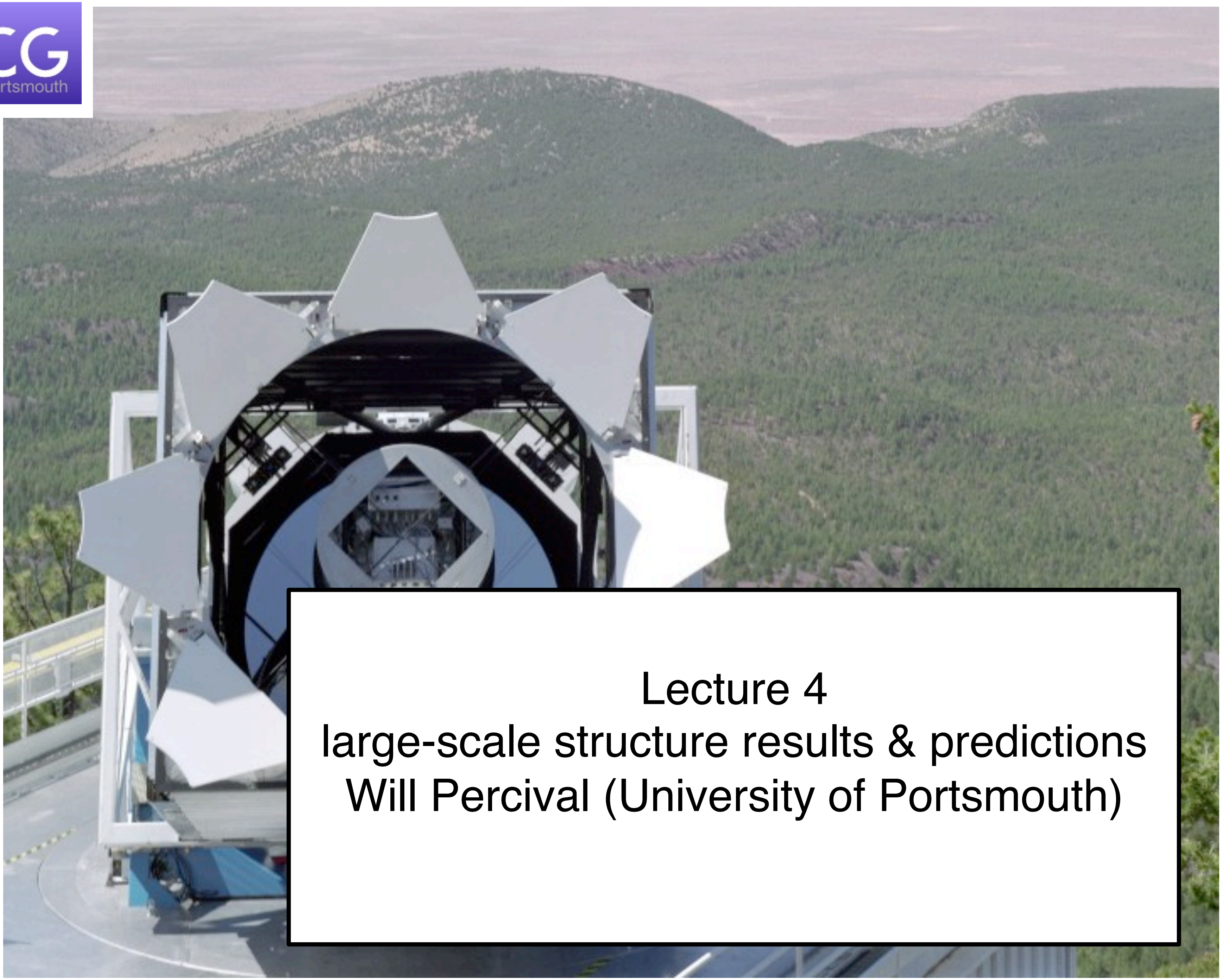
2354-19

Summer School on Cosmology

16 - 27 July 2012

Statistics and Data Analysis - Lecture 4

W. Percival
ICG, Portsmouth



Lecture 4

large-scale structure results & predictions

Will Percival (University of Portsmouth)

Review of BOSS

BOSS (part of the SDSS-III project)

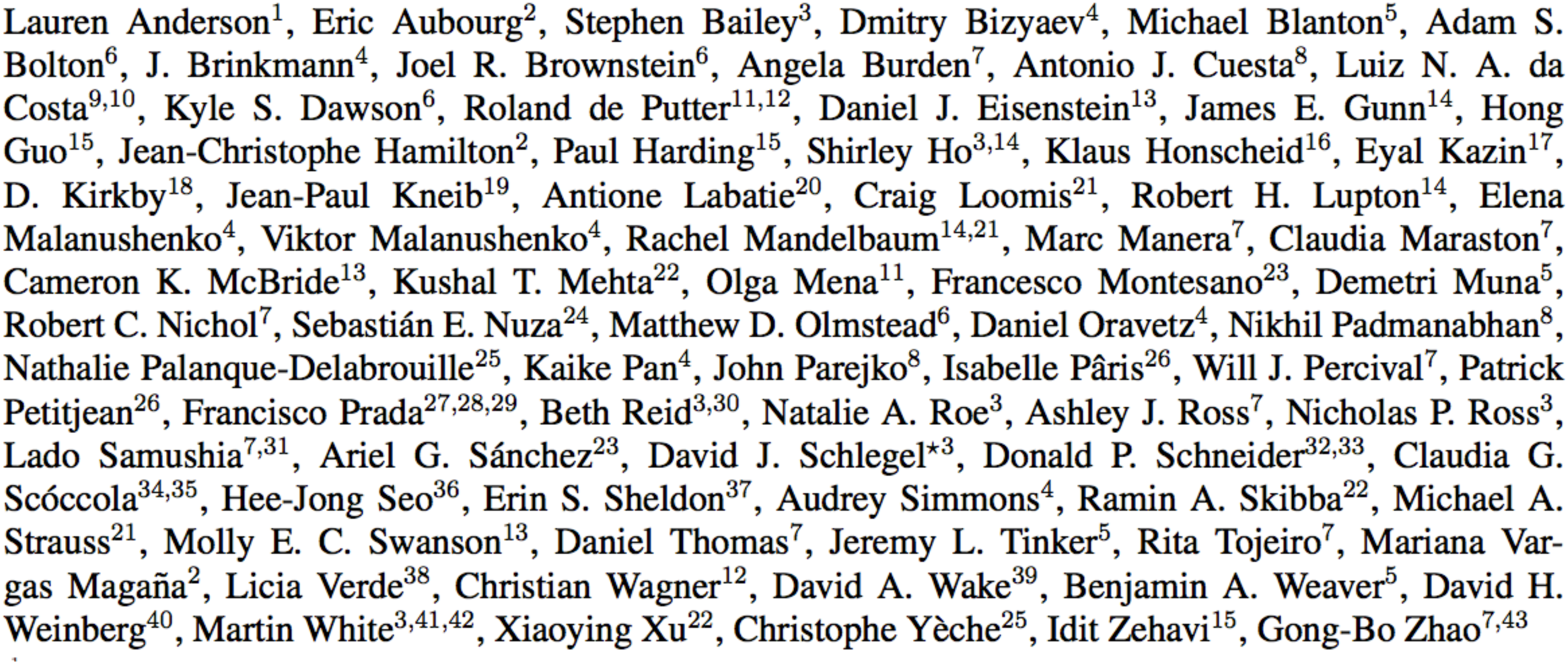
- Duration: Fall 2009 - Summer 2014, dark time
- Telescope: 2.5m Sloan
- Upgrade to SDSS-II spectrograph
  - – 1000 smaller fibers
  - – higher throughput
- Spectra:
  - – $3600^{\circ} A < \lambda < 10,000^{\circ} A$ New spectrograph
  - – $R = \lambda/\Delta\lambda = 1300 - 3000$
  - – (S/N) at mag. 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 $z = 2.5$

147 pages on “large-scale galaxy clustering”

- **Anderson et al.** (alphabetical) arXiv:1203.6565 - BAO measurement in power-spectrum and correlation function.
- **Reid et al.** arXiv:1203.6641- Anisotropic clustering, redshift-space distortion measurements.
- **Sanchez et al.** arXiv:1203.6616 - Fits to the full shape of the correlation function.
- **Ross et al.** arXiv:1203.6499 - Large-scale systematics.
- **Manera et al.** arXiv:1203.6609 - 600 PTHalo mocks.
- **Tojeiro et al.** arXiv:1203.6565 - Enhanced redshift-space distortion measurements.
- **Samushia et al.** arXiv:1206.5309 – Testing Λ & GR

- Plus more to come soon …

A collaborative effort …

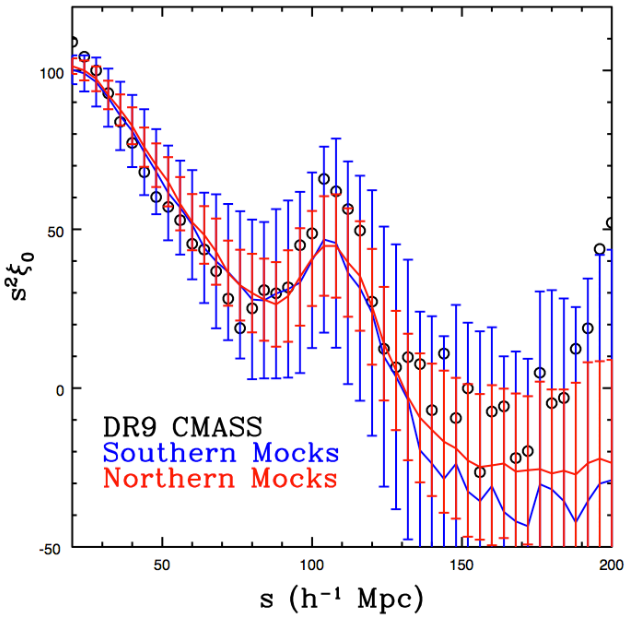


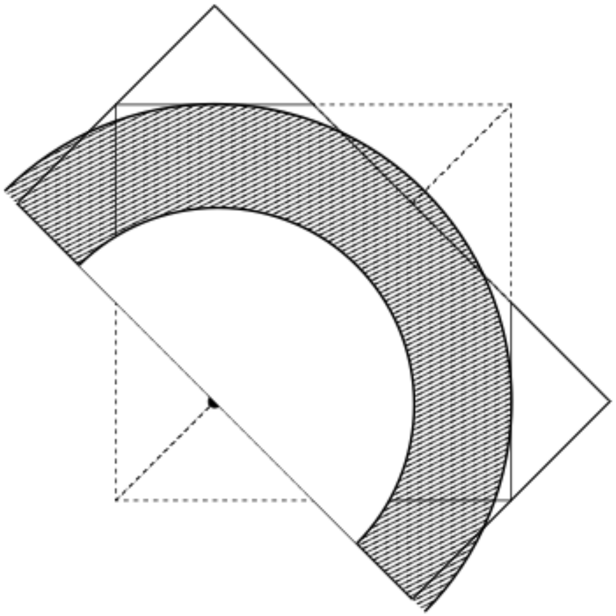
Lauren Anderson[1], Eric Aubourg[2], Stephen Bailey[3], Dmitry Bizyaev[4], Michael Blanton[5], Adam S. Bolton[6], J. Brinkmann[4], Joel R. Brownstein[6], Angela Burden[7], Antonio J. Cuesta[8], Luiz N. A. da Costa[9,10], Kyle S. Dawson[6], Roland de Putter[11,12], Daniel J. Eisenstein[13], James E. Gunn[14], Hong Guo[15], Jean-Christophe Hamilton[2], Paul Harding[15], Shirley Ho[3,14], Klaus Honscheid[16], Eyal Kazin[17], D. Kirkby[18], Jean-Paul Kneib[19], Antione Labatie[20], Craig Loomis[21], Robert H. Lupton[14], Elena Malanushenko[4], Viktor Malanushenko[4], Rachel Mandelbaum[14,21], Marc Manera[7], Claudia Maraston[7], Cameron K. McBride[13], Kushal T. Mehta[22], Olga Mena[11], Francesco Montesano[23], Demetri Muna[5], Robert C. Nichol[7], Sebastián E. Nuza[24], Matthew D. Olmstead[6], Daniel Oravetz[4], Nikhil Padmanabhan[8], Nathalie Palanque-Delabrouille[25], Kaike Pan[4], John Parejko[8], Isabelle Pâris[26], Will J. Percival[7], Patrick Petitjean[26], Francisco Prada[27,28,29], Beth Reid[3,30], Natalie A. Roe[3], Ashley J. Ross[7], Nicholas P. Ross[3], Lado Samushia[7,31], Ariel G. Sánchez[23], David J. Schlegel[⋆3], Donald P. Schneider[32,33], Claudia G. Scóccola[34,35], Hee-Jong Seo[36], Erin S. Sheldon[37], Audrey Simmons[4], Ramin A. Skibba[22], Michael A. Strauss[21], Molly E. C. Swanson[13], Daniel Thomas[7], Jeremy L. Tinker[5], Rita Tojeiro[7], Mariana Vargas Magaña[2], Licia Verde[38], Christian Wagner[12], David A. Wake[39], Benjamin A. Weaver[5], David H. Weinberg[40], Martin White[3,41,42], Xiaoying Xu[22], Christophe Yèche[25], Idit Zehavi[15], Gong-Bo Zhao[7,43]

Anderson et al.

Mock catalogues

- 600 mocks created by populating 2LPT field using the CMASS HOD
- Redshift-space effects added based on 2LPT velocities
- Matches simulation large-scale clustering at 10% level
- Used to test method and estimate covariances
- See Manera et al. for details





Manera et al.

BAO results

Measuring a distance

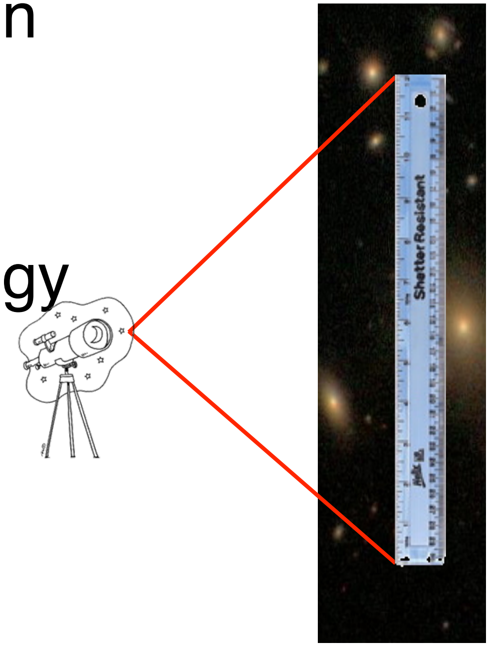
- Fit the observed acoustic feature using some way to parametrize over nuisance broad-band features (different approaches for P(k) and ξ(r))
- Use a fiducial model to compare against observed features in spherically averaged statistics. Departures quantified by dilation scale α:

$$P(k/\alpha) \quad \xi(\alpha r)$$

- The dilation scale α depends on cosmology through:

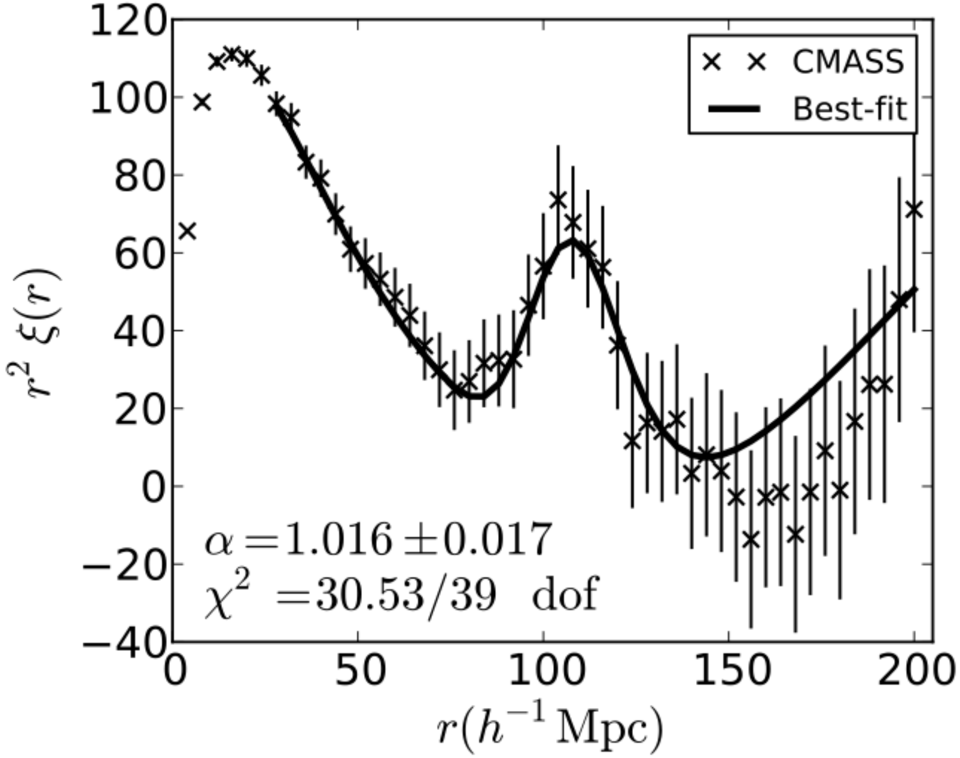
$$D_V / r_s = \alpha (D_V / r_s)_{\mathrm{fid}}$$

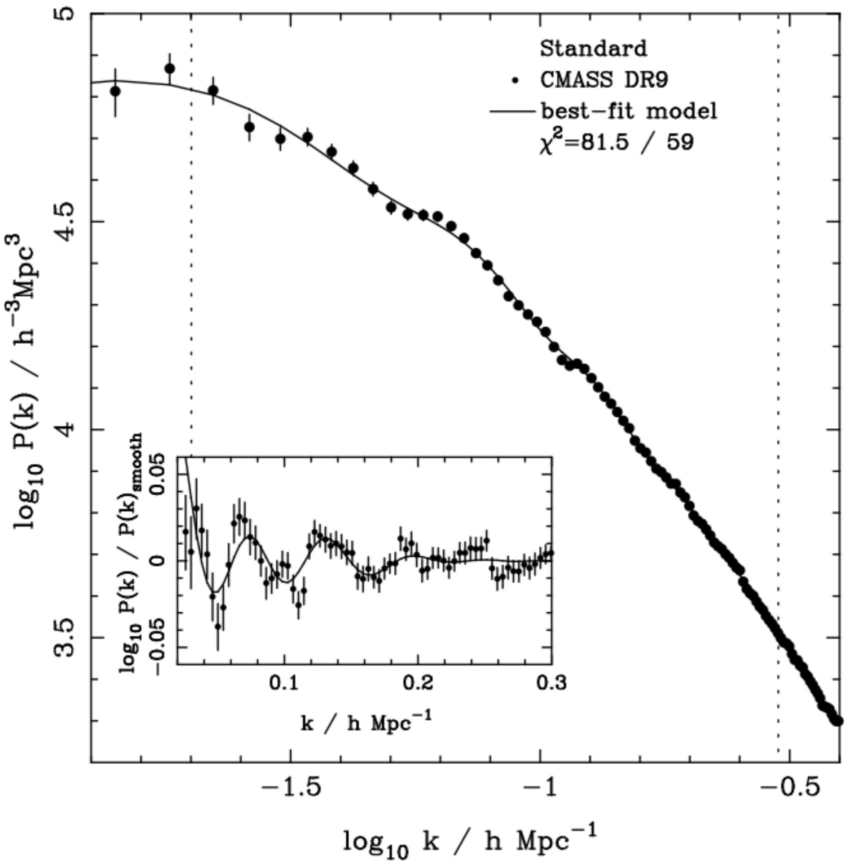
$$D_V = [cz(1 + z)^2 d_A{}^2 H^{-1}]^{1/3}$$



Anderson et al.

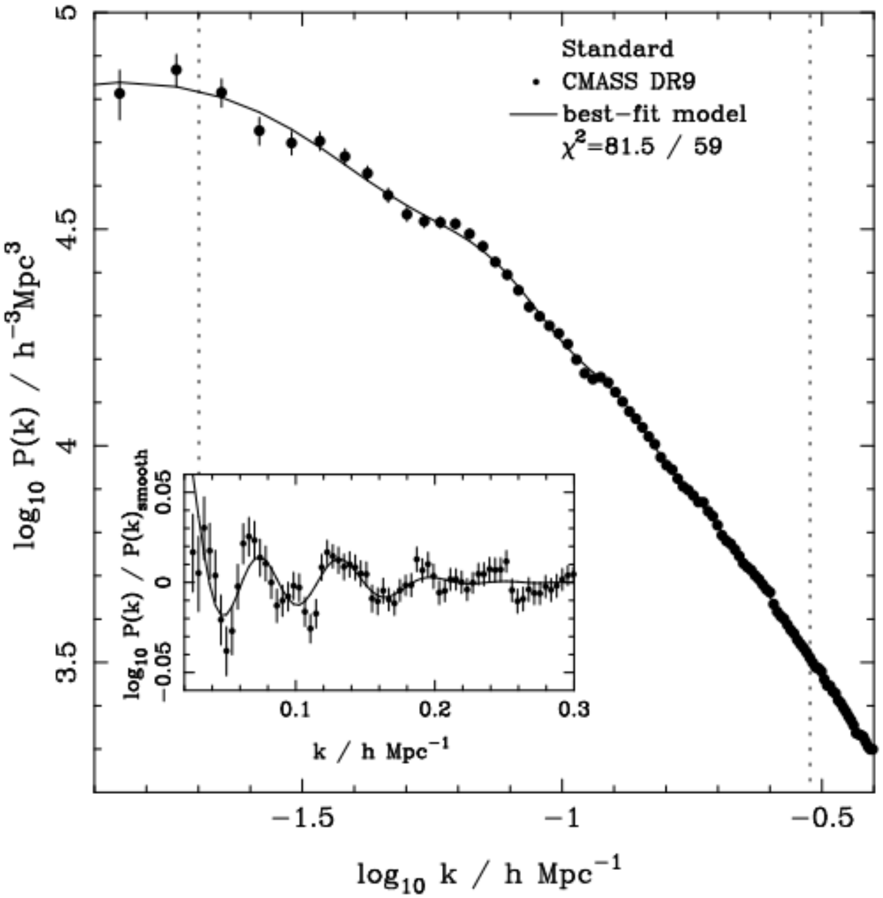
BOSS CMASS clustering measurements

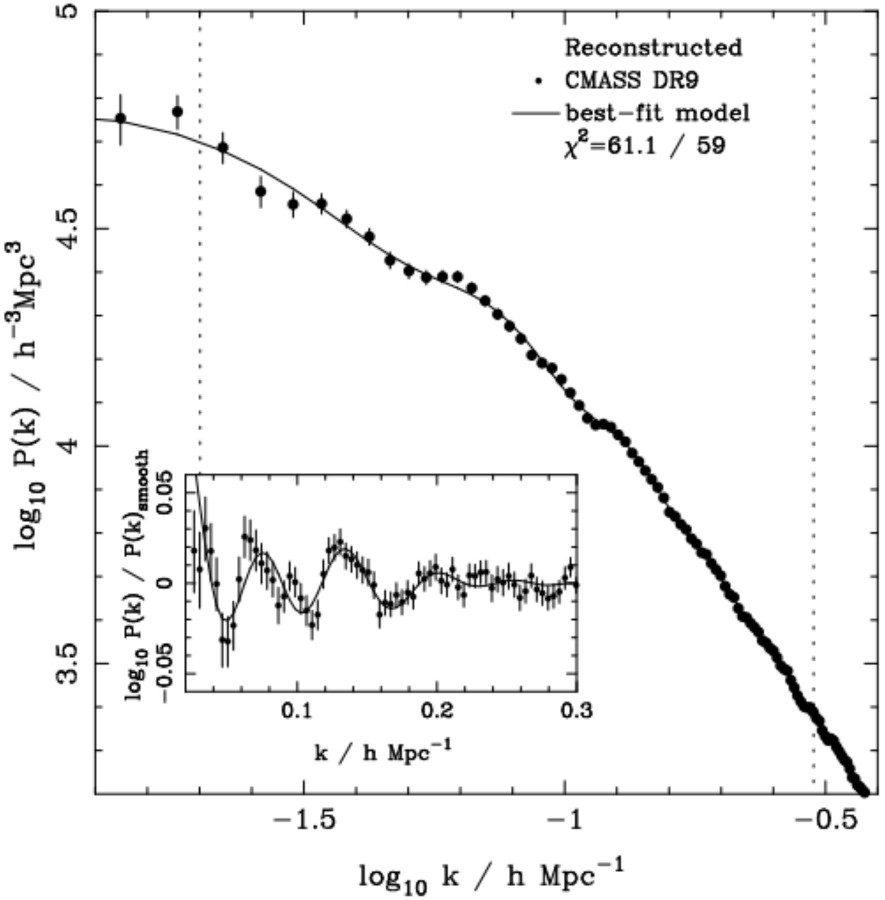




Anderson et al.

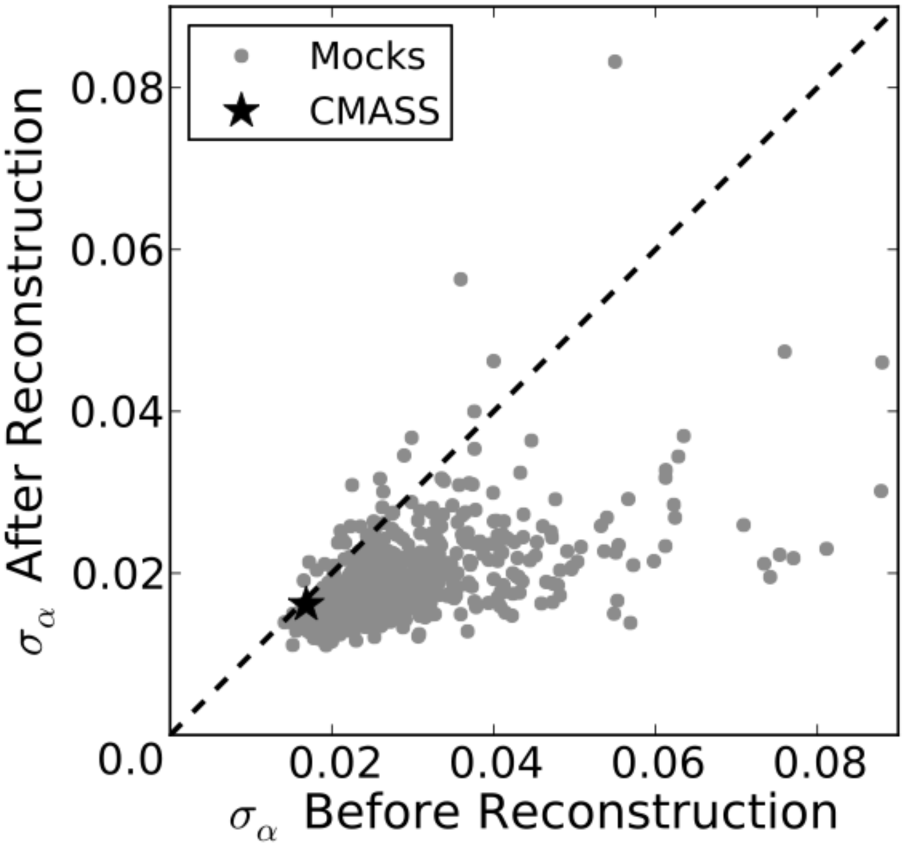
Reconstruction on CMASS





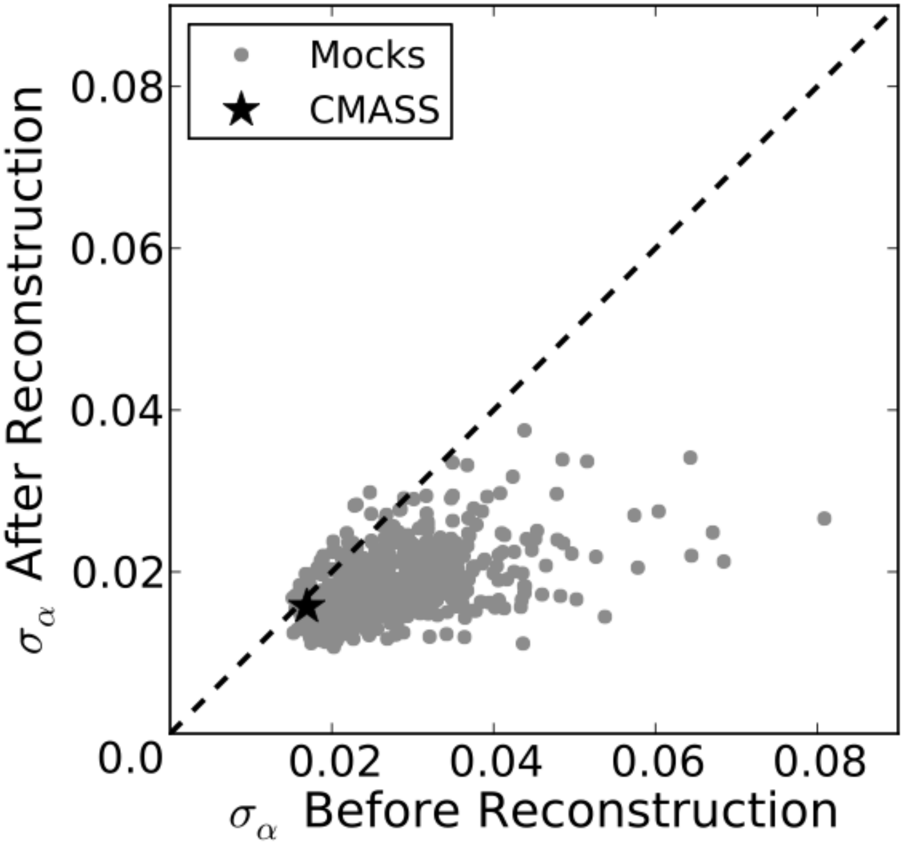
Anderson et al.

Reconstruction: error on α



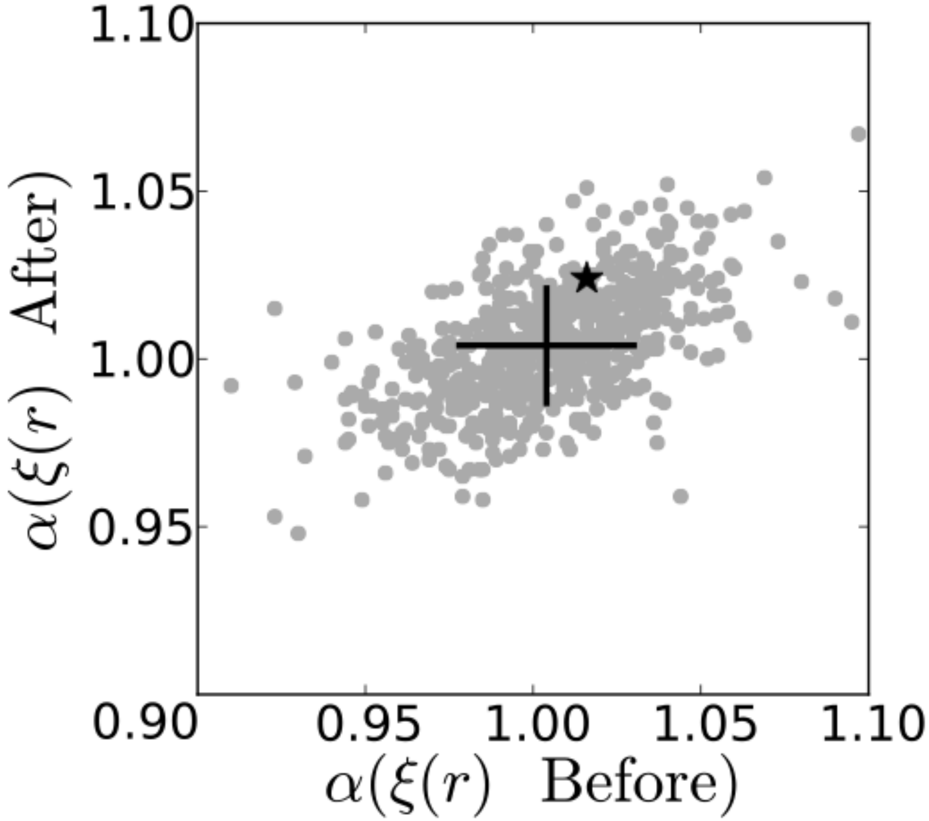
Correlation function

Power spectrum



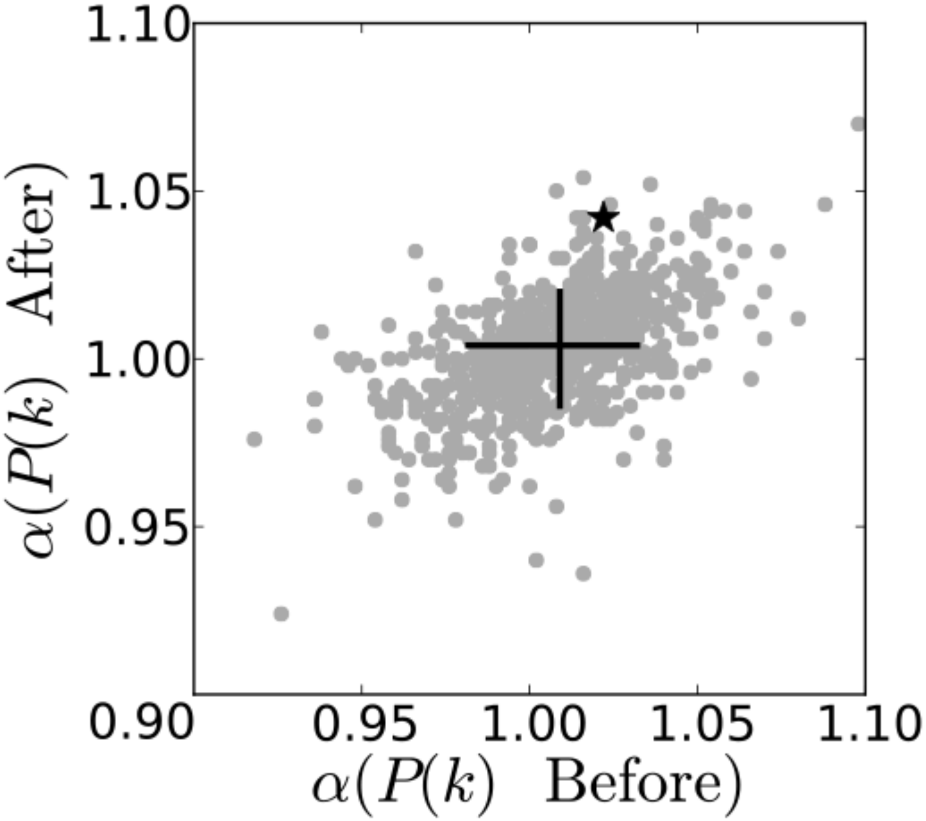
Anderson et al.

Reconstruction: α



Correlation function

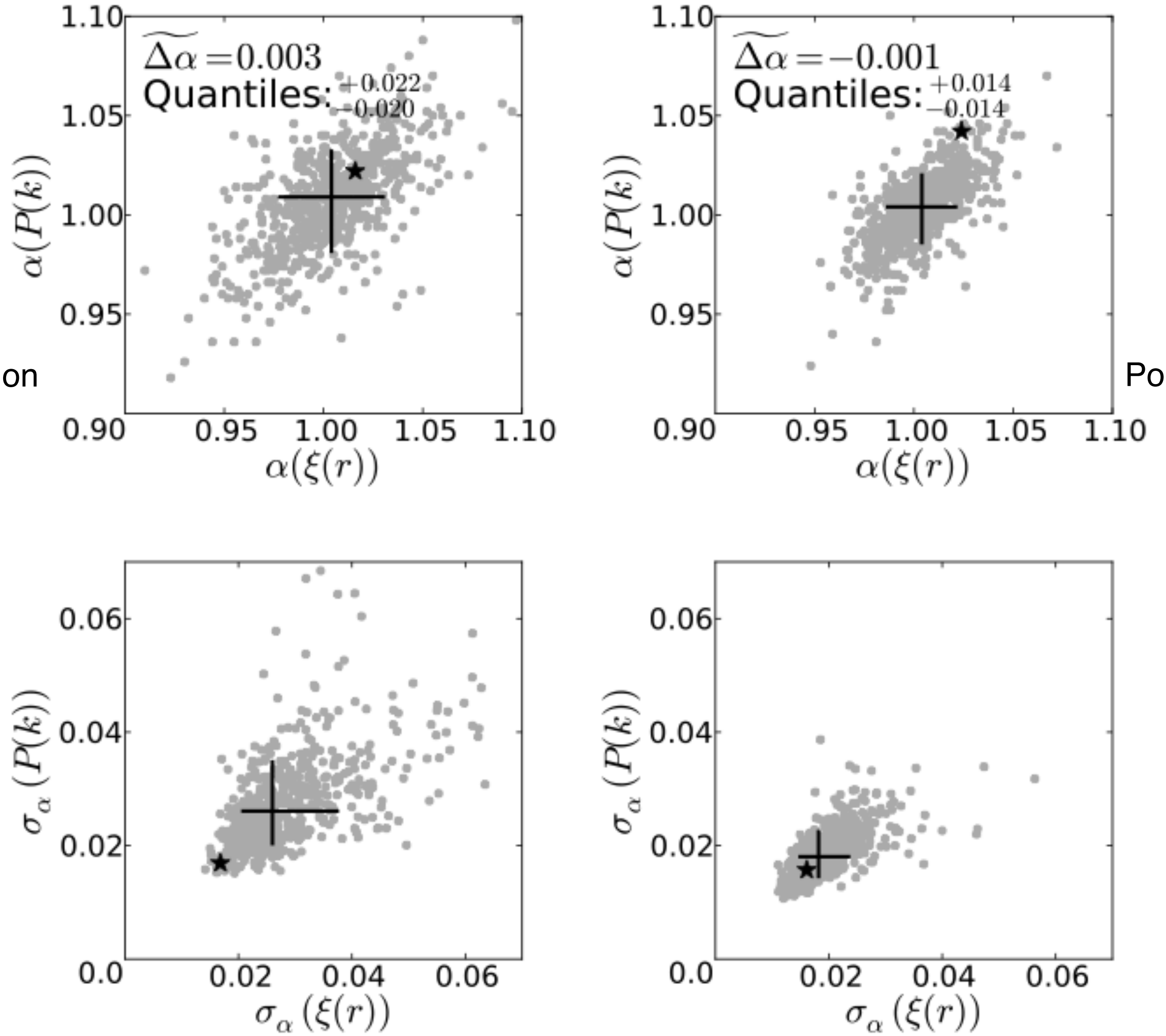
Power spectrum



Anderson et al.

Comparison of ξ(r) & P(k) measurements

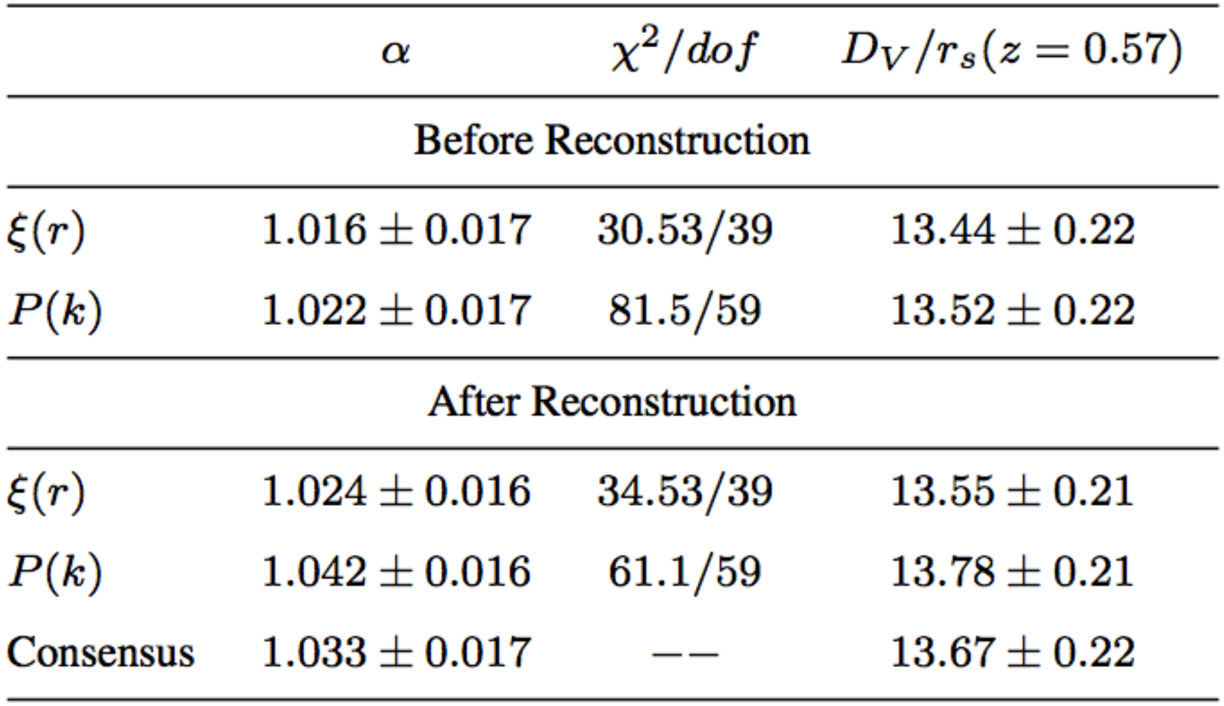
Pre-reconstruction



Post-reconstruction

Anderson et al.

Key BAO measurements

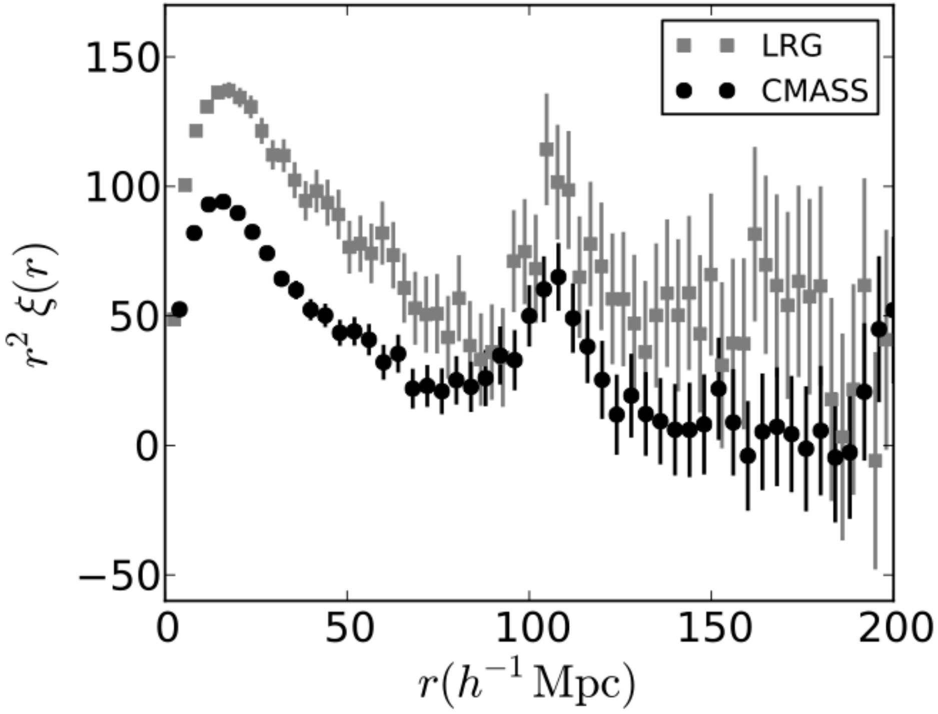


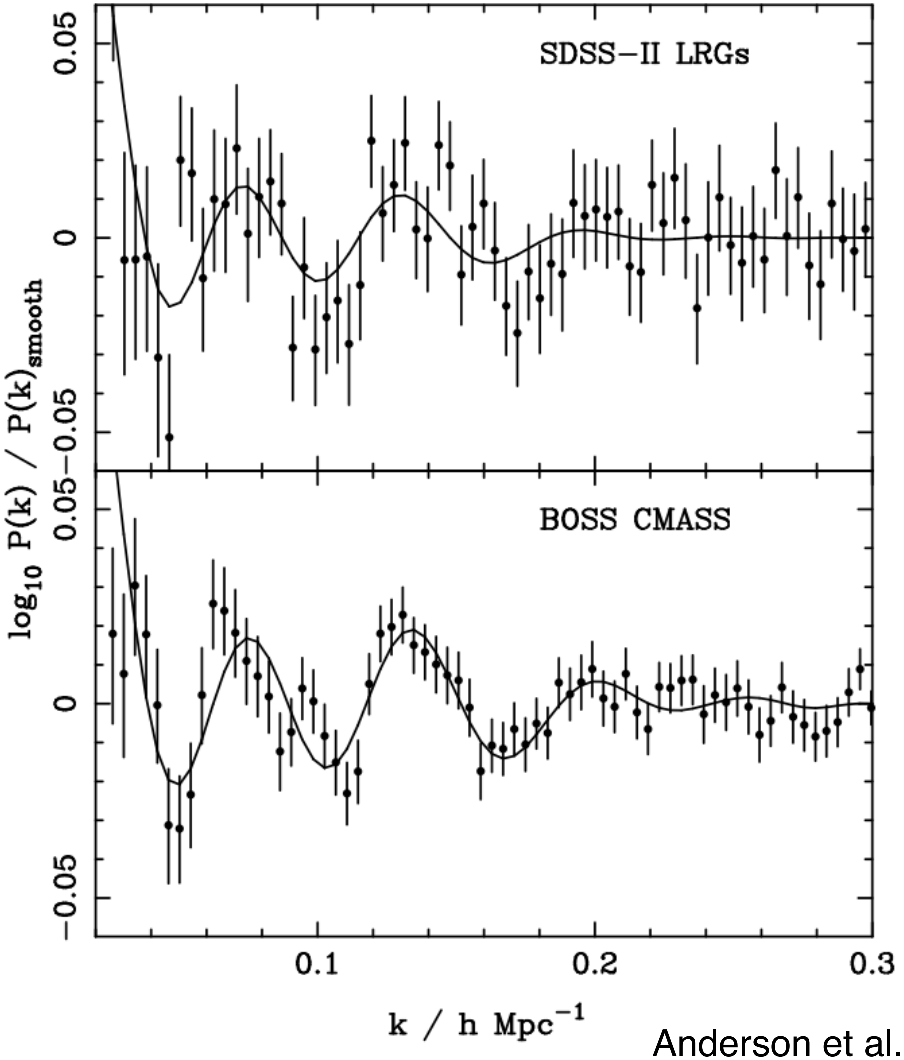
	α	χ^2/dof	$D_V/r_s(z=0.57)$
		Before Reconstruction	
$\xi(r)$	1.016 ± 0.017	$30.53/39$	13.44 ± 0.22
$P(k)$	1.022 ± 0.017	$81.5/59$	13.52 ± 0.22
		After Reconstruction	
$\xi(r)$	1.024 ± 0.016	$34.53/39$	13.55 ± 0.21
$P(k)$	1.042 ± 0.016	$61.1/59$	13.78 ± 0.21
Consensus	1.033 ± 0.017	$--$	13.67 ± 0.22

- 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.

Comparison of SDSS-II & CMASS results





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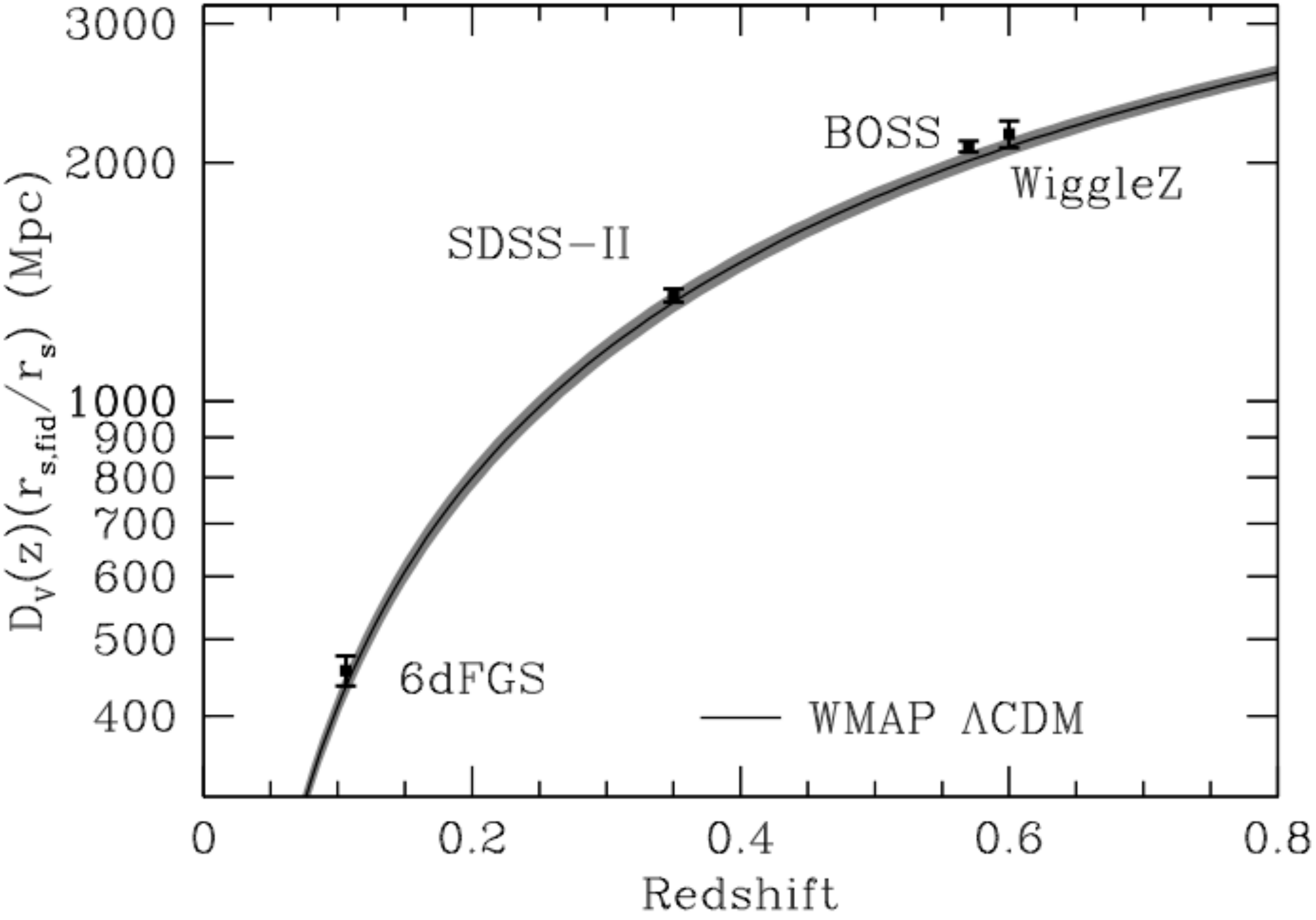
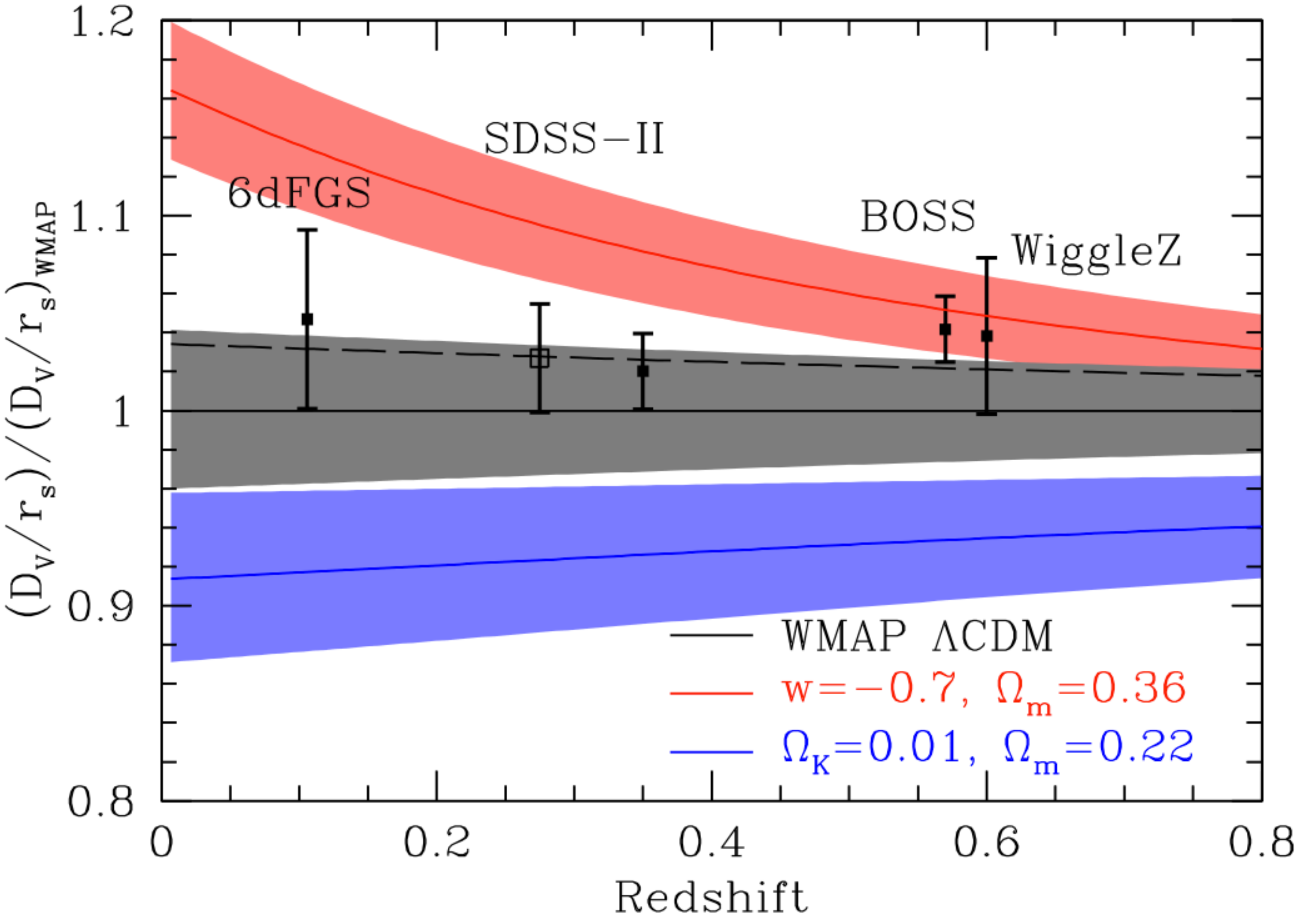
CMASS results



$$D_V(0.57)/r_s = 13.67 \pm 0.22$$

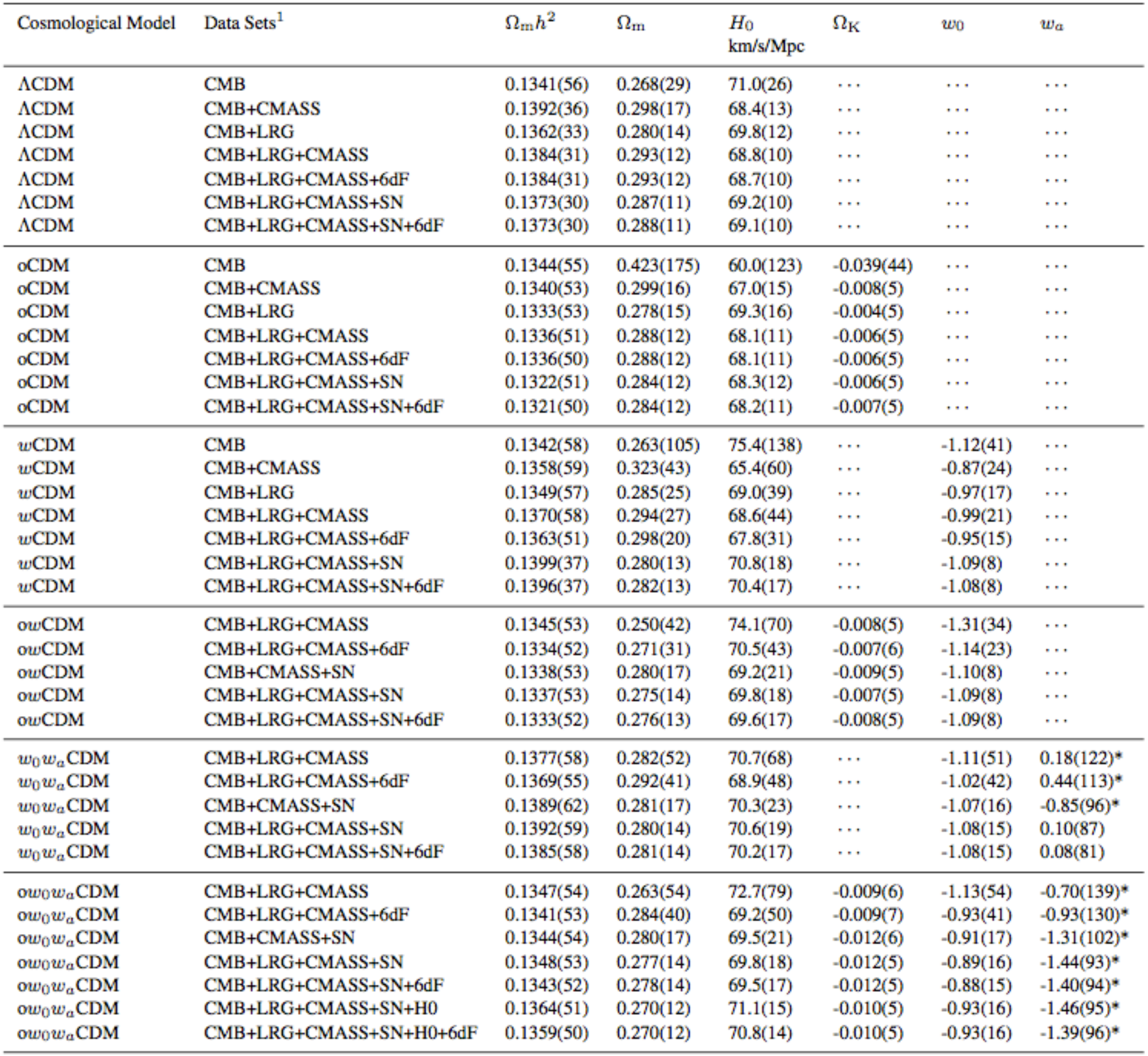
Anderson et al.

CMASS results



Anderson et al.

Cosmological results

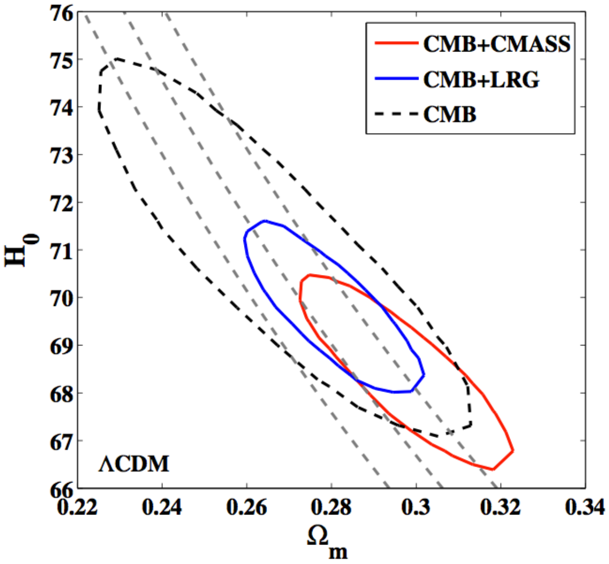


Cosmological Model	Data Sets[1]	$\Omega_m h^2$	Ω_m	H_0 km/s/Mpc	Ω_K	w_0	w_a
ΛCDM	CMB	0.1341(56)	0.268(29)	71.0(26)	···	···	···
ΛCDM	CMB+CMASS	0.1392(36)	0.298(17)	68.4(13)	···	···	···
ΛCDM	CMB+LRG	0.1362(33)	0.280(14)	69.8(12)	···	···	···
ΛCDM	CMB+LRG+CMASS	0.1384(31)	0.293(12)	68.8(10)	···	···	···
ΛCDM	CMB+LRG+CMASS+6dF	0.1384(31)	0.293(12)	68.7(10)	···	···	···
ΛCDM	CMB+LRG+CMASS+SN	0.1373(30)	0.287(11)	69.2(10)	···	···	···
ΛCDM	CMB+LRG+CMASS+SN+6dF	0.1373(30)	0.288(11)	69.1(10)	···	···	···
oCDM	CMB	0.1344(55)	0.423(175)	60.0(123)	-0.039(44)	···	···
oCDM	CMB+CMASS	0.1340(53)	0.299(16)	67.0(15)	-0.008(5)	···	···
oCDM	CMB+LRG	0.1333(53)	0.278(15)	69.3(16)	-0.004(5)	···	···
oCDM	CMB+LRG+CMASS	0.1336(51)	0.288(12)	68.1(11)	-0.006(5)	···	···
oCDM	CMB+LRG+CMASS+6dF	0.1336(50)	0.288(12)	68.1(11)	-0.006(5)	···	···
oCDM	CMB+LRG+CMASS+SN	0.1322(51)	0.284(12)	68.3(12)	-0.006(5)	···	···
oCDM	CMB+LRG+CMASS+SN+6dF	0.1321(50)	0.284(12)	68.2(11)	-0.007(5)	···	···
wCDM	CMB	0.1342(58)	0.263(105)	75.4(138)	···	-1.12(41)	···
wCDM	CMB+CMASS	0.1358(59)	0.323(43)	65.4(60)	···	-0.87(24)	···
wCDM	CMB+LRG	0.1349(57)	0.285(25)	69.0(39)	···	-0.97(17)	···
wCDM	CMB+LRG+CMASS	0.1370(58)	0.294(27)	68.6(44)	···	-0.99(21)	···
wCDM	CMB+LRG+CMASS+6dF	0.1363(51)	0.298(20)	67.8(31)	···	-0.95(15)	···
wCDM	CMB+LRG+CMASS+SN	0.1399(37)	0.280(13)	70.8(18)	···	-1.09(8)	···
wCDM	CMB+LRG+CMASS+SN+6dF	0.1396(37)	0.282(13)	70.4(17)	···	-1.08(8)	···
owCDM	CMB+LRG+CMASS	0.1345(53)	0.250(42)	74.1(70)	-0.008(5)	-1.31(34)	···
owCDM	CMB+LRG+CMASS+6dF	0.1334(52)	0.271(31)	70.5(43)	-0.007(6)	-1.14(23)	···
owCDM	CMB+CMASS+SN	0.1338(53)	0.280(17)	69.2(21)	-0.009(5)	-1.10(8)	···
owCDM	CMB+LRG+CMASS+SN	0.1337(53)	0.275(14)	69.8(18)	-0.007(5)	-1.09(8)	···
owCDM	CMB+LRG+CMASS+SN+6dF	0.1333(52)	0.276(13)	69.6(17)	-0.008(5)	-1.09(8)	···
$w_0 w_a$CDM	CMB+LRG+CMASS	0.1377(58)	0.282(52)	70.7(68)	···	-1.11(51)	0.18(122)*
$w_0 w_a$CDM	CMB+LRG+CMASS+6dF	0.1369(55)	0.292(41)	68.9(48)	···	-1.02(42)	0.44(113)*
$w_0 w_a$CDM	CMB+CMASS+SN	0.1389(62)	0.281(17)	70.3(23)	···	-1.07(16)	-0.85(96)*
$w_0 w_a$CDM	CMB+LRG+CMASS+SN	0.1392(59)	0.280(14)	70.6(19)	···	-1.08(15)	0.10(87)
$w_0 w_a$CDM	CMB+LRG+CMASS+SN+6dF	0.1385(58)	0.281(14)	70.2(17)	···	-1.08(15)	0.08(81)
o$w_0 w_a$CDM	CMB+LRG+CMASS	0.1347(54)	0.263(54)	72.7(79)	-0.009(6)	-1.13(54)	-0.70(139)*
o$w_0 w_a$CDM	CMB+LRG+CMASS+6dF	0.1341(53)	0.284(40)	69.2(50)	-0.009(7)	-0.93(41)	-0.93(130)*
o$w_0 w_a$CDM	CMB+CMASS+SN	0.1344(54)	0.280(17)	69.5(21)	-0.012(6)	-0.91(17)	-1.31(102)*
o$w_0 w_a$CDM	CMB+LRG+CMASS+SN	0.1348(53)	0.277(14)	69.8(18)	-0.012(5)	-0.89(16)	-1.44(93)*
o$w_0 w_a$CDM	CMB+LRG+CMASS+SN+6dF	0.1343(52)	0.278(14)	69.5(17)	-0.012(5)	-0.88(15)	-1.40(94)*
o$w_0 w_a$CDM	CMB+LRG+CMASS+SN+H0	0.1364(51)	0.270(12)	71.1(15)	-0.010(5)	-0.93(16)	-1.46(95)*
o$w_0 w_a$CDM	CMB+LRG+CMASS+SN+H0+6dF	0.1359(50)	0.270(12)	70.8(14)	-0.010(5)	-0.93(16)	-1.39(96)*

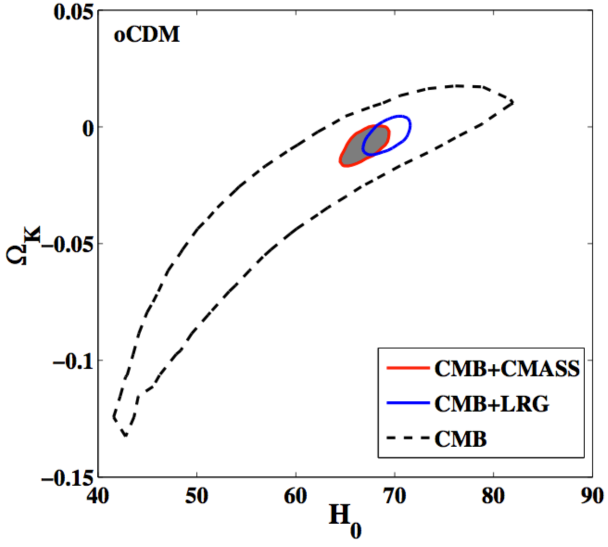
Anderson et al.

Constraints on Friedman equation

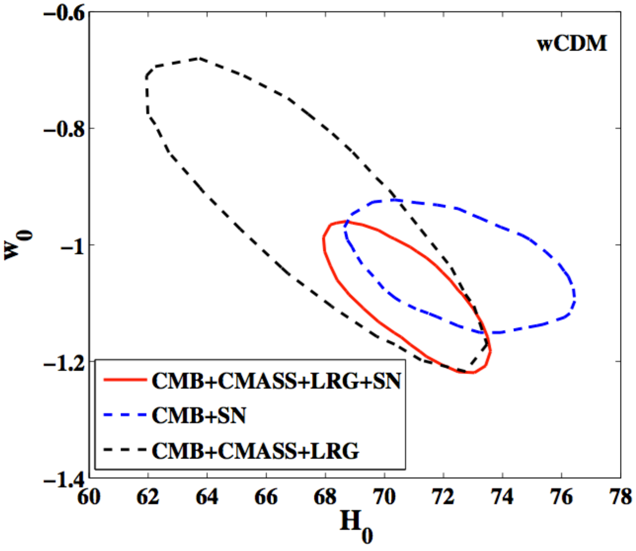
$$H^2(a) = H_0^2\Big[\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_{DE}\exp\left\{3\int_a^1 \frac{da'}{a'}\,[1+w(a')]\right\}\Big]$$



2-param ΛCDM model



3-param oCDM model

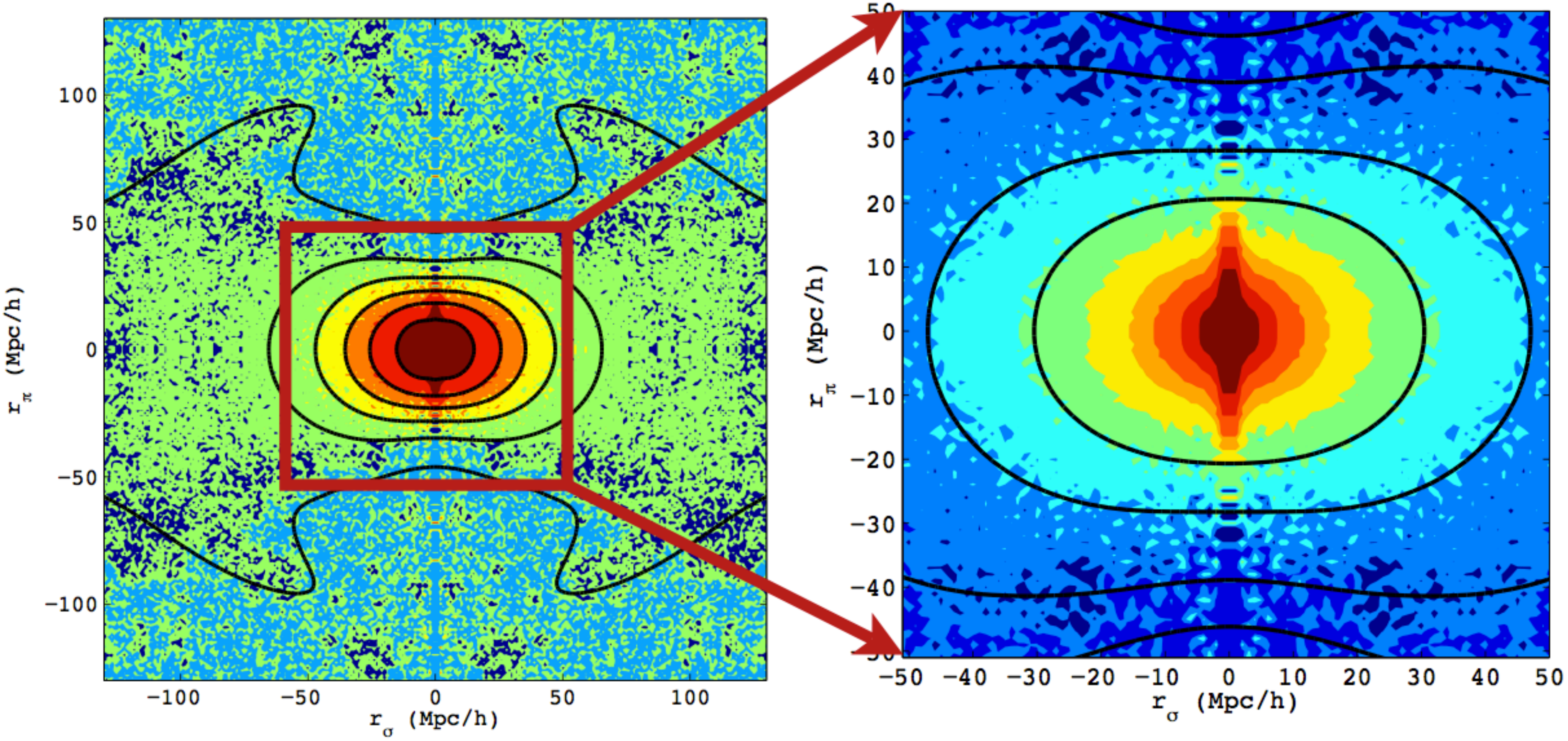


4-param wCDM model

Anderson et al.

Anisotropic clustering results

Anisotropic clustering measurements



Reid et al.

Extra information from anisotropic measurements

- Including the quadrupole allows us to measure H and d_A separately (or include an additional measurement of F)

$$F = (1+z)\, d_A(z) H(z)/c$$

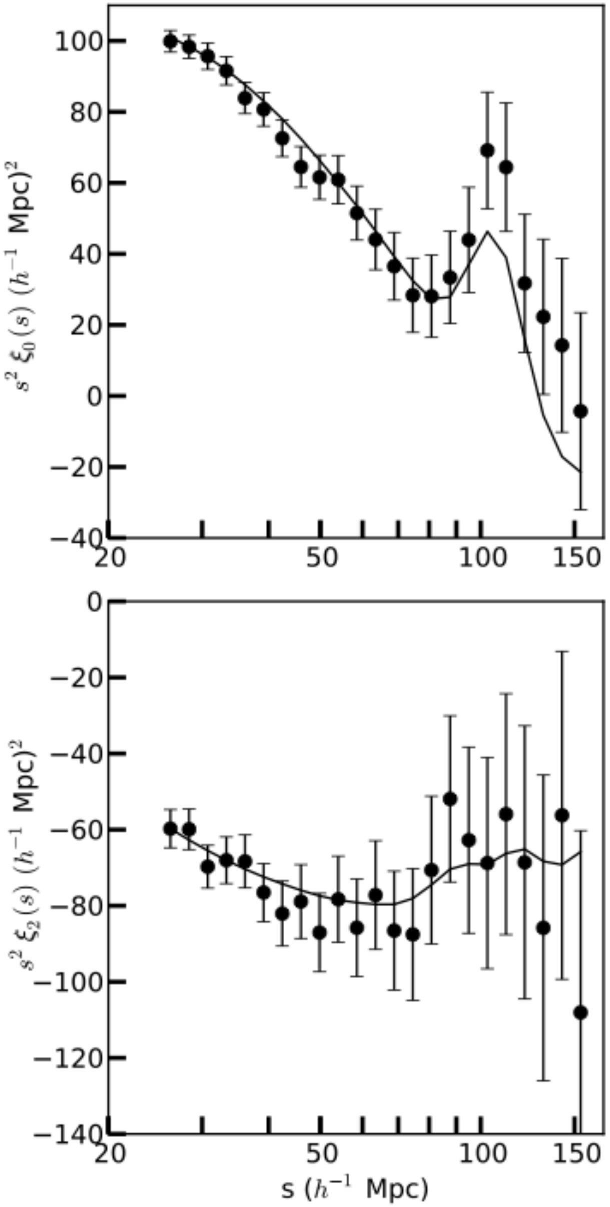
- F is sometimes called the Alcock-Paczynski parameter
- Can also measure the growth rate from the RSD contribution

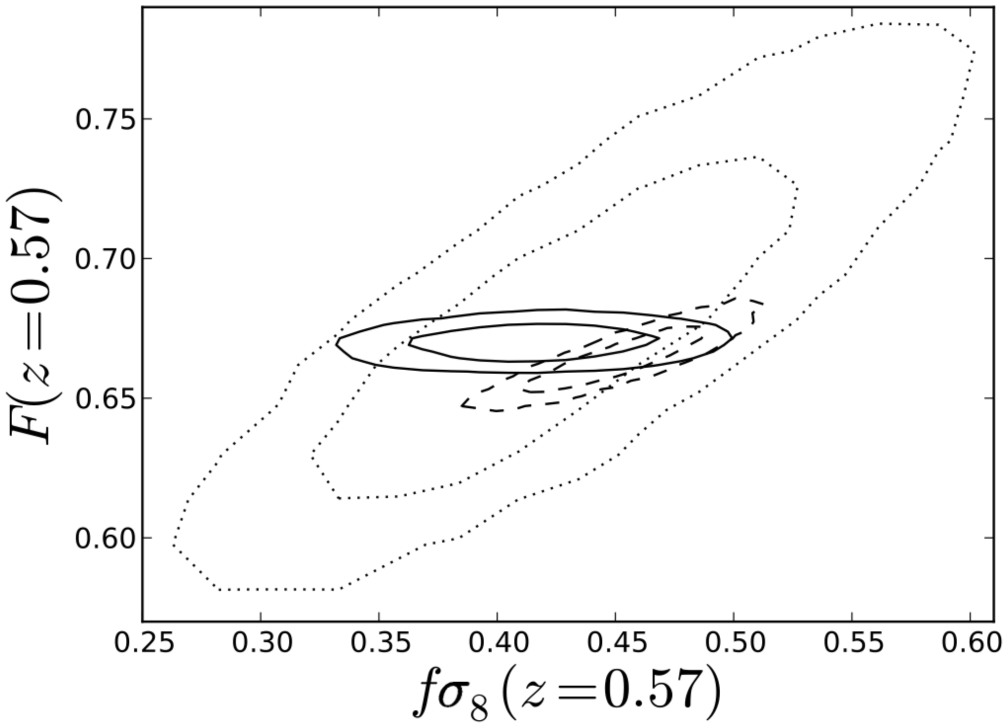
$$f\sigma_8(z=0.57)$$

- These are degenerate, but that degeneracy is not perfect

Reid et al.

Results of the anisotropic fit





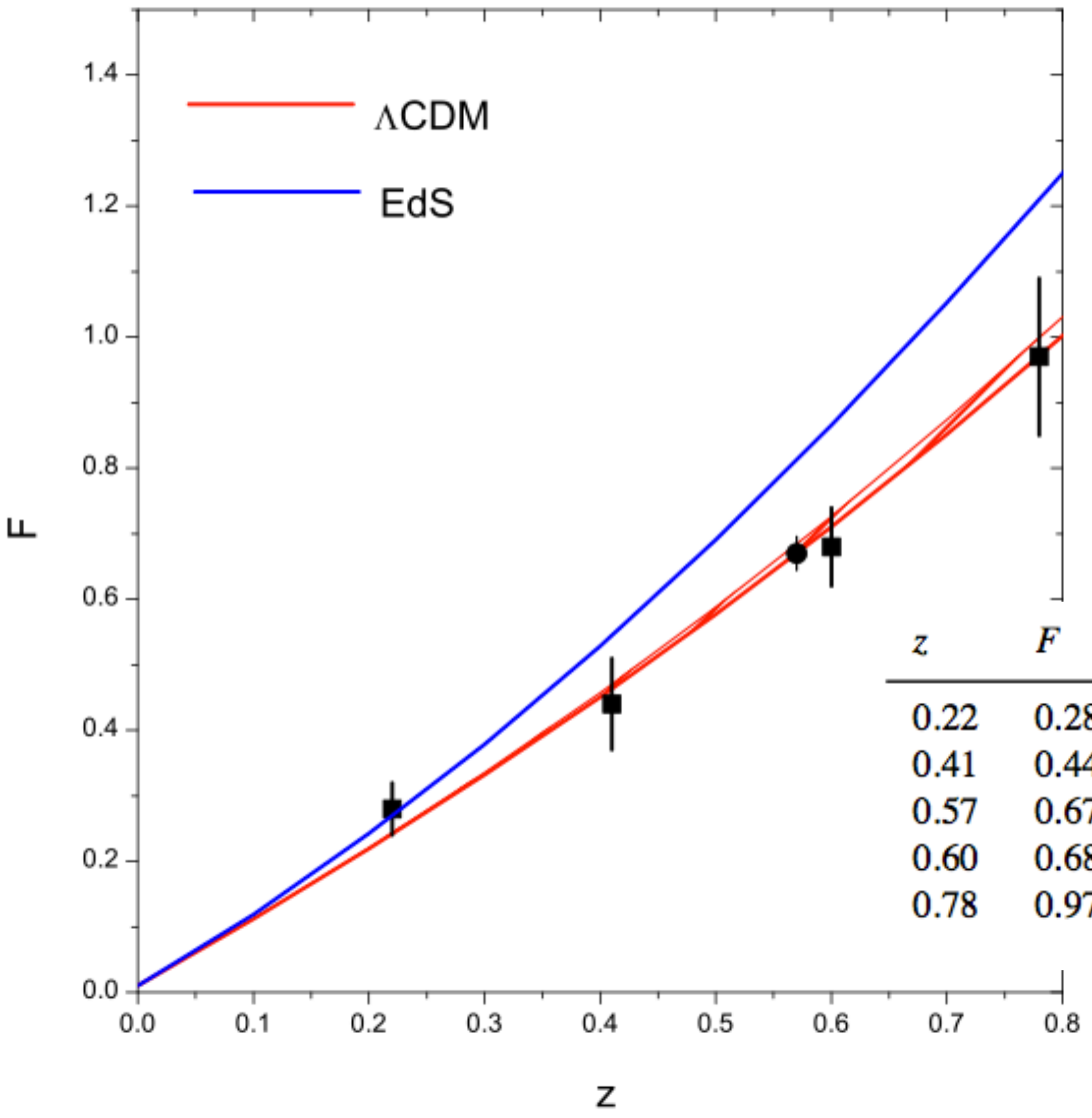
Dotted: free growth, geometry, ΛCDM prior on large-scale linear P(k) shape at z=0.57

Solid: F forced to match ΛCDM model

Dashed: WMAP ΛCDM+GR prediction

Reid et al.

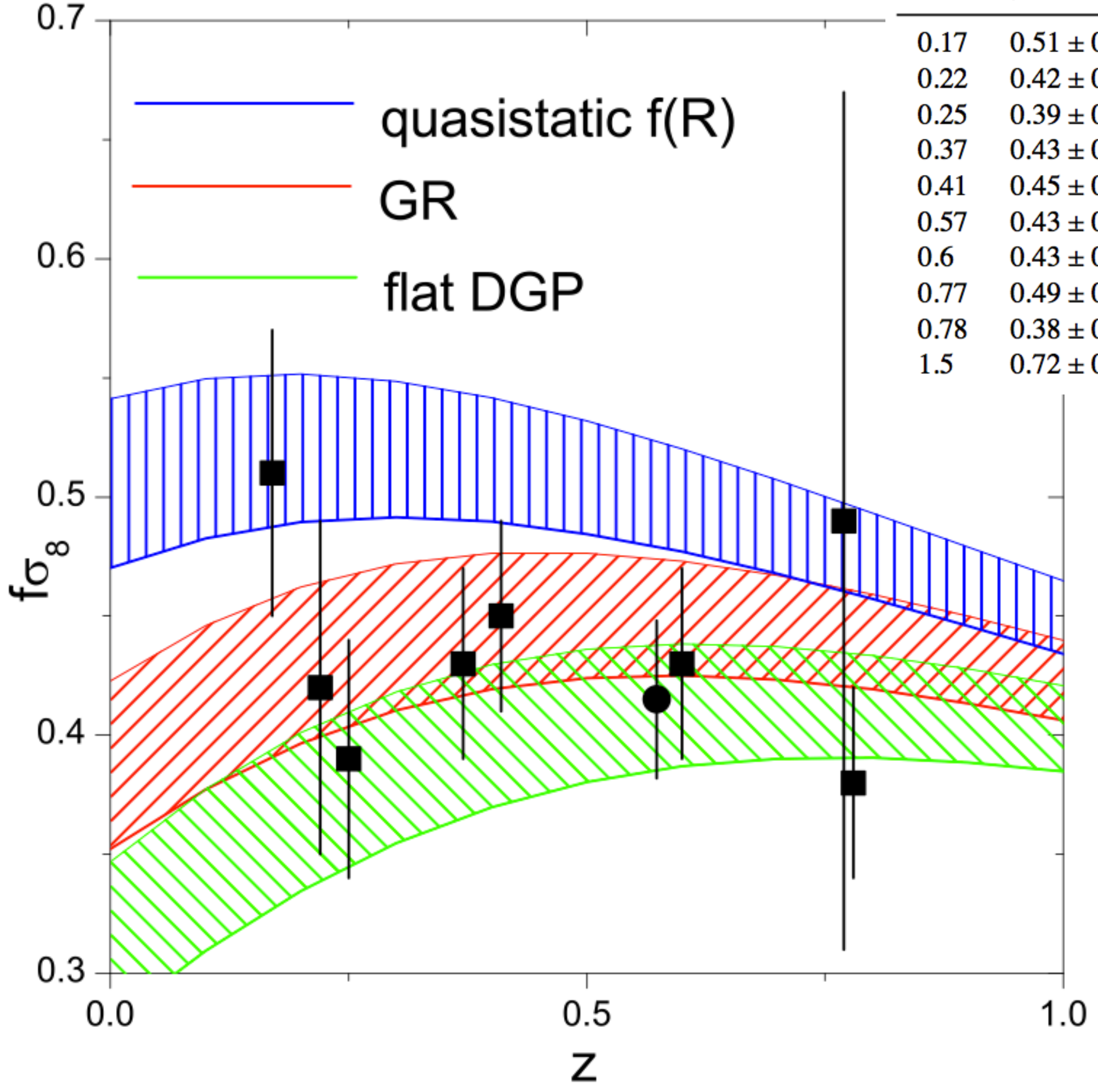
CMASS F measurements in context



z	*F*	survey	reference
0.22	0.28 ± 0.04	WiggleZ	Blake, et al. (2011c)
0.41	0.44 ± 0.07	WiggleZ	Blake, et al. (2011c)
0.57	0.67 ± 0.026	BOSS	Reid et al. (2012)
0.60	0.68 ± 0.06	WiggleZ	Blake, et al. (2011c)
0.78	0.97 ± 0.12	WiggleZ	Blake, et al. (2011c)

Samushia et al. (in prep), Reid et al.

CMASS RSD measurements in context

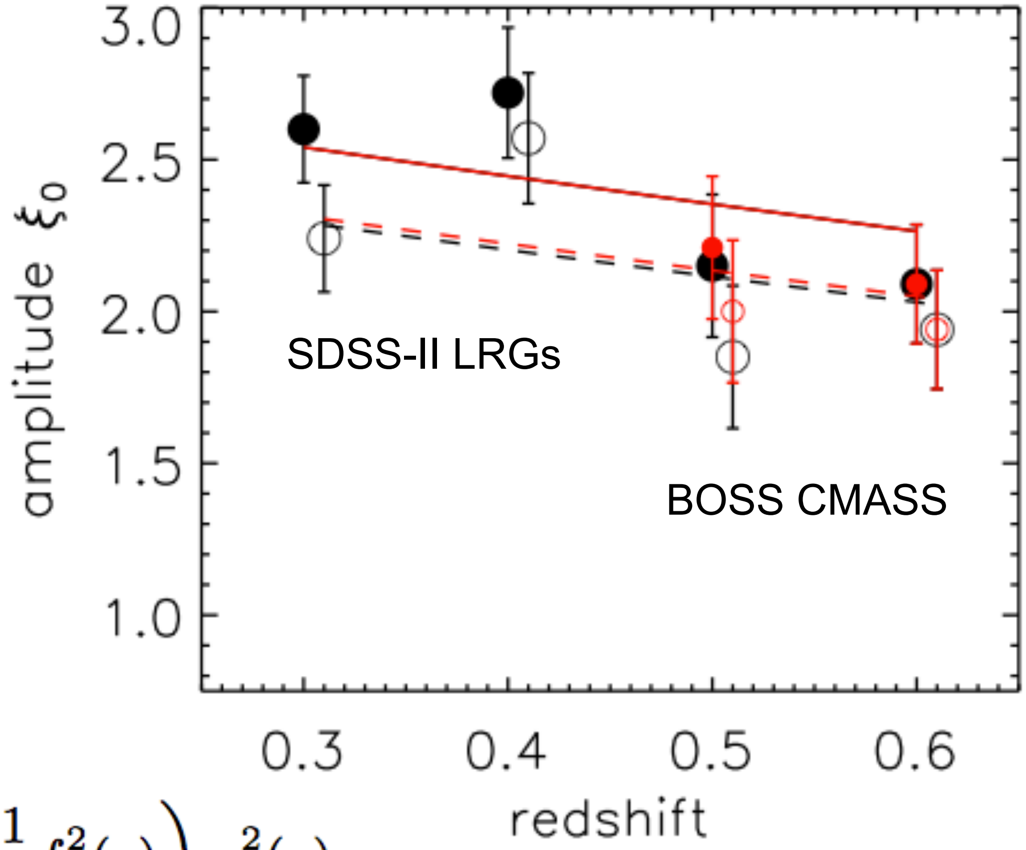


z	$f\sigma_8$	survey	reference
0.17	0.51 ± 0.06	2dFGRS	Percival et al. (2004)
0.22	0.42 ± 0.07	WiggleZ	Blake, et al. (2011b)
0.25	0.39 ± 0.05	SDSS	Samushia, Percival, & Raccanelli (2011)
0.37	0.43 ± 0.04	SDSS	Samushia, Percival, & Raccanelli (2011)
0.41	0.45 ± 0.04	WiggleZ	Blake, et al. (2011b)
0.57	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. (in prep), Reid et al.

Using passive evolution to enhance RSD measurements

Most luminous 40% of CMASS sample are direct and passive progenitors of the SDSS-II LRG sample to within ~2%



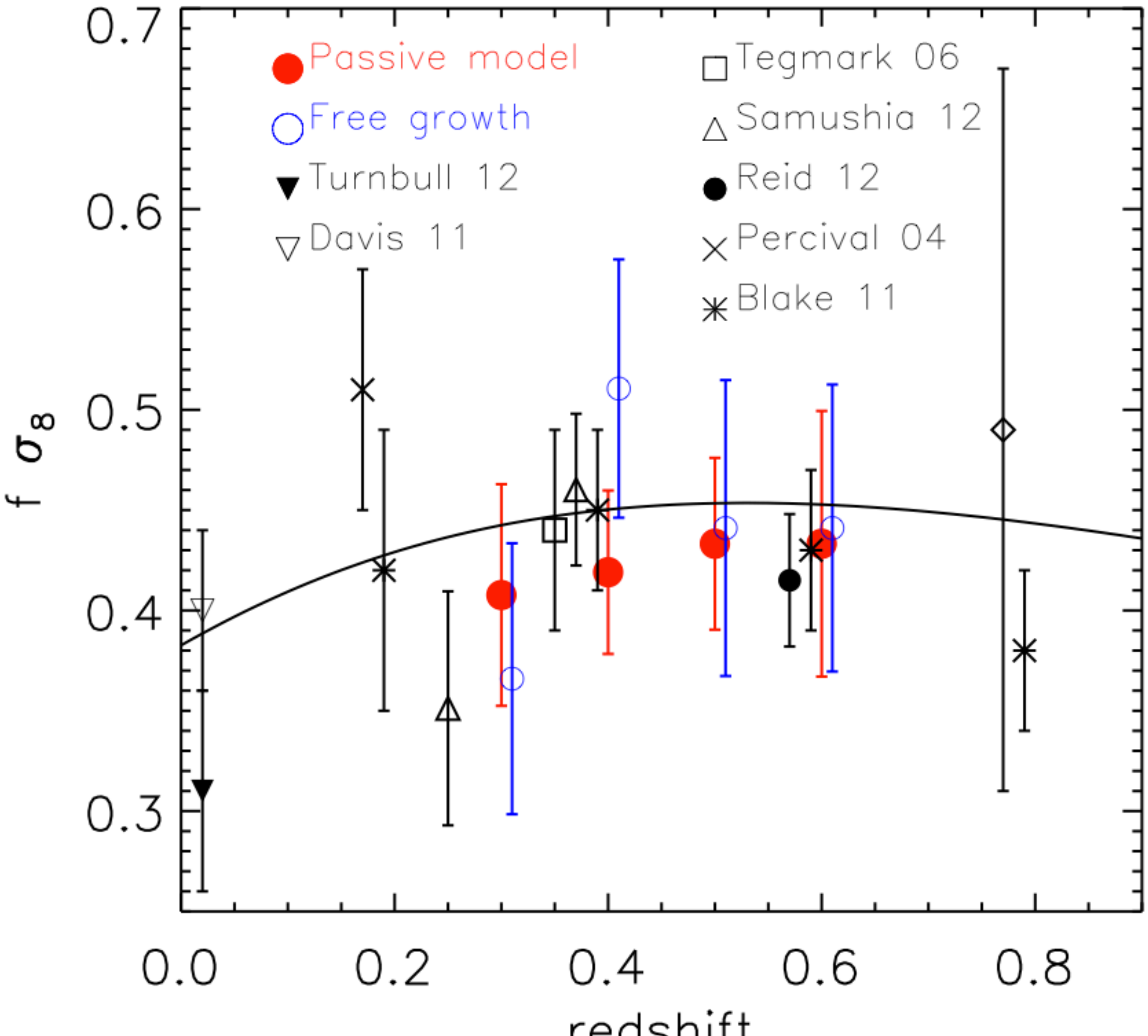
Line shows Fry (1996) model for a passively evolving population

$$A_0(z) = \left(b^2(z) + \frac{2}{3}f(z)b(z) + \frac{1}{5}f^2(z)\right)\sigma_8^2(z)$$

$$b(z) = [b(z_0) - 1]\frac{D(0)}{D(z_0)} + 1$$

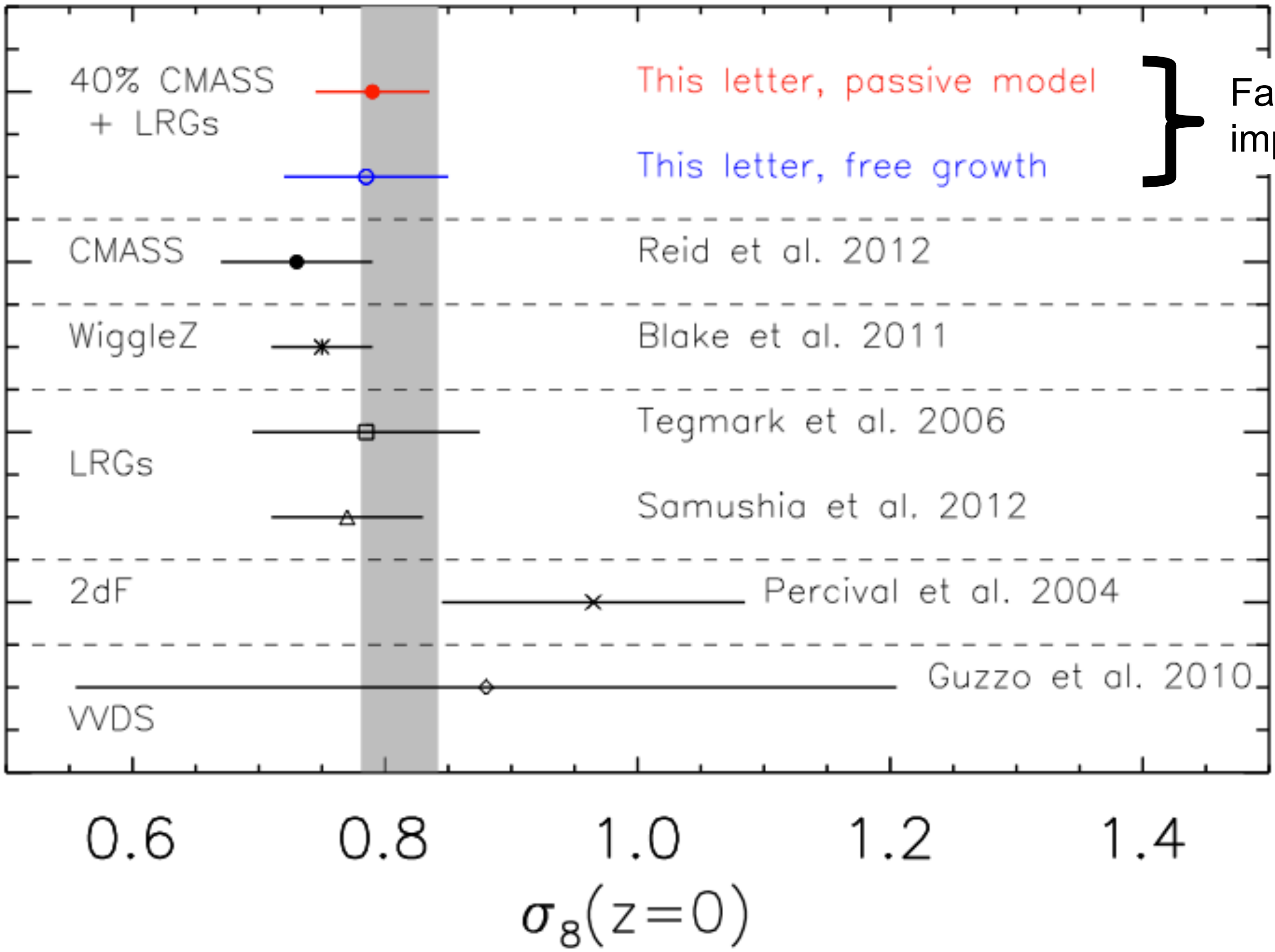
Tojeiro et al. 2012; arXiv:1202.6241

Using passive evolution to enhance RSD measurements



Tojeiro et al.

Converting to σ_8 measurements

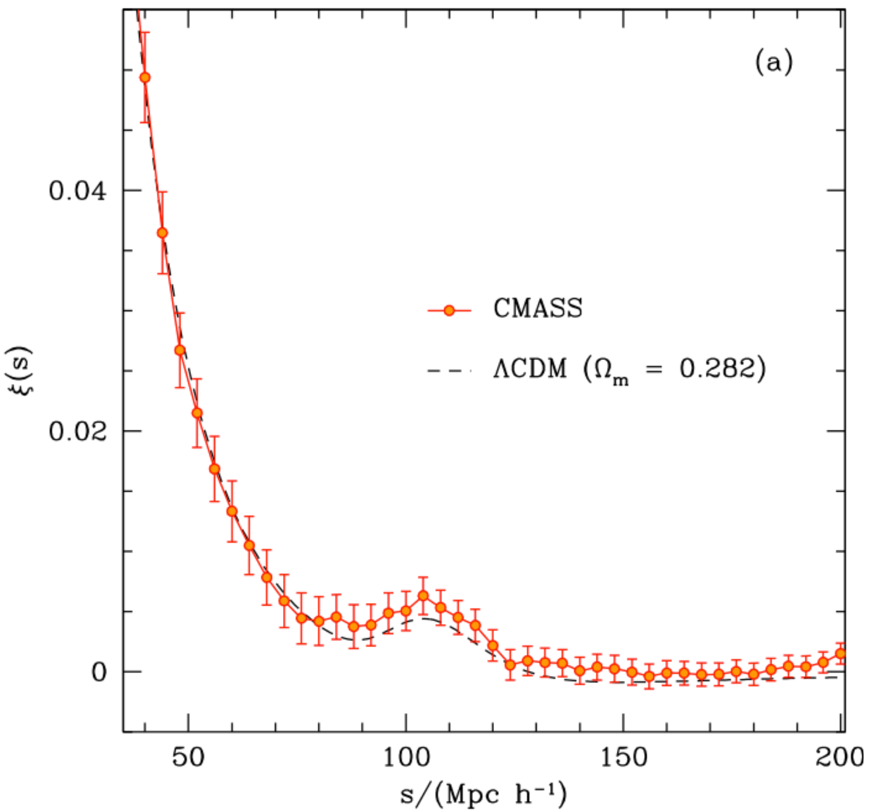


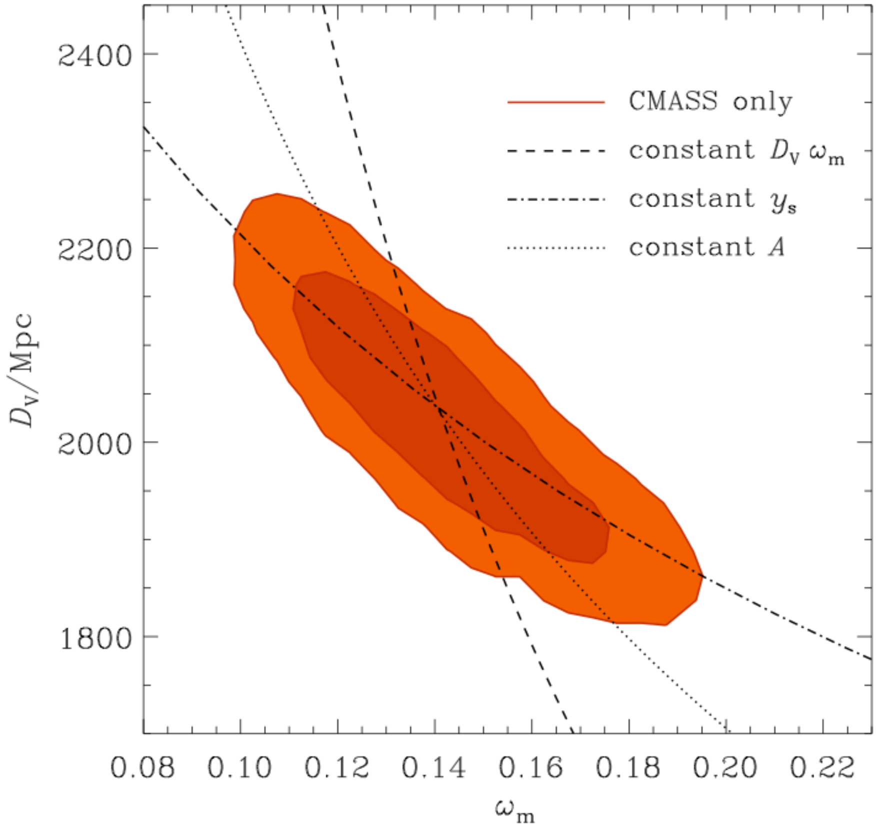
Factor 1.5 improvement

Tojeiro et al.

Fitting the full clustering signal

Fitting the full shape of the correlation function

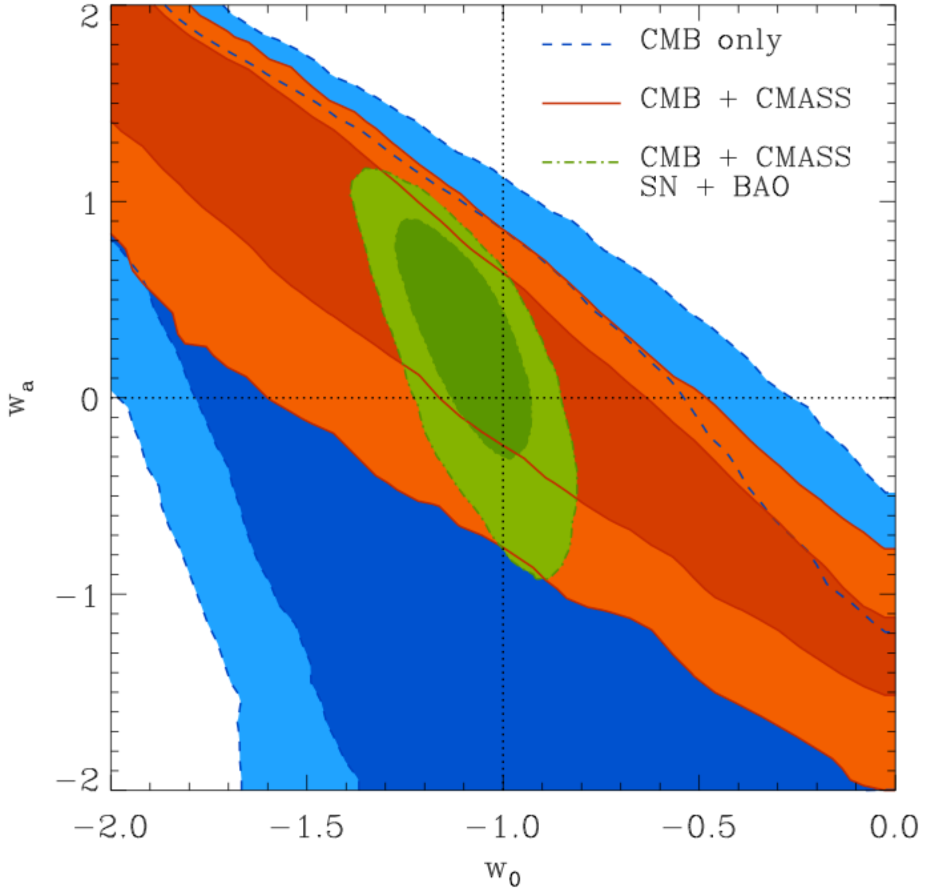




Sanchez et al.

Cosmological constraints from full fit

	CMB	CMB + CMASS	CMB + CMASS +SN	CMB + CMASS +BAO	CMB + CMASS + BAO + SN
w_0	$-1.12^{+0.52}_{-0.51}$	$-1.12^{+0.61}_{-0.58}$	$-1.09^{+0.11}_{-0.11}$	$-0.95^{+0.27}_{-0.27}$	$-1.08^{+0.11}_{-0.11}$
w_a	$-0.3^{+1.2}_{-1.7}$	$0.32^{+0.98}_{-0.99}$	$0.12^{+0.48}_{-0.47}$	$0.05^{+0.62}_{-0.61}$	$0.23^{+0.42}_{-0.42}$
100Θ	$1.0409^{+0.0016}_{-0.0016}$	$1.0409^{+0.0016}_{-0.0016}$	$1.0408^{+0.0015}_{-0.0016}$	$1.0409^{+0.0016}$	$1.0408^{+0.0016}$
$100\omega_b$	$2.219^{+0.042}_{-0.042}$	$2.218^{+0.042}_{-0.041}$	$2.215^{+0.040}_{-0.040}$		
$100\omega_{dm}$	$11.22^{+0.47}_{0.47}$	$11.31^{+0.46}_{-0.46}$	$11.40^{+0.45}_{-0.45}$		
τ	$0.0852^{+0.0061}_{-0.0069}$	$0.0833^{+0.0062}_{0.0067}$	$0.0823^{+0.0058}_{-0.0067}$		
n_s	$0.965^{+0.011}_{-0.011}$	$0.965^{+0.011}_{-0.011}$	$0.963^{+0.011}_{-0.011}$		
$\ln(10^{10}A_s)$	$3.083^{+0.030}_{-0.029}$	$3.082^{+0.030}_{-0.030}$	$3.083^{+0.029}_{-0.029}$		
$\Omega_{\rm DE}$	$0.760^{+0.081}_{-0.087}$	$0.722^{+0.081}_{-0.091}$	$0.730^{+0.016}_{-0.016}$		
$\Omega_{\rm m}$	$0.239^{+0.087}_{-0.081}$	$0.278^{+0.091}_{-0.081}$	$0.269^{+0.016}_{-0.016}$		
σ_8	$0.87^{+0.12}_{-0.12}$	$0.82^{+0.11}_{-0.11}$	$0.832^{+0.049}_{-0.049}$		
$t_0/{\rm Gyr}$	$13.64^{+0.22}_{-0.22}$	$13.79^{+0.16}_{-0.16}$	$13.763^{+0.089}_{-0.091}$		
$z_{\rm re}$	$10.4^{+1.2}_{-1.2}$	$10.3^{+1.2}_{-1.2}$	$10.2^{+1.2}_{-1.2}$		
h	$0.78^{+0.14}_{-0.14}$	$0.72^{+0.11}_{-0.11}$	$0.712^{+0.020}_{-0.020}$		
$D_{\rm V}(z_m)/{\rm Mpc}$	1974^{+86}_{-83}	2040^{+47}_{-45}	2027^{+25}_{-25}		
$f(z_{\rm m})$	$0.733^{+0.077}_{-0.078}$	$0.770^{+0.064}_{-0.069}$	$0.766^{+0.022}_{-0.022}$		

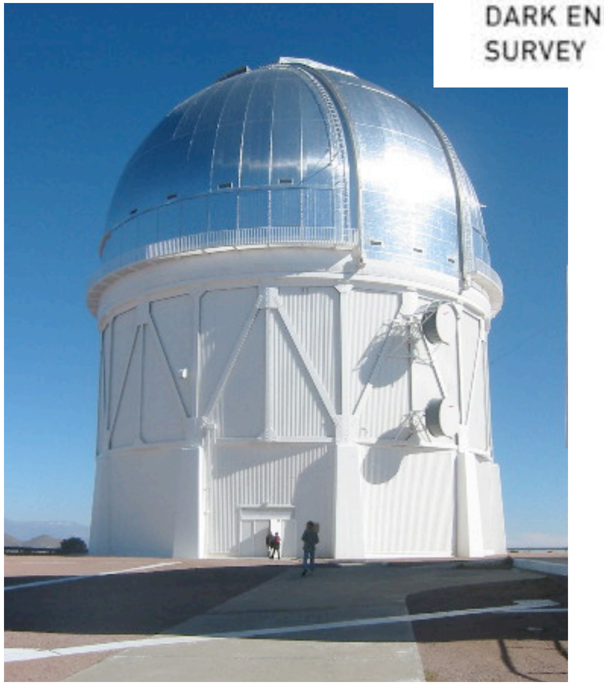


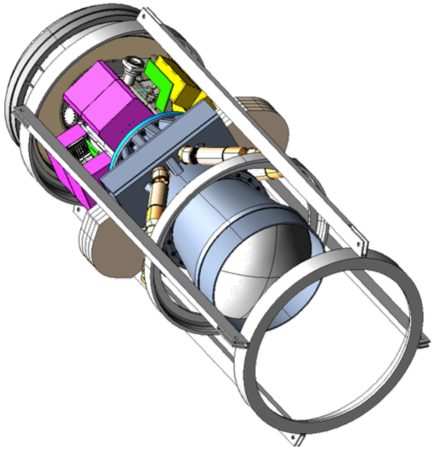
Sanchez et al.

The Future …

Dark Energy Survey (DES)

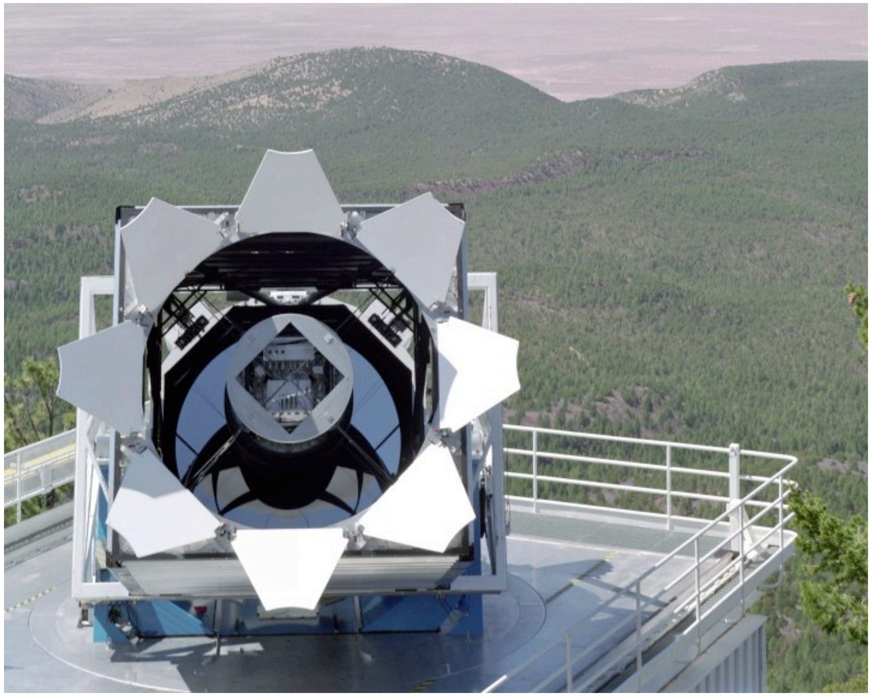
- New wide-field camera for the 4m Blanco telescope
- Currently being assembled on site, Survey due to start December 2012
- Ω = 5,000deg2
- multi-colour optical imaging (g,r,i,z) with link to IR data from VISTA hemisphere survey
- 300,000,000 galaxies
- Aim is to constrain dark energy using 4 probes
  - 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
  - $\Omega = 3{,}000\mathrm{deg}^2$
  - 1,000,000 galaxies (direct BAO)
  - 60,000 quasars (BAO from Ly-α forest)

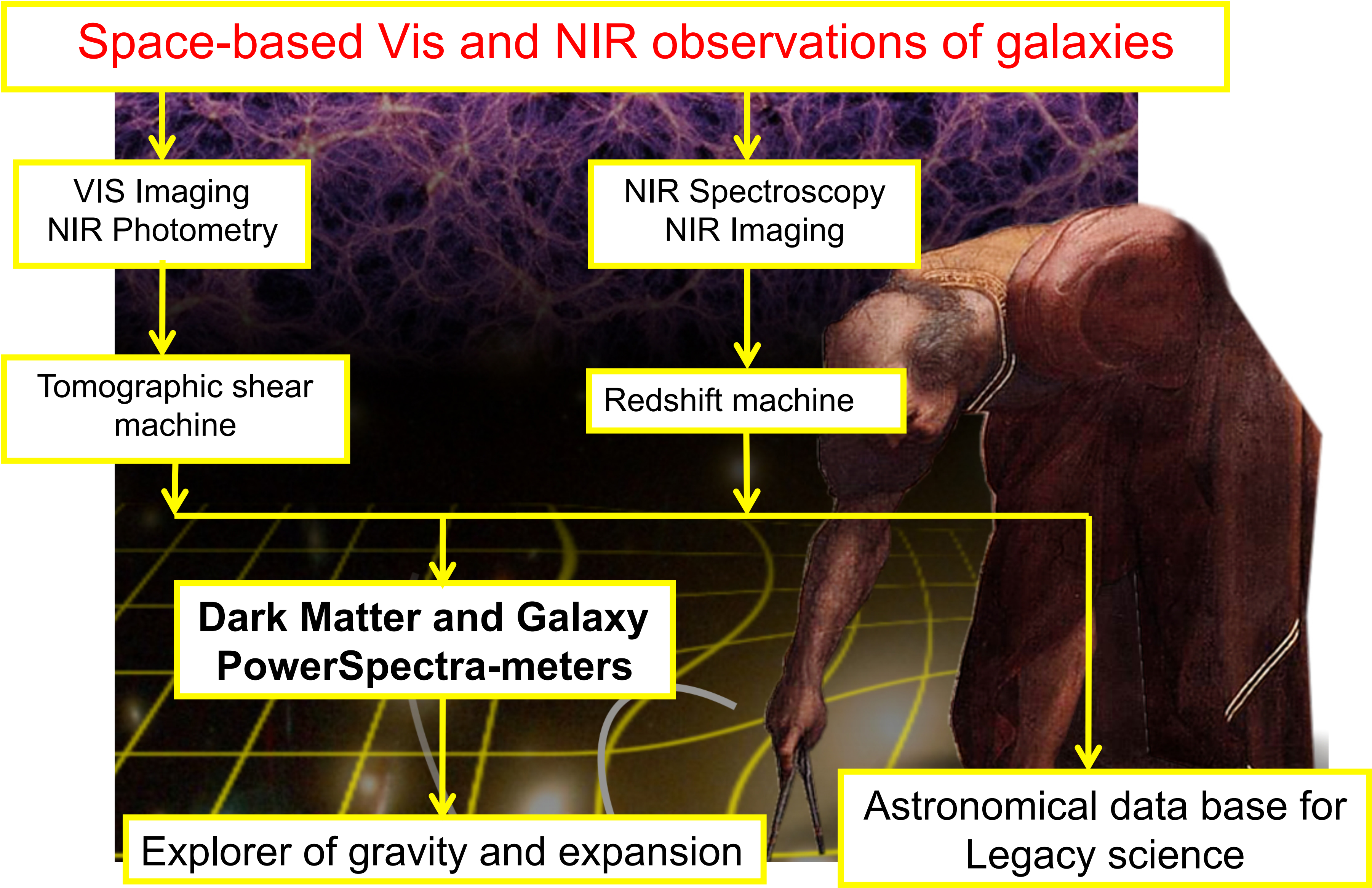


- Distance measurements
  - 1.6% at z=0.7 (LRGs)
  - 1.5% at z=0.9 (ELGs)
  - 3.0% at z=1.5 (QSOs)
  - 2.3% at z=2.5 (Ly-α forest)
- Survey would start 2014, and would last 4—6 years (depending on funding)
- Currently at the stage of requesting funding

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
  - $\Omega = 10{,}000\mathrm{deg}^2$
  - 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



Space-based Vis and NIR observations of galaxies

VIS Imaging
NIR Photometry

NIR Spectroscopy
NIR Imaging

Tomographic shear machine

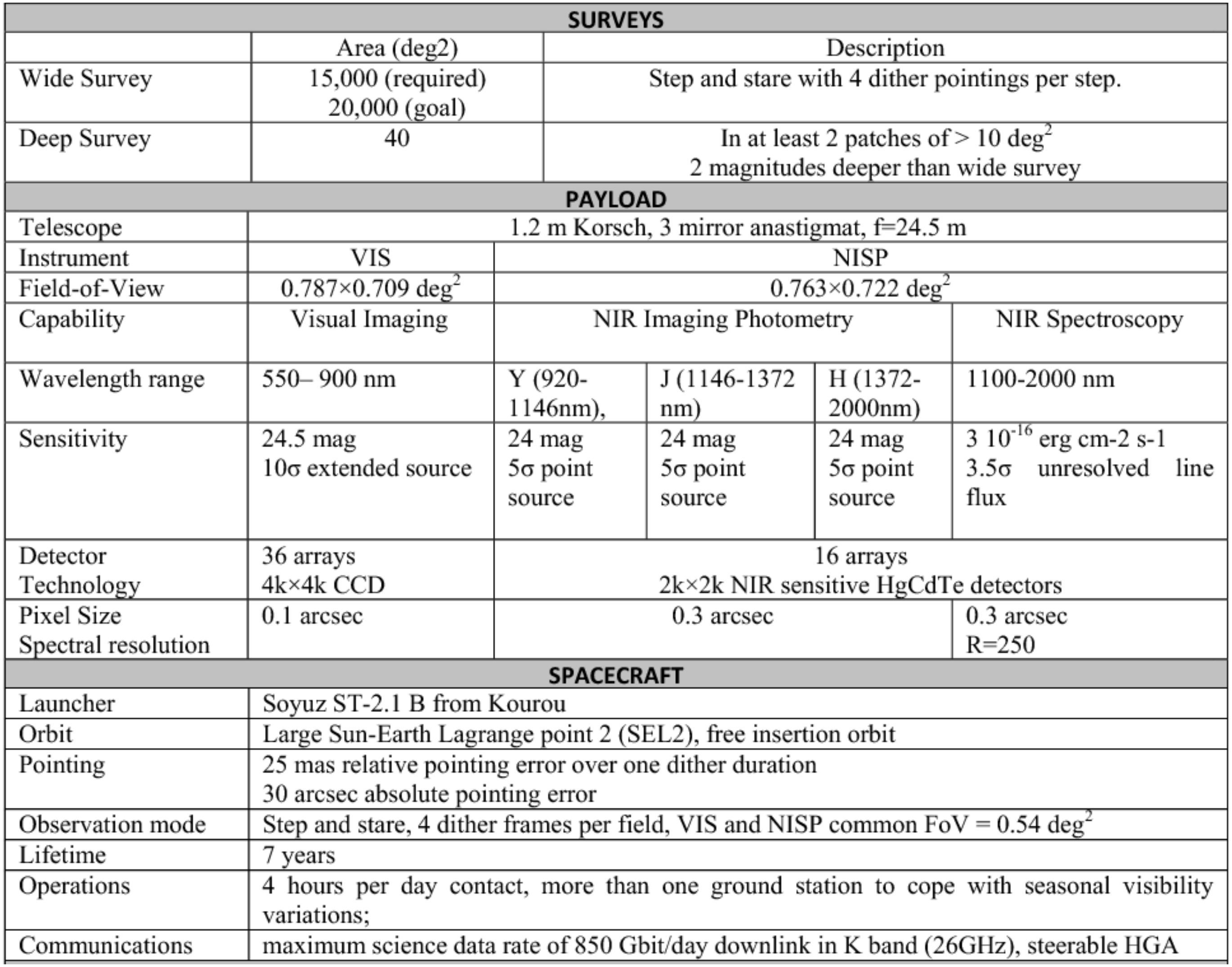
Redshift machine

Dark Matter and Galaxy PowerSpectra-meters

Explorer of gravity and expansion

Astronomical data base for Legacy science

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

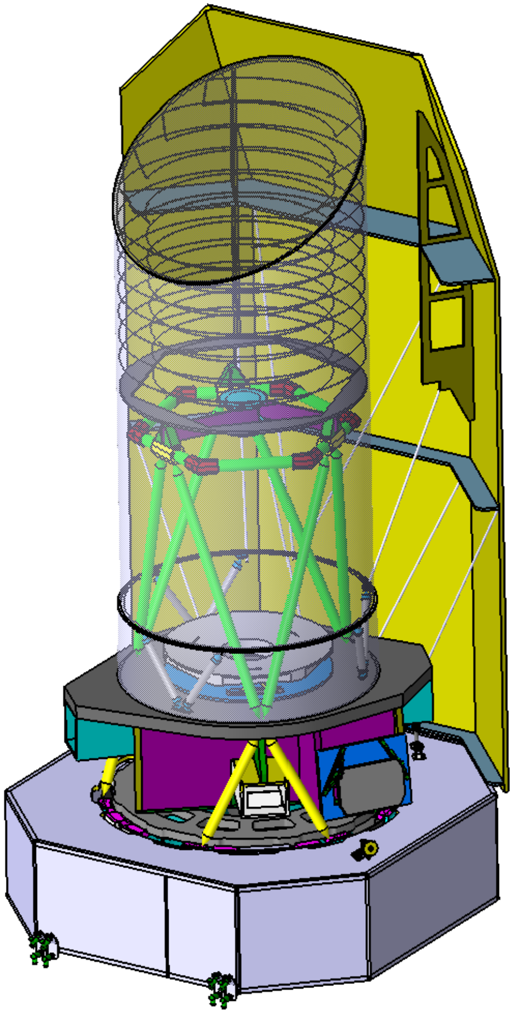
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	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

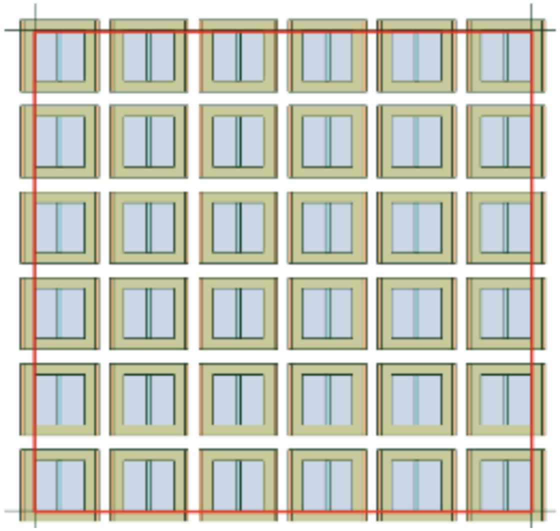
Hardware

Astrium

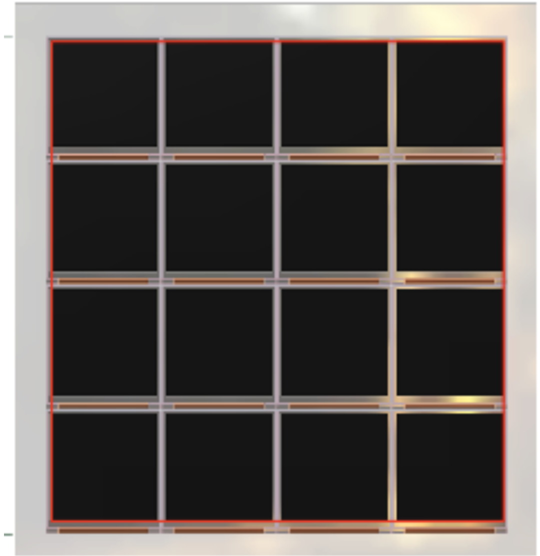


Thales

Visible FPA: 36 VIS CCD



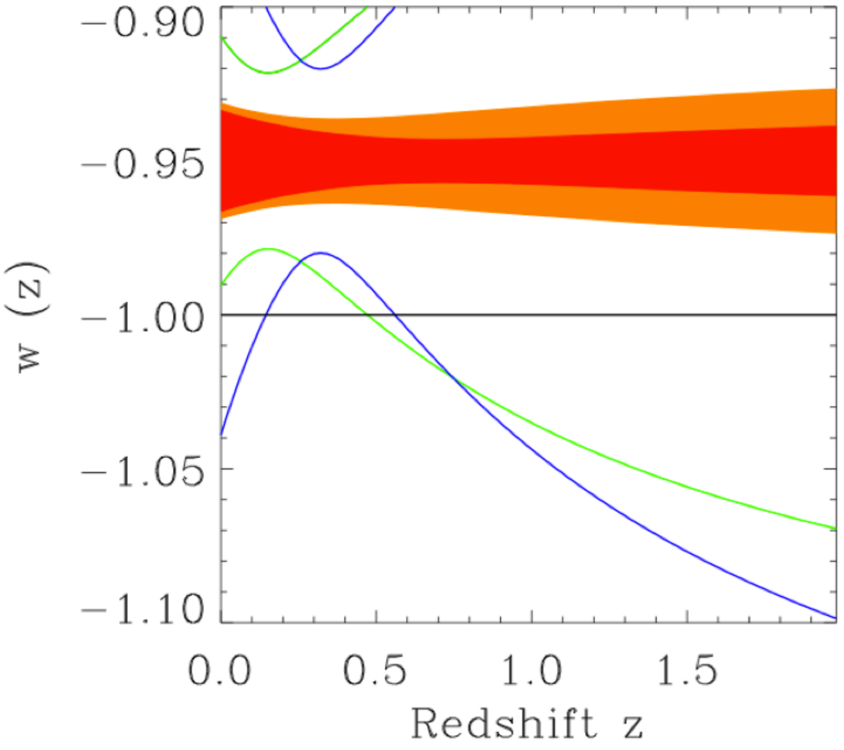
NIR FPA: 16 H2RG



0.5deg^2 FOV in optical/NIR

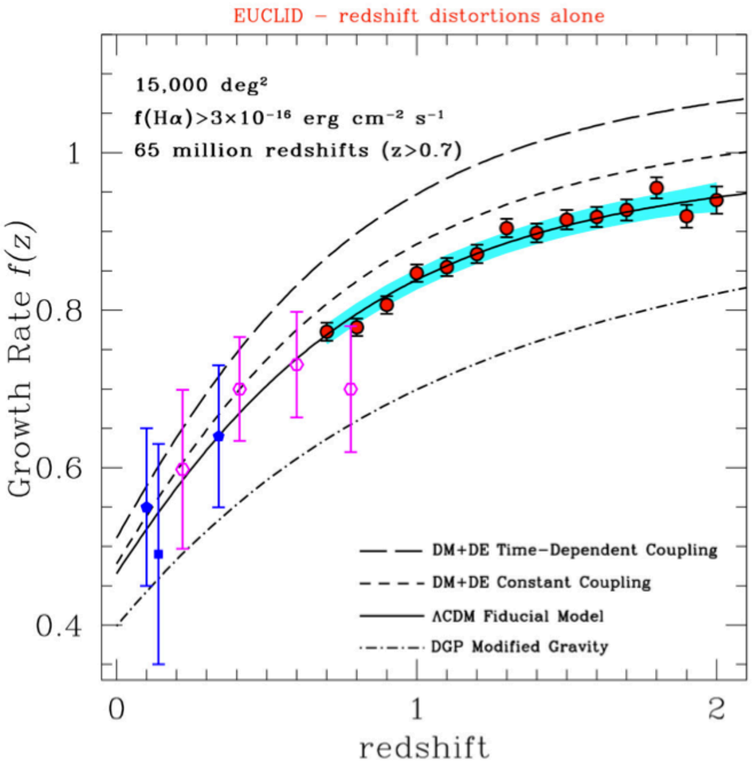
Measuring Dark Energy

- 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)
  $\mathrm{FoM} = 1/(\Delta wp\times\Delta wa)$
- Primary Euclid probes give a FoM>4
  with subdominant systematic uncertainties, matching the DETF definition of a stage-IV mission



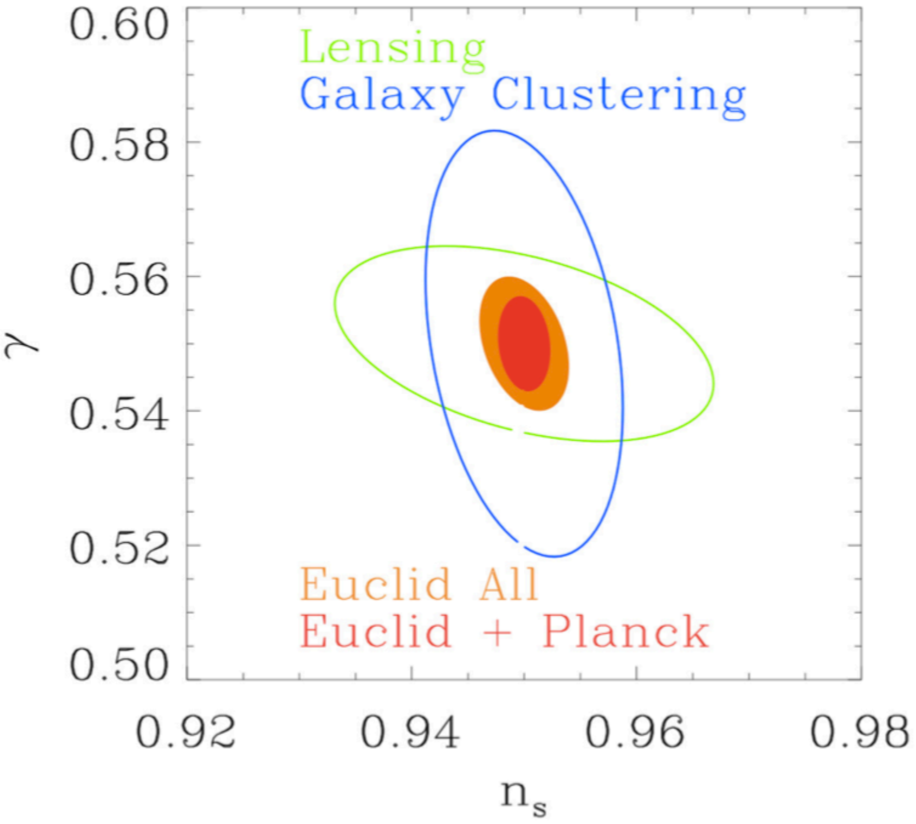
Measuring Modified Gravity

- 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

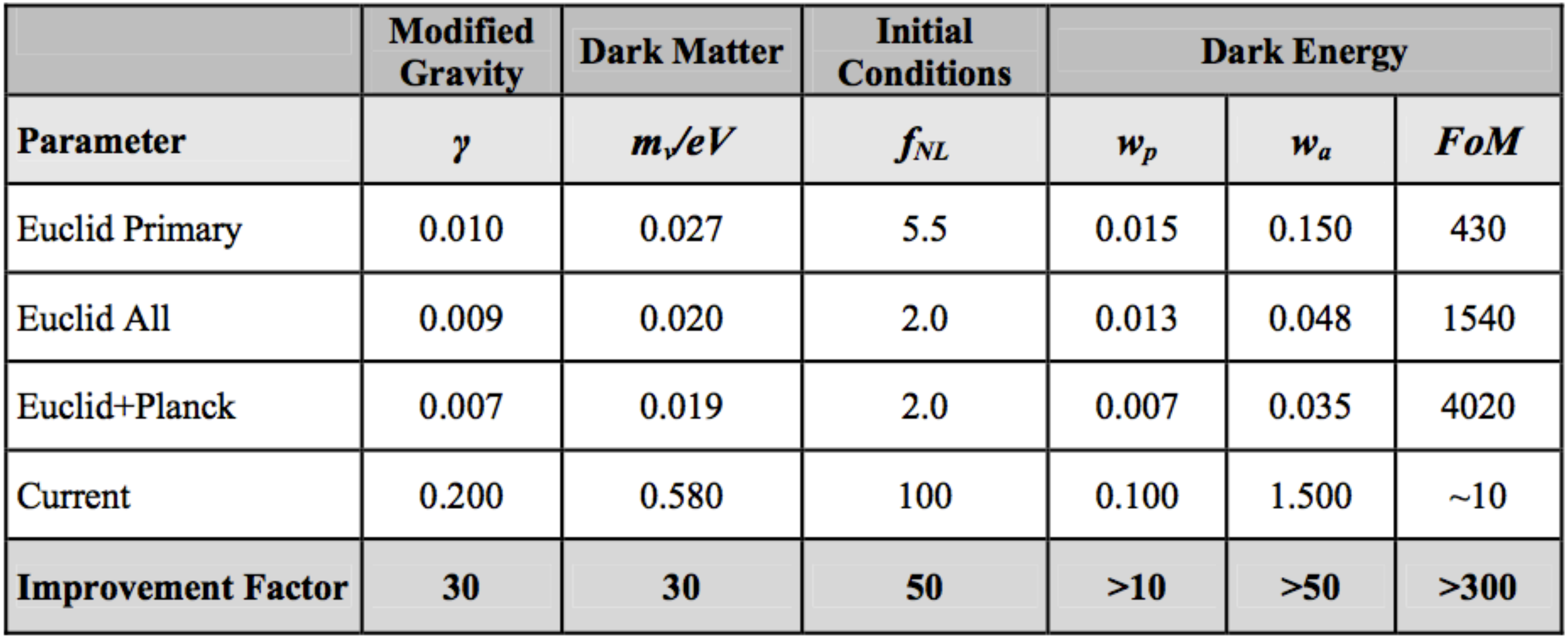
- Concordance cosmology assumes an initial Gaussian random field of perturbations, with power-law index n_s
- Euclid + Planck will provide a factor ~2 improved n_s measurement over Planck alone
- A detection of non-Gaussianity would signify a departure from this central assumption of the current standard 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 $\Delta m_\nu < 0.03$eV, sufficient to determine the neutrino mass hierarchy, if the total mass turns out to be small, $m_\nu < 0.1$ 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

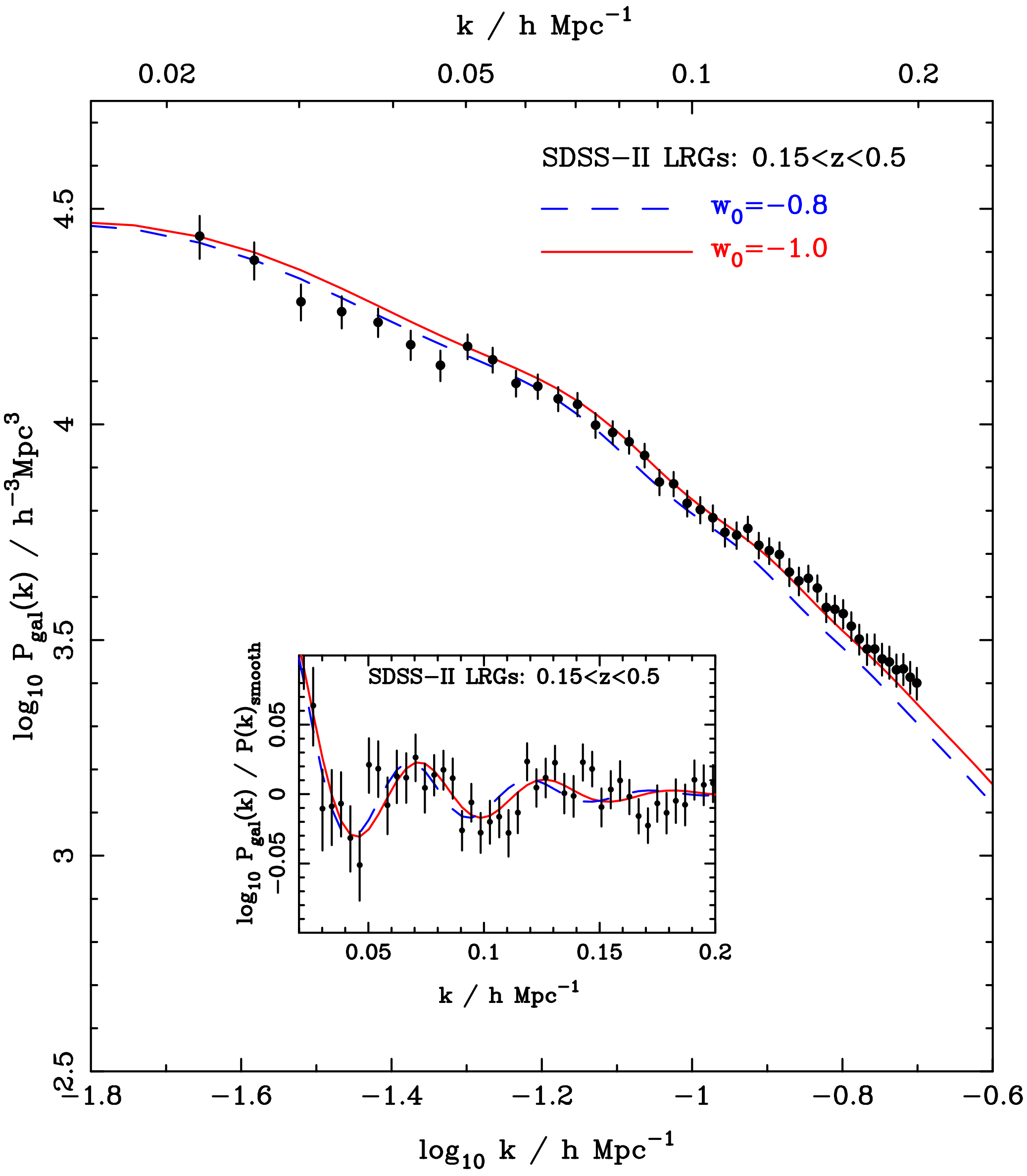
Euclid Legacy in numbers

What	Euclid	Before Euclid
Galaxies at 1<z<3 with good mass estimates	$\sim 2\times10^8$	$\sim 5\times10^6$
Massive galaxies (1<z<3) w/ spectra	~few x 10^3	~few tens
Hα emitters/metal abundance in z~2-3	$\sim 4\times10^7/10^4$	$\sim 10^4/\sim 10^2$?
Galaxies in massive clusters at z>1	$\sim 2\times10^4$	$\sim 10^3$?
Type 2 AGN (0.7<z<2)	$\sim 10^4$	$<10^3$
Dwarf galaxies	$\sim 10^5$	
T_{eff} ~400K Y dwarfs	~few 10^2	<10
Strongly lensed galaxy-scale lenses	~300,000	~10-100
z > 8 QSOs	~30	None

SDSS-II LRG clustering

SDSS LRGs at z~0.35

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

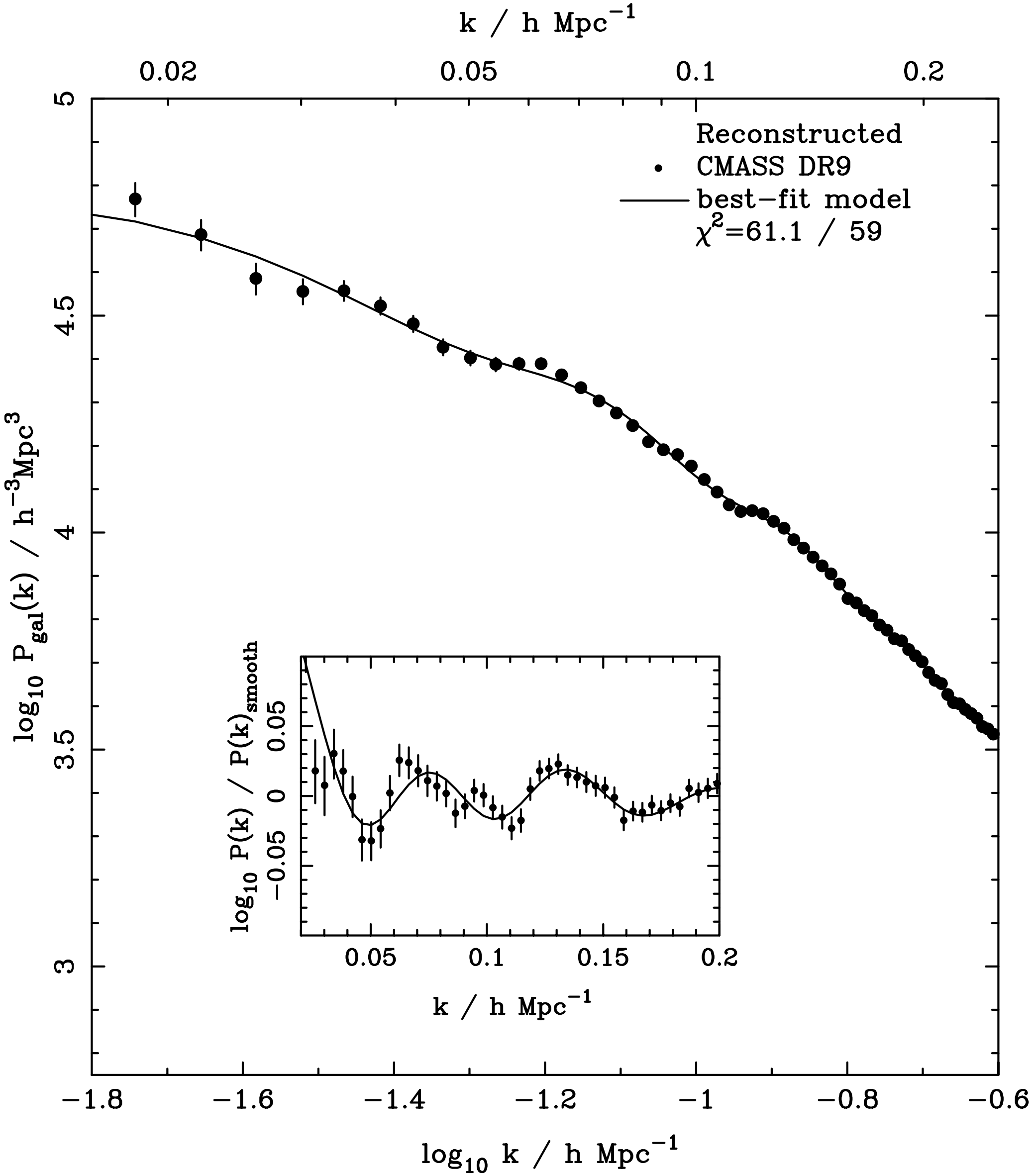


Percival et al. 2009; arXiv:0907.1660

BOSS CMASS DR9 galaxy clustering

BOSS CMASS galaxies at z~0.57

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

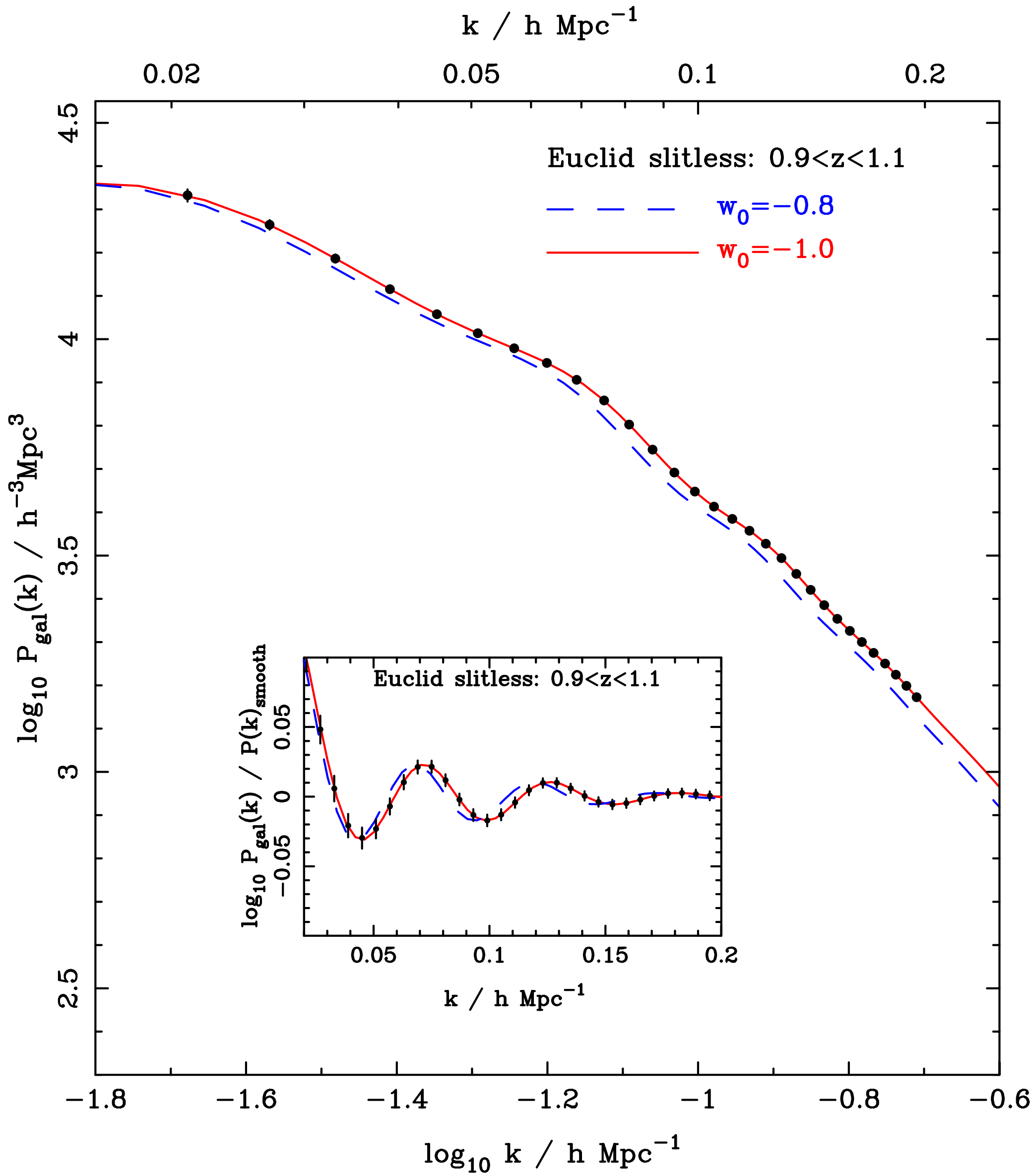


Anderson et al.

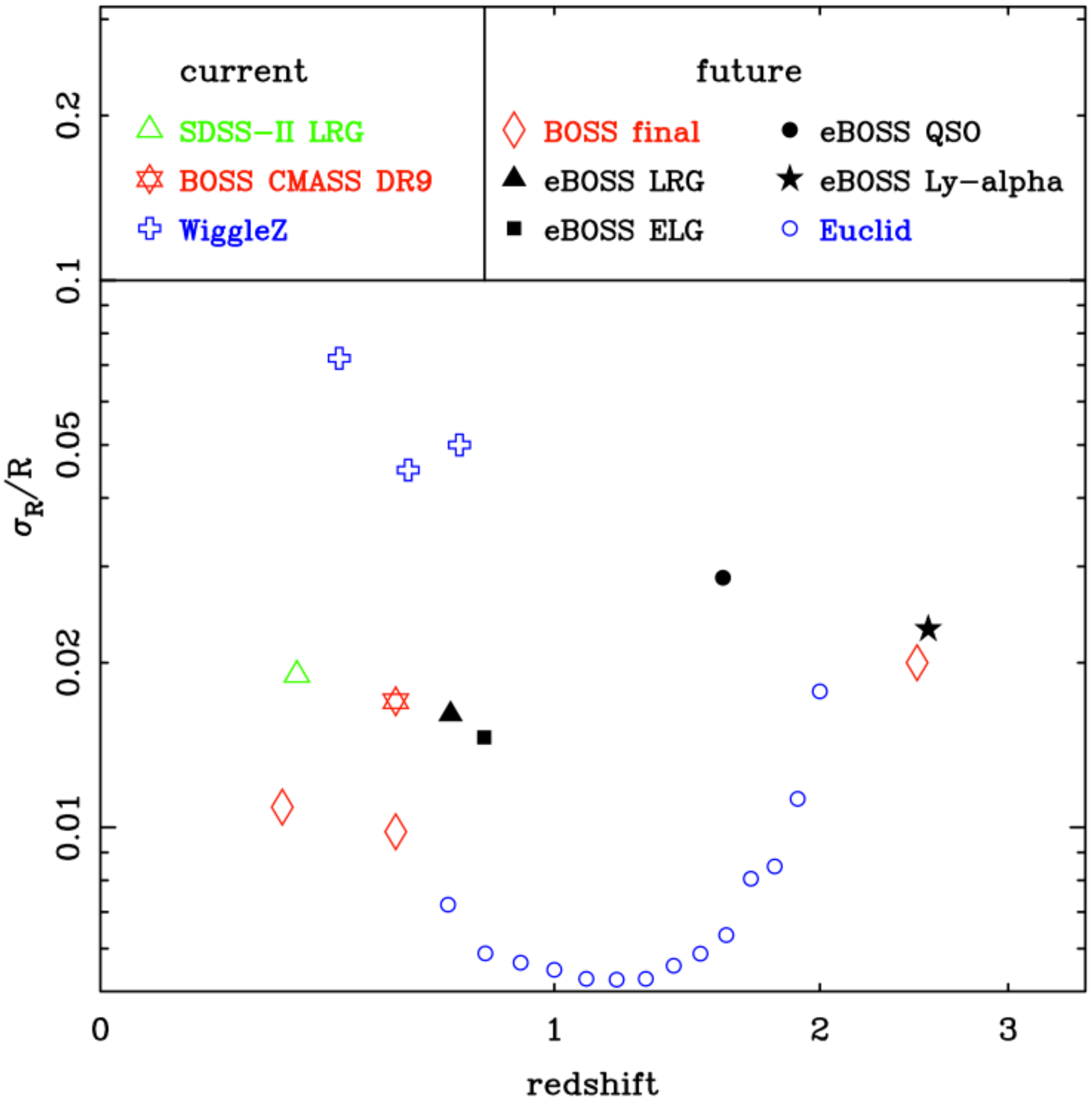
Predicted Euclid galaxy clustering

Redshift slice
0.9 < z < 1.1

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

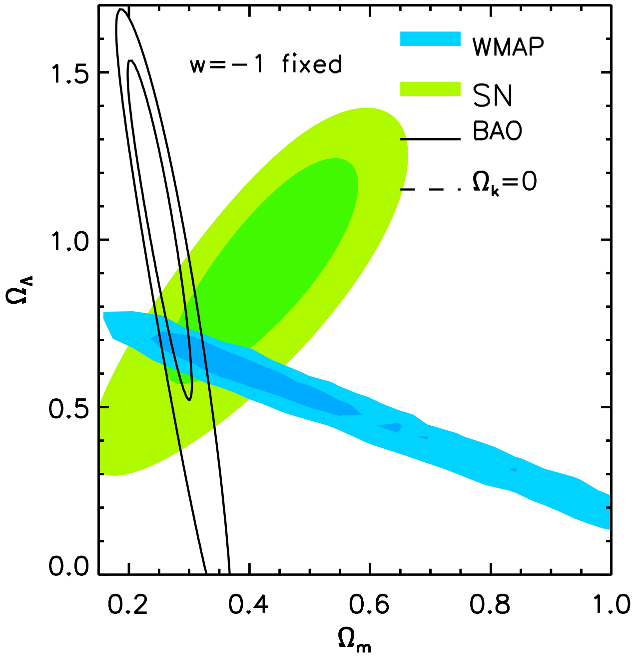


Distance measurements for future surveys

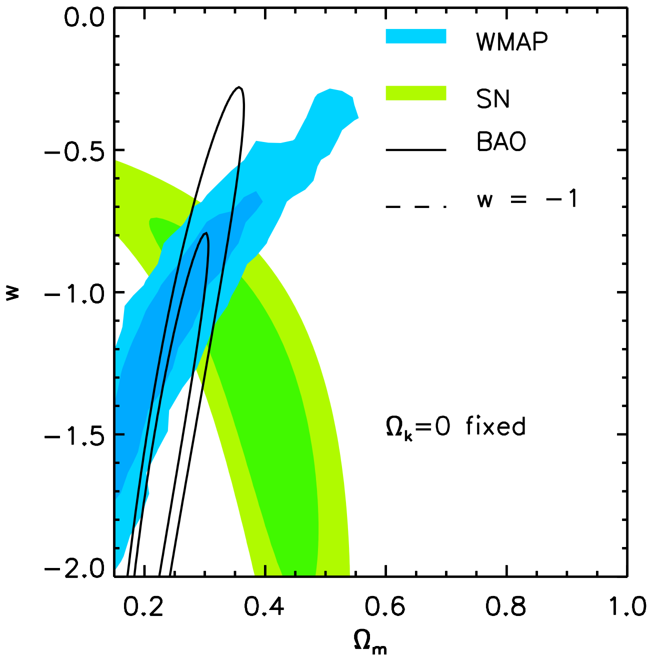


SDSS-II LRG BAO vs other data

ΛCDM models with curvature



flat wCDM models



🟨 Union supernovae

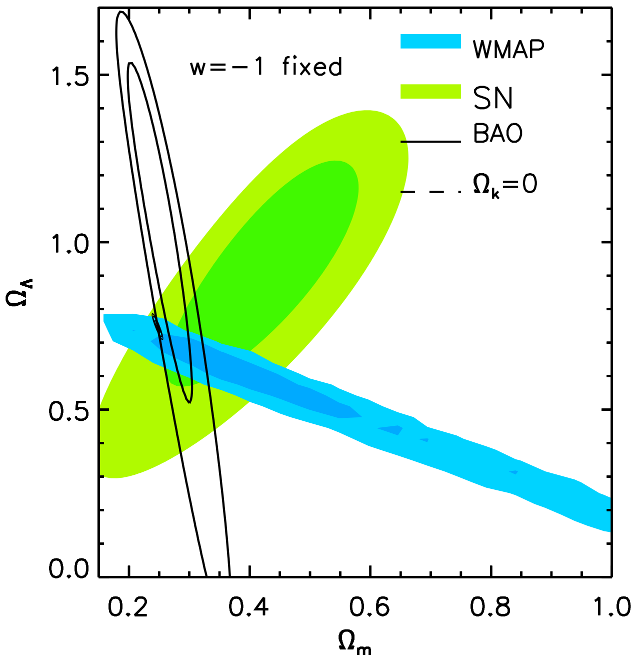
🟦 WMAP 5year

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

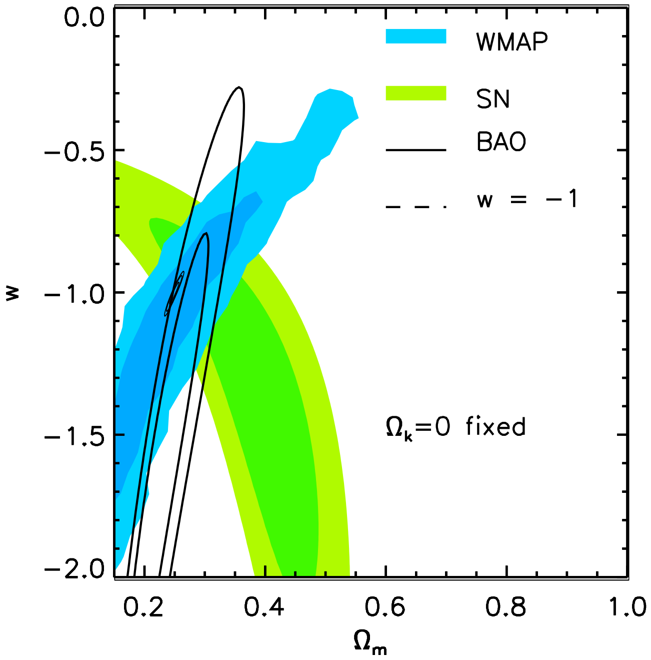
Percival et al. 2009; arXiv:0907.1660

Euclid BAO predictions

ΛCDM models with curvature



flat wCDM models



🟨 Union supernovae

🟦 WMAP 5year

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