Measurements of Dark Energy

Lecture 2: Expansion Kinematics with Galaxy Clusters and BAO

Phil Marshall
UCSB

SLAC Summer Institute
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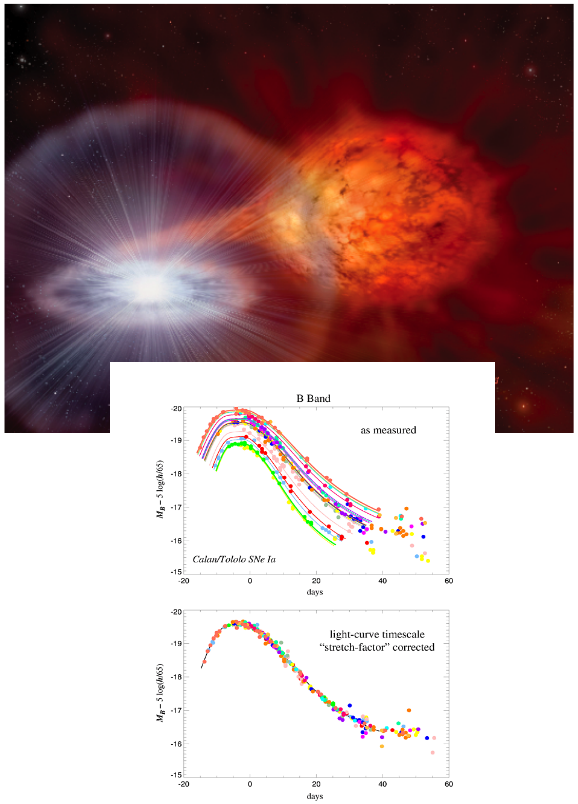
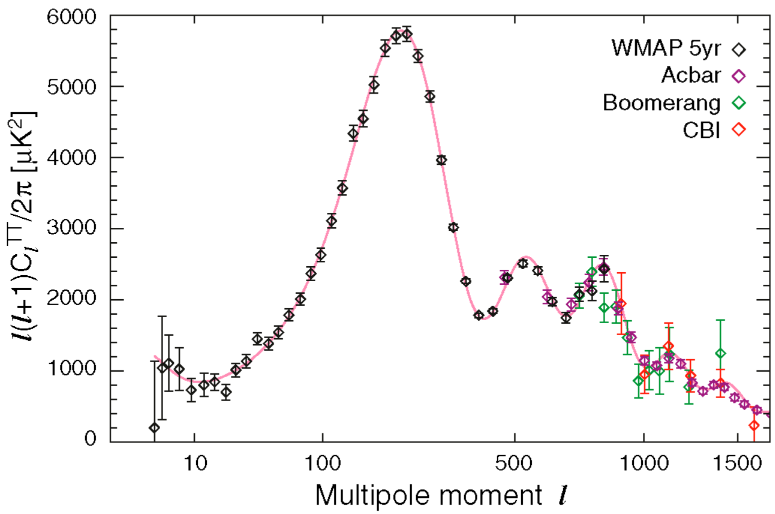
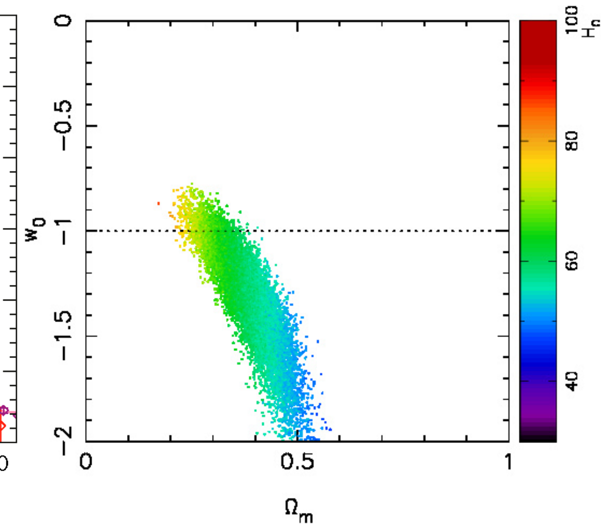
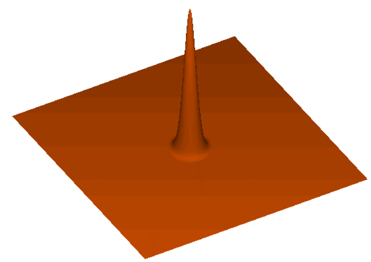
Recap of Lecture 1









Questions for Lecture 2:
How far can SNe get us? And the CMB?
What other kinematic probes do we have? How do they complement supernovae and the CMB?

Lecture 2

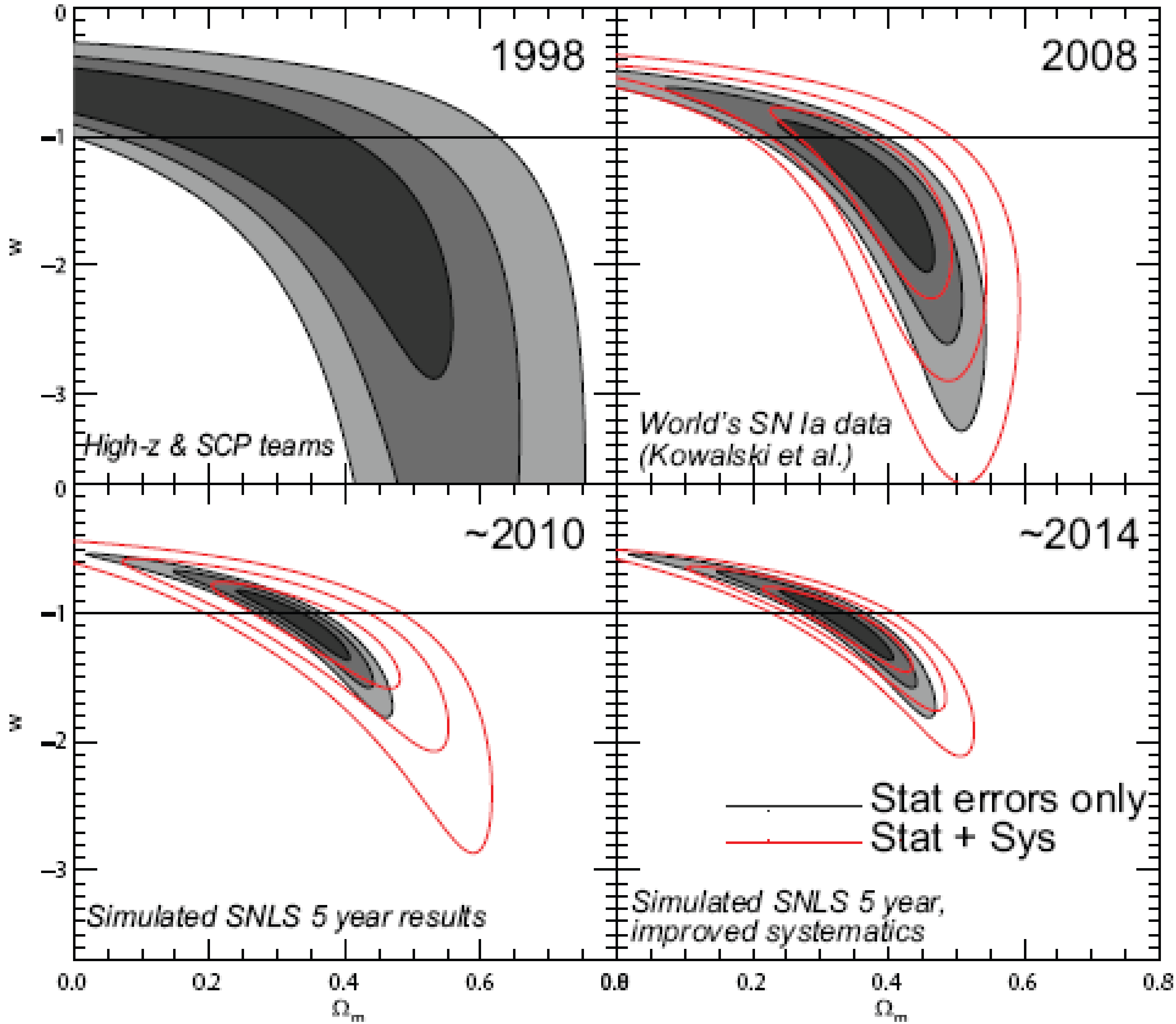
1) SNe and CMB in the next decade

2) Gas fractions in clusters as standard rulers

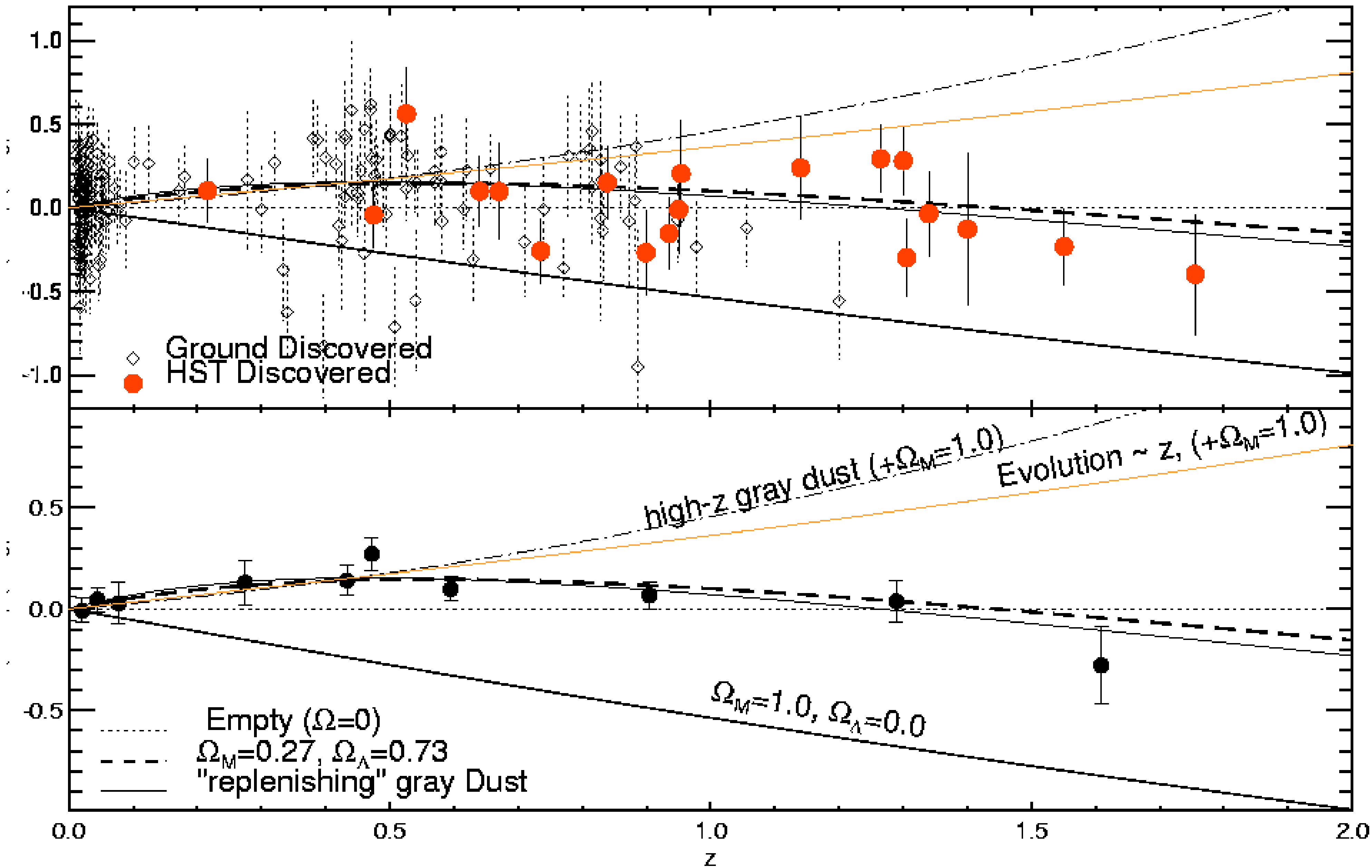
3) Baryonic Acoustic Oscillations again –
   but not in the CMB

Part 1: SNe and CMB in the next decade

Systematics Forecast



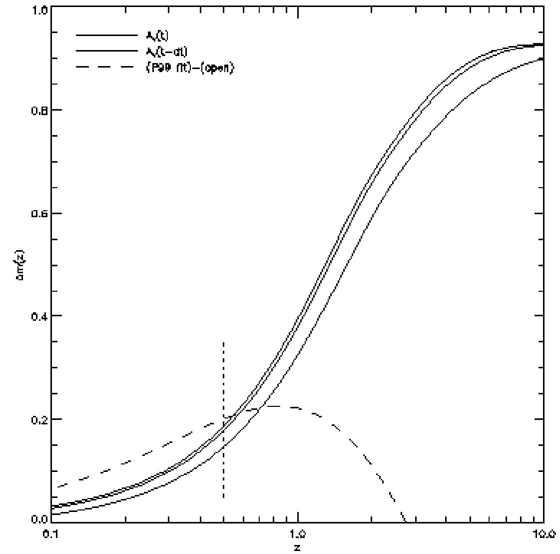
z > 1 SNe from HST GOODS Survey



Riess et al 2004

Can Grey Dust Mimic Dark Energy?

Large (> 0.1 micron) dust grains ejected into the intergalactic medium would appear optically grey **(absorb without reddening in optical bands)** and could possibly **dim the *z* ~ 0.5 SNe** by requisite amount



Aguirre 1999, Drell et al 2000

However:

1. Expected increase in peak dispersion not seen
2. Subsequent I-band observed SNe showed no effects
3. Colours of SNe do not evolve with *z*
4. Grains would re-radiate in FIR (vs. FIRAS background)
5. Continuing trend at higher *z* not observed

BUT: Dust and evolution remain largest future systematics: NIR

Precision SNe DE Measurements in the Next Decade

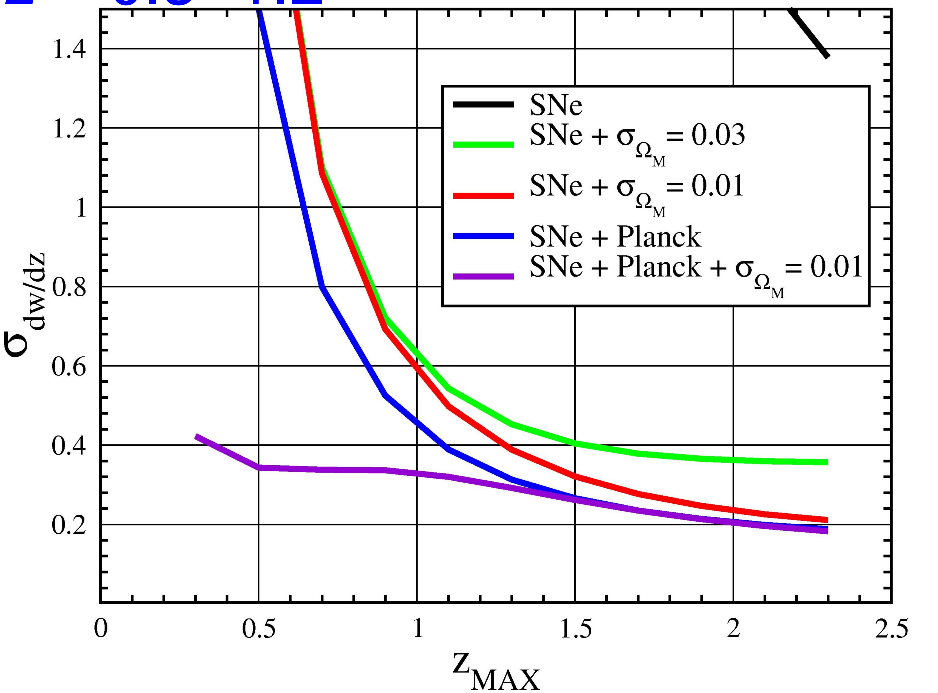
- Goal: Determine ***w_0* to ~10% and *w_a* to ~40%**

- Statistical Requirement: ~1% *relative* distance measurements (2% flux) in z~0.1 redshift bins to z = 1.2 (Frieman et al)
- Assume systematic error can be reduced to this level Kim, et al 2004, Kim & Miquel 2005
- Require ~1000 SNe spread over *z* ~ 0.3 -1.2 plus a low-z sample of matched accuracy

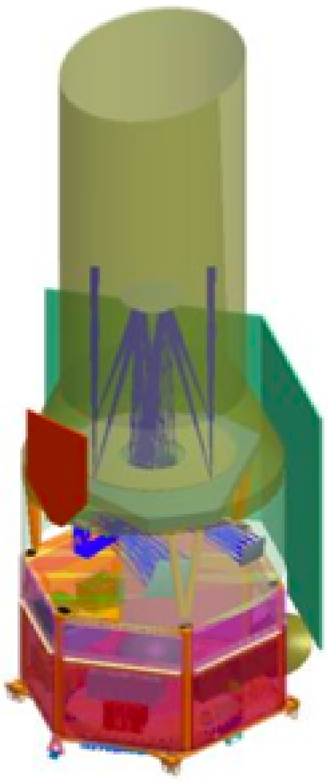
This will require:

*** NIR imaging**
*** High photometric stability**

and so a space-based mission



Precision SNe DE Measurements in the Next Decade



NASA/DoE Joint Dark Energy Mission (JDEM)

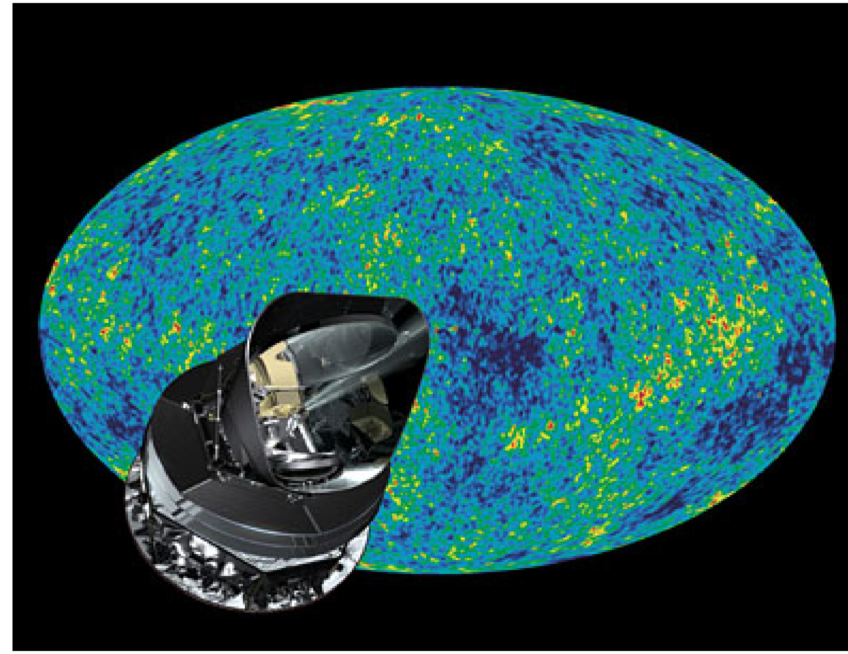
Reference mission defined,
call for proposals soon. Launch 2016?

Aiming for 1500 SNe z = 0.3 – 1.2
Discovered and typed in optical/NIR imaging,
optical/NIR spectroscopic follow-up

Aim to collect as much information as possible about each event, over the whole redshift range: apples with apples,
empirical systematics exploration

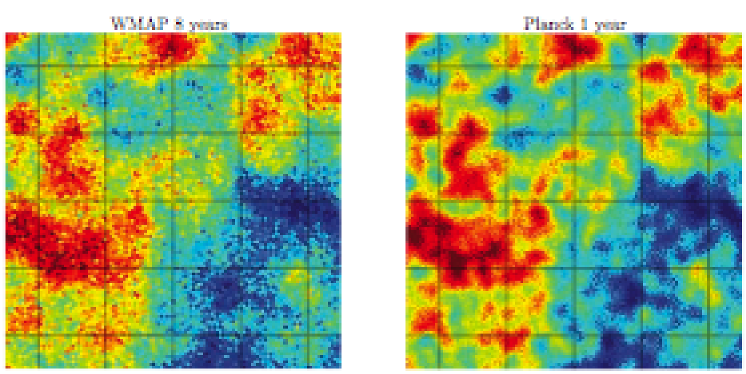
1.5m telescope, 0.36(0.18) sq deg optical(IR) imager,
with optical grism and NIR prism spectroscopy

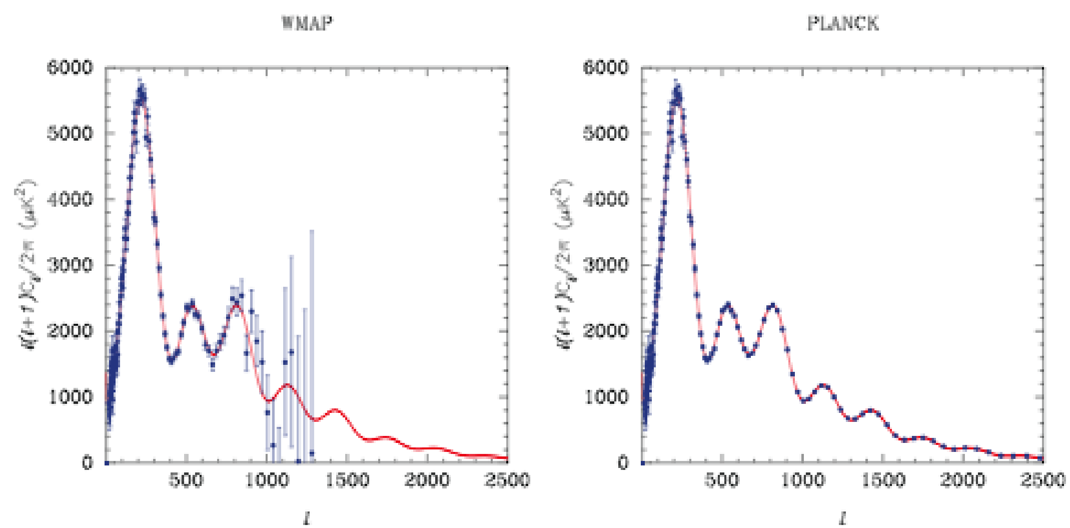
Precision CMB Measurements in the Next Decade



Planck – launched in May 2009, begins science observations later this year

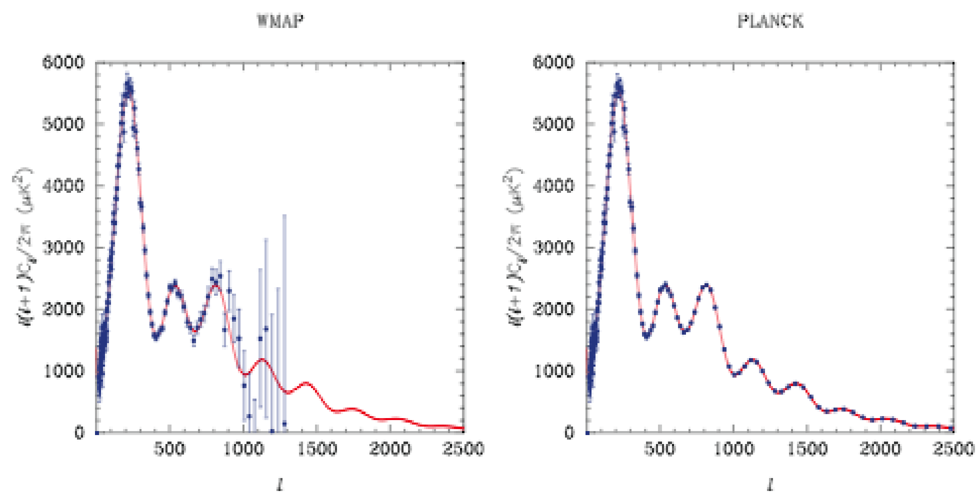
Higher angular resolution, lower noise imager than WMAP (wider frequency range)



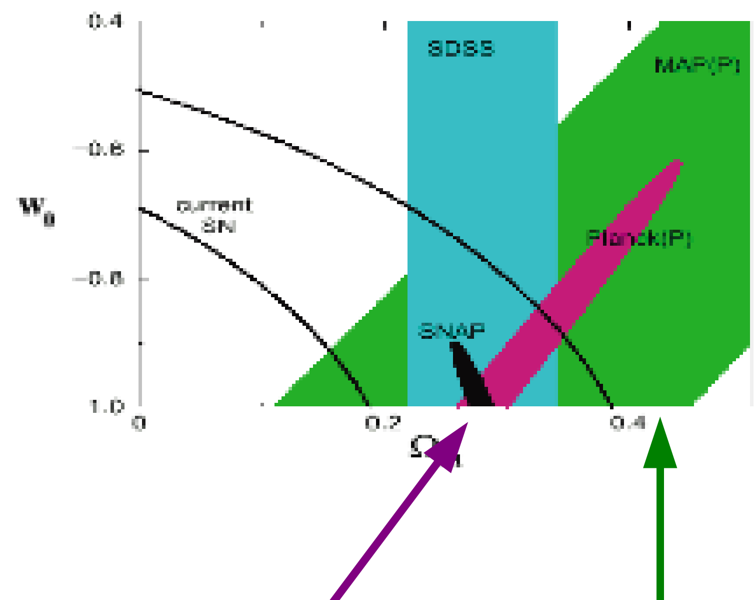


Planck Blue Book

Precision CMB Measurements in the Next Decade



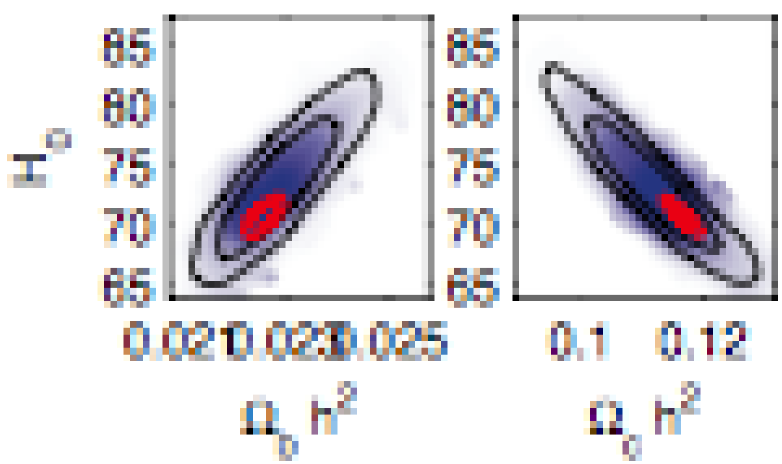
w-matter density degeneracy remains, but gets narrower as S/N increases and higher peaks are measured



Planck

WMAP

baryon/total matter density very well constrained



Planck Blue Book

DE Parameter Forecasting

Future probes are often discussed in terms of their contribution to the combination – most assume “Planck prior”

This implicitly assumes that systematics are re-parameterised into nuisance parameters and marginalised over...

Analysis can then be done using simple approximation to the joint likelihood – with all parameter degeneracies are broken, high S/N PDF is approximately Gaussian, use Fisher Matrix formalism

$$F_{ij} = \left\langle \frac{\partial^2 \log P}{\partial q_i q_j} \right\rangle$$

$$\langle \delta q_i \delta q_j \rangle = (F^{-1})_{ij}$$

- Independent datasets' likelihoods: add the Fisher matrices
- Same for (Gaussian) priors
- Marginalisation by excision of sub-matrices from inverse Fisher matrix (parameter covariance matrix)

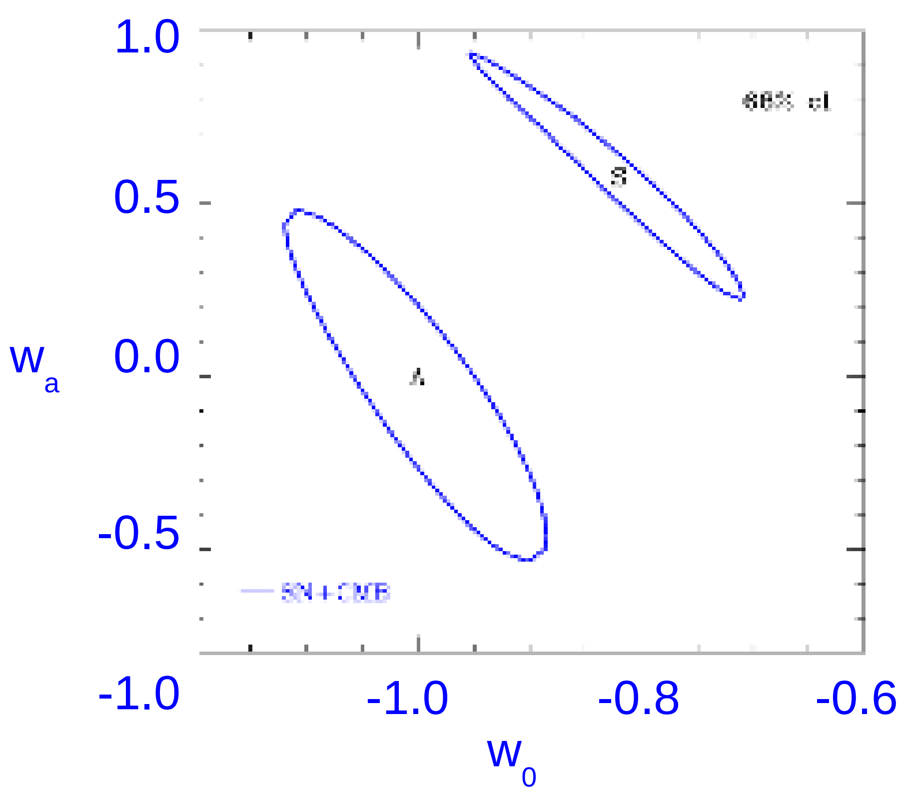
DE Parameter Forecasting

$$F_{ij} = \left\langle \frac{\partial^2 \log P}{\partial q_i q_j} \right\rangle$$

$$\langle \delta q_i \delta q_j \rangle = (F^{-1})_{ij}$$

eg SNAP(JDEM?) + Planck constraints on w(a), where

$$w(a) = w_0 + w_a(1-a)$$



Projected precision:
8% in w_0, 0.7 in w_a,
(95% confidence)

"Figure of Merit"
= 1 / (ellipse area)
= 20-30

~ 3-4 times higher than SNLS (~16%, 1.1)

SNAP collaboration (2005)
DETF report 2006

Part 2: Cluster gas fractions

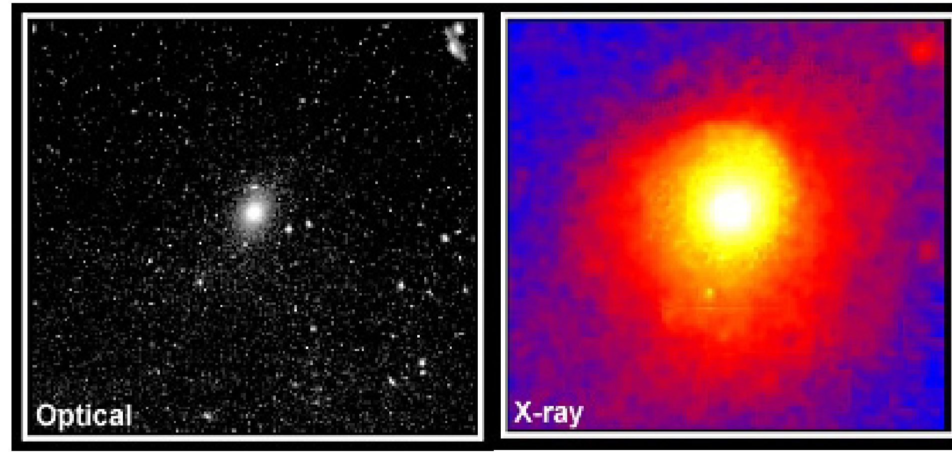
Standard buckets

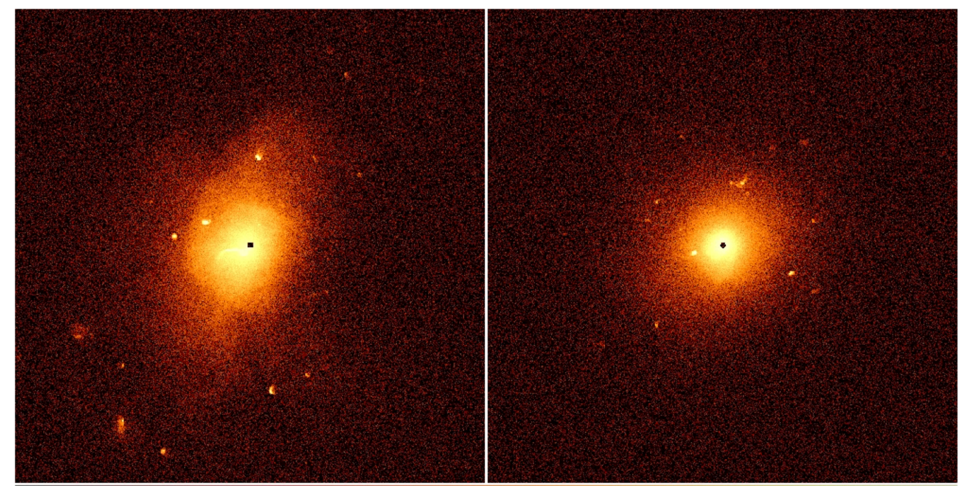
Clusters of galaxies are the biggest gravitationally bound structures in the Universe

They are expected to fairly sample the global baryon to total mass fraction

They are (relatively) easy to simulate - and it turns out that:

$$f_{\mathrm{b}} = b(z)\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}} = \frac{M_{*} + M_{\mathrm{gas}}}{M_{\mathrm{total}}}$$



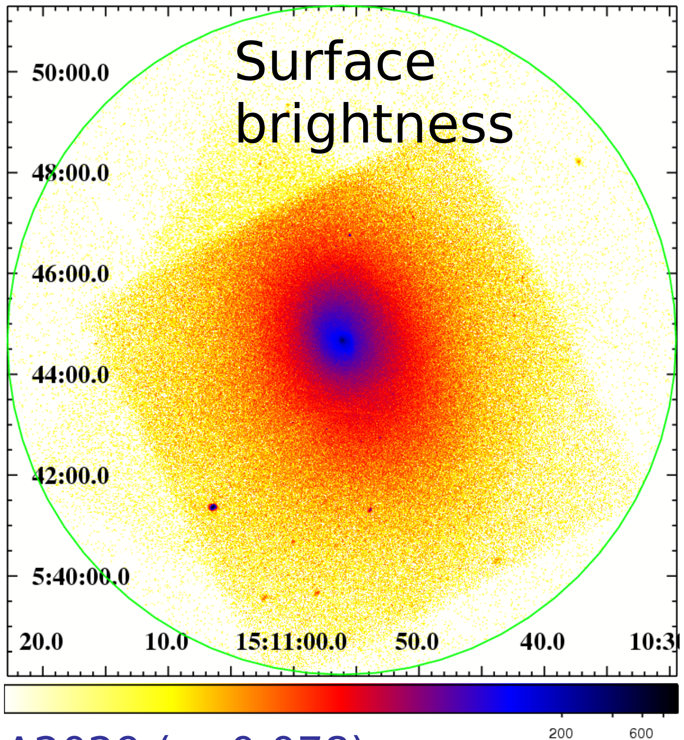


$$b(z) = (0.83 \pm 0.09)$$ constant!

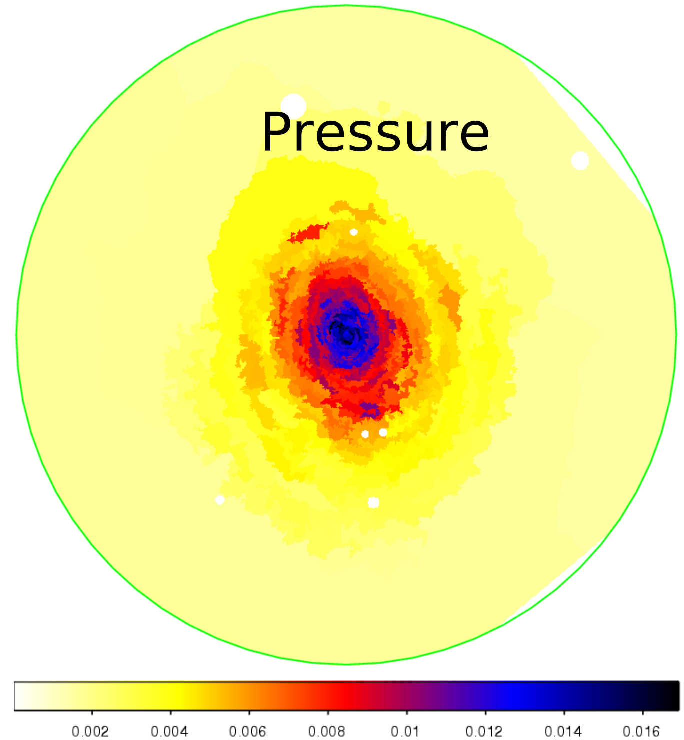
$$\frac{f_{*}}{f_{\mathrm{gas}}} = (0.16 \pm 0.05)$$

Eke et al 1998
Lin & Mohr 2004

Cluster Mass Modelling with X-ray Data



A2029 (z=0.078)



Hot gas in relaxed, approximately spherical clusters is in approximate hydrostatic equilibrium

Measure X-ray surface brightness (from image) and temperature profile (from spectrum), fit model for gravitational potential and reconstruct gas density and pressure

Cluster Mass Modelling with X-ray Data

Hot gas in relaxed, approximately spherical clusters is in approximate hydrostatic equilibrium

Measure X-ray surface brightness (from image) and temperature profile (from spectrum), fit model for gravitational potential and reconstruct gas density and pressure:

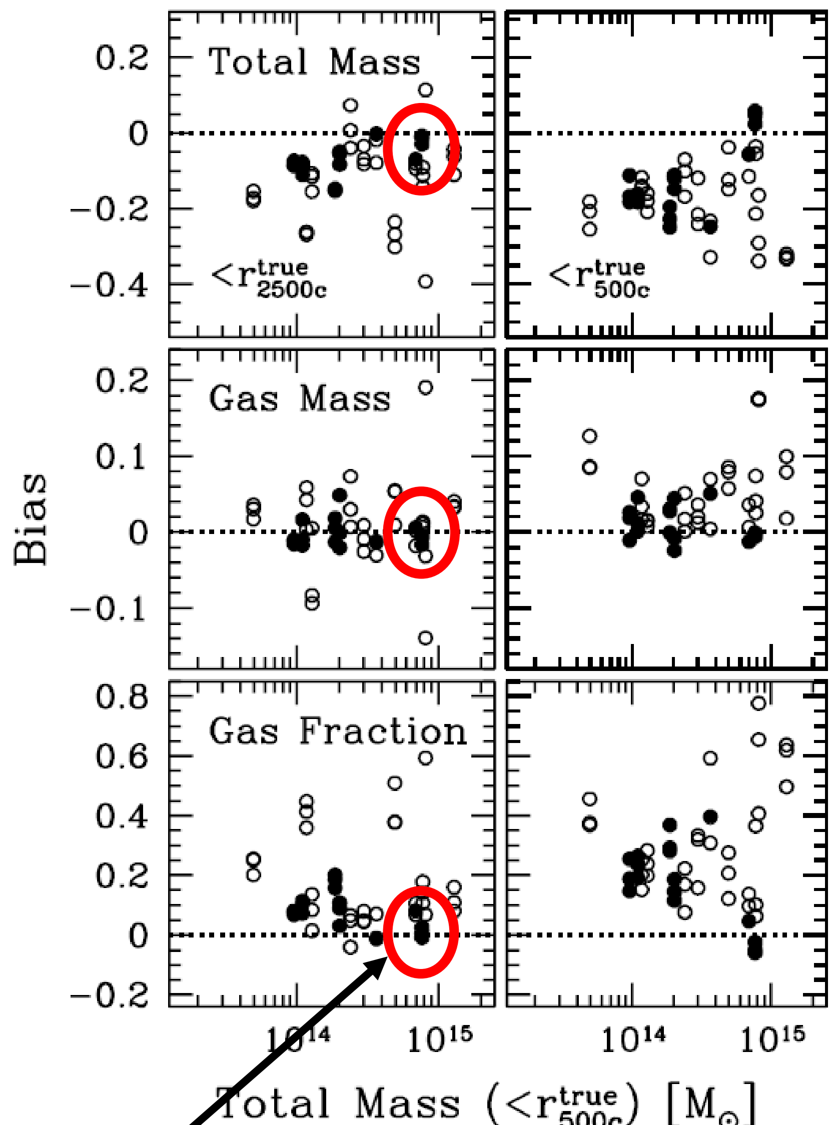
$$I_X \propto \int \rho_{\mathrm{gas}} T^{\frac{1}{2}} \mathrm{e}^{-\frac{h\nu}{kT}} dl \qquad M_{\mathrm{gas}} = 4\pi \int_0^R \rho_{\mathrm{gas}} r^2 dr$$

Total mass profile enters via HSE equation:

$$\frac{\partial}{\partial r} \left(\rho_{\mathrm{gas}} kT\right) \propto -\frac{G M_{\mathrm{total}} \rho_{\mathrm{gas}}}{r^2}$$

Cluster Mass Modelling with X-ray Data

Nagai, Vikhlinin & Kravtsov '07



Relaxed clusters (filled circles)

Select largest, relaxed clusters

(using X-ray morphology)

Measure masses at at r_{2500}

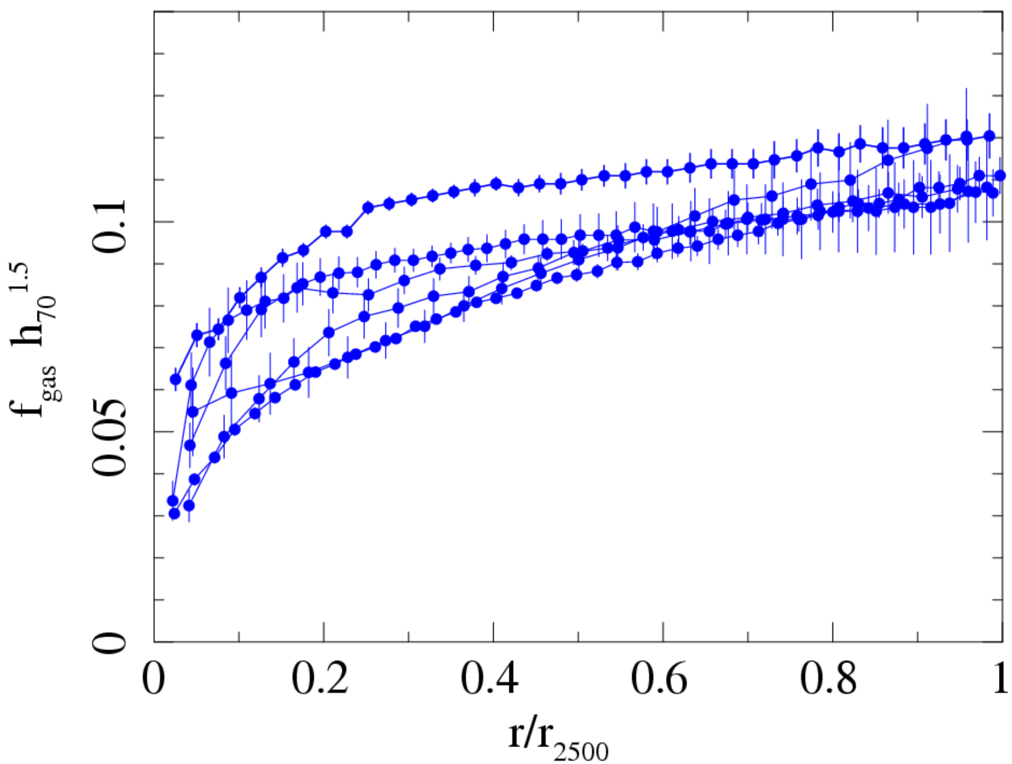
- X-ray gas mass to few % accuracy

- Total mass and fgas to better 10 % accuracy (both bias and scatter).

Primary uncertainty (beyond innermost core) is residual bulk motions in gas - gauge systematics from simulations

Train selection on simulations as well

Low redshift Chandra results



6 lowest redshift relaxed clusters ($0<z<0.15$) :

$f_{gas}(r) \rightarrow$ approximately universal value at r_{2500}

Fit constant value at r_{2500}

$f_{gas}(r_{2500})=(0.113\pm0.003)h_{70}^{-1.5}$

For $\Omega_b\, h^2=0.0214\pm0.0020$ (Kirkman et al. '03), $h=0.72\pm0.08$ (Freedman et al. '01), $b=0.83\pm0.09$ (Eke et al. 98 +10% allowance for systematics)

$$\Omega_m = \frac{(۰.۸۳\pm۰.۰۹)(۰.۰۴۳۷\pm۰.۰۰۴۱)h_{۷۰}^{-۰.۵}}{(۰.۱۱۳\pm۰.۰۰۳)(۱+[۰.۱۶\pm۰.۰۵]h_{۷۰}^{۰.۵})} = ۰.۲۷\pm۰.۰۴$$

Cluster Mass Modelling with X-ray Data

These integrals are over the physical size of the cluster - but we observe its angular size

Standard buckets implies standard rods -
clusters can be used to measure distances

$$I_X \propto \int \rho_{\rm gas} T^{\frac{1}{2}} e^{-\frac{h\nu}{kT}} dl$$

$$M_{\rm gas} = 4\pi \int_0^R \rho_{\rm gas} r^2 dr$$

$$\frac{\partial}{\partial r}(\rho_{\rm gas} kT) \propto -\frac{G M_{\rm total} \rho_{\rm gas}}{r^2}$$

$$dl, dr = D d\theta$$

-1

$$\rho_{\rm gas} \sim D^{-\frac{1}{2}}$$

$$M_{\rm gas} \sim \rho_{\rm gas} D^3 \sim D^{\frac{5}{2}}$$

$$M_{\rm total} \sim D$$

$$f_{\rm gas} \sim D^{\frac{3}{2}}$$

Parameterizing the Systematic Errors

1) The depletion factor (simulation physics, gas clumping etc.)

$b(z)=b_0(1+\alpha_b z)$ $\pm$20% uniform prior on b_0 (simulation physics)
$\pm$10% uniform prior on α_b (simulation physics)

2) Baryonic mass in stars: define s= f_{star}/f_{gas} $=0.16h_{70}^{0.5}$

$s(z)=s_0(1+\alpha_s z)$ 30% Gaussian uncertainty in s_0 (observational uncertainty)
$\pm$20% uniform prior on α_s (observational uncertainty)

3) Non-thermal pressure support in gas: (primarily bulk motions)

$\gamma= M_{true}/M_{X\text{-}ray}$ 20% weak uniform prior $[1<\gamma<1.2]$

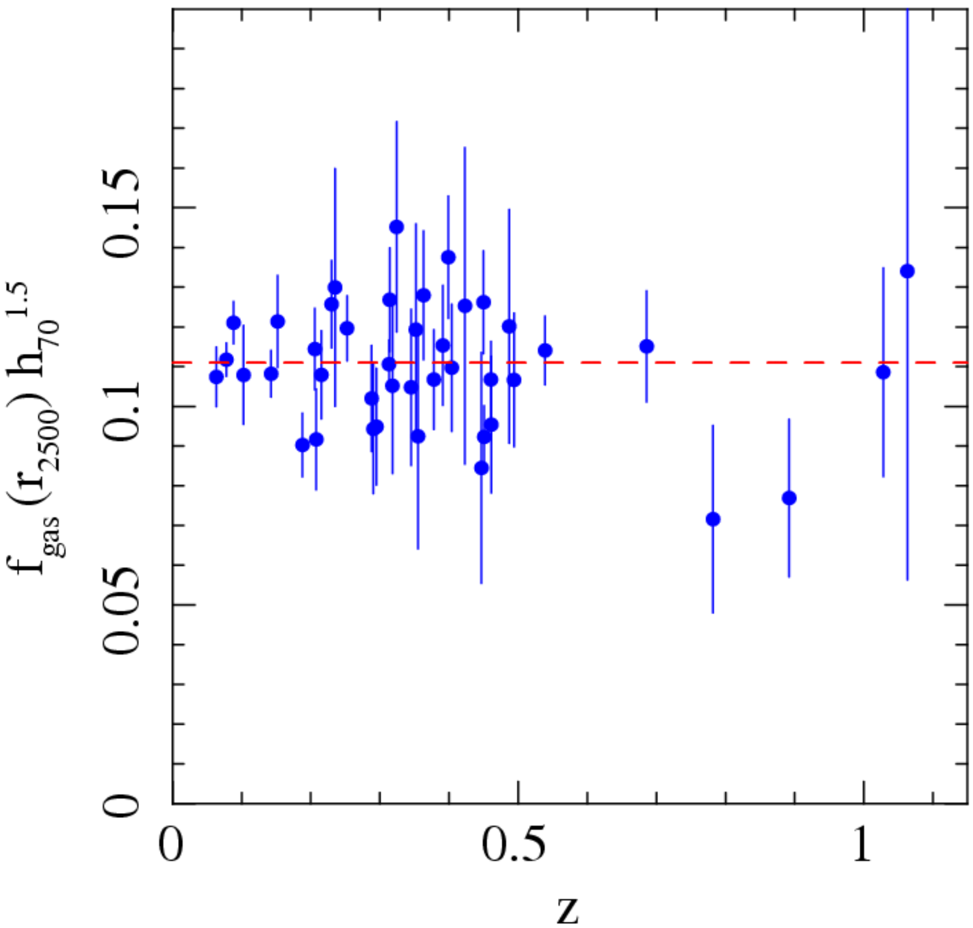
4) Instrument calibration, X-ray modelling

K 10% Gaussian uncertainty

Note approach:
Turn syst into stat errors
via nuisance parameters

Ask for plots!

Results (w = -1):



42 relaxed Chandra clusters, fit fgas data with distance-dependent model

Including priors:

$\Omega_b h^2 = 0.0214 \pm 0.0020$ (BBN)
$h = 0.72 \pm 0.08$ (HST)

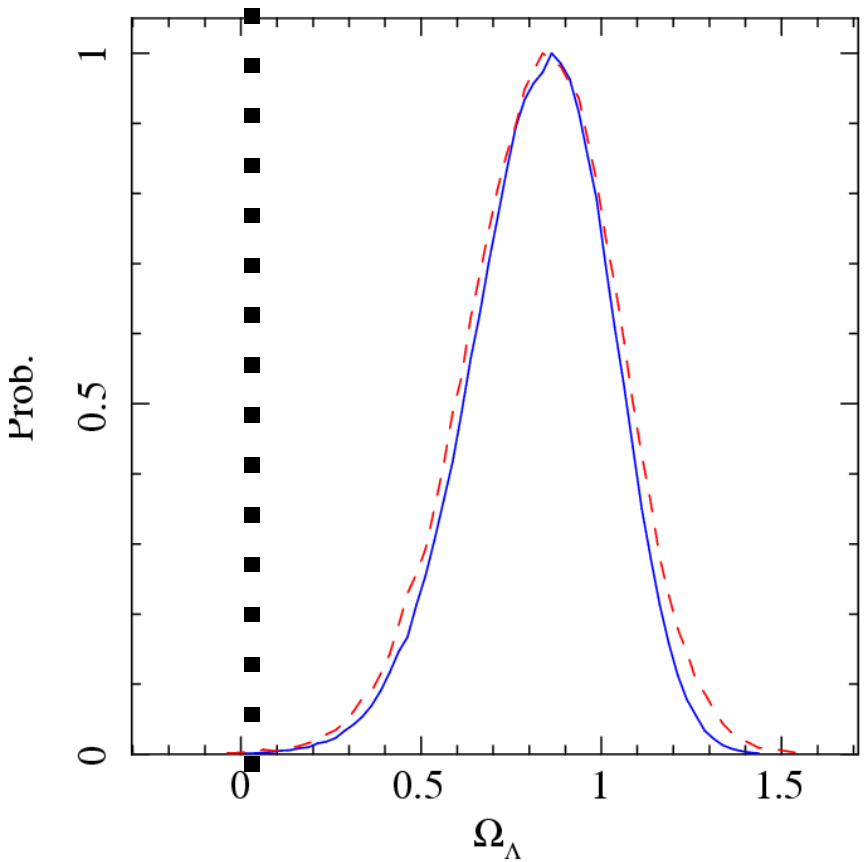
Best-fit parameters (ΛCDM):

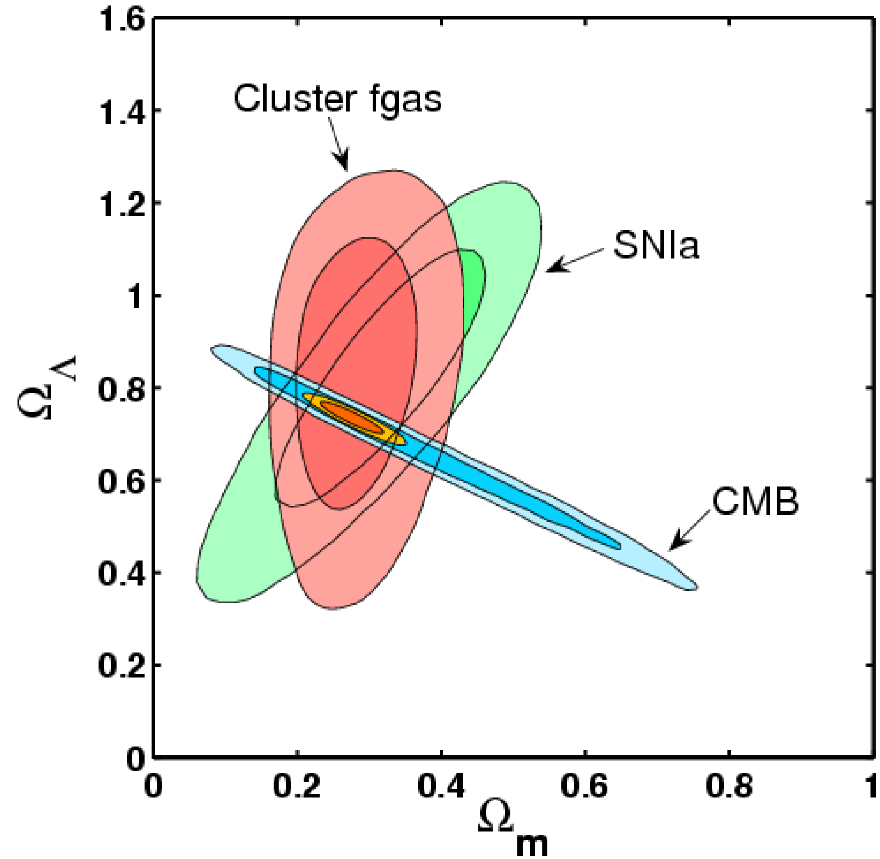
$\Omega_m = 0.27 \pm 0.06$, $\Omega_\Lambda = 0.86 \pm 0.19$

Good fit: chi-squared = 41.5/40

No scatter! Upper limit: 5%

Results (w = -1):



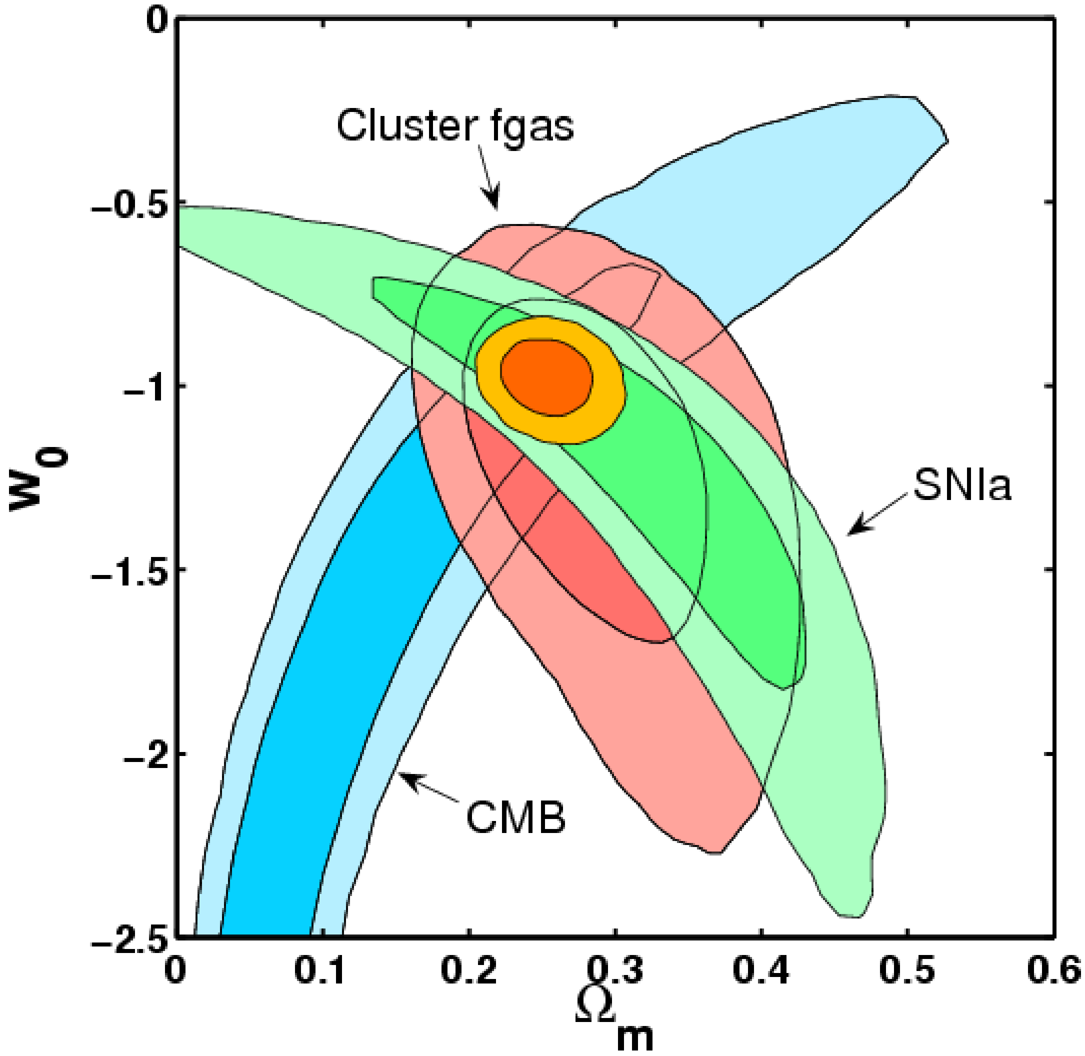


Independent confirmation of accelerating expansion

Comparable precision to SNe combined sample

Allen et al 2008

Results (flat universe):



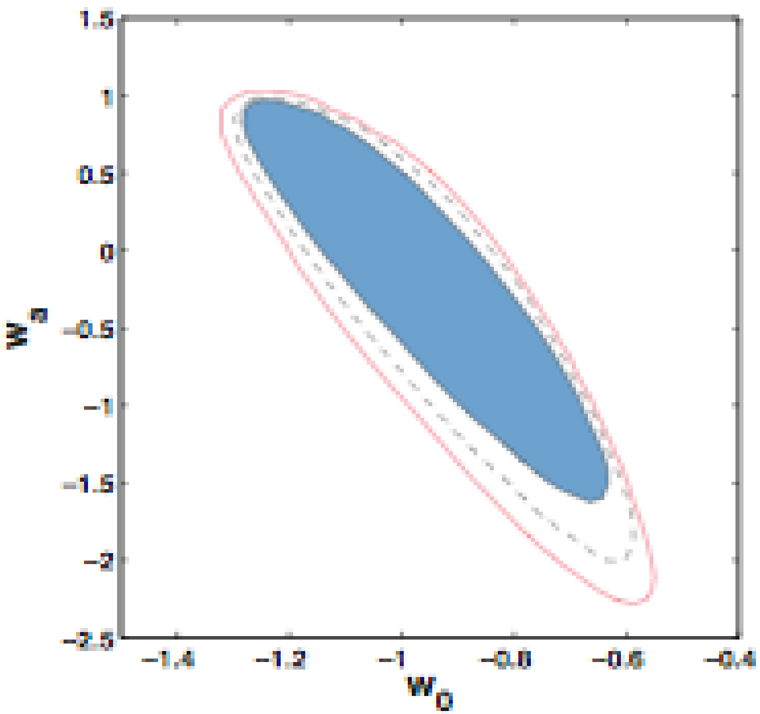
Combination with CMB removes need for
H and baryon density priors

Allen et al 2008

Future prospects

Future cluster surveys (Friday) will make samples of a few hundred relaxed clusters possible – follow-up will require a high throughput observatory: IXO?

Planned for launch in 2021: http://ixo.gsfc.nasa.gov/



500 clusters, 5% distance accuracy (as with Chandra)

Same systematic allowances

DETF Figure of Merit ~ 20

Competitive with JDEM SNe
- but when will it happen?

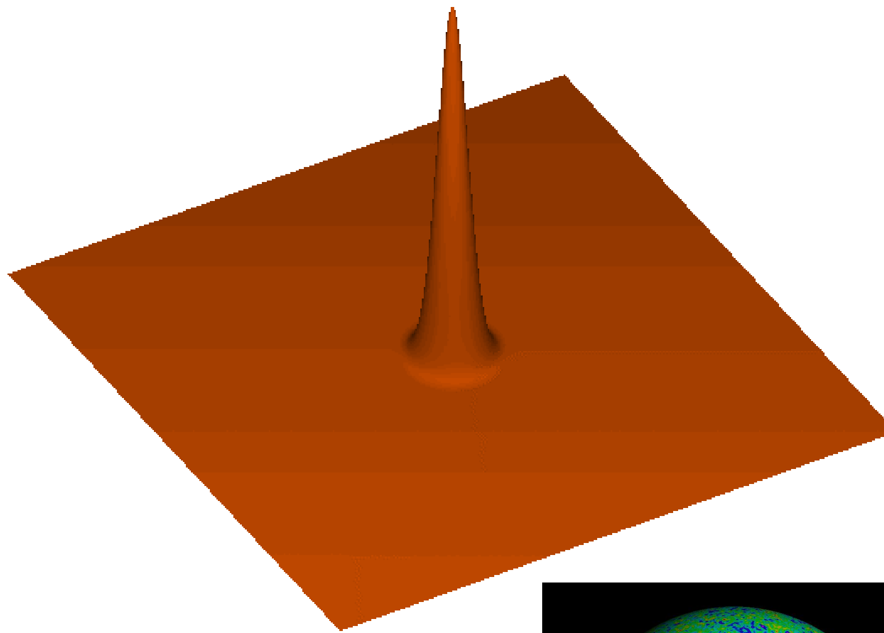
Rapetti et al 2008

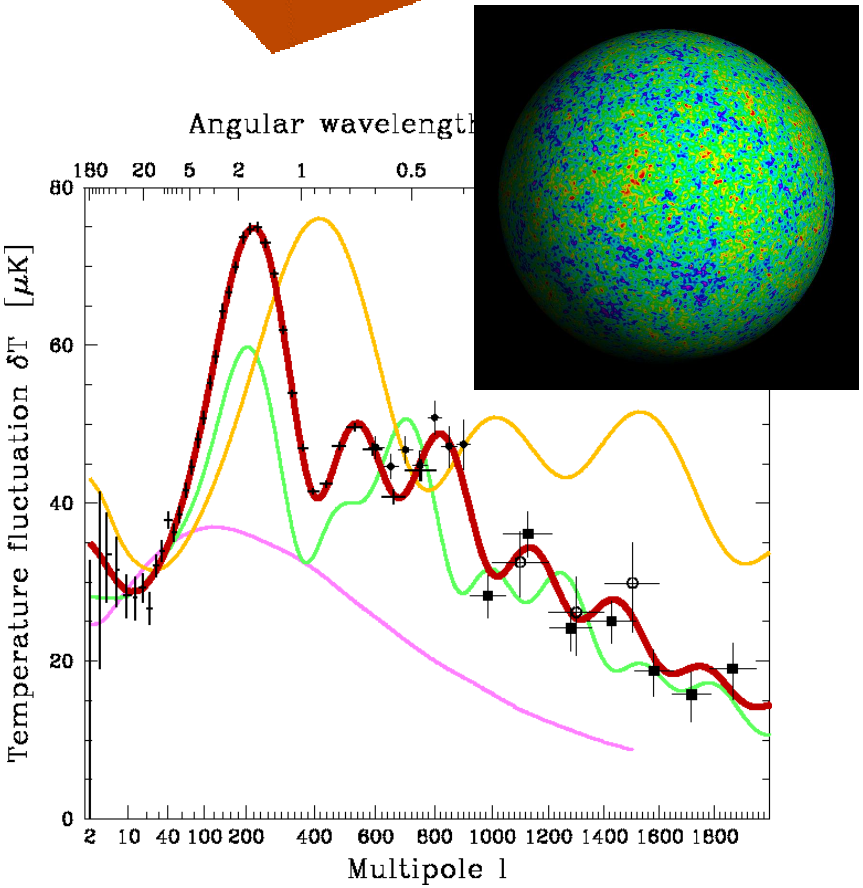
Part 4: Baryon Acoustic Oscillations (BAO)

CMB: sound waves

- Each initial overdensity (in dark matter & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at the sound speed c_s - 57% of the speed of light.
- Pressure-providing photons decouple at recombination - CMB radiation travels to us from these spheres.
- There is a maximum distance travellable by each wave, corresponding to the sound horizon at recombination:

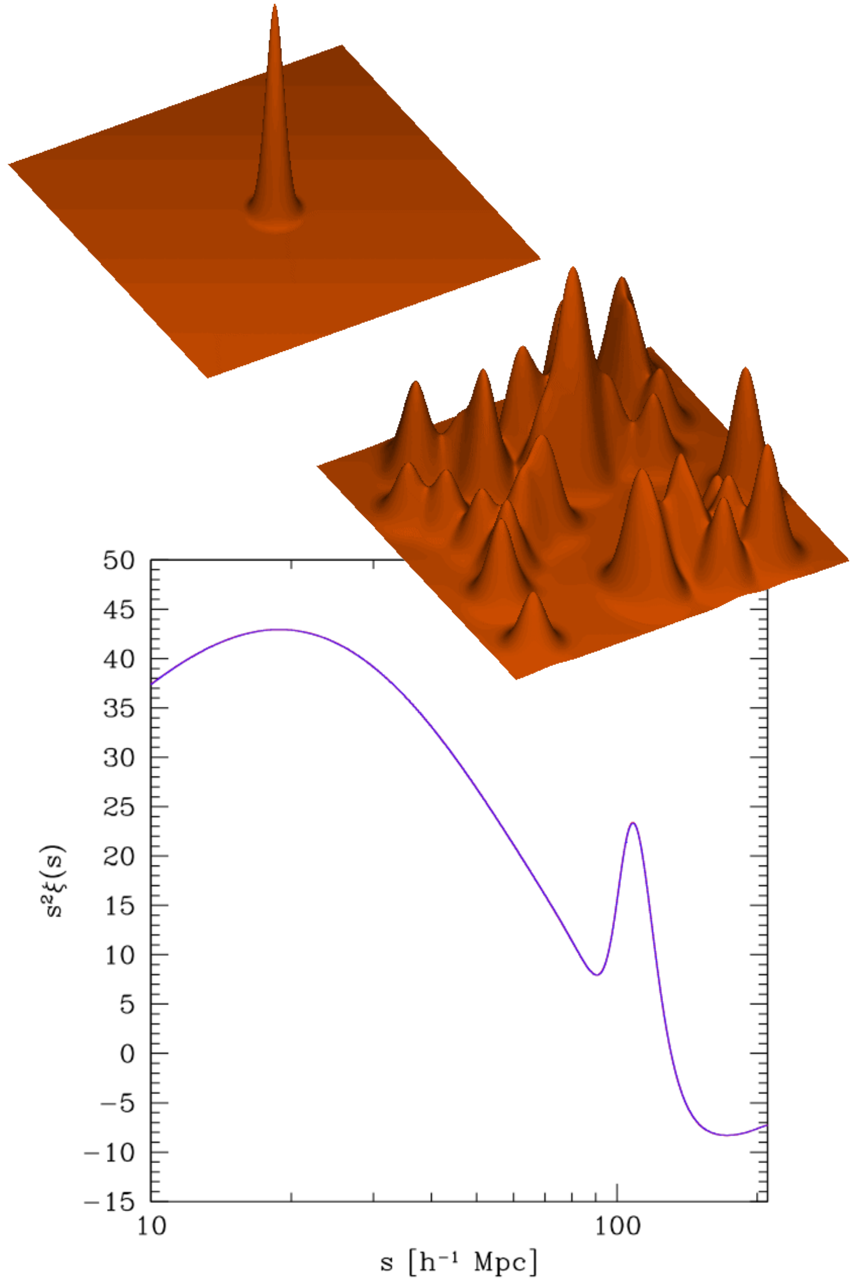
  ~ 150Mpc

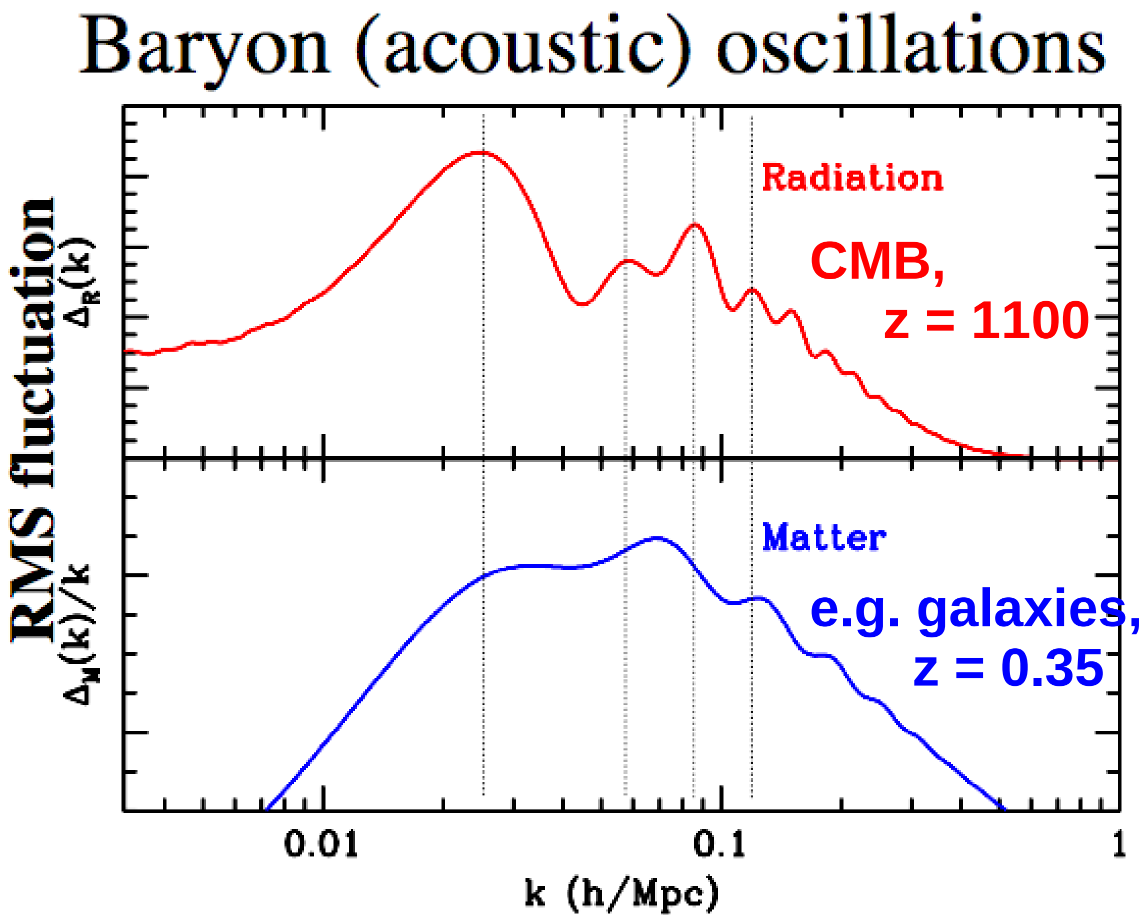




What happens after recombination?

- Pressure-providing photons decouple at recombination - CMB radiation travels to us from these spheres.
- After decoupling, the sound speed plummets, and the wave stalls at a radius of ~150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred galaxy separation of 150 Mpc
- Superposition of shells leads to statistical signal – bump in the galaxy correlation function at separation ~150 Mpc



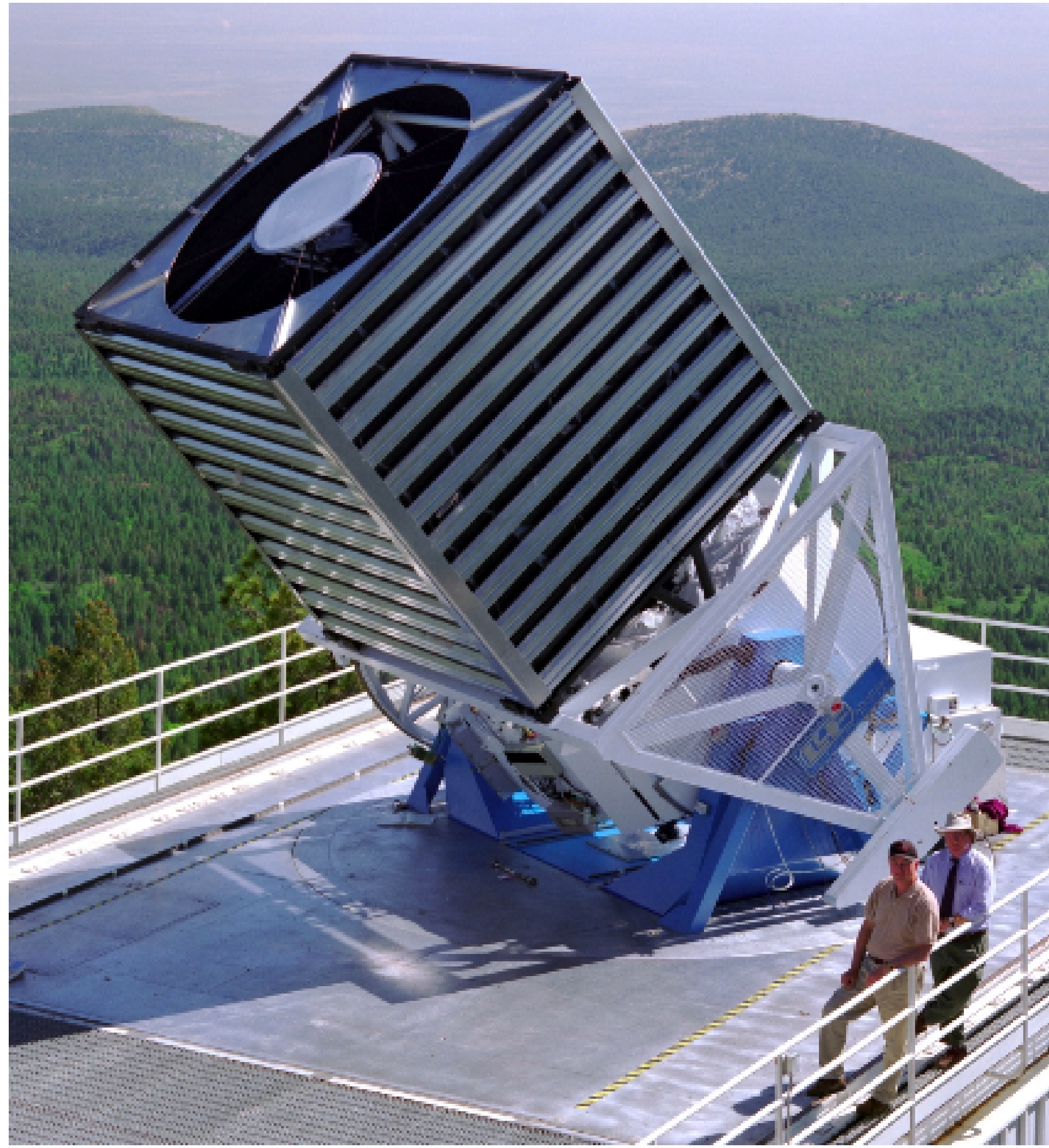


Spike in galaxy correlation function corresponds to acoustic series in matter power spectrum

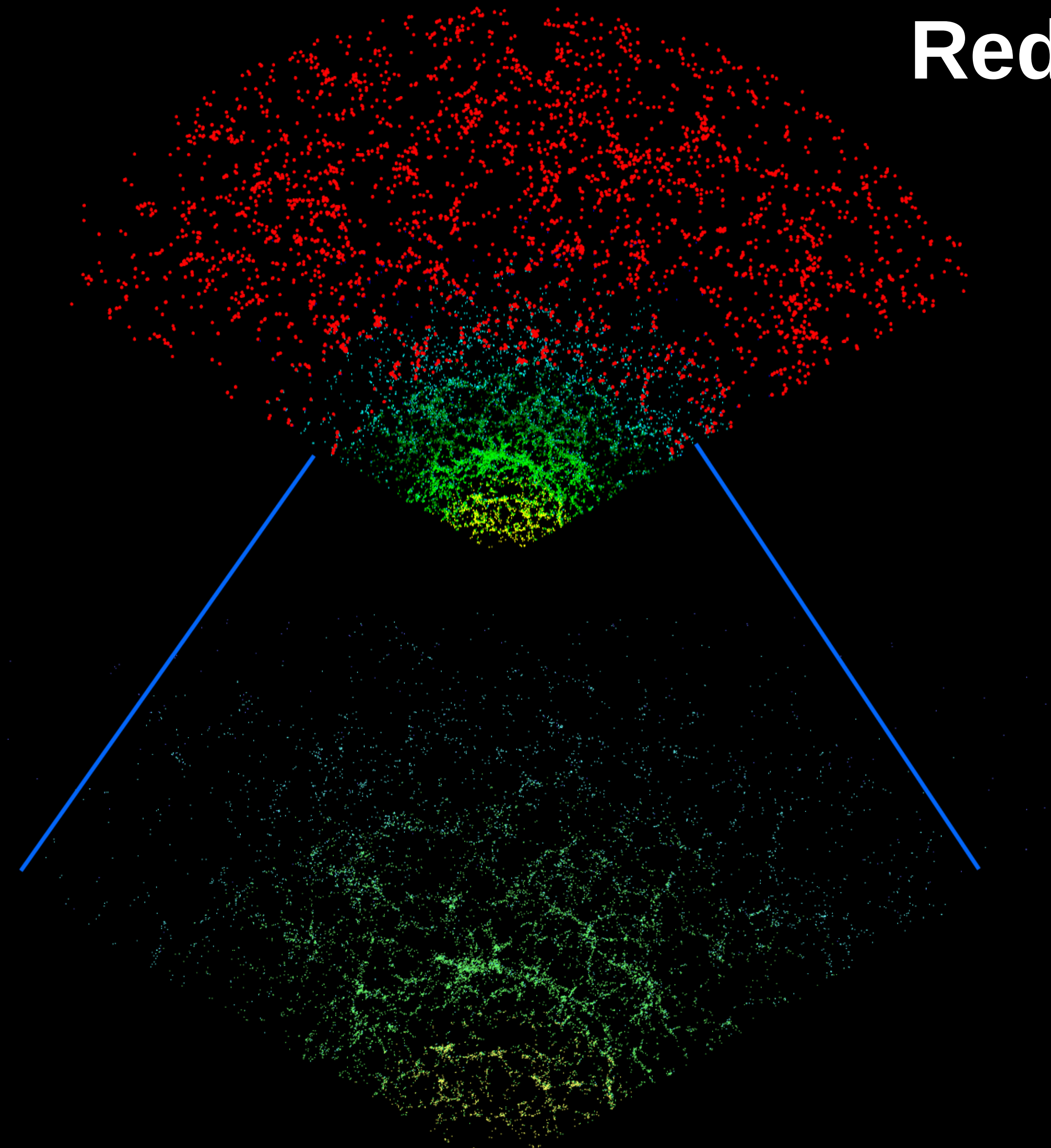
Know where to look in correlation function – just need a galaxy redshift survey big enough to measure many 150Mpc separations

Sloan Digital Sky Survey (SDSS)

- Largest survey to date in area + volume
- 10,000 deg^2 imaging in 5 filters (ugriz-bands) from drift-scanning
- Follow-up spectroscopy of selected objects
- Automated spectroscopic analysis pipeline, redshifts from PCA template fitting



SDSS Luminous Red Galaxies



40,000 galaxies
0.15 < z < 0.4
~1 Gpc radius

Main sample
800,000 galaxies
z < 0.15
< 500 Mpc radius

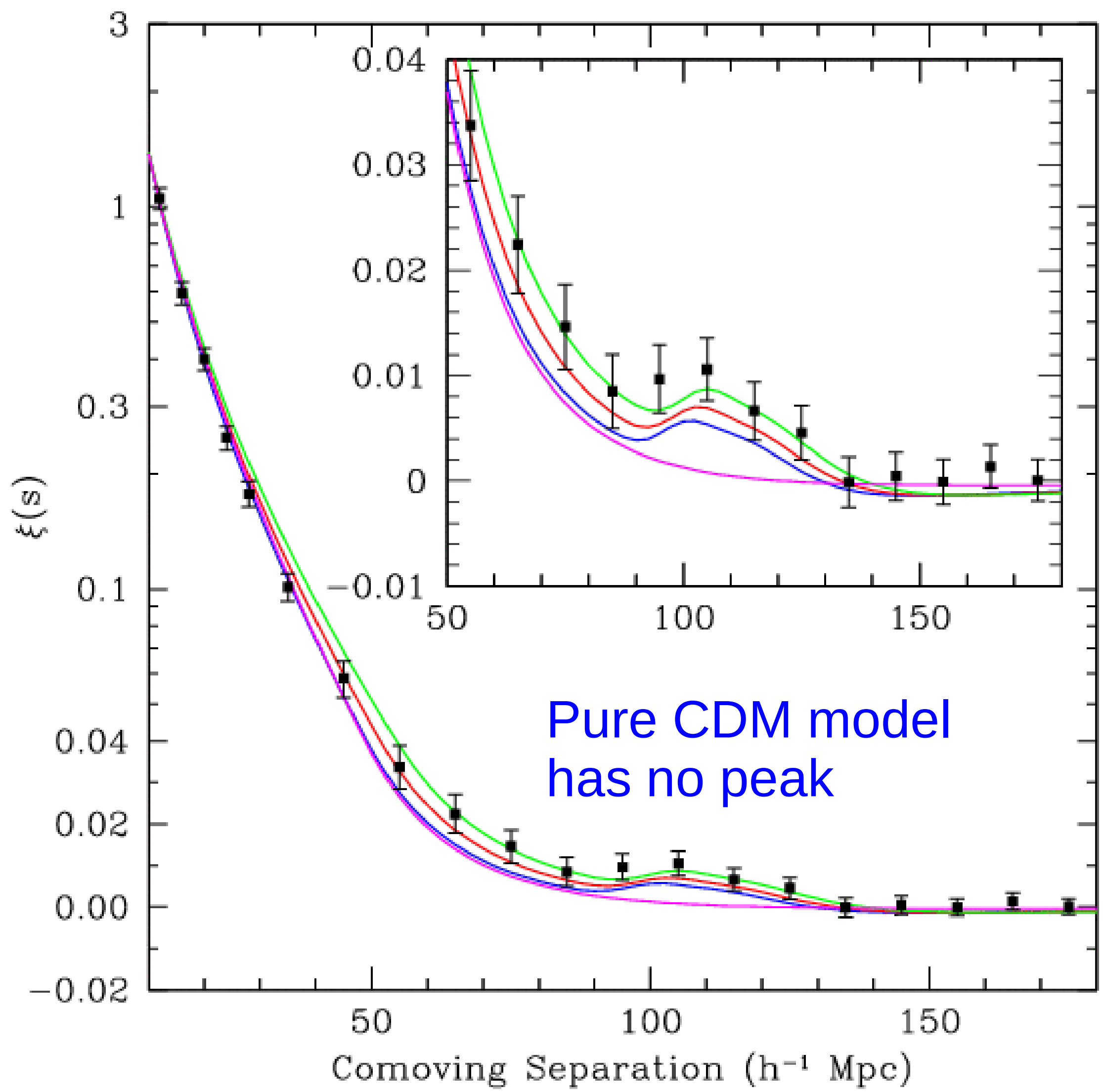
Large-scale Correlations of SDSS Luminous Red Galaxies

Redshift-space correlation function:

$$\xi(r) = \langle n(\mathbf{x}) n(\mathbf{x}+\mathbf{r}) \rangle$$

Error bars are correlated...

3.5 sigma detection, fixing baryon density and initial spectrum, and fitting for matter density in a flat universe (different colour curves)



Eisenstein, et al 2005

The BAO+CMB Standard Ruler

The physical sound horizon at last scattering is itself constrained to 2% by the CMB data (high-l peaks), making the position of the BAO feature a very good standard ruler

Since the acoustic waves were spherical,
the ruler can be used in 3D:

- In projection, the 2D correlation function allows us to measure the angular diameter distance as a function of z
- Correlation in redshift would allow us to probe H(z) directly

In practice, the reconstructed (in slices) 3-D power spectrum (from slices) is approximately sensitive to the geometric distance measure:

$$D_V = \left[\frac{(1+z)^2 D_A^2(z) cz}{H(z)}\right]^{\frac{1}{3}} \qquad \theta_{\rm BAO} = \frac{s}{D_V}$$

see Gaztanaga et al 2008 for a first attempt at H(z)

The BAO+CMB Standard Ruler

Principle limitation is the need for enormous galaxy surveys to high redshift – astrophysical systematic effects are thought to be smaller than other DE techniques

Although it is the youngest method...

Sources of systematic error:

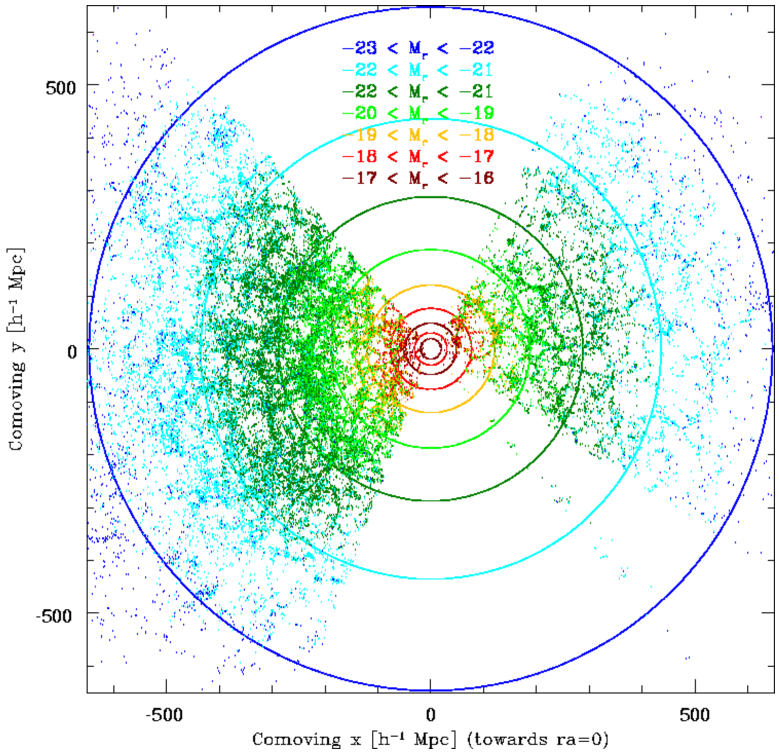
- Non-linear theory – have to predict the position of the BAO feature to better than it can be measured

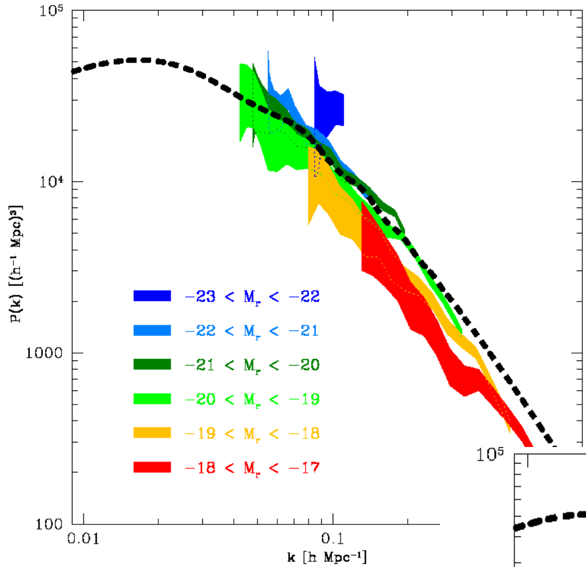
- Redshift space distortions – motions of galaxies can smear and possibly shift the BAO feature

- Galaxy "Bias" - galaxies are not perfect tracers of large scale structure: they cluster differently according to luminosity, type, colour etc. Bias may vary with scale – but on 150 Mpc scales?

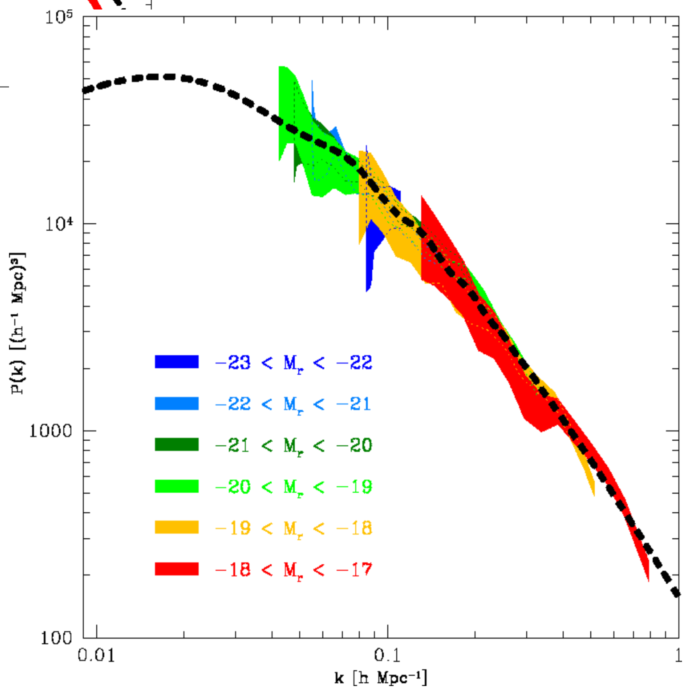
$$P(k,\text{galaxies}) = b^2\, P(k,\text{matter})$$

Galaxy Clustering with Luminosity





SDSS main galaxies, use bins in luminosity to measure power spectrum



Clustering amplitude can be explained with a simple scale-independent bias factor (that increases with luminosity): b = b(L)

Implies no effect on BAO feature – just use whichever galaxies you see, and marginalise out bias

Tegmark et al 2004

Non-linearities and distortions

• Structure growth is not very non-linear on 150Mpc scales – perturbation theory useful! Beware fitting functions for oscillations in P(k) – they can introduce *bogus ruler lengths*

• Motions of galaxies can be simulated quite accurately to account for peculiar velocities and un-smear BAO peaks

• There may also be information in the data to reconstruct the density field from the velocities – this was tried on cluster scales (few Mpc) in the past and abandoned, but life is much easier on 150Mpc scales

We should be optimistic about how clean BAO is – systematics above are predicted to be ~1% level effects

Key is that 150 Mpc is BIG!

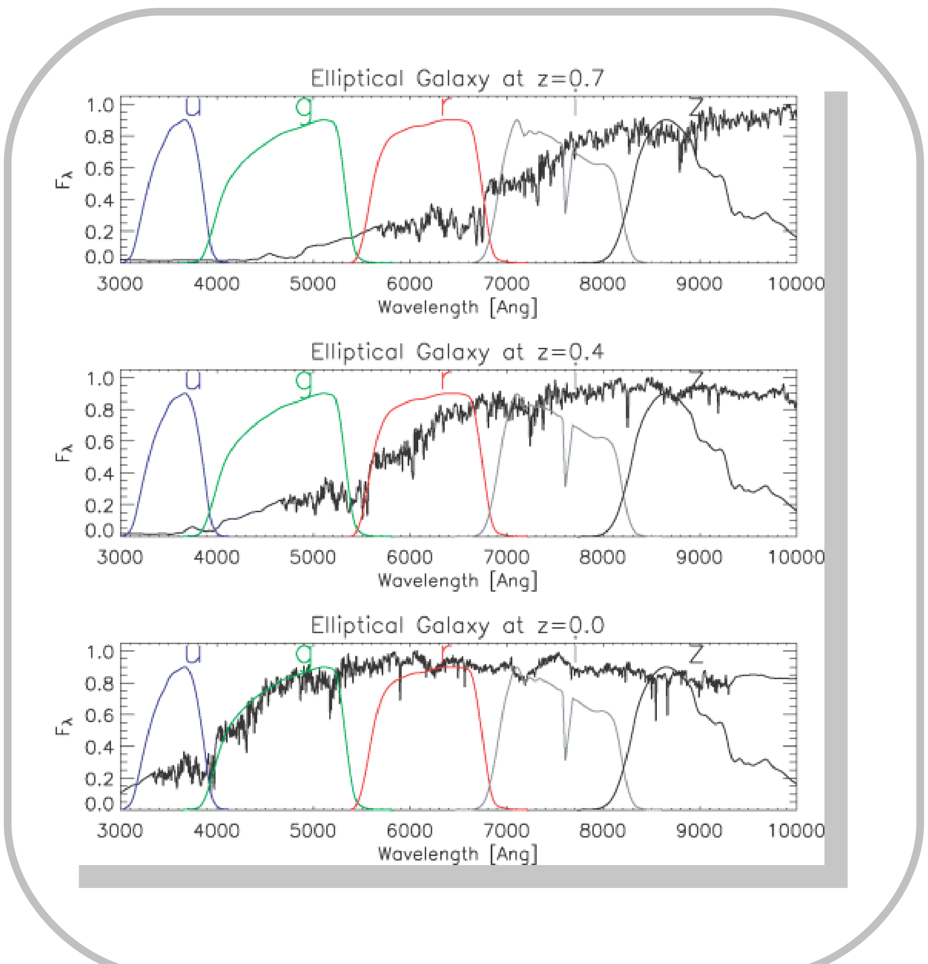
Watch out for end-to-end simulations of BAO signal in mock surveys though...

Photo-z surveys

- Spectroscopy is expensive, imaging is cheap
- Can we measure BAO with photometric redshifts?

Photometric redshifts

• Fit broadband photometry - fluxes in several bands – with galaxy spectra: **breaks** provide information, ellipticals easier
• Marginalise out spectral type – non-trivial! Priors on template types? Linear combinations? Neural networks? Empirical calibration to spectroscopic samples vital...



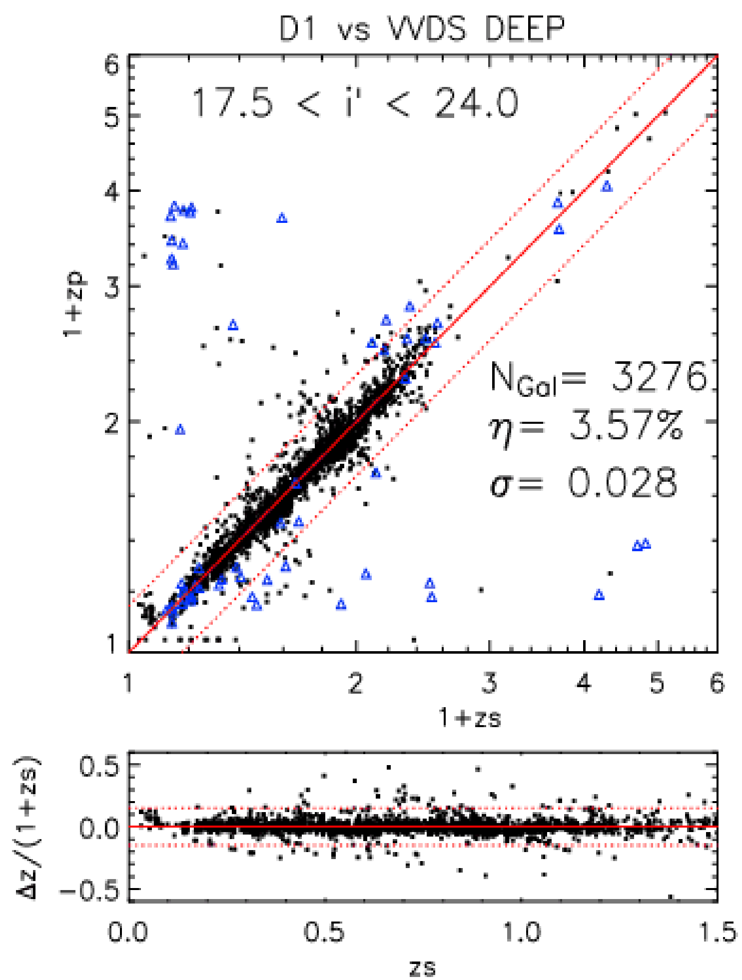
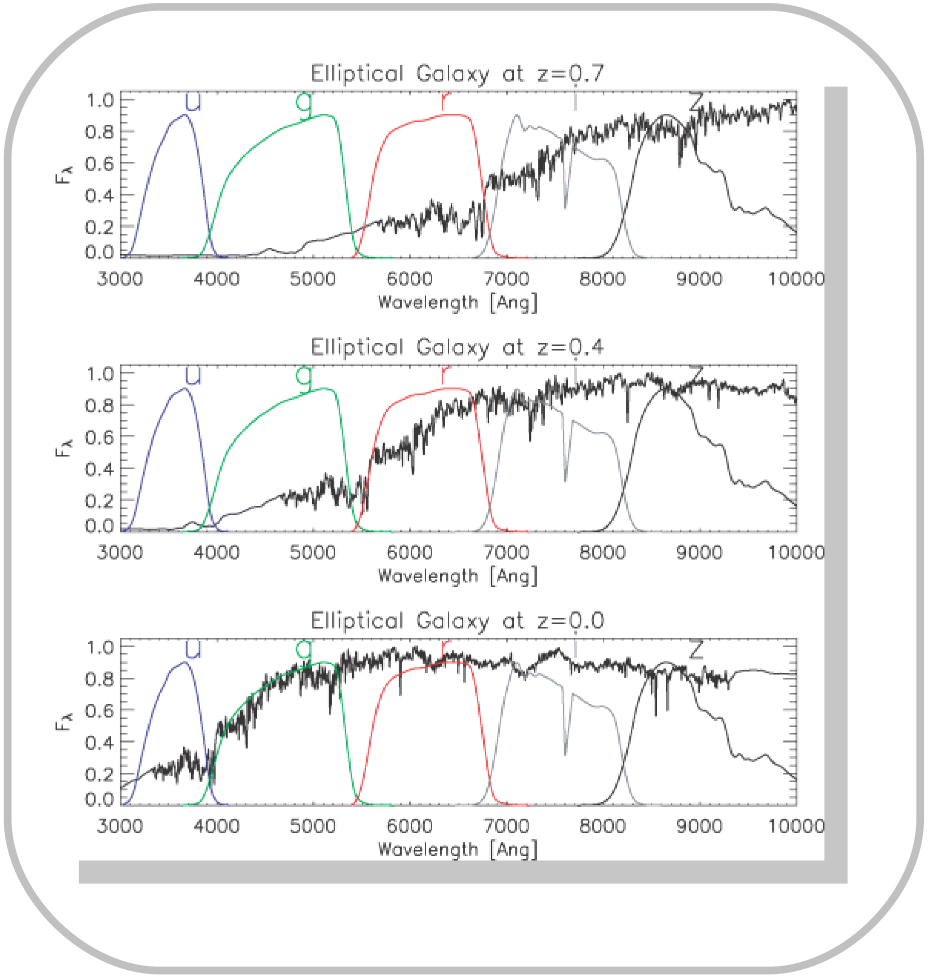


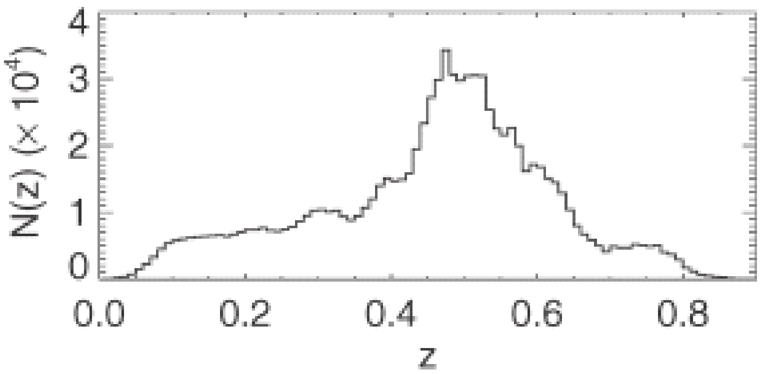
Photo-z surveys: SDSS

- Spectroscopy is expensive, imaging is cheap
- Can we measure BAO with photometric redshifts?
- Need:

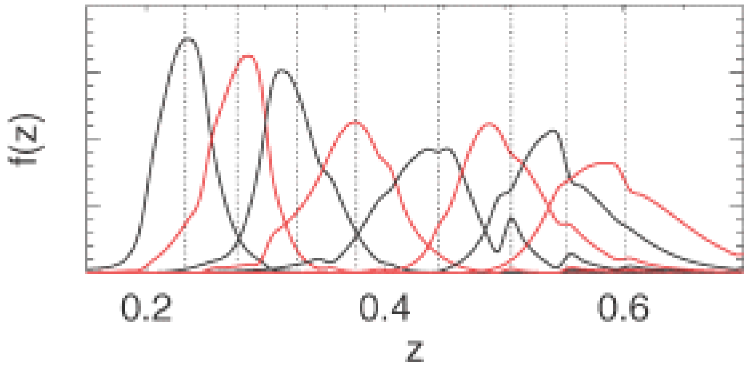
  Large number of tracers eg 600,000 SDSS photo LRGs

  High photo-z accuracy eg SDSS photo **LRGs, dz~0.03**





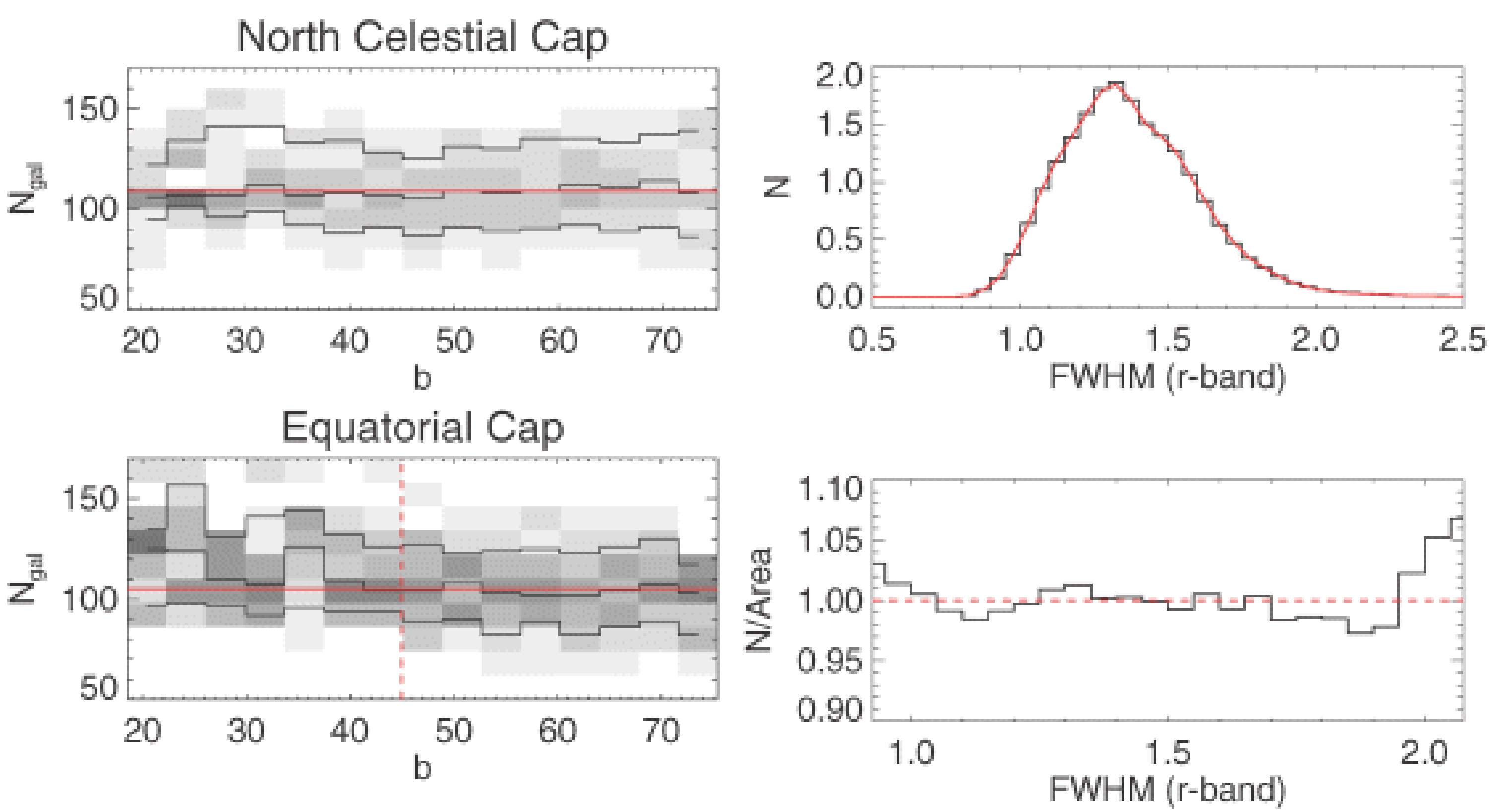
Broad bins in z



Padmanabhan et al 2007

BAO with photo-zs: systematics

- Measuring power spectrum/correlation function on very large scales puts new constraints on photometric calibration
- Accurate relative photometry relies on overlap regions between fields, and repeated observations of standard star network with same system (single telescope/camera)



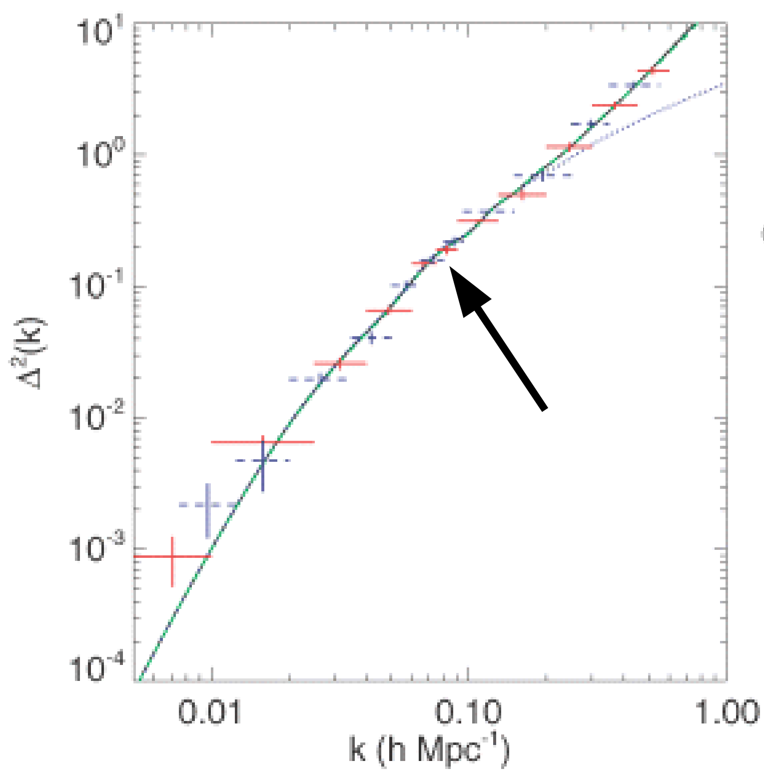
~Uniform density of galaxies, <1% stellar contamination after latitude cut – no obvious systematic

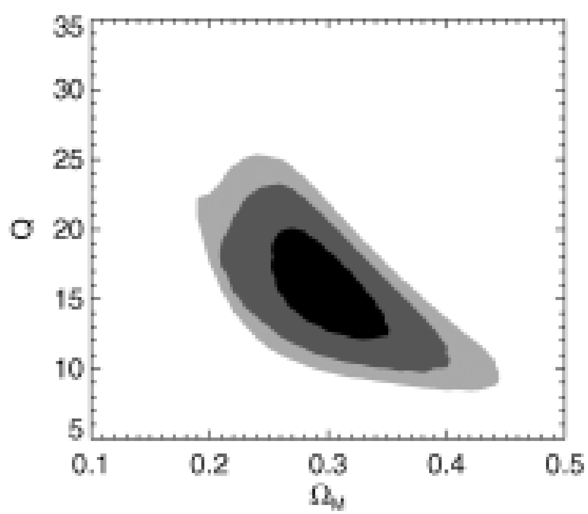
No effect of image resolution (seeing) on galaxy density

Padmanabhan et al 2007

BAO with photo-zs

- **2.5 sigma detection** of baryons in SDSS power spectrum (Padmanabhan et al 2007) – cf 3.5 sigma detection in spectroscopic LRGs (Eisenstein et al 2005)
- Larger volume, denser coverage, vs redshift accuracy
- **Proof of concept** – shows what needs to be done in even larger surveys





$$\frac{\Delta^2(k)}{\Delta^2_{lin}(k)} = b^2 \frac{1 + Qk^2}{1 + Ak},$$

Bias again - small correction for scale-dependence marginalised over,

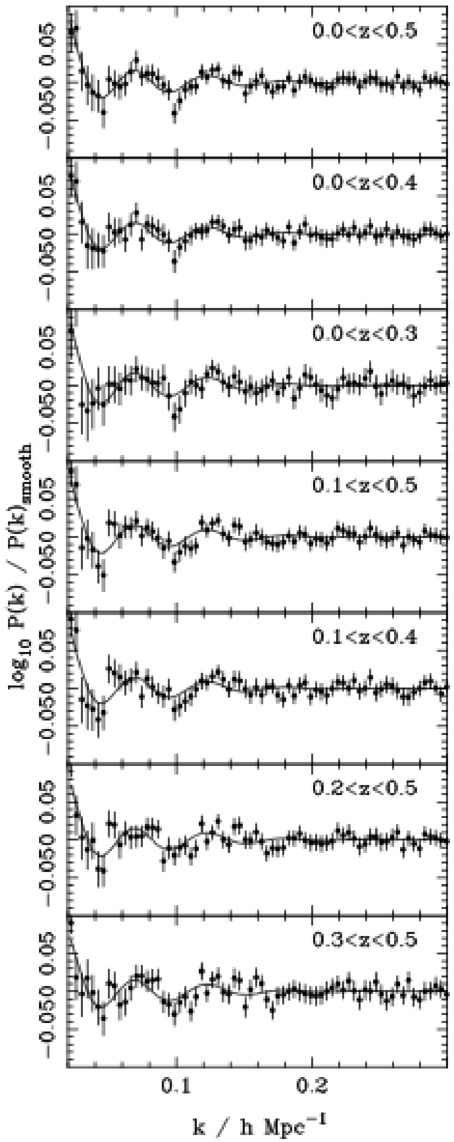
Weak functional form comes from simulations, and is needed for high k end not BAO

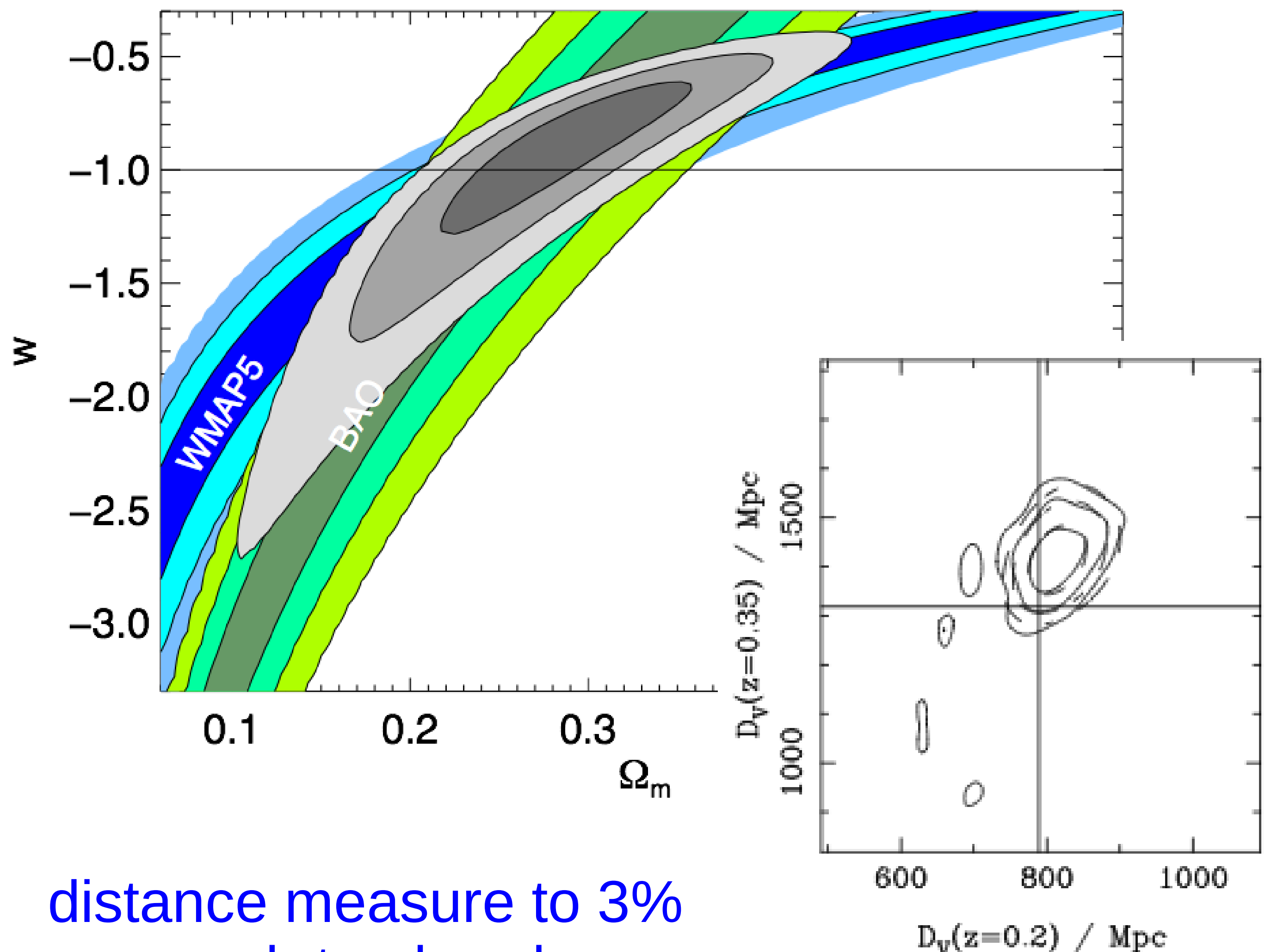
Q = 15, k ~ 0.1
15% effect – marginalised out. Remaining systematic is in residuals...

Padmanabhan et al 2007

Current constraints

Combined SDSS (DR7) and 2DF spectroscopic samples:

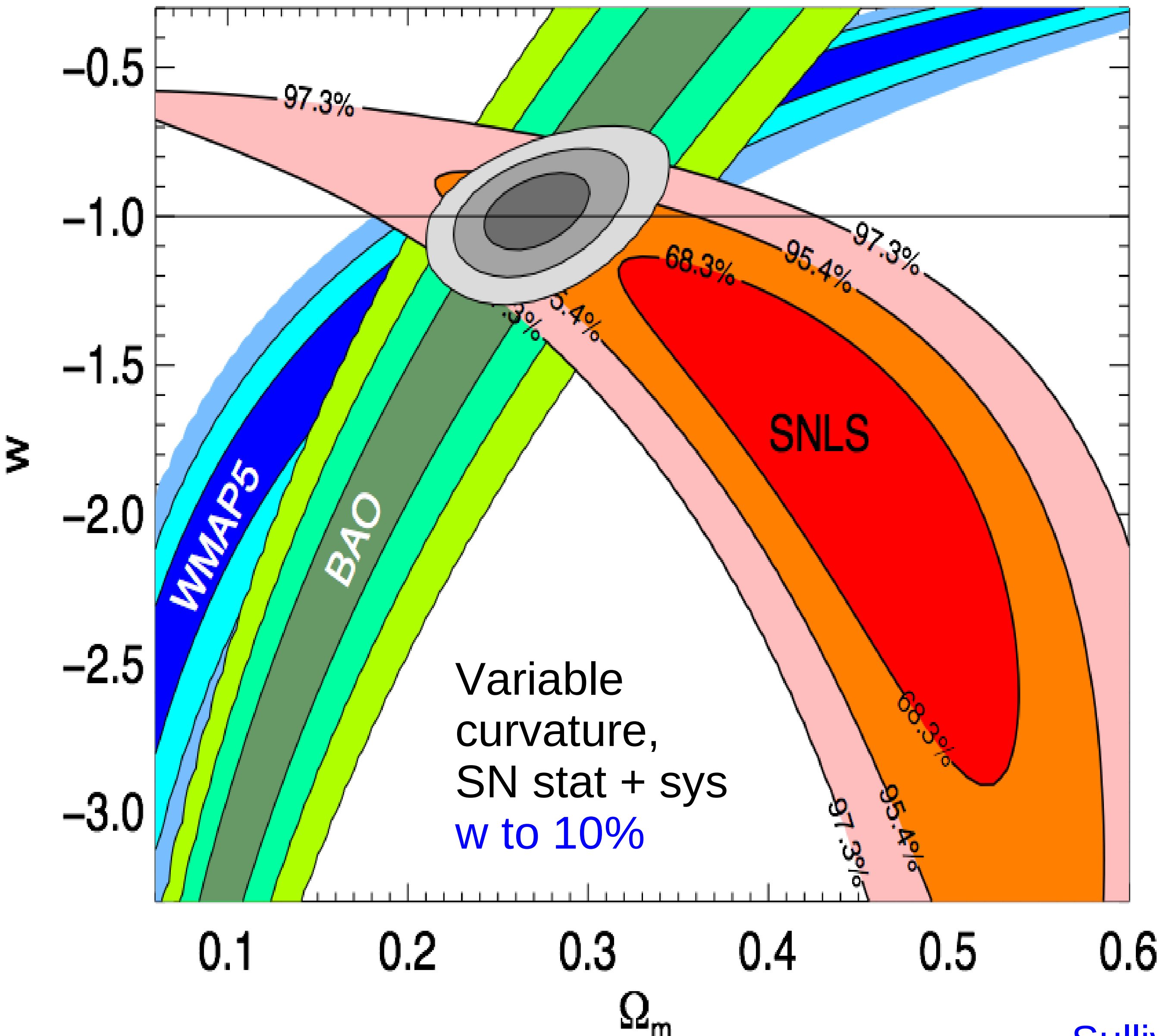




distance measure to 3%
 - enough to abandon
flatness assumption!

Percival et al 2009
Sullivan, Conley et al in prep

Kinematic Probes - 2009



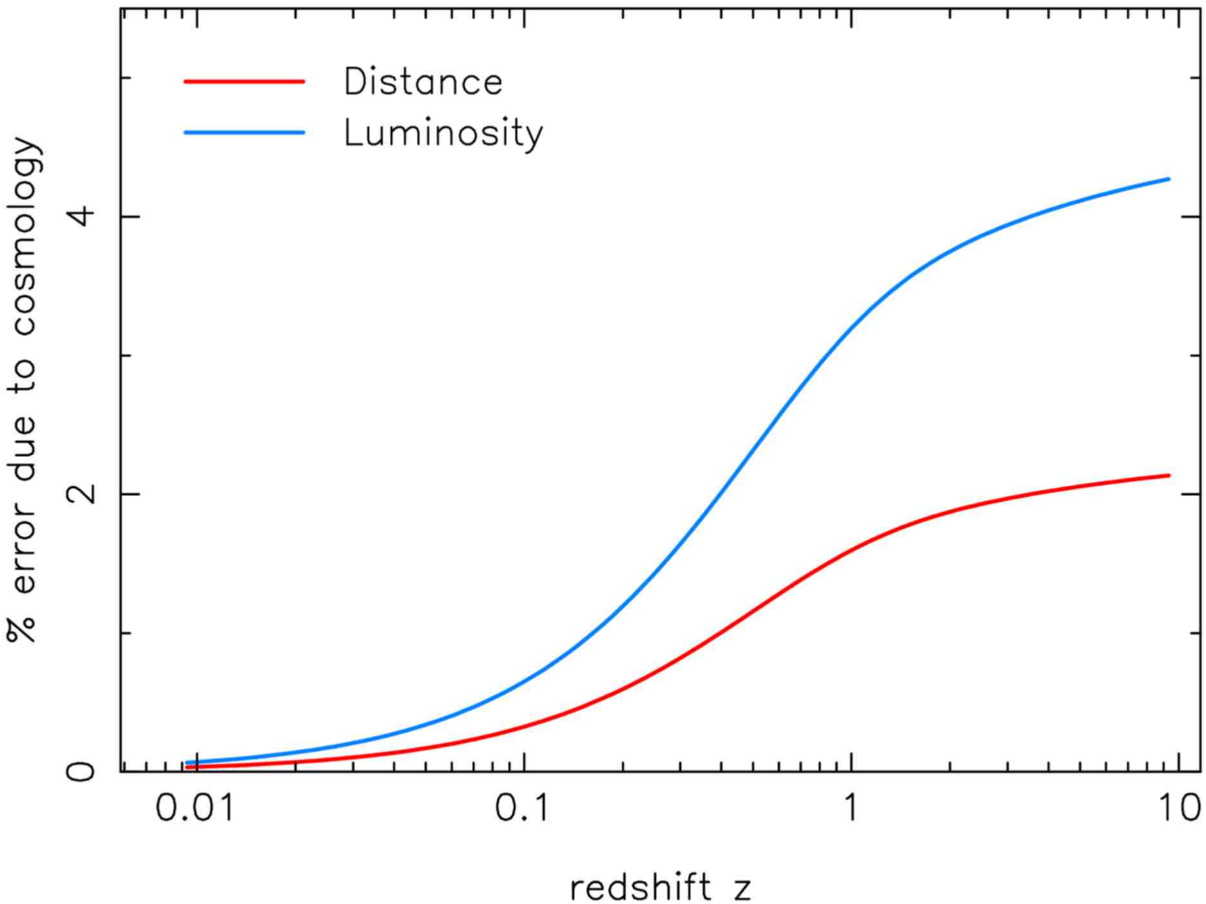
Distance data favour {0.3,0.7} LCDM (w = -1 to 10%)

We are now **very good** at measuring extragalactic distances!

Sullivan, Conley et al in prep

Kinematic Probes - 2009

We are now ***very good*** at measuring extragalactic distances: WMAP5+BAO+SNall samples, compute luminosity distance to redshift z for each one, take standard deviation to get error(z):



Other uncertainties (photometric calibration, K-corrections, extinction etc) likely to outweigh this

Dark energy is already well enough measured for accurate extragalactic astronomy!

Kinematic Probes - 2009

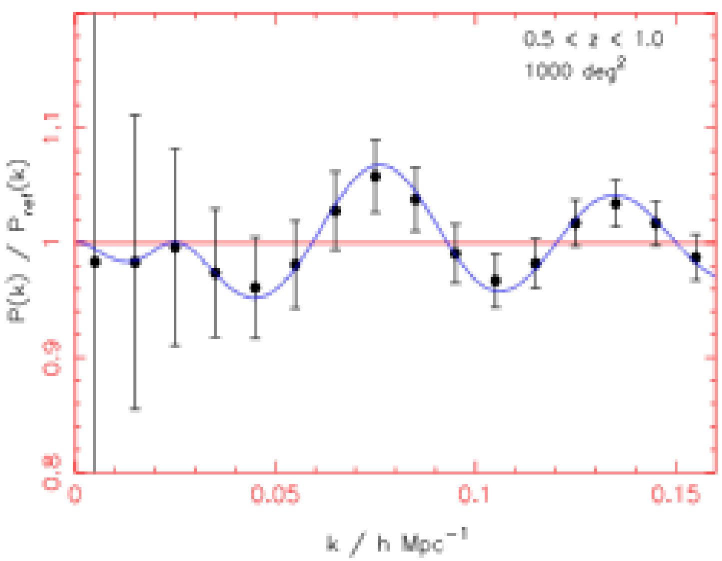
parameter	ΛCDM	oΛCDM	wCDM	owCDM	owCDM+SN	owCDM+H_0	owCDM+SN+H_0
Ω_m	0.278 ± 0.018	0.283 ± 0.019	0.283 ± 0.026	$0.240^{+0.044}_{-0.043}$	0.290 ± 0.019	$0.240^{+0.025}_{-0.024}$	0.279 ± 0.016
H_0	70.1 ± 1.5	$68.3^{+2.2}_{-2.1}$	69.3 ± 3.9	75.3 ± 7.1	67.6 ± 2.2	74.8 ± 3.6	69.5 ± 2.0
Ω_k	-	$-0.007^{+0.006}_{-0.007}$	-	-0.013 ± 0.007	-0.006 ± 0.008	-0.014 ± 0.007	-0.003 ± 0.007
w	-	-	-0.97 ± 0.17	$-1.53^{+0.51}_{-0.50}$	-0.97 ± 0.10	$-1.49^{+0.32}_{-0.31}$	-1.00 ± 0.10
Ω_Λ	0.722 ± 0.018	0.724 ± 0.019	0.717 ± 0.026	0.772 ± 0.048	0.716 ± 0.019	0.773 ± 0.029	0.724 ± 0.018
$100\Omega_b h^2$	2.267 ± 0.058	2.269 ± 0.060	2.275 ± 0.061	$2.254^{+0.062}_{-0.061}$	2.271 ± 0.061	$2.254^{+0.061}_{-0.062}$	2.284 ± 0.061
τ	0.086 ± 0.016	0.089 ± 0.017	0.087 ± 0.017	0.088 ± 0.017	0.089 ± 0.017	0.088 ± 0.017	$0.089^{+0.017}_{-0.018}$
n_s	0.961 ± 0.013	0.963 ± 0.014	0.963 ± 0.015	0.958 ± 0.014	0.963 ± 0.014	0.957 ± 0.014	0.964 ± 0.014
$\ln(10^{10} A_{05})$	$3.074^{+0.040}_{-0.039}$	3.060 ± 0.042	3.070 ± 0.041	$3.062^{+0.042}_{-0.043}$	$3.062^{+0.041}_{-0.042}$	3.062 ± 0.042	3.072 ± 0.042
$d_{0.275}$	0.1411 ± 0.0030	0.1387 ± 0.0036	$0.1404^{+0.0036}_{-0.0035}$	0.1382 ± 0.0037	0.1379 ± 0.0036	$0.1387^{+0.0036}_{-0.0037}$	$0.1402^{+0.0033}_{-0.0034}$
$D_V(0.275)$	1080 ± 18	1110^{+32}_{-31}	1089 ± 31	1111 ± 33	1115 ± 32	1107 ± 31	1091^{+27}_{-28}
f	1.6645 ± 0.0043	1.6643 ± 0.0045	1.661 ± 0.019	1.72 ± 0.056	1.660 ± 0.011	$1.7187^{+0.0337}_{-0.0334}$	1.6645 ± 0.0107
Age (Gyr)	13.73 ± 0.12	14.08 ± 0.33	$13.76^{+0.15}_{-0.14}$	14.49 ± 0.52	14.04 ± 0.36	14.48 ± 0.48	$13.86^{+0.34}_{-0.33}$
$\Omega_c h^2$	0.1139 ± 0.0041	$0.1090^{+0.0060}_{-0.0061}$	$0.1122^{+0.0068}_{-0.0069}$	$0.1107^{+0.0063}_{-0.0062}$	$0.1096^{+0.0061}_{-0.0062}$	$0.1108^{+0.0060}_{-0.0061}$	0.1115 ± 0.0061
Ω_{tot}	-	$1.007^{+0.006}_{-0.007}$	-	1.013 ± 0.007	1.006 ± 0.008	1.014 ± 0.007	1.003 ± 0.007
σ_8	0.813 ± 0.028	0.787 ± 0.037	$0.792^{+0.081}_{-0.082}$	0.907 ± 0.117	$0.780^{+0.052}_{-0.053}$	0.904 ± 0.074	$0.801^{+0.053}_{-0.052}$

Varying which datasets are combined leads to differences in parameter estimates as large as the statistical errors – a sign that we have reached the point where systematic errors are beginning to dominate

Precision cosmology - now accurate cosmology?

Percival et al 2009

The Next Step: WIGGLeZ



1000 square degree survey with Anglo-Australian Telescope (2DF)

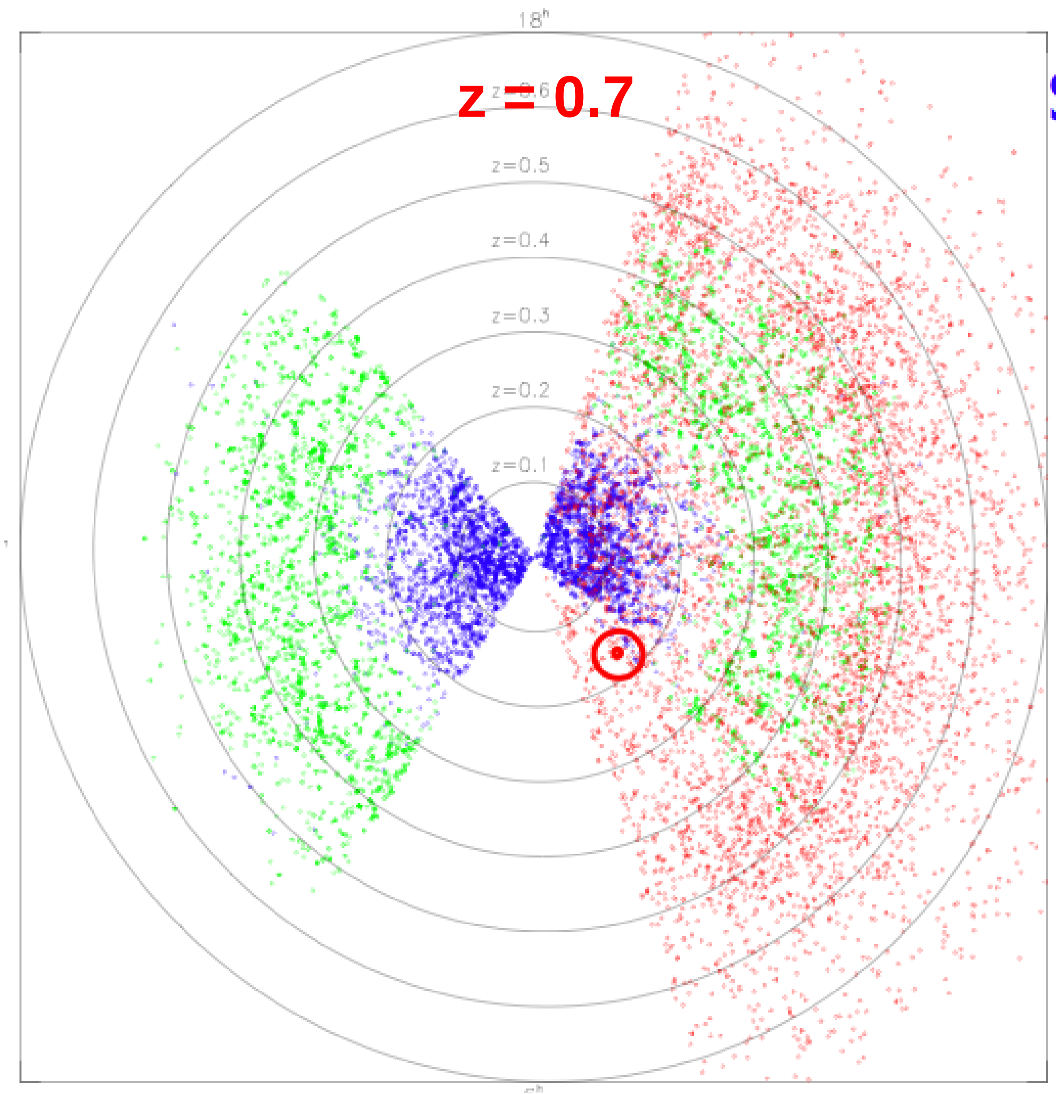
400,000 LRG redshifts to $z < 0.75$

Observing for 220 nights, during 2006-2009

Look out for results soon...

http://wigglez.swin.edu.au

The Step After That: BOSS



SDSS main survey (too small!)

SDSS-I + SDSS-II red galaxies
8000 deg^2 (finish in 2008)
samples 10^{-4} galaxies/Mpc^3

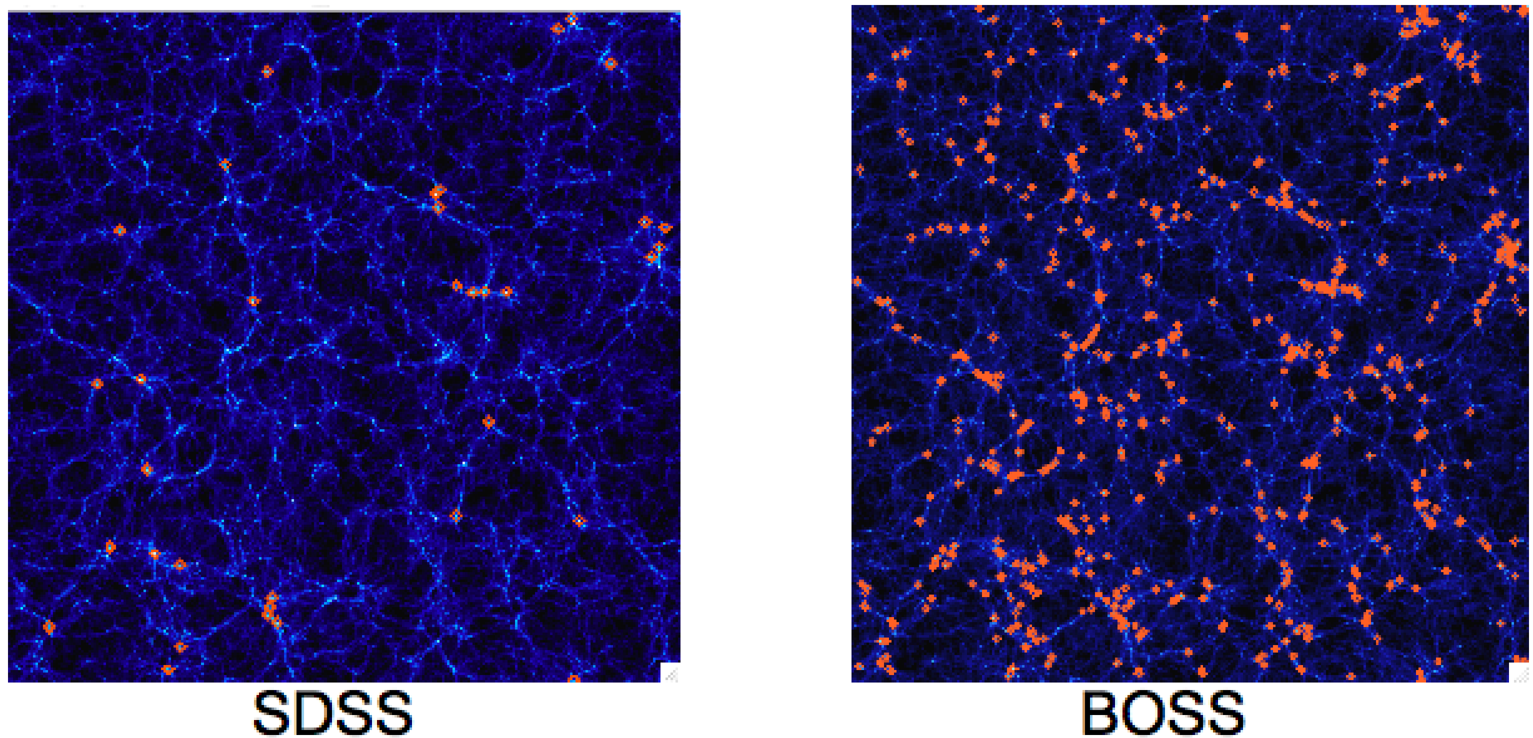
SDSS-III red galaxies
10,000 deg^2
5x sample density (shot noise)
2x volume

BOSS Proposal
Schlegel et al 2006

Moving to higher redshift

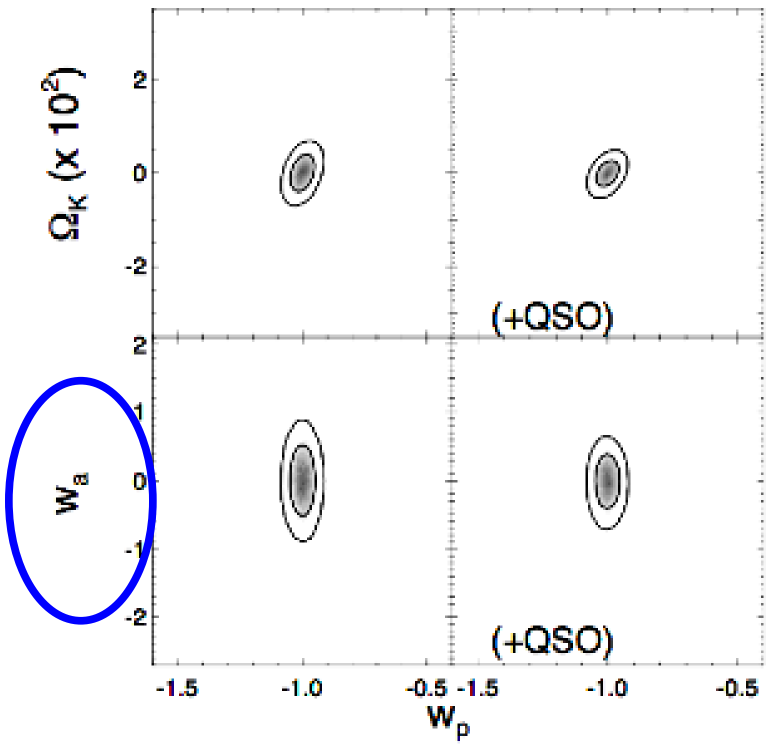
Fainter, redder objects at z~0.5:

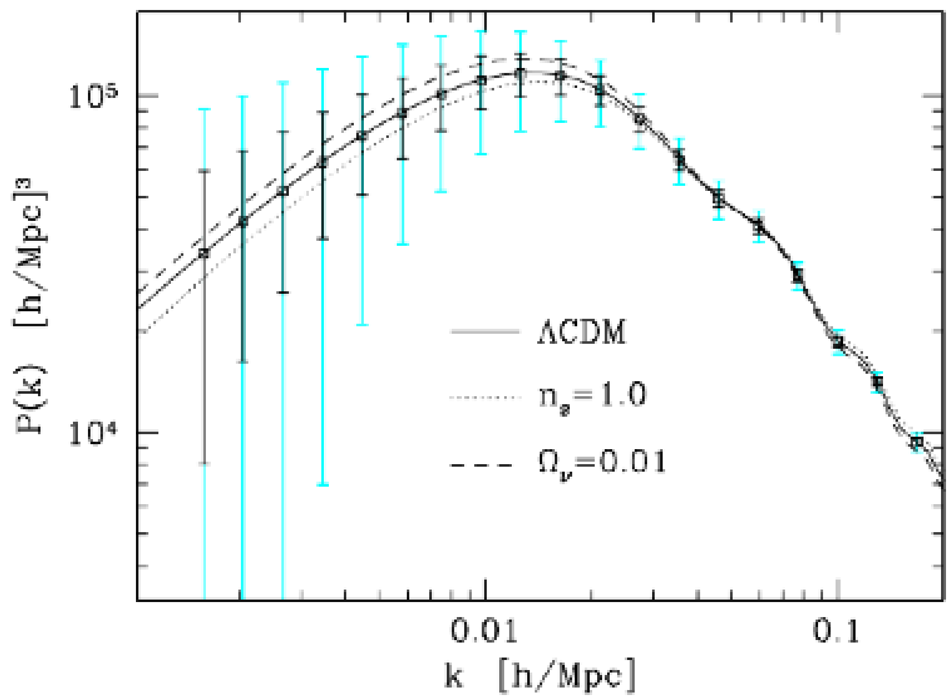
- refit spectrograph with red-sensitive CCDs,
- increase number of optical fibres too:



A slice 500h^{-1} Mpc across and 10 h^{-1} Mpc thick

BOSS science





Dark energy

Large-scale structure

δh~0.008, $\delta w_p(z$~$0.2)$~0.03, δw_a~0.3

x1/2 if can model broad-band power!

DETF Figure of Merit ~8
Team are more confident

Slide from M. White

BOSS observing Fall 2009

Local competition:
HETDEX (2010)
http://hetdex.org/

Dark time observations
Fall 2009 - Spring 2014

10,000 square degrees
1.5 million luminous red galaxy redshifts
to $z < 0.7$

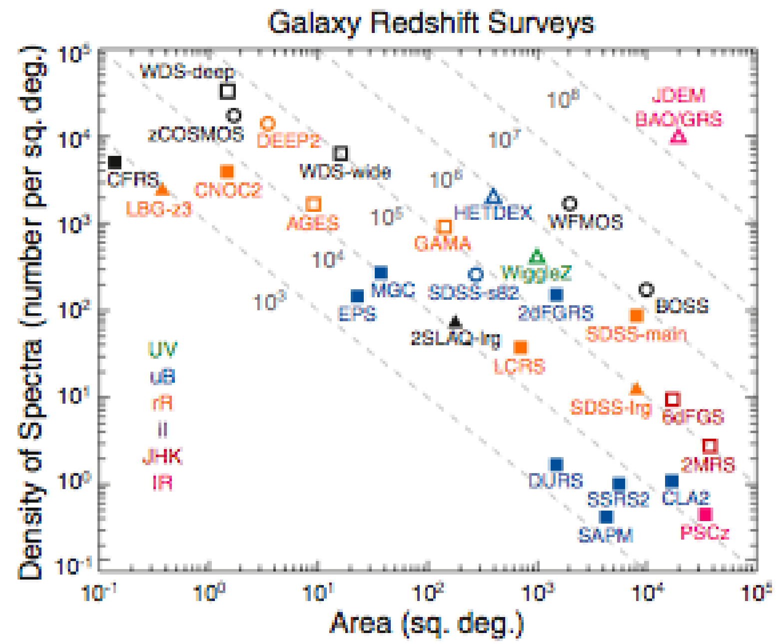
http://www.sdss3.org/cosmology.php

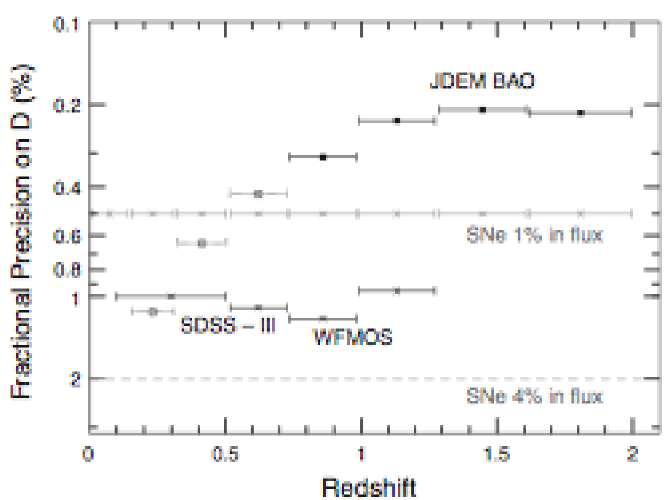
BAO with JDEM

NIR spectroscopic survey over 20,000 sq deg would substantially increase the number of tracer galaxies over the ground-based sample:

200 million galaxy redshifts

Systematics outlook is optimistic – claim is “statistics dominated to the cosmic variance limit”





Distance measurements to 0.2% per bin possible

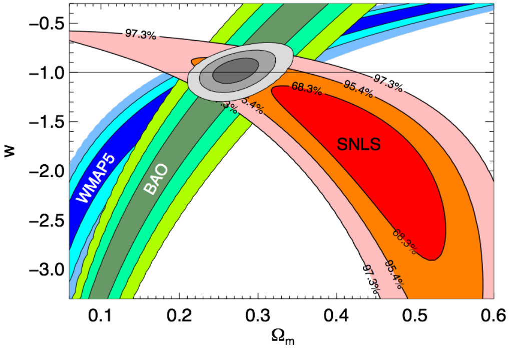
Eisenstein et al 2009

BAO with JDEM

NIR spectroscopic survey over 20,000 sq deg,
200 million galaxies, to z ~ 2

Distance measurements to 0.2% per bin possible

DETF figure of merit 20-40,
with w(a=0.61) to 5%, wa to +/-0.7 or so



Competitive with and complementary to SNe

Important: “pivot” redshifts, where the uncertainty on w(a) is smallest, are quite different:
~ 0 for SNe
~ 0.6 for BAO

BAO and SNe from NIR space mission makes sense
(although recall optimism of BOSS team!)

Kinematic Probes

We are already very good at measuring distances in cosmology – and are about to get better

SNe are already systematics limited – and will likely stay that way, with the systematic error floor decreasing with better data

BAO is a young technique, that promises a lot – will it really always be statistics limited?

A space-based JDEM mission including both BAO and SNe observations will make for a very large and *rich* dataset, driving both statistical and systematic errors down and enabling *evolution in w* to be constrained to a few tens of %

The next few years will be interesting:
Will WIGGLeZ, BOSS and HETDEX deliver?
Will JDEM stay on track? Will an IXO come into view?