Cosmology with Wide Field Astronomy

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LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Cosmology in 5 minutes…

- **History** (past and future)
- **Content**
- **Structure**

of the Universe

What cosmology with wide field optical surveys can say about particle physics ?

- Inflation theory
- Hidden matter
- Vacuum energy
- Neutrino mass

Observables:
Redshift z
Position (2 angles + Distance)
Time

The 4 cosmological distances

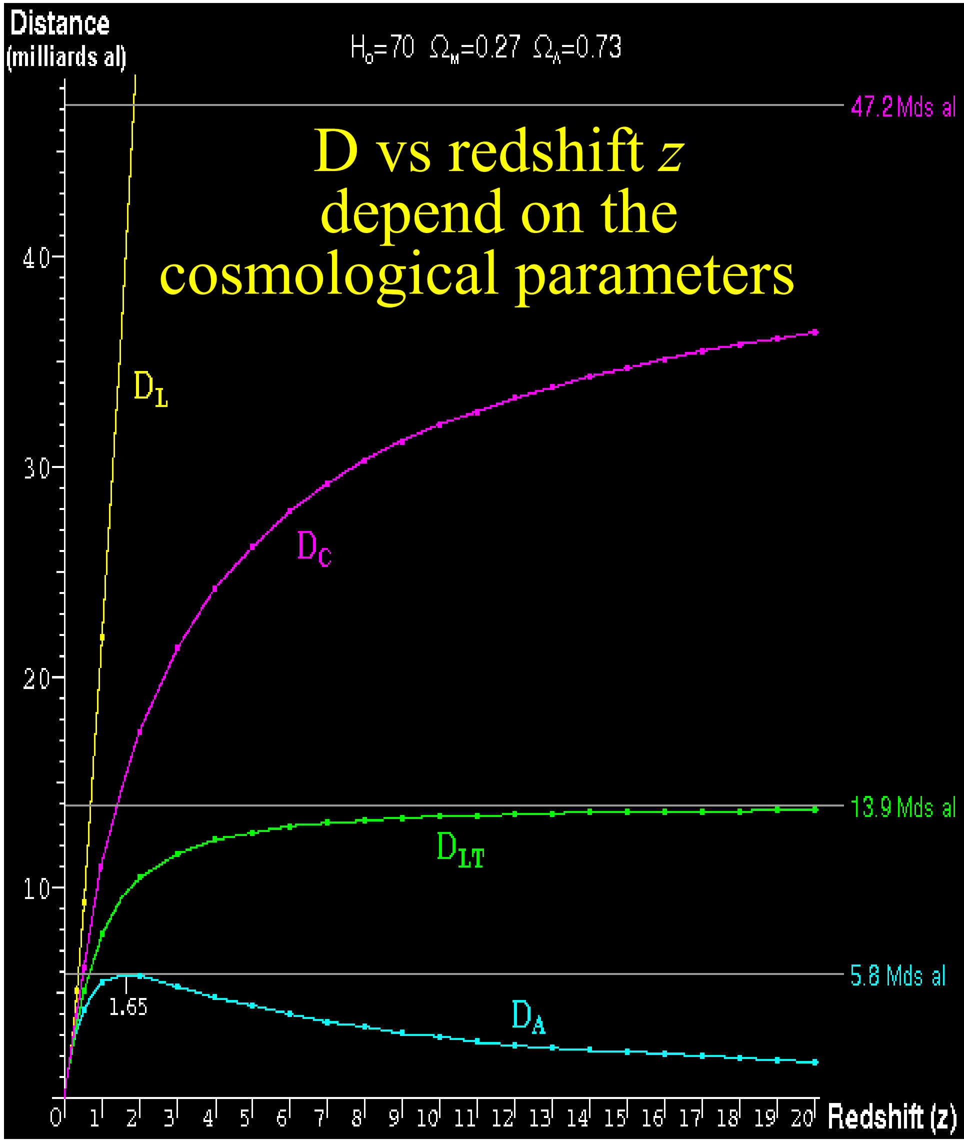
- *Comobile distance* $\mathbf{d_C}$
  Gives the present position of the object (even observed in a past situation)
- *Luminosity Distance* $\mathbf{d_L = d_C(1+z)}$
  depends on the repartition surface of the light
  - Used with luminosity markers

➢ ***Galaxies appear fainter than in a static Universe***

- *Angular distance* $\mathbf{d_A = d_C/(1+z)}$
  Galaxies were closer at the epoch of the light emission.
  - Used with size markers

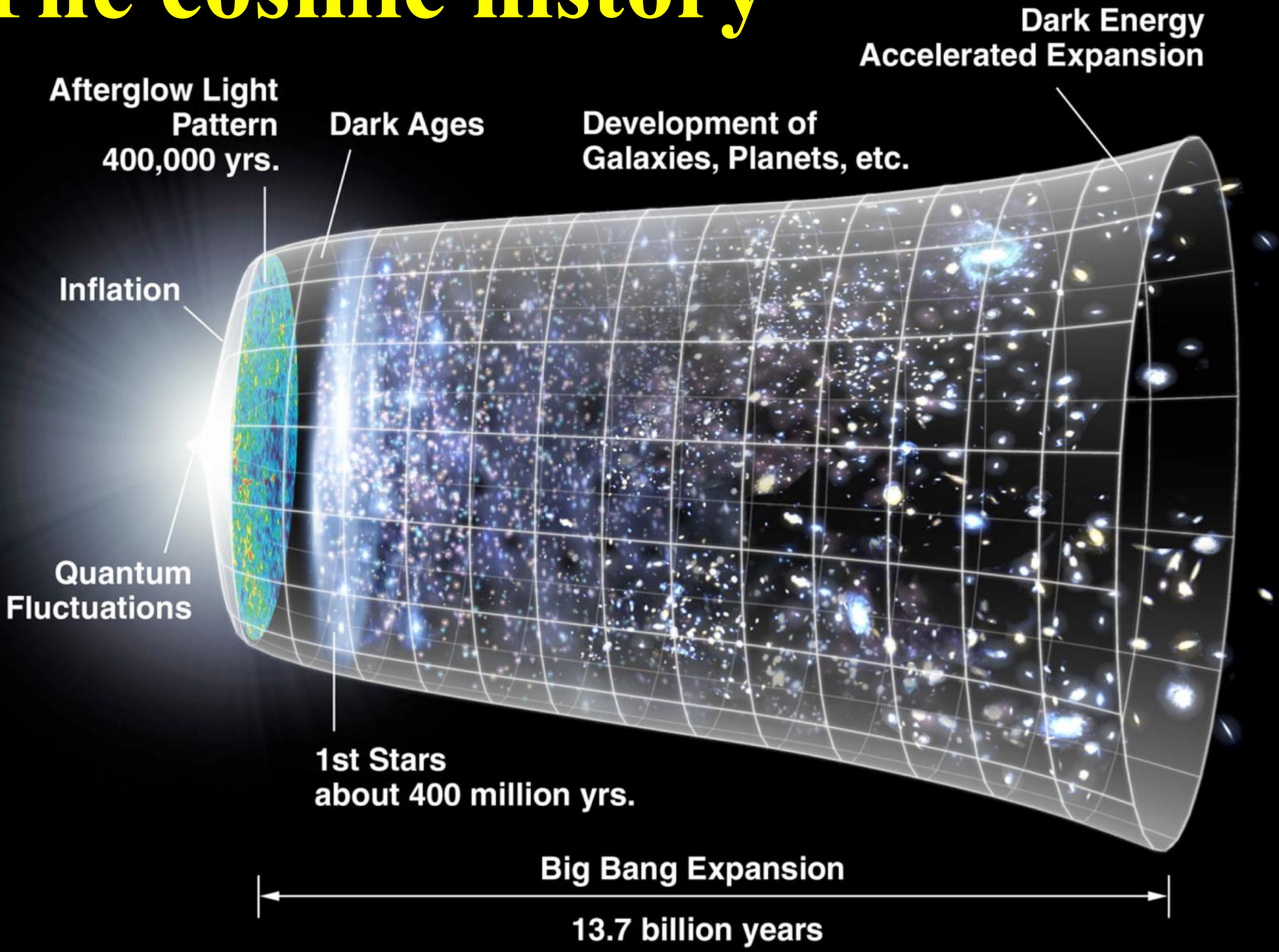
➢ ***Galaxies appear larger than in a static Universe***

- *Distance of photon propagation* $\mathbf{d_{LT}}$



D vs redshift *z* depend on the cosmological parameters

The cosmic history



NASA/WMAP Science Team

The content of the Universe

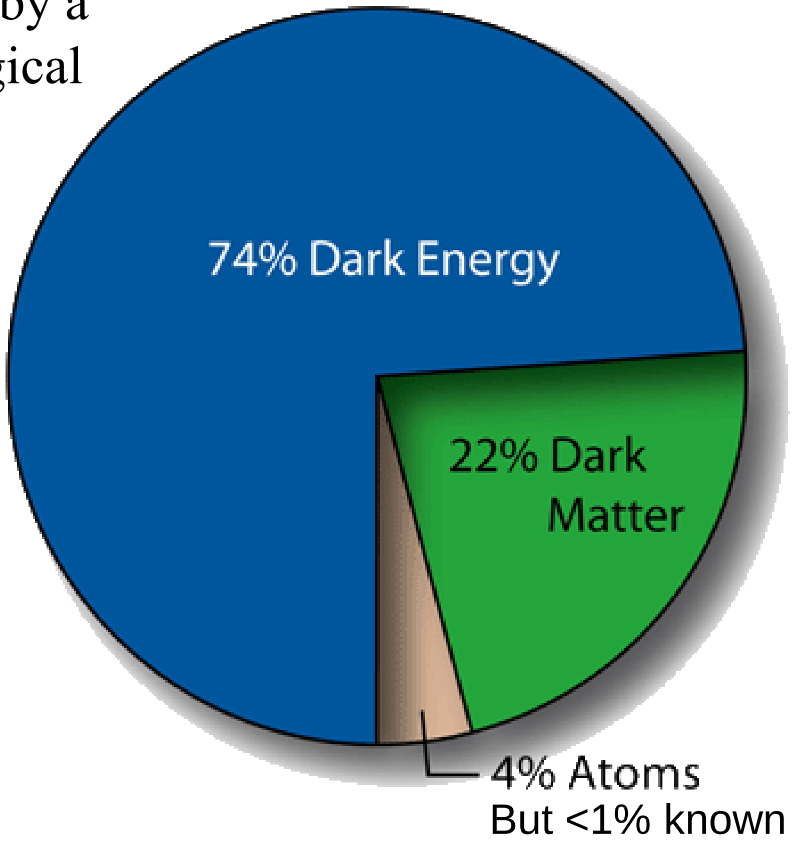
- Current observations in favor of a **flat Universe**
- Energy density seems now dominated by a component that behaves like cosmological constant ⊄

☐ ⊄ acts against gravity

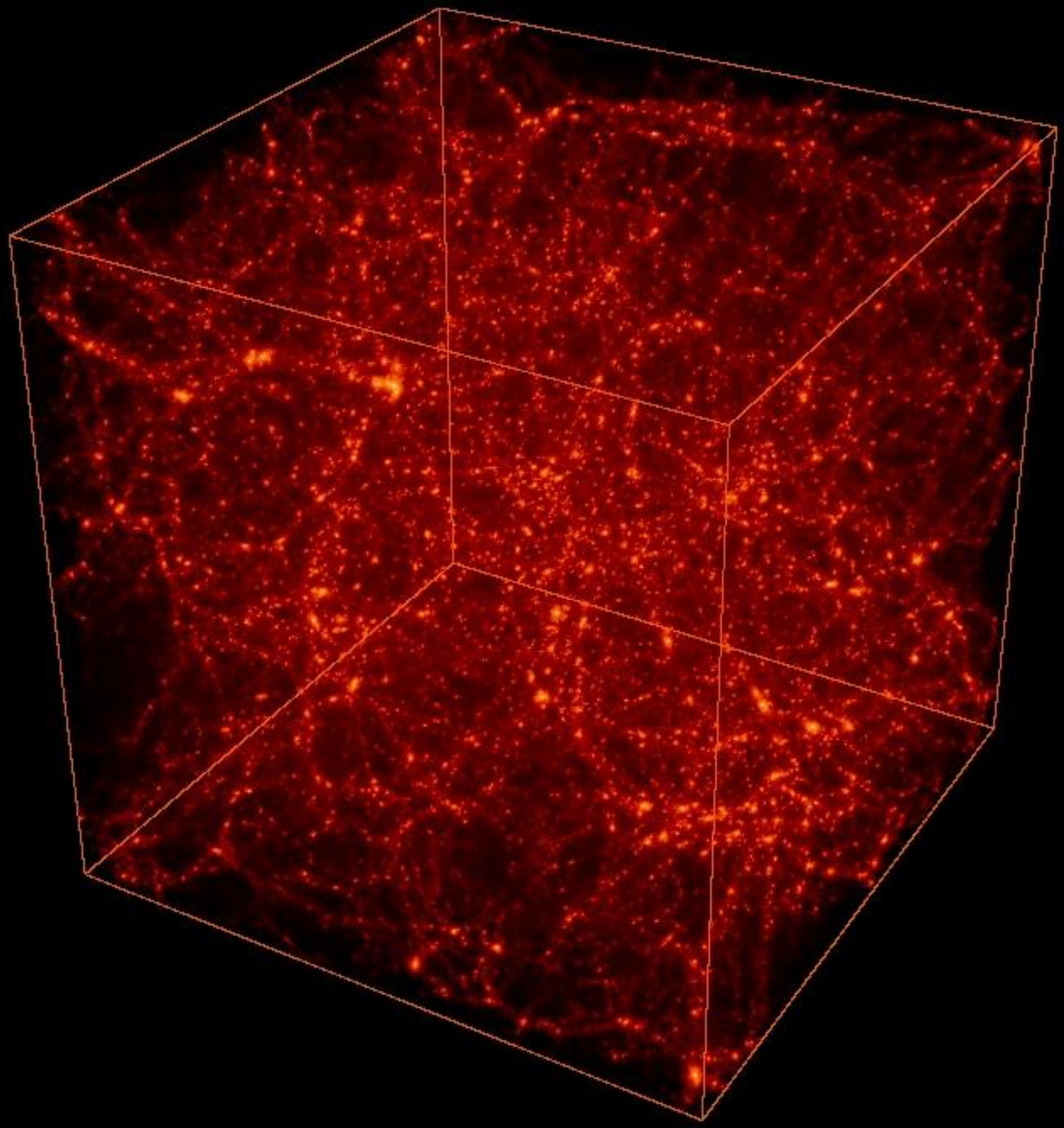
- Vacuum energy (quantum fluctuations) ➠ dark energy ?
- State equation for this new fluid :

  p = w(z) 〉

  w(z)=-1 for cosmological constant ⊄



Structuration



Cosmological parameters

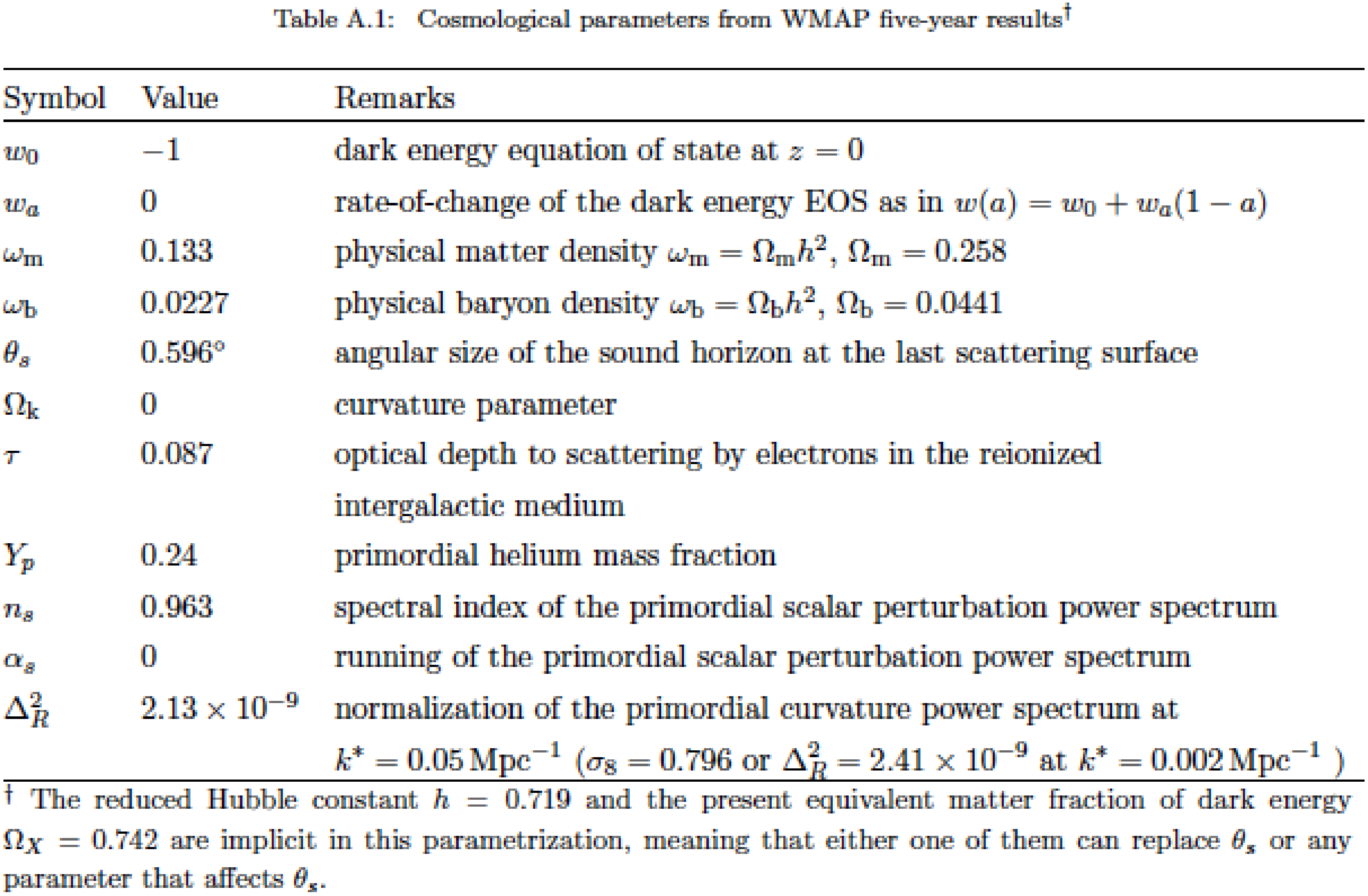
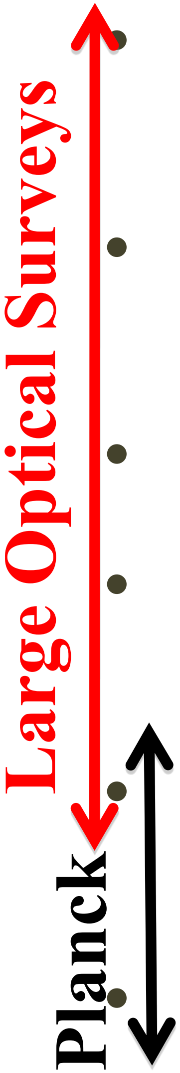


Table A.1: Cosmological parameters from WMAP five-year results[†]

Symbol	Value	Remarks
w_0	-1	dark energy equation of state at $z = 0$
w_a	0	rate-of-change of the dark energy EOS as in $w(a) = w_0 + w_a(1 - a)$
ω_m	0.133	physical matter density $\omega_\mathrm{m} = \Omega_\mathrm{m} h^2$, $\Omega_\mathrm{m} = 0.258$
ω_b	0.0227	physical baryon density $\omega_\mathrm{b} = \Omega_\mathrm{b} h^2$, $\Omega_\mathrm{b} = 0.0441$
θ_s	0.596°	angular size of the sound horizon at the last scattering surface
Ω_k	0	curvature parameter
τ	0.087	optical depth to scattering by electrons in the reionized intergalactic medium
Y_p	0.24	primordial helium mass fraction
n_s	0.963	spectral index of the primordial scalar perturbation power spectrum
α_s	0	running of the primordial scalar perturbation power spectrum
$\Delta^2_{\mathcal{R}}$	2.13×10^{-9}	normalization of the primordial curvature power spectrum at $k^* = 0.05\,\mathrm{Mpc}^{-1}$ ($\sigma_8 = 0.796$ or $\Delta^2_{\mathcal{R}} = 2.41 \times 10^{-9}$ at $k^* = 0.002\,\mathrm{Mpc}^{-1}$)

[†] The reduced Hubble constant $h = 0.719$ and the present equivalent matter fraction of dark energy $\Omega_X = 0.742$ are implicit in this parametrization, meaning that either one of them can replace θ_s or any parameter that affects θ_s.

Cosmological probes



- **Supernovae** : measure the apparent luminosity of the SNIa as a function of z → $\mathbf{d_L(z)}$ → H(z)
- **Gravitational weak lensing** : measure distorsions of the galaxy orientation distribution → $\mathbf{d_A(z)}$ → structures
- **Strong lensing time delays** : → $\mathbf{d_{LT}}$ → H_0
- **Galaxy clusters** : cluster counting and spatial distribution → $\mathbf{d_A(z)}$ → H(z), structure formation
- **Baryonic Acoustic Oscillations (BAO)** : measure a characteristic scale in matter spatial distribution → $\mathbf{d_A(z)}$ → H(z)
- **Integrated Sachs-Wolf effect**: descent and ascent of photons in a potential well that varies over time

Cosmology with optical surveys: aims and challenges

- **History**: go to ancient times => **large redshift *z***
  - Baryonic Acoustic Oscillations
  - Supernovæ => **photometry, time**

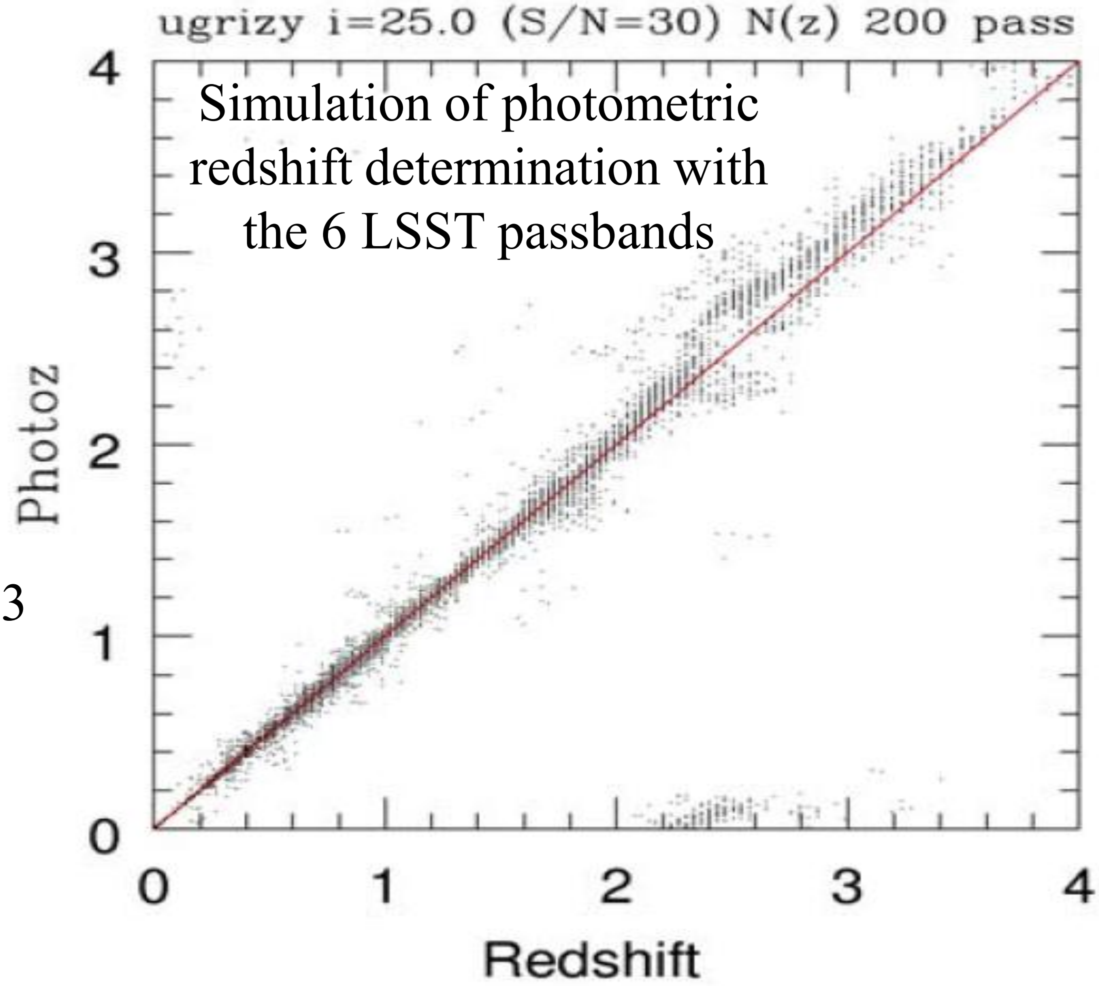
  => ***z* determination**
- **Content**: search for mass (even local)
  - Lensing (macro, micro, weak) => **photometry, astrometry, time**
  - Other indirect signatures of matter (velocity fields…)
- **Structuration**: statistical studies of large structures
  => **large volumes**
- **Tests of the cosmological hypothesis**: check anisotropy
  => **large volumes & angular coverage**

Note: determination (z, photometry, astrometry) means *precise* determination

Redshift determination

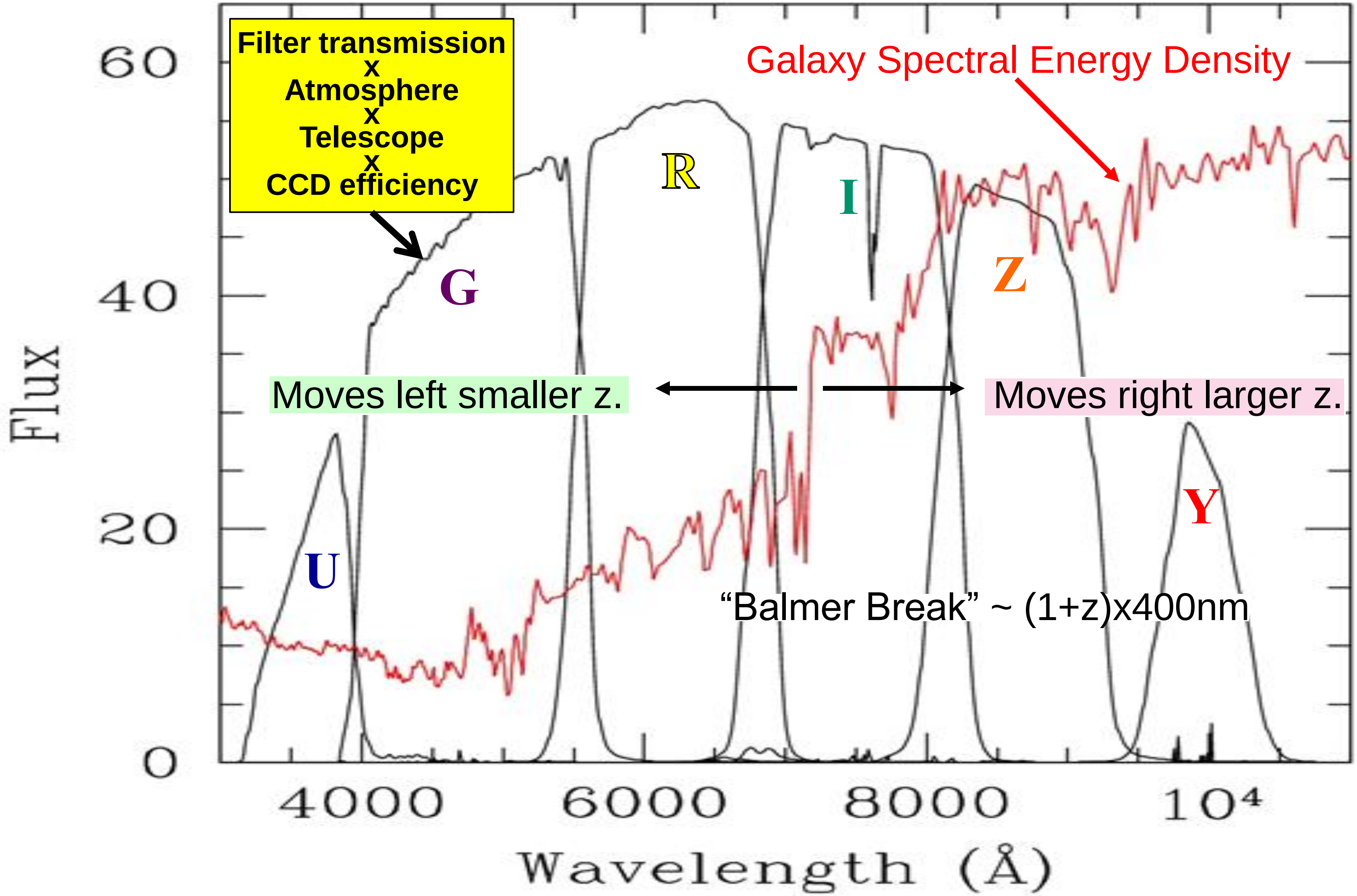
- **Photometric-*z* vs Spectroscopic-*z***

- LSST: Calibration until z=3
  -> need 75 000 spectra
  (~50% already exist)



Simulation of photometric redshift determination with the 6 LSST passbands

Photometric Redshift



Filter transmission
x
Atmosphere
x
Telescope
x
CCD efficiency

Galaxy Spectral Energy Density

Moves left smaller z.

Moves right larger z.

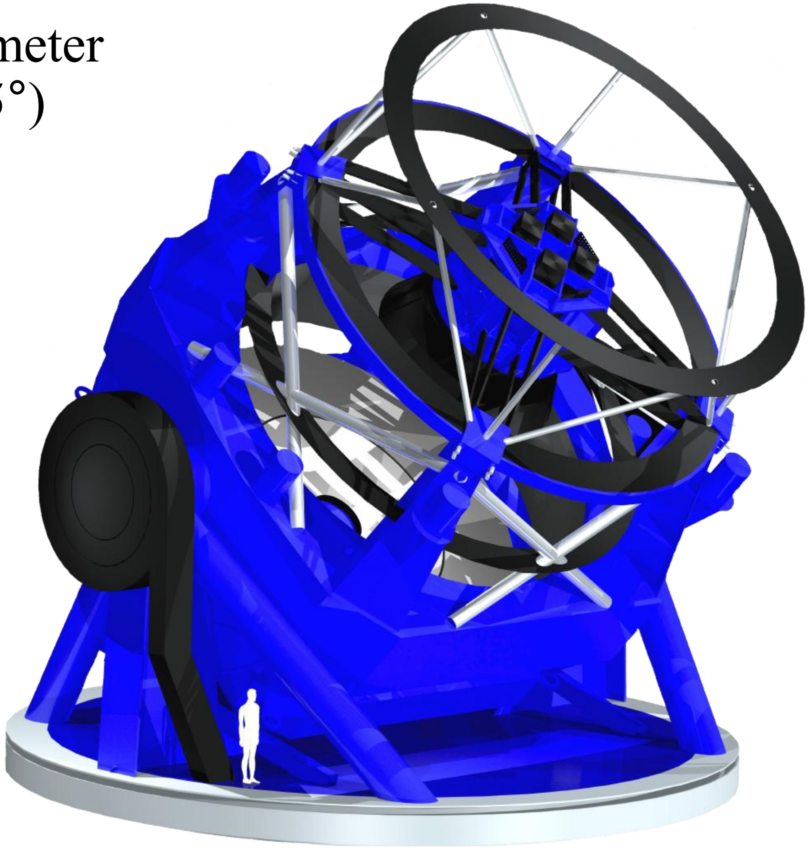
“Balmer Break” ~ (1+z)x400nm

Cosmological Surveys

- **Running / Near-future**
  - DES, Dark Energy Survey: 5000 deg2, tel. 4m -> SN, BAO
  - BOSS
  - HETDEX: 420 deg^2, tel. 9.2m, BAO **spectro**-z<3.8
  - HSC/WFMOS
  - Pan-STARRS4: 4x1.8m tel., SN
- **After 2015**
  - **LSST**: 20000 deg^2, tel. 8.4m -> SN, BAO, weak-lensing
  - **BigBOSS**: 10000 deg^2, tel. 2.4m, BAO 0.6<**spectro**-z<2.3
  - JDEM/Euclid (space) -> BAO
  - SKA (radio) -> BAO
  - Constellation-X

LSST : Large Synoptic Survey Telescope

- Optical telescope 8.4 m diameter with wide-field camera (3.5°)
- In Chile (Cerro Pachon)
- Concept from ‘90s
- 3.2 Gpixels camera
- Readout 2s
- 6 filters (ugrizy)
- Weak lensing up to z ~ 3
- SNIa up to z ~ 1
- Baryonic oscillations
- Galaxies and galaxy-clusters
- Transients



http://www.lsst.org/

LSST “mission”

Large Synoptic Survey Telescope

- Photometric survey of half of the sky (~ 20 000 sq. deg.)
- Complete coverage every 4 nights during 10 years
- One 10 sq. deg. field every 40 seconds
- Fast alert system (60s) for detection of violent phenomenon

Deliverables (cosmology)

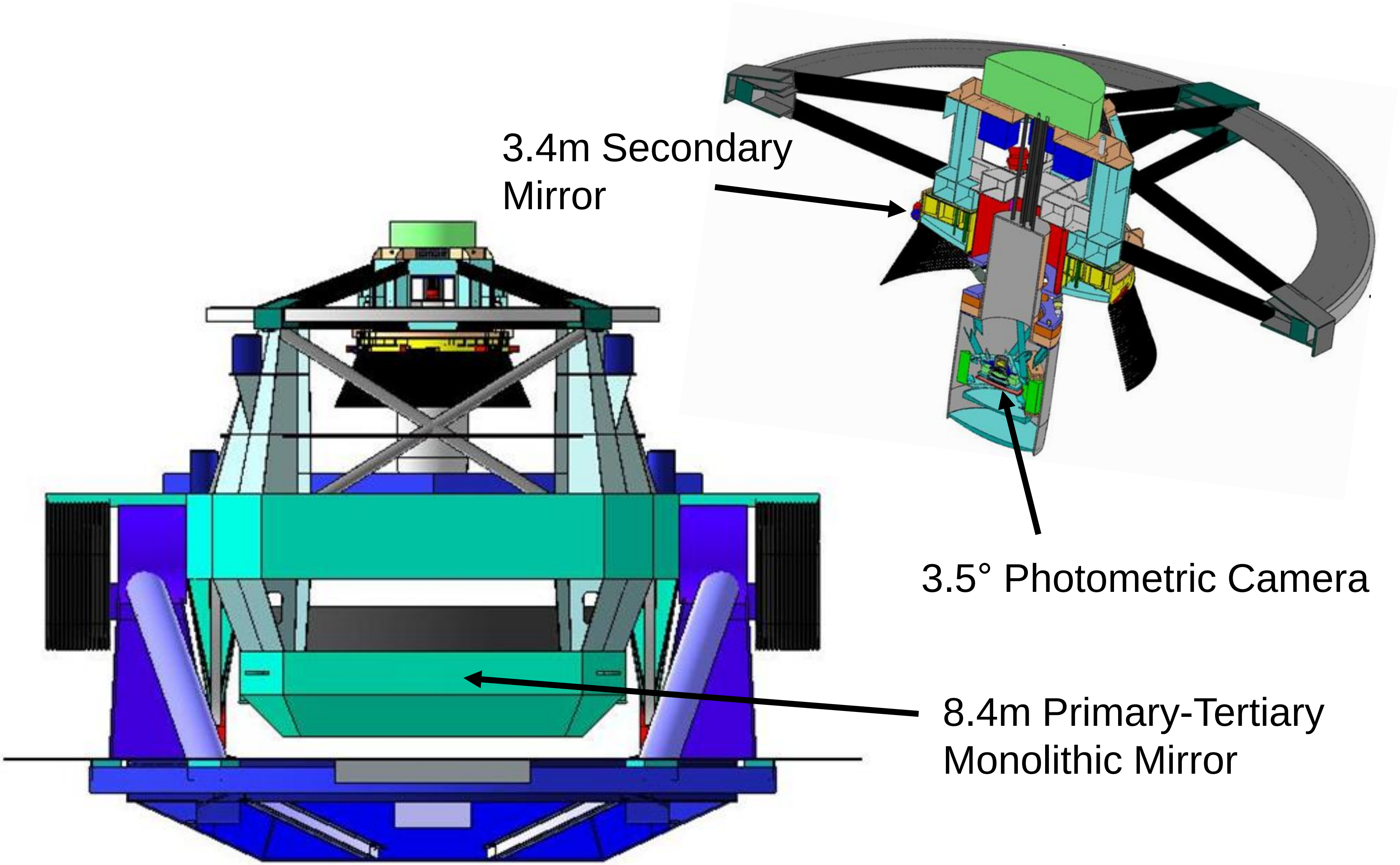
Archive more than $3x10^9$ galaxies with photometric redshifts up to z=3

Detection of 250 000 SN Ia per year (with photo-z < 0.8).

« 4D » mapping

(α,δ) position on the sky
Redshift *z*
Time variations (SN, lensing, AGN…)

Large Synoptic Survey Telescope

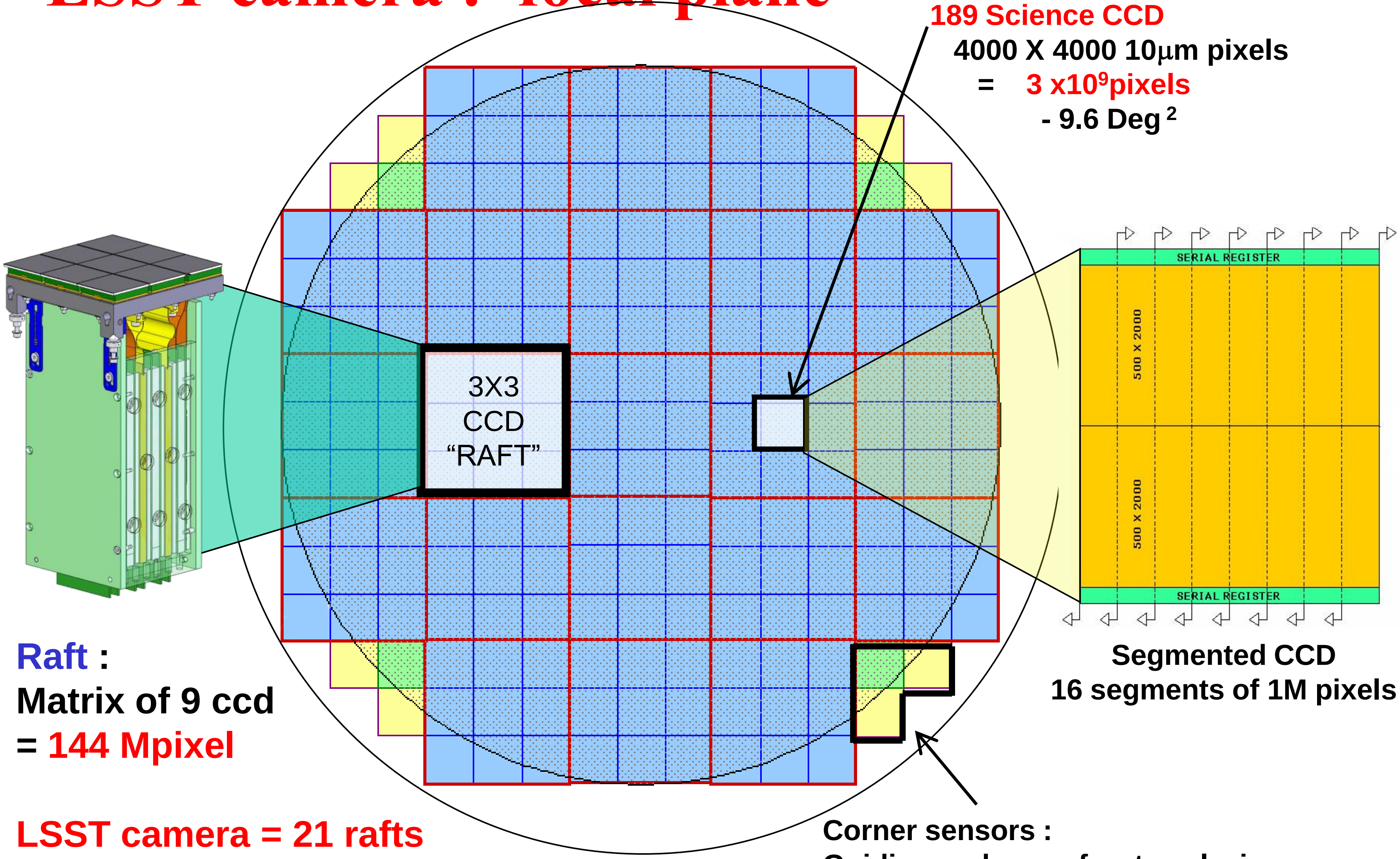


3.4m Secondary Mirror

3.5° Photometric Camera

8.4m Primary-Tertiary Monolithic Mirror

LSST camera : focal plane



189 Science CCD
4000 X 4000 10μm pixels
= 3 x10^9pixels
- 9.6 Deg ^{2}

Segmented CCD
16 segments of 1M pixels

Raft :
Matrix of 9 ccd
= 144 Mpixel

Corner sensors :
Guiding and wave-front analysis

LSST camera = 21 rafts

Cosmological probes for optical surveys

Large Optical Surveys

- **Supernovae** : measure the apparent luminosity of the SNIa as a function of z → $\mathbf{d_L(z)}$ → H(z)
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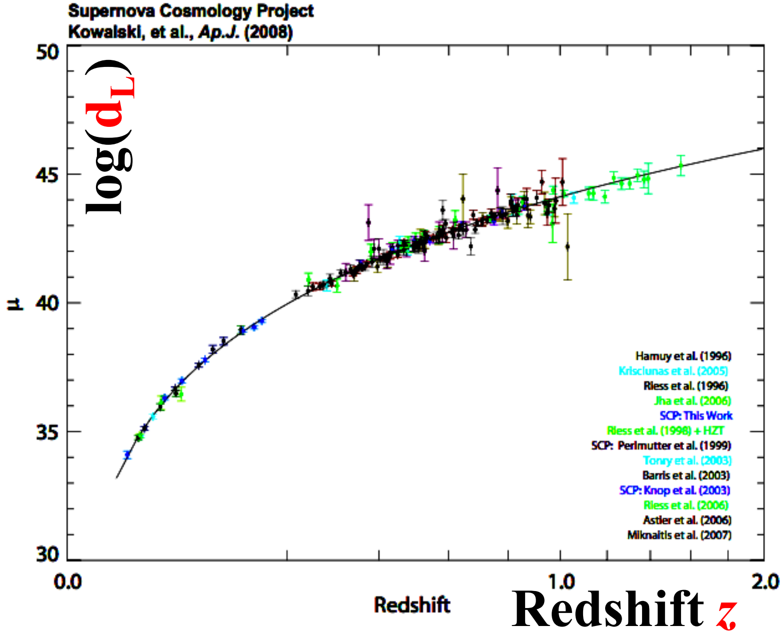
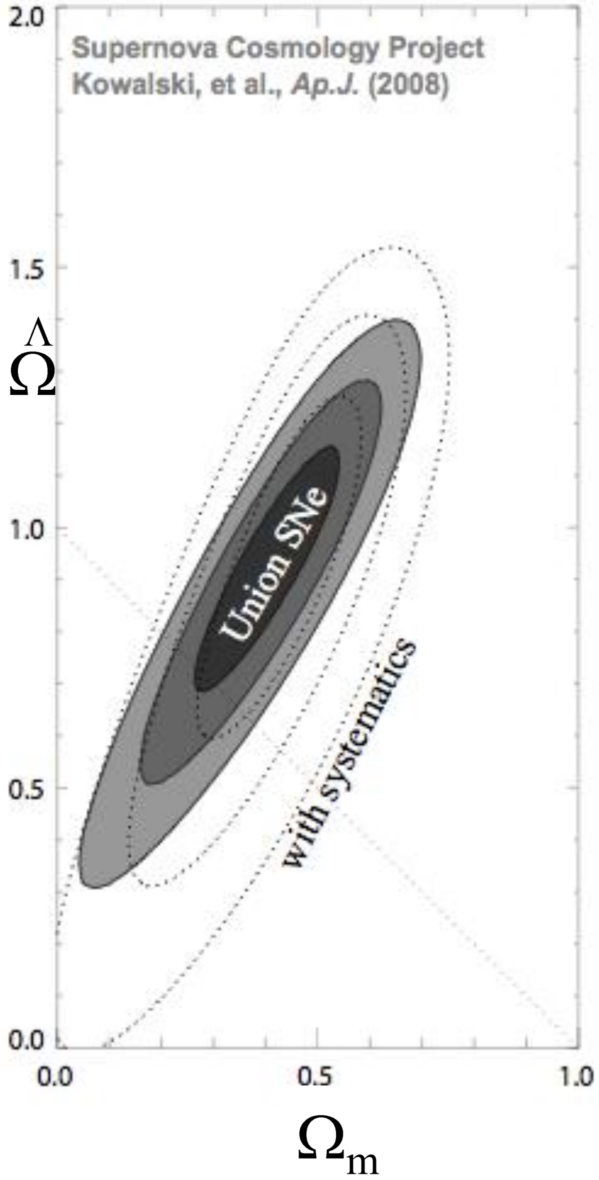
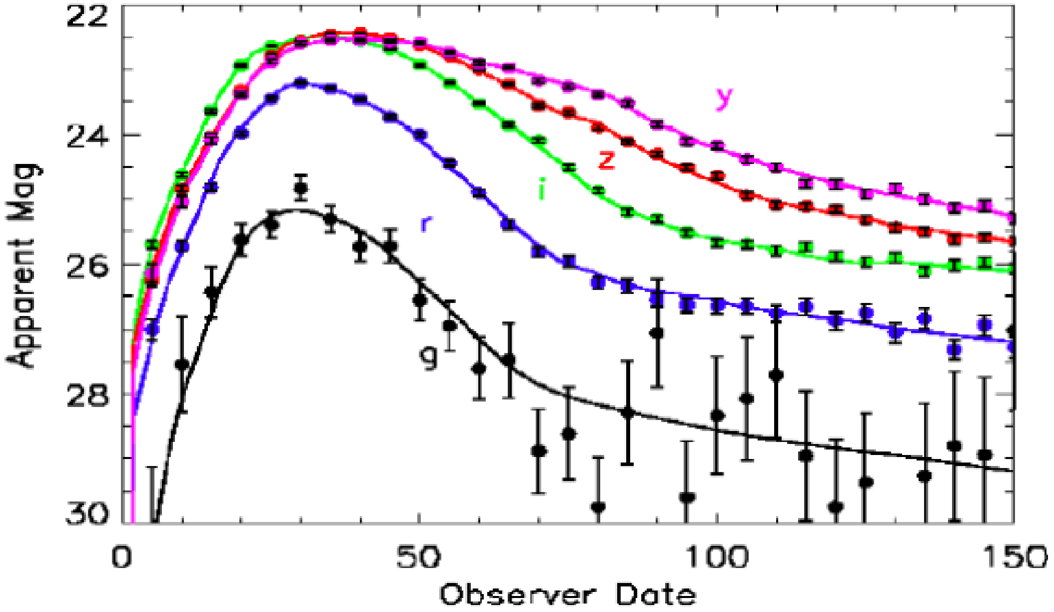
SN1a: Status


Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)
50
45
40
35
30
μ
$\log(d_L)$
0.0
1.0
2.0
Redshift
Redshift z
Hamuy et al. (1996)
Krisciunas et al. (2005)
Riess et al. (1996)
Jha et al. (2006)
SCP: This Work
Riess et al. (1998) + HZT
SCP: Perlmutter et al. (1999)
Tonry et al. (2003)
Barris et al. (2003)
SCP: Knop et al. (2003)
Riess et al. (2006)
Astier et al. (2006)
Miknaitis et al. (2007)

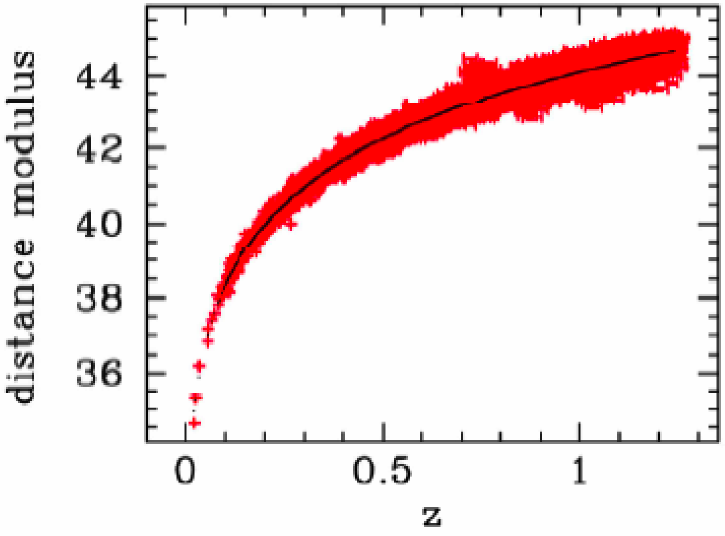

Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)
2.0
1.5
1.0
0.5
0.0
Ω_Λ
0.0
0.5
1.0
Ω_m
Union SNe
with systematics

SN1a: Expectations from LSST

250 000 SNIa @ $z < 1$ per year



Simulated light-curves of a SN1a @ $z = 0.832$

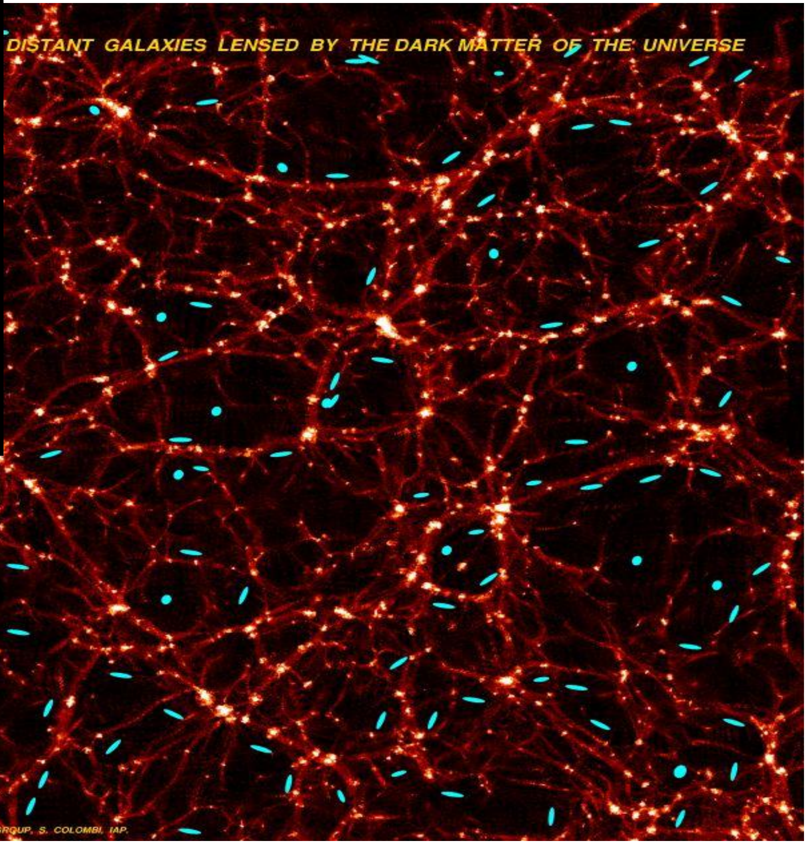


Expected Hubble diagram with 30 000 SN1a (photo-z)

Gravitational distorsions of distant galaxies

Simulation courtesy of S. Colombi (IAP, France).

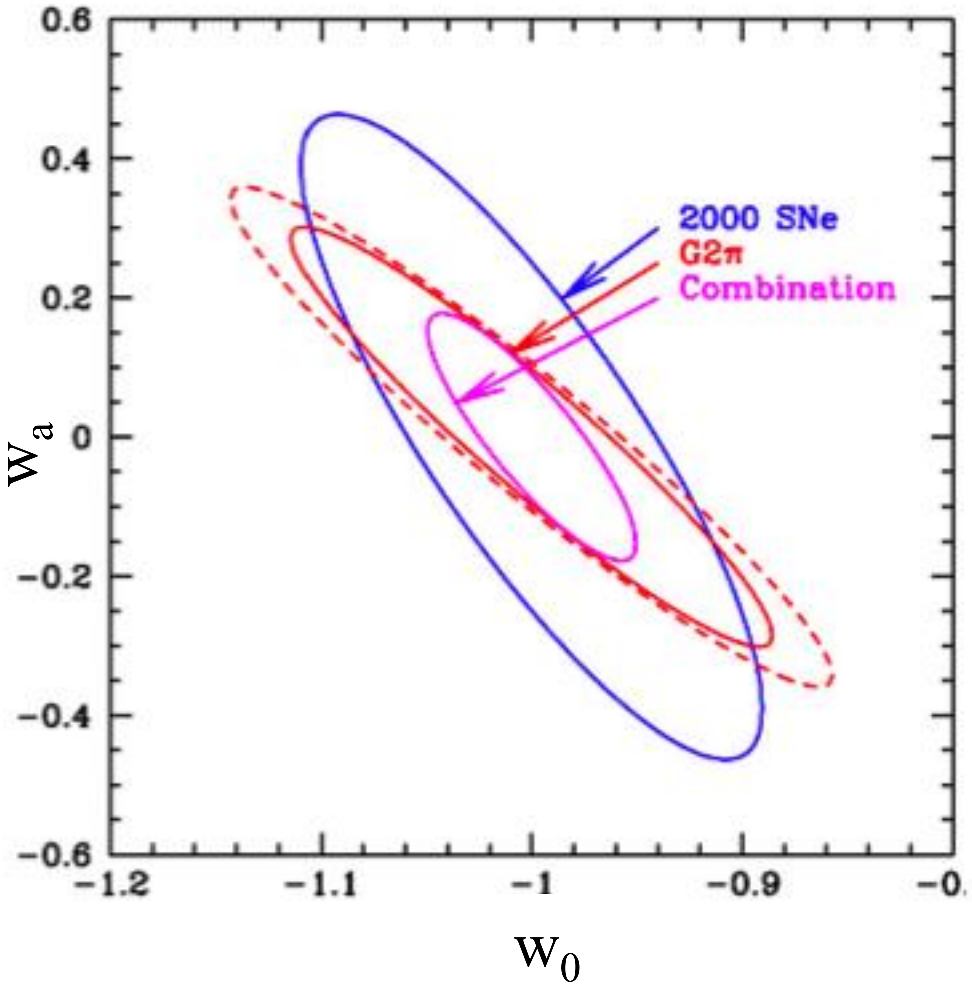
Galaxies act as lenses on more distant objects.



Sensitivity to large structures and to the nature of gravitation.

WL+SN: LSST expectations

- Measurement of the parameters of the dark energy state equation : **$p/\rangle = [w_0+w_a. z/(1+z)]\rho$**
- Expected precision with weak lensing and 2000 SN1a.

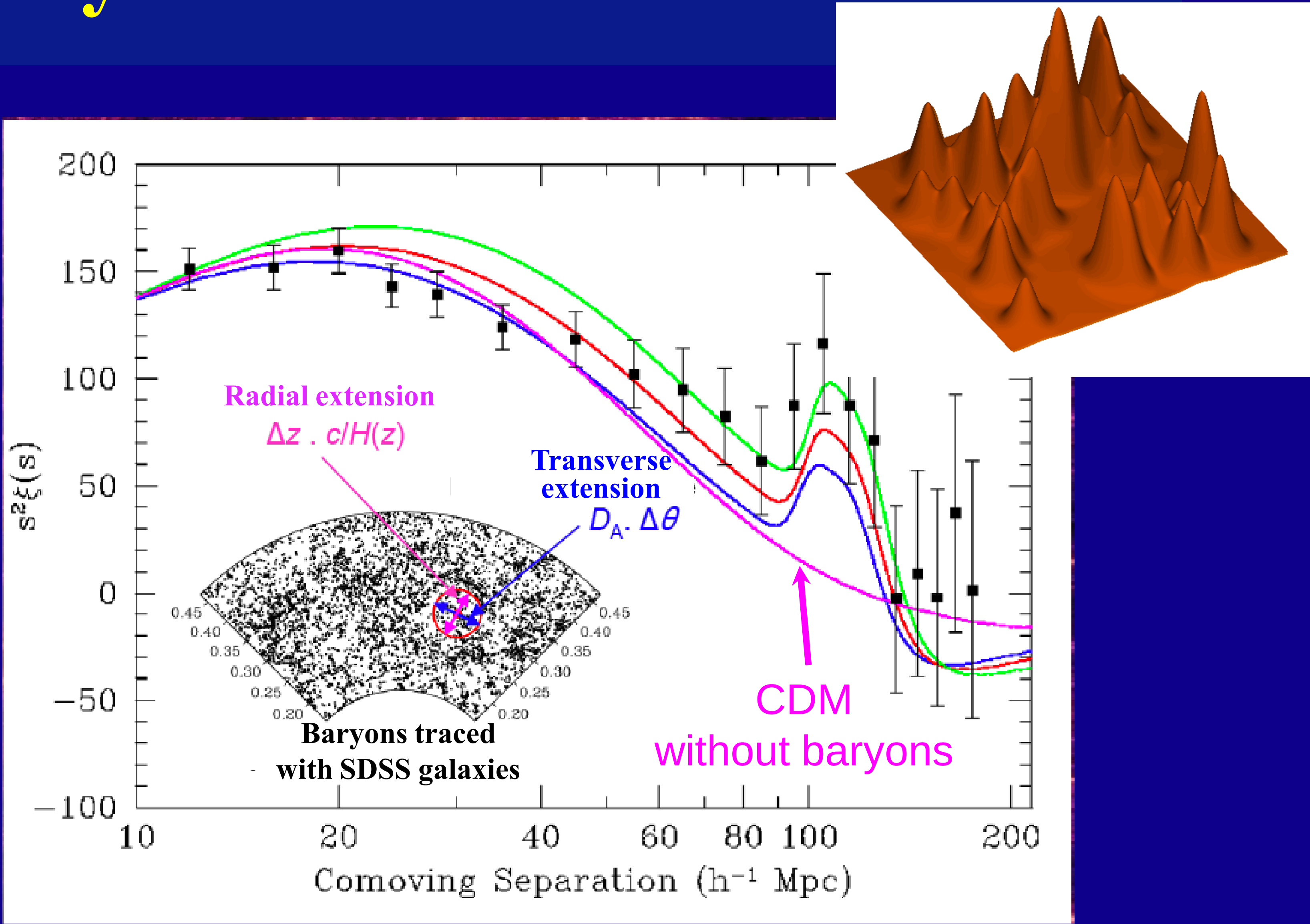


BAO : Baryonic Acoustic Oscillations

- Inprints of the oscillations of the baryon-photon fluid in the ordinary matter distribution after structure formation
- The baryonic matter distribution follows the dark matter modulation, in structures resulting from density fluctuation growing
- Cosmological probe of standard ruler type ($\mathbf{d}_A$)
  - With a measurement @ $z \sim 1100$ as a bonus (CMB anisotropies)
- Use tracers of baryonic matter:
  galaxies (LSST) or H_I (radio@21cm) with distinct biases

Baryonic Acoustic Oscillations

SDSS - D. Eisenstein et al.



Radial extension

$\Delta z\ .\ c/H(z)$

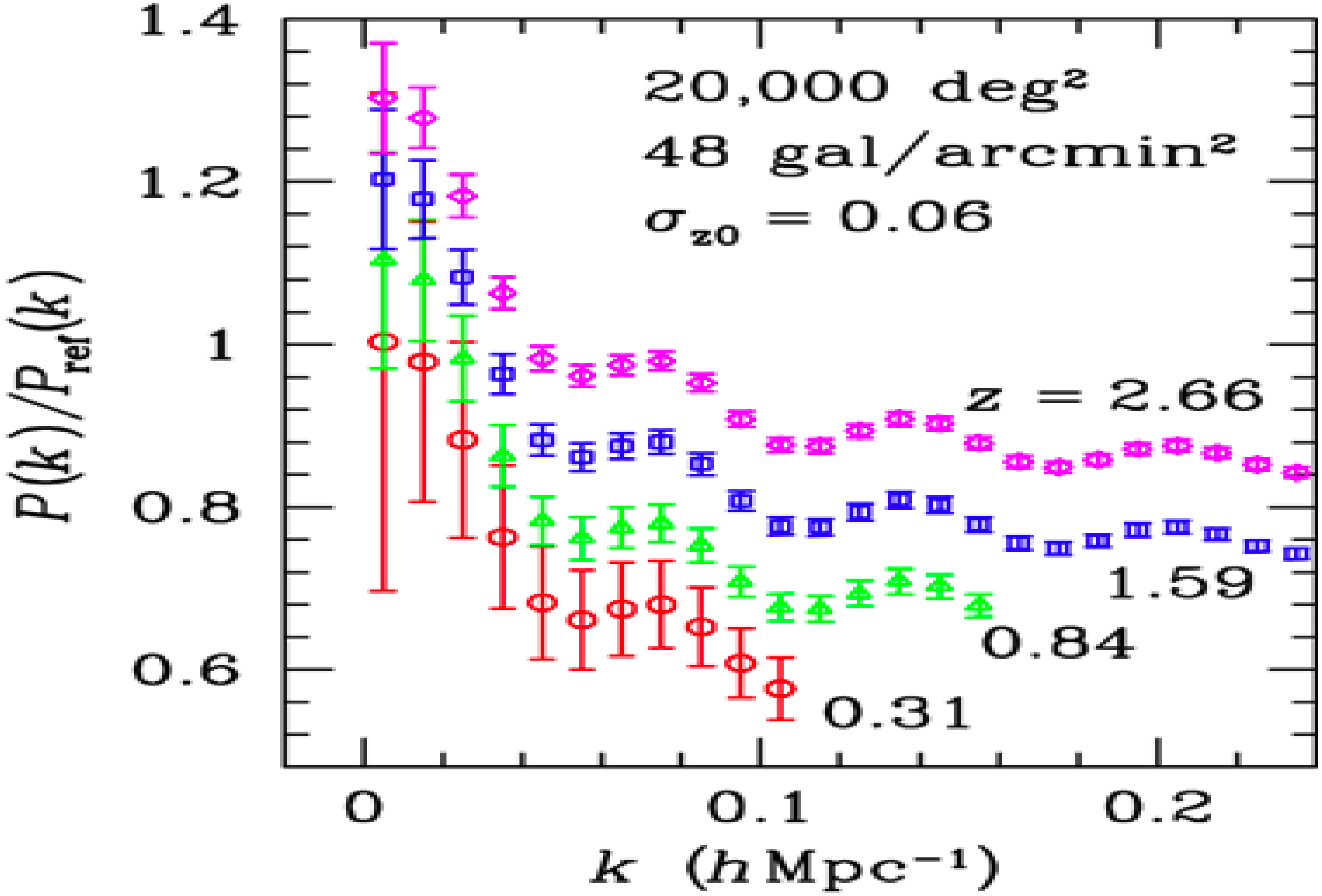
Transverse extension

$D_A .\ \Delta\theta$

Baryons traced with SDSS galaxies

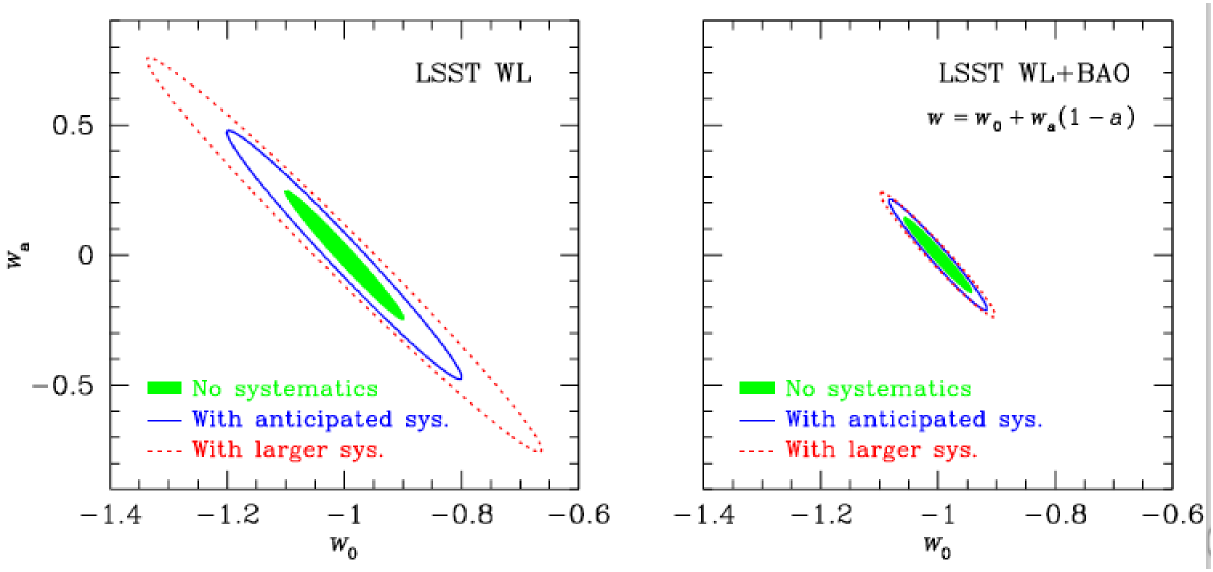
CDM without baryons

BAO: LSST expectations



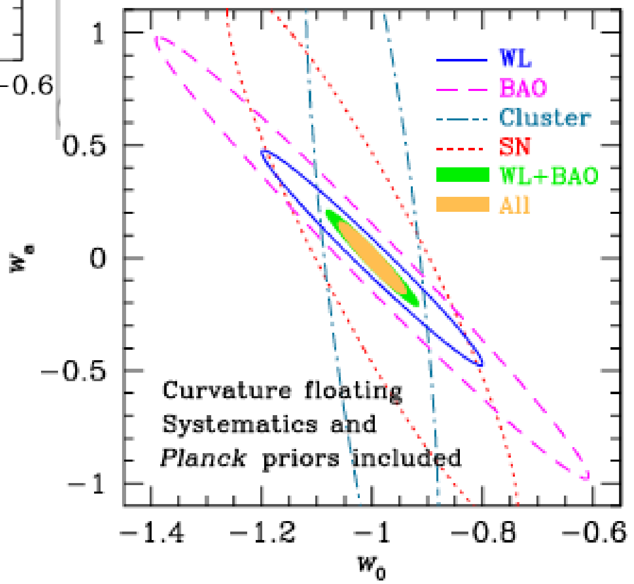
Constraints on Dark Energy

complementarity between probes (LSST)



different techniques have different systematic limitations

The combination will be significantly more precise than the individual determinations



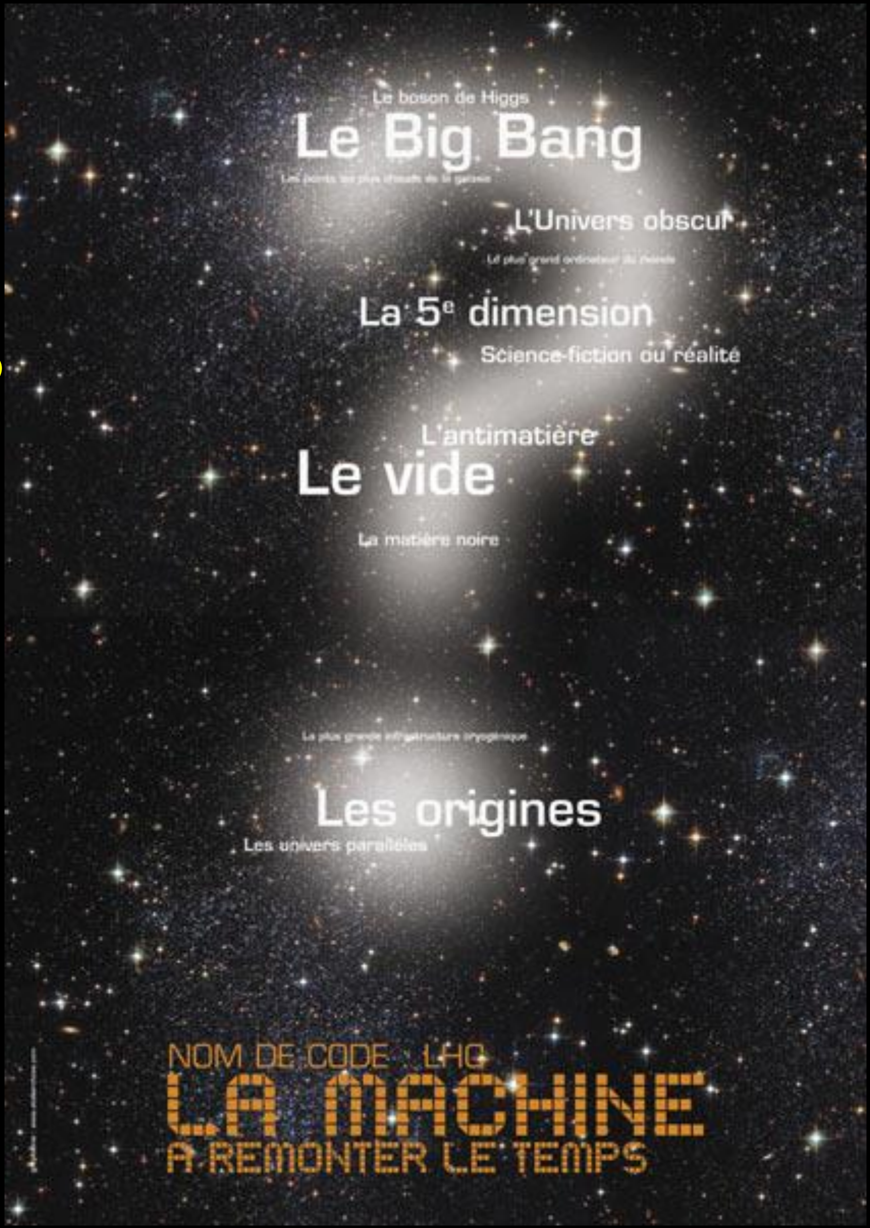
State equation

$$p = w(z)\rangle = [w_0 + w_a .\ z/(1+z)]\rho$$

Neutrino physics

- Since LHC is **the** machine to study the Big-Bang (according to many posters and press-releases)
- Cosmologists now study particle physics with telescopes

  => Neutrino physics

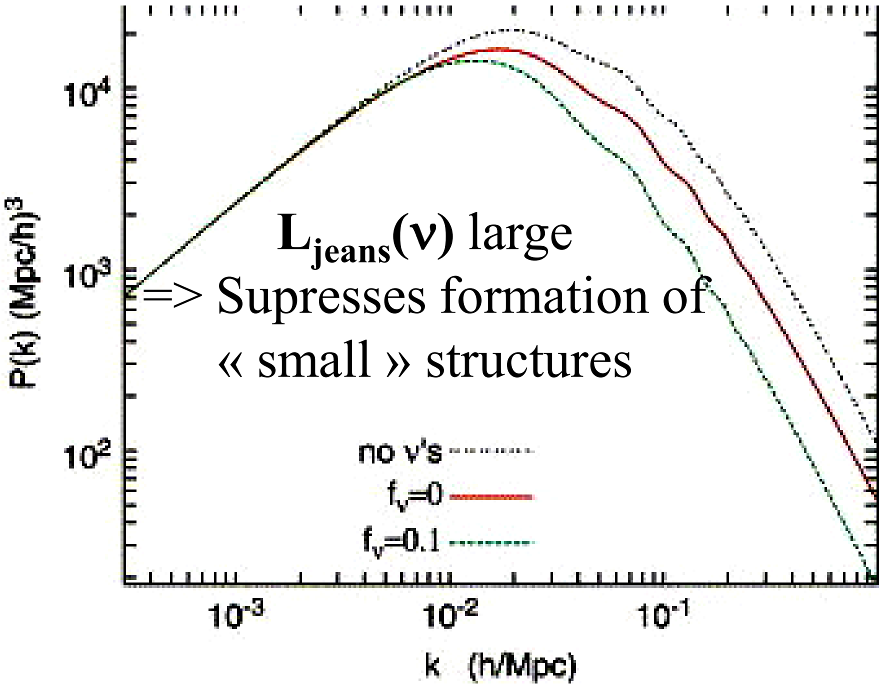


Neutrino mass

neutrino contribution to density:

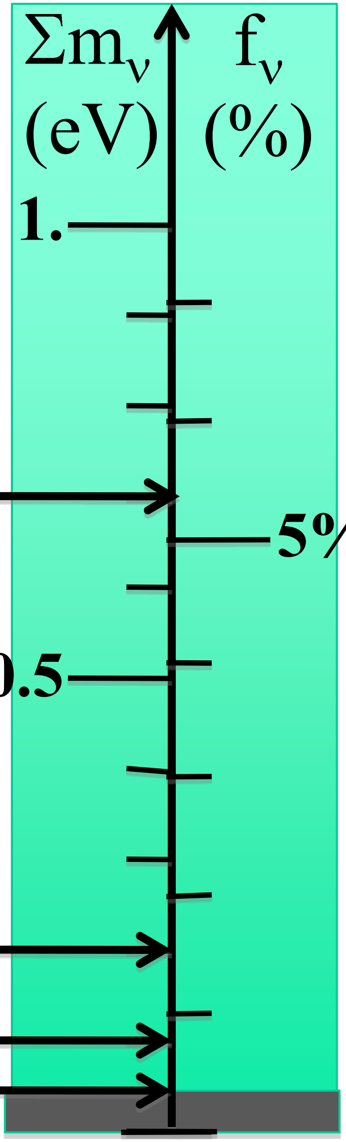
$\Sigma m_\nu = 94\text{eV}\ (\Omega_\nu\, h^2) = 13\text{eV x } f_\nu$

(f_ν = contribution of ν to matter)



$L_{jeans}(\nu)$ large

=> Supresses formation of « small » structures



< 0.7eV (WMAP+BAO)

0.2eV (Planck+BAO)

0.1eV (Planck+future BAO+weak lensing)

> 0.05eV (oscillations)

Conclusions

- Many perspectives connected with particle physics (dark energy and matter, neutrino)
- Complementarity of optical surveys with other astronomical surveys like microwave (Planck) and radio
- **LSST** **A leading cosmological project for the next decade**
  - Technology under control
  - Challenges : **atmospheric calibration and photometric redshift**
  - Every astronomical field is concerned

Complements

Large Synoptic Survey Telescope

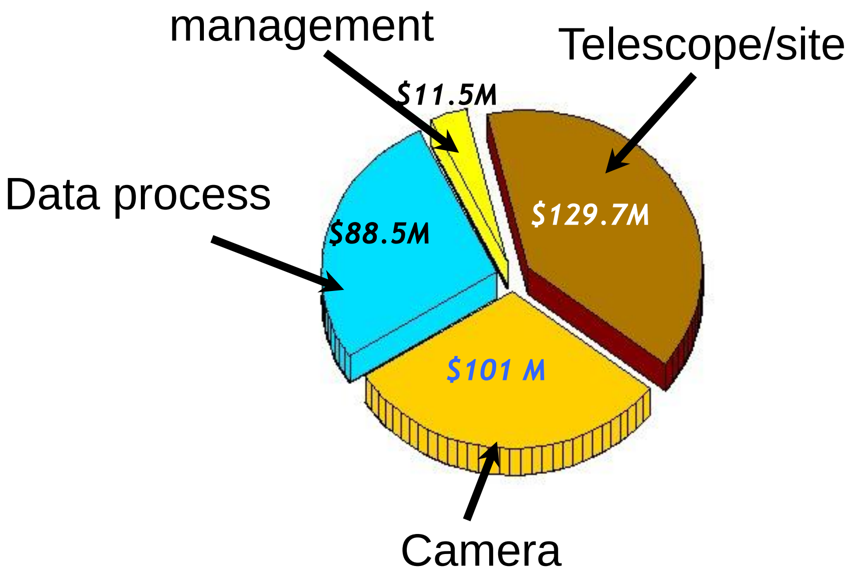
LSST collaboration

- Brookhaven National Laboratory
- California Institute of Technology
- Google Corporation
- Harvard-Smithsonian Center for Astrophysics
- Johns Hopkins University
- Las Cumbres Observatory
- Lawrence Livermore National Laboratory
- National Optical Astronomy Observatory
- Ohio State University
- Pennsylvania State University
- Princeton University
- Research Corporation
- Stanford Linear Accelerator Center
- Stanford University
- University of Arizona
- University of California, Davis
- University of Illinois
- University of Pennsylvania
- University of Washington

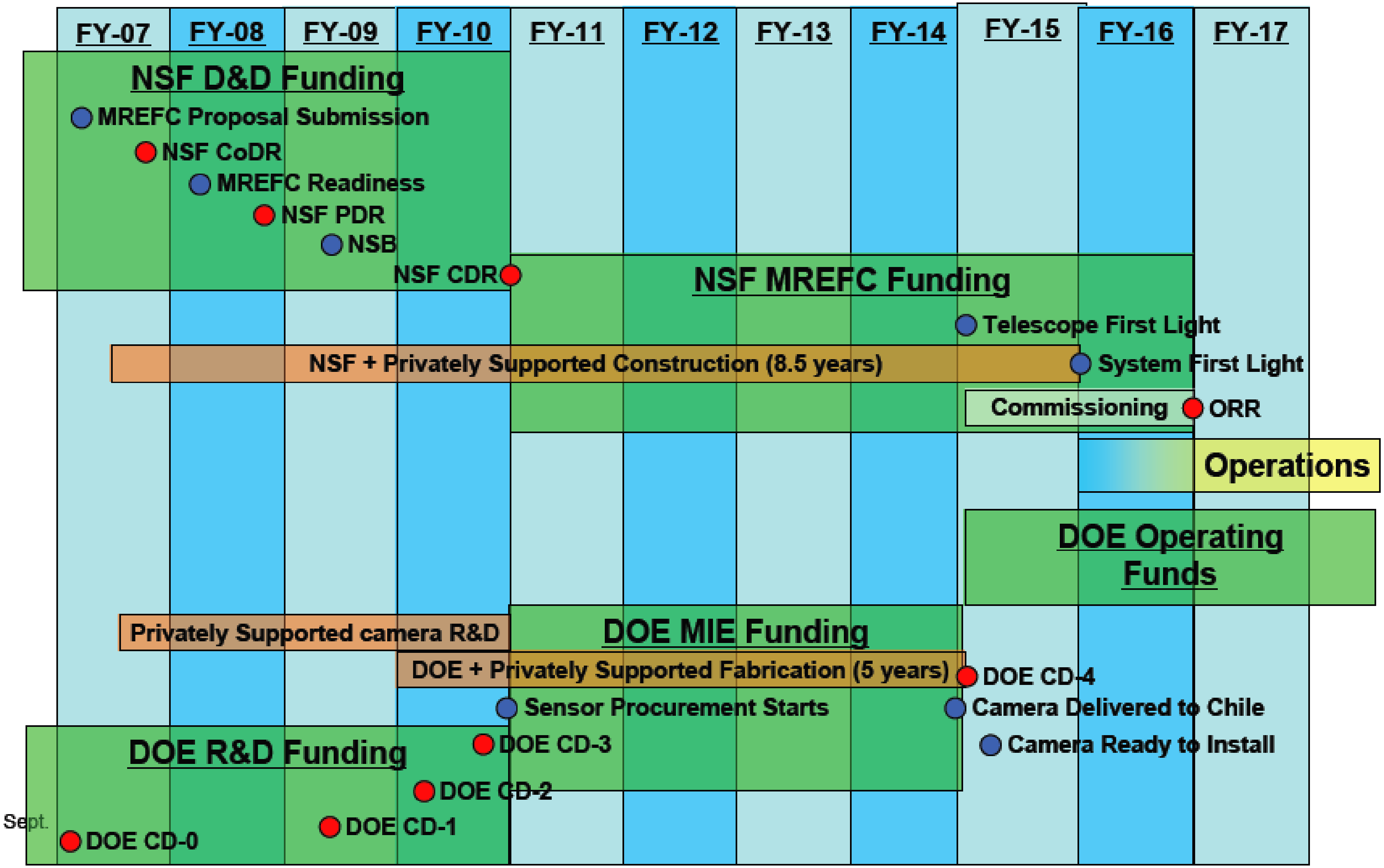
+… french connection

LSST : Planning / cost

- **2008-2011: R&D**
- 2011-2017 : Construction
- 2017-2027 : Observations
- Telescope/site : 130 M$
- Camera : 100 M$
- Data Proc : 88 M$
- Operation ~ 30 M$ / an



Planning (sept. 2008)



FY-07
FY-08
FY-09
FY-10
FY-11
FY-12
FY-13
FY-14
FY-15
FY-16
FY-17

NSF D&D Funding
- MREFC Proposal Submission
- NSF CoDR
- MREFC Readiness
- NSF PDR
- NSB
- NSF CDR

NSF MREFC Funding
- Telescope First Light
- System First Light
- ORR

NSF + Privately Supported Construction (8.5 years)

Commissioning

Operations

DOE Operating Funds

Privately Supported camera R&D

DOE MIE Funding

DOE + Privately Supported Fabrication (5 years)
- DOE CD-4
- Sensor Procurement Starts
- Camera Delivered to Chile
- Camera Ready to Install
- DOE CD-3

DOE R&D Funding
- DOE CD-2
- DOE CD-1
- DOE CD-0

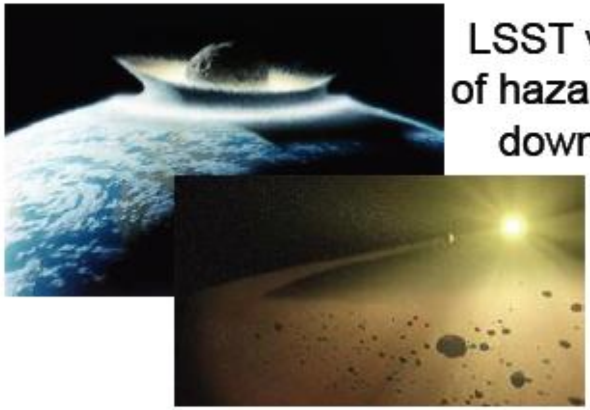
Sept.

LSST science: 4 domains

Dark Energy-Dark Matter

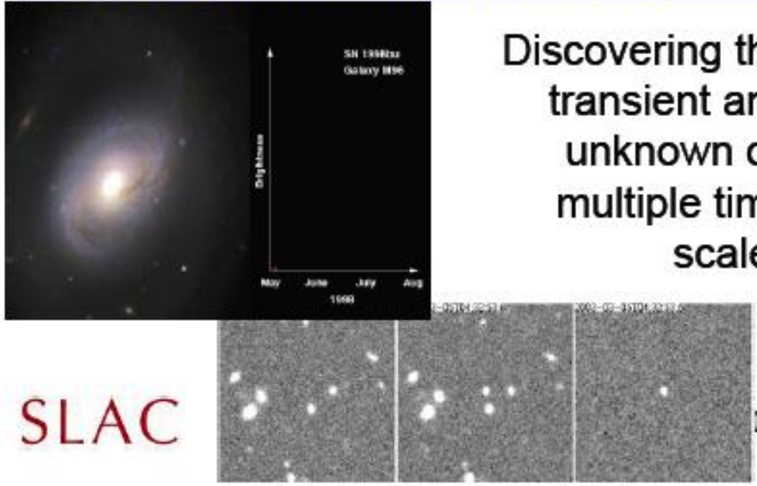
LSST enables multiple investigations into our understanding of the universe

Exploring our Solar System



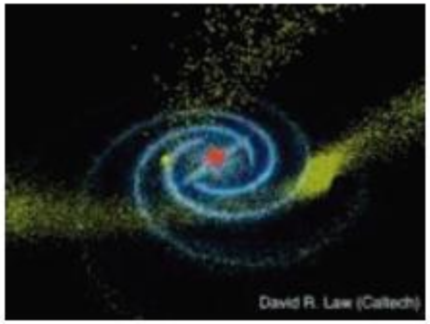
LSST will find 90% of hazardous NEOs down to 140 m in 10 yrs

"Movie" of the Universe: time domain



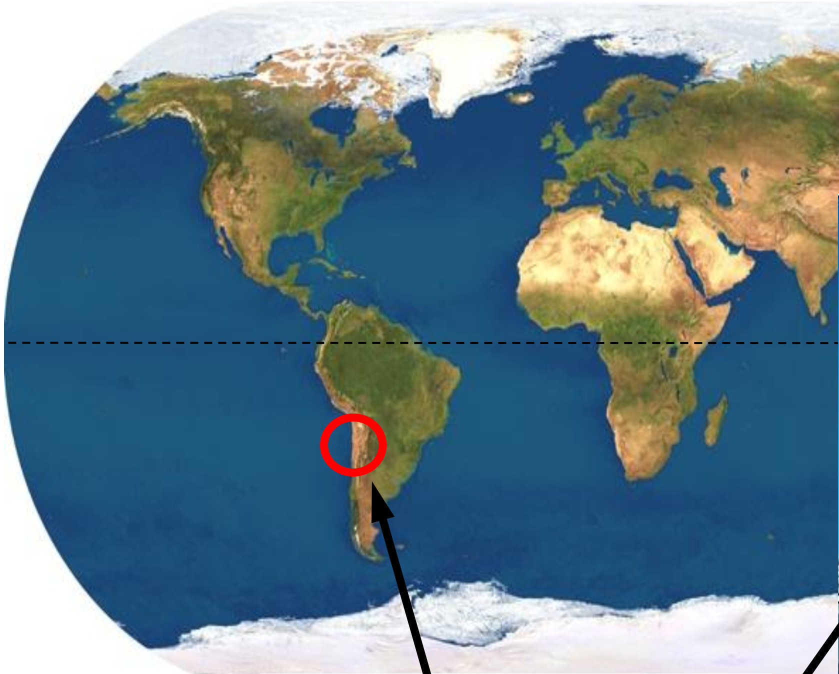
Discovering the transient and unknown on multiple time scales

Mapping the Milky Way



LSST will map the rich and complex structure of our Galaxy.

LSST Site



Cerro Pachón

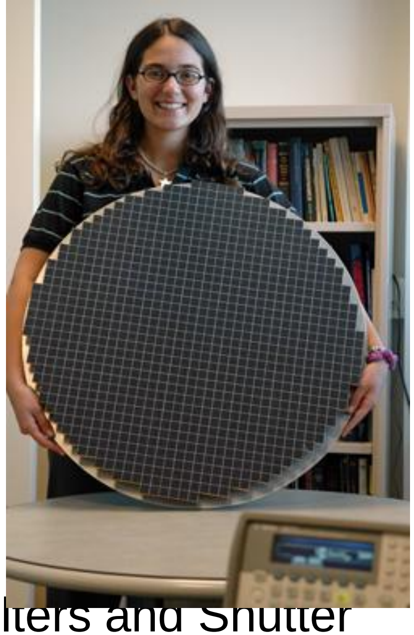
LSST Facility Sketch

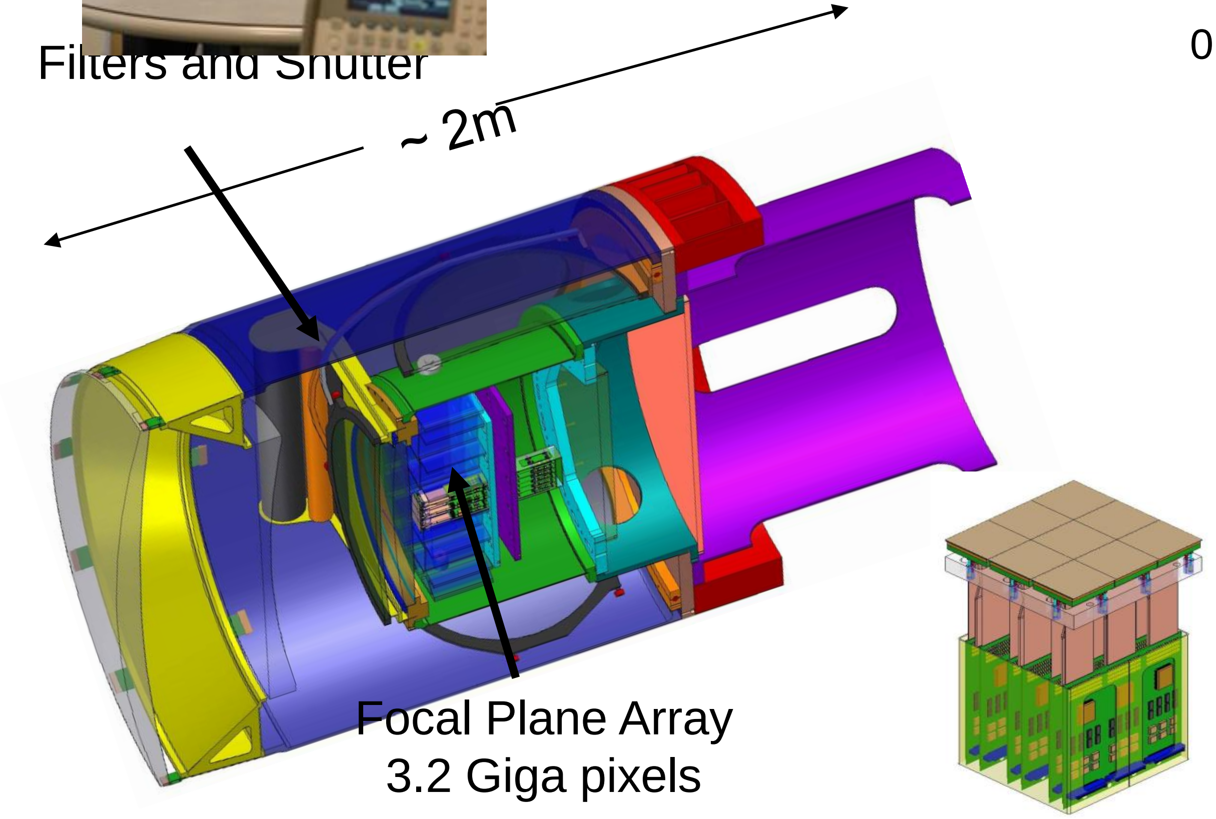
El Peñón

Gemini South
and SOAR

Typical “seeing” on Pachón is 0.7 arc-sec.

LSST Camera

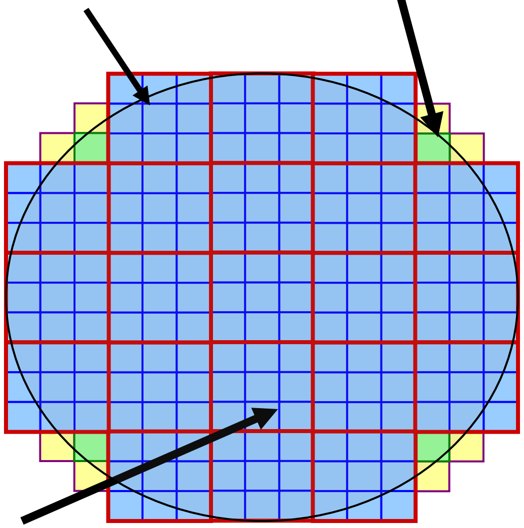




Filters and Shutter

~ 2m

Focal Plane Array
3.2 Giga pixels



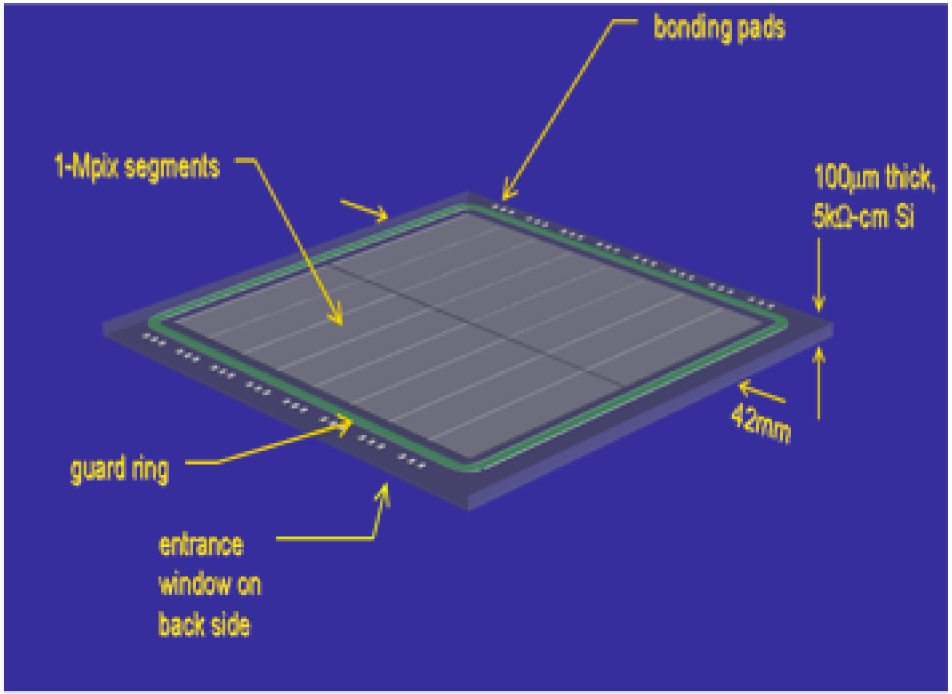
Wavefront Sensors and
Fast Guide Sensors

0.65m Diameter

“Raft” of nine
4kx4k CCDs.

Sensors: Reference Design

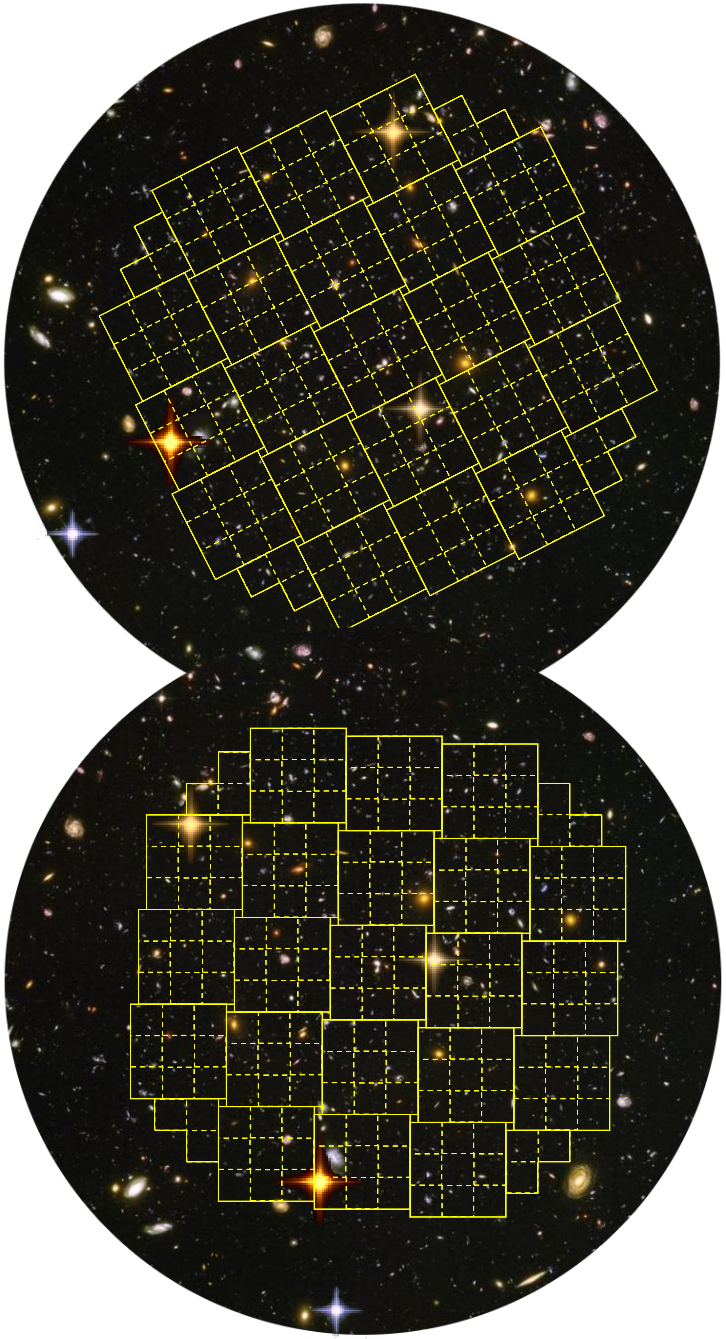
Reference Design Parameter	Value	Unit
Sensor technology	CCD	
Thickness	75-125	micron
Thickness tolerance	+/- 5	micron
Die size (Raft area per sensor)	42 x 42	mm
Sensor package outside dimensions	41.7 x 41.7	mm
Active area	40 x 40	mm
Fill factor (4-side butt-able)	95	%
Flatness (p-v)	5	micron
Format	4k x 4k	
Pixel size	10 x 10	micron
Point spread function (rms)	3.2	micron
Readout clock frequency	500	kHz
Readout time	2	sec
Readout segmentation	16, vertical	segments
Window (back side) bias	> 40	V
Read noise	< 6	e-, rms
Dark current	< 1	e-/s/pixel



CCD Design Parameters

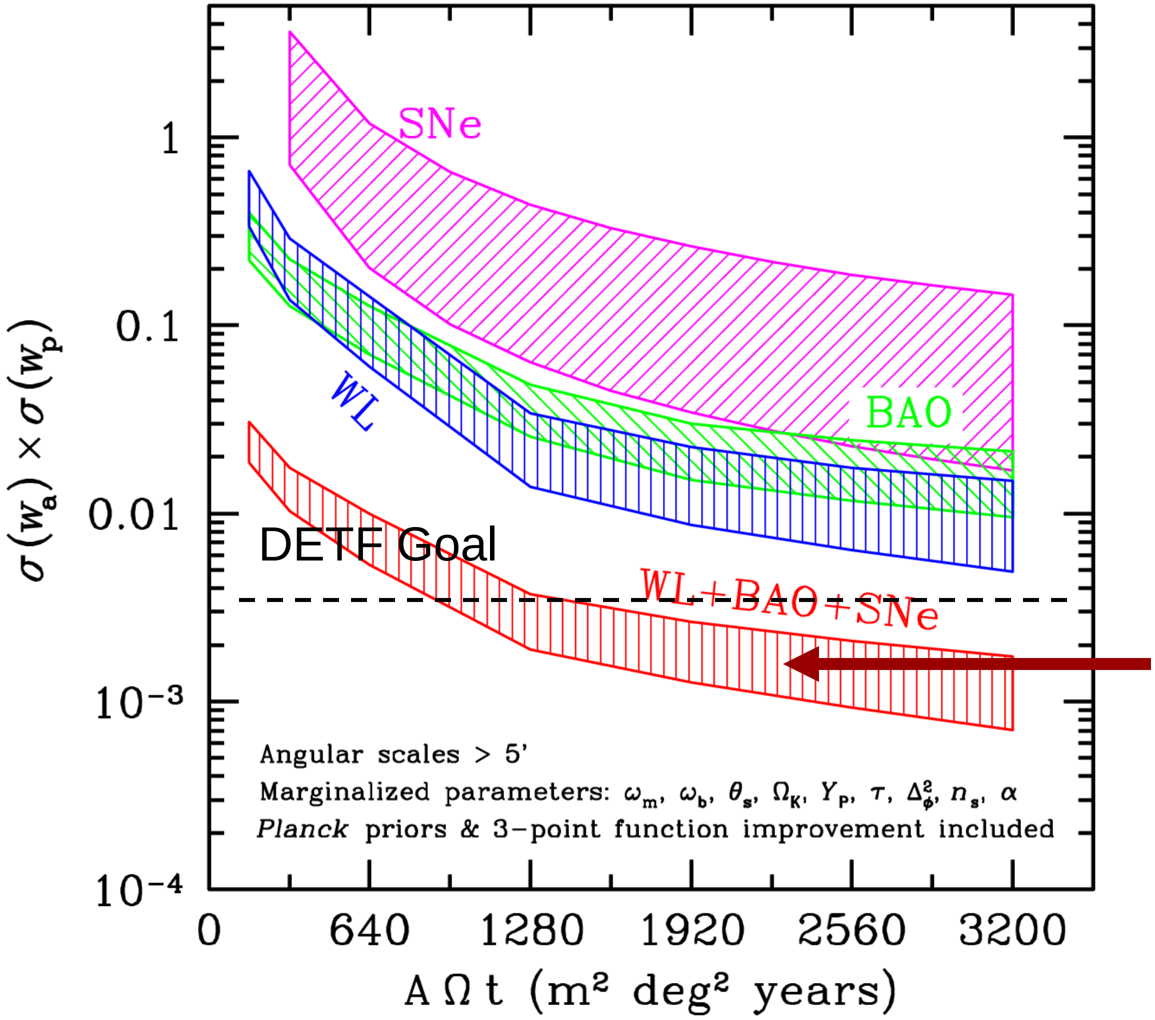
- *–Thickness optimized for best QE/PSF tradeoff*
- *–Thin, conductive entrance window to apply bias*
- *–16-fold segmentation for fast, low noise readout*
- *–Precision package for flat mosaic assembly*

Observational Strategy



- Multi-epoch observations
- 15s exposures
  - Variability studies
  - Co-addition of images taken in various conditions (instrumental and atmospheric)
- Uniform photometric quality
  - In any atmospheric condition
  - **Real time measurement of the atmospheric transmission**: auxilliary telescope

Precision on the determination of the dark energy state equation parameters



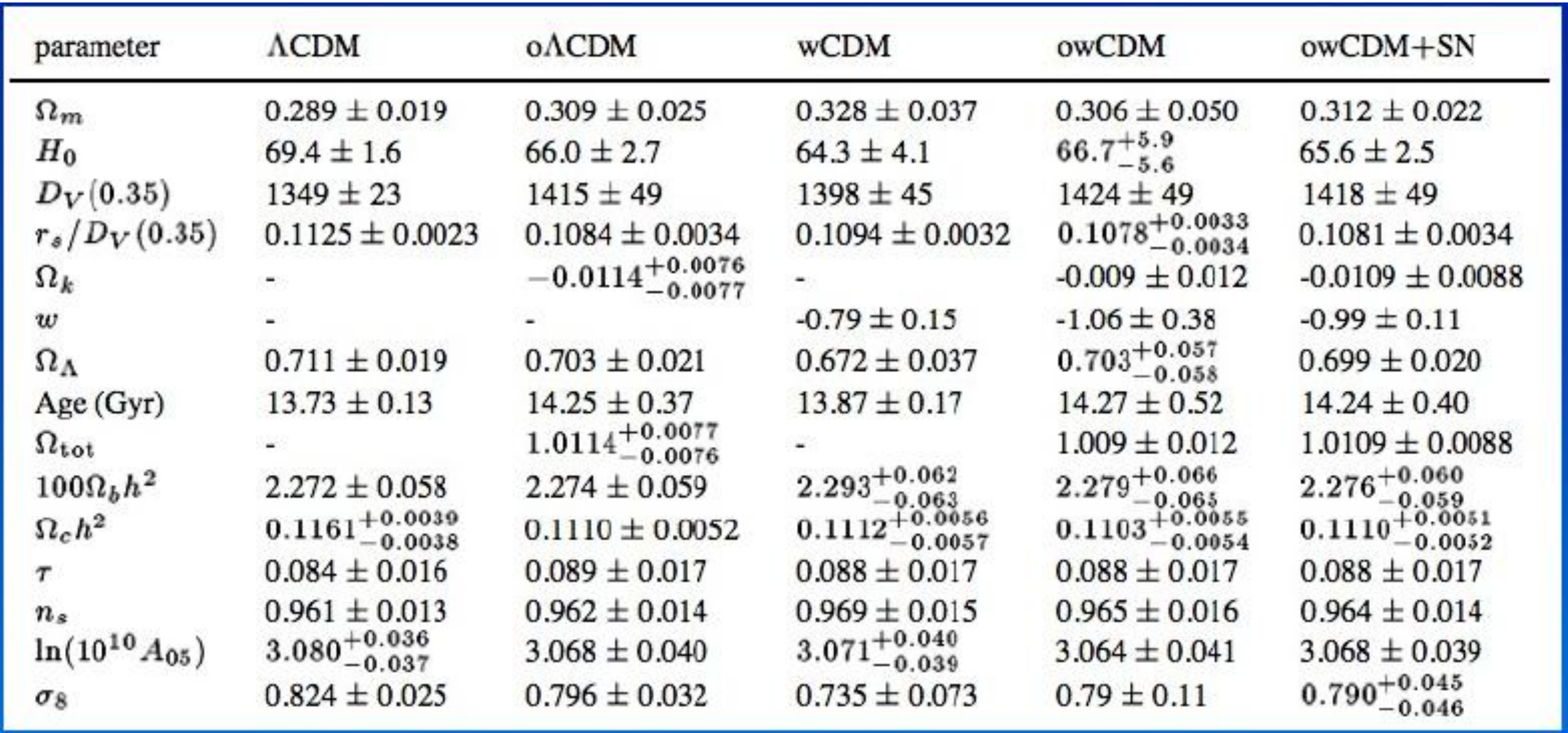
different techniques have different systematic limitations.

The combination is significantly more precise than the individual determinations.

Big astronomical projects

- **On Earth**
  - SDSS1-2-3 (Sloan Digital Sky Survey) BOSS / BigBOSS. (2009-2014). Spectroscopic survey. 10000 deg^2, telescope 2.4m. BAO $0.6 < z < 2.3$
  - CFHT/Megacam. Photometric survey griz, 288 Mpix CCD-camera, telescope 3.6m. SN
  - UKIDSS-VISTA (IR)
  - Pan-STARRS (4x1.8m telescopes, 4x1.4 Gpixel cameras)
  - LSST (8.4m telescope, 3.2 Gpixel camera)
  - SKA, Radio. BAO
  - DES): 300 Mgalaxies in 5 bands (grizy) to 24th magnitude. 3 deg2 camera, main survey 5000 dge2, SN1a survey 15 deg2. 520 Mpix CCD camera on CTIO 4m telescope. Start 2011, for 525 nights over 5 years.
  - Essence
  - ACT
  - SPT
  - HETDEX: spectrographic survey, telescope 9.2m, 420 deg2, 140 nights, 800000 redshifts 1.ç<z<3.8, 1000000 redshifts 0<z<0.5, de 2011 à 2013 pour BAO (spectro champ integral)
  - AAOmega quasar survey (multispectro sur télescope anglo-australien)
- **In space**
  - DUNE
  - GAIA
  - JDEM/EUCLID
  - HERSCHEL: 2.5 telescope, >160 microns; pas très wide field (max. 600 deg2)

Cosmological parameters



parameter	ΛCDM	oΛCDM	wCDM	owCDM	owCDM+SN
Ω_m	0.289 ± 0.019	0.309 ± 0.025	0.328 ± 0.037	0.306 ± 0.050	0.312 ± 0.022
H_0	69.4 ± 1.6	66.0 ± 2.7	64.3 ± 4.1	$66.7^{+5.9}_{-5.6}$	65.6 ± 2.5
$D_V(0.35)$	1349 ± 23	1415 ± 49	1398 ± 45	1424 ± 49	1418 ± 49
$r_s/D_V(0.35)$	0.1125 ± 0.0023	0.1084 ± 0.0034	0.1094 ± 0.0032	$0.1078^{+0.0033}_{-0.0034}$	0.1081 ± 0.0034
Ω_k	-	$-0.0114^{+0.0076}_{-0.0077}$	-	-0.009 ± 0.012	-0.0109 ± 0.0088
w	-	-	-0.79 ± 0.15	-1.06 ± 0.38	-0.99 ± 0.11
Ω_Λ	0.711 ± 0.019	0.703 ± 0.021	0.672 ± 0.037	$0.703^{+0.057}_{-0.058}$	0.699 ± 0.020
Age (Gyr)	13.73 ± 0.13	14.25 ± 0.37	13.87 ± 0.17	14.27 ± 0.52	14.24 ± 0.40
Ω_{tot}	-	$1.0114^{+0.0077}_{-0.0076}$	-	1.009 ± 0.012	1.0109 ± 0.0088
$100\Omega_b h^2$	2.272 ± 0.058	2.274 ± 0.059	$2.293^{+0.062}_{-0.063}$	$2.279^{+0.066}_{-0.065}$	$2.276^{+0.060}_{-0.059}$
$\Omega_c h^2$	$0.1161^{+0.0039}_{-0.0038}$	0.1110 ± 0.0052	$0.1112^{+0.0056}_{-0.0057}$	$0.1103^{+0.0055}_{-0.0054}$	$0.1110^{+0.0051}_{-0.0052}$
τ	0.084 ± 0.016	0.089 ± 0.017	0.088 ± 0.017	0.088 ± 0.017	0.088 ± 0.017
n_s	0.961 ± 0.013	0.962 ± 0.014	0.969 ± 0.015	0.965 ± 0.016	0.964 ± 0.014
$\ln(10^{10} A_{05})$	$3.080^{+0.036}_{-0.037}$	3.068 ± 0.040	$3.071^{+0.040}_{-0.039}$	3.064 ± 0.041	3.068 ± 0.039
σ_8	0.824 ± 0.025	0.796 ± 0.032	0.735 ± 0.073	0.79 ± 0.11	$0.790^{+0.045}_{-0.046}$

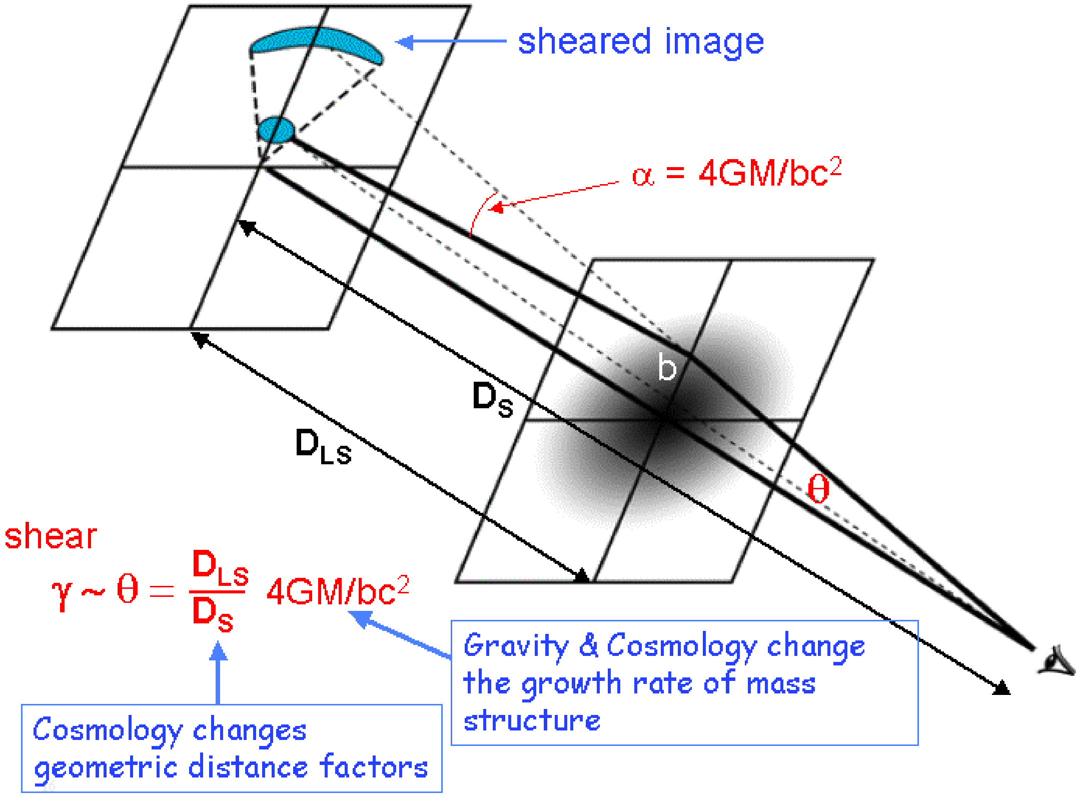
B.A. Reid et al. (2009)

Very stable results over time since WMAP (2003)

Weak shear

- Coherent distorsion of background images

$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \underset{\text{Magnification}}{\begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix}} + \underset{\text{Shear}}{\begin{pmatrix} -\gamma_1 & \gamma_2 \\ \gamma_2 & \gamma_1 \end{pmatrix}}$$



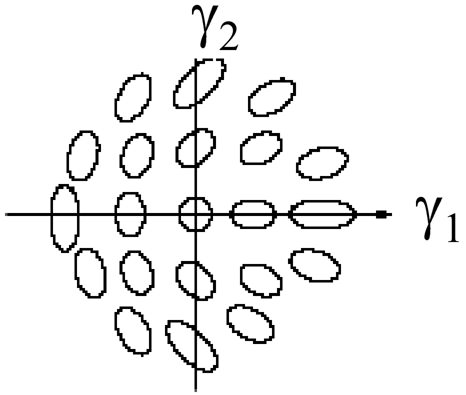
shear

$\gamma \sim \theta = \frac{D_{LS}}{D_S}$ 4GM/bc^2

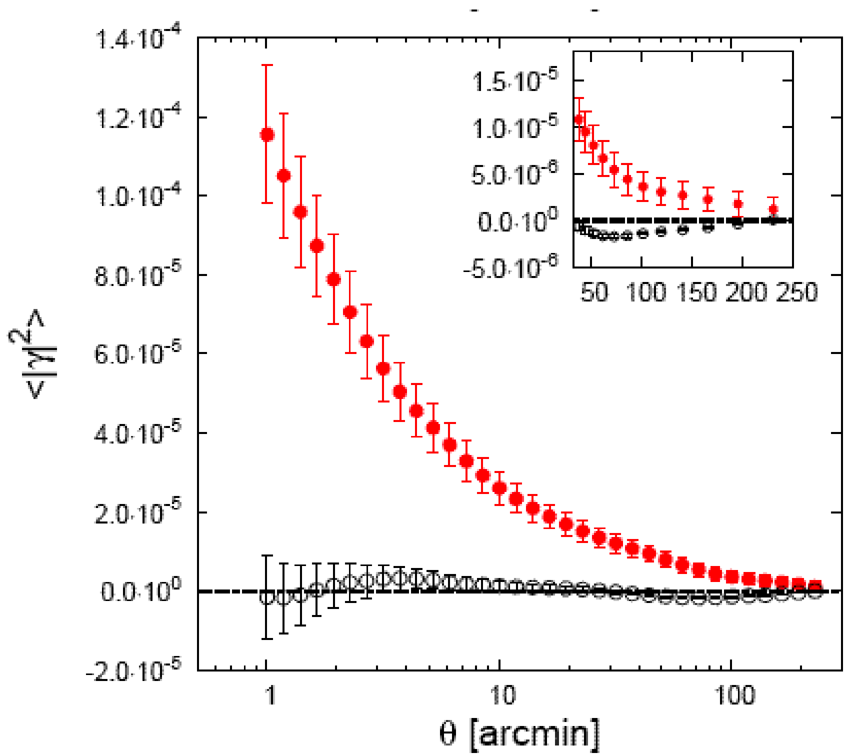
Gravity & Cosmology change the growth rate of mass structure

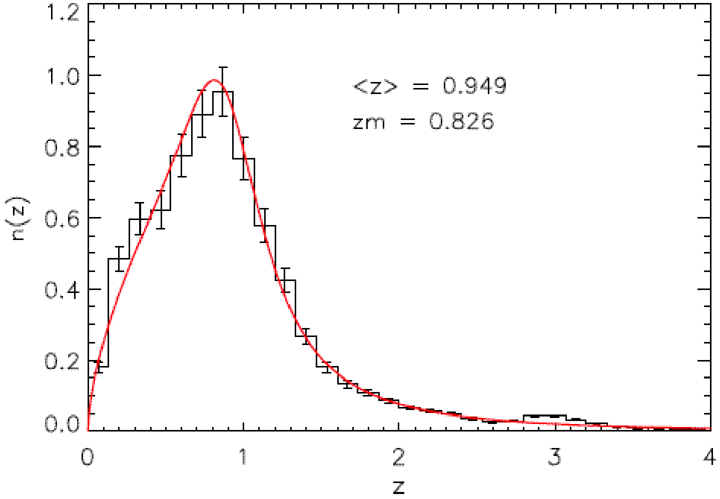
Cosmology changes geometric distance factors

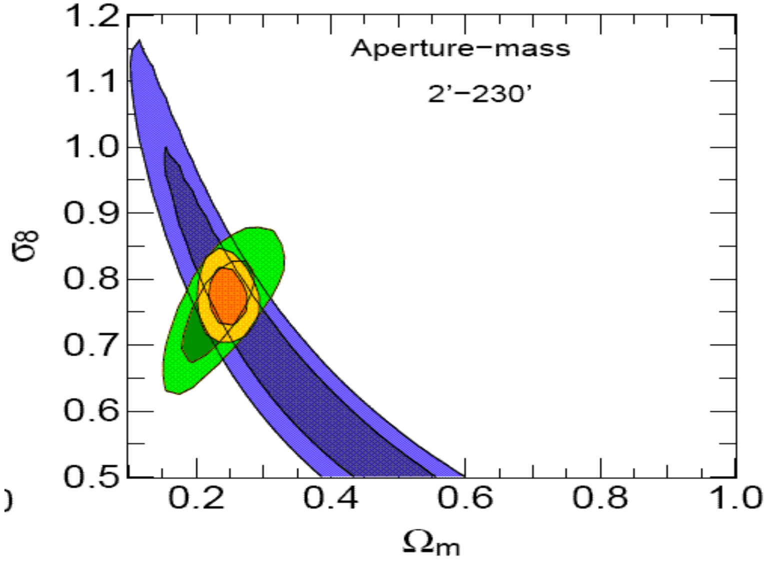
Complex shear $\gamma = \gamma_1 + i\,\gamma_2$



Recent results from CFHTLS



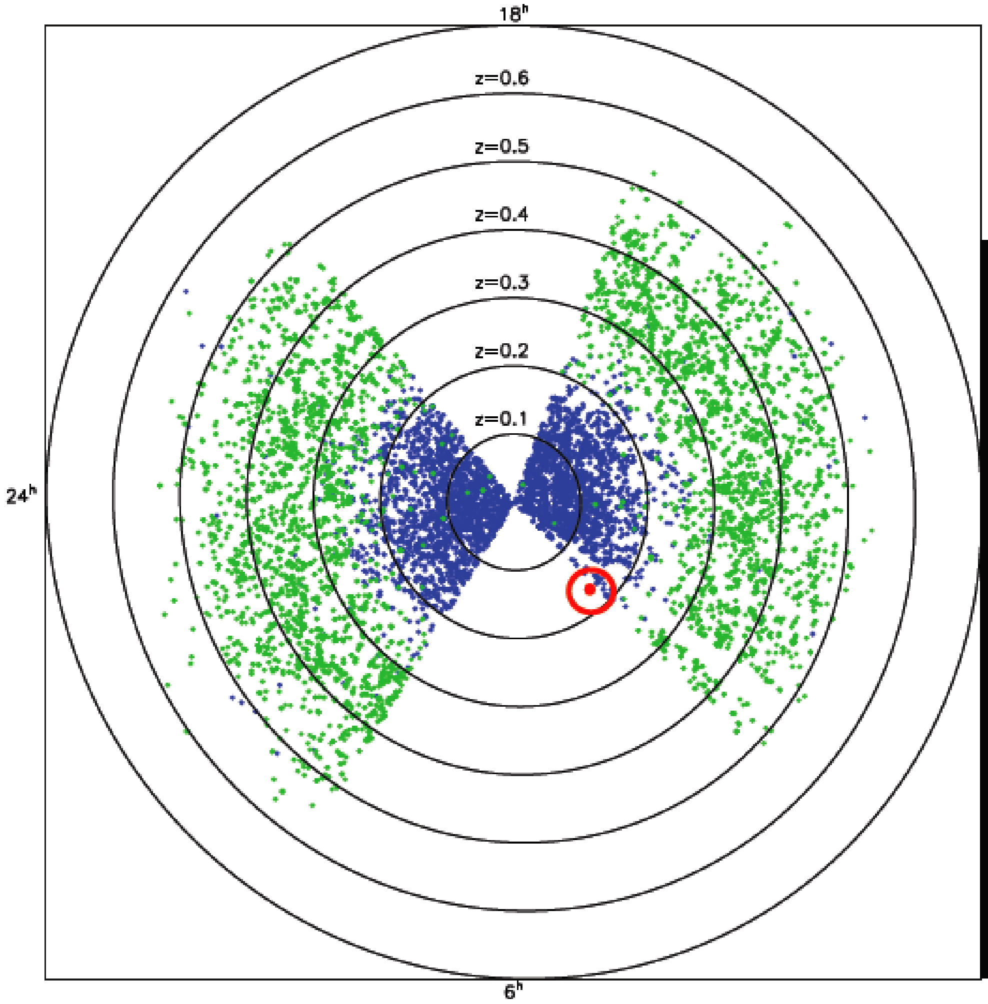




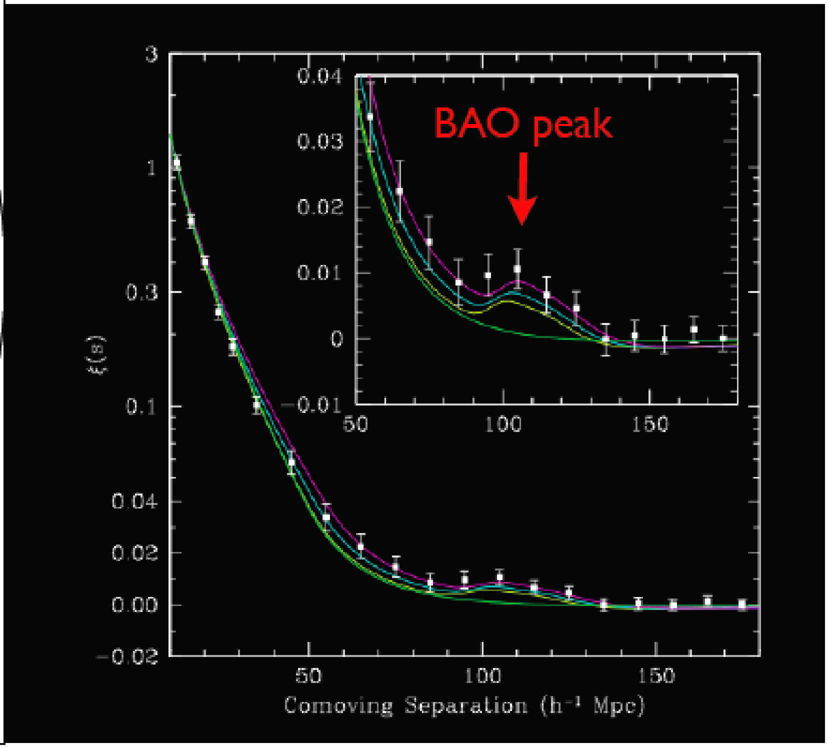
(Fu et al. 2008) 57 deg^2
median z = 0.95

BAO observations from 3-D maps: SDSS

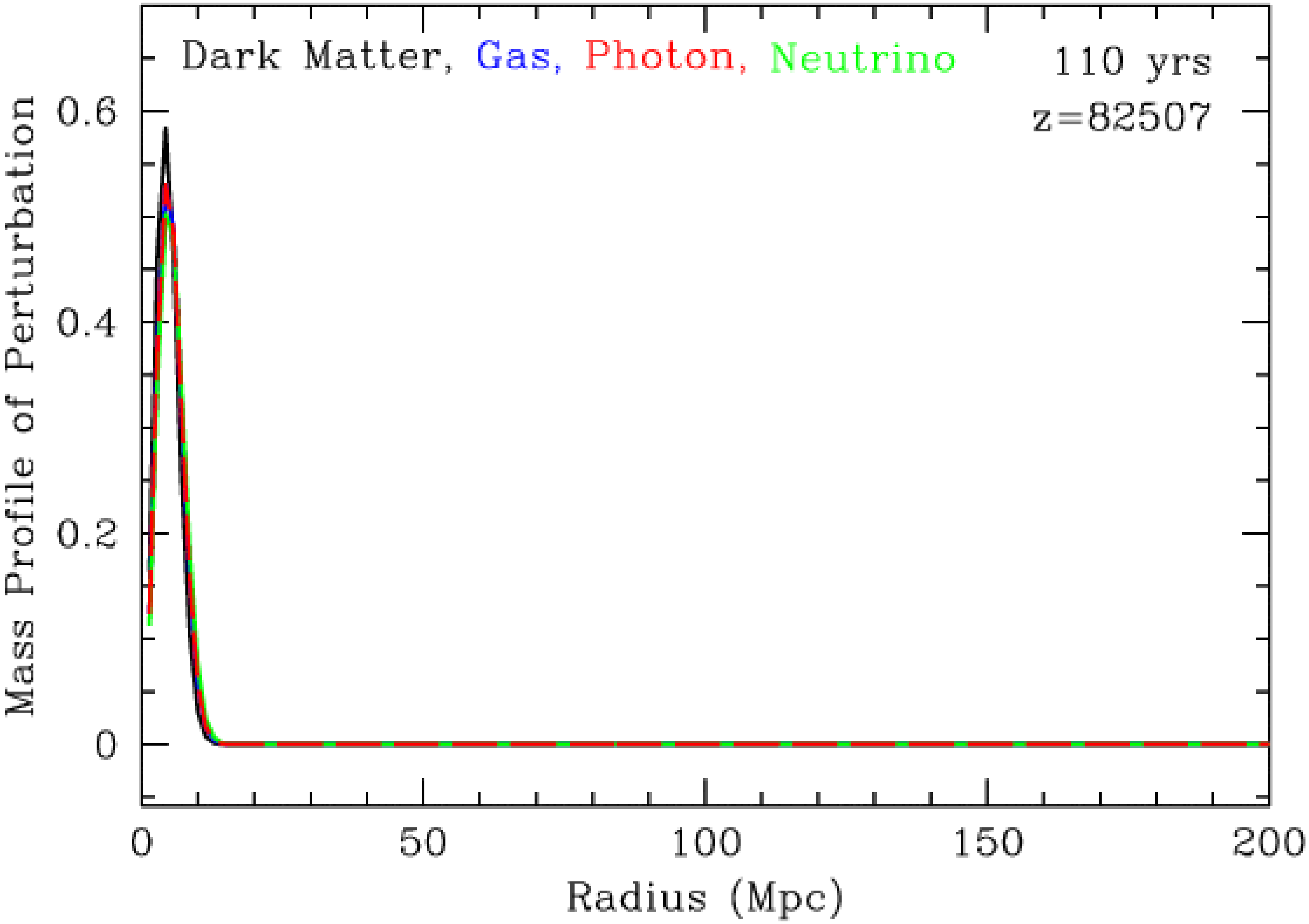
First detection



SDSS luminous red galaxies (LRGs)
- Sparse sampled at 10^{-4} galaxies/Mpc^3
- 47,000 galaxies over 4000 deg^2 by 2004
- 80,000 galaxies over 8000 deg^2 by July 2008

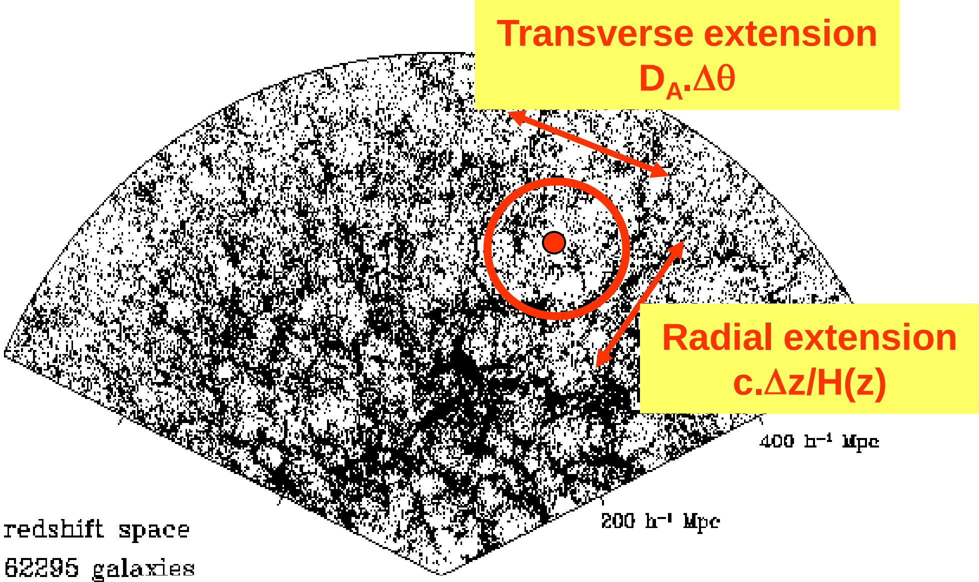


Eisenstein et al 2005


Dark Matter, Gas, Photon, Neutrino
110 yrs
z=82507
Mass Profile of Perturbation
0.6
0.4
0.2
0
0
50
100
150
200
Radius (Mpc)

Baryonic Acoustic Oscillation with microwave, optical and radio-detection

Microwave (CMB)
measures the BAO scale at z = 1100
Optical survey (SDSS)
measures the BAO scale at <z> = 0.35
with ~ 50000 galaxies
Future optical surveys (LSST, BigBOSS) should measure up to
z ~ 1.5 with up to 10^{10} galaxies but limited by the z determination (spectroscopy vs photo-z)
H_{21} radio-survey
can produce « low-resolution » maps of H_I (galaxies not resolved), but with excellent redshift determination (line of sight correlations easy)
-> BAO radial+transverse scales


Transverse extension
$D_A.\Delta\theta$

Radial extension
$c.\Delta z/H(z)$