# Wiggles and Bangs

*SDSS, DES, WFMOS teams*

# 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*

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**SDSS / SDSS-II / AS2**

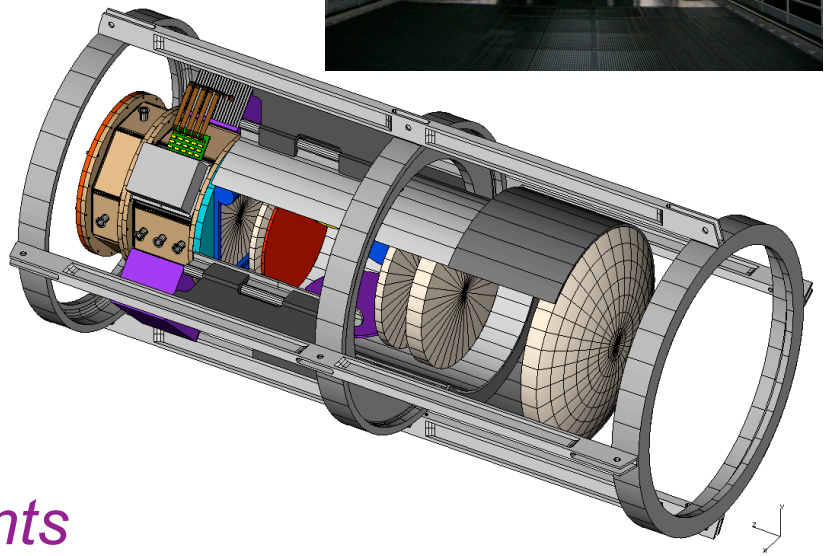
*SDSS SN Survey*

*Baryon Acoustic Oscillations (BAO)*

*ISW (ask me)*

**Dark Energy Survey (DES)**

*New SN Survey*



**WFMOS**

*Future BAO measurements*

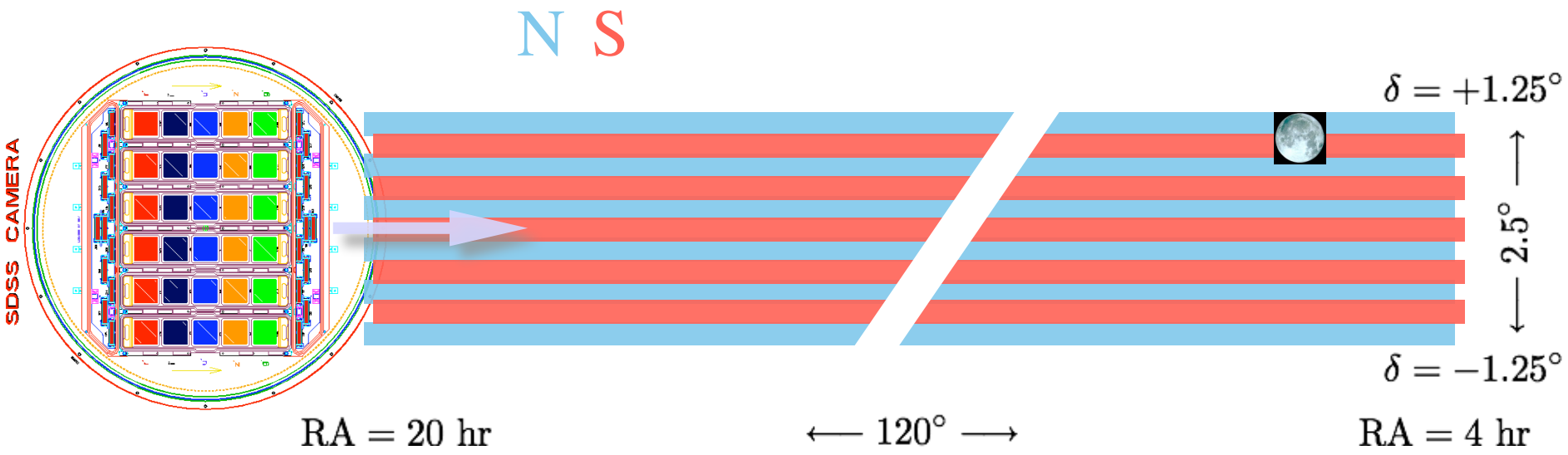
# SDSS

www.sdss.org.uk/dr5

DR5: Million spectra, 8000 sq degs

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

# SDSS SN Survey

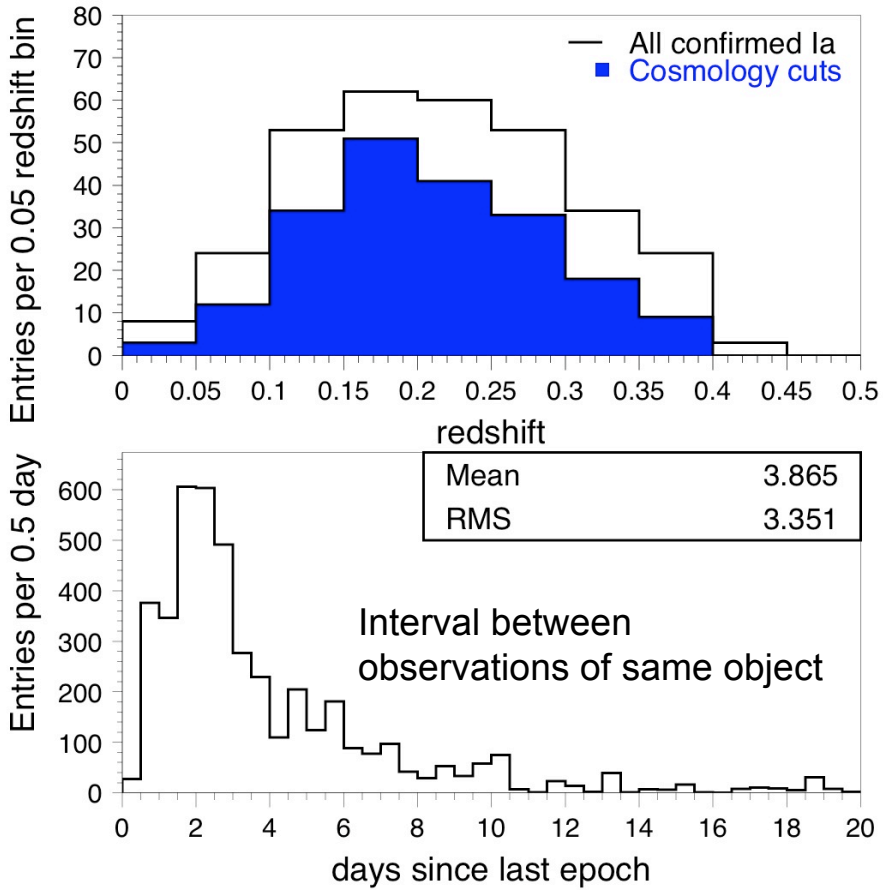



Use the SDSS 2.5m telescope

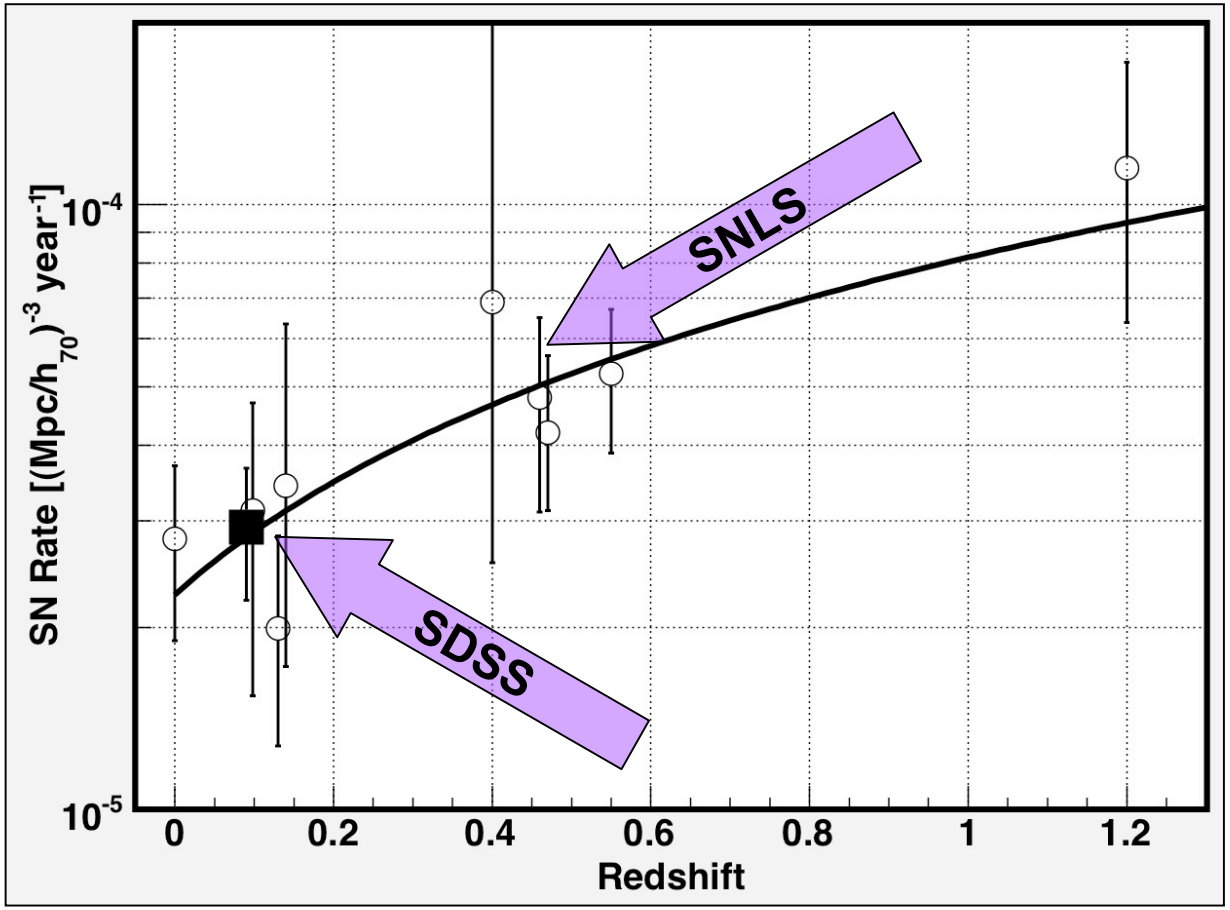
- September 1 - November 30 of 2005-2007
- Scan 300 square degrees of the sky every 2 days
- Data reduced in less than 24hours
- “Stripe82” (UKIDSS data)
- Many telescopes used for spectroscopic follow-up (NTT, NOT)

# 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

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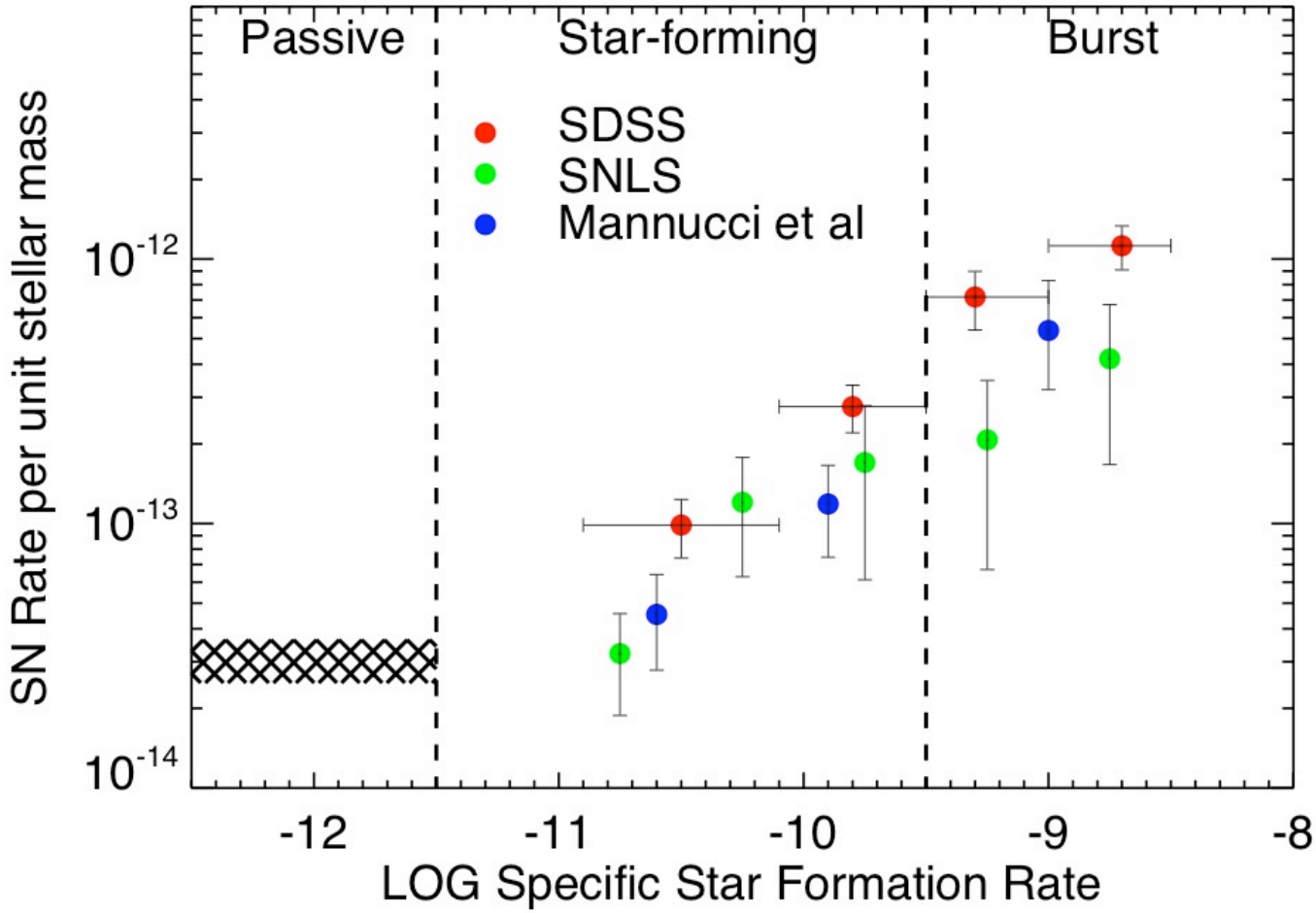

# Cosmology

*Still not ready, but close*

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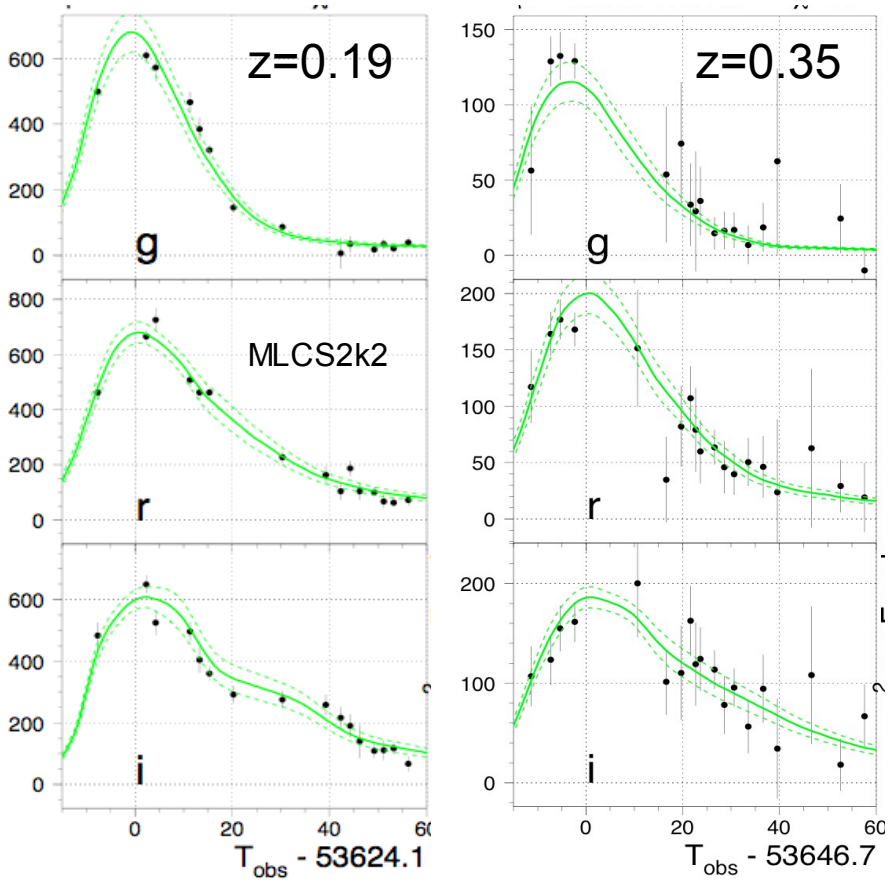
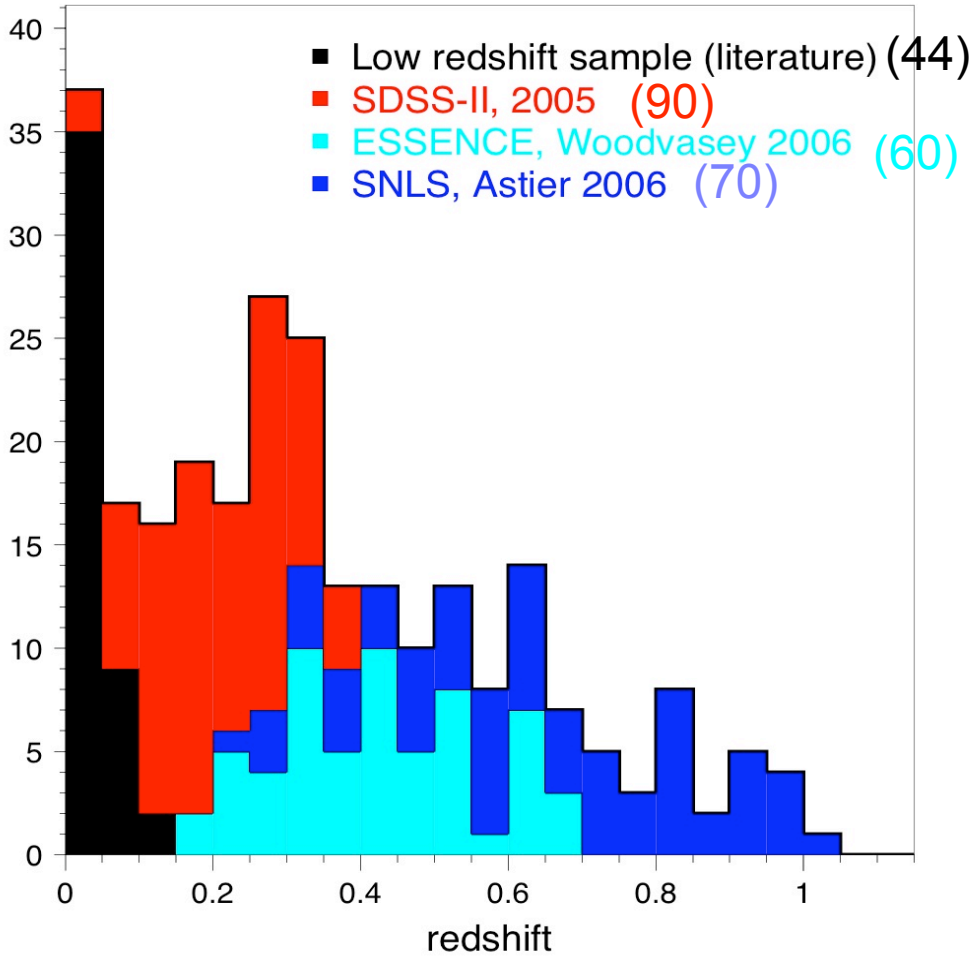



*i-band causing the problem*



# DES SN Survey

*SN surveys are systematics limited*

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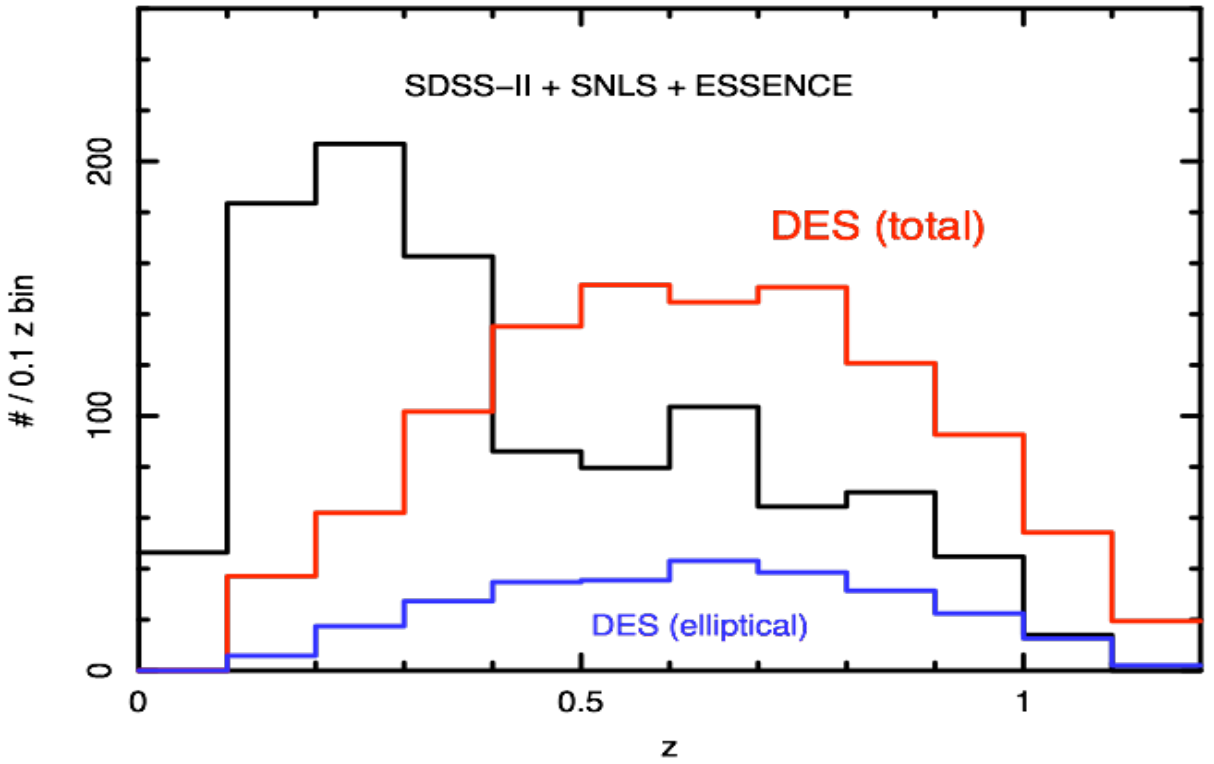
*Provide a large sample of high-redshift SN Ia (redshift > 0.7) with good rest-frame g-band (observer-frame z-band) light curves . Possible with enhanced red sensitivity of DECam.*

- 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*

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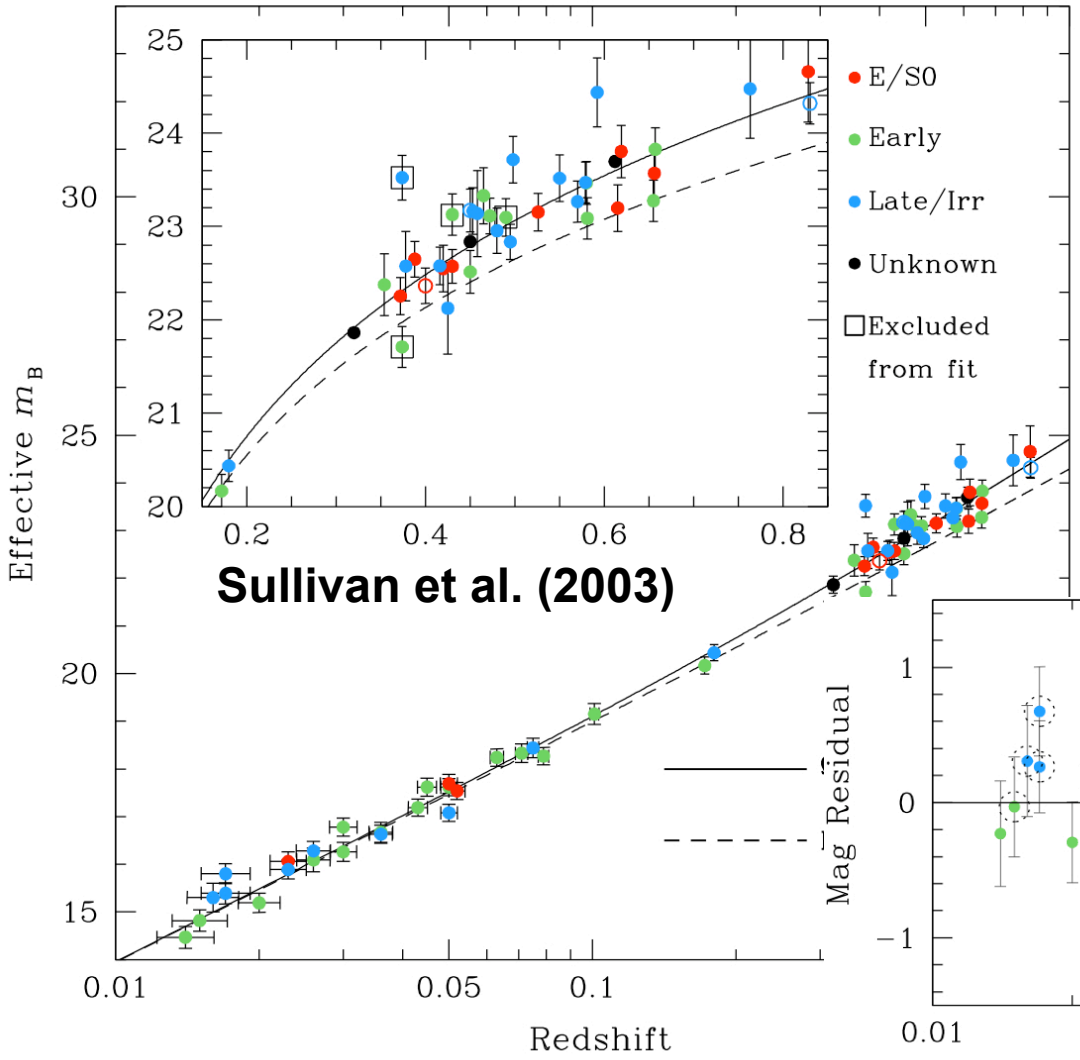


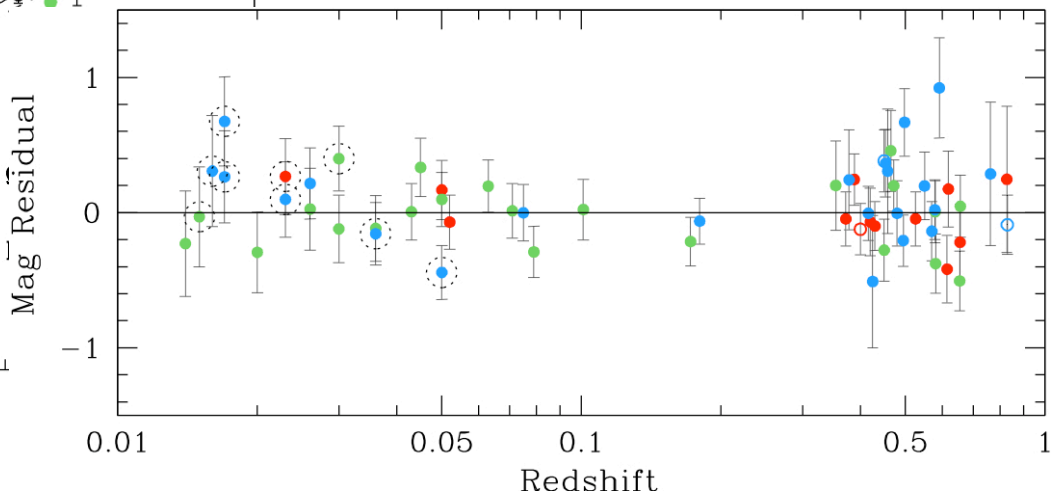


Focus spectroscopy on 300 Ia's in elliptical hosts as less dust and no SNII

Target high-z clusters

Monte Carlos simulations underway

# DES SN Survey

*Forecasts*

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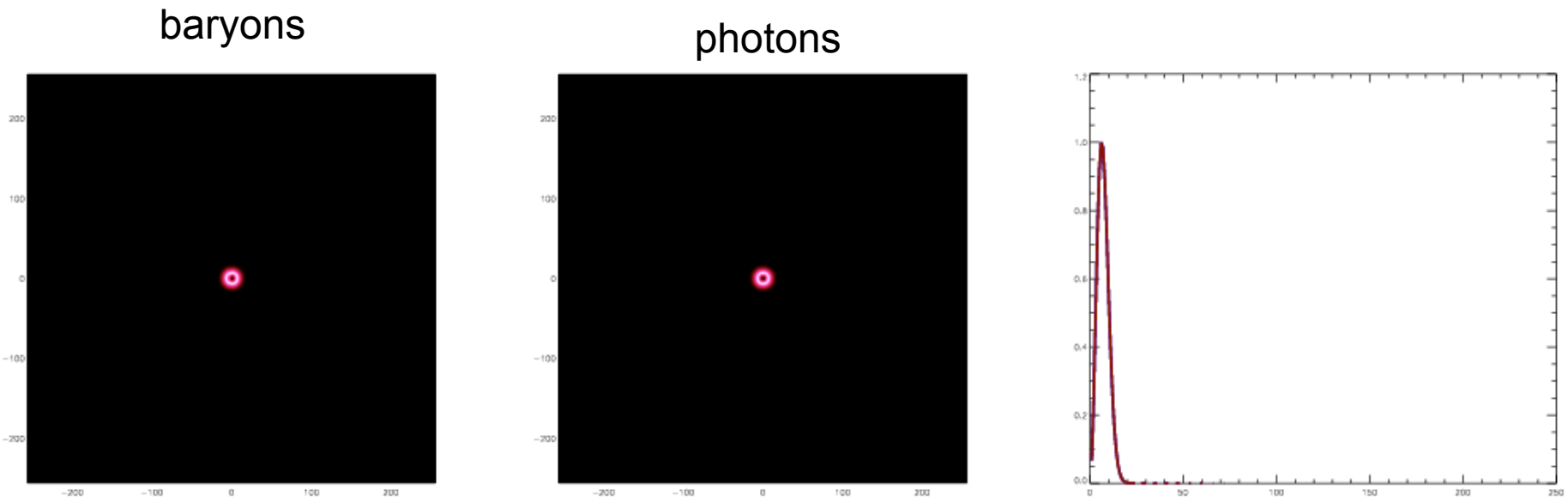
DETF FoM

| 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




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

**Courtesy of Martin White**

# Baryon Acoustic Oscillations

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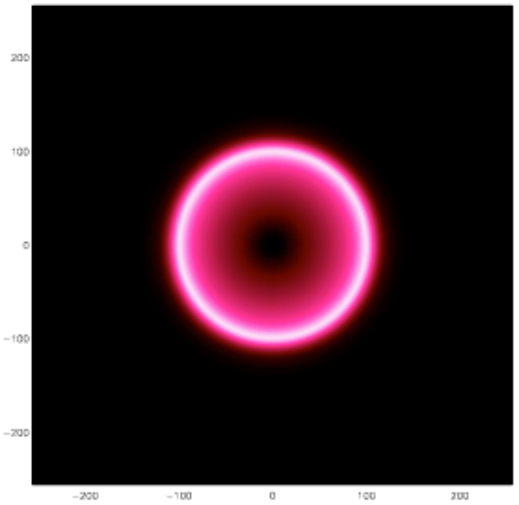
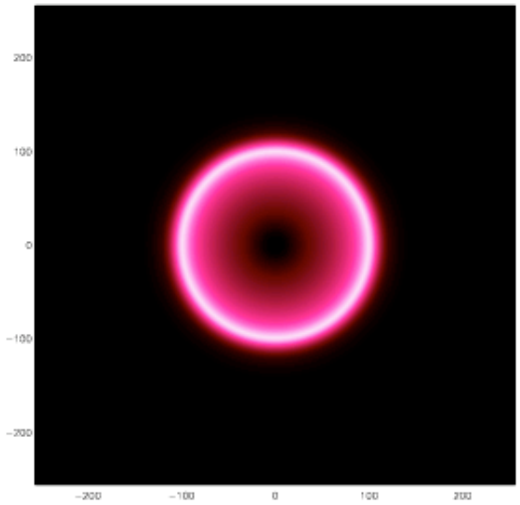
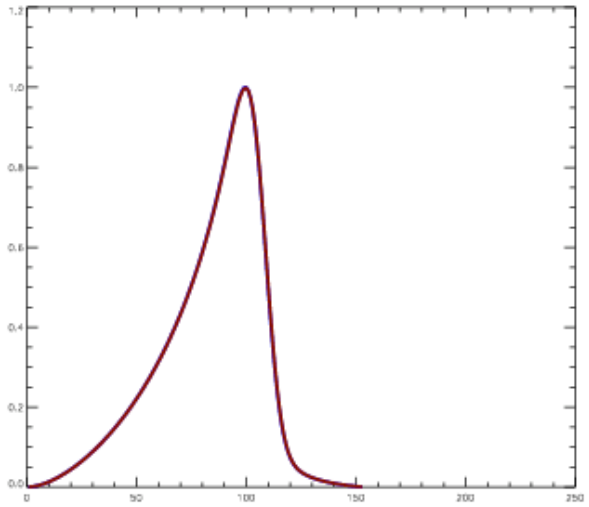
baryons

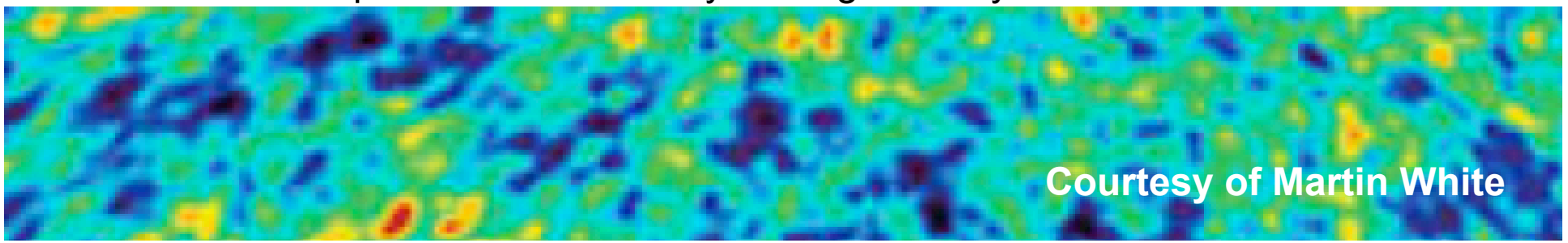


photons





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



# Baryon Acoustic Oscillations

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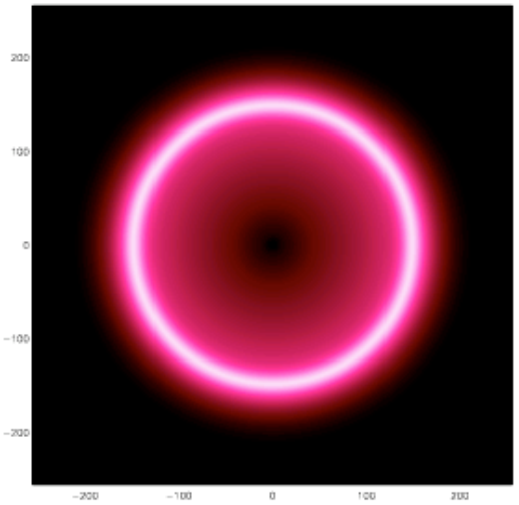
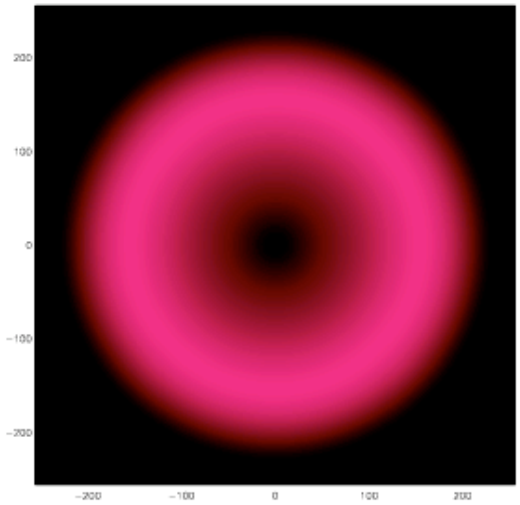
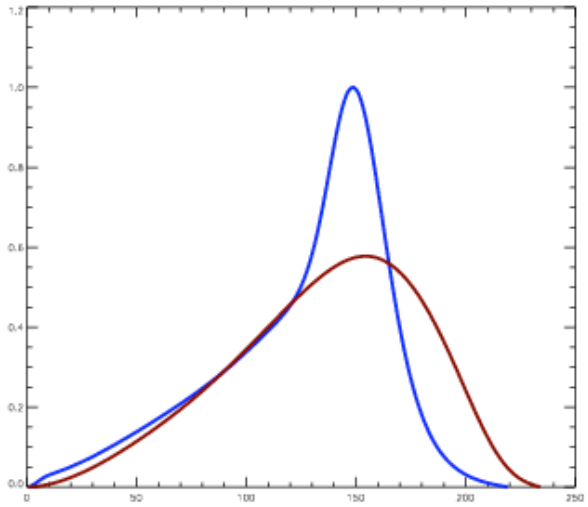
baryons



photons





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

**Courtesy of Martin White**

# Baryon Acoustic Oscillations

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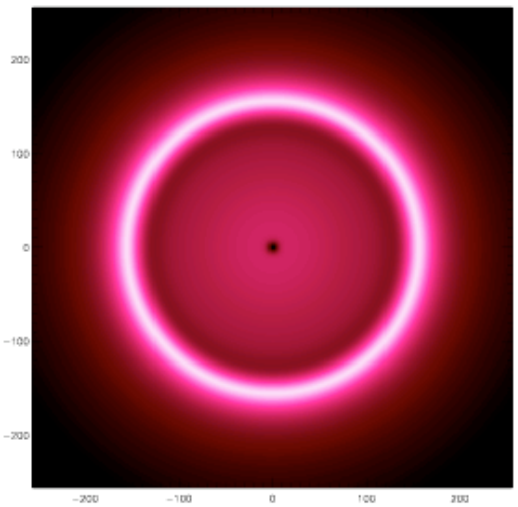
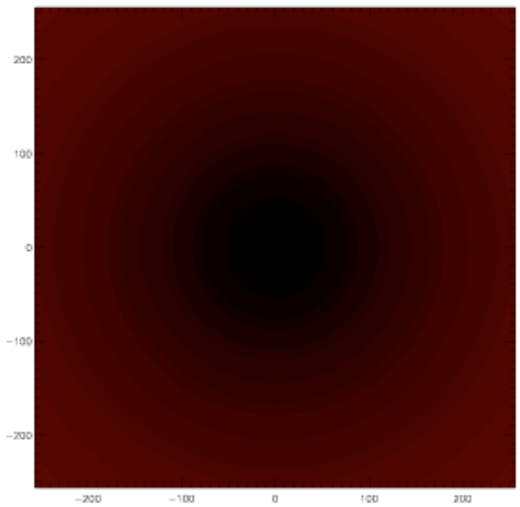
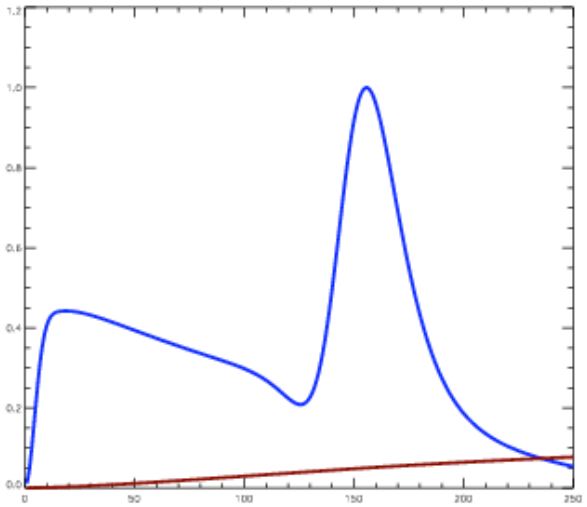
baryons

photons







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

**Courtesy of Martin White**

# Baryon Acoustic Oscillations

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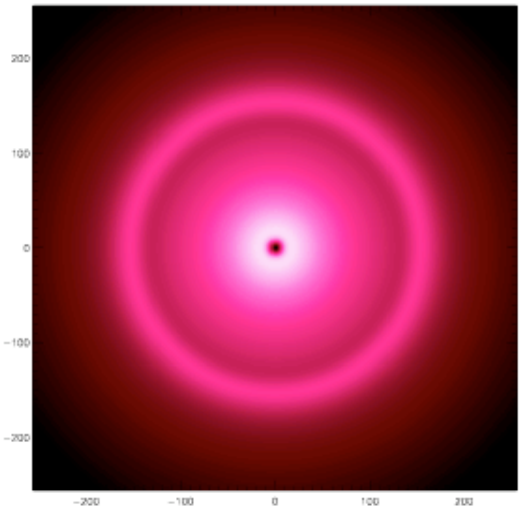
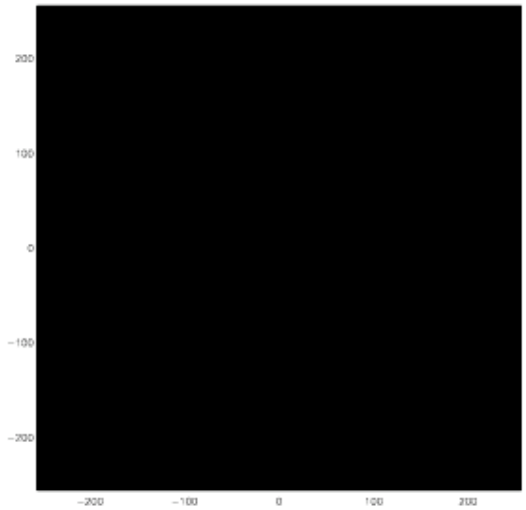
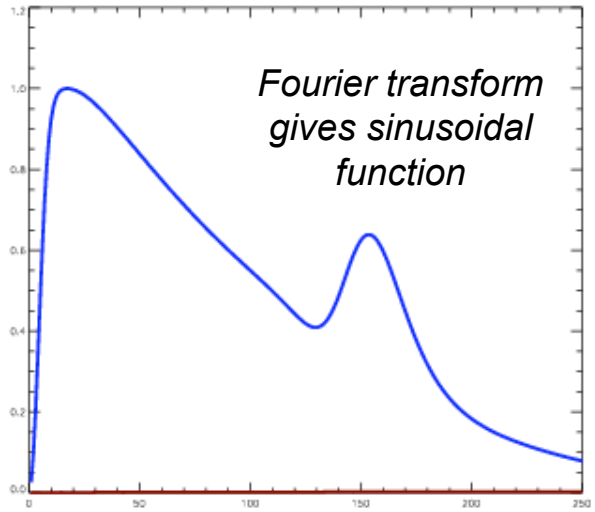
baryons



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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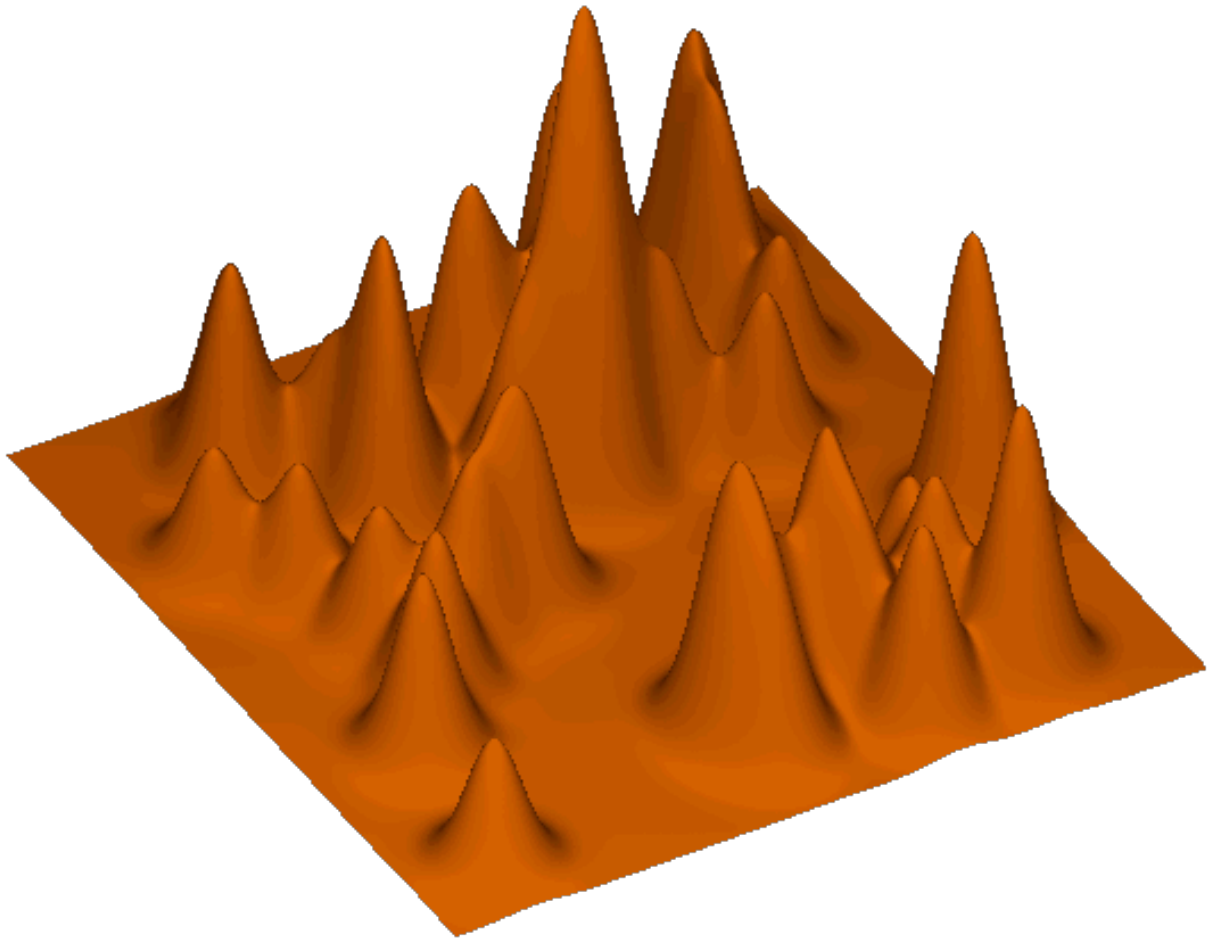
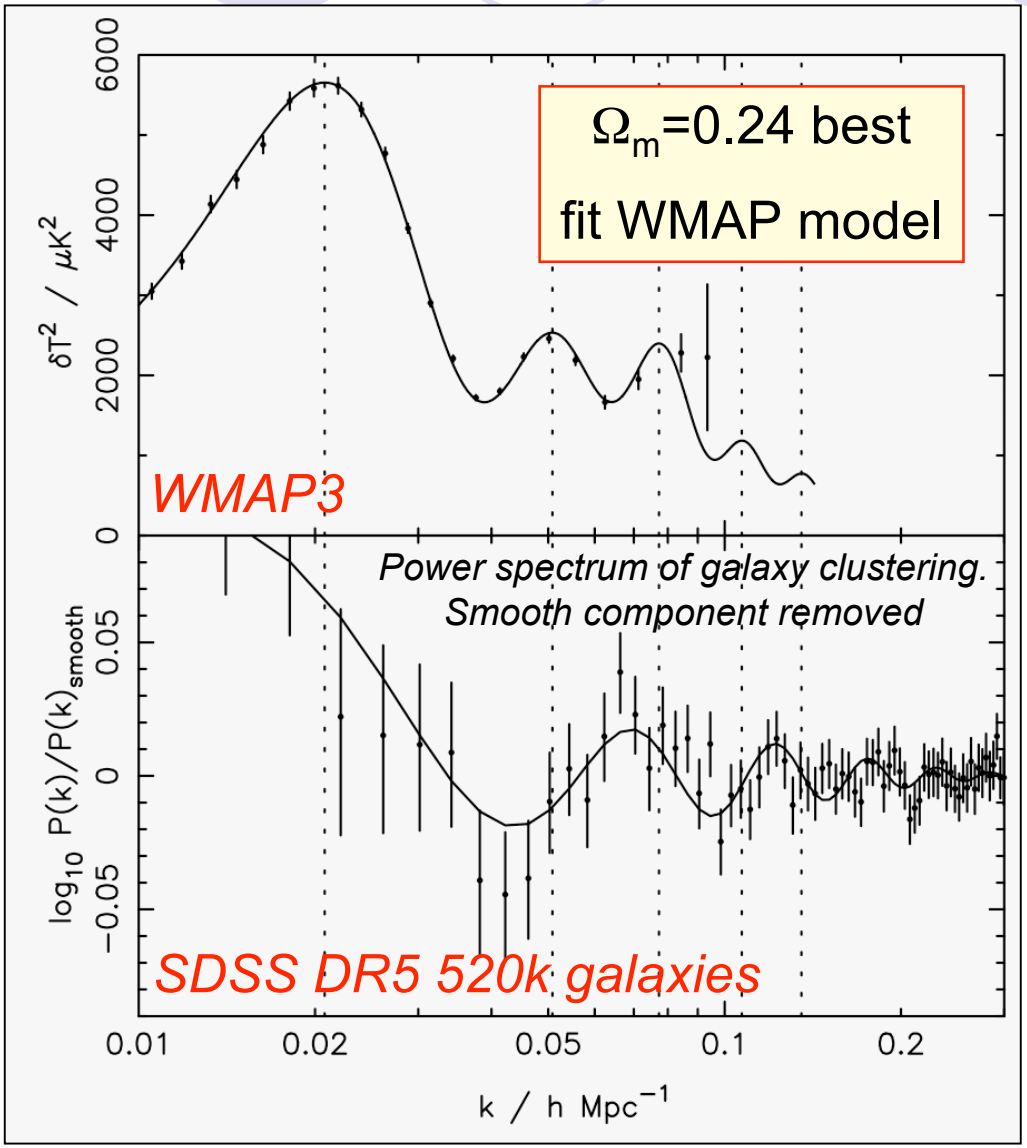


- Positions predicted once (physical) matter and baryon density known - calibrated by the CMB.

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

**Daniel Eisenstein**

# Baryon Acoustic Oscillations

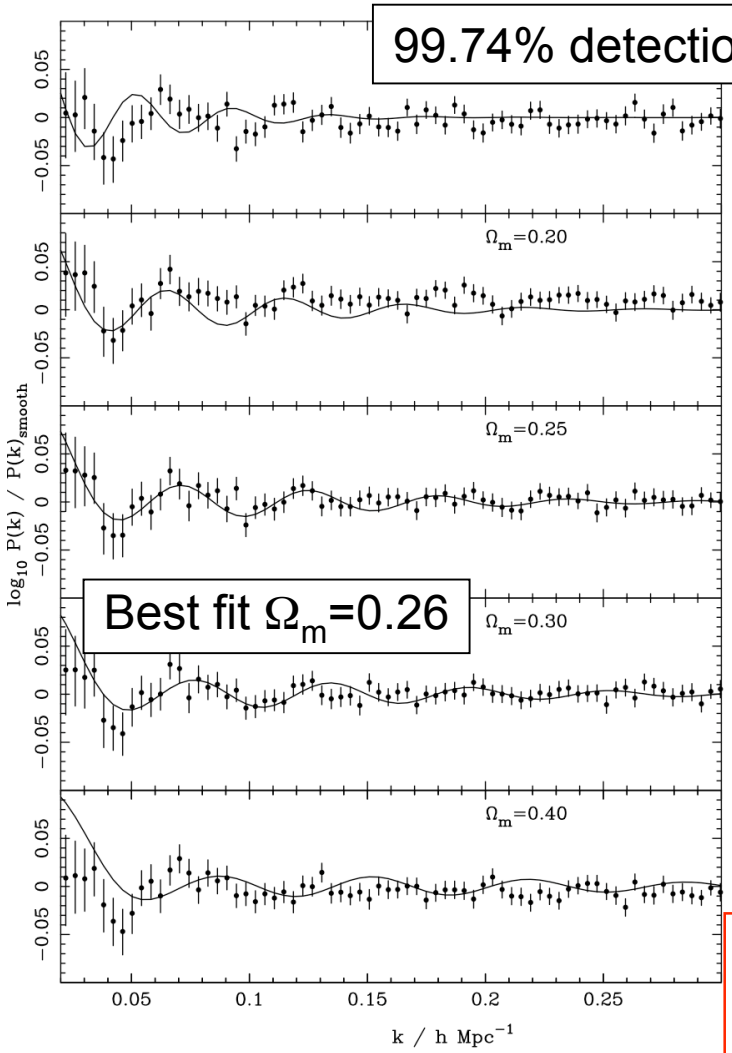



*Miller et al. 2001,*
*Percival et al. 2001,*
*Tegmark et al. 2001, 2006*
*Cole et al. 2005,*
*Eisenstein et al. 2005,*
*Hutsei 2006,*
*Blake et al. 2006,*
*Padmanabhan et al. 2006*

**Percival et al. 2006**

# Cosmological Constraints

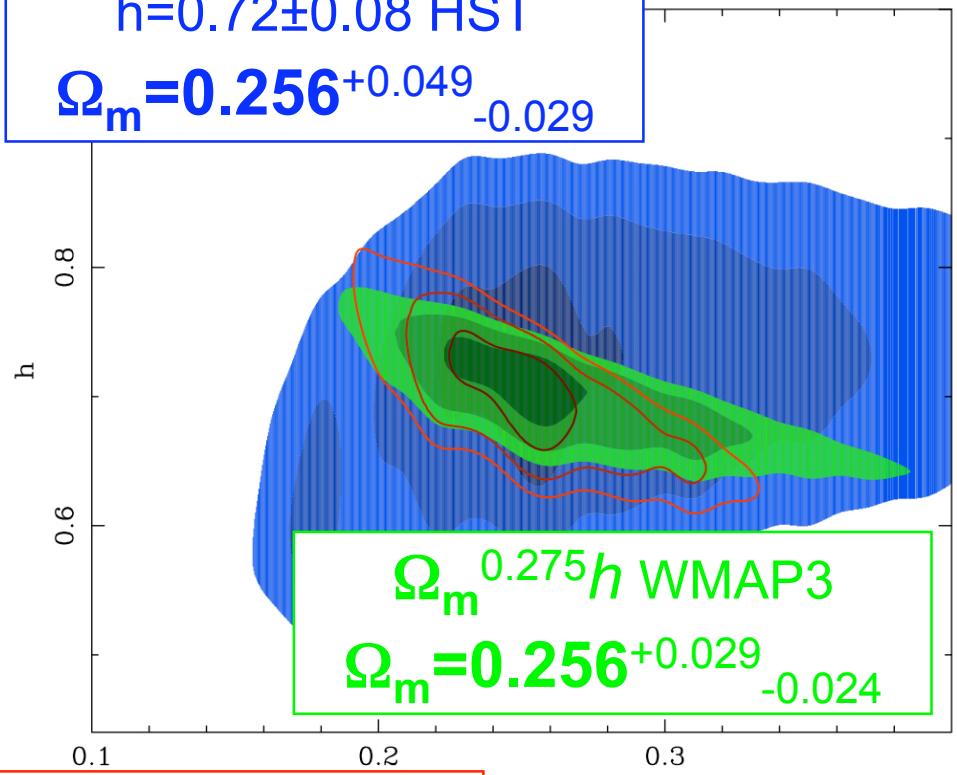
*Standard ruler (flat,h=0.73,$\Omega_b$=0.17)*




**Percival et al. (2006)**

h=0.72±0.08 HST

$\Omega_m = 0.256^{+0.049}_{-0.029}$



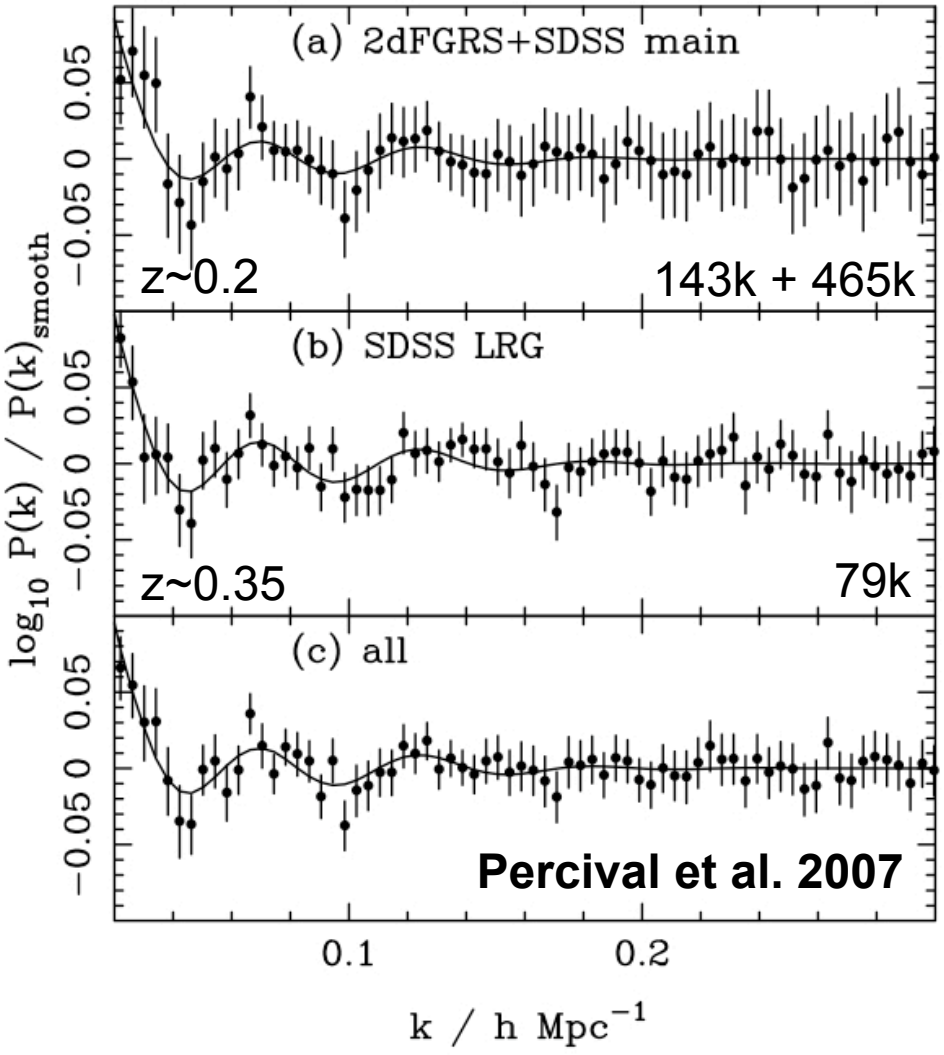

$\Omega_m^{0.275} h$ WMAP3

$\Omega_m = 0.256^{+0.029}_{-0.024}$

$\Omega_m h^2$ WMAP3

$\Omega_m = 0.256^{+0.019}_{-0.023}$

# BAO with Redshift



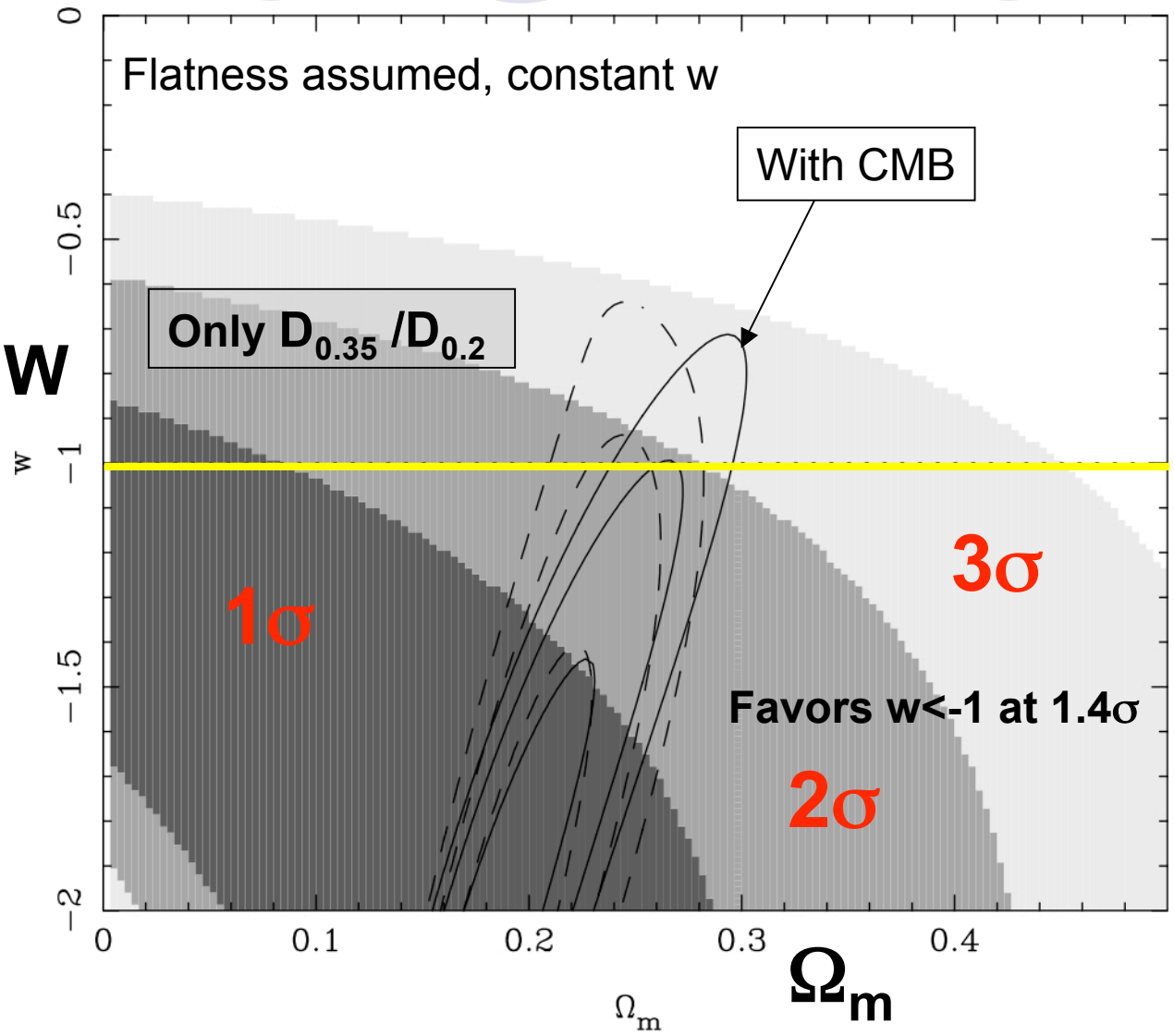

Measure ratio of angular-diameter distance between these redshifts ($D_{0.35}$ /$D_{0.2}$)

$D_{0.35}$ /$D_{0.2}$ = 1.812 ± 0.060

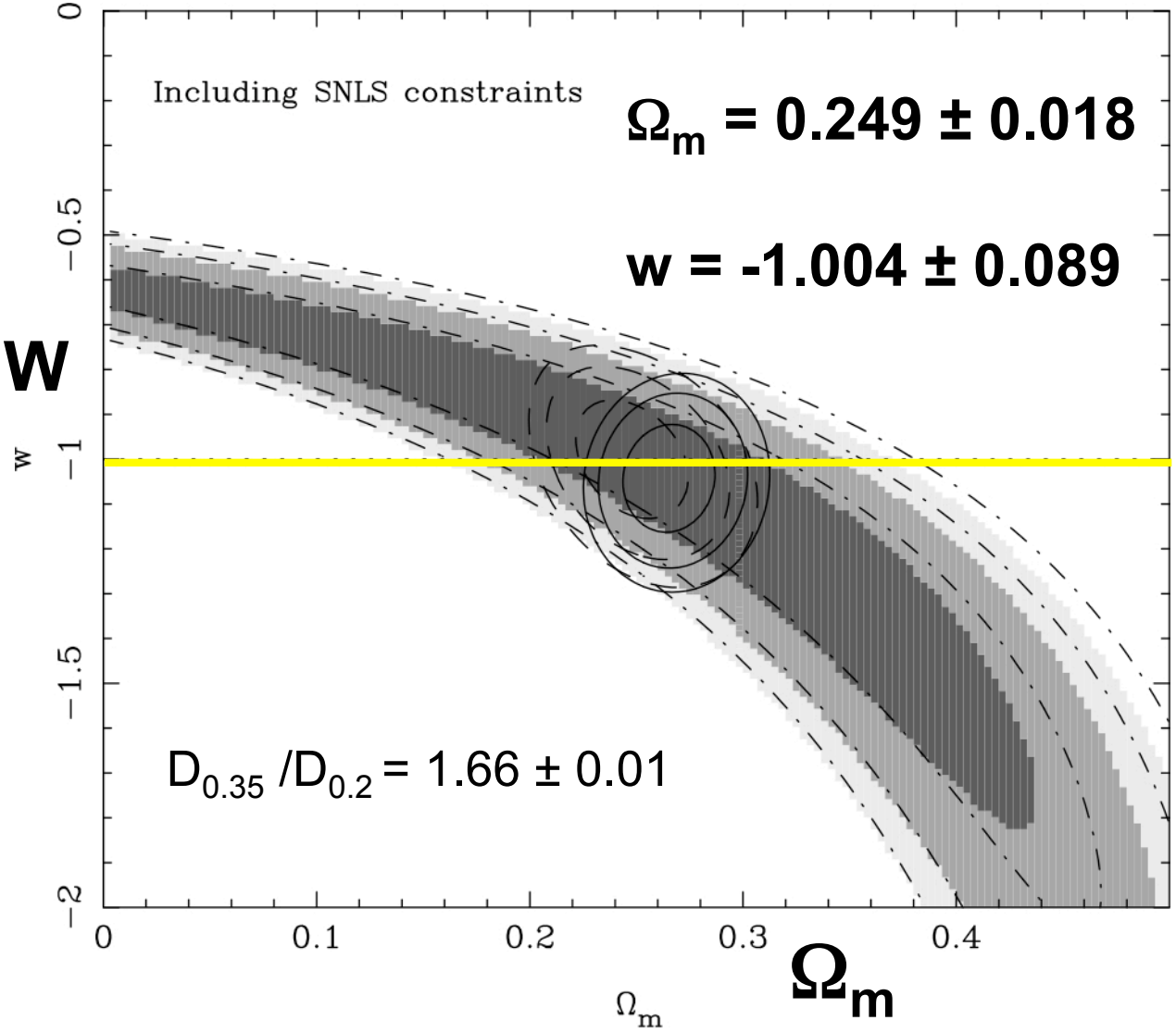
Flat ΛCDM = 1.67

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

# Cosmological Constraints



# Cosmological Constraints



# Discrepancy!
# What Discrepancy?


- 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)*

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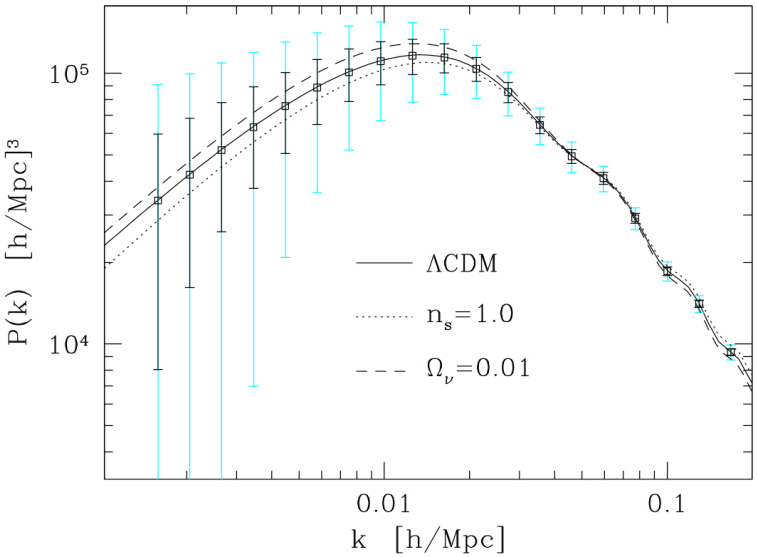
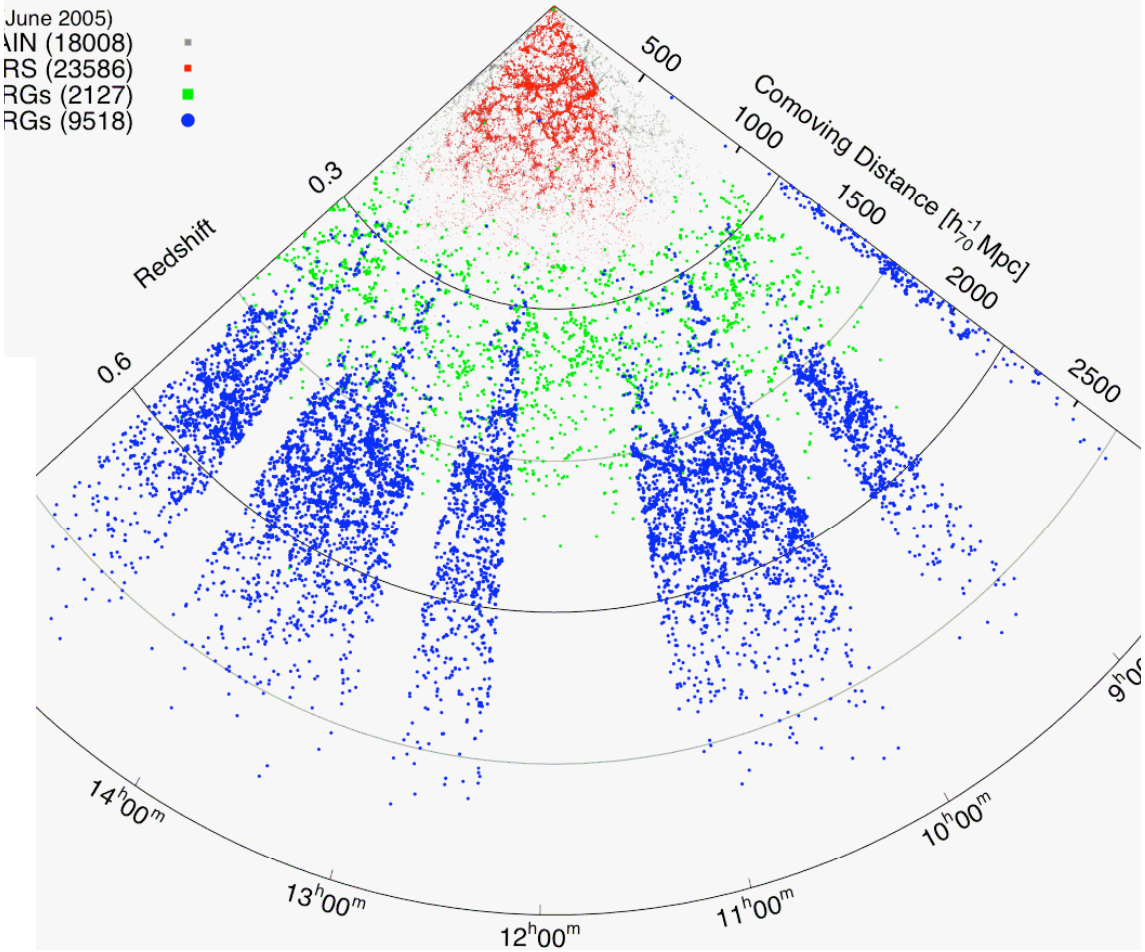
- Measure distance to ~1% at z=0.35 and z=0.6
- 10000 deg$^2$ with 1.5m LRGs to 0.2<z<0.8
- 160k quasars at 2.3<z<2.8
- Starting 2009
- h to 1% with SDSS SNe




## 2SLAQ (www.2slaq.info)



# WFMOS

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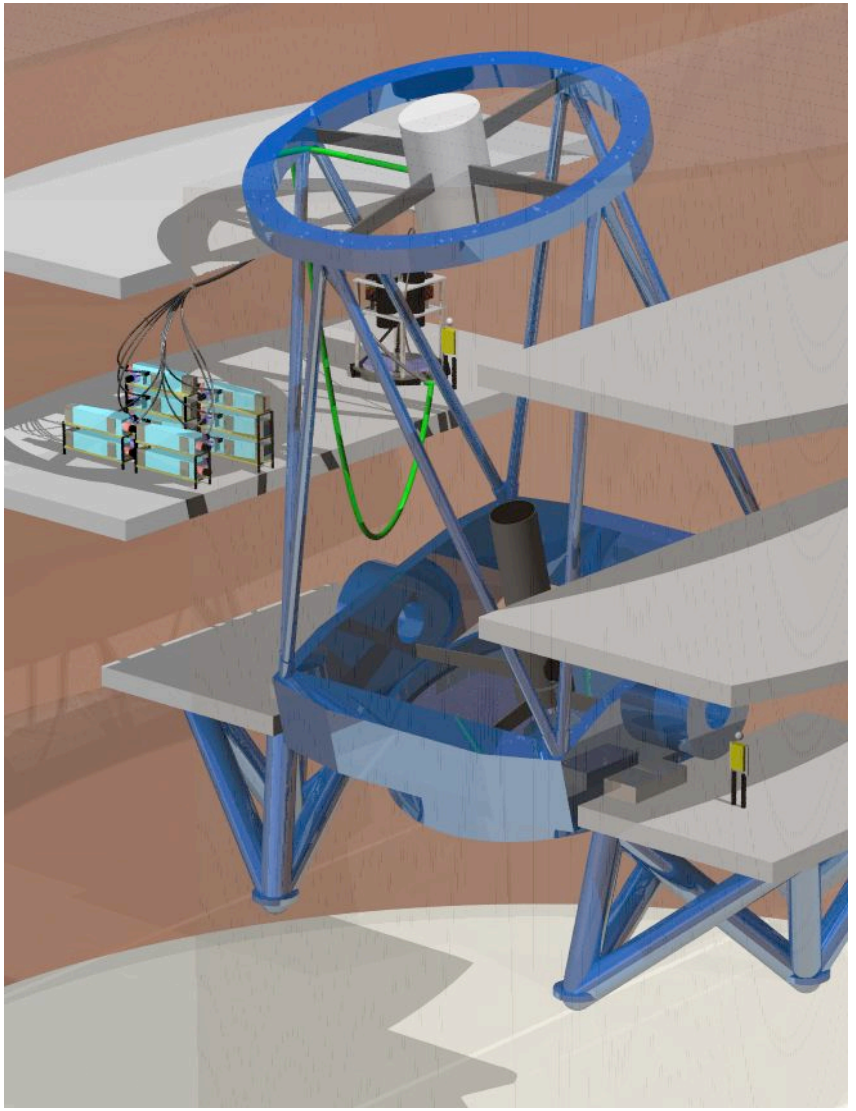
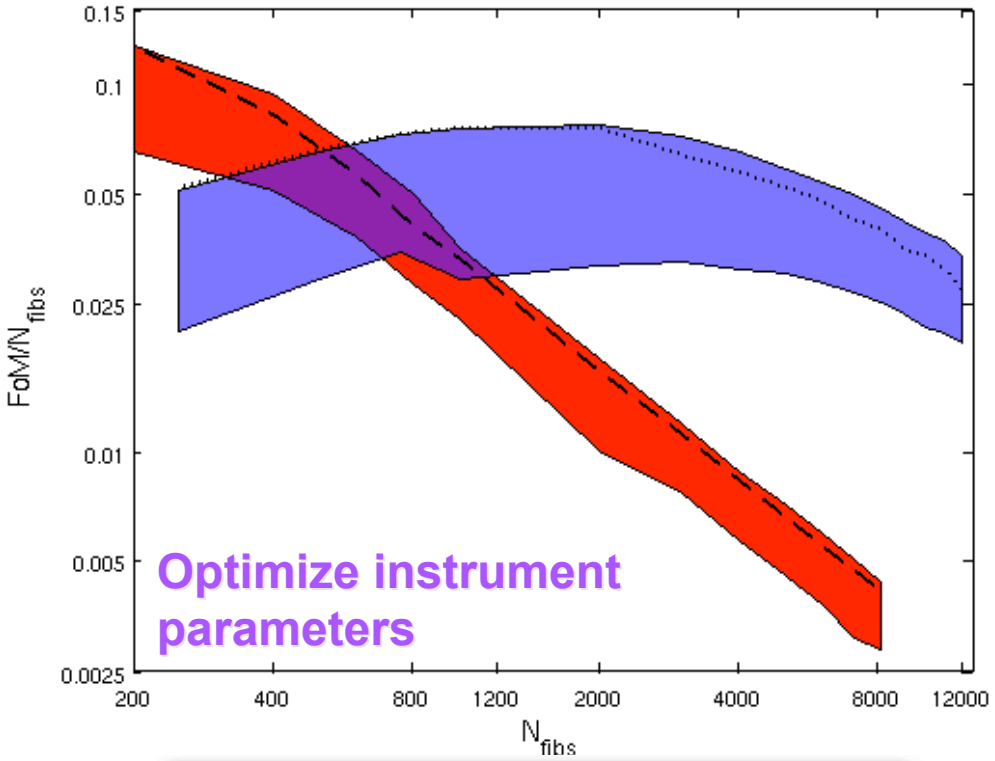
- Proposed MOS on Subaru via an international collaboration of Gemini and Japanese astronomers
- 1.5deg FOV with 4500 fibres feeding 10 low-res spectrographs and 1 high-res spectrograph
- ~20000 spectra a night *(2dfGRS at z~1 in 10 nights)*
- >$10^5$ redshifts for photo-z's (Peacock et al. report)
- 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

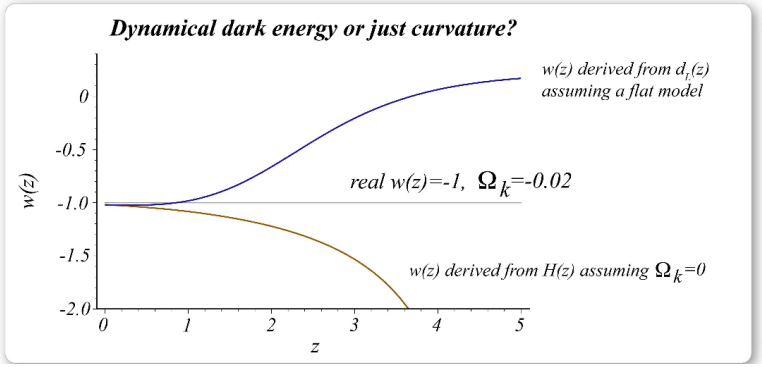


# WFMOS Surveys

- 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 (*dw* = 4%)
- Optimum is broadly peaked and insensitive to other surveys




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



# Conclusions

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- 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
- $2\sigma$ discrepancy with SNe? Curvature / w(z)?
- WFMOS and AS2 will move BAO to 1% level


2057 (April 1st 2007)

# Integrated Sachs-Wolfe Effect

Dark Energy effects the rate of growth of structure in Universe

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- Poisson equation with dark energy:

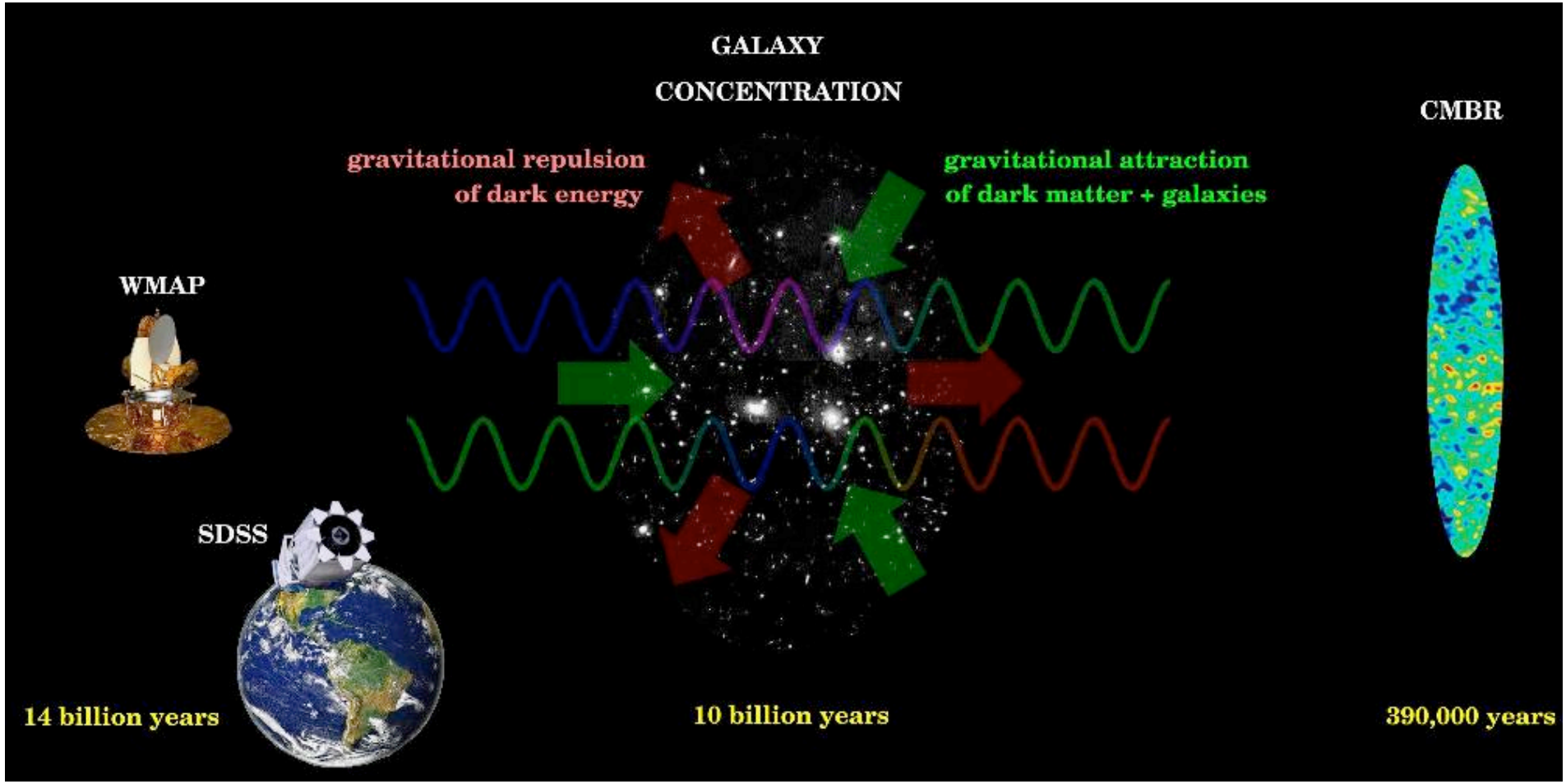
$$k^2\Phi' = -4\pi G \frac{d}{d\eta}\left[a^{-1}(\delta\rho_m + \delta\rho_{DE})\right]$$

- 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

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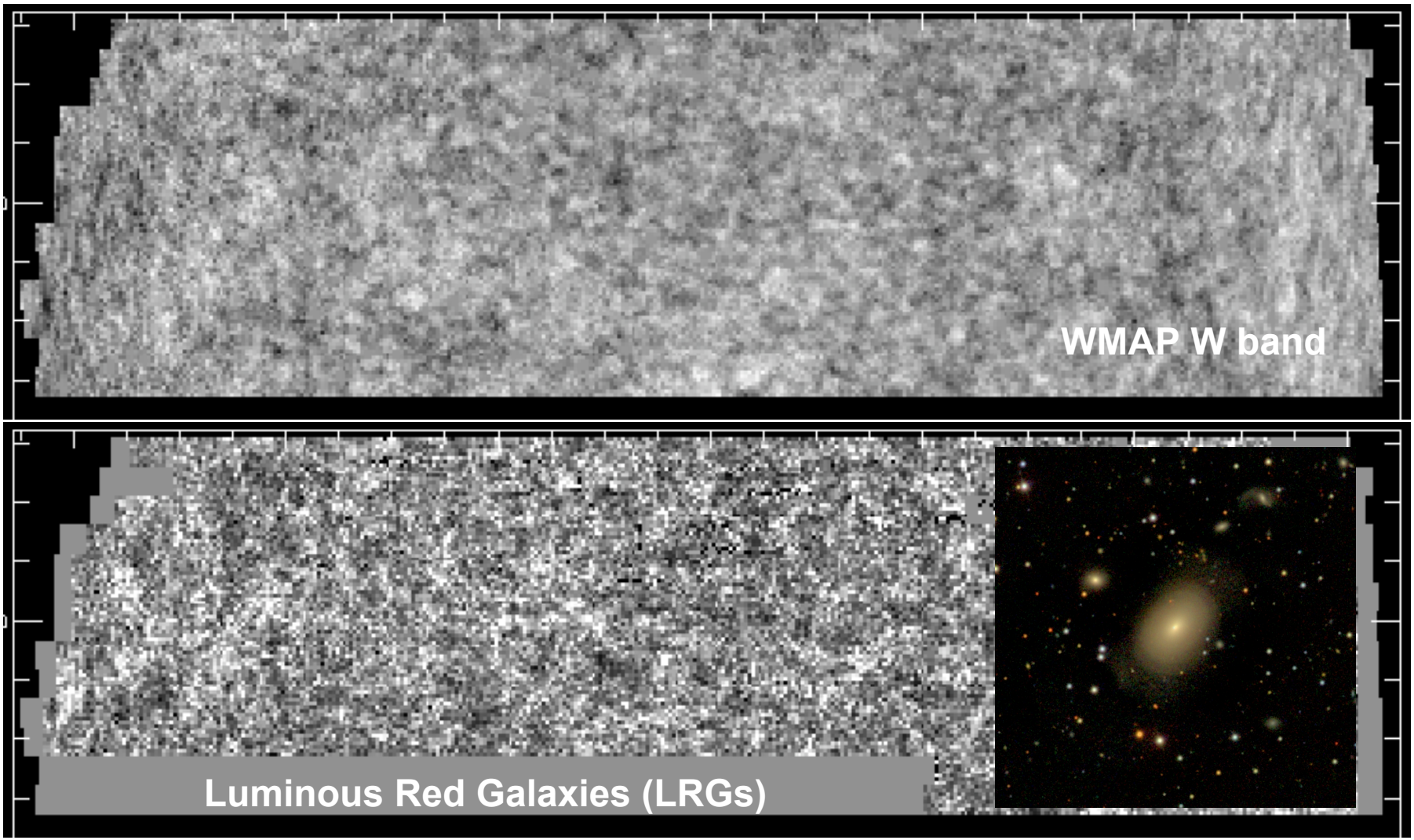

# ISW Detected

Update of the Scranton et al. (2003) paper

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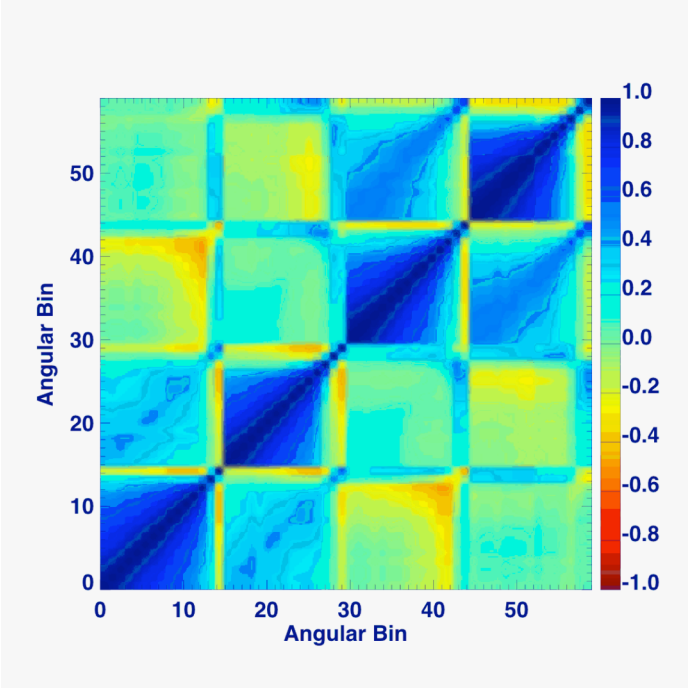
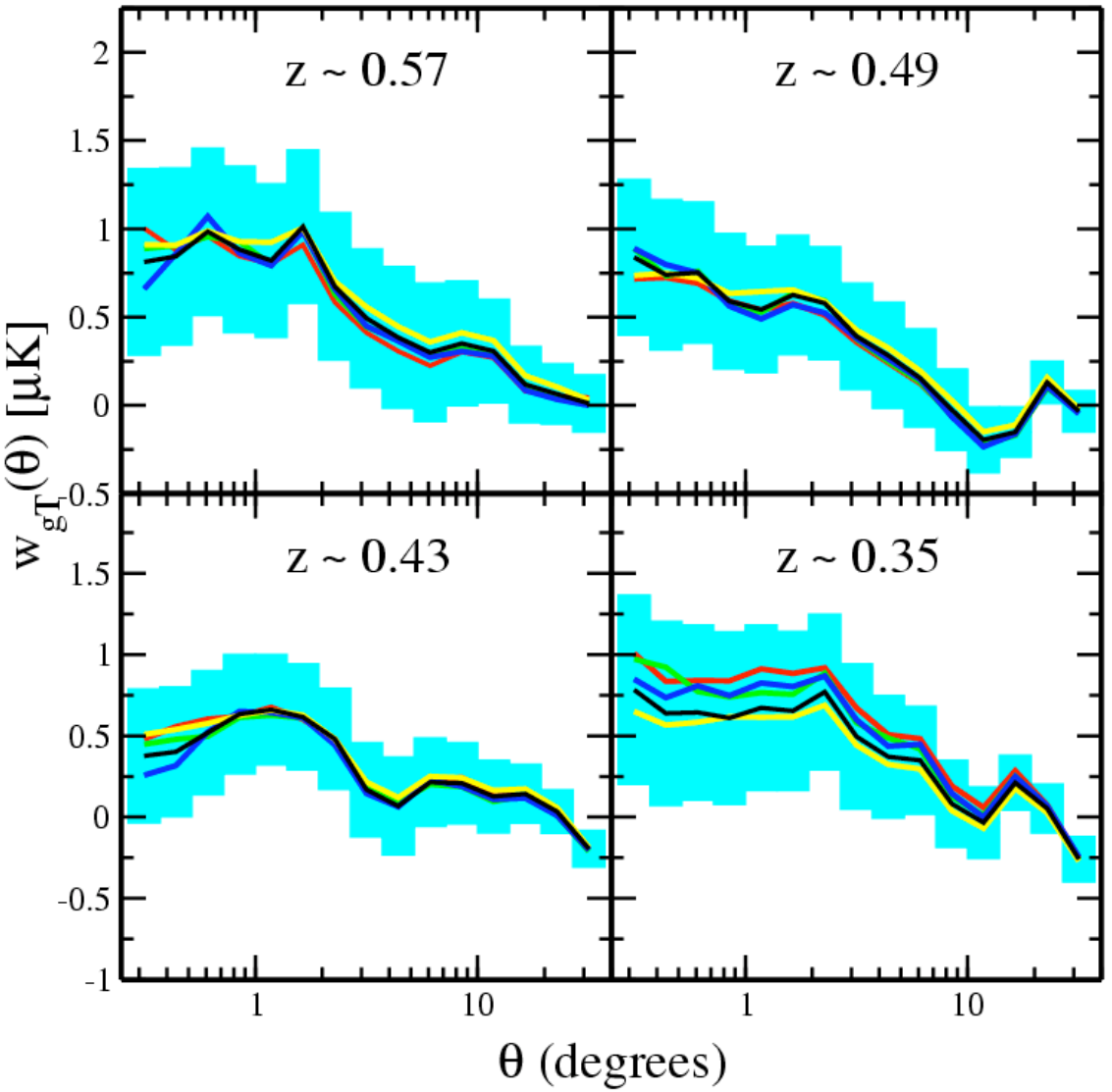
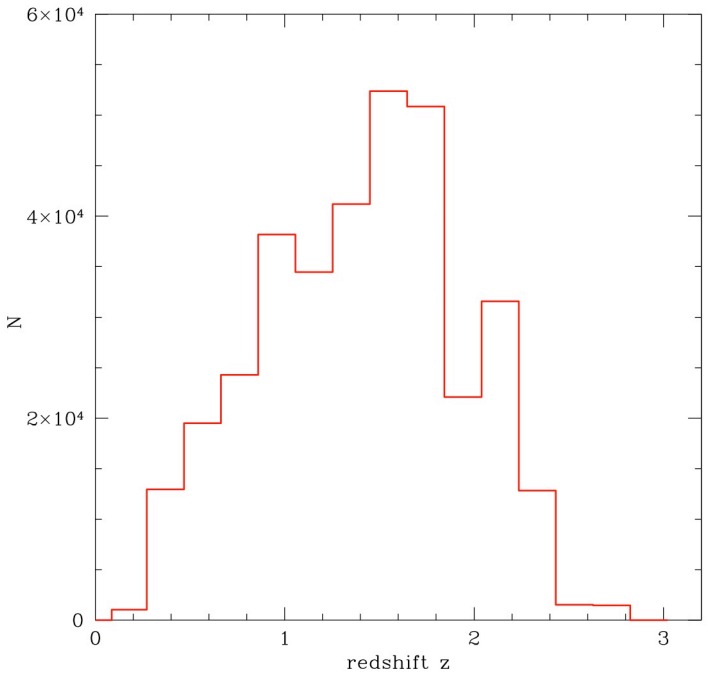
- 6300 sq degrees
- Achromatic
- 5σ detection

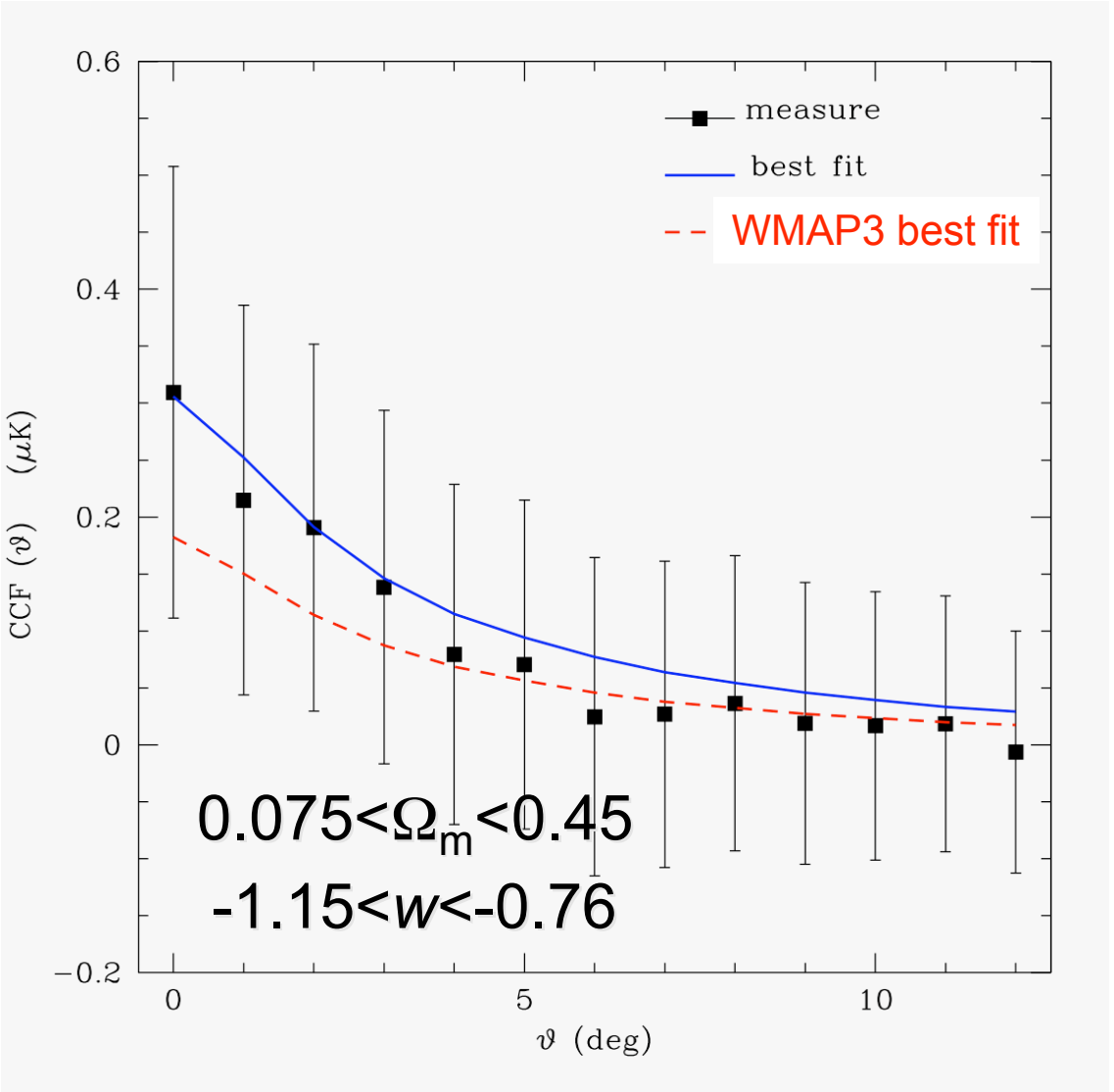


# Giannantonio et al. (2006)

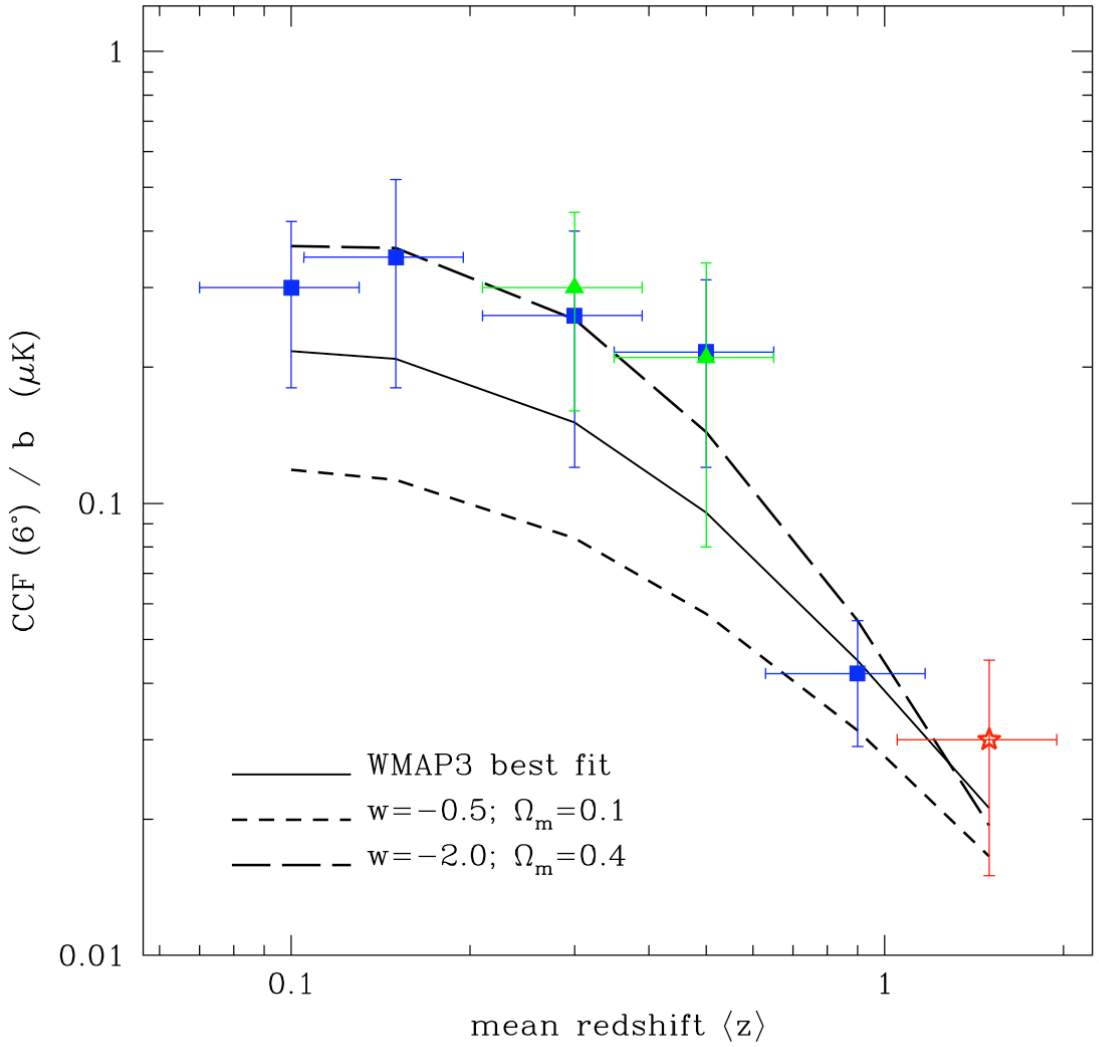
Cross-correlation of WMAP3 and SDSS quasars




***Detection of DE at z>1***

# Evolution of DE



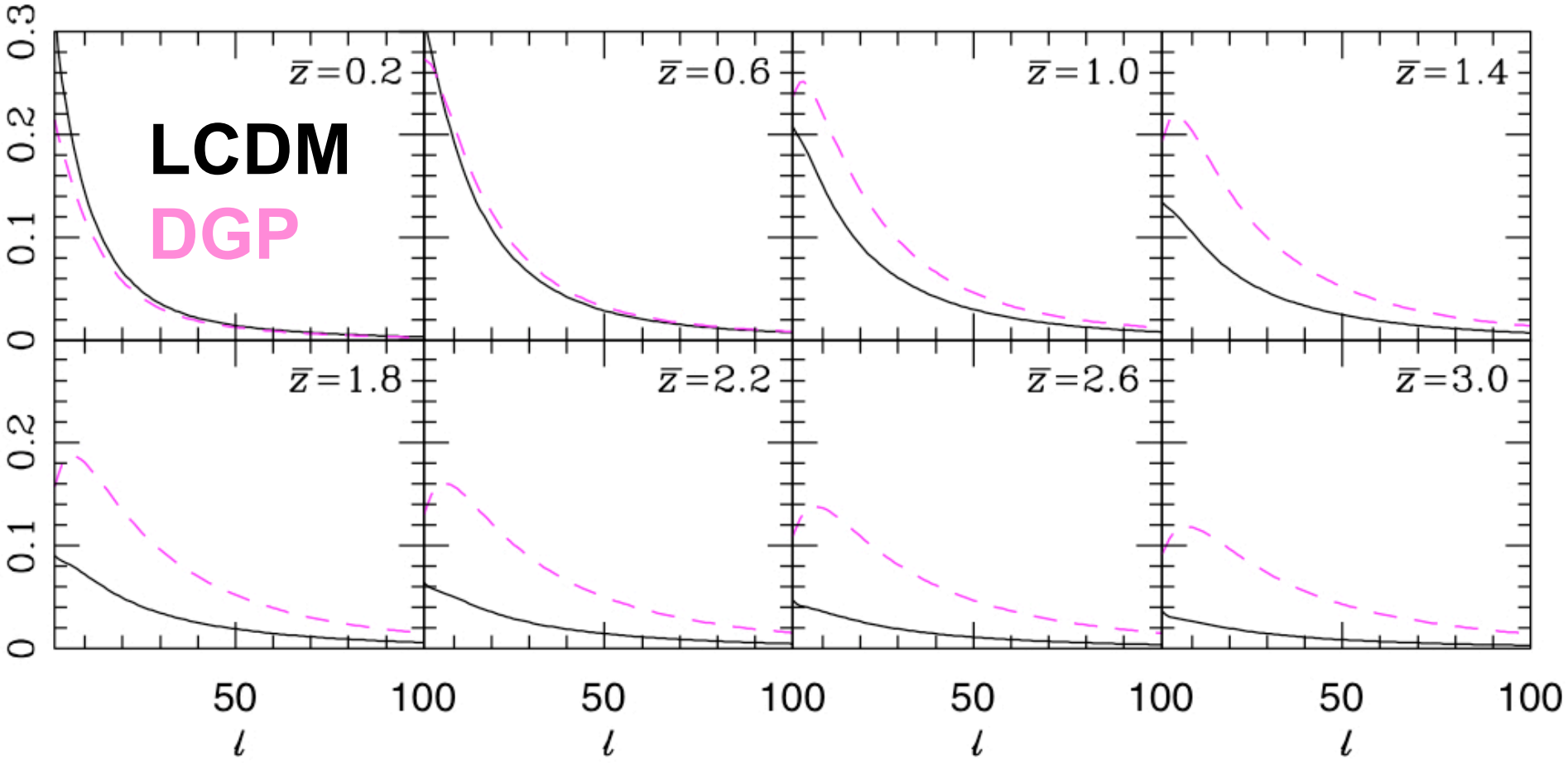

**Consistent with w=-1**

**Rules out models**

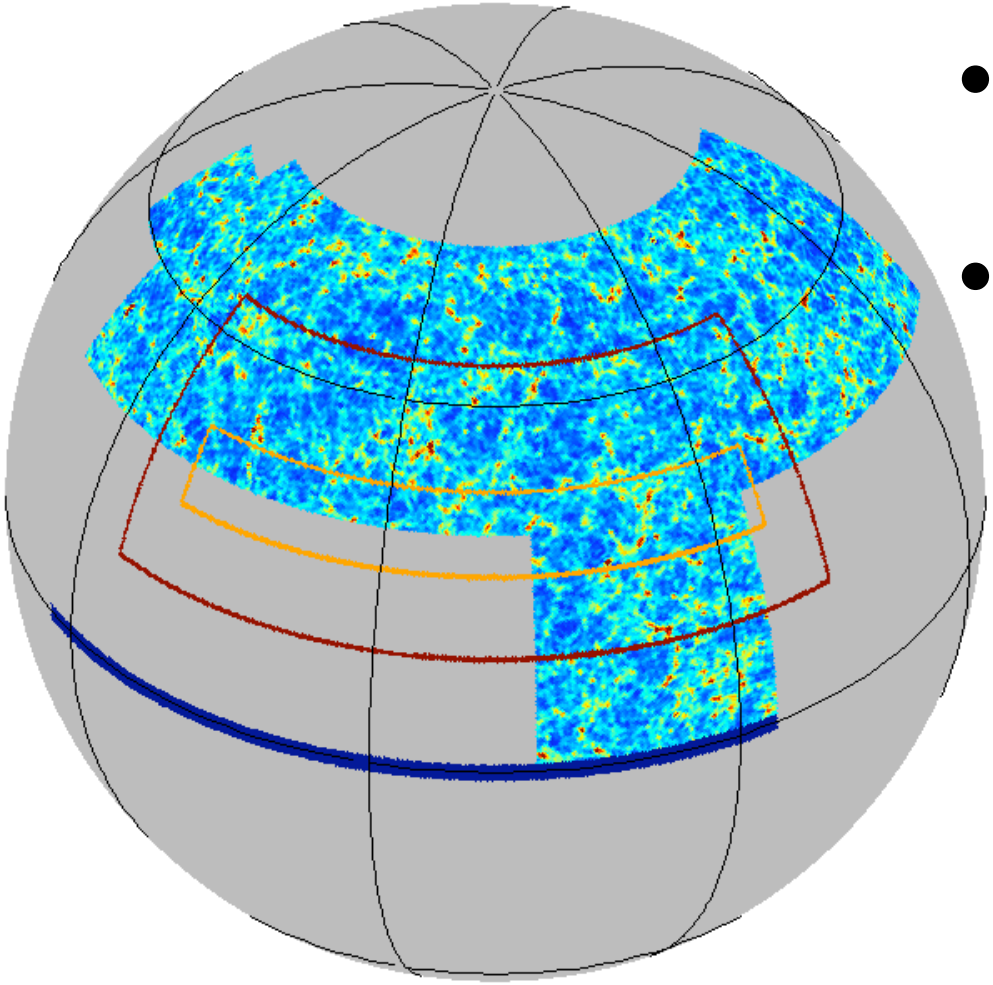
**$\Omega_{DE}(z=1.5) > 0.5$**

# 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)