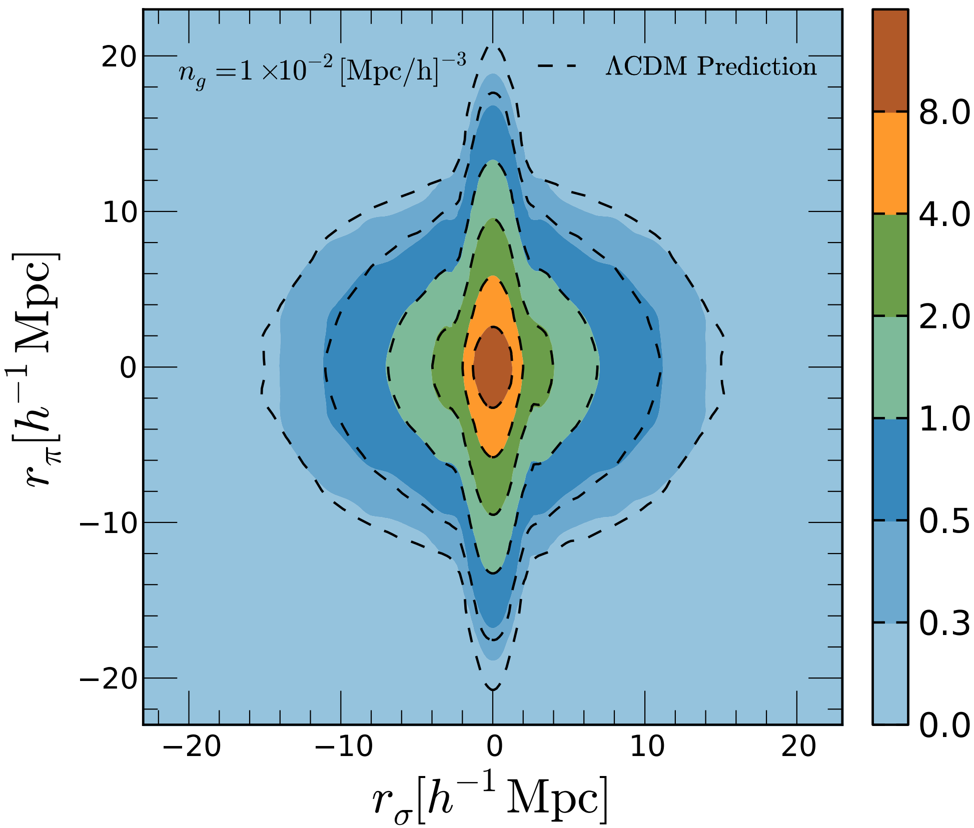
No evidence for departures from General Relativity from the clustering and velocities of galaxies on cosmological scales



Jianhua He

With Luigi Guzzo, Baojiu Li, Carlton Baugh

Sesto, Italy

03-07-2018

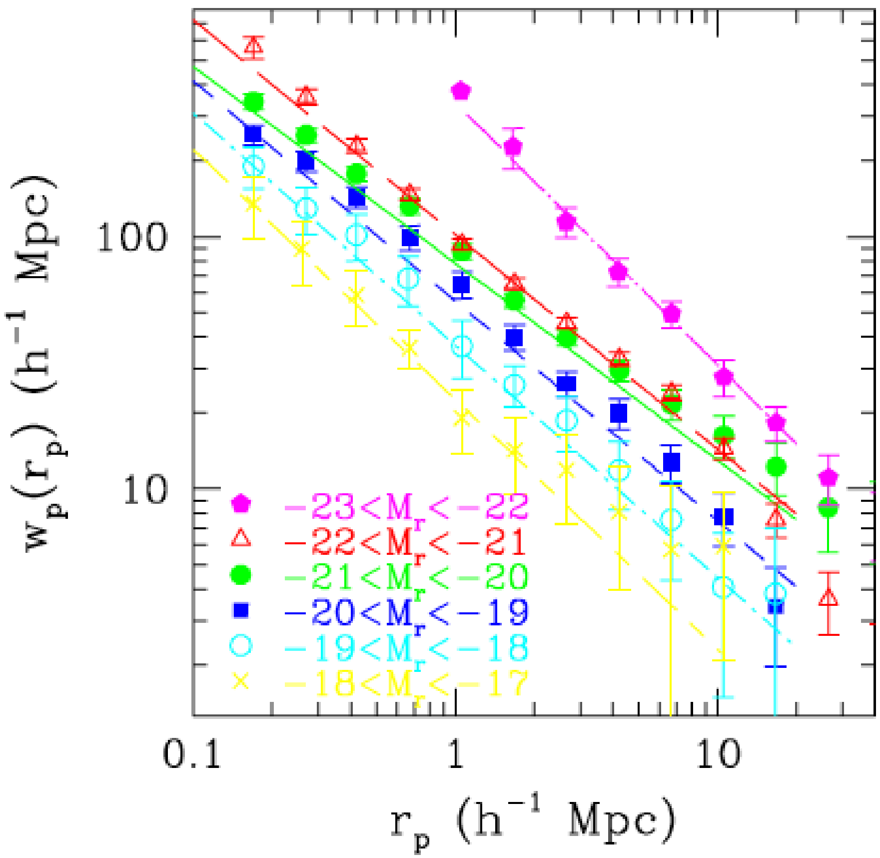
Outline

- Theory
- The theoretical challenge of testing theory of gravity
- How we can solve these problems
- Data
- What kind of data we need
- How to control systematics

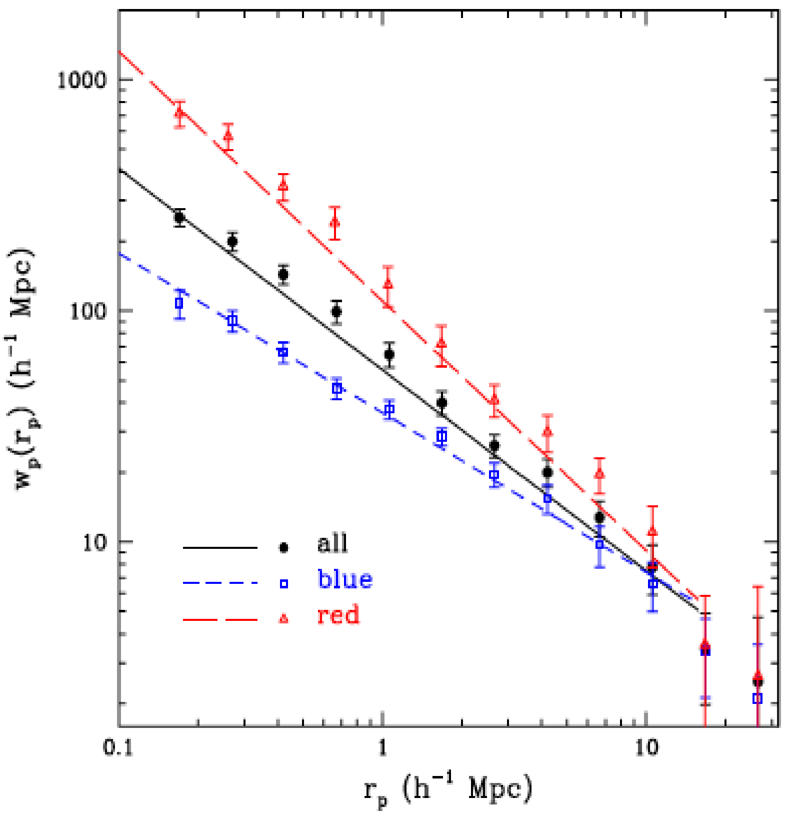
THEORY

The dependence of galaxy clustering on galaxy's property

Luminosity Dependence



Color Dependence

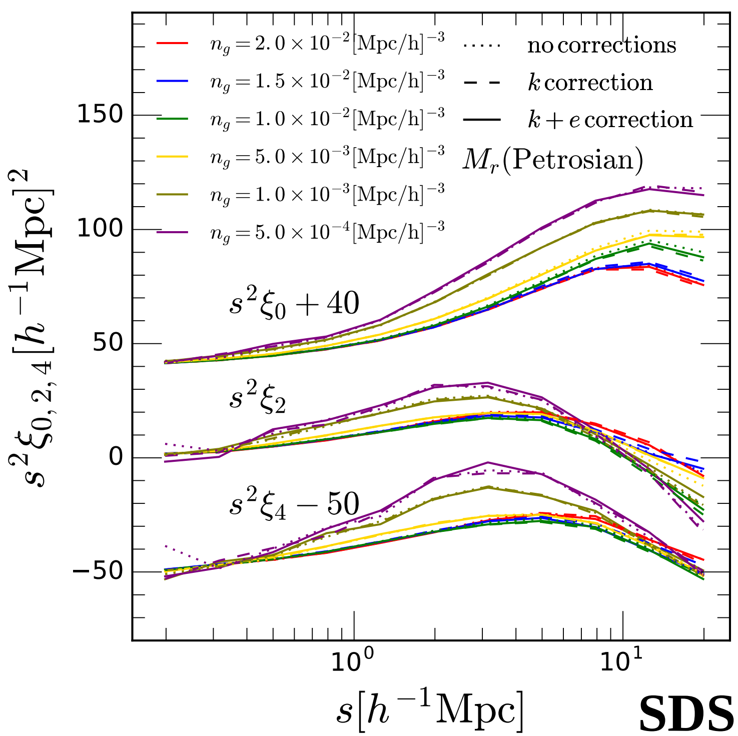


Zehavi, et al 2004

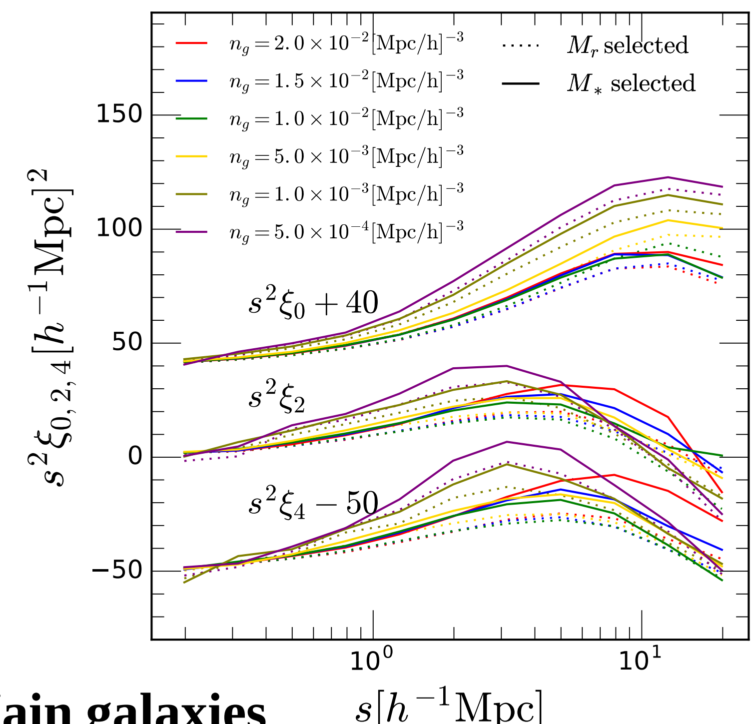
The dependence of redshift space galaxy clustering on galaxy's property

- For the *r*-band selection, galaxy clustering of volume-limited sample depends on the number density of samples
- For the same number density, *r*-band selected and stellar-mass selected galaxies have different clustering

r-band selection



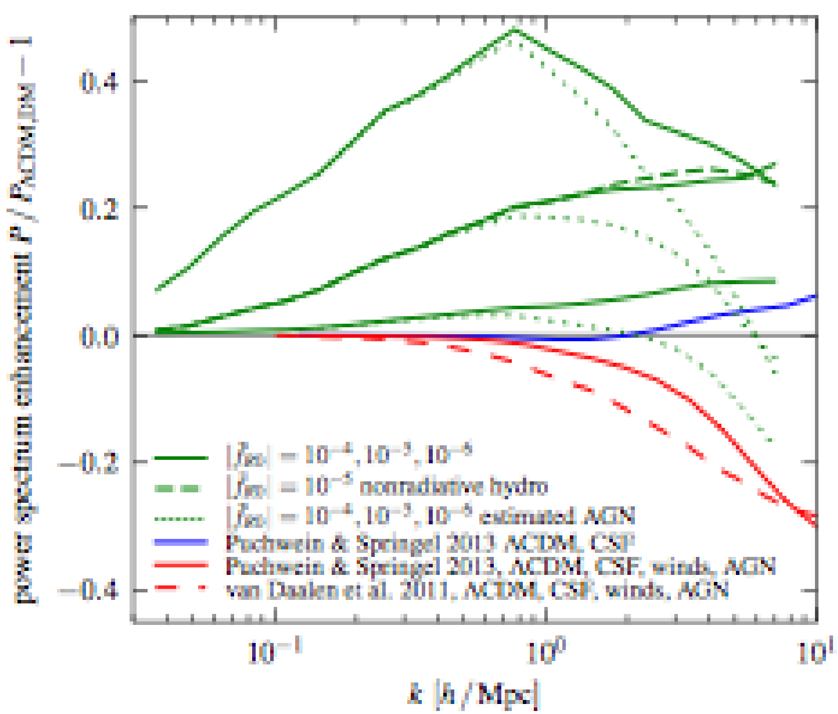
r-band VS stellar mass selection



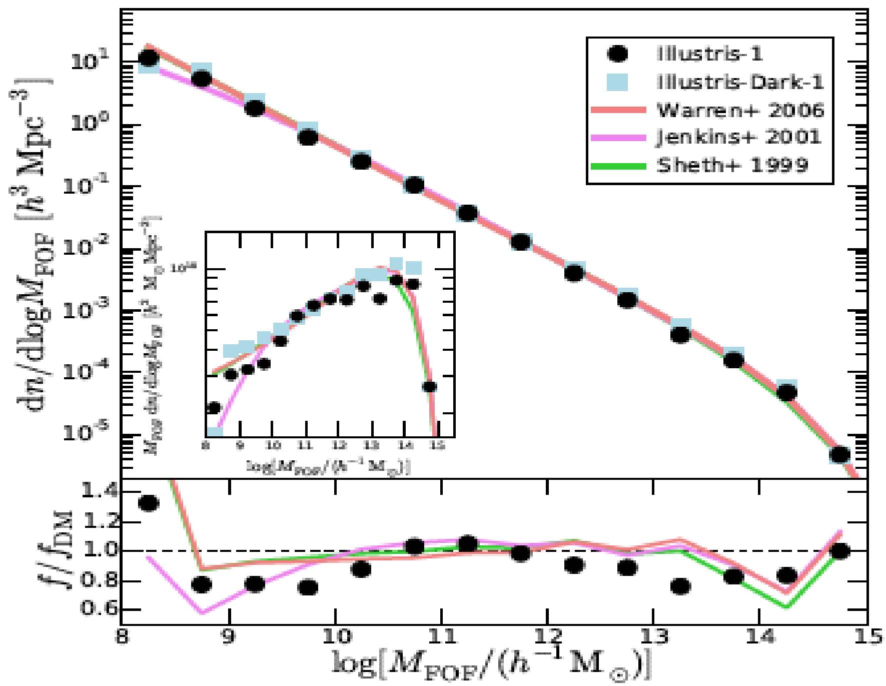
SDSS Main galaxies

The impact of baryon physics on the distribution of matter and abundance of halos

- AGN feedback changes the underlining distribution of the cold dark matter on small scales.
- AGN feedback changes halo mass function as well, even at the very massive end



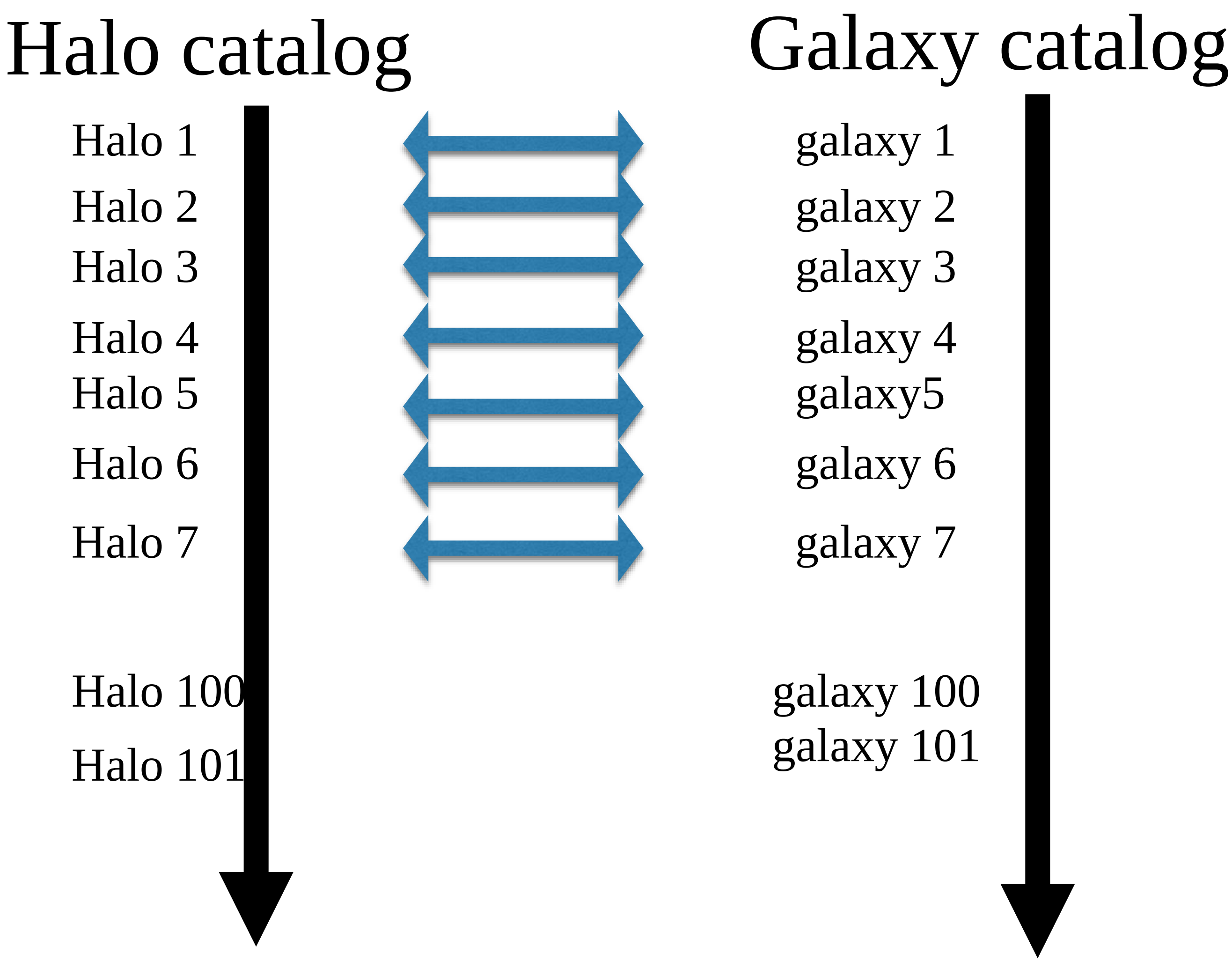
Puchwein et al (2013)



Mark Vogelsberger et al (2013)

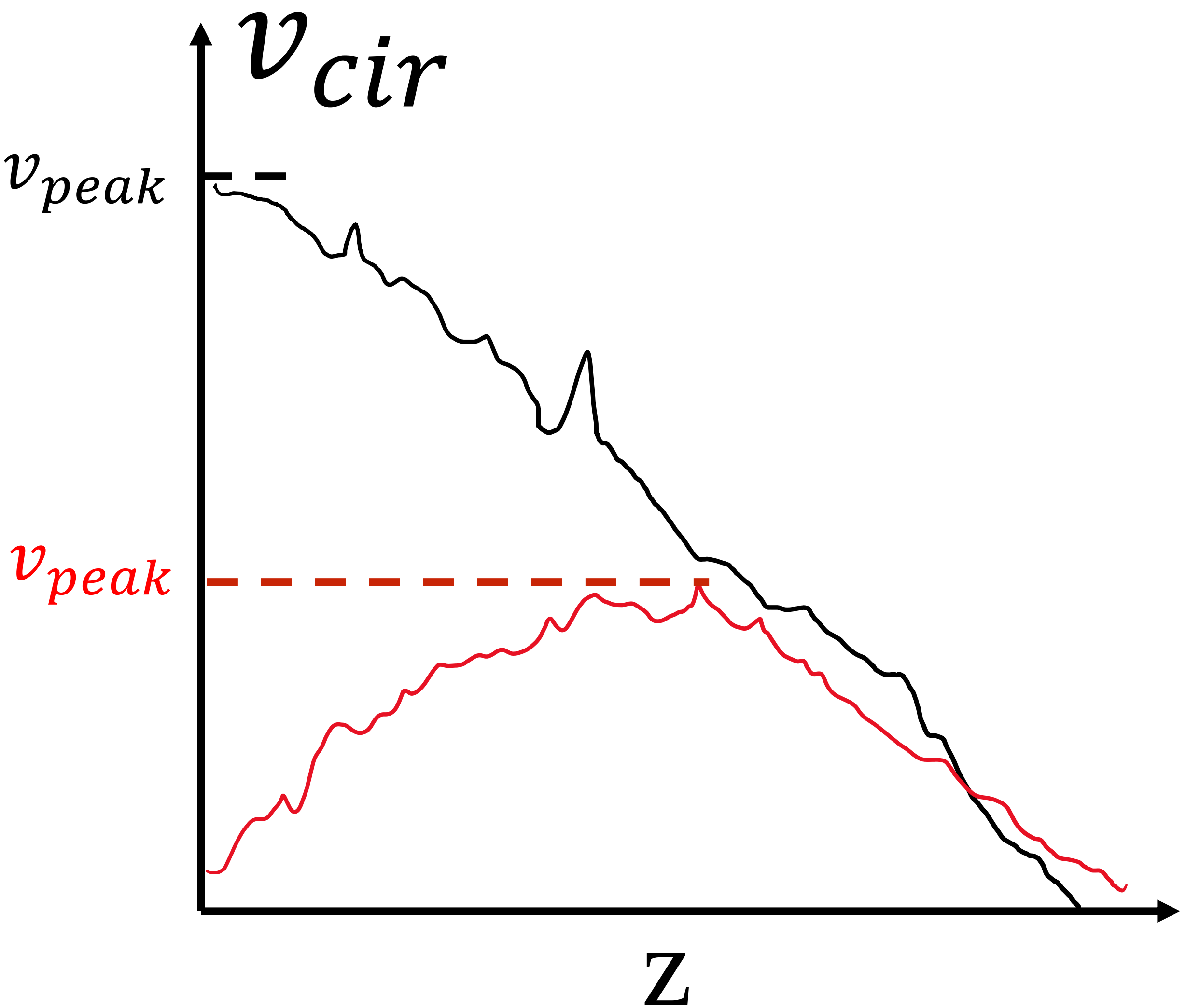
What can we do?

Halo property VS Galaxy property

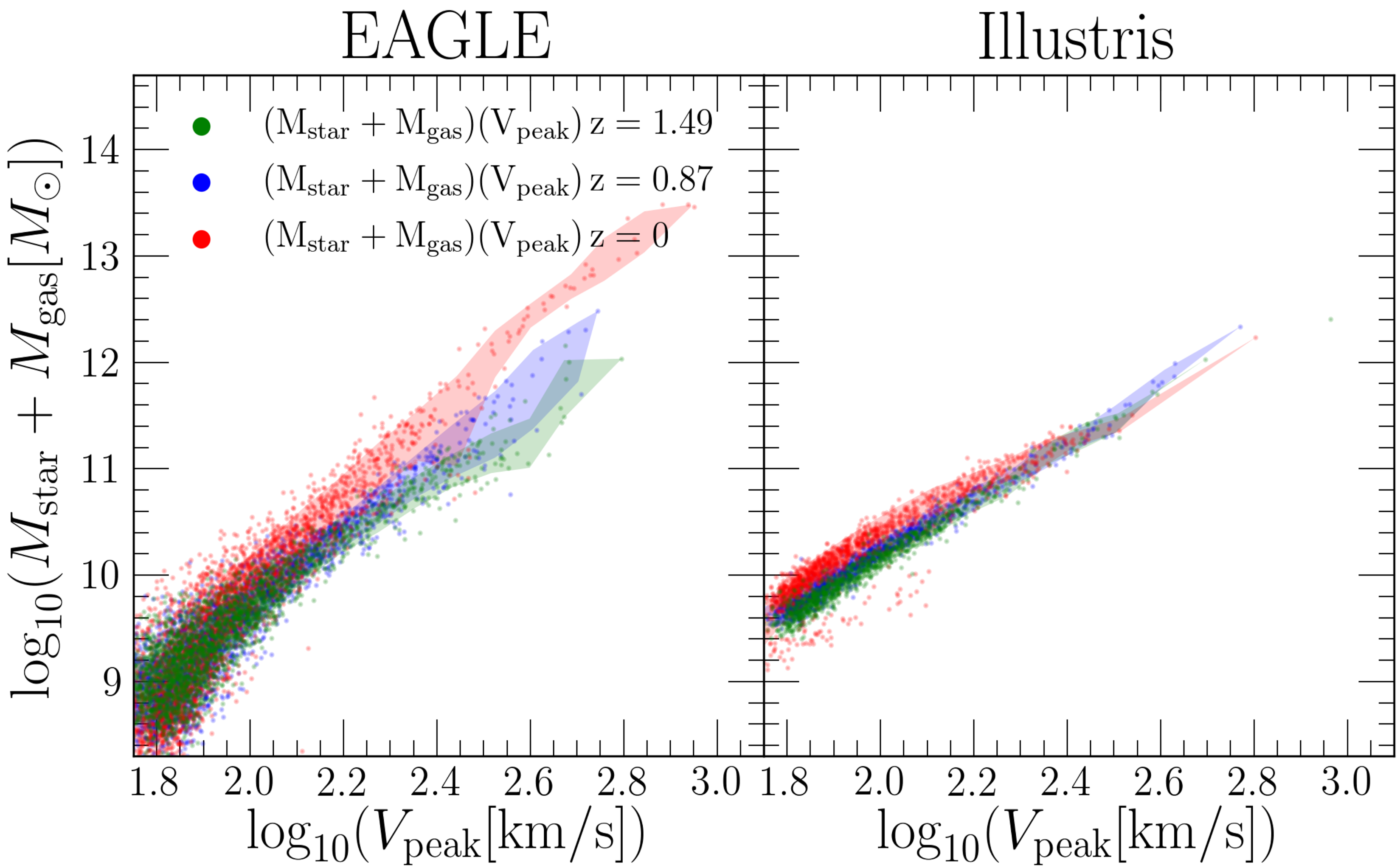


One to one map between halos and galaxies

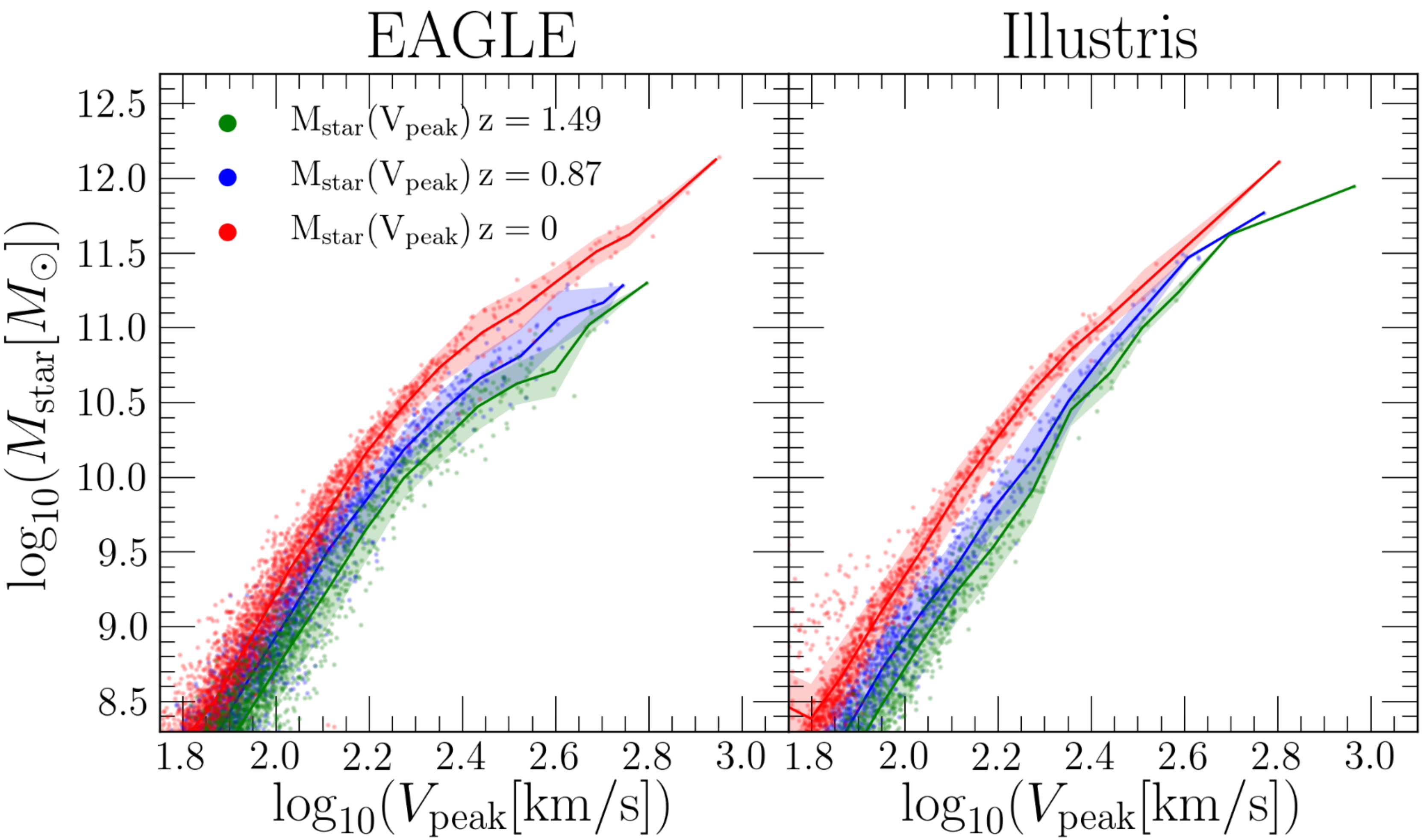
Dark matter halo accretion history



Total baryonic mass of galaxies at the epoch of V_{peak}

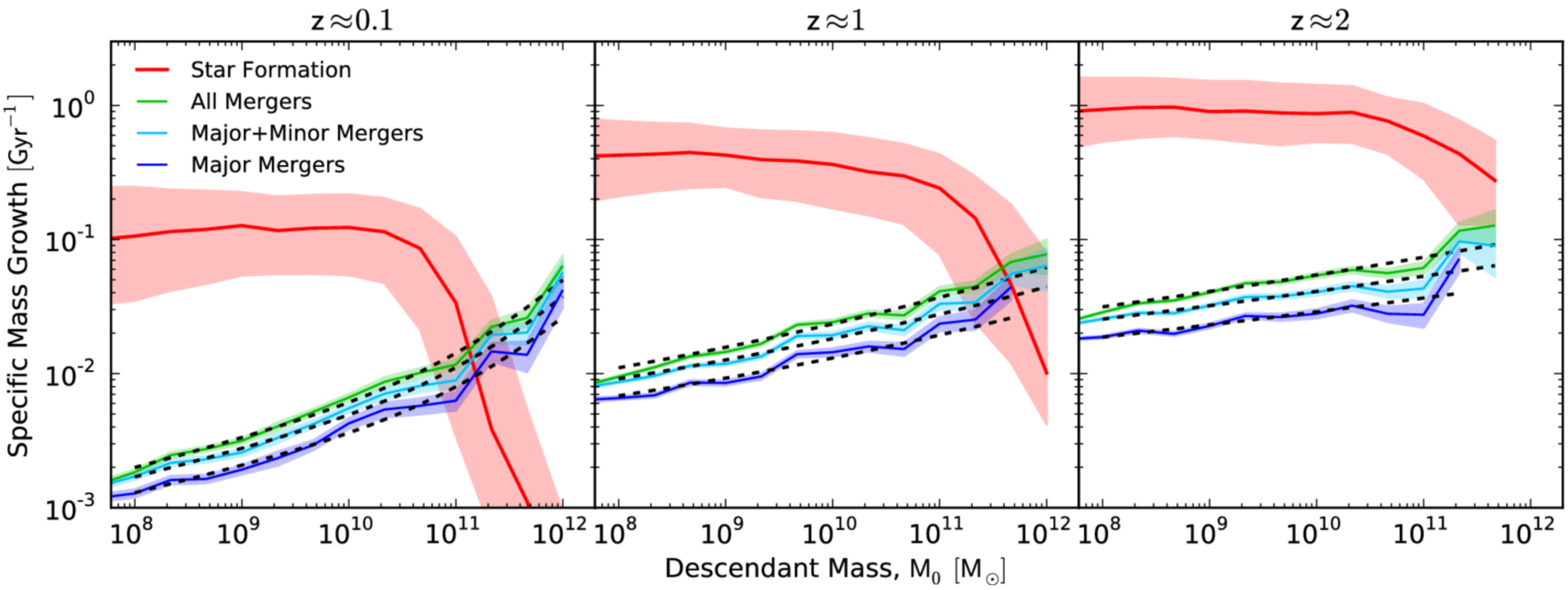


Stellar mass of galaxies at the epoch of V_{peak}



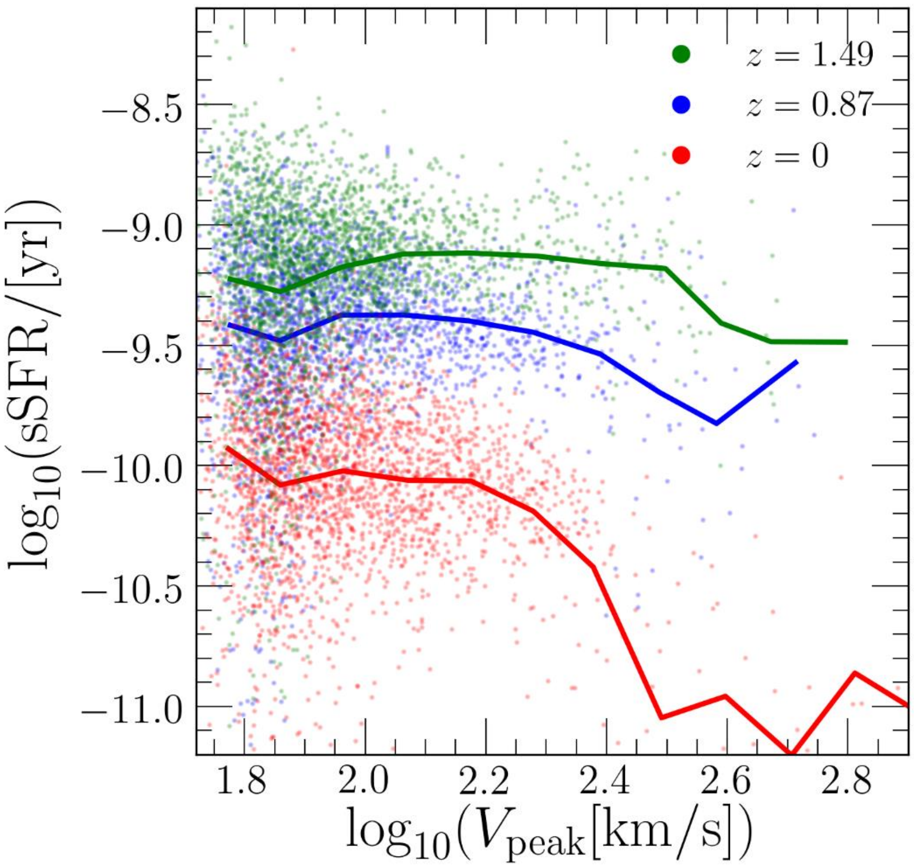
Stellar mass is gravity specific

- Most stellar mass of galaxies come from star forming while not from the merger of galaxies, except most massive ones



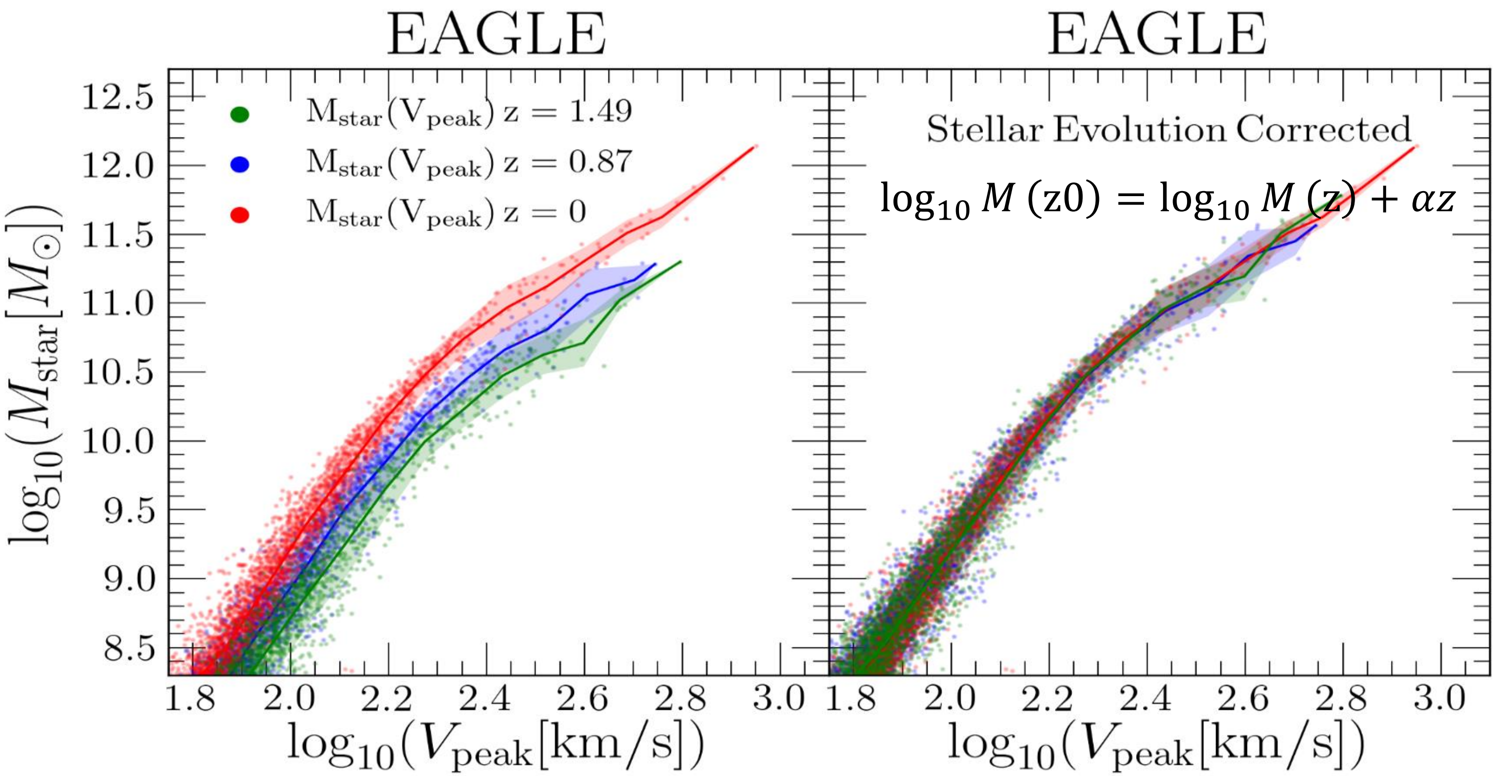
Stellar mass is gravity specific

- The specific star forming rate of the main sequence galaxies is nearly constant

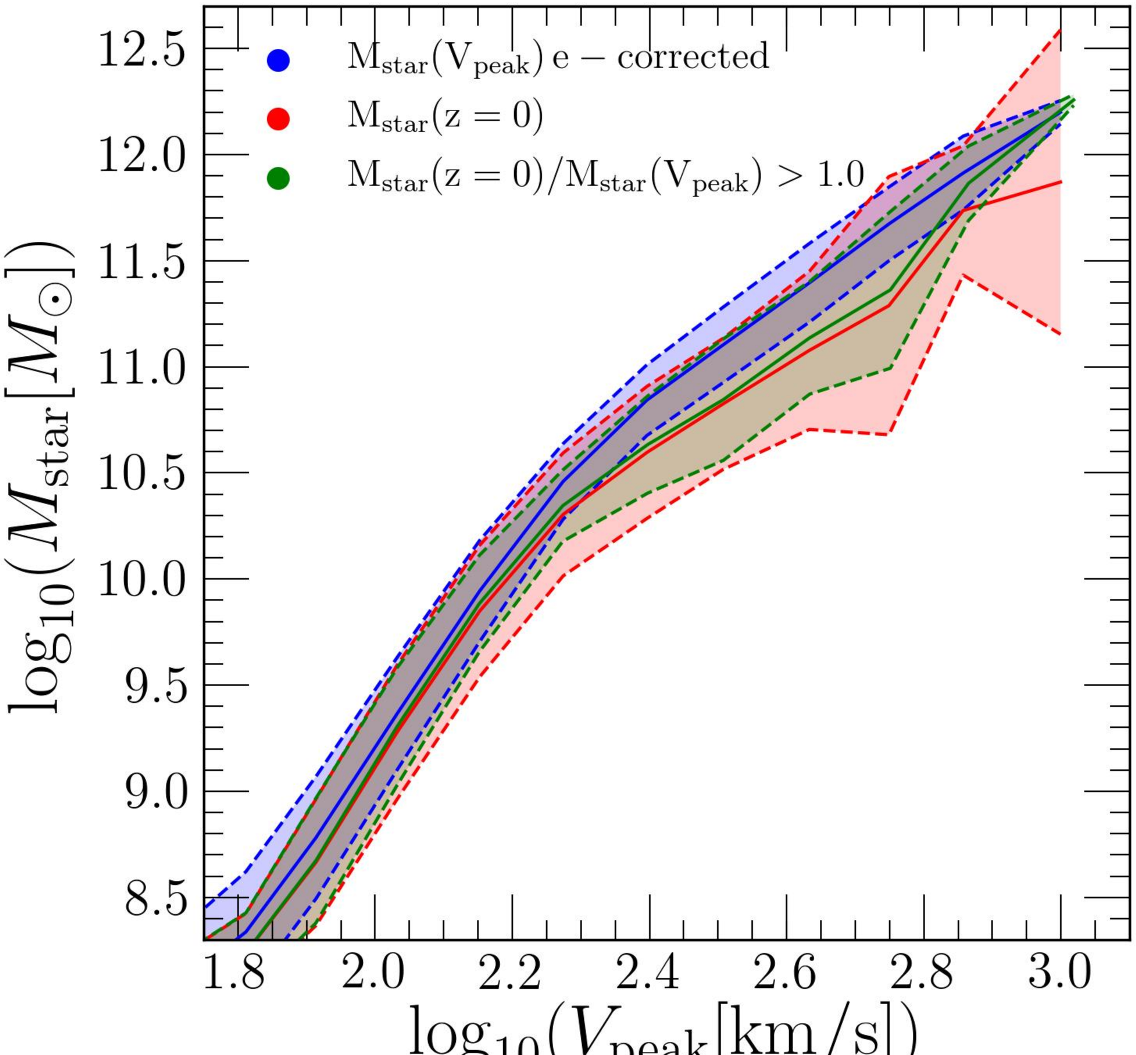


Stellar mass is gravity specific

- The scaling relation at different redshifts can be normalized to an epoch using a very simple evolution model
- M_* of a halo at the epoch of V_{peak} is only a function of $(V_{peak}, redshift)$
- The intrinsic scatter is very small

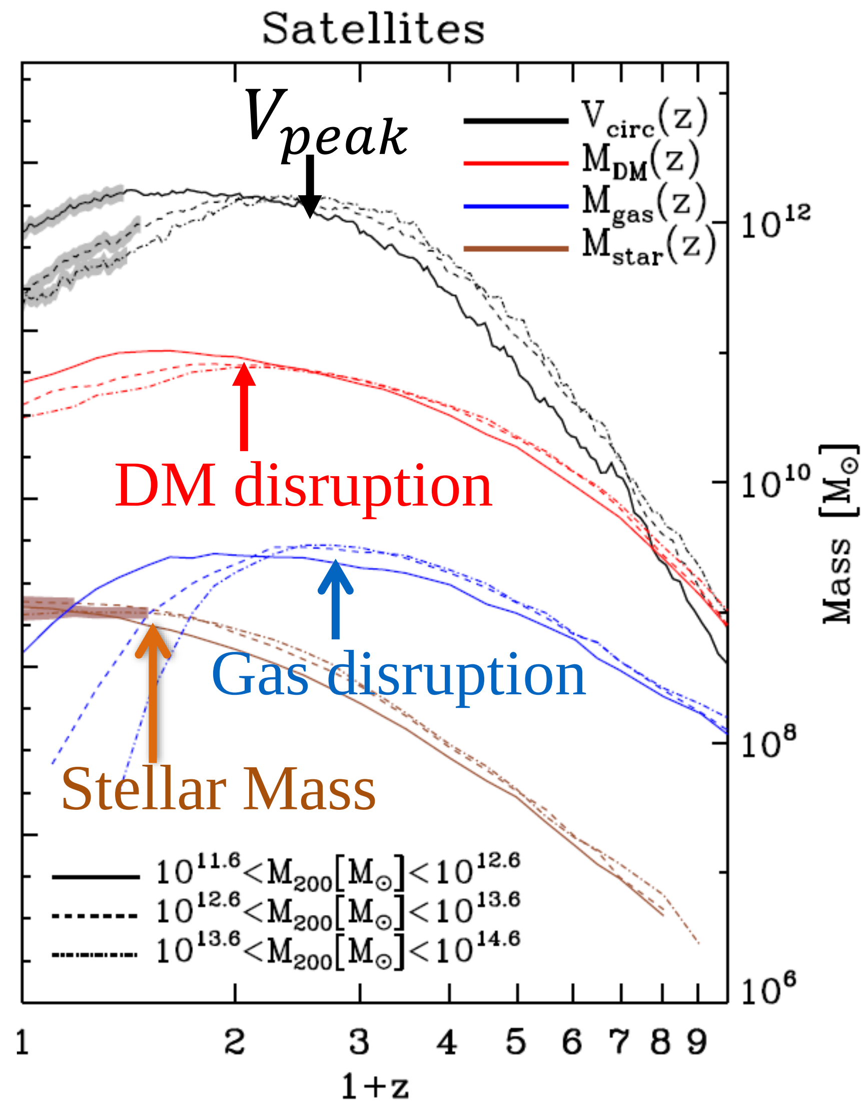


The scatter in $V_{peak} - M_*(z=0)$relation



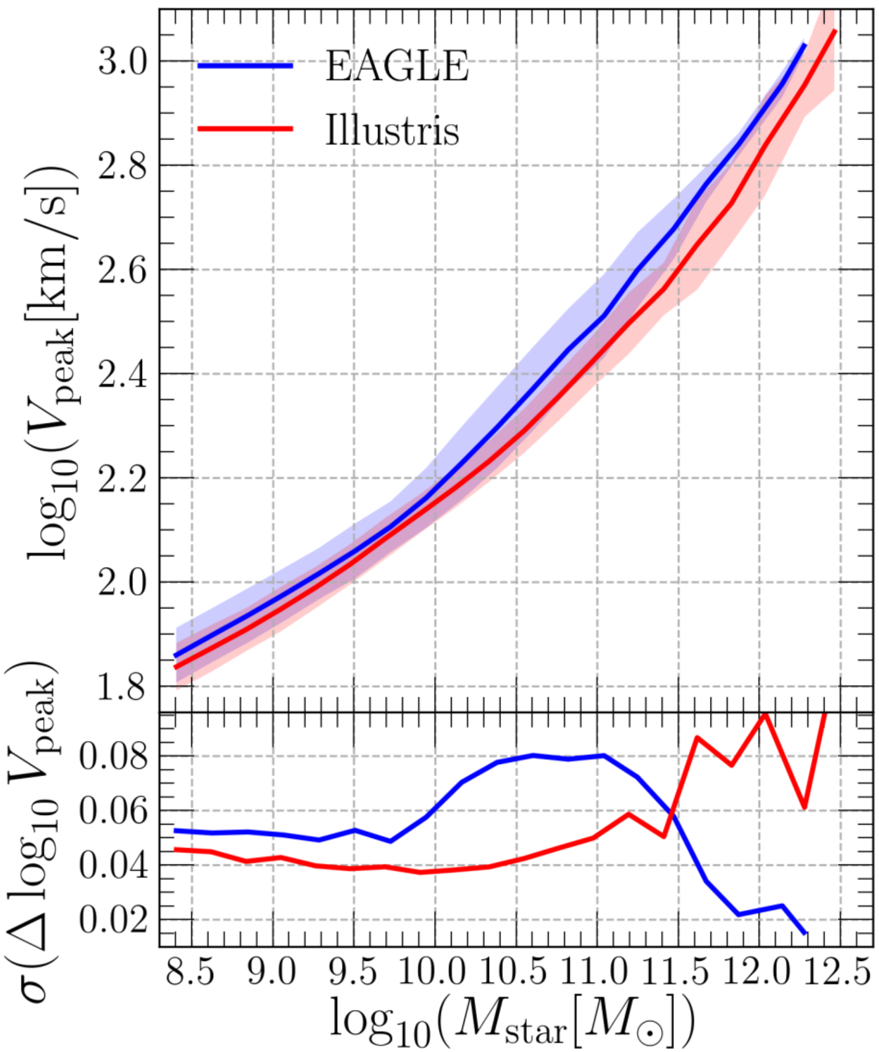
The origin of scatter in $V_{peak} - M_*(z=0)$relation

- Dark matter can be striped after V_{peak} due to gravitational tidal force
- Gas component can be more easily striped due to both tidal force and ram-pressure.
- After V_{peak} , stellar mass can grow due to the continuing of star forming. But stellar mass can also be lost due to stellar mass striping. These two effects cause the scatter in $V_{peak} - M_*(z=0)$ relation.



The origin of scatter in $V_{peak} - M_*(z=0)$relation

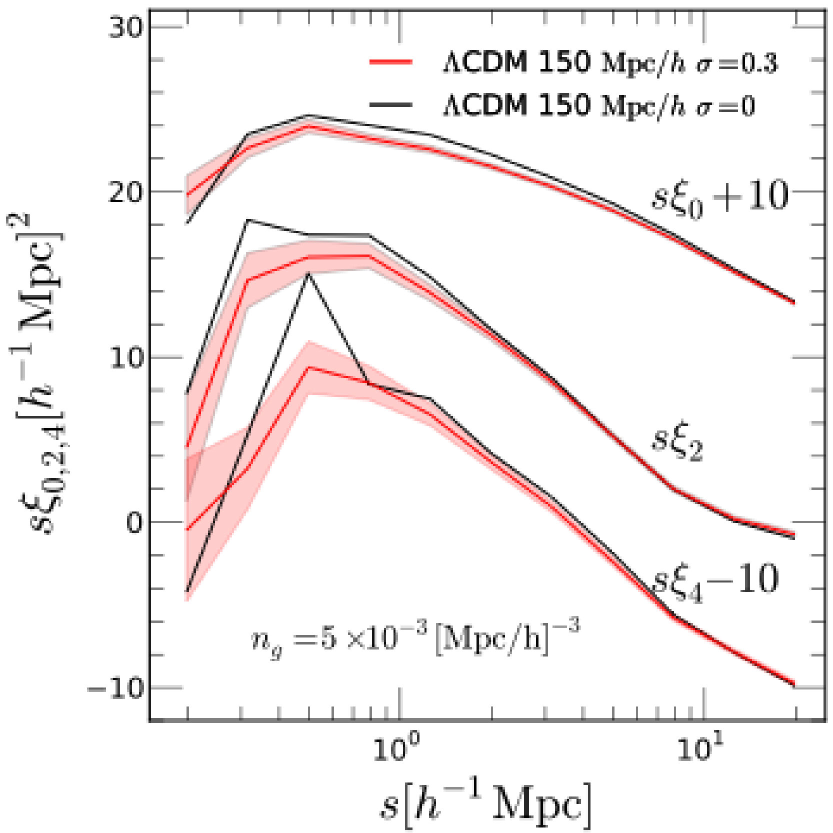
- Stellar mass striping is the major reason for the scatter but it is very like due to numerical issues but not real physical reason.
- Feedback does not blow a star away.
- The only interaction between stars is gravity.
- Massive stars can burn-out but they only sub-dominate the total stellar mass of a galaxy.
- A star falling onto a back hole is vary rare



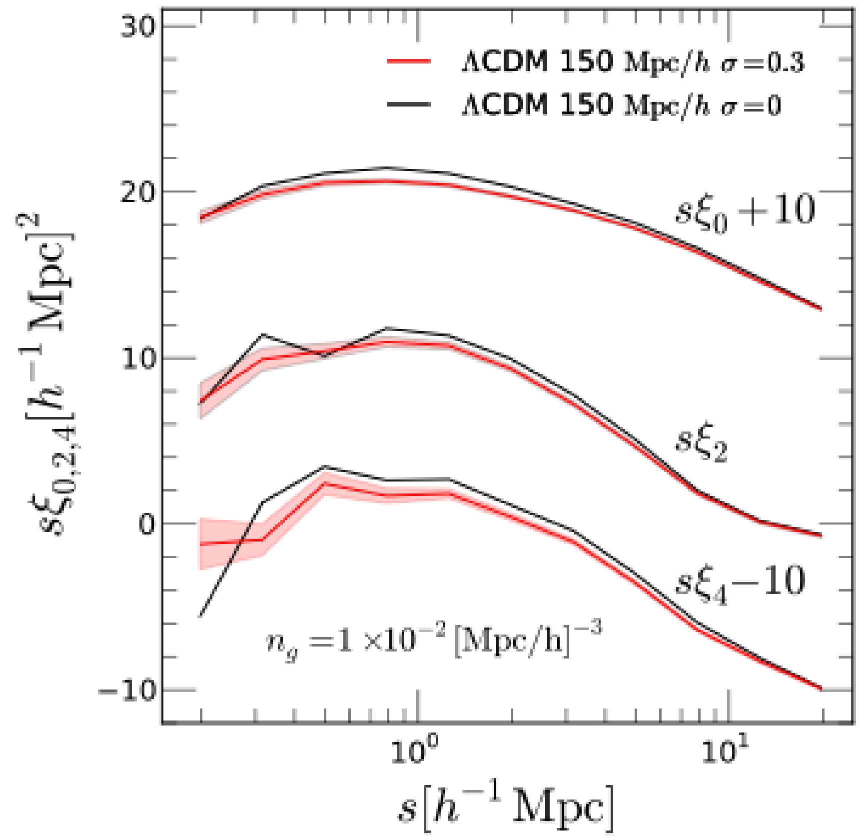
The impact of scatter on clustering

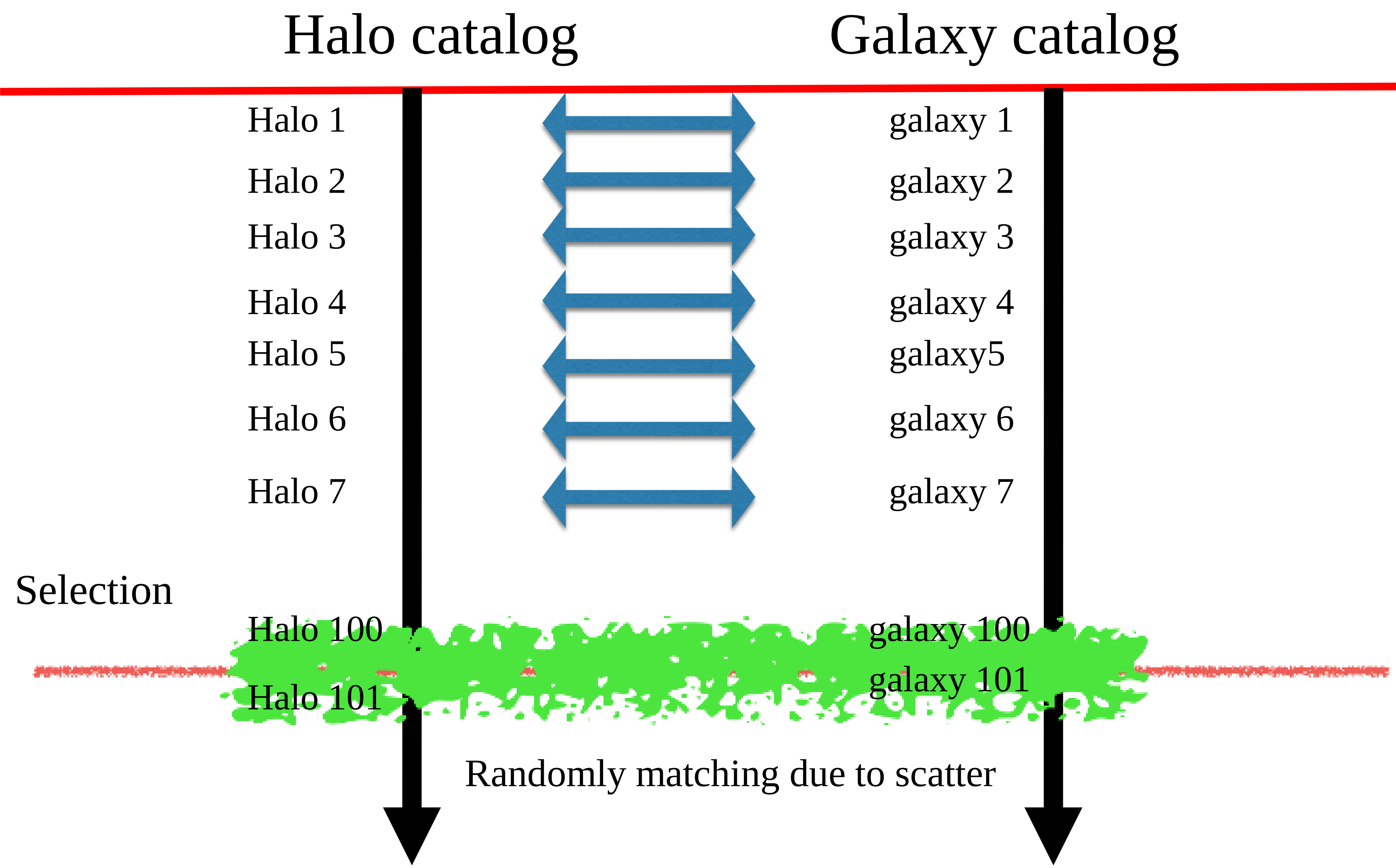
- The impact of scatter can be mitigated by high number densities
- High number density samples are less affected by scatter

Low density



High density

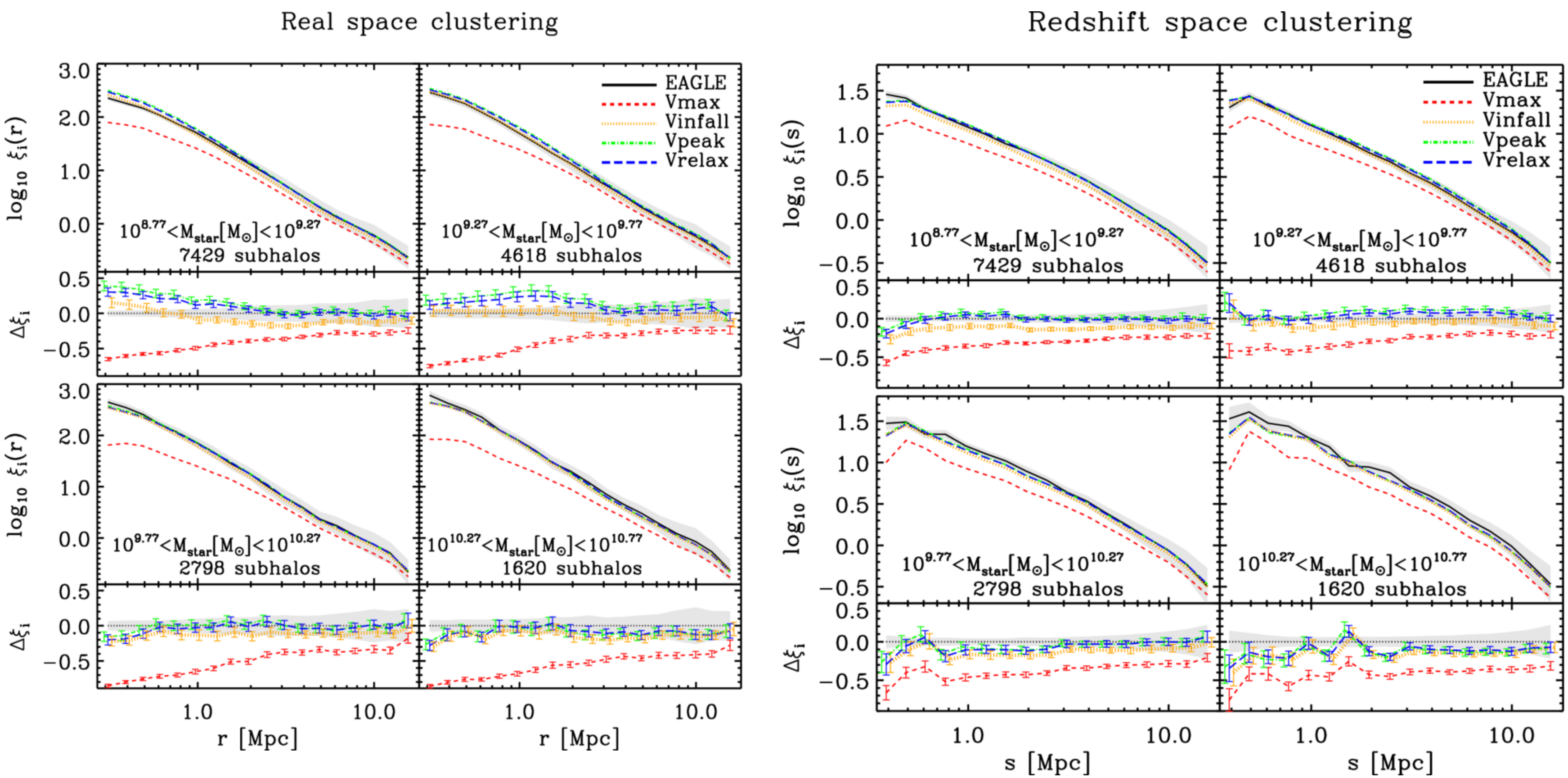




Only samples around the cut are affected by scatters

The impact of baryon physics on subhalo clustering

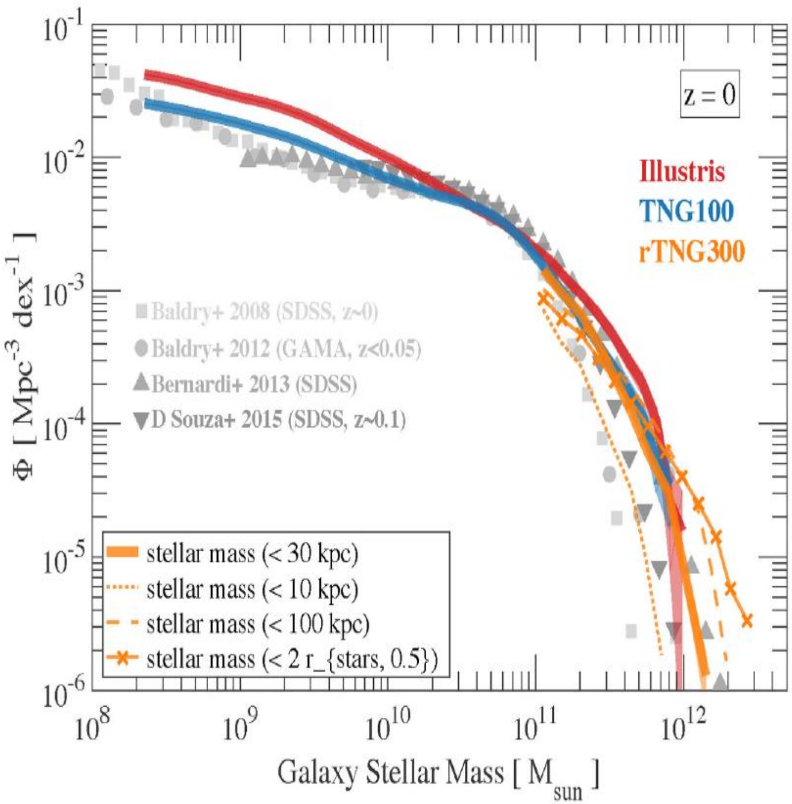
- From the EAGLE simulation, baryon physics has a limited impact on the positions of sub-halos on scales $r > 1\mathrm{Mpc}/h$



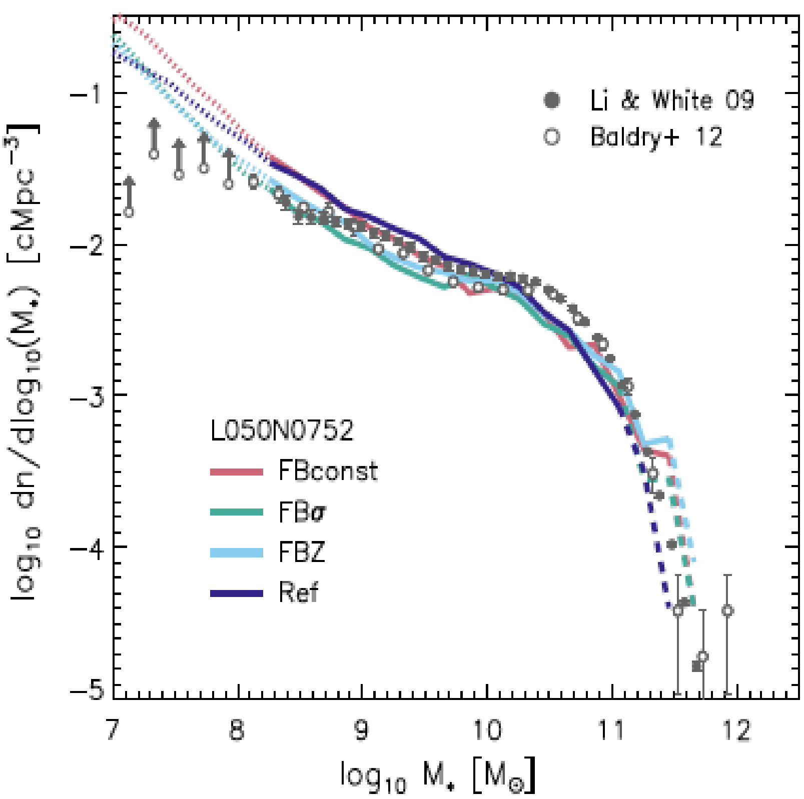
Jonas Chaves-Montero, et al 2015

Stellar mass function in hydro-dynamic simulations

Illustris and Illustris TNG

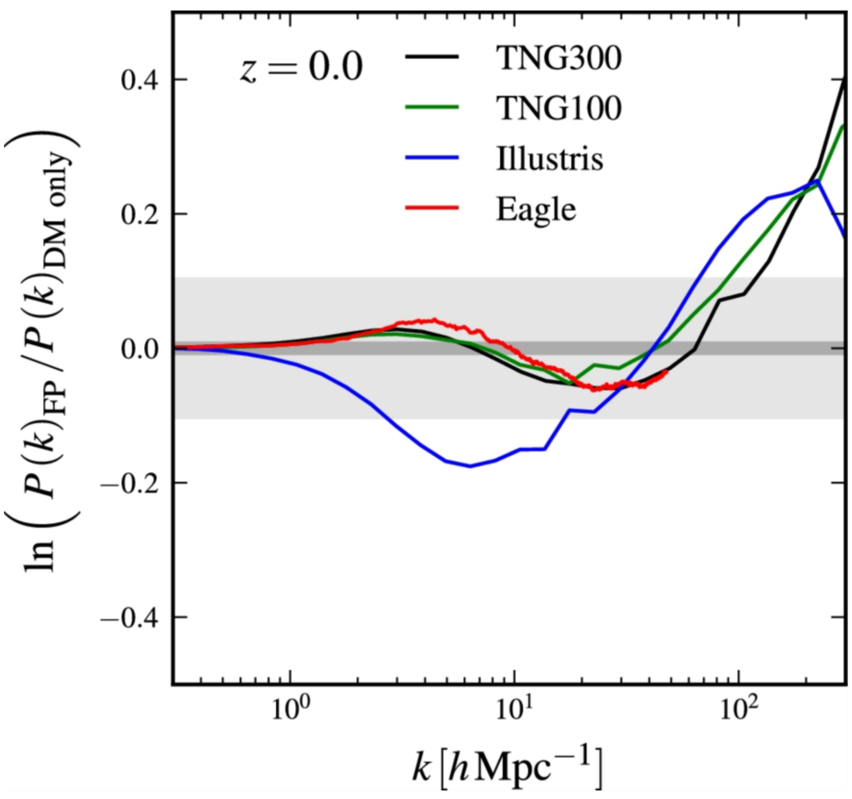


EAGLE

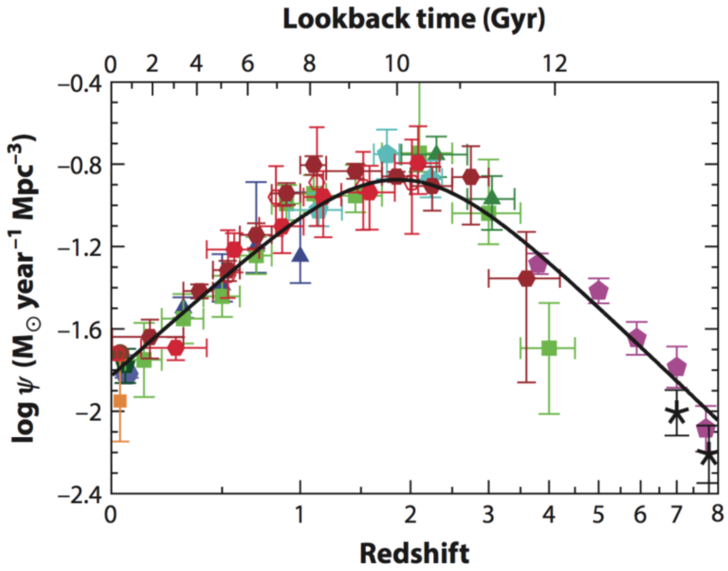


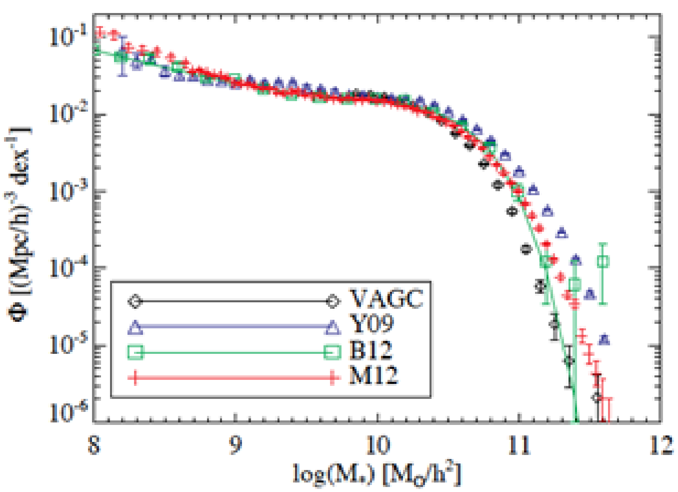
The impact of baryon physics on dark matter clustering

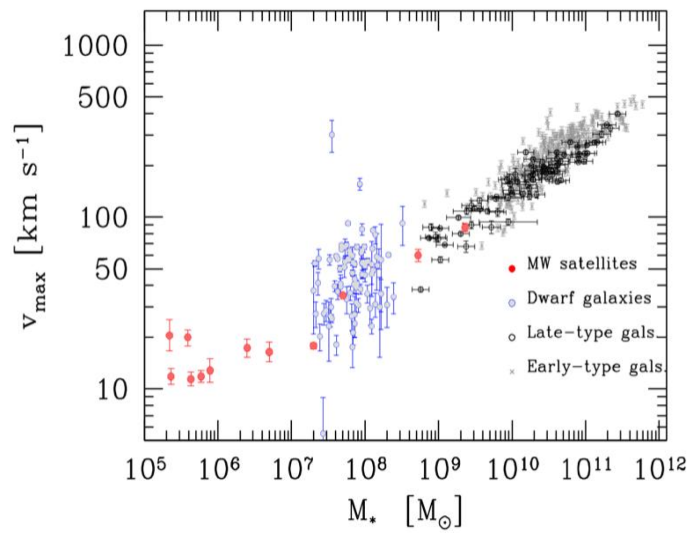
- The impact of baryon physics on dark matter clustering depends on the modeling of baryonic physics
- But observations put strong constraints on baryon physics models.
- It seems that if different galaxy formation models can reproduce the same stellar mass function, the impact on dark matter field is very similar.



Observational constraints on stellar components of galaxies

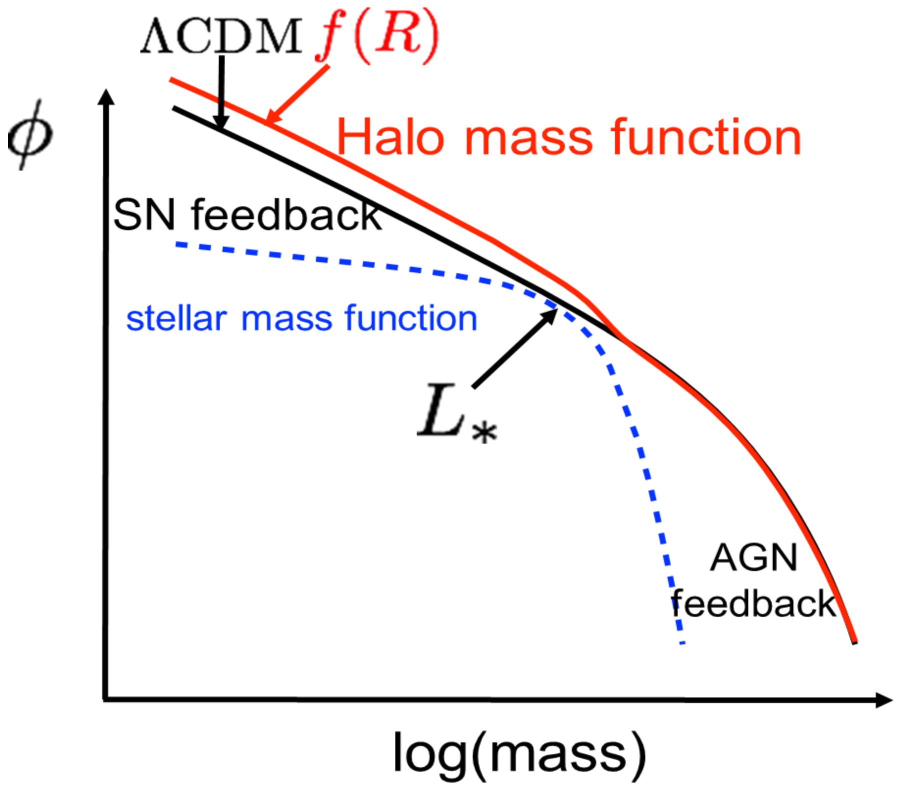






Abundance Matching

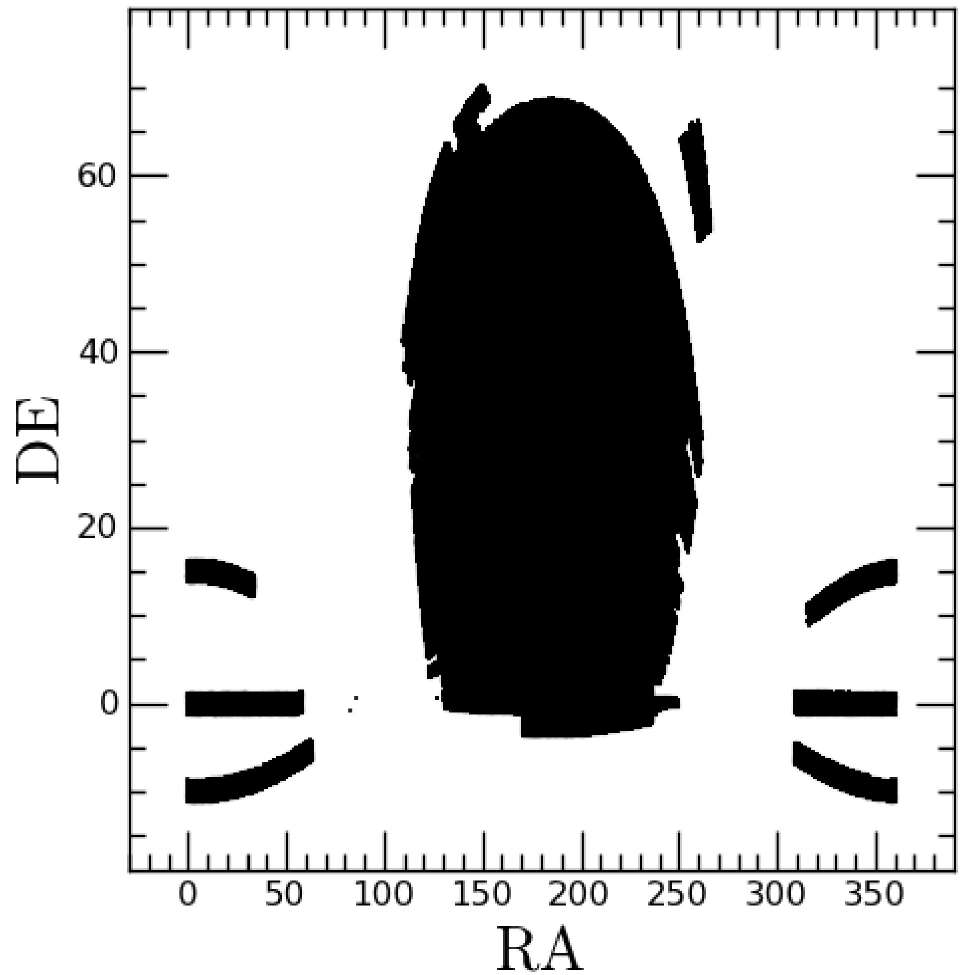
- Abundance matching does not have galaxy bias!
- The shape of the stellar mass function can put constraints on baryonic physics!!
- Baryonic physics in modified gravity models should be reasonable



DATA

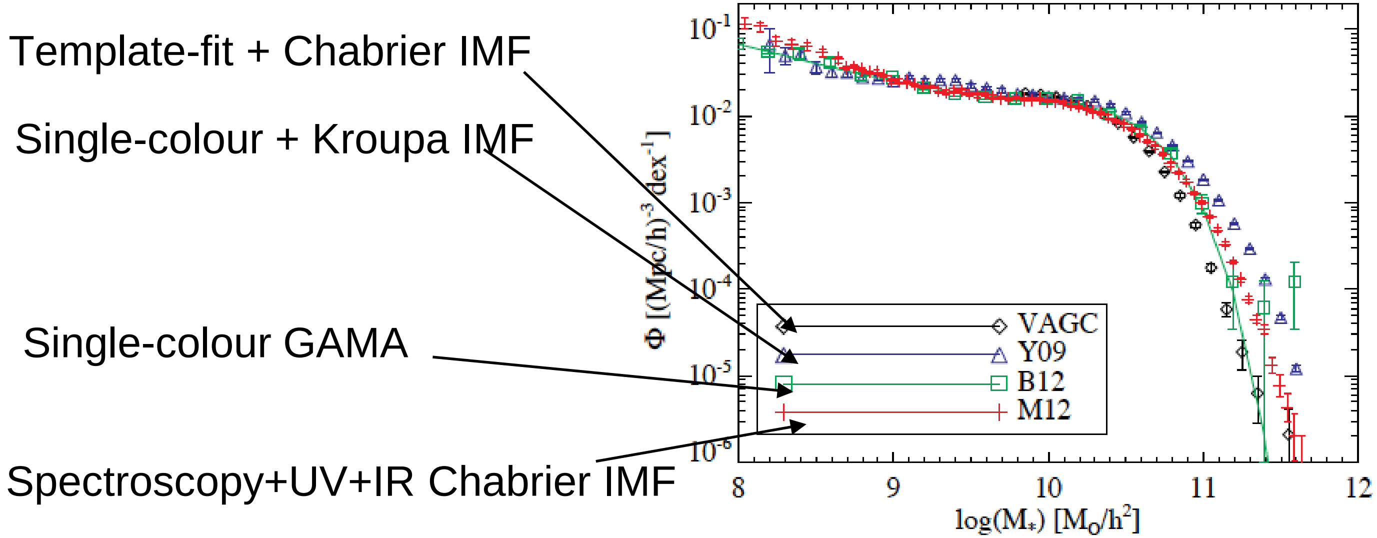
NYU Value-Added Galaxy Catalog

- VAGC is based on the SDSS 7 main galaxy sample
- Relative photometric calibration which uses the same objects in over laps (good ~1%)
- BBRIGHT sub-sample with a uniform *r*-band apparent magnitude limit r<17.60
- Without corrections for fibre collisions



Systematics in stellar mass

- Stellar initial mass function (IMF)
- Difficult to accurately determine the total flux of a galaxy from image data (aperture effect, background subtraction, dust extinction)
- Different Methods (e.g. photometric template fit, a combination of spectroscopy and photometric, a single-colour based estimator)



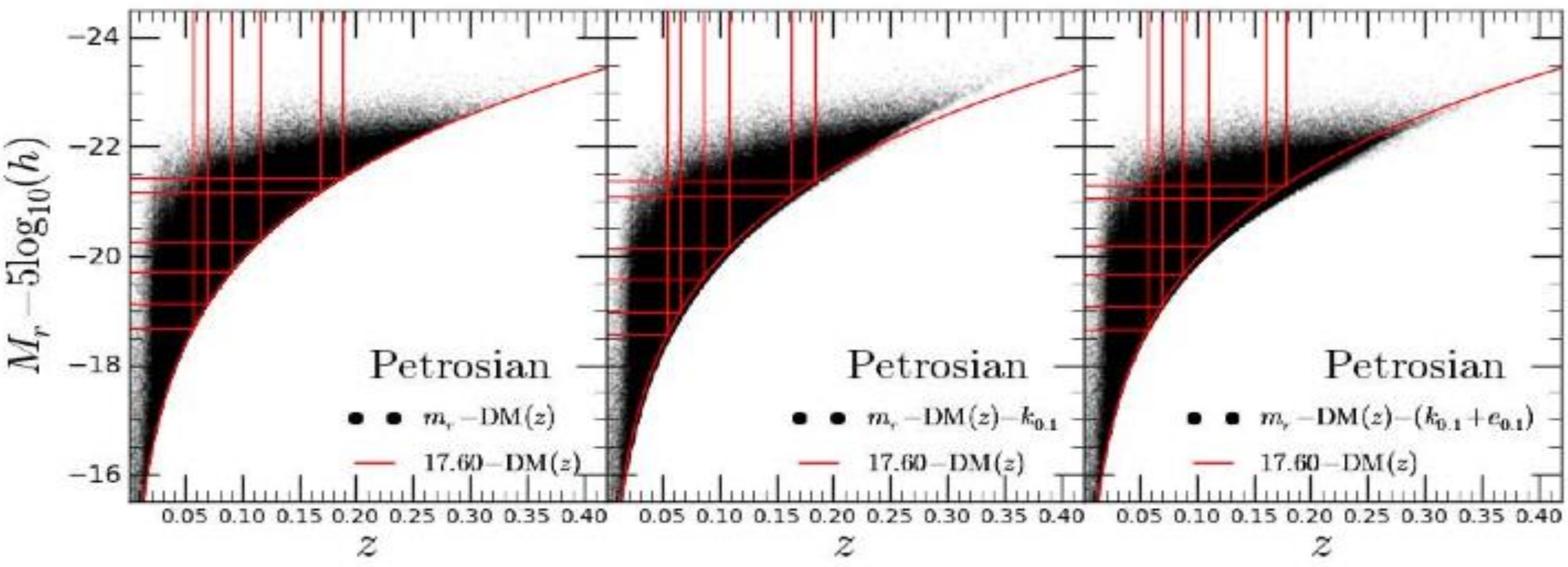
Use number densities and rank of galaxies

- Construct volume-limited samples with fixed number densities

Galaxies ranked by *r*-band magnitude

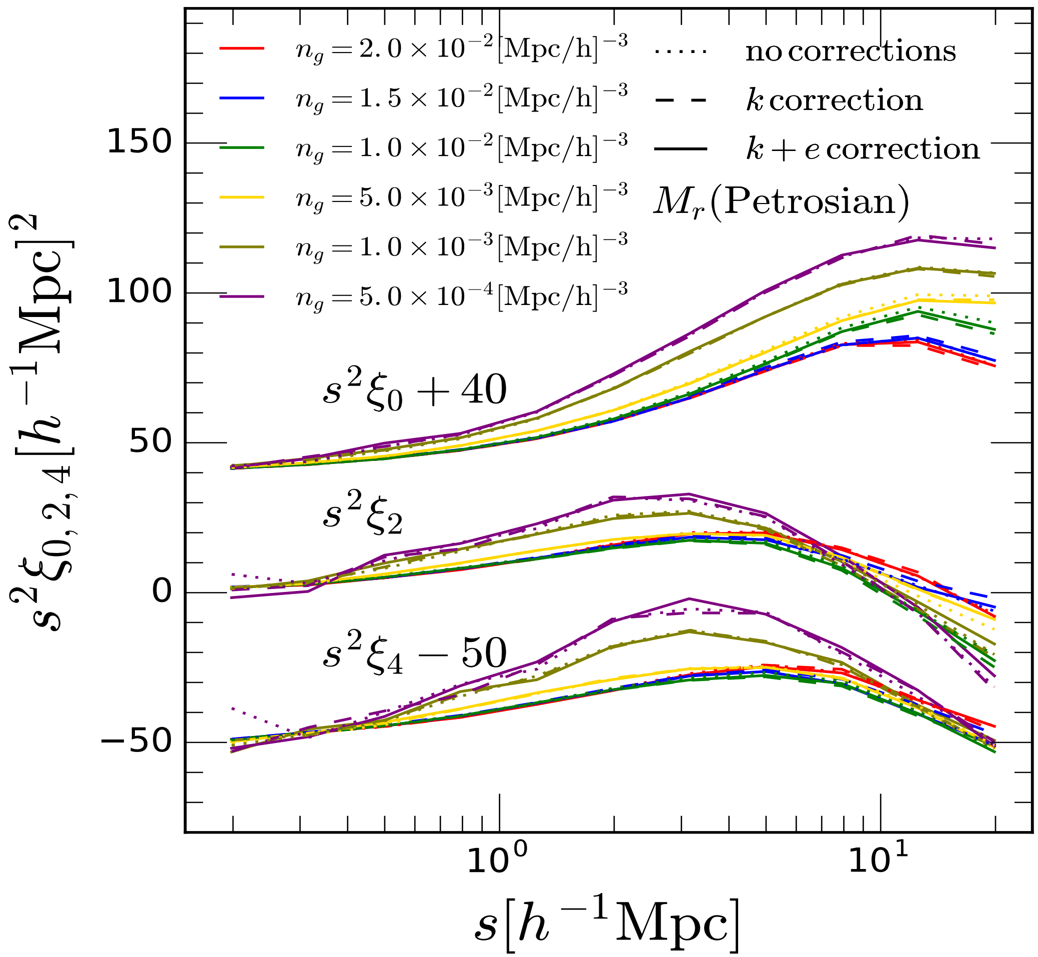
M(*z*) = *M*(*z=qz0*) - *q0* [1 + *q1* (*z* - *qz0*)] (*z-qz0*)

No correction | K correction | K+E correction



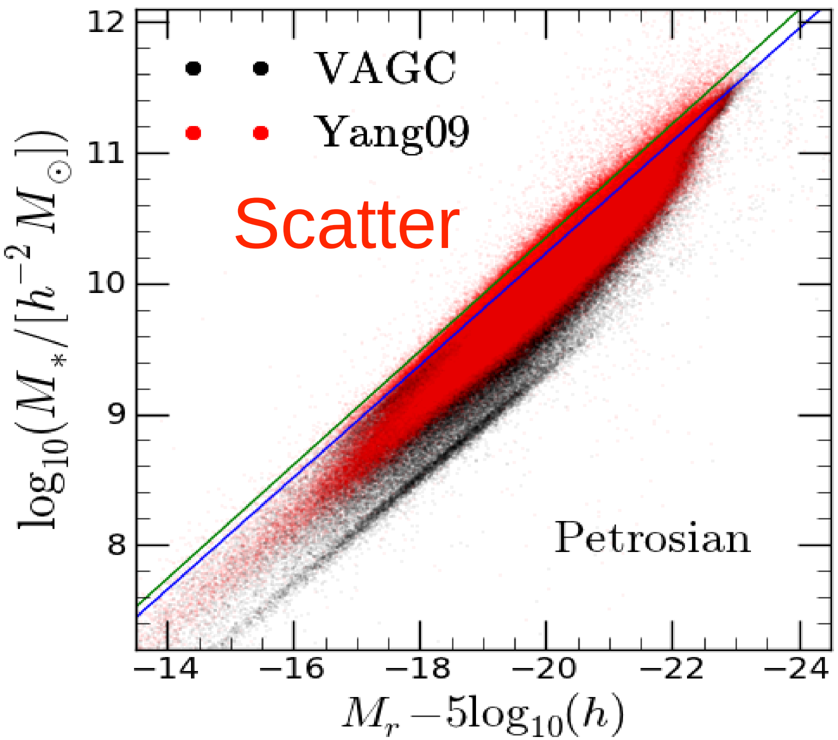
The impact of systematics on galaxy clustering

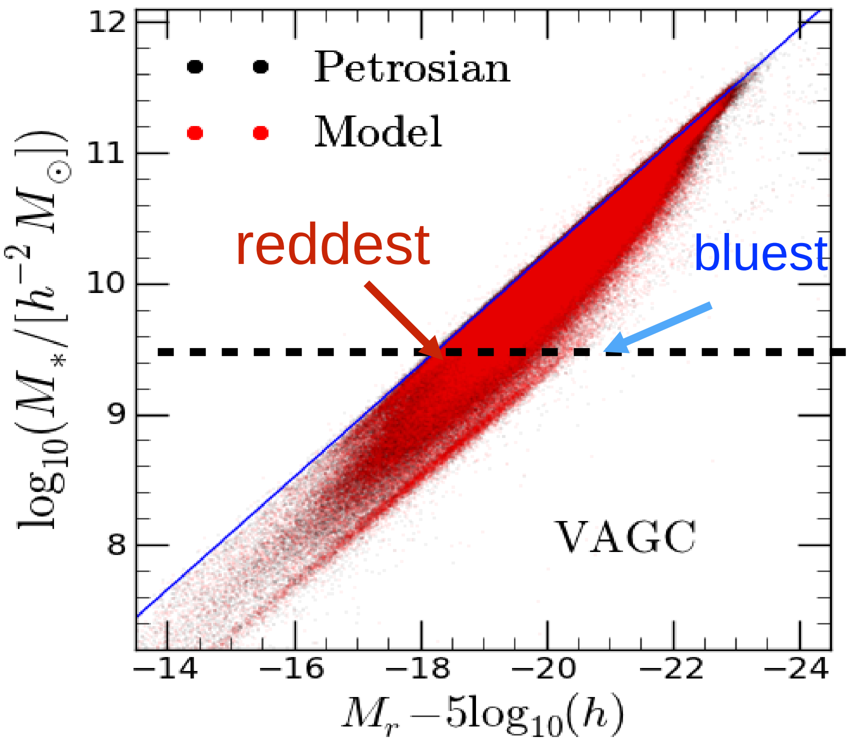
Galaxies ranked by *r*-band magnitude



Volume-limited sample complete in stellar mass

- A flux-limited survey (*r*-band)
- *r*-band mass-to-light ratio
- At a given redshift, for given stellar mass, find the reddest galaxy!





Galaxies ranked by stellar mass

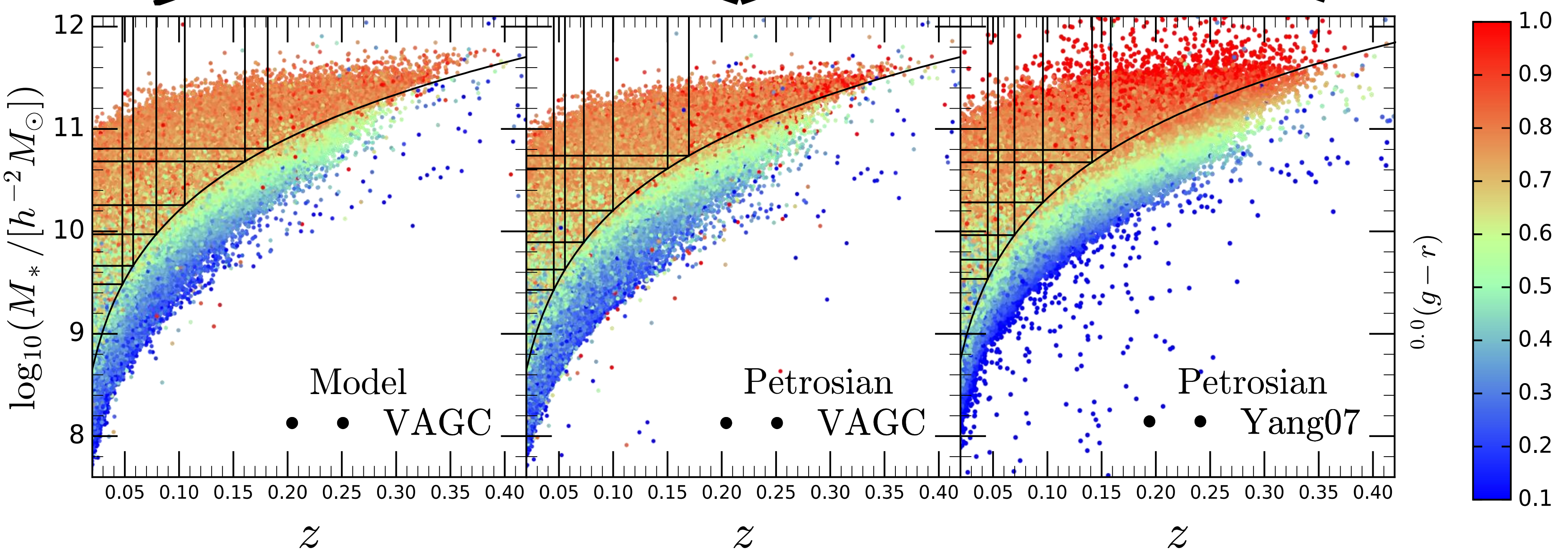
Systematics due to aperture.
SDSS model VS Petrosian magnitude
photometric template-fit
Chabrier IMF

A single-colour (Petrosian) estimator

$$\log_{10}(M_*/[h^{-2}M_\odot]) = -0.406 + 1.097[^{0.0}(g-r)] - 0.4(^{0.0}M_r - 5\log_{10}h - 4.64)$$

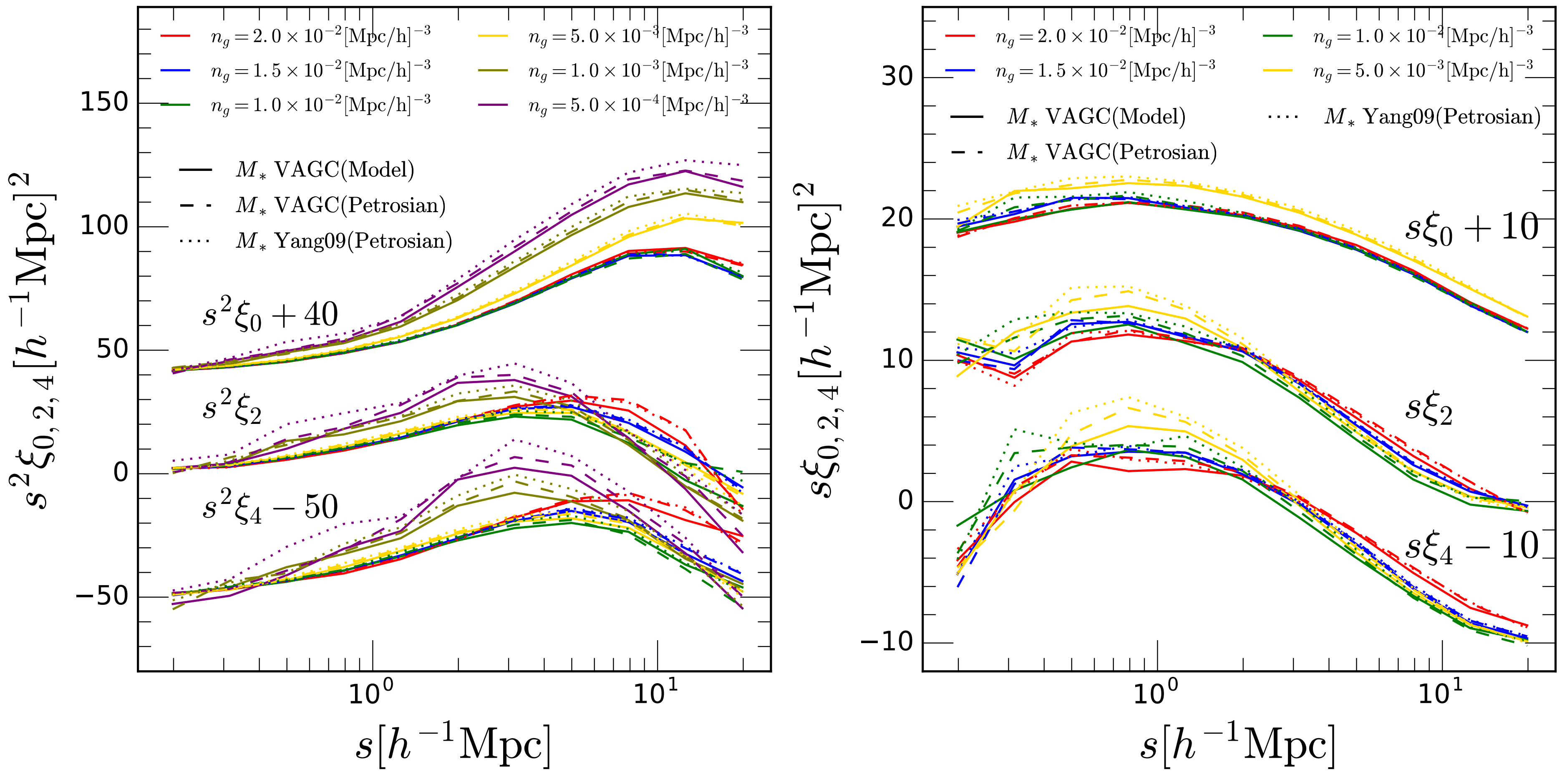
Kroupa IMF

Yang09

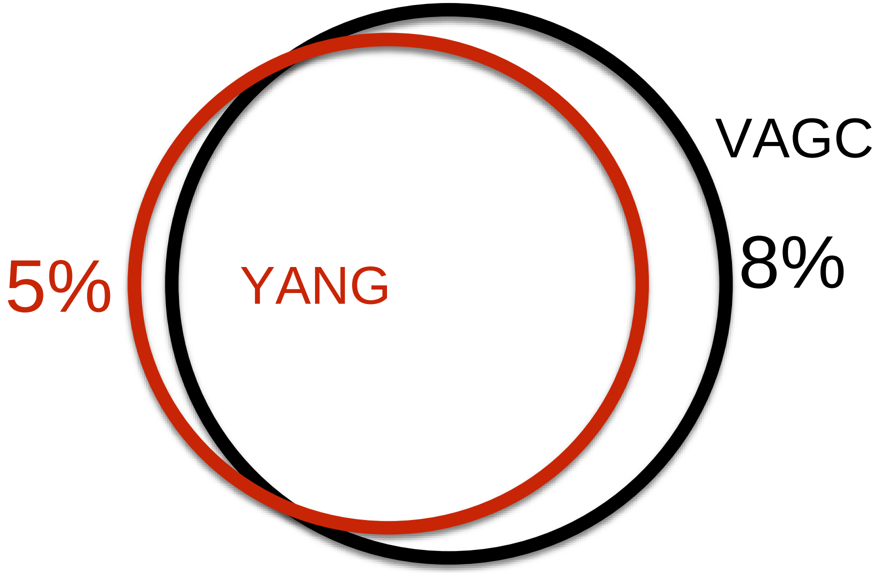


The impact of stellar mass systematics on galaxy clustering

Galaxies ranked by stellar mass



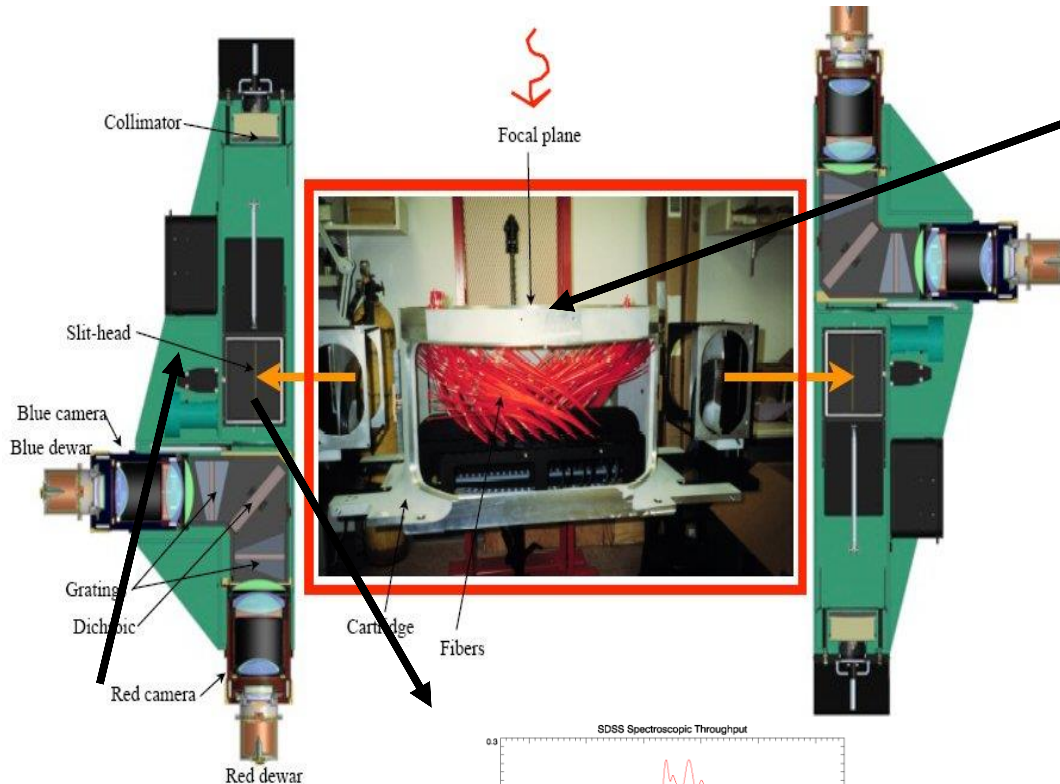
The faction of common galaxies



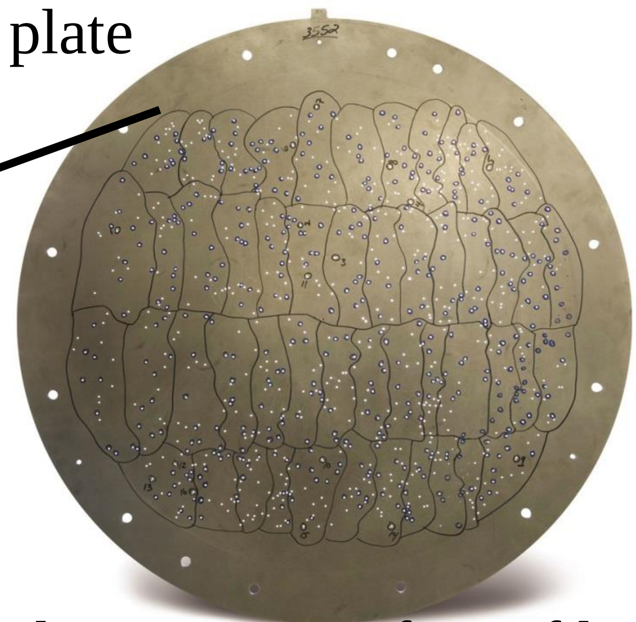
n_g	$N_{\rm com}/N_{\rm yang}$	$N_{\rm com}/N_{\rm vagc}$	$N_{\rm yang}/N_{\rm vagc}$
2.0×10^{-2}	96.1%	95.6%	99.5%
1.5×10^{-2}	96.5%	92.1%	95.4%
5.0×10^{-3}	94.9%	82.4%	86.8%
1.0×10^{-3}	95.1%	84.7%	89.1%
5.0×10^{-4}	88.6%	73.9%	83.5%

Fibre Collisions

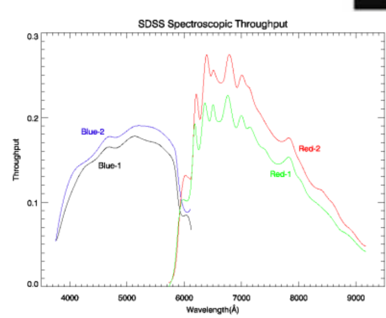
SDSS BOSS



plate



Spectrograph

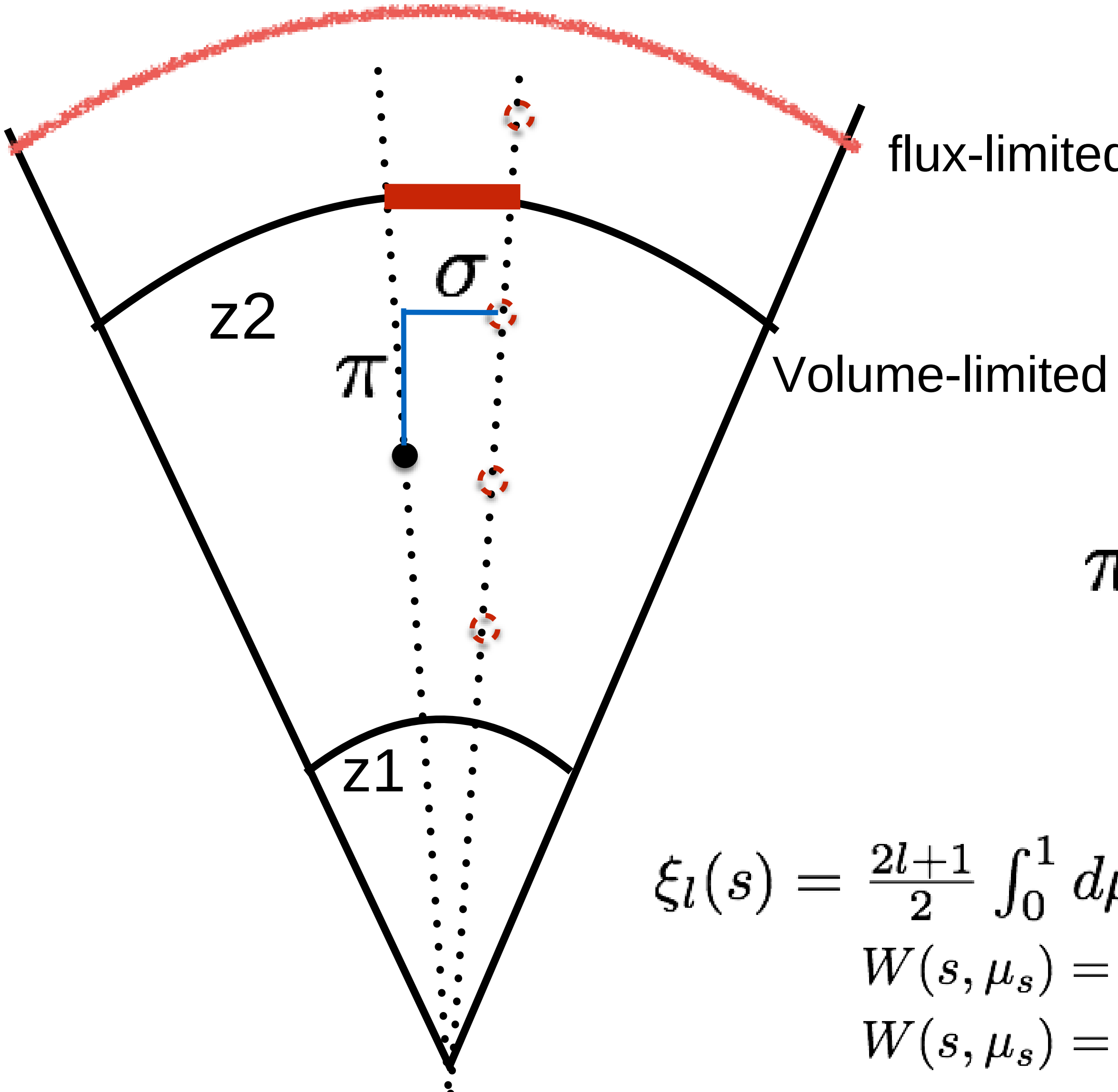


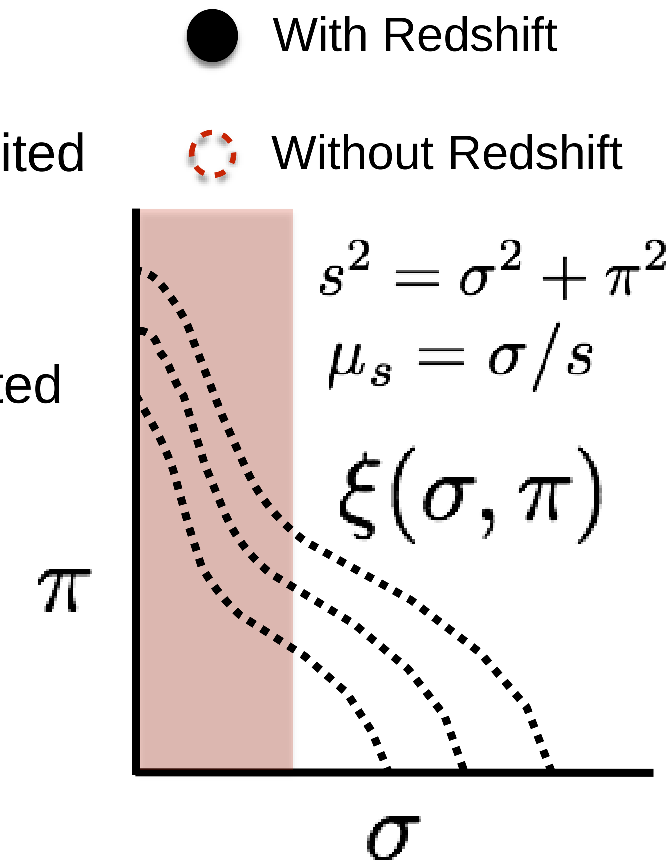
The positions of two fibres cannot be paced closer than 55” in SDSS-I and II(DR 7). 62’’ in SDSS-III.

$$z \sim 0.1$$

$$55'' \longrightarrow 0.1h^{-1}\mathrm{Mpc}$$

Fibre collisions mitigation





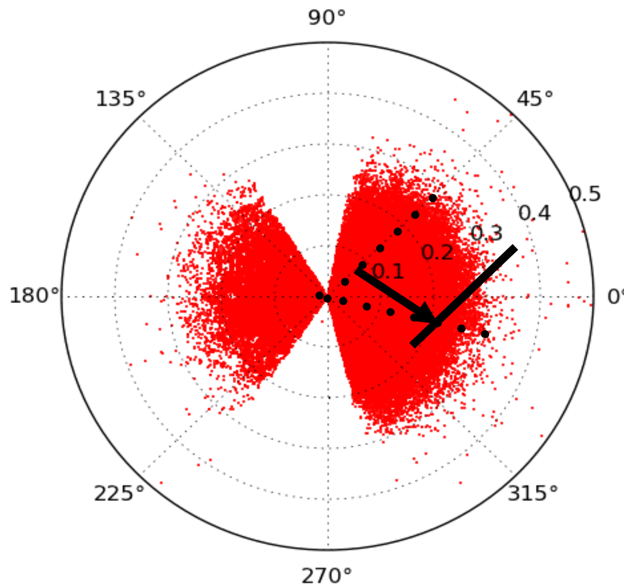
$$\xi_l(s) = \frac{2l+1}{2} \int_0^1 d\mu_s W(s, \mu_s) \xi(s, \mu_s) P_l(\mu_s)$$

$$W(s, \mu_s) = 1, \sigma > 0.2\mathrm{Mpc}/h$$

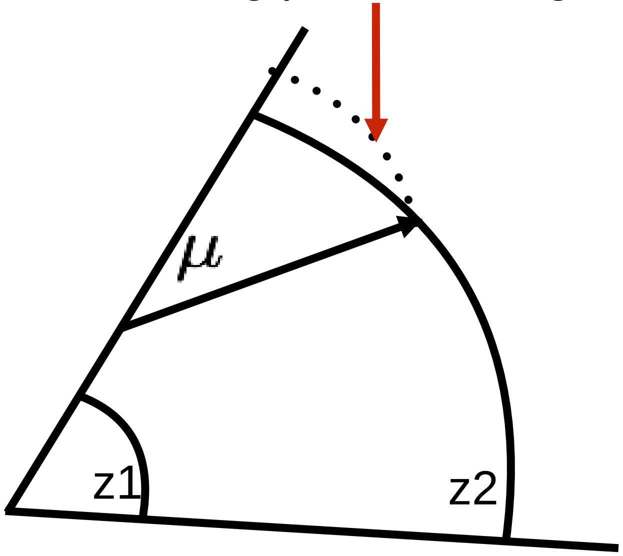
$$W(s, \mu_s) = 0, \sigma < 0.2\mathrm{Mpc}/h$$

Wide-angle and geometry effects

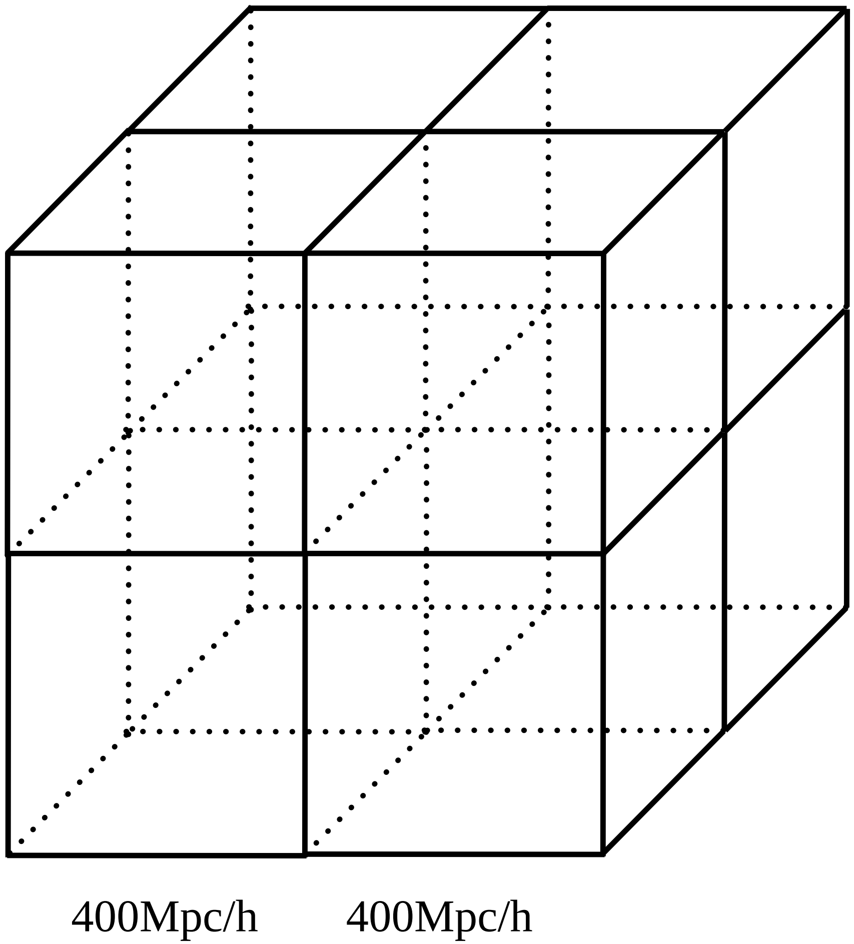
- Parallel approximation does not work for wide-angle galaxy pairs
- RSD is also affected by survey geometries!! Galaxy pairs within a certain range of angle might be lost due to the survey geometry effect.



Missing pairs due to geometry



SHAM mock

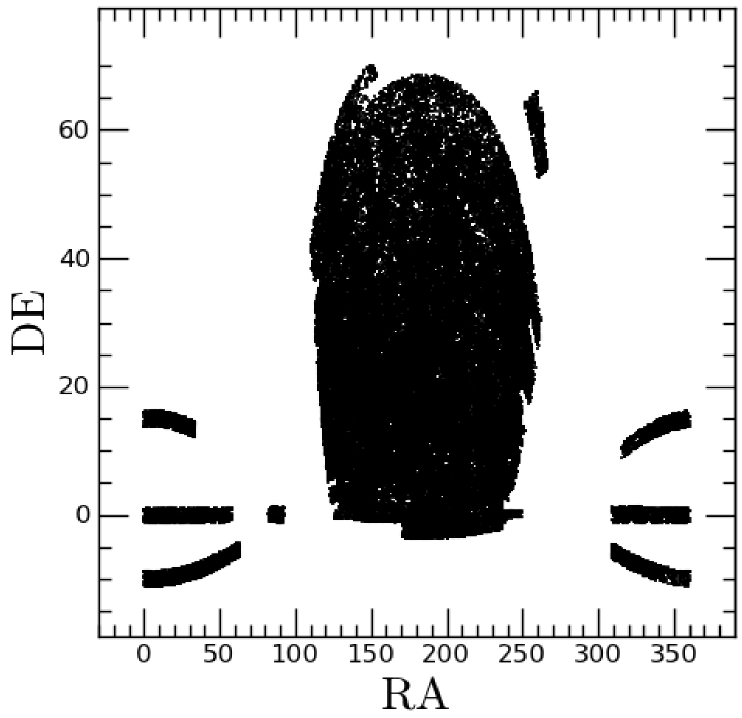


- Multidark Planck simulation
- Boxsize: 400Mpc/h
- 3840^3particles
- Mass resolution:$9.6 \times 10^7 M_\odot/h$

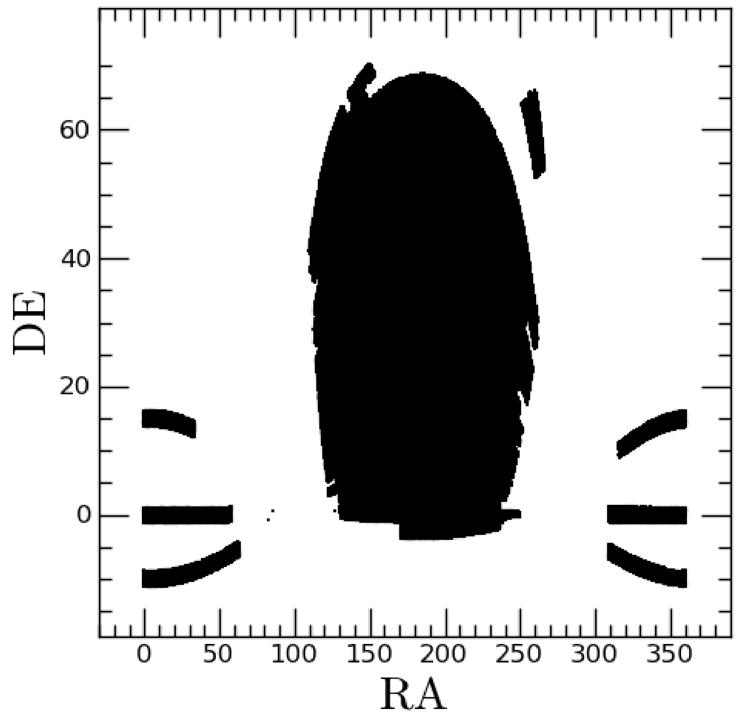
SHAM mock

- To address the wide-angle and geometry effects, a SHAM mock is necessary.
- The SHAM mock has exactly the same geometry as the real data.

SHAM mock (n_g=0.005)

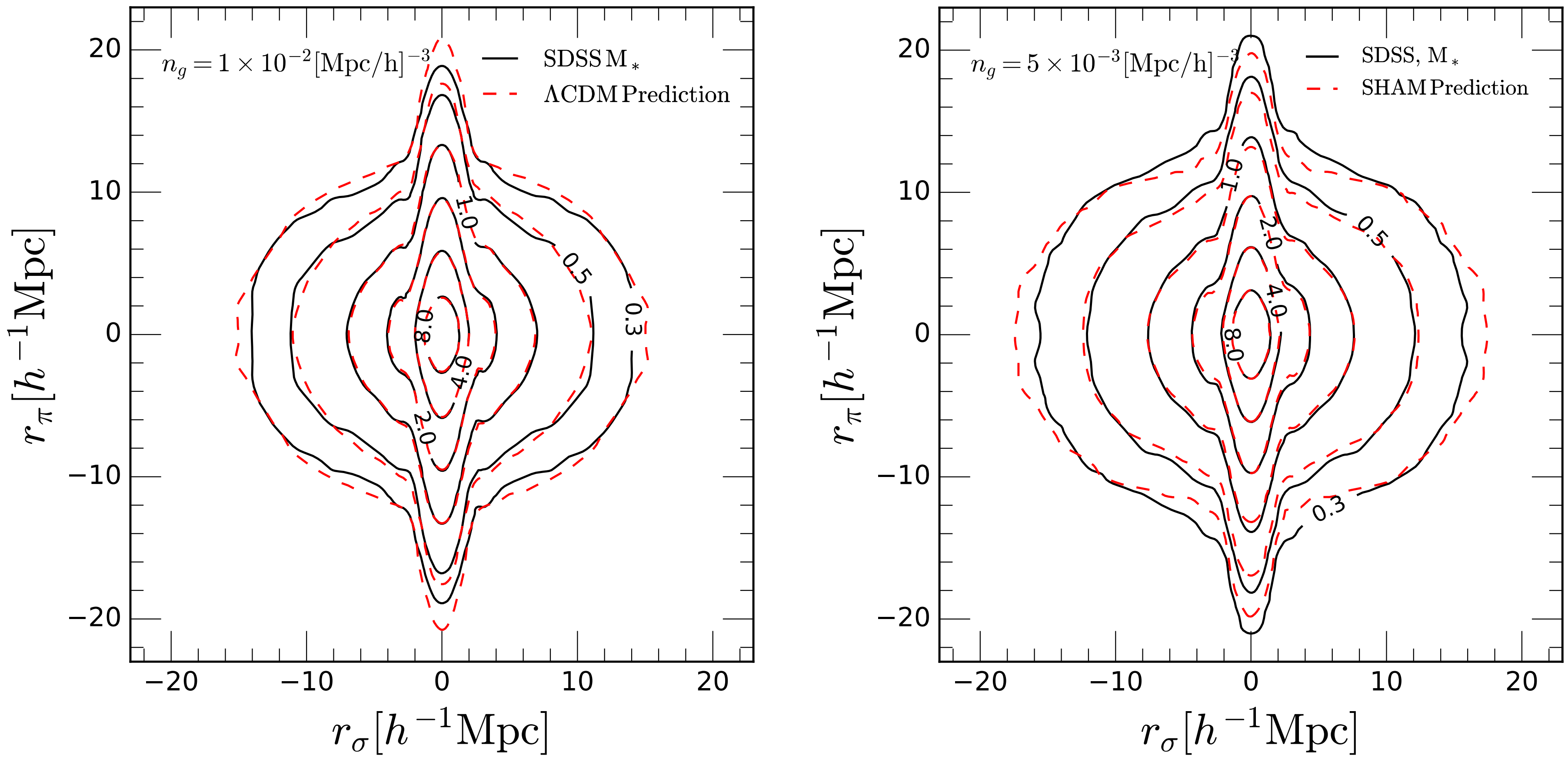


Real Data



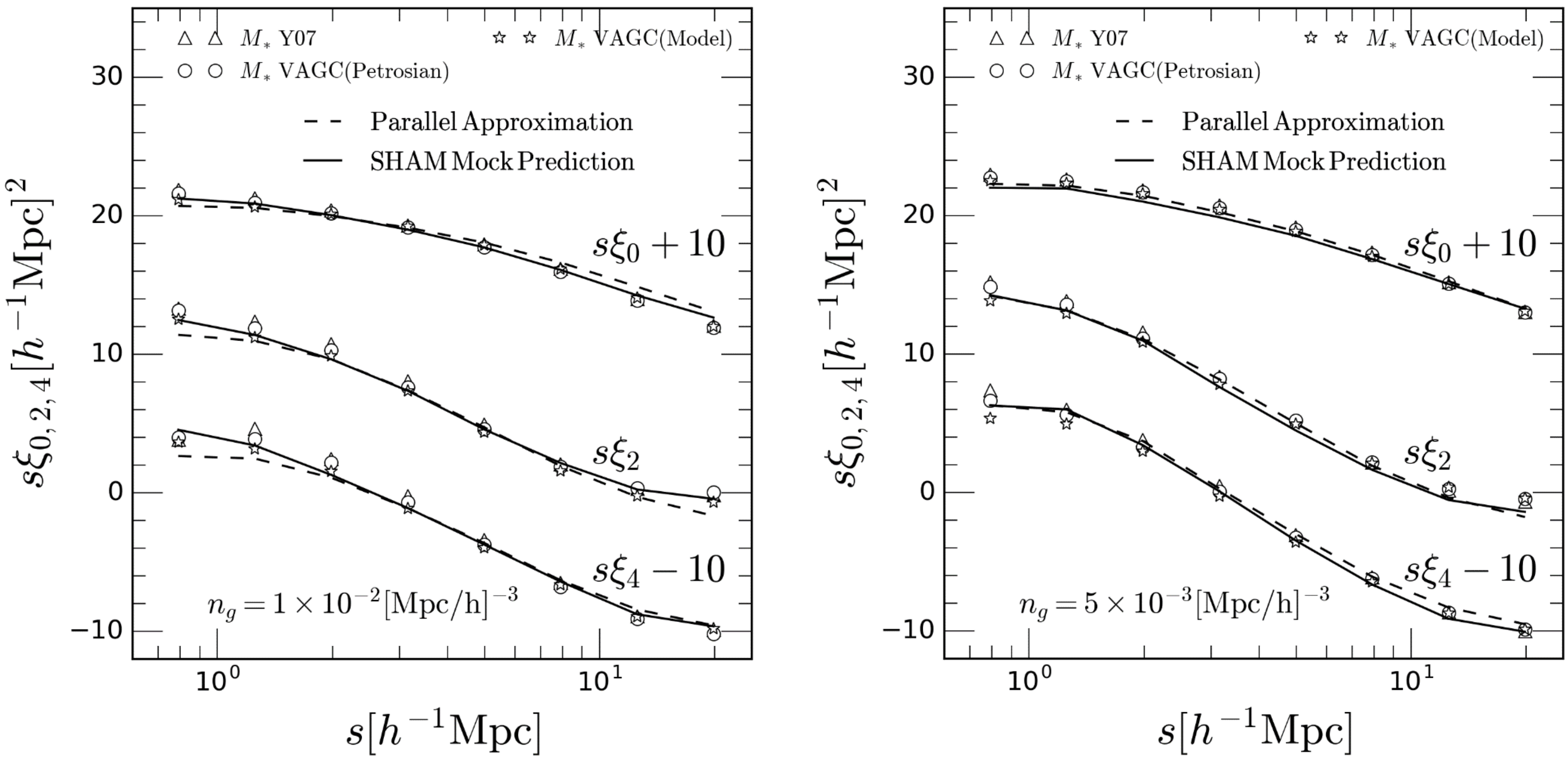
Theory VS Observation

Theory VS Observation



Theory VS Observation

LCDM is perfect !!!!!!



This is not tuned!!!

Modified Gravity

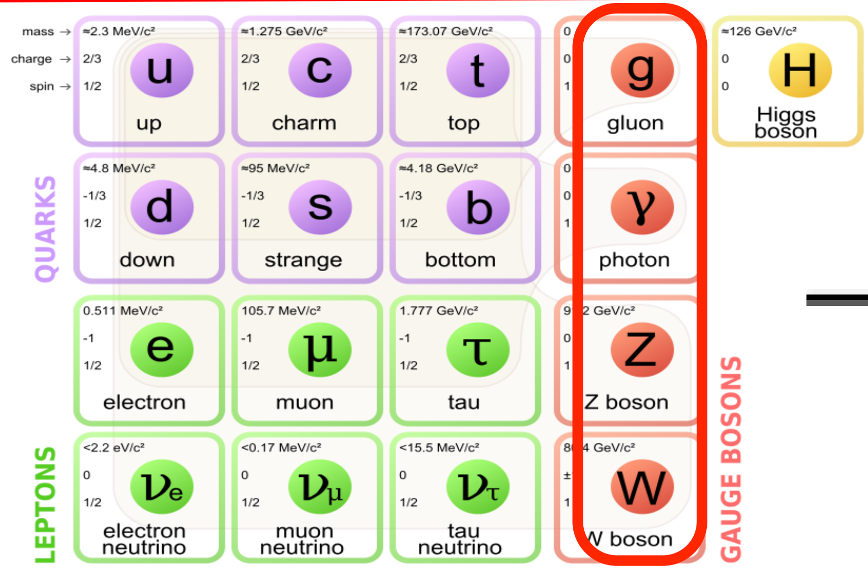
$$s = \frac{1}{2\kappa^2} \int dx^4 \, f(R)$$

Why $f(R)$?

The speed of gravitational wave

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [47] Brans-Dicke/$f(R)$ [48, 49] Kinetic Gravity Braiding [51]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [50] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [5], $f(\phi)\cdot$Gauss-Bonnet [53]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

$f(R)$



$+$ $\boxed{\text{cdm}}$

$$ds^2 = -(1+2\psi)dt^2 + (1+2\phi)dx^2$$

	$\Phi_- = \dfrac{\psi - \phi}{2}$ Massless particle		$\Phi_+ = \dfrac{\psi + \phi}{2}$ Massive particle
ΛCDM	Φ_-	$=$	Φ_+
$f(R)$	Φ_-	$\neq$	Φ_+

Effective density field in $f(R)$ gravity

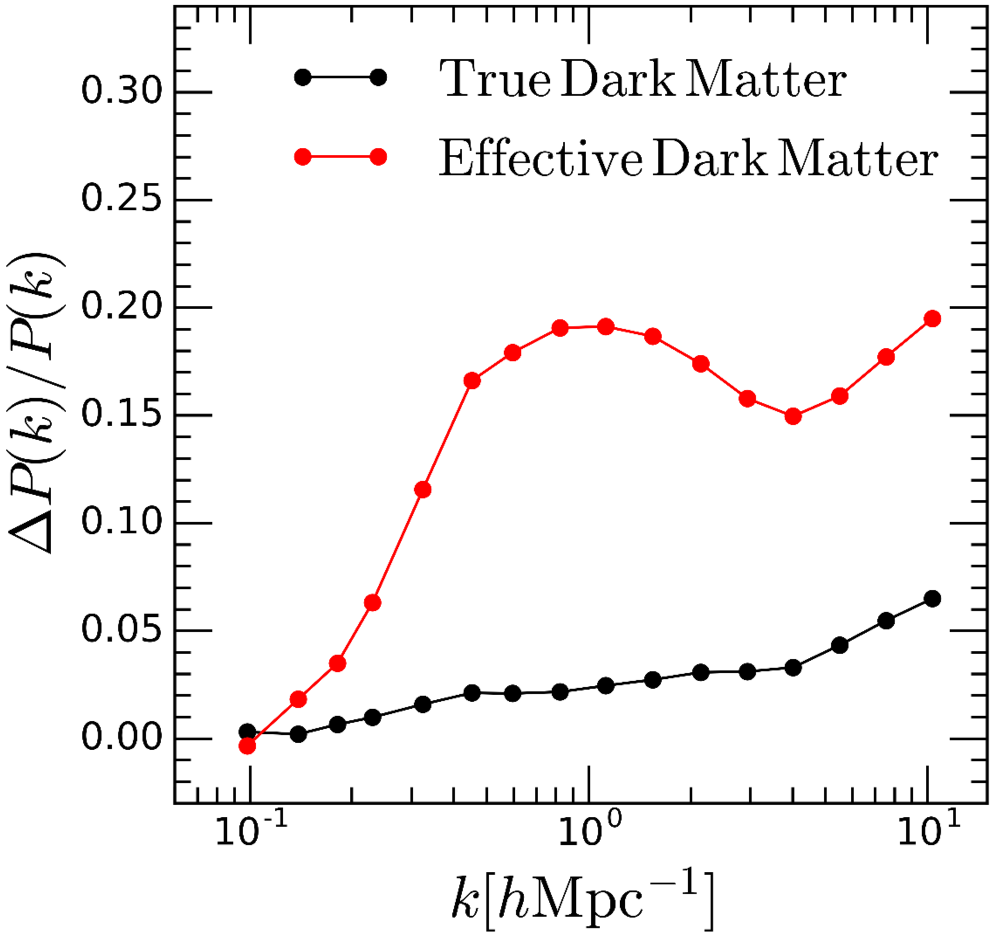
Dynamical Mass

$$\Phi_+ = \frac{\psi + \phi}{2} = 4\pi G \delta\rho_{eff}$$

Lensing Mass

$$\Phi_- = \frac{\psi - \phi}{2} = 4\pi G \delta\rho_m$$

$f_{R0} = -10^{-6}$



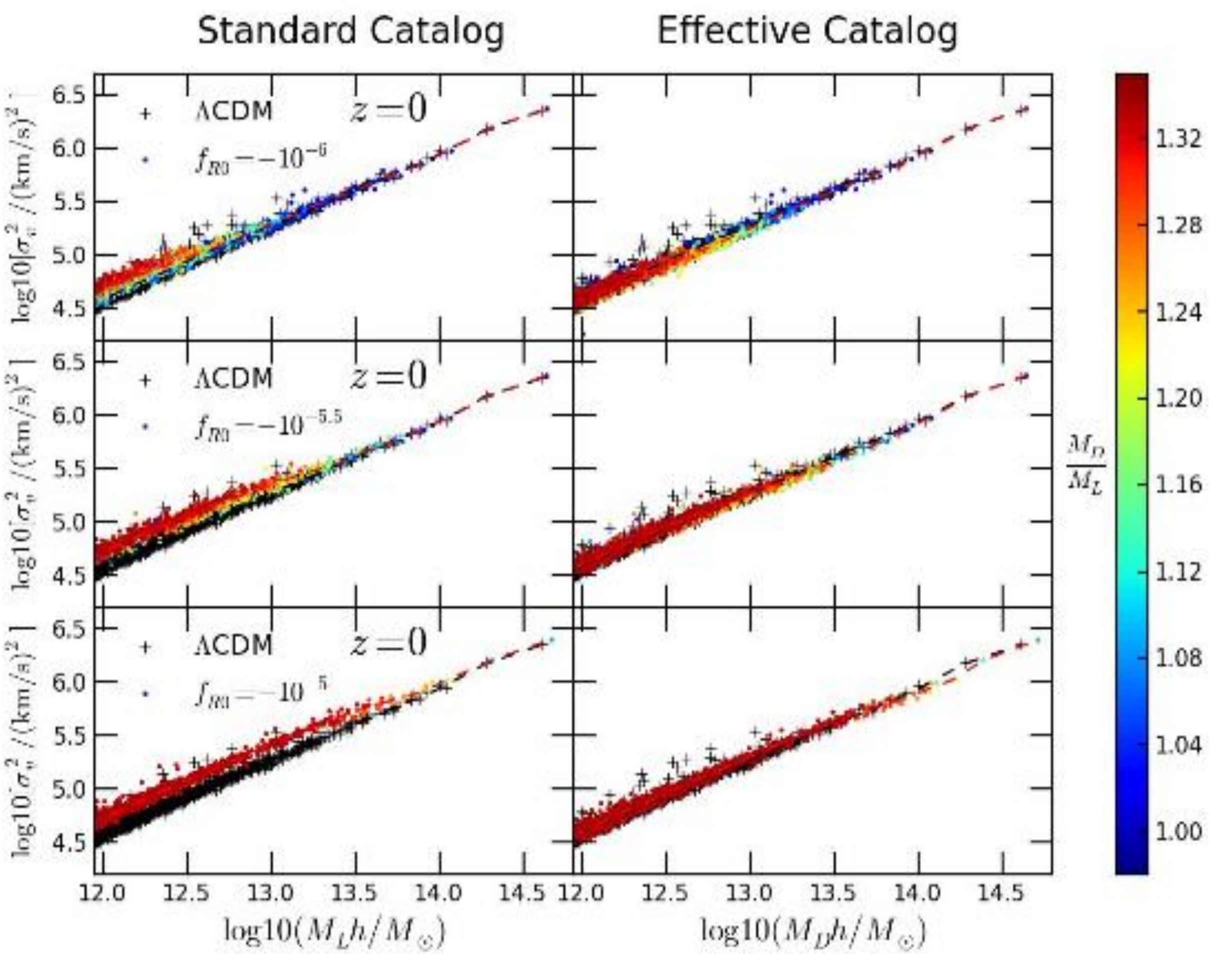
He, et al PRD 2015

Effective halo catalogue

$$\Phi_+ = 4\pi G \delta\rho_{eff}$$

$$v_{cir} = \sqrt{\frac{GM_{eff}}{r}}$$

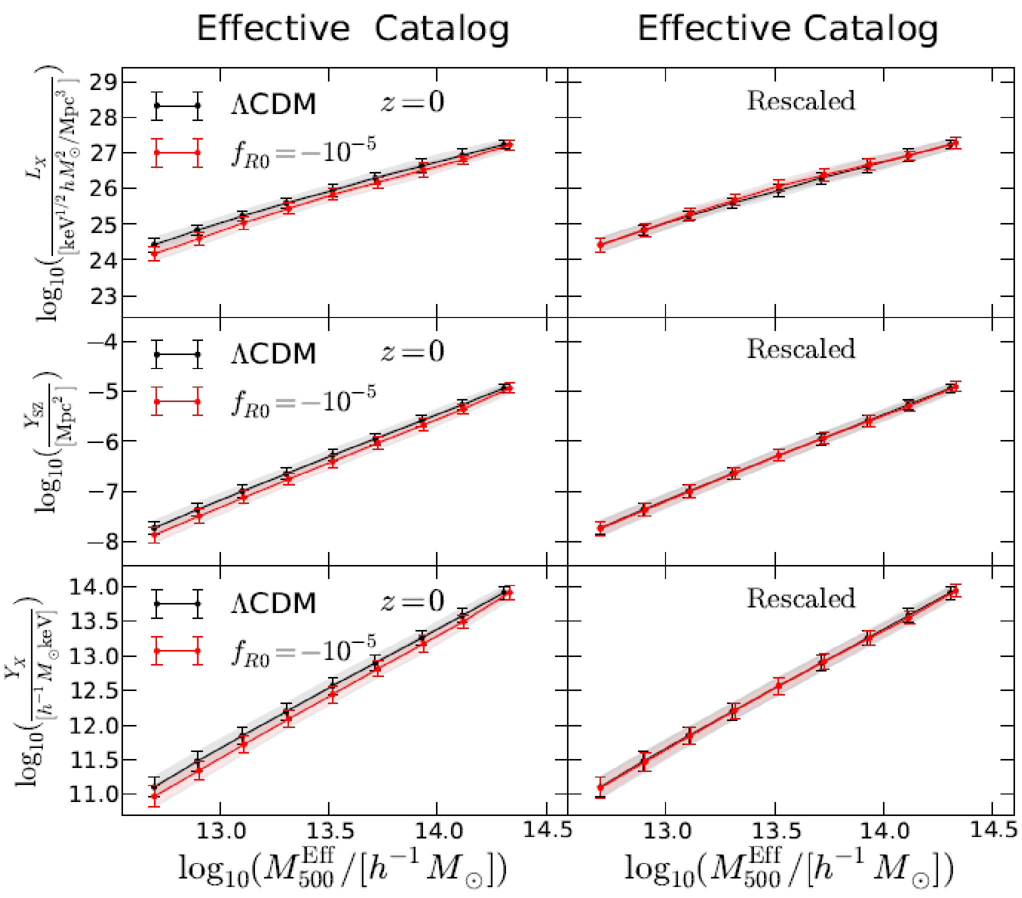
$$\sigma_v^2 \sim \Phi_+$$



He, et al PRL 2015

Effective halo catalogue

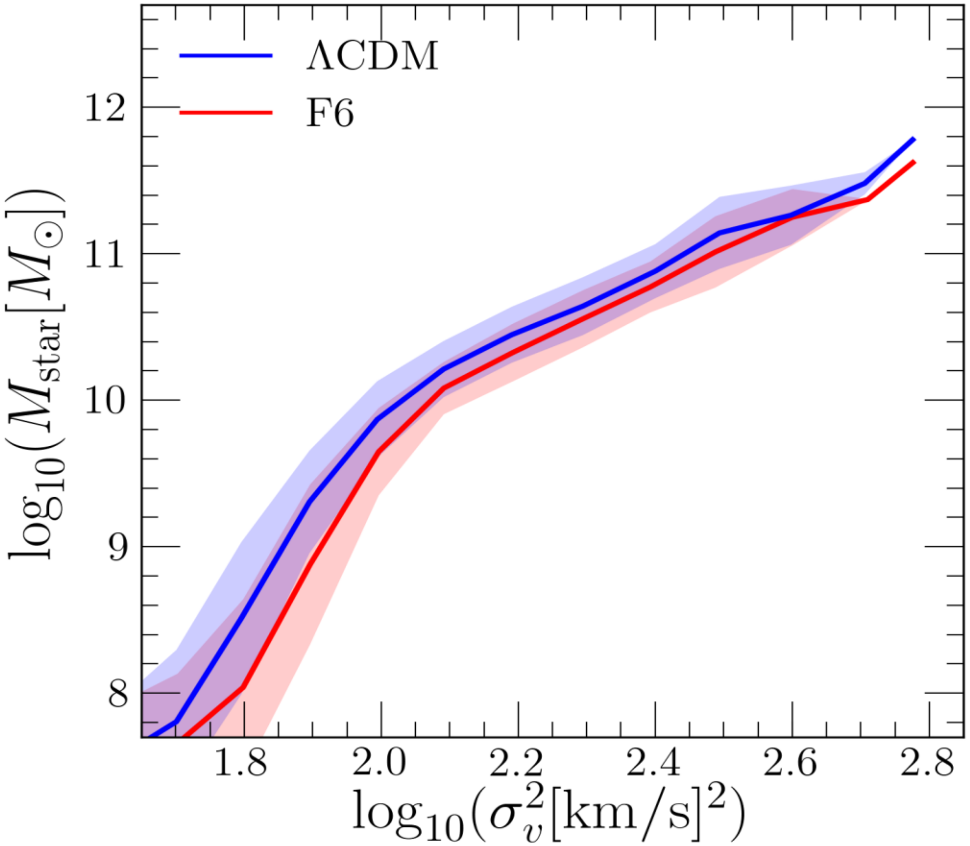
Adiabatic hydro-dynamical simulation



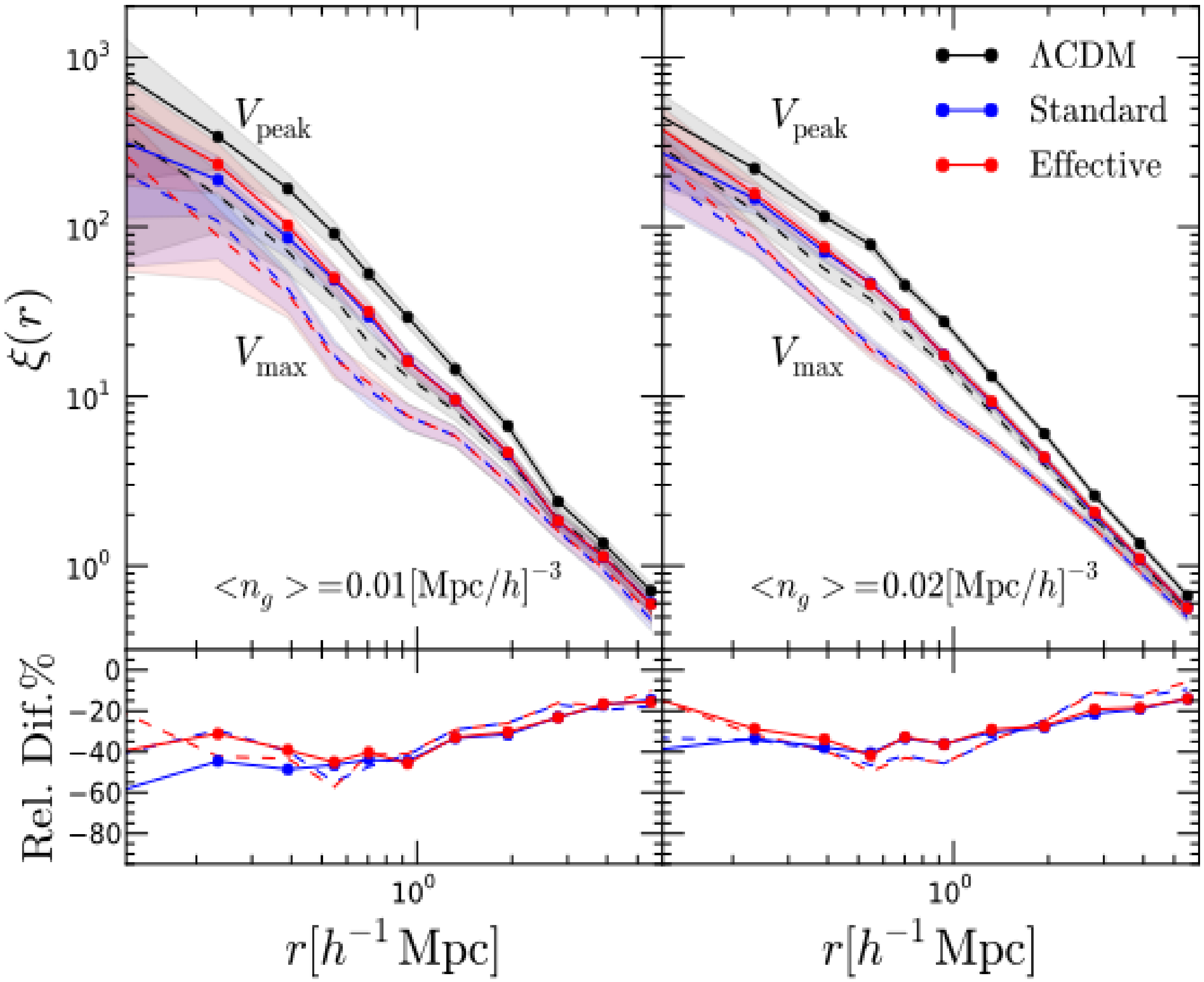
He, et al PRD 2015

Effective halo catalogue

- Illustris TNG full physics
- F6 with the same baryonic physics as LCDM

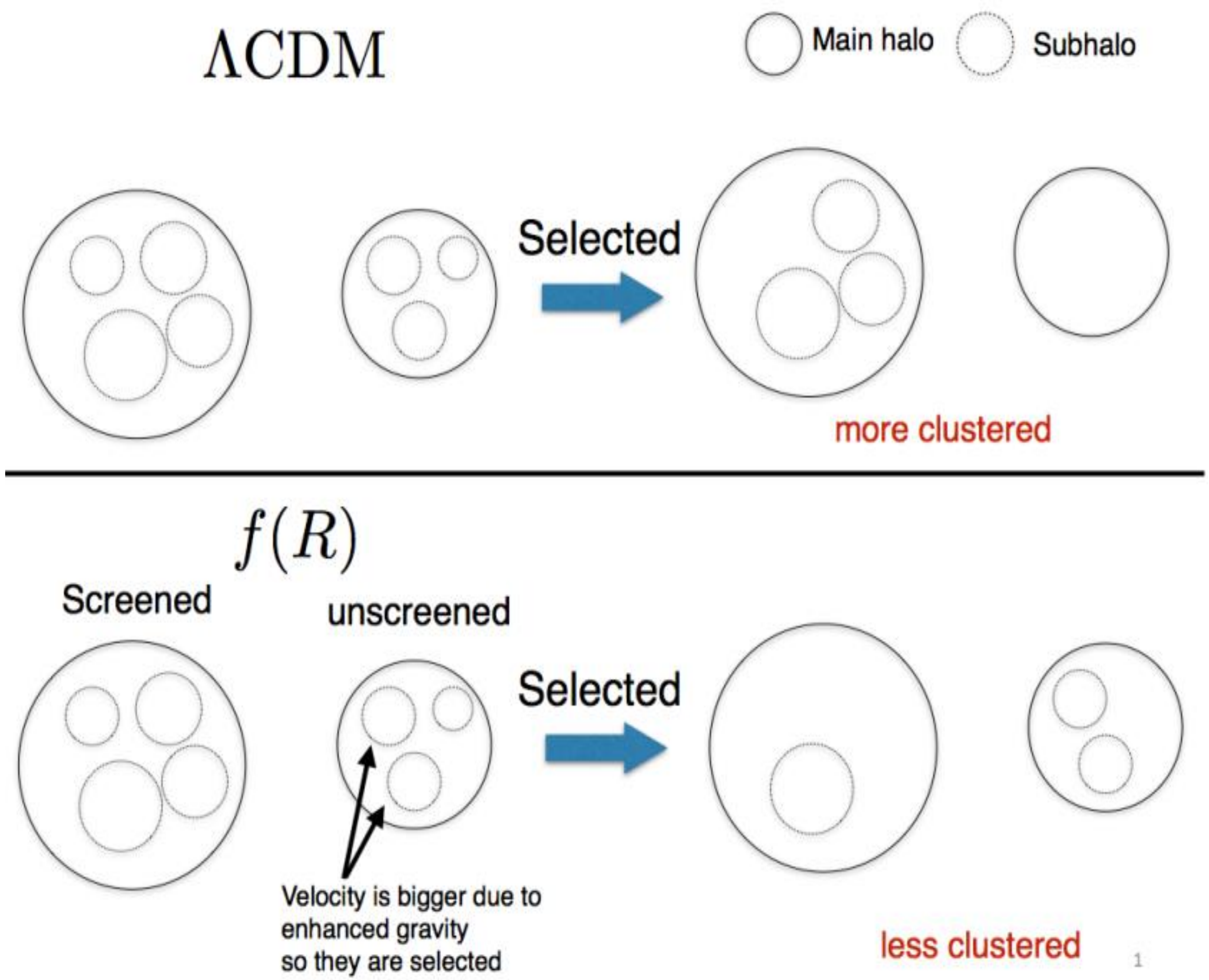


SHAM predictions in $f(R)$ gravity

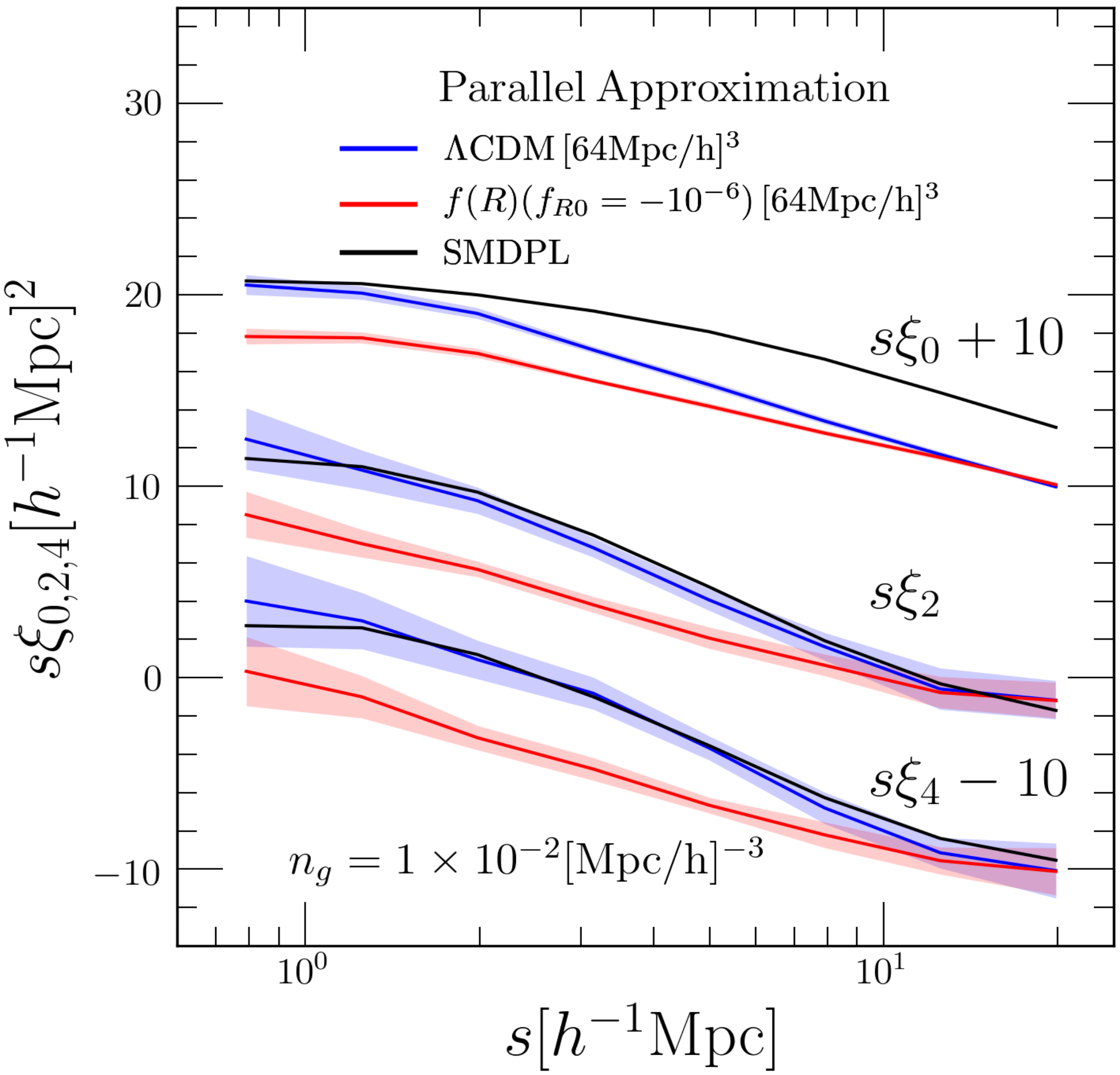


He, et al PRL 2016

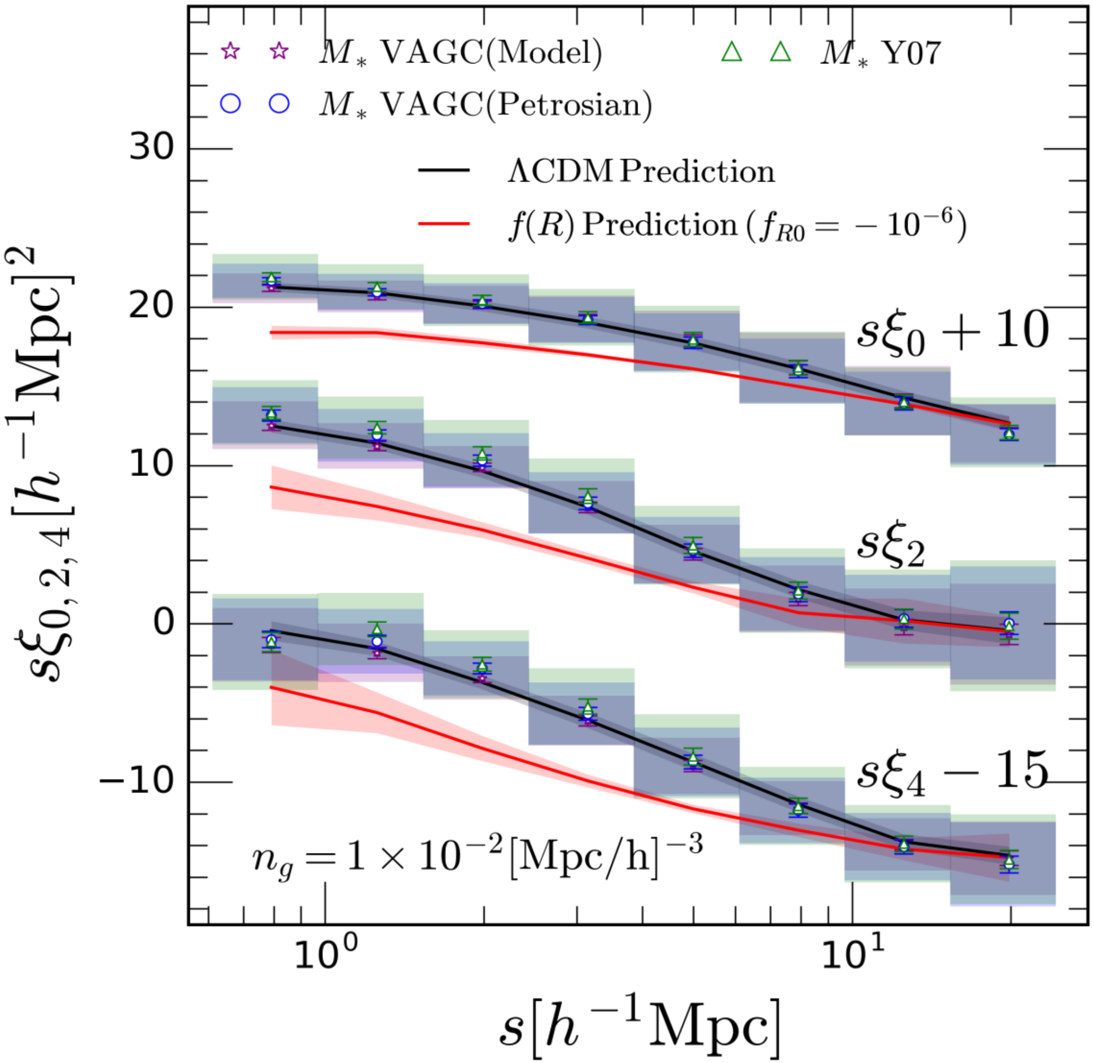
Screening mechanism in $f(R)$ gravity



SHAM predictions in Redshift space



Final results



Conclusions

LCDM is perfect!

Don’t mess with Einstein!!!!!

Thank you!