Introduction: $\Lambda$CDM

What do we know about dark energy?

Observational Probes of dark energy

Current Situation and future projects

Conclusion
The current standard model of cosmology, $\Lambda$CDM, is based on:

- General Relativity
- The Cosmological Principle
- Particle Physics in the early universe, including inflation

The Cosmological Principle: The Universe is HOMOGENEOUS and ISOTROPIC

![Graph and Planck Collaboration Image]
INTRODUCTION: FRW Metric

Cosmological Principle \( \rightarrow \) FRW metric

\[
ds^2 = dt^2 - a^2(t) \left[ dr^2 + S_k^2(r) (d\theta^2 + \sin^2 \theta d\phi^2) \right]
\]

\[
S_k(r) = \begin{cases} 
\sin(r \sqrt{|k|}) / \sqrt{|k|} & k > 0 \\
 r & k = 0 \\
\sinh(r \sqrt{|k|}) / \sqrt{|k|} & k < 0 
\end{cases}
\]

Universal time coordinate, cosmic time
We can define COMOVING COORDINATES, where galaxies are at rest
The expansion of space is described by the scale factor, a
INTRODUCTION

3 possible geometries

\[ k > 0 \]

\[ k = 0 \]

\[ k < 0 \]

Comoving coordinates

\[ \eta, a(t_1) \]

\[ \eta, a(t_2) \]
The light from the galaxies is redshifted by the expansion of the space → **Redshift**

\[ \frac{\lambda_e}{a(t_e)} = \frac{\lambda_o}{a(t_0)} \]

\[ a(t_e) = \frac{1}{1 + z} \]

The redshift is a **measurement of the scale factor** of the Universe when the light was emitted.
And it can be measured from the spectrum of the light:

$$z = \frac{(\lambda_o - \lambda_e)}{\lambda_e}$$
Friedmann Equations

Introducing the FRW metric in the Einstein´s equations:

\[ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left( \rho + \frac{3p}{c^2} \right) + \frac{\Lambda c^2}{3} \]

\[ \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3} \]

\[ \frac{H^2}{H_0^2} = \Omega_\Lambda + \frac{\Omega_k}{a^2} + \frac{\Omega_M}{a^3} + \frac{\Omega_r}{a^4} \]

\[ \Omega_i = \frac{\rho_i}{\rho_c} \]

\[ \rho_c = \frac{3H_0^2}{8\pi G} \]

\[ \begin{align*}
\rho > \rho_c & ; k > 0 \\
\rho = \rho_c & ; k = 0 \\
\rho < \rho_c & ; k < 0 
\end{align*} \]

**CRITICAL DENSITY:** Makes the Universe flat

**HUBBLE PARAMETER:** The expansion rate of the Universe

- \( G \): Newton´s constant
- \( \rho \): Energy density
- \( p \): pressure
- \( \Lambda \): Cosmological Constant
We need the equation of state of each component of the Universe

Ideal fluids: $T_{\mu \nu} = \text{diag}(-\rho, p, p, p)$
Barotropic fluids, $p = w \rho$

**Matter (ordinary or dark):** $p=0$, $w=0$
Radiation: $p=r/3$, $w=1/3$
**Cosmological Constant:** $p=-r$, $w=-1$
**Dark Energy:** $w=w(t)<-1/3$, $w = w_0 + w_a (1 - a)$
Distances

Scale factor is **related to observations through distances.**

Comoving distance:

\[
r(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_\Lambda + \Omega_k (1 + z')^2 + \Omega_M (1 + z')^3 + \Omega_r (1 + z')^4}}
\]

Several distances can be measured observationally

**Luminosity distance:** “Standard Candle” with luminosity \(L\)
\[\phi = \frac{L}{4\pi d_L^2}; \quad d_L = r(z)(1+z)\] (flat Universe)

**Angular diameter distance:** “Standard Ruler” with length \(l\)
\[\Delta\theta = \frac{l}{d_A}; \quad d_A = r(z)/(1+z)\] (flat Universe)

**Having a collection of standard candles or rulers at different known redshifts, we can reconstruct the densities and properties of the fluids in the Universe**
Distances

\((\Omega_M, \Omega_\Lambda) = (0.05, 0)\)

\((\Omega_M, \Omega_\Lambda) = (0.2, 0.8)\)

\((\Omega_M, \Omega_\Lambda) = (1, 0)\)

Angular Diameter Distance

Luminosity Distance

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Growth of Structure

$\Lambda$CDM is able to account for the observed structure in the Universe
- Structure grows due only to gravity (and dark energy) from initially small perturbations
- Cold Dark Matter
- Initial power spectrum of density perturbations nearly scale invariant (inflation)

$$\ddot{\delta}_k + 2H \dot{\delta}_k - 4\pi G \rho_M \delta_k = 0$$

The distribution of fluctuations depends on primordial perturbations and also on the composition of the universe

CDM: Small Structures form first
Growth of Structure

\[ z=0 \]

**SCDM**  
**τCDM**  

**ACDM**  
**OCDM**  

**COLD DARK MATTER**  
**WARM DARK MATTER**  
**HOT DARK MATTER**  

The VIRGO Collaboration 1996
Observations: Universe is flat

CMB $\rightarrow$ Universe is flat, density = critical density

ESA & Planck Collab.

\[ \Omega_{\text{tot}} \]

$\Lambda$CDM

Planck Data
Observations: Baryonic matter is 5%

Primordial abundances

Baryons are 5% of the total

From Ned Wright

Observations: Dark Matter is 26%

Dark matter is found in all scales $\rightarrow$ 26%

*Rotation/dispersion curves of galaxies*

*Mass to luminosity ratio of galaxy clusters*

*Gravitational lenses*

*Large Scale Structure*

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Millenium Simulation
G. Lemson & Virgo Consortium
http://www.mpa-garching.mpg.de/millenium
Observations: Dark energy 68%

Accelerated expansion $\rightarrow$ Dark Energy 68%

332 SNe SCP Union Catalog, Kowalski et al arXiv:0804.4142
462 SNe SNLS3 combined, Conley et al arXiv:1104.1443
The dark side

The most shocking consequence is that 95% of the matter-energy content of the Universe remains unexplained.

Cosmology requires physics beyond the Standard Model 3 times: dark matter, dark energy and the early Universe.
What do we mean by dark energy?

The discovery of the accelerated expansion of the Universe was a huge surprise, since gravity acting on matter slows down the expansion, so we expected a decelerating expansion, not an accelerating one.

Whatever mechanism causes the acceleration, we call it “dark energy”:
- Einstein’s cosmological constant
- Some new field (“quintessence”...)
- Modifications to General Relativity
- ...

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Evidence for dark energy

Huge progress from 1998

Supernova Cosmology Project
Perlmutter et al. (1998)

No Big Bang

42 Supernovae

Expands forever

Recollapses eventually

Flat Universe

$\Lambda = 0$

$\Omega_M$

$\Omega_\Lambda$

Betoule et al, 2014

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Evidence for dark energy

Planck 2015

$\Omega_\Lambda$

$\Omega_m$

$+\text{TE+EE}$

$+\text{lensing}$

$+\text{lensing+BAO}$

Planck 2015
What do we know about dark energy?

1) It does not emit nor absorbs electromagnetic radiation
2) It does not dilute with expansion → Negative pression
3) Its distribution is homogeneous. Dark Energy does not cluster significantly with matter on scales at least as large as galaxy clusters

Dark energy is qualitatively very different from dark matter. Its pressure is comparable in magnitude to its energy density (it is energy-like), while matter is characterized by a negligible pressure.

Dark energy is a diffuse, very weakly interacting with matter and very low energy phenomenon. Therefore, it will be very hard to produce it in accelerators. As it is not found in galaxies or clusters of galaxies, the whole Universe is the natural (and perhaps the only one) laboratory to study it.
The Cosmological Constant Case

All current observations are compatible with dark energy being the cosmological constant. This is the most plausible and the most puzzling dark energy candidate

\[ w = -1.006 \pm 0.045 \text{ from Planck 2015} \]

If it is the vacuum energy

\[ \Omega_\Lambda \sim 0.7 \implies \rho_\Lambda \sim (10 \text{ meV})^4 \]

while the estimate from QFT is

\[ \rho_\Lambda \sim m_{\text{Planck}}^4 \sim 10^{120} \times (10 \text{ meV})^4 \]

or from the Higgs potential, \( \rho_\Lambda \sim 10^{55} \times (10 \text{ meV})^4 \)

Why such a huge difference?
Observational Probes of dark energy

Test if \( w_0 = -1 \) and \( w_a \neq 0 \)

DETF Figure of merit: Inverse of the area of the error ellipse enclosing 95% confidence limit in the w0-wa plane. Standard way to compare sensitivities for dark energy projects

Standard Candles: Measure \( d_L = (1 + z) \, r(z) \)

Standard Rulers: Measure \( d_A = r(z)/(1 + z) \)

Number Counts: Measure \( \frac{dV}{dzd\Omega} = r^2(z)/\sqrt{(1 - kr^2(z))} \)

Growth of structure: A more complicated function of H(z)
Observational Probes of dark energy

Many practical implementations:

**Distance probes:** SN1a, BAO, CMB, weak lensing, galaxy clusters,...

**Growth of Structure probes:** CMB, redshift space distortions, weak lensing, galaxy clusters...

*No single technique is sufficiently powerful to improve the knowledge of dark energy at the level of one order of magnitude*

*Combination of techniques: More statistical power, ability to discriminate among dark energy models, robustness against systematic errors*
Observational Probes of dark energy

Supernovae Ia

Galaxy Clusters Counts

Gravitational Lensing

BAO

Redshift Space Distortions

Real-space Regime

linear turnaround nonlinear

Observer

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GRUV, ESA, and Z. Levay and A. Field (STScI)
Supernovae 1a

This is the technique that allowed the discovery of the dark energy
The most mature technique to date

SN1a are GOOD DISTANCE INDICATORS

1.- Monitor as many galaxies as you can, looking for supernovae through difference of images
Supernovae 1a

This is the technique that allowed the discovery of the dark energy
The most mature technique to date
SN1a are GOOD DISTANCE INDICATORS

2.- Classify supernovae by light curves and spectrum, to find type 1a

Adapted from Qing Zhang “Introduction to Supernovae”
Supernovae 1a

This is the technique that allowed the discovery of the dark energy
The most mature technique to date
SN1a are GOOD DISTANCE INDICATORS

3.- Calibrate supernovae luminosity

![Graph showing luminosity versus time for supernovae 1a]
Supernovae 1a

This is the technique that allowed the discovery of the dark energy
The most mature technique to date
SN1a are GOOD DISTANCE INDICATORS

4.- Build the Hubble diagram and fit the cosmological parameters

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Shallow field search for SNe Ia
Shallow field search for SNe Ia

Graphics: A. Papadopoulos
Shallow field search for SNe Ia

SN Ic $z=0.06$

DES13C1feu 9-Oct-2013
For $z>>1000$ the universe was a strongly coupled gas of photons and charged particles (and neutrinos and dark matter)

Overdensities make overpressures and a sound wave in the gas, which propagates with velocity $c/\sqrt{3}$

For $z \sim 1100$ ($t \sim 350,000$ yr), temperature is low enough (3000 K) for the formation of hydrogen. Photons decouple and propagate freely (CMB)

Photons quickly stream away, leaving the baryon peak stalled at $\sim 150$ Mpc.

There is a special separation between galaxies: 150 Mpc, that can be used as a STANDARD RULER
A standard ruler large enough to test the dark energy on cosmological scales. It is found in real data

1.- Select a sample of galaxies with known redshift and compute the 2-point correlation function
BAO

A standard ruler large enough to test the dark energy on cosmological scales. It is found in real data

2.- Localize the BAO peak position and measure the corresponding distance scale

SDSS III – BOSS, 2012
3. Build the Hubble diagram for standard rulers and fit the cosmological parameters.

A standard ruler large enough to test the dark energy on cosmological scales. It is found in real data.
The number of galaxy clusters as a function of redshift is very sensitive to the properties of the dark energy, and cosmological parameters in general.

\[
\frac{dN}{d\Omega \, dz} = \frac{dV}{d\Omega \, dz} \int_{M_{\text{min}}}^{\infty} dM \frac{dn}{dM}
\]

Mohr (2005)
Cluster Abell 1689
$z=0.1832$
Image from HST
Image distortion due to the effect of the matter on the space-time curvature

Small effect in the weak regime, \(~1\%\)
**The Forward Process.**

**Galaxies:** Intrinsic galaxy shapes to measured image:

1. Intrinsic galaxy (shape unknown)
2. Gravitational lensing causes a **shear (g)**
3. Atmosphere and telescope cause a convolution
4. Detectors measure a pixelated image
5. Image also contains noise

**Galaxy Cluster SDSSJ1050+0017**
Subaru Suprime-cam (gri)
The presence of masses distorts the shape of structures, since we measure the redshift and not the distance.

\[ P_g^s(k, \mu) = \left( b + f \mu^2 \right)^2 P_m^r(k) e^{-k^2 \sigma^2 \mu^2} \]

\[ \delta_g^s(k) = (b + f \mu_k^2) \delta_m^r(k) \]

\[ \mu_k^2 = k_z^2 / k^2 \]
REDSHIFT SPACE DISTORTIONS
REDSHIFT SPACE DISTORTIONS
3D Correlation function becomes anisotropic

Anisotropy depends on the growth of structure, and therefore, on the properties of gravitational force
CURRENT SITUATION: SN1a

\[ \mu = m_B^* - M(G) + \alpha X_1 - \beta C \]

Betoule et al., 2014, A&A 568
CURRENT SITUATION: BAO

BOSS, Anderson et al., 2013

\( D_L(z) \) vs. Redshift

- Planck \( \Lambda \)CDM
- BOSS CMASS
- WiggleZ
- BOSS LOWZ
- 6dFGS
CURRENT SITUATION: Compatibility

PDG 2014

Planck 2015
CURRENT SITUATION: RSD

BOSS, Beutler et al., 2013

Planck 2015

SDSS MGS
SDSS LRG
WiggleZ
VIPERS
6DFGS
BOSS LOWZ
BOSS CMASS
CURRENT SITUATION

Betoule et al., 2014

\[ w \] vs. \[ \Omega_m \]

-0.4
-0.6
-0.8
-1.0

-1.2
-1.4
-1.6
-1.8
-2.0

0.15
0.20
0.25
0.30
0.35
0.40
0.45

JLA
C11
Planck+WP
Planck+WP+BAO

WMAP9

Planck+WP+JLA
More data are needed to obtain better constraints on the redshift evolution of dark energy.

Larger and deeper galaxy surveys
CURRENT AND FUTURE PROJECTS

Dark Energy Experiments: 2013 - 2031

2013
BOSS

2015
PAU

2017
Dark Energy Survey (DES)

2019
HETDEX

2021
HSC imaging

2023
PFS spectroscopy

2025
Extended BOSS (eBOSS)

2027
Dark Energy Spec. Instrument (DESI)

2029
Euclid

2031
Large Synoptic Survey Telescope (LSST)

WFIRST-AFTA

Blue = imaging
Red = spectroscopy

Stage III
Stage IV
Two multiband surveys:

5000 deg$^2$ grizY to 24th mag
30 deg$^2$ repeat (Sne)

A new 3 deg$^2$ FOV camera (DECam)

~570 Mpx, New CCDs very sensitive to red part of the spectrum

Survey 2013-2018 (525 nights)
~300 scientists from 28 institutions from around the world

facebook.com/darkenergysurvey
http://darkenergysurvey.org

USA: Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Laboratory, Ohio State University, Santa Cruz/SLAC Consortium, Texas A&M University, CTIO (in Chile)

UK Consortium: UCL, Cambridge, Edinburgh, Portsmouth, Sussex, Nottingham

Germany: Munich

Switzerland: Zurich

Spain Consortium: CIEMAT, IEEC, IFAE

Brazil Consortium
4 Probes of Dark Energy

**Galaxy Clusters** (dist & struct)
Tens of thousands of clusters to \( z \sim 1 \)
Synergy with SPT, VHS

**Weak Lensing** (dist & struct)
Shape and magnification measurements of 200 million galaxies

**Baryon Acoustic Oscillations** (dist)
300 million galaxies to \( z \sim 1.4 \)

**Supernovae** (dist)
3500 well-sampled Sne Ia to \( z \sim 1 \)
4 Probes of Dark Energy

**Galaxy Clusters** (dist & struct)
Tens of thousands of clusters to z~1
Synergy with SPT, VHS

**Weak Lensing** (dist & struct)
Shape and magnification measurements of 200 million galaxies

**Baryon Acoustic Oscillations** (dist)
300 million galaxies to z~1.4

**Supernovae** (dist)
3500 well-sampled Sne Ia to z~1
DES: First Results

- $z=0.30$ Bullet Cluster
- $z=0.40$ SCSO J2351-5452
- $z=0.87$ “El Gordo”
- $z=0.53$ SCSO J2336-5352
- $z=0.76$ DES J0449-5909
- $z=0.83$ DES J0250+0008
Multi-color image of the inner 5 arcmin

Weak lensing aperture mass significance map of the inner 30 arcmin, overlaid with galaxies

The same galaxies, but for the entire useable field of view of 90 arcmin
New camera for WHT with 18 CCDs covering a 1 deg diameter field of view

40 Narrow band filters (100 A width) and wide band (u, g, r, i, z, Y) in movable trays

Provide low resolution spectra

Can cover ~2 sq-deg par night in all filters (>30000 galaxies, 5000 stars, 1000 quasars, 10 galaxy clusters per night)

Expected galaxy redshift resolution ~0.003(1+z)

Plan: 100-night survey in 4 years
PAU: Redshift Precision

- z-space, $\Delta z=0.03(1+z)$
  - + peculiar velocities (DES)
- z-space, $\Delta z=0.003(1+z)$
  - + peculiar velocities (PAU)
- z-space, perfect resolution + peculiar velocities
- Real space
The survey strategy produces 2 samples:
- “Spectroscopic” sample: Good photoz with narrow filters $z \leq 1$
- “Photometric” sample: Photoz with wide filters to $z \sim 1.4$

Main science case:
- Near sample for redshift space distortions
- Far sample for weak lensing magnification
- Combine both in the same sample $\rightarrow$ Unique advantage of PAU

Gaztañaga et al, 2012
PAU: Status

The construction of the PAU camera is basically finished. Data management system is written. PAUCam will be installed at the WHT on summer (june 2015). Commissioning and science verification in 2015.
Camera testing
The accelerating expansion of the Universe is a firmly established observation, but its physical origin remains a deep mystery.

All current data are consistent with $\Lambda$CDM (dark energy being the cosmological constant).

Probing the expansion history of the Universe and the growth of structure with much better precision can provide a strong boost to the current knowledge.

A number of large projects are under way or planned for the future, and hopefully, will bring significant progress.

Dark Energy is a very important question both for cosmology and particle physics.