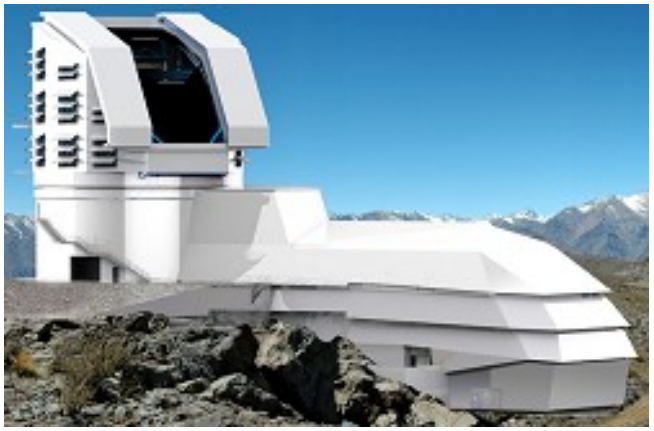
Observational Cosmology II: CMB and LSS surveys



Instituto de Física Teórica UAM-CSIC

Savvas Nesseris

IFT/UAM-CSIC, Madrid, Spain

excelencia Campus Internacional UAM+CSIC

Main points of the lecture

- Why do we need surveys (history & motivation)
- How to design a survey (requirements and steps)
- CMB surveys (COBE, WMAP, Planck, Litebird)
- LSS surveys (2dF, 6dF, SDSS/BOSS, Wigglez, DES, Euclid, LSST)
- Summary

Surveys in astronomy

1) A survey is a systematic observation and cataloging of a set of objects (stars etc). First star catalog in history by Hipparchus (190-120BC) in 129BC.

He also :
i) Determined distances and sizes of Moon and Sun!
ii) Discovered the precession of equinoxes.
iii) Measured the length of year to ~6 mins.

2) Hipparchus measured the right ascension, declination (equatorial), longitude (ecliptical) of 850 stars. Catalog lost, but Roman copy (150AD) of statue showing survived!

Surveys in astronomy

3) Due to Weber's law we measure magnitudes: all (most?) senses are logarithmic!

i) Sight → magnitudes (mag) → $m = -2.5 \log_{10}\left(\frac{F}{F_0}\right)$

ii) Sound → Decibels (dB) → $L_P = 10 \log_{10}\left(\frac{P}{P_0}\right) dB$

iii) Taste → Scoville scale (pungency) → $S_c \sim \log_{10}(\rho_{capsaicin})$

iv) Sense of weight (S=sense, I=intensity of stimulus):

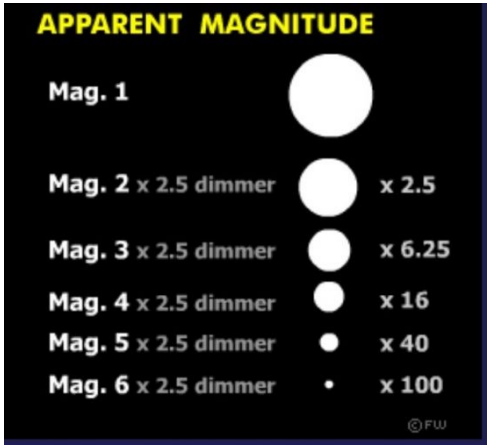
$S \sim \ln(I) \rightarrow \delta S \sim \frac{\delta I}{I}$ ⇒ $I \sim m\,g \rightarrow \delta I \sim \delta m\,g \rightarrow \delta S \sim \frac{\delta m}{m}$

- m=100gr, δm=100gr → δS~1
- m=2kg, δm=100gr → δS~0.05!

Surveys in astronomy

4) Curse of Hipparchus: catalog was in terms of magnitudes:

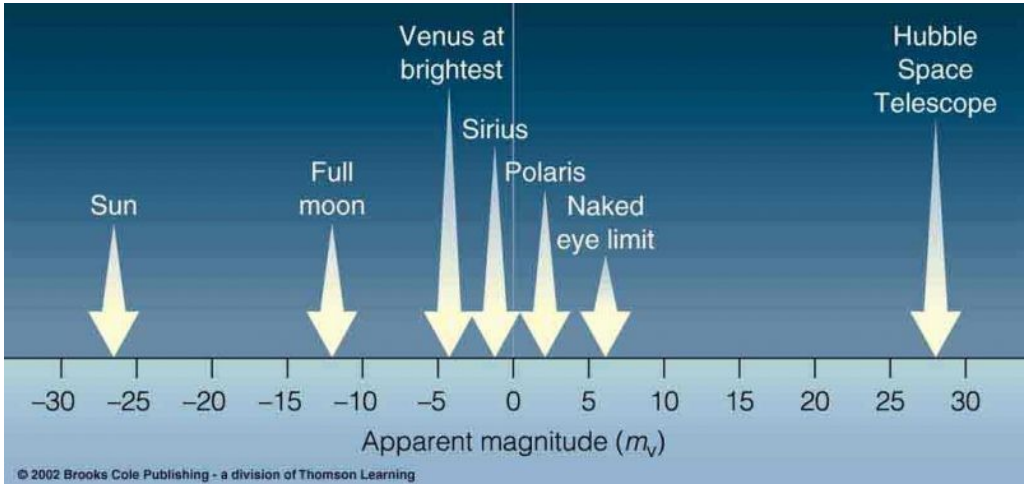
Brightest was first magnitude (m=1)
Faintest were sixth magnitude (m=6)
Definition $\Delta m=5 \rightarrow 100\ \Delta$ (brightness)



Weber's law

$$m = -2.5 \log_{10}\left(\frac{F}{F_0}\right)$$

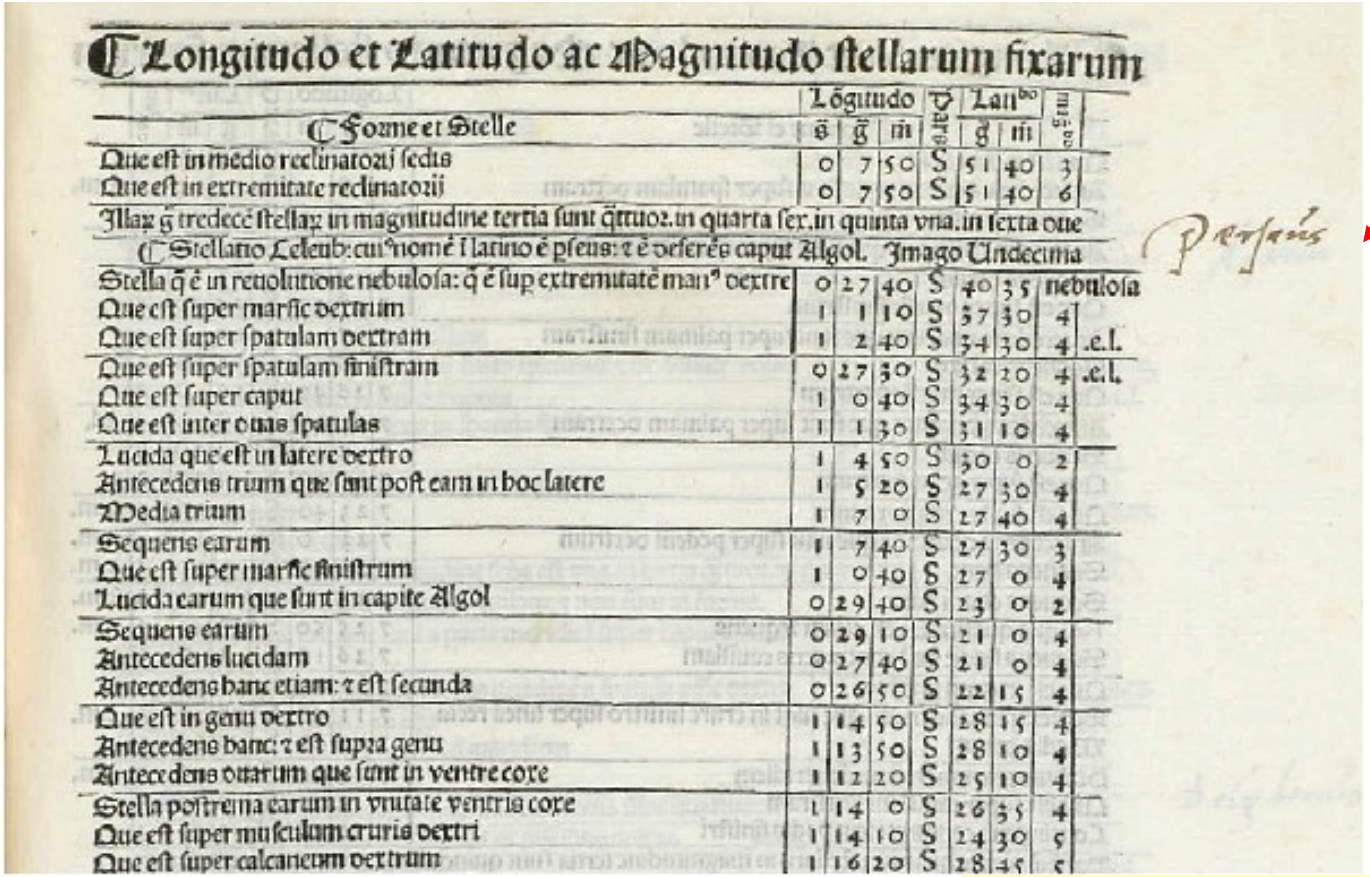
Match with Hipparchus: 100^(1/5)~2.5



Surveys in astronomy

5) Ptolemy (90-186AD) published his own catalog in Almagest with 1022 stars!
Golden standard for more than 8 centuries.

First printed edition ca 1515.
Downloadable on the web, google for it!



Longitudo et Latitudo ac Magnitudo stellarum fixarum

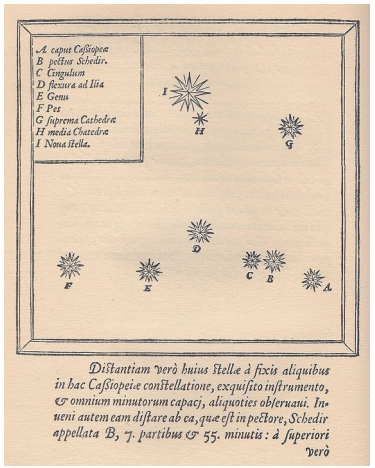
Forme et Stelle	Logitudo s	g	m	Pars	Latᵒ g	m	Mag.
Que est in medio reclinatorij sedis	0	7	50	S	51	40	3
Que est in extremitate reclinatorij	0	7	50	S	51	40	6
Illaꝝ ḡ tredecē stellaꝝ in magnitudine tertia sunt q̄tuor. in quarta sex. in quinta vna. in sexta due							
Stellarum Celeub: cui⁹ nomē Latino ē pseus: et ē veterēs caput Algol. Imago Undecima							
Stella q̄ ē in reuolutione nebulosa: q̄ ē sup extremitatē manꝰ dextre	0	27	40	S	40	35	nebulosa
Que est super marsic dextrum	1	1	10	S	37	30	4
Que est super spatulam dextram	1	2	40	S	34	30	4 .e.l.
Que est super spatulam sinistram	0	27	30	S	32	20	4 .e.l.
Que est super caput	1	0	40	S	34	30	4
Que est inter duas spatulas	1	1	30	S	31	10	4
Lucida que est in latere dextro	1	4	50	S	30	0	2
Antecedens trium que sunt post eam in hoc latere	1	5	20	S	27	30	4
Media trium	1	7	0	S	27	40	4
Sequens earum	1	7	40	S	27	30	3
Que est super marsic sinistrum	1	0	40	S	27	0	4
Lucida earum que sunt in capite Algol	0	29	40	S	23	0	2
Sequens earum	0	29	10	S	21	0	4
Antecedens lucidam	0	27	40	S	21	0	4
Antecedens hanc etiam: et est secunda	0	26	50	S	22	15	4
Que est in genu dextro	1	14	50	S	28	15	4
Antecedens hanc: et est supra genu	1	13	50	S	28	10	4
Antecedens duarum que sunt in ventre coxe	1	12	20	S	25	10	4
Stella postrema earum in virtute ventris coxe	1	14	0	S	26	35	4
Que est super musculum cruris dextri	1	14	10	S	24	30	5
Que est super calcaneum dextrum	1	16	20	S	28	45	5

Persaus

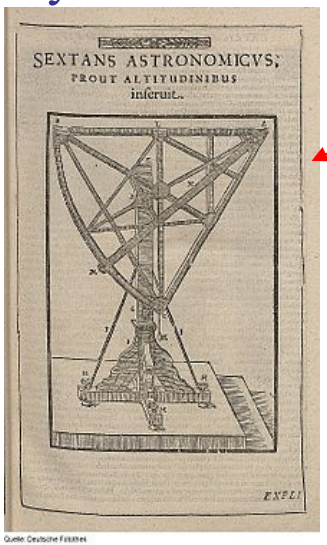
https://www.johnpratt.com/items/astronomy/ptolemy_stars.html
http://www.ianridpath.com/startales/almagest.htm

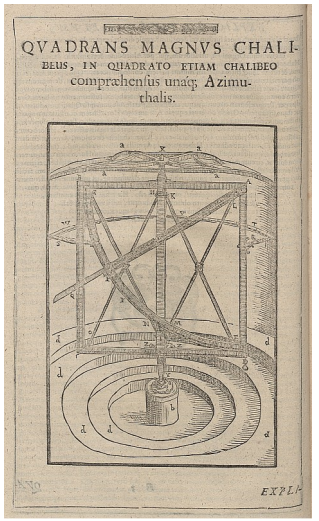
Surveys in astronomy

6) Tycho Brahe (1598AD) ~1000 stars in unprecedented precision (few arcmins).



7) Created very accurate instruments (sextant+quadrant)!





Surveys in astronomy

8) Messier and Hubble:

i) Messier published (1774AD) list of 110 nebulae and star clusters, eg M31=Andromeda galaxy

ii) Hubble (1922) measured distances to nebulae (eg M31) and found were too distant. Also found redshift increases with distance (Hubble's law)

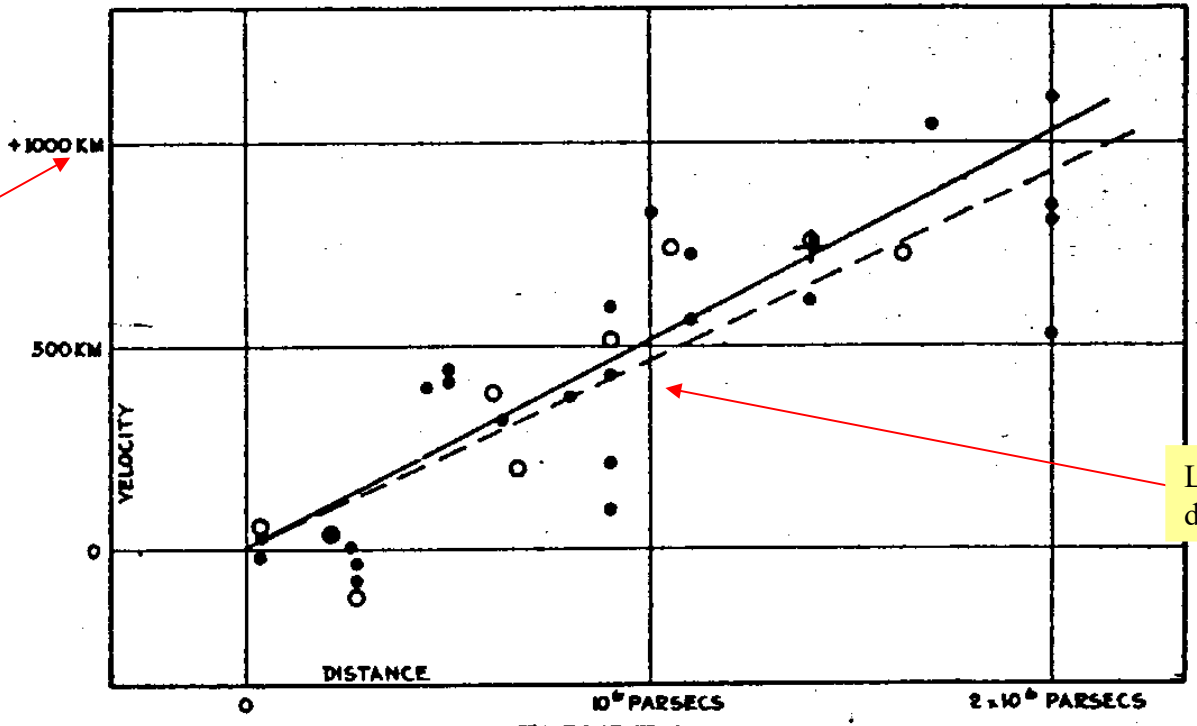


FIGURE 1

Typo!

Linear relationship between distance+velocity (redshift)

Surveys in astronomy

9) Discovery of Large Scale Structure (LSS) by Shapley & Zwicky (1930's)

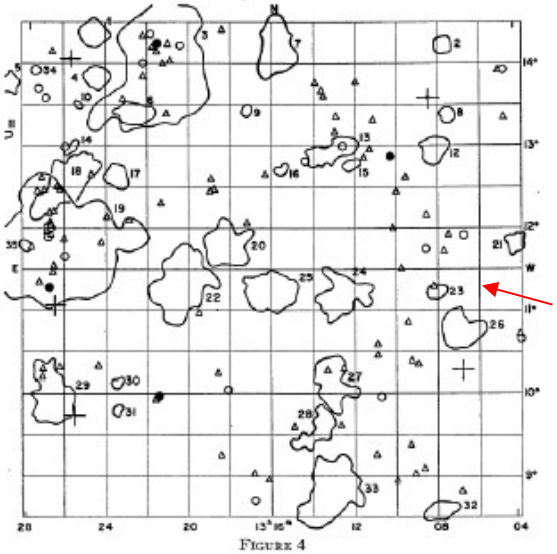
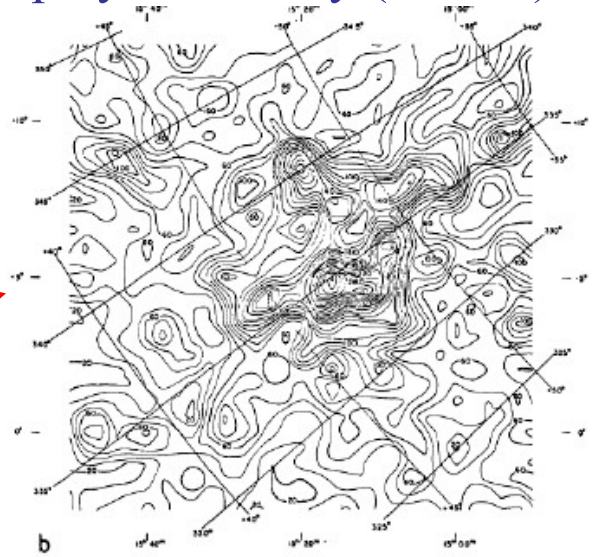
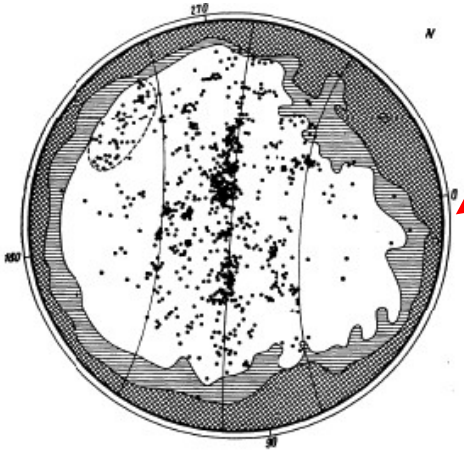


FIGURE 4

Overdensity (left) galaxy counts and density map (right)

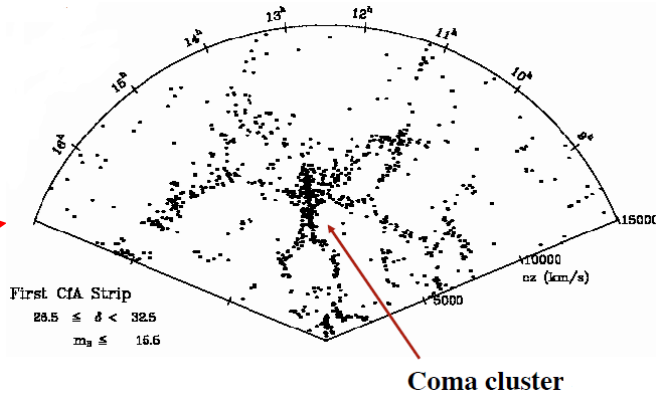


10) First redshift surveys by de Vaucouleurs, then CfA and Arecibo



The Local supercluster (~60Mpc structure)

The Coma supercluster (~100Mpc structure)



A hitchhikers guide to designing a survey

1) Identify science goals & objectives

2) Define survey strategy

3) Quantify performance of the survey

4) Publish proposal making scientific case

5) Request for funding (aka where most proposals fail)

6) Construction phase

7) Data acquisition (the fun begins!)

8) Pipelines and analysis (theory+data)

9) Publish data products and papers

A hitchhikers guide to designing a survey

1) Define science goals/objectives, eg

i) Understanding Dark Energy → measure cosmological parameters w (=-1?), γ (=6/11?).

ii) Testing homogeneity of LSS → measure fractal index D2(r) and correlation function ξ(r).

iii) Assessing accelerating expansion of Universe → measure Hubble parameter H_0 and deceleration parameter q_0.

iv) Is the Universe flat? → Measure location of 1st peak of CMB.

2) What survey strategy can we take?

i) What kinds of objects (galaxies, supernovae, CMB) should we target?

ii) At which redshift should we go? (this affects the instrument design)

iii) Should we survey a wide area at low z or a small area to greater depth (m)?

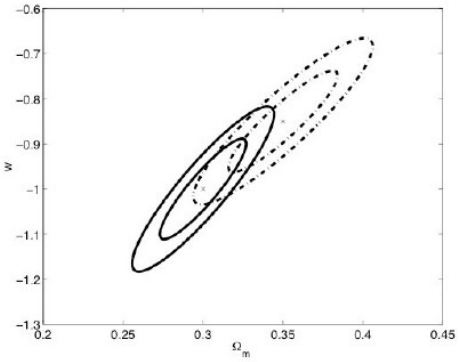
3) How to quantify the performance of the survey?

i) Fisher matrix

Errors ~Fij^-1

$$\ln L(\theta) \approx \ln L(\theta^{ML}) + \tfrac{1}{2}\sum_{ij}(\theta_i - \theta_i^{ML})^t H_{ij}(\theta_j - \theta_j^{ML})$$

$$H_{ij} = \left.\frac{\partial \ln L}{\partial \theta_i}\frac{\partial \ln L}{\partial \theta_j}\right|_{\theta^{ML}} \Rightarrow F_{ij} \equiv \langle H_{ij} \rangle$$



ii) Figure of Merit

(=1/Area of contour)

The higher the better

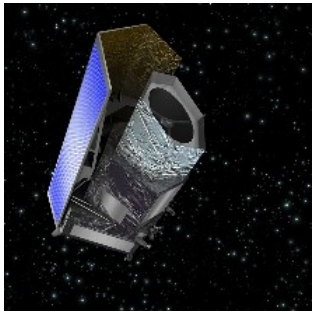
$$\mathrm{Vol}(M) = \int_C d^M a_i \qquad \mathrm{FoM} = \mathrm{Vol}(M)^{-1}$$

$$\Rightarrow \mathrm{FoM}(M) = |F|^{1/2}\frac{\Gamma(M/2+1)}{\pi^{M/2}}(\delta\chi^2)^{-M/2}$$

1210.7652

A hitchhikers guide to designing a survey

4) Publish proposal making scientific case, eg Euclid Definition Study Report.
arXiv: 1110.3193

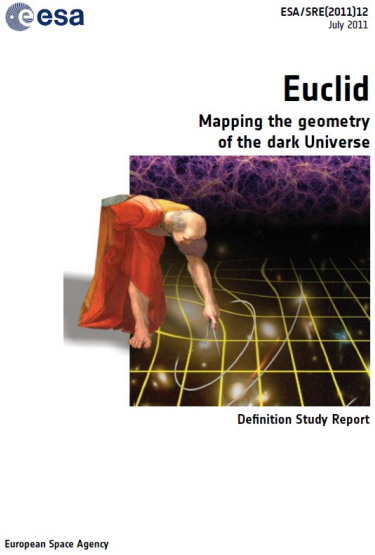


More on Euclid later!

Goals: Map the dark Universe!

Euclid Definition Study (aka Red book) contains info on:

i) Science objectives
ii) Scientific requirements
iii) Payload (instruments)
iv) Mission design
v) Performance
vi) Data handling
vii) Management


esa

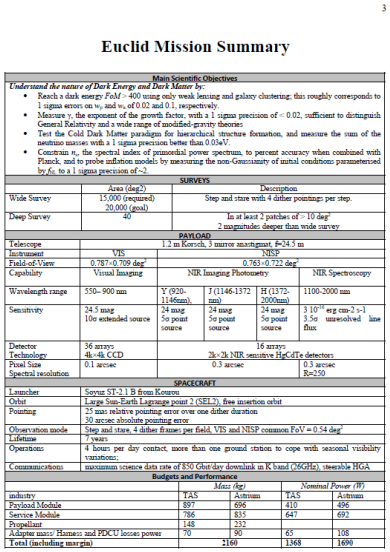
ESA/SRE(2011)12
July 2011

Euclid

Mapping the geometry of the dark Universe

Definition Study Report

European Space Agency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Euclid Mission Summary

Main Scientific Objectives					
Understand the nature of Dark Energy and Dark Matter by:					
• Reach a dark energy *FoM* ~ 400 using only weak lensing and galaxy clustering, this roughly corresponds to 1 sigma errors on w_i and w_a of 0.02 and 0.1, respectively.					
• Measure γ, the exponent of the growth factor, with a 1 sigma precision of < 0.02, sufficient to distinguish General Relativity and a wide range of modified-gravity theories.					
• Test the Cold Dark Matter paradigm for hierarchical structure formation, and measure the sum of the neutrino masses with a 1 sigma precision better than 0.03eV.					
• Constrain n_s, the spectral index of primordial power spectrum, to percent accuracy when combined with Planck, and to probe inflation models by measuring the non-Gaussianity of initial conditions parameterised by f_{NL} to a 1 sigma precision of ~2.					
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				
Budgets and Performance					
	Mass (kg)		*Nominal Power (W)*		
industry	TAS	Astrium	TAS	Astrium	
Payload Module	897	696	410	496	
Service Module	786	835	647	692	
Propellant	148	232			
Adapter mass/ Harness and PDCU losses power	70	90	65	108	
Total (including margin)	2160		1368	1690	

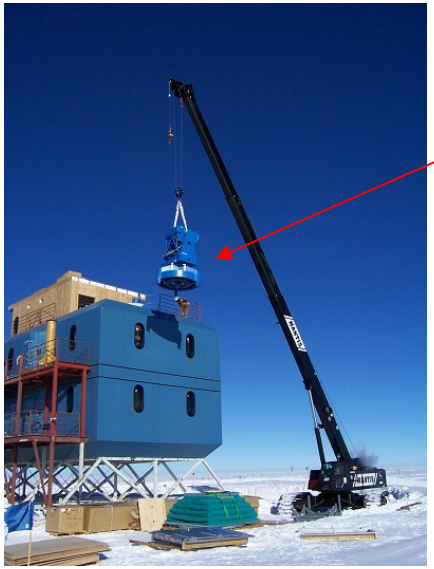
A hitchhikers guide to designing a survey

5) Request for funding: Very difficult step, most proposals fail at this step :(

Proposal for Euclid was submitted to "ESA Cosmic Vision program selection" and approved for funding (2012). Funding also comes from national agencies etc.

NASA has "Decadal Survey" to "...identify and prioritize leading-edge scientific questions and the observations required to answer them." Funding from NSF etc.

6) Construction phase



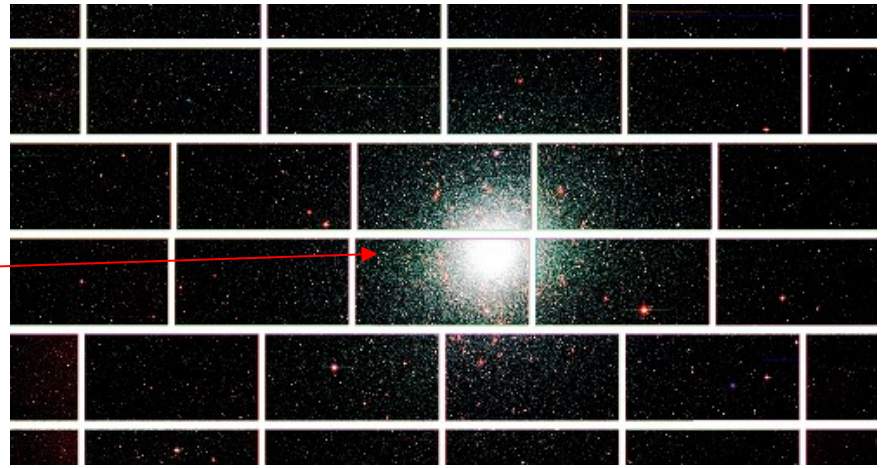
Bicep in South Pole.
Summer (!) of 2006

LSST telescope

A hitchhikers guide to designing a survey

7) Data acquisition (the fun begins!)

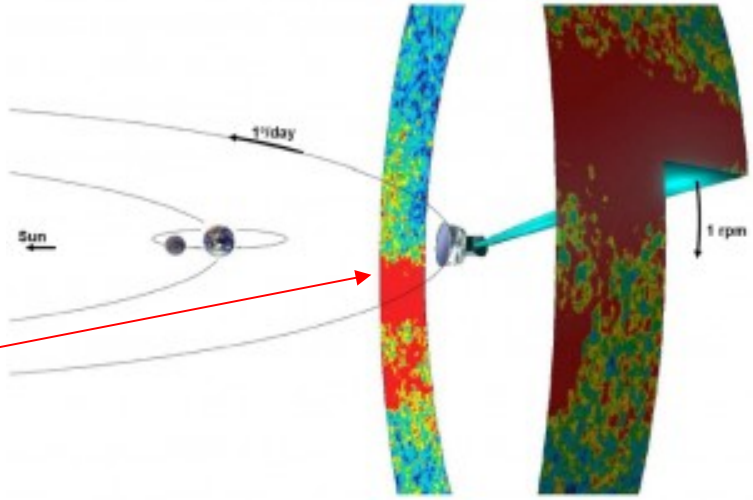
i) First light for DES telescope!



Star cluster 47 Tucanae

Serves as a test to make sure everything is working ok.

ii) Planck satellite taking full sky map



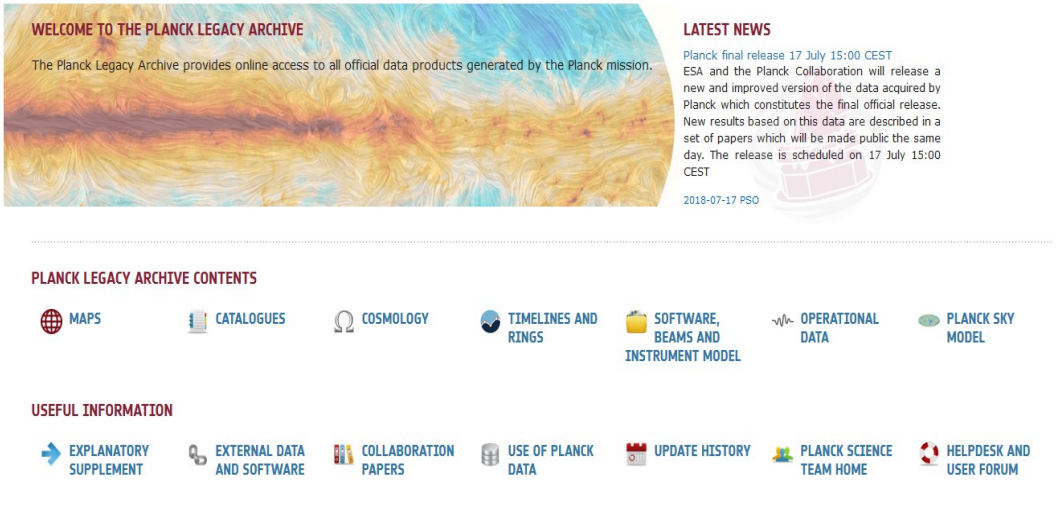
Planck satellite

A hitchhikers guide to designing a survey

8) Pipelines and analysis (theory+data)

i) Store and analyze data
ii) Make likelihoods (the χ^2) to fit data
iii) Other data products and codes

pla.esac.esa.int/pla/



9) Finally, publish papers

i) Provide key results
ii) Communicate science
iii) Credit authors
iv) Scientific Legacy
v) Data product description

https://www.cosmos.esa.int/web/planck/publications

PLANCK 2018 RESULTS

The final release of the 2018 PLANCK results using the full mission data are presented here. These recent results are produced by the Planck Collaboration. The papers are available online, and links to each are provided below. If you use any of these results for presentations, please acknowledge the corresponding paper, ESA/Planck, and the Planck Collaboration. **The Planck Legacy Archive (PLA) contains all public products originating from the Planck mission**.

Title	Authors	Publication
Planck 2018 results. I. Overview, and the cosmological legacy of Planck	Planck Collaboration	Submitted to A&A
Planck 2018 results. II. Low Frequency Instrument data processing	Planck Collaboration	Accepted by A&A
Planck 2018 results. III. High Frequency Instrument data processing and frequency maps	Planck Collaboration	Accepted by A&A
Planck 2018 results. IV. Diffuse component separation	Planck Collaboration	Submitted to A&A
Planck 2018 results. VI. Cosmological parameters	Planck Collaboration	Submitted to A&A
Planck 2018 results. VIII. Gravitational lensing	Planck Collaboration	Submitted to A&A
Planck 2018 results. X. Constraints on inflation	Planck Collaboration	Submitted to A&A
Planck 2018 results. XI. Polarized dust foregrounds	Planck Collaboration	Accepted by A&A
Planck 2018 results. XII. Galactic astrophysics using polarized dust emission	Planck Collaboration	Submitted to A&A

Note: papers V (Legacy Power Spectra and Likelihoods), VII (Isotropy and Statistics), and IX (Constraints on primordial non-Gaussianity) will be made public at a later time.

CMB surveys (past, current, future)

1) COBE:
Cosmic Background explorer (1989-1993)

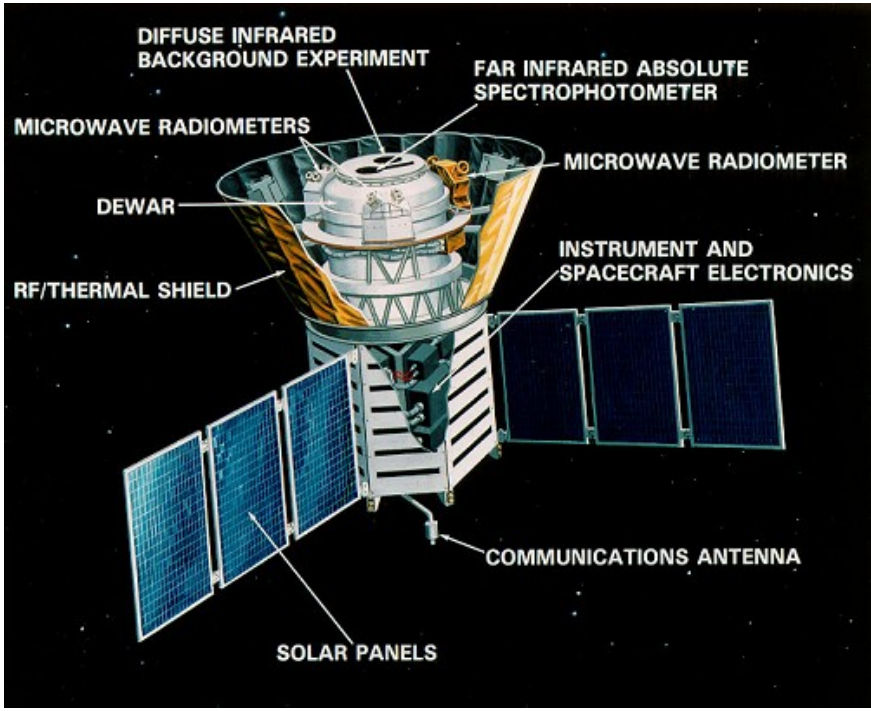
lambda.gsfc.nasa.gov/product/cobe

Instruments:

i) Differential Microwave Radiometer
For differential measurements of the CMB

ii) Far-InfraRed Absolute Spectrophotometer
To measure the CMB spectrum

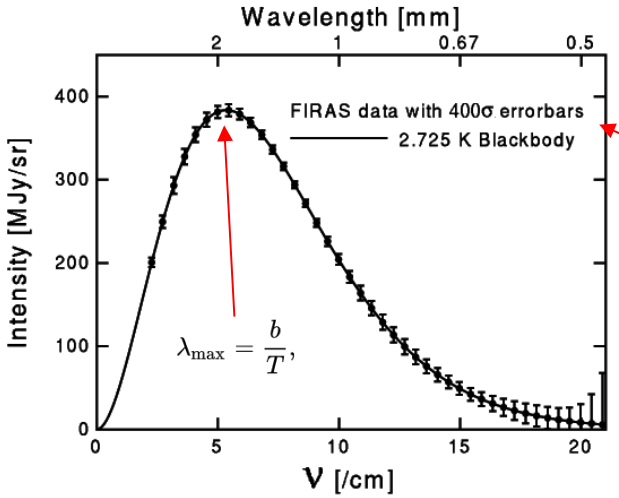
iii) Diffuse Infrared Background Experiment
To measure dust emission in Galaxy



CMB surveys (past, current, future)

Key findings:

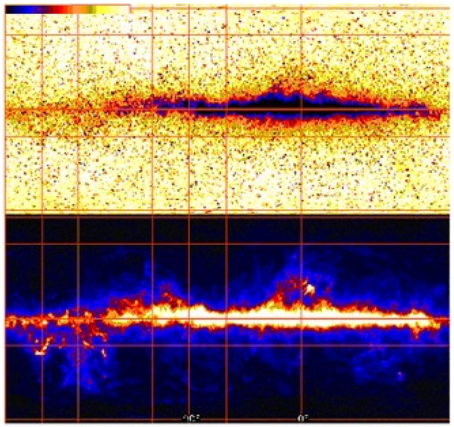
i) Black-body spectrum of the CMB



Errors x 400!!!

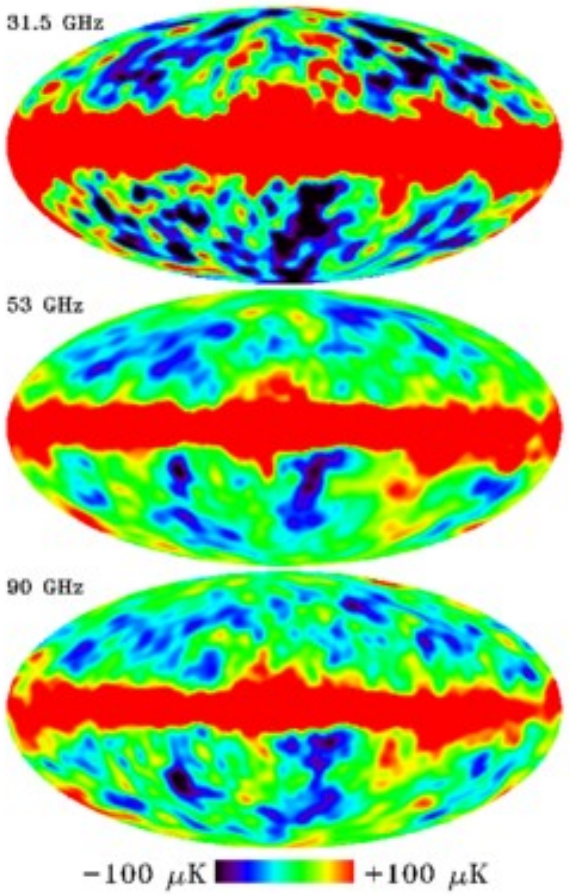
$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{k_B T}} - 1}$$

ii) Infrared background and galactic disk (effect of dust important!)

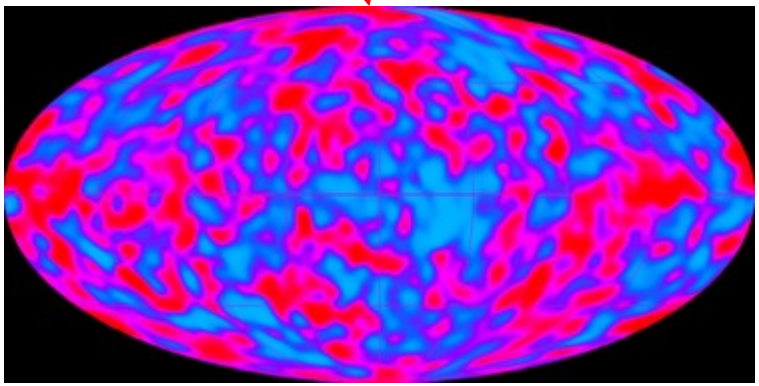


CMB surveys (past, current, future)

iii) CMB anisotropies (3 channels at 31.5GHz, 53GHz and 90 GHz)
→ T~2.7K and ΔT/T~10^-5



First anisotropy map!

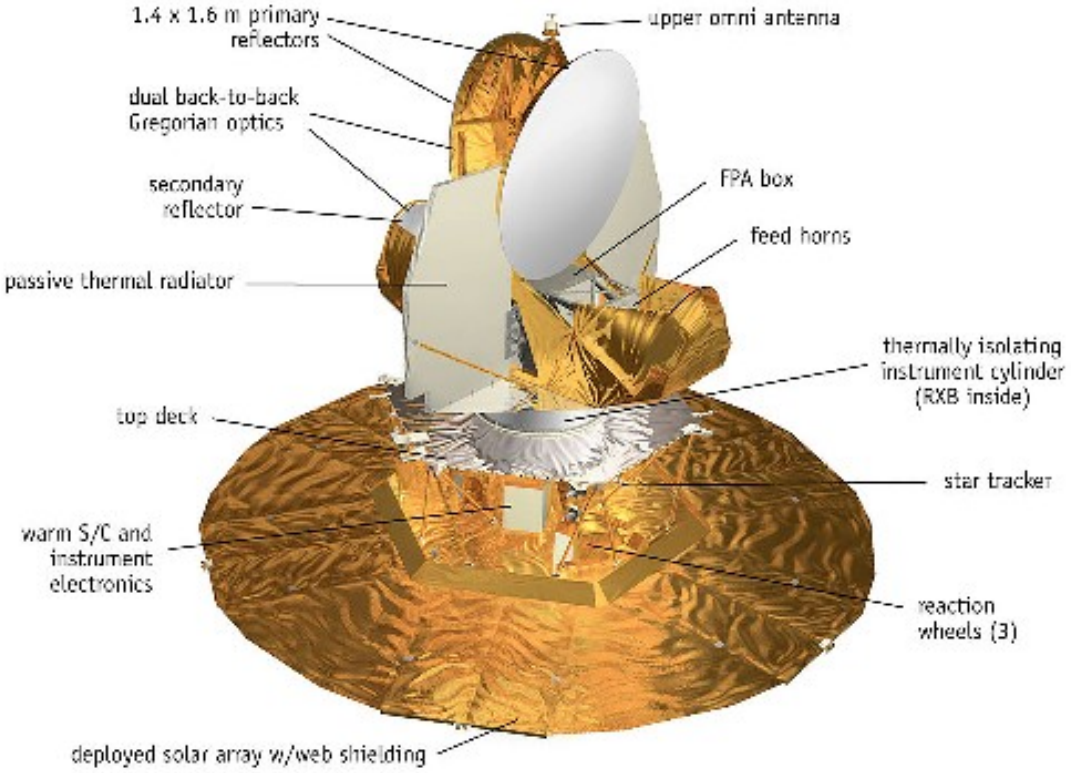


Nobel 2006!

CMB surveys (past, current, future)

2) WMAP (specifications, run, data, results)
Wilkinson Microwave Anisotropy Probe (2001-2010)

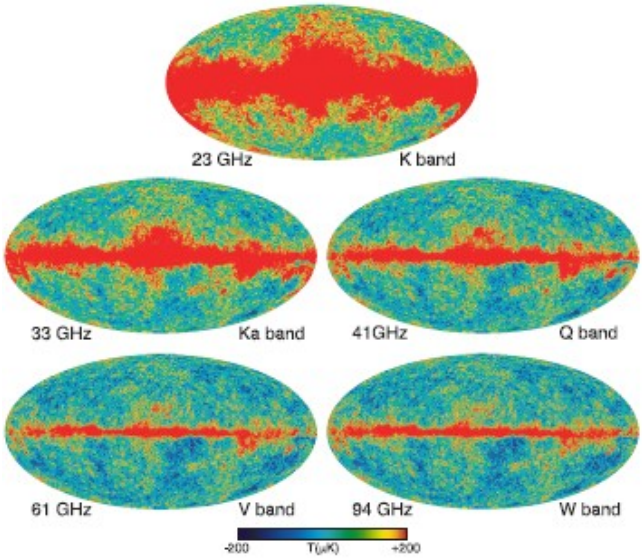
Instruments/probe components
i) Passive coolers (~90K)
ii) 5m Solar panel array
iii) Differential radiometers
iv) Low noise amplifiers
v) 5 frequency bands
(23, 33, 41, 61, 94 GHz)
vi) Reaction wheels, gyroscopes

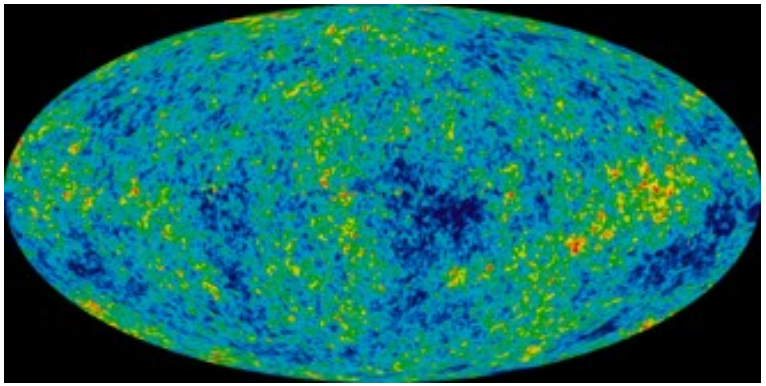


CMB surveys (past, current, future)

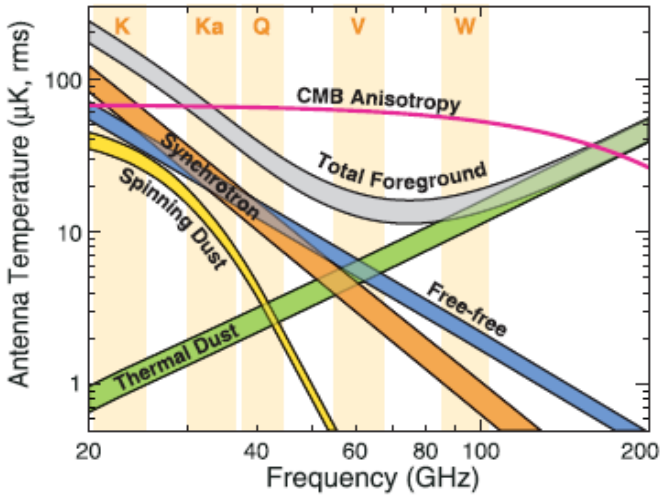
Key findings:

i) Most accurate CMB map up to that point





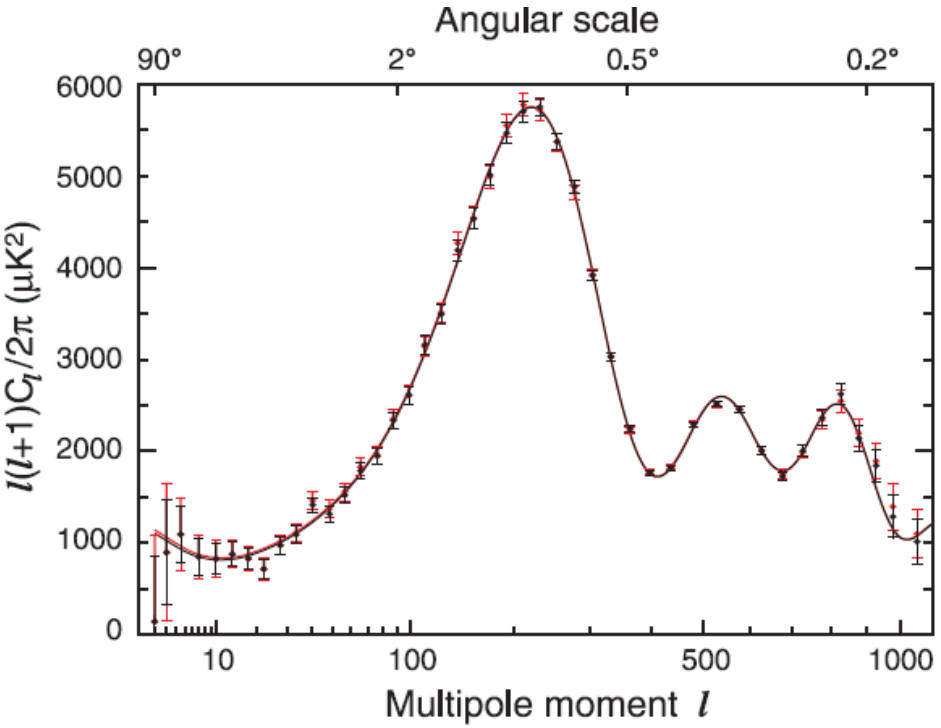
ii) Foreground spectra and CMB anisotropies

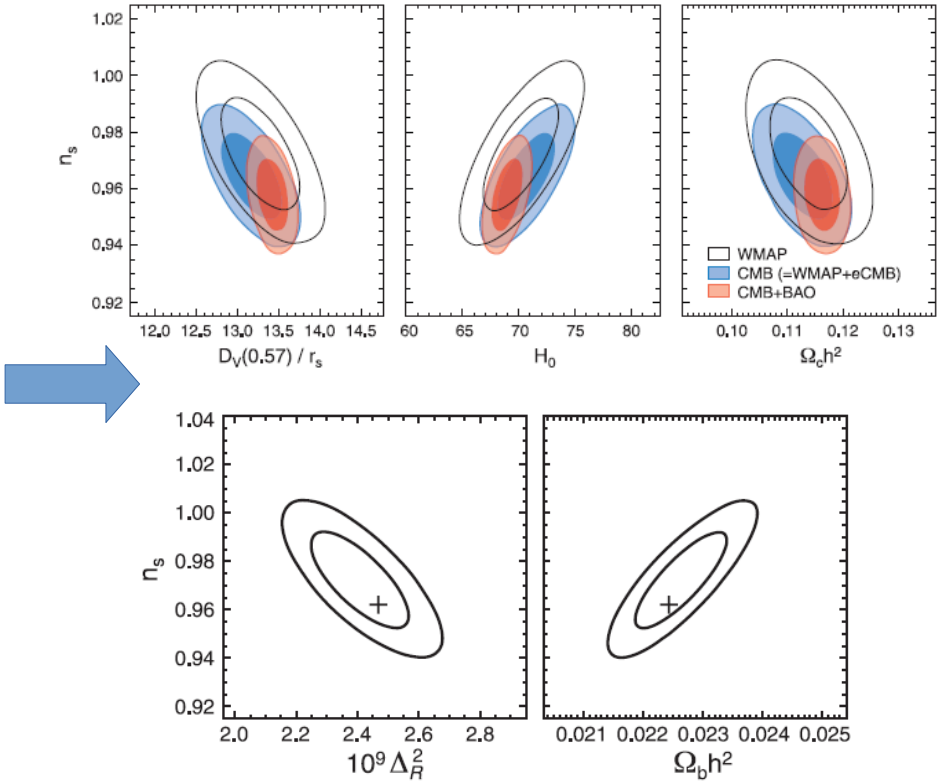


CMB surveys (past, current, future)

iii) Constraints on cosmological parameters

arXiv:1212.5225, 1212.5226





CMB surveys (past, current, future)

iii) Constraints on cosmological parameters (continued)

arXiv:1212.5225, 1212.5226

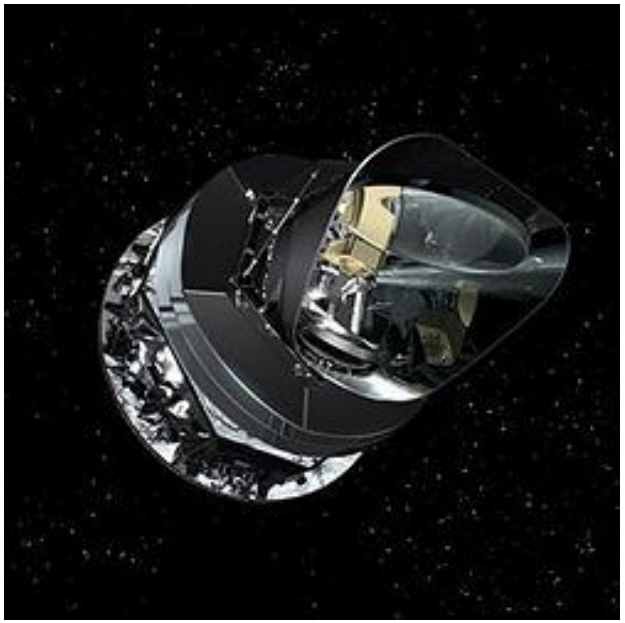
TABLE 3
WMAP Seven-year to Nine-year Comparison of the Six-Parameter ΛCDM Model[a]

Parameter	*WMAP*-only[b] Nine-year	*WMAP*-only[b] Nine-year (MASTER)[c]	*WMAP*-only[b] Seven-year	*WMAP*+BAO+H_0[b] Nine-year	*WMAP*+BAO+H_0[b] Seven-year
Fit parameters					
$\Omega_b h^2$	0.02264 ± 0.00050	0.02243 ± 0.00055	$0.02249^{+0.00056}_{-0.00057}$	0.02266 ± 0.00043	0.02255 ± 0.00054
$\Omega_c h^2$	0.1138 ± 0.0045	0.1147 ± 0.0051	0.1120 ± 0.0056	0.1157 ± 0.0023	0.1126 ± 0.0036
Ω_Λ	0.721 ± 0.025	0.716 ± 0.028	$0.727^{+0.030}_{-0.029}$	0.712 ± 0.010	0.725 ± 0.016
$10^9 \Delta^2_{\mathcal{R}}$	2.41 ± 0.10	2.47 ± 0.11	2.43 ± 0.11	$2.427^{+0.078}_{-0.079}$	2.430 ± 0.091
n_s	0.972 ± 0.013	0.962 ± 0.014	0.967 ± 0.014	0.971 ± 0.010	0.968 ± 0.012
τ	0.089 ± 0.014	0.087 ± 0.014	0.088 ± 0.015	0.088 ± 0.013	0.088 ± 0.014
Derived parameters					
t_0 (Gyr)	13.74 ± 0.11	13.75 ± 0.12	13.77 ± 0.13	13.750 ± 0.085	13.76 ± 0.11
H_0 (km/s/Mpc)	70.0 ± 2.2	69.7 ± 2.4	70.4 ± 2.5	69.33 ± 0.88	70.2 ± 1.4
σ_8	0.821 ± 0.023	0.818 ± 0.026	$0.811^{+0.030}_{-0.031}$	0.830 ± 0.018	0.816 ± 0.024
Ω_b	0.0463 ± 0.0024	0.0462 ± 0.0026	0.0455 ± 0.0028	0.0472 ± 0.0010	0.0458 ± 0.0016
Ω_c	0.233 ± 0.023	0.237 ± 0.026	0.228 ± 0.027	$0.2408^{+0.0093}_{-0.0092}$	0.229 ± 0.015
$z_{\rm reion}$	10.6 ± 1.1	10.5 ± 1.1	10.6 ± 1.2	10.5 ± 1.1	10.6 ± 1.2

CMB surveys (past, current, future)

3) Planck satellite (specifications, run, data, results)
(2009-2013)

Instruments/probe components (30-857GHz)
i) Low Frequency Instrument (LFI).
ii) High Frequency Instrument (HFI).
iii) Passive & active (liquid He) cooling (0.1K!).



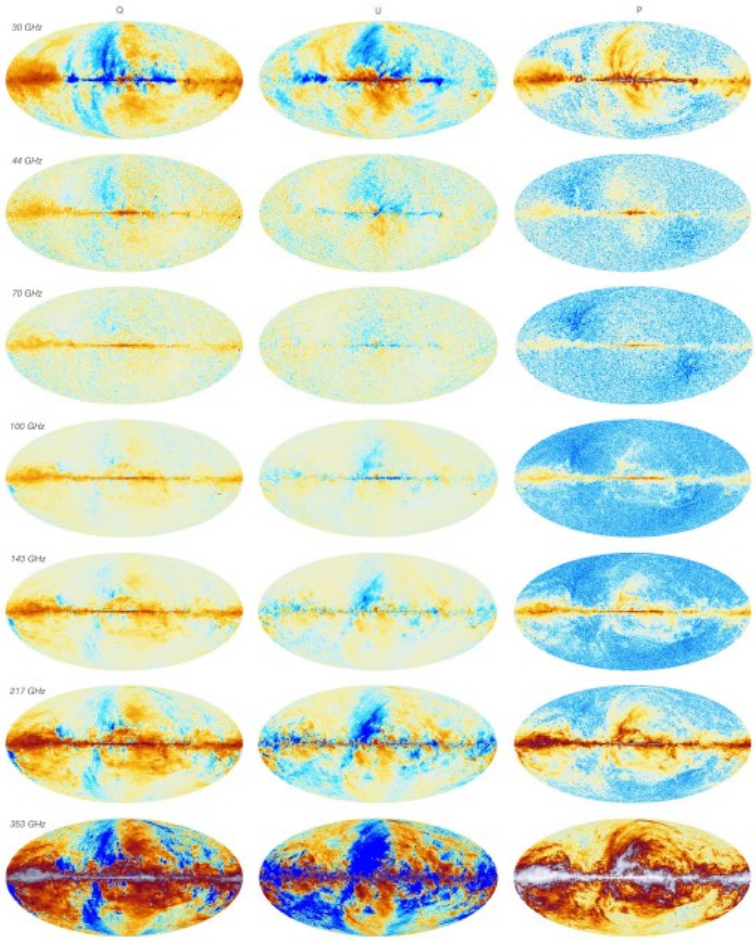
Objectives (both astro & cosmo!):
i) High resolution TT, TE and EE maps/spectra.
ii) Galaxy cluster catalog.
iii) Observations of Milky Way emission.
iv) Gravitational lensing and ISW effect.
v) Stringent constrains on cosmological parameters.

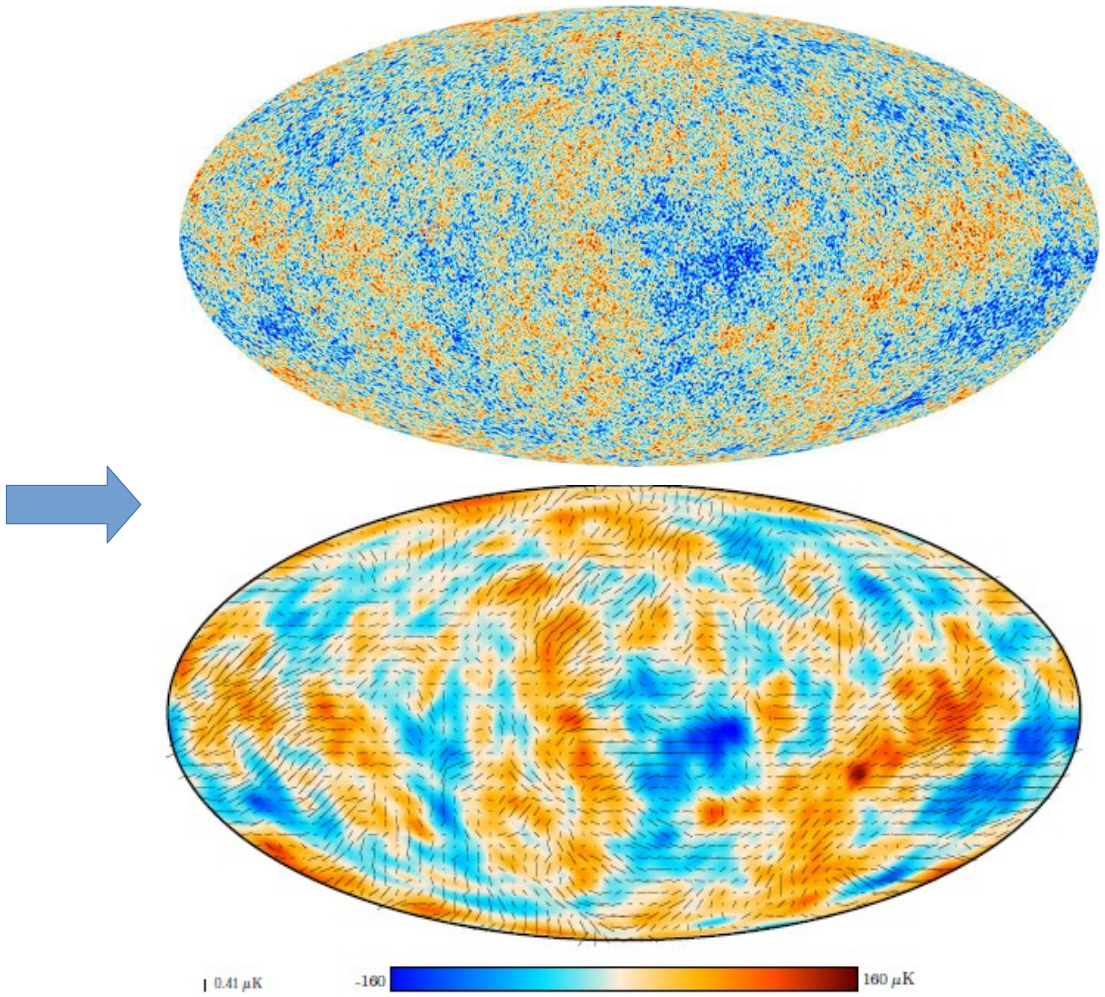
CMB surveys (past, current, future)

Key findings:

i) Most accurate CMB up to now

arXiv:1807.06205, 1807.06209, 1807.06211

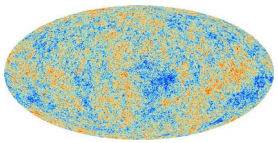


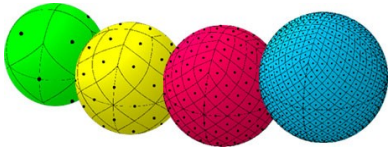


CMB surveys (past, current, future)

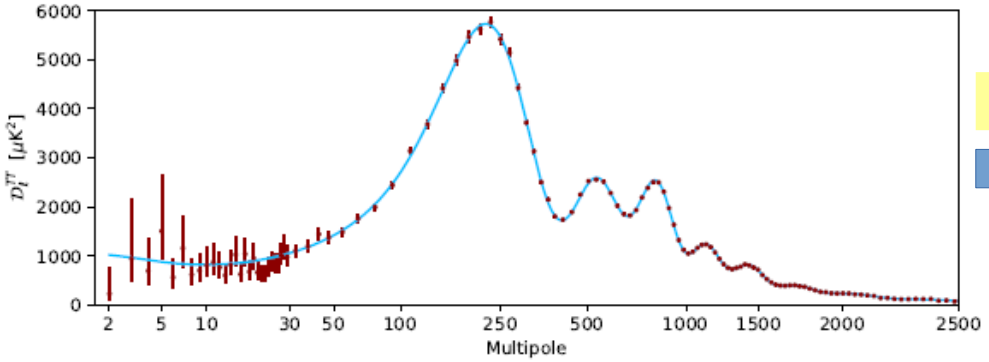
ii) Constraints on cosmological parameters

arXiv:1807.06205, 1807.06209, 1807.06211





Healpix

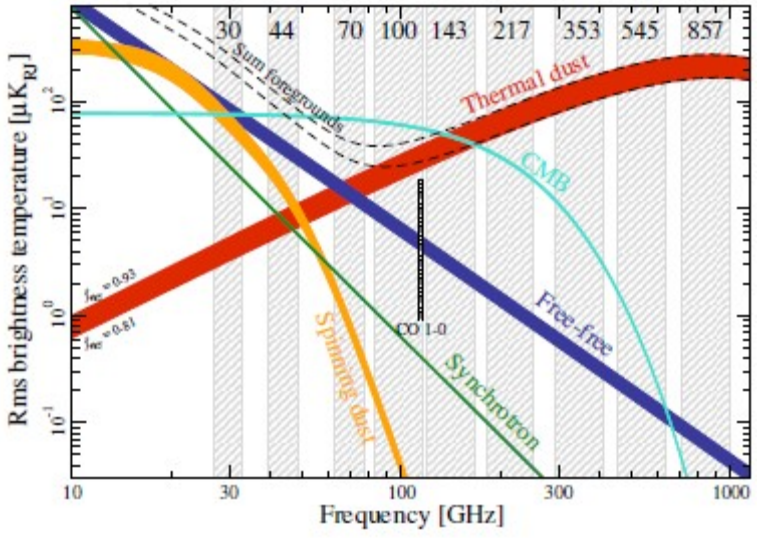


MCMC

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.022383	0.022447
$\Omega_c h^2$	0.12011	0.11923
$100\theta_{MC}$	1.040909	1.041010
τ	0.0543	0.0568
$\ln(10^{10} A_s)$	3.0448	3.0480
n_s	0.96605	0.96824
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.70
Ω_Λ	0.6842	0.6894
Ω_m	0.3158	0.3106
$\Omega_m h^2$	0.1431	0.1424
$\Omega_m h^3$	0.0964	0.0964
σ_8	0.8120	0.8110
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.8253
z_{re}	7.68	7.90
Age [Gyr]	13.7971	13.7839

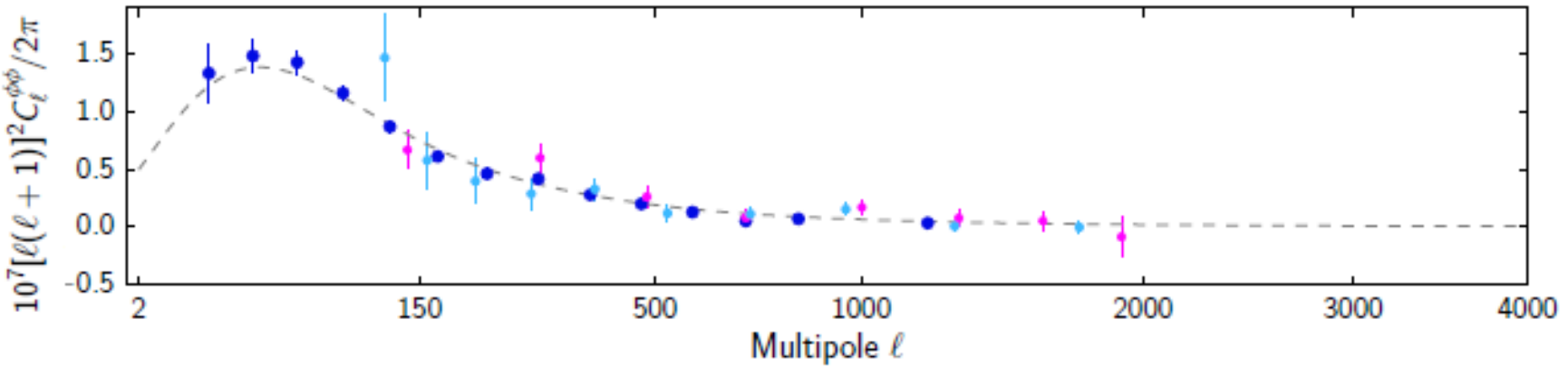
CMB surveys (past, current, future)

iii) Frequency dependence of temperature



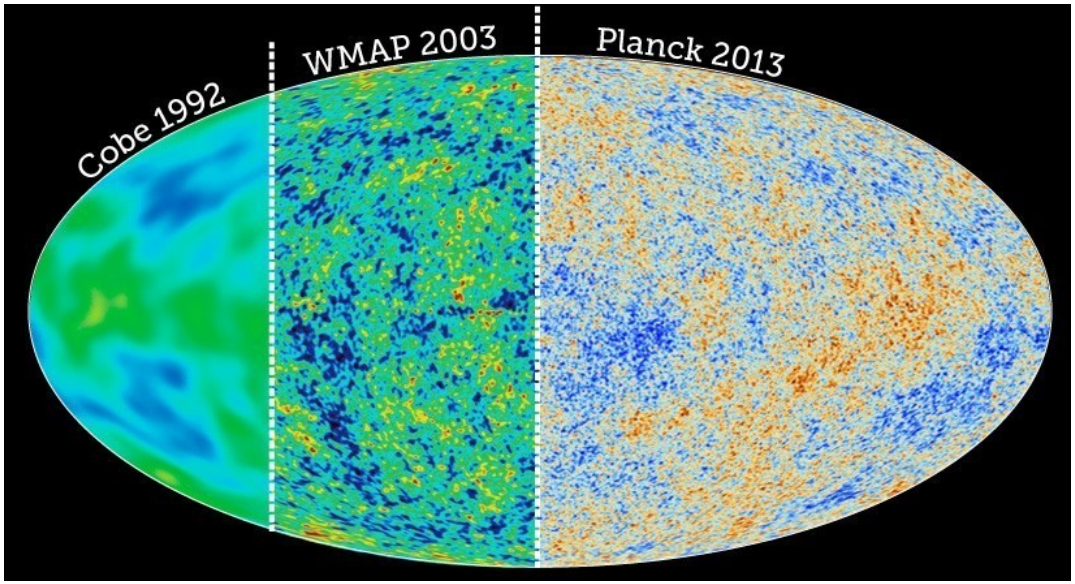
arXiv:1807.06205, 1807.06209, 1807.06211

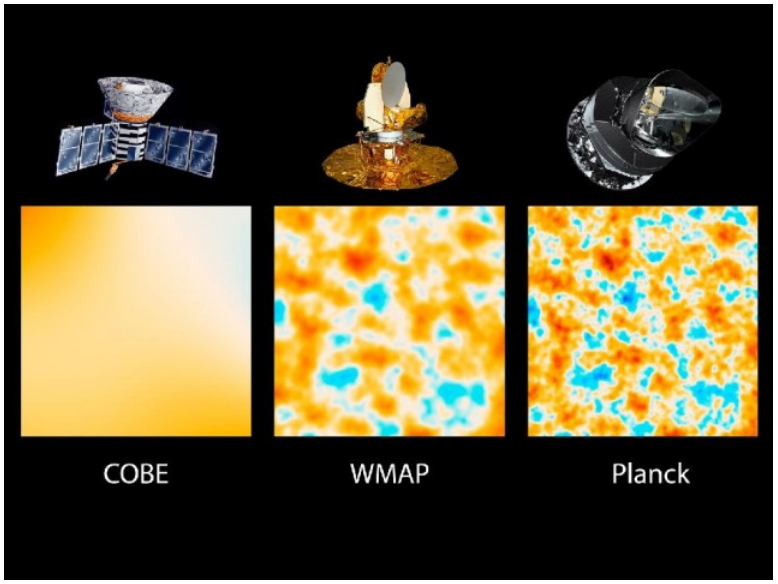
iv) Lensing power spectrum



CMB surveys (past, current, future)

Comparison of COBE, WMAP & Planck:





CMB surveys (past, current, future)

litebird.jp/

4) LiteBird (specifications, run, data, results)

Light satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (2020s)

Instruments/probe components (40-400GHz)

i) Superconducting polarimeter.

ii) Low frequency telescope (40-235GHz).

iii) High frequency telescope (280-400GHz).

iv) Passive and active cooling (5K).

Objectives:

i) B mode detection.

ii) Constraints on primordial GWs and inflation.

iii) Determination of scalar to tensor ratio $r=A_t/A_s$.

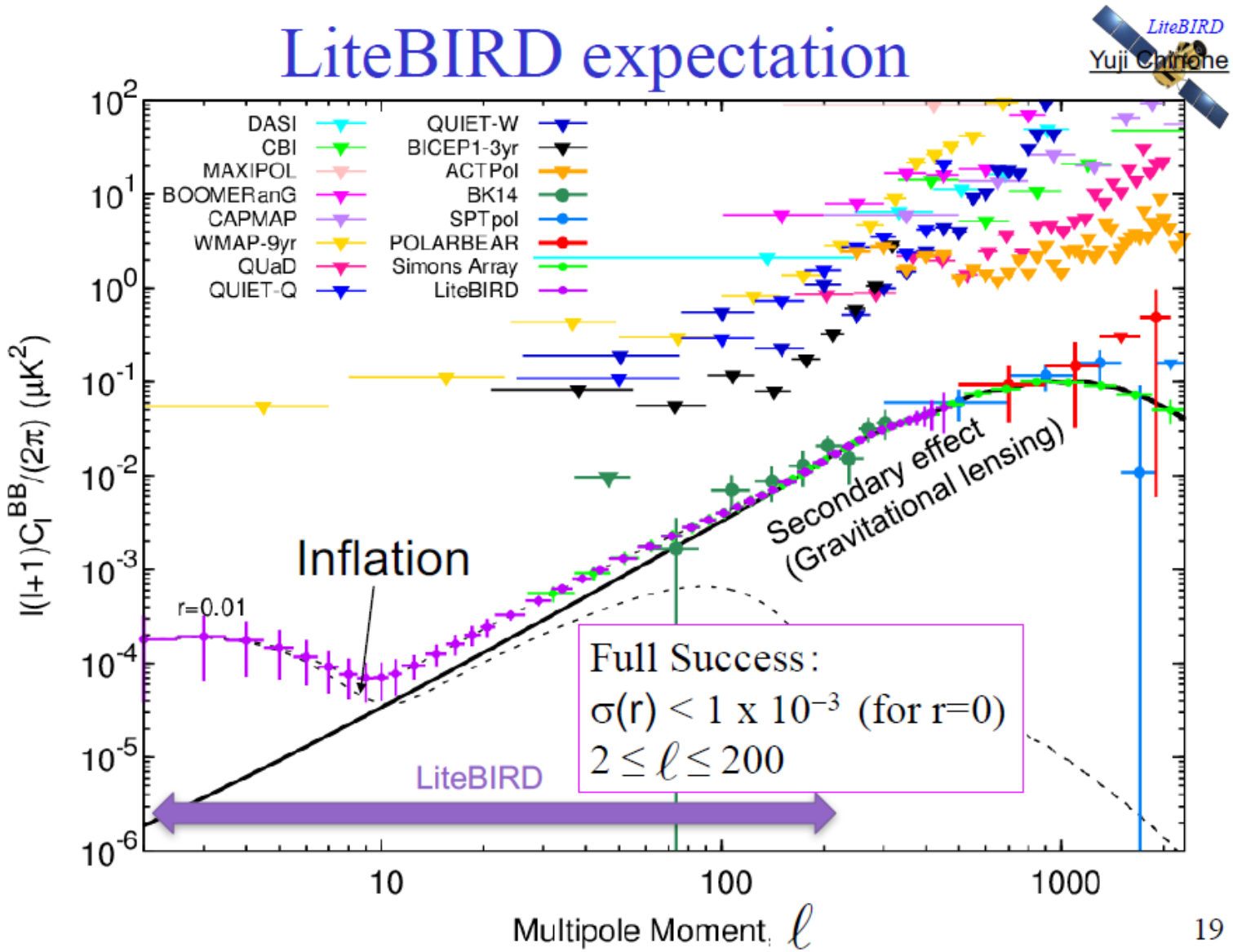
CMB surveys (past, current, future)

Main Specifications

Masashi Hazumi talk

Item	Specification
Launch year	2026-2027
Launch vehicle	JAXA H3
Observation type	All-sky CMB surveys
Observation time	3 years
Orbit	L2 Lissajous orbit
Scan strategy	Spin and precession ($\alpha = 45°$, $\beta = 50°$)
Observing frequencies	$34 - 448$ GHz
Number of bands	15
Sensitivity	2.5 μK′ (3 years)
Angular resolution	0.5° at 100 GHz (FWHM)
Mission instruments	· Superconducting detector arrays · Polarization modulator with continously-rotating half-wave plate (HWP) · Crossed-Dragone mirrors (LFT) + small refractive telescope (HFT) · 0.1K cooling chain (ST/JT/ADR)
Data size	4 GB/day
Mass	2.2 t
Power	2.5 kW

CMB surveys (past, current, future)



Masashi Hazumi talk

CMB surveys (past, current, future)

6) Bicep/Keck array (specifications, run, data, results)
CMB experiments in South Pole (2010-now)

Instruments/probe components (various phases)
i) BICEP1 → 98 sensors (100-150GHz)
ii) BICEP2 → 512 @150GHz
iii) Keck: 5 polarimeters w/ liquid He
iv) BICEP3 → 2560 sensors at 95 GHz

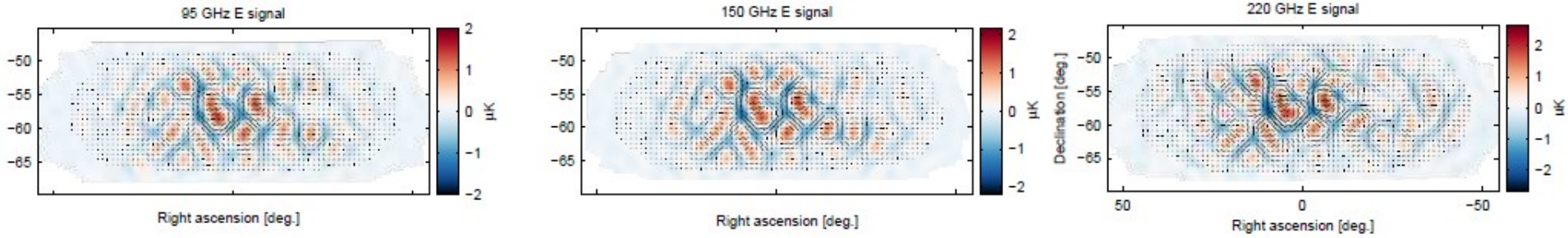
Objectives:
i) Measurements of polarization
ii) Emphasis on B mode
iii) Stringent constrains on tensor to scalar ratio ($r<0.07$)

CMB surveys (past, current, future)

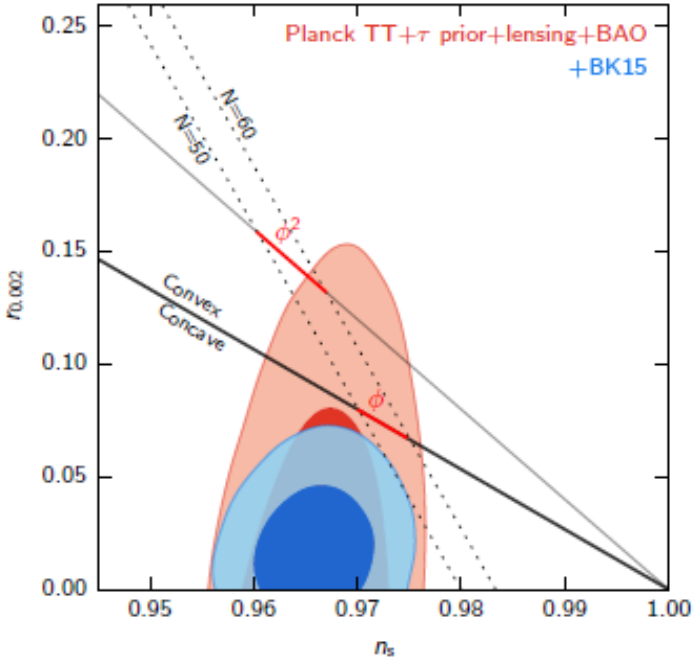
Bicep results (until 2015):

arXiv:1810.05216

i) Maps of E modes



ii) Constraints on n_s & r



LSS surveys (past, current, future)

1) LSS surveys can be:

i) Spectroscopic (BOSS, Euclid)
Split light into frequency bands and match absorption/emission lines → more accurate redshifts but harder to get (need fiber for every object!)

ii) Photometric (DES, Euclid, LSST)
Uses the total light received by telescope. Easier/faster to get, worse redshift determination

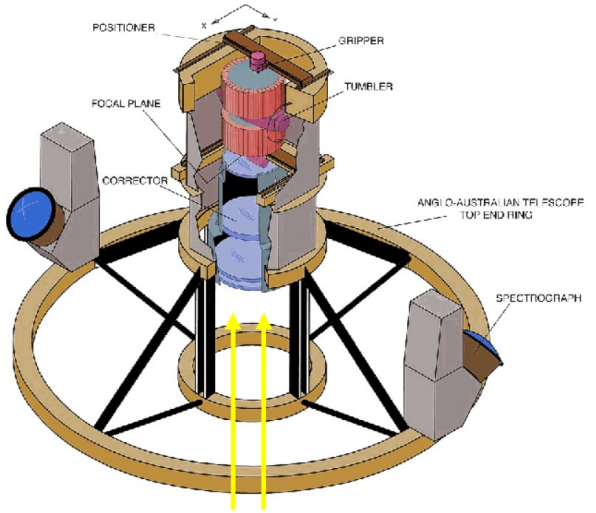
2) Main probes:

i) Gravitational lensing
ii) Type Ia Supernovae
iii) Galaxy cluster mass function and number counts
iv) Baryon Acoustic Oscillations
v) Lya quasars

LSS surveys (past, current, future)

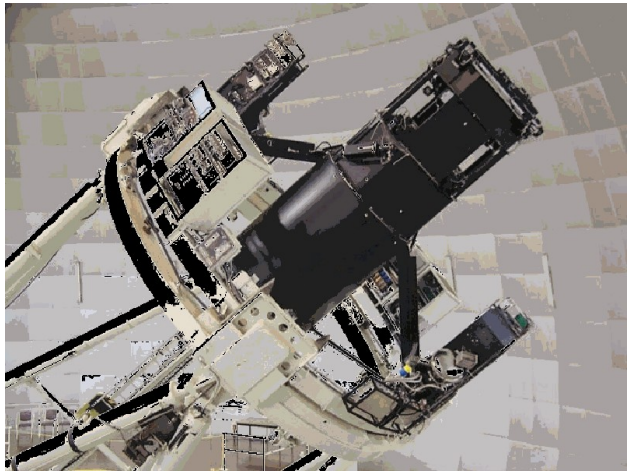
1) 2dF:
Two degree field Galaxy Redshift Survey (1997-2002)

http://www.2dfgrs.net/
http://www.2dfgrs.net/Public/Survey/



Instruments and components:
i) 4m telescope at Anglo-Australian Observatory.
ii) 2 degree field of view.
iii) 400 fibers!

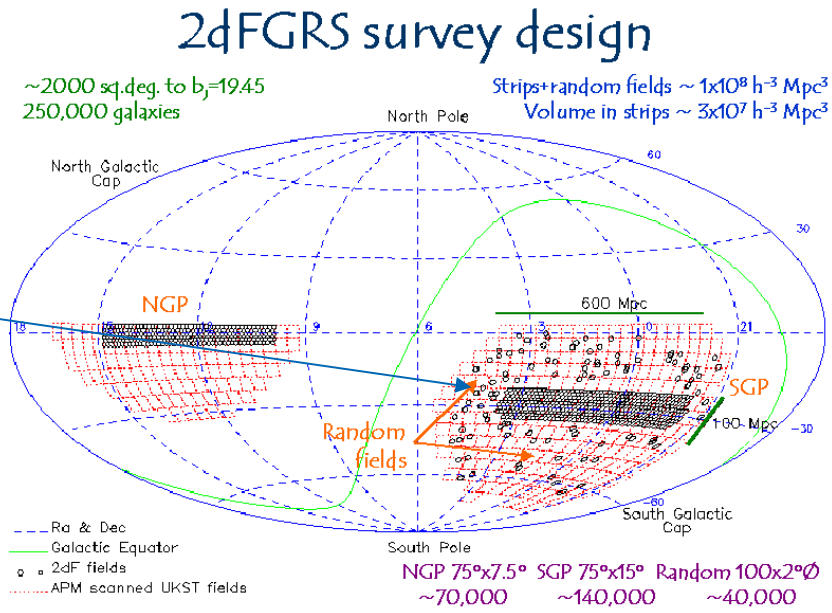
Objectives:
i) Obtain spectra for 245,591 objects
ii) Cover an area of approximately 1500 degrees^2
iii) Determine LSS up to 600Mpc
iv) Determine cosmological params and galaxy bias b



LSS surveys (past, current, future)

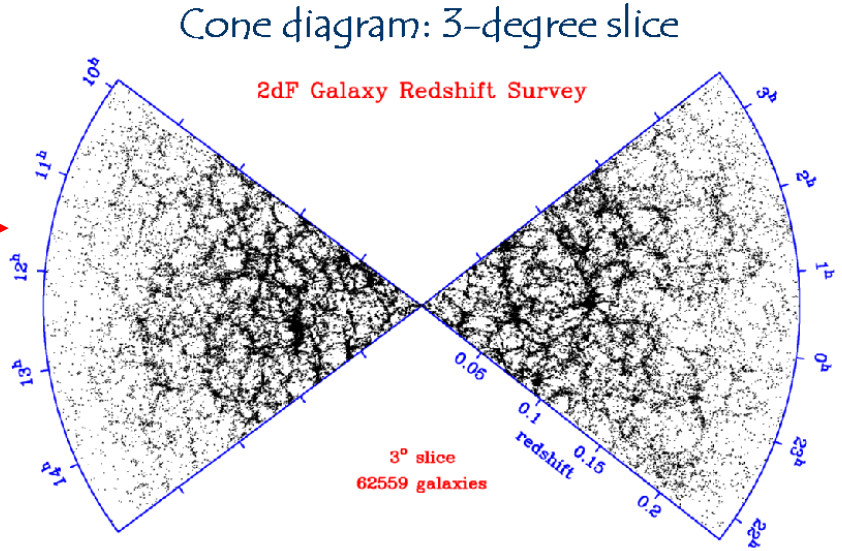
Survey strategy:
i) Choose the targets a priori
ii) Point and shoot at 2degrees

http://www.2dfgrs.net/



Cosmo results:

i) LSS up to 600Mpc/h
ii) Ω_m=0.30±0.06
iii) Ω_b/Ω_m=0.17±0.06 (Pl18:0.156)
iv) Bias b=0.96±0.08



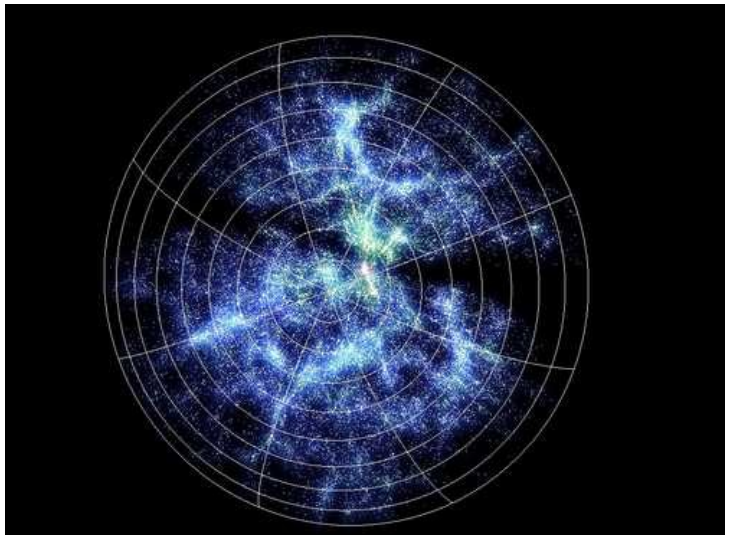
LSS surveys (past, current, future)

2) 6dF:
Six degree field Galaxy Redshift Survey (2001-2009)

http://www.6dfgs.net

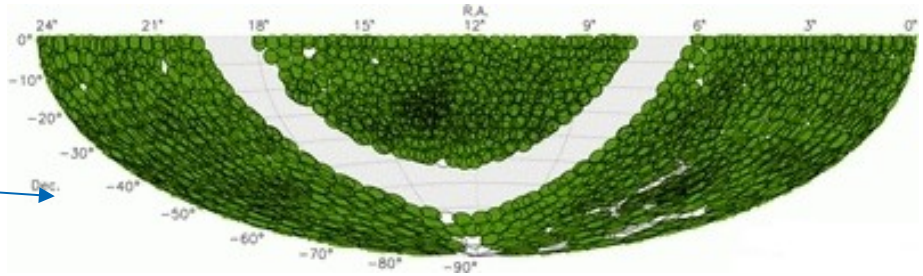
Instruments and components
i) 1.2m Schmidt telescope at UK
ii) 6 degree field of view
iii) Spectrograph with 150 fibers

Objectives:
i) Obtain spectra for 136,304 objects.
ii) Map nearby Universe over half the sky .
iii) Detect BAO.
iv) Determine peculiar velocity field (8885 gals).

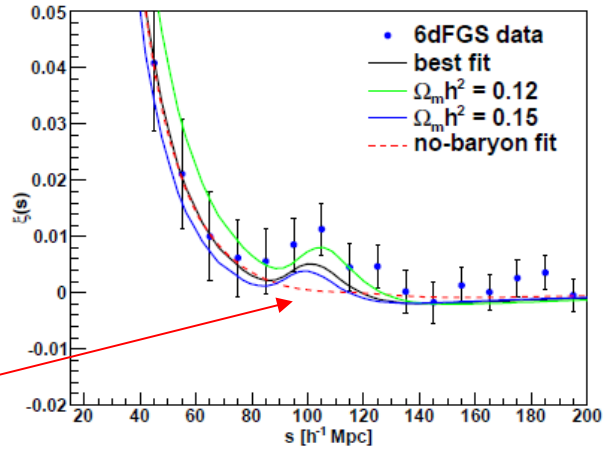


LSS surveys (past, current, future)

Survey strategy:
i) Choose the targets a priori
ii) Point and shoot at 6 degrees



http://www.6dfgs.net



Cosmo results:

i) BAO detection (2.4σ)
at ~105Mpc/h
ii) Ω_m=0.296±0.028
iii) H_0=67±3.2 km/s/Mpc
iv) Peculiar velocities for
8885 galaxies at z<0.055

$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H_0 E(z)}\right]^{1/3},$$

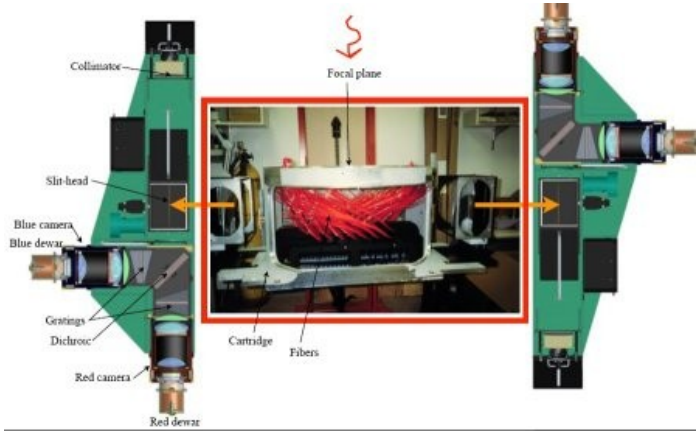
arXiv: 1106.3366

Summary of parameter constraints from 6dFGS		
$\Omega_m h^2$	0.138 ± 0.020 (14.5%)	
$D_V(z_{\rm eff})$	456 ± 27 Mpc (5.9%)	
$D_V(z_{\rm eff})$	459 ± 18 Mpc (3.9%)	[$\Omega_m h^2$ prior]
$\mathbf{r_s(z_d)/D_V(z_{eff})}$	$\mathbf{0.336 \pm 0.015}$ **(4.5%)**	
$R(z_{\rm eff})$	0.0324 ± 0.0015 (4.6%)	
$A(z_{\rm eff})$	0.526 ± 0.028 (5.3%)	
Ω_m	0.296 ± 0.028 (9.5%)	[$\Omega_m h^2$ prior]
$\mathbf{H_0}$	$\mathbf{67 \pm 3.2}$ **(4.8%)**	[$\mathbf{\Omega_m h^2}$ **prior**]

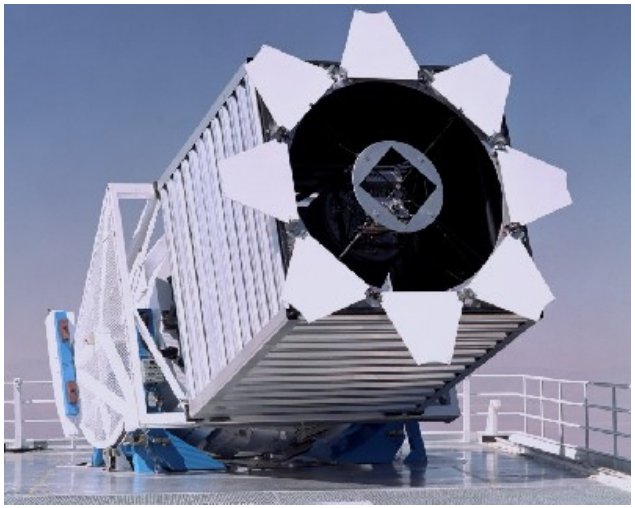
LSS surveys (past, current, future)

3) SDSS/BOSS: Sloan Digital Sky Survey
SDSS-I 2000-2005
SDSS-II 2005-2008
SDSS-III (BOSS) 2008-2014
SDSS-IV 2014-2020

http://www.sdss3.org



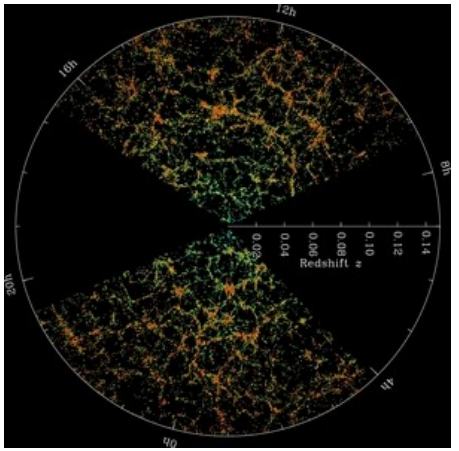
Instruments components
i) 2.5m telescope at New Mexico (USA).
ii) 120Mpixel camera!!!
iii) Spectrograph with 1000 fibers.
iv) Liquid Nitrogen cooling to reduce noise (190K).



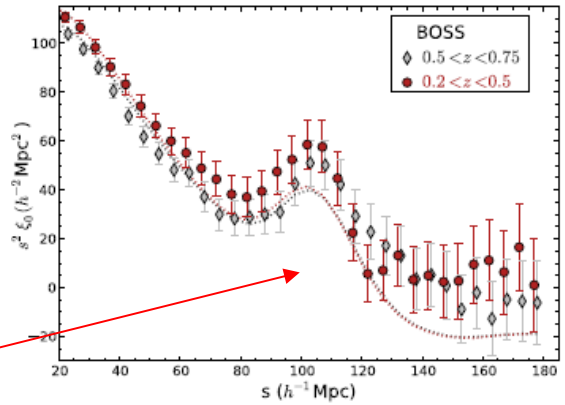
Objectives:
i) Obtain spectra for 4,355,200 objects!
ii) Both photometry and spectroscopy.
iii) High significance detection of BAO.
iv) Determine peculiar velocity field (8885 gals).

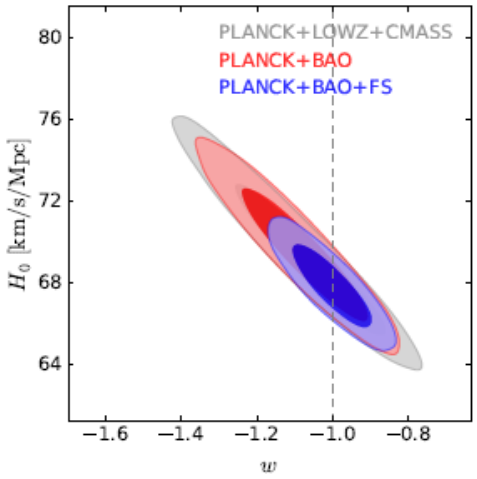
LSS surveys (past, current, future)

Observations/results:
i) Distribution of local galaxies
ii) Millions of objects and spectra
iii) Frequent data releases



http://www.sdss3.org





Cosmo results:
i) BAO detection (4.5σ)
at ~105Mpc/h
ii) Ω_m=0.310±0.006
iii) H_0=67.6±0.5 km/s/Mpc
iv) Detection of most distant quasars
(160,000 objects at 2.2<z<3)

arXiv: 1607.03155, 1607.06097

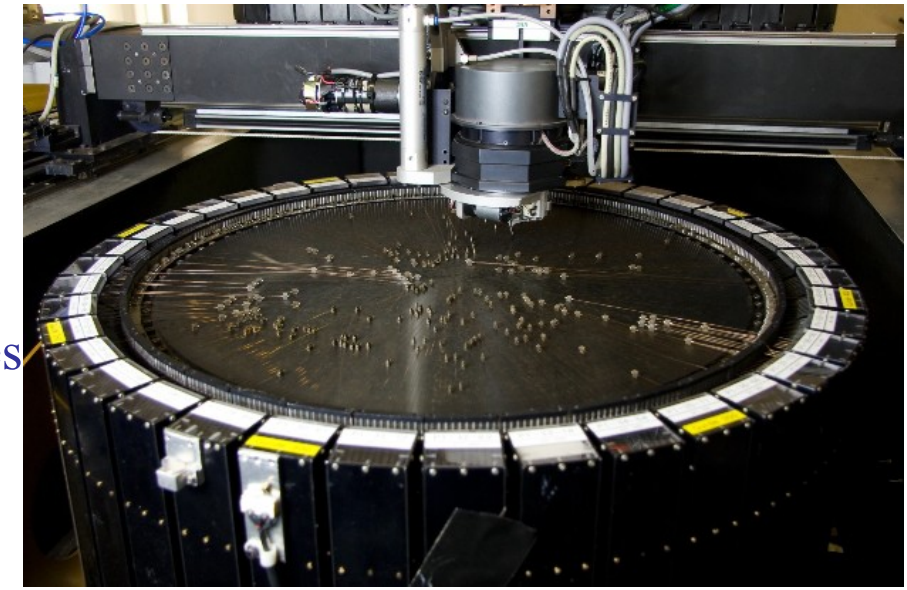
Cosmological Model	Data Sets	$\Omega_m h^2$	Ω_m	H_0 km/s/Mpc
ΛCDM	Planck	0.1429 (14)	0.317 (9)	67.2 (7)
ΛCDM	Planck + BAO	0.1418 (10)	0.309 (6)	67.7 (5)
ΛCDM	Planck + BAO + FS	0.1419 (10)	0.311 (6)	67.6 (5)
ΛCDM	Planck + BAO + FS + SN	0.1419 (10)	0.310 (6)	67.6 (5)

LSS surveys (past, current, future)

4) WiggleZ
WiggleZ Dark Energy Survey (2006-2011)

http://wigglez.swin.edu.au/site/

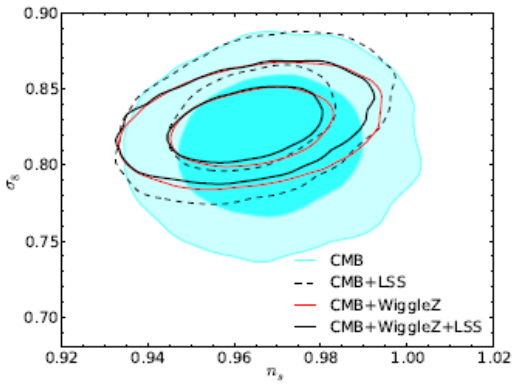
Instruments and components
i) 4m telescope at Anglo-Australian Observatory
ii) 2 degree field of view
iii) Spectrograph with 150 fibers

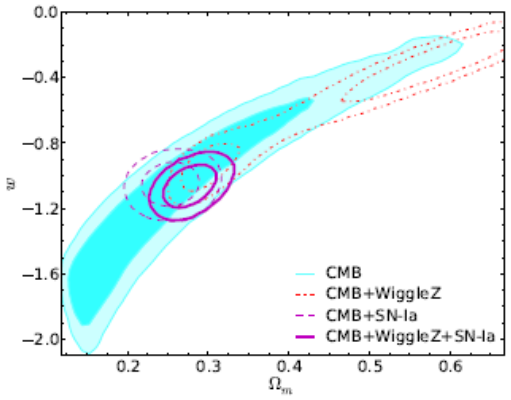


Objectives:
i) Improve understanding of DE.
ii) Measure the BAO (hence the wiggle!)
iii) Attempt to determine z 1/4*10^6 galaxies
iv) Cover 1000 square degrees.
v) Synergy with n-body sims (GiggleZ!).

LSS surveys (past, current, future)

Results:
i) Stringent constraints on ΛCDM
ii) Redshift of 240,000 gals
Iii) Constraints on ξ(r) & P(k)
iv) Constraints or r=At/As
v) Systematic test of ΛCDM
extensions.





ArXiv: 1210.2130

http://wigglez.swin.edu.au/site/

Cosmo results in detail:

i) Measurement of growth
@ z=(0.22, 0.41, 0.60, 0.78)
ii) Ωm=0.280±0.016
iii) σ8=0.825±0.017
iv) Σmν=0.58 eV
v) r<0.18

Model	Parameter	CMB + WiggleZ	+ H_0	+ SN-Ia	+ BAO	+ H_0 + BAO
Flat ΛCDM	$100\Omega_b h^2$	2.238 ± 0.052	2.255 ± 0.050	2.240 ± 0.053	2.239 ± 0.050	2.253 ± 0.050
	$\Omega_{CDM} h^2$	0.1153 ± 0.0027	0.1145 ± 0.0026	0.1150 ± 0.0028	0.1152 ± 0.0024	0.1146 ± 0.0024
	100θ	1.039 ± 0.002	1.040 ± 0.002	1.039 ± 0.003	1.039 ± 0.002	1.039 ± 0.002
	τ	0.083 ± 0.014	0.084 ± 0.014	0.083 ± 0.014	0.083 ± 0.014	0.084 ± 0.014
	n_s	0.964 ± 0.012	0.968 ± 0.012	0.965 ± 0.013	0.964 ± 0.012	0.968 ± 0.011
	$\log(10^{10} A_s)$	3.084 ± 0.029	3.086 ± 0.029	3.085 ± 0.030	3.083 ± 0.029	3.086 ± 0.029
	Ω_m	0.290 ± 0.016	0.283 ± 0.014	0.288 ± 0.017	0.289 ± 0.013	0.284 ± 0.012
	$H_0[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	68.9 ± 1.4	69.6 ± 1.3	69.1 ± 1.6	69.0 ± 1.2	69.5 ± 1.2
	σ_8	0.825 ± 0.017	0.825 ± 0.017	0.825 ± 0.017	0.825 ± 0.017	0.825 ± 0.017

LSS surveys (past, current, future)

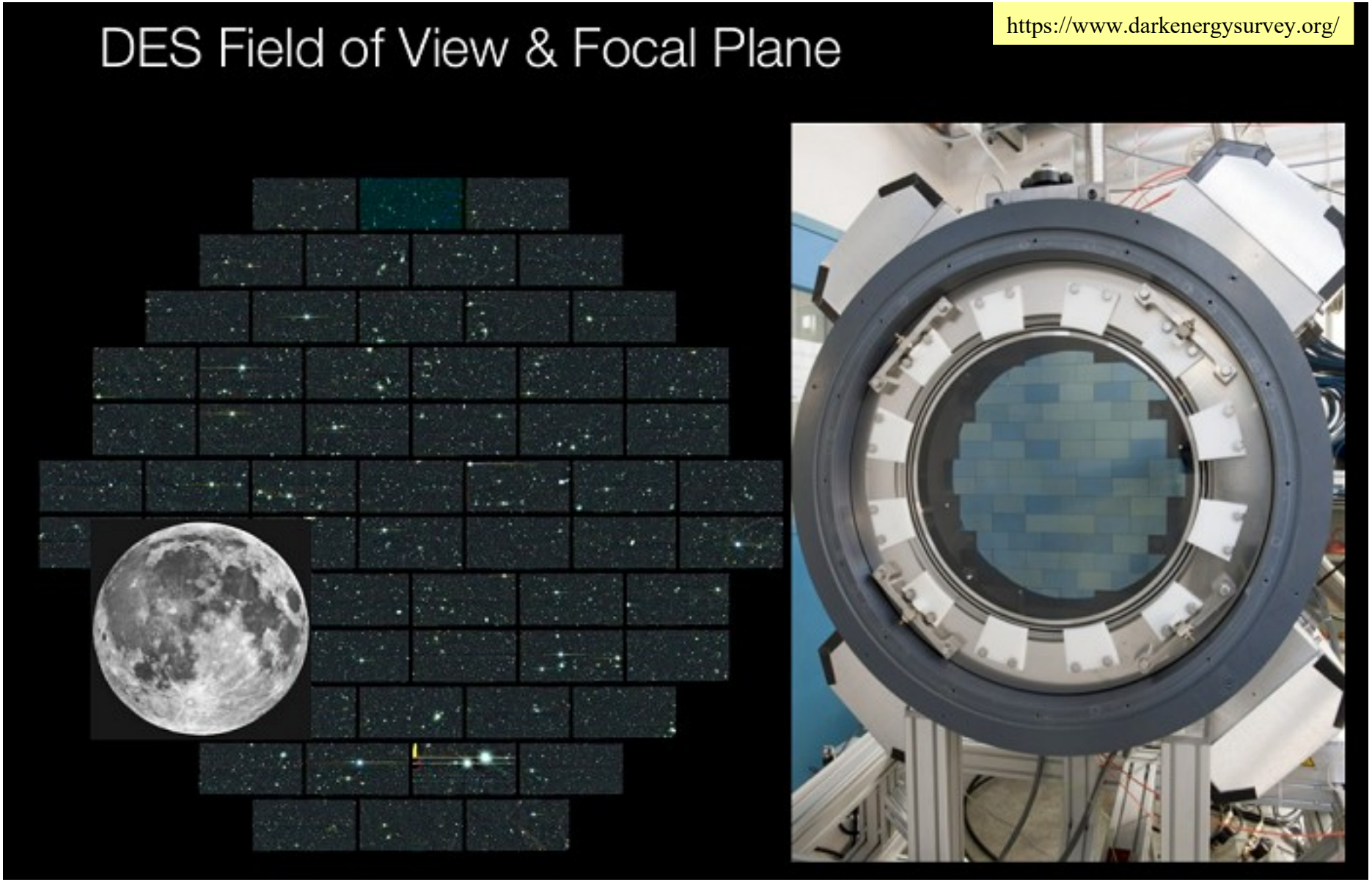
https://www.darkenergysurvey.org/

5) DES:
Dark Energy Survey (2012-)

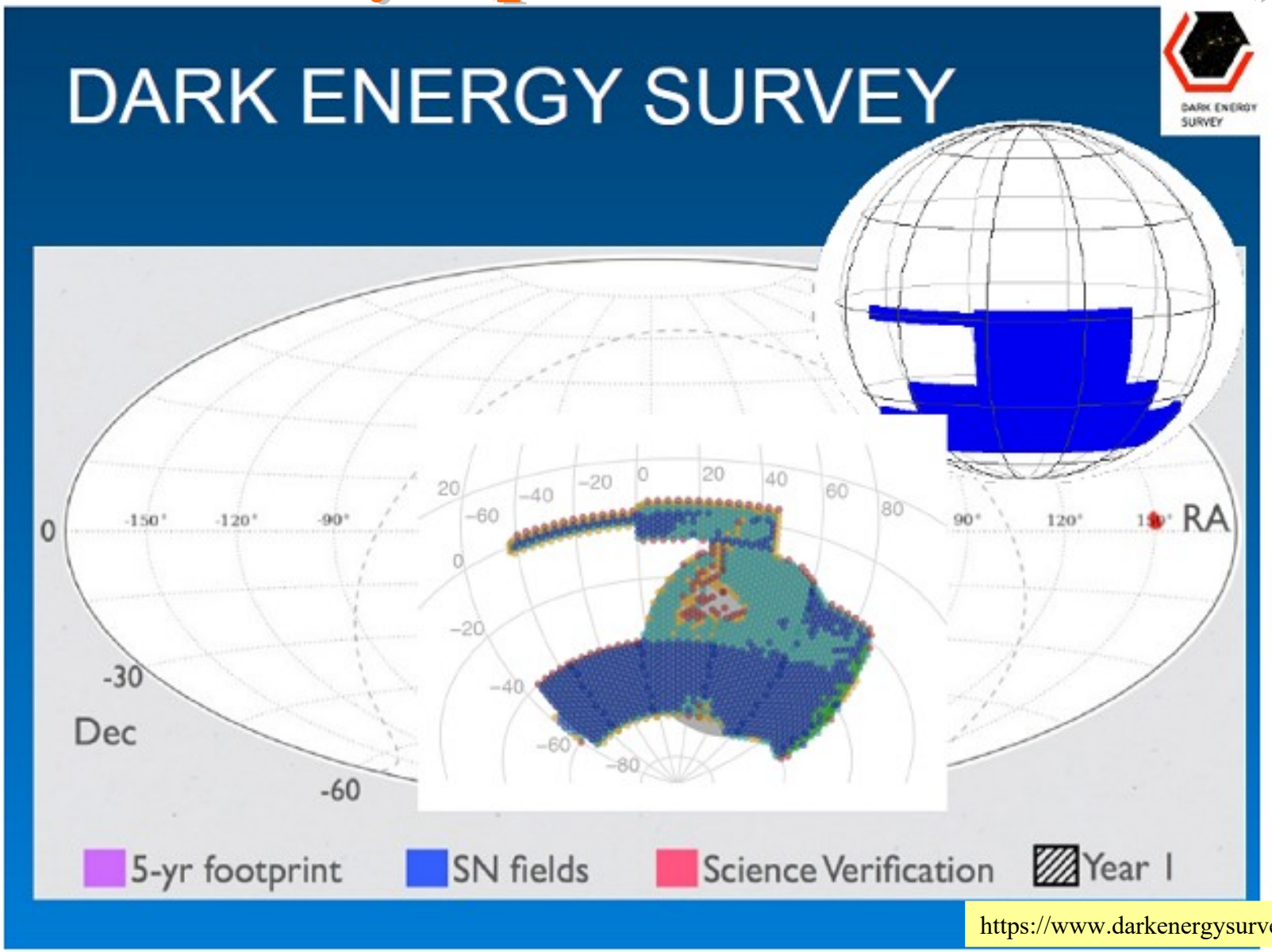
Instruments and components
i) Visible and infrared 4m telescope
at Cerro Tololo in Chile
ii) 2.2 degree field of view
iii) 5 photometric bands (g, r, i, z, Y)

Objectives:
i) Obtain spectra SnIa (~10,000).
ii) Find galaxy clusters.
iii) Sample 300*10^6 galaxies for BAO.
iv) Weak lensing constraints.
v) Find deviations from GR.

LSS surveys (past, current, future)

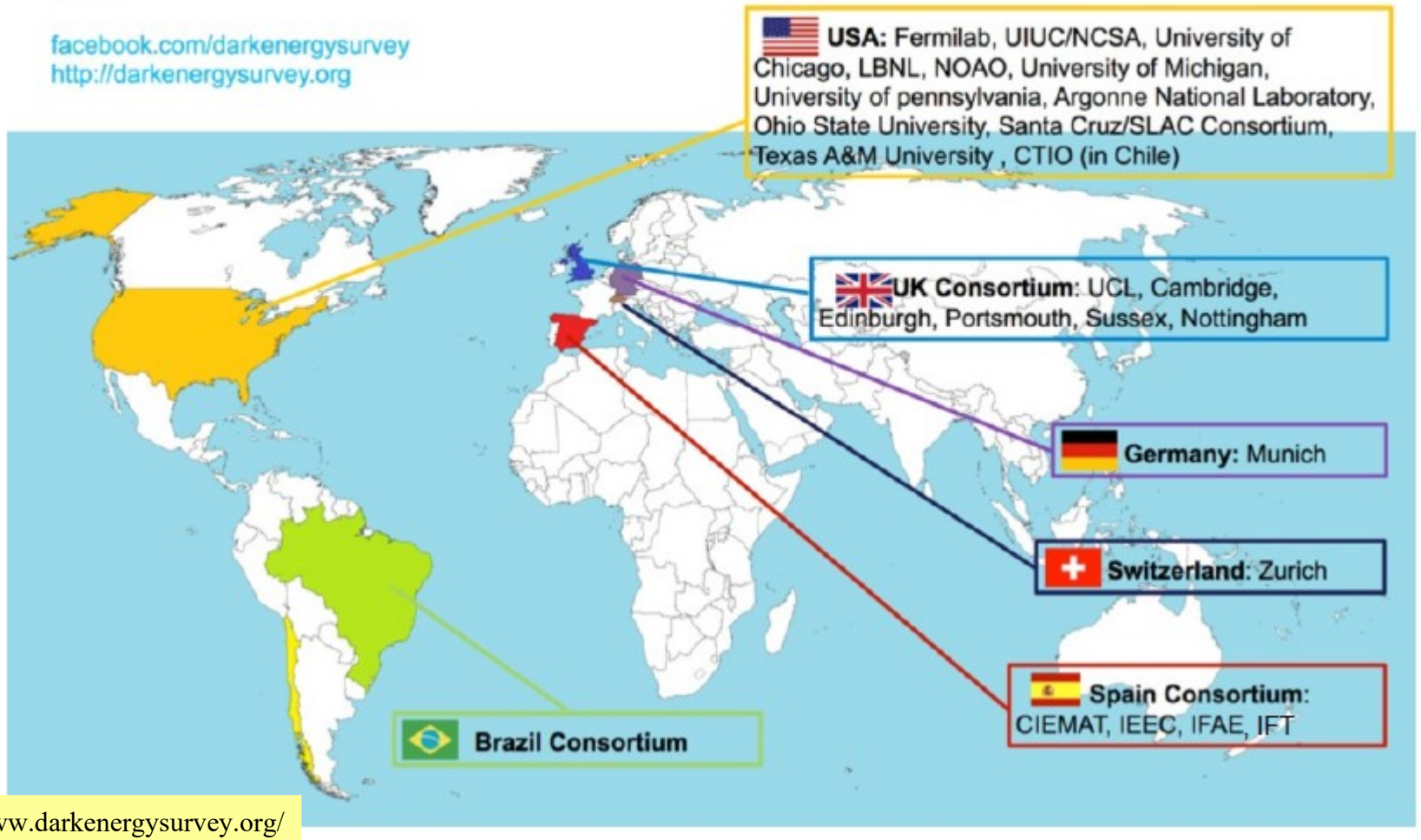


LSS surveys (past, current, future)



LSS surveys (past, current, future)

DES Collaboration:
~300 scientists from 28 institutions



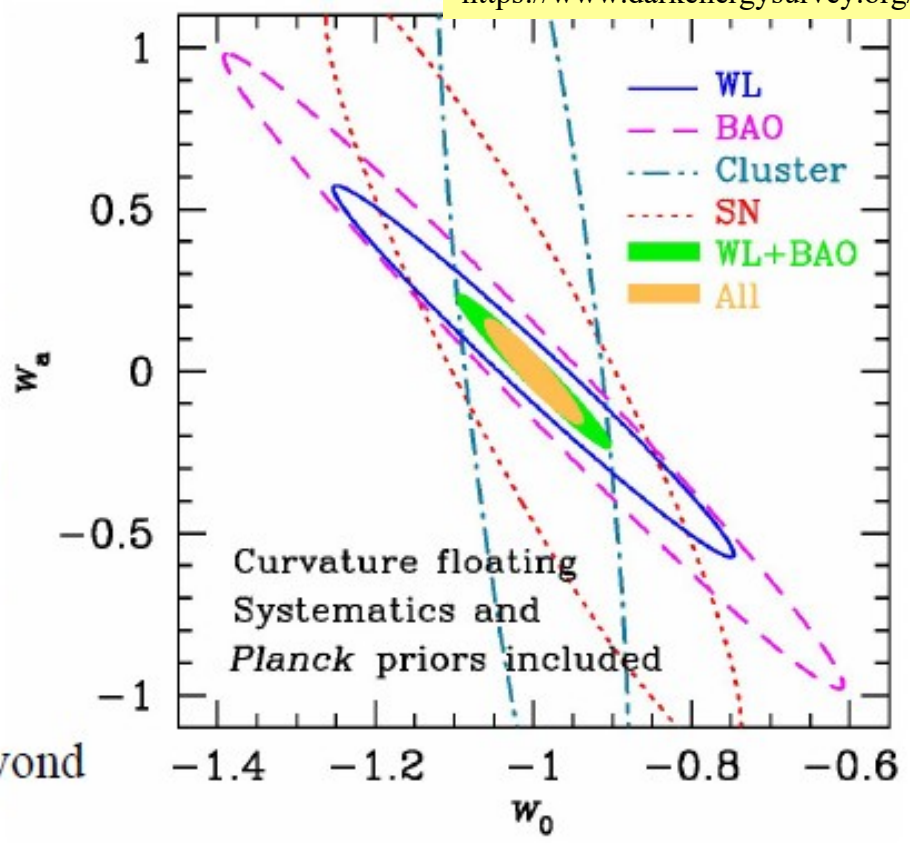
https://www.darkenergysurvey.org/

LSS surveys (past, current, future)

https://www.darkenergysurvey.org/

Four Probes of Dark Energy

- **Galaxy Clusters**
  - ~100,000 clusters to z>1
  - Synergy with SPT, VHS
  - Sensitive to growth of structure and geometry
- **Weak Lensing**
  - Shape measurements of 200 million galaxies
  - Sensitive to growth of structure and geometry
- **Baryon Acoustic Oscillations**
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- **Supernovae**
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

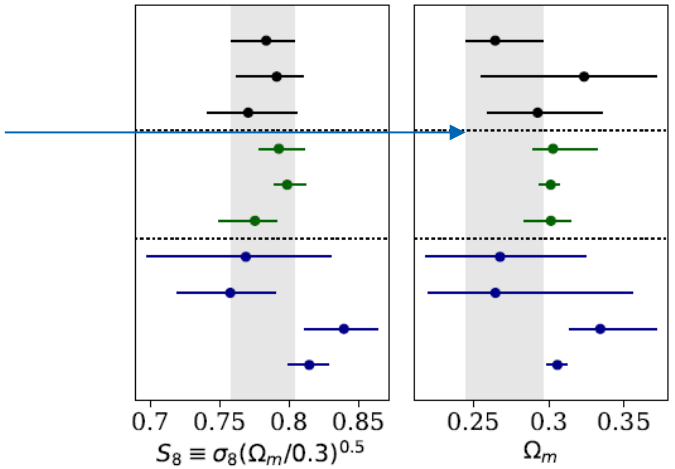


Factor 3-5 improvement over Stage II DETF Figure of Merit

LSS surveys (past, current, future)

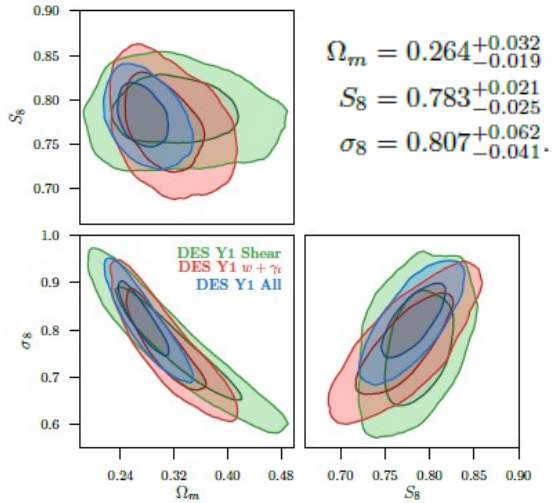
1) Resolved tension between low-z probes and Planck

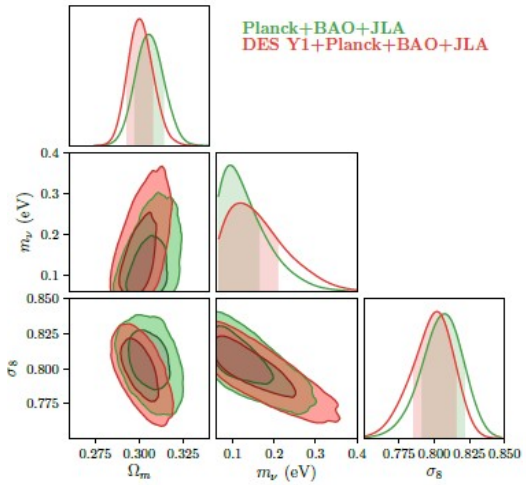
https://www.darkenergysurvey.org/



arXiv: 1708.01530

2) New improved constraints on ΛCDM and neutrinos



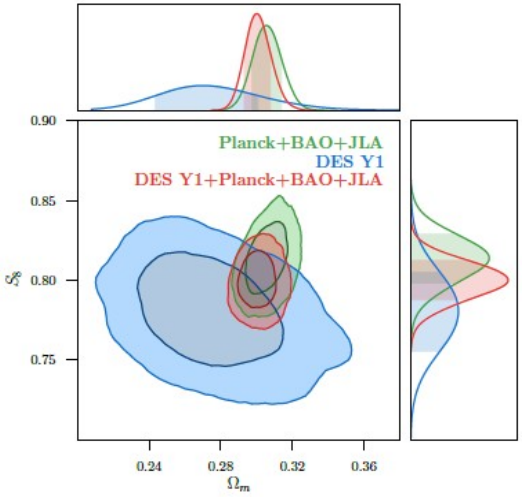


LSS surveys (past, current, future)

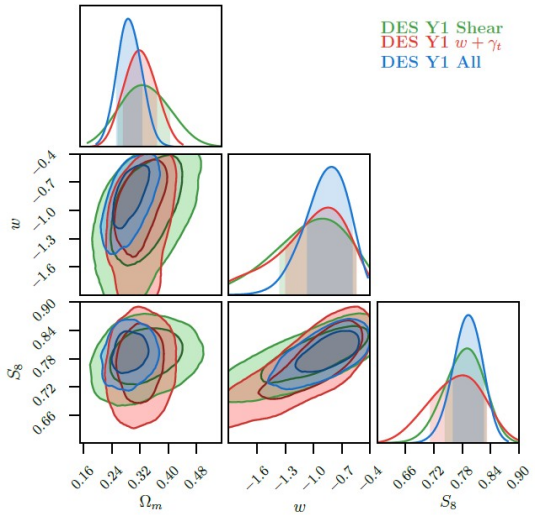
3) Joint DES-Planck results are astounding!

arXiv: 1708.01530

https://www.darkenergysurvey.org/



4) Constraints on wCDM as well!



Model	Data Sets	Ω_m	S_8	n_s	Ω_b	h	$\sum m_\nu$ (eV) (95% CL)	w
ΛCDM	DES Y1 $\xi_\pm(\theta)$	$0.323^{+0.048}_{-0.069}$	$0.791^{+0.019}_{-0.029}$	...	...	...	...	...
ΛCDM	DES Y1 $w(\theta)+\gamma_t$	$0.293^{+0.043}_{-0.033}$	$0.770^{+0.035}_{-0.030}$	...	...	...	...	...
ΛCDM	DES Y1 3x2	$0.264^{+0.032}_{-0.019}$	$0.783^{+0.021}_{-0.025}$	...	...	...	...	...
ΛCDM	Planck (No Lensing)	$0.334^{+0.037}_{-0.020}$	$0.840^{+0.024}_{-0.028}$	$0.960^{+0.006}_{-0.008}$	$0.0512^{+0.0036}_{-0.0022}$	$0.656^{+0.015}_{-0.026}$	...	...
ΛCDM	DES Y1 + Planck (No Lensing)	$0.303^{+0.029}_{-0.013}$	$0.793^{+0.018}_{-0.014}$	$0.971^{+0.006}_{-0.005}$	$0.0481^{+0.0040}_{-0.0010}$	$0.681^{+0.010}_{-0.025}$	< 0.62	...
ΛCDM	DES Y1 + JLA + BAO	$0.301^{+0.013}_{-0.018}$	$0.775^{+0.016}_{-0.027}$	$1.05^{+0.02}_{-0.08}$	$0.0493^{+0.006}_{-0.007}$	$0.680^{+0.042}_{-0.045}$	...	...
ΛCDM	Planck + JLA + BAO	$0.306^{+0.007}_{-0.007}$	$0.815^{+0.013}_{-0.015}$	$0.969^{+0.005}_{-0.005}$	$0.0485^{+0.0007}_{-0.0008}$	$0.679^{+0.005}_{-0.007}$	< 0.25	...
ΛCDM	DES Y1 + Planck + JLA + BAO	$0.301^{+0.006}_{-0.008}$	$0.799^{+0.014}_{-0.009}$	$0.973^{+0.005}_{-0.004}$	$0.0480^{+0.0009}_{-0.0006}$	$0.682^{+0.006}_{-0.006}$	< 0.29	...
wCDM	DES Y1 $\xi_\pm(\theta)$	$0.317^{+0.074}_{-0.054}$	$0.789^{+0.036}_{-0.038}$	...	...	...	...	$-0.82^{+0.26}_{-0.47}$
wCDM	DES Y1 $w(\theta)+\gamma_t$	$0.317^{+0.045}_{-0.041}$	$0.788^{+0.039}_{-0.067}$	...	...	...	...	$-0.76^{+0.19}_{-0.45}$
wCDM	DES Y1 3x2	$0.279^{+0.043}_{-0.022}$	$0.794^{+0.029}_{-0.027}$	...	...	...	...	$-0.80^{+0.20}_{-0.22}$
wCDM	Planck (No Lensing)	$0.220^{+0.064}_{-0.025}$	$0.798^{+0.035}_{-0.035}$	$0.960^{+0.008}_{-0.006}$	$0.0329^{+0.0100}_{-0.0030}$	$0.800^{+0.050}_{-0.090}$	...	$-1.50^{+0.34}_{-0.18}$
wCDM	DES Y1 + Planck (No Lensing)	$0.230^{+0.023}_{-0.015}$	$0.780^{+0.013}_{-0.023}$	$0.967^{+0.005}_{-0.004}$	$0.0359^{+0.0037}_{-0.0021}$	$0.785^{+0.023}_{-0.037}$	< 0.56	$-1.34^{+0.08}_{-0.15}$
wCDM	Planck + JLA + BAO	$0.304^{+0.008}_{-0.011}$	$0.814^{+0.013}_{-0.016}$	$0.968^{+0.005}_{-0.005}$	$0.0480^{+0.0010}_{-0.0020}$	$0.681^{+0.010}_{-0.009}$	< 0.29	$-1.03^{+0.05}_{-0.05}$
wCDM	DES Y1 + Planck + JLA + BAO	$0.299^{+0.009}_{-0.007}$	$0.798^{+0.012}_{-0.011}$	$0.973^{+0.005}_{-0.004}$	$0.0479^{+0.0015}_{-0.0012}$	$0.683^{+0.009}_{-0.010}$	< 0.35	$-1.00^{+0.04}_{-0.05}$

LSS surveys (past, current, future)

6) Euclid survey by ESA (2020?)

https://www.euclid-ec.org/

Red book: arXiv:1110.3193

Characteristics
i) Satellite at L2 Sun-Earth position.
ii) 1.2m telescope by Airbus.
iii) Wide survey 15,000 sq degrees.
iv) Deep survey 40 sq degrees.
v) Wavelengths 550-2000nm.
vi) Shapes of 1.5*10^9 galaxies!!
vii) Redshifts of 5*10^7 galaxies!
viii) Cost 1.25 billion €.

Objectives:
i) Weak lensing.
ii) Determine the BAO.
iii) Galaxy clustering.
iv) Goal: constrain deviations of GR.

LSS surveys (past, current, future)

https://www.euclid-ec.org/

Red book: arXiv:1110.3193

General expectations on parameters:

	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**

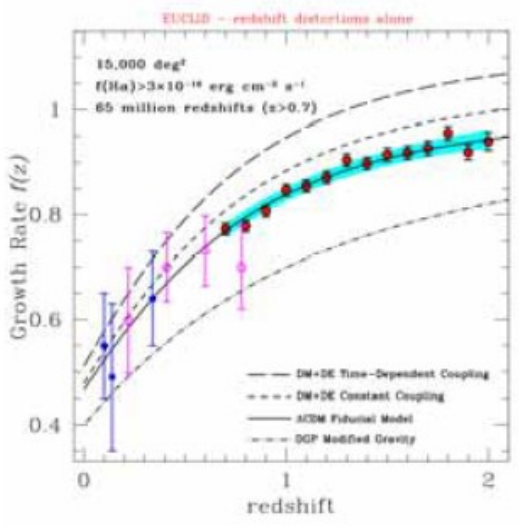
$$f = \frac{d\ln\delta}{d\ln a} = \Omega_m(z)^\gamma \qquad \gamma \approx \frac{6}{11}$$

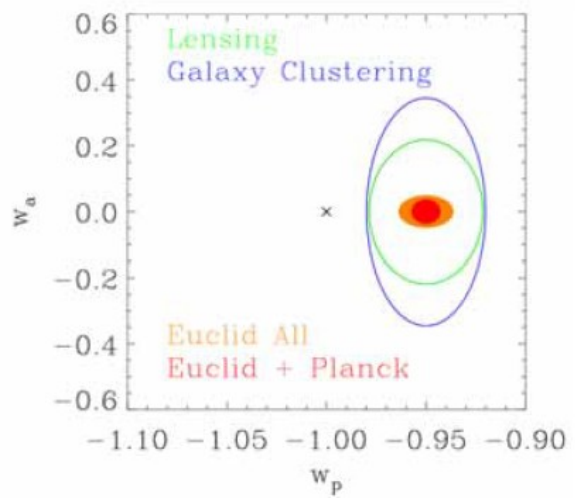
LSS surveys (past, current, future)

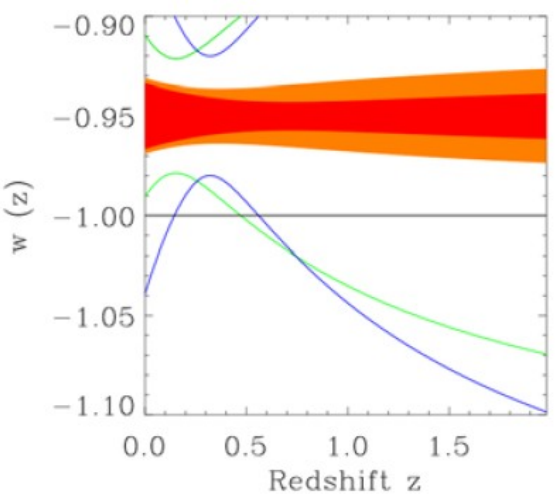
https://www.euclid-ec.org/

Red book: arXiv:1110.3193

Expectations on growth and equation of state w:



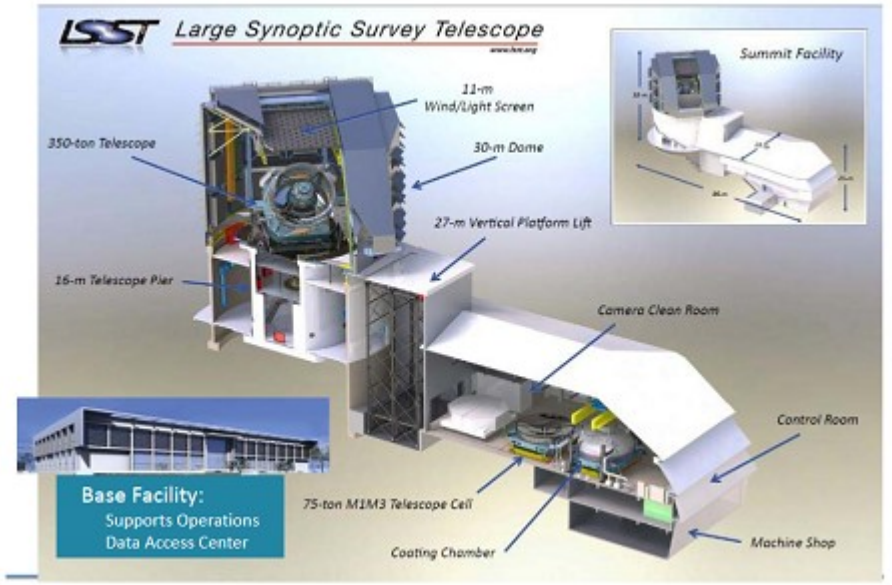




LSS surveys (past, current, future)

7) LSST: The Large Synoptic Telescope (2020??)
Now the Vera C. Rubin Observatory

https://www.lsst.org/
ArXiv: 0912.0201

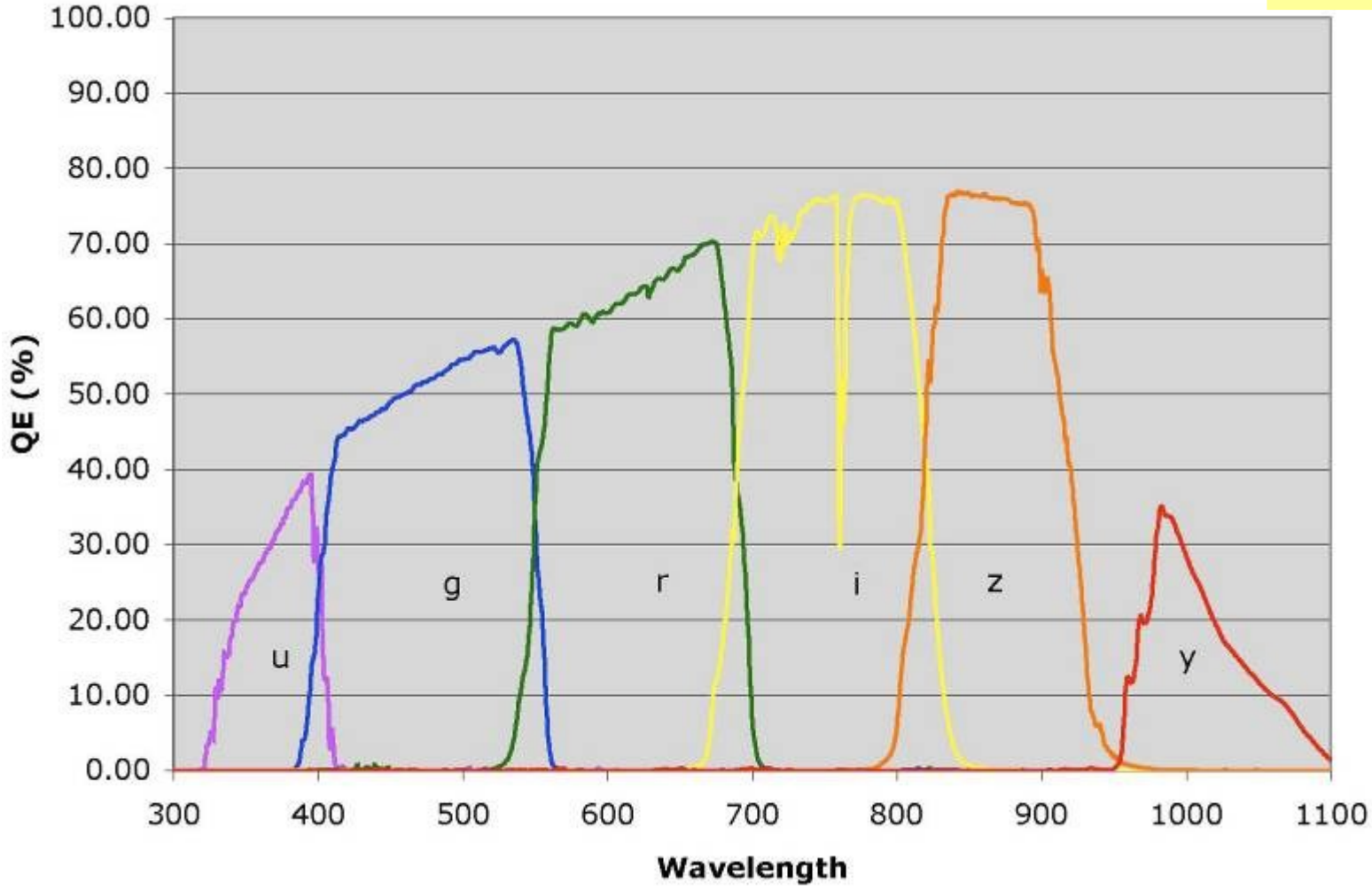


Instruments and components
i) Telescope at Cerro Pachon, Chile
ii) 9.6 sq degrees field of view
iii) 3.2 Gigapixels

Objectives:
i) Supernovae, GRBs
ii) Asteroids, Comets and motions of stars!
iii) Mapping the Milky Way (tidal streams and Galactic structure)
iv) DE and DM: Lensing, DE properties (w, γ) etc
v) Overall ~37 billion objects

LSS surveys (past, current, future)

https://www.lsst.org/
arXiv: 0912.0201

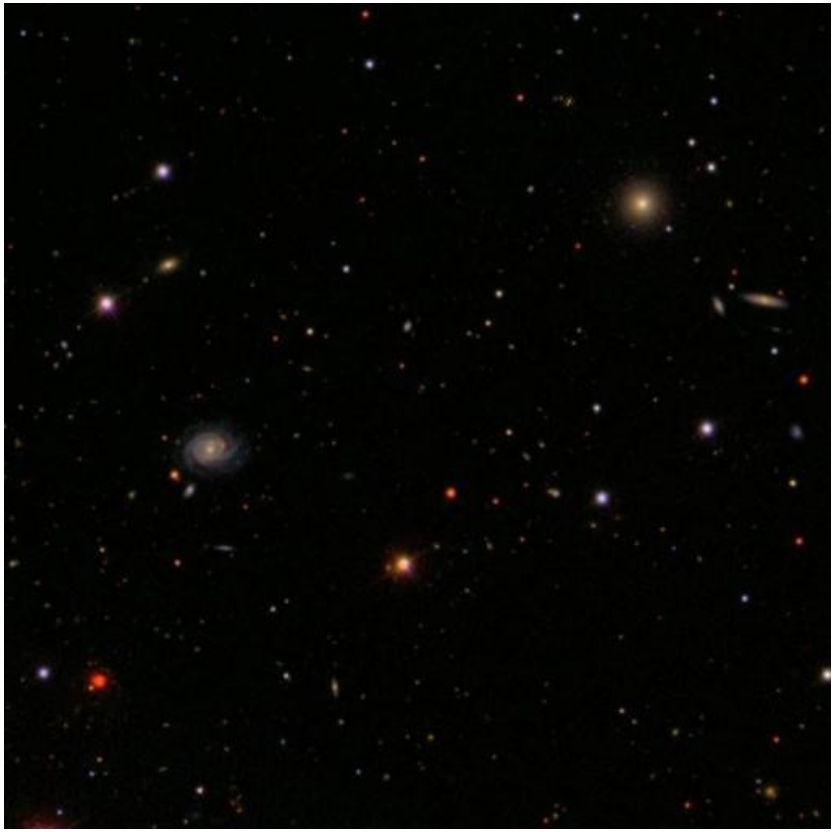


LSS surveys (past, current, future)

Comparison of LSST with other surveys:

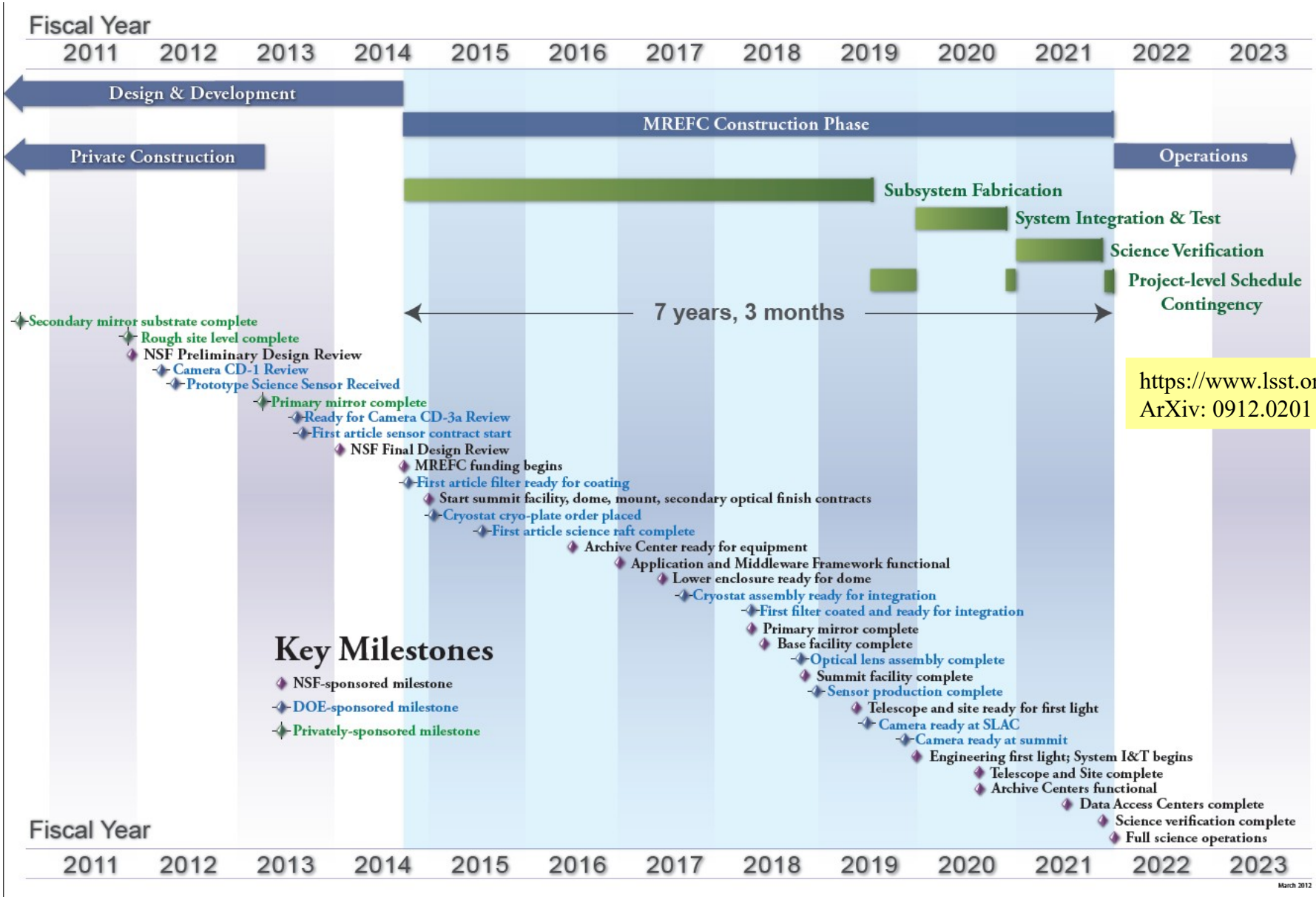
https://www.lsst.org/
ArXiv: 0912.0201

Left: SDSS



Right: LSST (simulation)

LSS surveys (past, current, future)



https://www.lsst.org/
ArXiv: 0912.0201

Summary

1) History and motivation for surveys in astro/cosmo.

2) Hitchhikers guide to designing a survey!

3) Synopsis of CMB surveys (COBE, WMAP, Planck, Bicep, Litebird).

4) Synopsis of LSS surveys (2dF, 6dF, SDSS, WiggleZ).

5) The future is bright, lots of activity happening (DES, Euclid, LSST).