

Large Scale Structure

TIARA Winter School, Taipei, February 2014

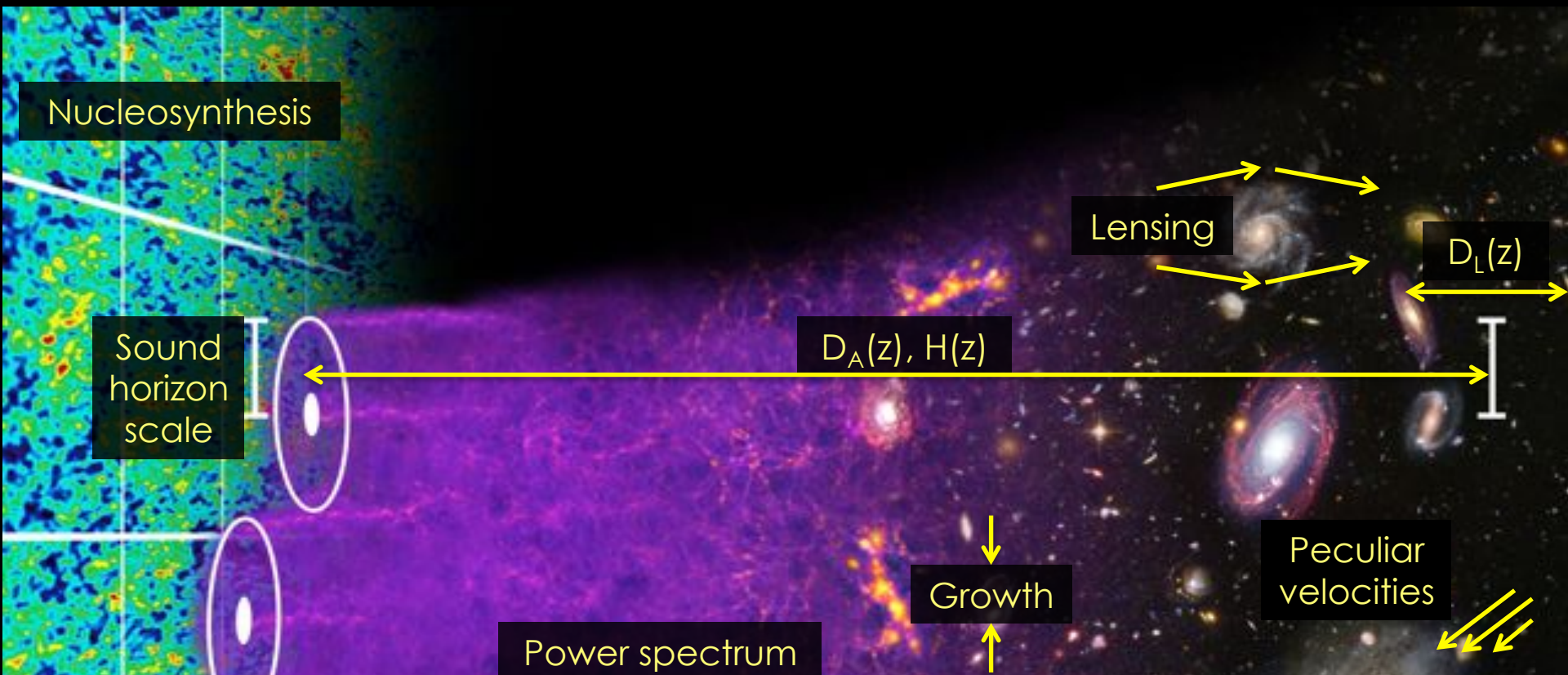
Lecture Two

Observations

Assoc. Prof. Tamara Davis

University of Queensland

Many types of observations = concordance



Parameter	<i>Planck</i> +WP		<i>Planck</i> +WP+highL		<i>Planck</i> +lensing+WP+highL		<i>Planck</i> +WP+highL+BAO	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017 1.4% precision
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025

Case Study: The WiggleZ Dark Energy Survey



The **highest-redshift** galaxy survey ever undertaken

$0.2 < z < 1.0$

220,000 **blue** galaxies

1 GPC³

Observations **finished** Jan 2011

THE 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

AAO: Matthew Colless, Rob Sharp, Sarah Brough

Sydney: Scott Croom, Ben Jelliffe

ANU: Mike Pracy

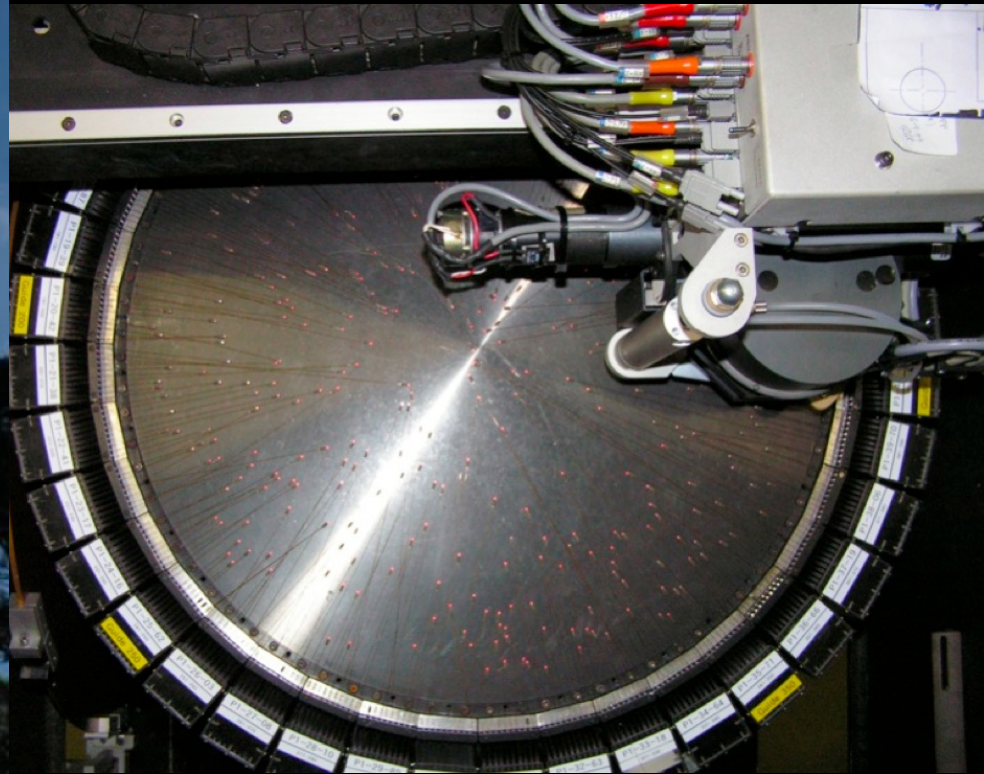
UBC: David Woods

Caltech: Chris Martin, Ted Wyder

Carnegie: Barry Madore

Plus students and associate members

WiggleZ - How



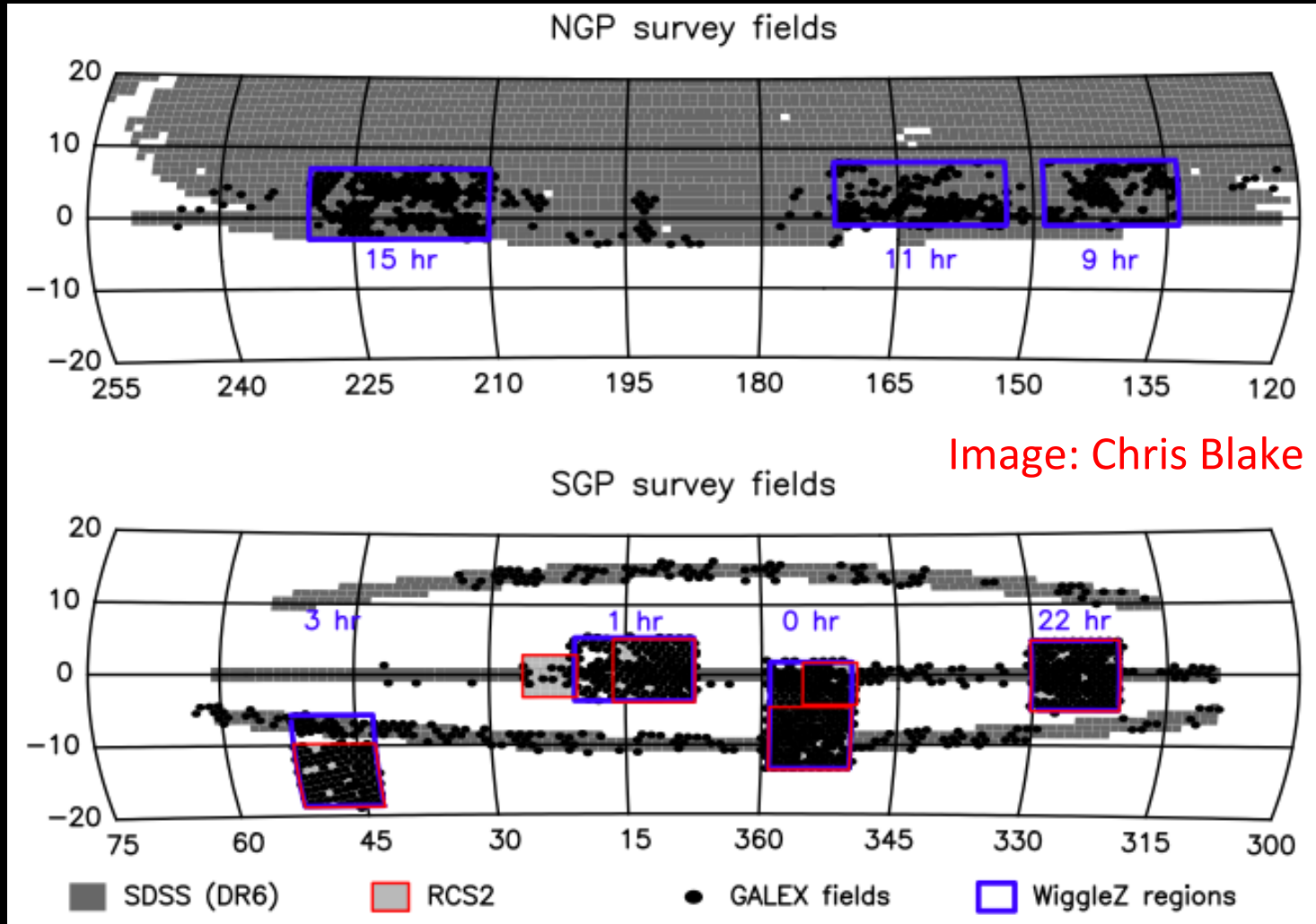
2dF on the
Anglo Australian Telescope

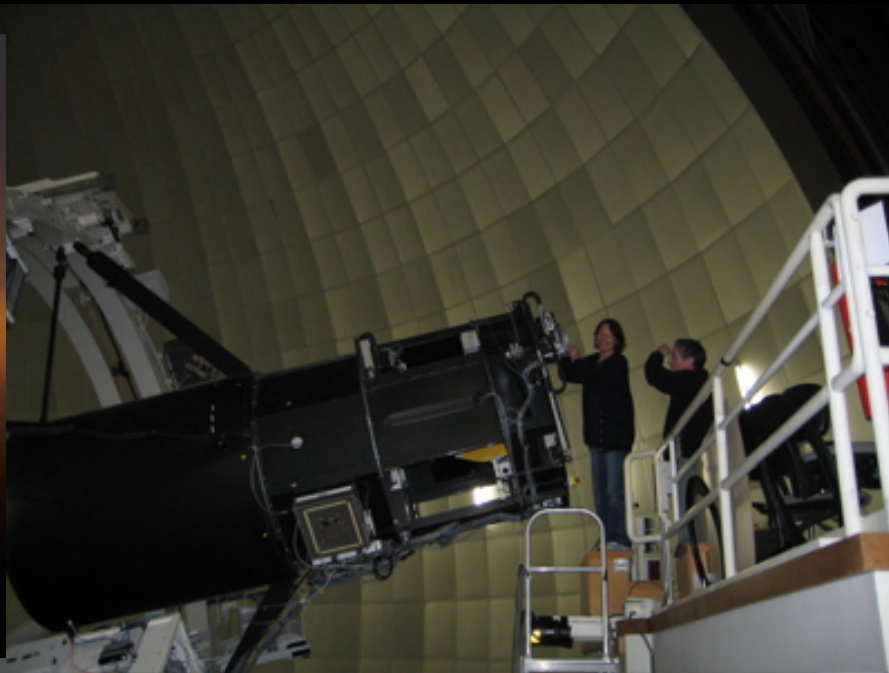


WiggleZ survey fields

7 equatorial fields, each 100-200 deg²
>9° on side, ~3 x BAO scale at $z > 0.5$

Physical size ~ 1300 x 500 x 500 Mpc/h

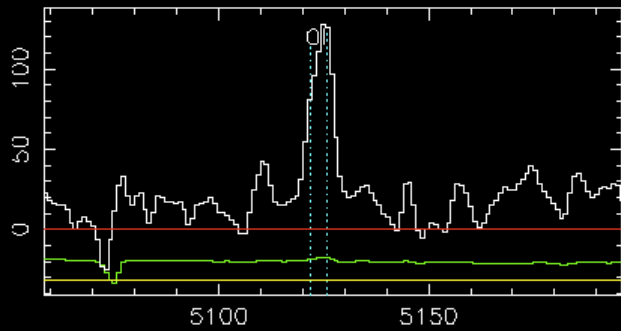




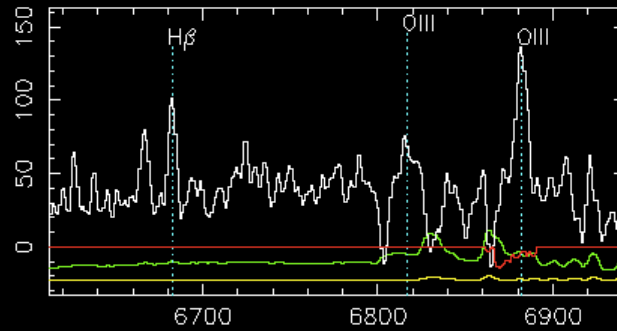


Example spectrum: $z=0.37$

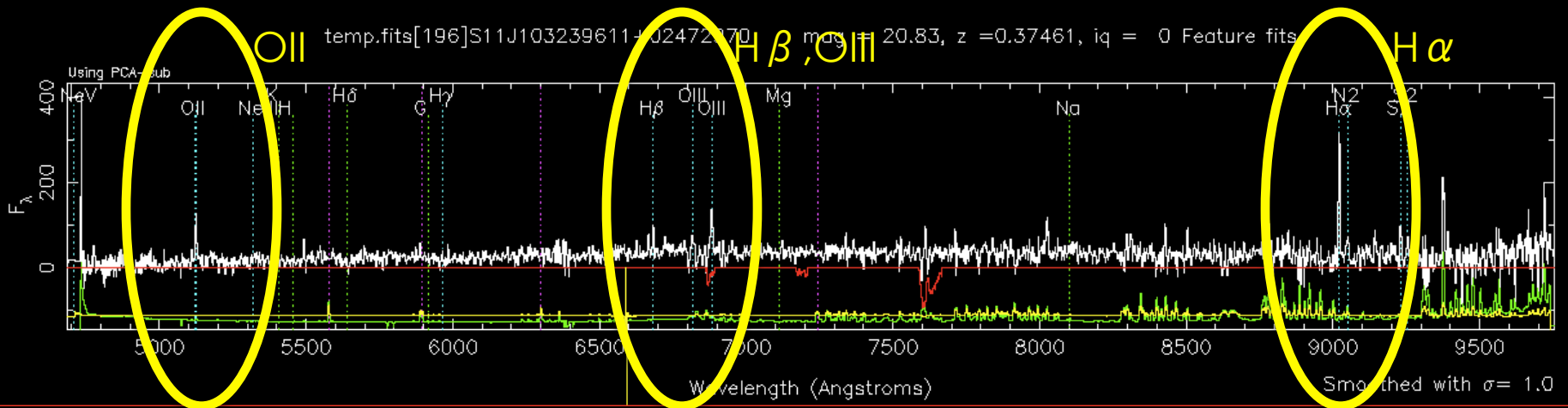
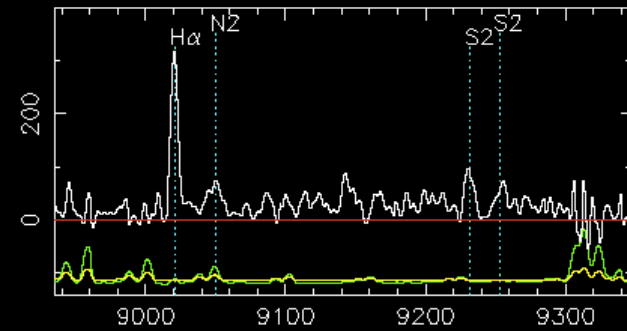
[OII] region



H β -[OIII] region

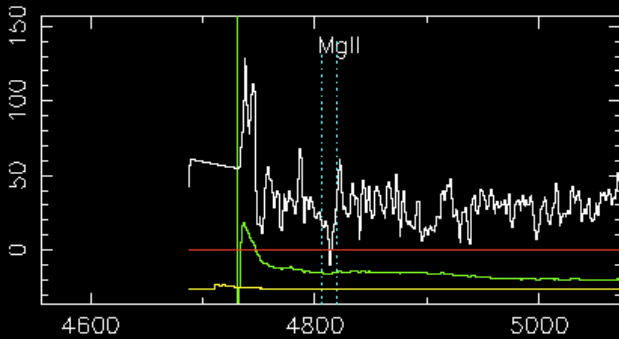


H α -[NII] region

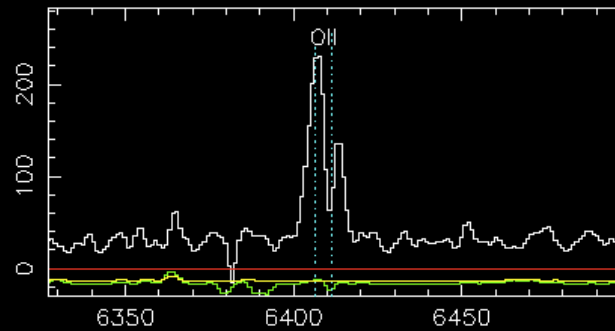


Example spectrum: $z=0.72$

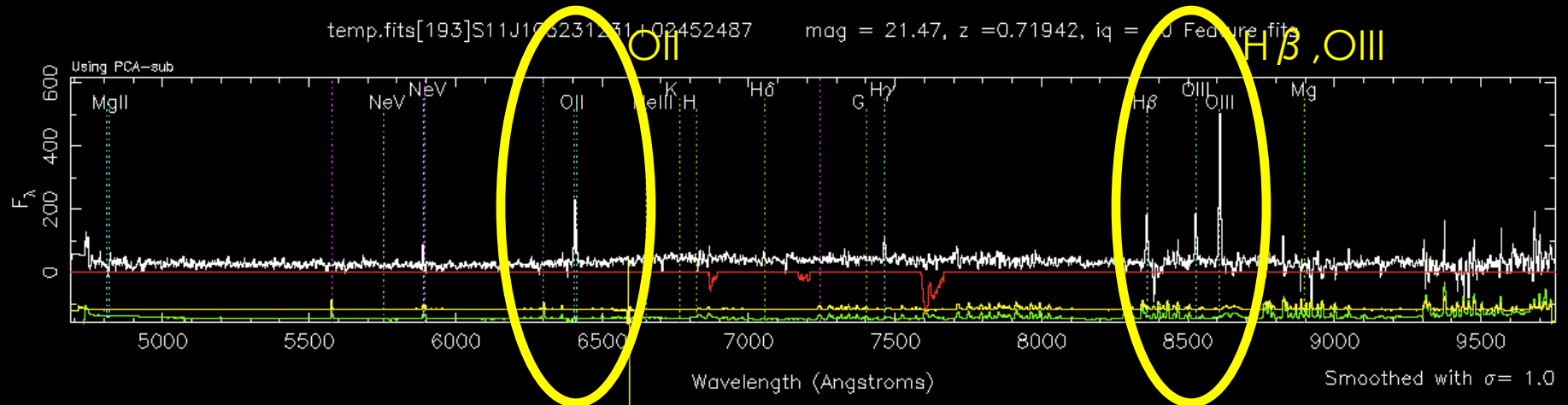
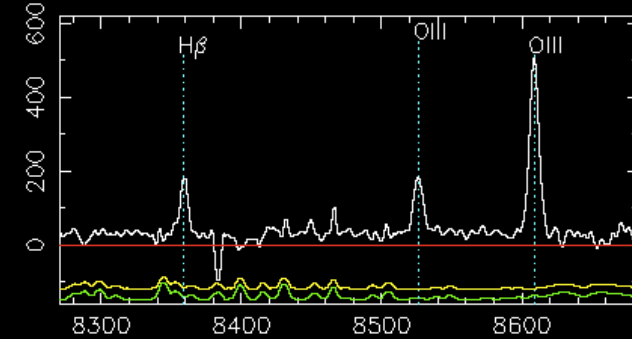
MgII region



[OII] region



$H\beta$ -[OIII] region



This light was emitted
6.5 billion years ago

My highest (speculative) $z=3.66$

Ly α -NV region

CIV region

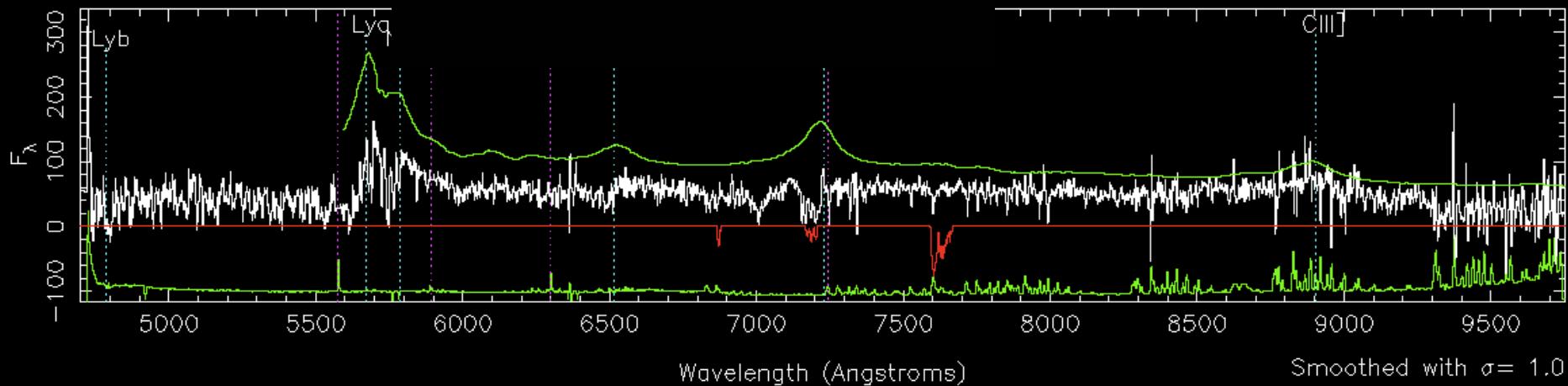
CIII] region

If correct,
this light was
emitted
12 billion
years ago

(This formed 4.5 billion years ago)

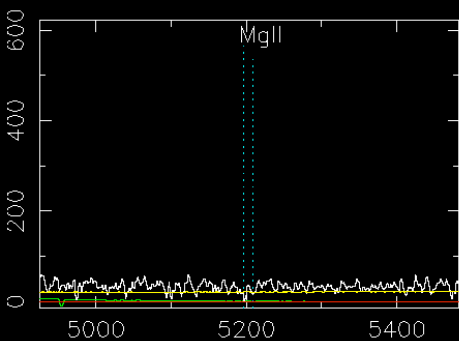
r09f41s0'

, z = 3.66600, iq = 0 Manual

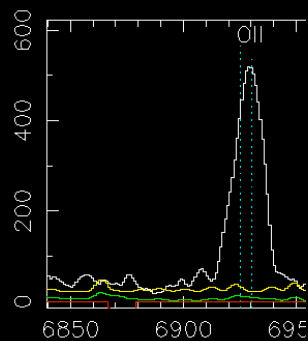


Double peaked profile

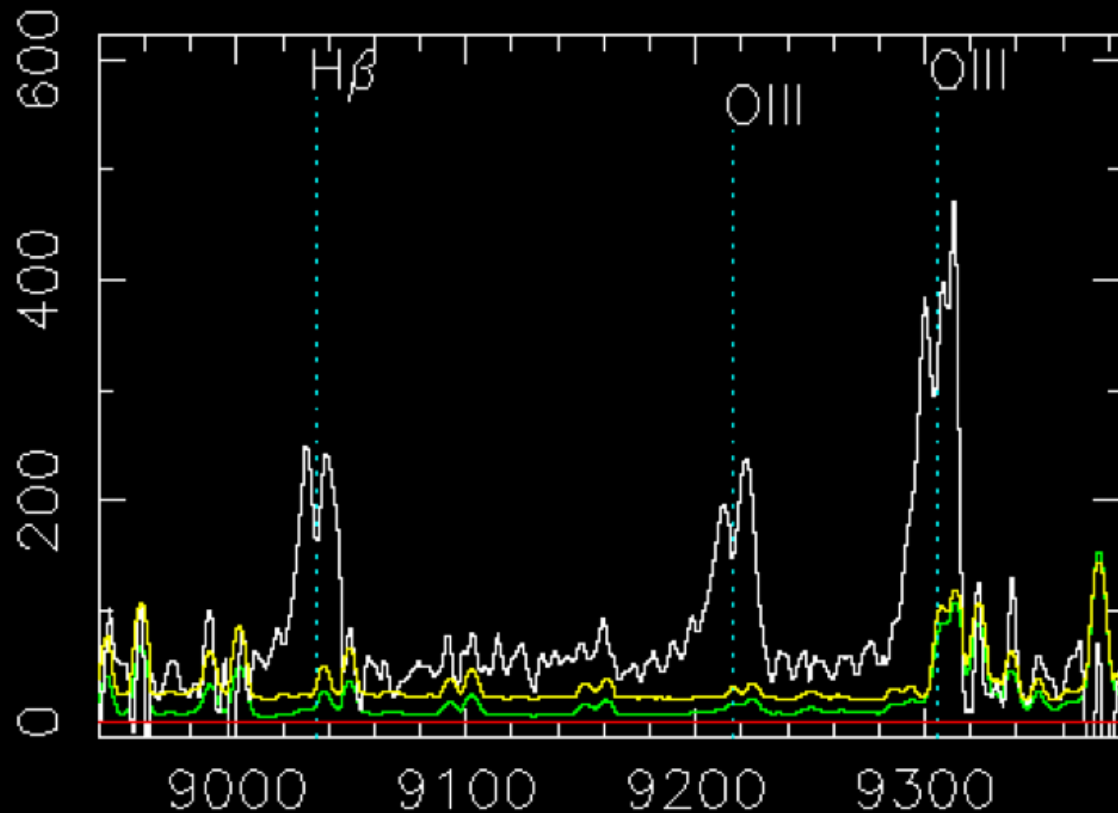
MgII region



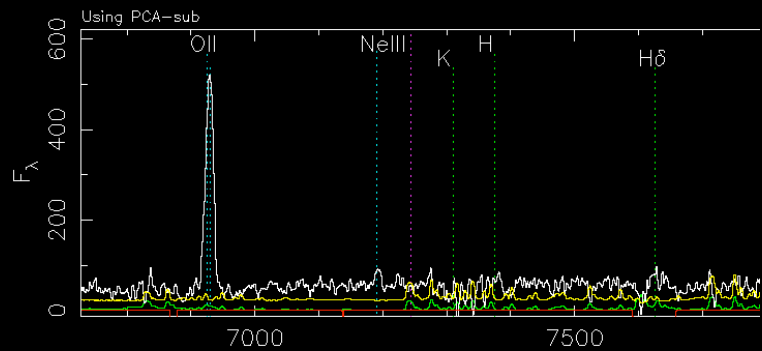
[OIII] region



H β - [OIII] region

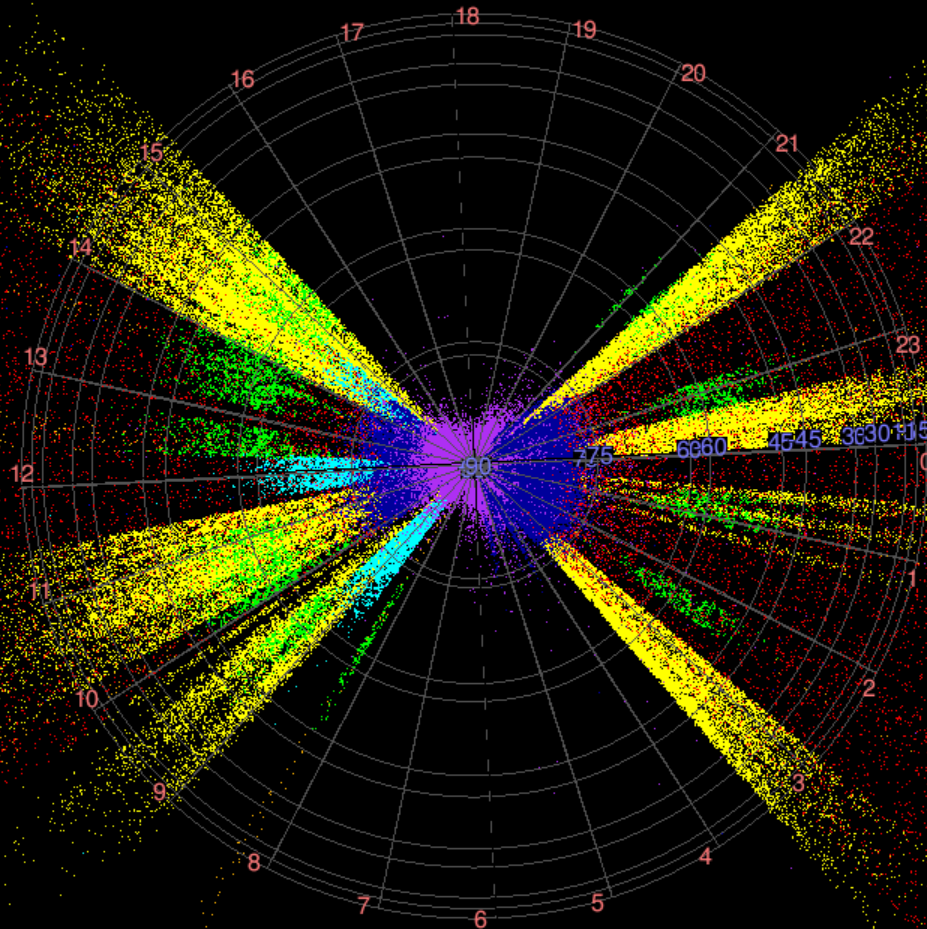


r15f15s01_090429_BR_ss.fits[:



WiggleZ survey fields (compared to other AAT surveys)

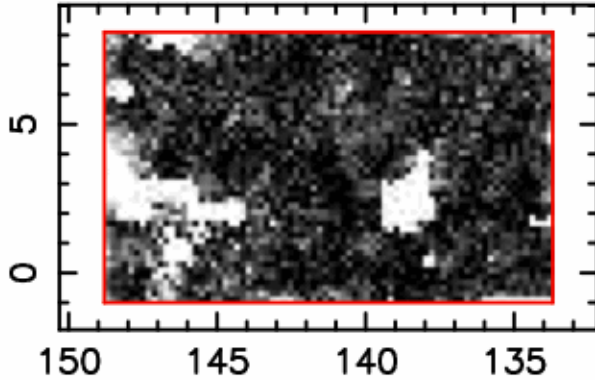
7 equatorial fields, each 100-200 deg²
>9° on side, ~3 x BAO scale at $z > 0.5$
Physical size ~ 1300 x 500 x 500 Mpc/h



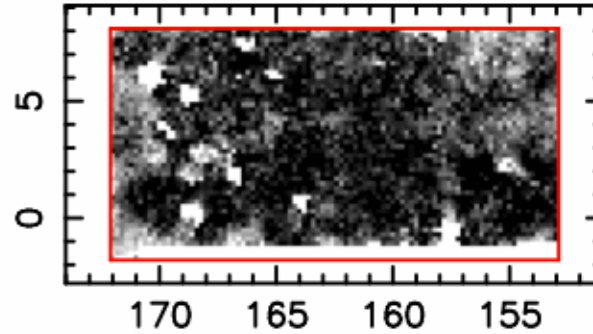
6dFGS (purple), 2dFGRS (blue), MGC (navy), GAMA (cyan), 2SLAQ-LRG (green),
WiggleZ (yellow), 2SLAQ-QSO (orange), 2QZ (red); the celestial sphere is at $z=1$.

Measuring $P(k)$ and $\xi(r)$: the practical

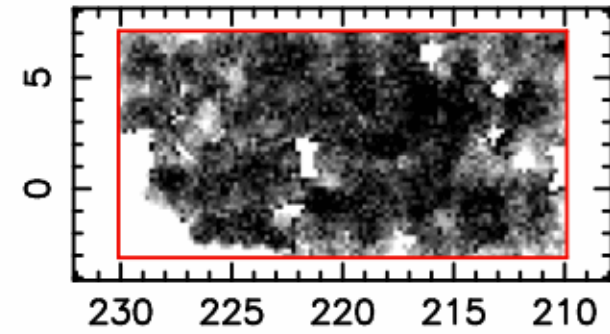
9-hr region



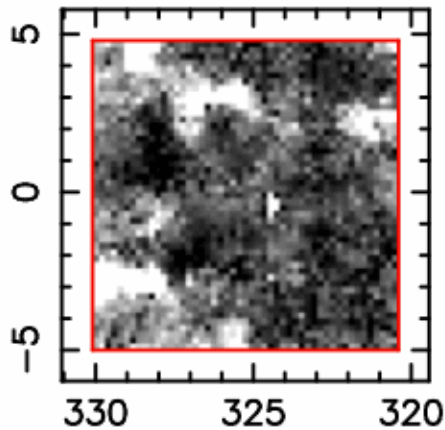
11-hr region



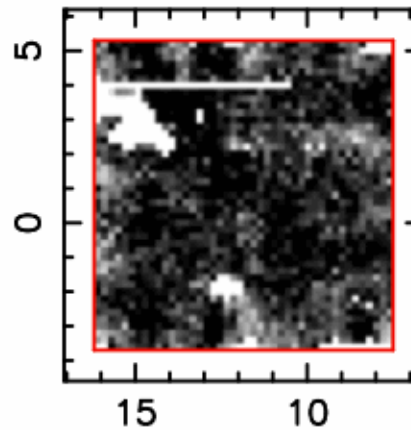
15-hr region



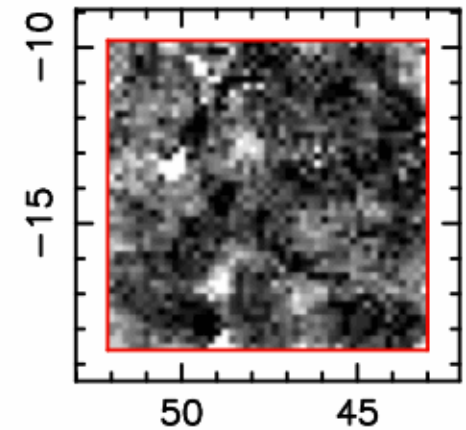
22-hr region



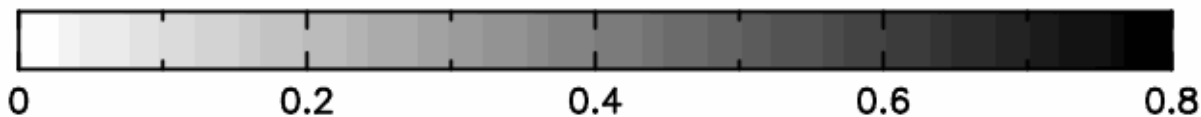
1-hr region



3-hr region



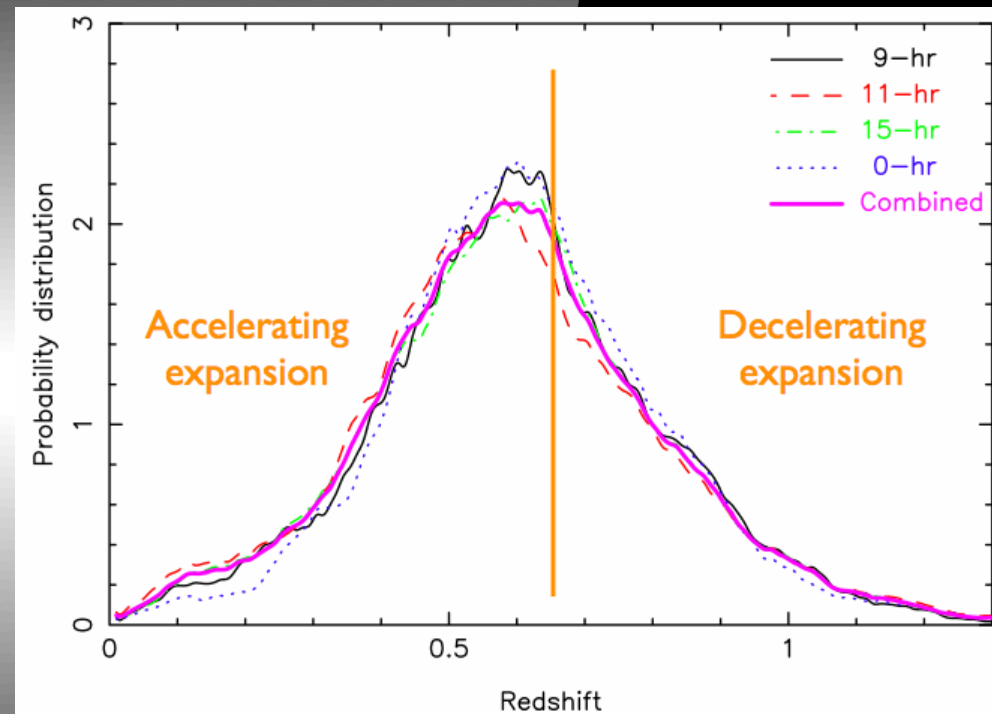
Redshift completeness



Understanding our survey

$z=1.0$

Redshift distribution



$z=0.2$

Understanding our survey

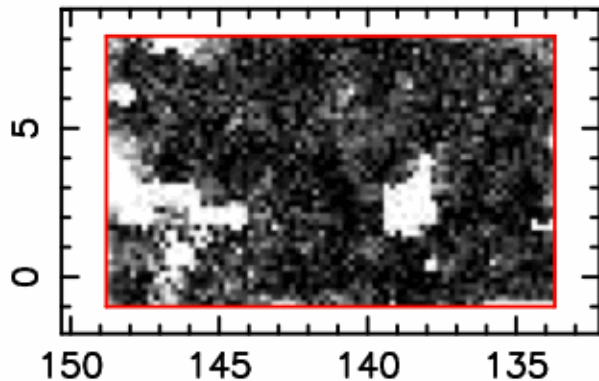
$z=1.0$



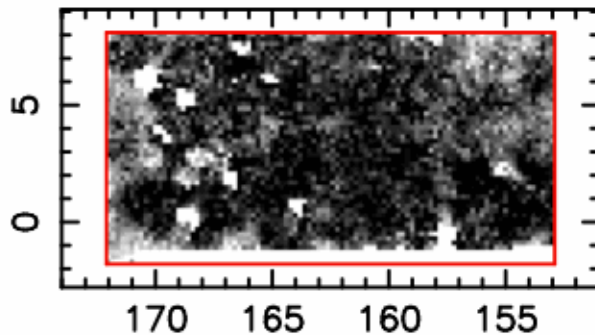
$z=0.2$

WiggleZ regions

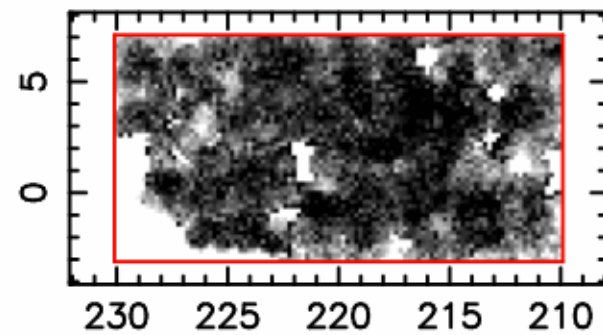
9-hr region



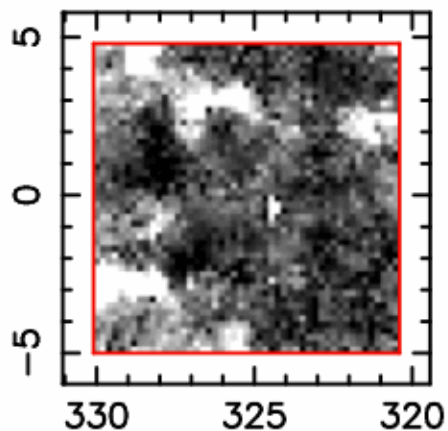
11-hr region



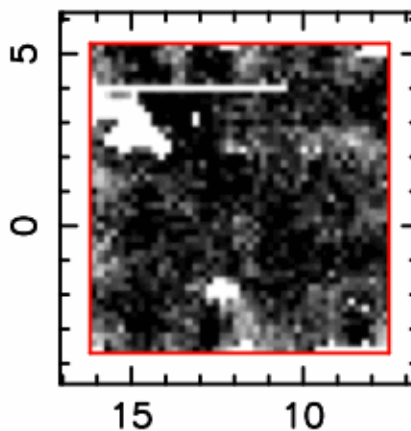
15-hr region



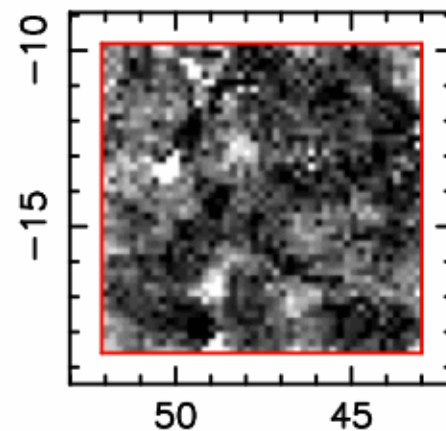
22-hr region



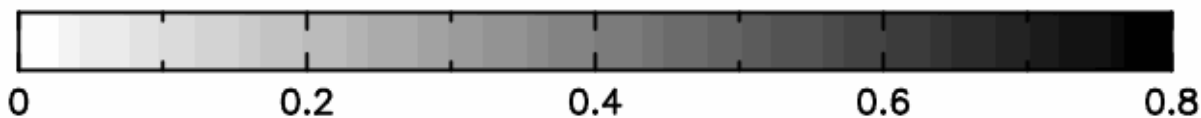
1-hr region



3-hr region



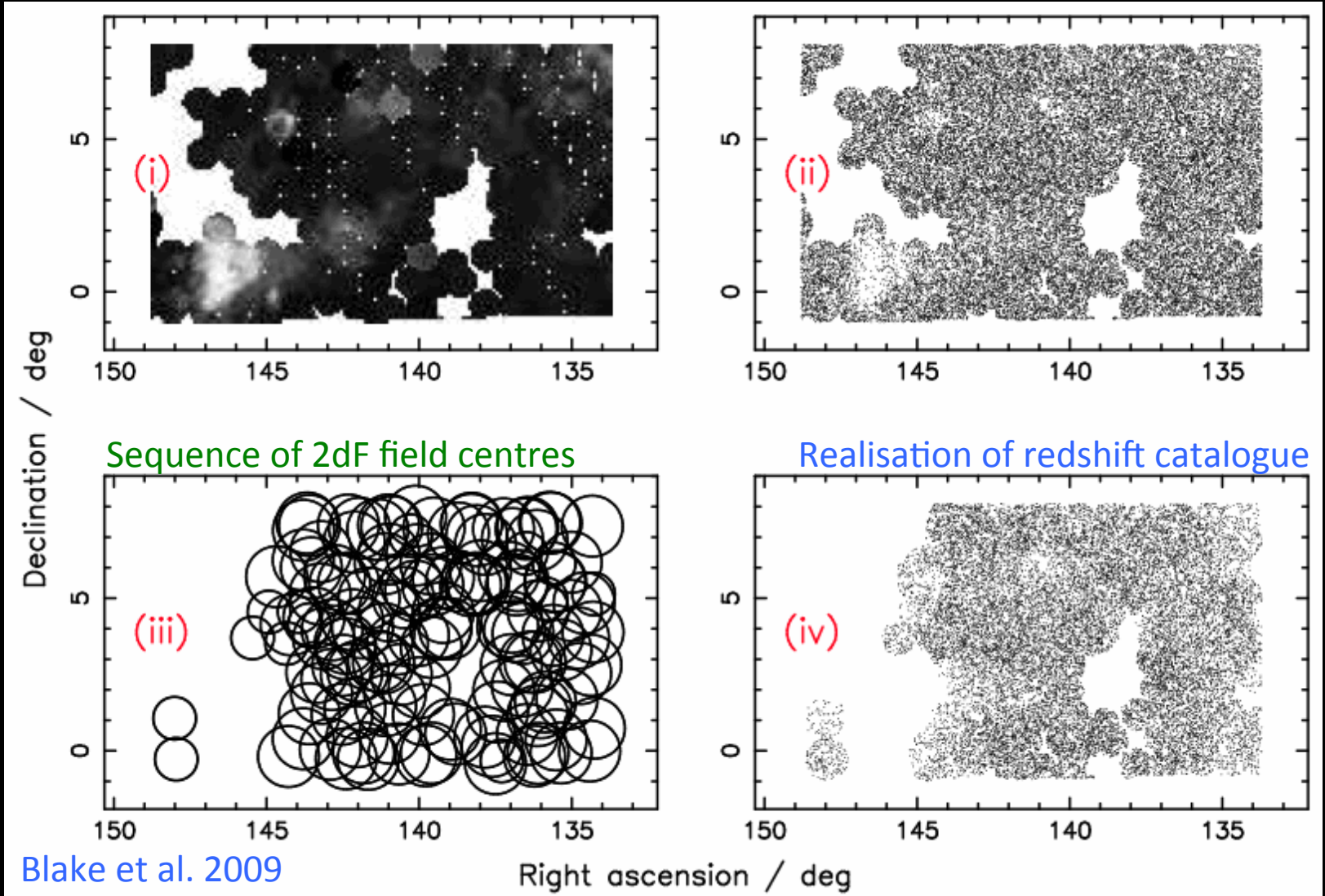
Redshift completeness



Selection function

Angular completeness of parent catalogue

Realisation of parent catalogue

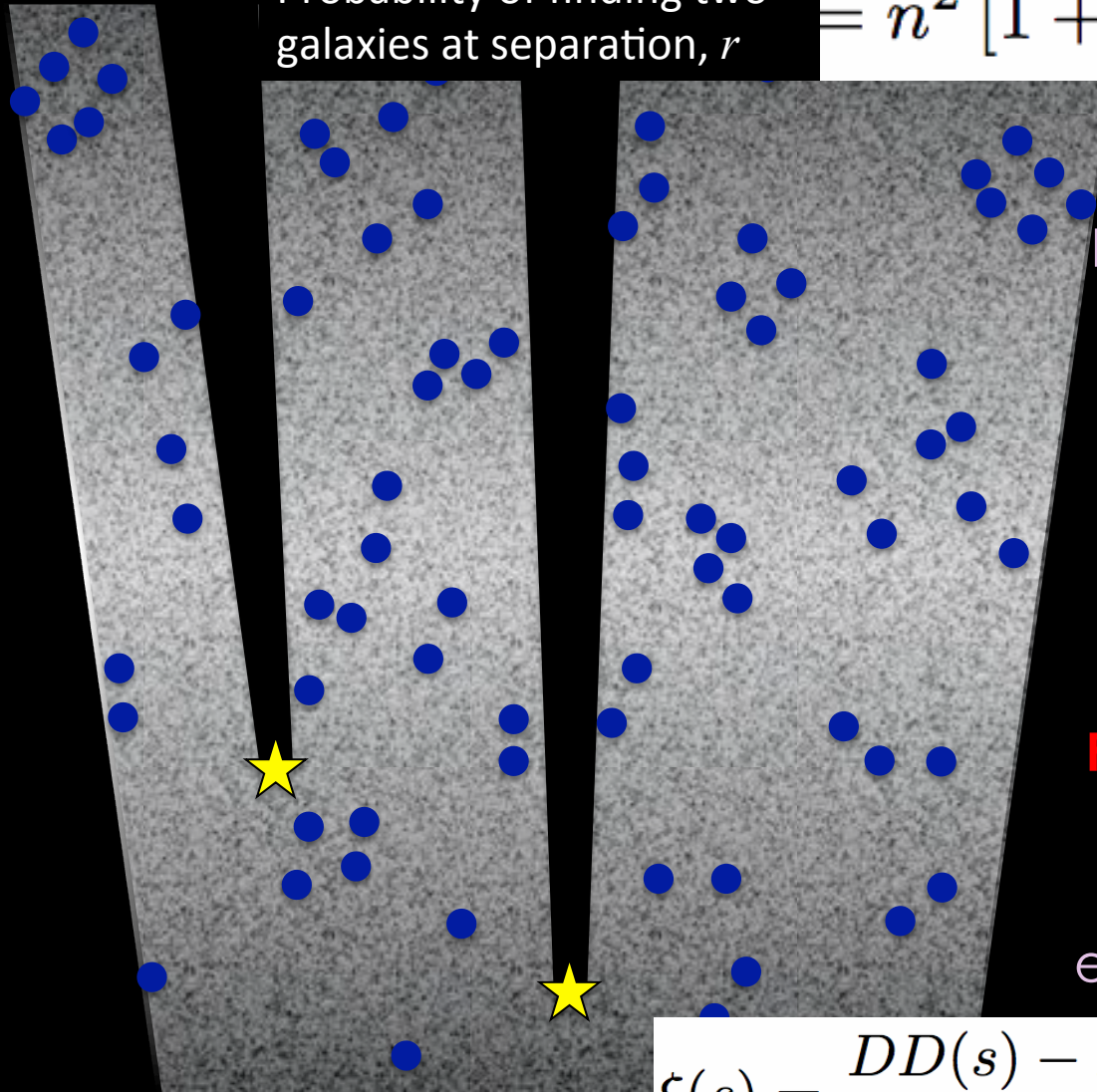


Blake et al. 2009

Right ascension / deg

Understanding our survey

$z=1.0$



Probability of finding two galaxies at separation, r

$$= \bar{n}^2 [1 + \xi(r)] \delta V_1 \delta V_2$$

Excess likelihood of finding two galaxies at separation r

Need to calculate distances!!

Fiducial model.

Landy-Szalay estimator (1993)

$z=0.2$

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

Correlation func & power spectrum

Correlation function

$$\xi(\mathbf{x}_1, \mathbf{x}_2) \equiv \langle \delta(\mathbf{x}_1) \delta(\mathbf{x}_2) \rangle$$

Power spectrum

$$P(\mathbf{k}_1, \mathbf{k}_2) = \frac{1}{(2\pi)^3} \langle \delta(\mathbf{k}_1) \delta(\mathbf{k}_2) \rangle$$

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

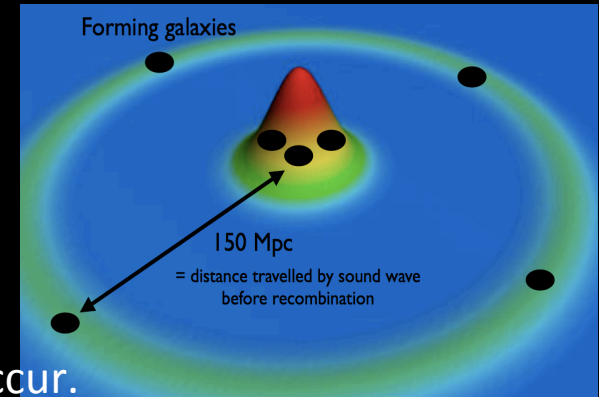
Fourier transforms

$$P(k) \equiv \int \xi(r) e^{i\mathbf{k}\cdot\mathbf{r}} d^3r$$
$$\xi(r) = \int P(k) e^{-i\mathbf{k}\cdot\mathbf{r}} \frac{d^3k}{(2\pi)^3}$$

- For the mathematics behind correlation functions and power spectra see Percival et al. 2006, "Cosmological constraints from galaxy clustering", <http://arxiv.org/abs/astro-ph/0601538>

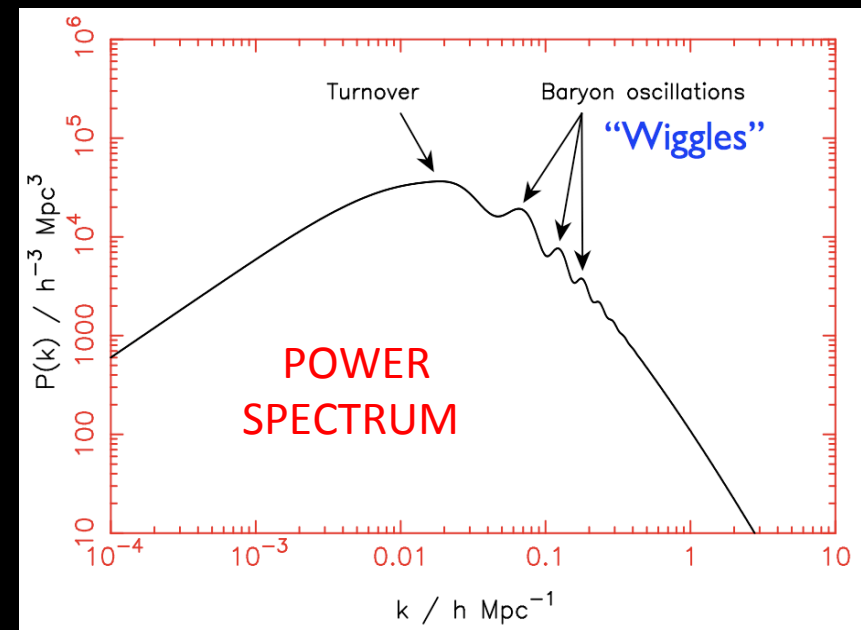
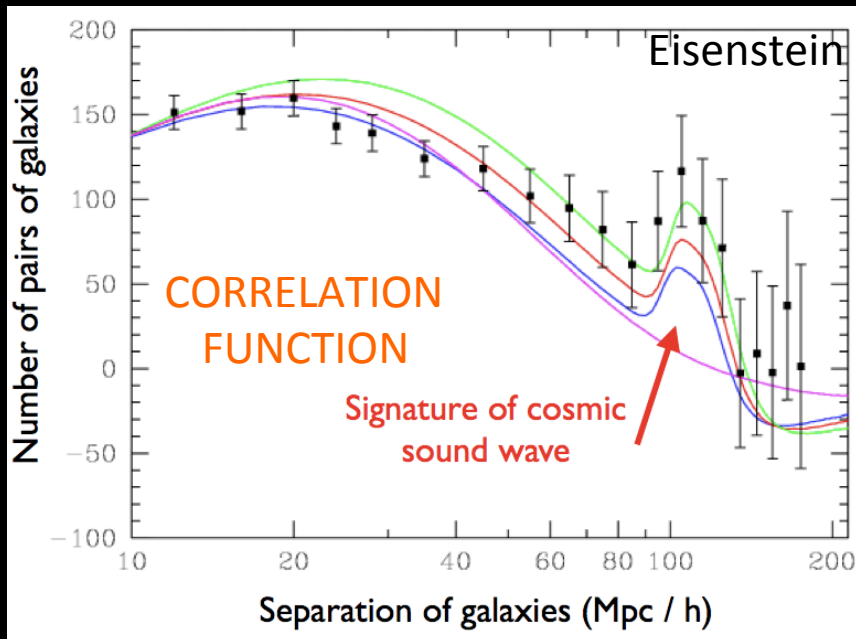
Baryon acoustic oscillations and LSS

- Baryon acoustic oscillation scale appears as a 'bump' in the galaxy correlation function and as 'wiggles' in galaxy power spectrum

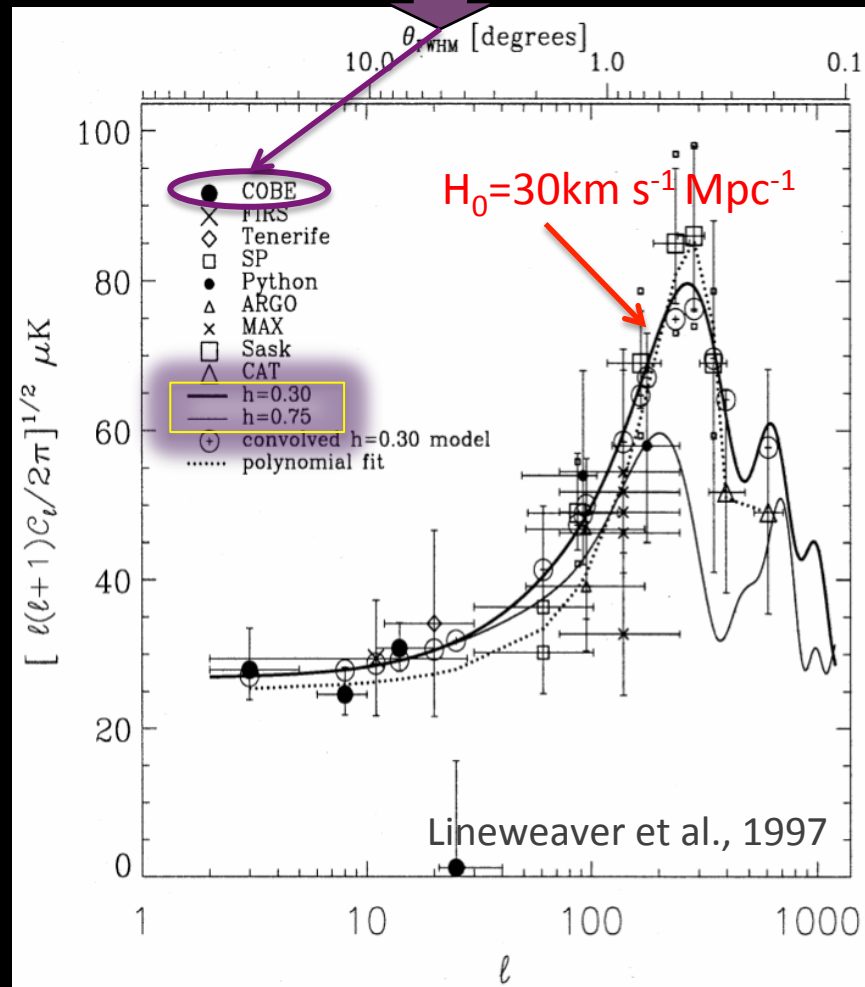
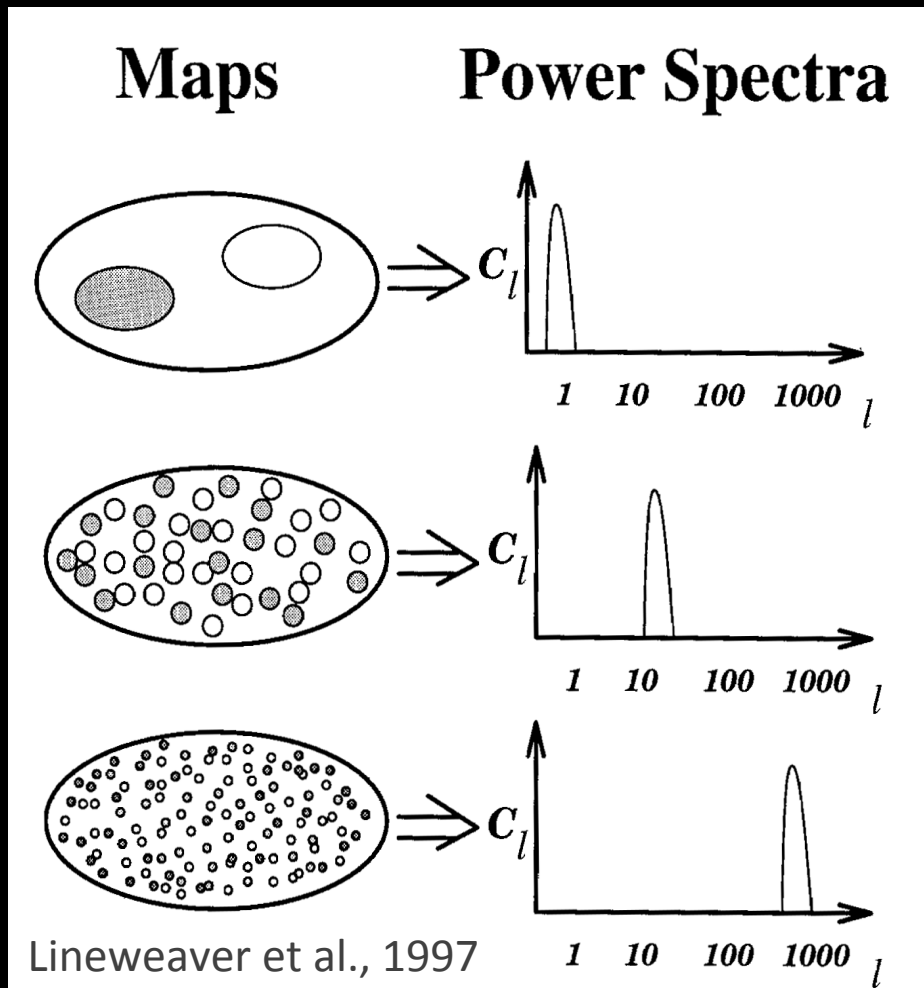


Power spectra measure how often certain *frequencies* occur.

Correlation functions measure how often certain *separations* occur.

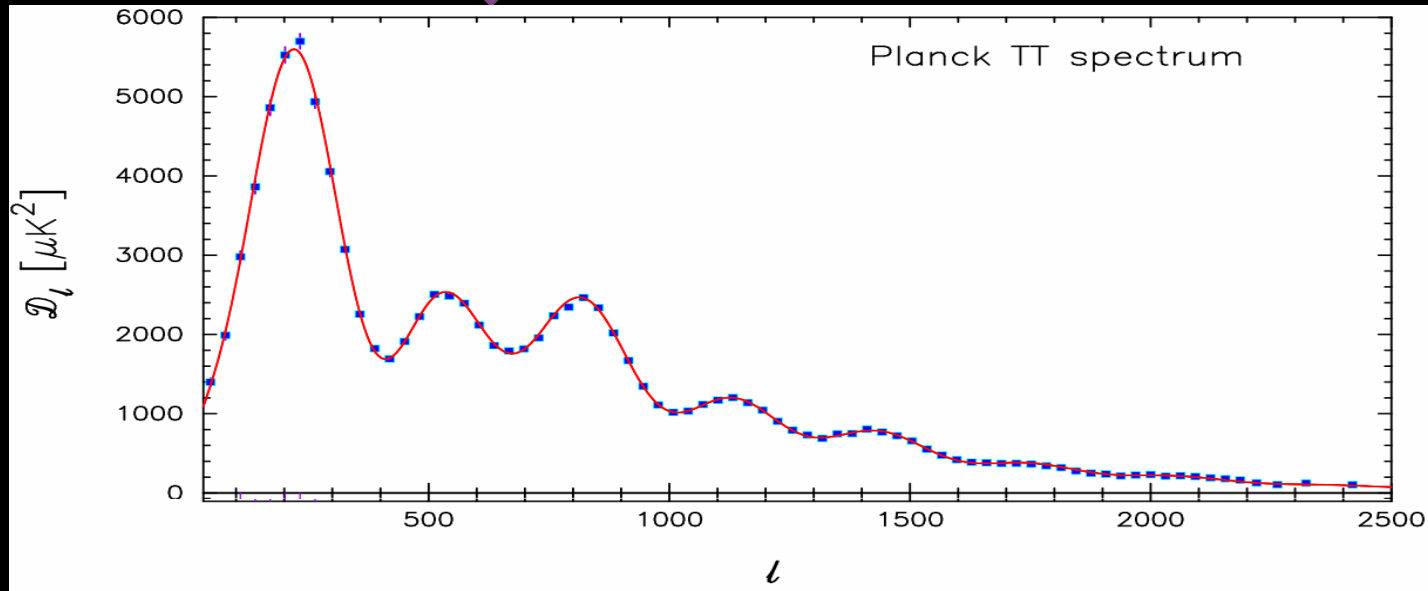
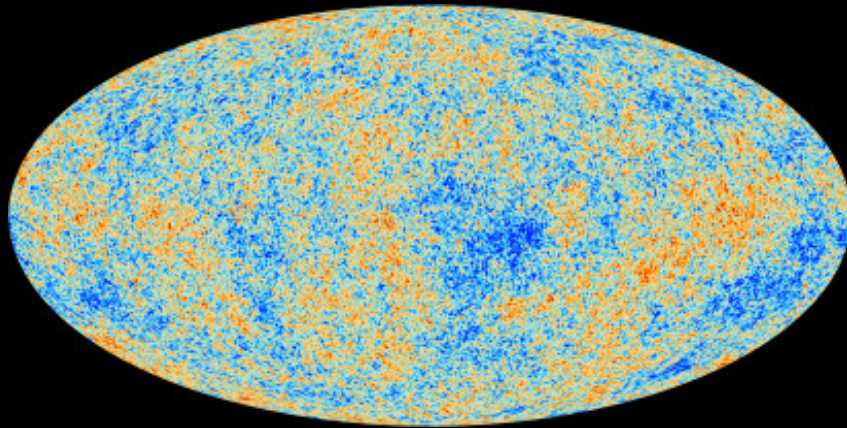


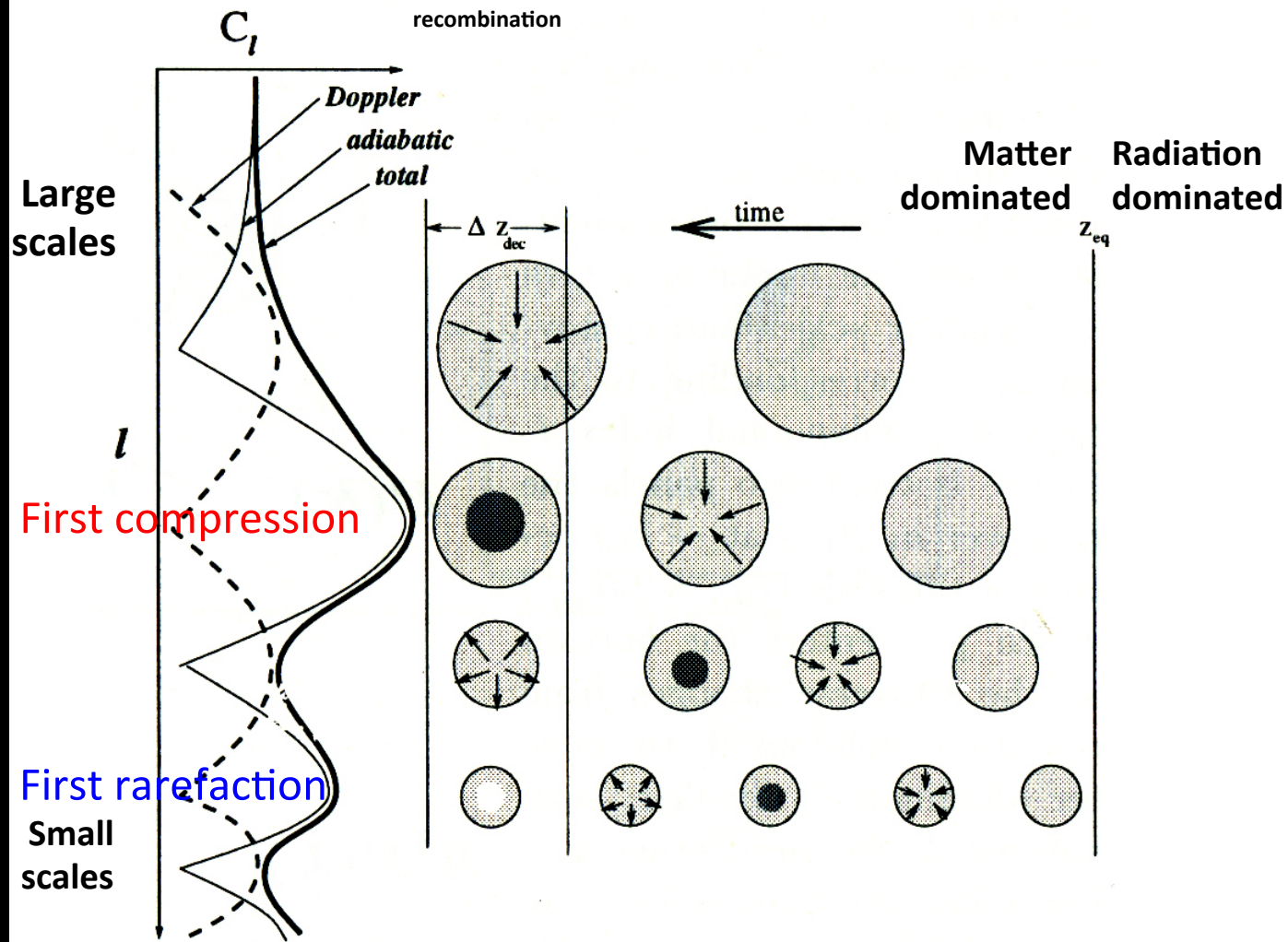
Early CMB results



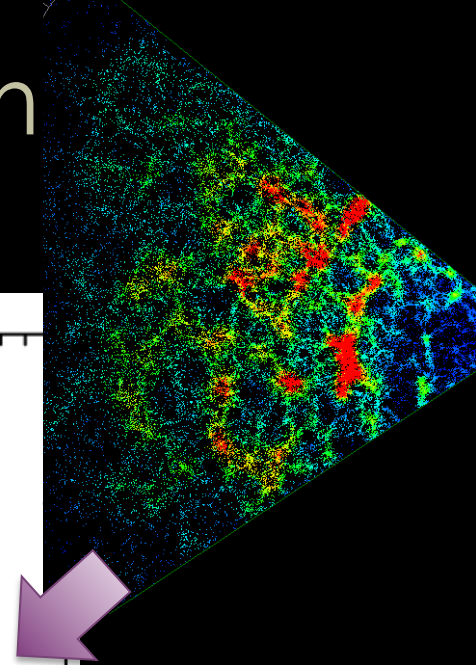
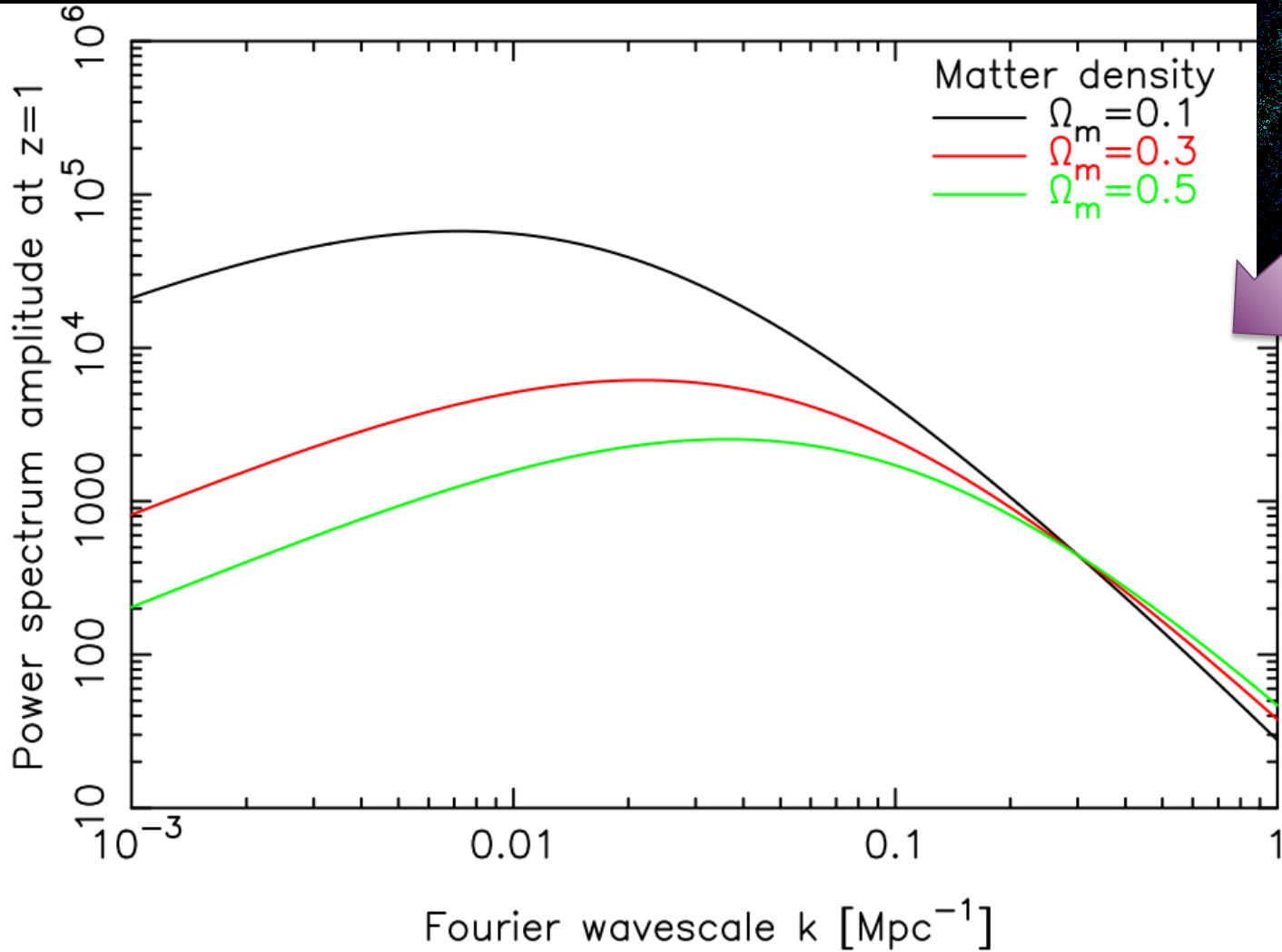
Latest CMB results – Planck ++

(SPT and ACT)

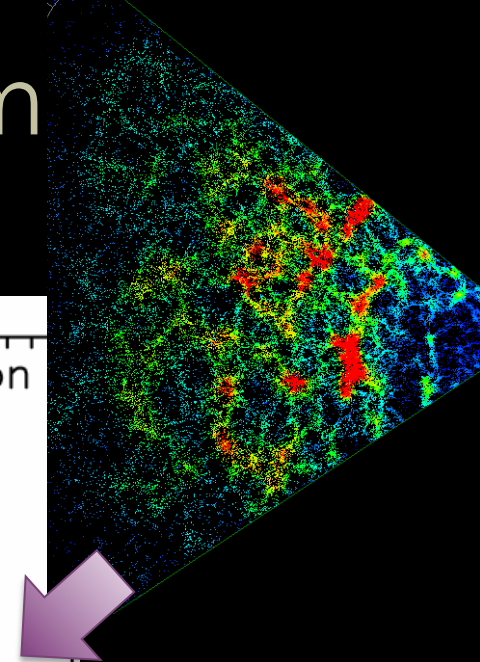
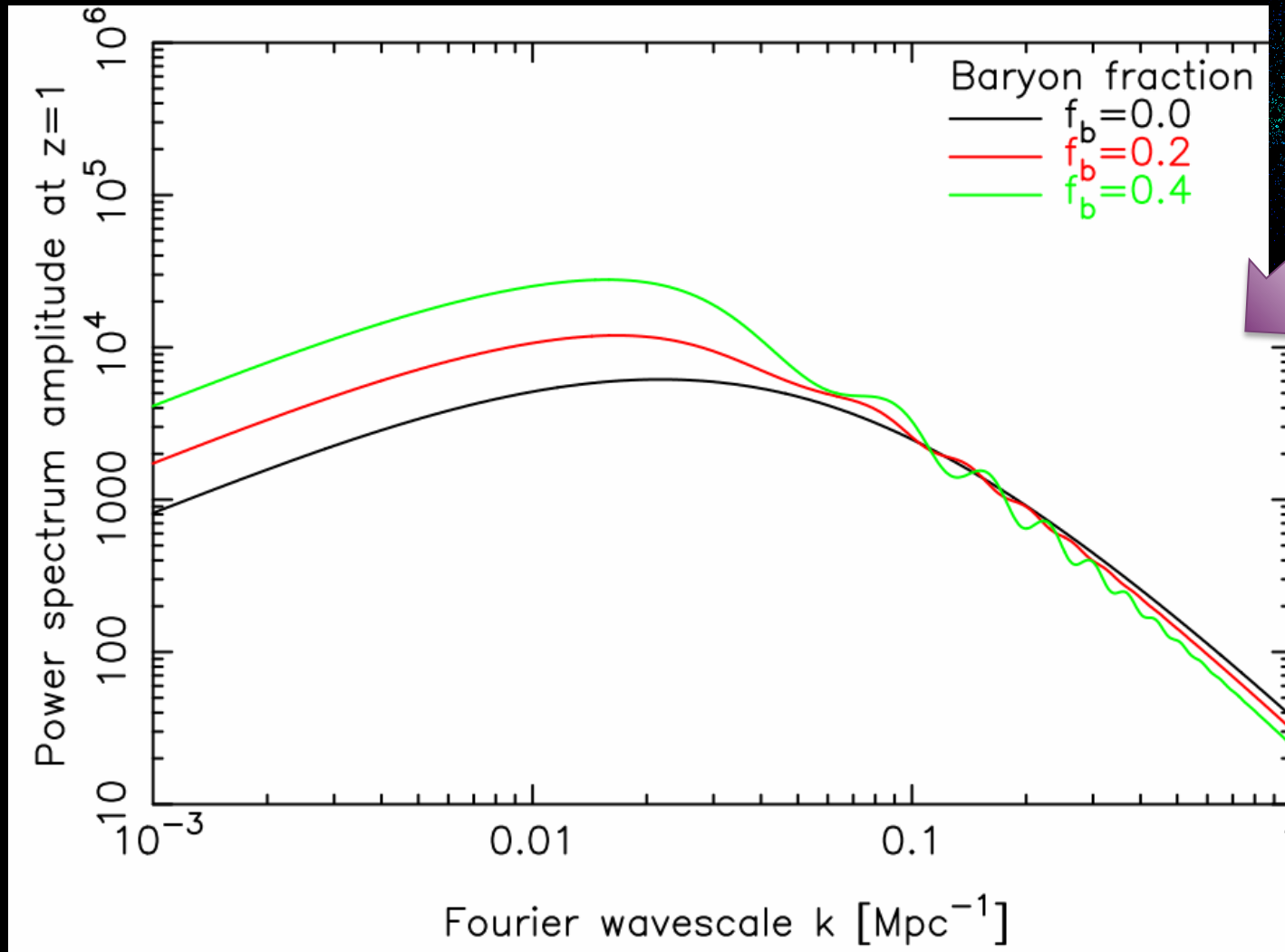




Matter power spectrum



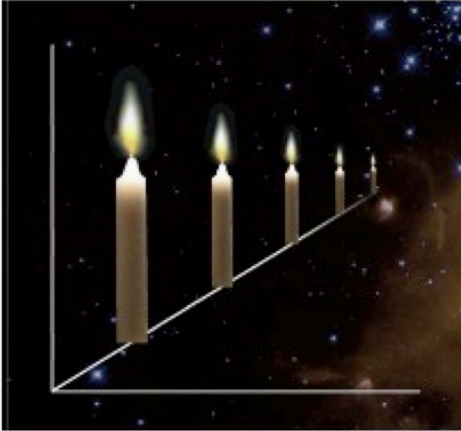
Matter power spectrum



MEASURING THE DISTANCE SCALE

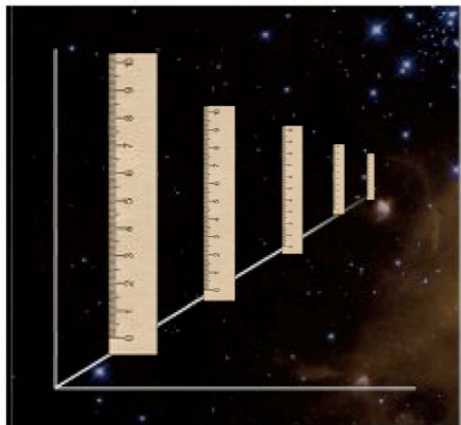
BAO – a standard ruler in 3D

Standard candle



Supernova

Standard ruler



Cosmic sound wave

- SNe = radial
- CMB = tangential info (surface of sphere)
- BAO can be applied radially to give $H(z)$ AND tangentially to give $D_A(z)$

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

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

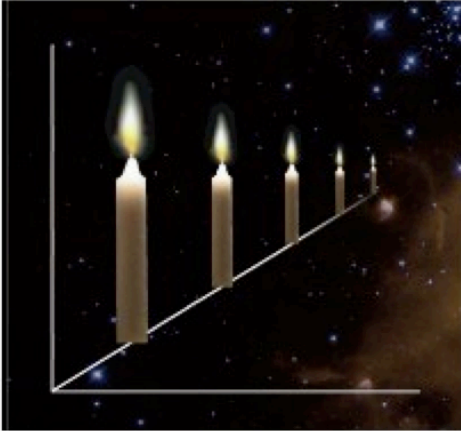
Δz = apparent redshift extent
~ 0.06 at $z=1$

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

The diagram illustrates the geometry of BAO measurements. It shows a cone representing the angular size $\Delta\theta$ and a ruler representing the redshift extent Δz . The angular size is shown as a cone with a ruler on the right side. The redshift extent is shown as a ruler on the bottom right side.

BAO – a standard ruler in 3D

Standard candle



Supernova

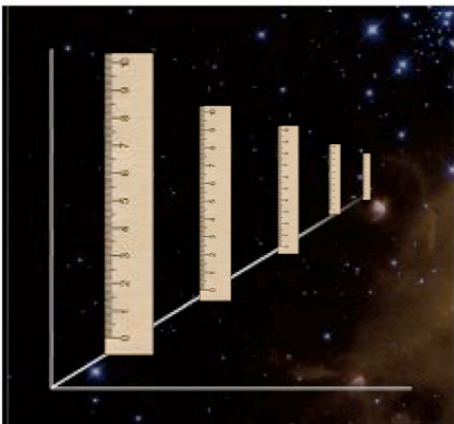
- SNe = radial
- CMB = tangential info (surface of sphere)
- But usually we start with the ANGLE AVERAGED measurement

2 parts tangential

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

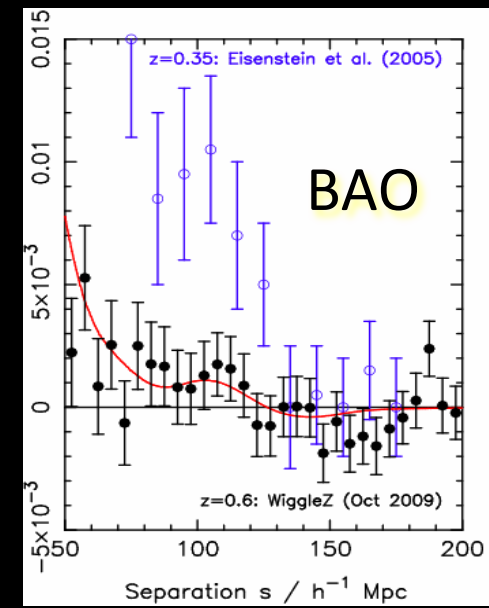
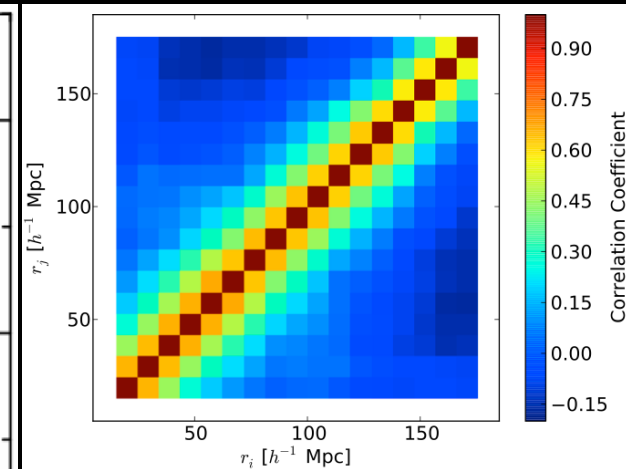
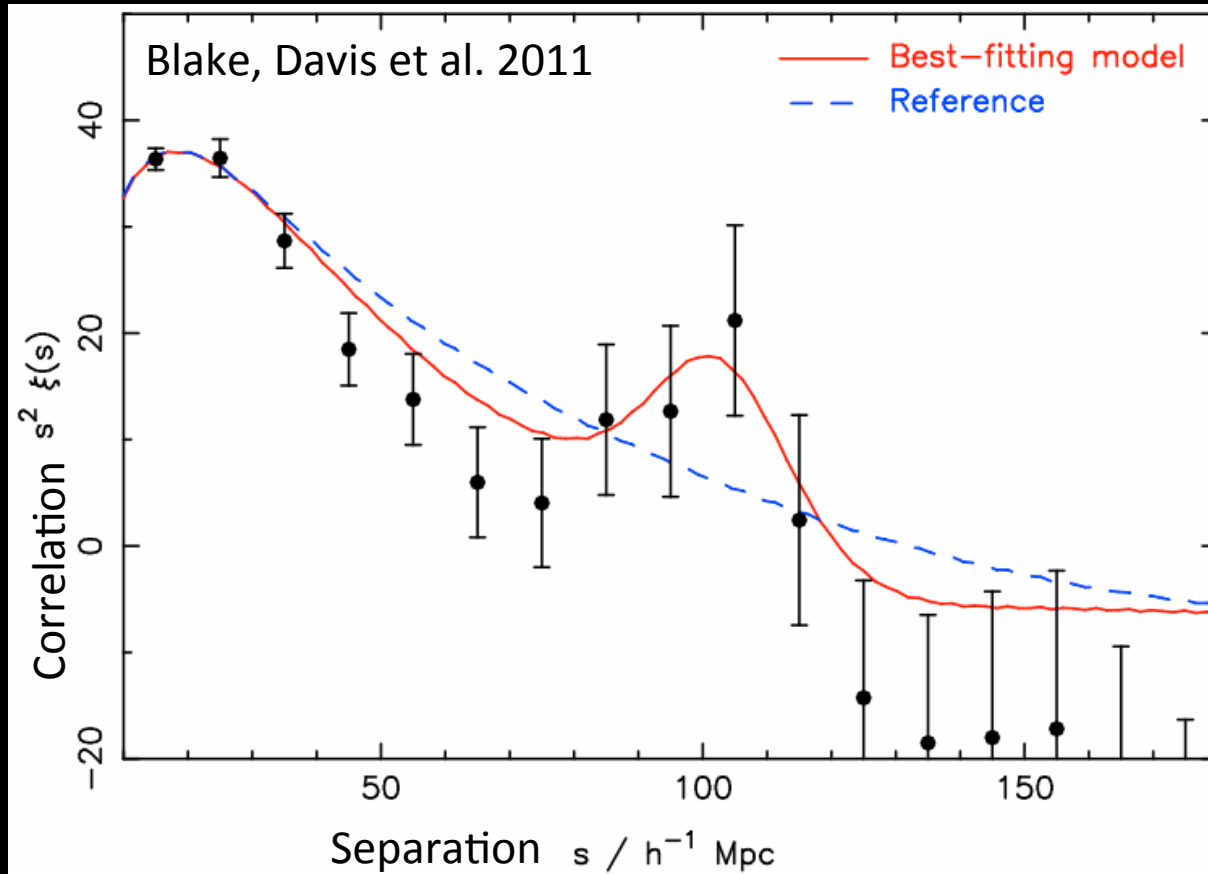
1 part radial

Standard ruler



Cosmic sound wave

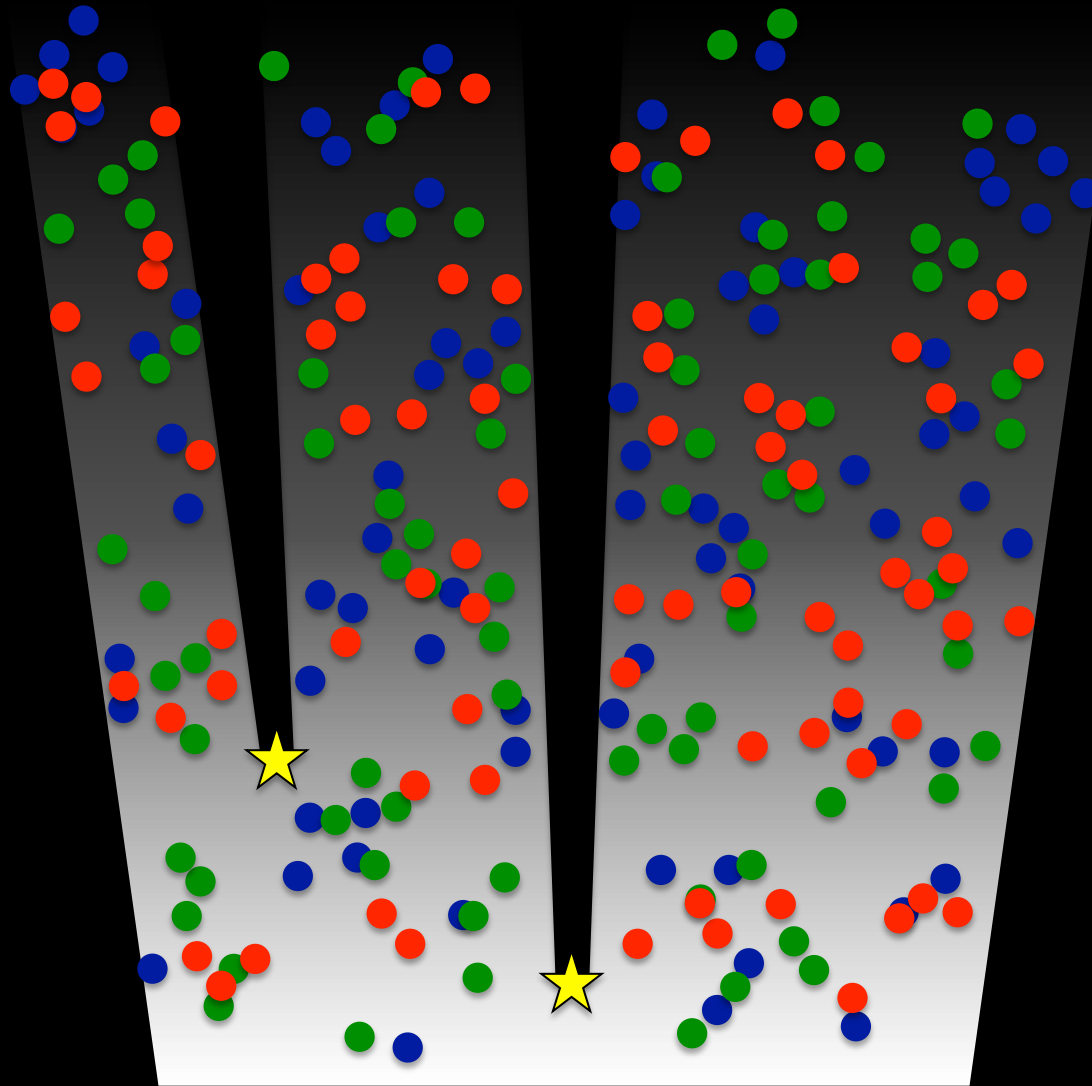
WiggleZ detection of BAO at $z=0.6$



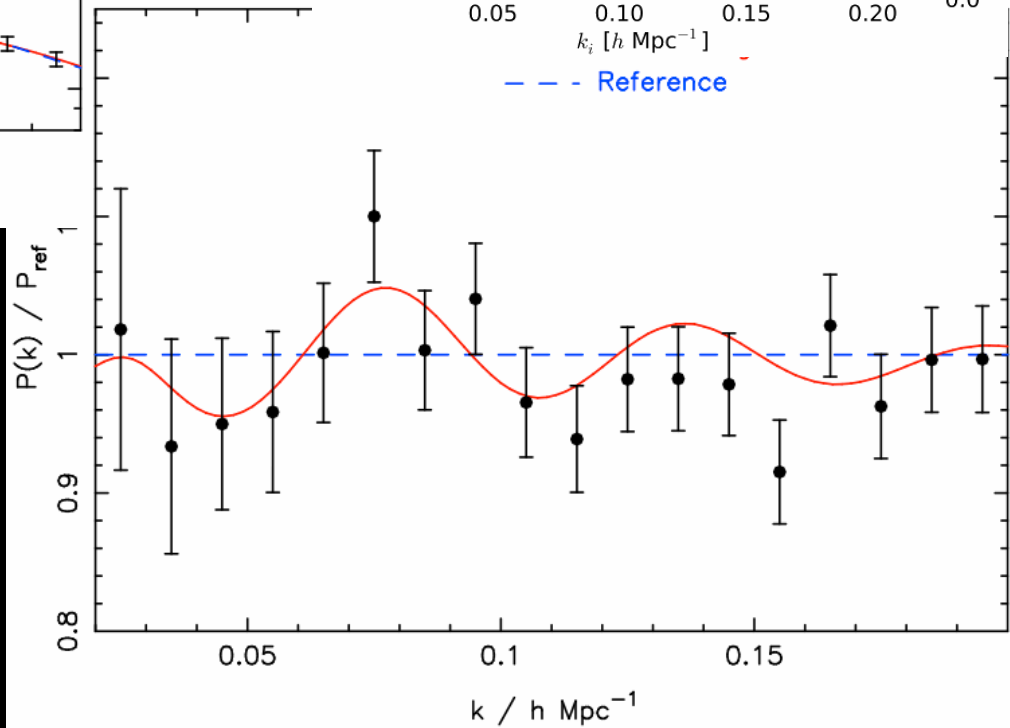
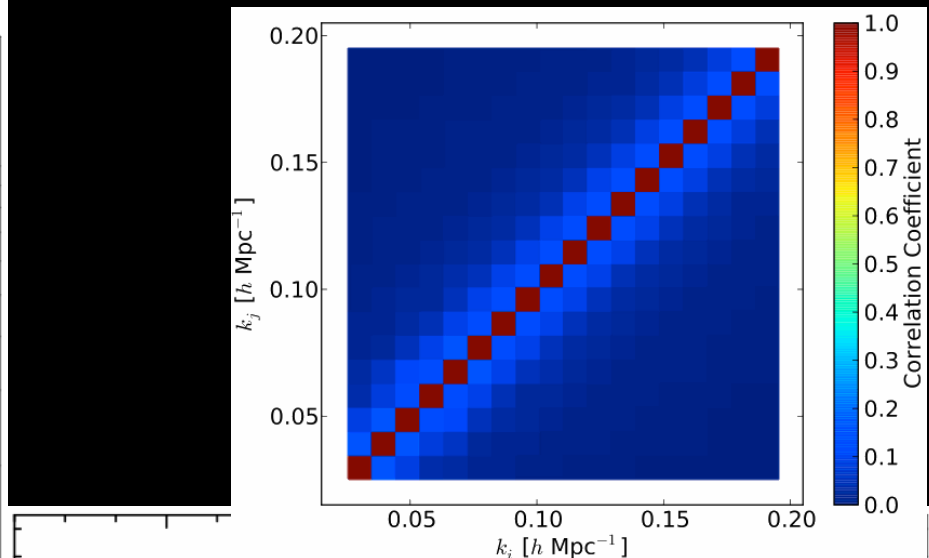
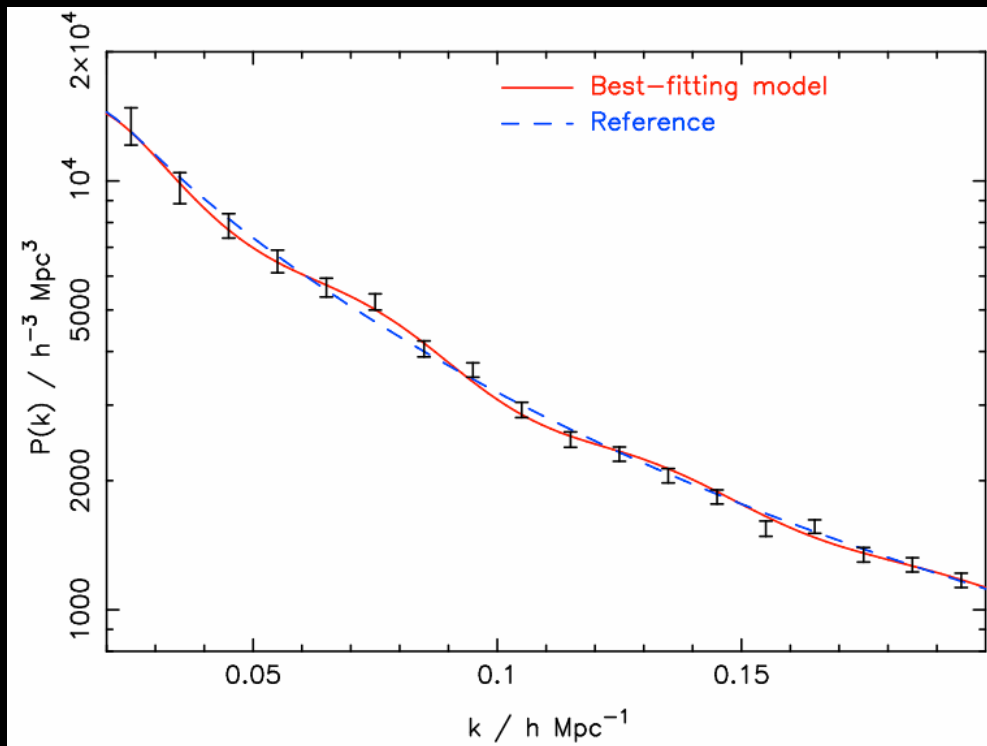
Understanding our survey

$z=1.0$

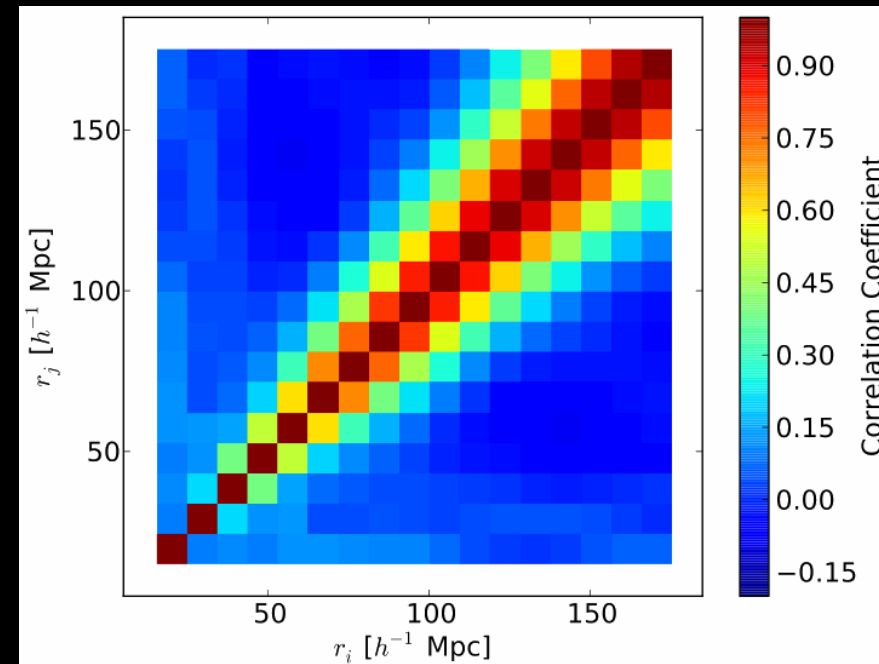
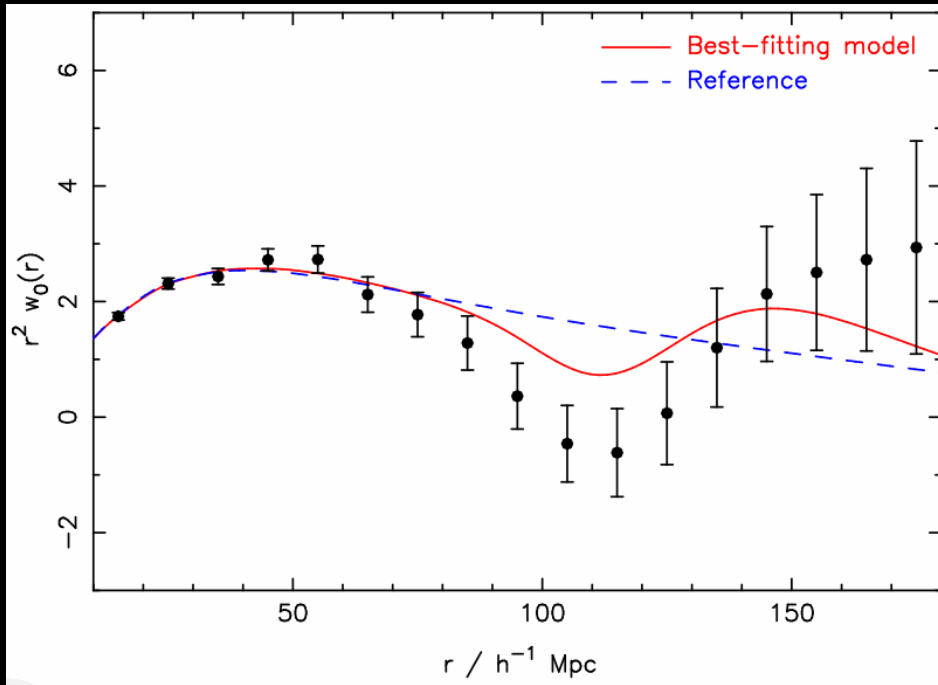
$z=0.2$



WiggleZ power spectrum at $z=0.6$



WiggleZ band-filtered correlation fn



Correlation function weighted so it reduces the sensitivity to small and large scale power

(Small are subject to non-linearities – hard to model)

(Large are sensitive to selection function – hard to model)

Measuring the distance scale

Two Tangential One Radial

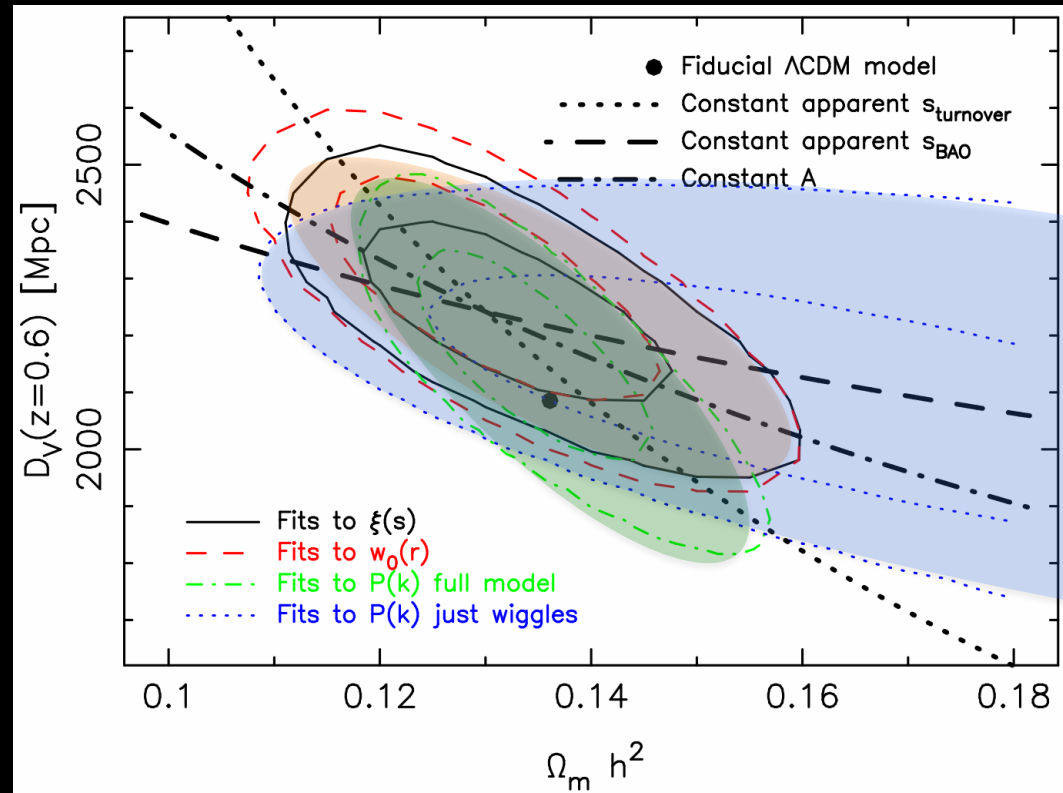
$$D_V(z) = \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)} \right]^{1/3}$$

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

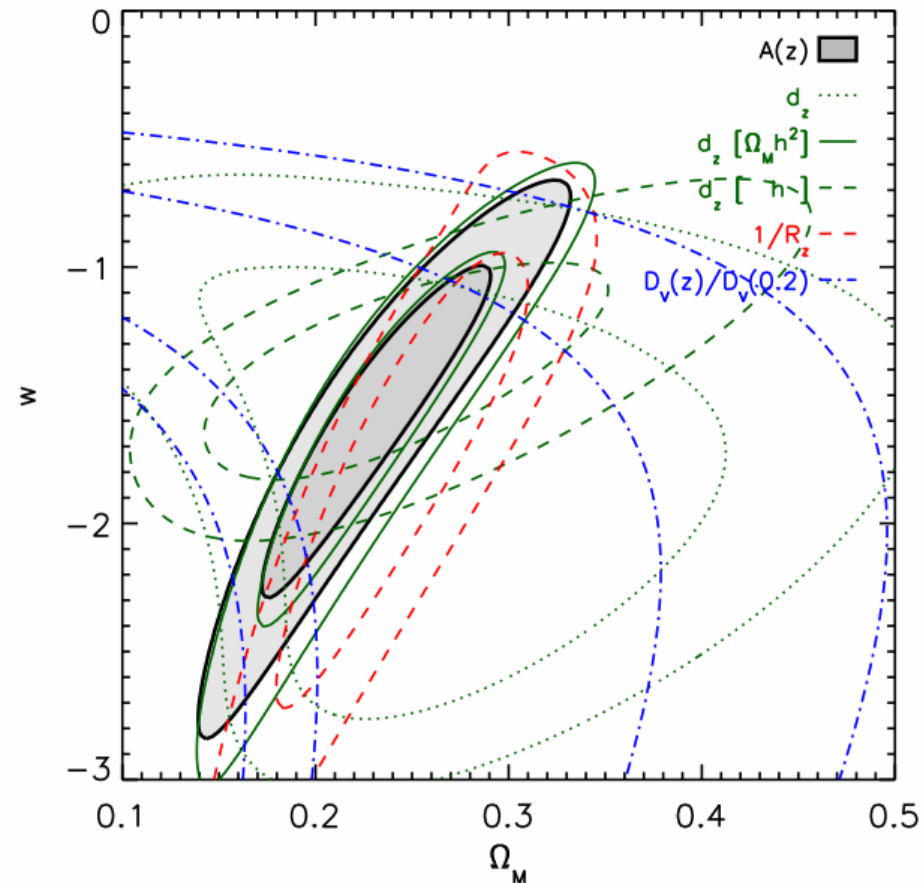
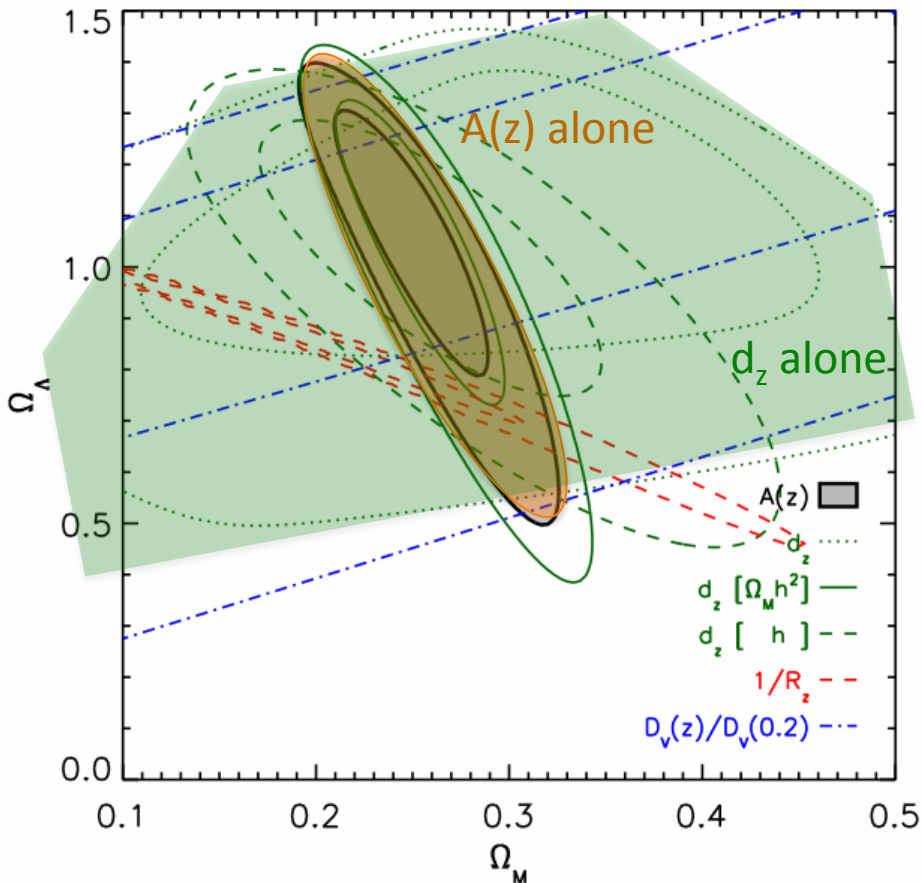
$$A(z) = \frac{\sqrt{\Omega_m H_0^2}}{cz} D_V(z)$$

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

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

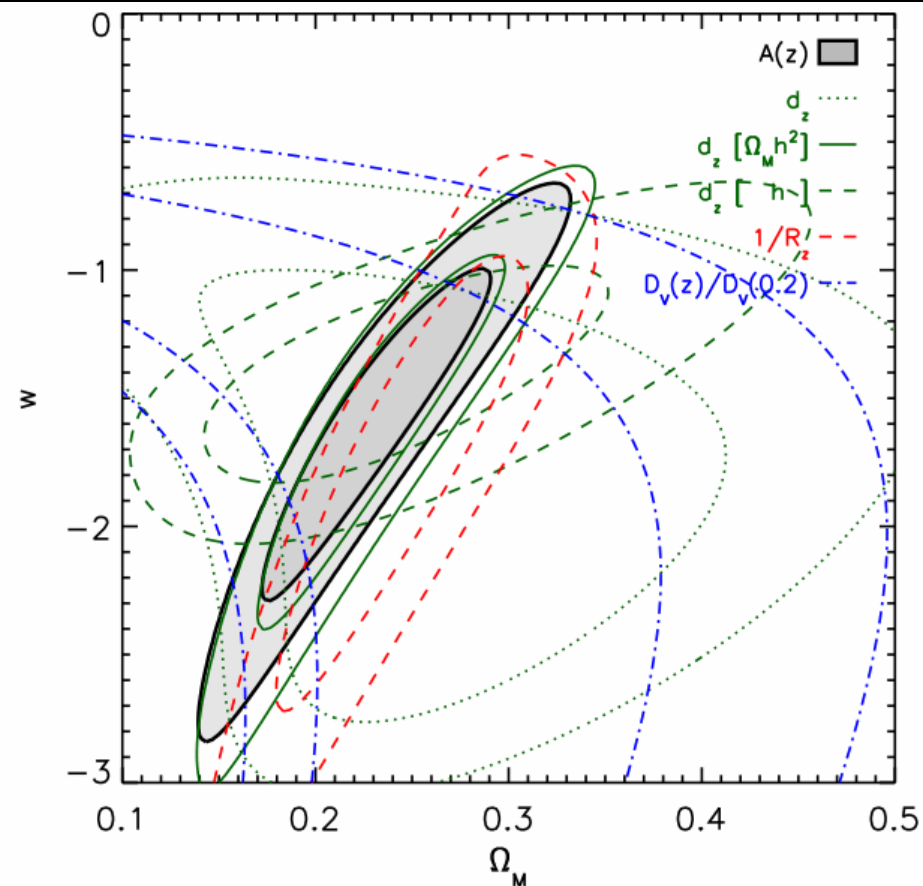
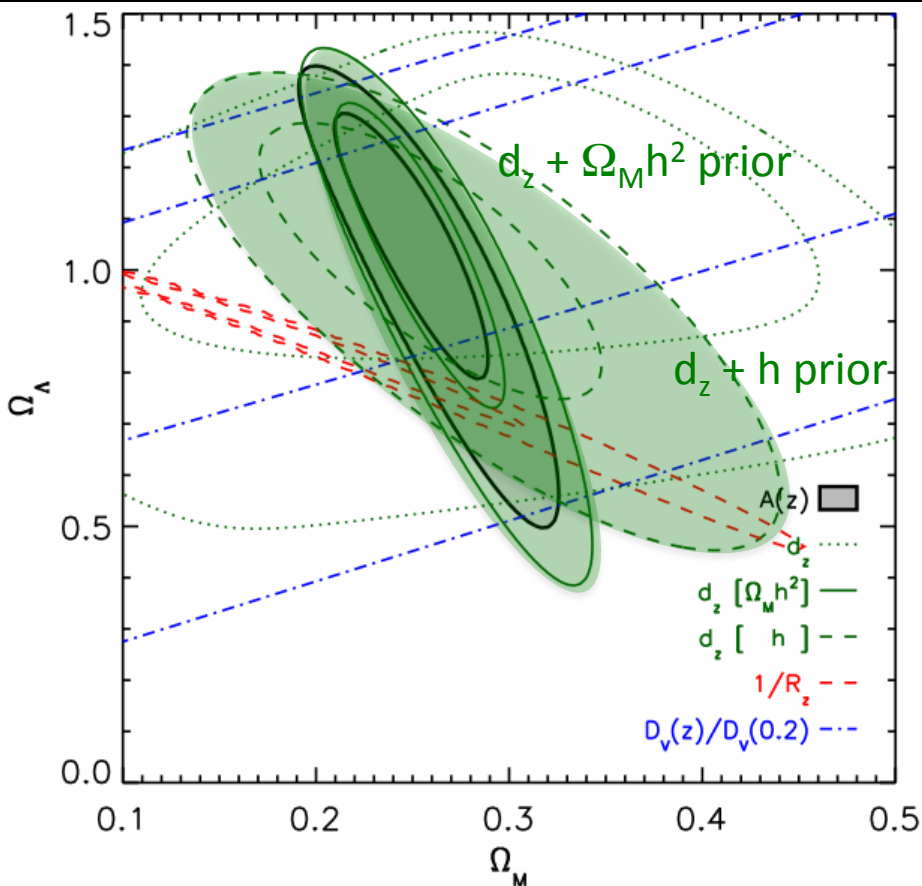


Many ways to use BAO



$$A(z) = \frac{\sqrt{\Omega_m H_0^2}}{cz} D_V(z) \quad d_z \equiv \frac{r_s(z_d)}{D_V(z)}$$

Many ways to use BAO



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

Measuring acceleration more directly

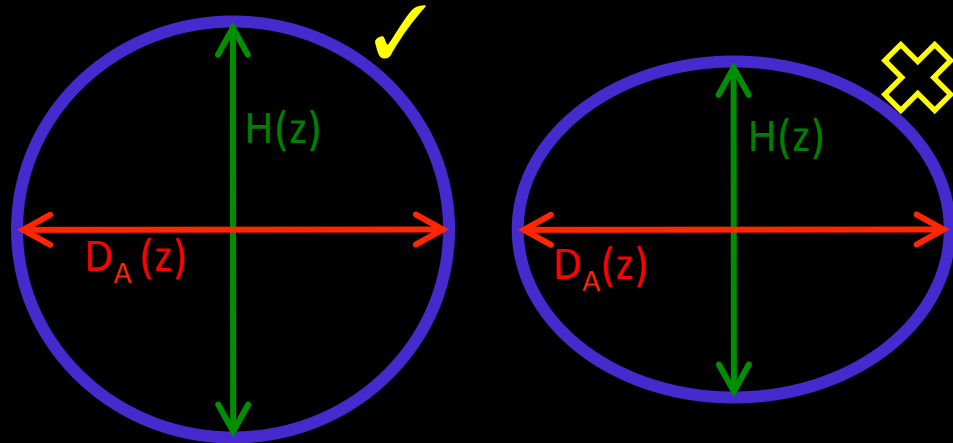
STANDARD SPHERES

- H(Z) ALCOCK-PACZYNSKI

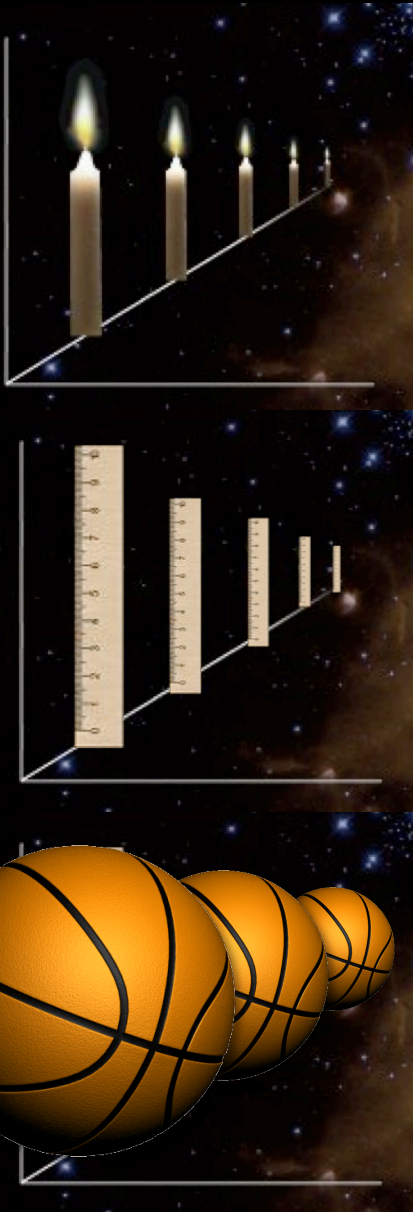
BAO – a standard sphere

- SNe = **radial**
- CMB = **tangential** info (surface of sphere)
- BAO can be applied **radially** to give $H(z)$ AND **tangentially** to give $D_A(z)$

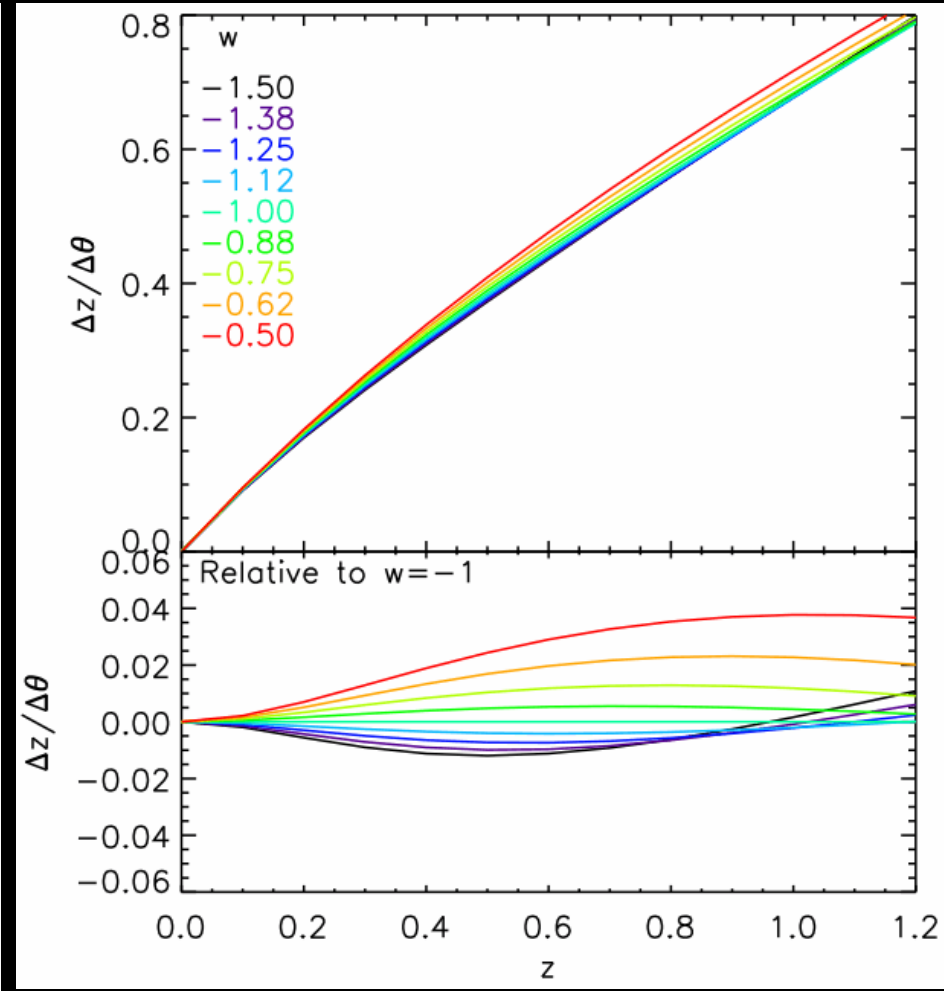
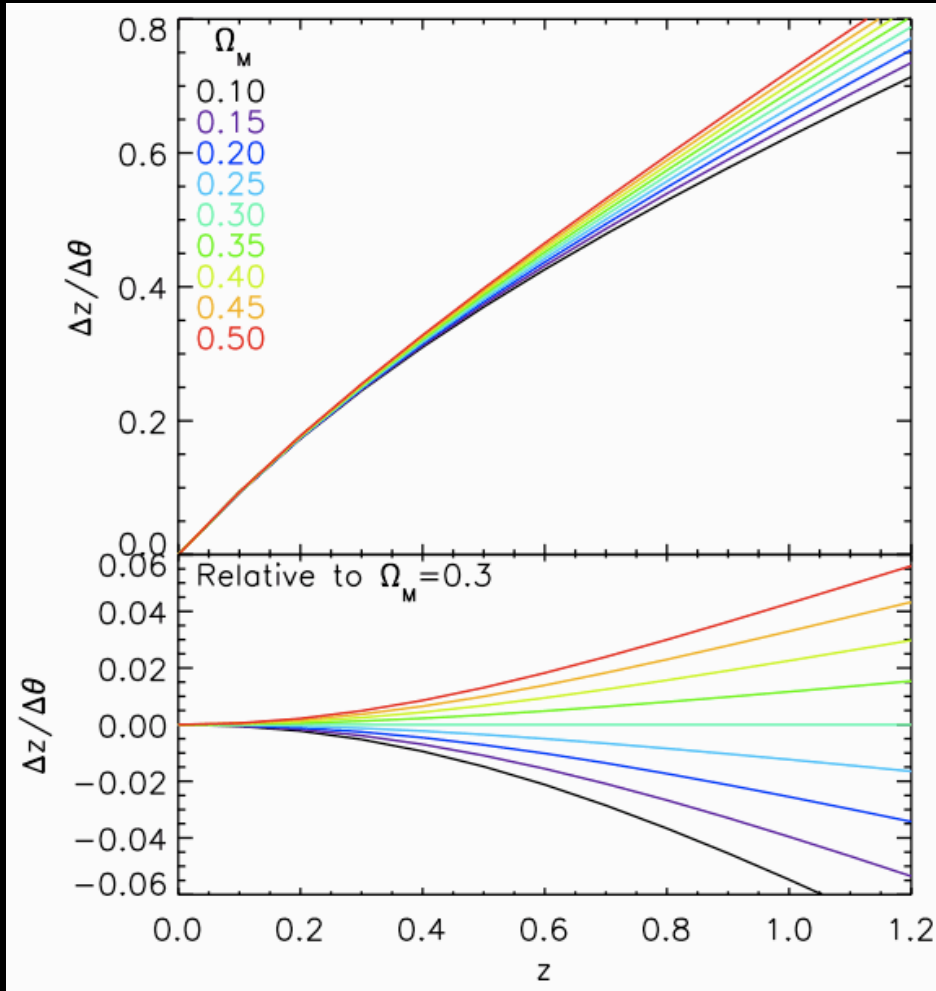
Alcock-Paczynski test:



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

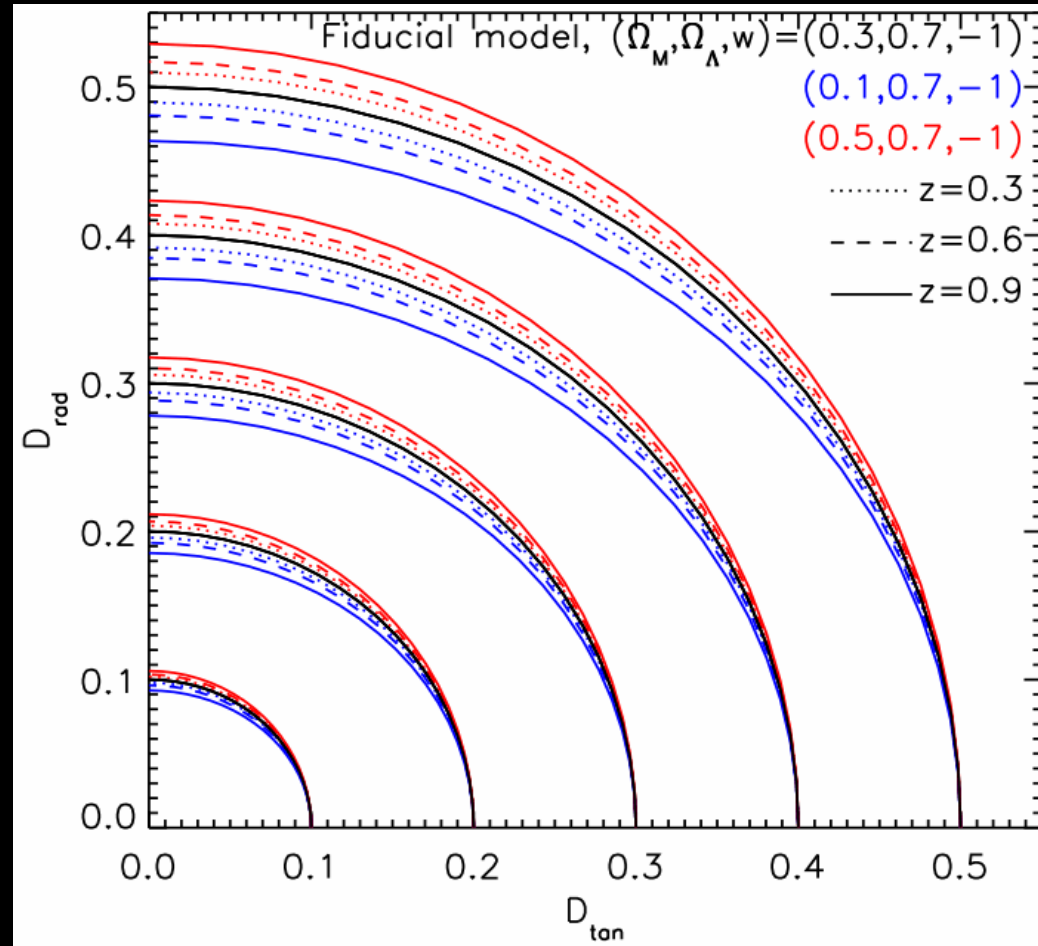


The sphericity of spheres

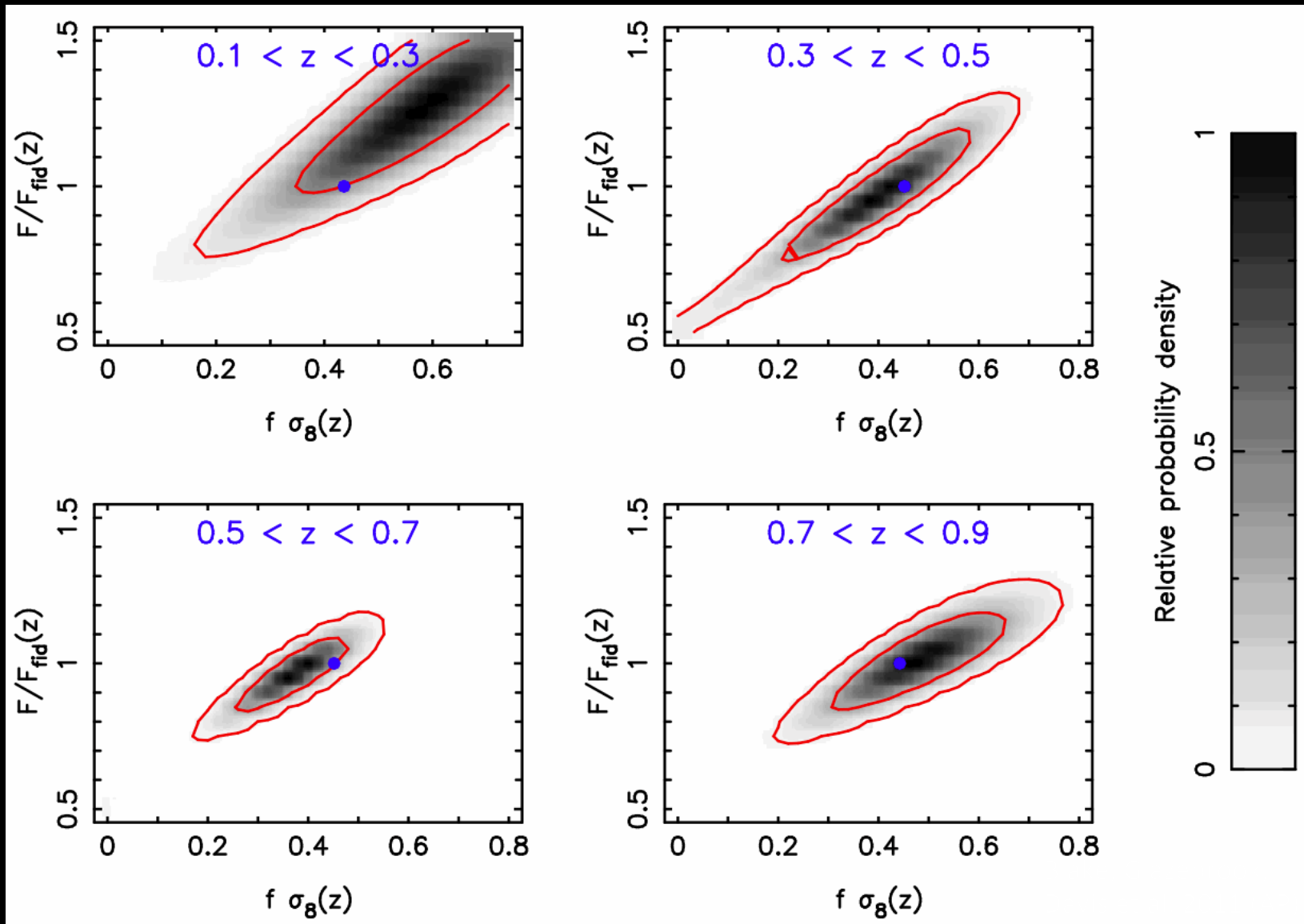


The sphericity of spheres

- Alcock-Paczynski test
 - Ratio of observed angular size to radial size **varies with cosmology**
 - Measure distortions of a sphere and you can measure cosmological parameters.
 - BAO are a standard sphere.
 - So is the power spectrum (but you don't know the radius a-priori)



Alcock-Paczynski / z-space distortions



Measurement of $H(z)$

AP measures

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

Supernovae measure

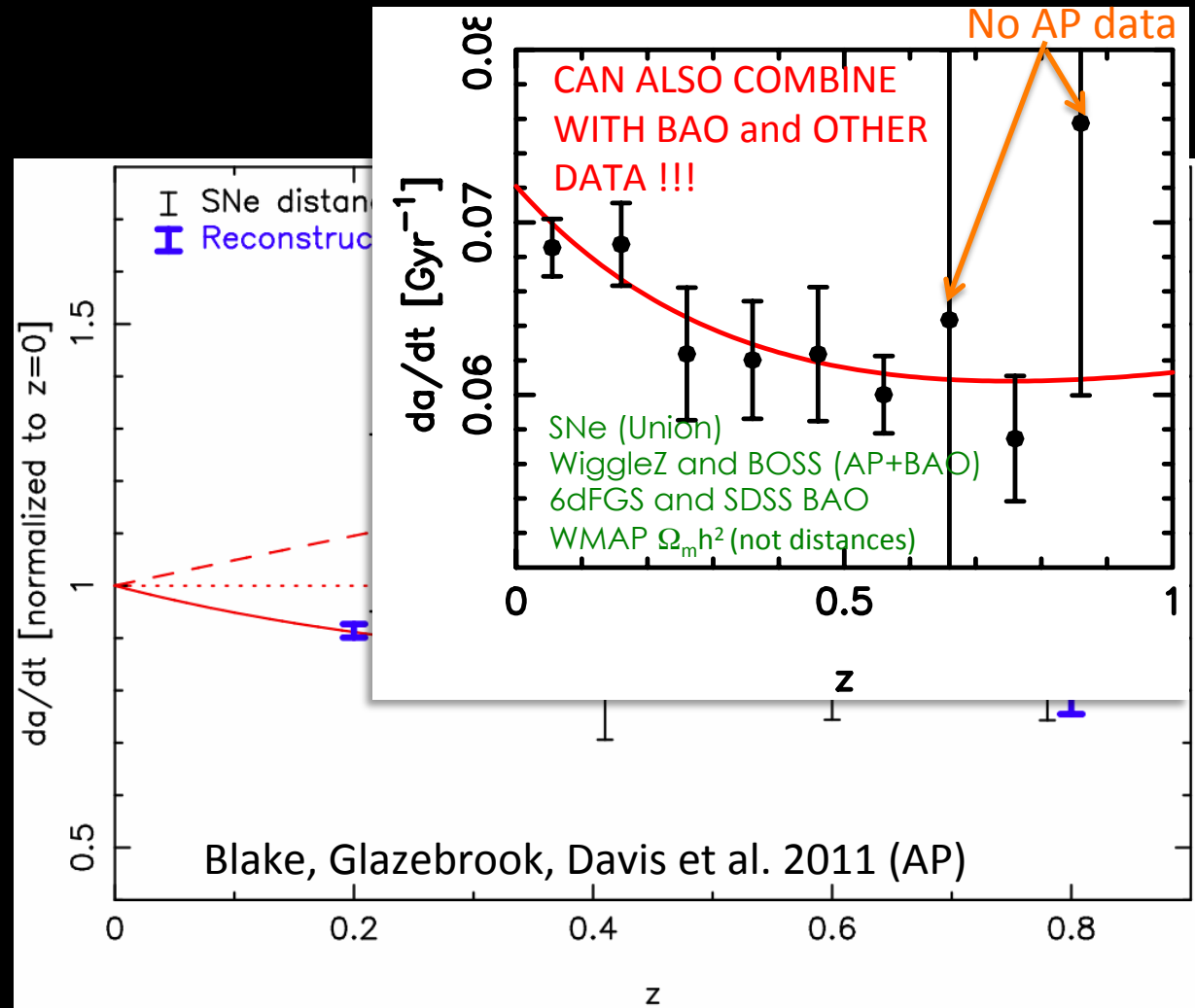
$$D_L(z)H_0/c$$

Distances are related by

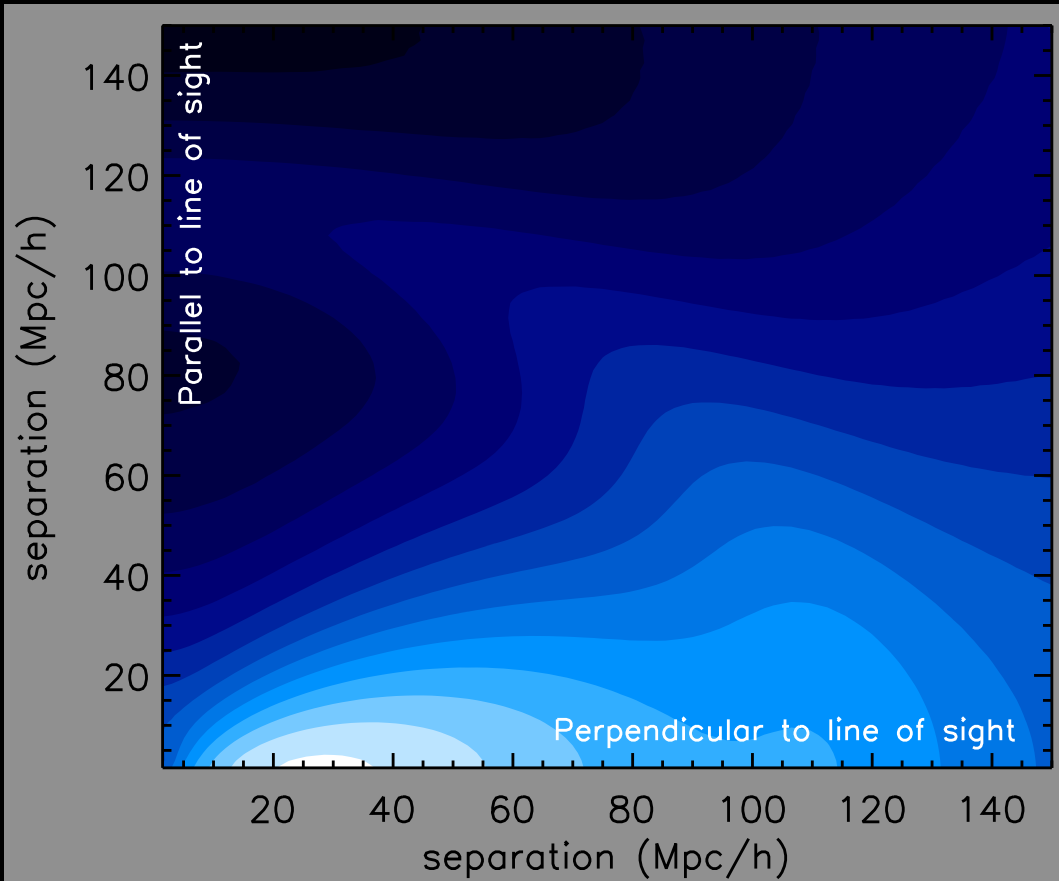
$$D_L(z) = D_A(z) (1+z)^2$$

So the ratio gives

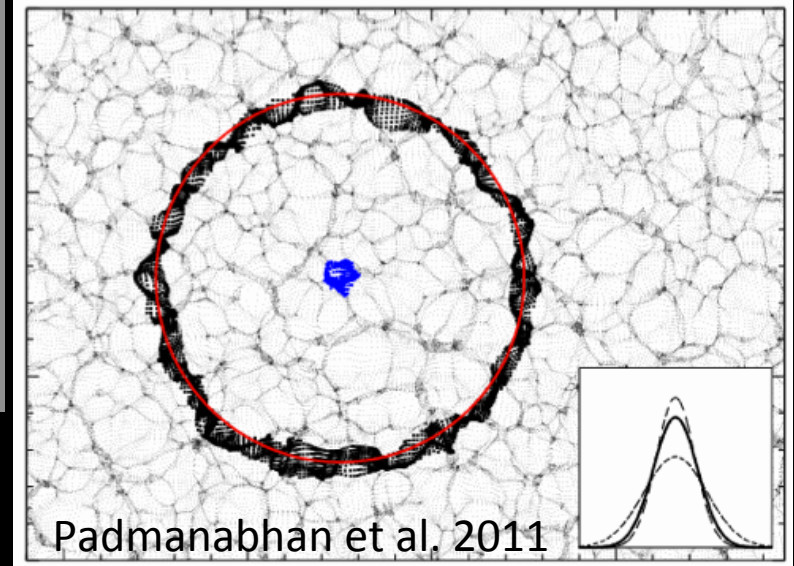
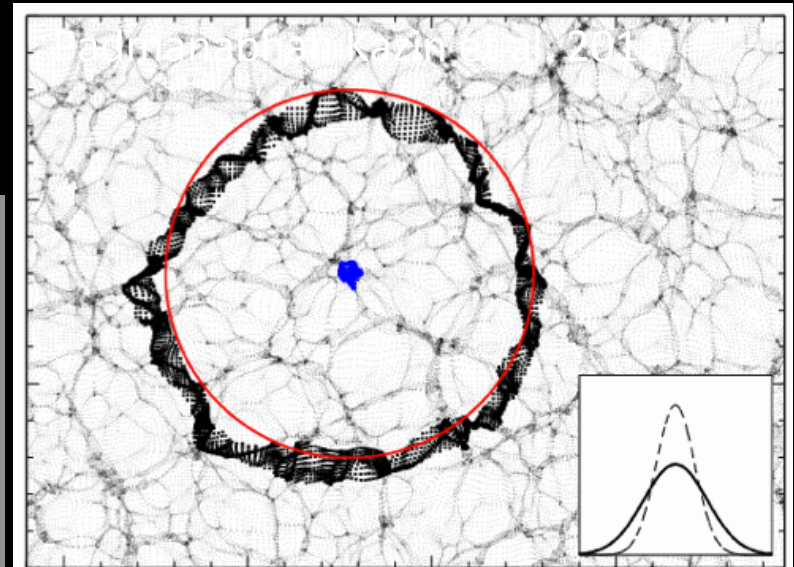
$$H(z)/H_0$$



2D BAO

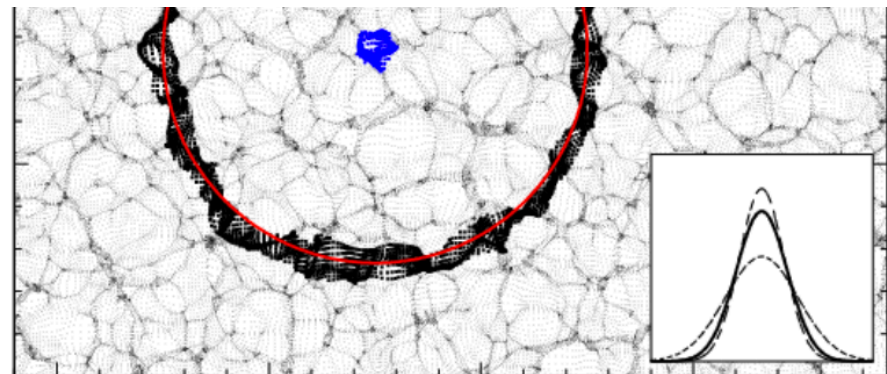
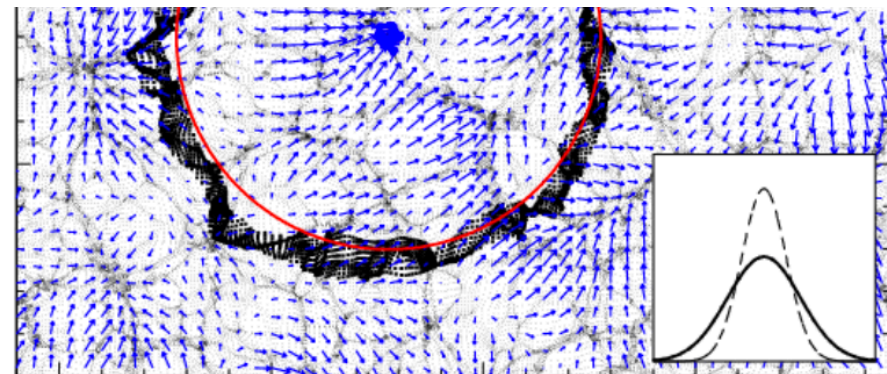
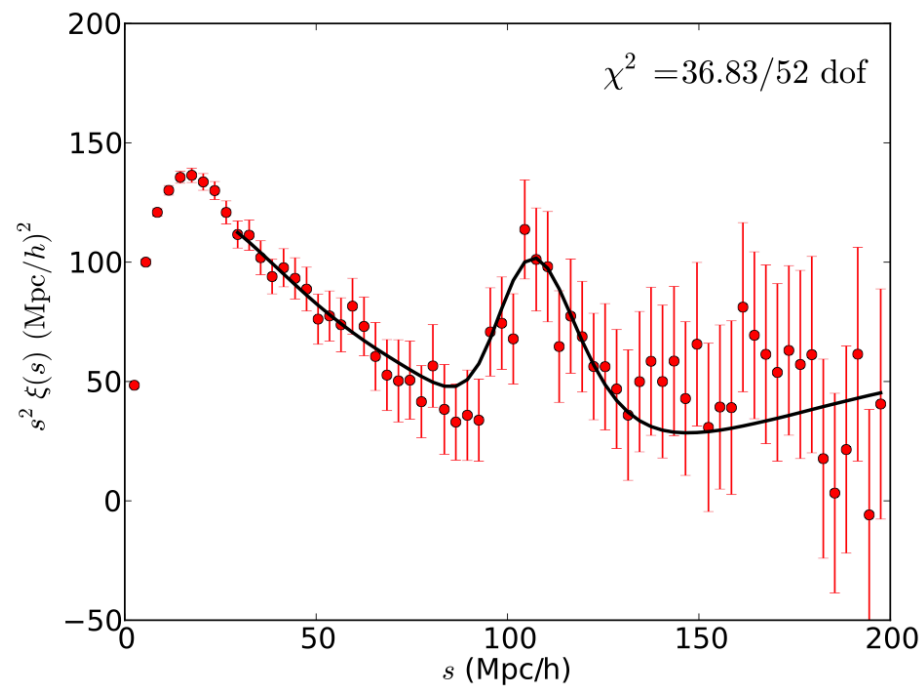
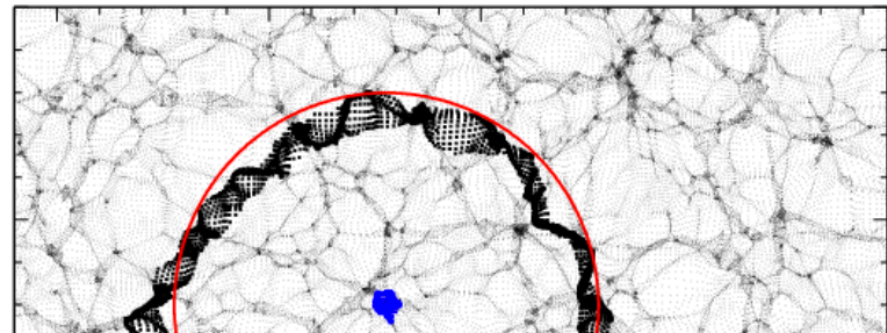
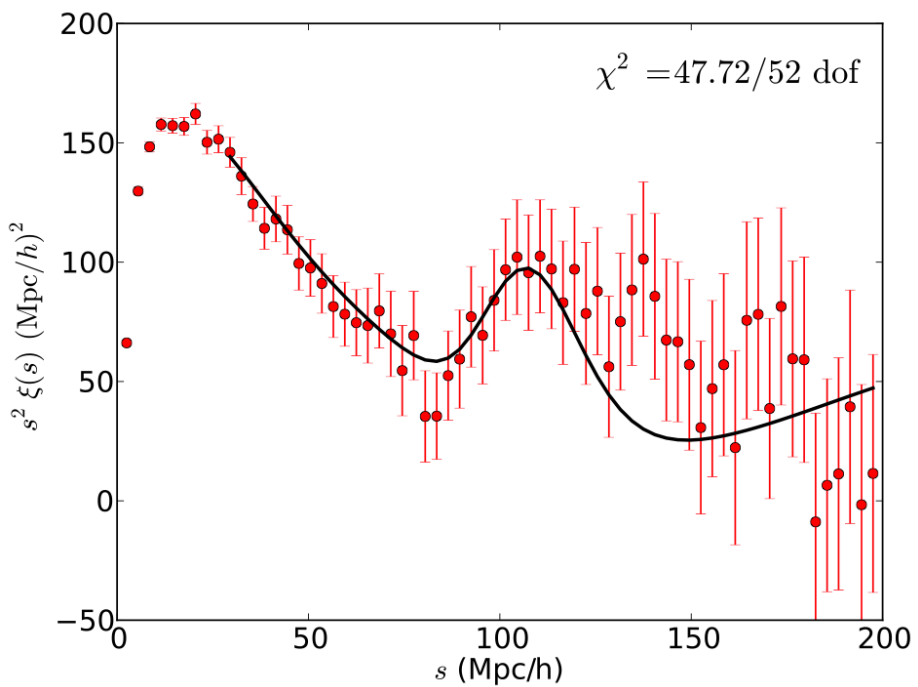
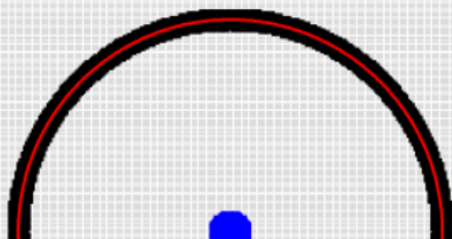


Reconstruction



Padmanabhan et al. 2011

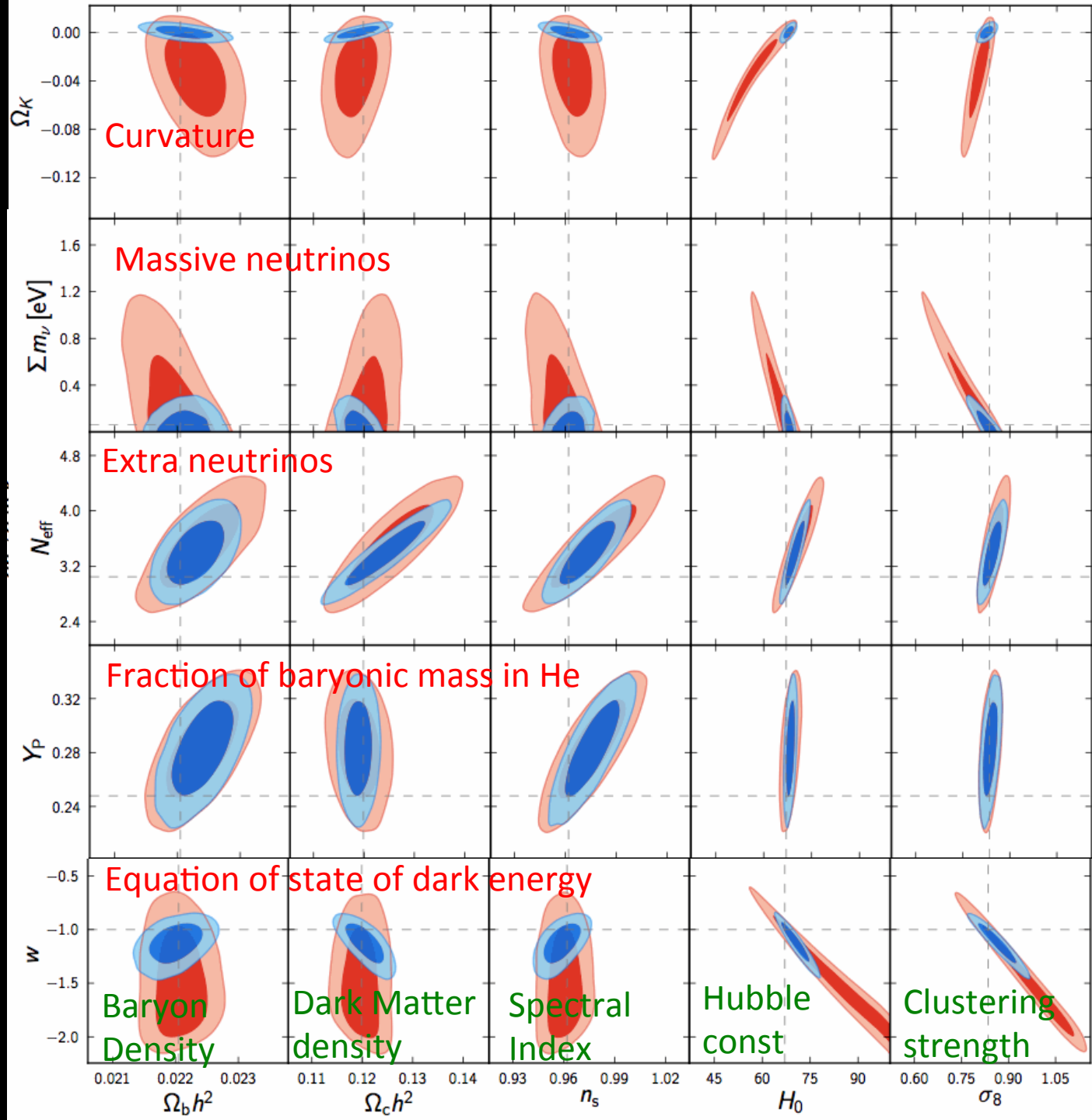
Padmanabhan et al. 2011



Model testing vs parameter fitting

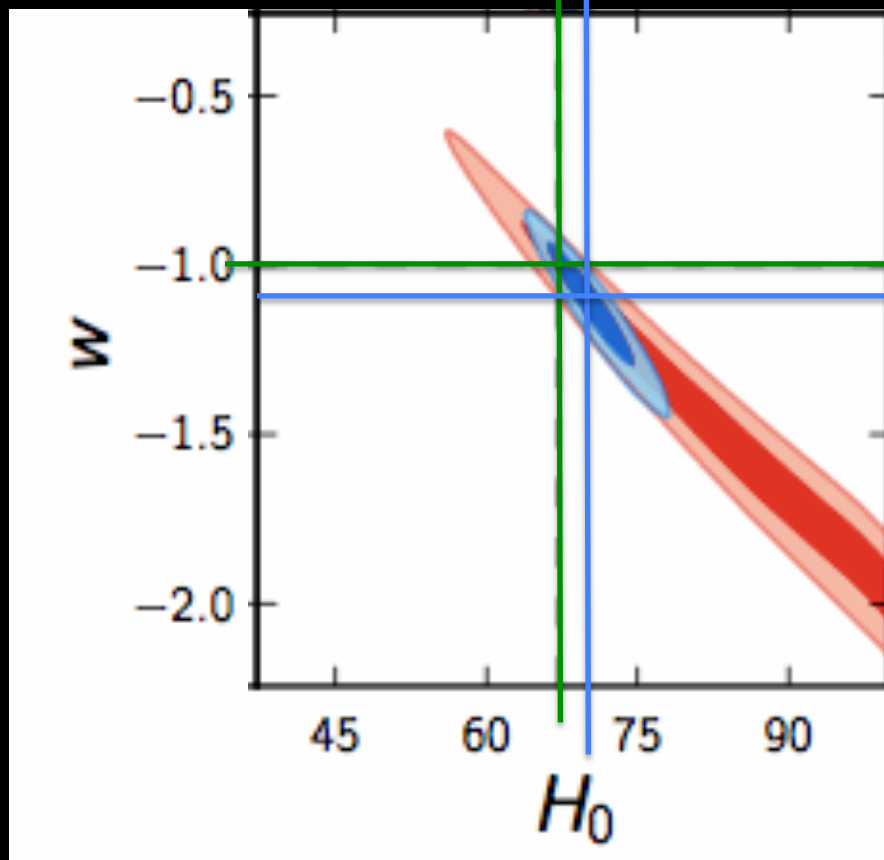
INTERLUDE...

- A CAUTIONARY TALE



CMB: Model extensions

Dark energy
equation
of state



Hubble's constant

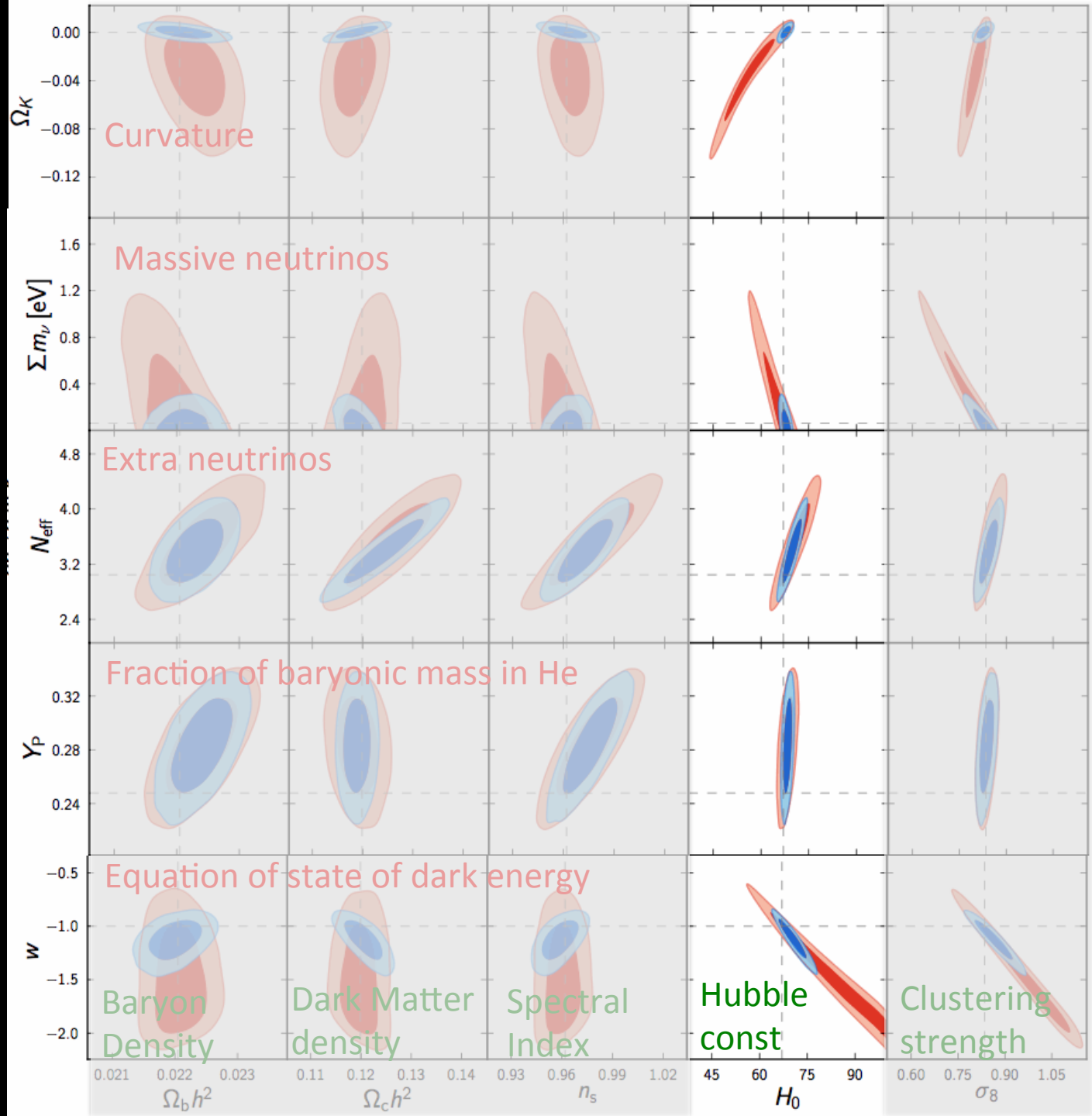
Best fit in
extended model
(w CDM)

Planck+WP+highL
+BAO

$$H_0 = 67.80 \pm 0.77$$

Planck+WP+highL
+BAO

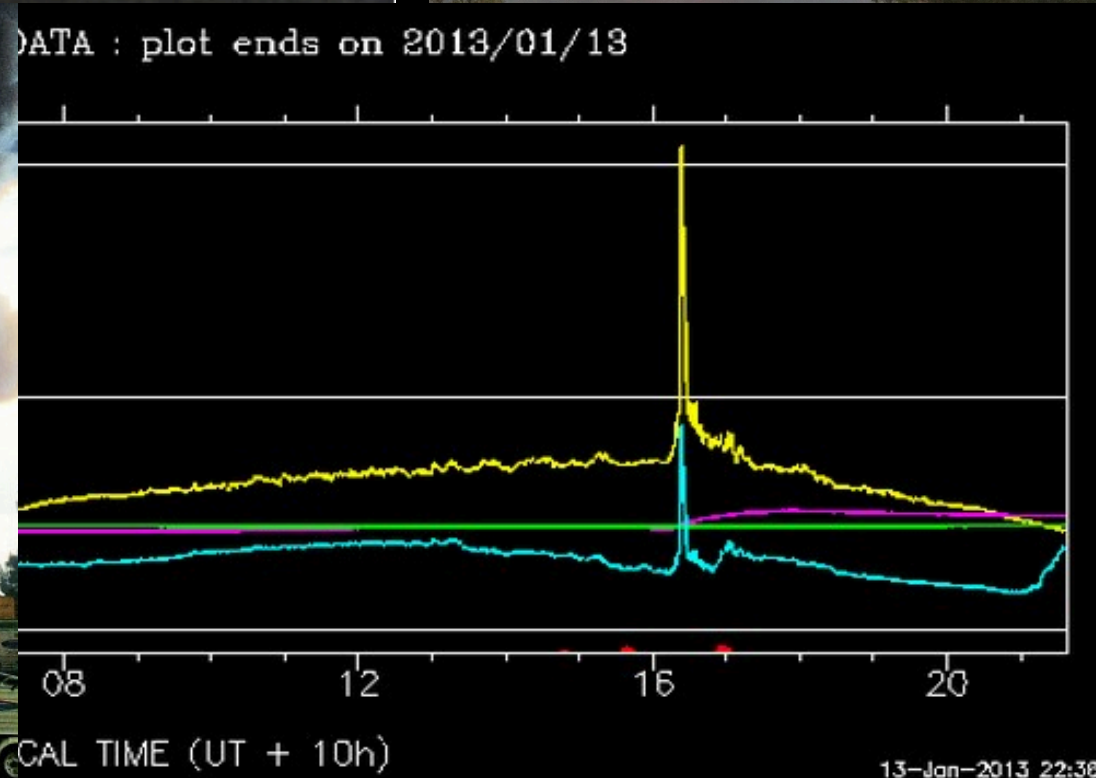
$$H_0 = 71 \pm 4 (?)$$



**OTHER RESULTS FROM
LARGE SCALE STRUCTURE**

The AAT in January 2013...





point magenta: dome air temperature green: mirror temperature

FTS site webcam 2013-01-13 10:06:05



FTS site webcam 2013-01-13 10:51:19



HATSouth @ SSO 2013-01-13 22:15:30



FTS site webcam 2013-01-13 10:06:05



2013-01-13 10:06:35



House



Mopra SkyCam 2013-01-13 17:58:00



But all is well.

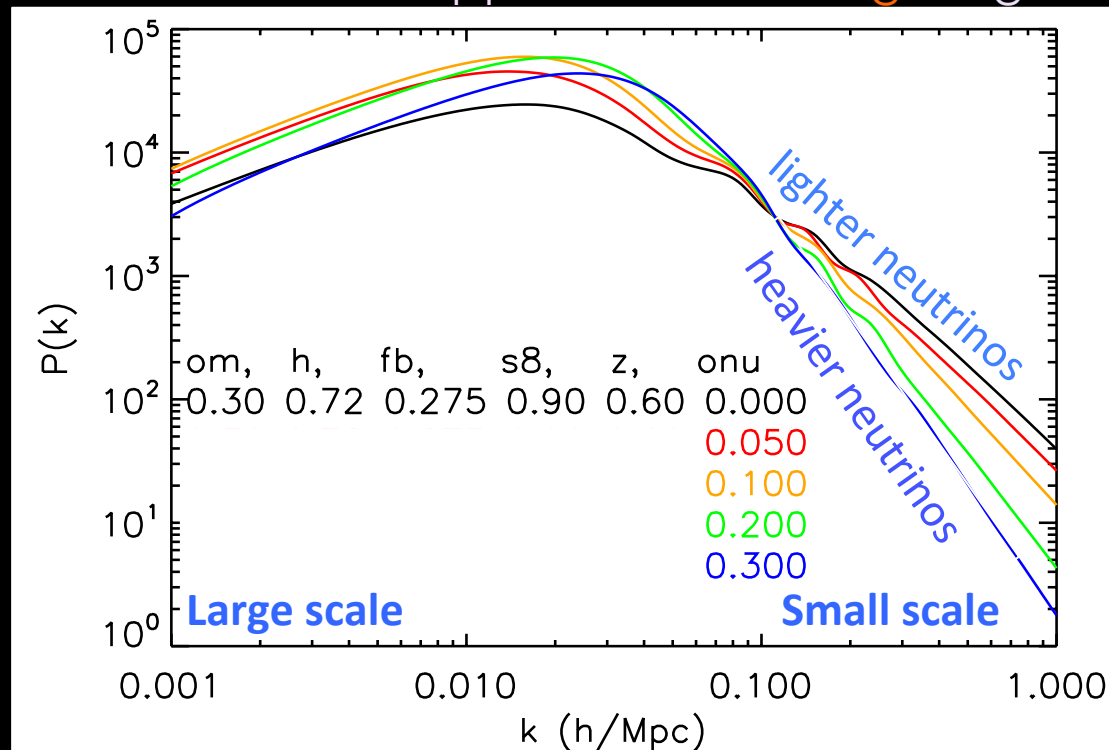


(Small print: This photo was taken before the fires.)

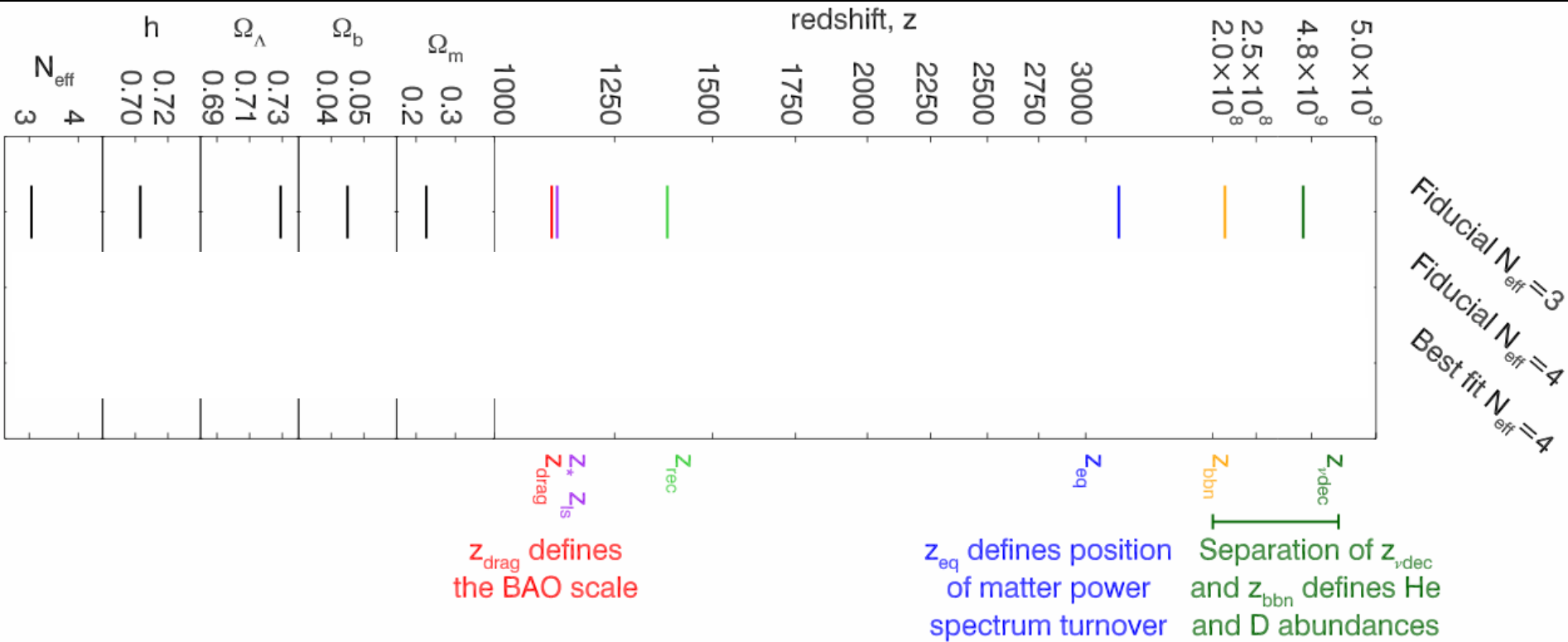
NEUTRINO MASS & NUMBER OF SPECIES

Other things we can do with $P(k)$

- Neutrinos *suppress structure formation* on small scales by free-streaming out of initial density perturbations.
- The free streaming length is lower for higher neutrino masses, since velocities decay
 - **Heavy neutrinos** = **strong** suppression over **short** range
 - **Light neutrinos** = **weak** suppression over **long** range



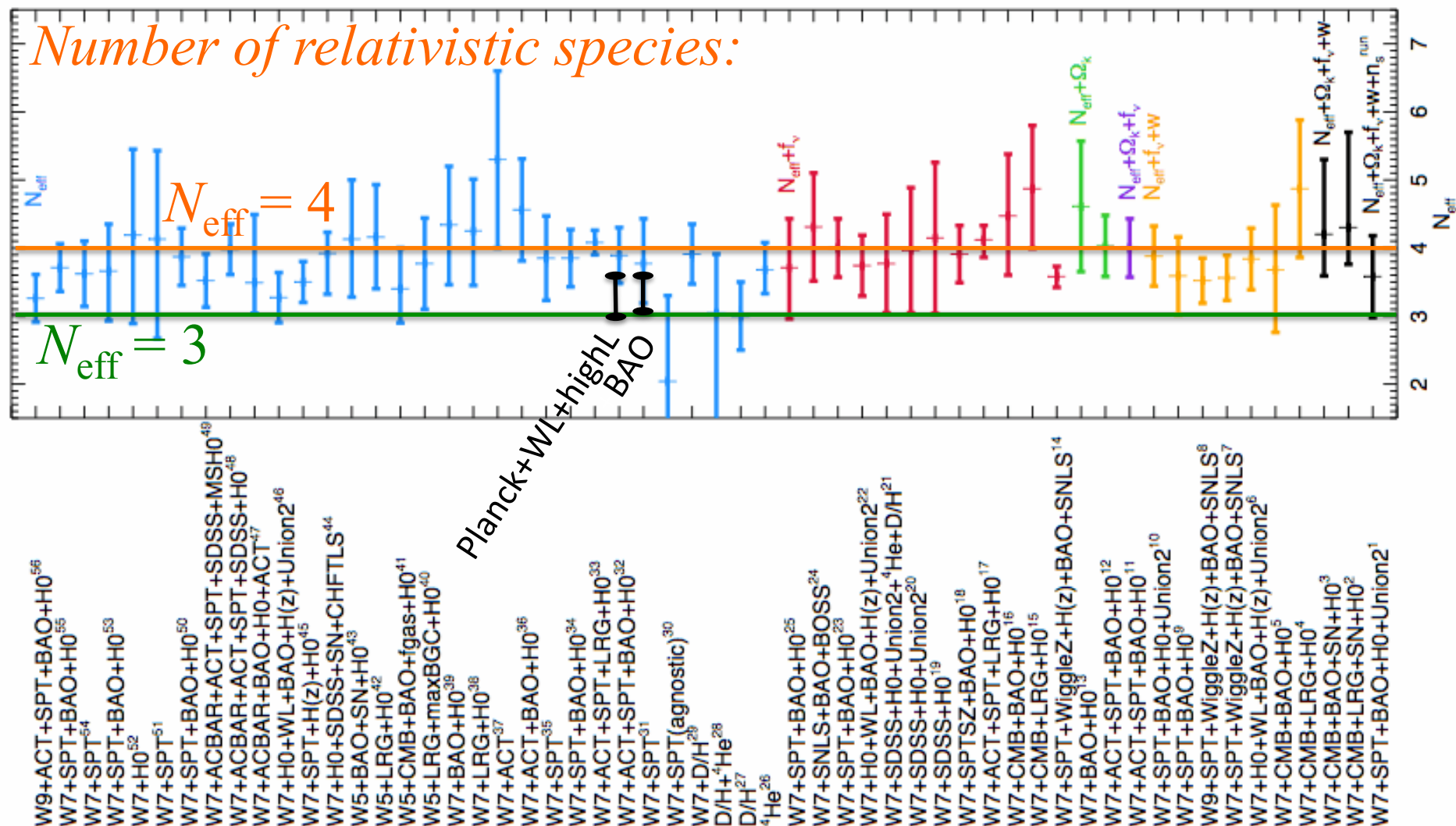
Neutrino effects – N_{eff}



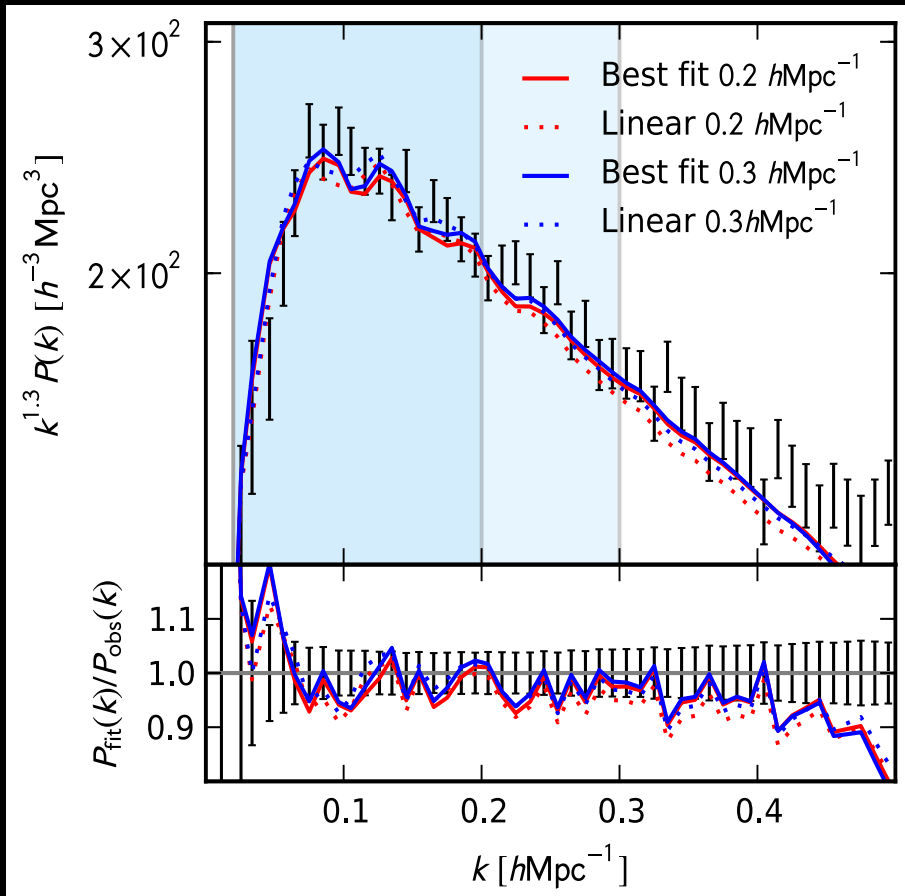
Existing measurements

Total Mass: (e.g.)

SDSS (Reid+ 10)	$\Sigma m_\nu < 0.62\text{eV}$
Photo (Thomas+ 10,	
dePutter+ 12)	$\Sigma m_\nu < 0.28\text{eV}$
Ly- α (Seljak+ 06)	$\Sigma m_\nu < 0.17\text{eV}$



Details: Power spectrum



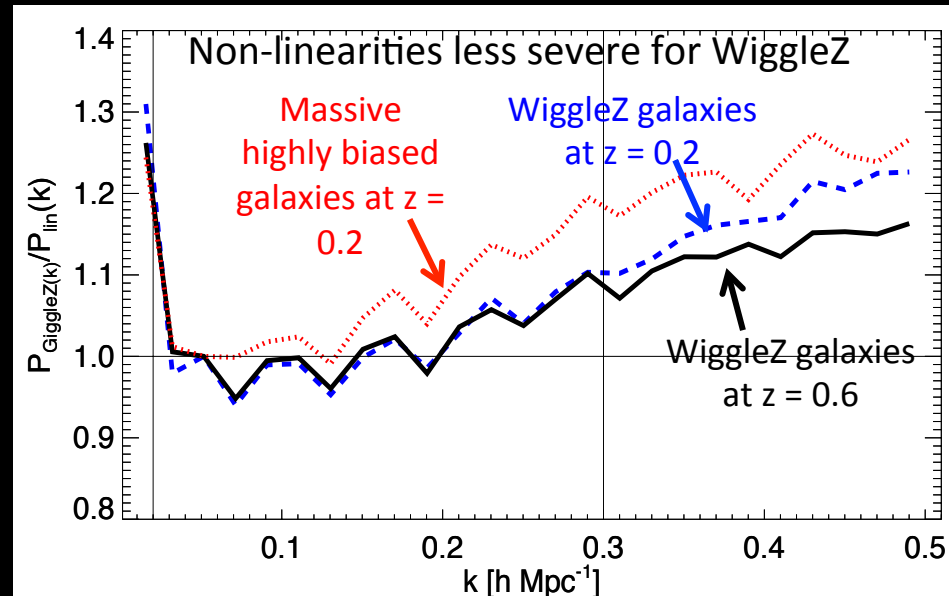
WiggleZ power spect. (black bars)

Best fit Λ CDM models for

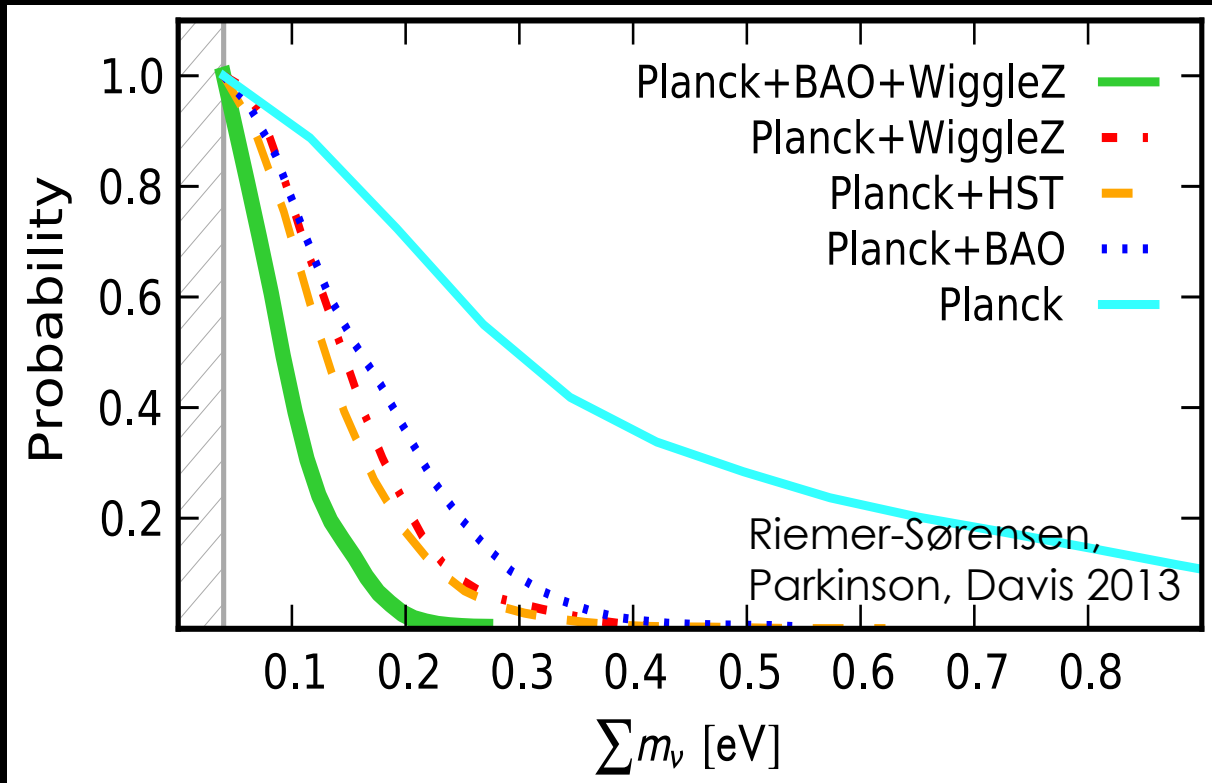
$k_{\text{max}} = 0.2 h\text{Mpc}^{-1}$ (red solid)

$k_{\text{max}} = 0.3 h\text{Mpc}^{-1}$ (blue solid)

Linear CLASS models for the same parameters (dotted).



Upper-limit on neutrino mass



Planck+BAO
 $\Sigma m_\nu < 0.247 \text{ eV}$

Planck+BAO+P(k)
 $\Sigma m_\nu < 0.15 \text{ eV}$
= 50% improvement
on Planck+BAO
alone

$$0.05 \text{ eV} < \Sigma m_\nu < 0.15 \text{ eV}$$

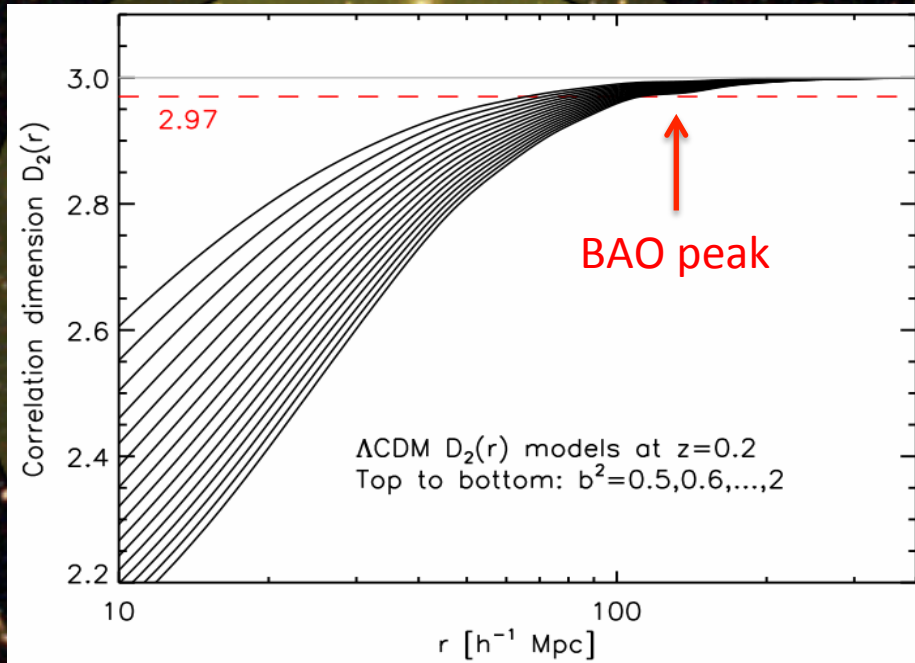
(lab oscillation expts)

(cosmology, 95% confidence,
Flat Λ CDM model)

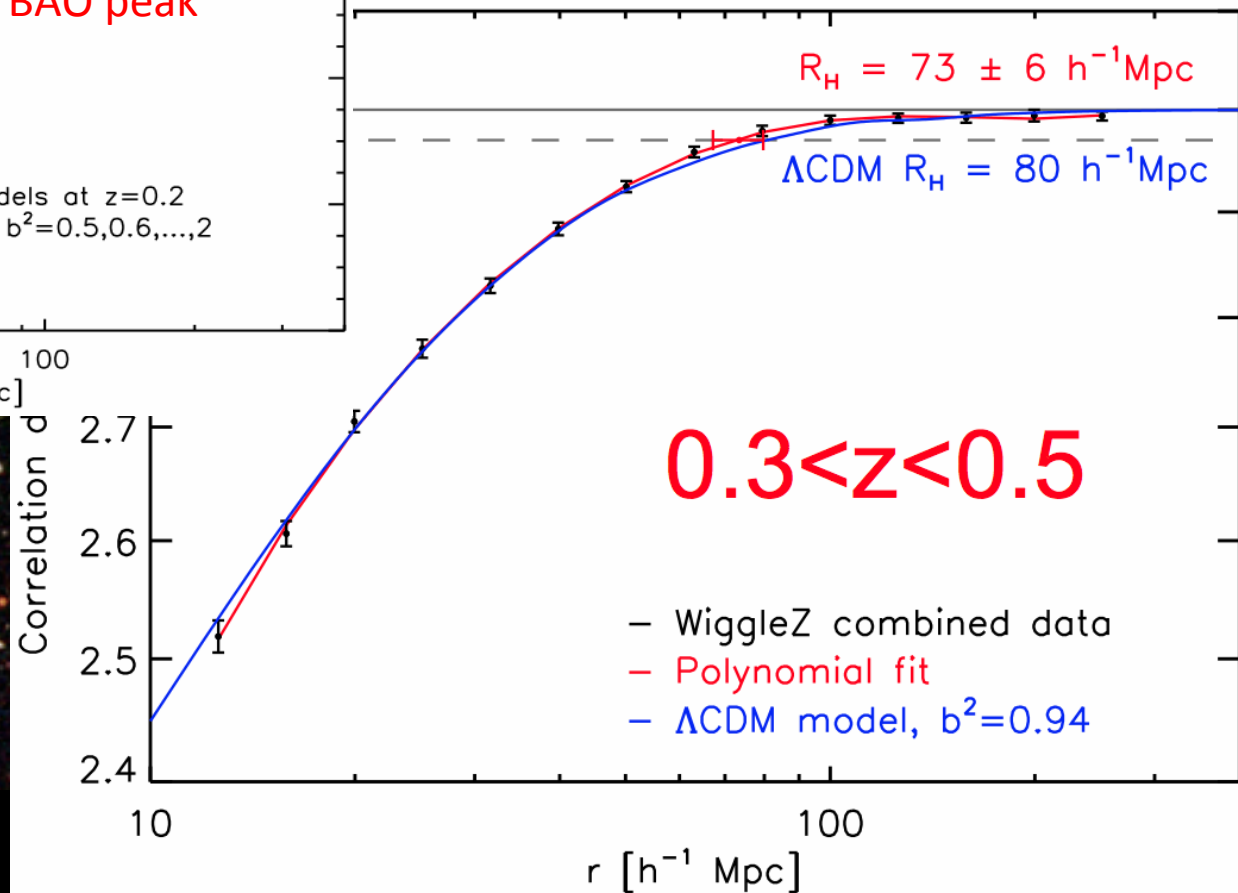
HOMOGENEITY

Fractal dimension (Scrimgeour et al., 2012)

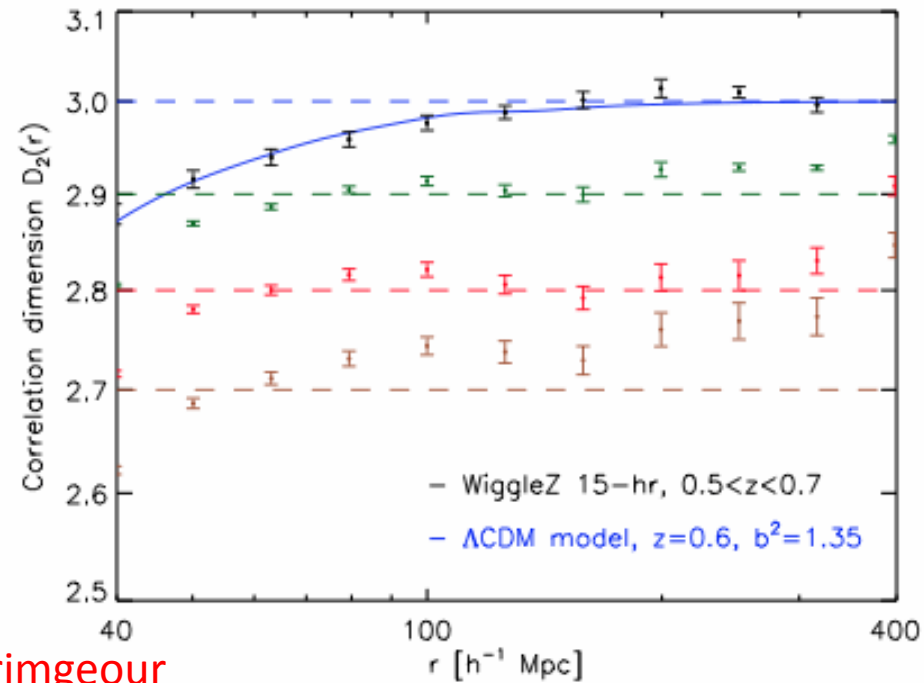
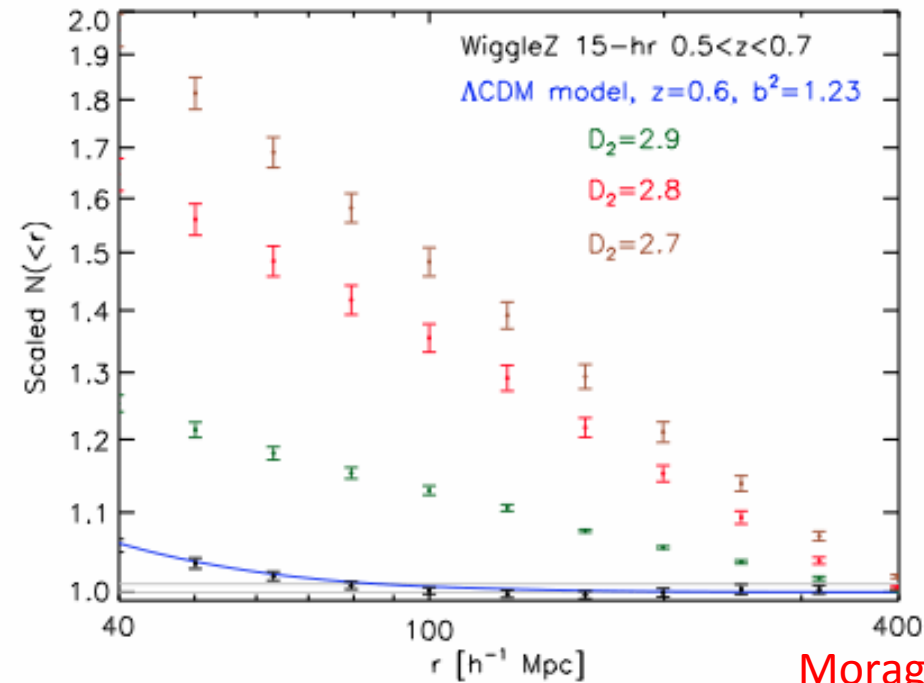
$$N(< r) \propto r^{D_2}$$



$0.3 < z < 0.5$



Testing fractal universes



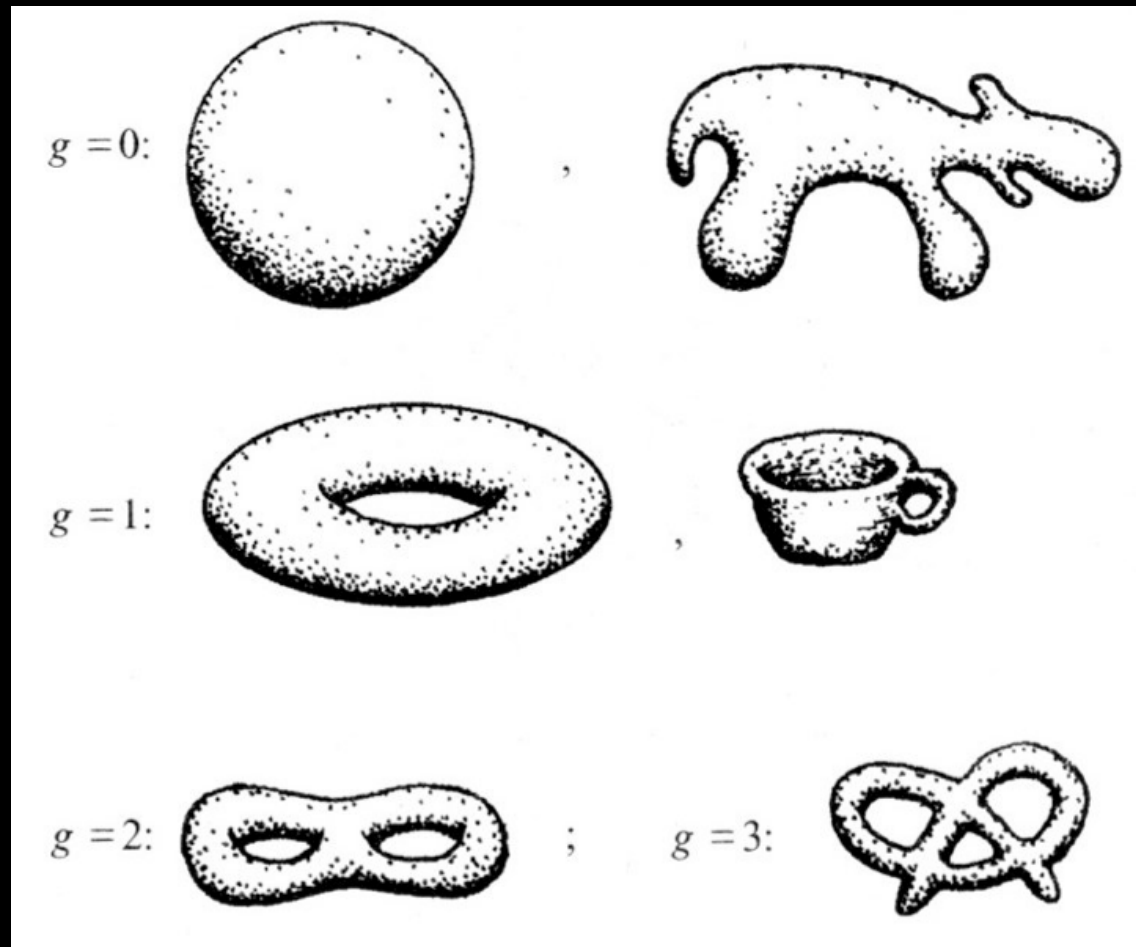
Morag Scrimgeour

NEW STANDARD RULER

- TOPOLOGY

What is genus?

Genus is a measure of topology



The genus statistic

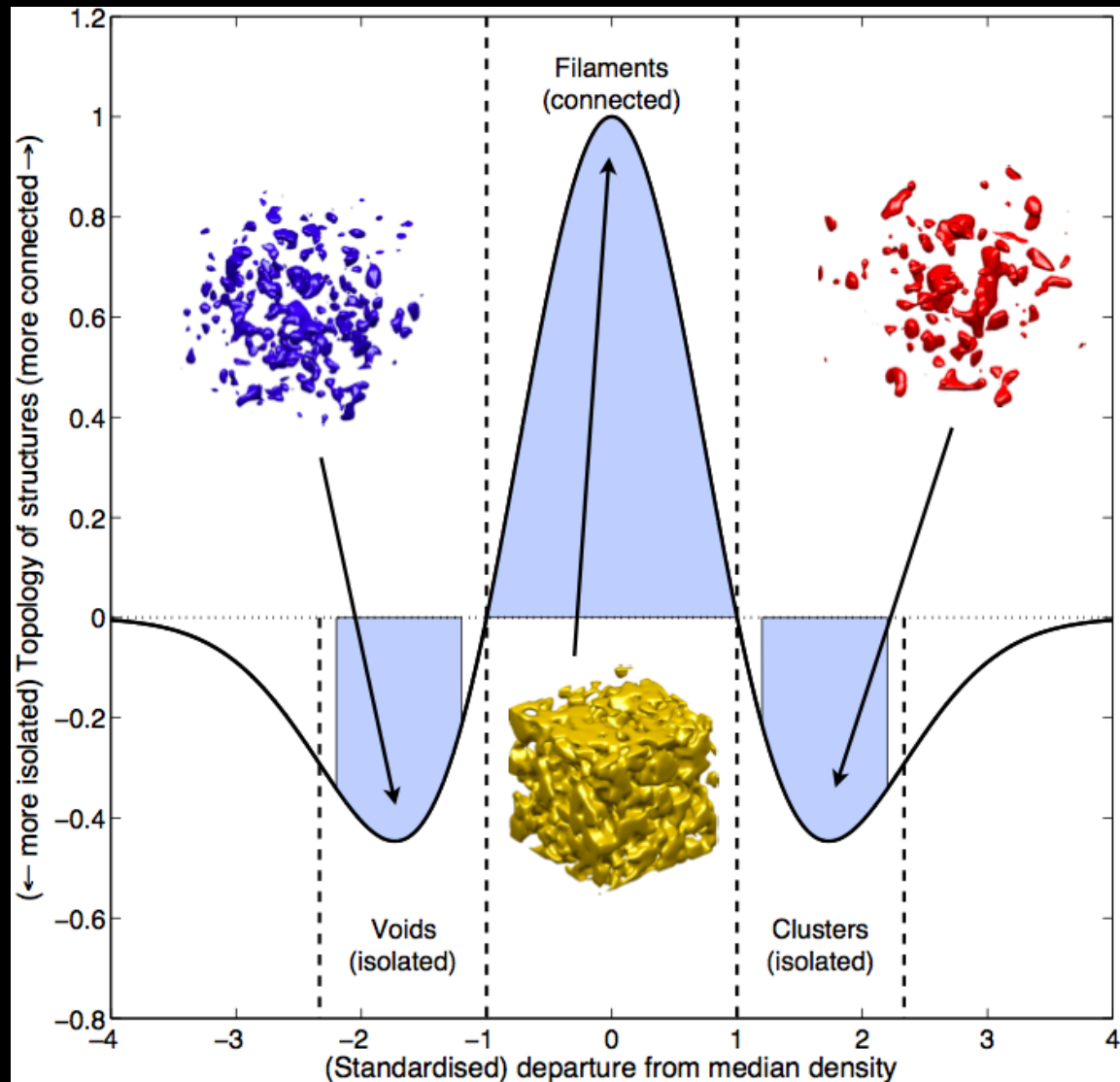
The genus statistic measures the topology of structure

Gaussian random fields have a specific topology

By measuring the genus we can detect non-gaussianity

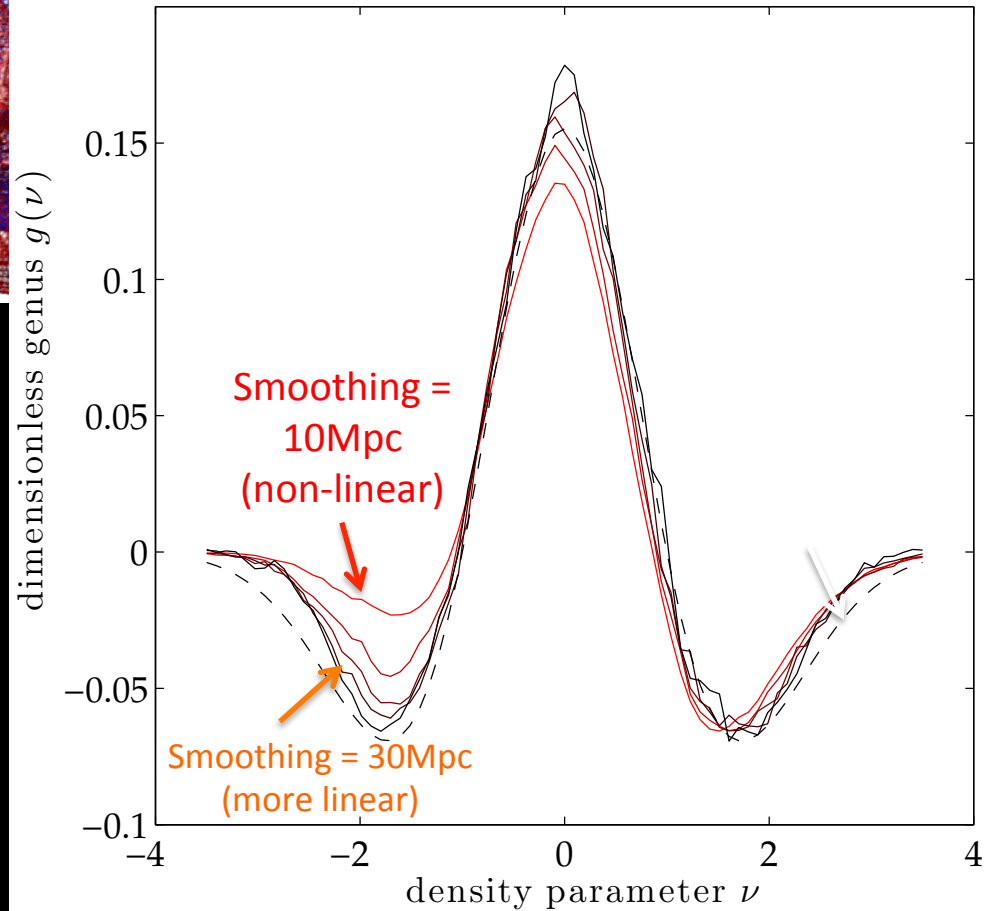
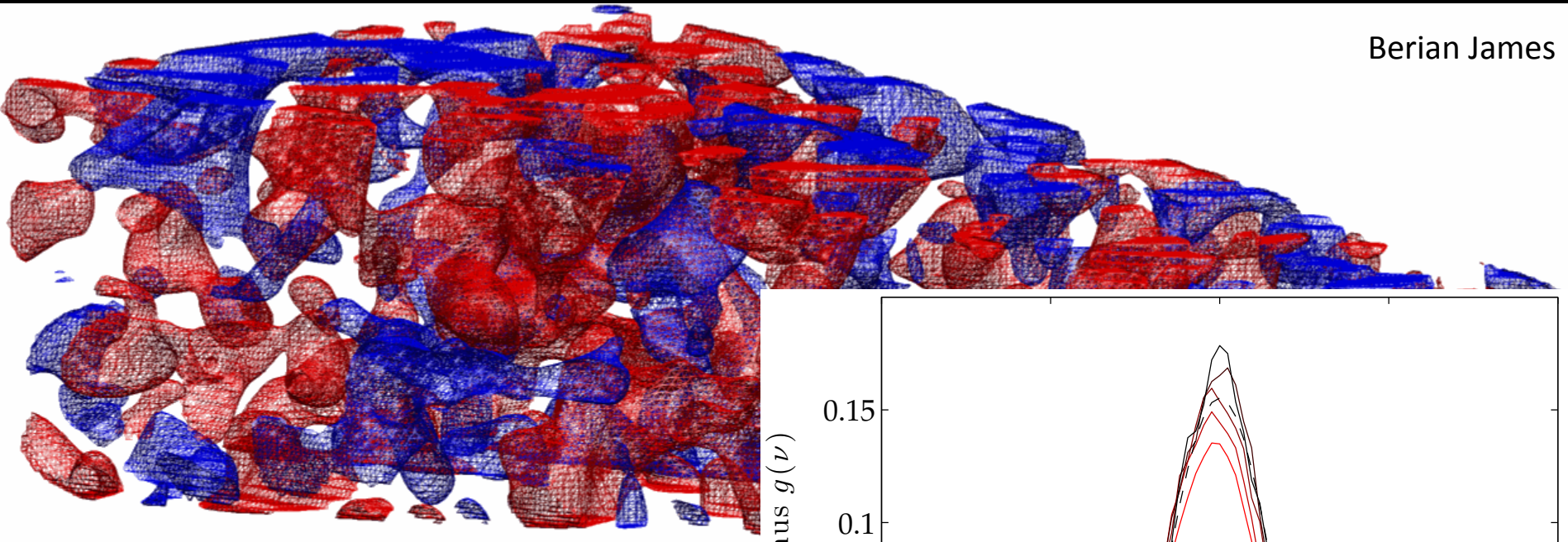
Large scales – primordial non-gaussianity

Small scales – non-linear structure



Topology: Genus curve

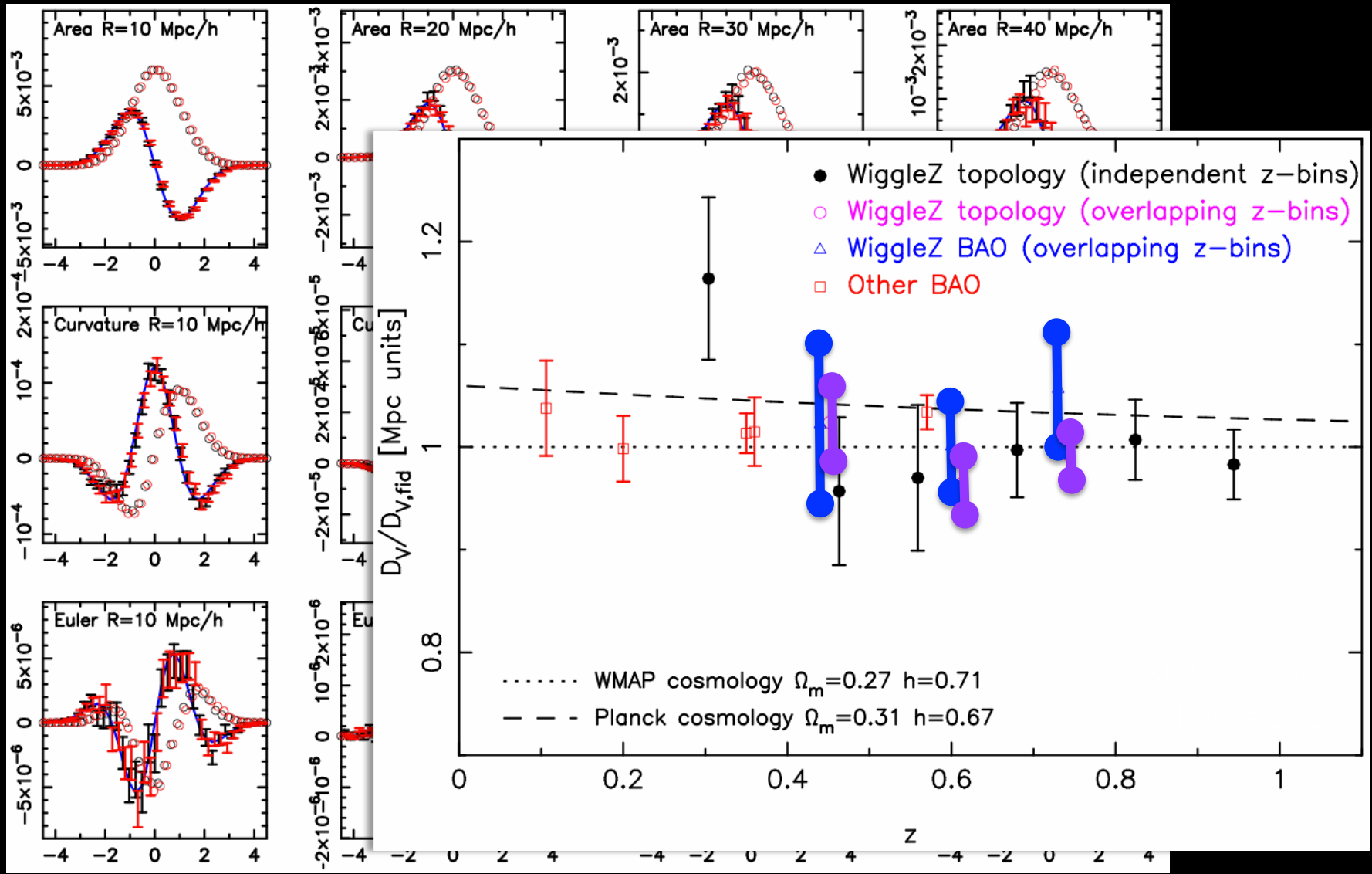
Berian James



Quantifying Topology

– Minkowski Functionals

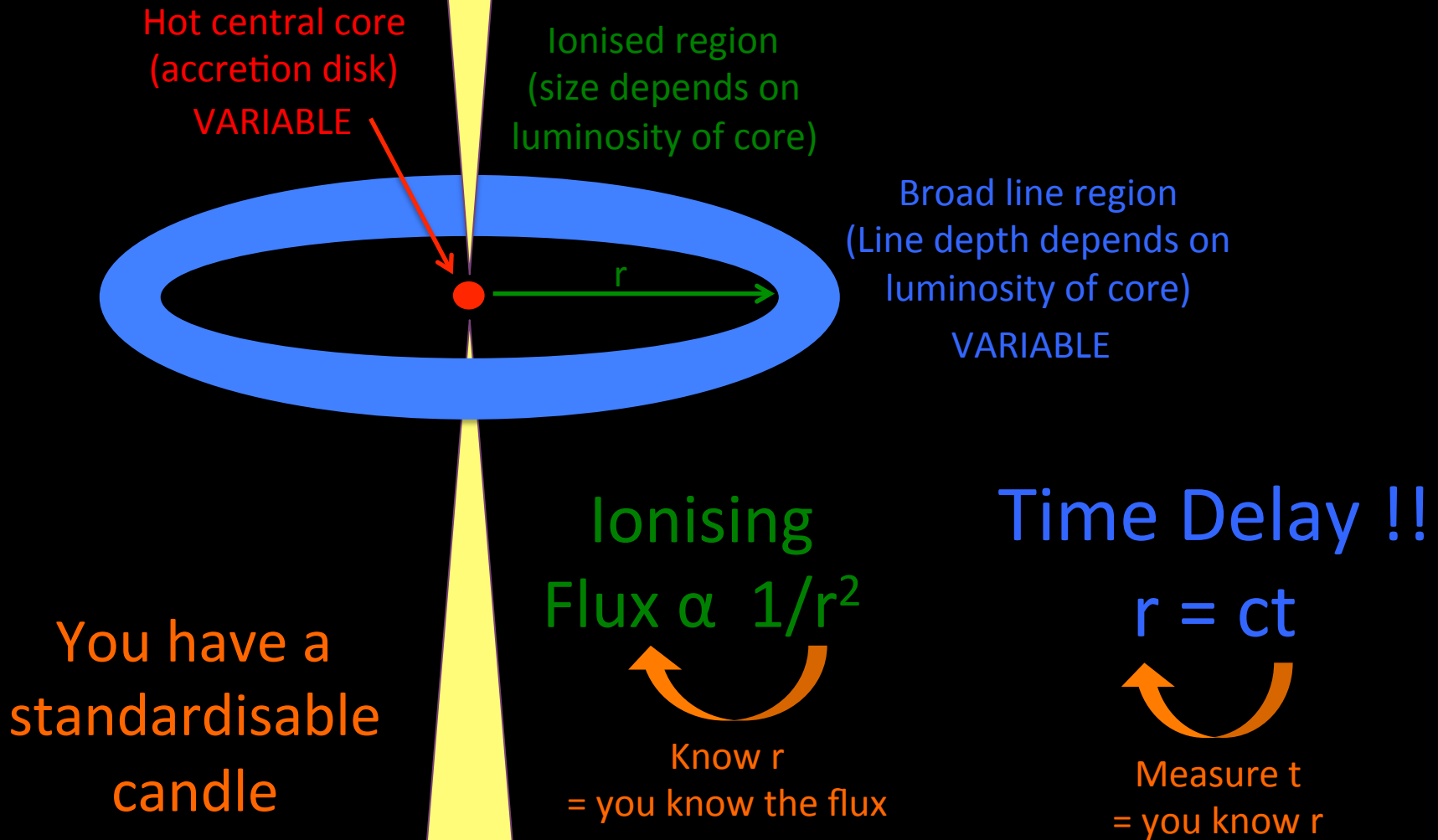
Red = GiggleZ



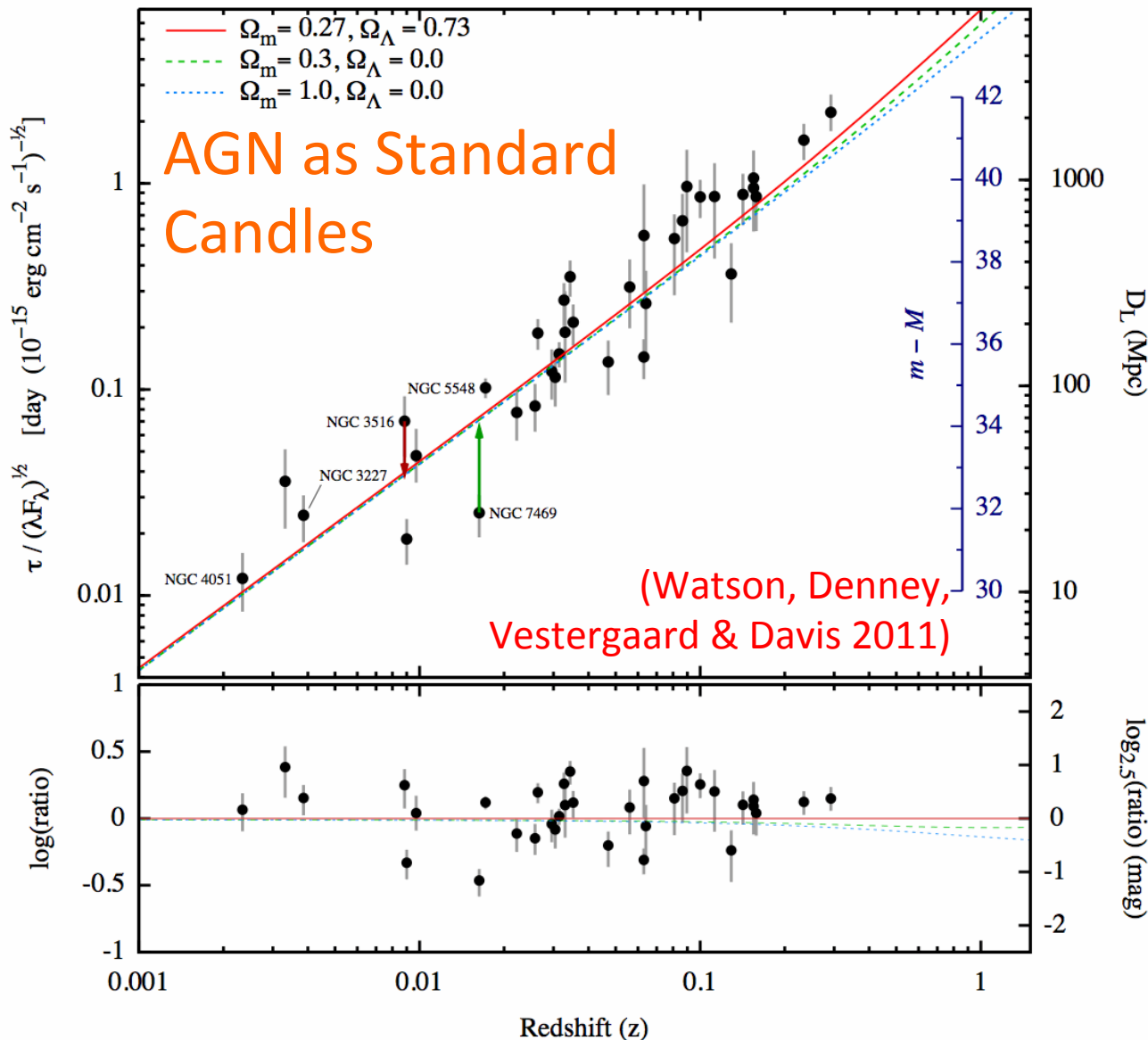
NEW STANDARD CANDLE?

- QUASARS (AGN)

Active galaxies – reverberation mapping



First Quasar Hubble Diagram



There's lots to do!!!
 Good luck with your
 research!

