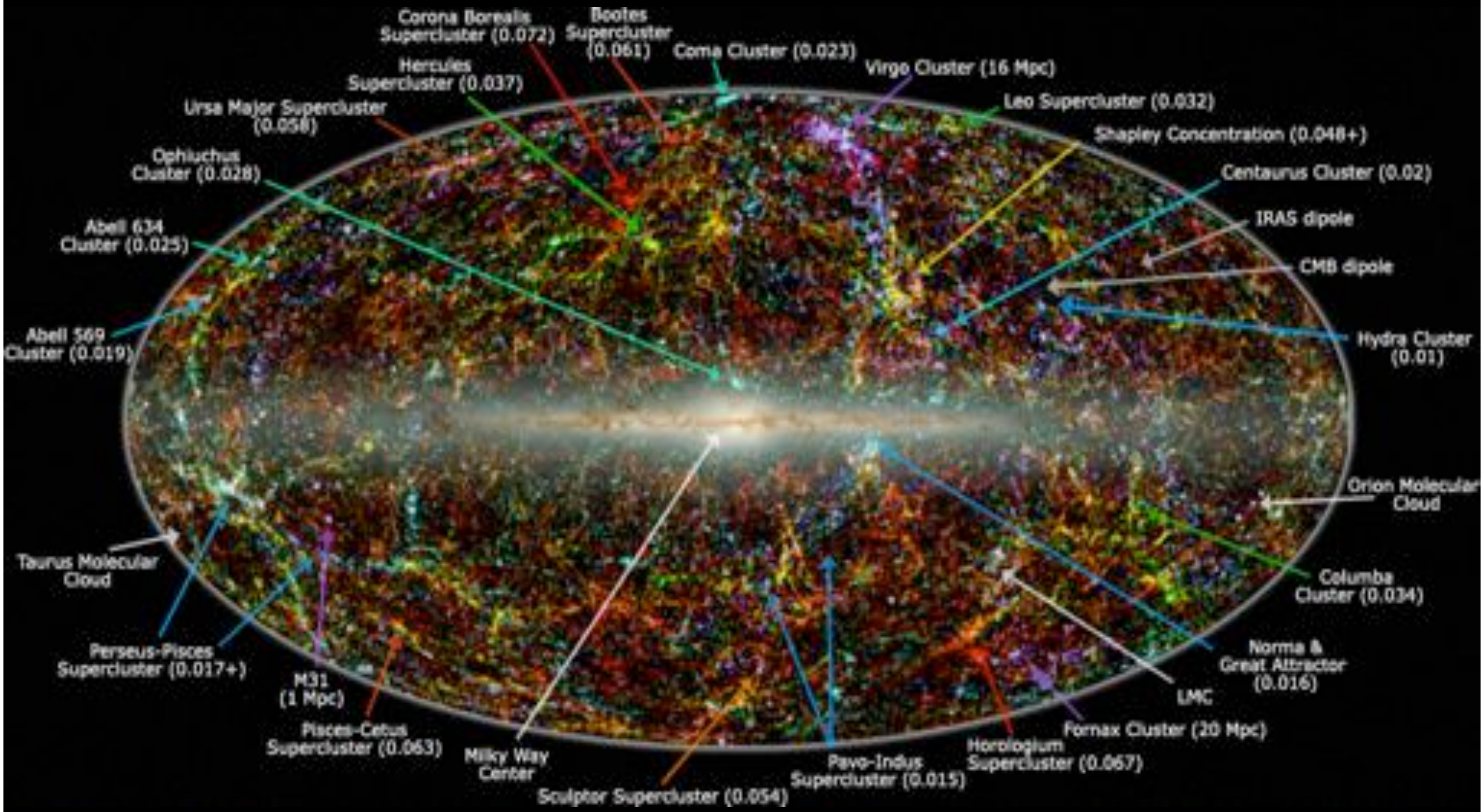
LSS: Achievements & Goals



John Peacock **LSS @ Munich** **20 July 2015**

Outline

- (pre-)history and empirical foundations
- The ΛCDM toolkit
- Open issues and outlook
  - Fundamentalist
  - Astrophysical

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

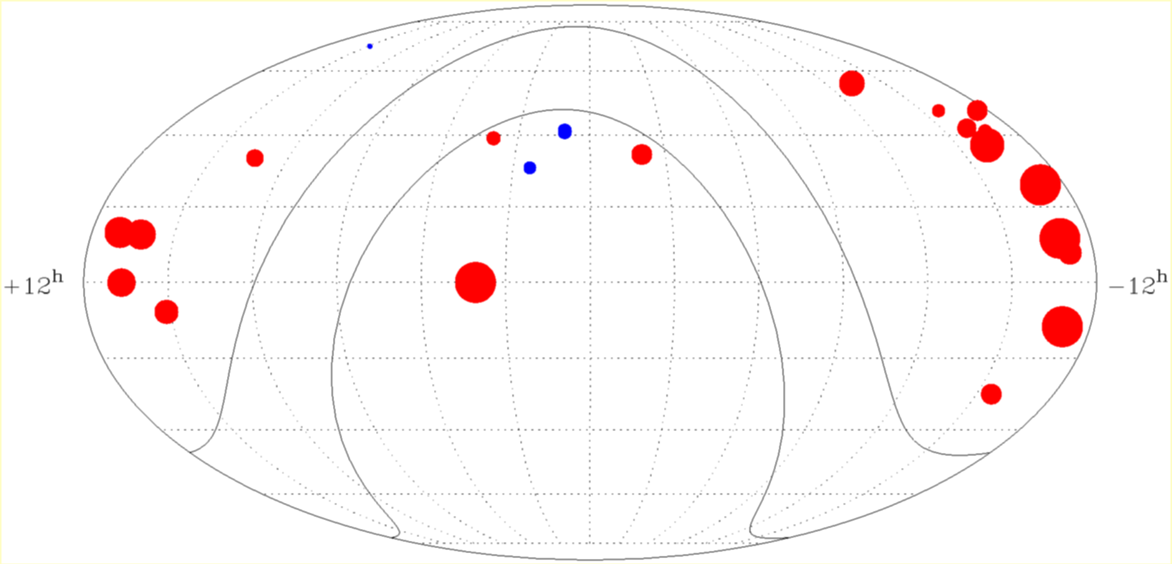
1915: 11/15 v>0

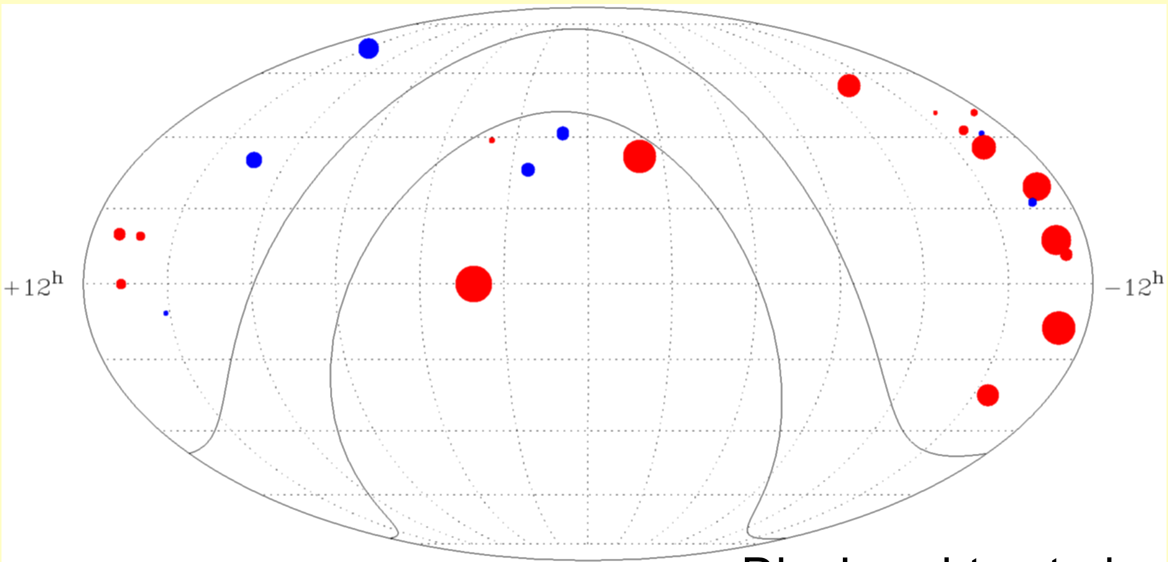
1917: 21/25 v>0

1923: 36/41 v>0

The expanding universe

LSS predates expansion

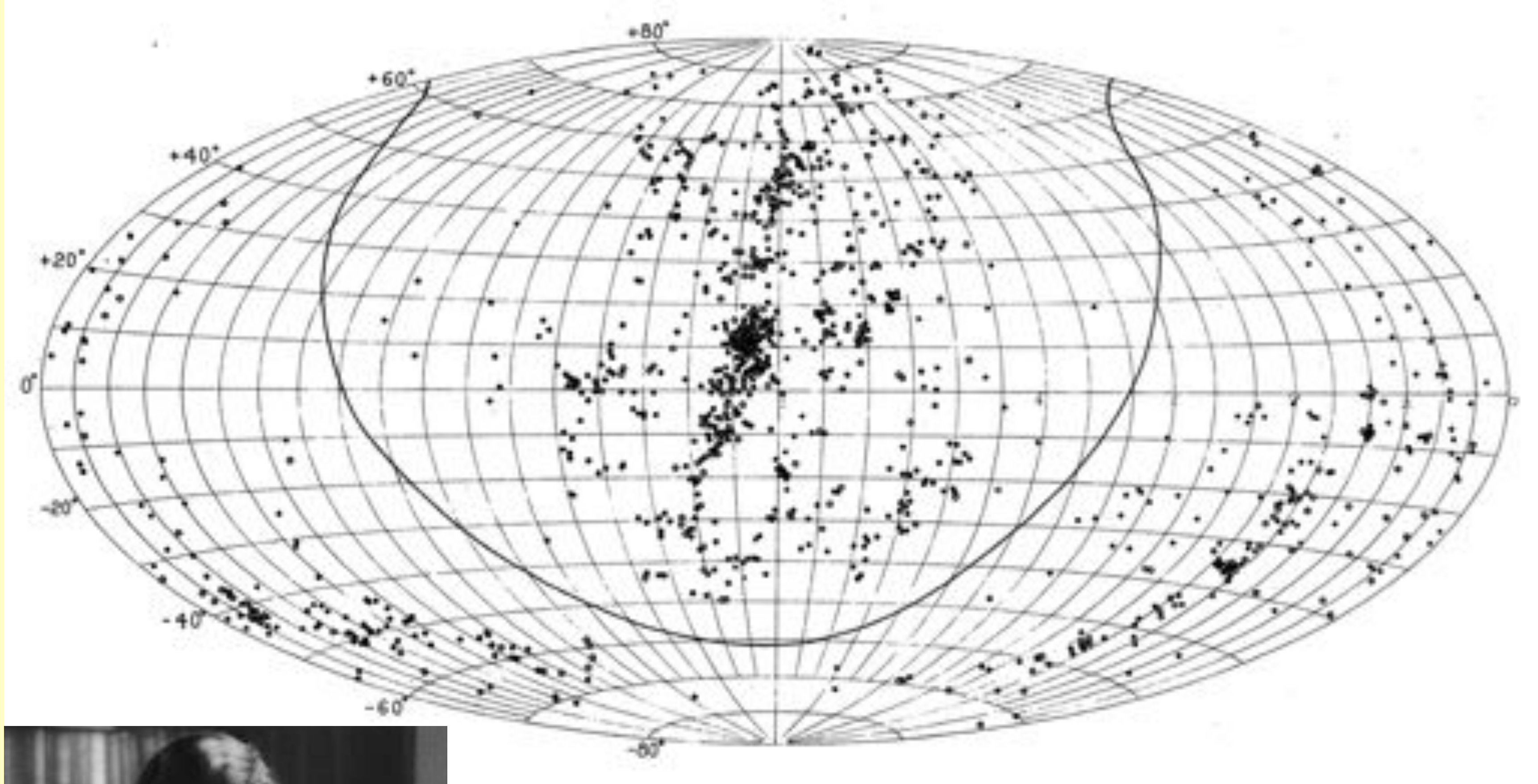




Dipole subtracted

Slipher (1917): MW moves at 700 km/s wrt other nebulae (for which rms v is 400 km/s):

Discovery of cosmic peculiar velocity field

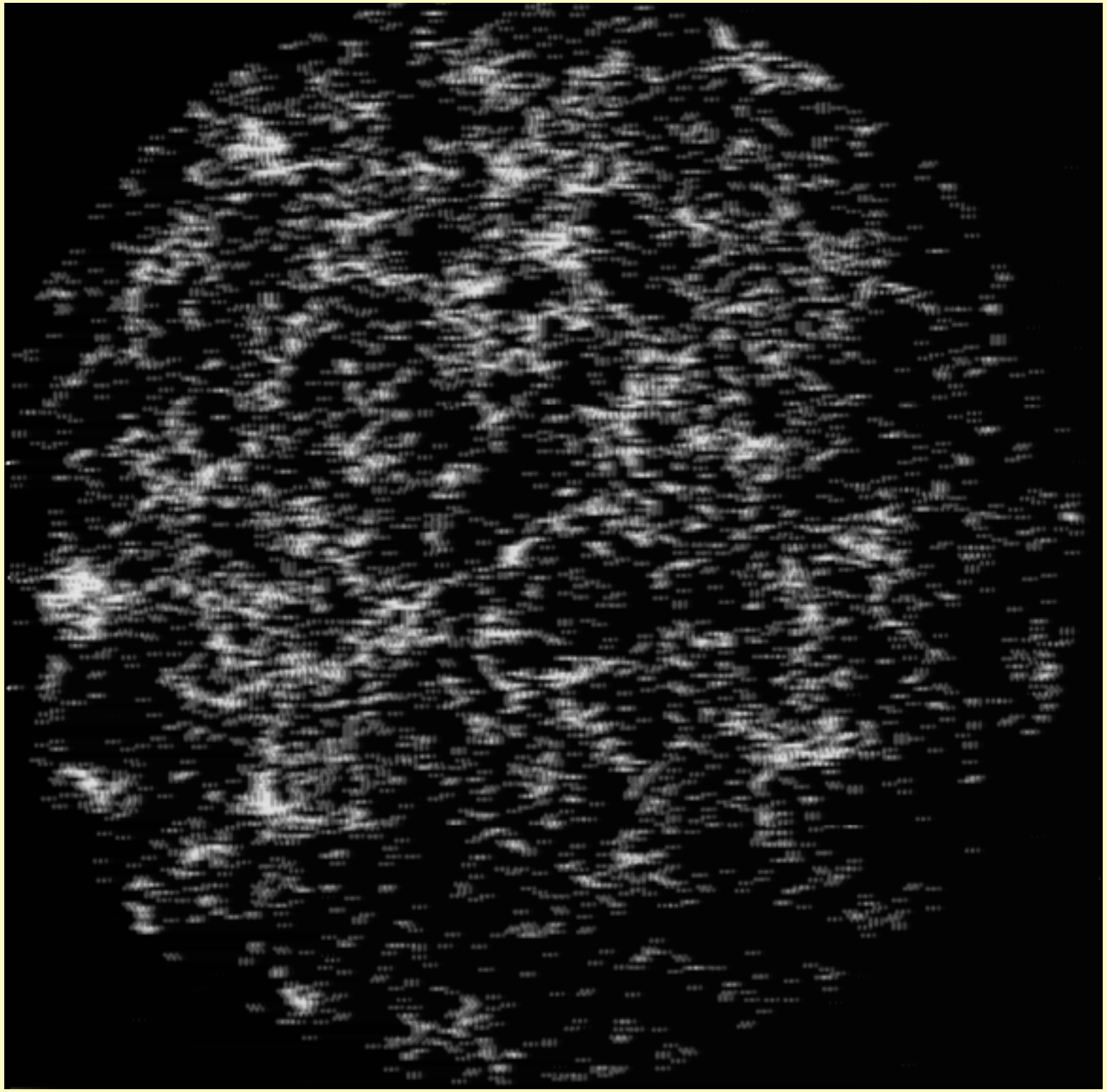


Adelaide Ames (1900-1932)

Shapley & Ames (1932):
1249 galaxies m < 13

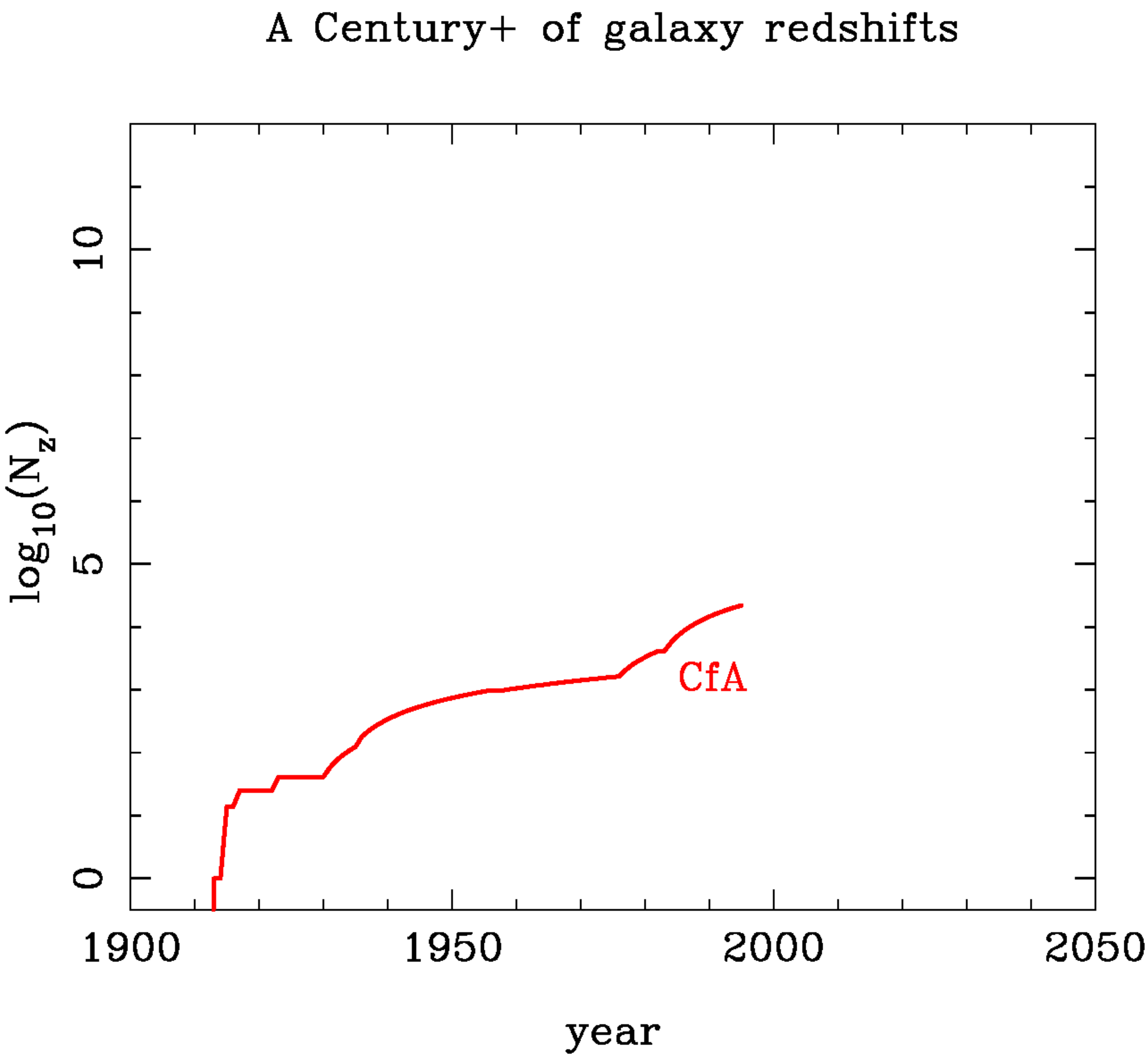
"conspicuous vacant regions"

Pre-1980s: continued angular studies

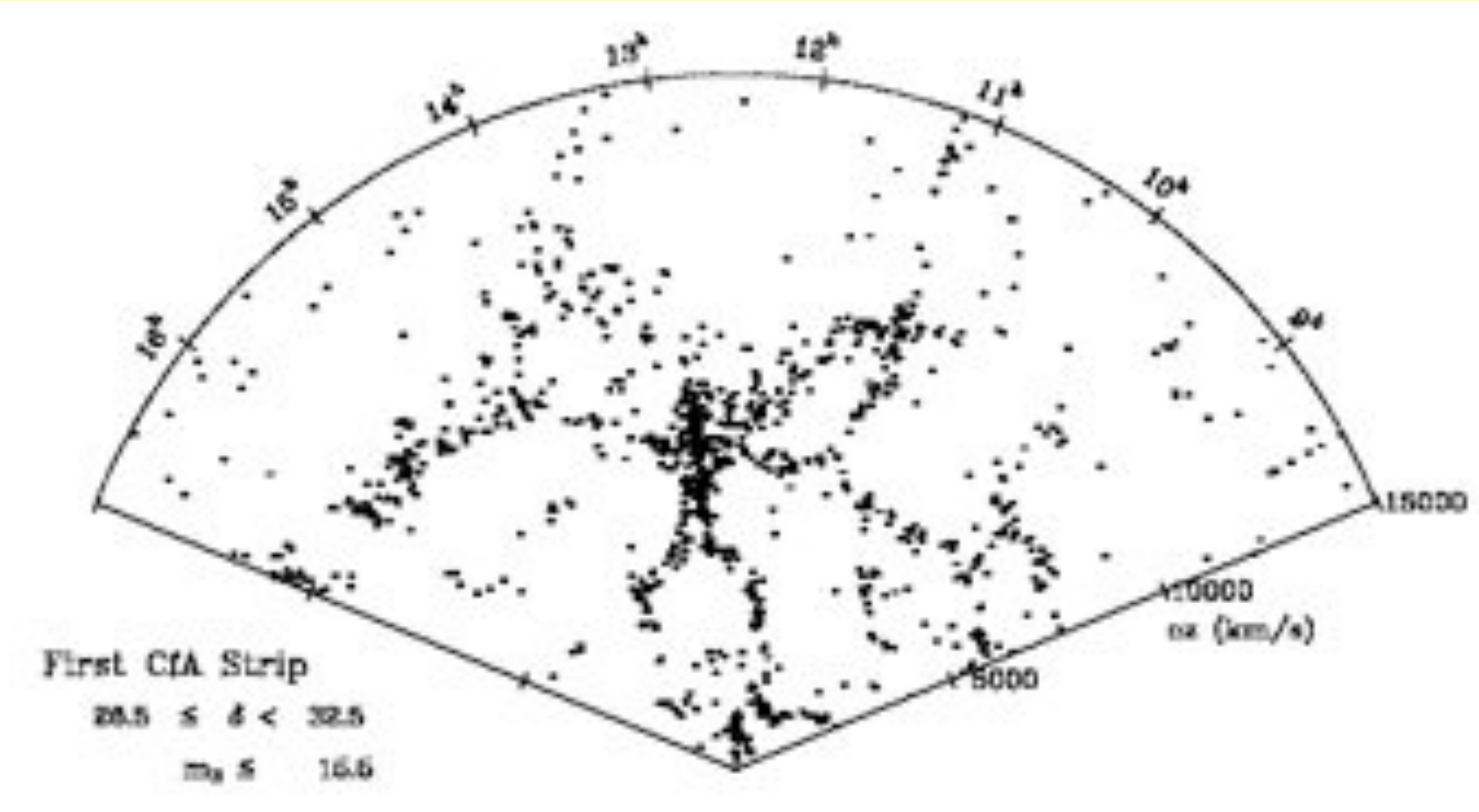


Peebles correlation-function programme, applied to Shane-Wirtanen Lick galaxy map.

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


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

CfA surveys



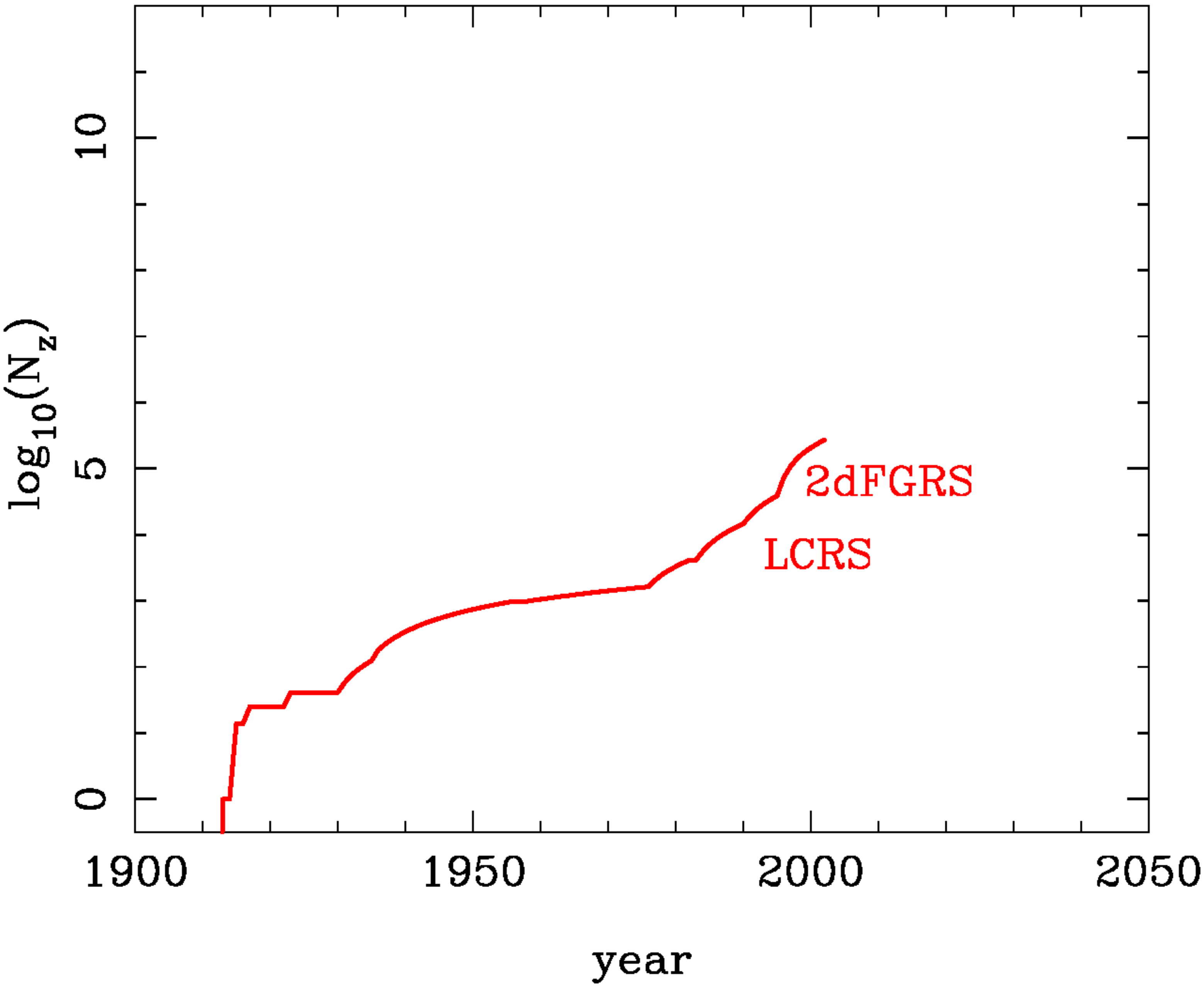
Accelerated progress from electronic detectors

CfA1: 2396 z's 1977-1982

CfA2 : 18,000 z's 1984-1995

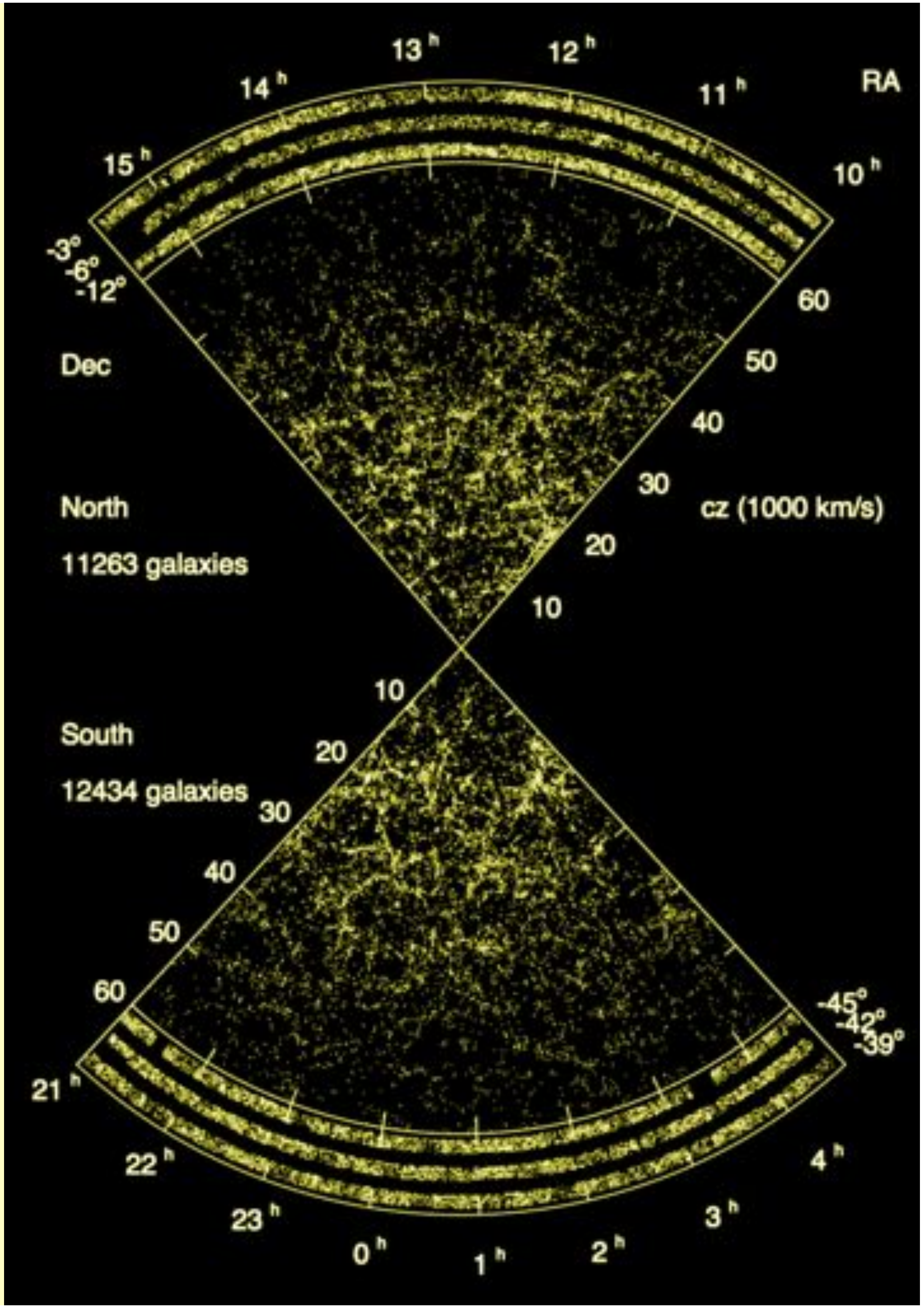
The multiplex revolution: fibres

A Century+ of galaxy redshifts

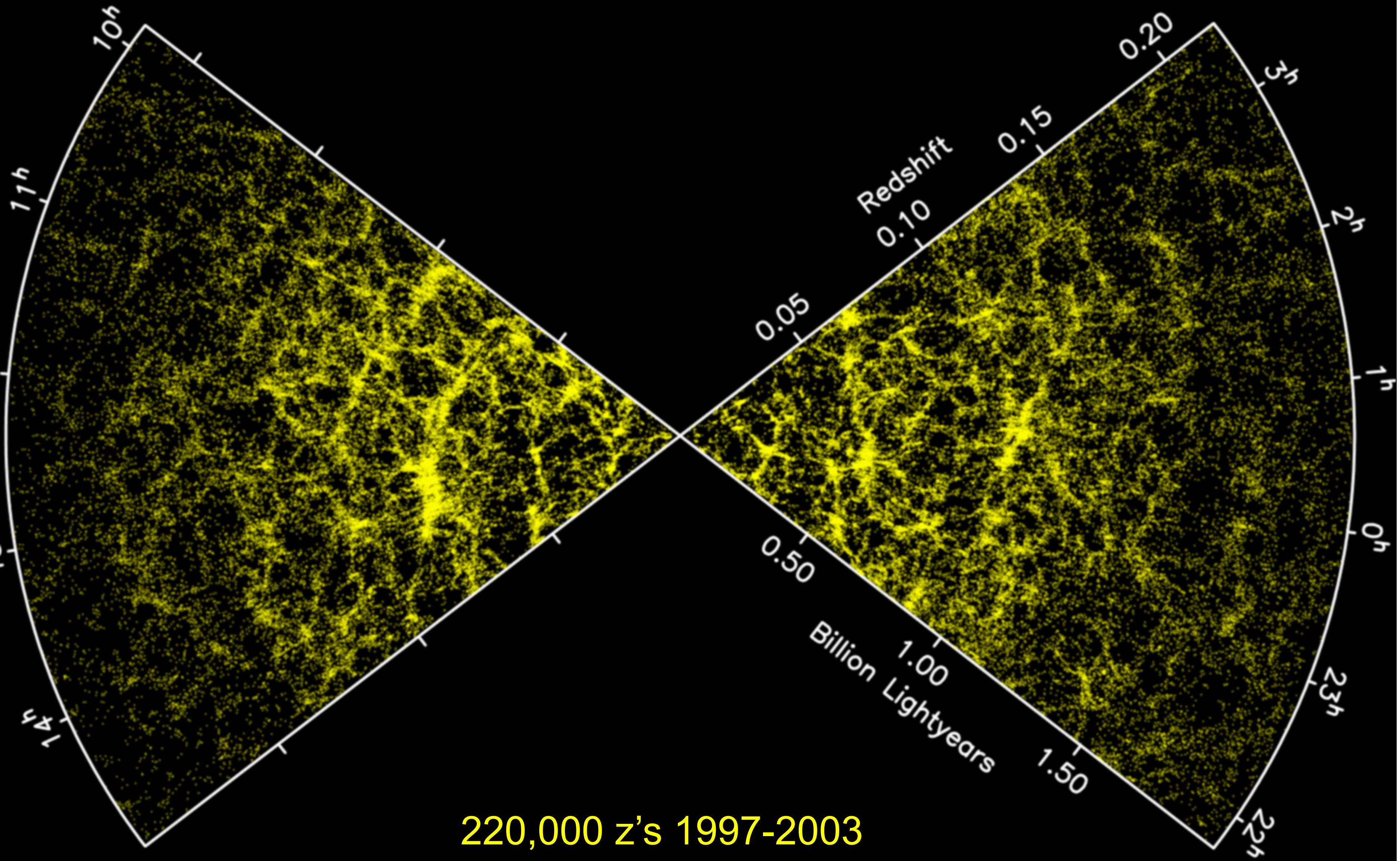


LCRS

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



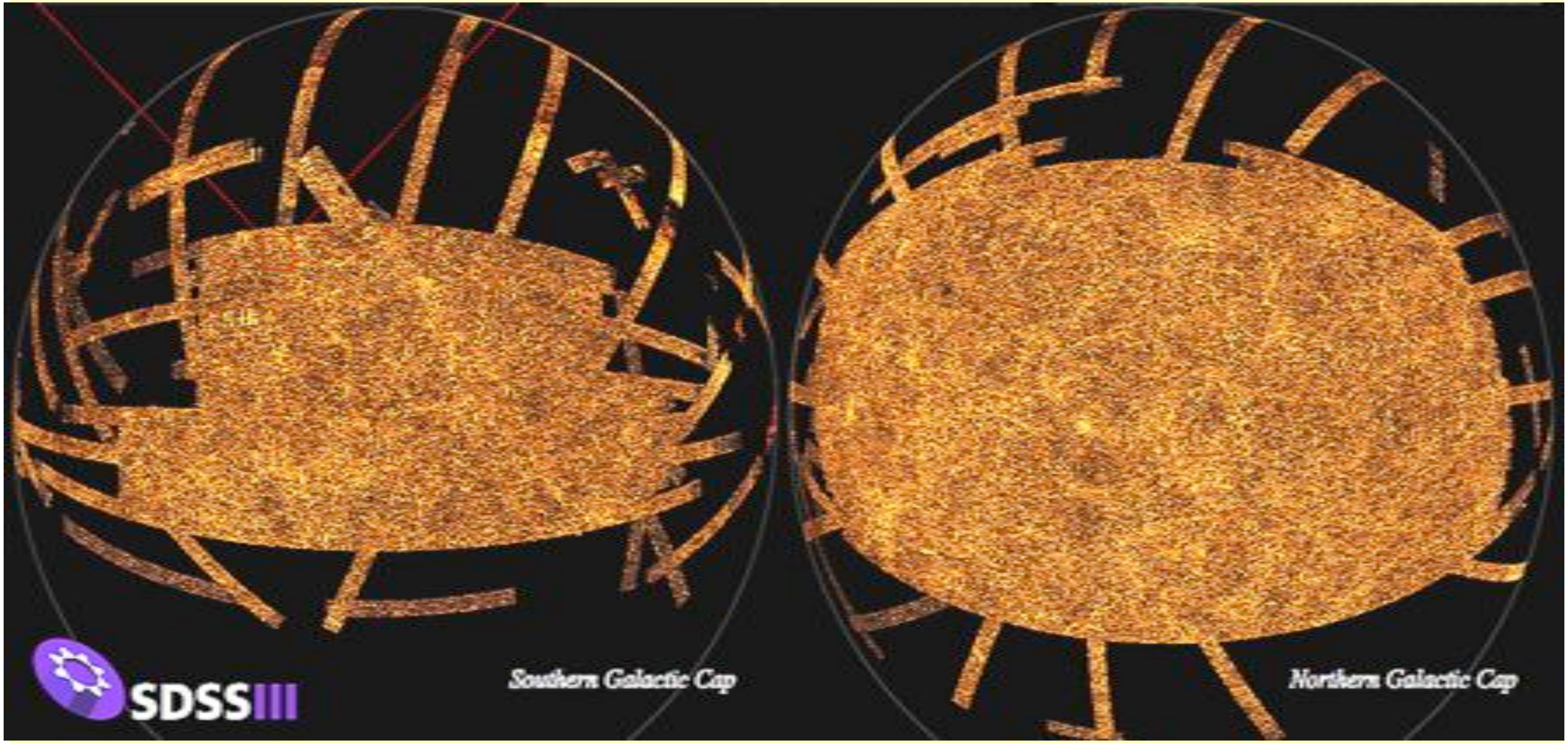
2dFGRS

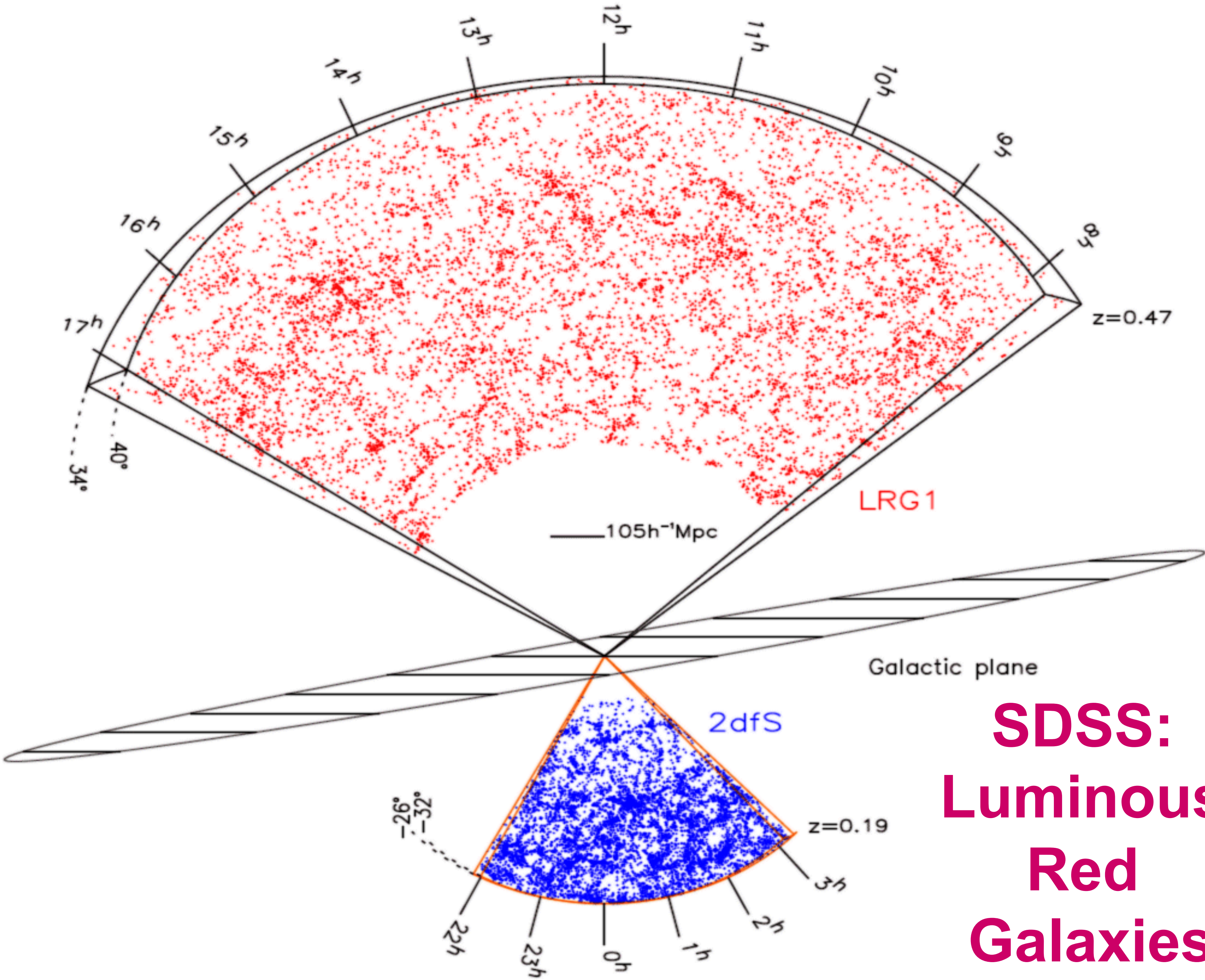


220,000 z's 1997-2003

SDSS

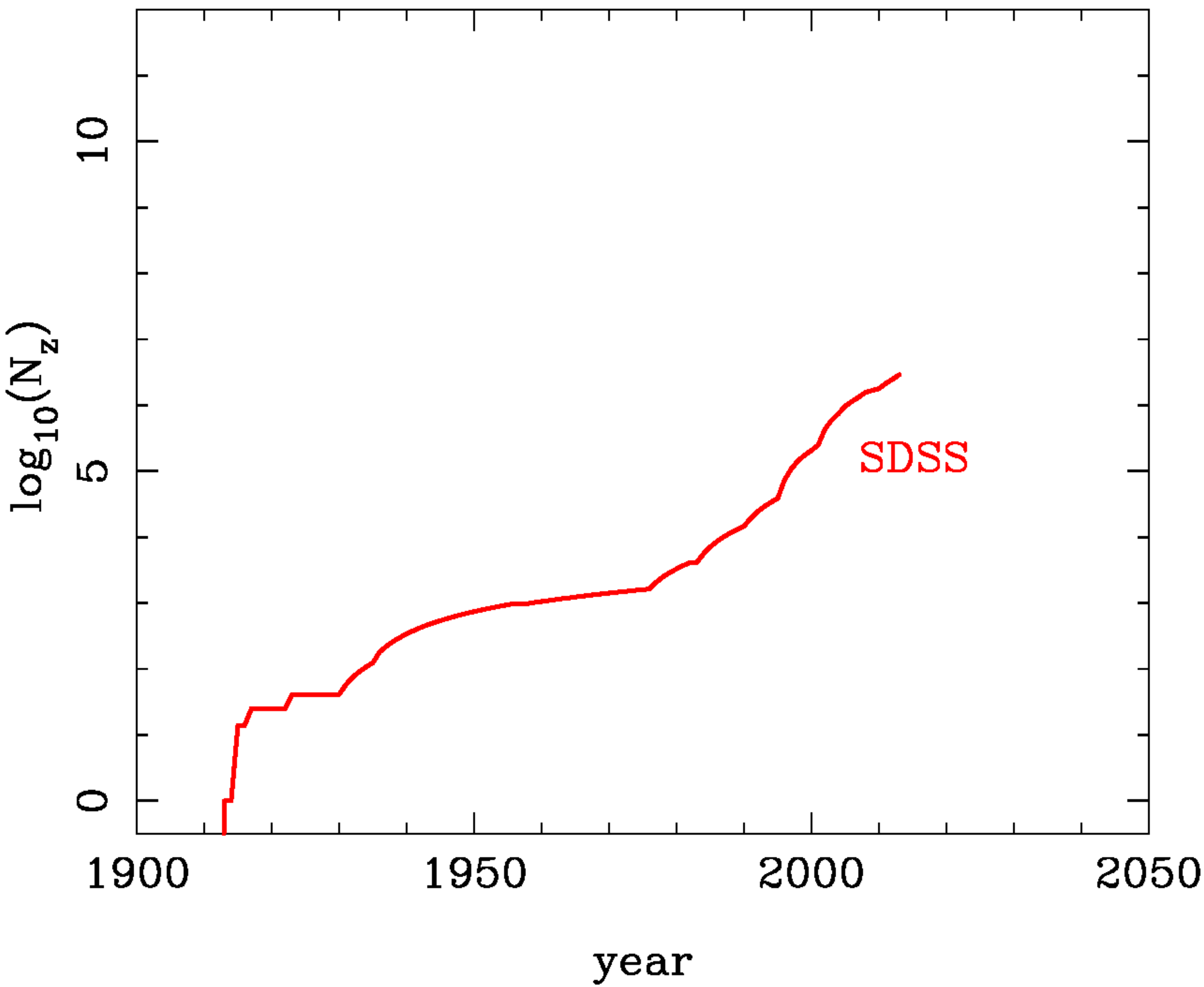
- Current state of the art
- 2M z's 2002-present





SDSS: Luminous Red Galaxies

A Century+ of galaxy redshifts



z surveys and CDM started in 1982

THE ASTROPHYSICAL JOURNAL, 253:423–445, 1982 February 15

A SURVEY OF GALAXY REDSHIFTS. II. THE LARGE SCALE SPACE DISTRIBUTION

MARC DAVIS, JOHN HUCHRA, DAVID W. LATHAM, AND JOHN TONRY
Harvard-Smithsonian Center for Astrophysics
Received 1981 May 14; accepted 1981 August 17

ABSTRACT

We have finished a redshift survey of galaxies complete to 14.5 m_B in the north and south galactic polar caps above declination $=0°$ and containing some 2400 galaxies. We present here various projections of the resulting redshift-space maps. While different in detail, the statistical nature of the redshift-space distribution is very similar between the north and south. The space distribution of galaxies is frothy, characterized by large filamentary superclusters of up to 60 Mpc in extent, and corresponding large holes devoid of galaxies. We also present redshift-space maps generated from *n*-body simulations, which very roughly match the density and amplitude of the galaxy clustering but fail to match the frothy nature of the actual distribution. Our results present a severe challenge to all theories of galaxy and cluster formation.

THE ASTROPHYSICAL JOURNAL, 263:L1–L5, 1982 December 1

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University
Received 1982 July 2; accepted 1982 August 13

ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto$ wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, m_x, if $m_x \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.

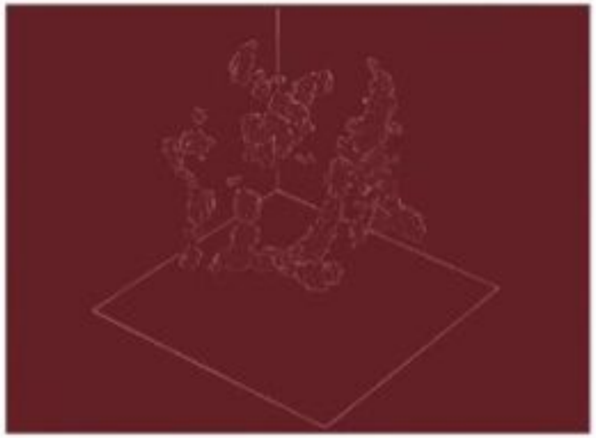
IAU104: bad timing

INTERNATIONAL ASTRONOMICAL UNION

SYMPOSIUM No. 104

EARLY EVOLUTION
OF THE UNIVERSE
AND ITS PRESENT STRUCTURE

Edited by G. O. ABELL and G. CHINCARINI



INTERNATIONAL ASTRONOMICAL UNION
D. REIDEL PUBLISHING COMPANY
DORDRECHT / BOSTON / LANCASTER

Oort opening talk:

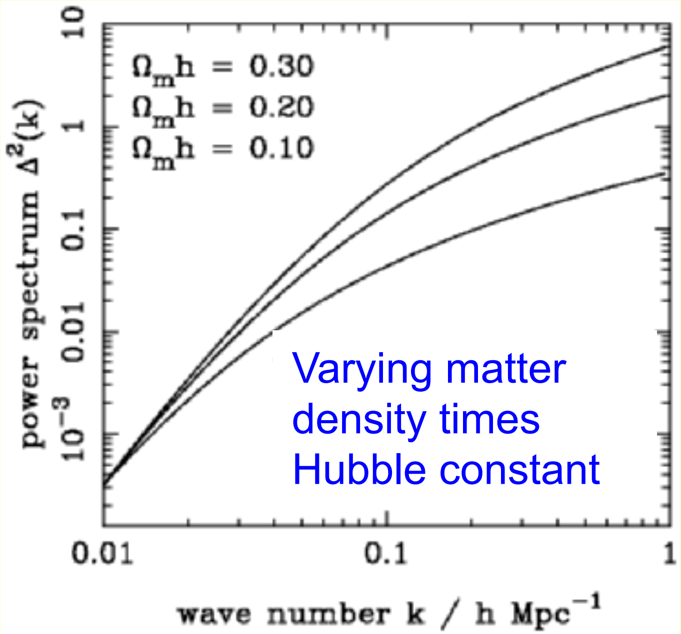
simulations can reproduce in a striking manner the observerved covariance function. The marvellous outcome of these calculations naturally prompts one to ask whether also the larger structures might be explained this way. On the basis of our present knowledge the answer must probably be "No, at least not all such structures." In particular, it seems doubtful whether, starting from a random distribution, the strongly flattened, or elongated, shapes and the sometimes enormous dimensions can be produced that are characteristic of many superclusters. I mention, however, that interesting simulations have recently been made that do produce supercluster-like formations, by choosing initial conditions in which fluctuations beneath a certain, rather large, scale are suppressed or by having galaxies formed at a very early epoch.

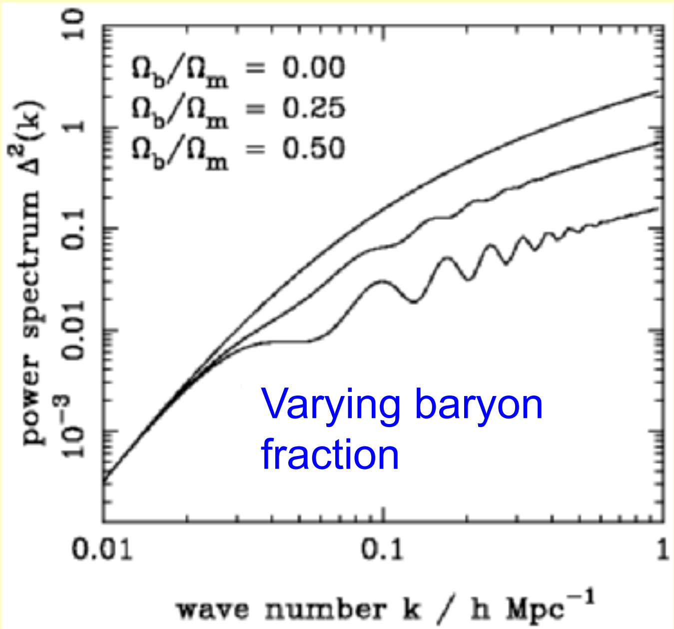
We have arrived here at one of the crucial questions for this symposium, viz., do the large structures we observe around us teach us something about the Universe before decoupling?

CDM rapidly became the leading model

- Included DM but preserved galaxy-scale structure

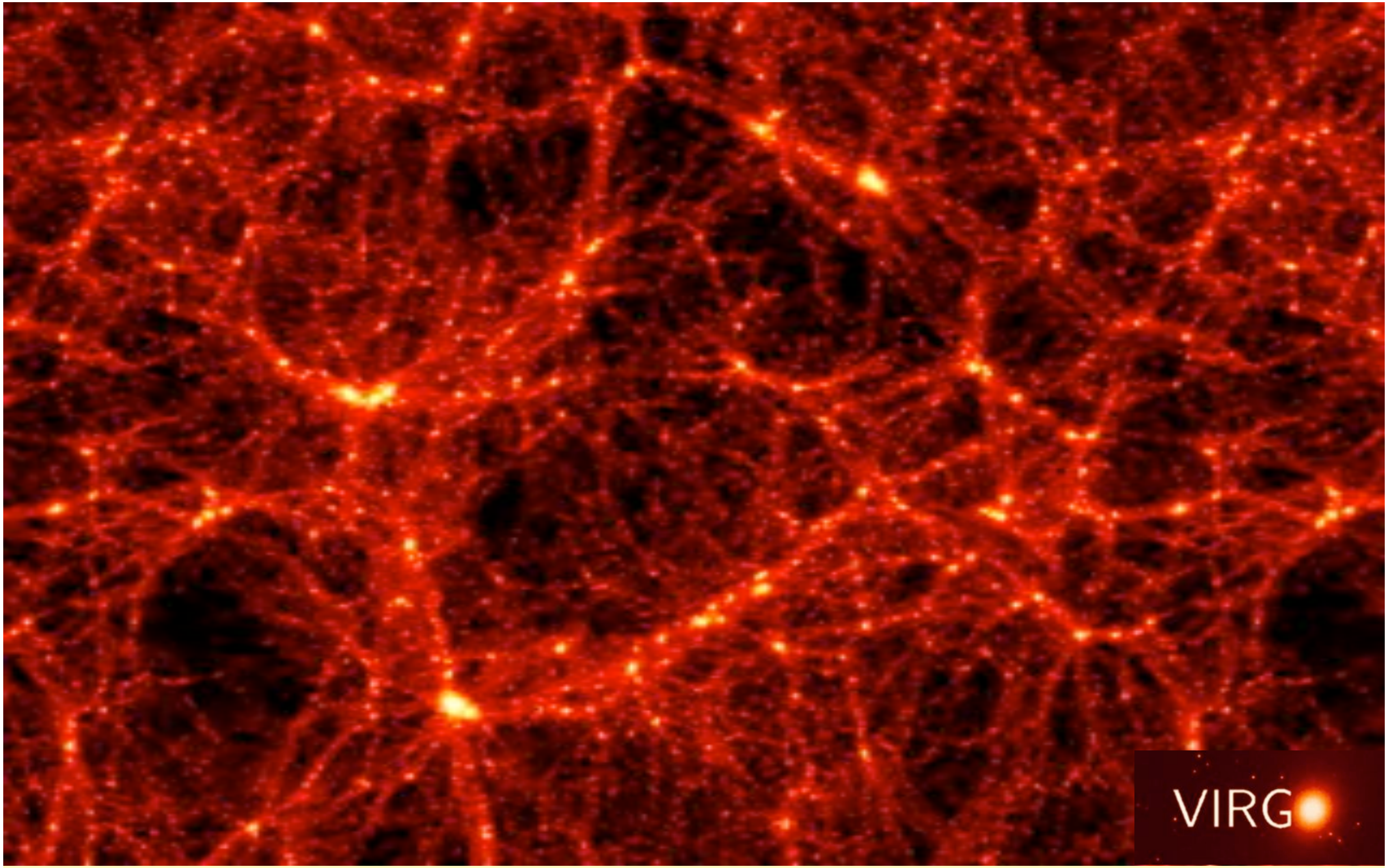
- Predictive (linear relics plus N-body)
  - (so were baryon-only models, but little data then)





Cosmic web: voids, sheets, filaments

Peebles: this would only arise via ‘Zeldovich pancakes’ − collapse of a matter distribution with only large-scale structures (pure baryons; massive neutrinos)



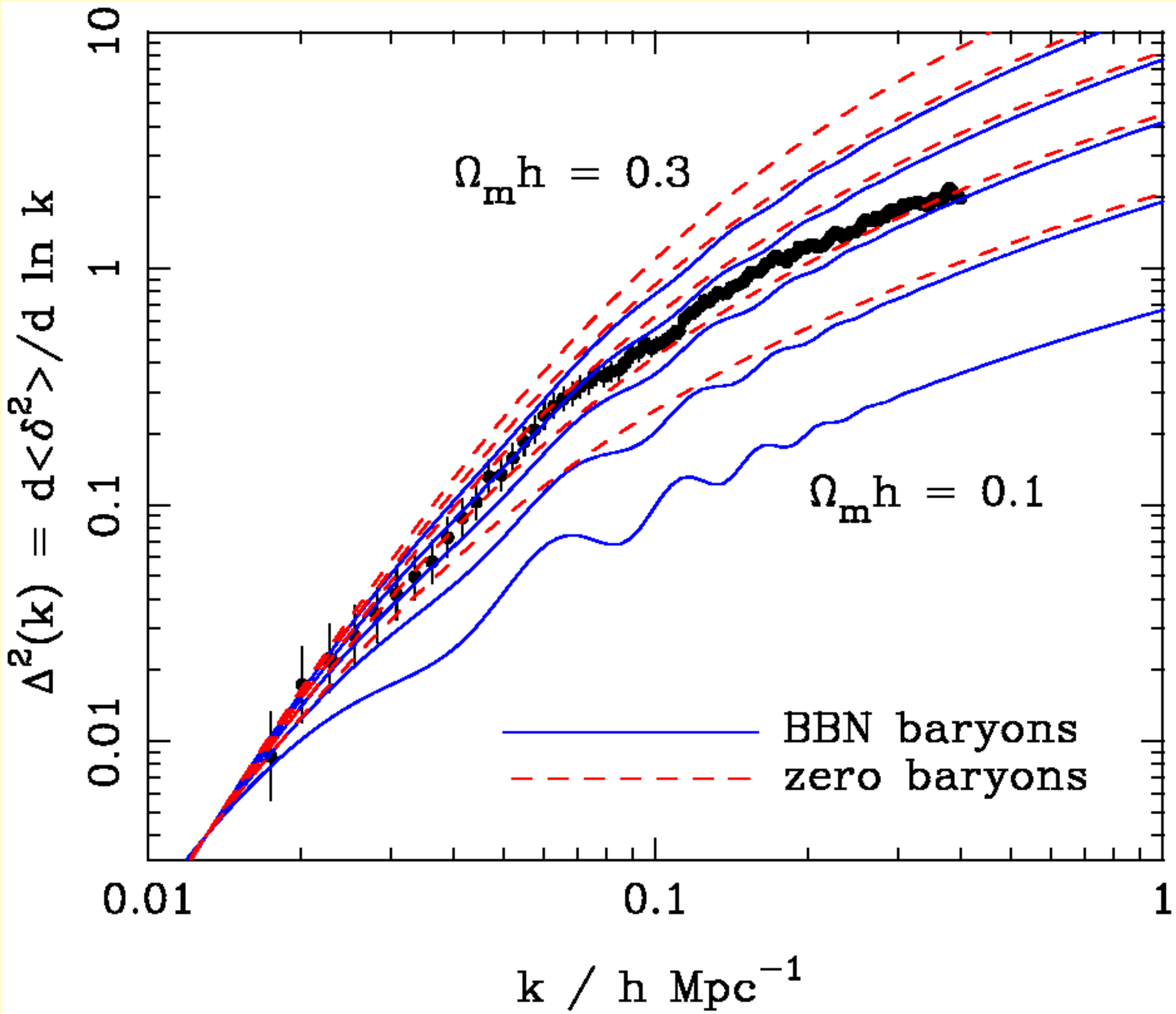
But 1990s Cold Dark Matter simulations clearly showed filaments as chains of dark-matter haloes

The LSS-CDM toolkit

2dFGRS power spectrum: small BAO proves DM

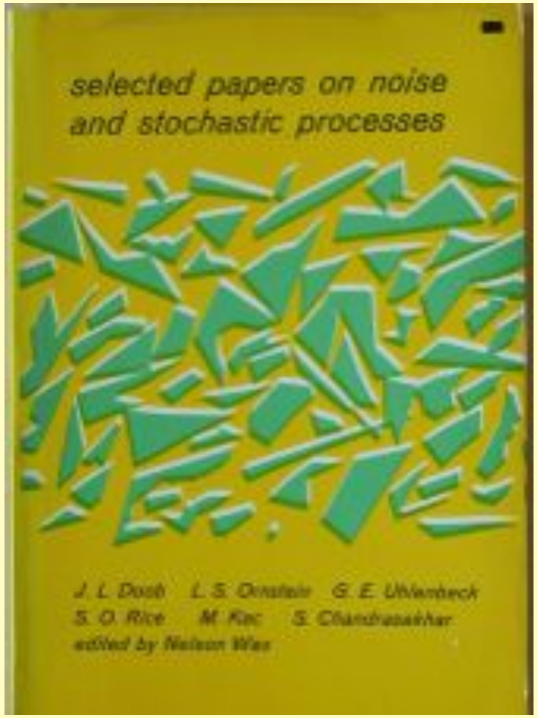
Dimensionless power:

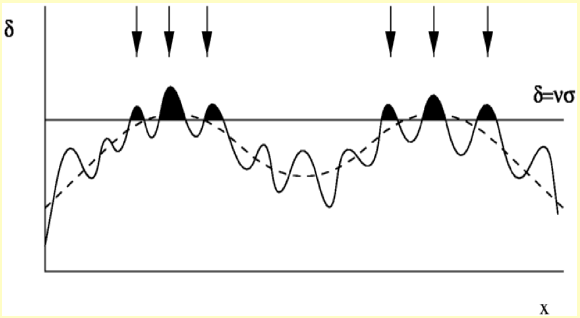
d (fractional variance in density) / d ln k



Percival et al. MNRAS 327, 1279 (2001)

Bias, haloes, and all that





$$\delta_{\text{peaks}} \simeq \frac{\nu}{\sigma}\,\delta_{\text{mass}}$$

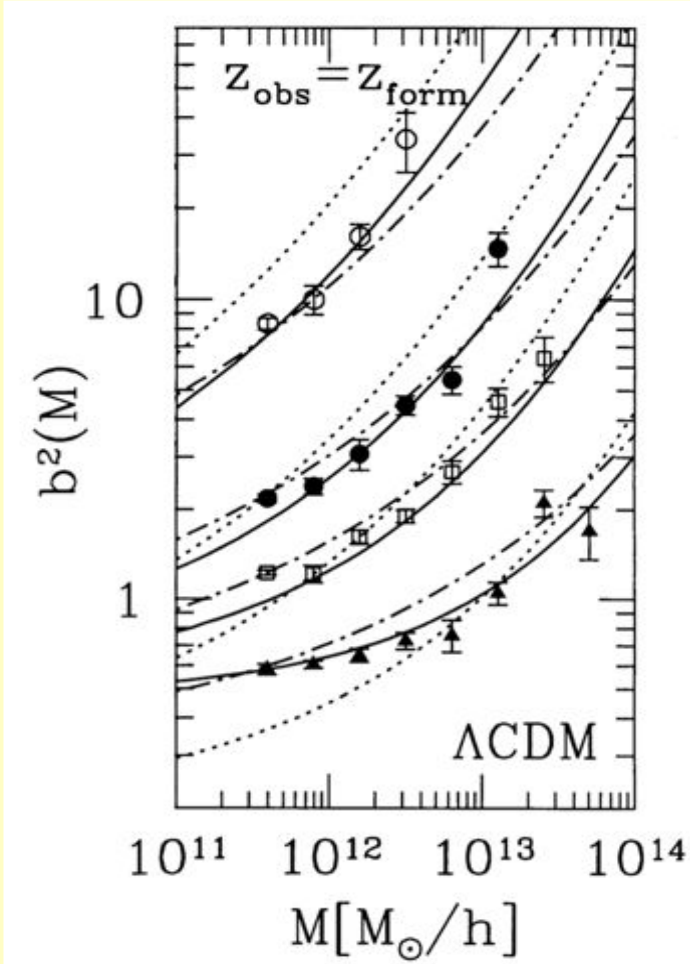
The Rice goldmine

Kaiser (1984) explained enhanced clustering of Abell clusters

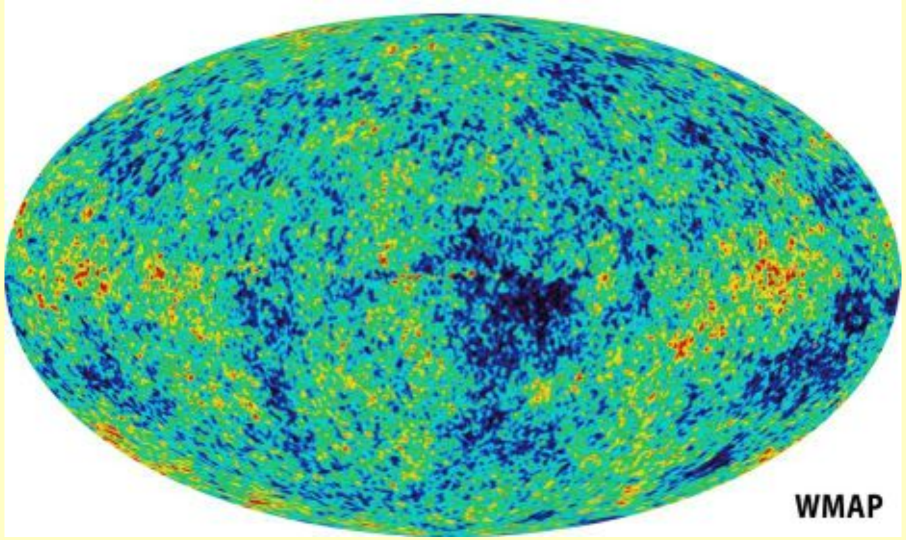
(not galaxy bias)

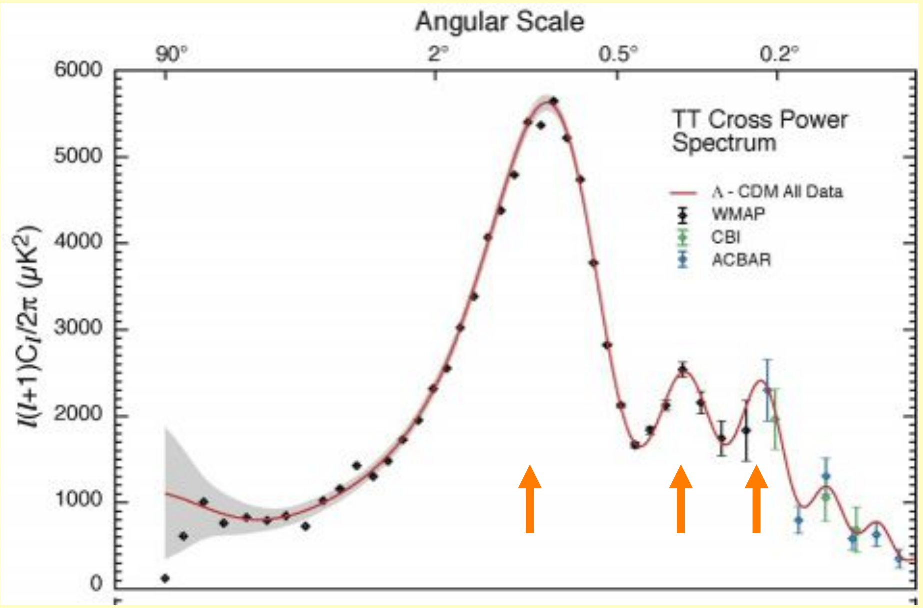
1980s/1990s high-bias distraction

Clarified by Sheth & Tormen (1999)



Baryon Acoustic Oscillations





The (comoving) distance that sound waves travel by recombination sets the length of the BAO cosmic ruler at t = 380,000 years:

$$l_{\mathrm{BAO}} = \int_0^{t_{\mathrm{rec}}} \frac{c_s}{a}\, dt \approx \frac{c}{\sqrt{3}} \frac{t_{\mathrm{rec}}}{a_{\mathrm{rec}}}$$

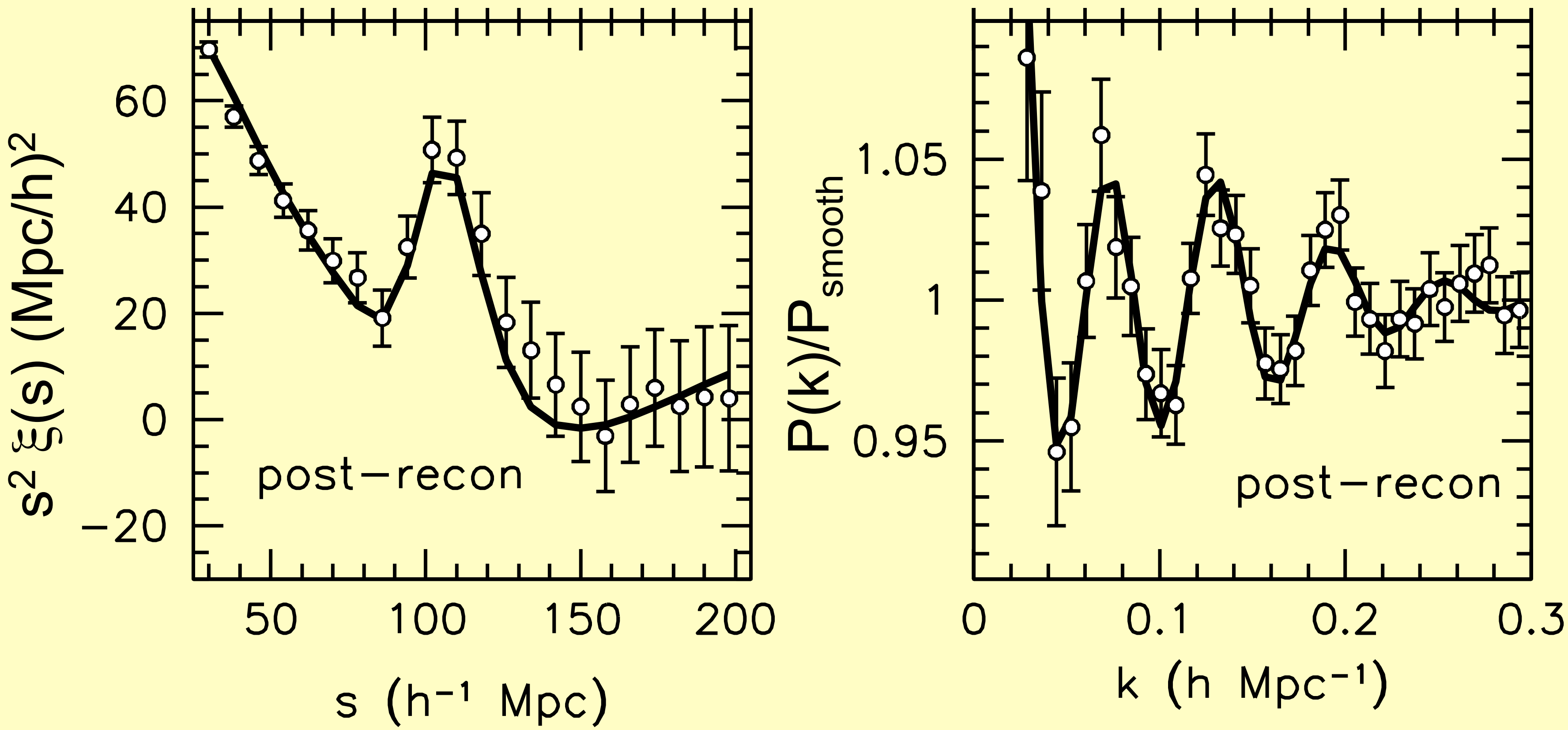
$$a_{\mathrm{rec}} = 1/1100$$

'Baryon wiggles' at 1 degree (& 0.3, 0.2, 0.1...): 150 Mpc at 13 Gpc

Oscillations of baryonic gas falling under dark matter gravity

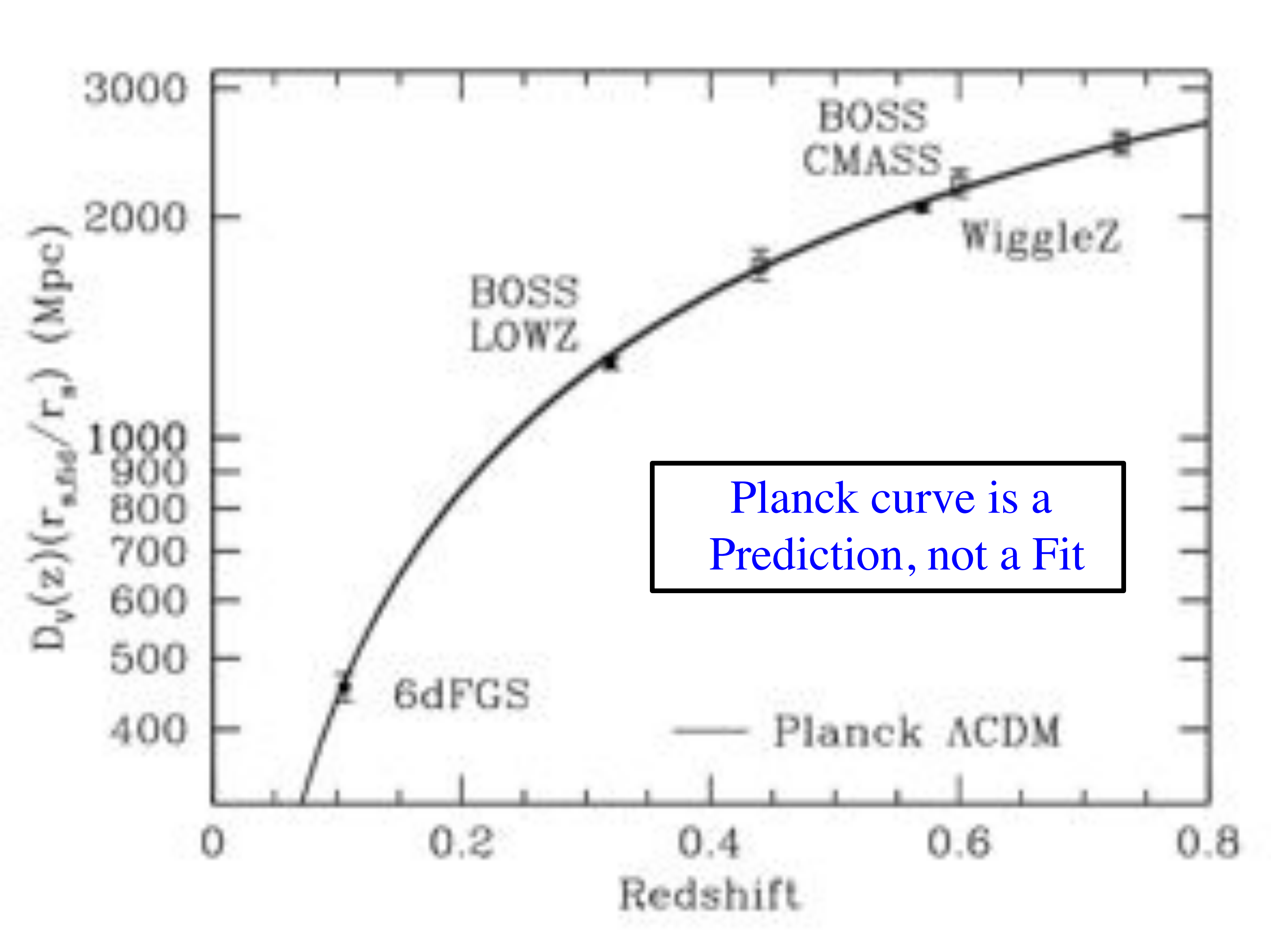
Acoustic Peak from BOSS

- SDSS-III BOSS gives a strong BAO detection, measuring the acoustic scale to 1% at z=0.57.



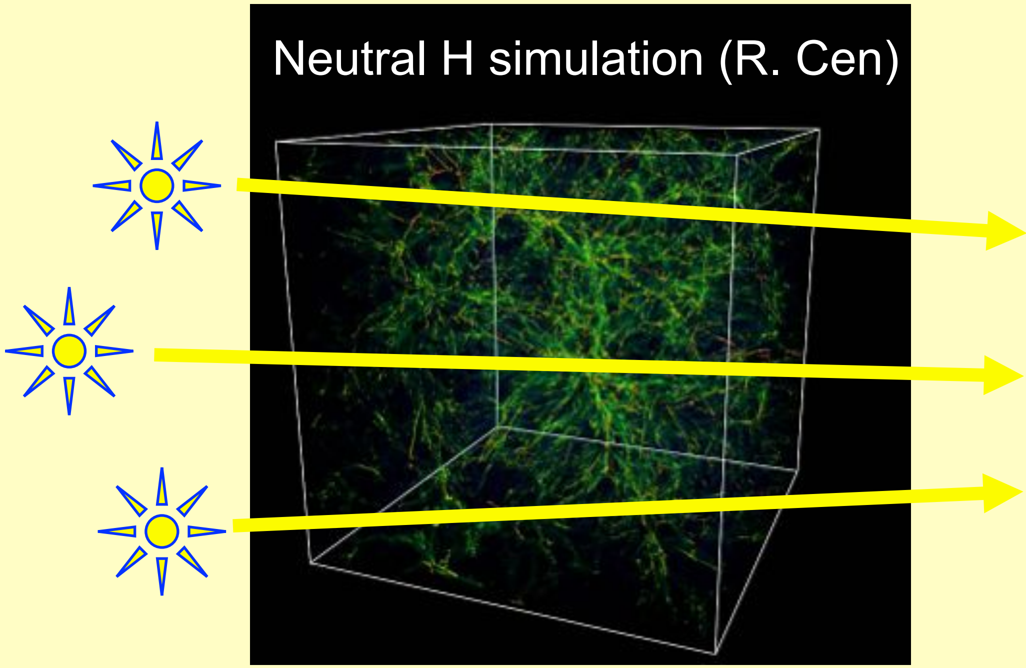
Anderson et al. (2014)

The Cosmic Distance Scale



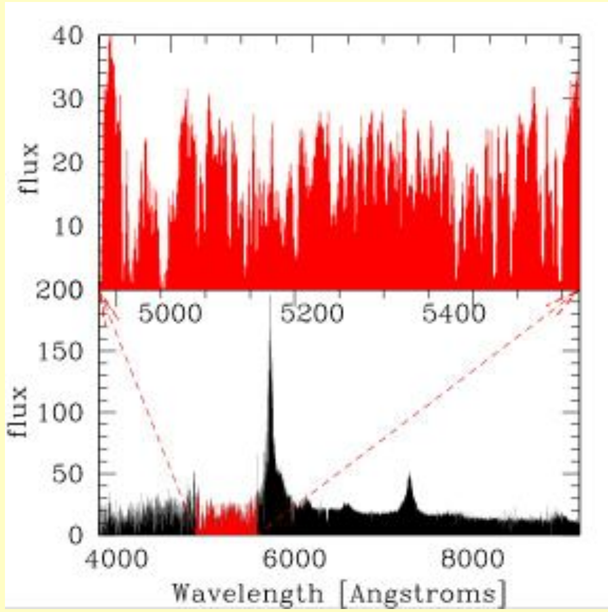
Anderson et al. (2014)

The Lyman α Forest



Neutral H absorption observed

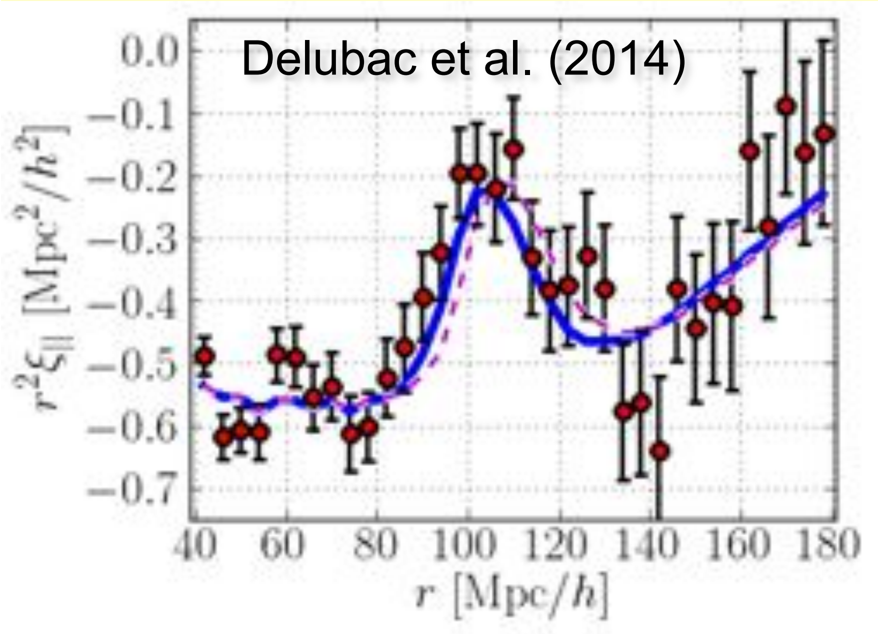
in quasar spectrum at z=3.7

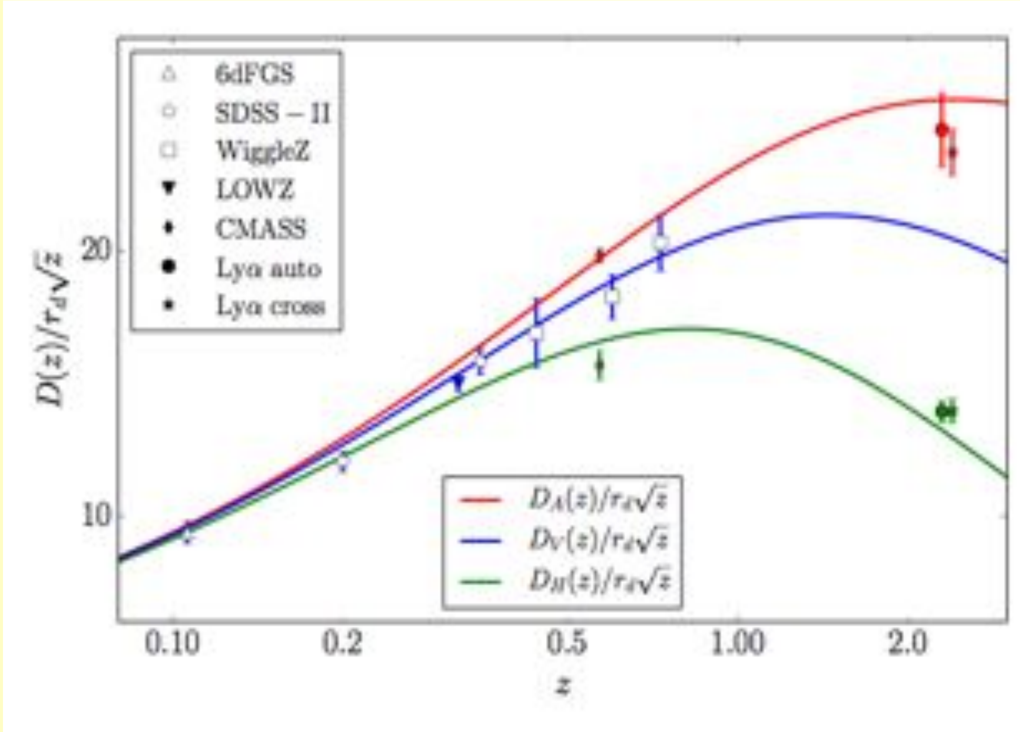


- The Lyα forest in each quasar spectrum tracks the density of the intergalactic medium along each line of sight.
- A grid of sightlines can map the 3-d density at z>2.
- An efficient way to measure the BAO at *z*>2.

White (2004); McDonald & Eisenstein (2006)

BAO in the Forest

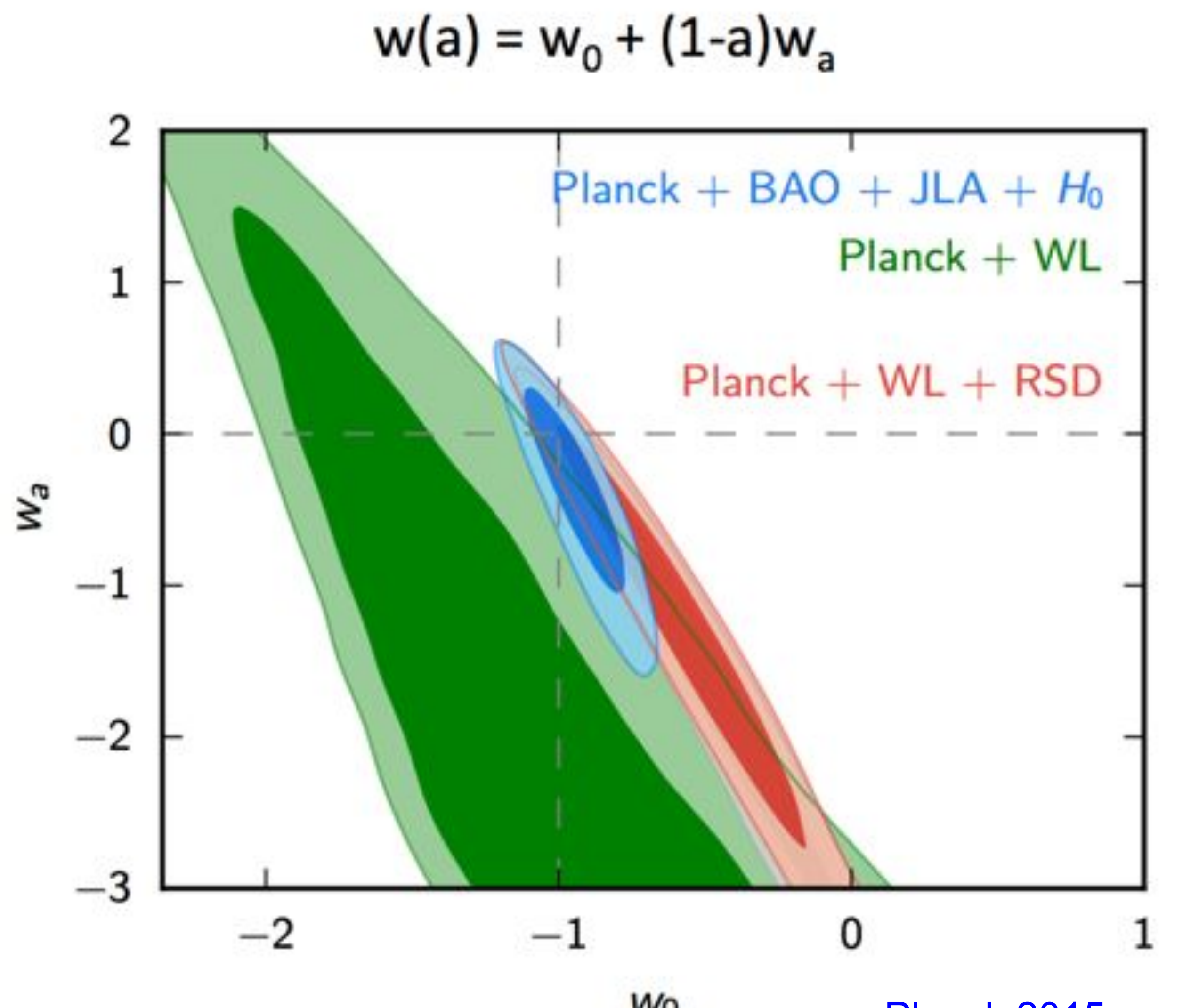




BAO detection transversely and radially from correlations between 140,000 z>2 quasar spectra:

Busca et al., Slosar et al. Delubac et al., Font-Ribera et al.

BAO limits on DE equation of state ($w = P / \rho c^2$)



Planck 2015

$w = -1$ +/- 0.06 if unevolving:

DE looks like cosmological constant

What else can LSS do?

Fundamentalist:

- Matter content (neutrino mass)
- Peculiar velocities and modified gravity
- Non-Gaussianity

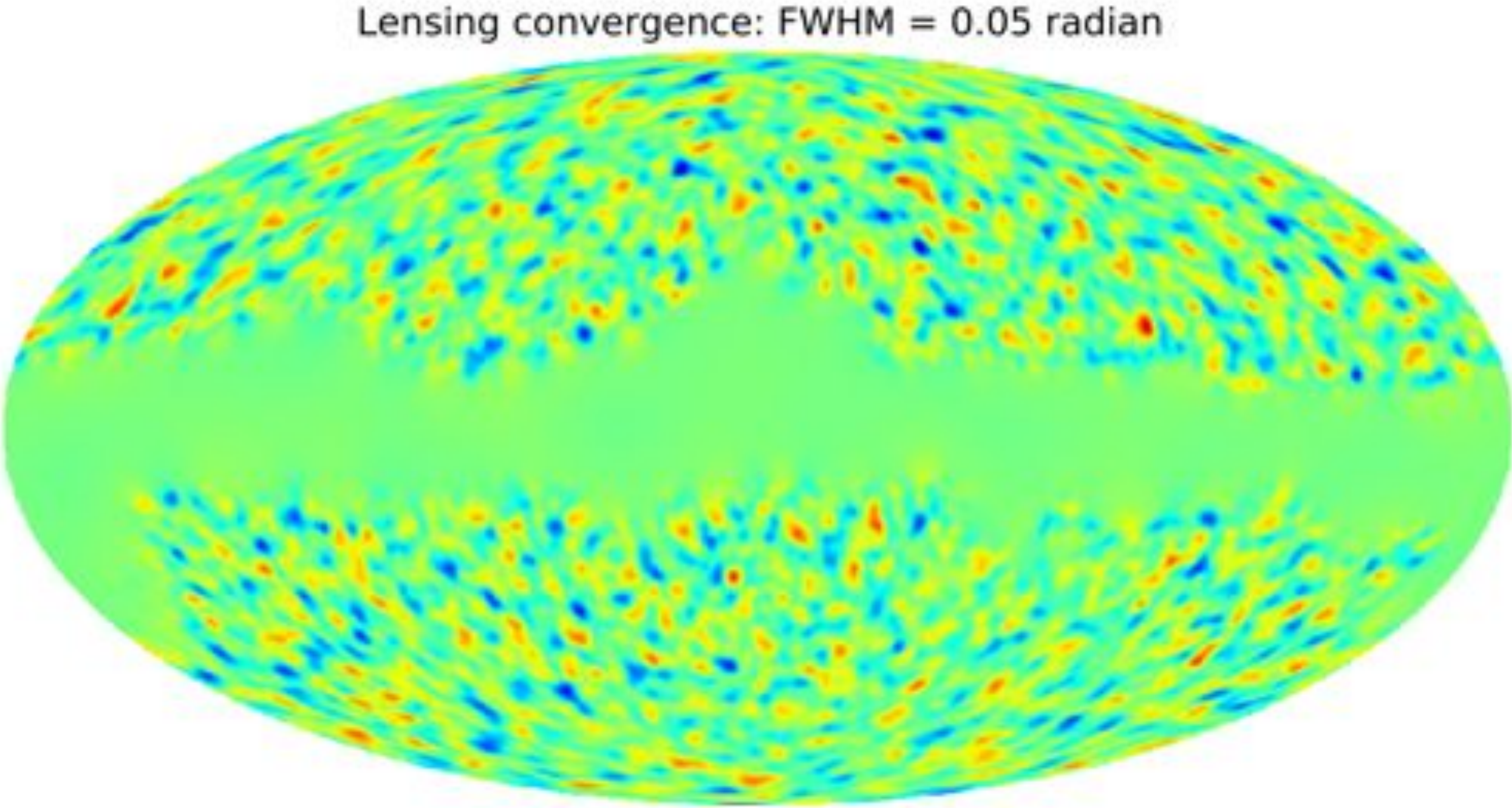
Astrophysical:

- Calibrating the halo-galaxy connection
- Environmental effects on galaxy formation
- Finding the gas

Requires other probes

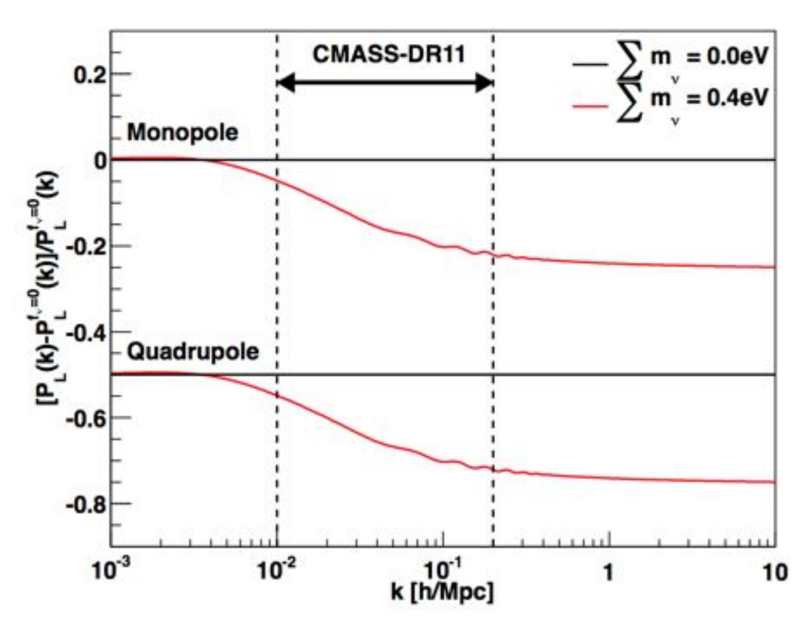
$$\nabla^2\Phi = 4\pi G\rho a^2\,\delta; \qquad \nabla\cdot u = -\dot{\delta}$$

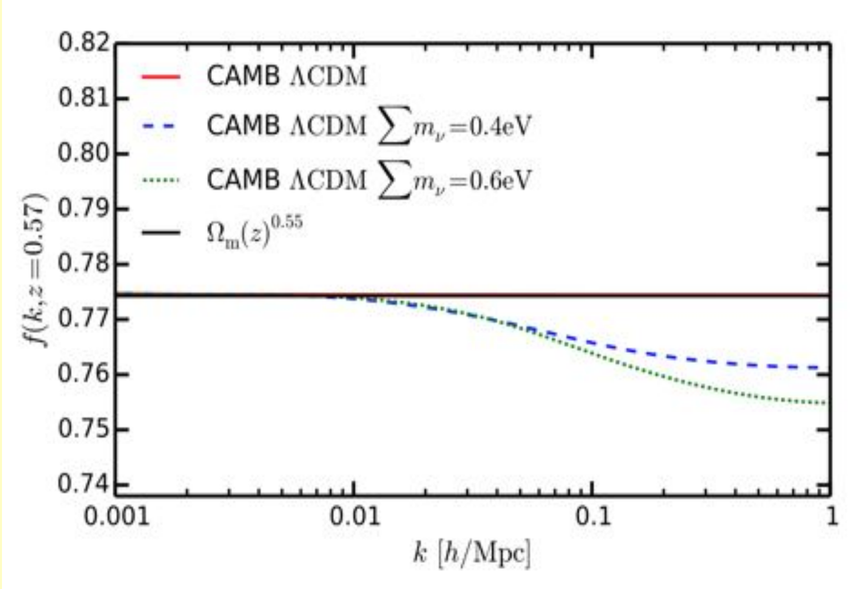
$$\delta \longleftrightarrow \Phi \longleftrightarrow \mathbf{u}$$



Projected mass distribution back to z = 1100

Neutrinos



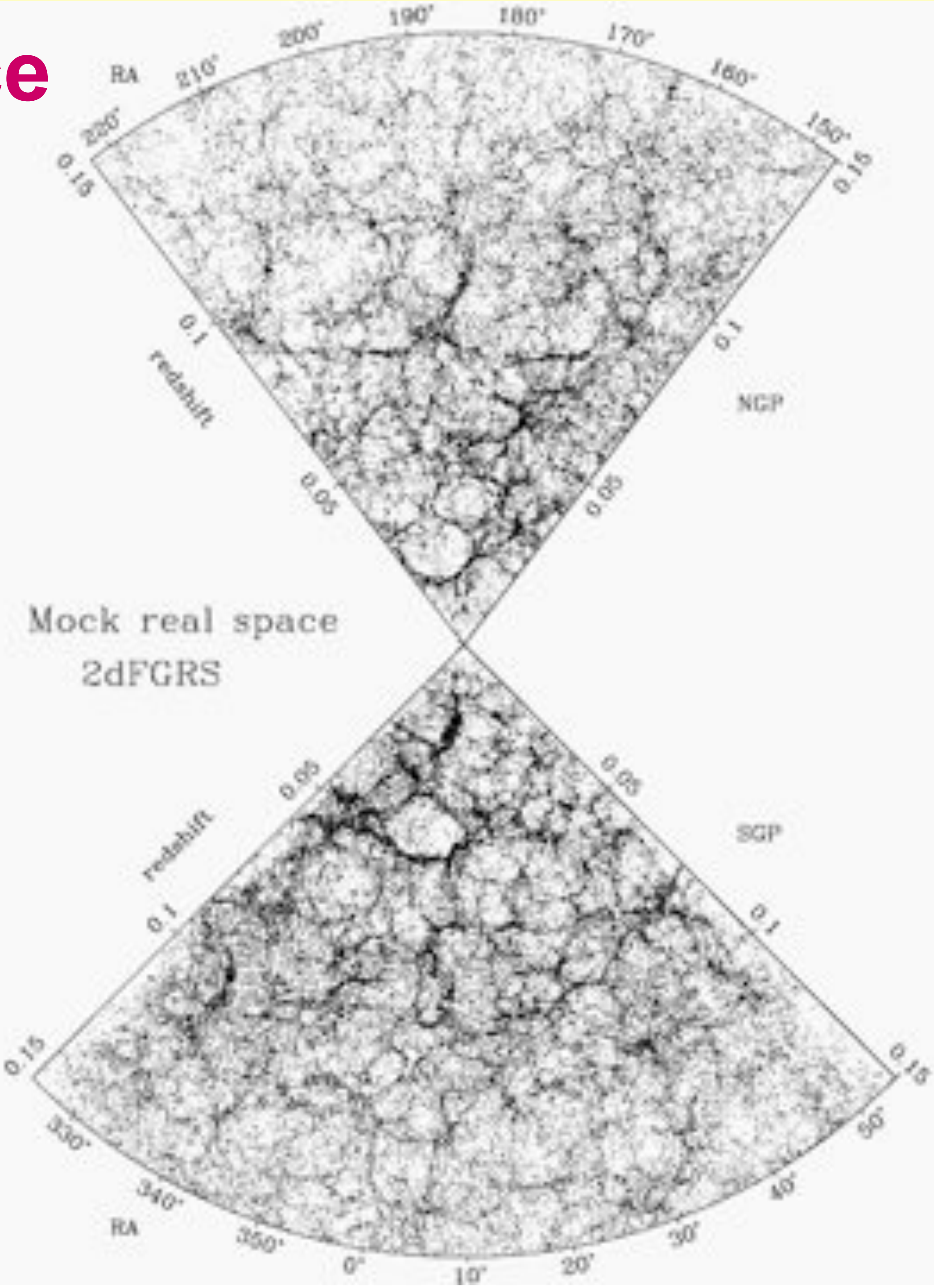


Reduced growth rate for k > ~ 0.05 − reduced σ_8

Claims of detection at m = 0.36 +/- 0.10 eV (1403.4599)

Planck 2015: m < 0.23 eV (0.06 eV smallest possible)

Redshift-space distortions of clustering



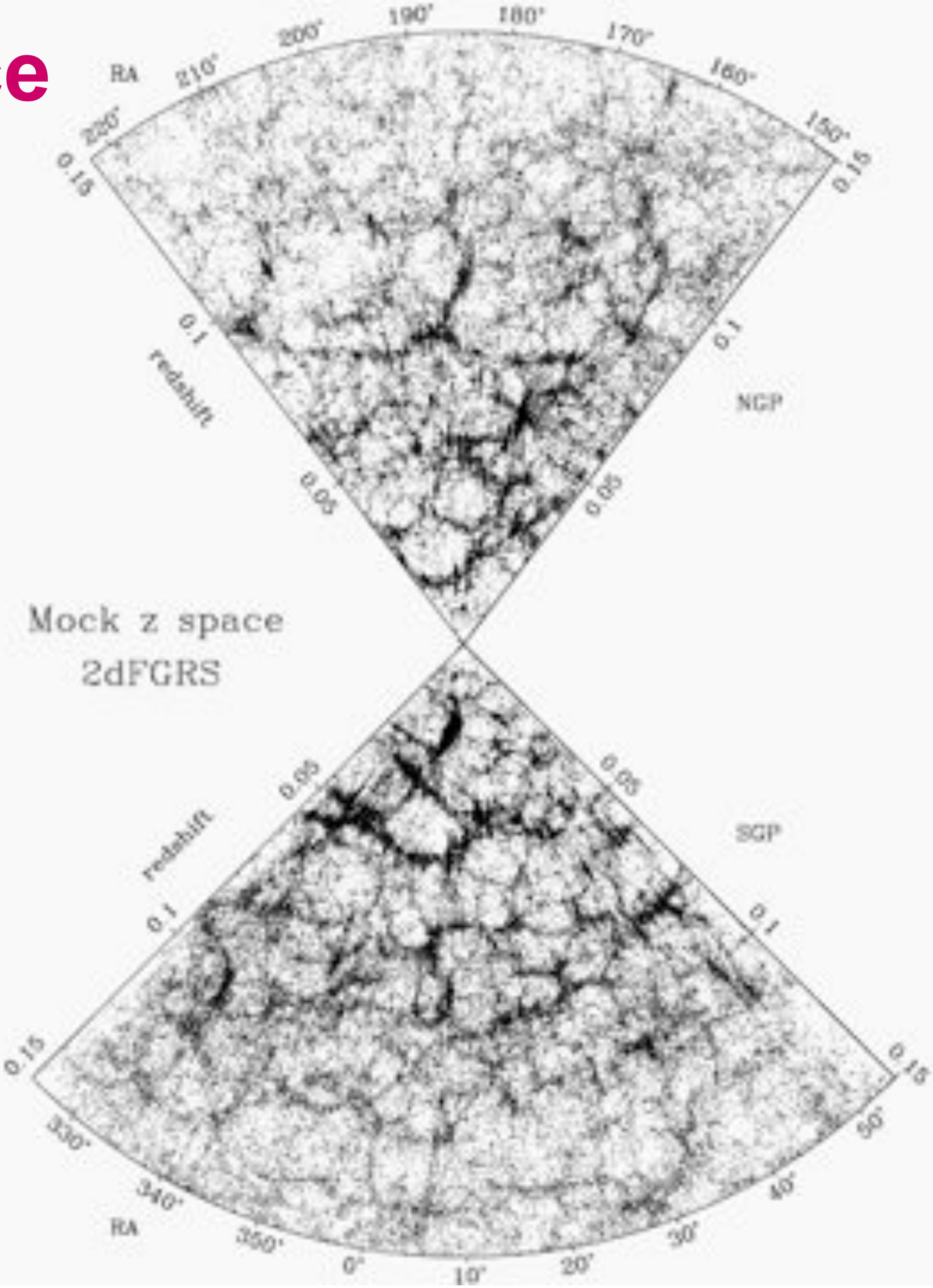
Mock 2dFGRS from Hubble volume

real space

Eke, Frenk, Cole, Baugh + 2dFGRS 2003

Redshift-space distortions of clustering

2dFGRS first survey to benefit from detailed mock samples

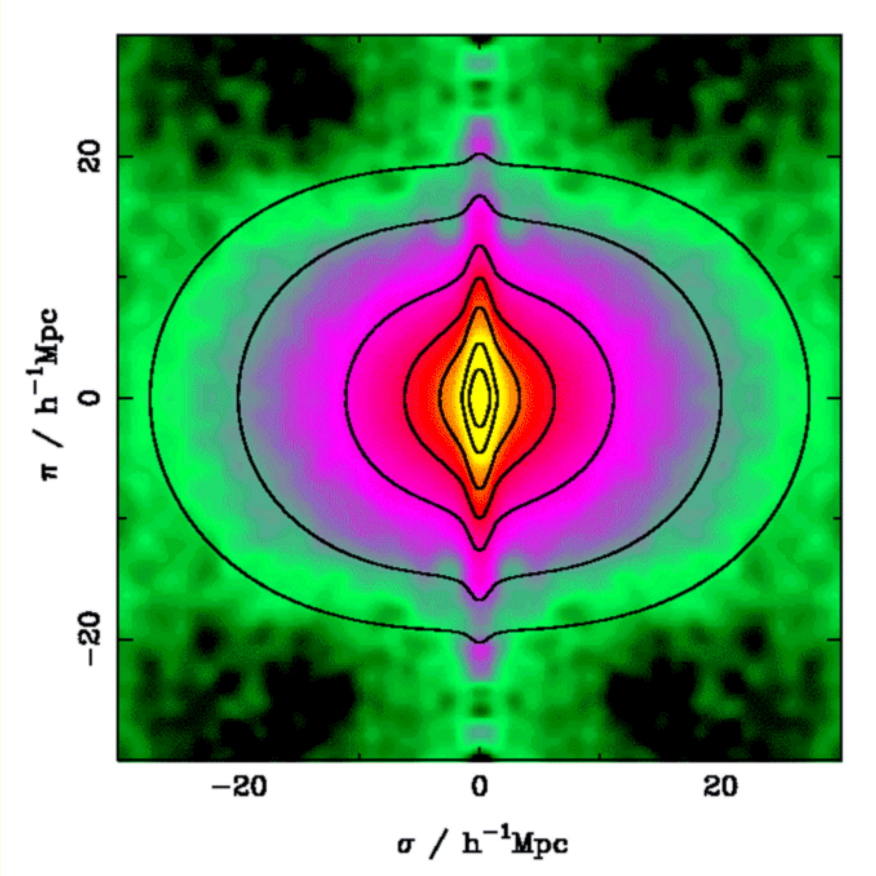


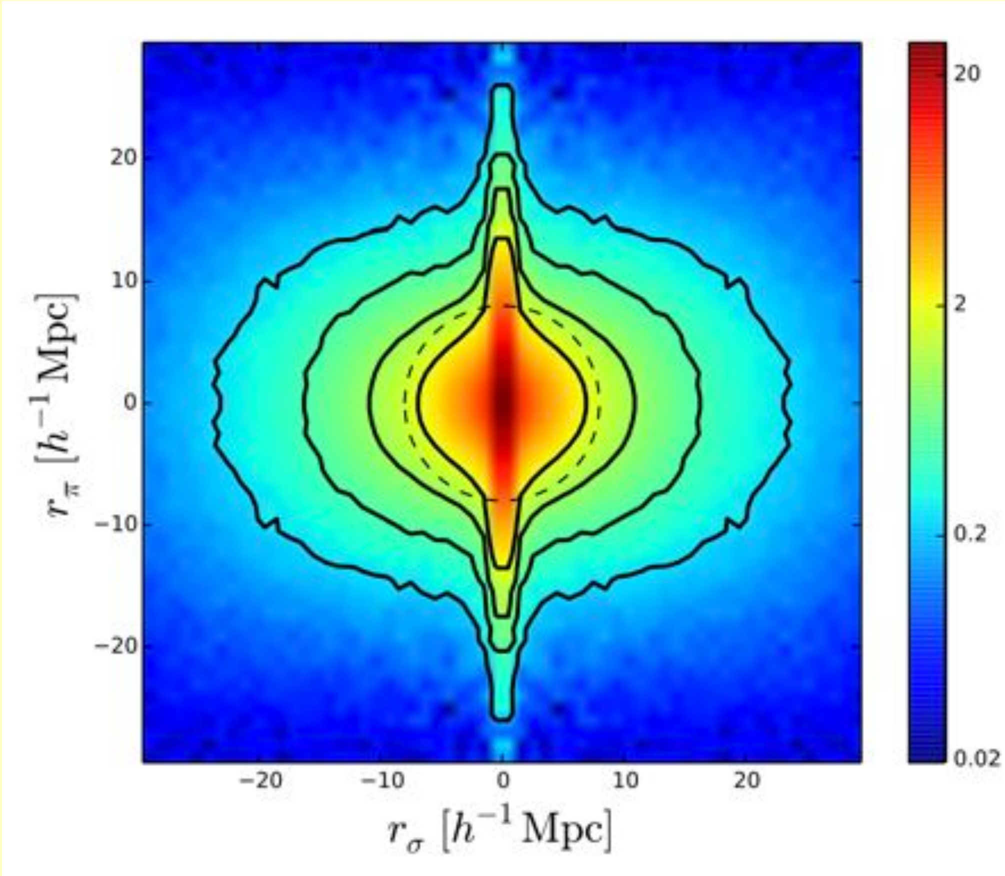
Mock 2dFGRS from Hubble volume

z space

Eke, Frenk, Cole, Baugh + 2dFGRS 2003

14 years of RSD

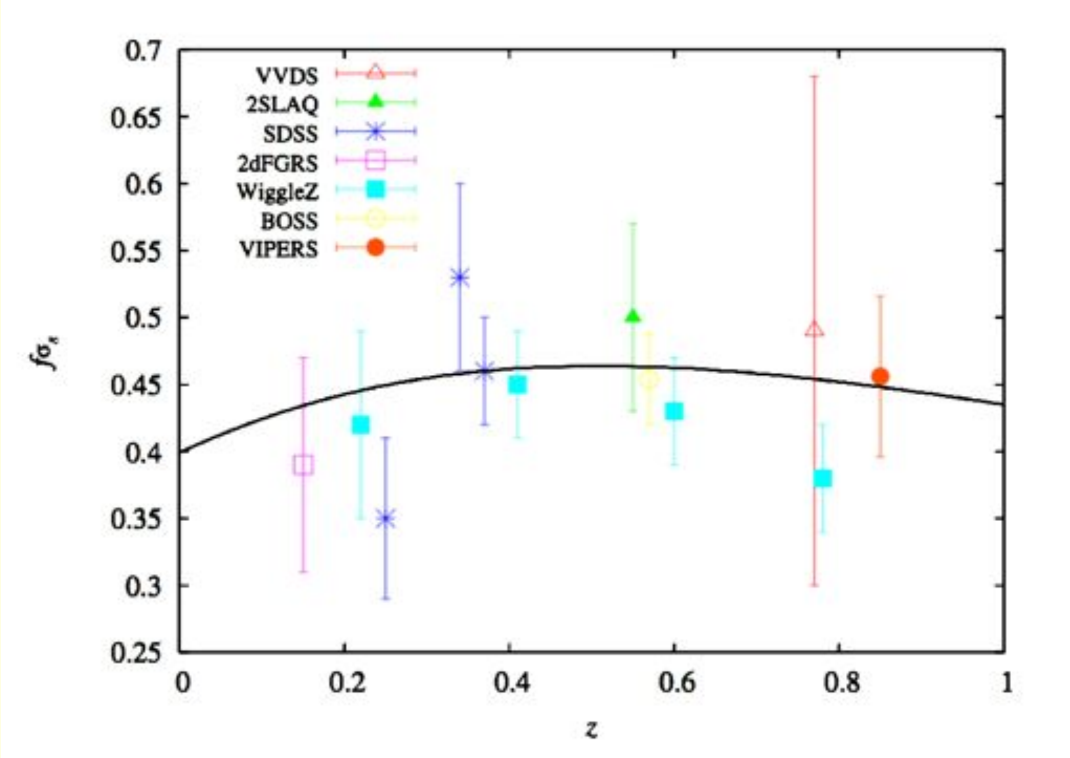


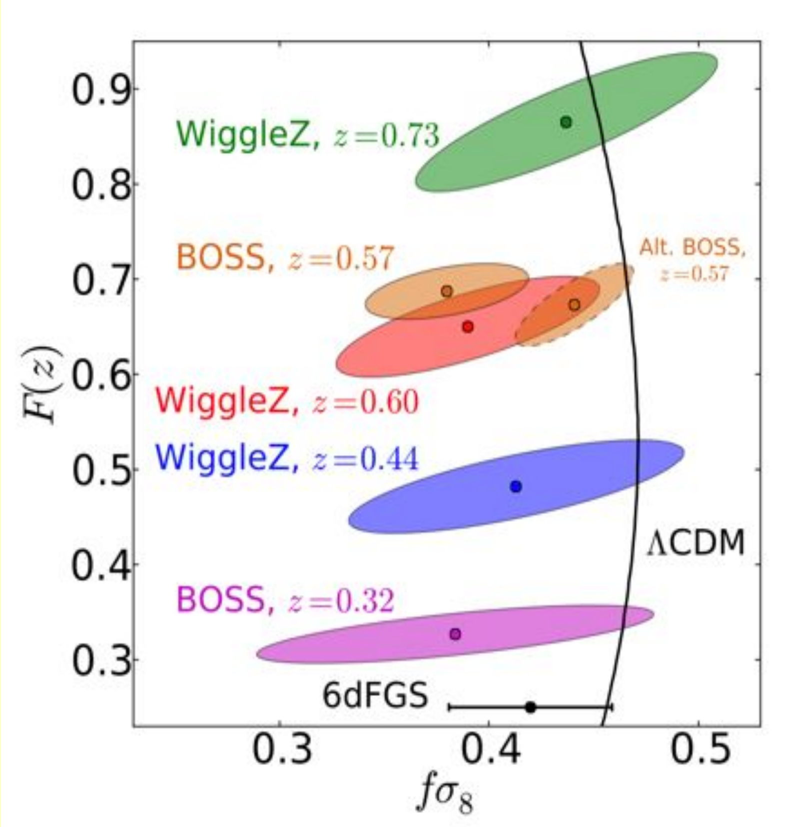


2001: 2dFGRS 8% on f_g

2014: SDSS LRG 2.5% on f_g

Growth rate: current state



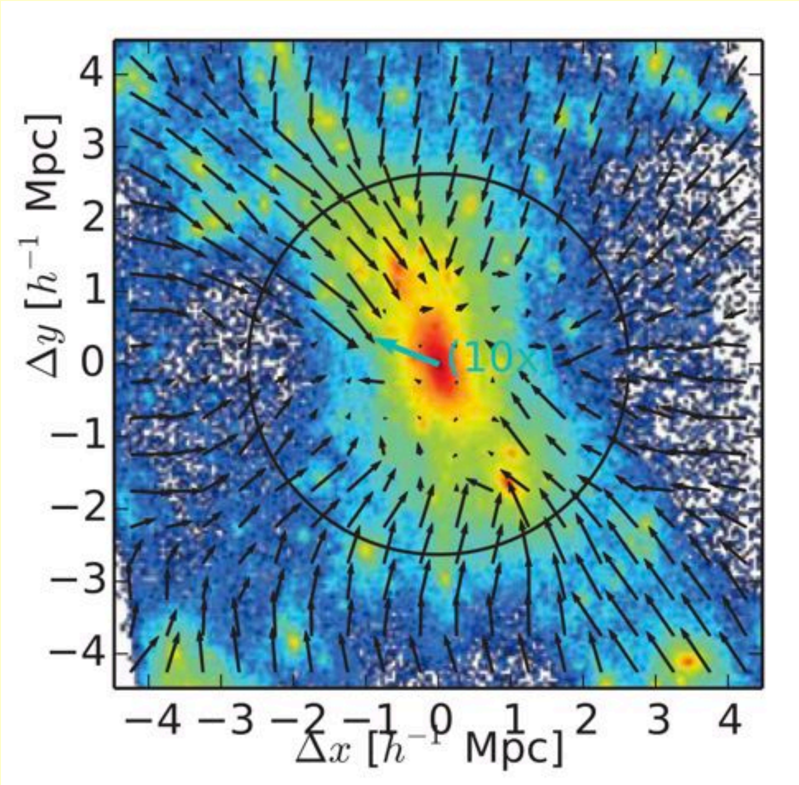


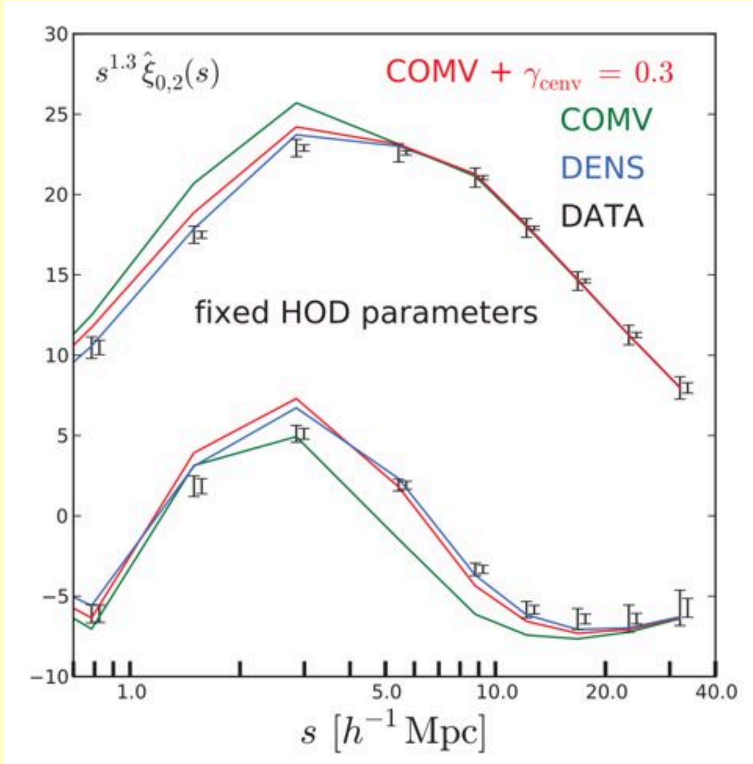
Ruiz & Huterer 1410.5832

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

$$F(z) \equiv (1+z)H(z)D_A(z)/c$$

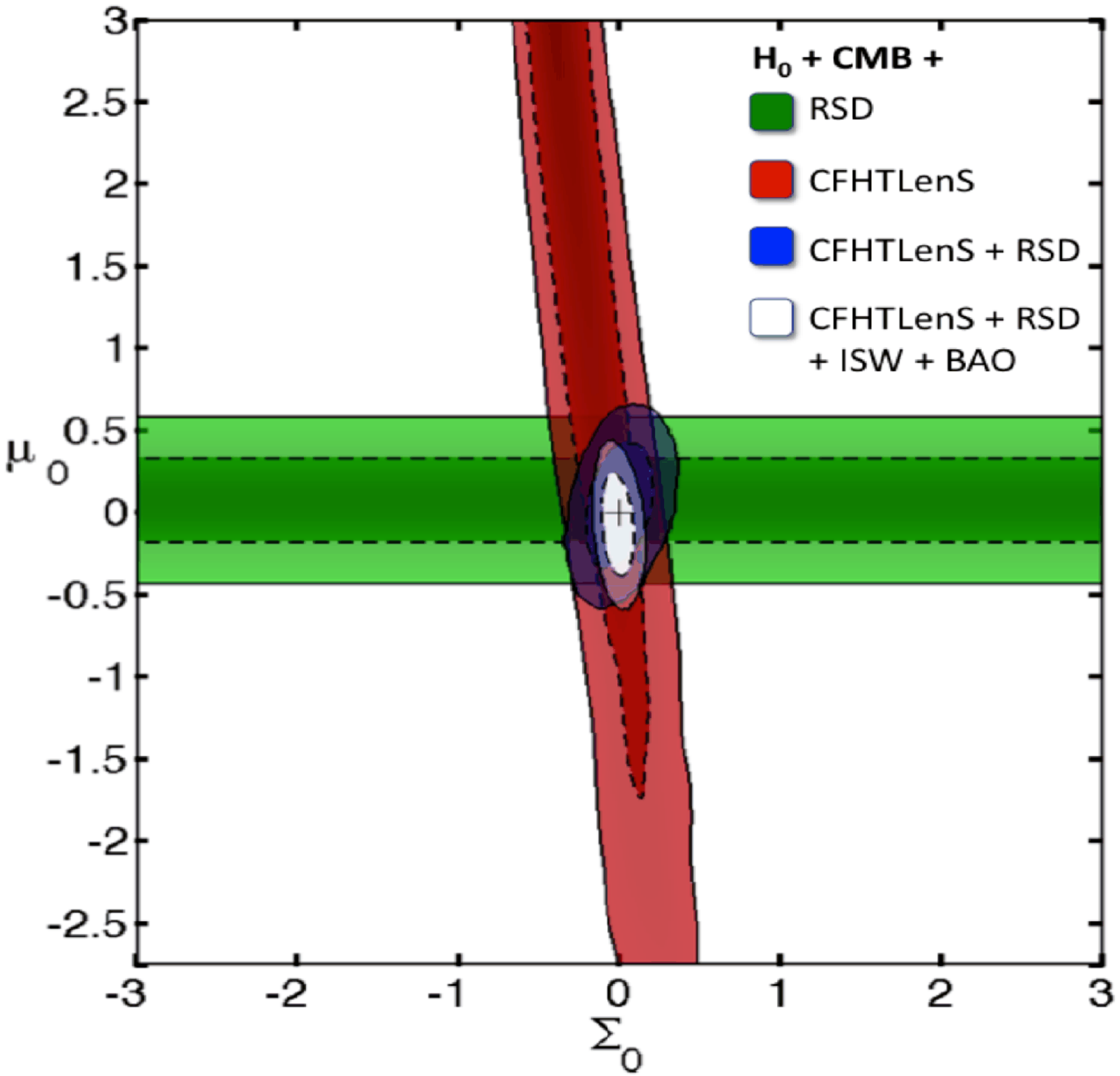
But systematics can wreck these precise goals





e.g. Reid et al. (2014): central galaxy velocity offset matters in RSD modelling at % level

Add lensing for overall MG constraints (1212.3339)



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

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

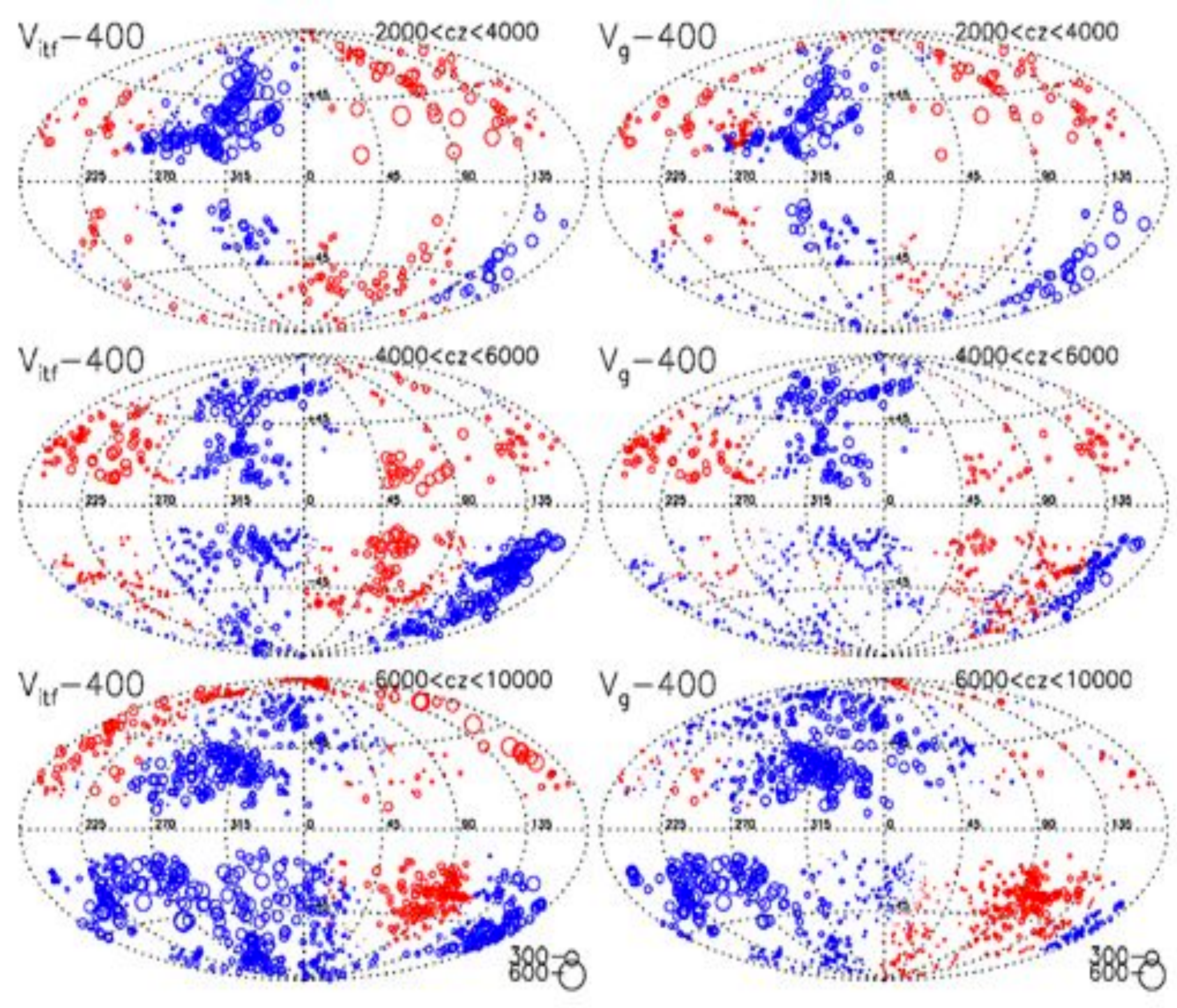
Relation to effective G and slip are

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

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

Einstein gravity OK
at 10% level

Direct peculiar velocities



Davis & Nusser: exquisite match of TF v with 2MRS gravity:

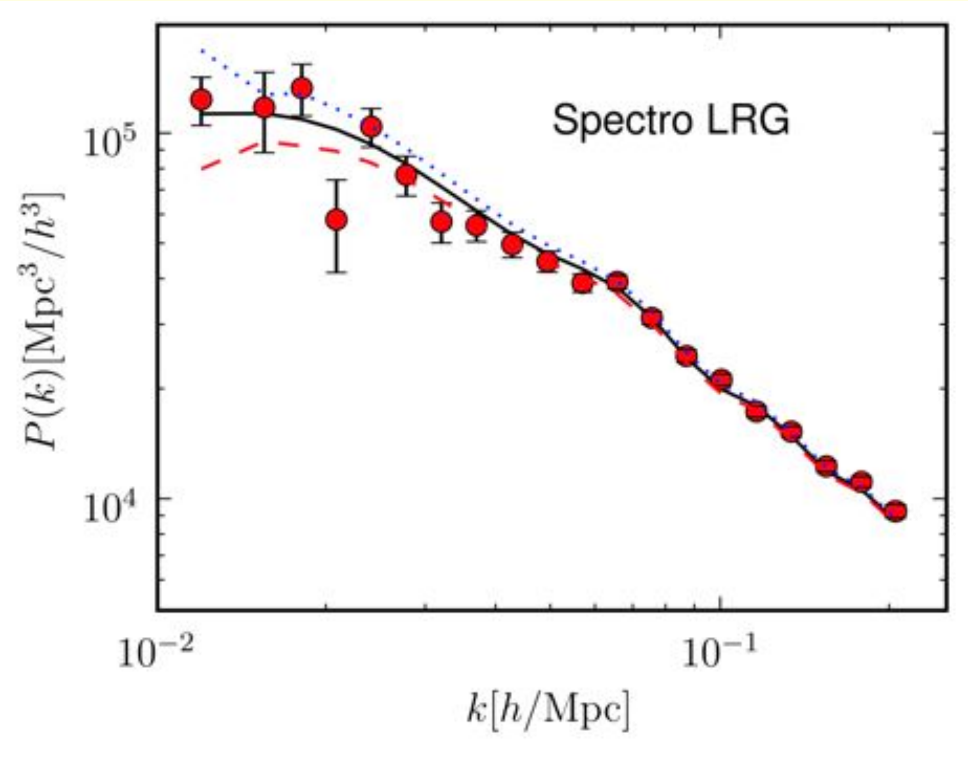
$\beta = f_g/b$

$= 0.33 \pm 0.04$

− cf. 1980s POTENT $\beta = 1$

Non-Gaussianity

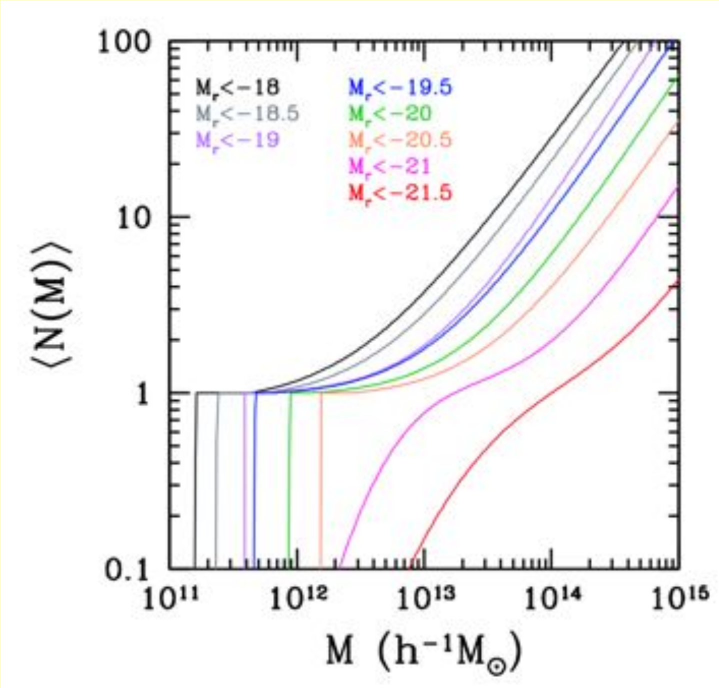
$$b_L(M,k) = b_L^{\mathrm{Gaussian}}(M) + 2 f_{\mathrm{NL}} \frac{\mathrm{d}\phi_l(k)}{\mathrm{d}\delta_l(k)} \frac{\partial \ln n}{\partial \ln \sigma_8^{\mathrm{local}}}$$



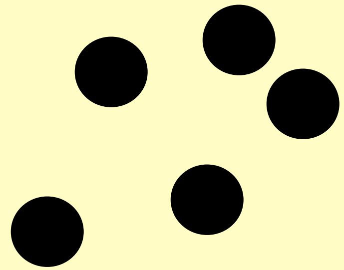
Scale-dependent bias limits f_{NL} with precision ~ 10 (but probably not much better)

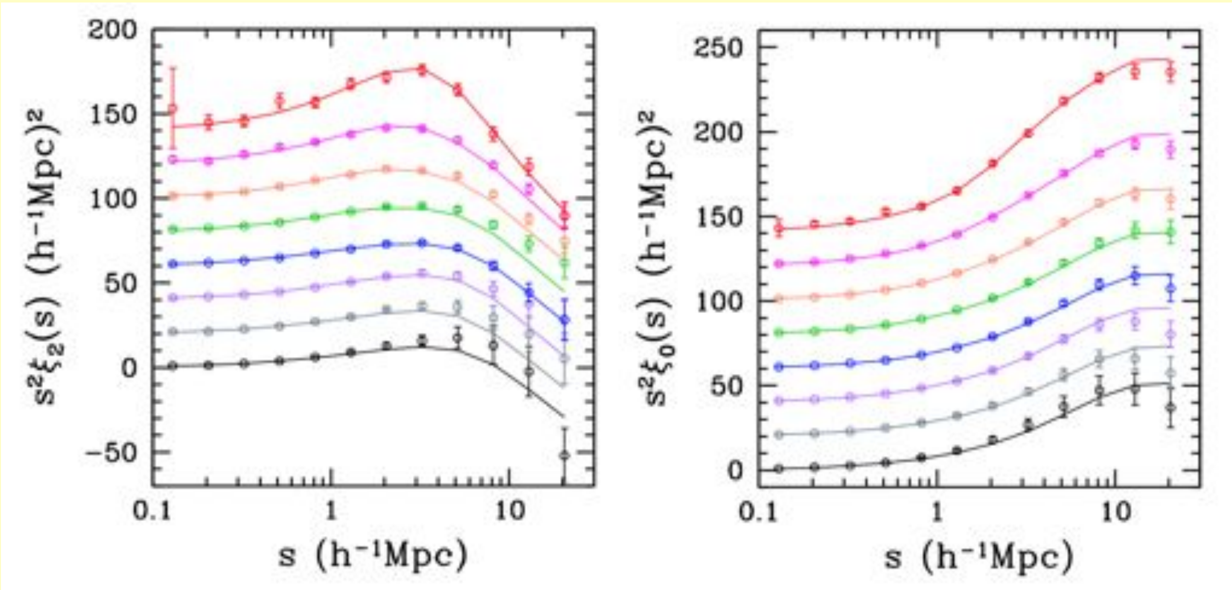
Dalal et al., Matarrese & Verde, Slozar et al., 2008

Occupying the haloes

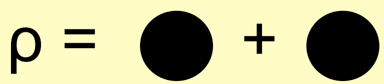


Fitting SDSS:
Guo et al.
1505.07861

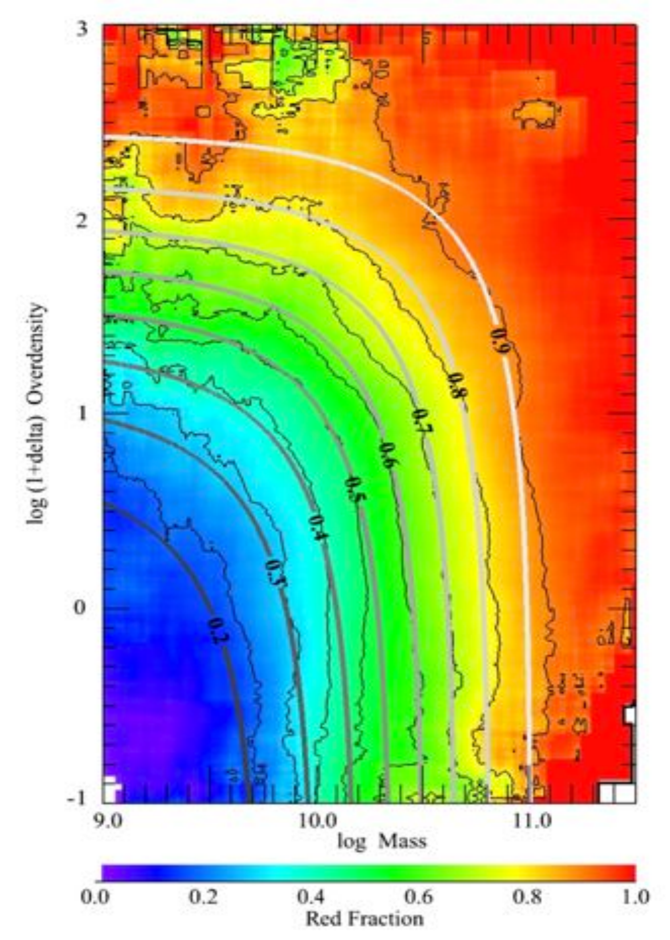




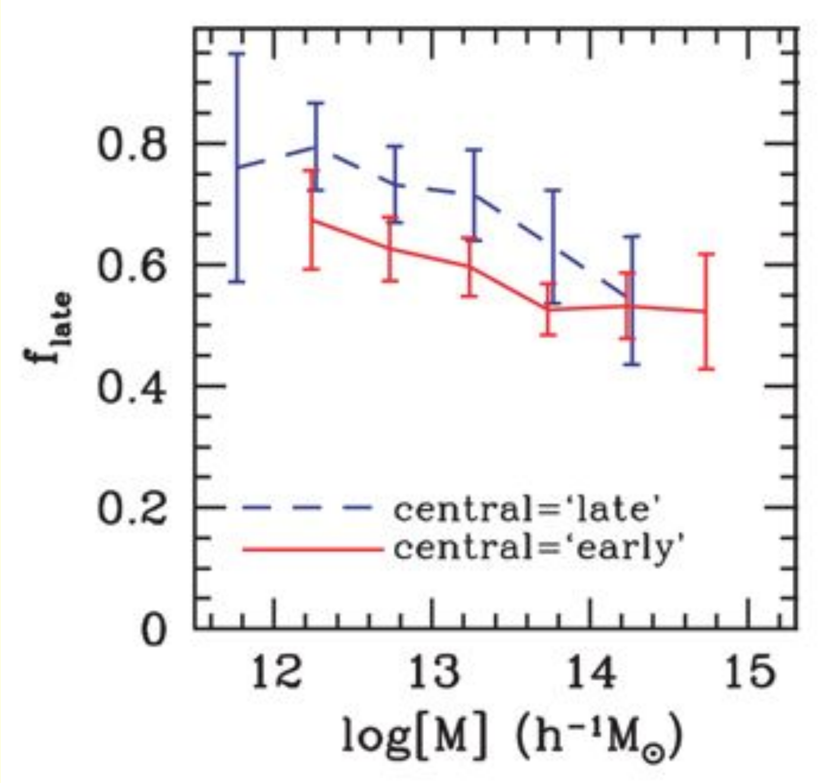
Halo model:



Environment and galaxy formation



Quenching empirically relates to environment (Peng et al. 2010)

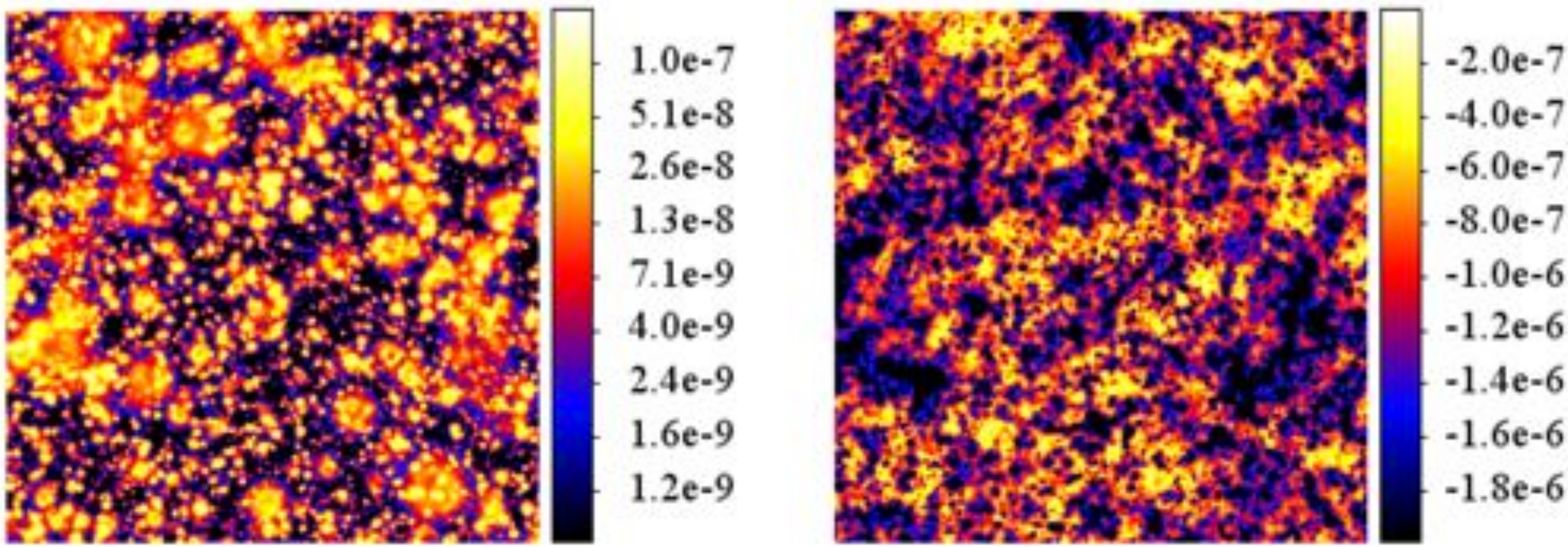


Whole-halo phenomenon: ‘galactic conformity’ as sign of assembly bias (Weinmann et al. 2006)

Finding the baryons

Most gas predicted to be in the $10^5 - 10^7$ K WHIM

− seek via cross-correlation



X-ray 1405.5225 SZ

What are the next big expected LSS probes?

DESI

DOE proposal for KPNO 4m over 2018-2022:

5000 Fibres; 3-deg field

28M galaxies

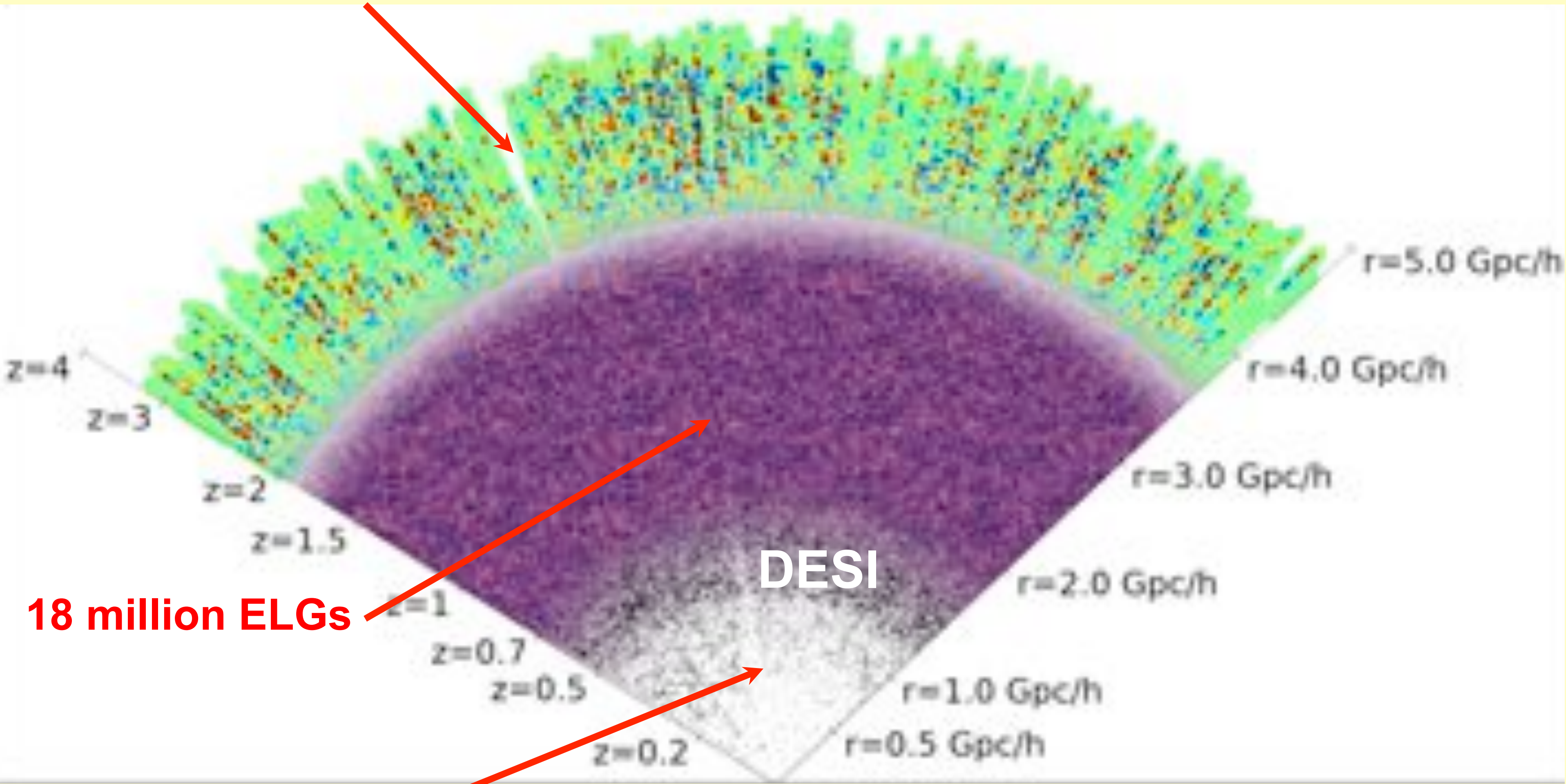
− LRGs to z = 0.9

− OII ELGs to z = 1.7

− QSOs to z = 3

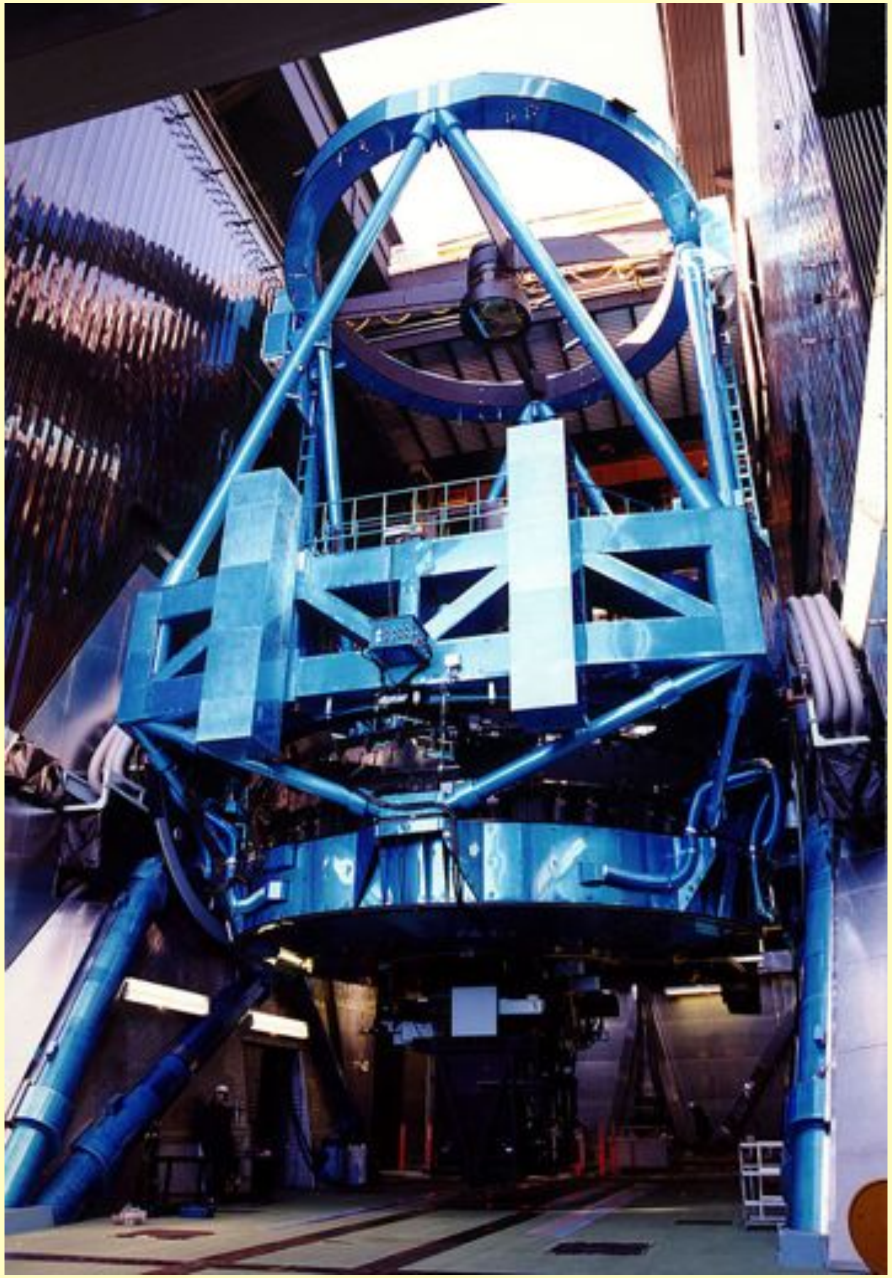
DESI coverage

3 million QSOs



18 million ELGs

4 million LRGs



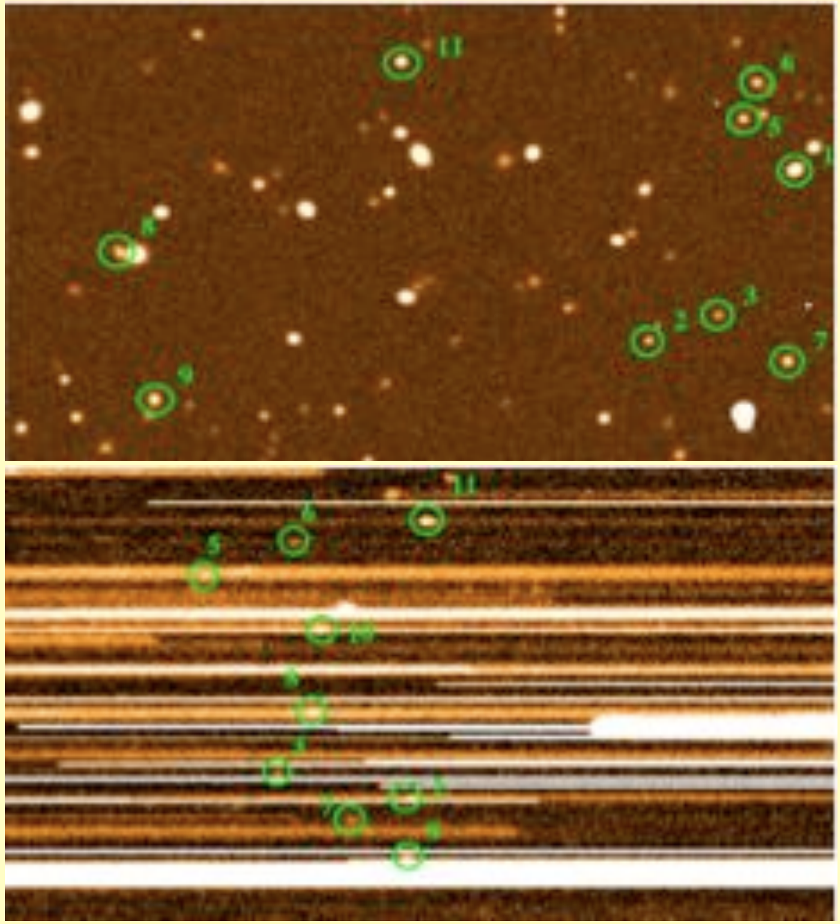
Subaru PFS

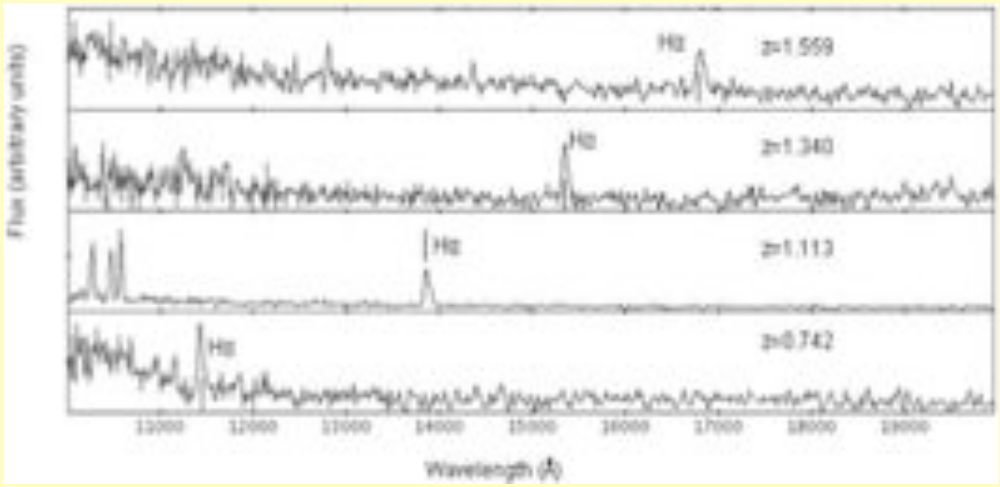
- 2400 Fibres over 1.3-deg field on 8.2m
- R=3000 spectra from 0.4 to 1.3 microns
- Multinational project led by IPMU Tokyo
- Planned first light 2017
- Shared telescope: sufficient time?

Euclid slitless spectroscopy

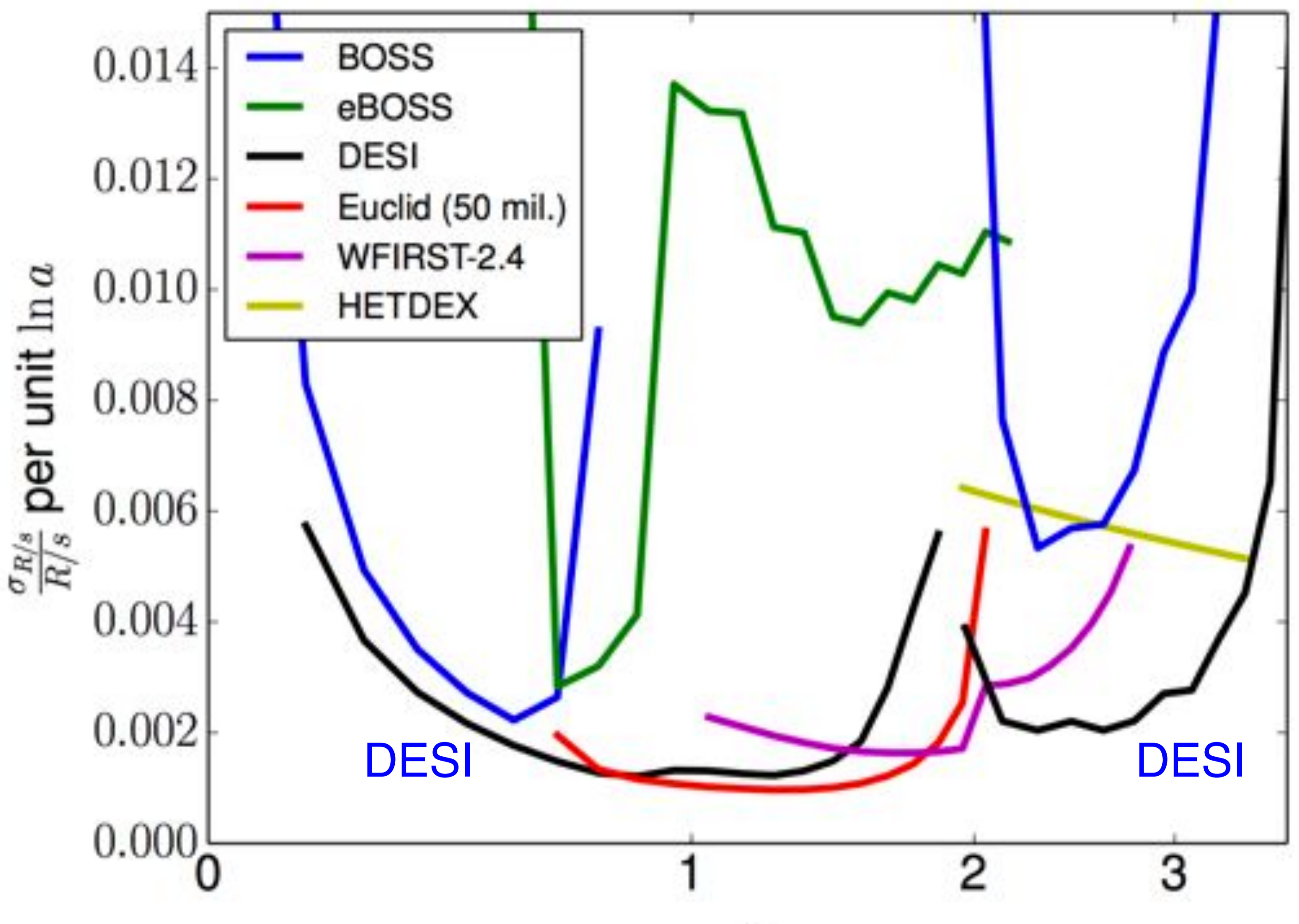
NIS Instrument:

- ~ 25M redshifts in 1<z<2
- 15,000 deg^2
- H < 19.5





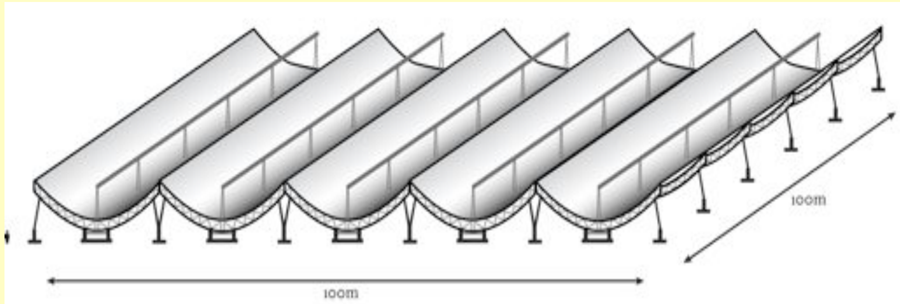
Outlook: 0.1% cosmology



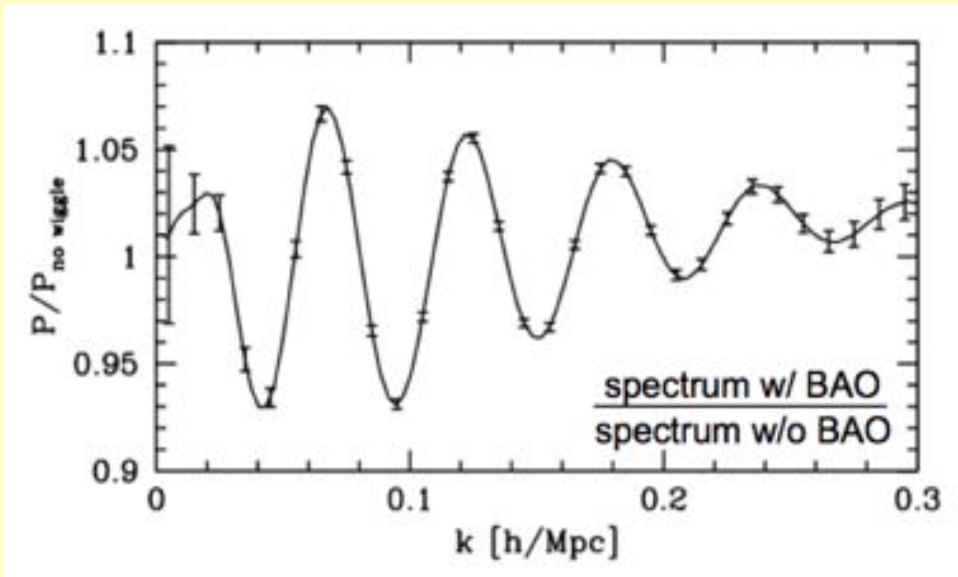
Font-Ribera et al. 2013; arXiv:1308.4164

HI Intensity Mapping

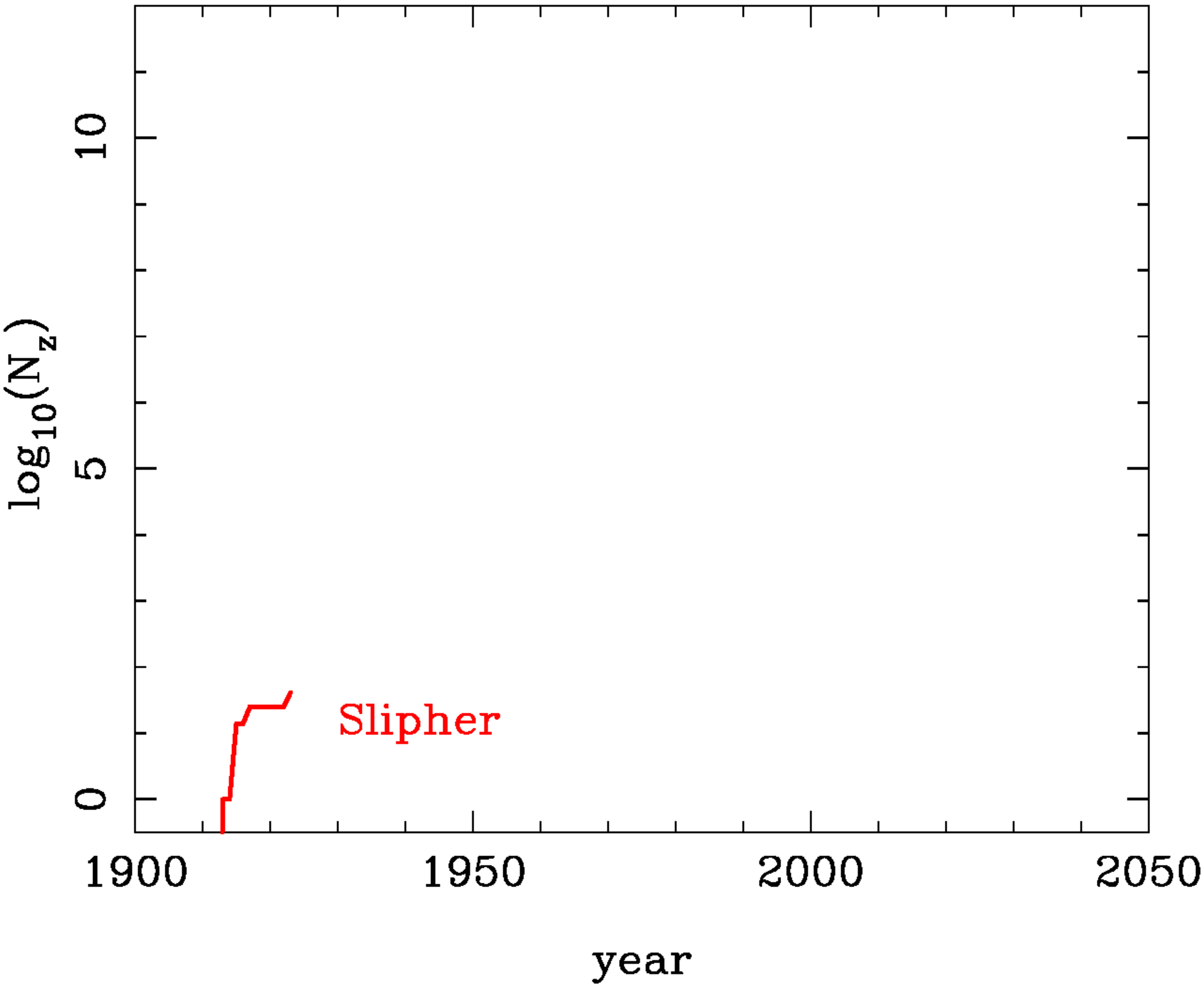
Even with SKA, 21-cm z's hard. But who needs galaxies? Cover large areas of sky at low resolution.



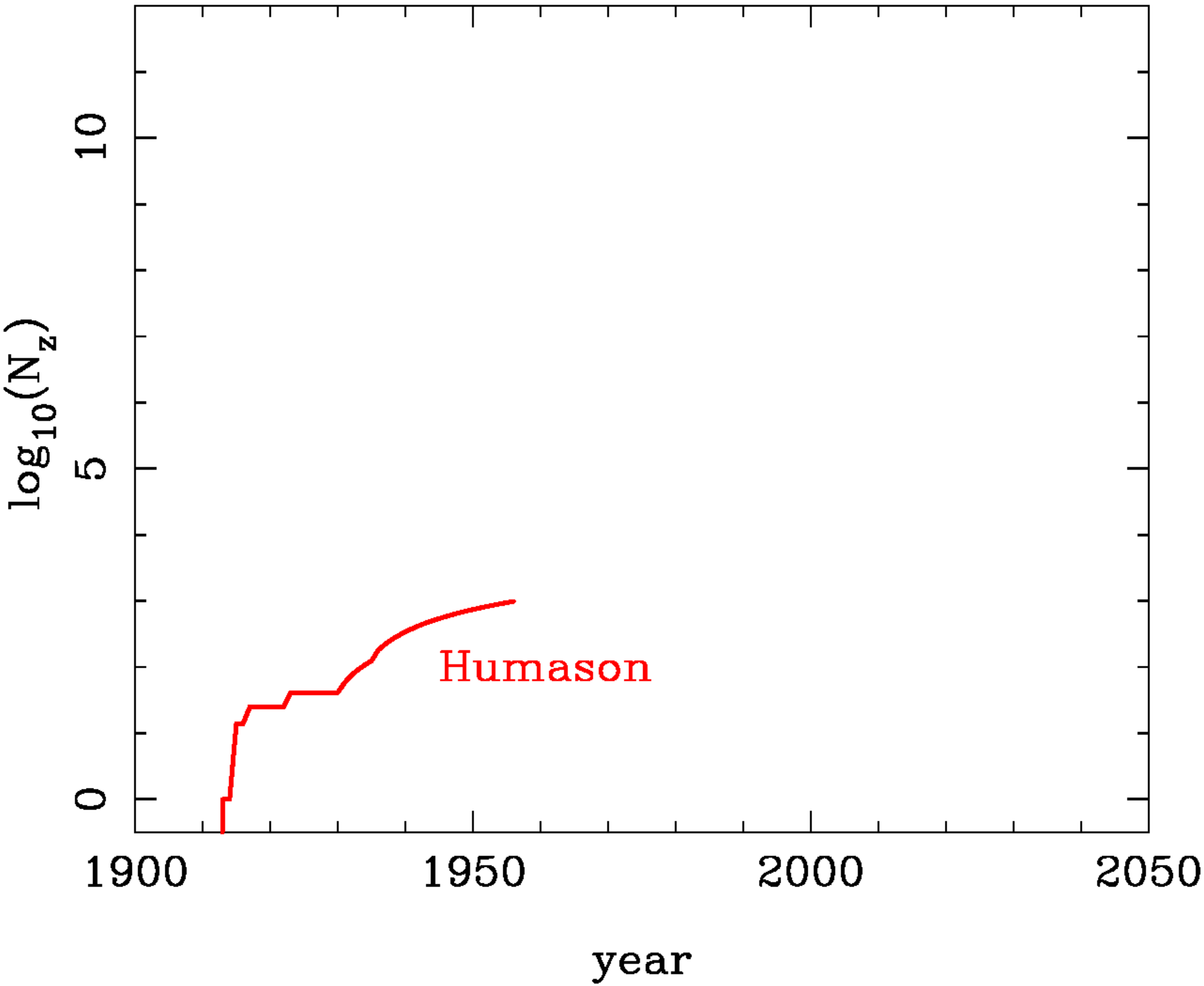
CHIME: 400−800 MHz (z=0.8−2.5). Hemisphere survey 2016-18. 0.5% in D(z)



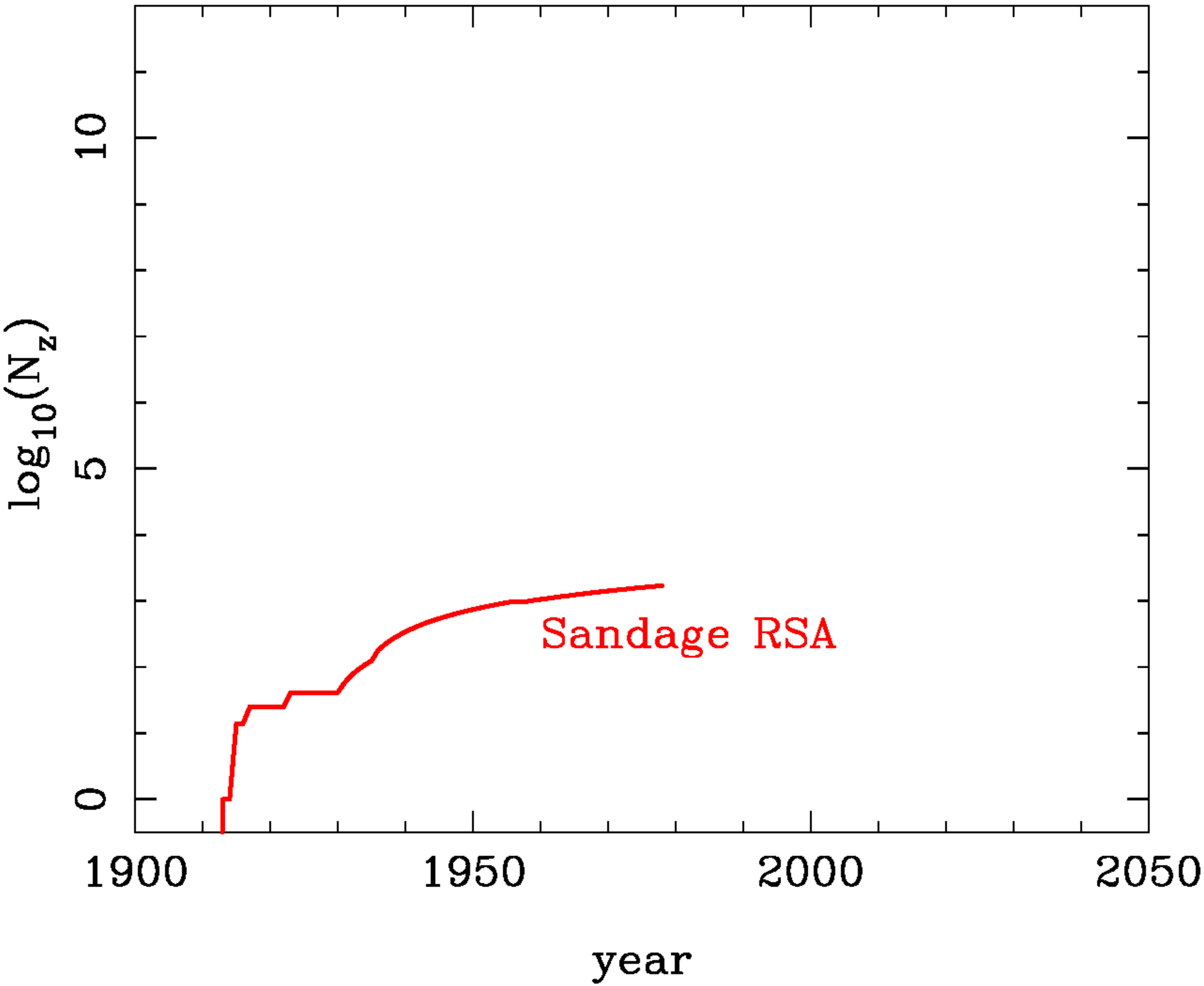
A Century+ of galaxy redshifts

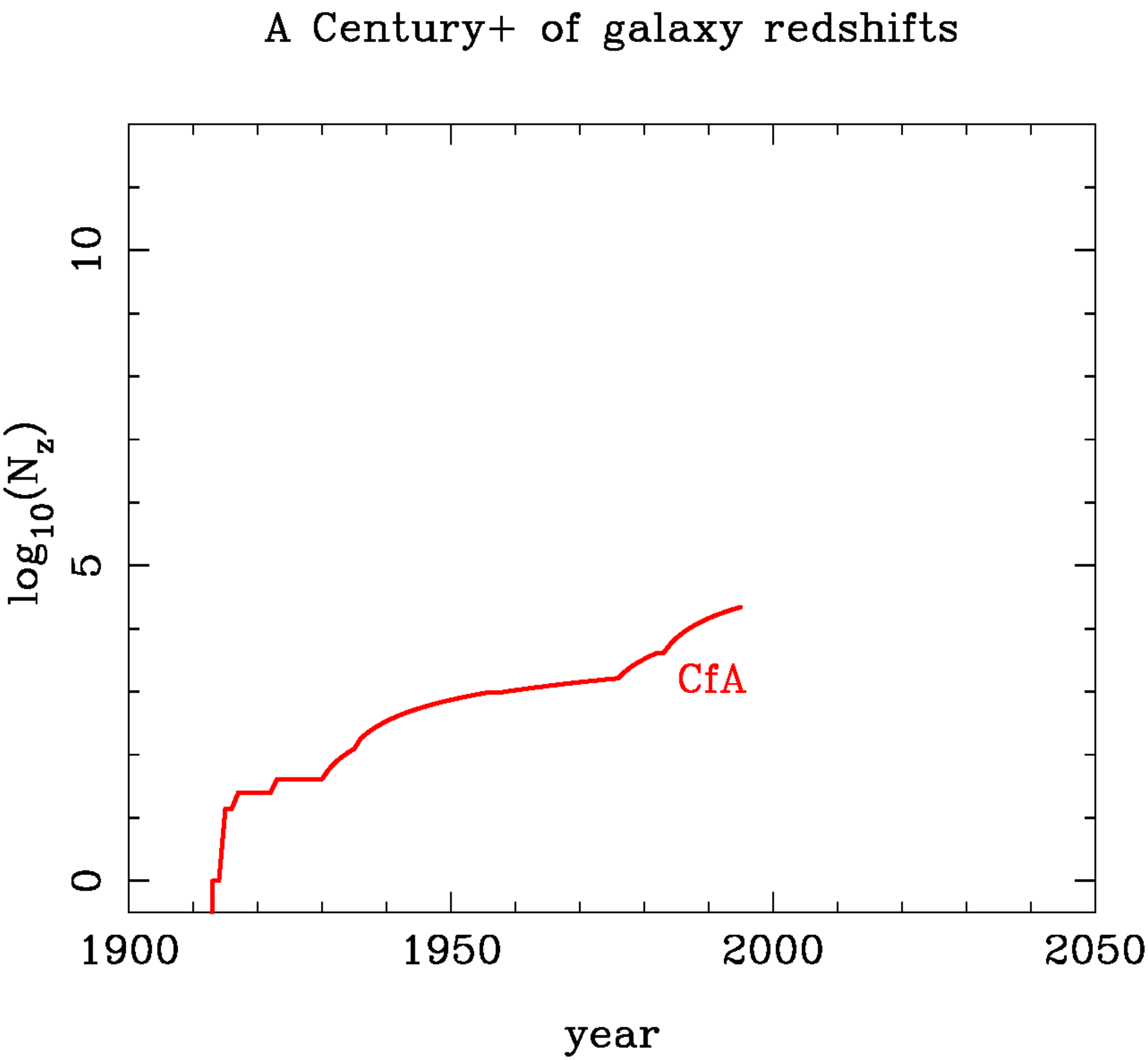


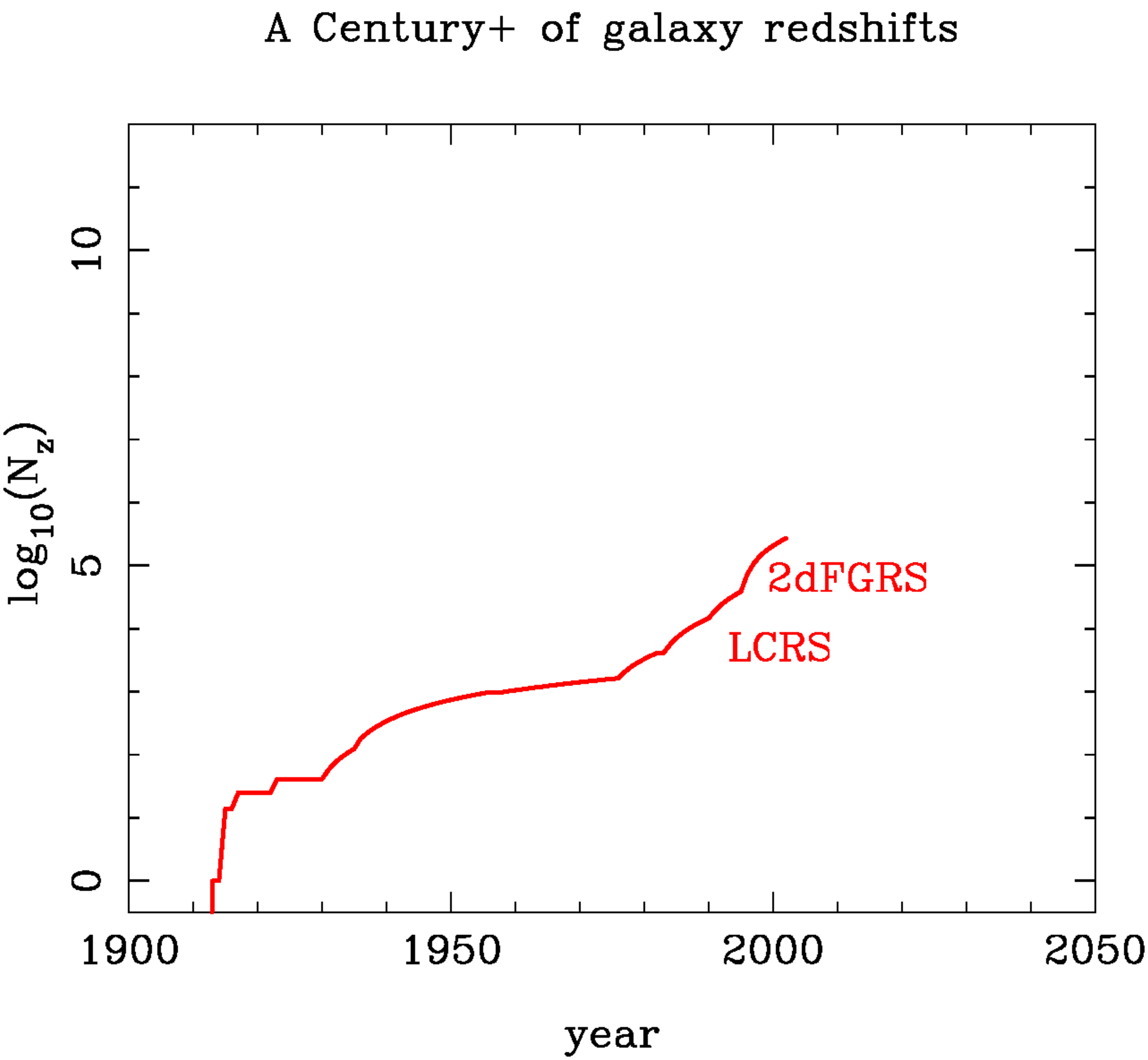
A Century+ of galaxy redshifts



A Century+ of galaxy redshifts

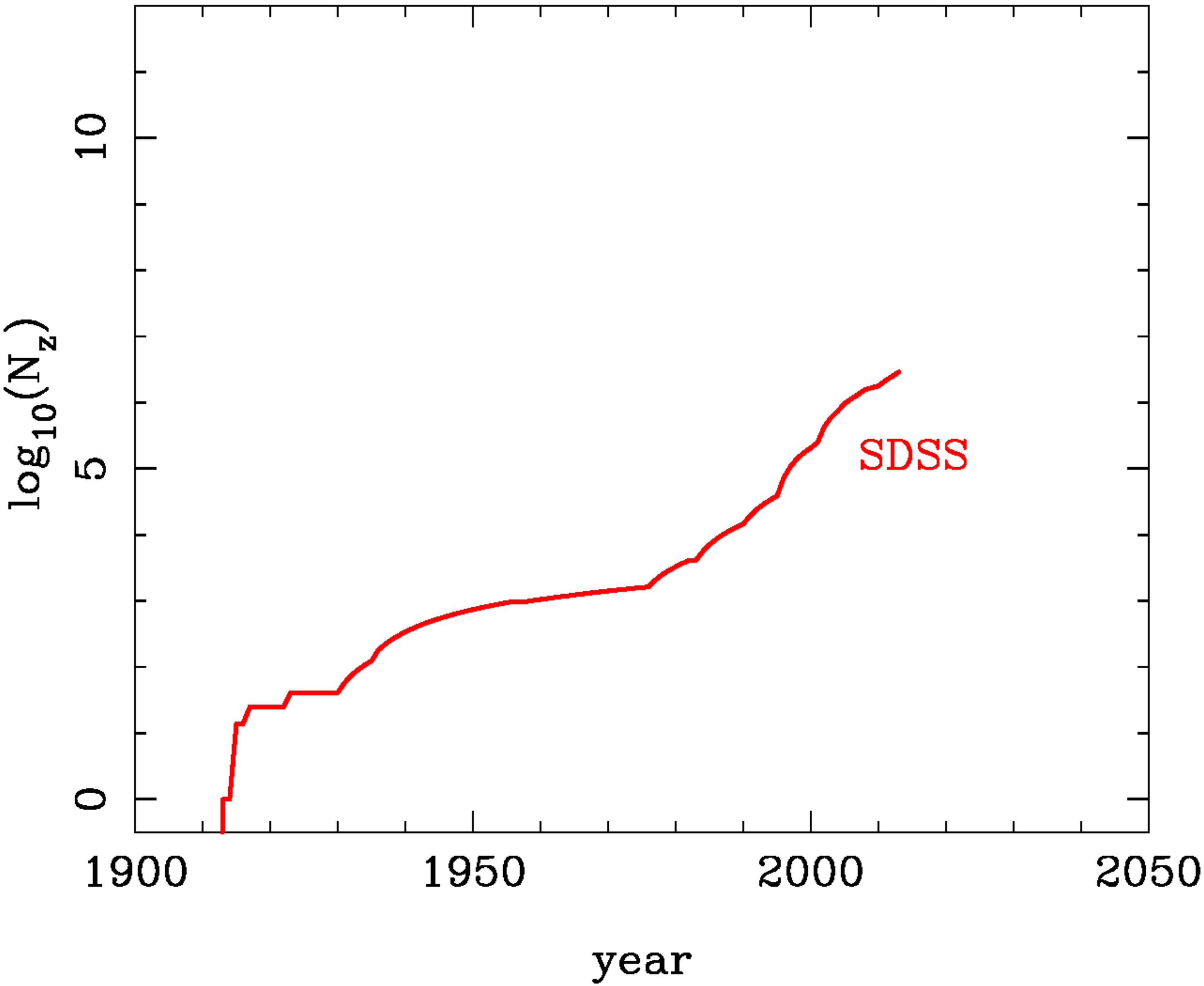



A Century+ of galaxy redshifts
10
5
0
$\log_{10}(N_z)$
1900
1950
2000
2050
year
CfA

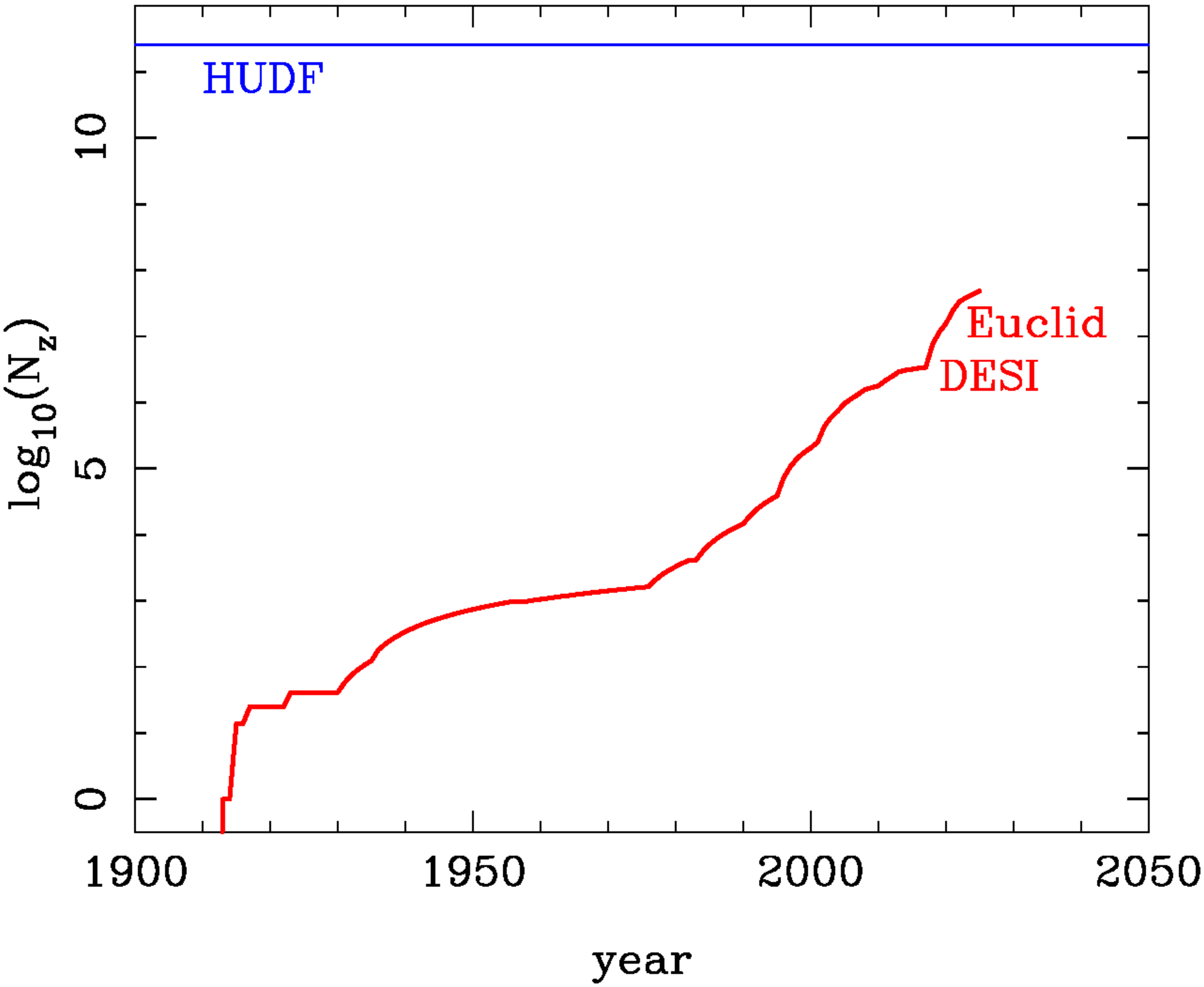


A Century+ of galaxy redshifts
$\log_{10}(N_z)$
0
5
10
1900
1950
2000
2050
year
2dFGRS
LCRS

A Century+ of galaxy redshifts



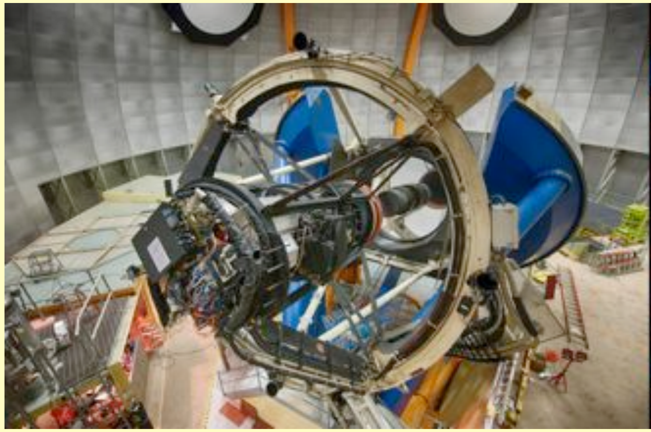
A Century+ of galaxy redshifts

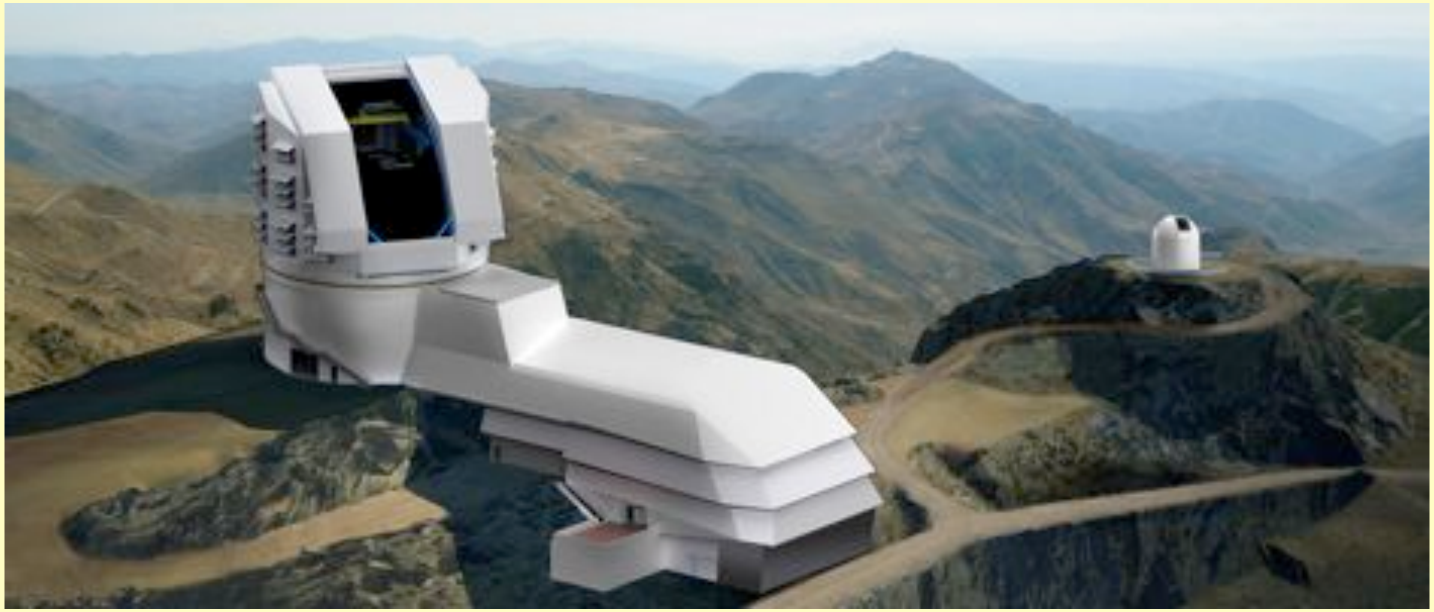


DARK ENERGY SURVEY

LSST Large Synoptic Survey Telescope

The future is photometric



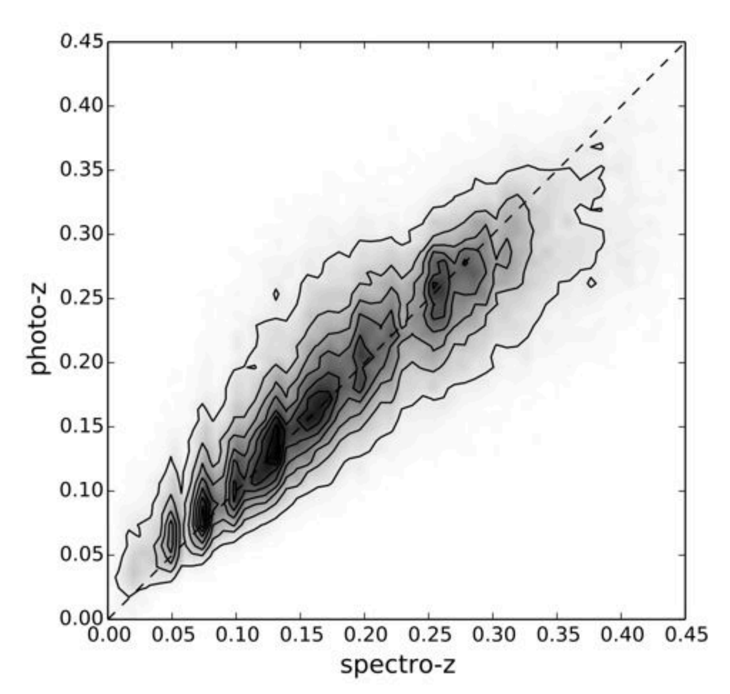


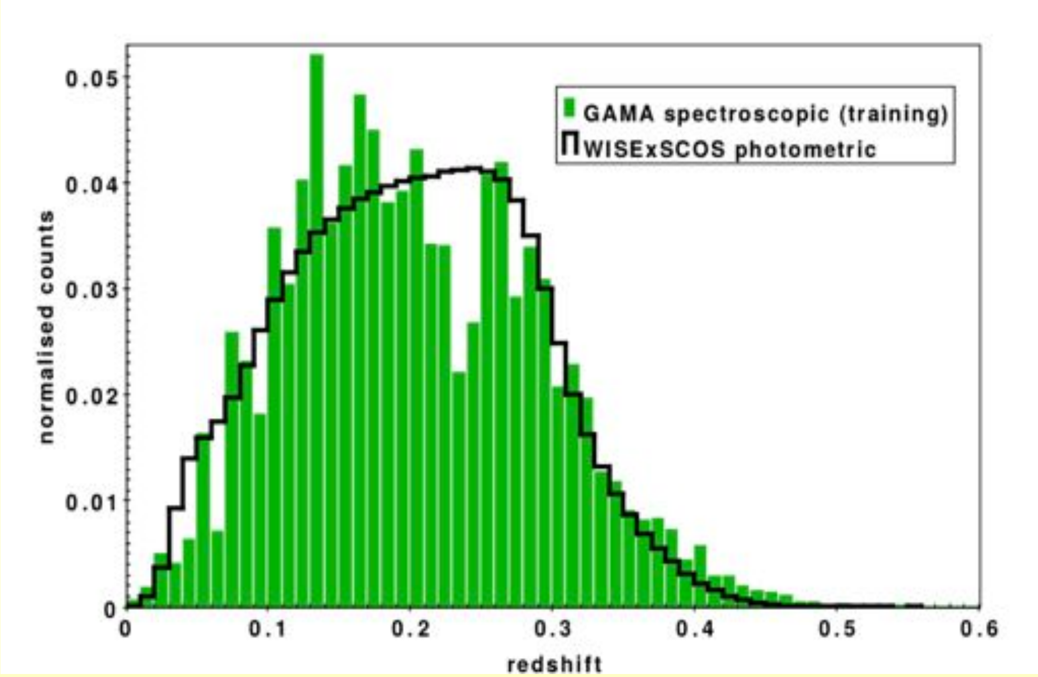
All-sky photo-z for WISE+SuperCOSMOS
(Bilicki; Jarrett; JAP)

ANNz Using (B,R,W1,W2) and GAMA spectroscopy

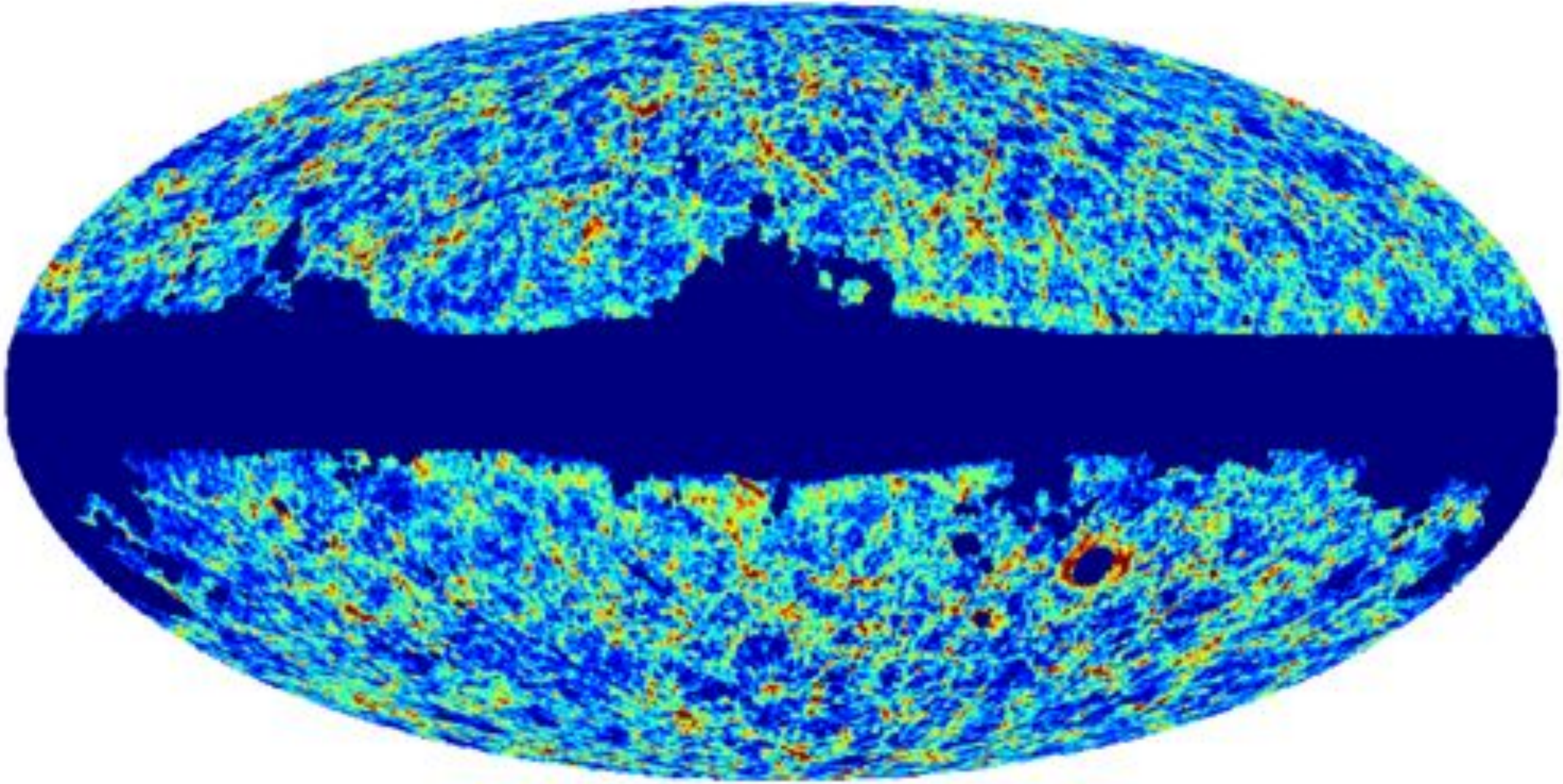
$\sigma_z / (1+z) = 0.032$

Median z = 0.2; useful signal out to z = 0.4

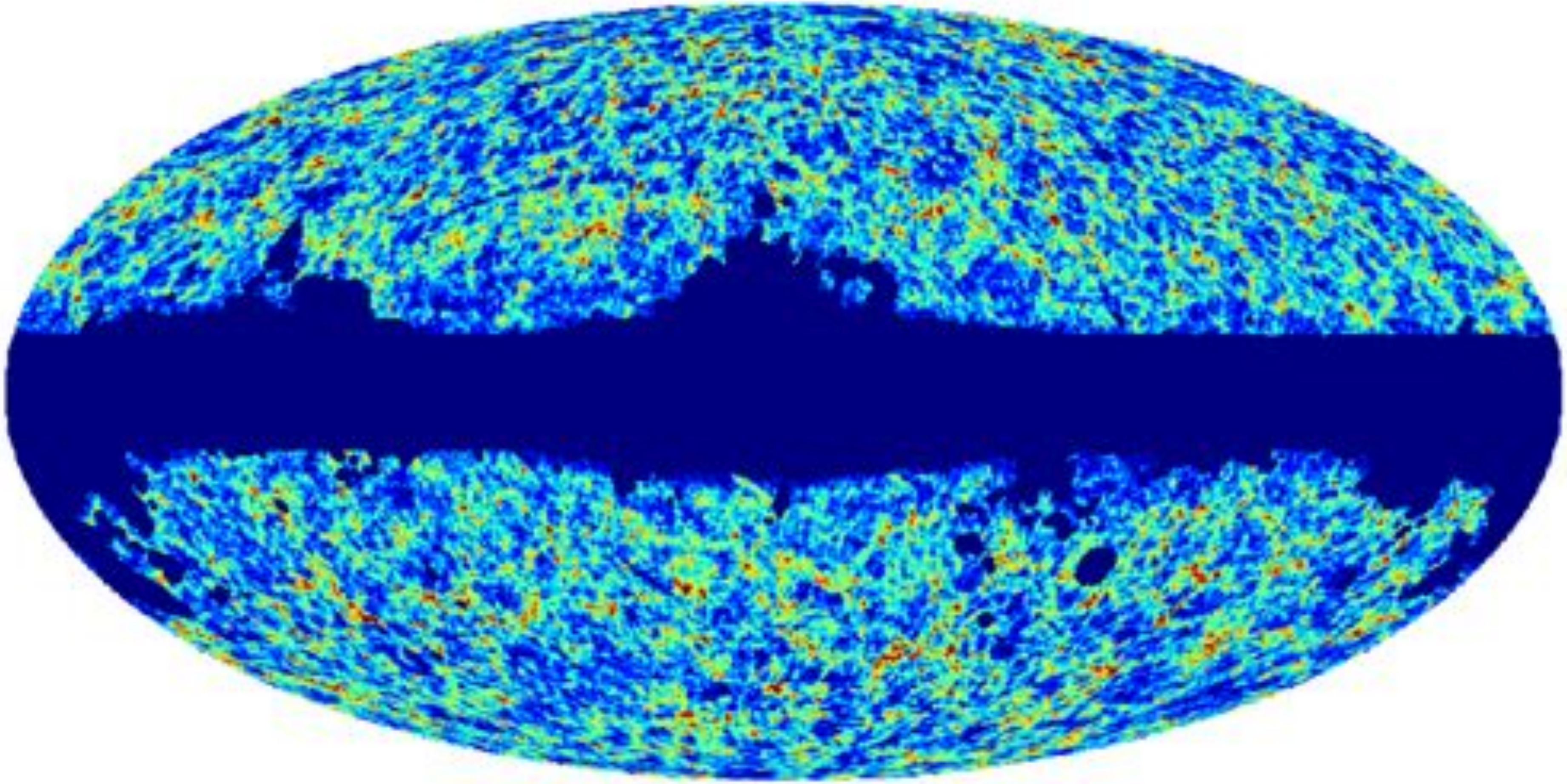




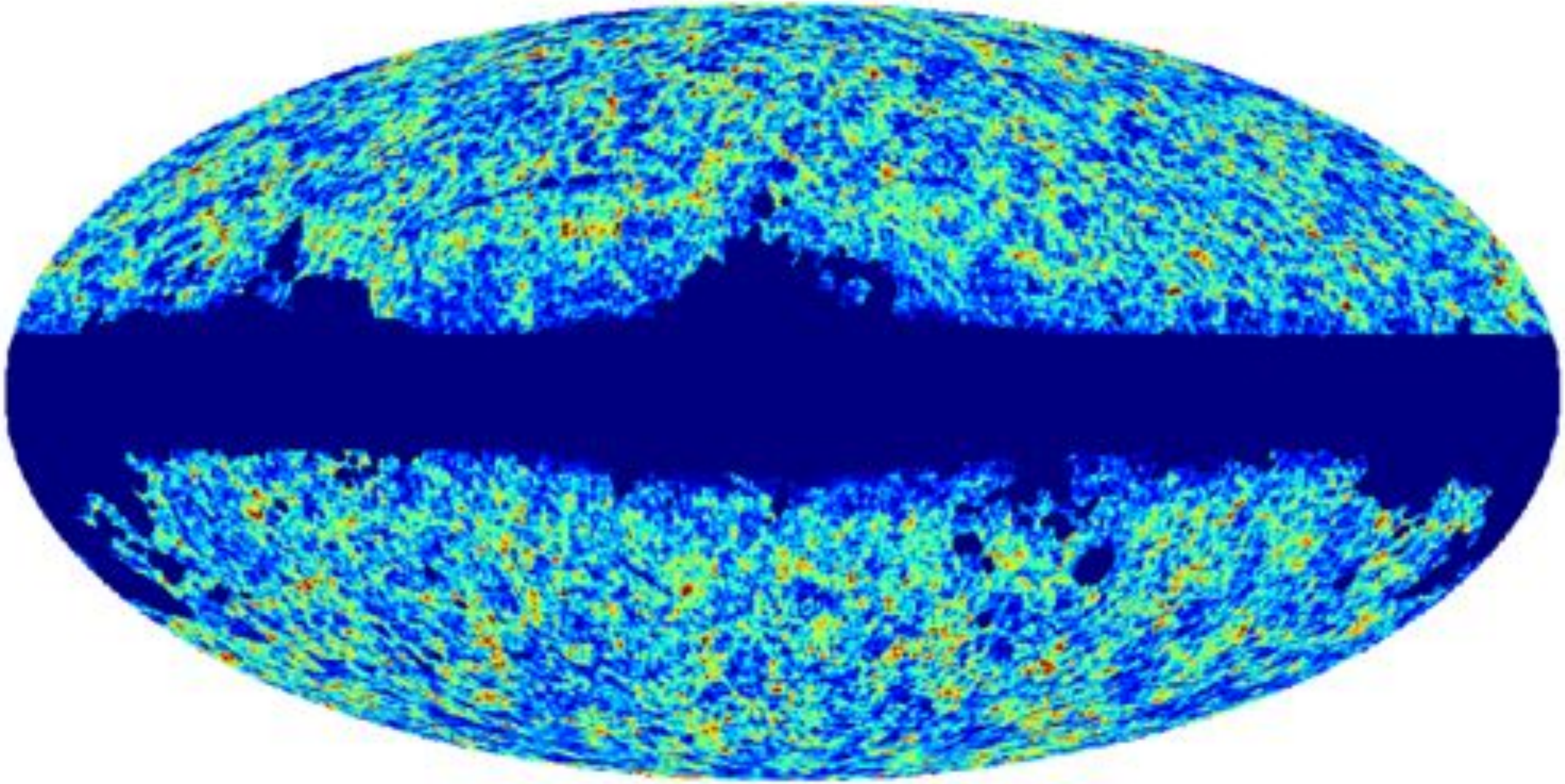
0.1 < z < 0.15



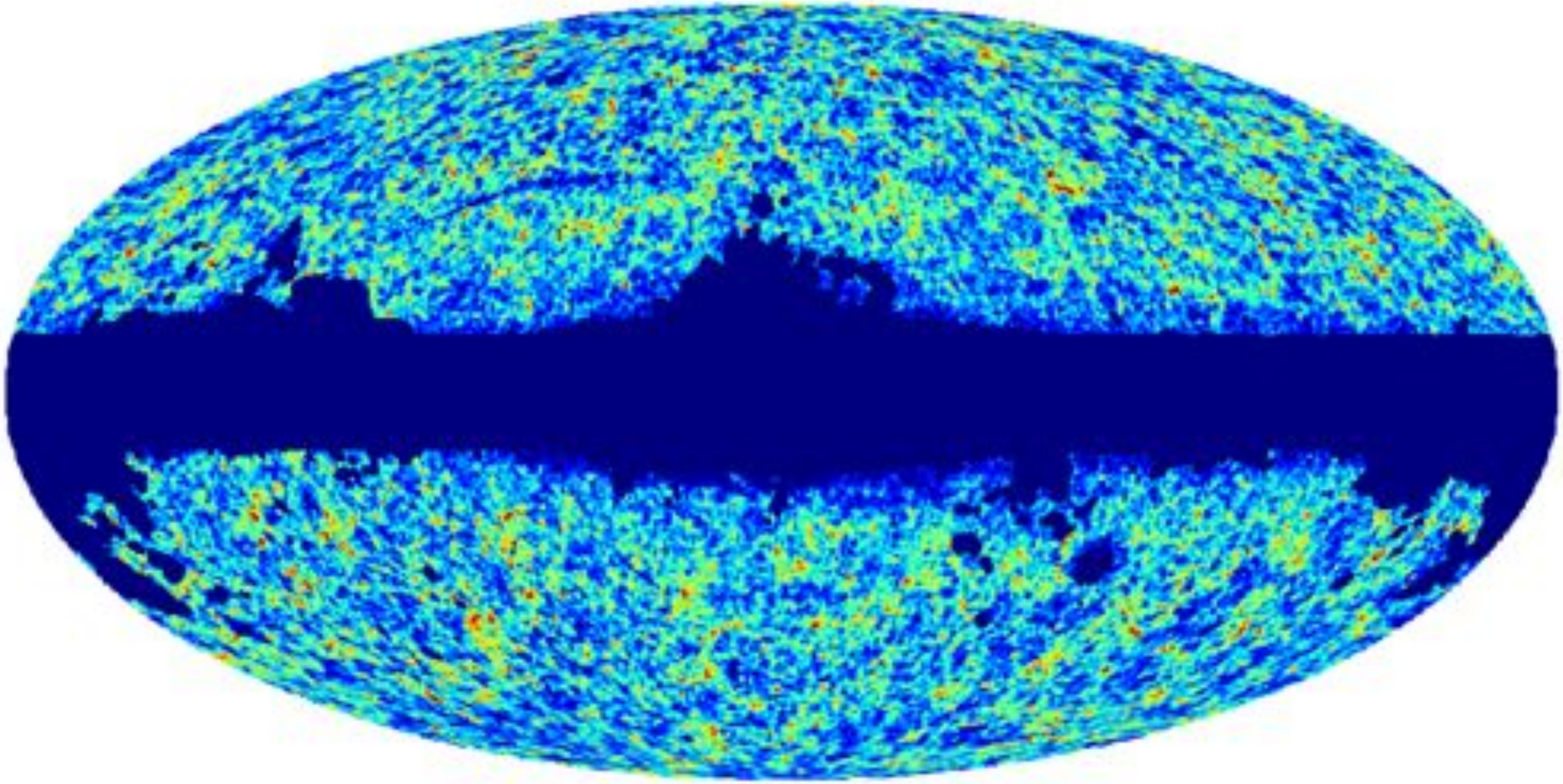
0.15 < z < 0.2

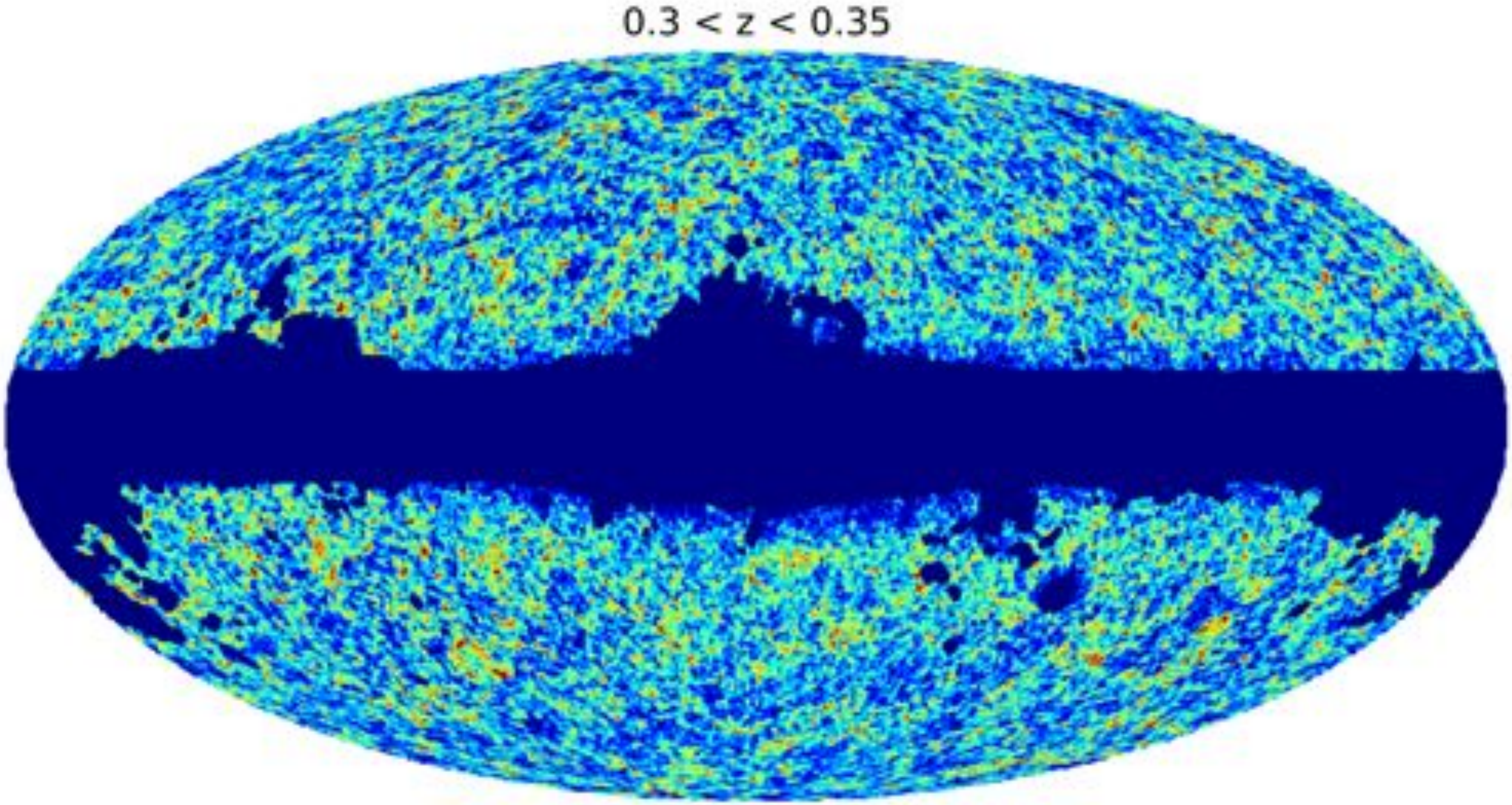


$0.2 < z < 0.25$

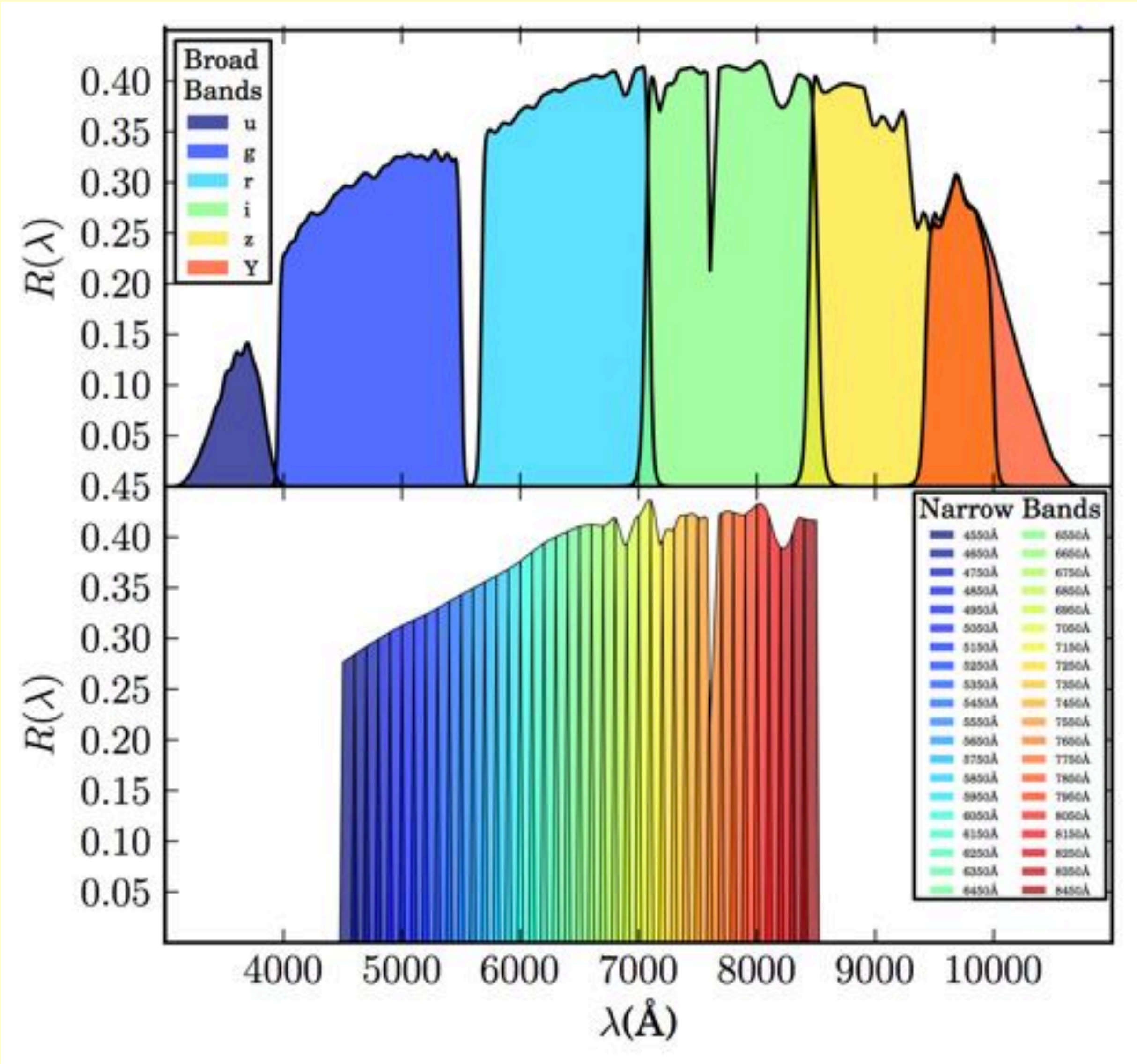


0.25 < z < 0.3




0.3 < z < 0.35

PAU: Photo-z on steroids



40-band survey using WHT:

dz / (1+z) = 0.0035

(12 Mpc/h @ z=1)

Significant effects on BAO & RSD, but can be modelled

Conclusions

- LSS has a tremendous record of recent achievements
  - Detailed probe of ΛCDM
  - Validation of fundamentals of model at 10% level
- Huge surveys in prospect for the next decade
  - Prospect of factor 10 improvement in precision
  - Hard work to nail systematics
- Can theory keep pace?