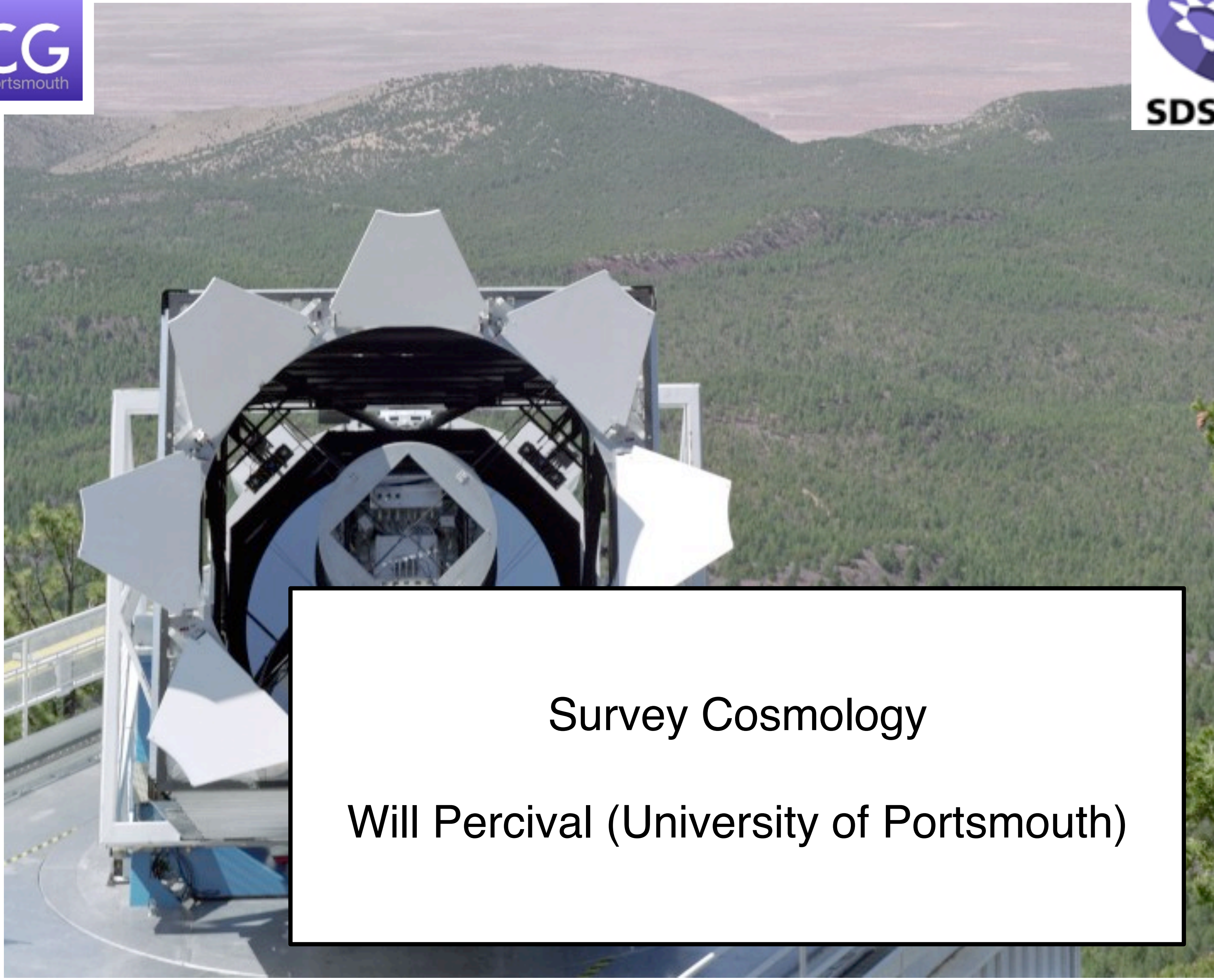


Survey Cosmology

Will Percival (University of Portsmouth)

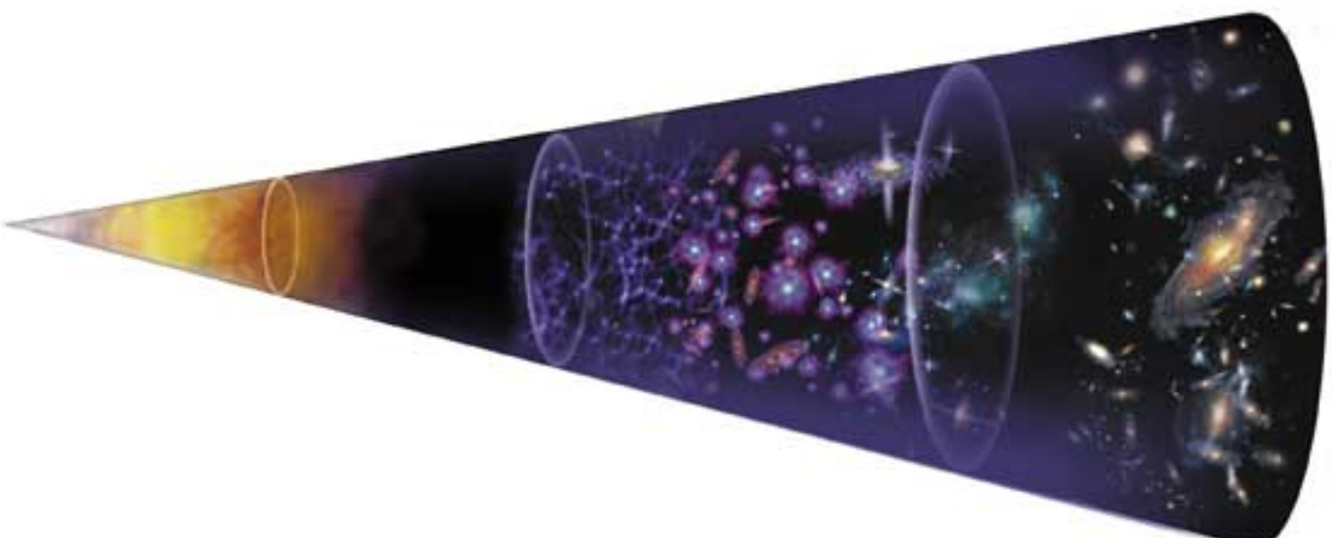
The standard "model" for cosmology 16 years ago

expansion rate
of the Universe

radiation content

matter content $\Omega_m = 1$

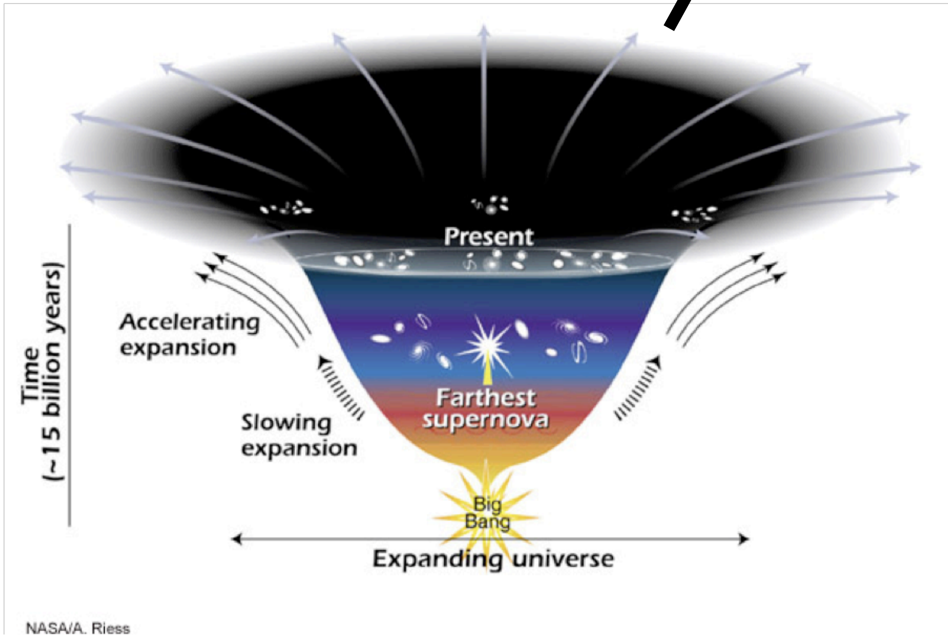
$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3}$$

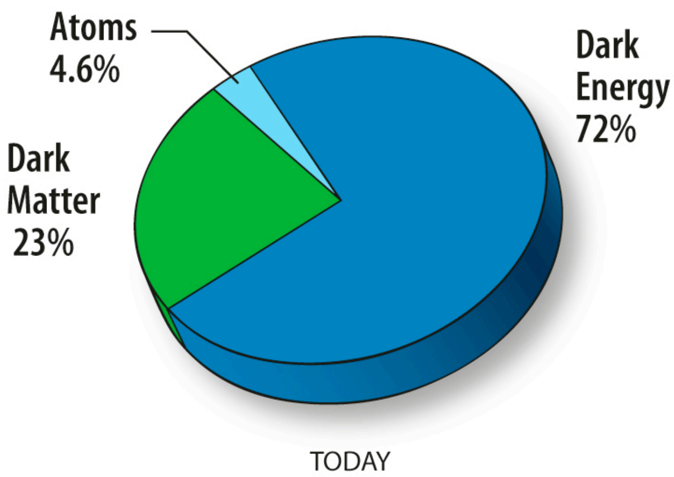


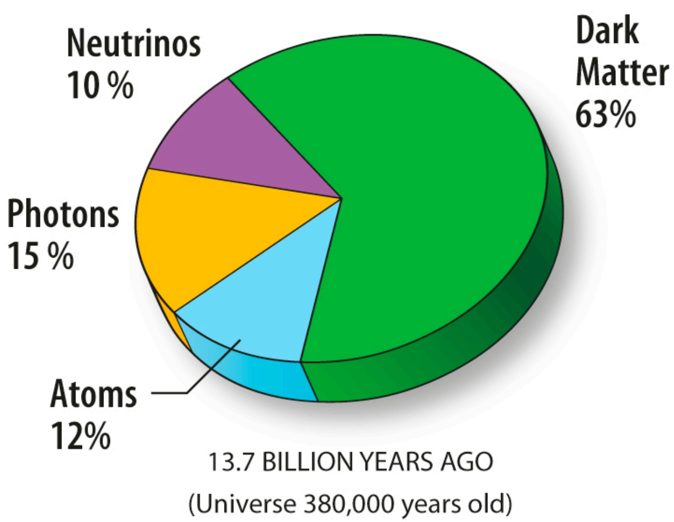
© Don Dixon/cosmographica.com 2002

The standard "model" for cosmology now

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$



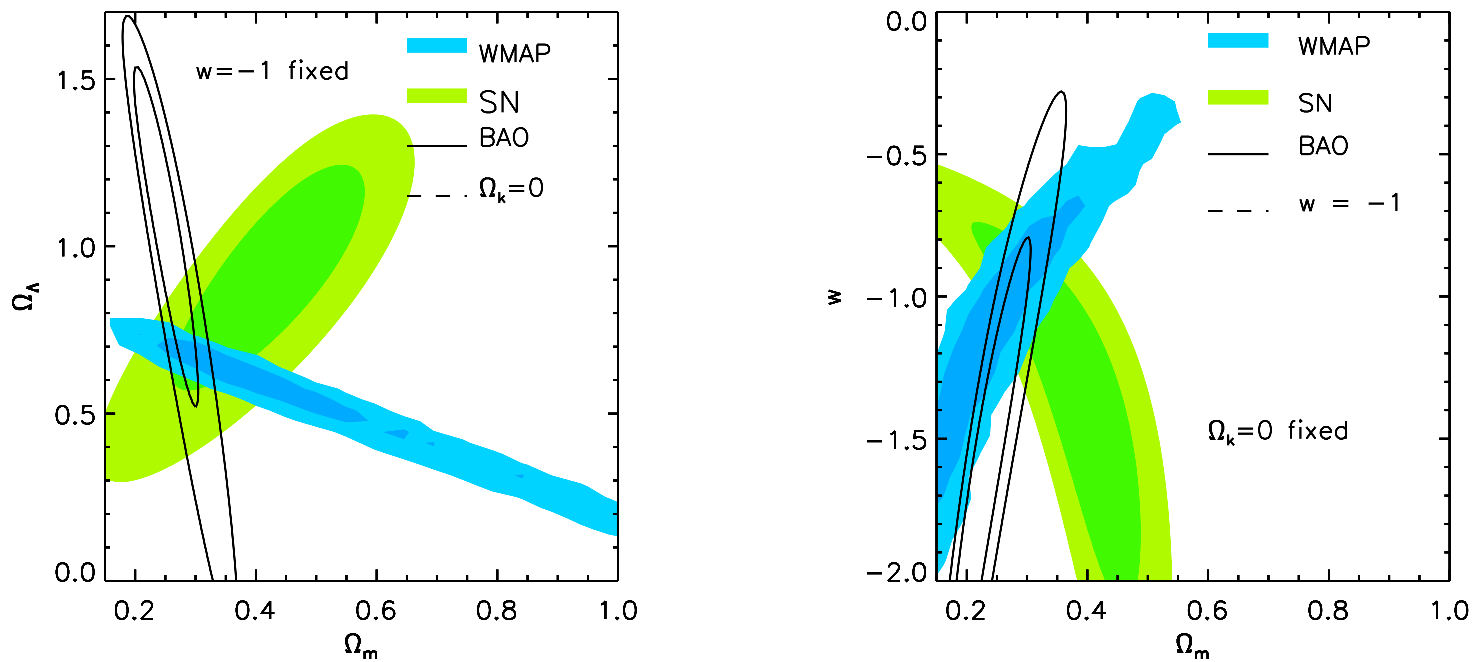




Concordance model?

ΛCDM models with curvature

flat wCDM models



Union supernovae

WMAP 5year

SDSS-II BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

Percival et al. 2009; arXiv:0907.1660

The problem of Λ

- ΛCDM fits all (believable?) current data well
- It's the simplest model available
- But … we cannot explain Λ
  - why so small?

$$\rho_\Lambda|_{\rm obs} = \frac{\Lambda}{8\pi G} \sim (10^{-3}\,{\rm eV})^4$$

$$\rho_\Lambda|_{\rm theory} \sim (M_{\rm new\ \ physics})^4 \sim (1\,{\rm TeV})^4 >> \rho_\Lambda|_{\rm obs}$$

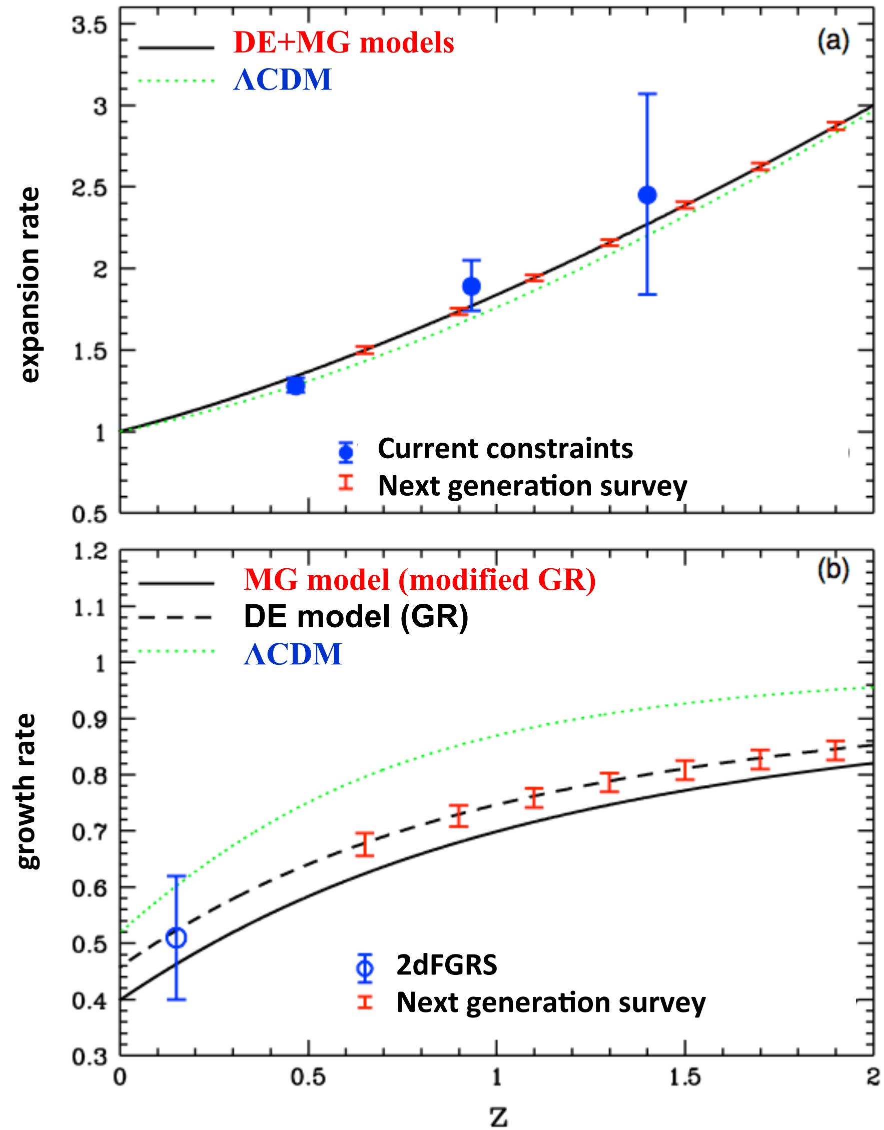
  - why so fine tuned?

$$\rho_\Lambda \lesssim \rho_m \quad : \quad \text{crucial for structure formation}$$

$$\text{but } \rho_\Lambda \propto a^0 \text{ while } \rho_m \propto a^{-3}$$

- Many alternative explanations
  - modify gravity on large-scales or at low densities
  - more general scalar field model?
  - link with Dark Matter?

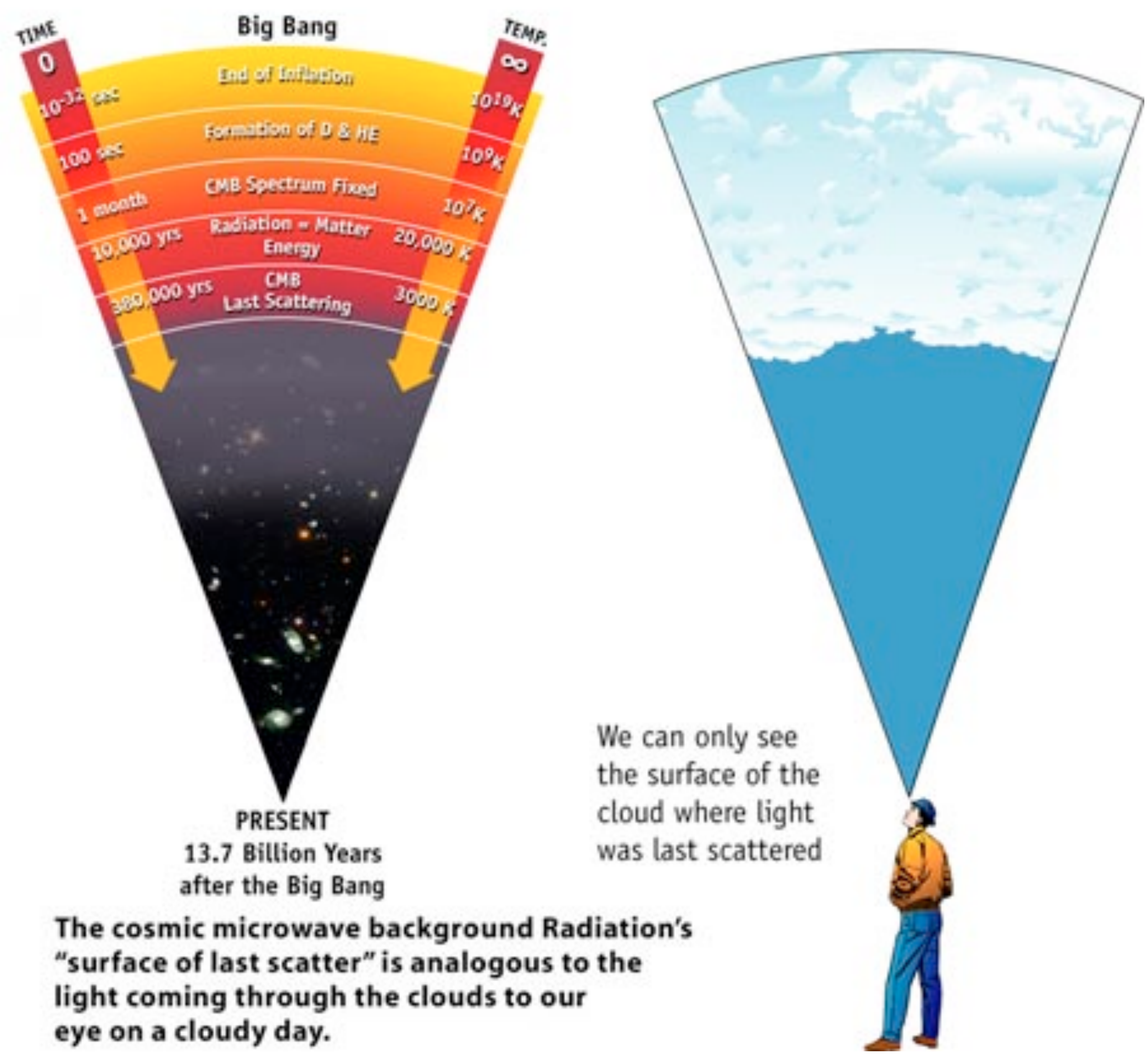
Complementarity of growth & expansion



Wang 2008: JCAP, 05, 21

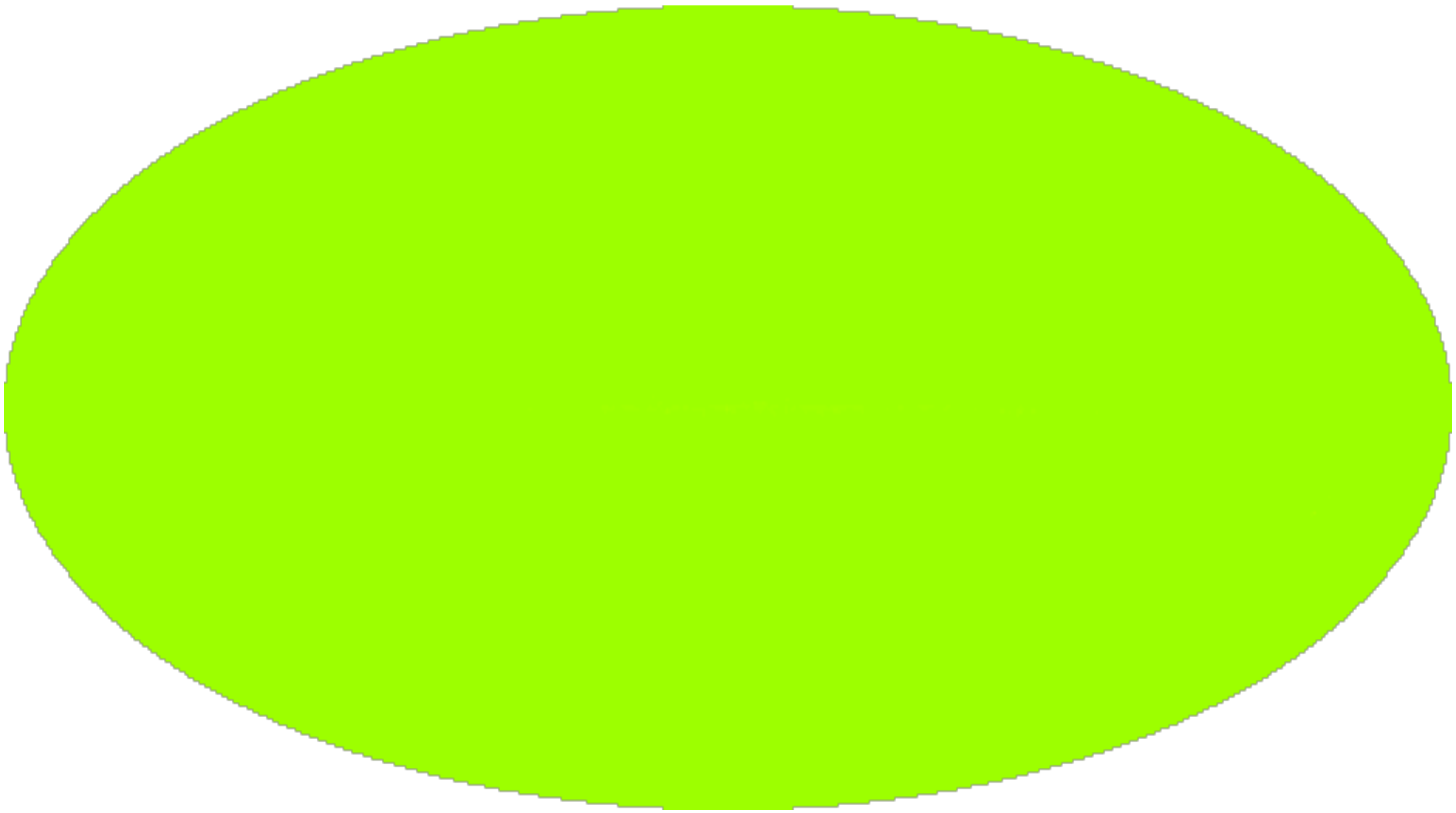
The Cosmic Microwave Background

Looking back in time



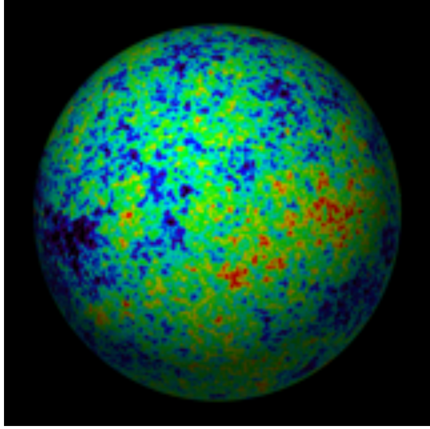
from WMAP website

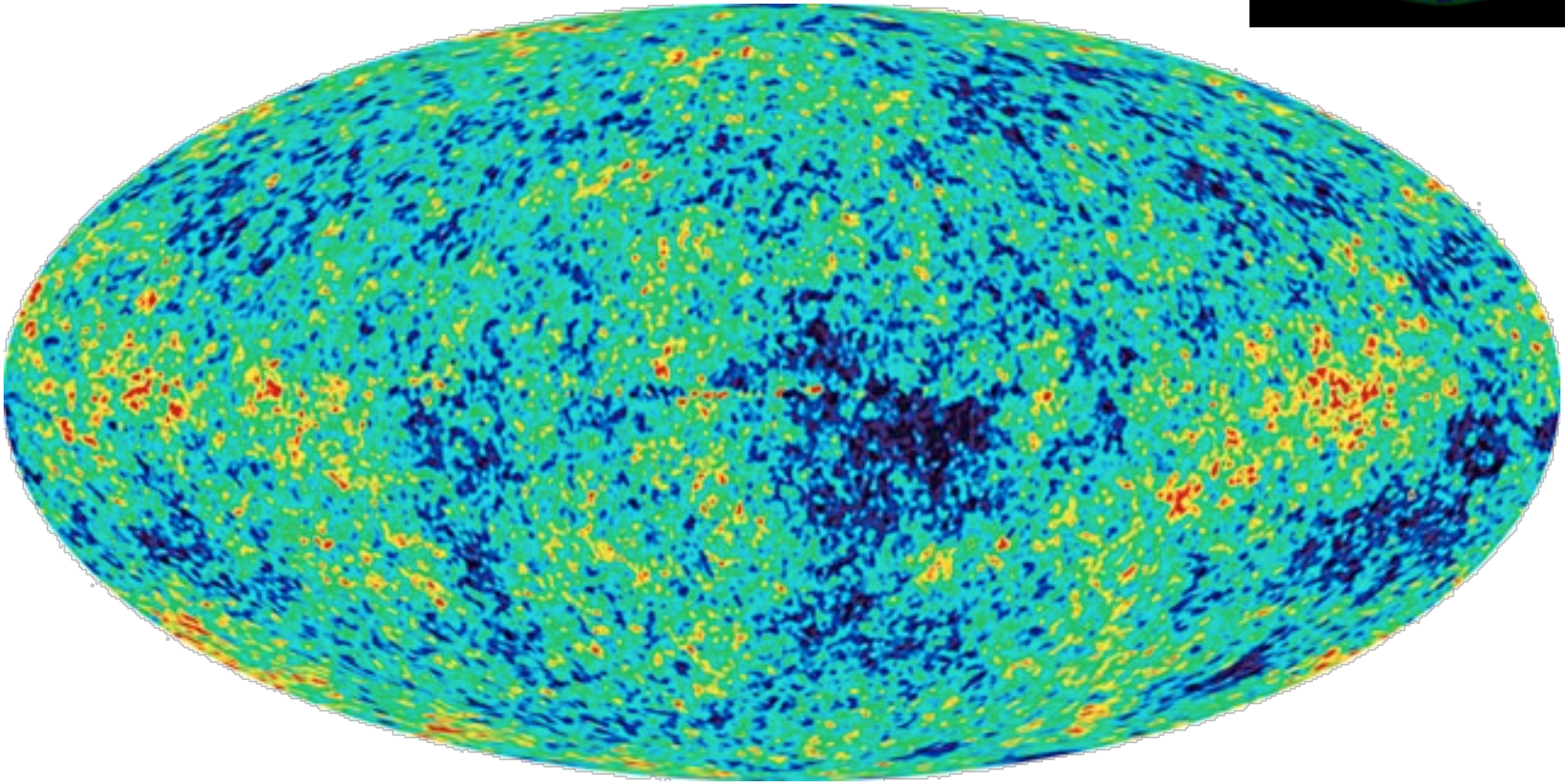
a map of the CMB



from WMAP website

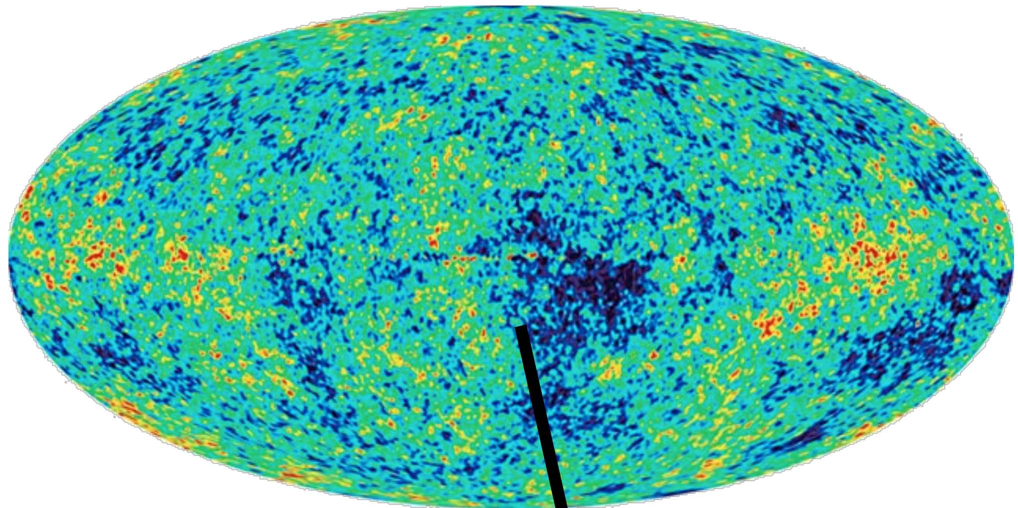
Fluctuations in the CMB



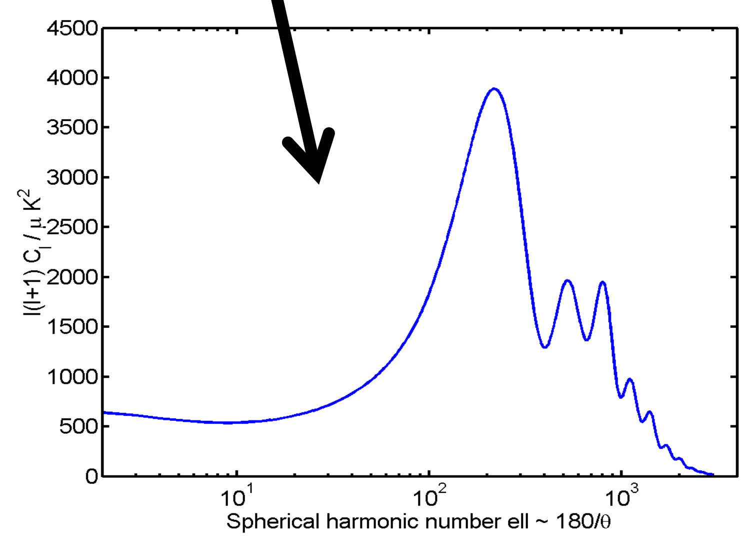


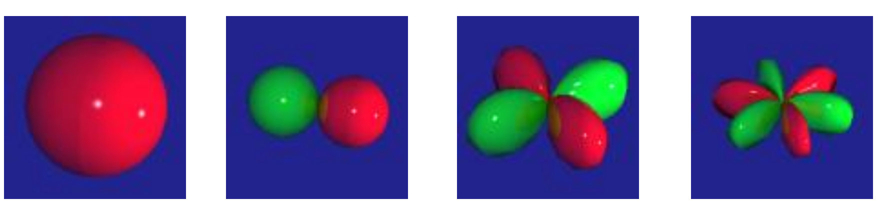
from WMAP website

Statistical analysis

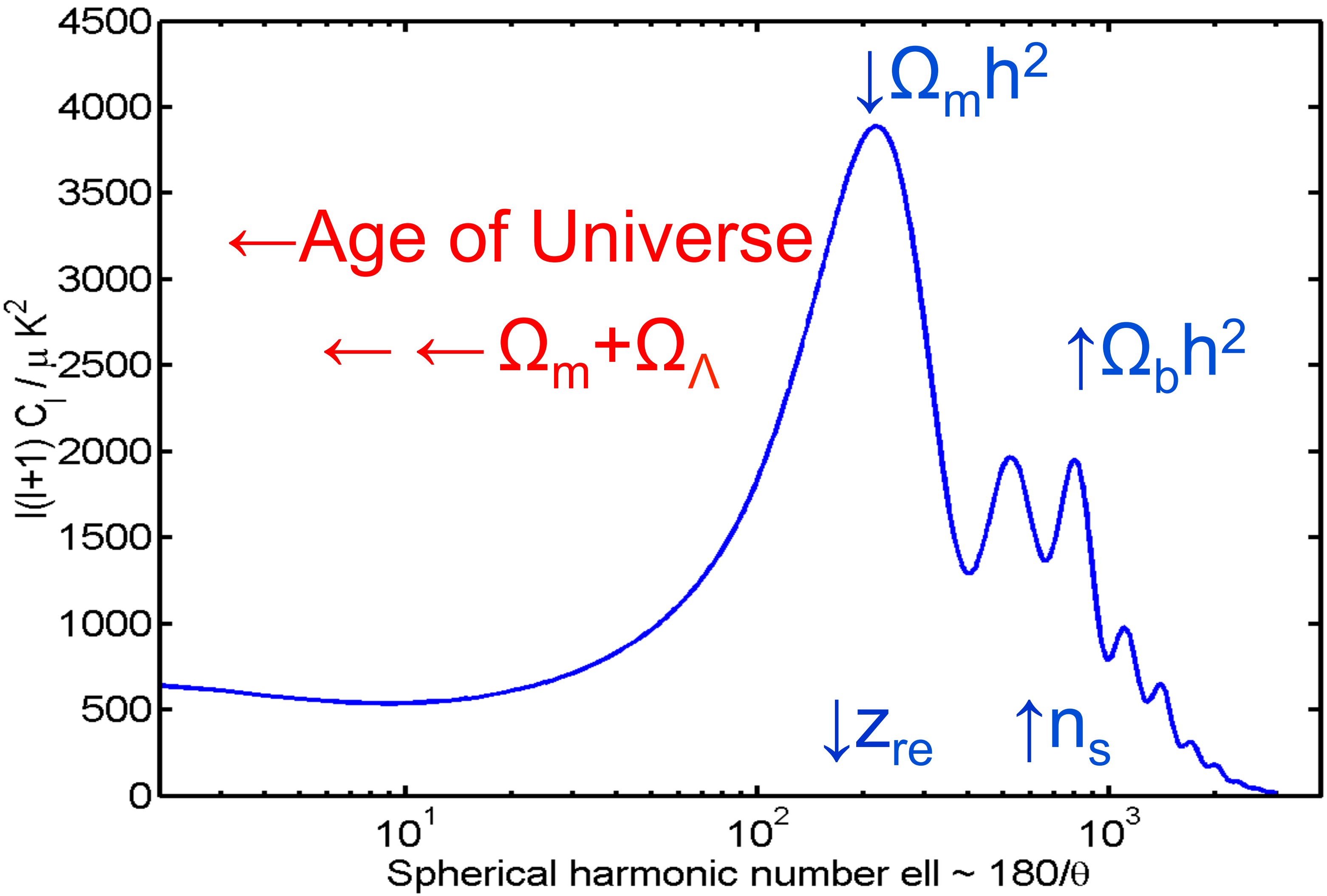


$$
\begin{aligned}
T_{CMB} &= 2.726K \\
\Delta T(\theta,\phi) &= T(\theta,\phi) - T_{CMB} \\
a_{lm} &= \int \frac{\Delta T(\theta,\phi)}{T_{CMB}} Y_{lm}(\theta,\phi) d\Omega \\
C_l &= \langle |a_{lm}|^2 \rangle
\end{aligned}
$$

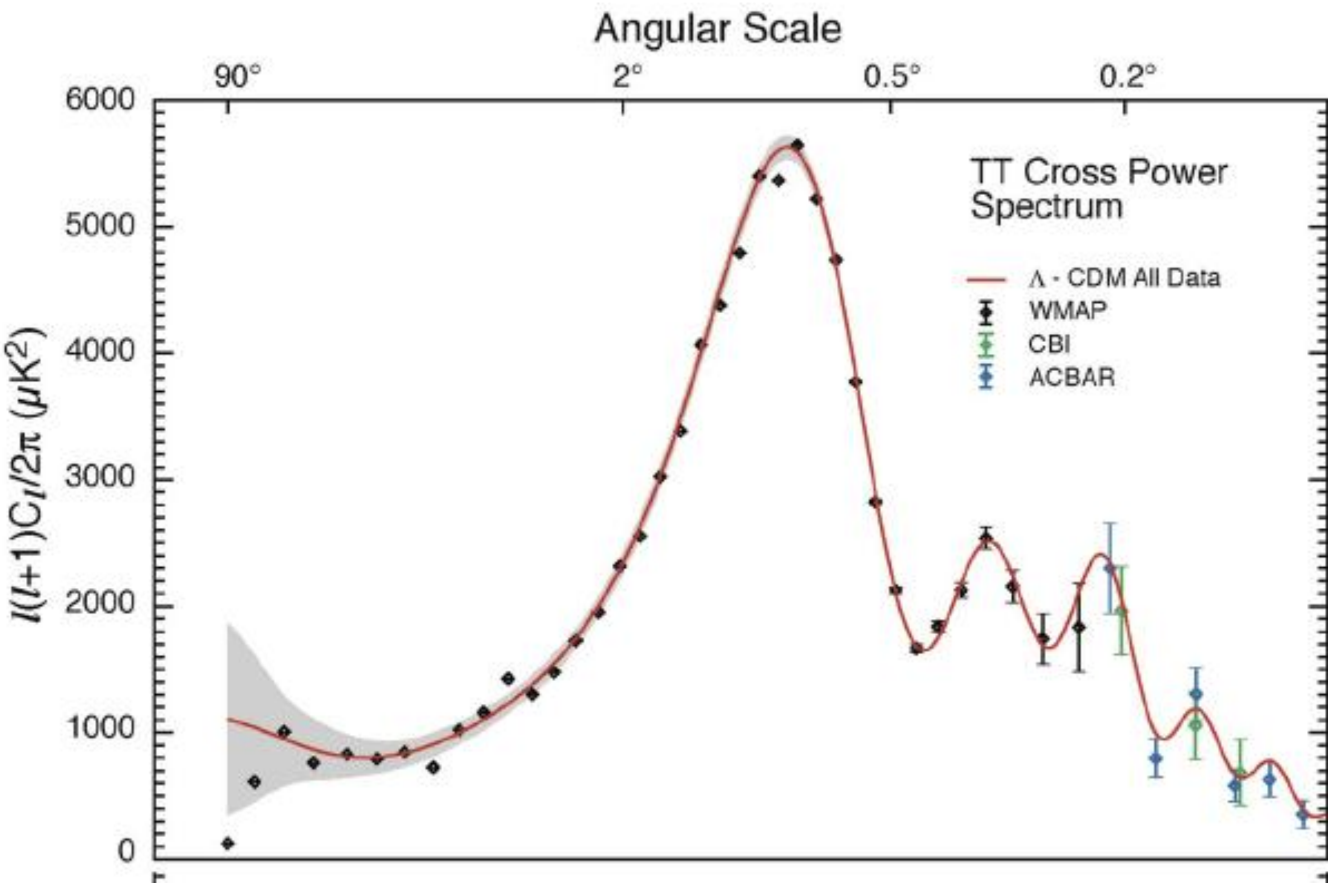




Rough guide to the CMB measurements



WMAP power spectrum

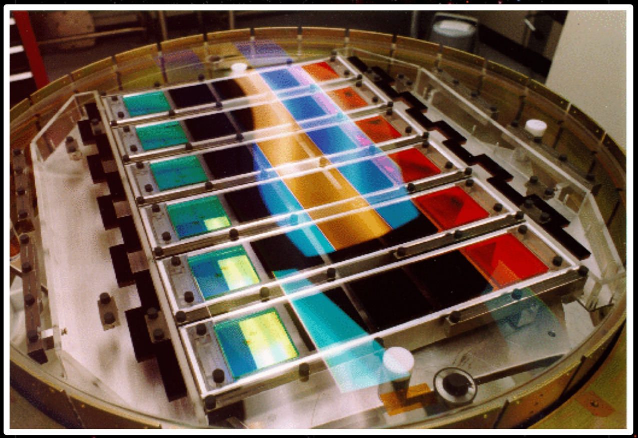


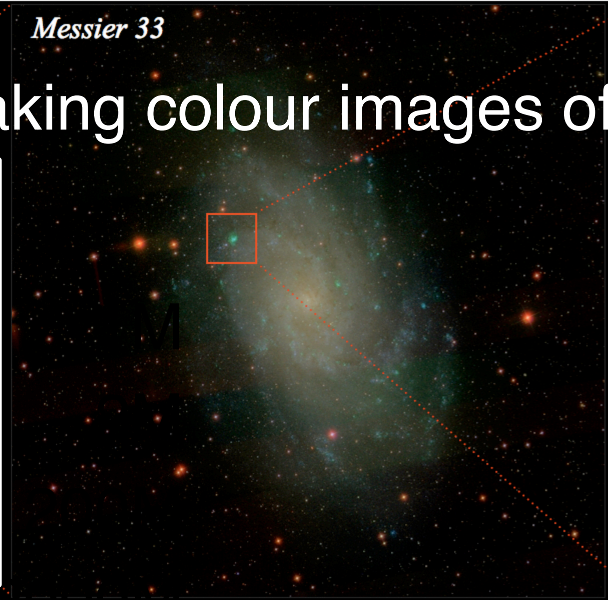
But only provides one line-of-sight to last scattering surface through accelerating Universe

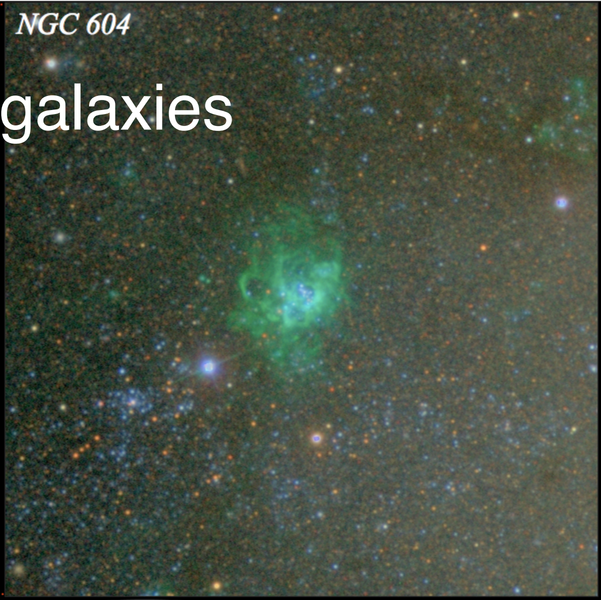
from WMAP website

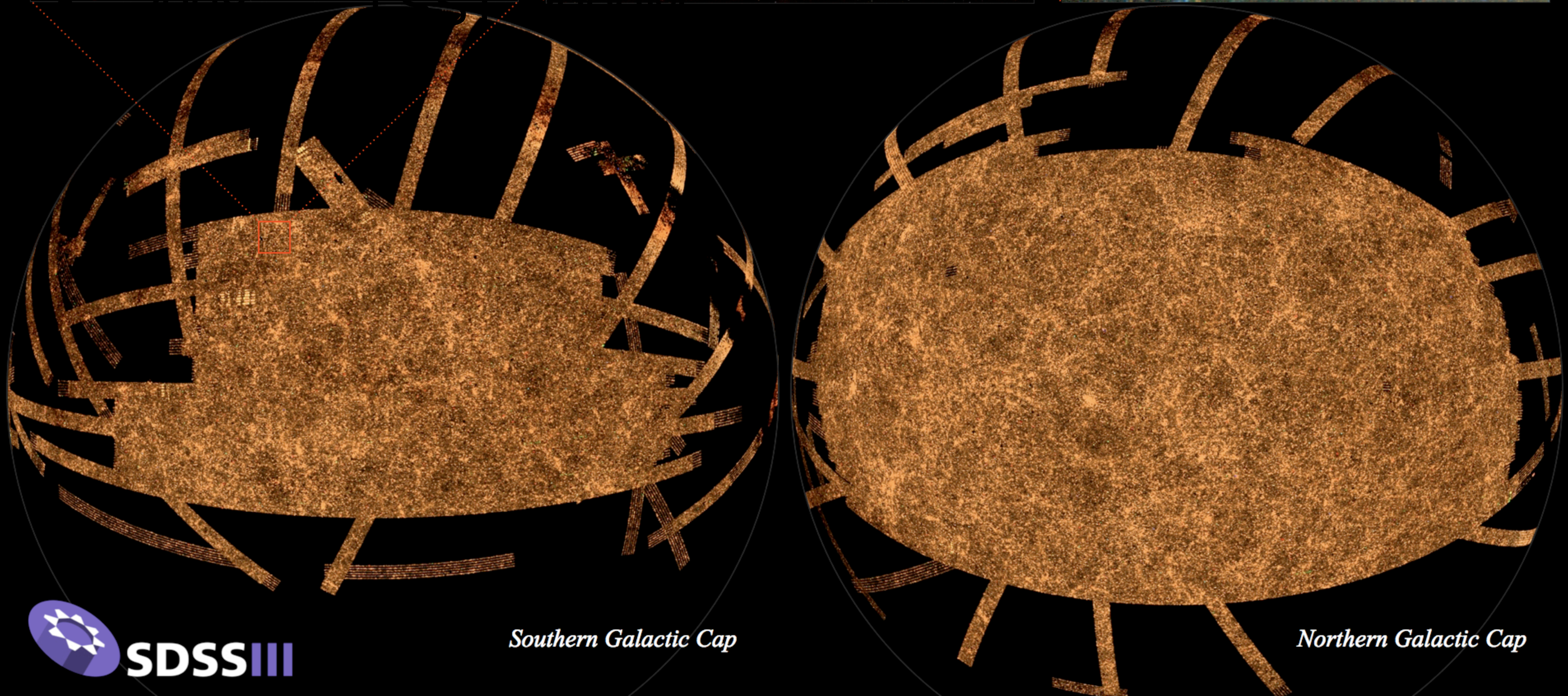
Galaxy surveys

Taking colour images of galaxies



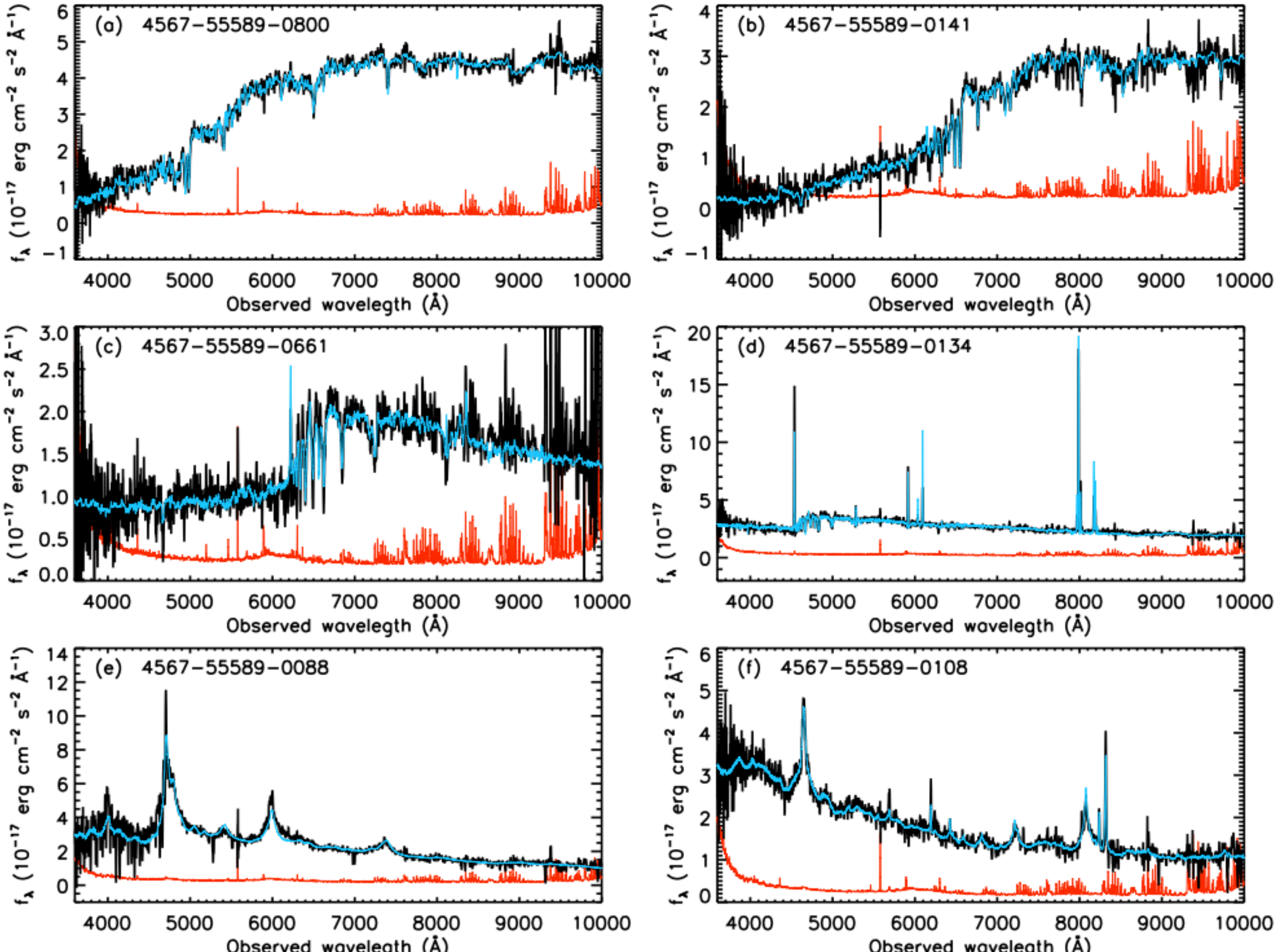






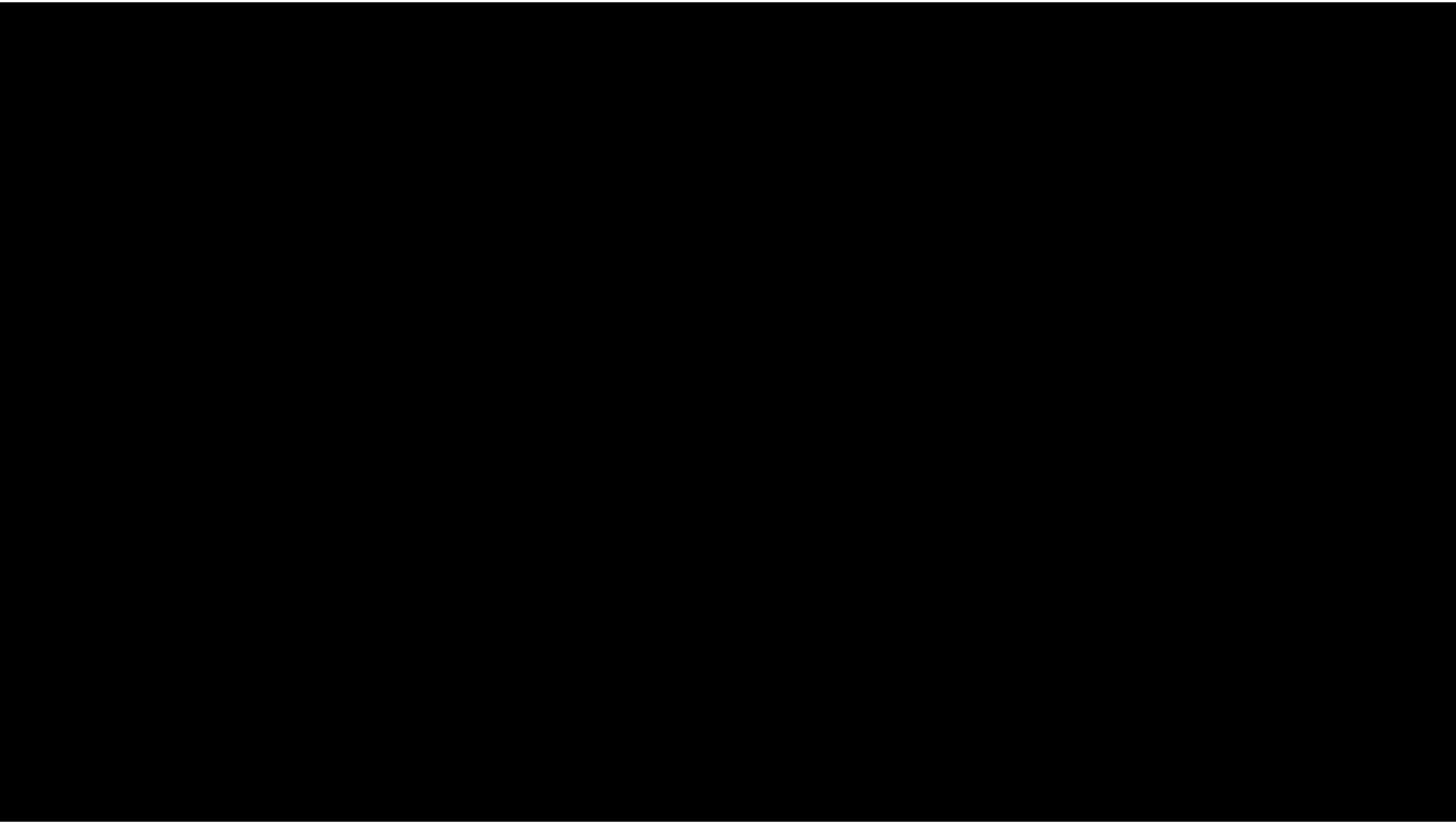
SDSSIII

Spectra gives recession velocities and redshifts

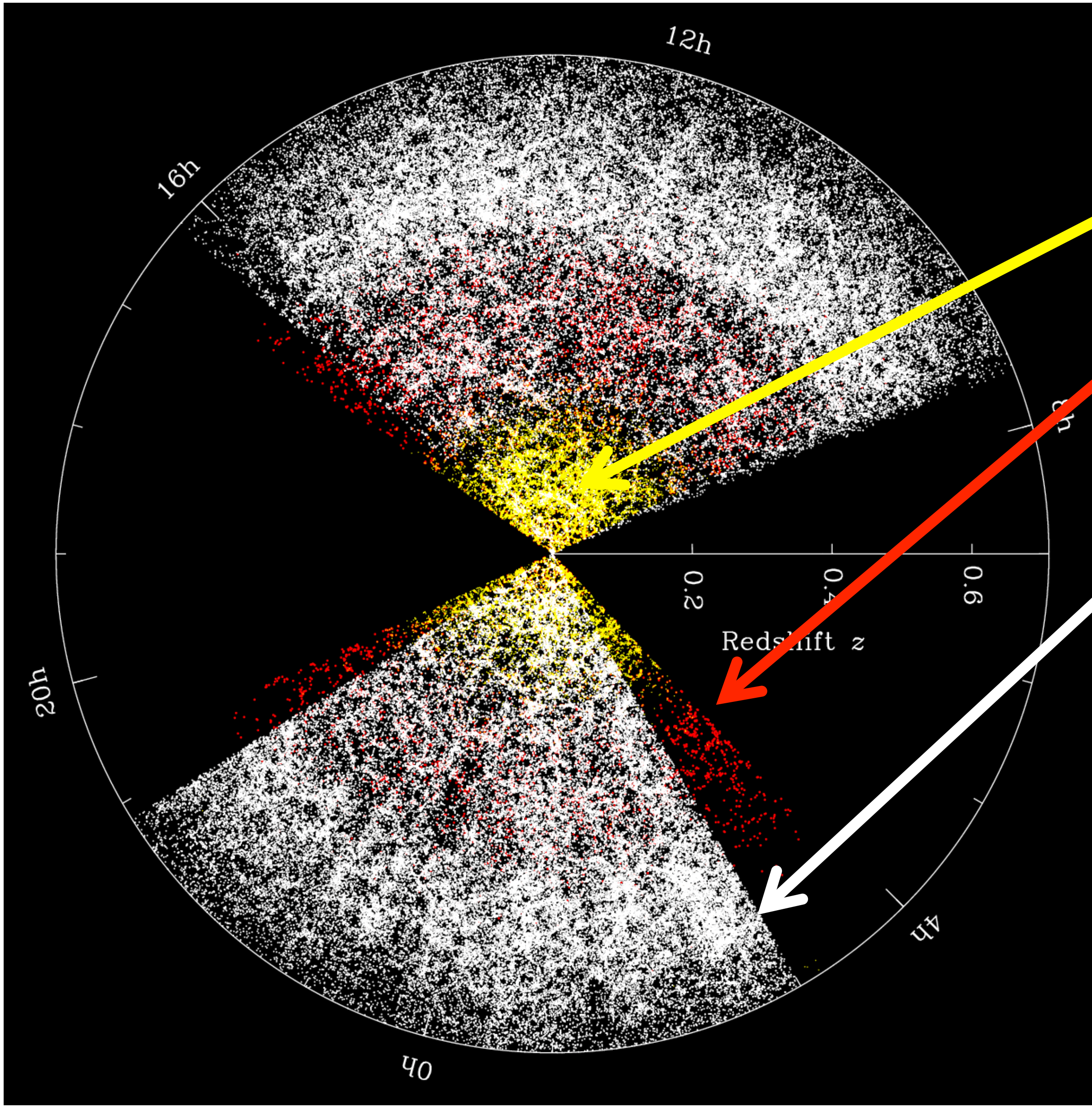


Bolton et al. 2012

Spectra allows us to recover 3D information



Large-scale galaxy distribution



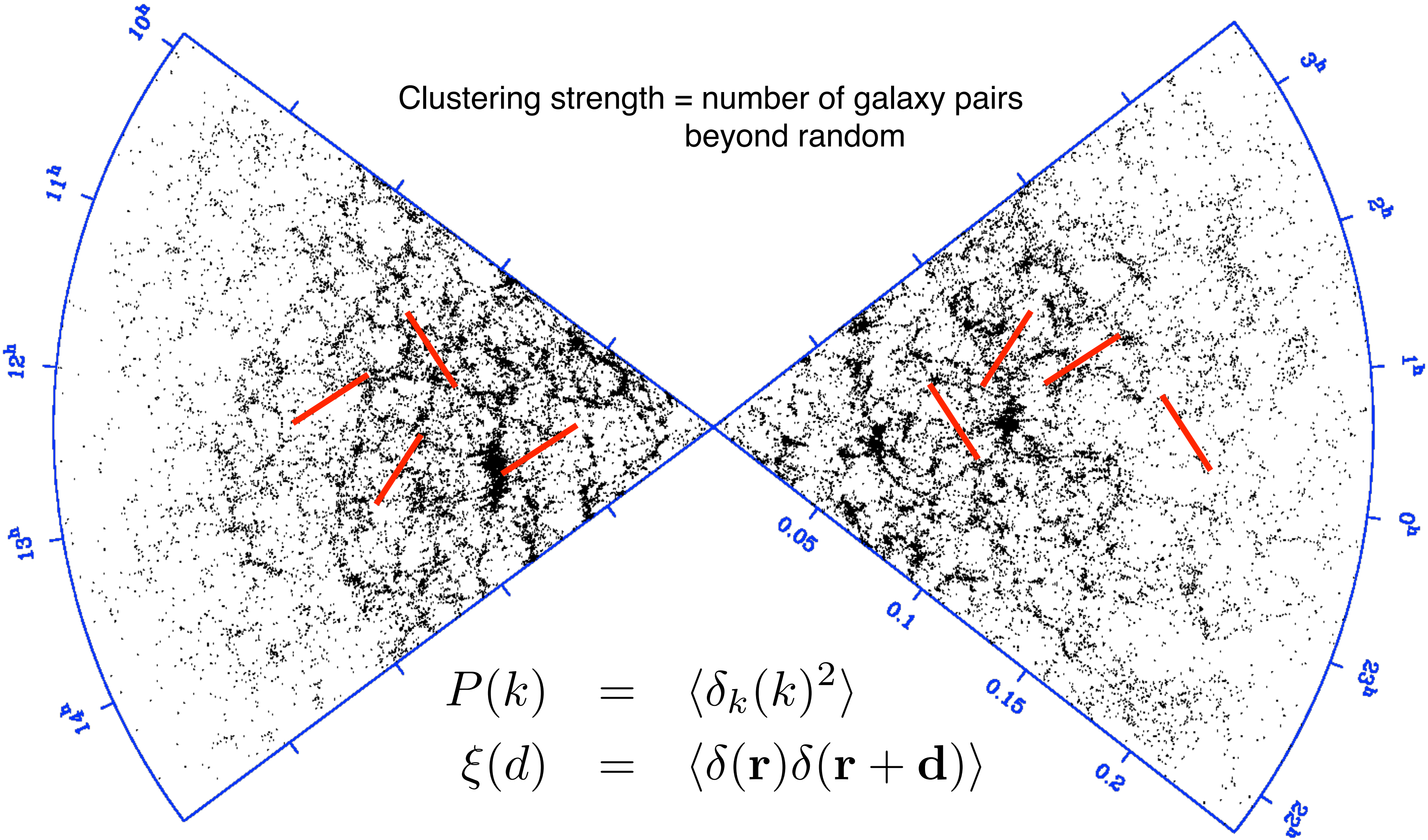
SDSS-II main galaxies

SDSS-II LRGs

BOSS CMASS galaxies

Image credit: Blanton

What does “galaxy clustering” mean?

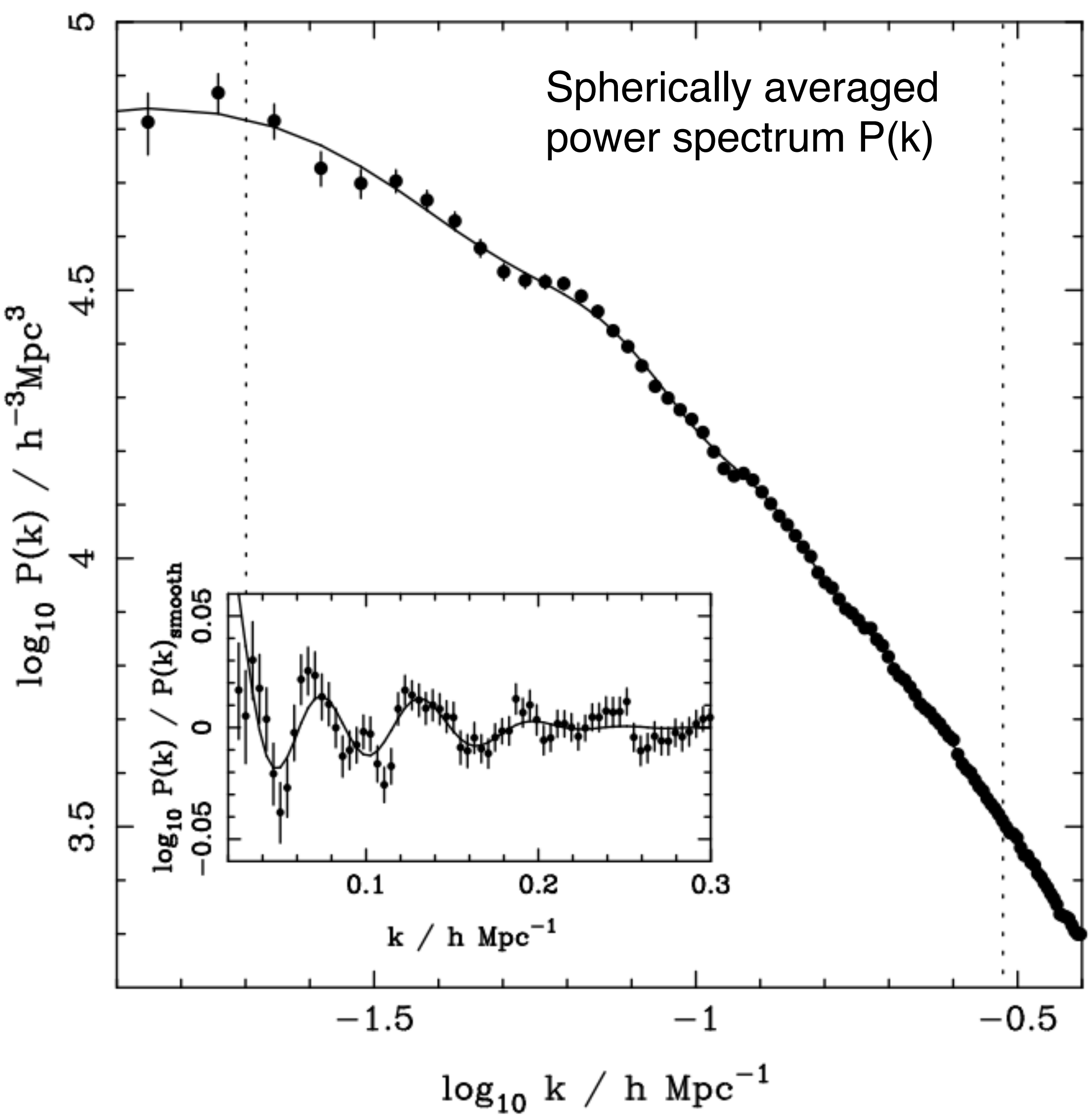


Clustering strength = number of galaxy pairs beyond random

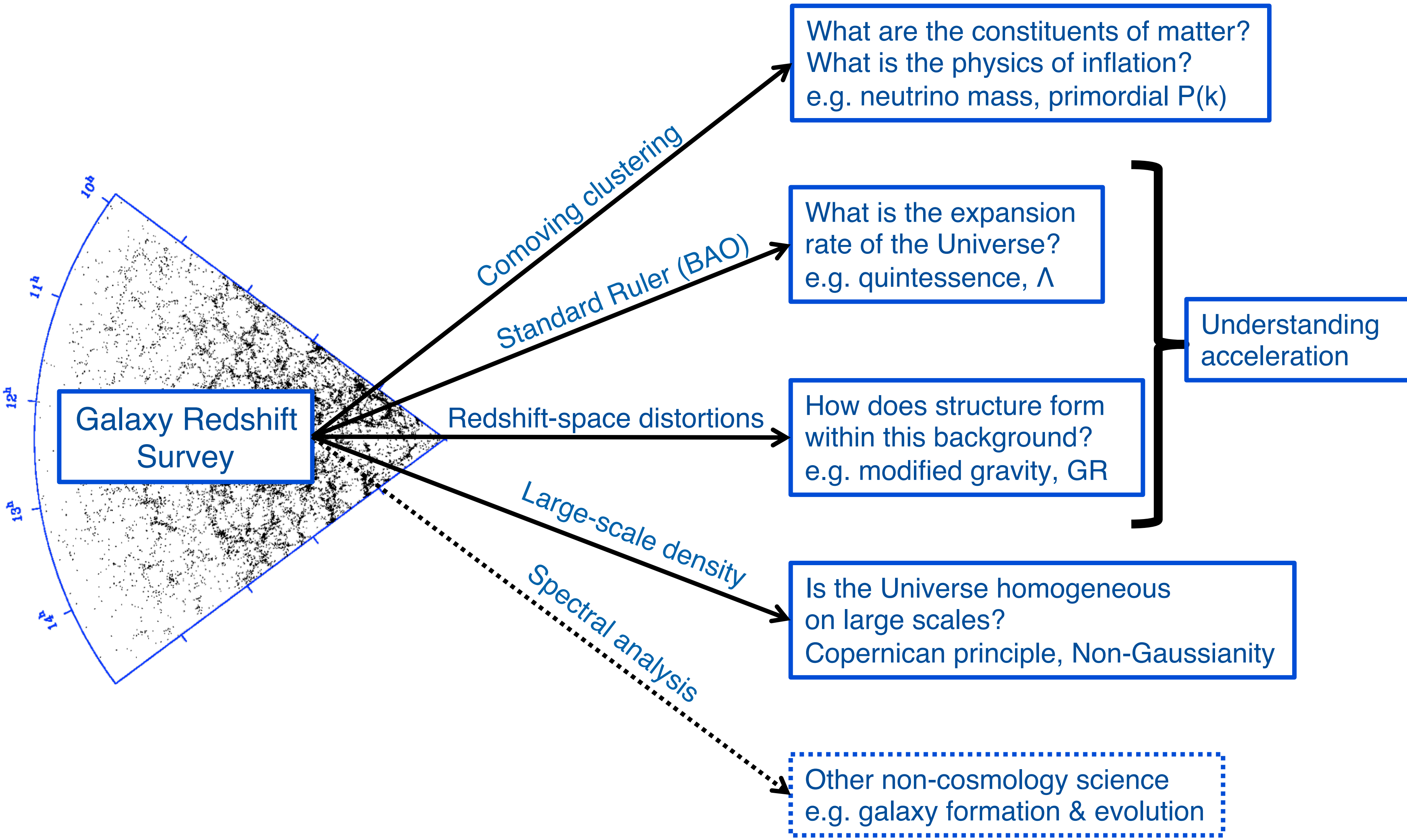
$$P(k) = \langle \delta_k(k)^2 \rangle$$
$$\xi(d) = \langle \delta(\mathbf{r})\delta(\mathbf{r}+\mathbf{d}) \rangle$$

2dFGRS

Power spectrum (preview)

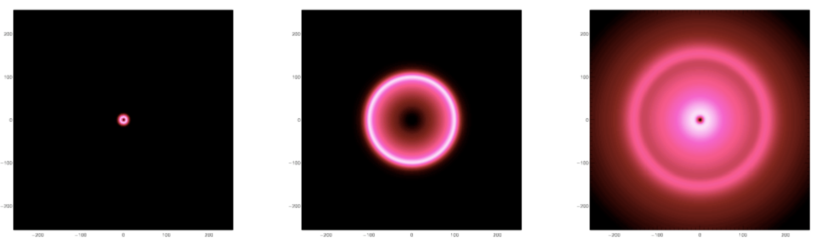


Cosmology from Spectroscopic Galaxy Surveys

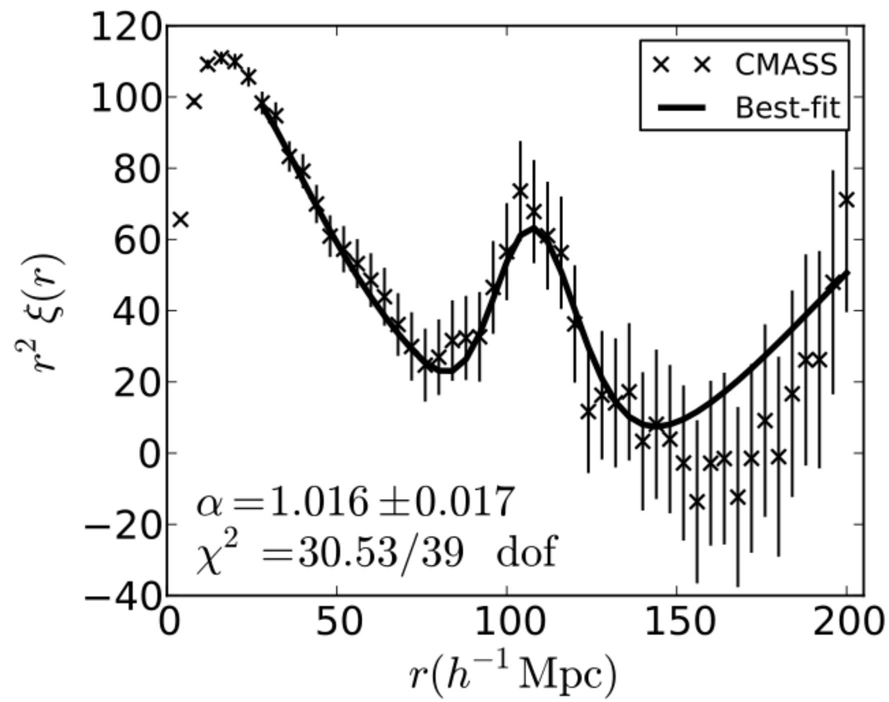


Using primordial sound waves to measure cosmic expansion

Baryon Acoustic Oscillations (BAO)



(images from Martin White)

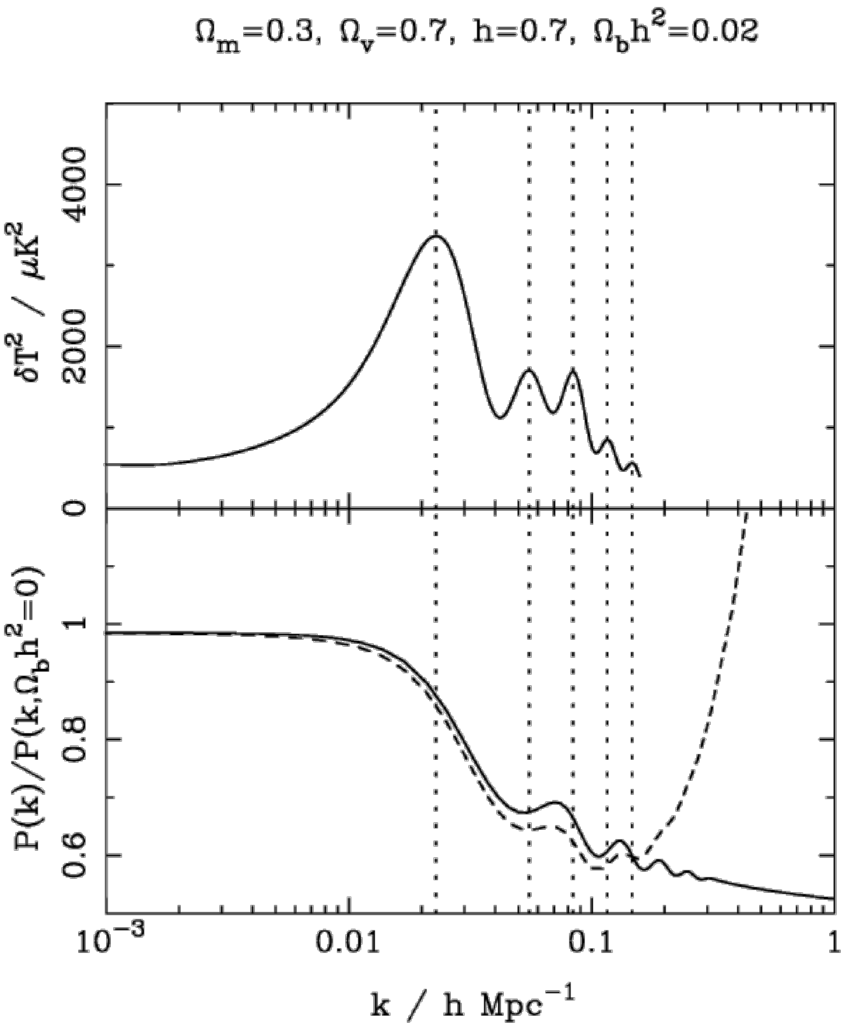


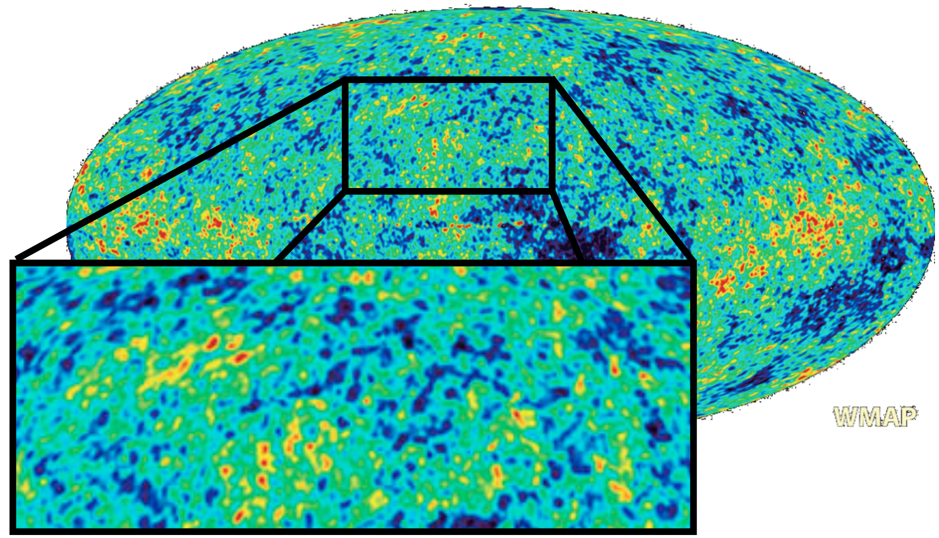
To first approximation, comoving BAO wavelength is determined by the comoving sound horizon at recombination

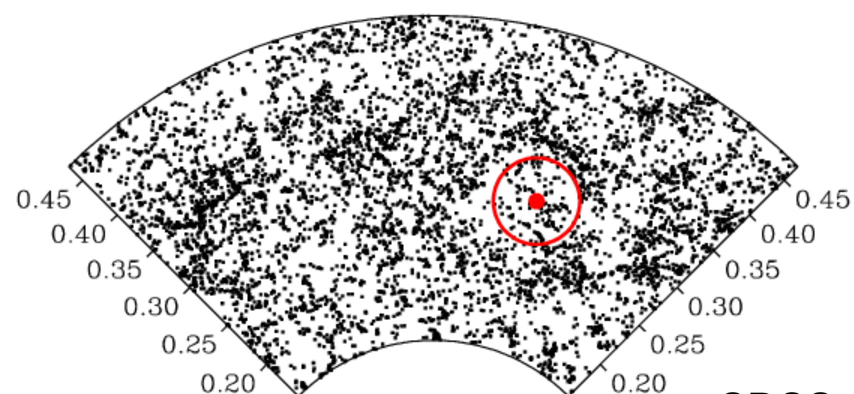
$$r_s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{eq})^{1/2}}$$

comoving sound horizon ~110h^{-1}Mpc, BAO wavelength 0.06hMpc^{-1}

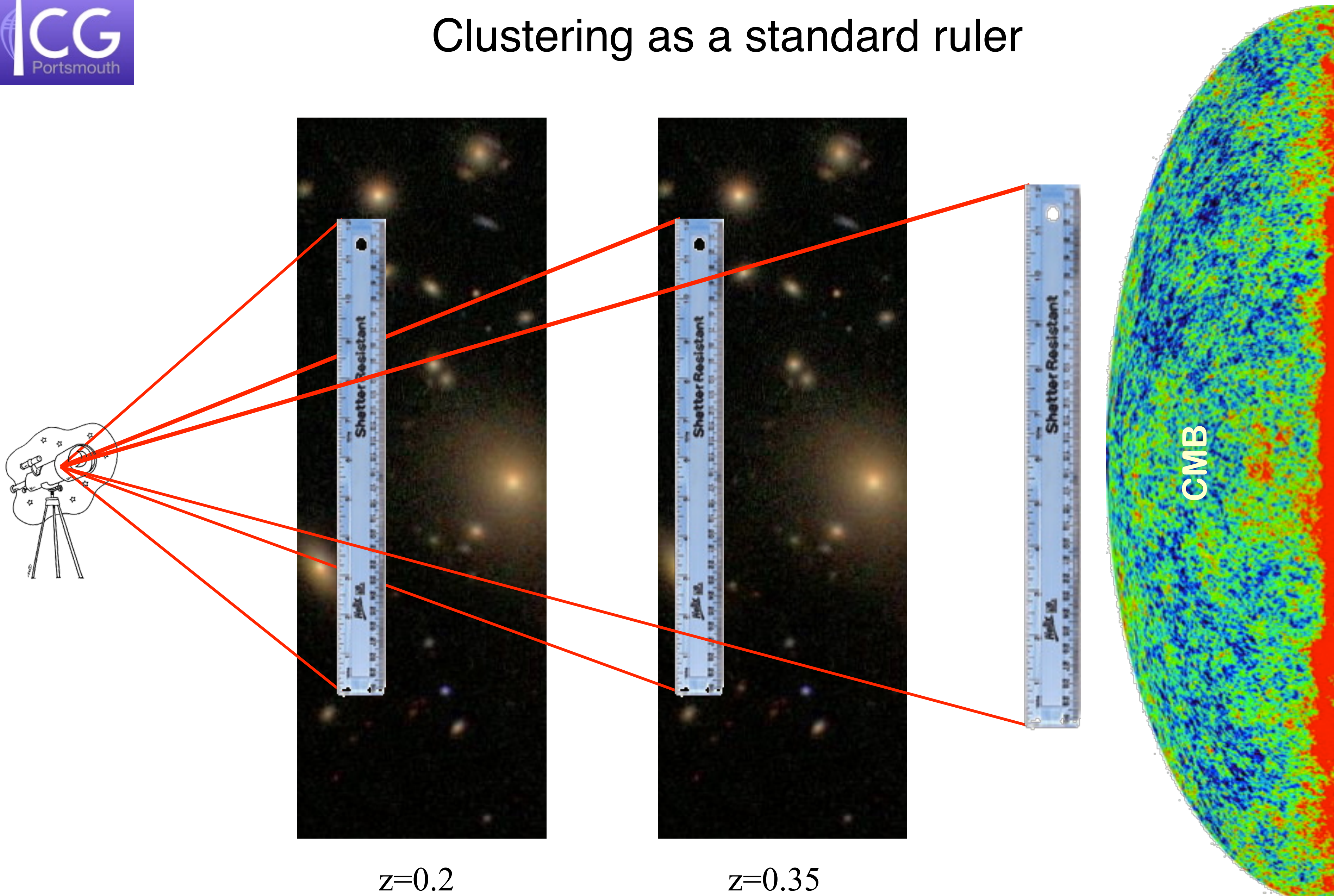
Relationship between CMB and LSS power spectra







Clustering as a standard ruler



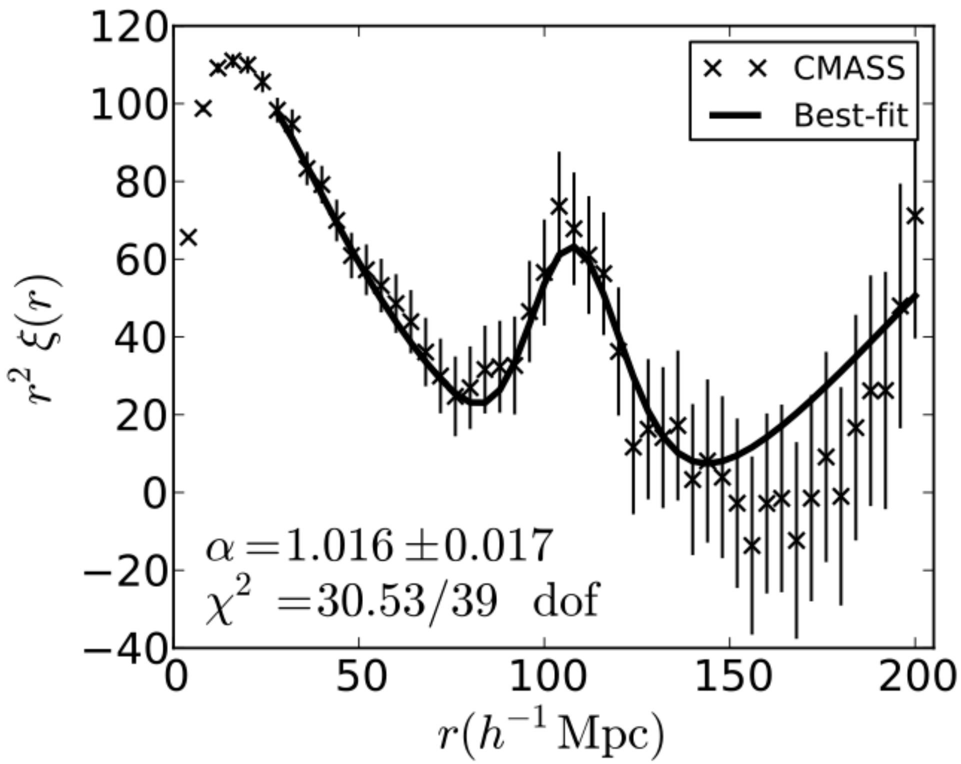
CREDIT: WMAP & SDSS websites

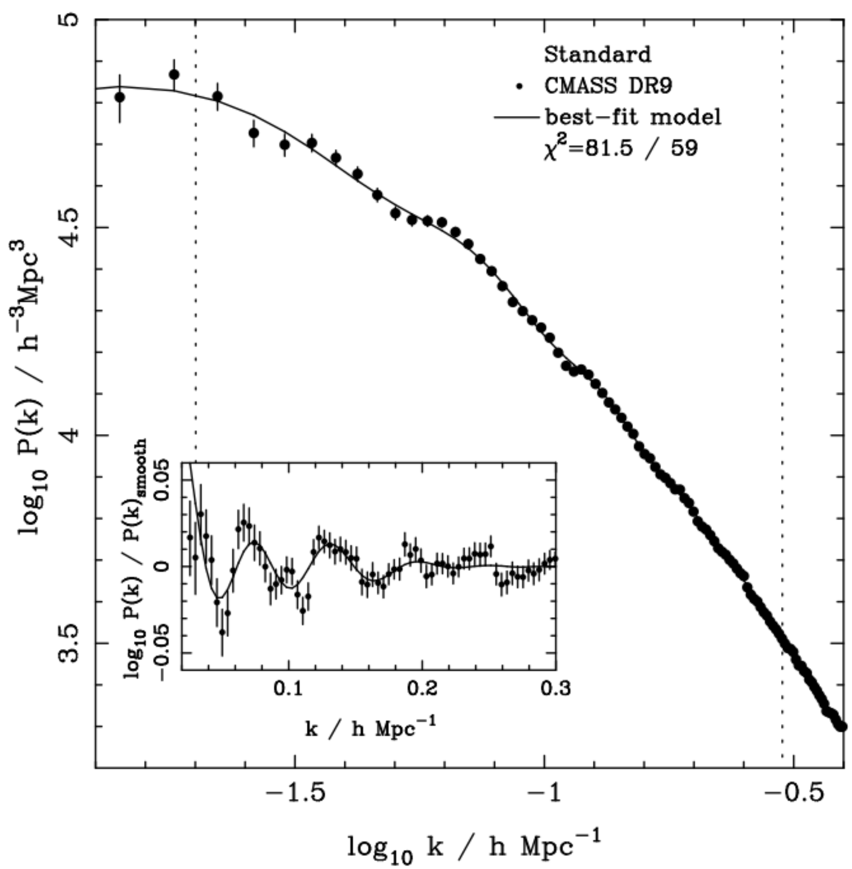
Recent measurements from the
Baryon Oscillation Spectroscopic Survey

BOSS (part of the SDSS-III project)

- Duration: Fall 2009 - Summer 2014, dark time
- Telescope: 2.5m Sloan
- Upgrade to SDSS-II spectrograph
  - 1000 smaller fibers
  - higher throughput
- Spectra:
  - $3600\mathring{A} < \lambda < 10,000\mathring{A}$ New spectrograph
  - $R = \lambda/\Delta\lambda = 1300 - 3000$
  - (S/N) at mag. limit
    - 22 per pix. (averaged over 7000-8500Å)
    - 10 per pix. (averaged over 4000-5500Å)
- Area: 10,000 deg2
- Targets:
  - 1.5×10^6 massive galaxies, $z < 0.7$, $i < 19.9$
  - 1.5×10^5 quasars, $z>2.2$, $g<22.0$ selected from 4×10^5 candidates
  - 75,000 ancillary science targets, many categories
- Measurements from Galaxies:
  - $d_A(z)$ to 1.2% at $z = 0.35$ and 1.2% $z = 0.6$
  - $H(z)$ to 2.2% at $z = 0.35$ and 2.0% at $z = 0.6$
- Measurements from Lyα Forest:
  - $d_A(z)$ to 4.5% at $z = 2.5$ $H(z)$ to 2.6% at $z = 2.5$

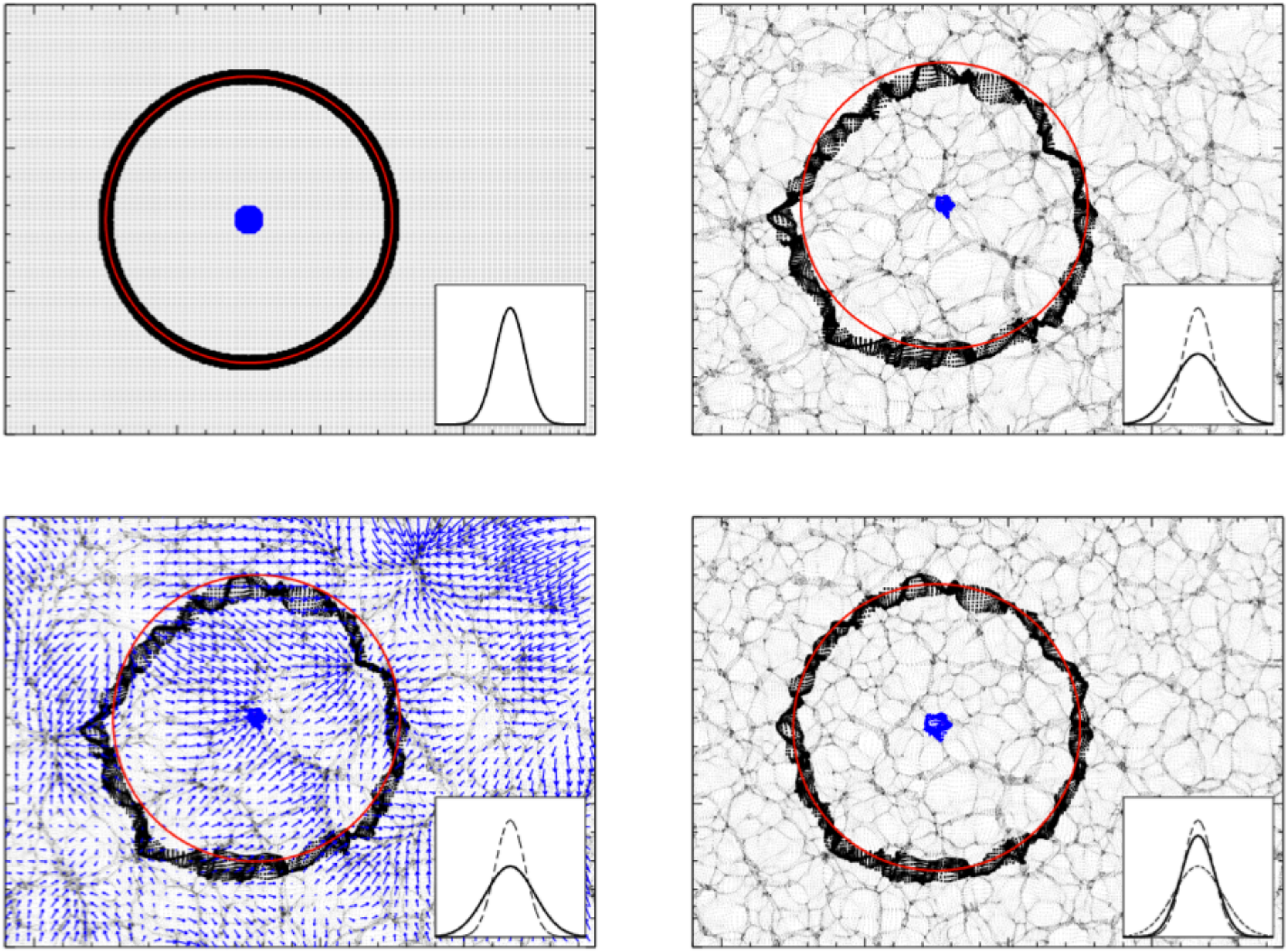
BOSS CMASS clustering measurements





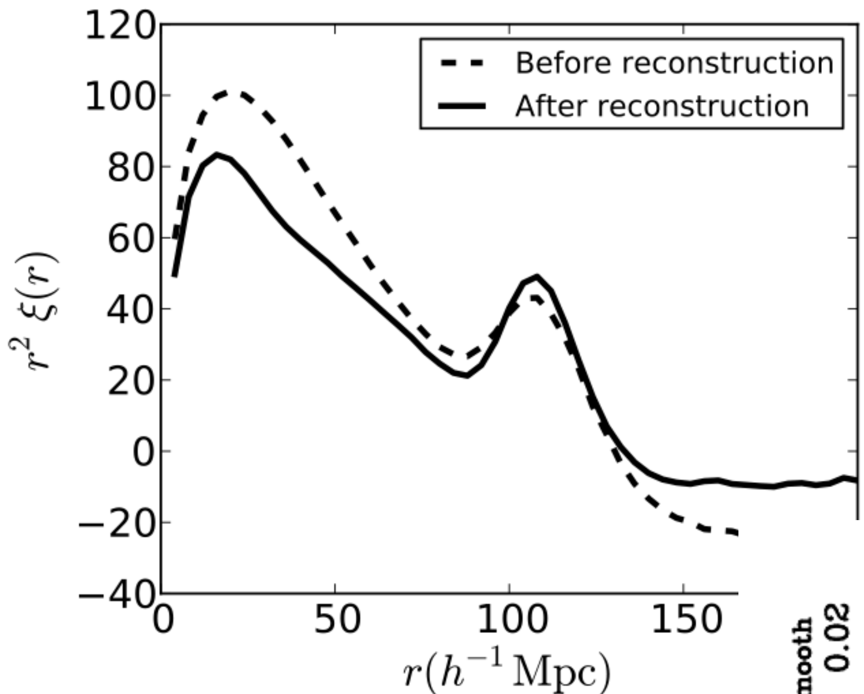
Anderson et al.

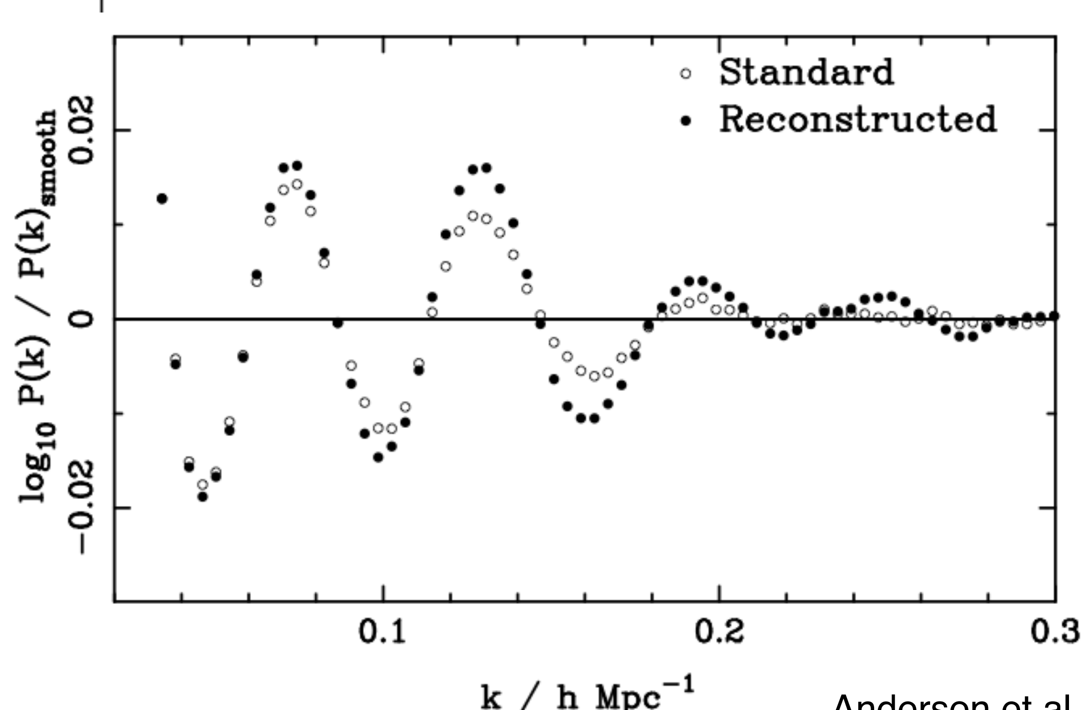
Reconstruction of linear positions



Padmanabhan et al. 2012; arXiv:1202.0090

Reconstruction on CMASS mocks





Anderson et al.

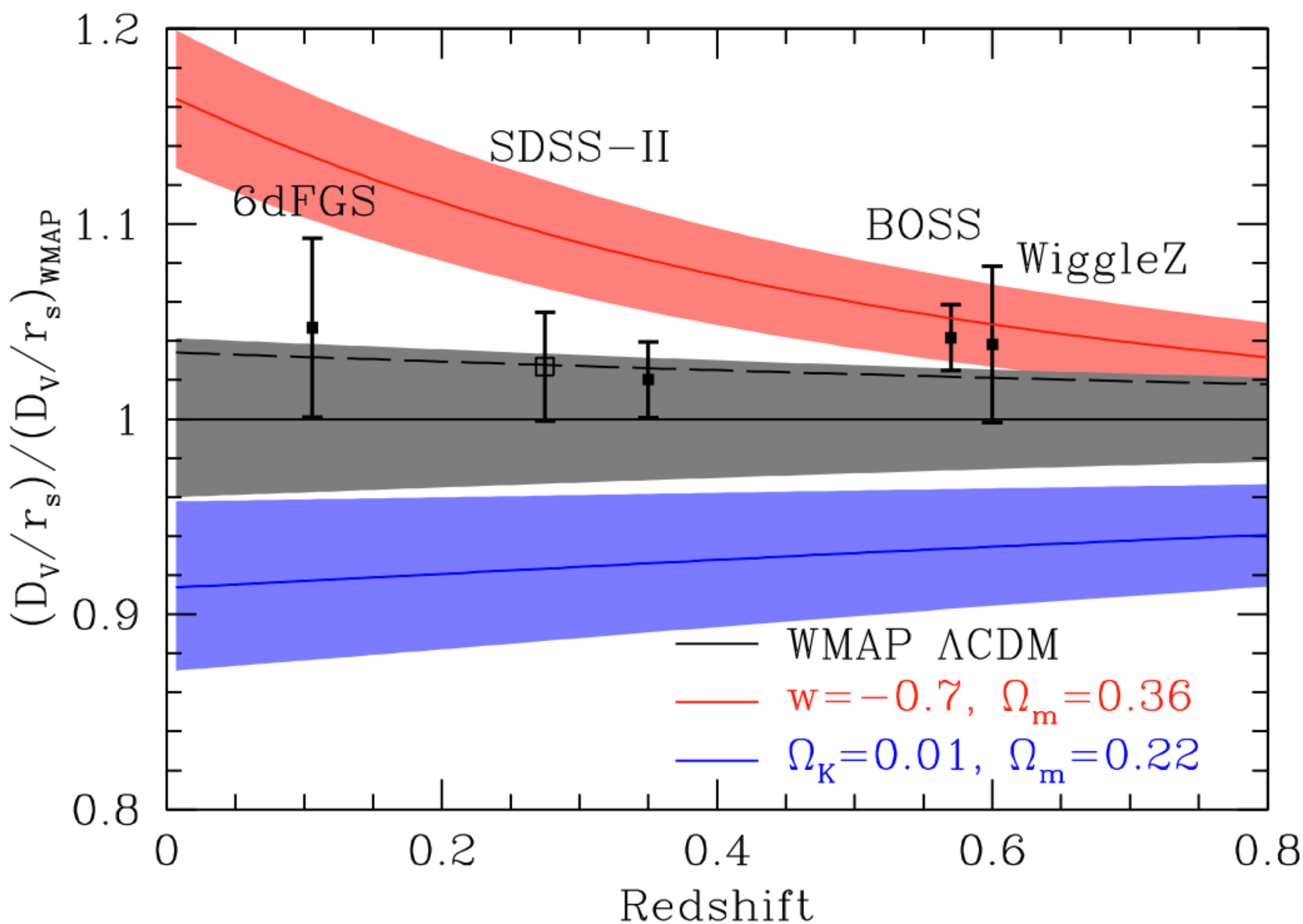
Key BAO measurements

	α	χ^2/dof	$D_V/r_s(z=0.57)$
		Before Reconstruction	
$\xi(r)$	1.016 ± 0.017	$30.53/39$	13.44 ± 0.22
$P(k)$	1.022 ± 0.017	$81.5/59$	13.52 ± 0.22
		After Reconstruction	
$\xi(r)$	1.024 ± 0.016	$34.53/39$	13.55 ± 0.21
$P(k)$	1.042 ± 0.016	$61.1/59$	13.78 ± 0.21
Consensus	1.033 ± 0.017	$--$	13.67 ± 0.22

- ξ(r) and P(k) based estimations are **appropriate** and **unbiased,** but they include the noise from small scales and shot noise differently
- We **average** the two results, and compute the error bar using the **observed scatter** of the average value in the mocks. This shows no significant departure from a Gaussian distribution

Anderson et al.

BAO fitting gives distance vs redshift



Anderson et al. 2012

Measuring Growth with Anisotropic Clustering

Redshift-space distortions

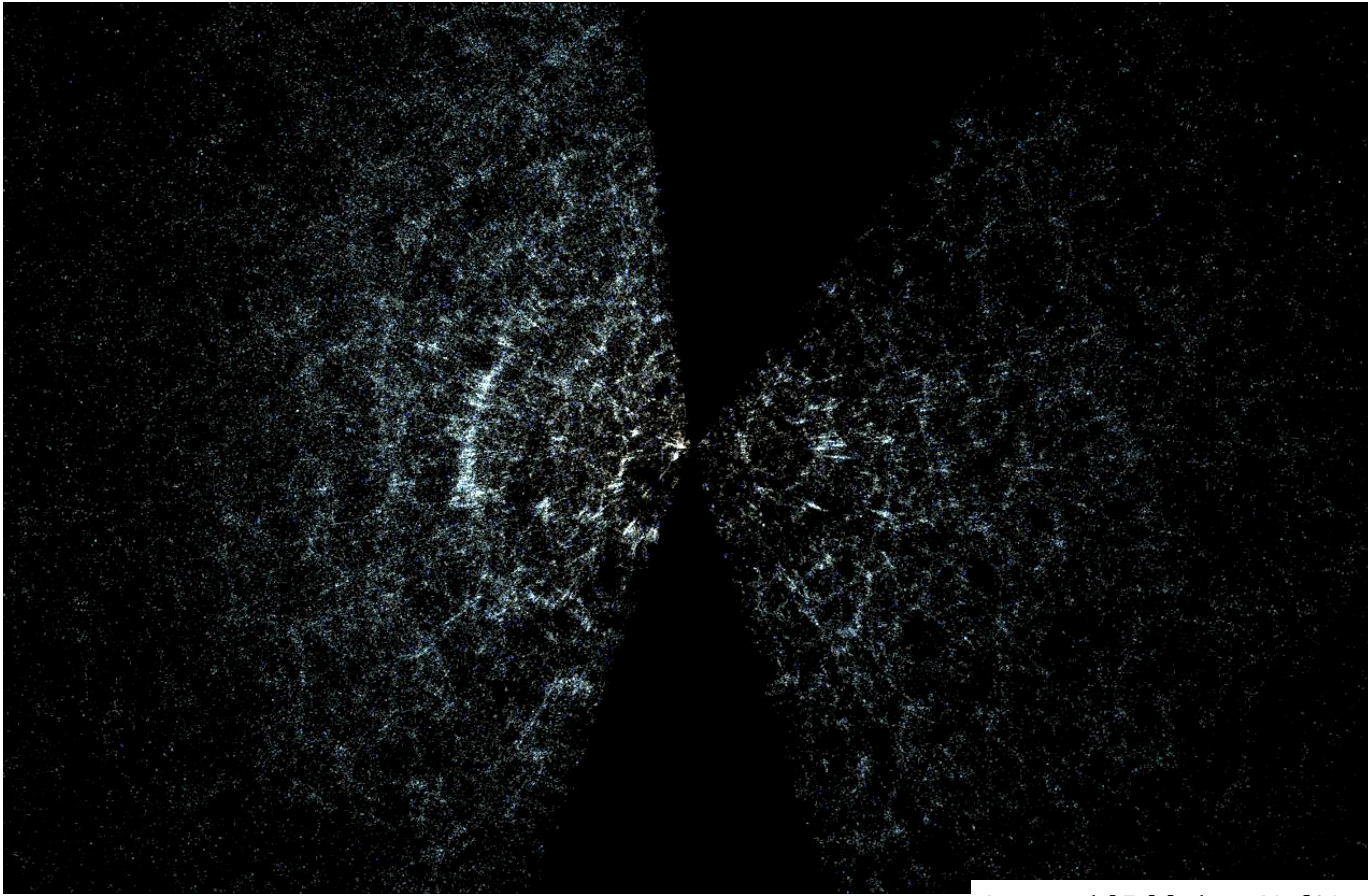
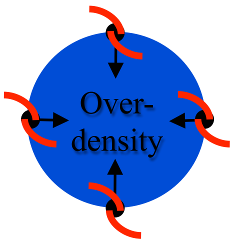
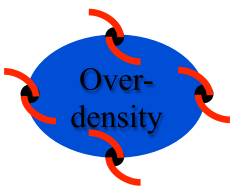


Image of SDSS, from U. Chicago

Redshift Space Distortions



Actual shape



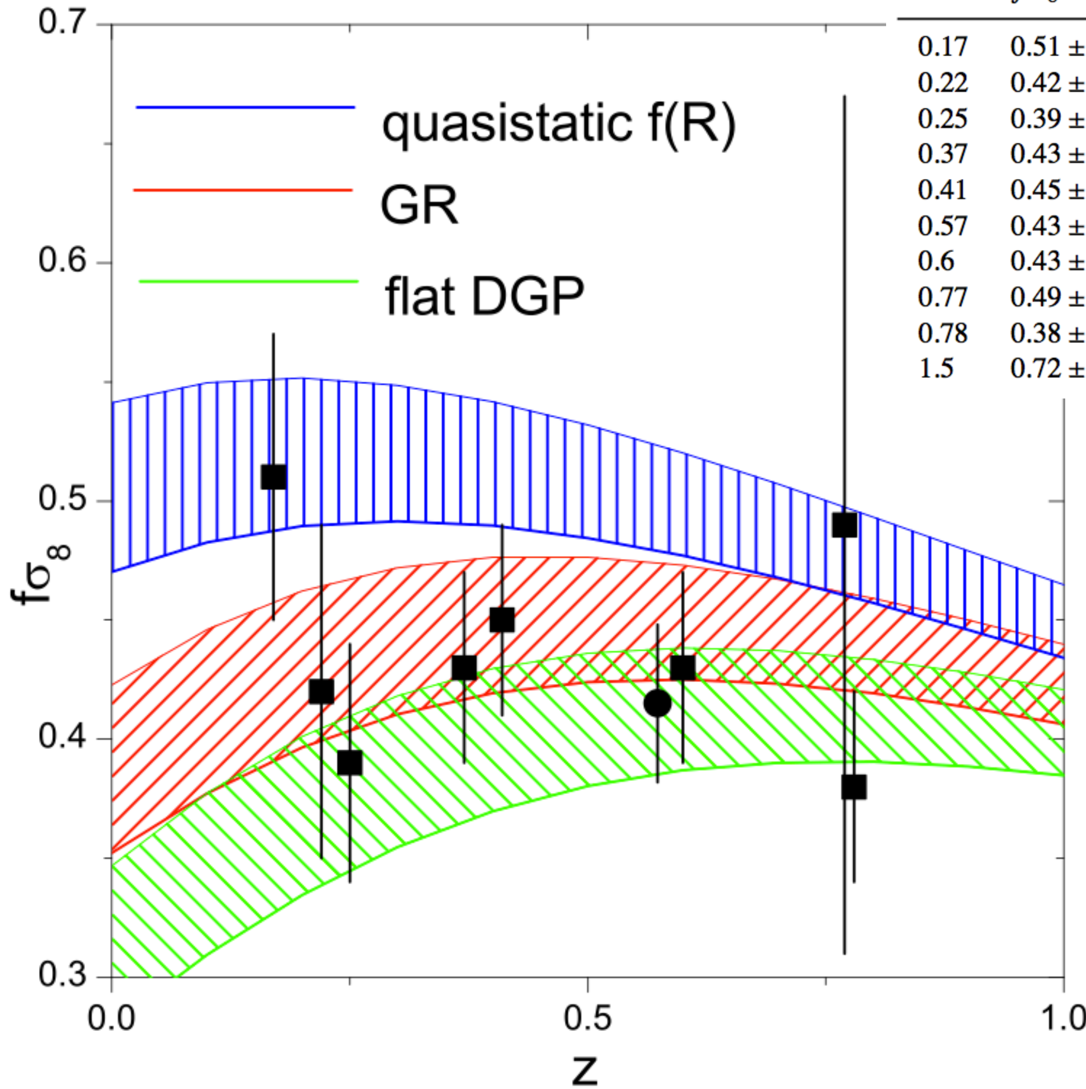
Apparent shape (viewed from below)

- Observed redshift depends on both Hubble expansion and additional “peculiar velocity”
- Galaxies move because cosmological structure is growing
- Resulting change in redshift is coherent with structure
- extra component depends on amplitudes of peculiar velocities

$$f(z)\sigma_8(z) \propto \frac{dG}{d\log a}$$

  – where G is the linear growth rate

Recent RSD measurements



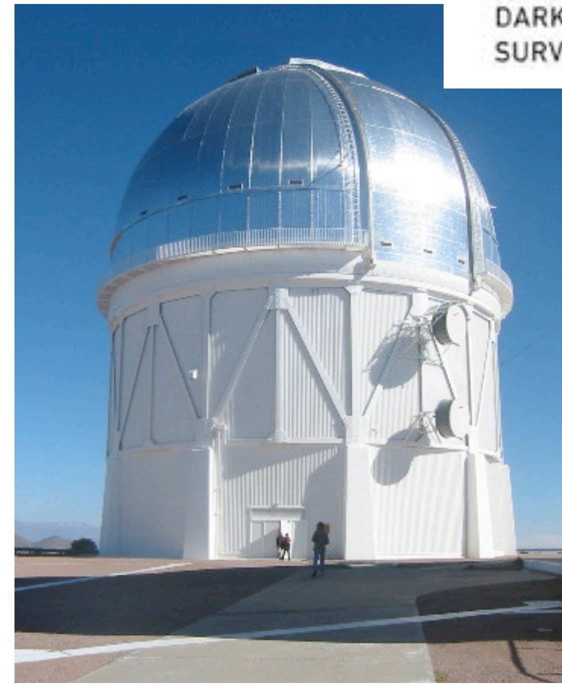
z	$f\sigma_8$	survey	reference
0.17	0.51 ± 0.06	2dFGRS	Percival et al. (2004)
0.22	0.42 ± 0.07	WiggleZ	Blake, et al. (2011b)
0.25	0.39 ± 0.05	SDSS	Samushia, Percival, & Raccanelli (2011)
0.37	0.43 ± 0.04	SDSS	Samushia, Percival, & Raccanelli (2011)
0.41	0.45 ± 0.04	WiggleZ	Blake, et al. (2011b)
0.57	0.43 ± 0.03	BOSS	Reid et al. (2012)
0.6	0.43 ± 0.04	WiggleZ	Blake, et al. (2011b)
0.77	0.49 ± 0.18	VVDS	Guzzo et al. (2007)
0.78	0.38 ± 0.04	WiggleZ	Blake, et al. (2011b)
1.5	0.72 ± 0.15	2SLAQ	da Angela et al. (2008)

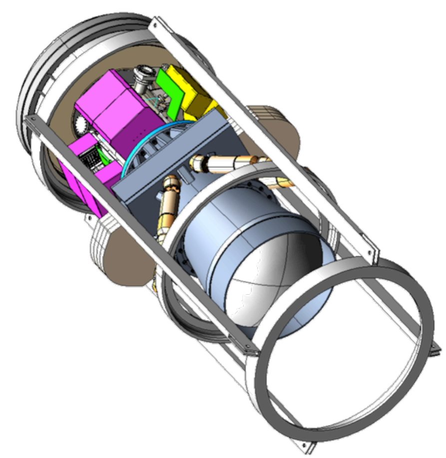
Samushia et al., Reid et al.

Future Surveys

Dark Energy Survey (DES)

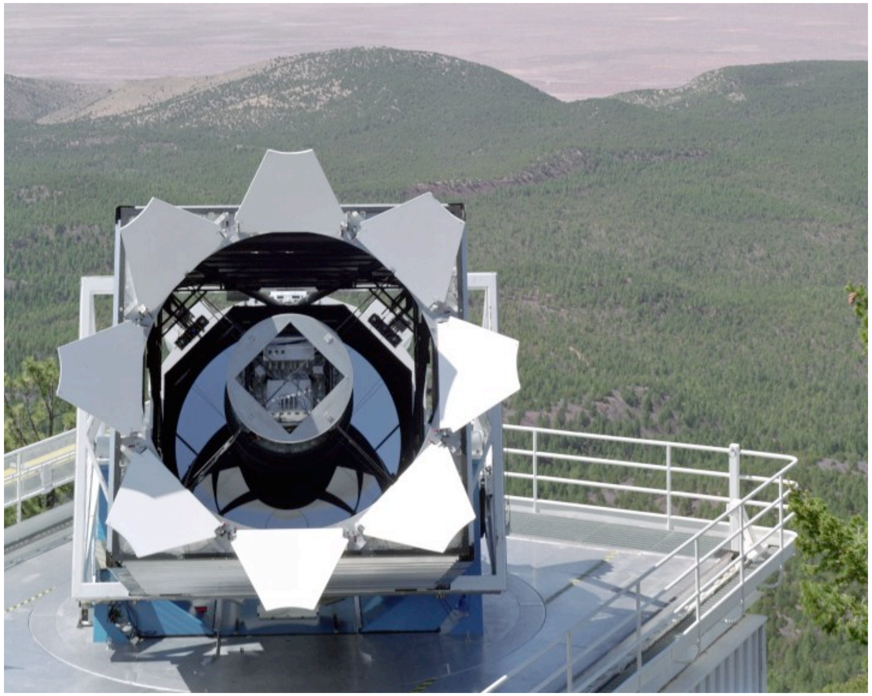
- New wide-field camera for the 4m Blanco telescope
- Currently being assembled on site,
  Survey due to start December 2012
- Ω = 5,000deg2
- multi-colour optical imaging (g,r,i,z) with link to IR data from VISTA hemisphere survey
- 300,000,000 galaxies
- Aim is to constrain dark energy using 4 probes
  LSS/BAO, weak lensing, supernovae
  cluster number density
- Redshifts based on photometry
  weak radial measurements
  weak redshift-space distortions
- See also: Pan-STARRS, VST-VISTA, SkyMapper





eBOSS

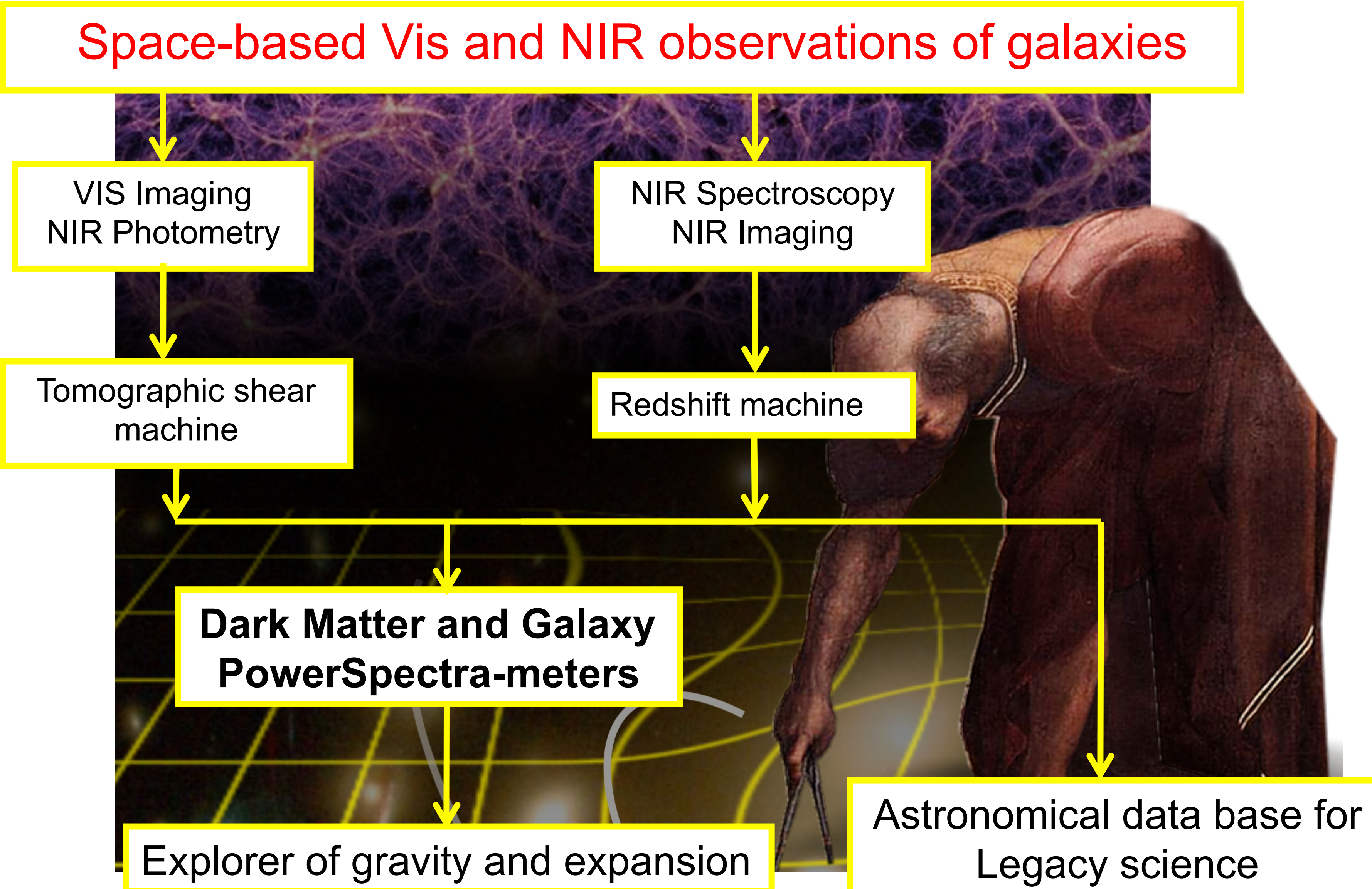
- Use the Sloan telescope and MOS to observe to higher redshift
- Basic parameters
  - Ω =3,000deg^2
  - 1,000,000 galaxies (direct BAO)
  - 60,000 quasars (BAO from Ly-α forest)
- Distance measurements
  - 1.6% at z=0.7 (LRGs)
  - 1.5% at z=0.9 (ELGs)
  - 3.0% at z=1.5 (QSOs)
  - 2.3% at z=2.5 (Ly-α forest)
- Survey would start 2014, and would last 4—6 years (depending on funding)
- Currently at the stage of requesting funding



MOS on 4m-telescope

- New fibre-fed spectroscopes proposed for 4m telescopes
  - Mayall (BigBOSS)
  - Blanco (DESpec)
  - WHT (WEAVE)
  - VISTA (4MOST)
- Various stages of planning & funding
- All capable of observing
  - Ω =10,000deg^2
  - 10,000,000 galaxies (direct BAO)
  - 600,000 quasars (BAO from Ly-α forest)
- Cosmic variance limited to $z \sim 1.4$

The ESA Euclid Mission

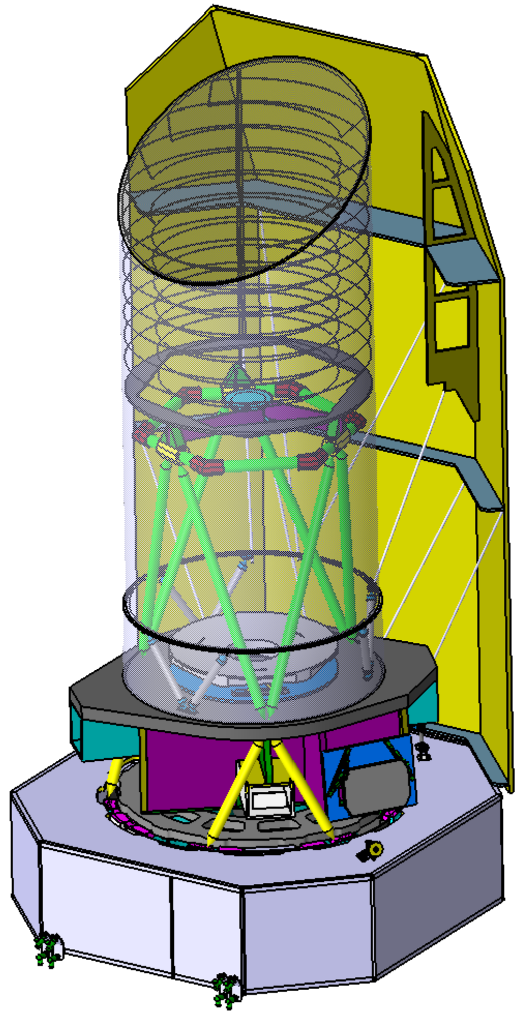


The ESA Euclid Mission

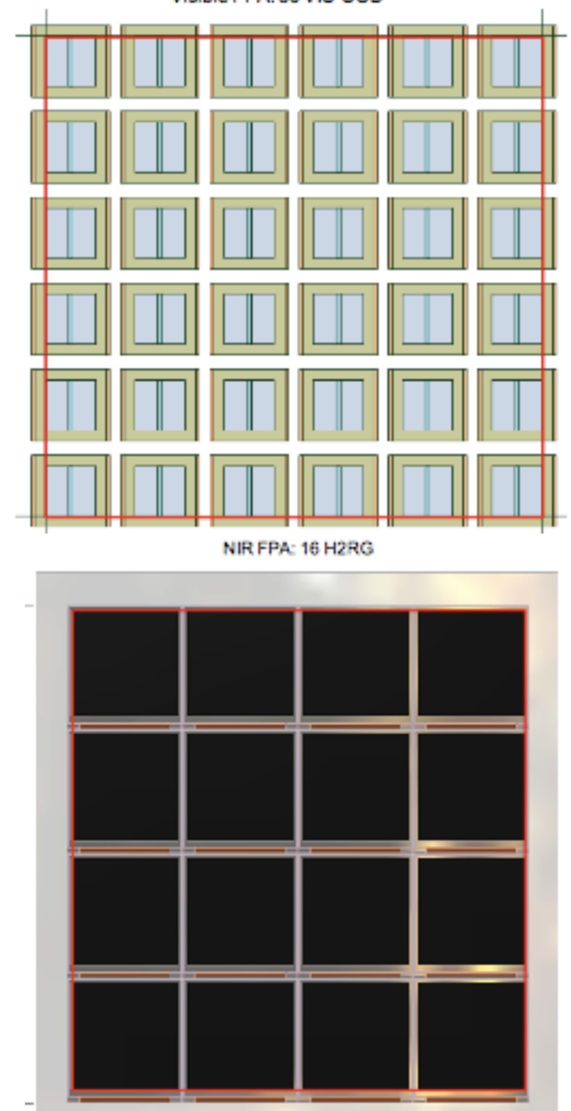
SURVEYS					
	Area (deg2)	Description			
Wide Survey	15,000 (required) 20,000 (goal)	Step and stare with 4 dither pointings per step.			
Deep Survey	40	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey			
PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	$3\ 10^{-16}$ erg cm-2 s-1 3.5σ unresolved line flux
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250
SPACECRAFT					
Launcher	Soyuz ST-2.1 B from Kourou				
Orbit	Large Sun-Earth Lagrange point 2 (SEL2), free insertion orbit				
Pointing	25 mas relative pointing error over one dither duration 30 arcsec absolute pointing error				
Observation mode	Step and stare, 4 dither frames per field, VIS and NISP common FoV = 0.54 deg^2				
Lifetime	7 years				
Operations	4 hours per day contact, more than one ground station to cope with seasonal visibility variations;				
Communications	maximum science data rate of 850 Gbit/day downlink in K band (26GHz), steerable HGA				

Hardware

Astrium



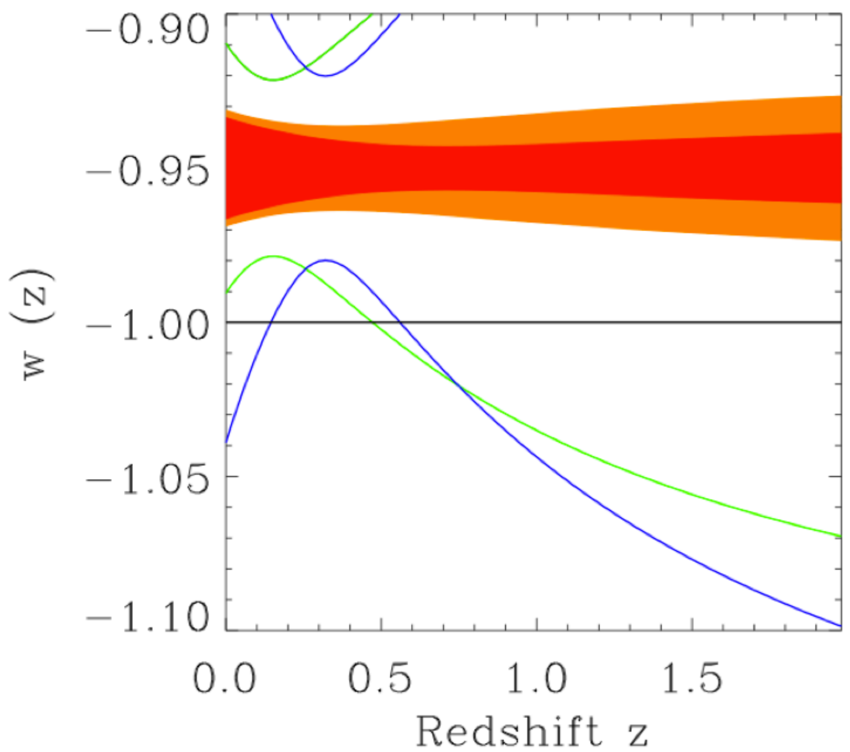
Thales



0.5deg^2 FOV in optical/NIR

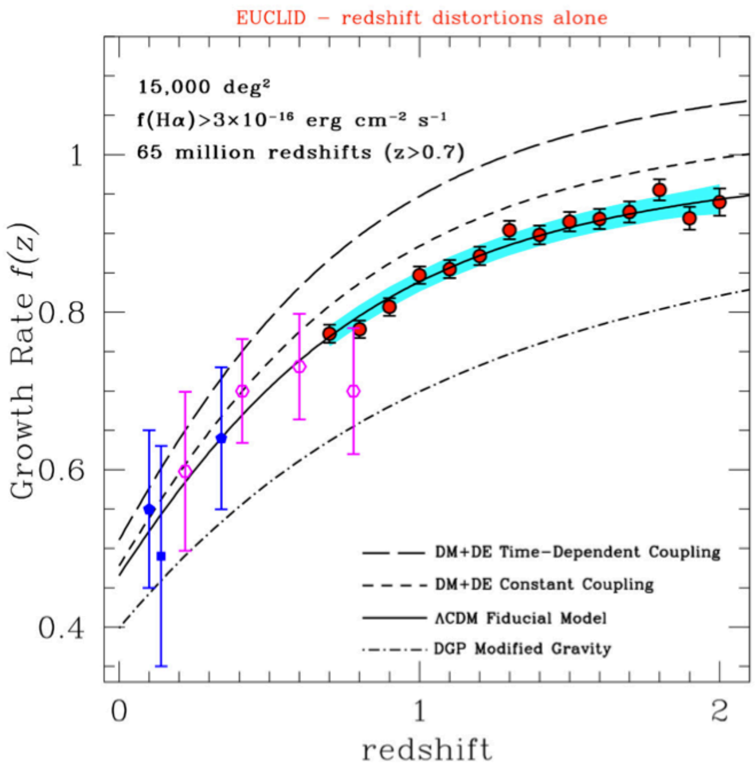
Measuring Dark Energy

- The dark energy equation of state is the ratio of the pressure to density of dark energy $p(a) = w(a) \times \rho(a) c^2$.
- This dependence can be parameterised using a first order Taylor expansion with respect to the scale factor $a=1/(1+z)$,
  $w(a)= w_p+(a_p-a)w_a$.
- Detecting $w(a)\neq-1$ at any redshift would demonstrate that dark energy is not a cosmological constant, but rather a dynamical field
- Define a Figure-of-Merit (FoM)
  FoM = $1/(\Delta wp \times \Delta wa)$
- Primary Euclid probes give a FoM>4(with subdominant systematic uncertainties, matching the DETF definition of a stage-IV mission



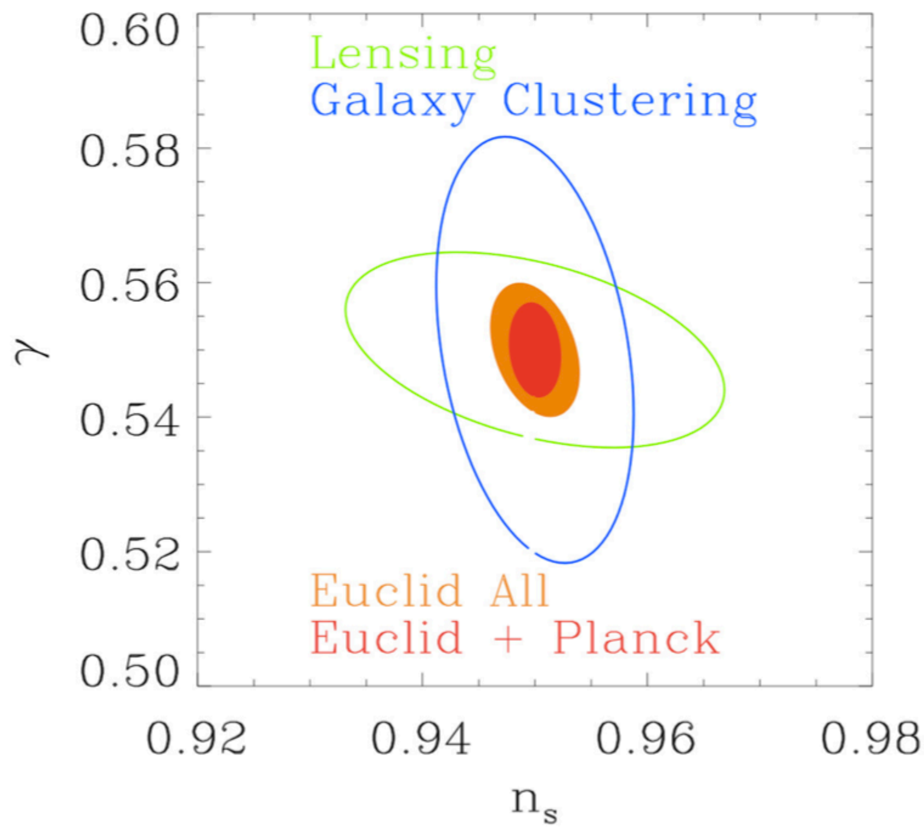
Measuring Modified Gravity

- The growth factor [or its derivative, the growth rate f(z)] quantifies the efficiency with which cosmological structure is built.
- A detection of $\gamma \neq 0.55$ would indicate a deviation from General Relativity, and thus a completely different origin of cosmic acceleration, rather than dark energy.
- The growth rate well described by $f(z)=\Omega_m(z)^\gamma$.
- Euclid can constrain this parameter to 0.01 (where ΛCDM corresponds to $\gamma=0.55$).
- the γ-parameterisation is merely an example. In general, Euclid will provide tight constraints on the cosmological growth rate.



Measuring initial conditions

- Concordance cosmology assumes an initial Gaussian random field of perturbations, with power-law index n_s
- Euclid + Planck will provide a factor ~2 improved n_s measurement over Planck alone
- A detection of non-Gaussianity would signify a departure from this central assumption of the current standard model. The f_{NL} parameter is a way to quantify the amplitude of this effect.
- Euclid will measure f_{NL} with an accuracy of 2, compared to Planck which measures f_{NL} to an accuracy 5 with a complementary approach



Measuring Neutrino Masses

- The total neutrino mass is the sum of the masses of the three known species (electron, muon and tau neutrinos).
- Massive neutrinos damp structure growth on small scales. The larger the mass, the more damping occurs, leaving a clear signature in the matter power spectrum observed by Euclid.
- particle physics experiments have established that at least two of the three neutrino species have non-zero mass, with the larger mass difference of the order of 0.06 eV
- Euclid will measure $\Delta m_v < 0.03$eV, sufficient to determine the neutrino mass hierarchy, if the total mass turns out to be small, $m_v < 0.1$ eV.
- i.e. will show if neutrinos obey a normal (two light neutrinos, one massive neutrino) or inverted (two massive neutrinos, one light neutrino) hierarchy; understanding this will give indications about the mechanism that gave neutrinos their mass.

Science summary

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	FoM
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

Legacy science

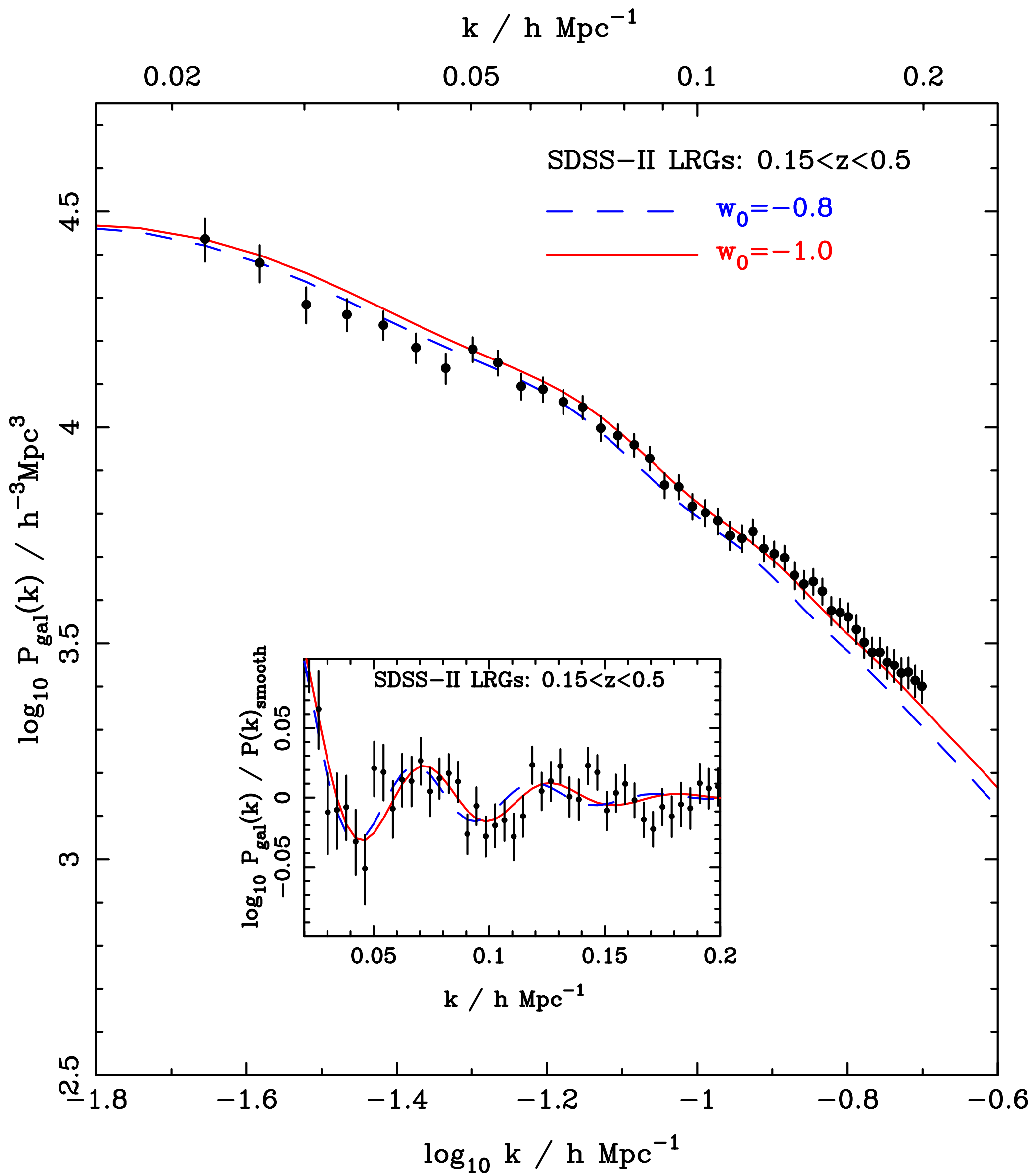
- Wide survey 15,000 deg2 YJHAB=24 would take 680 years with VISTA or 66 years with SASIR (2017)
- Deep survey 40 deg2 YJHAB=26 would take 72 years with VISTA or 7 years with SASIR
- The Euclid surveys are >100 times more ambitious than anything underway and at least >10 times more ambitious than anything else currently conceived

The next 16 years will see a greater transition in our level of ignorance about the Universe than the last 16 years …

SDSS-II LRG clustering

SDSS LRGs at z~0.35

Total effective volume $V_{eff} = 0.26\ Gpc^3h^{-3}$

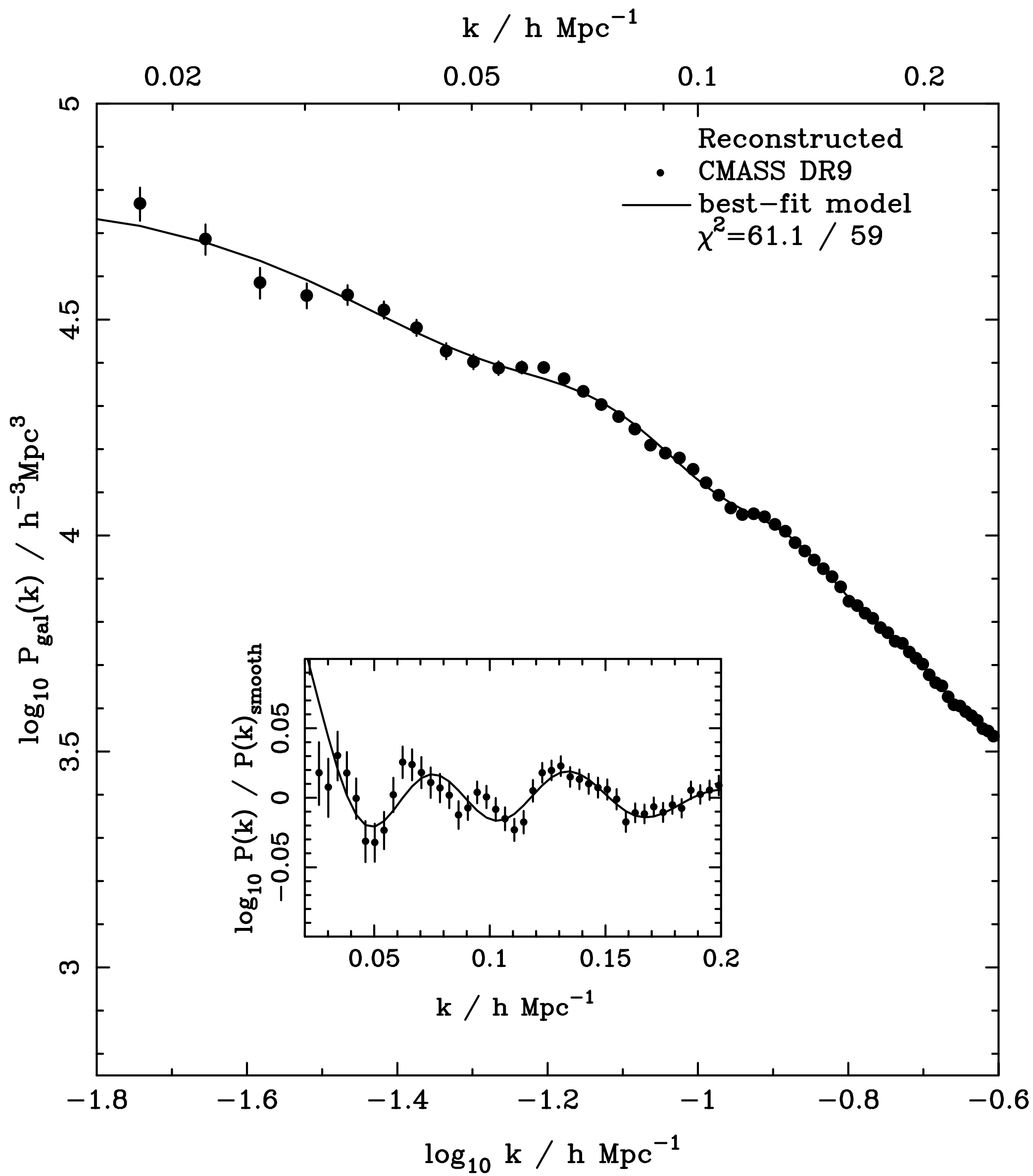


Percival et al. 2009; arXiv:0907.1660

BOSS CMASS DR9 galaxy clustering

BOSS CMASS galaxies at z~0.57

Total effective volume
$V_{eff} = 0.77\ Gpc^3h^{-3}$

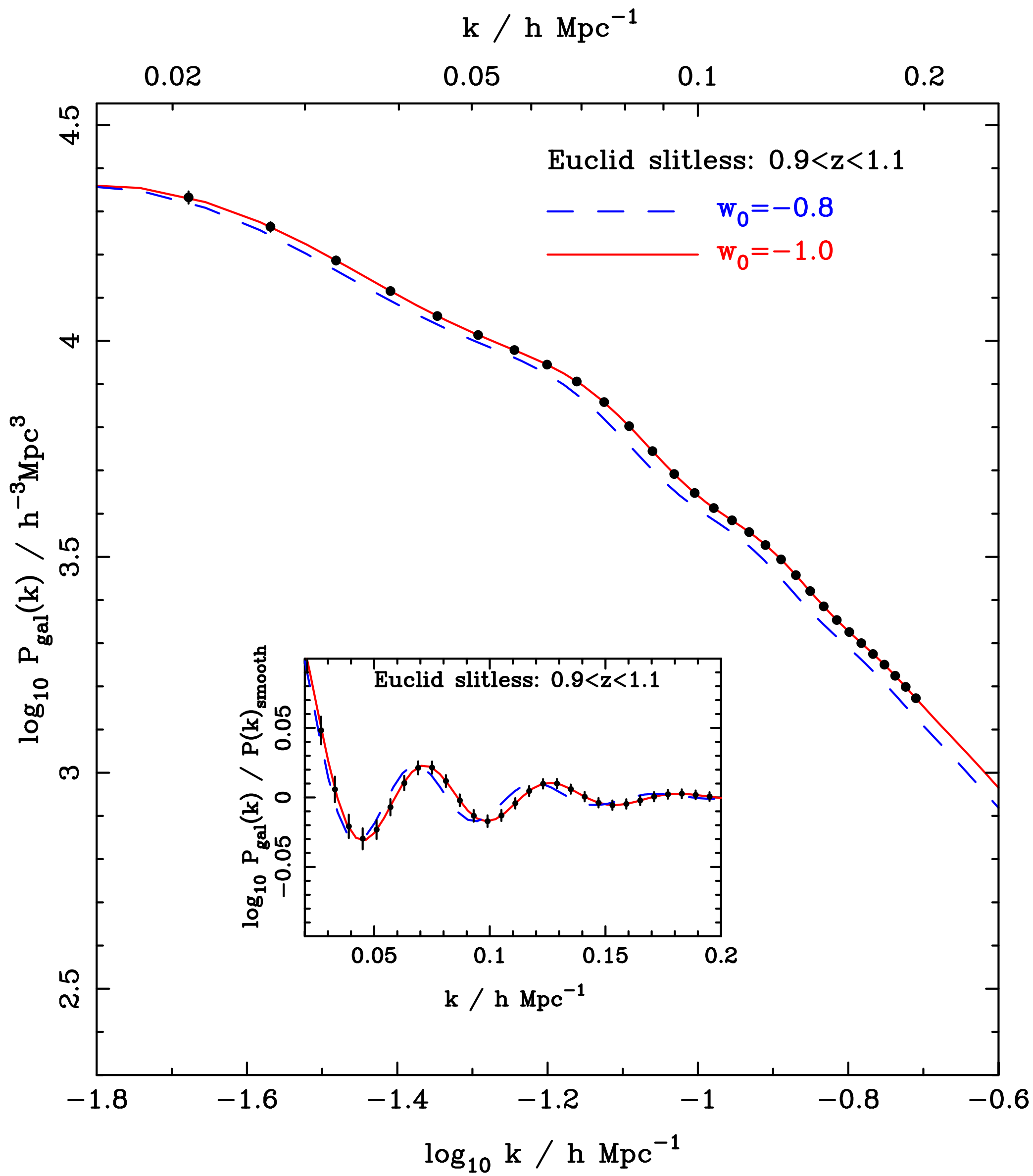


Anderson et al.

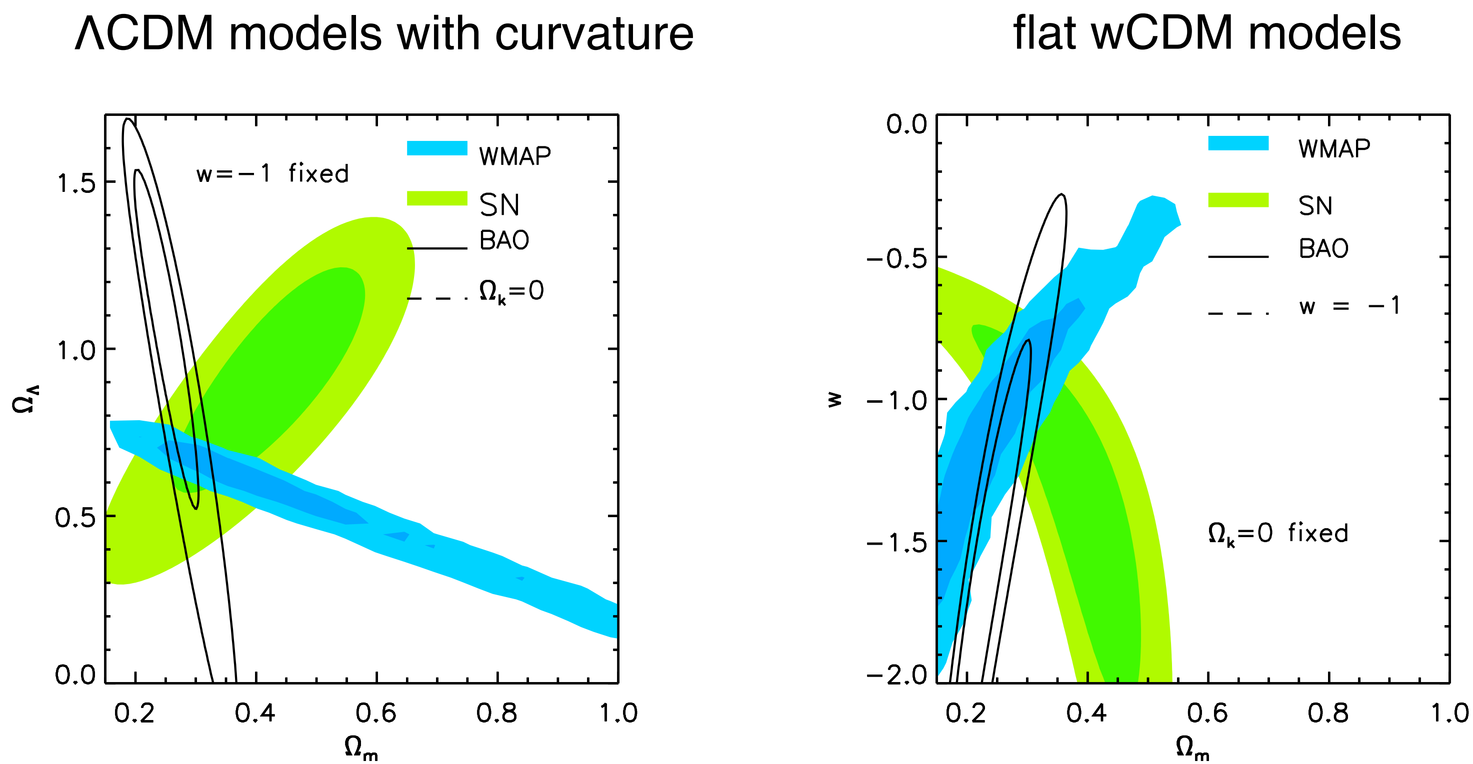
Predicted Euclid galaxy clustering

Redshift slice
$0.9 < z < 1.1$

Total effective volume (of Euclid)
$V_{eff} = 19.7\ Gpc^3h^{-3}$



SDSS-II LRG BAO vs other data



Union supernovae

WMAP 5year

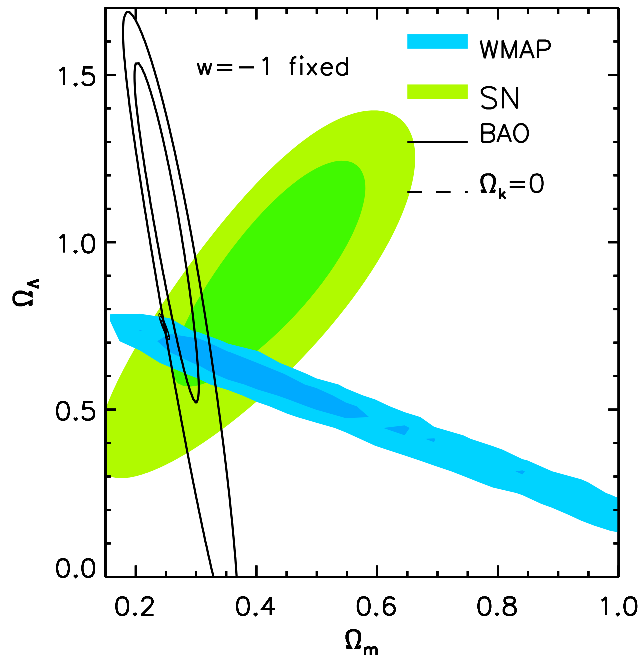
SDSS-II BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

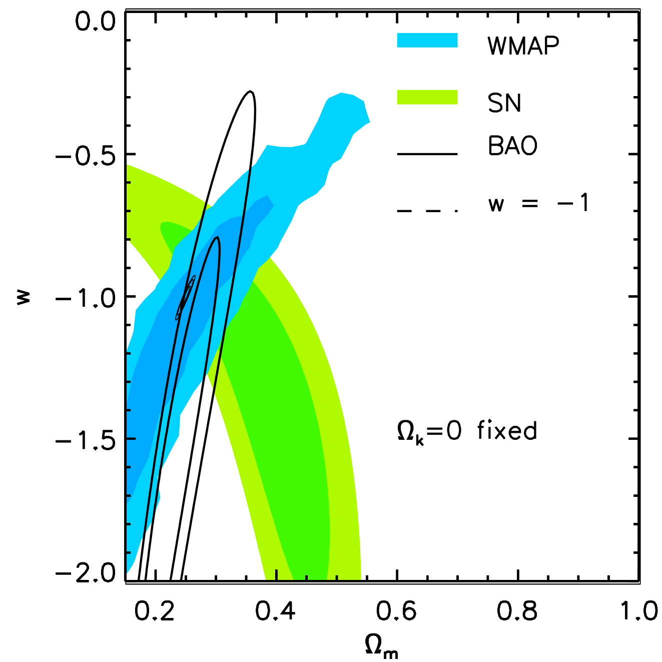
Percival et al. 2009; arXiv:0907.1660

Euclid BAO predictions

ΛCDM models with curvature

flat wCDM models





Union supernovae

WMAP 5year

SDSS-II BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

The most exciting things you will discover in the next few years will be unexpected!