Modelling the clustering properties of emission line galaxies in new-generation cosmological surveys

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esa

KAVLI - IPMU, May 2019

KAVLI IPMU

Motivations and outline

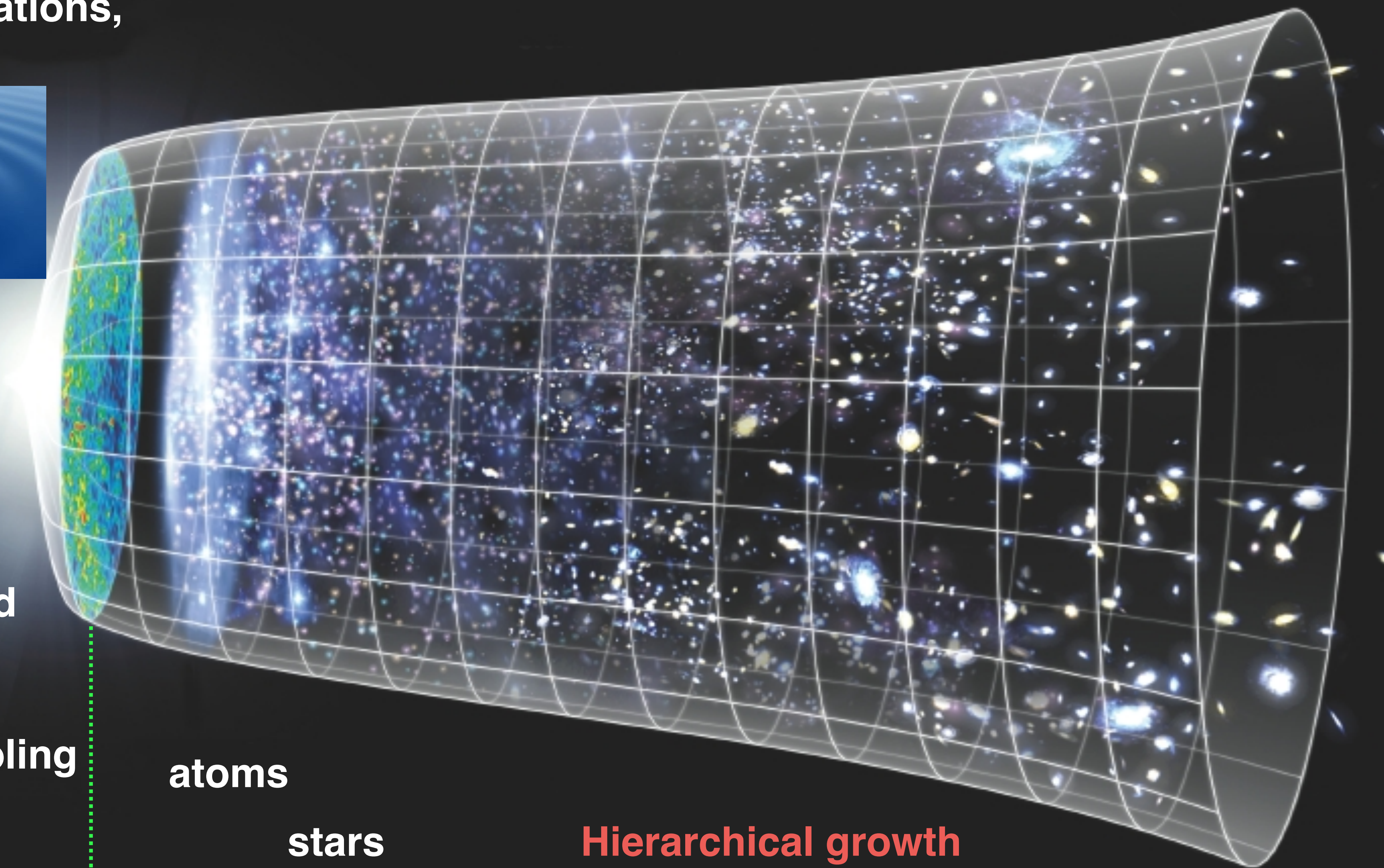
We aim to build a high-fidelity galaxy clustering model for new-generation surveys able to accurately predict the clustering properties of different tracers (ELGs and LRGs), their halo occupation distribution (M_{halo}, V_{max}, f_{sat}), bias and redshift-space distortions.

- Cosmological framework
- Large-volume cosmological surveys: past, present, future
- Methods for measuring and modelling galaxy clustering
- Results:
  - SDSS Hα and [OII] emission line galaxies (ELGs) at z~0.1
  - g-selected [OII] emitters at z~0.8
  - WISP/HST Hα emitters at 0.9<z<1.6 in preparation to Euclid
- Summary & future

Cosmological Framework

Big Bang t=0 → Today t=13.82 x 10^9 yrs

Quantum fluctuations,
over densities



Photon-baryon
plasma
Universe ionised

Inflation, cooling

atoms

stars

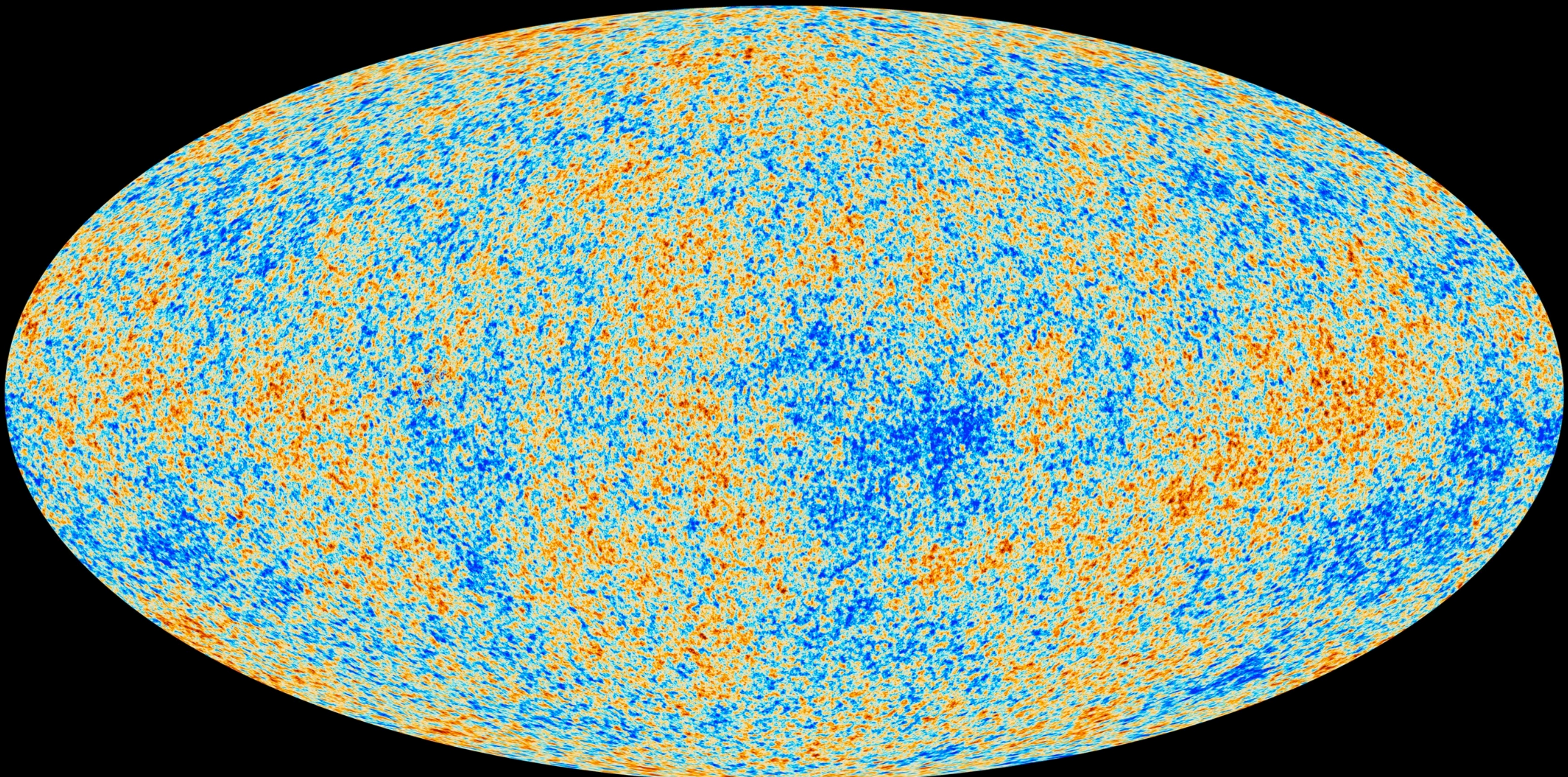
Hierarchical growth
of structure through
gravitational instability

Accelerated expansion,
Dark Energy?

First light: 380,000 yrs CMB radiation
Universe neutral and transparent

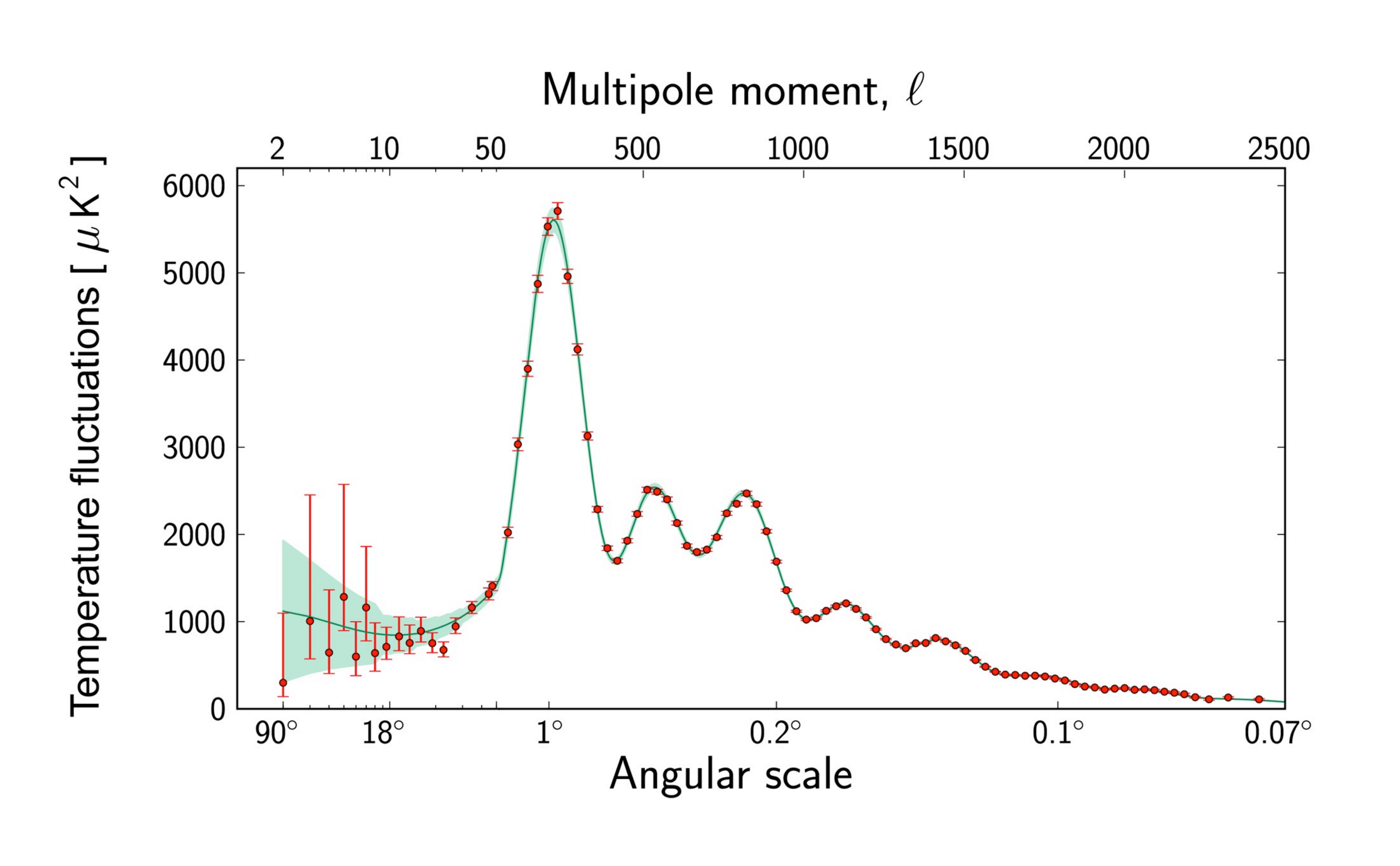
Primordial quantum fluctuations propagate as sound waves, or ripples in the cosmic pond, leaving their imprint in the CMB as temperature/density fluctuations.

These are the seeds of the large scale structure we see today in the Universe



ESA Planck Collaboration, 2013

Temperature Power Spectrum

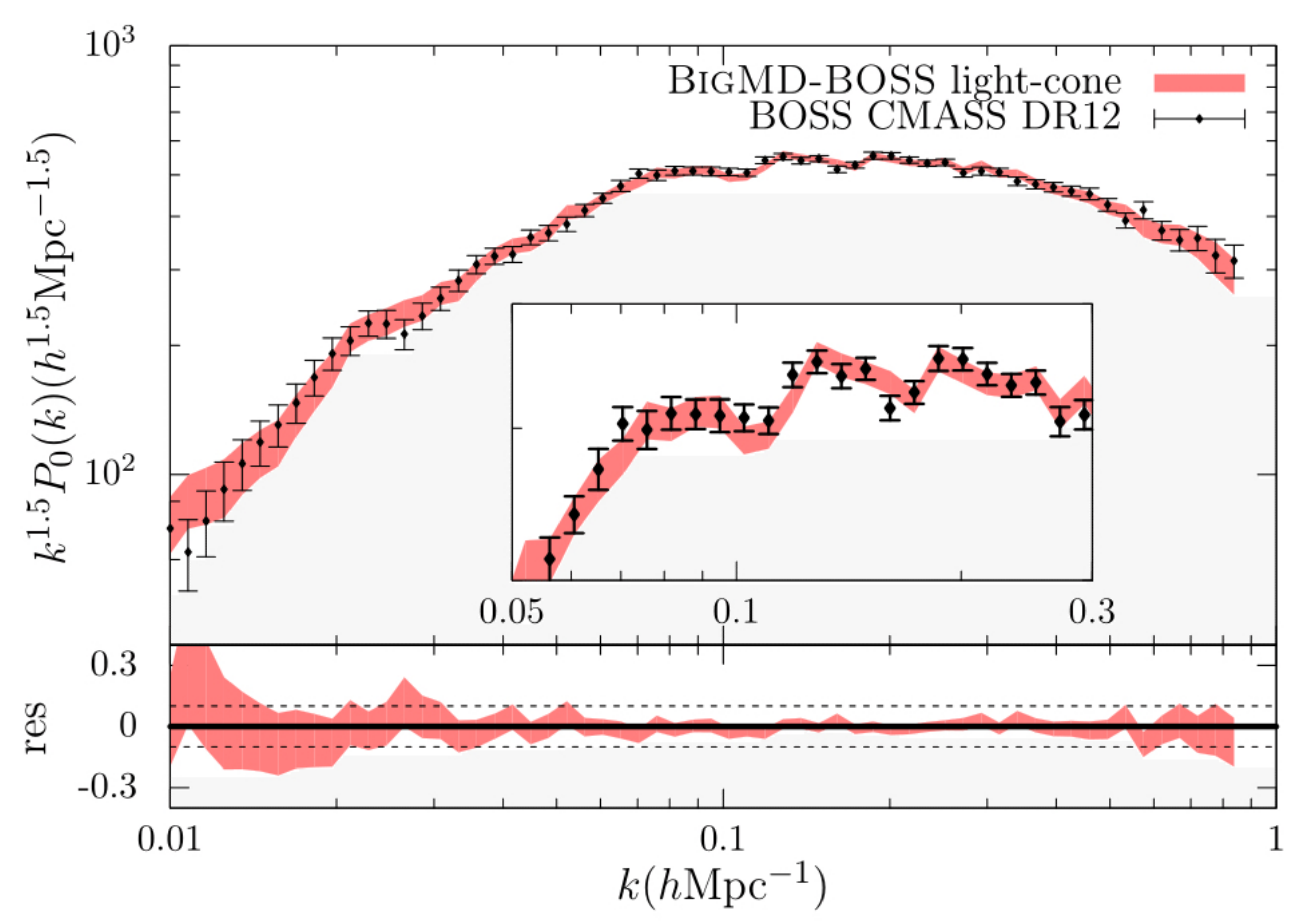


ESA Planck Collaboration, 2013

Galaxy Power Spectrum

P(k) = <|δk|²> = Ak^n

FFT of the primeval density fluctuations

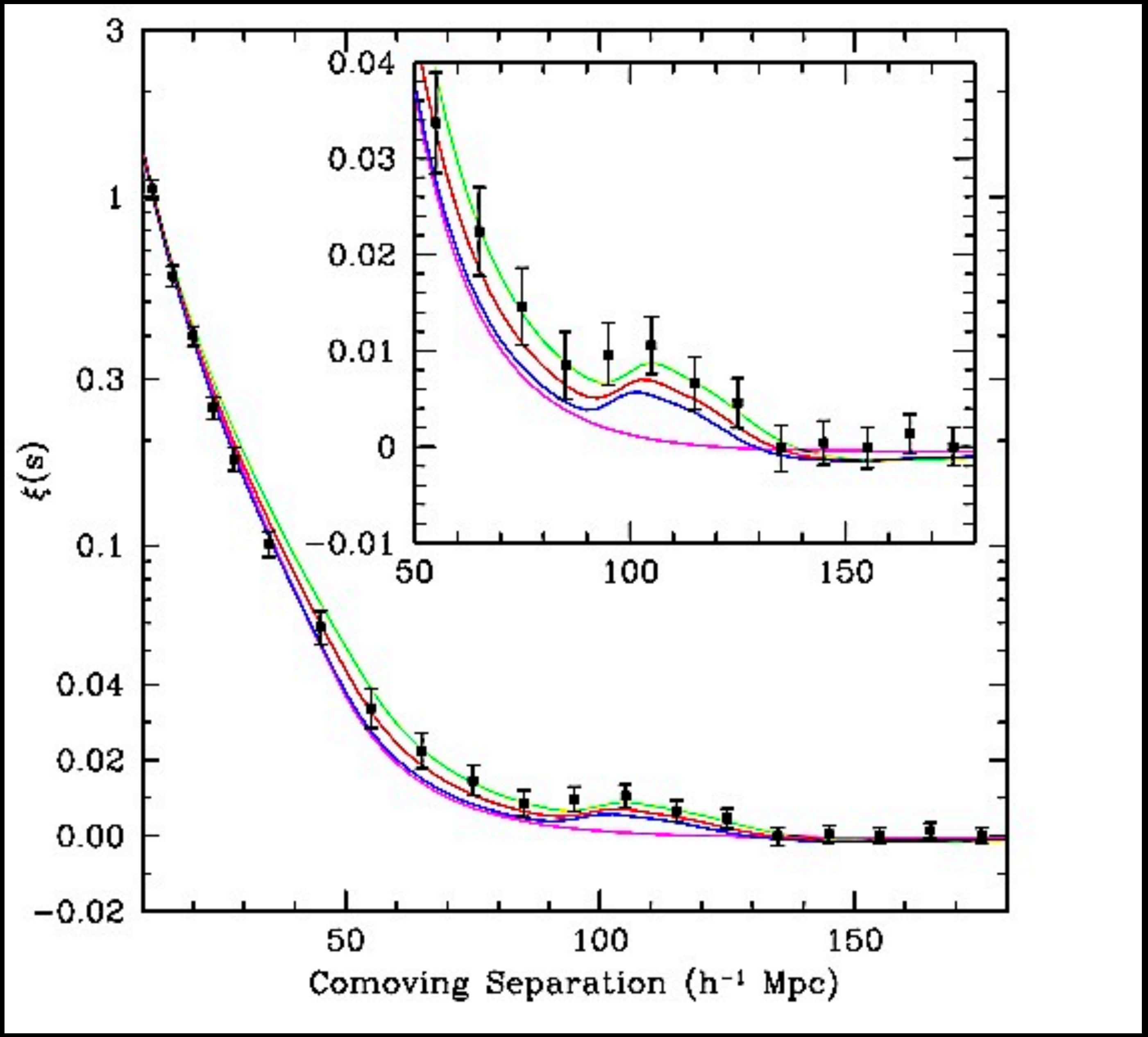


Rodríguez-Torres,+, Favole et al. 2016, MNRAS 460 1173

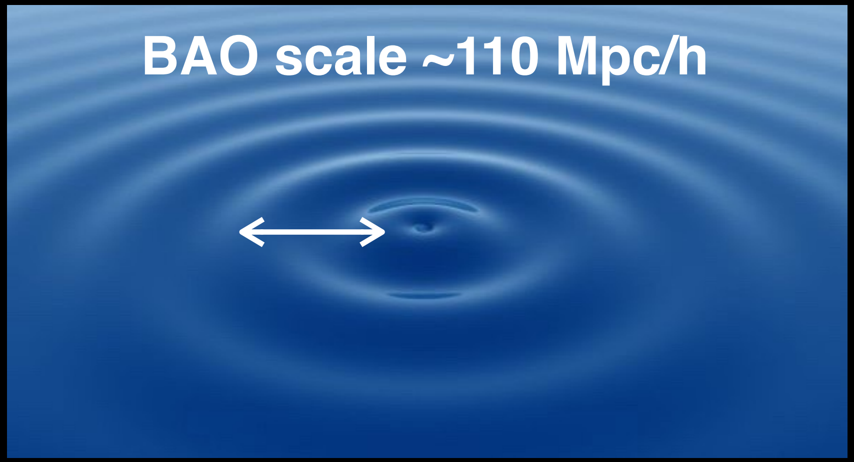
Galaxy 2-point correlation function

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

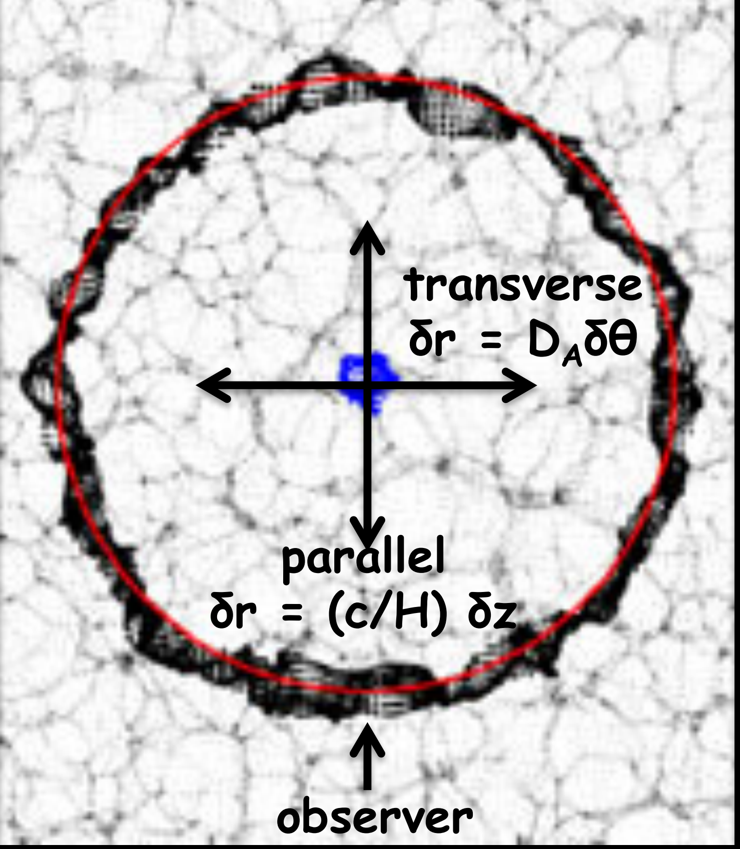
FFT of the power spectrum



Eisenstein et al. 2005, ApJ 633 560



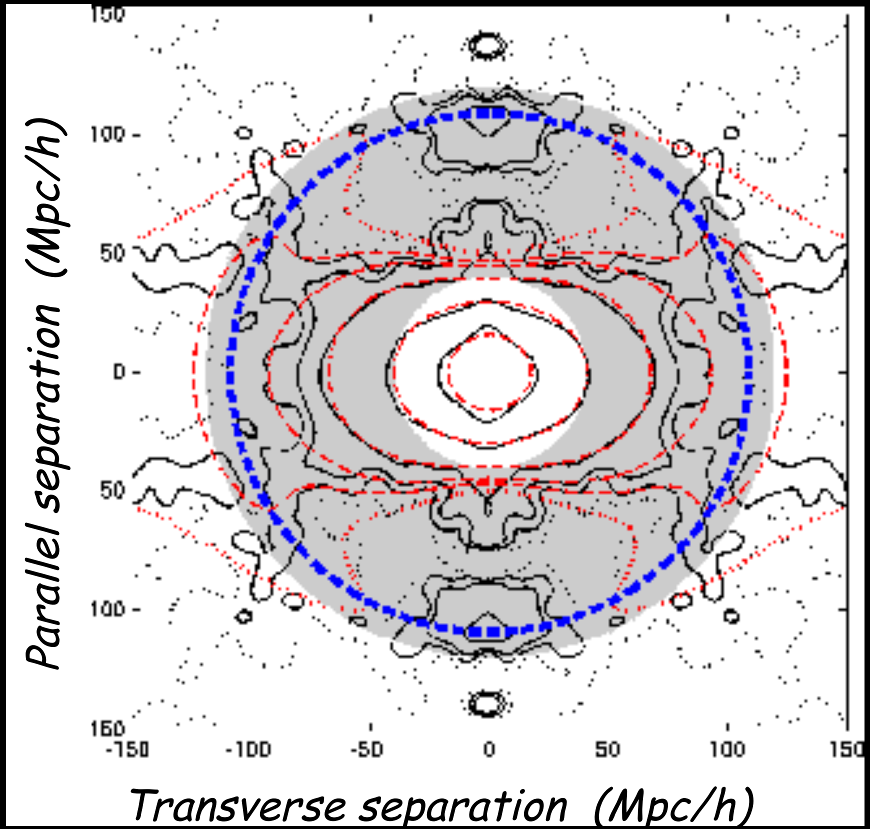
BAO scale is a standard ruler
for cosmological distances



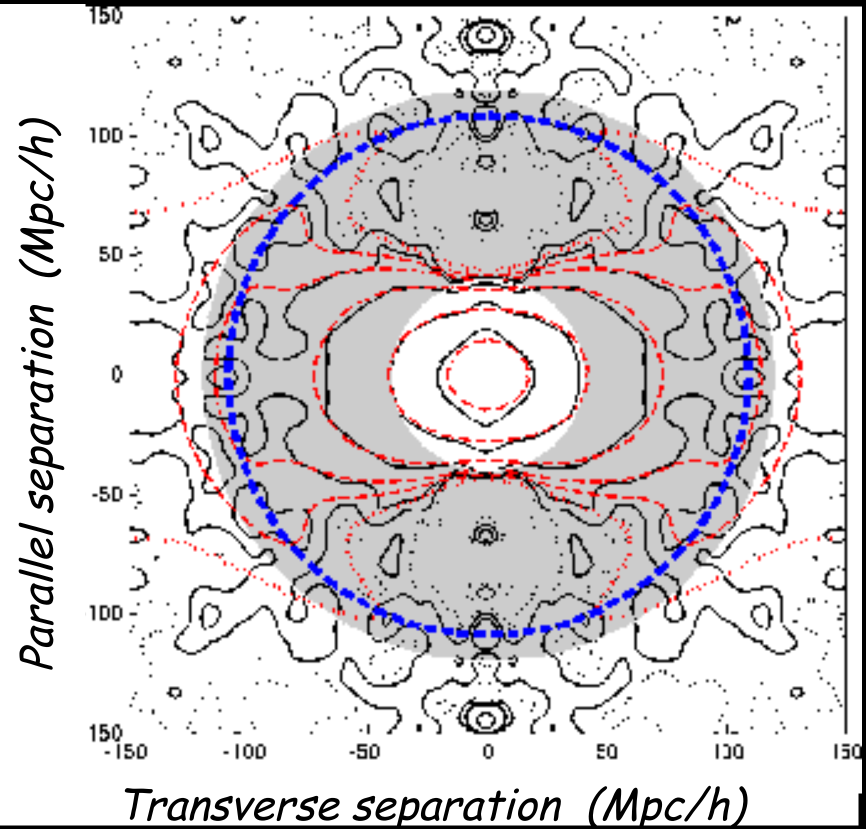
The acoustic oscillation scale in galaxy redshift surveys can be measured along and across the line of sight (LOS) to derive the angular diameter distance $D_A(z)$ and the Universe expansion rate $H(z)$

These are uncorrelated measurements used to constrain dark energy in combination with CMB

Las Damas mock catalogs



SDSS LRG data at z~0.35

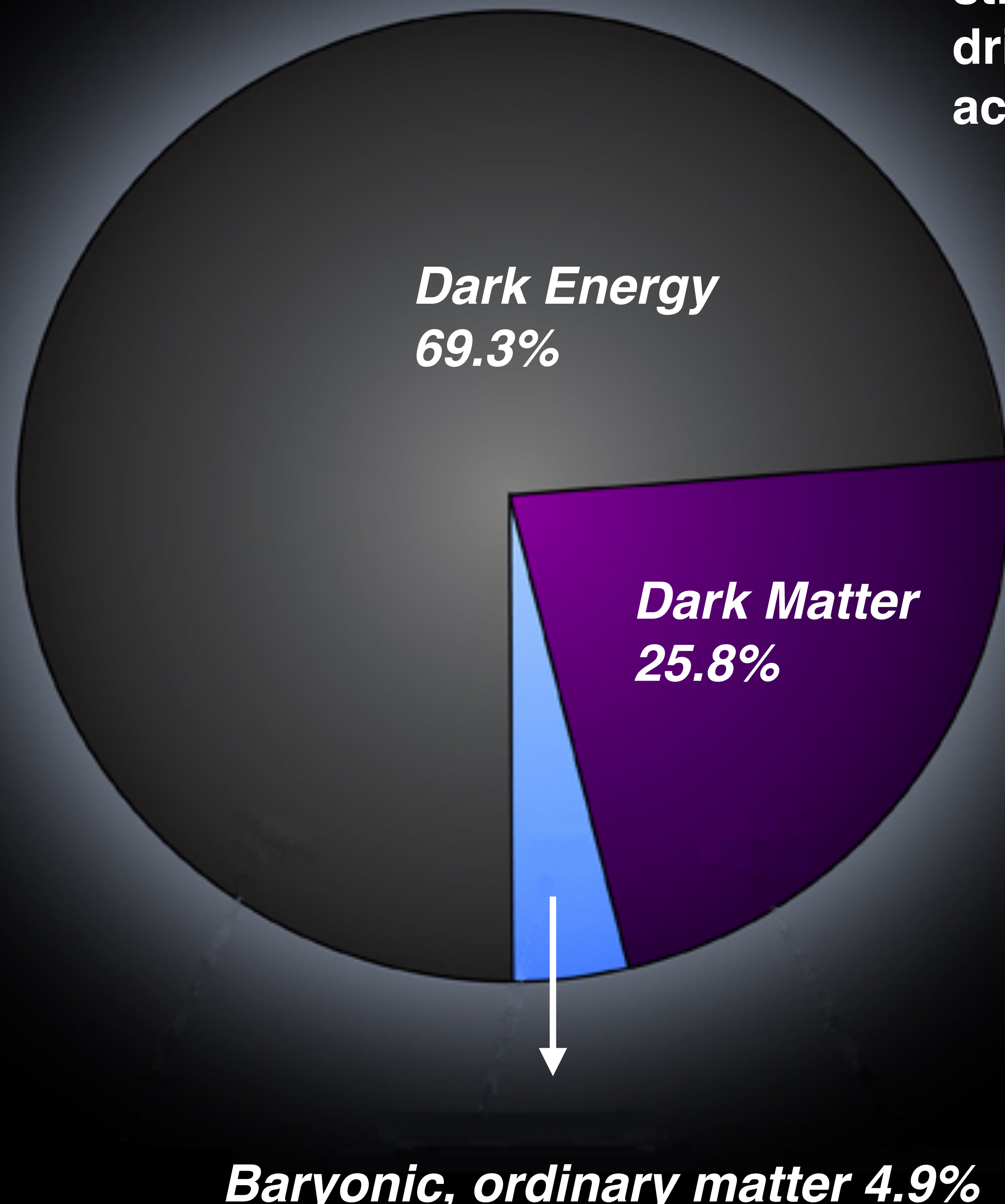


$D_A(z=0.35) = 1048^{+60}_{-58}$ Mpc

$H(z=0.35) = 82.1^{+4.8}_{-4.9}$ km/s/Mpc

Chuang & Wuang 2012, MNRAS 426 226

The energy budget of the Universe



mysterious component still unknown which might drive the Universe accelerated expansion

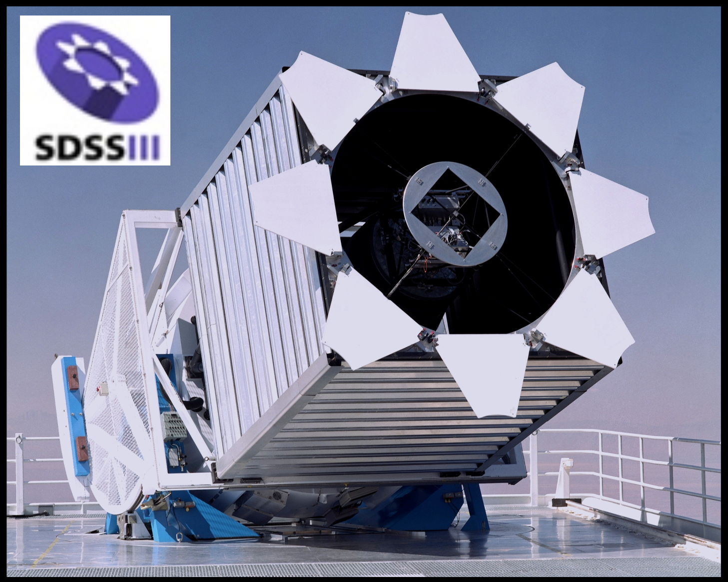
Spectroscopic surveys

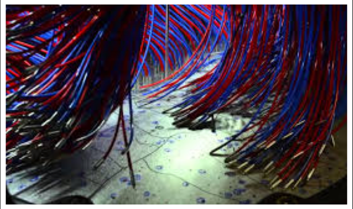
Past:

SDSS-I/II (2005-2009)
SDSS-III/BOSS (2009-2014)

2.5m telescope at Apache Point Observatory, New Mexico

5 photometric bands (*u, g, r, i, z*)



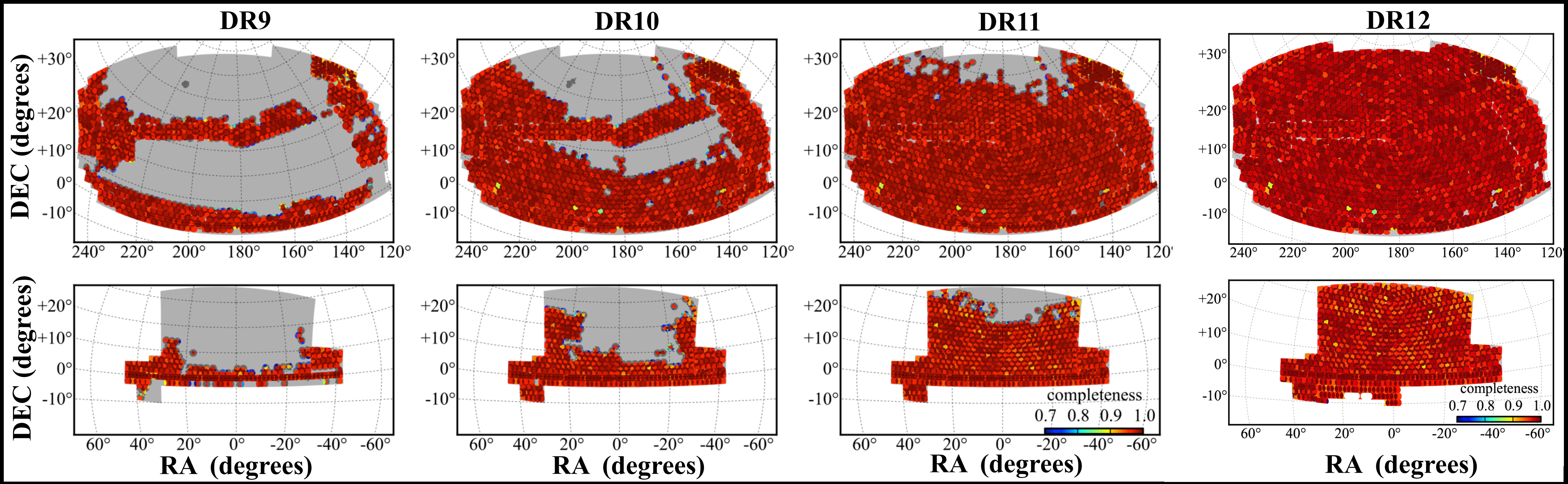


sdss3.org

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

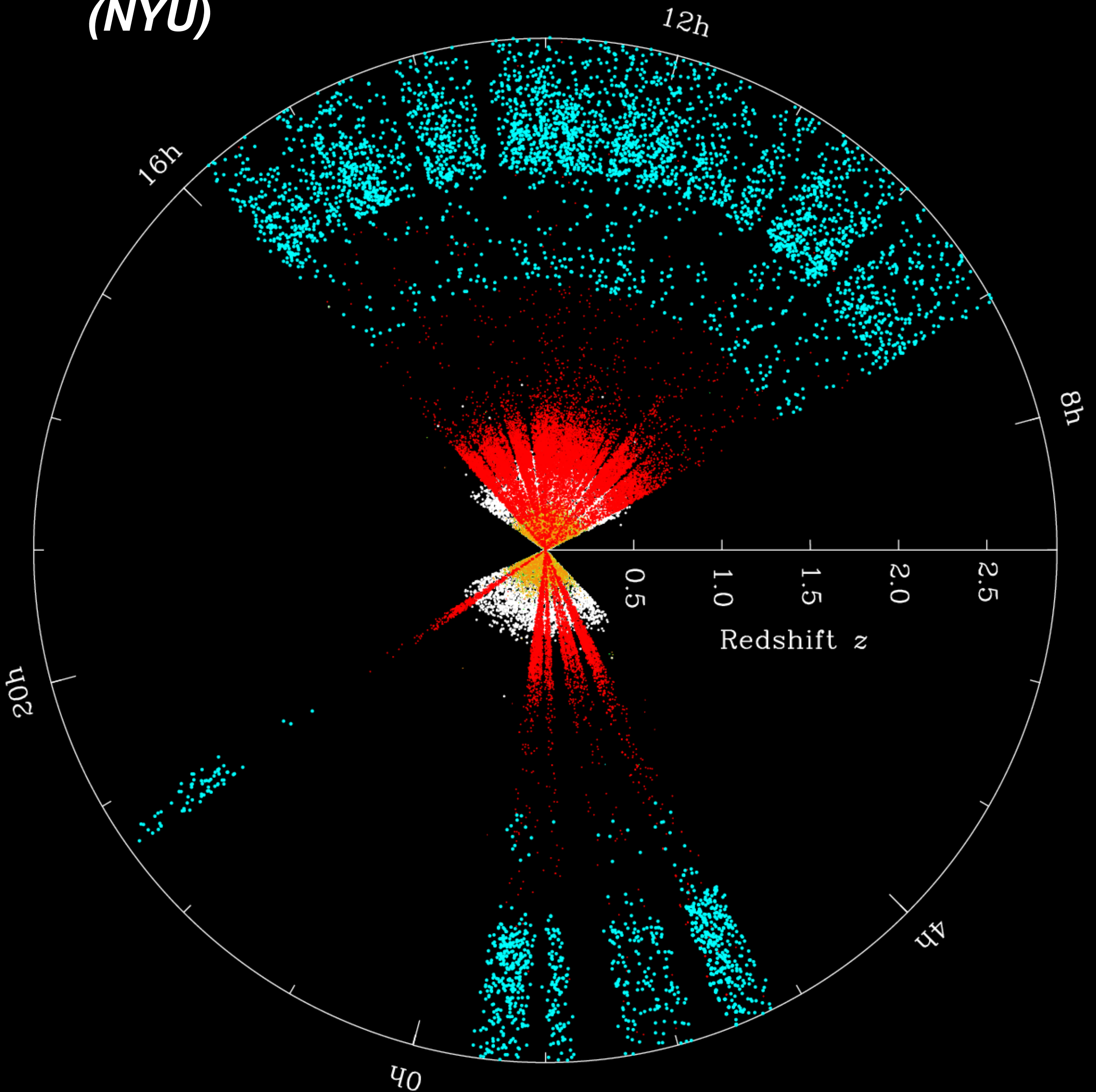
NGC

SGC

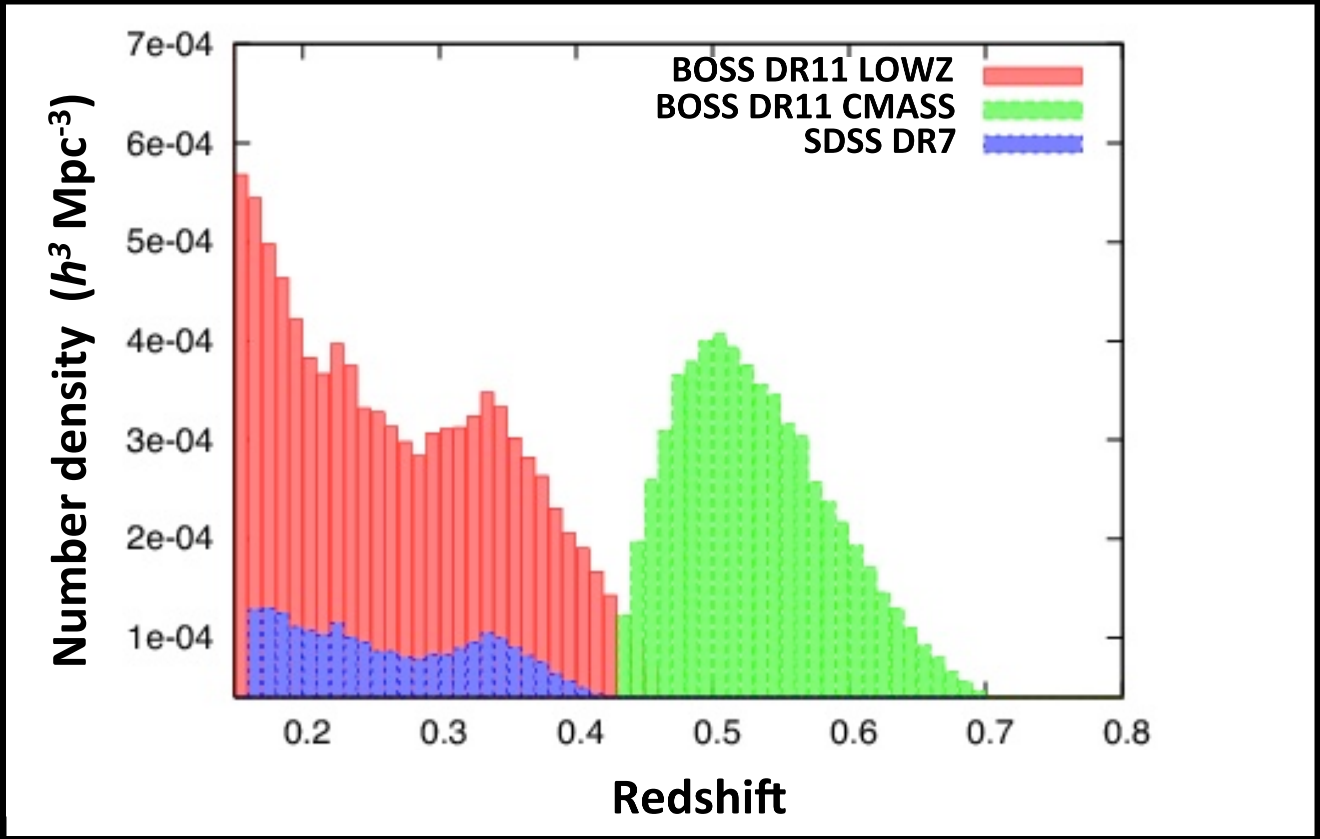


Anderson+ 2014

M. Blanton (NYU)



Two main BOSS samples:
LOWz z < 0.43, CMASS 0.43 < z < 0.7

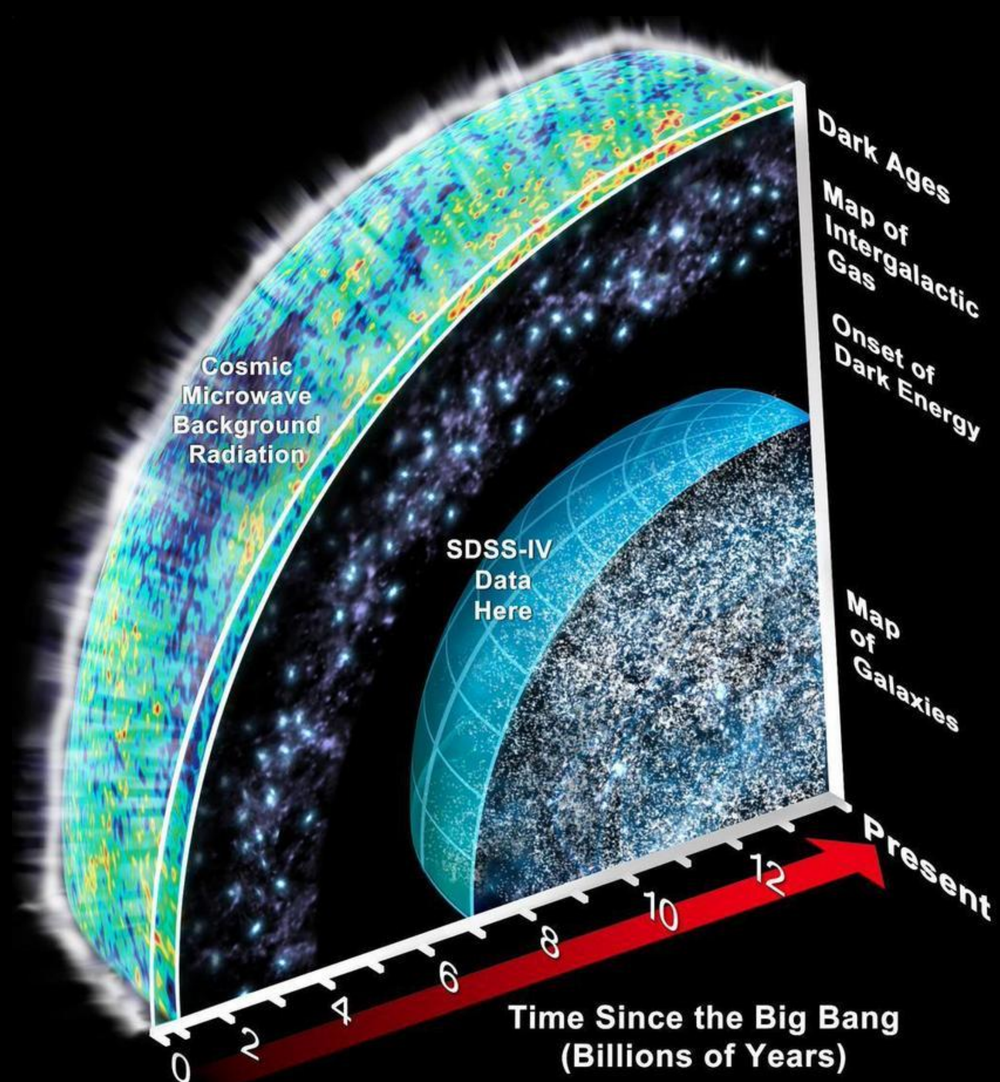


SDSS Main **SDSS LRGs**

BOSS LRGs **BOSS QSOs**

Ongoing:

SDSS-IV/eBOSS (2014-2020)



~7500 deg²

375,000 LRGs 0.6 < z < 0.8
260,000 ELGs 0.6 < z < 1

740,000 QSOs z < 2, Lyα z< 3.5

https://www.sdss.org/surveys/eboss/

Future:

DESI (operations 2020)

4m Mayall telescope, Kitt Peak, AZ
14,000 deg^2 , 10M spectra
LRGs z<1
[OII] ELGs 0.5<z<1.7
QSOs 1.2<z<3.5

Subaru PFS (operations 2022)

8.2m optical/NIR Mauna Kea
multi-object fiber spectrograph
1400 deg^2, 4M spectra
[OII] ELGs 0.8<z<2.4

SuMIRe Project
Subaru Measurement of Images and Redshifts
FIRST - 最先端研究開発支援プログラム -

4MOST (2020)

4m Vista telescope, Paranal
VIS+NISP deep instruments
4 deg^2 , 1M AGNs z<5
[OII] ELGs z<2

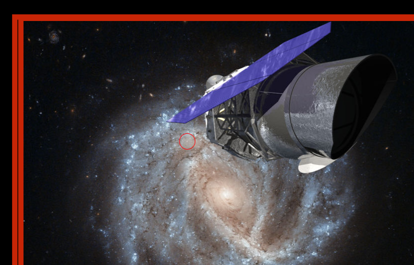
Euclid (launch 2022)

NIR slitless spectroscopy
1.2m telescope
VIS+NISP deep instruments
15,000 deg^2 , 50M spectra
Hα ELGs z<2

SKA (2020)

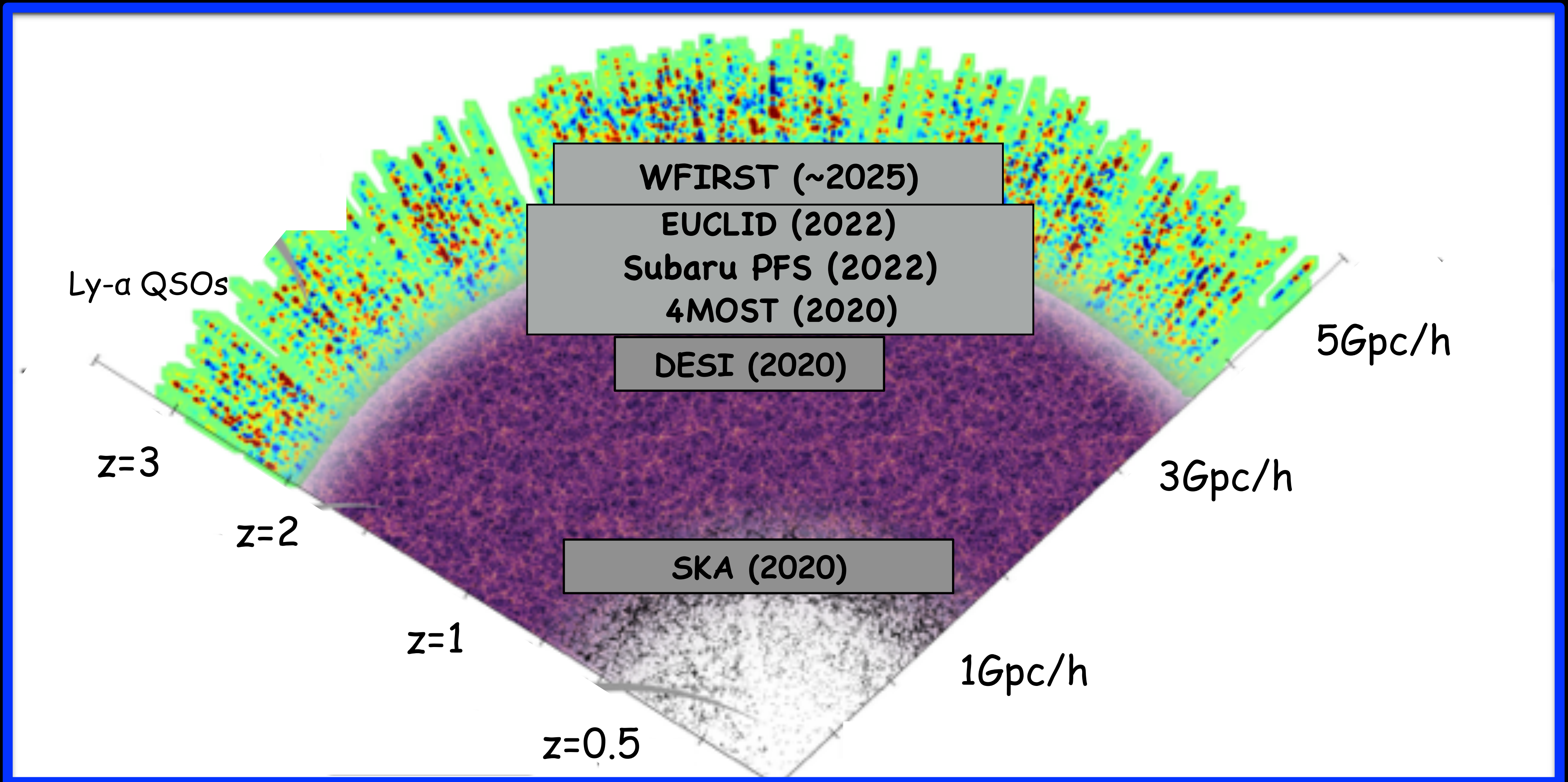
Fastest radio telescope ever built
South Africa+Australia
total area 1km^2
Galaxy clusters with 21-cm emission line at z>1

WFIRST (~2025)



2.4m telescope, 2200 deg^2
20M Hα ELGs 1<z<2
2M [OIII] ELGs 2<z<3
WL shapes 500M galaxies
and 40k massive clusters

and LSST (2023), ….

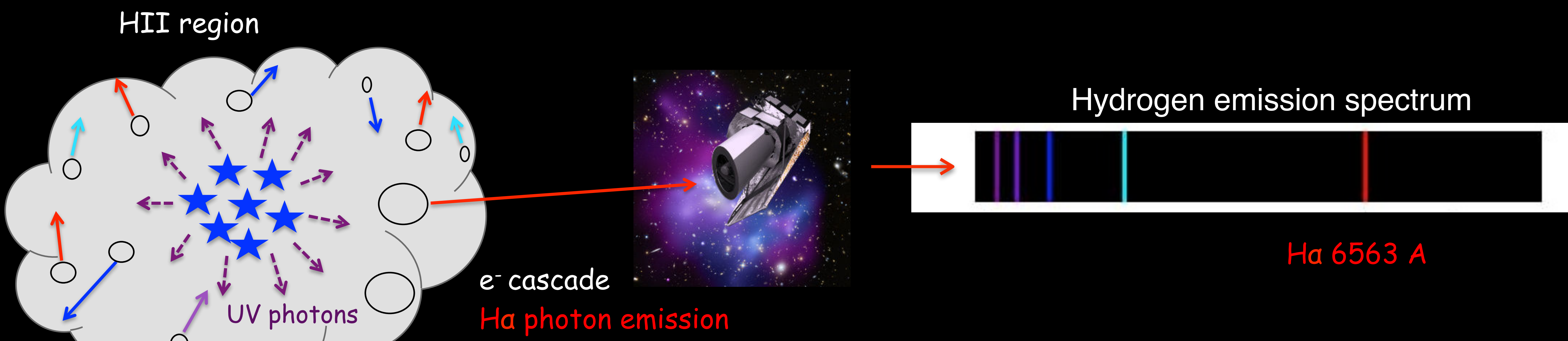


All these surveys will target emission line galaxies (ELGs) out to z~2 to trace the BAO feature in their clustering signal, deliver 3D maps of the Universe with unprecedented accuracy, measure the growth rate of structure and unveil the nature of Dark Energy.

Understanding how to best measure and precisely model the ELG clustering properties is crucial for the optimal exploitation of near-future missions.

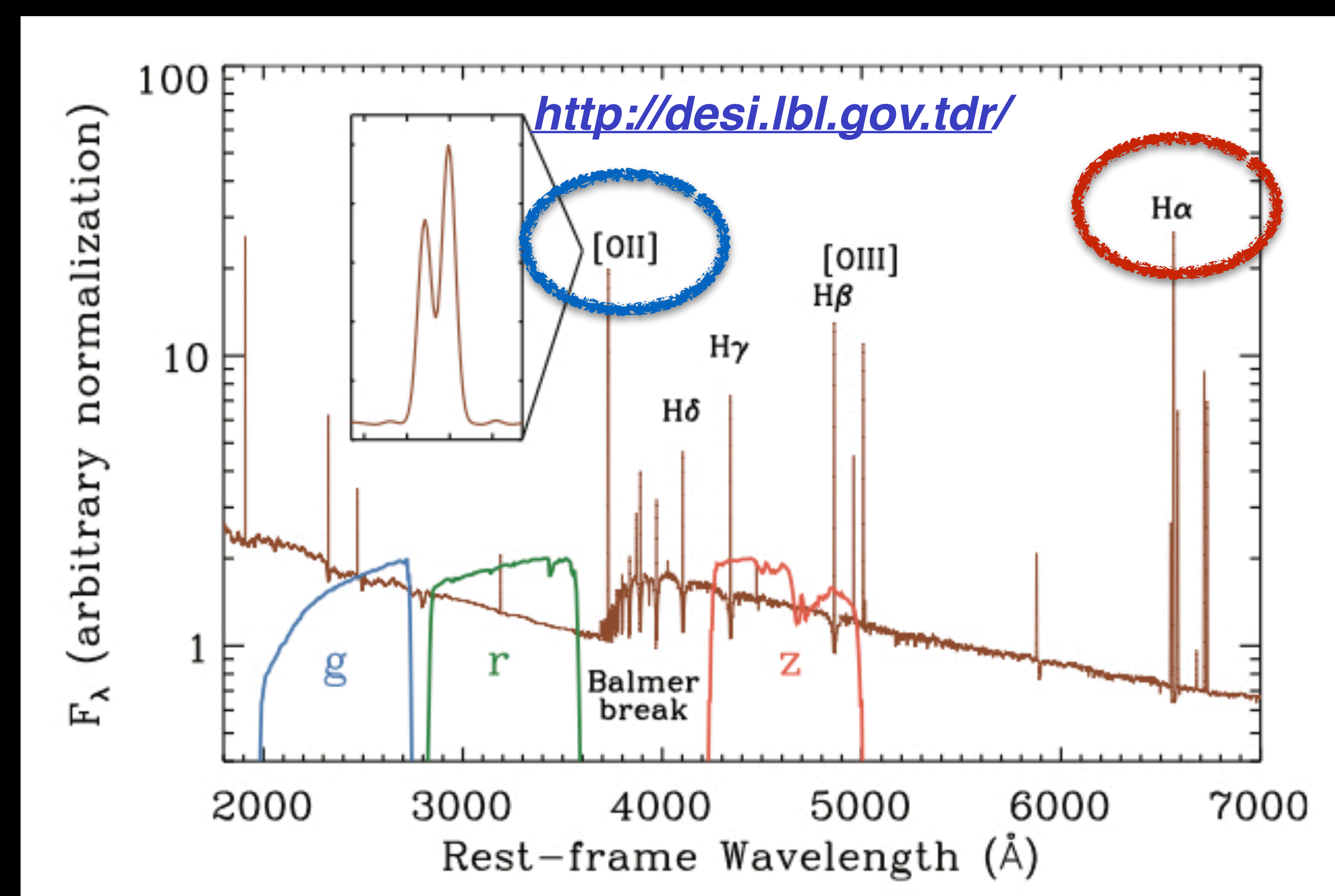
Emission line galaxies

In HII nebular regions young, massive stars photoionize the surrounding gas particles



[OII] doublet (3727-3729 A) is the strongest feature in UV

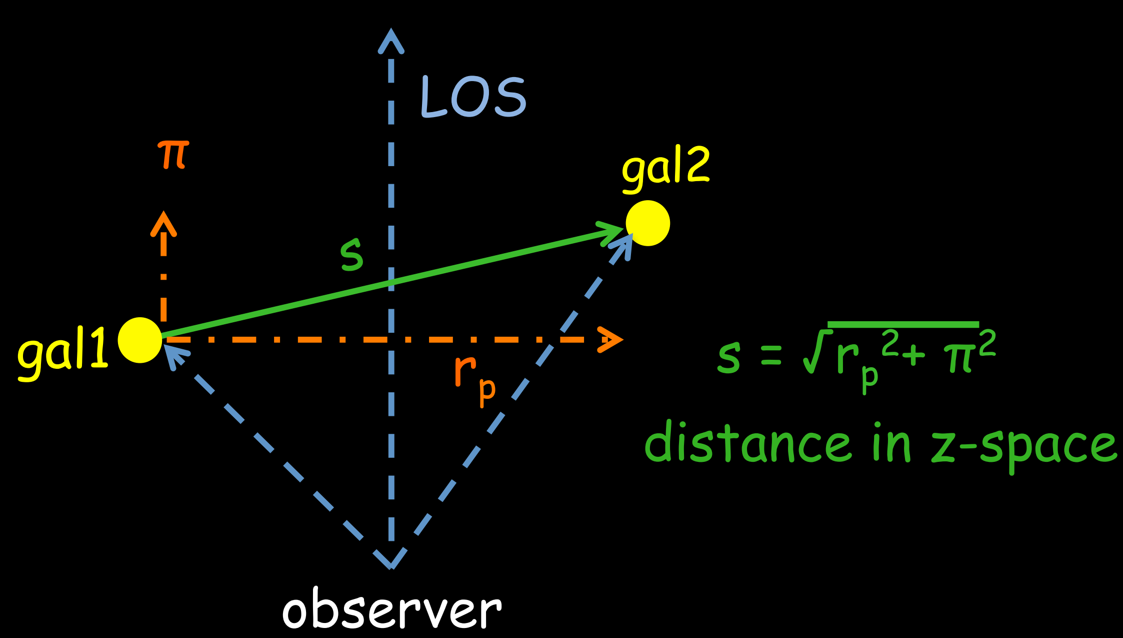
Hα is the most prominent line in the IR, preferred SFR tracer

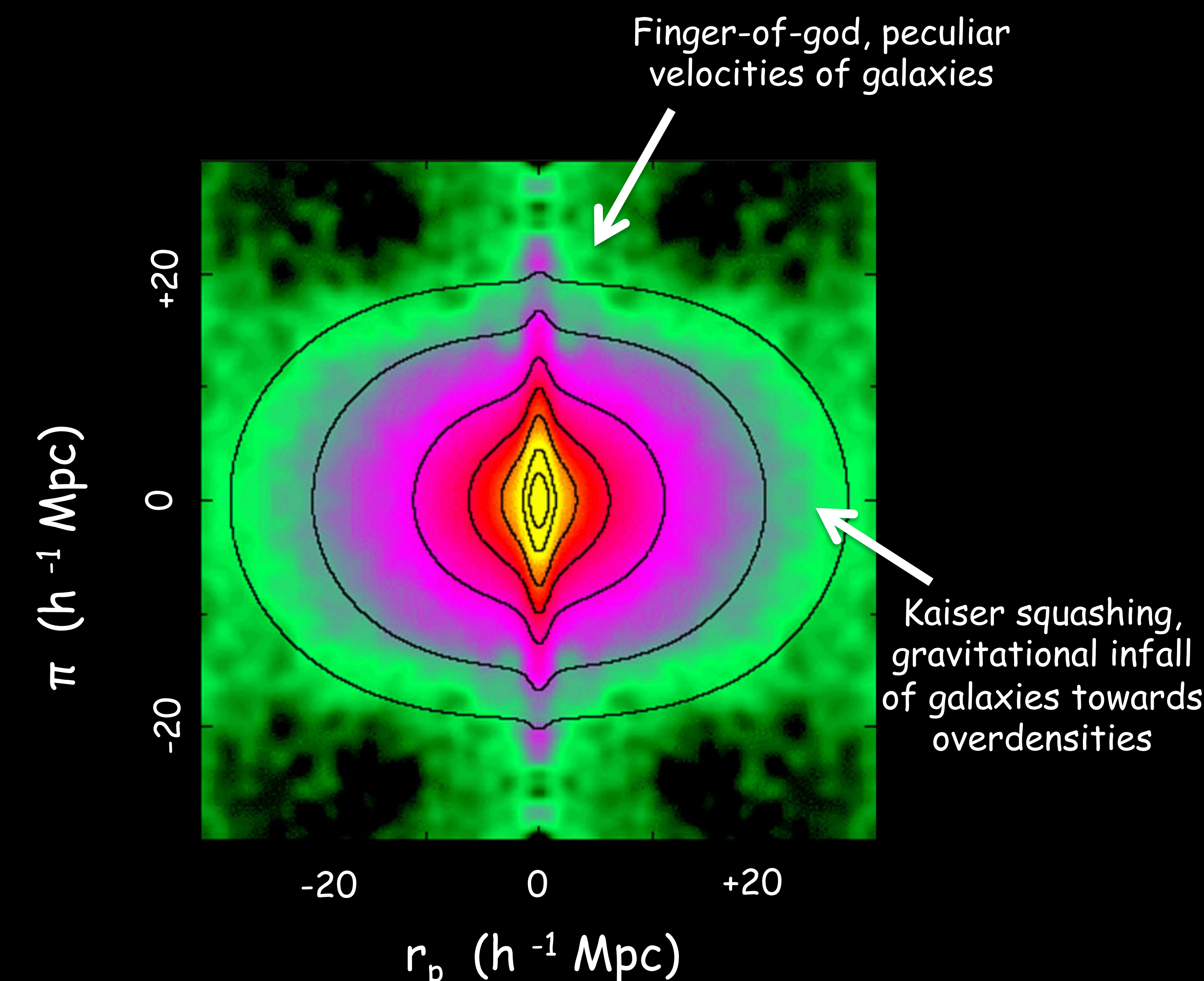


2-point correlation functions (2PCF)

Excess probability over randoms to find a pair of galaxies in two volume elements *dV1* and *dV2*, with mean number density *n*, separated by a distance *s*:

$$dP = n^2[1+ [1+\xi(s)]_1 dV_2$$





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 $\xi(r_p, \pi)$ in Legendre polynomial we find the 2PCF multipoles:

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

l=0 monopole, spherical average

l=2 quadrupole, satellites

The projected 2PCF mitigates the peculiar velocity (RSD) contribution:

$$\boxed{w_p(r_p) = 2 \int_{0}^{\infty} \xi(r_p, \pi)\, d\pi}$$

real-space measurement useful to estimate galaxy bias

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

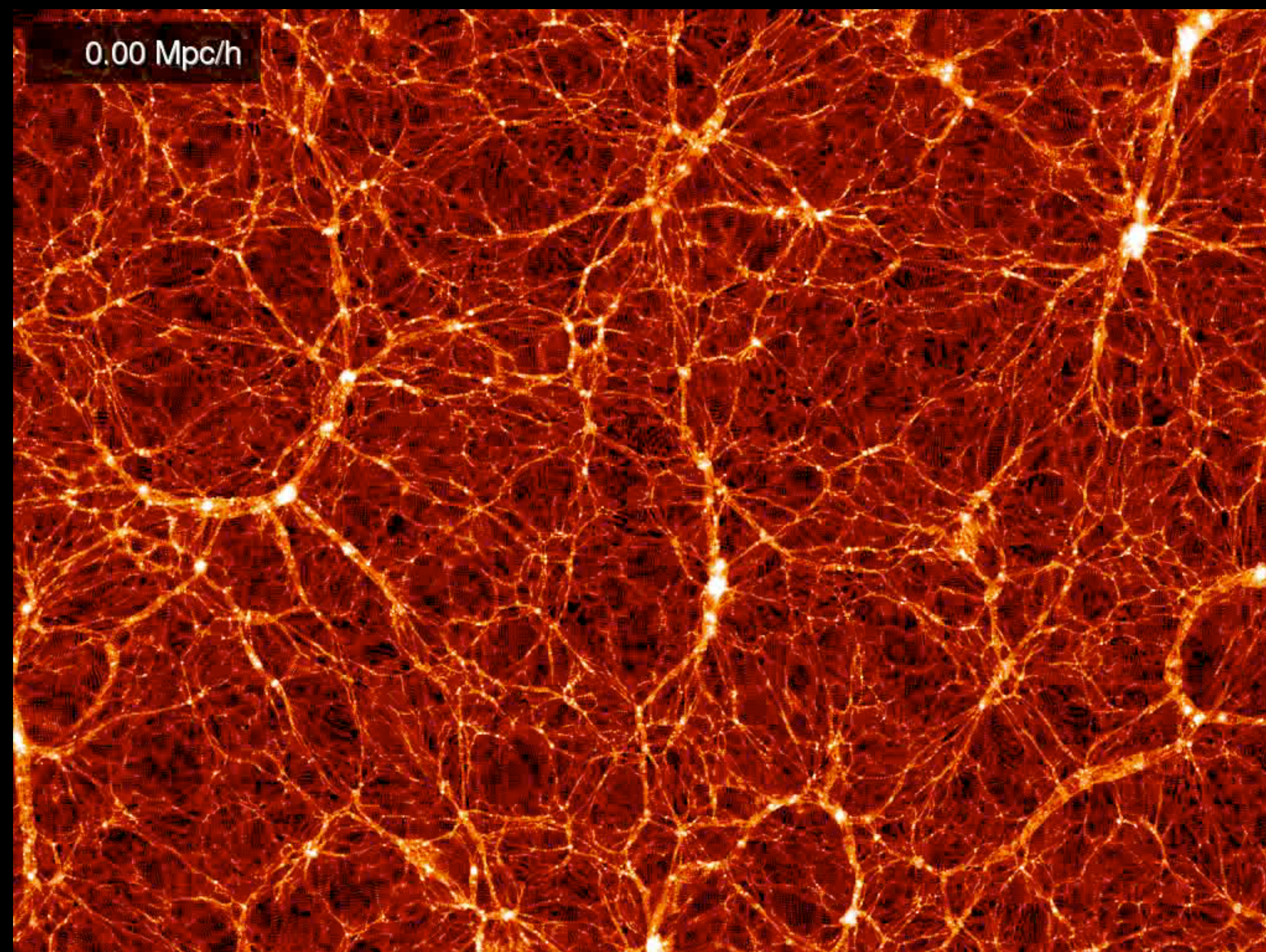
Each 2PCF is more sensitive to a physical process or effect happening on a particular scale.

N-body DM-only cosmological simulations

Computationally expensive: solve equation of motion of N particle interacting gravitationally

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

current depth:



A flight through SMD slices

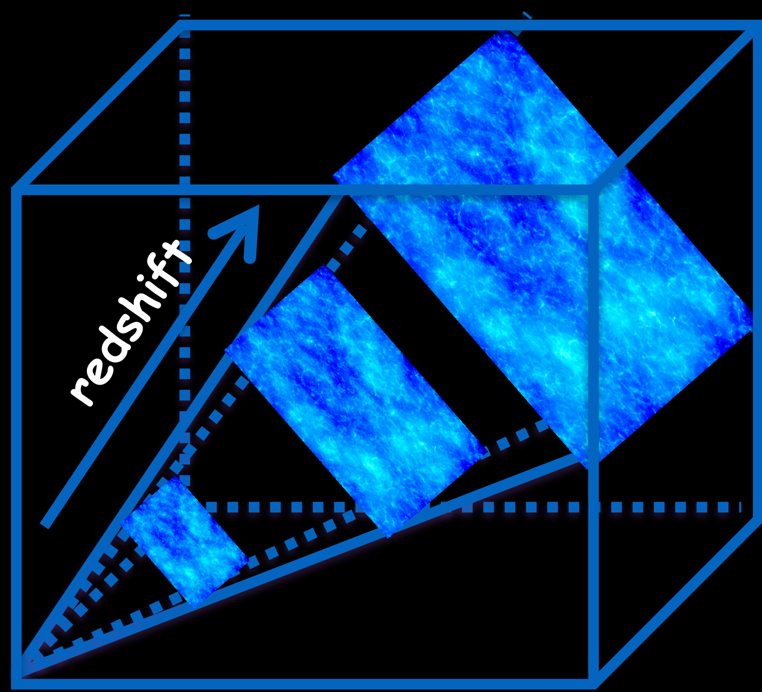
MultiDark
Multimessenger Approach for Dark Matter Detection

cosmosim.org

	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}

Light-cones

We build high-fidelity light-cones using the SUrvey GenerAtoR code applied to any simulation volume



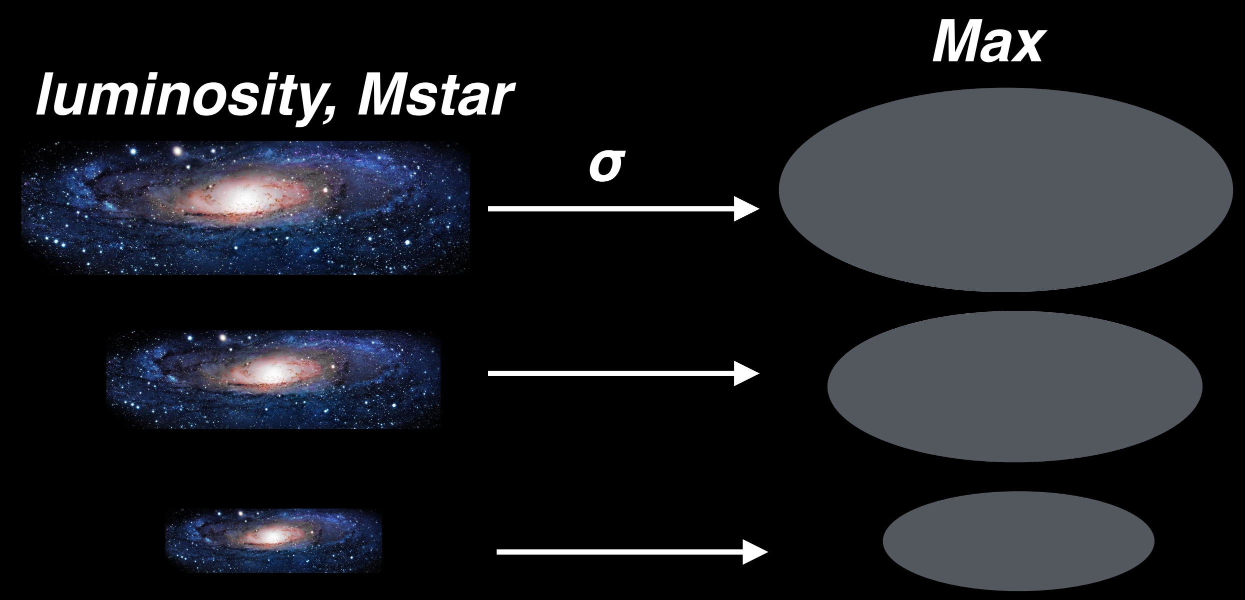
Rodríguez-Torres, +, Favole et al. 2016, MNRAS 460 1173

More realistic than single slice:
it predicts full redshift evolution and density fluctuations observed in real data

Galaxy-halo connection

I. SubHalo Abundance Matching (SHAM)

More luminous galaxies live in more massive haloes



Need to modify SHAM to account for ELG stellar mass incompleteness (*Comparat et al. 2013, MNRAS 433 1146*):

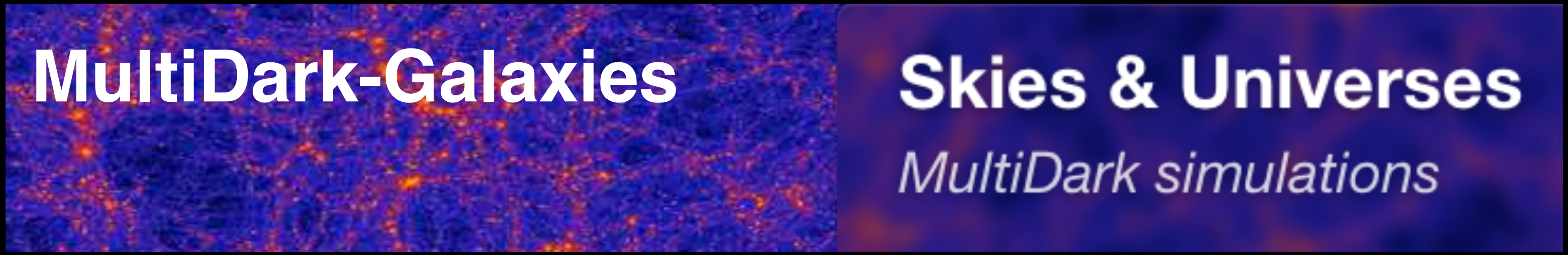
$$\boxed{P(V_{max}, \sigma_V, f_{sat}) = f_{sat}\, G_{sat}(V_{max}, \sigma_V, f_{sat}) + (1-f_{sat})\, G_{cen}(V_{max}, \sigma_V, f_{sat})}$$

Favole et al. 2016, MNRAS 461 3421
Rodríguez-Torres et al. 2017, MNRAS 468 728

II. Semi-analytic models of galaxy formation (SAMs)

Approximate, analytic techniques to populate DM haloes with observed galaxies. Less expensive than N-body and very informative on baryonic galaxy properties.

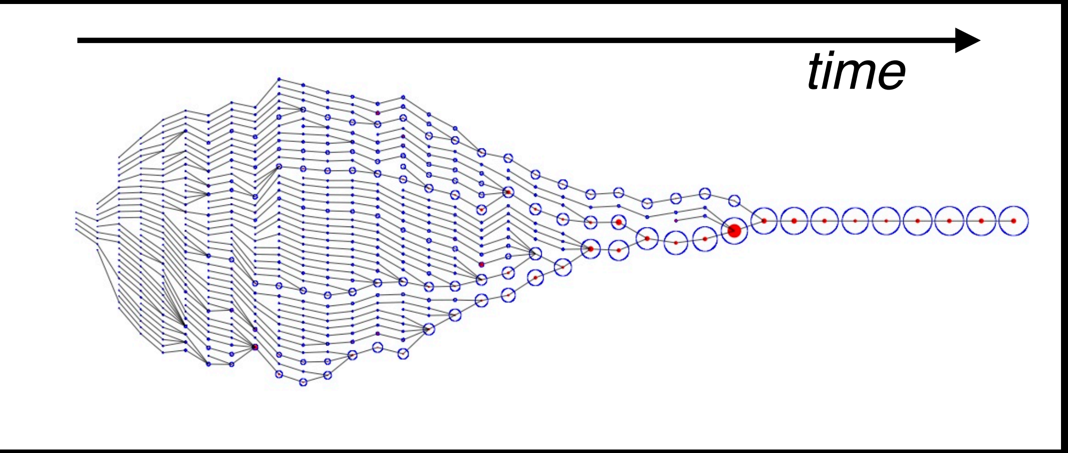
Phenomenological recipes for key processes that are thought to shape galaxy formation (e.g. gas accretion and cooling, star formation and stellar feedback, chemical enrichment, black hole formation and feedback, halo merging history, etc ...) are implemented within N-body simulations by calibrating free parameters to match observations.



Knebe et al. 2018, MNRAS 474 5206 [***skiesanduniverses.org***]

MDPL2 volumes + 3 different SAMs run on top:

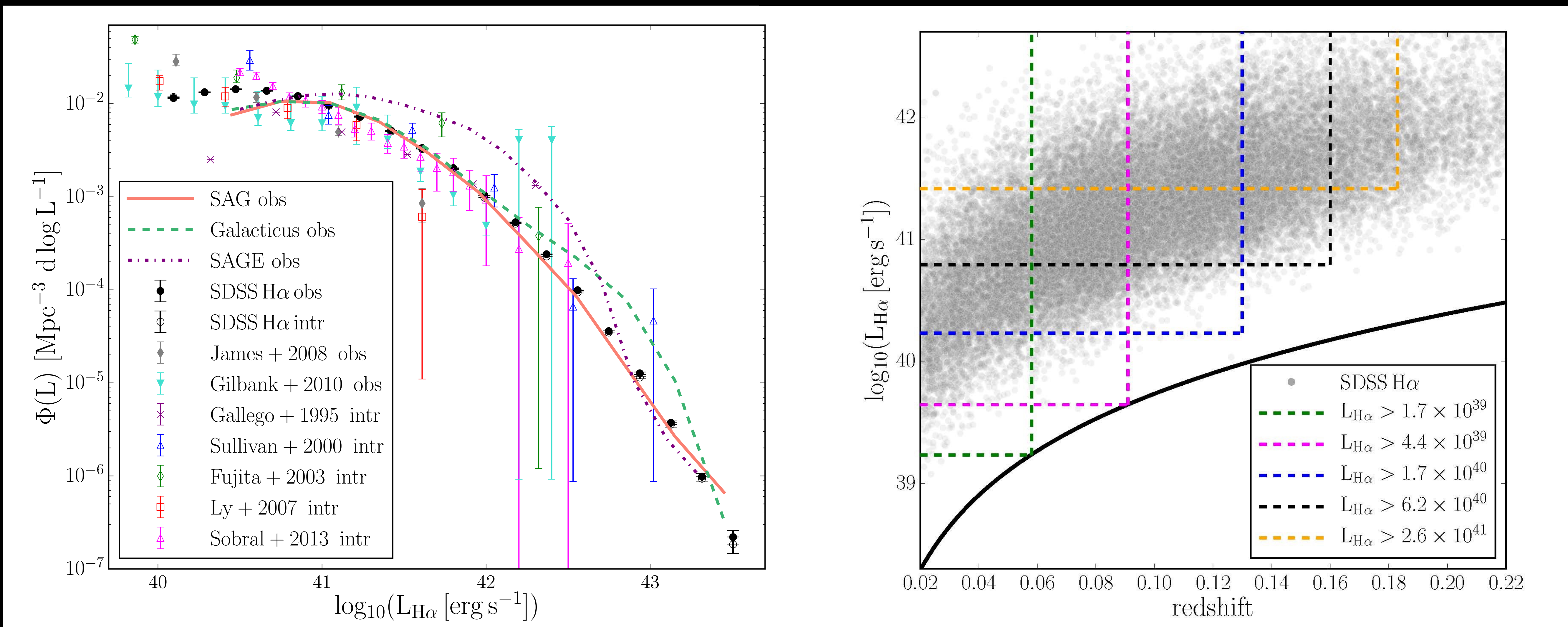
SAG - *Cora et al. 2018, MNRAS 479 2*
SAGE - *Croton et al. 2016, ApJS 222 22*
Galacticus - *Benson et al. 2012, AJ 17 175*



Results

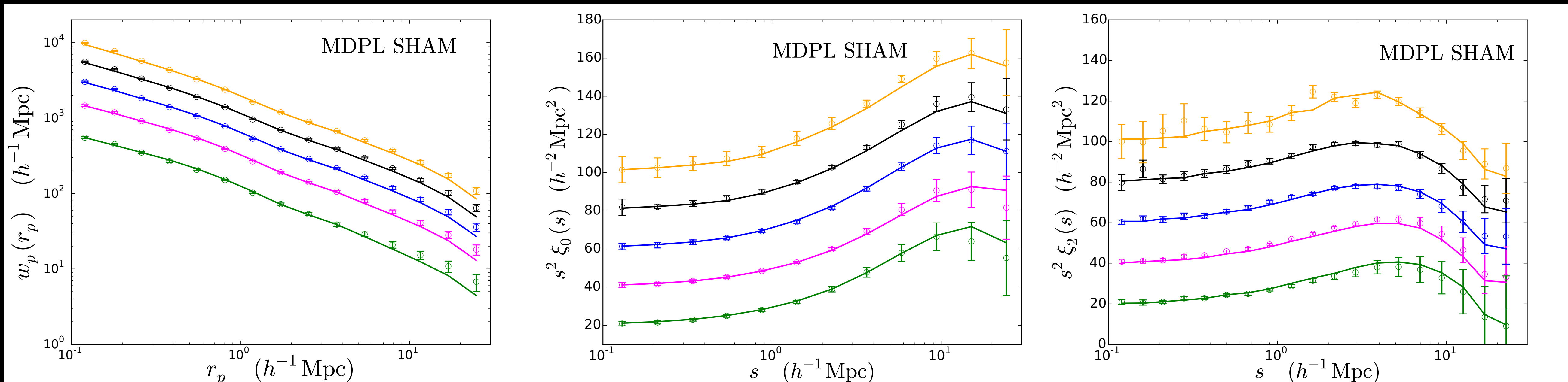
I. SDSS Hα ELGs at 0.02<z<0.22 (z~0.1)

~250,000 SDSS MPA-JHU DR7 Hα spectra with r < 17.77, flux>2×10^{-16} erg/cm²/s (Euclid forecasts) over 0.02<z<0.22:



Favole et al. 2019, on arXiv soon

MultiDark 1Gpc/h light-cone + modified SHAM prediction:



More luminous galaxies are more strongly clustered, they live in more massive haloes with higher V_{max} and lower satellite fraction

We find:

$z_{\max}$	$L^{min}_{\mathrm{H}\alpha}$ [erg s^{-1}]	N_{gal}	$\bar{n}_g$ [$10^{-3}h^3\mathrm{Mpc}^{-3}$]	Vol [$10^6 h^{-3}\mathrm{Mpc}^3$]	f_{sat} [%]	V_{peak} [km s^{-1}]	M_h [$10^{12}\,h^{-1}\mathrm{M}_\odot$]
0.058	1.7×10^{39}	32623	9.11	3.58	35.8±0.1	272±129	0.32±0.02
0.091	4.4×10^{39}	78914	5.66	13.95	30.0±0.4	312±103	0.65±0.03
0.130	1.7×10^{40}	116280	2.92	39.81	23.1±0.7	342±96	1.52±0.09
0.160	6.2×10^{40}	111663	1.54	72.71	19.1±0.4	286±135	2.91±0.19
0.183	2.6×10^{41}	55536	0.52	106.97	17.2±0.5	308±144	5.47±0.35

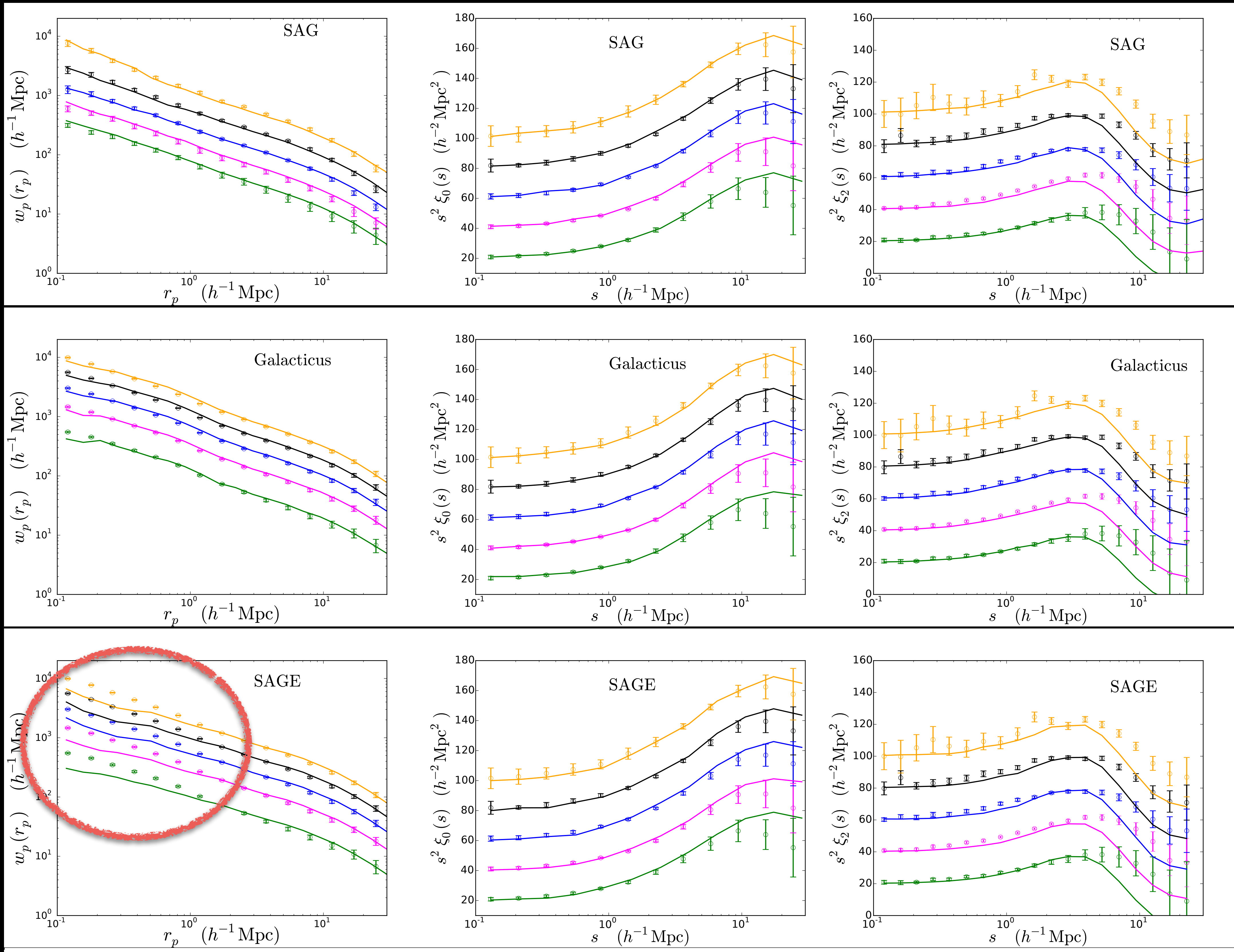
M_{halo}~(2.2 +/- 0.1)x10^{12} M_{sun}/h

f_{sat}=(25.0 +/- 0.4)% mean bias~1

Favole et al. 2019, on arXiv soon

MultiDark-Galaxies SAM predictions:

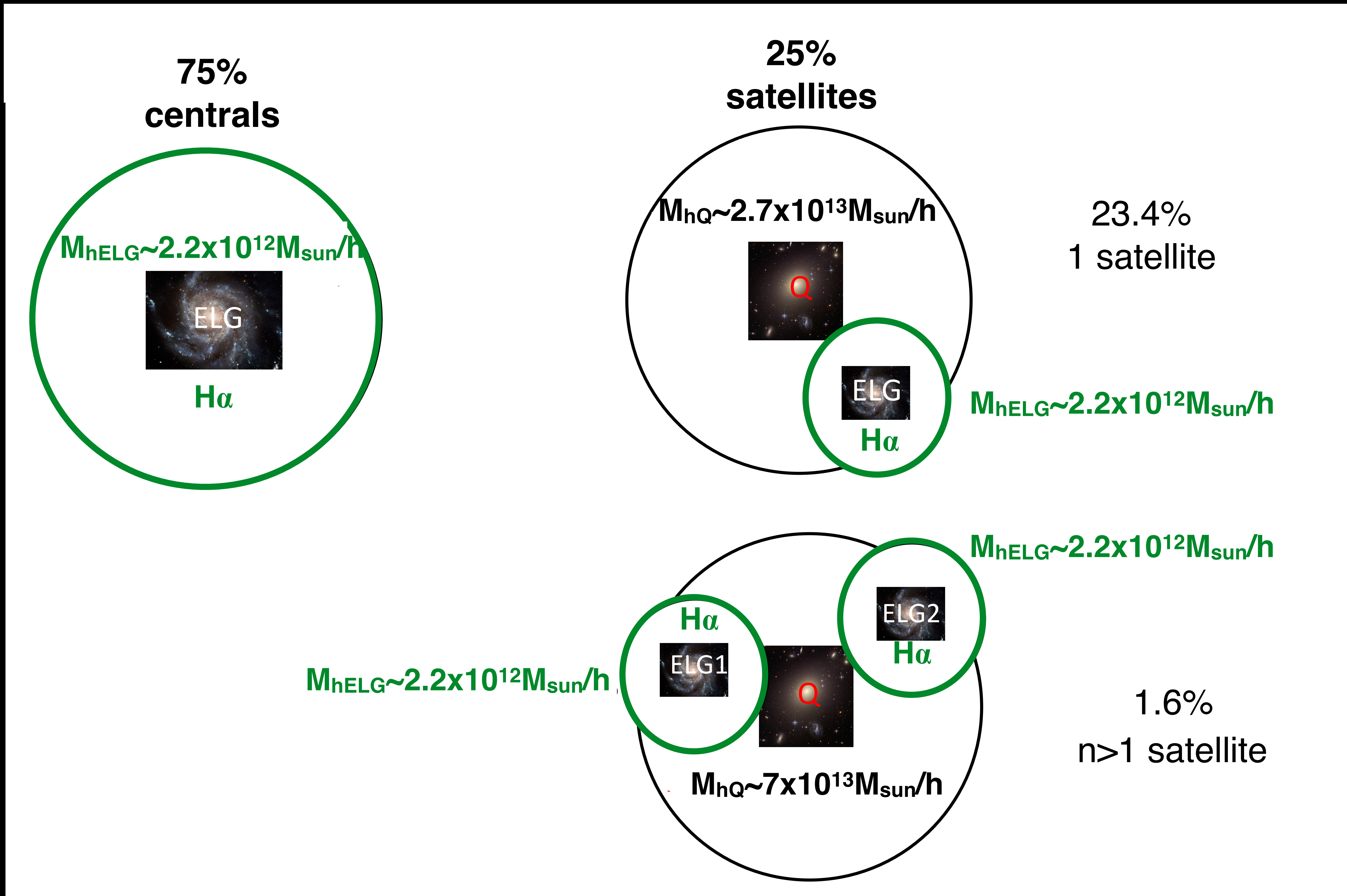
SAMs are applied photometric + spectroscopic data selection



SAGE lacks satellites

Favole et al. 2019, on arXiv soon

SDSS Hα ELG halo occupation distribution at z~0.1 (average among the 5 samples):

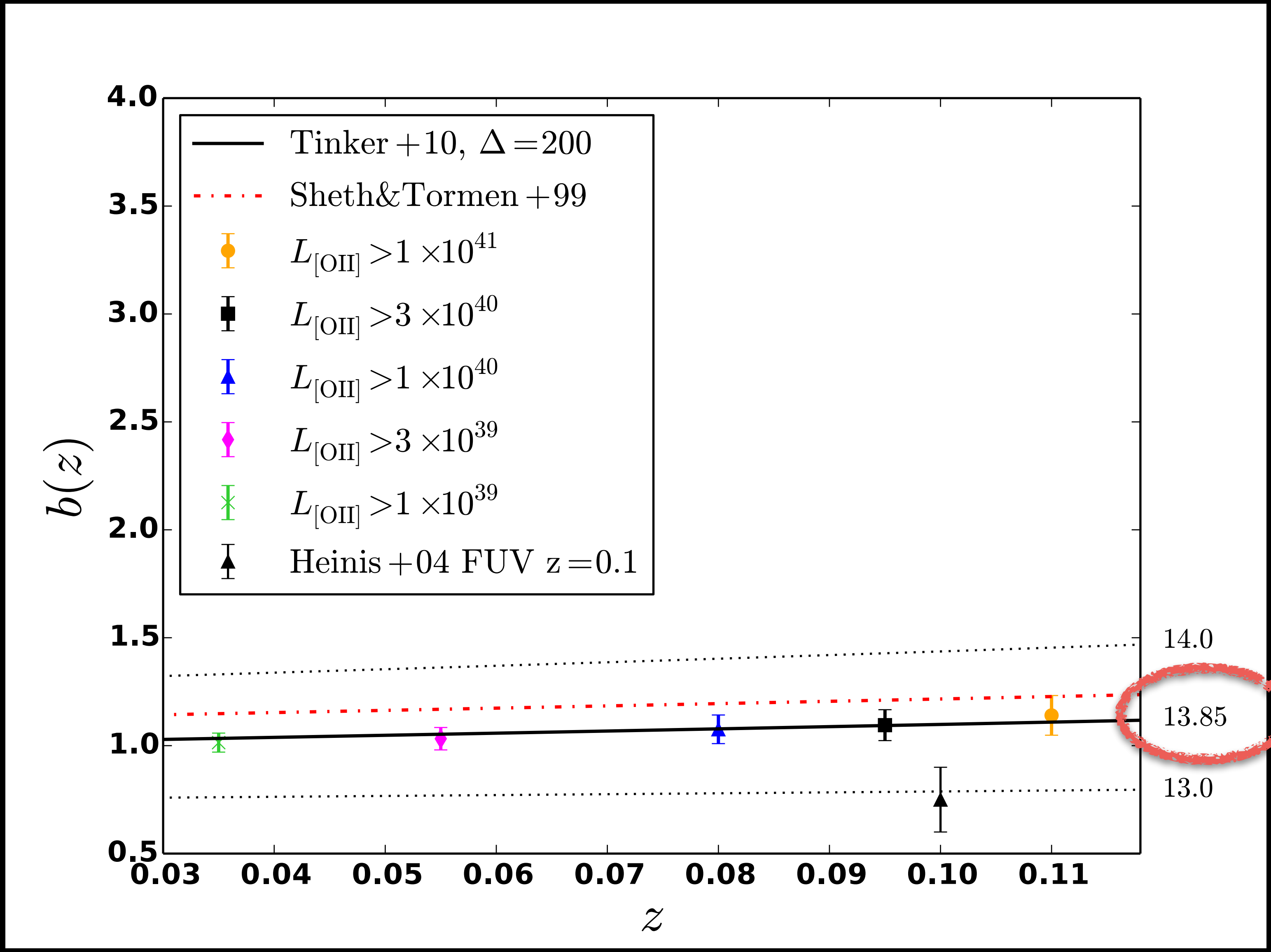


Favole et al. 2019, on arXiv soon

II. SDSS [OII] ELGs at z~0.1

~430,000 SDSS MPA-JHU [OII] spectra with r < 17.77, flux>3×10^{-16} erg/cm^2/s at 0.02<z<0.22:

We find clustering results and HOD fully consistent with Hα emitters at z~0.1



More luminous galaxies are more clustered, live in more massive haloes with lower satellite fraction.

[OII] ELG bias driven by the central halo hosting the satellite ELG. The central galaxy is quiescent.

Bias is mildly correlated with both L[OII] and z

Favole et al. 2017, MNRAS 472 550

We find:

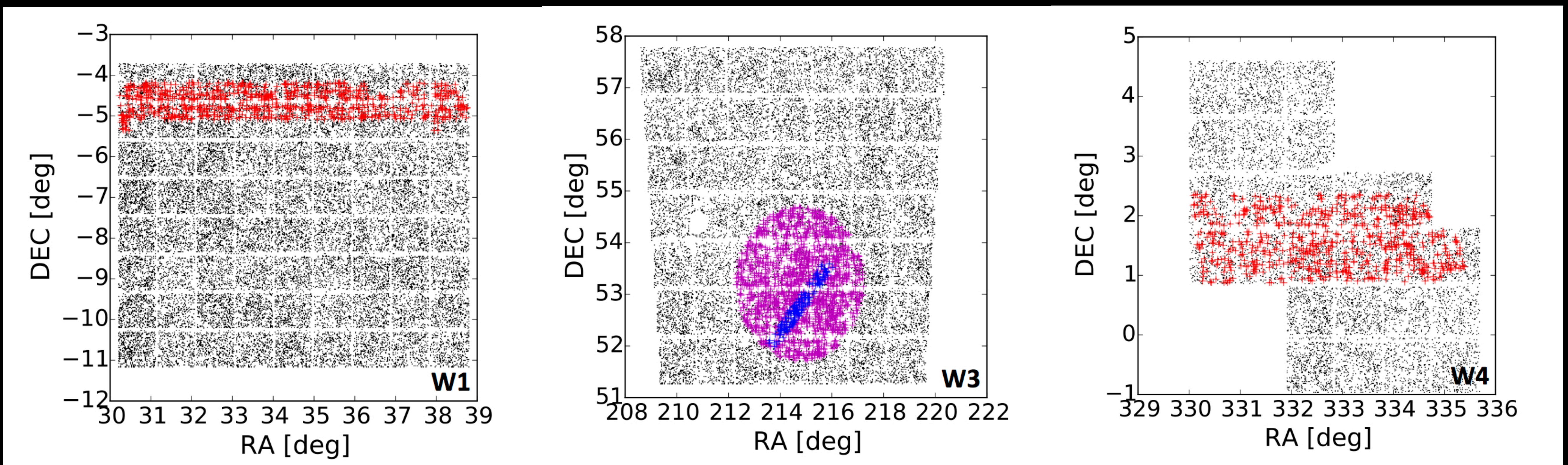
M_{halo}=(2.2 +/- 0.1)x10^{12} M_{sun}/h

f_{sat}=(24.2 +/- 0.4)%   mean bias~1

III. g-selected [OII] ELGs at 0.6<z<1 (z~0.8)

~4000 spectra of [OII] ELGs at 0.6<z<1 from BOSS, VIPERS, DEEP2 in CFHT-LS Wide fields

g-band magnitude cuts to select bright [OII] emitters with low dust

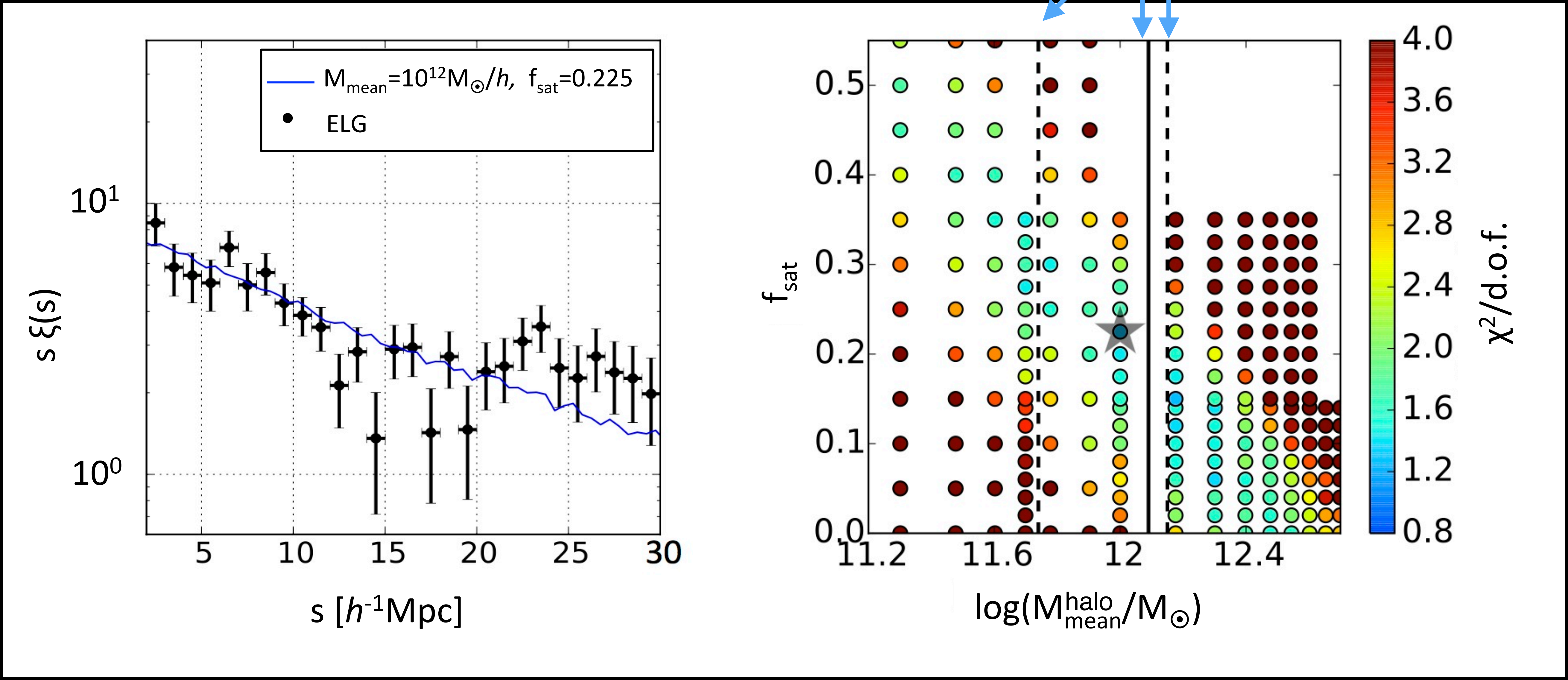


Favole et al. 2016, MNRAS 461 3421

VIPERS: 5.478 deg^2 in W1; 5.120 deg^2 in W4
BOSS: 6.67 deg^2 in W3
DEEP2: 0.5 deg^2 in W3

Combined clustering+weak lensing analysis using modified SHAM:

independent WL measurements



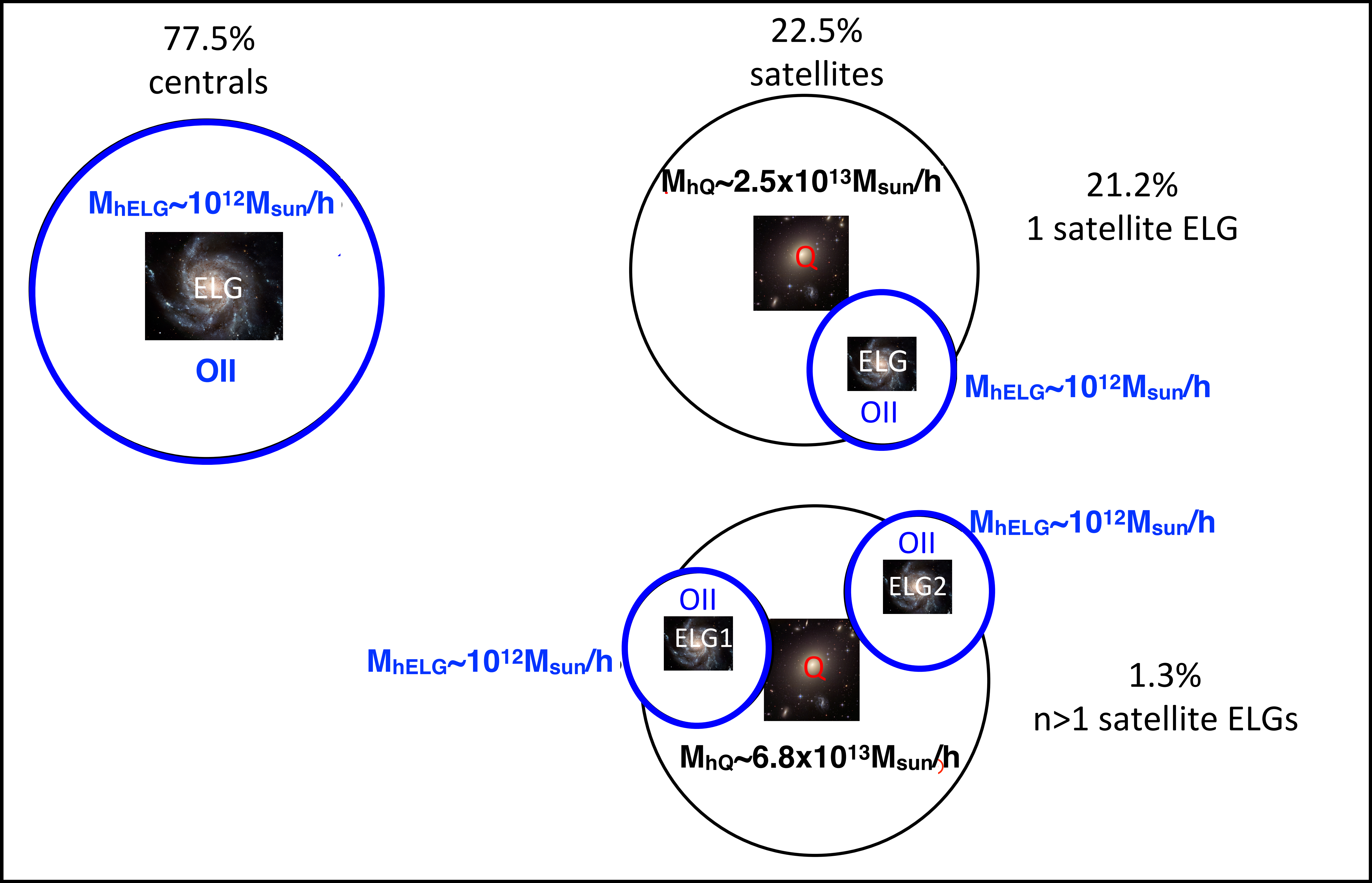
Favole et al. 2016, MNRAS 461 3421

We find:

M_{halo}=(1 +/- 0.5)x10^{12} M_{sun}/h

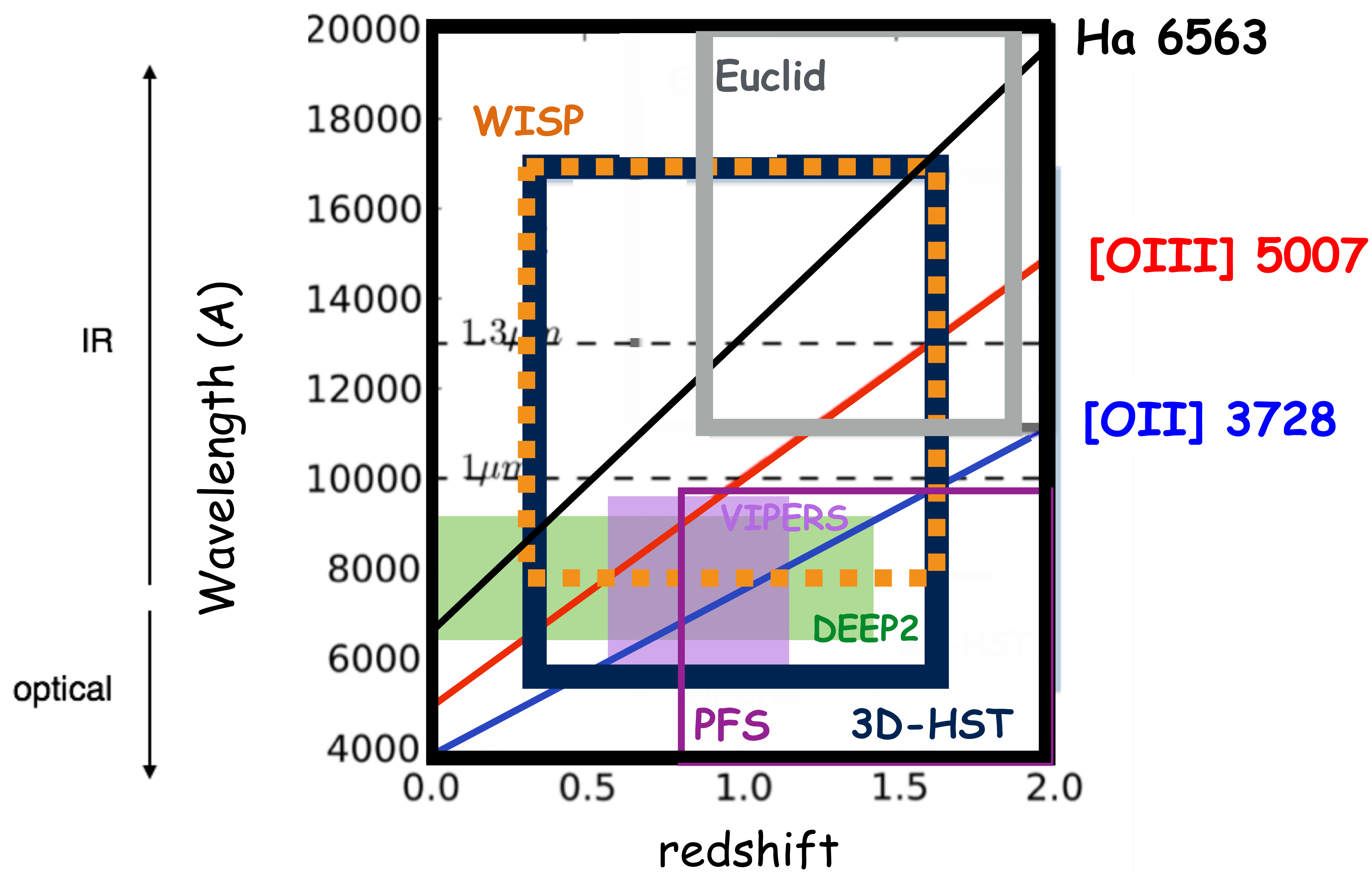
f_{sat}=(22.5 +/- 2.5)% **mean bias~1**

[OII] ELG halo occupation distribution at z~0.8:



Favole et al. 2016, MNRAS 461 3421

IV. WISP/HST Hα emitters at 0.9 < z < 1.6 (z~1.3)



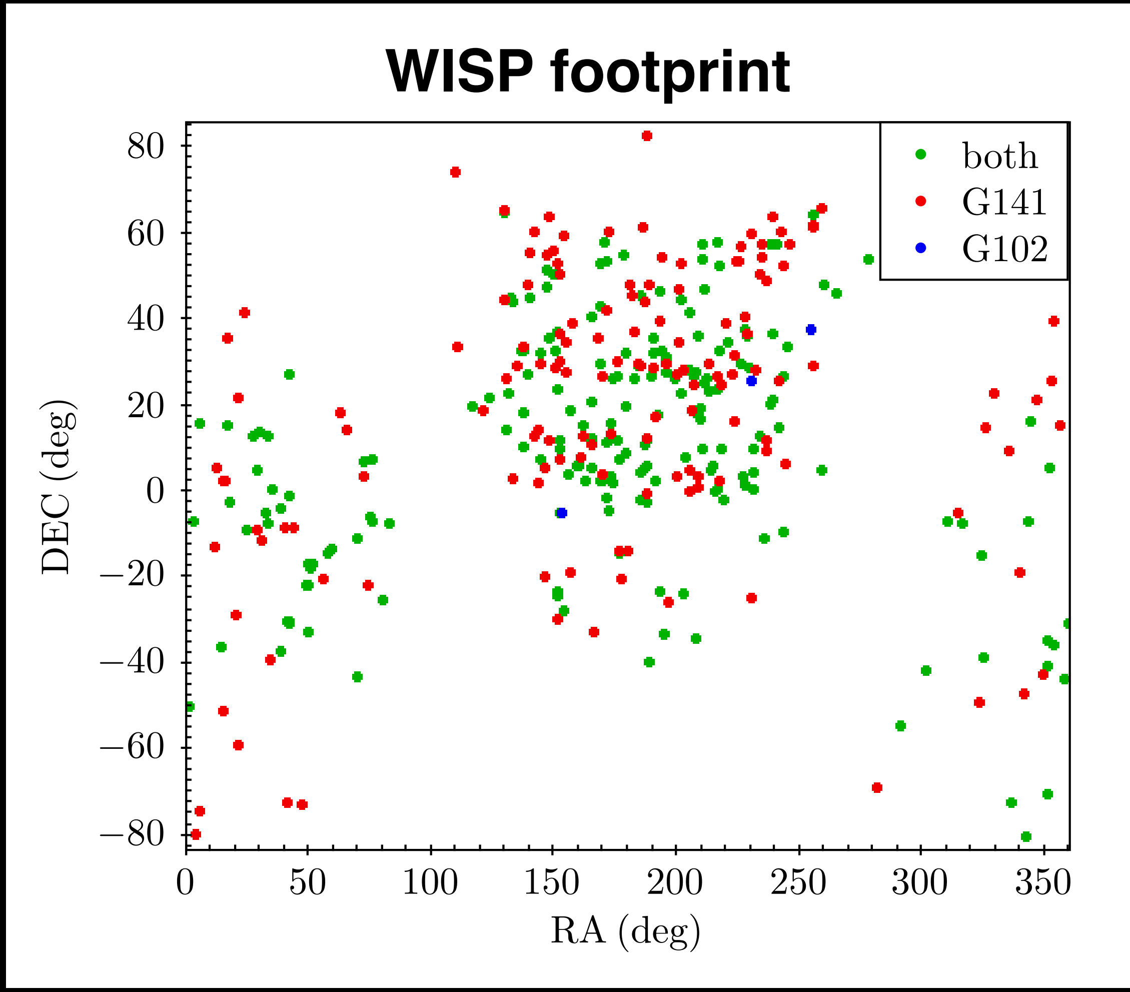
In preparation to Euclid

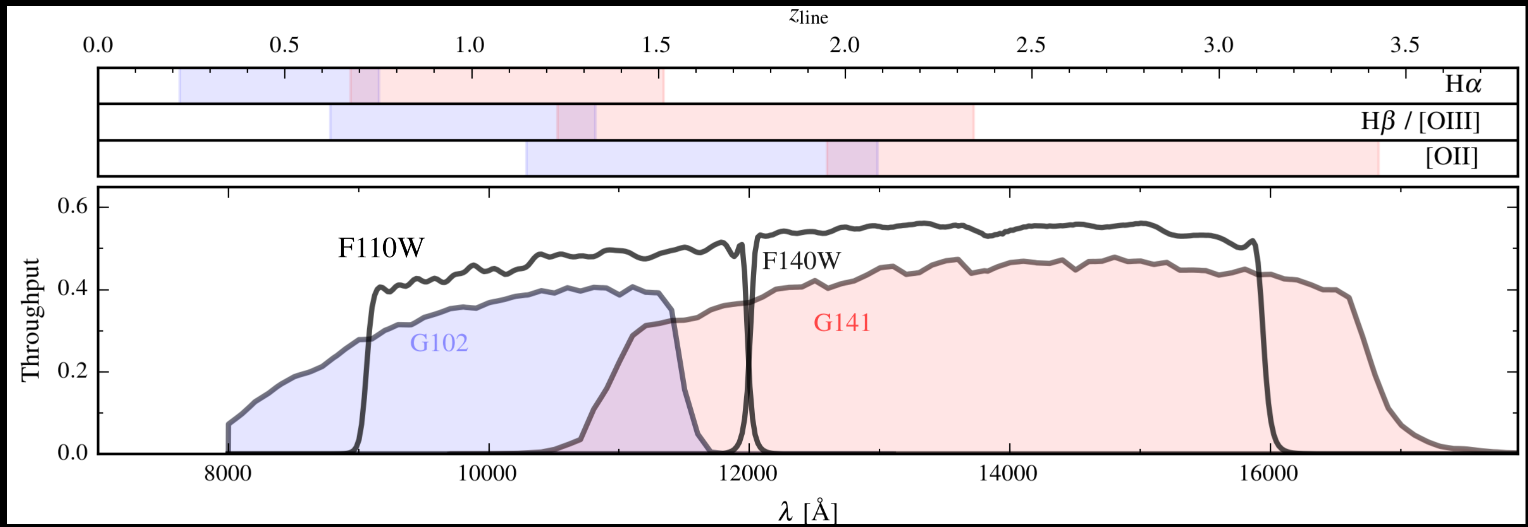
Euclid

Grisms: 1 blue (0.92 - 1.25μm, R~380); 3 red (1.25 - 1.85μm, R~380)
FoV~15,000deg², NISP+VIS, Imaging in Y, J, H down to 24 AB mags

WISP

Pure parallel HST programme, FoV~0.37deg²
Grisms: G102 (0.8 - 1.17μm, R~210); G141 (1.11 - 1.67μm, R~130)
Imaging in J, H bands with broadband filters F110W, F140W, F160W
Deeper than Euclid in blue, key for constraining faint-end LF and SF history



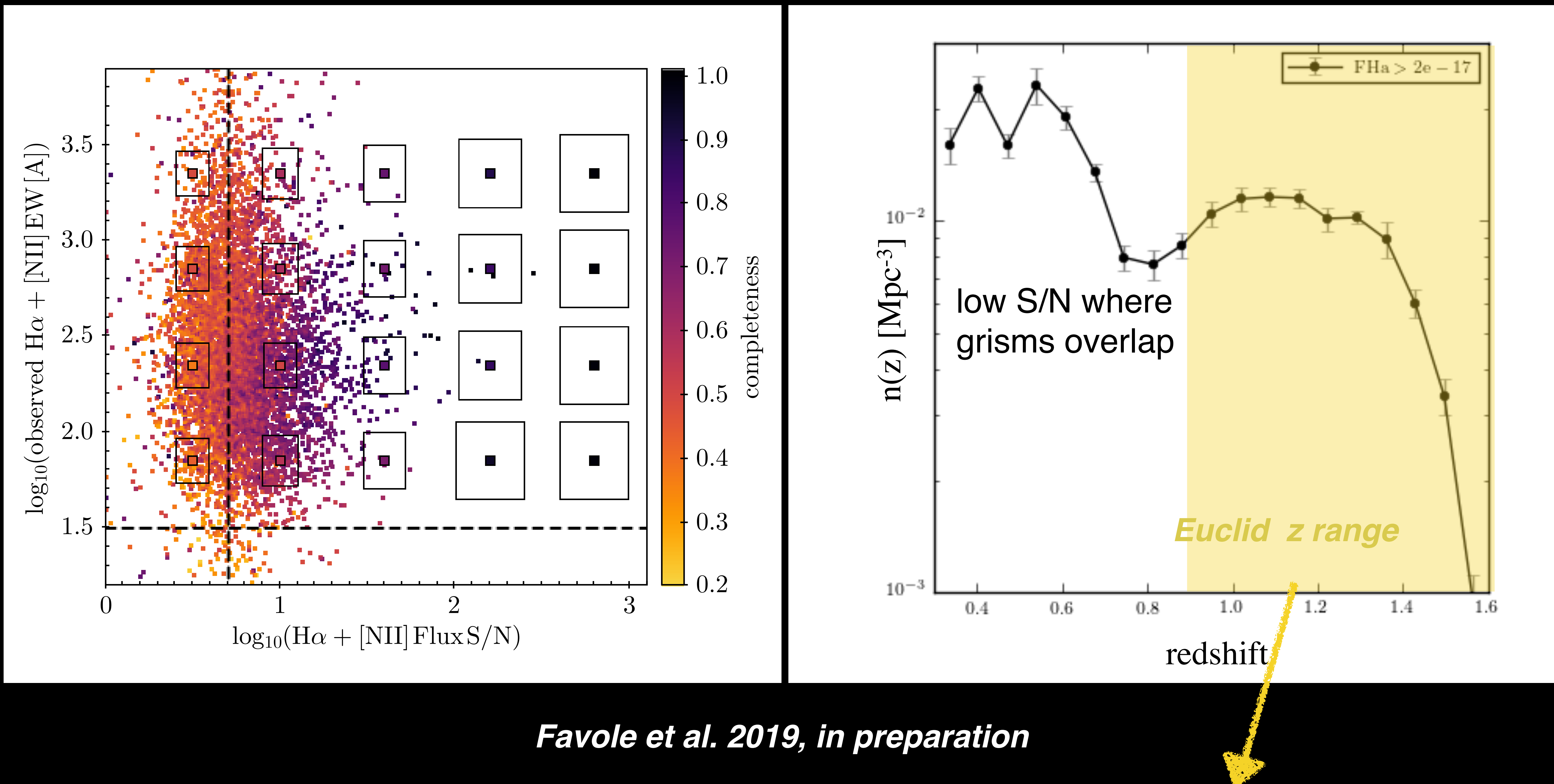


378 reduced fields, very patchy footprint
Aeff ~ 0.35 deg² , difficult mask for clustering

Each field is ~ 1Mpc/h on a side at z=1.6

Only small scale clustering can be measured !

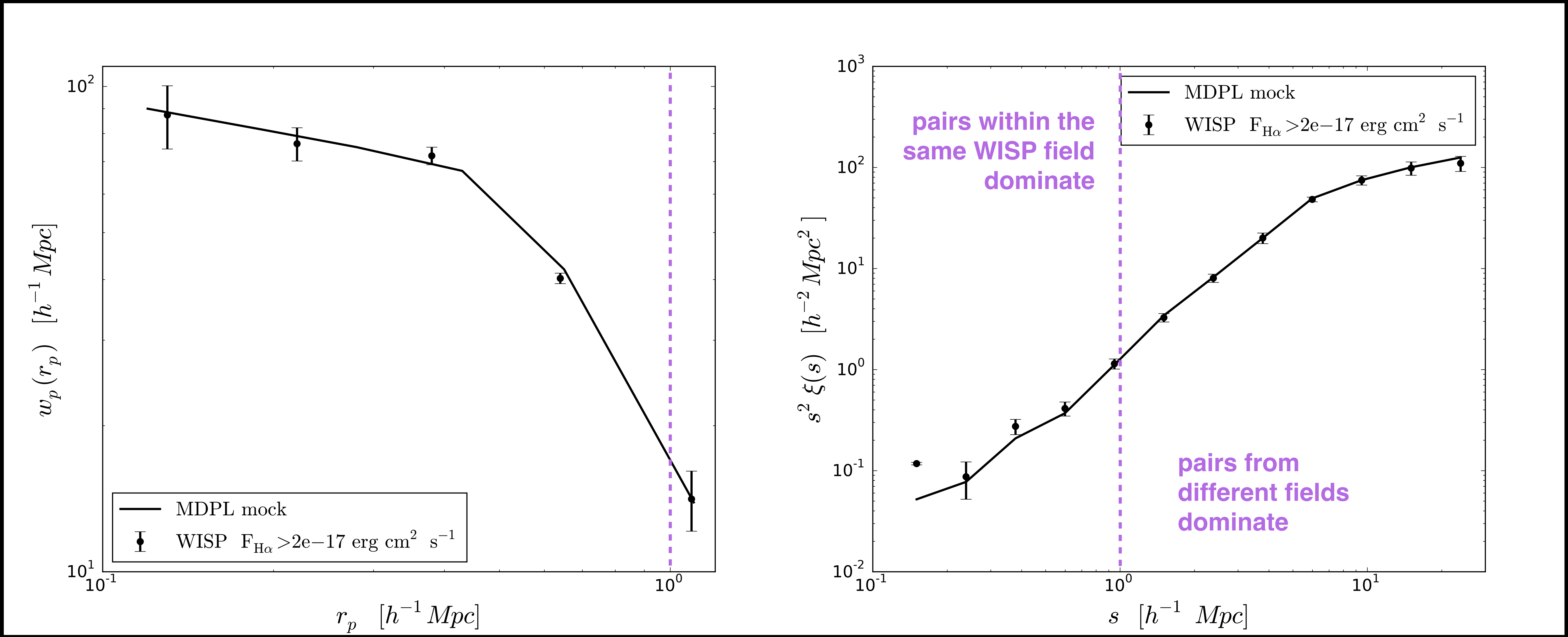
4079 Hα emitters over 0.3< z <1.6 with flux > 2e-17erg cm^{-2} s^{-1}
completeness: EW_{obs} > 40A, S/N > 5 *(Colbert+13, arXiv: 1305.1399)*
27% of the sample is [NII] contaminated, i.e. $L_{H\alpha+[NII]} = L_{H\alpha} / 0.73$



Favole et al. 2019, in preparation

At the Euclid flux> 2e-16 erg cm^{-2} s^{-1} and redshift range of interest 0.9< z <1.6
we observe 2188 Hα+[NII]/deg^2 and 4122 deg^{-2} completeness corrected *(credit: Scarlata)*

At z~1.6 a WISP field is ~1Mpc on a side in Planck+15 cosmology



Favole et al. 2019, in preparation

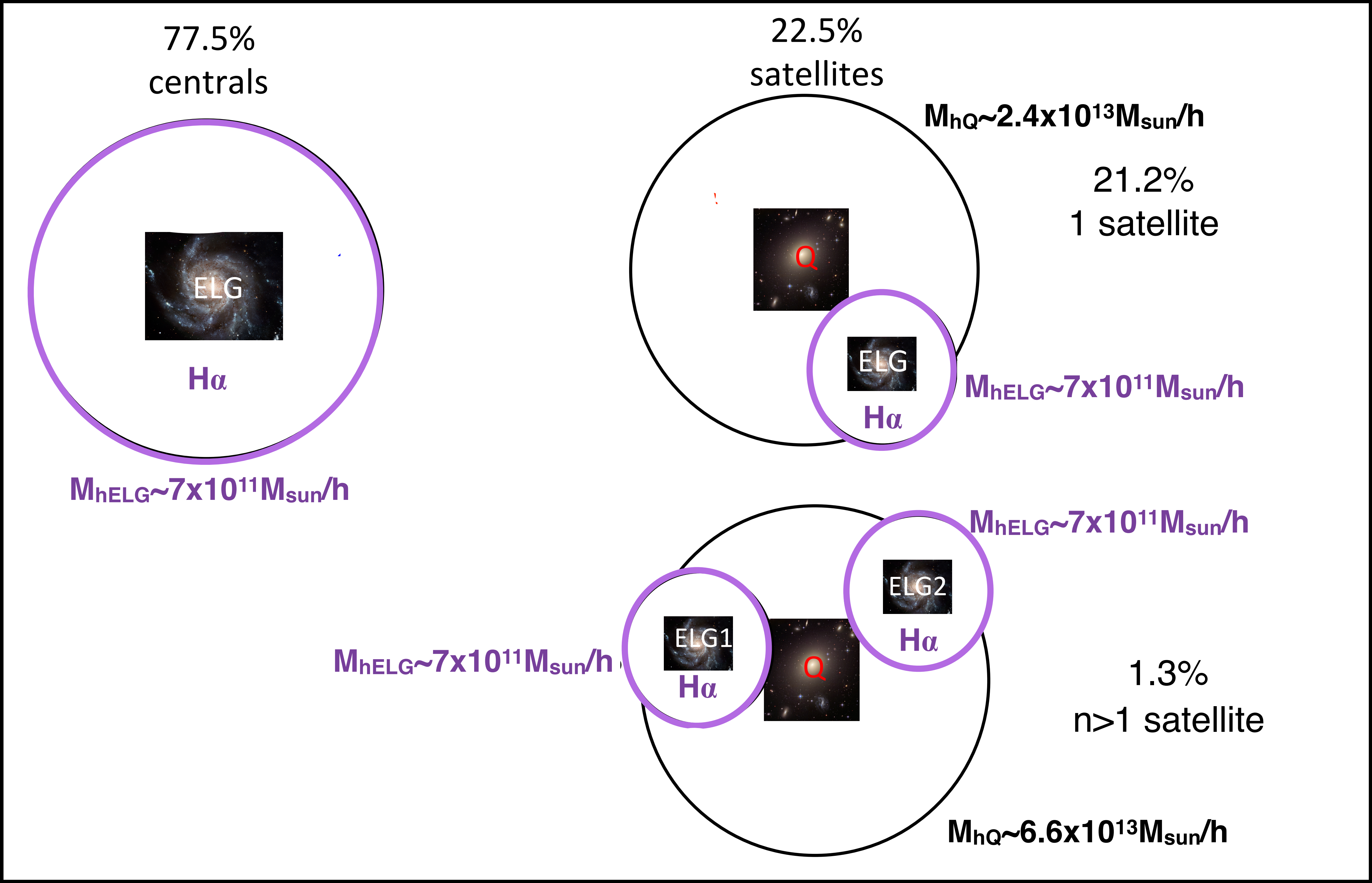
monopole has more power since spherical average

We find:

$M_h \sim (7.0 \pm 0.3) \times 10^{11}\ M_\odot/h$ $R_{vir} \sim (150 \pm 38)$ kpc/h bias ~ 1

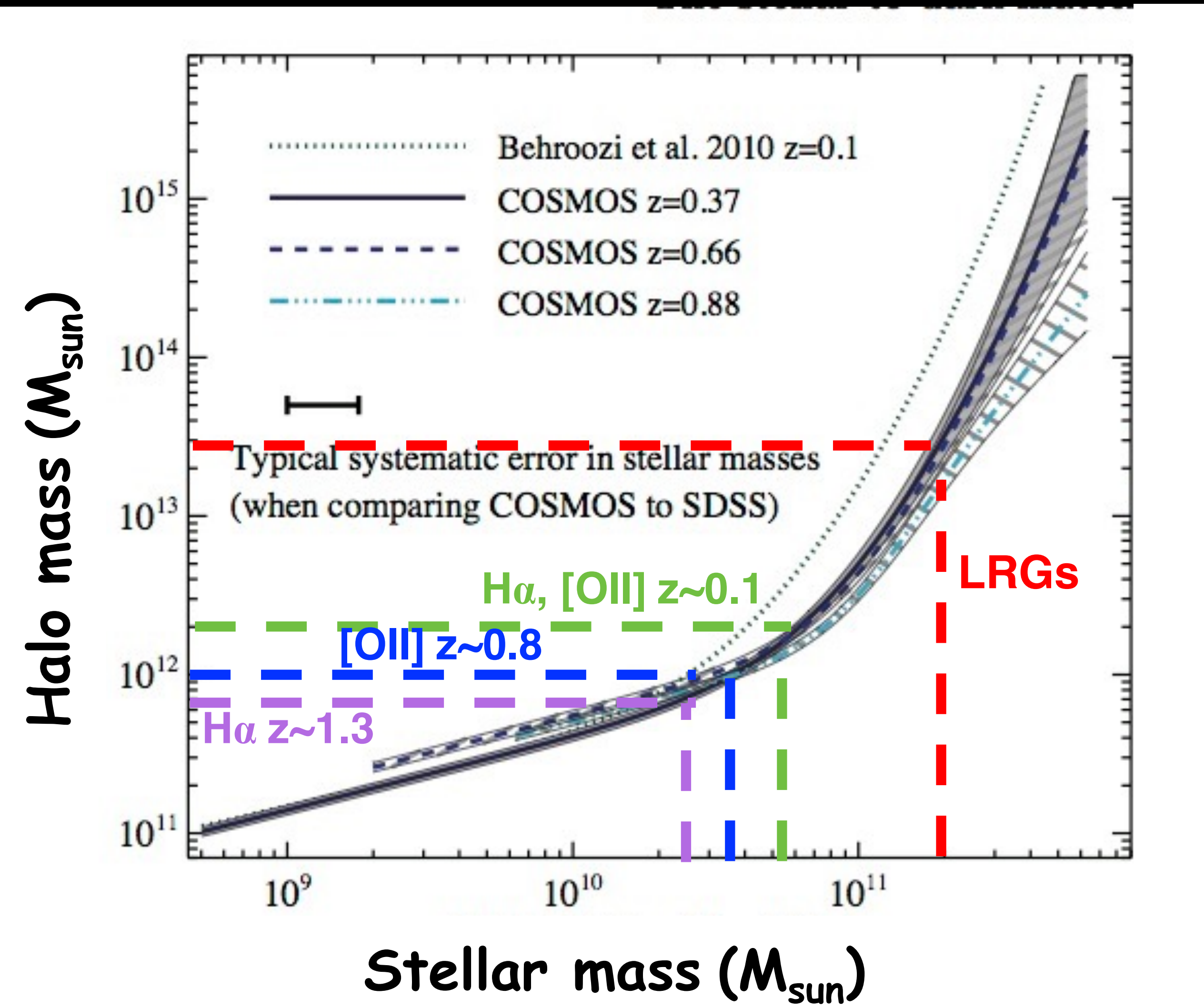
$V_{peak} \sim (185 \pm 67)$ km/s $f_{sat} \sim (22.5 \pm 2.1)\%$

Hα ELG halo occupation distribution at 0.9<z<1.6:

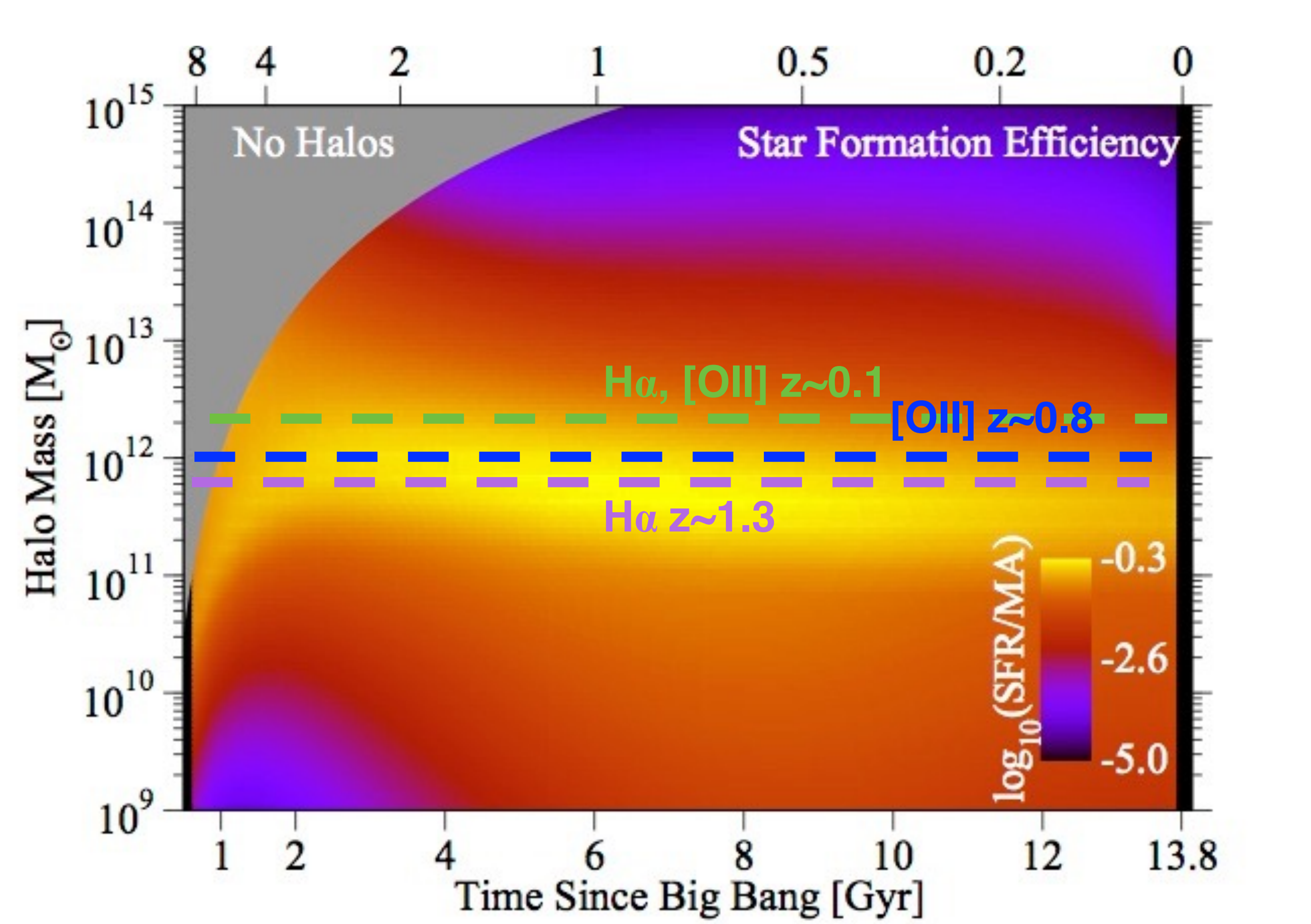


Favole et al. 2019, in preparation

Leauthaud et al. 2011, ApJ 738 45



Behroozi et al. 2013, ApJ 762 L31



Hα and [OII] z~0.1 ELGs with $M_{hELG} = 2.2 \times 10^{12}$ M_{sun} have Mstar~5.3×10^{10} M_{sun}

[OII] z~0.8 ELGs with $M_{hELG} \sim 10^{12}$ M_{sun} have Mstar~3.5×10^{10} M_{sun}

Hα z~1.3 ELGs with $M_{hELG} = 7 \times 10^{11}$ M_{sun} have Mstar~2.5×10^{10} M_{sun}

We are sampling those halos that most efficiently form stars

Summary

- [OII] and Hα emitters at $0.1 < z < 1.6$ share the same clustering properties, bias and halo occupation distribution. More luminous galaxies are more clustered, more biased, they occupy more massive halos with less satellites. Results are consistent within the errors

- The [OII] and Hα halo model does not show significant evolution at $0.1<z<1.6$

	Hα z~0.1:	[OII] z~0.1:	[OII] z~0.8:	Hα z~1.3:
f_{sat} (%)	25.0 ± 0.4	24.2 ± 0.4	22.5 ± 2.5	22.5 ± 2.1
M_{halo} ($M_\odot$/h)	$(2.2 \pm 0.1)\times10^{12}$	$(2.2 \pm 0.1)\times10^{12}$	$(1.0 \pm 0.5)\times10^{12}$	$(7 \pm 0.3)\times10^{11}$
M_{star} ($M_\odot$/h)	$\sim5.3\times10^{10}$	$\sim5.3\times10^{10}$	$\sim3.5\times10^{10}$	$\sim2.5\times10^{10}$
bias	~1	~1	~1	~1

Future prospects

- Next-generation surveys will enable us to push the clustering analysis down to scales until now unexplored

- Combining high-quality data (spectroscopy + imaging) with unprecedented statistics with high-resolution, large-volume simulations we will fully understand the complex mechanisms that regulate galaxy formation/evolution and precisely constrain the galactic morphology

- We will be able to build combined clustering+lensing models with unprecedented accuracy

- Combining different tracers of the underlying DM field (ELGs and LRGs have different bias), we will be able to dramatically reduce cosmic variance


ありがとうございます！