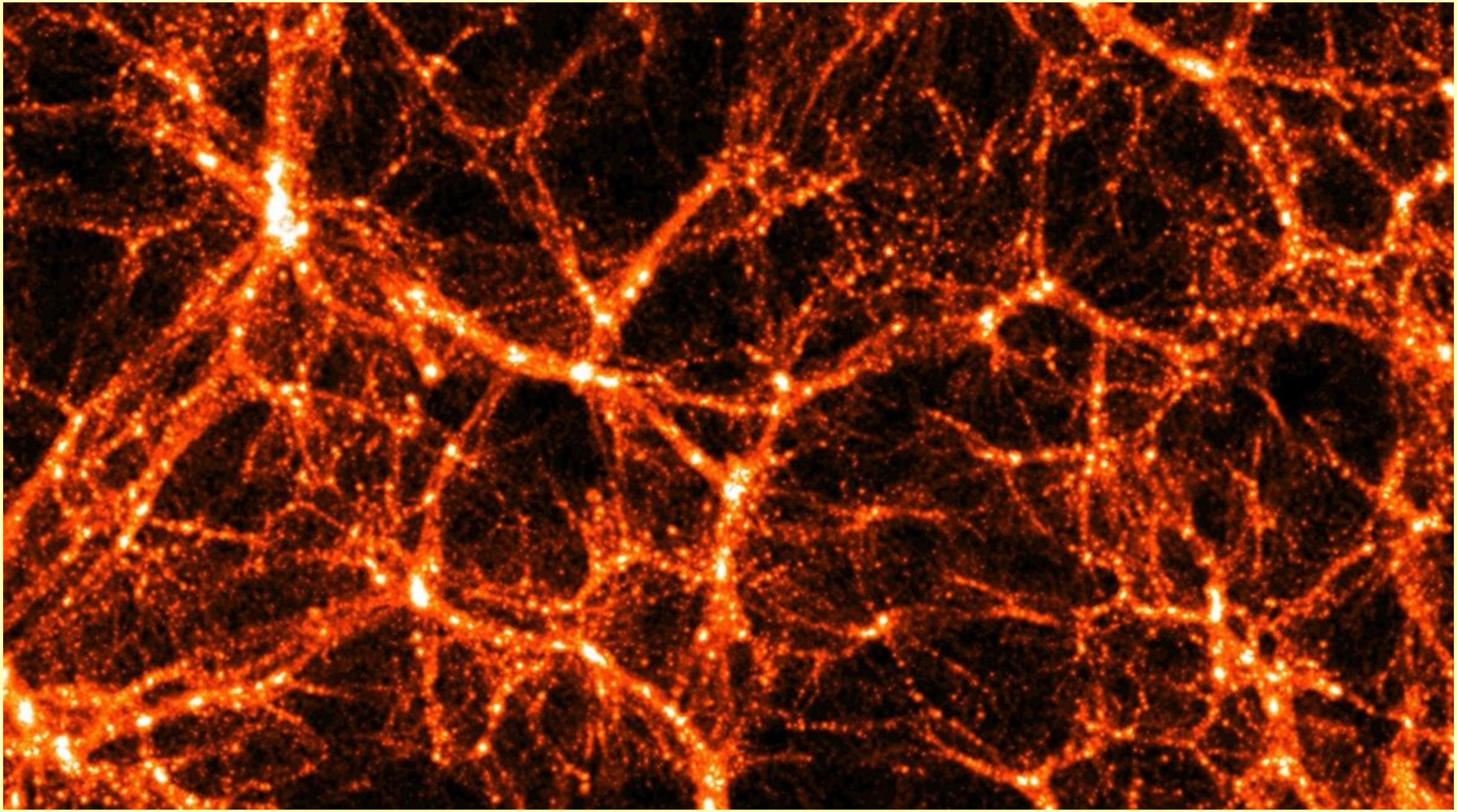
Large-scale structure in the 2020s



John Peacock ESO in the 2020s 21 Jan 2015

Outline

- Past advances and tools of the trade
- Current and near-term goals
- Planned experiments and alternatives

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)

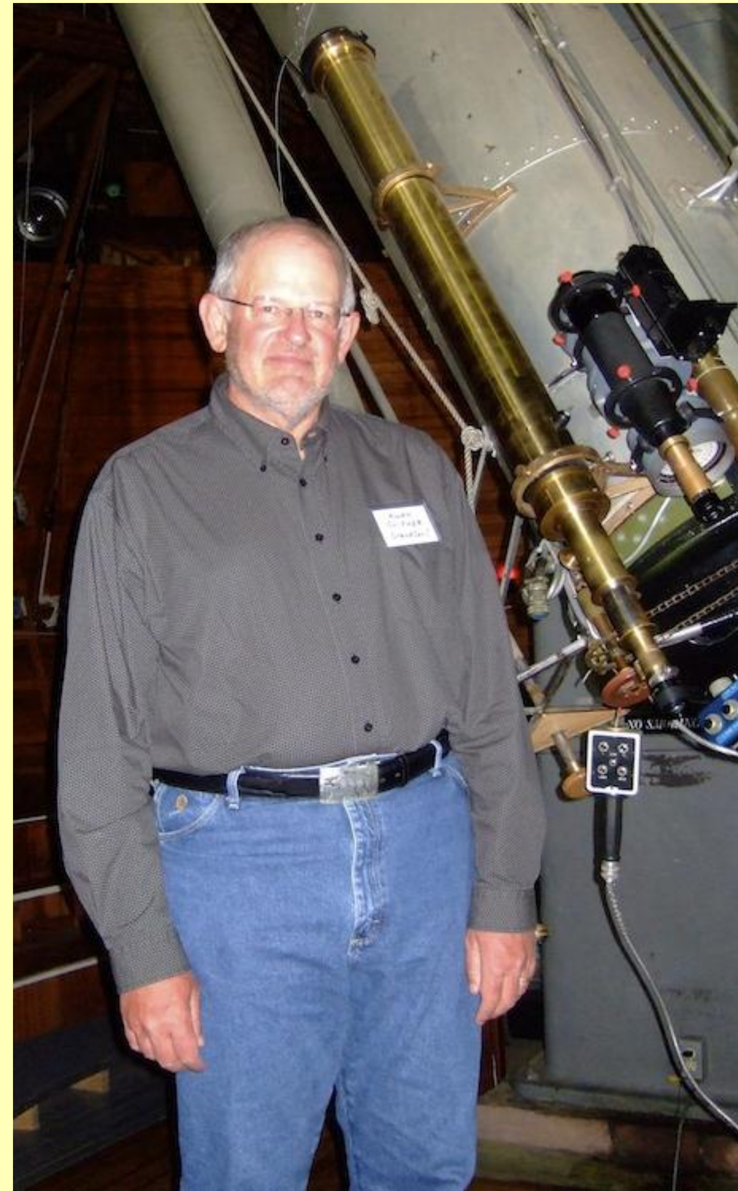
1913: M31 v<0

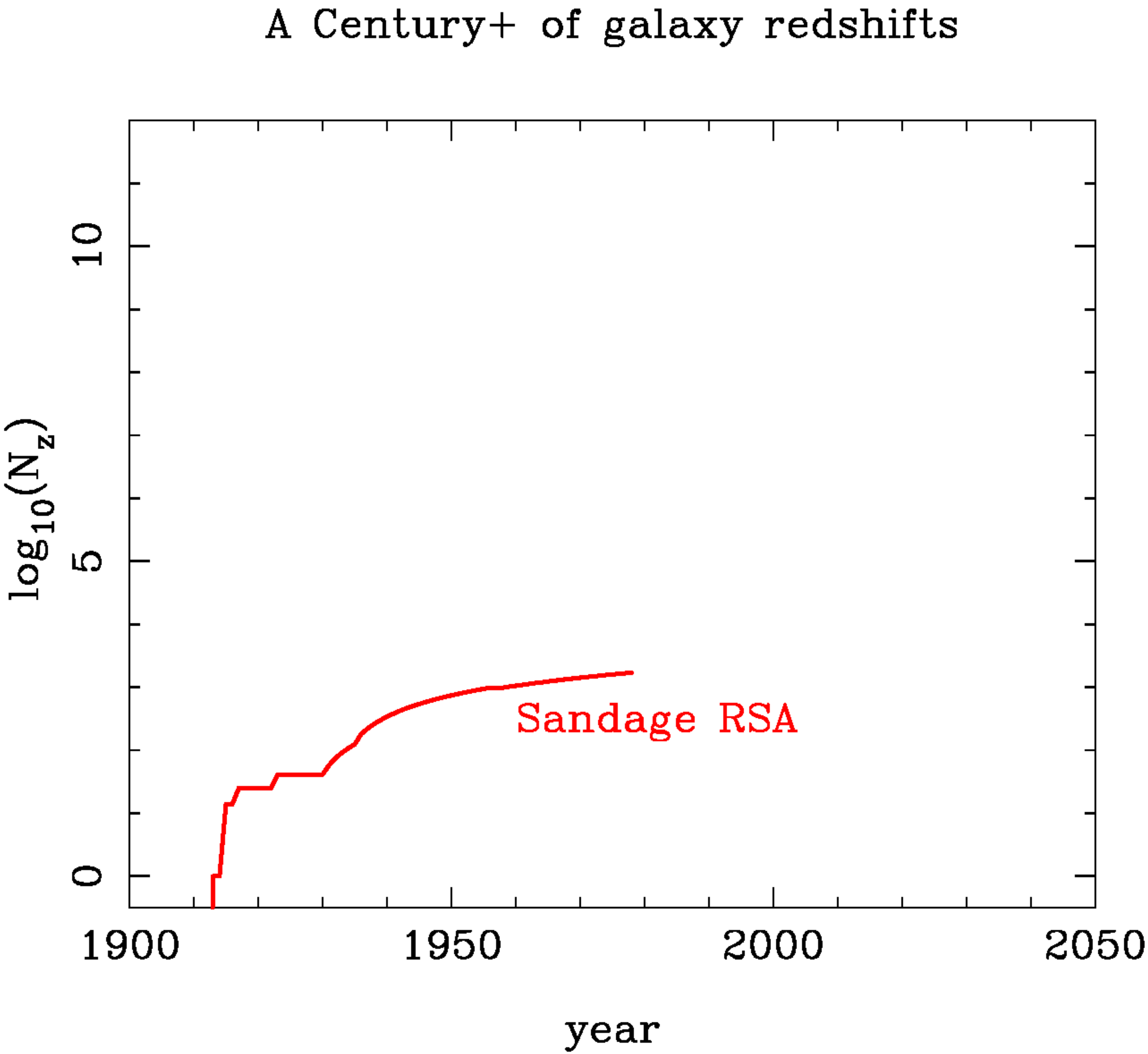
1915: 11/15 v>0

1917: 21/25 v>0

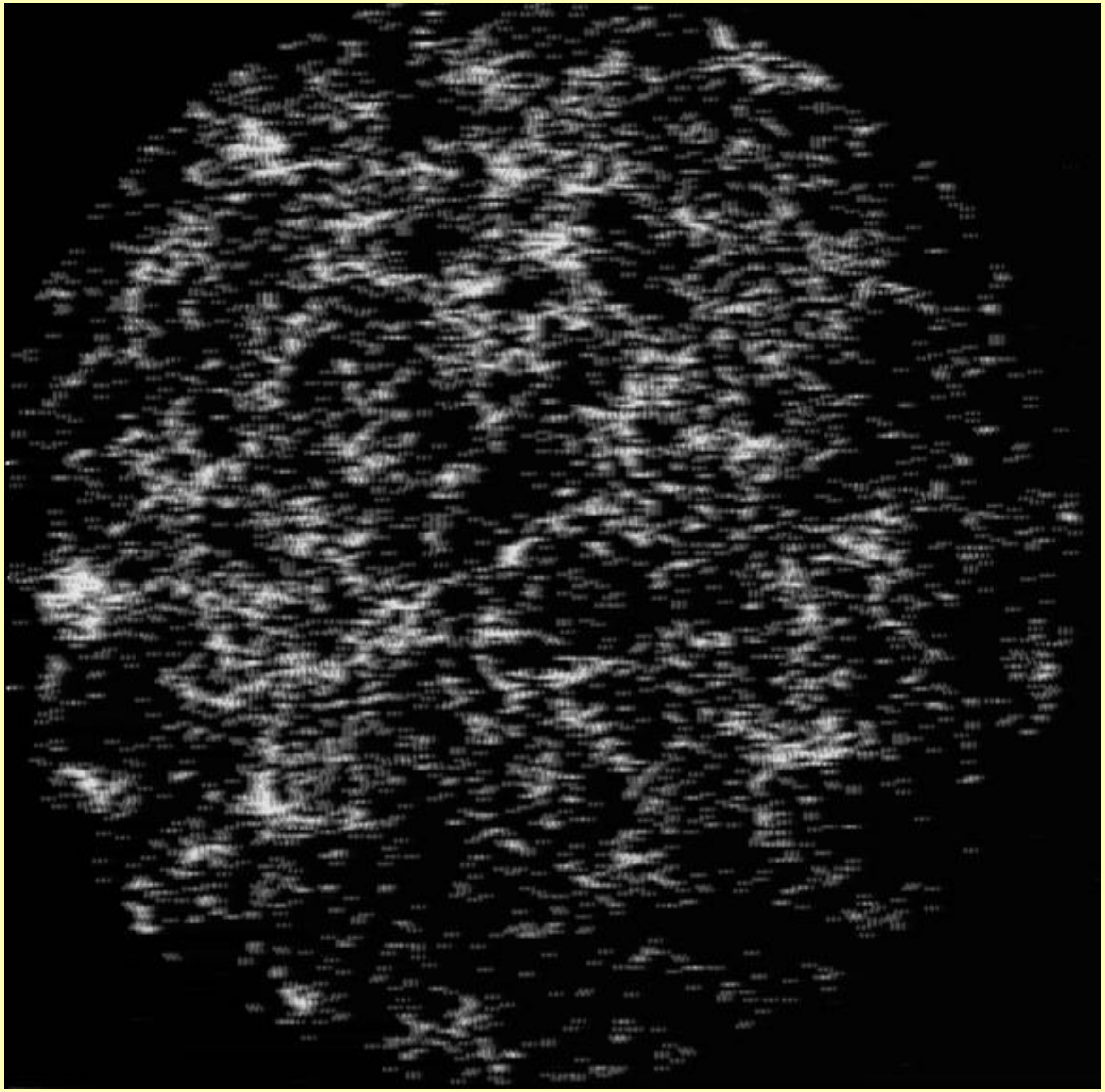
1923: 36/41 v>0

The expanding universe




A Century+ of galaxy redshifts
log10(Nz)
0
5
10
1900
1950
2000
2050
year
Sandage RSA

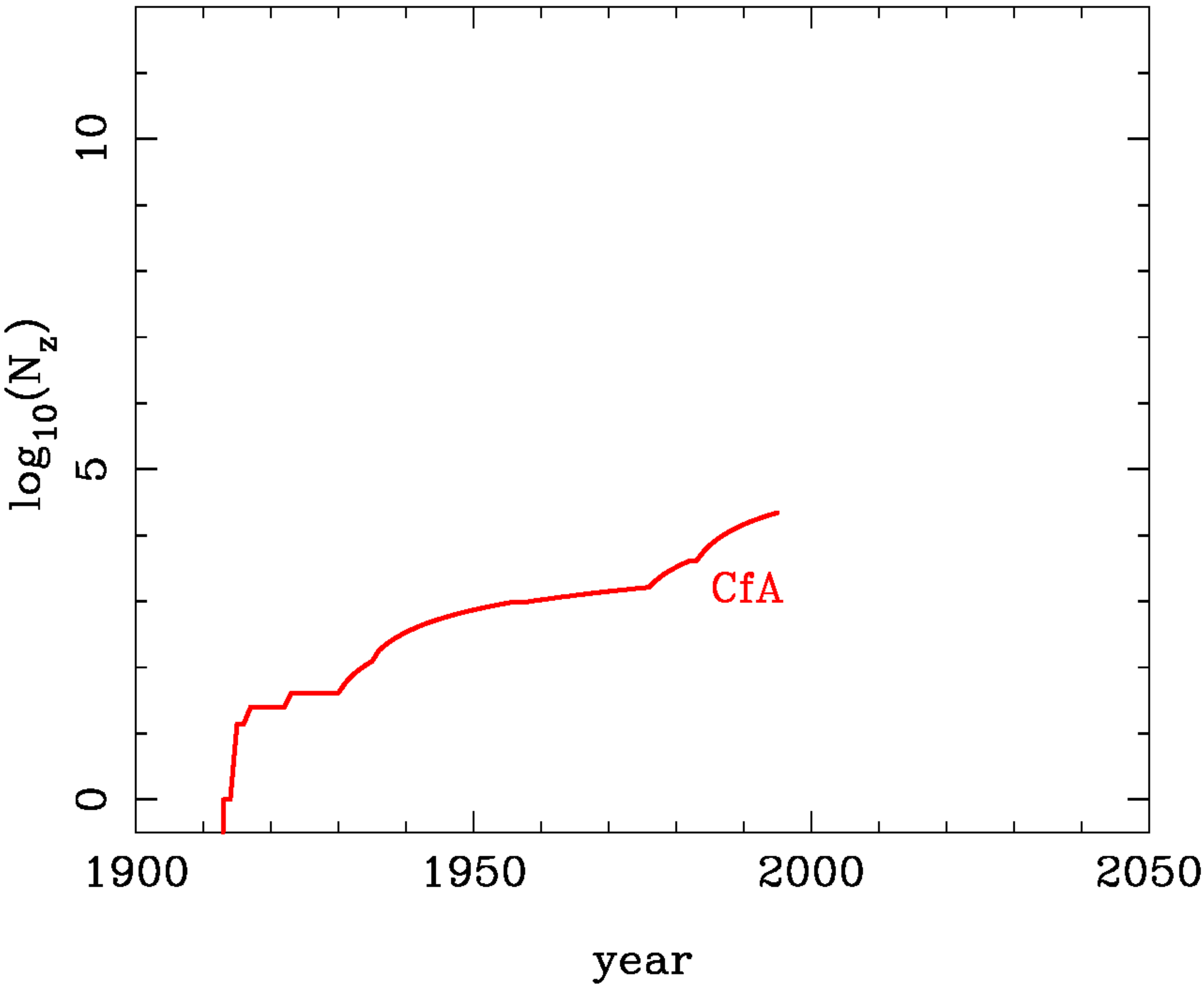
Pre-1980s: angular studies



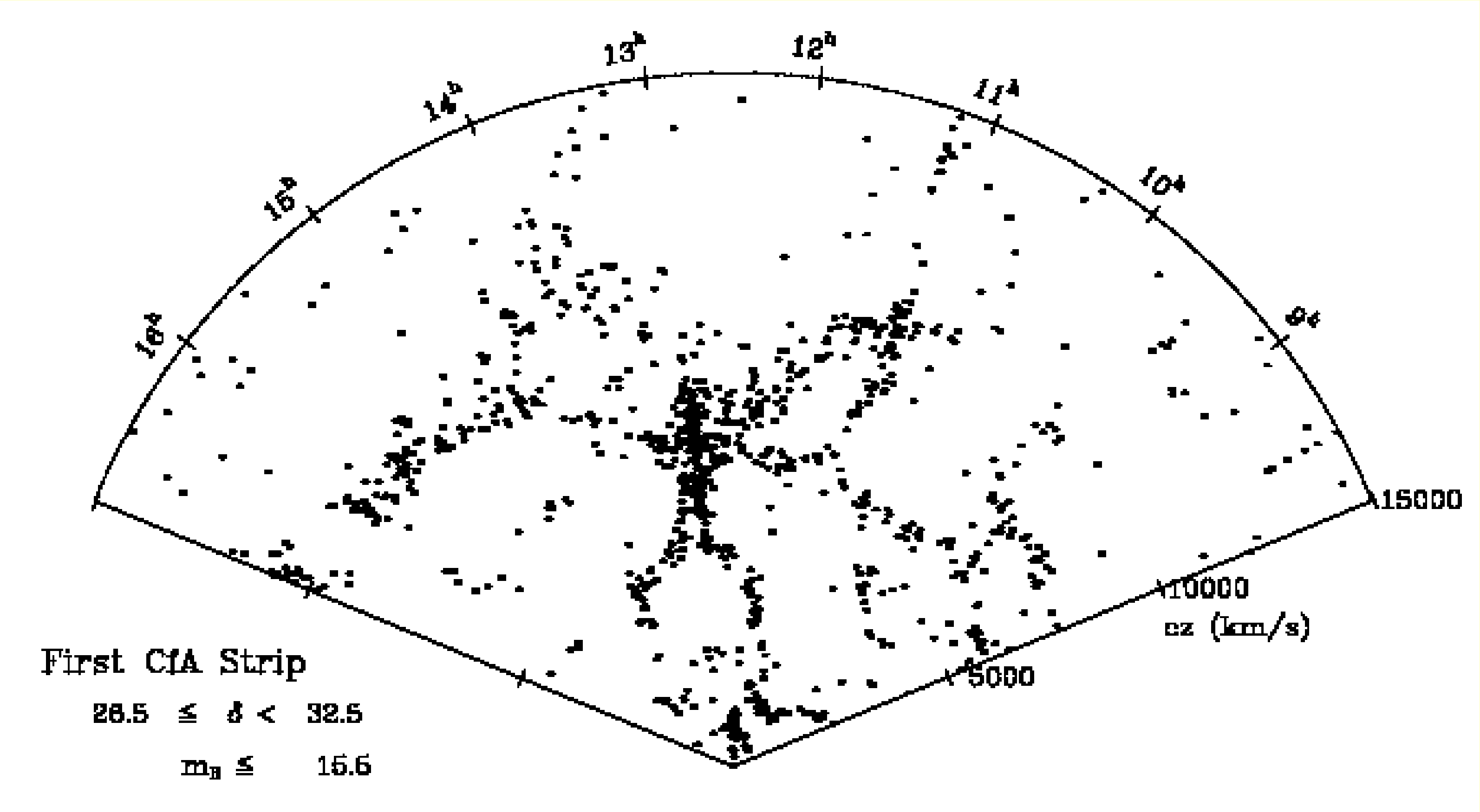
Peebles correlation-function programme, applied to Shane-Wirtanen Lick galaxy map.

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

A Century+ of galaxy redshifts



CfA surveys

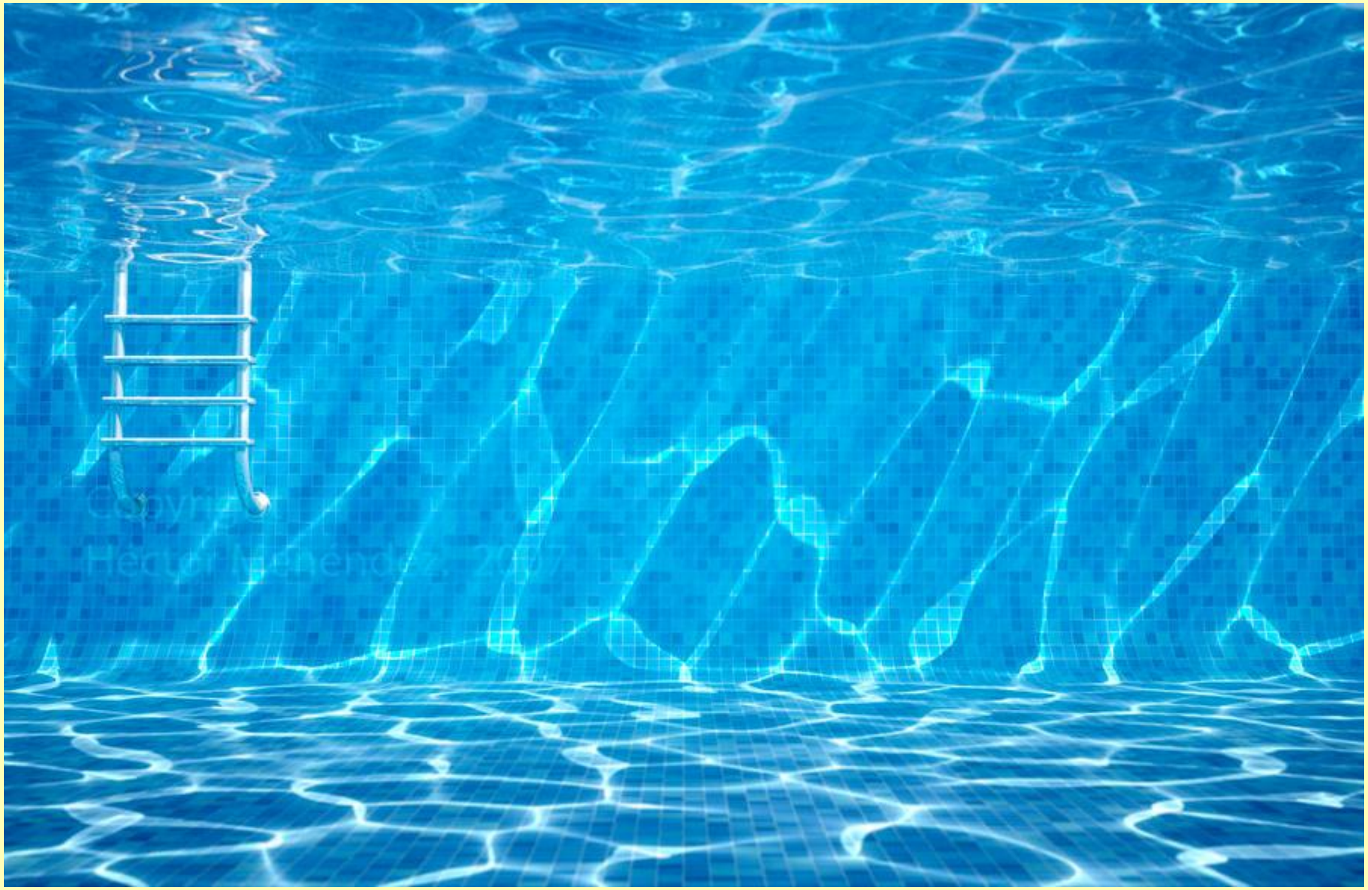


Accelerated progress from electronic detectors

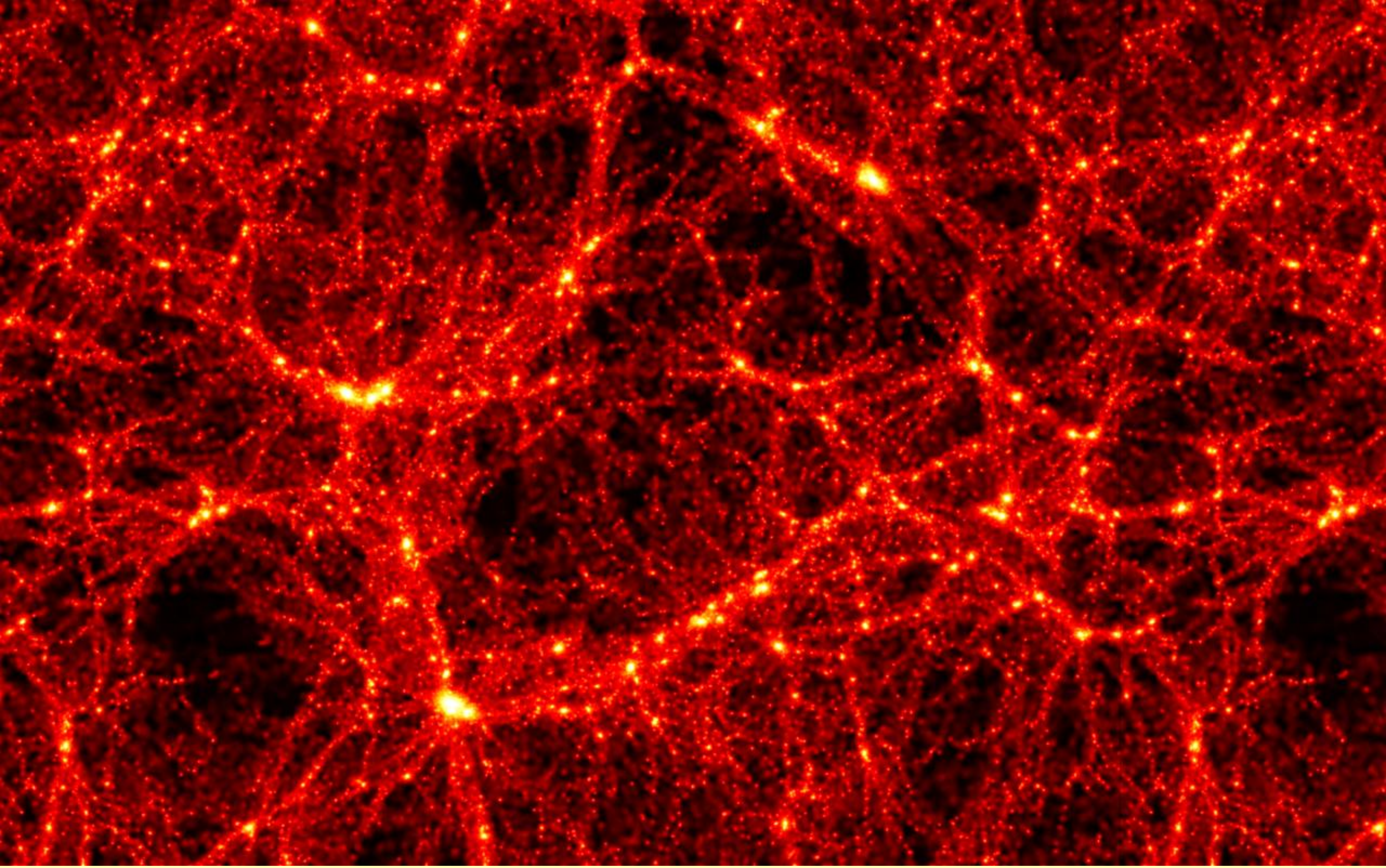
CfA1: 2396 z’s 1977-1982

CfA2 : 18,000 z’s 1984-1995

Cosmic web: voids, sheets, filaments



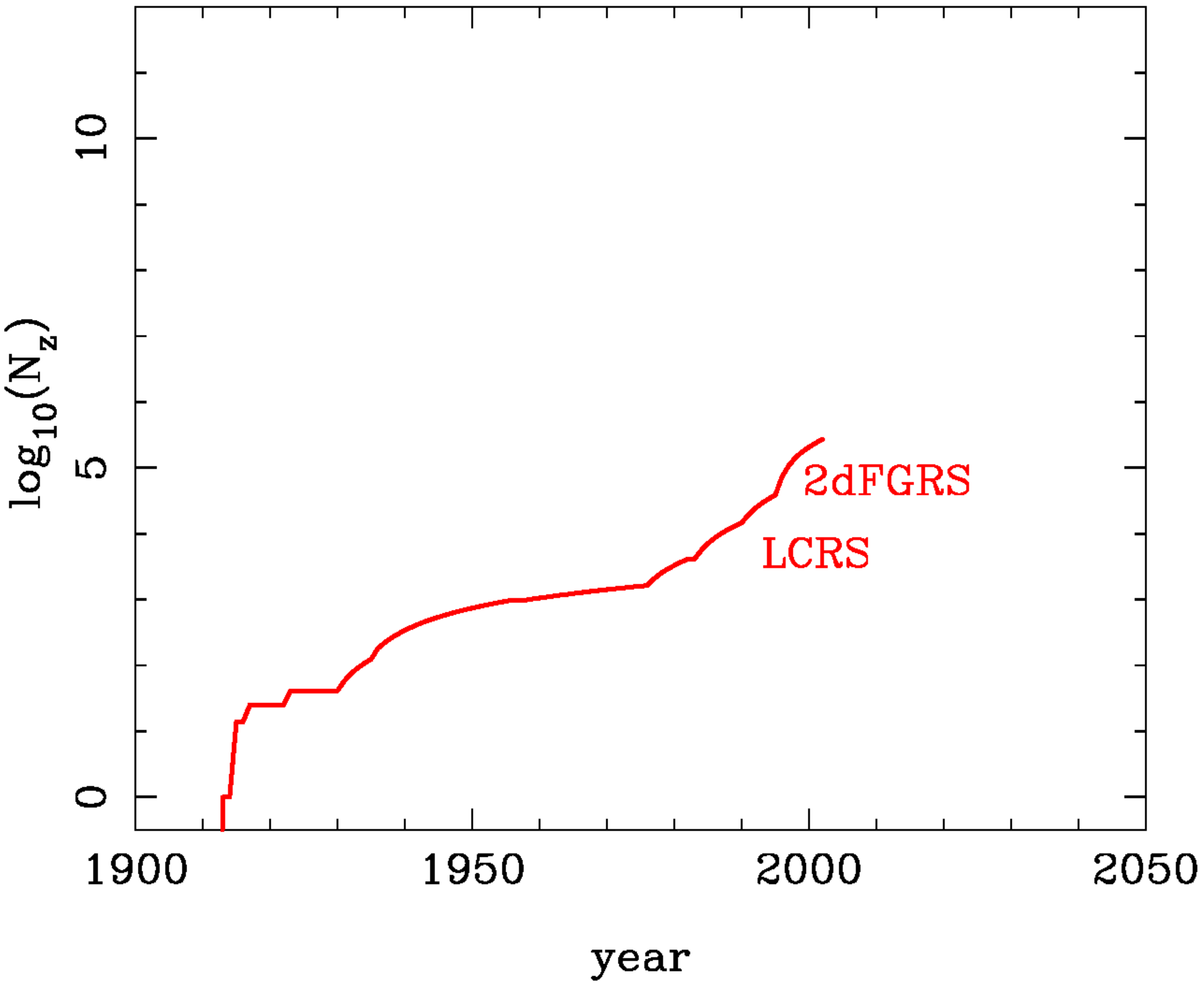
Peebles: this would only arise via ‘Zeldovich pancakes’ − collapse of a matter distribution with only large-scale structures (pure baryons; massive neutrinos)



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

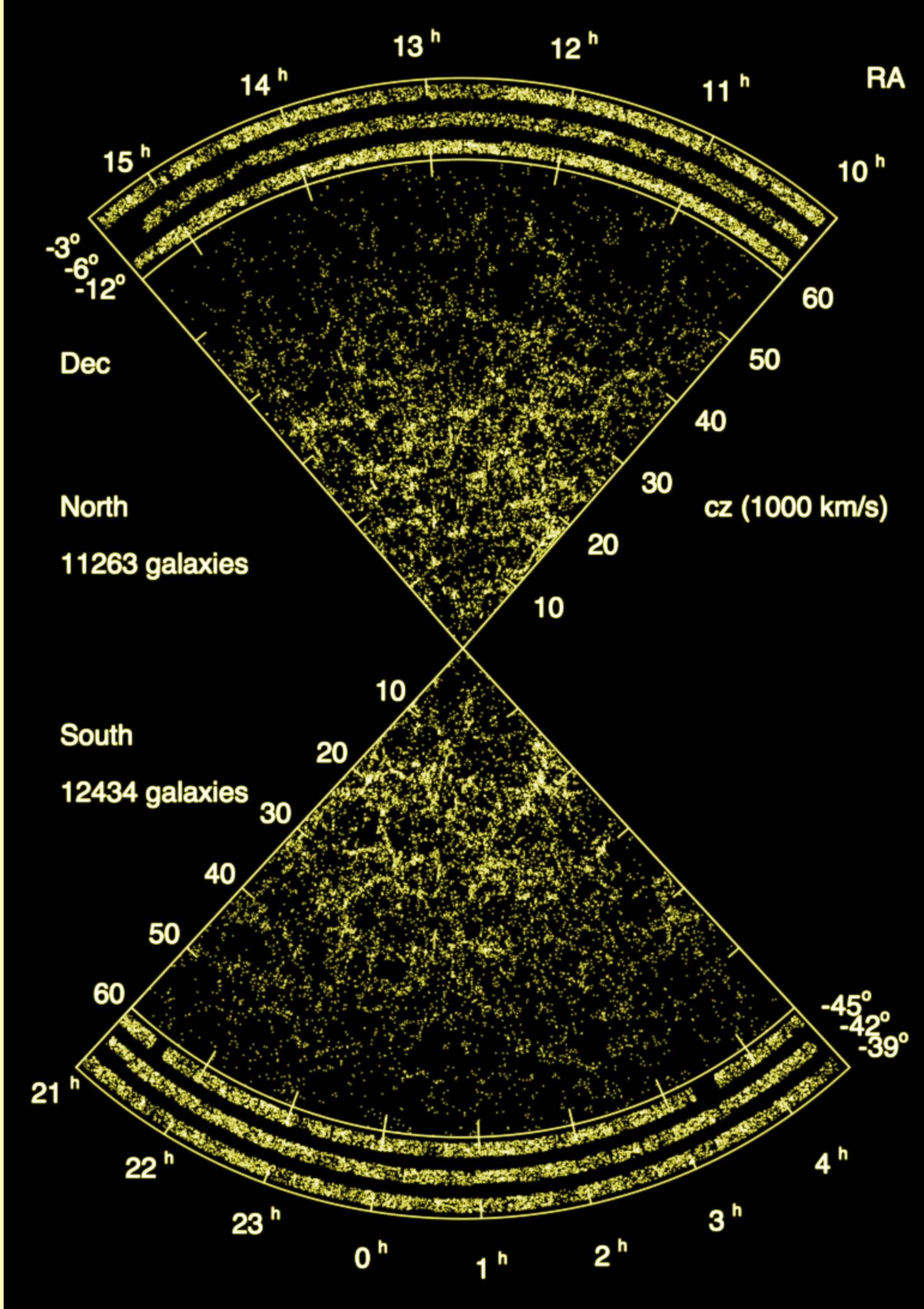
The multiplex revolution: fibres

A Century+ of galaxy redshifts

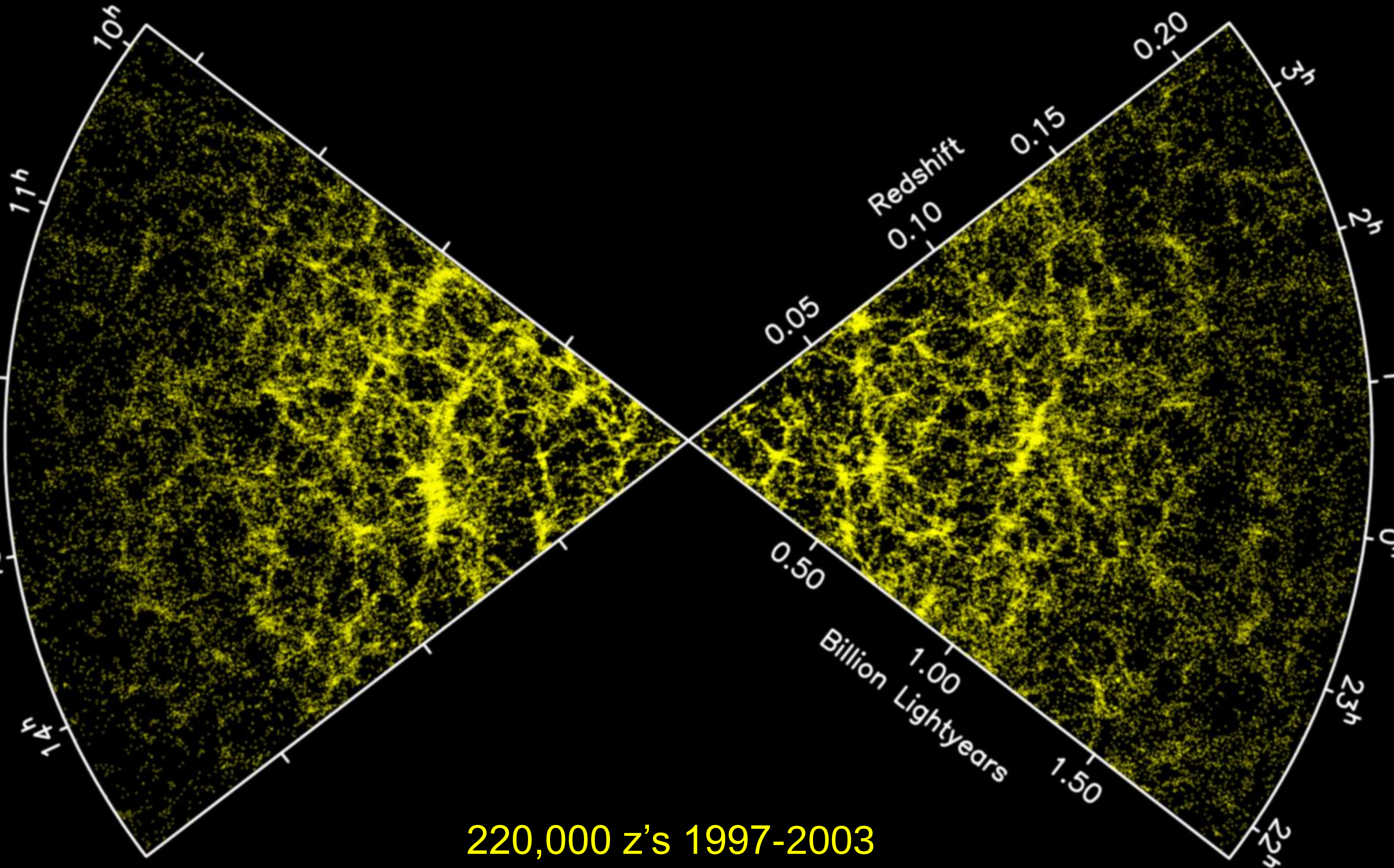


LCRS

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



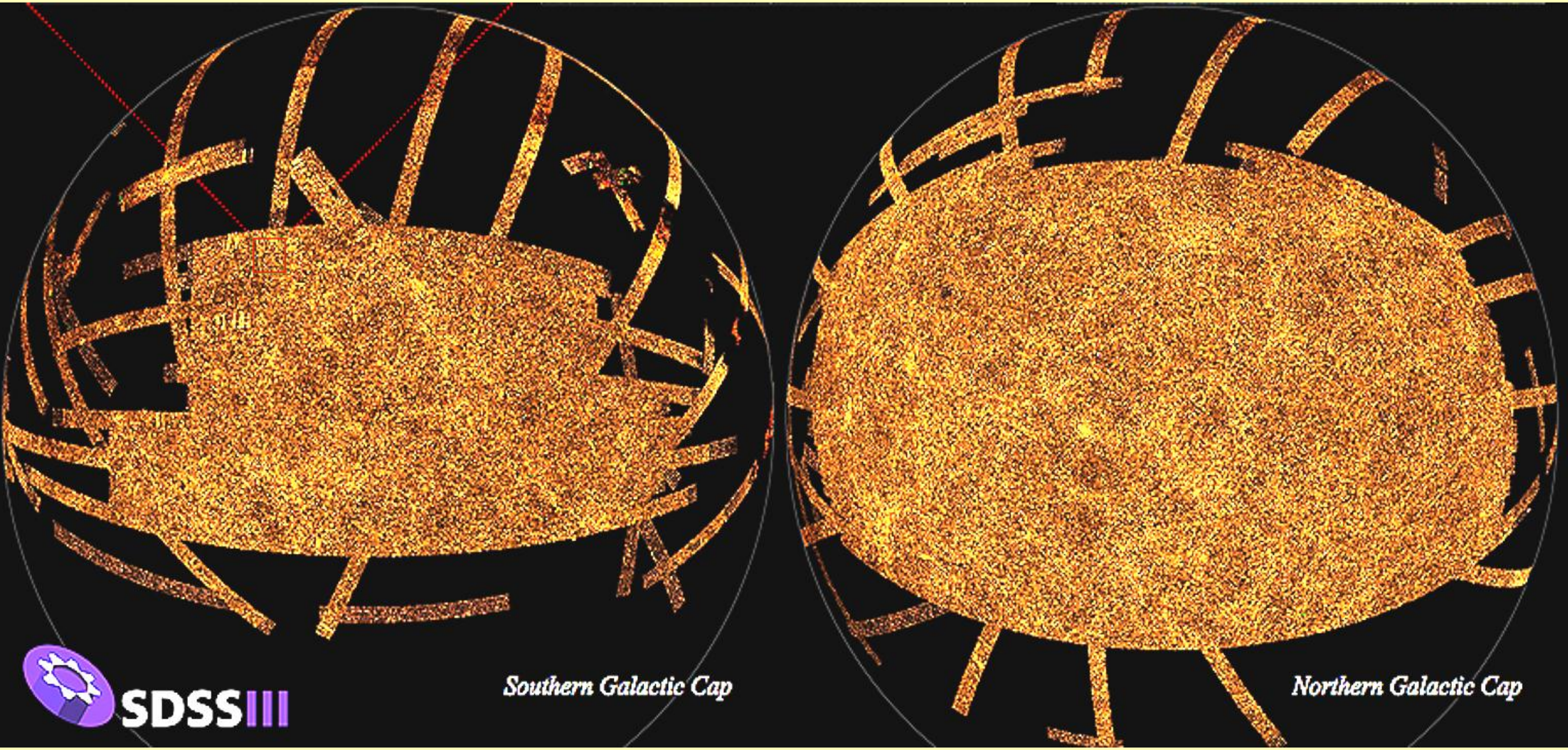
2dFGRS



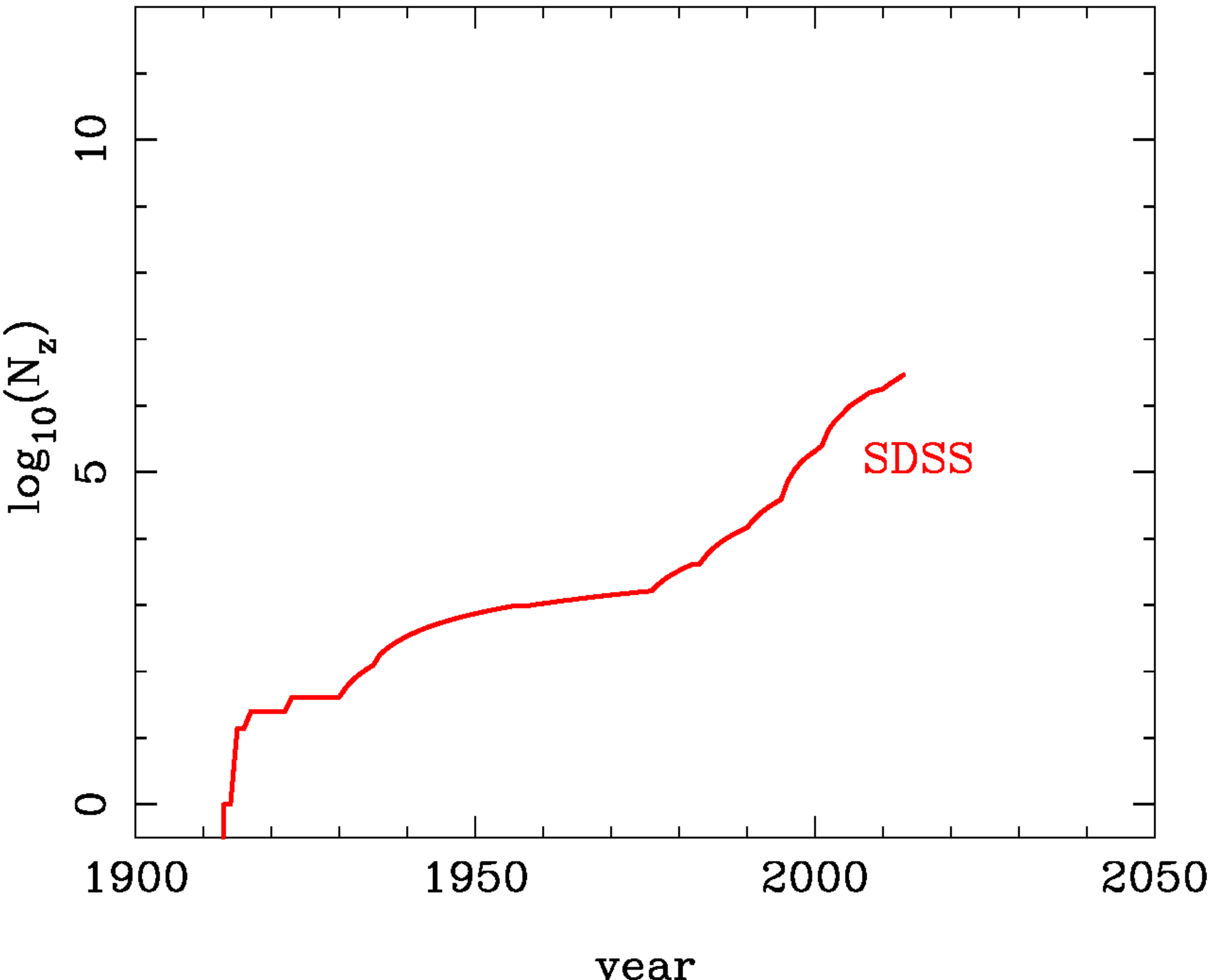
220,000 z's 1997-2003

SDSS

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



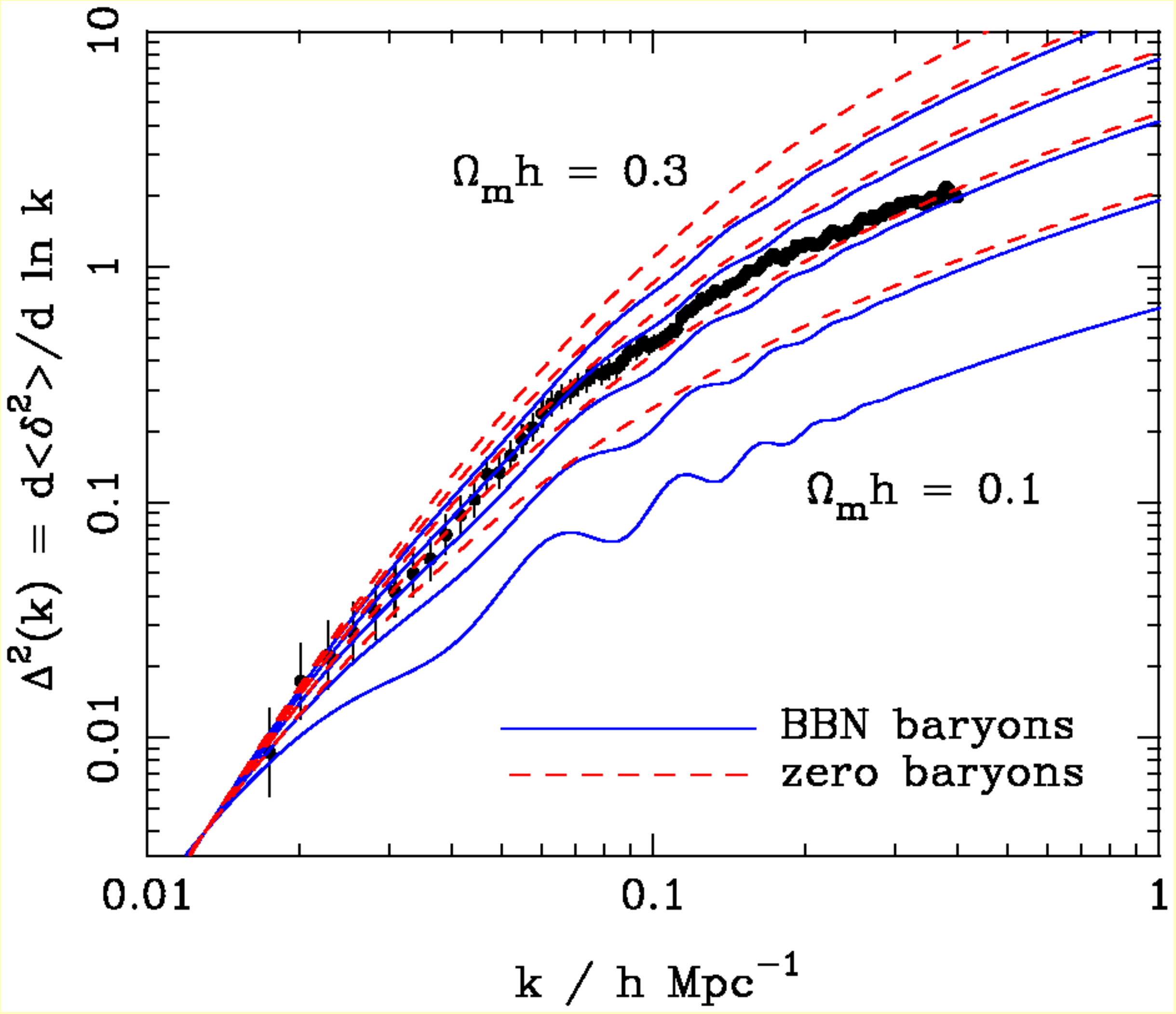
A Century+ of galaxy redshifts



2dFGRS power spectrum: small BAO proves DM

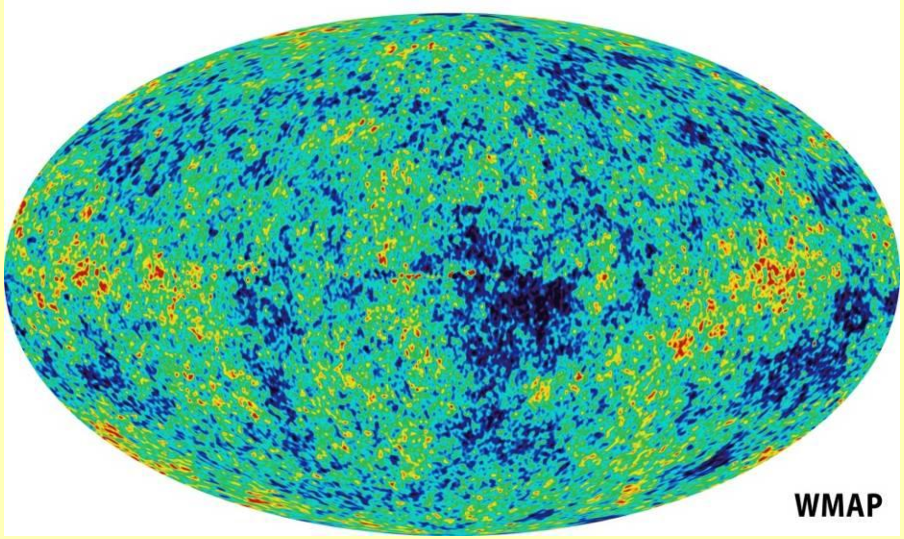
Dimensionless power:

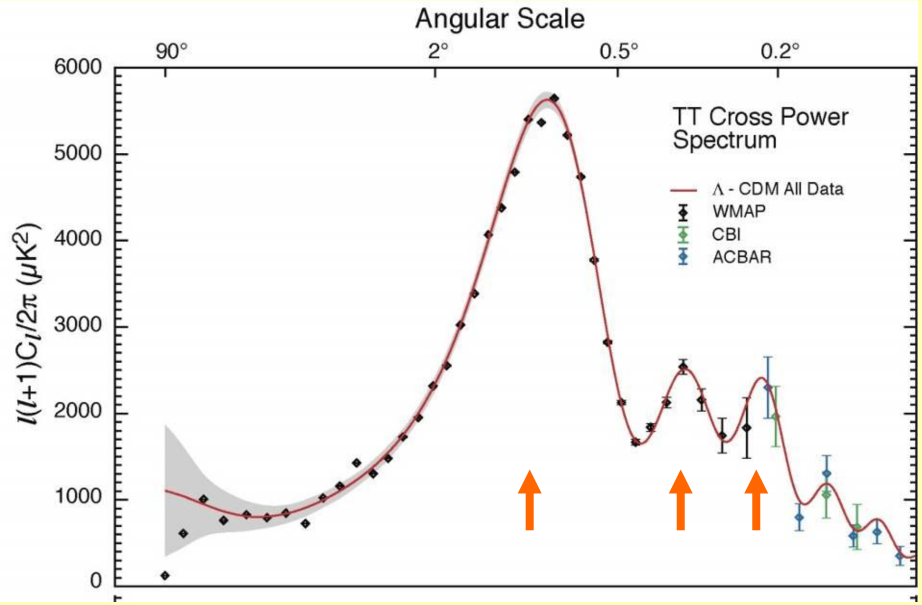
d (fractional variance in density) / d ln k



Percival et al. MNRAS 327, 1279 (2001)

Baryon Acoustic Oscillations in the CMB





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

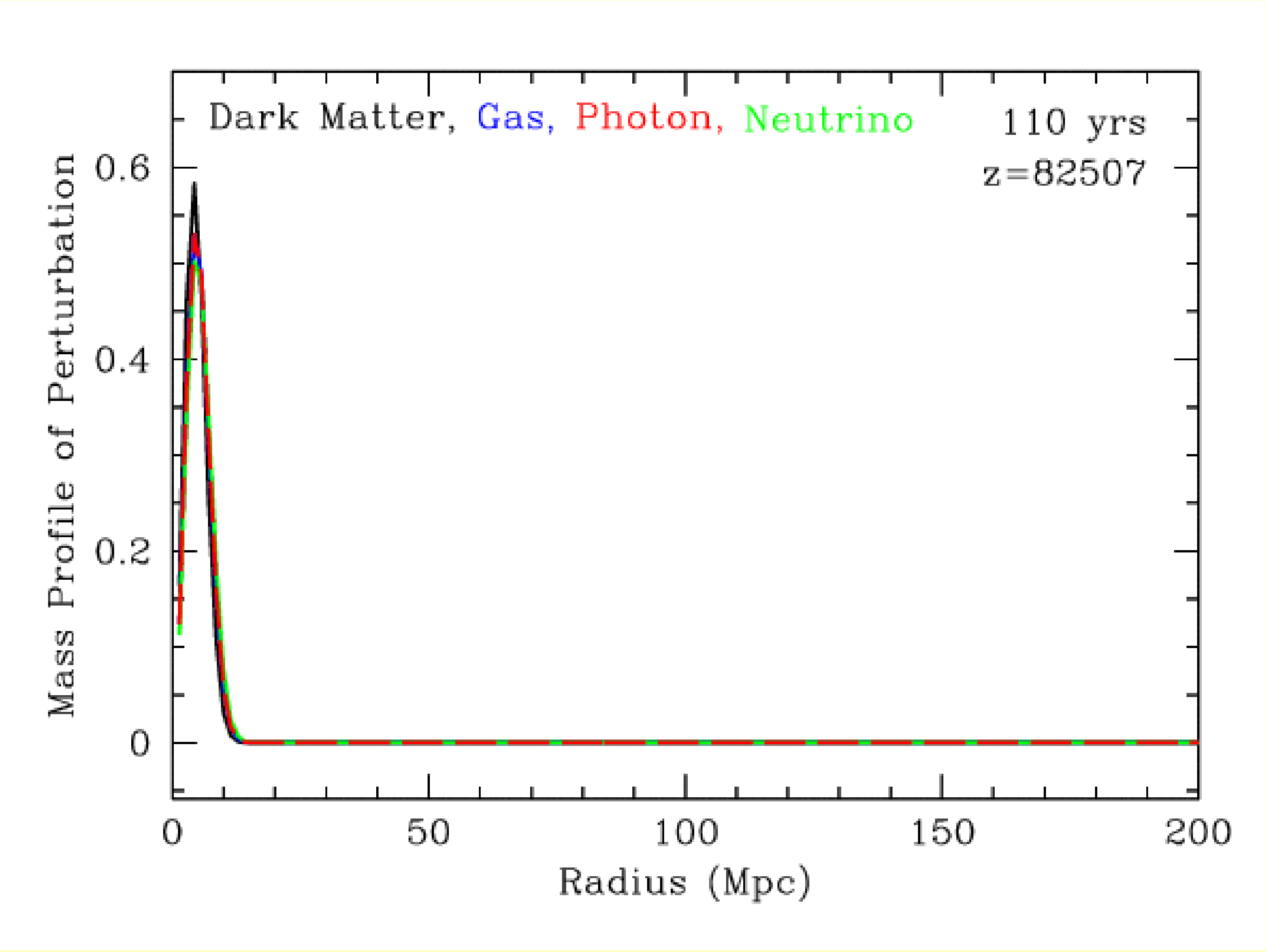
$$l_{\mathrm{BAO}} = \int_0^{t_{\mathrm{rec}}} \frac{c_s}{a}\, dt \approx \frac{c}{\sqrt{3}} \frac{t_{\mathrm{rec}}}{a_{\mathrm{rec}}}$$

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

'Baryon wiggles' at 1 degree (& 0.3, 0.2, 0.1...):

oscillations of baryonic gas falling under dark matter gravity

Freezing in the BAO scale

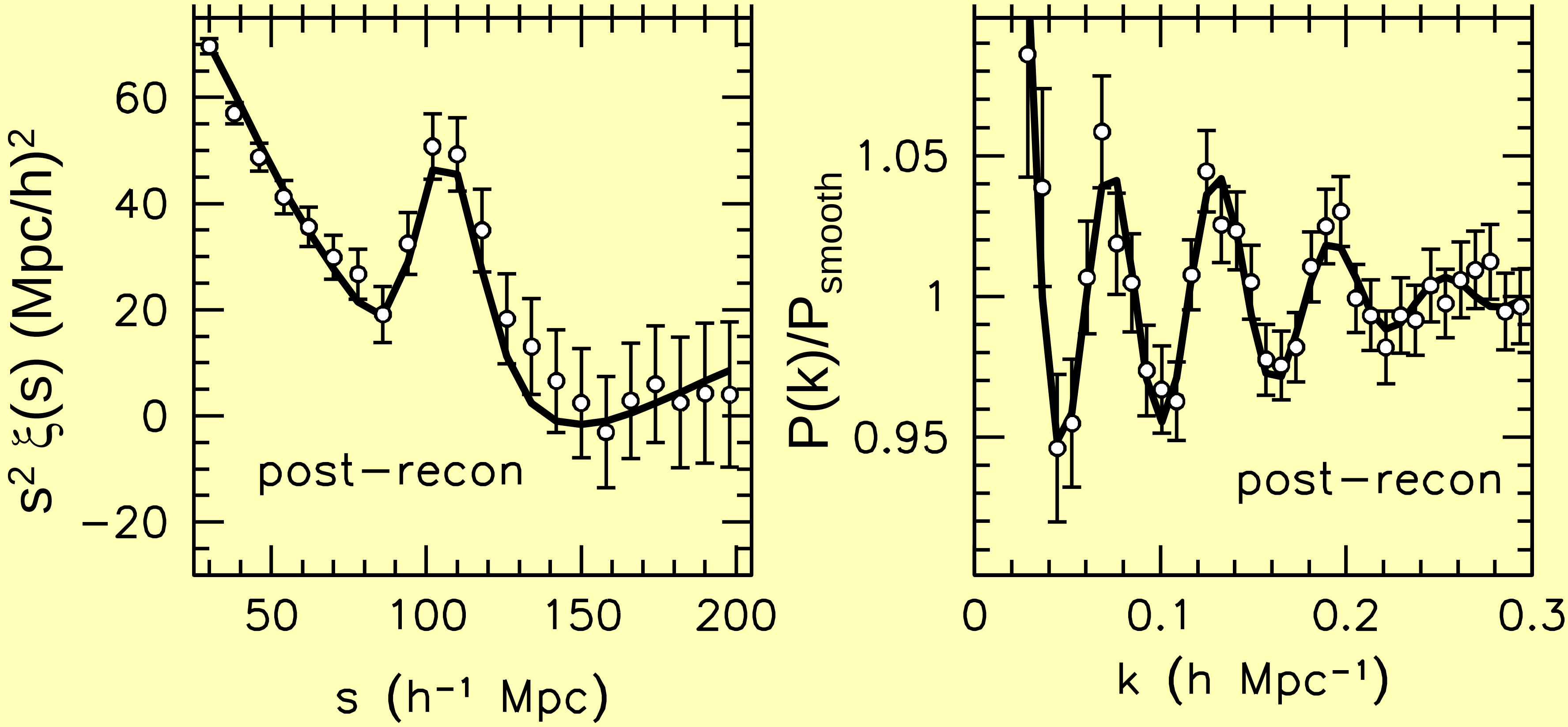


Care: not the origin of fluctuations.
BAO smooths existing structure

Based on CMBfast outputs (Seljak & Zaldarriaga). Green's function view from Bashinsky & Bertschinger 2001

Acoustic Peak in 2014

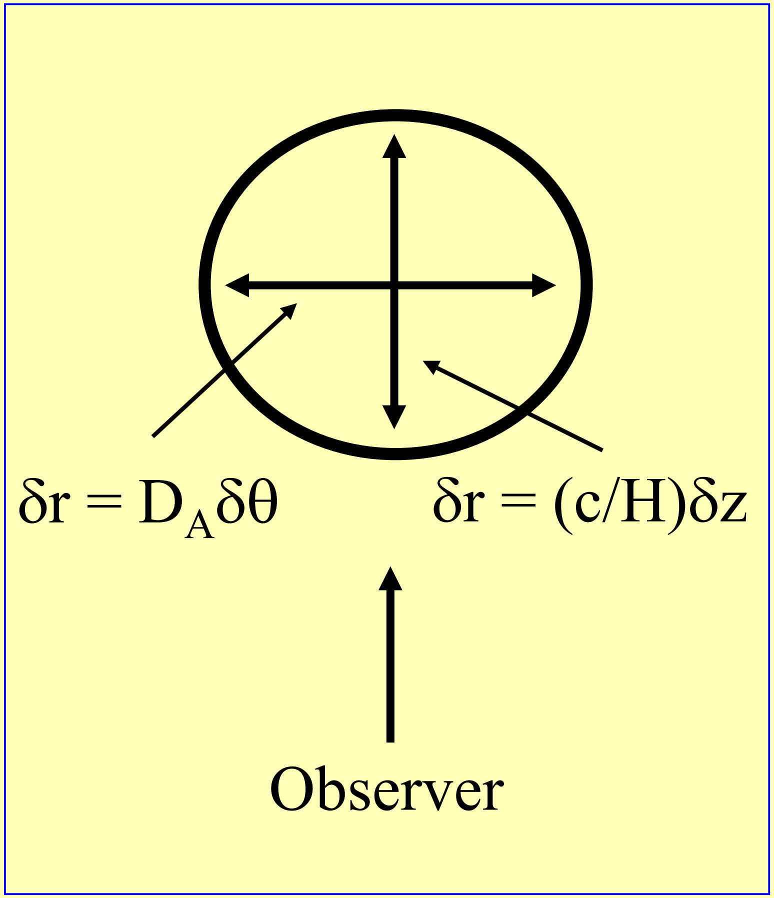
- SDSS-III BOSS gives a strong BAO detection, measuring the acoustic scale to 1% at z=0.57.



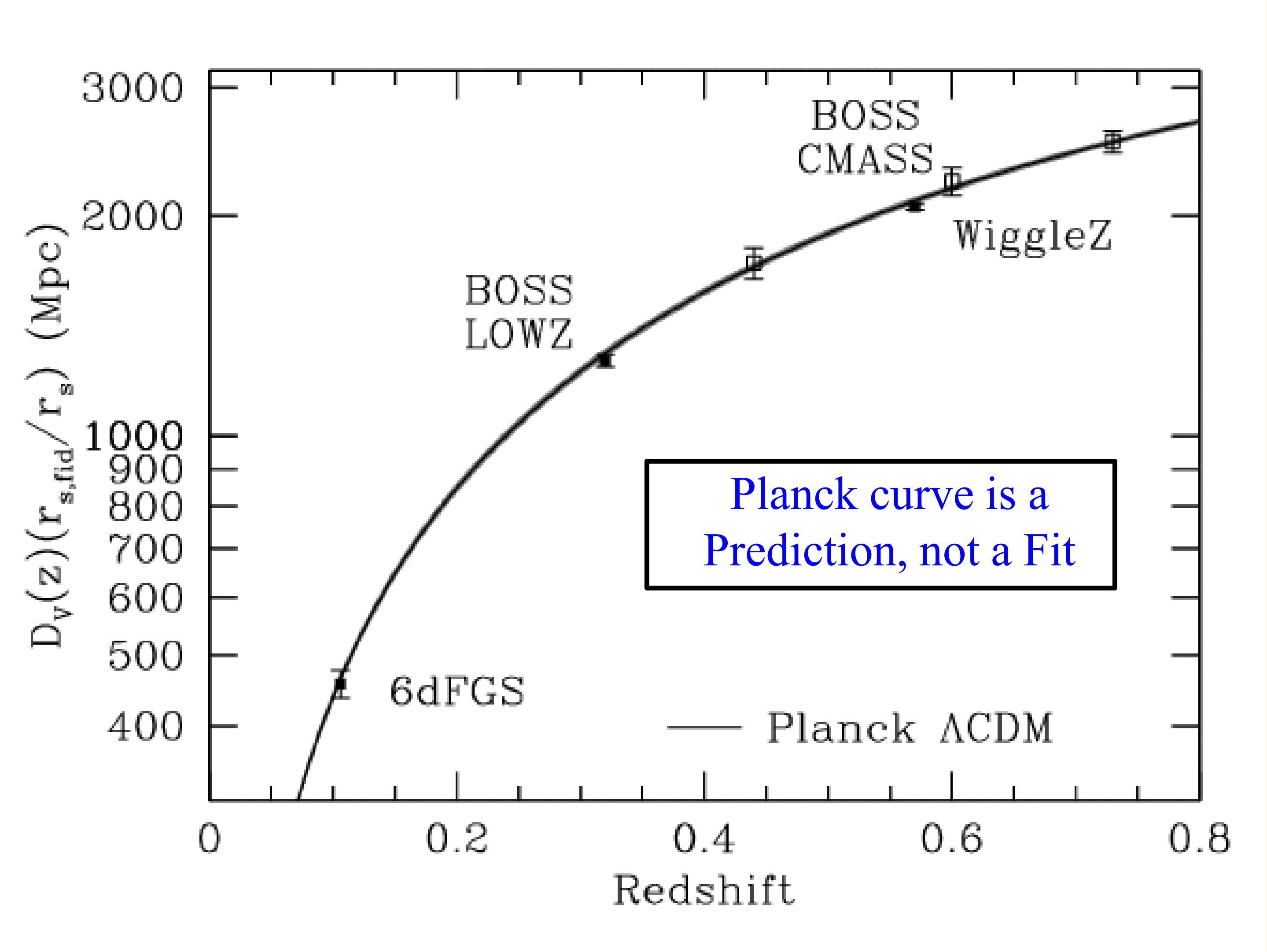
Anderson et al. (2014)

A Standard Ruler

- The acoustic oscillation scale depends on the sound speed and the propagation time.
  - These depend on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$).
- Measurements of CMB anisotropies imply these and fix the acoustic scale.
- In a redshift survey, we can measure this along and across the line of sight.
- Yields $H(z)$ and $D_A(z)$

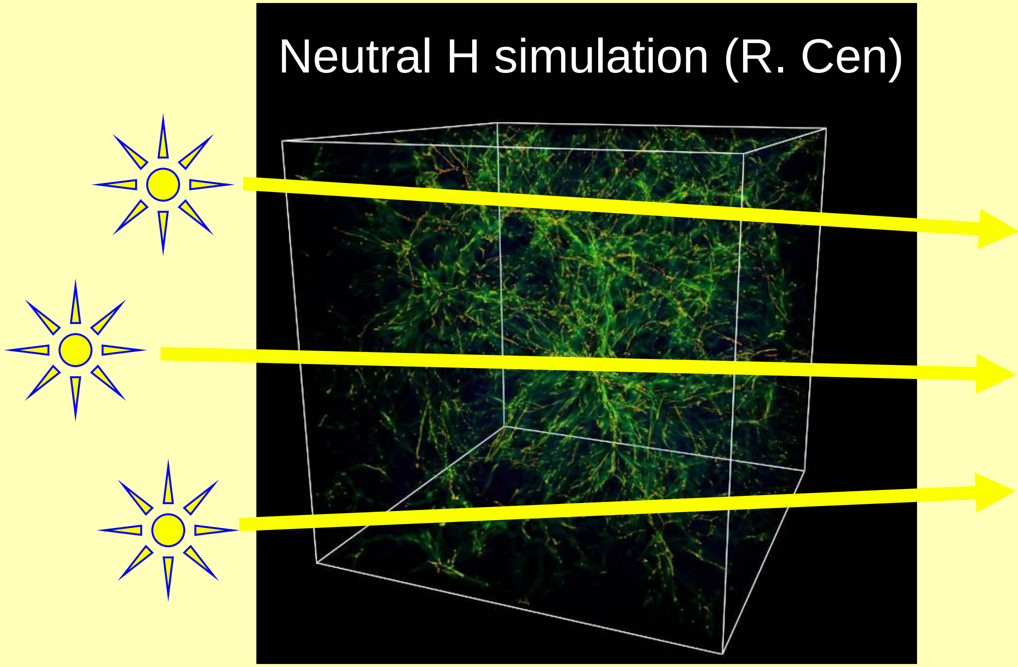


The Cosmic Distance Scale



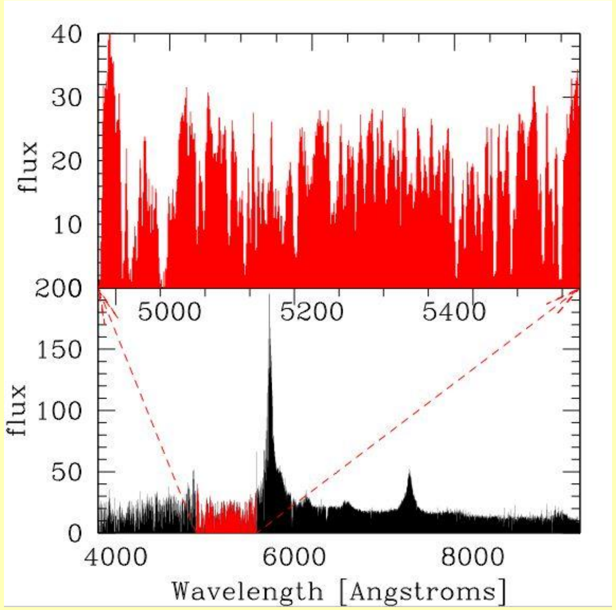
Anderson et al. (2014)

The Lyman α Forest



Neutral H absorption observed

in quasar spectrum at z=3.7



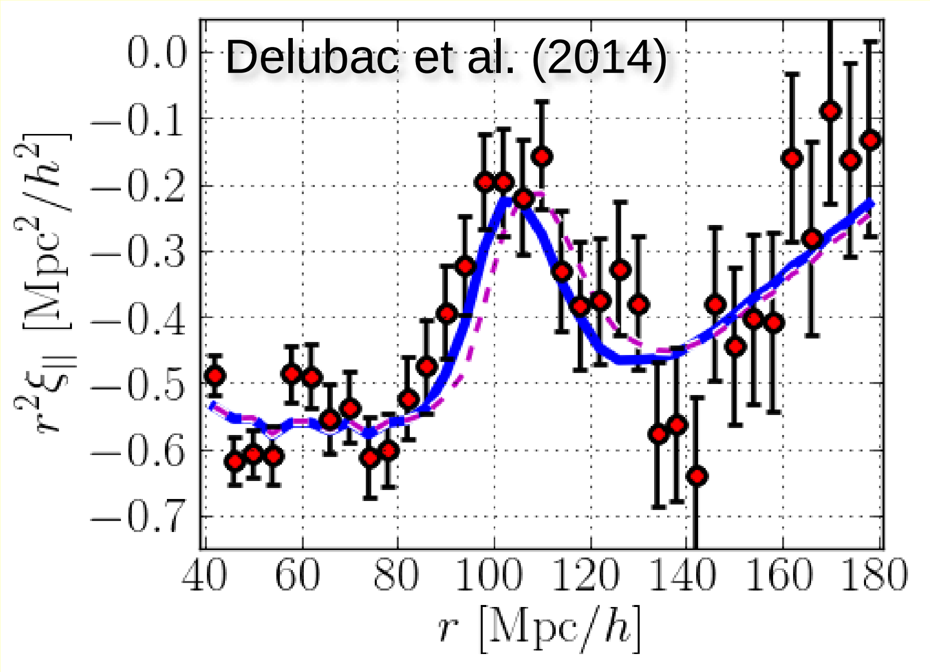
- The Lyα forest in each quasar spectrum tracks the density of the intergalactic medium along each line of sight.
- A grid of sightlines can map the 3-d density at z>2.
- An efficient way to measure the BAO at *z*>2.

White (2004); McDonald & Eisenstein (2006)

BAO in the Forest in 2014

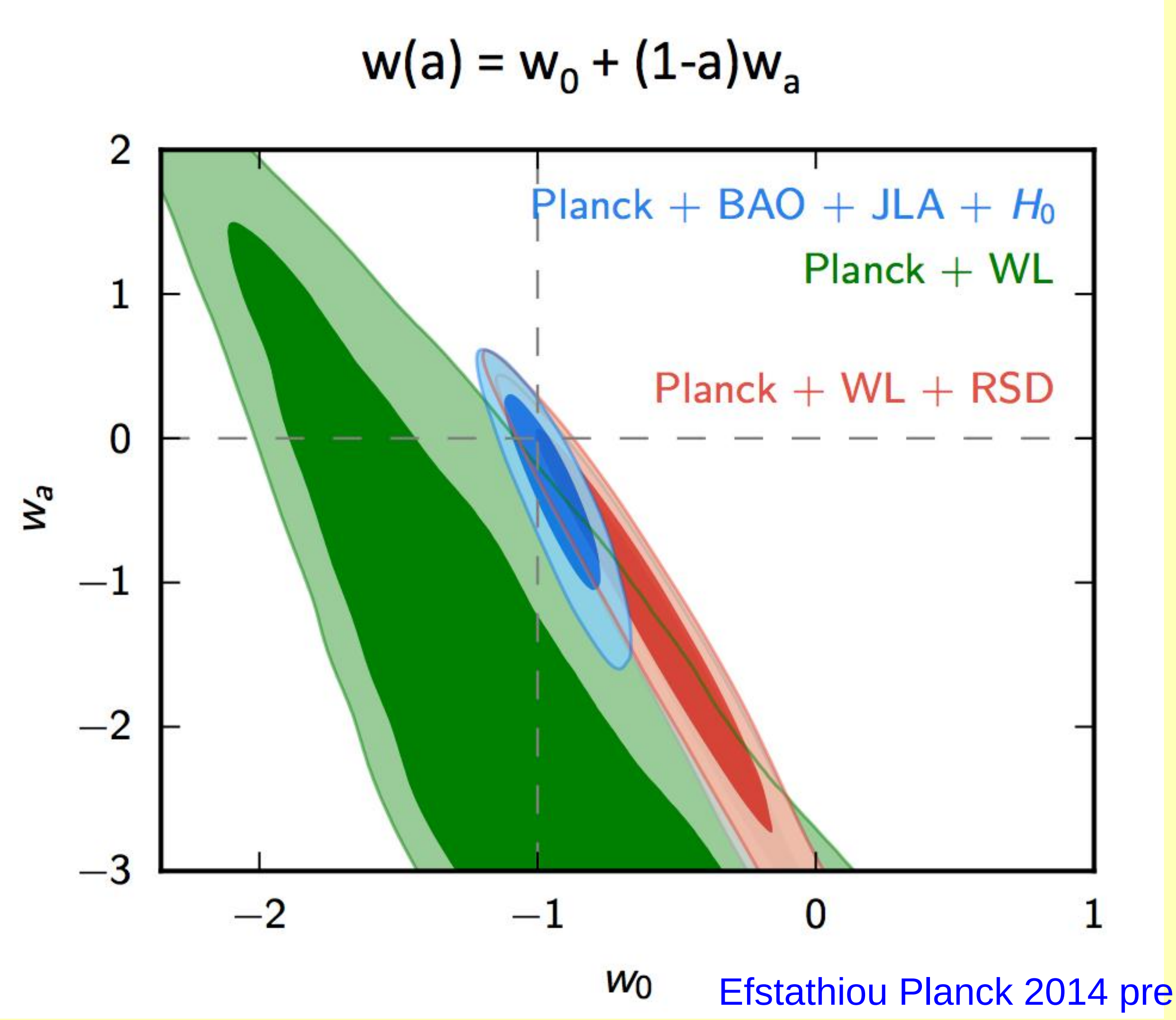
- BOSS has now produced a strong detection (>5σ) of the BAO in the correlations of the Ly α forest

- Tight measurement of the Hubble parameter and angular diameter distance at z=2.4.



BAO detection along the line of sight 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 ($w = P / \rho c^2$)

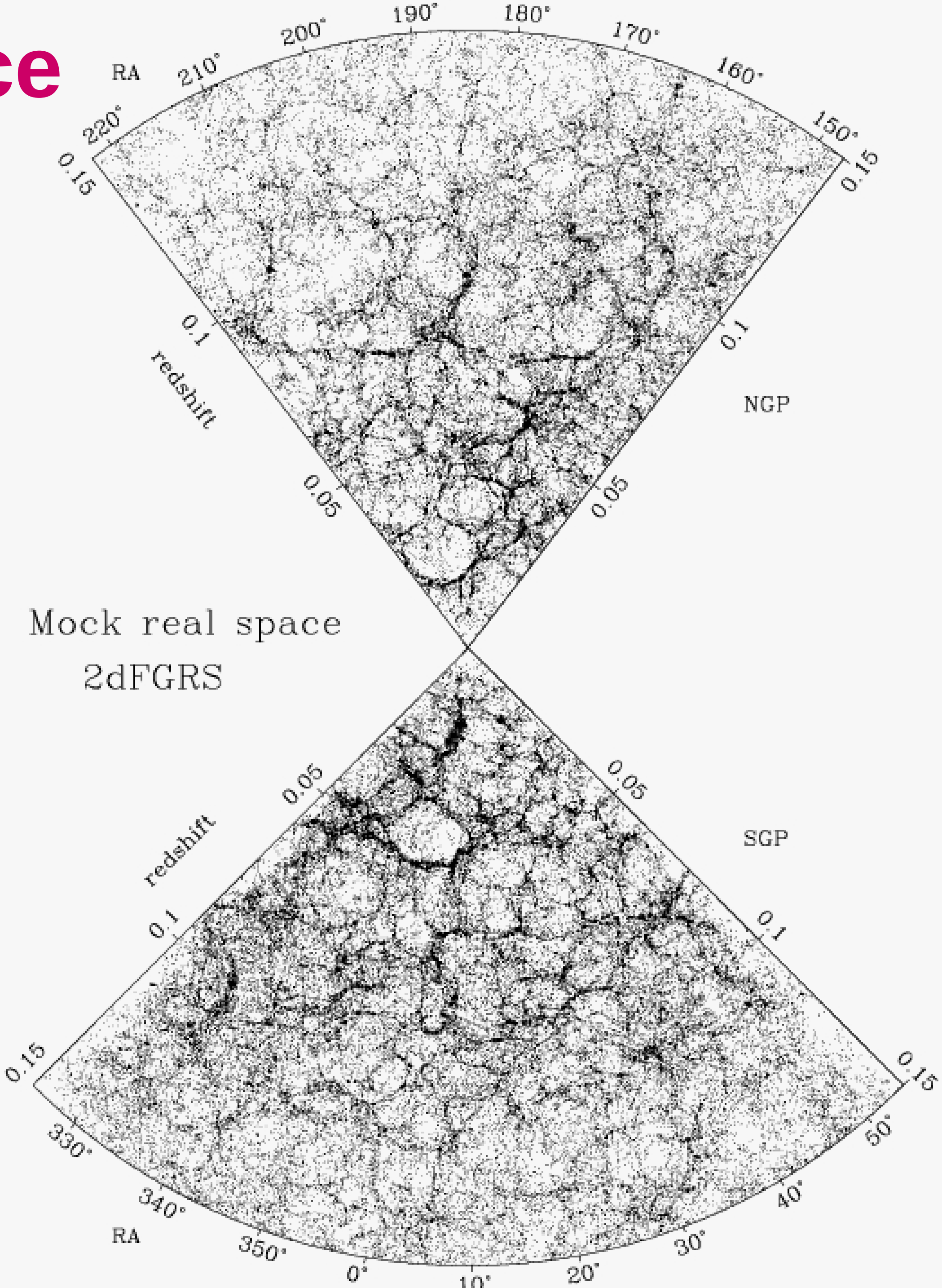


w = − 1 +/- 0.06 if unevolving:

DE looks like cosmological constant

Efstathiou Planck 2014 preliminary

Redshift-Space distortions of clustering



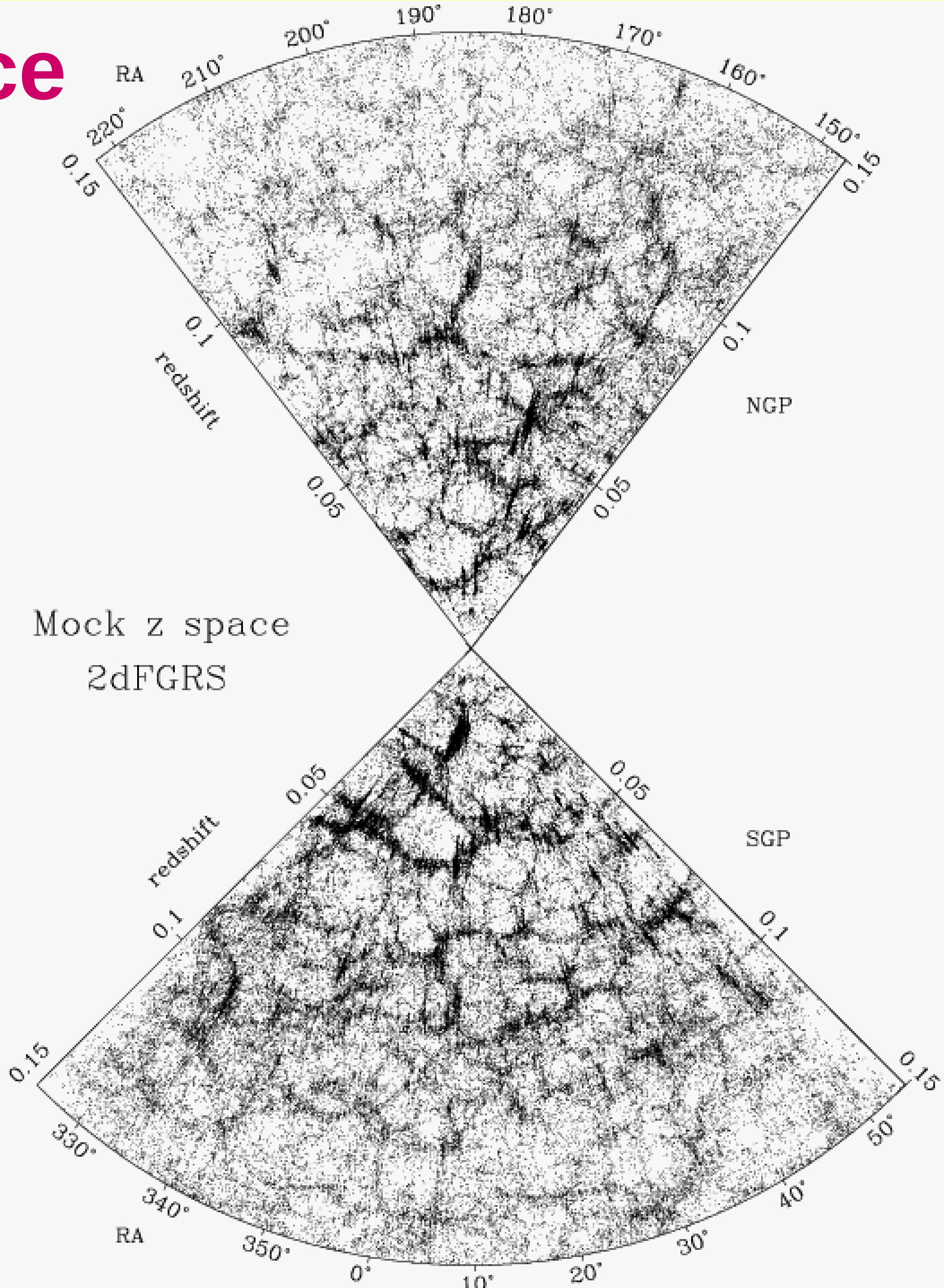
Mock 2dFGRS from Hubble volume

real space

Eke, Frenk, Cole, Baugh + 2dFGRS 2003

Redshift-Space distortions of clustering

2dFGRS first survey to benefit from detailed mock samples

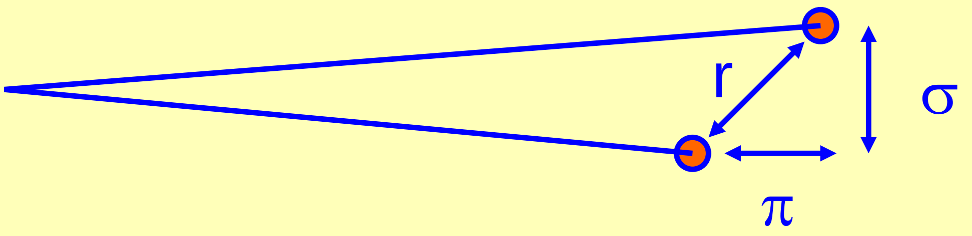


Mock 2dFGRS from Hubble volume

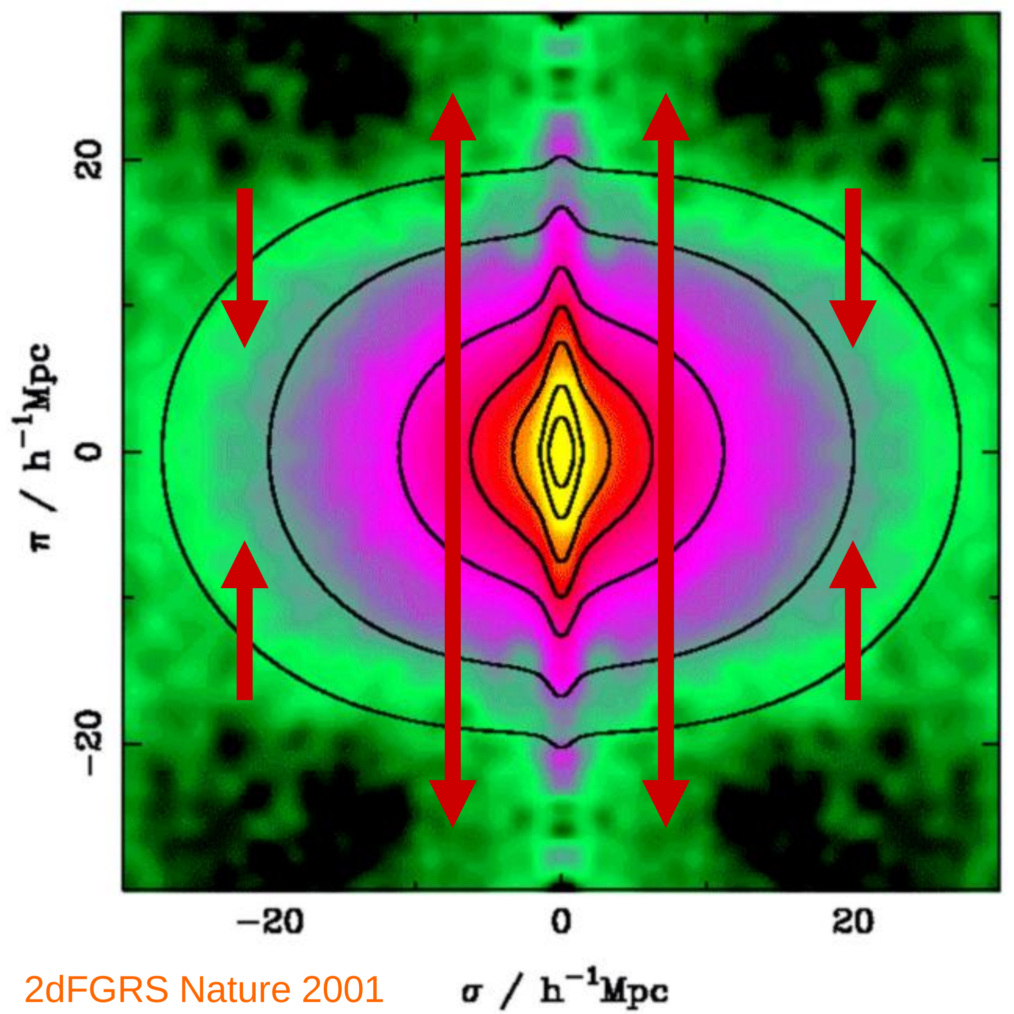
z space

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

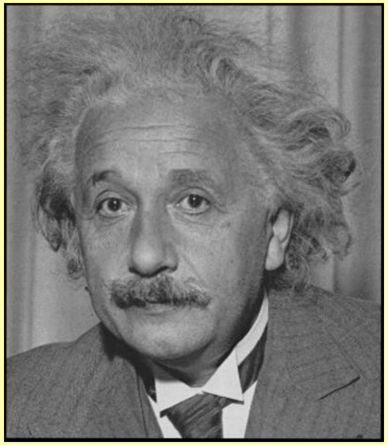
A route to modified gravity

Cosmology needs to test Einstein gravity

Dark energy: all current measurements relate to expansion rate, assuming H(z) comes from Friedmann equation

$$H^2(z) = H^2_0 \; [\, (1-\Omega)\,(1+z)^2 + \Omega_M\,(1+z)^3 + \Omega_R\,(1+z)^4 + \Omega_{DE}\,(1+z)^{3\,(1+w)} \,]$$

Curvature | matter | radiation | extra term from non-Einstein?



?

RSD as test of modified gravity
(Guzzo et al. 2008)

- Adopt longitudinal gauge (in effect gauge-invariant)

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

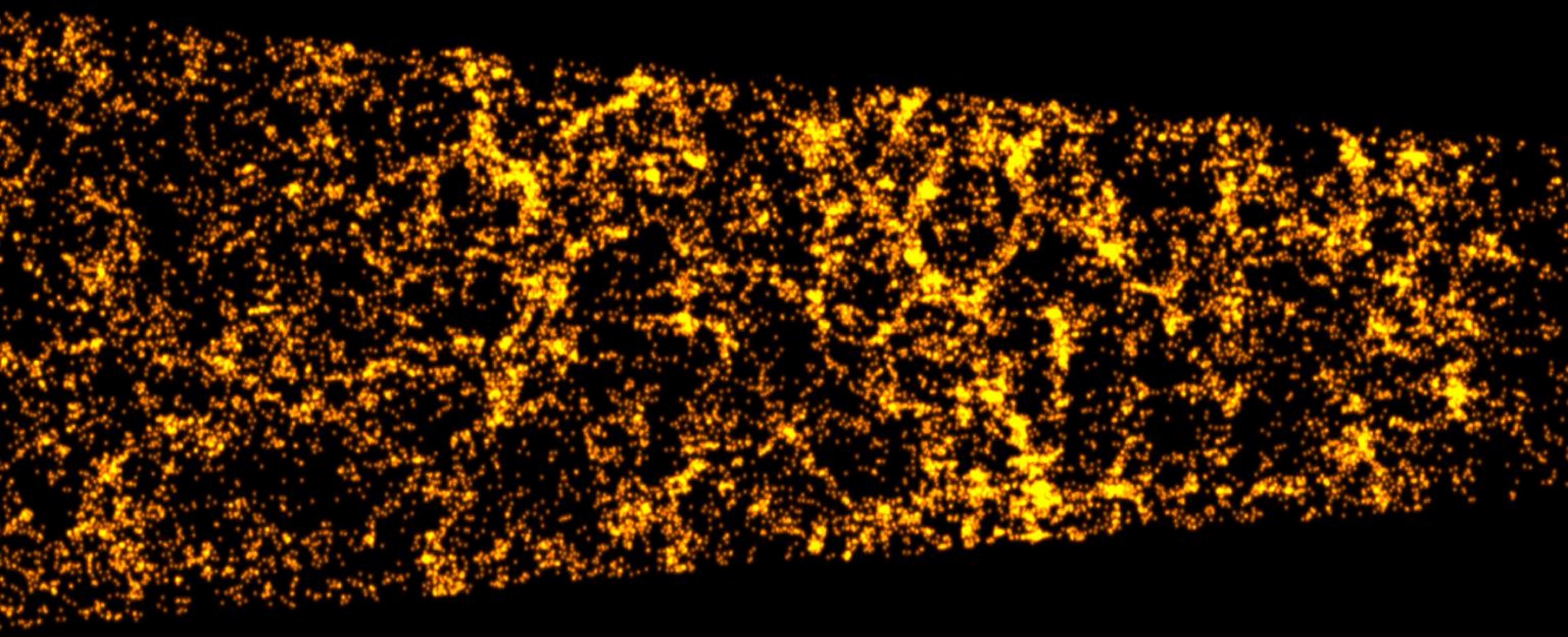
- In MG, potentials can differ ('slip': affects lensing), plus Poisson equation is modified.

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

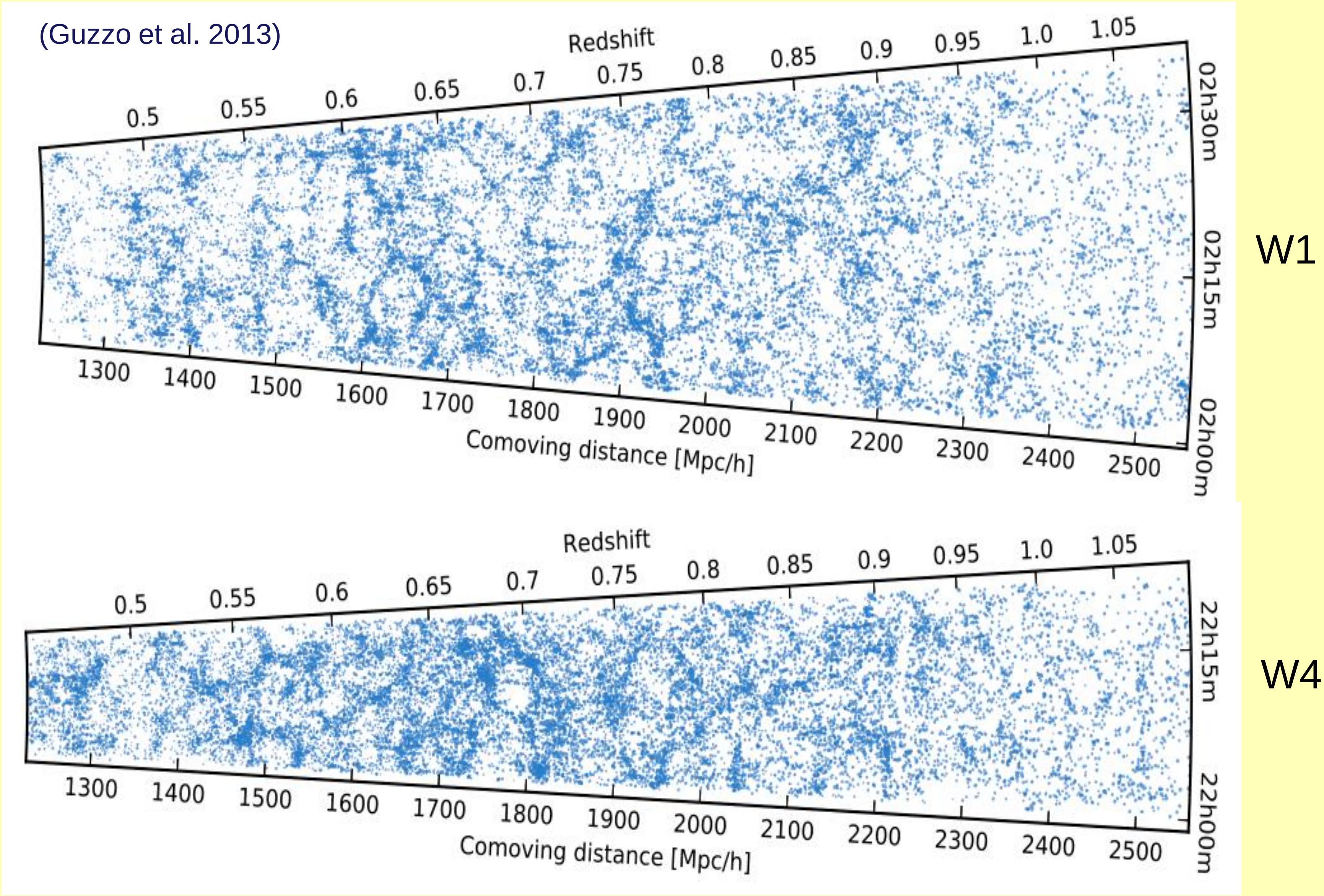
- Combine to affect growth of fluctuations

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

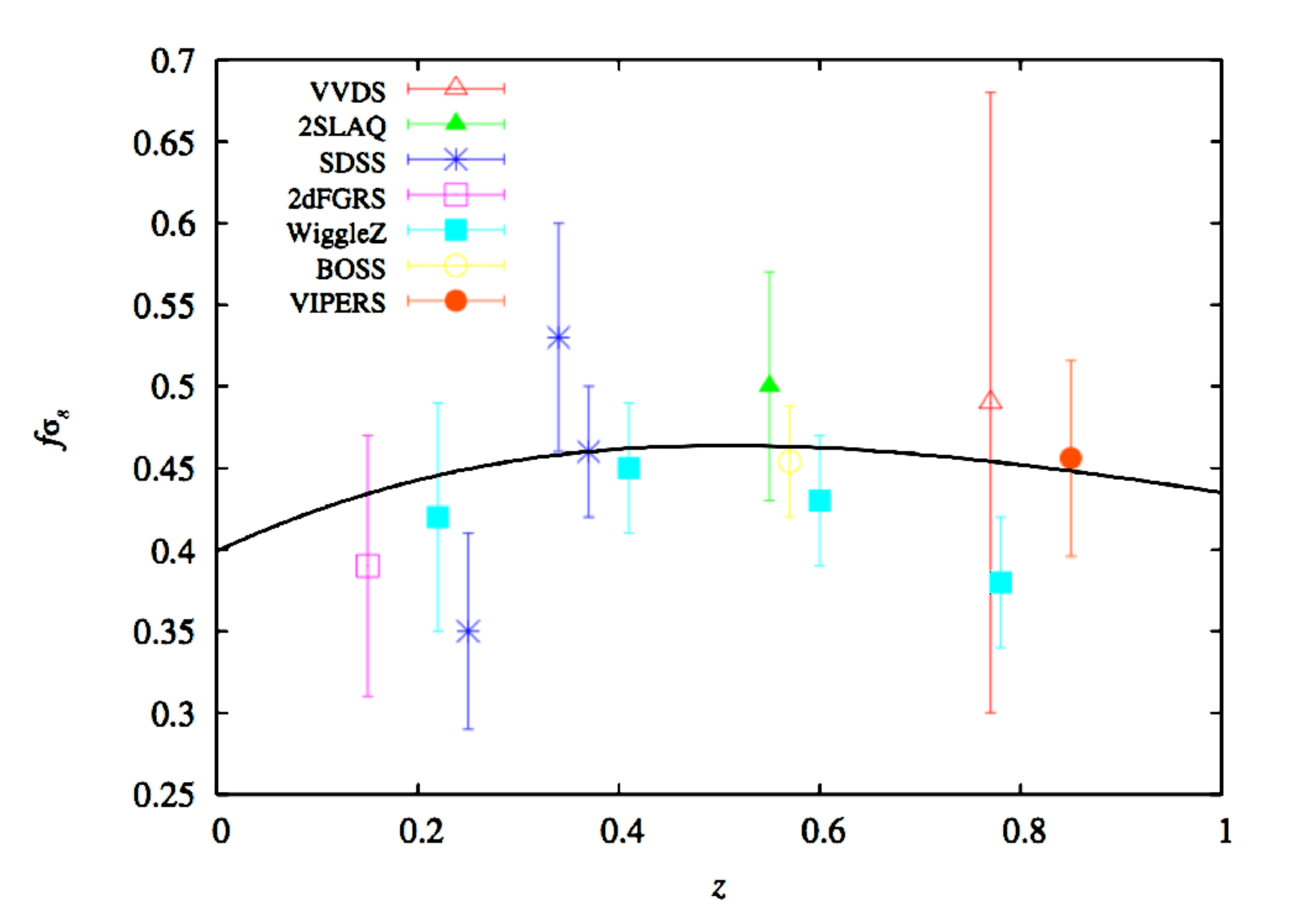
Studying the cosmic web at redshift 1 with VIPERS



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

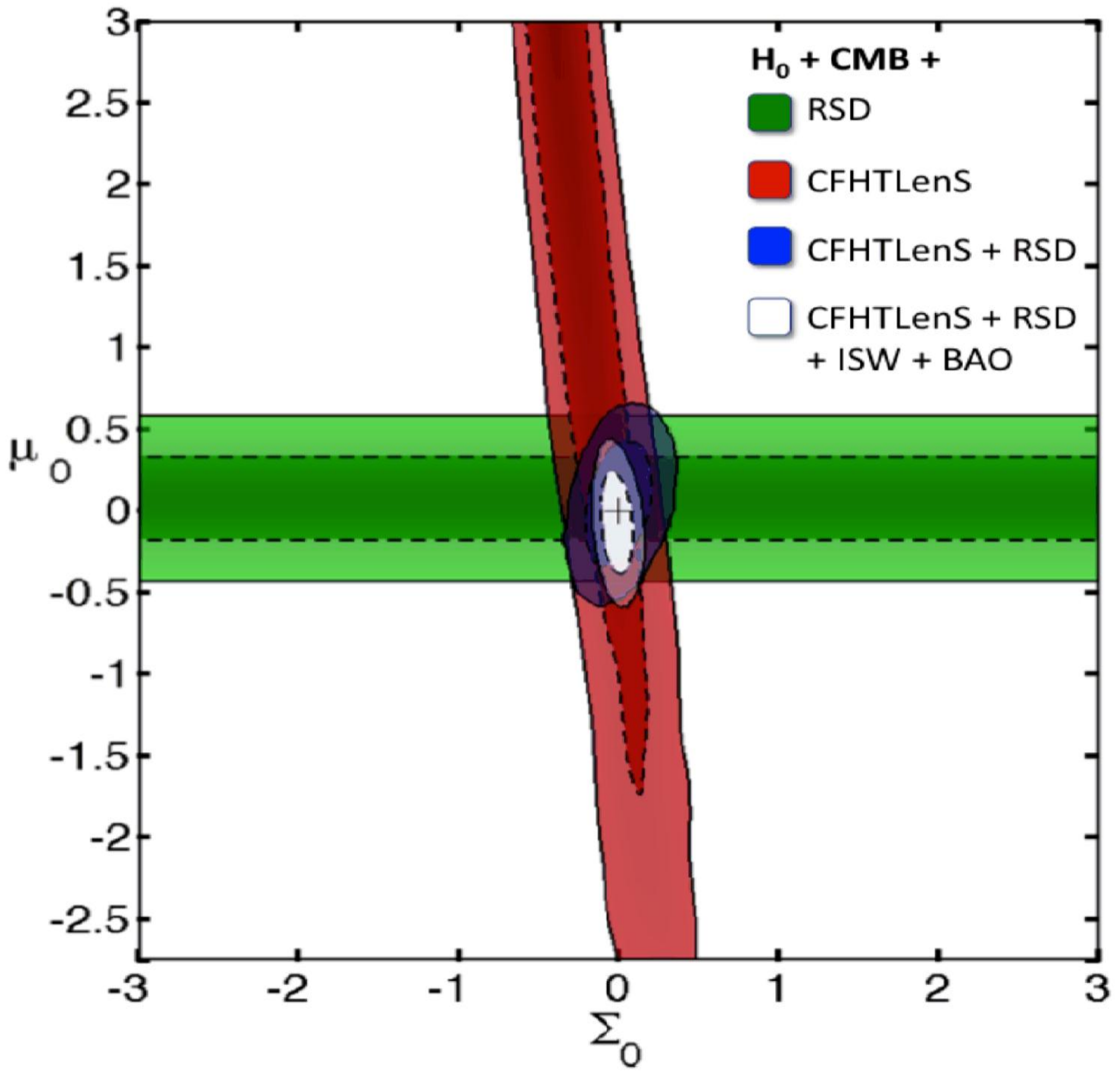


Growth rate: current state



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

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

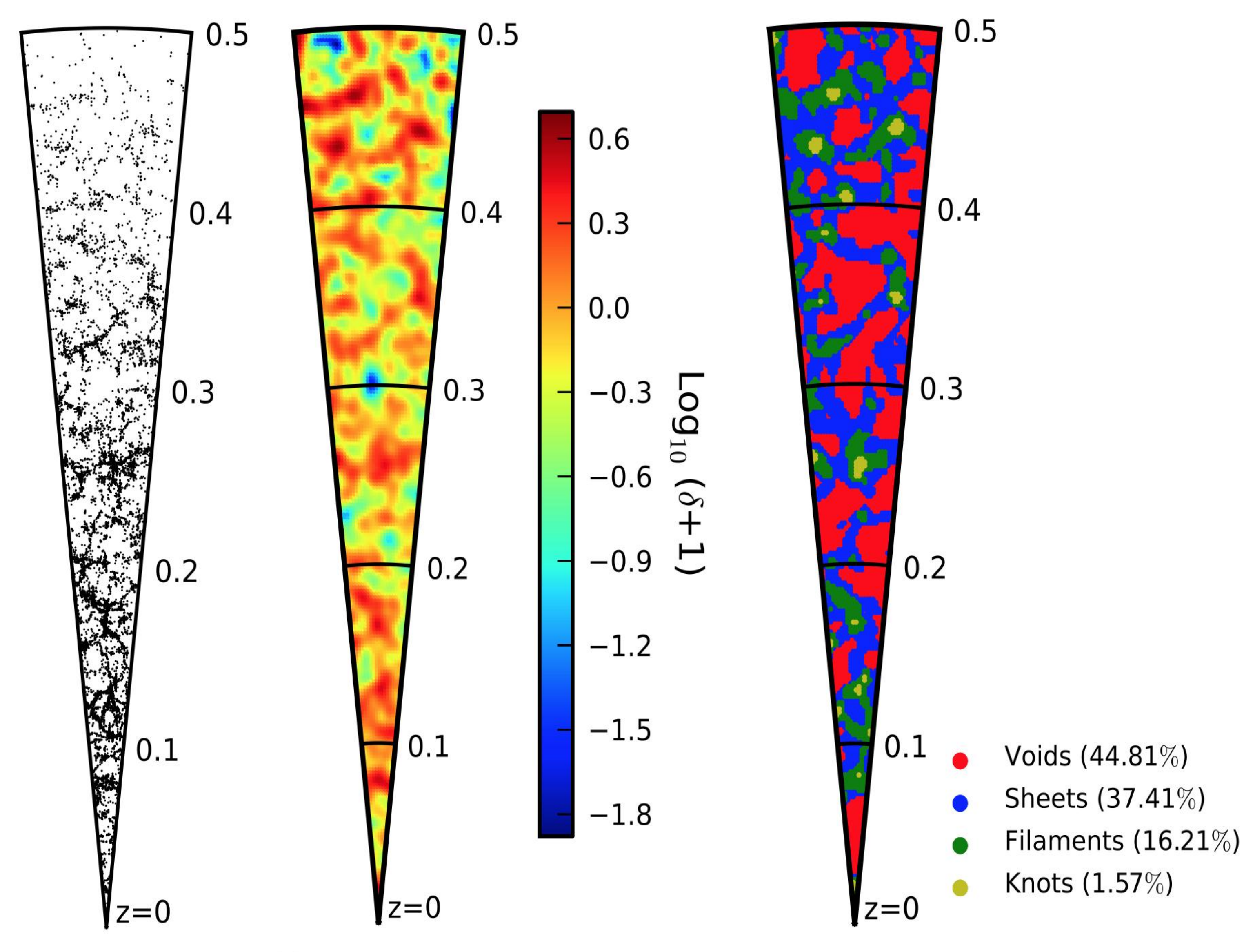
$$1 + \mu = (G'/G)/\eta;$$
$$1 + \Sigma = (G'/2G)(1 + 1/\eta)$$

Einstein gravity OK at 10% level

Amicable divorce in LSS

- Astrophysicists
  - Want to understand galaxy formation within LSS
  - Want highest possible number density (deep)
  - Want high-quality spectra
  - Happy with representative volume (<1 Gpc^3)
- Fundamentalists
  - Want better precision on DE/MG
  - Need volume − wide area, not depth
  - Happy with redshifts only

Empirical cosmic web in GAMA

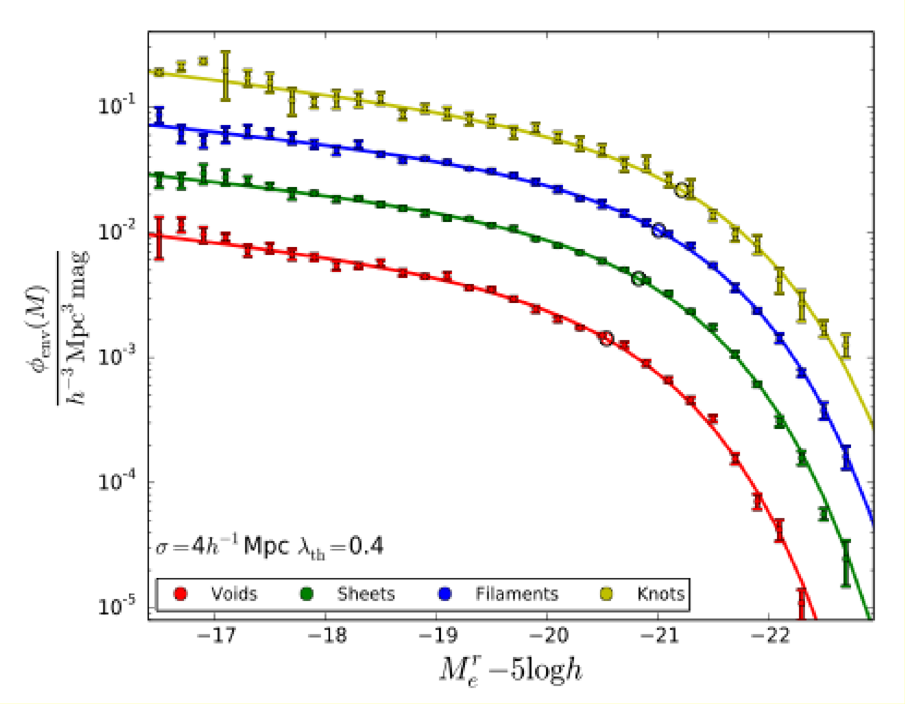


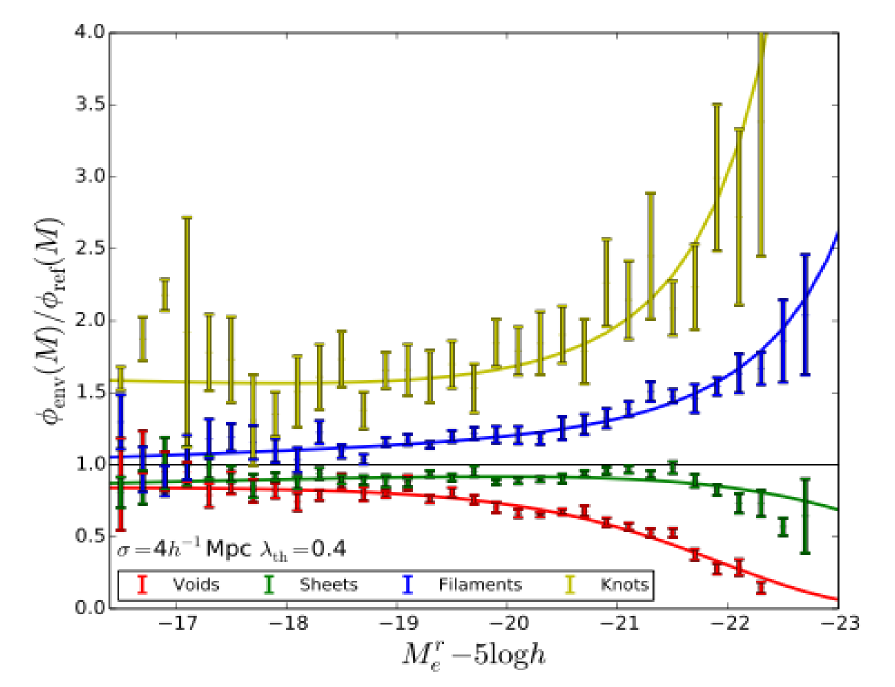
Eardley et al. 1412.2141

GAMA = 2dFGRS + 2 mag (250k z's)

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

Empirical cosmic web in GAMA





Change in shape of galaxy LF within web − but consistent with correlation with local overdensity only: no impact of tidal forces on formation history

Data needs

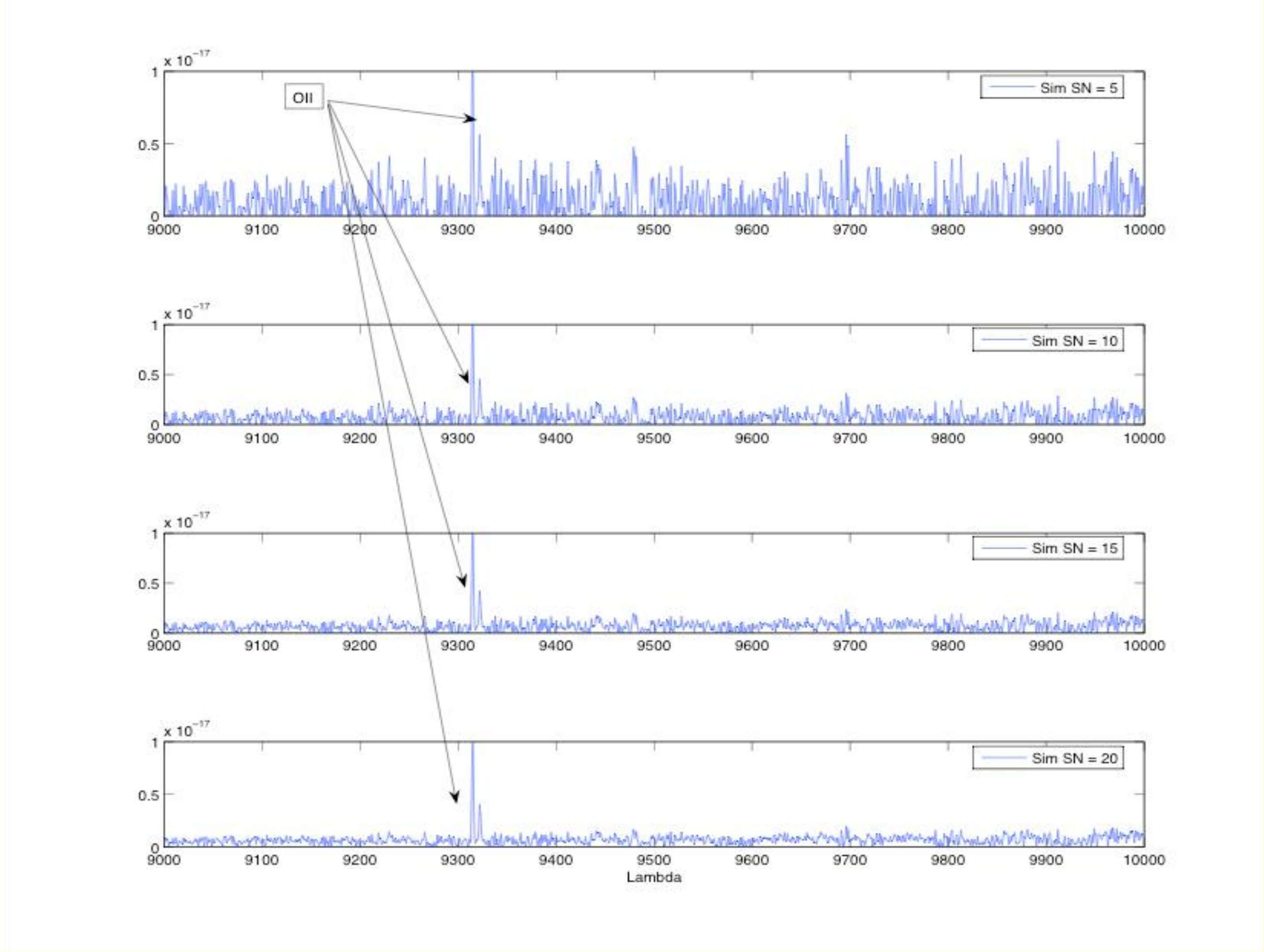
BAO % D error = $(V / 5\ h^{-3}\ Gpc^{3})^{-1/2}$ £ $(k_{max} / 0.2\ h\ Mpc^{-1})^{-1/2}$ £(1+1/nP)/2

- Fundamentalism limited by cosmic variance based on mode counting
  - With typical P=2500 $(h^{-1}Mpc)^{3}$) need n >= 4 £10^{-4} $(h^{-1}Mpc)^{-3}$. Shot noise unimportant beyond this

- Over 0.5 < z < 1.5, V = $1h^{-3}\ Gpc^{3}$ needs 375 deg^{2}
  - So all sky (33M z's) gives 0.25% (x4 improvement)

- Astrophysics probably happy with $0.1h^{-3}\ Gpc^{3}$ at n = 0.02
  - 2M z's over 40 deg^{2} − feasible with MOONS

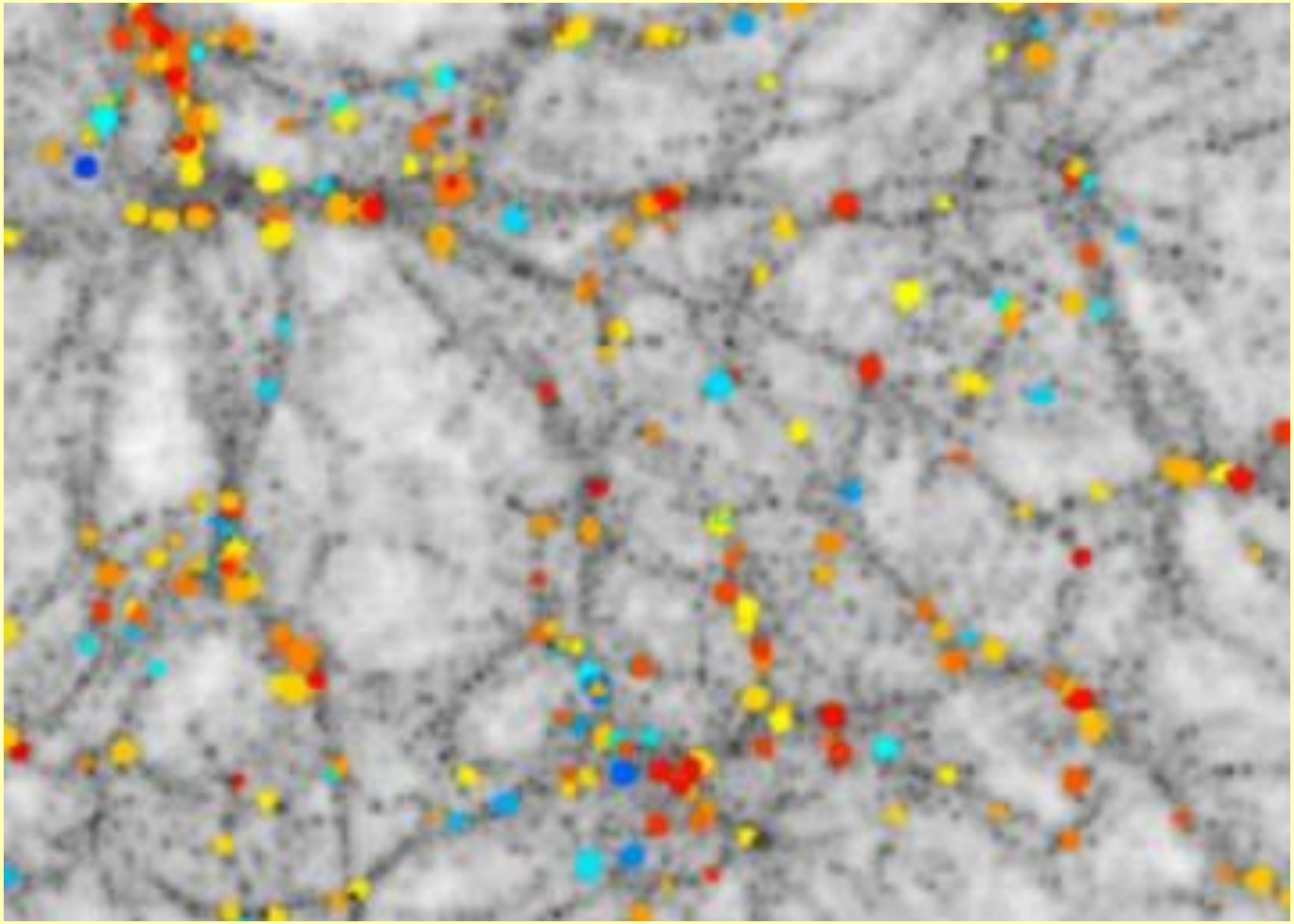
Area more important than quality



Simulated spectra for Subaru PFS: detect OII 3727 only.
Legacy value is a big issue

Alternatives?

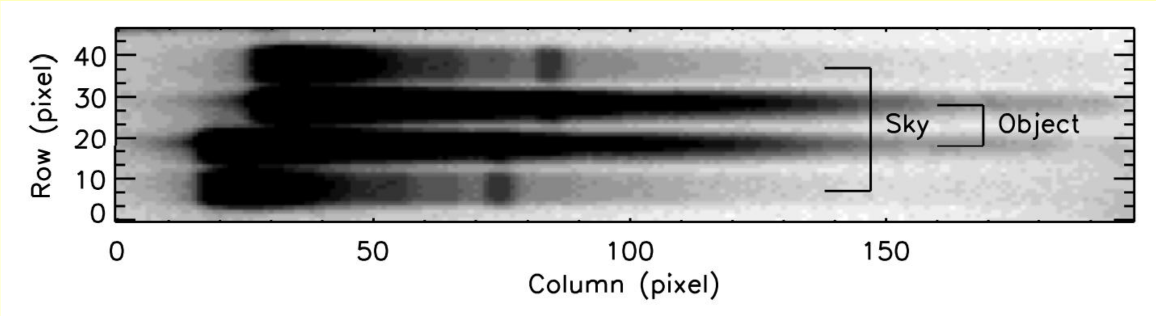
Multi-tracer analysis



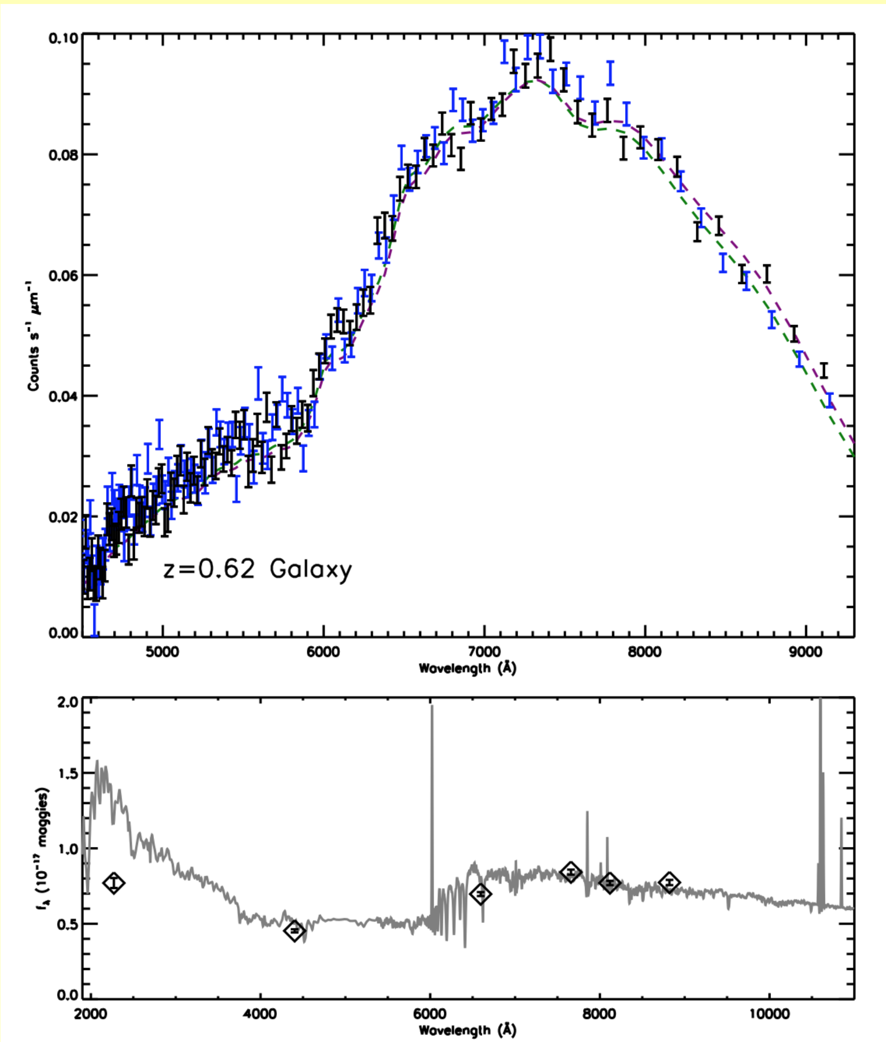
McDonald & Seljak (0810.0323. See also 1003.3238): cosmic variance from finite numbers of superclusters is in common between red & blue. No good with dilute tracers

Studying LSS without spectra?

- Dispersed imaging
- Photometric redshifts
- Radio imaging and intensity mapping



PRIMUS



Magellan prism:

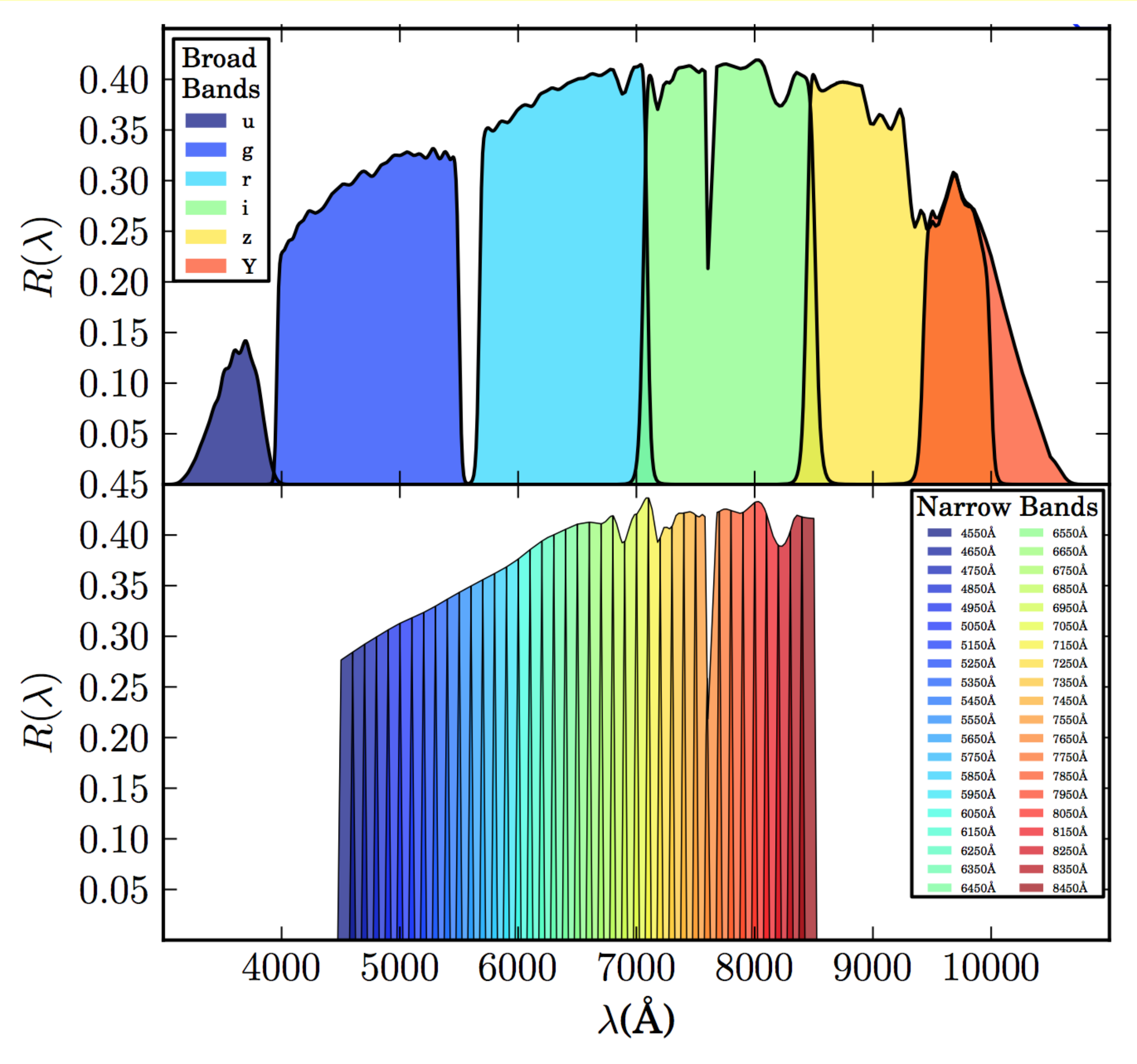
dz / (1+z) = 0.005

(17 Mpc/h @ z=1)

Resolution limits both evolution and LSS studies

130k to r = 23 over 9 deg^2

PAU: Photo-z on steroids



40-band survey using WHT:

dz / (1+z) = 0.0035

(12 Mpc/h @ z=1)

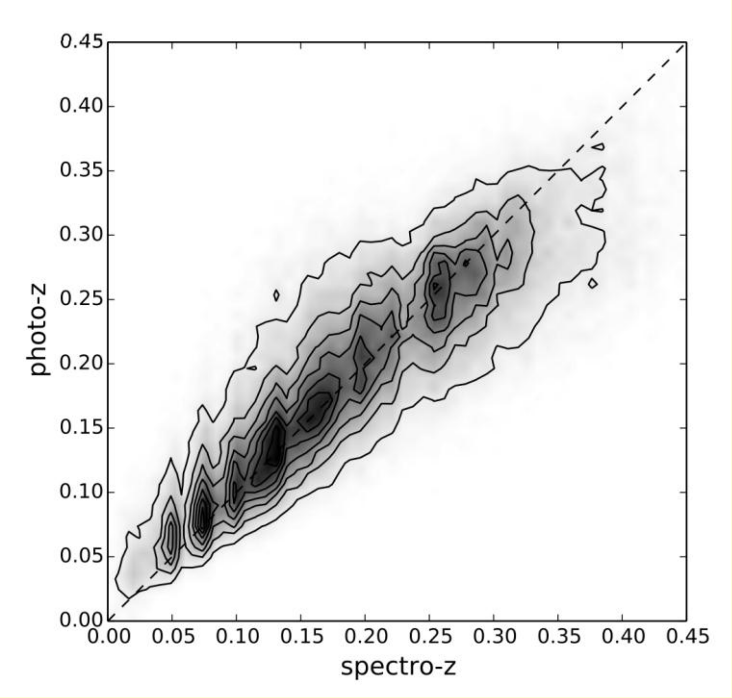
Significant effects on BAO & RSD, but can be modelled

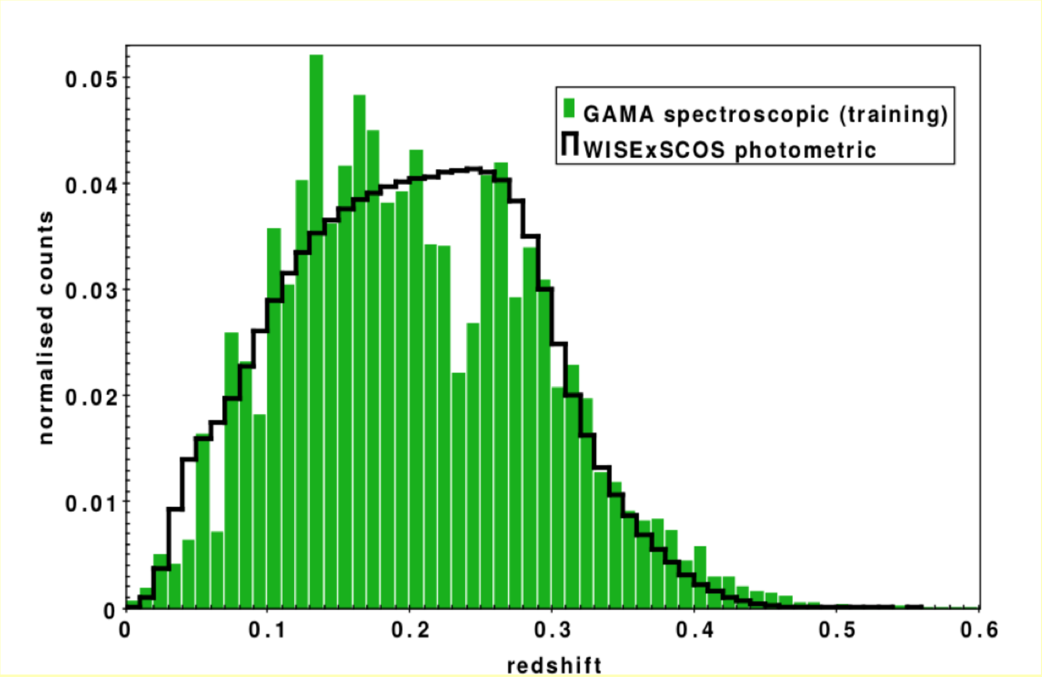
All-sky photo-z for WISE+SuperCOSMOS

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

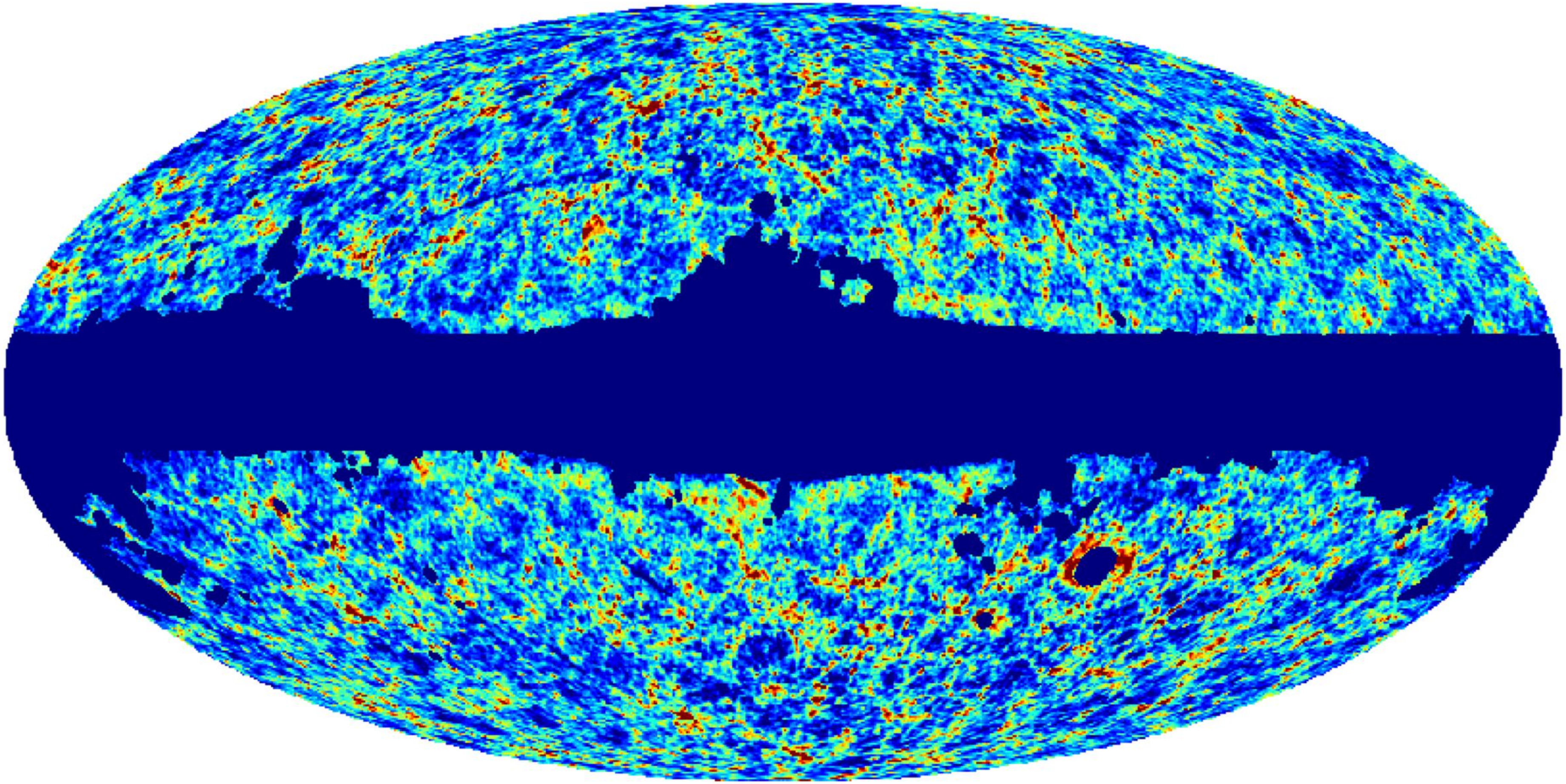
σ_z / (1+z) = 0.032 (0.015 with 2MASS)

Median z = 0.2; useful signal out to z = 0.4 (double 2MASS)

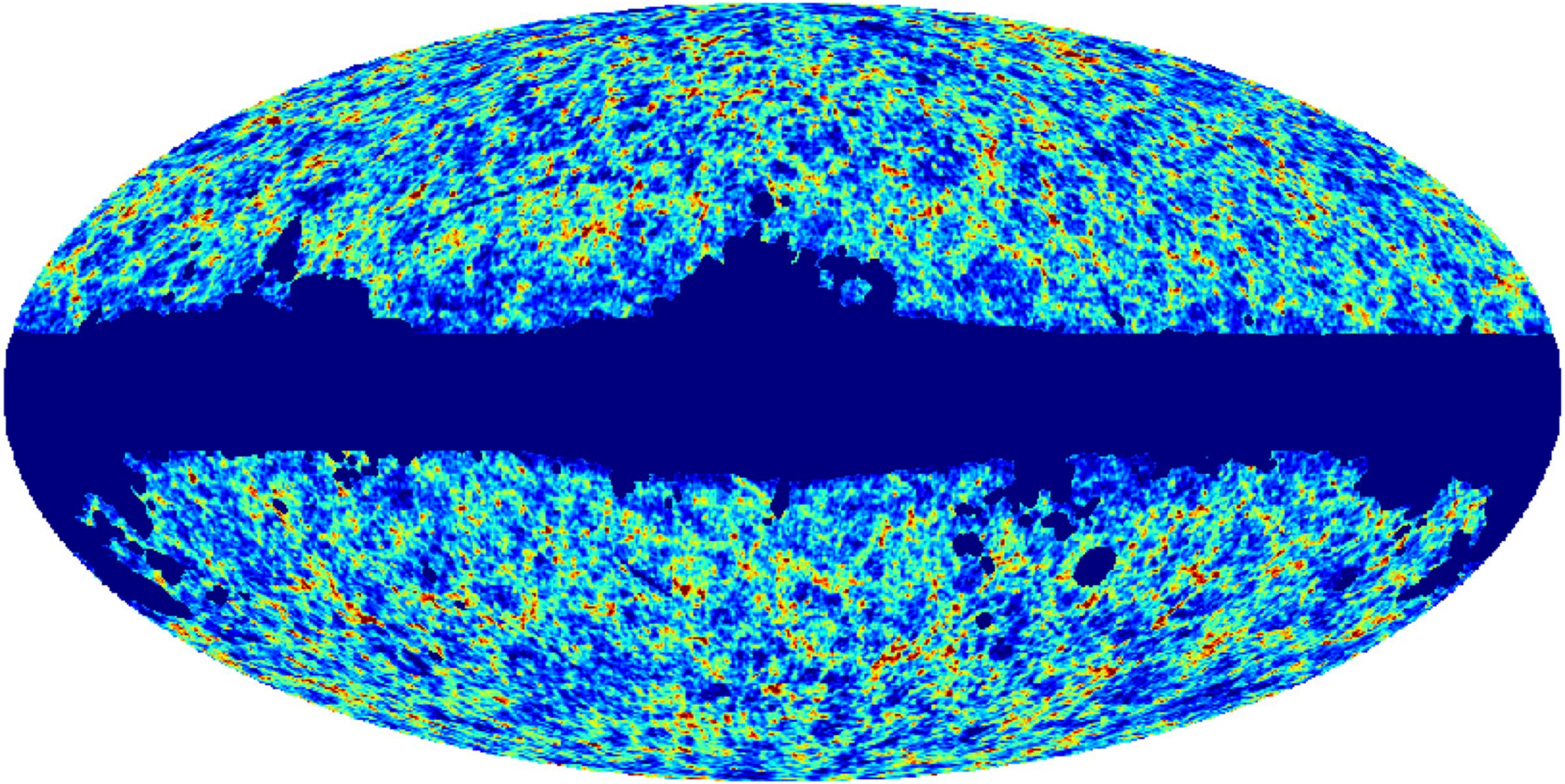




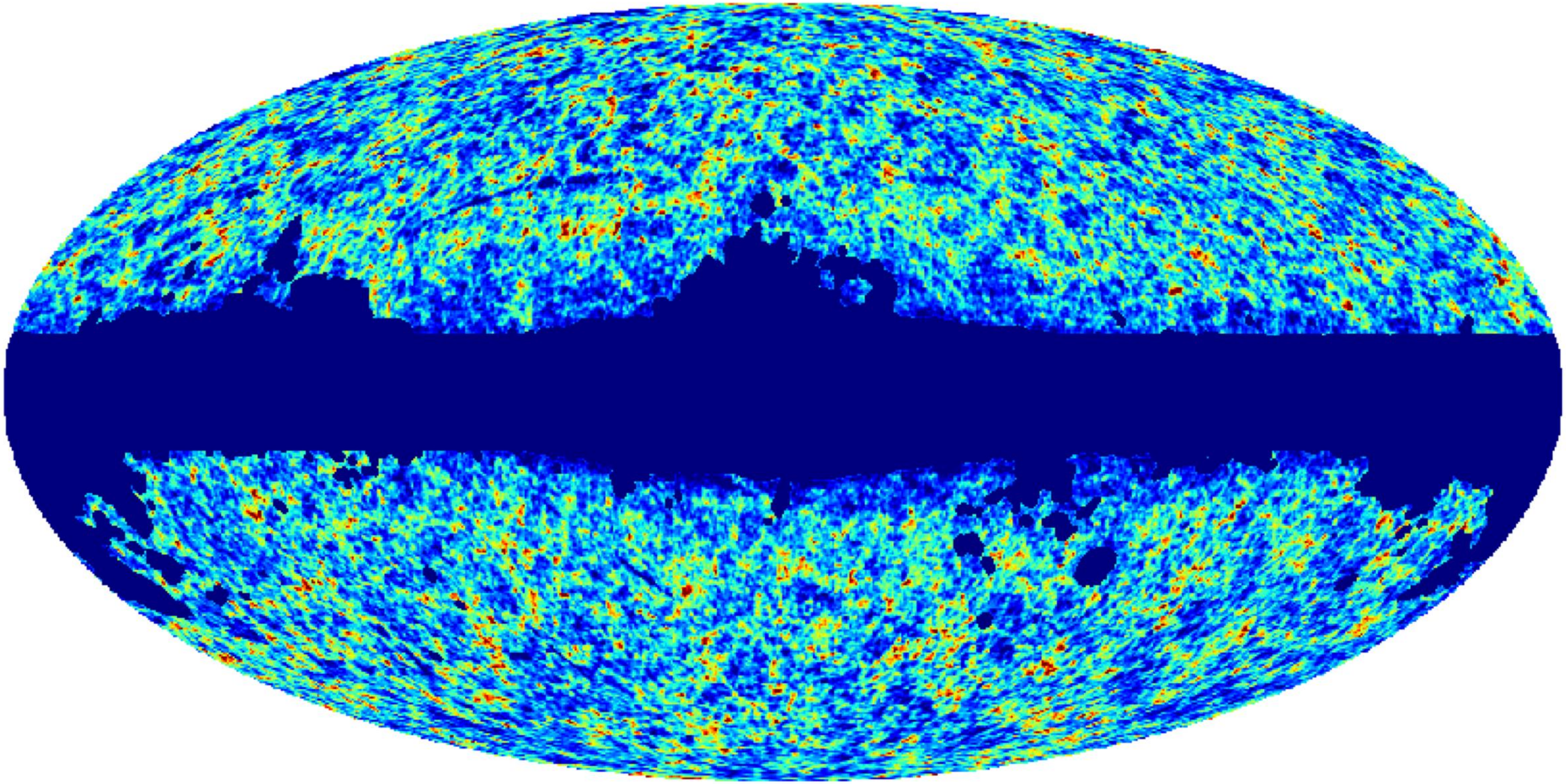
$0.1 < z < 0.15$



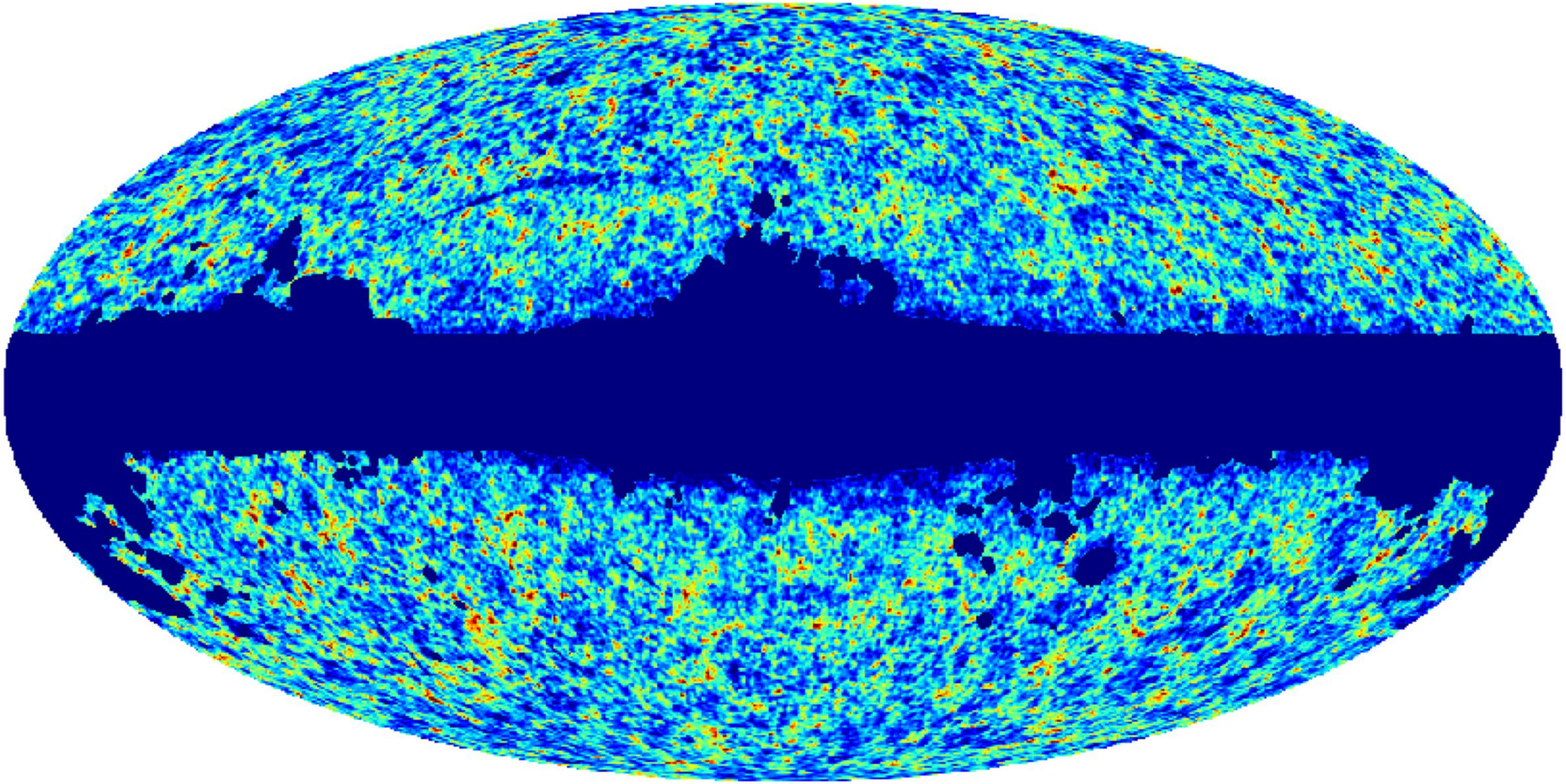
0.15 < z < 0.2



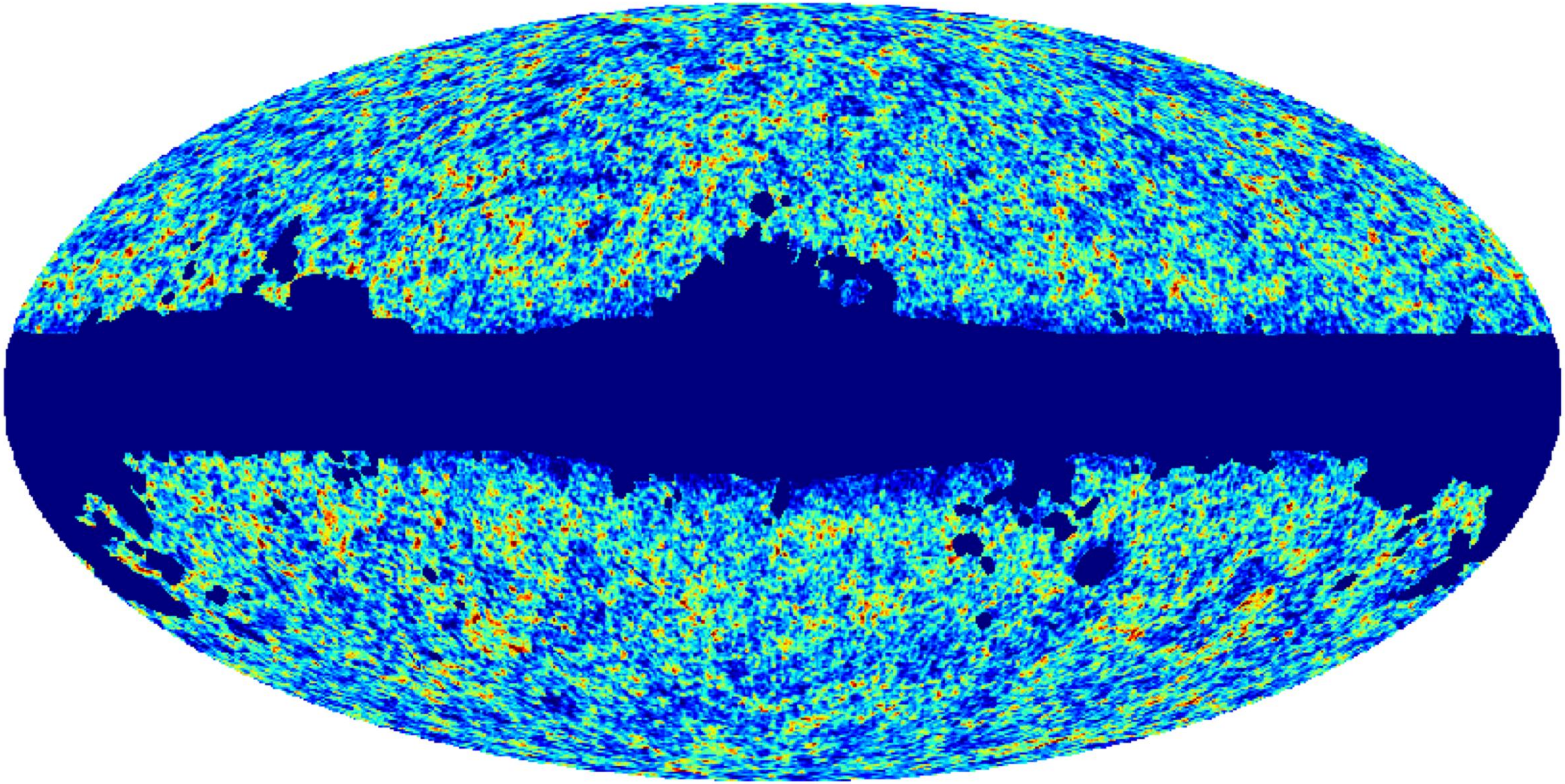
0.2 < z < 0.25



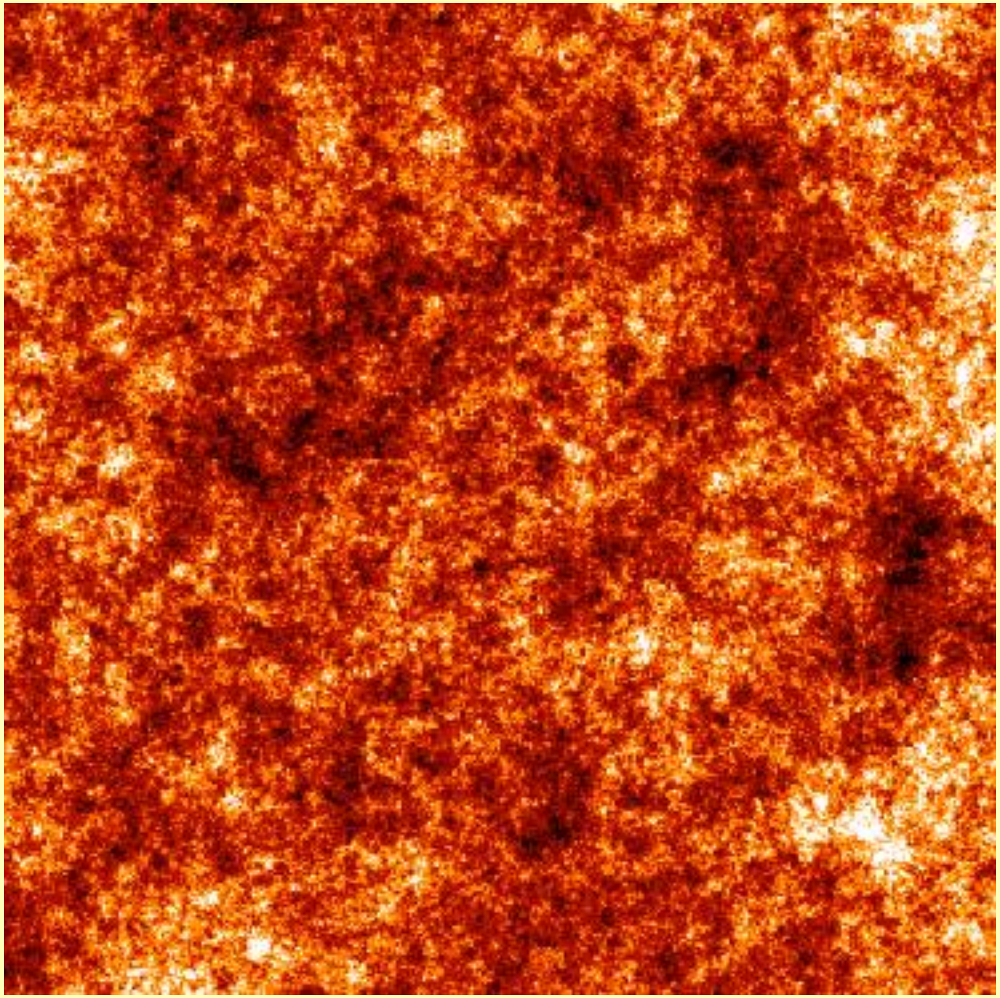
0.25 < z < 0.3



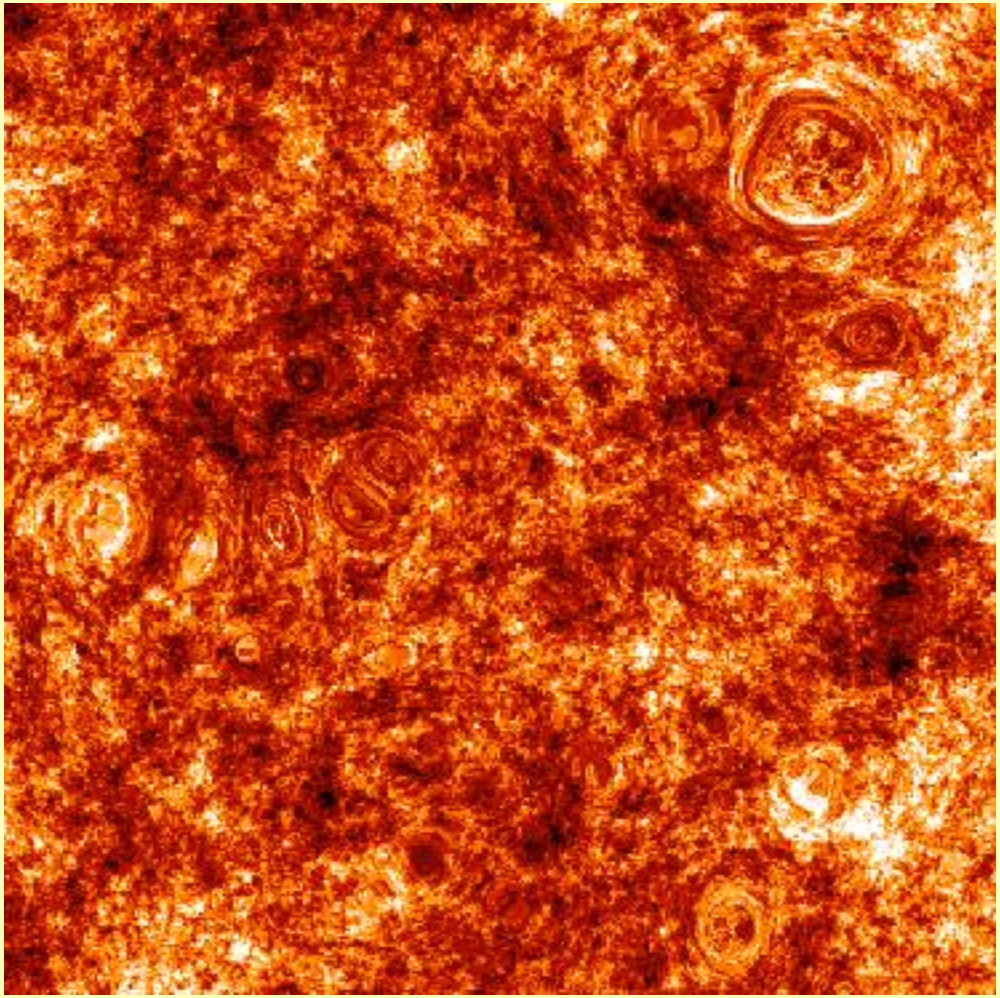
0.3 < z < 0.35

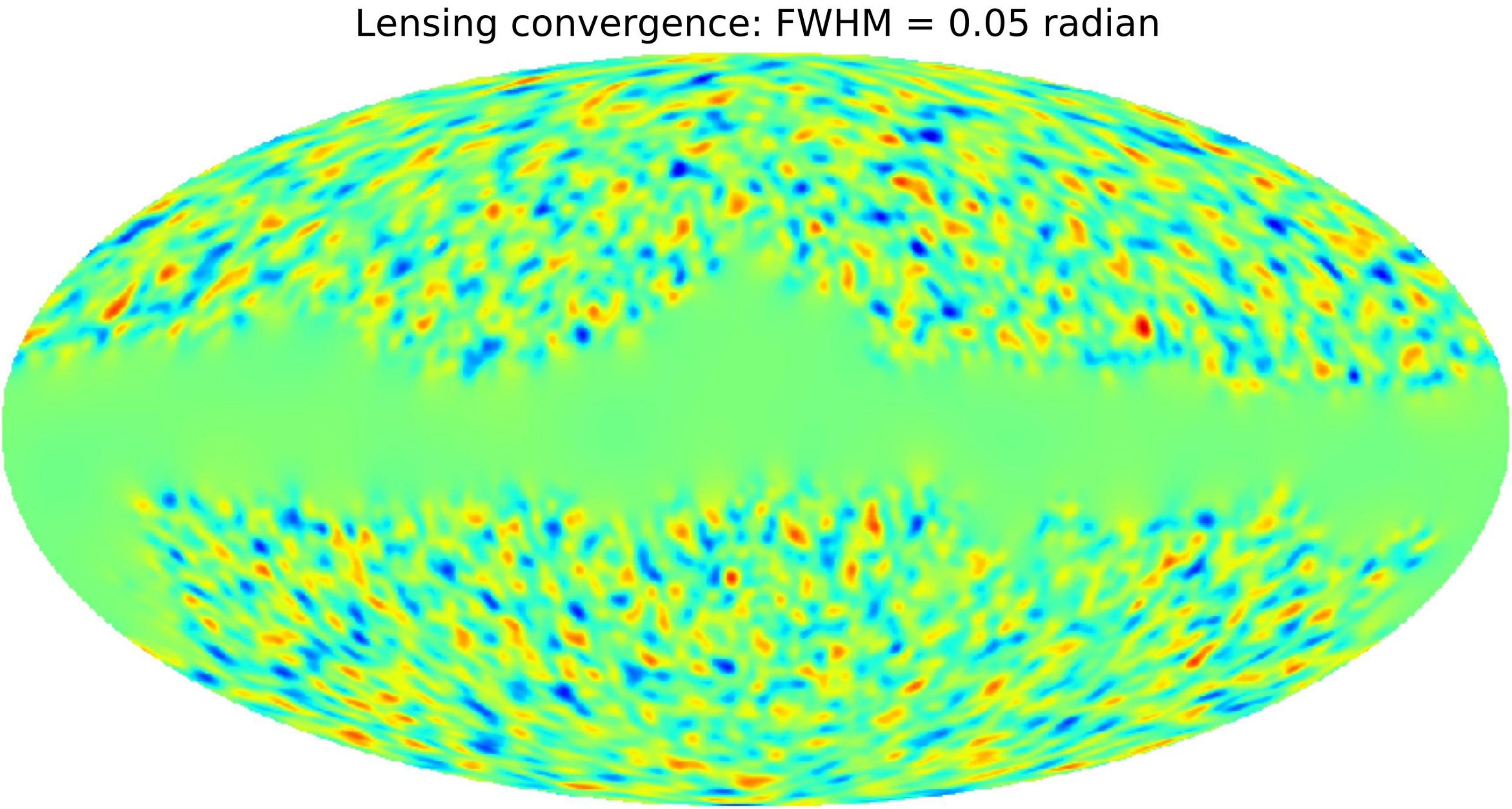


Unlensed CMB: 6 arcmin image (MPIA)



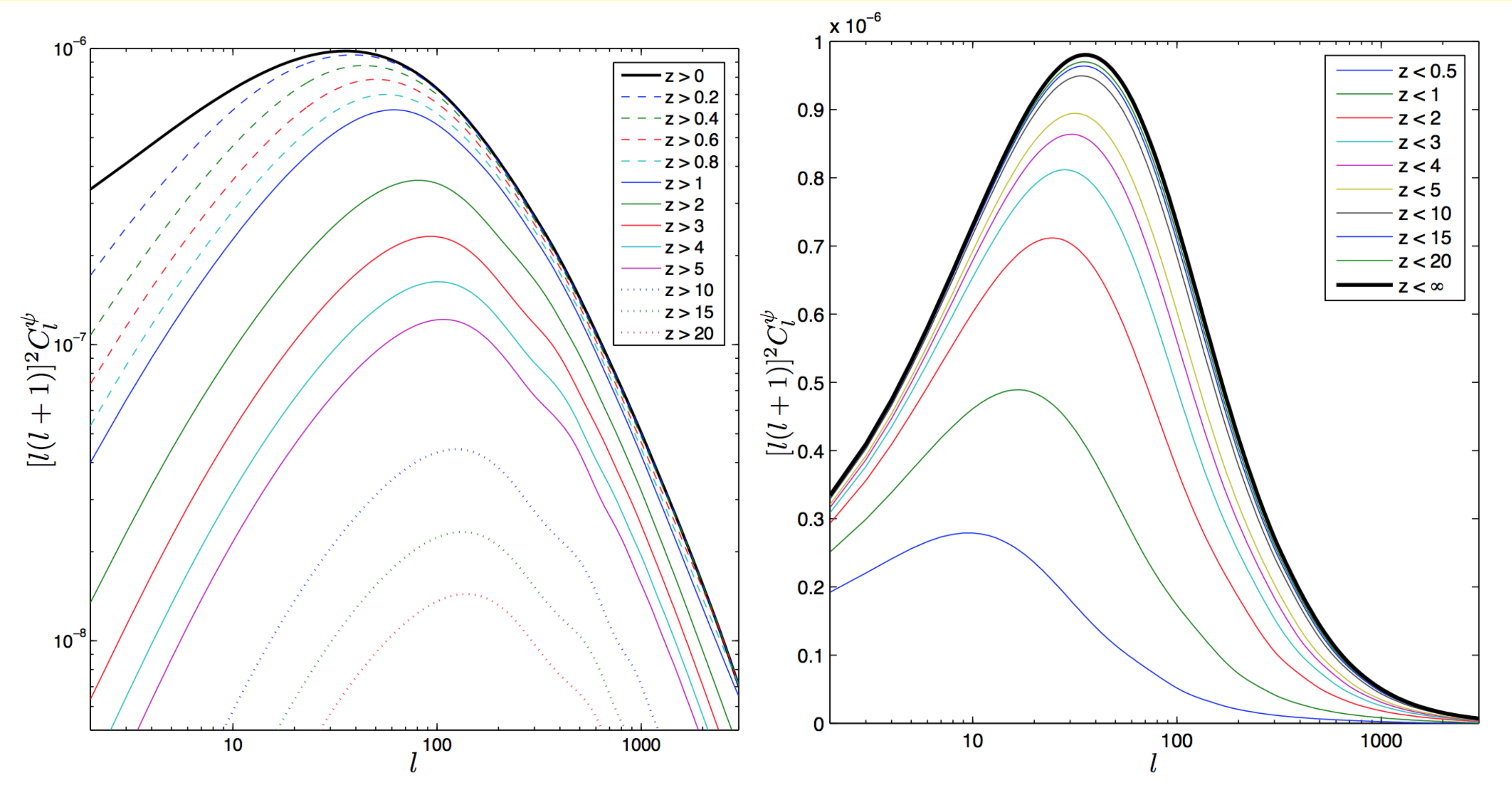
Lensed CMB: 6 arcmin image (MPIA)





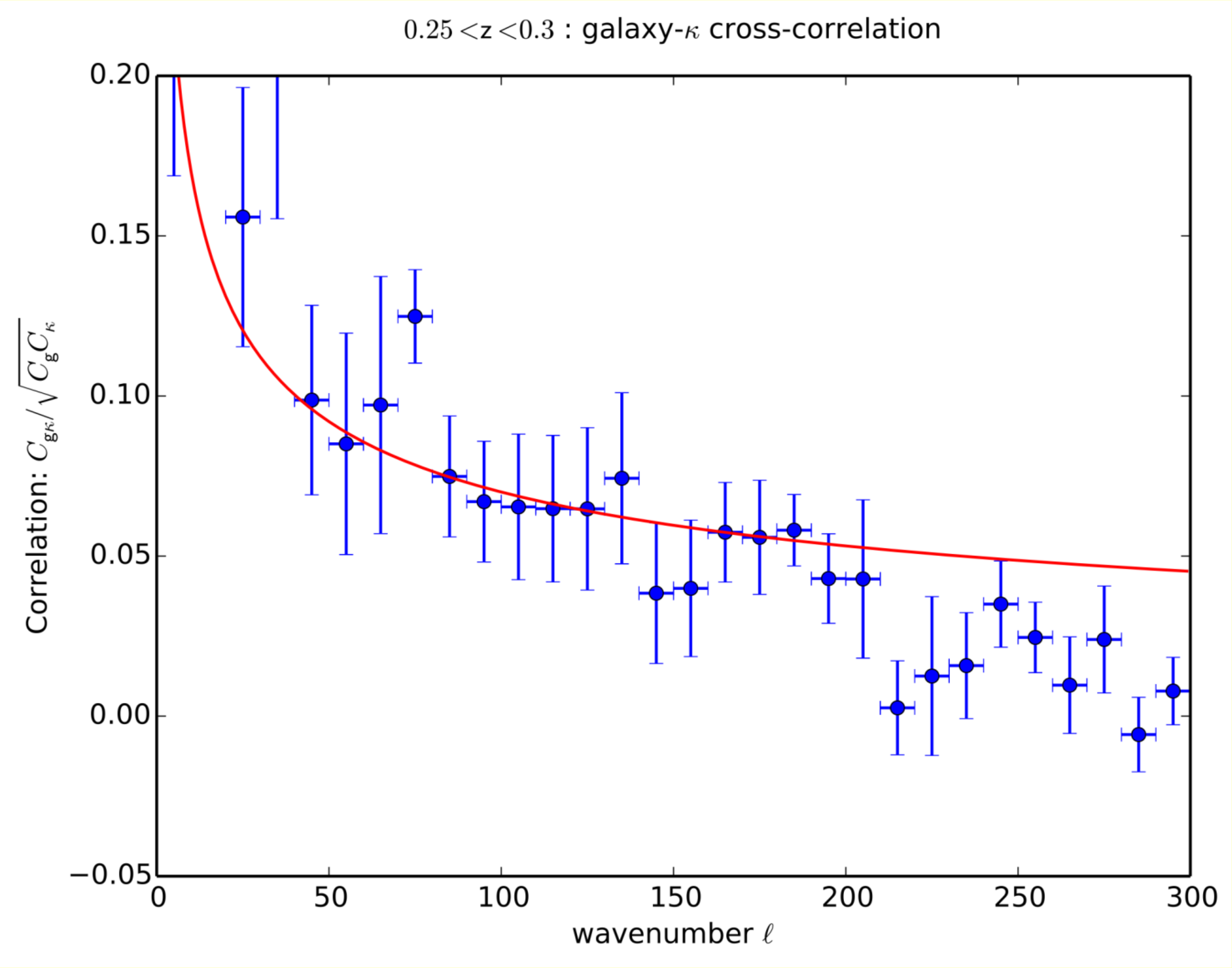
Projected mass distribution back to z = 1100

Theory (Hu; Lewis & Challinor)



Low z: C(<z) / C = 0.1 z (l / 100)$^{-0.8}$

Implies correlation 0.07 (l / 100)$^{-0.4}$ in all dz = 0.05 slices



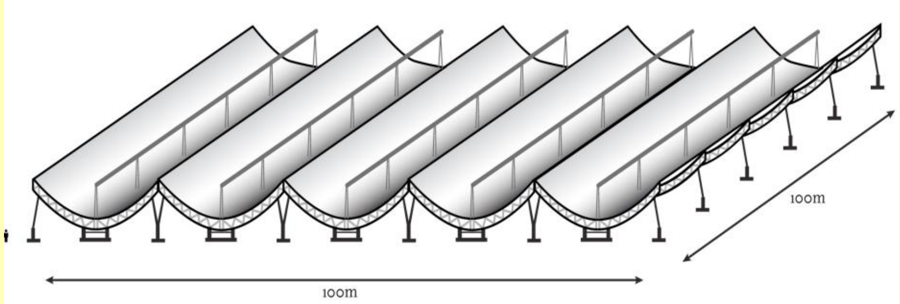
Direct measure of growth of DM fluctuations: should be signal up to z > 5

Lesson: power of all-sky surveys

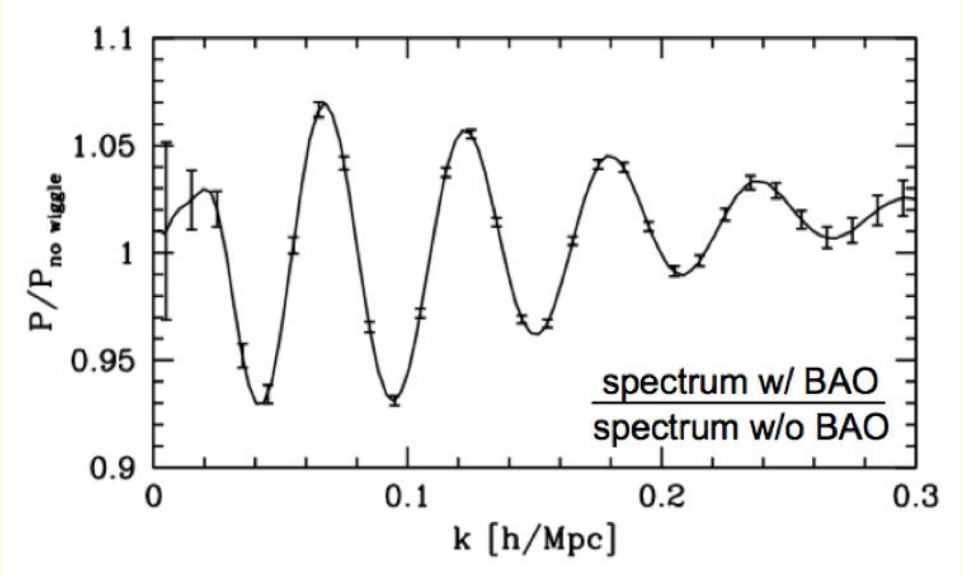
- Finish VHS; UKIRT alternative?
- Northern complement to LSST? (Nice for Euclid)

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)



Back to spectroscopy:

What are the expected LSS probes in the 2020s?

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

(+800k QSOs)

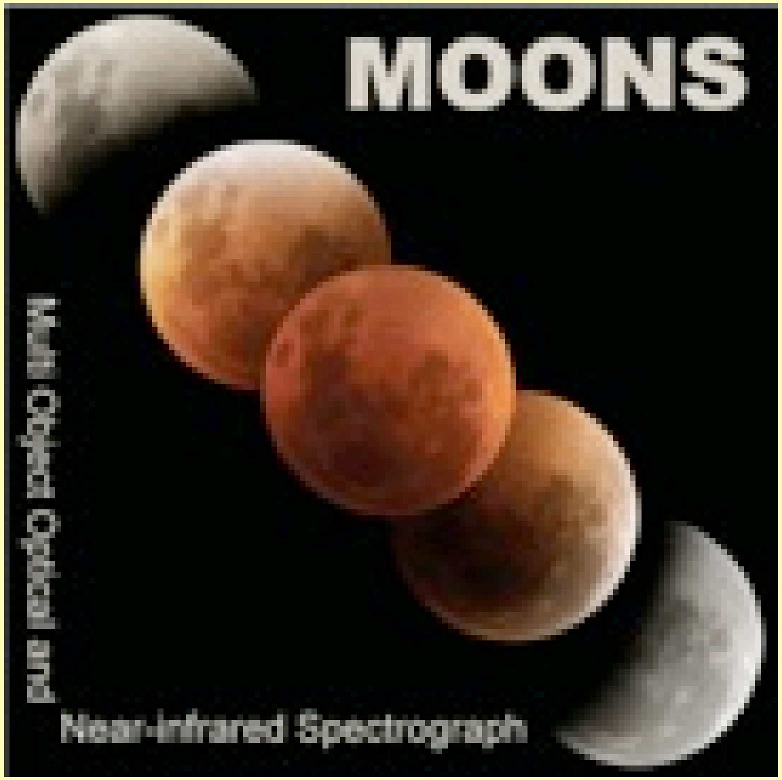
Other 4m projects: 4MOST & WEAVE

4MOST: 2000 fibres; 2.3-deg field on VISTA. 2019−

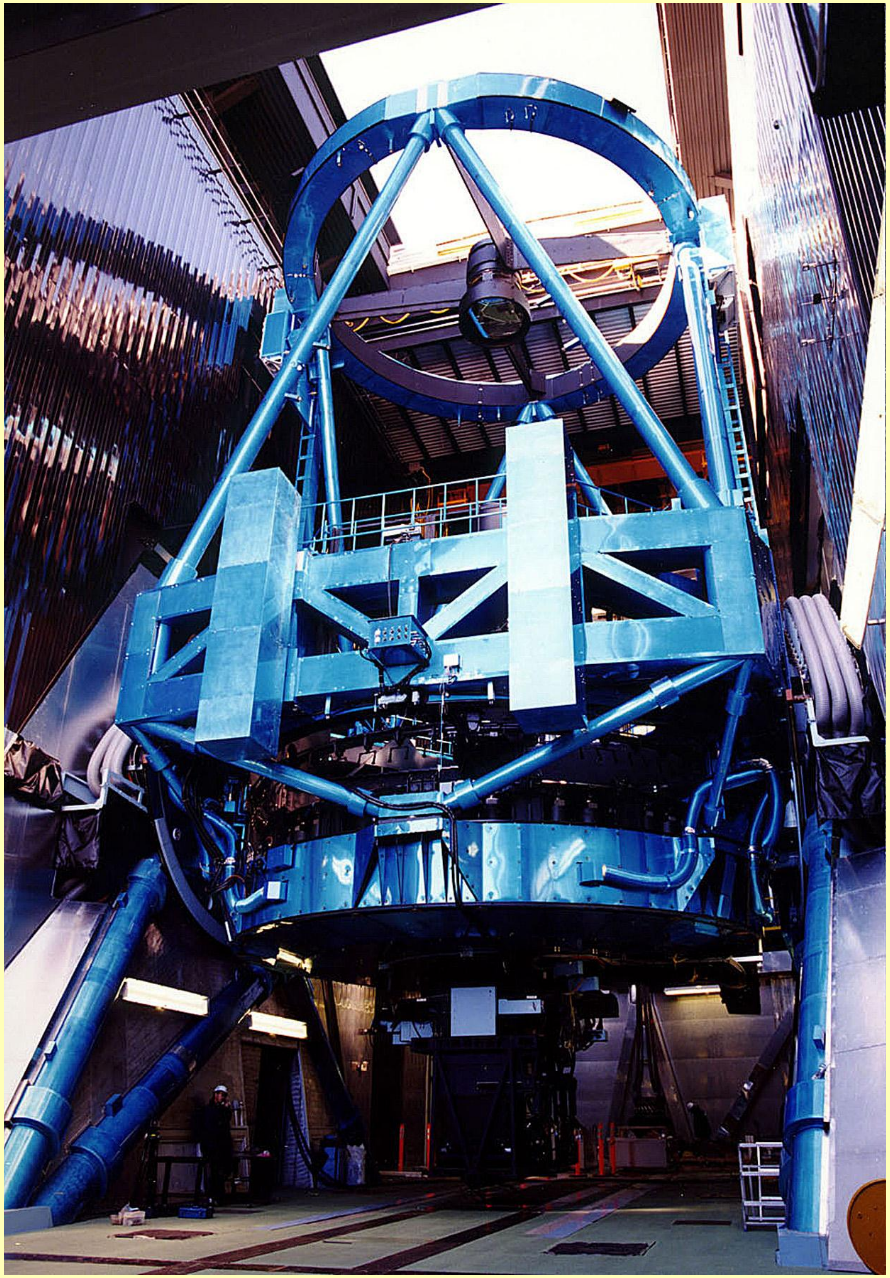
WEAVE: 1000 fibres; 2-deg field in WHT. 2017−

Both motivated primarily by GAIA follow-up. Also BAO surveys, but not fully specified yet

MOONS



- 1000 Fibres on VLT
- 0.6 to 1.8 microns
- Perfect for galaxy evolution over $0.8 < z < 1.8$
- But limited by 28-arcmin Nasmyth field

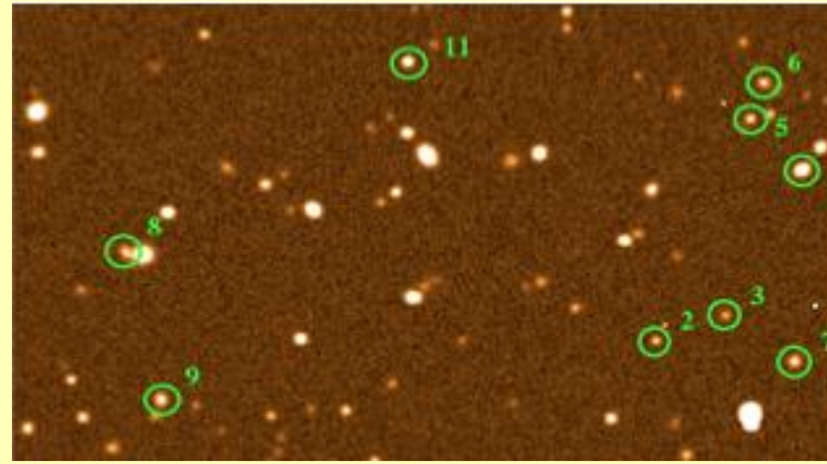


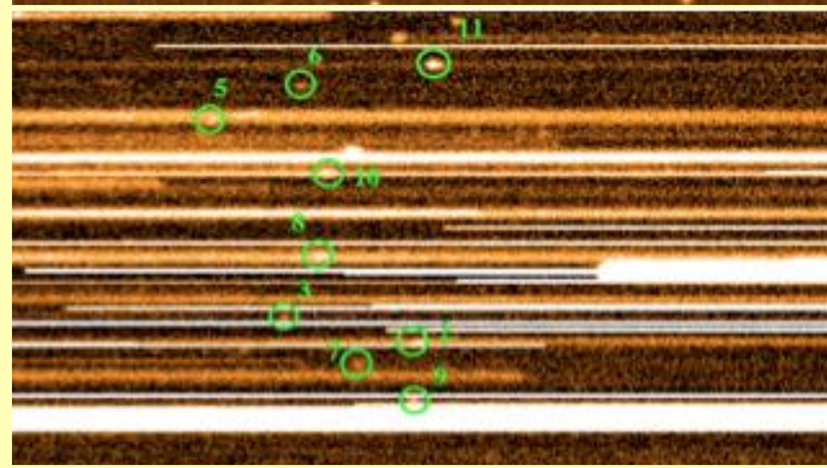
Subaru PFS

- 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?

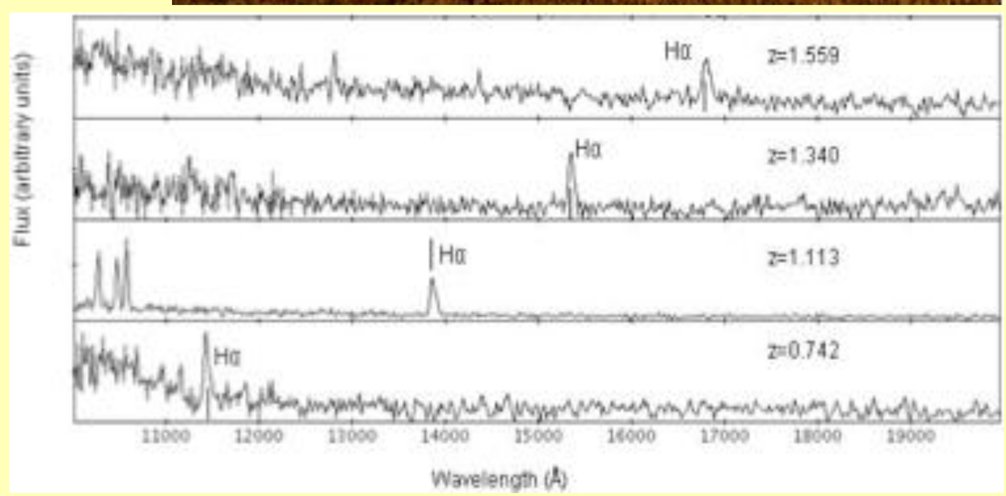
Euclid slitless spectroscopy

NIS Instrument:

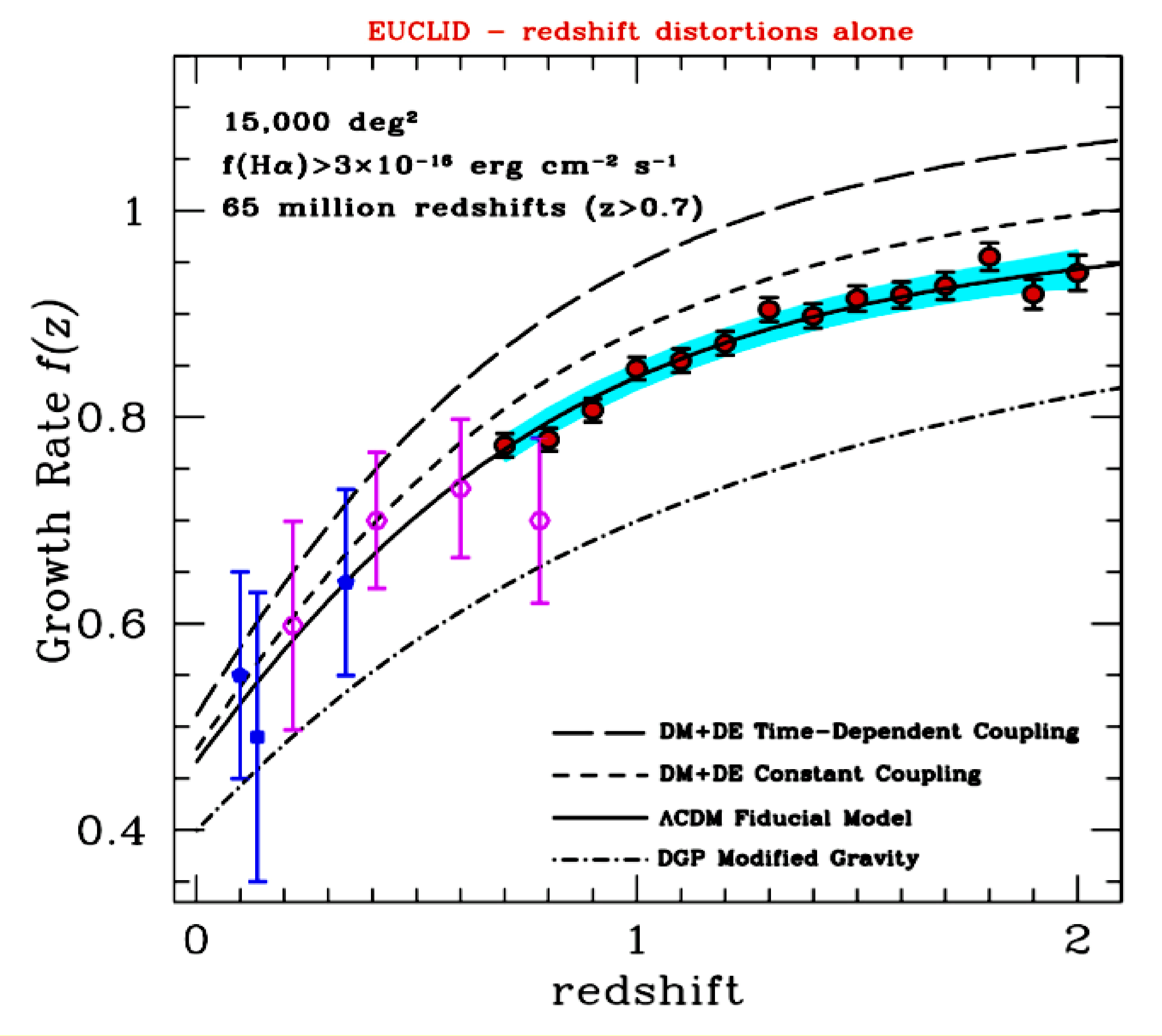




- ~ 25M redshifts in 1<z<2
- 15,000 deg^2
- H < 19.5

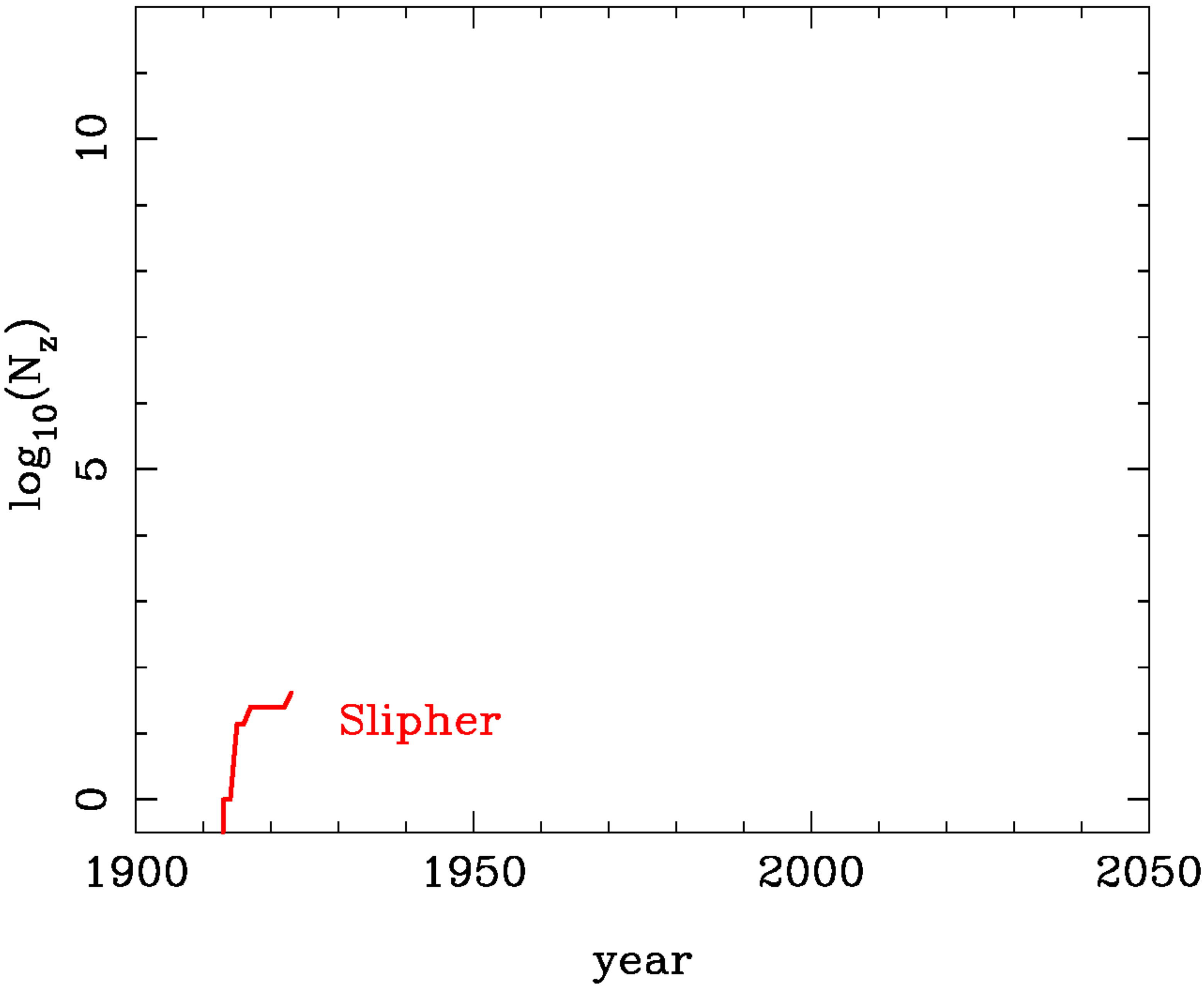


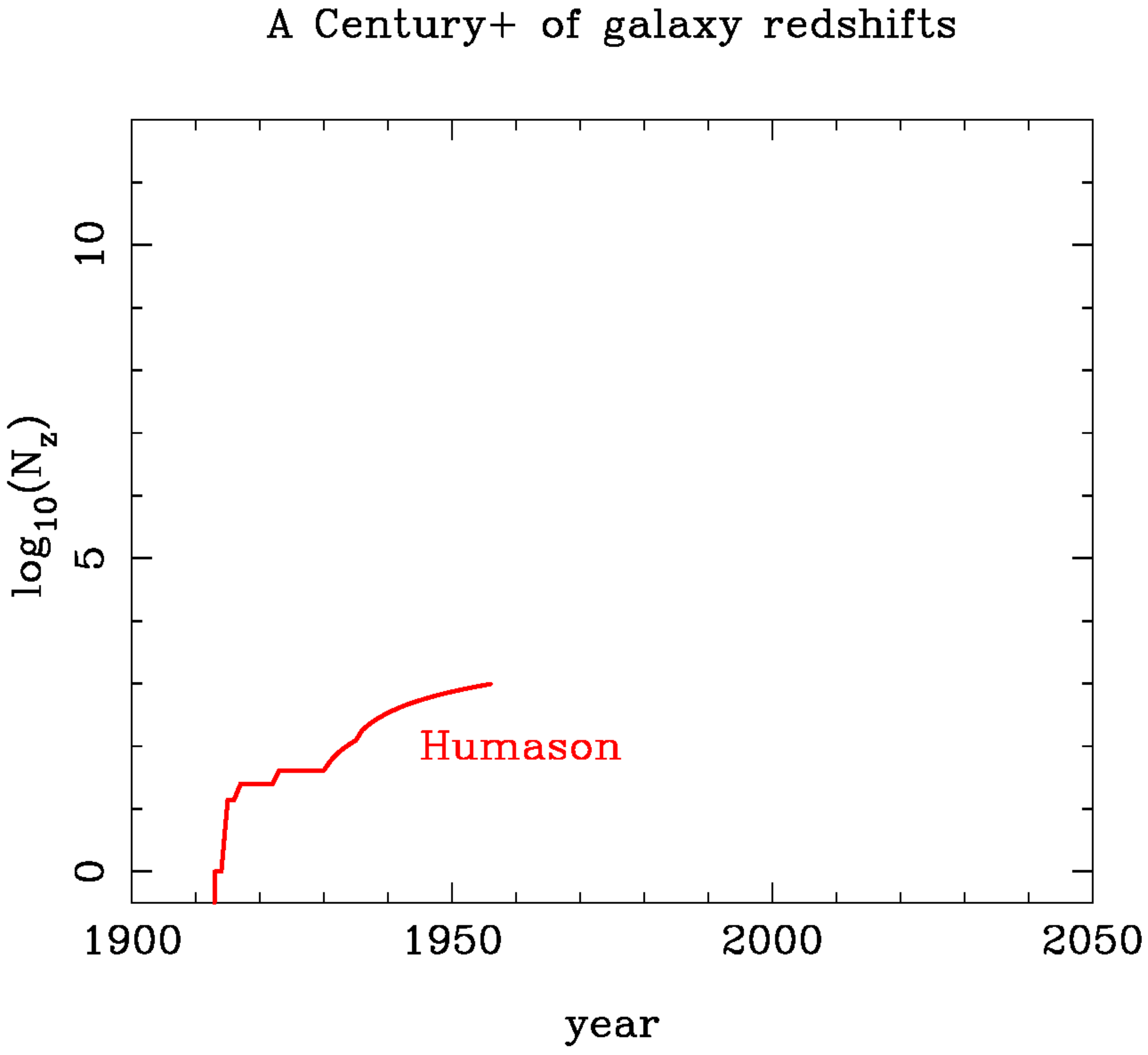
Euclid (2020-)



Need sub-% accuracy modelling: is this feasible?

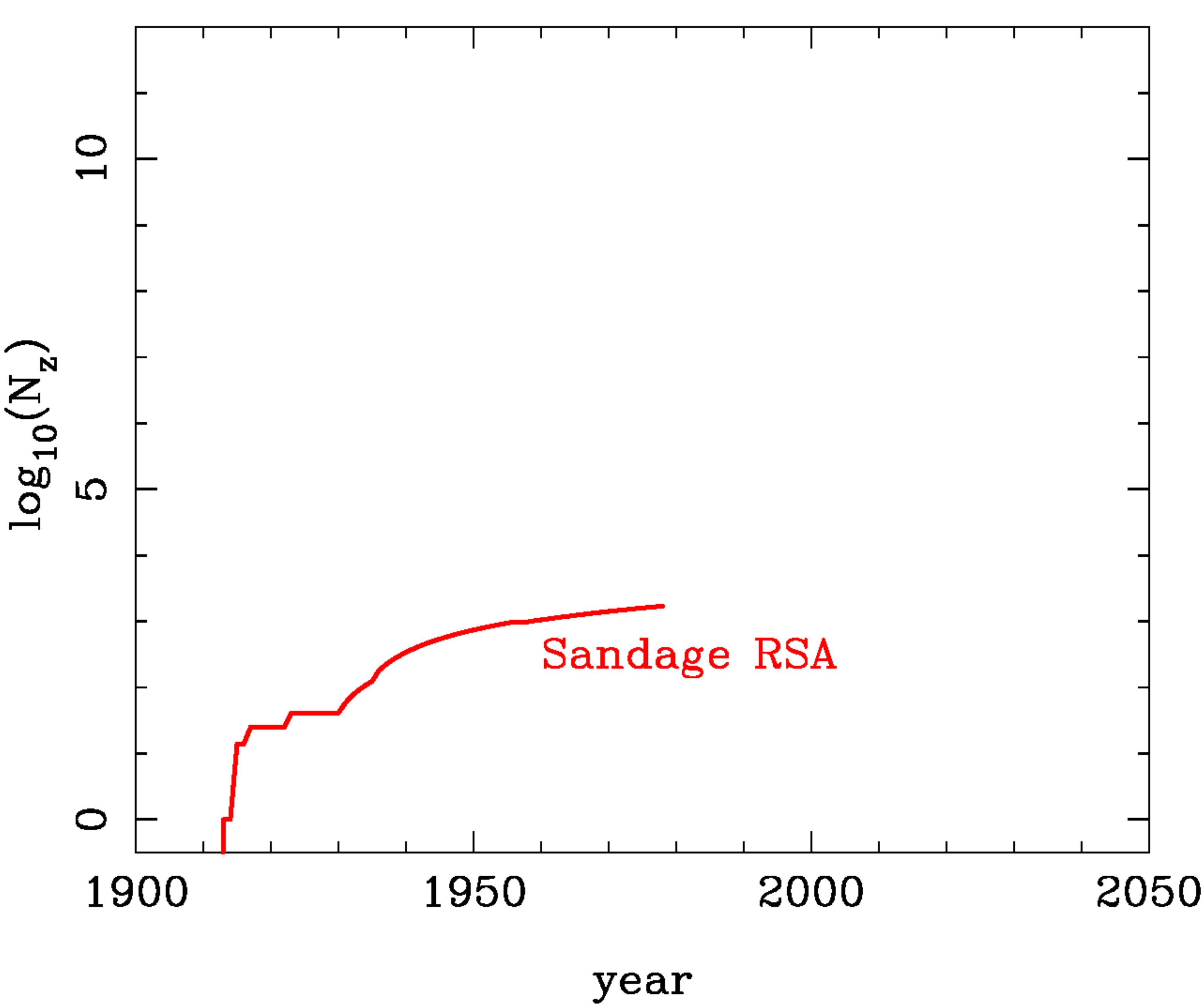
A Century+ of galaxy redshifts



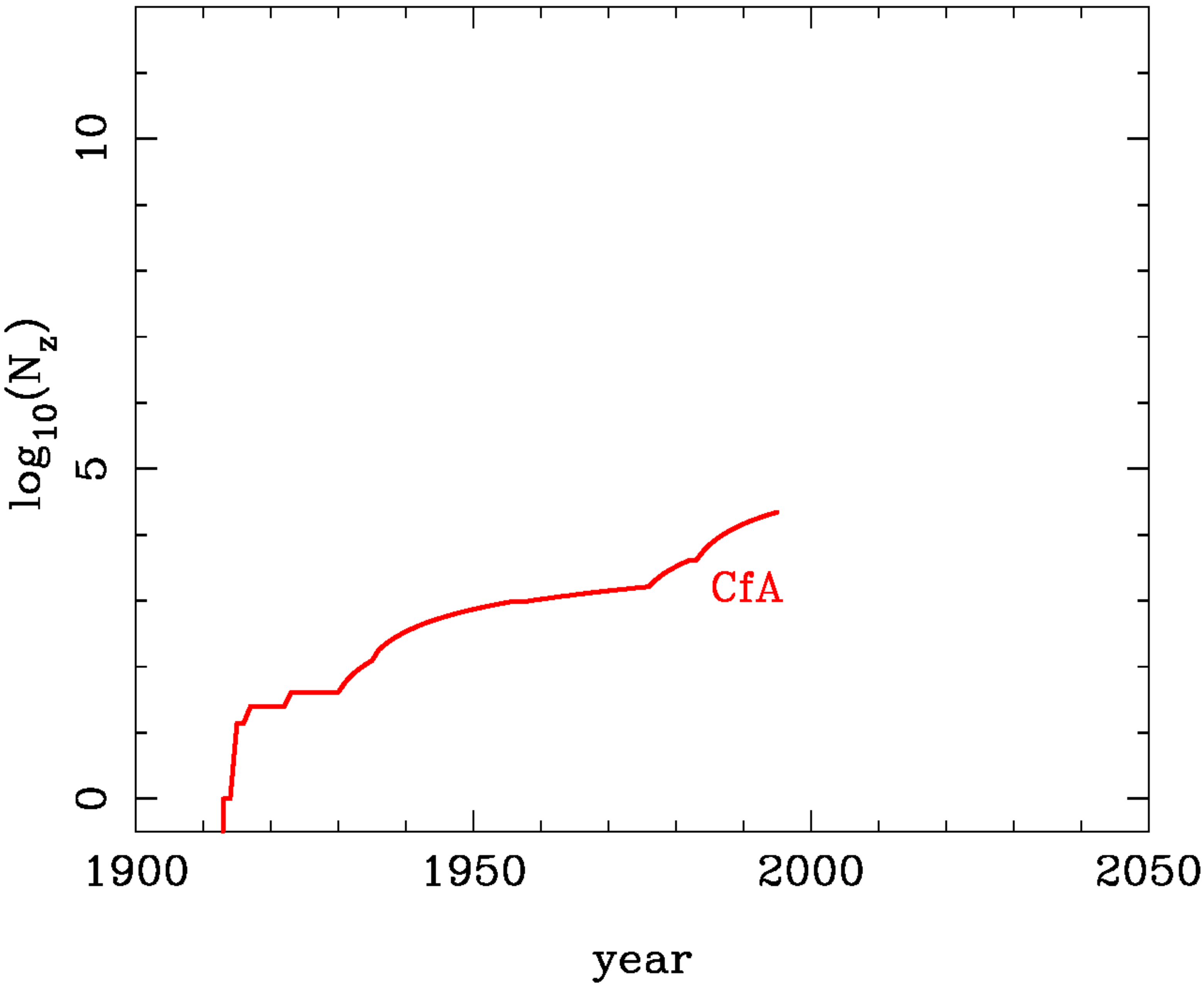


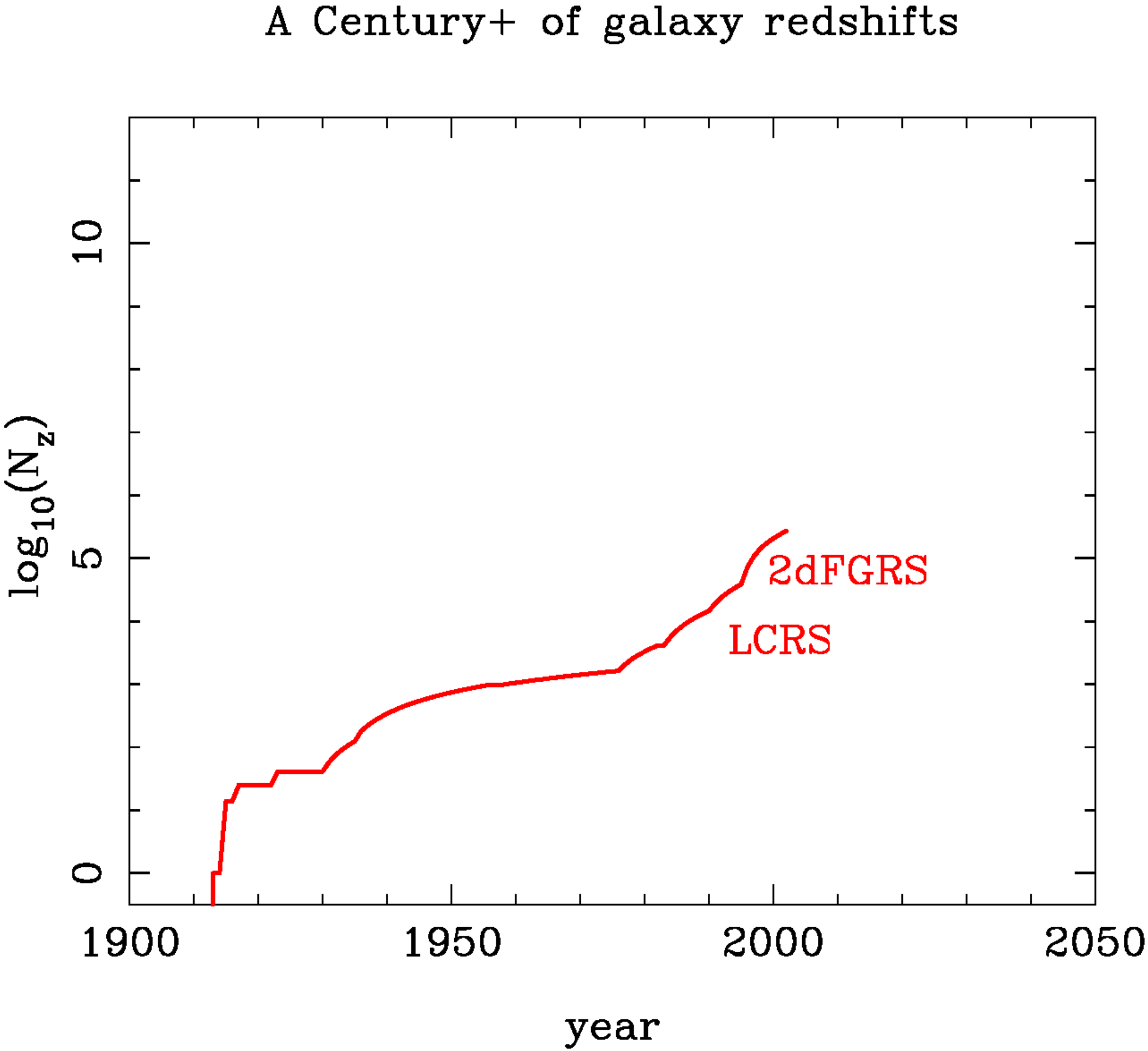
A Century+ of galaxy redshifts
log10(Nz)
10
5
0
1900
1950
2000
2050
year
Humason

A Century+ of galaxy redshifts

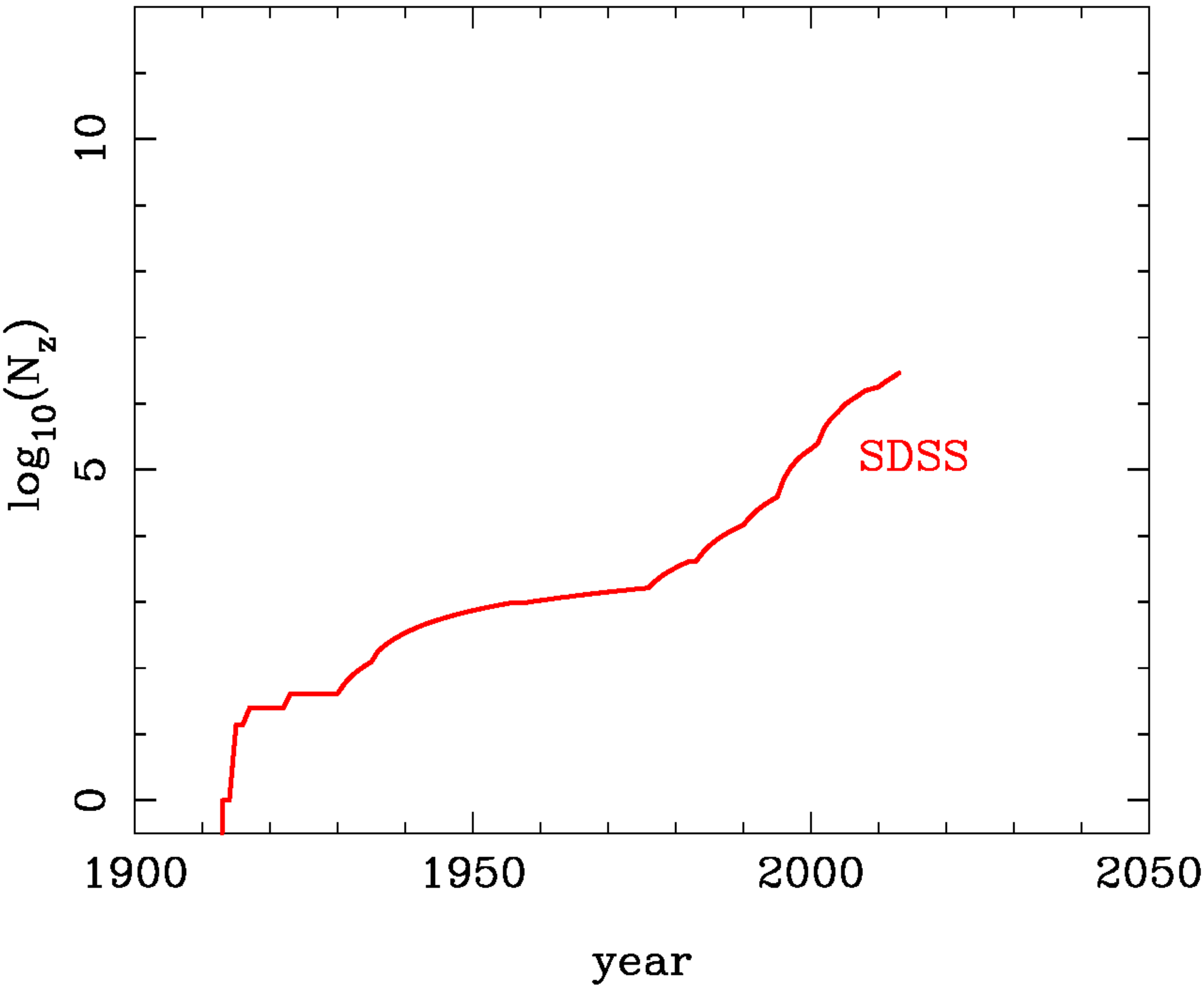


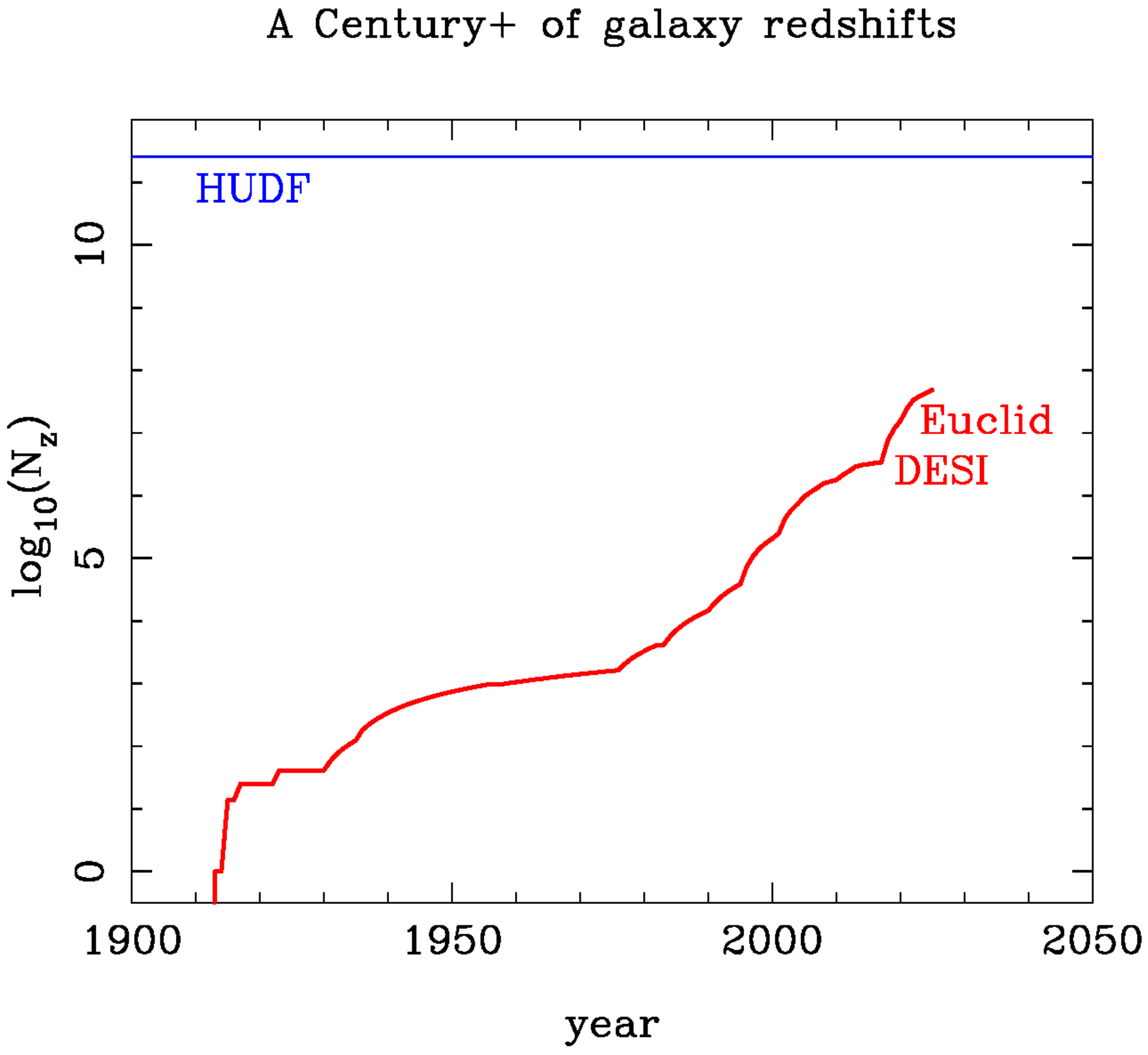
A Century+ of galaxy redshifts




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

A Century+ of galaxy redshifts




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

Fantasy facilities

- Fundamental cosmology wants ~ 10^4 deg^2 spectroscopy
  - Legacy and robustness demands good S/N
  - 4m inadequate: need 8m-10m telescope
  - Dedicated PFS equivalent needed: still room for VLT5

- Strong need for all-sky data − at least in imaging
  - New VST camera for southern Pan-STARRS?
  - VISTA/UKIRT could still do deeper 2MASS
  - Northern LSST?

- ALMA-style global collaboration needed