Multi-tracer cosmology trough the lens of SHAM

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Latin American Workshop on Observational Cosmology
ICTP-SAIFR, São Paulo,15 December 2020

Motivations

Improve the current galaxy-halo connection to be able to accurately predict the galaxy clustering signal of the multi-tracers (ELGs, LRGs, QSOs) from the upcoming surveys as a function of different baryonic properties.

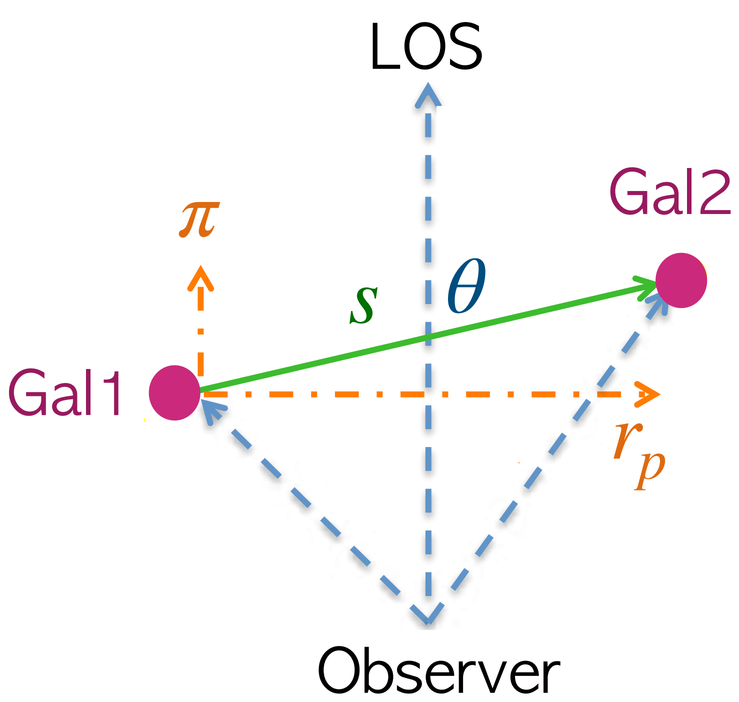
In particular, we implement an extension of the Subhalo abundance matching (SHAM) model including different halo/galaxy secondary properties from the IllustrisTNG300 hydrosim to improve our knowledge of secondary halo bias and its connection with the environment (tidal tensor).

Galaxy two-point correlation function (2PCF)

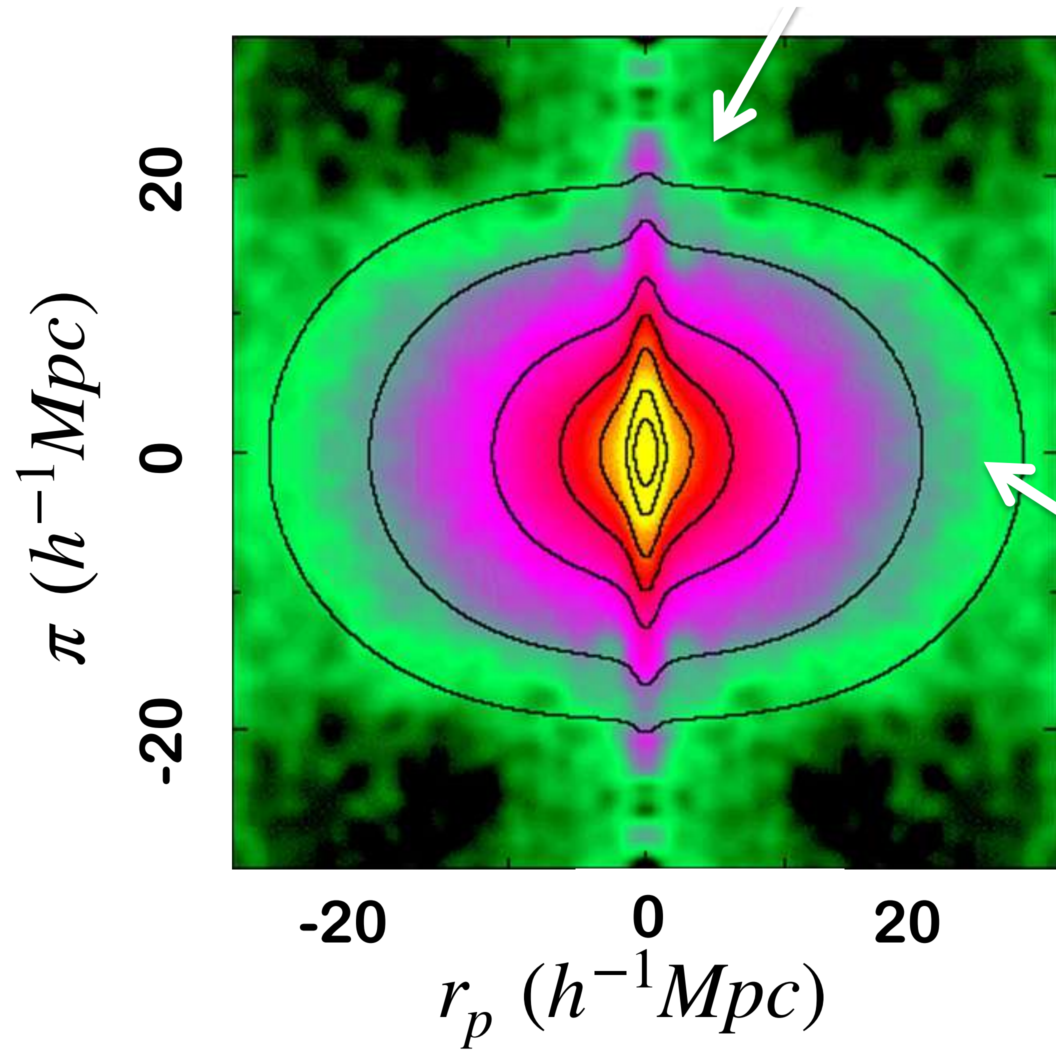
$$dP = n^2[1 + \xi(s)]dV_1 dV_2$$

Excess probability over randoms to find 2 galaxies separated by a distance s in z-space:

$$s = \sqrt{r_p^2 + \pi^2}$$



Finger-of-god, peculiar velocities of galaxies



Kaiser squashing, gravitational infall of galaxies towards over densities

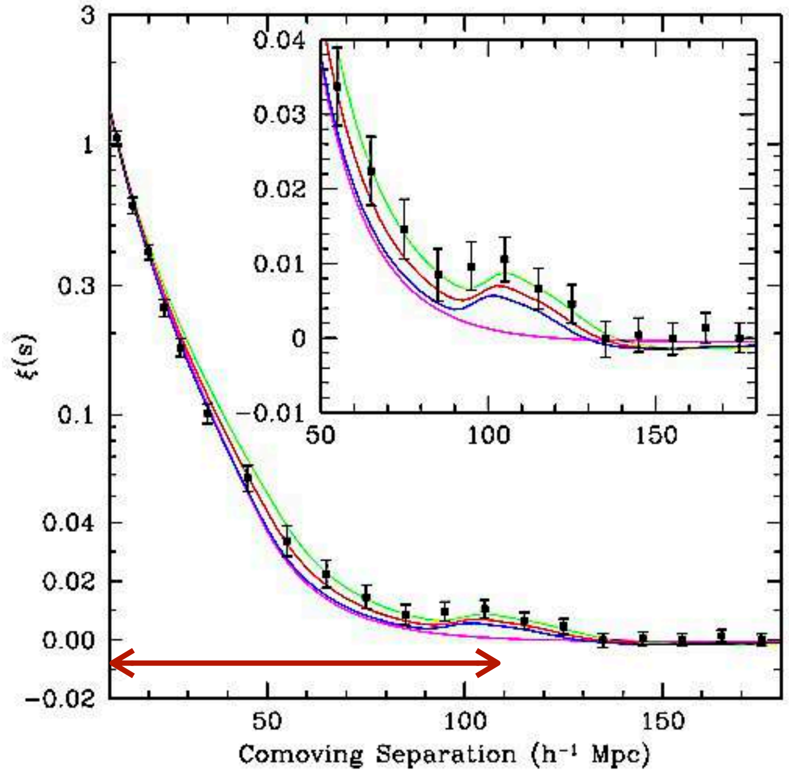
Landy & Szalay 1993 estimator:

$$\xi(r_p, \pi) = \frac{DD(r_p, \pi) - 2DR(r_p, \pi) + RR(r_p, \pi)}{RR(r_p, \pi)}$$

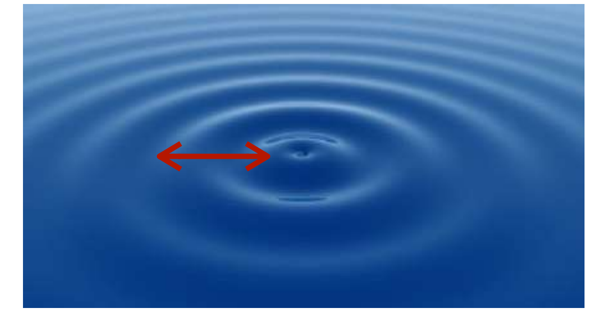
Expanding in Legendre polynomial we find the 2PCF multipoles:

$$\xi_l(s) = \frac{2l+1}{2}\int_{-1}^{+1}\xi(s,\mu)P_l(\mu)d\mu$$

l=0 monopole, spherical average
l=2 quadrupole traces satellites



Eisenstein et al. 2005



BAO scale ~110 Mpc/h

standard ruler for cosmological distances

The projected 2PCF mitigates the redshift-space distortions:

$$w_p(r_p) = 2\int_0^{\infty}\xi(r_p,\pi)d\pi$$

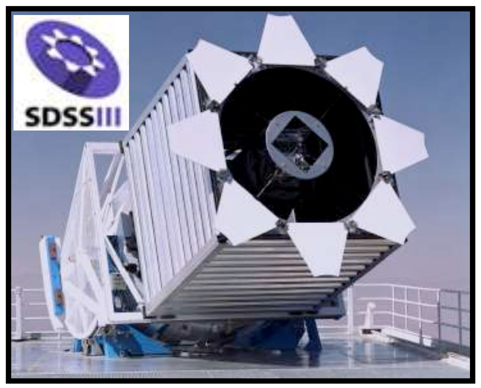
$$b(r_p) = \sqrt{\frac{w_p^{gal}(r_p)}{w_p^{m}(r_p)}}$$

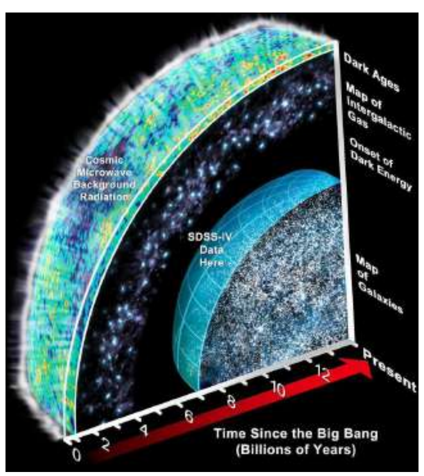
Large-scale structure surveys

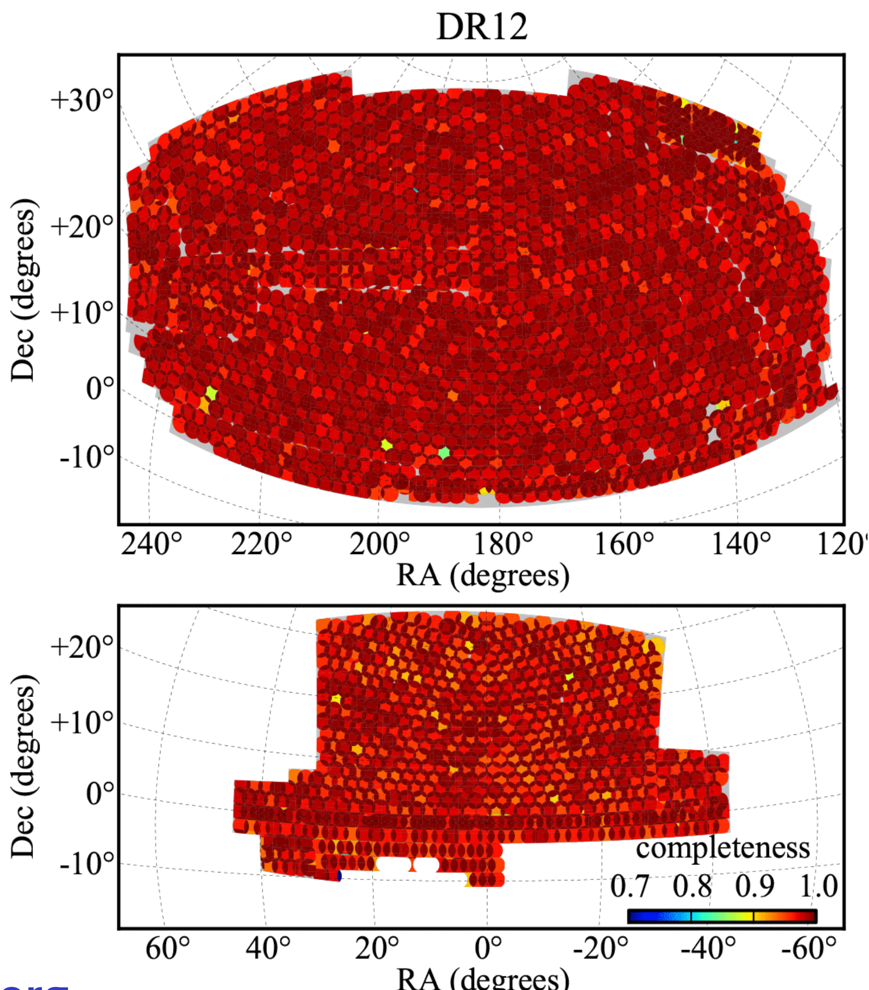
Past & Ongoing

SDSS-I/II (2005-09), SDSS-III/BOSS (2009-14)

SDSS-IV/eBOSS (2014-20)







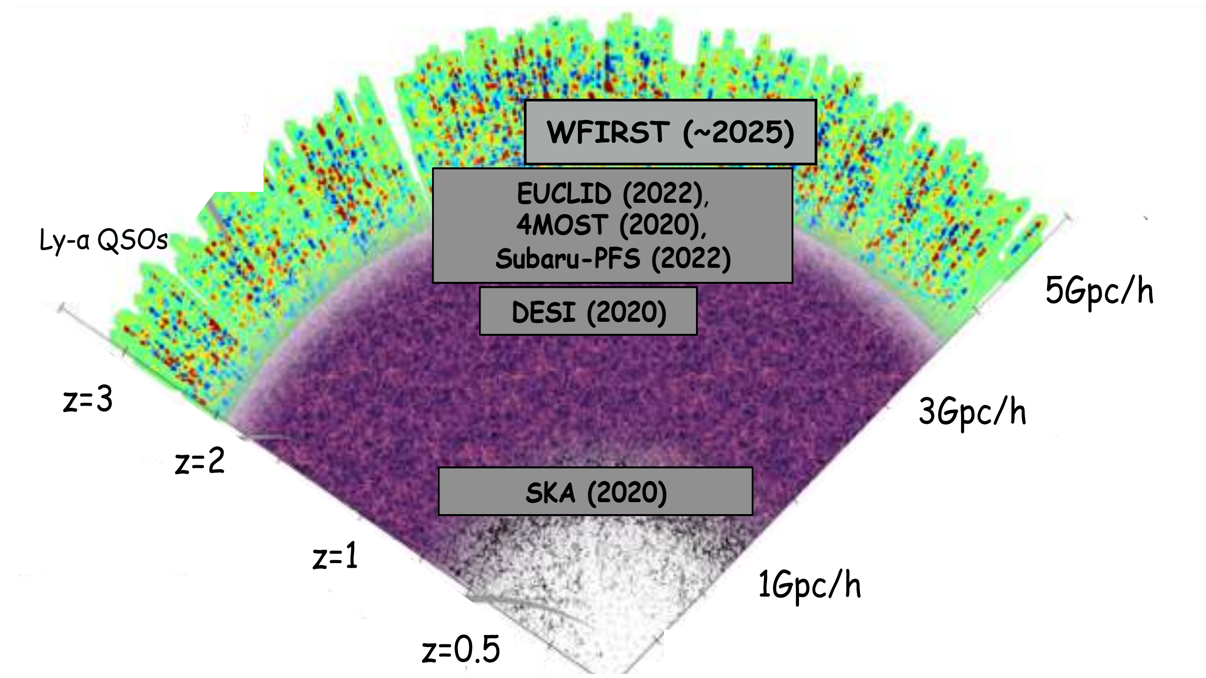
www.sdss.org

BOSS: 1.5M galaxies, mostly LRGs z<0.7, over ~10,000 deg^2

eBOSS: 375k LRGs z<0.8, 260k [OII] ELGs z<1, 740k QSOs, over ~7500 deg^2

multi-tracers

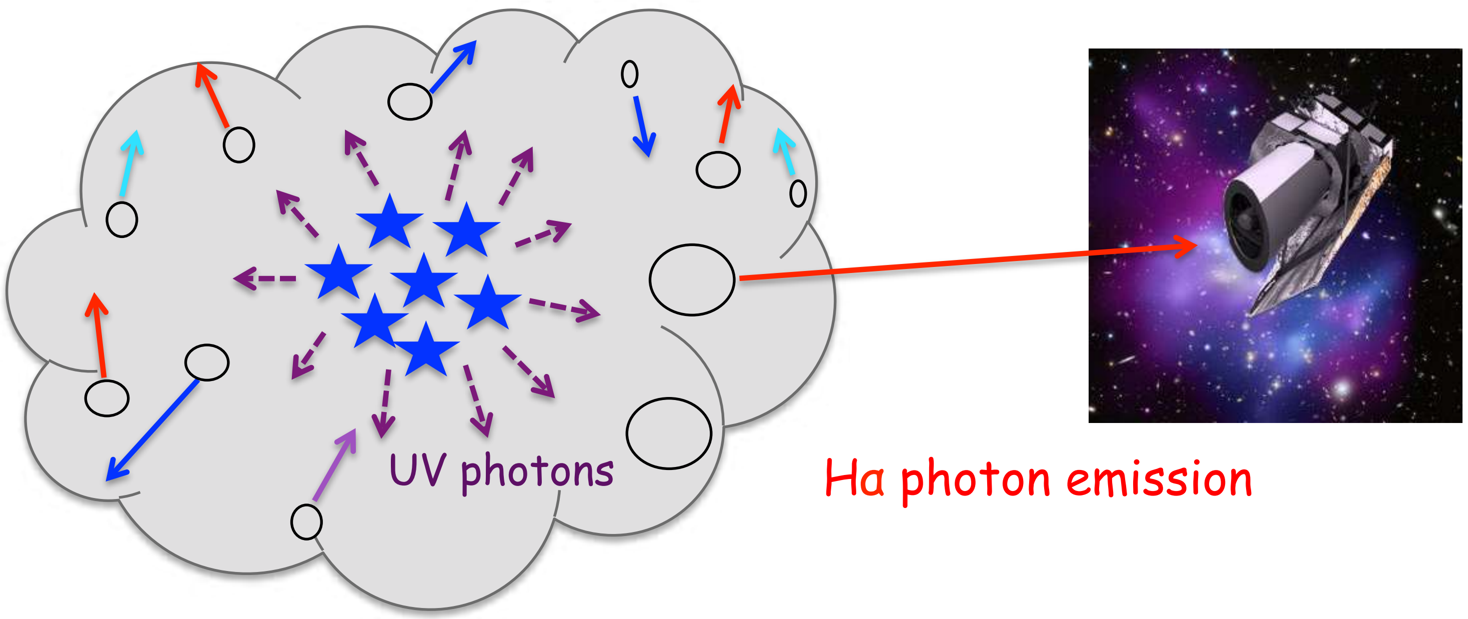
Future



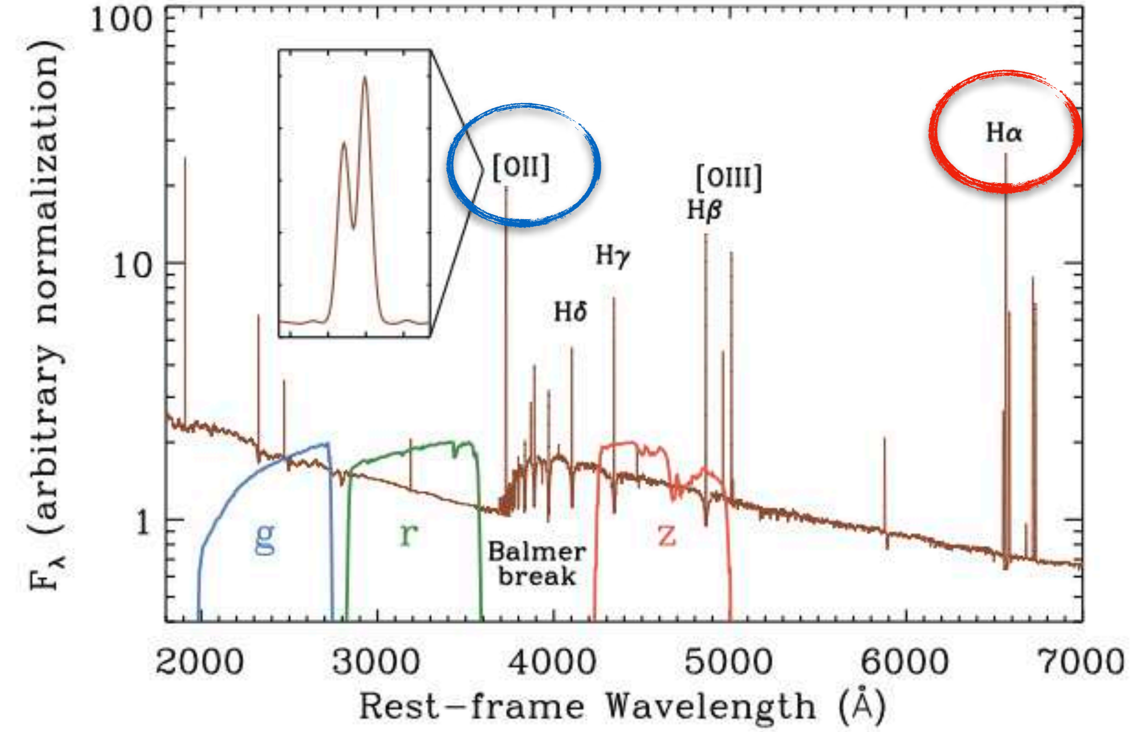
EUCLID: 50M Hα ELGs at z<2 with flux> 3×10^{-16}erg/s, over ~15,000 deg^2

DESI: 10M [OII] ELGs z<1.7 over ~14,000 deg^2

Emission line galaxies (ELGs)



http://desi.lbl.gov.tdr/



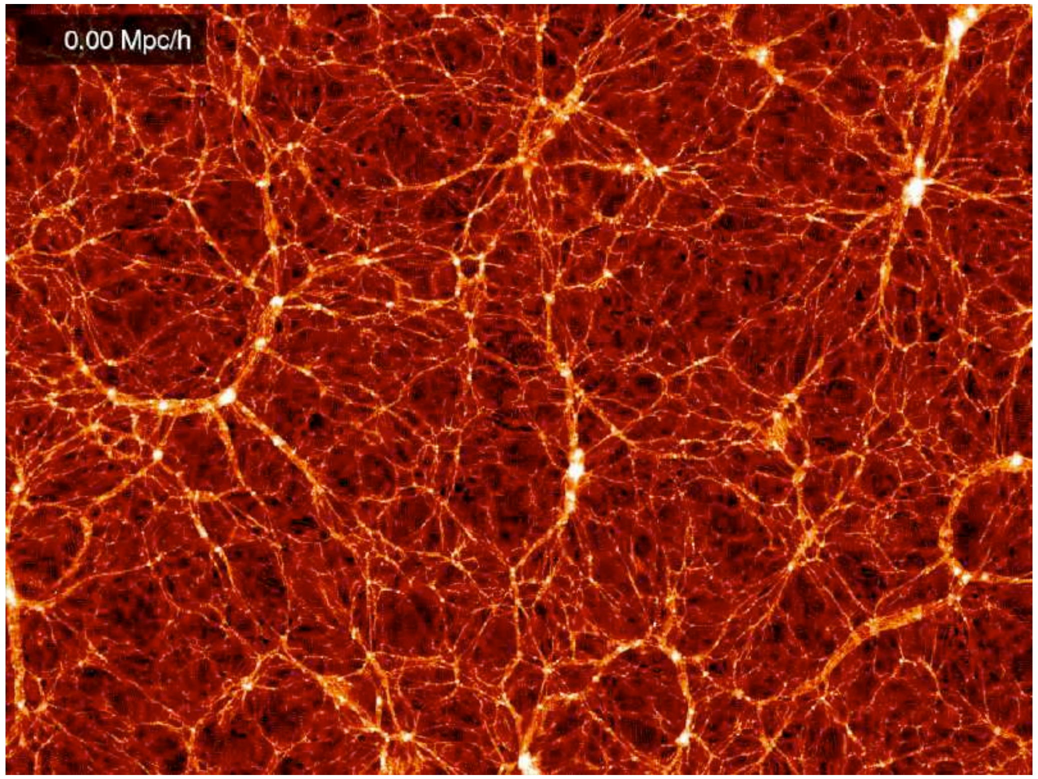
New-generation surveys will target ELGs out to z~2 to trace the BAO in their clustering, deliver 3D maps of the Universe with unprecedented accuracy, measure the growth of structure f(z), and the Universe expansion history H(z).

N-body cosmological simulations

Collisionless, cold DM particles are thrown in a cubic box with some initial conditions and let evolve under gravity. Halos are identified using halo finders: BDM, Rockstar, FOF

Expensive: solve equation of motion of N particle interacting gravitationally.

MultiDark



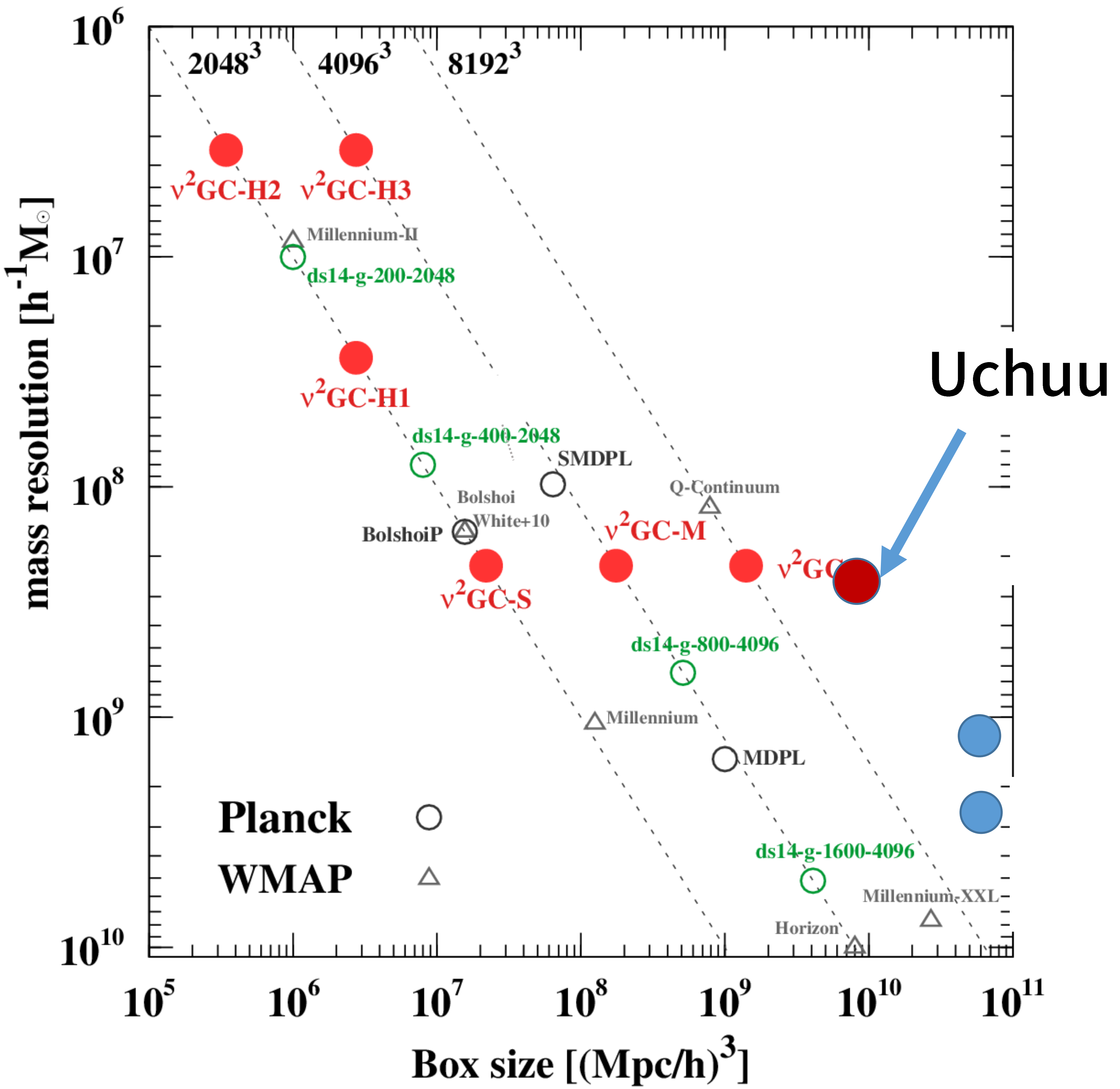
	N particles	Lbox (Mpc/h)	mass resolution (M_{sun}/h)
BigMD	3840^3	2500	2.36×10^{10}
MDPL2	3840^3	1000	1.5×10^9
SMD	3840^3	400	9.63×10^7

cosmosim.org

N particles	Lbox (Mpc/h)	mass resolution (M_{sun}/h)
12800^3	2000	3.27×10^8

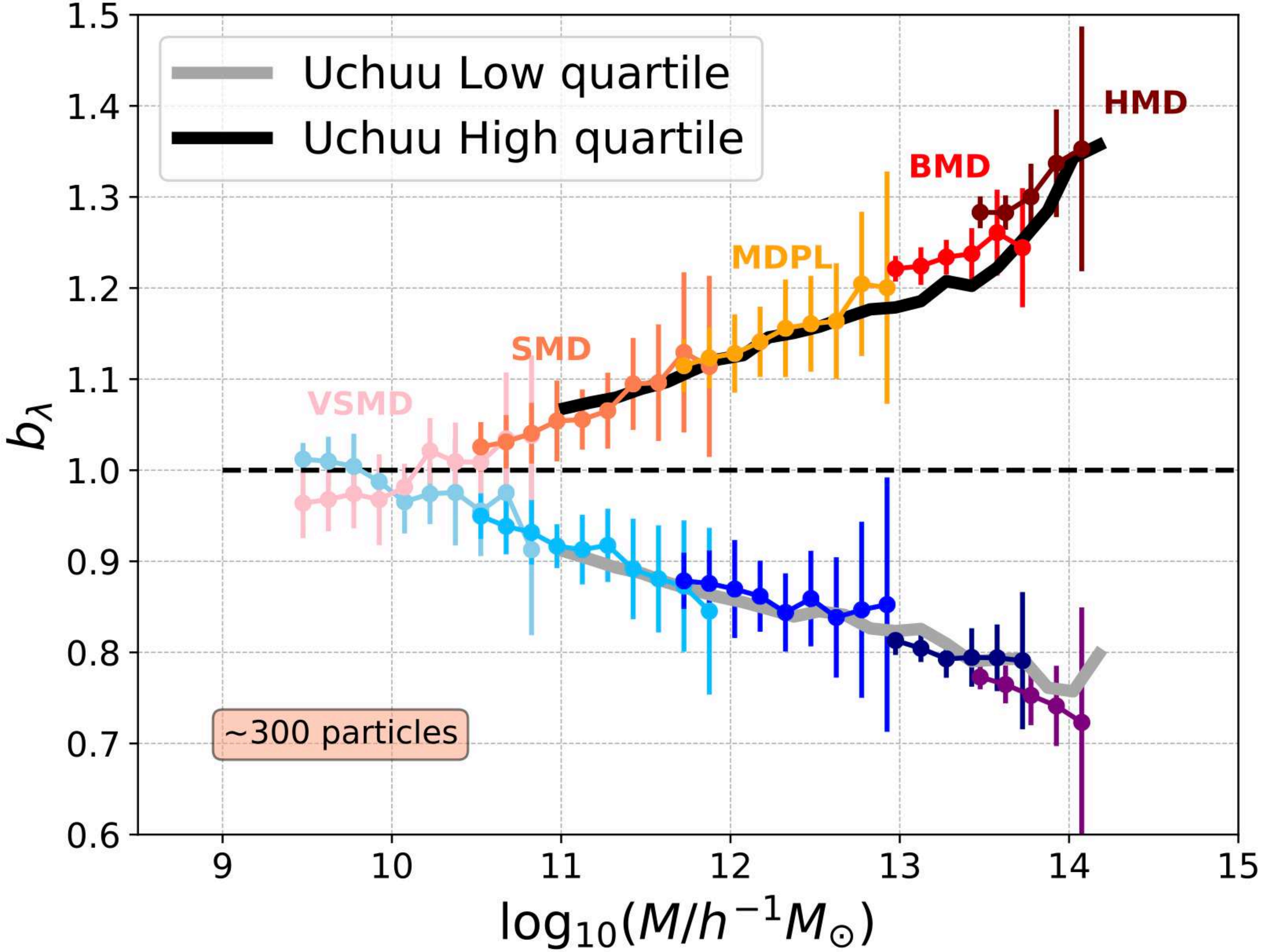
skiesanduniverses.org

Uchuu high resolution will be key for resolving the small halo masses of ELGs:



Courtesy of Tomoaki Ishiyama, Chiba U.

Uchuu will allow us to investigate the secondary bias parameter over 4 orders of magnitude:



Courtesy of Antonio D. Montero-Dorta

The galaxy-halo connection

Galaxies are biased tracers of the underlying dark matter distribution. We populate DM haloes with galaxies using 2 methods:

I. Halo Occupation Distribution (HOD)

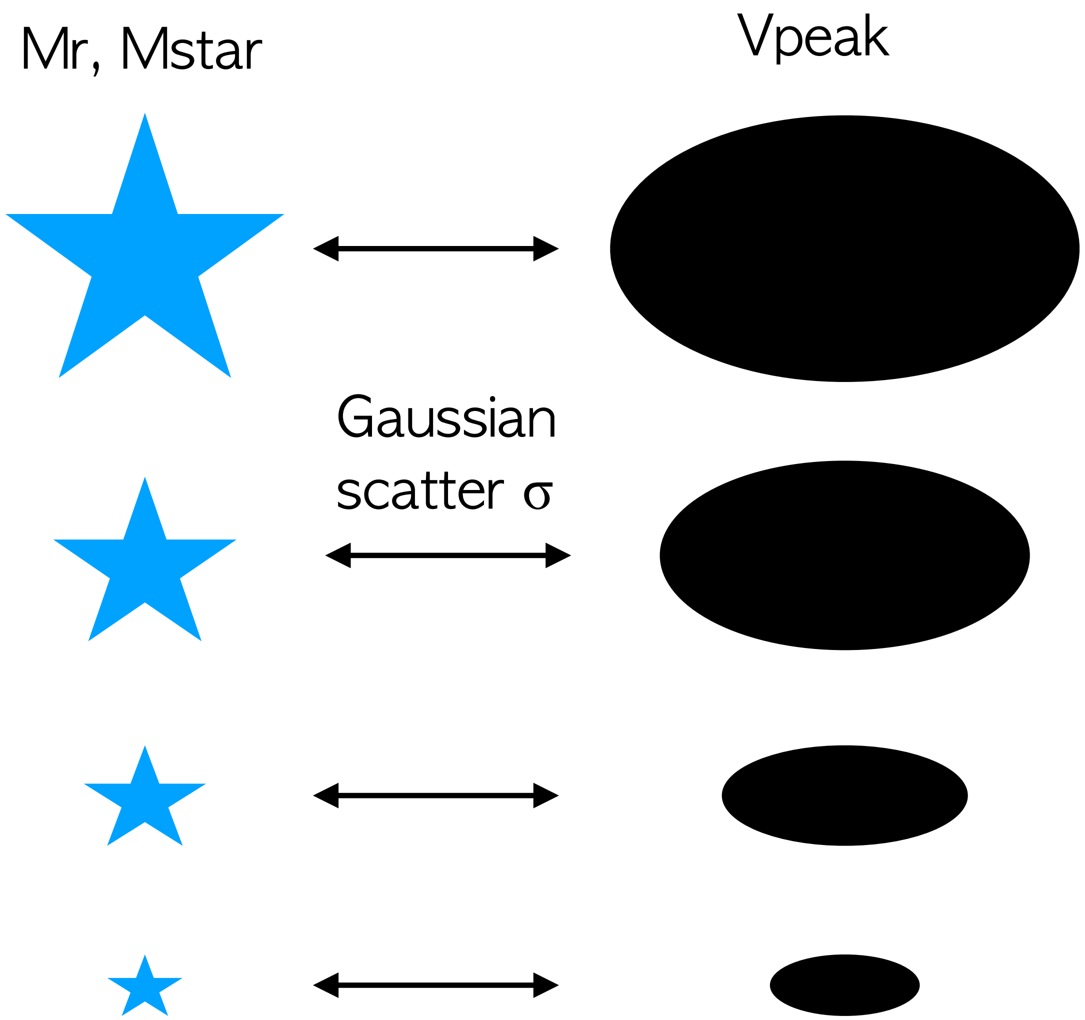
Cooray+02; Berlin & Weinberg+02; Kravtsov+04; Zheng+05,07

II. SubHalo Abundance Matching (SHAM)

Conroy+06, 09; Behroozi+10; Trujillo-Gomez+11

SubHalo Abundance Matching (SHAM)

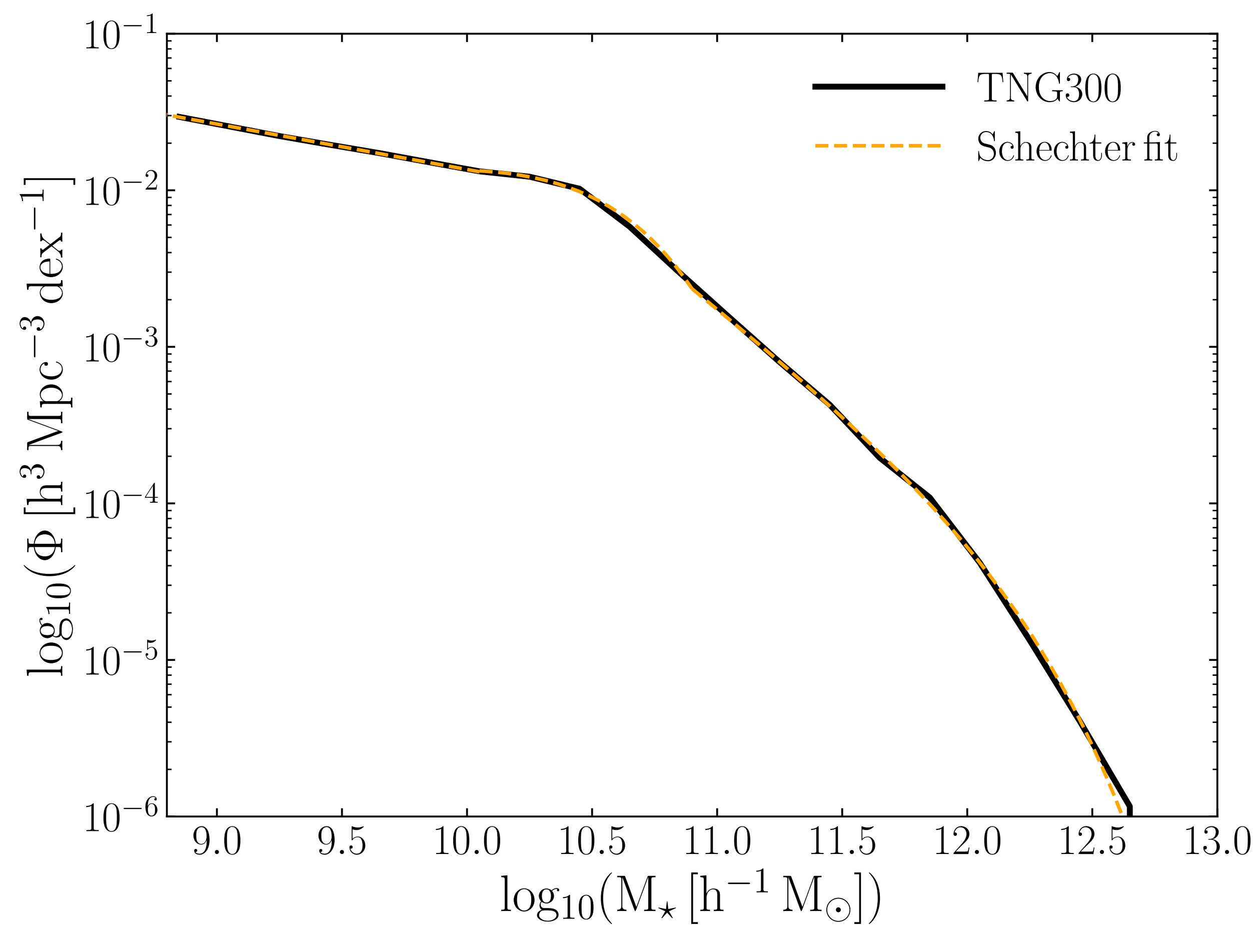
Rank order haloes and galaxies using their proxies:



Basic assumption: more massive/luminous galaxies occupy more massive haloes

Sample Mr/Mstar from the observed cumulative stellar mass/luminosity function until the observed number density n(z) is reached.

$$n_{\rm gal}(>M_\star) = n_{\rm h}(>V_{\rm peak})$$



Standard SHAM works well only for complete galaxy samples

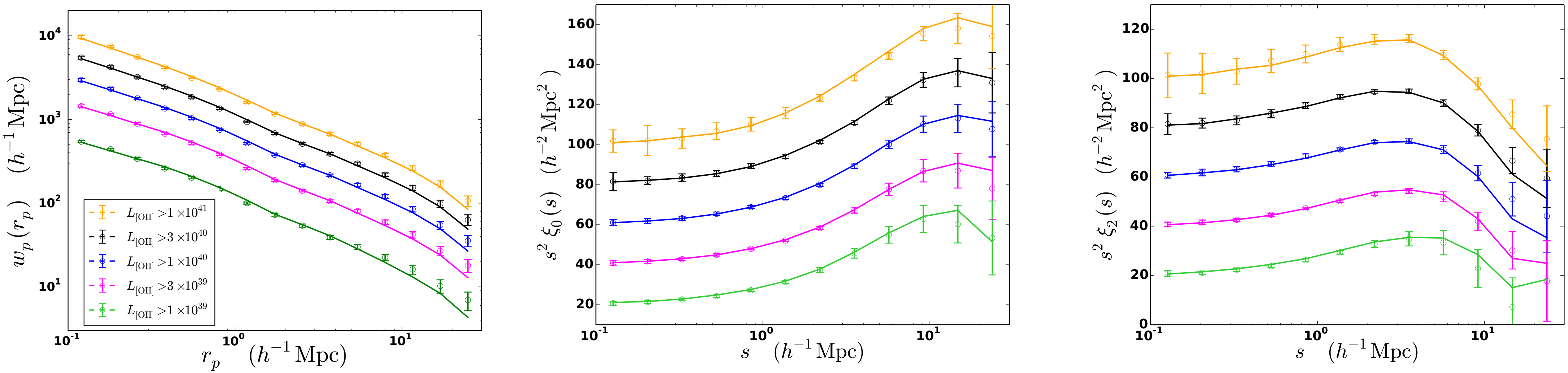
Modified SHAM

ELGs are very incomplete in Mstar, thus a modification is needed:

$$\mathrm{PDF}(V_{\rm peak}, \sigma_V, f_{\rm sat}) = f_{\rm sat} G_{\rm s}(V_{\rm peak}, \sigma_V, f_{\rm sat}) + (1 - f_{\rm sat}) G_{\rm c}(V_{\rm peak}, \sigma_V, f_{\rm sat})$$

Favole et al. 2016a, 2017

SDSS [OII] ELGs at z~0.1:



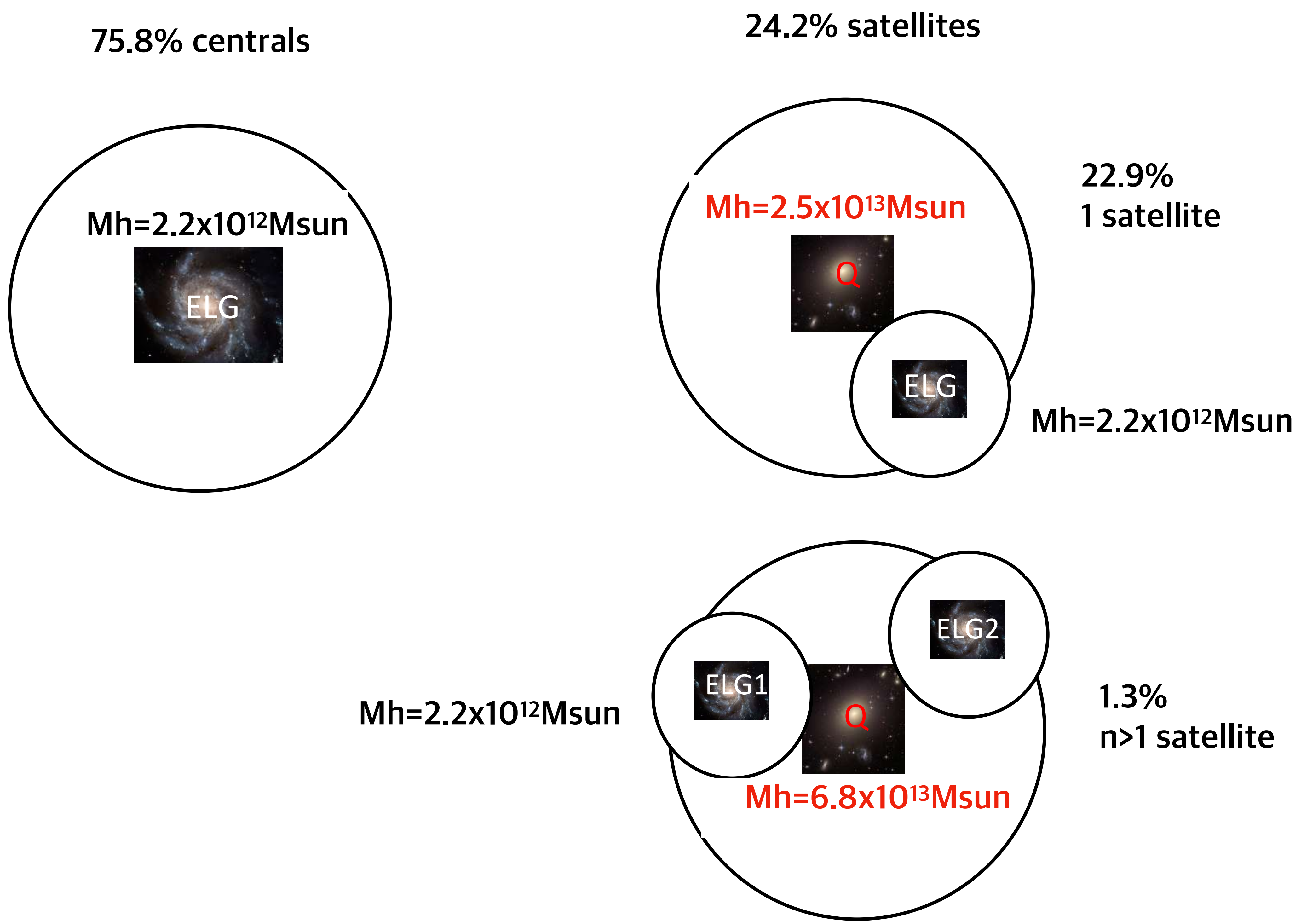
z_{max}	$\mathrm{L}^{min}_{[\mathrm{O_{II}}]}$ [erg s^{-1}]	$f_{\rm sat}$ [%]	typical $V_{\rm peak}$ [km s^{-1}]	typical M_h [$h^{-1}\mathrm{M}_\odot$]
0.05	1×10^{39}	33.4±0.1	127±58	(3.17±0.19)×10^{11}
0.09	3×10^{39}	27.9±0.4	177±53	(6.64±0.41)×10^{11}
0.14	1×10^{40}	22.5±0.7	201±86	(1.54±0.09)×10^{12}
0.17	3×10^{40}	19.4±0.4	283±117	(2.92±0.18)×10^{12}
0.20	1×10^{41}	18.0±0.5	341±140	(5.49±0.34)×10^{12}

On average:

$$M_{halo} = (2.2 \pm 0.1)\times10^{12}\,h^{-1}M_\odot$$

$$f_{sat} = (24.2 \pm 0.4)\,\%$$

[OII] ELG halo occupation distribution at z~0.1:



SHAM + Age Matching in IllustrisTNG300

Age-Matching (Hearin et al 2013): SHAM + secondary matching between galaxy color (g-r) and halo z_{starve}.

We implement AM using different halo/galaxy secondary properties from IllustrisTNG300 to improve our knowledge of secondary halo bias and its connection with the environment (tidal tensor).

IllustrisTNG300

L_{box} = 205 Mpc/h

$M_{DM} = 5.9 \times 10^7 M_{sun}$

$N_{DM} = 2500^3$

$M_{gas} = 1.7 \times 10^7 M_{sun}$

TNG300 GALAXIES -> Hydrosim

I: Mstar

II: color sSFR size

OUR DATA

TNGDMO300 HALOES -> DM-only

I: Vpeak

II: z_{starve} c_{infall} δ^{env}

Tidal density & anisotropy

+ SHAM - AM

OUR MOCKS

Halo tidal properties

Compute the halo tidal tensor on a cubic lattice using the **SPIDER** code (Martizzi et al. 2019; https://github.com/dmartizzi/spider-public):

$$T_{ij}(\vec{x}) = \partial_i \partial_j \psi_R(\vec{x})$$ gravitational potential smoothed at R

Poisson: $$\nabla^2 \psi_R(\vec{x}) = \delta_R(\vec{x})$$ smoothed density contrast

In Fourier space: $$\delta_R(\vec{k}) = \delta(\vec{k}) e^{-k^2 R^2/2}$$ Gaussian smoothing

We interpolate the tensor at each halo location (x, y, z) and the smoothing scale R at the halo radius to create a halo-by-halo catalogue of tidal estimates.

Diagonalize it and extract the **eigenvalues** $\lambda_1, \lambda_2, \lambda_3$ that give us a **LSS classification**:

knots:	$\lambda_{i,j,k} \geq 0.3$
filaments:	$\lambda_{i,j} \geq 0.3$
sheets:	$\lambda_i \geq 0.3$
voids:	$\lambda_{i,j,k} < 0.3$

Halo tidal overdensity:

$$\delta_{\mathrm{R}} = \lambda_1 + \lambda_2 + \lambda_3$$

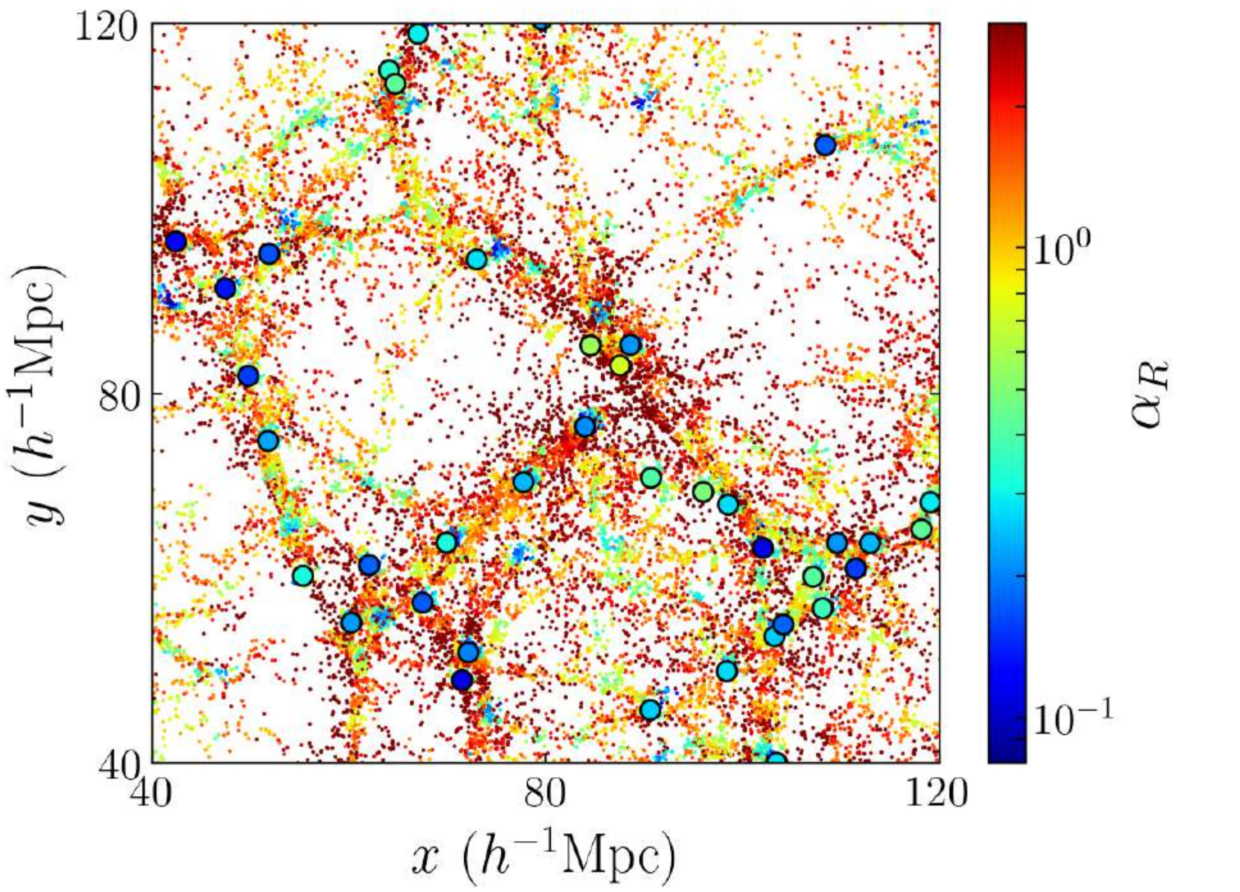
Tidal anisotropy parameter:

$$\alpha_{\mathrm{R}} \equiv (1 + \delta_{\mathrm{R}})^{-1}\sqrt{q^2}$$

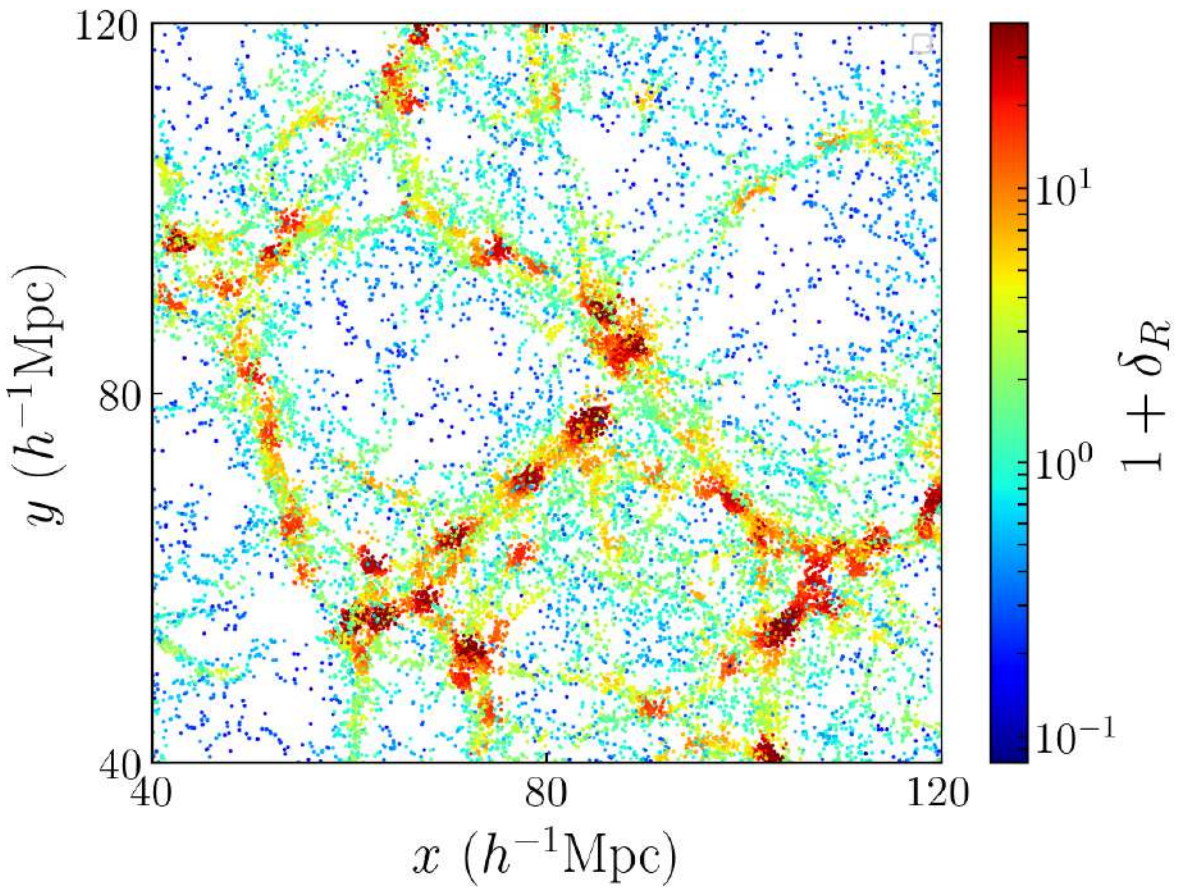
$$q^2 = \frac{1}{2}\left[(\lambda_2 - \lambda_1)^2 + (\lambda_3 - \lambda_1)^2 + (\lambda_3 - \lambda_2)^2\right]$$

Paranjape et al. 2018; Ramakrishnan et al. 2019

The anisotropy parameter is a **mediator between the internal and large-scale properties of haloes**

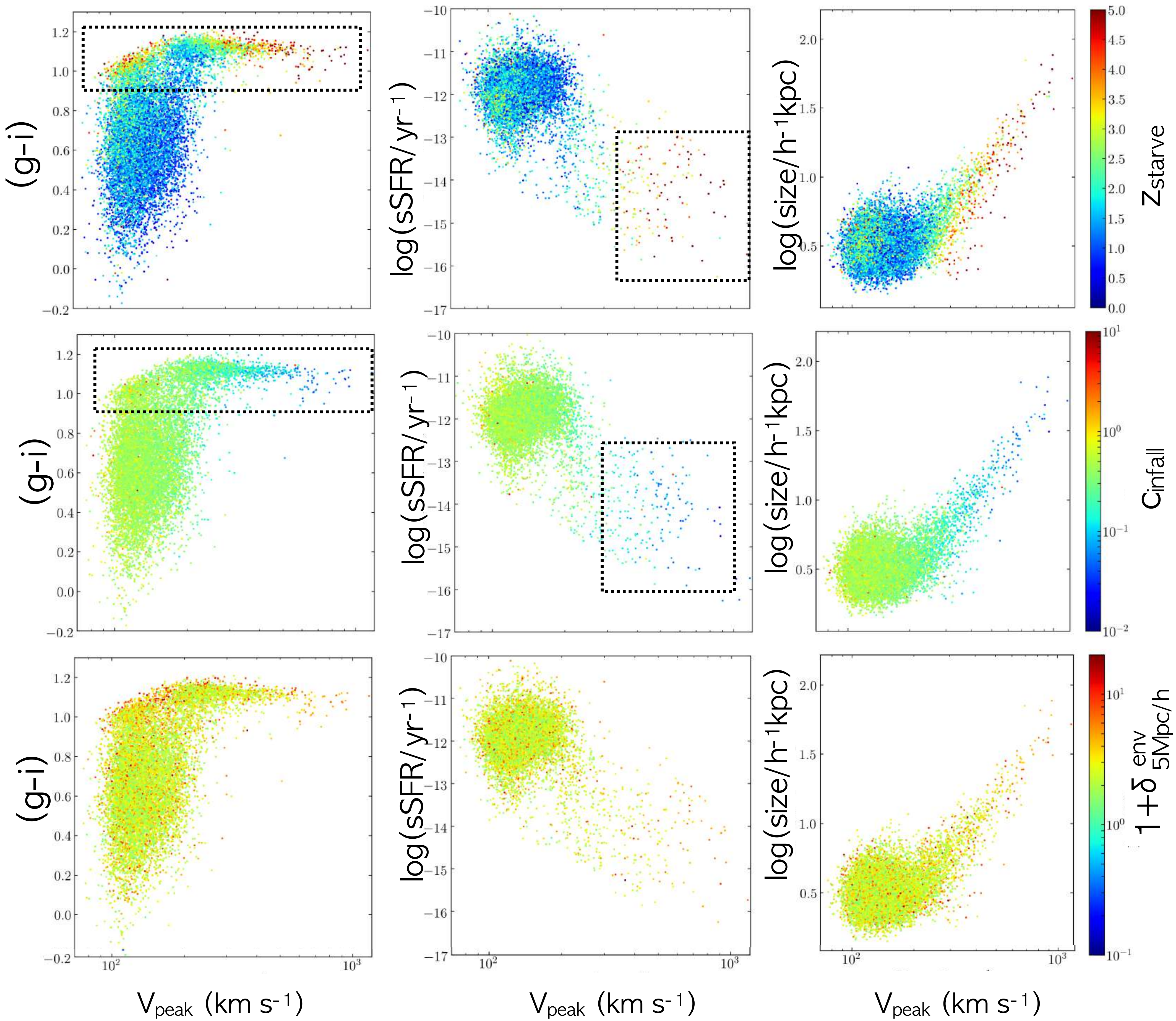


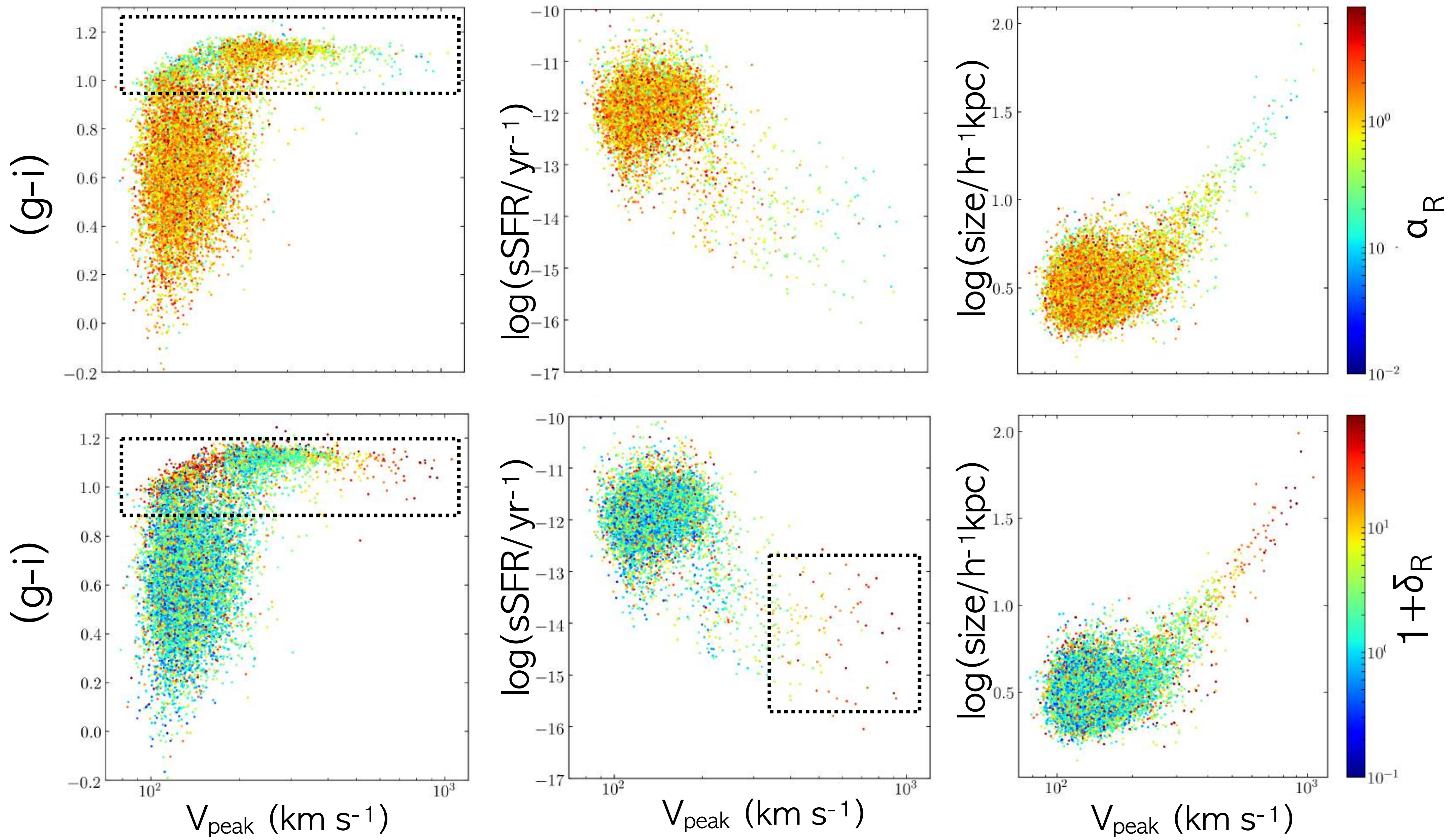
Anisotropy is higher in filaments an lower in knots



δ_R traces well the LSS

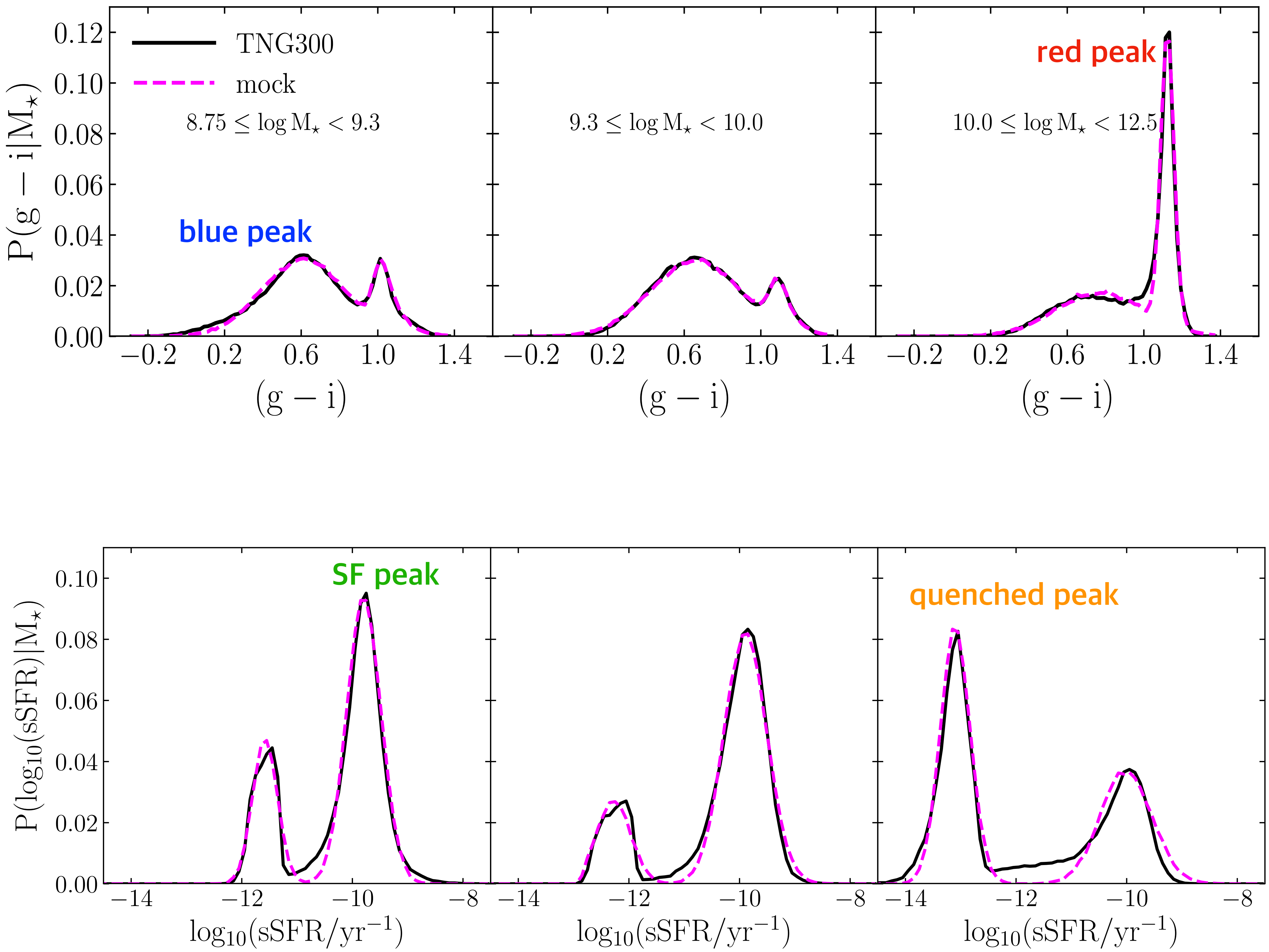
Correlations between halo/galaxy secondary properties:



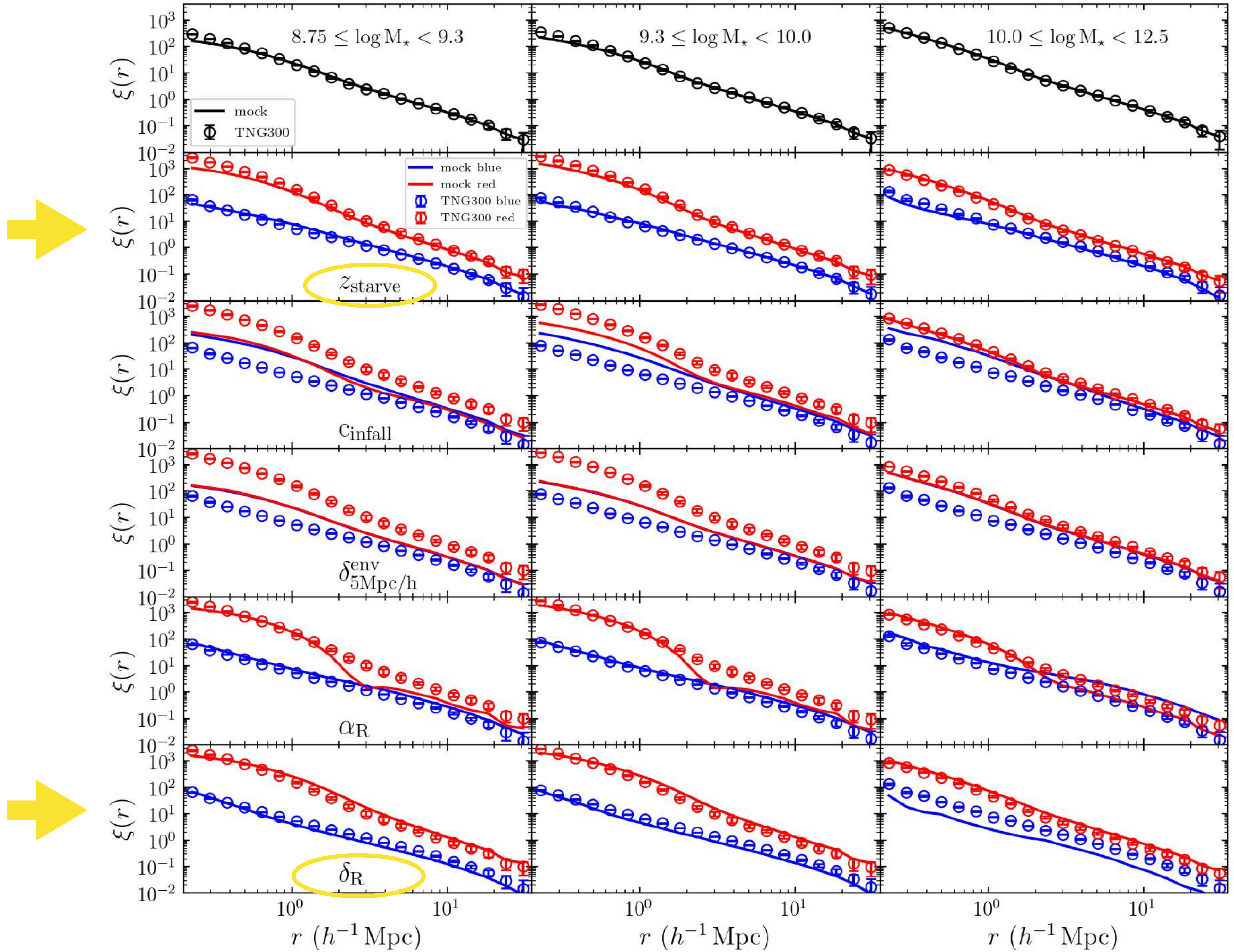


Even if apparently mild, these correlations are the drivers to obtain a good secondary matching

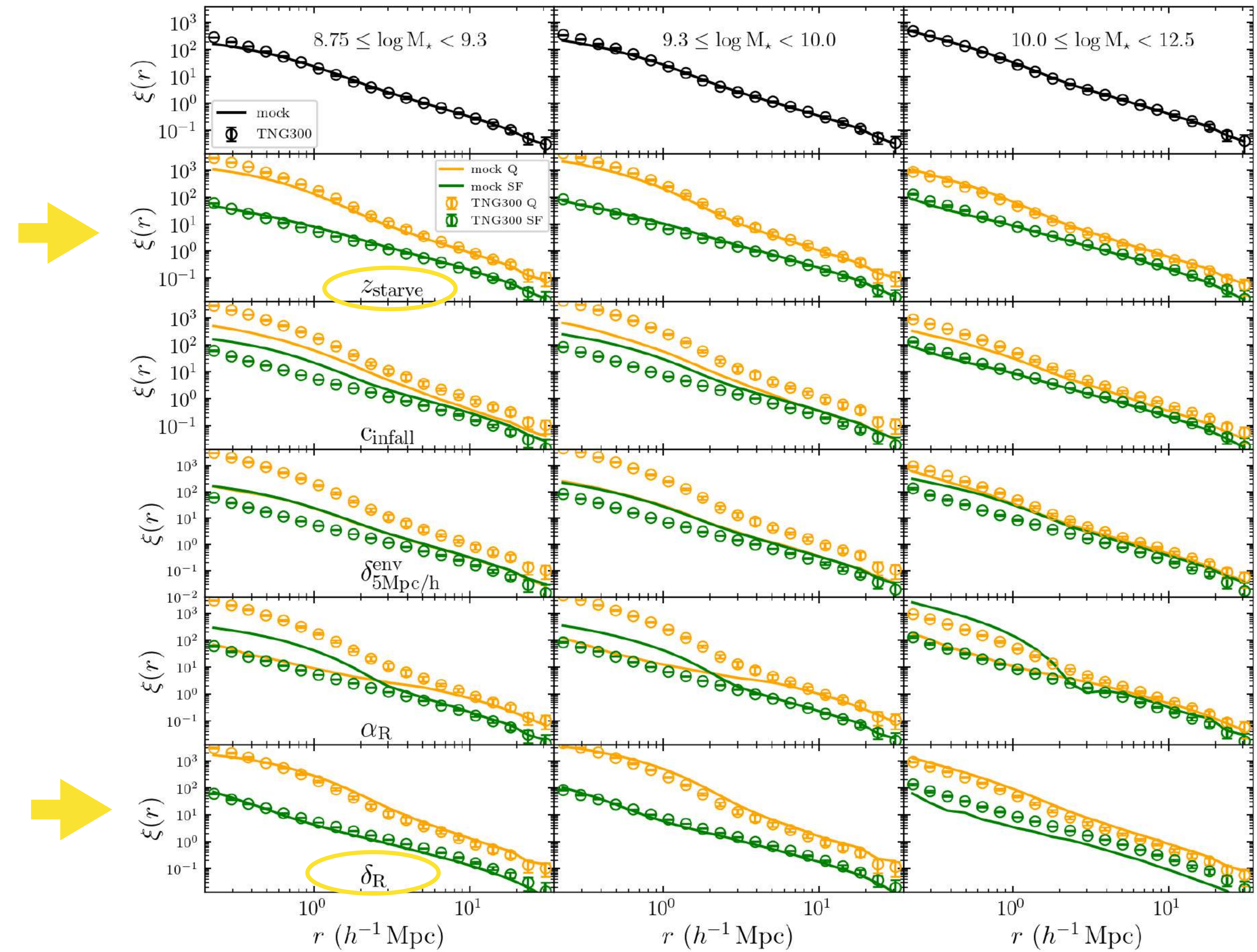
The secondary matching is performed through conditional PDFs in bins of stellar mass:



Clustering results galaxy color - halo props: Red : $(g - i) \geq 0.85$ Blue : $(g - i) < 0.85$



Clustering results galaxy sSFR - halo props: **Quiescent:logsSFR < -10.7** **Star-forming: logsSFR ⩾ -10.7**



Summary Part I

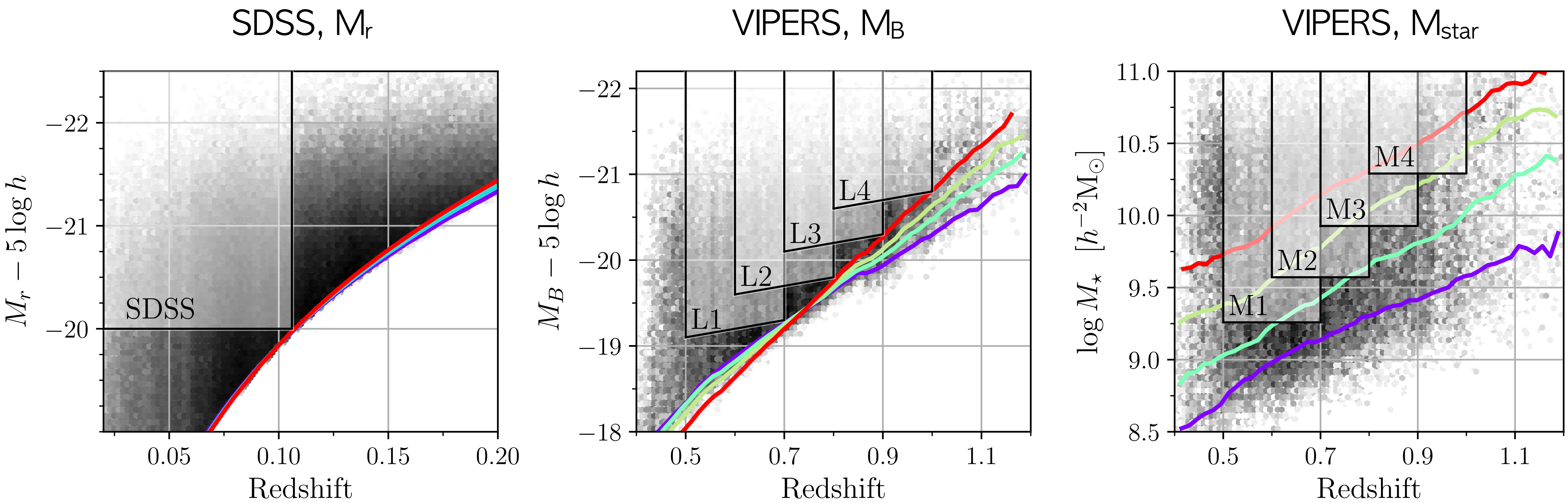
- SHAM is a simple, yet powerful, prescription able to place galaxies into their host DM haloes reproducing the clustering of ~ complete samples.

- DESI, Euclid, LSST, etc … will target millions of galaxy **multi-tracers**, most of them incomplete in many parameter spaces. Therefore, a **sophisticated modification of SHAM is needed**.

- **SHAM+Age Matching links the internal and large-scale galaxy/halo properties** allowing us to model the **clustering of multi-tracers** on all scales, properly including the **secondary halo bias** and the physics of **galaxy formation/evolution**.

- The **accuracy** of this method **strongly depends on the halo/galaxy secondary proxies** chosen. The more they correlate, the better is the secondary matching, the higher the accuracy in the 2PCF modelling. Among the proxies we have tested the best are: galaxy color, sSFR and halo z_{starve}, δ_R

Constraining the growth history $\sigma_8(z)$ using basic SHAM

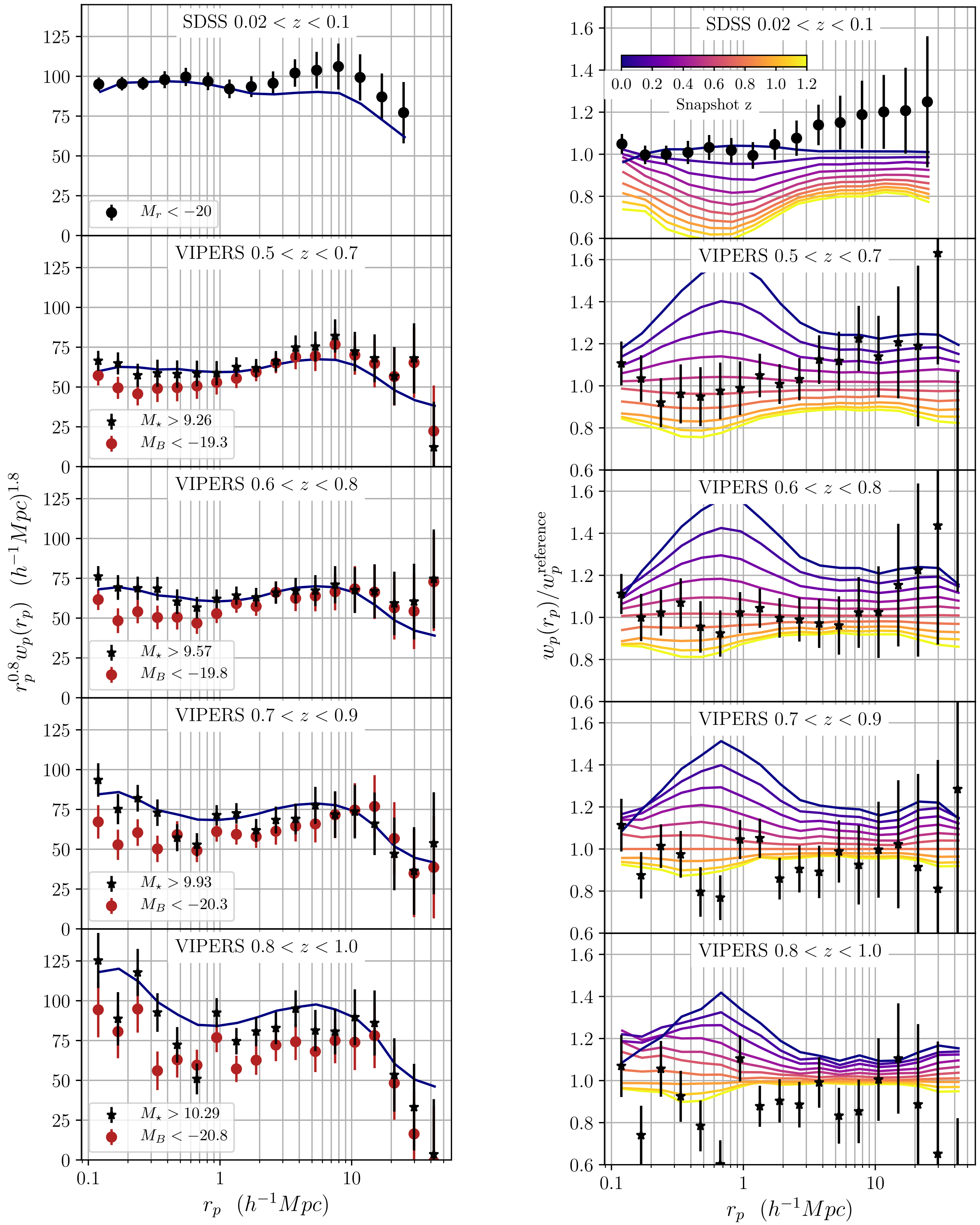


Granett, Favole, Montero-Dorta et al. 2019

Sample	Redshift	Mean z	Threshold	Count	Volume $10^6 h^{-3}\mathrm{Mpc}^3$	Density $10^{-3} h^3\mathrm{Mpc}^{-3}$
SDSS	$0.020 < z < 0.106$	0.063	$M_r < -20.0$	117959	21.90	5.85
L1	$0.5 < z < 0.7$	0.61	$M_B < -19.3 + (0.7 - z)$	23352	4.93	11.8
M1	$0.5 < z < 0.7$	0.61	$\log M_\star > 9.26 h^{-2}\mathrm{M}_\odot$	22508	4.93	11.8
L2	$0.6 < z < 0.8$	0.70	$M_B < -19.8 + (0.8 - z)$	20579	5.98	8.57
M2	$0.6 < z < 0.8$	0.70	$\log M_\star > 9.57 h^{-2}\mathrm{M}_\odot$	19577	5.98	8.57
L3	$0.7 < z < 0.9$	0.80	$M_B < -20.3 + (0.9 - z)$	13046	6.96	4.79
M3	$0.7 < z < 0.9$	0.80	$\log M_\star > 9.93 h^{-2}\mathrm{M}_\odot$	12270	6.96	4.79
L4	$0.8 < z < 1.0$	0.90	$M_B < -20.8 + (1.0 - z)$	6305	7.86	2.13
M4	$0.8 < z < 1.0$	0.89	$\log M_\star > 10.29 h^{-2}\mathrm{M}_\odot$	5881	7.86	2.13

We use basic SHAM with no parameters to avoid limiting the cosmological interpretation Small MultiDark (L=400 Mpc/h) simulation with Planck15 fiducial cosmology

M_B selected 2PCFs are lower since the bluer VIPERS rest-frame is more sensitive to recent SF activity and less to total mass

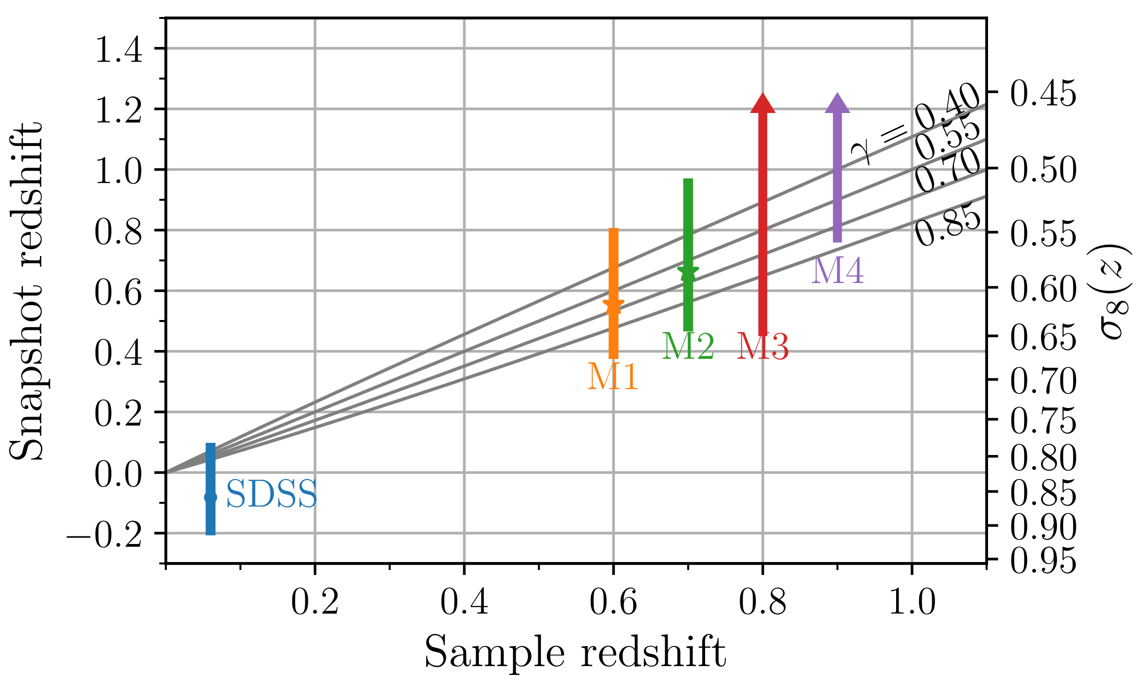


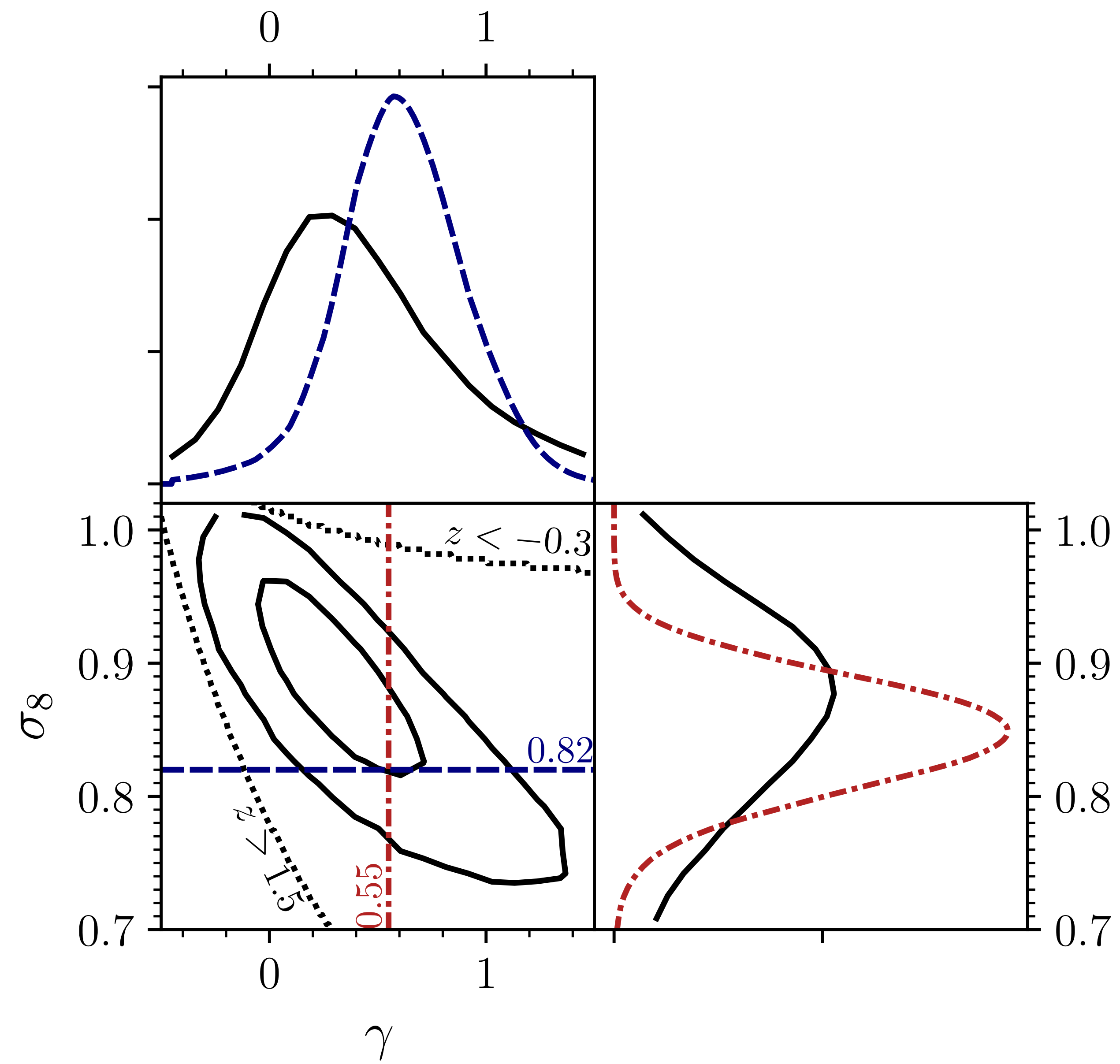
Granett, Favole, Montero-Dorta et al. 2019

The growth history $\sigma_8(z)$ can be parametrised in terms of the growth index γ as:

$$\sigma_8(z) = \sigma_8(0)\exp\left[-\int_0^z \Omega_m(z')^{\gamma} d\ln(1+z')\right]$$

$\sigma_8(z)$ in the fiducial cosmology is fixed at the simulation snapshot. So $w_p(r_p)$ measured in the simulation implicitly gives us $w_p(\sigma_8)$ and, by minimising the likelihood, we infer $\sigma_8(w_p^{obs})$.





We fix $\sigma_8(0) = 0.82$ from the fiducial cosmology and get: $\gamma = 0.6 \pm 0.3$

We fix $\gamma = 0.55$ from the fiducial cosmology and get: $\sigma_8 = 0.85 \pm 0.04$

Summary Part II

- Our results can be considered model dependent as they rely on SHAM
- But they are not calibrated on CMB, which tightens the errors
- Our errors are better than VIPERS estimates from RSD only
- With future surveys we will measure the growth history at low z with no need of CMB
- **Next step is to constrain $\sigma_8(z)$ using SHAM + Age Matching**
- **Future: comprehensive clustering + weak lensing model able to accurately predict both observables for galaxy multi-tracers**