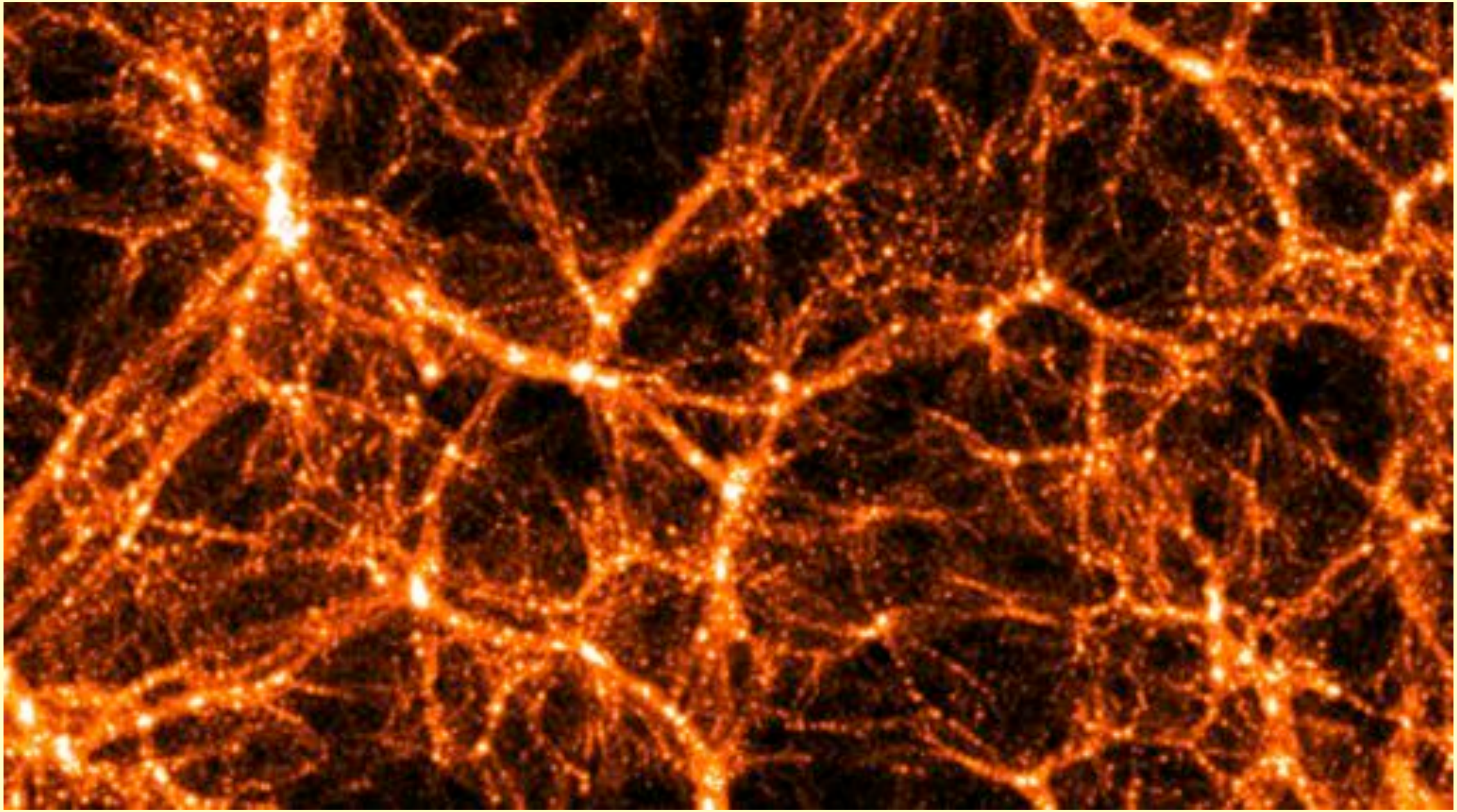
Surveying and modelling the cosmic web: a selective history and outlook



John Peacock Tallinn 24 June 2014

Outline

- Selected landmarks in surveying the galaxy distribution

- Key conceptual advances and shifting goals

- Outlook for the field

A century of galaxy redshifts

LOWELL OBSERVATORY

BULLETIN No. 58

VOL. II — No. 8

THE RADIAL VELOCITY OF THE ANDROMEDA NEBULA

1912, September	17,	Velocity,	—284 km.
November	15–16,	"	296
December	3–4,	"	308
December	29–30–31,	"	—301
	Mean velocity,		—300 km.

V.M. Slipher (1875-1969)

1913: M31 v<0

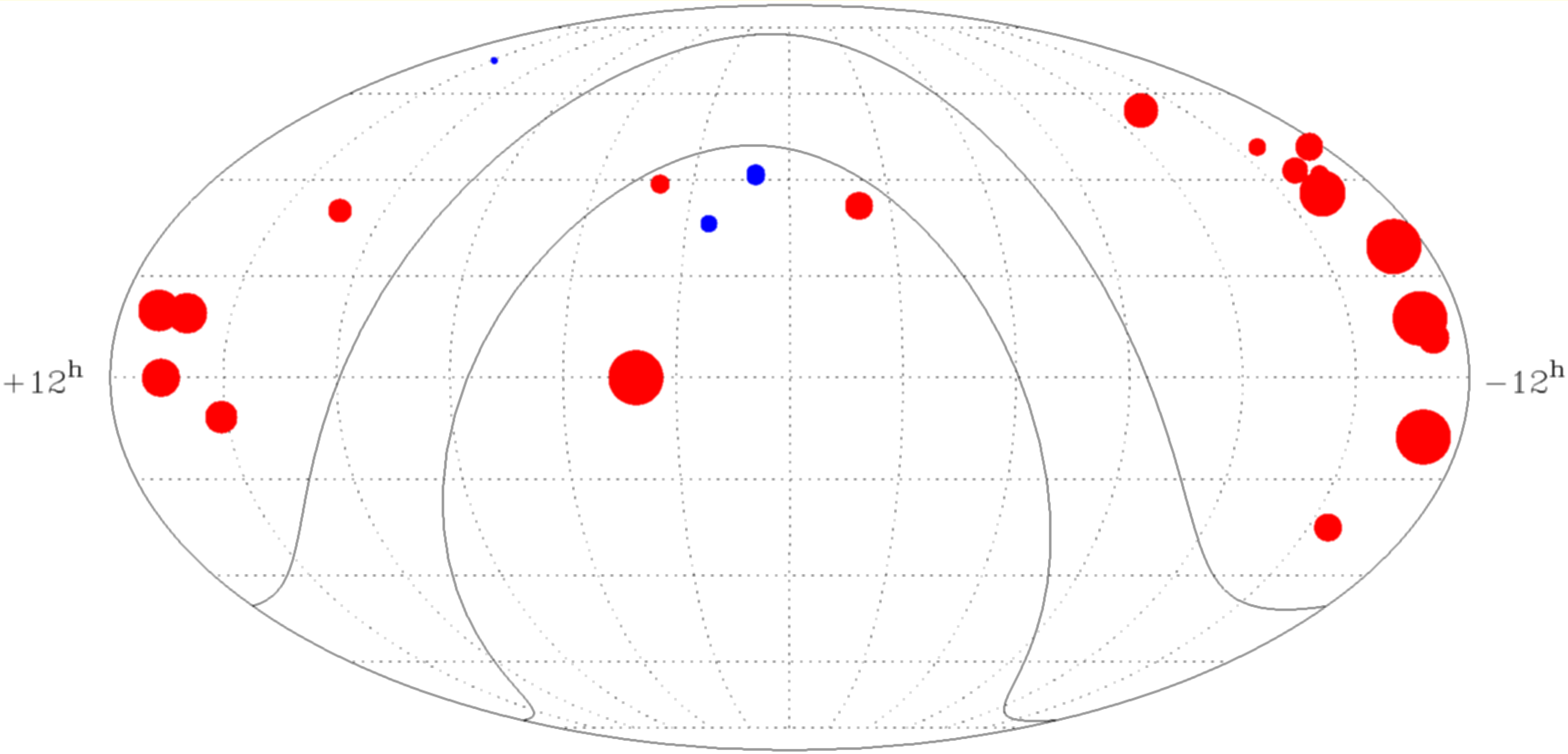
1915: 11/15 v>0

1917: 21/25 v>0

1923: 36/41 v>0

The expanding universe?

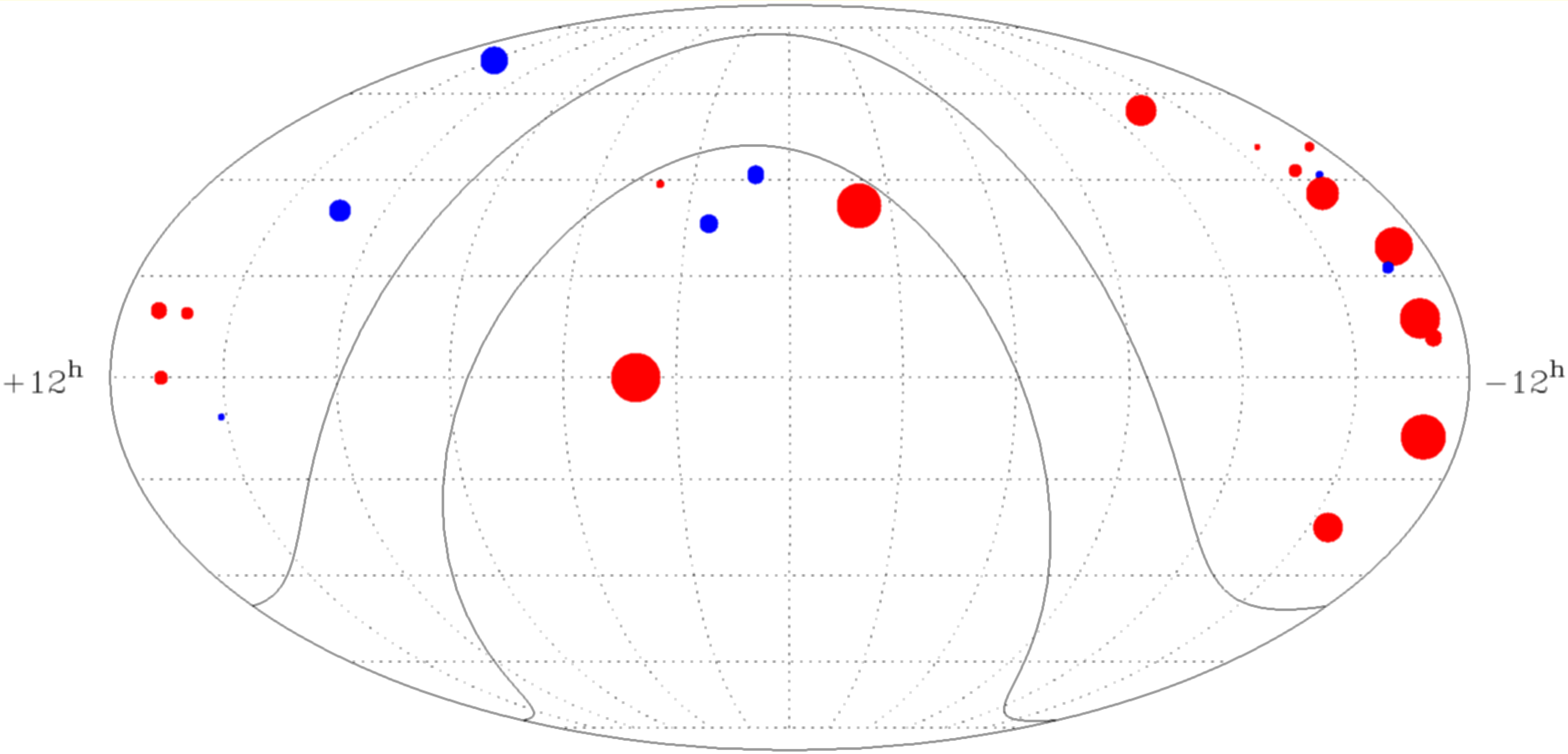
Slipher's 1917 data



-300 to +1100 km s^{-1}

The mean of the velocities with regard to sign is positive, implying the nebulæ are receding with a velocity of nearly 500 km. This might suggest that the spiral nebulæ are scattering but their distribution on the sky is not in accord with this since they are inclined to cluster.

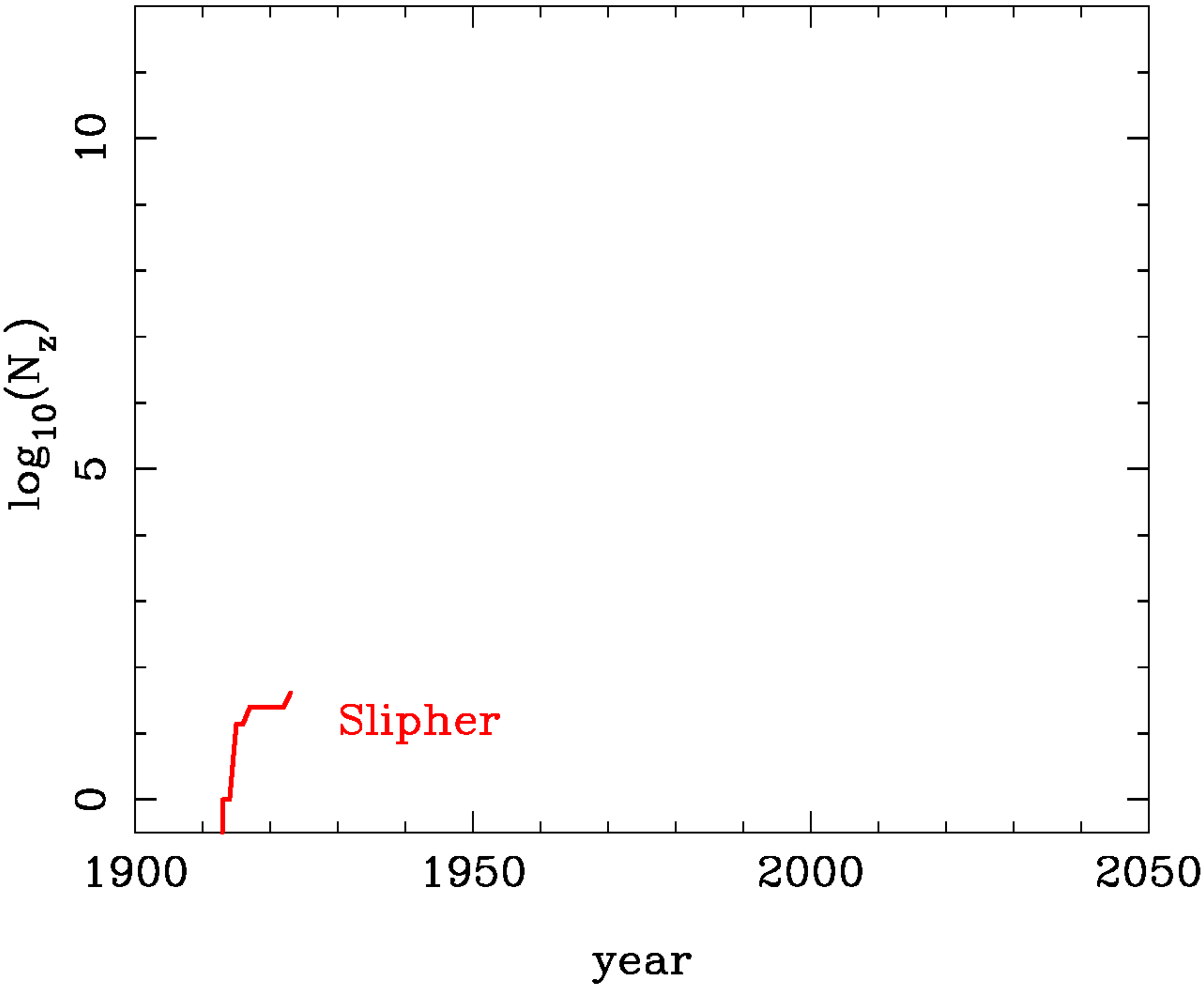
Slipher's 1917 data: dipole corrected



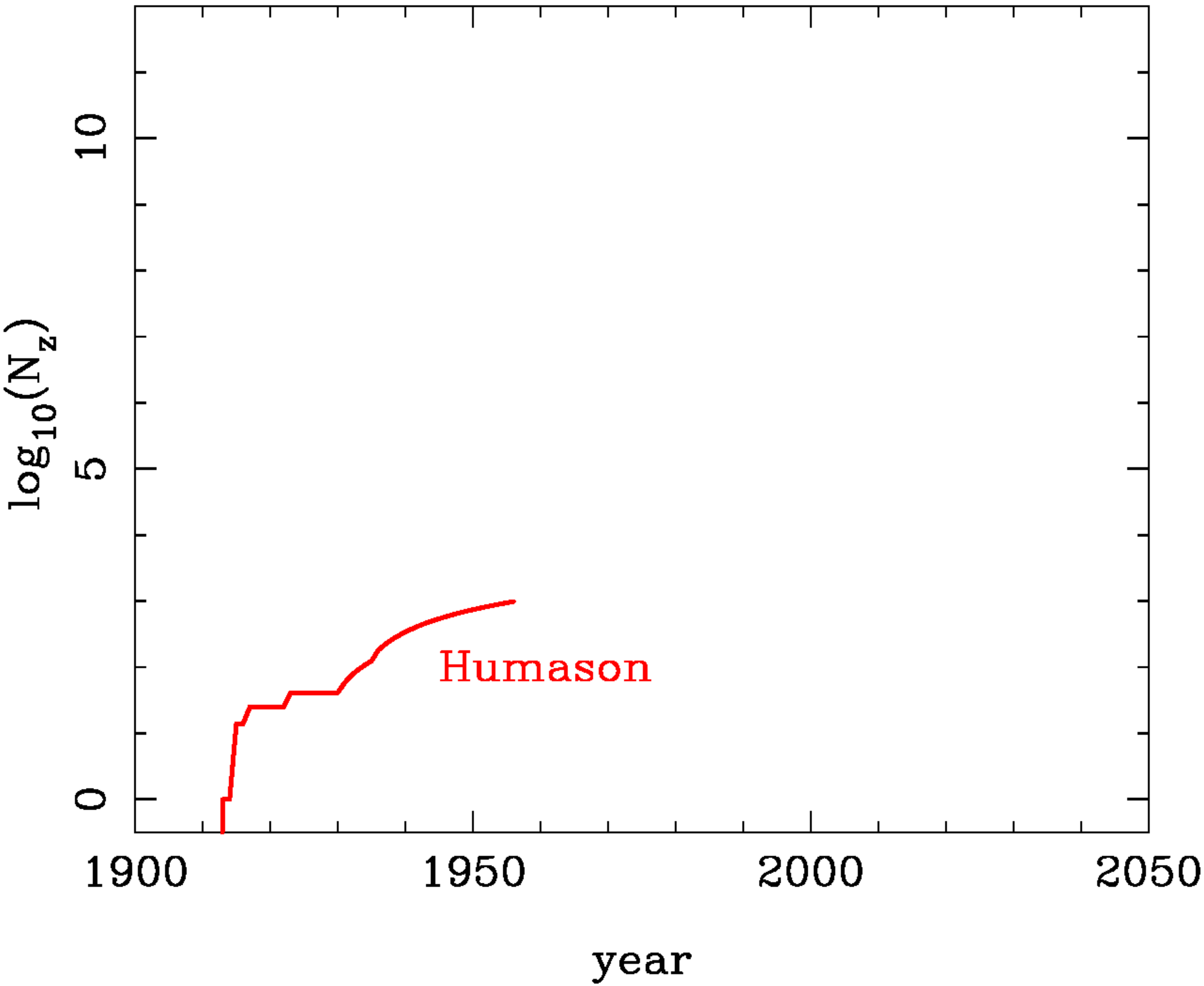
V_{sun} = 700 km s^{-1} towards 22^h -22^o

Reduces <V> from 502 to 143 − but still >0 at 8σ (14σ in 1923)

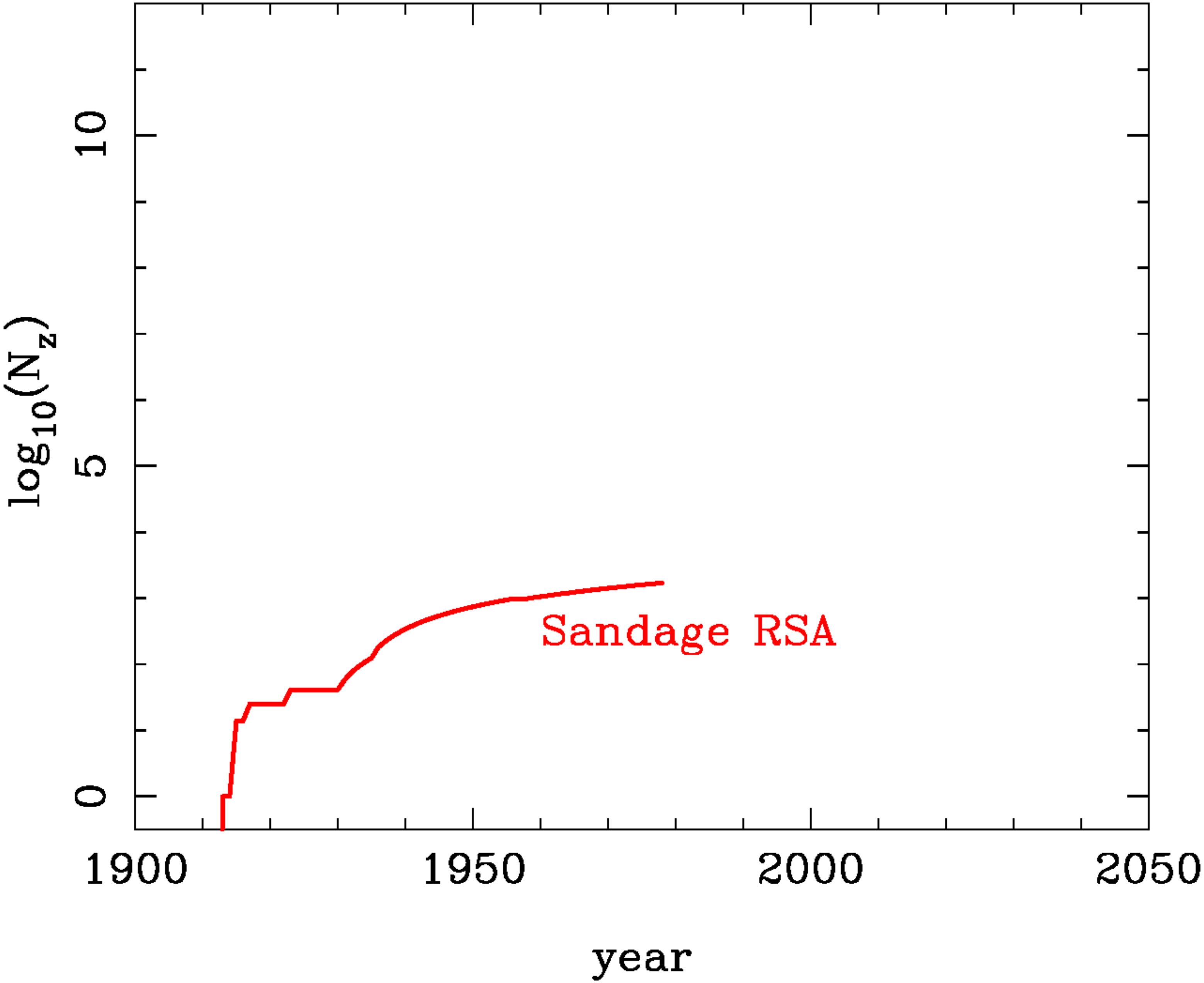
A Century+ of galaxy redshifts



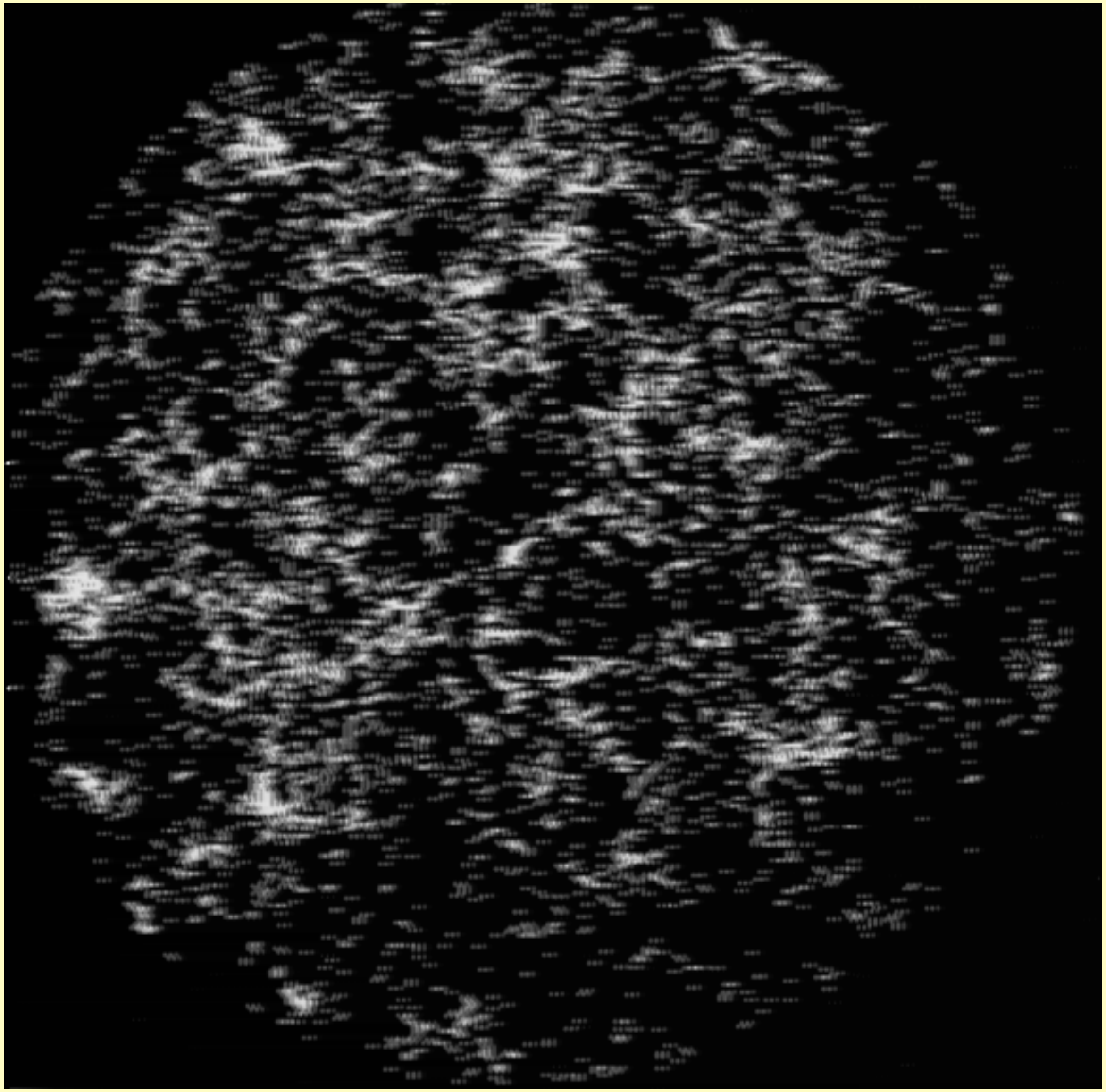
A Century+ of galaxy redshifts



A Century+ of galaxy redshifts



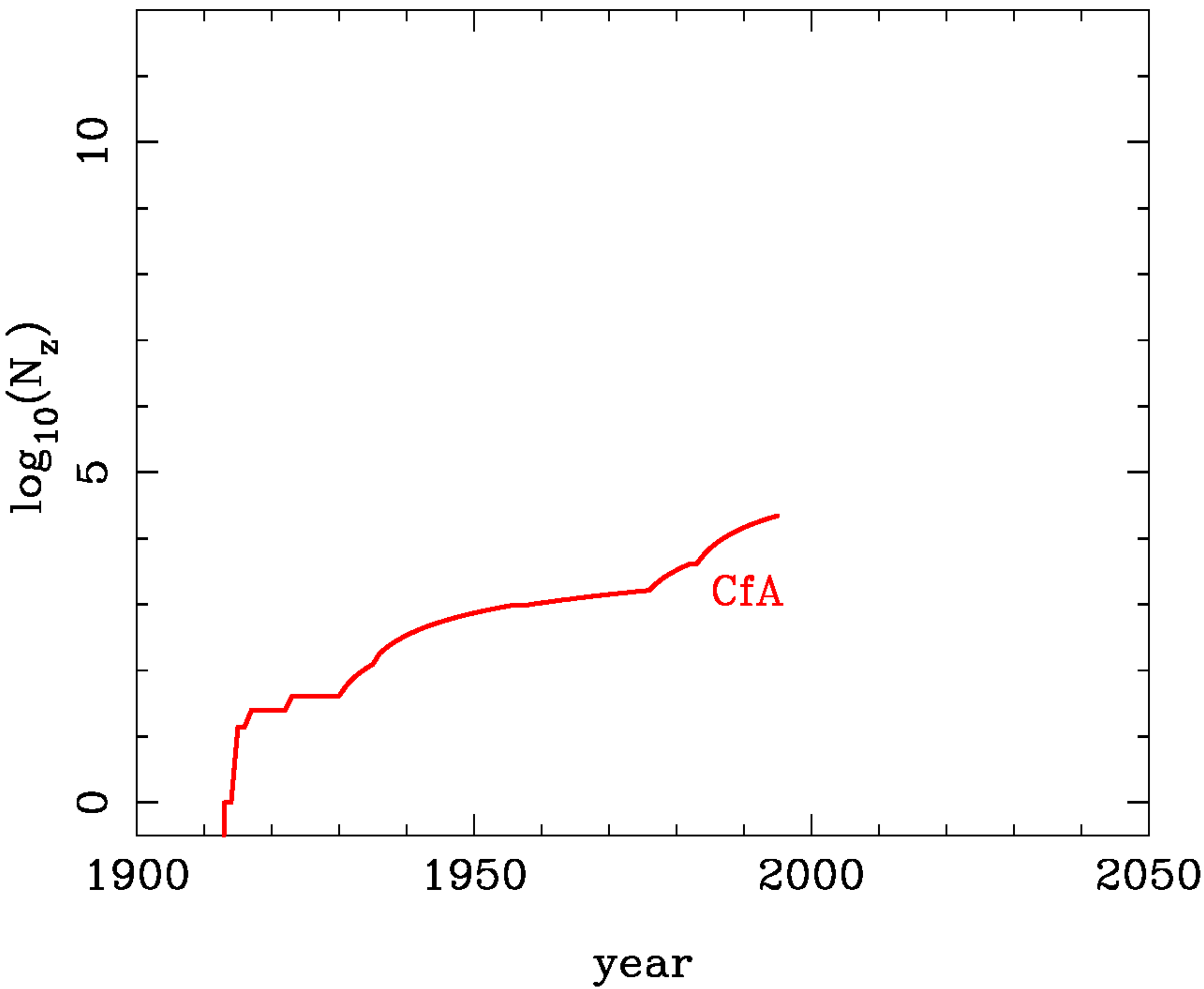
Pre-1980s: angular studies



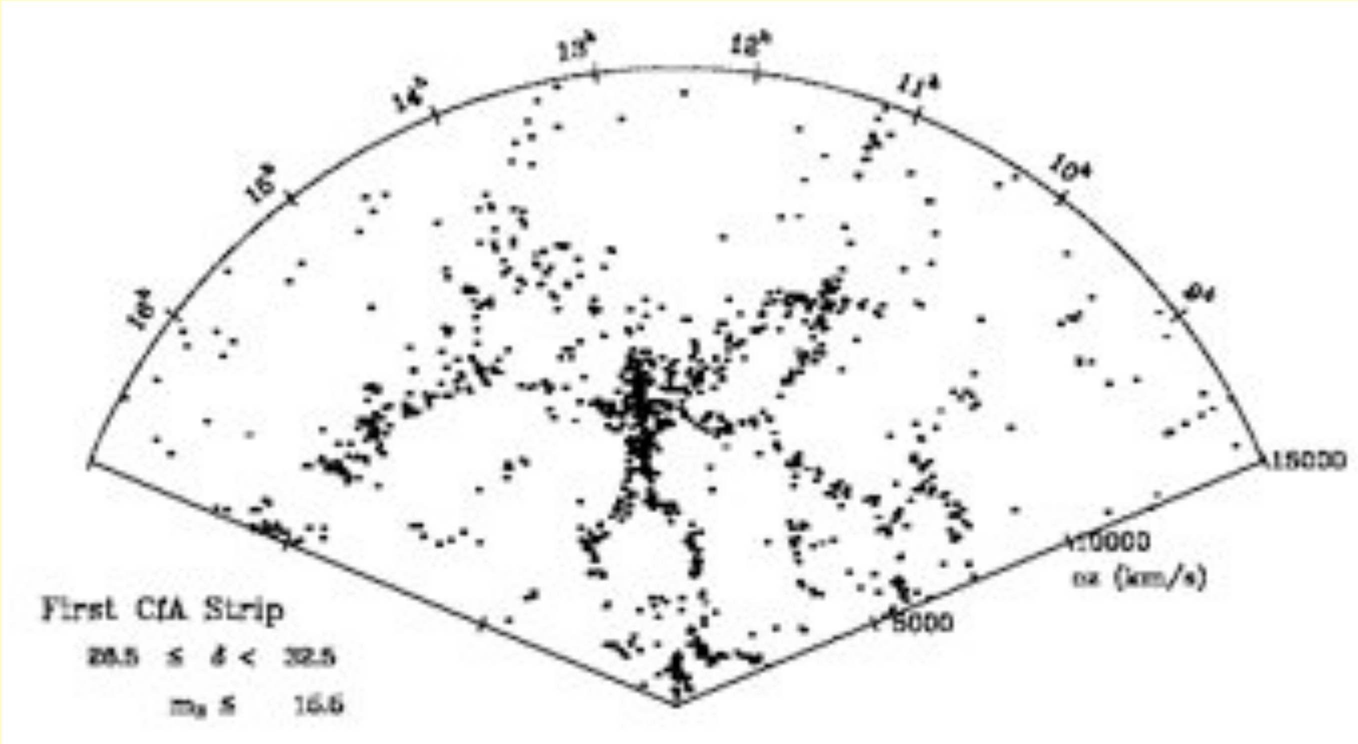
Peebles correlation-function programme, applied to Shane-Wirtanen Lick galaxy map.

'morphological segregation' − i.e. different correlations for different galaxy types (Davis & Geller 1976)

A Century+ of galaxy redshifts



CfA surveys



Accelerated progress from electronic detectors

CfA1: 2396 z’s 1977-1982

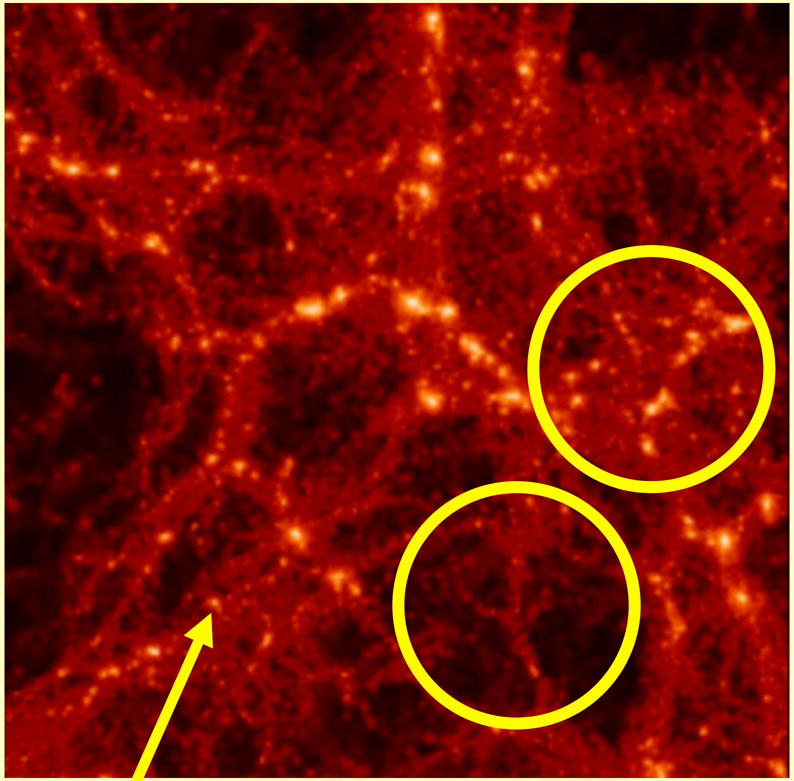
CfA2 : 18,000 z’s 1984-1995

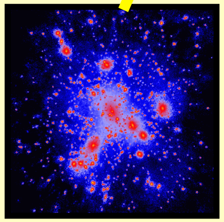
What did we learn from this?

3 great 1980s concepts that dominate the field today:

- Bias (1984)
- Sparse sampling (1986) − i.e. just need nP > 1 (FKP1994)
- Redshift-space distortions (1987)

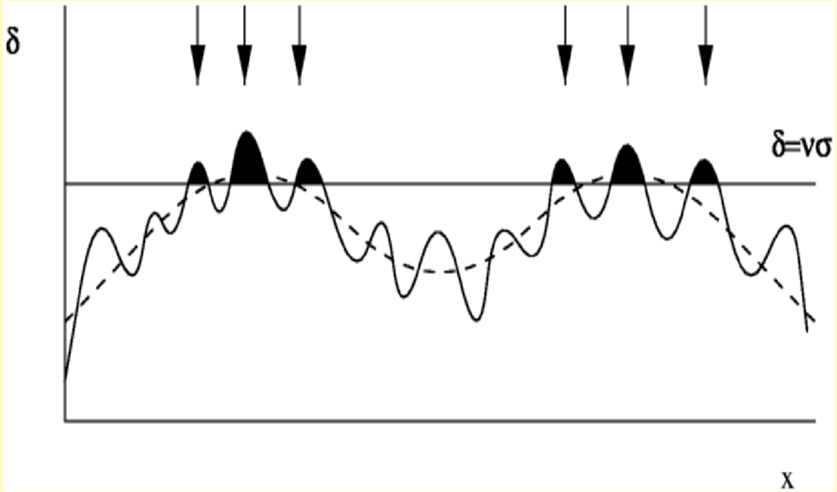
Bias: environment perturbs halo formation





DM halo: group of

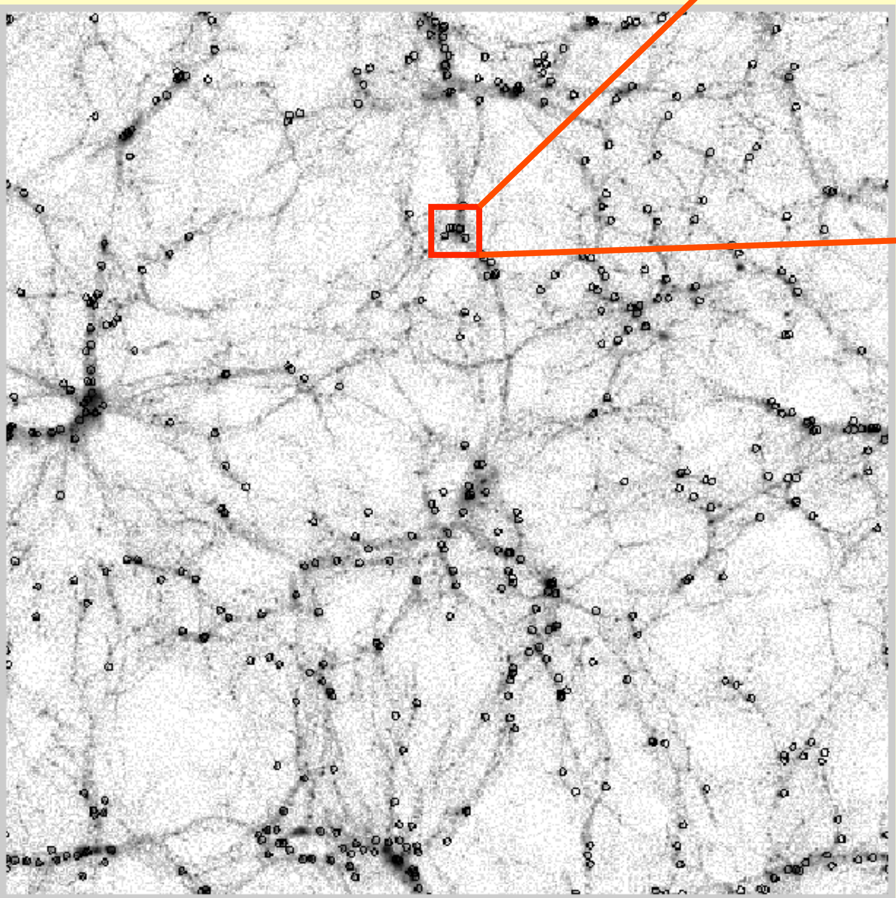
Galaxies in practice

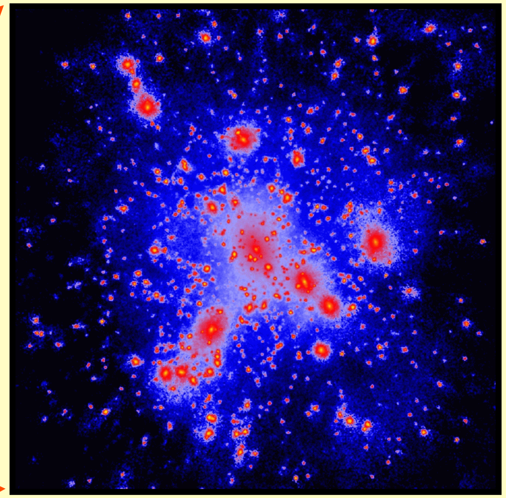


• Kaiser (1984), via EPS & Mo +White (1996): shift in halo mass function in regions of different large-scale density

• Hence biased halo clustering: $\delta_{halo}=b(M)\ \delta_{mass}$

The Halo Model: Neyman & Scott (1959)++

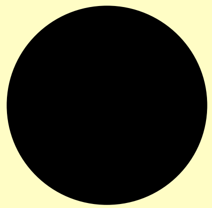




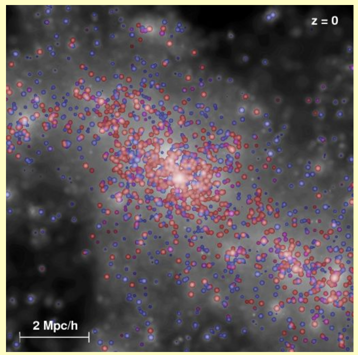
Close pairs from 1-halo clustering:

$\rho = [\ y(1+y)^2\ ]^{-1}$; $y = r/r_c$ (NFW)

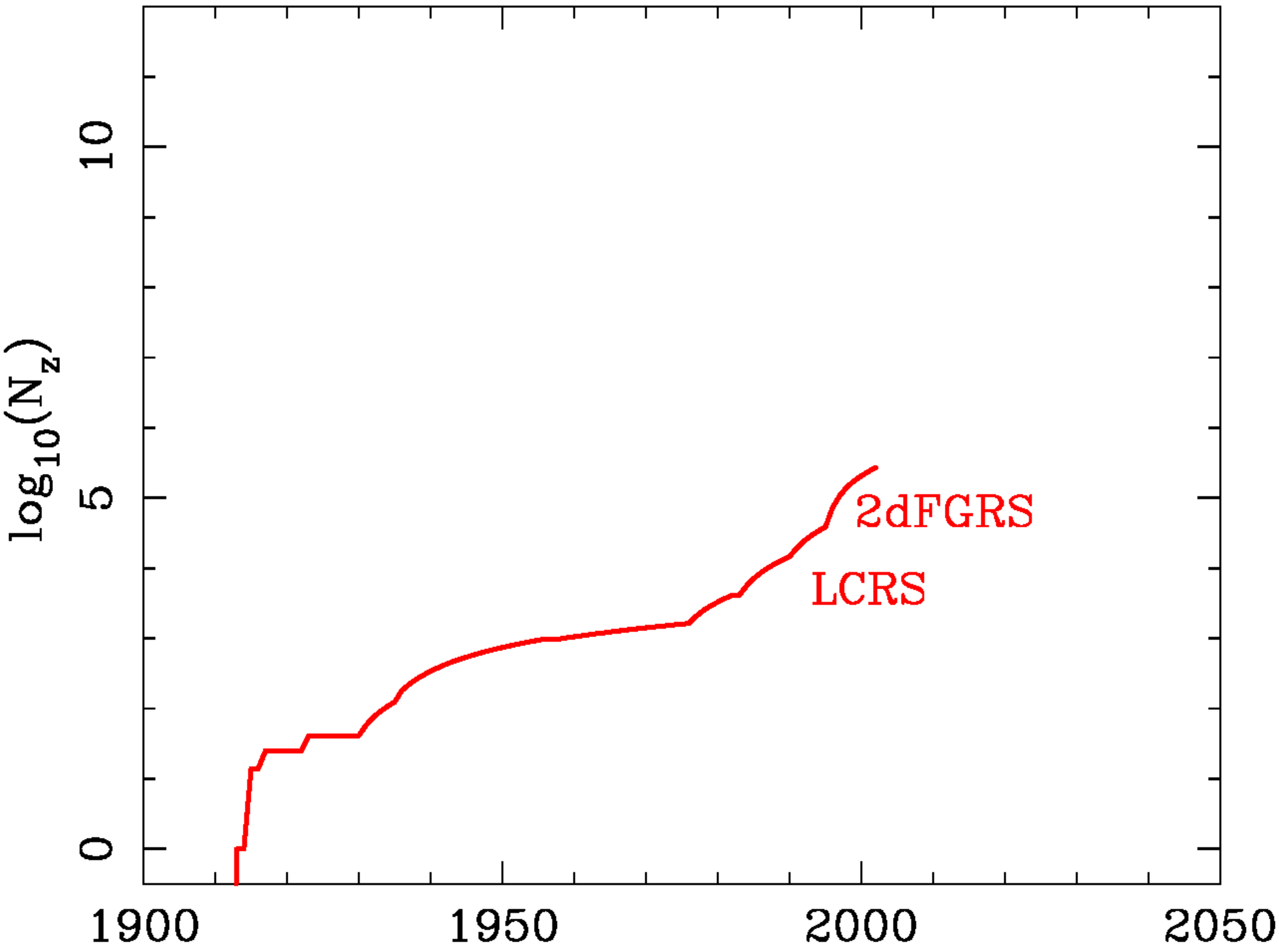
(cf. Isothermal sphere $\rho = 1/y^2$)



Need to know the galaxy content

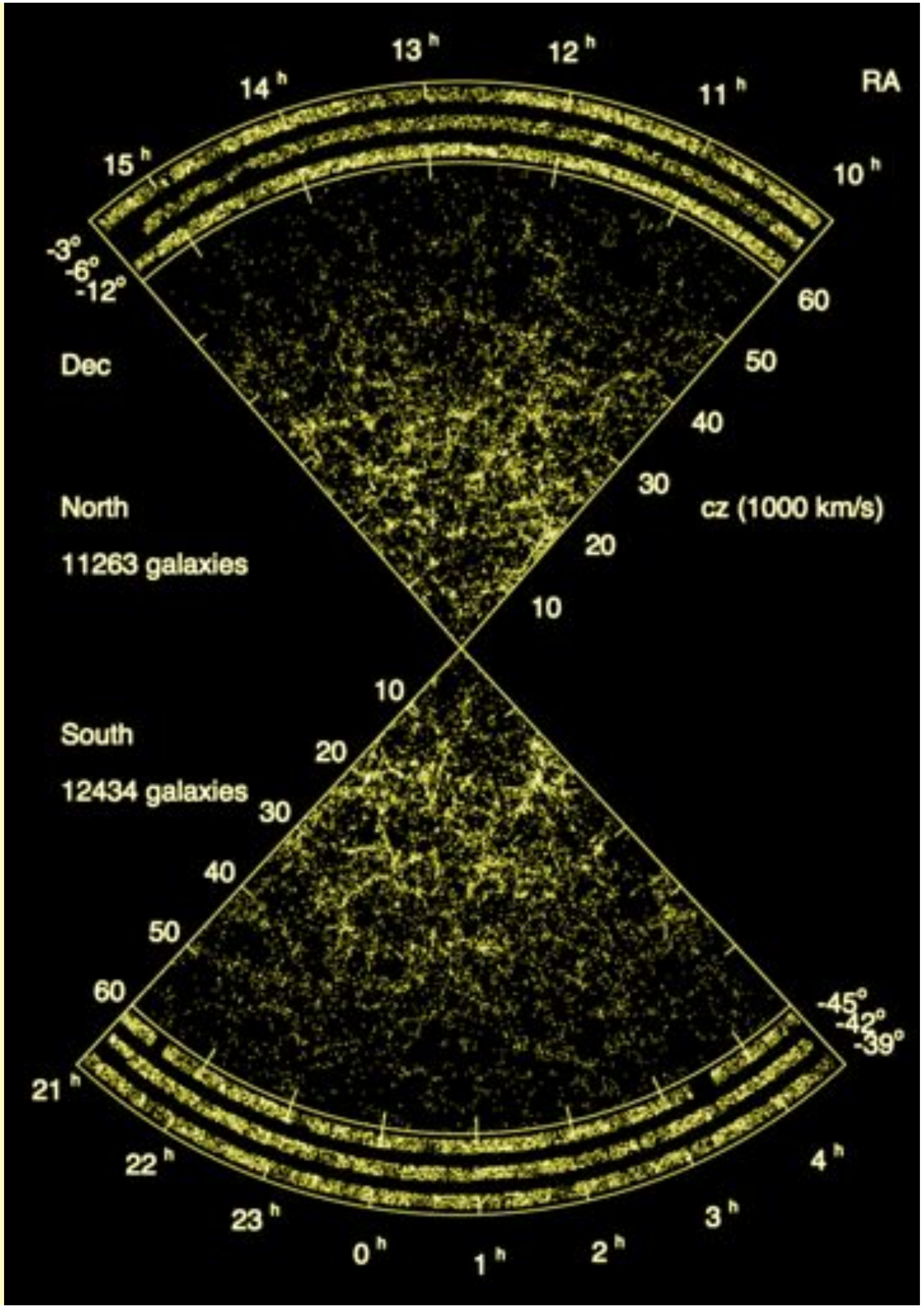


A Century+ of galaxy redshifts

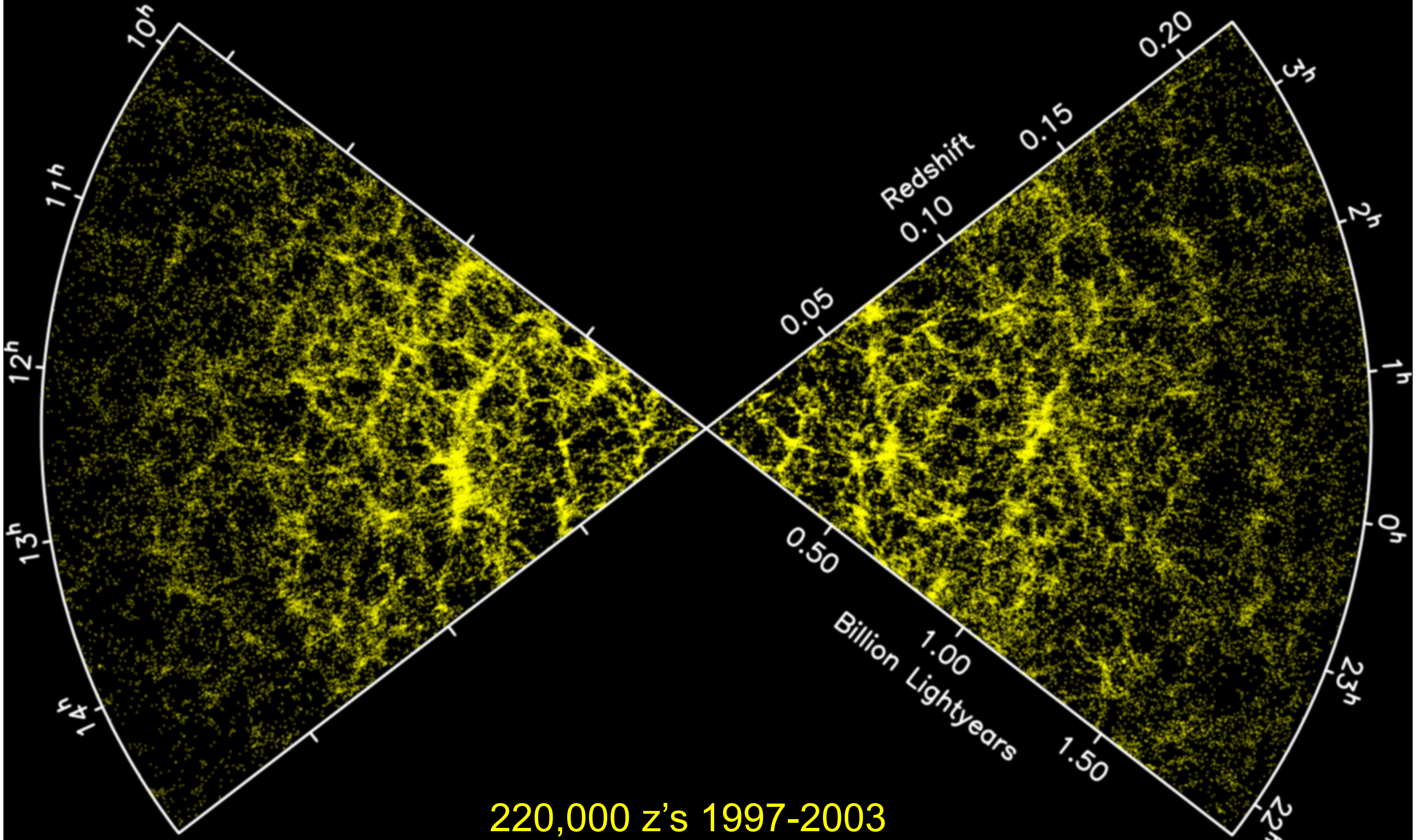


LCRS

- 26,418 z's
  1991-1998
- Demonstrated the 'end of greatness'



2dFGRS

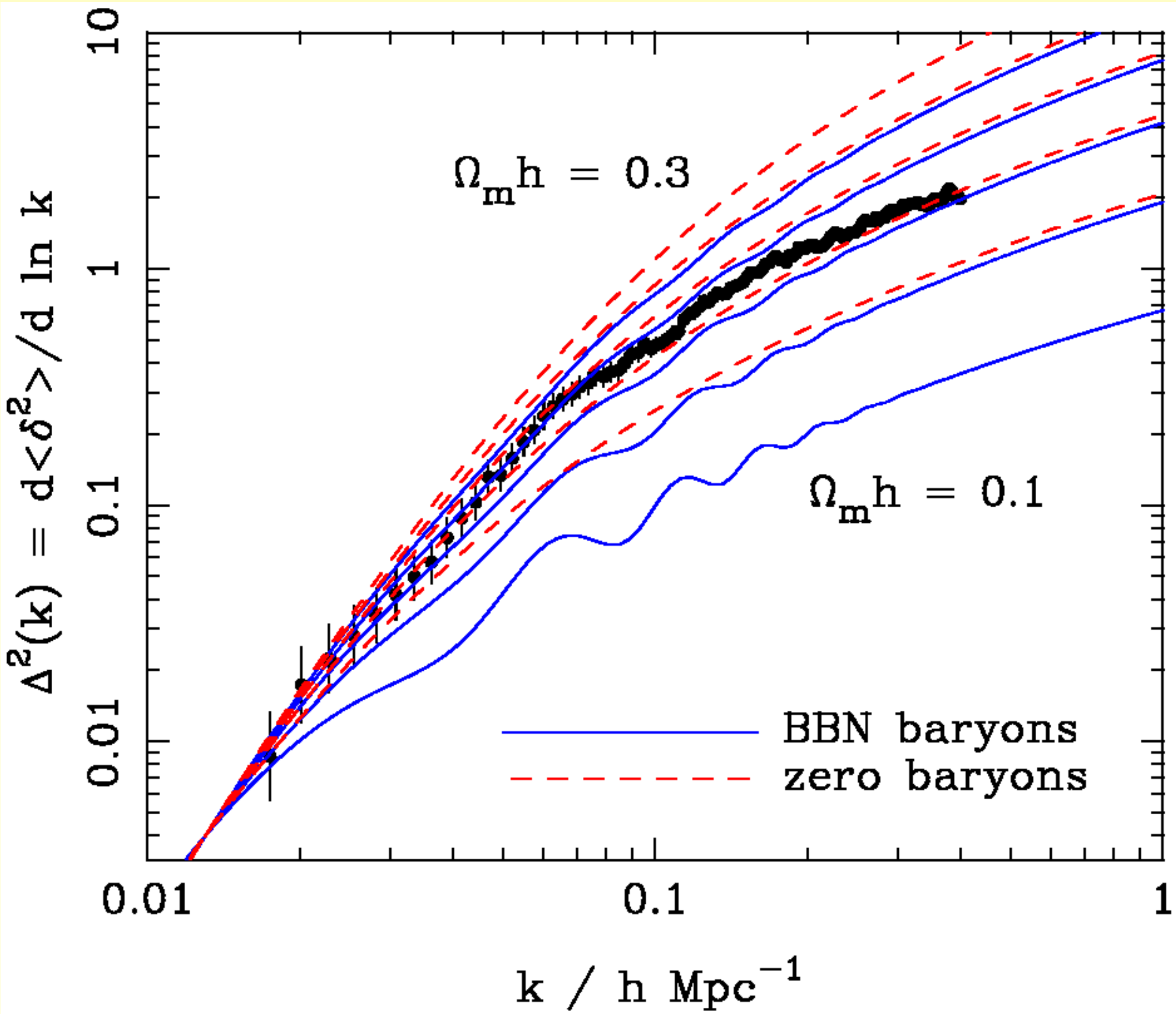


220,000 z's 1997-2003

2dFGRS power spectrum: small BAO proves DM

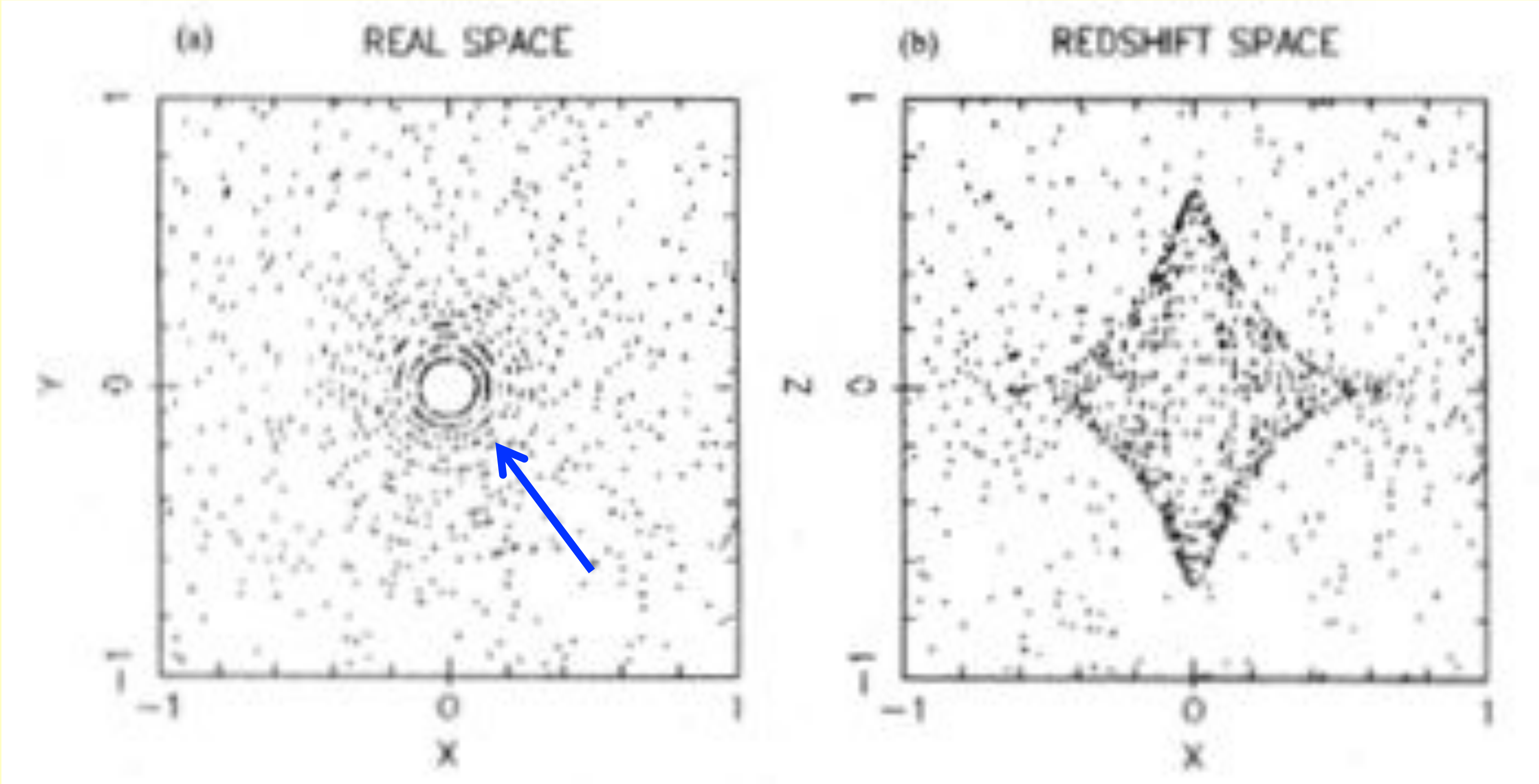
Dimensionless power:

d (fractional variance in density) / d ln k



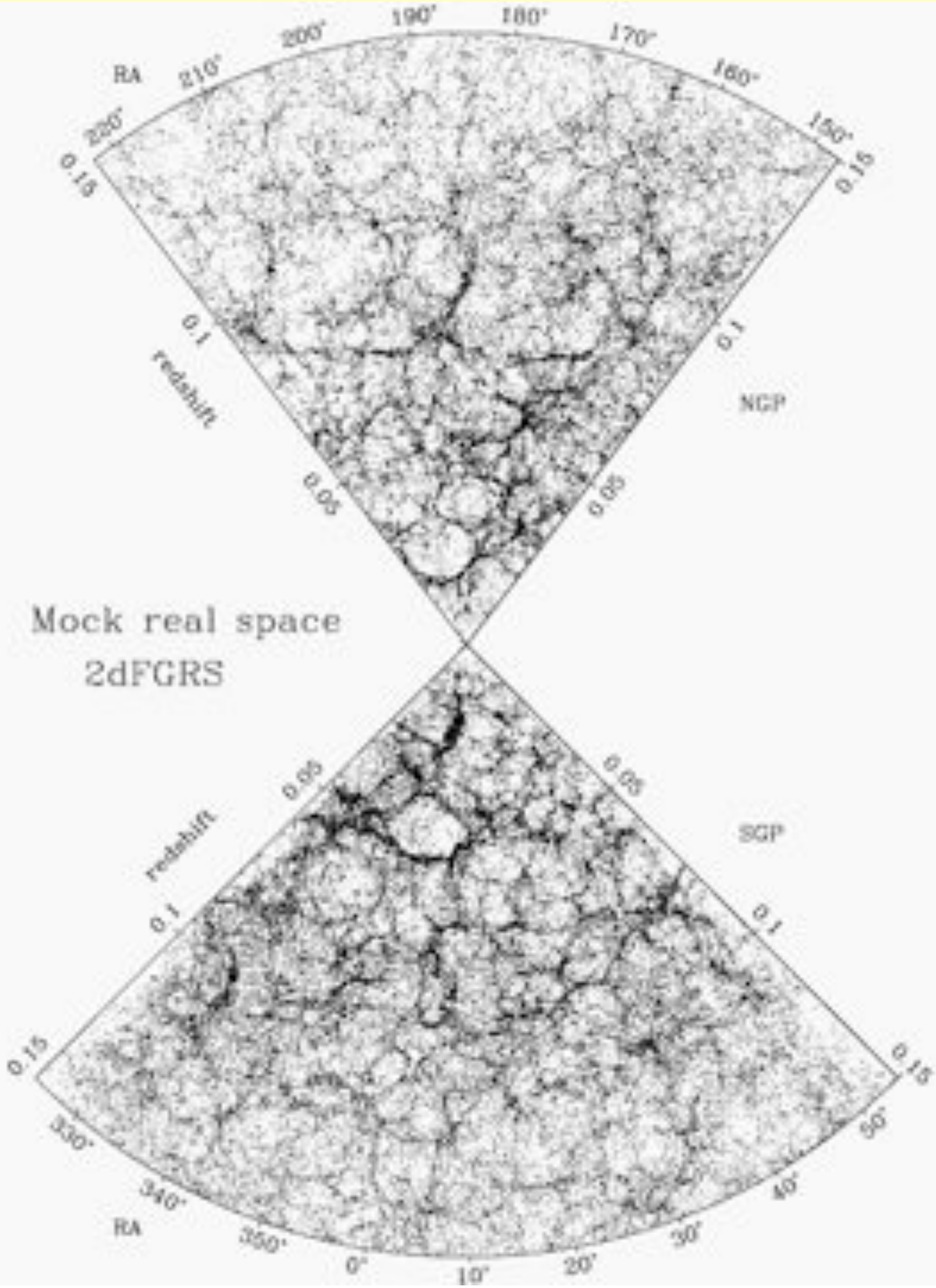
Percival et al. MNRAS 327, 1279 (2001)

Kaiser (1987): z-space distortions



Spherical infall flattens on large scales, inverts on small

Redshift-Space distortions of clustering



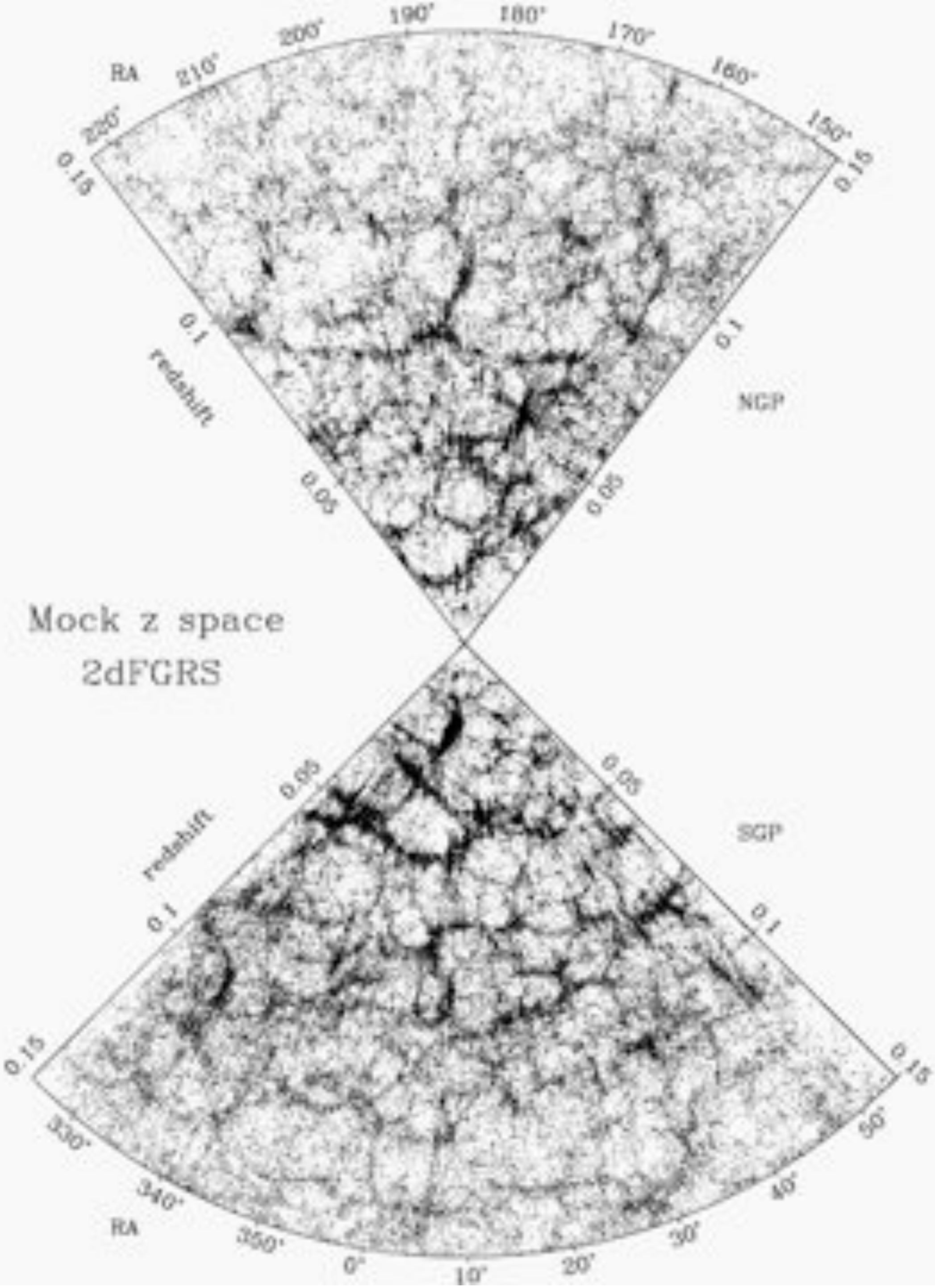
Mock 2dFGRS from Hubble volume

real space

Eke, Frenk, Cole, Baugh + 2dFGRS 2003

Redshift-Space distortions of clustering

2dFGRS first survey to benefit from detailed mock samples

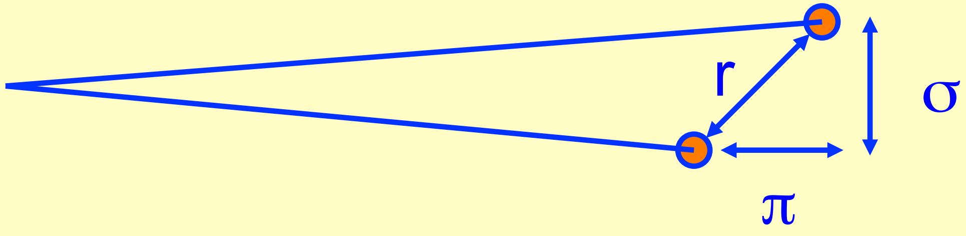


Mock 2dFGRS from Hubble volume

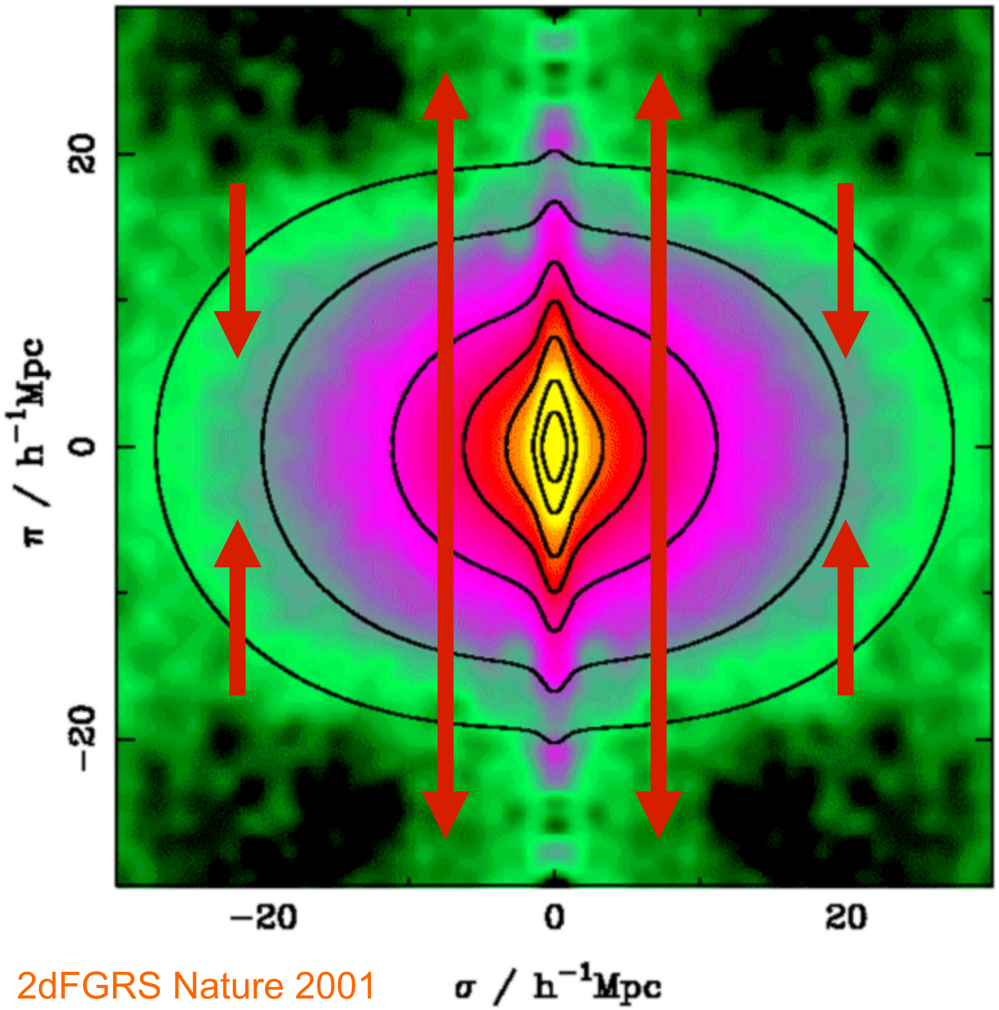
z space

Eke, Frenk, Cole, Baugh + 2dFGRS 2003

Redshift-Space Correlations

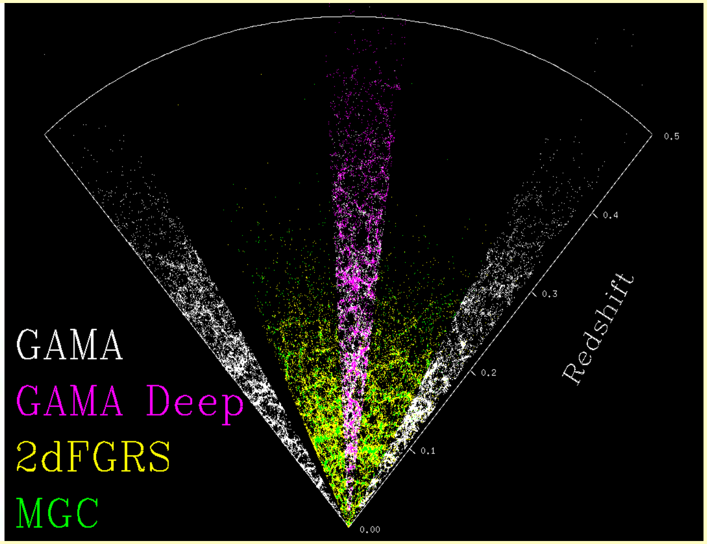


- RSD due to peculiar velocities are quantified by correlation fn (excess fraction of pairs) $\xi(\sigma,\pi)$
- Two effects visible:
  - Small separations on sky: 'Finger-of-God';
  - Large separations on sky: flattening along line of sight.



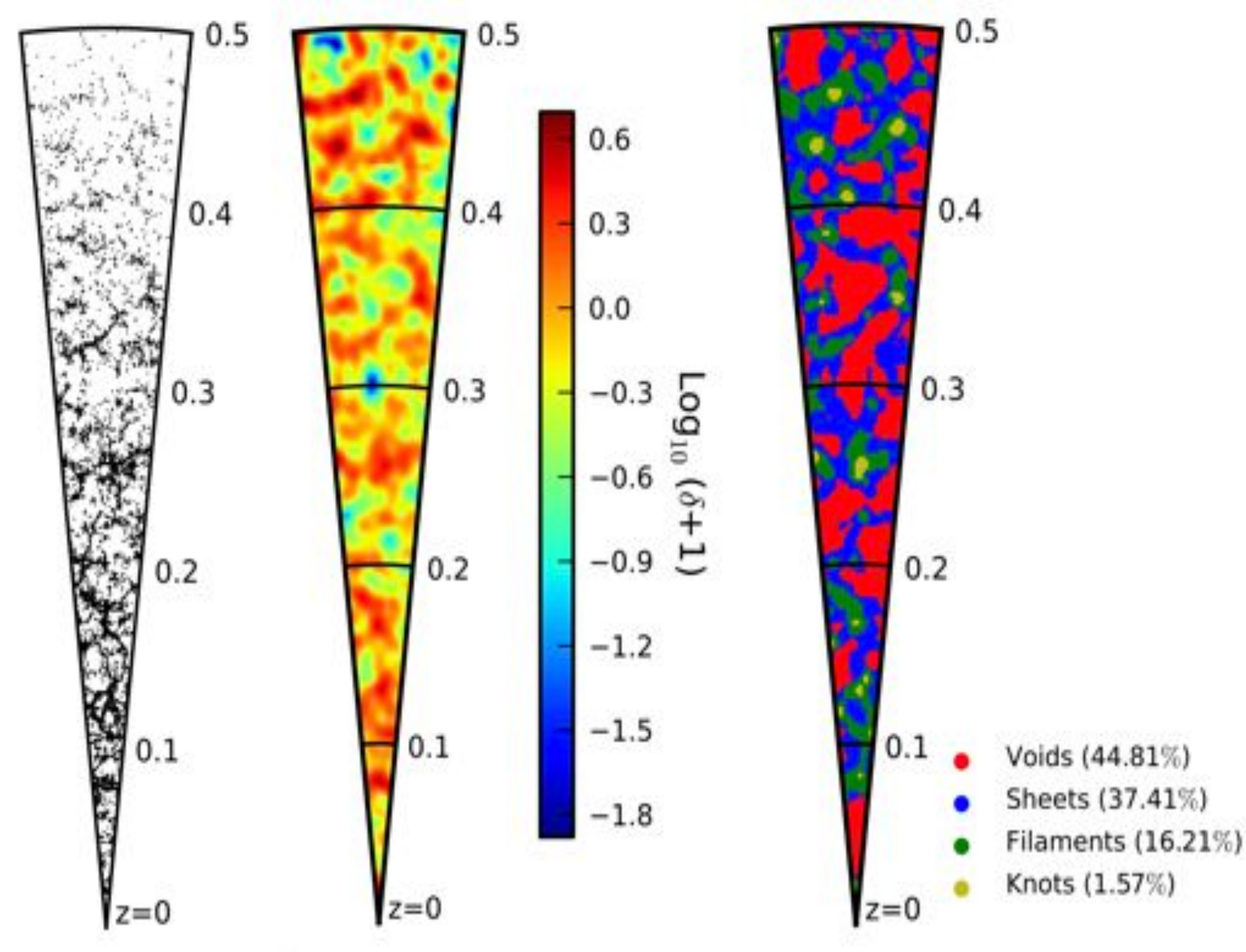
2dFGRS Nature 2001

Galaxy And Mass Assembly – GAMA



- 300 deg^2 in 6 fields
- to r < 19.4 / 19.8 (GAMA deep) – cf. SDSS 17.8
- Aim for >200,000 redshifts
- GAMA I 2008-2010; 150 deg^2:
    - Over 160k including 2dFGRS/SDSS
- GAMA-II 2011-15; should reach 400k z's

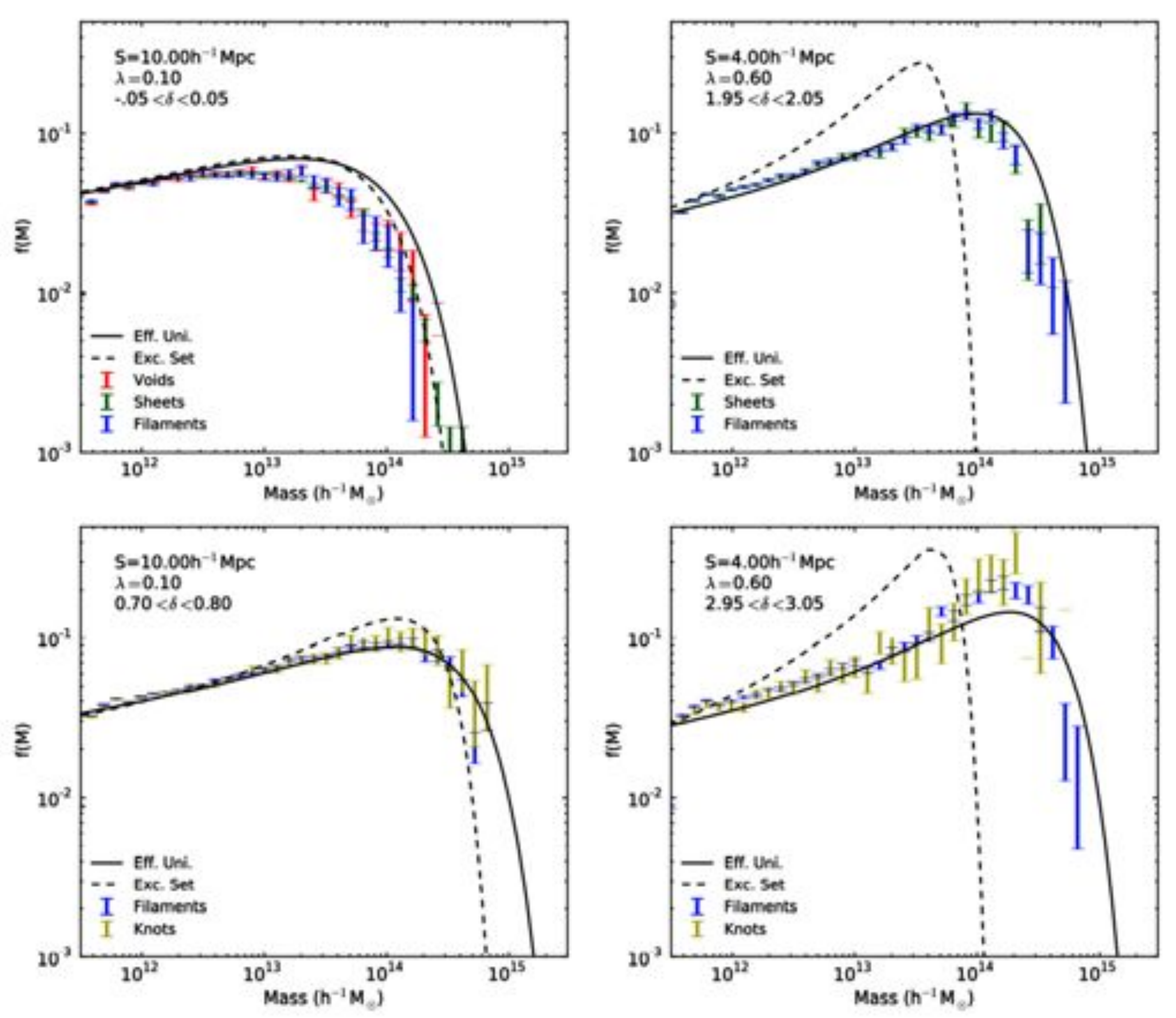
Geometrical environments



Eardley et al. GAMA:

Follow Forero-Romero et al. (2009): Take Hessian of potential and count eigenvalues above threshold ~1

Effect of geometry on haloes

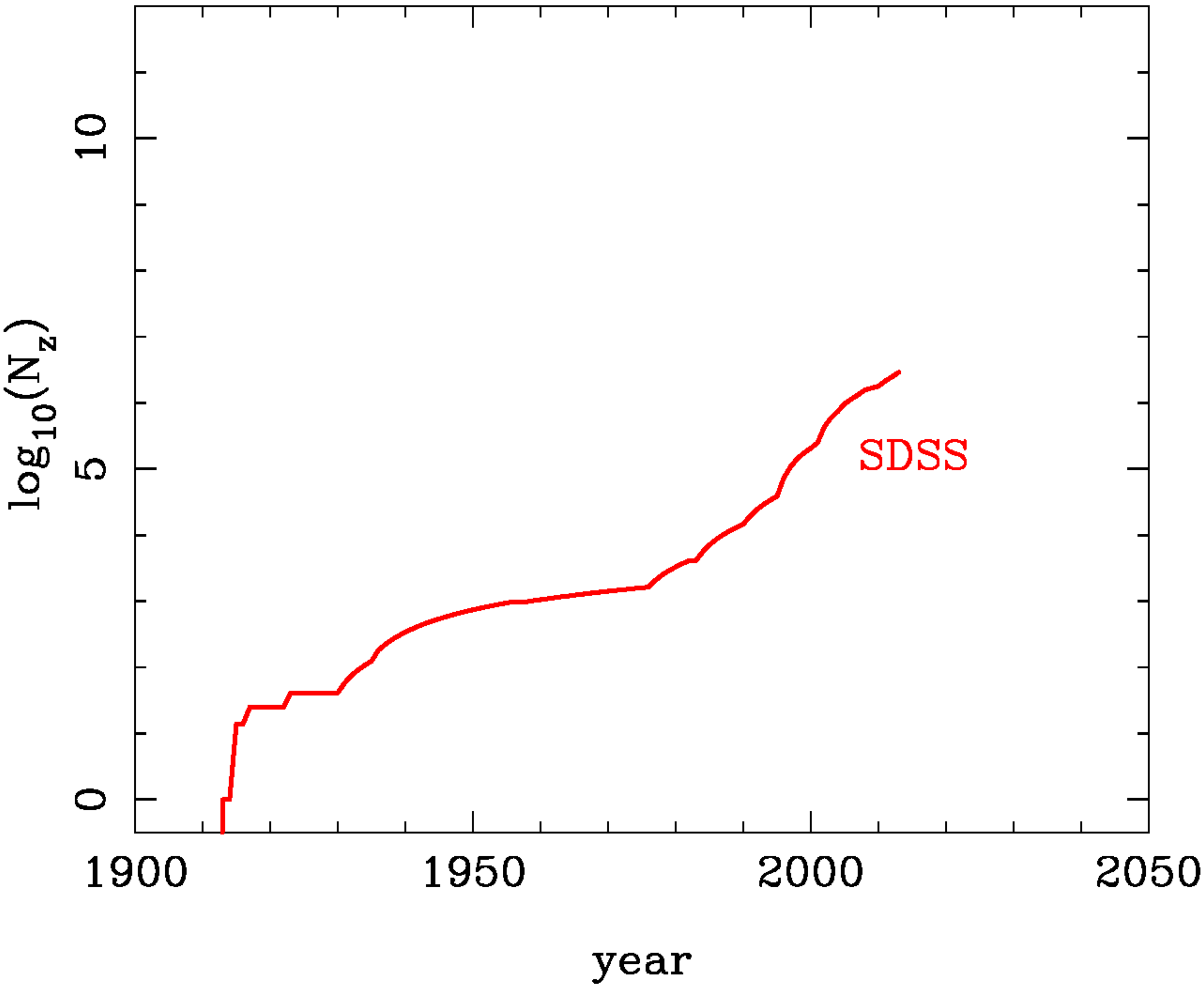


Alonso et al. 1406.4159:

Gaussian theory suggests should be no dependence of conditional mass function on geometry at given overdensity

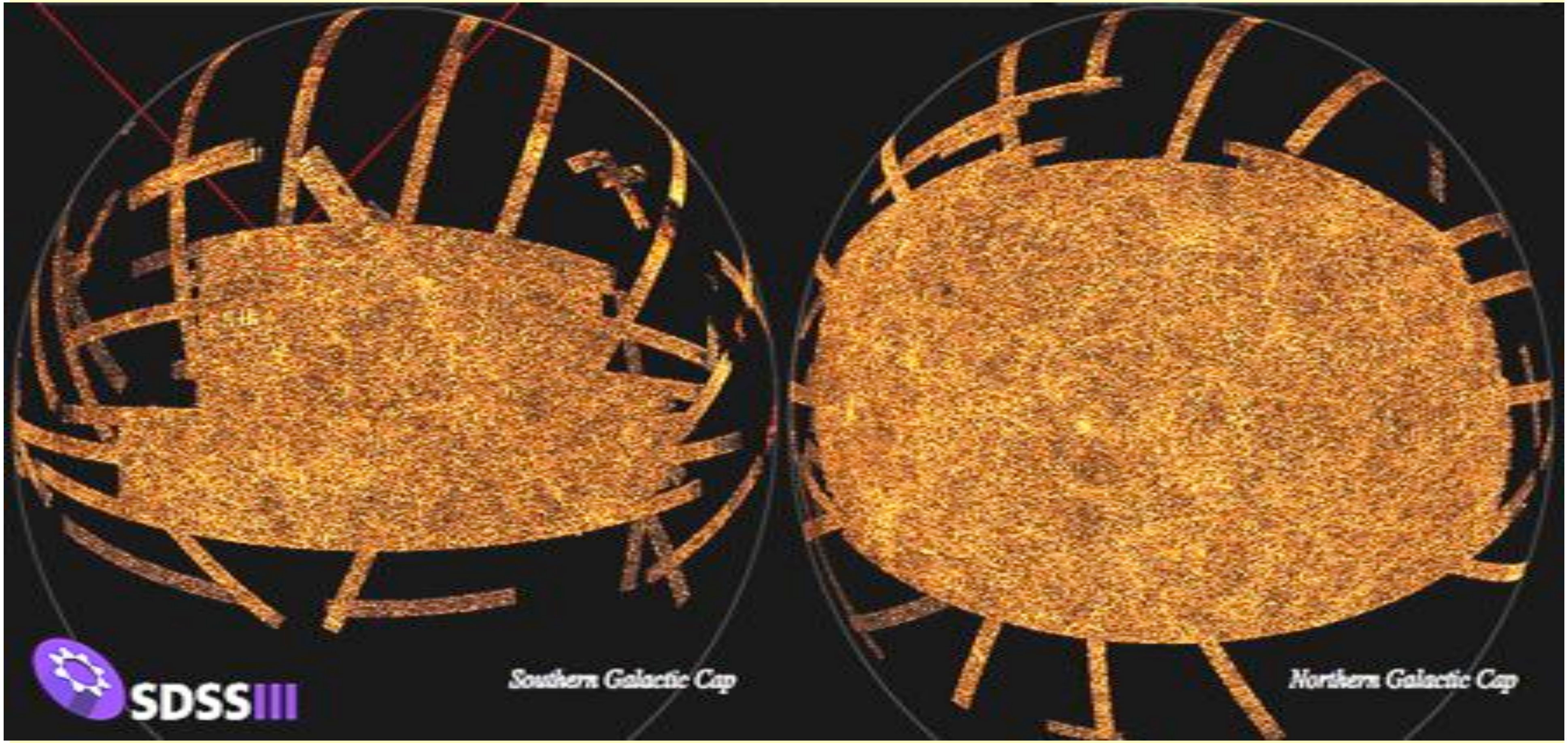
− seems to hold in MultiDark simulations. No halo 'assembly bias'?

A Century+ of galaxy redshifts

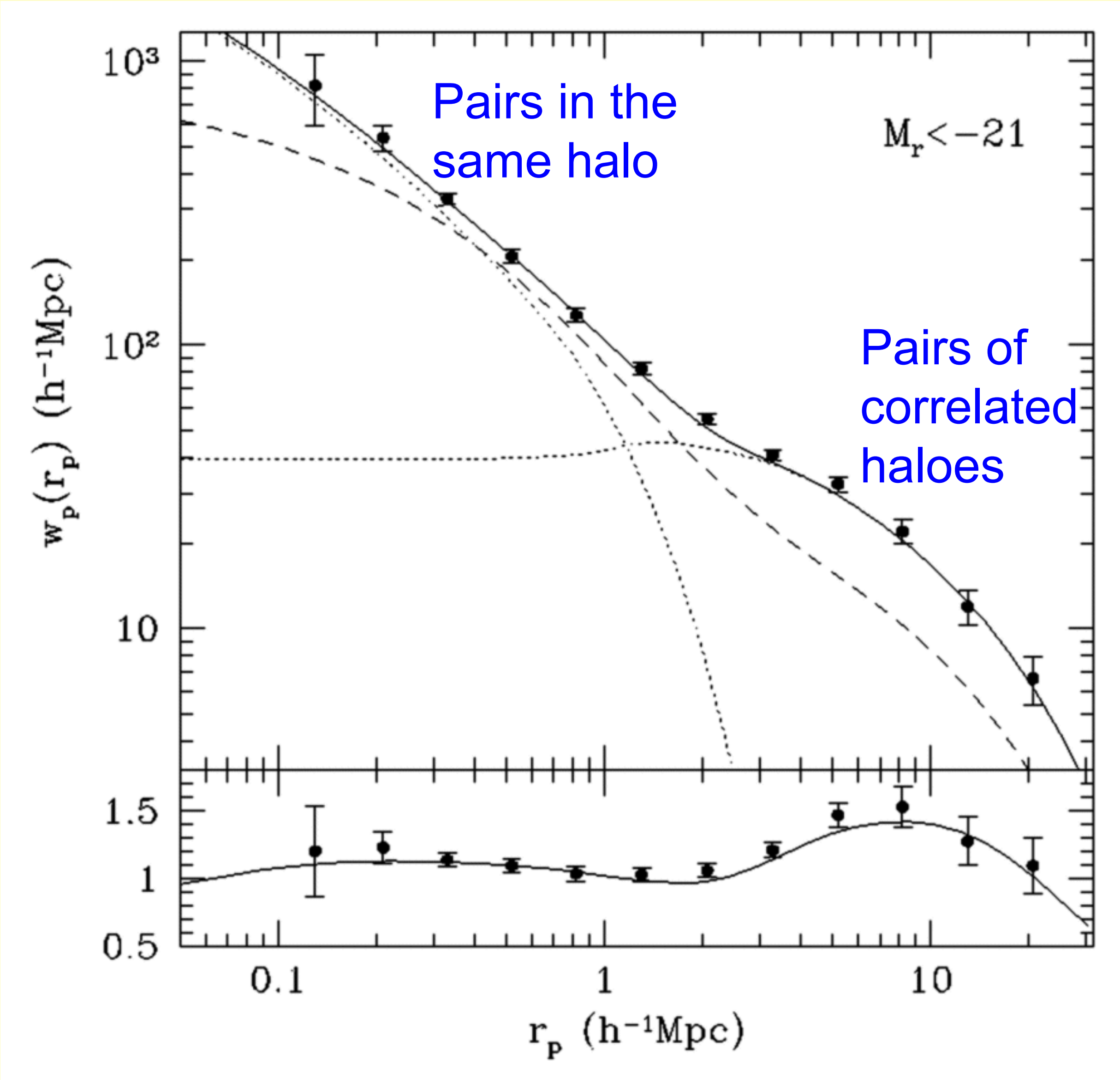


SDSS

- Current state of the art
- 1.8M z's 2002-2013



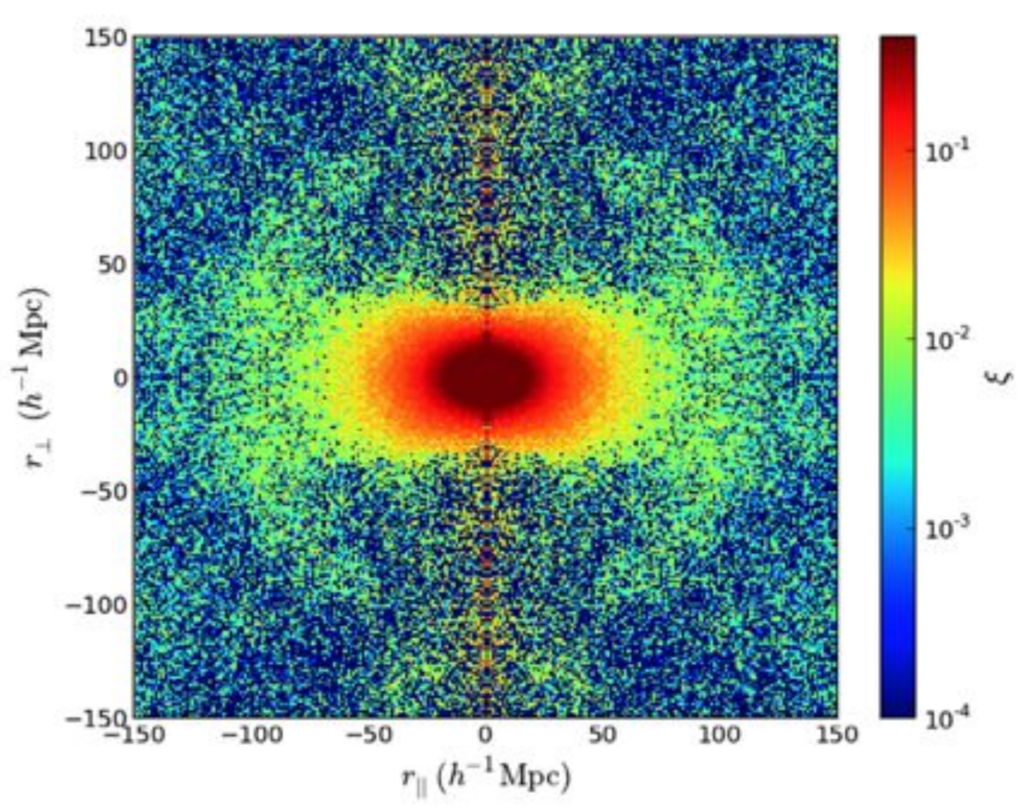
1-halo to 2-halo transition seen

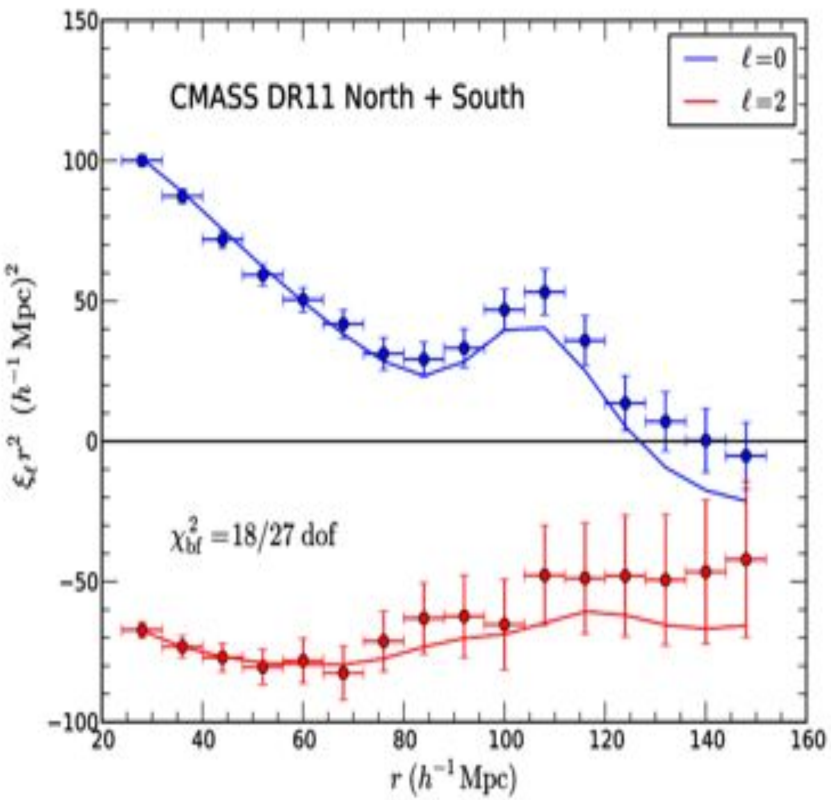


Zehavi et al. 2003

Luminous SDSS galaxies need weight $M^{-0.11}$ for $M > M_{min} = 10^{13.6}$

BOSS DR11 (Samushia et al. 1312.4899)





690826 galaxies over 8498 deg^2 (V=6.0 Gpc^3)

Growth rate: $f\,\sigma_8$ = 0.447 ± 0.028 (6%)

Big SDSS achievement: use of BAO ruler for D(z)

eBOSS (2014-2019): 10 X BOSS volume

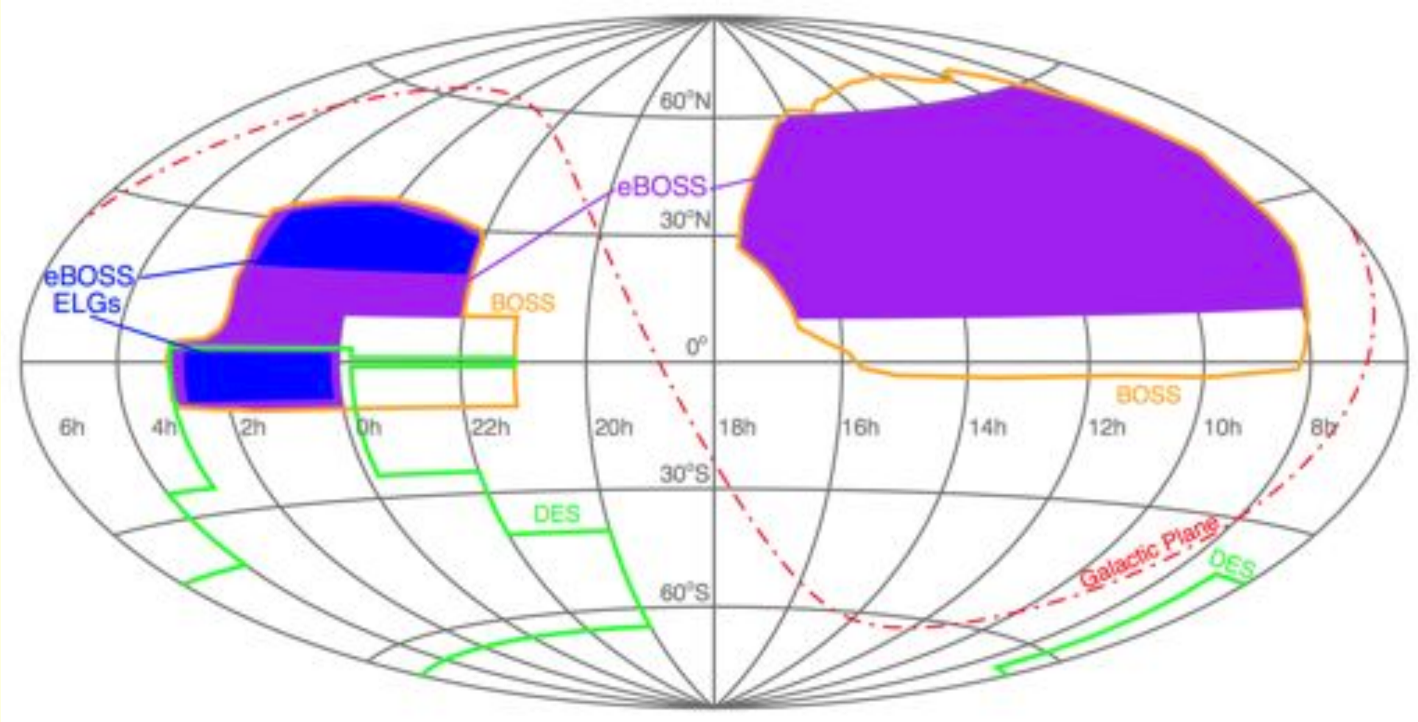
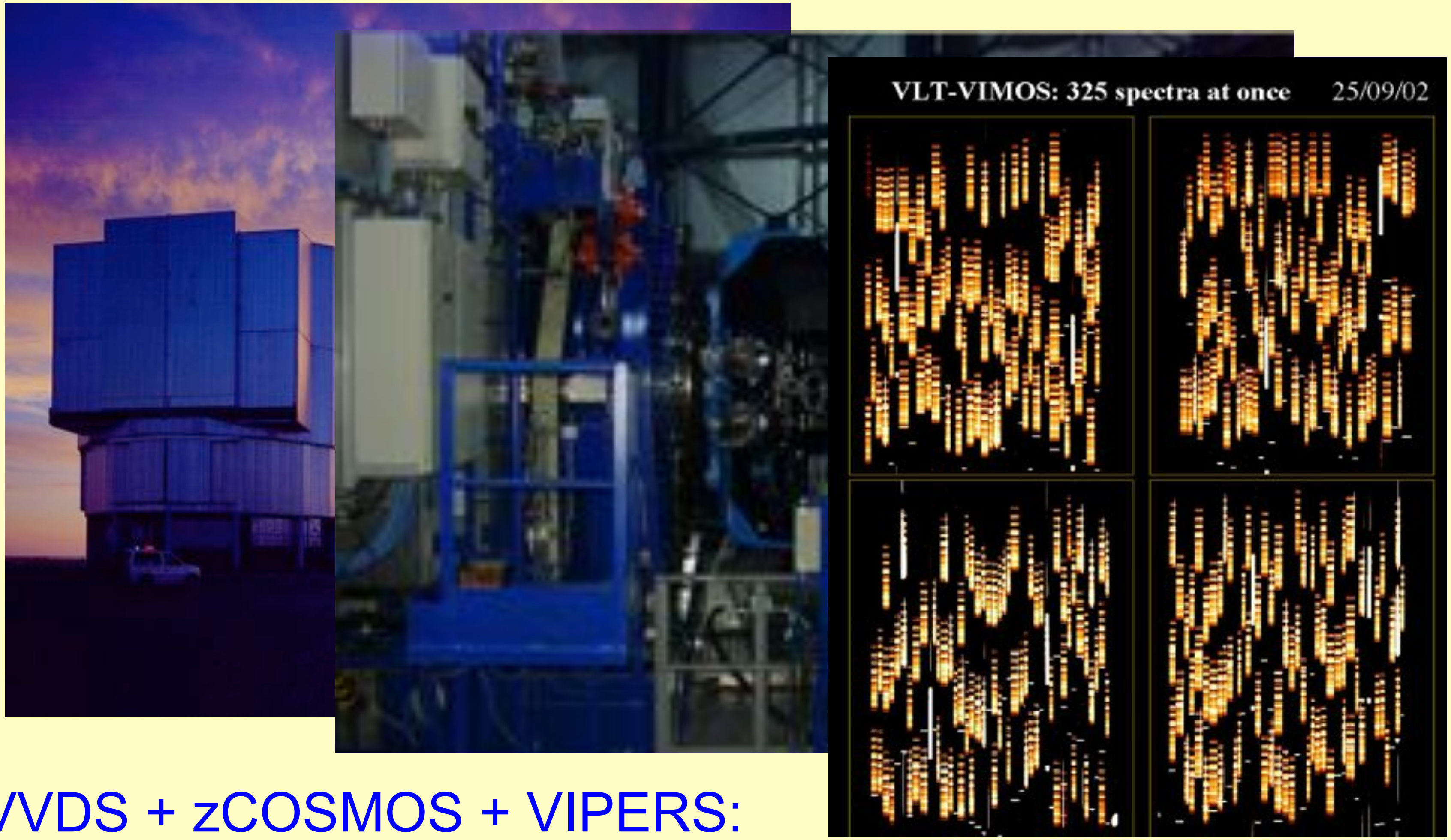


Table 1: Basic parameters expected for each eBOSS sample, together with predictions for the effective volumes and fractional constraints on BAO distance measurements and growth of structure.

Sample	N_{target}	purity	$\bar{n}_{peak}$ $(h^{-1}\mathrm{Mpc})^{-3}$	V_{eff} Gpc^3	σ_R/R	$\sigma_{f\sigma_8}/f\sigma_8$
LRGs $0.6 < z < 0.8$	375,000	95%	1.4×10^{-4}	4.5	0.009	0.029
ELGs $0.6 < z < 1$	270,000	80%	3.4×10^{-4}	2.1	0.018	0.035
Quasars $1 < z < 2.2$	675,000	70%	0.21×10^{-4}	4.4	0.020	0.036
BOSS LyA Quasars	160,000	—	–	–	0.015	–
BOSS + eBOSS LyA Quasars	310,000	70%	–	–	0.011	–

Focus on N(z) is unfair on high-z surveys

VIMOS: Multi-Slit Spectroscopy at the VLT: 4 x (7’ x 8’)

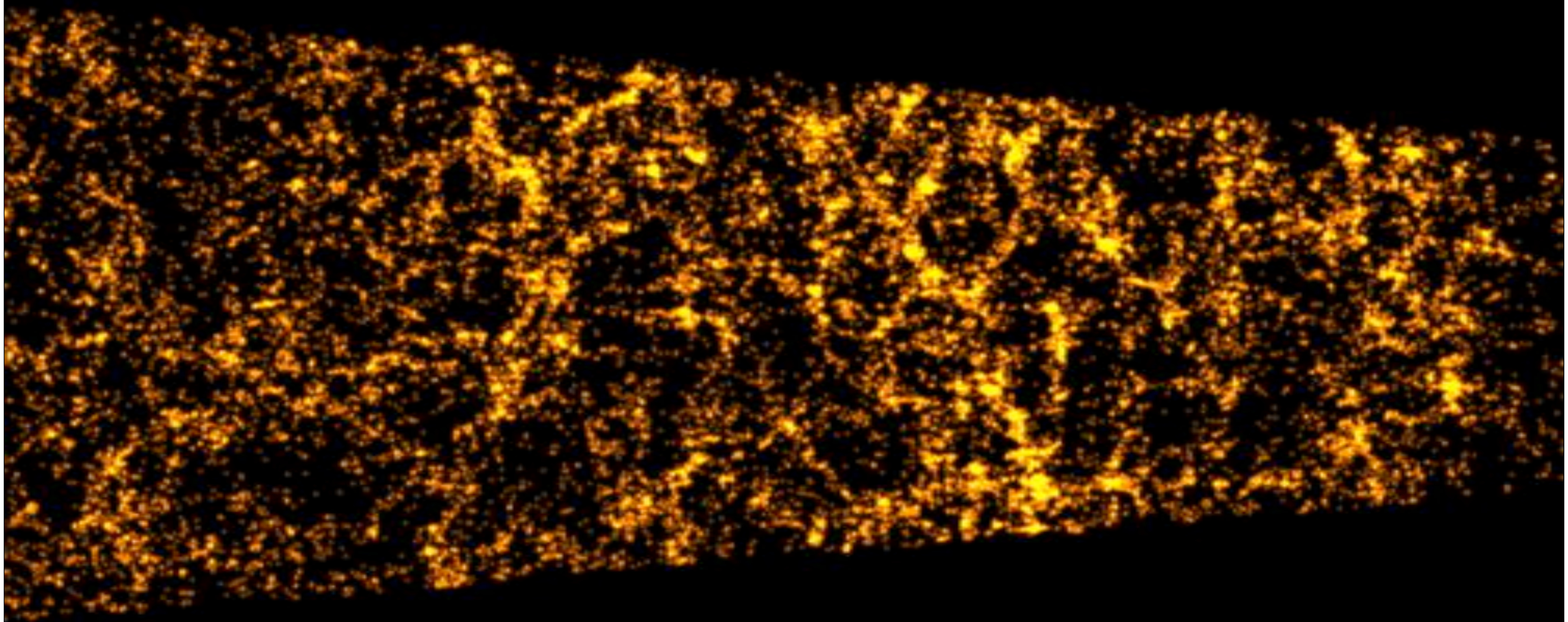


VVDS + zCOSMOS + VIPERS:

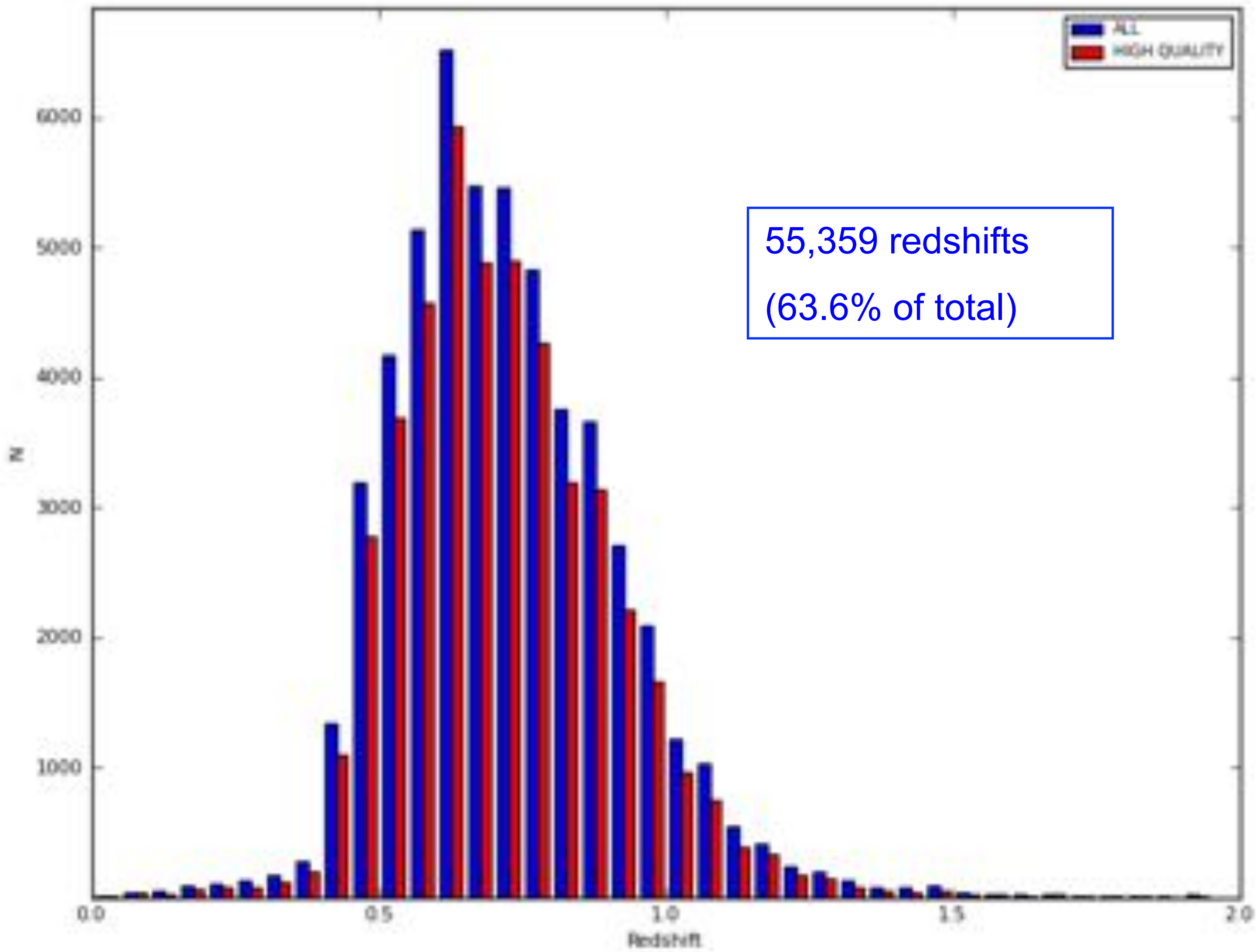
180,000 z’s up to z~1 over 2003-2014

− also DEEP2: 38,000 z’s on Keck 2002-2005

Studying the cosmic web at redshift 1 with VIPERS

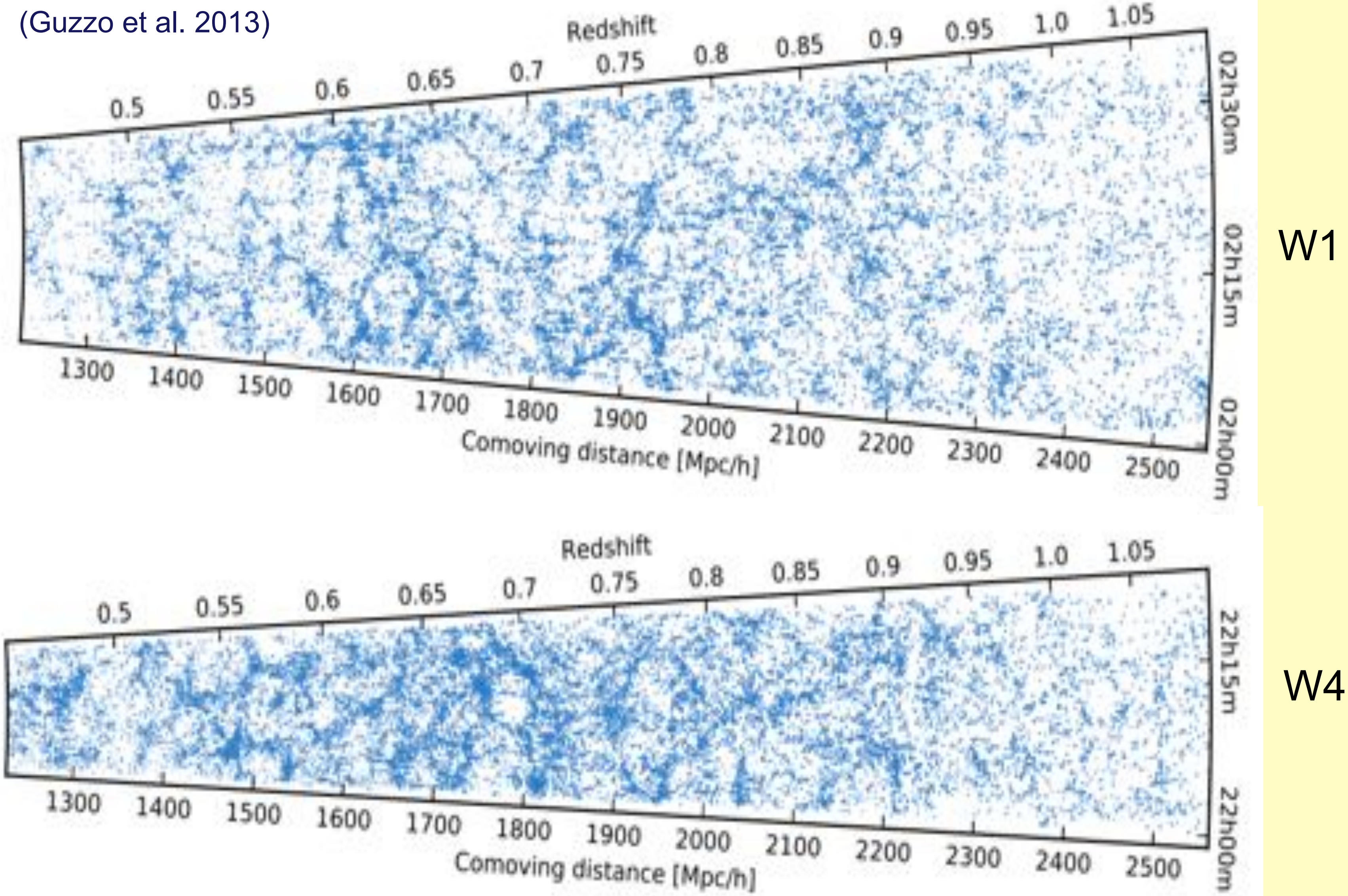


Colour cut to focus on z > 0.6



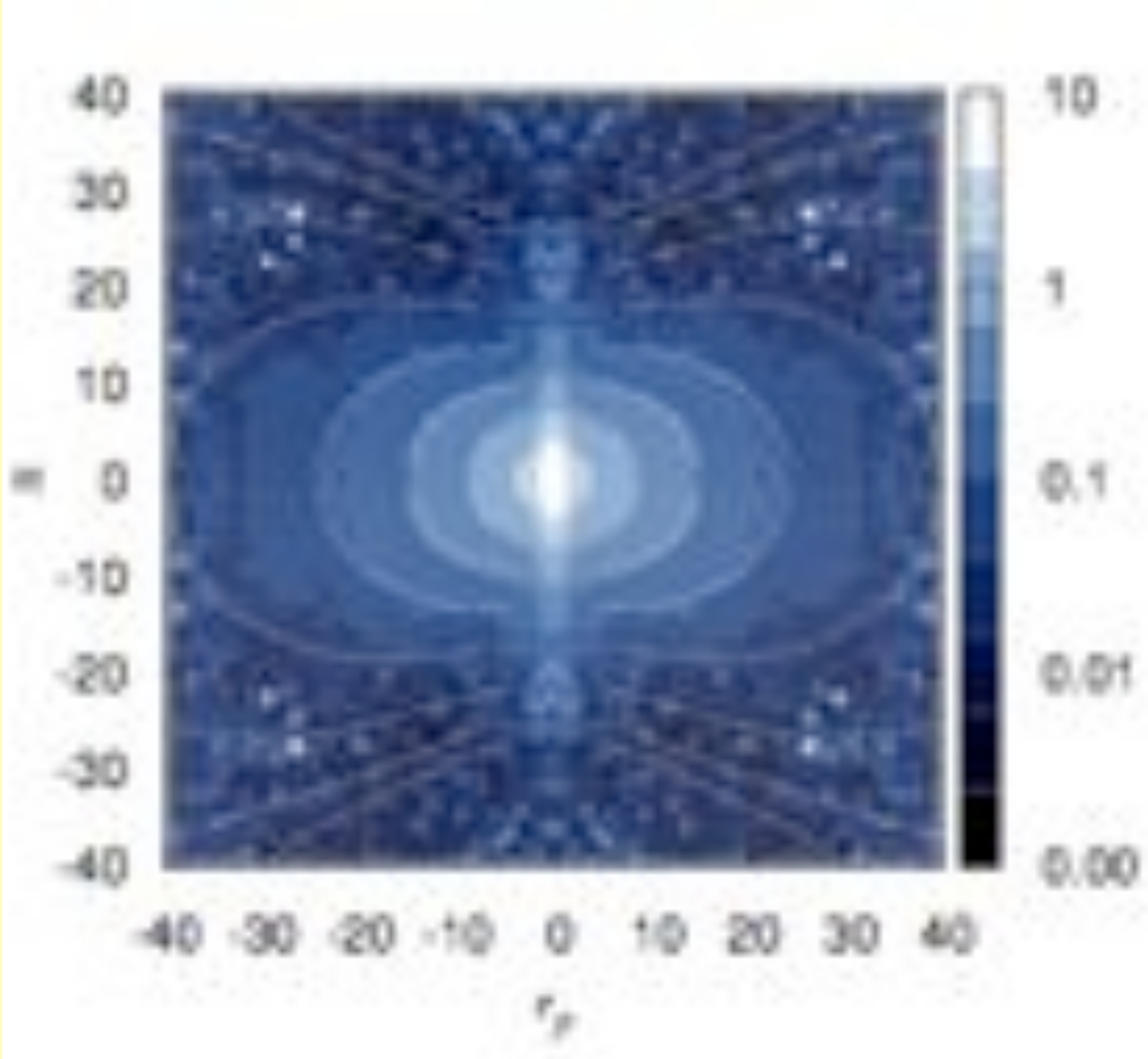
VIPERS V3.0 density field: 55,359 redshifts (64% of total survey)

(Guzzo et al. 2013)

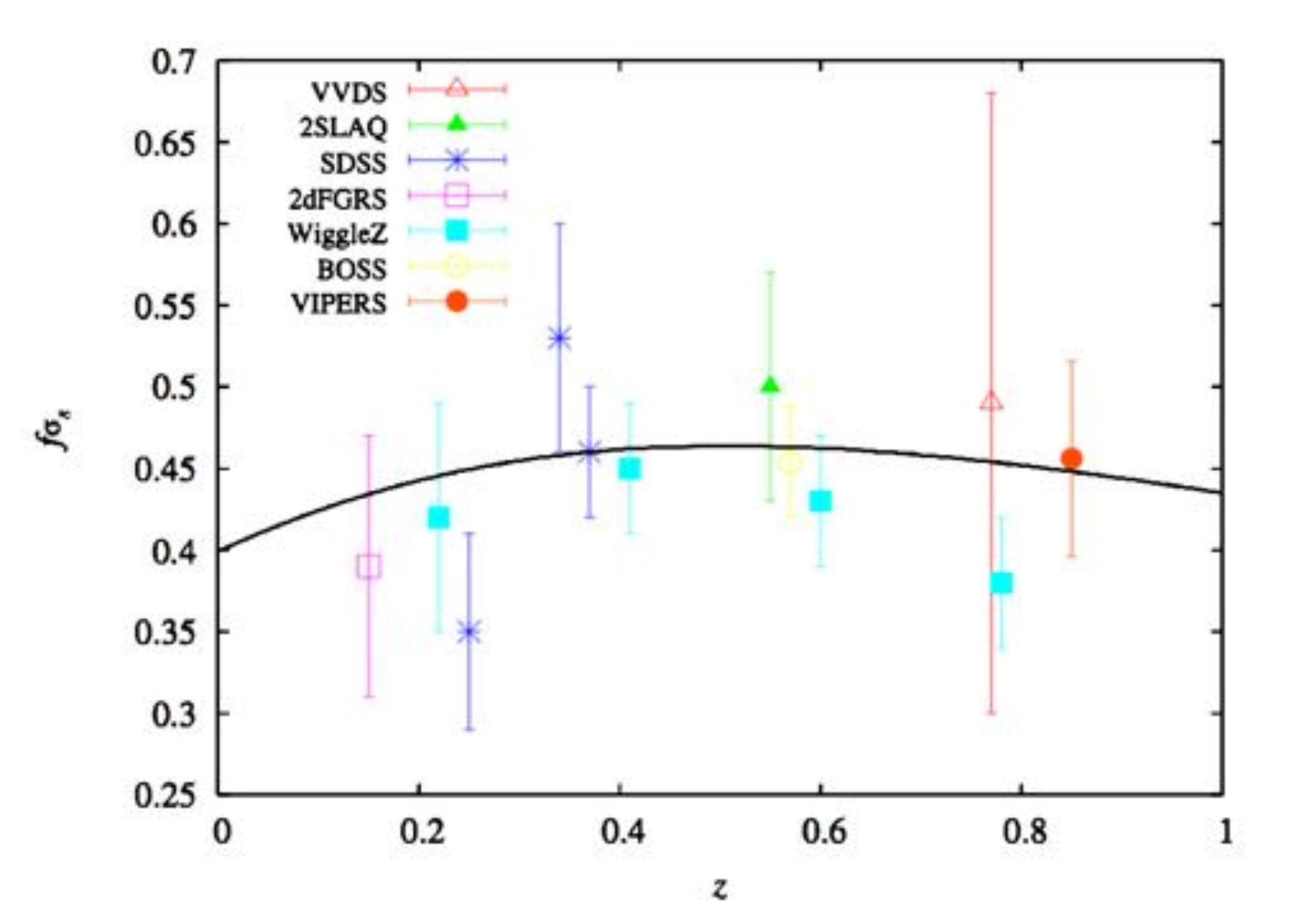


2D correlation function

- VIPERS 3.0 sample is mostly probing to nonlinear and quasi-nonlinear scales: need non-linear modelling
- Fitting scales: 5 Mpc/h $< r_p <$ 40 Mpc/h
- Small-scale slit-collision bias corrected
- Proper covariance matrix using realistic mock surveys (de la Torre et al. 2013)
- $f\sigma_8$ = 0.47 ± 0.08 at $\langle z \rangle$=0.85



Growth rate: current state



DESI (BigBOSS), eBOSS (SDSS-IV), Sumire-PFS (WFMOS), Euclid will push towards 1% precision at higher z – eventually

RSD as test of modified gravity

(Guzzo et al. 2008)

- Adopt longitudinal gauge (in effect gauge-invariant)

$$d\tau^2 = (1+2\Psi)dt^2 - (1-2\Phi)\gamma_{ij}\, dx^i\, dx^j$$
$$\text{Einstein: } \nabla^2\Phi/a^2 = 4\pi G\,\bar\rho\,\delta \text{ and } \Psi = \Phi$$

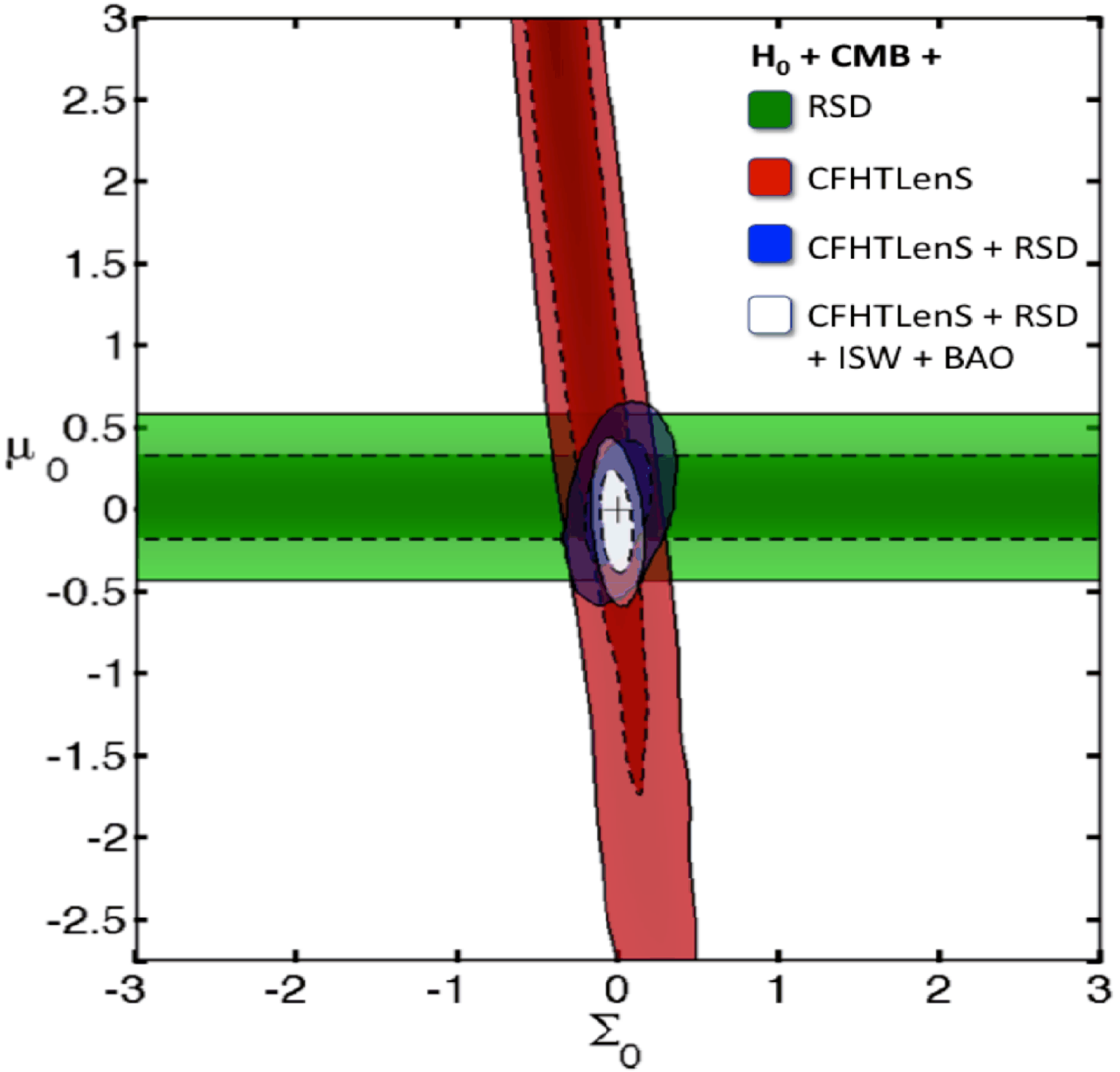
- In MG, potentials can differ (‘slip’: affects lensing), plus Poisson equation is modified.
- No standard notation. Good refs are Skordis (0806.1238) or Daniel et al. (1002.1962). Assume modifications negligible at high z, since no DE then:

$$\Phi = (1+\varpi(a,k))\Psi; \qquad \nabla^2\Phi = \mu(a,k)\,4\pi G\,\bar\rho\,\delta$$

- Combine to affect growth of fluctuations

$$d\ln\delta/d\ln a \simeq \Omega_m(a)^\gamma; \qquad \gamma_{\rm Einstein} = 0.55$$

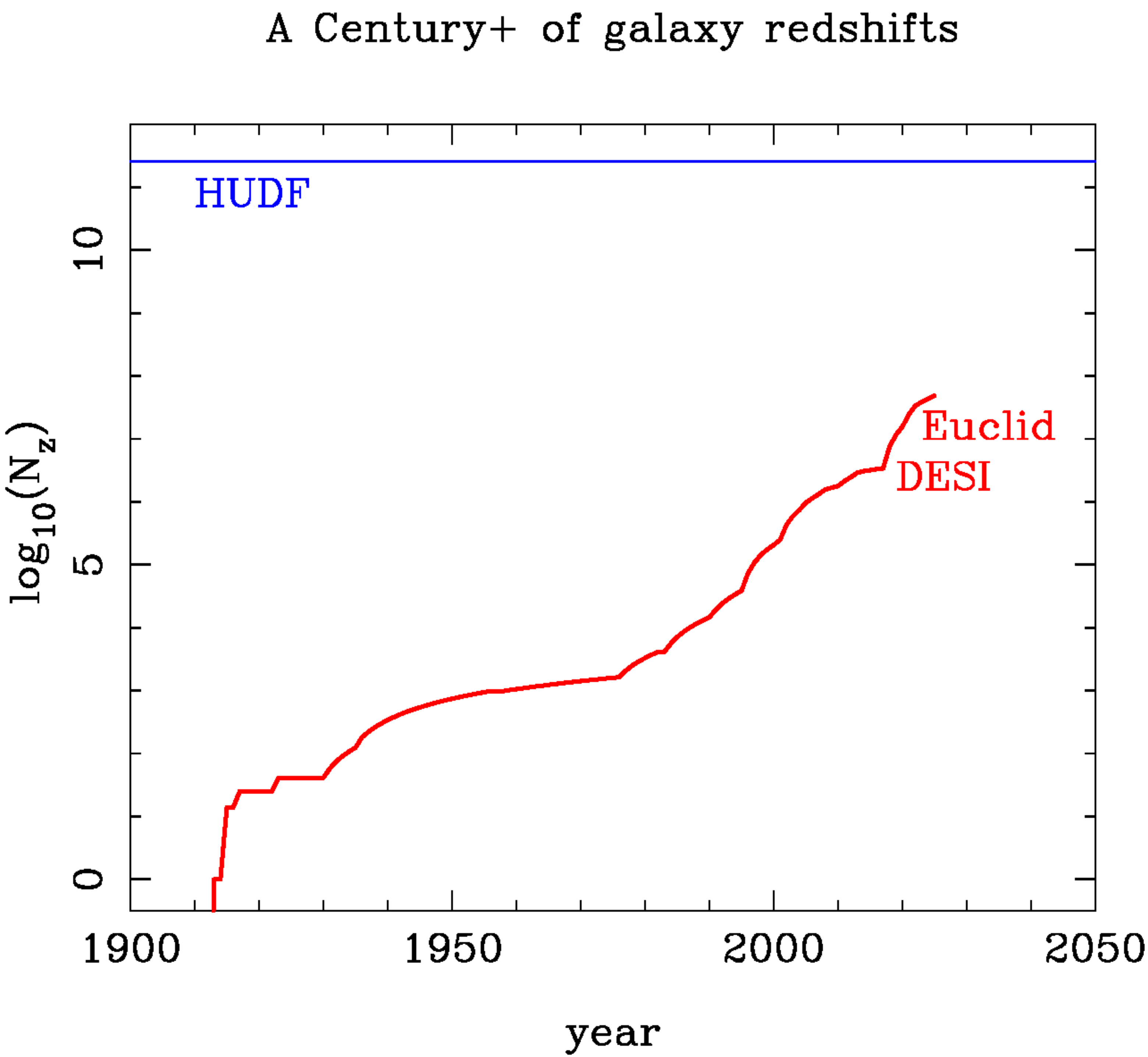
Add lensing for overall MG constraints (1212.3339)



$$\Psi = [1 + \mu(k,a)]\Psi_{\rm E}$$
$$(\Psi + \Phi) = [1 + \Sigma(k,a)](\Psi_{\rm E} + \Phi_{\rm E})$$

Relation to effective G and slip are

$$1 + \mu = (G'/G)/\eta;$$
$$1 + \Sigma = (G'/2G)(1 + 1/\eta)$$



A Century+ of galaxy redshifts
HUDF
Euclid
DESI
$\log_{10}(N_z)$
0
5
10
1900
1950
2000
2050
year

DESI

DOE proposal for KPNO 4m over 2018-2022:

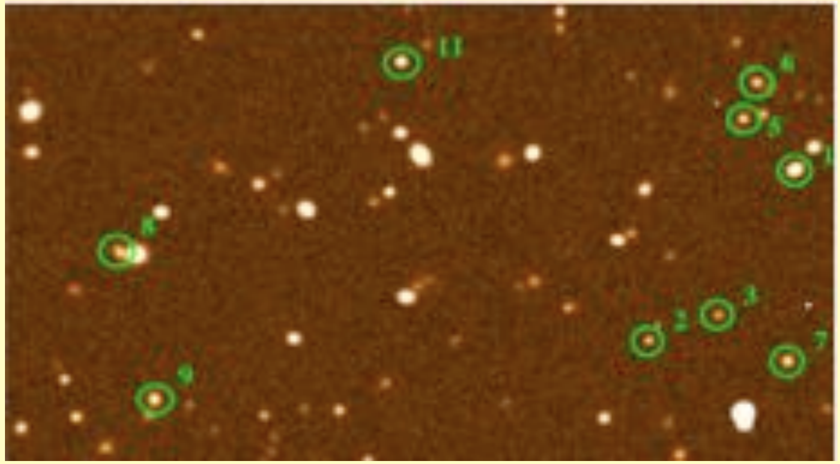
28M galaxies

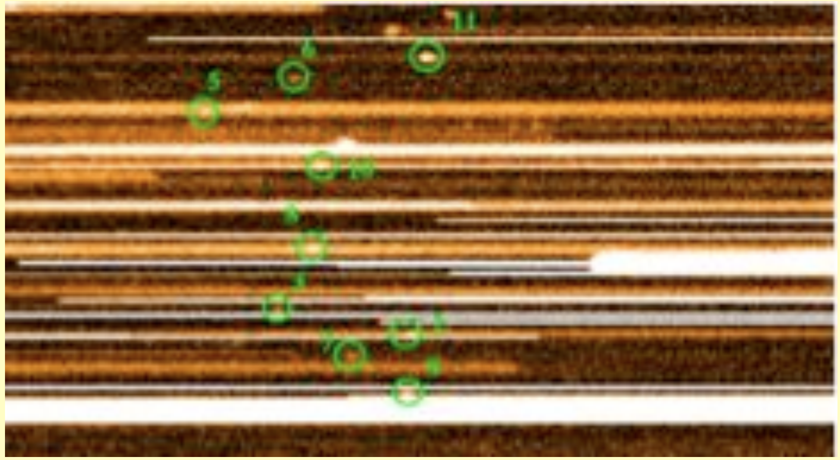
− LRGs to z=0.9

− OII ELGs to z=1.7

(+800k QSOs)

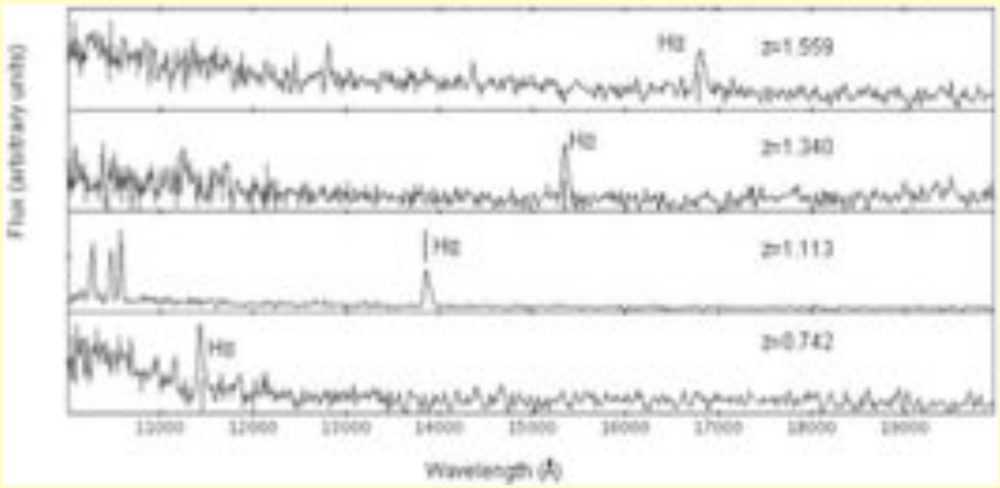
Euclid slitless spectroscopy



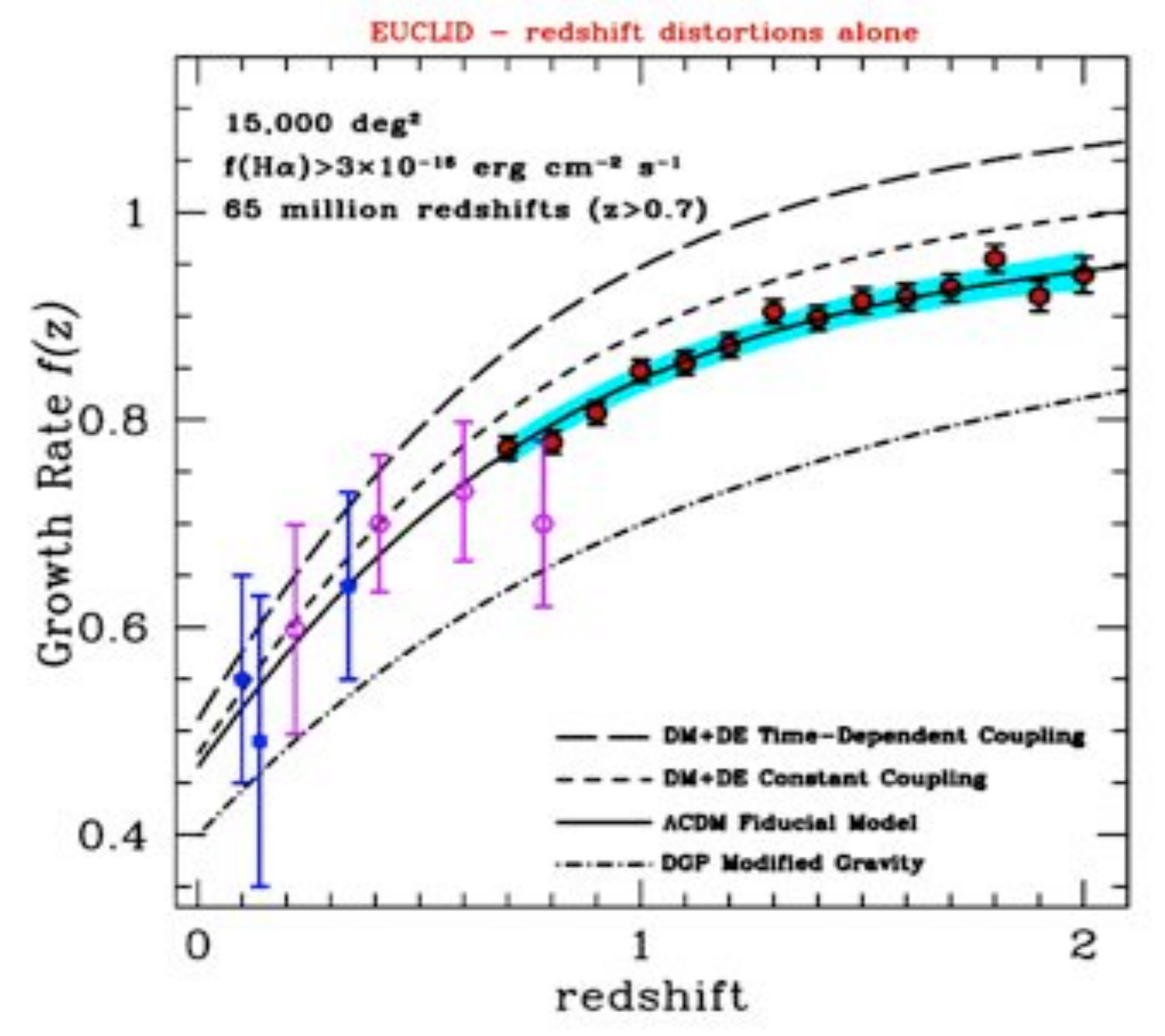


NIS Instrument:

- ~ 25M redshifts to z~2
- 15,000 deg^2
- H < 19.5

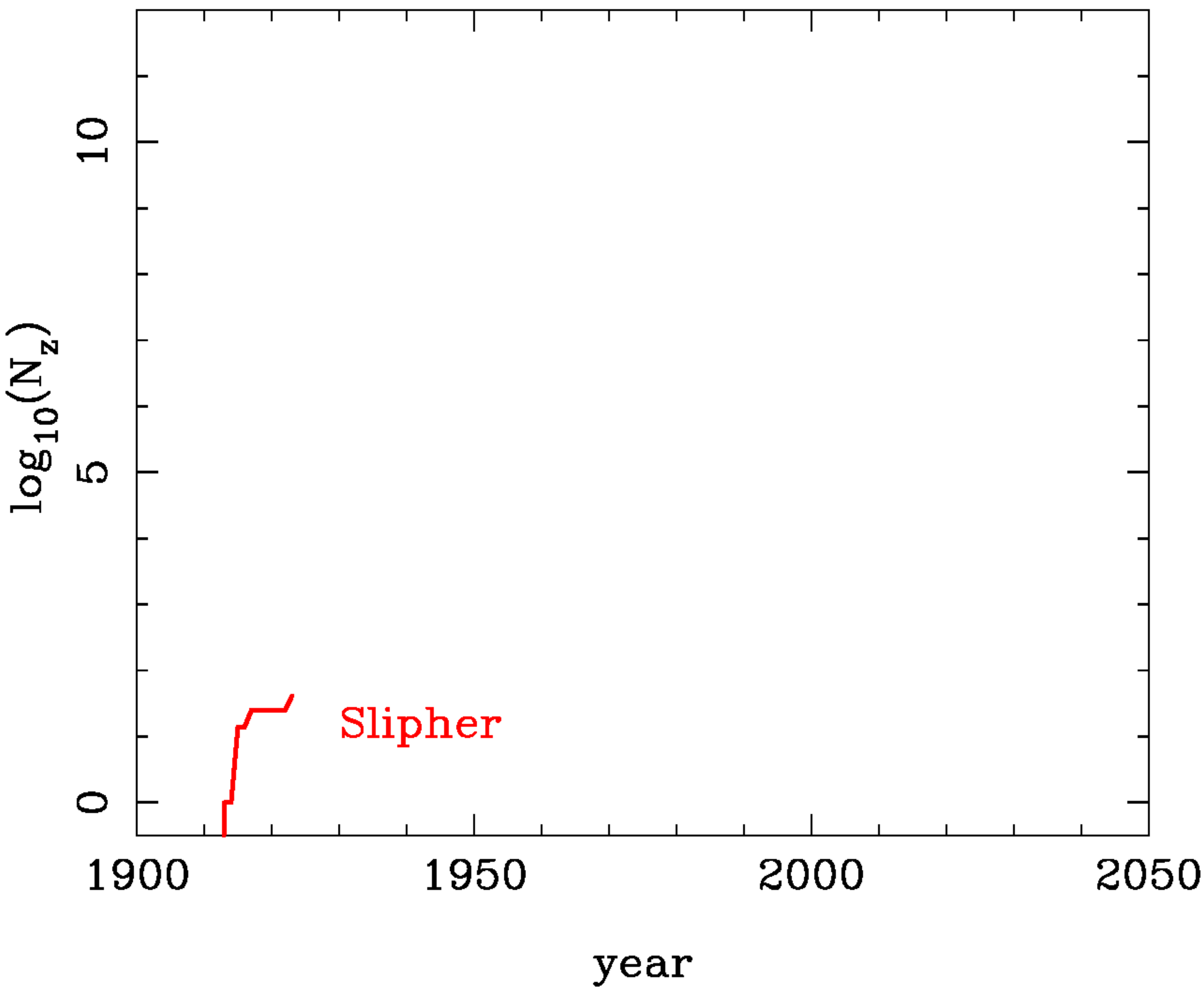


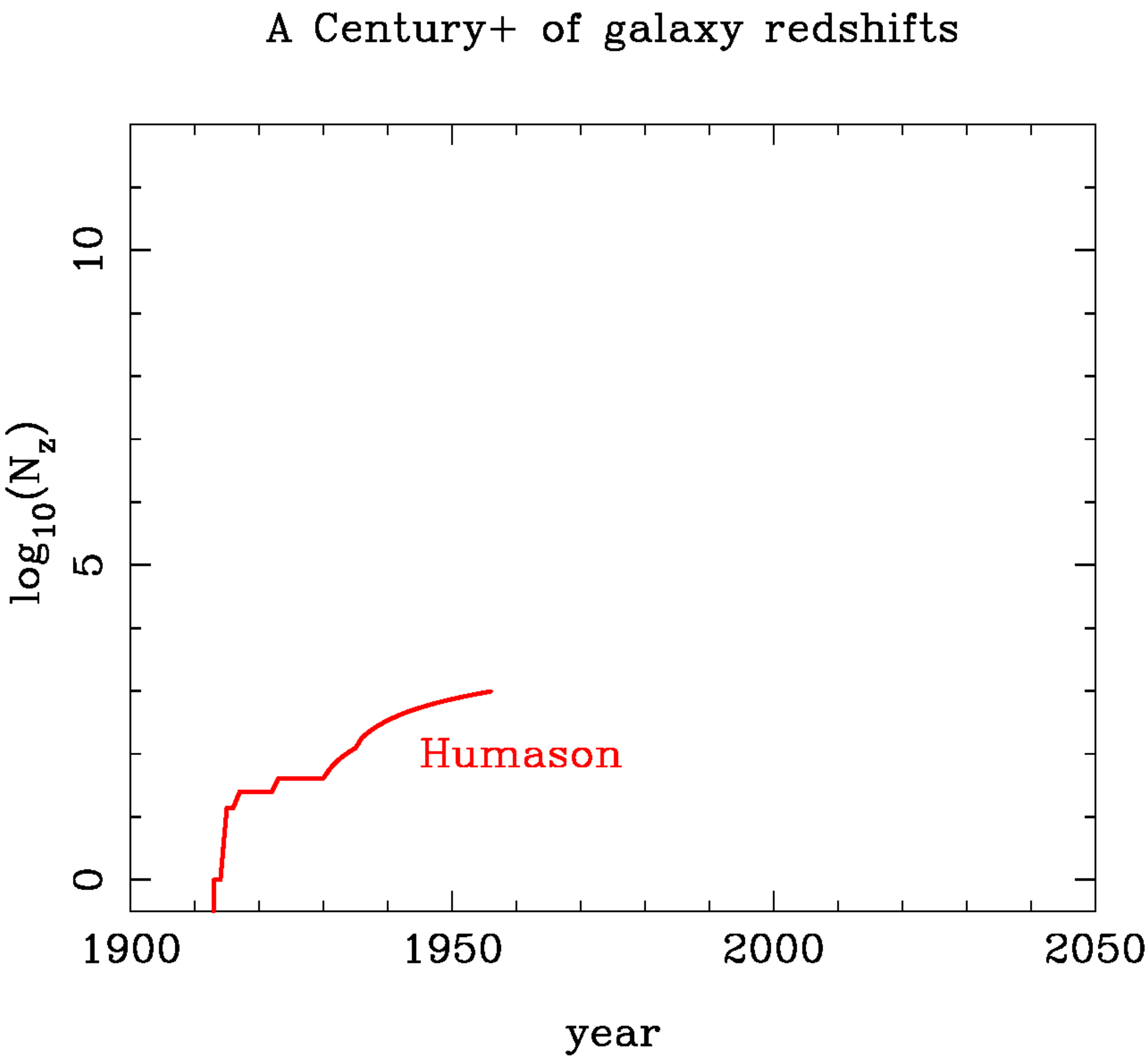
Euclid (2020-)



Need sub-% accuracy modelling: is this feasible?

A Century+ of galaxy redshifts




A Century+ of galaxy redshifts
$\log_{10}(N_z)$
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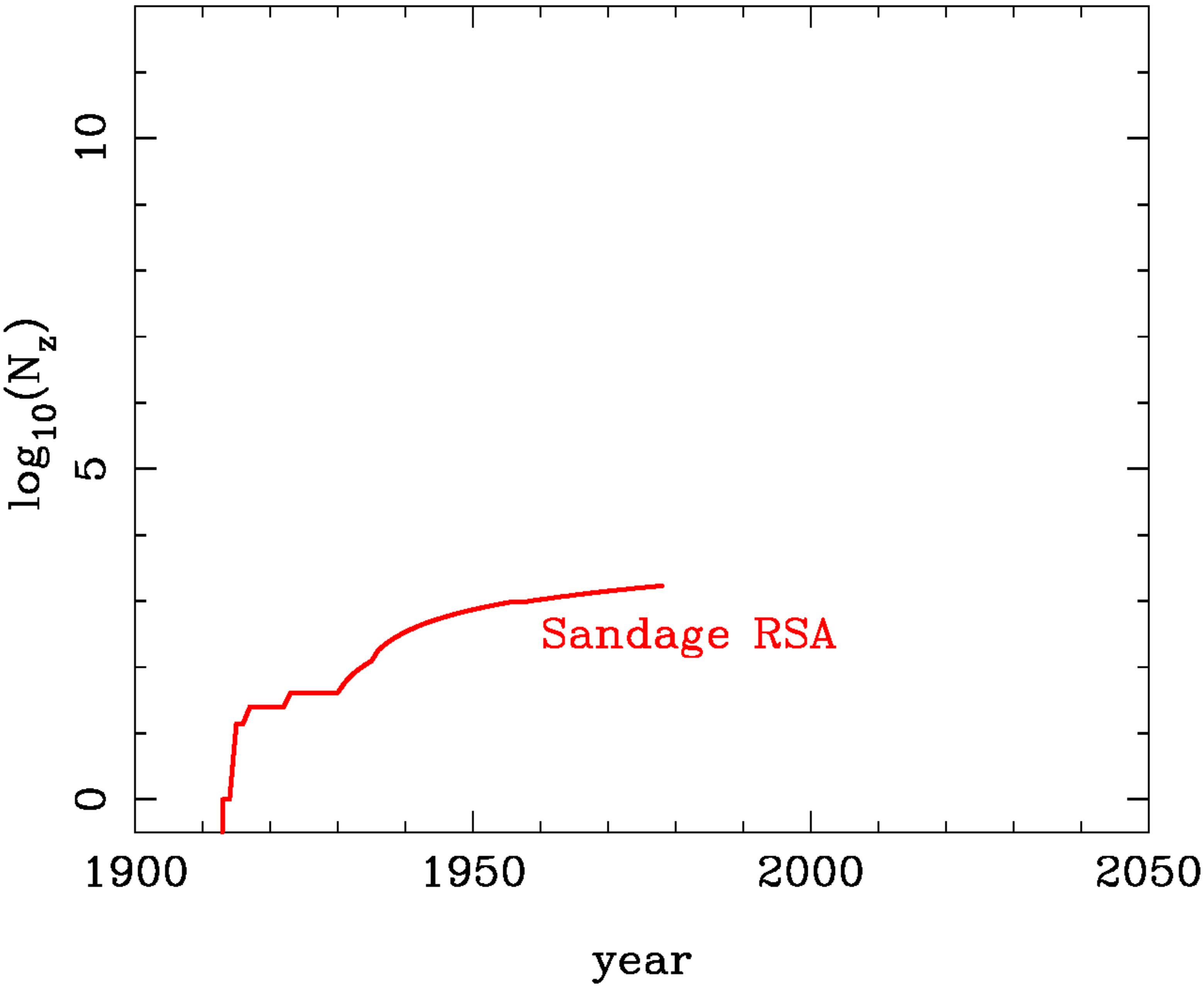
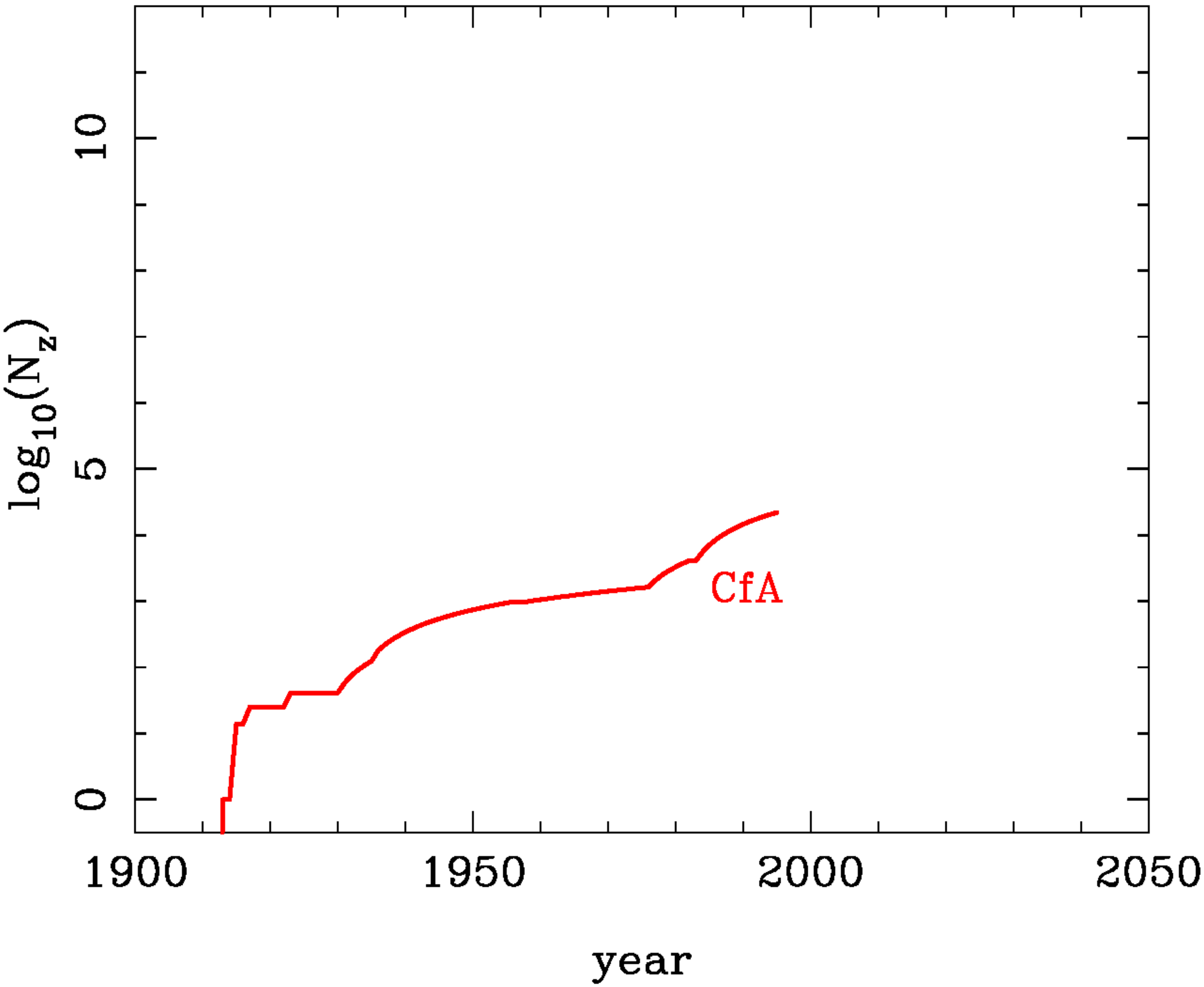
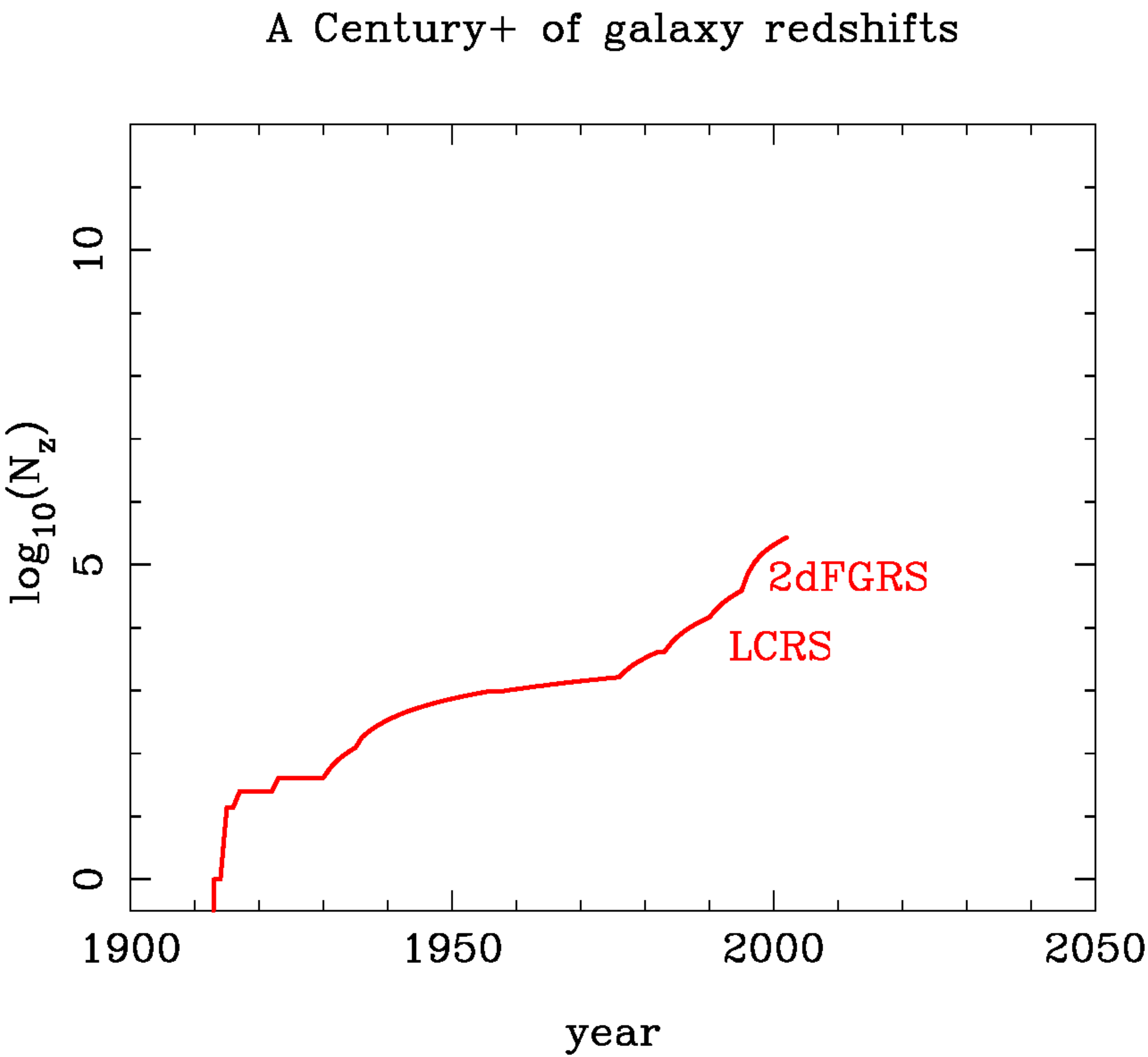
A Century+ of galaxy redshifts



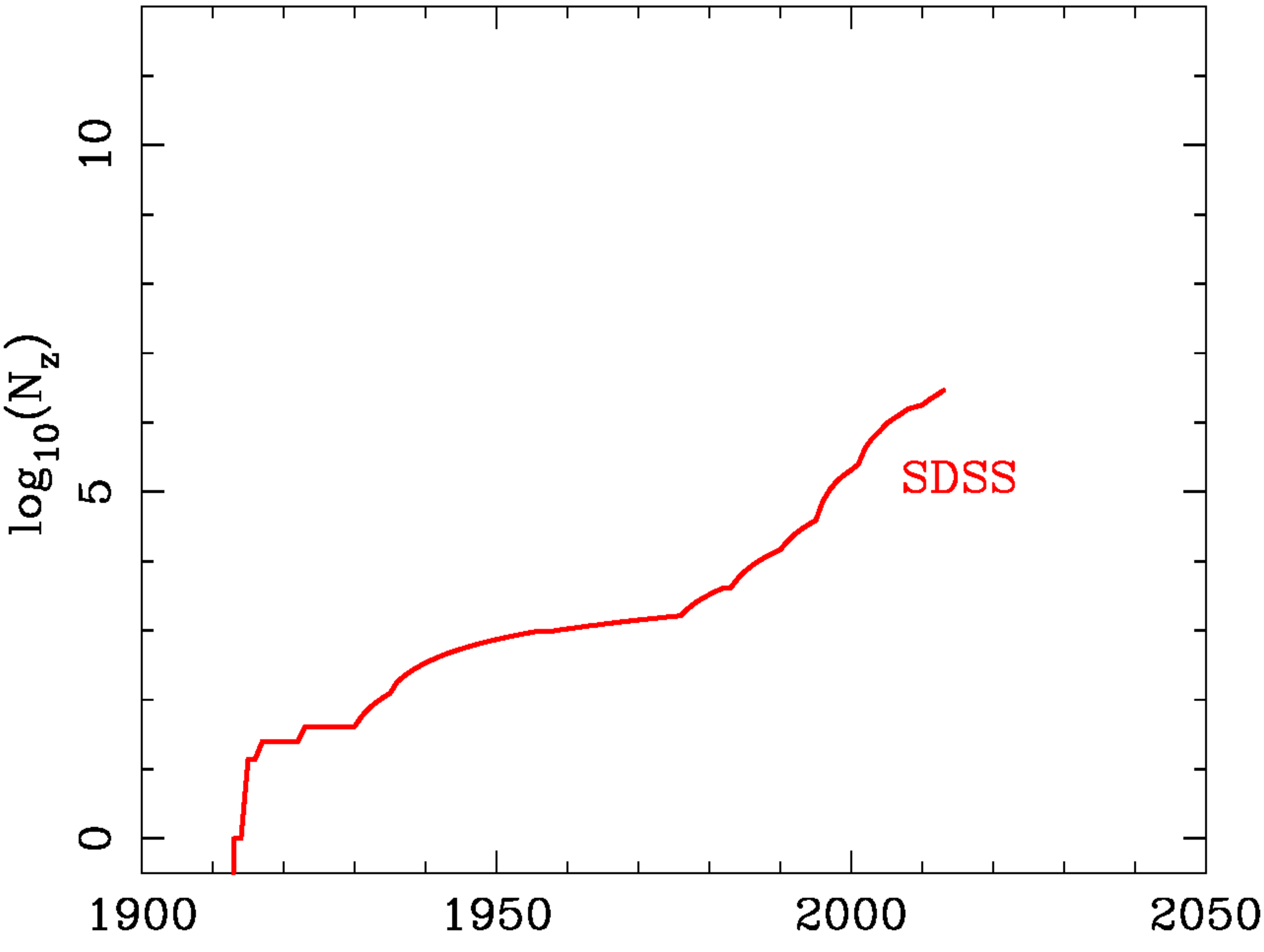
A Century+ of galaxy redshifts



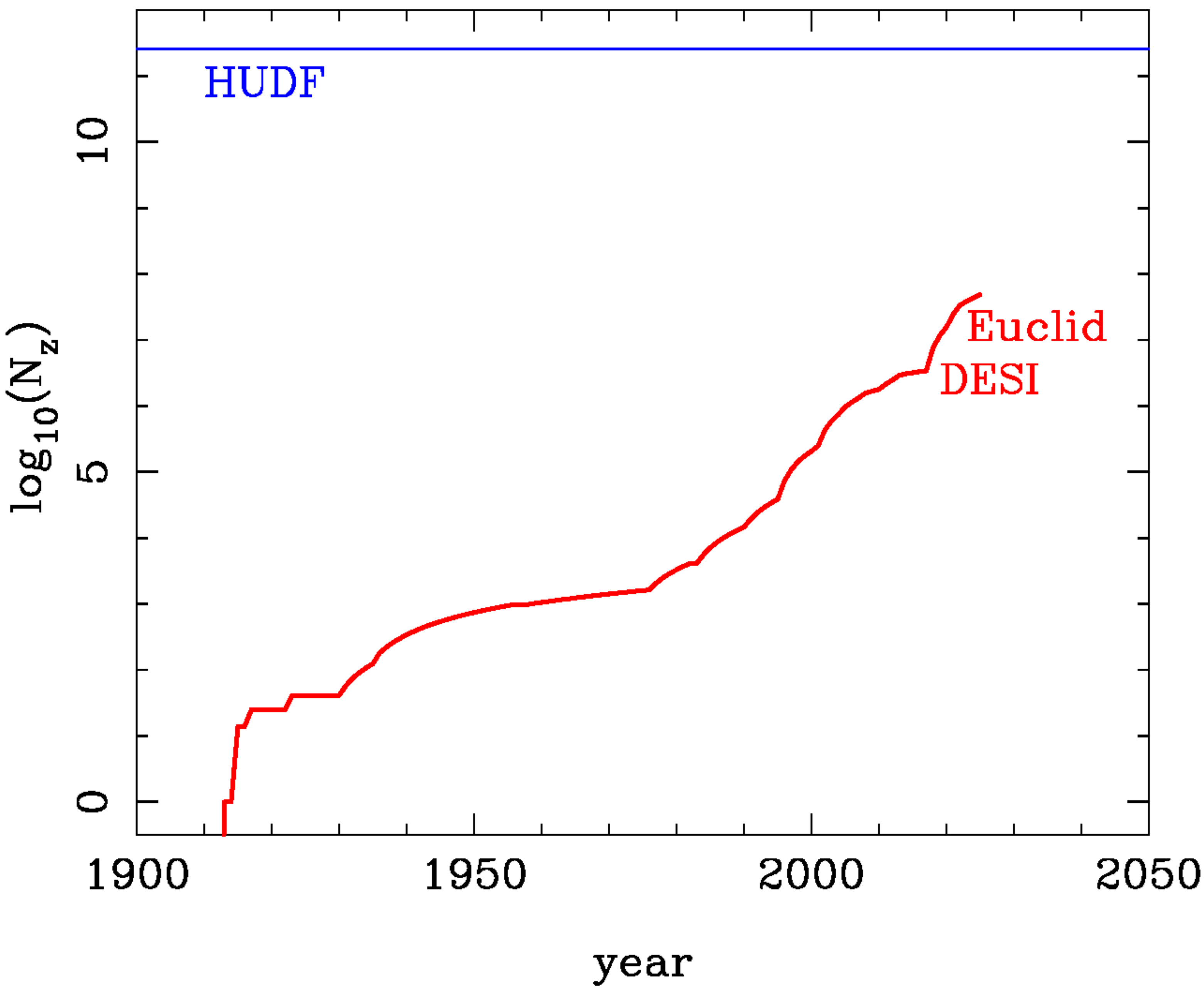


A Century+ of galaxy redshifts
log10(Nz)
0
5
10
1900
1950
2000
2050
year
2dFGRS
LCRS

A Century+ of galaxy redshifts



A Century+ of galaxy redshifts



Conclusions & outlook

- For the past 30 years, MooreZ law: stock of redshifts doubles every 2.6 years
  - Set to continue till 2025 (End of Euclid)
  - 1-10 Billion z's by 2050

- Perhaps no need to go further
  - Other probes may dominate (e.g. reionization-era HI)
  - Will theory be accurate enough to match the data?