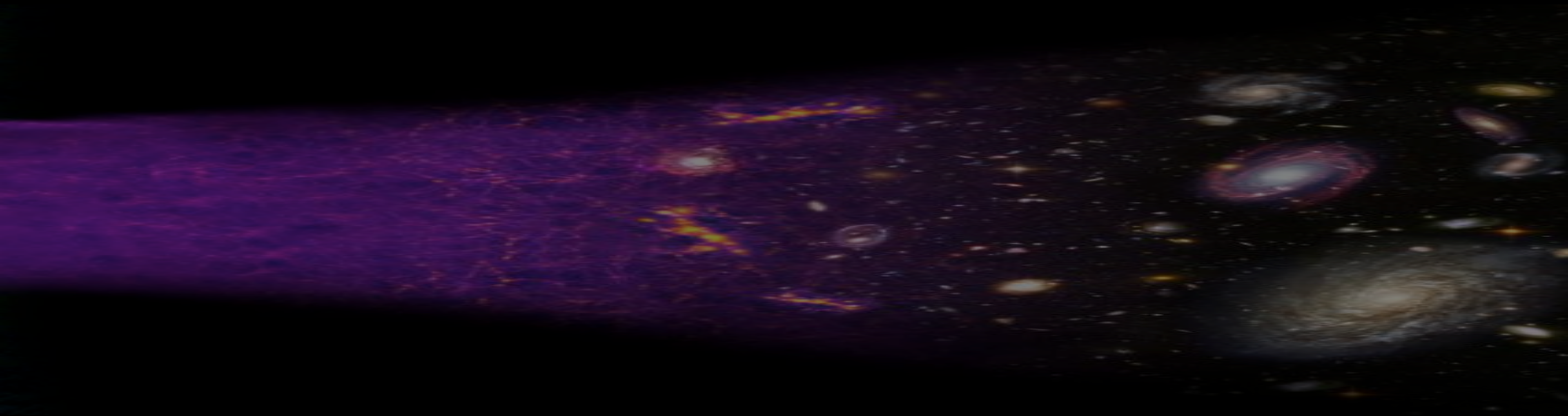

WiggleZ Final Results (almost!)

Tamara Davis

University of Queensland

and the whole WiggleZ team

UQ: Michael Drinkwater, Tamara Davis, David Parkinson, Signe Riemer-Sorensen, Russell Jurek (now at ATNF)
Swinburne: Warrick Couch, Chris Blake, Karl Glazebrook, Greg Poole, Darren Croton, Eyal Kazin, Felipe Marin
AAO: Matthew Colless, Rob Sharp, Sarah Brough; Sydney: Scott Croom, Ben Jellife; ANU: Mike Pracy;
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Plus students and associate members

+

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Theoretician was incorrect

+

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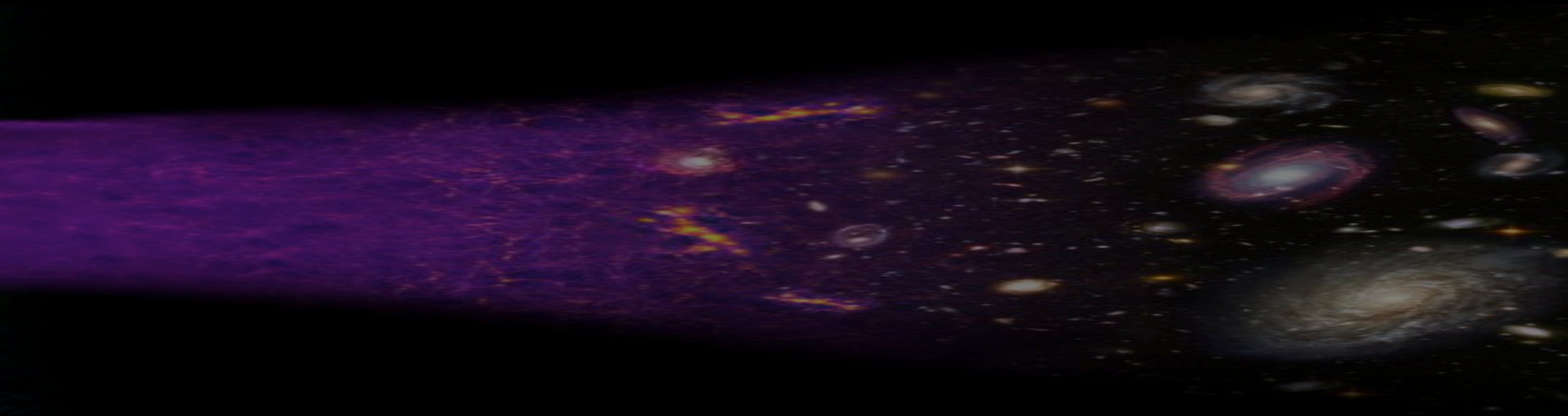

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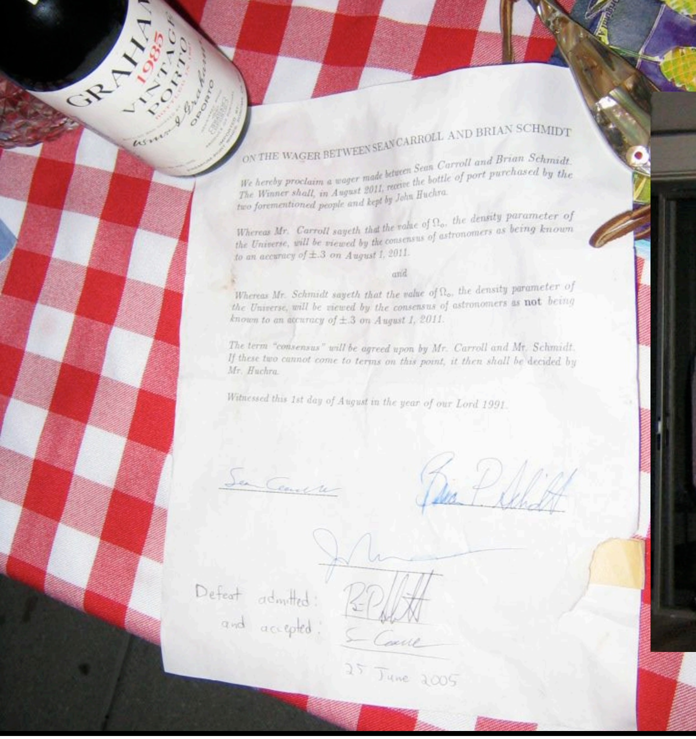
The prize



ON THE WAGER BETWEEN SEAN CARROLL AND BRIAN SCHMIDT

We hereby proclaim a wager made between Sean Carroll and Brian Schmidt. The Winner shall, in August 2011, receive the bottle of port purchased by the two forementioned people and kept by John Huchra.

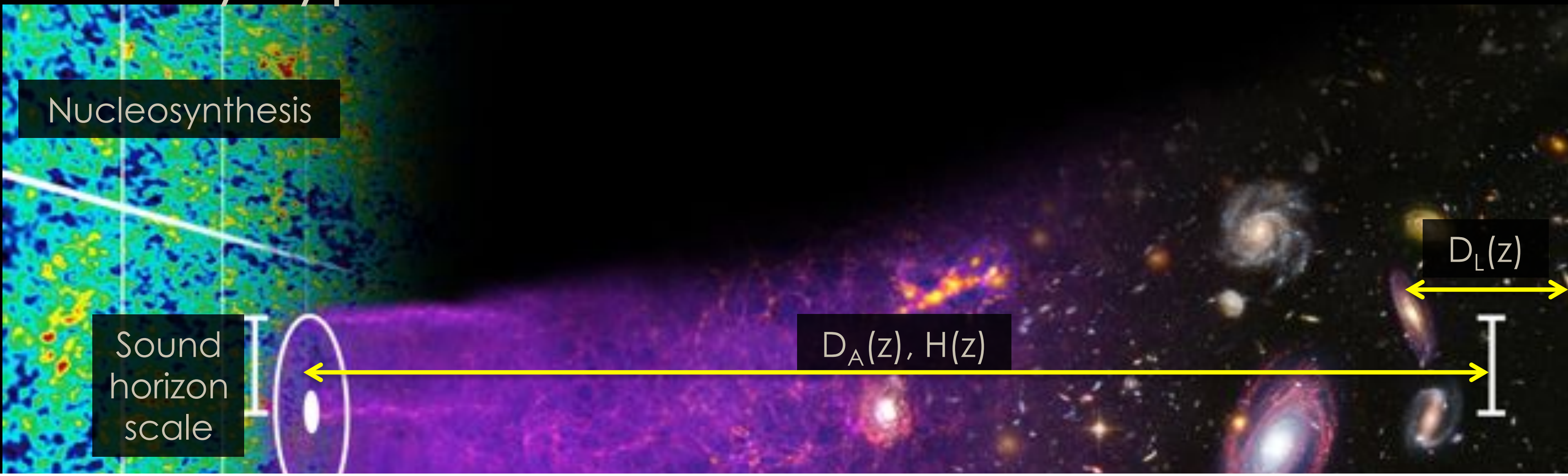
Whereas Mr. Carroll sayeth that the value of Ω_0, the density parameter of the Universe, will be viewed by the consensus of astronomers as being known to an accuracy of ±0.3 on August 1, 2011.

Whereas Mr. Schmidt sayeth that the value of Ω_0, the density parameter of the Universe, will be viewed by the consensus of astronomers as **not** being known to an accuracy of ±0.3 on August 1, 2011.

The tern "consensus" will be agreed upon by Mr. Carroll and Mr. Schmidt. If these two cannot come to terms on this point, it then shall be decided by Mr. Huchra

Witnessed this 1st day of August in the year of our Lord 1991.

Many types of observations = concordance



THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 192:18 (47pp), 2011 February KOMATSU ET AL.

Table 1
Summary of the Cosmological Parameters of ΛCDM Model[a]

Class	Parameter	*WMAP* Seven-year ML[b]	*WMAP*+BAO+H_0 ML	*WMAP* Seven-year Mean[c]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.227	2.253	$2.249^{+0.056}_{-0.057}$	2.255 ± 0.054
	$\Omega_c h^2$	0.1116	0.1122	0.1120 ± 0.0056	0.1126 ± 0.0036
	Ω_Λ	0.729	0.728	$0.727^{+0.030}_{-0.029}$	0.725 ± 0.016
	n_s	0.966	0.967	0.967 ± 0.014	0.968 ± 0.012
	τ	0.085	0.085	0.088 ± 0.015	0.088 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[d]	2.42×10^{-9}	2.42×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.430 \pm 0.091) \times 10^{-9}$
Derived	σ_8	0.809	0.810	$0.811^{+0.030}_{-0.031}$	0.816 ± 0.024
	H_0	$70.3\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.4\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.4 \pm 2.5\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.2 \pm 1.4\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$
	Ω_b	0.0451	0.0455	0.0455 ± 0.0028	0.0458 ± 0.0016
	Ω_c	0.226	0.226	0.228 ± 0.027	0.229 ± 0.015
	$\Omega_m h^2$	0.1338	0.1347	$0.1345^{+0.0056}_{-0.0055}$	0.1352 ± 0.0036
	z_{reion}[e]	10.4	10.3	10.6 ± 1.2	10.6 ± 1.2
	t_0[f]	13.79 Gyr	13.76 Gyr	13.77 ± 0.13 Gyr	13.76 ± 0.11 Gyr

Overview

What is WiggleZ?

Cosmology Results I'll talk about

Distances using BAO
Paper 1: z = 0.6
Paper 2: z=0.44, 0.6, 0.73

Homogeneity

Growth at high-z

Neutrinos
Paper 1: mass
Paper 2: N_{eff}

H(z) using Alcock-Paczynski
Paper 1: +SNe
Paper 2: +BAO

Full P(k) analysis
Data Release
CosmoMC

Results I'll skip

2D BAO

Reconstruction

Non-Gaussianity with Higher-order clustering

Genus/Topology

Non-standard cosmologies

Variations in G

WiggleZ papers

Paper	Lead authors	Title: "The WiggleZ Dark Energy Survey:"	arXiv
BAO's at z=0.6	Blake, Davis, Poole, Parkinson et al., 2011	testing the cosmological model with baryon acoustic oscillations at z= 0.6	1105.2862
BAO's in 3 redshift bins	Blake, Kazin, Beutler, Davis, Parkinson, et al. 2011	mapping the distance-redshift relation with baryon acoustic oscillations	1108.2635
Growth in 4 redshift bins	Blake, et al. 2011	the growth rate of cosmic structure since redshift z=0.9	1104.2948
Alcock-Paczynscki + SNe	Blake, Glazebrook, Davis, et al. 2011	measuring the cosmic expansion history using the Alcock-Paczynski test & distant Se	1108.2637
Alcock-Paczynscki + BAO	Blake, et al. 2012	joint measurements of the expansion and growth history at z < 1	1204.3674
Homogeneity	Scrimgeour, Davis, Blake, James, Poole, Staveley-Smith et al. 2012	the transition to large-scale cosmic homogeneity	1205.6812
Neutrino mass	Riemer-Sørensen, Blake, Parkinson, Davis, et al. 2012	Cosmological neutrino mass constraint from blue high-redshift galaxies	1112.4940
Small-scale clustering	Blake, Jurek, et al. 2009	small-scale clustering of Lyman-break galaxies at z < 1	0901.2587
WiggleZ overview	Drinkwater, ++ et al. 2010	survey design and first data release	0911.4246
Blue galaxy intrinsic alignments	Mandelbum et al. 2011	direct constraints on blue galaxy intrinsic alignments at intermediate redshifts	0911.5347
Selection function	Blake et al. 2011	the selection function and z = 0.6 galaxy power spectrum	1003.5721
Kinematics of luminous star-forming galaxies	Wisnioski, Glazebrook, Blake, Wyder, Martin, Poole, Sharp, Couch, Kacprzak, et al.	high-resolution kinematics of luminous star-forming galaxies	1107.3338
Galaxy evolution	Li, Yee, et al. 2012	Galaxy Evolution at 0.25 < z < 0.75 Using the Second Red-Sequence Cluster Survey	1201.1013

WiggleZ papers

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In preparation	Nominal lead authors
Final data release and cosmology results	Parkinson, Riemer-Sørensen, Blake, Poole, Davis, et al.
Number of neutrinos	Riemer-Sørensen, Parkinson, Davis, et al.
BAO theory	Davis, Beutler, Blake, Parkinson, Scrimgeour et al.
2D BAO's	Davis, Kazin, Blake, et al.
Higher-order correlations	Marin et al.
Growth – beyond standard cosmologies	Parkinson et al.
Distances – beyond standard cosmologies	Peet, Davis, et al.
Reconstruction	Kazin et al.

The WiggleZ Dark Energy Survey

Five-year (final) results

High-z galaxy survey
$0.2 < z < 1.0$

238,000 blue galaxies

1 GPc^3

Observations finished 2011

Advantages:
Low-bias
High-redshift

THE TEAM:

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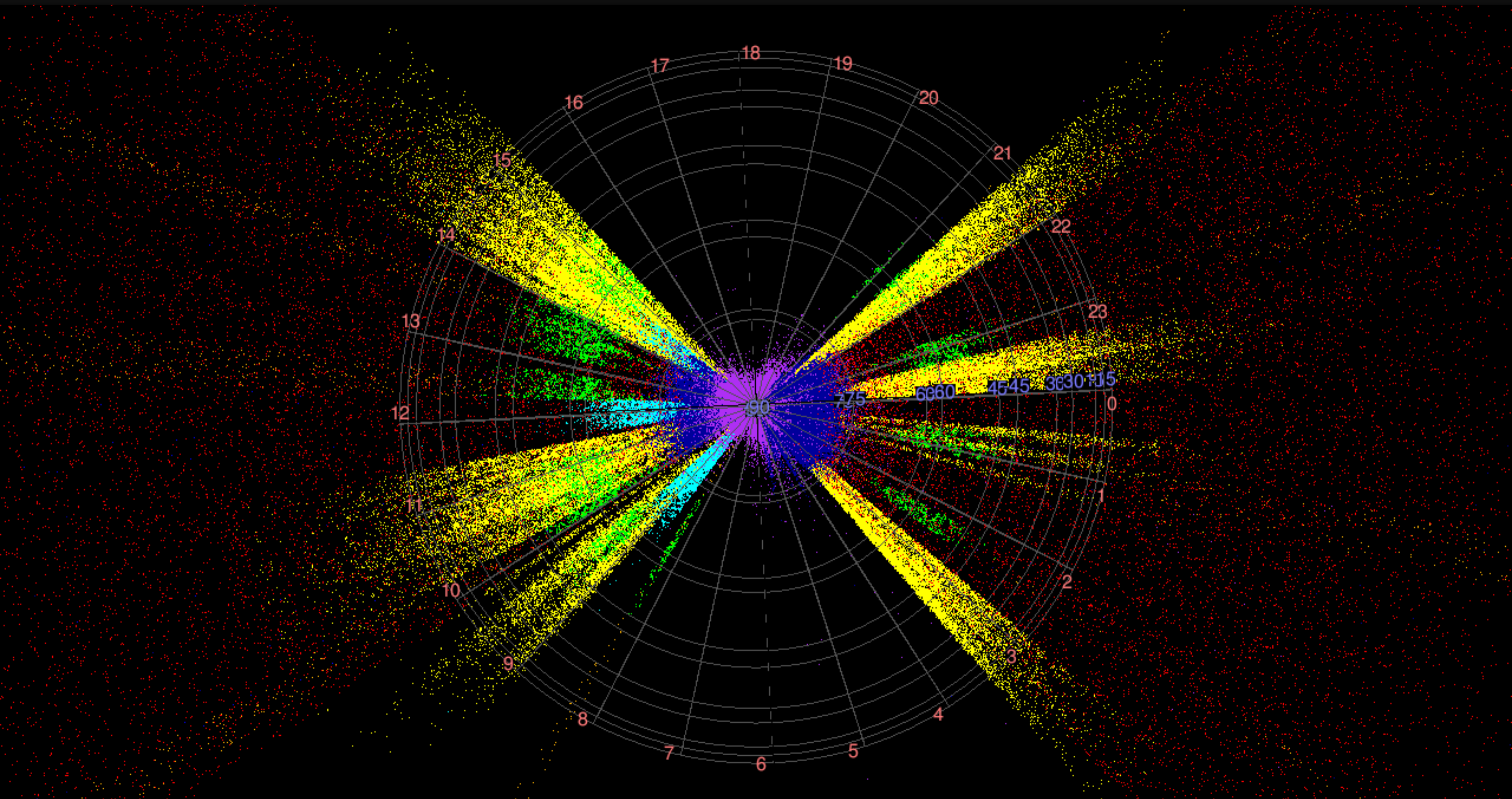
Plus students and associate members

WiggleZ survey fields
(compared to other AAT surveys)

7 equatorial fields, each 100-200 deg^2

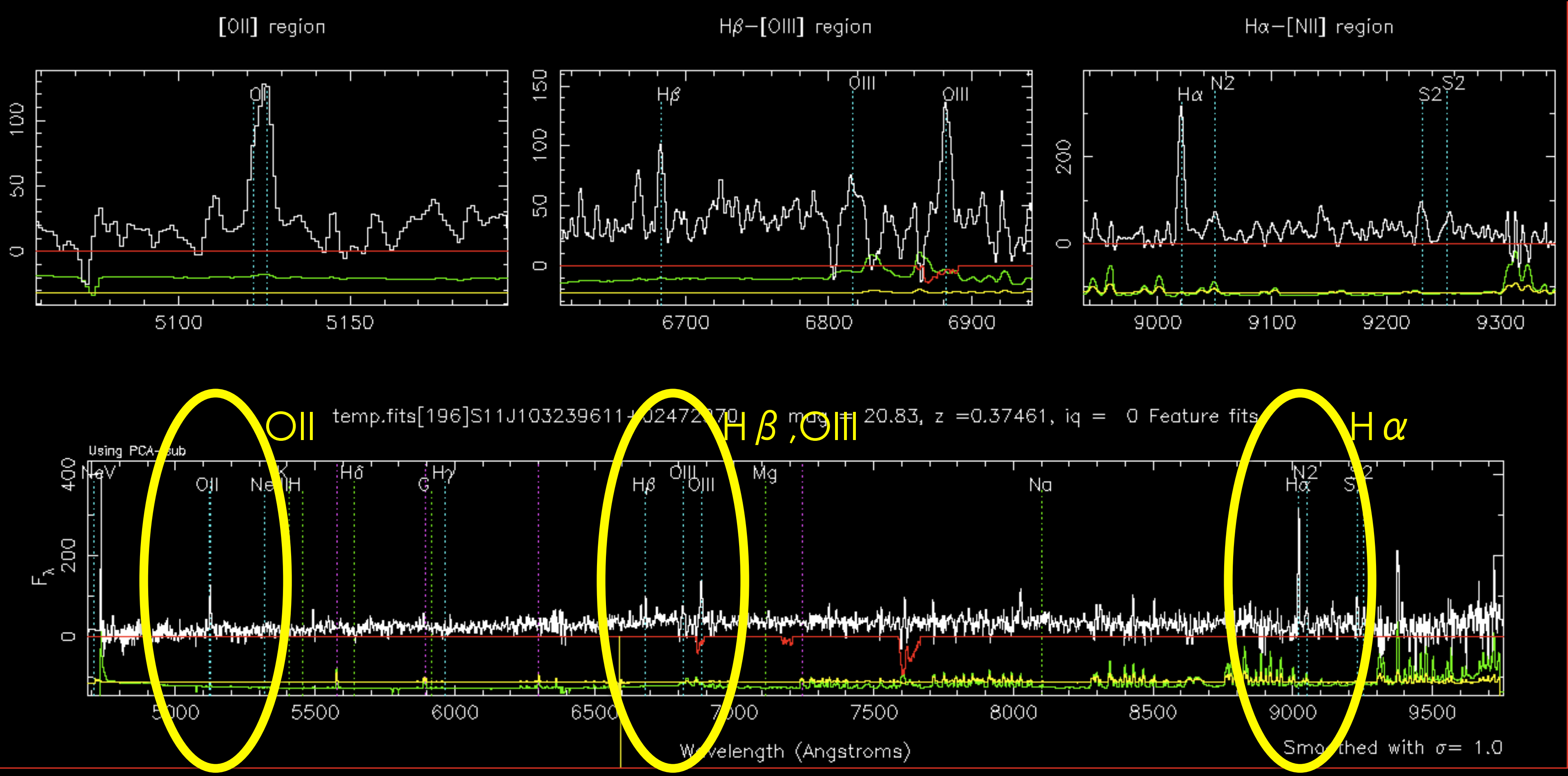
>9° on side, ~3 x BAO scale at $z > 0.5$

Physical size ~ 1300 x 500 x 500 Mpc/h

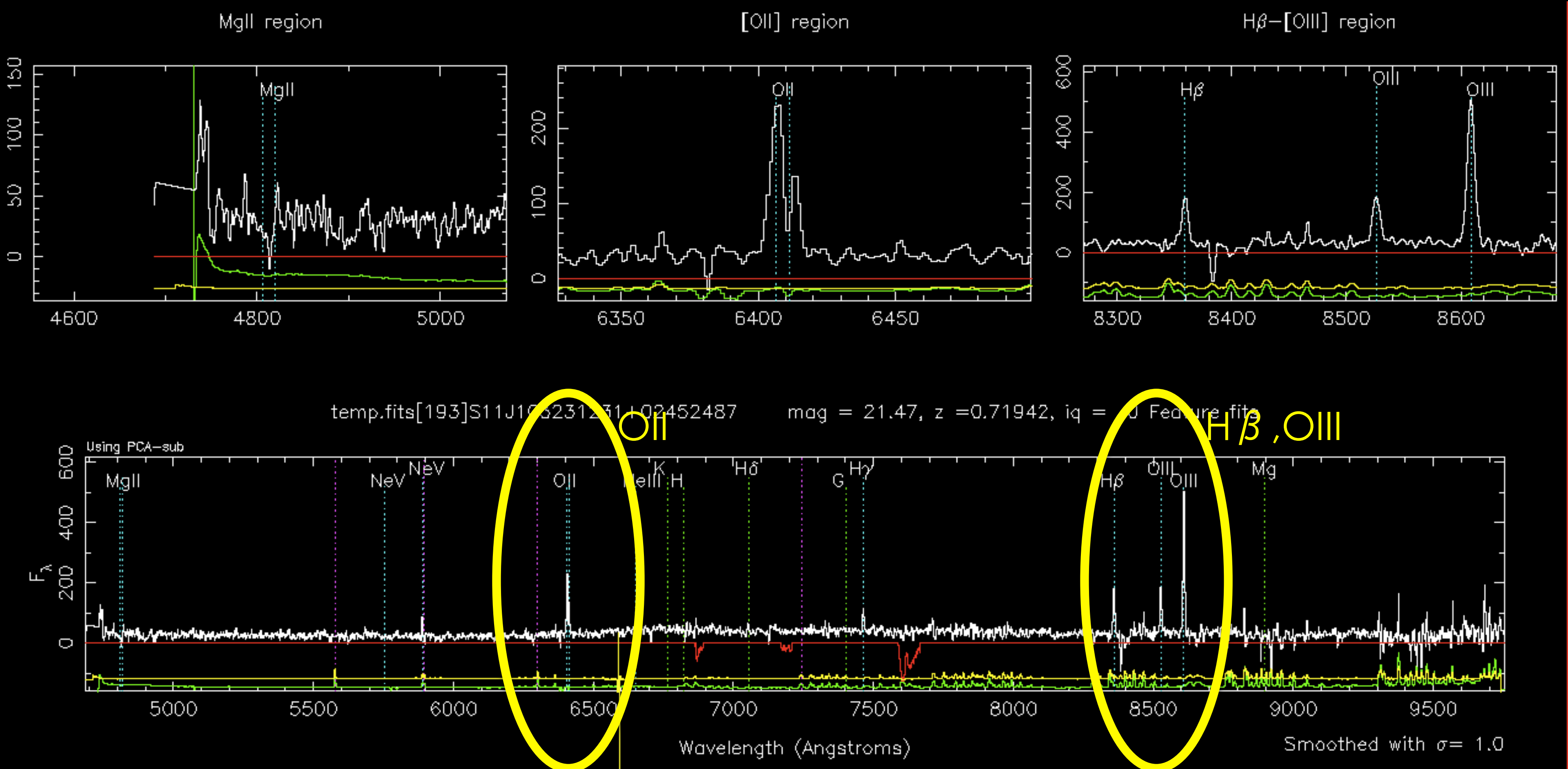


6dFGS (purple), 2dFGRS (blue), MGC (navy), GAMA (cyan), 2SLAQ-LRG (green), WiggleZ (yellow), 2SLAQ-QSO (orange), 2QZ (red); the celestial sphere is at z=1.

Example spectrum: z=0.37

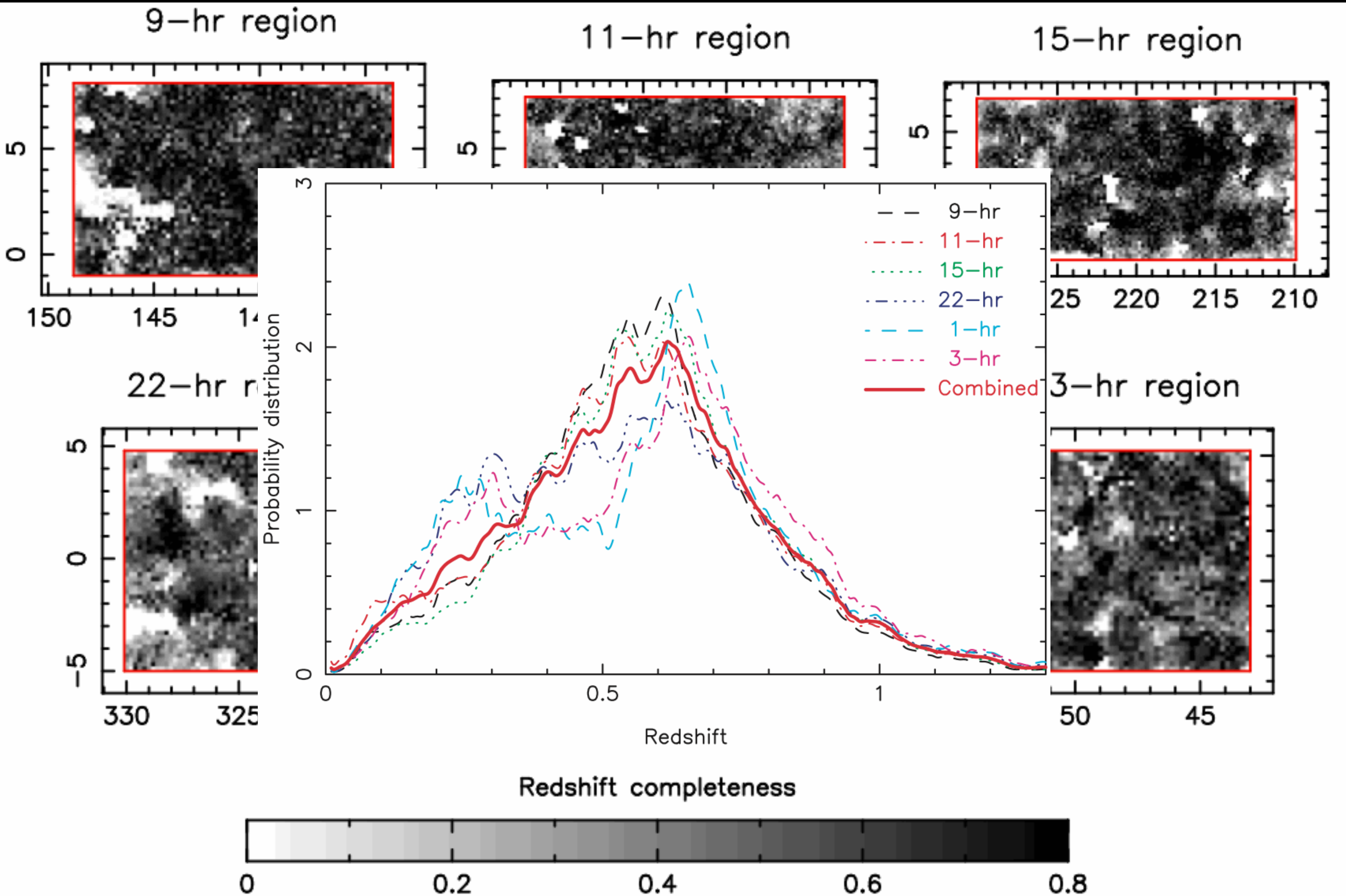


Example spectrum: z=0.72

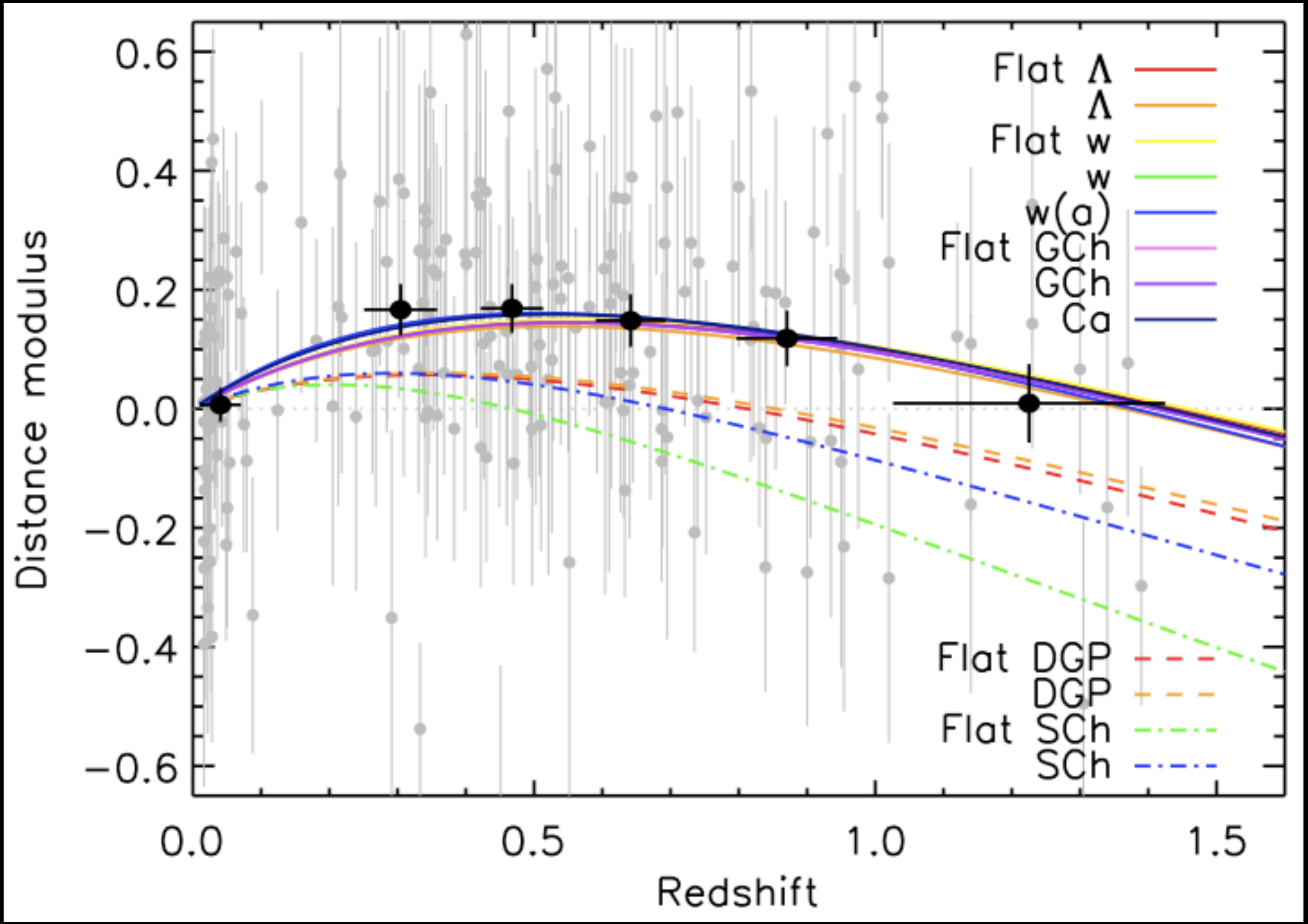


Redshifts become less certain above $z \sim 1$ because we lose $H\beta$

WiggleZ regions



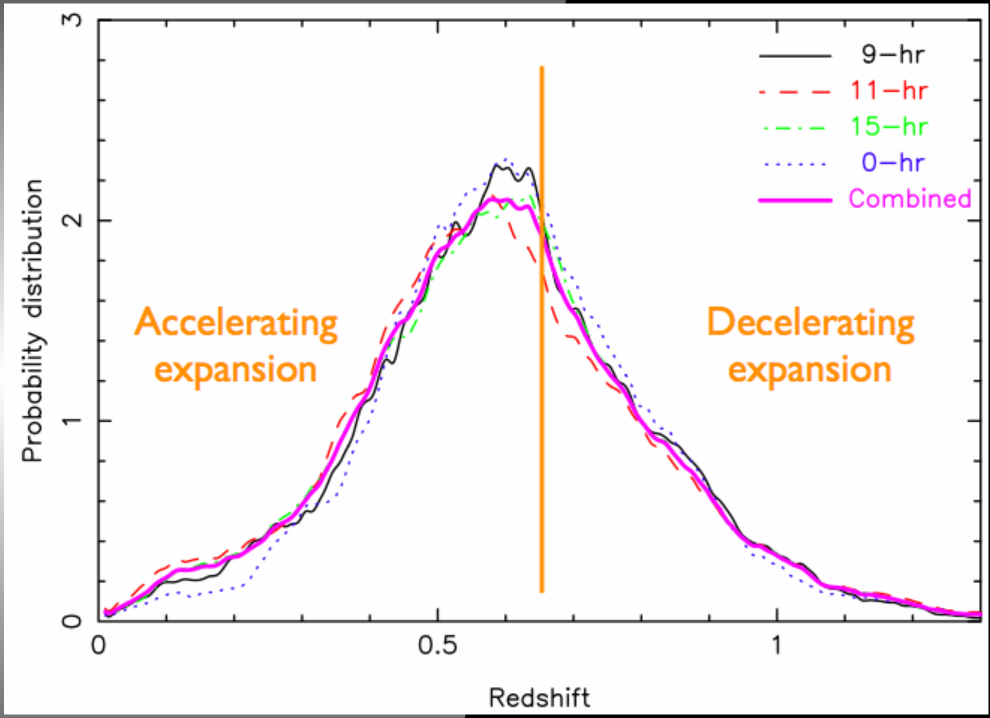
Dirty laundry…



Understanding our survey

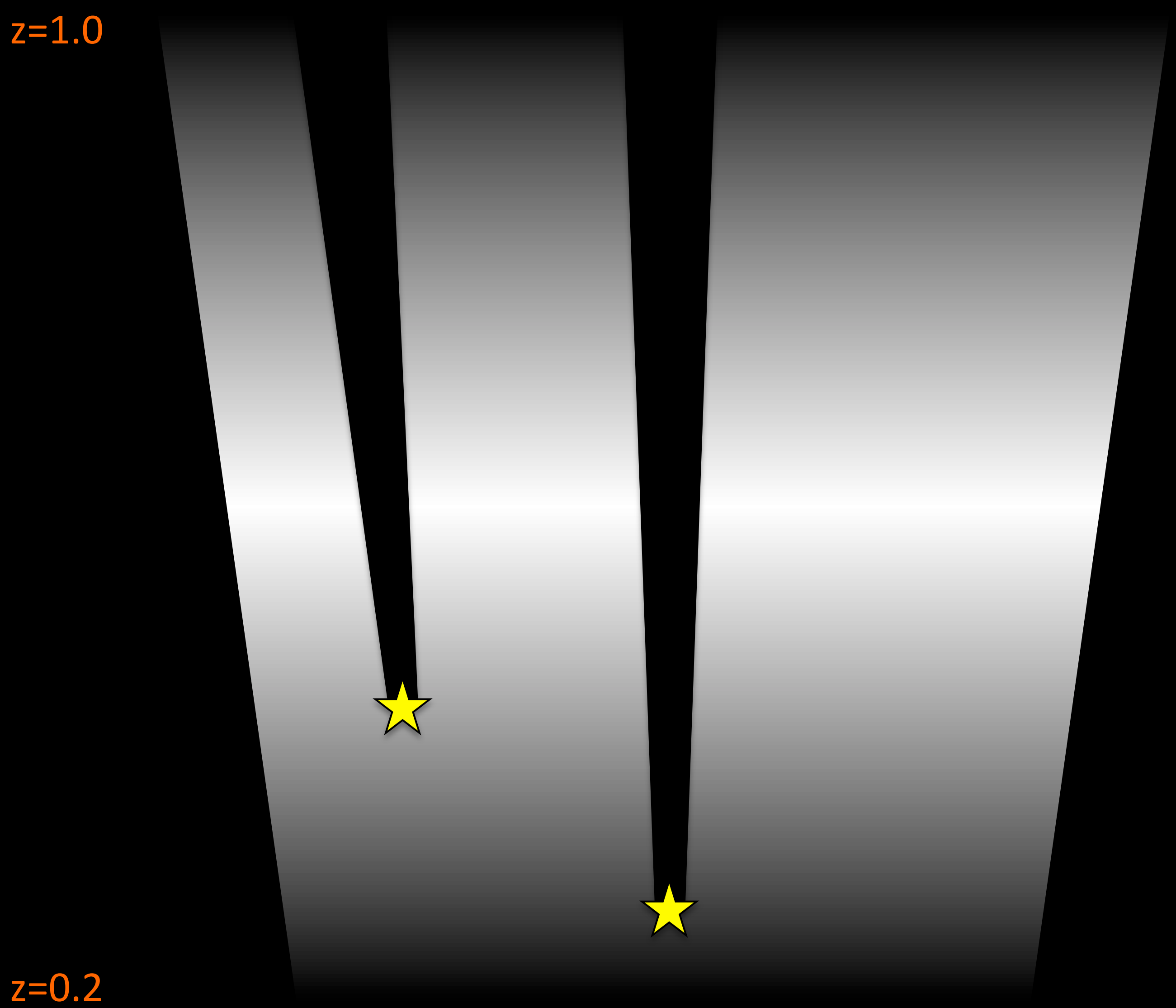
z=1.0

Redshift distribution

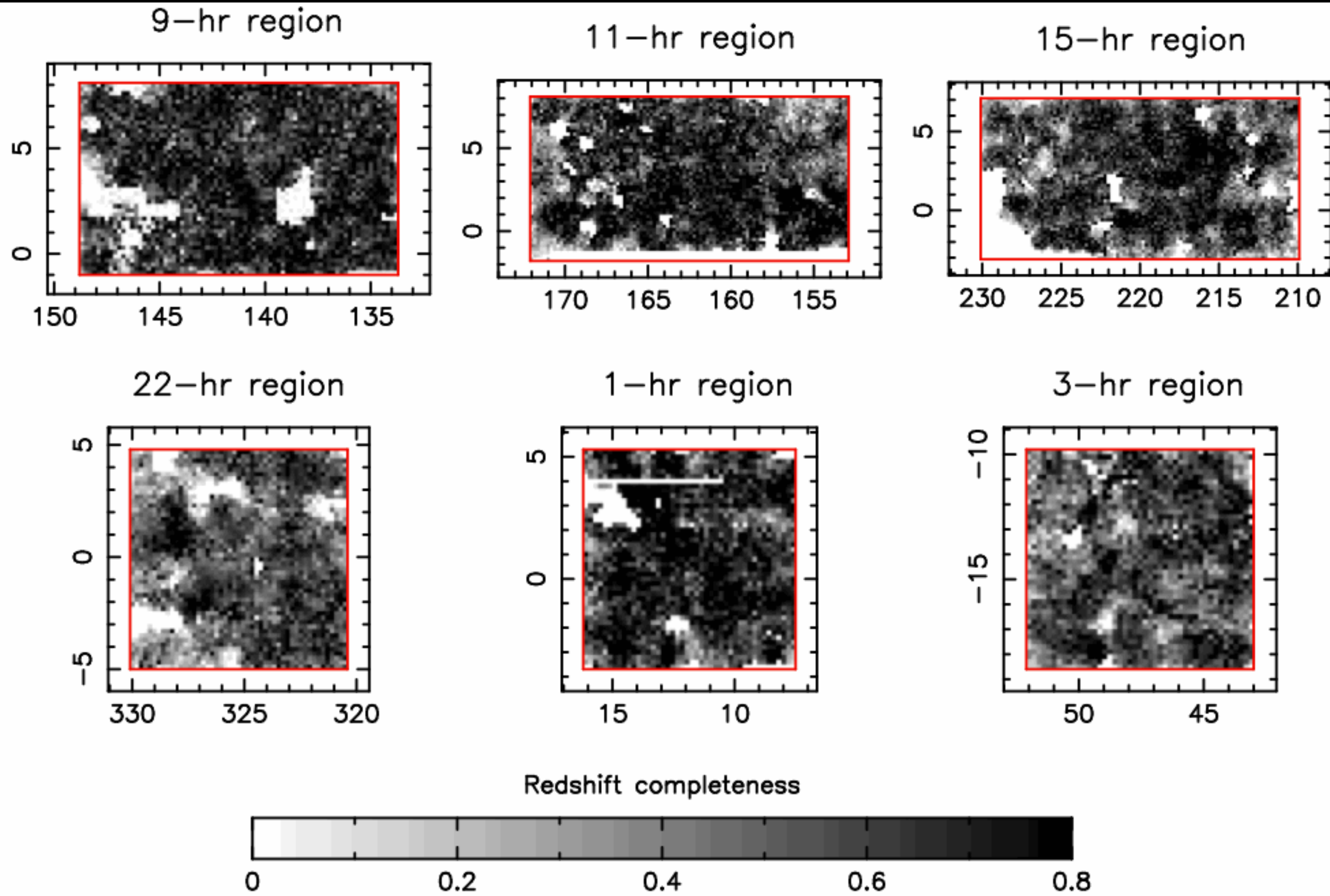


z=0.2

Understanding our survey

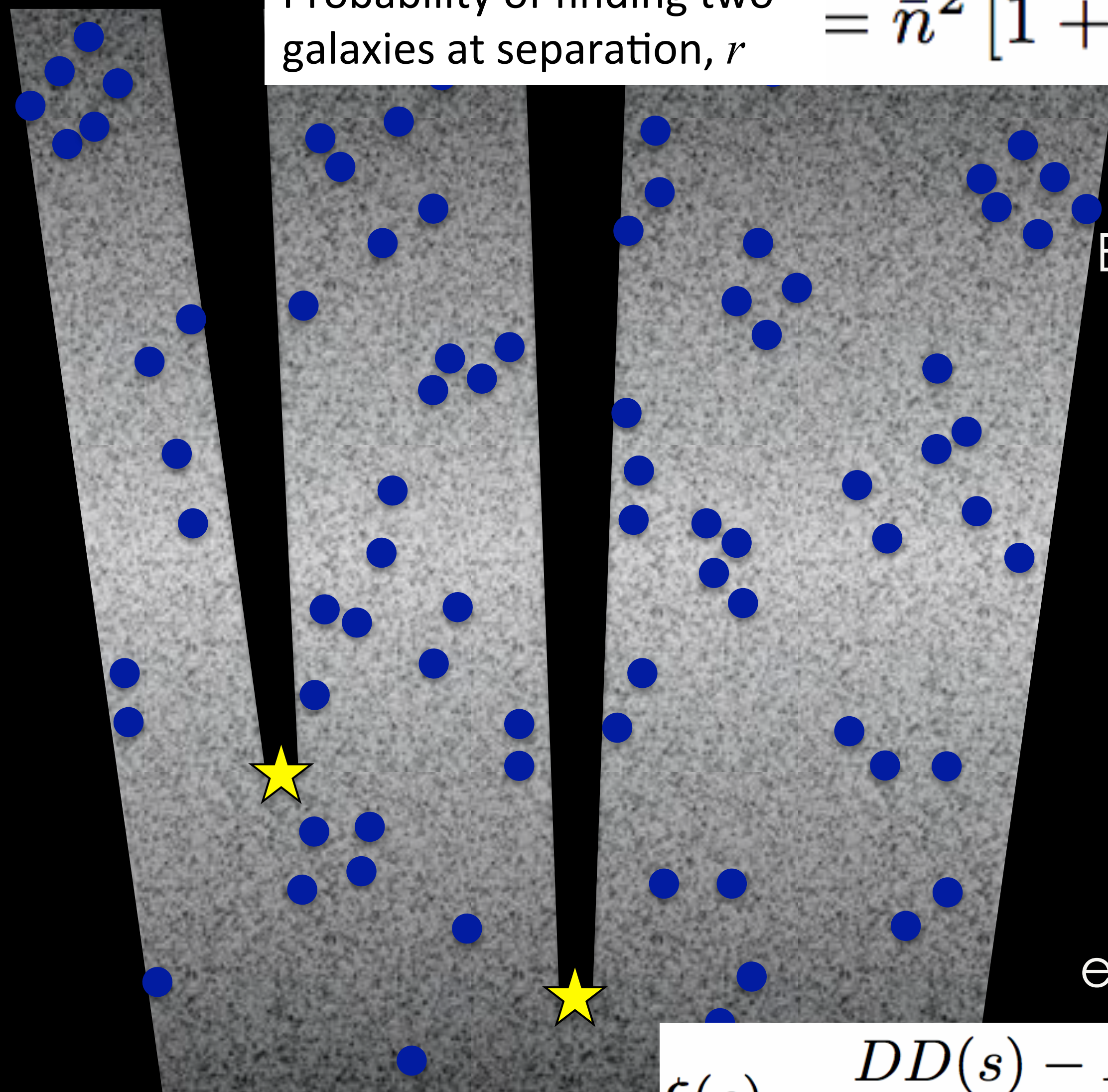


WiggleZ regions



Understanding our survey

z=1.0



z=0.2

Probability of finding two galaxies at separation, r $= \bar{n}^2 \left[1 + \xi(r)\right] \delta V_1 \delta V_2$

Excess likelihood of finding two galaxies at separation r

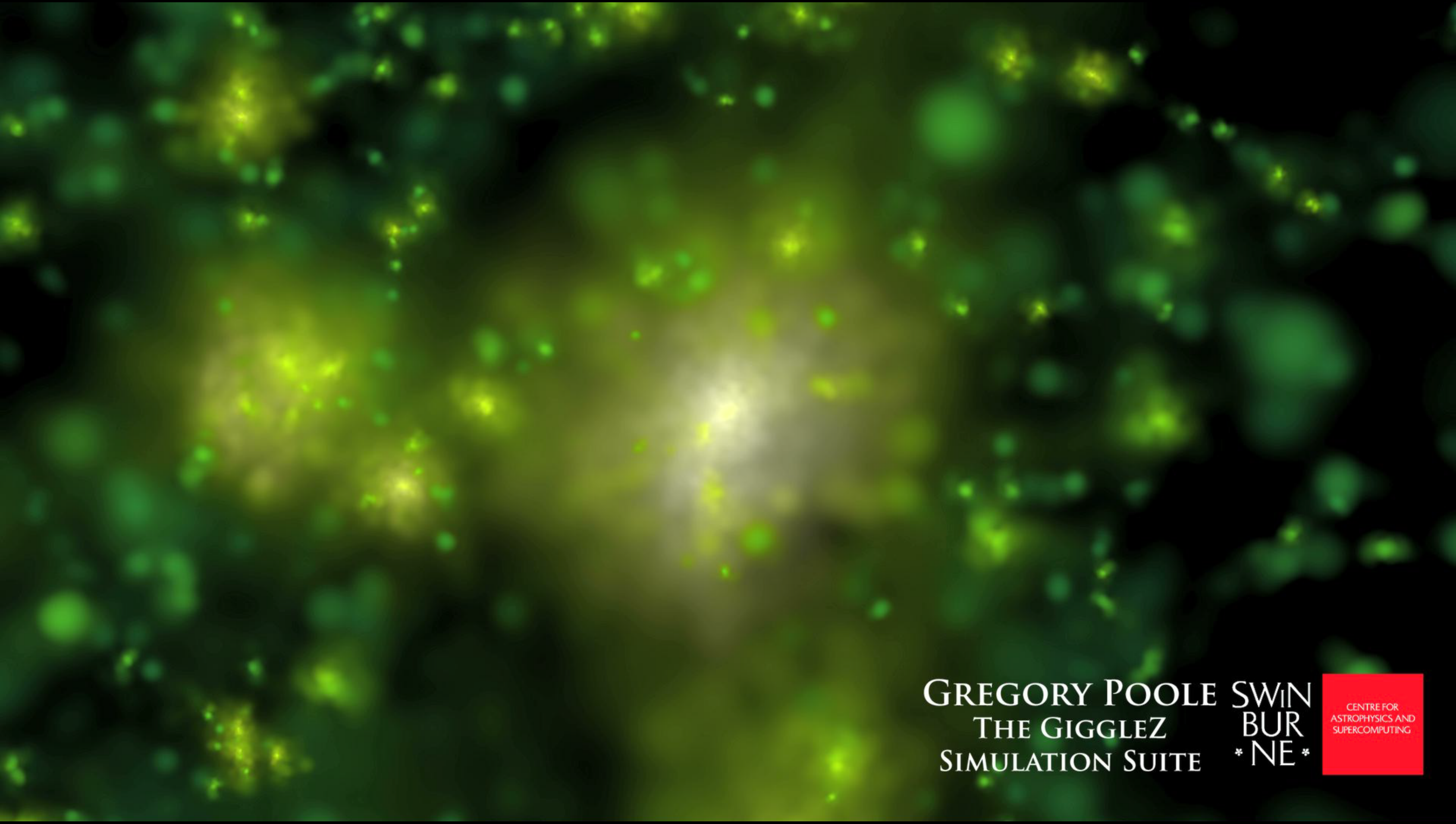
Landy-Szalay estimator (1993)

$$\xi(s) = \frac{DD(s) - DR(s) + RR(s)}{RR(s)}$$

Gregory Poole
The GiggleZ
Simulation Suite

SWINBURNE

CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

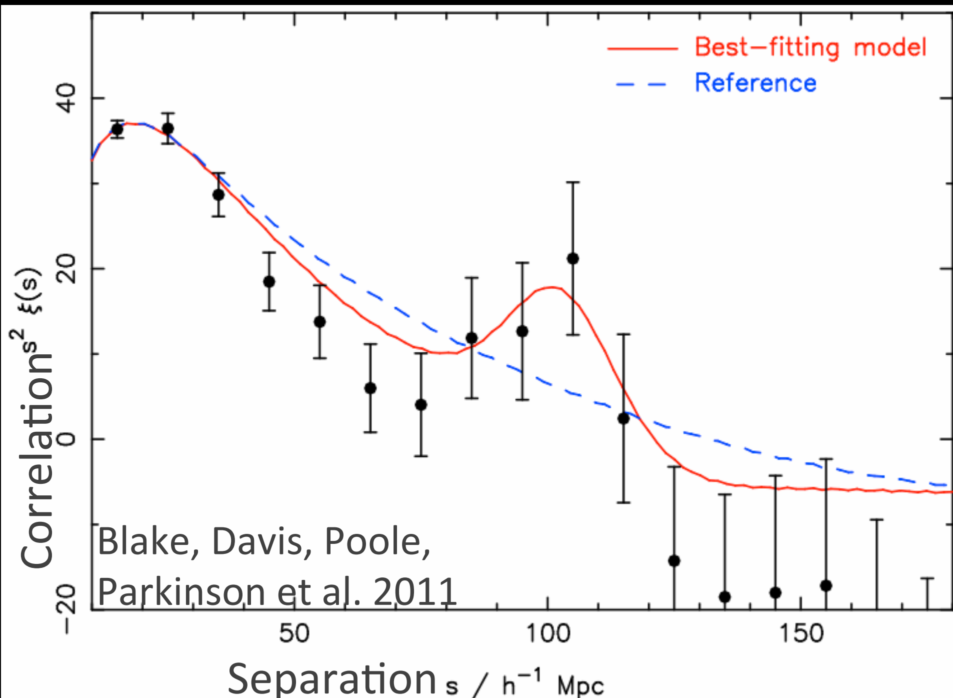

GREGORY POOLE
THE GIGGLEZ
SIMULATION SUITE
SWIN BUR NE
CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

Blake, Davis, Poole, Parkinson et al. 2011
Blake, Kazin, Beutler, Davis, Parkinson et al. 2011

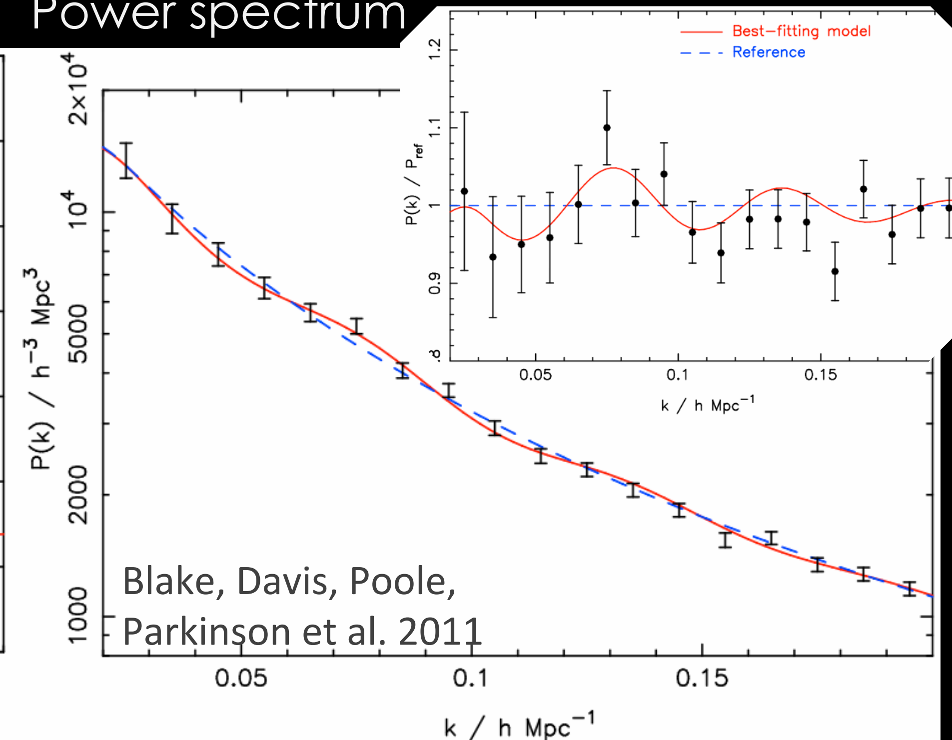
1. BARYON ACOUSTIC OSCILLATIONS

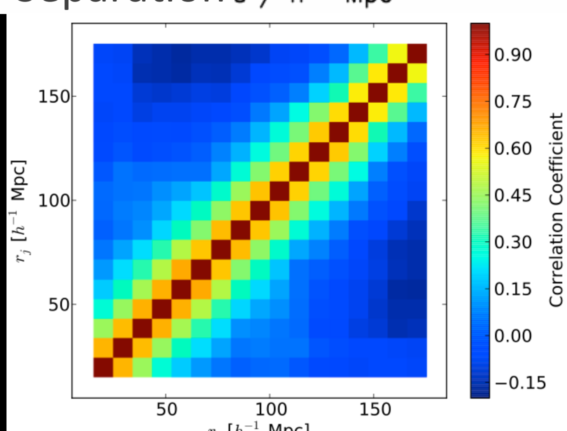
BAO-1: Single redshift bin

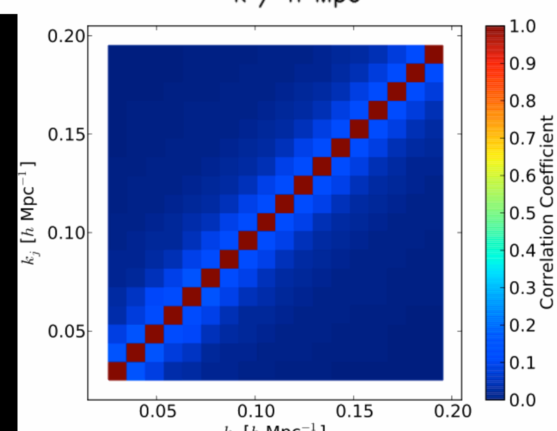
Correlation Function



Power spectrum







Measuring the distance scale

$$d_z \equiv \frac{r_s(z_d)}{D_V(z)}$$

BAO

$$A(z) = \frac{\sqrt{\Omega_m H_0^2}}{cz} D_V(z)$$

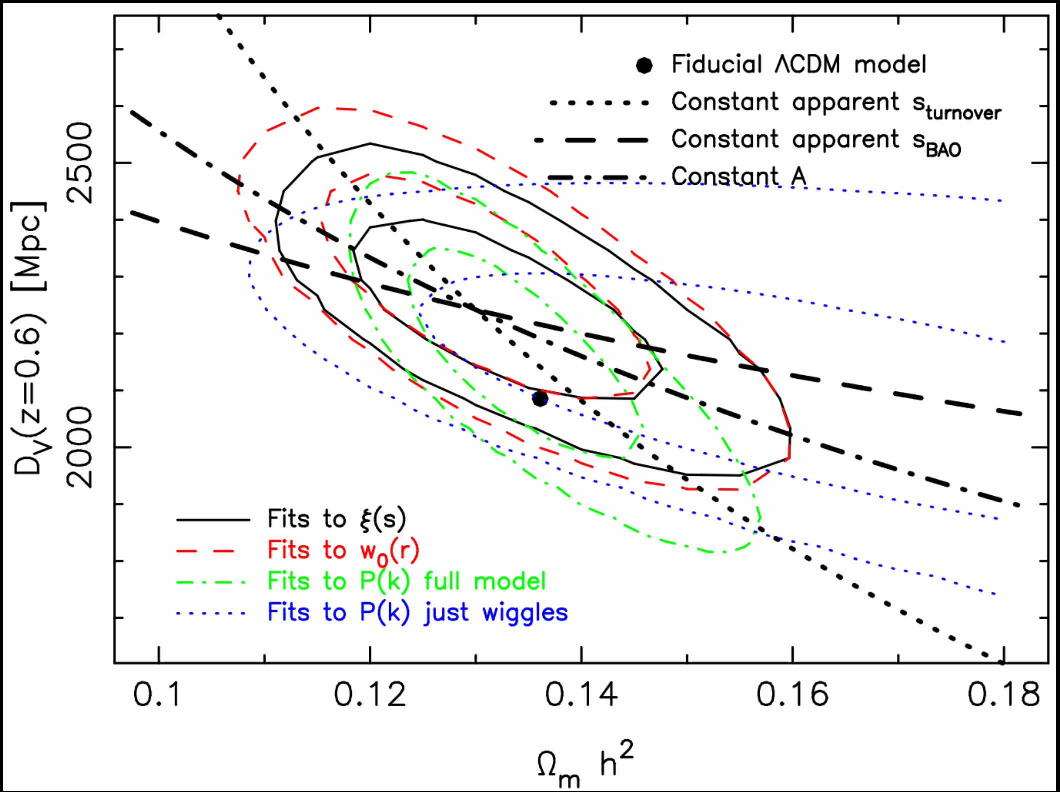
$$\theta_A \equiv \frac{r_s(z_*)}{d_A(z_*)}$$

CMB

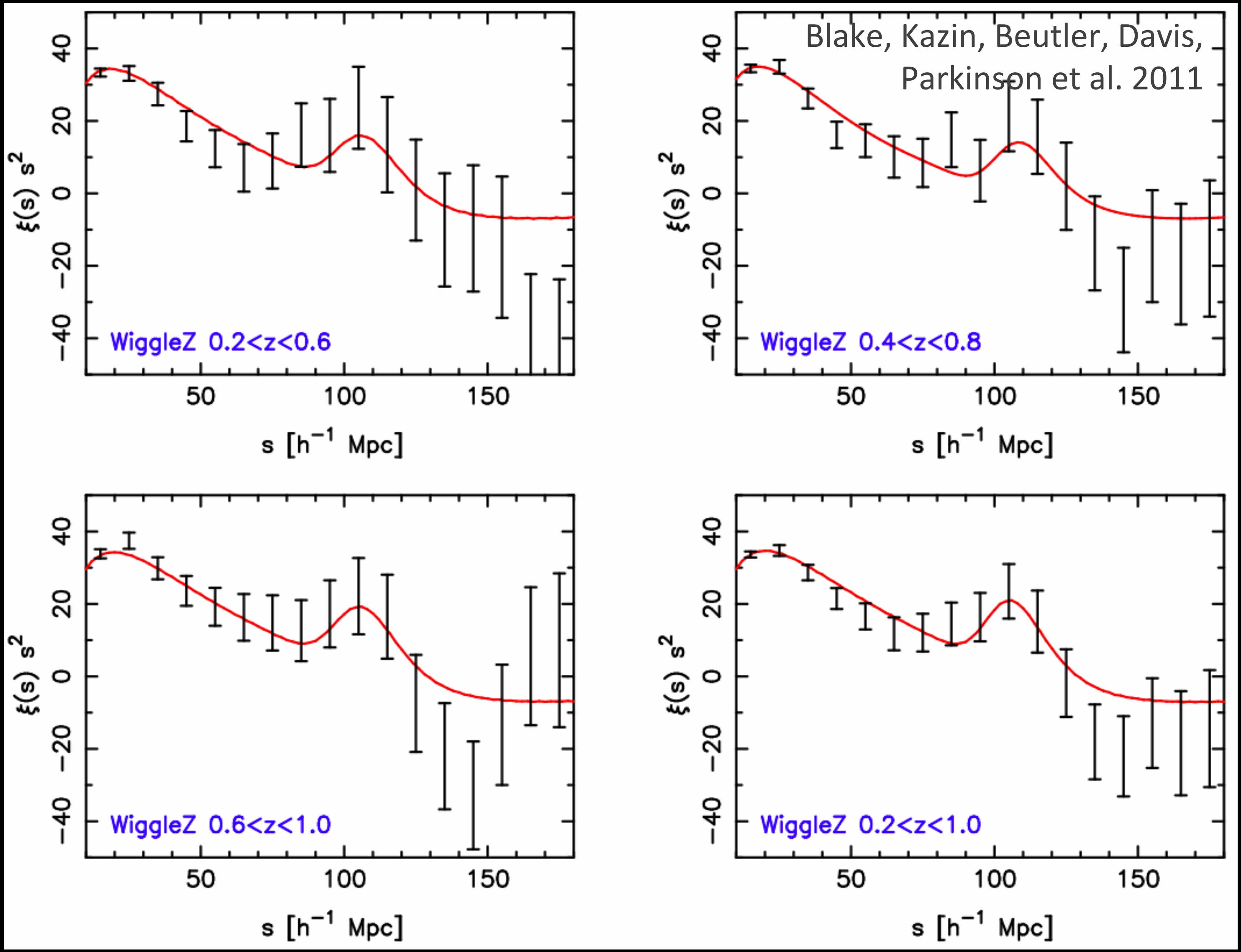
$$\mathcal{R}(z_*) = \sqrt{\Omega_m h^2}\, d_A(z_*)$$

Two Tangential — One Radial

$$D_V(z) = \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)}\right]^{1/3}$$

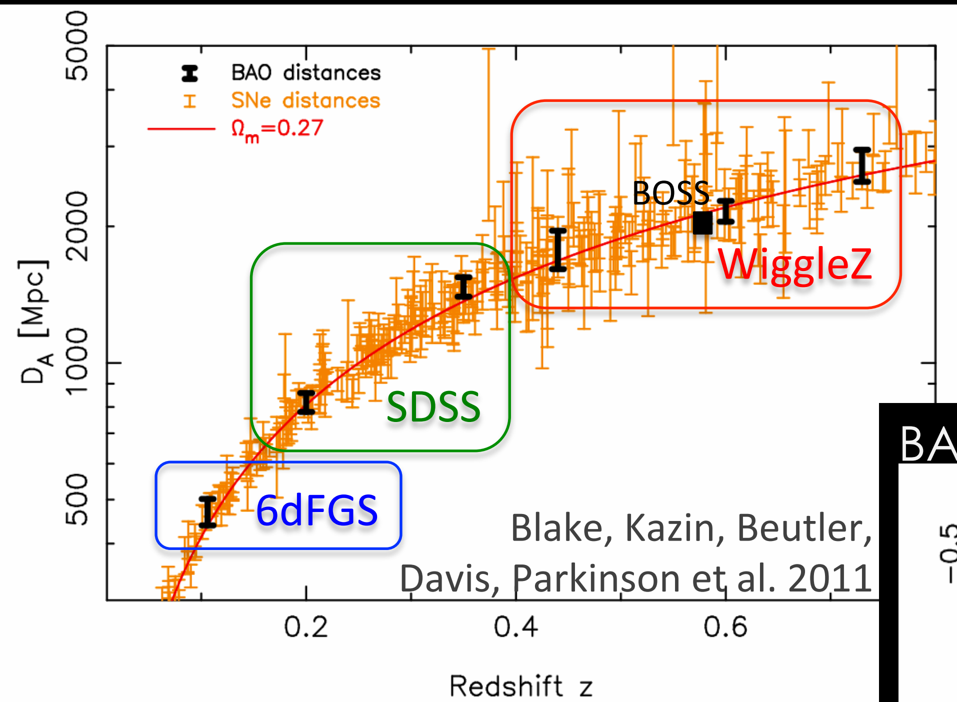


BAO-2: Three redshift bins



WiggleZ – Baryon Acoustic Oscillations

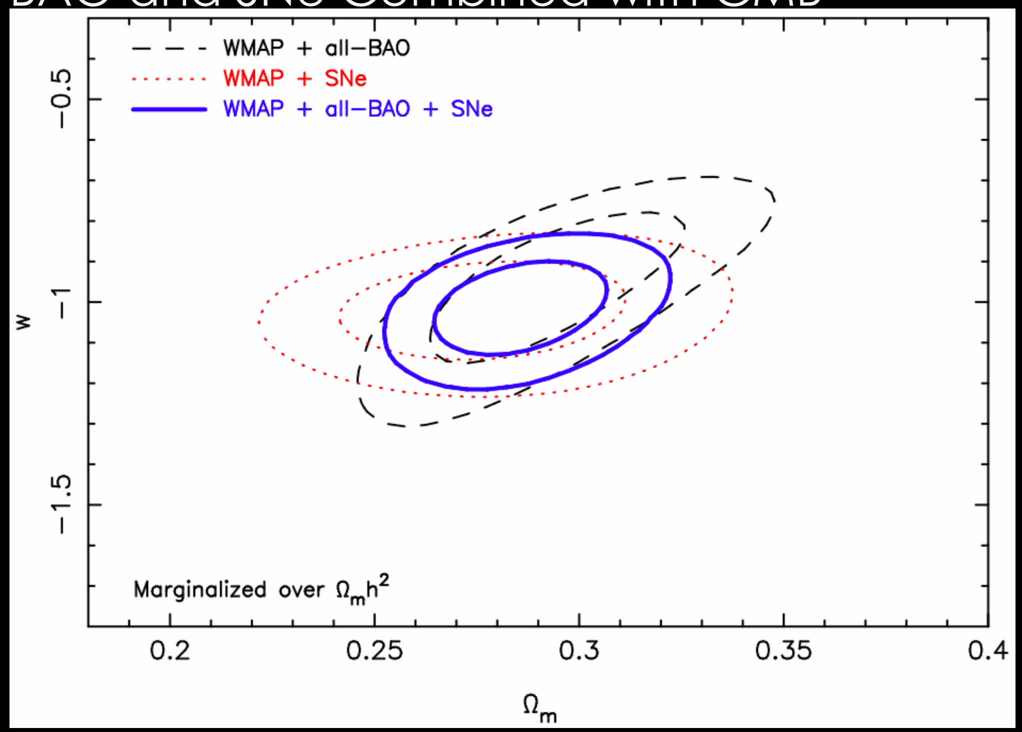
Compared to supernovae



No longer need SNe!

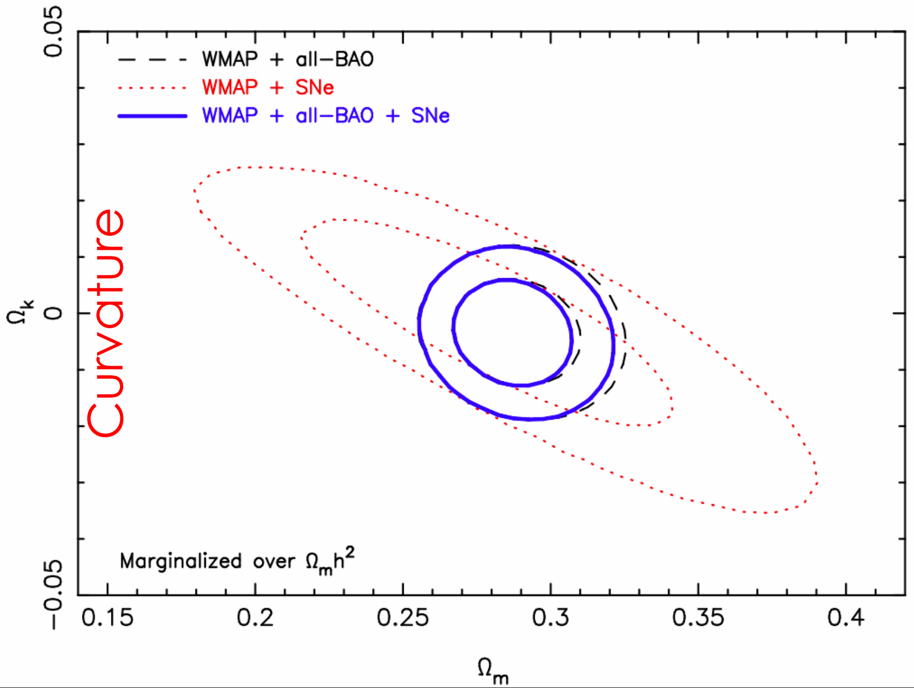
BAO distances alone now require acceleration!

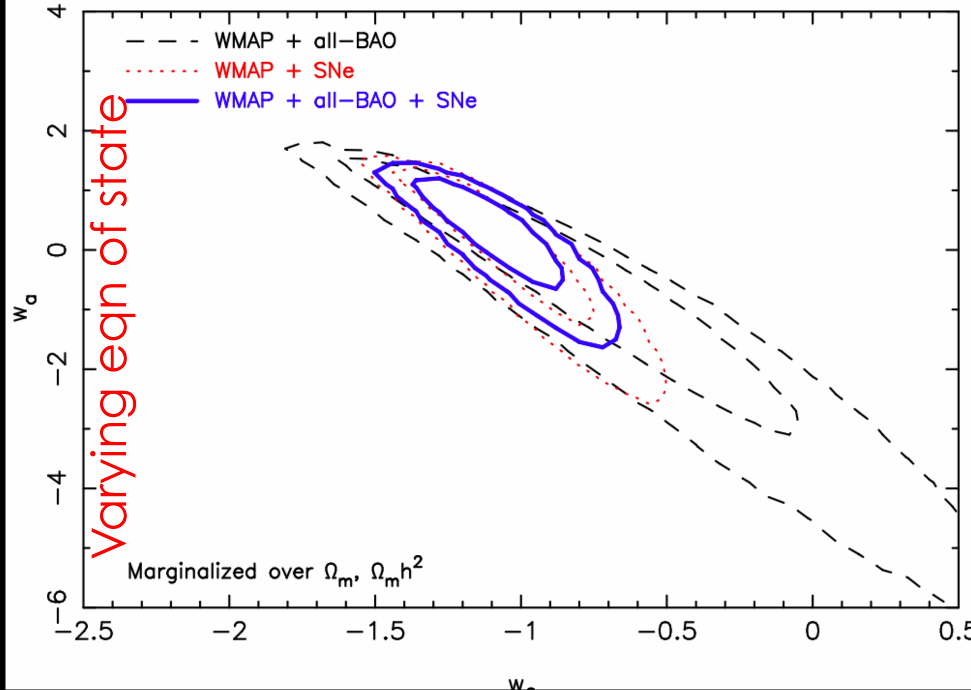
BAO and SNe Combined with CMB



We don't know what is causing the acceleration

(And the leading candidate, vacuum energy, is 10^{120} too large)

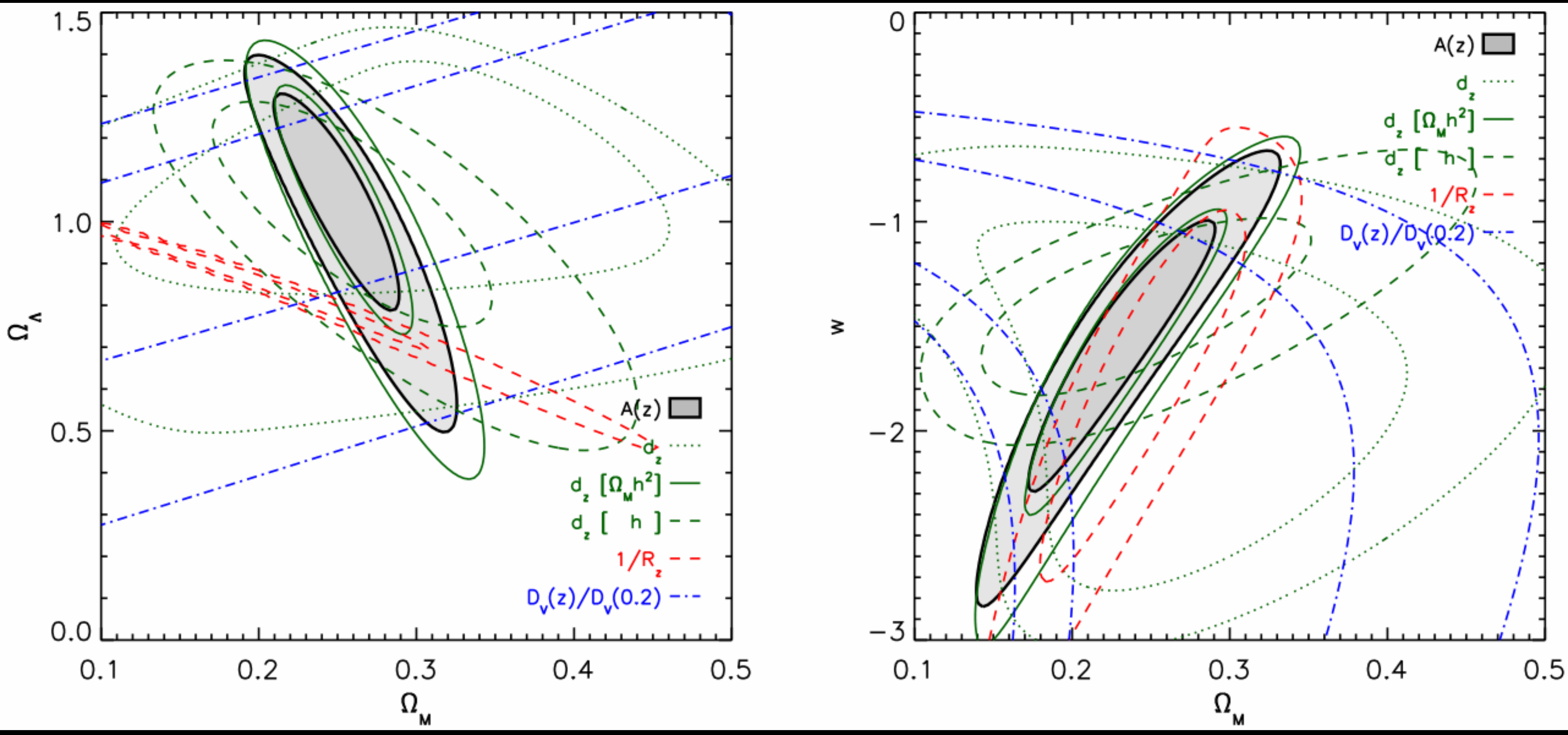




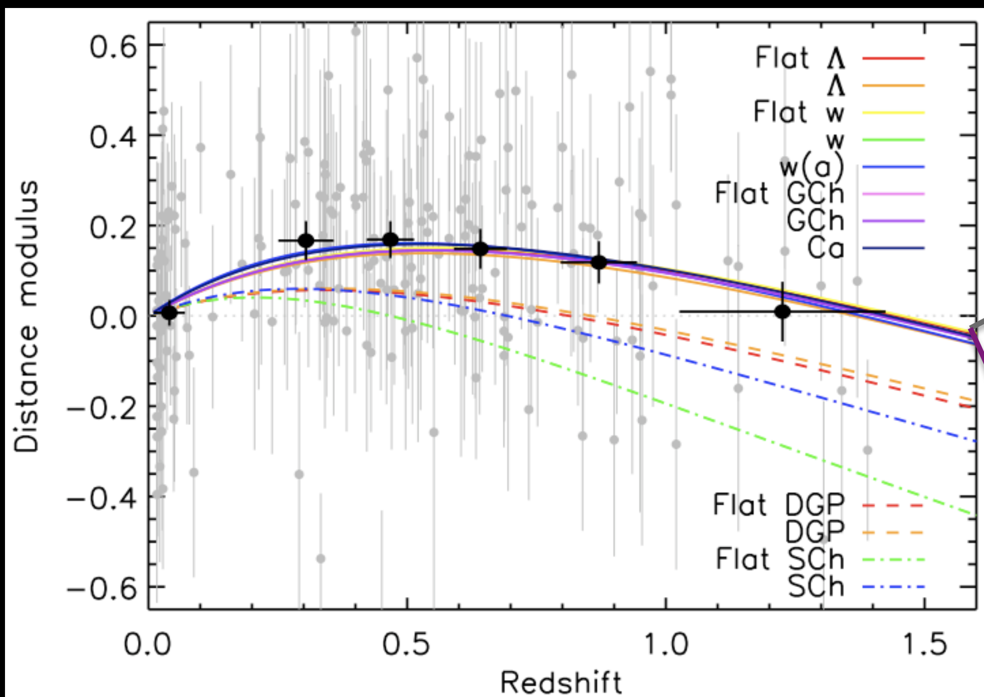
Final combined results

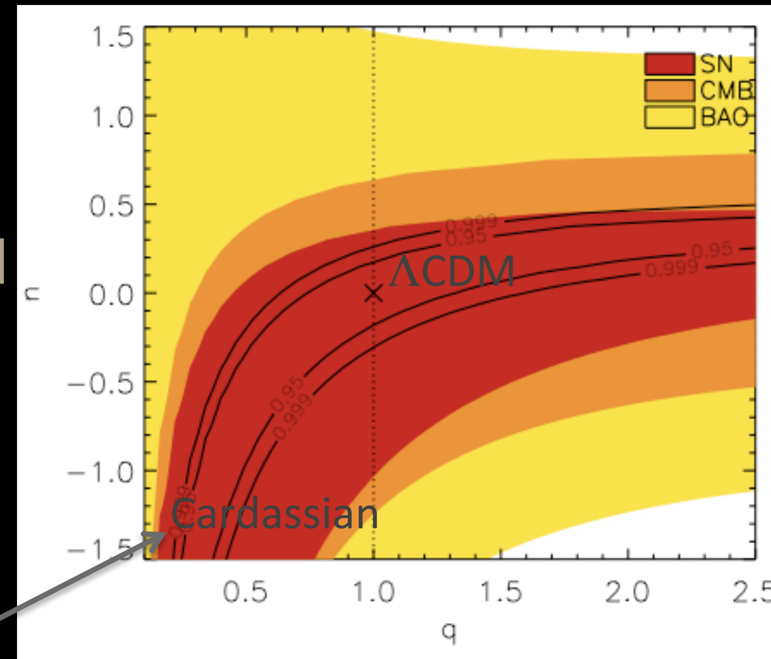
Model	χ^2	d.o.f.	Ω_m	$\Omega_m h^2$	h	Ω_k	w_0	w_a
Flat ΛCDM	533.1	564	0.290 ± 0.014	0.1382 ± 0.0029	0.690 ± 0.009	–	–	–
Flat wCDM	532.9	563	0.289 ± 0.015	0.1395 ± 0.0043	0.696 ± 0.017	–	-1.034 ± 0.080	–
Curved ΛCDM	532.7	563	0.292 ± 0.014	0.1354 ± 0.0054	0.681 ± 0.017	-0.0040 ± 0.0062	–	–
Curved wCDM	531.9	562	0.289 ± 0.015	0.1361 ± 0.0055	0.687 ± 0.019	-0.0061 ± 0.0070	-1.063 ± 0.094	–
Flat $w(a)$CDM	531.9	562	0.288 ± 0.016	0.1386 ± 0.0053	0.695 ± 0.017	–	-1.094 ± 0.171	0.194 ± 0.687

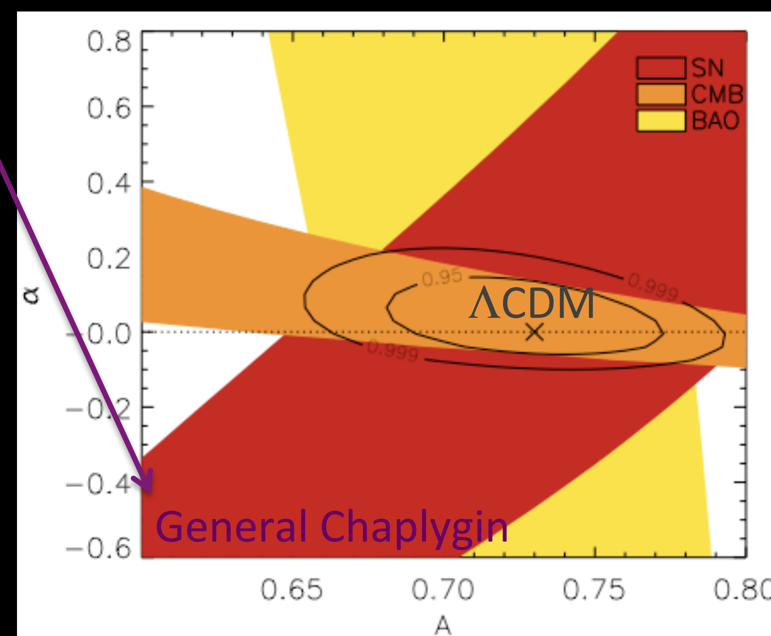
Many ways to use BAO



Some models can't be distinguished using only distance data







Davis et al. 2007

Other types of measurements needed

- Growth

overdensity

$$f = \frac{d(\ln \delta)}{d(\ln a)} \sim \Omega_M(z)^\gamma$$

γ = 6/11 in ΛCDM
γ = 6/10 in CDM
γ = 11/16 in DGP

γ is different in different models

- Amplitude of density fluctuations at present day

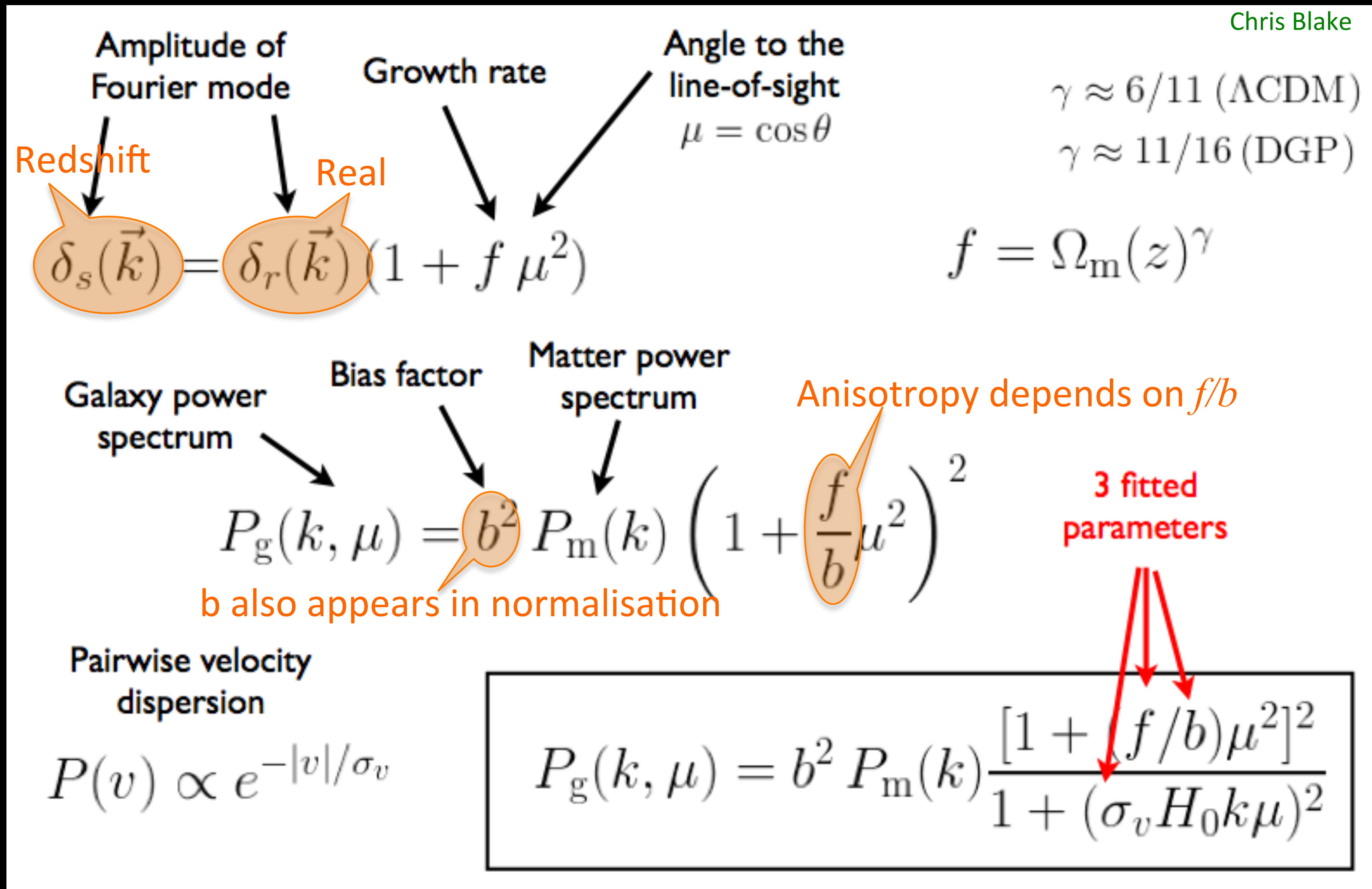
$$\sigma_8$$

1. measure density in spheres 8 Mpc in radius
2. calculate the dispersion

Blake et al. 2011

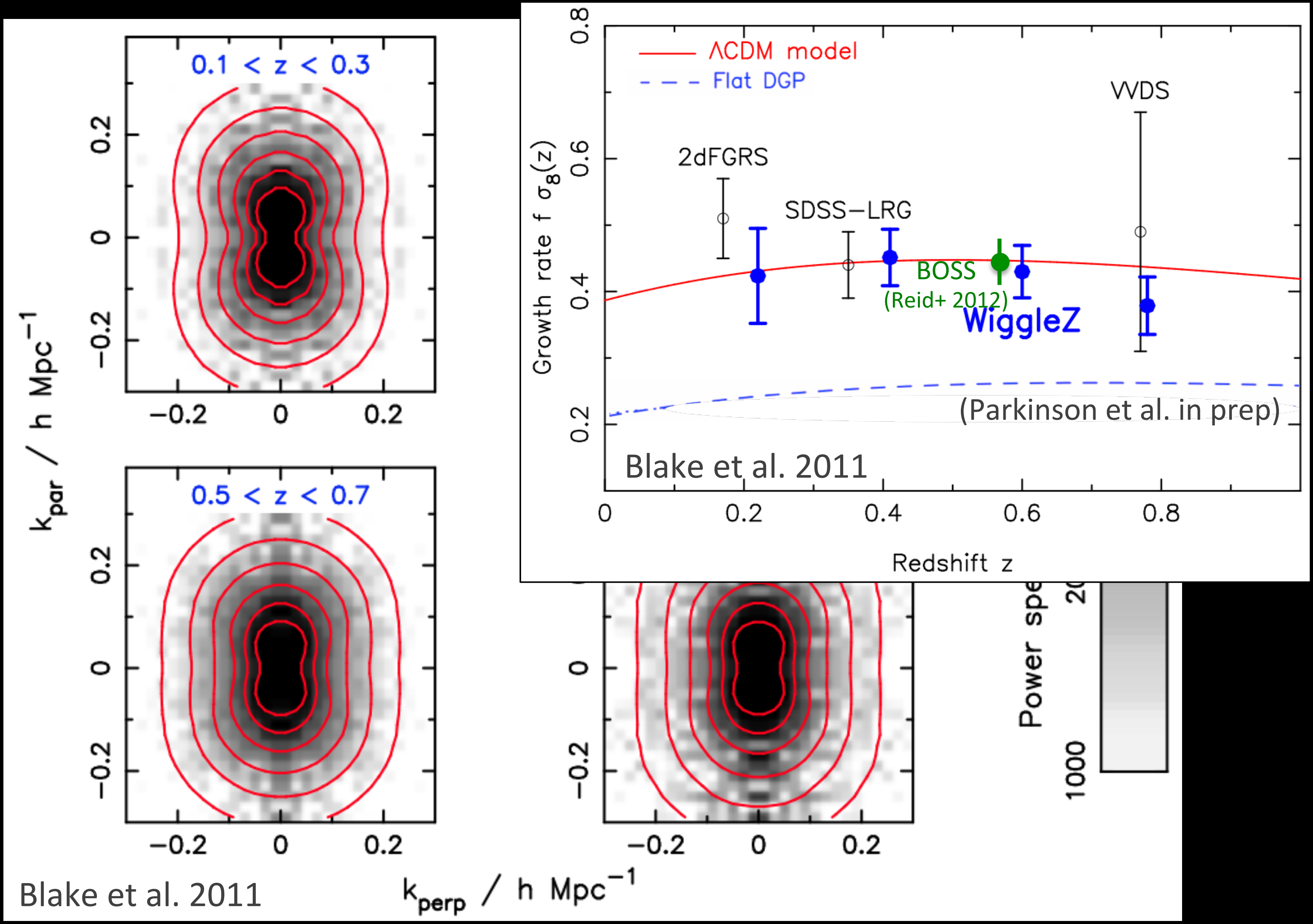
2. GROWTH OF STRUCTURE

Redshift space distortion model

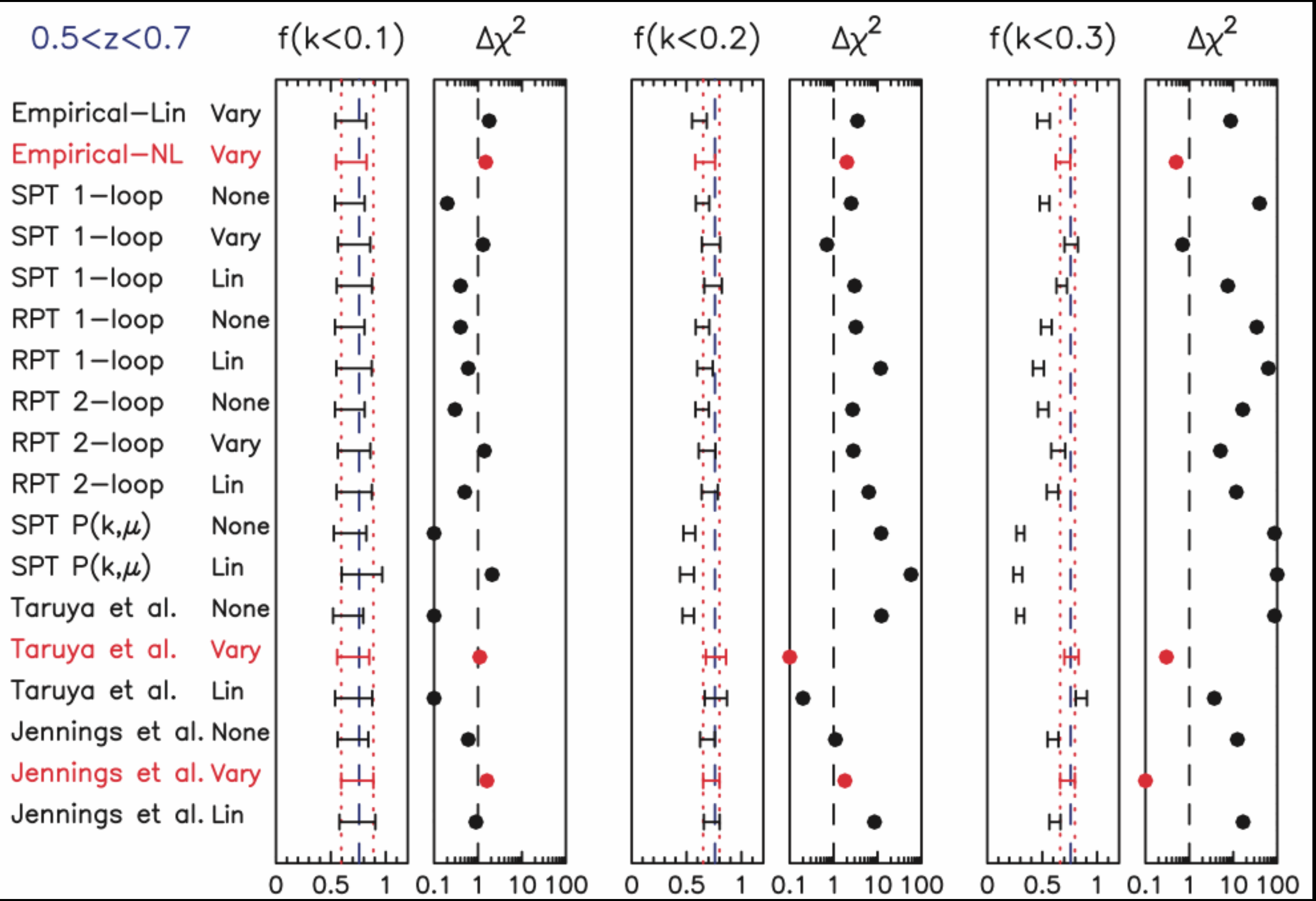


Therefore observations are sensitive to $f\,\sigma_8$

WiggleZ – Growth of Structure



Growth vs model

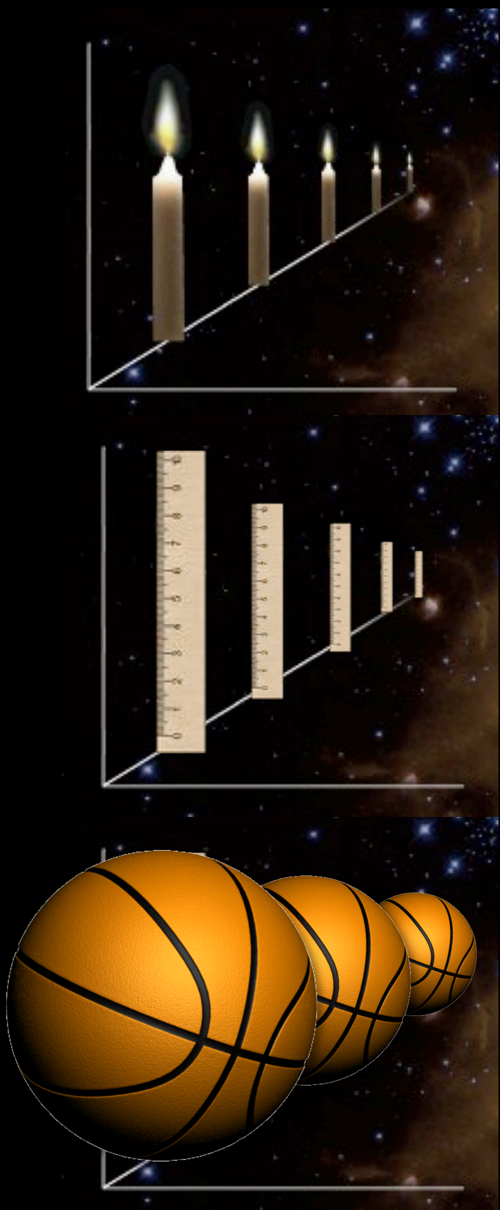


Blake et al. 2011 (Growth)

Blake, Glazebrook, Davis et al. 2011

3A. H(Z) ALCOCK-PACZYNSKI + SN

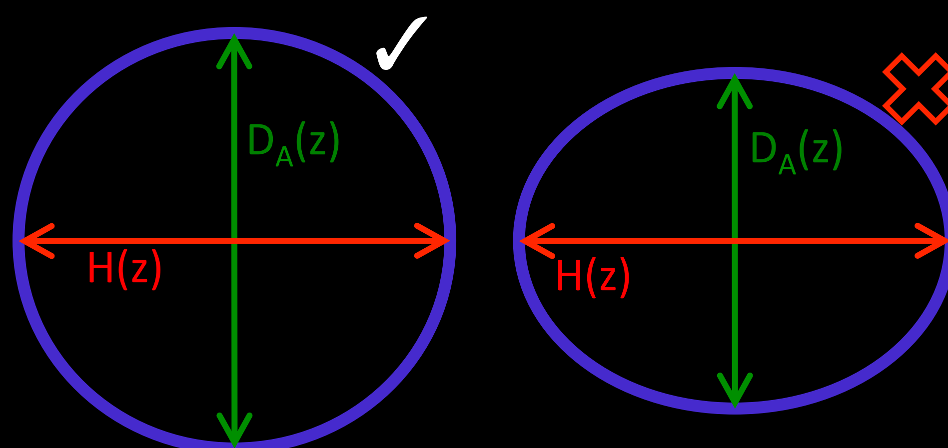
BAO – a standard sphere



- SNe = radial info (line of sight)
- CMB = tangential info (surface of sphere)

- BAO can be applied radially to give H(z) AND tangentially to give $D_A(z)$

Alcock-Paczynski test:



WiggleZ – Measurement of H(z)

WiggleZ measures

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

Supernovae measure

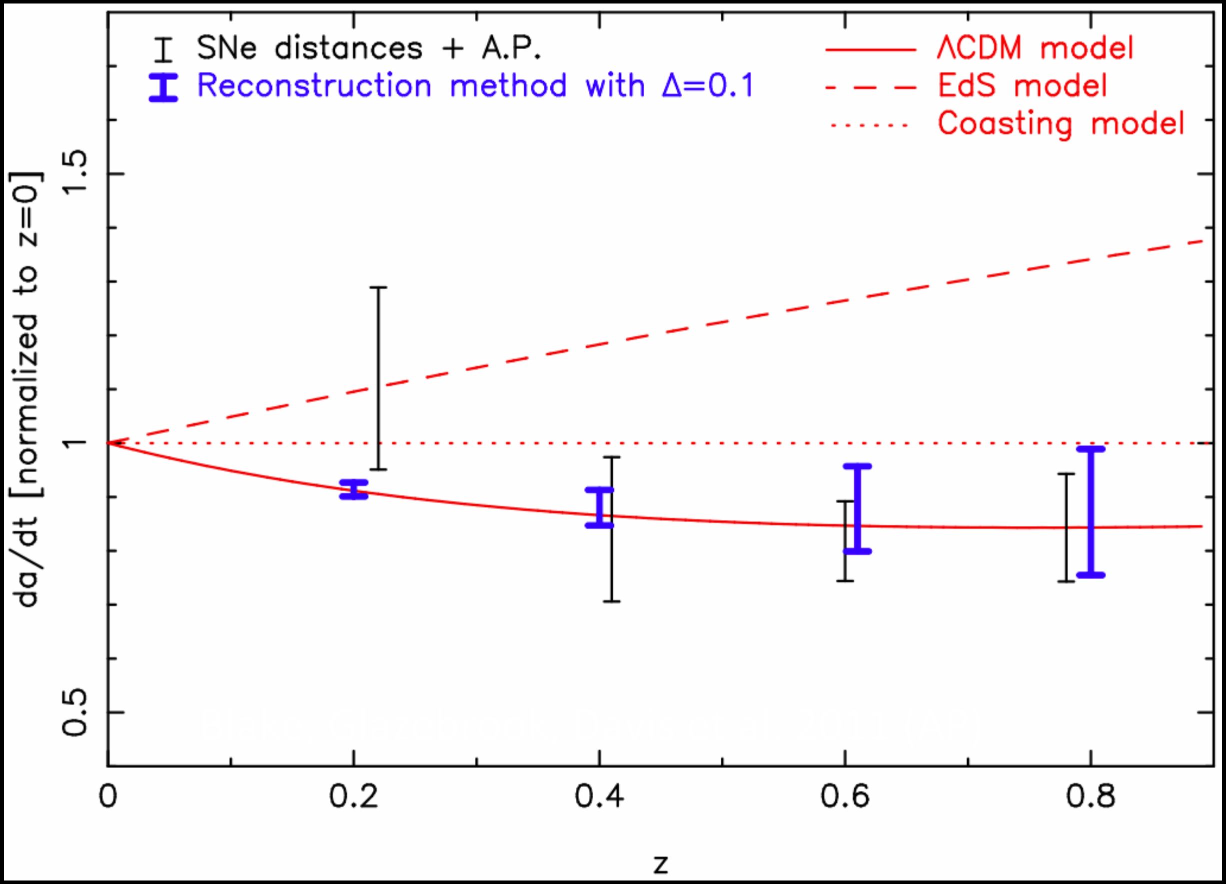
$$D_L(z)\,H_0/c$$

Distances are related by

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

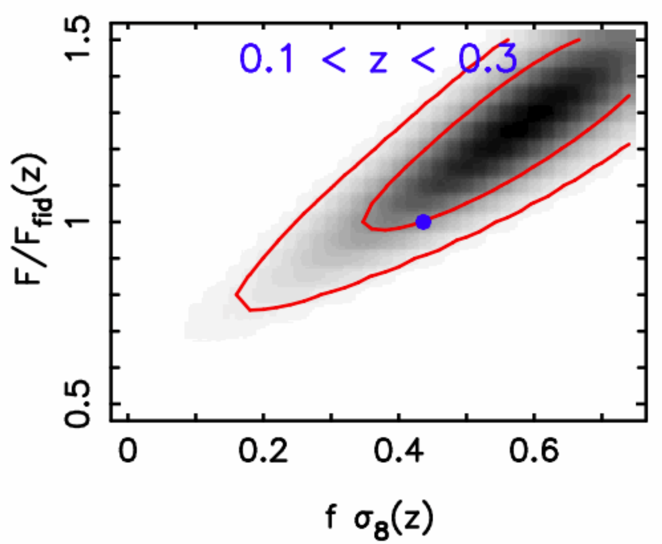
So the ratio gives

$$H(z)/H_0$$



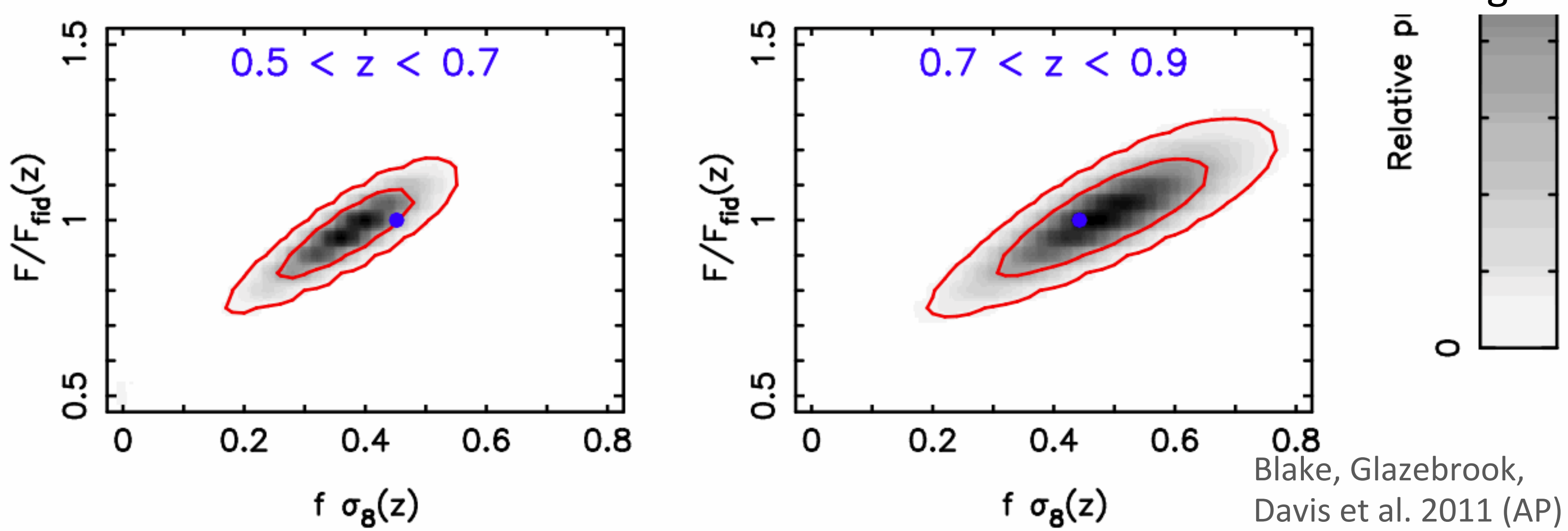
Alcock-Paczynski / z-space distortions

H_{fid}/H $D_A/D_{A,fid}$



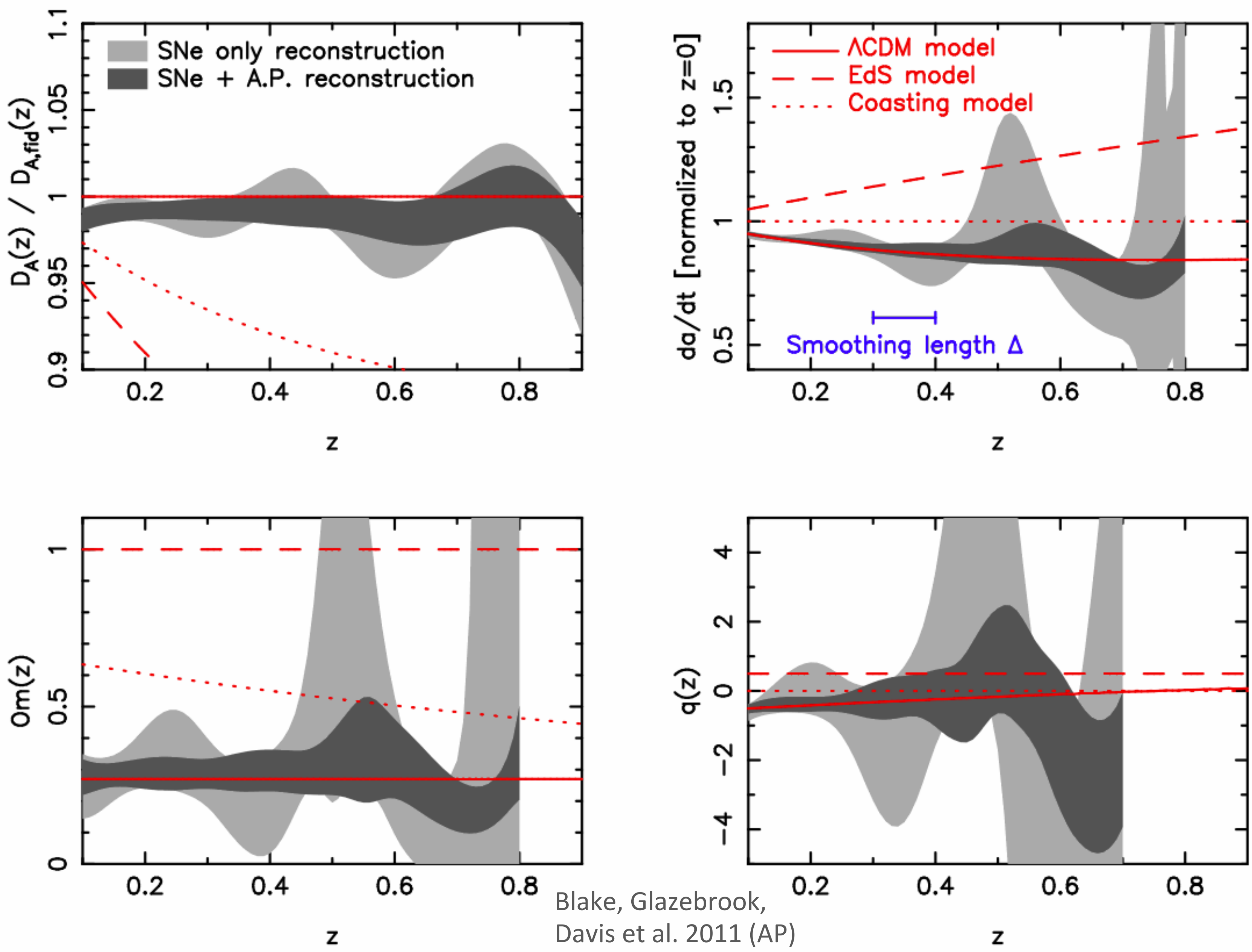
$$
\begin{aligned}
P'_{\rm gal}(k') \;=\; & \frac{1}{f_\perp^2 f_\parallel} b^2 P_m \left(\frac{k'}{f_\perp} \sqrt{1+\mu'^2\left(\frac{1}{(f_\parallel/f_\perp)^2}-1\right)} \right) \\
& \times \left[1+\mu'^2\left(\frac{1}{(f_\parallel/f_\perp)^2}-1\right) \right]^{-2} \\
& \times \left[1+\mu'^2\left(\frac{\beta+1}{(f_\parallel/f_\perp)^2}-1\right) \right]^{2} \\
& \times D\left(\frac{k'_\parallel \sigma_v}{f_\parallel} \right)
\end{aligned}
$$

Ballinger et al. 1996



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

Reconstructions



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

Blake et al. 2012

3B. H(Z) ALCOCK-PACZYNSKI + BAO

WiggleZ growth + AP + BAO

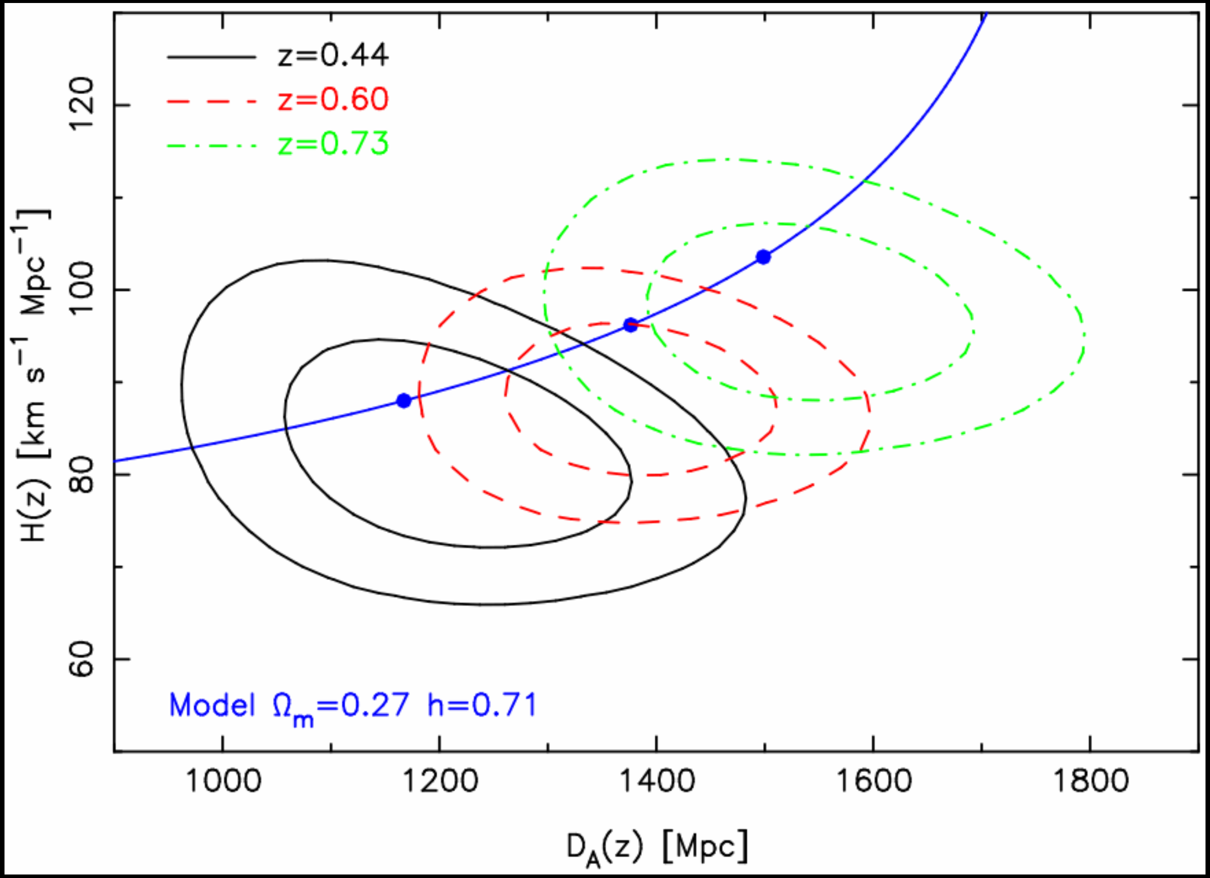
WiggleZ AP measures

$$F \propto D_A H$$

WiggleZ BAO measures

$$A \propto (D_A^2/H)^{1/3}$$

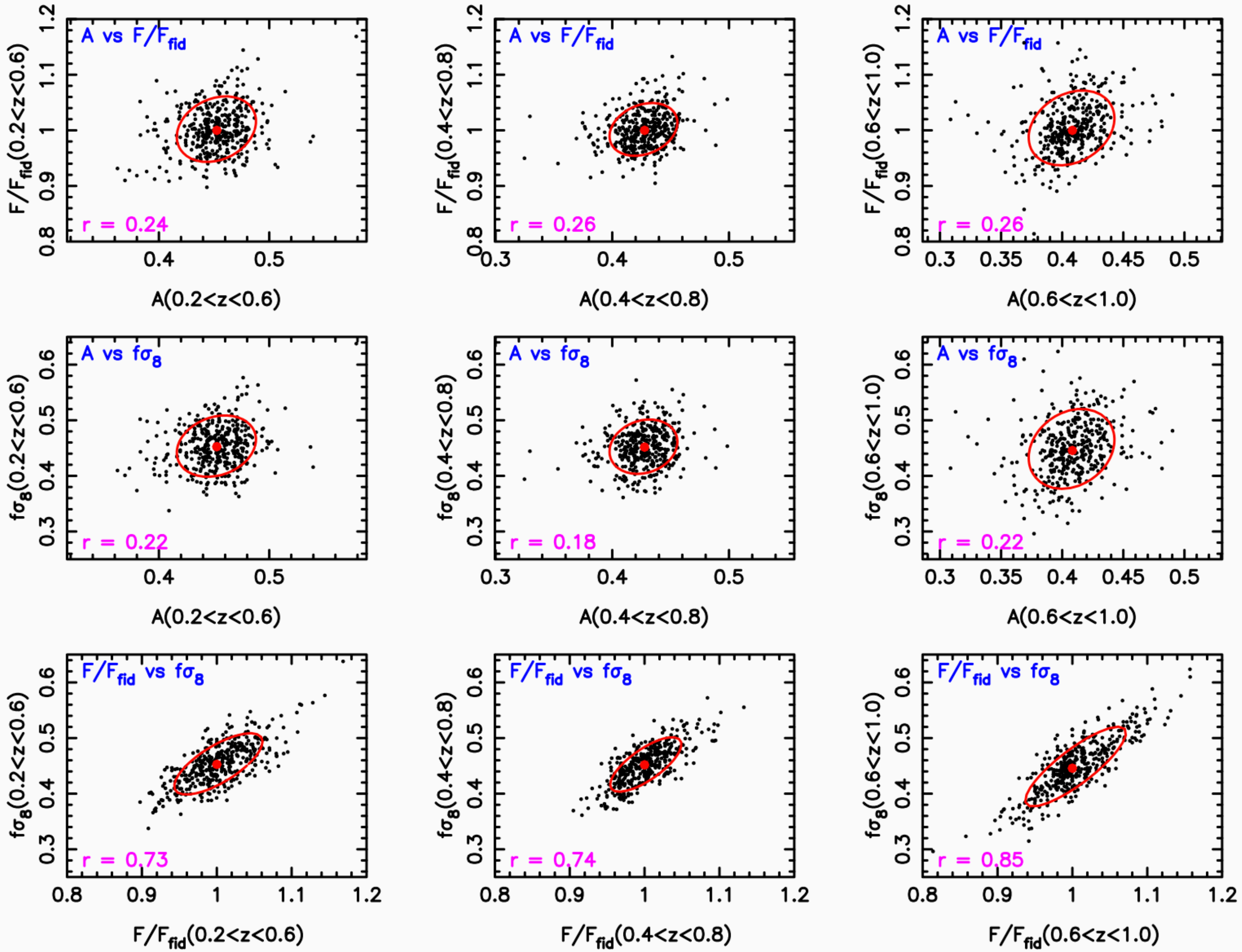
So the combination allows us to measure distance and expansion rate separately



Marginalized over $\Omega_m h^2$, with CMB prior (Komatsu et al. 2009) of 0.1345±0.0055

Covariances

400 lognormal realizations per WiggleZ field and per z-slice (7200 total)

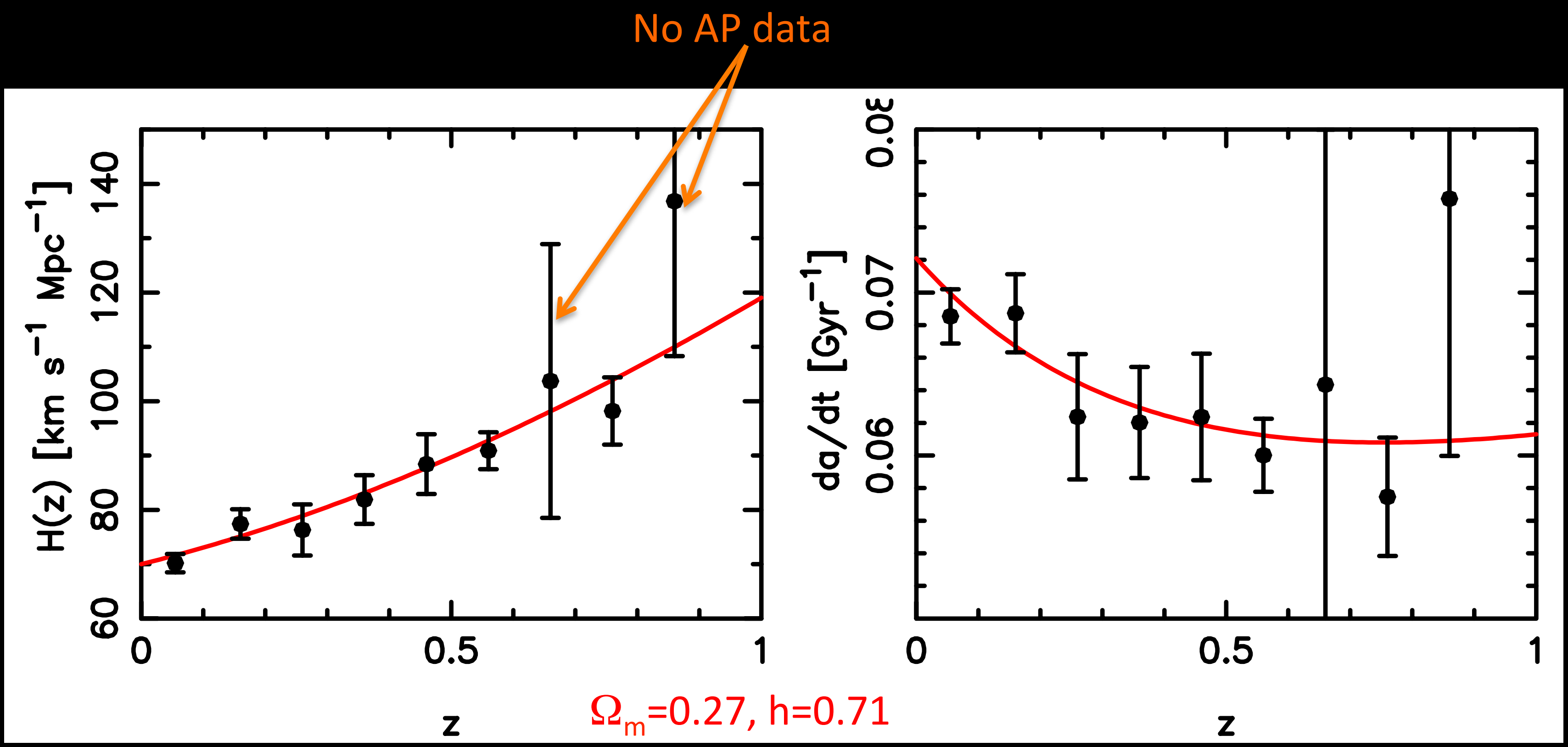


Covariance matrix – (2nd AP paper)

Table 2. This Table lists the values of $10^3\underline{\underline{C}}$, where $\underline{\underline{C}}$ is the covariance matrix of measurements from the WiggleZ Survey data of the acoustic parameter $A(z)$, the Alcock-Paczynski distortion parameter $F(z)$ and normalized growth rate $f\sigma_8(z)$, where each parameter is measured in three overlapping redshift slices (z_1, z_2, z_3) with effective redshifts $z_{\rm eff} = 0.44$, 0.6 and 0.73, respectively, where $z_1 = [0.2, 0.6]$, $z_2 = [0.4, 0.8]$ and $z_3 = [0.6, 1.0]$. The data vector is ordered such that $\underline{Y}_{\rm obs} = (A_1, A_2, A_3, F_1, F_2, F_3, f\sigma_{8,1}, f\sigma_{8,2}, f\sigma_{8,3}) = (0.474, 0.442, 0.424, 0.482, 0.650, 0.865, 0.413, 0.390, 0.437)$. The chi-squared statistic for any cosmological model vector $\underline{Y}_{\rm mod}$ can be obtained via the matrix multiplication $\chi^2 = (\underline{Y}_{\rm obs} - \underline{Y}_{\rm mod})^T \underline{\underline{C}}^{-1} (\underline{Y}_{\rm obs} - \underline{Y}_{\rm mod})$. The matrix is symmetric; we just quote the upper diagonal.

Parameter	$A(z_1)$	$A(z_2)$	$A(z_3)$	$F(z_1)$	$F(z_2)$	$F(z_3)$	$f\sigma_8(z_1)$	$f\sigma_8(z_2)$	$f\sigma_8(z_3)$
$A(z_1)$	1.156	0.211	0.000	0.400	0.234	0.000	0.598	0.129	0.000
$A(z_2)$	-	0.400	0.189	0.118	0.276	0.336	0.080	0.227	0.230
$A(z_3)$	-	-	0.441	0.000	0.167	0.399	0.000	0.146	0.333
$F(z_1)$	-	-	-	2.401	1.350	0.000	2.862	1.080	0.000
$F(z_2)$	-	-	-	-	2.809	1.934	1.611	2.471	1.641
$F(z_3)$	-	-	-	-	-	5.329	0.000	1.978	4.468
$f\sigma_8(z_1)$	-	-	-	-	-	-	6.400	2.570	0.000
$f\sigma_8(z_2)$	-	-	-	-	-	-	-	3.969	2.540
$f\sigma_8(z_3)$	-	-	-	-	-	-	-	-	5.184

Combined with other BAO, SNe, and $\Omega_m h^2$



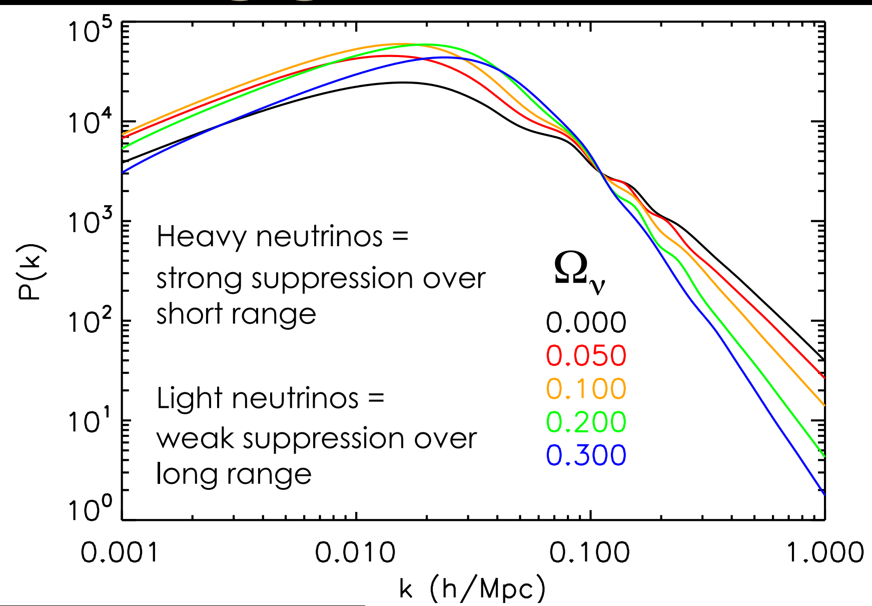
WiggleZ and BOSS (AP+BAO)
6dFGS and SDSS BAO
SNe (Union)
WMAP $\Omega_m h^2$ (not distances)

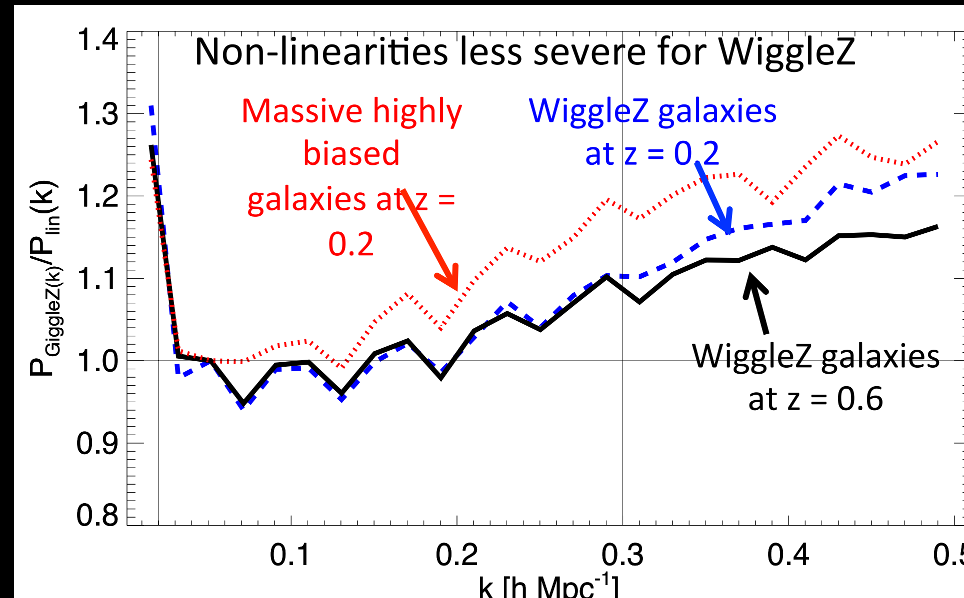
Riemer-Sørensen et al. 2012
Riemer-Sørensen et al. 2012 (in prep)

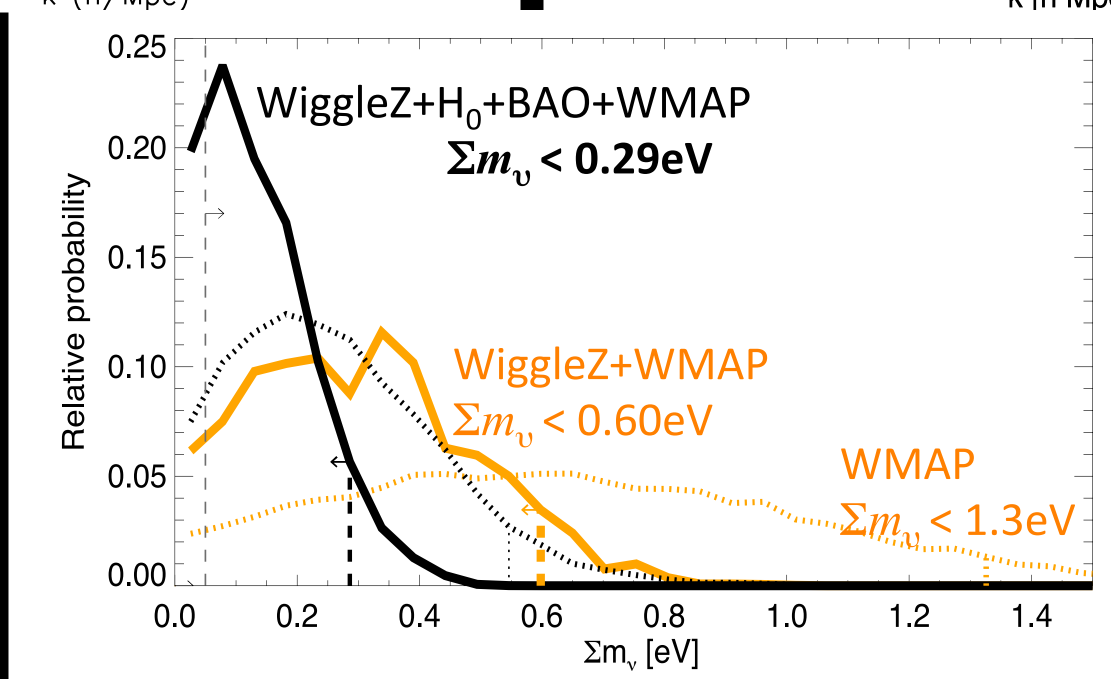
4. NEUTRINO MASS AND N_{EFF}

WiggleZ: Neutrino mass

Riemer-Sørensen et al. 2012





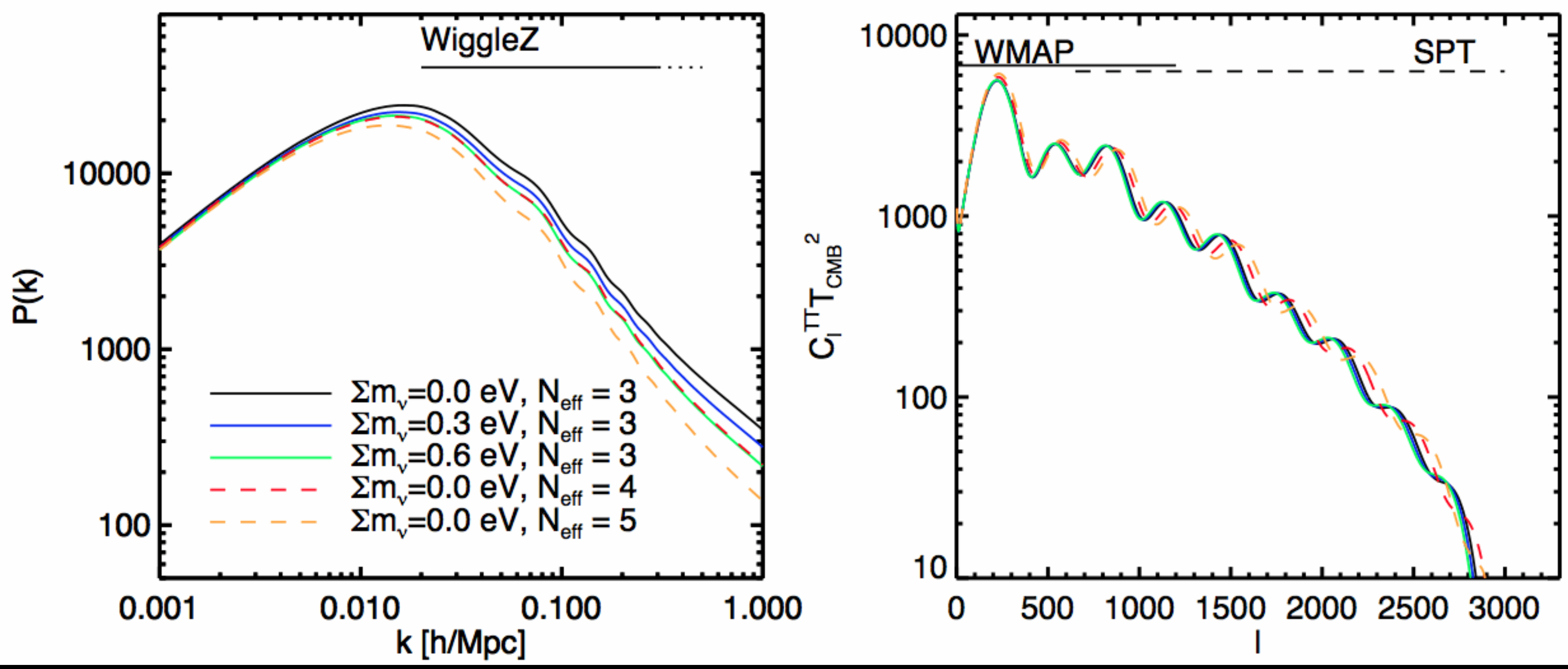


SDSS (Reid et al. 10)
Σm_υ < 0.62eV
Photo (dePutter 12)
Σm_υ < 0.28eV
Ly-α (Seljak et al. 06)
Σm_υ < 0.17eV

h=0.742±0.036
Reiss et al. 09

To k=0.3;
To k=0.1 we get
Σm_υ < 0.39eV

Paper 2: Neutrino mass + number

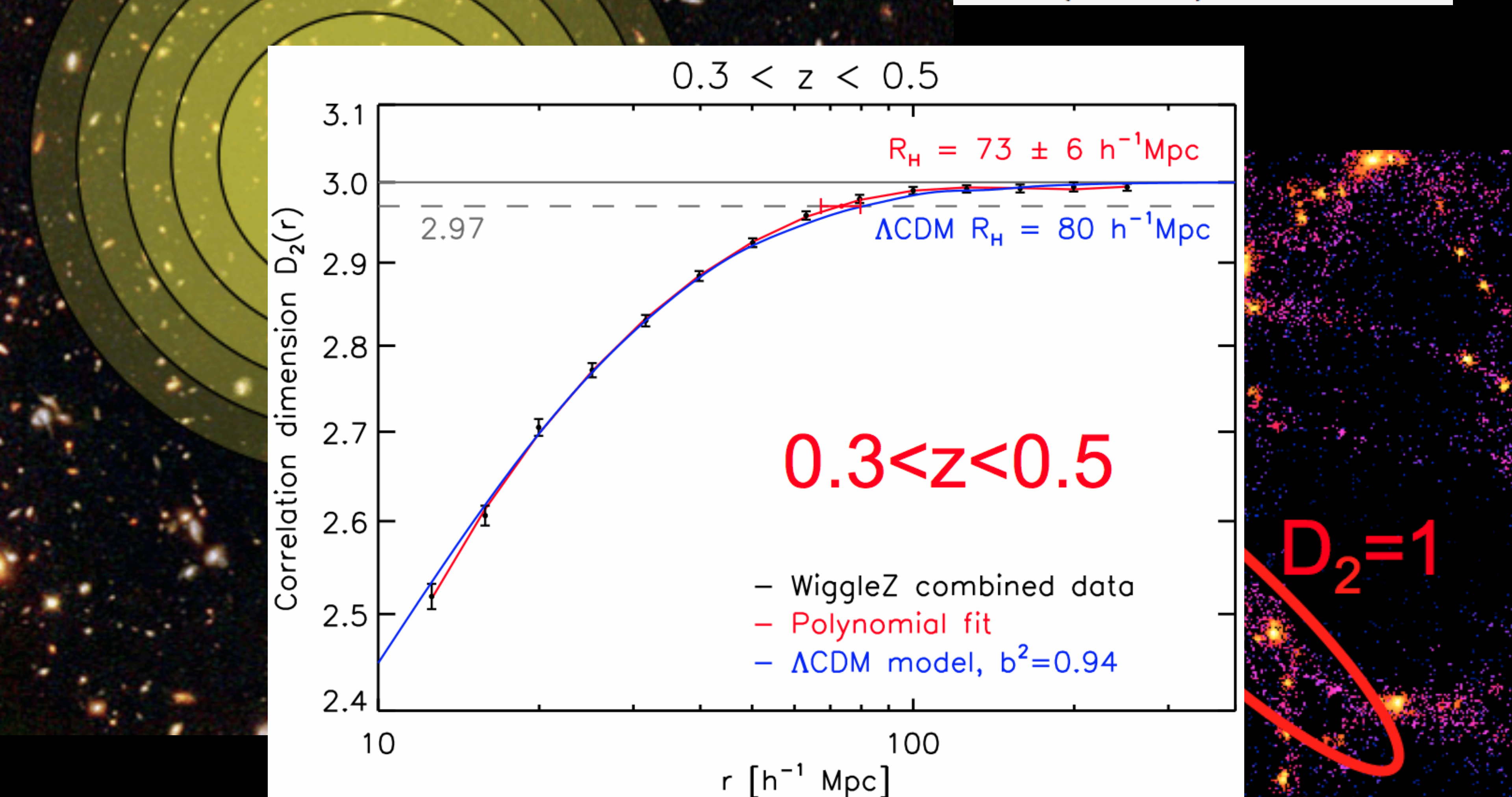


Scrimgeour, Davis, Blake et al. 2012

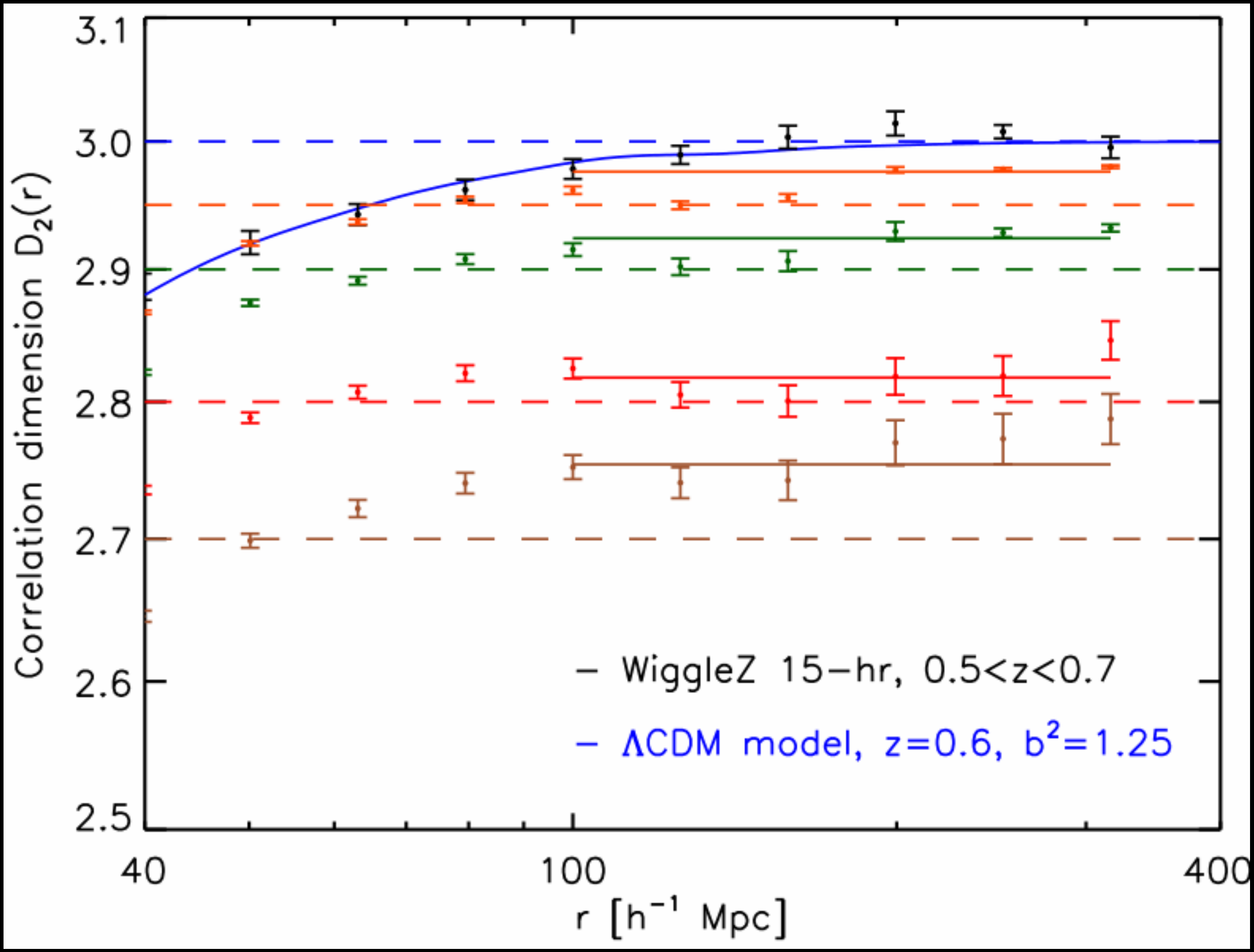
5. HOMOGENEITY

Fractal dimension (Morag Scrimgeour, ICRAR)

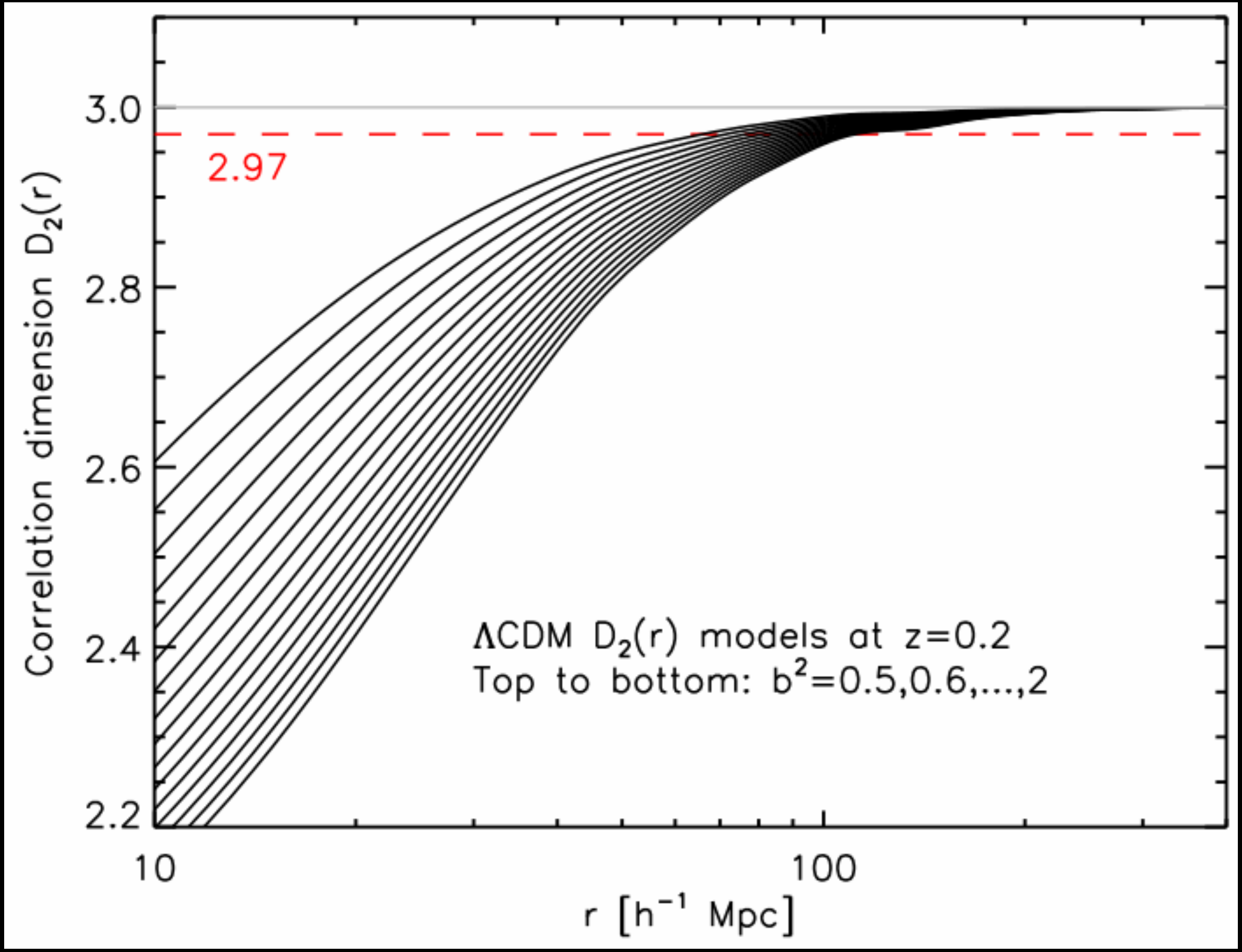
$$N(<r) \propto r^{D_2}$$



Fractal models



Dependence on bias



Parkinson, Riemer-Sørensen, Blake, Poole, Davis, et al. in prep

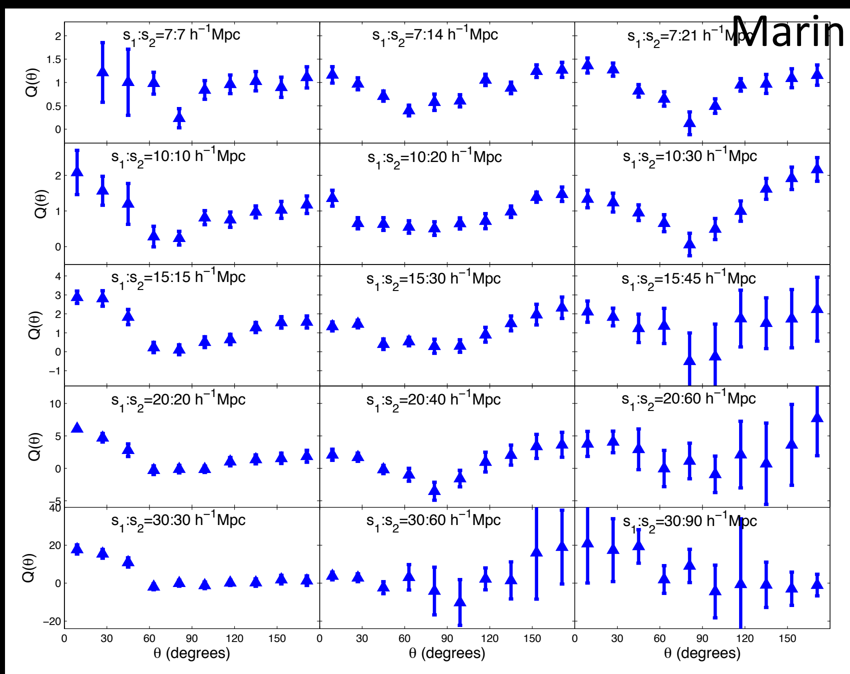
6. FULL POWER SPECTRUM DATA RELEASE + COSMOMC

Watch this space.

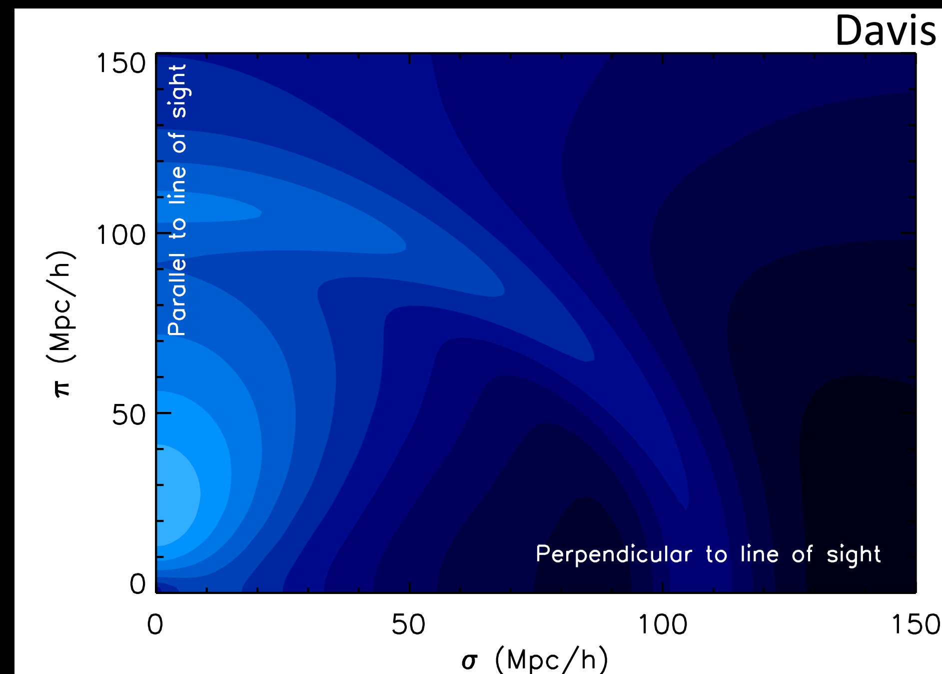
(ΛCDM wins)

Other Upcoming Results (with WigglerZ at this conference)

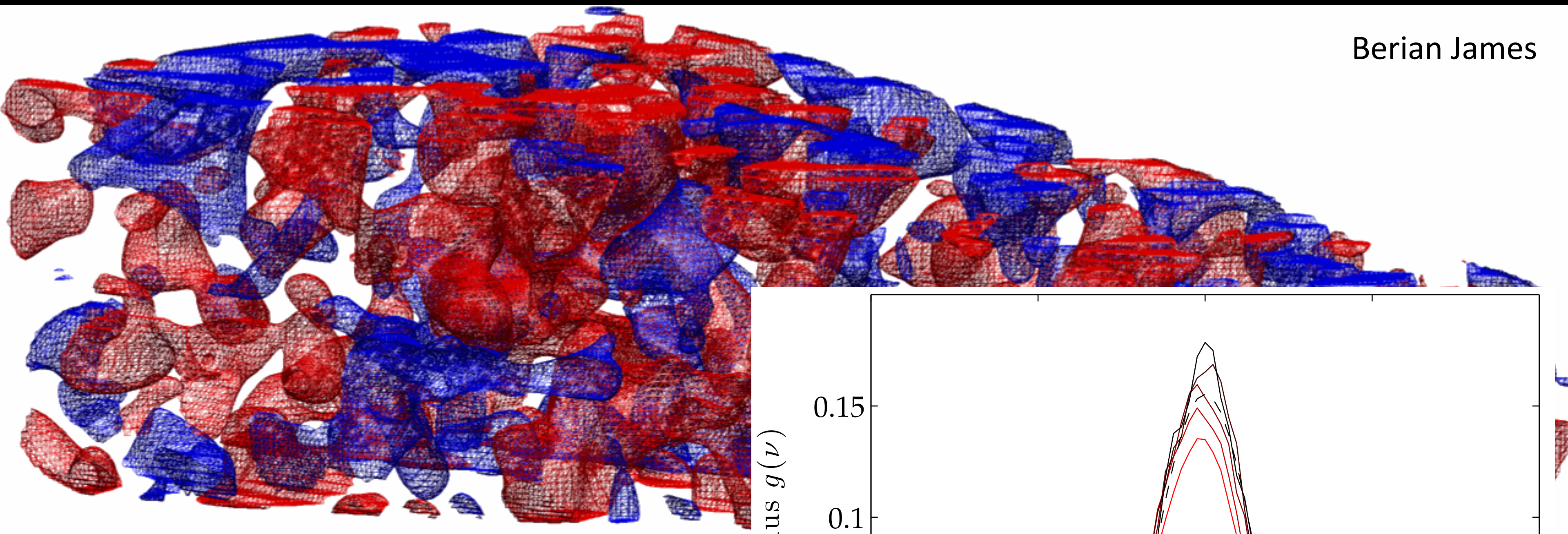
Higher-order statistics (see Felipe Marin)

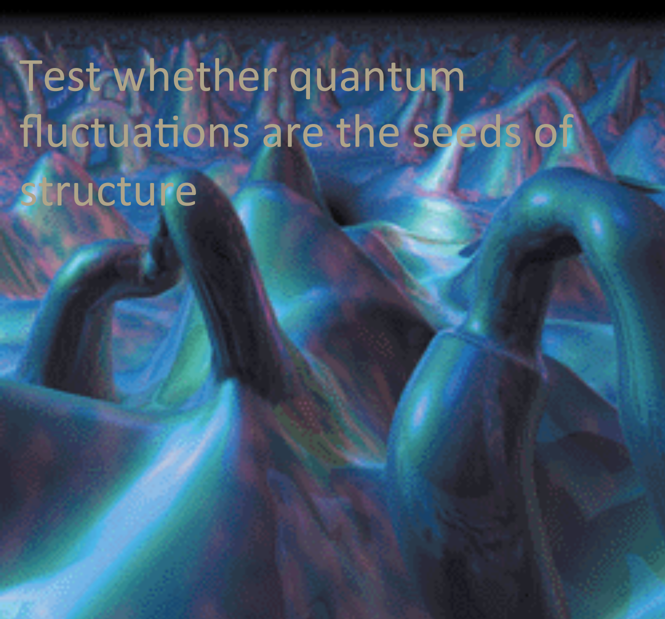


2D BAO and reconstruction (see Eyal Kazin)

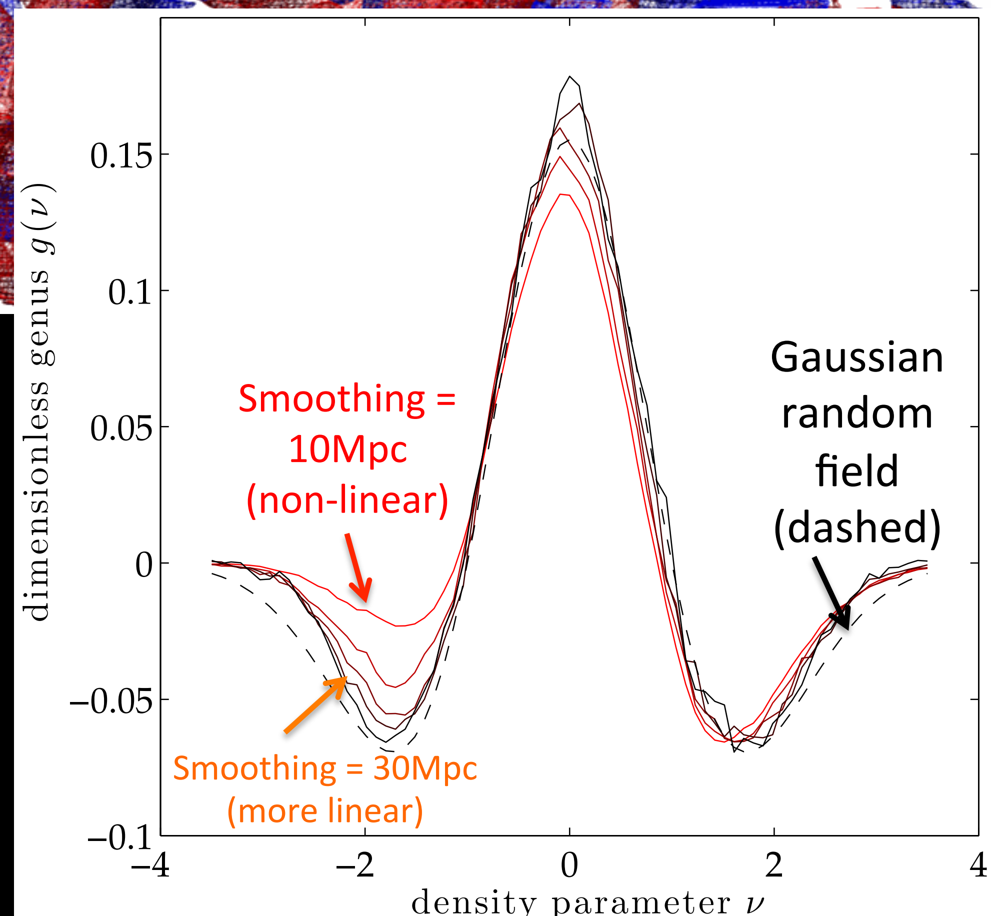


Topology: Genus curve

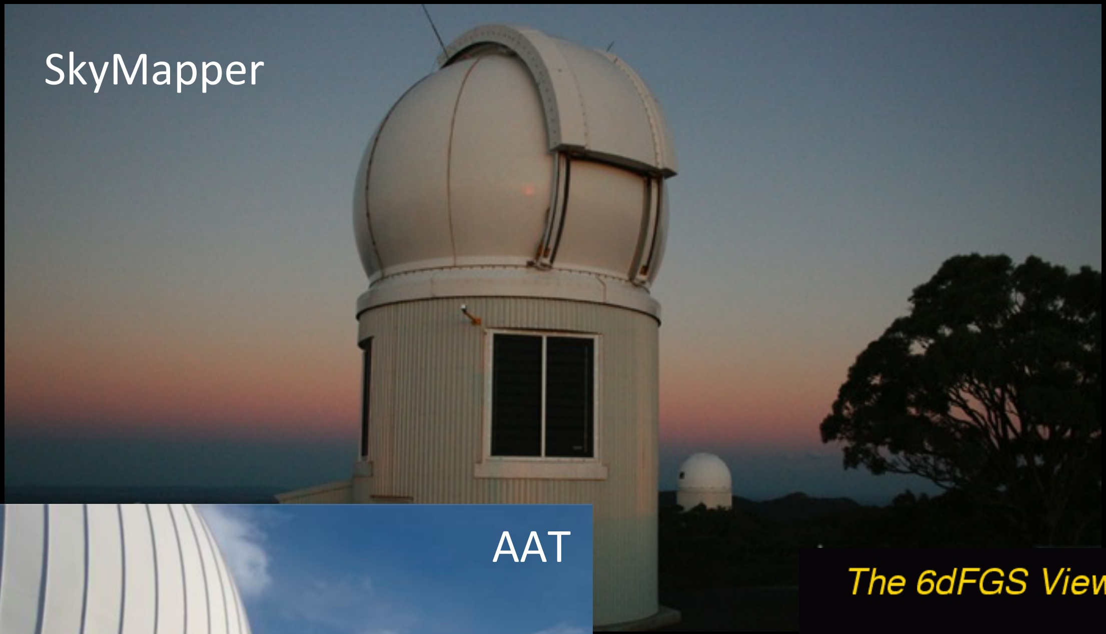


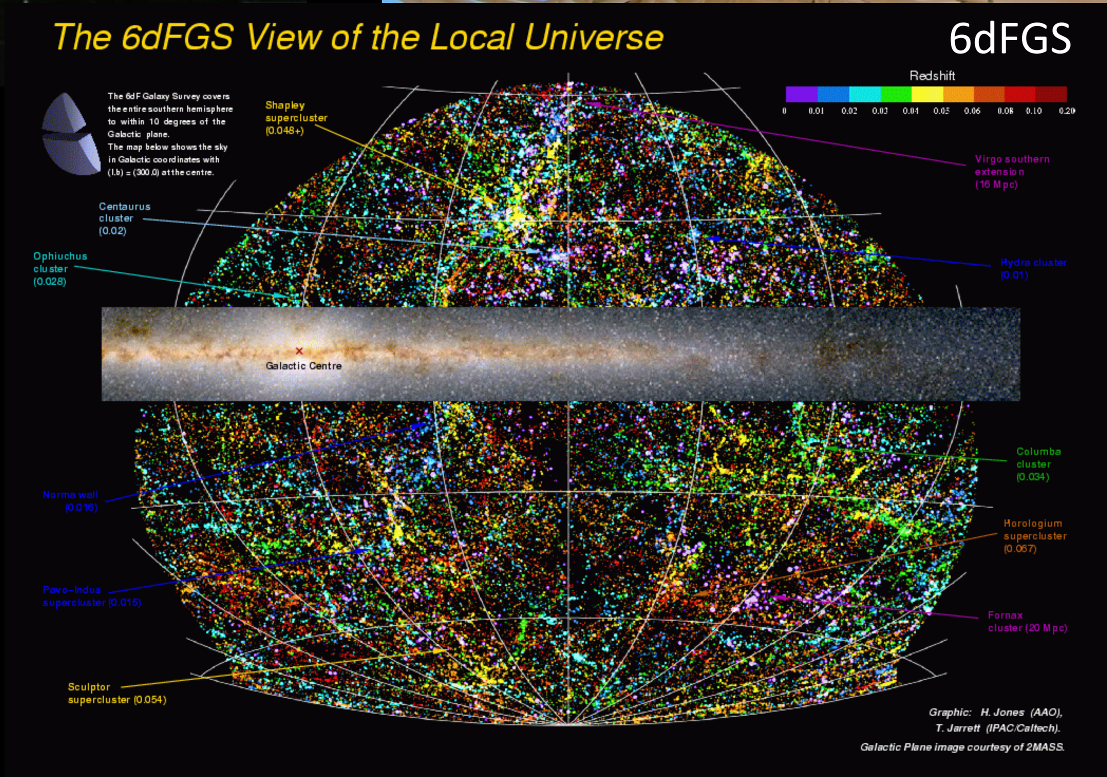


Test whether quantum fluctuations are the seeds of structure



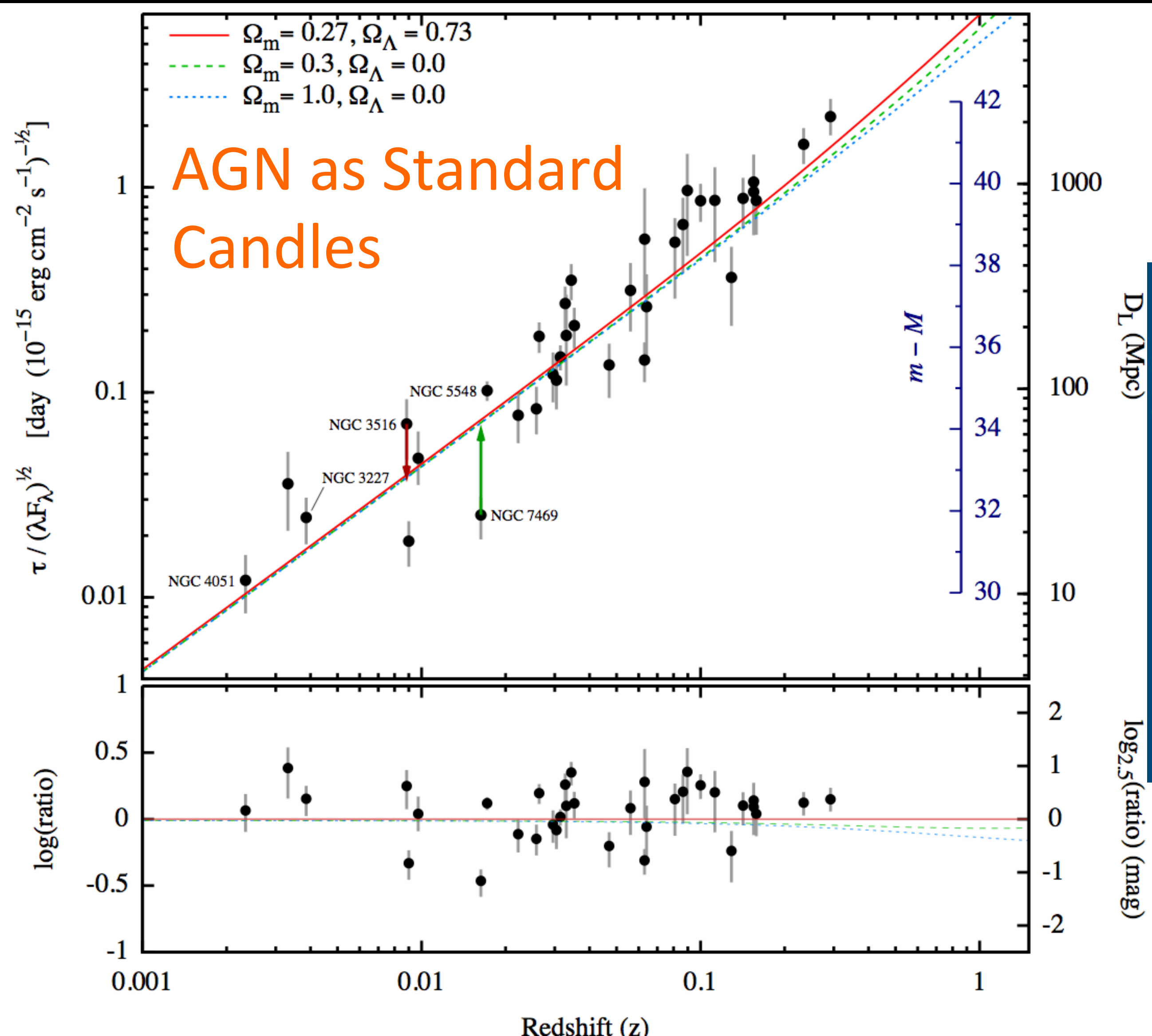
Upcoming Australian Measurements

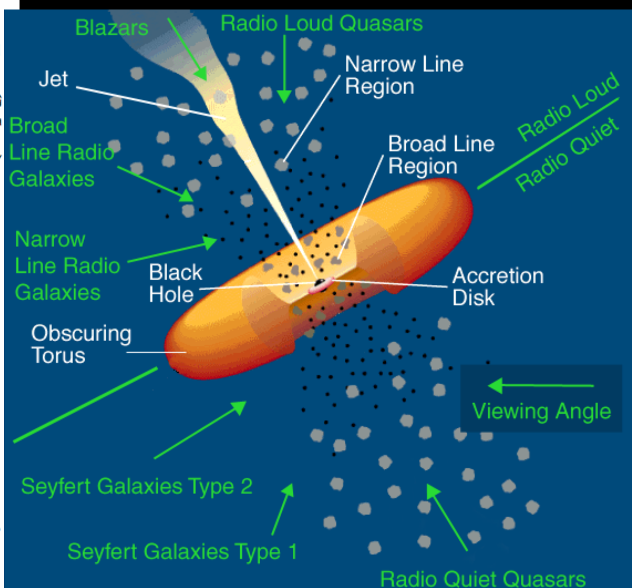


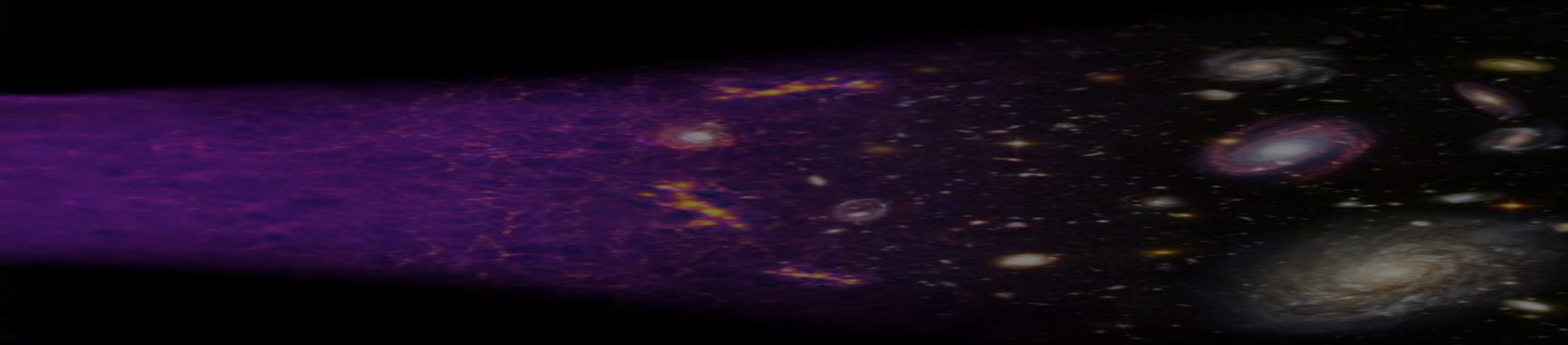


Potentially add new distance data??

(Watson, Denney, Vestergaard & Davis 2011)







Summary

WiggleZ is a great data set, with many interesting cosmology results

We're about to release our data and CosmoMC module

We hope you would like to use it and are happy to work with you to help