Modified Gravity Models and Large-scale Structures

Tsz Yan LAM (MPA)

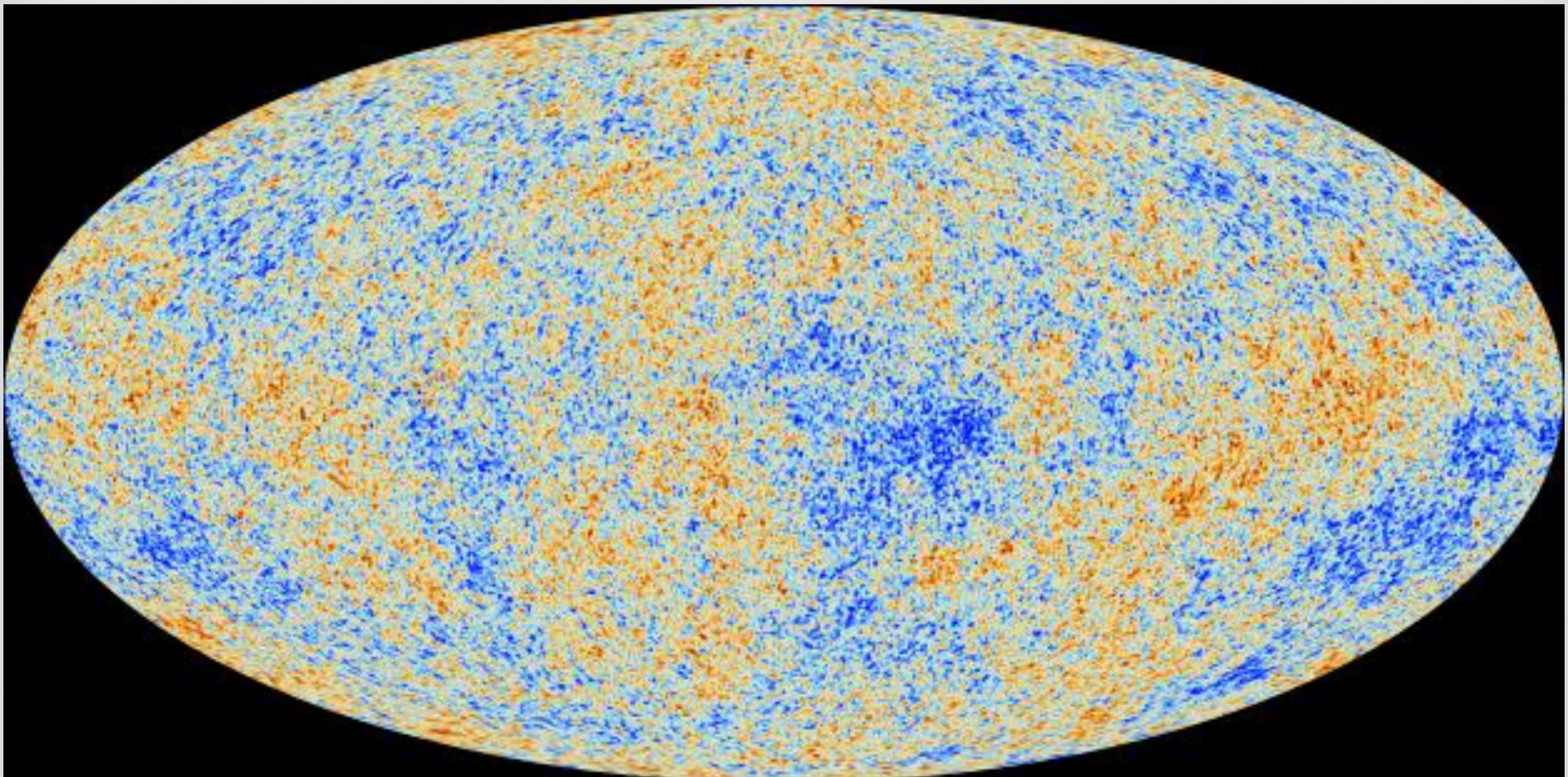
PASCOS 2013

Collaborators: M. Takada, J. Clampitt, Y. Cai, F. Schmidt, B. Li, T. Nishimichi

1. PRL, 2012, 109, 051301
2. MNRAS, 2012, 425, 730
3. MNRAS, 2012, 428, 3260
4. PRD, 2013, 88, 023012

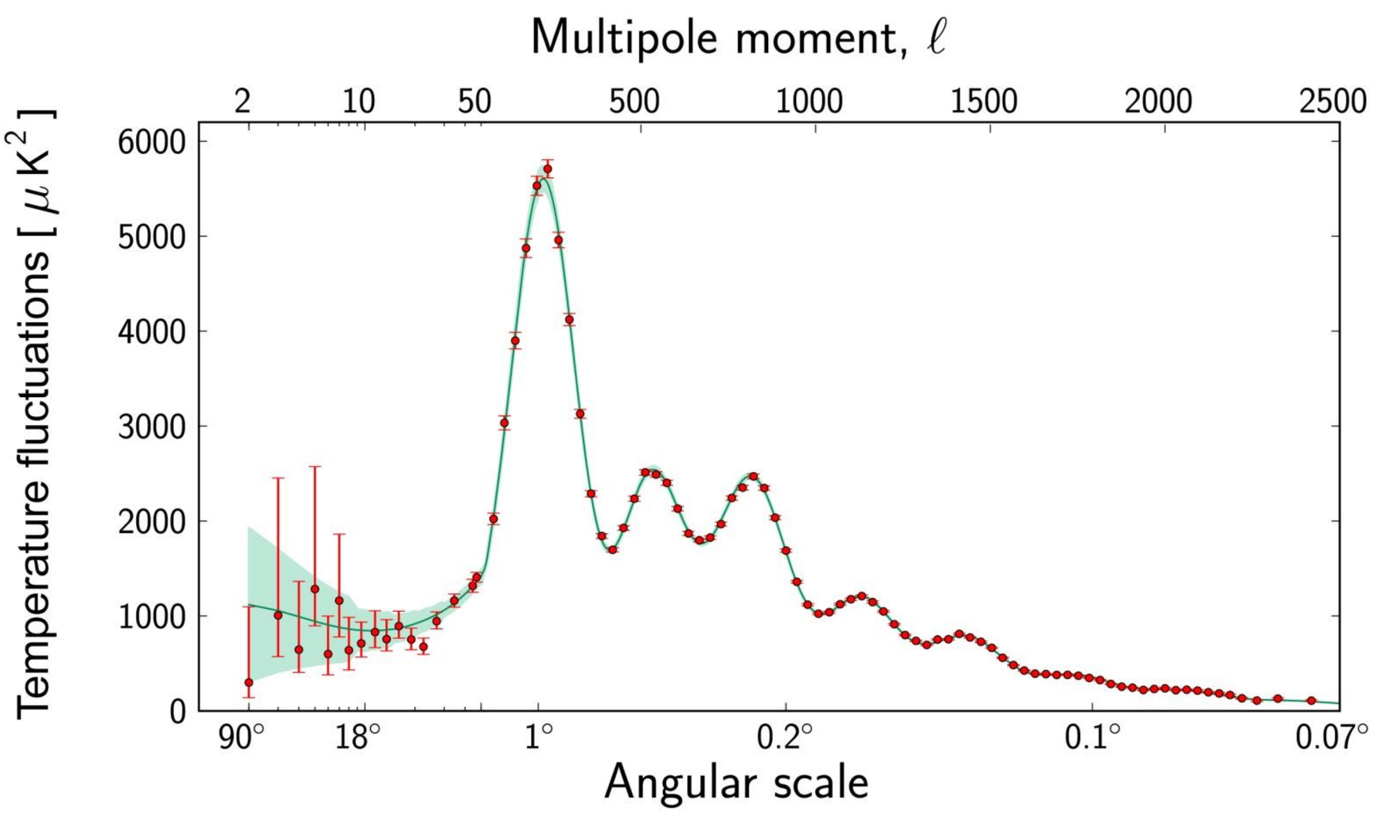
Max Planck Institute for Astrophysics

A glimpse of the early Universe



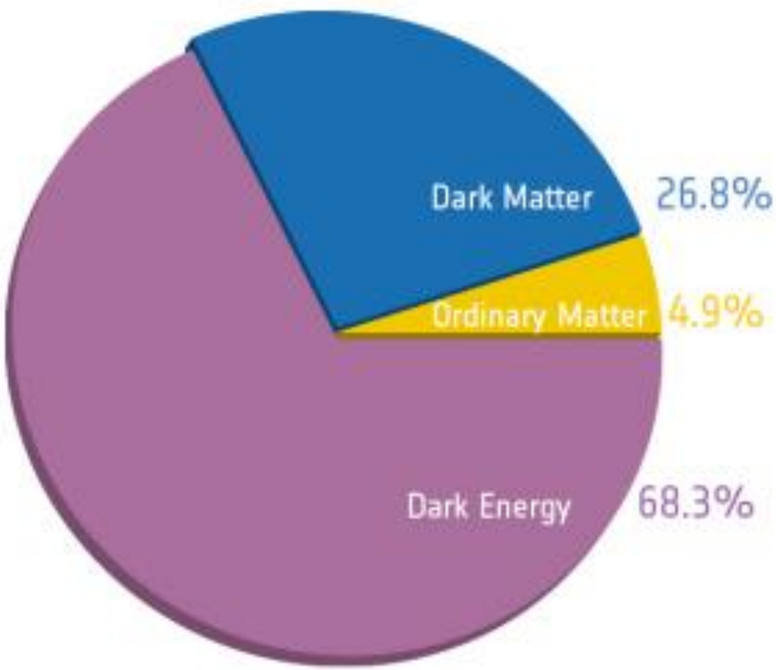
Planck Collaboration

Initial fluctuations are set



Planck Collaboration

LCDM: Lambda and CDM



Planck Collaboration

Standard Concordance Cosmology:

5% ordinary matter

27% cold dark matter

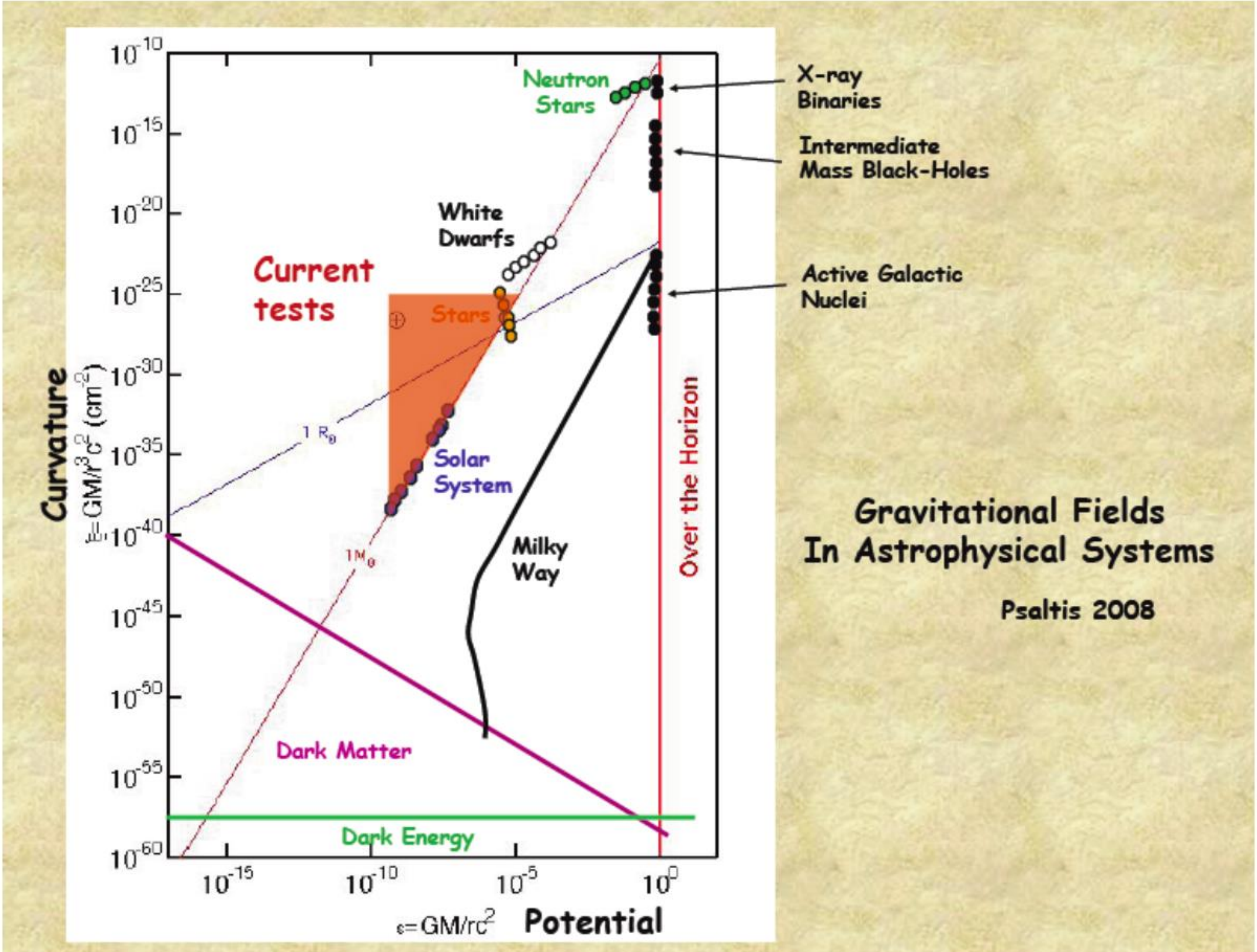
68% dark energy

Late-time cosmic acceleration

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

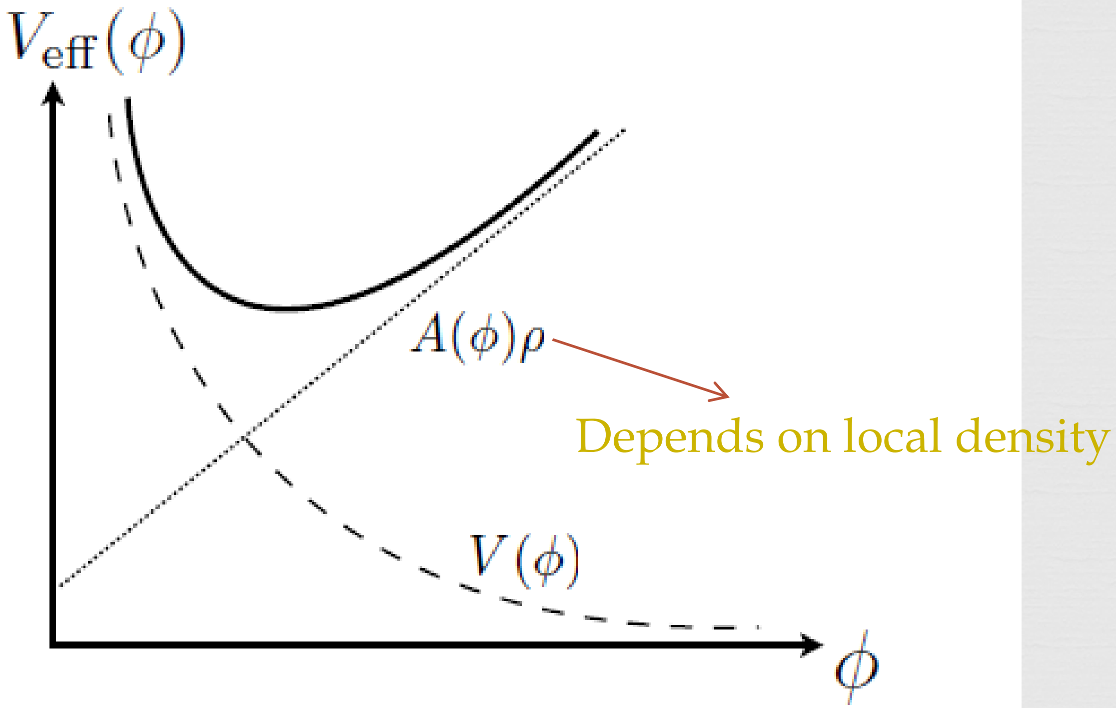


Slide taken (stolen) from Ferreira's talk

Coupling scalar field with chameleon mechanism

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

Chameleon mechanism



Jain & Khoury (2010)

Model Specification

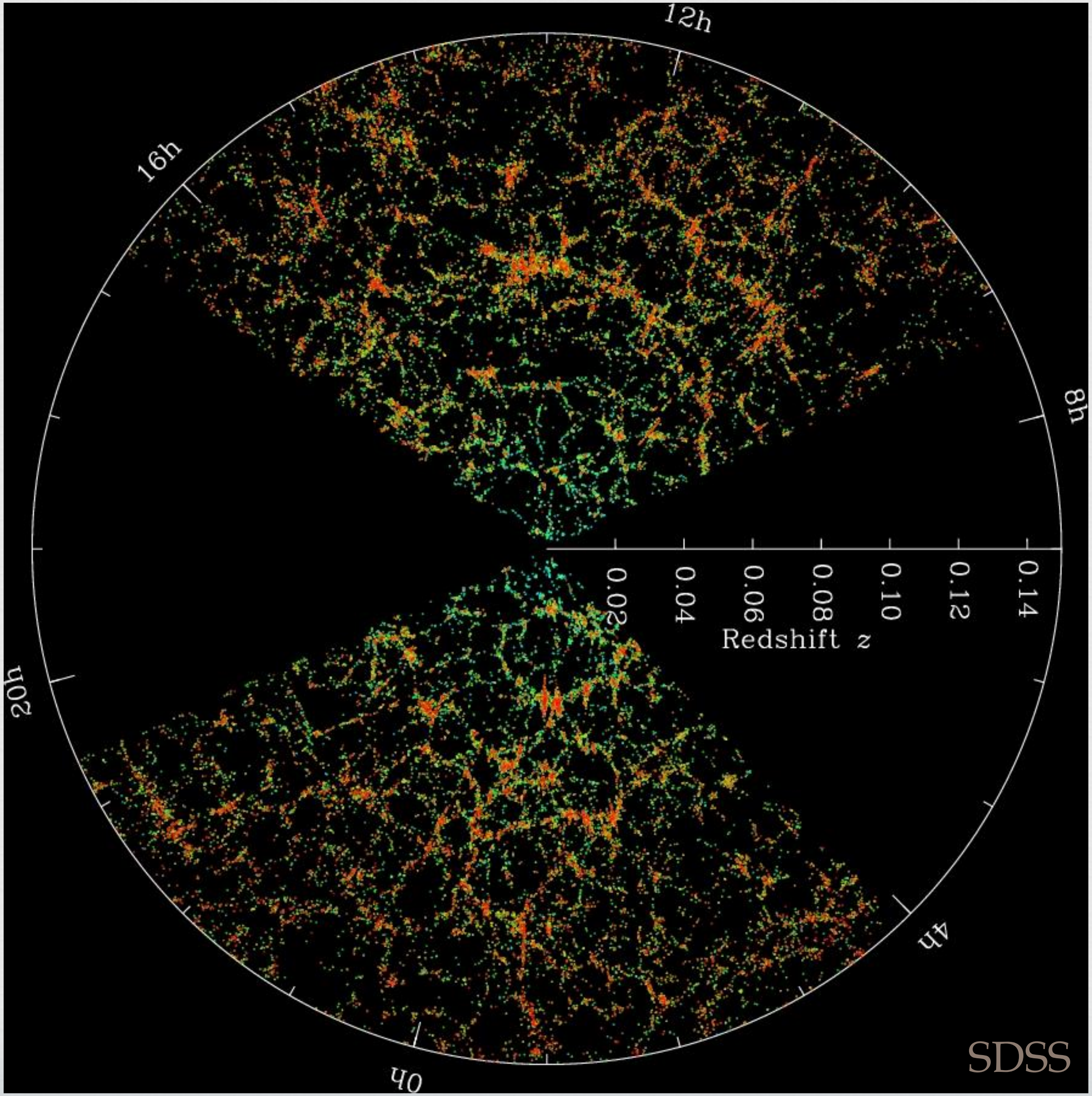
$$\mathcal{L} = \frac{1}{2}\left[\frac{\mathcal{R}}{8\pi G} - \nabla^a \nabla_a \phi\right] + V(\phi) - A(\phi)\mathcal{L}_{DM} + \mathcal{L}_S$$

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

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

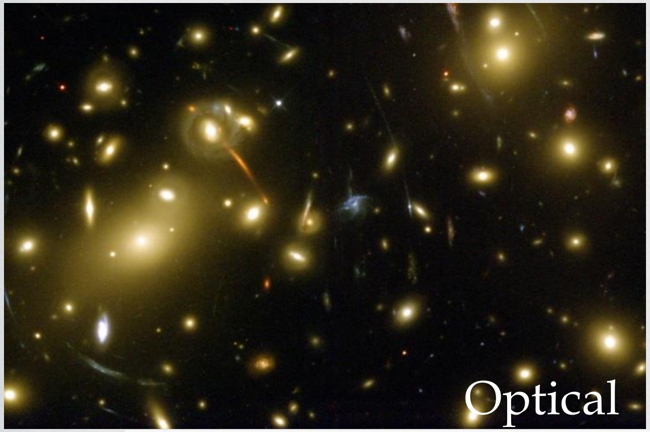
This model is equivalent to popular f(R) model, in which the Einstein-Hilbert action contains an additional f(R) piece to the original R.

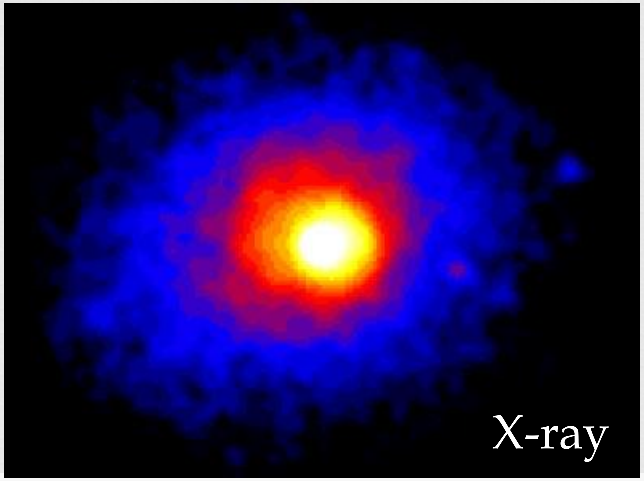
Late-time Universe

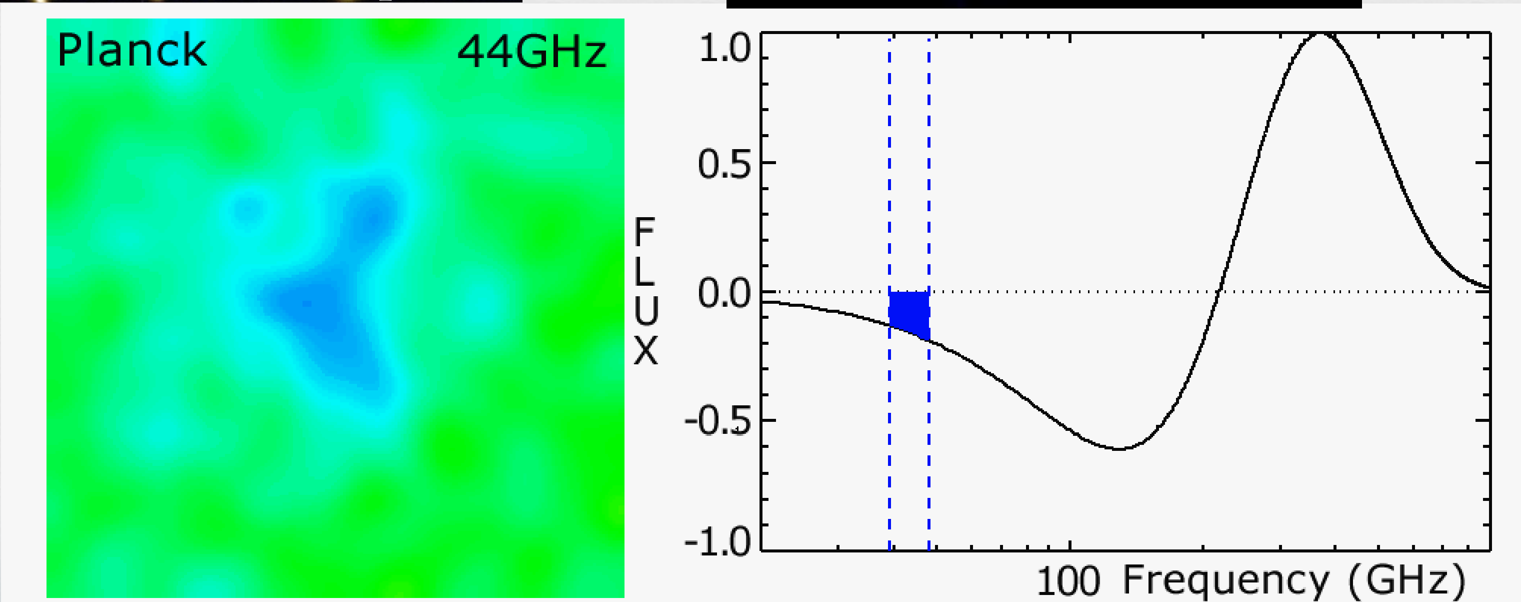


Part 1: Abundance of Rare Objects

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

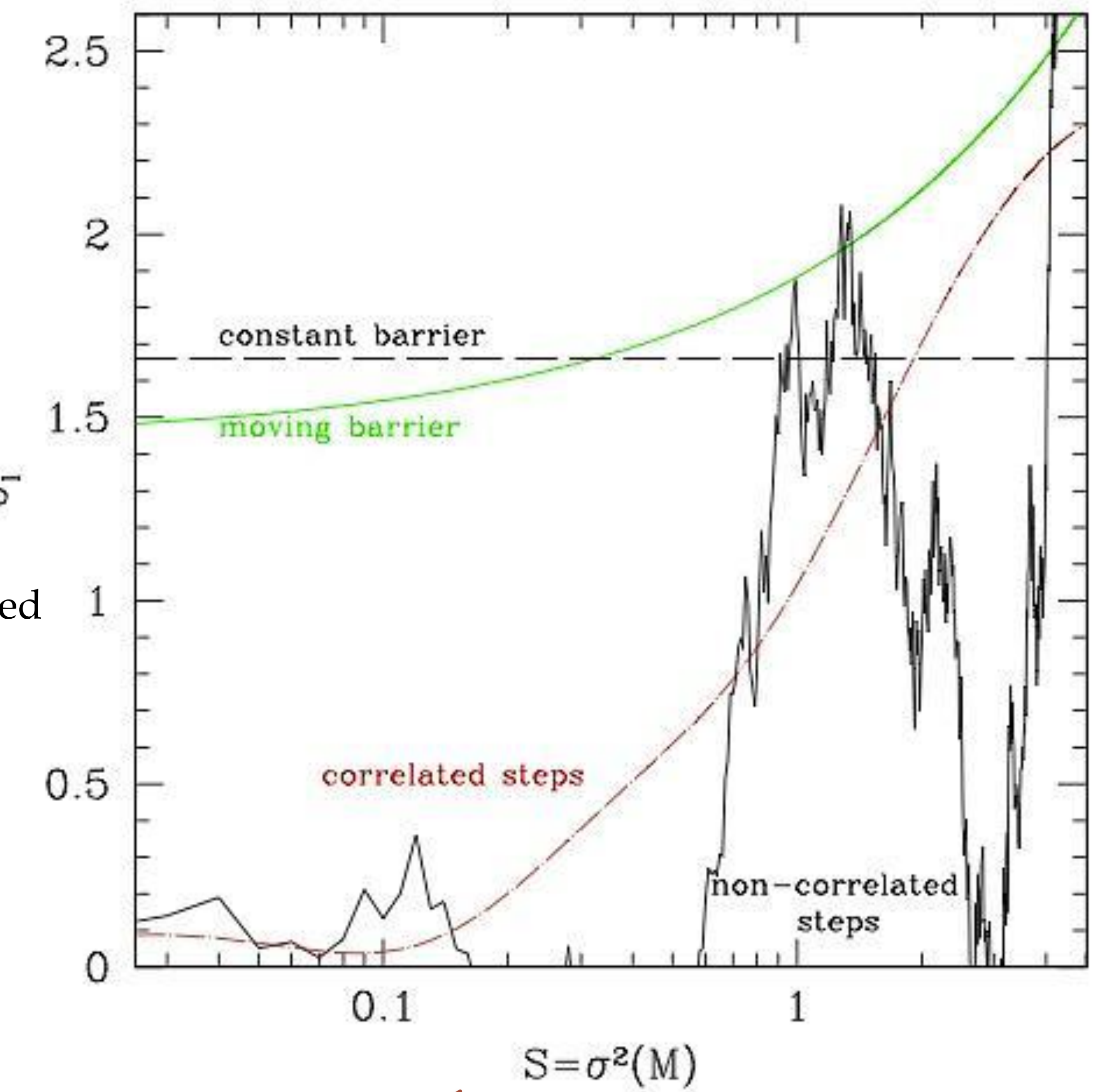






Excursion Set Approach

- 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.

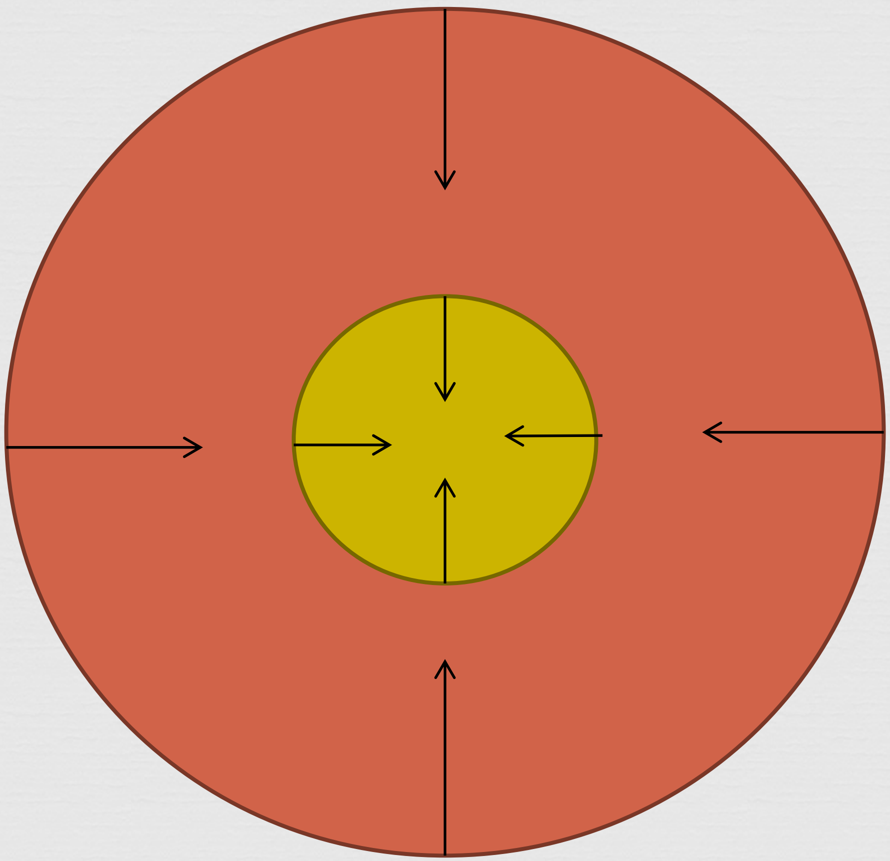


Linearly extrapolated density contrast

Increasing mass

Only *FIRST* crossing counts!

Both smoothing scales exceed δ_c



Only count the biggest scale to avoid double-counting

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

$$f(S)dS = \frac{M}{\bar{\rho}} n(M)dM \longleftarrow \text{Total mass conservation}$$

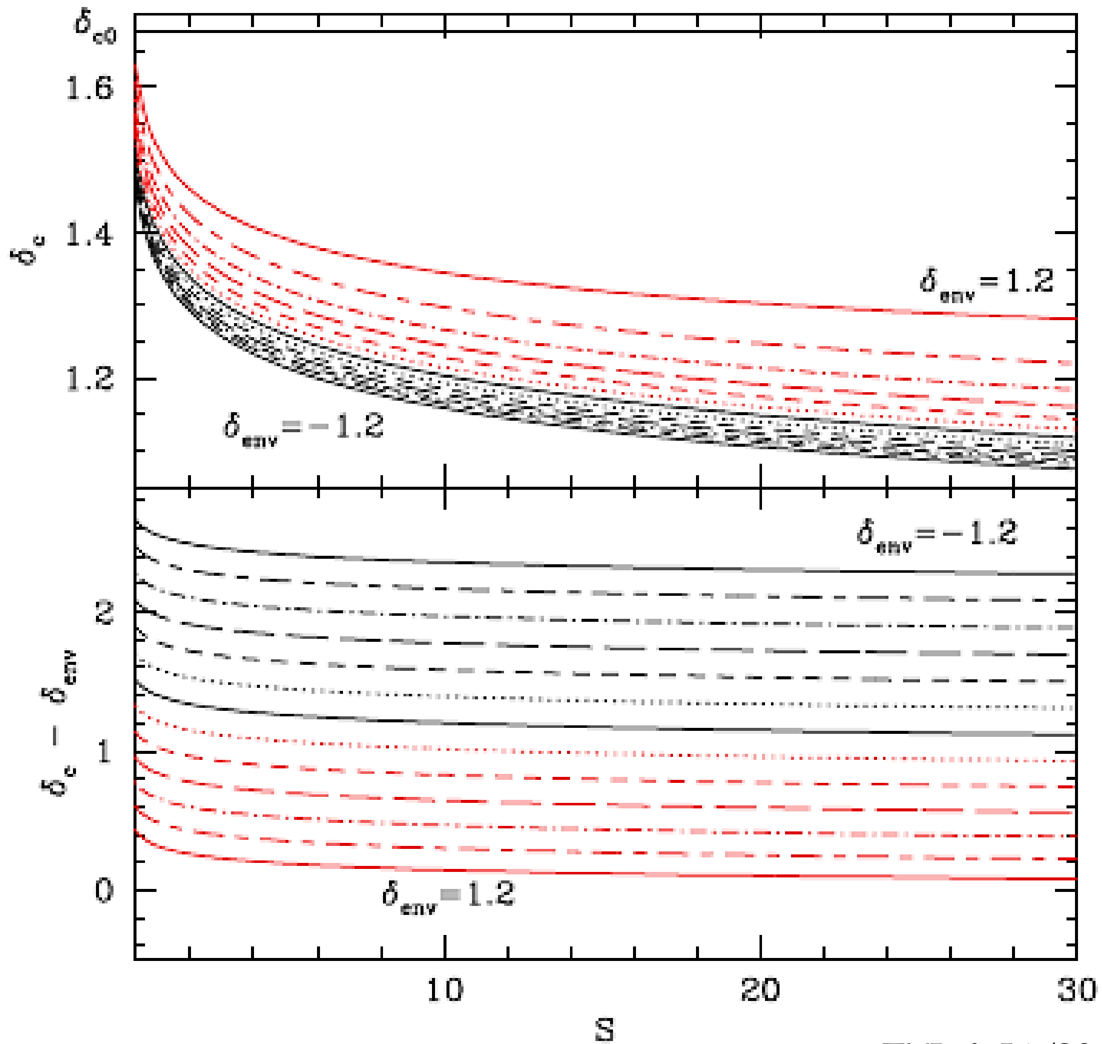
$n(M)$ = number density of halos with mass $(M + dM)$

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

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



TYL & Li (2012)

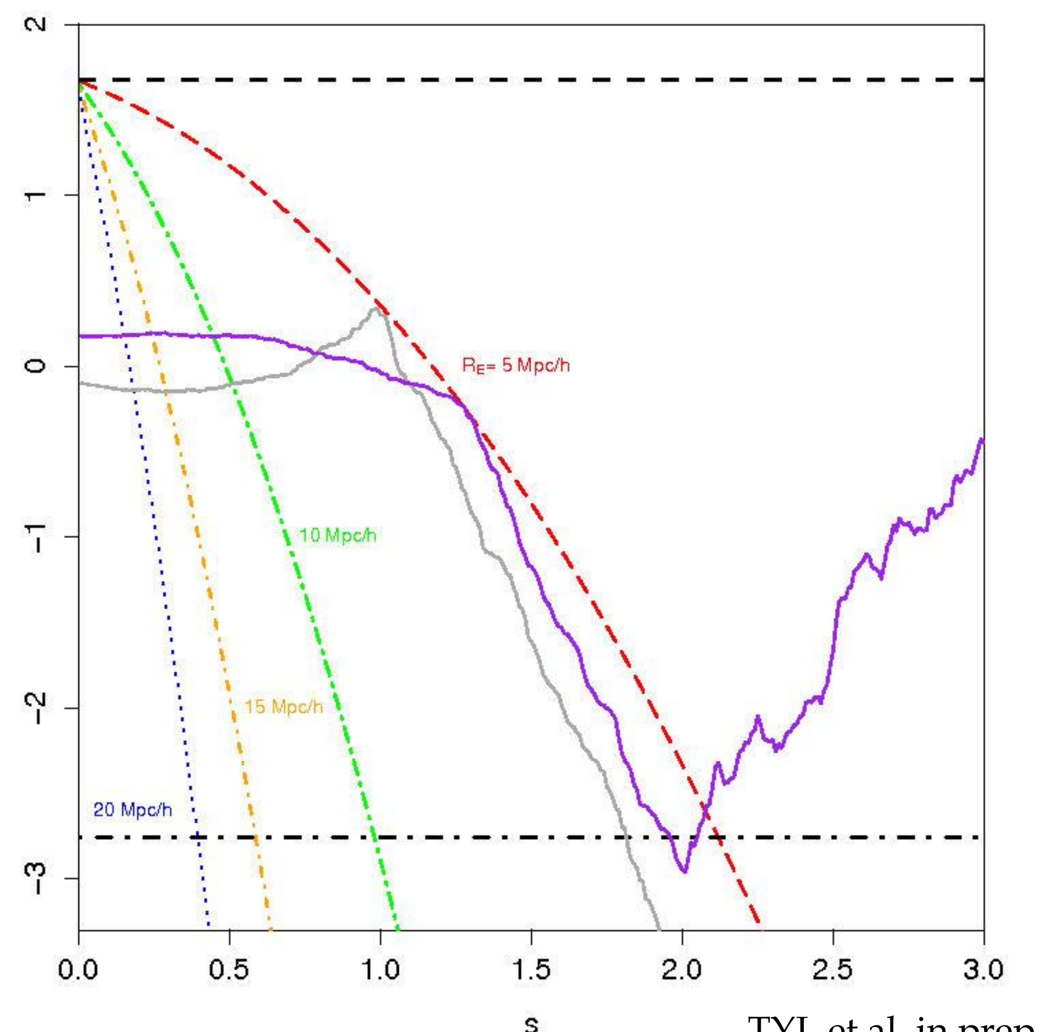
Methodology

- For a given δ_{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 δ_{env}

Question: What is the probability of having δ_{env}?

Eulerian barriers and excursion set

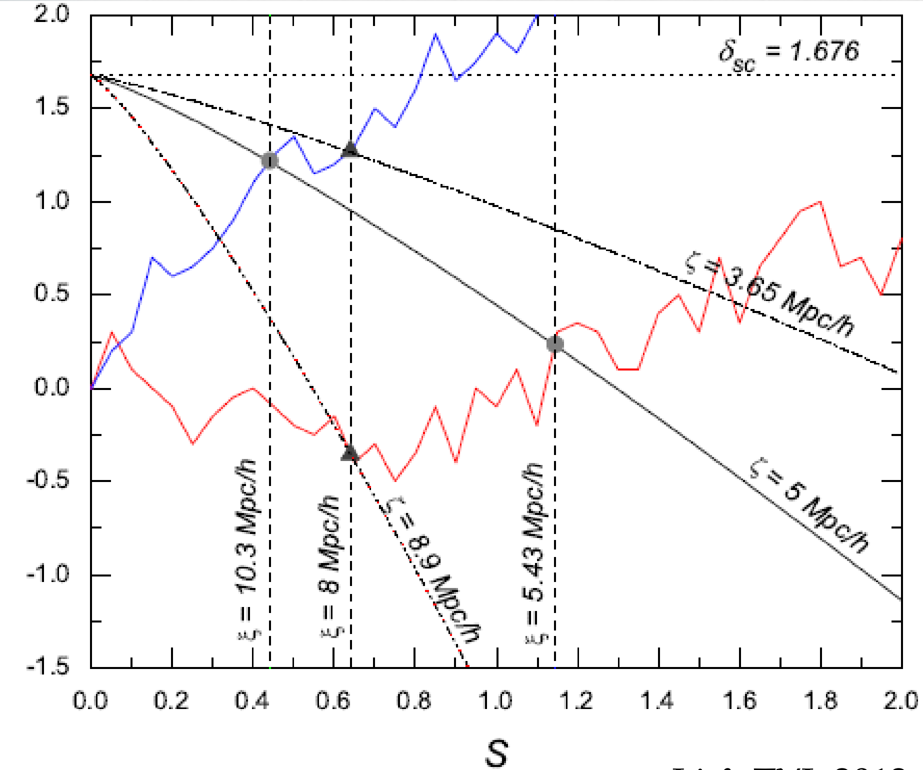
(Sheth 1998; TYL & Sheth 2008a,b)



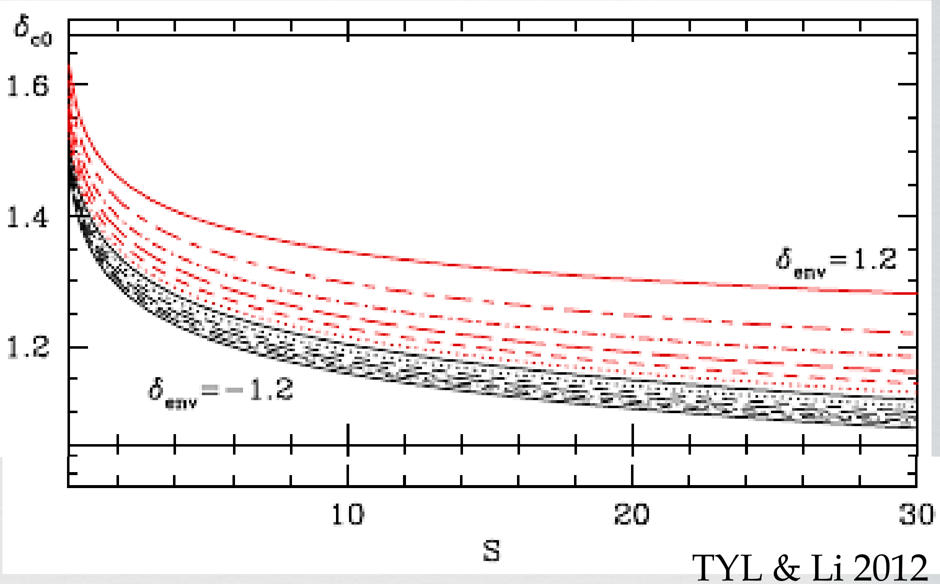
TYL et al. in prep

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

First Crossing Probability

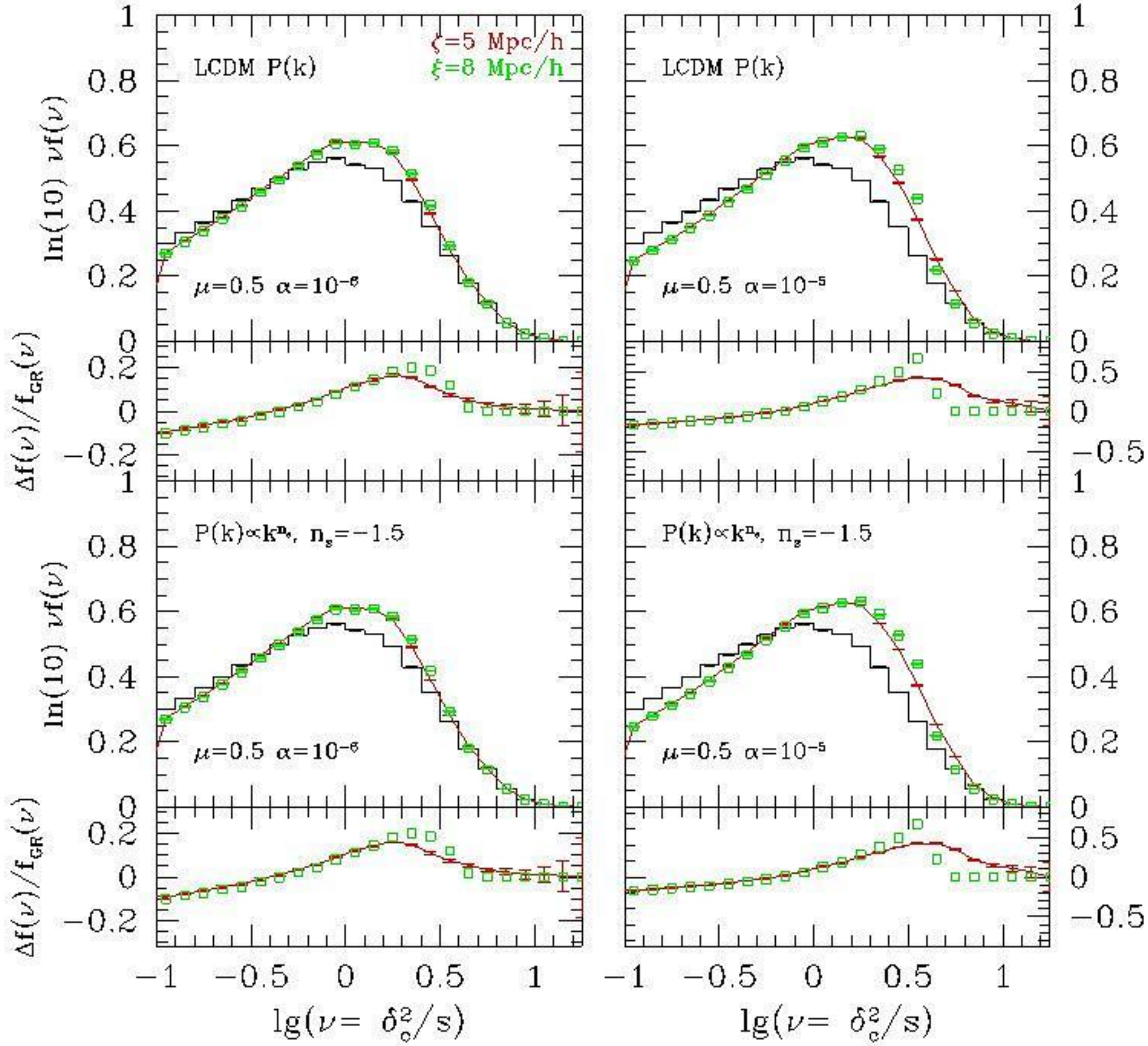


Li & TYL 2012



TYL & Li 2012

Results



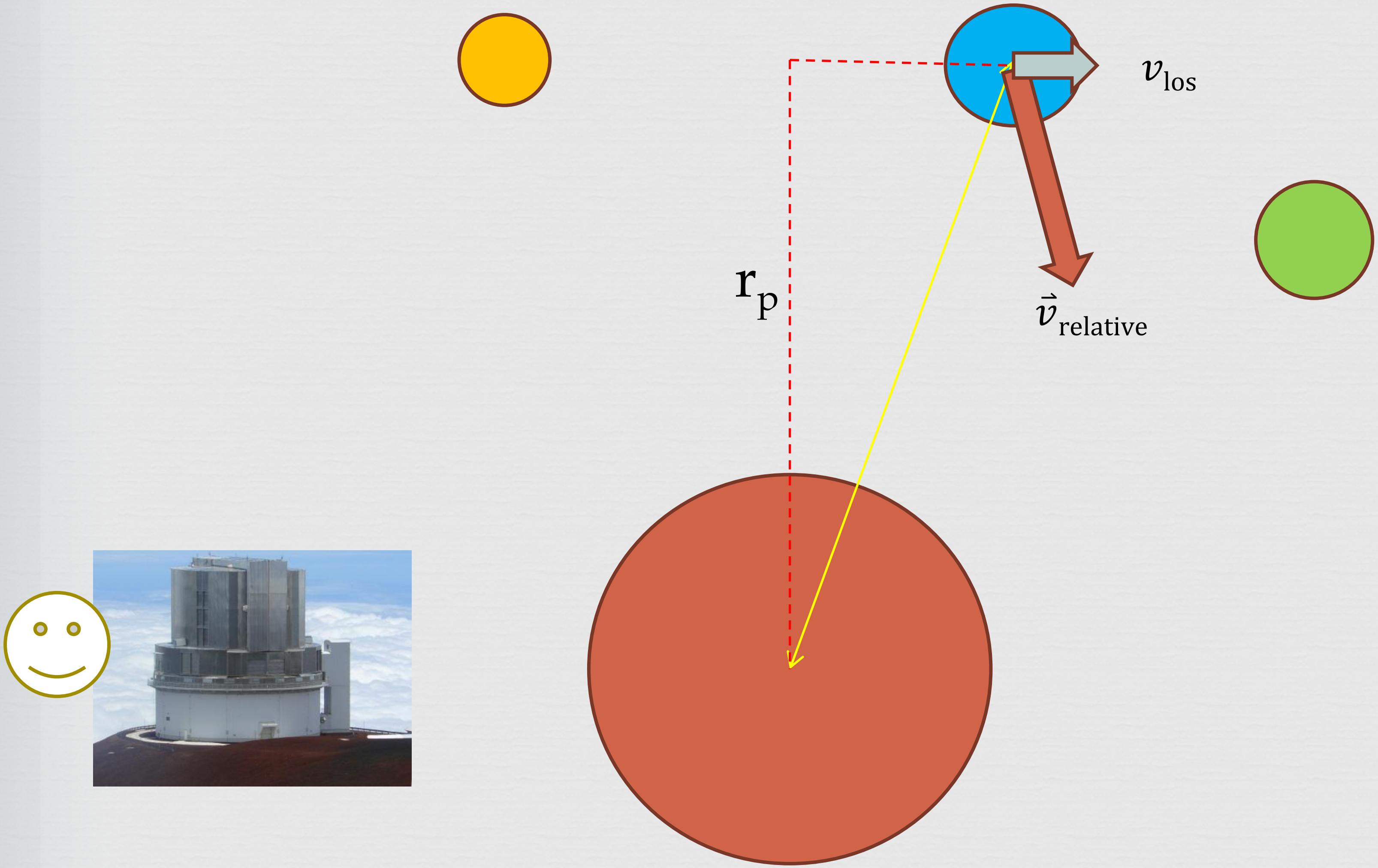
Li & TYL 2012

Part 2: Gravitational lensing masses vs dynamical masses

Model Independent test of gravity

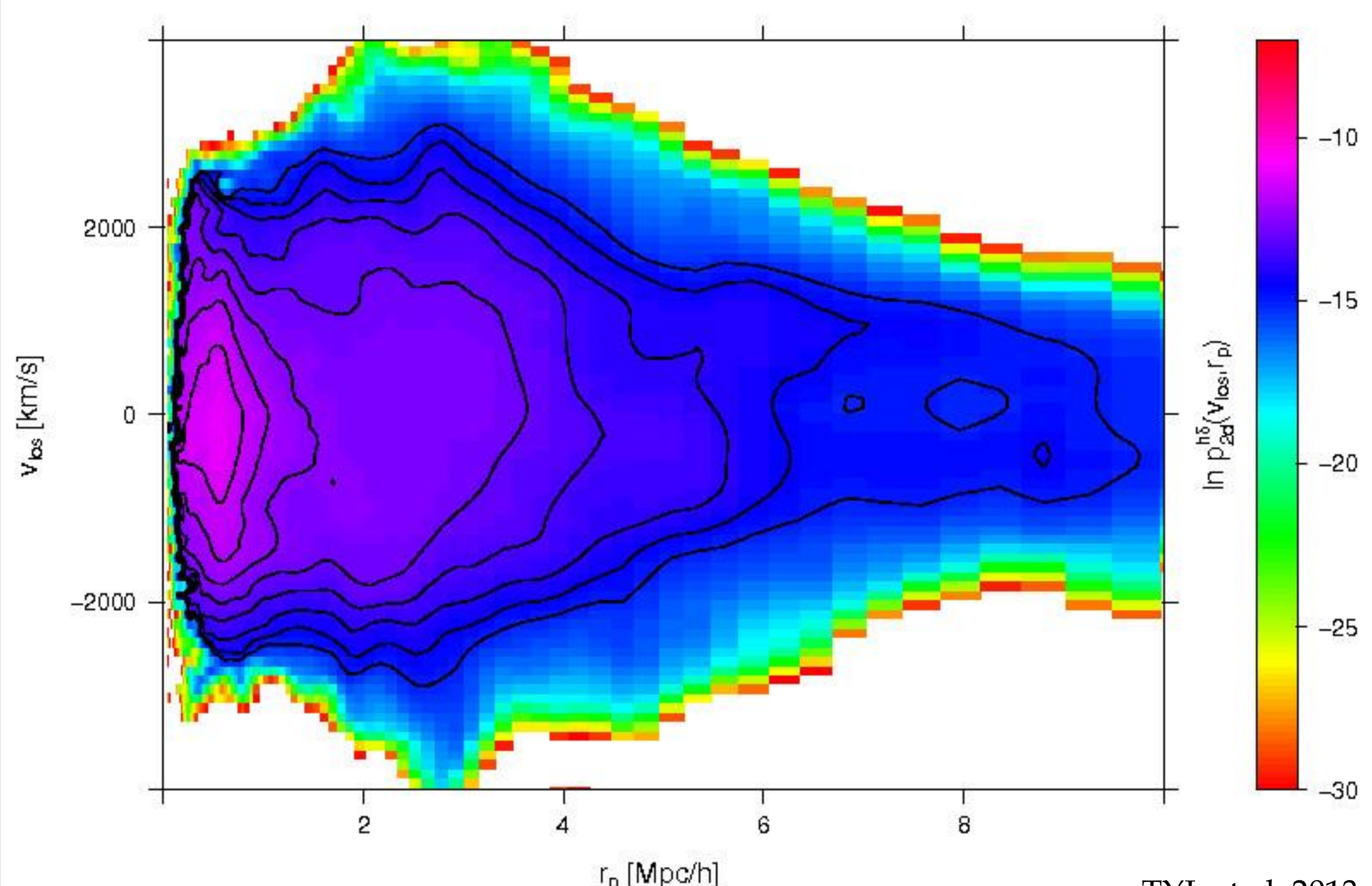
- In GR, lensing mass = dynamical mass – the two scalar perturbations are the same.
- In MG models, it is generally not the same.
- Need imaging + spectroscopic surveys (SDSS; HSC + PFS)
- Focus on massive clusters: dominate the environment makes modeling easier.

Unique signature of MG models



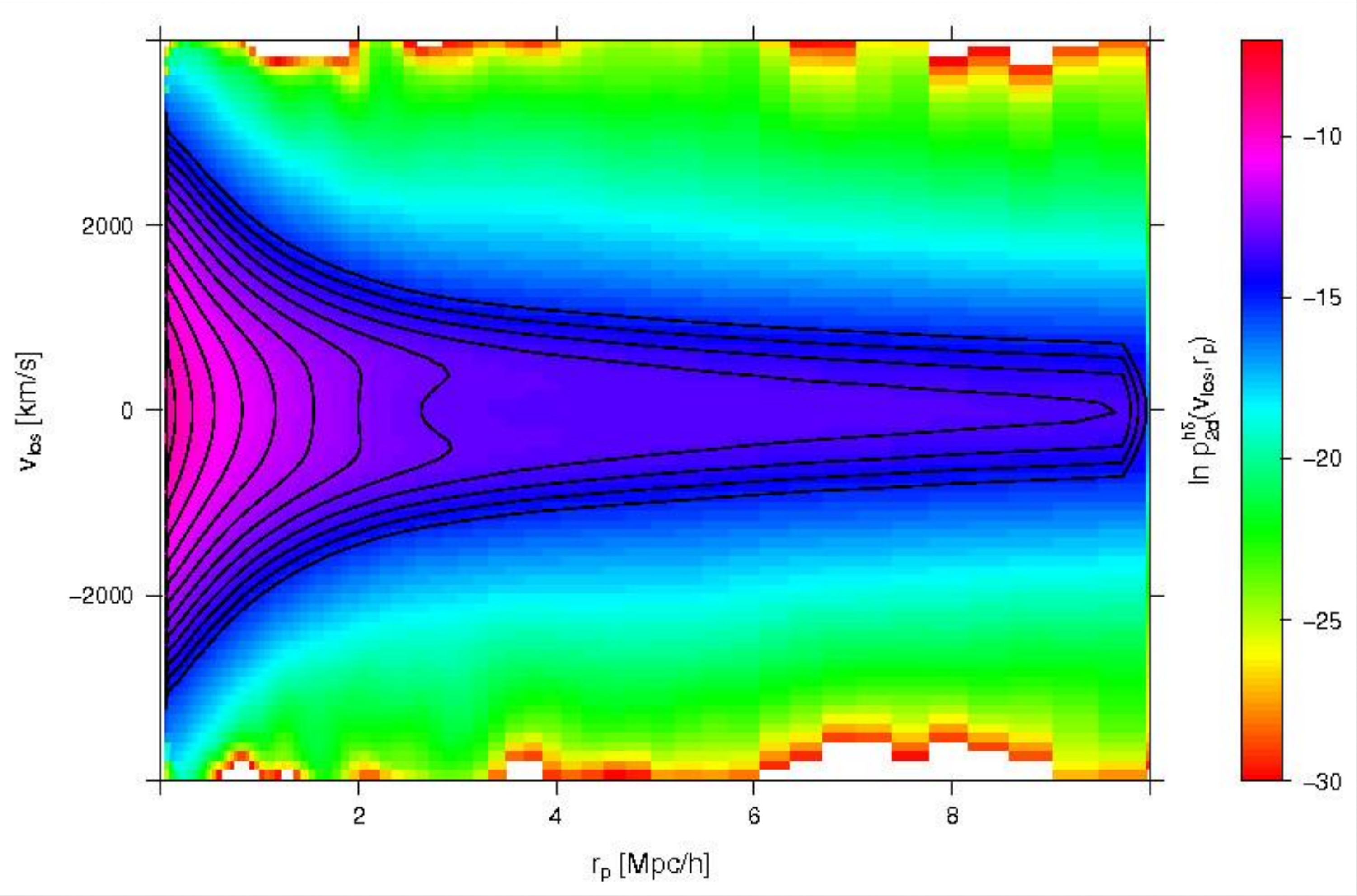
Observables: r_p and v_{los}

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

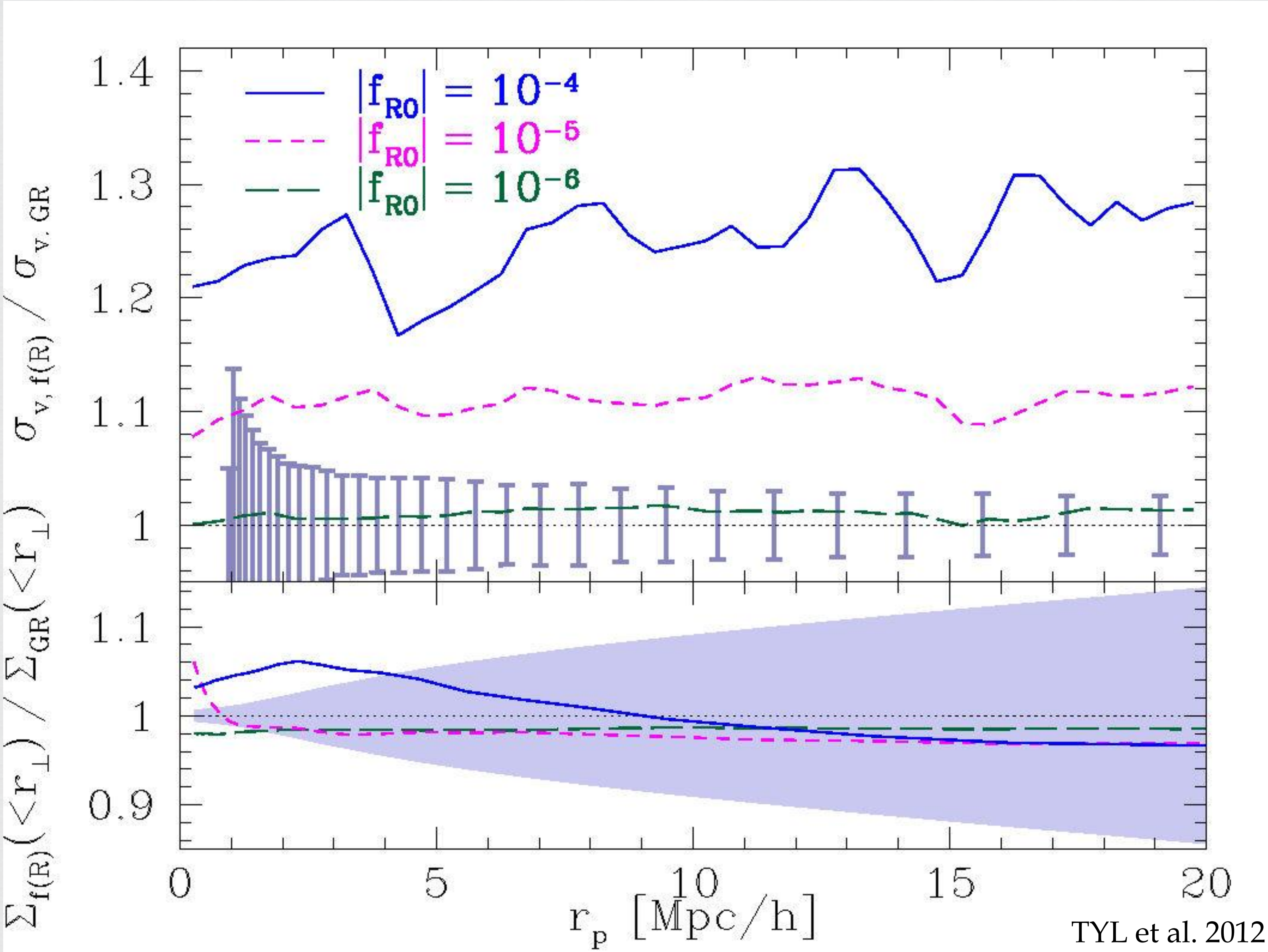


TYL et al. 2013

Stacking 2000 clusters

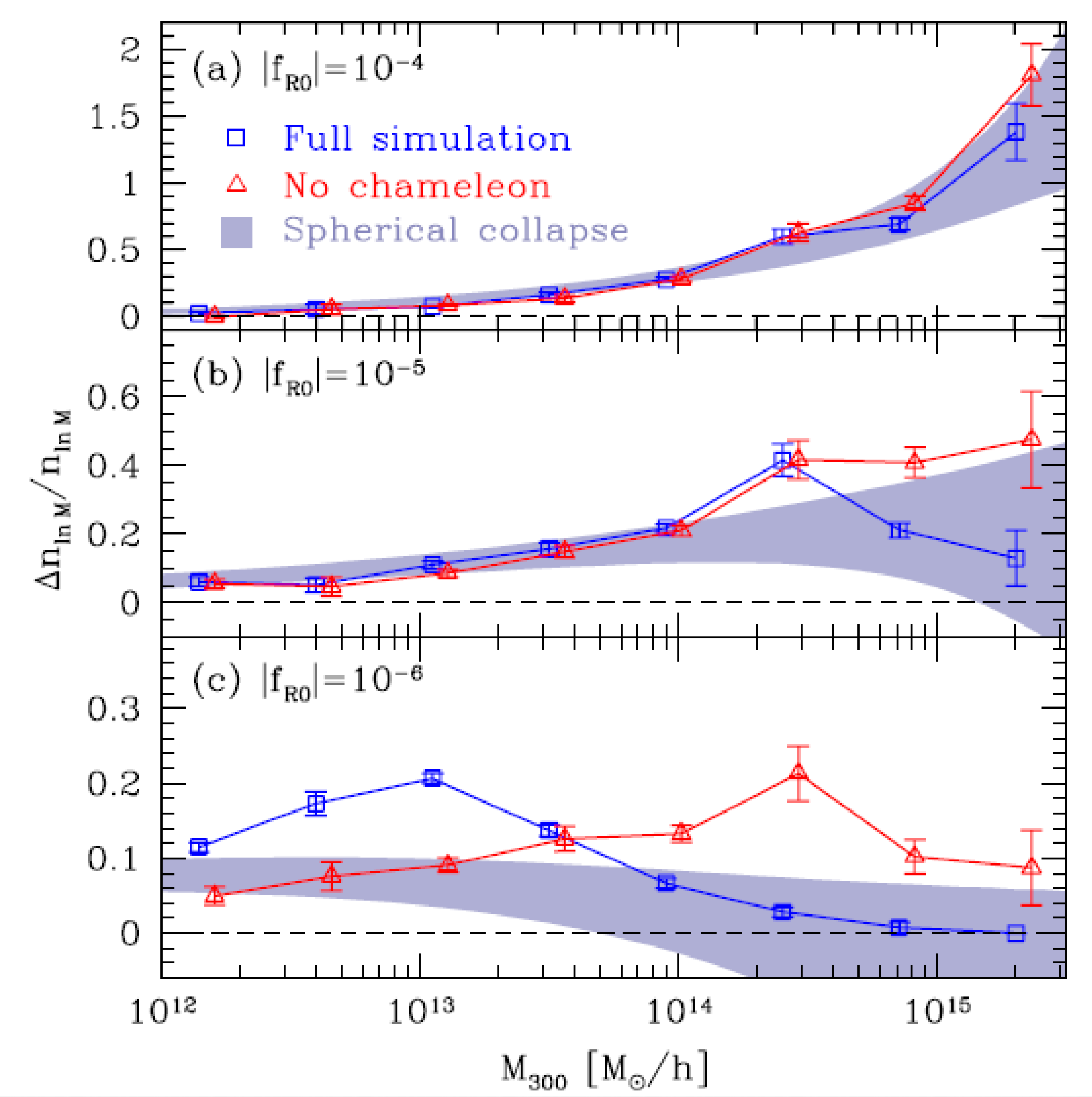


TYL et al. 2013



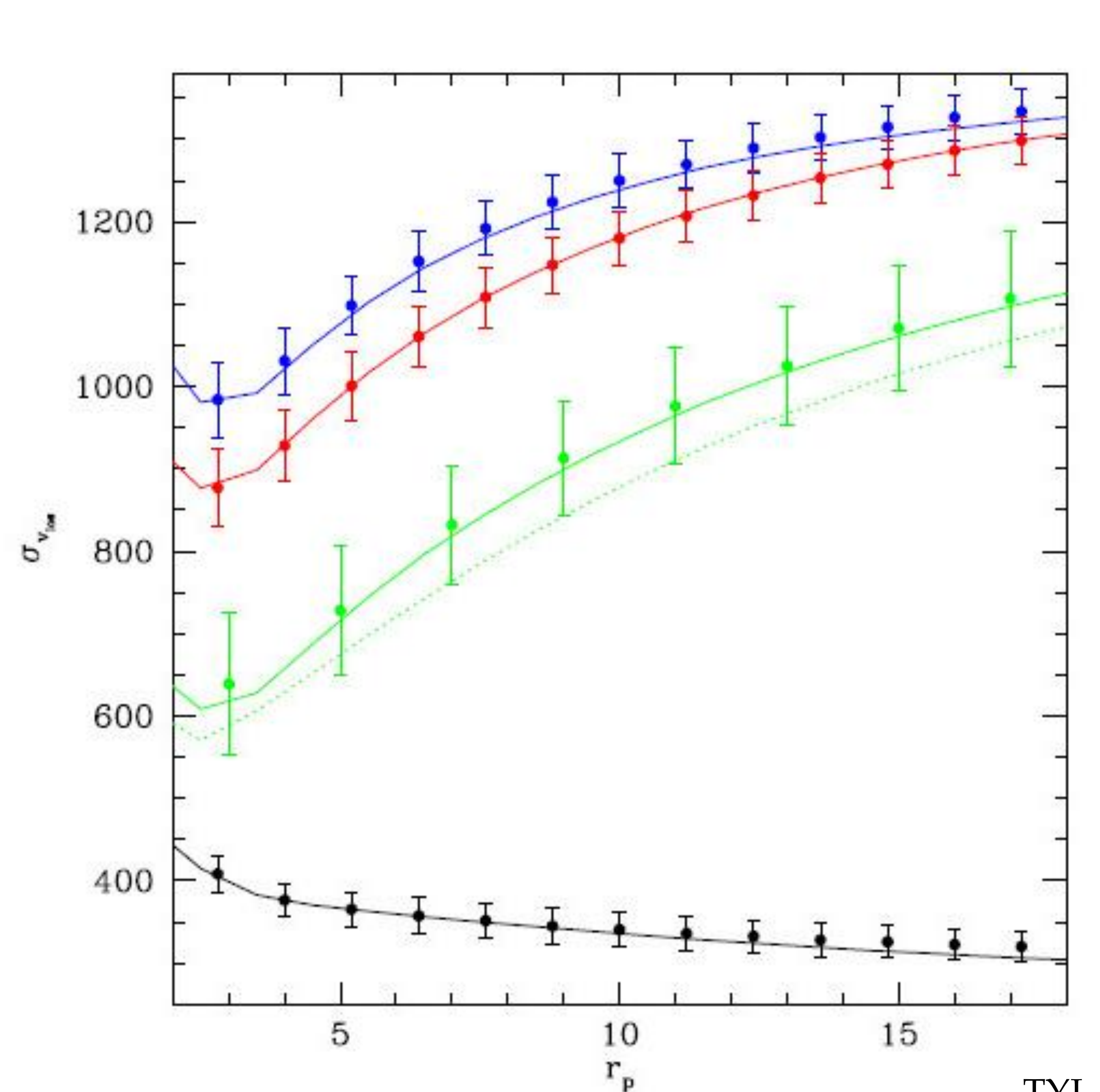
Significant modification in (line-of-sight) velocity dispersion

Same model, but showing change in the mass function



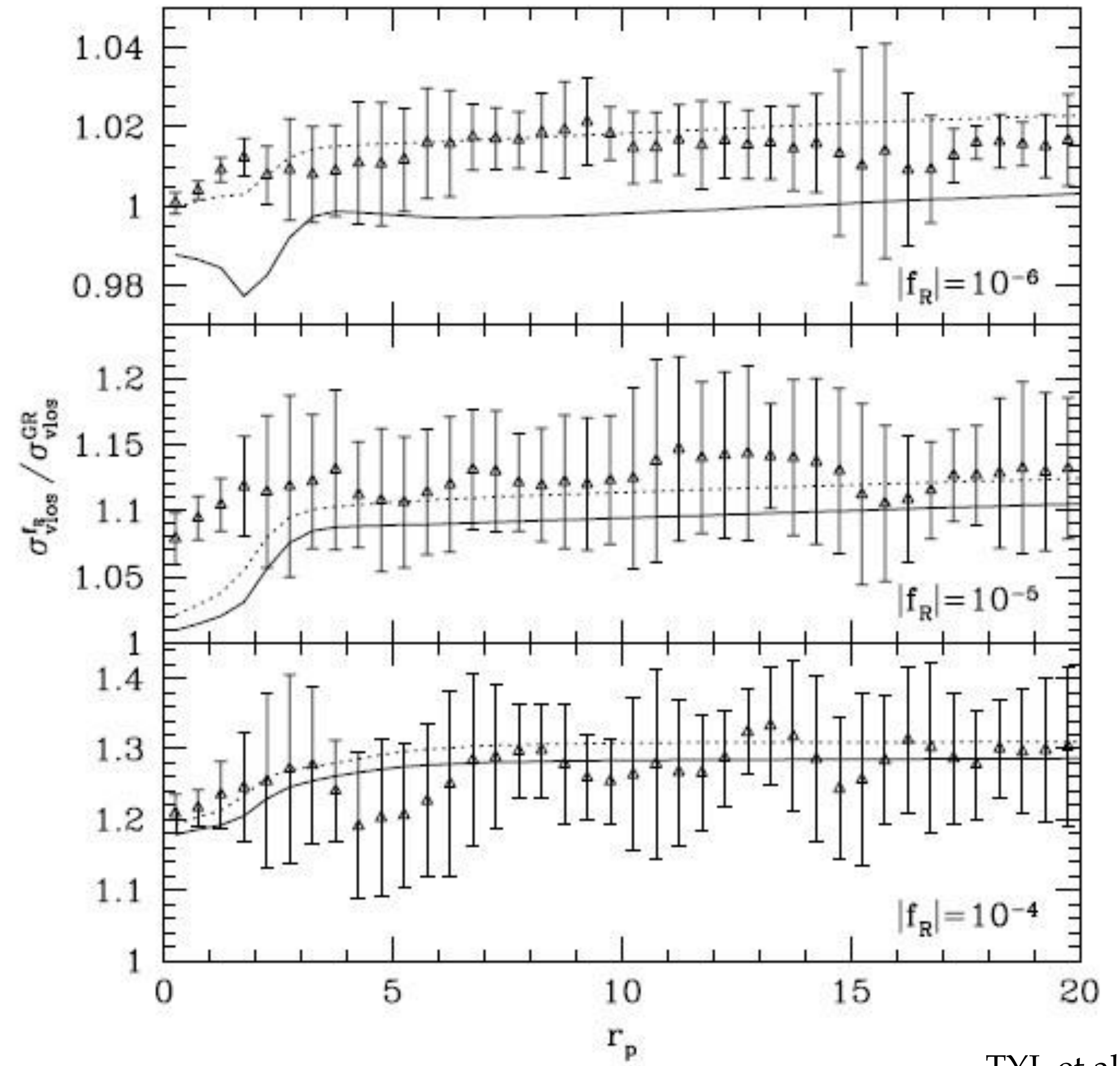
Schmidt et al. 2009

We construct a model to describe this phase-space distribution



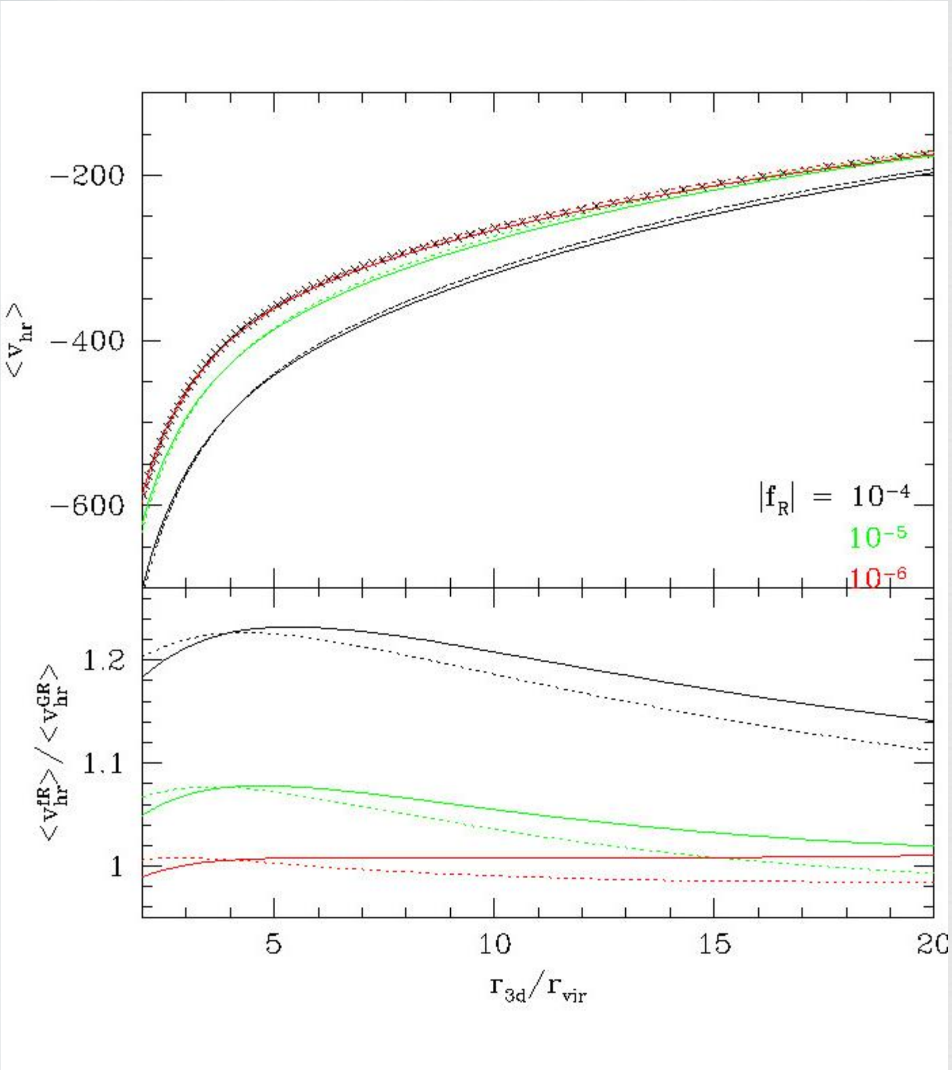
TYL et al. 2013

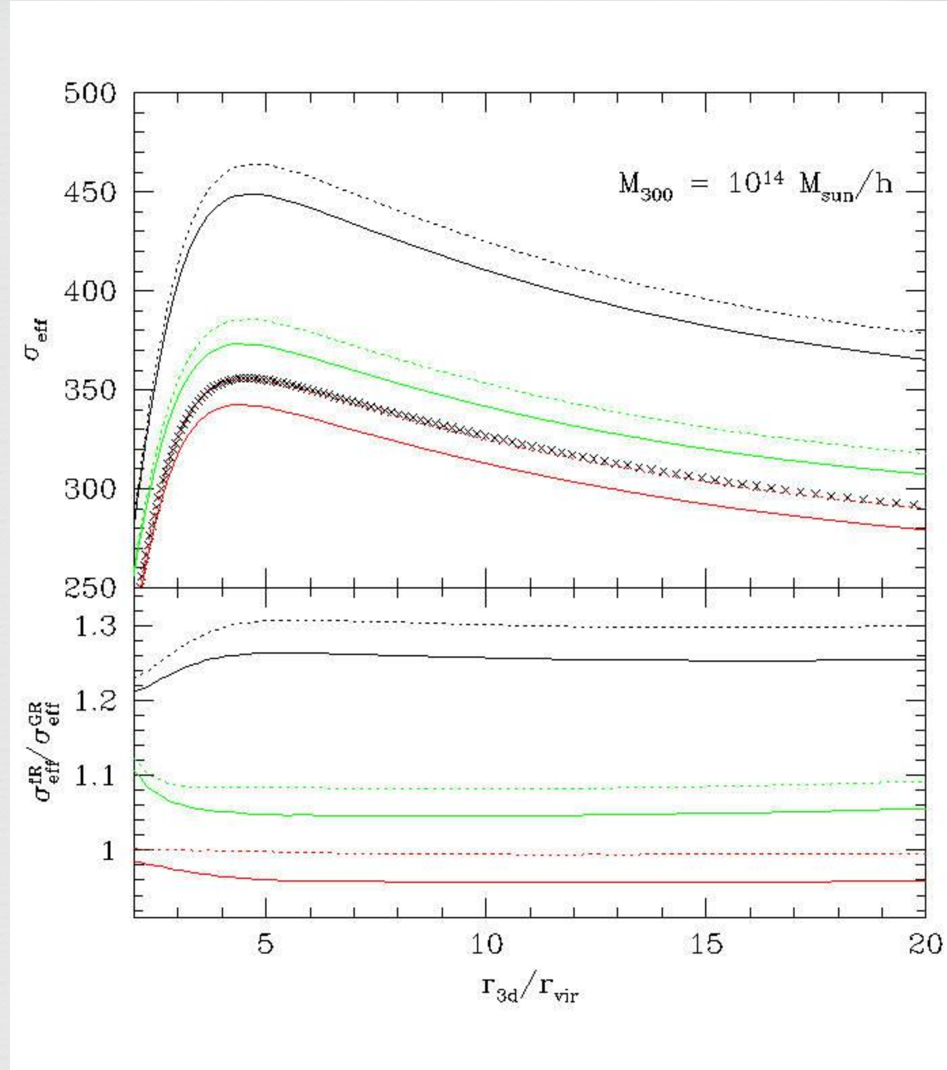
Halo-halo pairs, GR



TYL et al. 2013

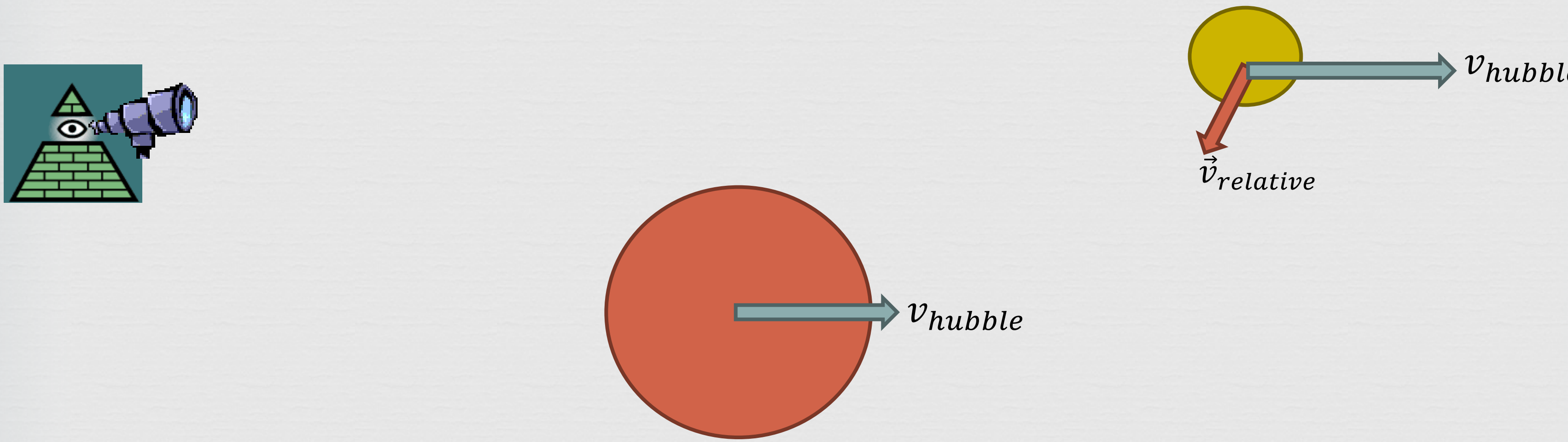
Models match well with measurements from f(R) simulation





Modification in velocity dispersion comes from different components: 2 examples in which the signature is unique in MG models

But life is not that easy…

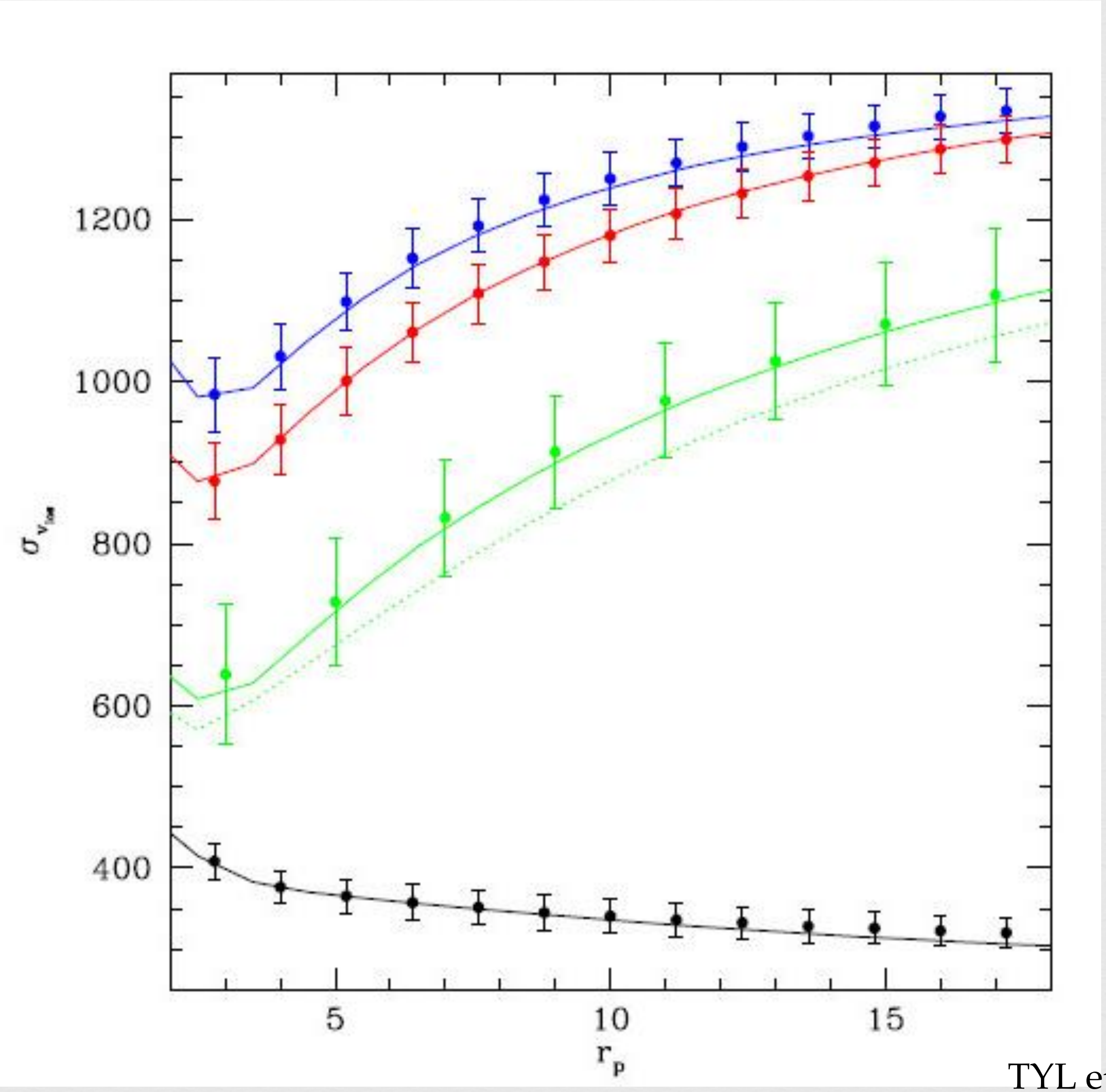


1. $\mathrm{v}_{\mathrm{los}} = \vec{\mathrm{v}}_{\mathrm{relative}} \cdot \hat{\mathrm{z}} + \Delta \mathrm{v}_{\mathrm{hubble}}$

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.

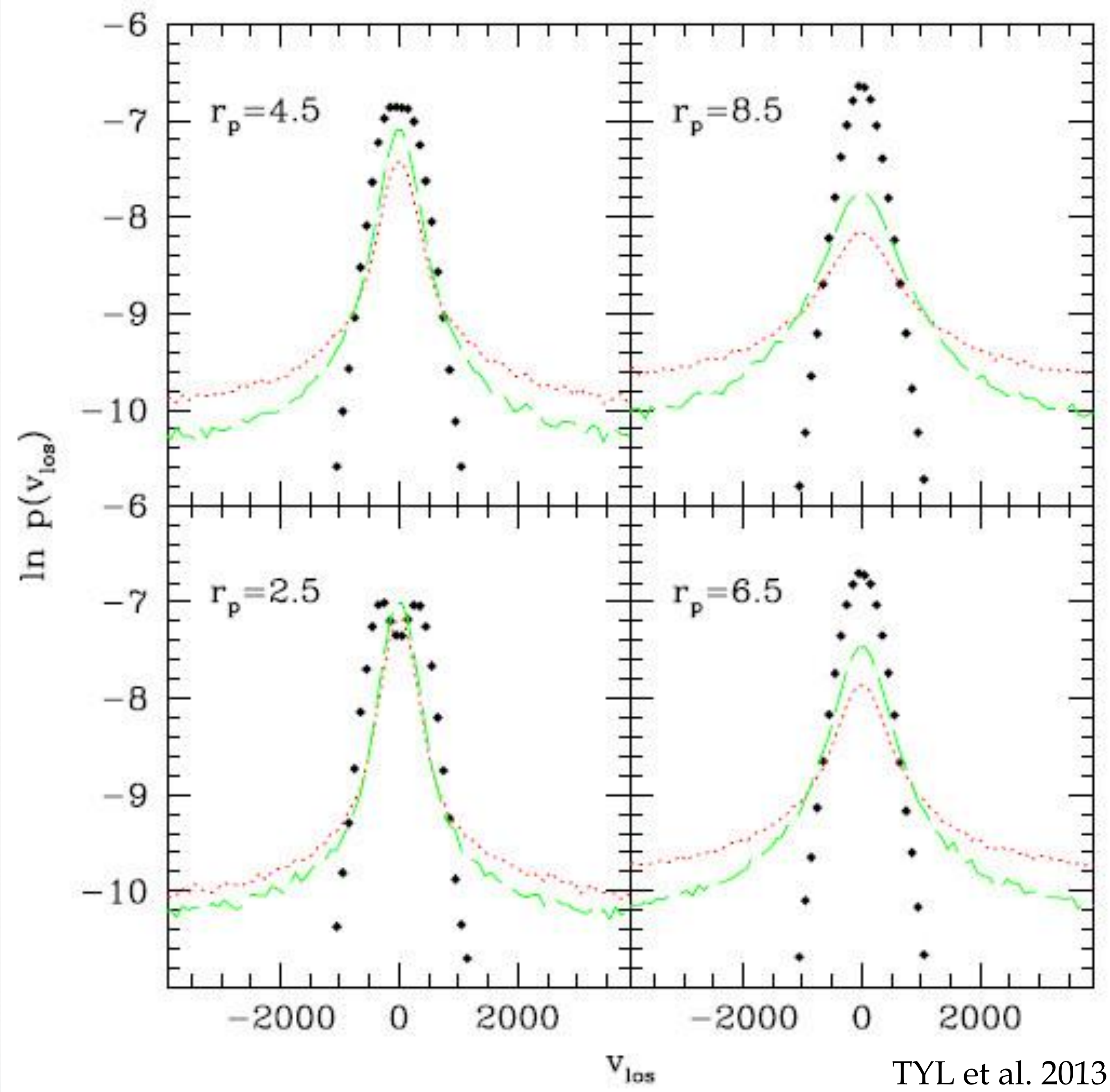
Hubble Flow contamination



TYL et al. 2013

Halo-halo pairs, GR

Information in the full phase-space distribution



TYL et al. 2013

- 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

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.