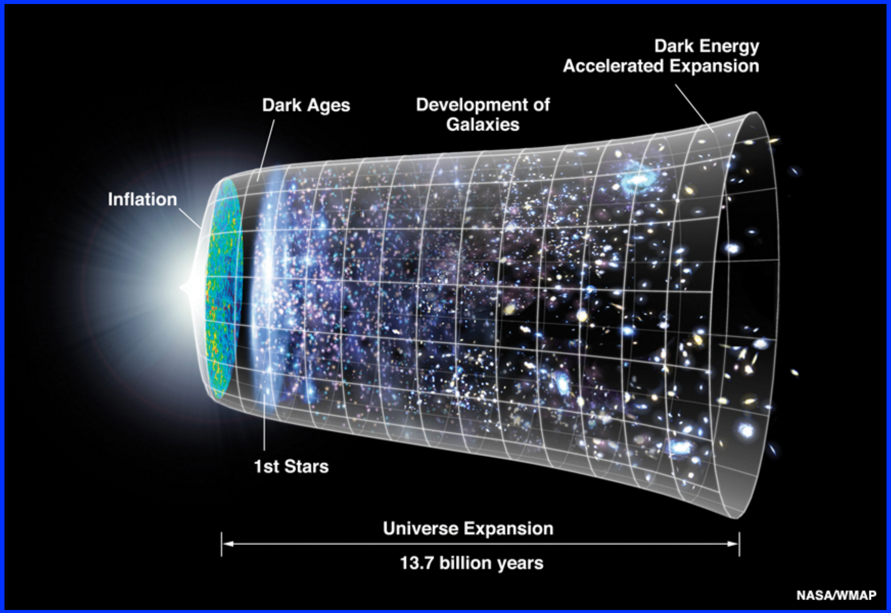
PROSPECTS FOR UNDERSTANDING DARK ENERGY

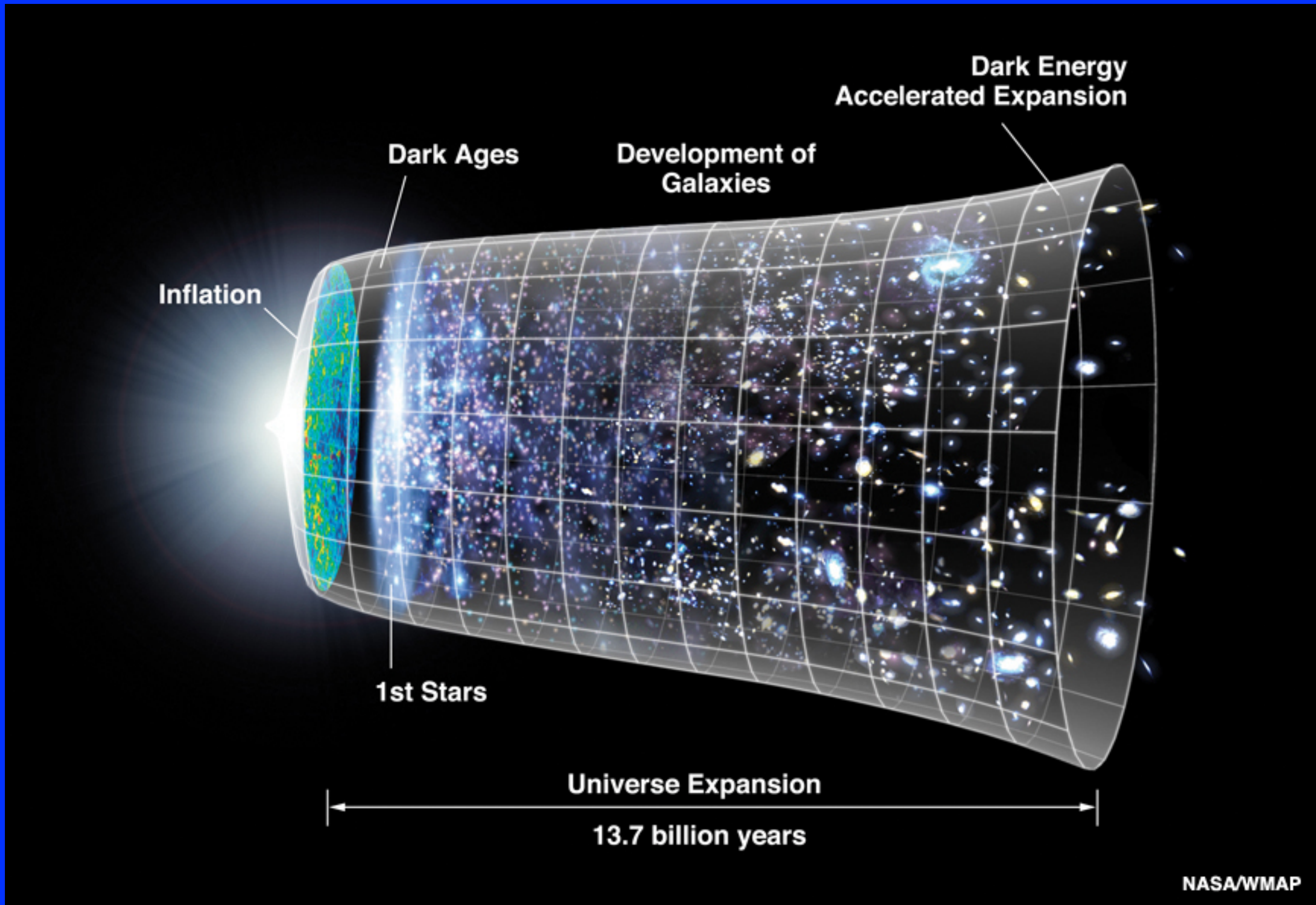


Reynald Pain
CNRS/IN2P3, Paris

UNDERSTANDING DARK ENERGY

- Dark Energy against Gravity
- How to probe Dark Energy
- Current constraints on DE Equation of State
- The example of Supernova Cosmology
- 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

- $t \sim 10^{-35}$ 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/ρ $= -1$

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

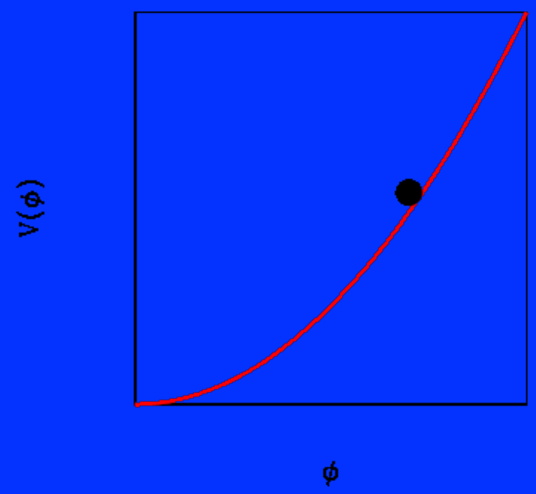
Require roughly constant energy density

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 …

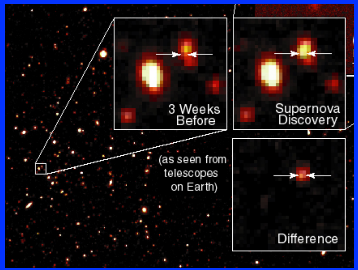
and the acceleration equation generalizes to:

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

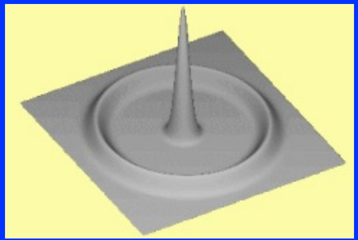
Get acceleration if these terms are positive

WILL WE BE ABLE TO TELL? : DARK ENERGY PROBES

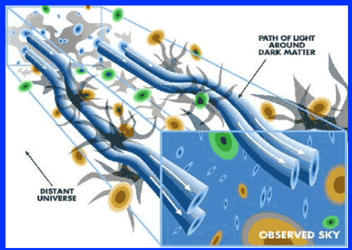
Growth of Structure - Expansion History



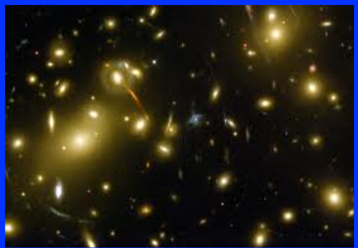
Supernova Brightness



Baryon Acoustic Oscillations

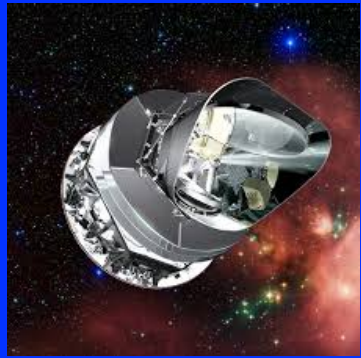


Gravitational Lensing

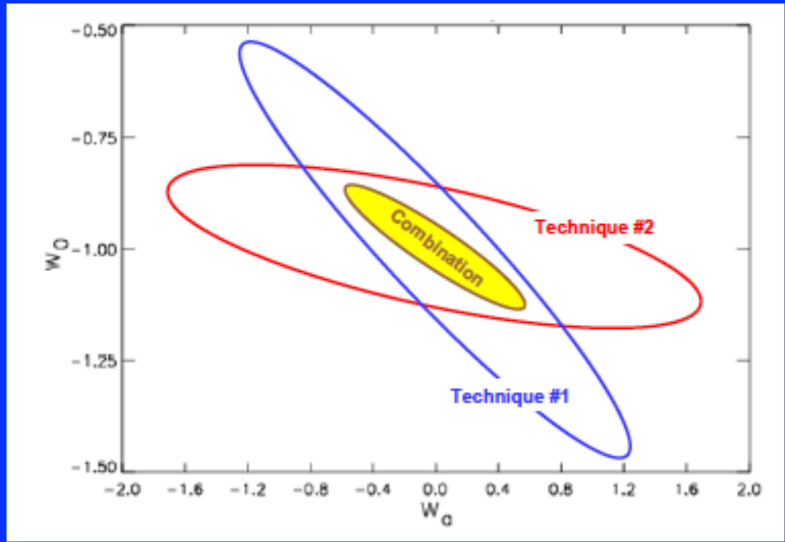


Galaxy Cluster Abundance

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)

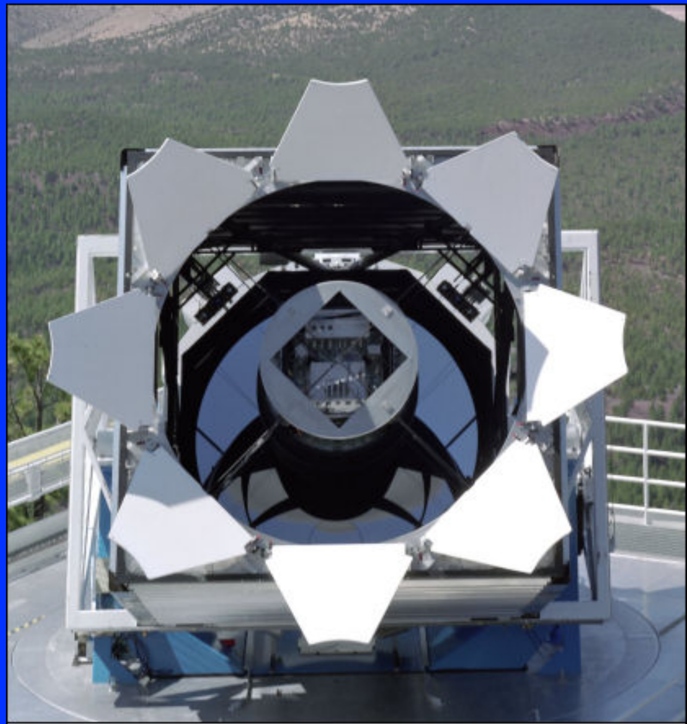
SDSS : THE SLOAN DIGITAL SKY SURVEY

Imaging and spectroscopic survey

Dedicated 2.5 m telescope
(Apache Point, New Mexico)

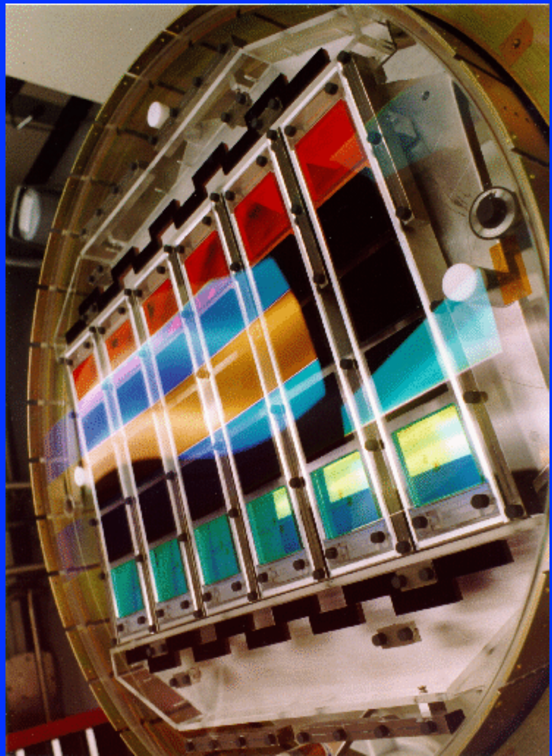
Reached 8000 deg^2
~700,000 galaxy spectra
+ quasars, stars, ...

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

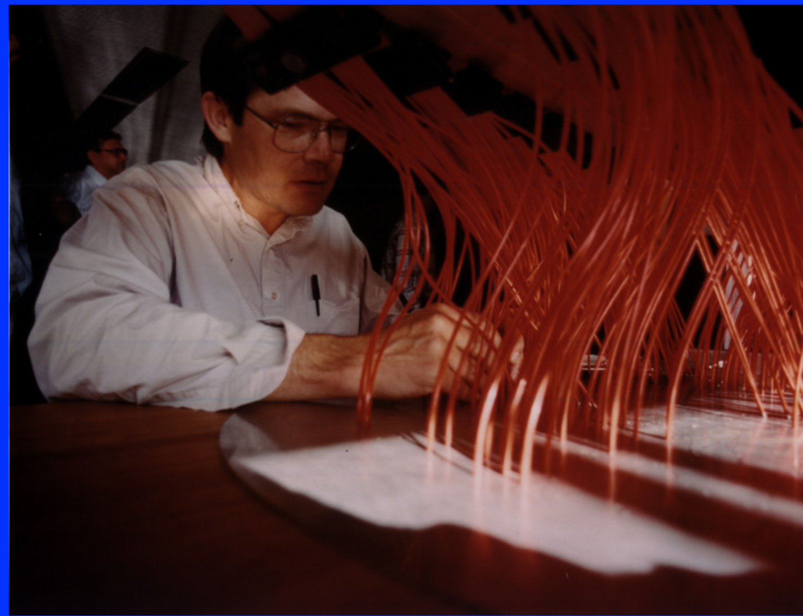


SDSS SURVEY TELESCOPE

SDSS IMAGING CAMERA AND SPECTROGRAPH



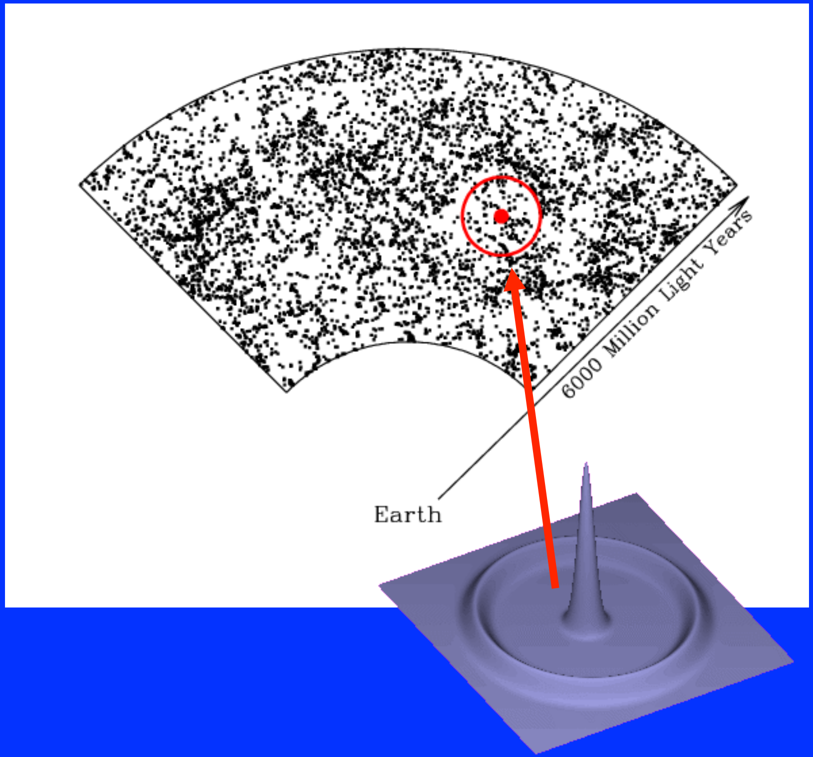
Drift scanning (56 s/band)
~ 225 deg^2 per night



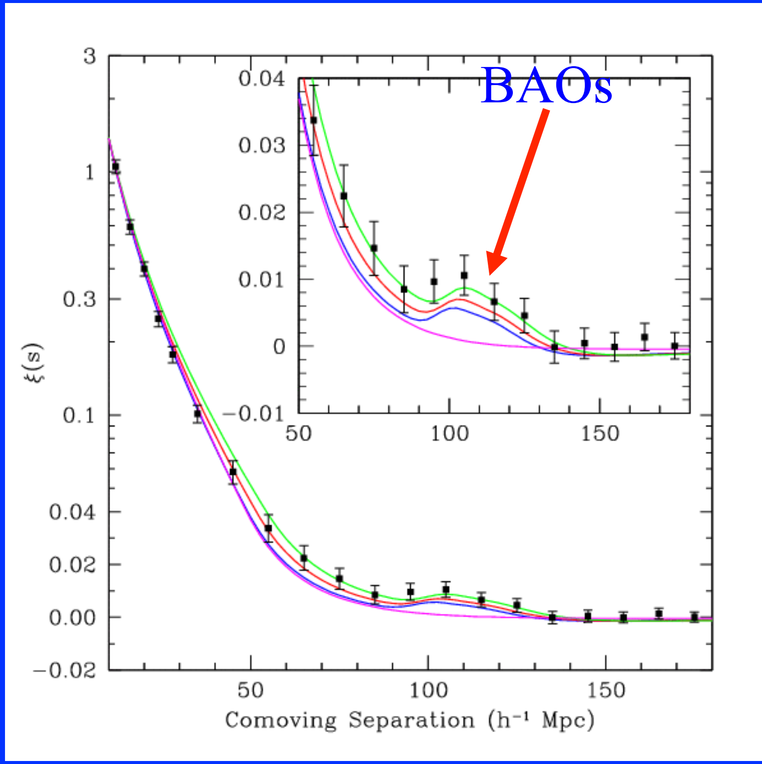
- Fiber-fed spectrograph : 7 deg^2 field-of-view.
  ~ 600 objects per pointing
- Fibers (manually) plugged in precision-drilled plates

SDSS : CORRELATION FUNCTION OF LRGs

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



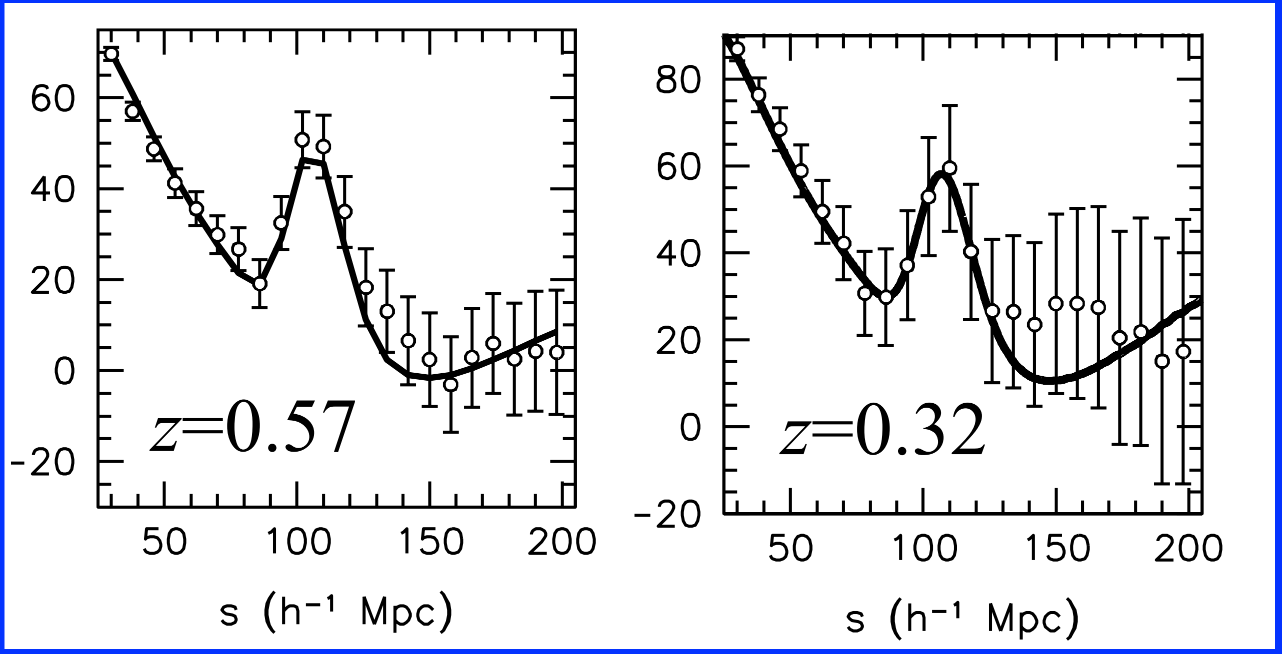
Eisenstein et al [SDSS Collab.] 2005



SDSS-III BARYON OSCILLATION SPECTROSCOPIC SURVEY (BOSS)

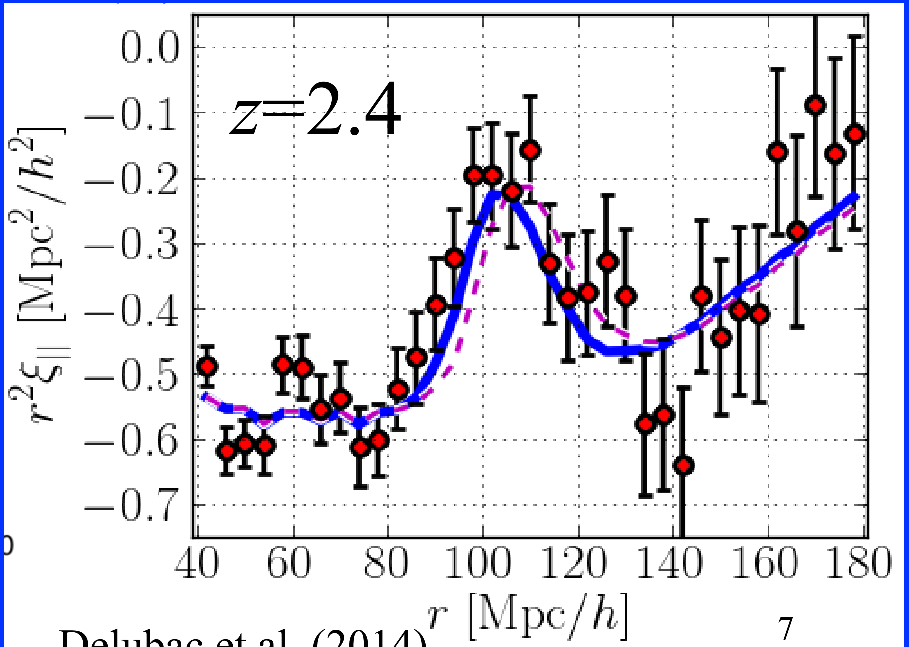
2 million targets over 10000 square degrees

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



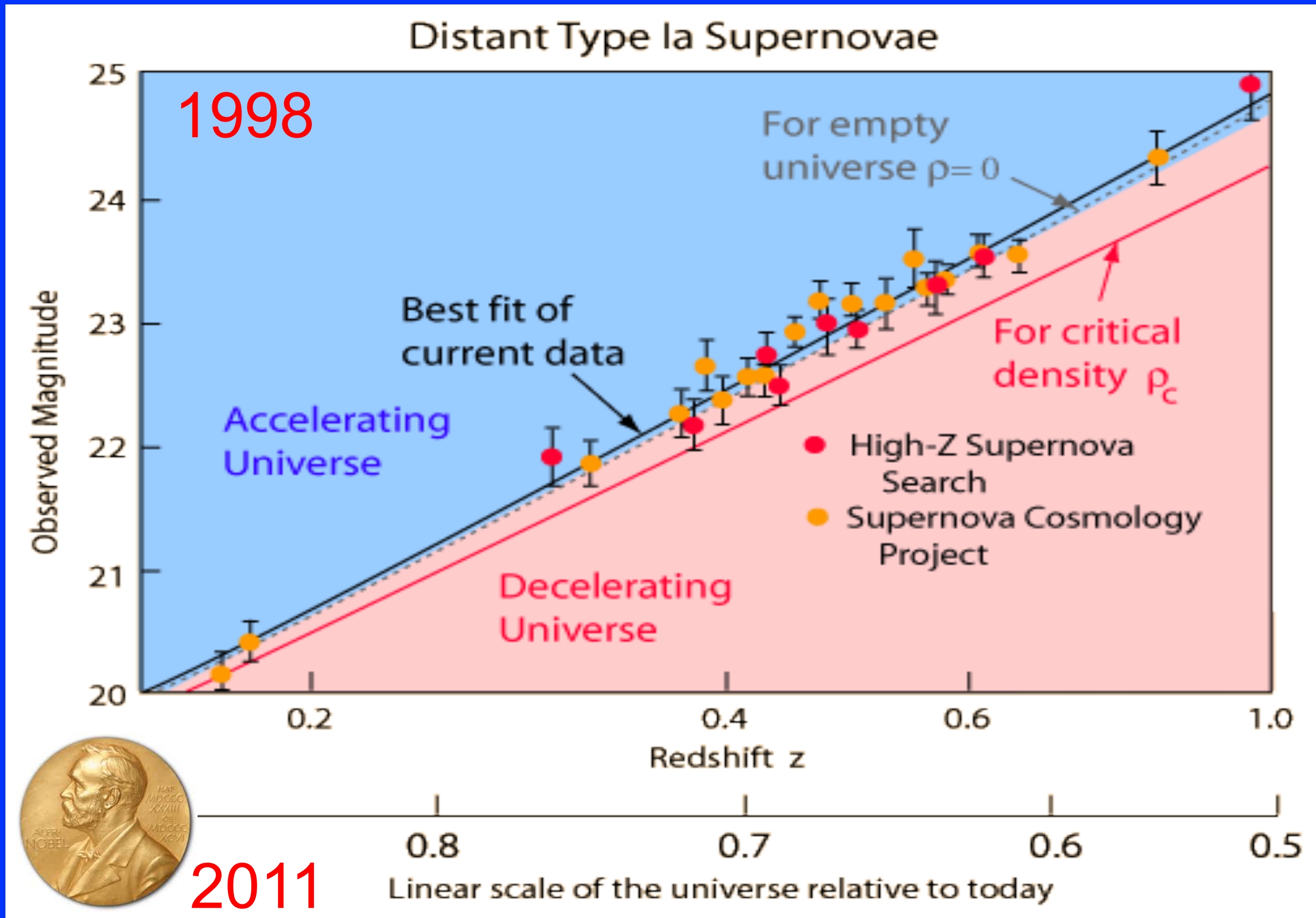
BAO DETECTION IN THE INTERGALACTIC MEDIUM

- 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



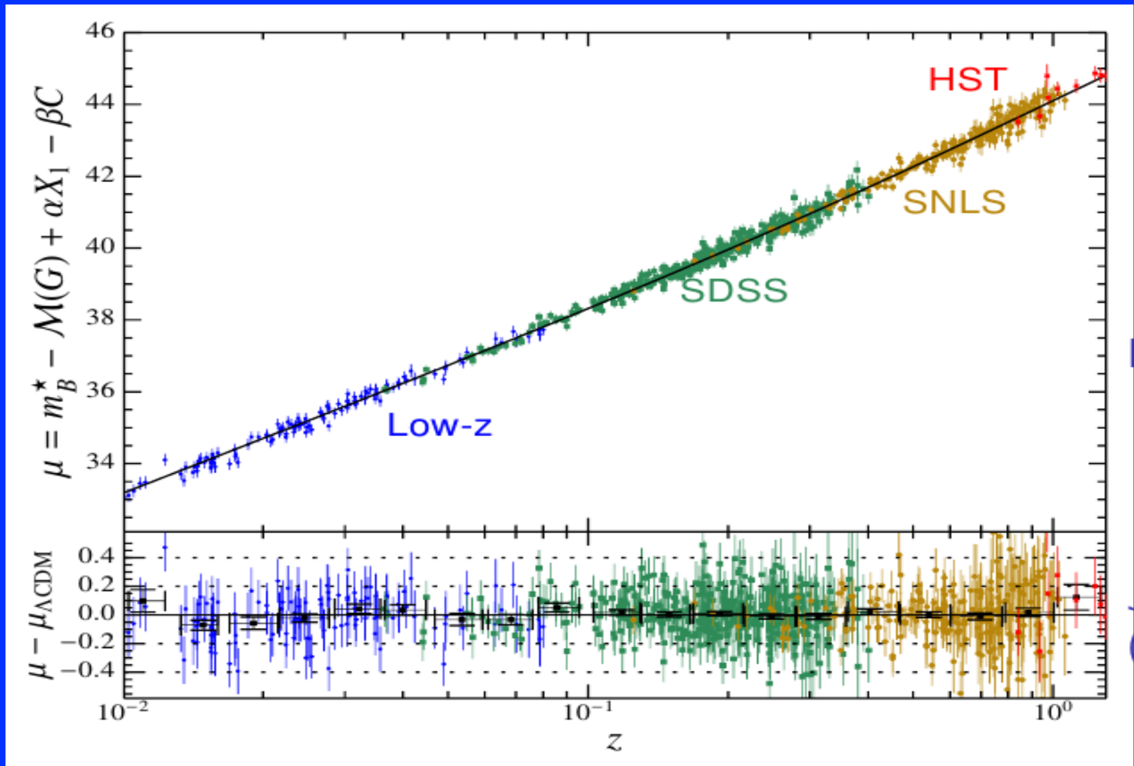
Delubac et al. (2014)

THE HUBBLE DIAGRAM OF TYPE IA SUPERNOVAE

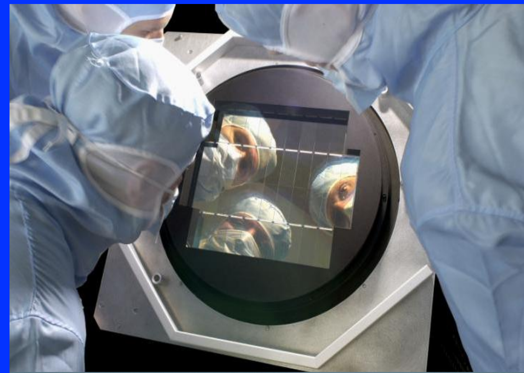


The Hubble diagram of Type Ia Supernovae

Latest High-z Supernova compilation (JLA : 2014)



4m telescope with ~deg2 camera for imaging



8m telescopes for SN id and z

Supernova Cosmology

2 observables :

flux: f

Redshift: z

$$d_L^2 = \mathcal{L}/4\pi f$$

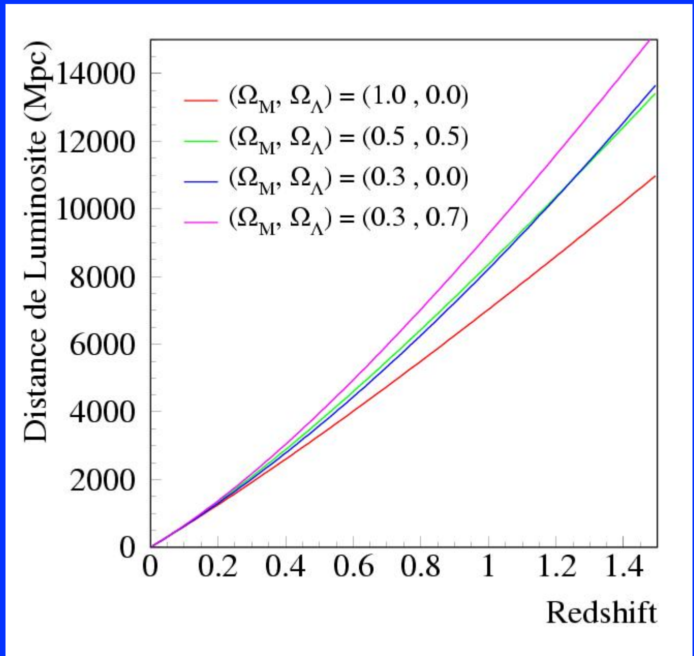
Use Supernovae as distance indicators to measure the Luminosity distance d_L

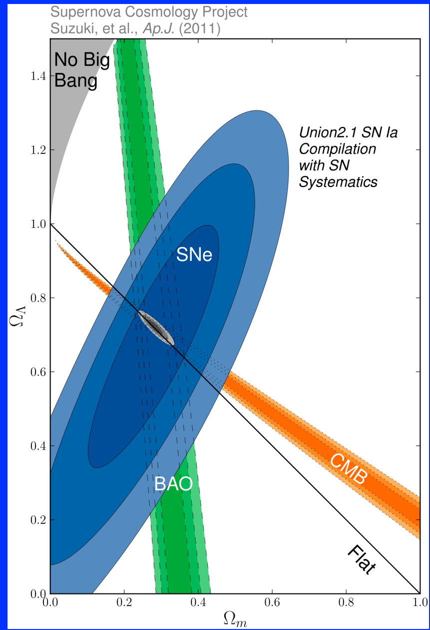
d_L is sensitive to the expansion rate and to the Energy content of the Universe

THE LUMINOSITY DISTANCE

Assuming the Universe is composed of 2 « fluids » : Masse and X of density ρ_X

$$d_L(z) = (1+z)\frac{c}{H_0}\int dz' \left(\Omega_M(1+z')^{-3} + (1-\Omega_M)\frac{\rho_X(z')}{\rho_X(0)}\right)^{-1/2}$$



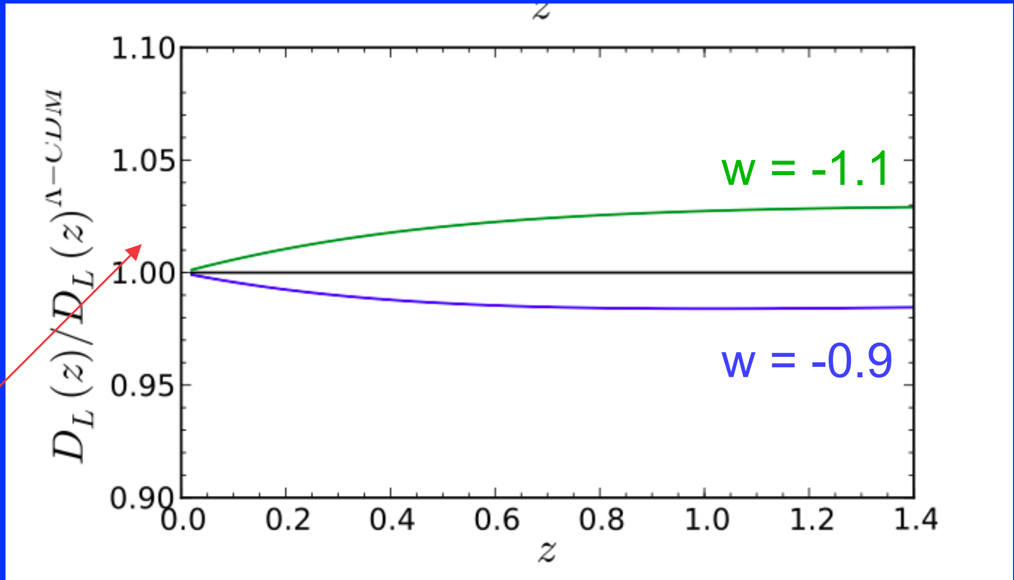


Union sample
Suzuki et al, 2012

PROBING DARK ENERGY

$$\rho(z) = \rho_0 \exp\left(\int 3\frac{w(z)+1}{1+z}dz\right)$$

Equ. of State $$w = \frac{p}{\rho}$$

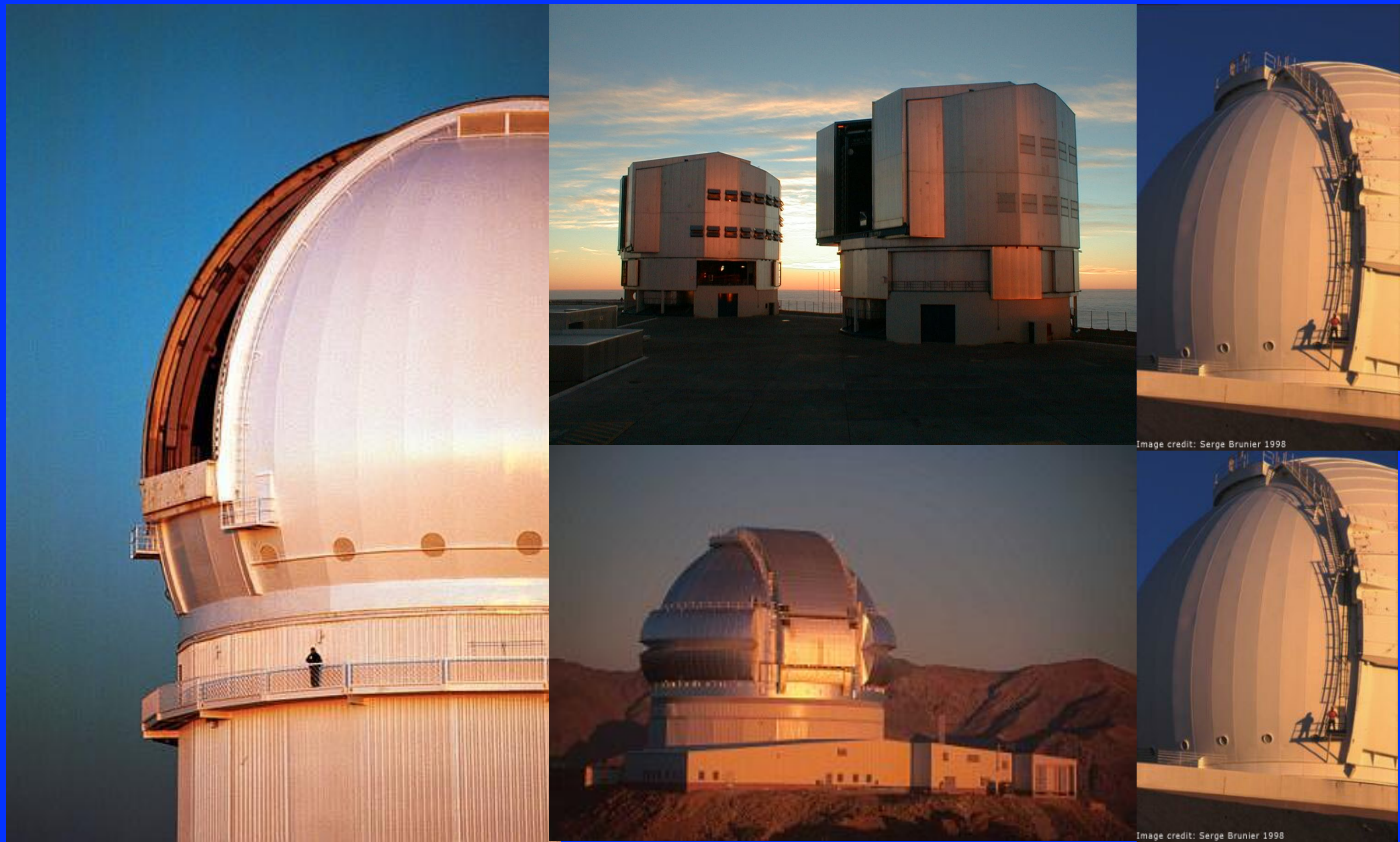


δw (w=-1) ~ 2.5 δm

Measurement ingredients:

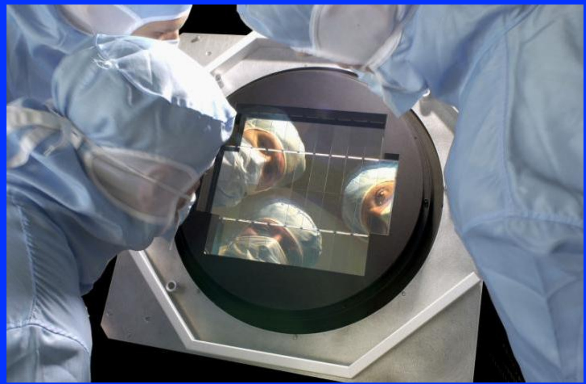
- (High) redshift Type Ia Supernovae (SN Ia)
- additional constraint on Ω_M-> increase precision

SNLS – THE SUPERNOVA LEGACY SURVEY



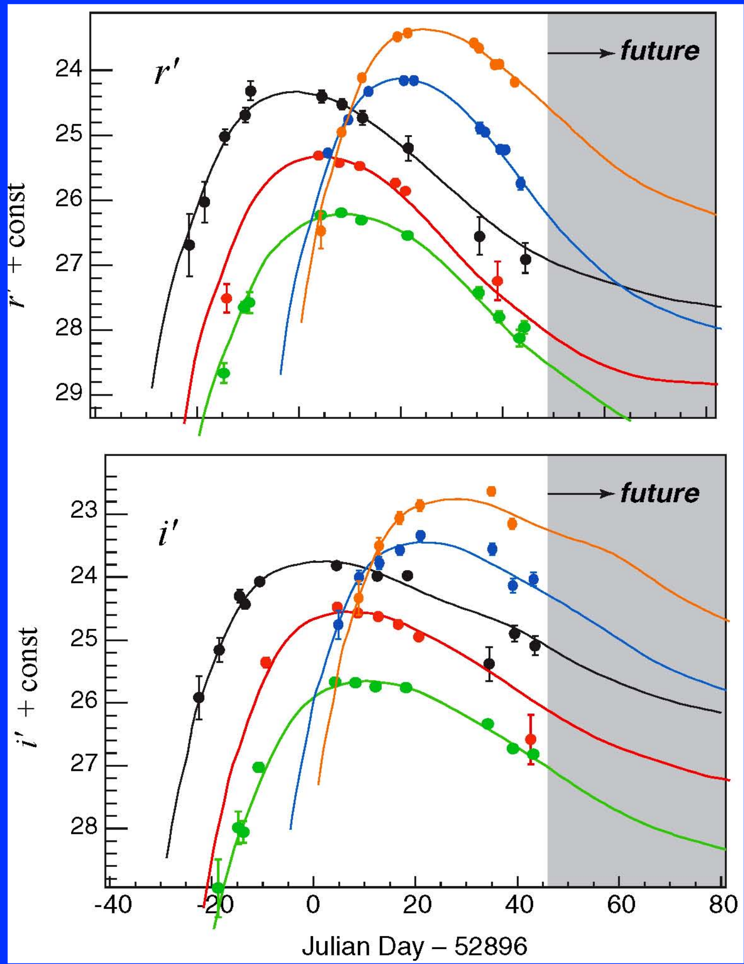
http://www.cfht.hawaii.edu/SNLS

A "ROLLING" (SUPERNOVA) SURVEY



Each lunation (~18 nights) :
repeated observations
(every 3-4 night) of
2 fields in four bands (griz)+u
for as long as the fields stay
visible (~6 months)

=> ~500 SN Ia identified
(+ ~300 « photometric »)
Observed between 2003 and 2008



using ~1500h of 4m for imaging
and ~1500 h of 8m for spectroscopy

A Empirical Approach

A (linearized) distance indicator :

$$\mu_B = m_B - M_B + \alpha(s-1) - \beta c$$

Absolute magnitude at maximum

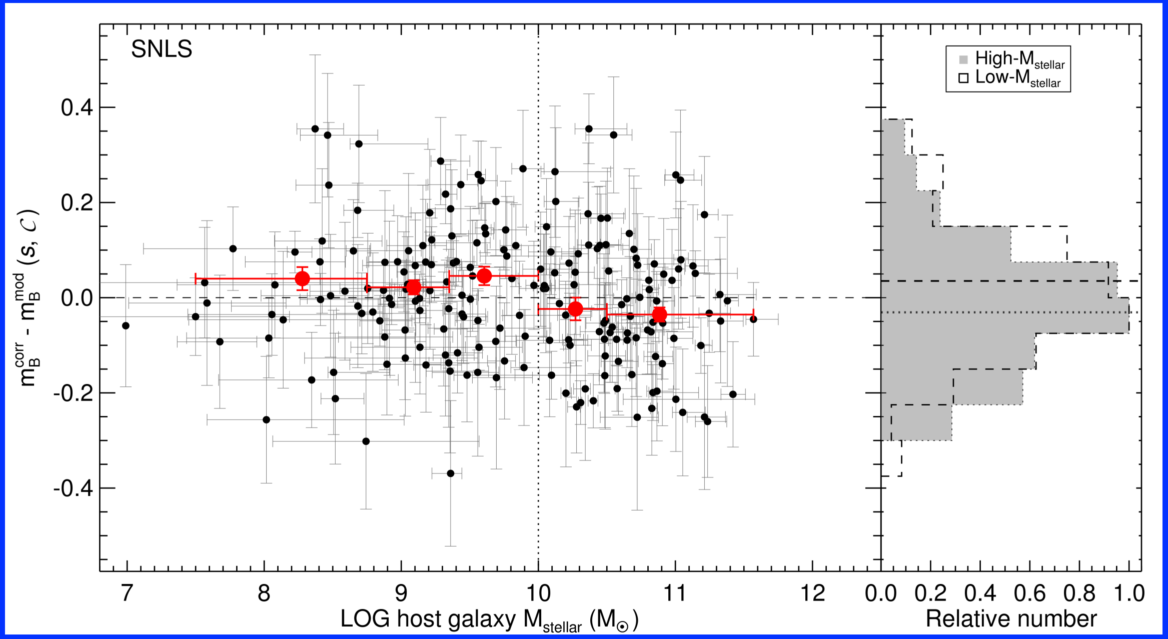
Light curve shape correction

Resframe apparent magnitude at maximum

Color correction. Accounts for
- extinction by dust
- intrinsic color variations

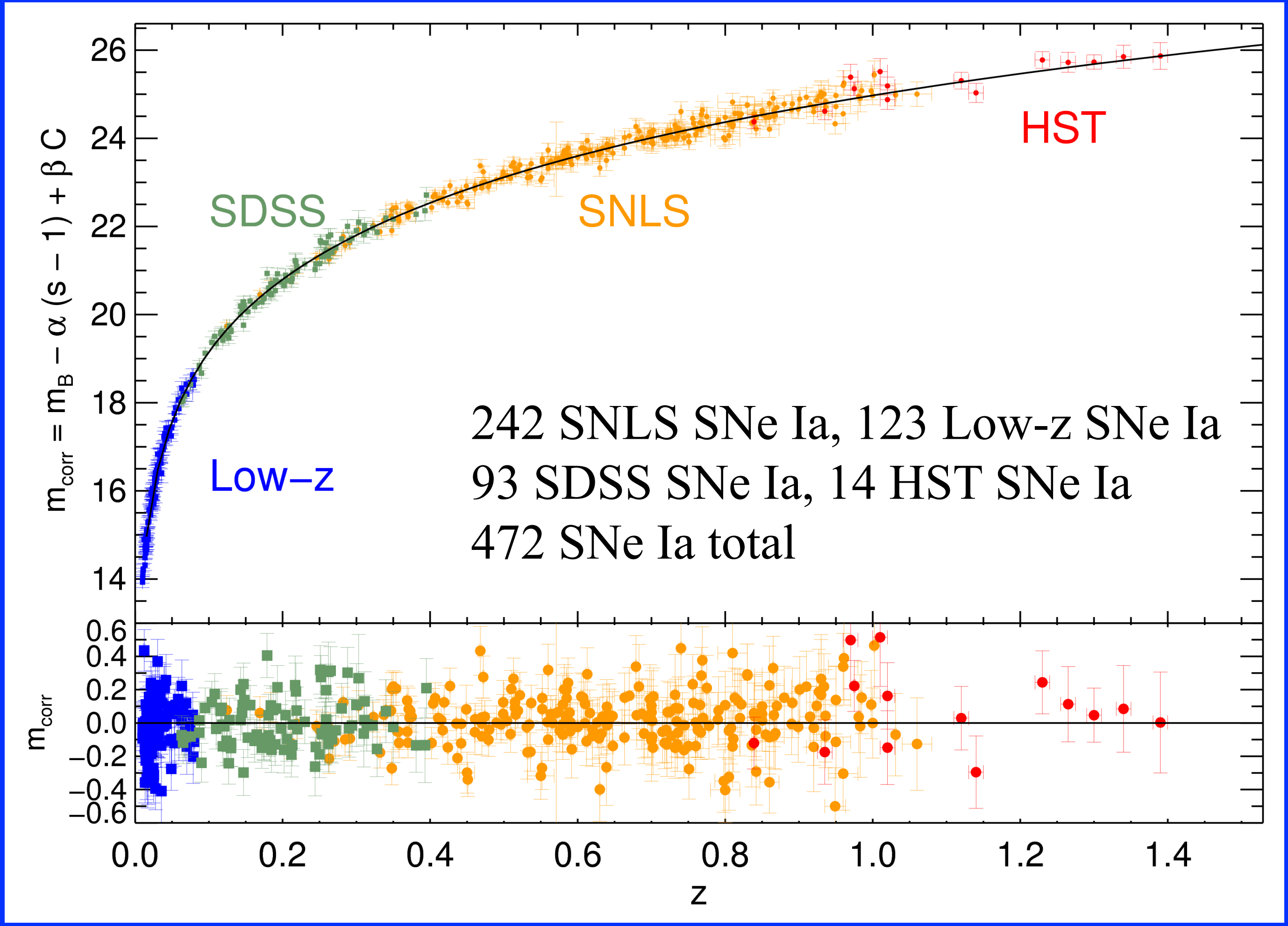
ASTROPHYSICS MATTERS

SNe Ia appear brighter (4σ) in massive galaxies after lightcurve shape and color correction

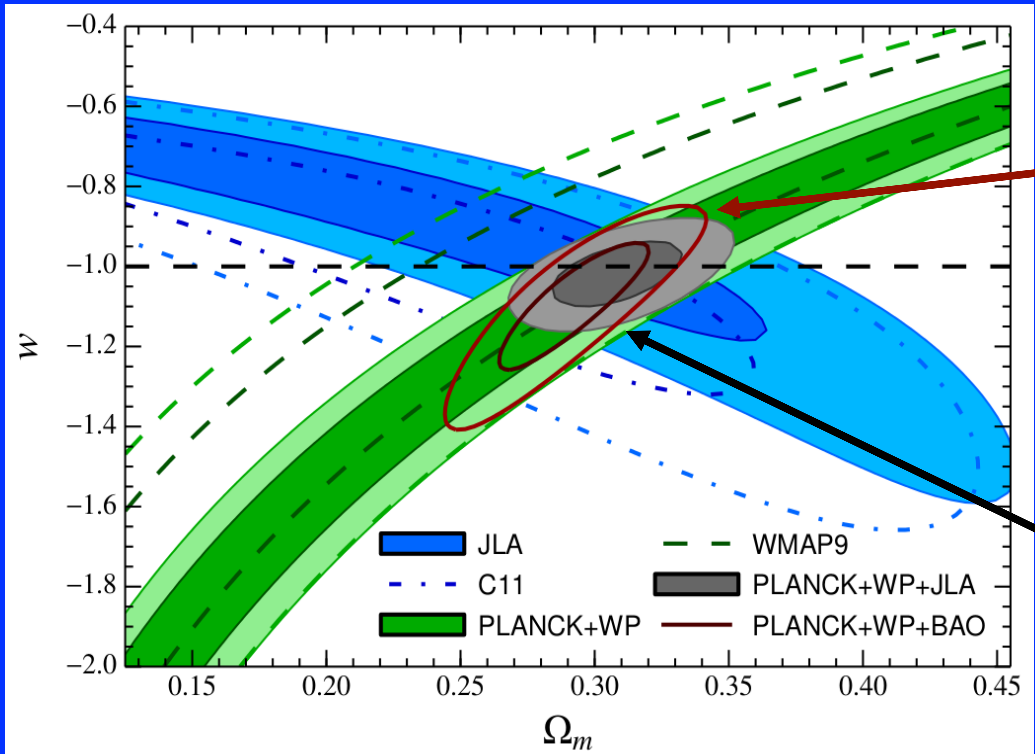


Subtle effect – 0.08mag – smaller than stretch and color corrections

The JLA (2014) SN Ia Combined Hubble Diagram



CURRENT CONSTRAINTS IN A FLAT wCDM MODEL



Planck + BA0

w = -1.01 ± 0.08

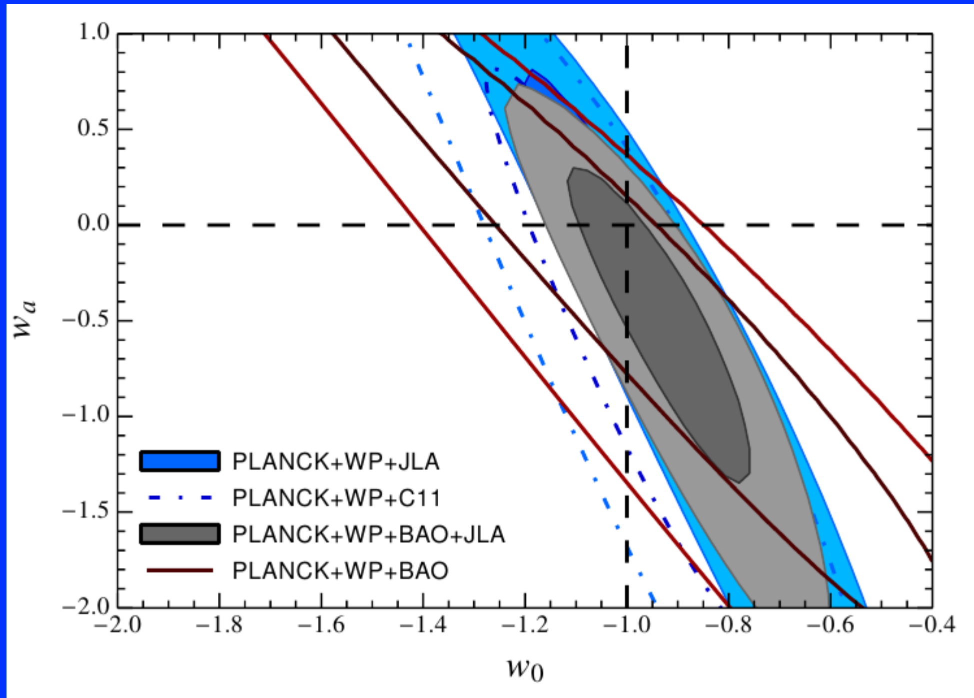
Planck + SNe

w = -1.018 ± 0.057

Betoule et al, 2014

IS DARK ENERGY THE COSMOLOGICAL CONSTANT ?

We now start to put (weak) 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):

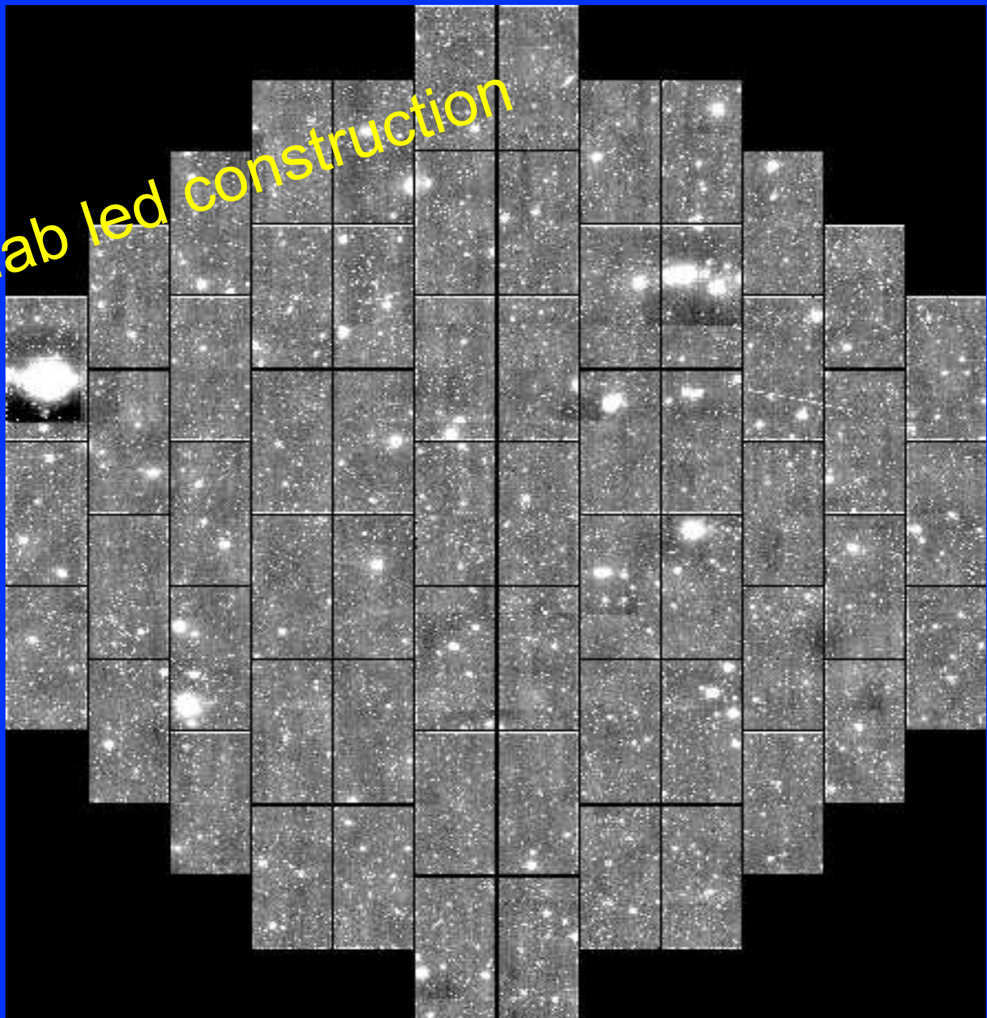
- 5000 deg^2 to 24th magnitude in grizY bands
- 30 deg^2 repeat scan SN survey (~10% of observing time)

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:

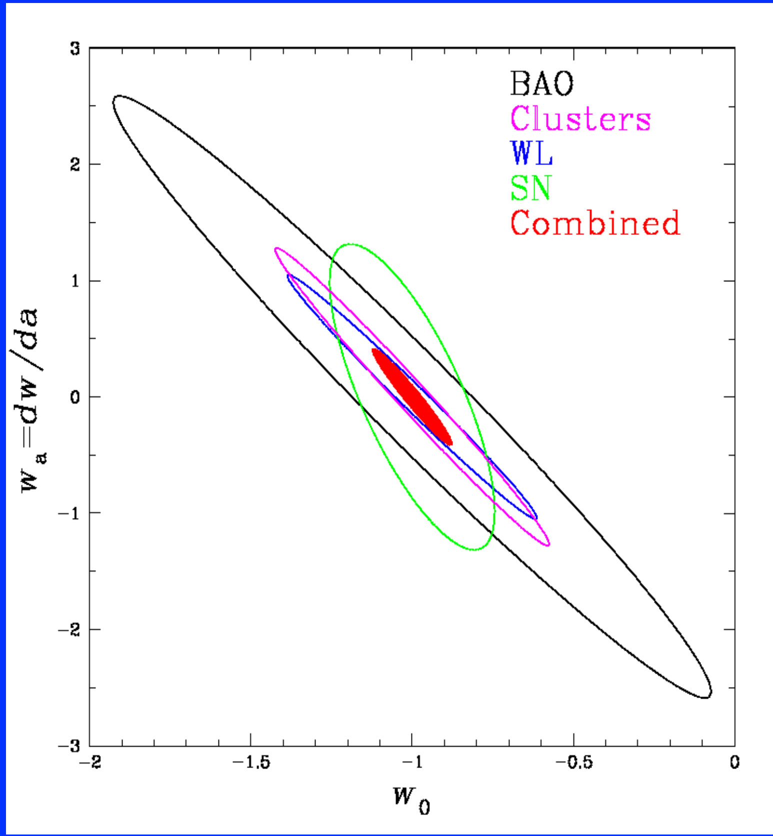
- 200,000 galaxies
- 100 galaxy clusters

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



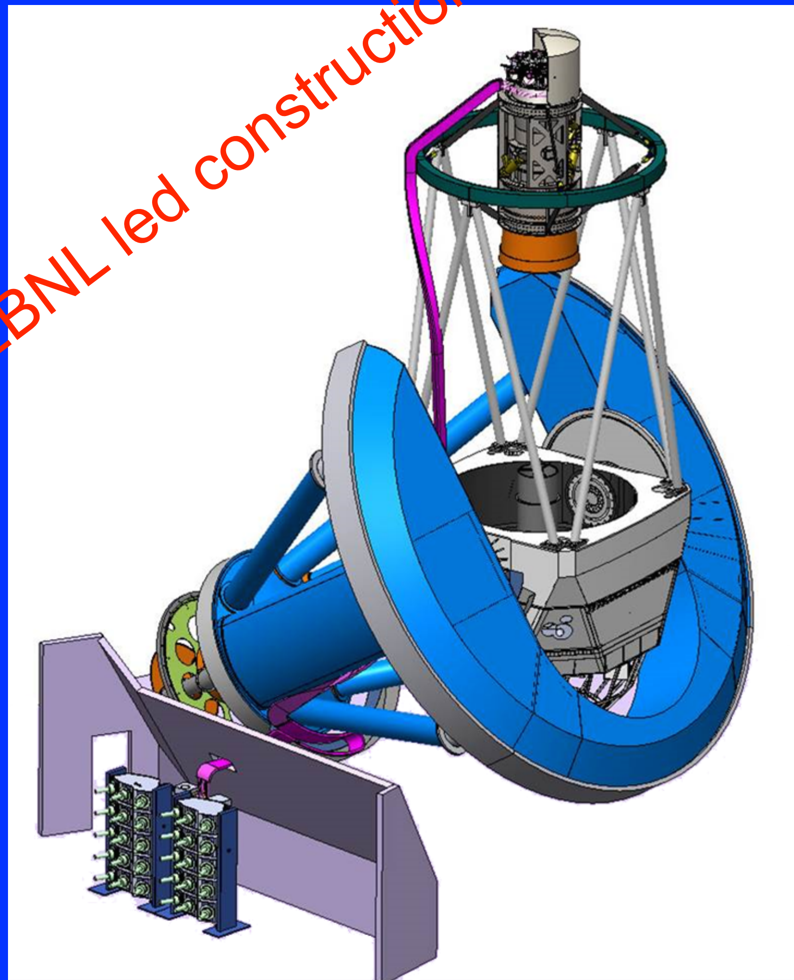
DESI : Dark Energy Spectroscopic Instrument

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

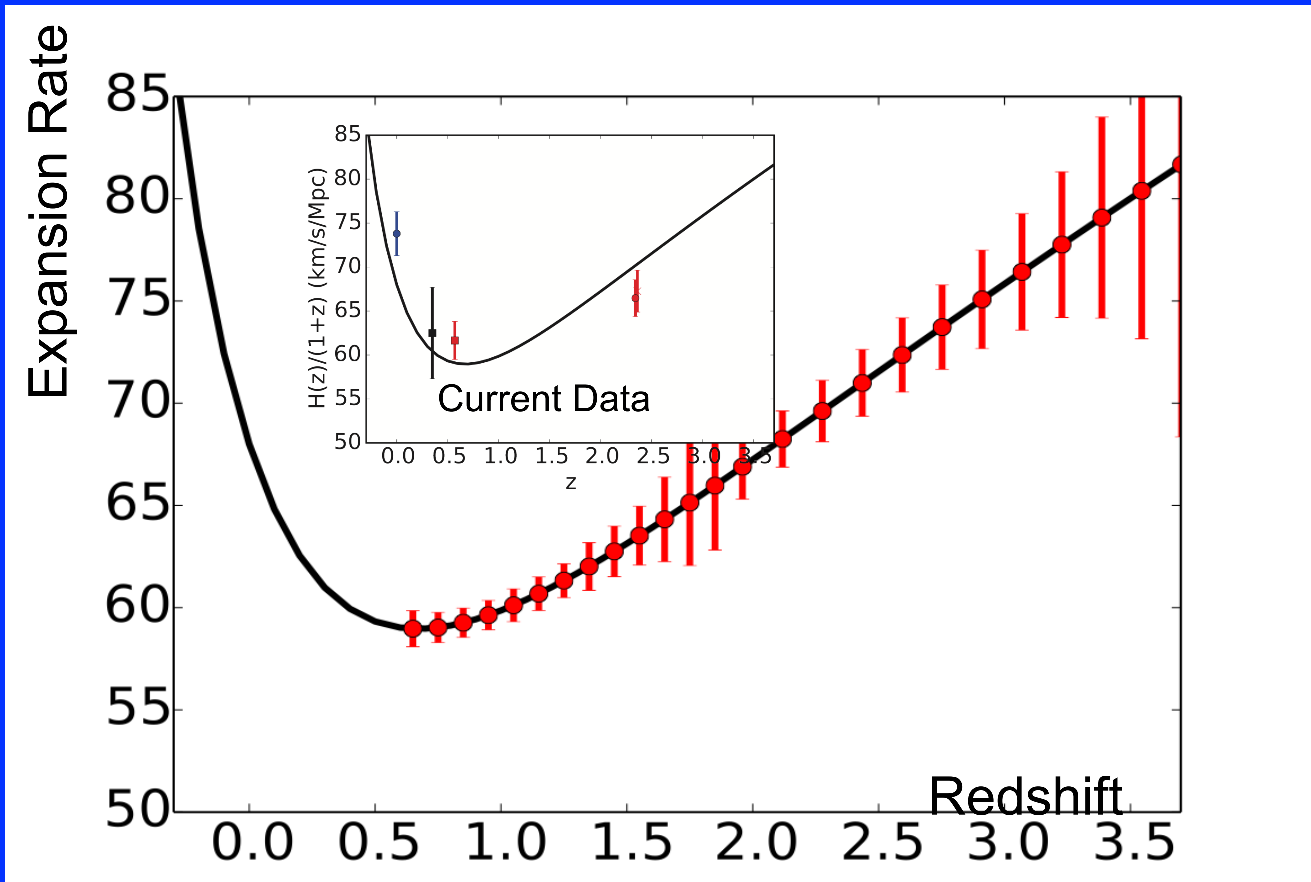
- will be installed on the Mayall 4m Telescope at Kitt Peak, Tucson, AZ

- Expect data taking : 2018-2022

LBNL led construction



(EXPECTED) DESI BAO HUBBLE DIAGRAM

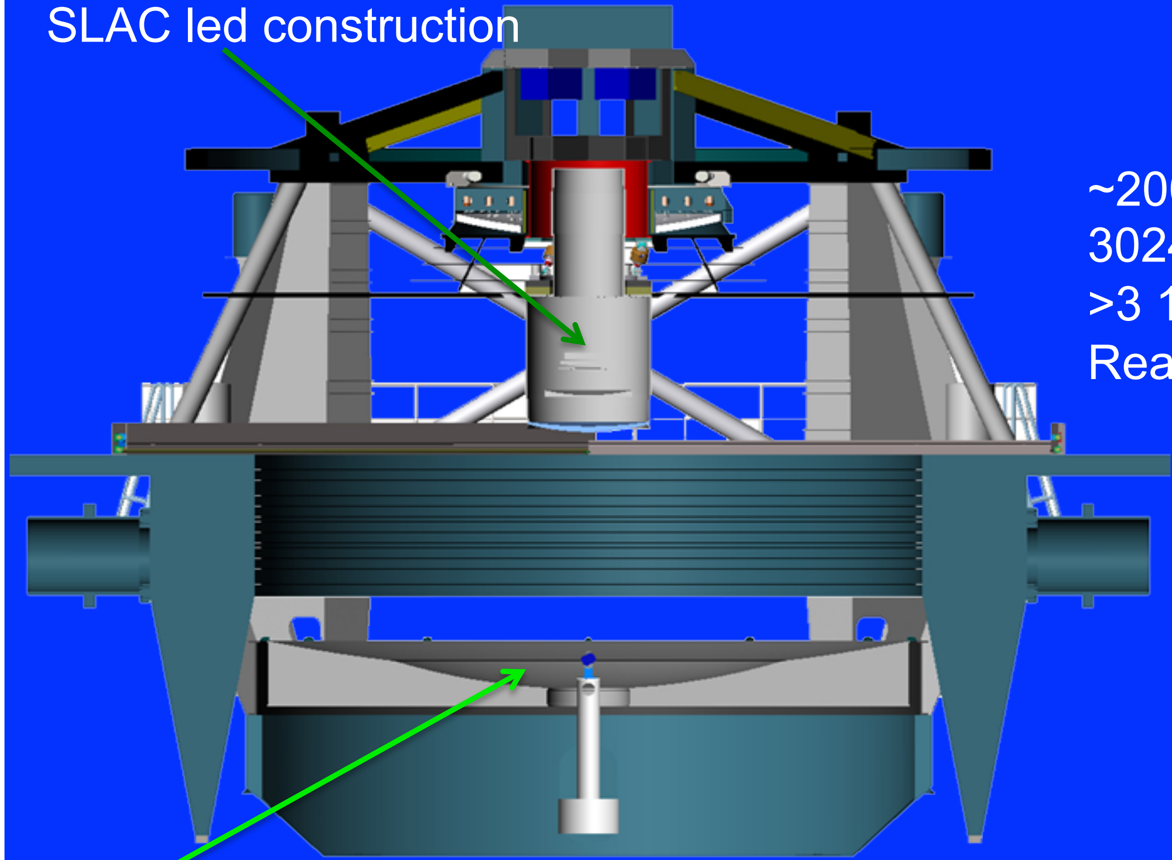


w_0/w_a FoM : ~300-600


LSST
Large Synoptic Survey Telescope
Sept 22, 2015
HAP workshop

LSST : Wide Deep and Fast

Camera
SLAC led construction

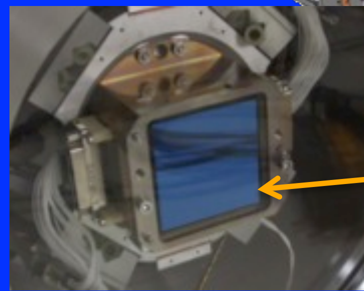


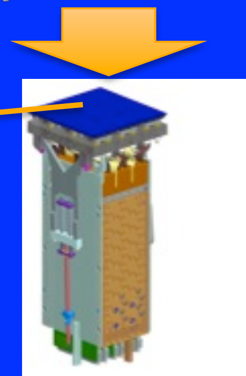
M1M3 primary (8.4m) & Tertiary mirrors

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





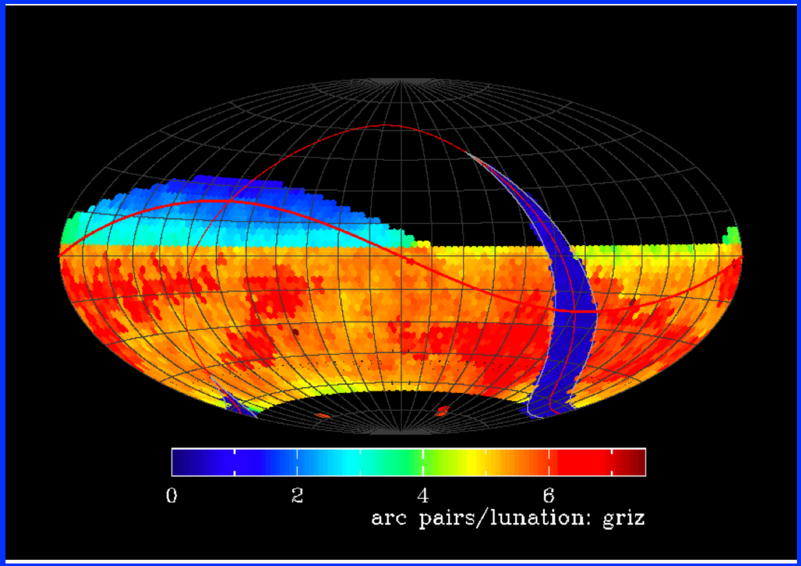
10 μm pixels CCDs
UV to NIR sensitive

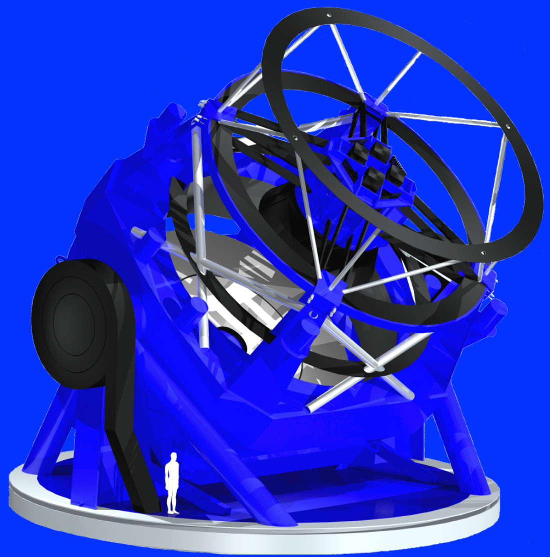
A SINGLE OBSERVATION PLAN & MANY SCIENCE TOPICS

- 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

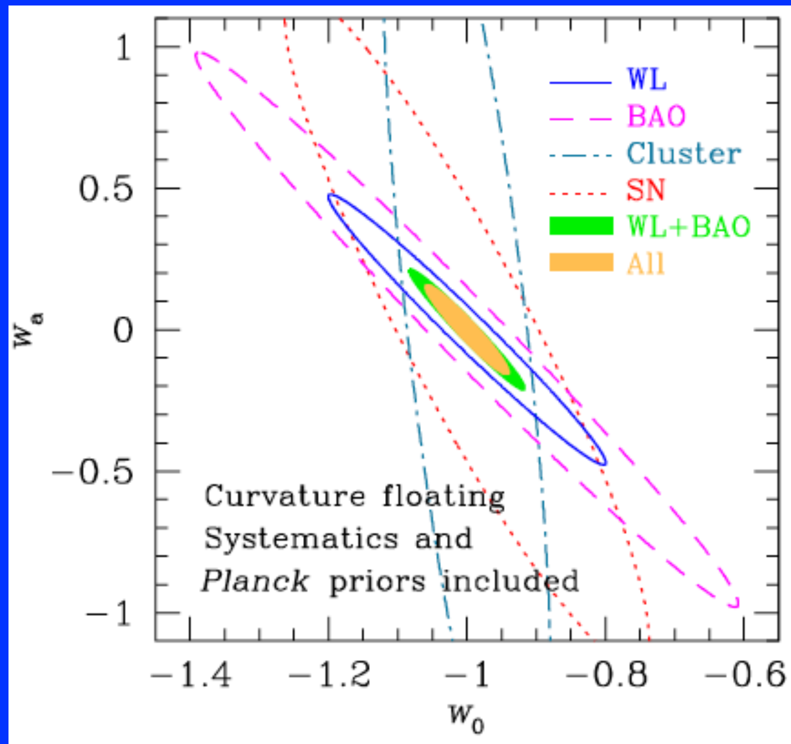
Survey start date : 2022

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

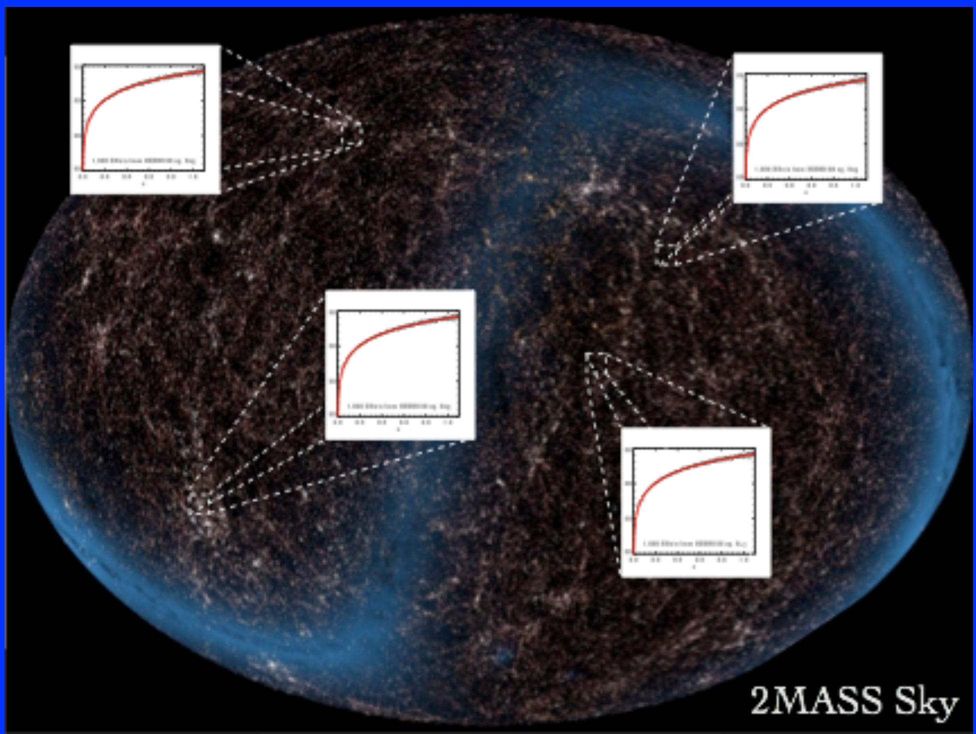


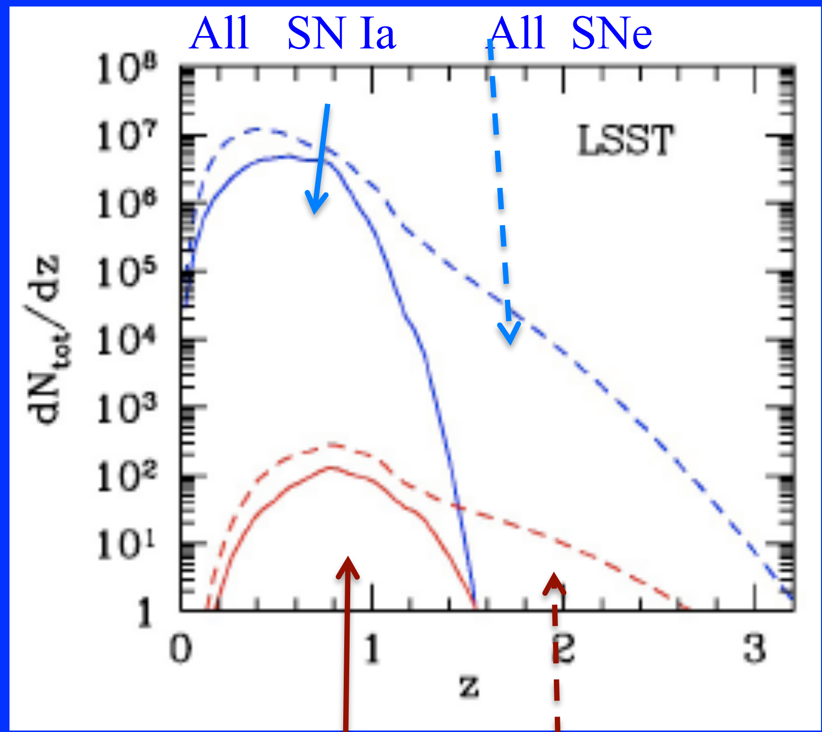
LSST : DE SCIENCE WITH HIGH STATISTICS SN IA

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



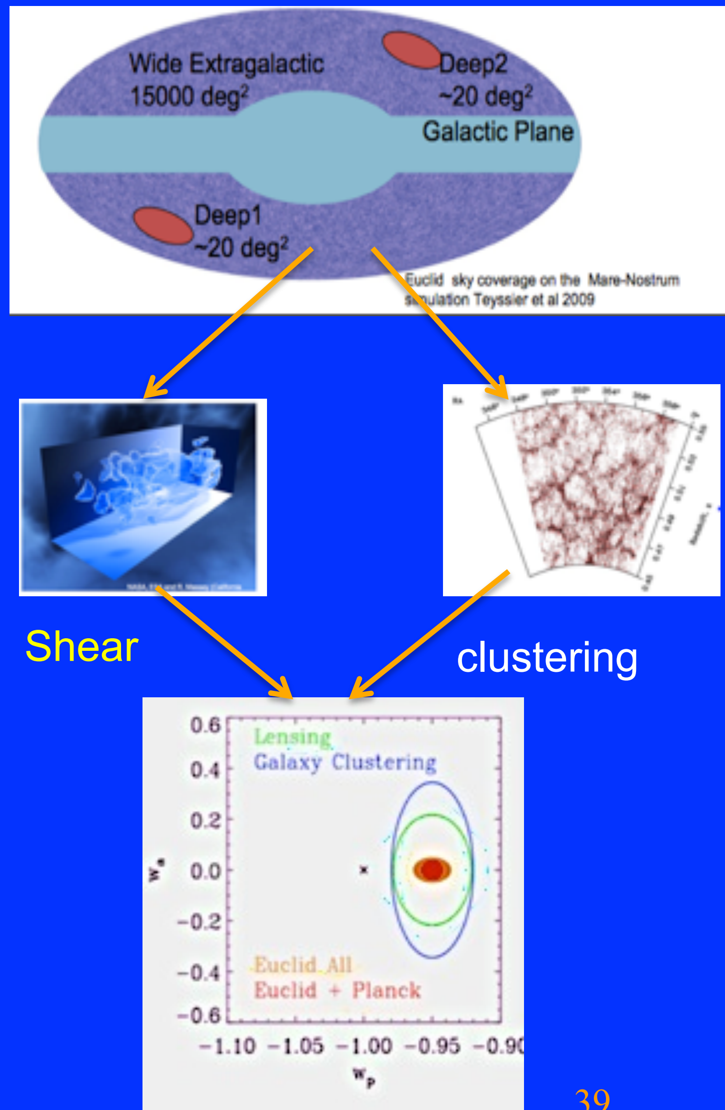


Lensed SN Ia

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 –