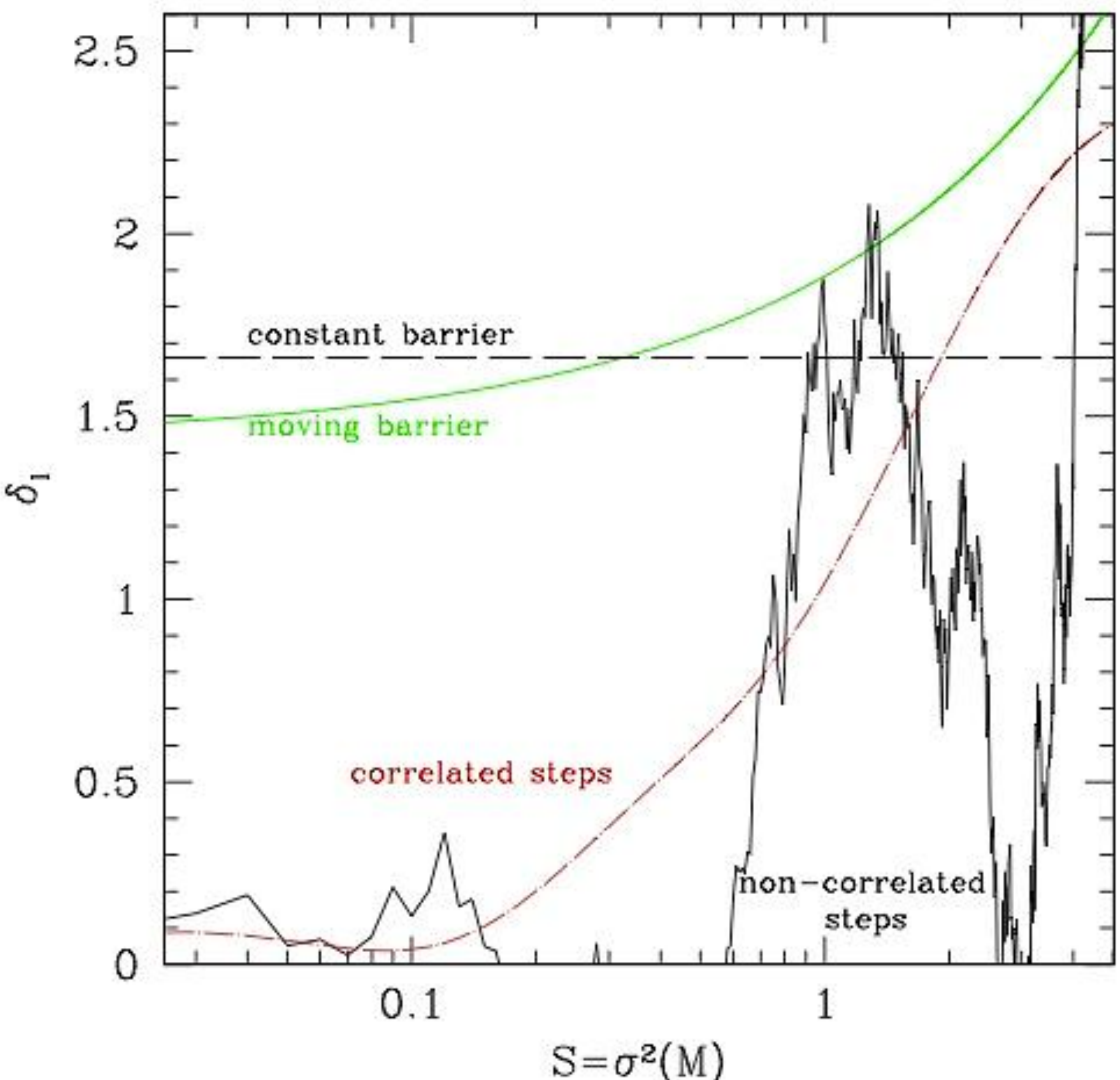



Springel et al. (2005)

# Both smoothing scales exceed $\delta_c$



Only count the biggest scale to avoid double-counting




Increasing mass

Only *FIRST* crossing counts!

# Excursion Set Approach

* Essential Ingredients:
  1. Barriers (Structure formation threshold in linear density contrast)
  2. First crossing probability across barriers
* Halos; Mass in Eulerian volume; Voids

$$f(S)\,dS = M/\bar{\rho}\; n(M)\,dM$$

← Total mass conservation

$n(M)$ = number density of halos with mass ($M+dM$)

$f(S)$ = first crossing probability of the critical barrier at $S$

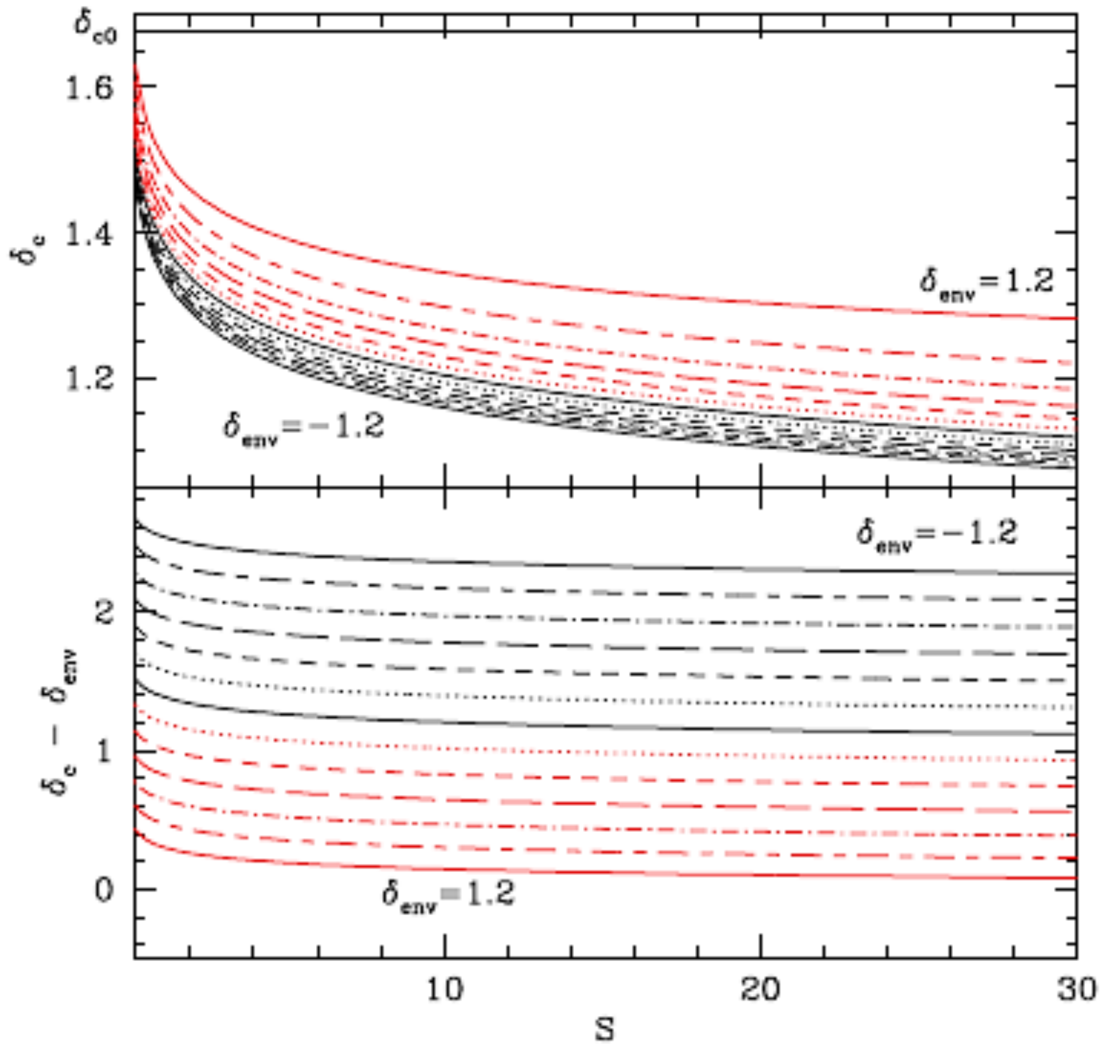
# Recent Developments

- Analytical solution is known for Markovian (uncorrelated) random walk (Chandrasekhar 1943; Zhang & Hui 2006; TYL & Sheth 2009)
- For non-Markovian walk approximations are available (Peacock & Heavens 1990; Maggiore & Riotto 2009a; Paranjape, TYL & Sheth 2011; Musso & Sheth 2013a,b)
- Stochastic barriers (Maggiore & Riotto 2009b)

# Extension to MG model

* The presence of the fifth force modifies structure formation.
* Chameleon mechanism screens the fifth force in high density environment.
* The formation of structures differ depending on the environment density.

# Collapse Threshold in MG model



# Methodology

- For a given $\delta_{env}$, we have a new barrier $\delta_c(\delta_{env})$
- Get the first crossing probability for this $\delta_c(\delta_{env})$: $f(s|\delta_c(\delta_{env}))$
- Marginalize over $\delta_{env}$

Question: What is the probability of having $\delta_{env}$?

# Spherical Collapse Approximation

Relate the initial density contrast to the evolved density

Initial density contrast

$$M/\rho V = 1 + \delta_{NL} = (1 - \delta_l/\delta_c)^{-\delta_c}$$

Total mass within a volume V

Density contrast (late-time)

Spherical collapse parameter (cosmology dependent, ≈1.676)

(Bernadeau 1994; Sheth 1998)

# Eulerian Barrier

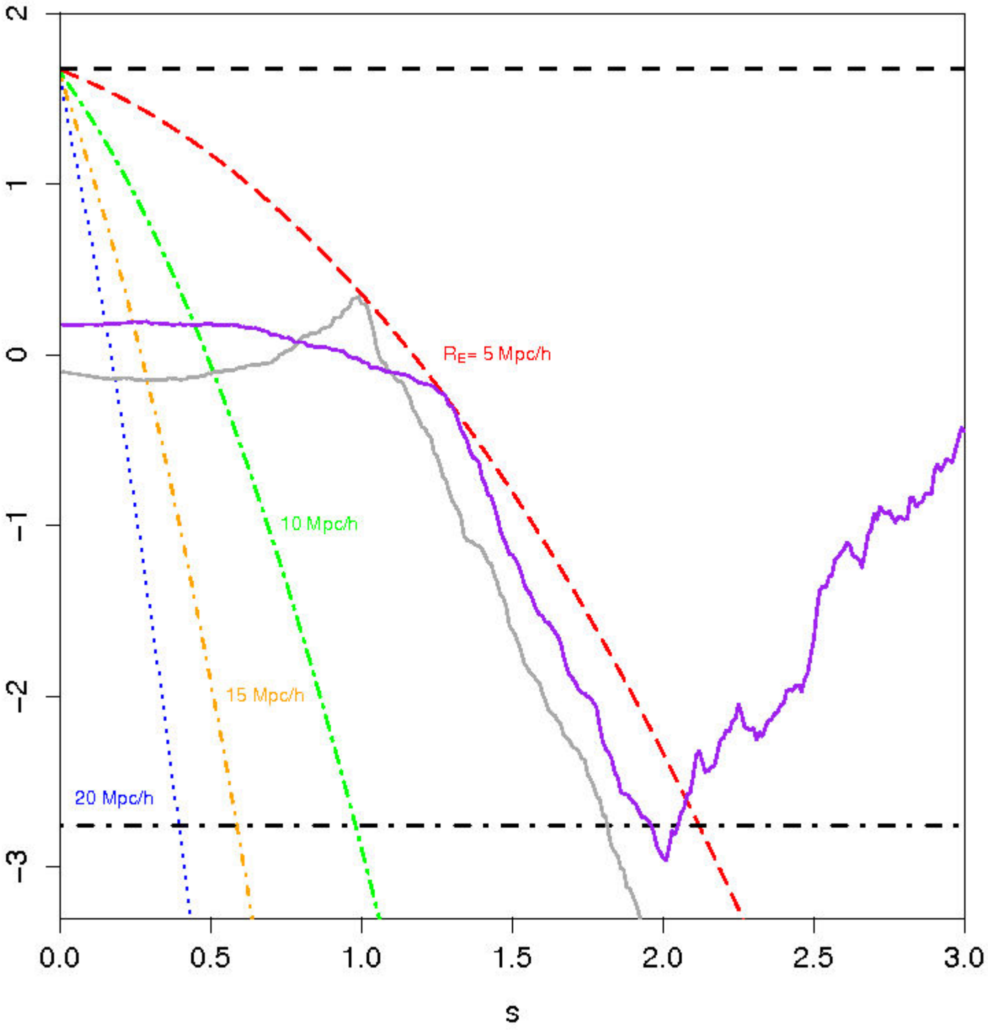
The above approximation can be used to obtain a relation between M and $\delta_l$

$$\delta_l/\delta_c = 1-(M/\rho V)^{-1/\delta_c}$$

- For very large M (or very small V), $\delta_l \rightarrow \delta_c$
- No lower bound on $\delta_l$
- Upper bound of $\delta_l$ is $\delta_c$

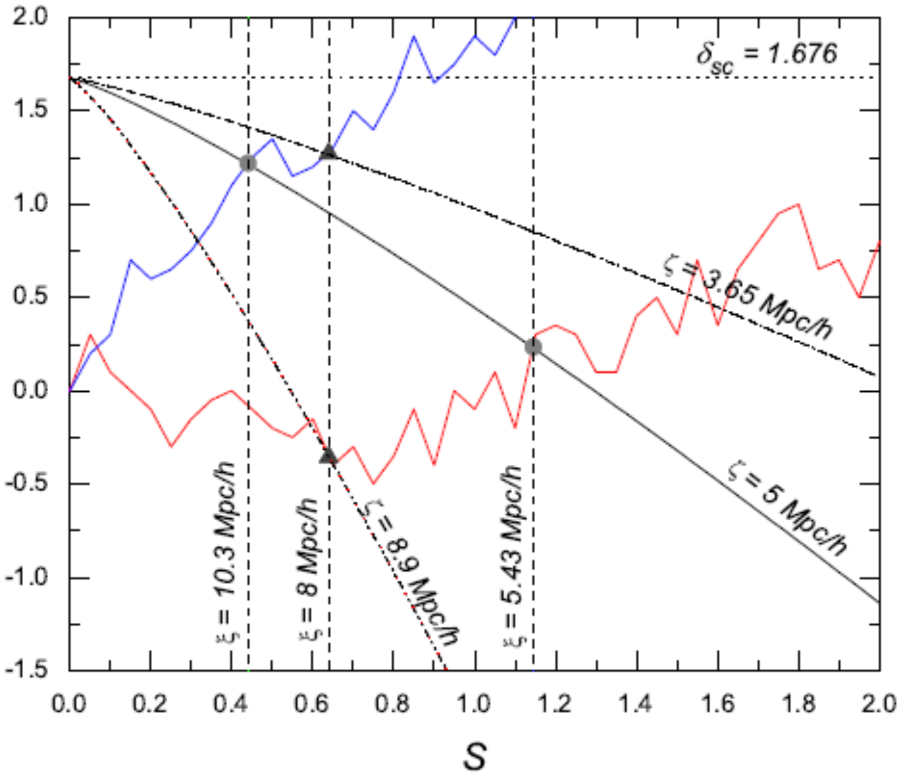
# Eulerian barriers and excursion set

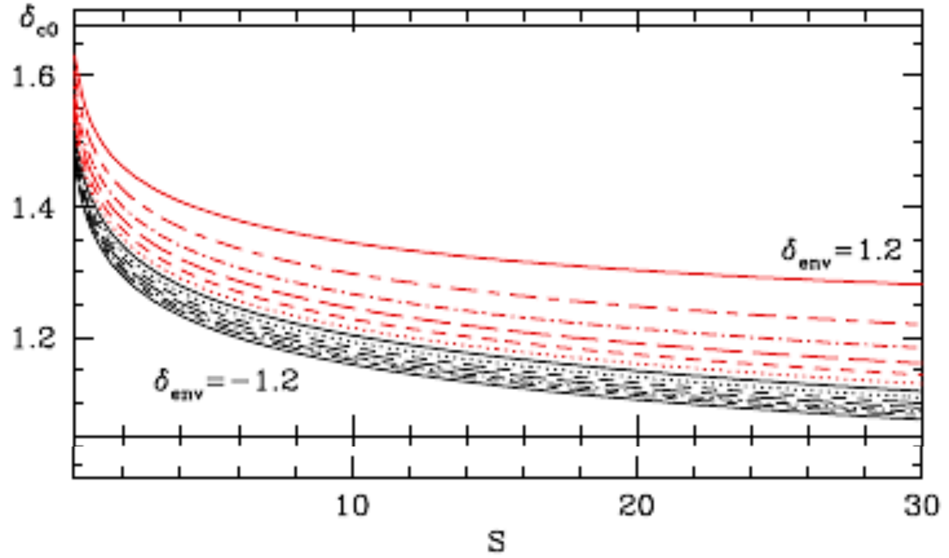
(Sheth 1998; TYL & Sheth 2008a,b)



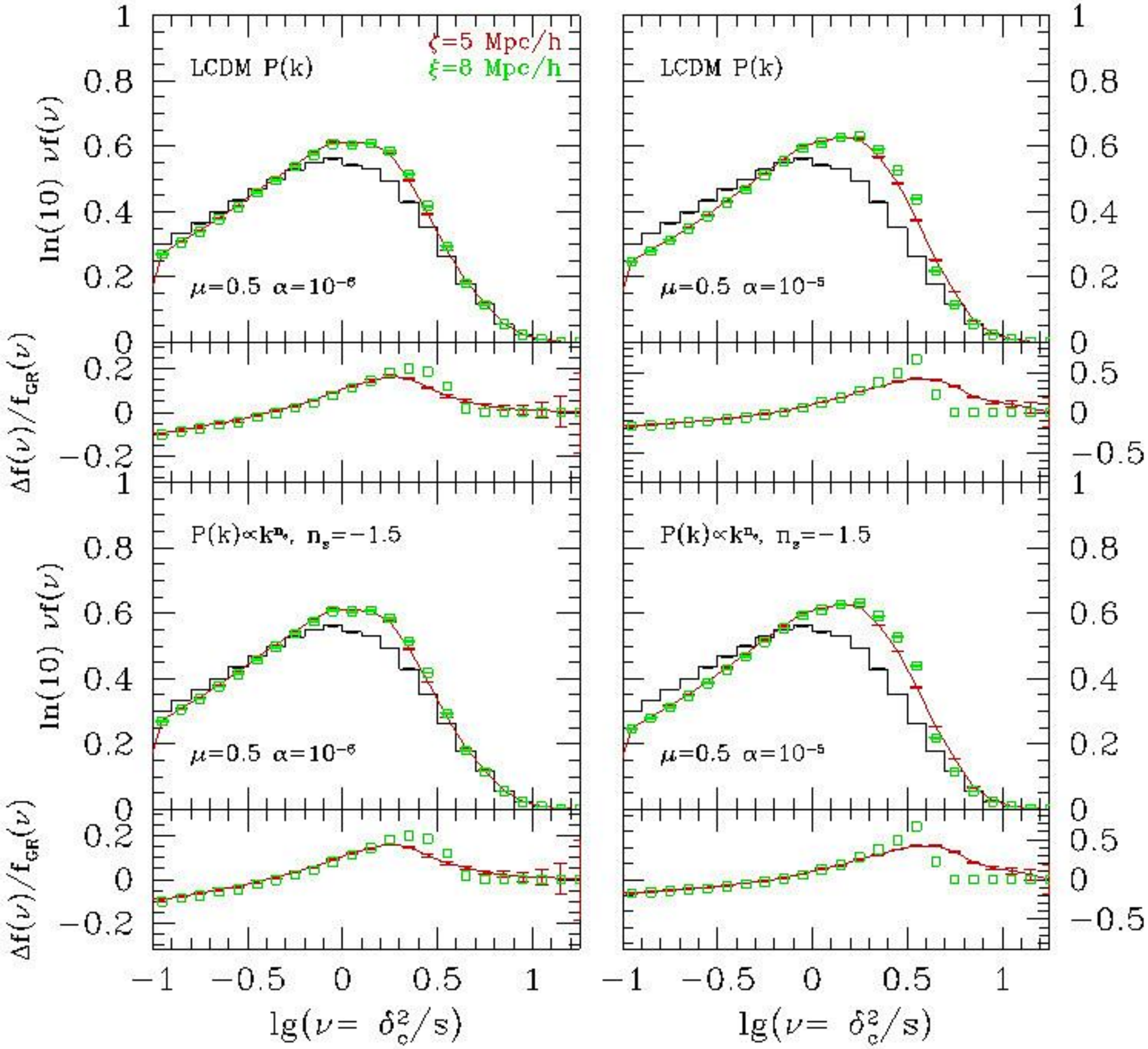

- Nested barriers: small volume at top
- Start at $\delta_c$ when s = 0
- Again the first crossing counts!

# First Crossing Probability



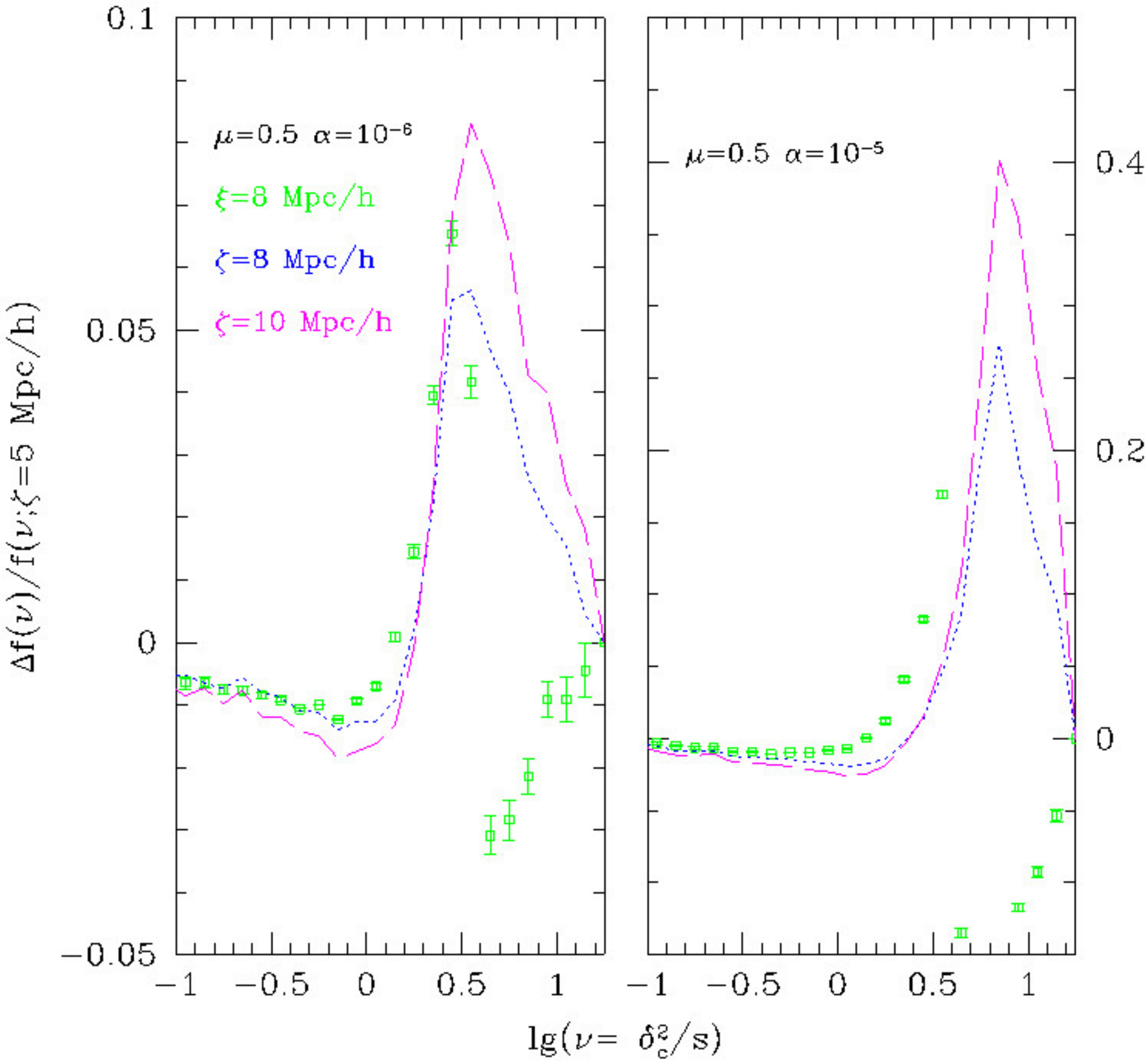



# Results



ζ=5 Mpc/h
ξ=8 Mpc/h
LCDM P(k)
μ=0.5 α=10⁻⁶
μ=0.5 α=10⁻⁵
P(k)∝k^{n_s}, n_s=−1.5
ln(10) νf(ν)
Δf(ν)/f_GR(ν)
lg(ν= δ_c²/s)

# Dependence on environments

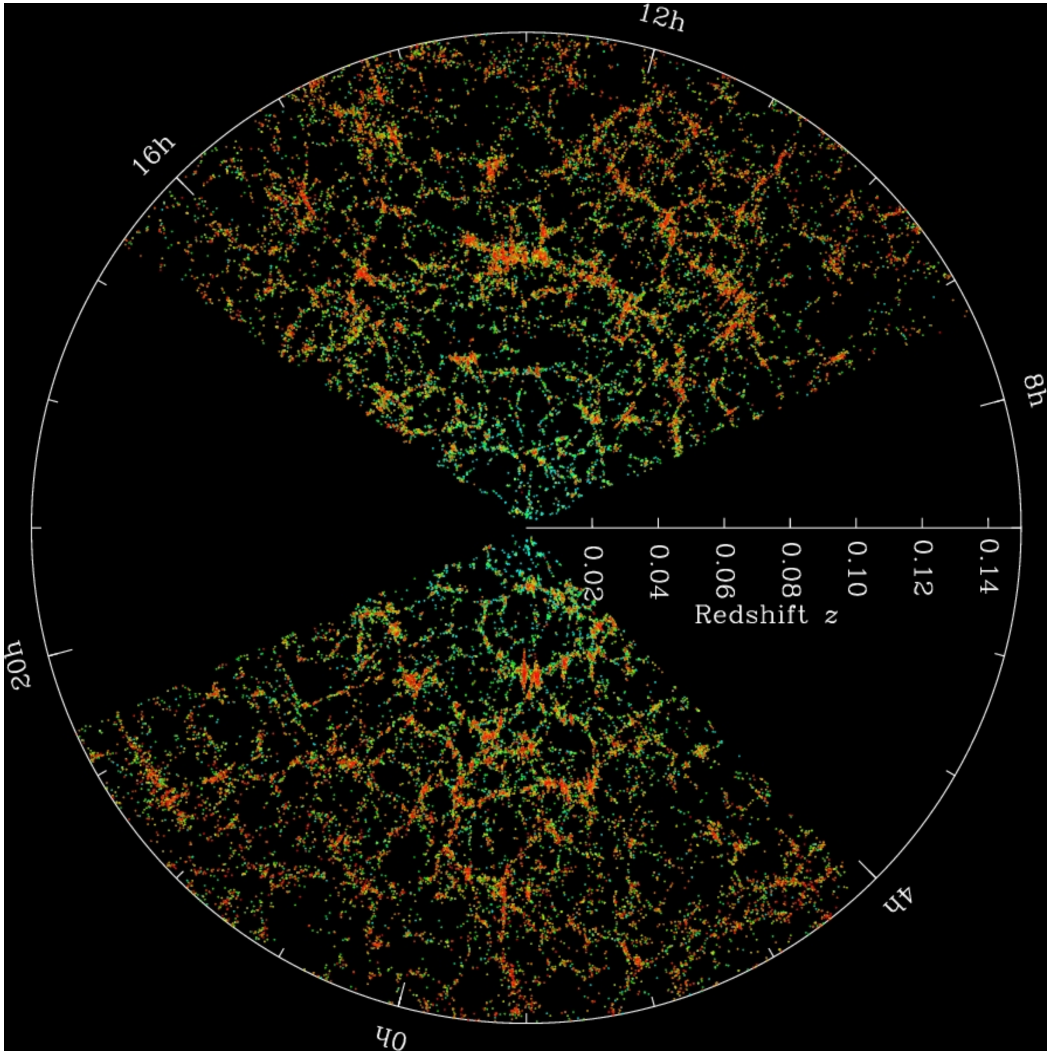


# Short Summary

- Abundance of massive clusters shows signature of MG
- Enhancement in intermediate mass clusters (fifth force enhances growth of structure)
- Detriment in low mass end (mass are distributed to intermediate mass)
- No change in high mass end (effective screening mechanism)
- Choice of environment (secondary compared to the MG effect) – using correlated random walks relieve this dependence (see Lam & Li 2012 for details).

Chameleon effect is screening the fifth force in high density region…

How about looking at underdense regions?

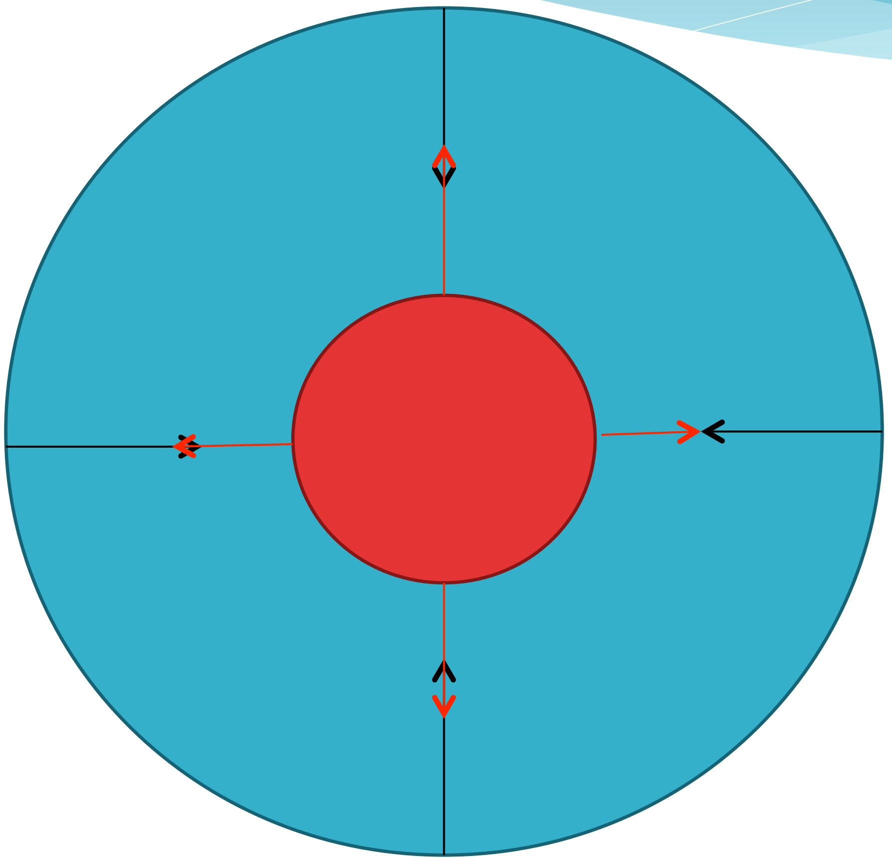



SDSS

# Definition of Voids

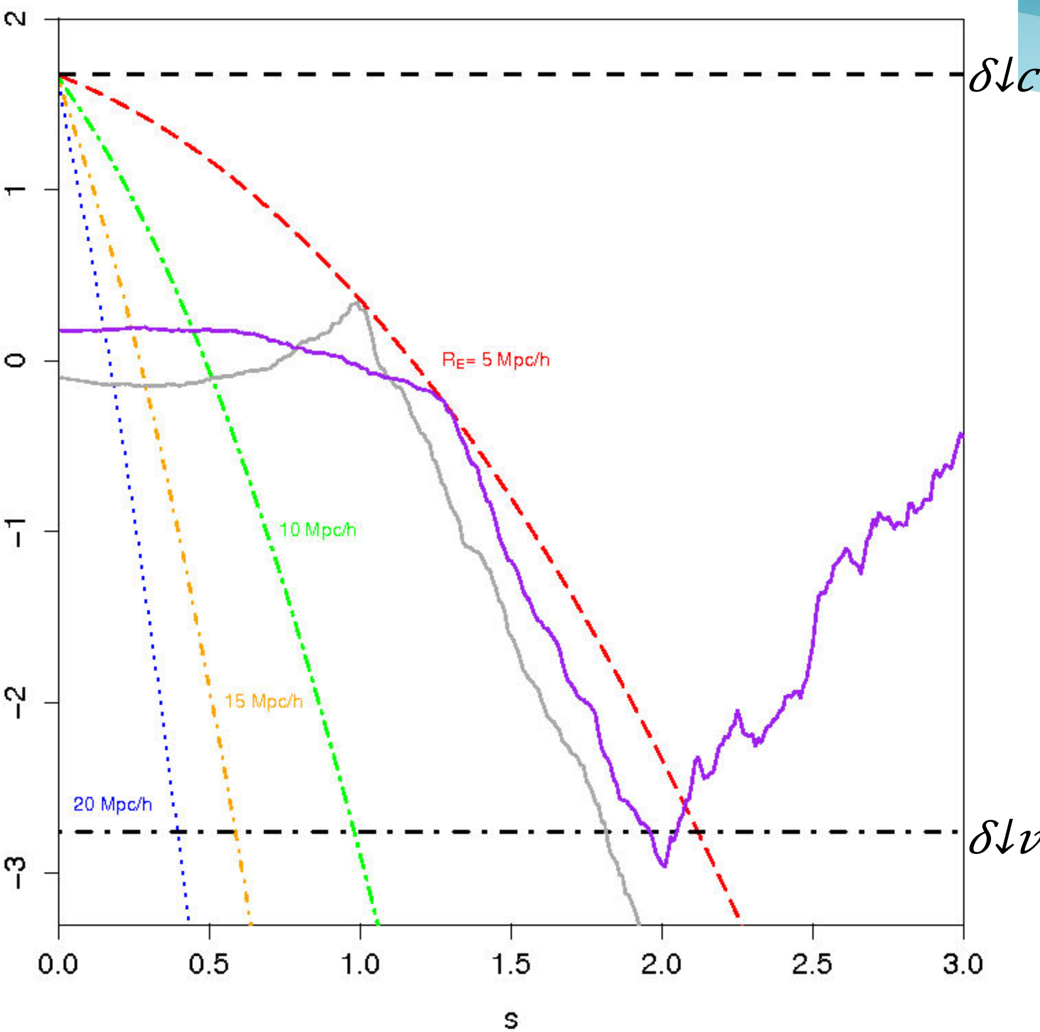
- Voids – underdense regions, occupying most volumes of the universe
- Density ~ 20% of the background density
- $\delta_l/\delta_c = 1-(M/\rho V)^{-1/\delta_c}$ tells us $\delta_l \approx -2.76$
- Reminder: $\delta_l$ is the linearly extrapolated density contrast, not the physical one!

# Void-in-cloud



Only count walks that NEVER crossed $\delta_c$ at bigger smoothing scales

# Void Assignment -- Lagrangian



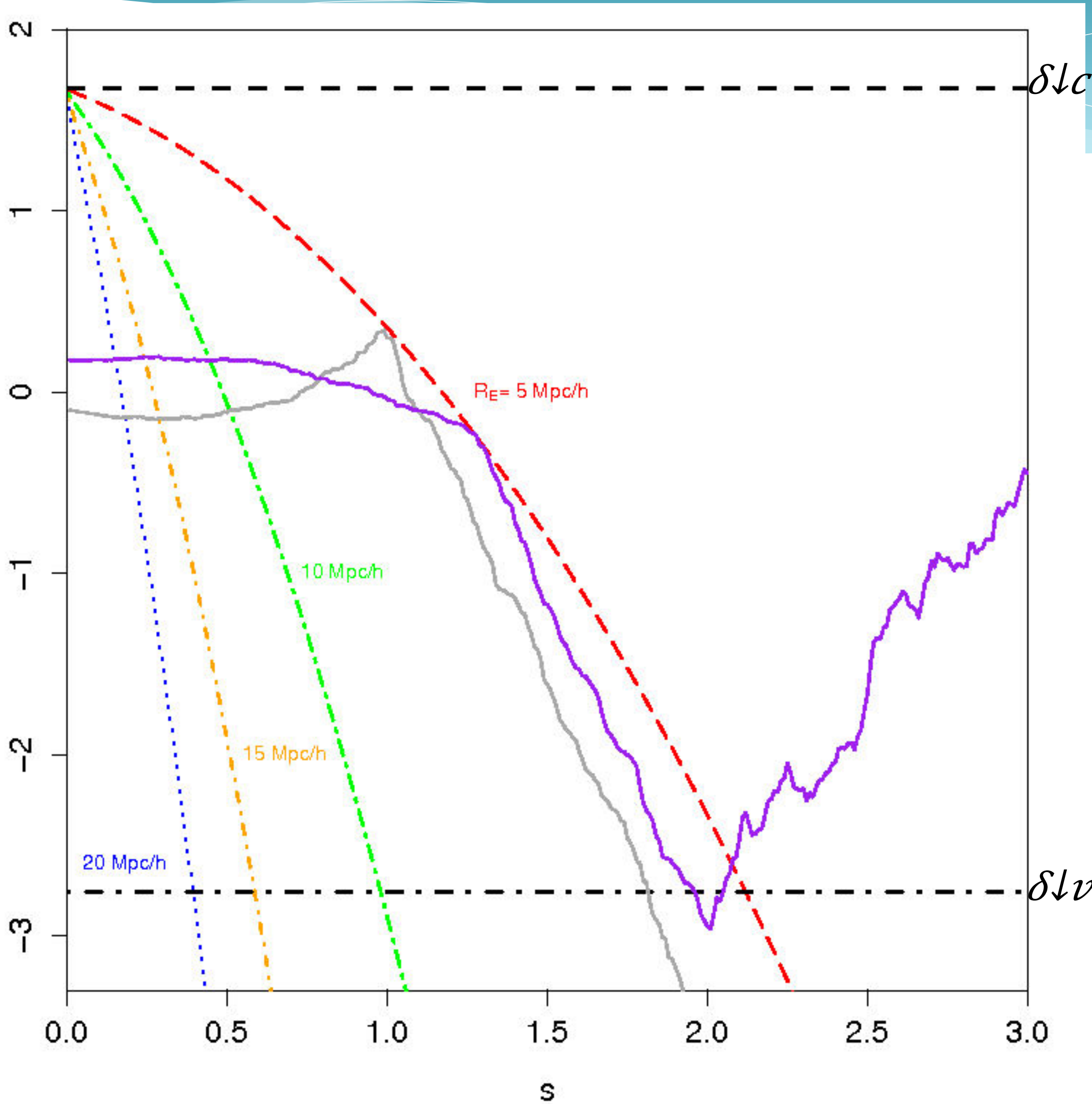

1. Just the first crossing of the $\delta_v$ barrier?
2. How about random walks that has up-crossed $\delta_c$ at $s_1$, then down-crossed $\delta_v$ at $s_2$ $(>s_1)$?
3. An overdense regions (for $s_1$) enclosing an underdense regions (for $s_2$).
4. Comoving size corresponding to $s_1$ is shrinking, crush the 'expanding' regions for $s_2$.
5. It is called Void-in-Cloud.

Lagrangian assignment: First crossing across $\delta_v$, but only those never crossed $\delta_c$. (Sheth & van de Weygart 2004)

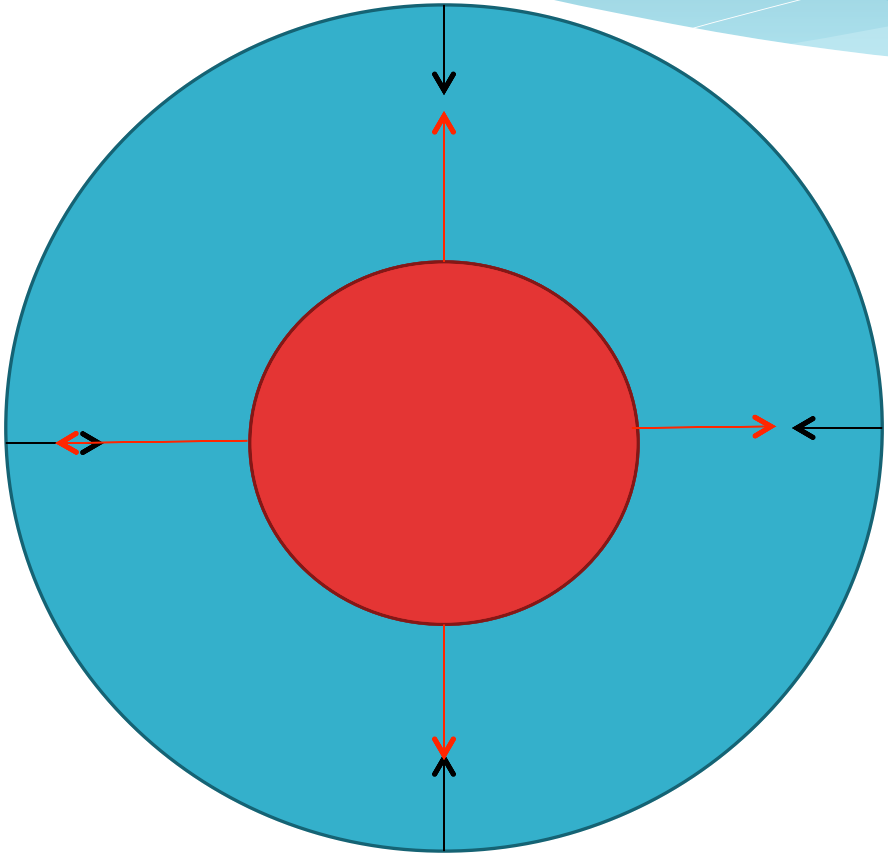
# But…

Can an underdense region really expand its comoving volume 5 times?

# How about those Eulerian barriers?



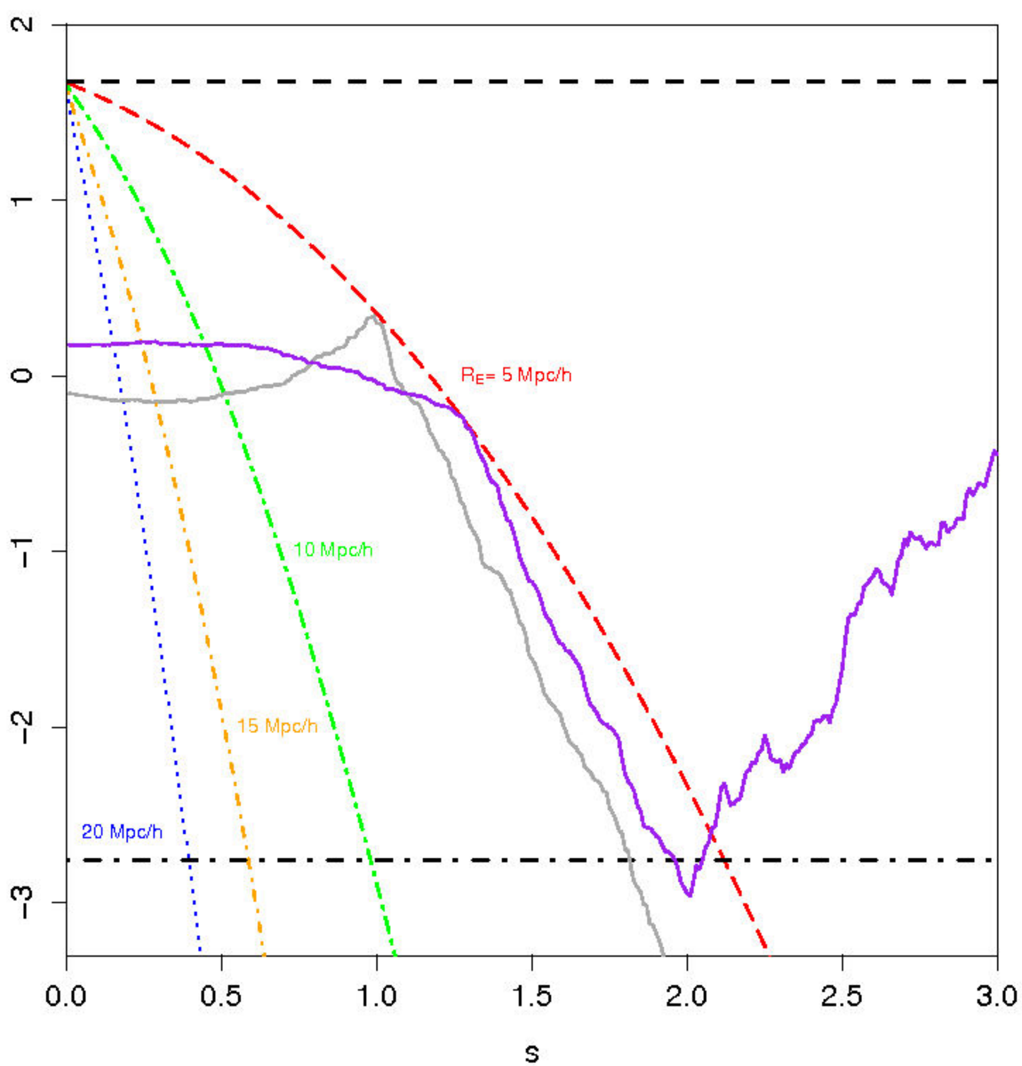
# Eulerian Environment



Surrounding environment may restrict the growth (expansion) of the underdense region: eulerian void assignment!

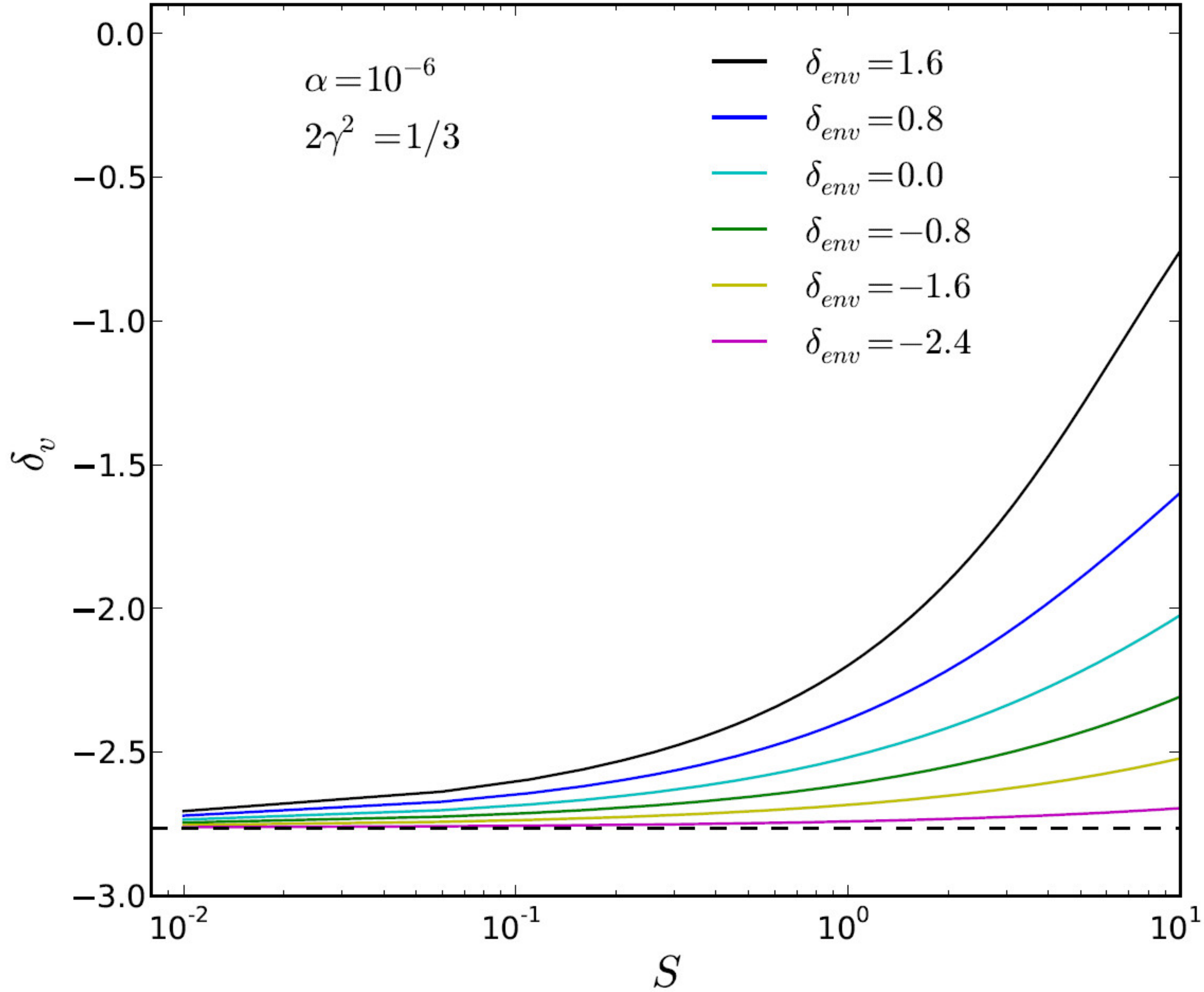
# Eulerian Void Assignment (Paranjape, TYL & Sheth 2012)

Look for the biggest *Eulerian volume* that has a density 20% of the background

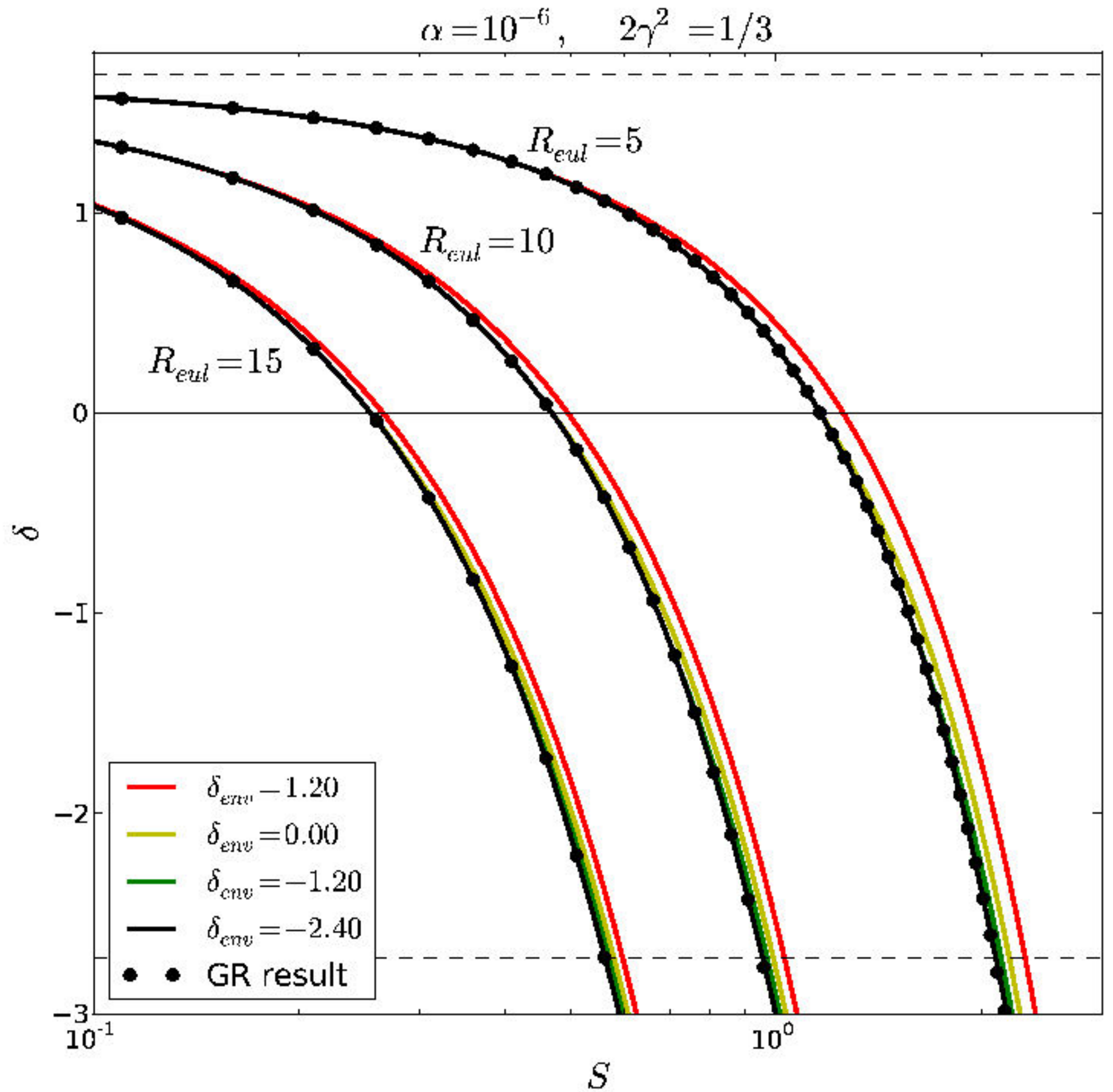



- NOT all Lagrangian-assigned voids are Eulerian voids (not including voids of vanishing sizes)
- If they are, the corresponding Eulerian voids are always smaller.

# Back to MG… void formation threshold is modified



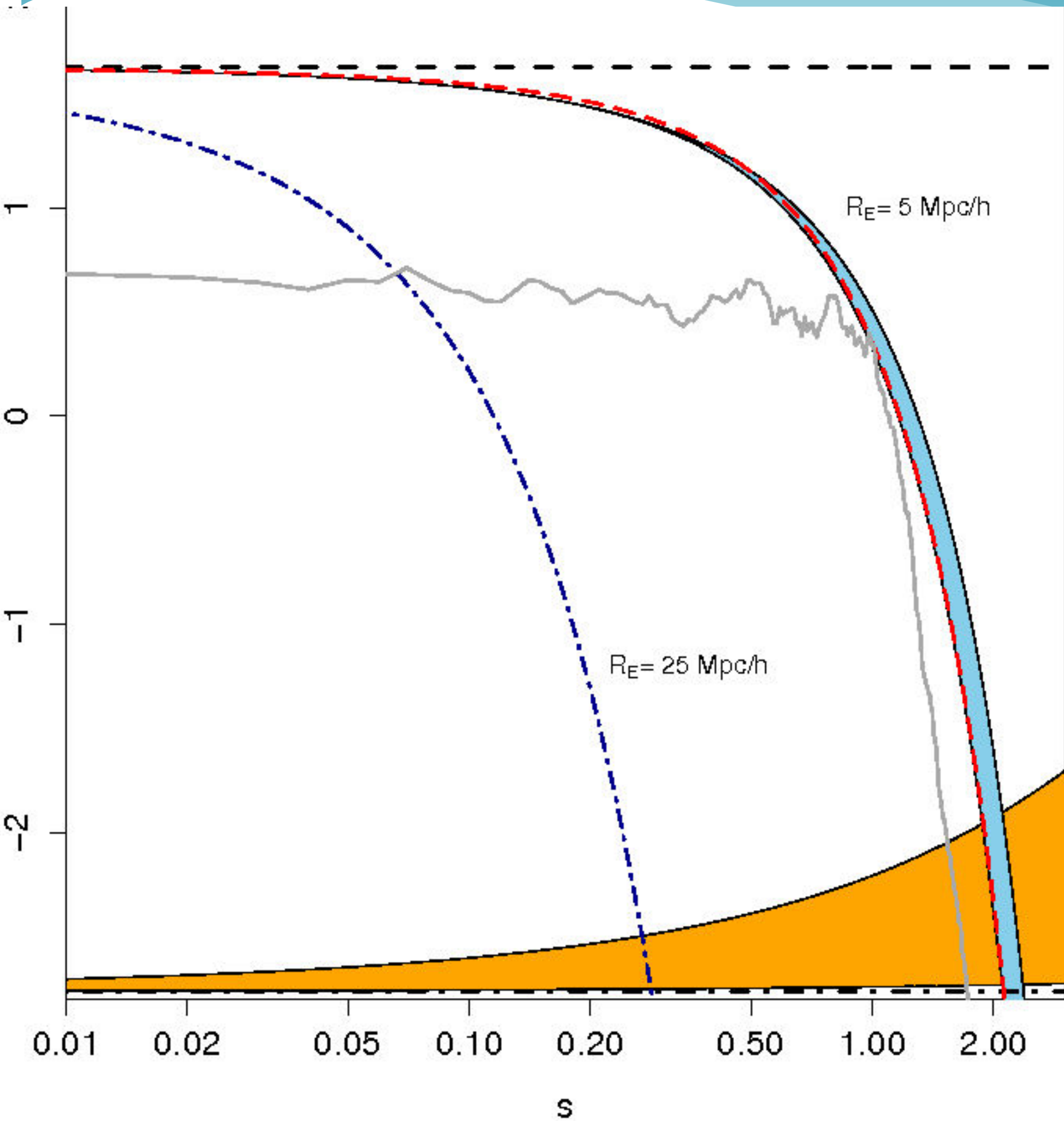
We also need to know how the Eulerian barriers are modified in MG models



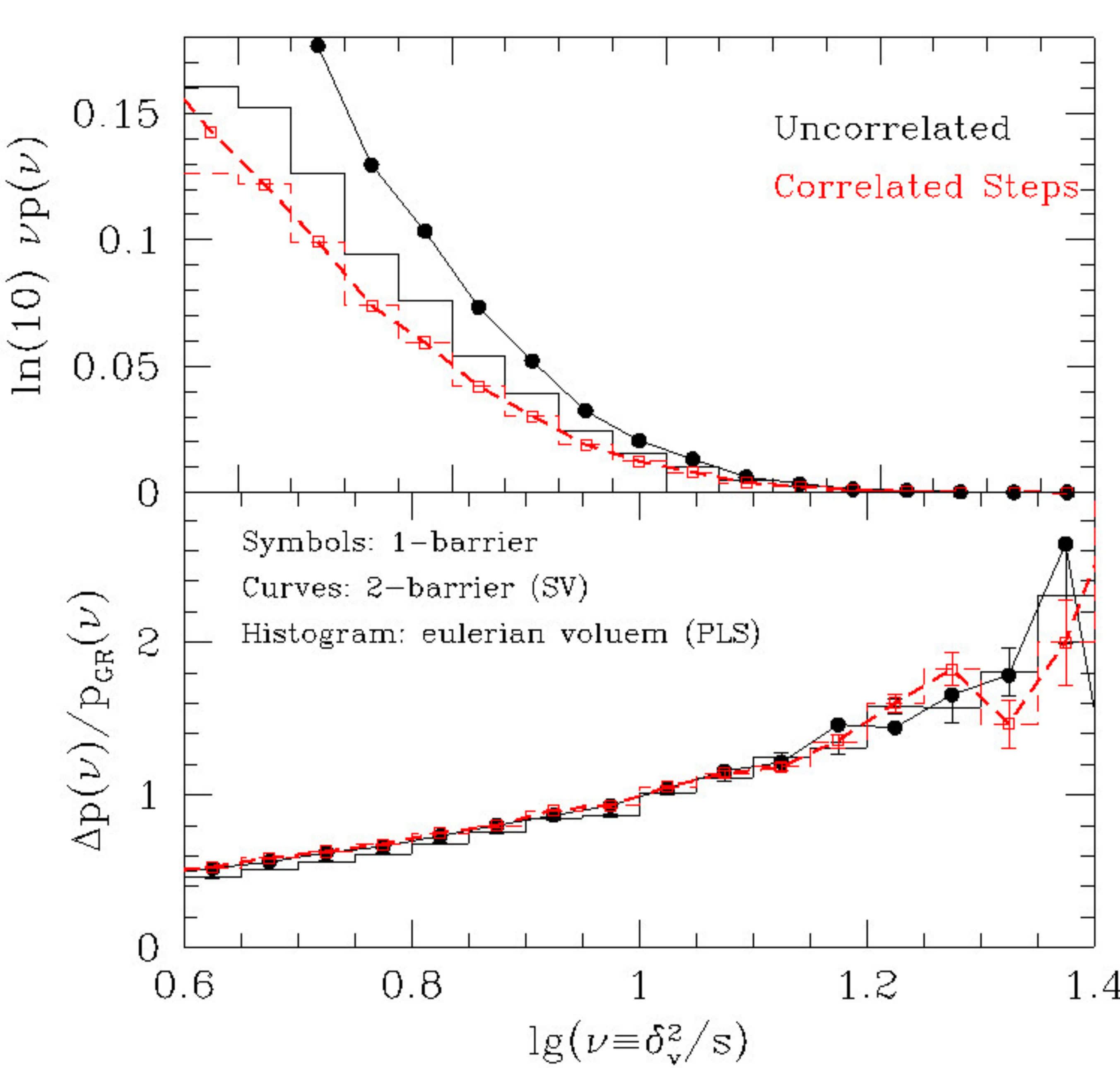
Multiple scales involved:

- Various eulerian scales where the density condition is checked
- Their associated environments (5 times the eulerian scales – see Clampitt, Cai & Li 2013)
- Environment for halo formation (Use 5 Mpc/h – same scale as in Lam & Li 2012)
- Recall that for barriers of all environments are GR

# Eulerian-Void Assignment in MG models




1. First draw the (GR) halo environment barrier;
2. Make sure random walk never cross the modified $\delta_c$ barrier;
3. For each step of the random walks $(s, \delta_l)$, make an initial guess of the Eulerian size $R_E$;
4. From this initial guess, $R_{env} = 5R_E$;
5. Draw GR barrier for $R_{env}$;
6. First crossing of $R_{env}$ gives $\delta_{env}$;
7. Consistence check for $(s, \delta_l | \delta_{env})$;
8. Back to step 4 until converges.



Uncorrelated
Correlated Steps
Symbols: 1-barrier
Curves: 2-barrier (SV)
Histogram: eulerian voluem (PLS)
$\ln(10)\ \nu p(\nu)$
$\Delta p(\nu)/p_{GR}(\nu)$
$\lg(\nu \equiv \delta_v^2/s)$
0.15
0.1
0.05
0
2
1
0
0.6
0.8
1
1.2
1.4

# Short Summary 2

- Void abundance  is also enhanced in MG models
- No chameleon effect: the number for large voids keeping increasing
- Note: MG is NOT the only cosmological model that would enhance both the halo/void abundance
- Example: higher $\sigma_8$, primordial non-Gaussianity ($\tau_{nl}$ or $g_{nl}$)
- The signature of the screening mechanism (effective in high mass end but negligible in underdense regions) would single out MG models.

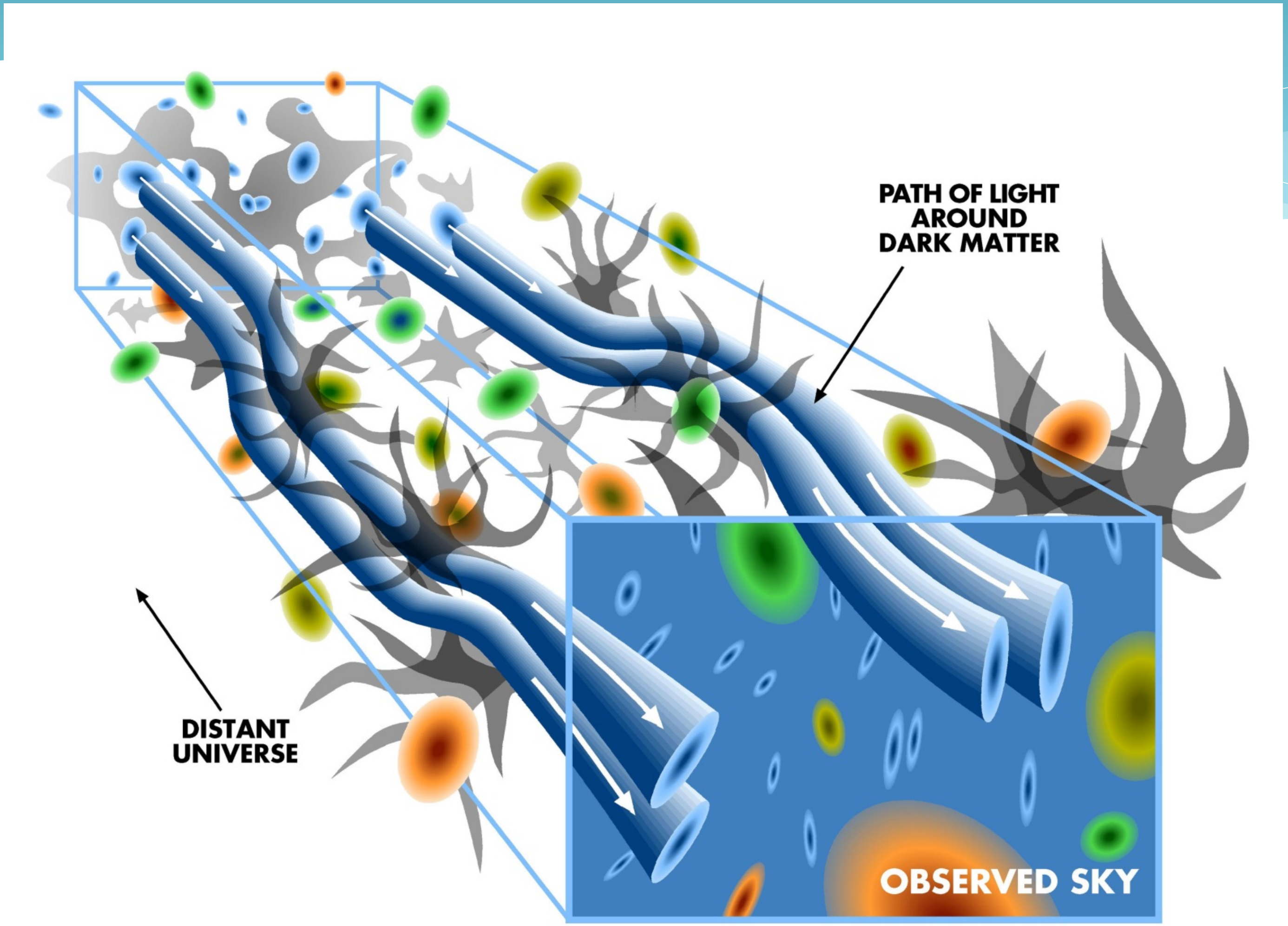
## Part 2: Gravitational lensing masses vs dynamical masses

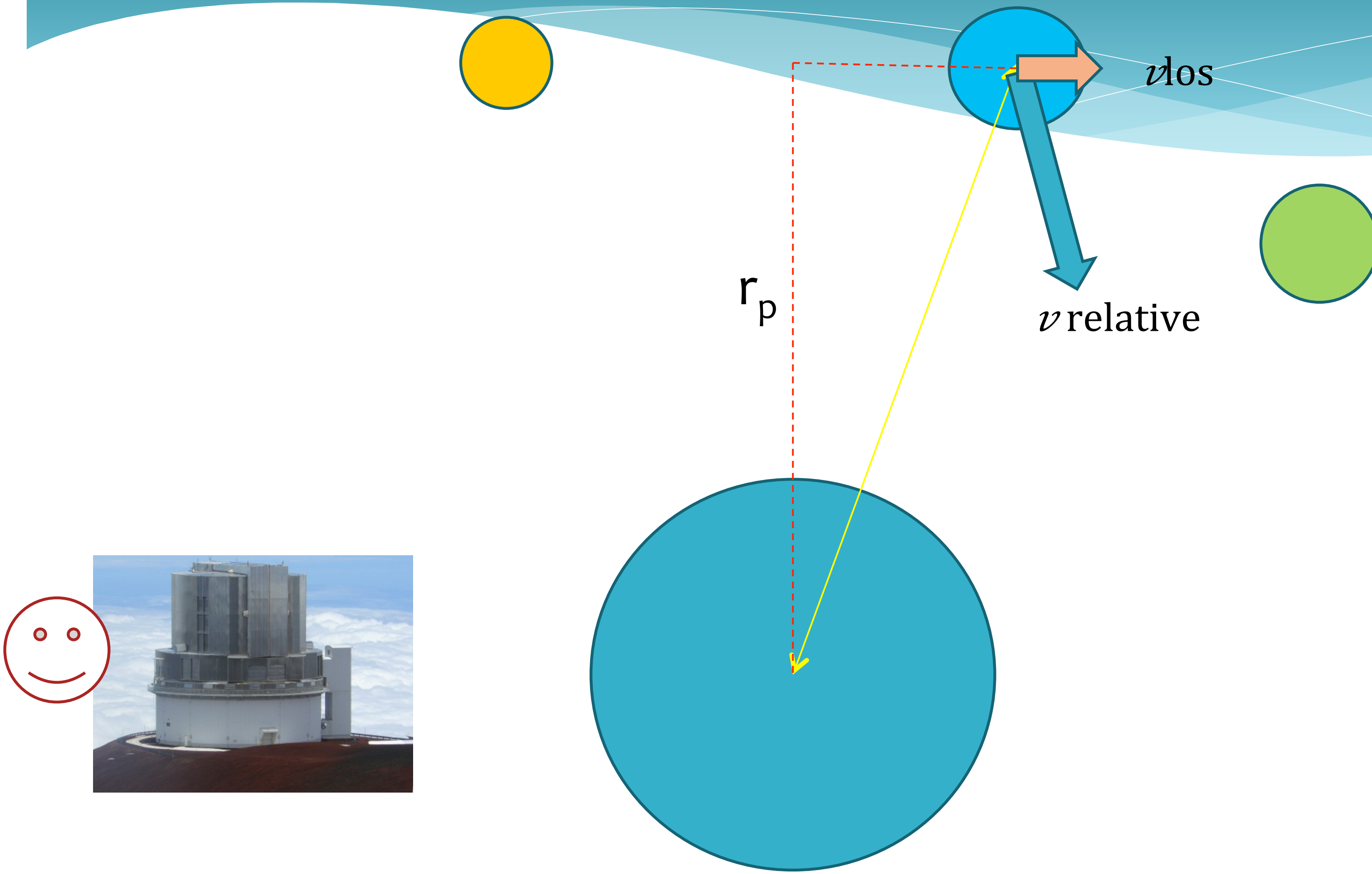
# Model Independent test of gravity

- In GR, lensing mass = dynamical mass – the two scalar perturbations are the same.
- In MG models, it is generally not the same.
- Need imaging + spectroscopic surveys (SDSS; HSC + PFS)
- Focus on massive clusters: dominate the environment makes modeling easier.

***Unique signature of MG models***

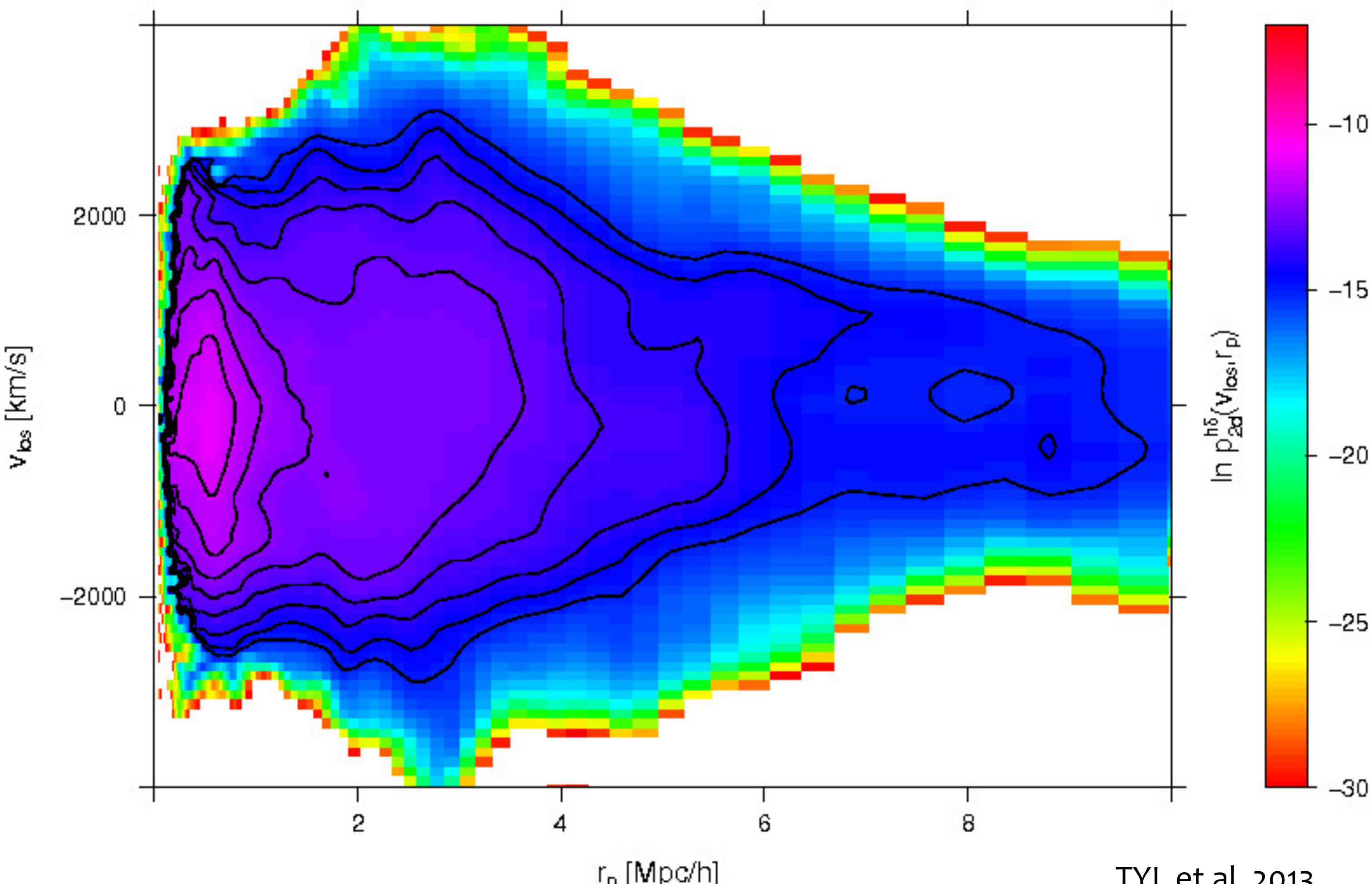
# Gravitational Lensing





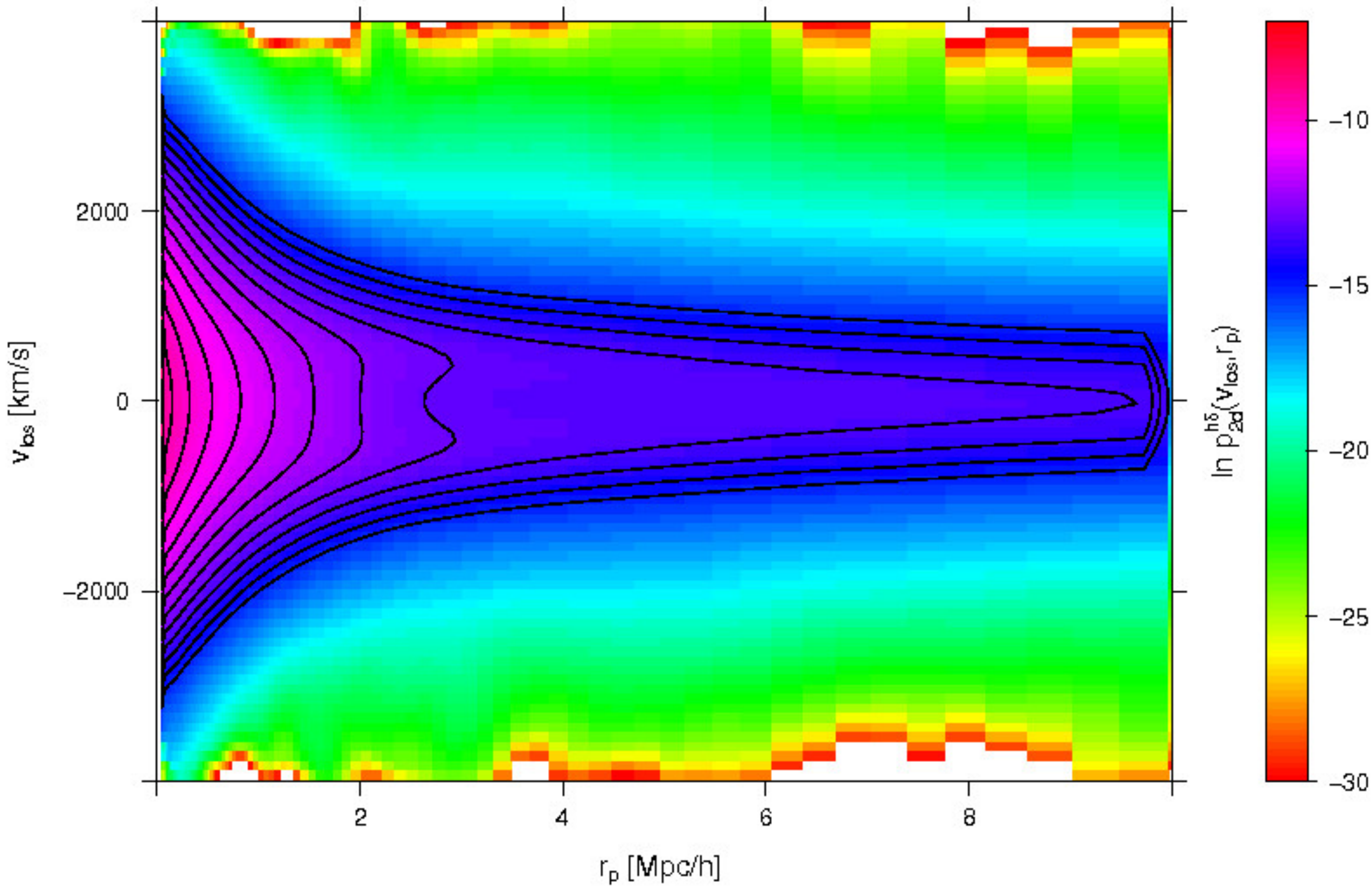

Observables: $r_p$ and $v_{los}$

# ln $p_{2D}(r_p,v_{los})$

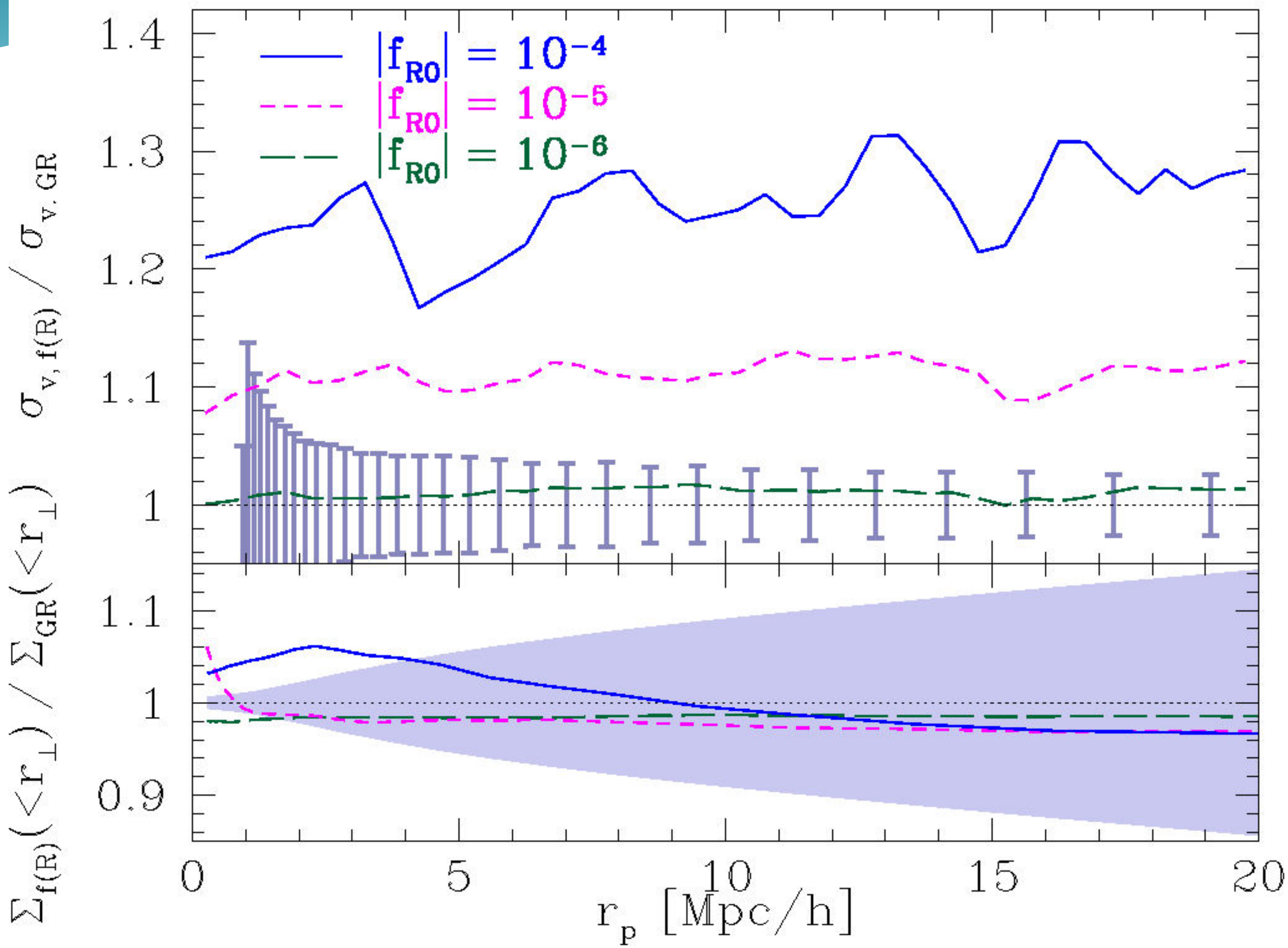



TYL et al. 2013

# Stacking 2000 clusters

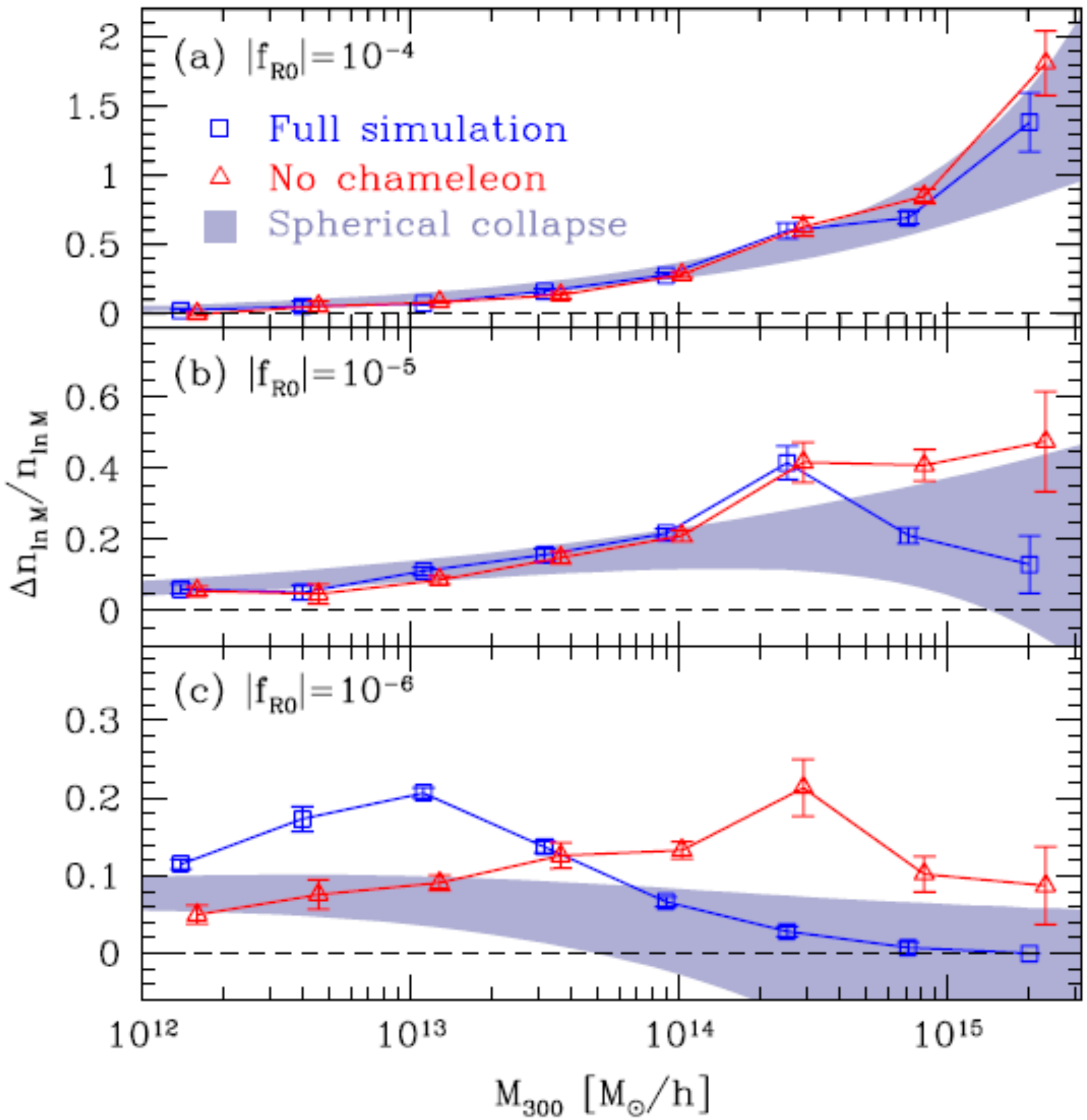



TYL et al. 2013



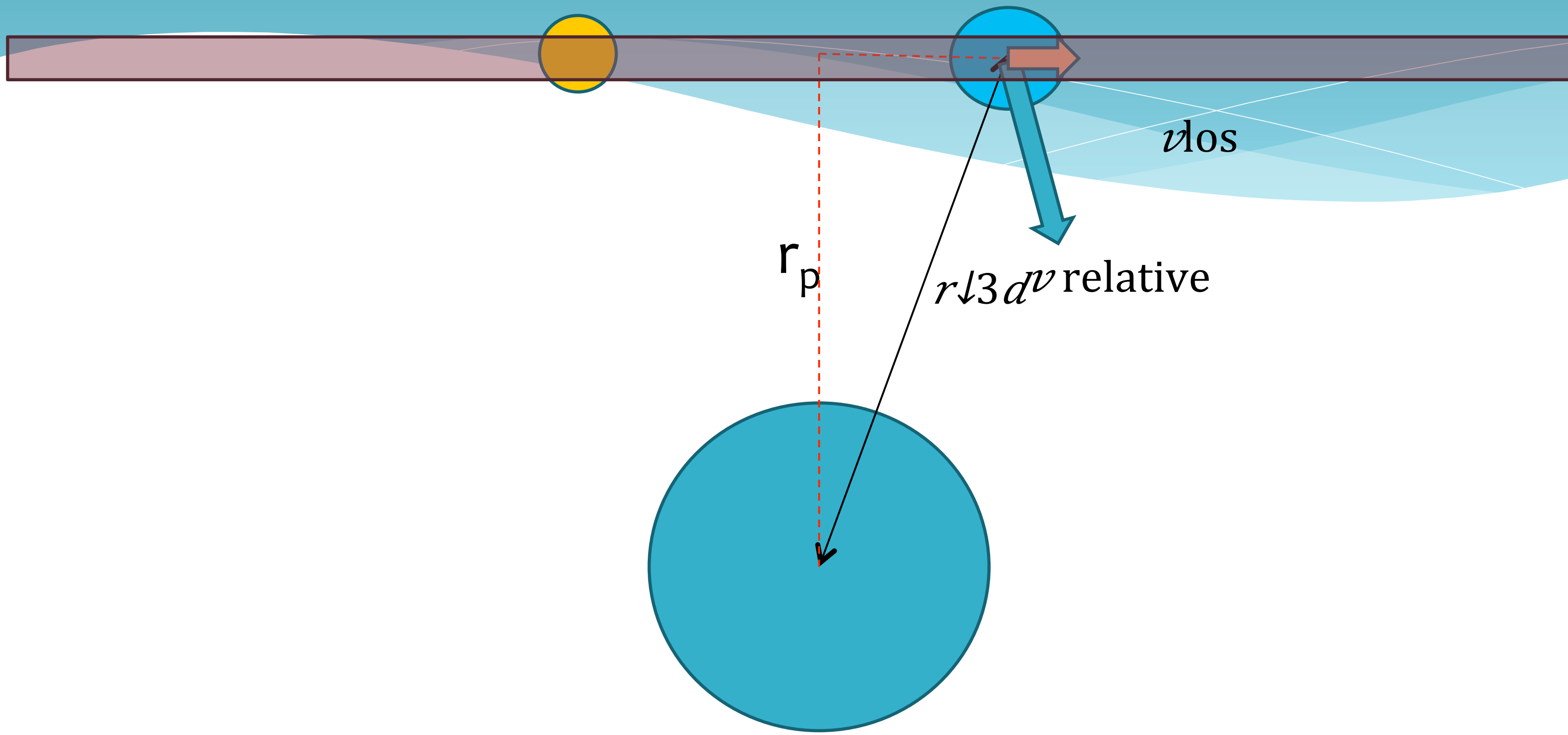

Significant modifications in (line-of-sight) velocity dispersion

Same model, but showing change in the mass function




Schmidt et al. 2009

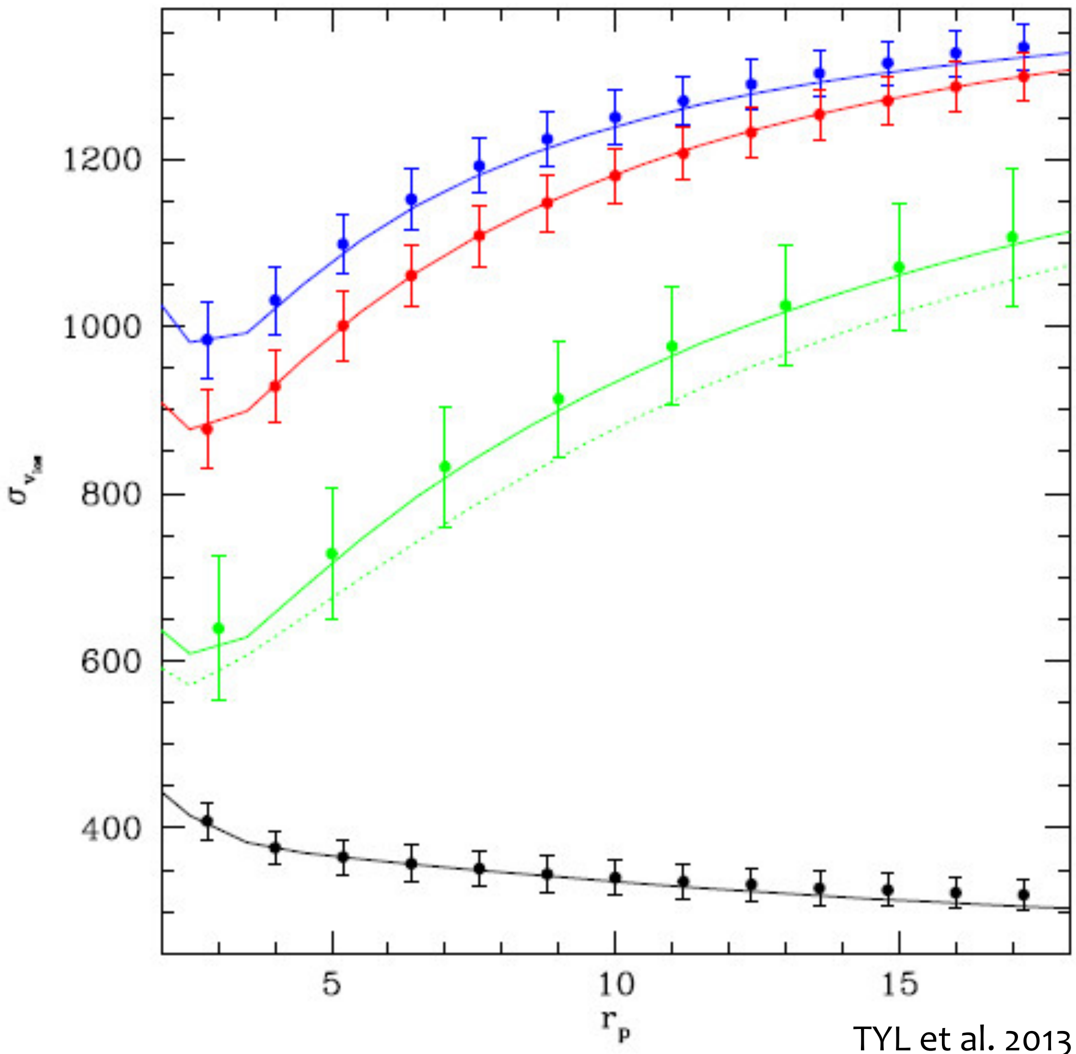
# Halo Model Approach




Ingredients:

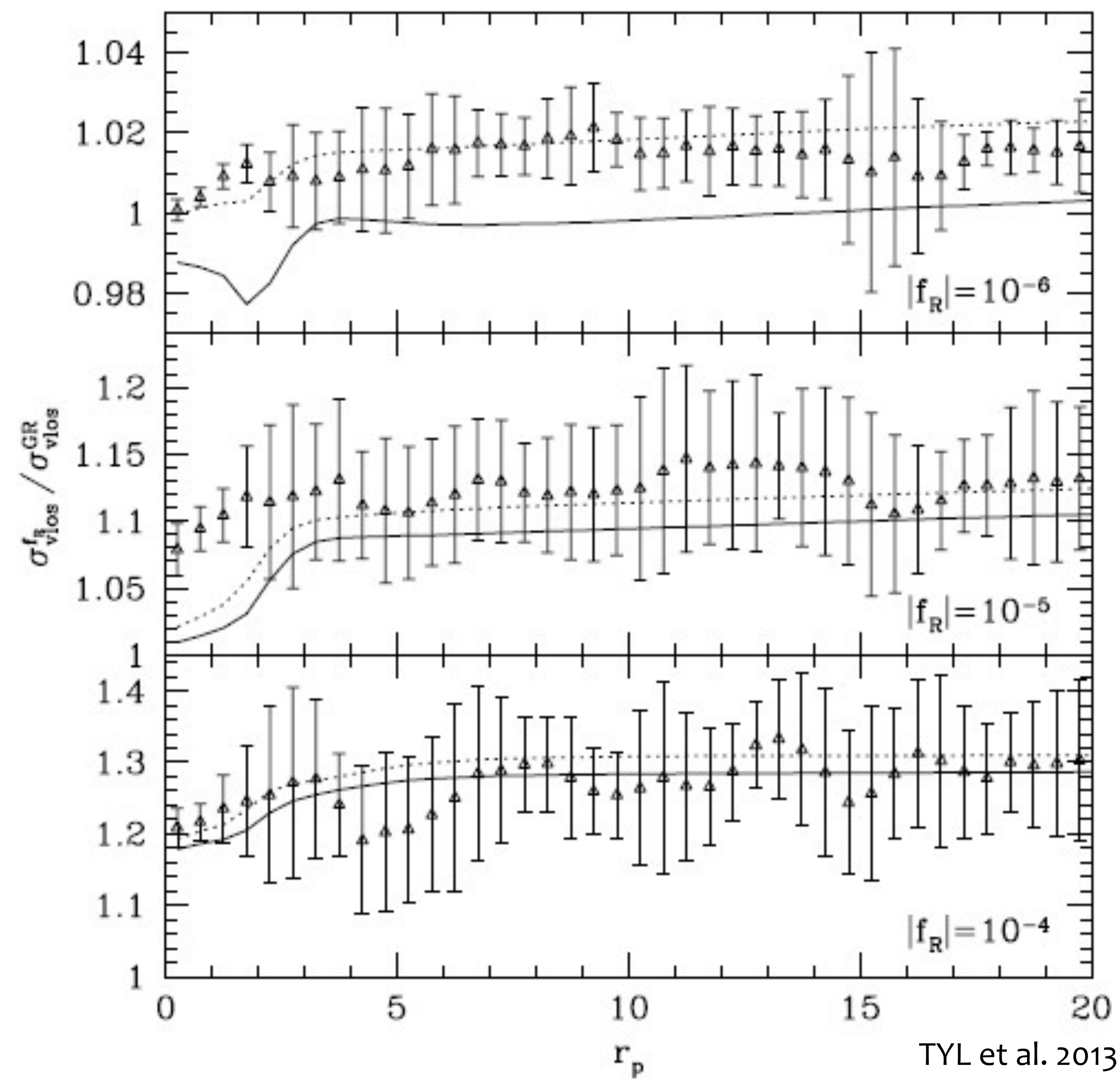
1. Halo Mass Function
2. Halo Clustering
3. Virial velocity
4. Halo-halo pairwise velocity

# Model Prediction matches N-body simulation measurements



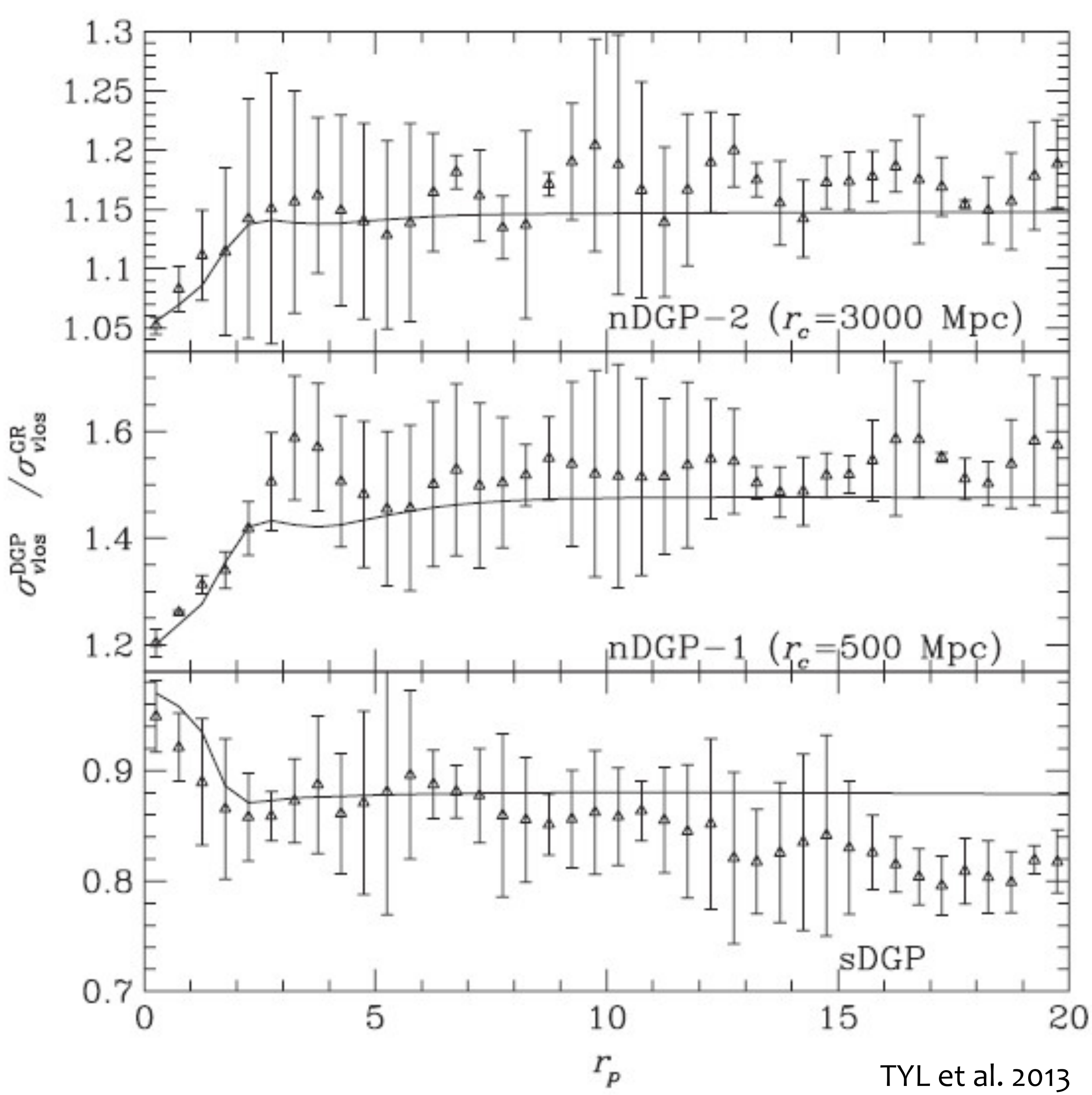

TYL et al. 2013

Halo-halo pairs, GR




TYL et al. 2013

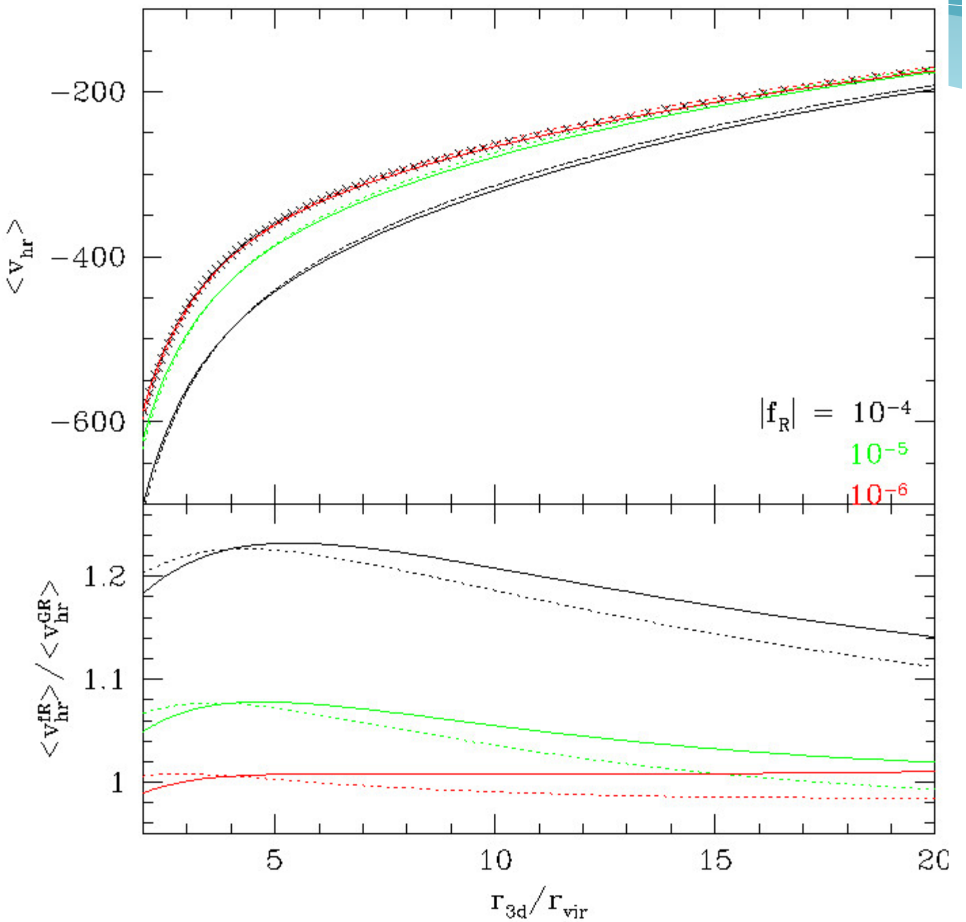
Models match well with measurements from f(R) simulation



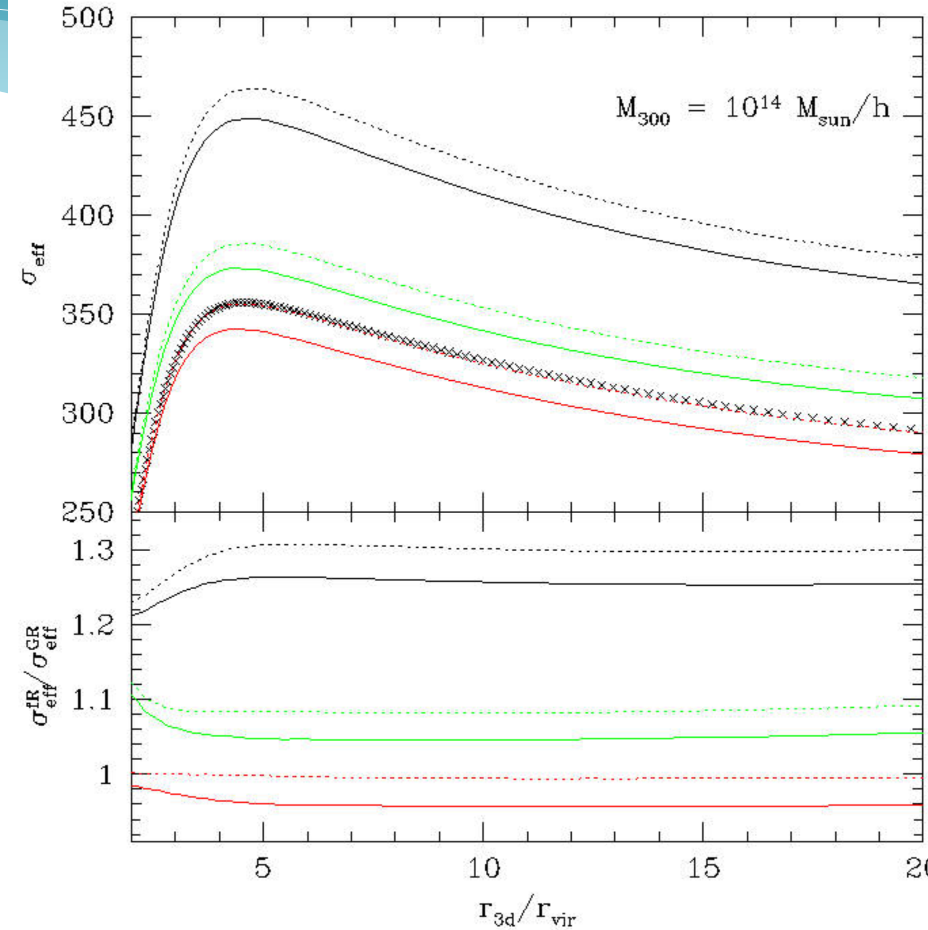

TYL et al. 2013

The same model also predicts the velocity dispersion of the DGP model

## Mean infall

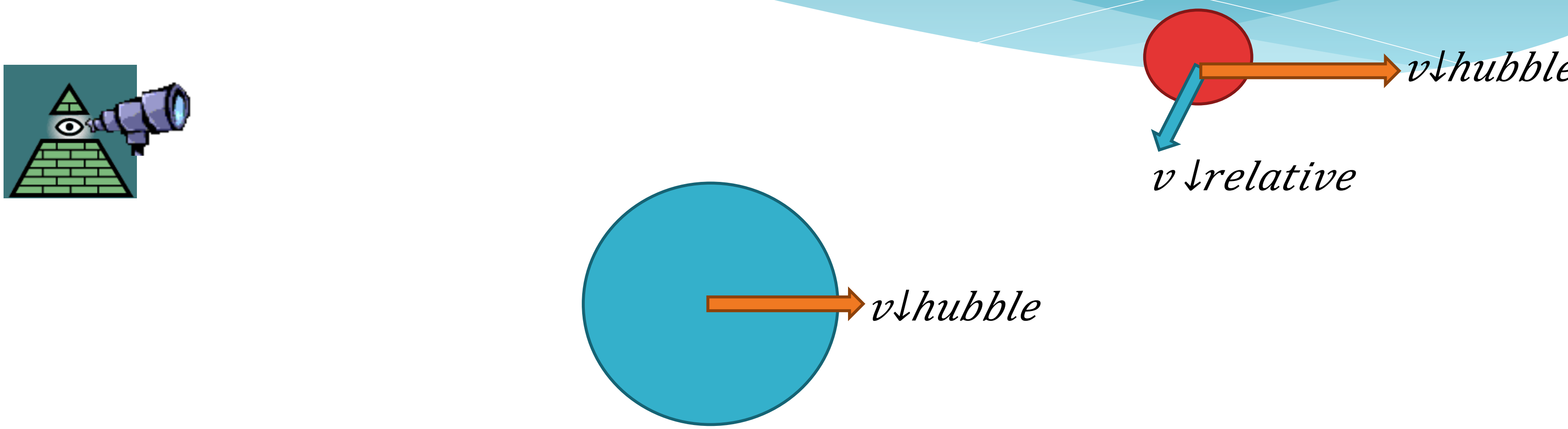



## Effective Virial velocity dispersion




Modification in velocity dispersion comes from different components

# But life is not that easy…

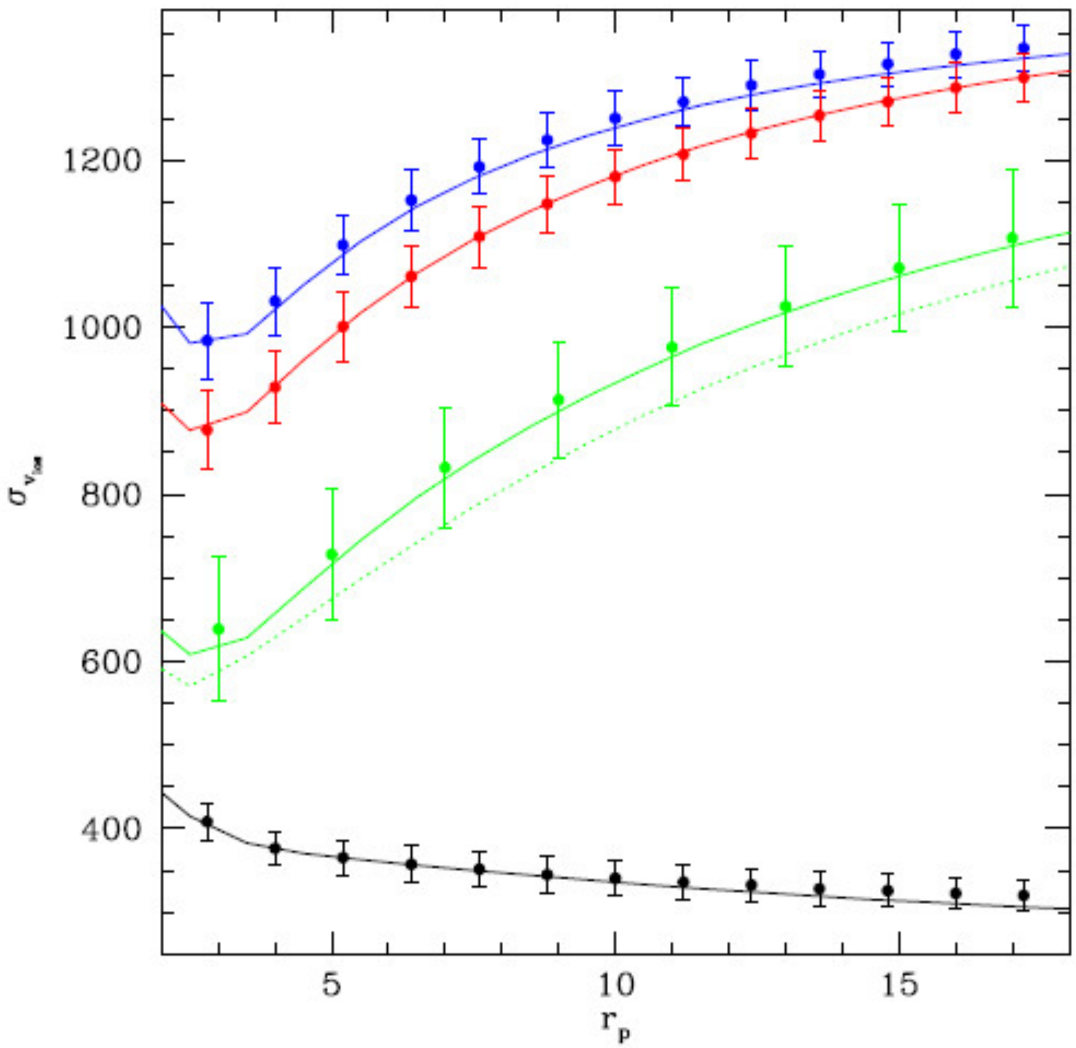



1. $v_{los} = v_{relative} \cdot z + \Delta v_{hubble}$

2. Cannot make sharp cut in line-of-sight separation: the unit in the line-of-sight direction is differential redshift.

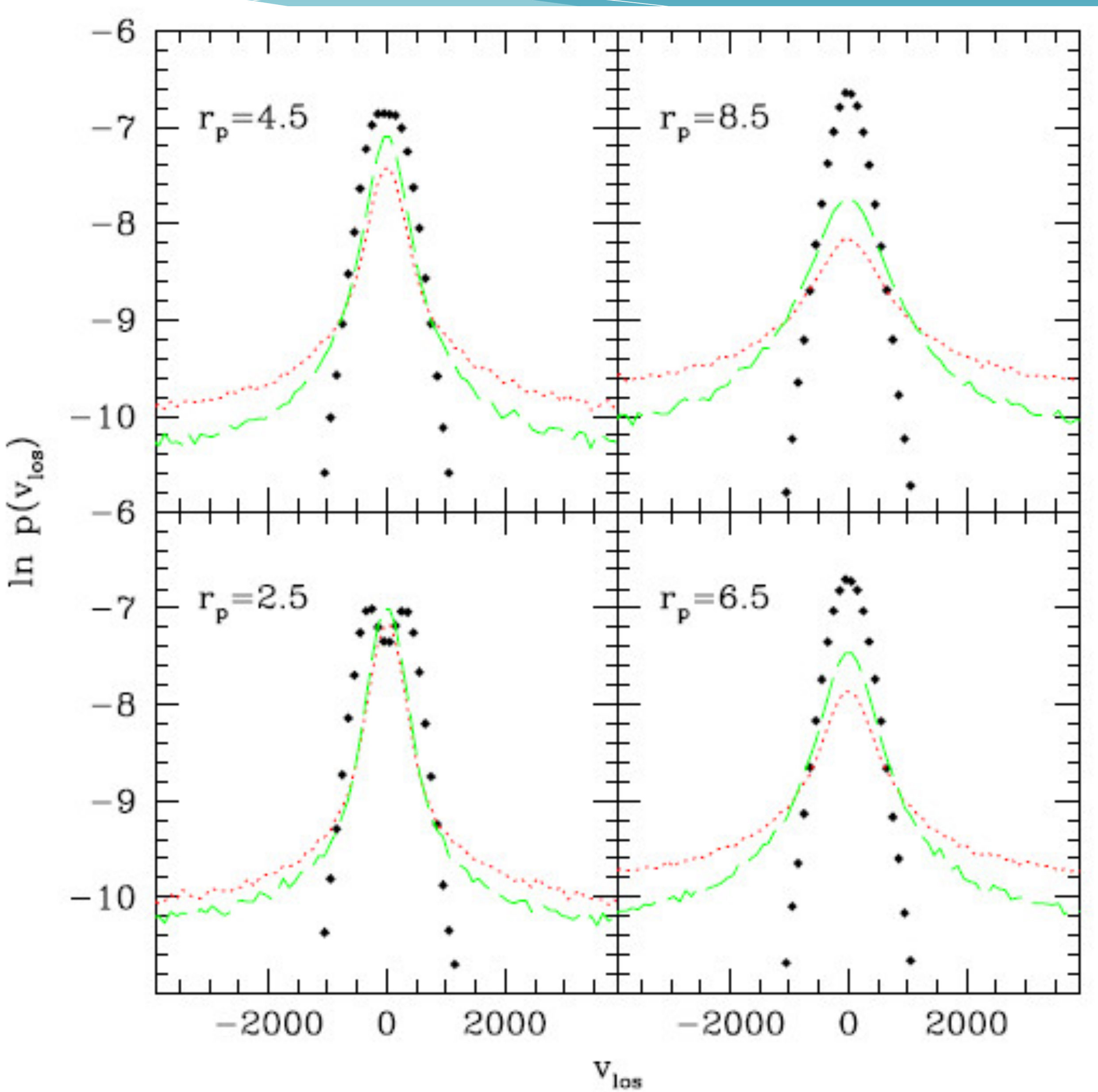
   a) Measure velocity dispersion within a predefined $v_{cut}$.
   b) Hubble flow contributes a constant background: subtract that constant and evaluate the velocity dispersion.

# Hubble Flow contamination




Halo-halo pairs, GR

# Information in the full phase-space distribution

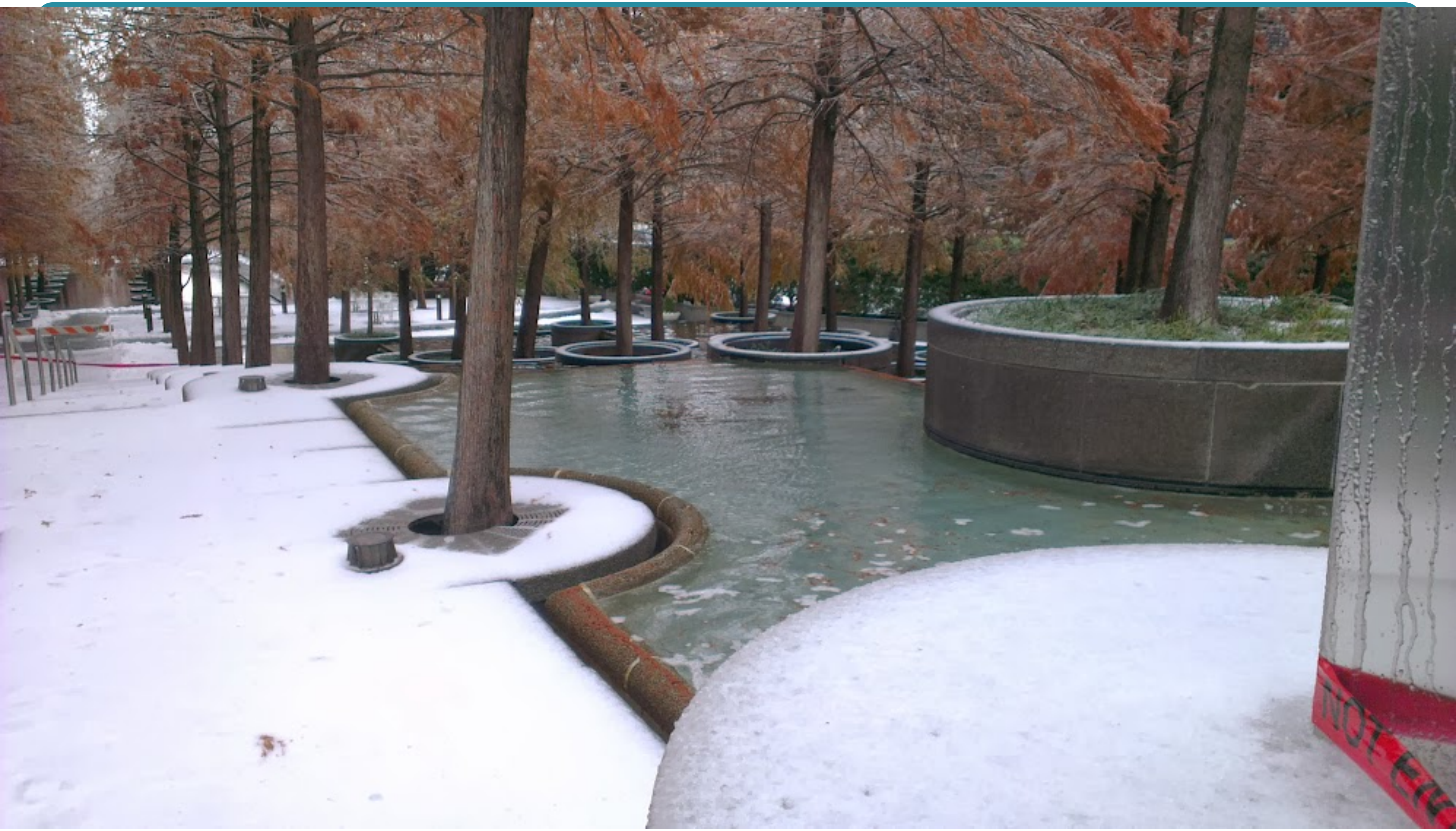


# Summary

- Gravitational lensing vs dynamical mass as a model Independent test for gravity models is promising
- Handling of systematics still requires improvements

Work in progress:

1. Removal of the Hubble flow contamination (deconvolution method);
2. Applying models to SDSS data




Happy Winter

# Conclusion

- LSS provides various probes to MG models
- Fifth force enhances growth of structure
- Screening mechanisms screen the fifth force and gravity restores to GR
- Model-independent test using gravitational lensing mass against dynamical mass is promising, but more work are still neeed.