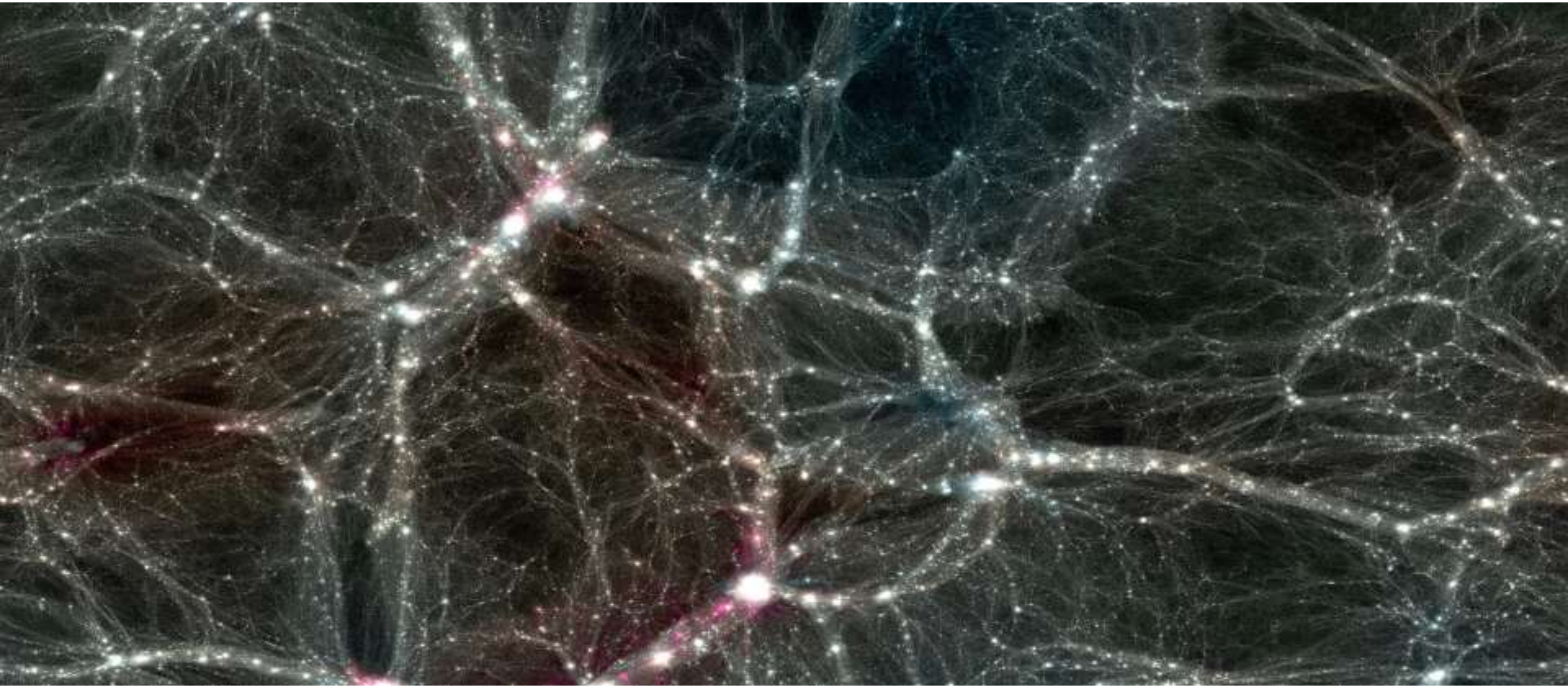
Testing modifications of gravity from galaxy motions on cosmological scales



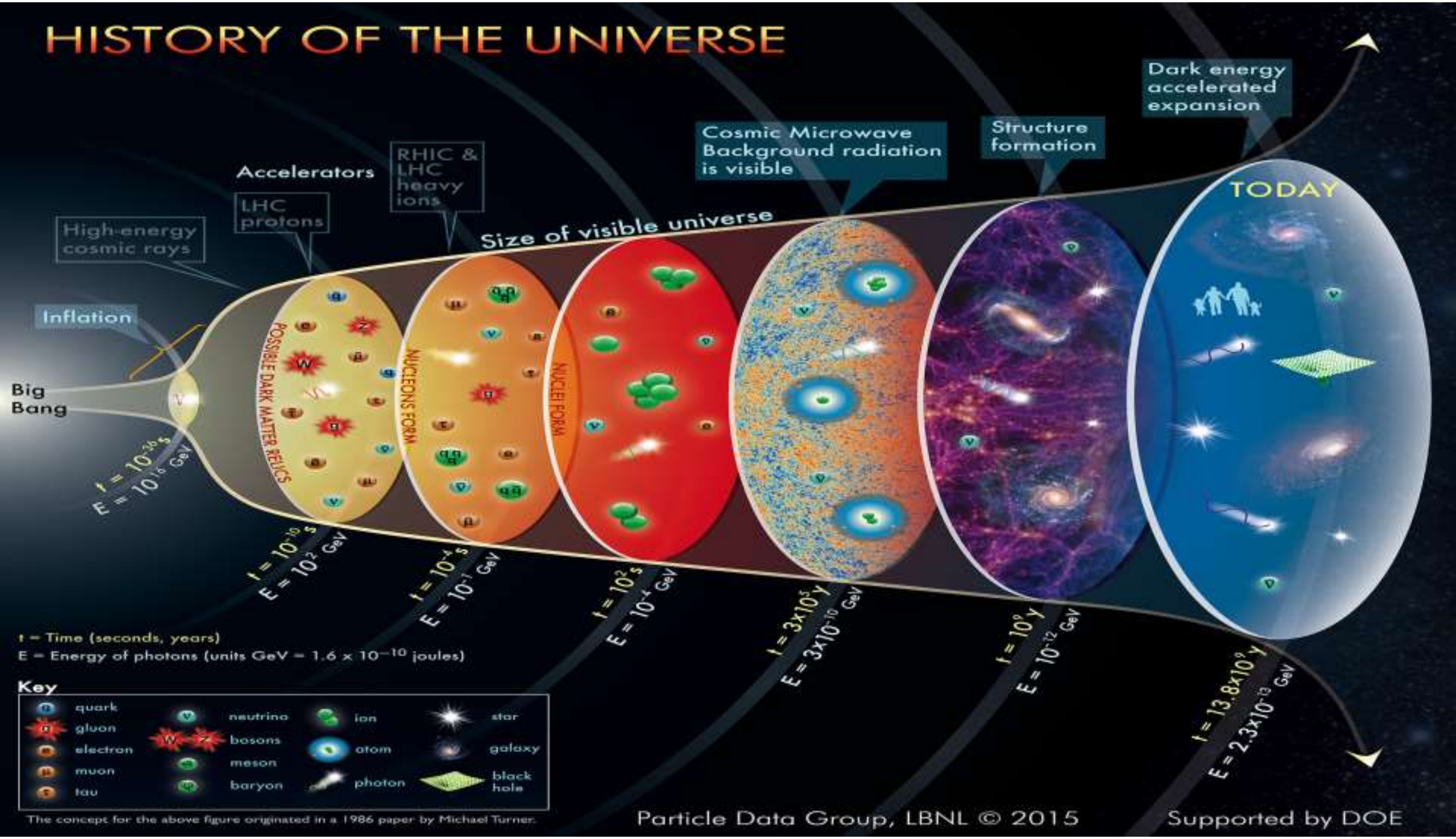
Jianhua He

With Luigi Guzzo, Baojiu Li, Carlton Baugh

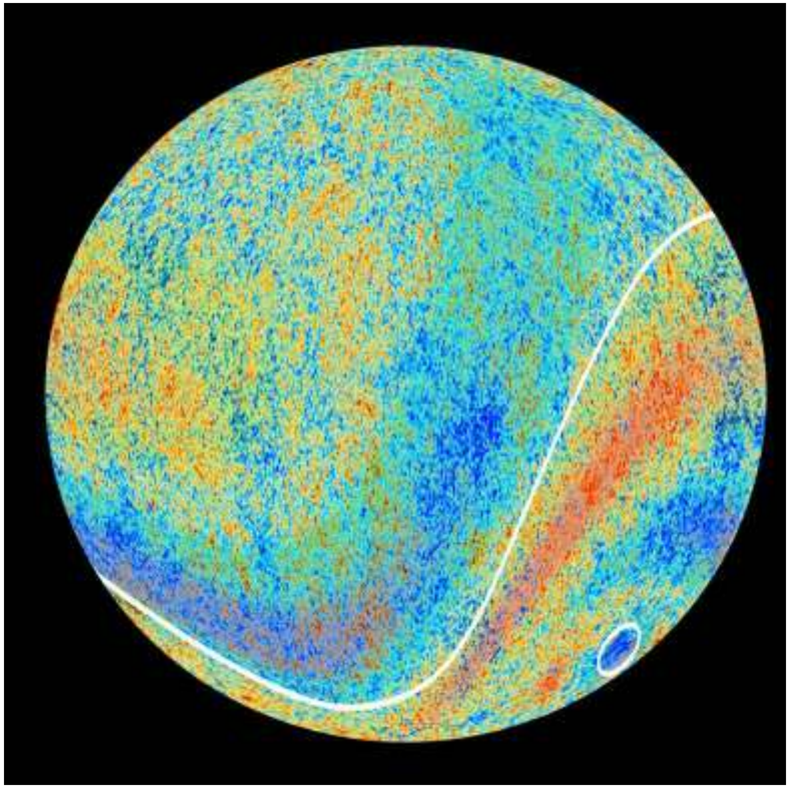
NAOC, CHINA

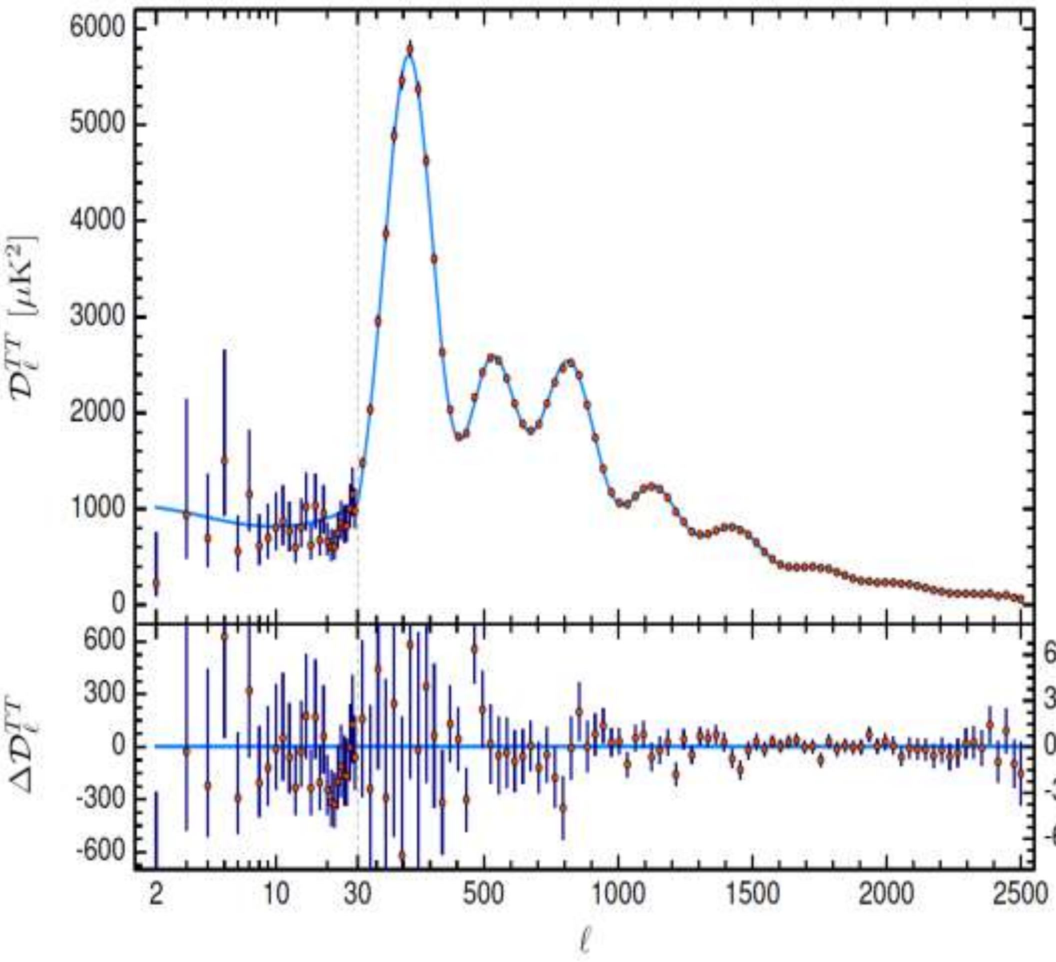
10-12-2020

The standard cosmological model

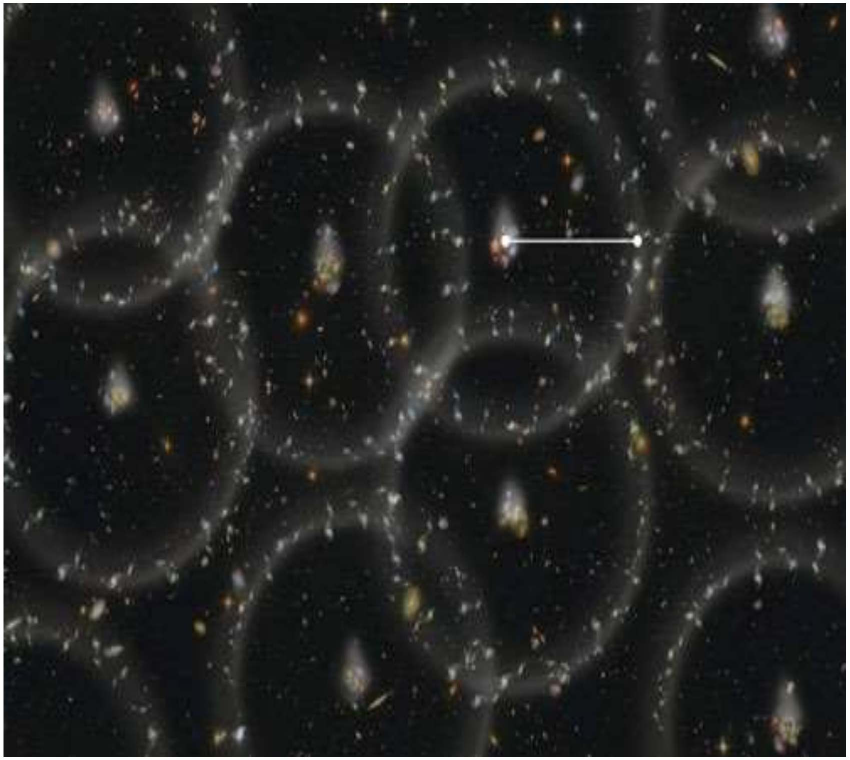


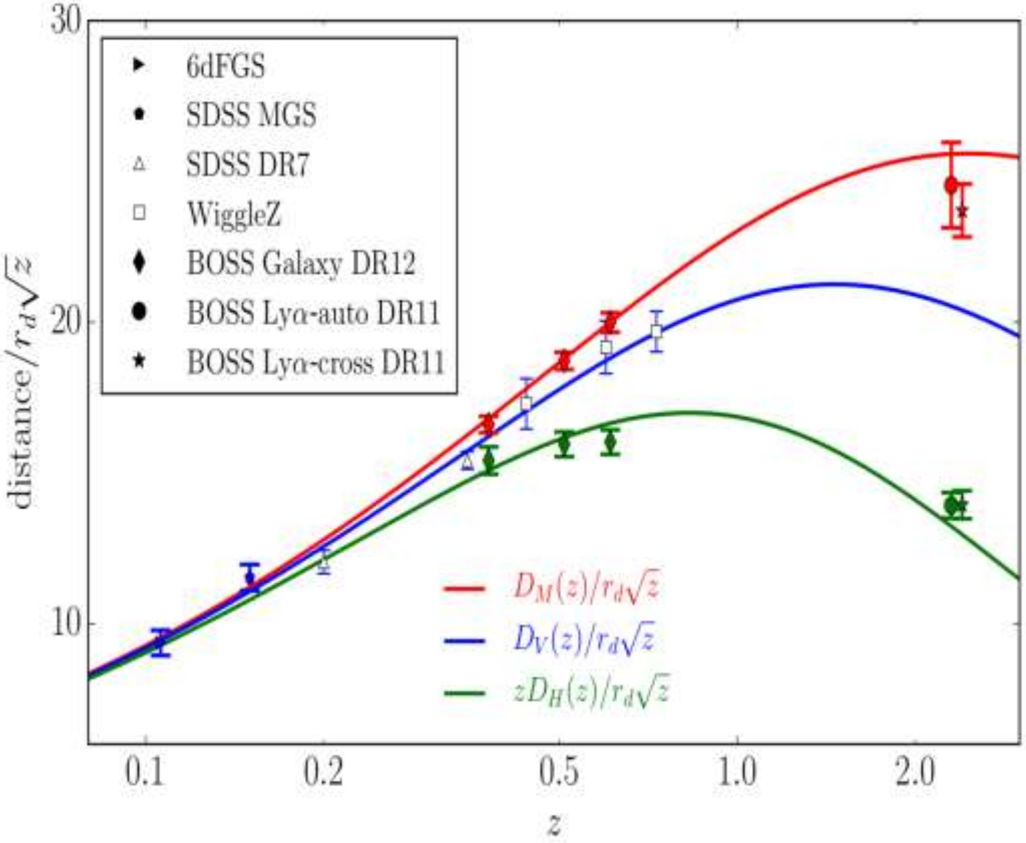
CMB observations





Baryon acoustic oscillations



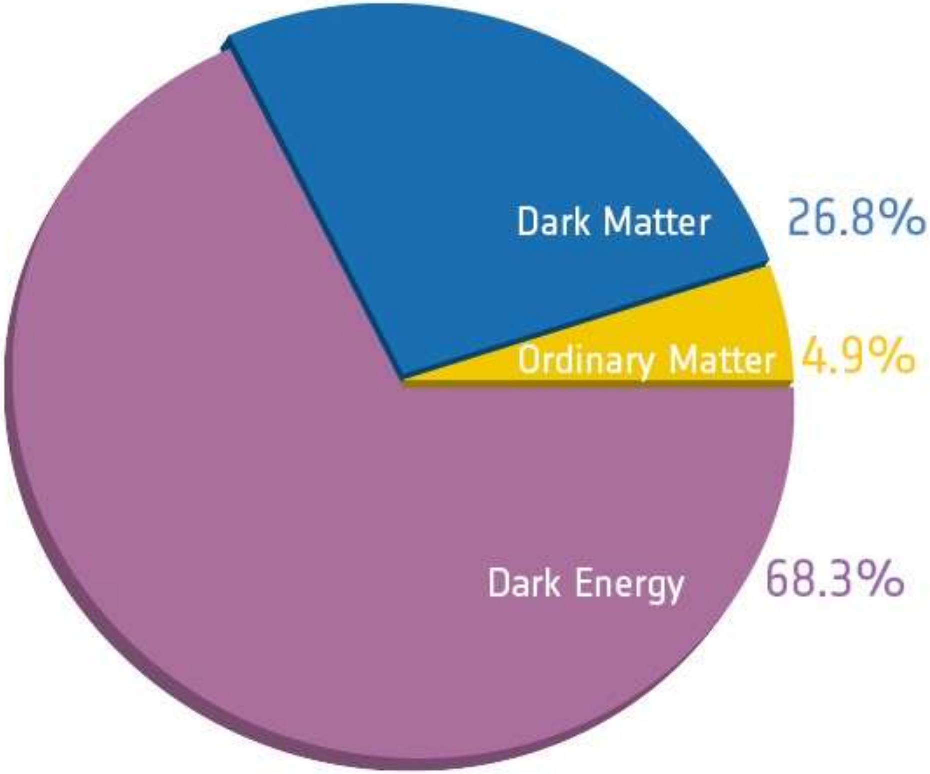


Precision Cosmology

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$

What is dark energy?



Dark Energy VS Modified Gravity

Dark Energy

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

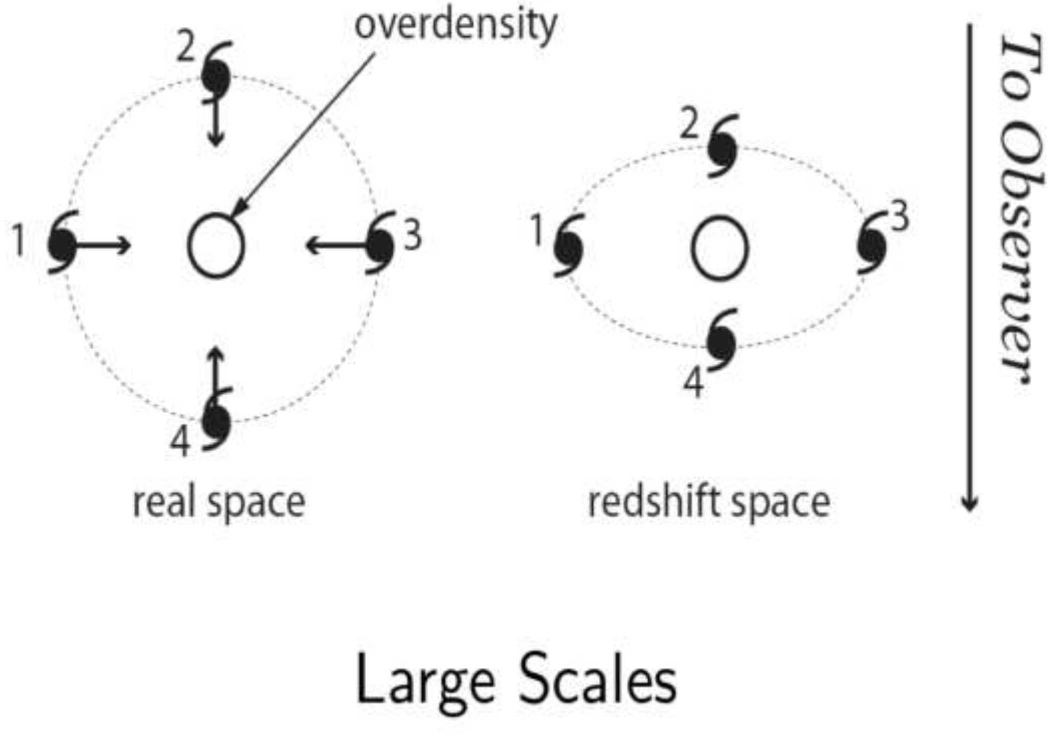
$$\downarrow$$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Geometry/modified gravity

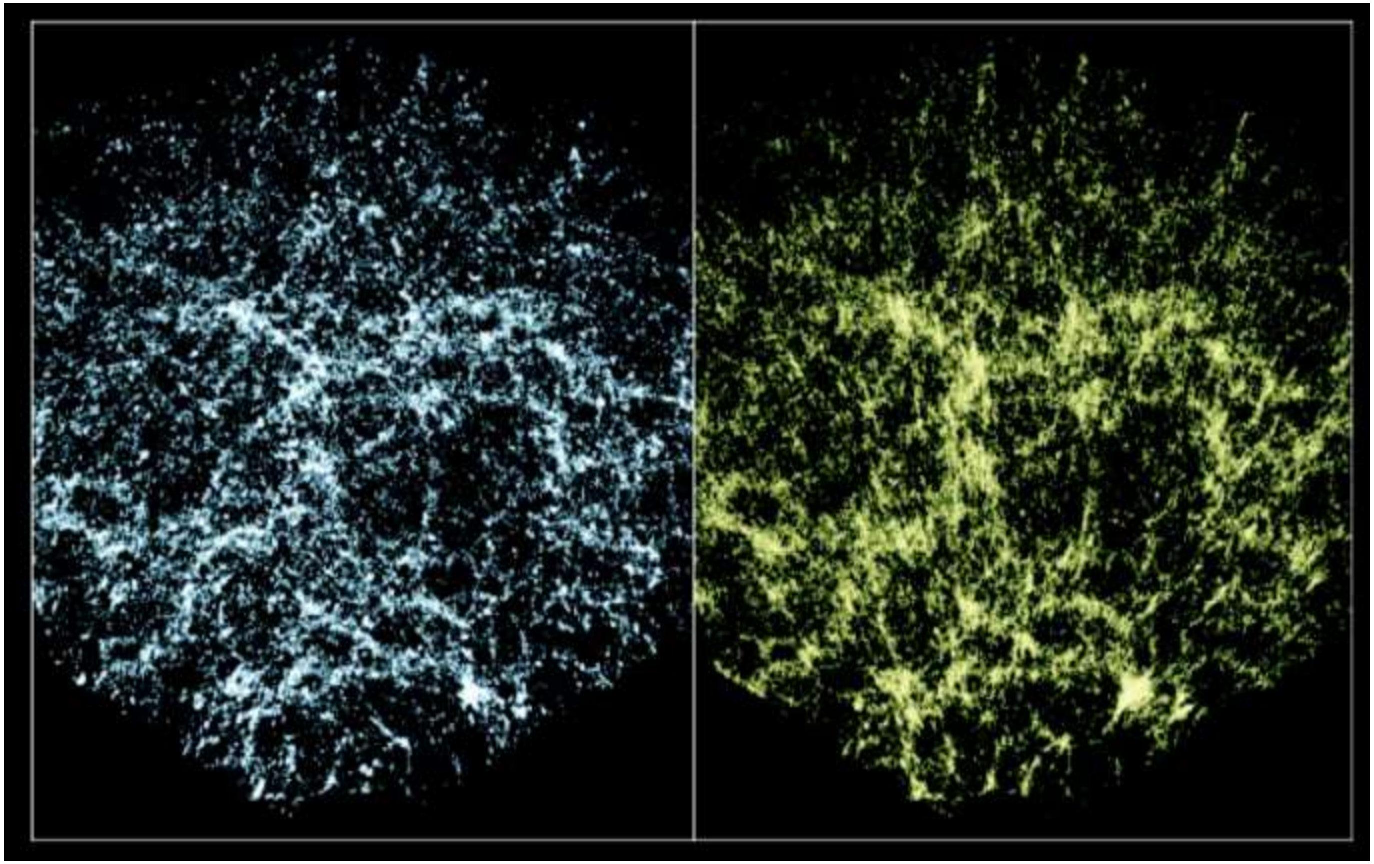
Peculiar motion of galaxies

$$cz = H_0 r + v_p$$



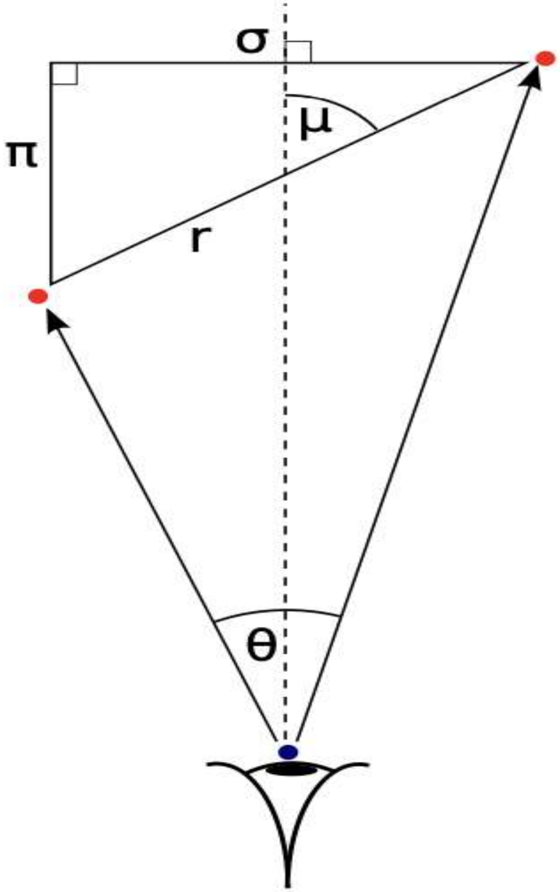
Peculiar motion of galaxies

Real Space | Redshift Space

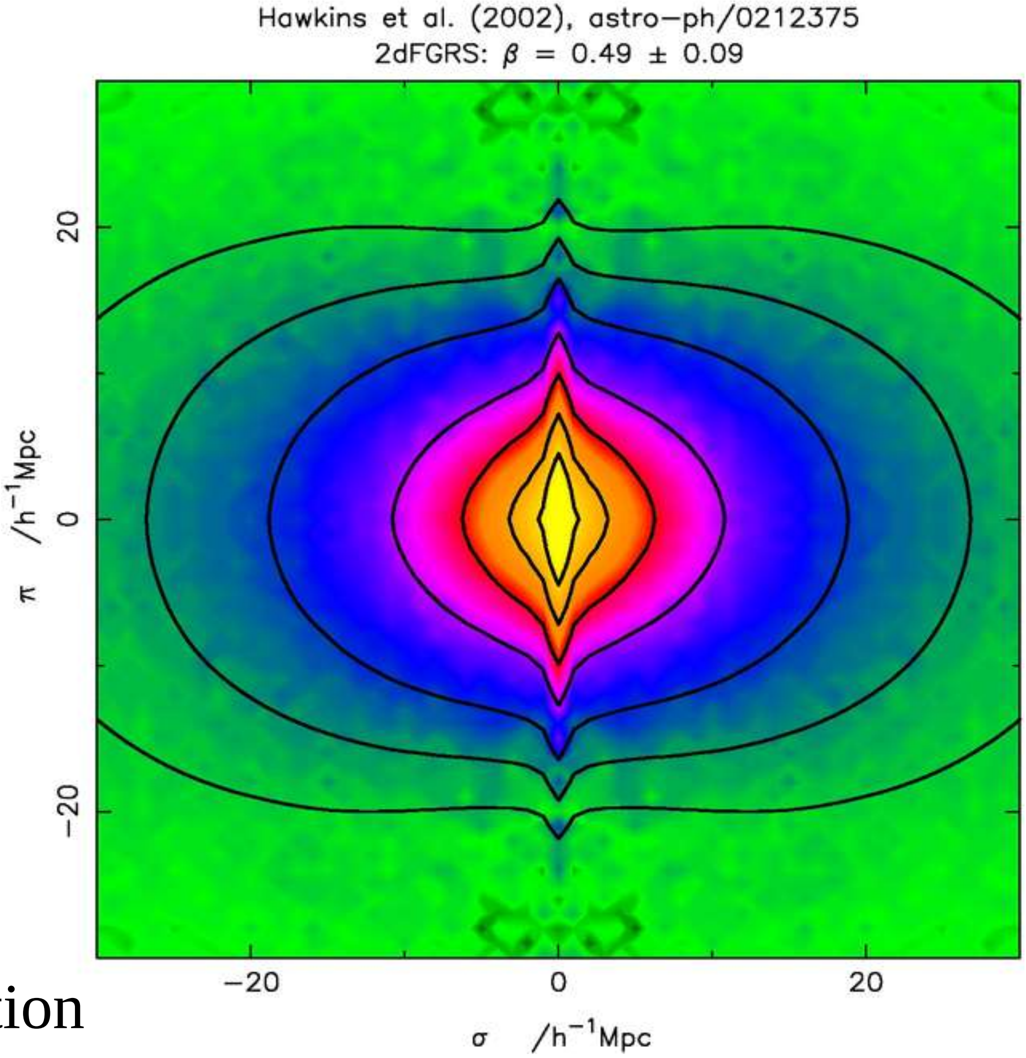


Redshift space distortions

$$\xi(r, \mu)$$



Two-point correlation function



Testing gravity using RSD is challenging!

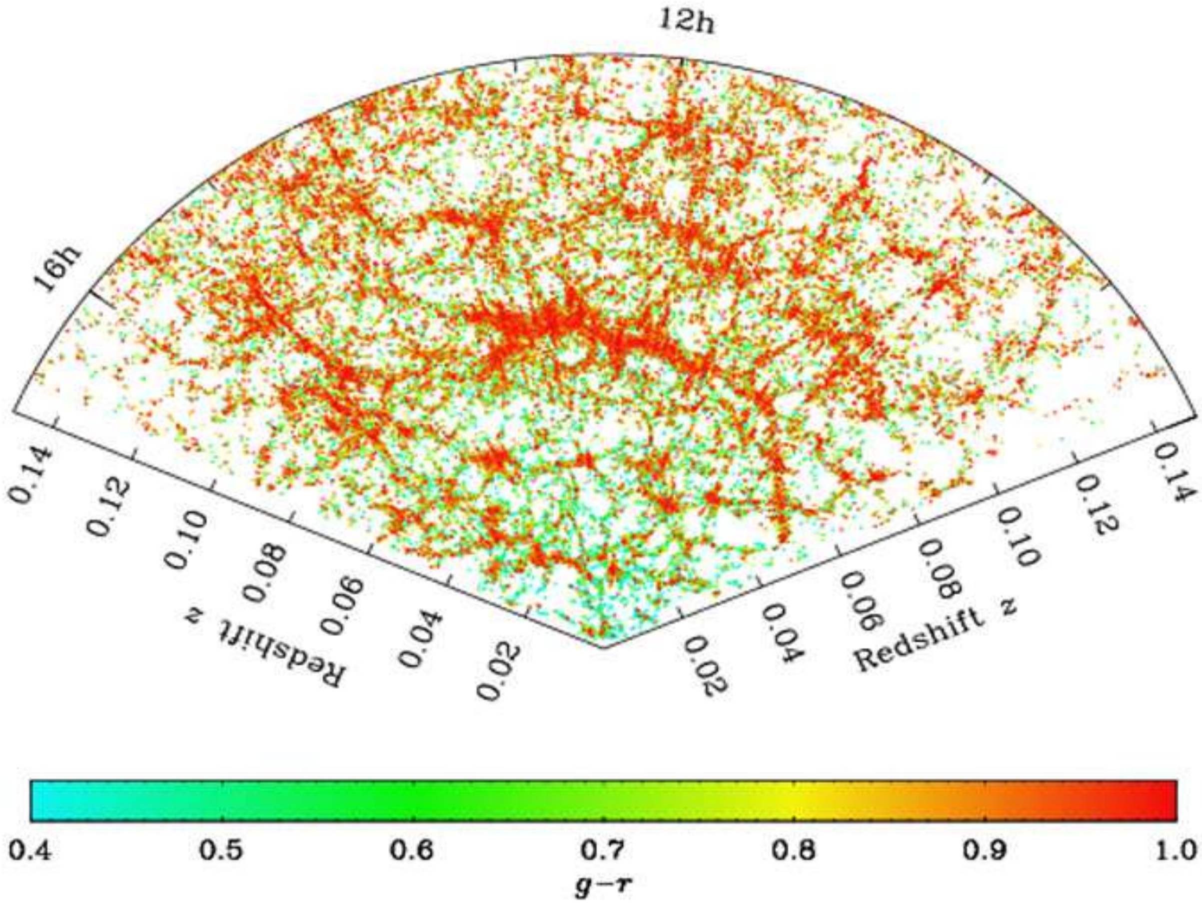
- Galaxy bias
- Effects of Baryons
- Observational Systematics
- Genuine Tests

Outline

- Theory
- Observation

THEORY

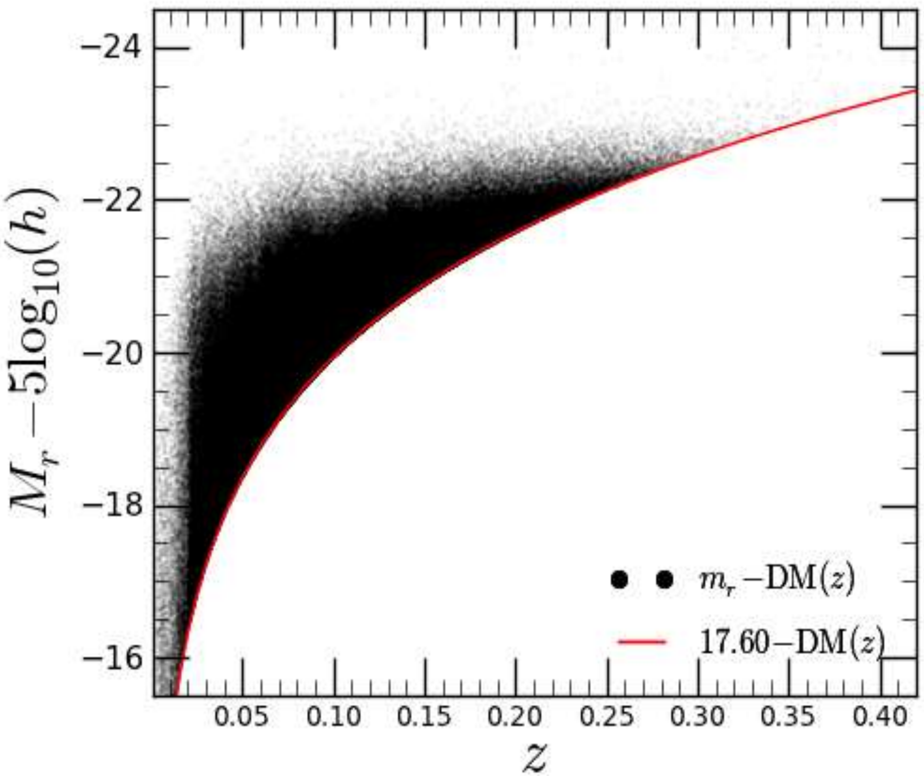
Galaxies, tracers of dark matter?



Galaxy Bias

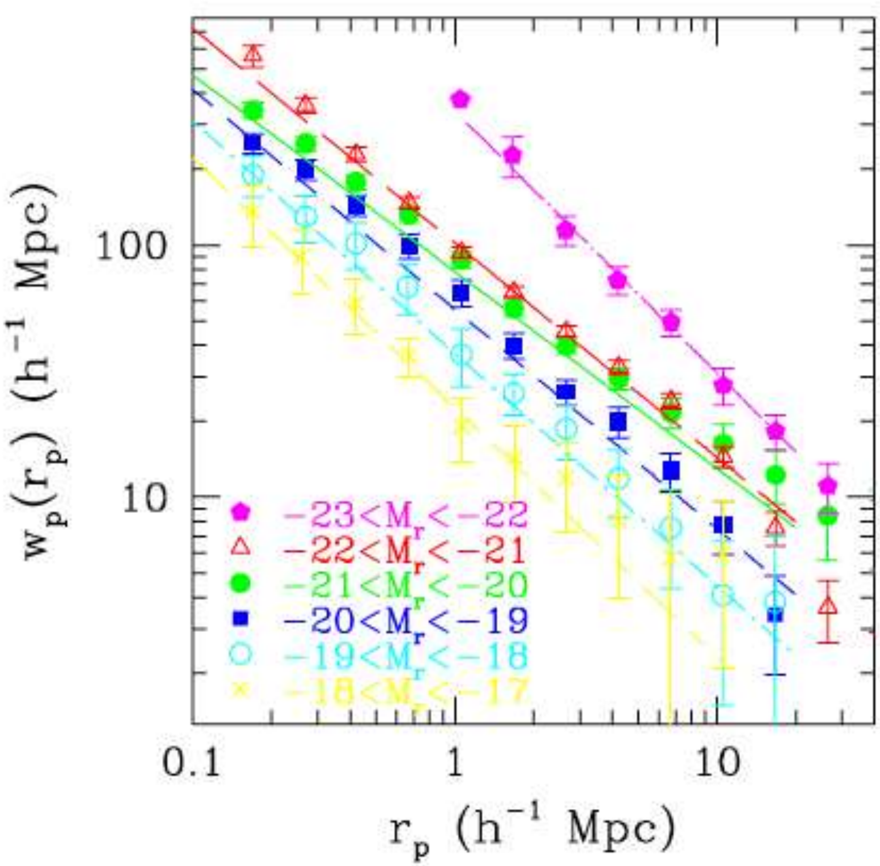
The selection bias

Observation limitations

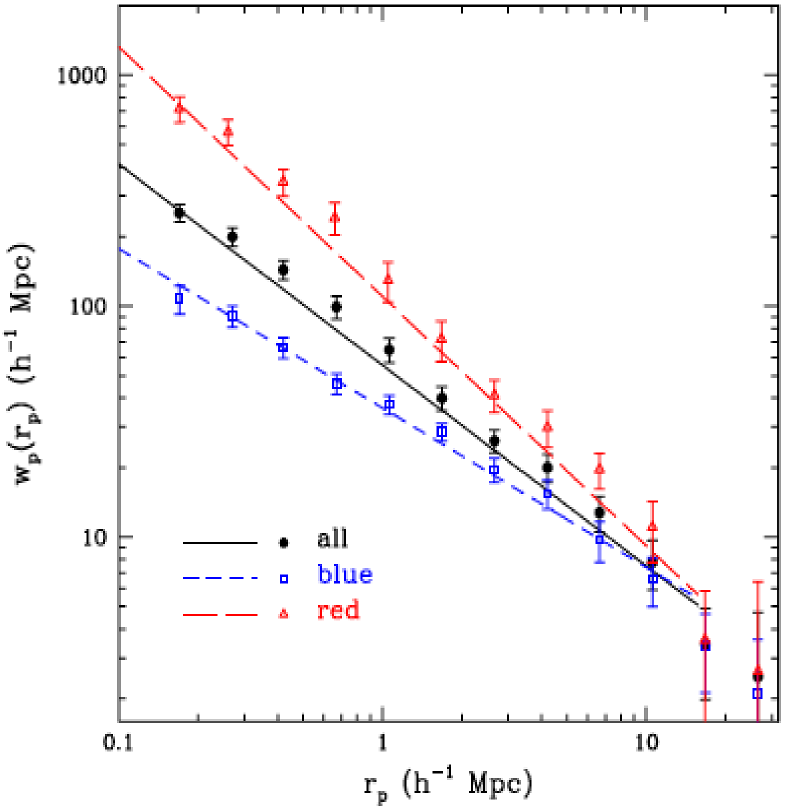


The selection bias

Luminosity Dependence



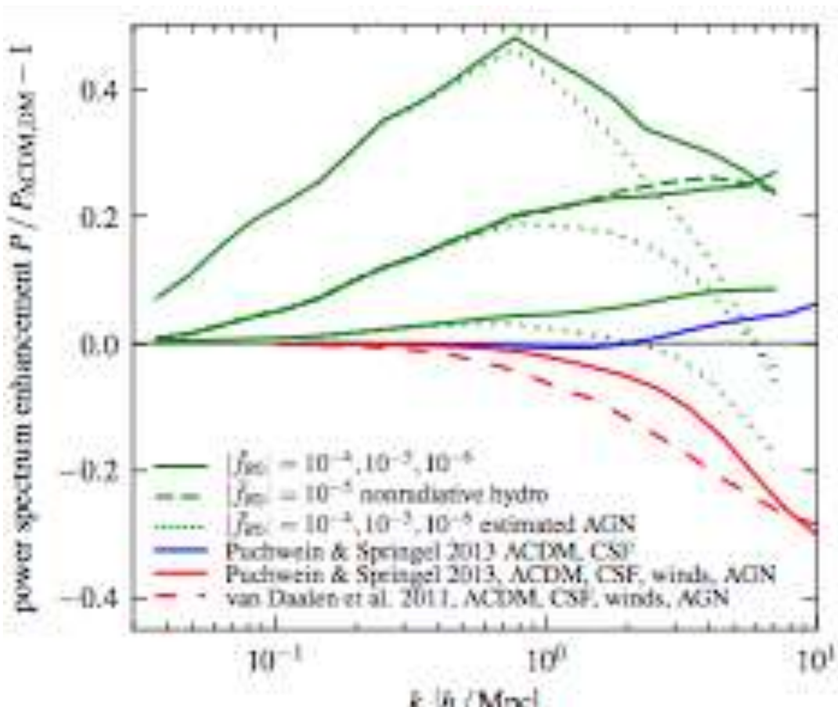
Color Dependence



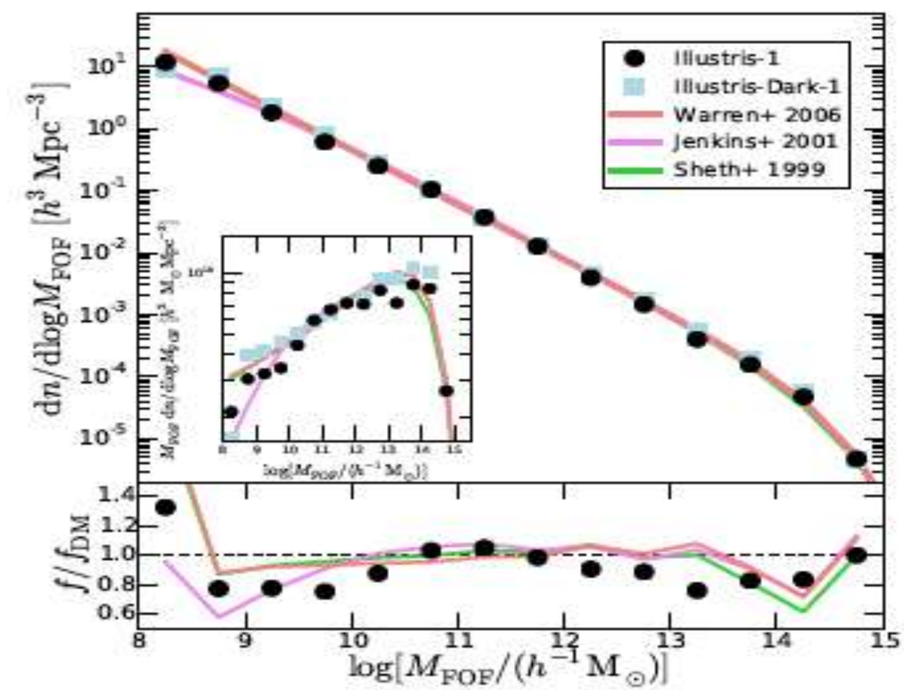
Zehavi, et al 2004

The impact of baryons

- AGN feedback changes the underlying distribution of the cold dark matter on small scales.
- AGN feedback changes halo mass function as well

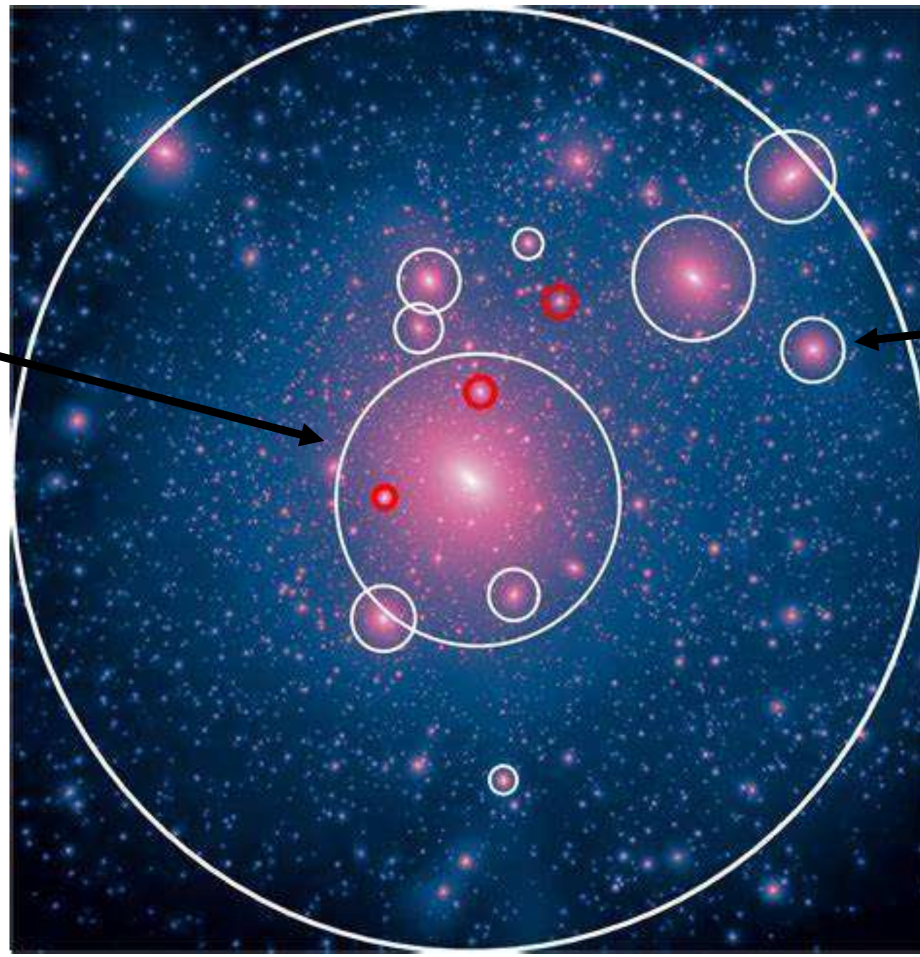


Puchwein et al (2013)

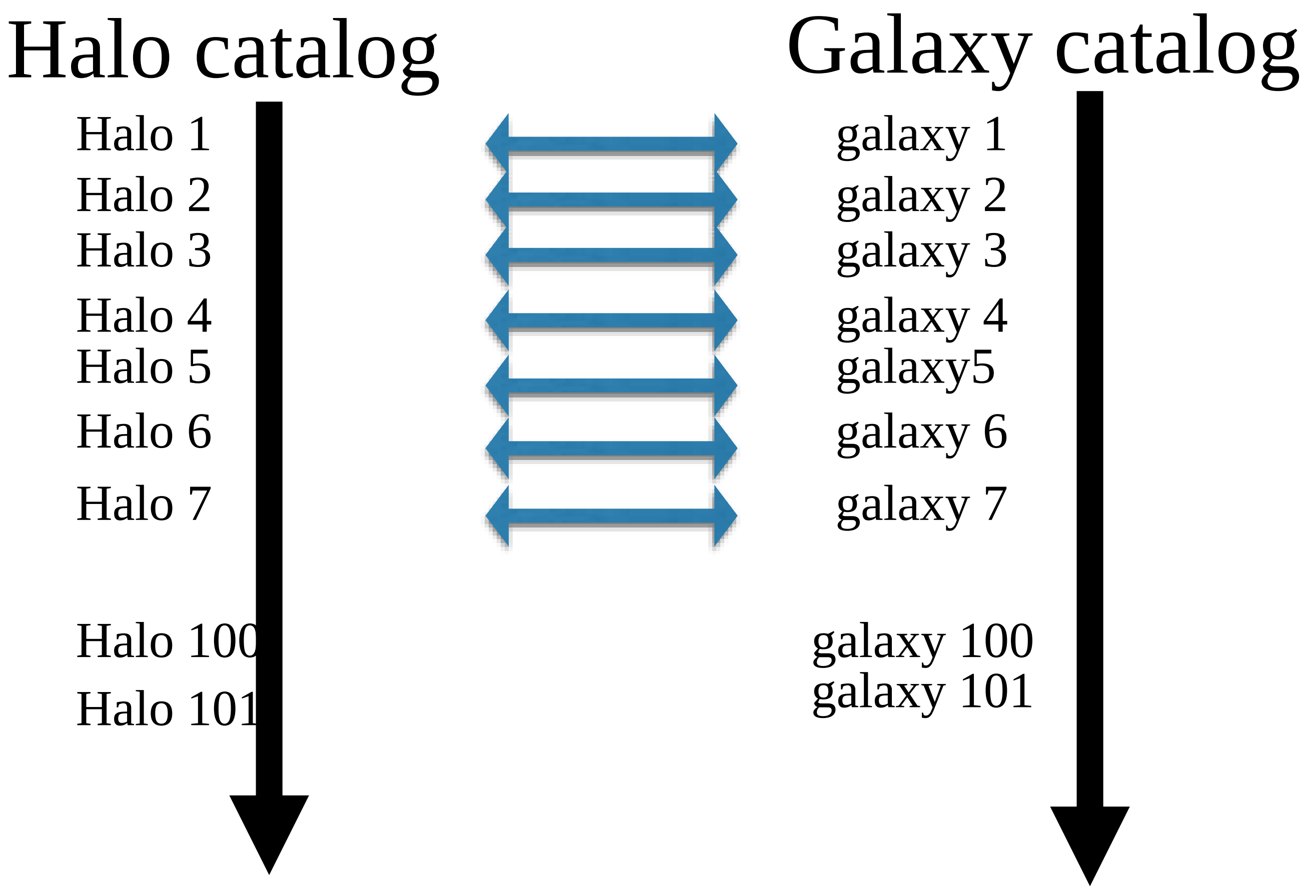


Mark Vogelsberger et al (2013)

Dark matter halos

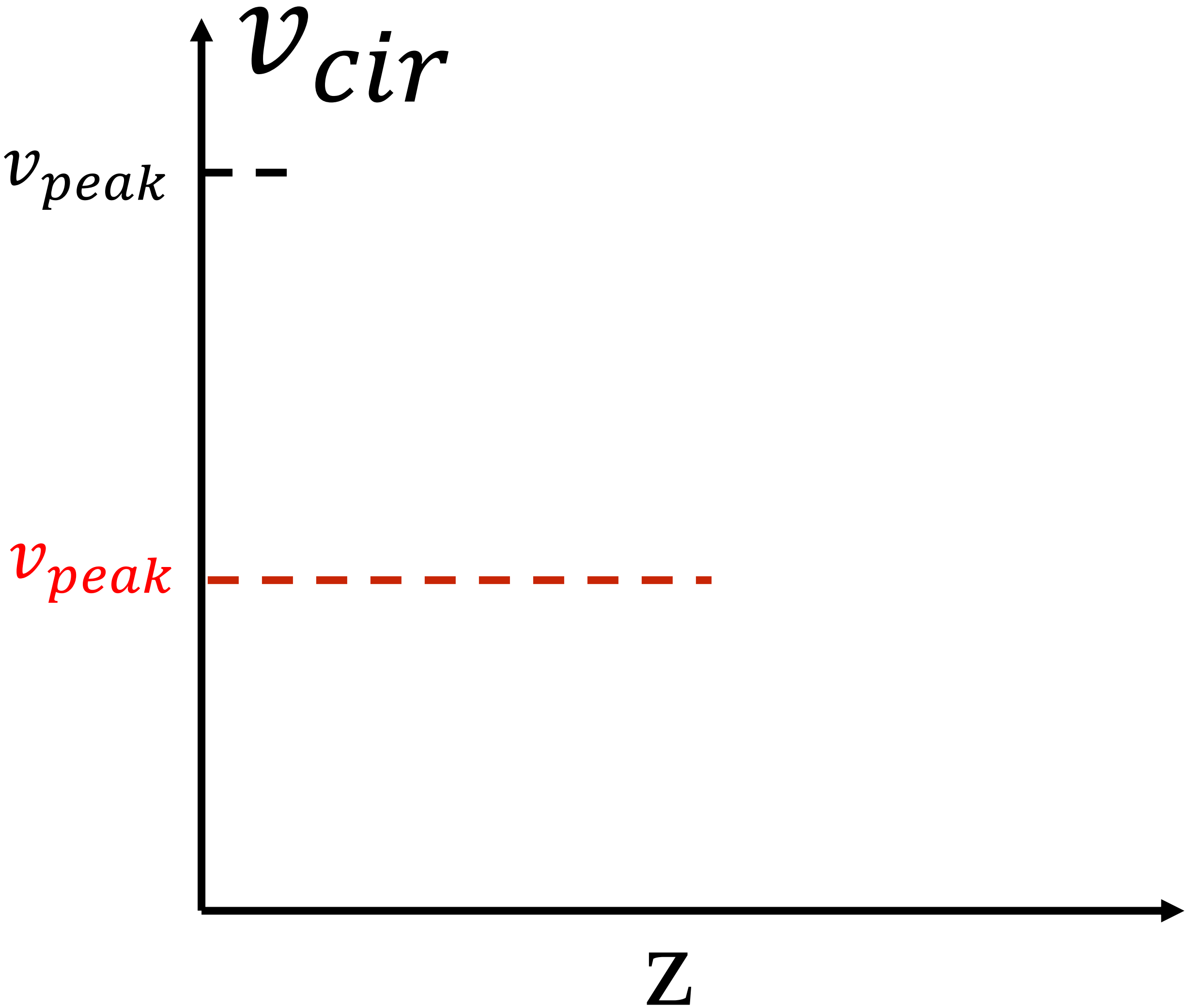


Galaxies are tracers of halos



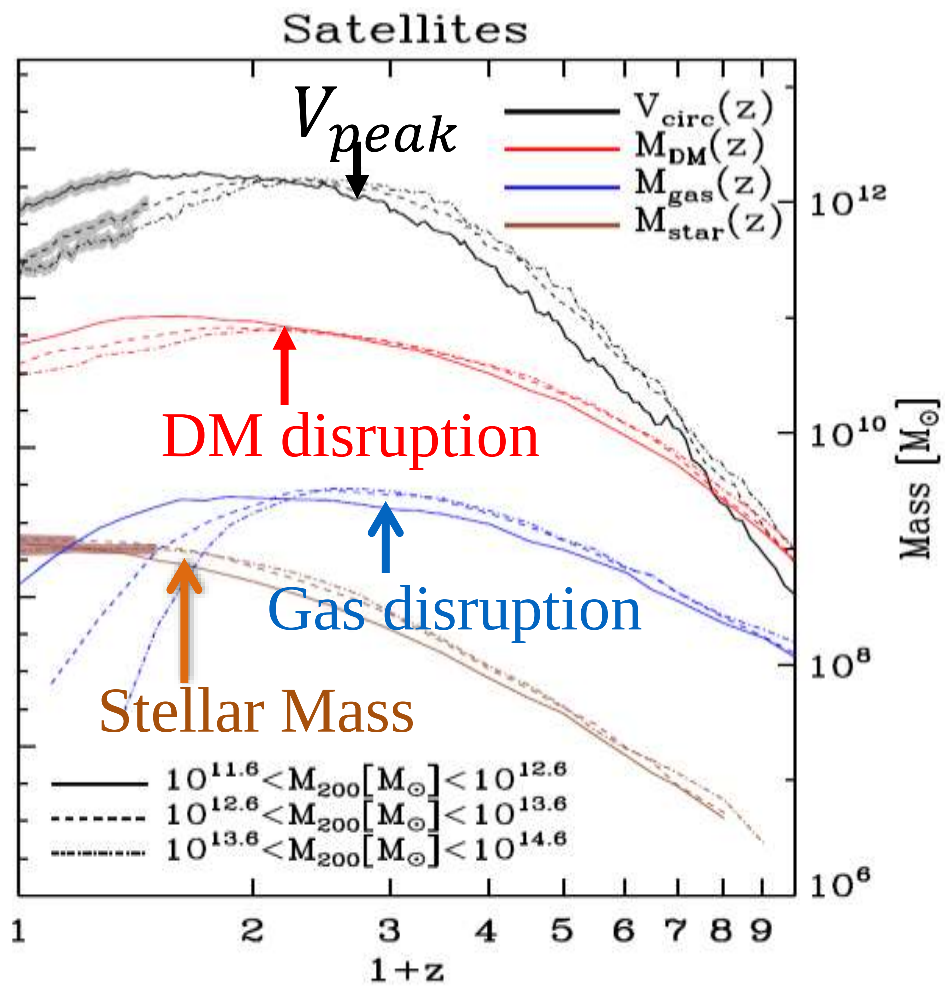
Which property?

Dark matter accretion history



Stellar mass and gas mass accretion history

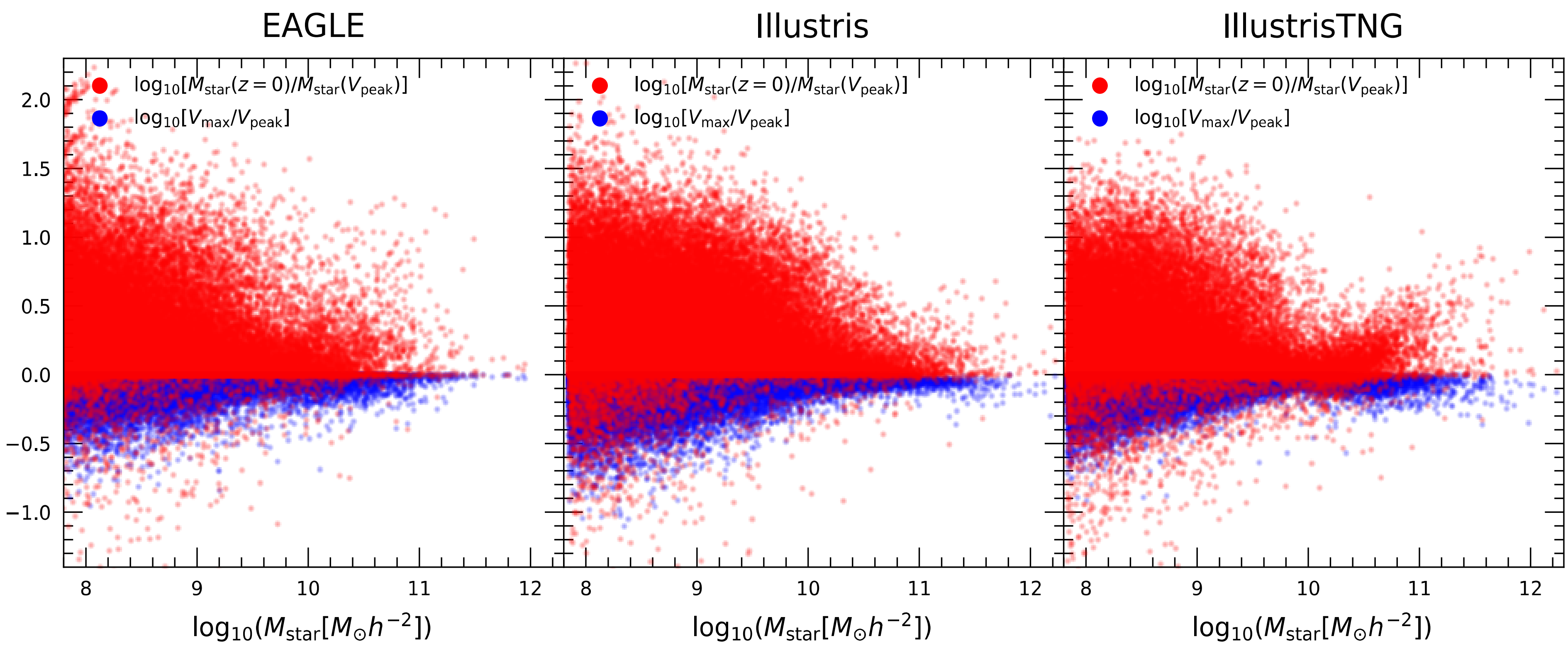
- Dark matter can be striped after V_{peak} due to gravitational tidal force
- Gas component can be more easily striped due to both tidal force and non-gravitational interactions.
- After V_{peak} , stellar mass can grow due to the remaining star forming.



Jonas Chaves-Montero, et al 2015

Stellar mass and gas mass accretion history

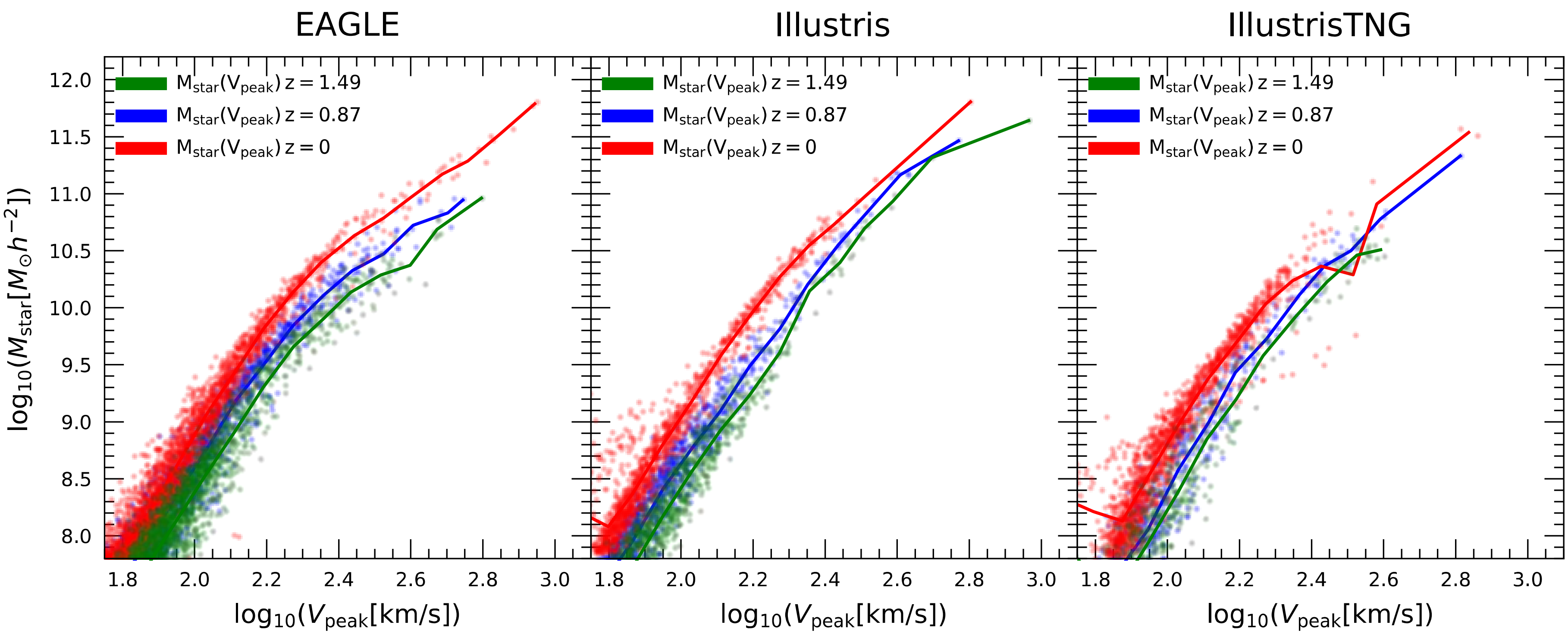
- The disruption of dark matter is prevalent
- However, most galaxies can still gain stellar mass after accretion



He, MNRAS 2019

Galaxy properties Pre-disruption

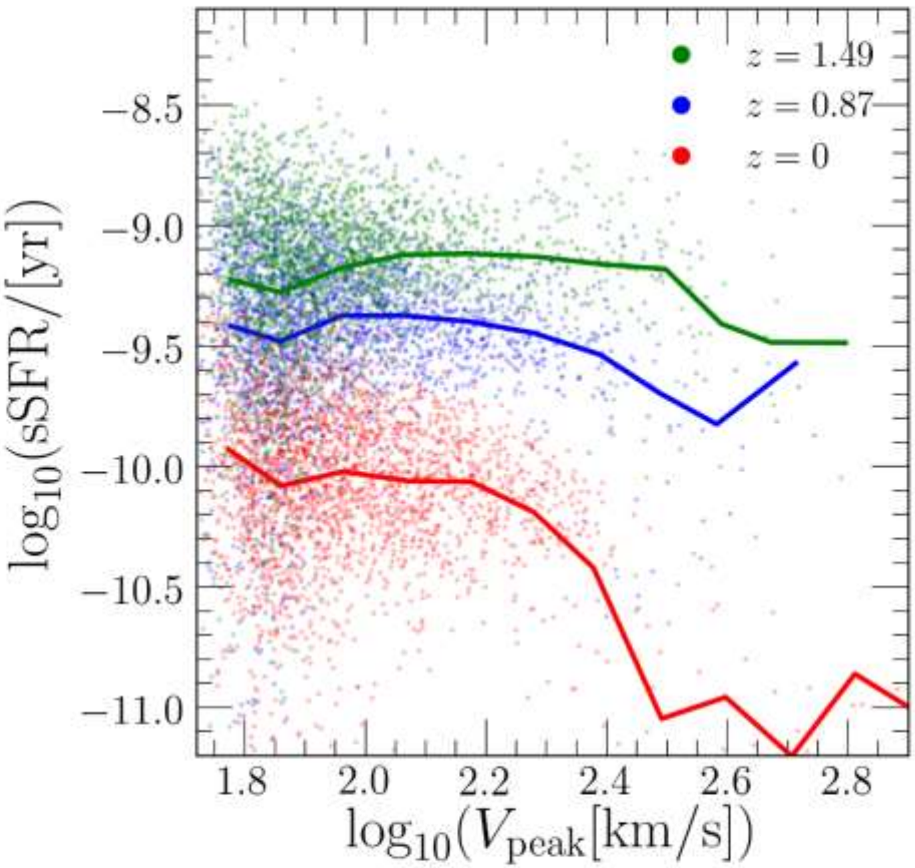
- Stellar mass-V_{peak} relation from hydrodynamical simulations



He, MNRAS 2019

Stellar mass evolution

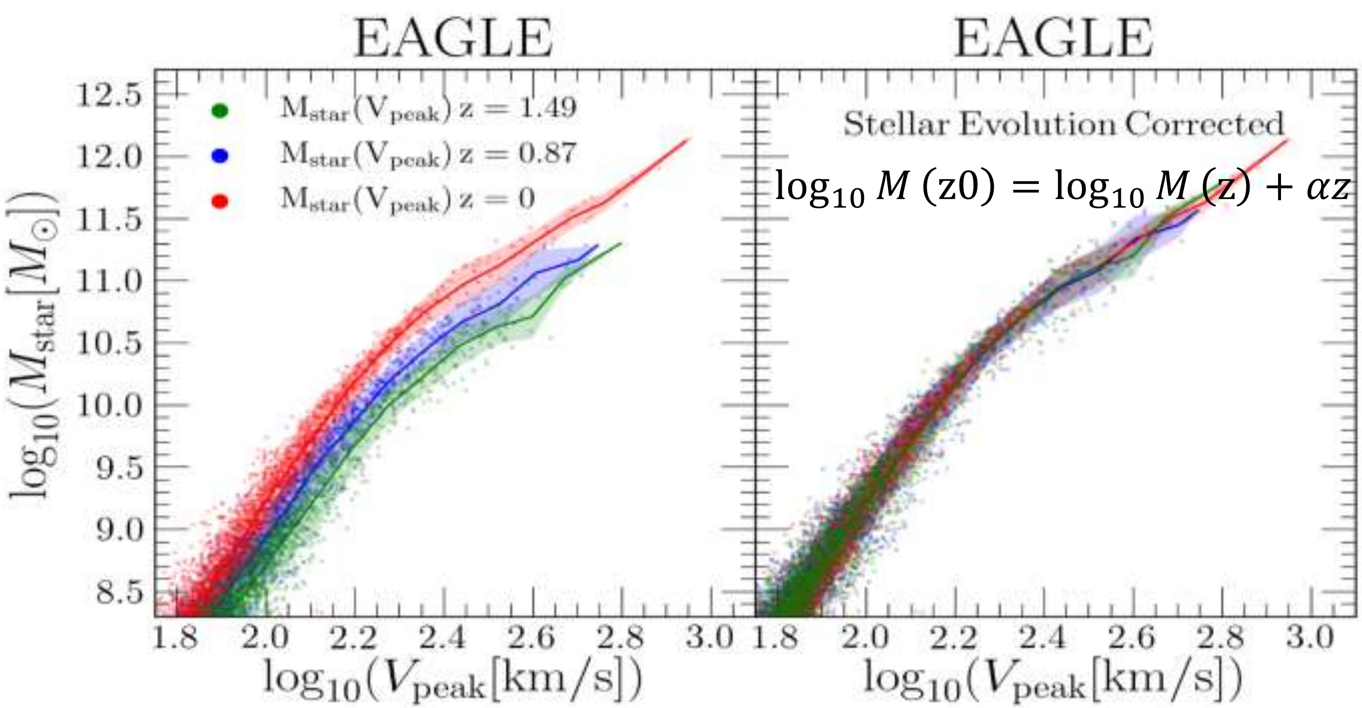
- The specific star forming rate of the main sequence galaxies is nearly a constant



He, MNRAS, 2019

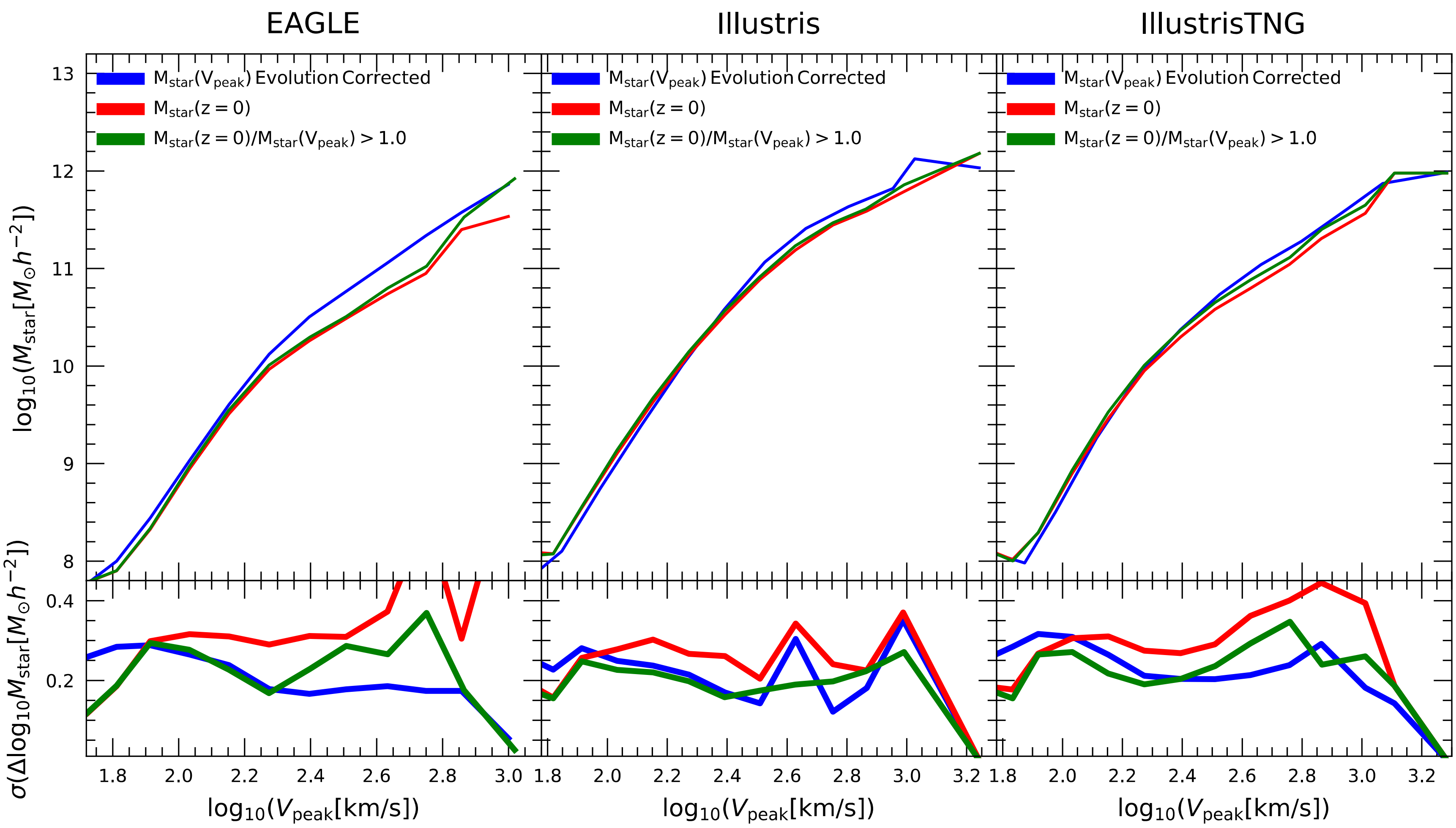
Modelling stellar mass evolution

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



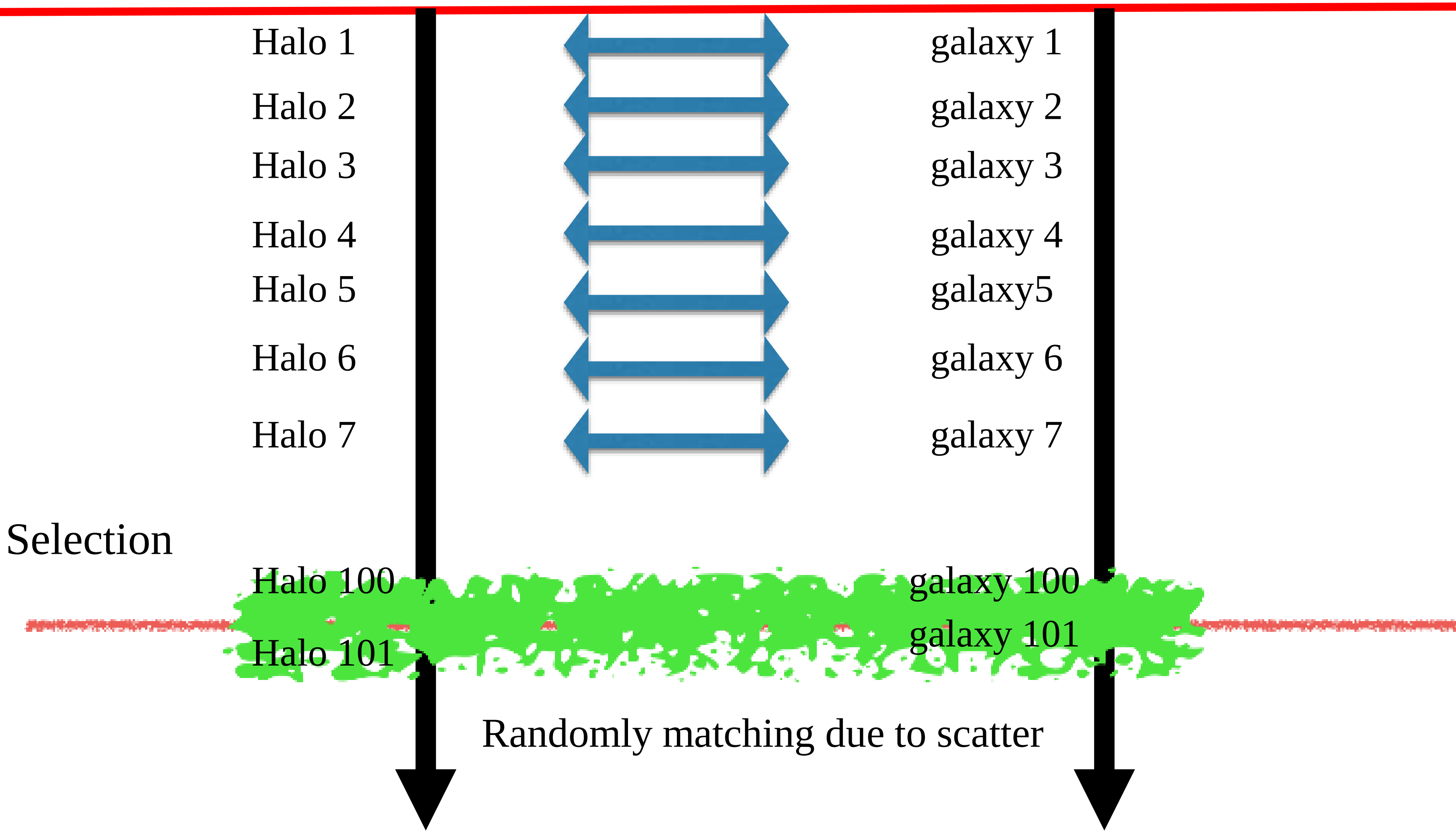
He, MNRAS 2019

Post-disruption $V_{peak} - M_*(z=0)$relation



He, MNRAS, 2019

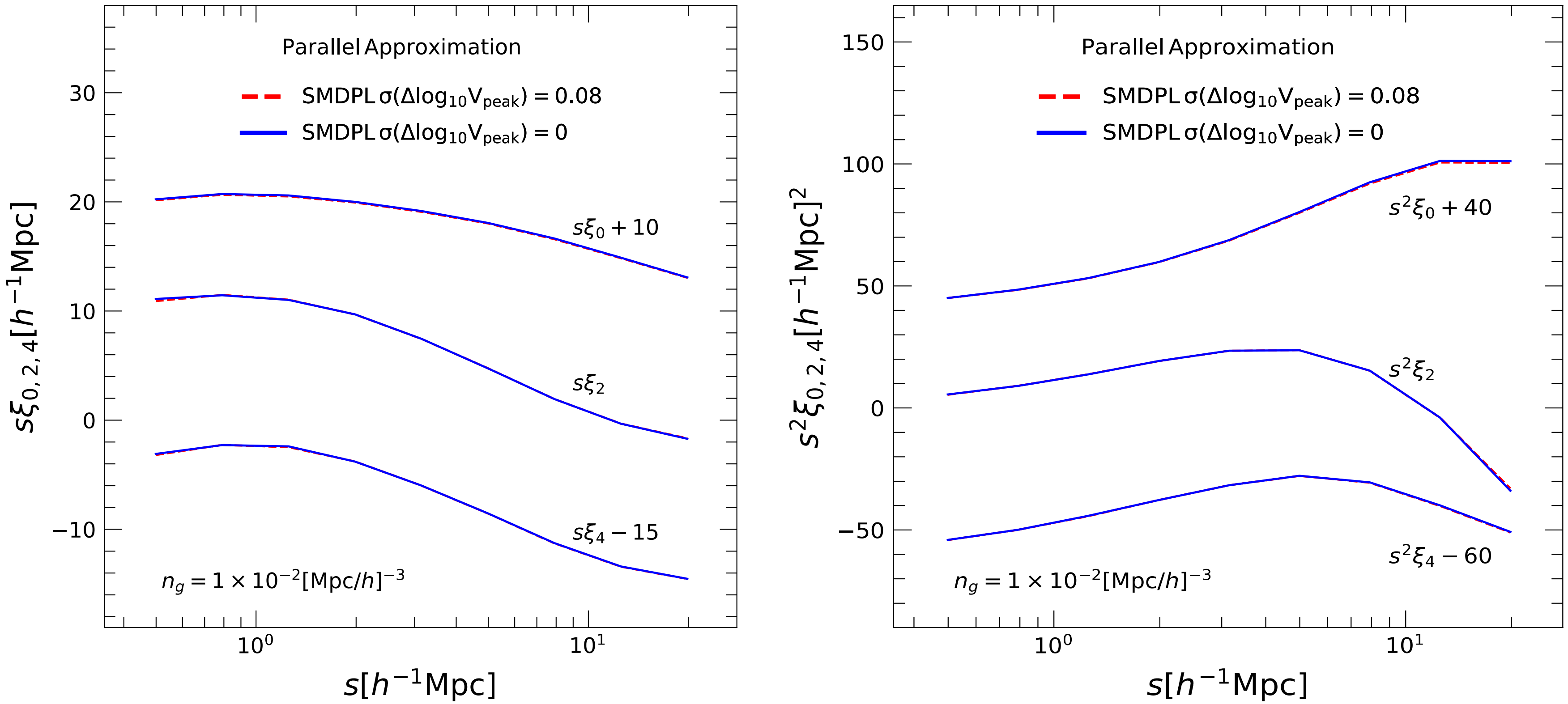
Halo catalogue Galaxy catalogue



Only samples around the threshold are affected by scatters

The impact of scatter on clustering

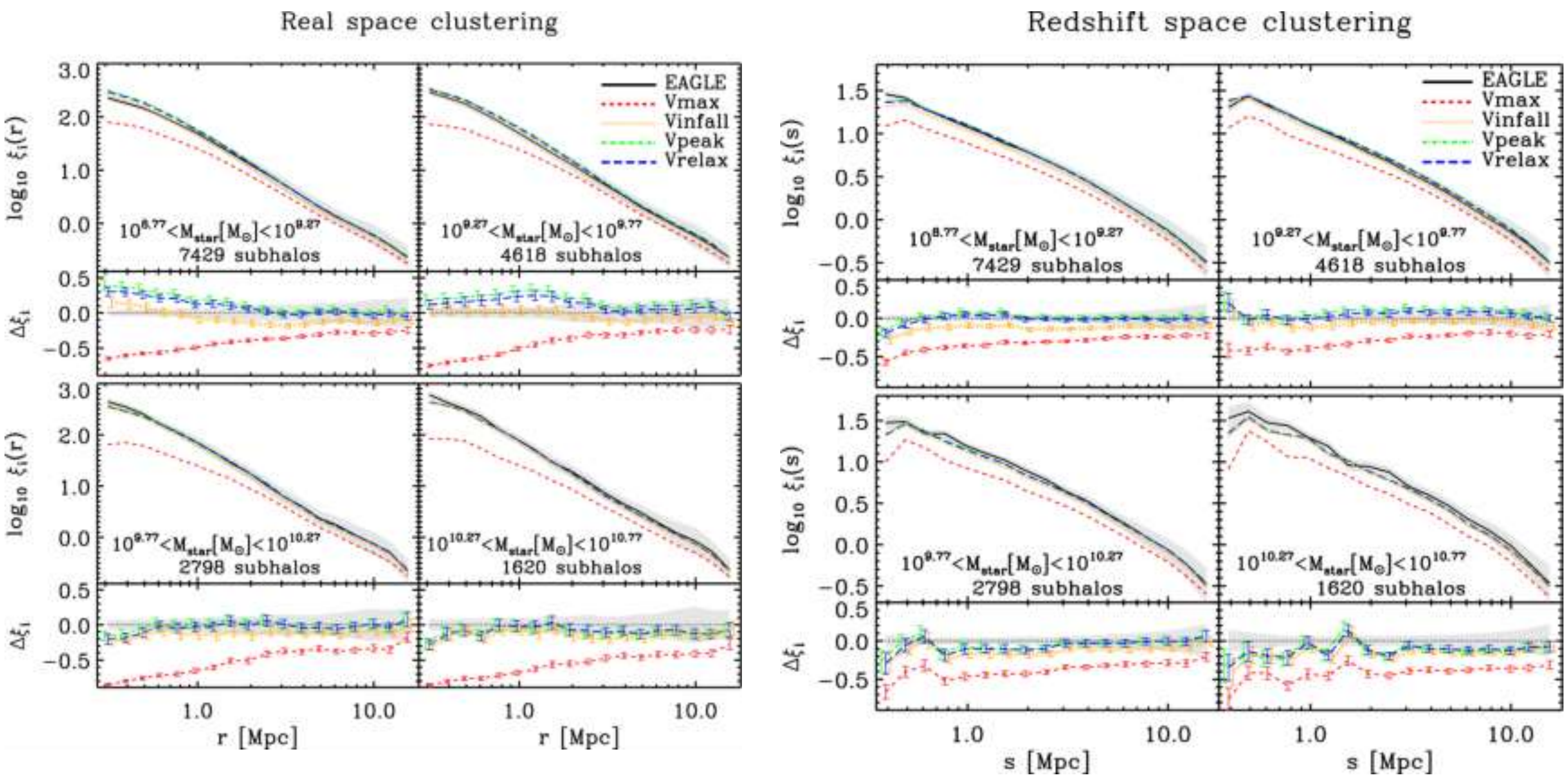
- The impact of scatter can be mitigated by high number densities
- High number density samples are less affected by scatter



He, MNRAS, 2019

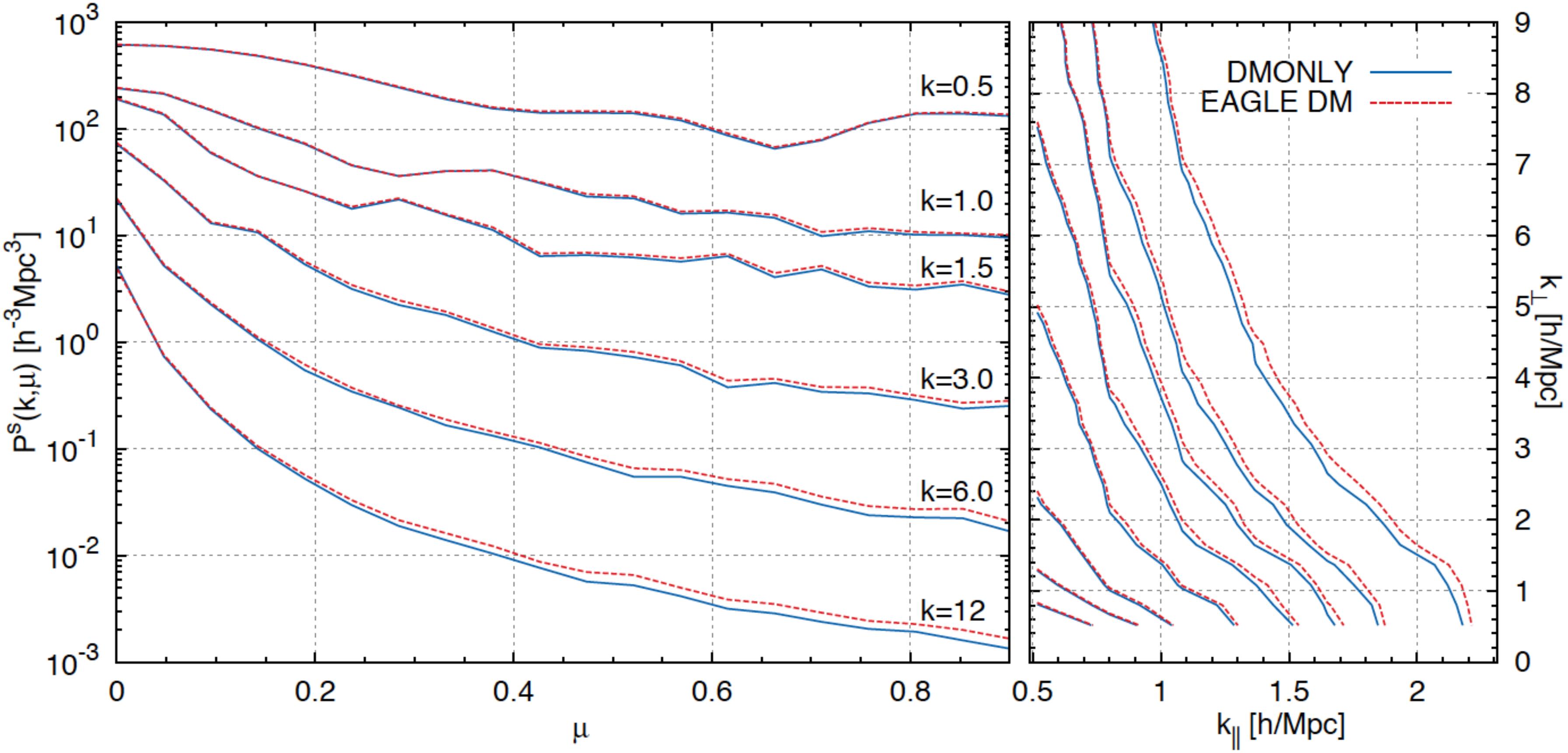
The impact of baryons on the absolute positions and motions of subhalos

- 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

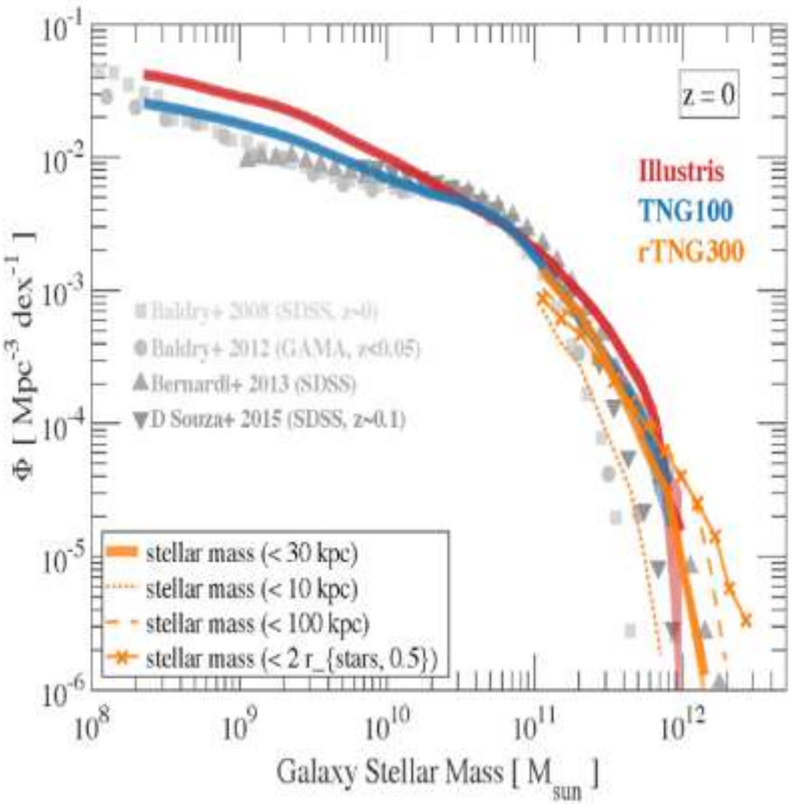
The impact of baryons on the absolute positions and motions of subhalos



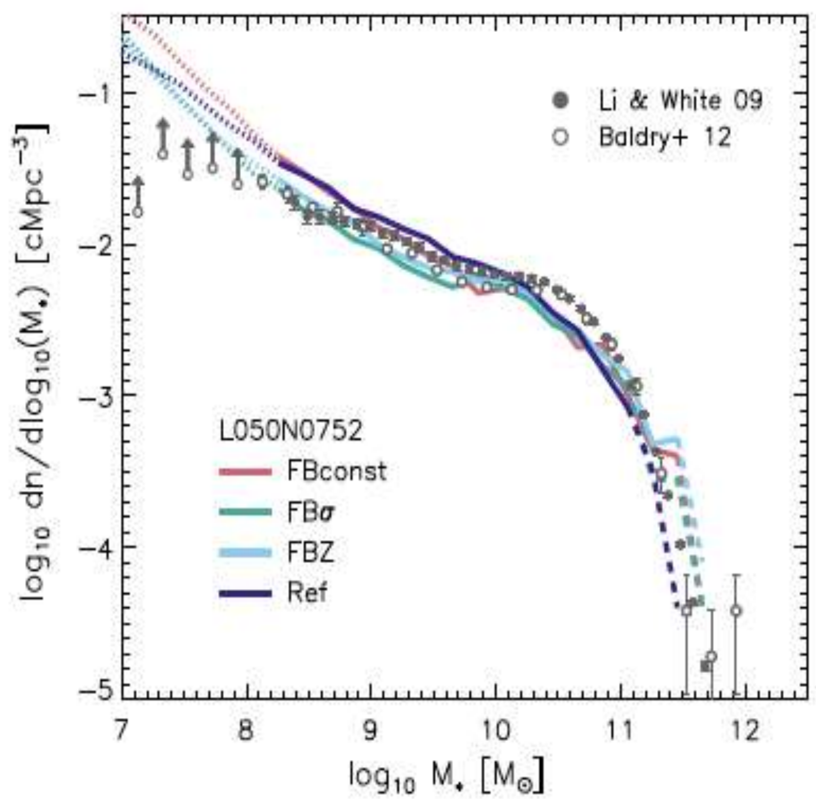
Hellwing et. al. 2016

Stellar mass function in hydro-dynamic simulations

Illustris and Illustris TNG

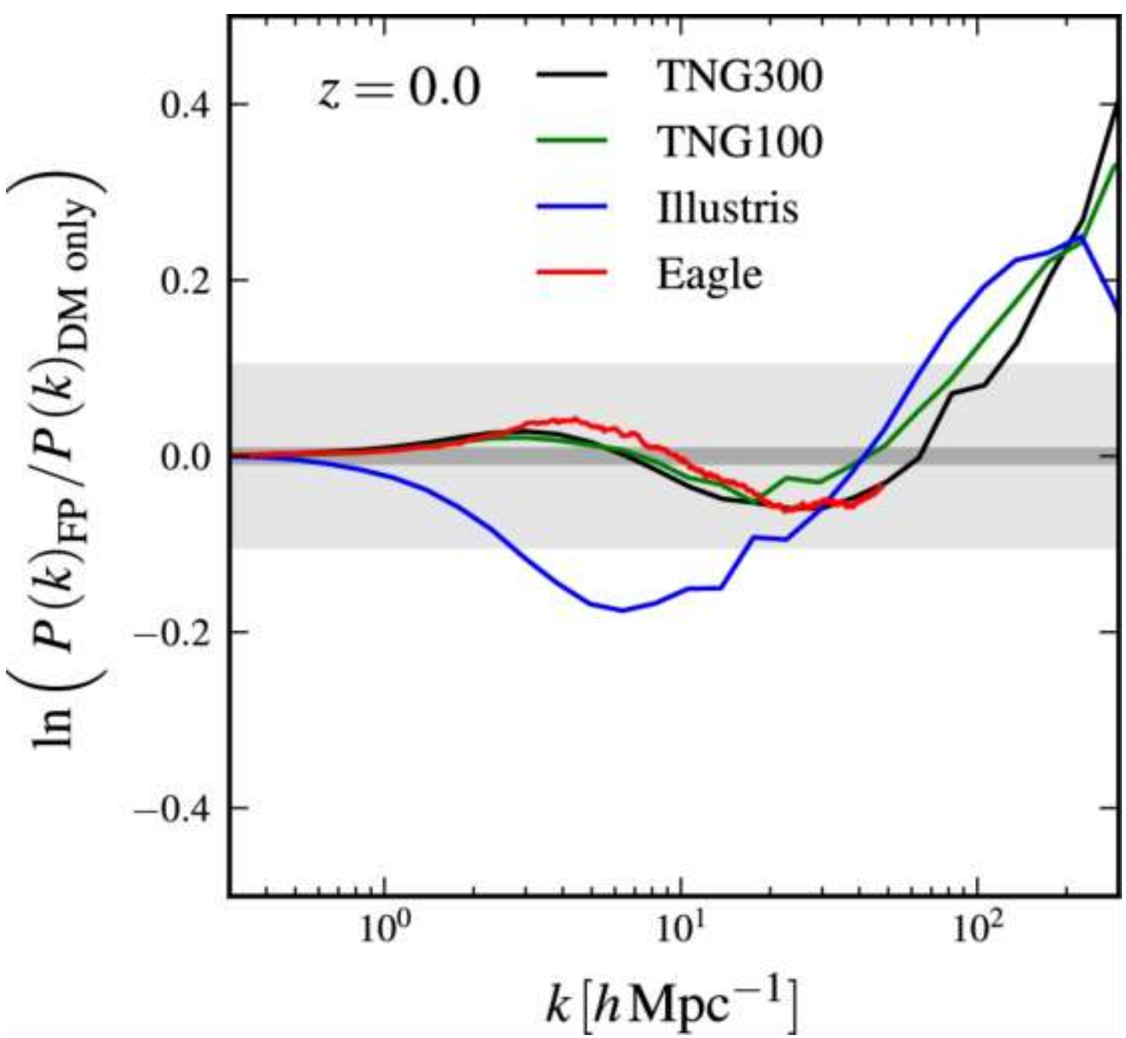


EAGLE



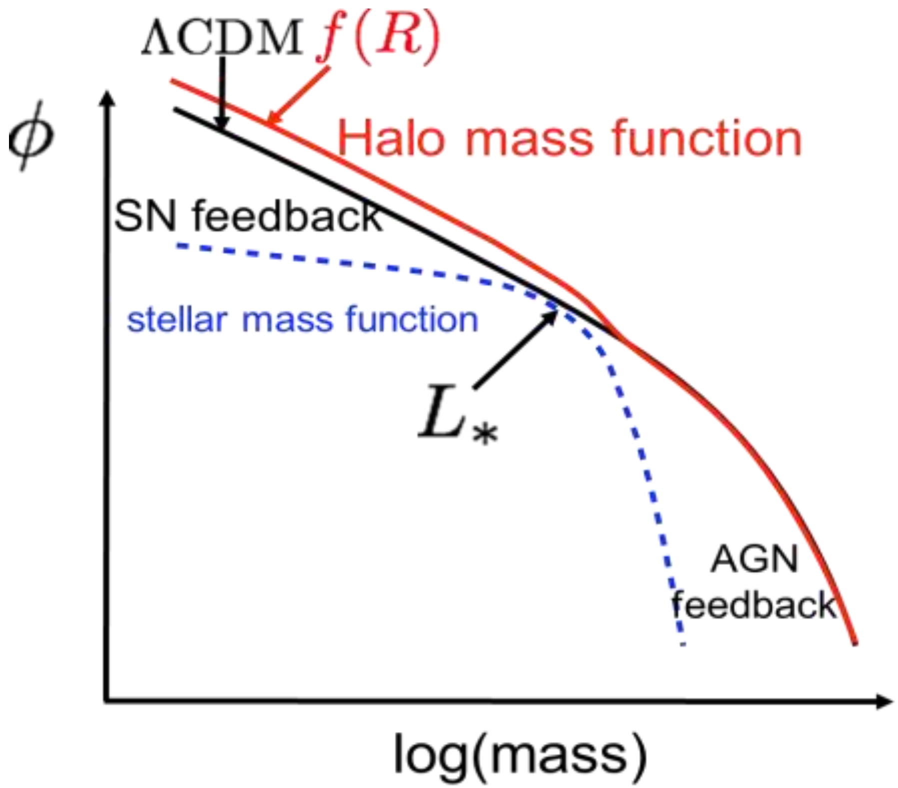
Baryon physics is constrained by stellar mass function

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



Abundance Matching

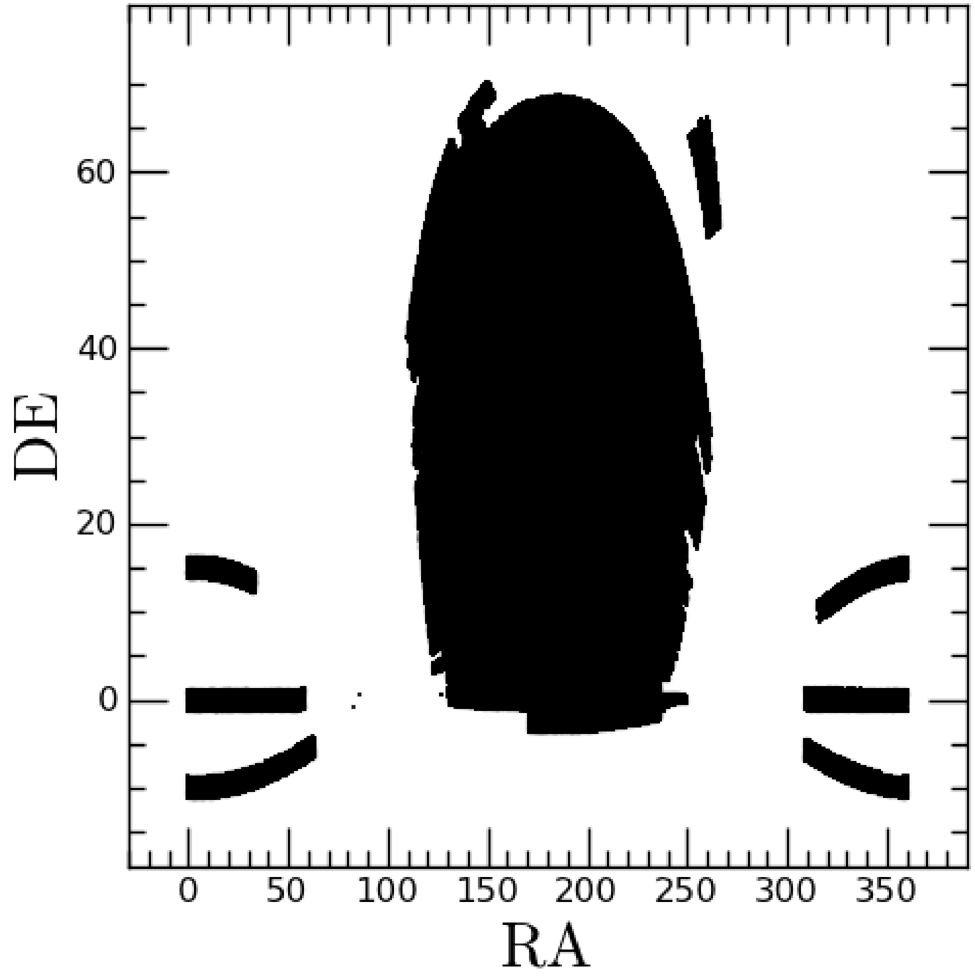
- Abundance matching does not have galaxy bias
- The shape of stellar mass function can put constraints on baryon physics!!
- Baryon physics in modified gravity models should be reasonable



DATA

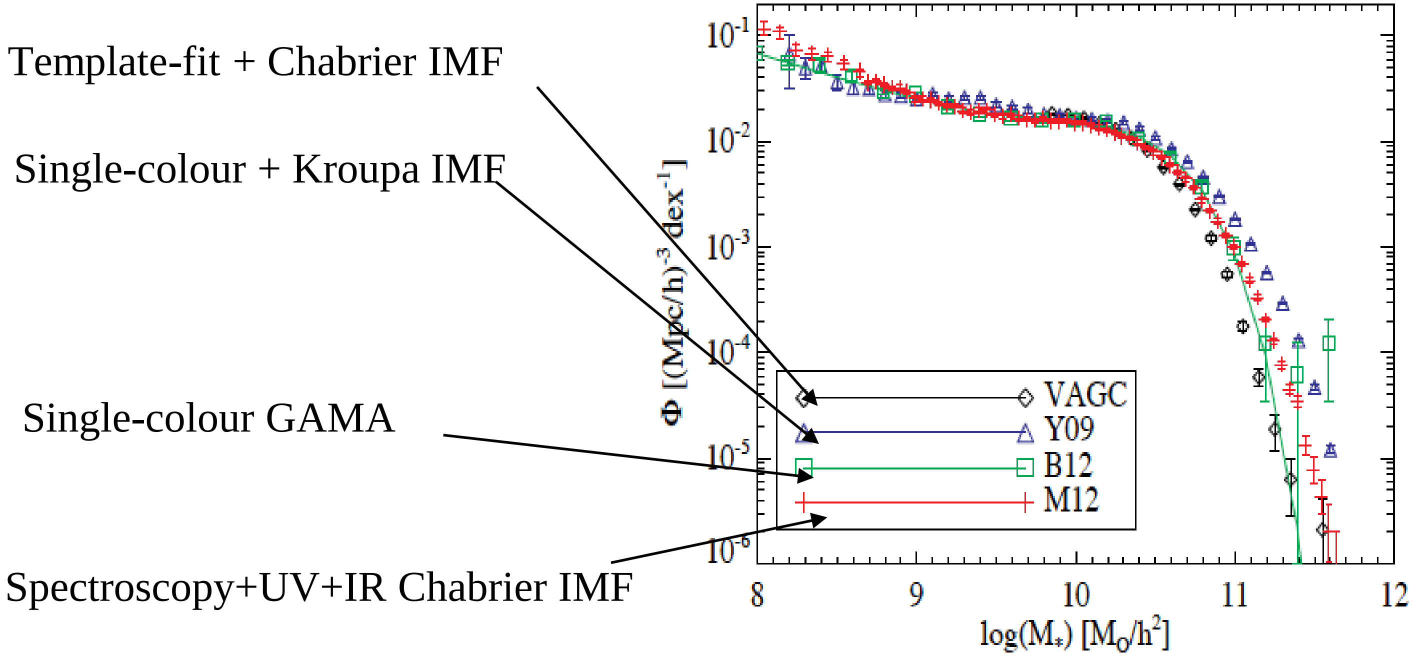
NYU Value-Added Galaxy Catalog

- VAGC is based on the SDSS 7 main galaxy sample
- Relative photometric calibration which uses the same objects in overlaps (good ~1%)
- BBRIGHT sub-sample with a uniform *r*-band SDSS Petrosian 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 the image data (aperture effect, background subtraction, dust extinction)
- Different methods (e.g. photometric template fit, a combination of spectroscopy and photometry, a single-color based estimator)



Volume-limited sample complete in stellar mass

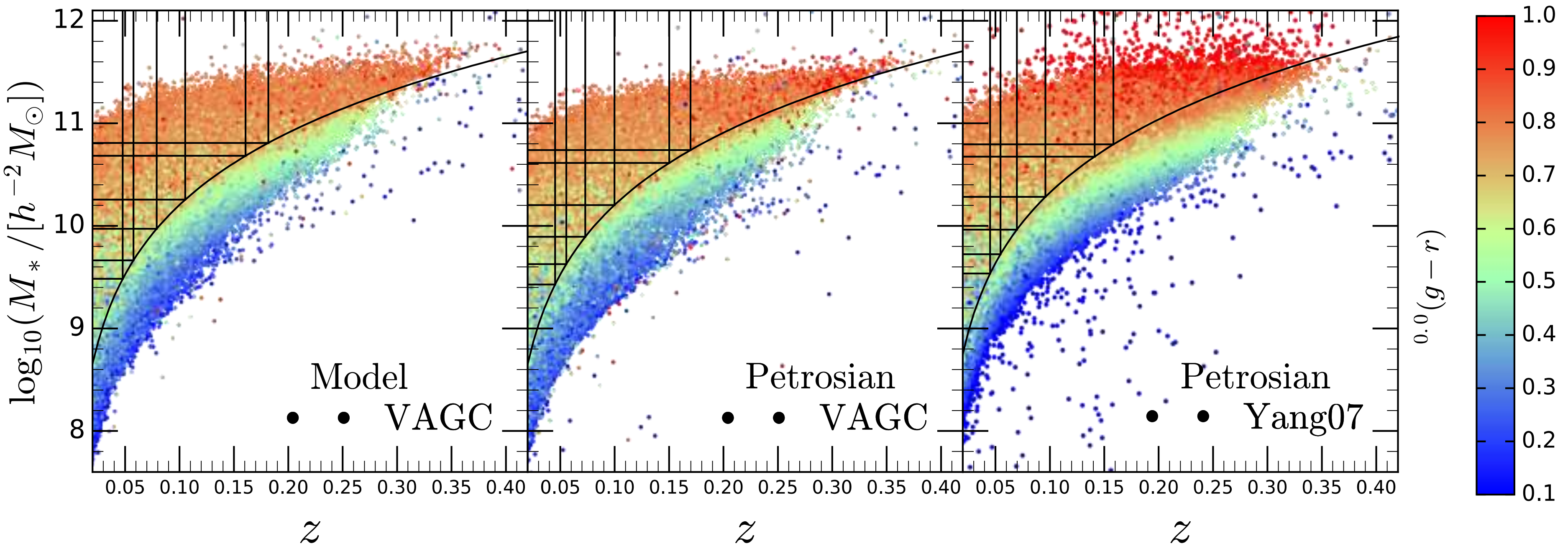
Systematics due to aperture
SDSS model VS Petrosian magnitude
photometric template-fit
Chabrier IMF

A single-colour (Petrosian) estimator

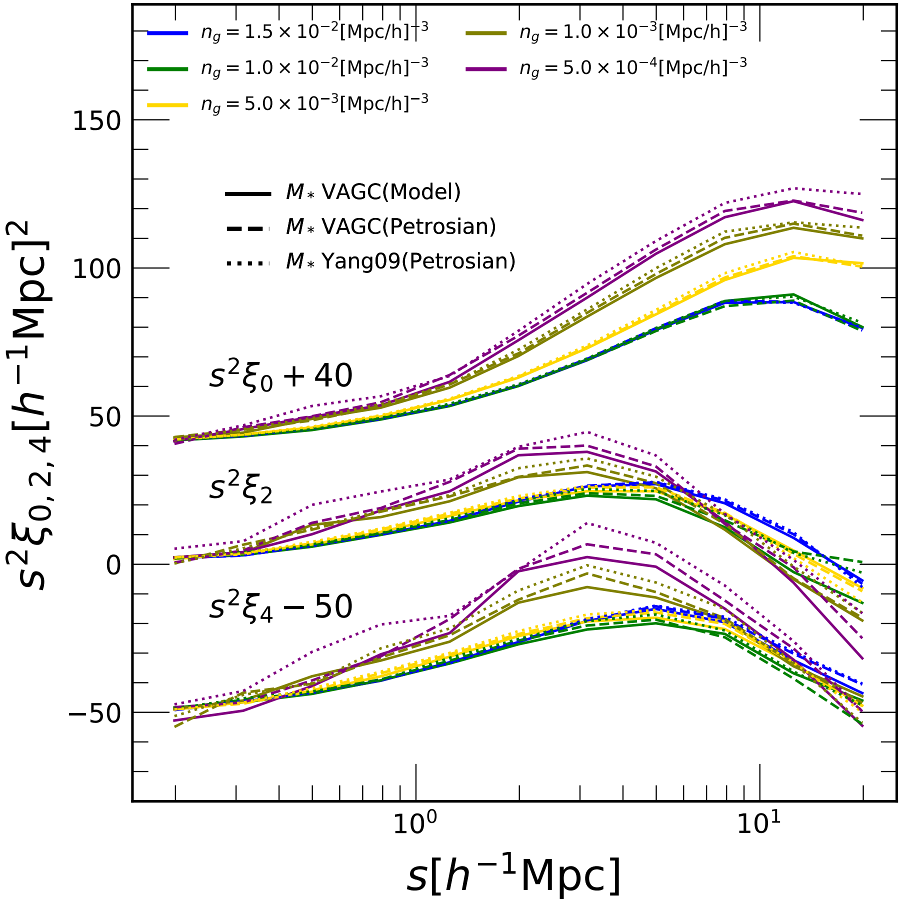
$$\log_{10}(M_*/[h^{-2}M_\odot]) = -0.406 + 1.097[^{0.0}(g-r)] - 0.4(^{0.0}M_r - 5\log_{10}h - 4.64)$$

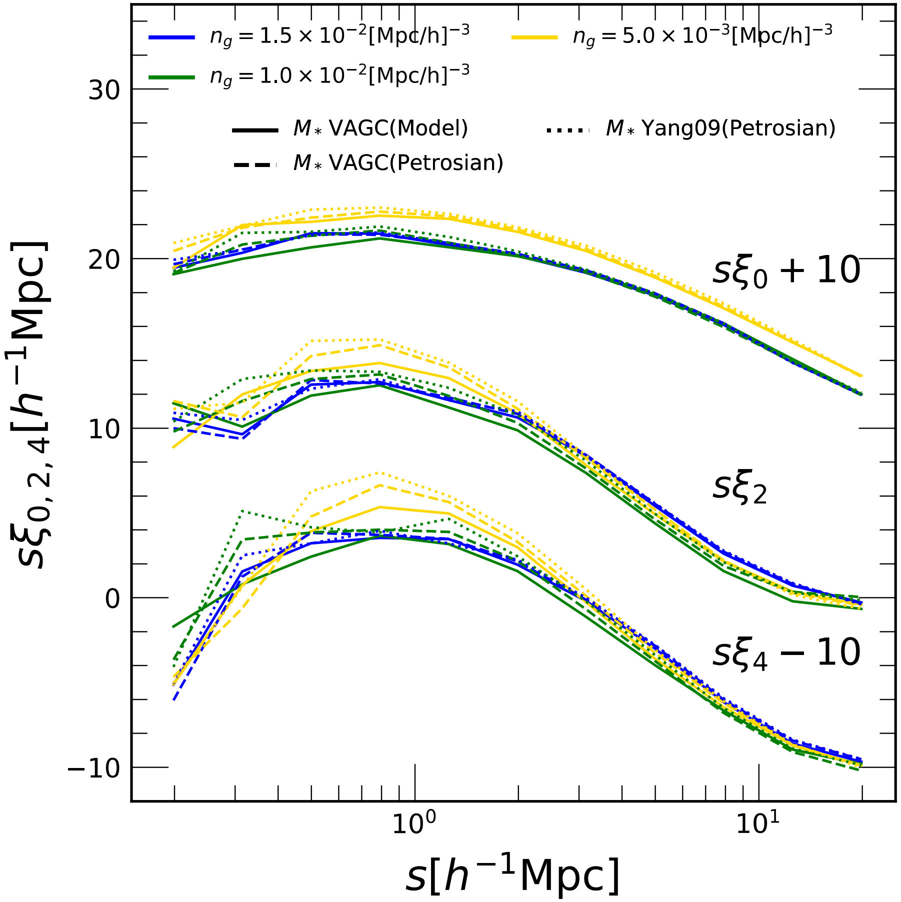
Kroupa IMF

Yang07



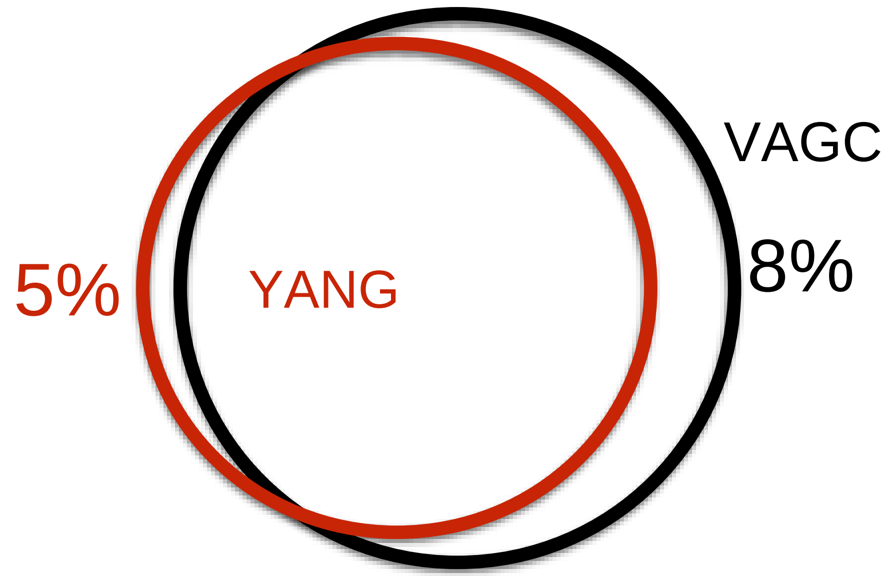
Galaxies ranked by stellar mass





He. et. al. 2018

The fraction of common galaxies

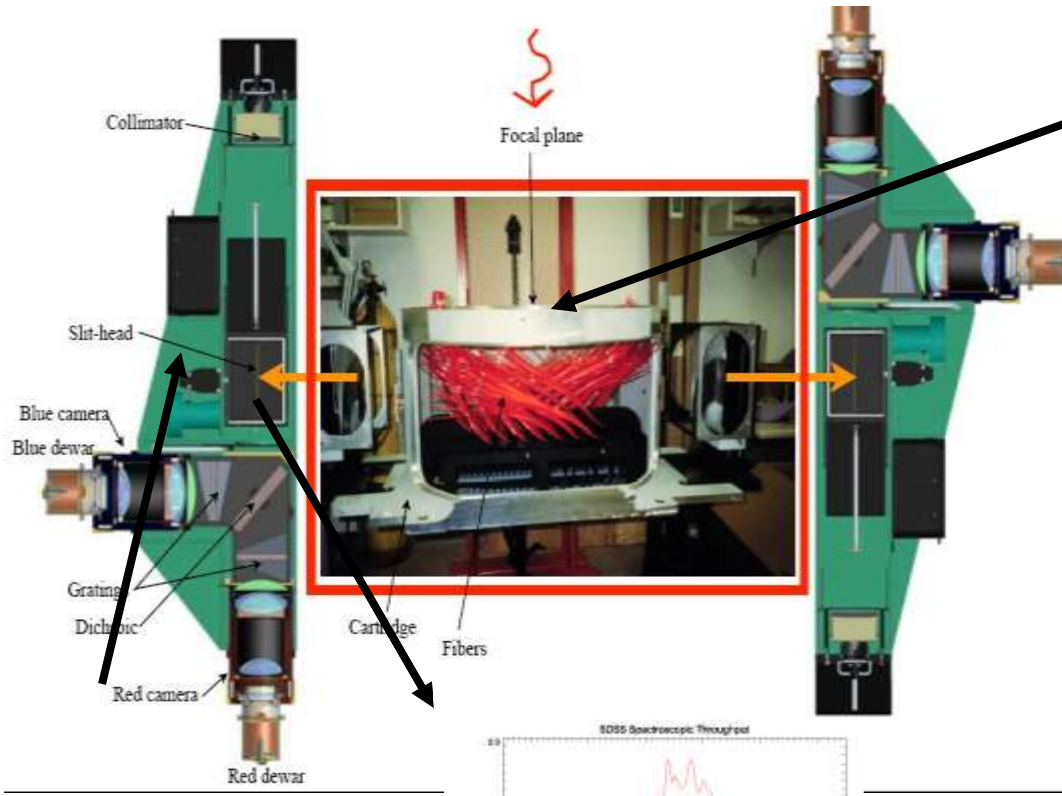


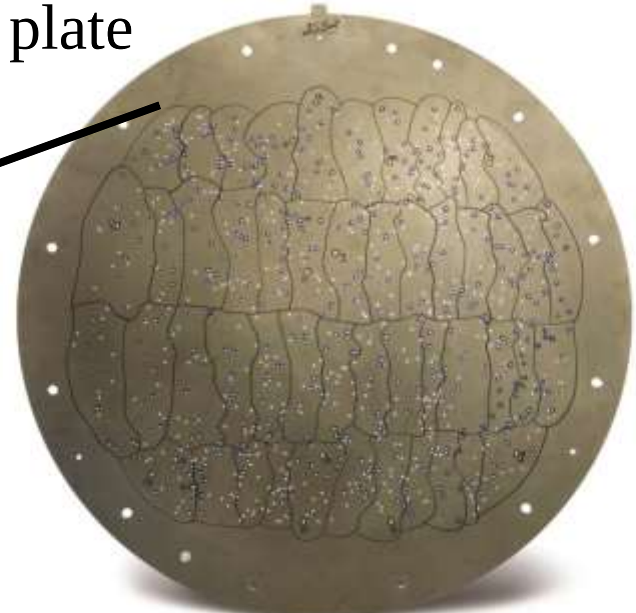
n_g	$N_{\rm com}/N_{\rm yang}$	$N_{\rm com}/N_{\rm vagc}$	$N_{\rm yang}/N_{\rm vagc}$
2.0×10^{-2}	96.1%	95.6%	99.5%
1.5×10^{-2}	96.5%	92.1%	95.4%
5.0×10^{-3}	94.9%	82.4%	86.8%
1.0×10^{-3}	95.1%	84.7%	89.1%
5.0×10^{-4}	88.6%	73.9%	83.5%

Fiber Collisions

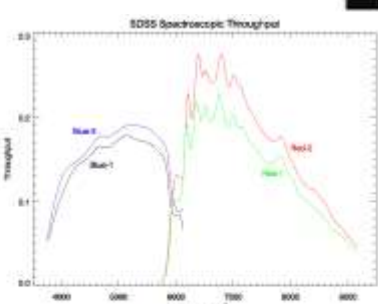
SDSS

plate





Spectrograph

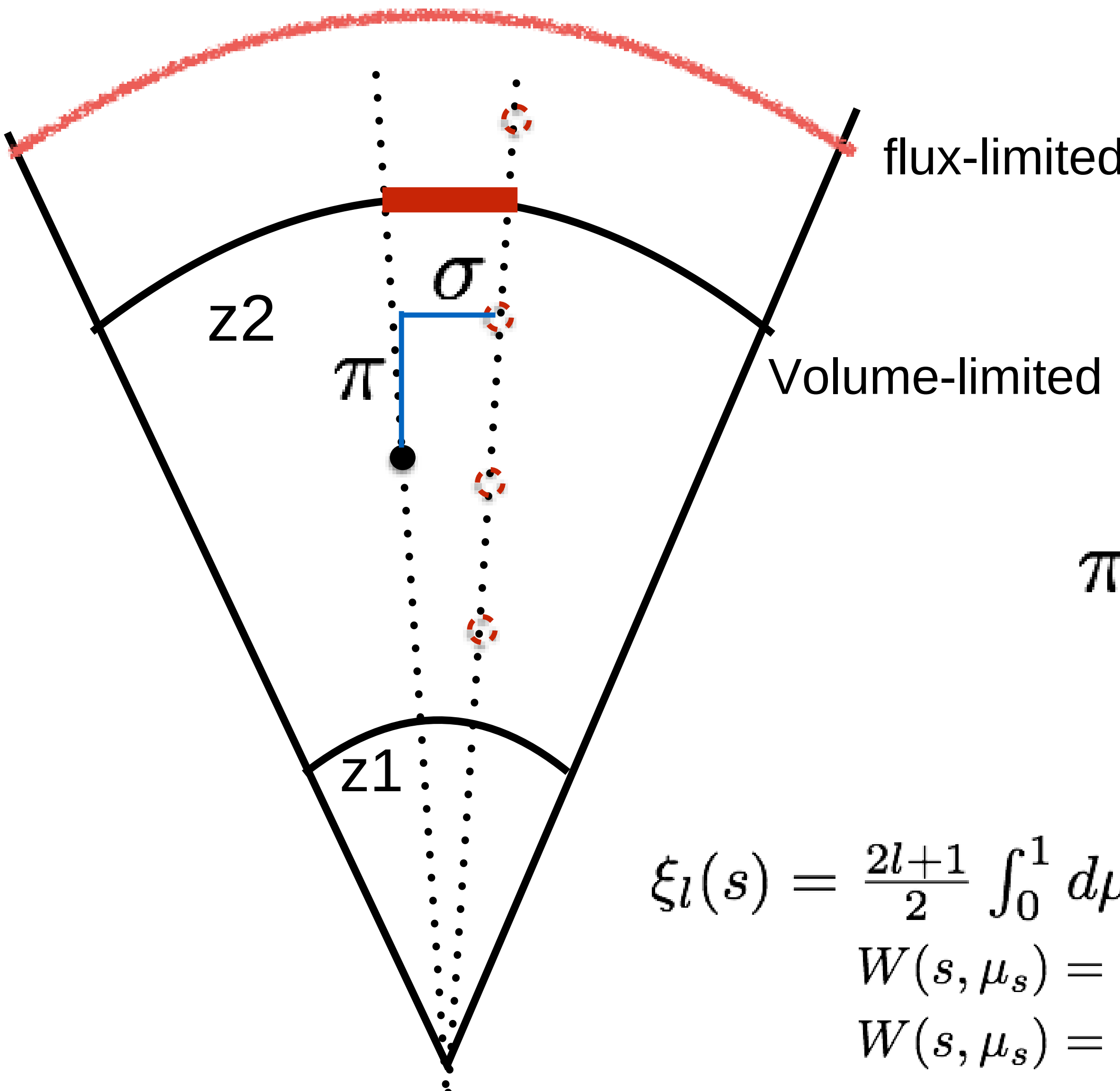


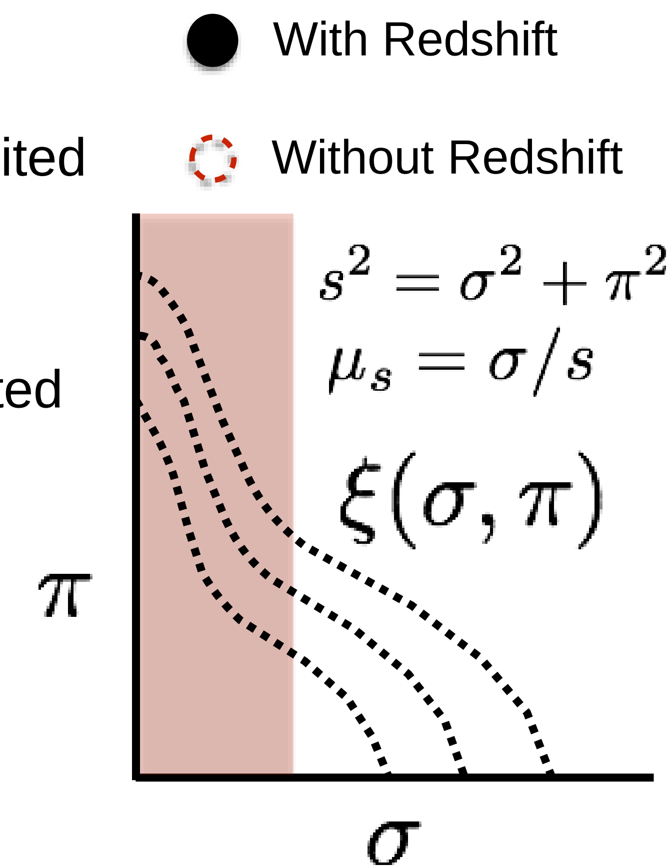
The positions of two fibres cannot be paced closer than 55” in SDSS-I and II(DR 7). 62’’ in SDSS-III.

$z \sim 0.1$

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

Fiber collisions mitigation





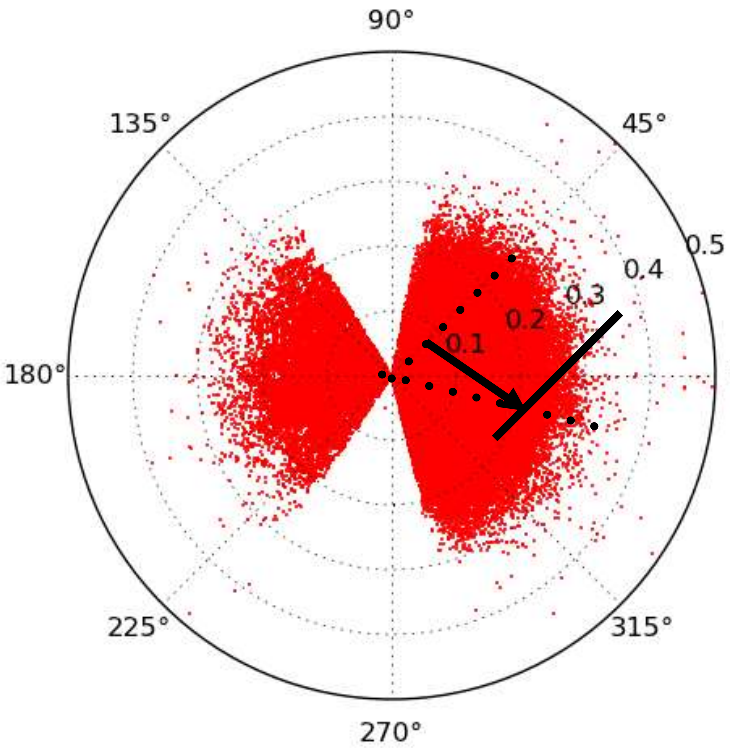
$$\xi_l(s) = \frac{2l+1}{2} \int_0^1 d\mu_s W(s, \mu_s) \xi(s, \mu_s) P_l(\mu_s)$$

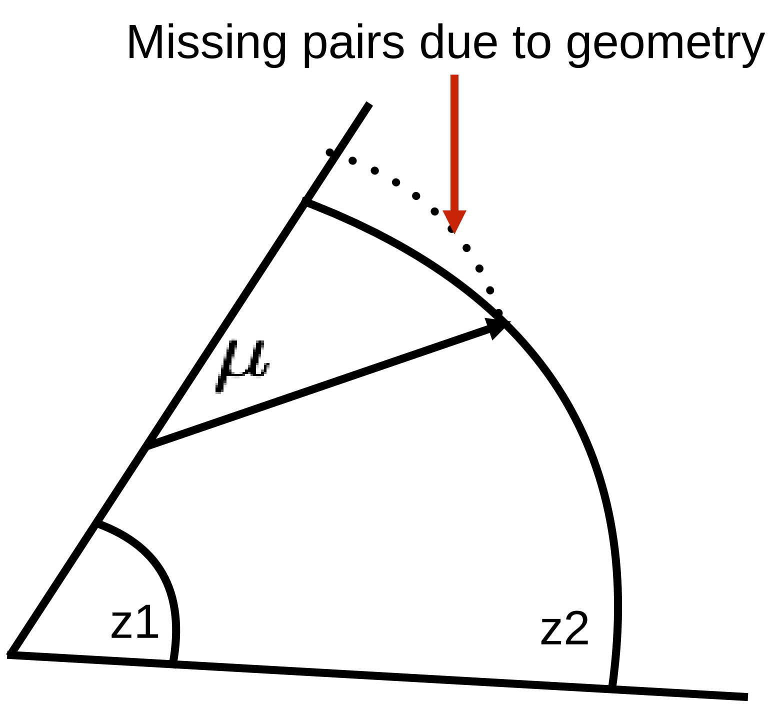
$$W(s, \mu_s) = 1, \sigma > 0.2 \mathrm{Mpc}/h$$

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

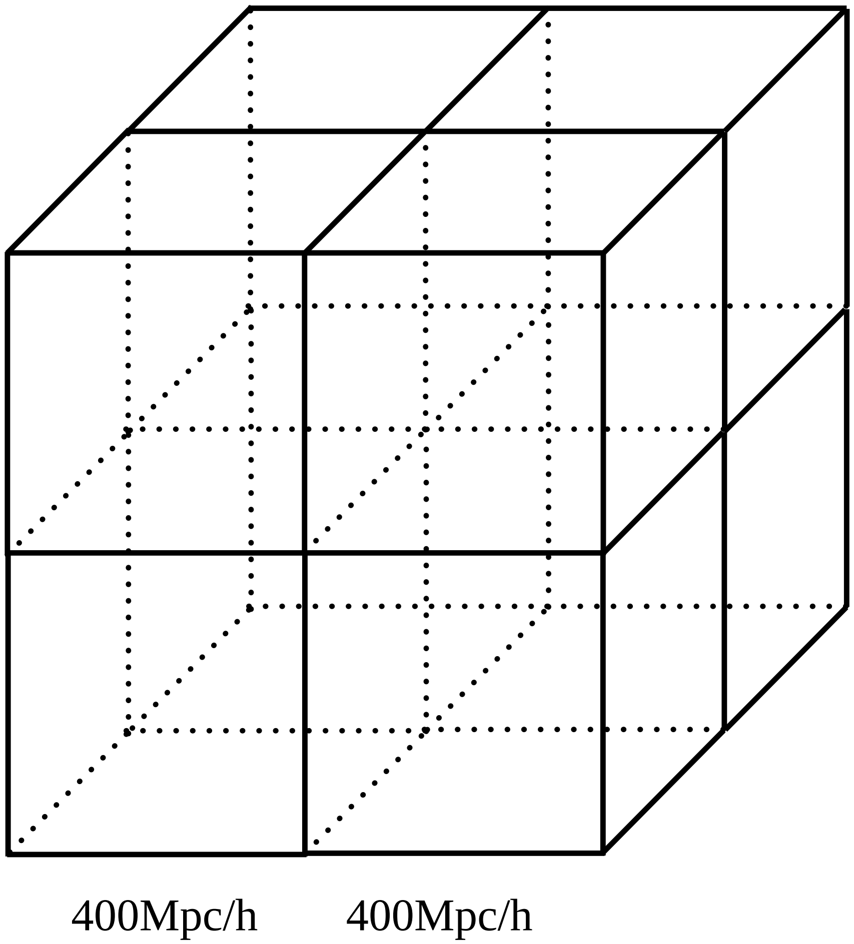
Wide-angle and geometry effects

- 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 geometries.





SHAM mock

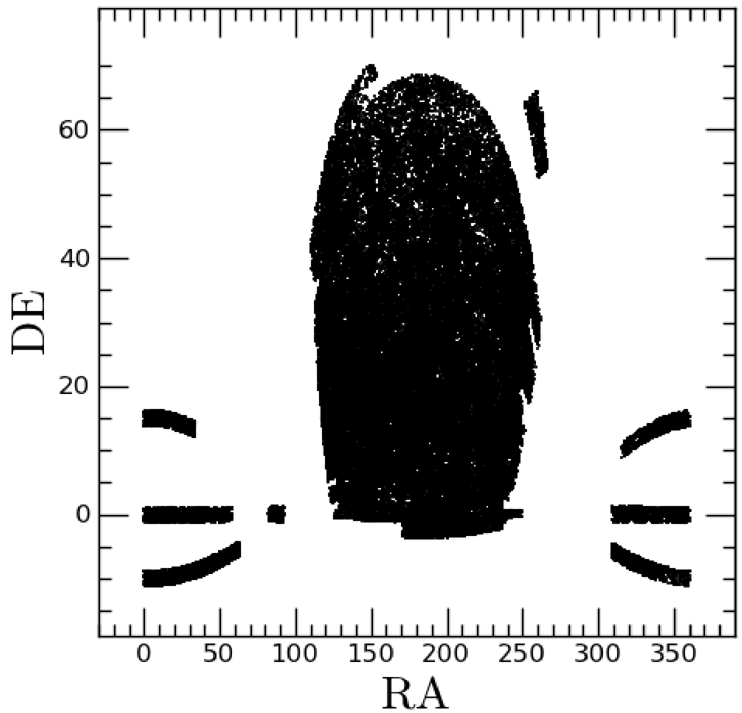


- Multidark Planck simulation
- Boxsize: 400Mpc/h
- 3840^3particles
- Mass resolution:$9.6 \times 10^7 M_{\odot}/h$

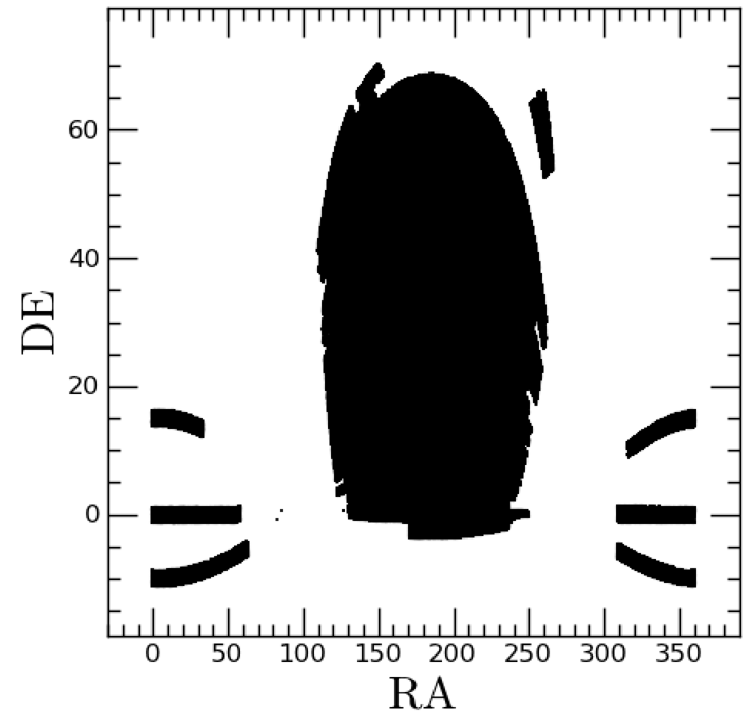
SHAM mock

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

SHAM mock (n_g=0.005)

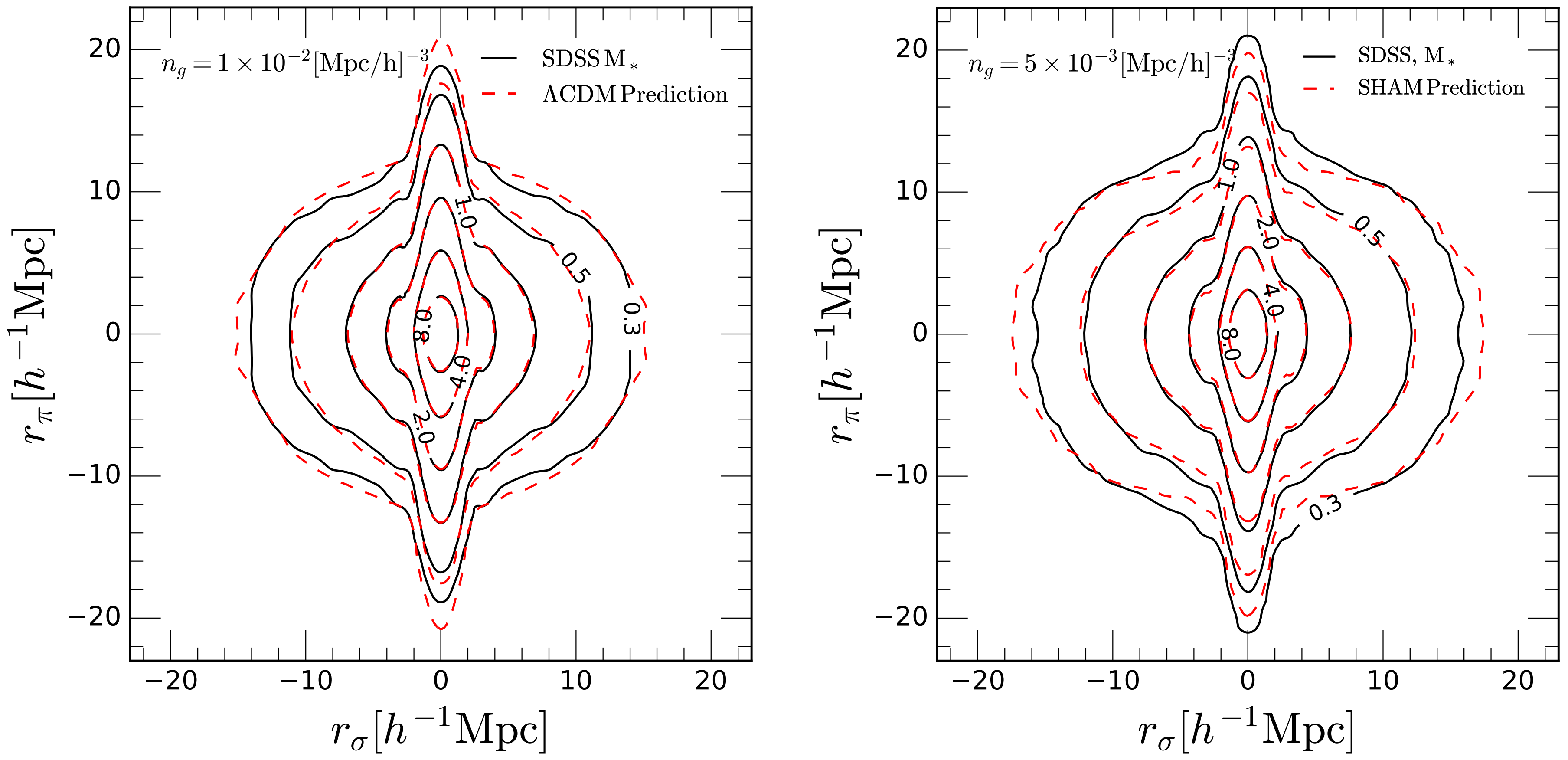


Real Data



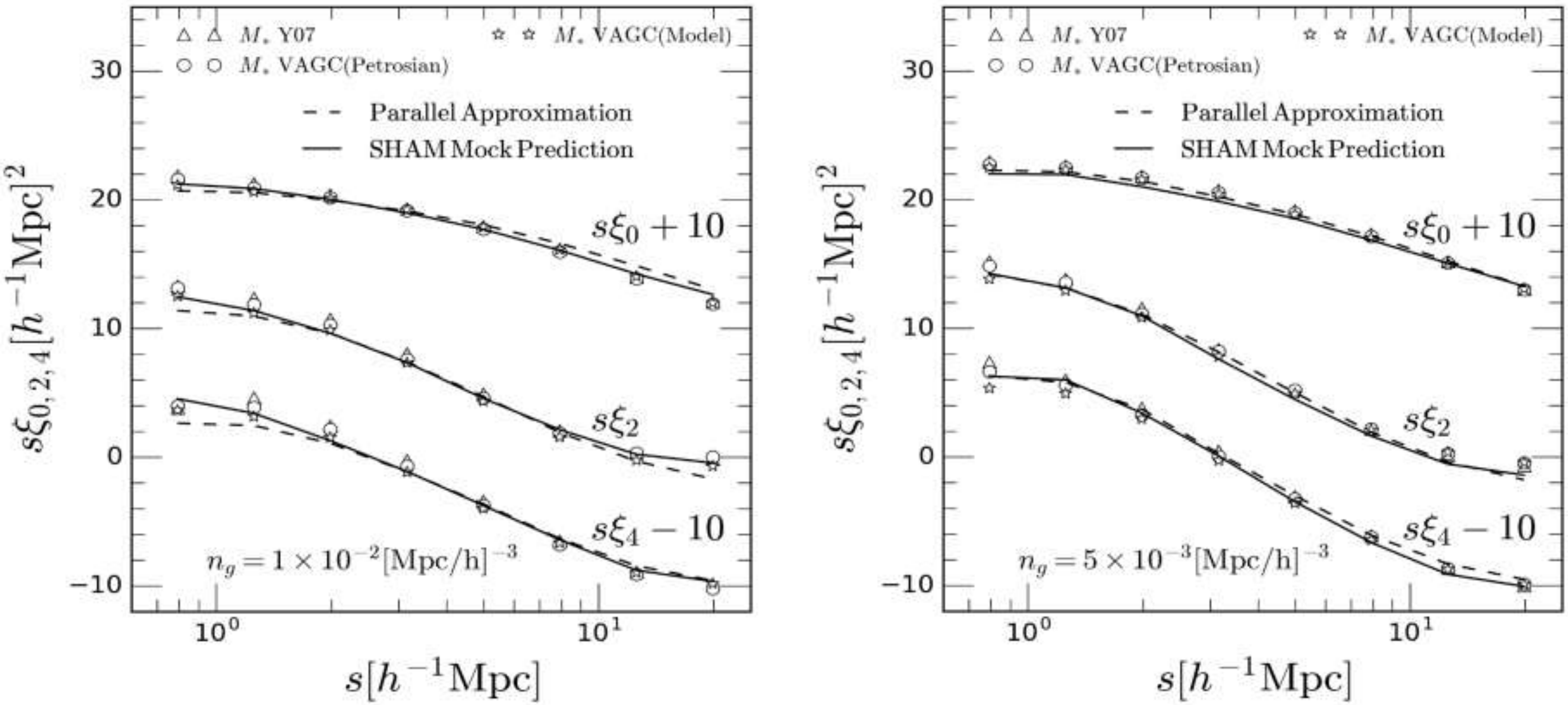
Theory VS Observation

Theory VS Observation



Theory VS Observation

No free parameter!!!



He. et. al. 2018

Modified Gravity

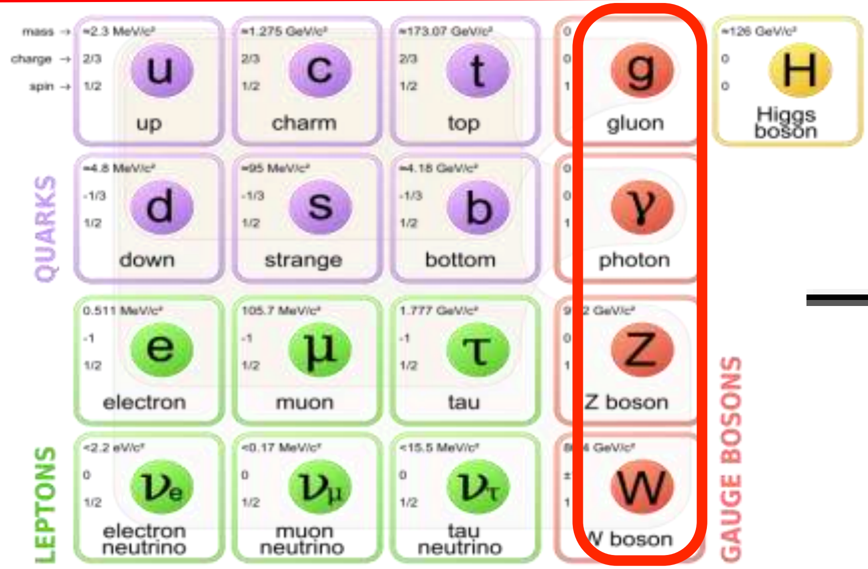
$$s = \frac{1}{2\kappa^2} \int dx^4 \, f(R)$$

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

$f(R)$



+ cdm

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

$$\Phi_- = \frac{\psi - \phi}{2} \qquad \Phi_+ = \frac{\psi + \phi}{2}$$

	Massless particle		Massive particle
ΛCDM	Φ_-	$=$	Φ_+
$f(R)$	Φ_-	$\neq$	Φ_+

Effective density field in $f(R)$ gravity

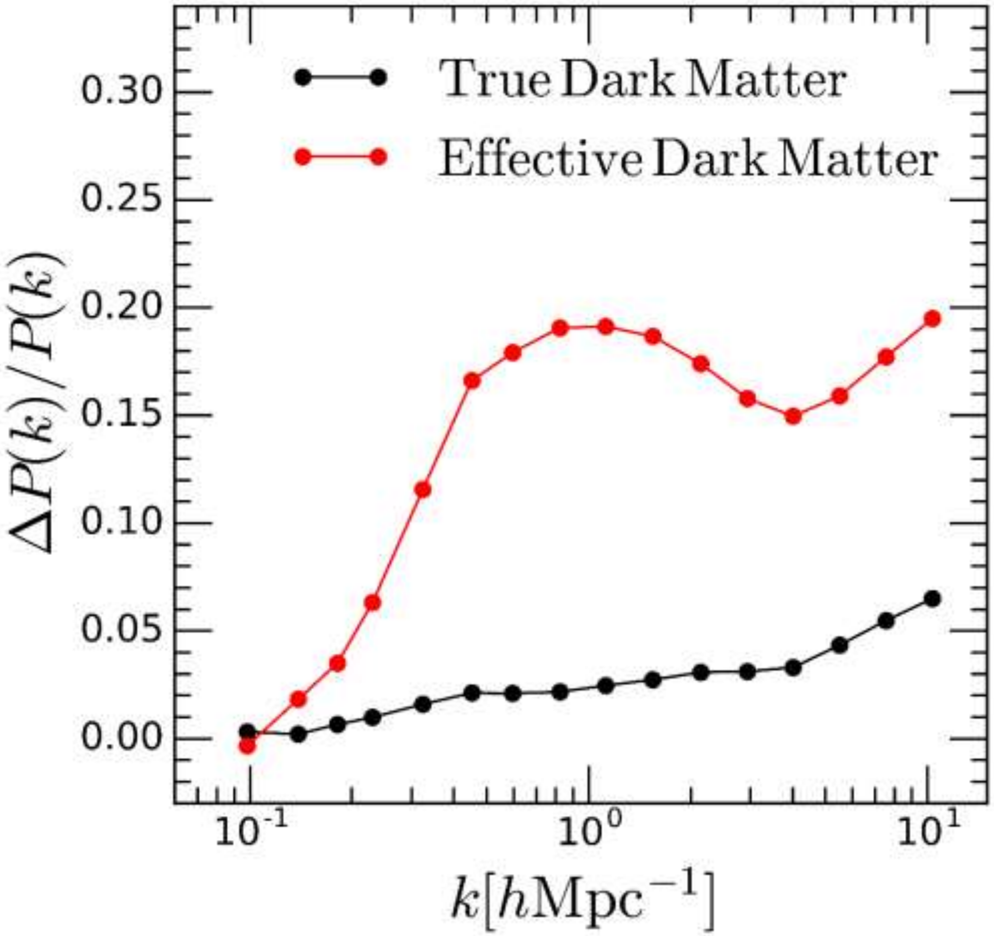
$f_{R0} = -10^{-6}$

Dynamical Mass

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

Lensing Mass

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



He, et al PRD 2015

Galaxy formation in $f(R)$ gravity

Effective halo

$$f(R) \longrightarrow \Lambda\text{CDM}$$

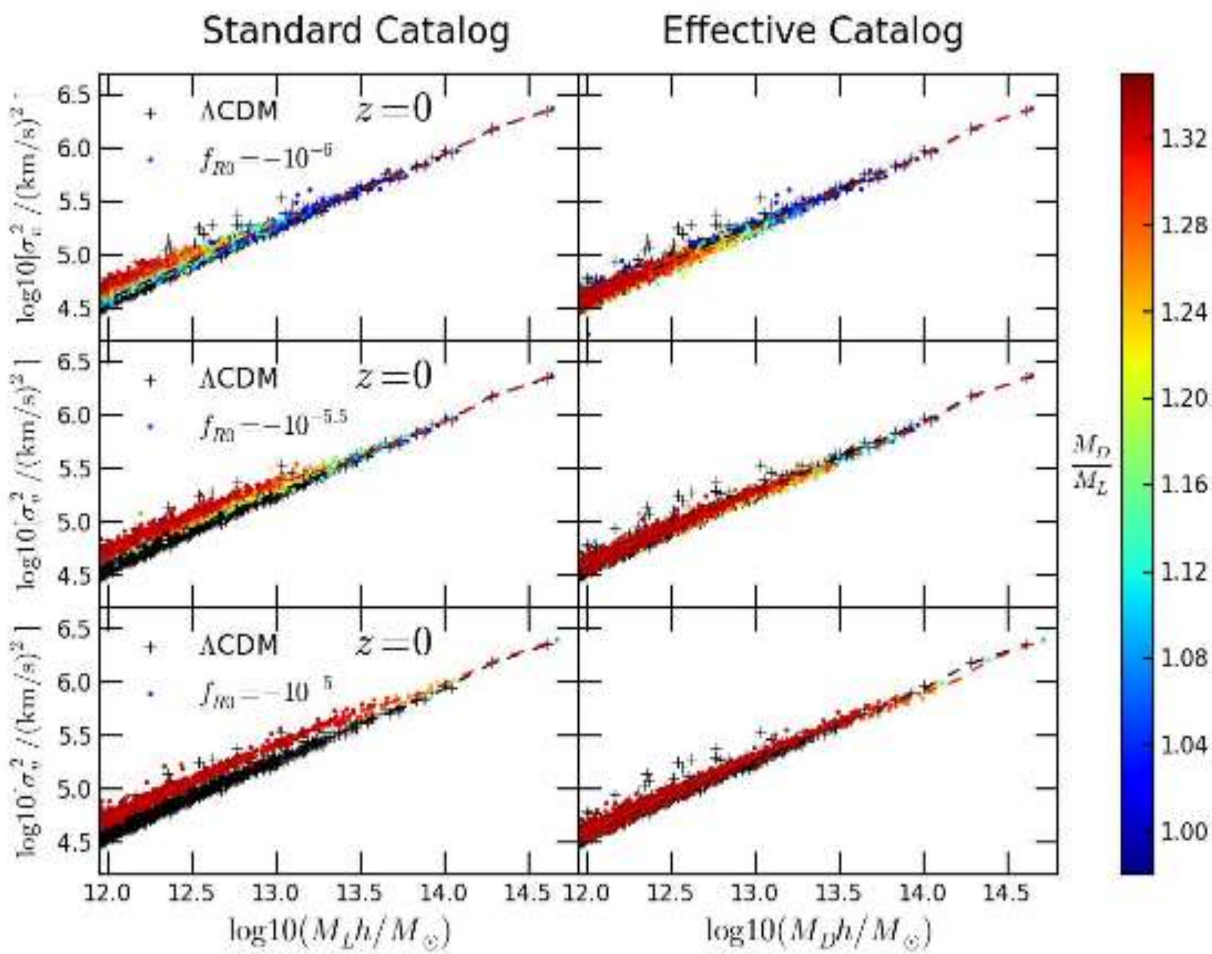
mapping

Effective halo catalogue

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

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

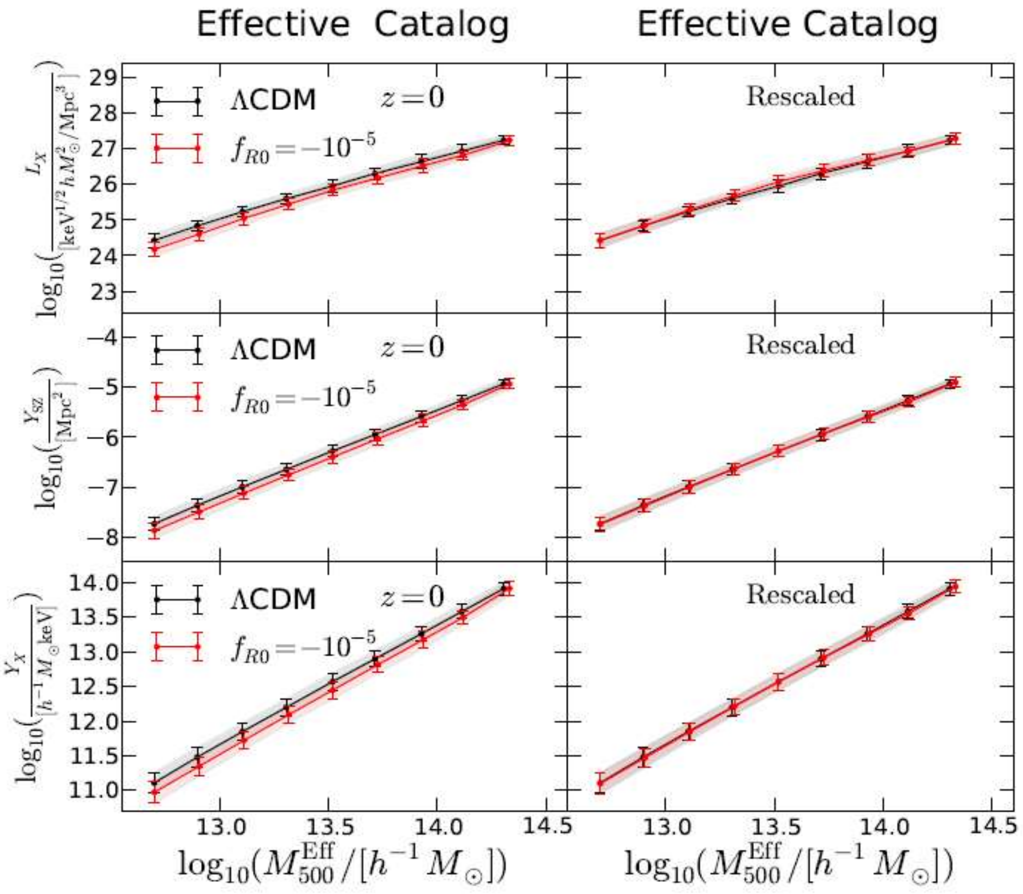
$$\sigma_v^2 \sim \Phi_+$$



He, et al PRL 2015

Effective halo catalogue

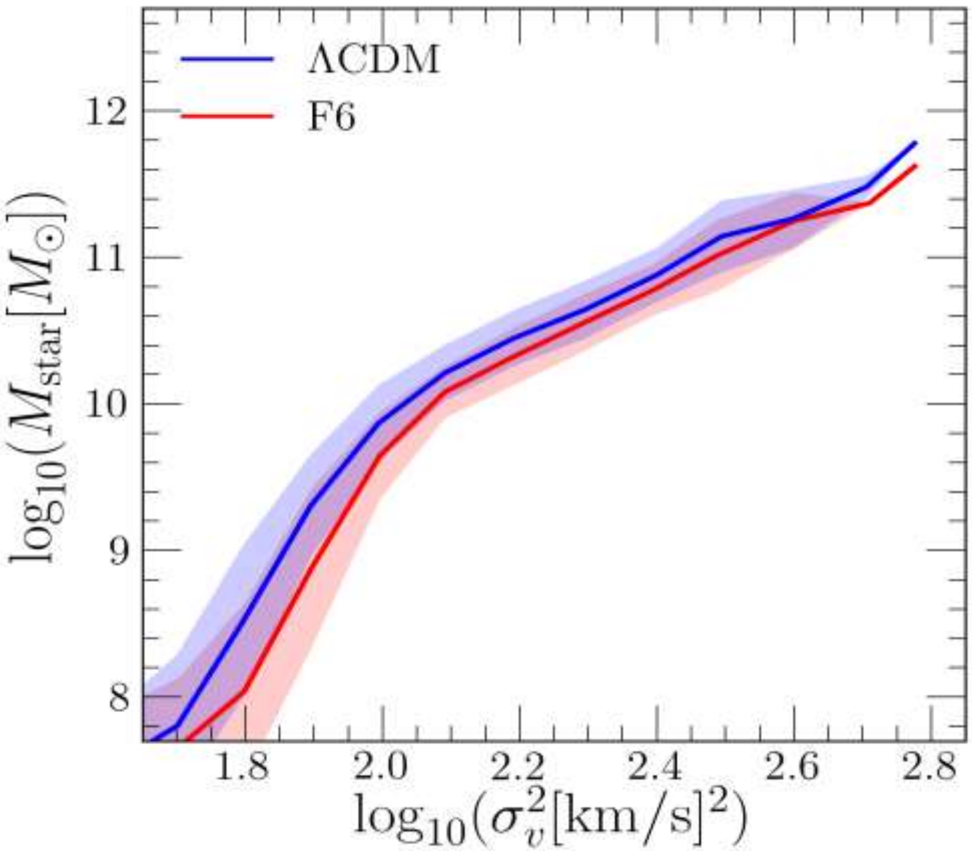
Adiabatic hydro-dynamical simulation



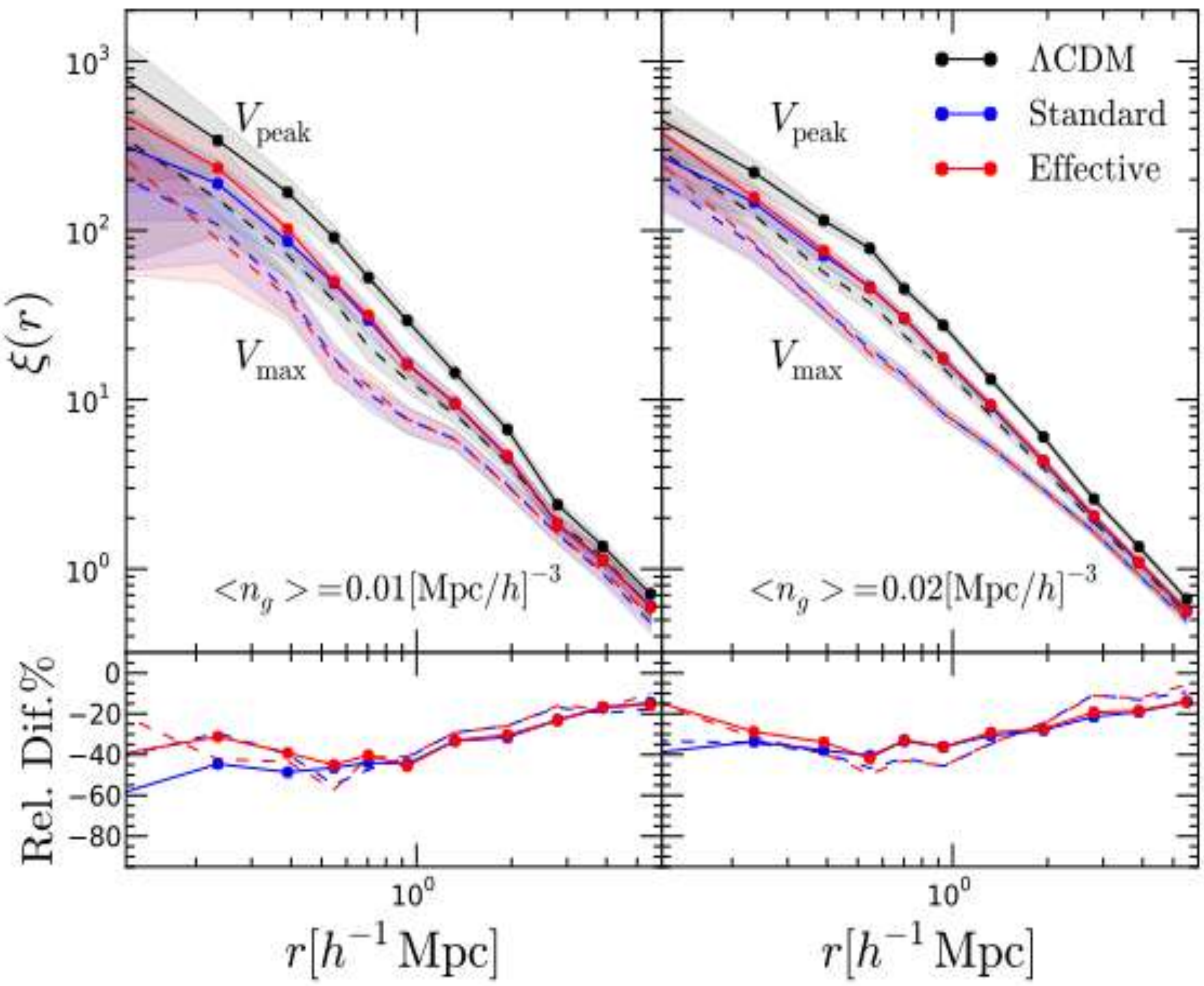
He, et al PRD 2015

Effective halo catalogue

- Illustris TNG full baryonic physics
- F6 Illustris TNG full baryonic physics

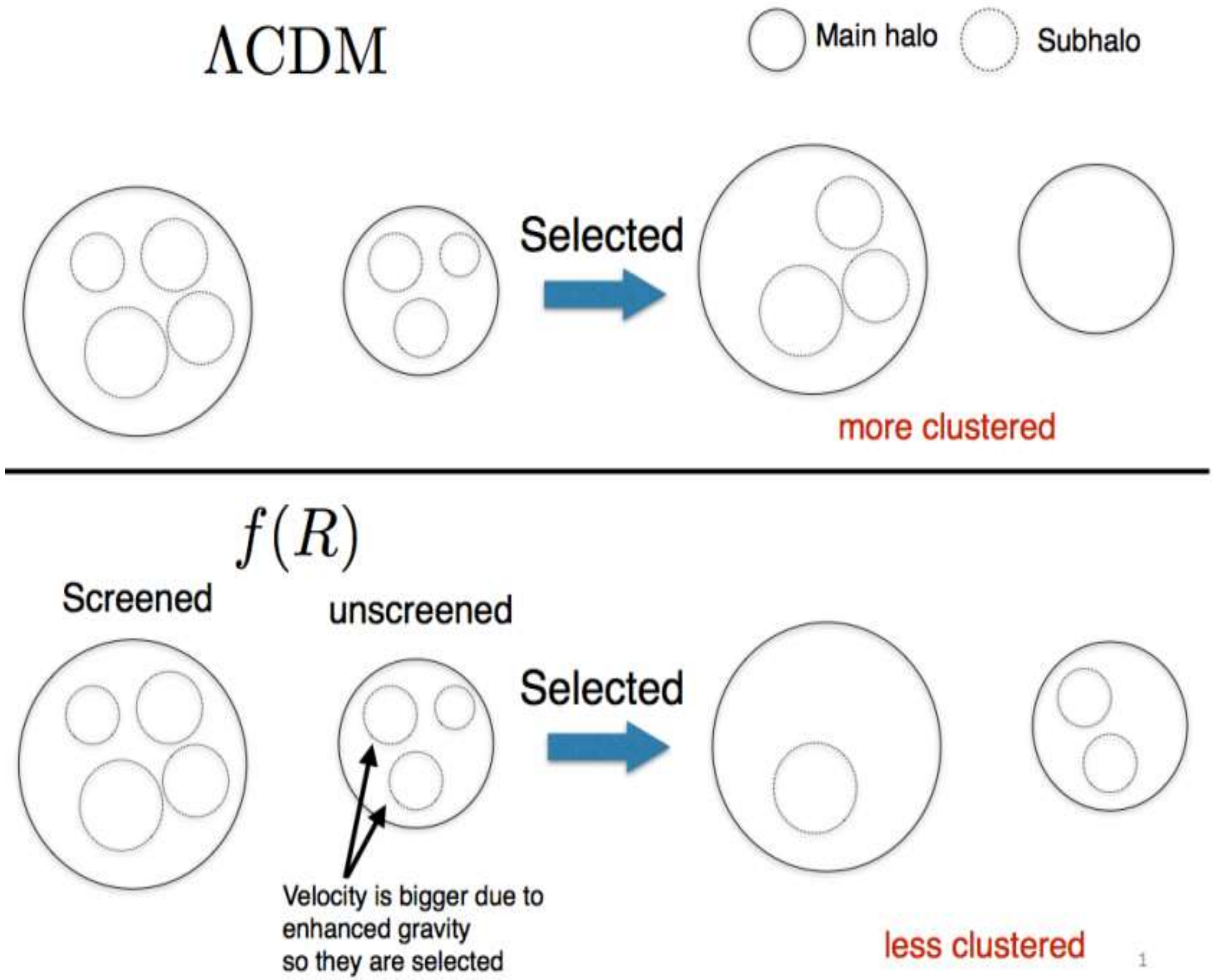


SHAM predictions in $f(R)$ gravity

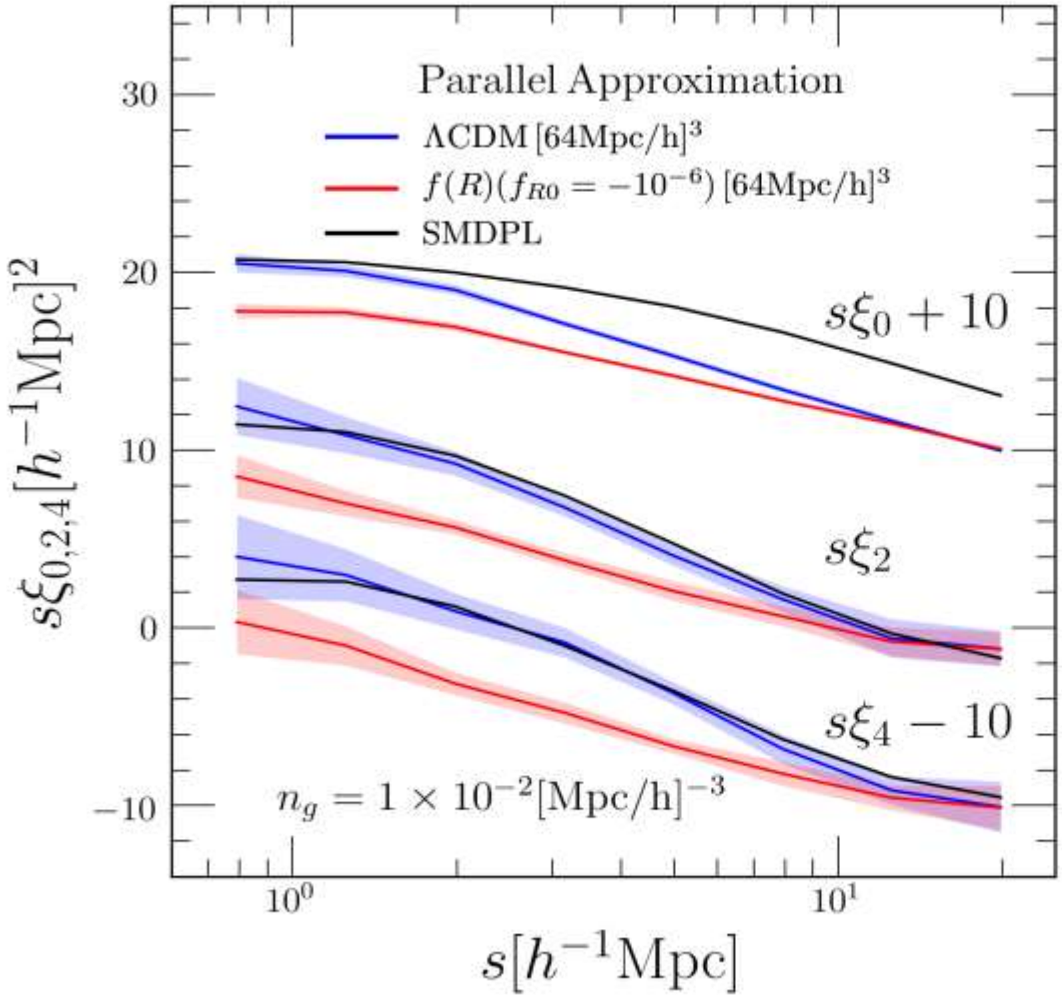


He, et al PRL 2016

Screening mechanism in $f(R)$ gravity

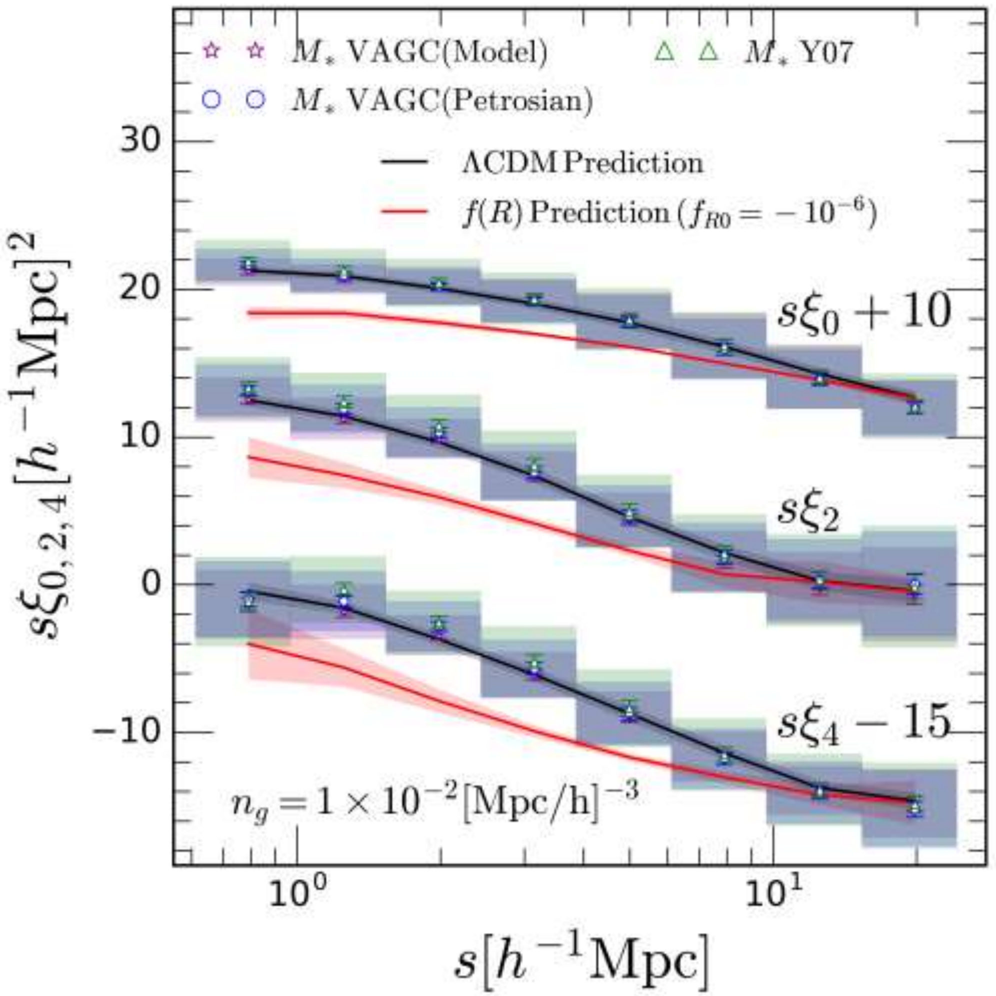


The robustness of RSD predictions



He. et. al. 2018

Final Results



He. et. al. 2018

Conclusions

LCDM is good!

Don’t mess with Einstein!

Thank you!