Cosmology

Current Surveys and Instrumentation

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Multi-Object Spectroscopy in the Next Decade

Santa Cruz de La Palma

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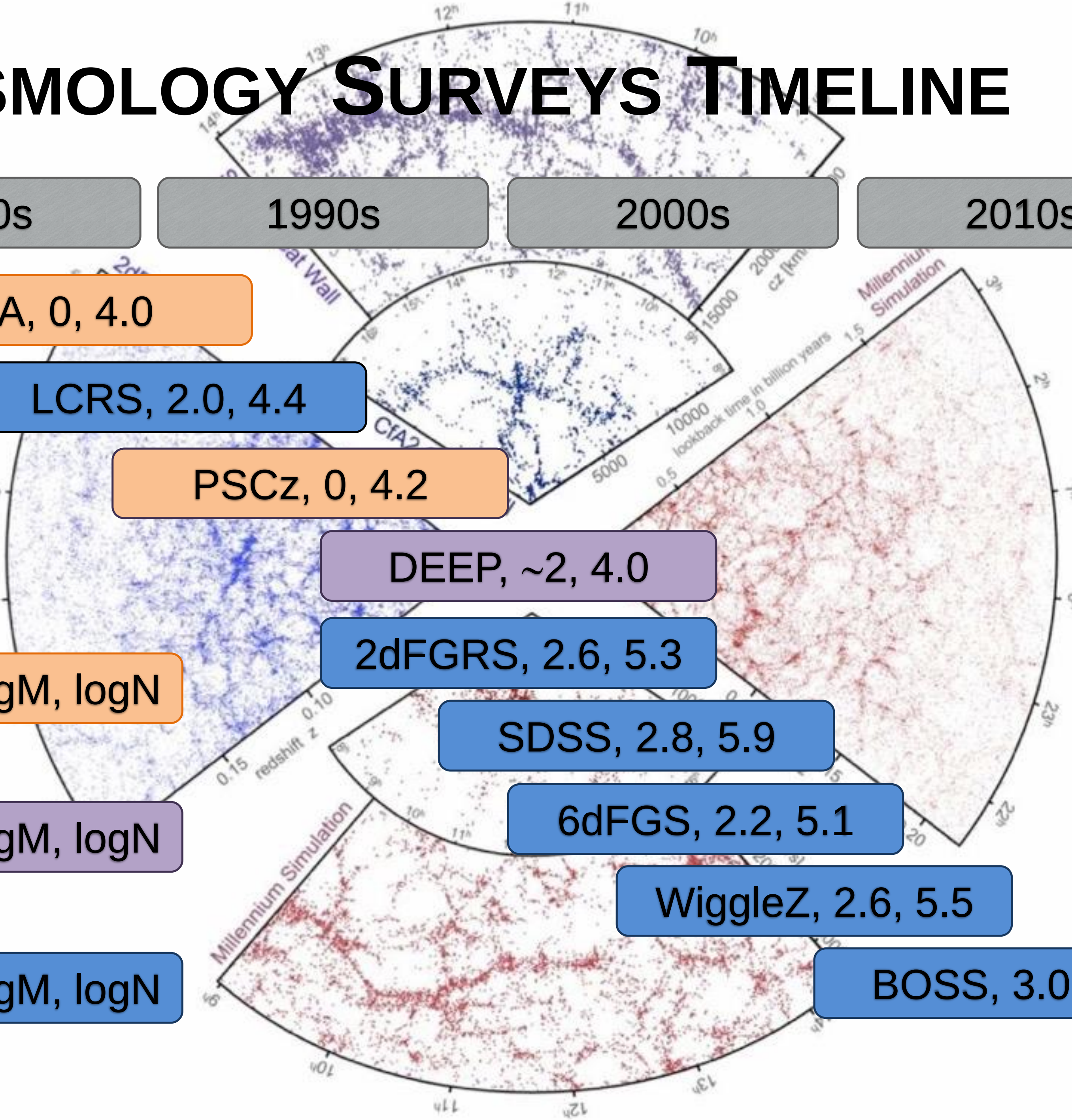
WHY SURVEYS? WHY MOS?

- ASTRONOMY IS AN OBSERVATIONAL SCIENCE DEALING WITH LARGE POPULATIONS OF COMPLEX OBJECTS THAT FORM STRUCTURES IN SPACE AND EVOLVE IN TIME
- SURVEYS ALLOW US TO STUDY LARGE POPULATIONS, TO MAP STRUCTURES, AND TO TRACK EVOLUTION
- "A PICTURE IS WORTH A THOUSAND WORDS",
  BUT, TO AN ASTRONOMER,
  "A SPECTRUM IS WORTH A THOUSAND IMAGES"
- MULTI-OBJECT SPECTROSCOPY (MOS) IS THE MOST EFFICIENT WAY TO GATHER ASTROPHYSICAL INFORMATION FOR LARGE POPULATIONS SCATTERED OVER TIME AND SPACE
- SO…IN THE LAST FEW DECADES MOS SURVEYS HAVE TRANSFORMED OBSERVATIONAL COSMOLOGY

Cosmology Surveys Timeline



1980s	1990s	2000s	2010s

CfA, 0, 4.0

LCRS, 2.0, 4.4

PSCz, 0, 4.2

DEEP, ~2, 4.0

2dFGRS, 2.6, 5.3

SDSS, 2.8, 5.9

6dFGS, 2.2, 5.1

WiggleZ, 2.6, 5.5

BOSS, 3.0, 6.2

non-MOS

Survey, logM, logN

slit MOS

Survey, logM, logN

fibre MOS

Survey, logM, logN

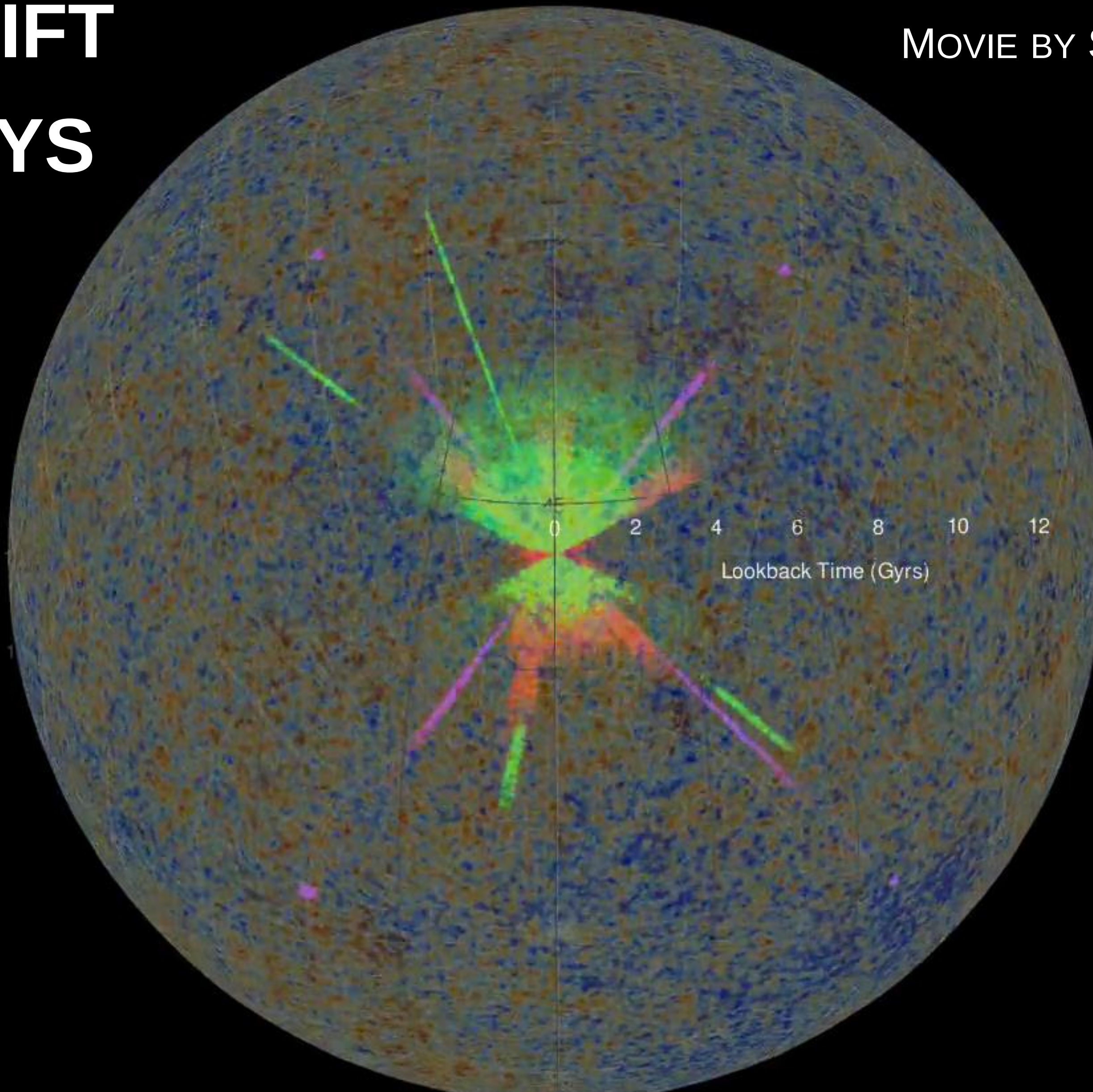
MOS INSTRUMENTS FOR COSMOLOGY

- 1D (MULTI-FIBRES)
  - LAS CAMPANAS FIBRE SYSTEM (LCRS)
  - 2DF (2DFGRS,2QZ) → AAΩ (WIGGLEZ,GAMA,OZDES)
  - 6DF (6DFGS) → TAIPAN (TAIPAN)
  - SDSS (SDSS-I, SDSS-II) → BOSS (BOSS, EBOSS)
- 2D (MULTI-SLITS)
  - DEIMOS (DEEP, DEEP-2)
- 3D (MULTI-IFUS)
  - MUSE(?)
  - HET/VIRUS (HETDEX)

FIBRES DOMINATE MOS COSMOLOGY SURVEYS BECAUSE SCIENCE DRIVERS ARE MULTIPLEX AND AREA

Redshift Surveys

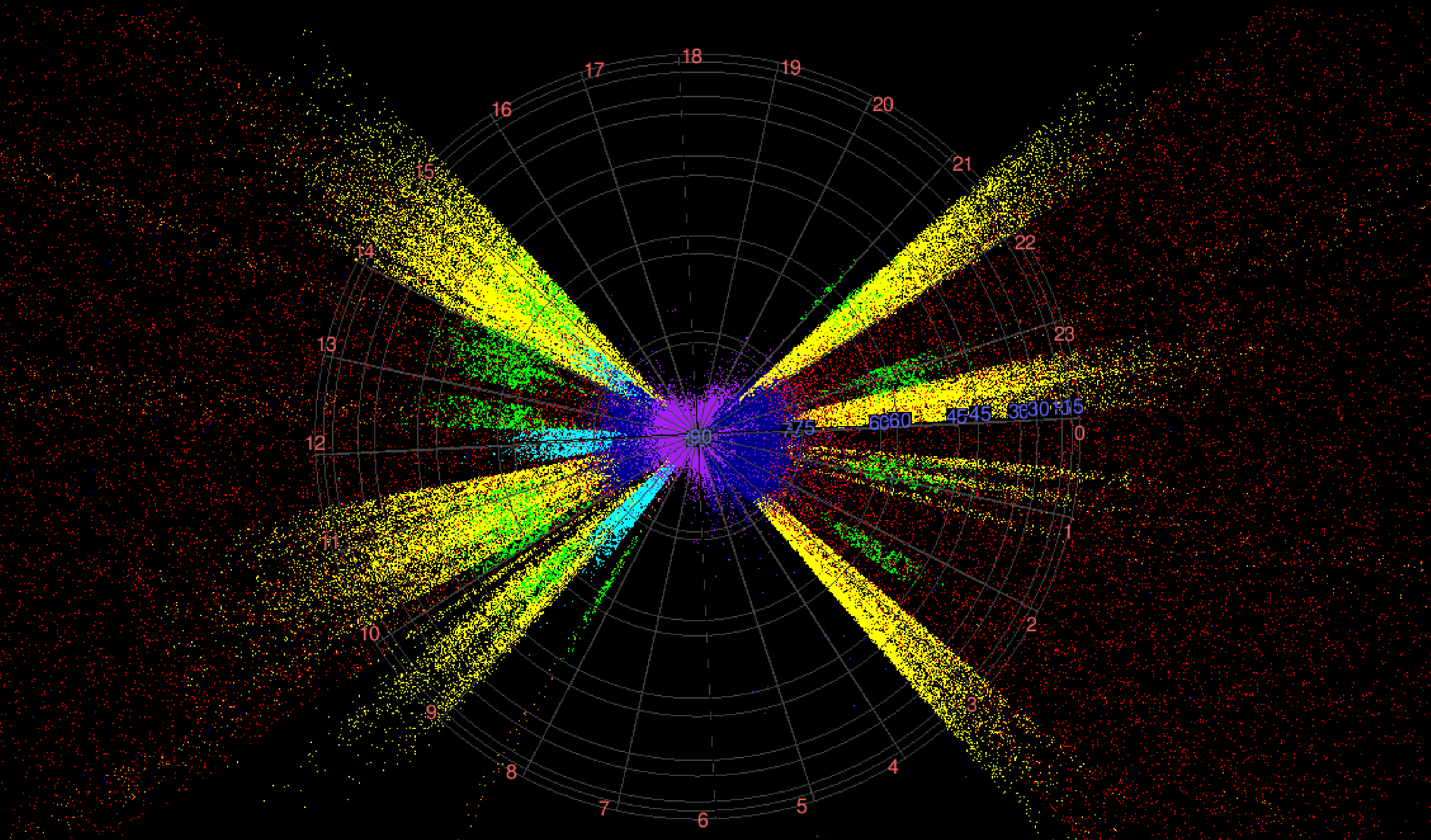
Movie by Simon Driver



Redshift Surveys: US surveys, European surveys, Australian surveys; celestial sphere is at CMB

AAO z-surveys

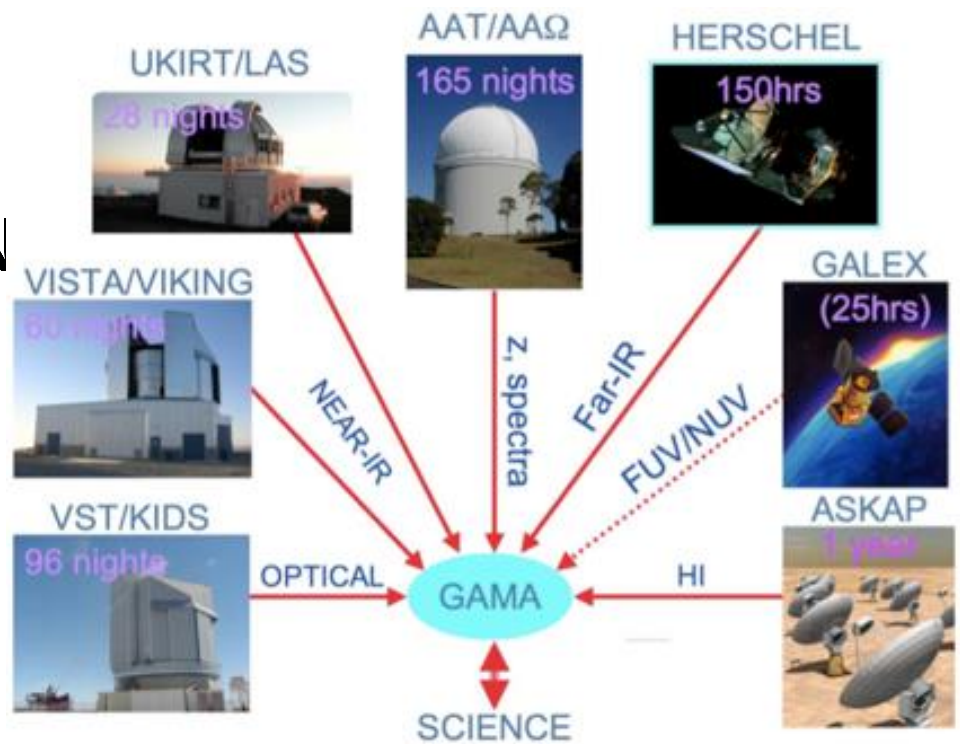
Movie by Simon Driver

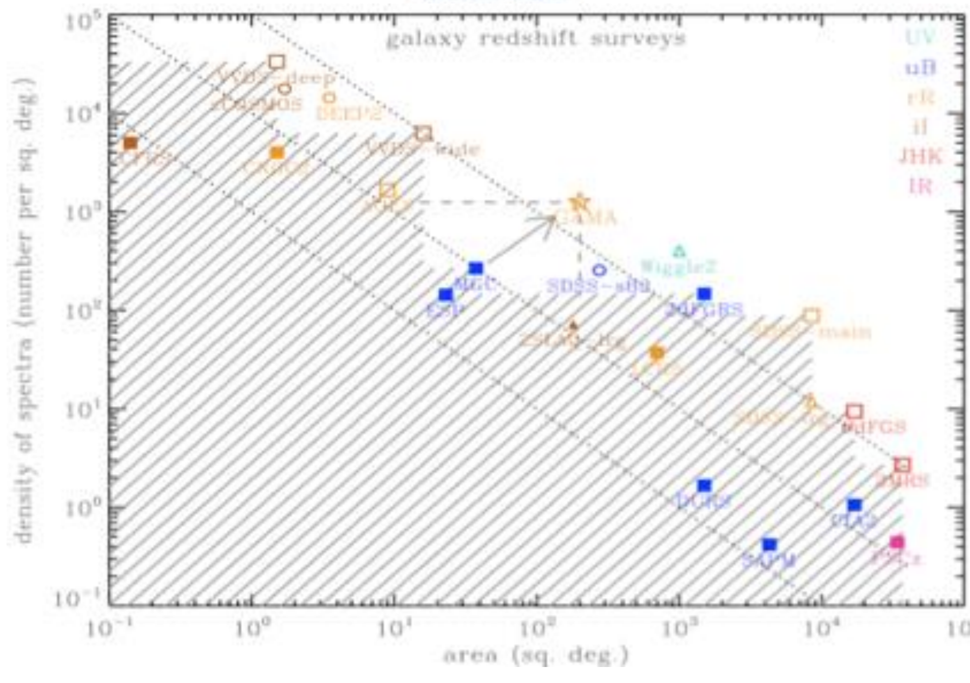


2dFGRS, 2QZ, 2SLAQ-LRG, 2SLAQ-QSO, 6dFGS, GAMA, WiggleZ; celestial sphere at z=1

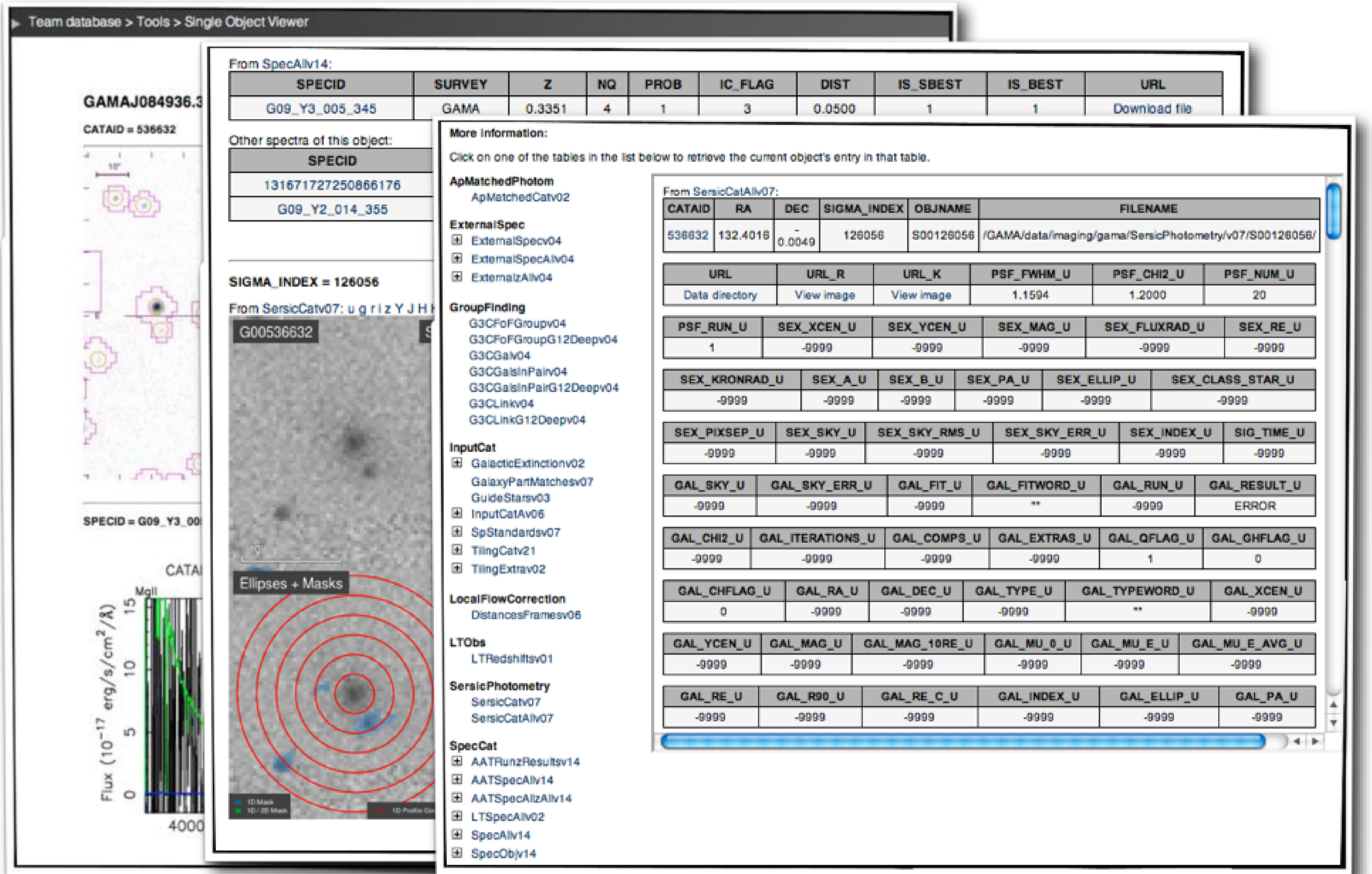
GAMA: The very model of a modern redshift survey

- Galaxy And Mass Assembly survey
- Federative, multi-λ, and multi-facility
  - Galaxy SEDs from UV to Radio using existing surveys & new observations
  - Also multi-z when ASKAP provides HI redshifts

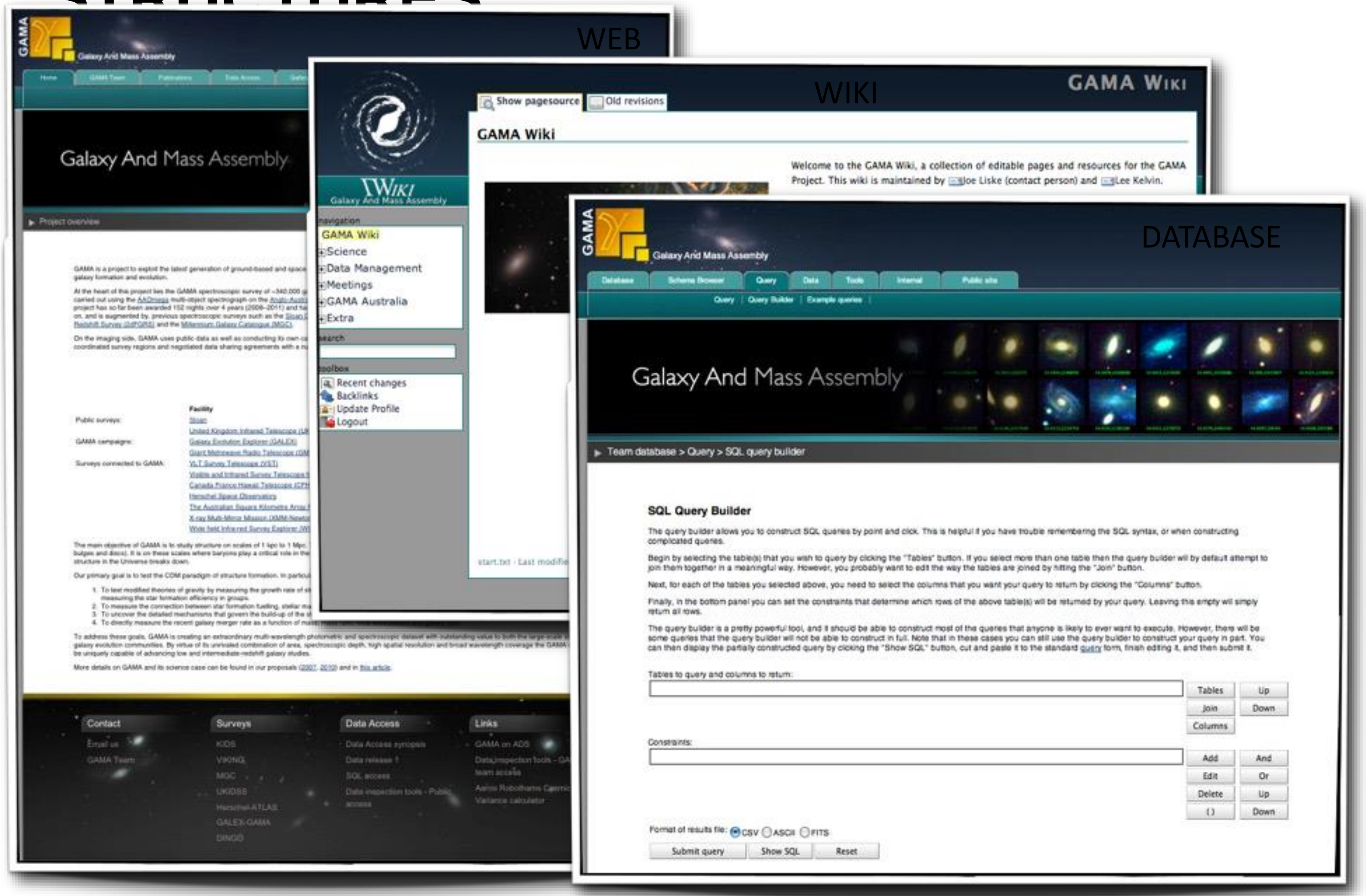




...RICH SURVEY DATABASE



…COMPLEX INFORMATION STRUCTURES



MOS Surveys/Instruments here

Telescope : Instrument	Survey(s)
AAT : AAΩ, HERMES, SAMI	WiggleZ, GAMA, GALAH, SAMI
UKST : 6dF, TAIPAN	RAVE, 6dFGS, Taipan
SDSS 2.5m : SDSS, BOSS, MaNGA	SDSS, BOSS, eBOSS, MaNGA
WHT : ISIS, WEAVE	WEAVE
GTC : OSIRIS, EMIR, MEGARA	
VLT : VIMOS, KMOS, MUSE, MOONS	VANDELS, VIPERS, LEGA-C,…
VISTA : 4MOST	4MOST, WAVES
LAMOST	LEGUE
Calar Alto : CALIFA	CALIFA
Magellan : PRIMUS	PRIMUS
Subaru : FMOS, PFS	FastSound
HET : VIRUS	HETDEX
GAIA	GAIA
KPNO 4m : DESI	DESI
Euclid	Euclid
LSST:MOS / MSE / WFIRST	…

MANY TELESCOPES, MANY INSTRUMENTS, MANY SURVEYS

AN INDUSTRY, NOT A NICHE!

Impact of MOS Surveys - 1

- Literature analysis by Trimble & Ceja (2008) looked at 11,831 papers published in 2001-3 (dated, but results still applicable)
- The most-cited optical/infrared facilities…

Facility	Citations	Papers
HST	15390	1063.1
Keck	8122	365.6
SDSS	7235	161
VLT	5696	345.5
AAT	4592	170.2
Schmidts	3430	247.8
2MASS	2937	182.9

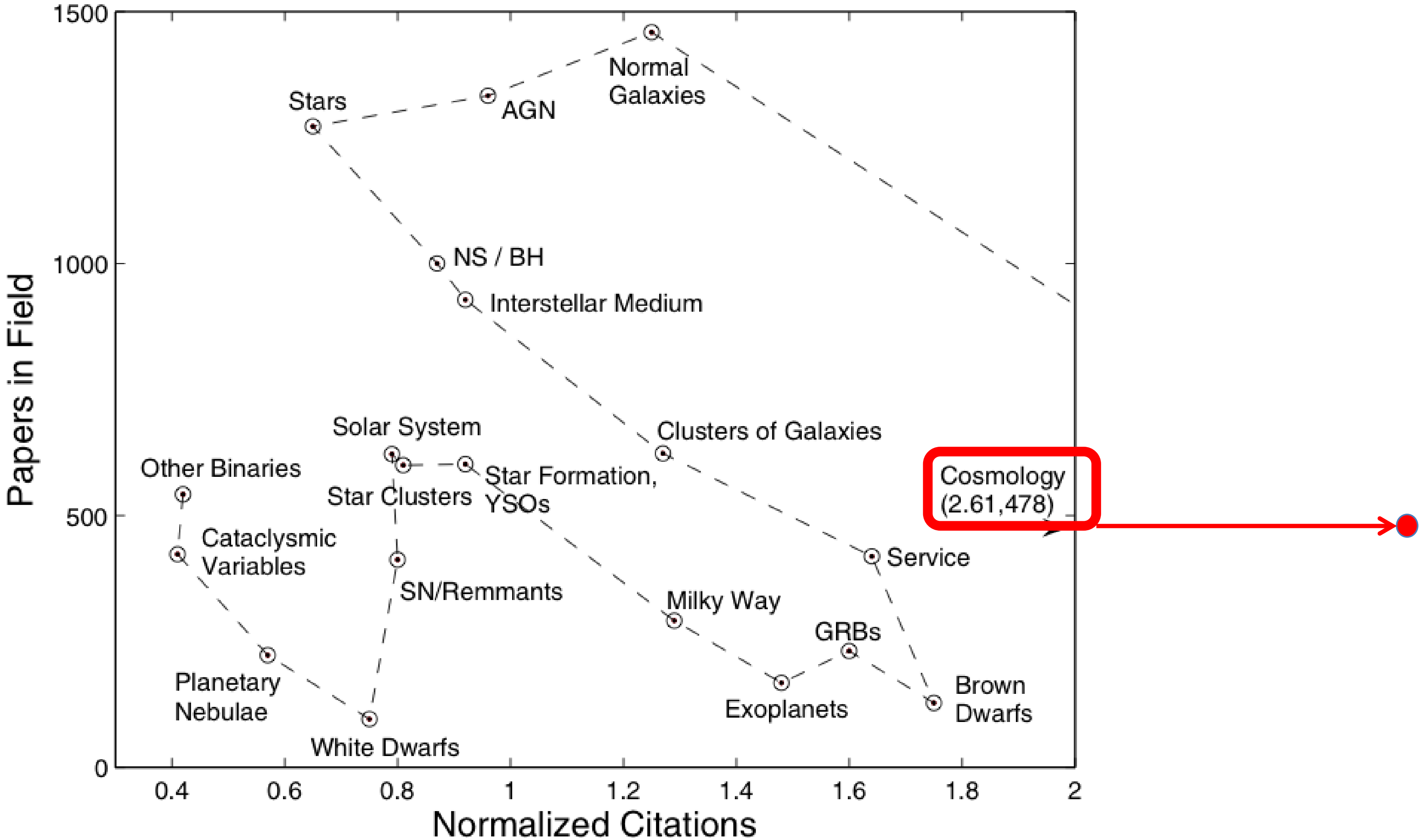
IMPACT OF MOS SURVEYS - 2

20 MOST-CITED PAPERS 2001-3

Citations	Journal	Subject	Facilities
2770	ApJS	Cosmology	WMAP, ACBAR, CBI, AAT, HST, other optical
1301	ApJS	Cosmology	WMAP, optical & X-Ray unidentified
632	ApJ	Cosmology	HST
466	ApJS	Cosmology	WMAP
450	MNRAS	Galaxies	JKT, Siding Spring 2.3m, SDSS, IUE
397	ApJ	Cosmology	CFHT, CTIO-4, Keck II & I, CTIO-1.5, VLT, UKIRT, UHi 2.2, Vatican, WIYN, HST, SDSS
383	ApJS	Cosmology	WMAP, CBI, ACBAR, AAT, other optical
380	A&A	Service	XMM
375	AJ	Service	SDSS
370	A&A	Service	XMM
313	AJ	Service	SDSS
309	Nature	GRB	VLT 1 & 2
306	A&A	Service	XMM
298	ApJLett	GRBs	VLA, Keck, Palomar 5-m
281	ApJS	Cosmology	WMAP
281	ApJLett	GRBs	MMT, Magellan, Whipple-1.5
279	MNRAS	Galaxies	AAT
277	AJ	Service	Schmidt surveys (USNO catalogue)
275	ApJ	Cosmology	Boomerang
258	ApJ	Cosmology	HST, Keck, WIYN, ESO-3.6, CFHT, INT, ESO-NTT, CTIO-4

TRIMBLE & CEJA (2008)

SURVEY IMPACT BY FIELD



Physics from Large-Scale Structure

Rich information encoded in LSS

Information from power spectrum shape
- Matter density
- Baryon Acoustic Oscillations
- Neutrino mass
- Inflation fluctuation spectrum

Information from geometry
- Galaxy clustering as a standard ruler
- BAO or full power spectrum
- Alcock-Paczynski effect

Information from large scale bias
- f_{NL}

$$P^s_{gg}(k,\mu,z) = k^n T^2(k) G^2(z) \left[b(z,k) + f(z)\mu^2\right]^2$$

Information from structure growth
- amplitude of power spectrum
- Redshift-Space Distortions

k = comoving wavenumber
μ = cos(angle to line-of-sight)
a = cosmological scale factor
b = galaxy bias factor
G = linear growth rate
f = dlnG/dlna

Sidebar: Spectro-z's vs Photo-z's

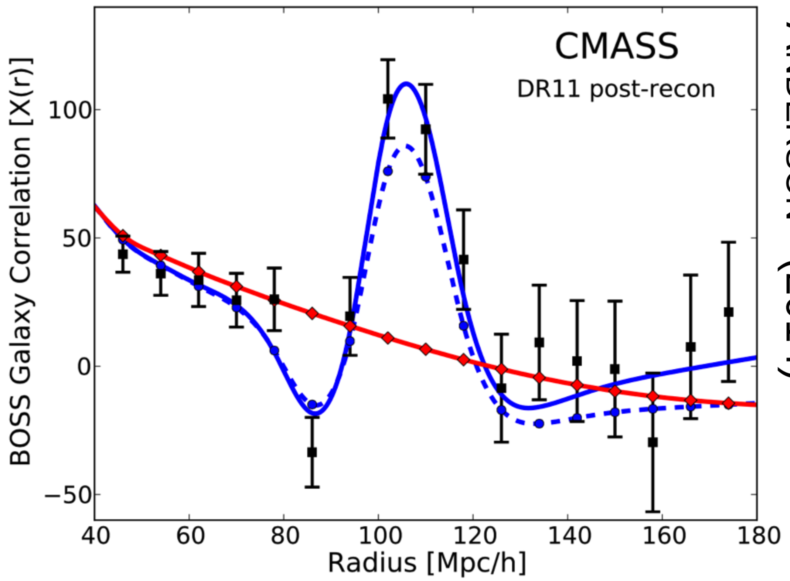
- Photo-z's are potentially a cheap way to measure many galaxy redshifts and hence the BAO peak
- Problem is large errors - for z-errors >1000 km/s, BAO peak is smeared out & H(z) cannot be measured; full information requires z-errors <300 km/s
- To measure $D_A(z)$, a precision of $\sigma_z/(1+z) \lesssim 4\%$ is required; worse precision causes catastrophic cancellation of BAO signal over width of z-shell
- However 3-4% precision yields poor constraints on the BAO per unit volume; a photo-z survey needs ~10x more volume than a spectro-z survey
- Better precision helps, but at z<0.7, spectro-z surveys are already covering large fraction of sky, so photo-z surveys only competitive at higher z's
- Photo-z surveys require stringent calibration and more extensive modeling than spectro-z surveys

Cosmology from 2dFGRS

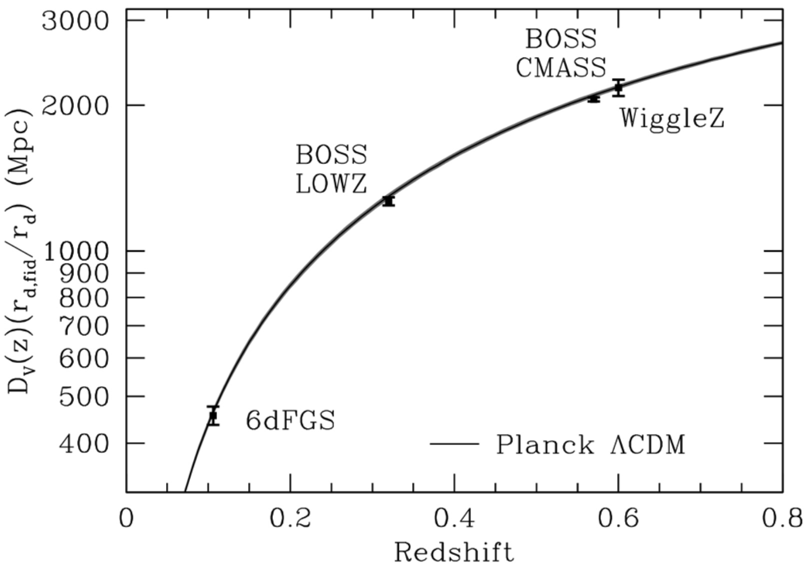
- 2dFGRS measured 221,000 z's over 2000 deg^2
- Large-scale structure of the galaxy distribution precisely mapped on scales of 10^6–10^9 light-years
- The form of large-scale structure is consistent with growth by gravitational instability ⇒ quantum fluctuations from the Big Bang are amplified by gravity to become galaxies, clusters & superclusters
- The total density of all types of matter is $\Omega_M = 0.23$ ⇒ there is only 23% of the matter needed to make a critical-density (i.e. flat = zero-curvature) universe
- The total density in ordinary matter is $\Omega_B = 0.04$ ⇒ baryons are 17% & CDM 83% of the total matter
- Neutrinos make up less than 13% of all matter ⇒ total mass of 3 neutrino species is less than 0.7 eV
- Baryon Acoustic Oscillations detected at 2.5σ

Cosmology from MOS – BAO

- Baryon acoustic oscillations (BAO) provide standard ruler
- BAO result from pressure waves in pre-recombination photon-baryon fluid imprinting the sound horizon scale on the matter distribution
- Galaxy redshift surveys yield angular diameter distances $D_A(z)$ & expansion rates $H(z)$
- BAO map expansion history both along and across the line of sight, probing both Dark Energy and Gravity
- A well-understood, precise tool; main limitation is the scale of the surveys required



Anderson+ (2014)



BAO surveys

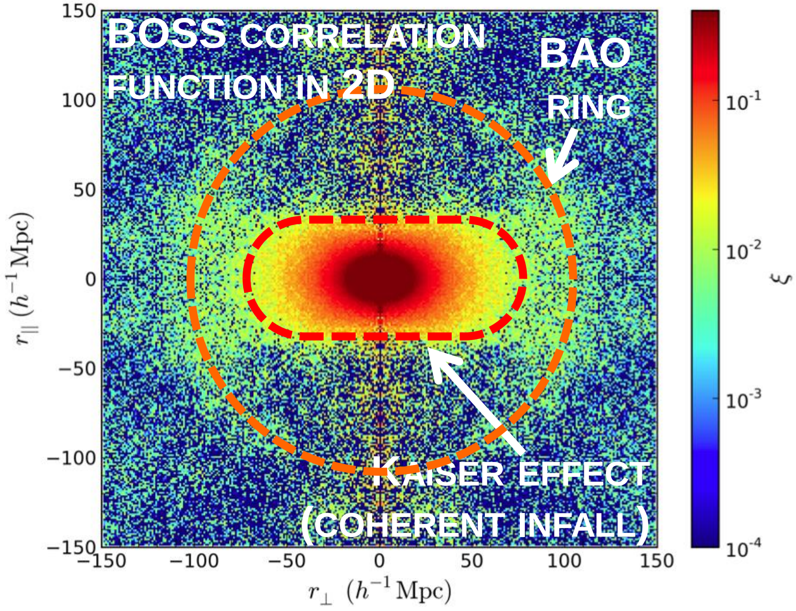
- BAO first detected in galaxy distribution (at 2.5σ) by 2dFGRS and SDSS (Cole+ 2005, Eisenstein+ 2005)
- The WiggleZ survey observed 2x10^5 emission-line galaxies over 800 deg^2 and measured BAO at $0.5<z<1$ with 3.8% precision at $z=0.6$ (Blake+ 2011)
- Beutler+ (2011) used 6dFGS to make a low-redshift ($z<0.1$) BAO distance measurement with 4.5% precision
- Kazin+ (2010) used the full LRG sample from DR7 to measure the galaxy correlation function and obtain a 3.5% measurement of the BAO scale at $z = 0.35$
- Percival+ (2010) used 900,000 galaxies over 9100 deg^2 from the combined 2dFGRS, SDSS DR7/LRG samples to obtain the BAO scale at $z=0.27$ with 2.7% precision
- Padmanabhan+ (2012) showed that density field reconstruction could improve these BAO measures by about a factor of 2

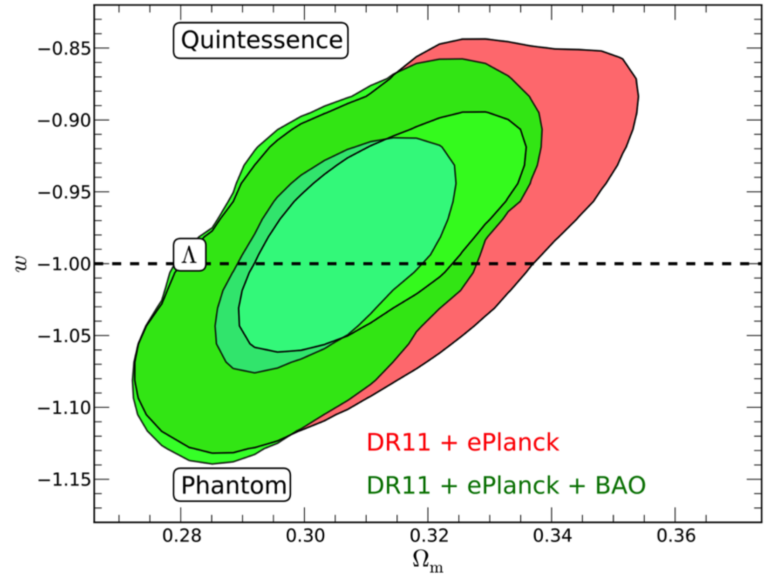
COSMOLOGY FROM MOS - RSD

- REDSHIFT-SPACE DISTORTIONS RESULT FROM PECULIAR MOTIONS DUE TO GRAVITY AND MEASURE THE GROWTH OF STRUCTURE
- RSD MEASURE THE COMBINATION

  $f(z)\sigma_8(z)$

  WHERE $f(z)=\Omega_M(z)^{©}$ AND σ_8 IS FLUCTUATION IN 8 MPC/h SPHERE
- RSD CONSTRAINTS COME FOR FREE WITH ANY LARGE GALAXY z-SURVEY
- MAIN UNCERTAINTY IS THEORETICAL MODELING OF THE NON-LINEAR GRAVITATIONAL EVOLUTION AND NON-LINEAR BIAS; CURRENTLY THIS LIMITS APPLICATION OF RSD METHOD TO CO-MOVING SEPARATIONS r > 10 MPC/h (OR k < 0.2 h/MPC)

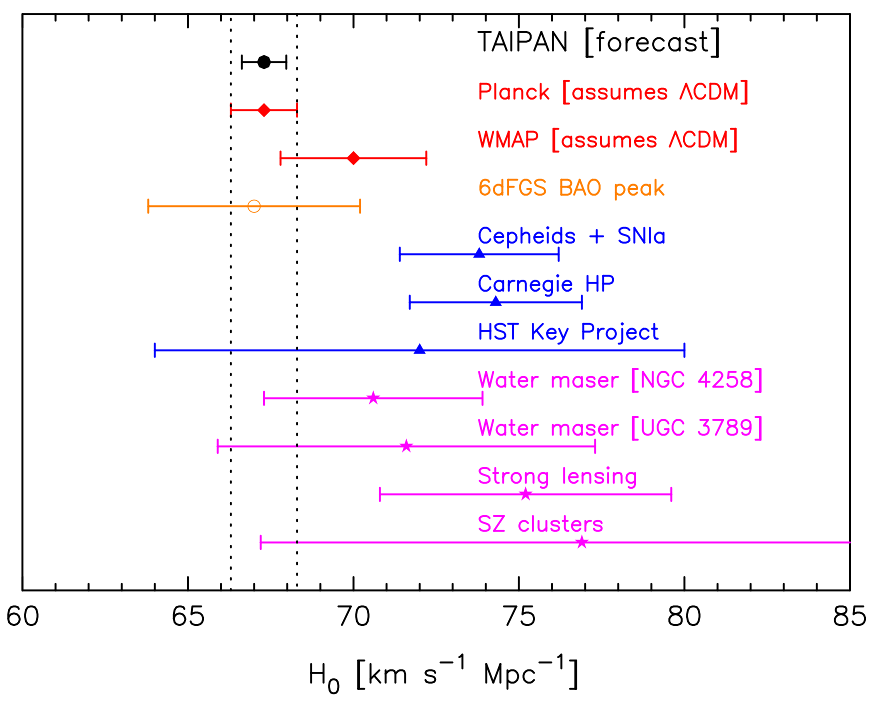


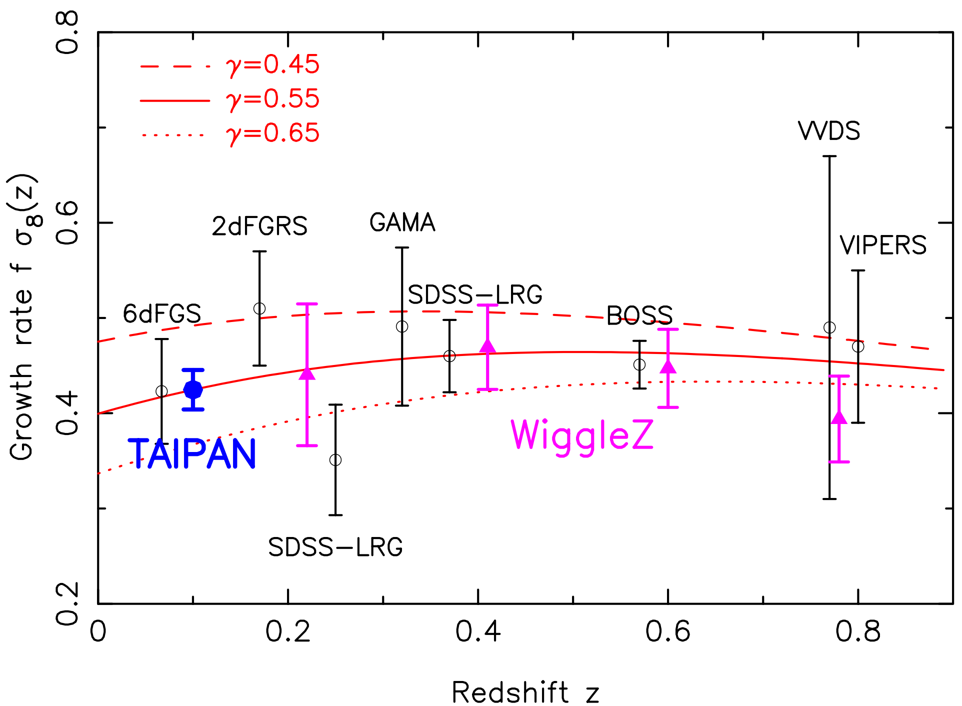


SAMUSHIA+ (2014)

Low-z Cosmology Surveys

- 6dFGS, though smaller than 2dFGRS & SDSS, gives valuable constraints on cosmology at low z, notably a direct measure of H_0 and Growth of Structure
- The Taipan survey (Hopkins talk) will have 4x the sample size & volume of 6dFGS and give H_0 with ~1% precision and growth of structure to 5% at ⟨z⟩≈0.1
- Dark Energy is a late-time (low-redshift) phenomenon!

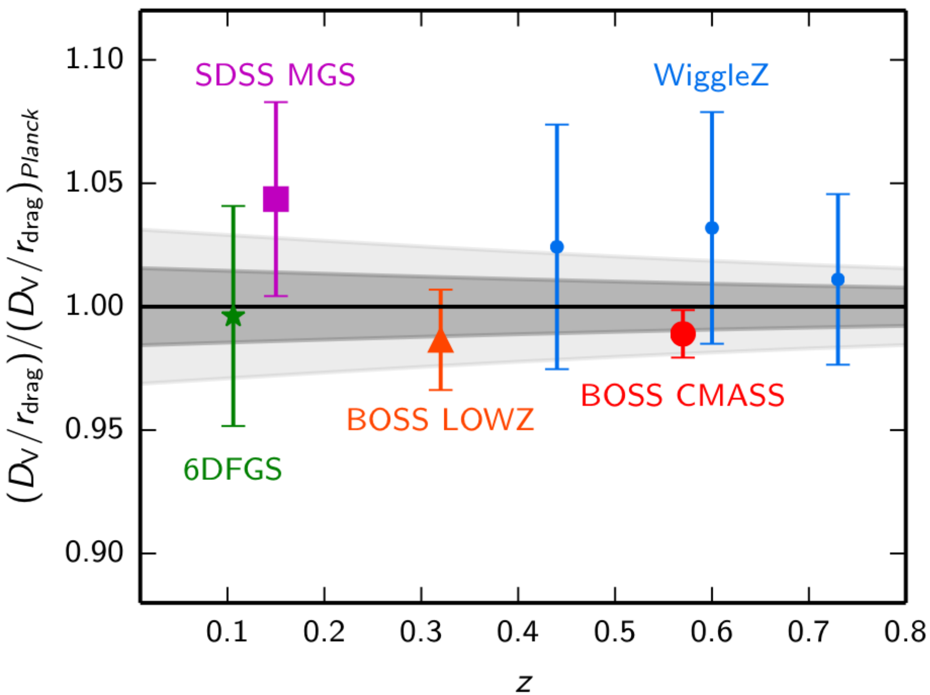




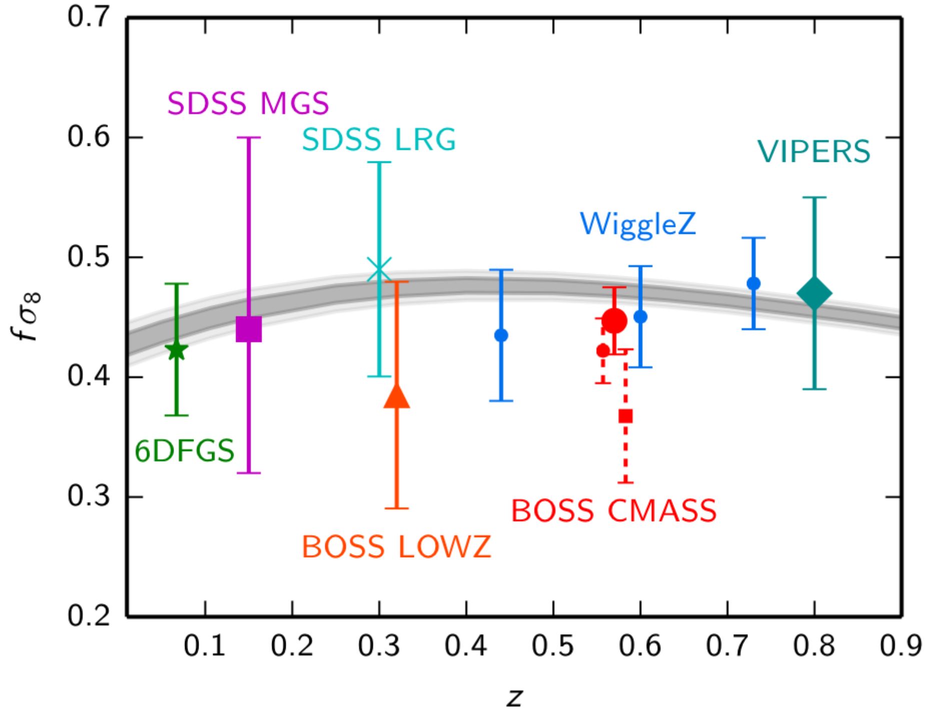
HIGH-Z COSMOLOGY SURVEYS

- REDSHIFT SURVEYS COVERING A RANGE OF EPOCHS (WIGGLEZ, BOSS…) CONSTRAIN THE EVOLUTION OF THE GEOMETRY OF THE UNIVERSE AND THE GROWTH OF STRUCTURE OVER COSMIC TIME

BAO: DEVIATIONS FROM ΛCDM GEOMETRY



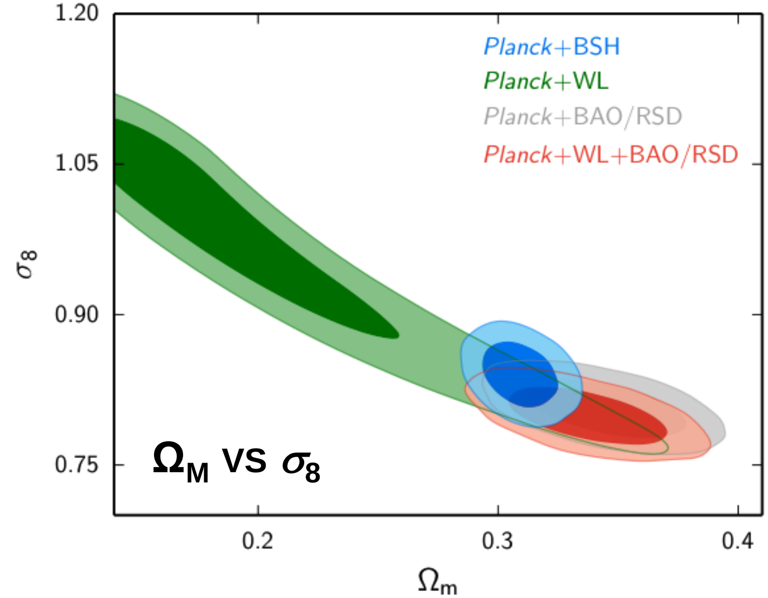
RSD: GROWTH RATE OF STRUCTURE



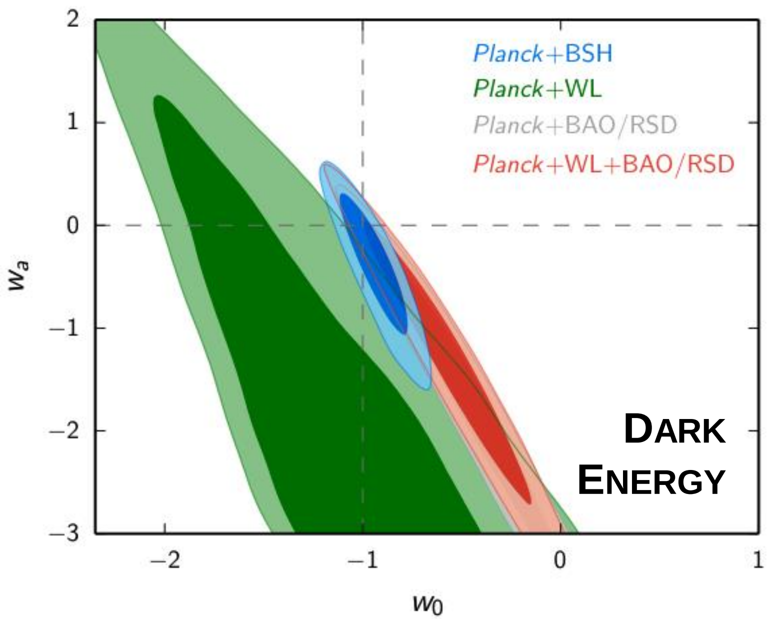
PLANCK COLLABORATION (PAPER XIII, 2015)

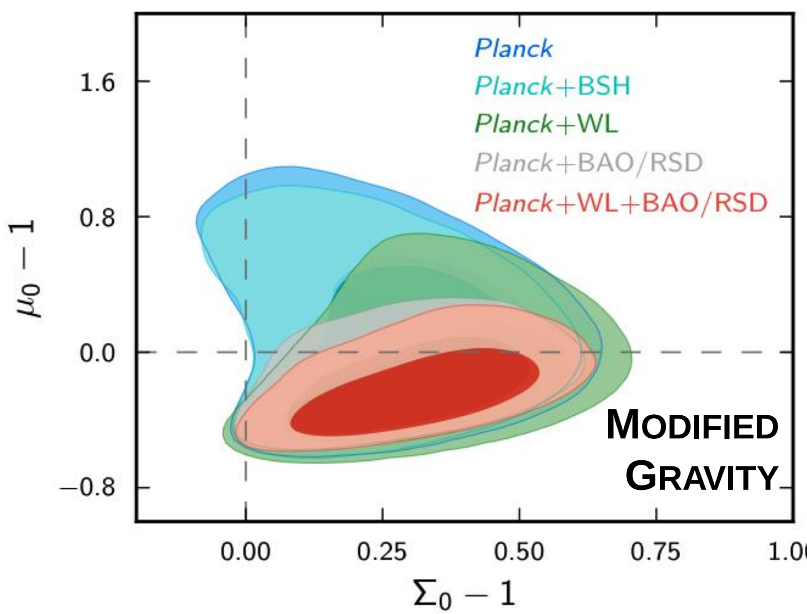
Cosmological Power of MOS

- The added information given by MOS surveys is quantified by the tighter constraints on Dark Energy and Modified Gravity relative to those from the CMB alone



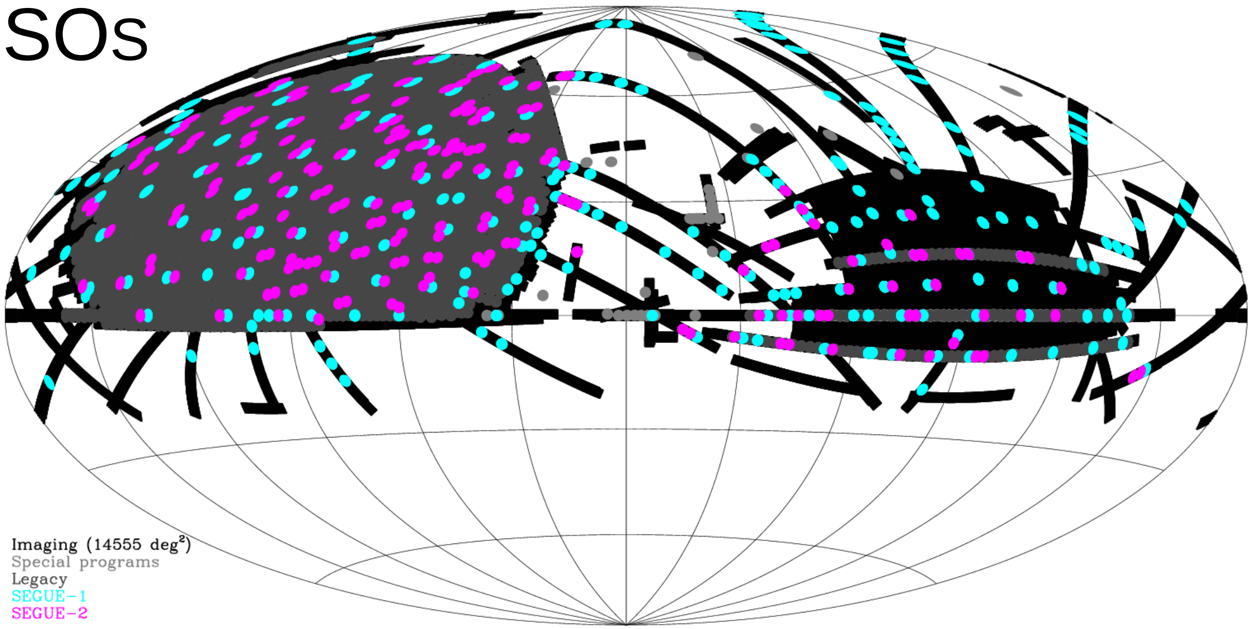
Planck Collaboration (Paper XIV, 2015)



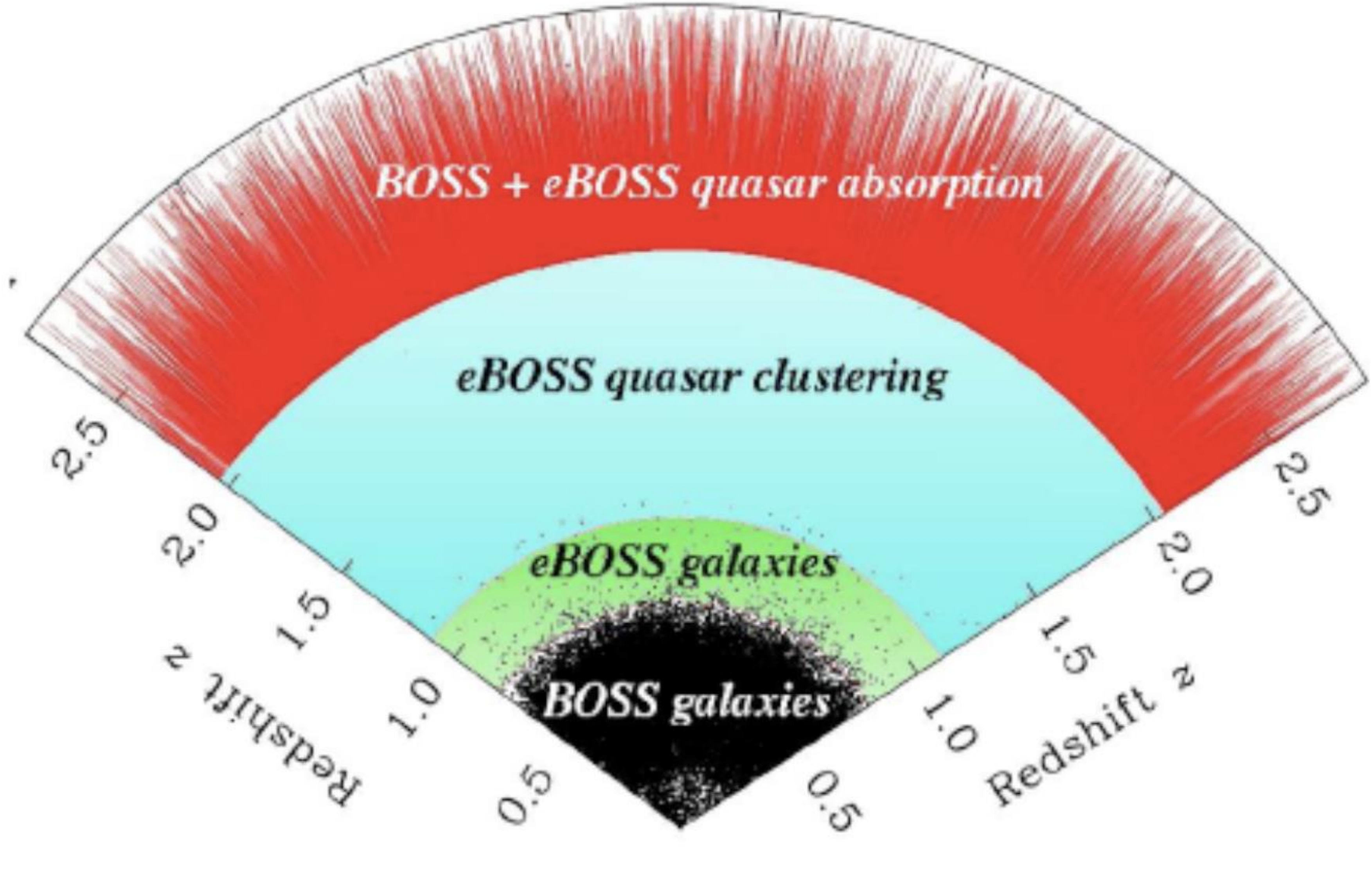


BOSS: THE STATE OF THE ART

- GOAL: MEASURE BAO OVER LARGER VOLUME AND Z-RANGE THAN ALL PREVIOUS Z-SURVEYS
- FINAL DATASET IS SDSS DR12 (TO JULY 2014)
- GALAXIES: 1.4×10^6 AT $z<0.7$ ($i<19.9$) OVER 10^4 DEG^2
  - FORECAST: D_A TO 1.0% AND $H(z)$ TO 1.8% AND 1.7% AT $z=0.3$ AND $z=0.57$
- Lyα: 1.6×10^5 QSOS WITH $g<22$ AT $2.15<z<3.5$
  - FORECAST: OVERALL DILATION FACTOR TO 1.9% AT $z<2.5$



BOSS AND eBOSS

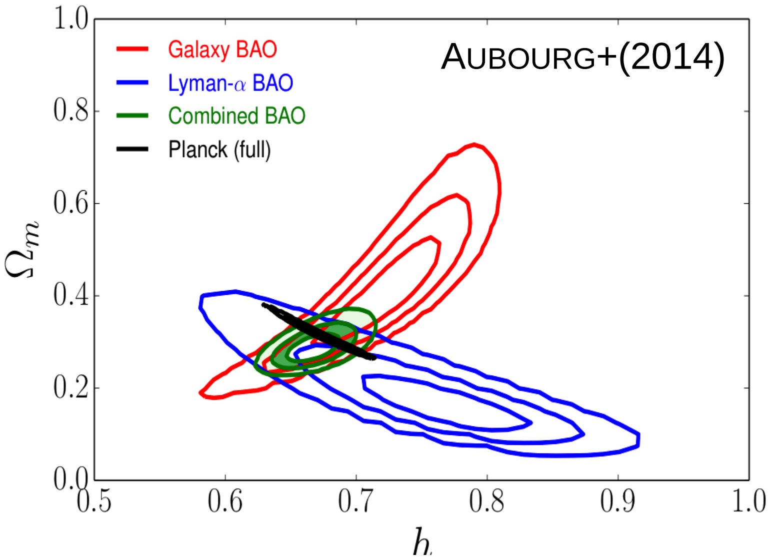


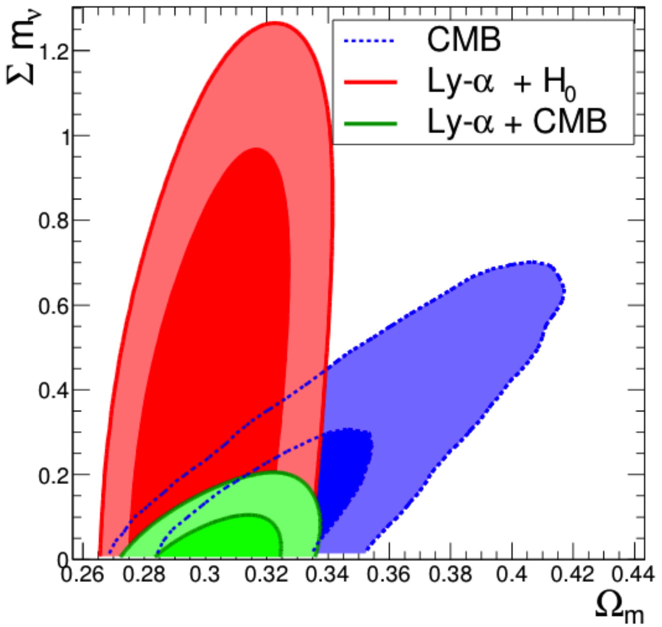
BOSS: THE STATE OF THE ART

- BOSS DETECTS BAO FEATURE AT 7σ IN GALAXIES AND 5σ IN Lyα FOREST
- BAO ALONE YIELD A HIGH CONFIDENCE DETECTION OF DARK ENERGY AND, WITH THE CMB ACOUSTIC SCALE, BAO IMPLY A NEARLY FLAT UNIVERSE
- BAO+CMB+SN DATA JOINTLY GIVE $H_0 = 67.3 \pm 1.1$ KM/S/MPC (1.7%) ROBUST TO ASSUMPTIONS ABOUT DARK ENERGY OR SPACE CURVATURE
- FOR CONSTANT DARK ENERGY (Λ), BAO+CMB+SN YIELDS

$$\Omega_M = 0.301 \pm 0.008 \quad (2.7\%)$$
$$\Omega_K = -0.003 \pm 0.003$$

- FOR EVOLVING FORMS DARK ENERGY, BAO+CMB+SN DATA ARE ALWAYS CONSISTENT WITH FLAT ΛCDM AT ~1σ
- BAO+PLANCK-WL GIVES A SUMMED MASS OF NEUTRINOS $\Sigma M_\nu < 0.25$ eV

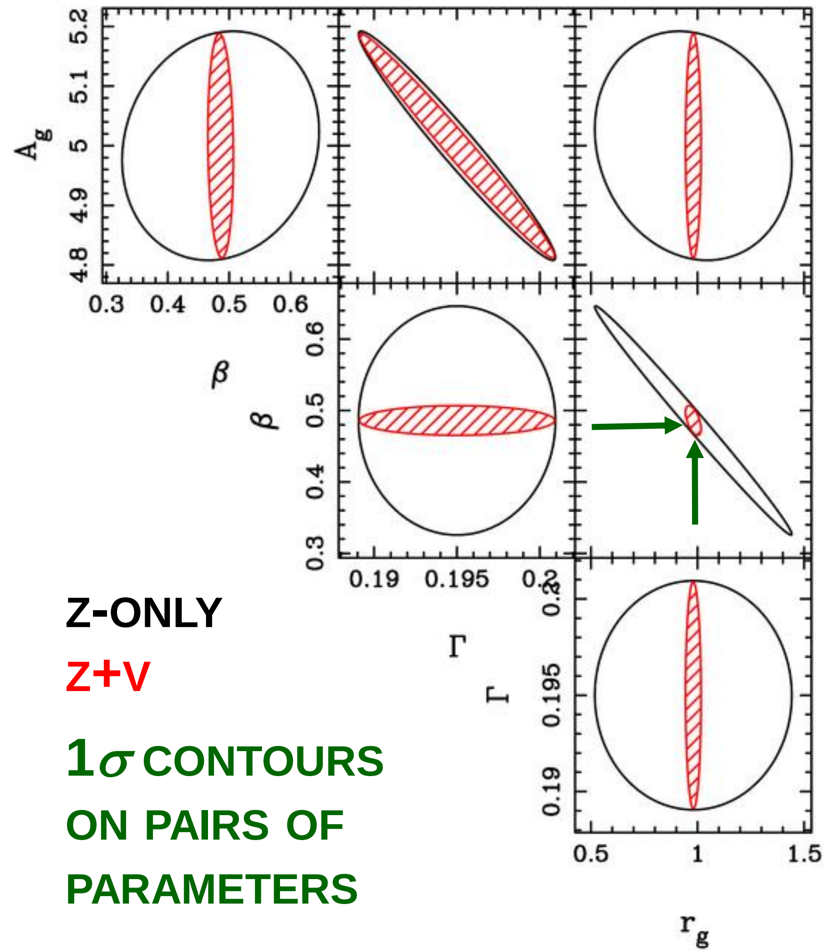




PALANQUE-DELABROUILLE+ (2014)

COSMOLOGY - PECULIAR VELOCITIES

- MOS COSMOLOGY IS NOT JUST ABOUT REDSHIFTS!
- PECULIAR VELOCITY SURVEYS (V-SURVEYS) CAN PROVIDE ADDITIONAL INFORMATION REMOVING SOME DEGENERACIES INTRINSIC TO Z-SURVEYS (E.G. BETWEEN β AND r_g)
- V-SURVEYS ARE NECESSARILY LOW-REDSHIFT DUE TO FIXED FRACTIONAL DISTANCE ERRORS
- DISTANCE ERRORS ARE TYPICALLY SIGNIFICANT (E.G. 20-25% FOR TF AND FP, BUT 5-8% FOR SNE)
- 6DFGRS IS THE CURRENT STATE-OF-THE-ART Z+V-SURVEY:
  - 125,000 REDSHIFTS AND 9000 PECULIAR VELOCITIES (USING FUNDAMENTAL PLANE DISTANCES FOR EARLY-TYPE GALAXIES)
  - V-SURVEY COVERS 17000 DEG^2 TO DEPTH OF ~16000 KM/S



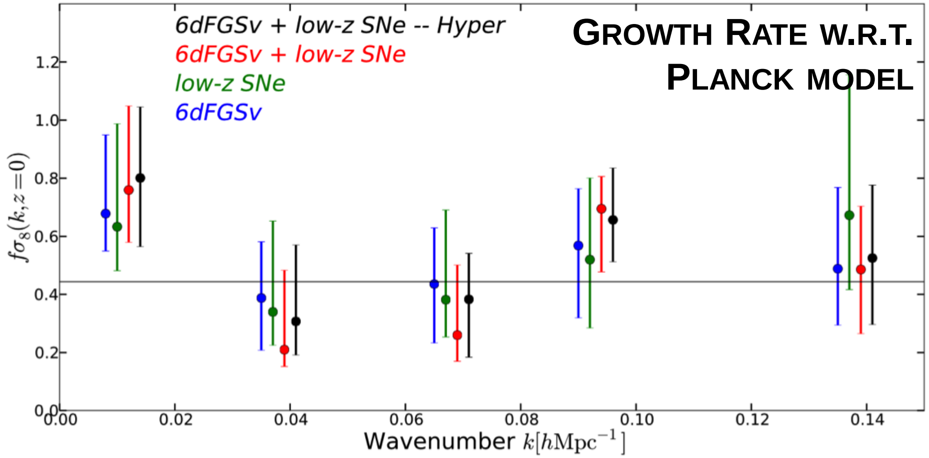
Z-ONLY

Z+V

1σ CONTOURS ON PAIRS OF PARAMETERS

V-survey Cosmology

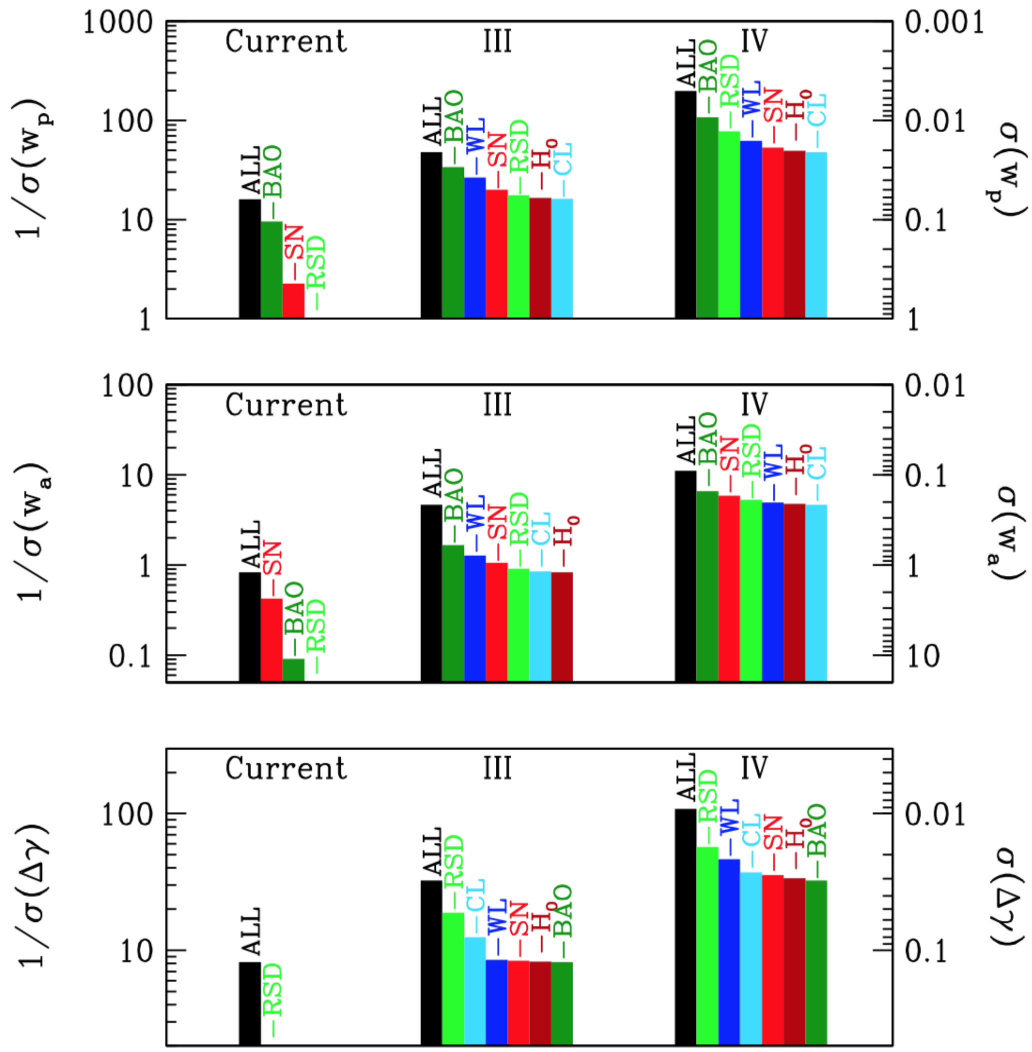
- Johnson+ (2014) use the power spectrum of the 6dFGS peculiar velocities to obtain first scale-dependent measurements of the growth rate of structure $f\sigma_8$ (in combination with z<0.07 SNe)
- Measured the growth rate in Δk=0.03 h/Mpc bins to ~35% precision, incl. a measurement on scales >300 h/Mpc, the largest-scale measurement of the growth rate to date



- No evidence for a scale dependence in growth rate or variation from predictions of Planck ΛCDM model
- Combining all scales, the growth rate at z=0 is measured with ~ 15% precision, independent of galaxy bias & in good agreement with RSD growth rate measurements from 6dFGS z-survey
- Future peculiar velocity surveys will allow us to understand in detail the growth of structure in the low-redshift universe, providing strong constraints on the nature of dark energy

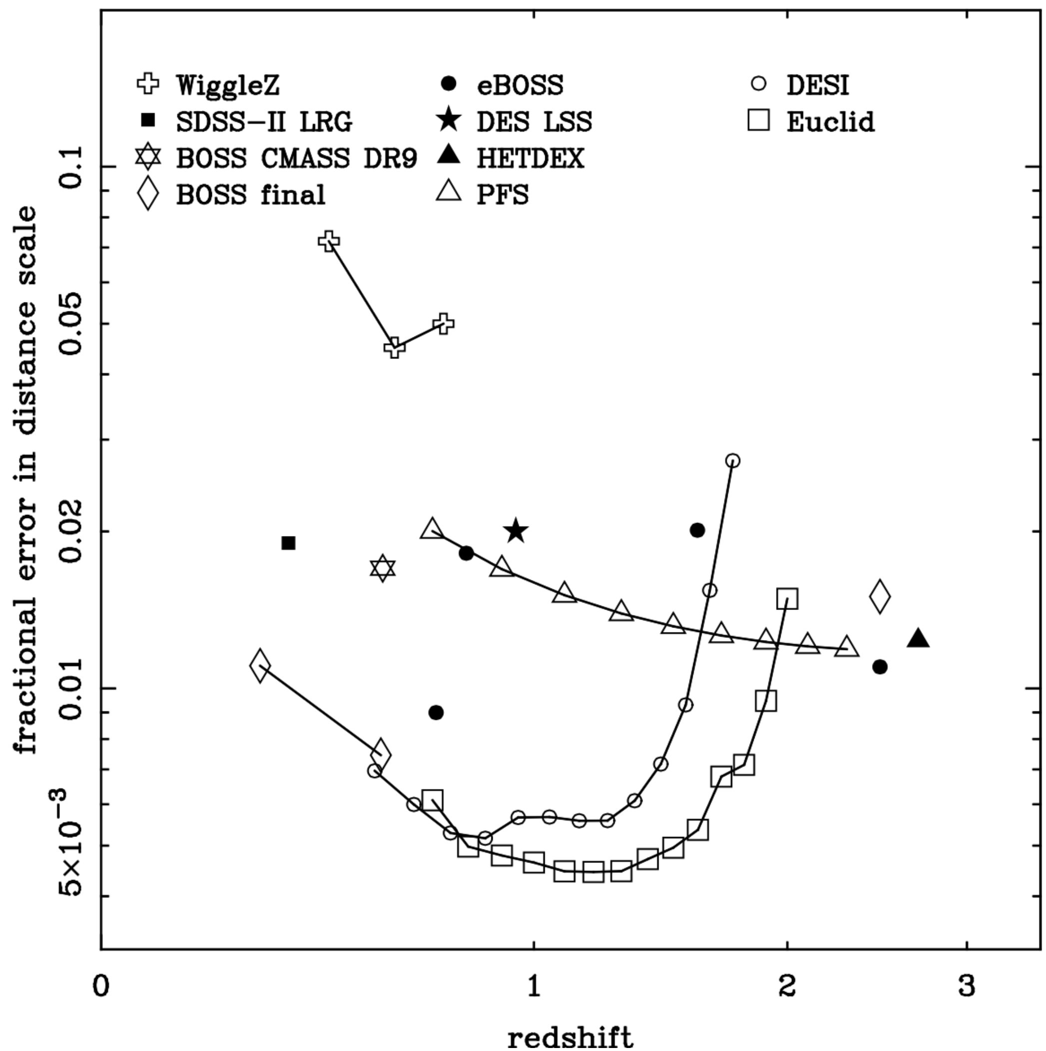
Dark Energy – future progress

- All observations to date of the cosmic expansion history and the growth of structure are consistent with a flat ΛCDM + GR model with $\Omega_M \approx 0.3$ and $\Omega_\Lambda \approx 0.7$
- Z-survey methods (BAO, RSD) are expected in future to provide 10x better constraints on the Dark Energy equation of state



CONSTRAINTS FROM MOS SURVEYS

- FISHER MATRIX PREDICTIONS FOR PRECISION OF BAO DISTANCE SCALE MEASUREMENTS AS A FUNCTION OF REDSHIFT
- THE BOSS SURVEY ACHIEVES ~2% FOR Z<1 AND AT Z~2.5
- THE DESI & EUCLID SURVEYS WILL ACHIEVE 0.5-1% OUT TO Z=2



PERCIVAL (2013)

MOS Cosmology in 2025

- What will MOS cosmology look like in 2025? Some safe predictions…
  1. Redshift surveys exist totaling a few x 10^7 galaxies out to z~1.7 and a few x 10^6 galaxies/QSOs out to z~3
  2. Peculiar velocity surveys (optical and HI) exist totaling >10^5 galaxies in the nearby universe
  3. LSST provides ultimate target list for MOS surveys; how can we fully exploit this? Need dedicated 8m MOS!
  4. A common federated database system has emerged from a heterogeneous set of surveys and software
  5. Many more papers are based on archival MOS spectra and databases than on fresh observations
  6. 'Data Scientists' outnumber 'Observers' (and have more kudos and better career prospects)
  7. Team leaders are still complaining that science outputs from their surveys are person-/brain-power-limited

Future MOS Instruments

- Every self-respecting general-purpose 4m or 8m-class telescope needs MOS capability
- MOS is expanding in new directions: not just high-multiplex but also high-resolution and multi-IFUs (& eventually MOAO multi-IFUs)
- In the ELT era, most 8m-class telescopes will have a MOS instrument of some variety as their cutting-edge facility
- GMT to have highly versatile MOS/multi-IFU capability provided by the MANIFEST facility
  - Coupled to large optical/NIR spectrographs (both medium and high resolution)
  - AΩ = 25m aperture x 20 arcmin diameter field
  - Operating in natural seeing and GLAO modes

In Memoriam

This talk is dedicated to

Professor Peter McGregor

A fine astronomer, a superb instrumentalist

and a wonderful colleague

at the Australian National University

who passed away 5 March 2015