Cosmology with Wide Field Astronomy

ICHEP, Paris, 23 July 2010
Marc Moniez
Cosmology in 5 minutes...

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

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** $d_C$
  Gives the present position of the object (even observed in a past situation)

- **Luminosity Distance** $d_L = d_C(1+z)$
  depends on the repartition surface of the light
  - Used with luminosity markers
  - **Galaxies appear fainter than in a static Universe**

- **Angular distance** $d_A = d_C/(1+z)$
  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** $d_{LT}$
The cosmic history

Afterglow Light Pattern
400,000 yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy
Accelerated Expansion

Inflation

Quantum Fluctuations

1st Stars
about 400 million yrs.

Big Bang Expansion
13.7 billion years
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 $\phi$
  - $\phi$ acts against gravity
- Vacuum energy (quantum fluctuations) $\Rightarrow$ dark energy?
- State equation for this new fluid: $p = w(z)$
  - $w(z) = -1$ for cosmological constant $\phi$

But <1% known
Structuration
## Cosmological parameters

### Table A.1: Cosmological parameters from WMAP five-year results

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_0$</td>
<td>$-1$</td>
<td>dark energy equation of state at $z = 0$</td>
</tr>
<tr>
<td>$w_a$</td>
<td>$0$</td>
<td>rate-of-change of the dark energy EOS as in $w(a) = w_0 + w_a(1 - a)$</td>
</tr>
<tr>
<td>$\omega_m$</td>
<td>$0.133$</td>
<td>physical matter density $\omega_m = \Omega_m h^2$, $\Omega_m = 0.258$</td>
</tr>
<tr>
<td>$\omega_b$</td>
<td>$0.0227$</td>
<td>physical baryon density $\omega_b = \Omega_b h^2$, $\Omega_b = 0.0441$</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>$0.596^\circ$</td>
<td>angular size of the sound horizon at the last scattering surface</td>
</tr>
<tr>
<td>$\Omega_k$</td>
<td>$0$</td>
<td>curvature parameter</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.087$</td>
<td>optical depth to scattering by electrons in the reionized intergalactic medium</td>
</tr>
<tr>
<td>$Y_p$</td>
<td>$0.24$</td>
<td>primordial helium mass fraction</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.963$</td>
<td>spectral index of the primordial scalar perturbation power spectrum</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>$0$</td>
<td>running of the primordial scalar perturbation power spectrum</td>
</tr>
<tr>
<td>$\Delta^2_R$</td>
<td>$2.13 \times 10^{-9}$</td>
<td>normalization of the primordial curvature power spectrum at $k^* = 0.05 \text{ Mpc}^{-1}$ ($\sigma_8 = 0.796$ or $\Delta^2_R = 2.41 \times 10^{-9}$ at $k^* = 0.002 \text{ Mpc}^{-1}$)</td>
</tr>
</tbody>
</table>

† 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 $\theta_s$ or any parameter that affects $\theta_s$. 
Cosmological probes

- **Supernovae**: measure the apparent luminosity of the SNIa as a function of $z$ → $d_L(z) → H(z)$
- **Gravitational weak lensing**: measure distortions of the galaxy orientation distribution → $d_A(z) →$ structures
- **Strong lensing time delays**: → $d_{LT} → H_0$
- **Galaxy clusters**: cluster counting and spatial distribution → $d_A(z) → H(z)$, structure formation
- **Baryonic Acoustic Oscillations (BAO)**: measure a characteristic scale in matter spatial distribution → $d_A(z) → H(z)$
- **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

Galaxy Spectral Energy Density

Filter transmission \times Atmosphere \times Telescope \times CCD efficiency

"Balmer Break" ~ (1+z)\times400nm

Moves left, smaller z.

Moves right, larger z.
Cosmological Surveys

• **Running / Near-future**
  - DES, Dark Energy Survey: 5000 deg², tel. 4m -> SN, BAO
  - BOSS
  - HETDEX: 420 deg², tel. 9.2m, BAO spectro-z<3.8
  - HSC/WFMOS
  - Pan-STARRS4: 4x1.8m tel., SN

• **After 2015**
  - **LSST**: 20000 deg², tel. 8.4m -> SN, BAO, weak-lensing
  - **BigBOSS**: 10000 deg², 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”

• 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 $3 \times 10^9$ galaxies with photometric redshifts up to $z=3$

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

« 4D » mapping

$(\alpha, \delta)$ position on the sky

Redshift $z$

Time variations (SN, lensing, AGN….)
Large Synoptic Survey Telescope

8.4m Primary-Tertiary Monolithic Mirror

3.5° Photometric Camera

3.4m Secondary Mirror
LSST camera: focal plane

189 Science CCD
4000 x 4000 10μm pixels
= 3 x 10^9 pixels
- 9.6 Deg^2

Corner sensors:
Guiding and wave-front analysis

Raft:
Matrix of 9 ccd
= 144 Mpixel

LSST camera = 21 rafts

Segmented CCD
16 segments of 1M pixels

3X3 CCD
"RAFT"
Cosmological probes for optical surveys

- **Supernovae**: measure the apparent luminosity of the SNIa as a function of $z \rightarrow d_L(z) \rightarrow H(z)$

- **Gravitational weak lensing**: measure distortions of the galaxy orientation distribution $\rightarrow d_A(z) \rightarrow$ structures

- **Strong lensing time delays**: $\rightarrow d_{LT} \rightarrow H_0$

- **Galaxy clusters**: cluster counting and spatial distribution $\rightarrow d_A(z) \rightarrow H(z)$, structure formation

- **Baryonic Acoustic Oscillations (BAO)**: measure a characteristic scale in matter spatial distribution $\rightarrow d_A(z) \rightarrow H(z)$
SN1a: Status

\[ \log(d_L) \]

\[ z \]

\[ \Omega_m \]

Supernova Cosmology Project
SN1a: Expectations from LSST

250 000 SNIa $\Rightarrow z < 1$ per year

Simulated light-curves of a SN1a $\Rightarrow z = 0.832$

Expected Hubble diagram with 30 000 SN1a (photo-z)
Gravitational distortions 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: 
  \[ p/\rho = [w_0 + w_a \cdot z/(1+z)] \rho \]

- 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 ($d_A$)
  - 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

Radial extension

Transverse extension

Baryons traced with SDSS galaxies

CDM without baryons
BAO: LSST expectations
The combination will be significantly more precise than the individual determinations.

State equation

\[ p = w(z) = \left[ w_0 + w_a \cdot \frac{z}{1+z} \right] \rho \]
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:
\[ \Sigma m_\nu = 94 \text{eV} \left( \Omega_\nu h^2 \right) = 13 \text{eV} \times f_\nu \]
\( f_\nu = \text{contribution of } \nu \text{ to matter} \)

\[ L_{\text{jeans}}(\nu) \text{ large} \quad \Rightarrow \quad \text{Supresses formation of } \ll \text{small } \text{structures} \]

\[ \begin{align*}
\Sigma m_\nu &\leq 0.7 \text{eV} \\
&\text{(WMAP+BAO)} \\
&\leq 0.2 \text{eV} \\
&\text{(Planck+BAO)} \\
&\leq 0.1 \text{eV} \\
&\text{(Planck+future BAO+weak lensing)} \\
&> 0.05 \text{eV} \quad \text{(oscillations)}
\end{align*} \]
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
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)
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

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

Filters and Shutter

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 Parameters

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

- 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

<table>
<thead>
<tr>
<th>parameter</th>
<th>$\Lambda$CDM</th>
<th>o$\Lambda$CDM</th>
<th>wCDM</th>
<th>owCDM</th>
<th>owCDM+SN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_m$</td>
<td>0.289 ± 0.019</td>
<td>0.309 ± 0.025</td>
<td>0.328 ± 0.037</td>
<td>0.306 ± 0.050</td>
<td>0.312 ± 0.022</td>
</tr>
<tr>
<td>$H_0$</td>
<td>69.4 ± 1.6</td>
<td>66.0 ± 2.7</td>
<td>64.3 ± 4.1</td>
<td>66.7±5.9</td>
<td>65.6 ± 2.5</td>
</tr>
<tr>
<td>$D_V$ (0.35)</td>
<td>1349 ± 23</td>
<td>1415 ± 49</td>
<td>1398 ± 45</td>
<td>1424 ± 49</td>
<td>1418 ± 49</td>
</tr>
<tr>
<td>$r_s/D_V$ (0.35)</td>
<td>0.1125 ± 0.0023</td>
<td>0.1084 ± 0.0034</td>
<td>0.1094 ± 0.0032</td>
<td>0.1078+0.0033 -0.0034</td>
<td>0.1081 ± 0.0034</td>
</tr>
<tr>
<td>$\Omega_k$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.009 ± 0.012</td>
<td>-0.0109 ± 0.0088</td>
</tr>
<tr>
<td>$w$</td>
<td>-</td>
<td>-</td>
<td>-0.79 ± 0.15</td>
<td>-1.06 ± 0.38</td>
<td>-0.99 ± 0.11</td>
</tr>
<tr>
<td>$\Omega_\Lambda$</td>
<td>0.711 ± 0.019</td>
<td>0.703 ± 0.021</td>
<td>0.672 ± 0.037</td>
<td>0.703+0.057 -0.058</td>
<td>0.699 ± 0.020</td>
</tr>
<tr>
<td>Age (Gyr)</td>
<td>13.73 ± 0.13</td>
<td>14.25 ± 0.37</td>
<td>13.87 ± 0.17</td>
<td>14.27 ± 0.52</td>
<td>14.24 ± 0.40</td>
</tr>
<tr>
<td>$\Omega_{tot}$</td>
<td>-</td>
<td>1.0114+0.0077</td>
<td>-</td>
<td>1.009 ± 0.012</td>
<td>1.0109 ± 0.0088</td>
</tr>
<tr>
<td>100$\Omega_b h^2$</td>
<td>2.272 ± 0.058</td>
<td>2.274 ± 0.059</td>
<td>2.293+0.062 -0.063</td>
<td>2.279+0.066 -0.065</td>
<td>2.276+0.060 -0.059</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1161+0.0039</td>
<td>0.1110 ± 0.0052</td>
<td>0.1112+0.0056 -0.0057</td>
<td>0.1103+0.0055 -0.0054</td>
<td>0.1110+0.0051 -0.0052</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.084 ± 0.016</td>
<td>0.089 ± 0.017</td>
<td>0.088 ± 0.017</td>
<td>0.088 ± 0.017</td>
<td>0.088 ± 0.017</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.961 ± 0.013</td>
<td>0.962 ± 0.014</td>
<td>0.969 ± 0.015</td>
<td>0.965 ± 0.016</td>
<td>0.964 ± 0.014</td>
</tr>
<tr>
<td>$\ln(10^{10} A_0)$</td>
<td>3.080+0.036 -0.037</td>
<td>3.068 ± 0.040</td>
<td>3.071+0.040 -0.039</td>
<td>3.064 ± 0.041</td>
<td>3.068 ± 0.039</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.824 ± 0.025</td>
<td>0.796 ± 0.032</td>
<td>0.735 ± 0.073</td>
<td>0.79 ± 0.11</td>
<td>0.790+0.045 -0.046</td>
</tr>
</tbody>
</table>

B.A. Reid et al. (2009)

Very stable results over time since WMAP (2003)
Weak shear

- Coherent distortions of background images

\[ A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \begin{pmatrix} 1 - \kappa & 0 \\ 0 & 1 - \kappa \end{pmatrix} + \begin{pmatrix} -\gamma_1 & \gamma_2 \\ \gamma_2 & \gamma_1 \end{pmatrix} \]

Magnification \quad \text{Shear}

Complex shear \( \gamma = \gamma_1 + i \gamma_2 \)

\[ \gamma \sim \Theta = \frac{D_{LS}}{D_S} \frac{4GM}{bc^2} \]

Gravity & Cosmology change the growth rate of mass structure

Cosmology changes geometric distance factors
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
Mass Profile of Perturbation

Dark Matter, Gas, Photon, Neutrino

110 yrs

z = 82507

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 $\sim 50000$ galaxies

**Future optical surveys** (LSST, BigBOSS) should measure up to $z \sim 1.5$ 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$_1$ (galaxies not resolved), but with excellent redshift determination (line of sight correlations easy)

$\Rightarrow$ BAO radial+transverse scales