The WiggleZ Dark Energy Survey…

shows that dark energy is real

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shows that dark energy is real

THE TEAM:

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ANU: Mike Pracy

UBC: David Woods

Caltech: Chris Martin, Ted Wyder

Carnegie: Barry Madore

Plus students and associate members

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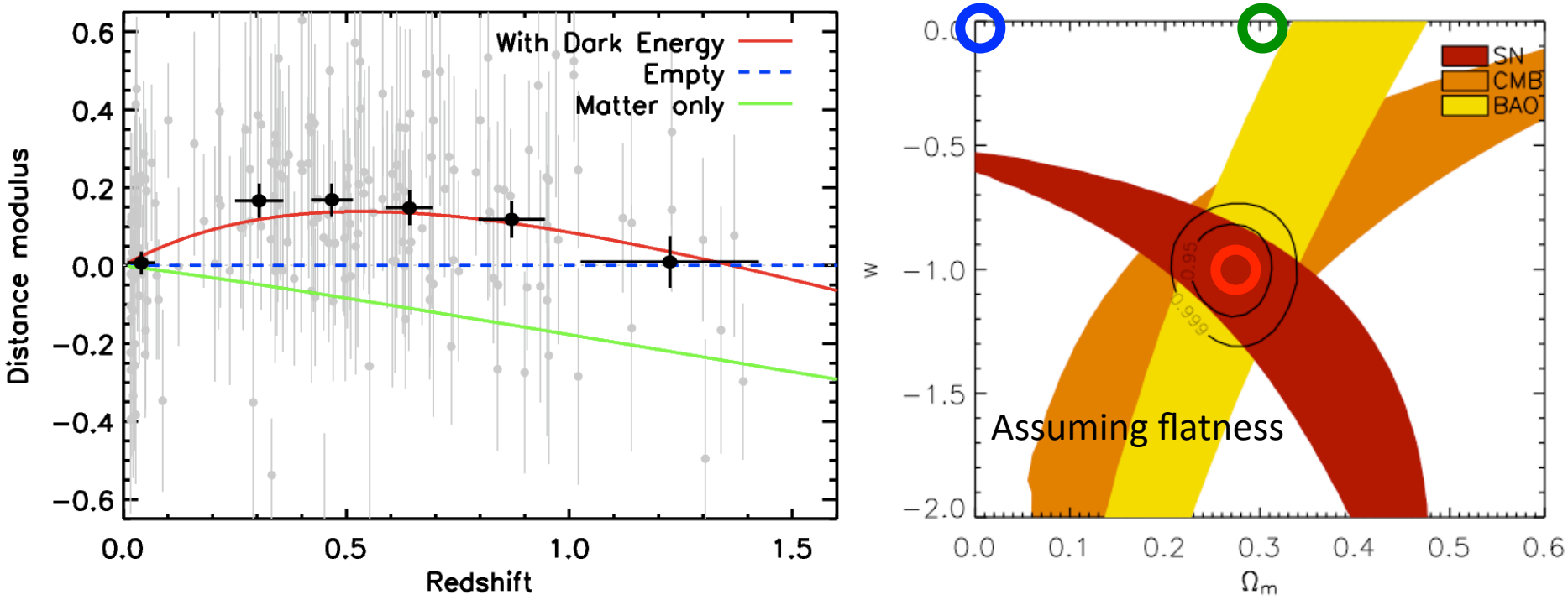
Outline

- Motivation
- Our Survey
- Growth of structure test ✔
- Geometric proof of acceleration ✔
- Standard ruler test ✔
- Neutrino mass

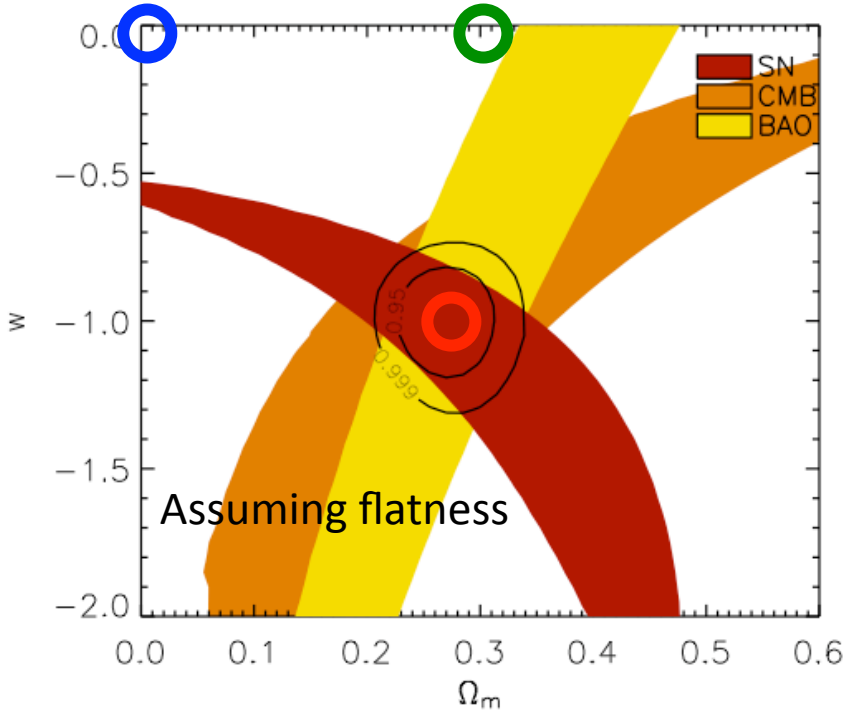
Motivation: distance indicators show acceleration



(Normalised) Luminosity distances for supernovae vs. redshift
-clearly inconsistent with **models** of empty or decelerating universes

What model are we fitting?

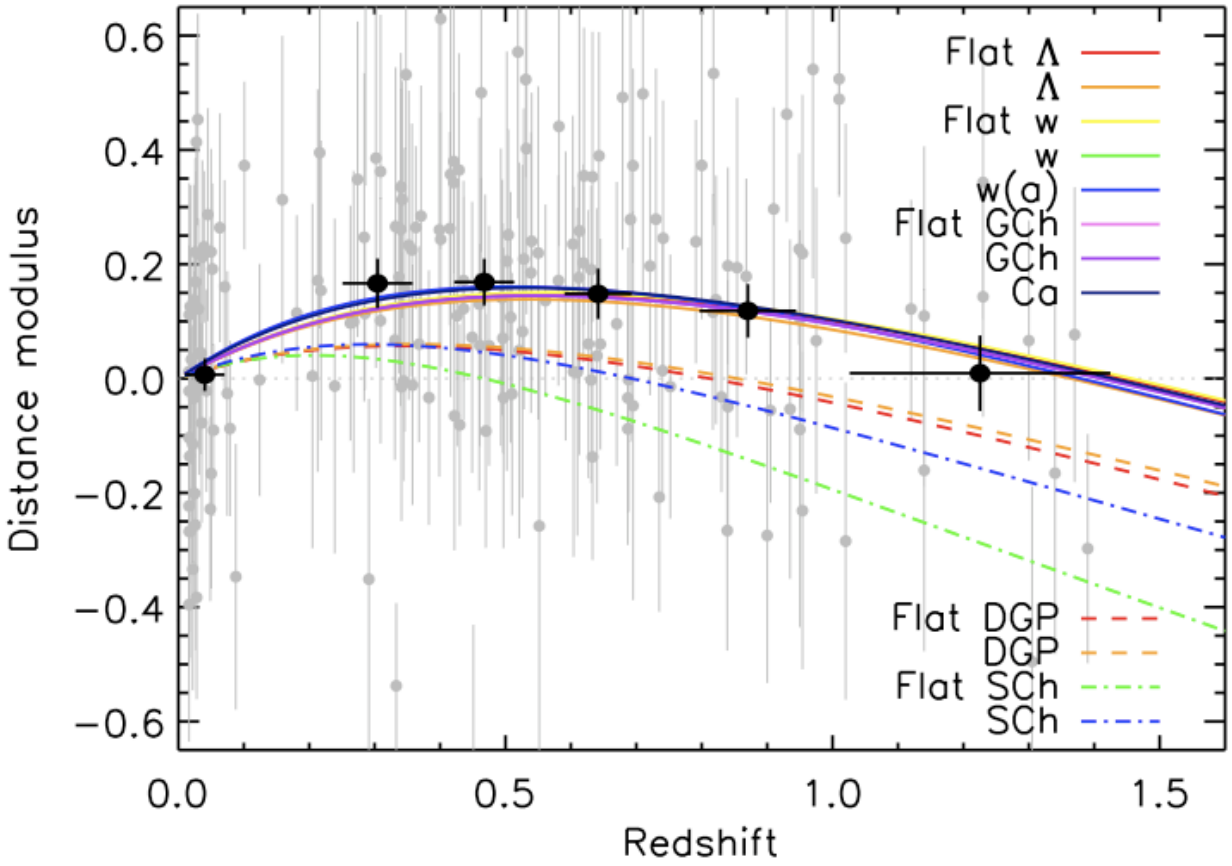
- Three parts of LCDM
  - Gravity (Einstein's GR)
  - Cold Dark Matter
  - Dark Energy which could be a cosmological constant L (or Λ)
- Dark energy
  - Equation of state: p = w ρ
  - Evolution: $\rho \infty a^{-3(1+w)}$
- Options for w
  - Normal matter w=0
  - Accelerating universe: w<-1/3
  - Cosmological costant: w=-1
  - New physics: w = w(z)



$$\rho \propto a^{-3(1+w)}.$$

Distance indicators can't distinguish between some models

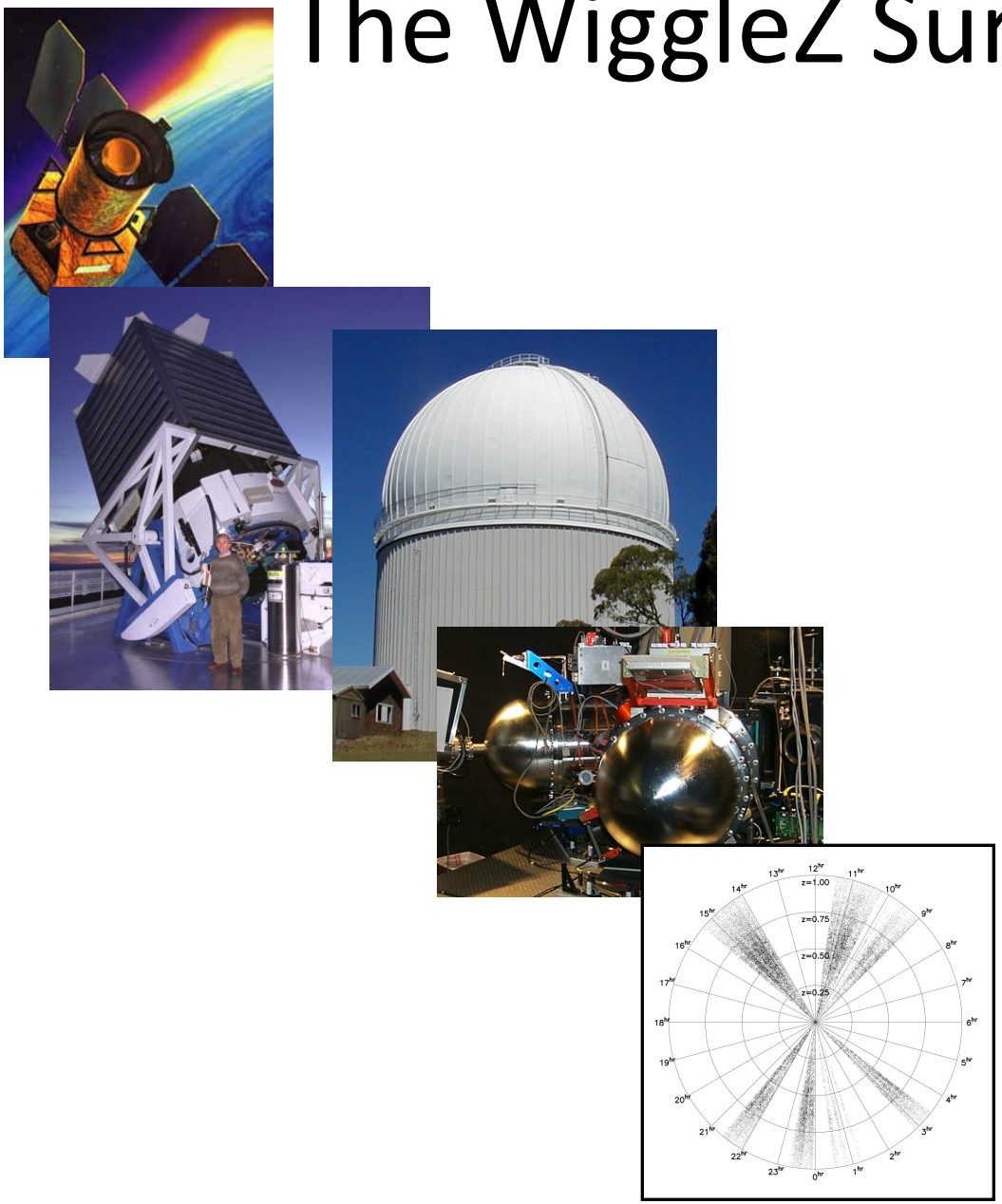
- 12 models including modified gravity
  - All models fitting data can mimic LCDM for some parameters
  - All models not fitting data could not mimic LCDM
- Measurements of the expansion cannot separate some models, even in the limit of perfect data.
- We need other *types* of tests.



Davis et al. 2007 (ESSENCE)

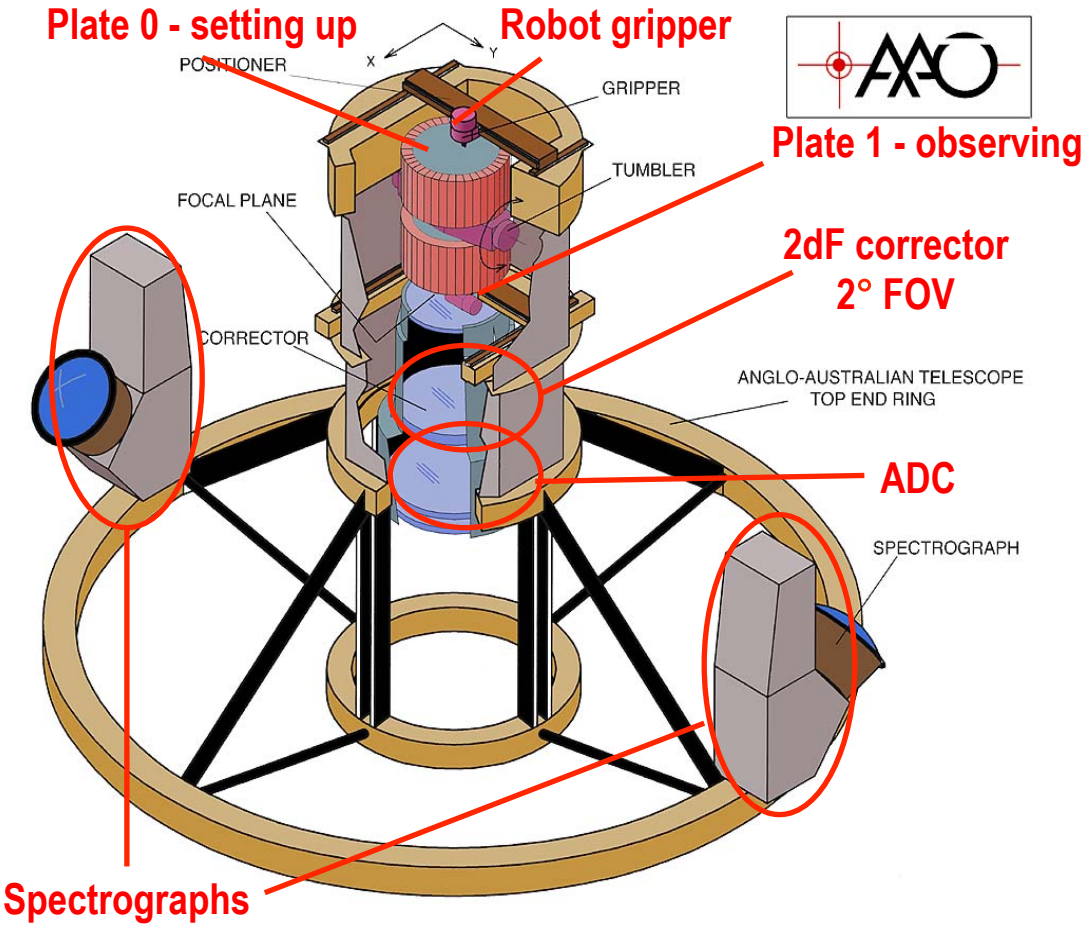
Our survey:
we use LARGE SCALE STRUCTURE

The WiggleZ Survey Plan



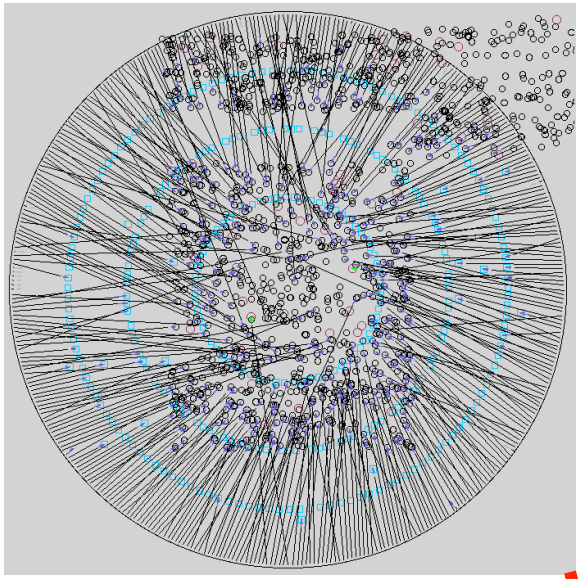
- Find galaxies with GALEX (UV) satellite
- Get accurate positions from Sloan (optical) Sky Survey
- Win **220 nights** of time on Anglo-Australian Telescope
- Measure 240,000 galaxy redshifts with **new facility**
- Use large-scale galaxy distribution **to test dark energy theory**

The AAO 2 Degree Field Spectrograph

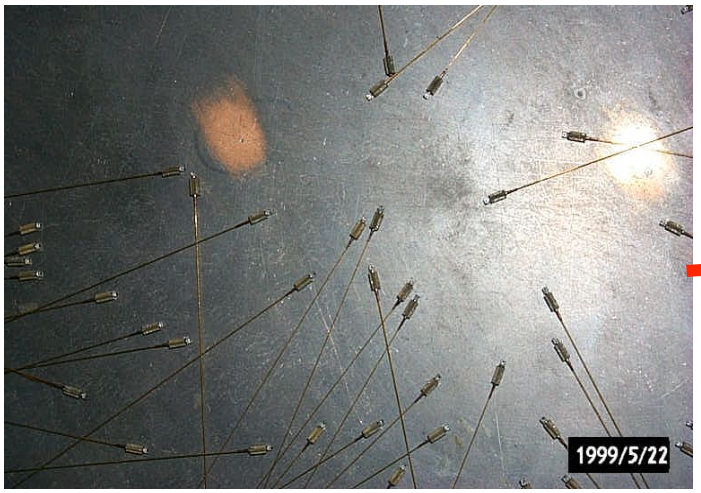


400 Optical Fibres: ‘Byzantine tangles’

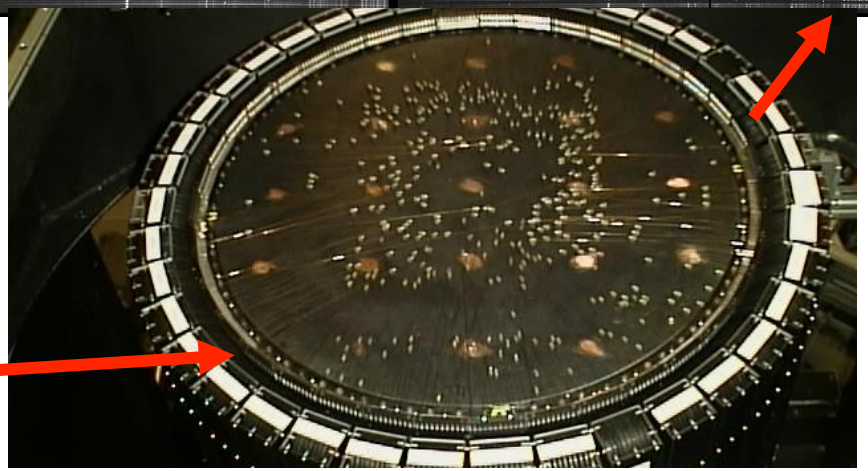
1. Configuration software



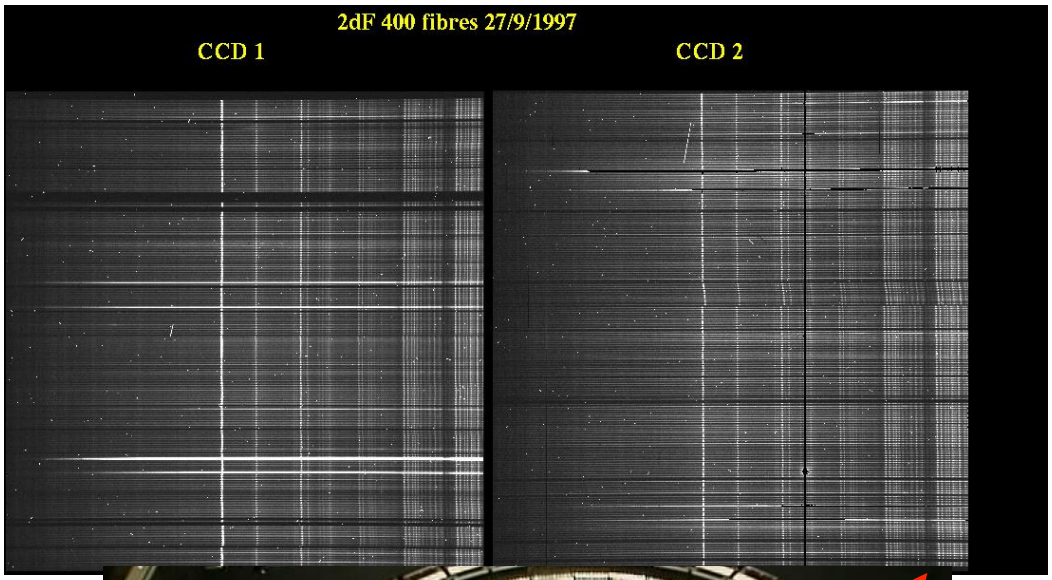
2. Fibre positioning by robot



3. Completed field plate



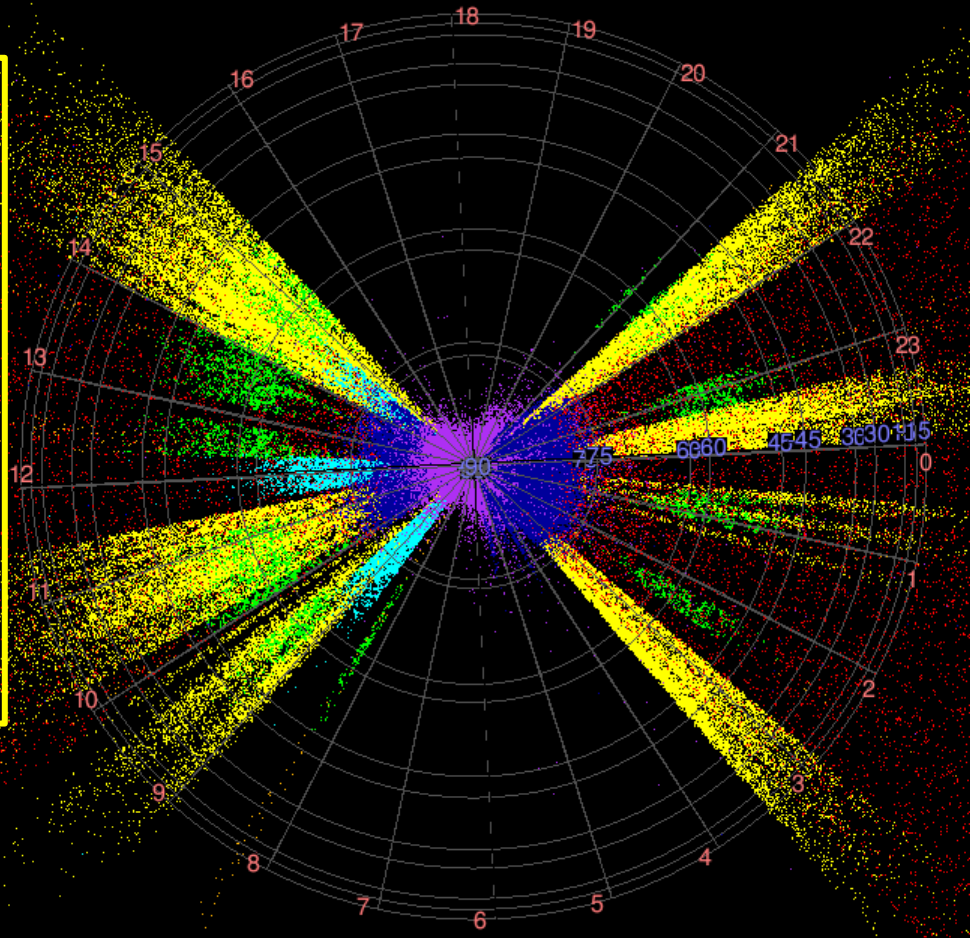
4. Results: 400 spectra on 2 CCDs



WiggleZ survey fields
(compared to other AAT surveys)

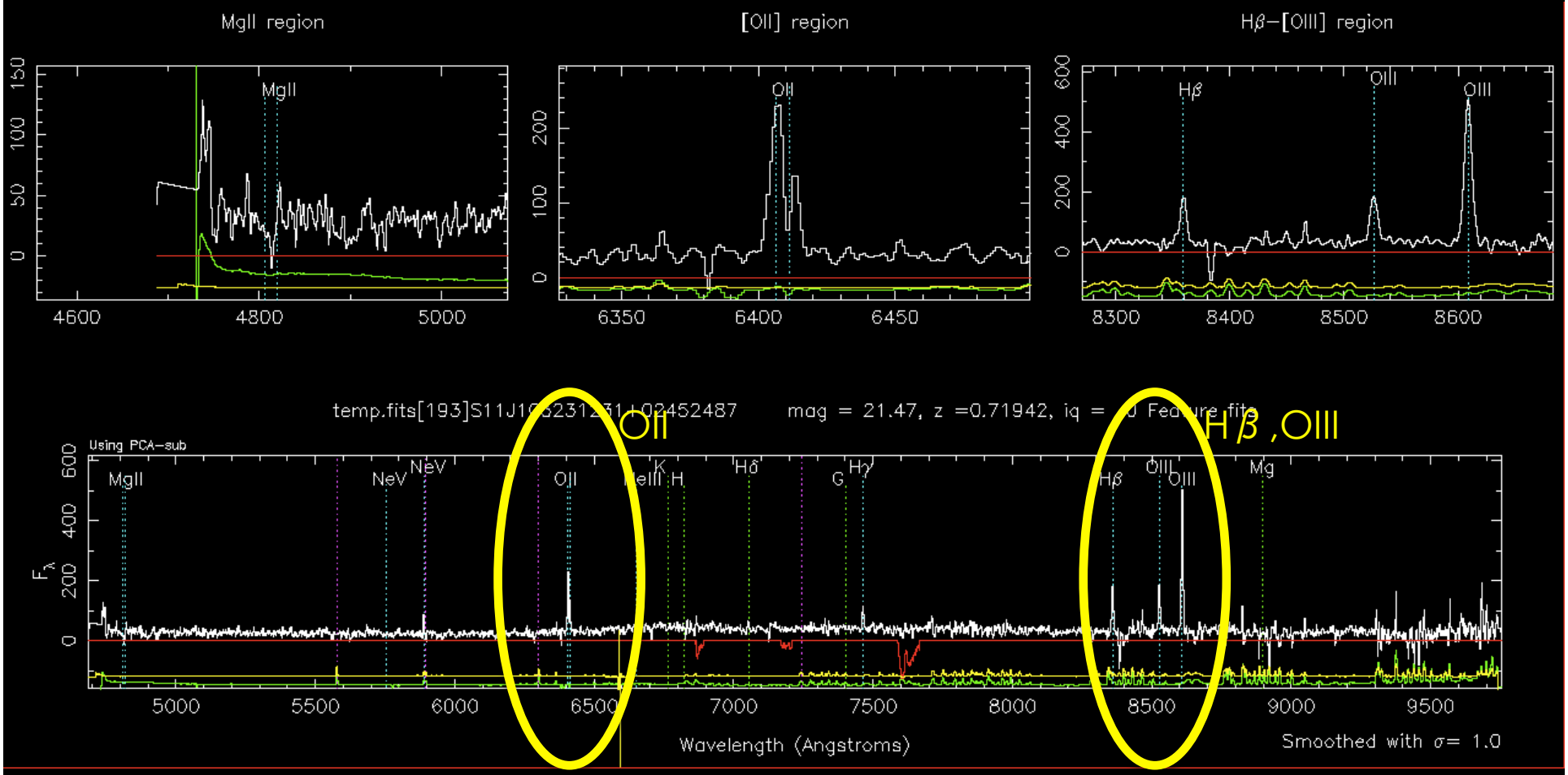
7 equatorial fields, each 100-200 deg^2
>9° on side, ~3 x BAO scale at z > 0.5
Physical size ~ 1300 x 500 x 500 Mpc/h

- highest-ever redshift galaxy survey
- 0.2 < z < 1.0
- 220,000 blue galaxies
- 1 GPc^3
- Observations finished Jan 2011



6dFGS (purple), 2dFGRS (blue), MGC (navy), GAMA (cyan), 2SLAQ-LRG (green), WiggleZ (yellow), 2SLAQ-QSO (orange), 2QZ (red); the celestial sphere is at z=1.

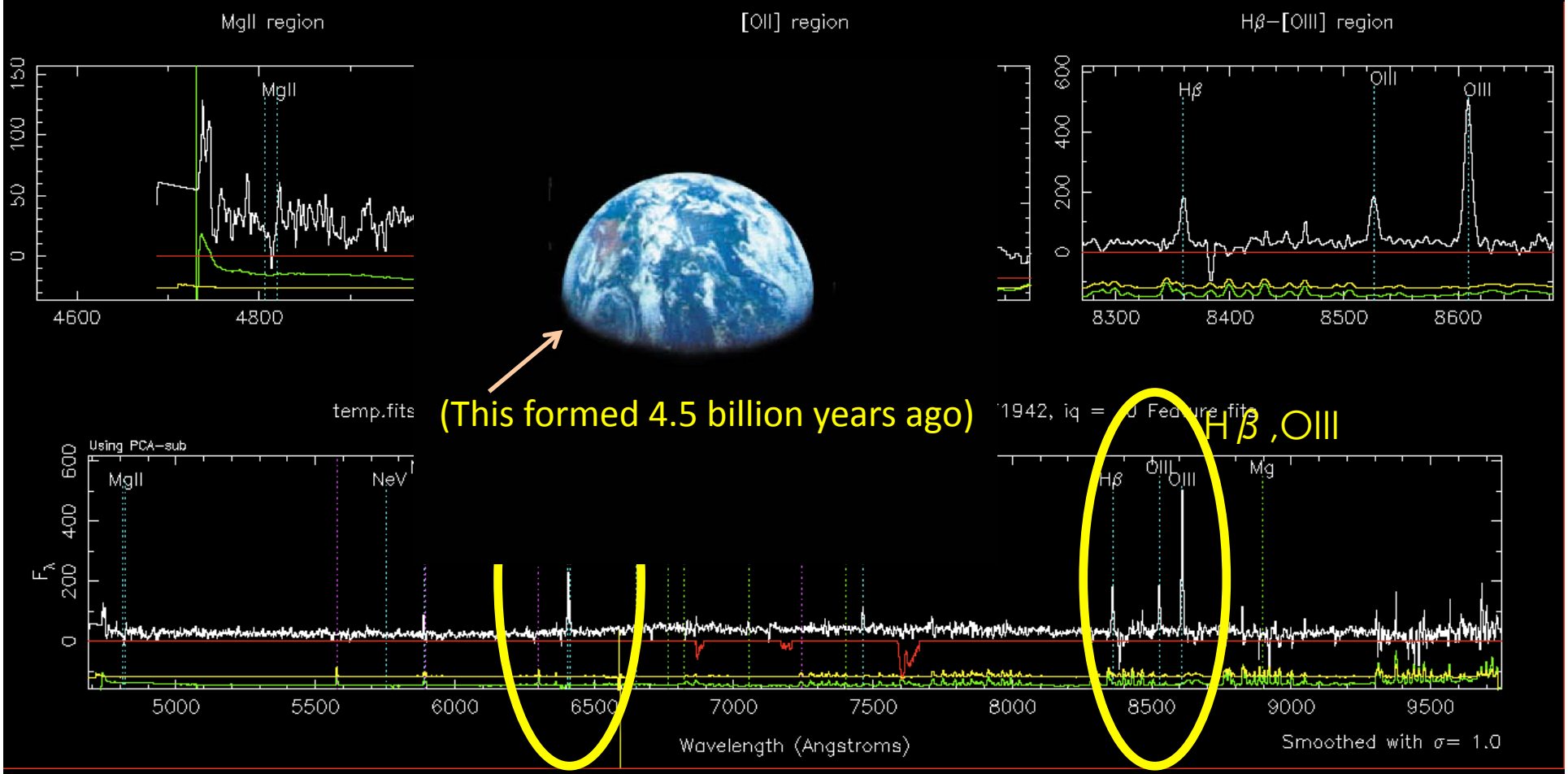
Example spectrum: z=0.72



This light was emitted

6.5 billion years ago

Example spectrum: z=0.72



This light was emitted

6.5 billion years ago

New WiggleZ results

- Today I'll present our major results:
  1. First high-redshift measurements of the growth of structure ➔ redshift space distortions confirm LCDM
  2. Geometric measurement of expansion rate [i.e. H(z)] with Alcock-Paczynski test ➔ model independent confirmation of acceleration
  3. First high-redshift measurement of Baryon Acoustic Oscillations ➔ standard rulers confirm LCDM
  4. Upper limit on the neutrino mass, using damping of structure on small scales

1. GROWTH OF STRUCTURE

Growth of structure

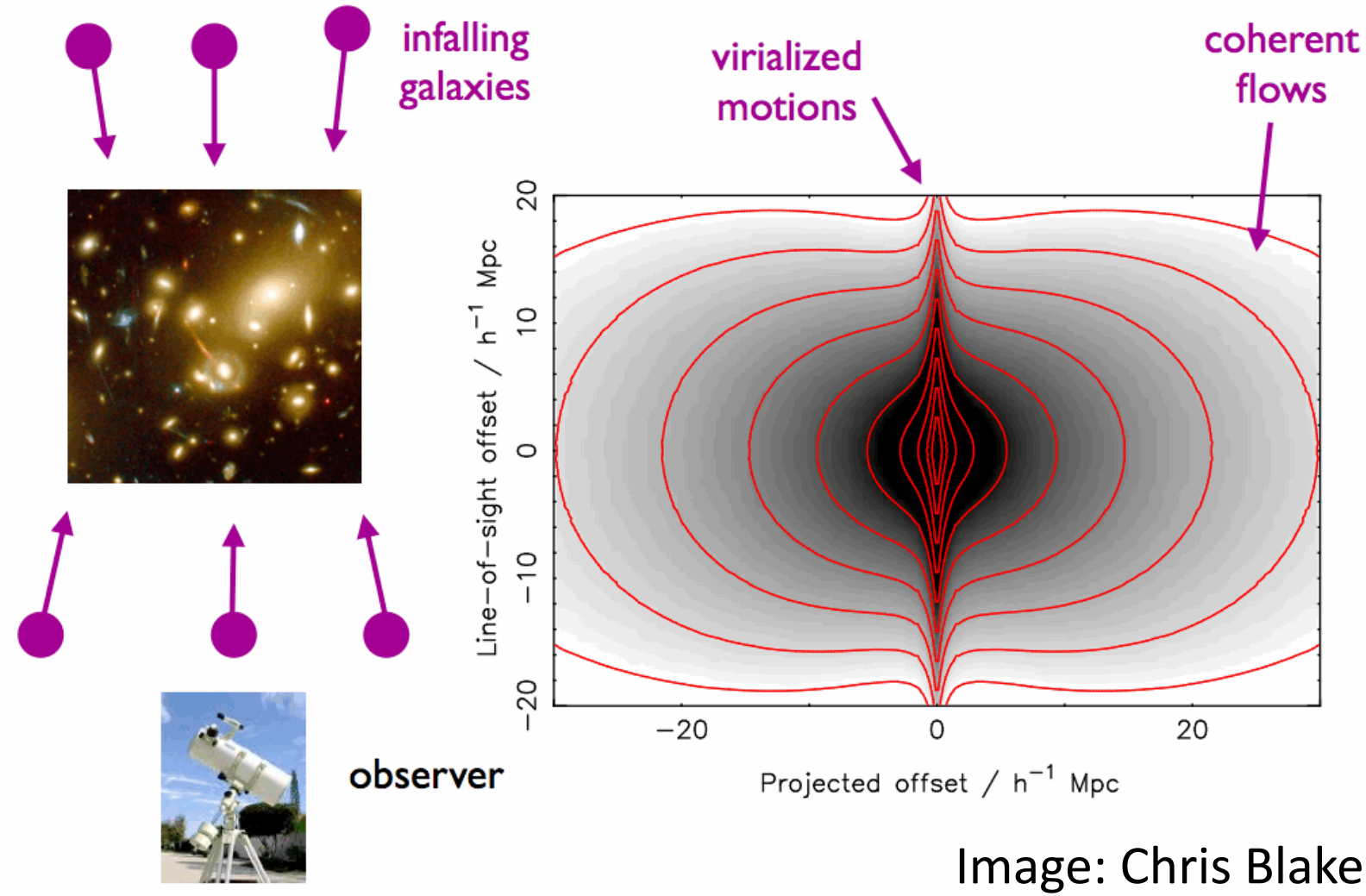
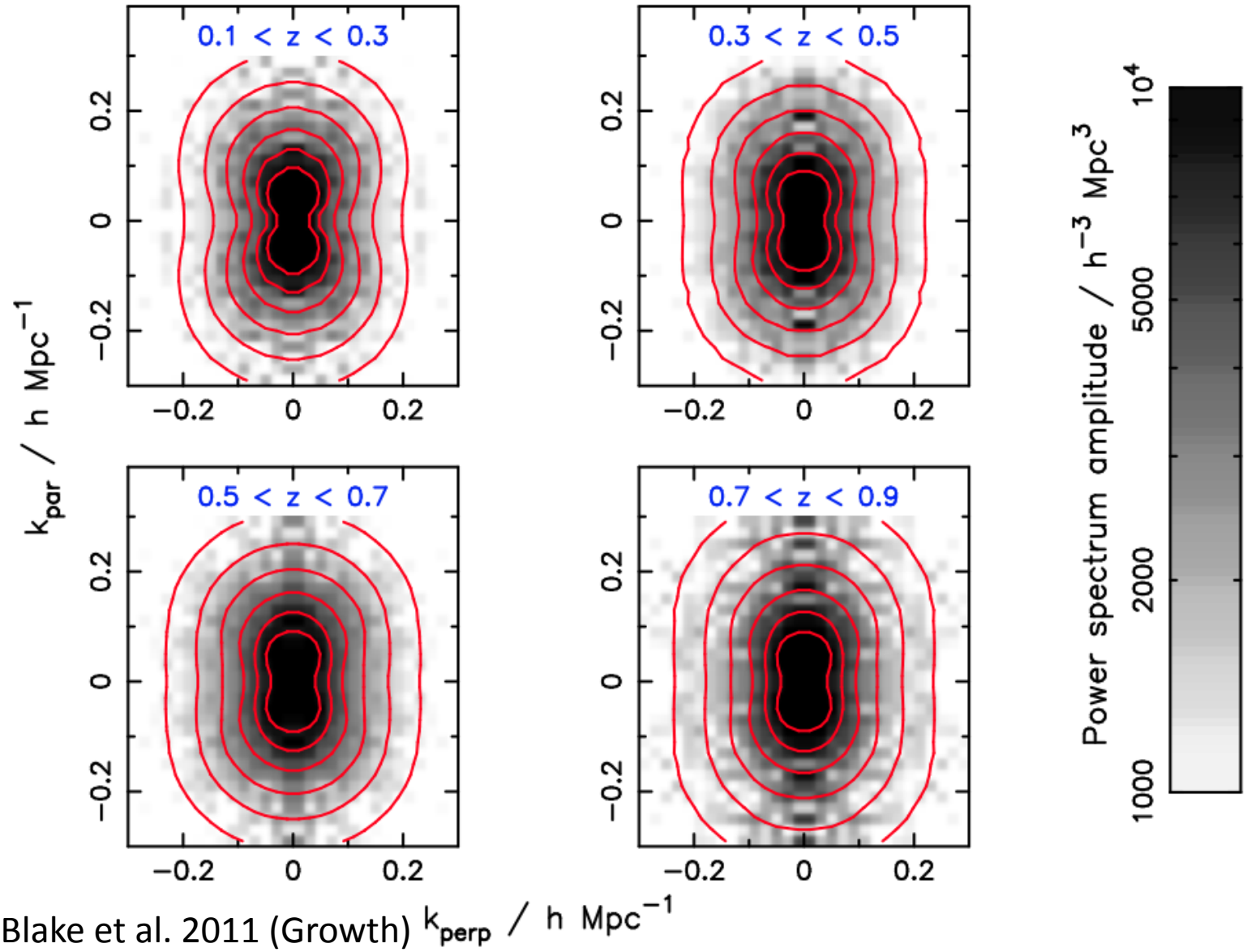


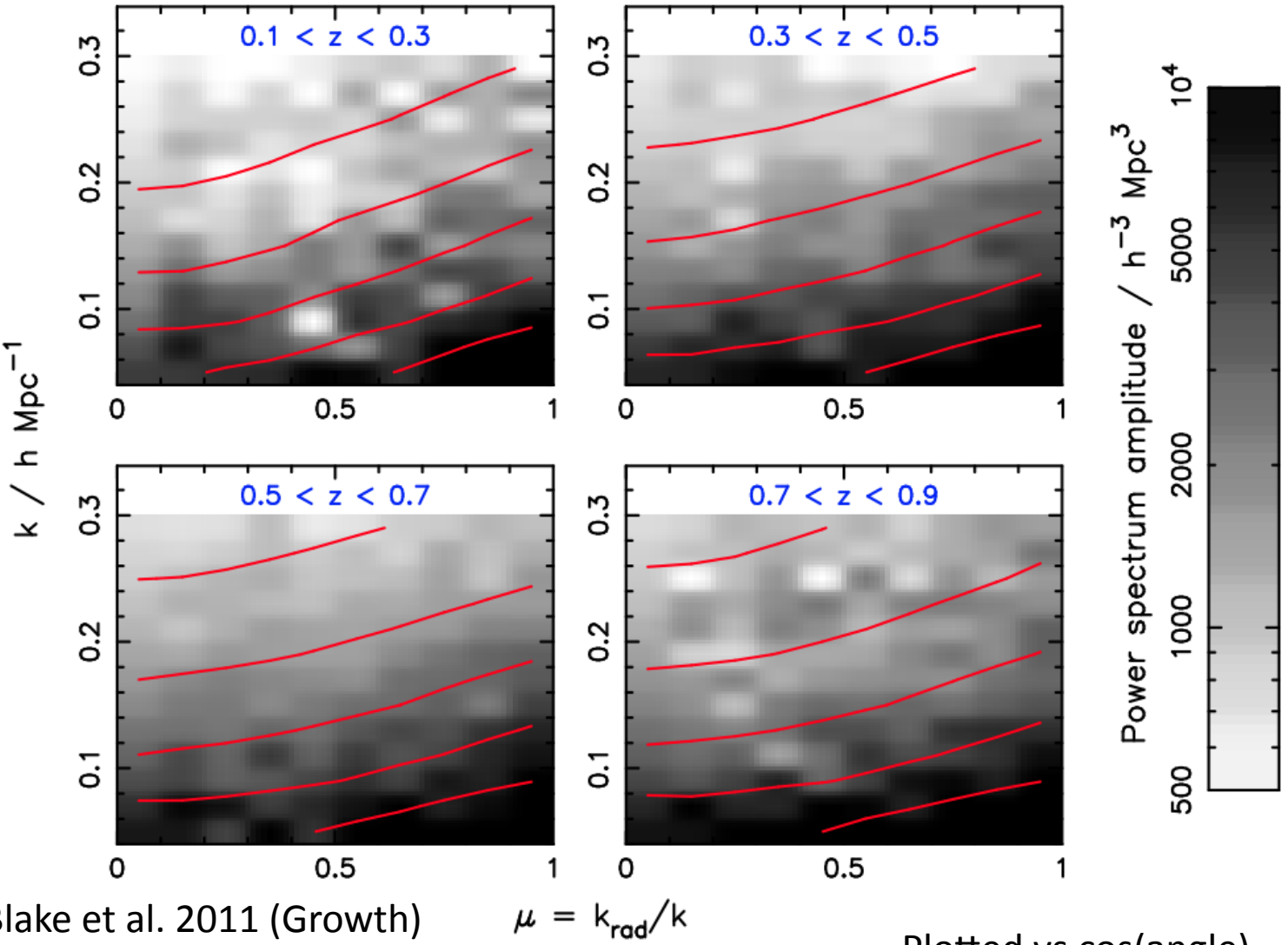
Image: Chris Blake

Growth of Structure – WiggleZ final



Blake et al. 2011 (Growth)

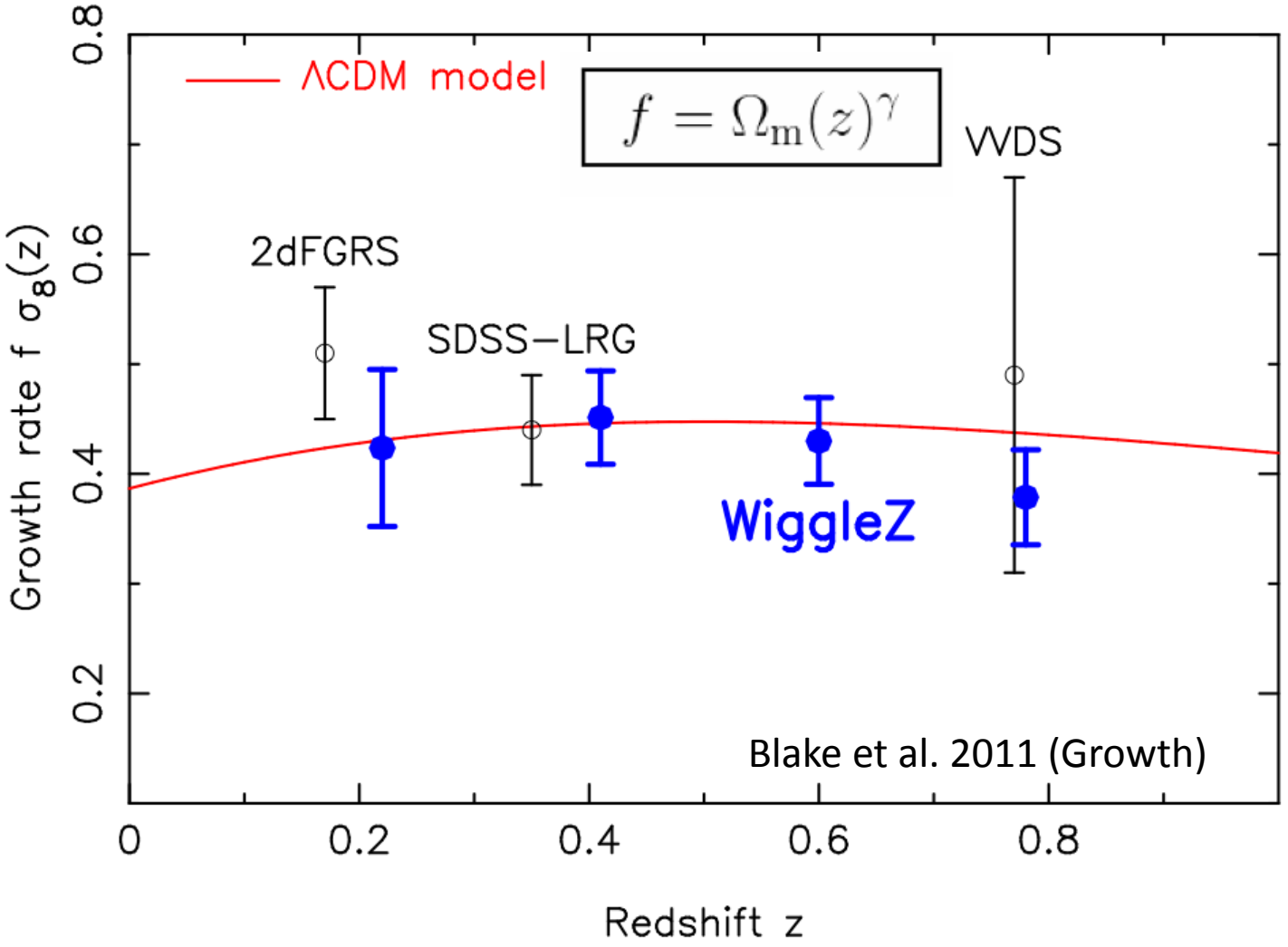
Growth of Structure – WiggleZ final



Blake et al. 2011 (Growth)

Plotted vs cos(angle)

Growth vs redshift



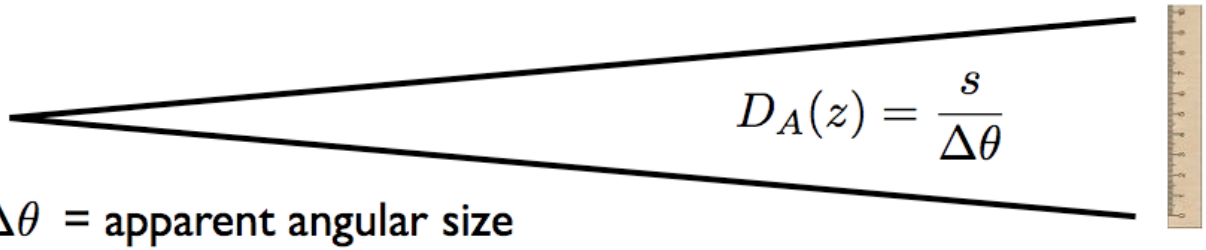
Blake et al. 2011 (Growth)

For other models see Parkinson et al. (in prep)

2. GEOMETRIC PROOF OF ACCELERATED EXPANSION:
H(Z) – ALCOCK PACZYNSKI TEST

Alcock-Paczynski test (spheres in space!!)

- Needs a standard ruler in 3D!
- Our standard sphere is the power spectrum

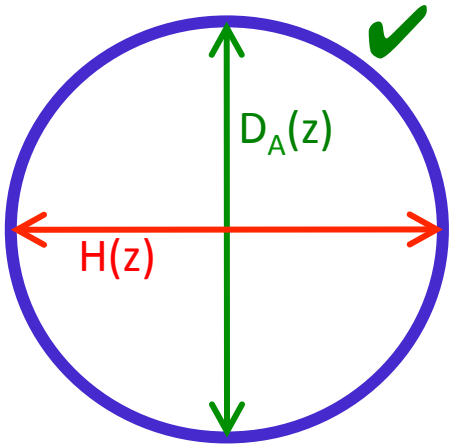


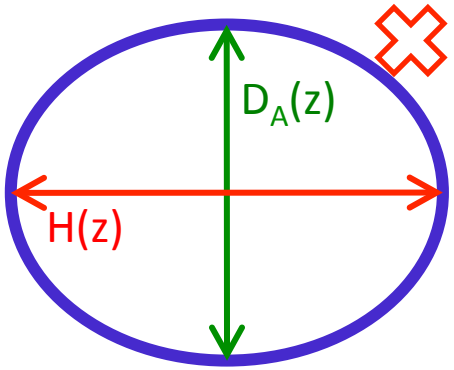
$$D_A(z) = \frac{s}{\Delta\theta}$$

$\Delta\theta$ = apparent angular size
~ 2.6 deg at z=1

Δz = apparent redshift extent
~ 0.06 at z=1

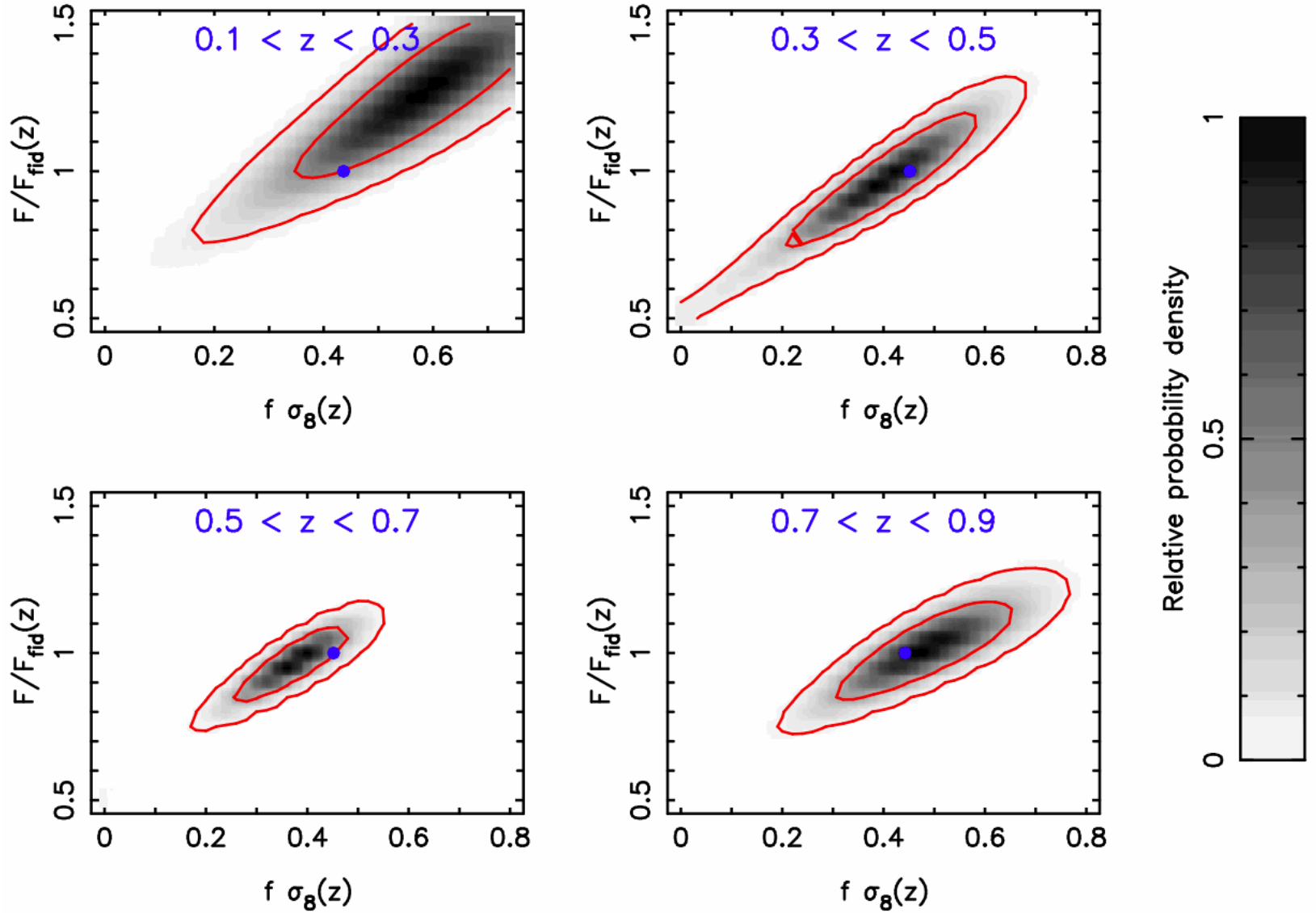
$$H(z) = \frac{c\,\Delta z}{s}$$





- We can measure ratio Δθ/Δz without knowing size s

Alcock-Paczynski / z-space distortions



Blake, Glazebrook, Davis et al. 2011 (AP)

First accurate measurement (no model) of Expansion rate vs redshift

WiggleZ measures ratio

$$(1+z)D_A(z)H(z)/c$$

Supernovae measure

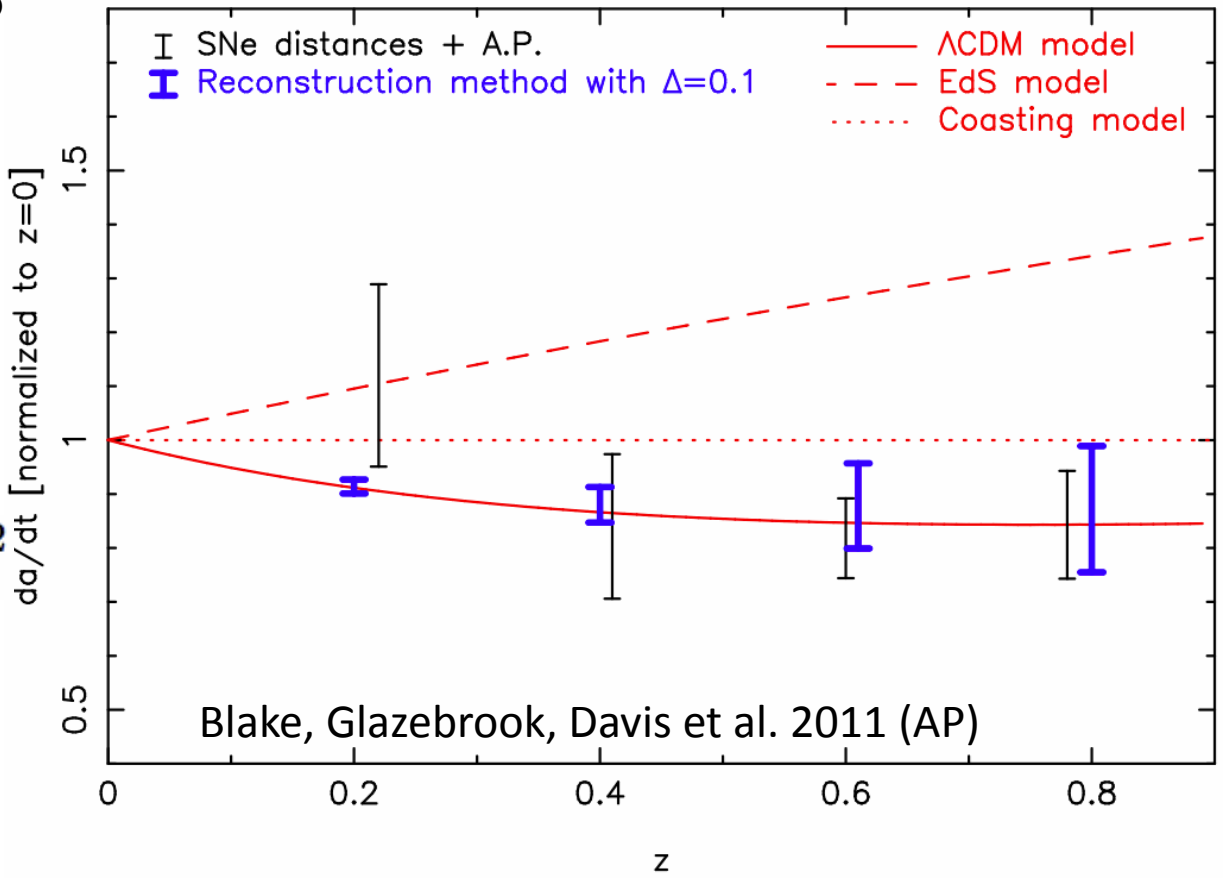
$$D_L(z)\,H_0/c$$

So we can eliminate D_A using:

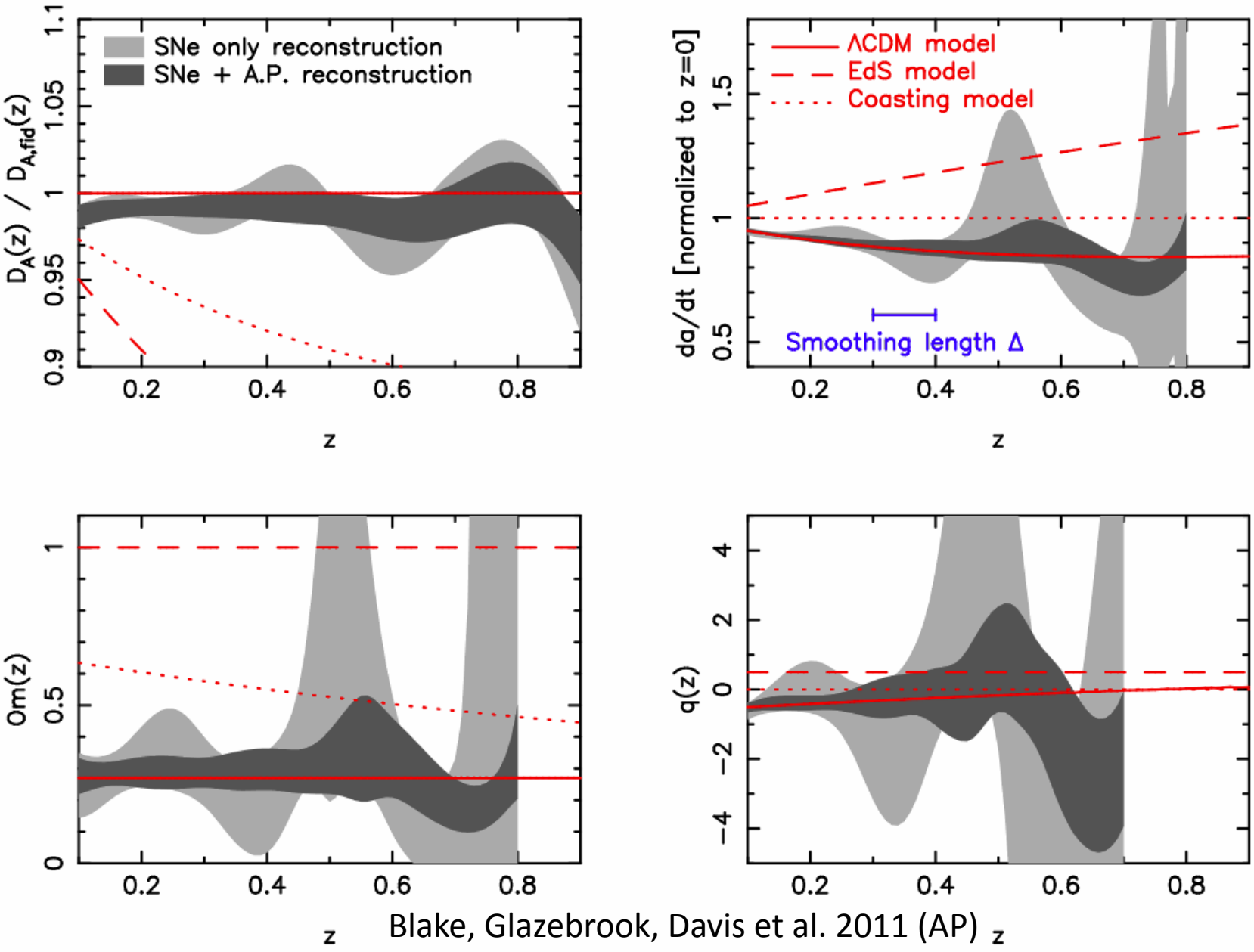
$$D_L(z) = D_A(z)\,(1+z)^2$$

So we can now **measure**

$$H(z)/H_0$$

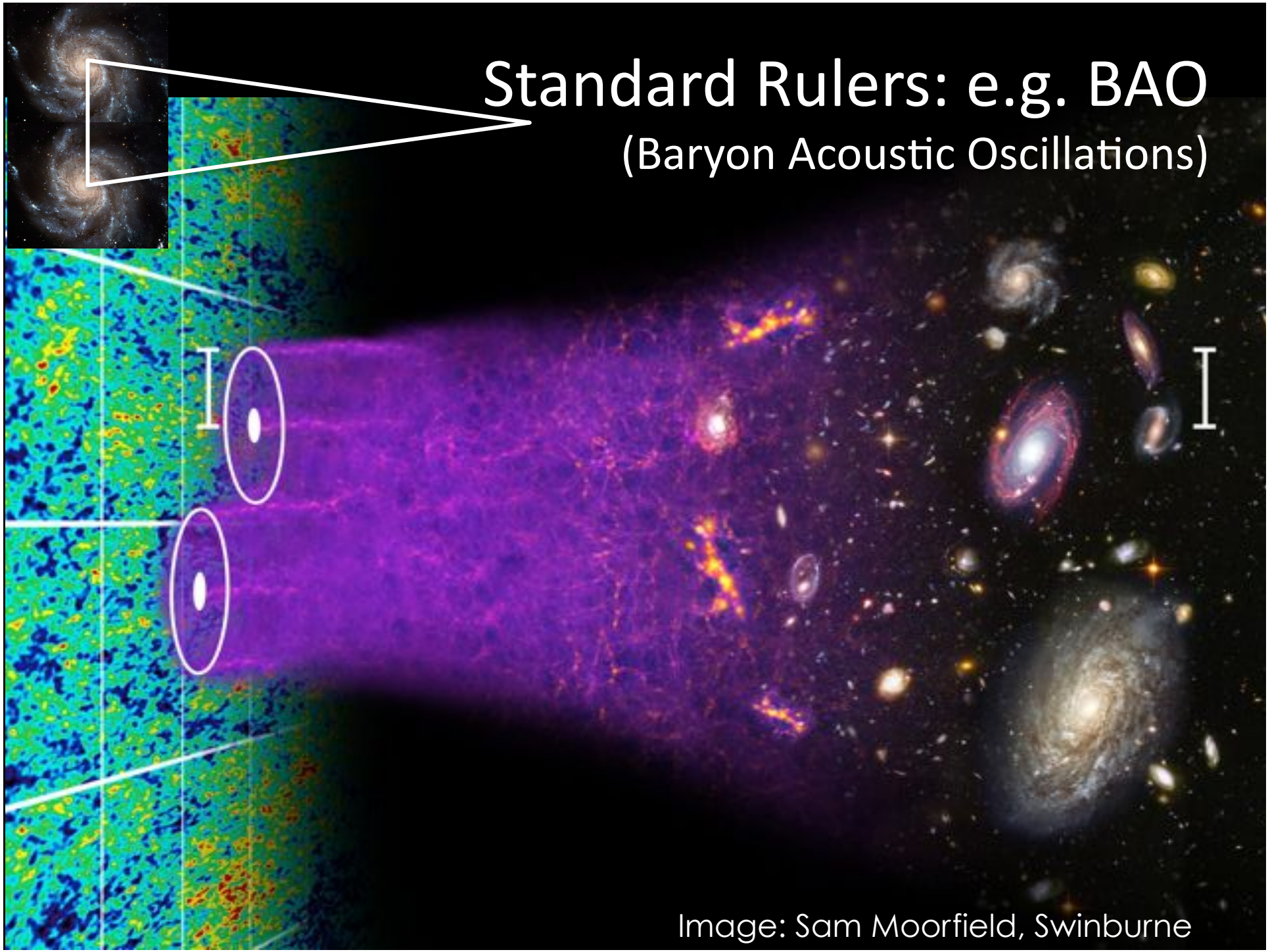


Reconstructions

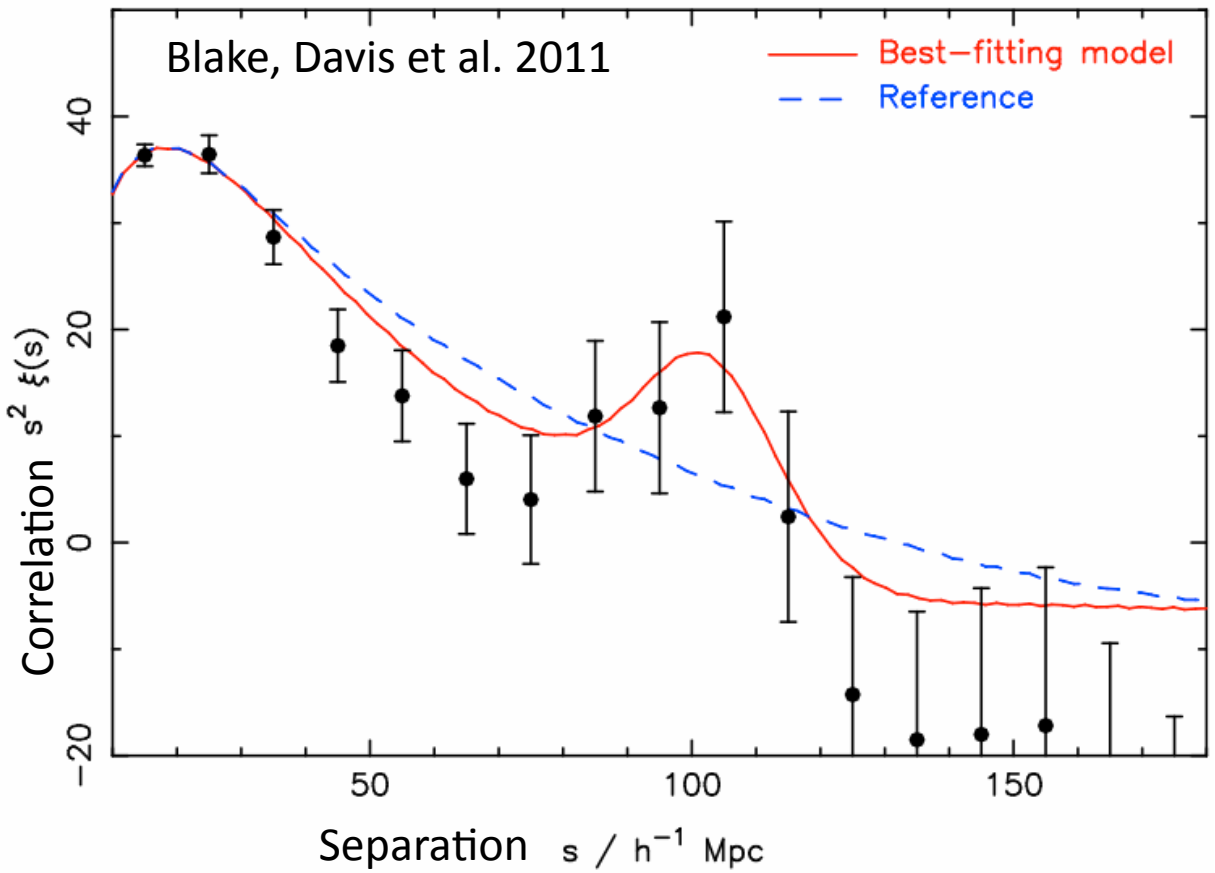


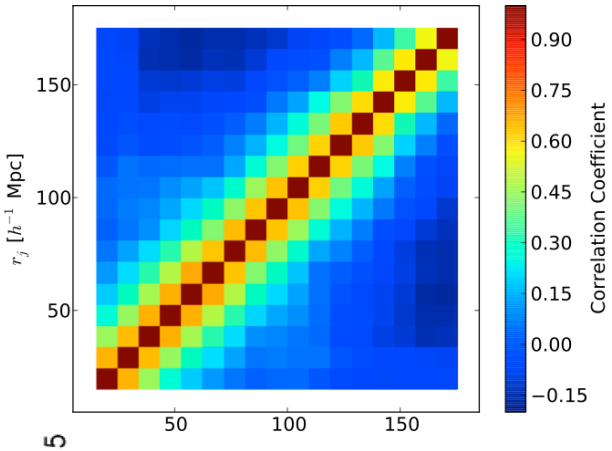
Blake, Glazebrook, Davis et al. 2011 (AP)

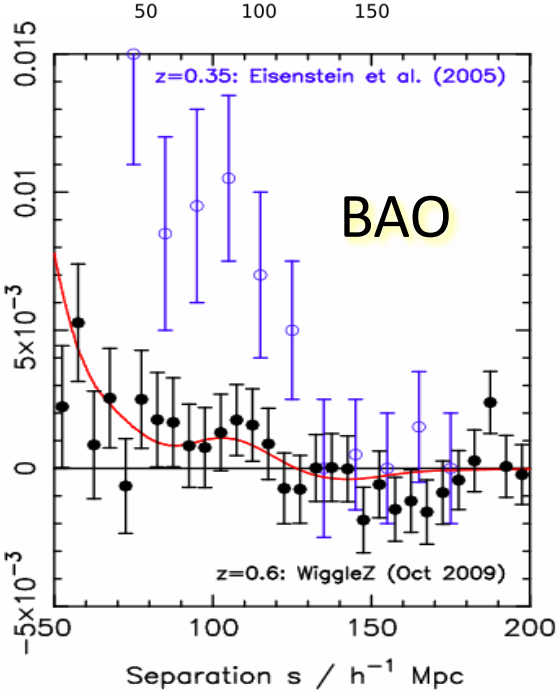
3. $D_A(Z)$ – BARYON ACOUSTIC OSCILLATIONS


Standard Rulers: e.g. BAO
(Baryon Acoustic Oscillations)
Image: Sam Moorfield, Swinburne

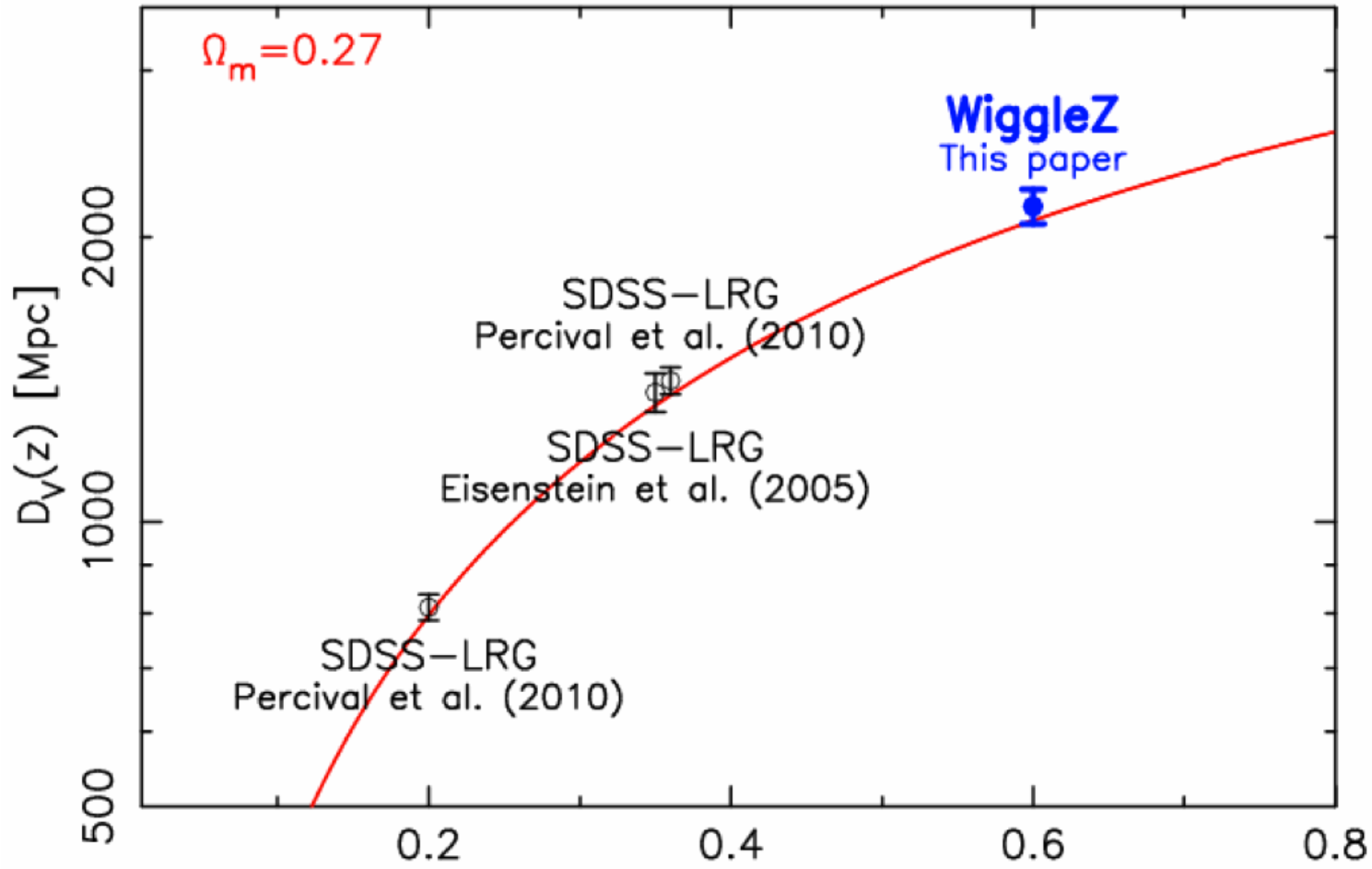
WiggleZ detection of BAO at z=0.6







Distance-redshift relation at =0.6

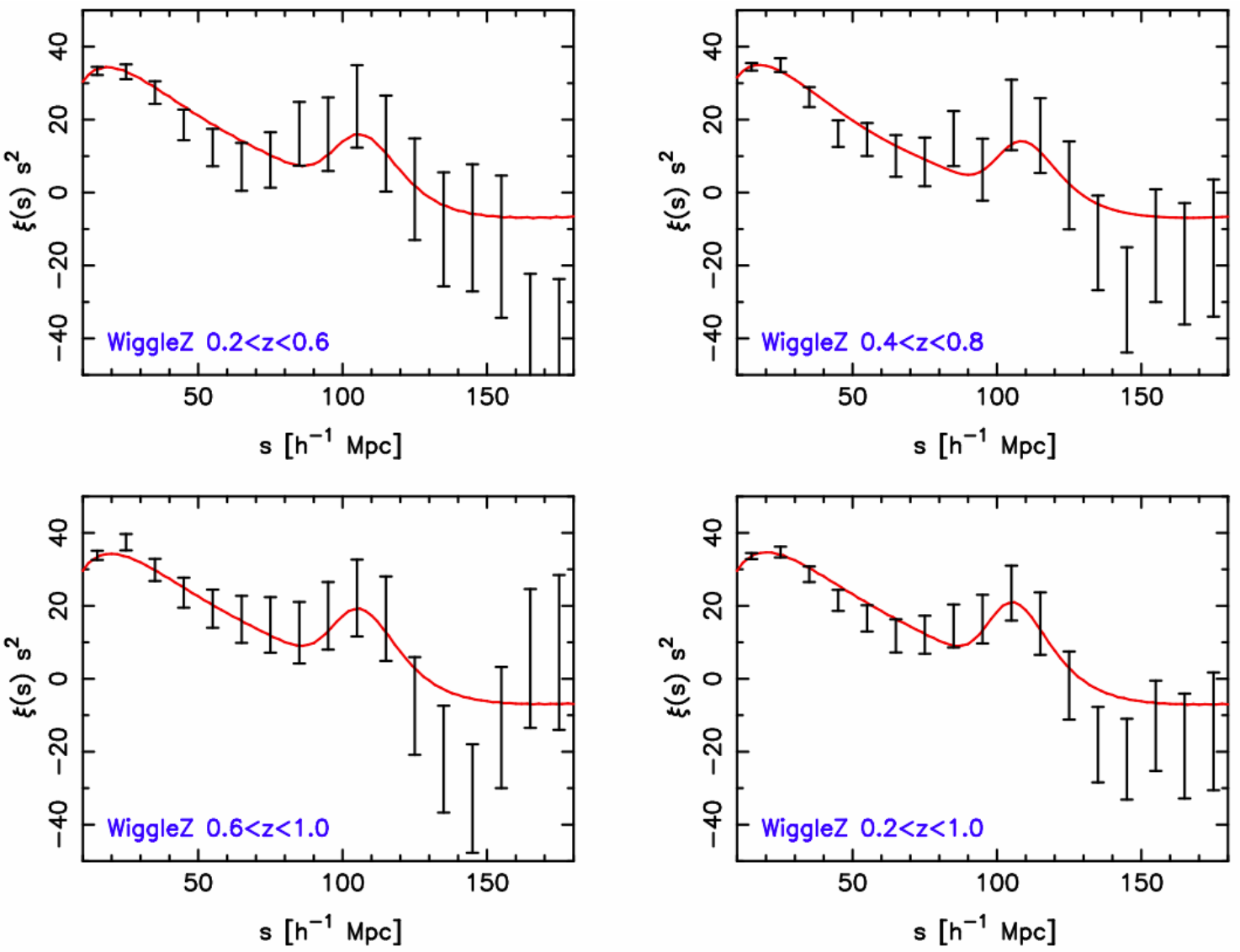


All that effort = one number!

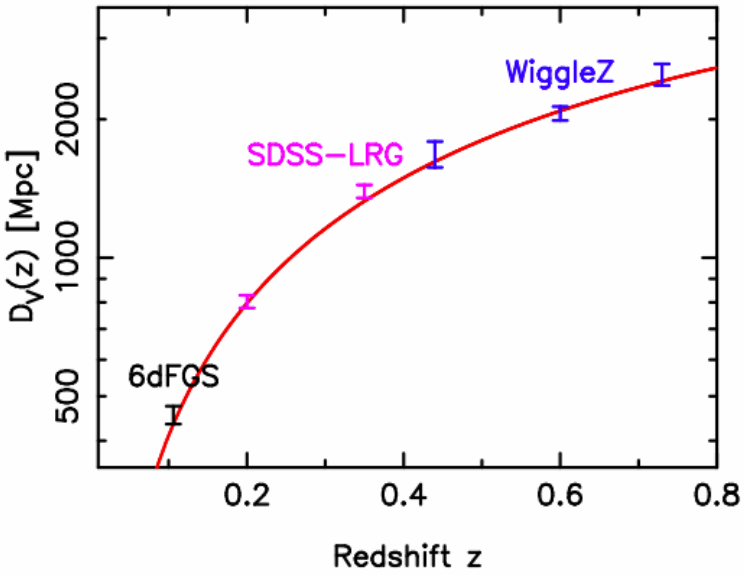
Strong confirmation of LCDM model

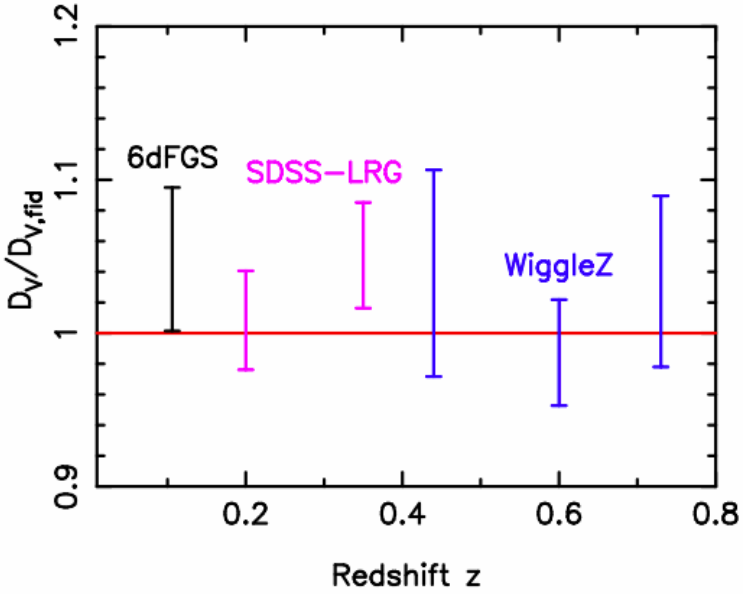
Hot off* the press!

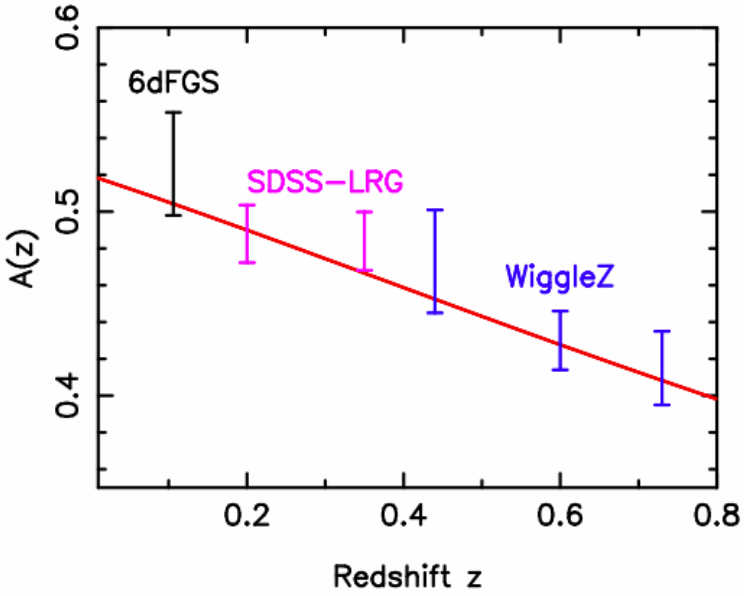
* (Well, hopefully on its way to press!)

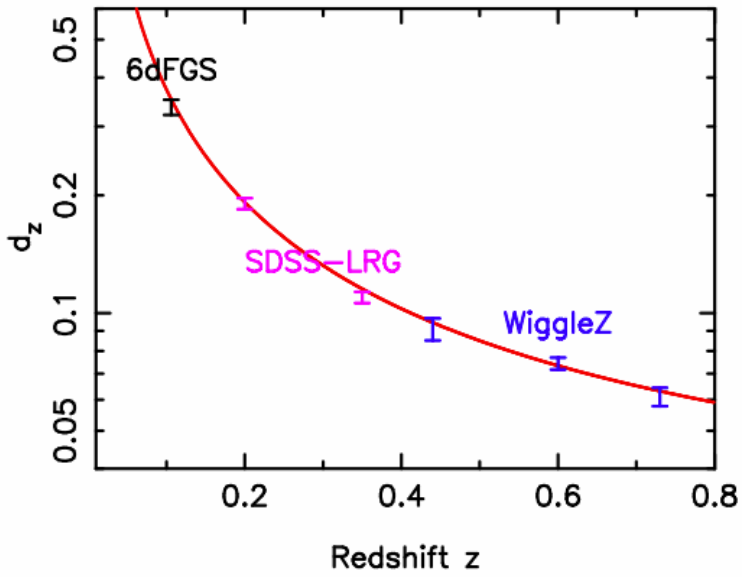


Final WiggleZ BAO results



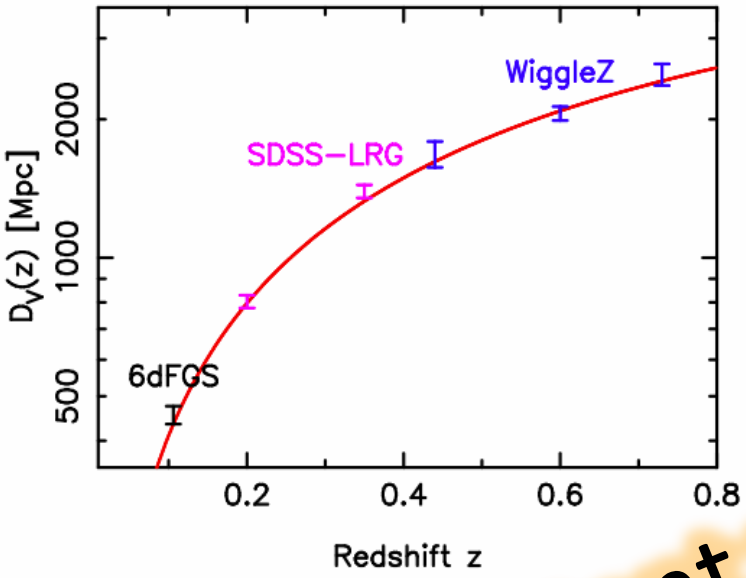


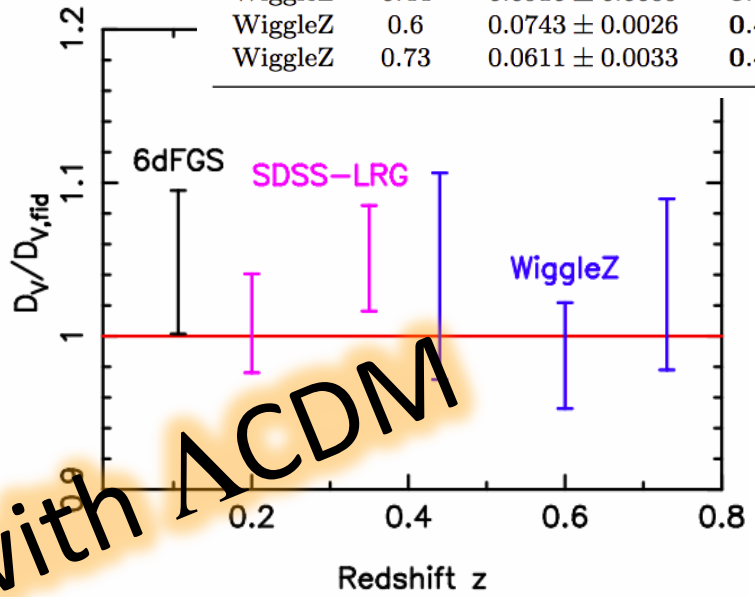




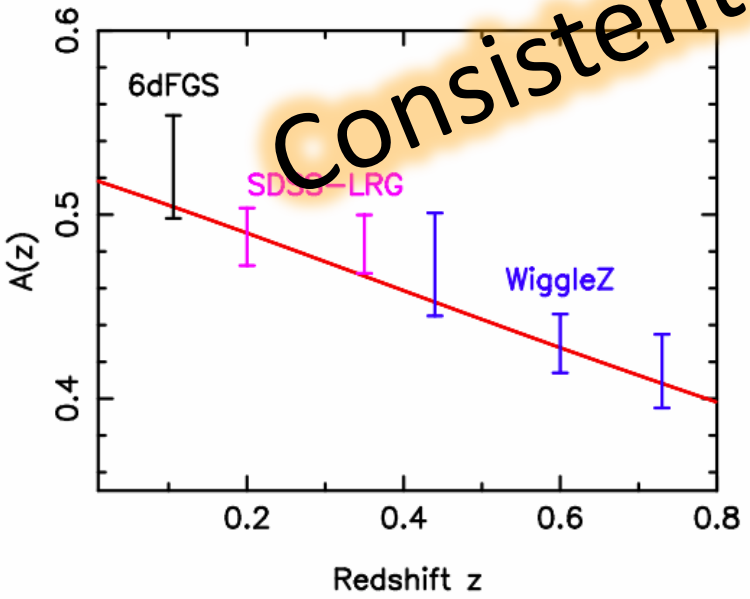
Final WiggleZ BAO resu

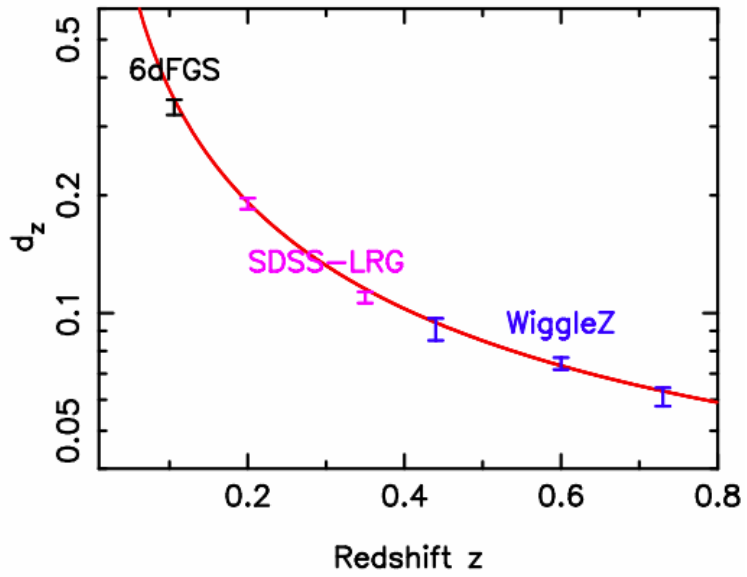
Sample	z	d_z	$A(z)$
6dFGS	0.106	$\mathbf{0.336 \pm 0.015}$	0.526 ± 0.028
SDSS	0.2	$\mathbf{0.1905 \pm 0.0061}$	0.488 ± 0.016
SDSS	0.35	$\mathbf{0.1097 \pm 0.0036}$	0.484 ± 0.016
WiggleZ	0.44	0.0910 ± 0.0059	$\mathbf{0.473 \pm 0.028}$
WiggleZ	0.6	0.0743 ± 0.0026	$\mathbf{0.430 \pm 0.016}$
WiggleZ	0.73	0.0611 ± 0.0033	$\mathbf{0.415 \pm 0.020}$





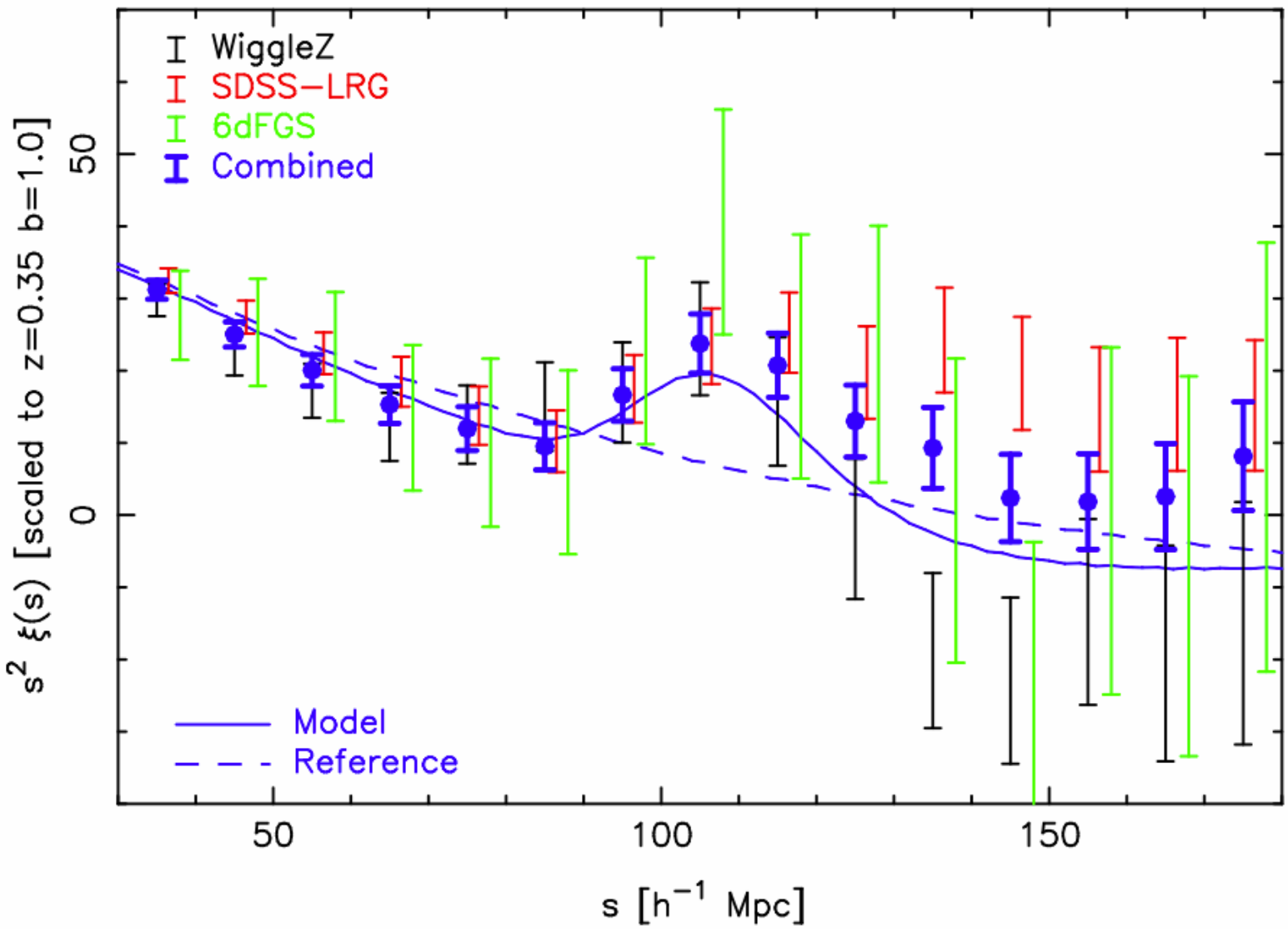
Consistent with ΛCDM



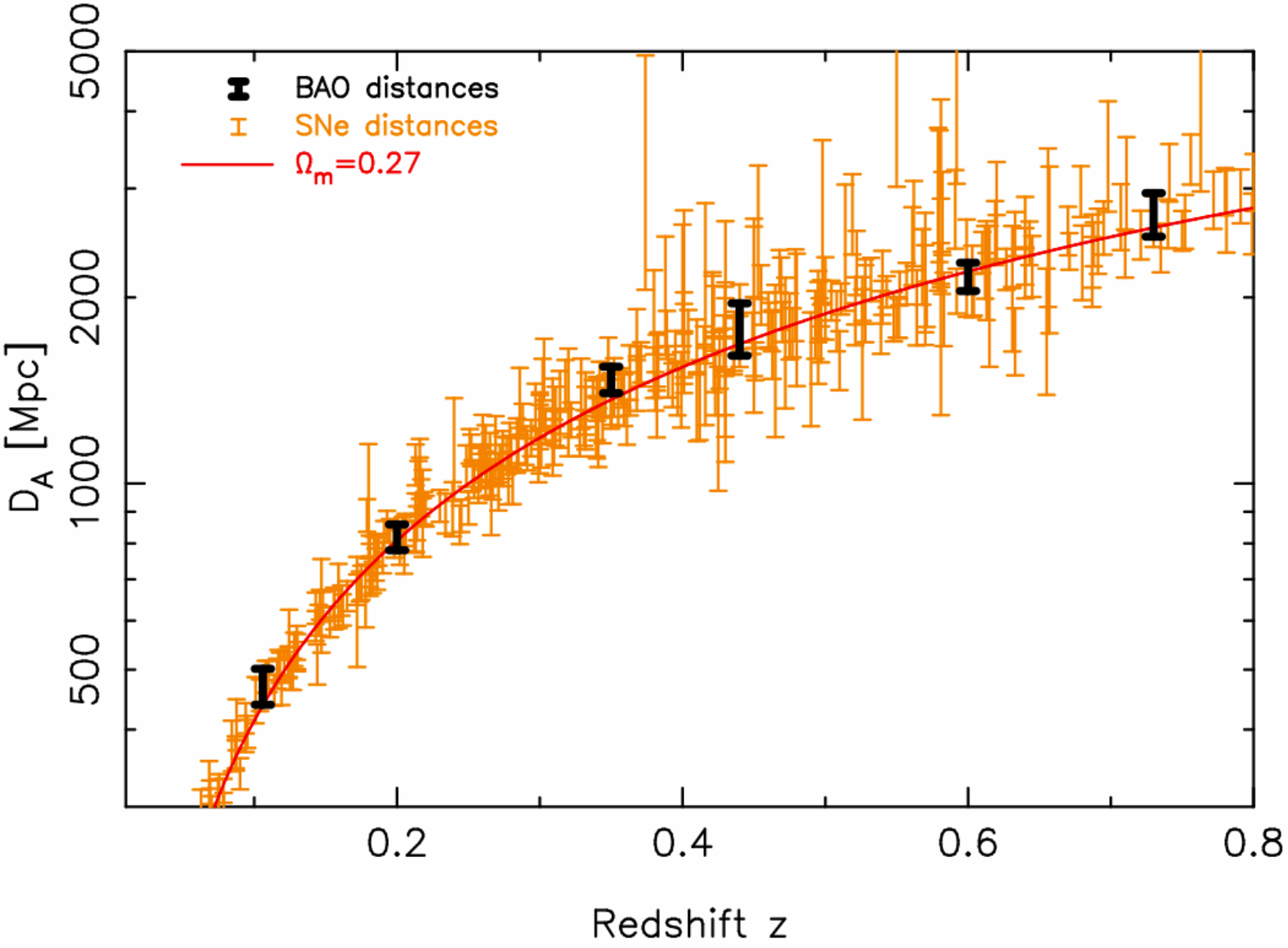


How significant is the BAO detection?

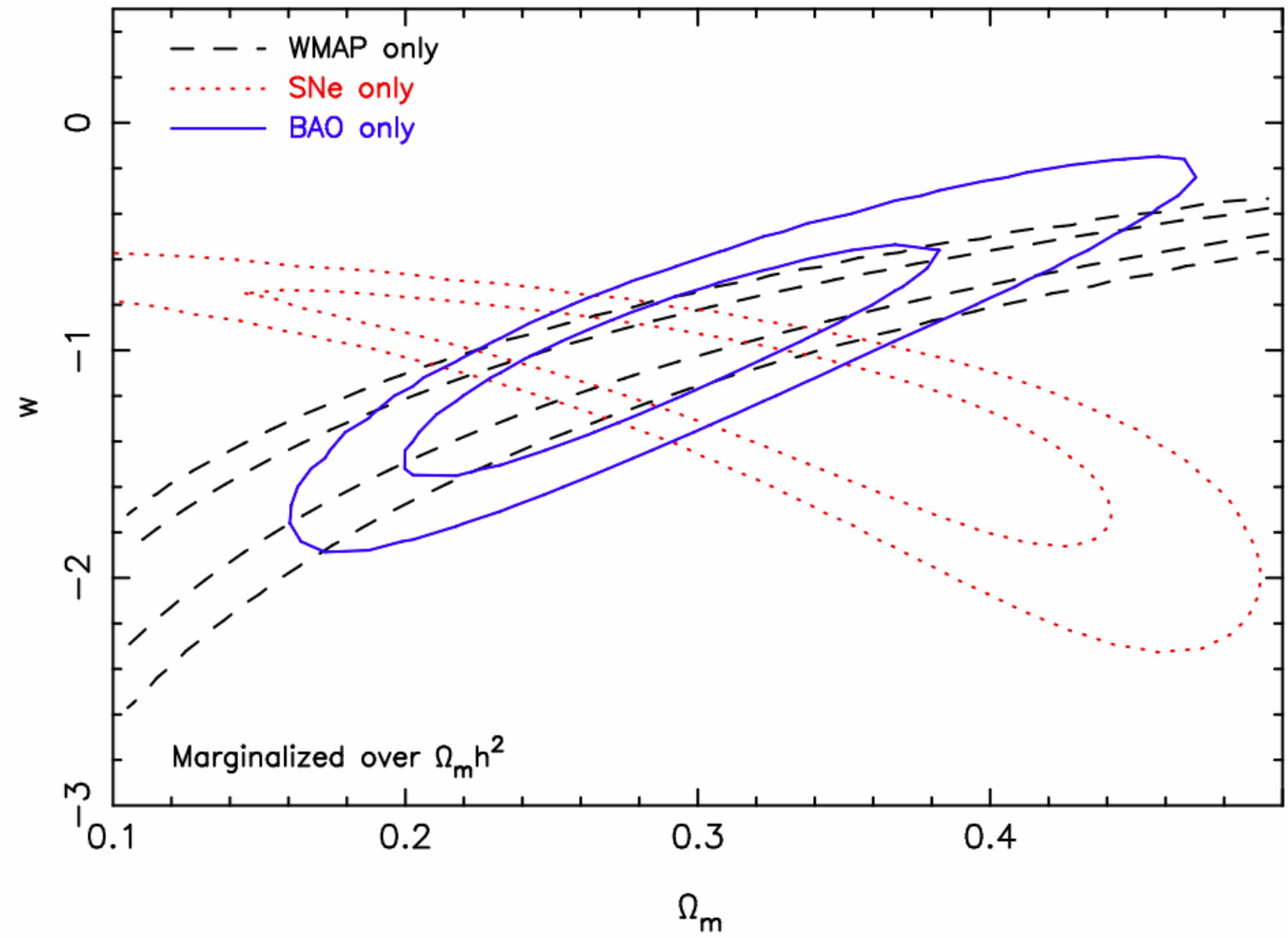
Stacked correlation function = 5σ detection



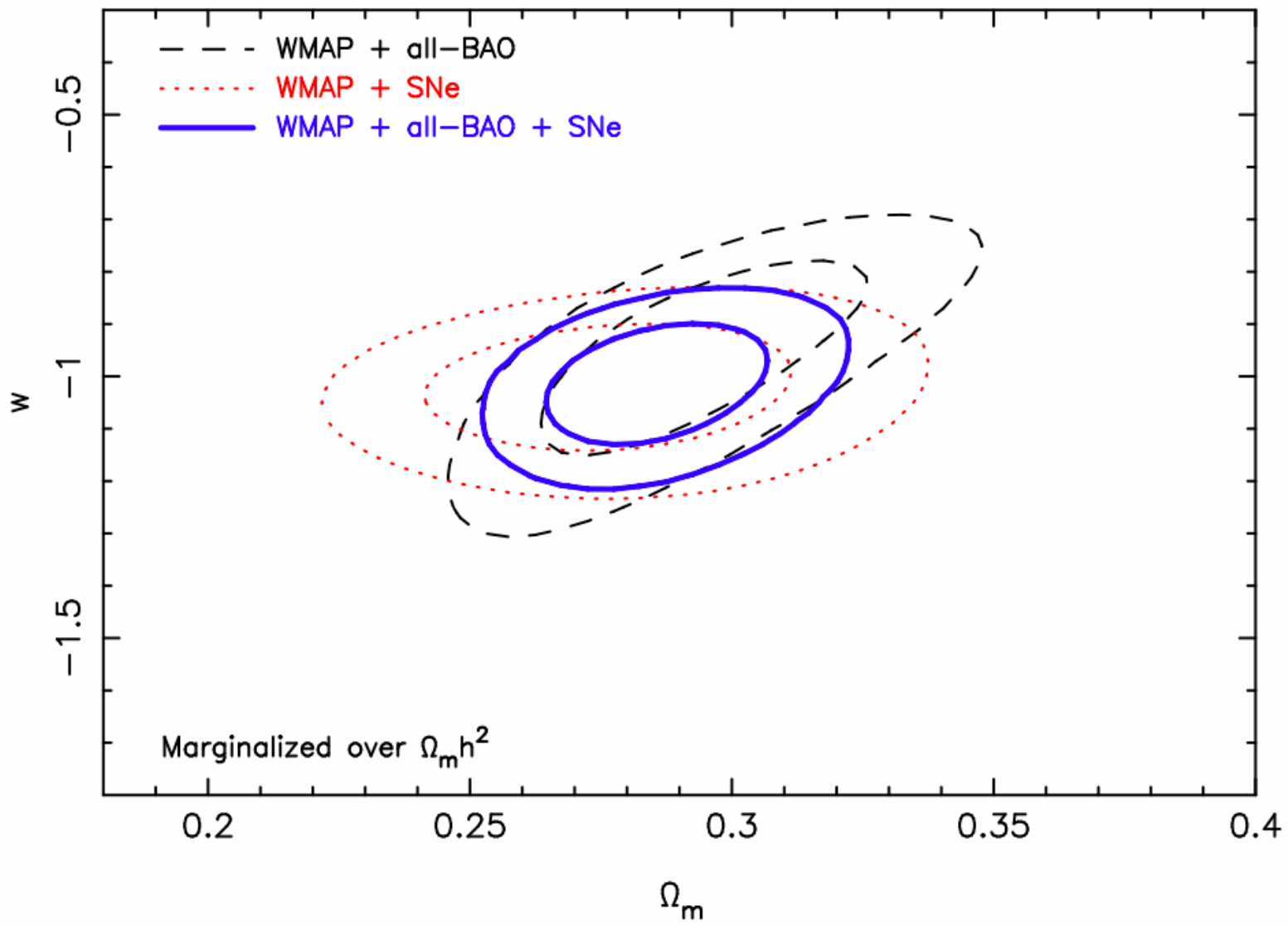
Compared to supernovae



Cosmological parameter constraints



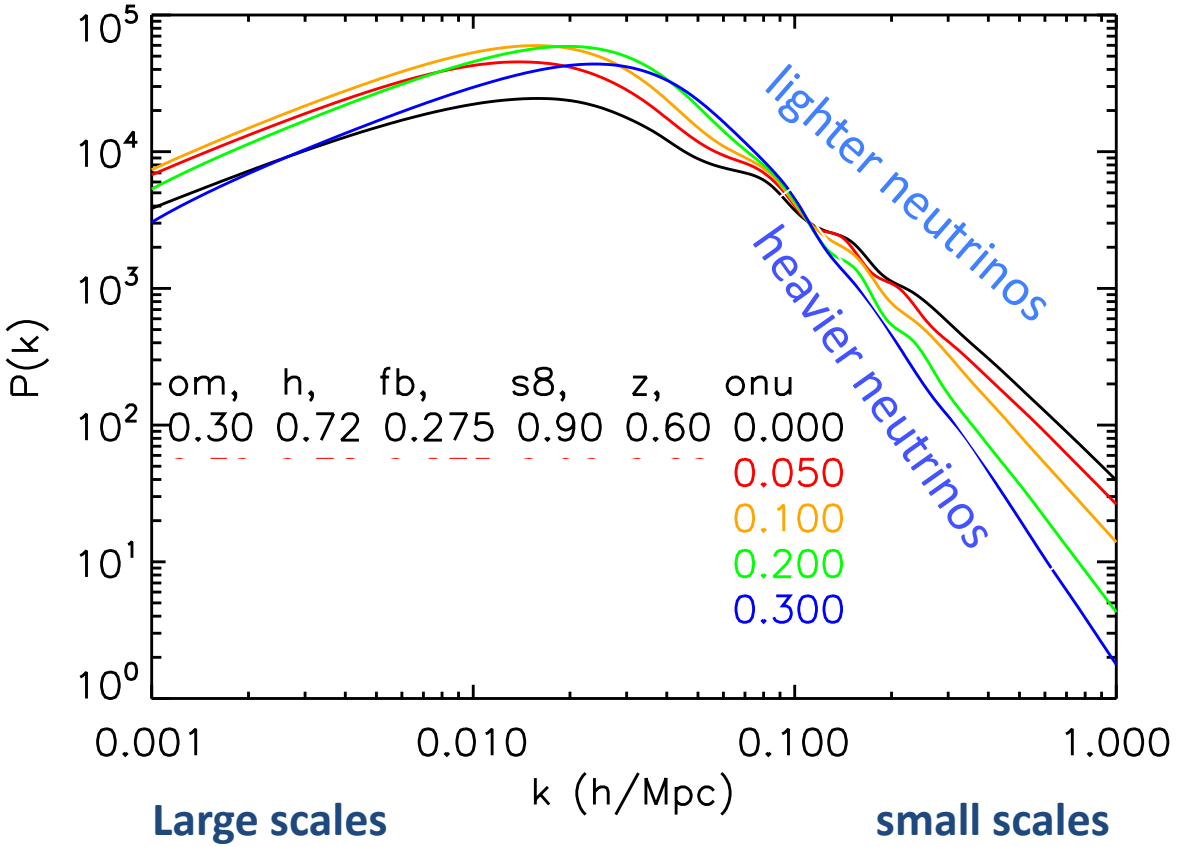
Cosmological parameter constraints



4. MASS OF THE NEUTRINO

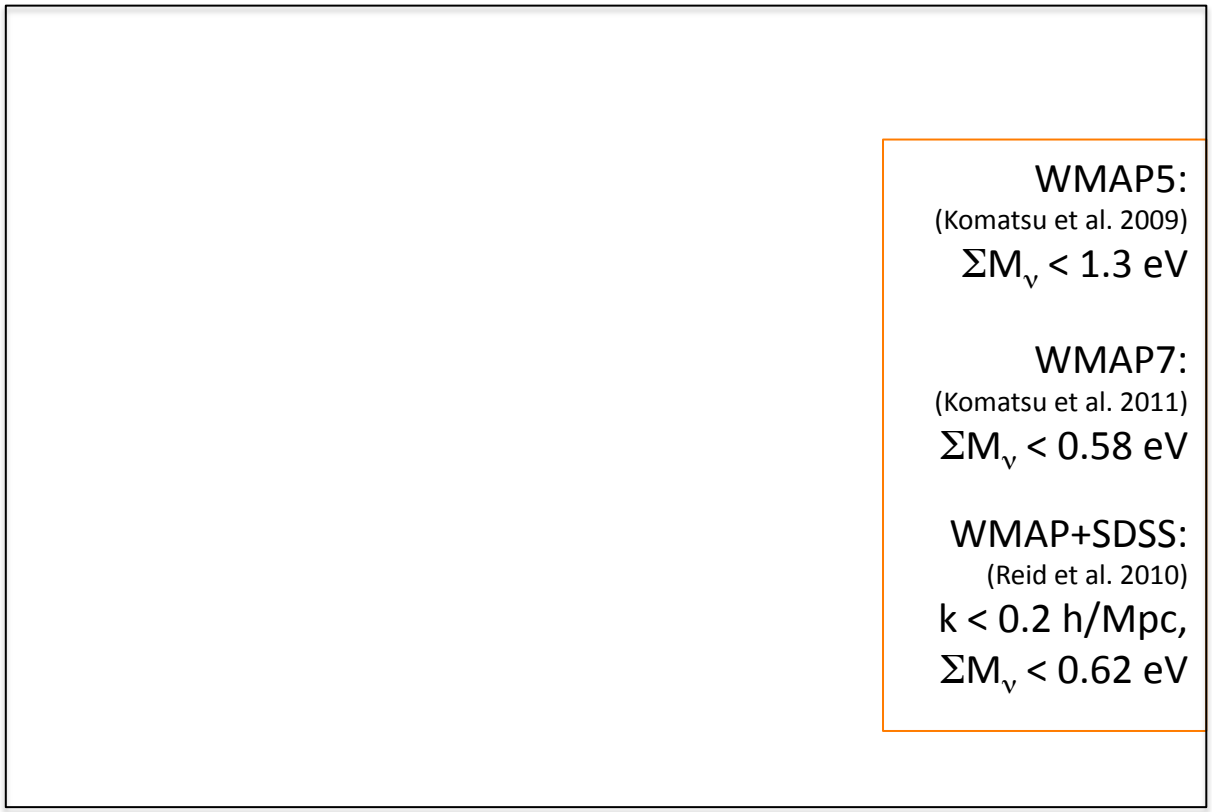
Neutrino mass

- Particle physics measures mass differences, but absolute mass limits are weak
  - $m_{ve} \leq 2.05$eV from Troitsk beta decay experiment
- Cosmology can measure total mass
  - Massive neutrinos free stream out of over-densities and *damp power on small scales*



Neutrino mass – preliminary results

- WiggleZ is at higher redshift and is less biased than SDSS
- Therefore we have very robust constraints on neutrino mass
- Linear out to k~0.15 (confirmed with GiggleZ sims to better than 1%)



WMAP5:
(Komatsu et al. 2009)
$\Sigma M_\nu < 1.3$ eV

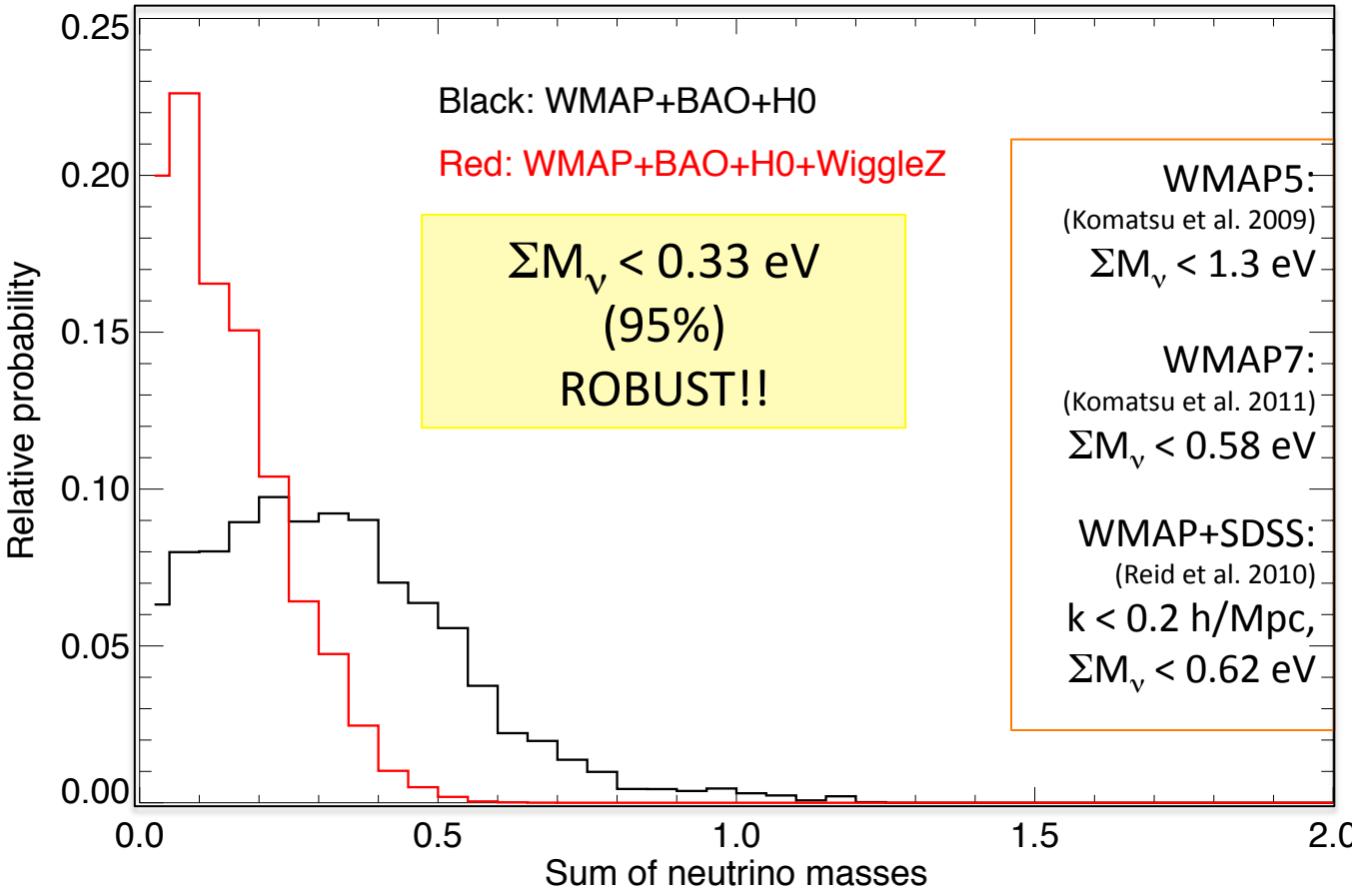
WMAP7:
(Komatsu et al. 2011)
$\Sigma M_\nu < 0.58$ eV

WMAP+SDSS:
(Reid et al. 2010)
$k < 0.2$ h/Mpc,
$\Sigma M_\nu < 0.62$ eV

Neutrino mass – preliminary results

- WiggleZ is at higher redshift and is less biased than SDSS
- Therefore we have very robust constraints on neutrino mass
- Linear out to k~0.15 (confirmed with GiggleZ sims to better than 1%)

- Riemer-Sørensen et al. (in prep)
- Fit only over k=0.02-0.15h/Mpc
- No damping model needed (linear regime only)
- Will do better, modeling higher-k region, but more susceptible to systematics



Summary:

1. **Growth of structure – confirms LCDM model**
   1. Blake et al. 2011, MNRAS (in press: 1104.2948)
2. **BAO standard ruler $D_V(z)$ – confirms LCDM model**
   1. Blake, Davis et al. 2011, MNRAS (in press: 1105.2862)
   2. Blake, Kazin, Beutler, Davis et al. (submitted)
3. **Expansion rate H(z) – geometric proof of acceleration**
   1. Blake, Glazebrook, Davis et al. (submitted)
4. **Neutrino mass – new upper mass limit**
   1. Riemer-Sørensen et al. (in prep)

- Also…
- WiggleZ survey description:
  - Drinkwater et al. 2010 MNRAS 401(3), 1429
- WiggleZ selection function and power spectrum:
  - Blake et al. 2010, MNRAS 406(2), 803