Wiggles and Bangs

SDSS, DES, WFMOS teams

(Bob Nichol, ICG Portsmouth)

nergy

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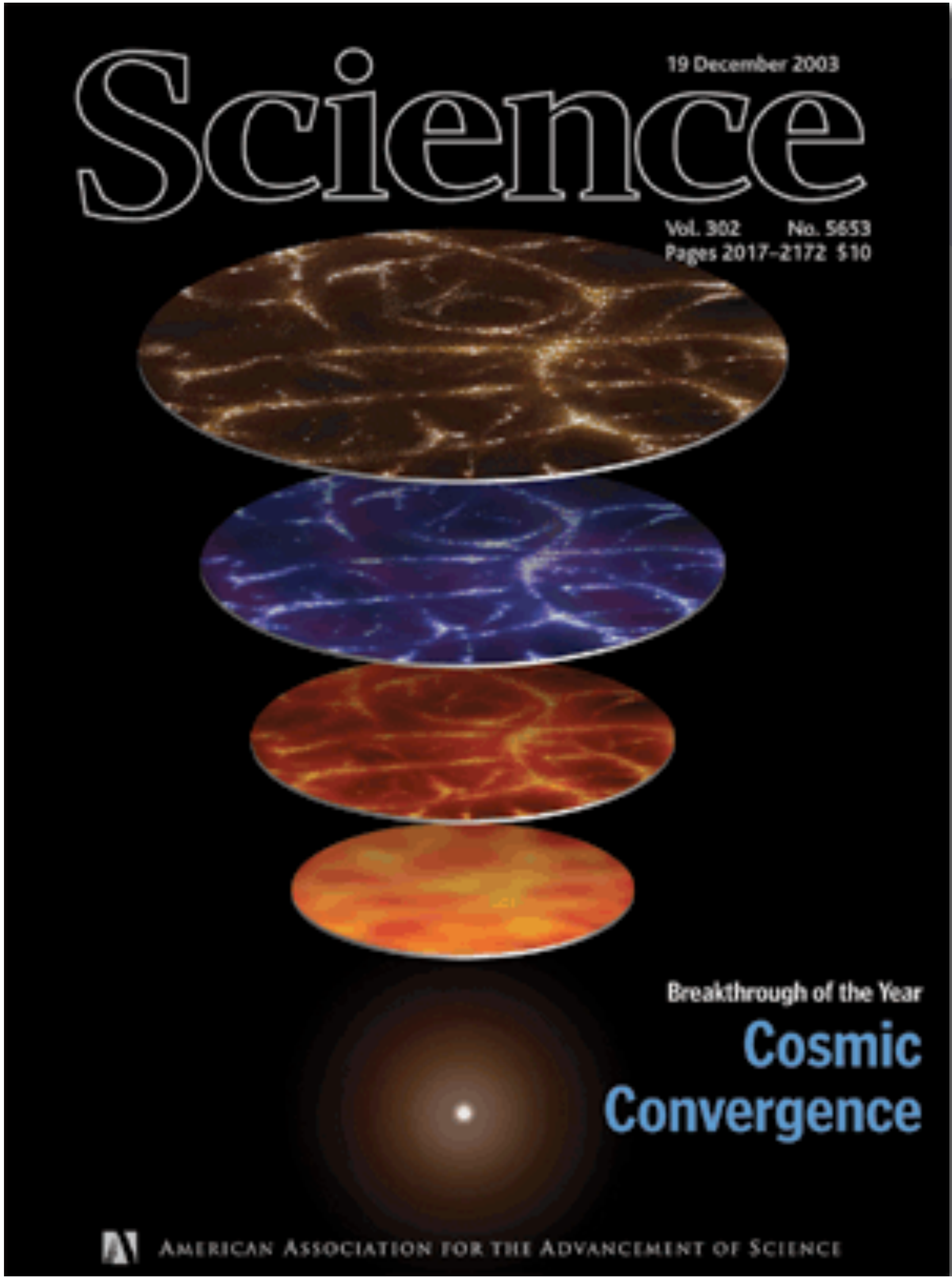

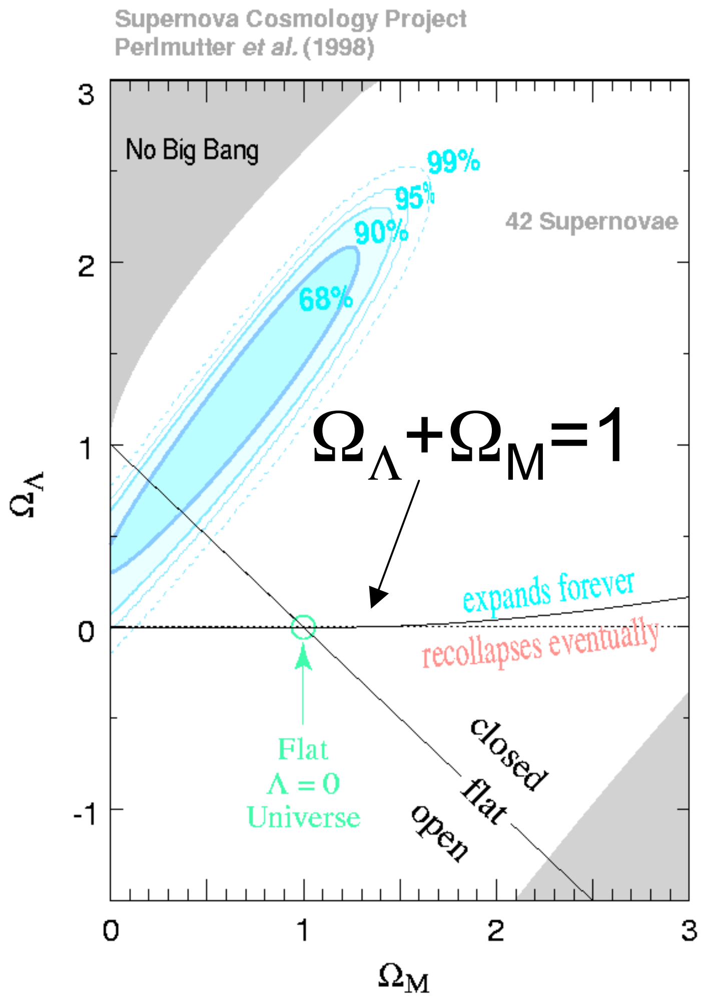

Understanding Dark Energy

Observers Prospective

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We can make progress on questions:

- **Is DE just a cosmological constant (w(z)=-1)?**
  (Make better observations and push to higher z)
- **Is DE a new form of matter (with negative effective pressure) or a breakdown of GR?**
  (Study DE using different probes)

But there are only two broad avenues:

- Geometrical tests *(SN, BAO)*
- Growth of structure *(ISW, lensing, clusters)*

No compelling theory, must be observational driven

Massive Surveys

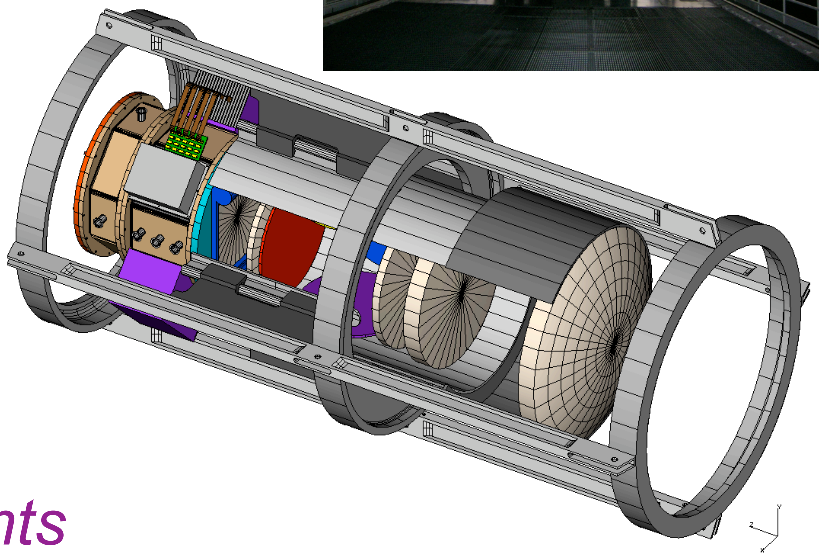
Need large surveys of the Universe to measure DE accurately

SDSS / SDSS-II / AS2

- *SDSS SN Survey*
- *Baryon Acoustic Oscillations (BAO)*
- *ISW*

Dark Energy Survey (DES)

- *New SN Survey*

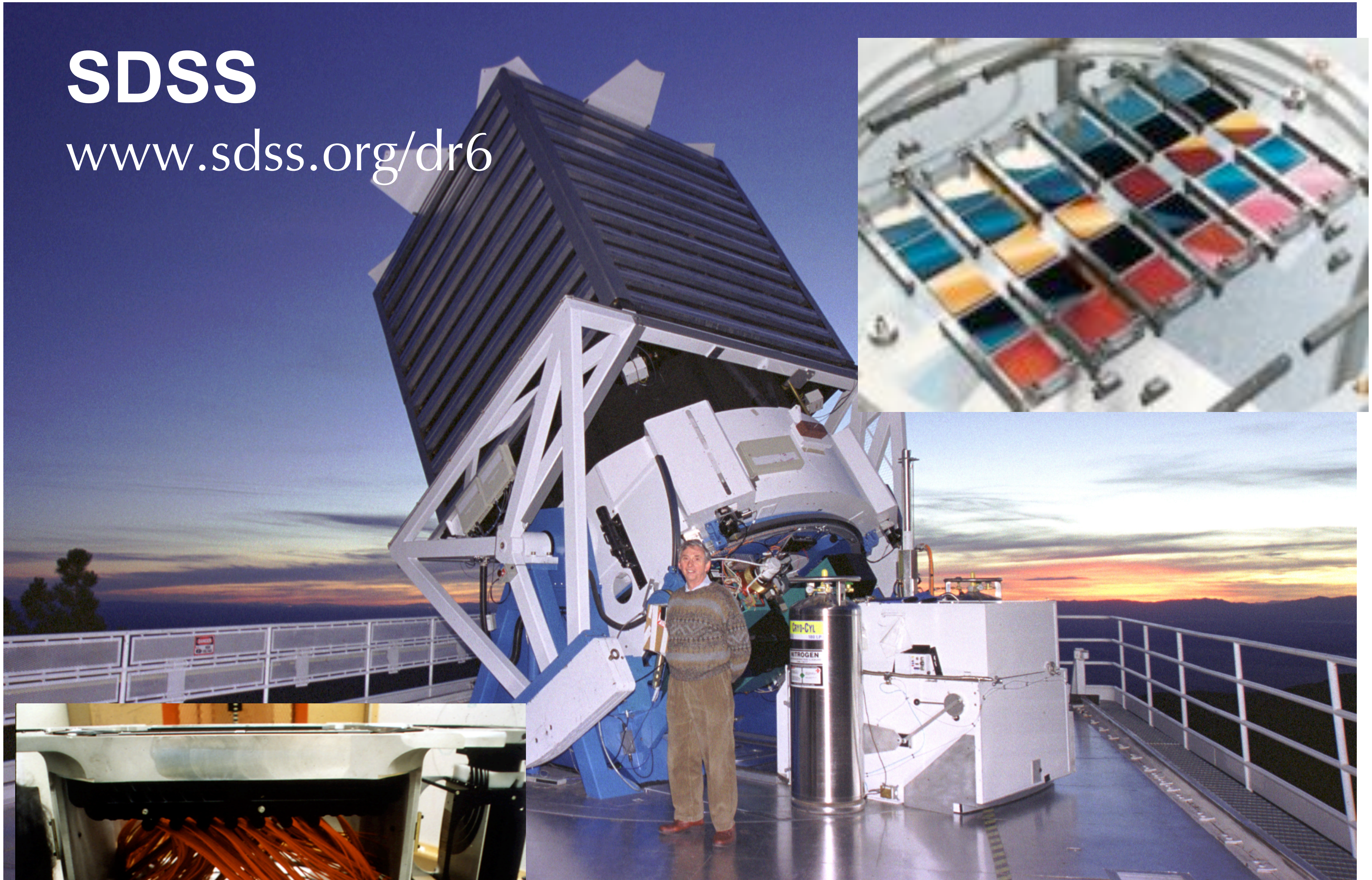


WFMOS

- *Future BAO measurements*

SDSS

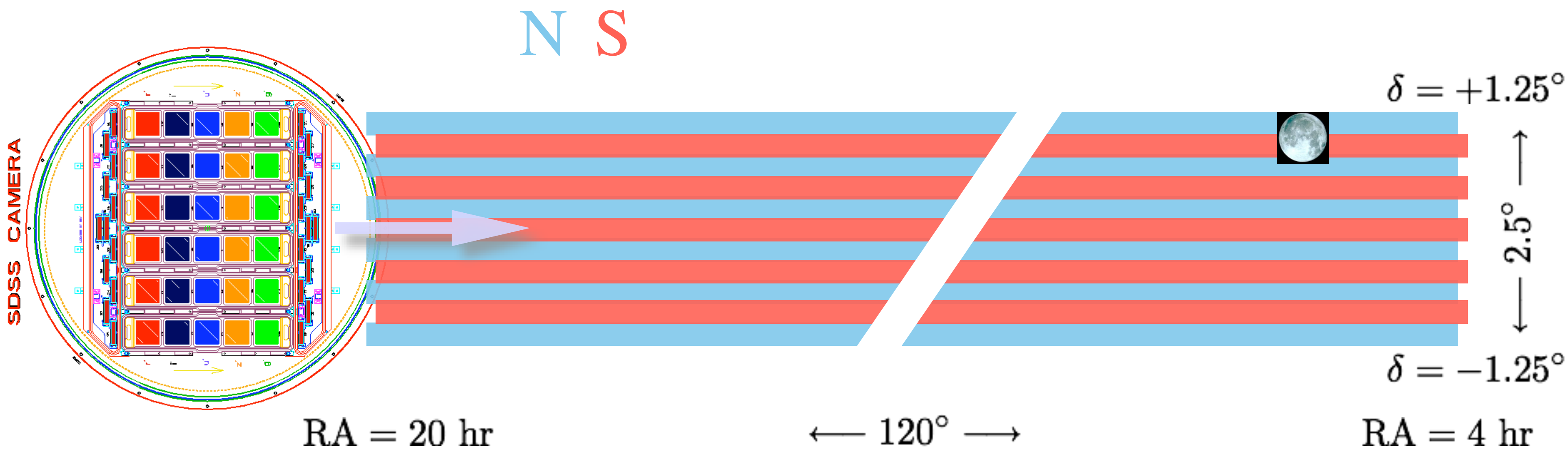
www.sdss.org/dr6



DR6: 790860 gal, 8417 deg^2, 1271680 spectra

Extension (2005-2008): Legacy, SNe, Galaxy

SDSS SN Survey



Use the SDSS 2.5m telescope

- September 1 - November 30 of 2005-2007
- Scan 300 square degrees of the sky every 2 days
- Data reduced in less than 24hours
- "Stripe82" (UKIDSS data)
- Many telescopes used for spectroscopic follow-up (NTT, NOT)

Redshift and Cadence

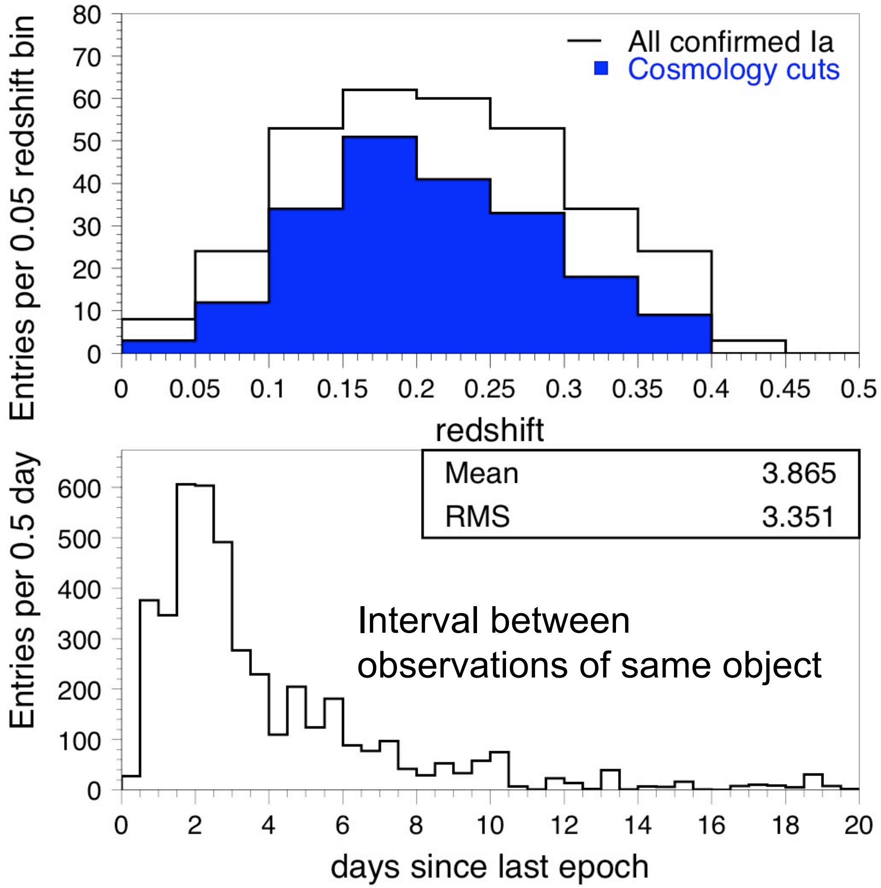
325 spectro Ia's

31 spectro probable Ia's

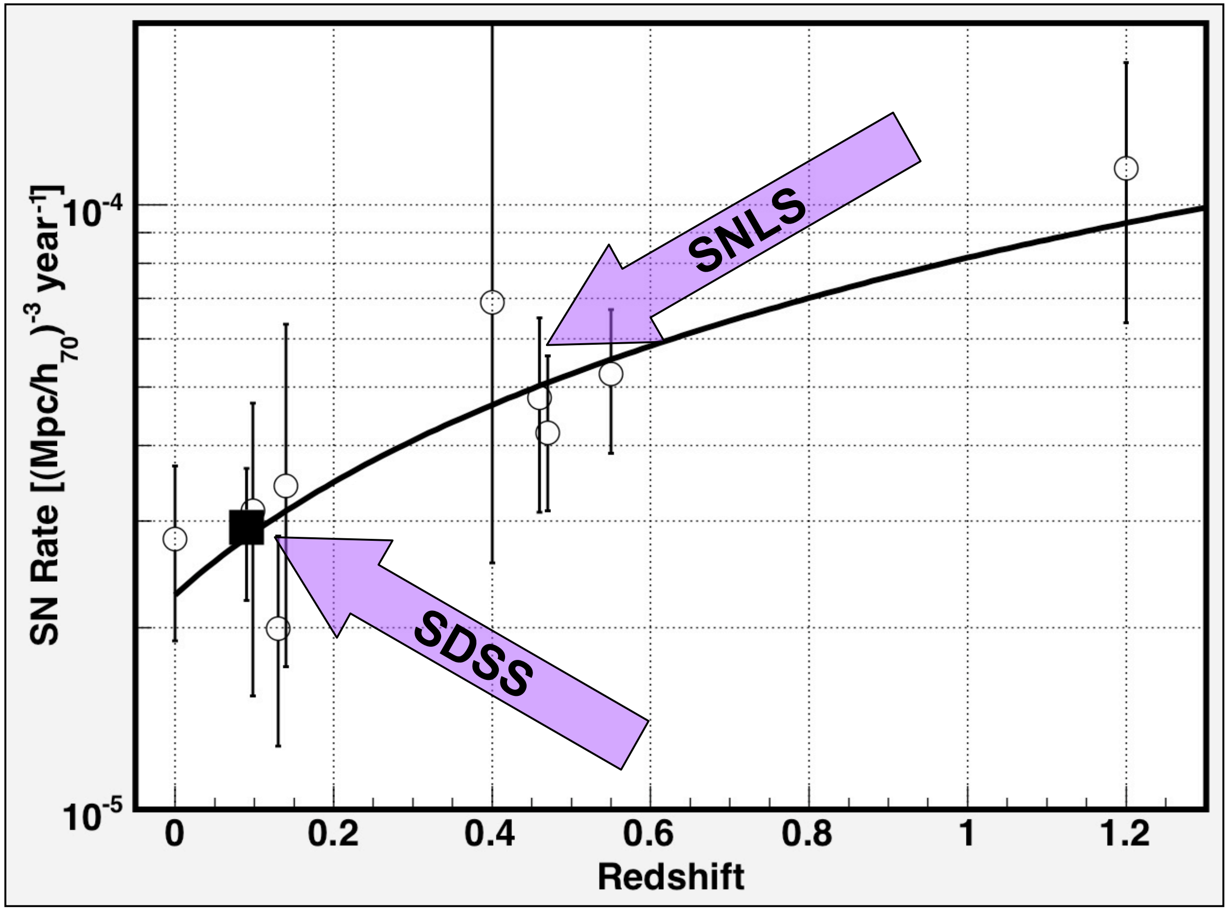
80 photo Ia's with host z

14 spectro Ib/c

30 spectro II

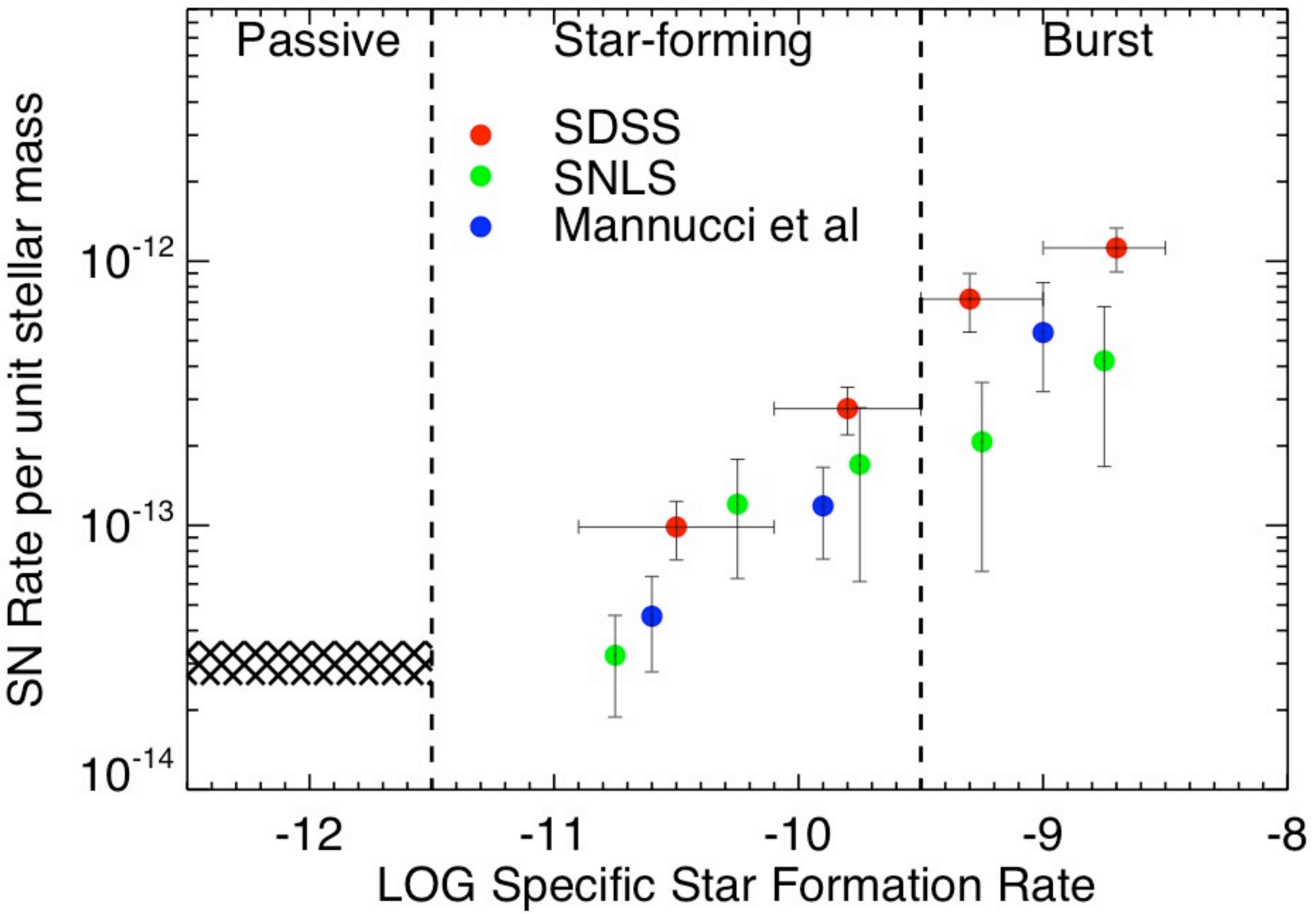


SN Rate



SN Rate (z < 0.12) = $[2.9 \pm 0.7_{stat} \pm 0.3_{syst}] \times 10^{-5} (Mpc/h_{70})^{-3} yr^{-1}$

SN Rate vs Galaxy Type



Cosmology

Still not ready, but close

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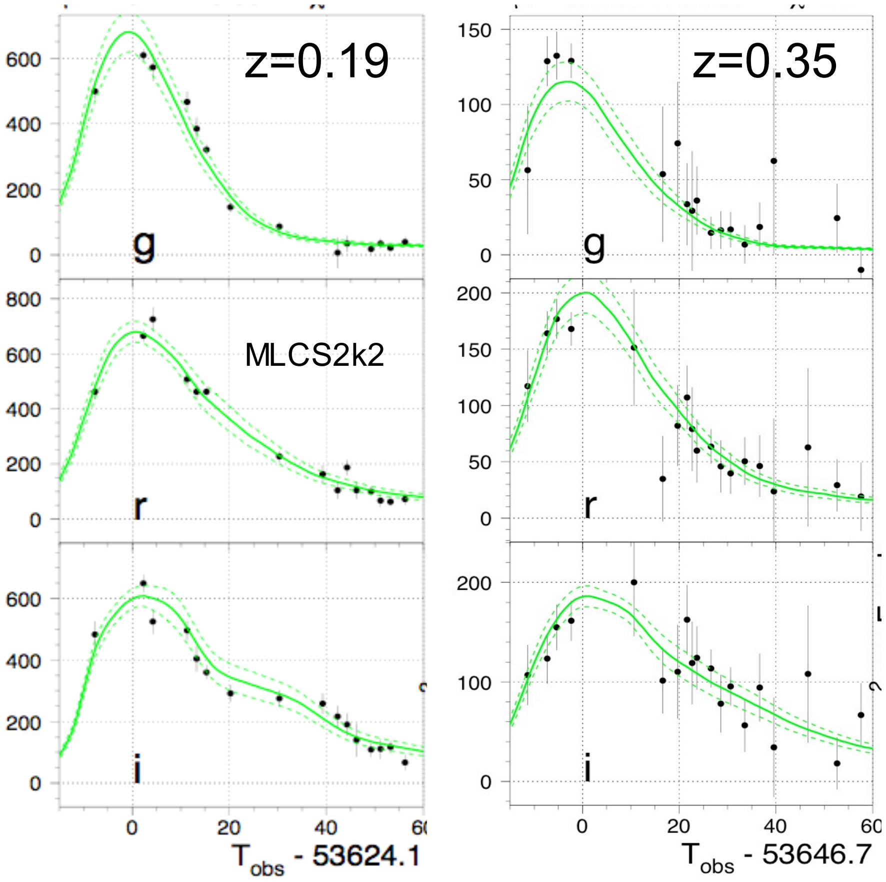
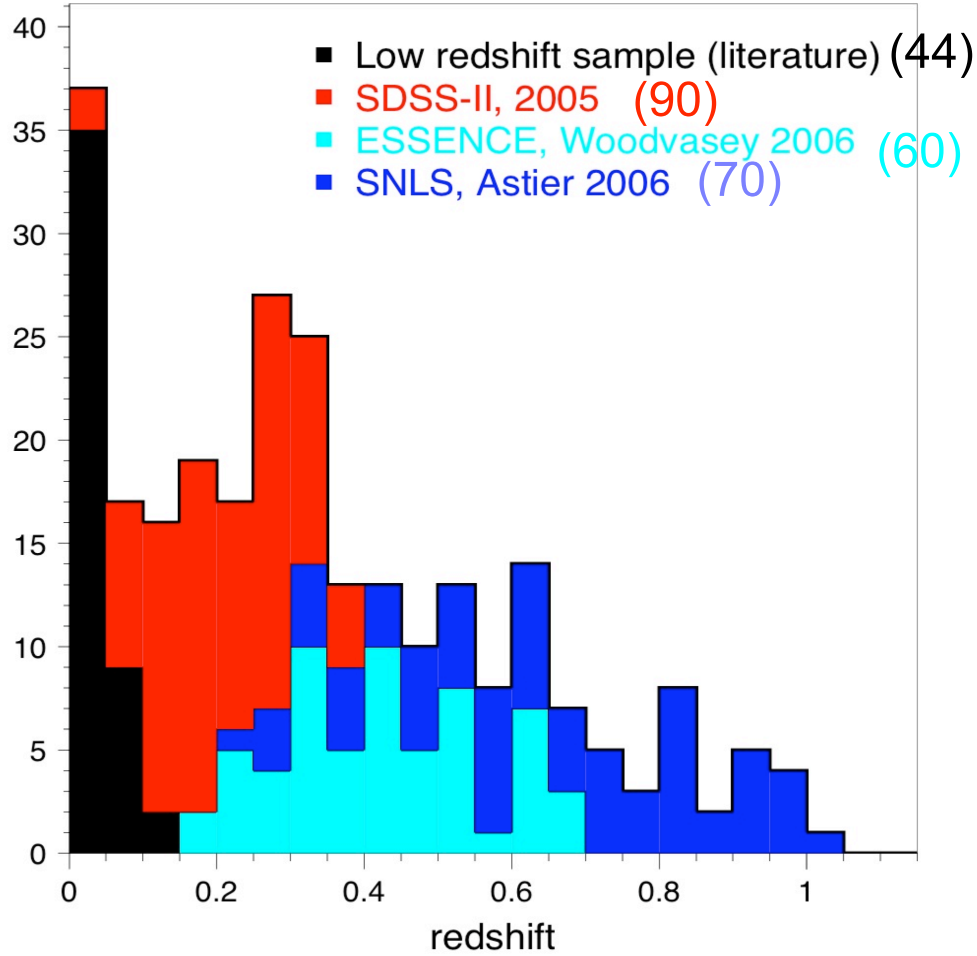


i-band causing the problem

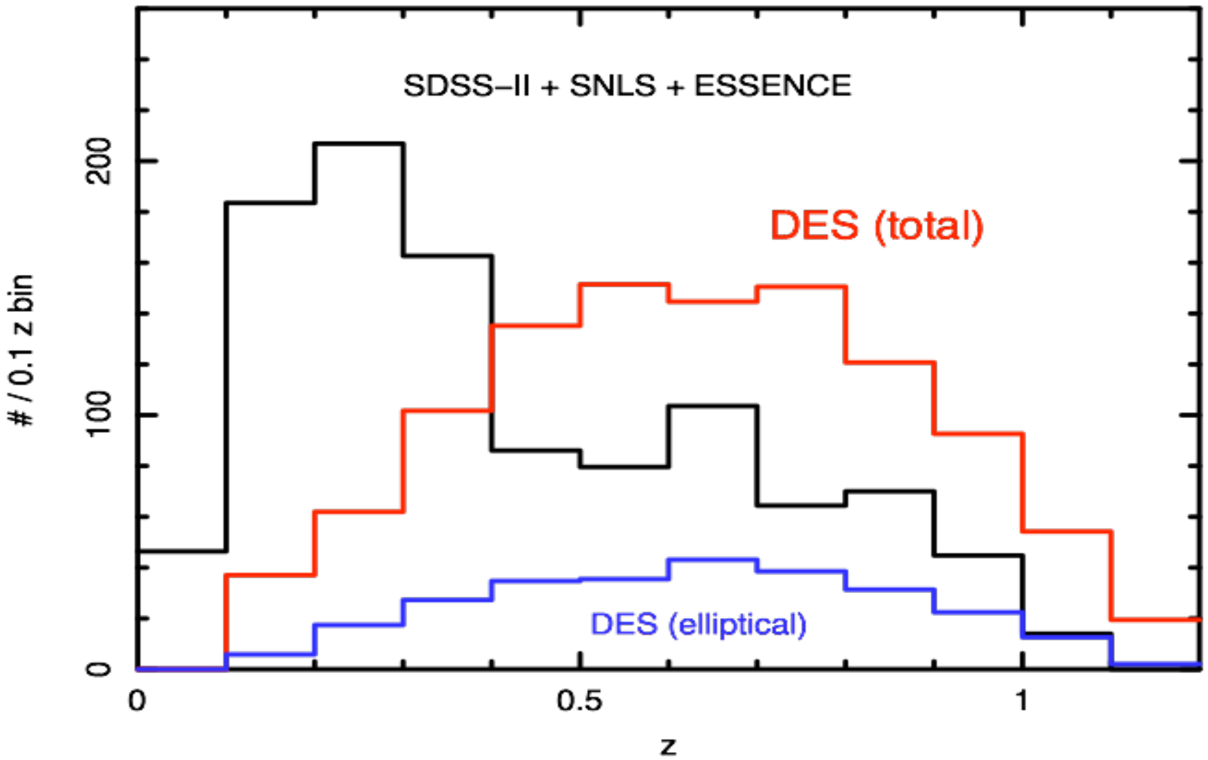


DES SN Survey

SN surveys are systematics limited

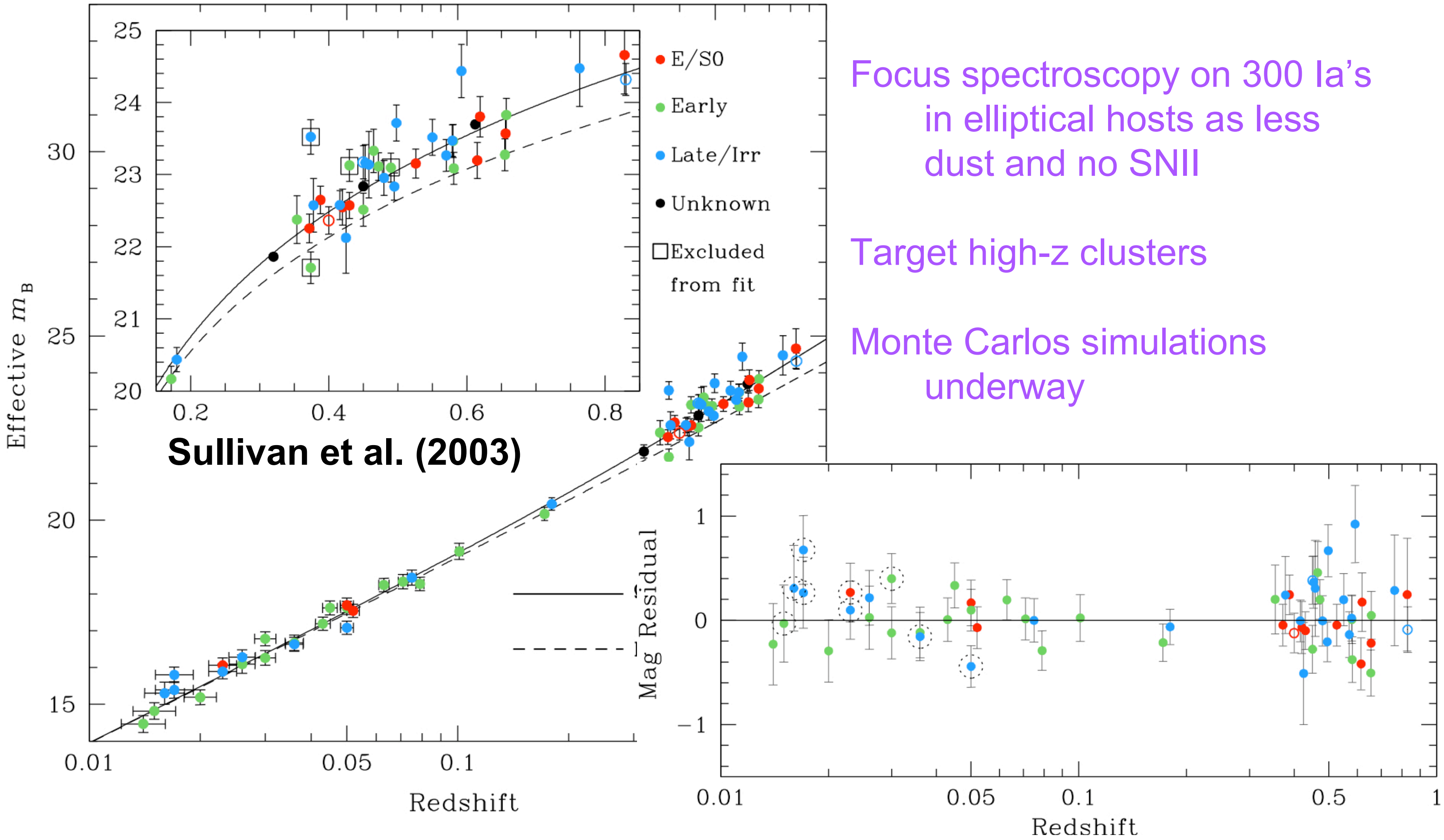
Provide a large sample of high-redshift SN Ia (redshift > 0.7) with good rest-frame g-band (observer-frame z-band) light curves . Possible with enhanced red sensitivity of DECam.

- 750 hrs time
- 9 deg^2
- 4 - 6 days in riz
- Possible Y
- 1400 Ia's
- 0.2 < z < 1



DES SN Survey

Spectroscopic Follow-up



Focus spectroscopy on 300 Ia's in elliptical hosts as less dust and no SNII

Target high-z clusters

Monte Carlos simulations underway

DES SN Survey

Forecasts

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DETF FoM

Method	$\sigma(\Omega_{DE})$	$\sigma(w_0)$	$\sigma(w_a)$	z_p	$\sigma(w_p)$	$[\sigma(w_a)\sigma(w_p)]^{-1}$
BAO	0.010	0.097	0.408	0.29	0.034	72.8
Clusters	0.006	0.083	0.287	0.38	0.023	152.4
Weak Lensing	0.007	0.077	0.252	0.40	0.025	155.8
Supernovae	0.008	0.094	0.401	0.29	0.023	107.5
Combined DES	0.004	0.061	0.217	0.37	0.018	263.7
DETF Stage II Combined	0.012	0.112	0.498	0.27	0.035	57.9

Table 1: 68% CL marginalized forecast errorbars for the 4 DES probes on the dark energy density and equation of state parameters, in each case including Planck priors *and* the DETF Stage II constraints. The last column is the DETF FoM; z_p is the pivot redshift. Stage II constraints used here agree with those in the DETF report to better than 10%.

- Well known and proven
- Nearly factor of 5 improvement in FoM
- These predictions include systematic errors as well

Baryon Acoustic Oscillations

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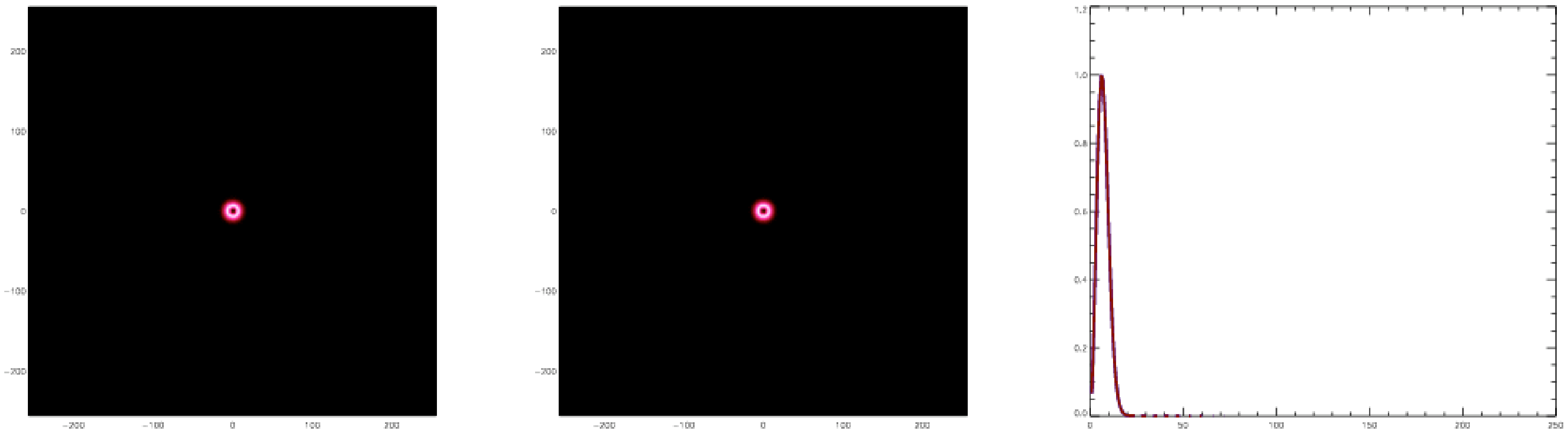
baryons

photons



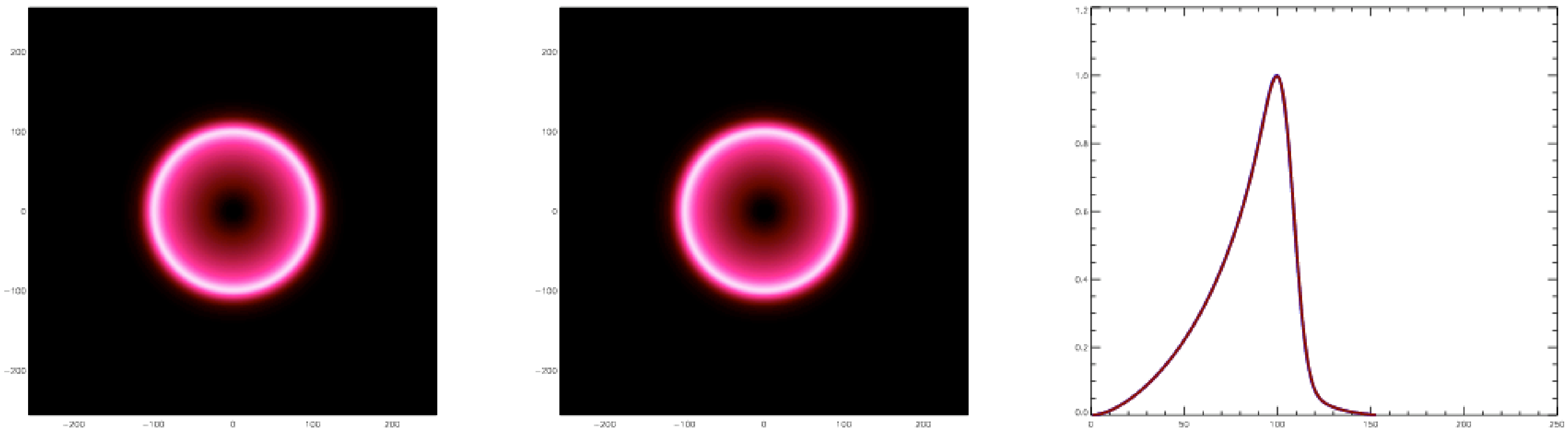
Initial fluctuation in DM. Sound wave driven out
by intense pressure at 0.57c.

Courtesy of Martin White

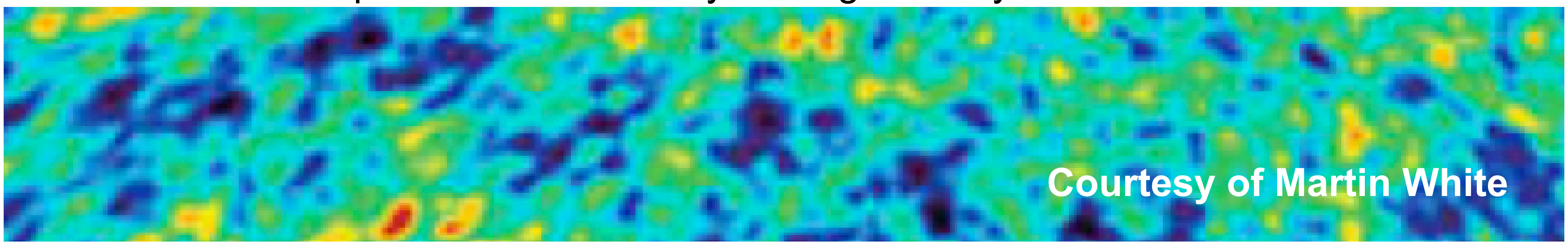
Baryon Acoustic Oscillations

baryons

photons

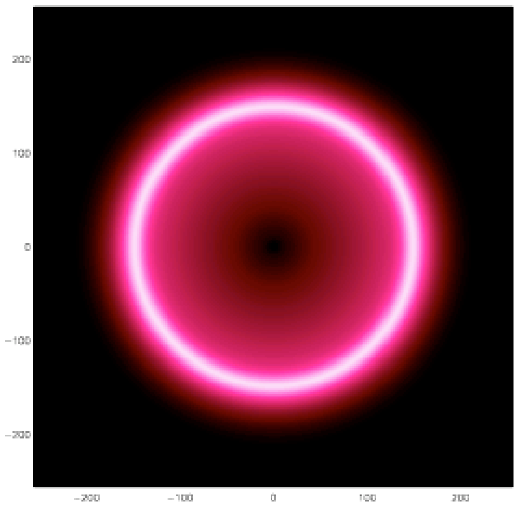


After 10^5 years, we reach recombination and photons stream away leaving the baryons behind

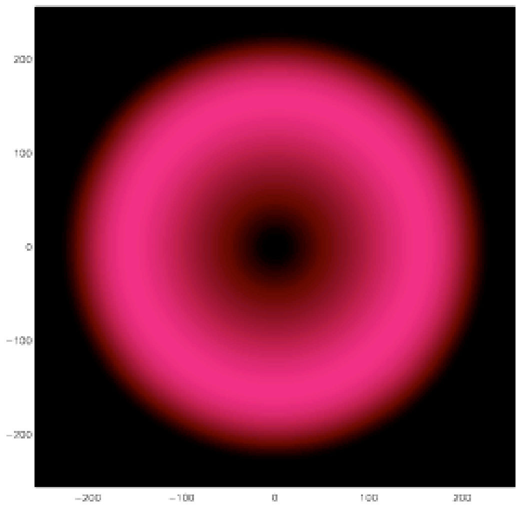


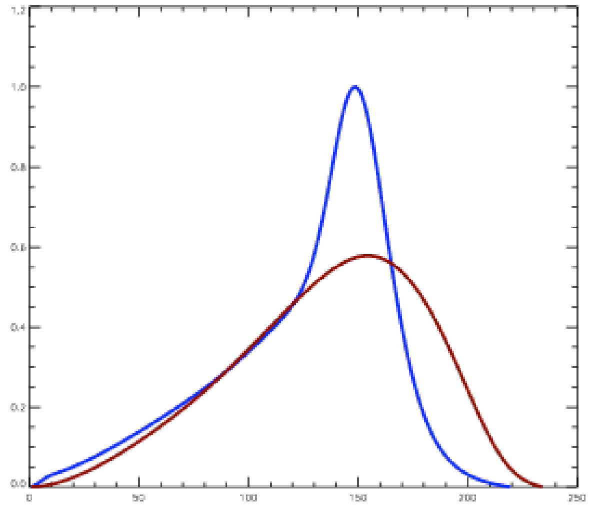
Baryon Acoustic Oscillations

baryons



photons



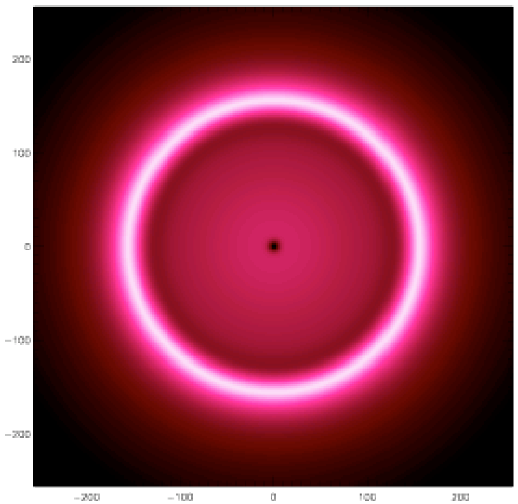


Photons free stream, while baryons remain still as pressure is gone

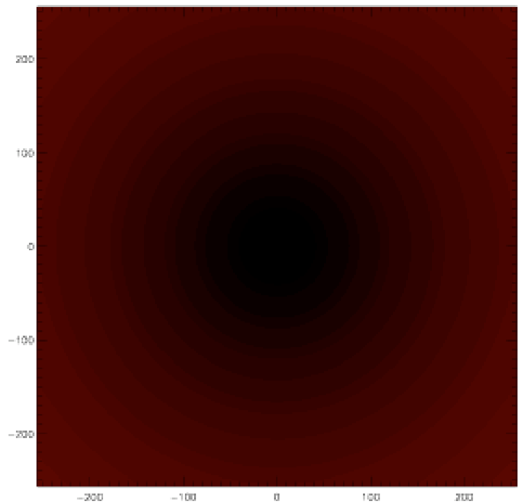
Courtesy of Martin White

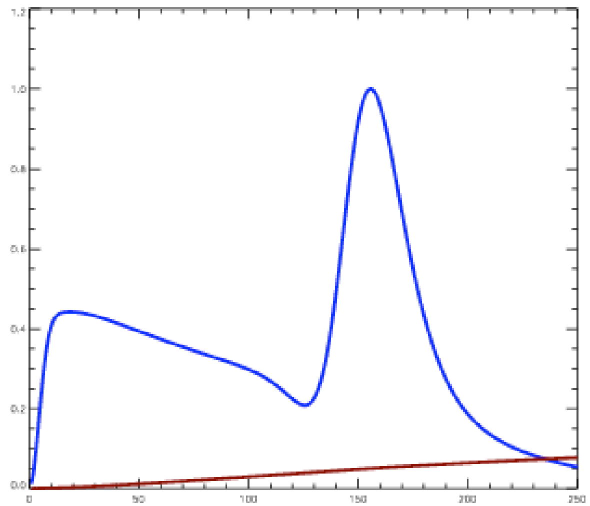
Baryon Acoustic Oscillations

baryons



photons



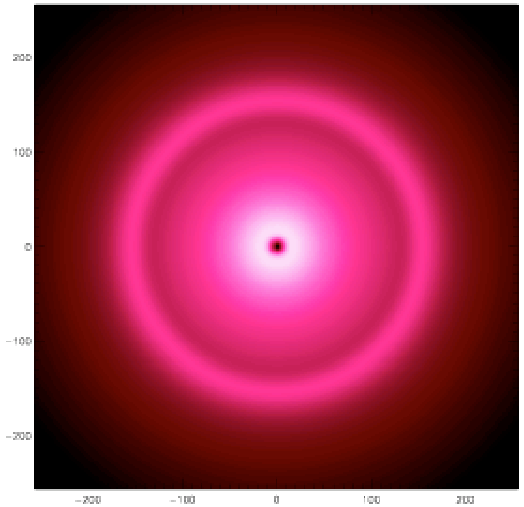


Photons almost fully uniform, baryons are attracted back by the central DM fluctuation

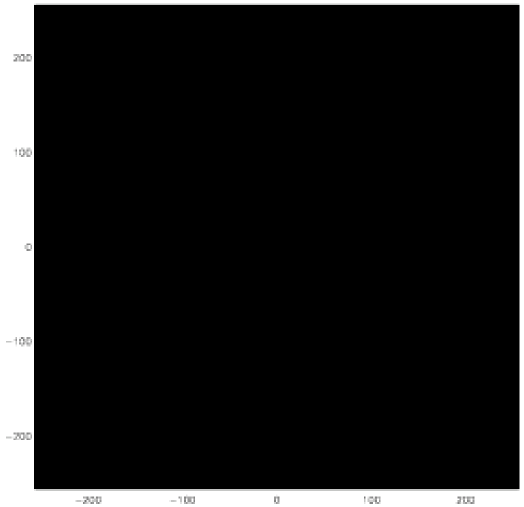
Courtesy of Martin White

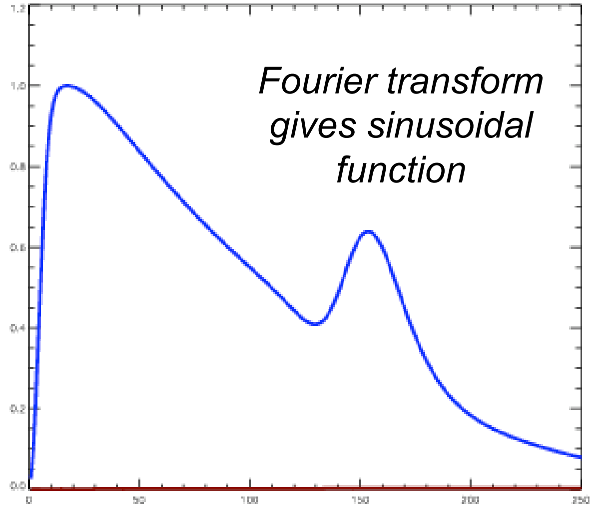
Baryon Acoustic Oscillations

baryons



photons





Today. Baryons and DM in equilibrium. The final configuration is the original peak at the center and an echo roughly 100Mpc in radius

Courtesy of Martin White

Baryon Acoustic Oscillations

Many superimposed waves. See them statistically

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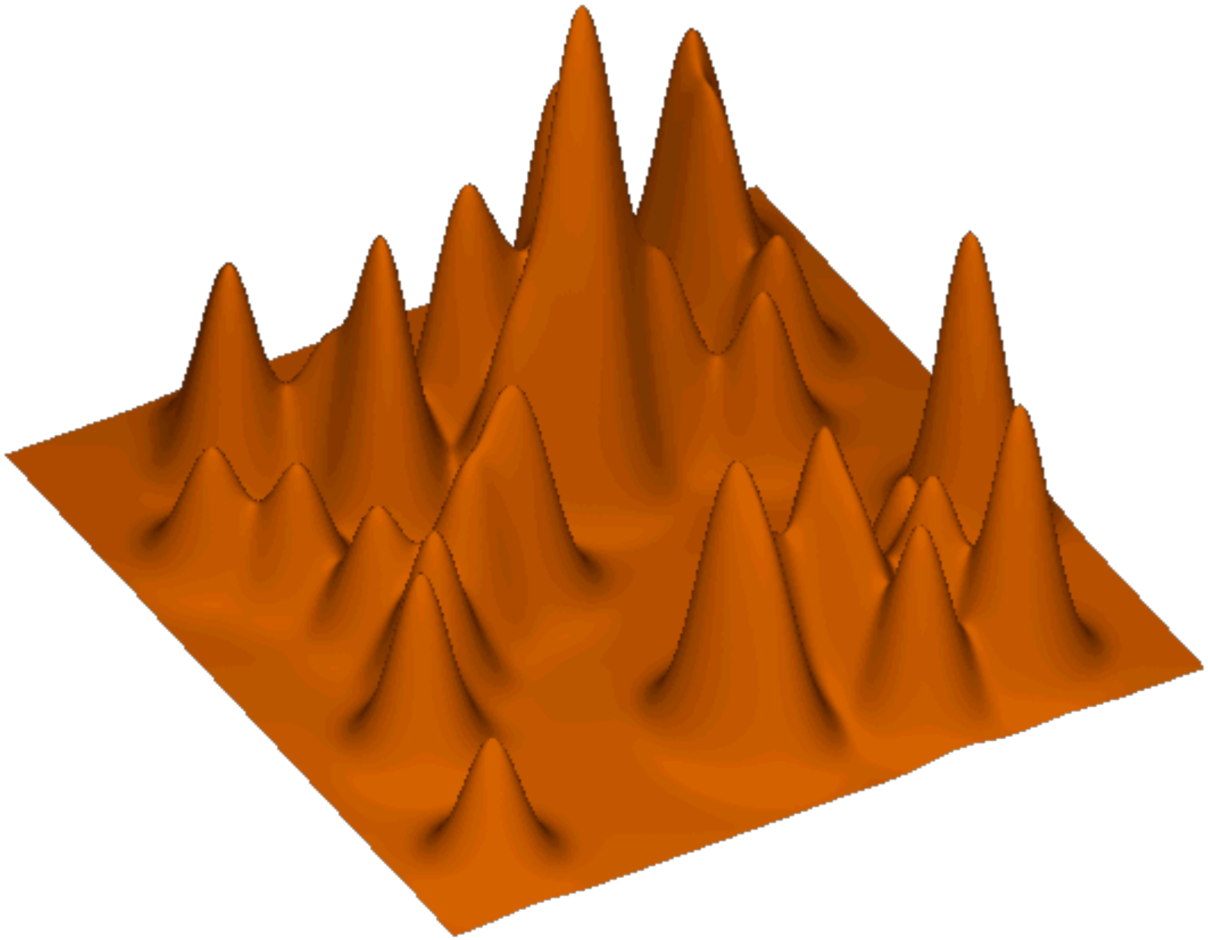
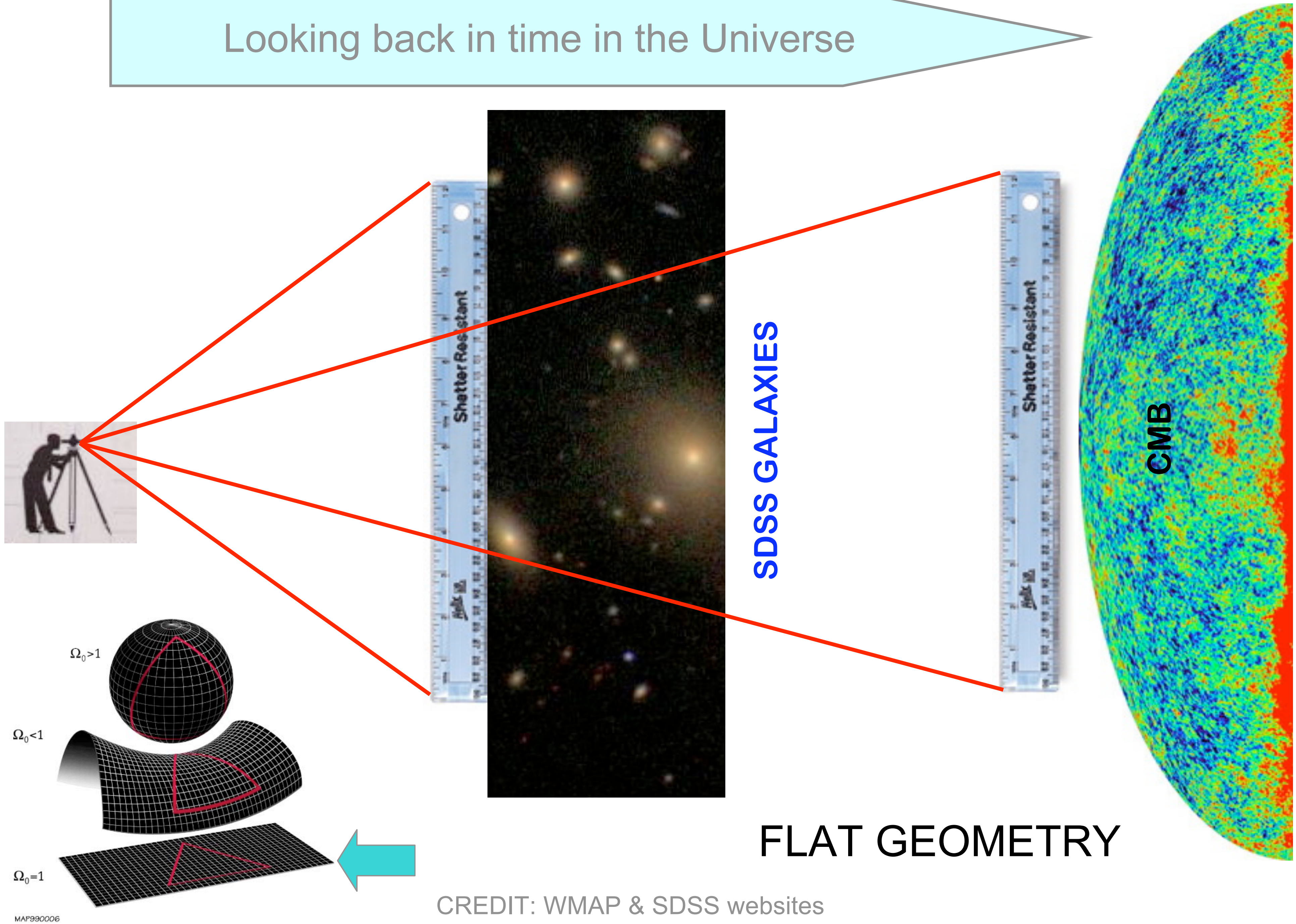


- Positions predicted once (physical) matter and baryon density known - calibrated by the CMB.

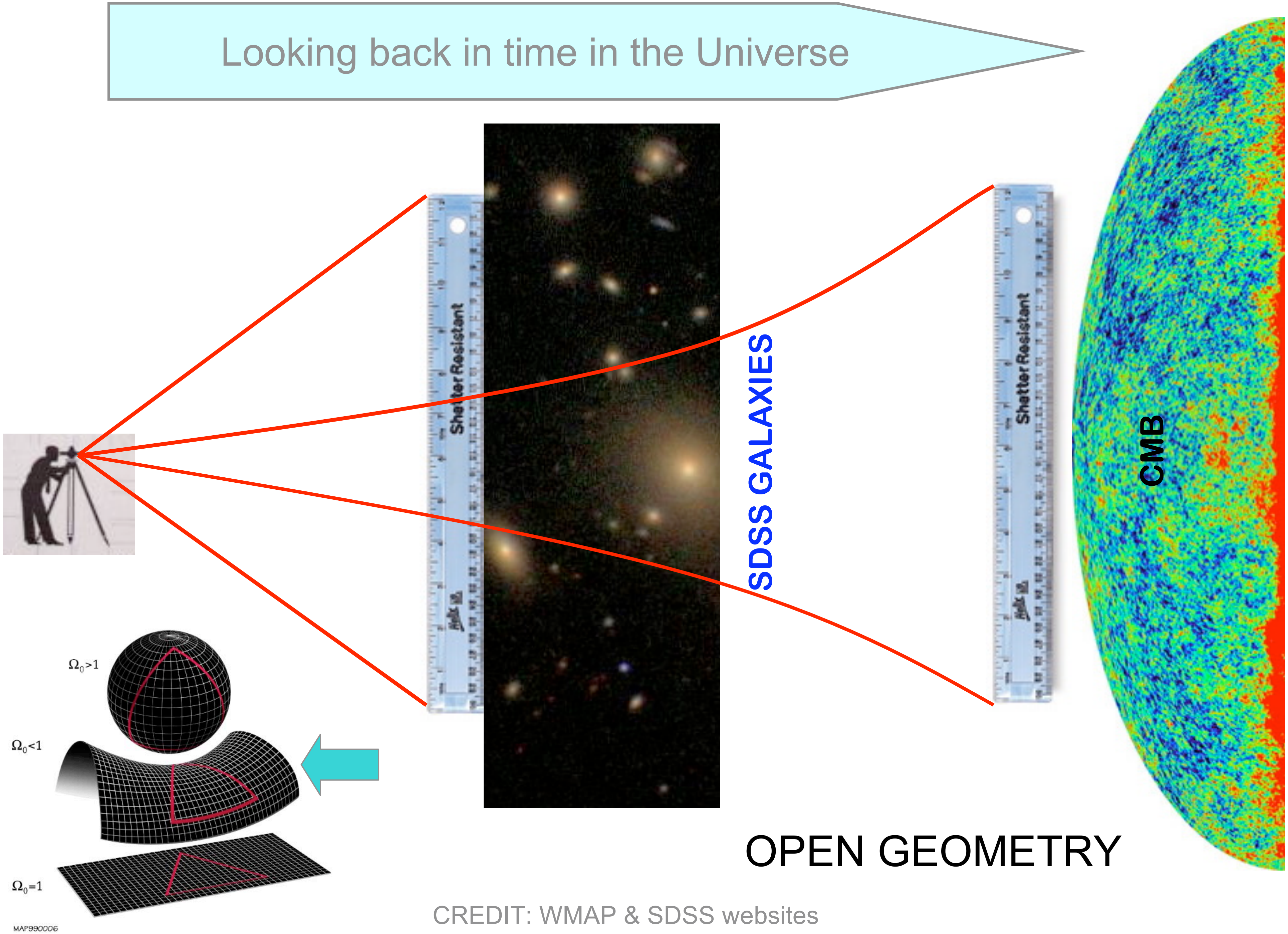
- Oscillations are sharp, unlike other features of the power spectrum

Daniel Eisenstein

Looking back in time in the Universe



CREDIT: WMAP & SDSS websites



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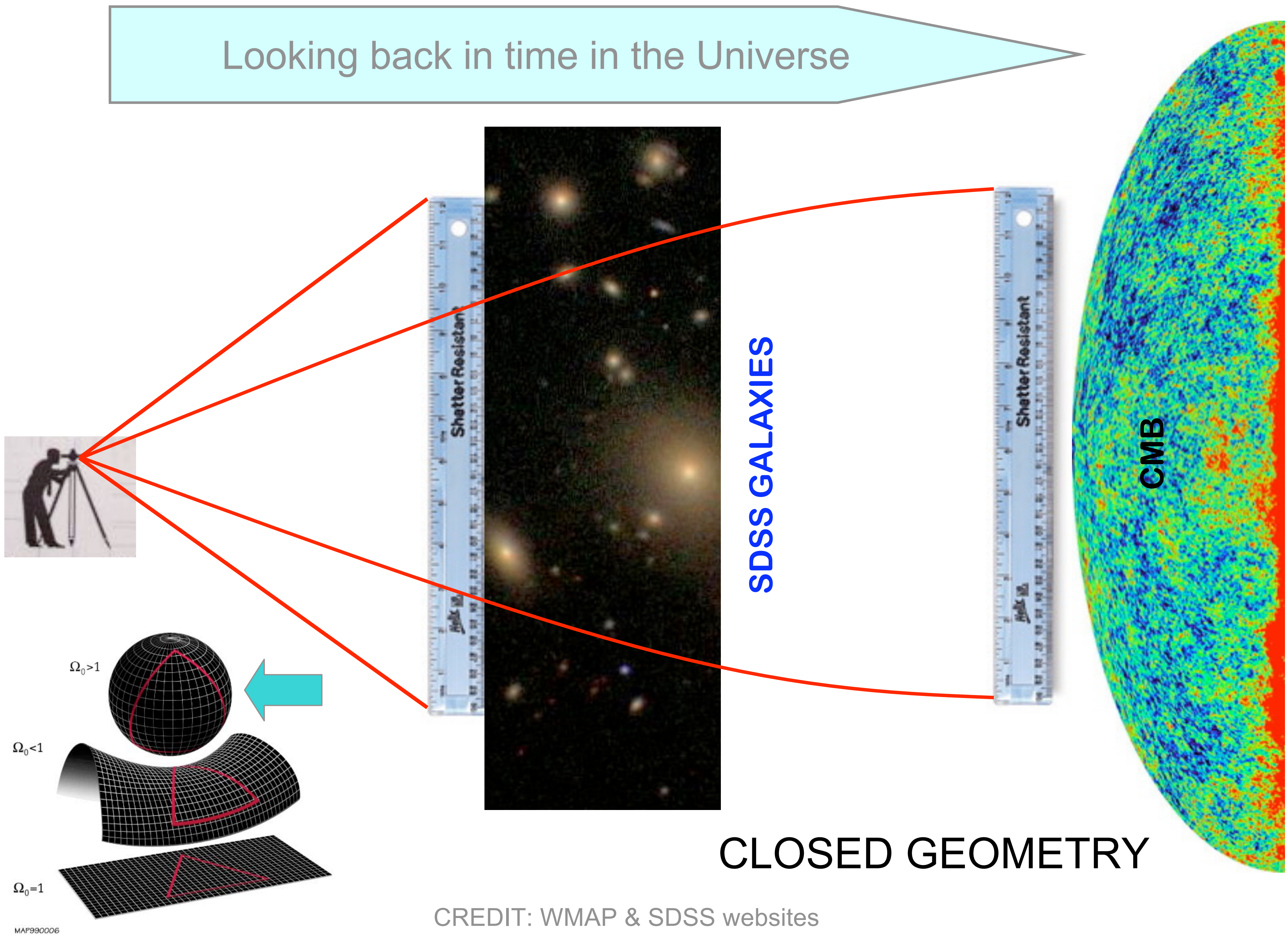
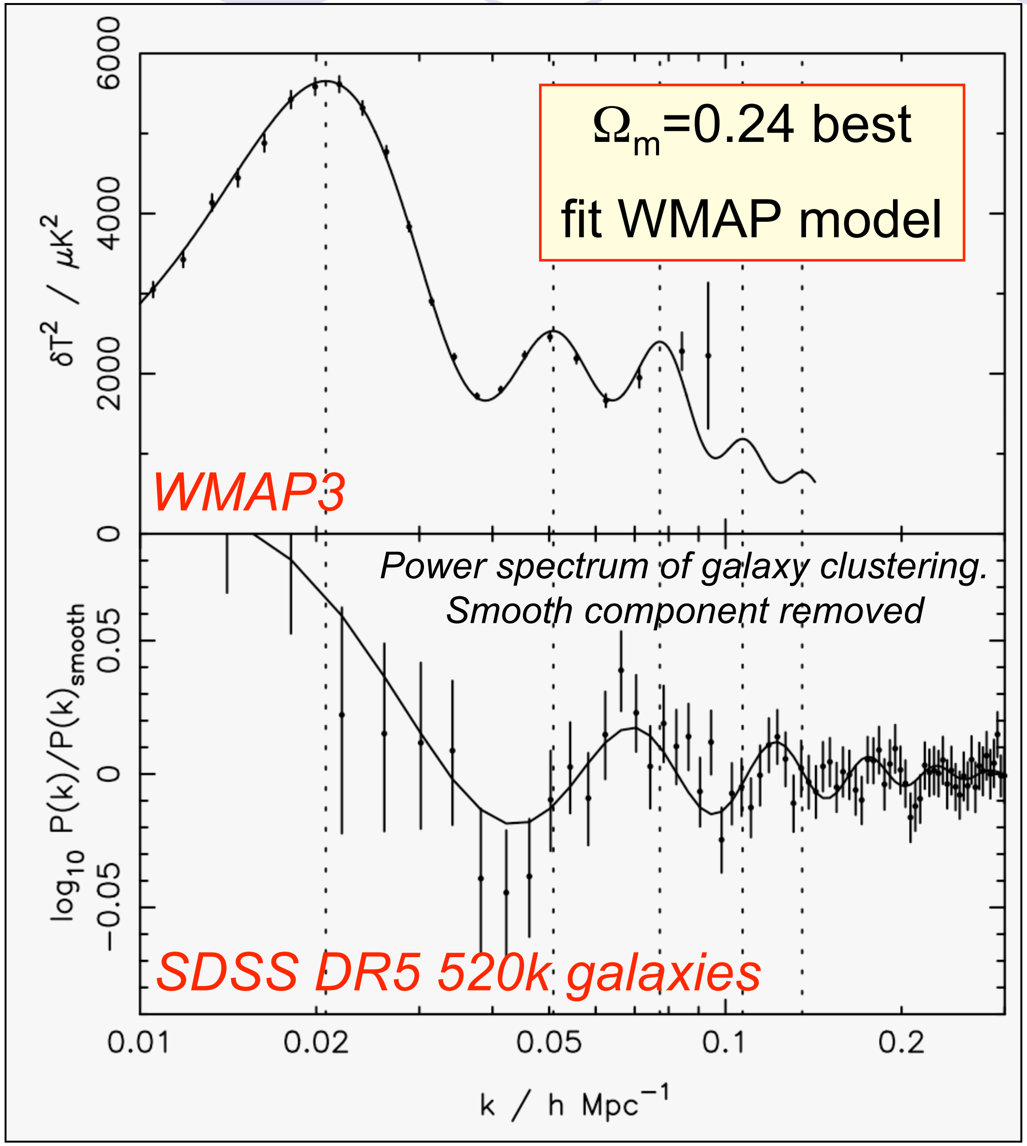


CREDIT: WMAP & SDSS websites

Baryon Acoustic Oscillations



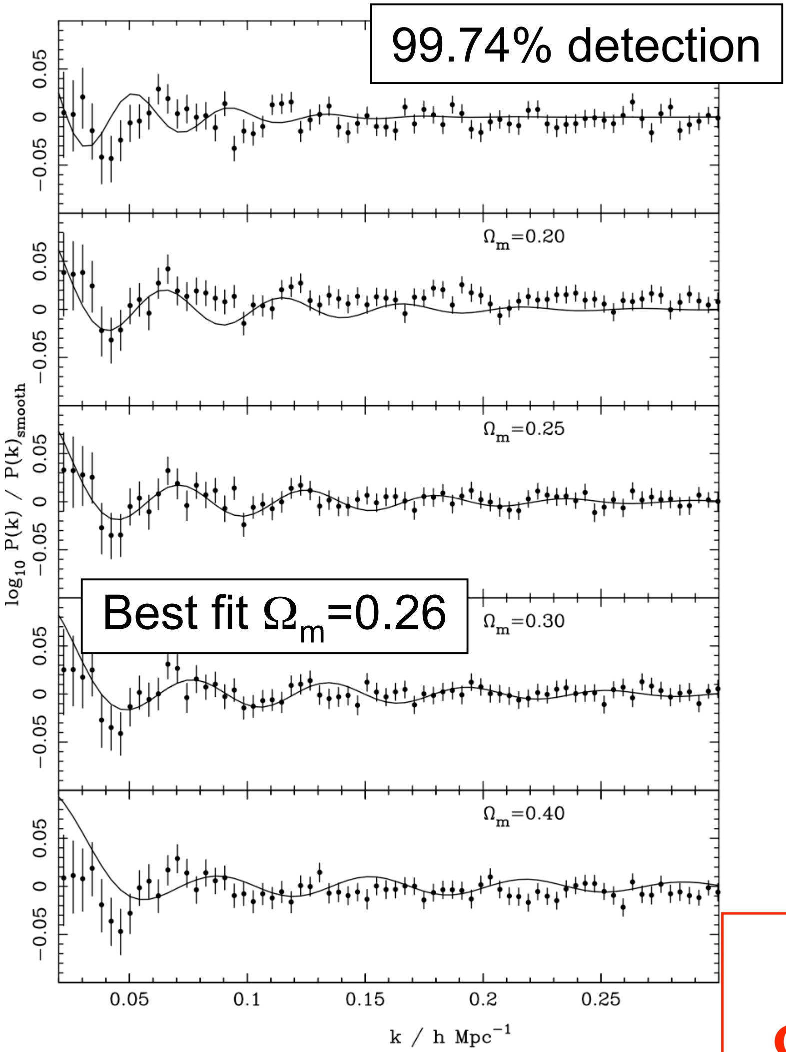
Miller et al. 2001,
Percival et al. 2001,
Tegmark et al. 2001, 2006
Cole et al. 2005,
Eisenstein et al. 2005,
Hutsei 2006,
Blake et al. 2006,
Padmanabhan et al. 2006

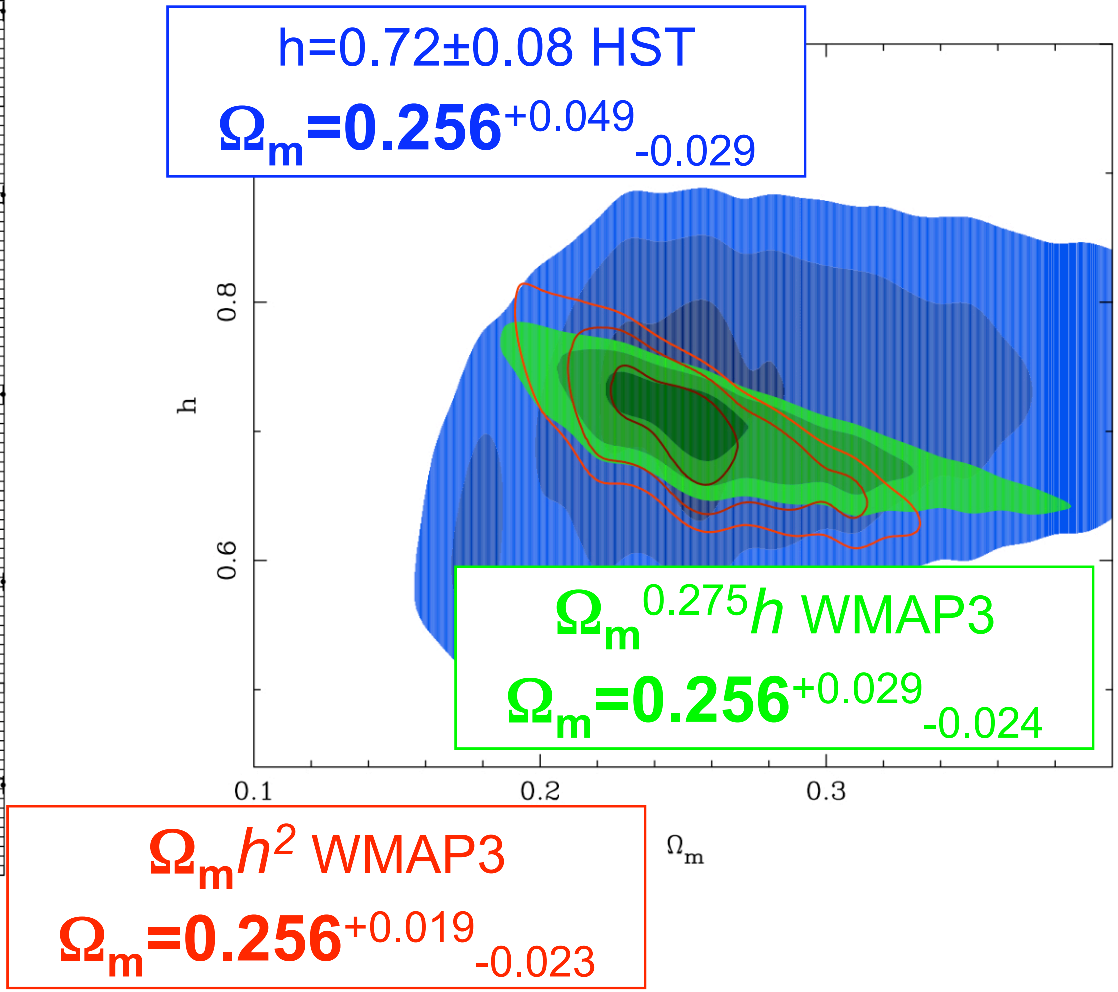
Percival et al. 2006

Cosmological Constraints

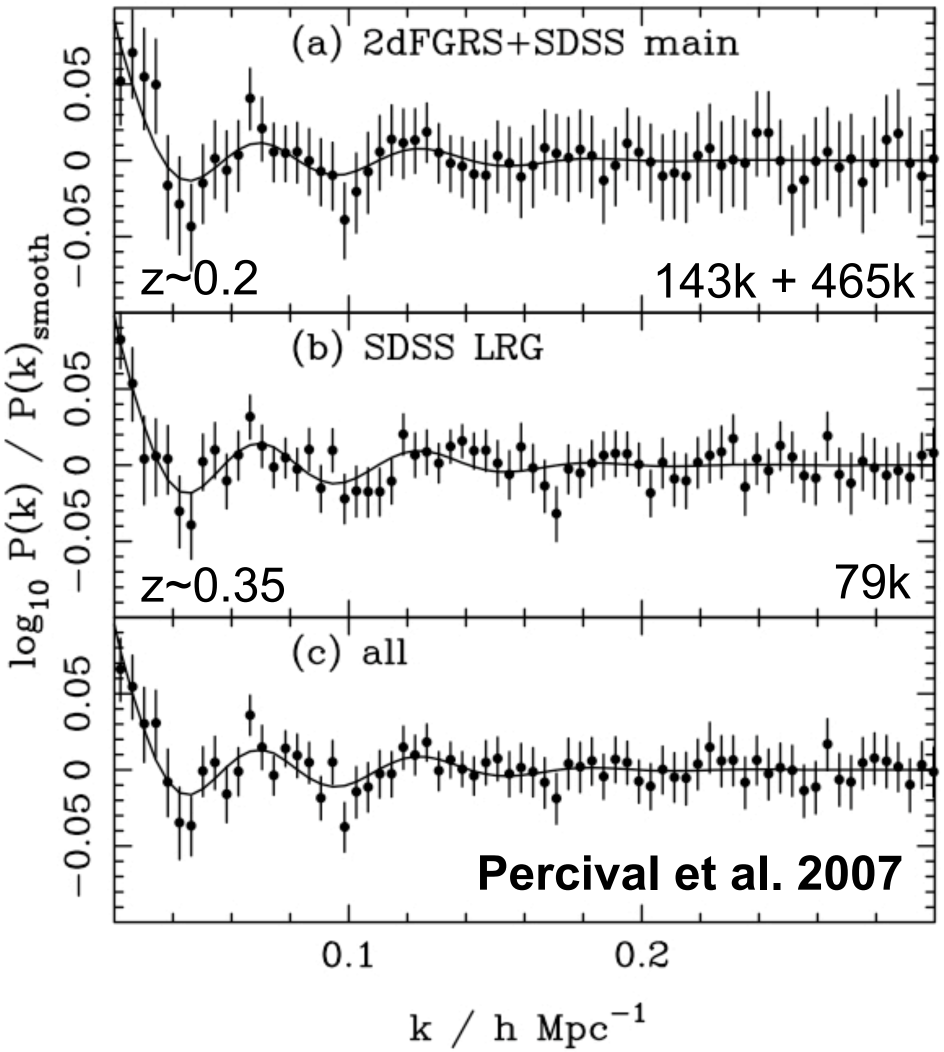
Standard ruler (flat, h=0.73, Ω_b=0.17)

Percival et al. (2006)





BAO with Redshift



Measure ratio of volume averaged distance

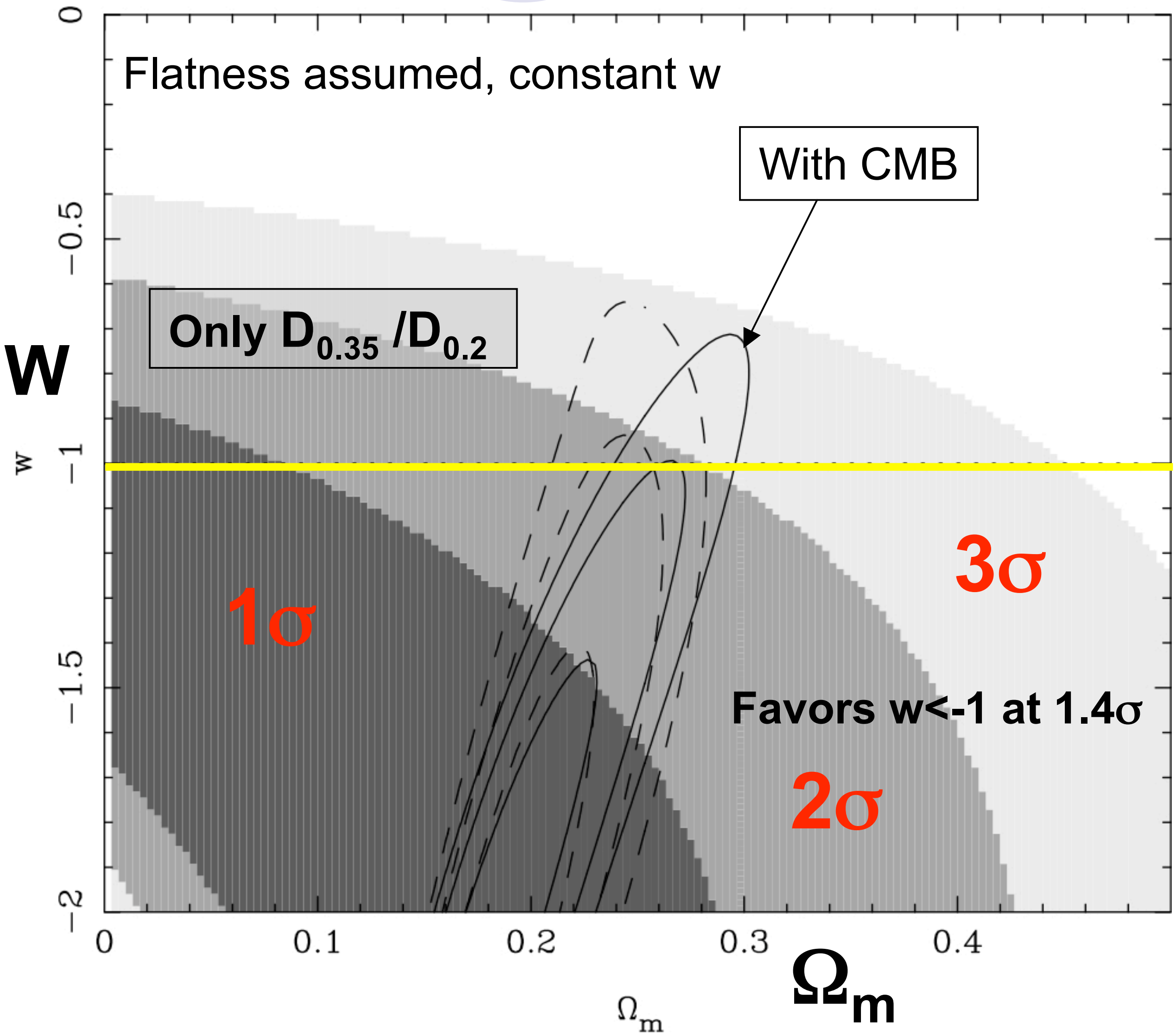
$$D_v(z) = \left[\frac{(1+z)^2 czD_A(z)^2}{H(z)} \right]^{\frac{1}{3}}$$

$D_{0.35} / D_{0.2} = 1.812 \pm 0.060$

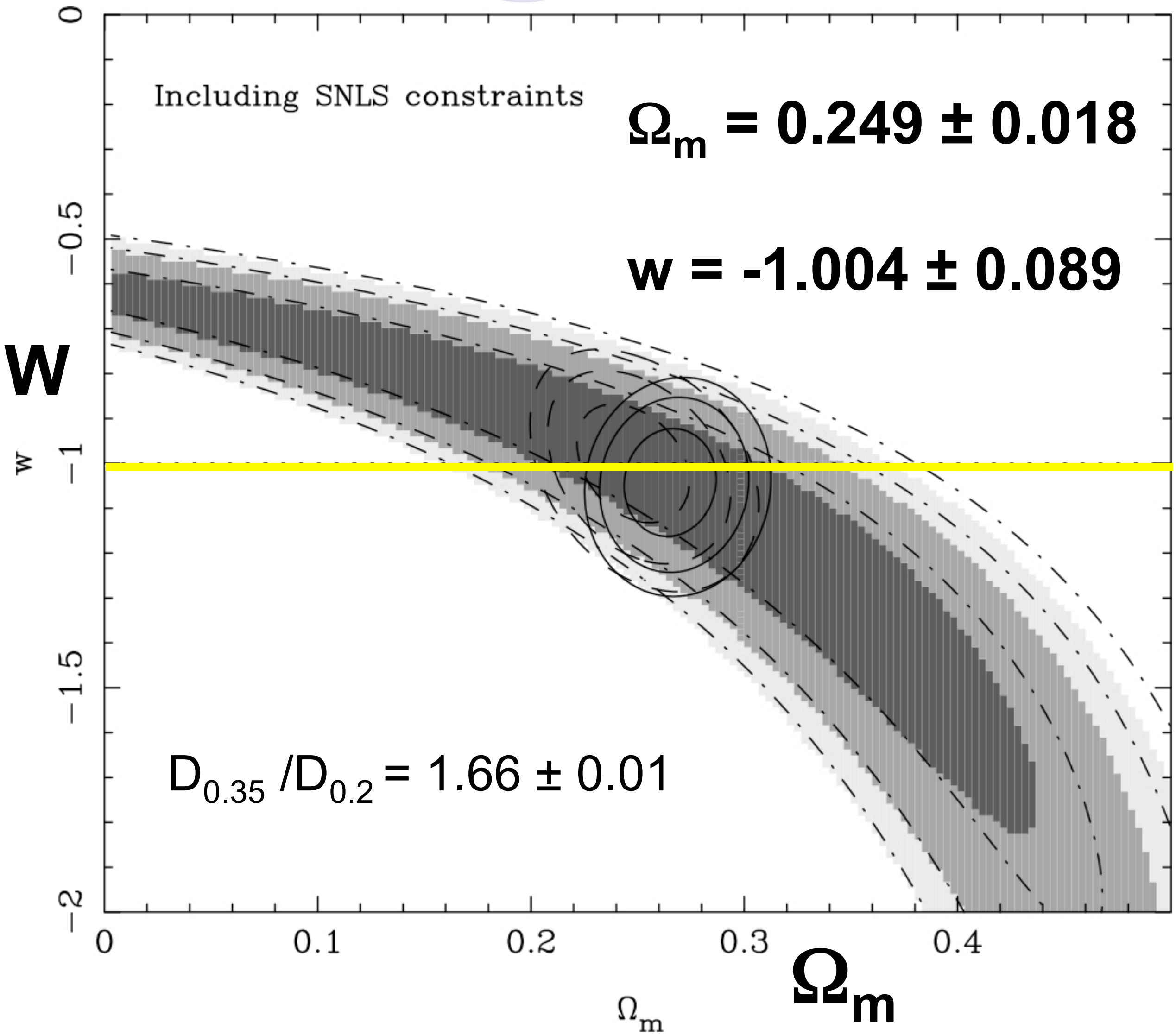
Flat ΛCDM = 1.67

Systematics (damping, BAO fitting) also ~1σ. Next set of measurements will need to worry about this

Cosmological Constraints



Cosmological Constraints



Discrepancy!
What Discrepancy?

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- 2.4σ difference between SN & BAO. The BAO want more acceleration at $z<0.3$ than predicted by $z>0.3$ SNe (revisit with SDSS SNe)

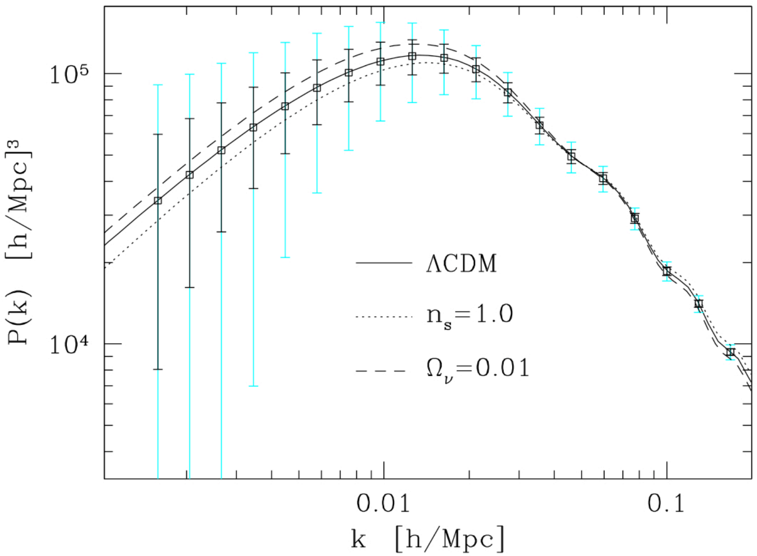
- ~1σ possible from details of BAO damping - more complex then we thought

- Assumption of flatness and constant w needs to be revisited

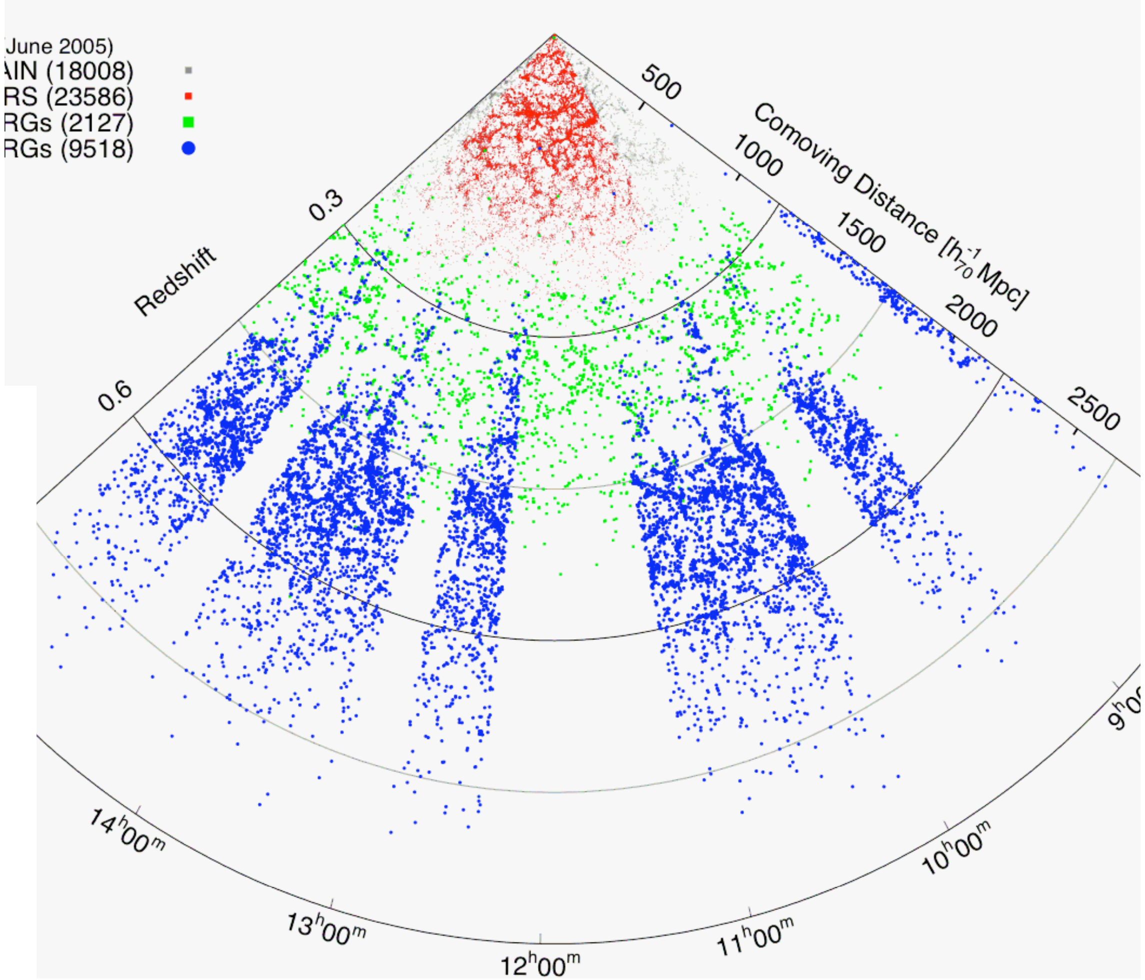
After SDSSII (AS2)

Baryon Oscillation Spectroscopic Survey (BOSS)

- Measure distance to ~1% at z=0.35 and z=0.6
- 10000 deg^2 with 1.5m LRGs to 0.2<z<0.8
- 160k quasars at 2.3<z<2.8
- Starting 2009
- h to 1% with SDSS SNe

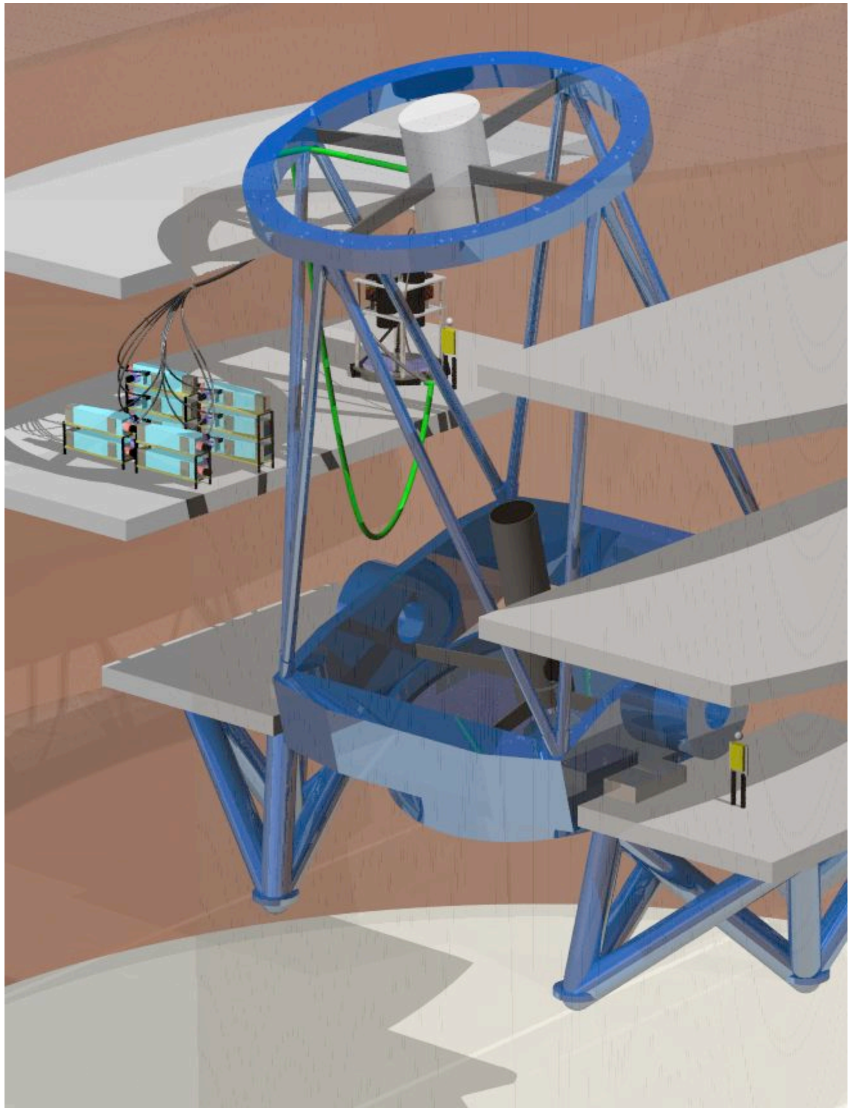


2SLAQ (www.2slaq.info)



WFMOS

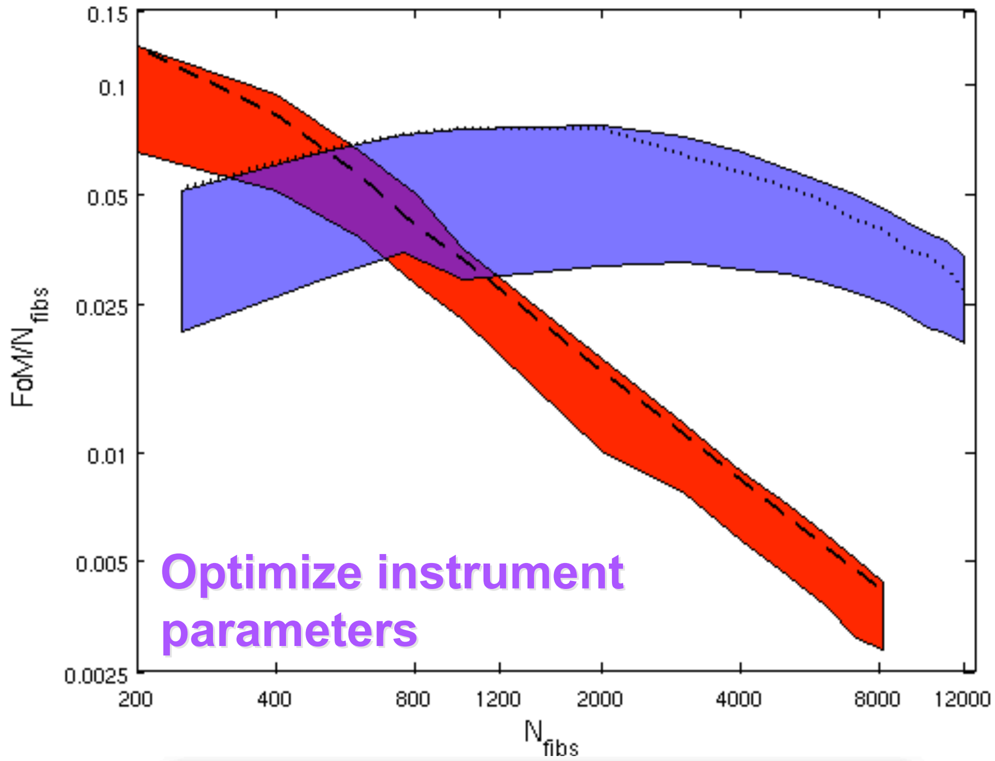
- Proposed MOS on Subaru via an international collaboration of Gemini and Japanese astronomers
- 1.5deg FOV with 4500 fibres feeding 10 low-res spectrographs and 1 high-res spectrograph
- ~20000 spectra a night *(2dfGRS at z~1 in 10 nights)*
- $>10^5$ redshifts for photo-z's (Peacock et al. report)
- DE science, Galactic archeology, galaxy formation studies and lots of ancillary science from database
- Design studies underway; on-sky by 2013
- Next Generation VLT instruments; meetings in Marseilles & Garching

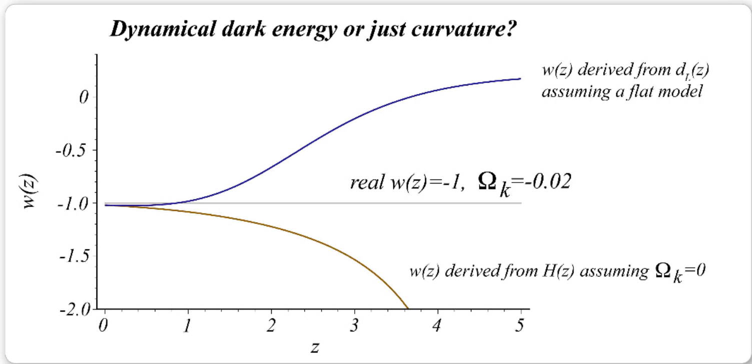


WFMOS Surveys

- Parkinson et al. (2007)
- Emission-line galaxies
- 5600 deg^2 at z=1.1 (*dz* = 0.3)
- > 5 million galaxies
- 150 deg^2 at z=3.15 (*dz* = 0.2)
- FoM an order of magnitude larger than SDSS
- Optimum is broadly peaked and insensitive to other surveys

- Now investigating curvature and other w(z) models (Clarkson et al. 2007)





Integrated Sachs-Wolfe Effect

Dark Energy effects the rate of growth of structure in Universe

- Poisson equation with dark energy:

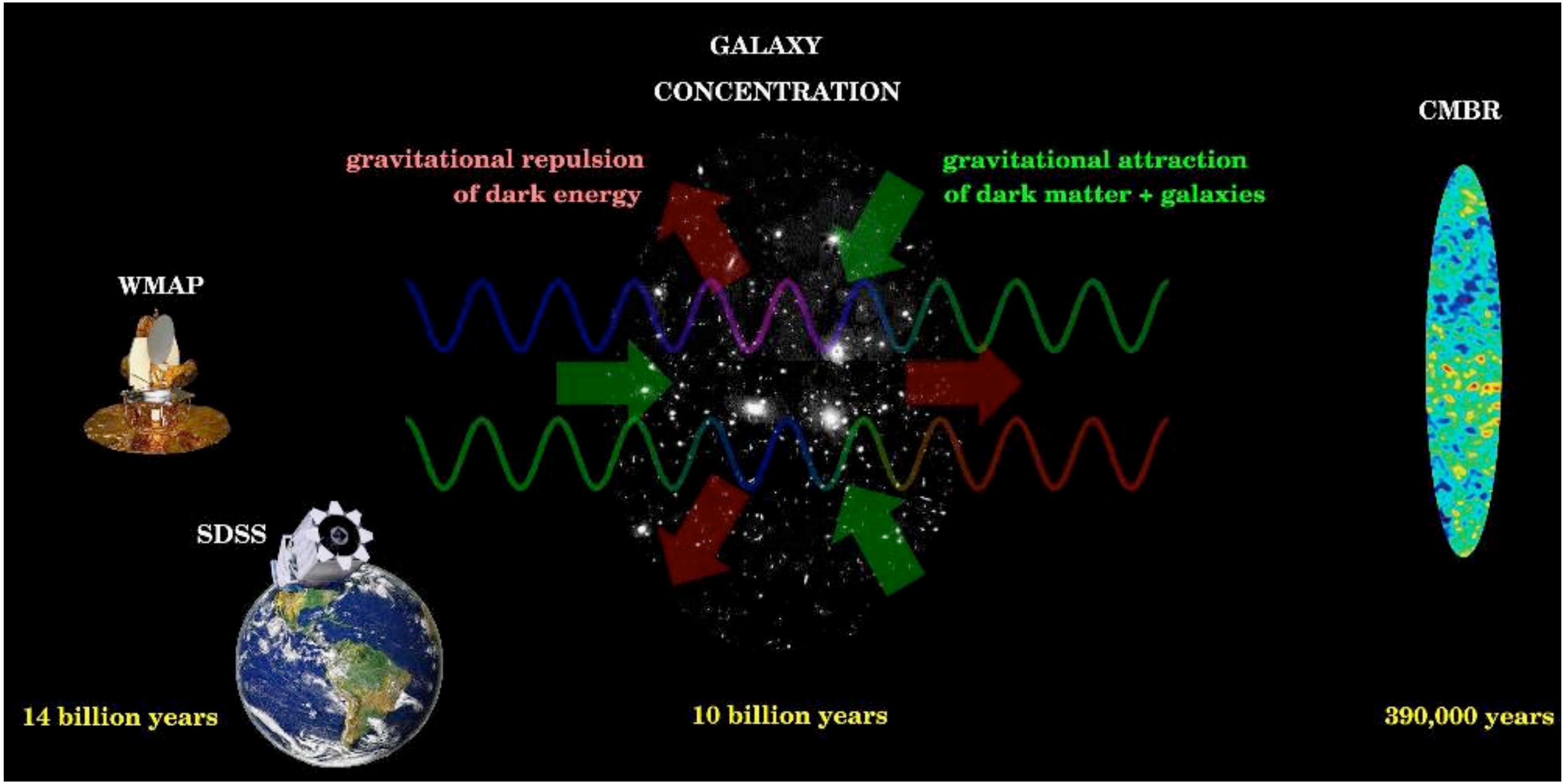
$$k^2\Phi' = -4\pi G \frac{d}{d\eta}\left[a^{-1}(\delta\rho_m + \delta\rho_{DE})\right]$$

- In a flat, matter-dominated universe (CMB tells us this), then density fluctuations grow as:

$$\delta\rho_m \propto a \Rightarrow d\Phi / d\eta = 0$$

- Therefore, curvature or DE gives a change in the gravitational potential

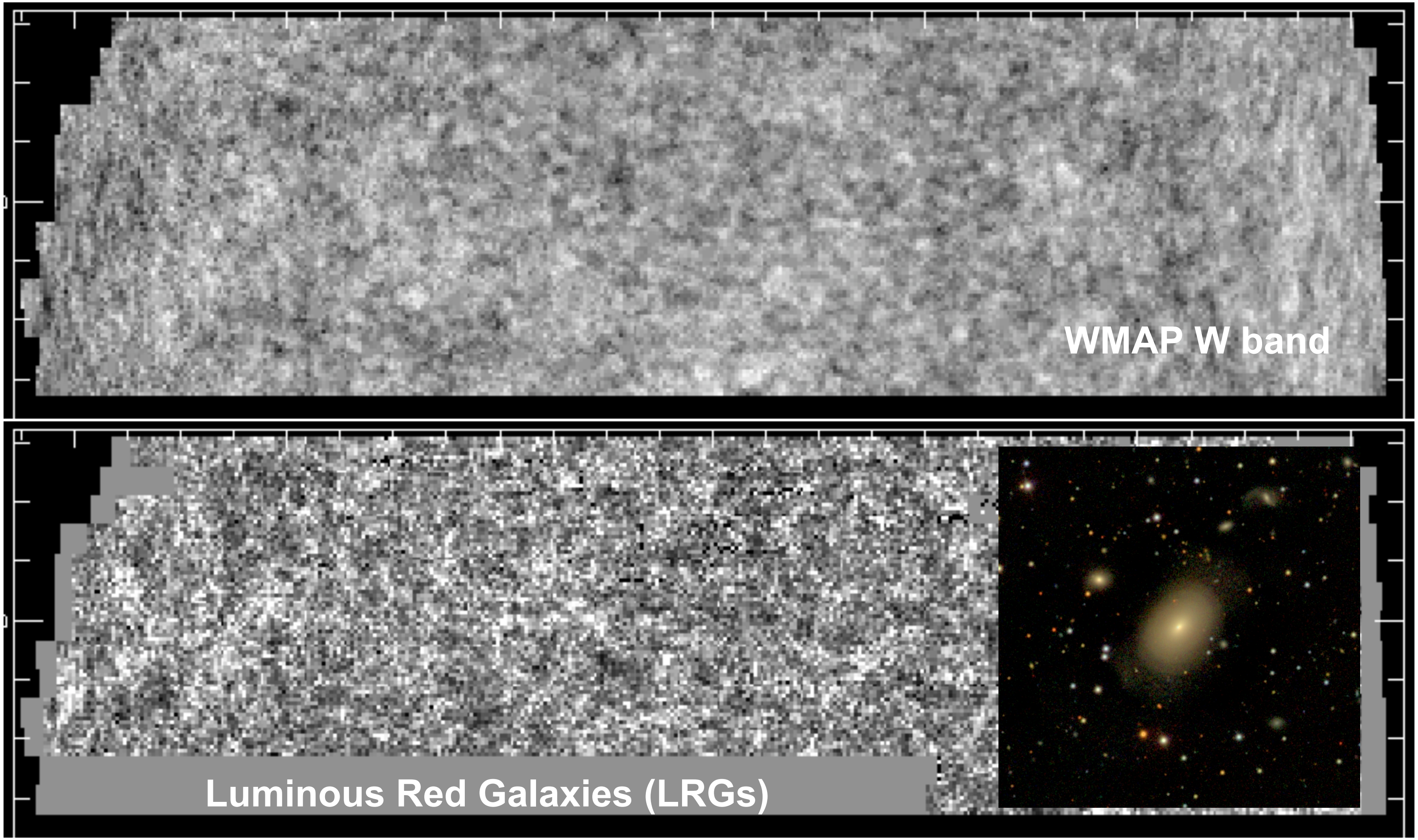
Experimental Set-up



Nolta et al, Boughn & Crittenden, Myers et al, Afshordi et al, Fosalba et al., Gaztanaga et al., Rassat et al.

WMAP-SDSS Correlation

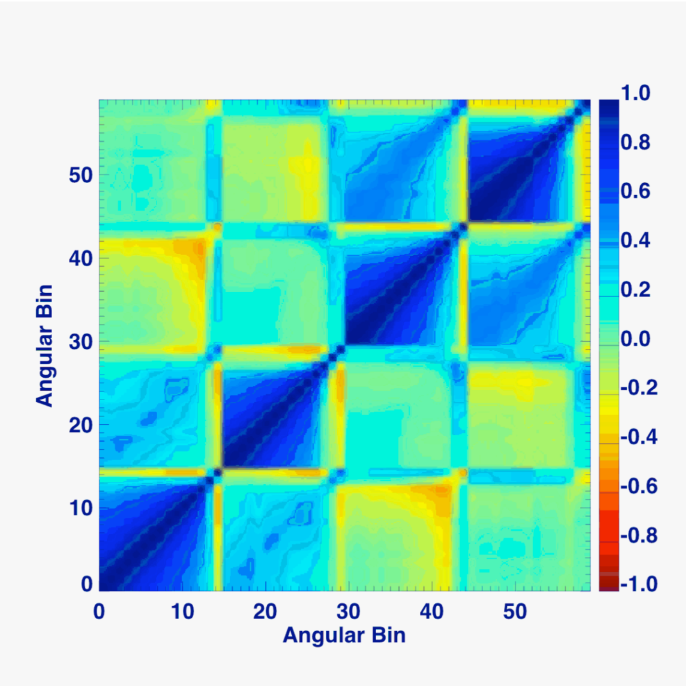
No signal in a flat, matter-dominated Universe

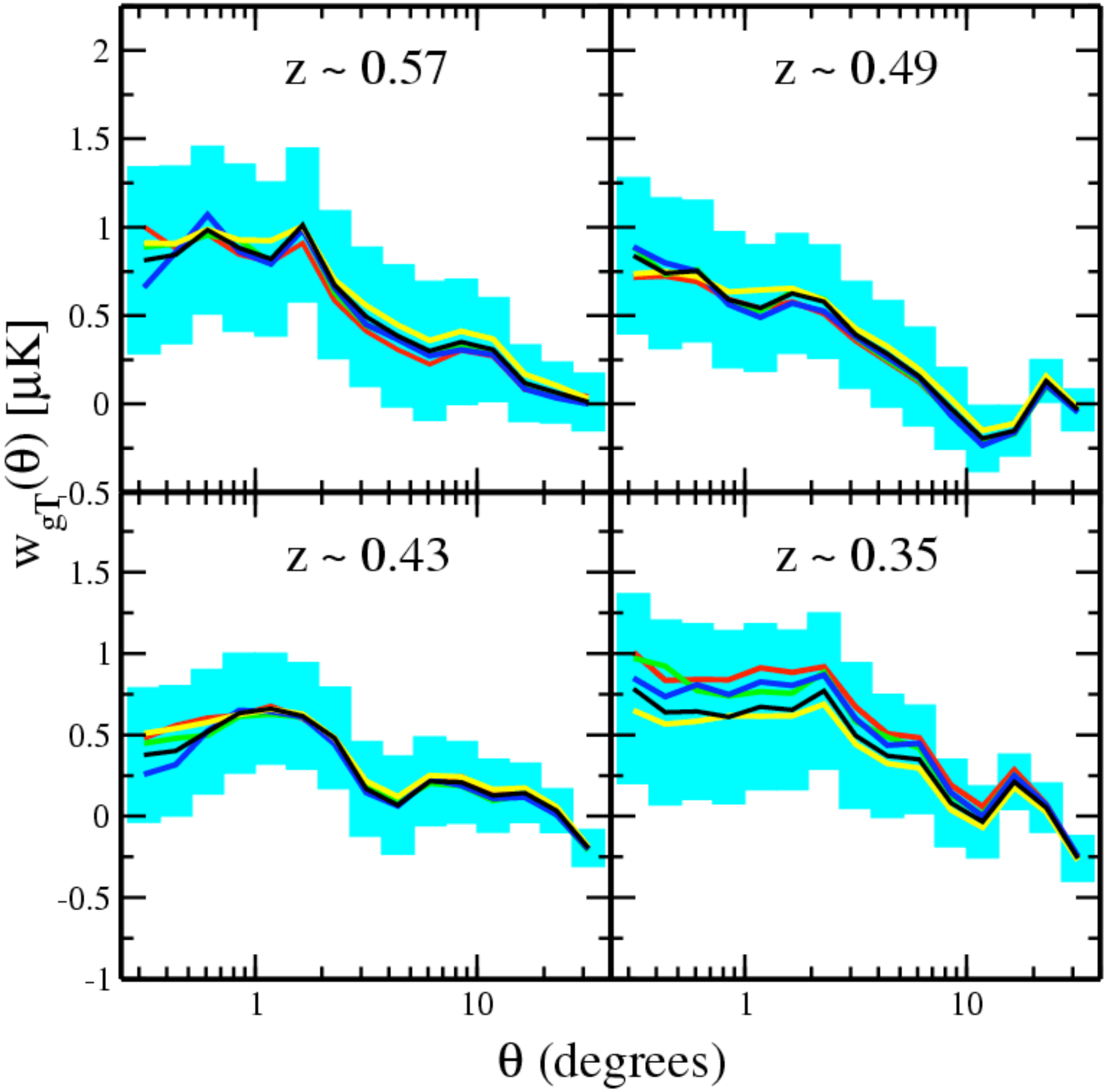


ISW Detected

Update of the Scranton et al. (2003) paper

- 6300 sq degrees
- Achromatic
- 5σ detection





Giannantonio et al. (2006)

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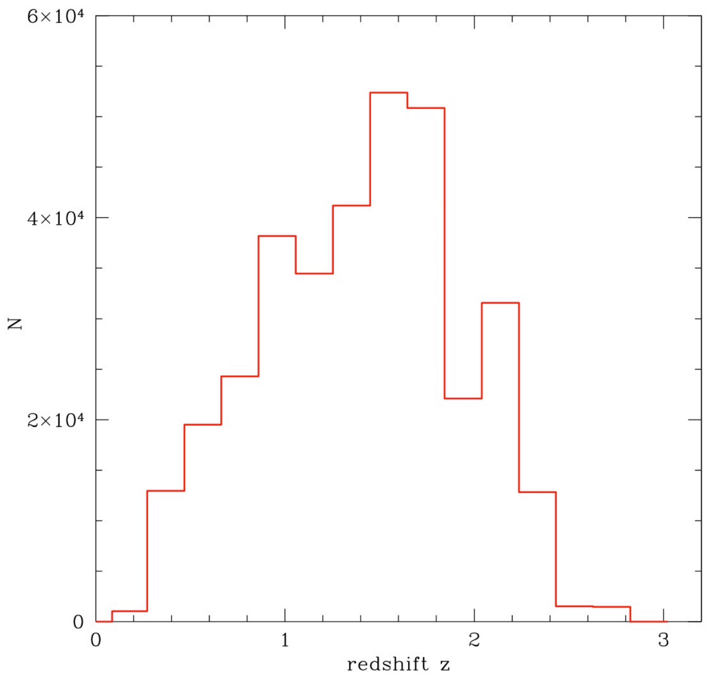
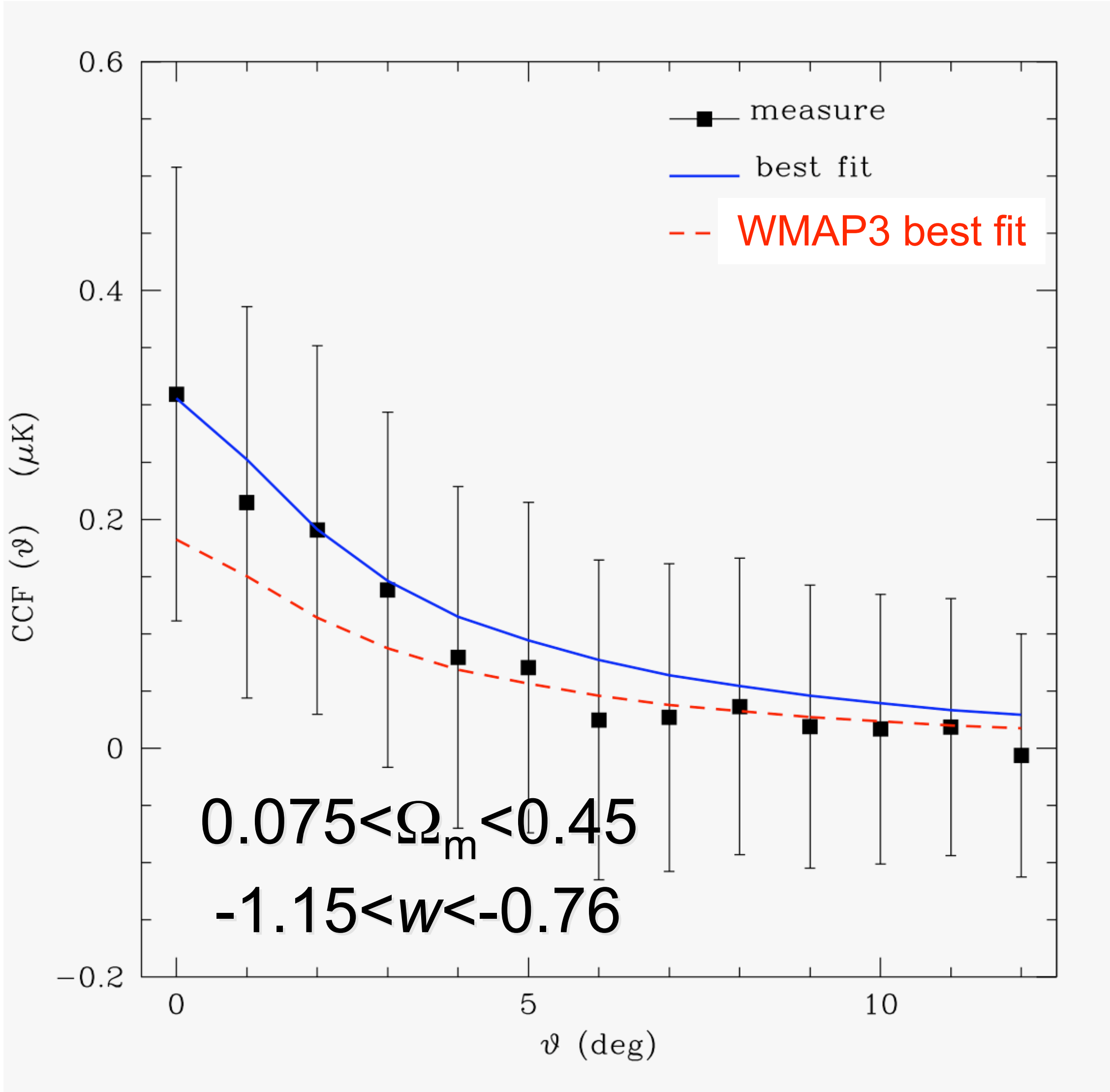
Cross-correlation of WMAP3 and SDSS quasars



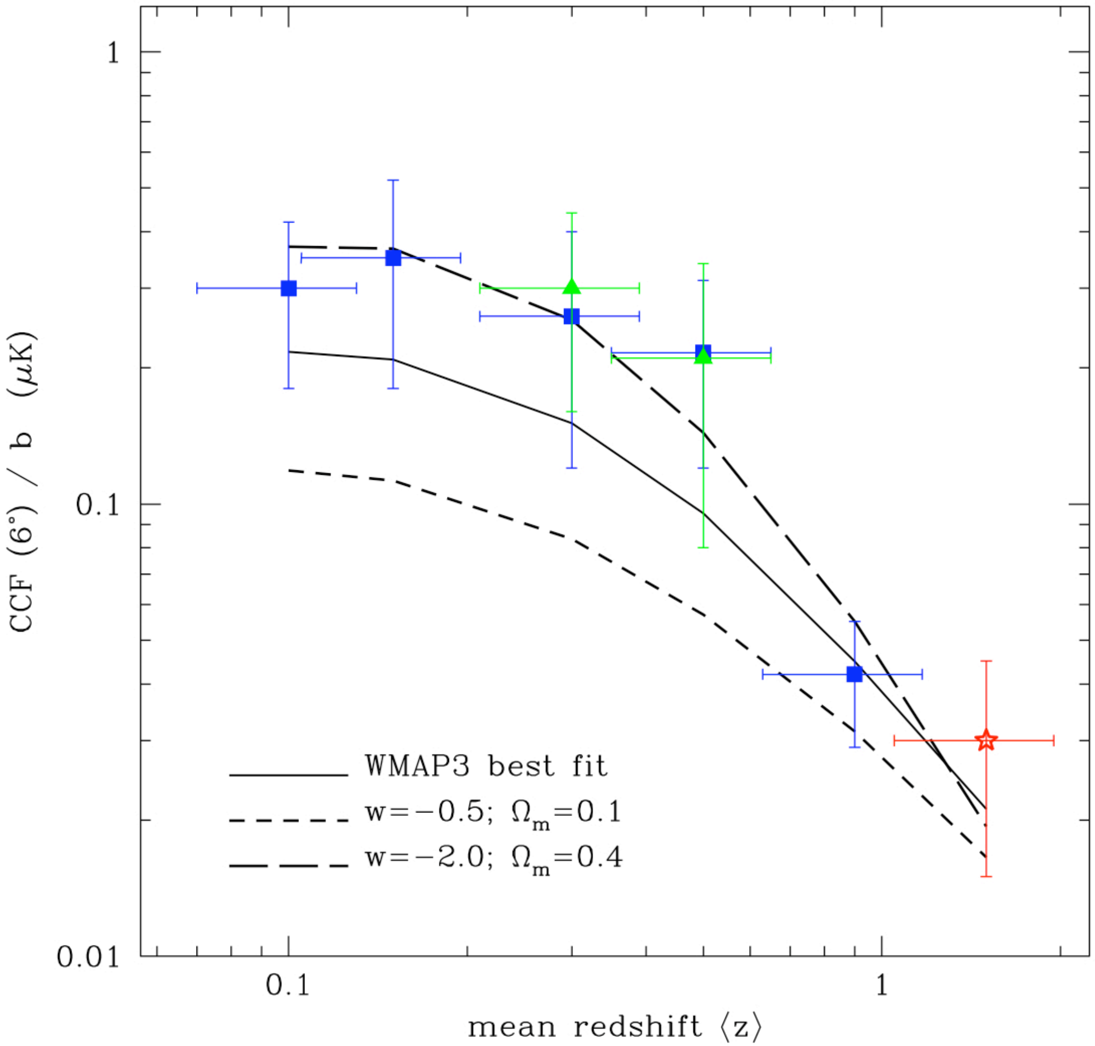


$0.075<\Omega_m<0.45$

$-1.15<w<-0.76$

Detection of DE at z>1

Evolution of DE

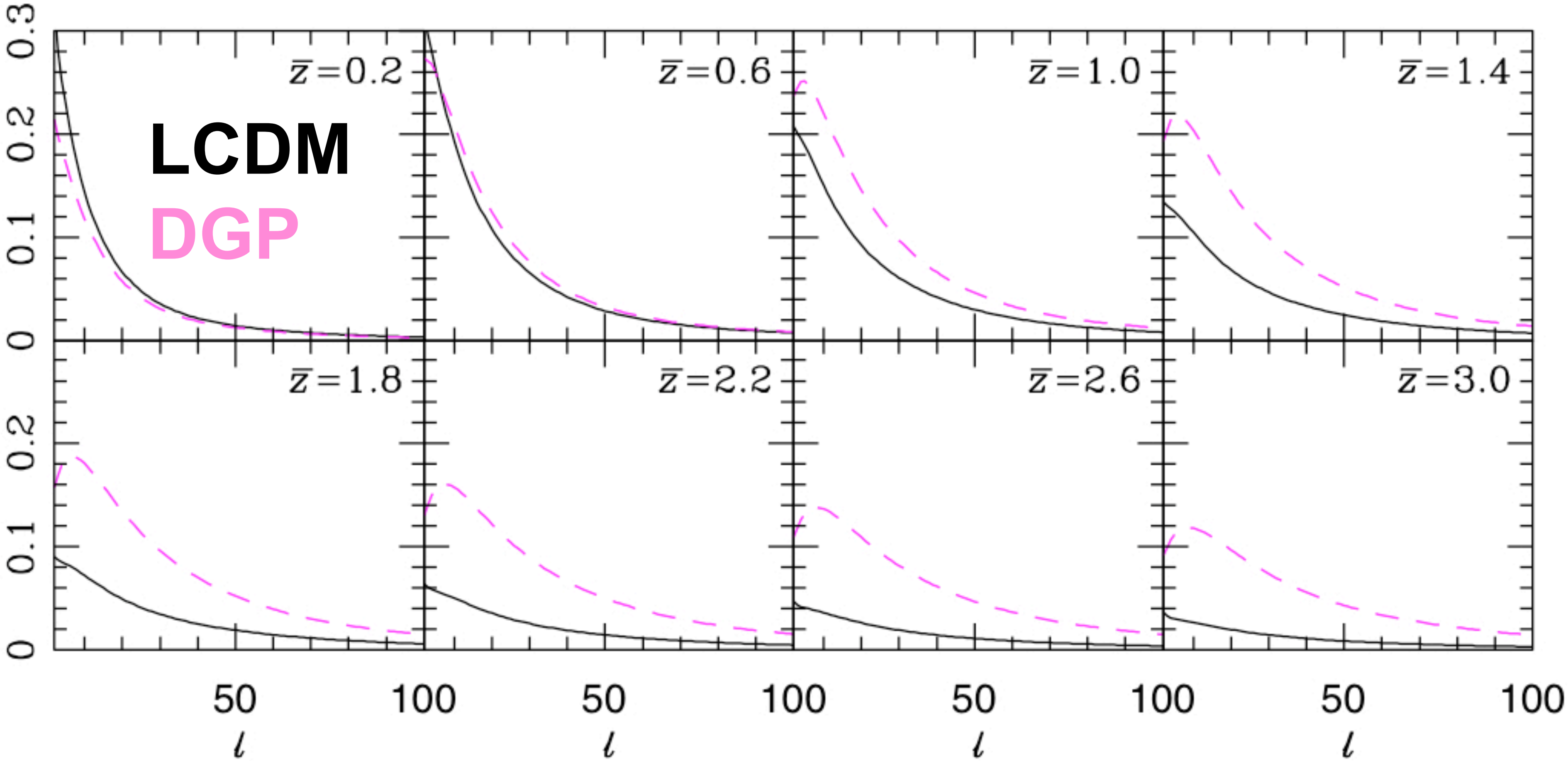


Consistent with w=-1

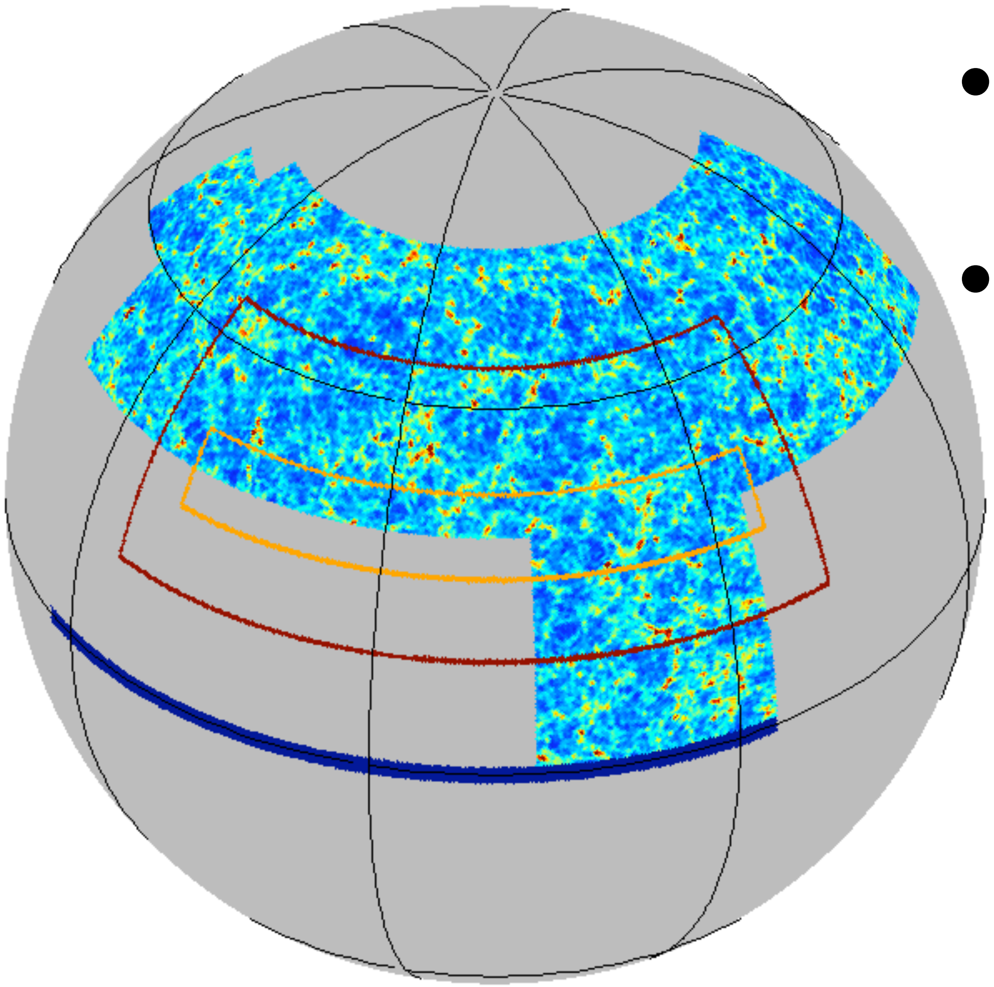
Rules out models
$\Omega_{DE}(z=1.5) > 0.5$

Modified Gravity

Song et al. (2006)



DES+VISTA



- Give photo-z's to z~2 with $\sigma < 0.1$
- ISW will be competitive with SNAP for non-constant w (Pogosian et al. 2005)

Conclusions

- SDSS SN Survey on target to deliver >500 Ia's
  DES will exploit Ia's in elliptical galaxies
- SDSS BAO measures are delivering sub 10% measurements of cosmological parameters
- 2σ discrepancy with SNe? Curvature / w(z)?
- WFMOS and AS2 will move BAO to 1% level
- ISW will be competitive for investigating new physics (w(z), MG, sound speed, DE clustering)