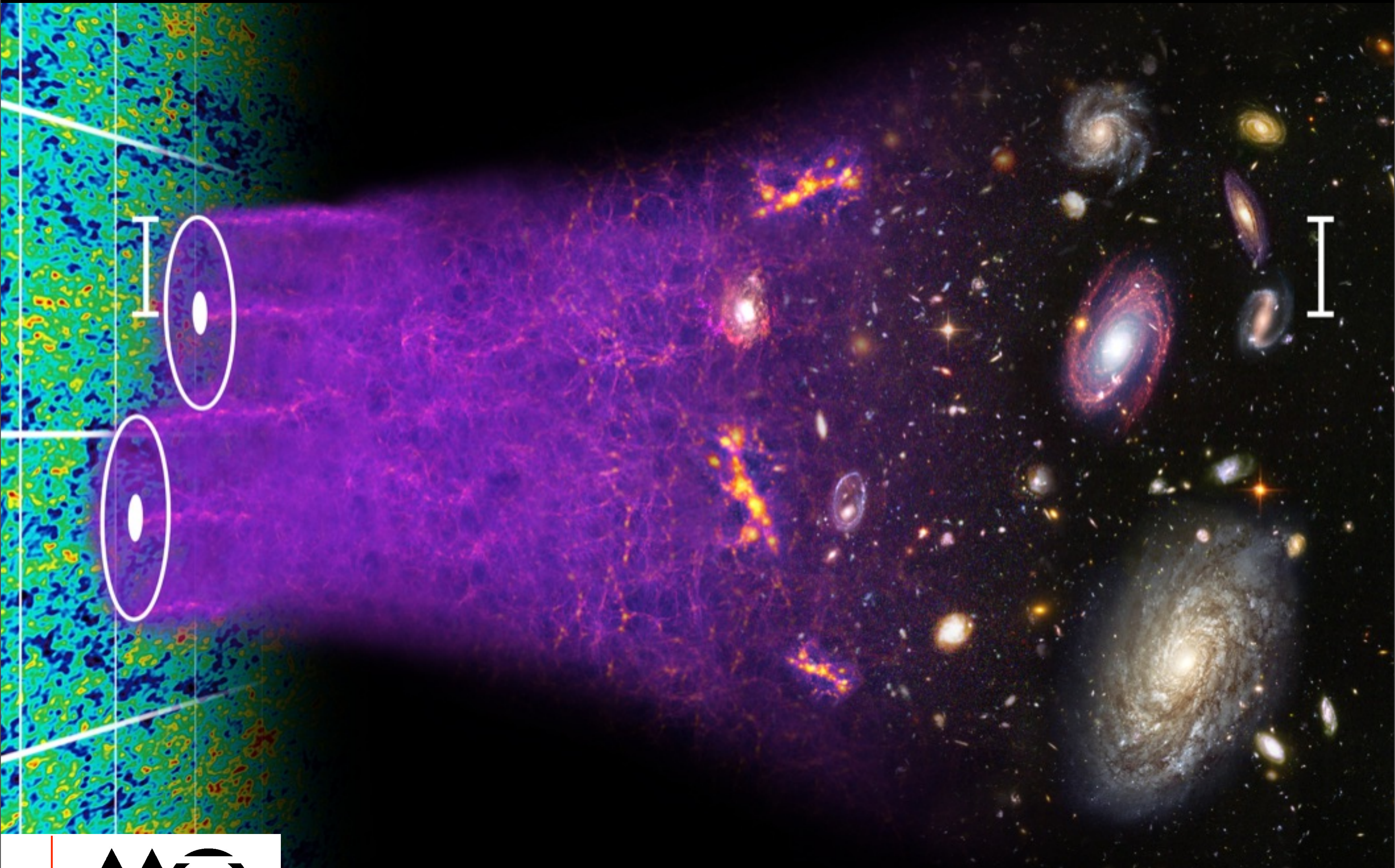
The WiggleZ Dark Energy Survey



Matthew Colless, KIAS Workshop, 27 Oct 2008

The WiggleZ team

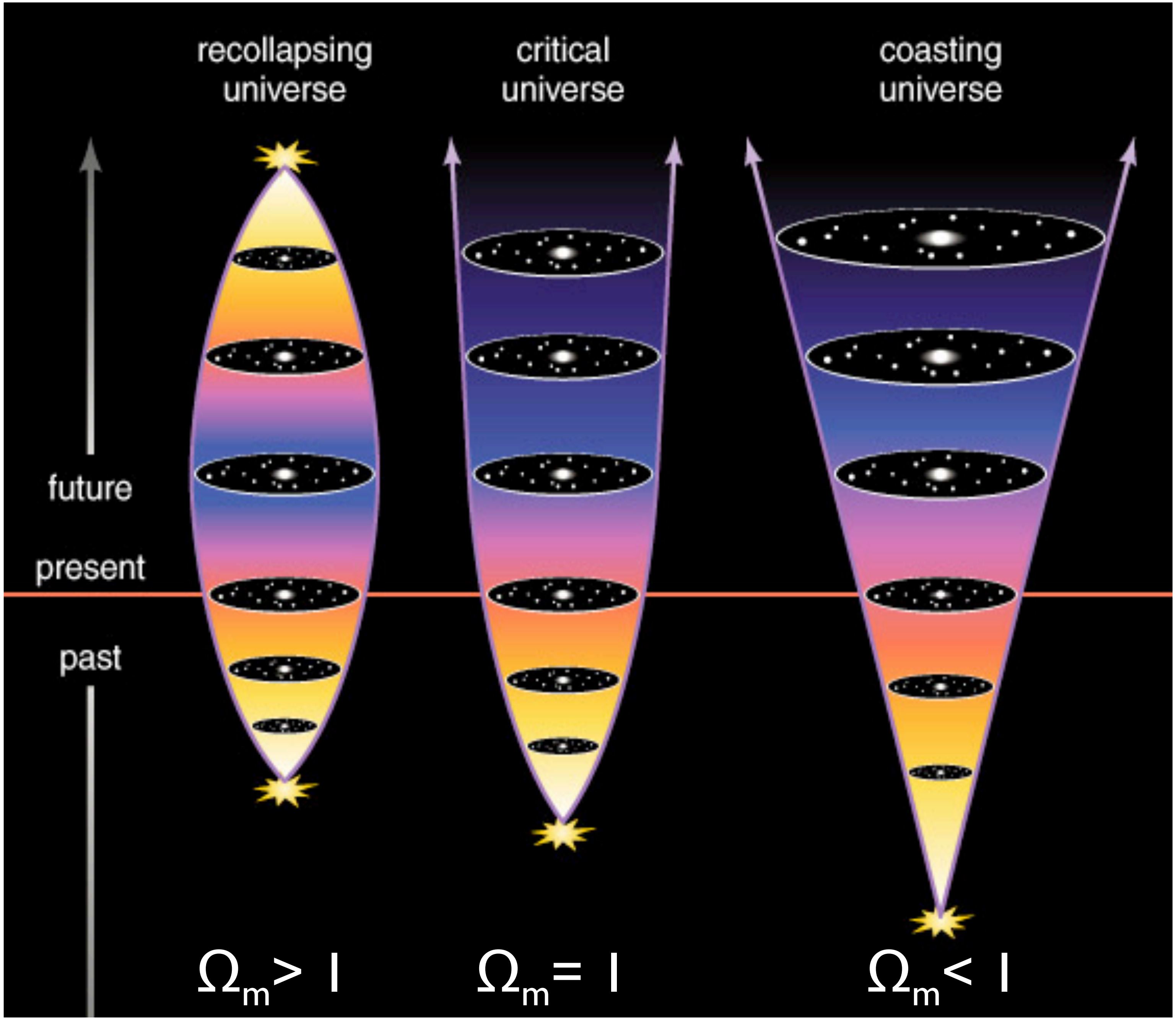
- Warrick Couch, Karl Glazebrook, Chris Blake, Sarah Brough, Greg Poole, Darren Croton (Swinburne U.)
- Michael Drinkwater, Russell Jurek, Kevin Pimbblet, Tamara Davis (U. Queensland)
- Matthew Colless, Rob Sharp (AAO)
- Scott Croom, Ben Jelliffe (U. Sydney)
- David Woods (UNSW)
- Mike Pracy (ANU)
- Chris Martin, Ted Wyder (Caltech)
- Barry Madore (Carnegie)
- *plus students and associate members*

What is dark energy?

- Concordance cosmology requires ‘dark energy’
  - Observations show a spatially flat, accelerating, low-density universe
  - This is consistent with cosmological constant/vacuum energy model with $\Omega_m \approx 0.25$, $\Omega_\Lambda \approx 0.75$
- This implies new physics - one of the “Key Science Questions for the New Century” (US National Academies, 2003)
- Cosmological constant problematic (natural scale 10^{122} larger)
- Many alternative dark energy or modified GR ‘explanations’...

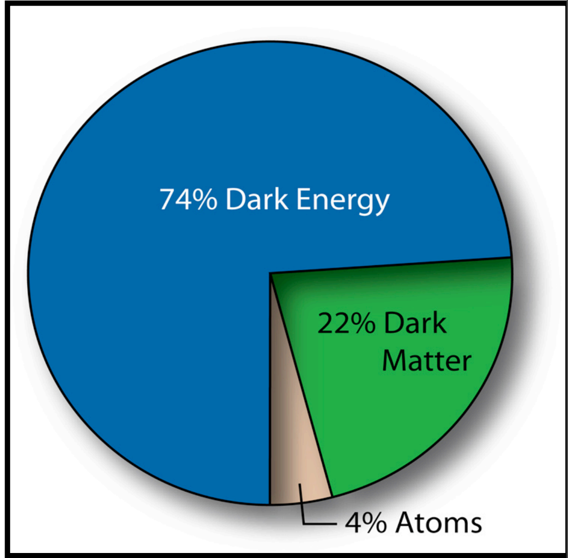
...tracker quintessence, single exp quintessence, double exp quintessence, pseudo-Nambu-Goldstone boson quintessence, holographic dark energy, cosmic strings, cosmic domain walls, axion-photon coupling, phantom dark energy, Cardassian model, brane cosmology (extra-dimensions), Van Der Waals quintessence, dilaton, generalized Chaplygin gas, quintessential inflation, unified dark matter and dark energy, superhorizon perturbations, ndulant universe, quiessence, general oscillatory models, Milne-Born-Infeld model, k-essence, chameleon, k-chameleon, f(R) gravity, perfect fluid dark energy, adiabatic matter creation, varying G, scalar-tensor gravity, double scalar field, scalar+spinor, quintom model, SO(1,1) scalar field, five-dimensional Ricci flat bouncing cosmology, scaling dark energy, radion, DGP gravity, Gauss-Bonnet gravity, tachyons, power-law expansion, phantom k-essence, vector dark energy, dilatonic ghost condensate dark energy, quintessential Maldacena-Maoz dark energy, superquintessence, vacuum-driven metamorphosis, wet dark fluid...

The universe: geometry & history



The contents of the universe set the evolution of its geometry:

- dark matter
- baryons
- neutrinos
- photons
- dark energy



Dark energy equation of state

- The dark energy equation of state relates the pressure to the density: $P = w(z)\,\rho$
- For w(z) constant: $\rho(z) \propto (1+z)^{3(w+1)}$
  - $w_m = 0 \Rightarrow \rho \propto V^{-1}$; $w_r = 1/3 \Rightarrow \rho \propto V^{-4/3}$; $w_\Lambda = -1 \Rightarrow \rho \propto V^0$
- For w(z) varying with redshift:

$$\rho(z) \propto (1+z)^3 \exp\left[3\int_0^z w(z')\frac{dz'}{1+z'}\right]$$

  - Quintessence: $w(z) = -1/3$ to -1; phantom energy: $w(z) < -1$
- The equation of state thus determines the geometry and evolution of the universe:

$$H(z)^2 = \frac{8\pi G}{3}\rho(z) - Kc^2(1+z)^2 \qquad D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz'}{H(z')}$$

Probes of the equation of state

- Standard rulers (e.g. BAO) probe $D_A(z)$ transverse to the line of sight and $H(z)$ radially along the line of sight

$$H(z) = \frac{c\Delta z}{L(rod)_{comov}}$$

- Standard candles (e.g. SNe) probe $D_L(z) = D_A(z)(1+z)^2$
- Age measurements probe look-back time

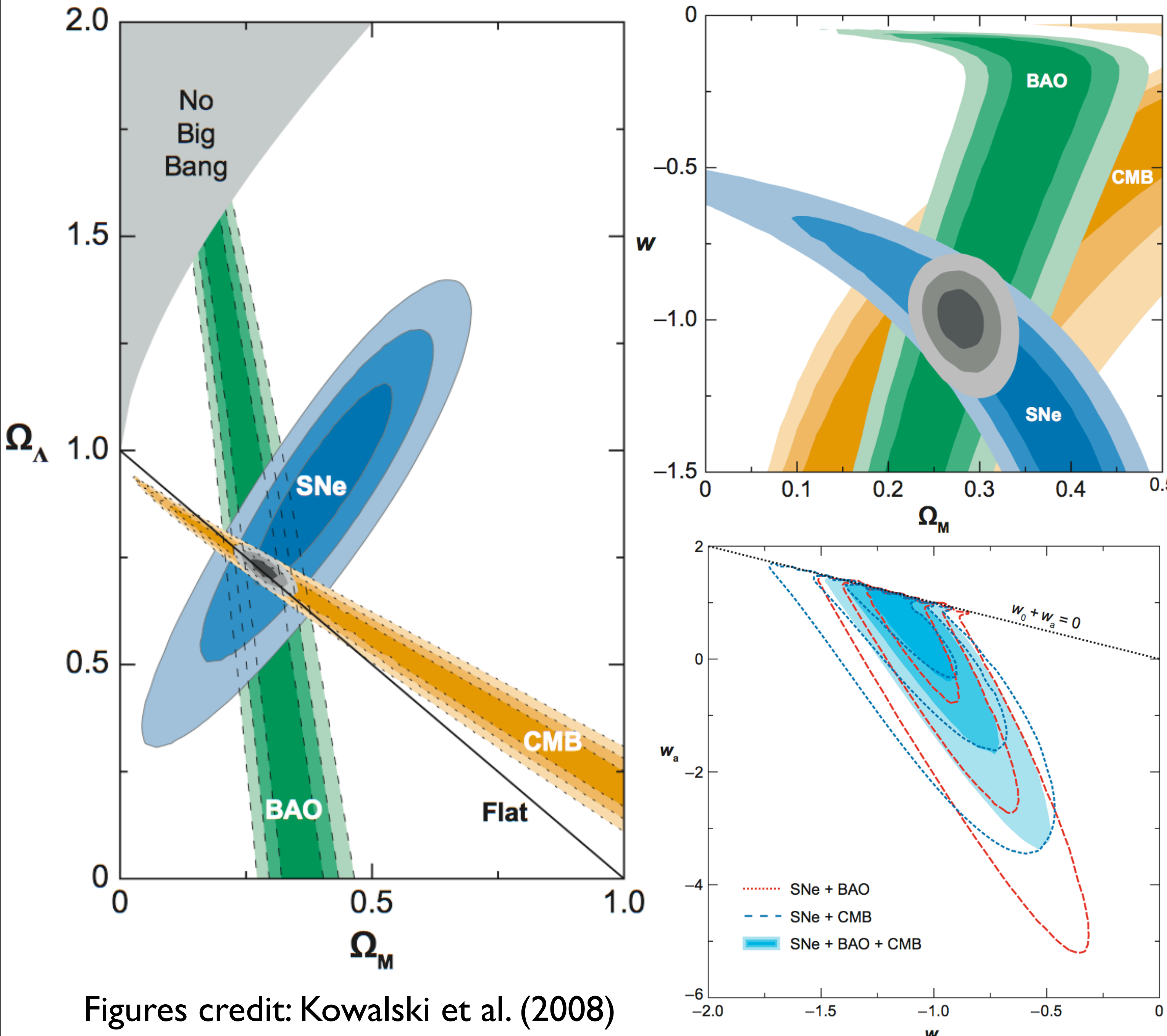
$$t(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')}$$

- Clustering measurements probe growth of structures

$$\ddot{D}_1 + 2H(z)\dot{D}_1 - \frac{3}{2}\Omega_m H_0^2 (1+z)^3 D_1 = 0$$

- Alcock-Paczynski effect probes $H(z)D_A(z)$

Current constraints



Figures credit: Kowalski et al. (2008)

Assuming zero curvature (i.e. Ω_0=1) and w(z) constant, the constraints are:

- $\Omega_\Lambda \approx 0.75 \pm 0.02$
- $\Omega_m \approx 0.25 \pm 0.02$
- $w \approx -1.0 \pm 0.1$

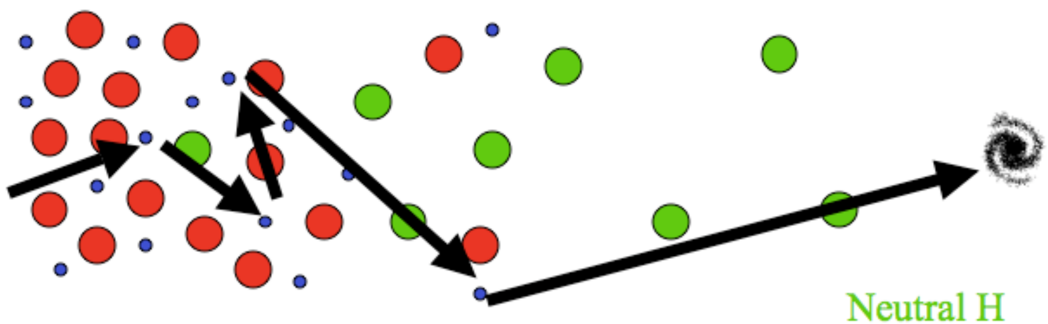
Allowing curvature as a free parameter:

- $\Omega_0 \approx 1.0 \pm 0.02$
- $w \approx -1.0 \pm 0.1$

Allowing w(z) to vary, $w=w_0+(1-a)w_a$, the constraints are:

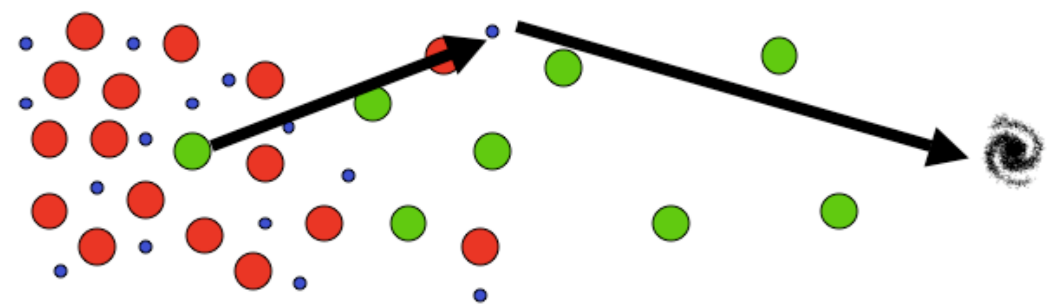
- $w_0 \approx -1.0 \pm 0.2$
- $w_a \approx 0 \pm 1$

Baryon Acoustic Oscillations - 1



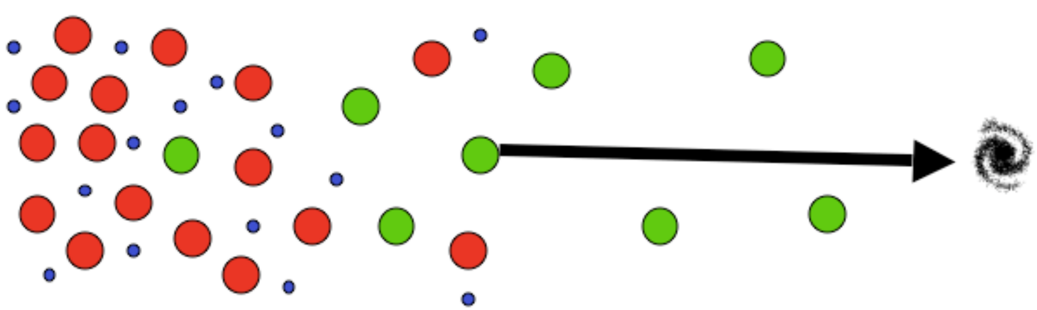
Photon emitted at z=2000

Before recombination, universe is opaque, so photons & baryons couple; interplay of gravity (DM, baryons) and photon pressure
⇒ acoustic waves propagate



Photon emitted at z=1200

At recombination, photons scatter for the last time (‘surface of last scattering’)



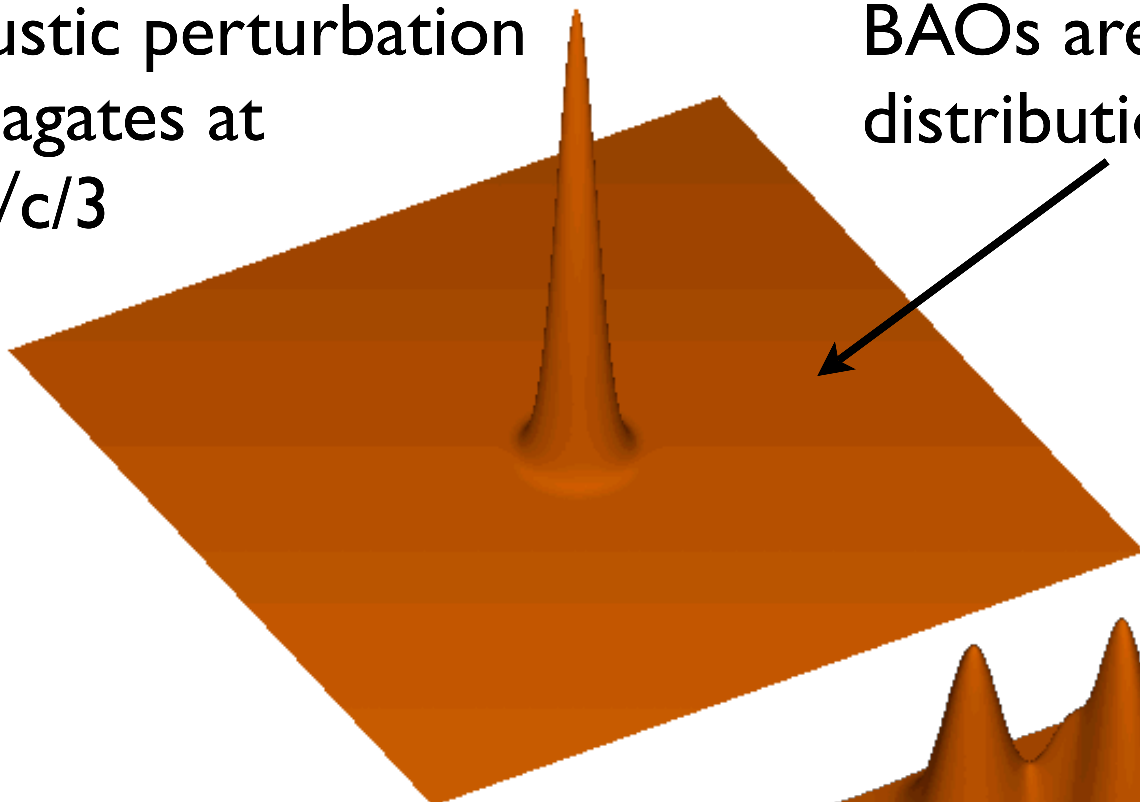
Photon emitted at z=1000

After recombination, the universe is transparent, so photons can stream freely
⇒ acoustic waves frozen

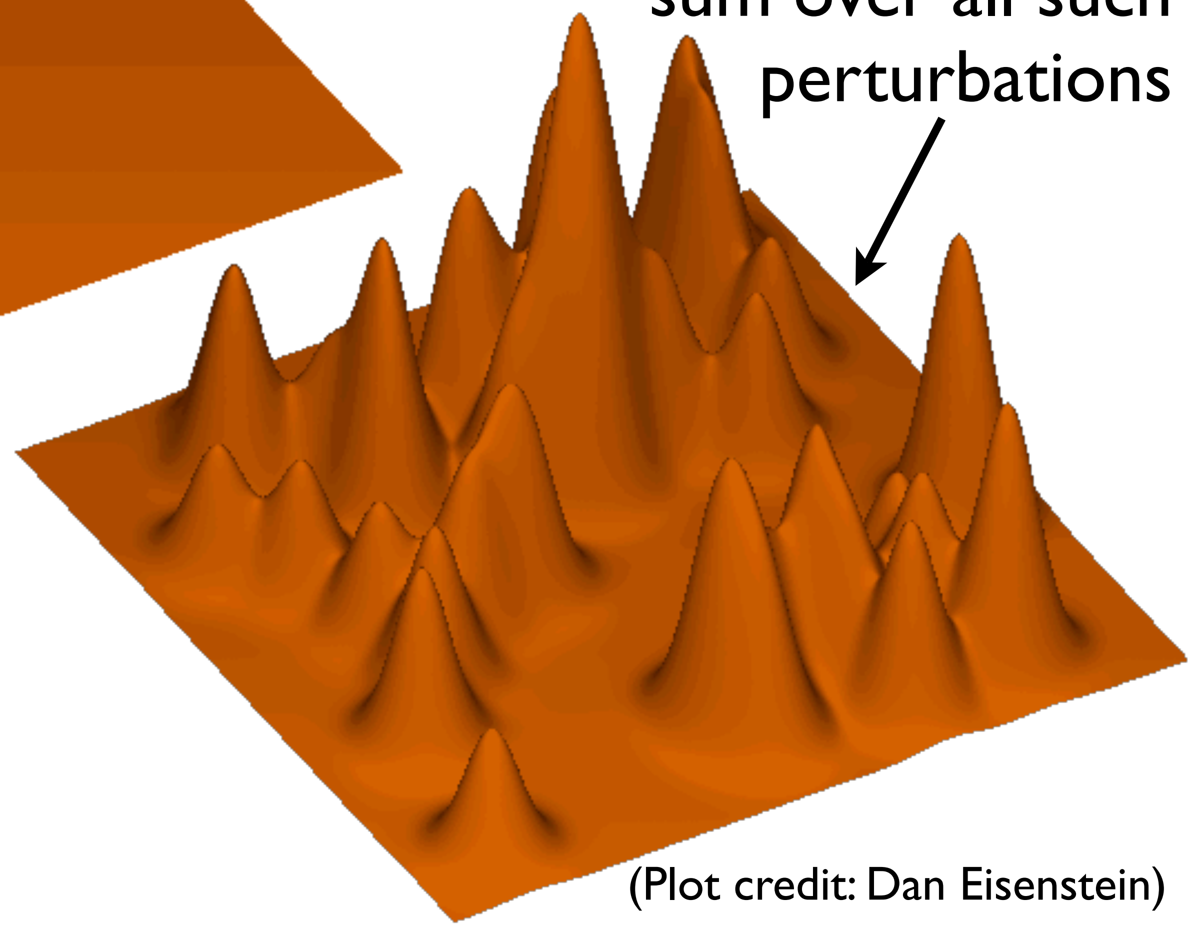
Baryon Acoustic Oscillations - 2

Acoustic perturbation propagates at $v_s \approx \sqrt{c/3}$

BAOs are frozen into matter distribution at $t \approx t_{rec}$



Final distribution is sum over all such perturbations

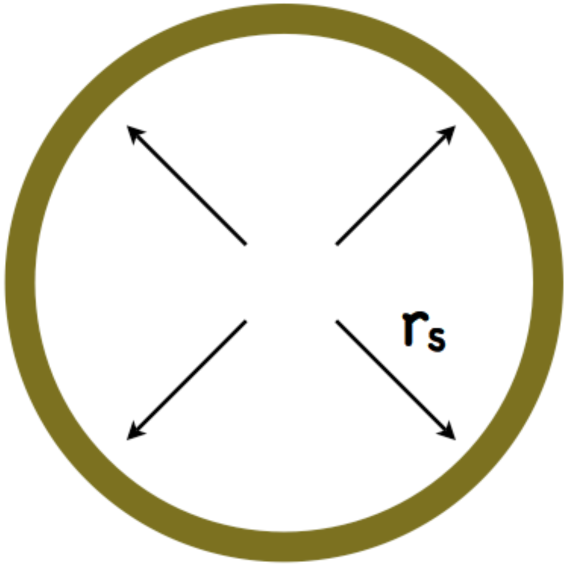


BAO scale is $r_s \approx v_s t_{rec}$ = 150 Mpc (co-moving)

$$= \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_r} \frac{c_s}{(a + a_{eq})^{1/2}} da$$

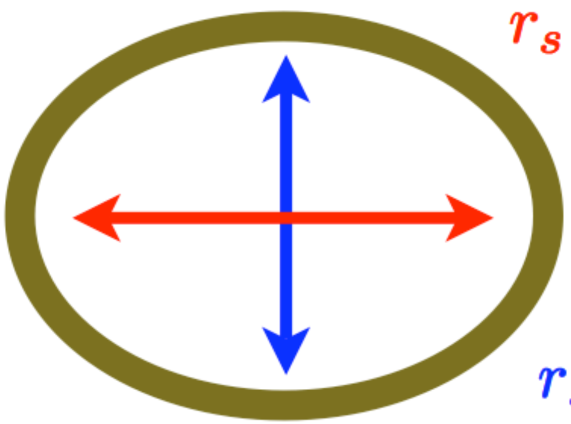
(Plot credit: Dan Eisenstein)

BAOs and geometry



- In rest-frame the BAO feature is spherical with scale r_s=150 Mpc

- Observed at redshift z, however, the apparent transverse and radial scales differ:



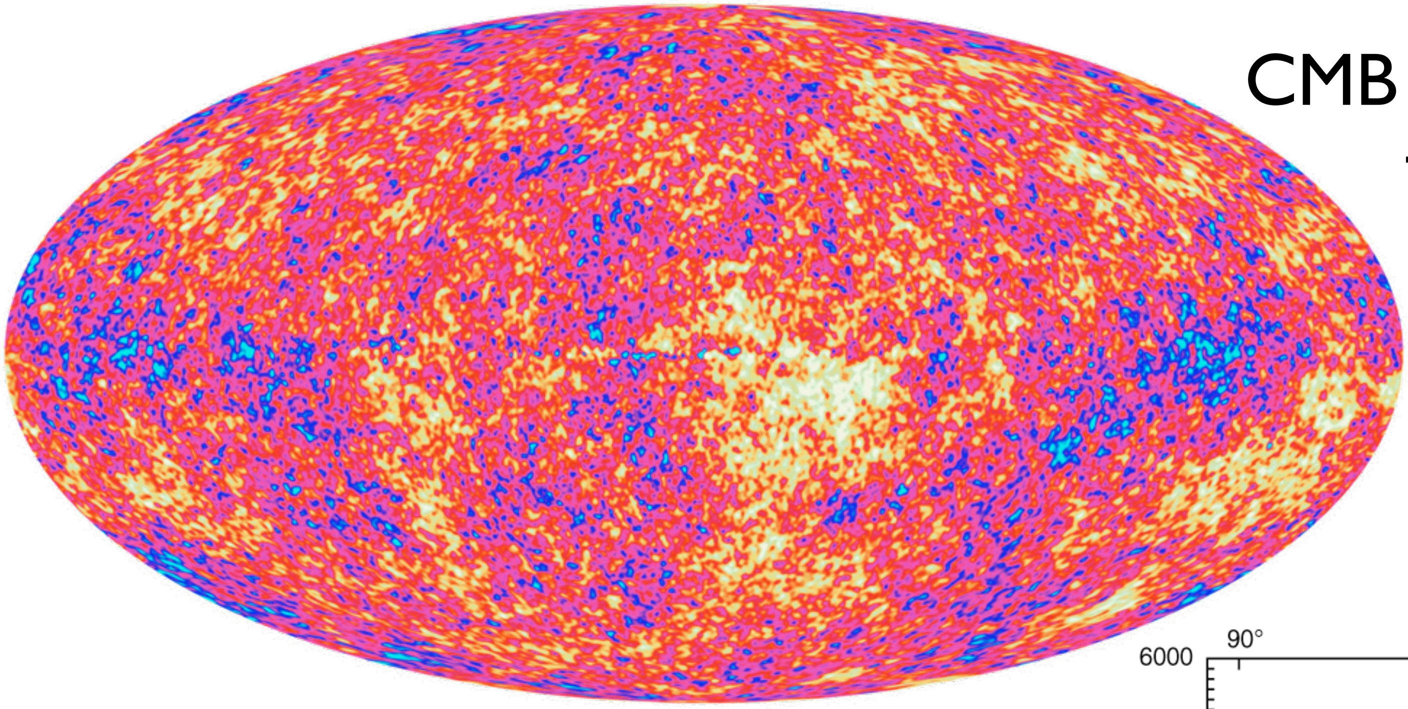
$$r_s = D_A(z)\,\Delta\theta$$

$$r_s = \frac{c}{H(z)}\Delta z$$

$$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz'}{H(z')}$$

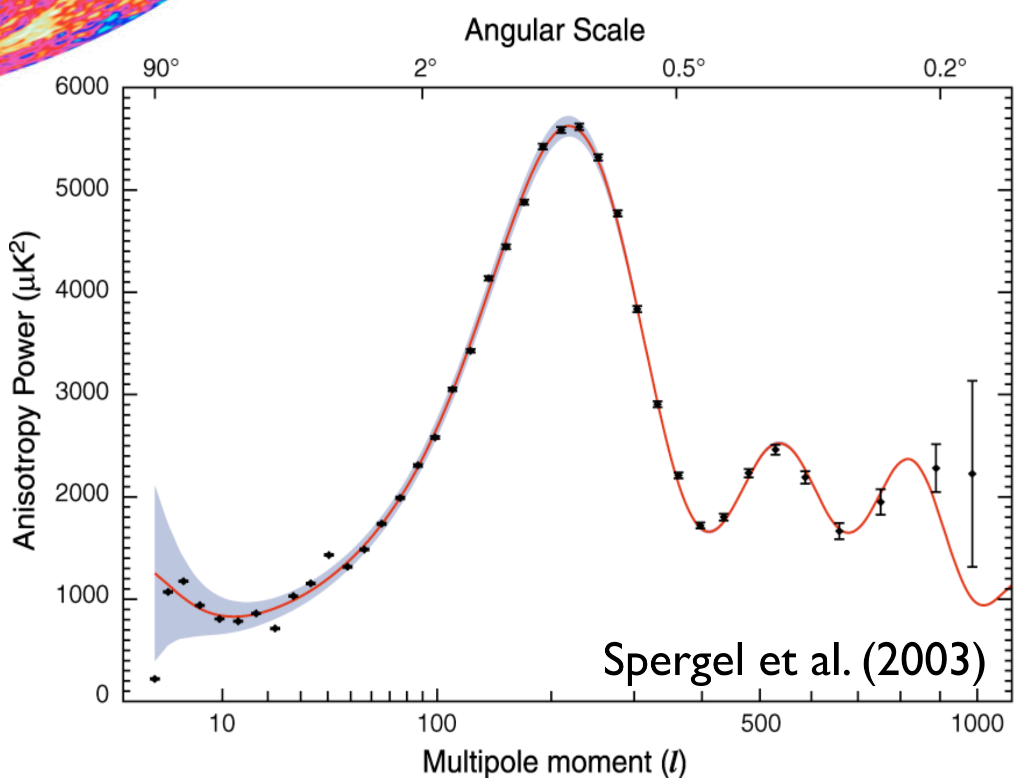
$$H(z)^2 = \frac{8\pi G}{3}\rho(z) - Kc^2(1+z)^2$$

Measuring BAOs - 1



CMB anisotropies from WMAP

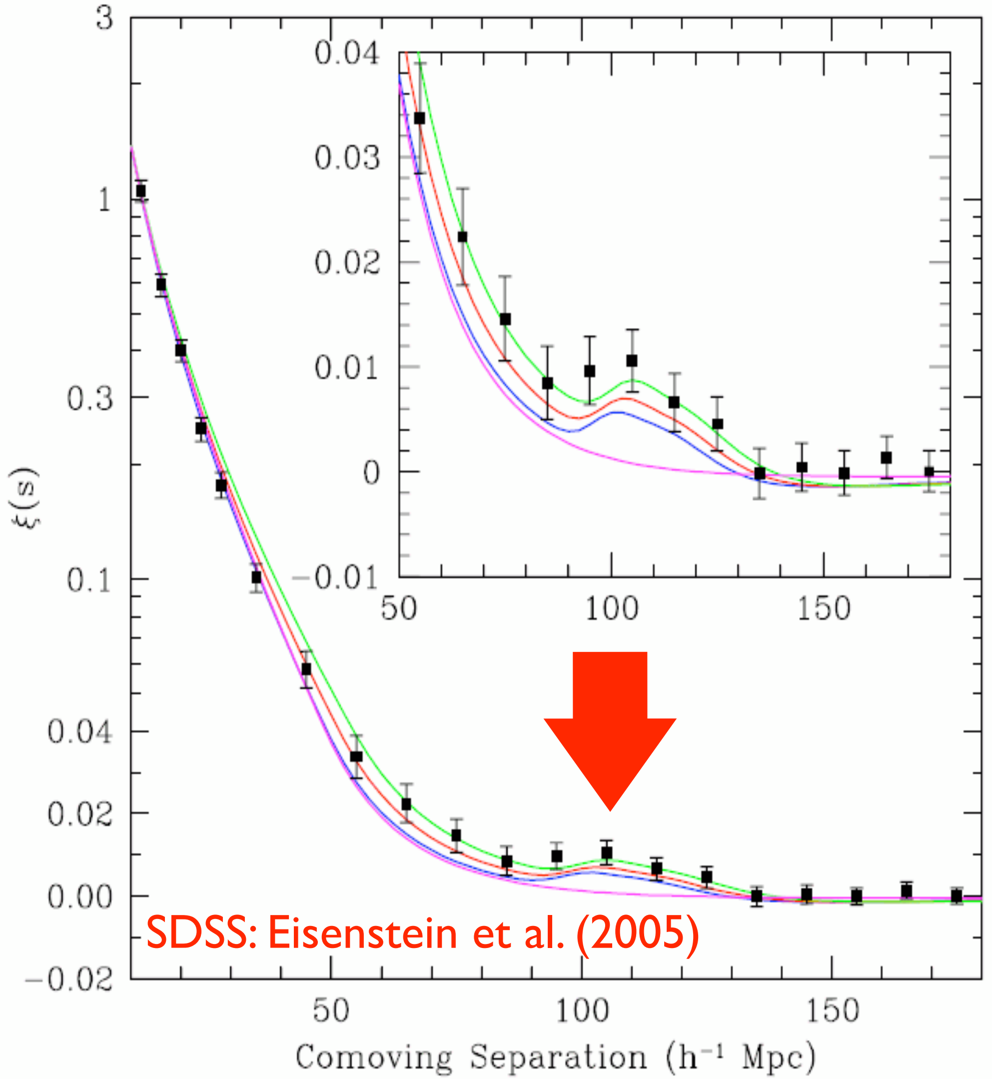
CMB power spectrum gives a very precise measurement of the BAO scale at z=1100: r_s = 147 ± 2 Mpc

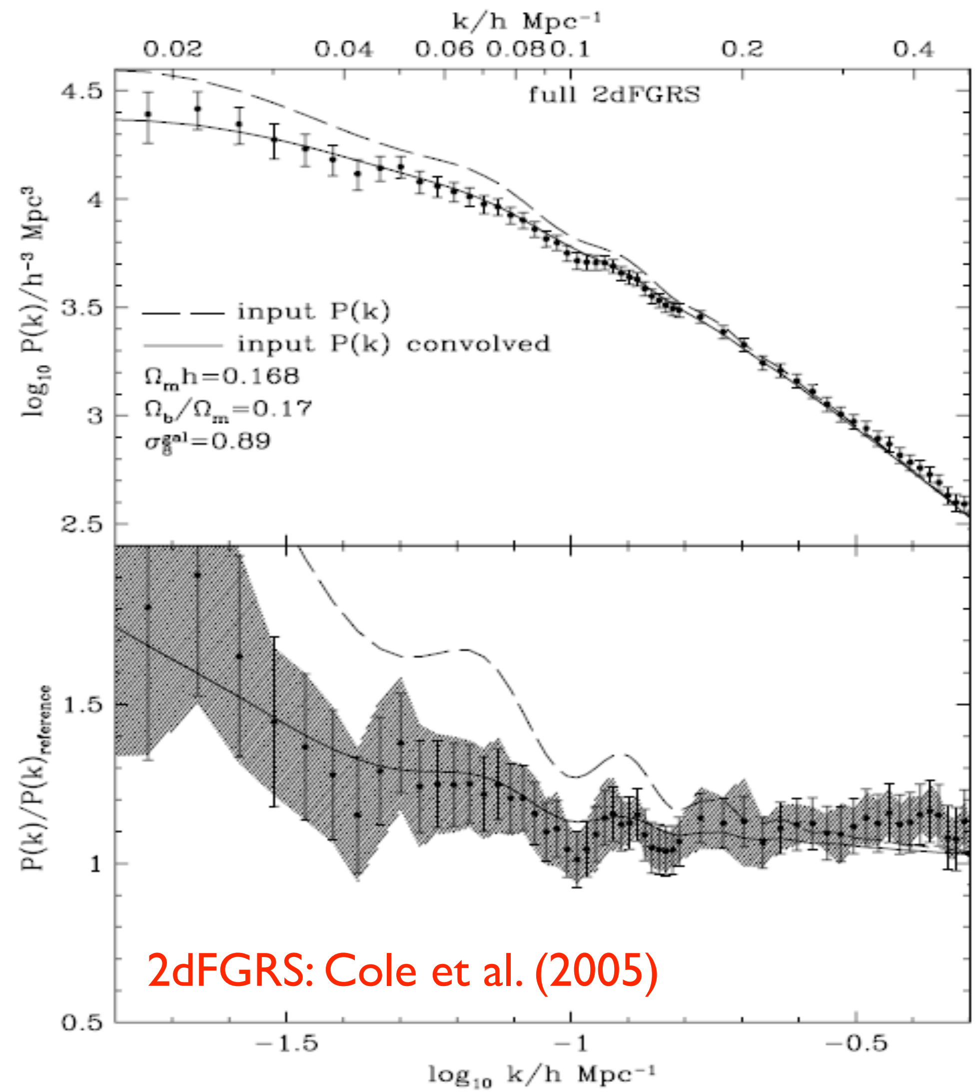


Spergel et al. (2003)

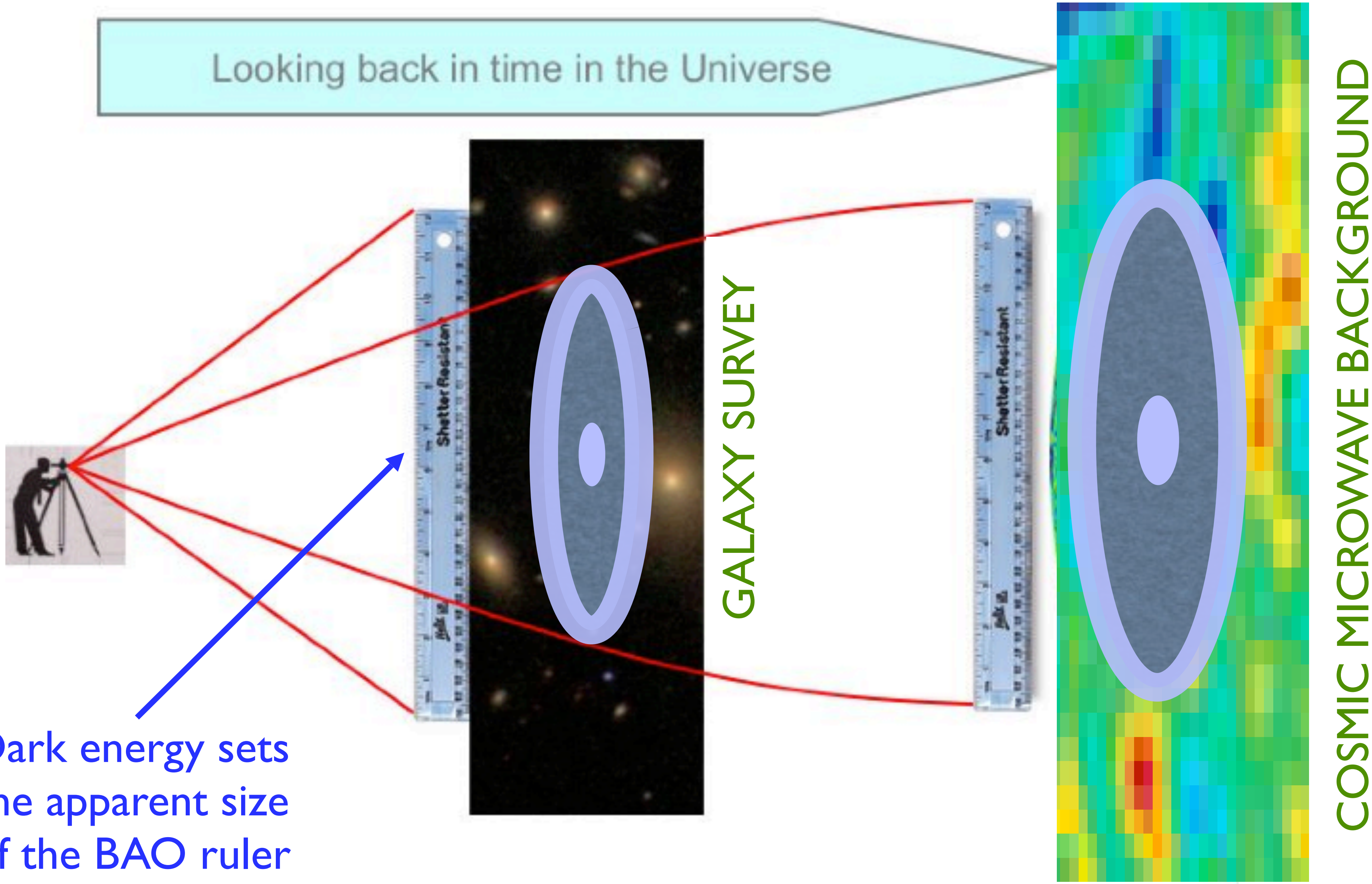
Measuring BAOs - 2

Galaxy surveys can measure 3D structure and determine the BAO scale over a wide range in redshift





A cosmic standard measuring rod



Dark energy sets the apparent size of the BAO ruler

Advantages of BAO surveys

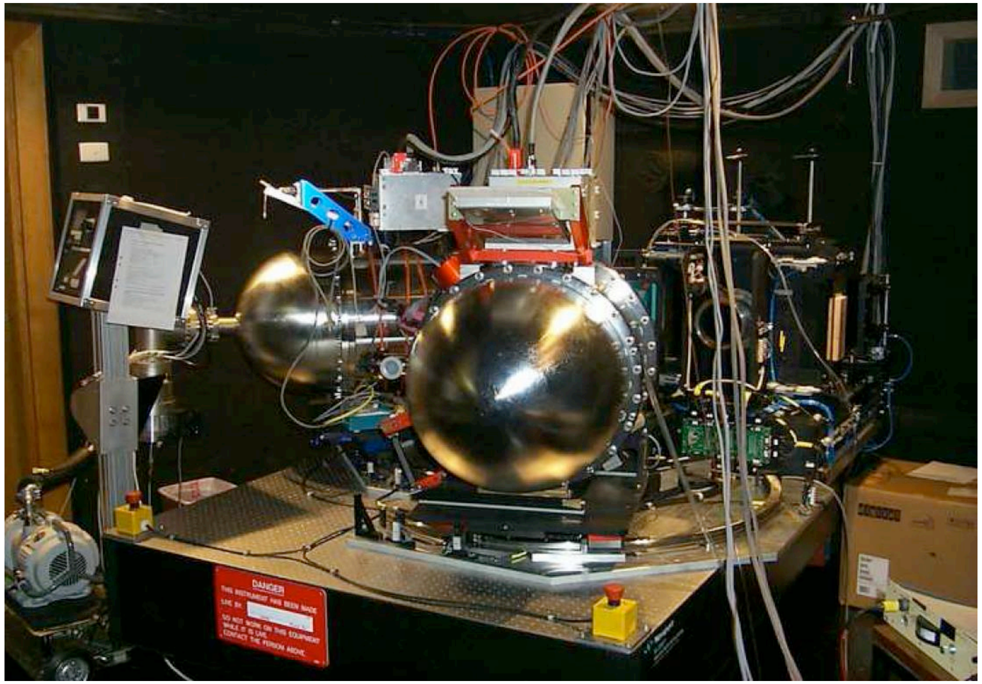
- Cosmic absolute standard rule calibrated by CMB...
  - well-understood linear physics; depends only on ρ_m & ρ_b
  - CMB calibration at z=1100 (breaks curvature-w degeneracy)
- Can in principle obtain ~1% distances over wide range of redshifts, so a potent probe of dark energy...
  - can measure H(z) radially and $D_A(z)$ tangentially
  - but requires large samples: ~10^6 galaxies over ~1 Gpc^3
- Complementary to other dark energy probes...
  - measures different cosmological properties
  - has different physical basis and different systematics...
    - clustering is non-linear on small scales (less so at higher z)
    - redshift-space distortions of the clustering pattern
    - possible scale-dependent bias of galaxies w.r.t. dark matter

The WiggleZ survey

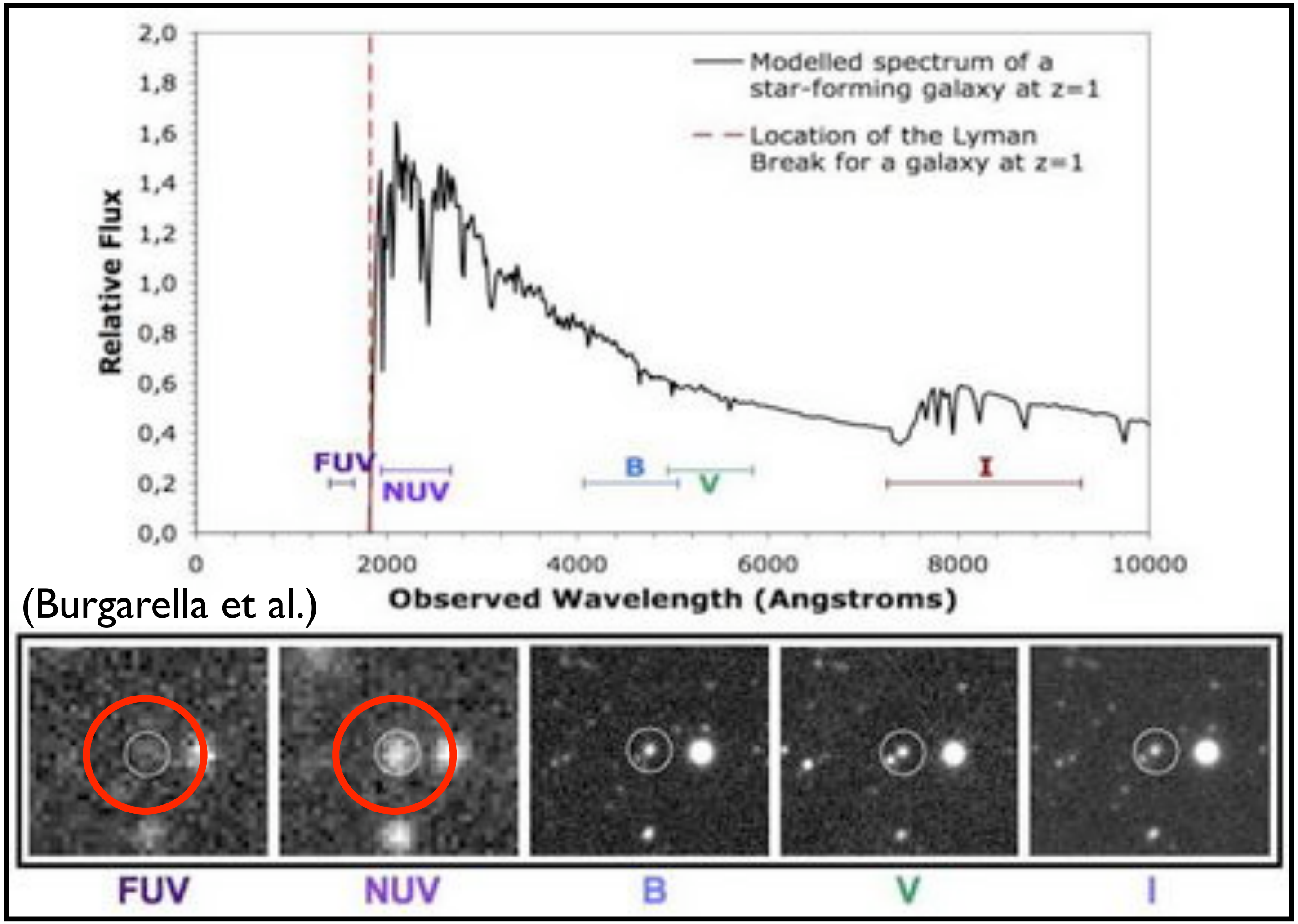
- Project goals:
  - to be the first high-z ($z>0.5$) BAO survey to measure $w(z)$
  - to survey ~240,000 galaxies with median redshift $z\sim0.6$
  - to measure BAO scale to 2% and test $w_0=-1$ over $z\sim0.3$-0.9
- Survey observations and sample:
  - Star-forming galaxies from GALEX (UV) & SDSS/RCS2 (opt)
  - FUV vs NUV colour selects 'Lyman-break' galaxies at $z>0.5$
  - Sample covers ~1000 deg^2 on sky and a volume of ~1 Gpc^3
- Status and results:
  - About 50% complete; finish observations in early 2010
  - Some early results plus forecasts for the completed survey

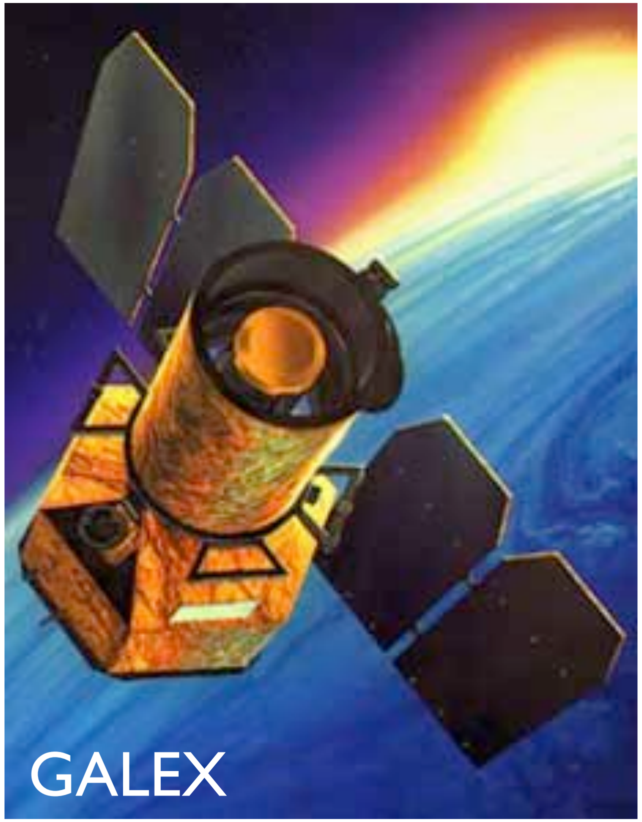
AAOmega spectrograph

- AAT + 2dF + AAOmega
  - AAOmega peak thruput 21%
  - LBGs at z~1 in 1 hour!



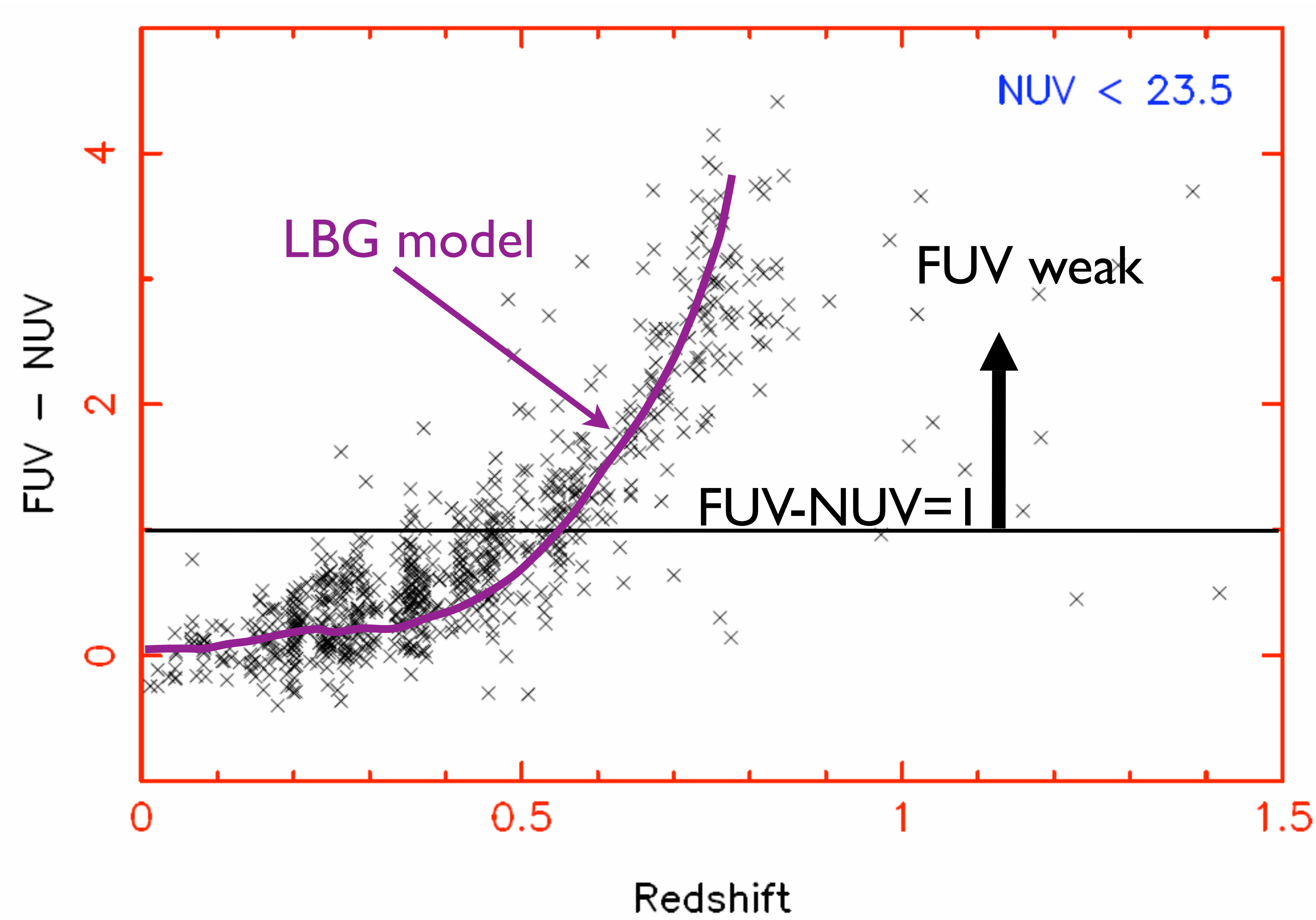
WiggleZ sample selection - 1





- Below the Lyman break at 912Å, hydrogen absorbs the galaxy light
- Corresponds to ~1400-1800Å at z~0.5-1 ⇒ FUV-NUV drop-outs

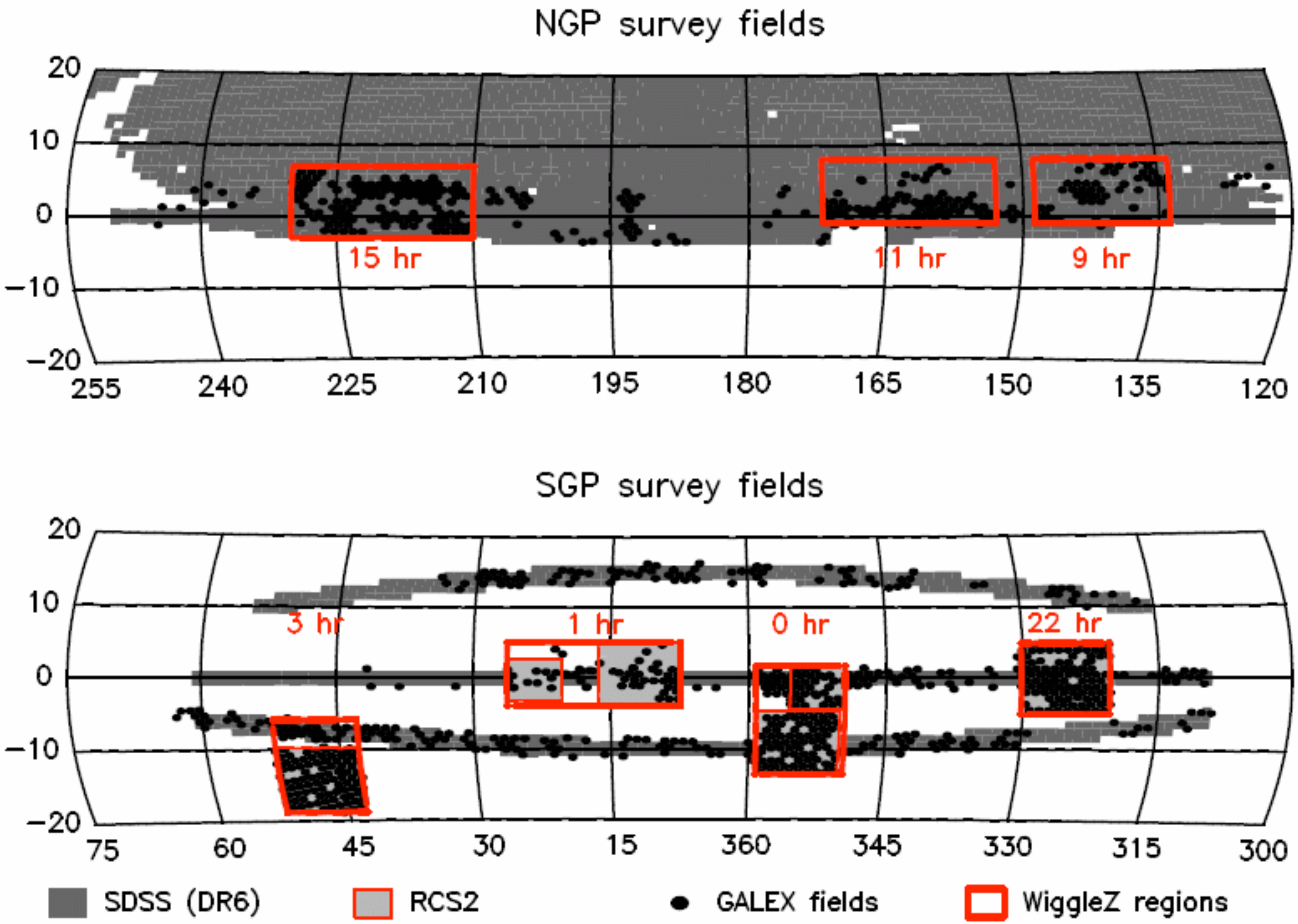
WiggleZ sample selection - 2



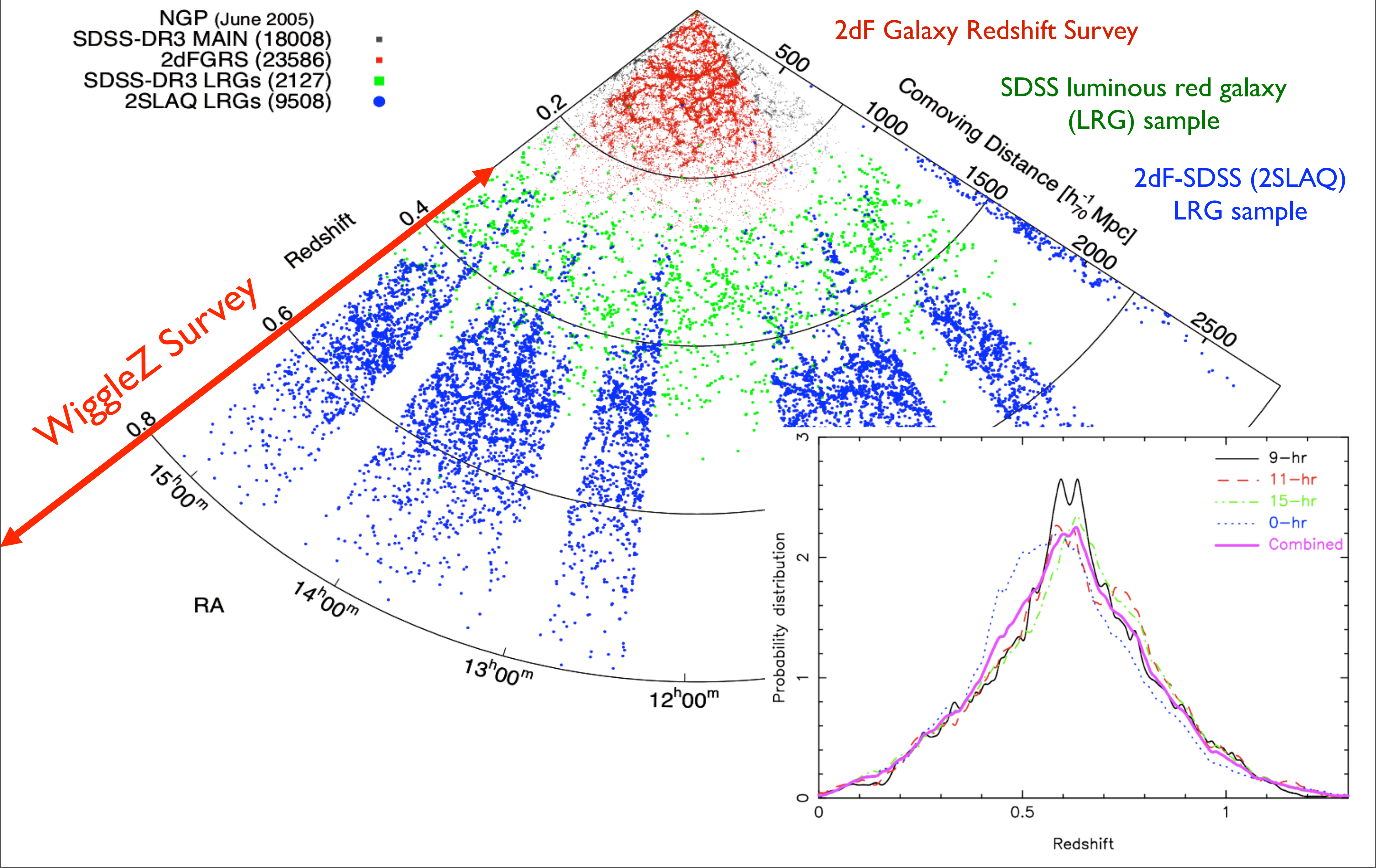
WiggleZ vital statistics

Survey parameter	Target	Current
Sky coverage	1000 deg^2	450 deg^2
Number of nights	220	112
Good weather fraction	0.75	0.65
Number of WiggleZ spectra	340,000	180,000
Number of WiggleZ good z's	240,000	97,000
WiggleZ redshift completeness	0.70	0.69
Number of AAT pointings	1200	551
Number of GALEX orbits	1250	787
Duration of survey	Aug 2006 – Jul 2010	

WiggleZ sky coverage

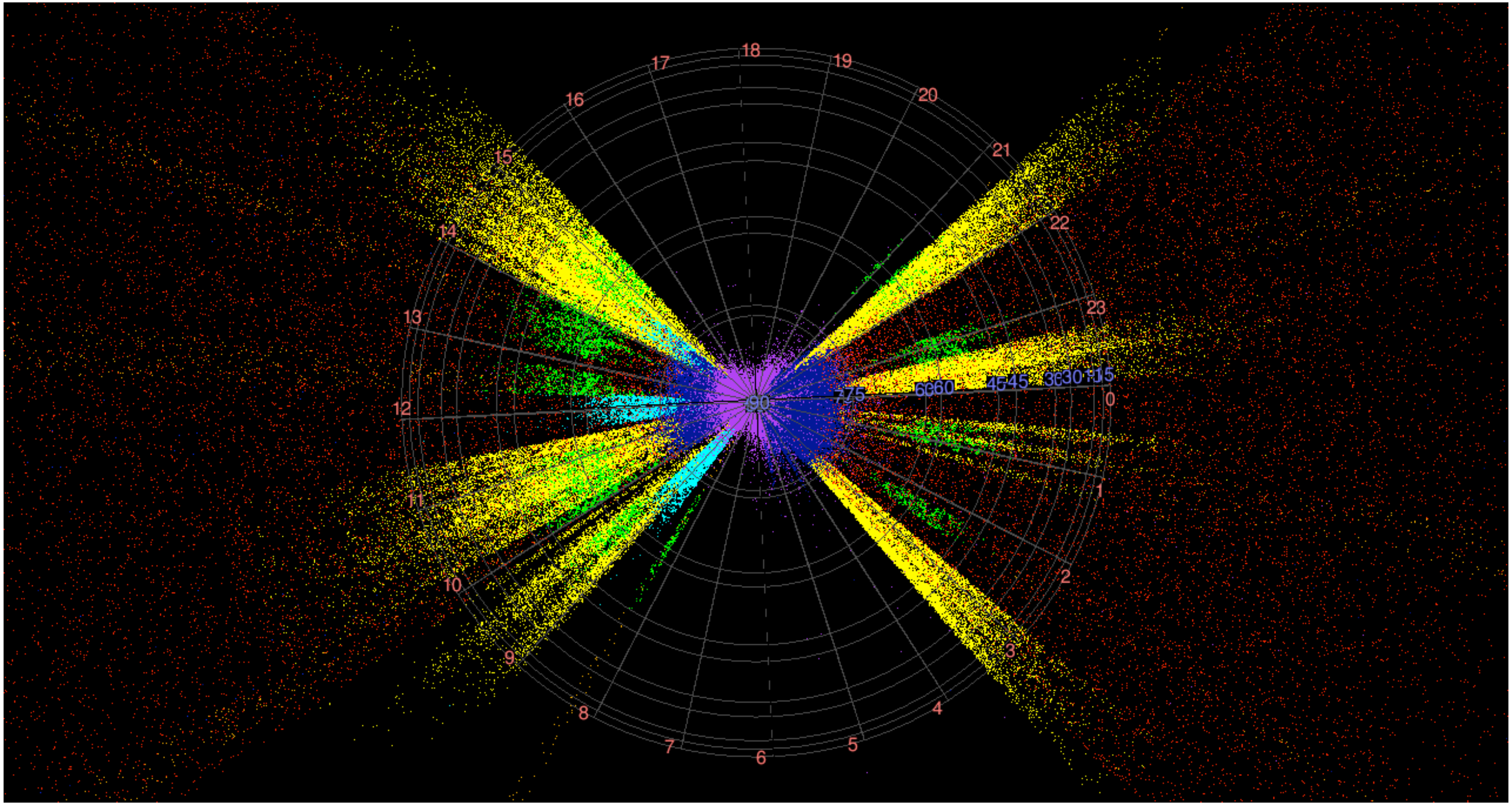


WiggleZ redshift coverage



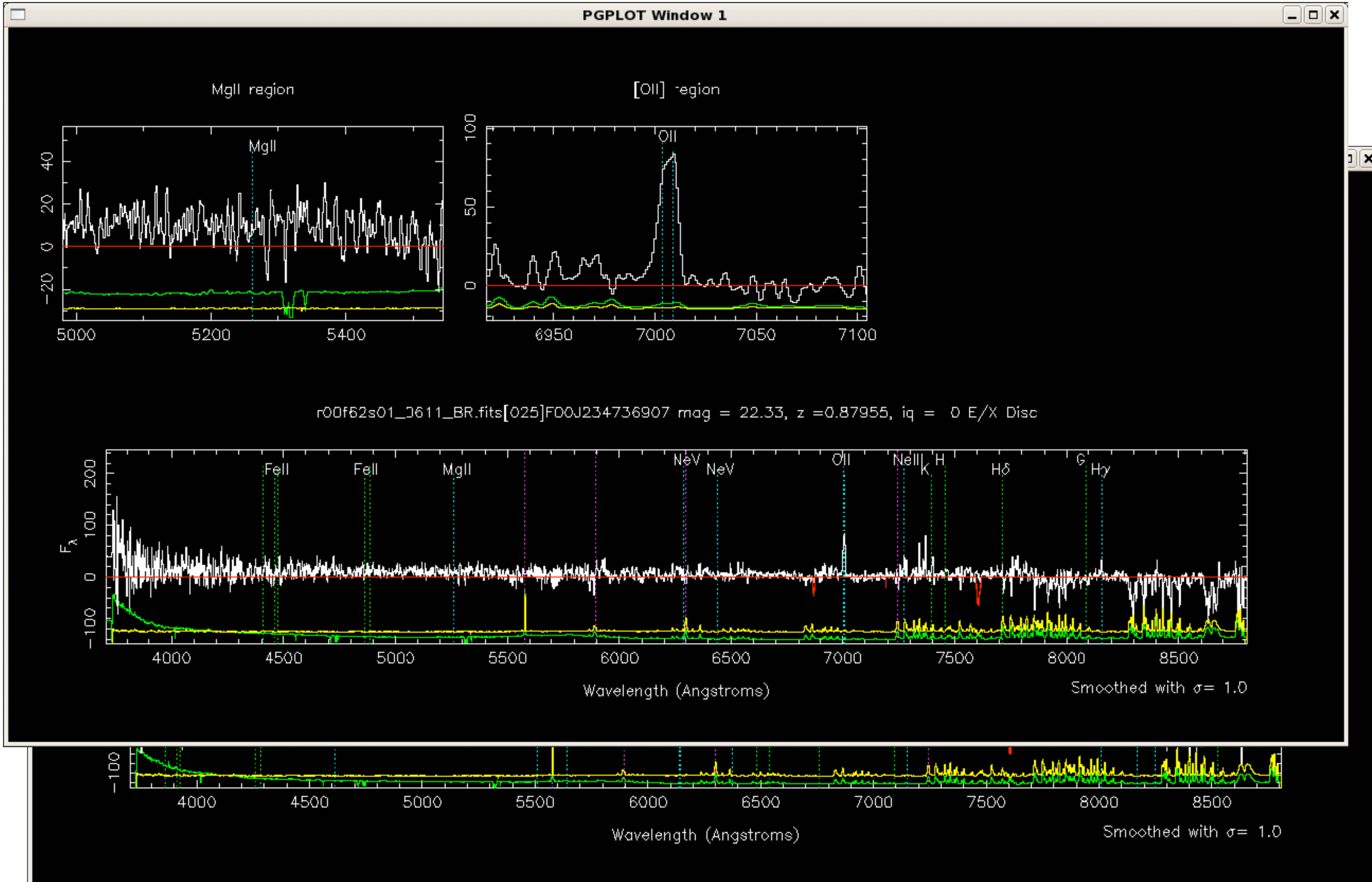
AAO redshift surveys

- AAT & UKST have measured 550,000 z's (36% of 1,500,000 known z's)
- Ongoing AAOmega surveys (WiggleZ & GAMA) rapidly measuring more



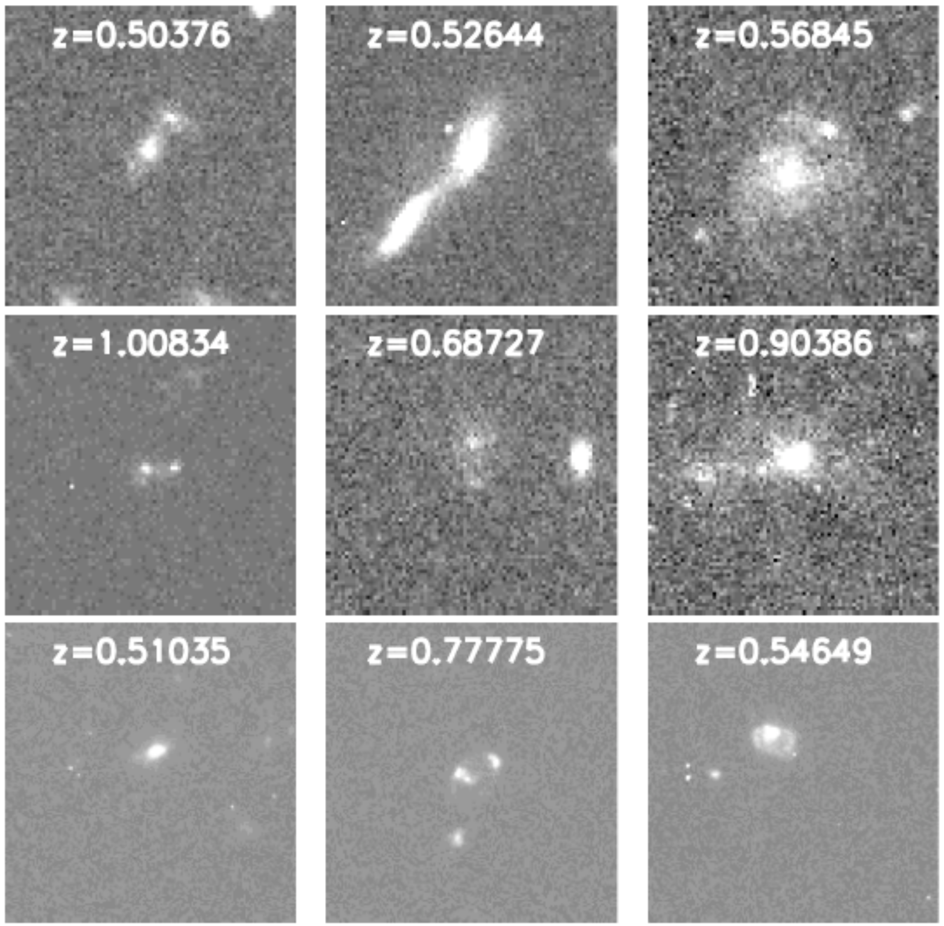
AAT & UKST redshift surveys: 6dFGS (purple), 2dFGRS (blue), MGC (darkblue), GAMA (cyan), 2SLAQ-LRG (green), WiggleZ (yellow), 2SLAQ-QSO (orange), 2QZ (red); the celestial sphere is at z=1.0.

WiggleZ spectra



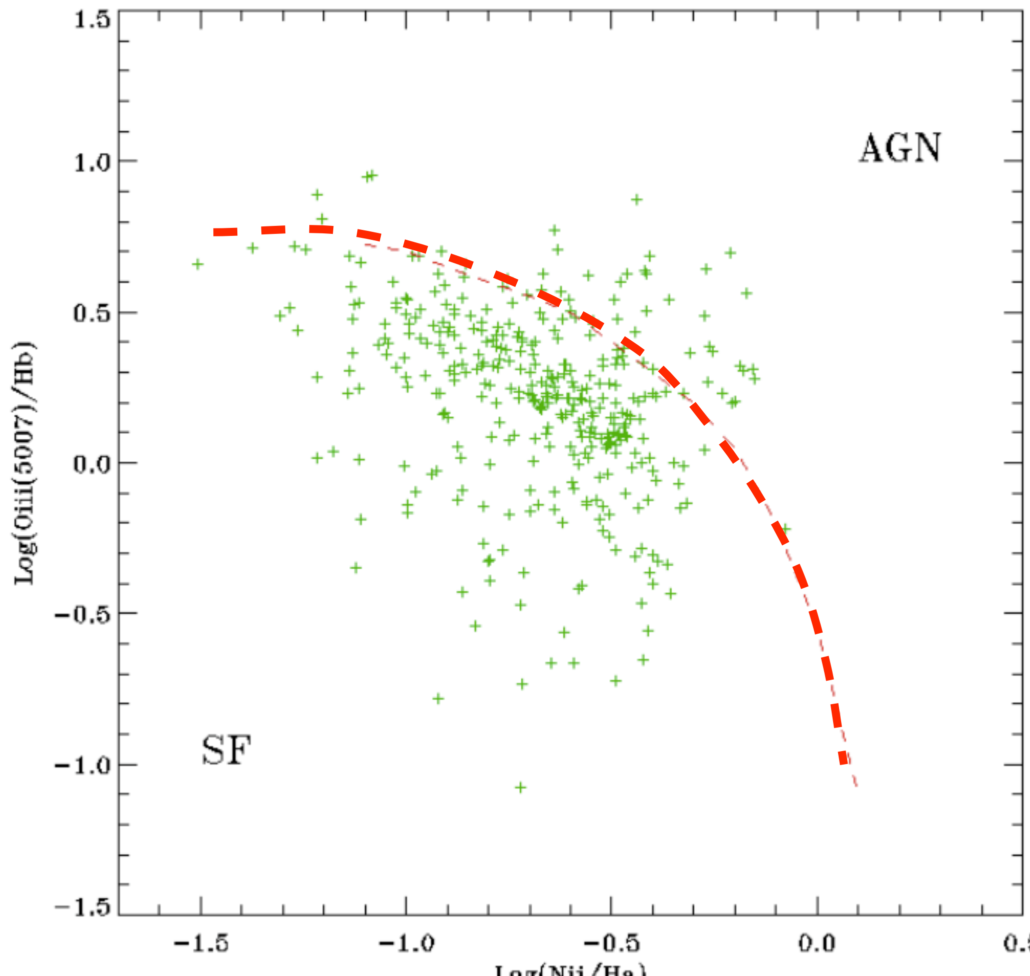
WiggleZ galaxies

HST archive images...



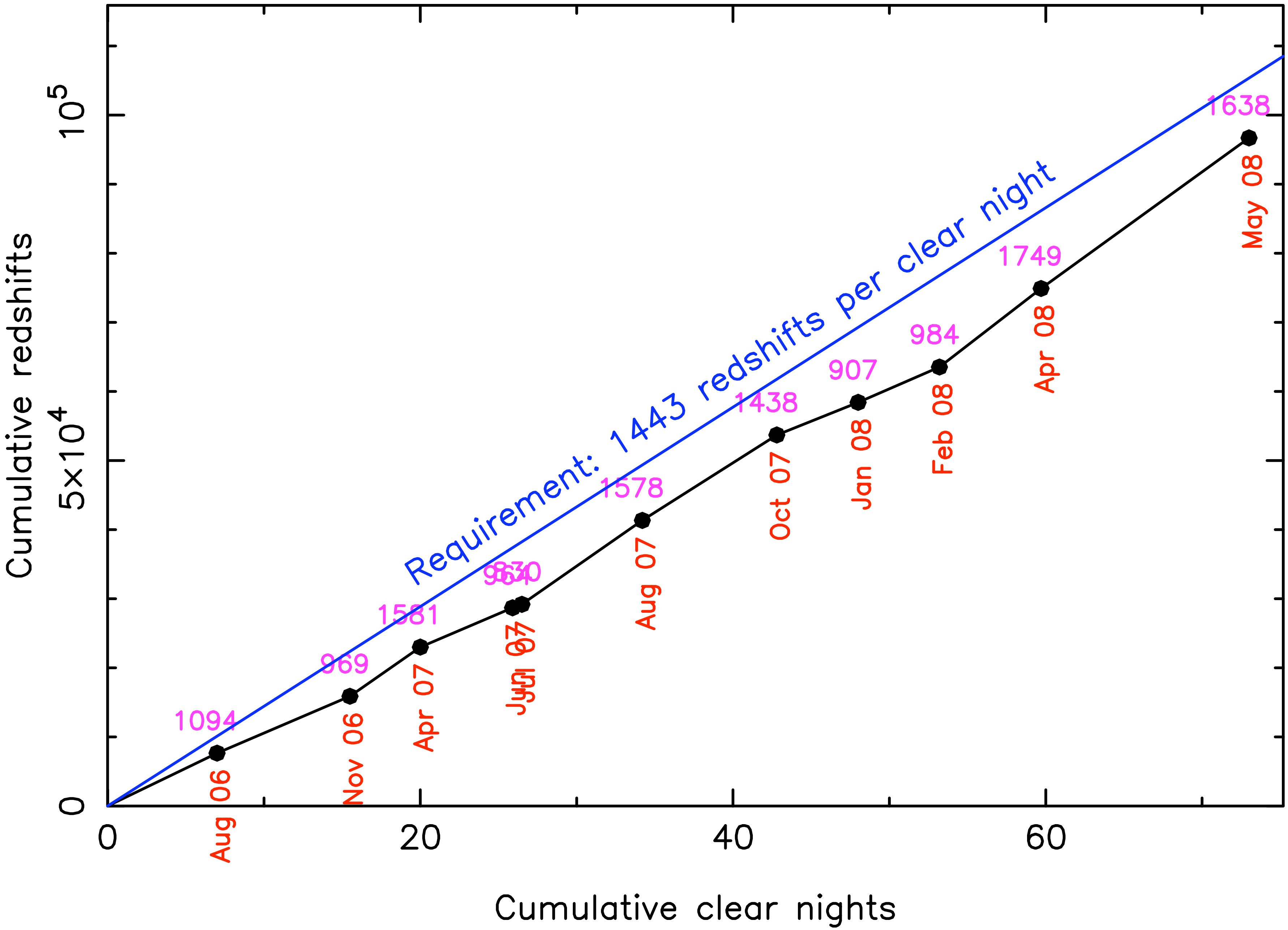
⇒ often disturbed/interacting

Spectral line indices...



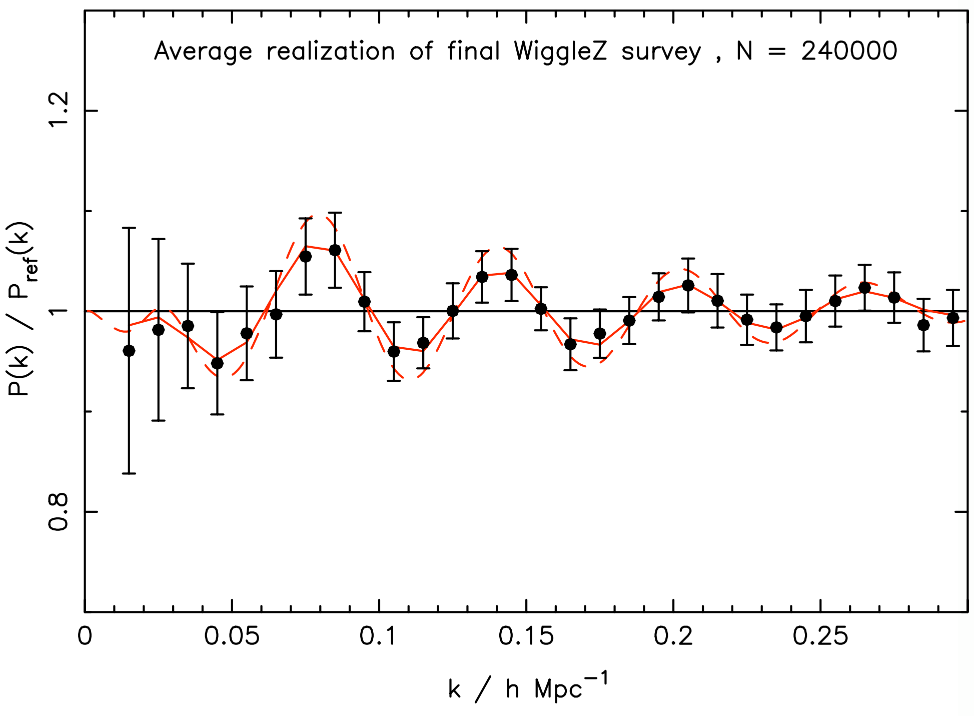
⇒ strongly star-forming galaxies

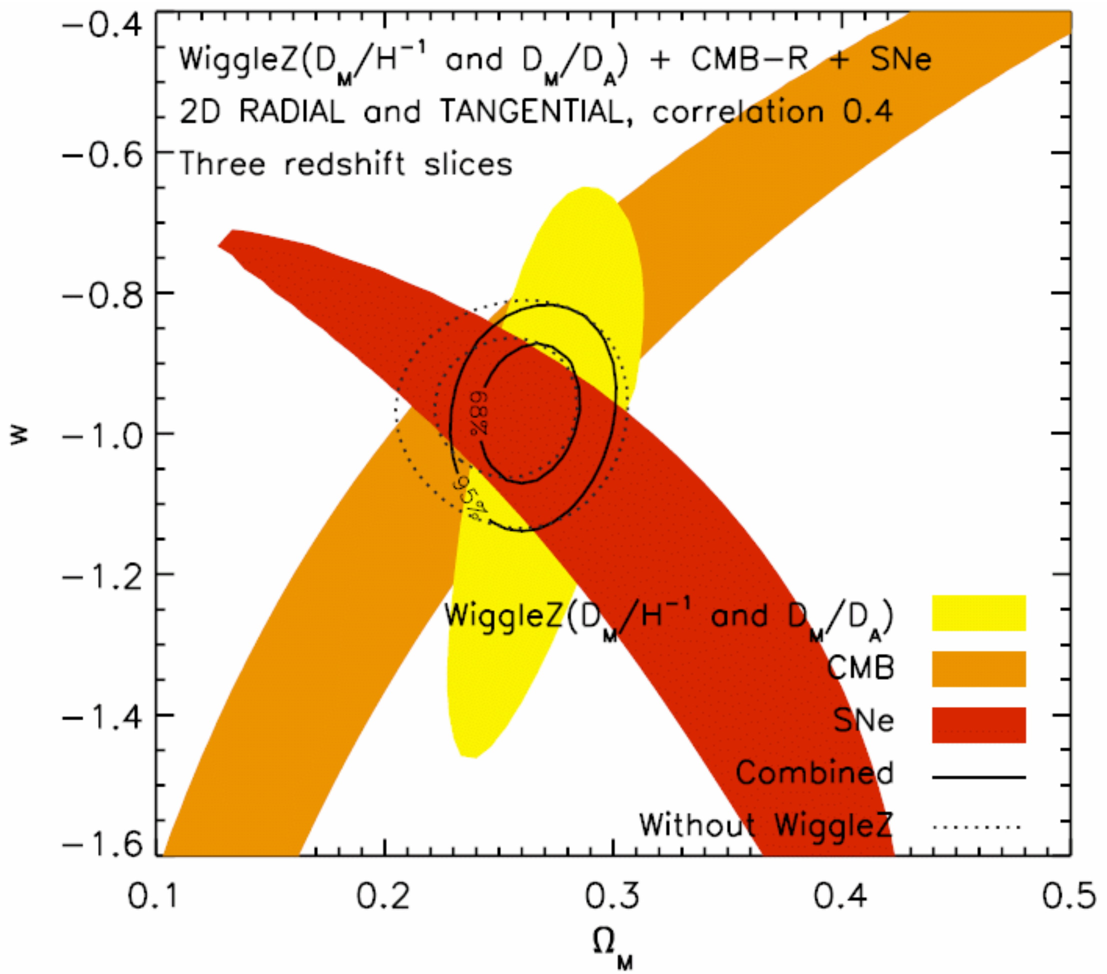
Survey progress



Survey forecasts

- Predicted results:
  - 2.5% precision on measurement of overall BAO scale...
  - ...or 5.7%, 3.4% and 4.6% in 3 redshift intervals

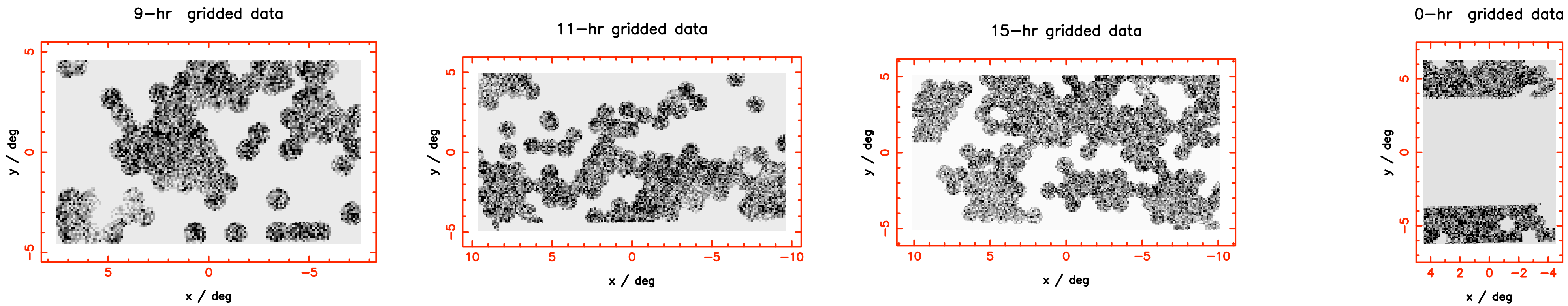




$\Rightarrow$ $\sigma(\Omega_m)=0.02$, $\sigma(w_0)=0.07$

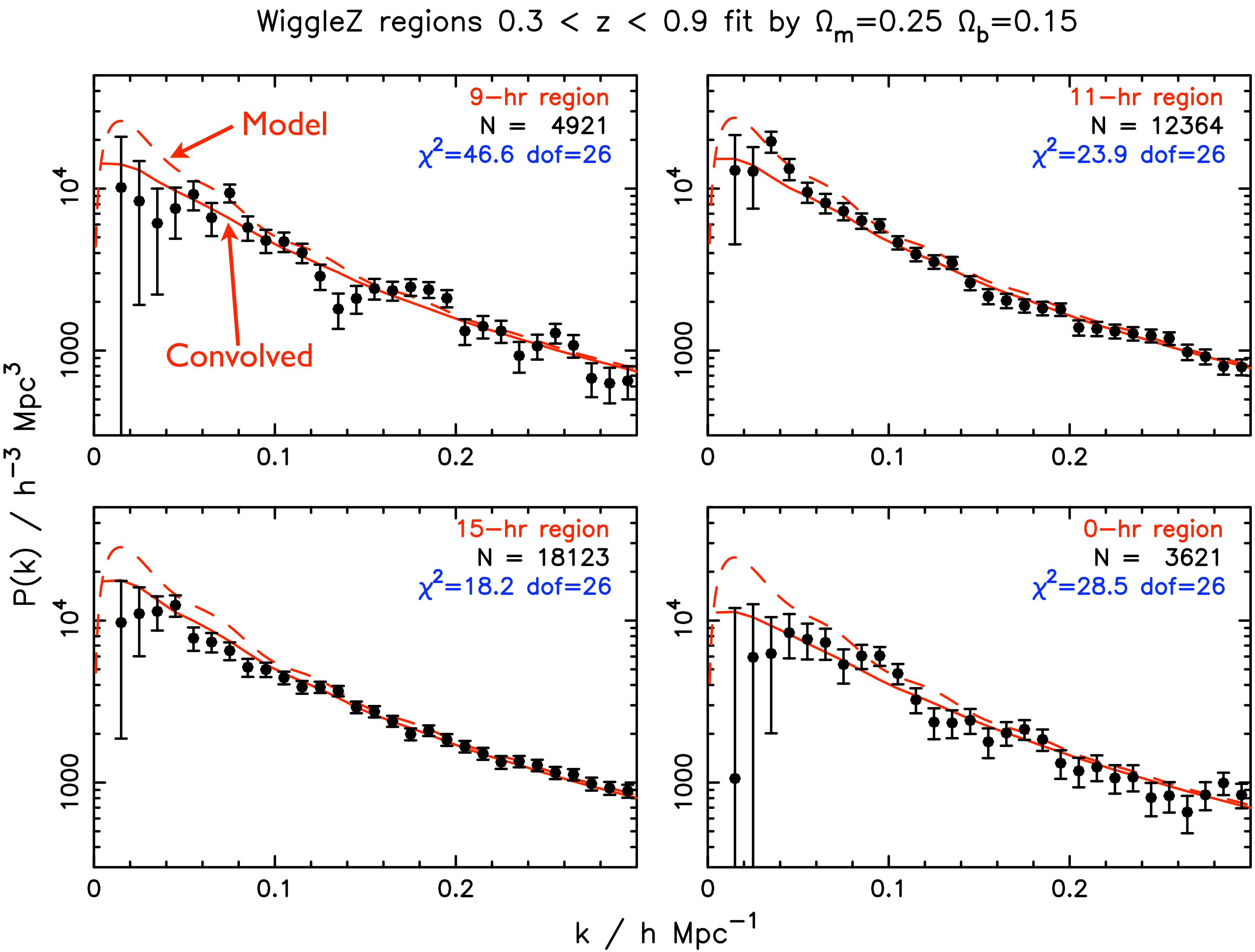
Large-scale clustering

- Preliminary analysis based on ~40k galaxies (cf. 240k)
  - uses only 0hr, 9hr, 11hr & 15hr SDSS regions
  - restrict redshift range to $0.3 < z < 0.9$
  - correct for (patchy) window function & redshift blunders

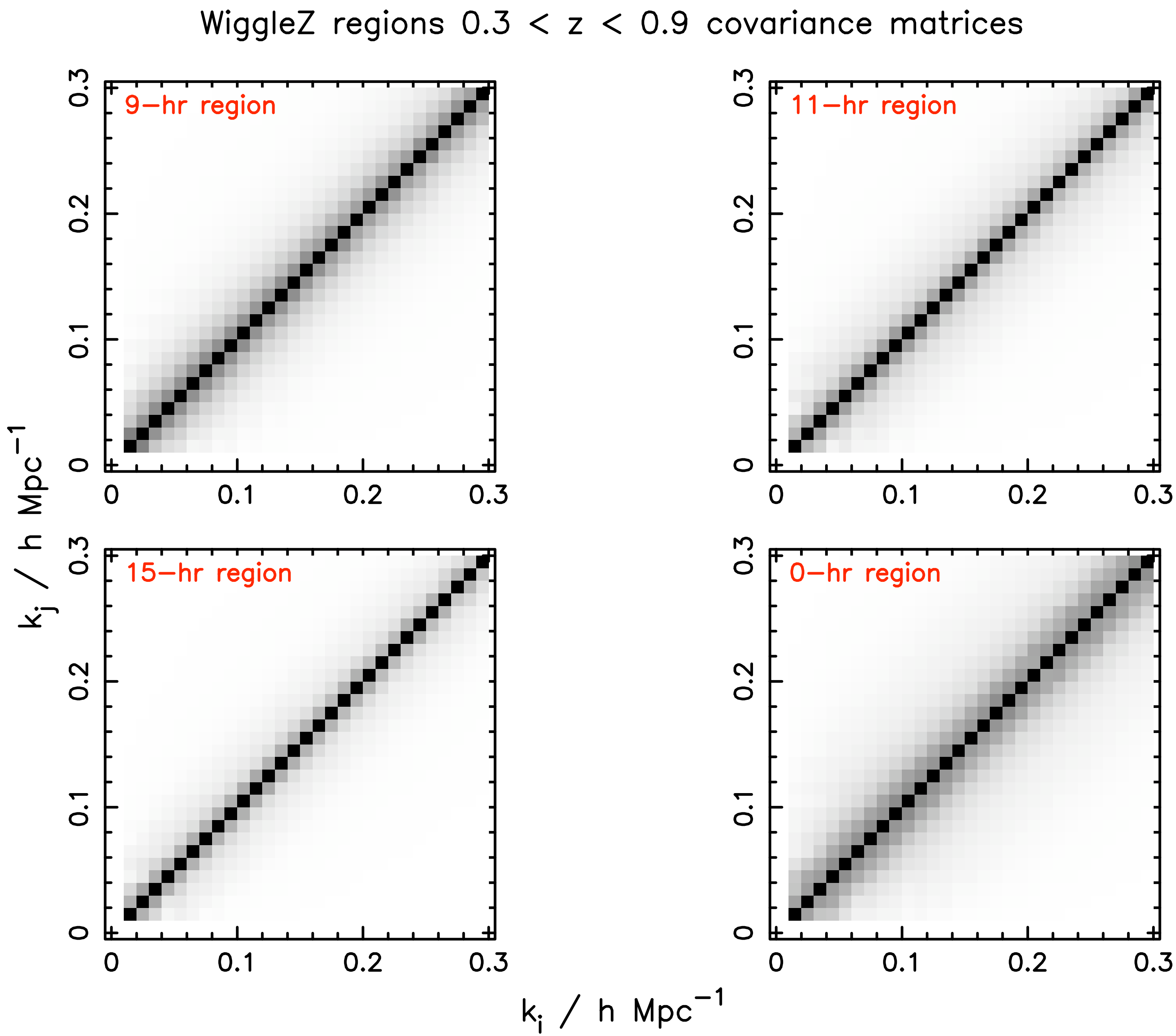


- Measured power spectra and covariance matrices using standard estimators
- Fit for matter and baryon densities to $k < 0.3$ h/Mpc marginalizing over galaxy bias

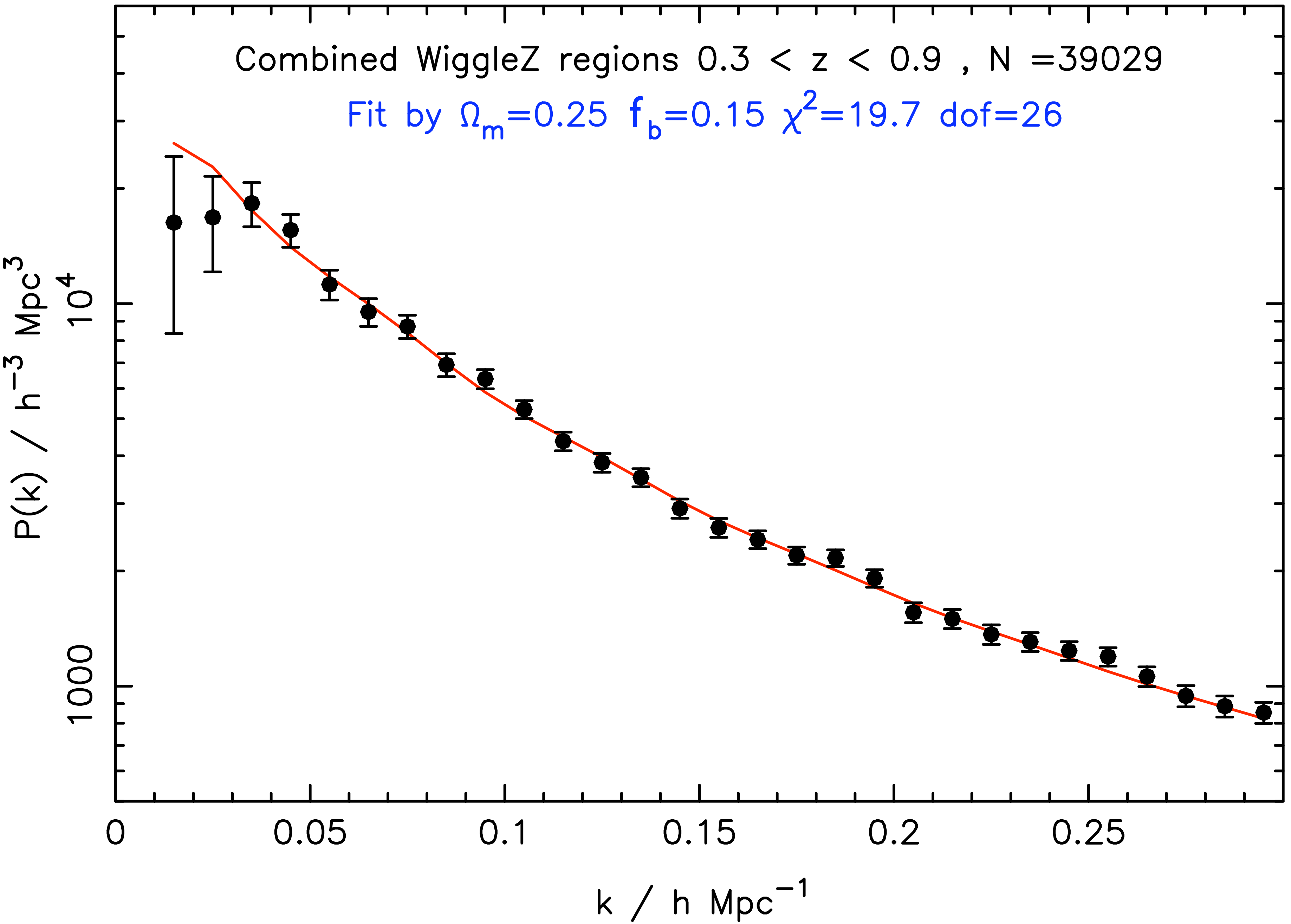
P(k) region-by-region - I



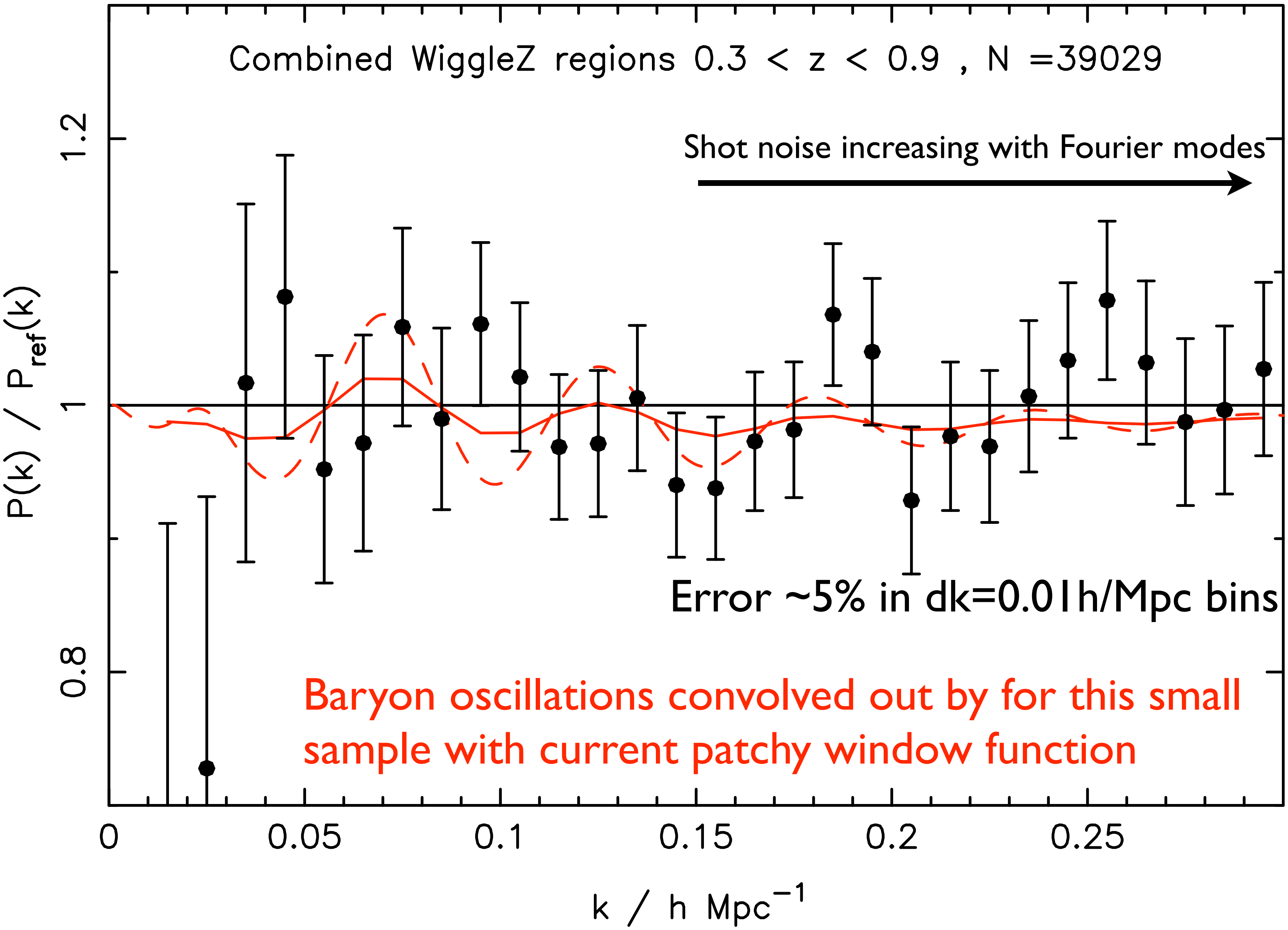
P(k) region-by-region - 2



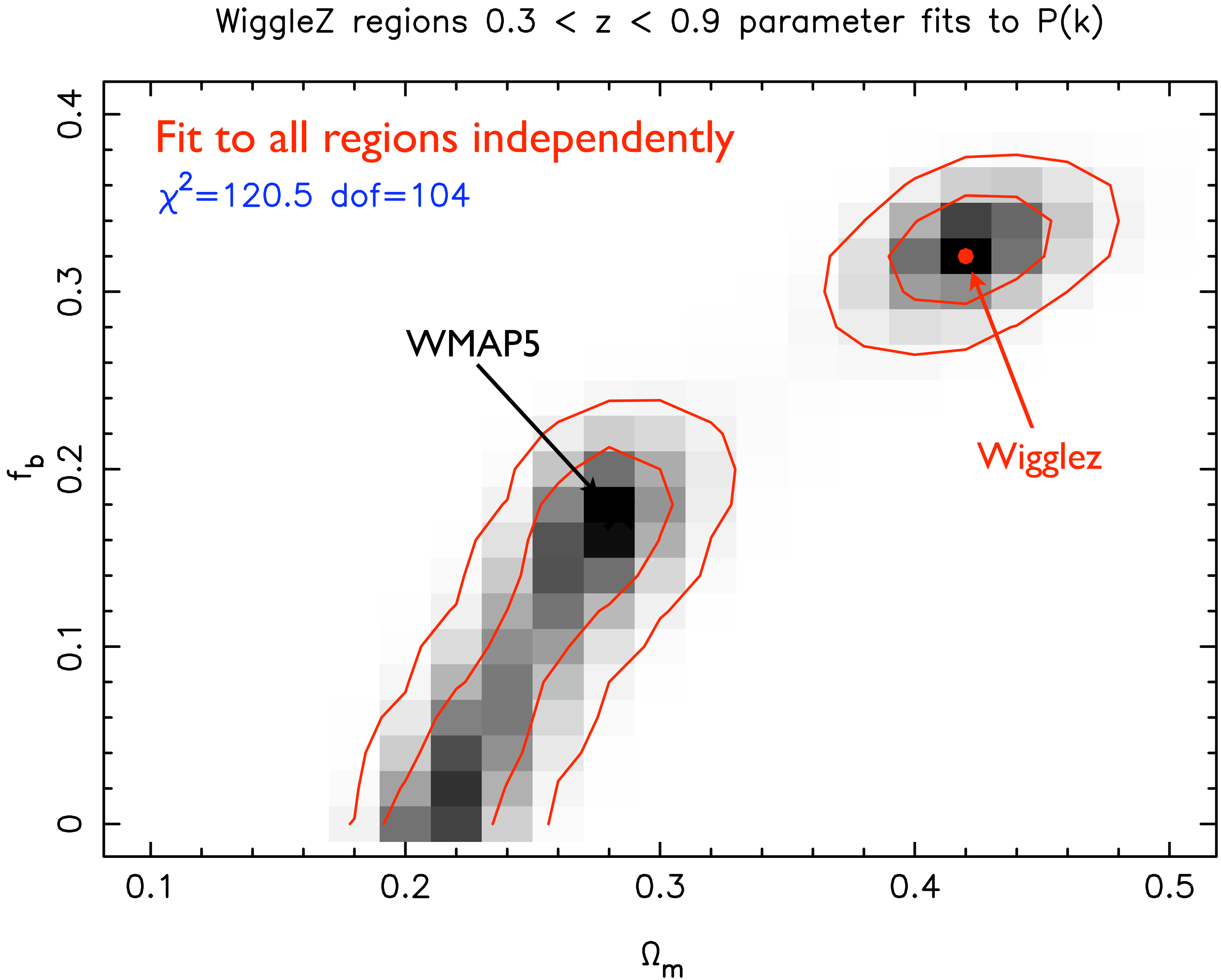
Combined P(k) - 1



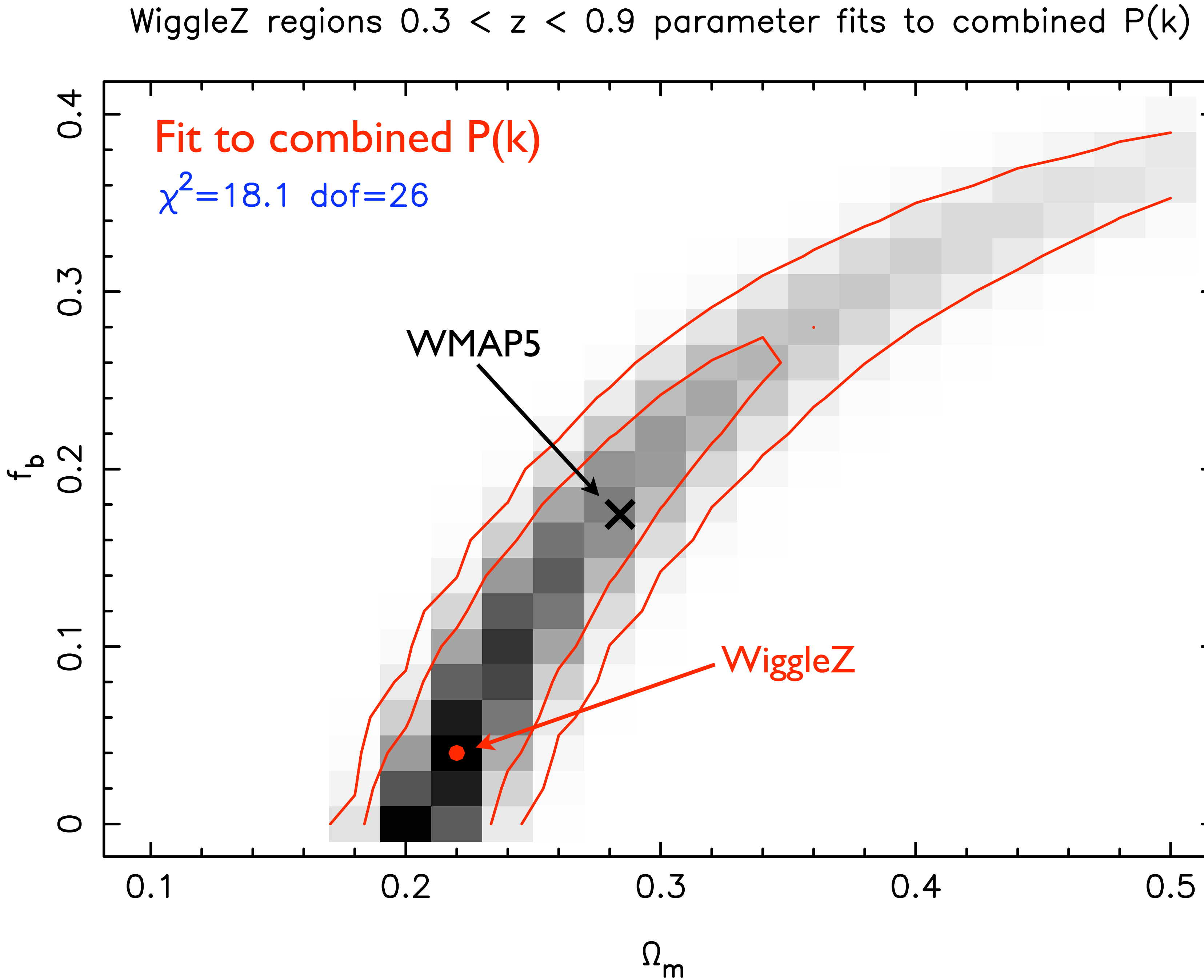
Combined P(k) - 2



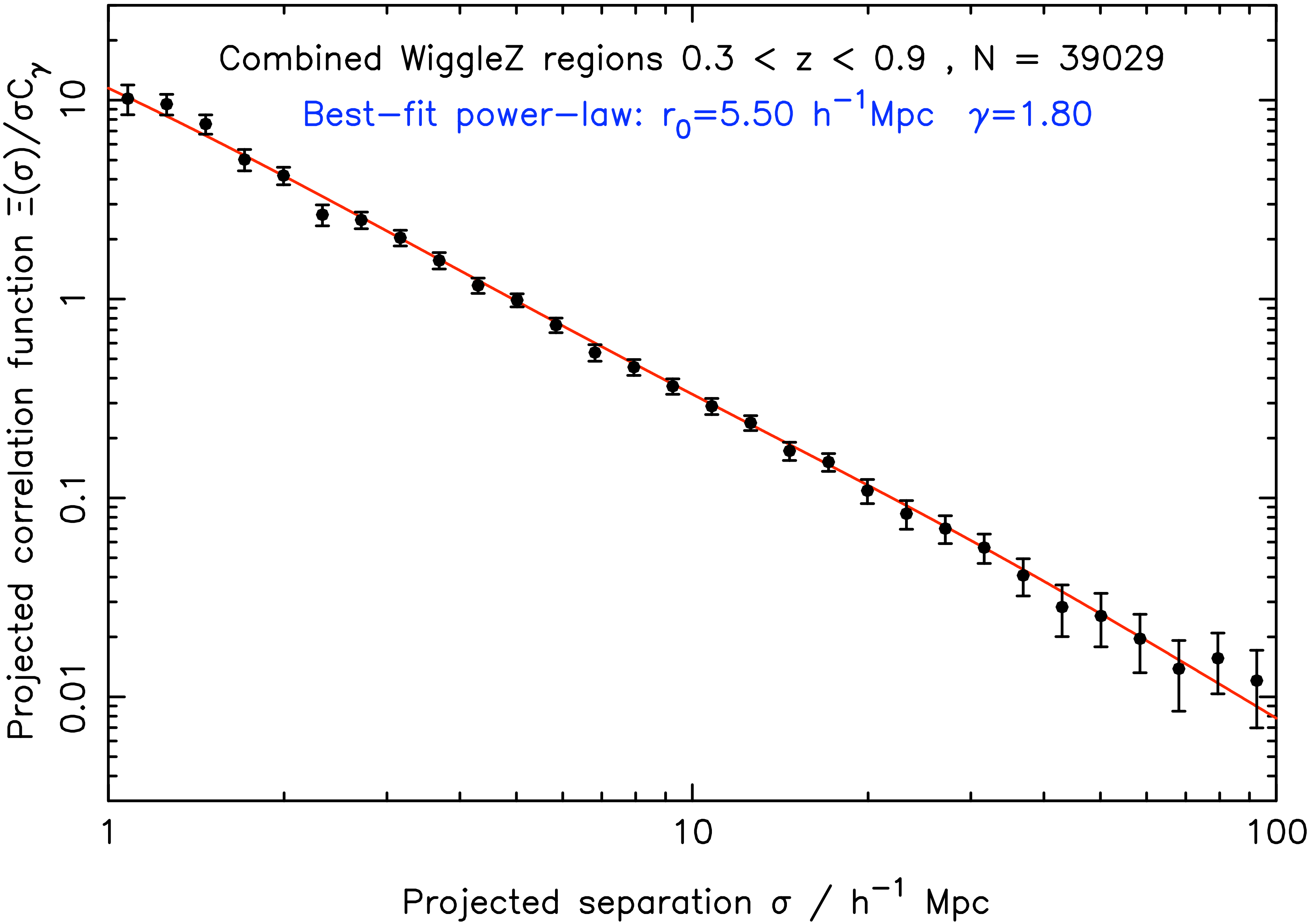
Parameter fits - 1



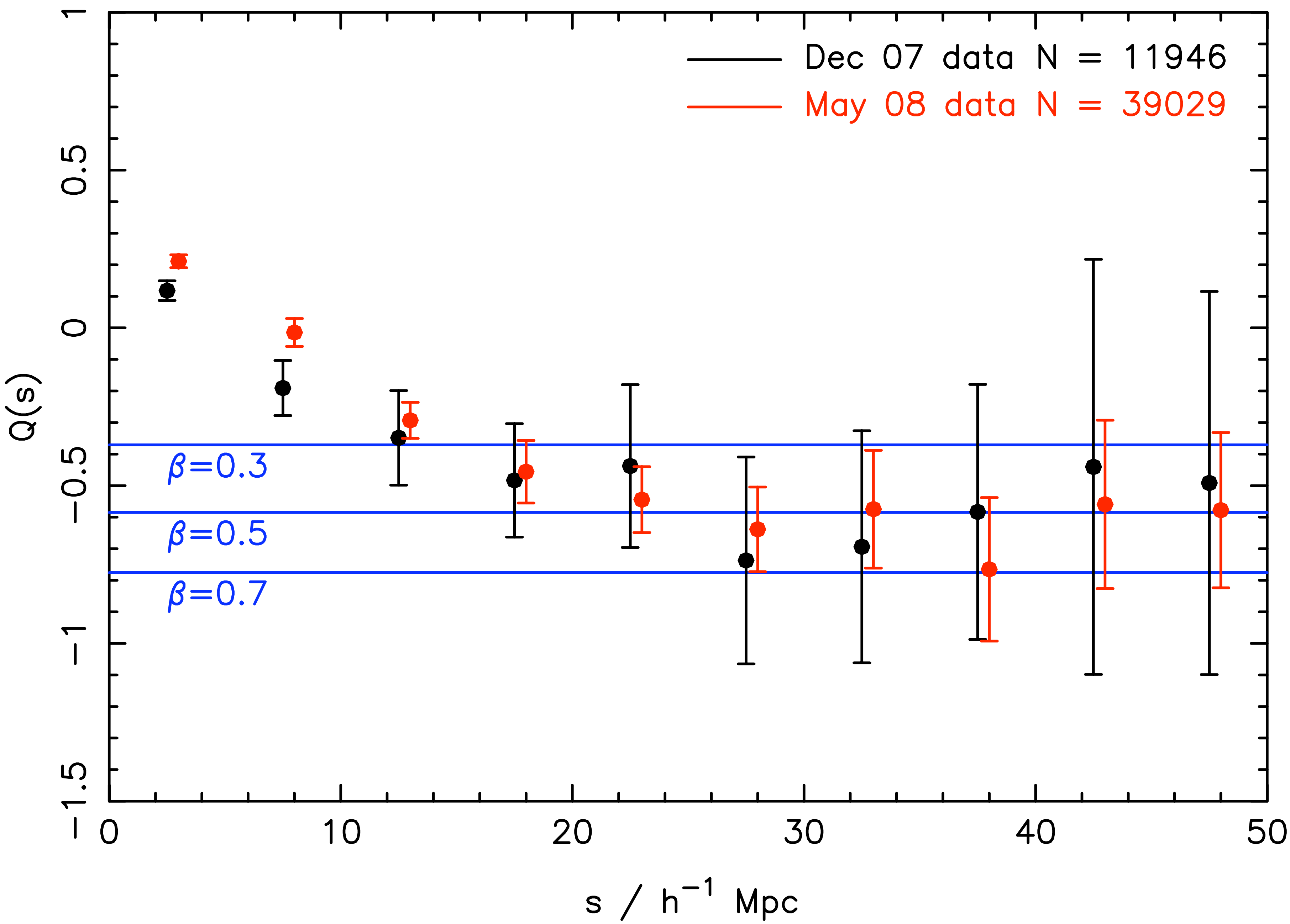
Parameter fits - 2



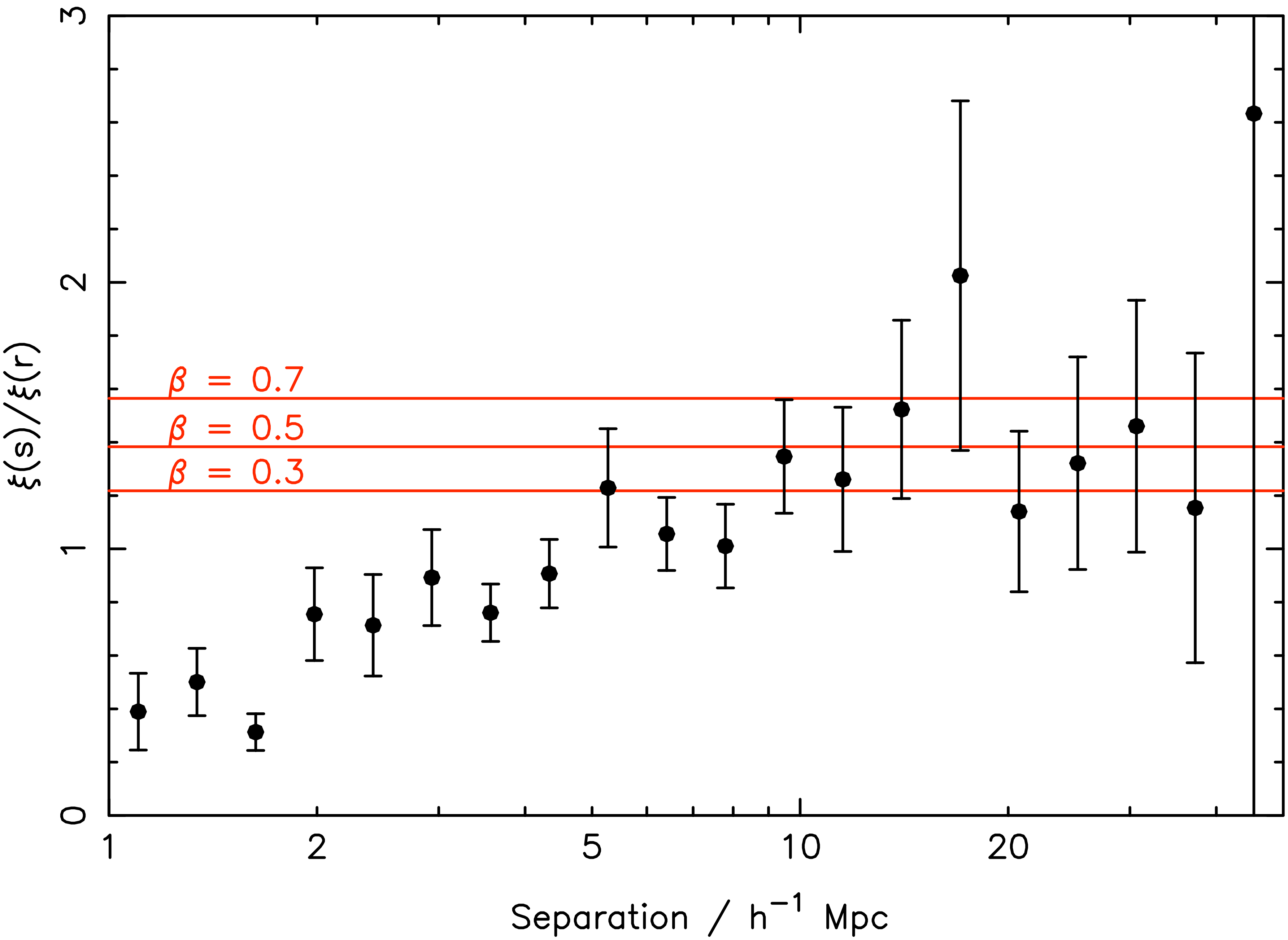
Small-scale clustering



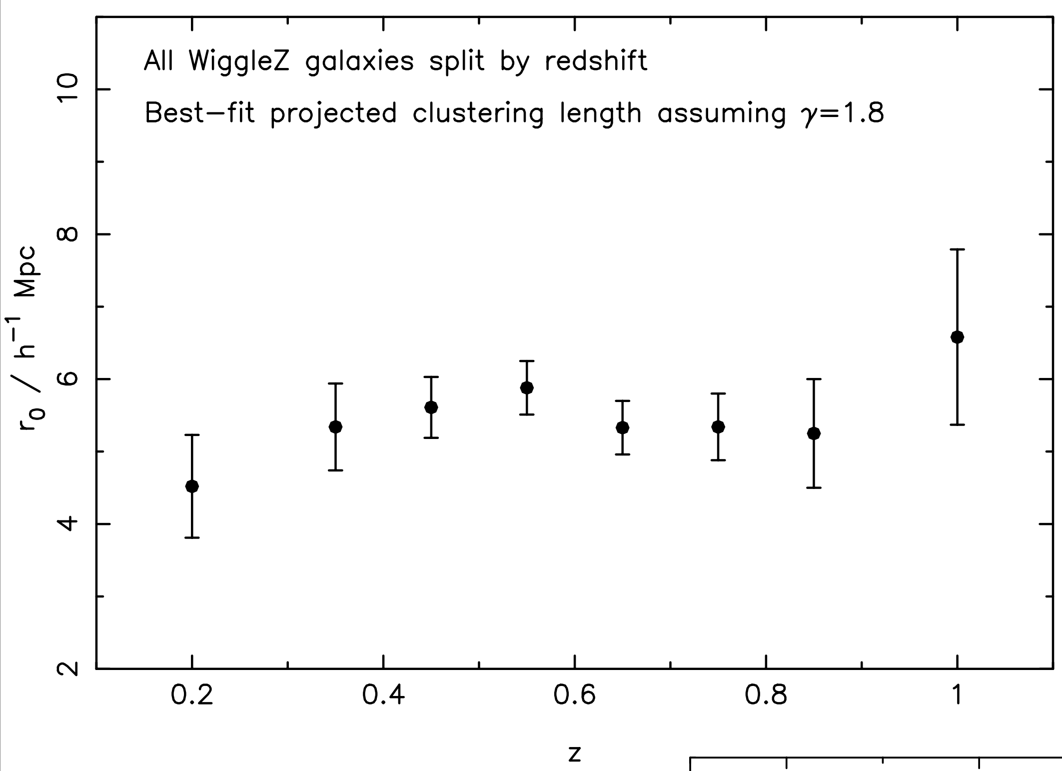
Redshift-space distortions and β

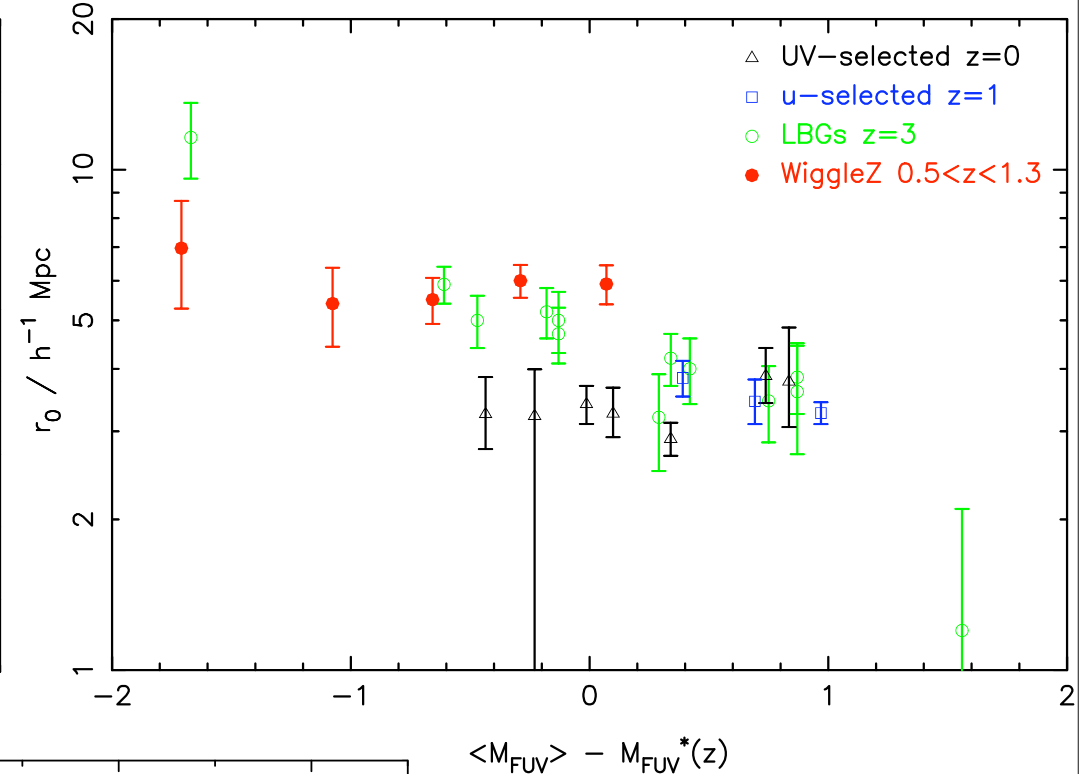


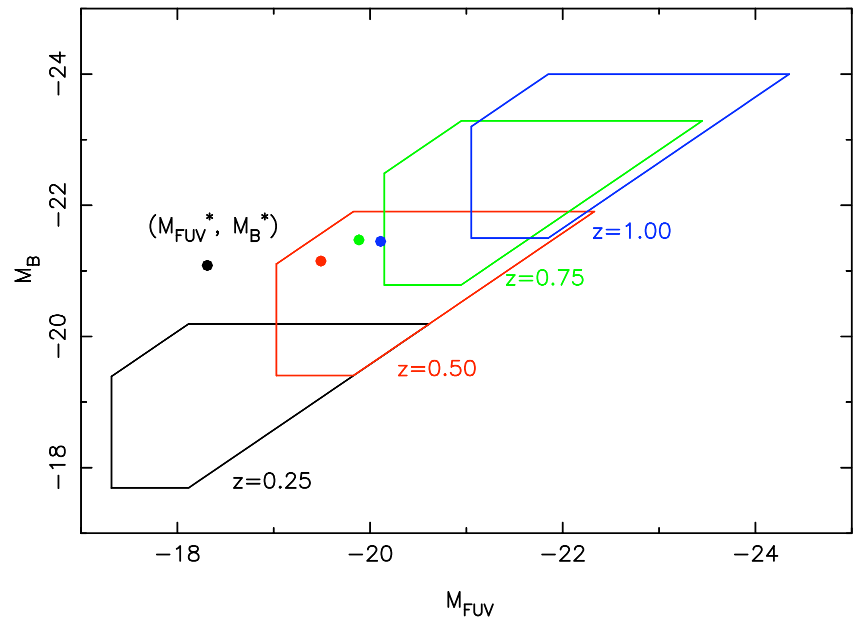
Correlation function ratio and β



Evolution of r_0 with z and L



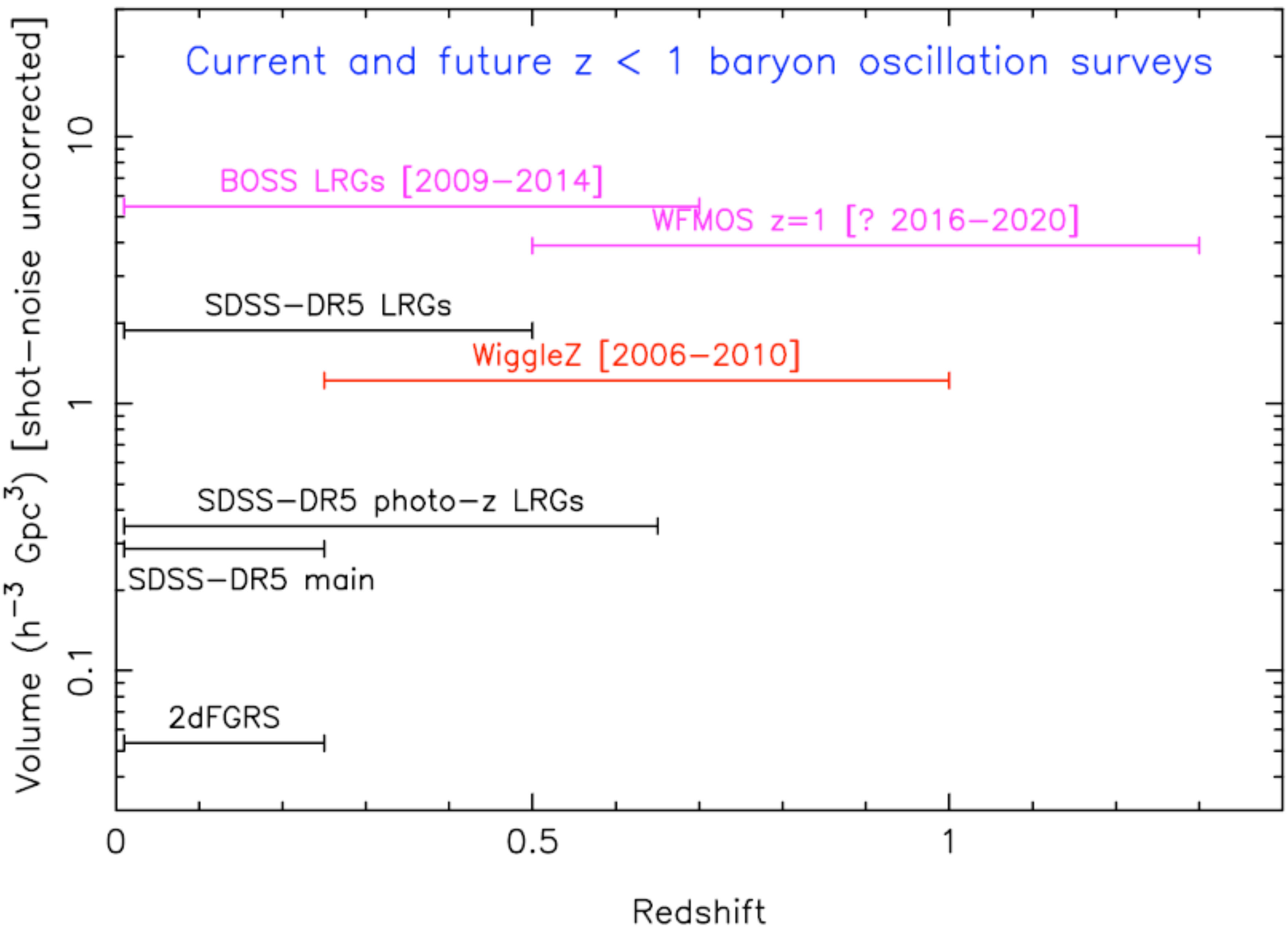




Future BAO surveys

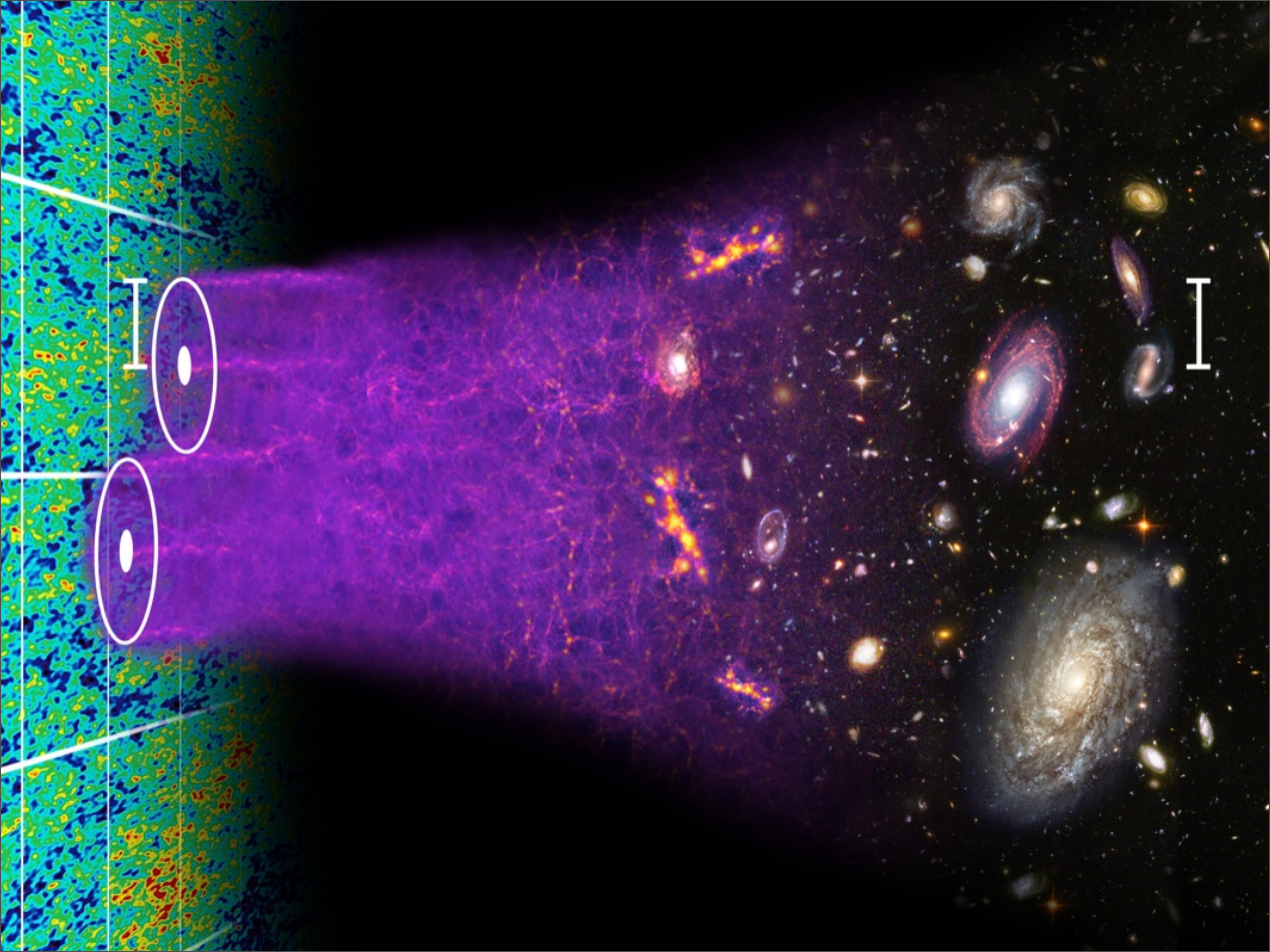
Name	Telescope	$N(z) / 10^6$	Dates	Status
2SLAQ	SDSS/AAT	0.8	2005-2007	Done
WiggleZ	AAT (AAOmega)	0.2	2007-2010	In progress
FastSound	Subaru (FMOS)	0.6	2009-2012	Proposal
BOSS	SDSS	1.5	2009-2013	Proposal
HETDEX	HET (VIRUS)	1.0	2010-2013	Part funded
WFMOS	Subaru	>2	2013-2016	Part funded
ADEPT	NASA (space)	>100	2012+	JDEM
SKA	SKA	>100	2020+	Long term

Survey comparison

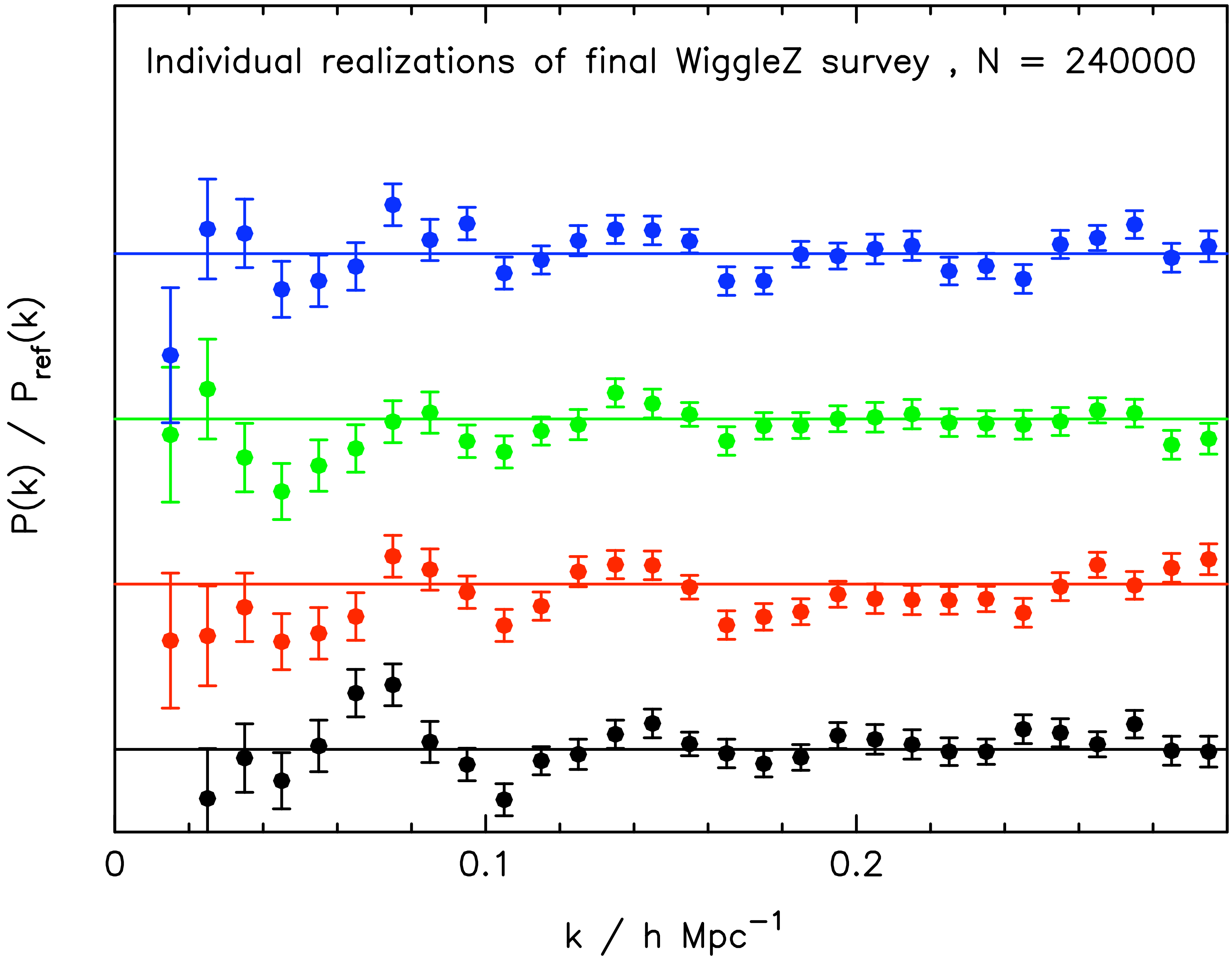


Summary

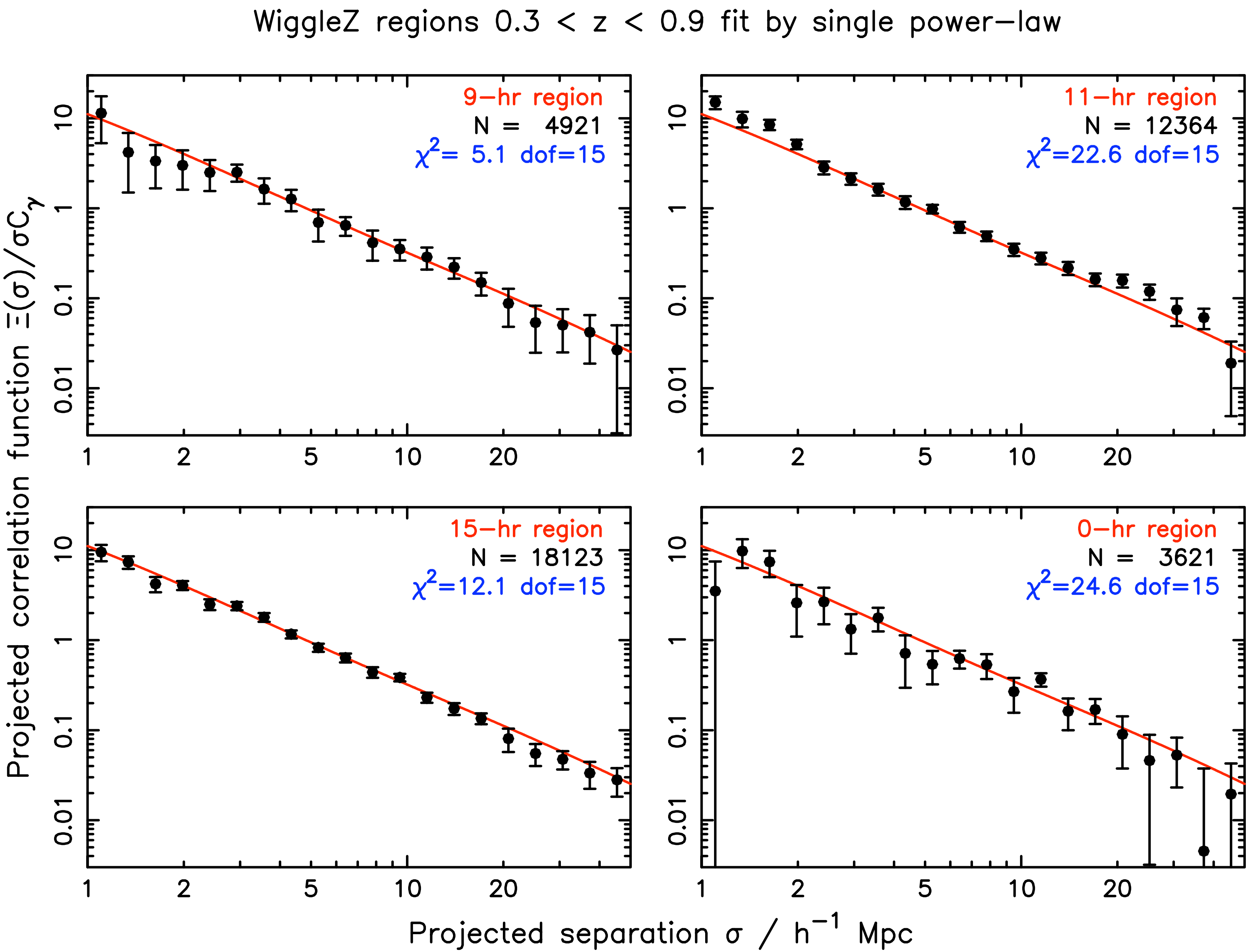
- Baryon acoustic oscillations provide a powerful tool for probing the nature of the dark energy
- The WiggleZ survey is the only project currently measuring dark energy via baryon acoustic oscillations
- We target UV-selected star-forming galaxies and seek a sample of 240k galaxies over 1000 deg^2 at z~0.3-0.9
- When the WiggleZ survey is completed, the forecast predicts that it will constrain Ω_m to 2% and w_0 to 7%
- This is only the next step in BAO surveys - future surveys with FMOS, WFMOS & SKA will refine these constraints further and test whether $w \neq$ constant



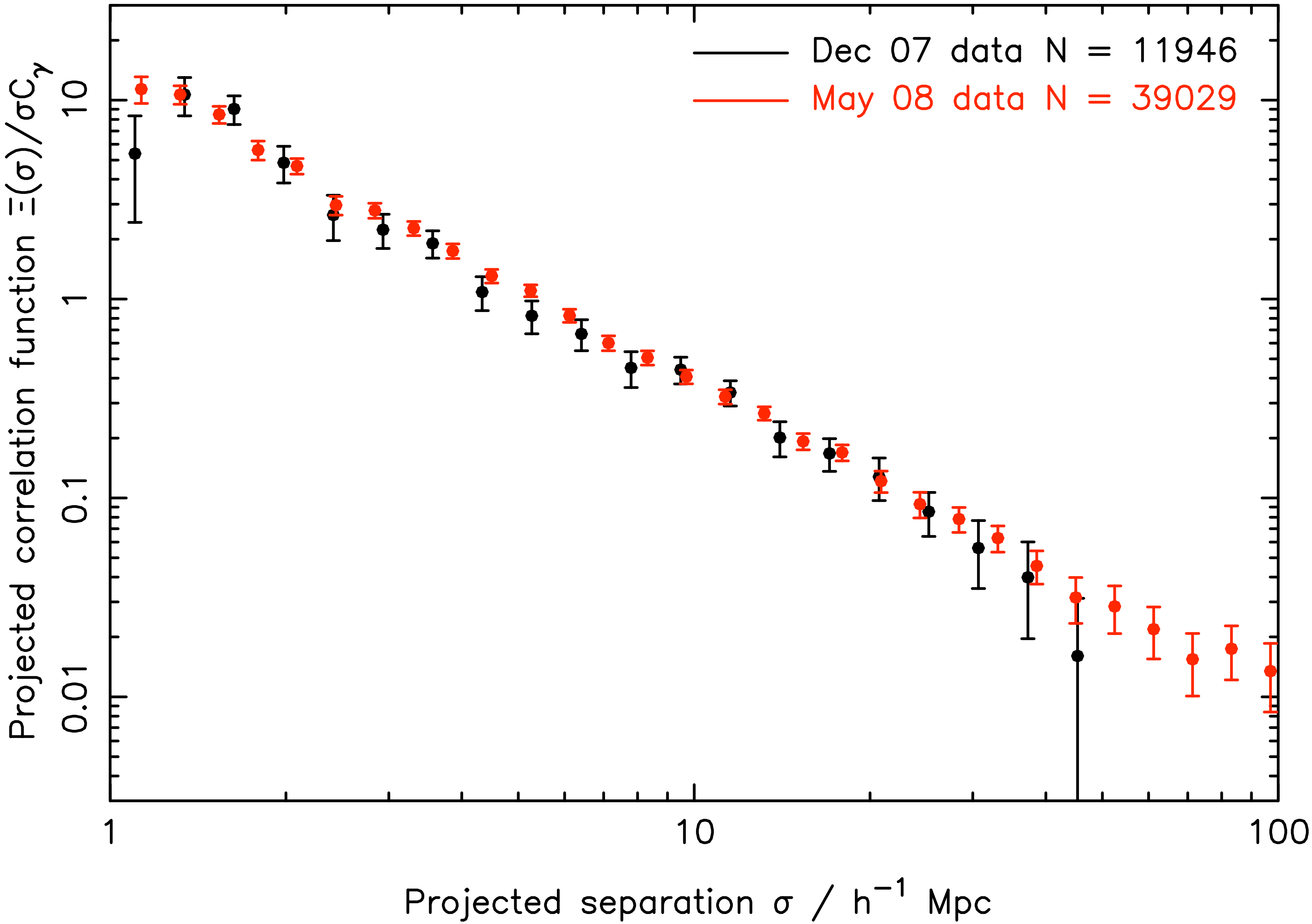
P(k) simulation for final survey - 2



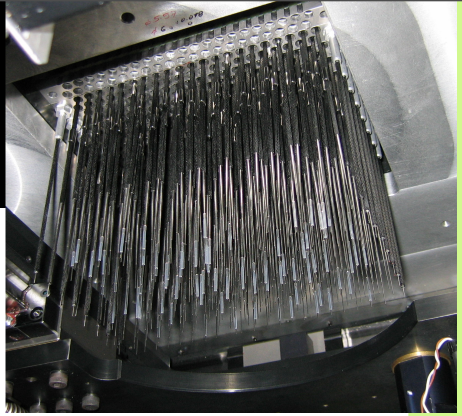
Correlation function by region



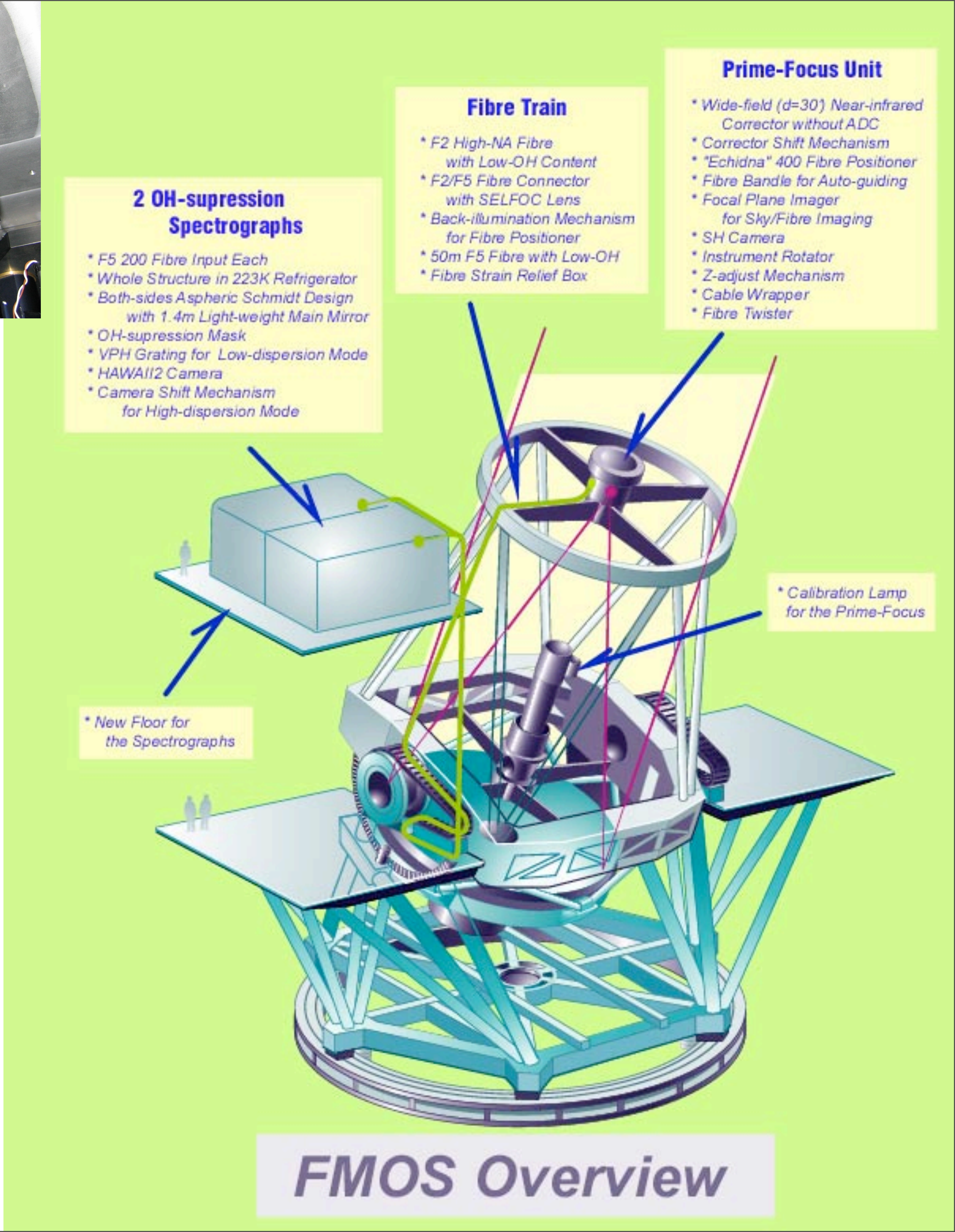
Comparison with paper



FMOS

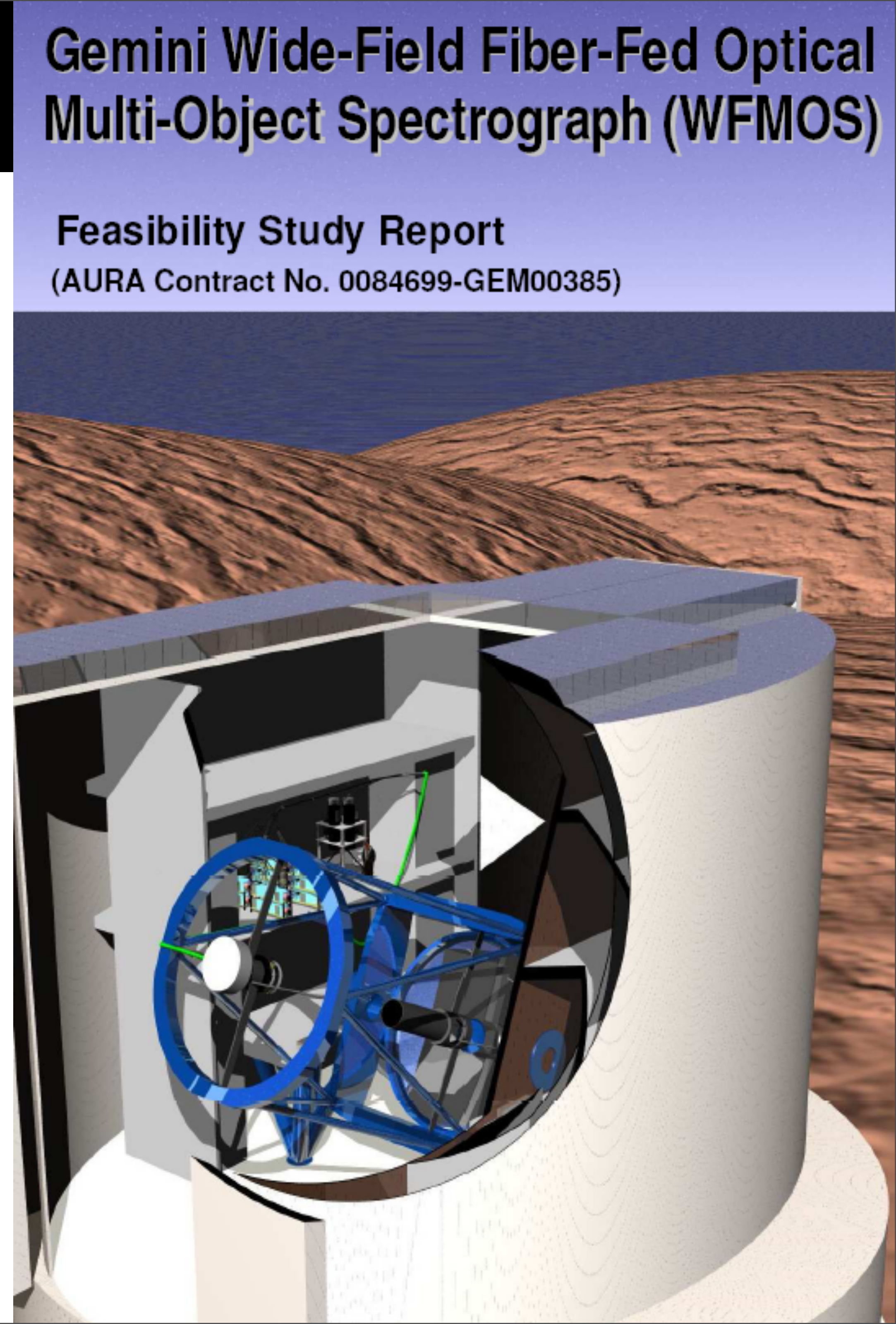


- FMOS
  - Near-IR (1-1.8um) OH-suppression spectrographs
  - Echidna 400-fibre positioner
  - Commissioning now
- FastSound BAO survey
  - Japan/Australia/UK collaboration
  - 600k galaxies, 1 Gpc^3, $0.5 < z < 1.5$



WFMOS

- A collaboration between Gemini and Subaru
- Motivated by 1.5–2 deg HyperSuprimeCam under construction for Subaru
- Two competing design studies for WFMOS now underway
- Decision on construction due in May 2009
- Original concept: 4000 fibres with Echidna positioner feeding low- and high-resolution spectrographs



The Square Kilometre Array