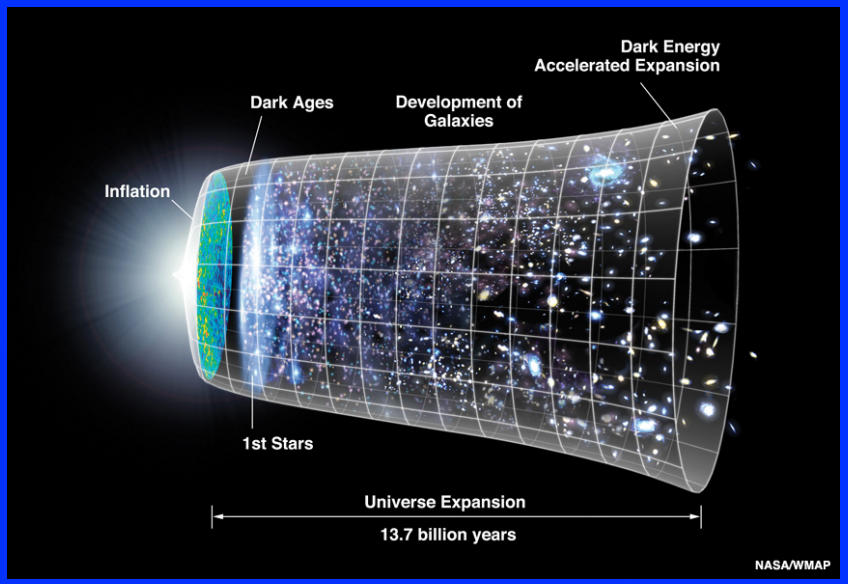
THE FUTURE OF OBSERVATIONAL COSMOLOGY

Prospects for understanding Dark Energy

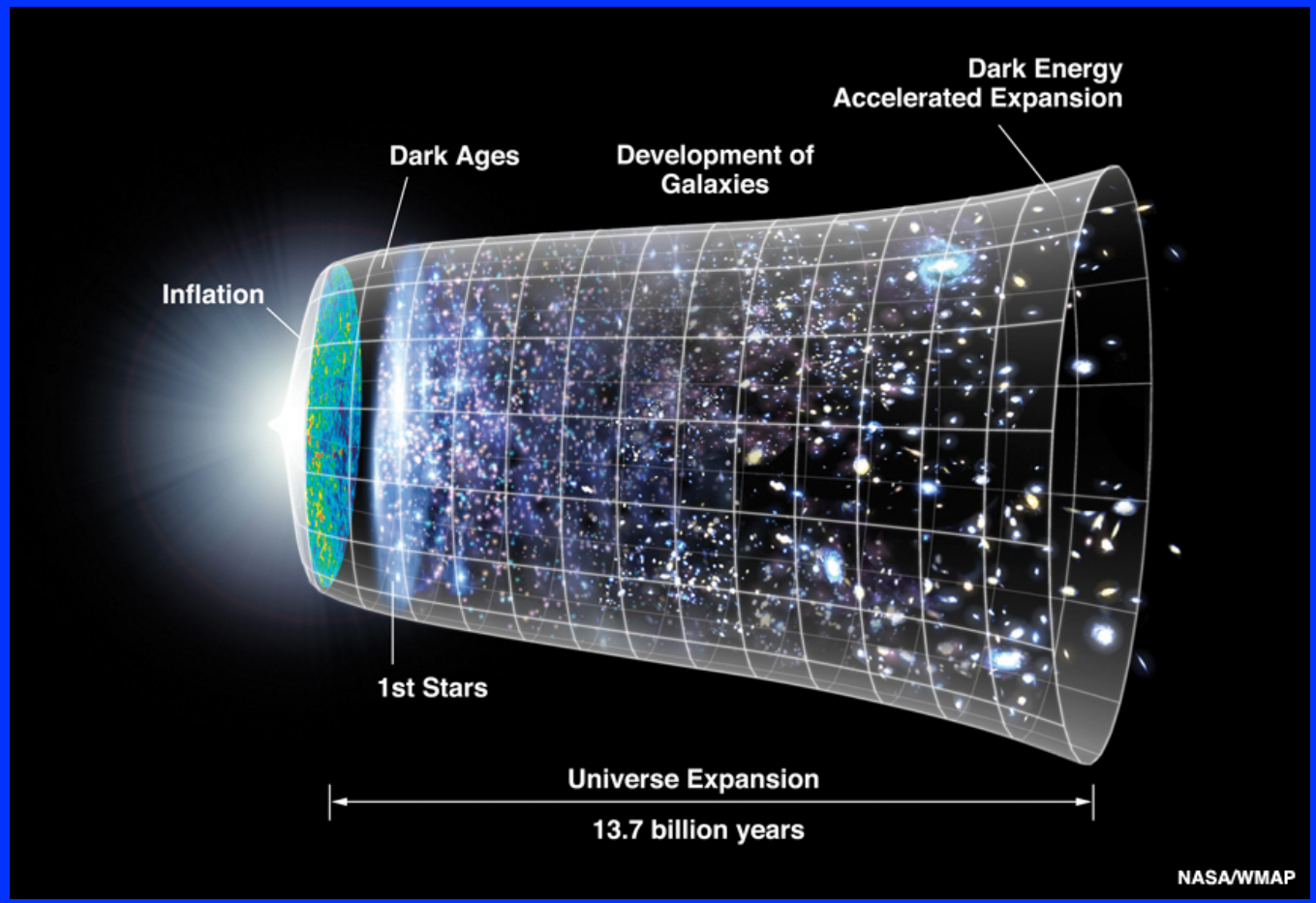


Reynald Pain
CNRS/IN2P3, Paris

UNDERSTANDING DARK ENERGY

- Dark Energy against Gravity
- How to probe Dark Energy
- Current constraints on DE Equation of State
- Ongoing and future (large) DE projects

How did the initial fluctuations evolve in the structures we see today?



THREE EPOCHS, EACH DOMINATED BY DIFFERENT PHYSICS

- t~10^{-35} sec: Early acceleration, *Inflation*
- 300,000 years < t < 8 B-yrs: Growth of Structure, fueled by *Dark Matter*
- t > 8 B-yrs: Late Acceleration, associated with *Dark Energy*

described by GR : $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

Observed late-time acceleration points to *Dark Energy* that remains roughly constant

Equation of State of Dark Energy : $w = p/\rho \sim -\text{constant}$

COSMOLOGICAL CONSTANT/VACUUM ENERGY

Constant Energy Density
associated with empty space

$$T_{\mu\nu} = g_{\mu\nu} \frac{\Lambda}{8\pi G}$$

and $w=p/\rho = -1$

Could it be quantum fluctuations ?
which are expected to contribute to the vacuum energy

But expected amplitude is (much) too large
(by 120 orders of magnitude..)

Another Possibility: Scalar Field

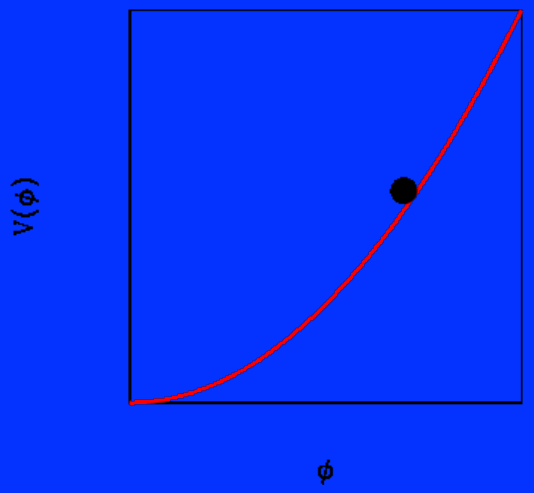
Require roughly constant energy density

Potential energy larger than kinetic energy

Mass must be very small: $m<10^{-33}$ eV (Hubble rate today) or else field oscillates

Slowly rolling field has equation of state *w* different from -1

$$\ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0$$



BUT MAYBE GR DOES NOT DESCRIBE THE EXPANSION

General Relativity has to be modified …

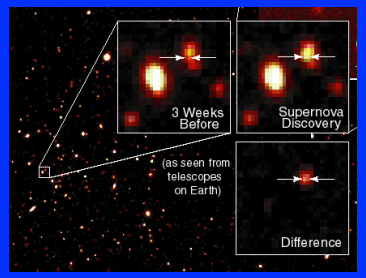
and the acceleration equation generalizes to:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \left[\frac{\partial f}{\partial R}H^2 - \frac{f}{6} - \frac{\partial \ddot{f} / \partial R}{2}\right]$$

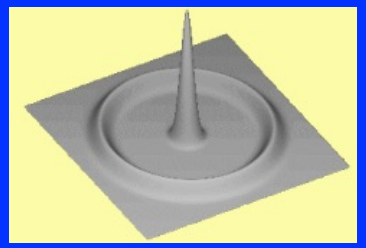
Get acceleration if these terms are positive

WILL WE BE ABLE TO TELL? : DARK ENERGY PROBES

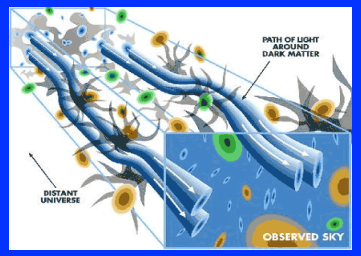
Growth of Structure - Expansion History



Supernova Brightness



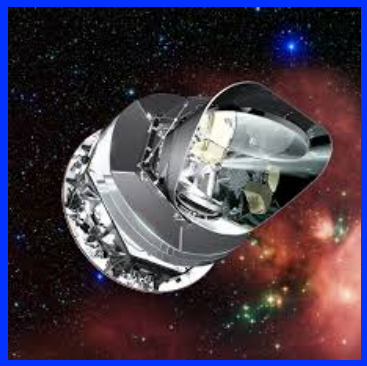
Baryon Acoustic Oscillations



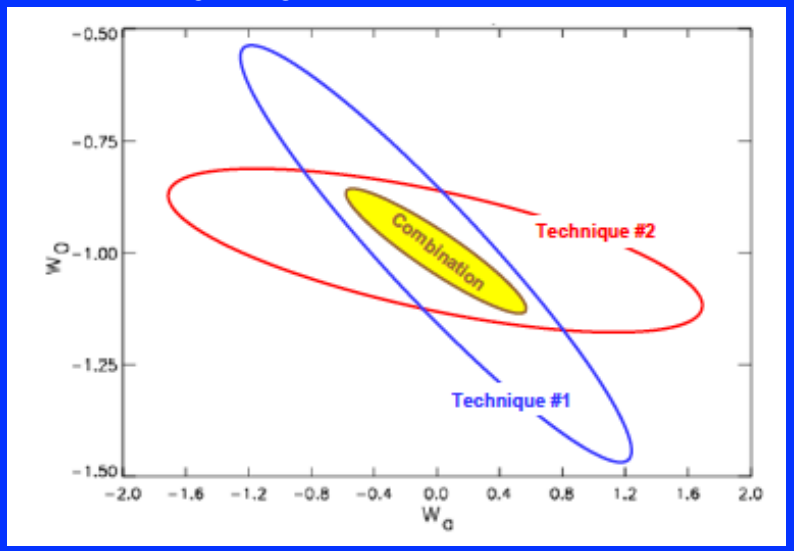
Gravitational Lensing

Galaxy Cluster Abundance

Cosmic Microwave Background
precise cosmology
(Planck 2015)



$w(z)=w_0+w_a z/(1+z)$



Constraints on the DE EoS : w_0, w_a

WHERE DO WE STAND TODAY?

The most precise constraints on DE today come from measurements of the expansion history from Supernovae and Baryon Acoustic Oscillations

- BAO from The Sloan Digital Sky Survey (SDSS)
- SN from SDSS and The SuperNova Legacy Survey (SNLS)

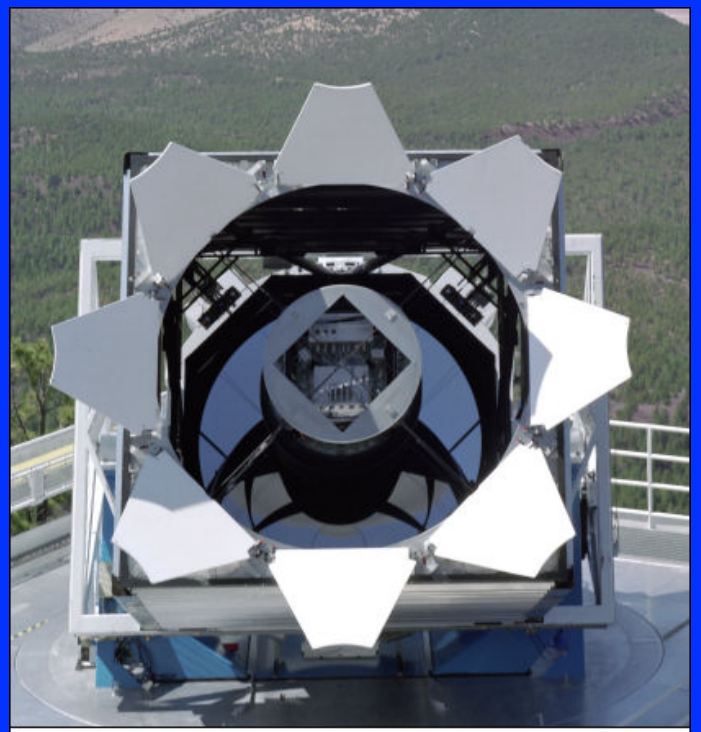
SDSS : The Sloan Digital Sky survey

Imaging and spectroscopic survey

Dedicated 2.5 m telescope
(Apache Point, New Mexico)

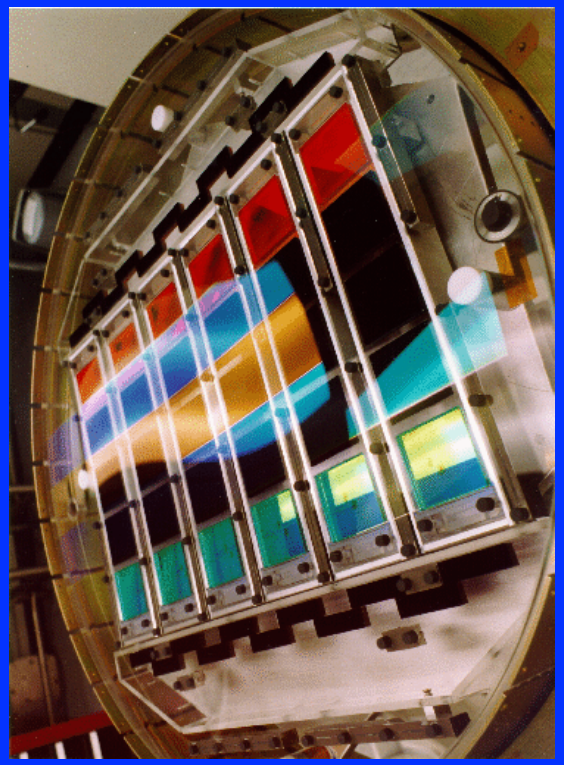
Reached 8000 deg^2
~700,000 galaxy spectra
+ quasars, stars, ...

Since 2000 in 4 phases producing
Images, spectra & catalogs
~ once a year

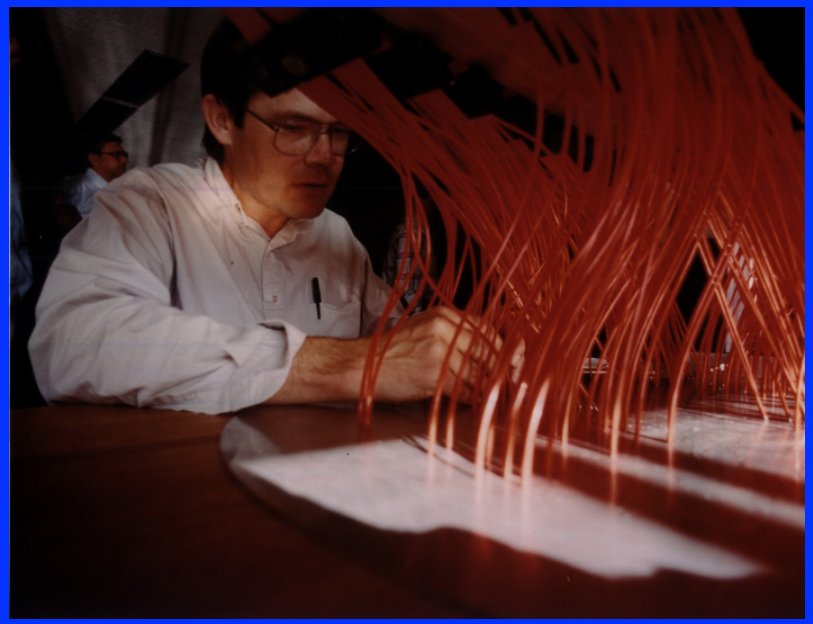


SDSS SURVEY TELESCOPE

SDSS IMAGING CAMERA AND SPECTROGRAPH



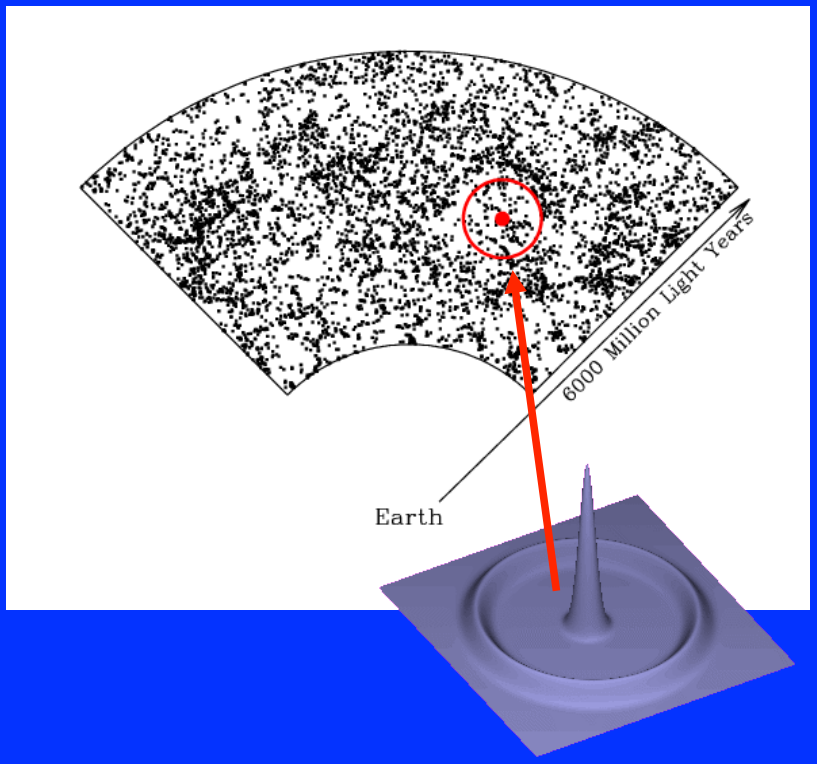
Drift scanning (56 s/band)
~ 225 deg^2 per night



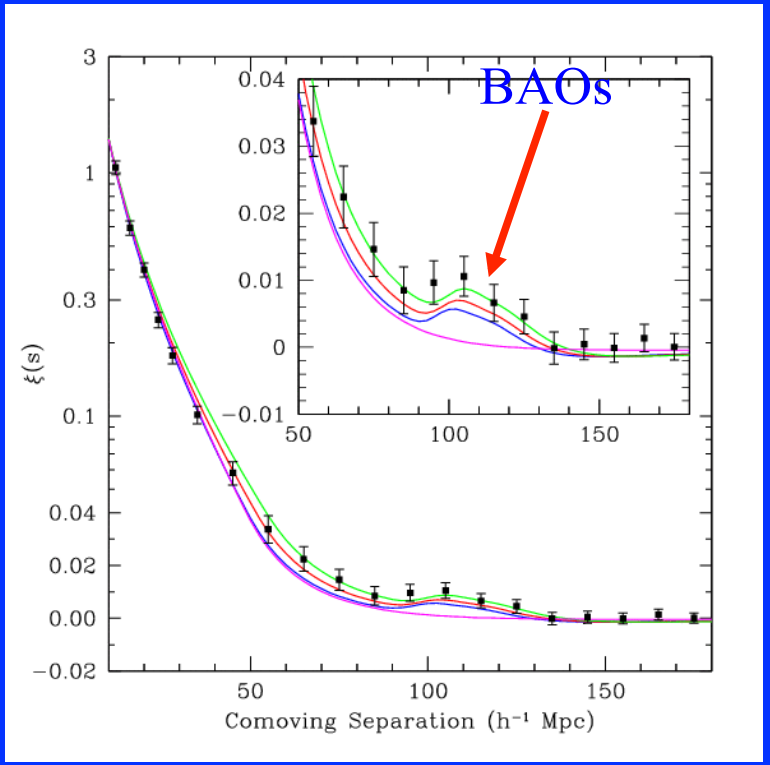
- Fiber-fed spectrograph : 7 deg^2 field-of-view.
  ~ 600 objects per pointing
- Fibers (manually) plugged in precision-drilled plates

SDSS : CORRELATION FUNCTION OF LRGS

55000 Luminous Red Galaxies
Over 4000 deg^2 up to z~0.48
<z> = 0.35



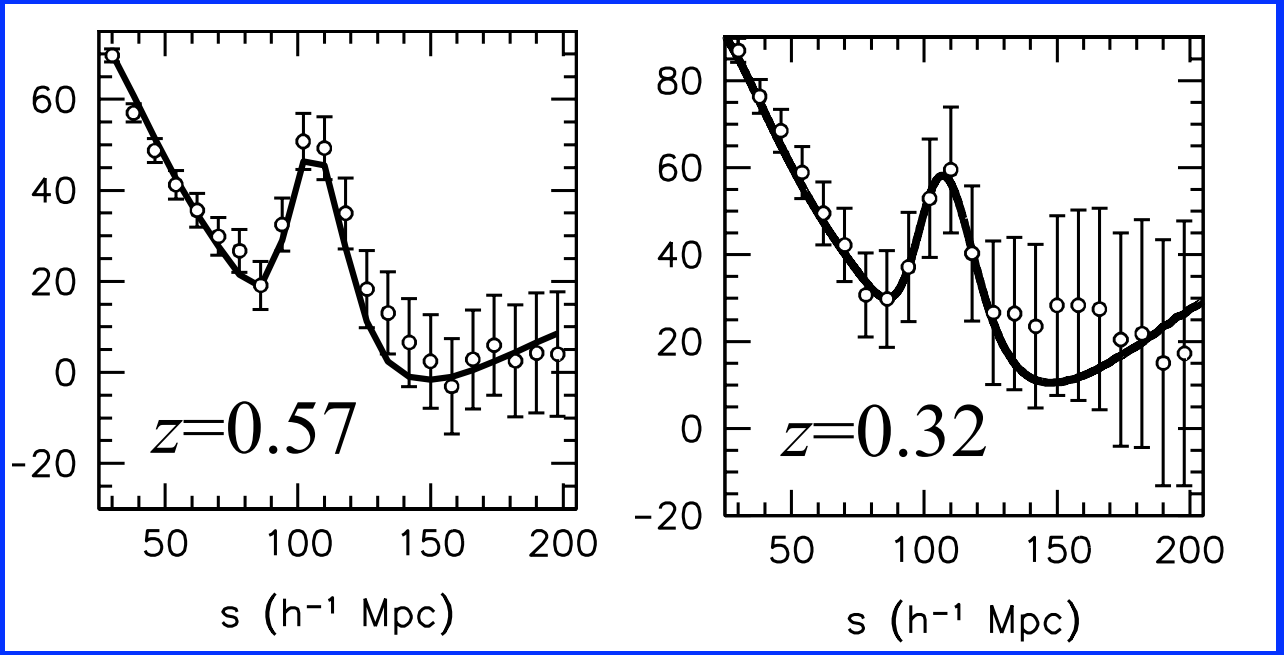
Eisenstein et al [SDSS Collab.] 2005



SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS)

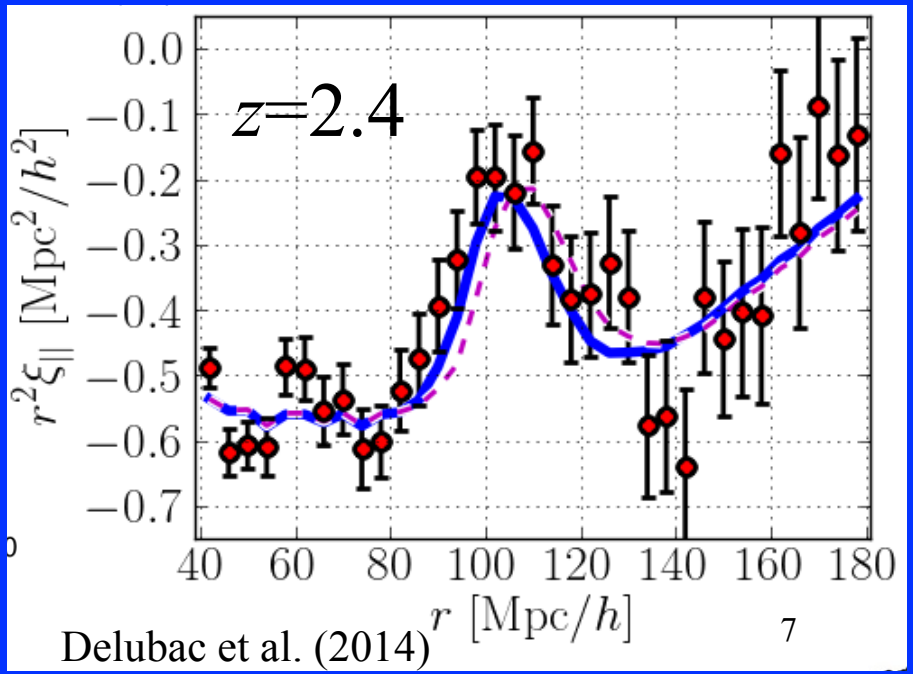
2 million targets over 10000 square degrees

2.1% distance measurement to z=0.32 (1% to z=0.57)



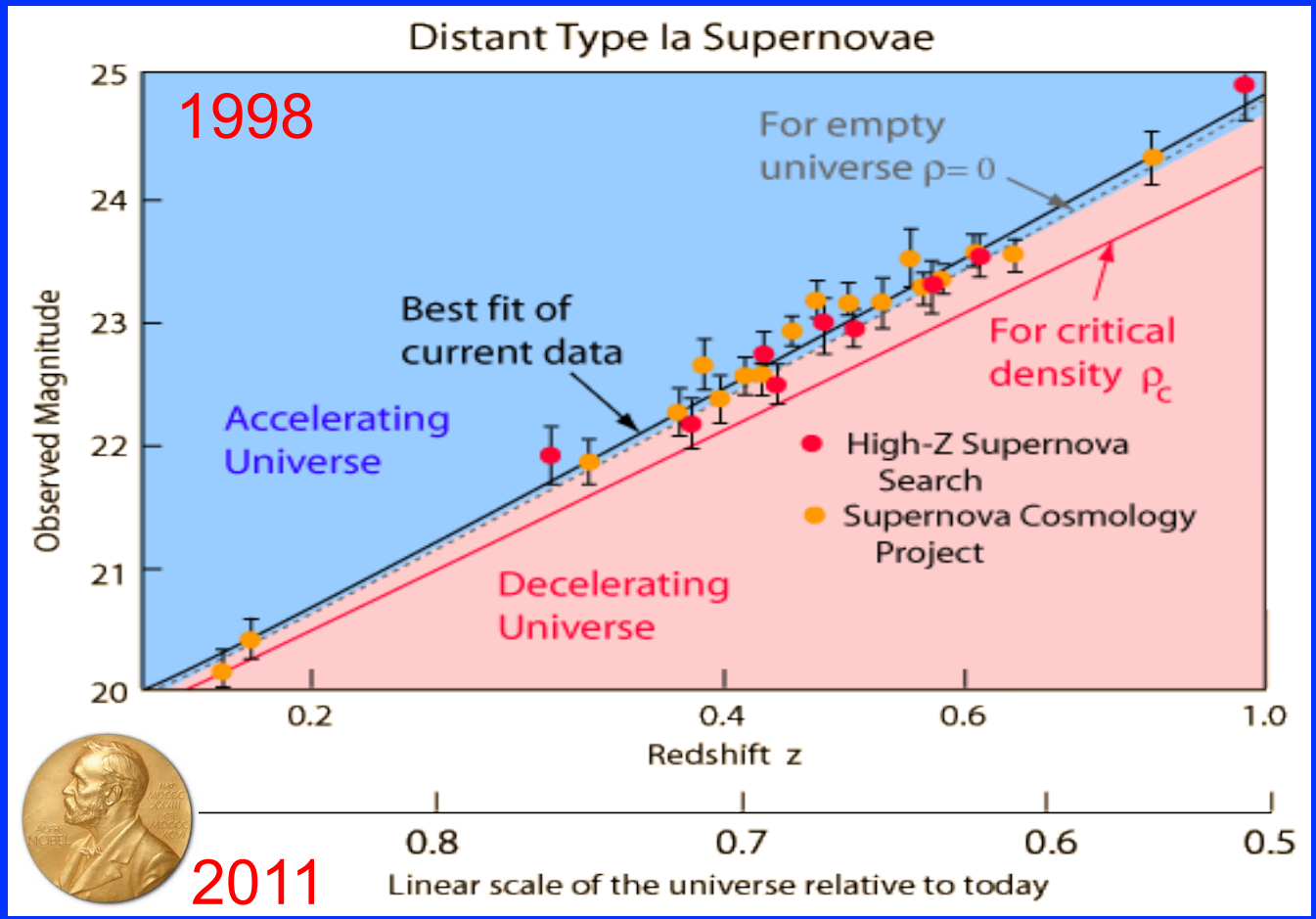
BAO DETECTION IN THE INTERGALACTIC MEDIUM

- Use Lyman α Forest from 160000 quasars to produce a map of intergalactic neutral hydrogen
- BAO detection at 5 σ : a 3% measurement of H at z=2.4



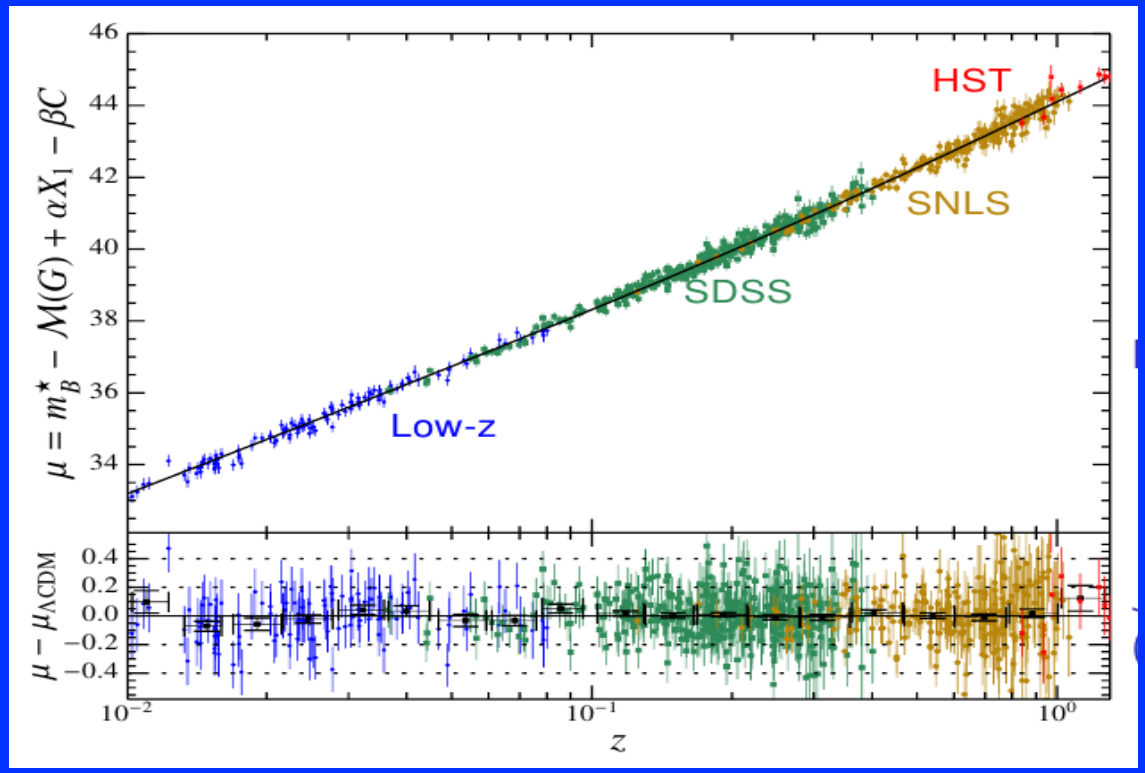
Delubac et al. (2014)

The Hubble diagram of Type Ia Supernovae

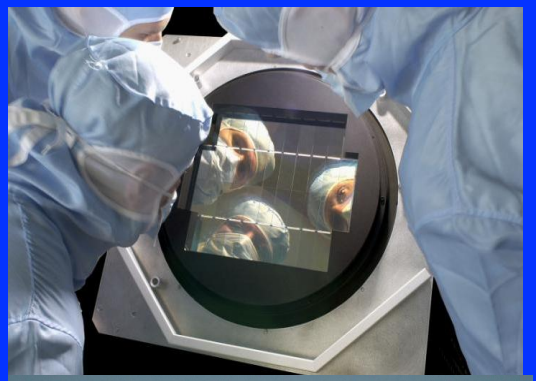


The Hubble diagram of Type Ia Supernovae

Latest High-z Supernova compilation (JLA : 2014)

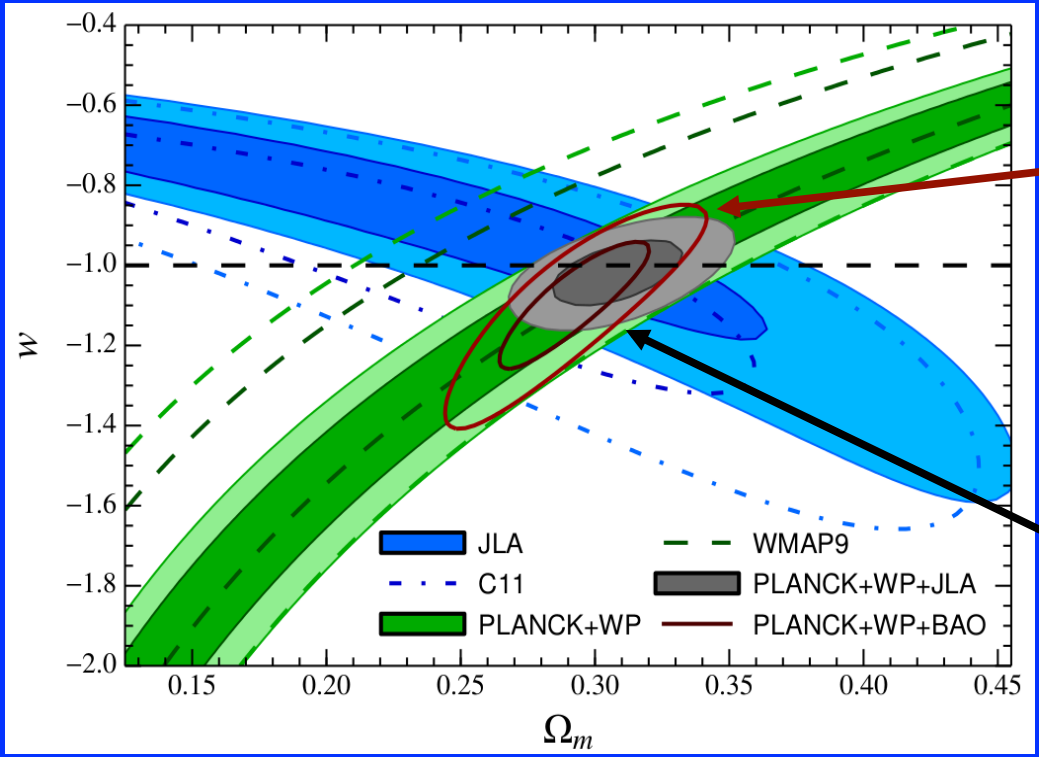


4m telescope with ~deg2 camera for imaging



8m telescopes for SN id and z

CURRENT CONSTRAINTS IN A FLAT wCDM MODEL



Betoule et al, 2014

Planck + BA0

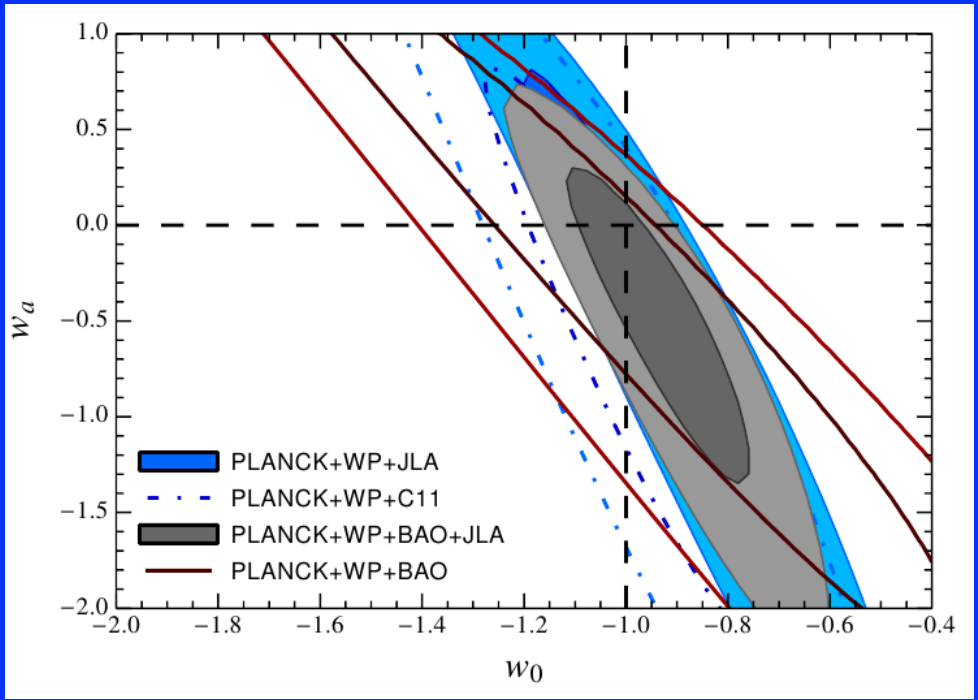
w = -1.01 ± 0.08

Planck + SNe

w = -1.018 ± 0.057

IS DARK ENERGY THE COSMOLOGICAL CONSTANT ?

We now start to put (week) constraints on w(z)



A World Wide Effort to Understand Dark Energy : ongoing and planned surveys

Sloan Digital Sky Survey (SDSS), including the Baryon Oscillation Spectroscopic Survey (BOSS) and e-BOSS, – Canada France Legacy Survey (CFHTLS), including the SNLS – DEEP II Redshift Survey - Virmos VLT Deep Survey (VVDS) - Panoramic Survey Telescope and Rapid Response System (Pann Starrs), 2 degrees Field (2DF) – 6 degree field (6DF) - Palomar Transient Factory (PTF) – Dark Energy Survey (DES) – VLT survey telescope (VST) – WiggleZ Dark Energy Survey (WIGGLEZ) – Stromlo Southern Sky Survey (SkyMapper), Large Synoptic Survey Telescope (LSST) – 2 MASS near IR survey – UKIRT, UKIDS Survey - Visible and Infrared Survey Telescope for Astronomy (VISTA) – Vista Hemisphere Survey (VHS) – Subaru HSC and PFS surveys – South Pole Telescope (SPT) – Antartica Survey Telescopes (AST) – Dark Energy Spectroscopic Instrument (DESI) – Euclid – Wide Field Infrared Survey Telescpe (WFIRST), …

+ Radio (21 cm) surveys such as the planned Square Km Array (SKA)

4 EXAMPLES : DES, DESI, LSST, EUCLID, …

- DES : The Dark Energy Survey
- DESI : The Dark Energy Spectroscopic Instrument
- LSST : The Large Synoptic Survey Telescope
- The Euclid space project

An important goal of these surveys is to see whether the cosmological constant (w_0=-1; w_a=0) drives acceleration

Use Figure of Merit =1/(area of w_0-w_a ellipse) [~20 today]

The Dark Energy Survey

Build a new 3 deg^2, 570 Mpix camera (DECam) and Data Management system, and carry out two multi-band optical surveys (~500 nights):

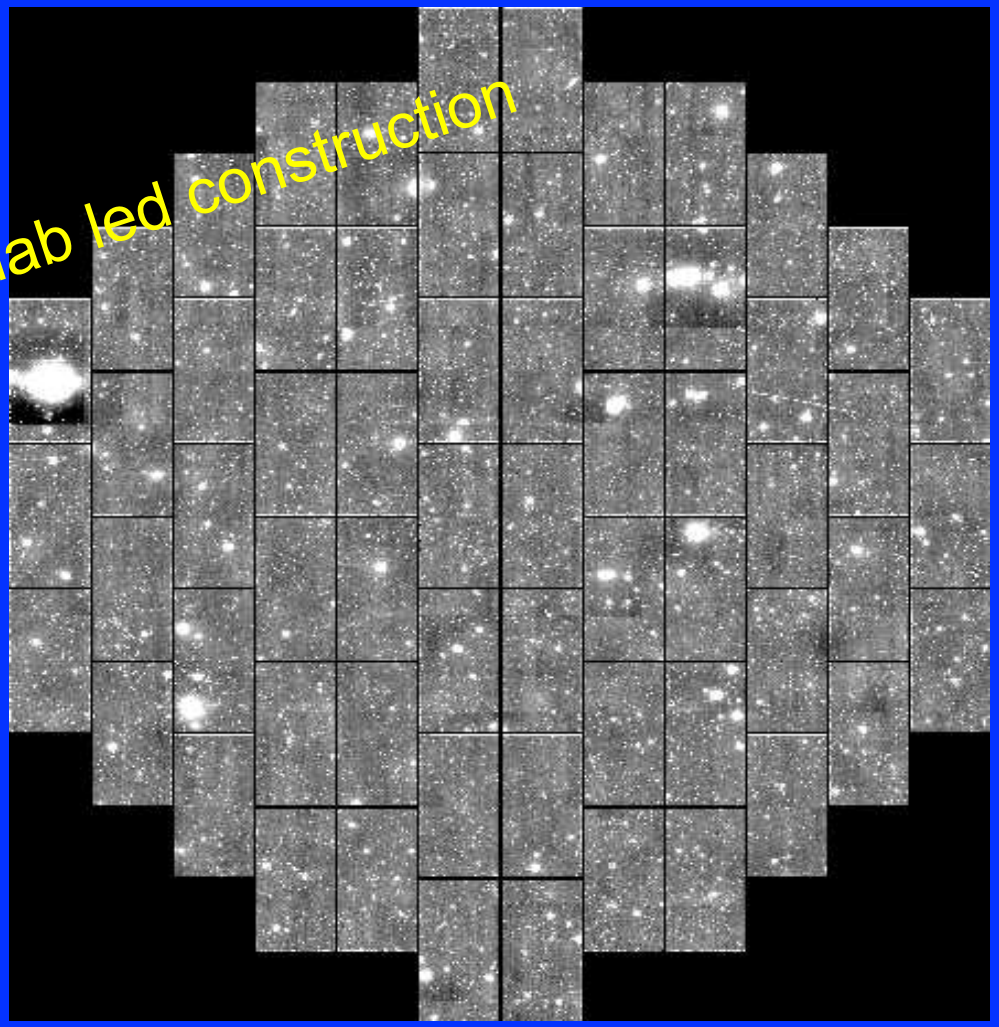
- 5000 deg^2 to 24th magnitude in grizY bands
- 30 deg^2 repeat scan SN survey (~10% of observing time)

Four complementary approaches to DE science:

- Galaxy cluster counts
- Weak gravitational lensing and cosmic shear
- Large scale structure / baryon acoustic oscillations
- Type Ia supernova

Factor of 10 more cosmic volume than SDSS, and over 1 PB of public image and catalog data

DECAM (LARGE) IMAGES



Each DES field contains approximately:

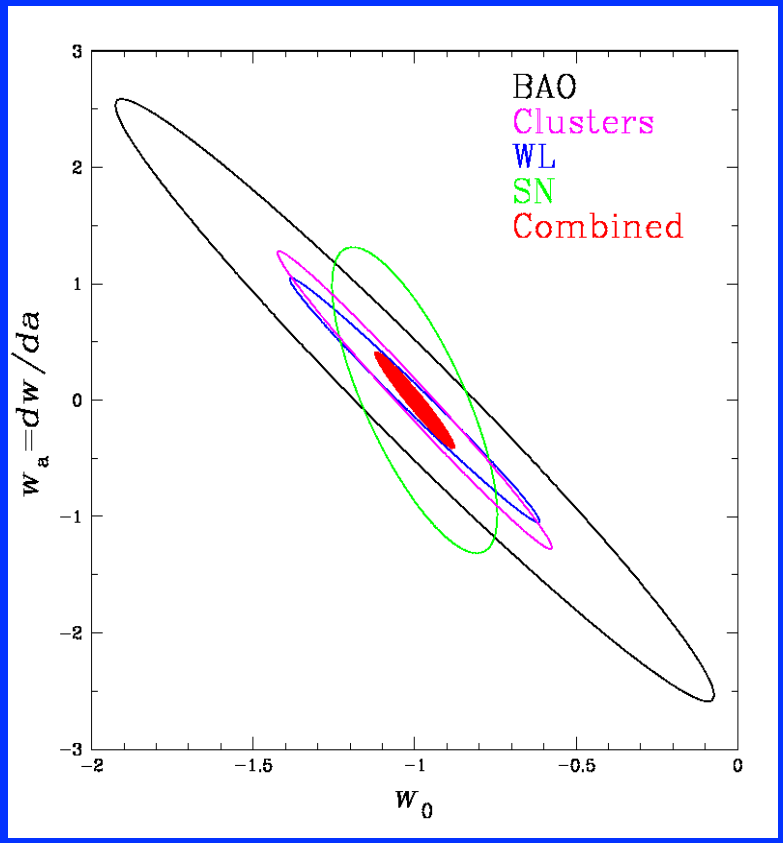
- 200,000 galaxies
- 100 galaxy clusters

6 yr data taking : 2013-2018

← simulated image

DES EXPECTED PRECISION ON W_0, W_A

- Dark Energy Survey will measure fluxes in 5 bands to map the Universe out to ~10^7 Light-yr away (*z=1)* in 2.5 dimensions (*photometric)*
- Will map 5000 square degrees with more than 10^8 galaxies
- Clusters, SN, WL, 2.5D BAO
- Increase Figure of Merit by ~5

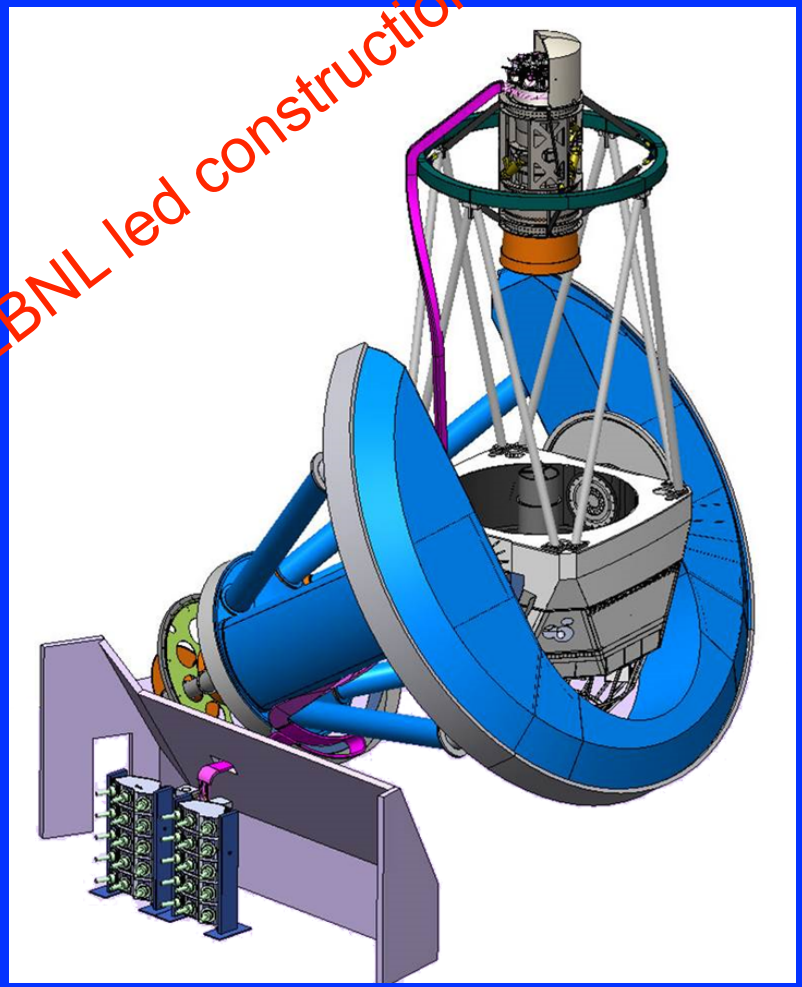


DESI : Dark Energy Spectroscopic Instrument

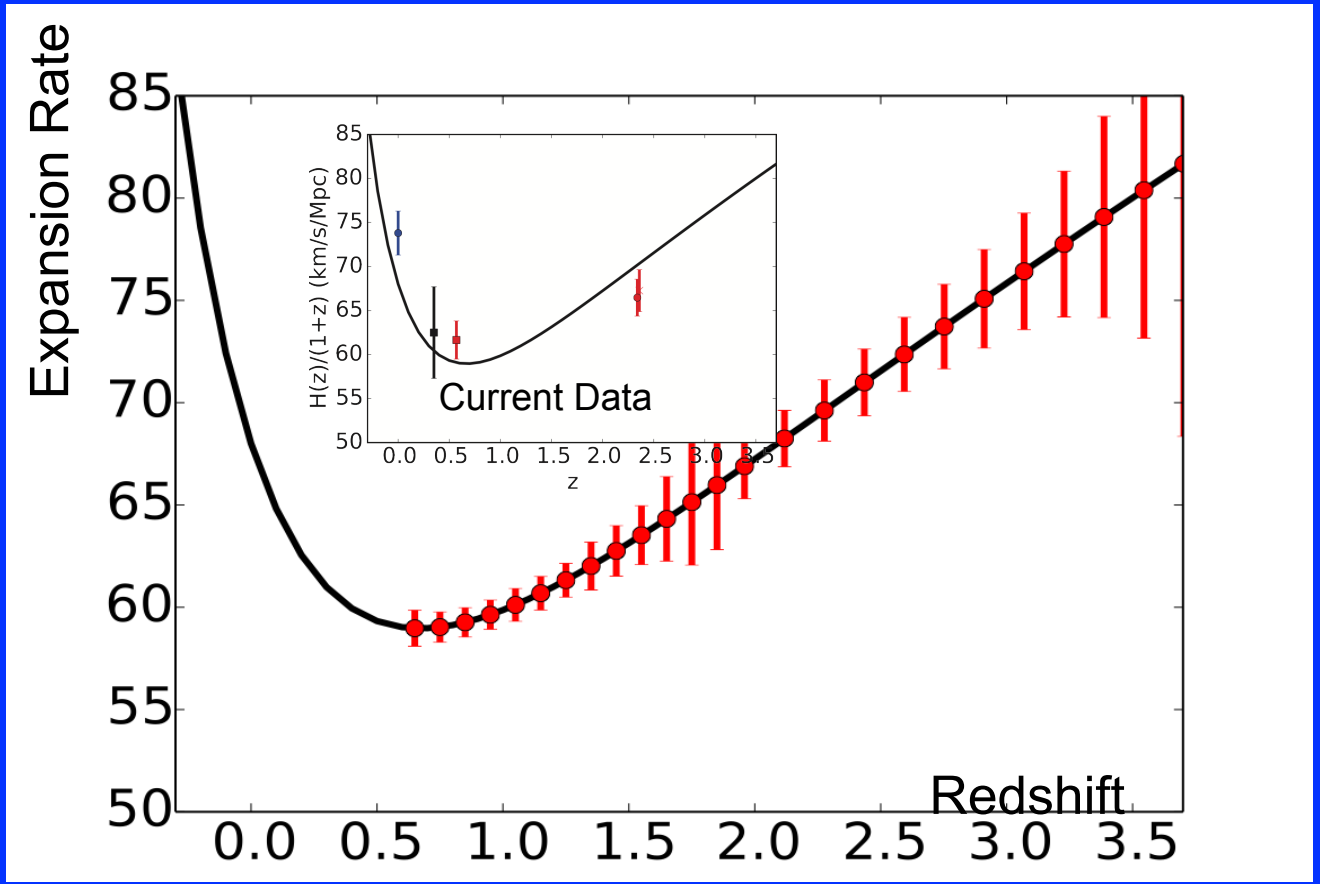
- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view
- 10 spectrographs

- will be installed on the Mayall 4m Telescope at Kitt Peak, Tucson, AZ

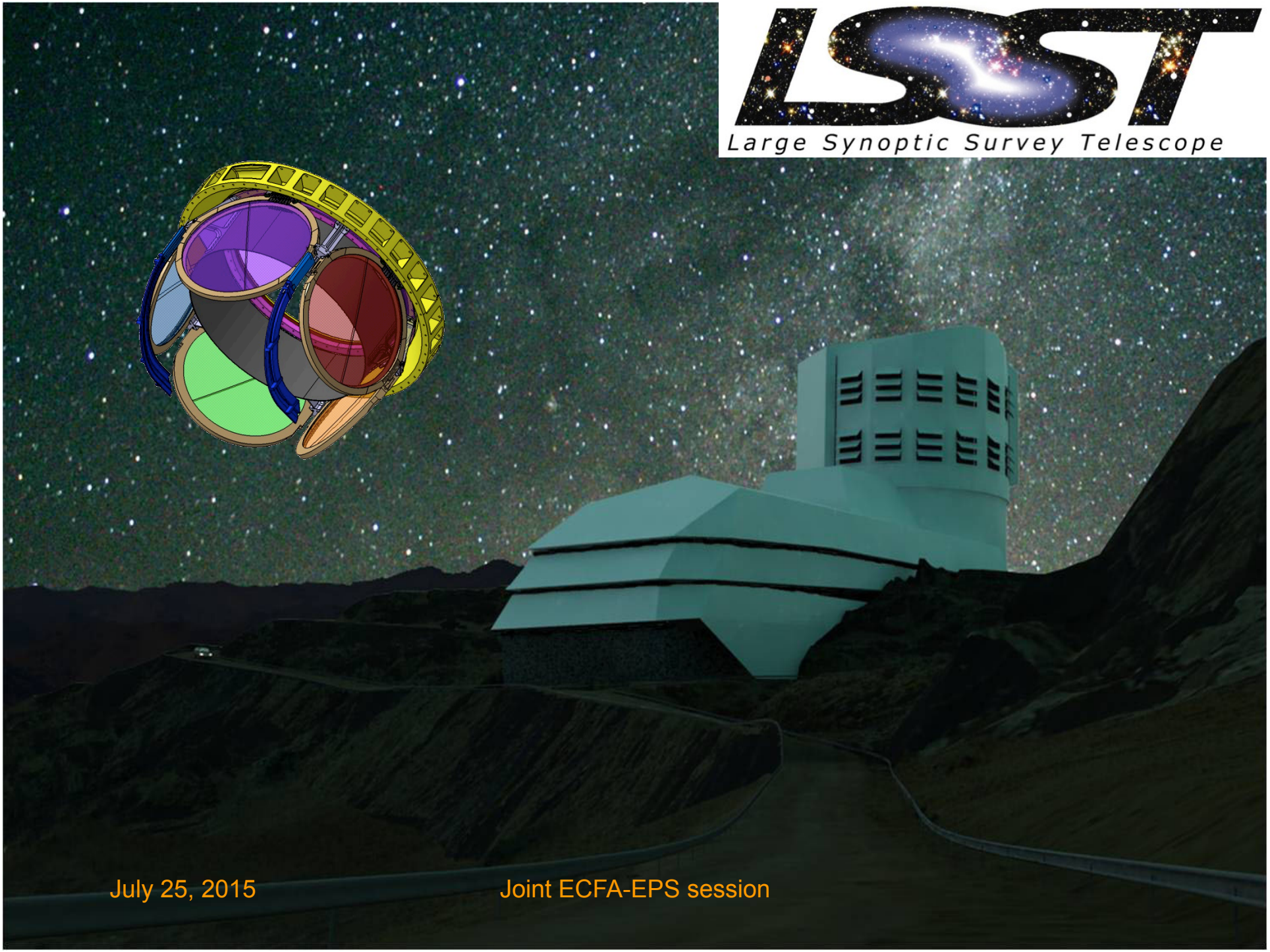
- Expect data taking : 2018-2022



(EXPECTED) DESI BAO HUBBLE DIAGRAM

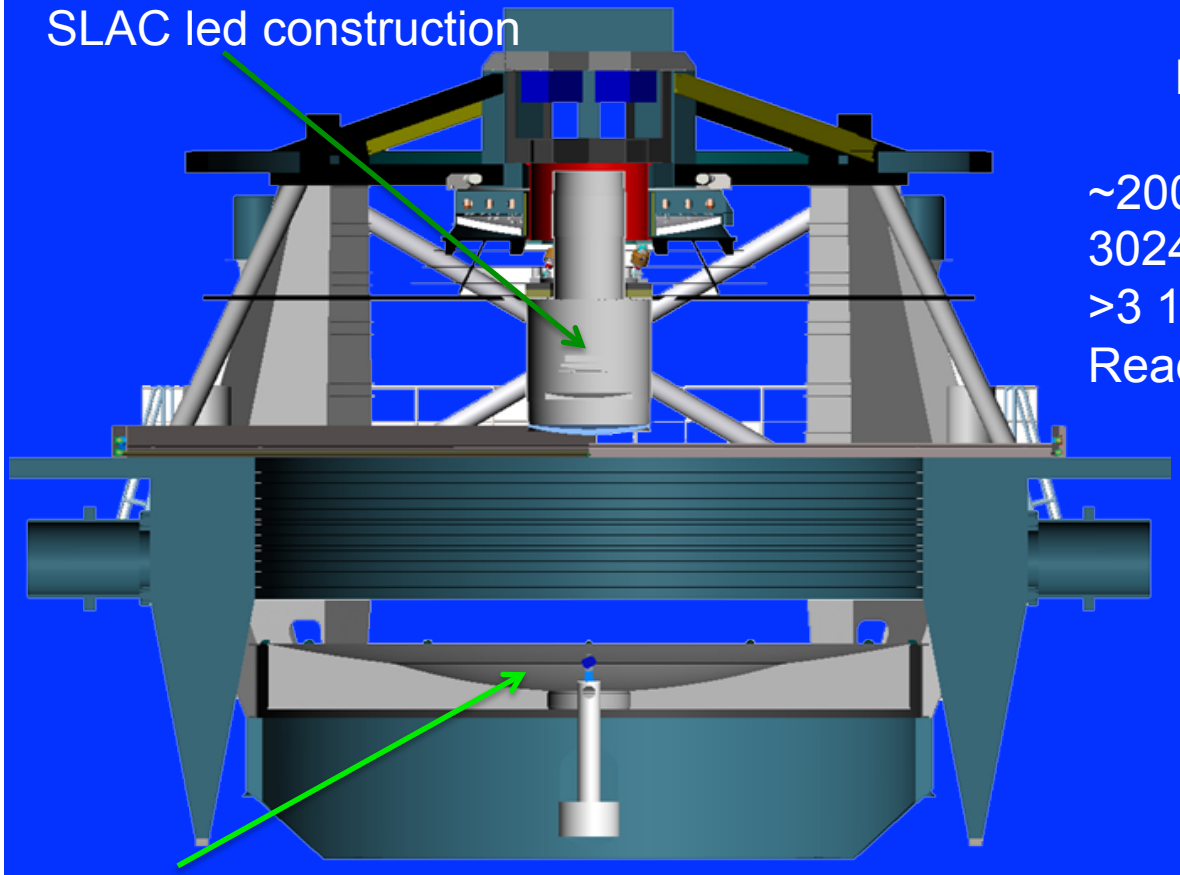


w_0/w_a FoM : ~300-600


LSST
Large Synoptic Survey Telescope
July 25, 2015
Joint ECFA-EPS session

LSST : Wide Deep and Fast

Camera
SLAC led construction

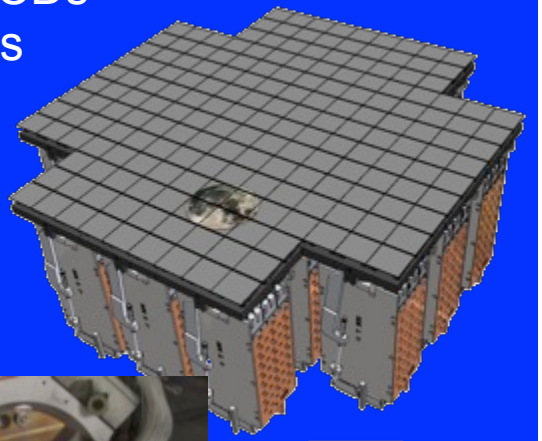


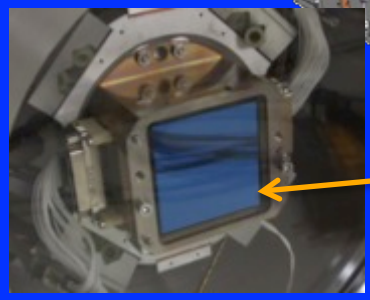
M1M3 primary
(8.4m) &
Tertiary mirrors

Moving Structure 350 tons
60 tons optical systems

Field of view :
3.5 deg (9.6 deg^2)
Focal plane diameter : 64 cm

~200 4kx4k CCDs
3024 Channels
>3 10^9 pixels
Readout: 2s





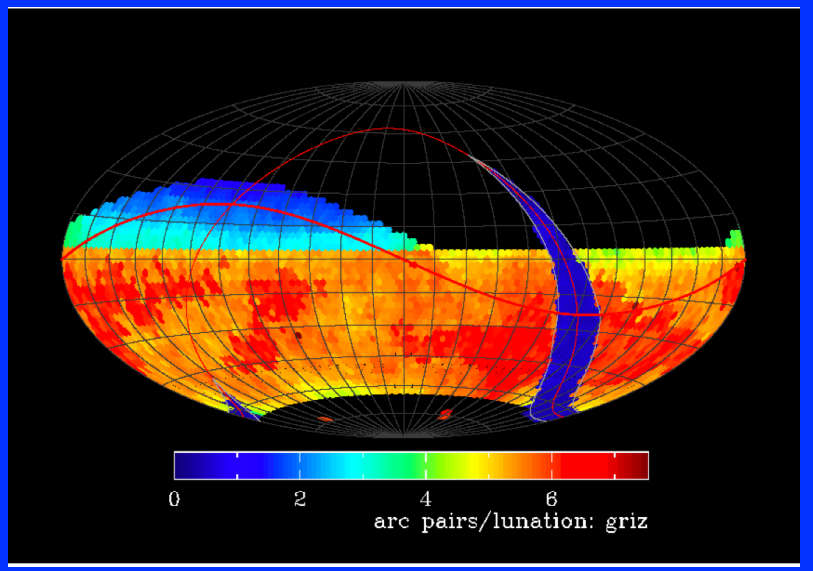
10 µm pixels CCDs
UV to NIR sensitive

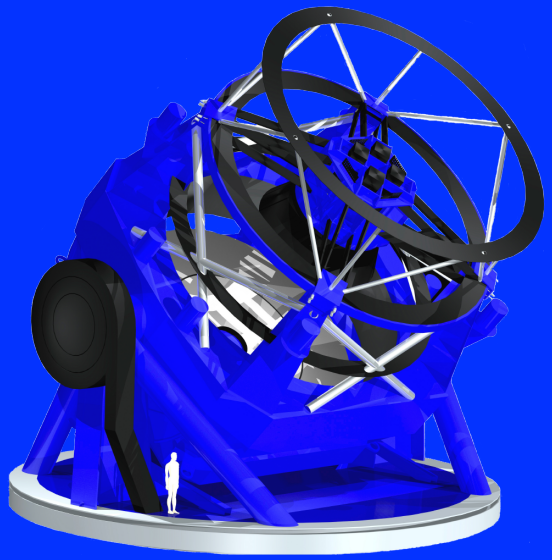
A SINGLE OBSERVATION PLAN & MANY SCIENCE TOPICS

- 6-band Survey: ugrizy 320–1080 nm
- Sky area covered: > 20,000 deg2,
  0.2 arcsec / pixel

- Each 9.6 sq.deg FOV revisited ~ 1000 times
  during 10-Year Duration:

- Photometric precision: 0.01 absolute; 0.0005 mag repeatability





> $5x10^6$ exposure :
15 s pose + 2 s read + 15 s pose =>
Points to new positions every 37 seconds

15 TB and 10 M transients per night
=> 0.5 Exabyte images total

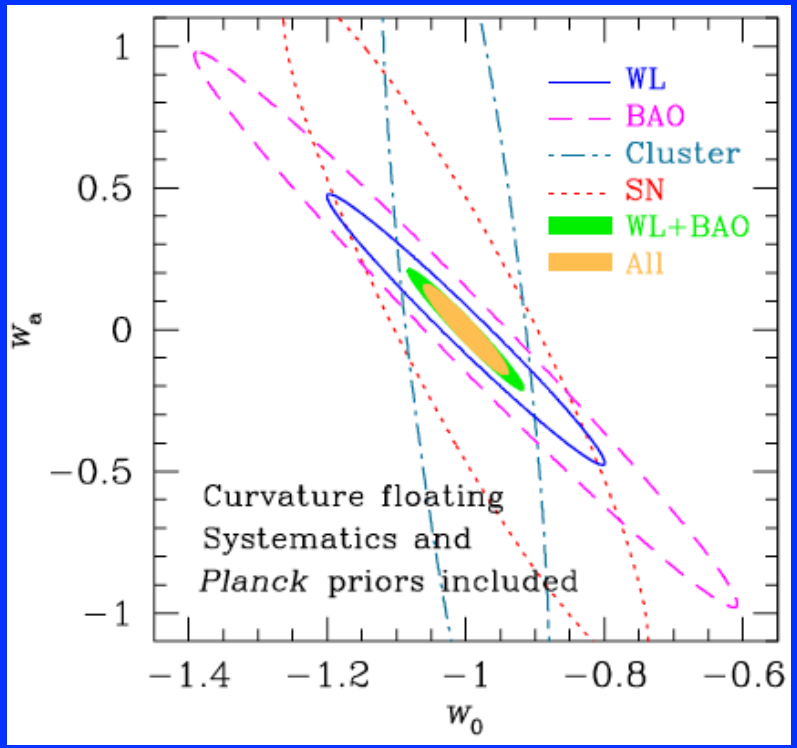
Survey start date : 2022

EXPECTED PRECISION ON DE FROM THE LSST

Will map 20000 square degrees with 4 Billion galaxies

All 4 probes + more

Figure of Merit by 2030 will be close to ~1000

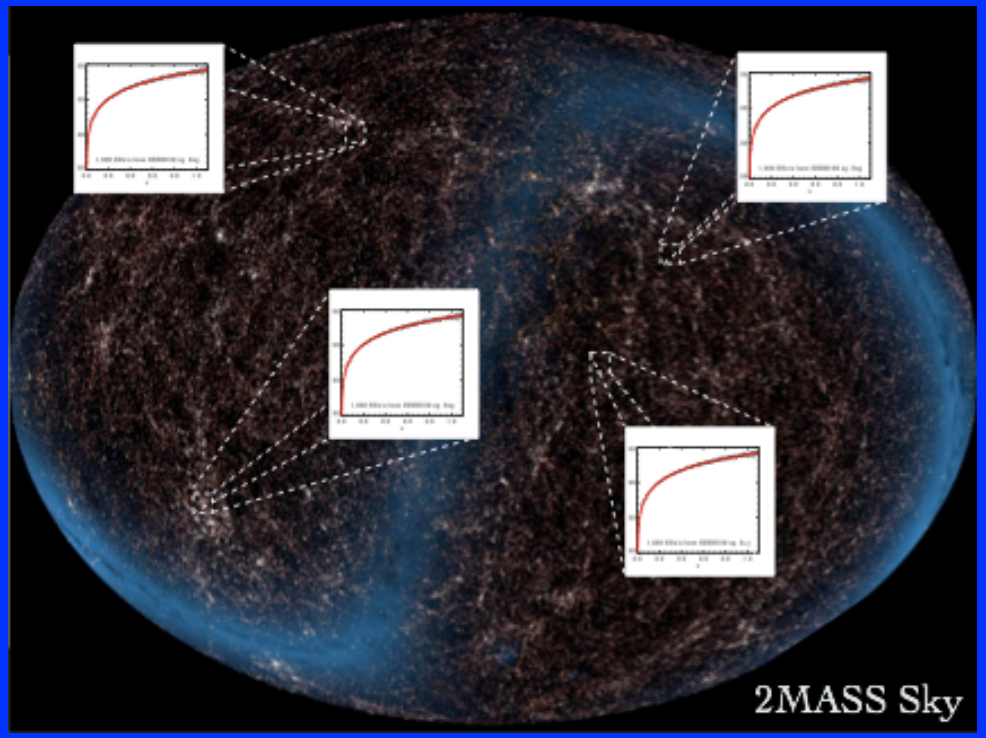


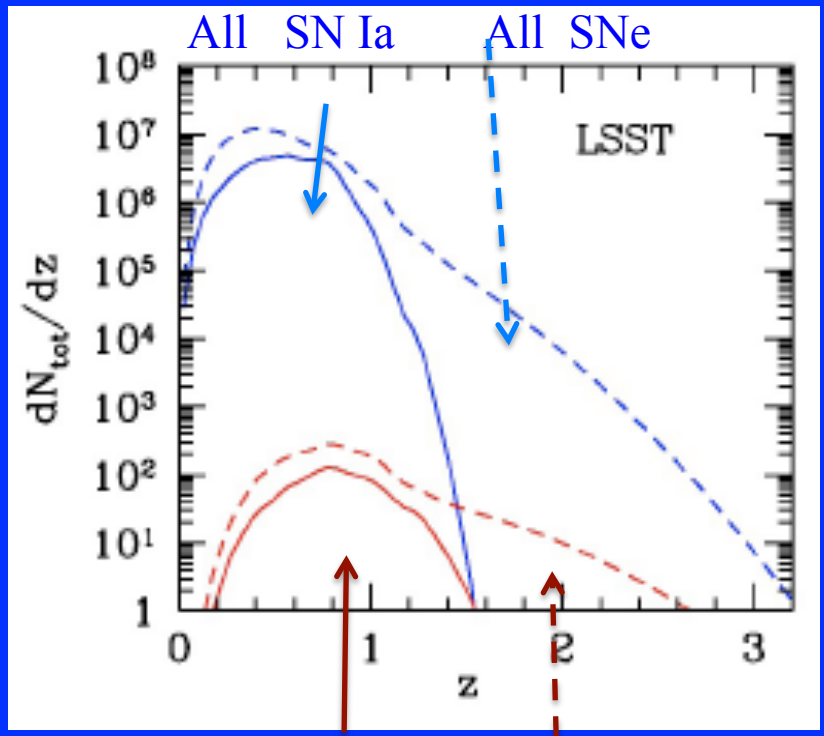
LSST : DE SCIENCE WITH HIGH STATISTICS SN IA

The large SN Ia statistic will allow to build SN Ia Hubble diagram for different directions in the sky.

Will provide time-dependent imaging of an unprecedented sample of rare strong gravitational lensing events.

=> sensitive to H(z) at the lens location



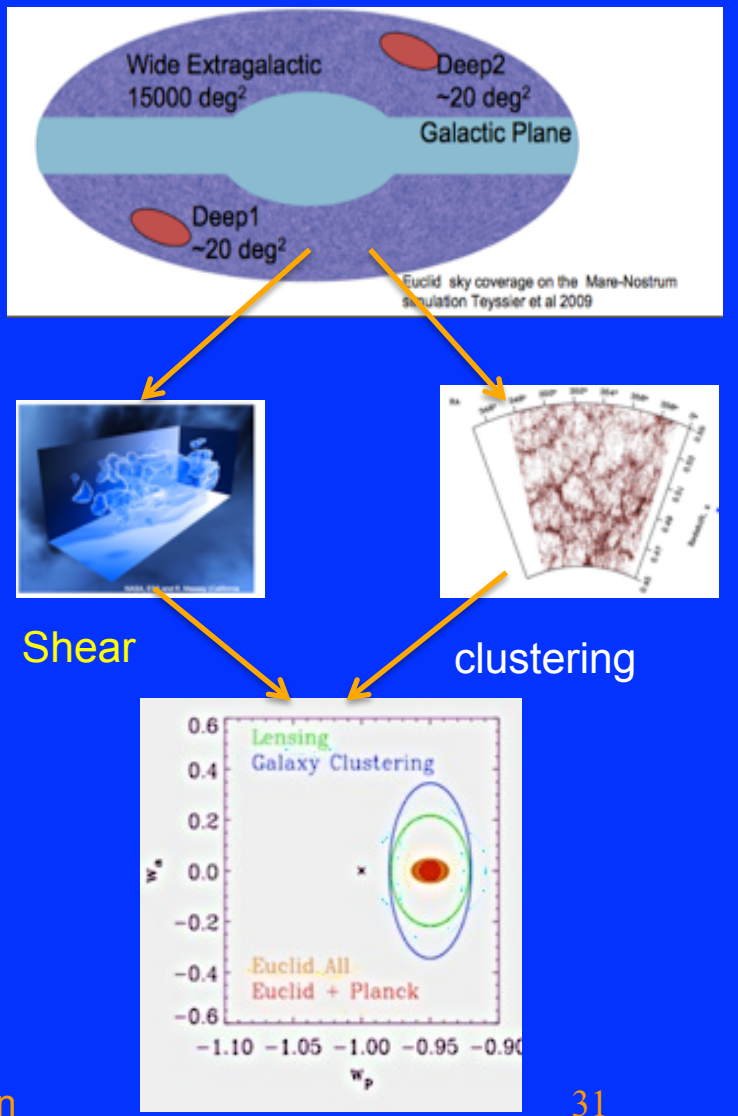


Lensed SN Ia

All Lensed SNe

THE EUCLID SPACE MISSION

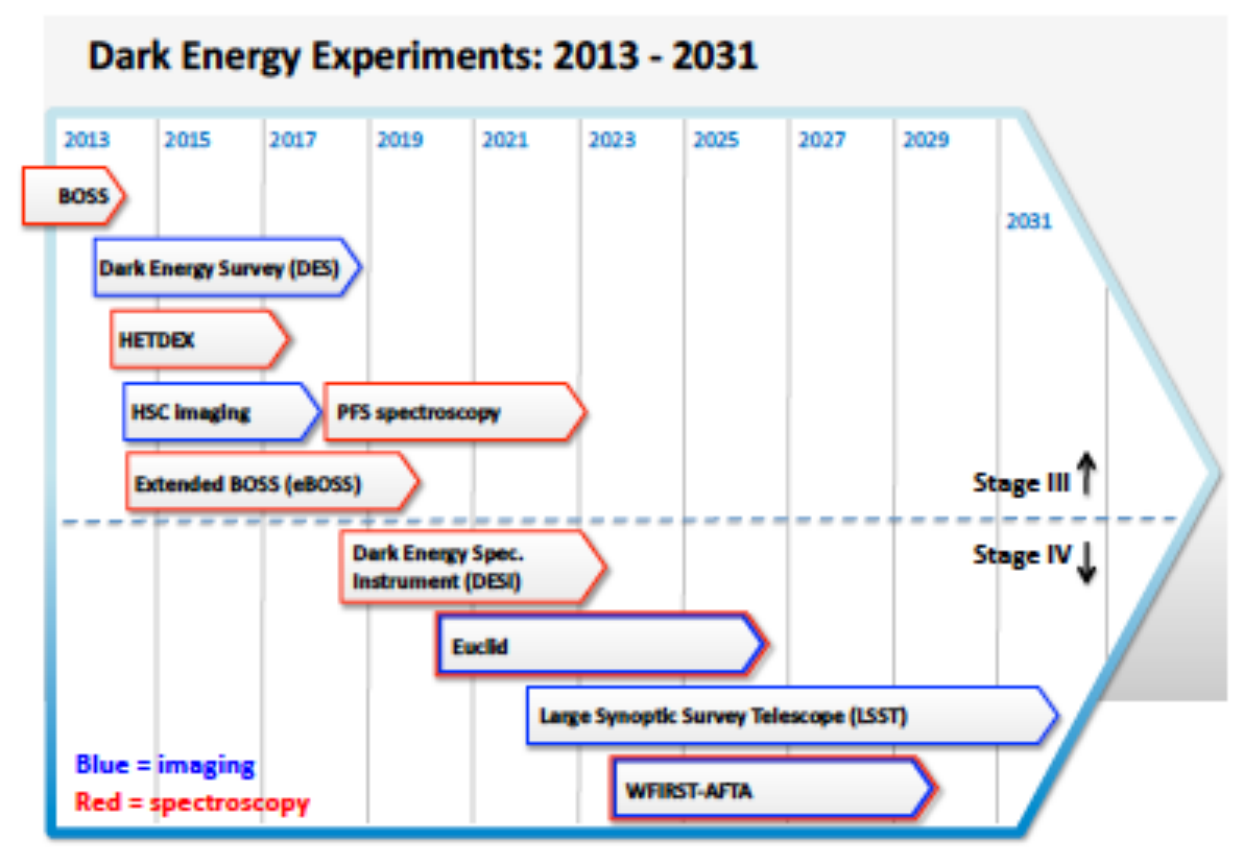
- A ESA space mission with visible and Infrared observations of all sky, both in photometry and spectroscopy
- a wide survey of 15000 deg^2 and a deep survey of 40 deg^2
- Will measure the expansion history H(z) to unprecedented accuracy, with good control of systematic effects:
  - Using Weak Gravitational Lensing from high-resolution imaging survey
  - Using Baryonic Acoustic Oscillations from a large spectroscopic survey
- Expected launch date : ~2020
- FoM after 6 years ~1000



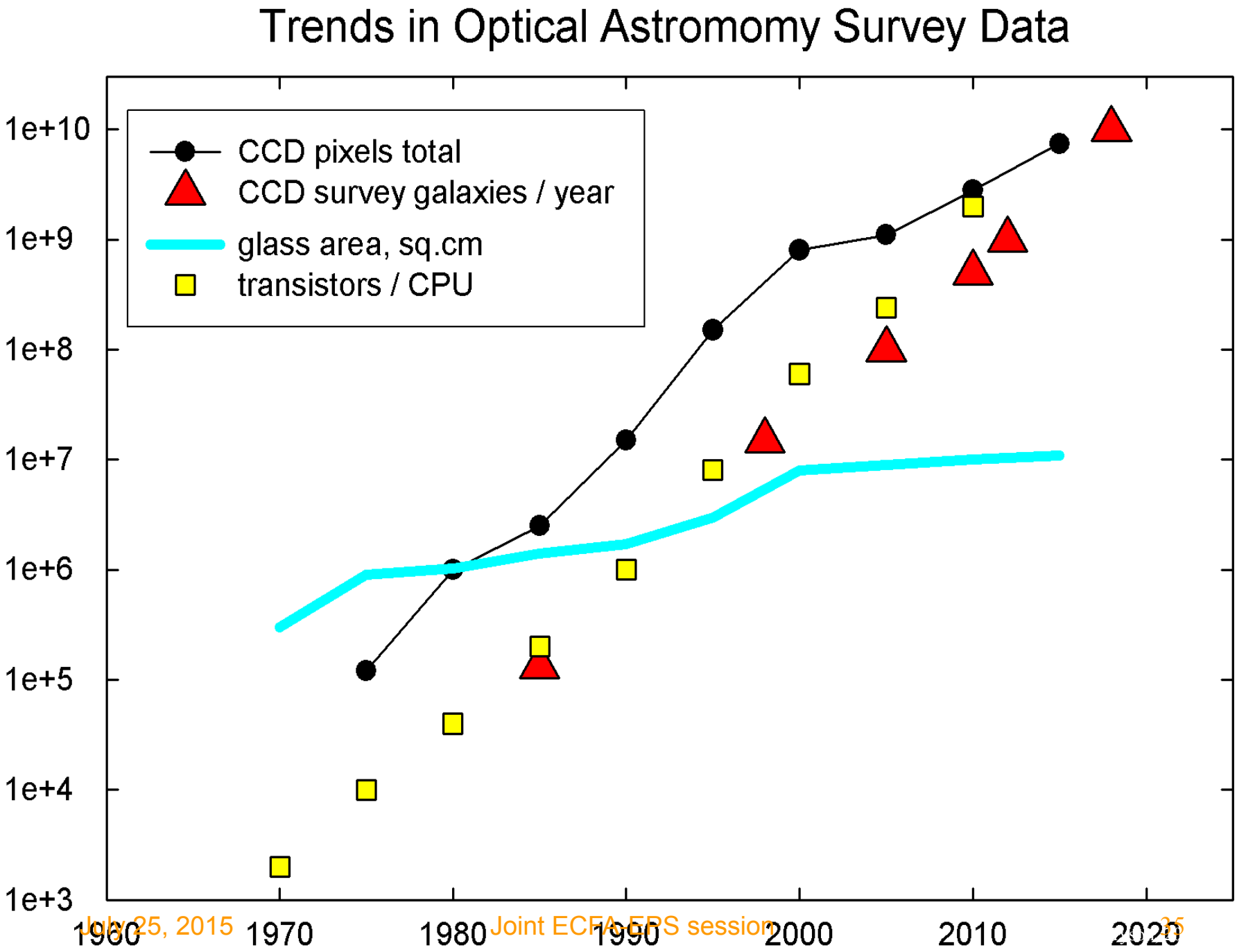
SUMMARY

- Understanding Dark Energy is a key question - New physics may be at reach
- Several approaches are followed, based on astronomical observations, and implemented in several (large) world wide efforts
- Using Multiple and Combined probes is key to reduce uncertainties (incl. systematics) and allows testing of GR
- An ambitious program : building instruments, software, simulation, analyses, … is now being put together
- Lots of data to come –

UNDERSTANDING THE MECHANISM DRIVING ACCELERATION



Extracted from the US P5 planning exercise


Trends in Optical Astromomy Survey Data
CCD pixels total
CCD survey galaxies / year
glass area, sq.cm
transistors / CPU
1e+10
1e+9
1e+8
1e+7
1e+6
1e+5
1e+4
1e+3
1960
1970
1980
1990
2000
2010
2020