Review on Dark Energy

E. Sánchez
CIEMAT
XLIII International Meeting on Fundamental Physics
Benasque 2015

OUTLINE

Introduction: ΛCDM

What do we know about dark energy?

Observational Probes of dark energy

Current Situation and future projects

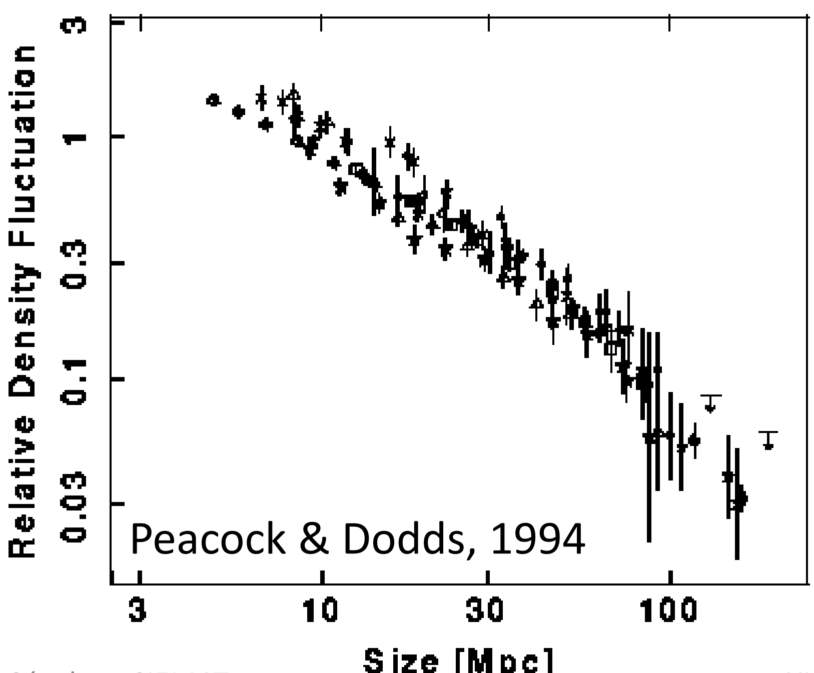
Conclusion

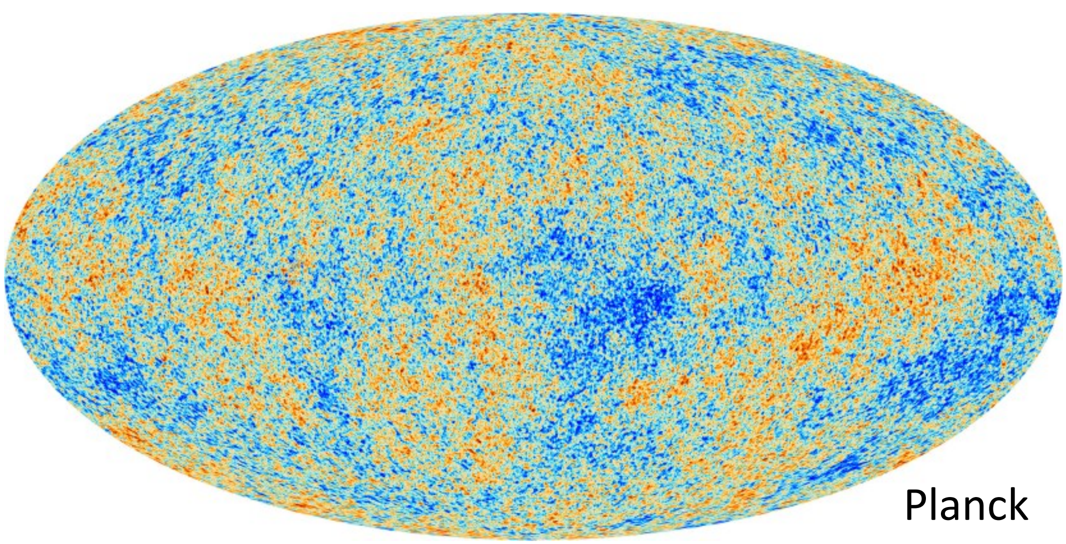
INTRODUCTION: Basis of ΛCDM

The current standard model of cosmology, ΛCDM, 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**





Planck Collaboration

INTRODUCTION: FRW Metric

Cosmological Principle → FRW metric

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

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

Universal time coordinate, **cosmic time**

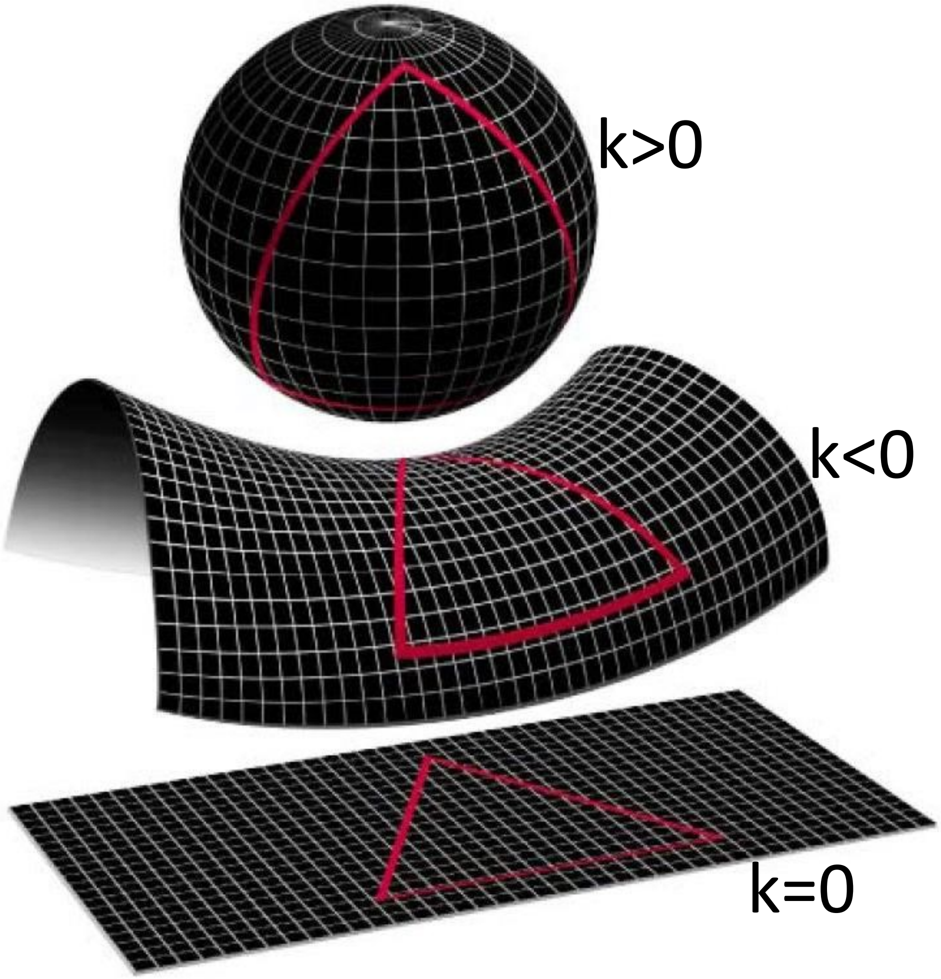
We can define **COMOVING COORDINATES**,

where galaxies are at rest

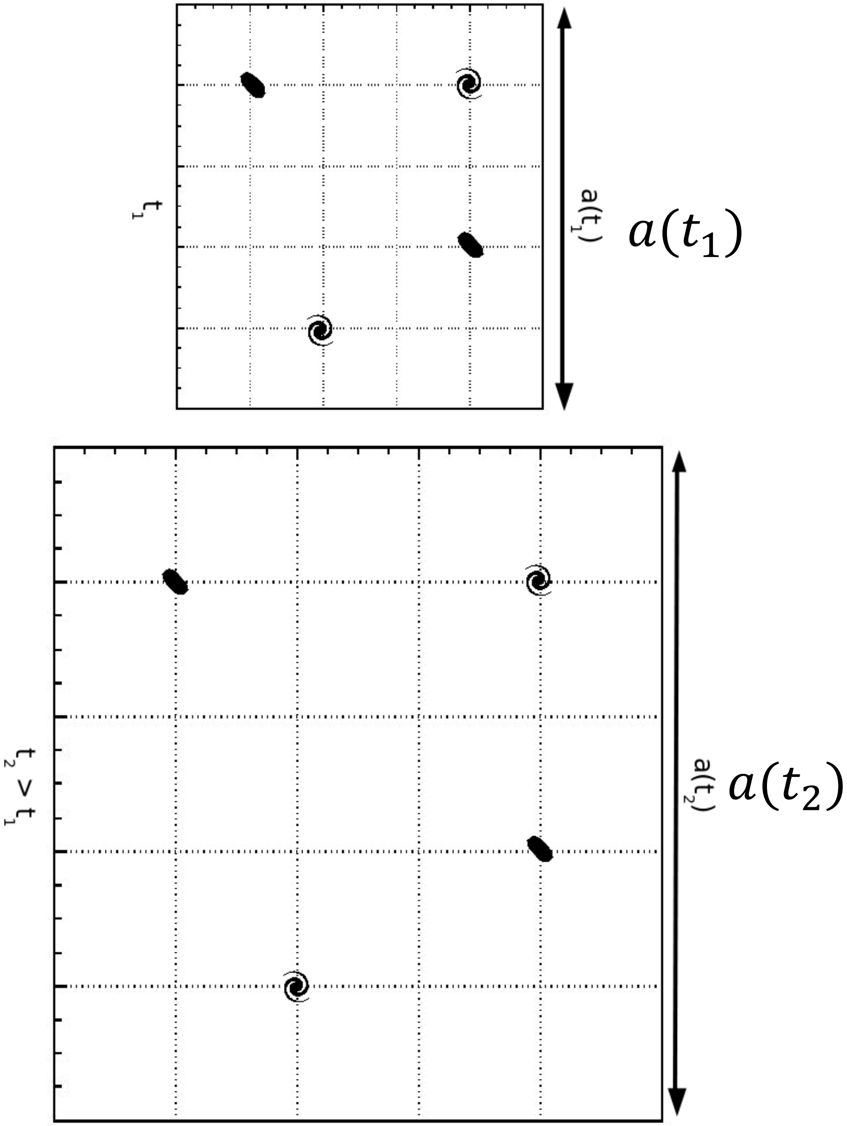
The expansion of space is described by the scale factor, a

INTRODUCTION

3 possible geometries

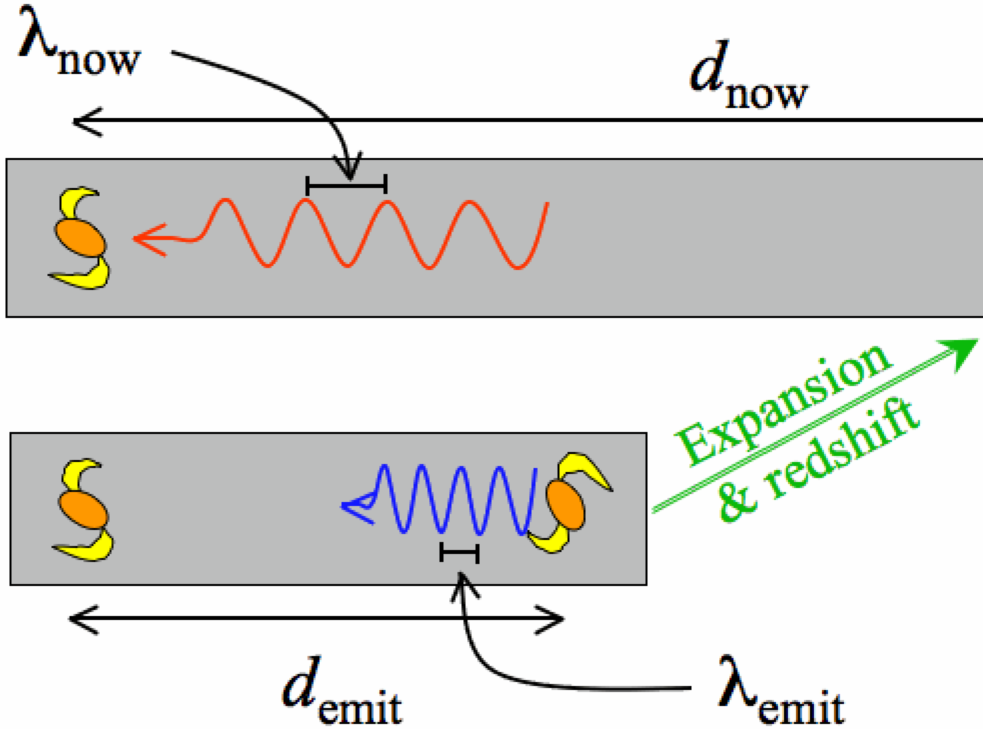


Comoving coordinates



REDSHIFT

The light from the galaxies is redshifted by the expansion of the space → **Redshift**



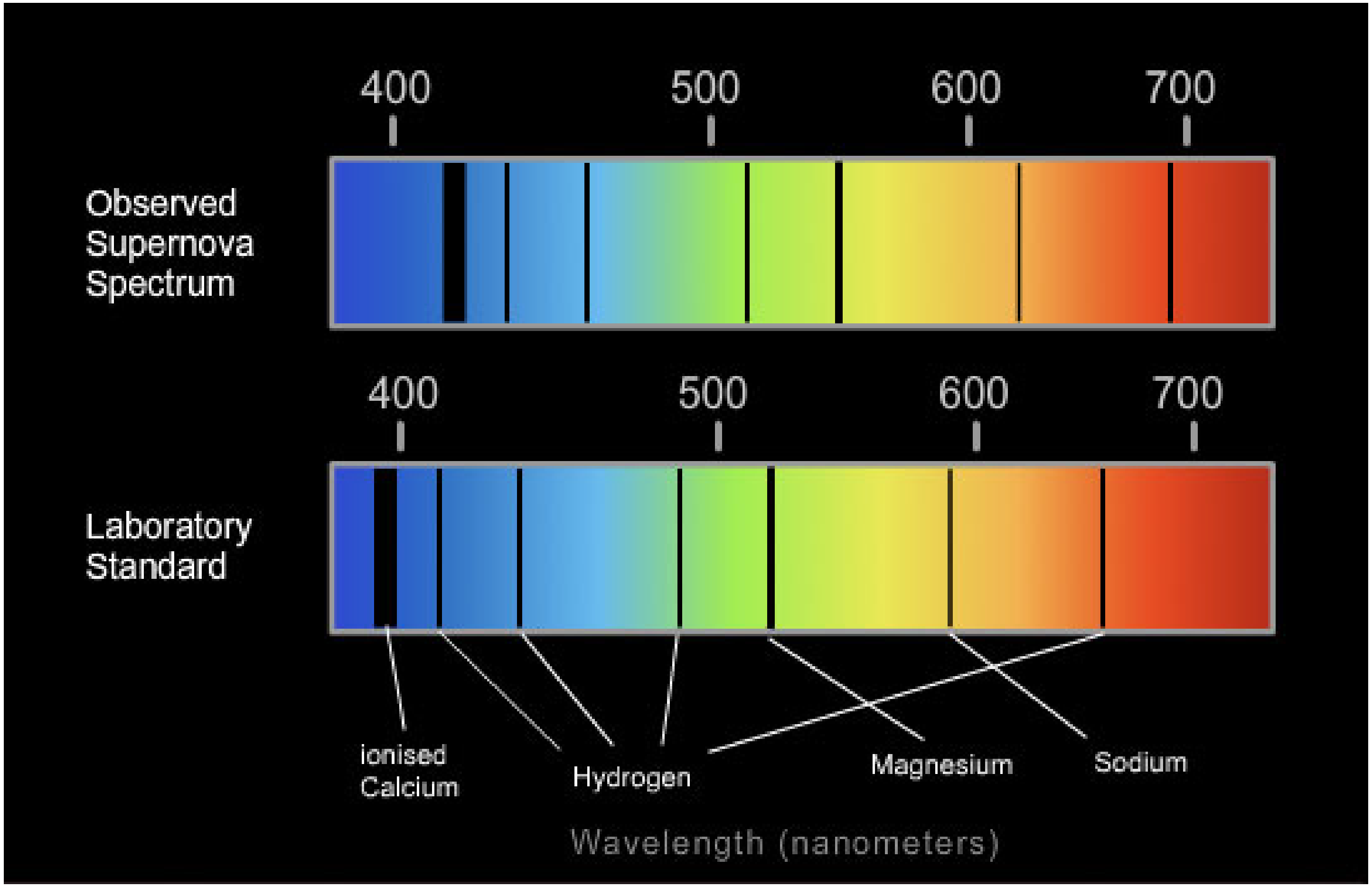
$$\frac{\lambda_e}{a(t_e)} = \frac{\lambda_o}{a(t_0)}$$

$$a(t_e) = 1/(1+z)$$

The redshift is a **measurement of the scale factor** of the Universe when the light was emitted

REDSHIFT

And it can be measured from the spectrum of the light



$$z = (\lambda_o - \lambda_e) / \lambda_e$$

Friedmann Equations

Introducing the FRW metric in the Einstein´s equations:

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

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

G: Newton´s constant
ρ: Energy density
p: pressure
Λ: Cosmologcial Constant

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

$$\Omega_i = \frac{\rho_i}{\rho_c}$$

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

$\rho > \rho_c$; $k > 0$
$\rho = \rho_c$; $k = 0$
$\rho < \rho_c$; $k < 0$

CRITICAL DENSITY: Makes the Universe flat

$$H = \frac{\dot{a}}{a}$$

HUBBLE PARAMETER: The expansion rate of the Universe

Friedmann Equations

We need the
equation of state of each component of the Universe

Ideal fluids: $T_{\mu\nu}$ = diag(-ρ,p,p,p)
Barotropic fluids, p=wρ

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 , $\boldsymbol{w = w_0 + w_a(1-a)}$

Distances

Scale factor is **related to observations through distances.**
Comoving distance:

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

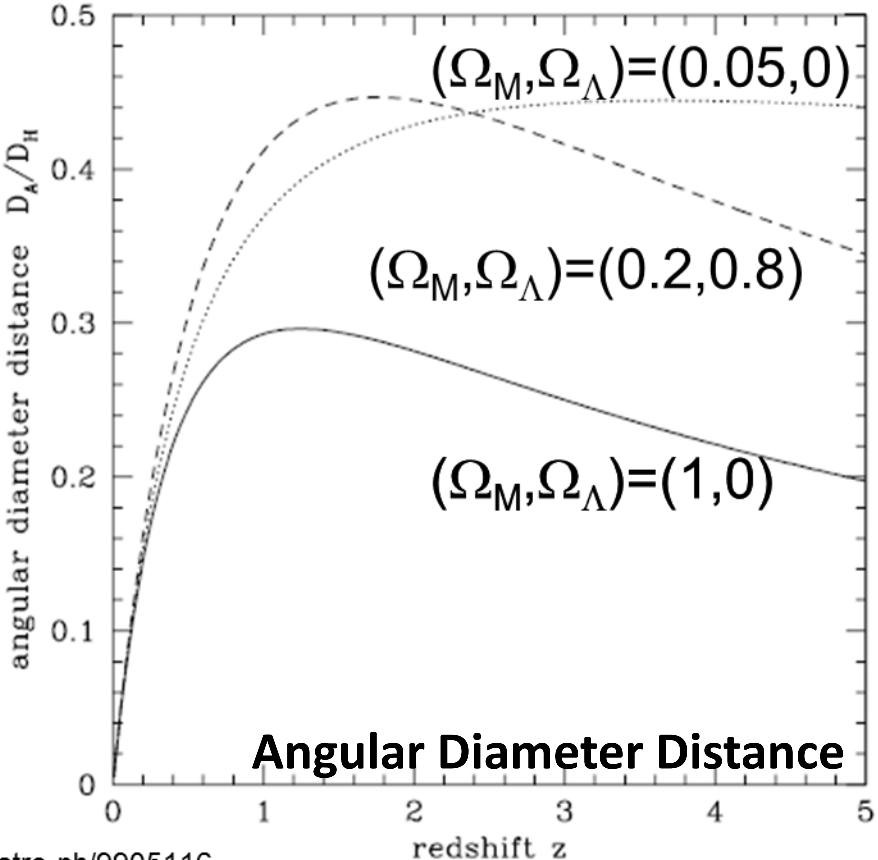
Several distances can be measured observationally

Luminosity distance: "Standard Candle" with luminosity L
$\phi = L/4\pi d_L^2$; $d_L = r(z)(1+z)$ (flat Universe)

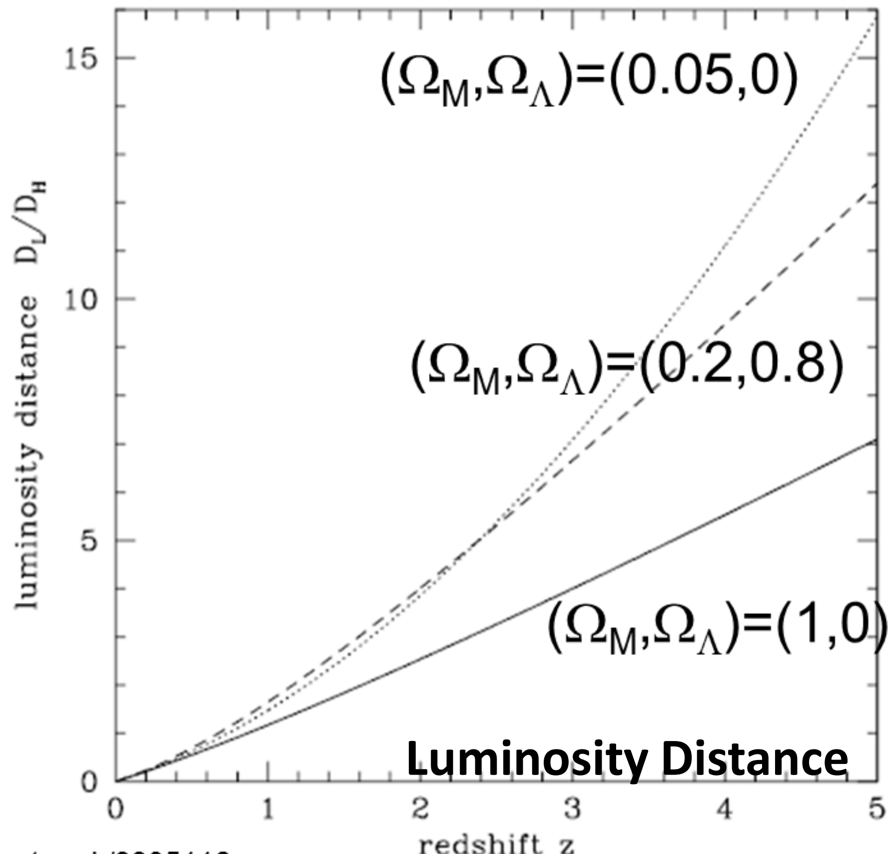
Angular diameter distance: "Standard Ruler" with length l
$\Delta\theta = l/d_A$; $d_A = r(z)/(1+z)$ (flat Universe)

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

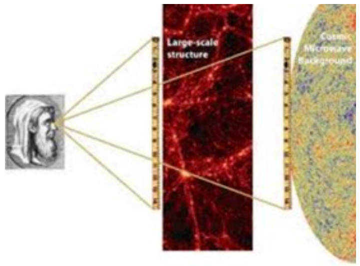
Distances



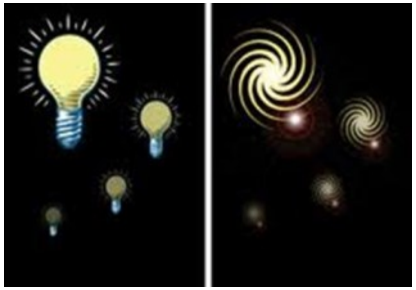
astro-ph/9905116



astro-ph/9905116



STANDARD RULERS



STANDARD CANDLES

Growth of Structure

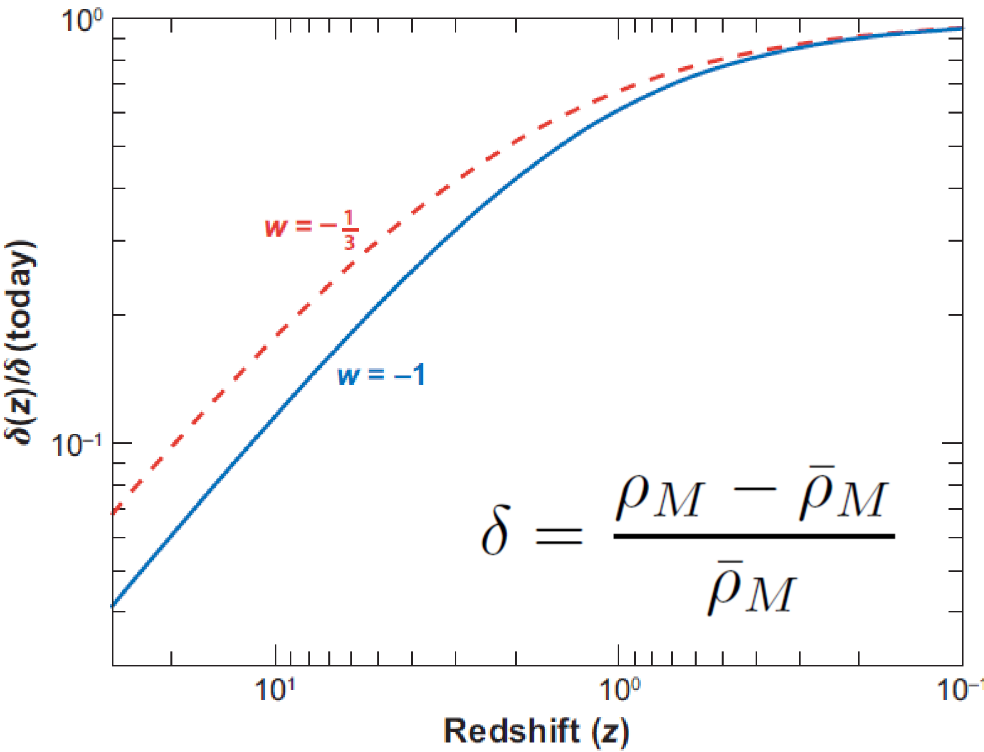
ΛCDM is able to account for the observed structure in the Universe

- Structure grows due only to gravity (and dark energy) from initally small perturbations
- Cold Dark Matter
- Initial power spectrum of density perturbations nearly scale invariant (inflation)

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

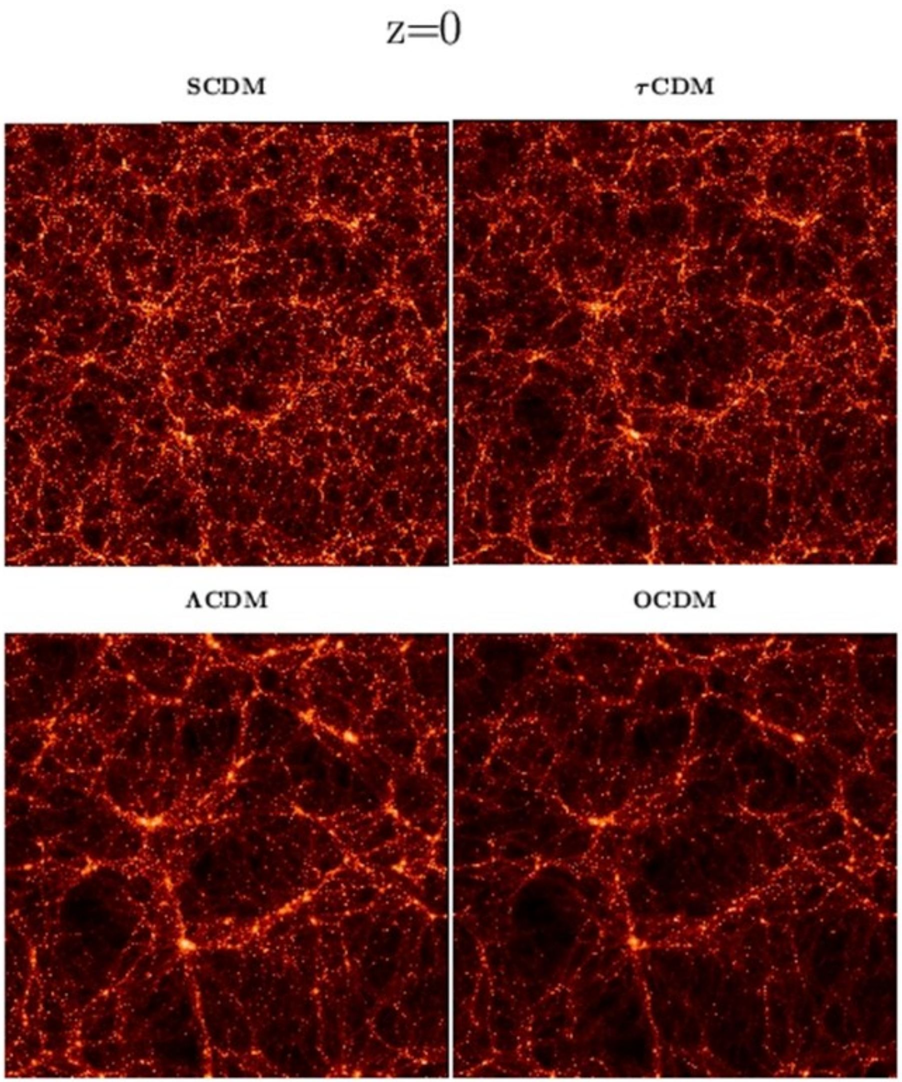
The distribution of fluctuations depends on primordial perturbations and also on the composition of the universe

CDM: Small Structures form first

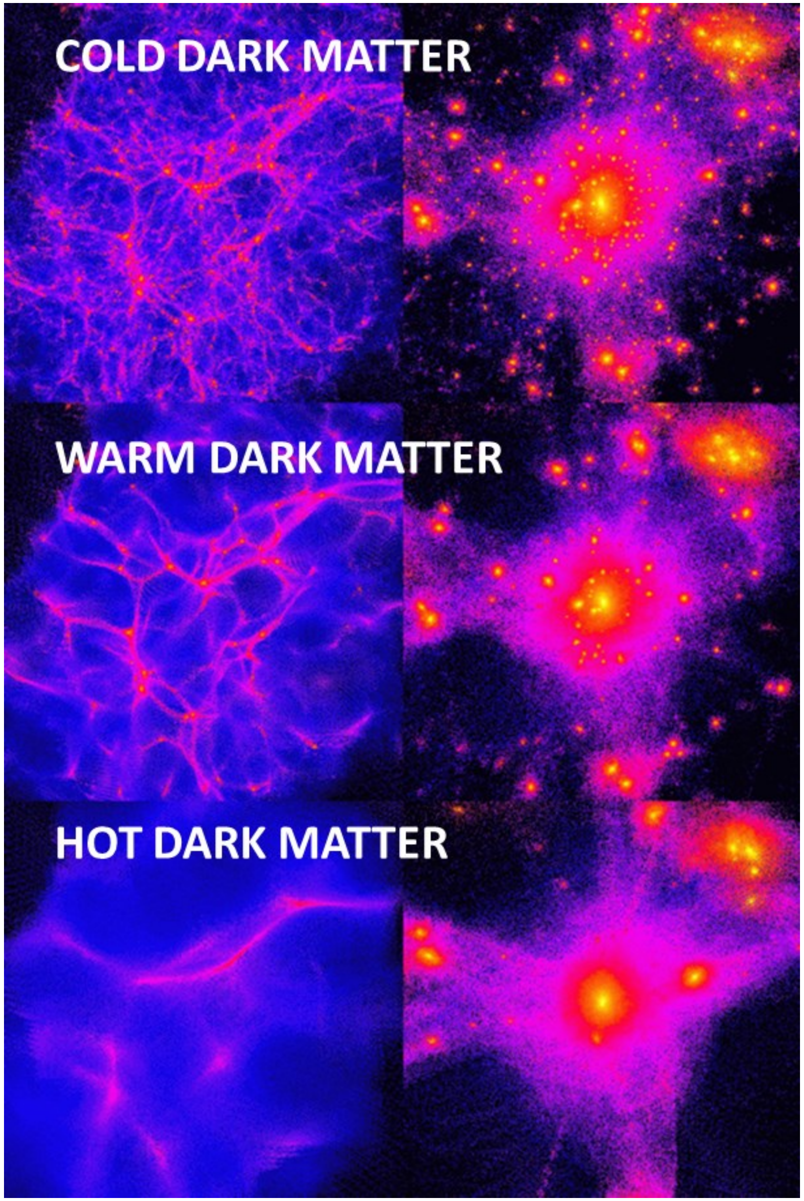


$$\delta = \frac{\rho_M - \bar{\rho}_M}{\bar{\rho}_M}$$

Growth of Structure

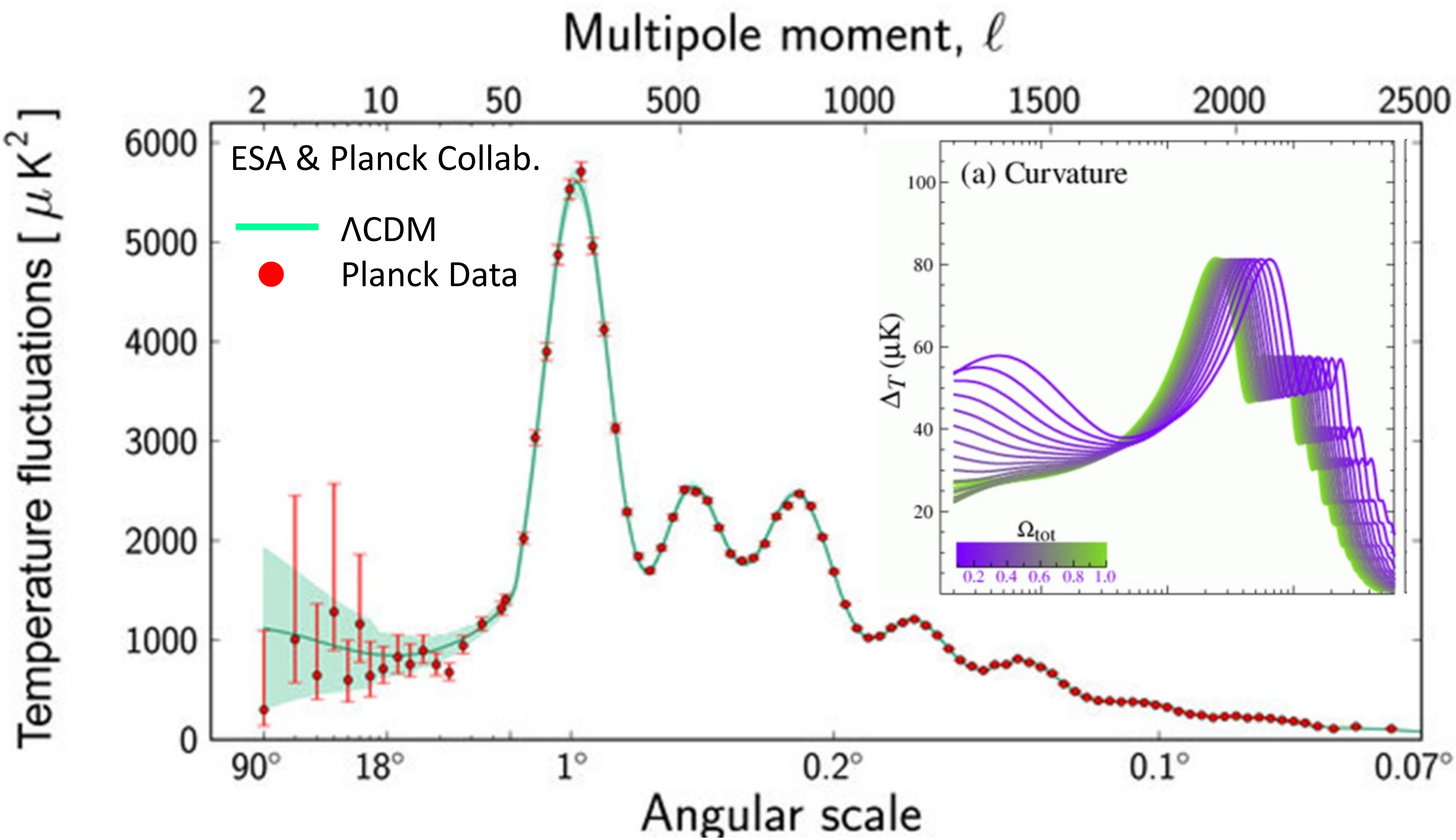


The VIRGO Collaboration 1996



Observations:Universe is flat

CMB → Universe ins flat, density=critical density

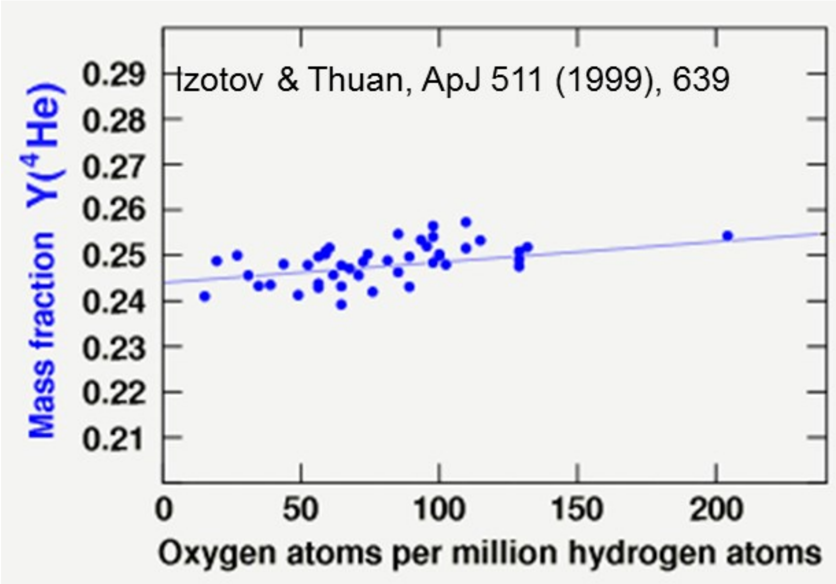


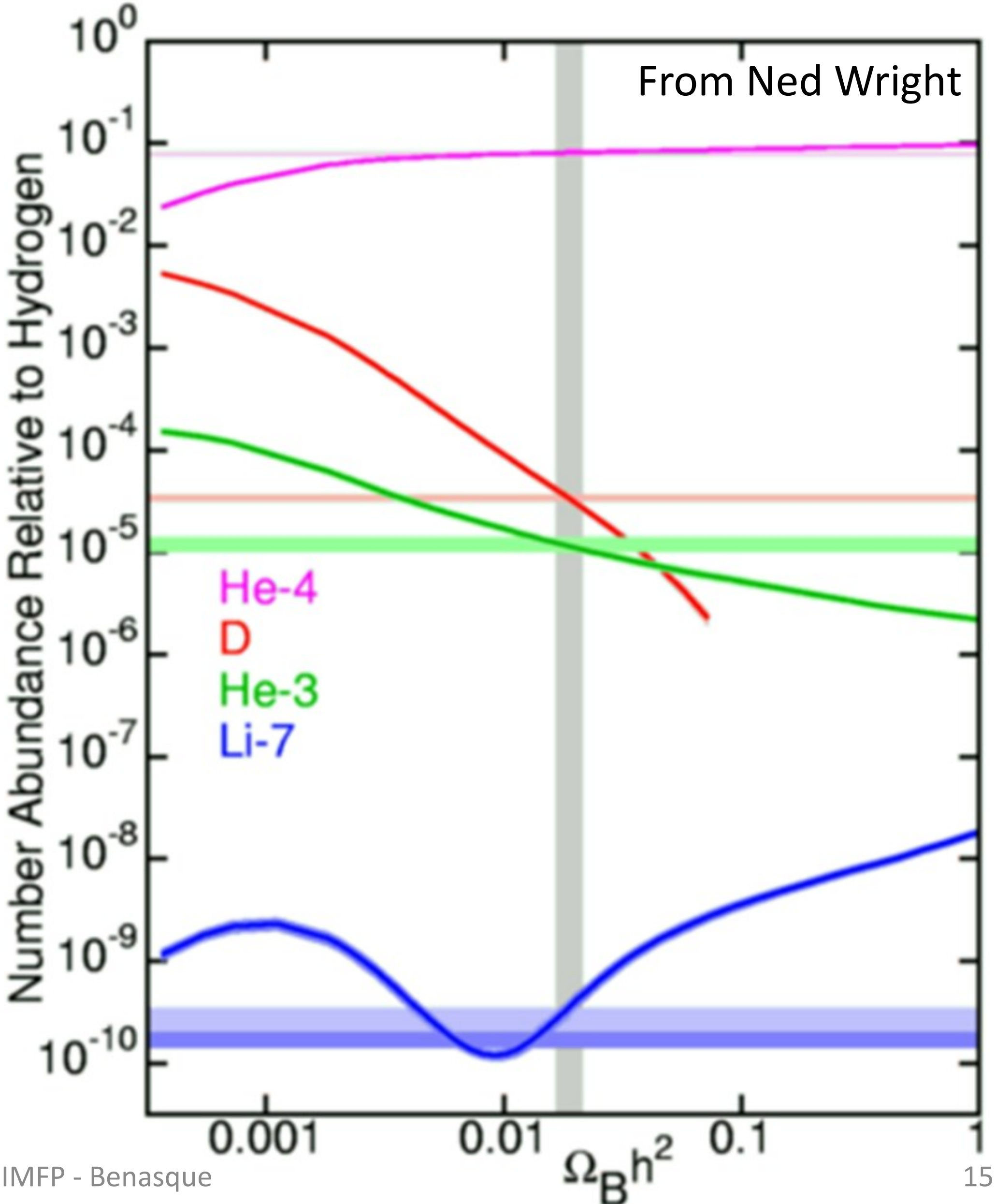
Observations: Baryonic matter is 5%

Primordial abundances

⬇

Baryons are 5% of the total





Observations: Dark Matter is 26%

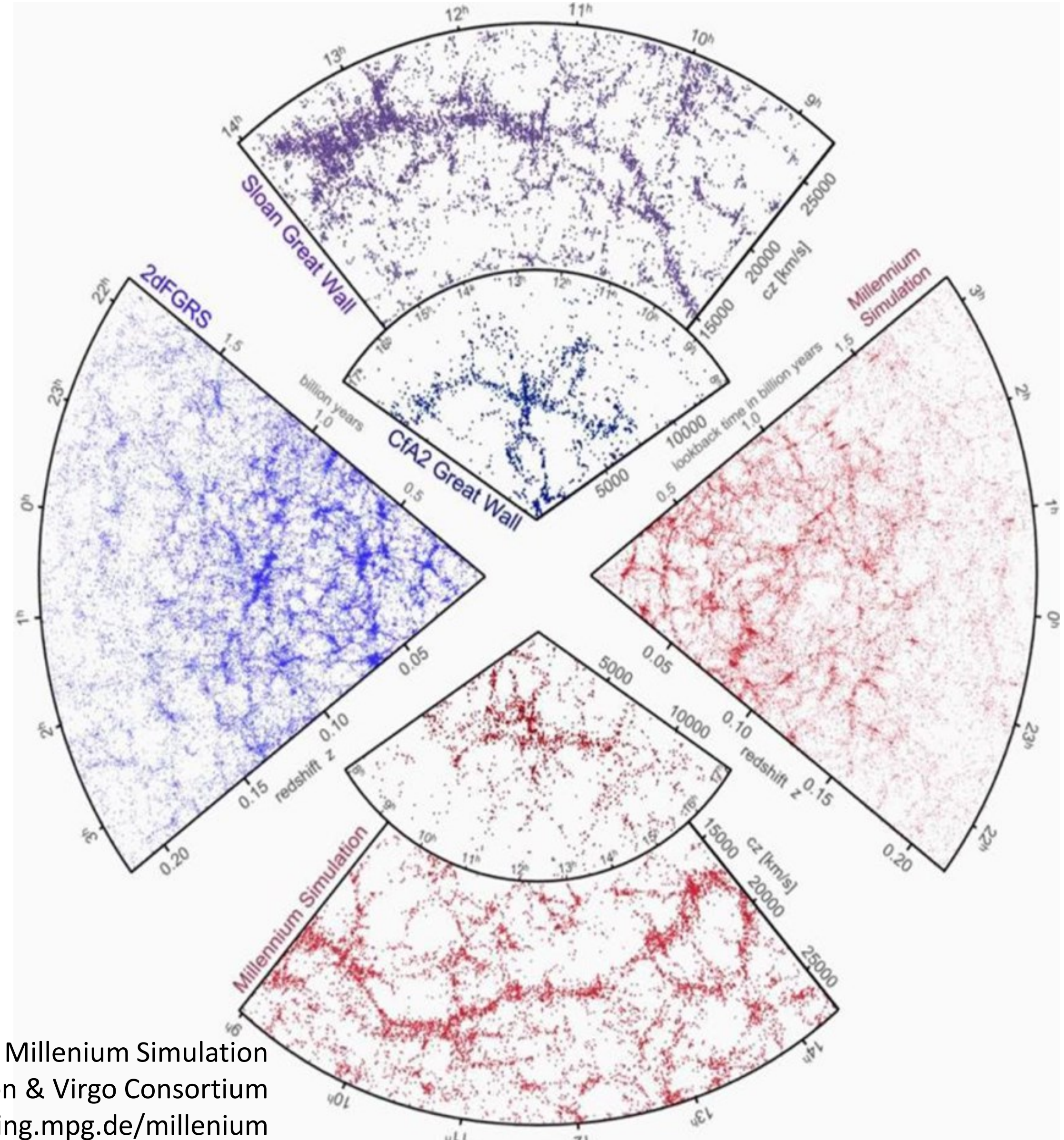
Dark matter is found in all scales → 26%

Rotation/dispersion curves of galaxies

Mass to luminosity ratio of galaxy clusters

Gravitational lenses

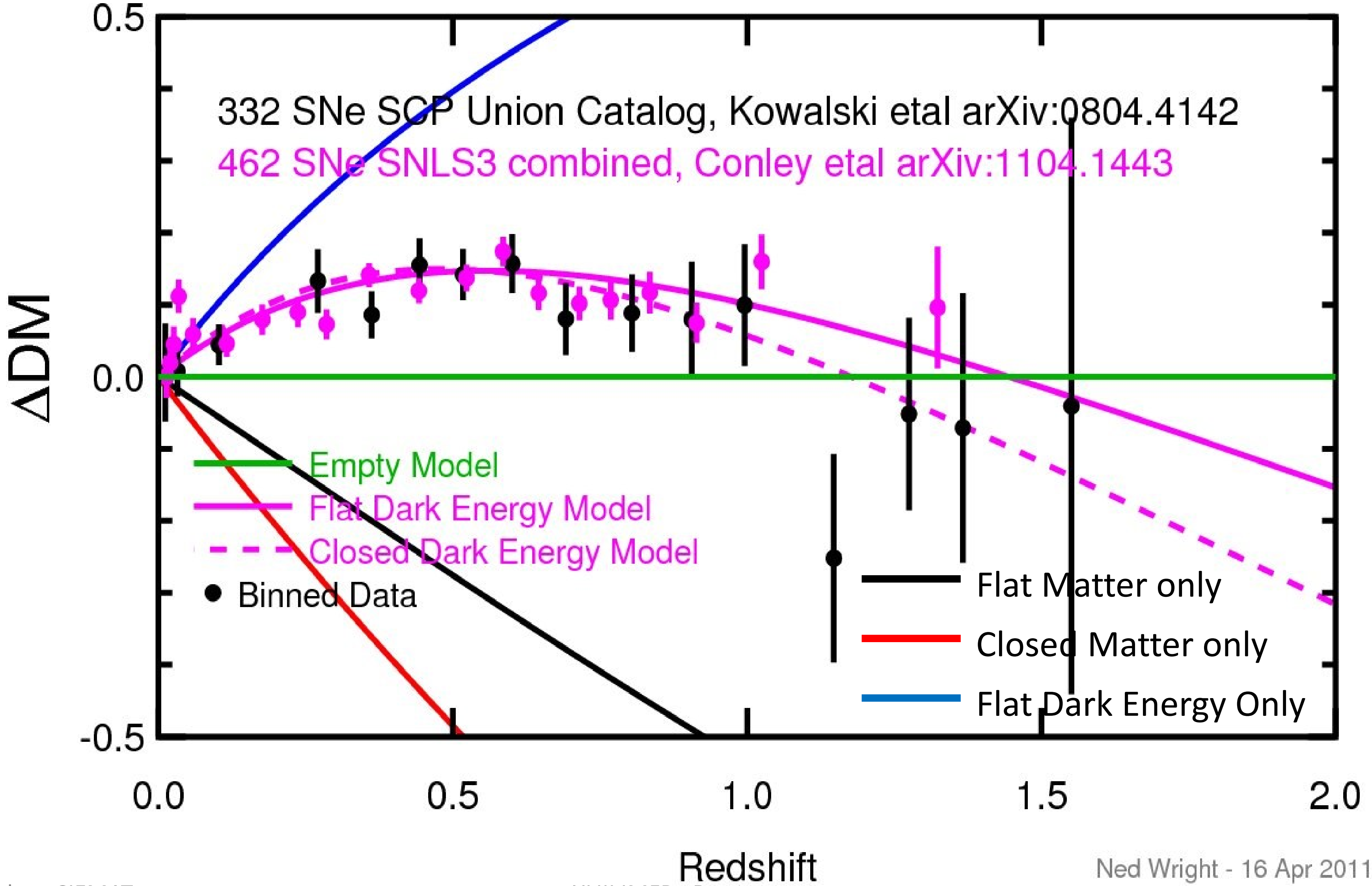
Large Scale Structure



Millenium Simulation
G. Lemson & Virgo Consortium
http://www.mpa-garching.mpg.de/millenium

Observations: Dark energy 68%

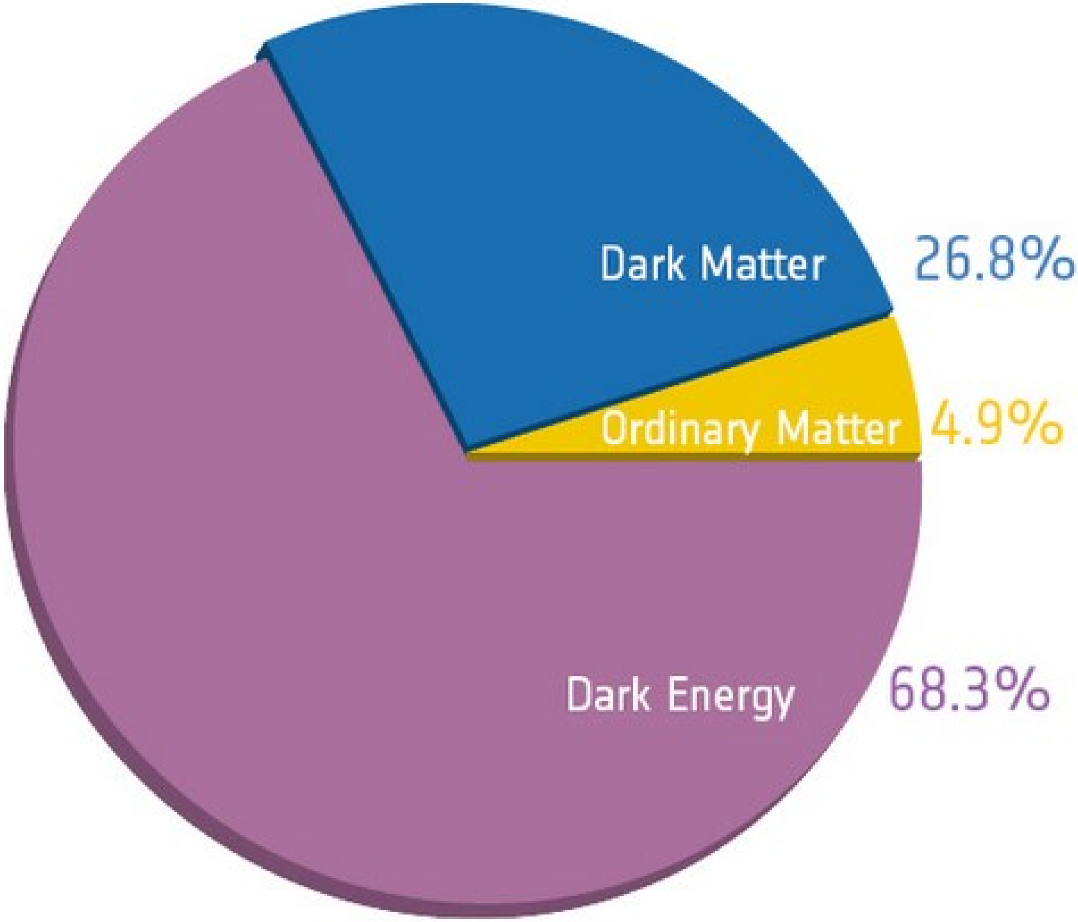
Accelerated expansion → Dark Energy 68%



The dark side

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

Cosmology requires physics beyond the Standard Model 3 times: dark matter, dark energy and the early Universe



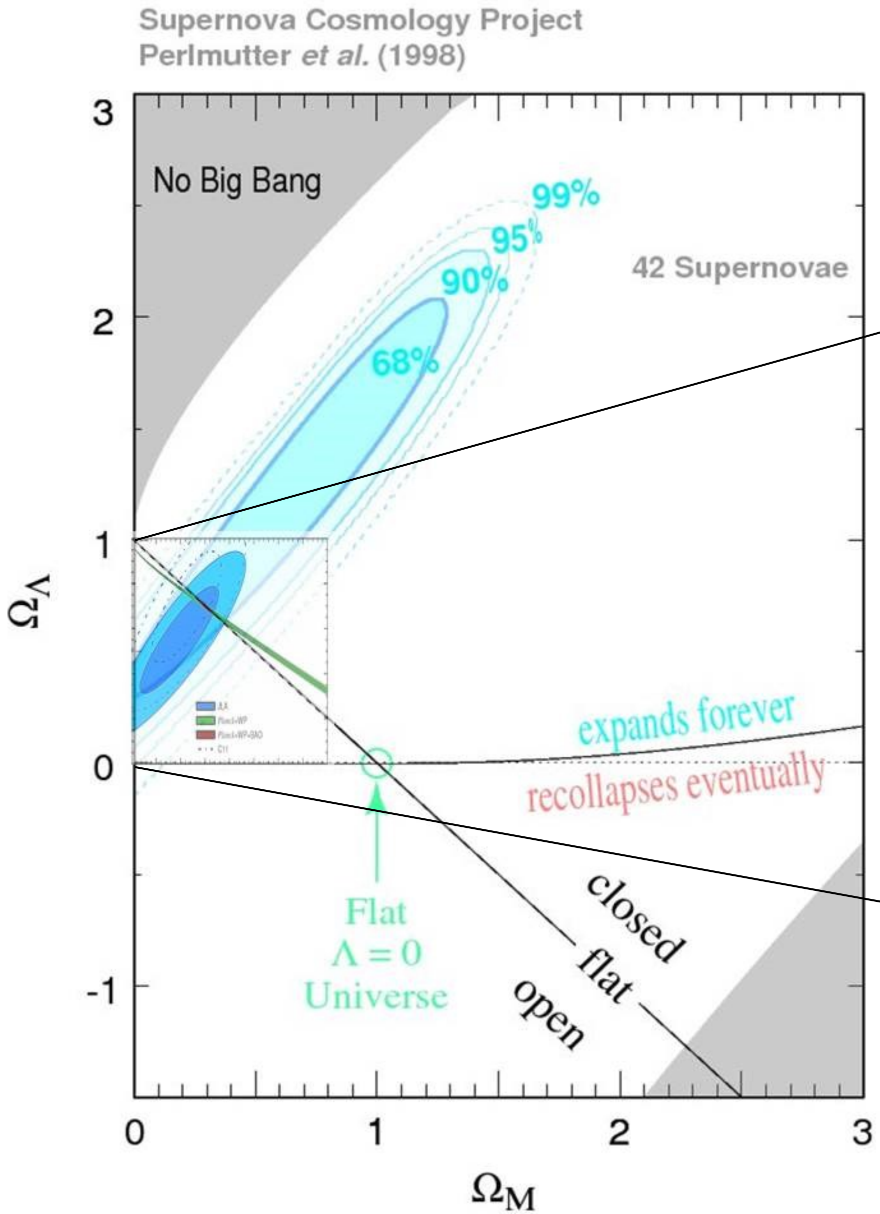
What do we mean by dark energy?

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 deccelerating expansion, not an accelerating one

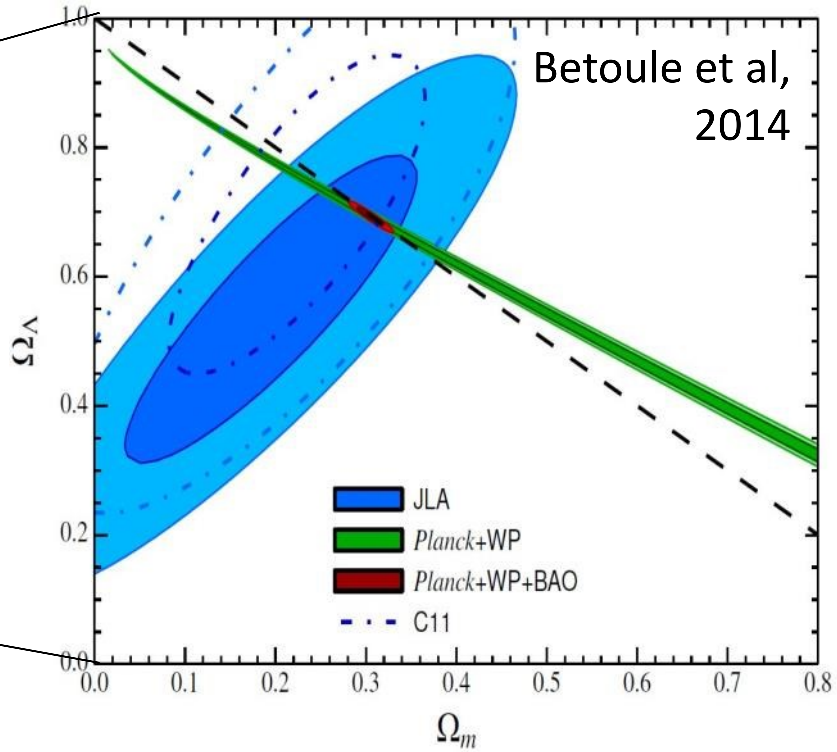
Whatever mechanism causes the acceleration, we call it "dark energy":

- Einstein´s cosmological constant
- Some new field ("quintessence"…)
- Modifications to General Relativity
- …

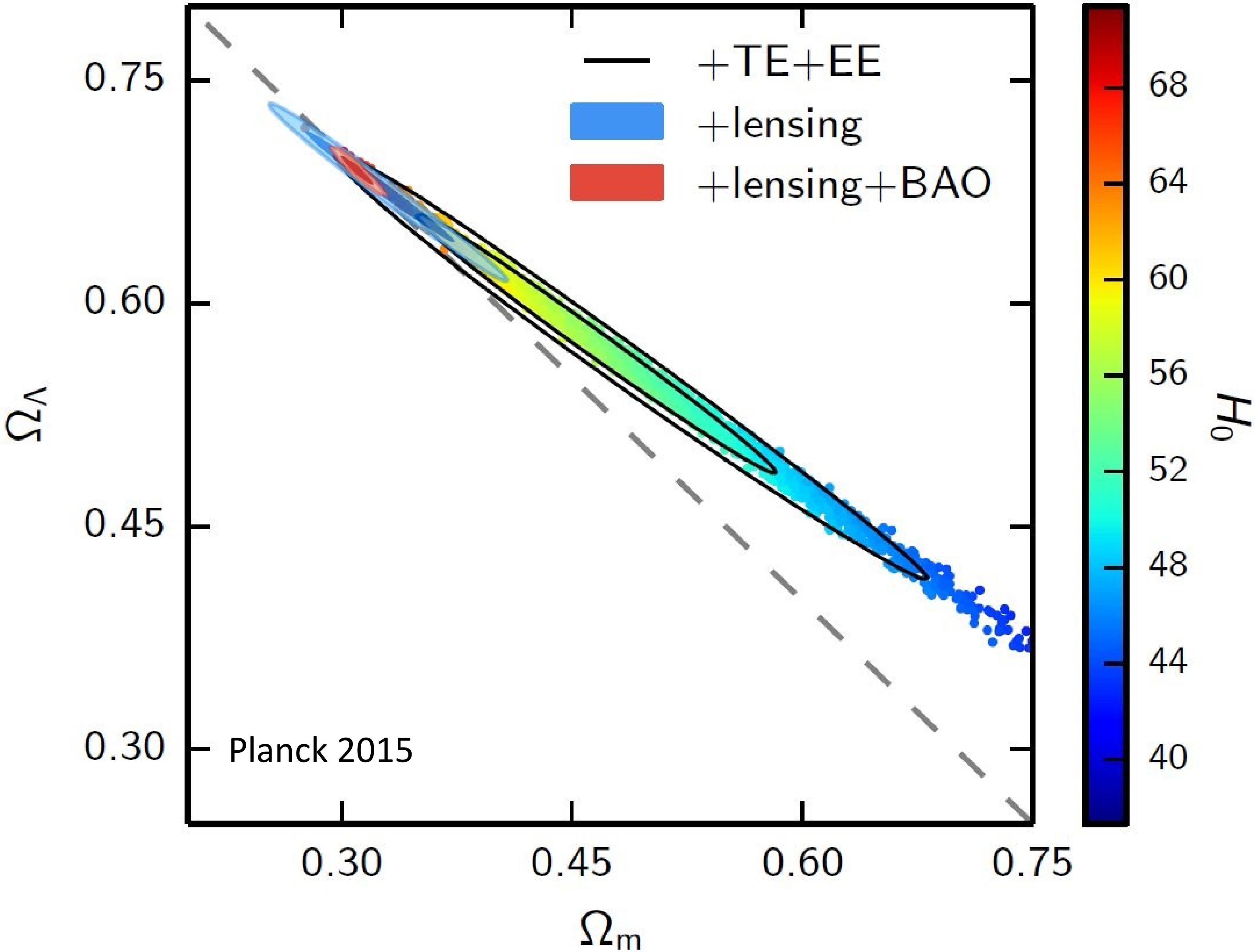
Evidence for dark energy



Huge progress from 1998



Evidence for dark energy



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 ± 0.045 from Planck 2015

If it is the vacuum energy

$$\Omega_\Lambda \sim 0.7 \rightarrow \rho_\Lambda \sim (10\ \mathrm{meV})^4$$

while the estimate from QFT is

$$\rho_\Lambda \sim m_{Planck}^4 \sim 10^{120} \times \sim (10\ \mathrm{meV})^4$$

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

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 $\frac{dV}{dz d\Omega} = r^2(z)/\sqrt{(1 - kr^2(z))}$

Growth of structure: A more complicated function of H(z)

Observational Probes of dark energy

Many practical implementations:

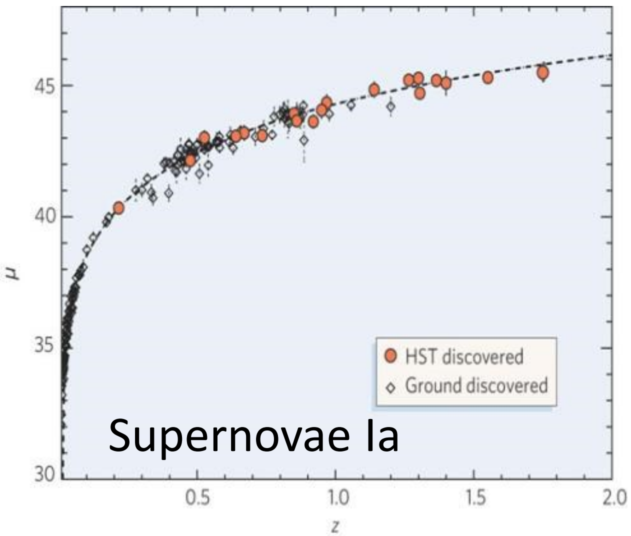
Distance probes: SN1a, BAO, CMB, weak lensing, galaxy clusters,…

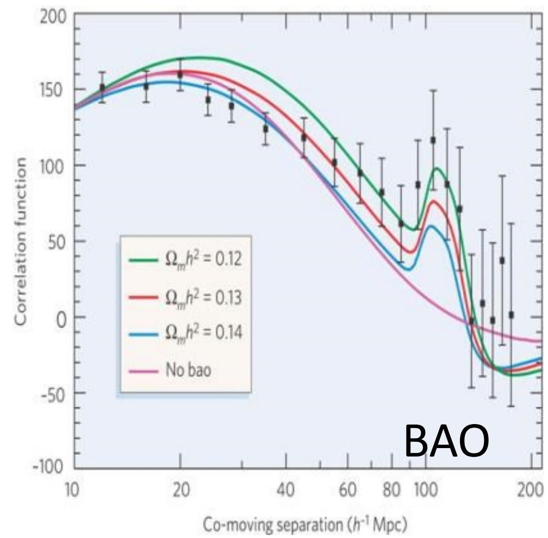
Growth of Structure probes: CMB, redshift space distortions, weak lensing, galaxy clusters…

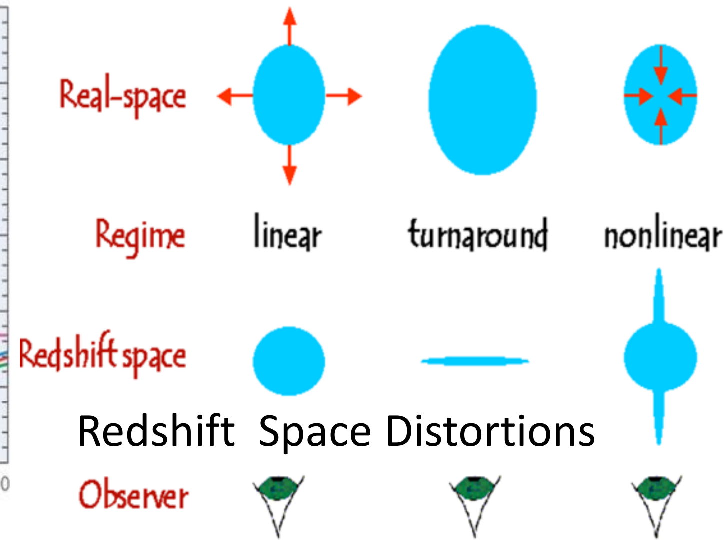
No single technique is sufficiently powerful to improve the knowledge of dark energy at the level of one order of magnitude

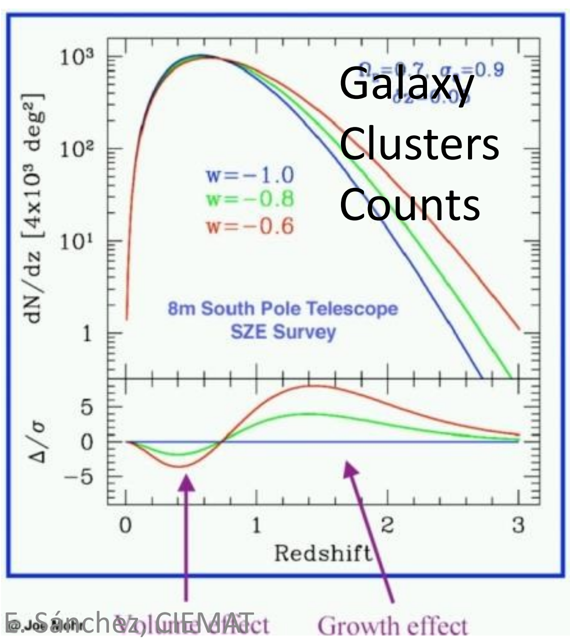
Combination of techniques: More statistical power, ability to discriminate among dark energy models, robustness against systematic errors

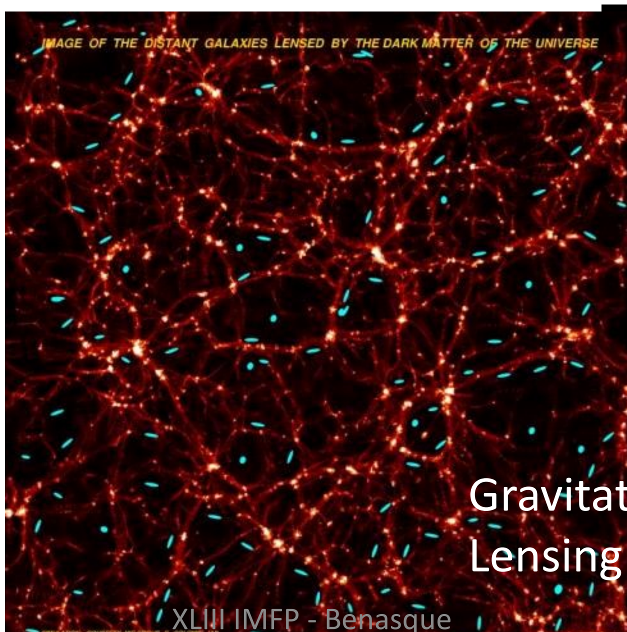
Observational Probes of dark energy

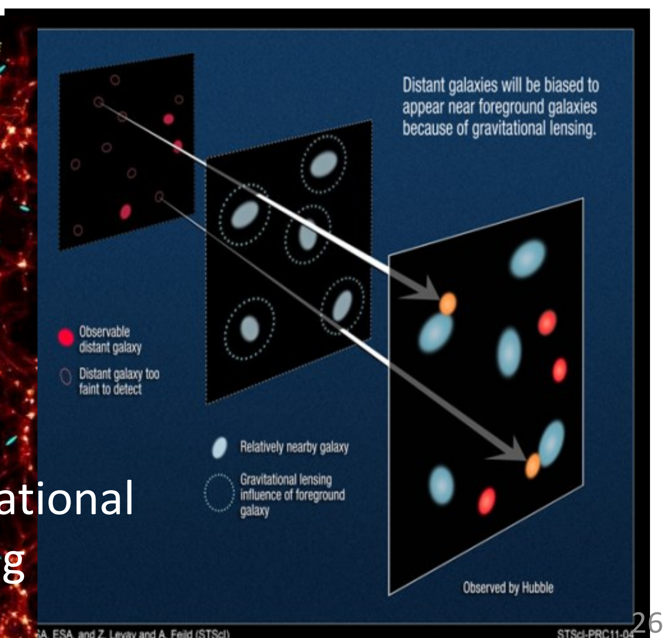












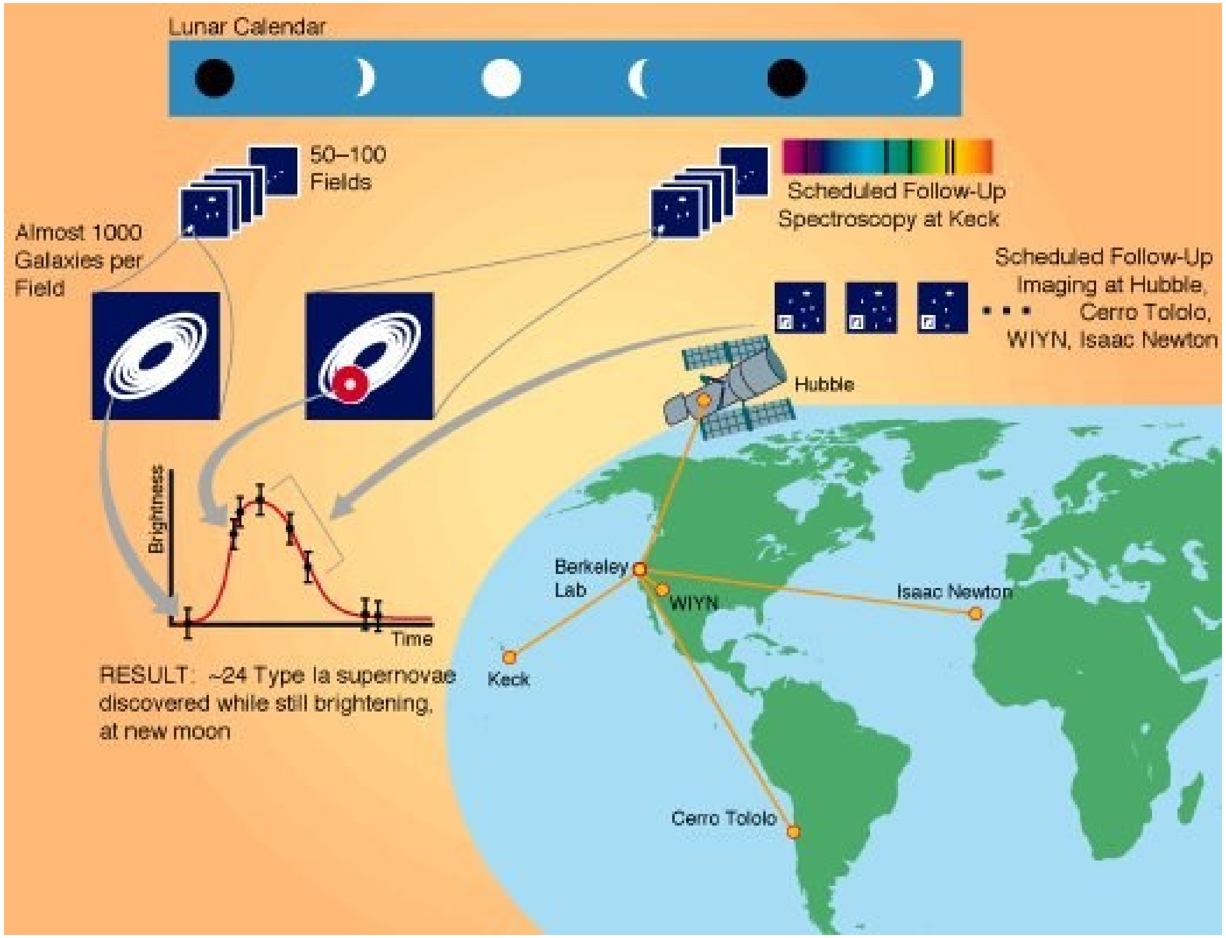
Supernovae 1a

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



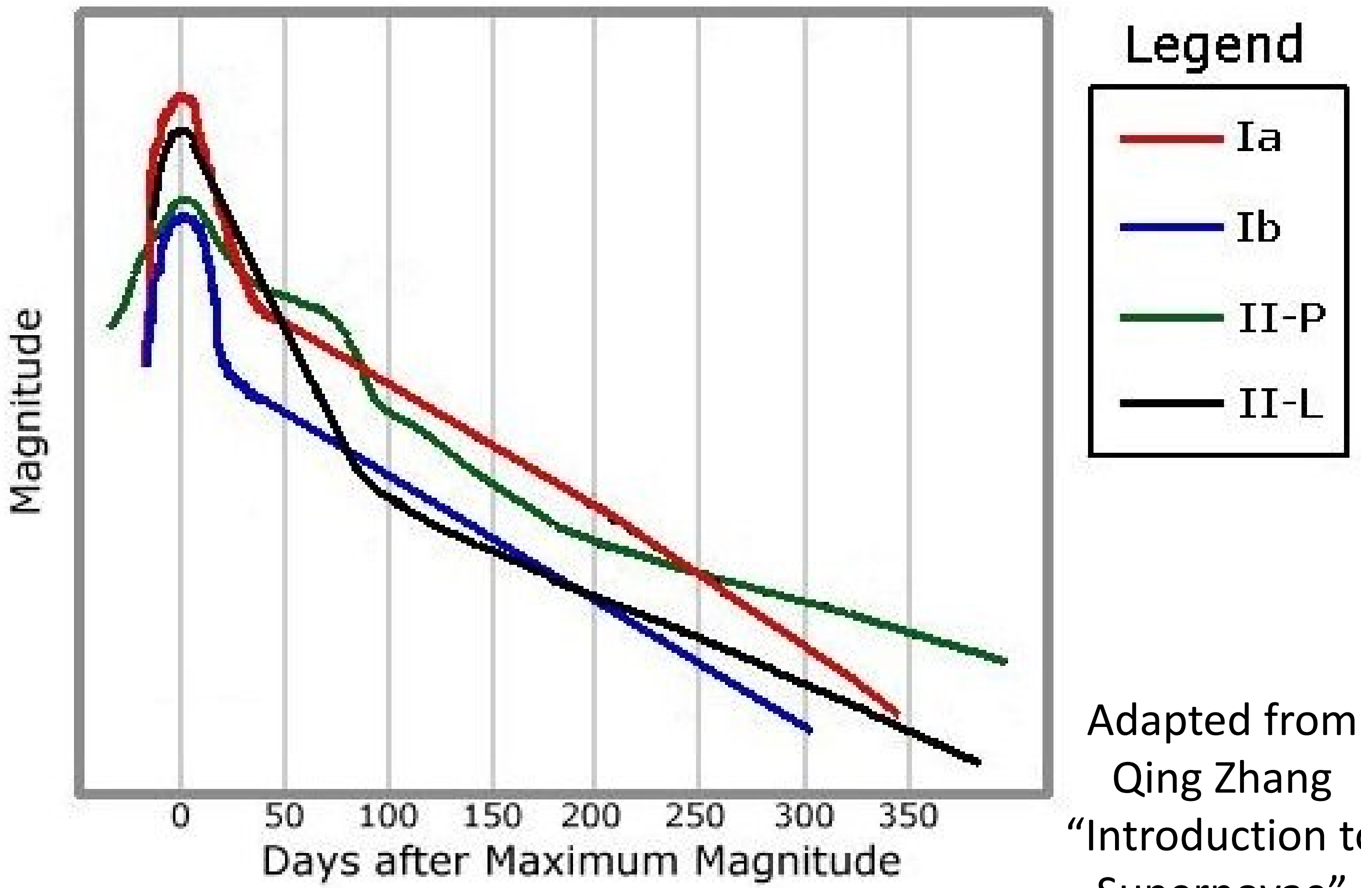
Supernovae 1a

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”

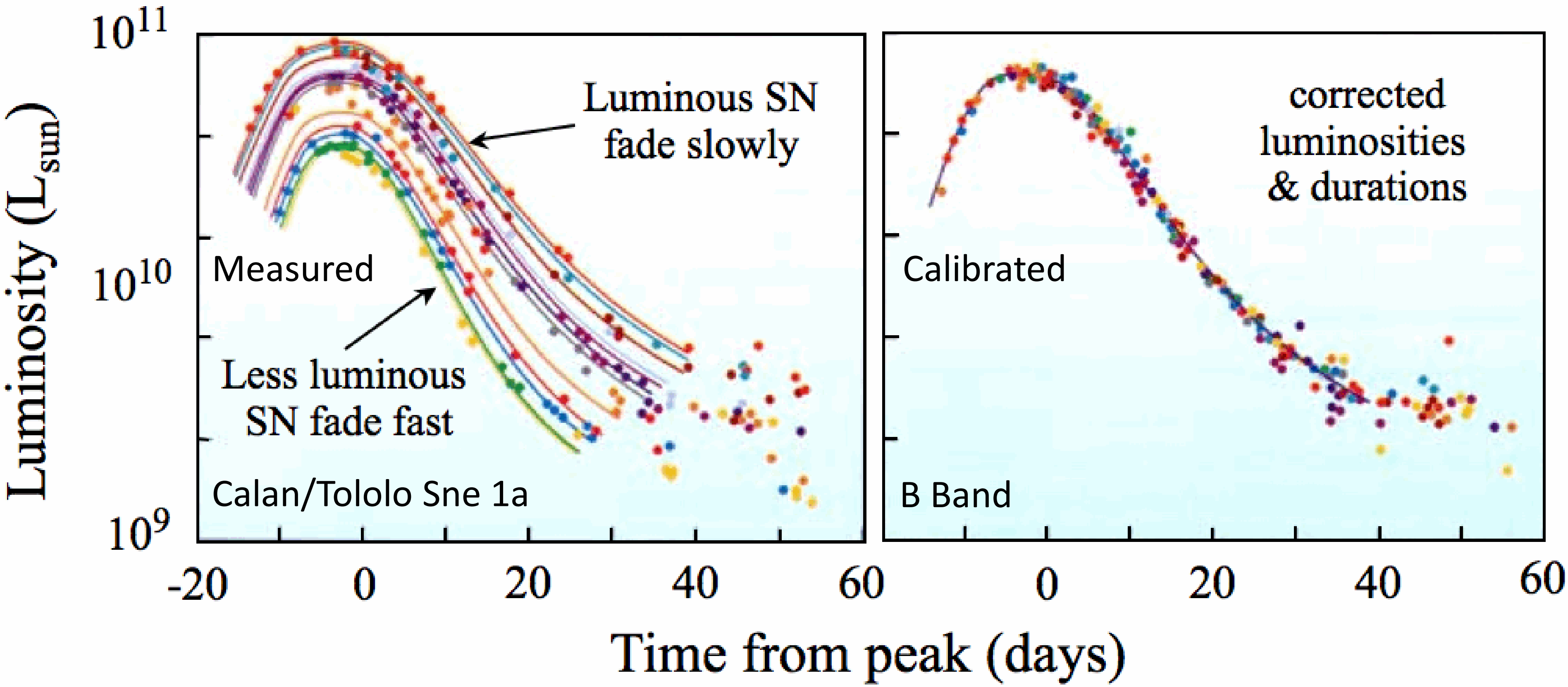
Supernovae 1a

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



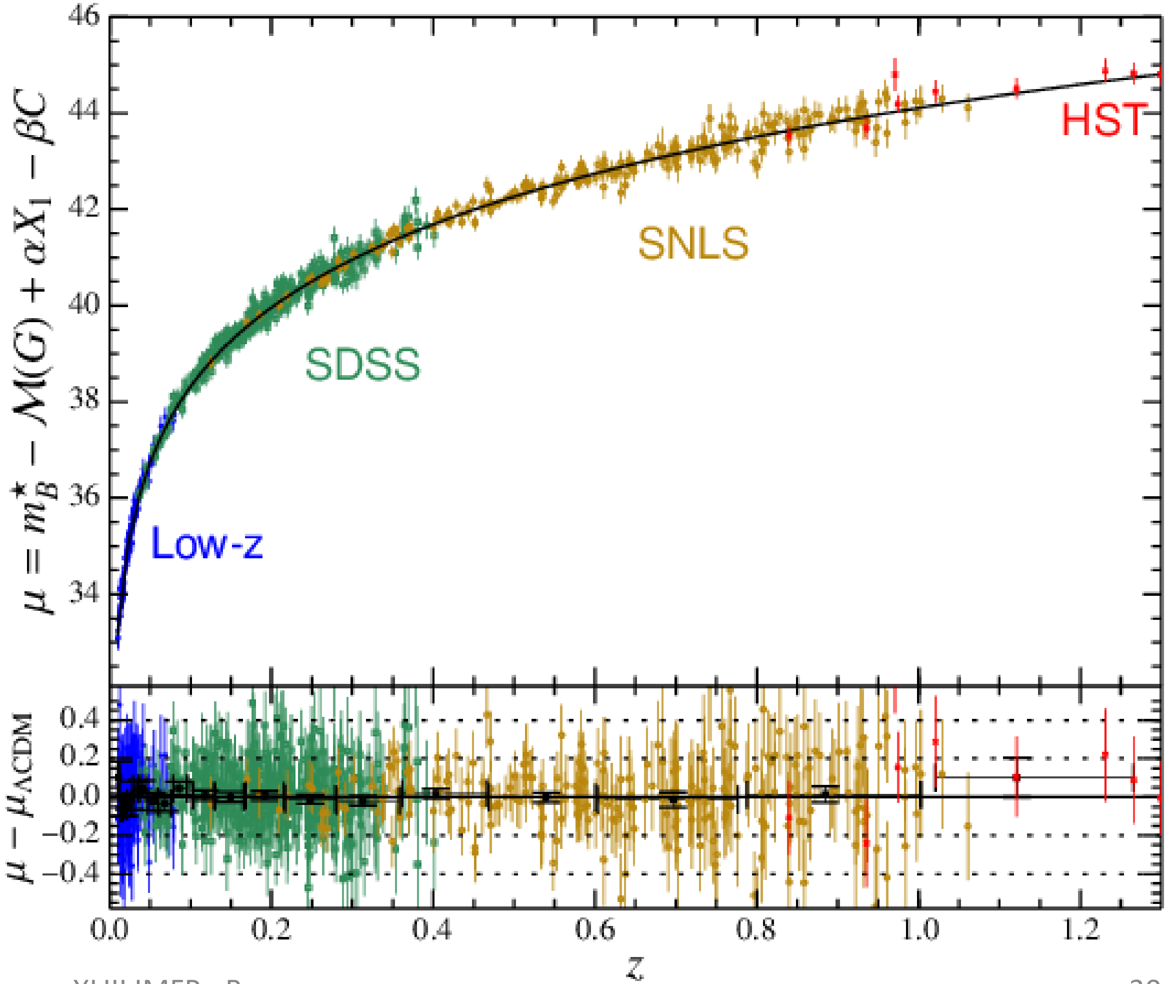
Supernovae 1a

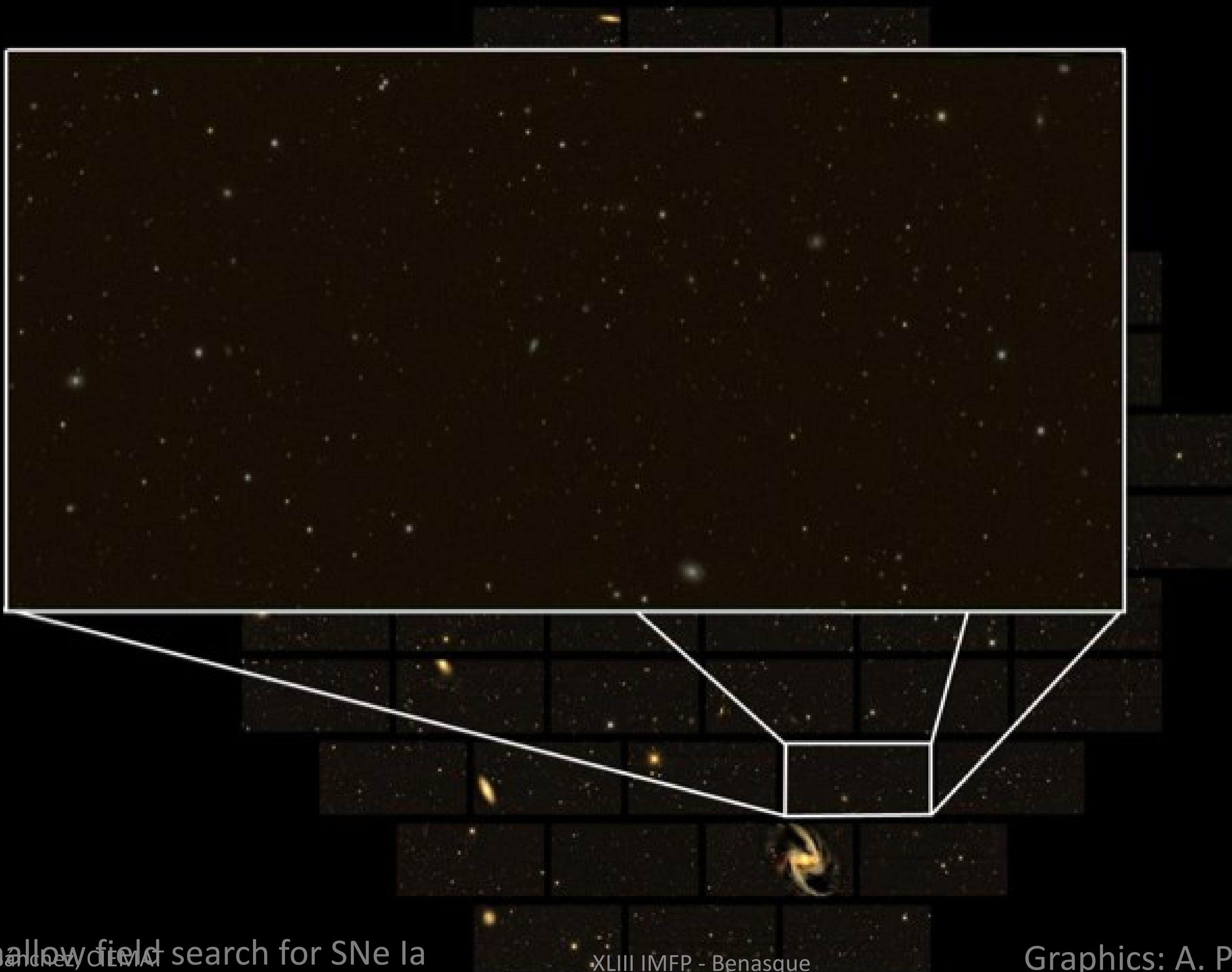
This is the technique that allowed the discovery of the dark energy

The most mature technique to date

SN1a are GOOD DISTANCE INDICATORS

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

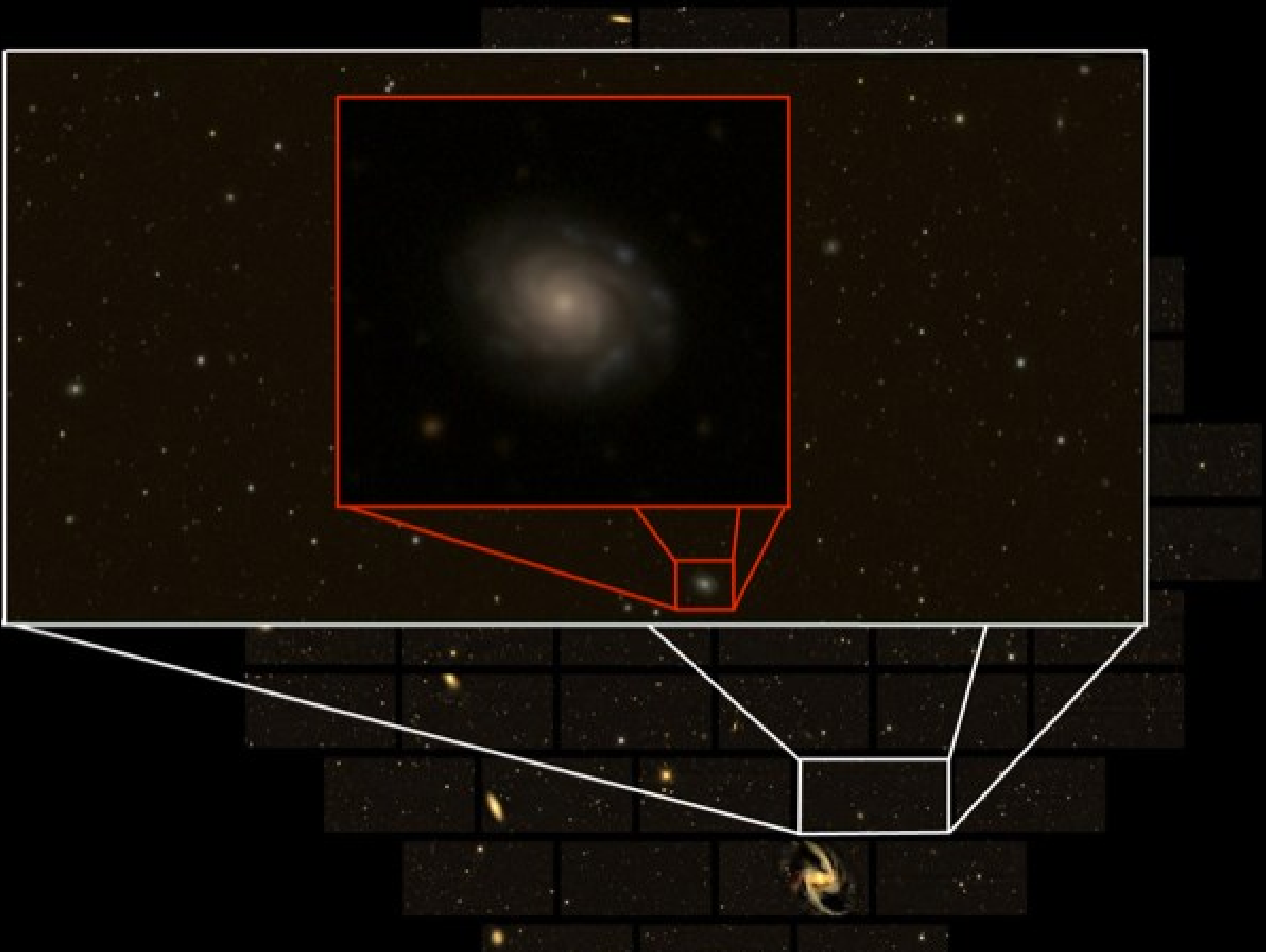




Shallow field search for SNe Ia

Graphics: A. Papadopoulos

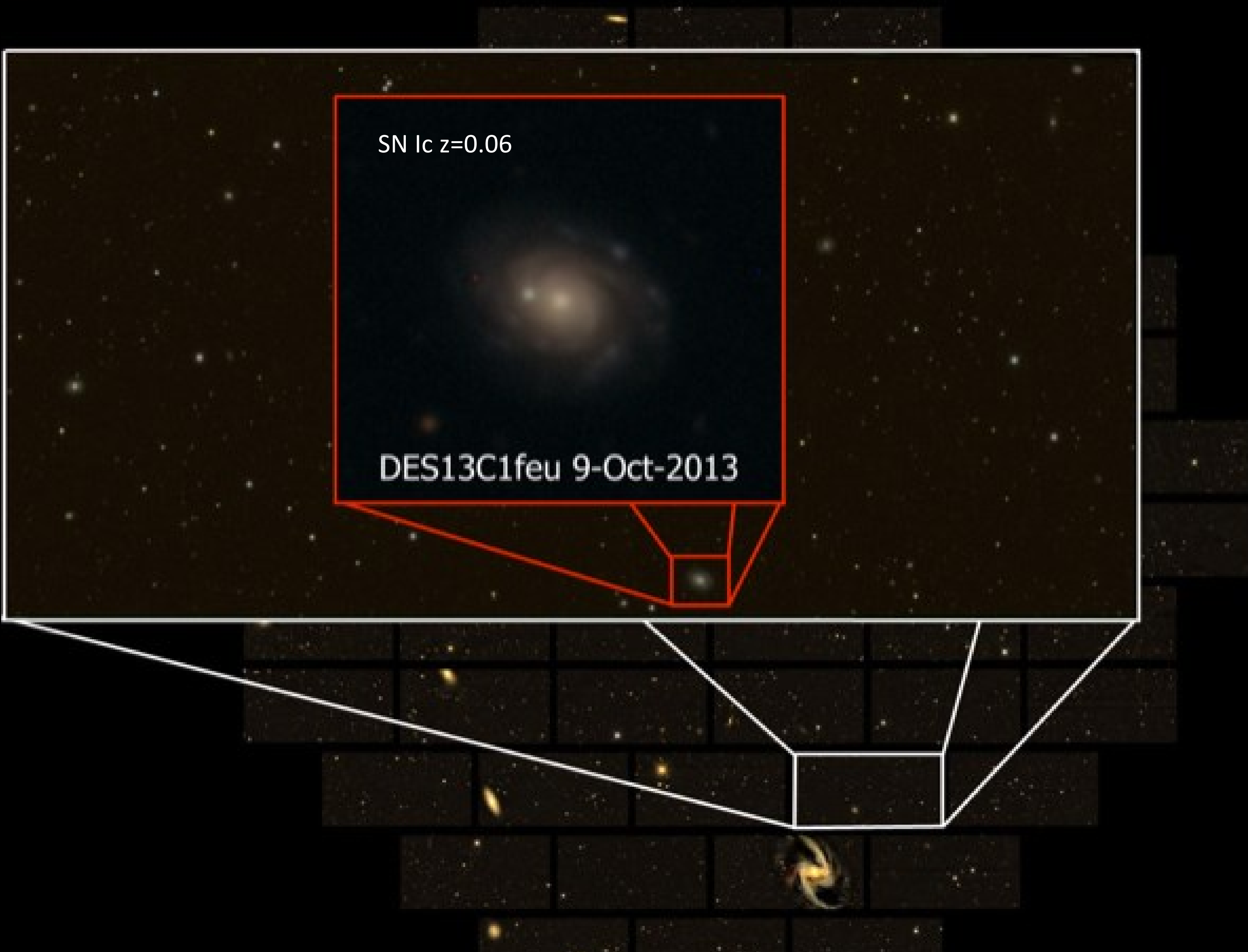
THE DARK ENERGY SURVEY



Shallow field search for SNe Ia

Graphics: A. Papadopoulos

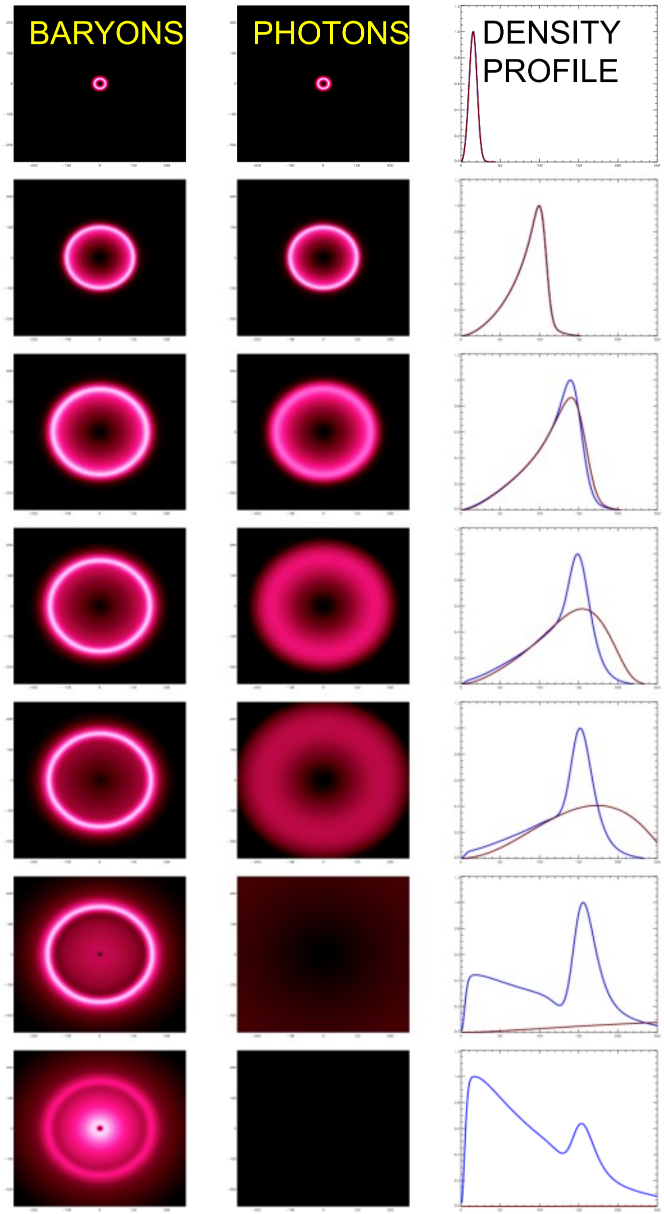
THE DARK ENERGY SURVEY



Shallow field search for SNe Ia

Graphics: A. Papadopoulos

BAO



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, wich propagates with velocity $c/\sqrt{3}$

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

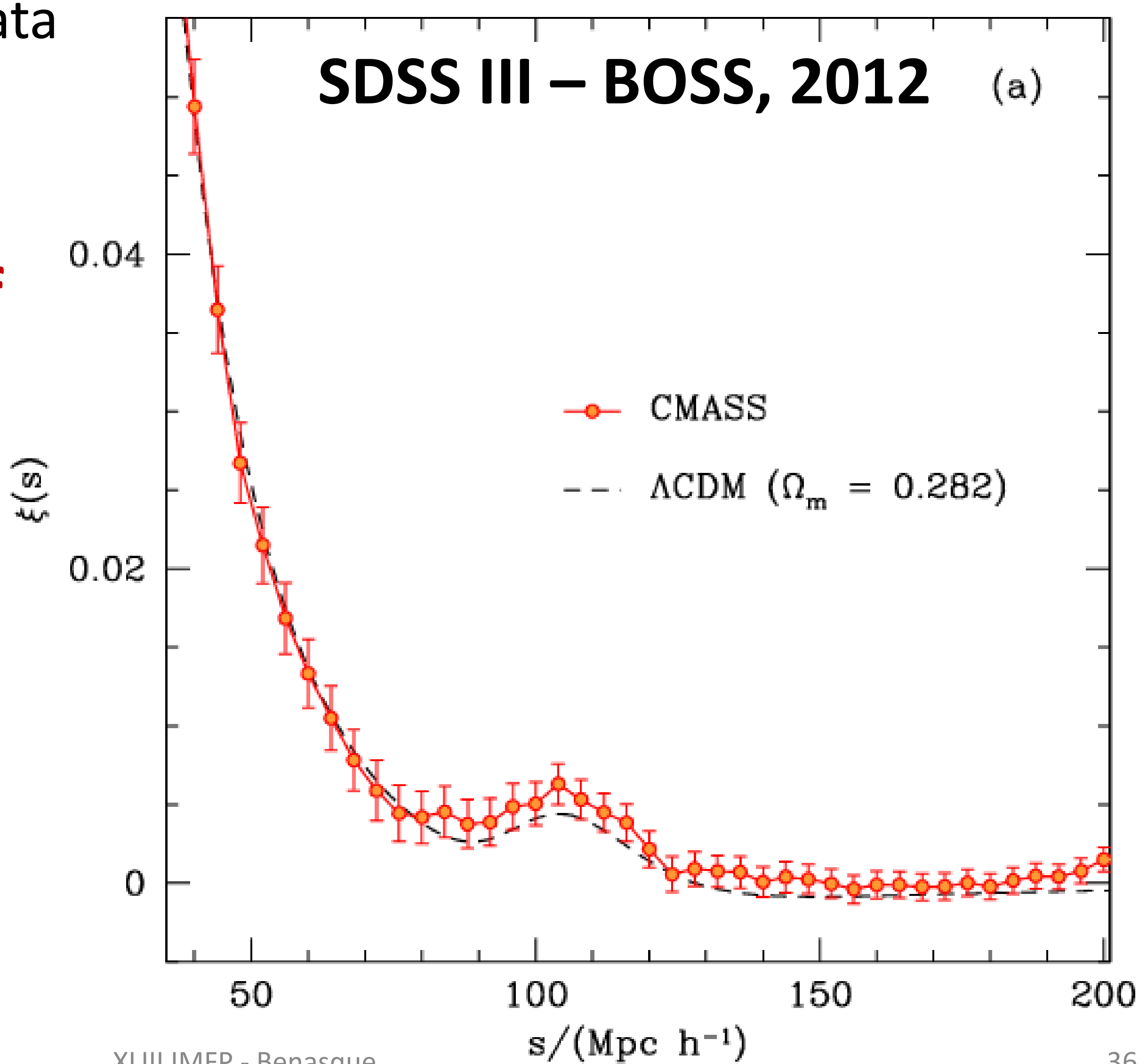
Photons quickly stream away, leaving the baryon peak stalled at ~150 Mpc.

There is a special separation between galaxies: 150 Mpc, that can be used as a STANDARD RULER

BAO

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

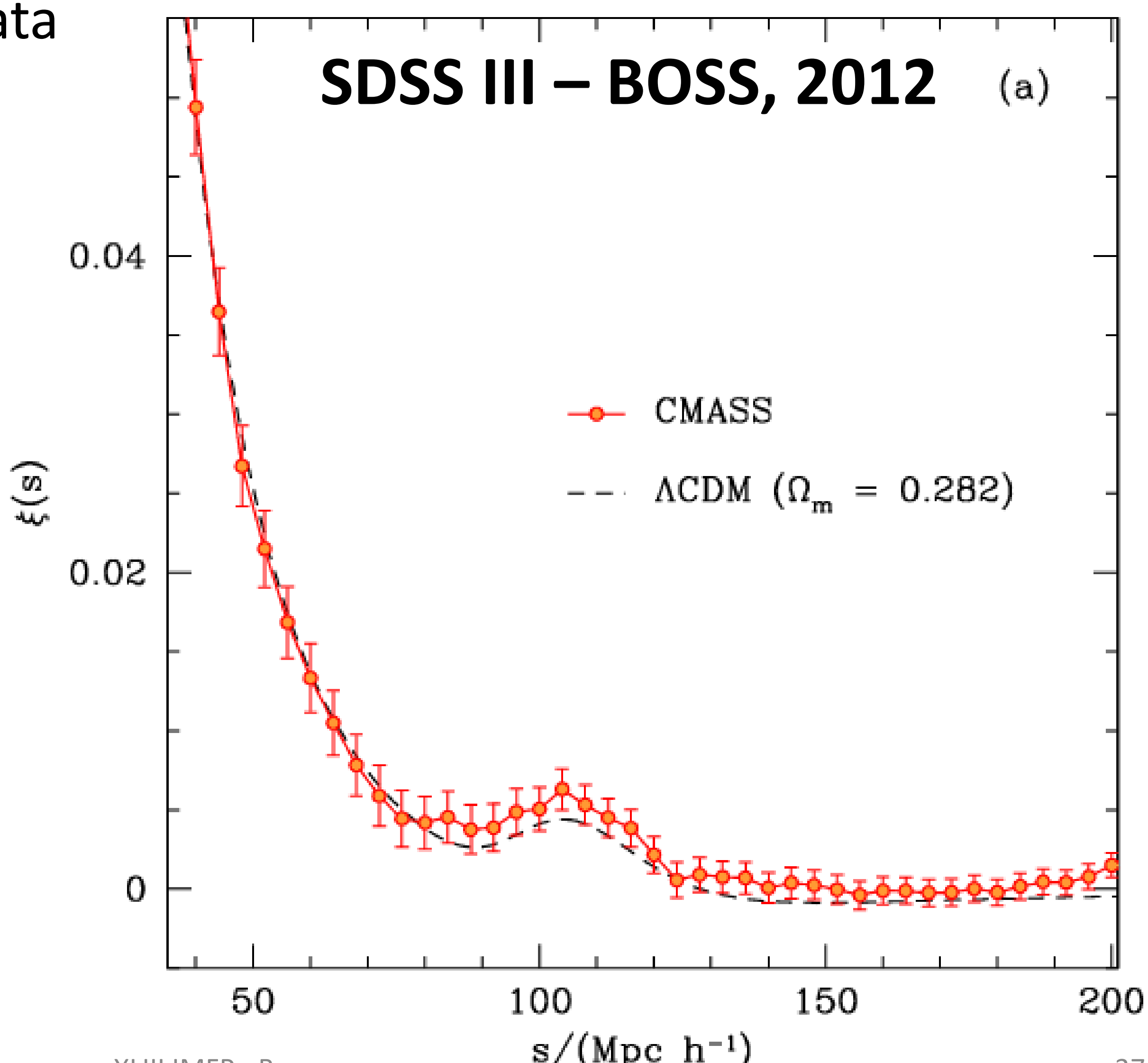
1.- Select a sample of galaxies with known redshifta and compute the 2-point correlation funcion



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



BAO

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

3.- Build the Hubble diagram for standard rulers and fit the cosmological parameters

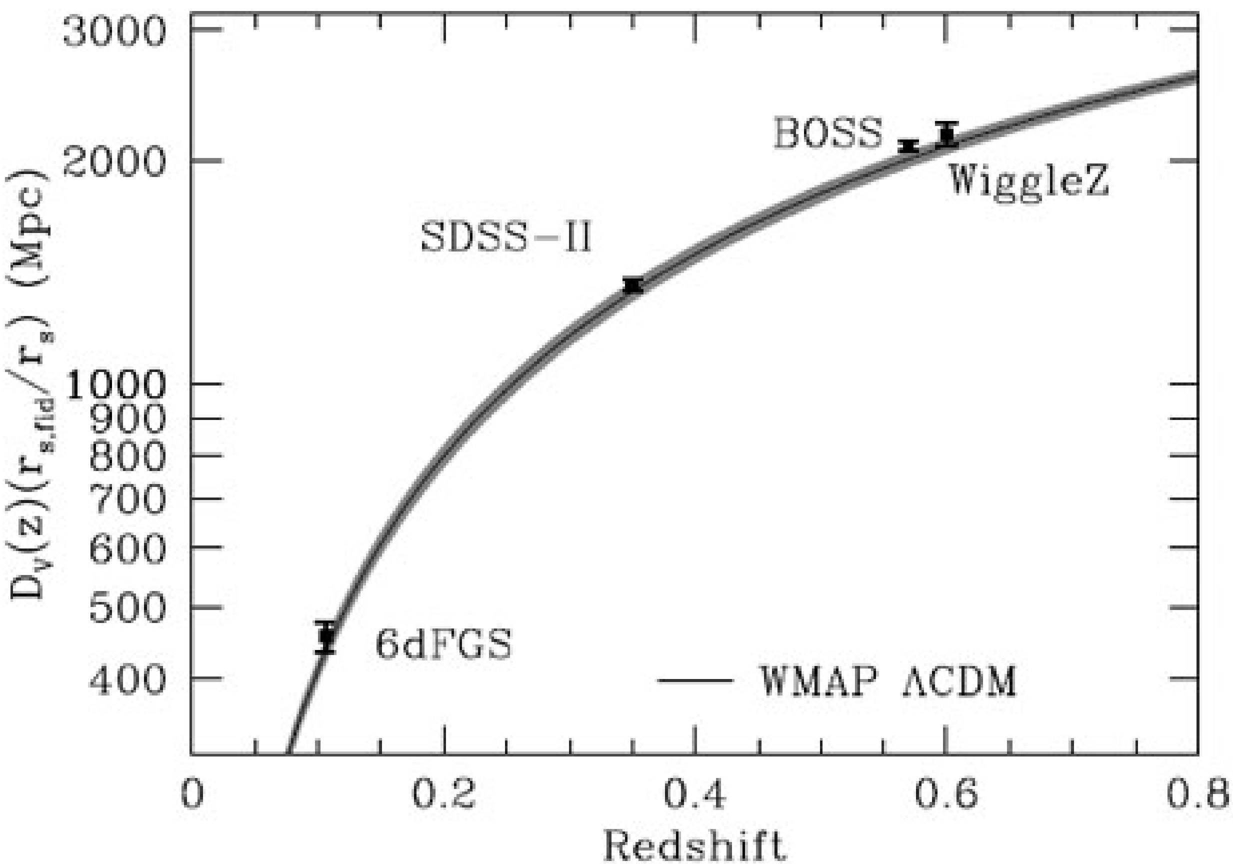


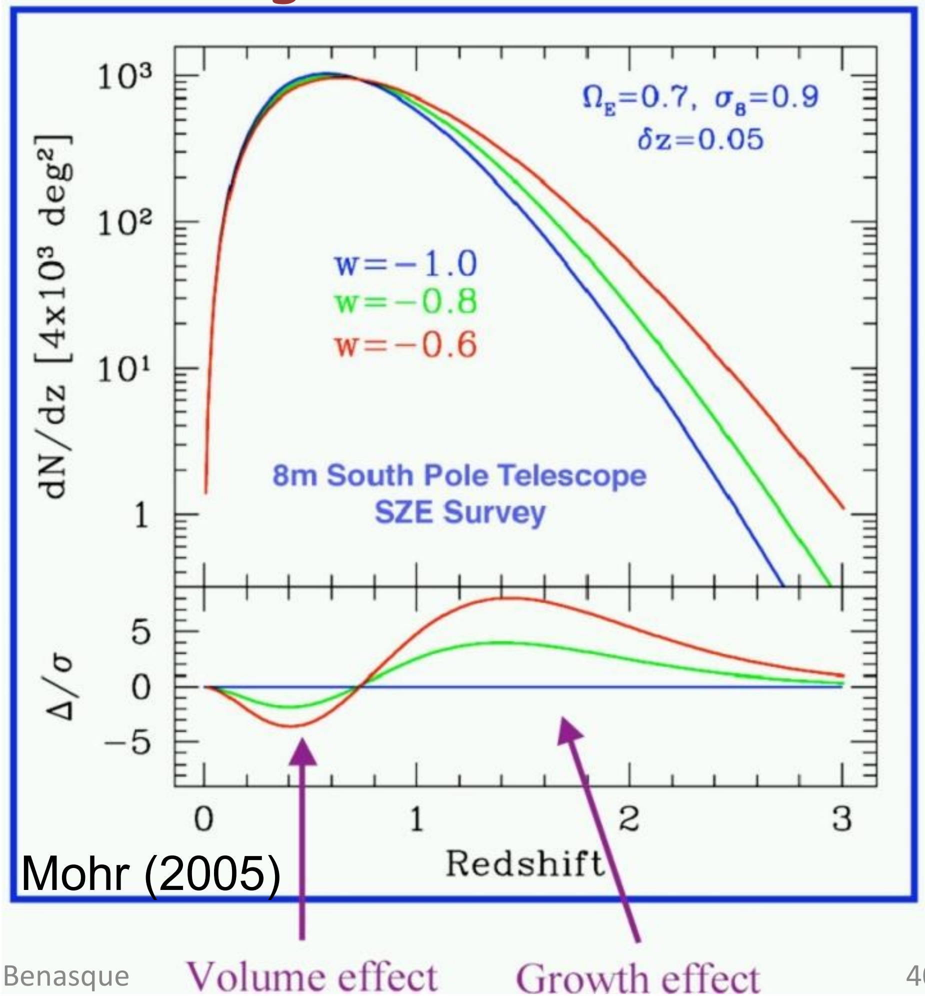
Image: Dark Energy Survey Collaboration
www.darkenergydetectives.org

GALAXY CLUSTERS COUNTS

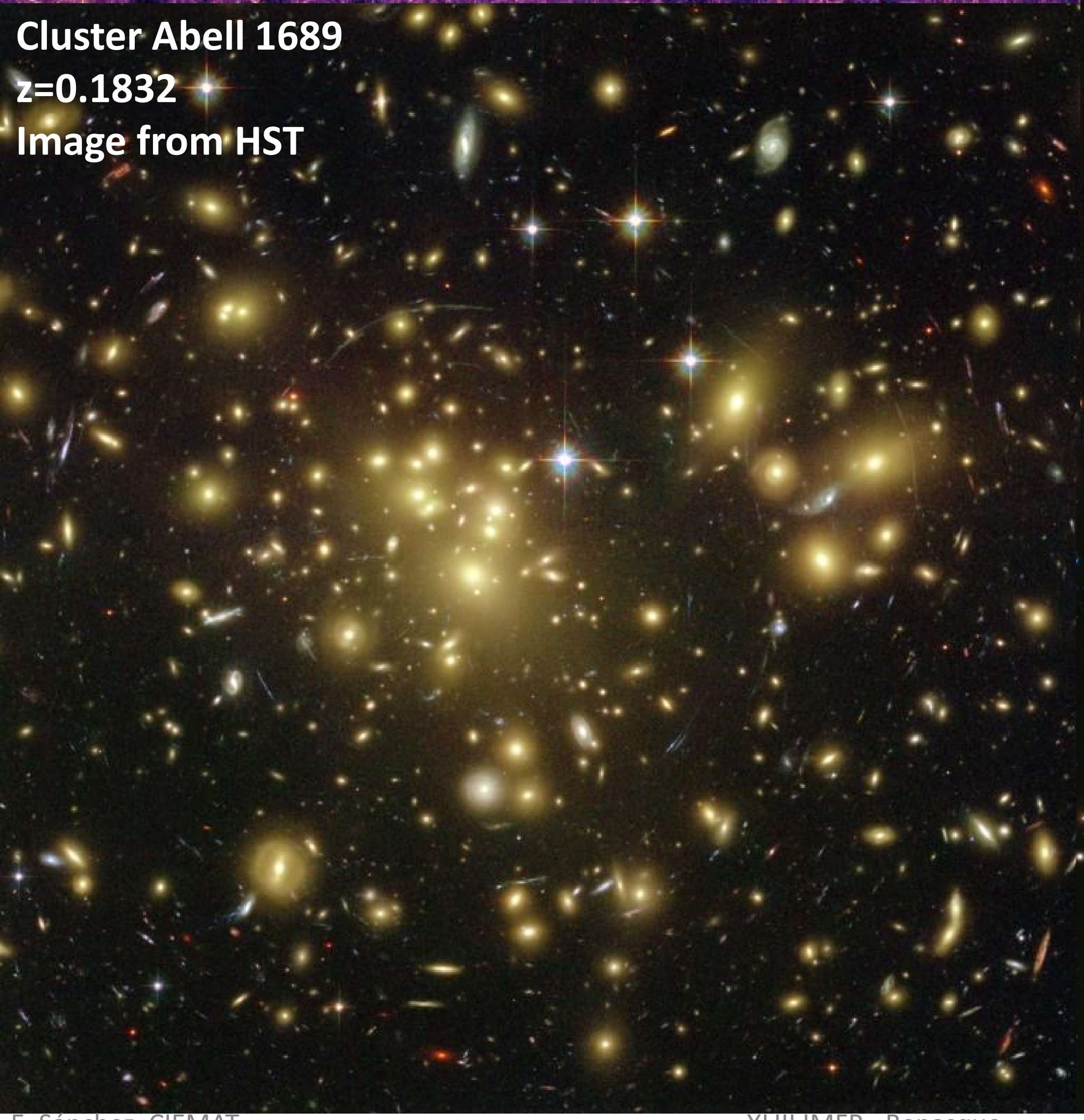
The number of galaxy clusters as a function of redshift is very sensitive to the properties of the dark energy, and cosmological parameters in general

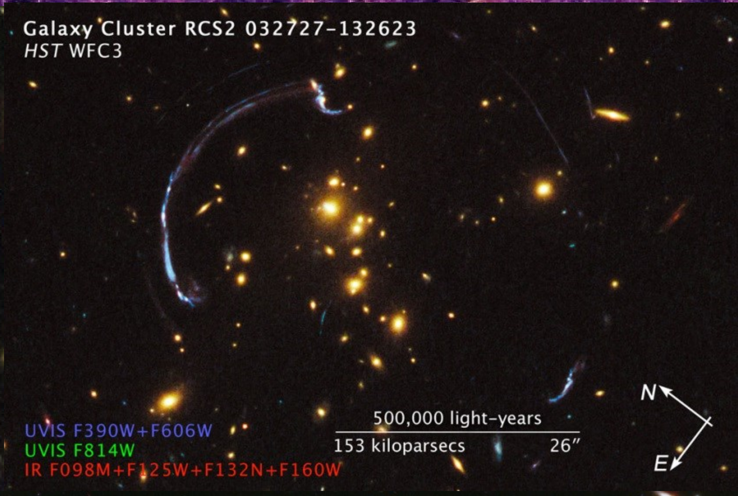
Sensitive to distance and structure growth

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



GALAXY CLUSTERS COUNTS





GRAVITATIONAL LENSING

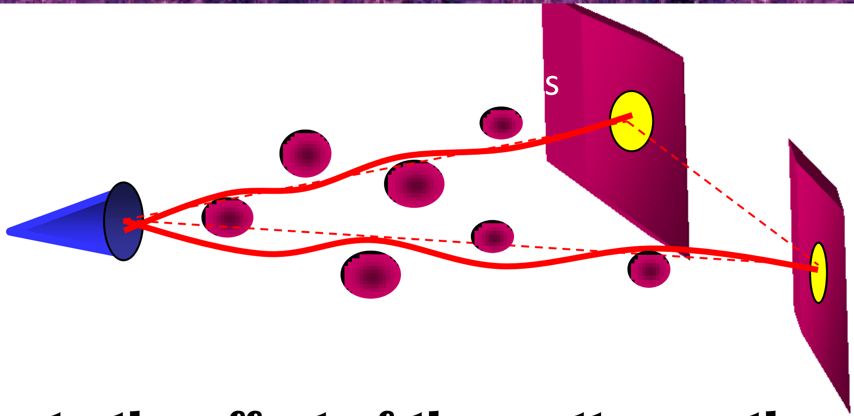
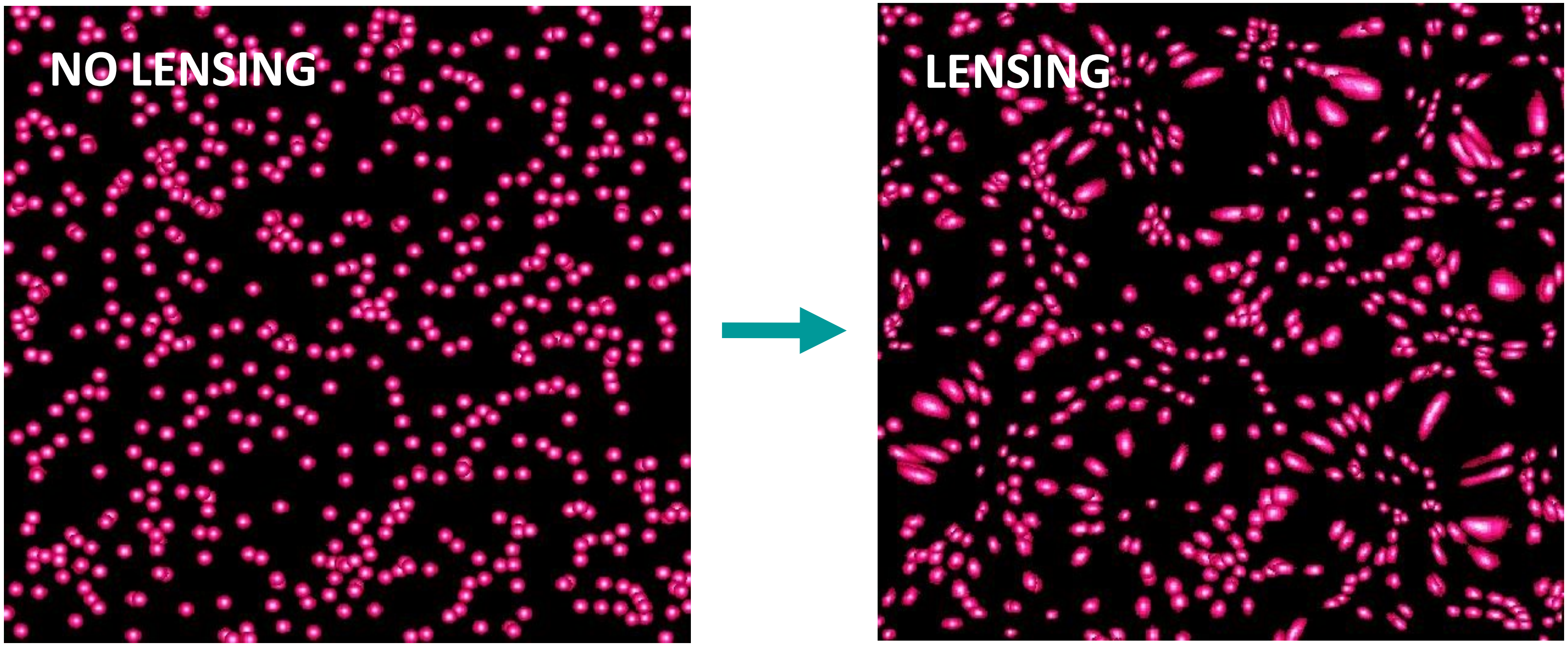


Image distortion due to the effect of the matter on the space-time curvature

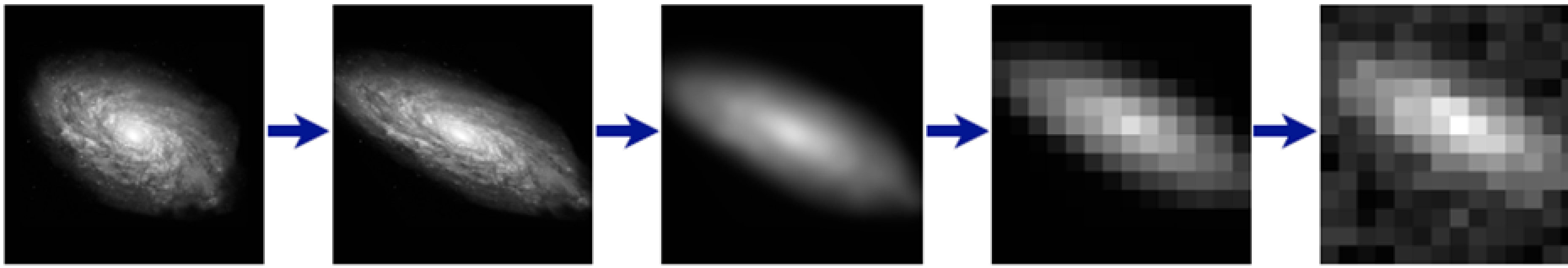
<u>Small effect in the weak regume, ~1%</u>



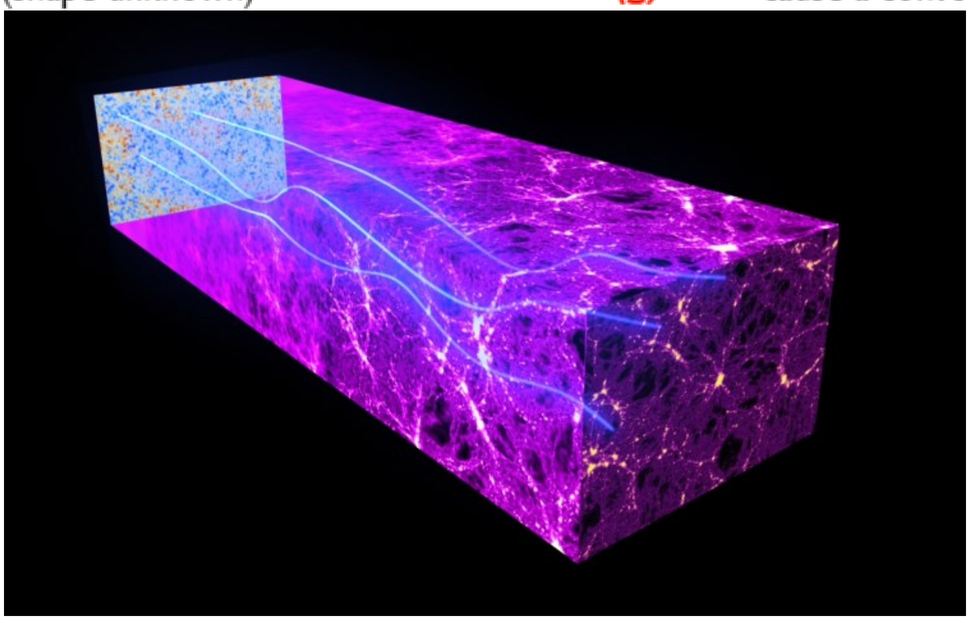
GRAVITATIONAL LENSING

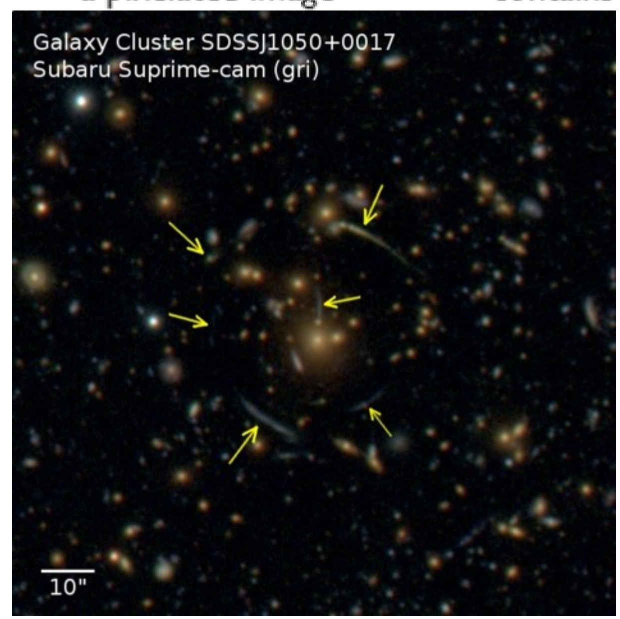
The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:



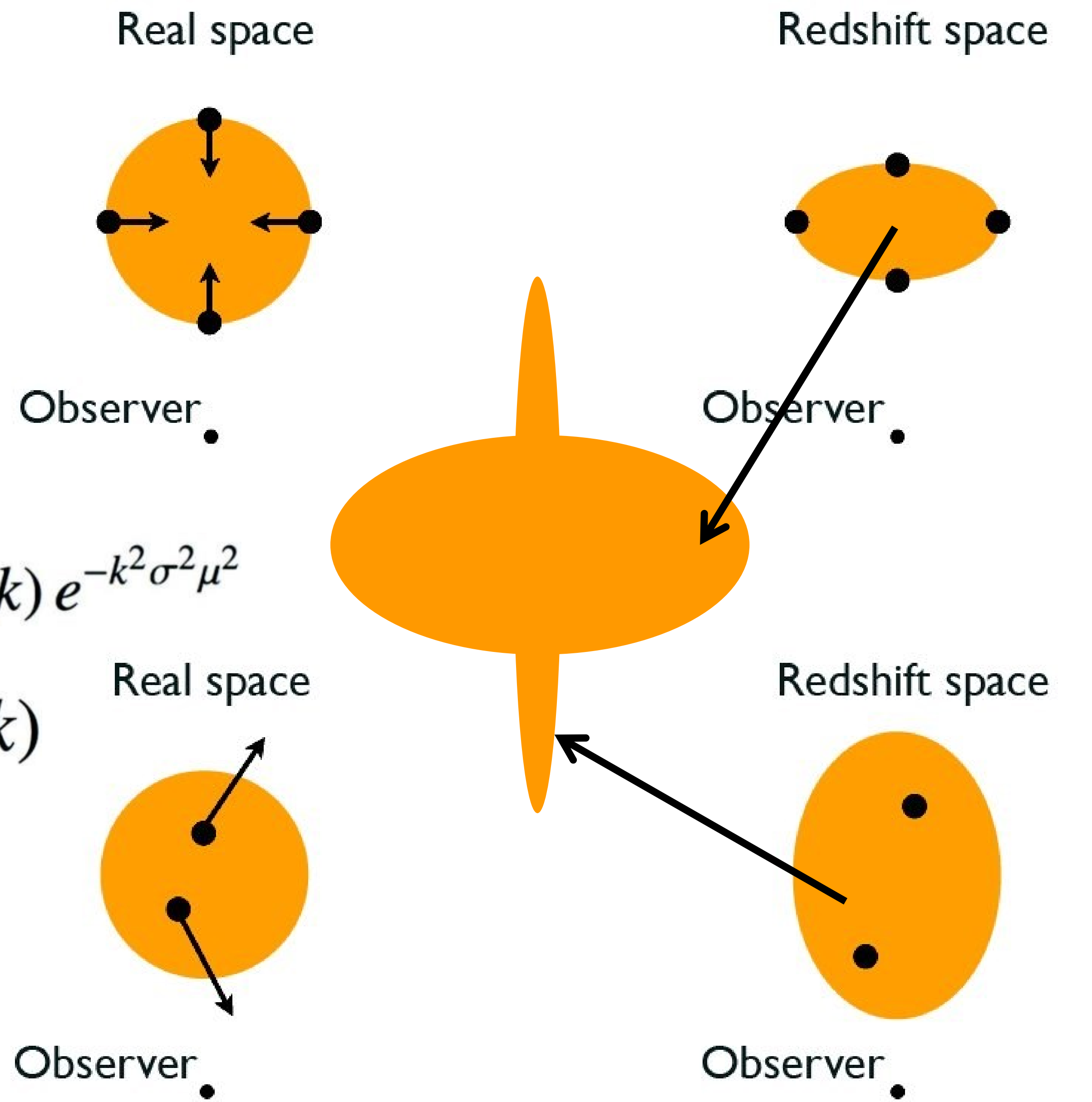
Intrinsic galaxy (shape unknown) → Gravitational lensing causes a ***shear (g)*** → Atmosphere and telescope cause a convolution → Detectors measure a pixelated image → Image also contains noise





REDSHIFT SPACE DISTORTIONS

The presence of masses distorts the shape of structures, since we measure redshift and not the distances

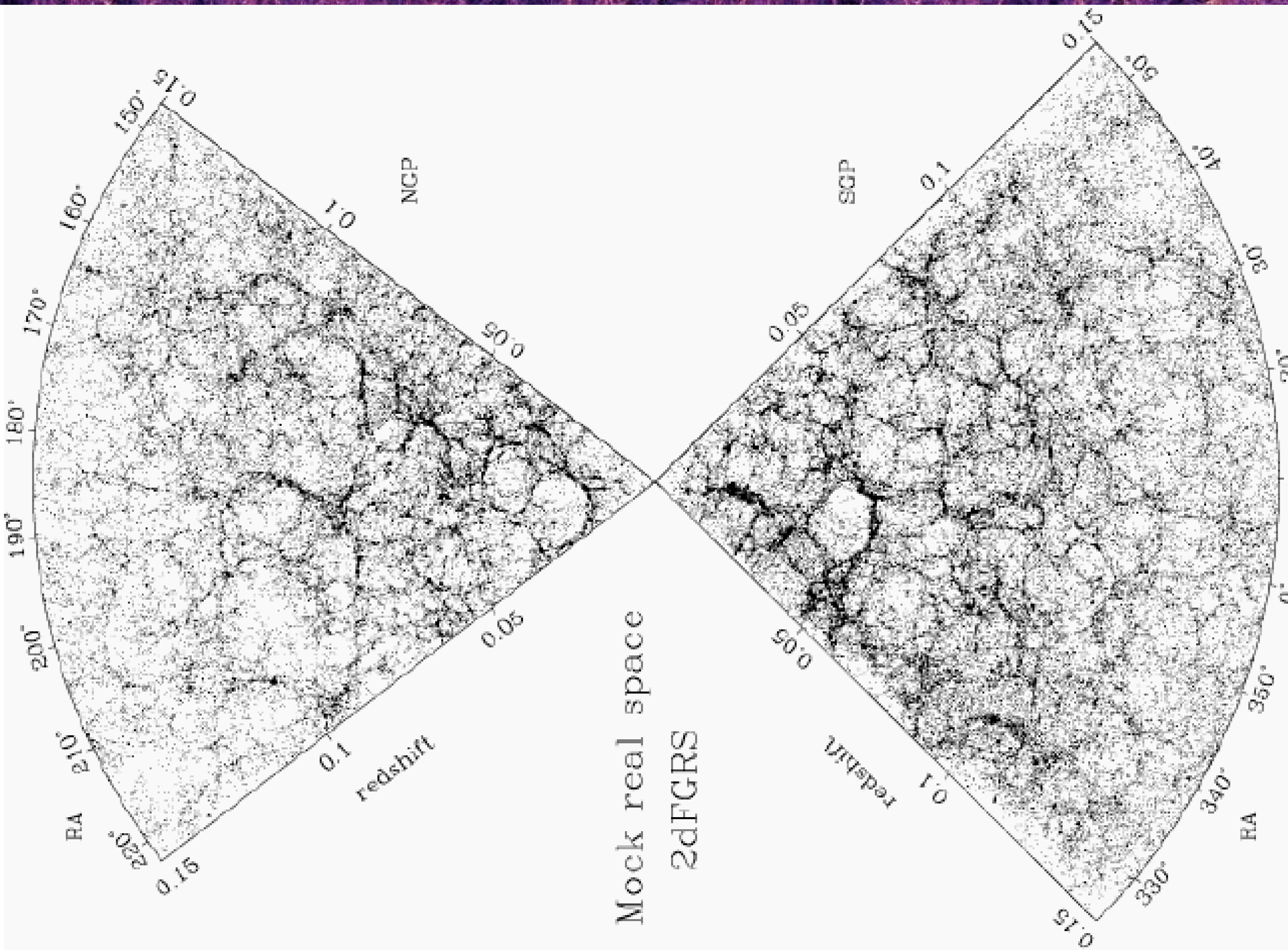


$$P_g^s(k,\mu) = \left(b + f\mu^2\right)^2 P_m^r(k)\, e^{-k^2\sigma^2\mu^2}$$

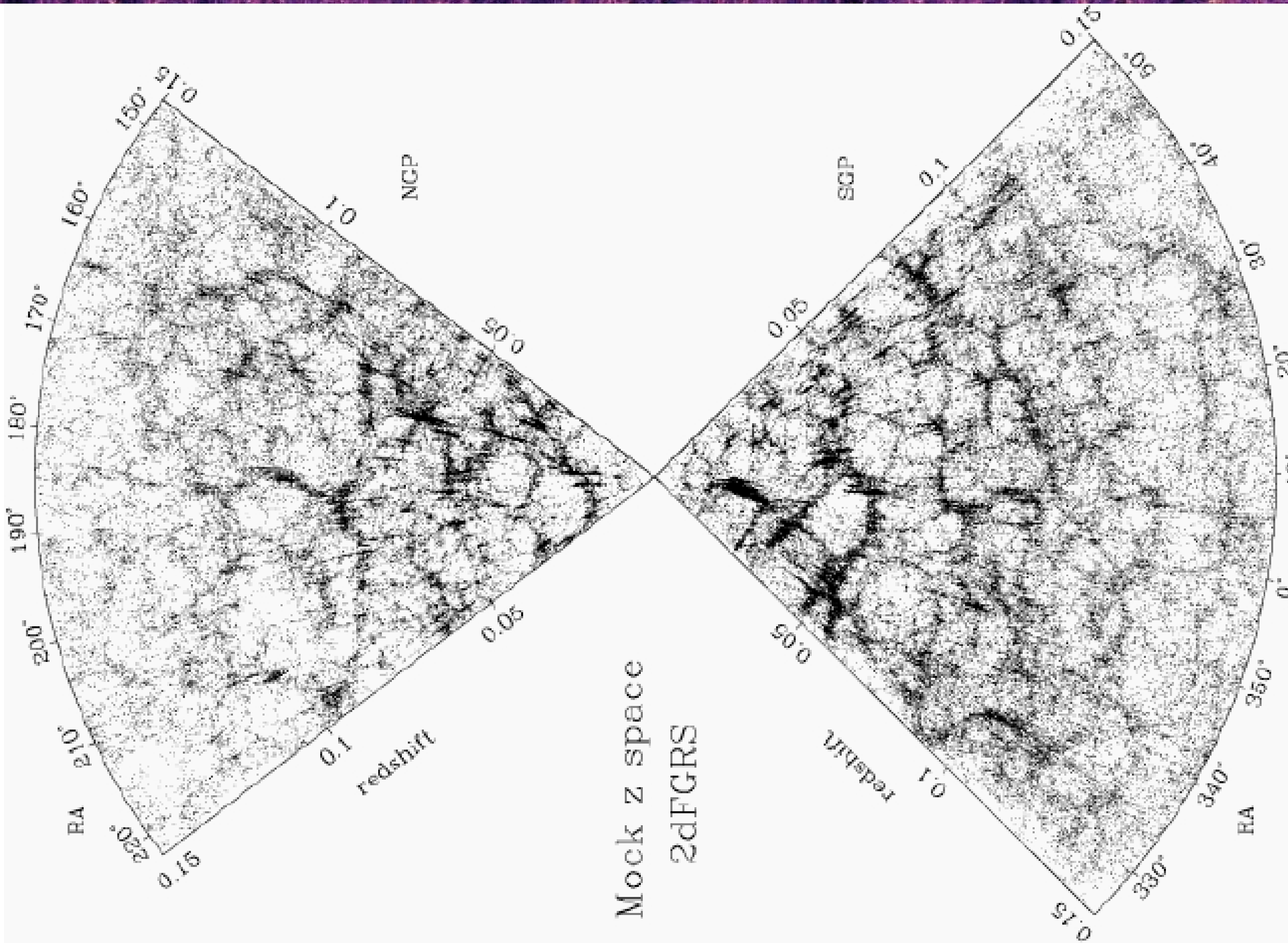
$$\delta_g^s(k) = (b + f\mu_k^2)\delta_m^r(k)$$

$$\mu_k^2 = k_z^2/k^2$$

REDSHIFT SPACE DISTORTIONS



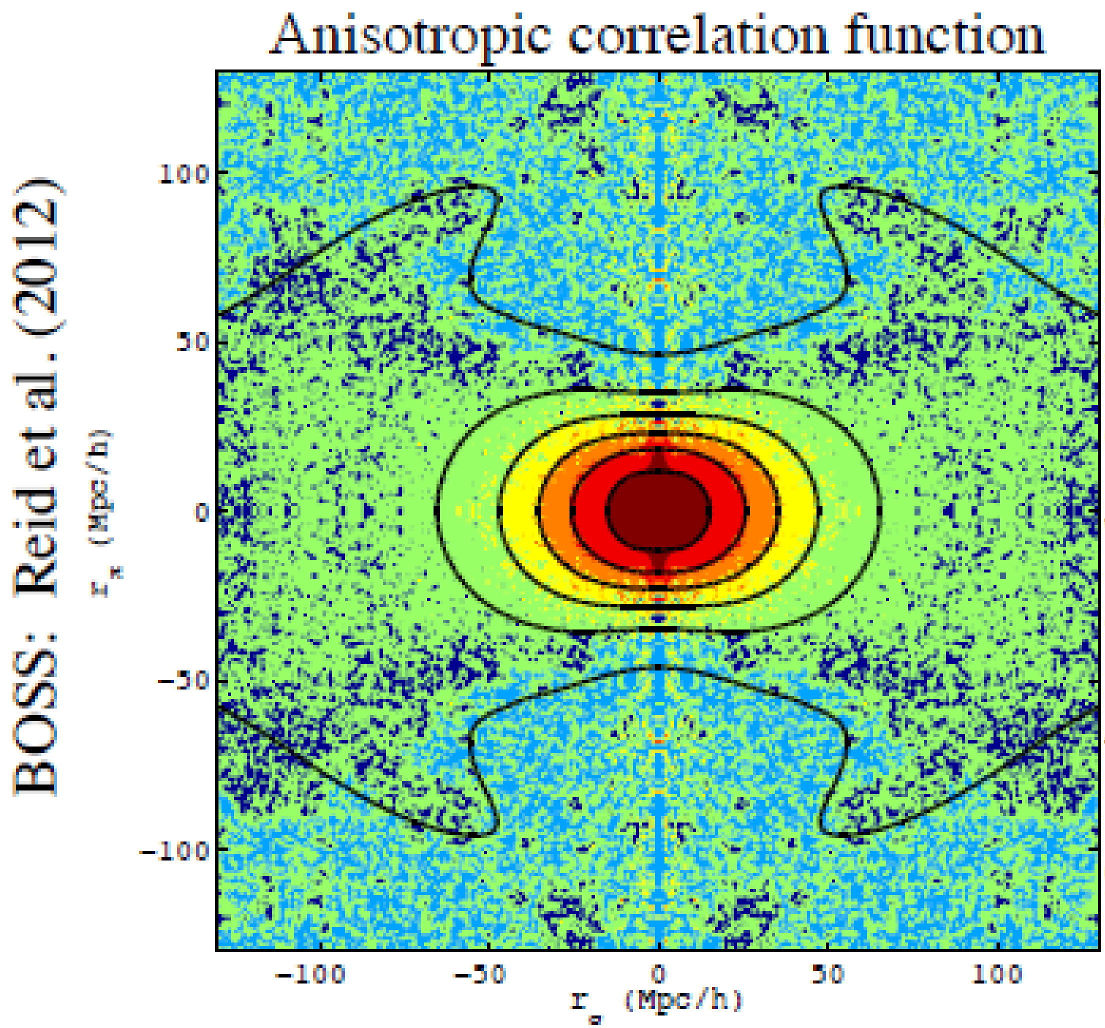
REDSHIFT SPACE DISTORTIONS



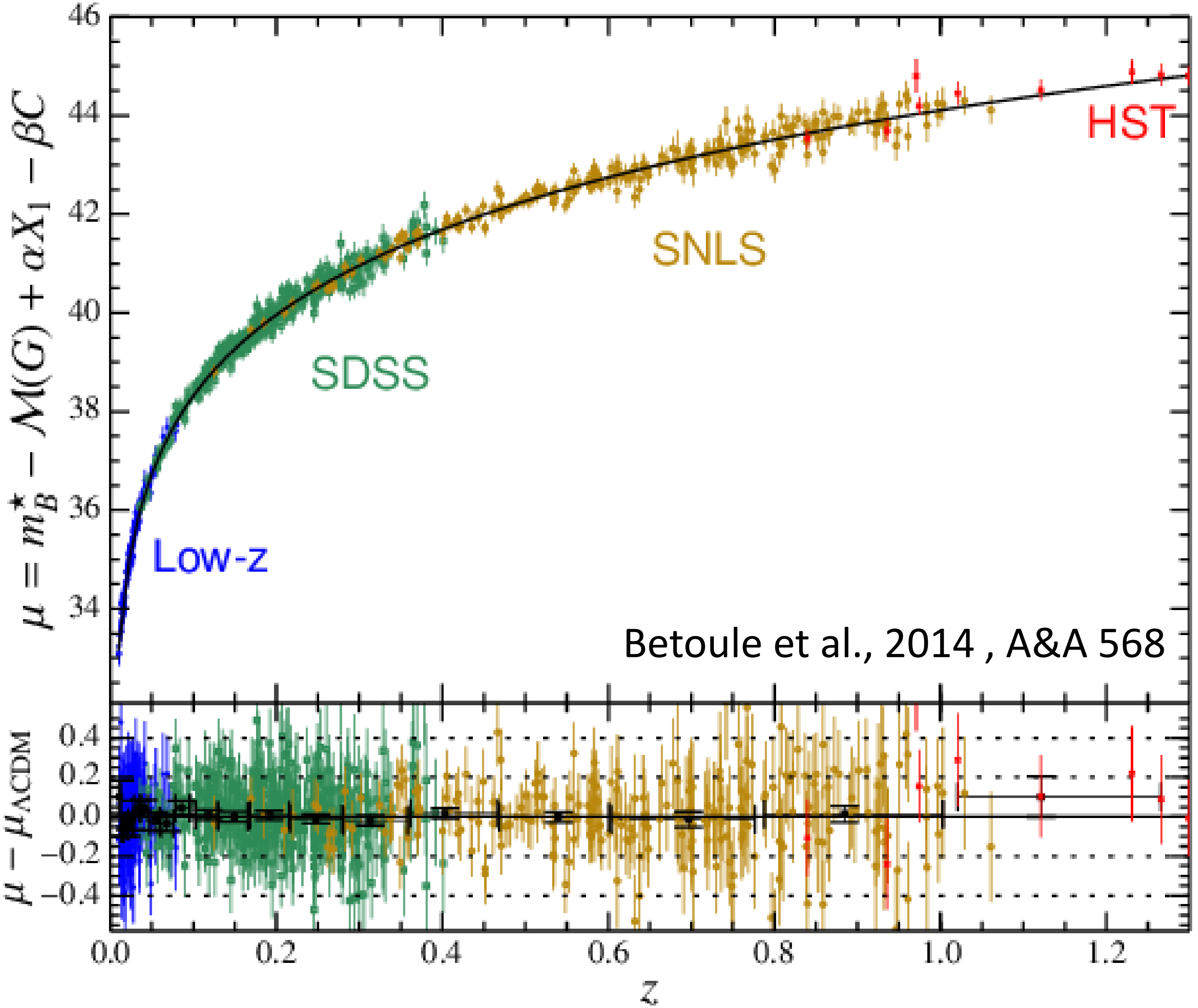
REDSHIFT SPACE DISTORTIONS

3D Correlation function becomes anisotropic

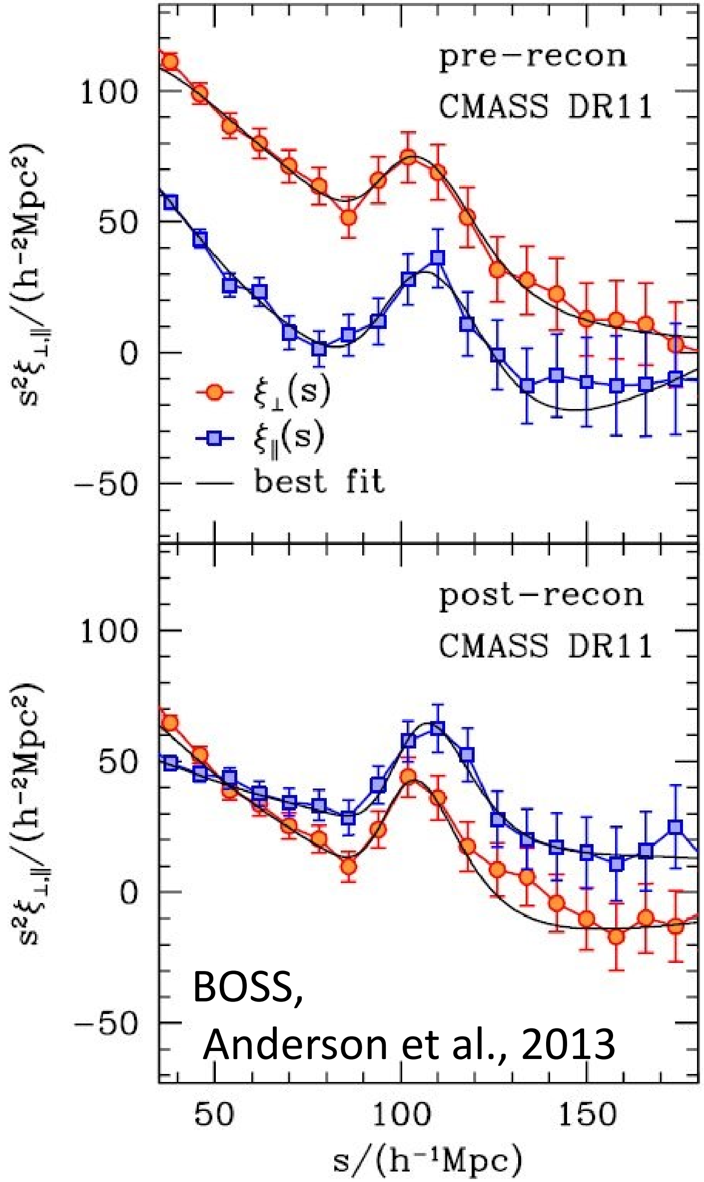
Anisotropy depends on the growth of structure, and therefore, on the properties of gravitational force



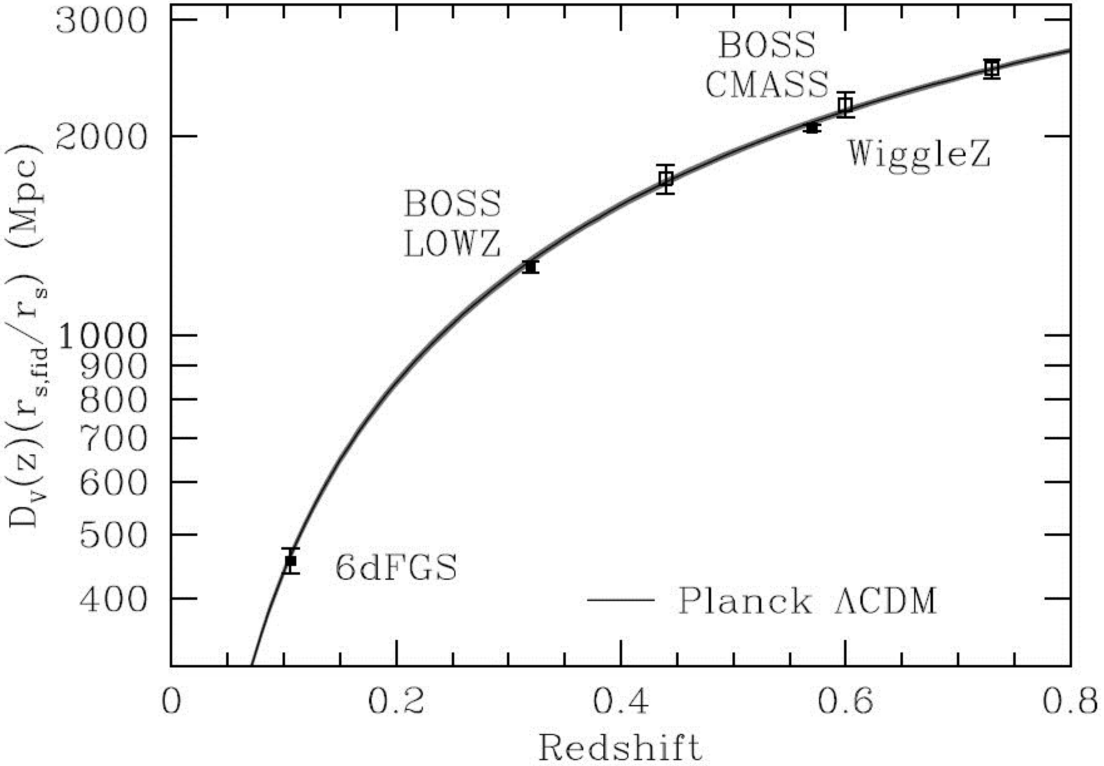
CURRENT SITUATION: SN1a



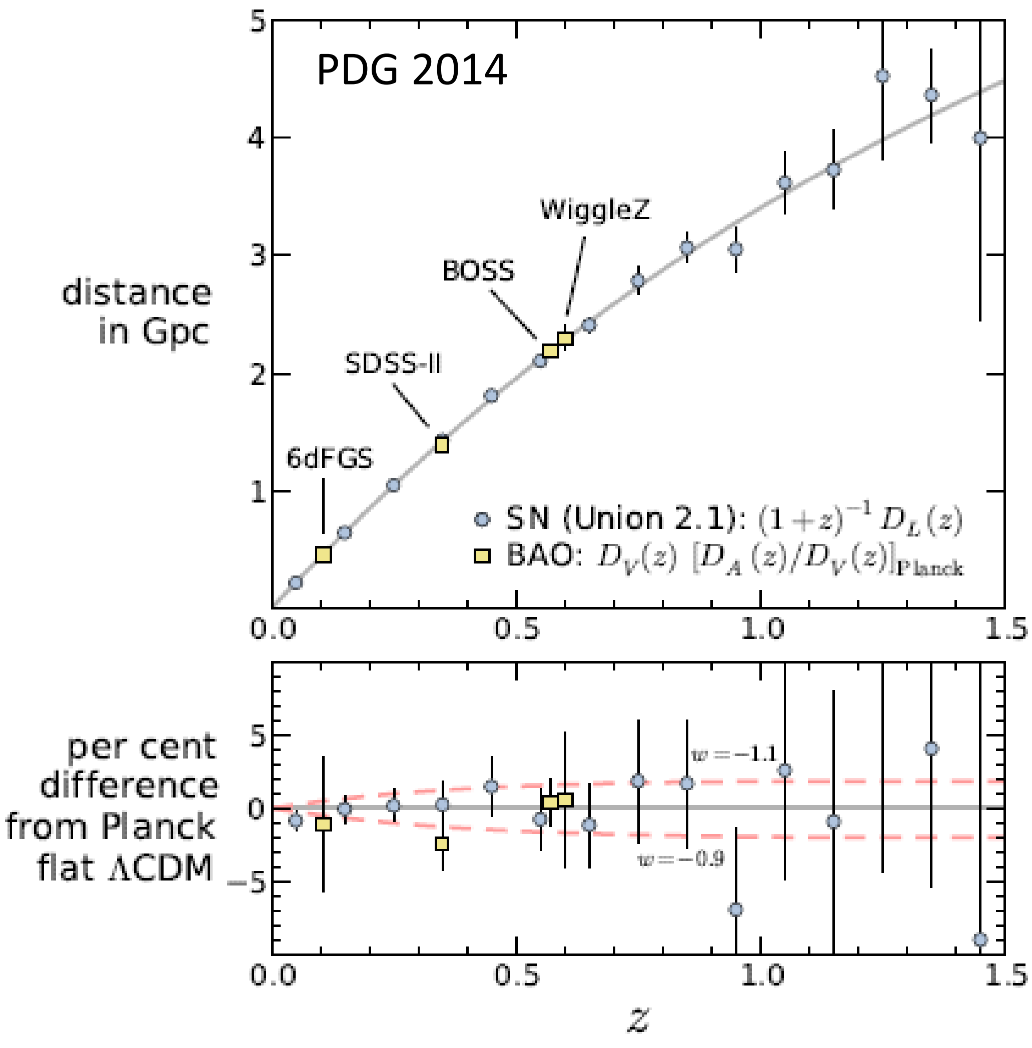
CURRENT SITUATION: BAO

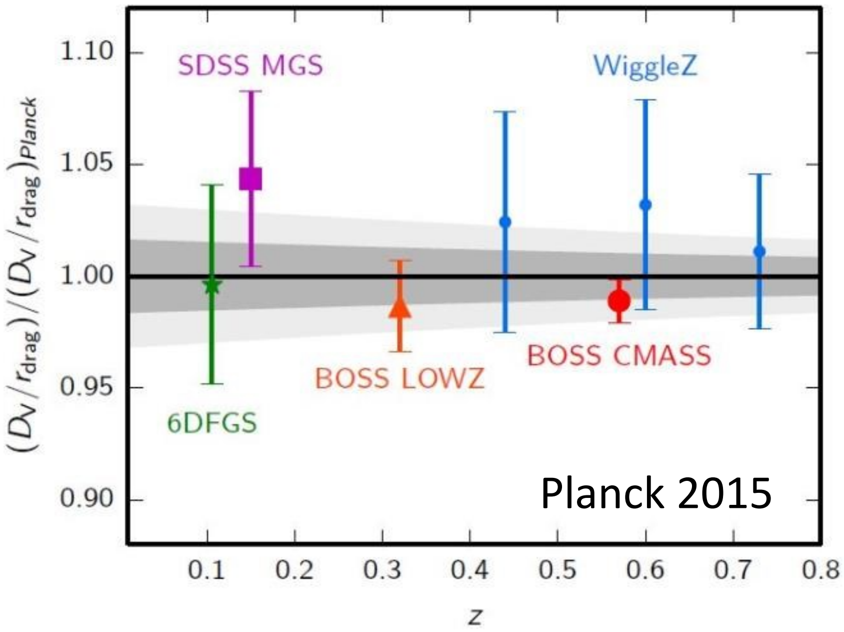


BOSS, Anderson et al., 2013



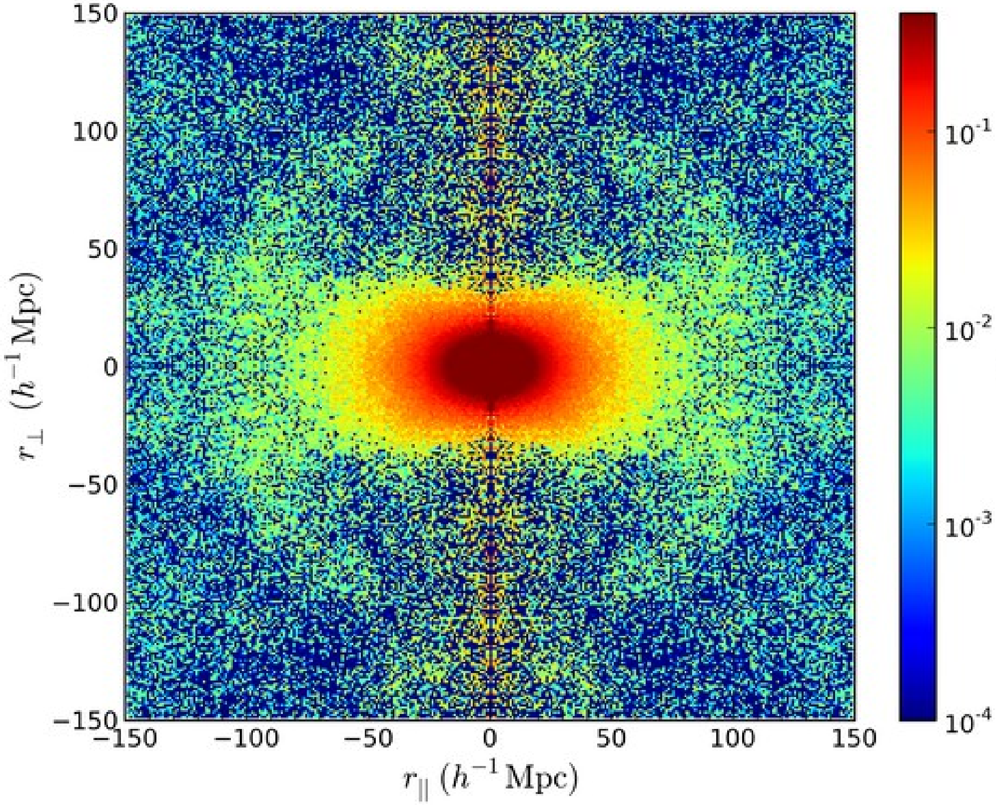
CURRENT SITUATION: Compatibility

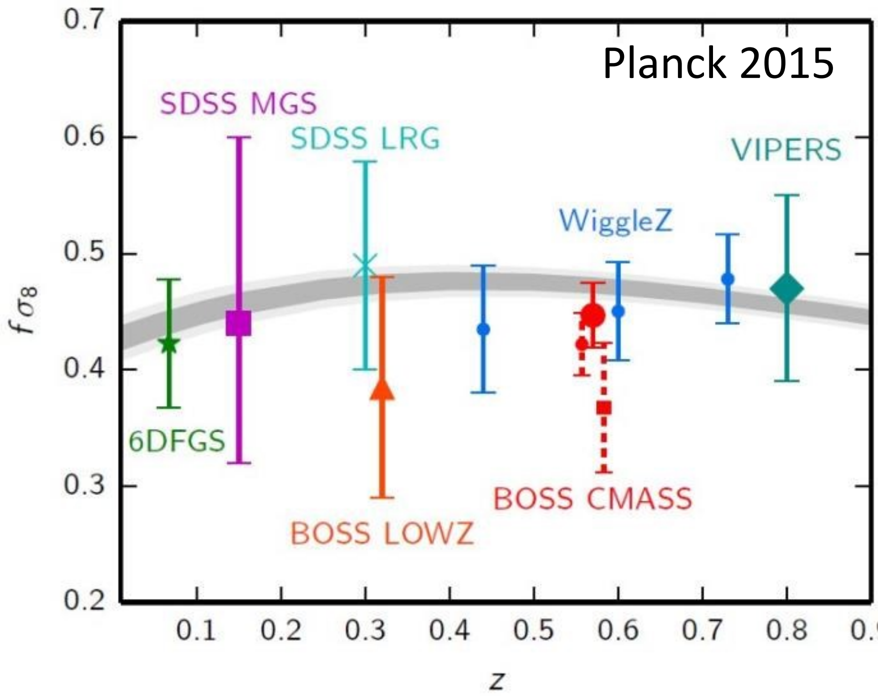




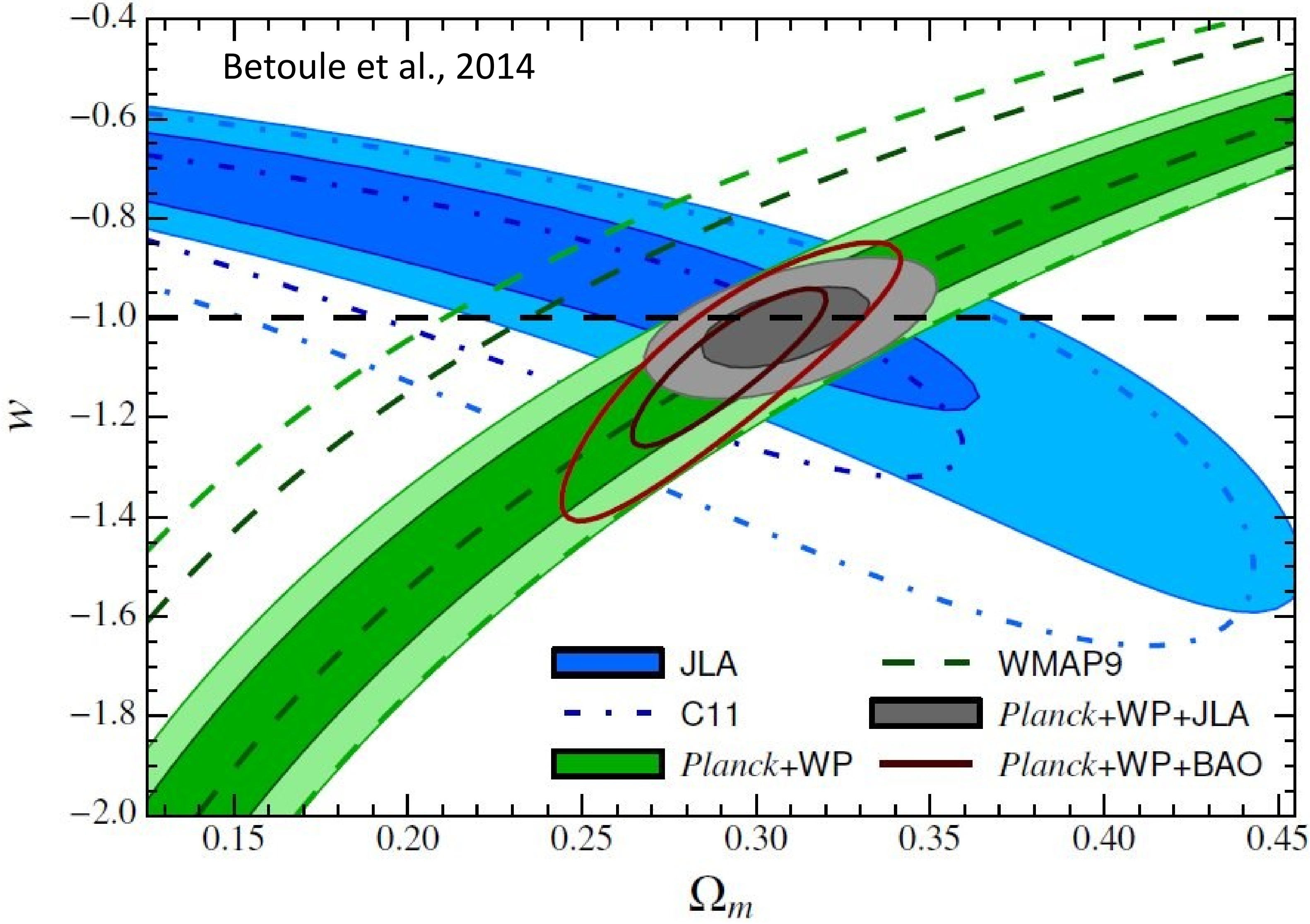
CURRENT SITUATION: RSD

BOSS, Beutler et al., 2013





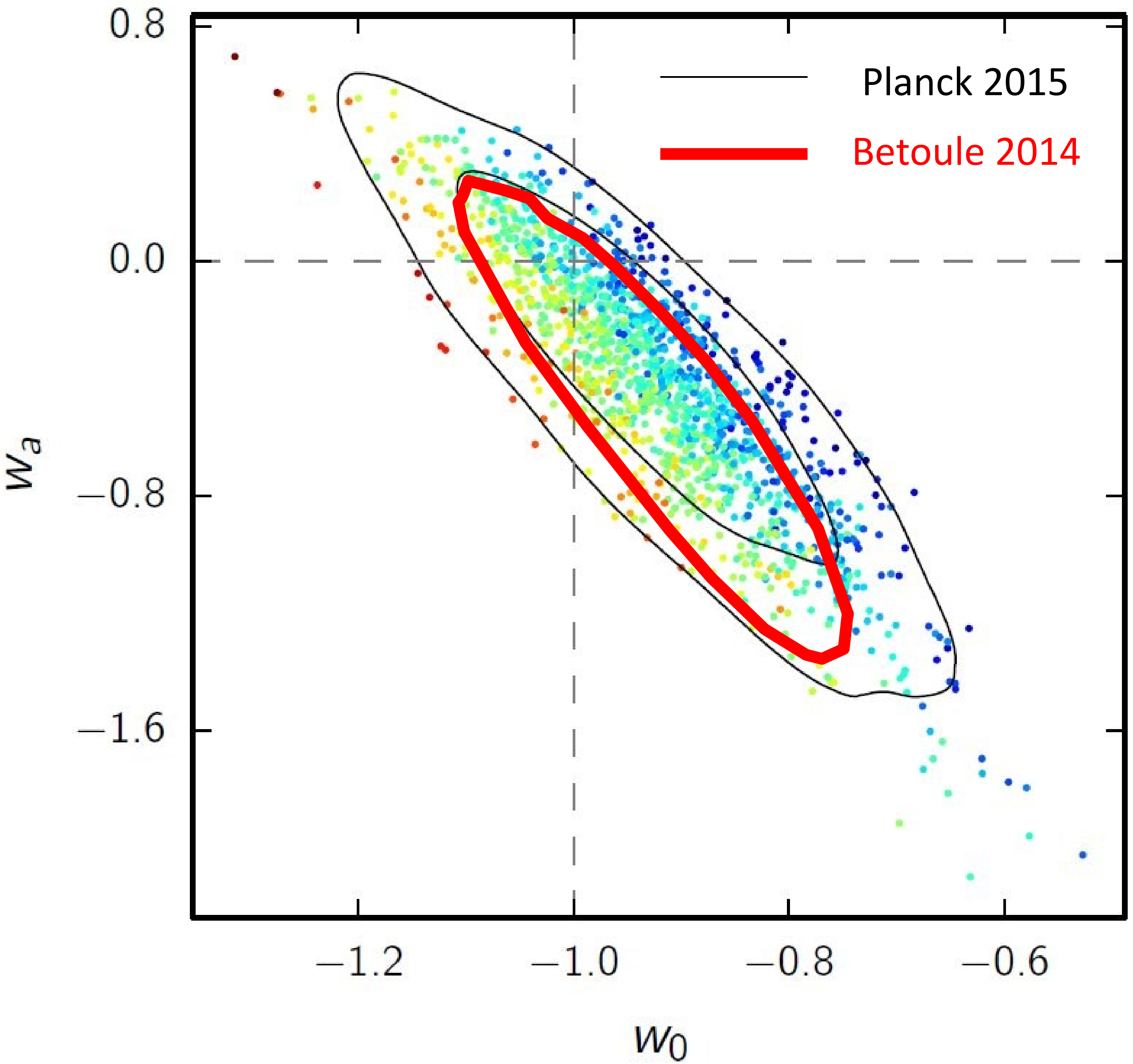
CURRENT SITUATION



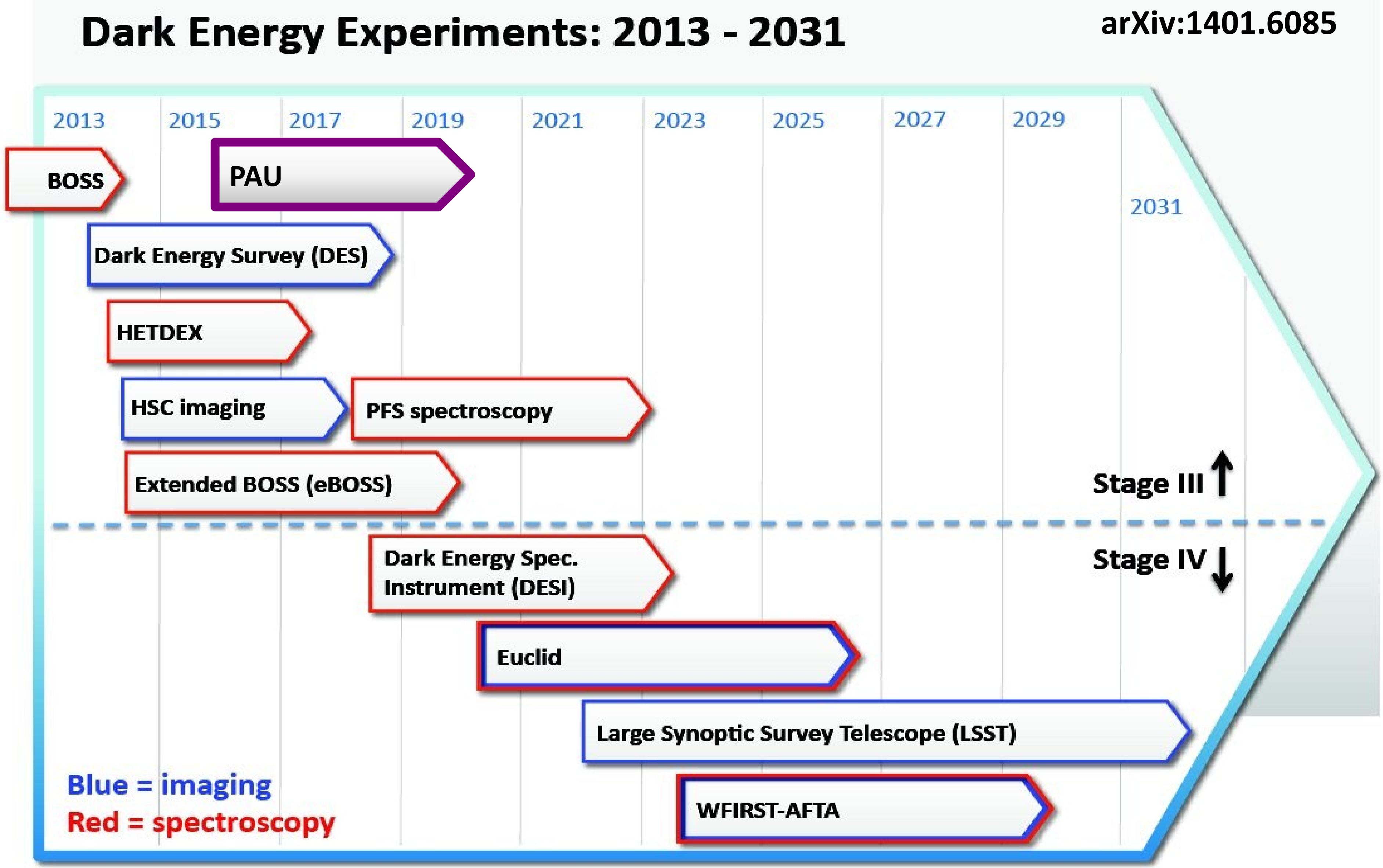
CURRENT SITUATION

More data are needed to obtain better constraints on the redshift evolution of dark energy

Larger and deeper galaxy surveys



CURRENT AND FUTURE PROJECTS



DES & PAU


DES (Dark Energy Survey)
DARK ENERGY
SURVEY


PAU (Physics of the Accelerating universe)
PAU

DES

Two multiband surveys:

5000 deg^2 *grizY* to 24th mag

30 deg^2 repeat (Sne)

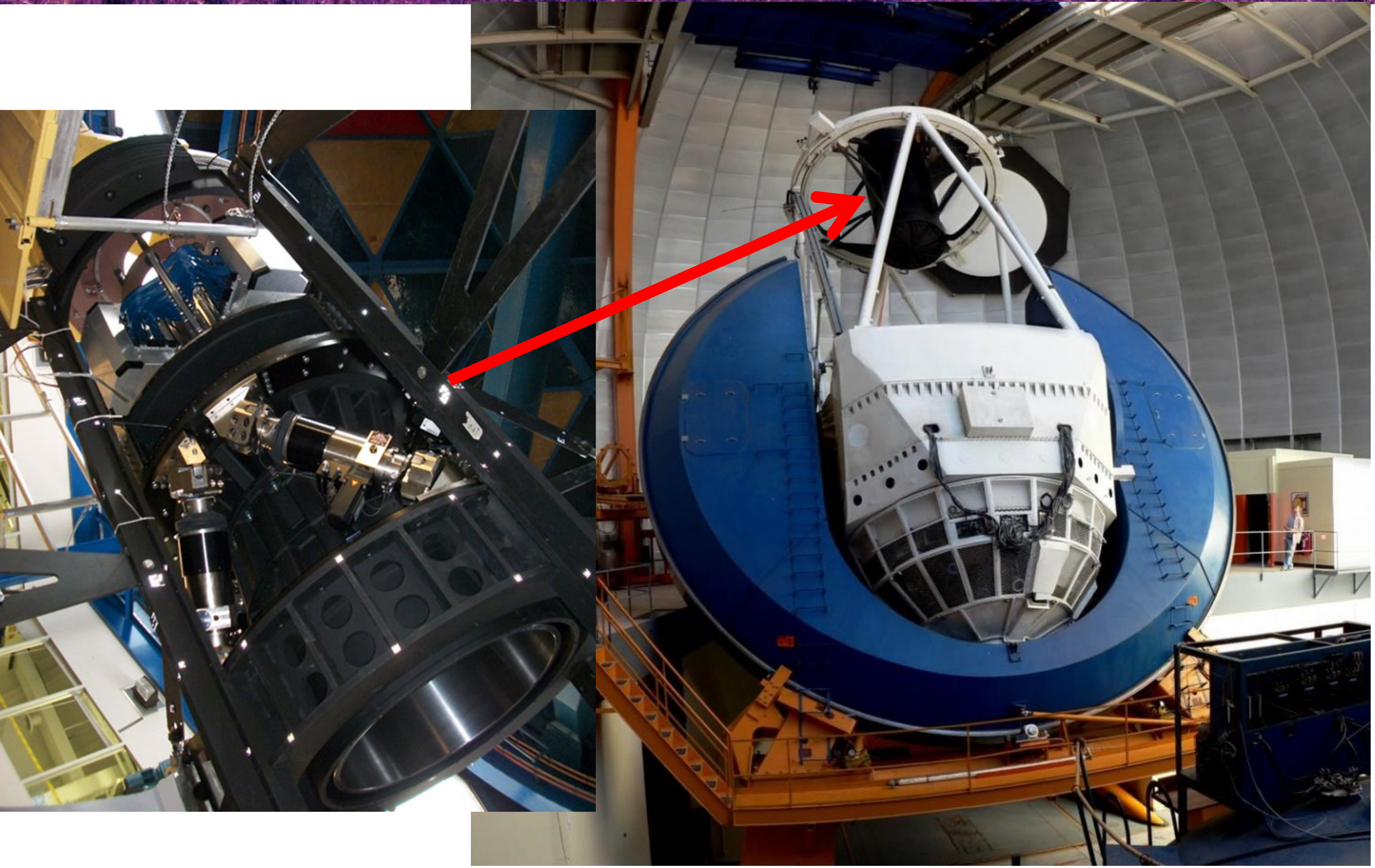
A **new 3 deg^2 FOV camera** (DECam)

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

Survey 2013-2018 (525 nights)

DARK ENERGY SURVEY

DES

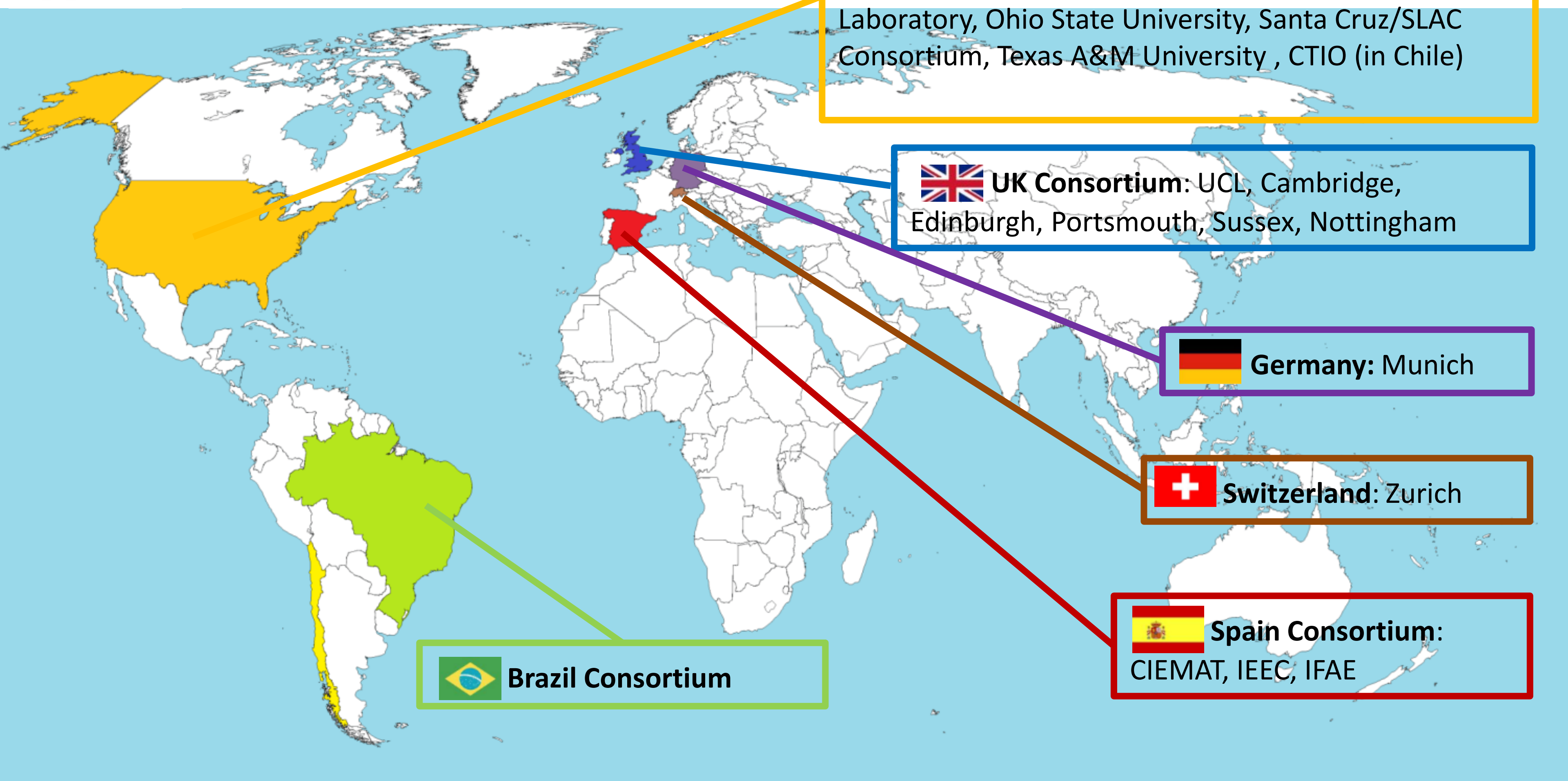


DES

DARK ENERGY SURVEY

~300 scientists from 28 institutions from around the world

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



DES

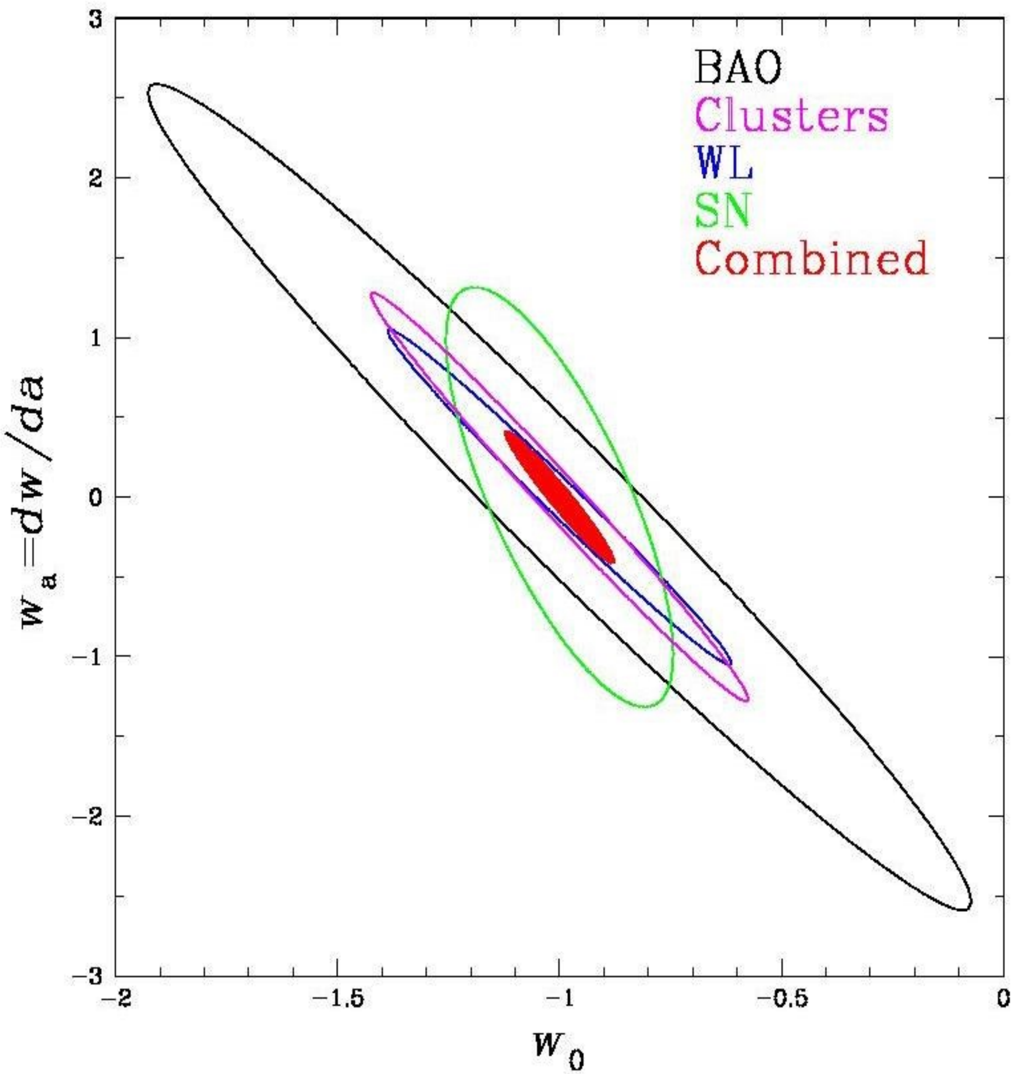
4 Probes of Dark Energy

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

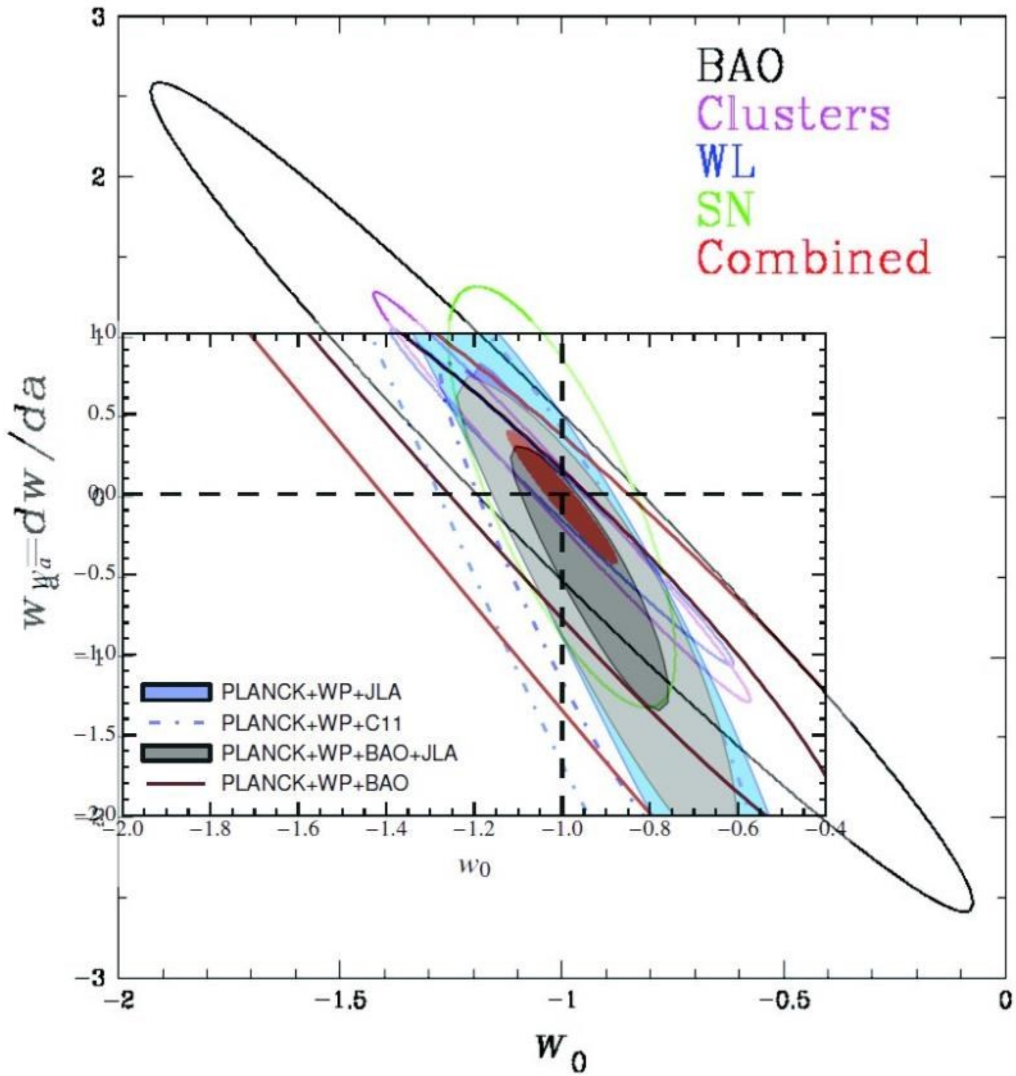
4 Probes of Dark Energy

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

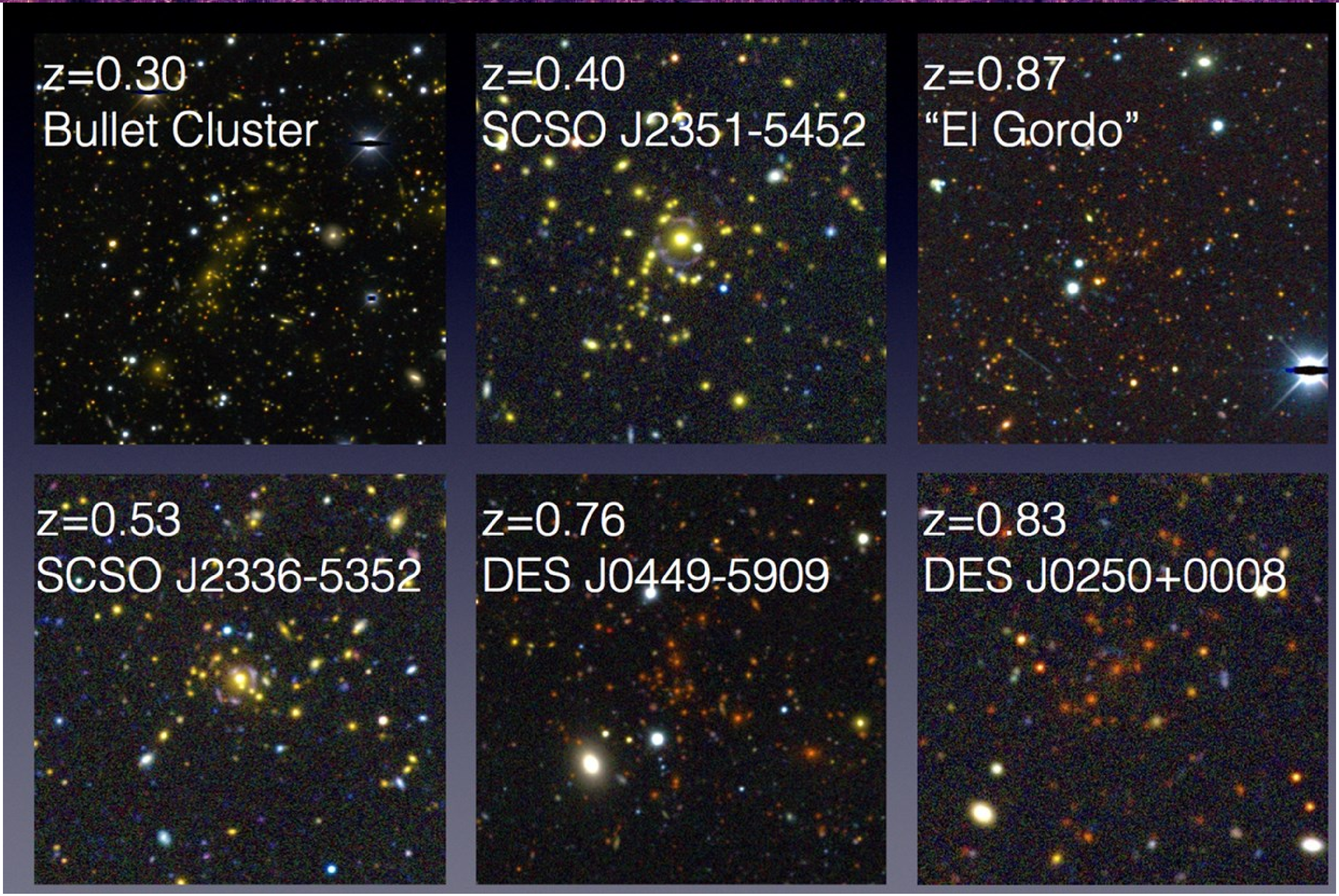
Weak Lensing (dist & struct)
Shape and magnification
measurements of 200 million galaxies

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

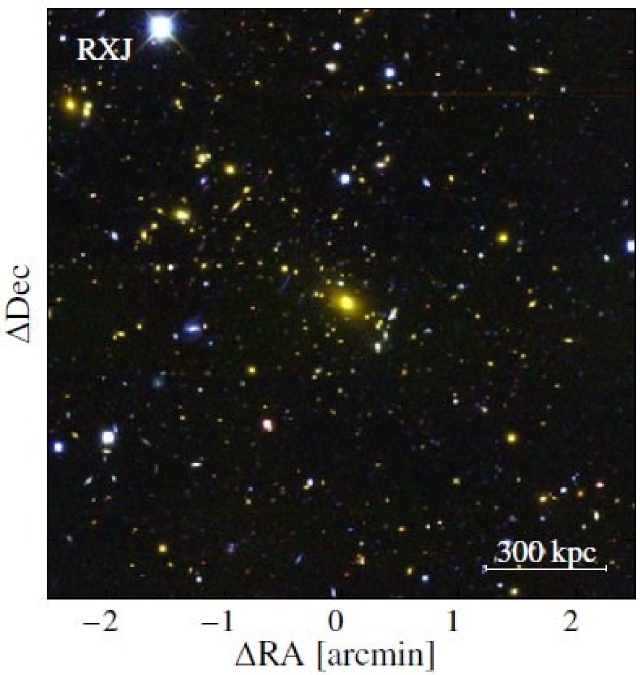
Supernovae (dist)
3500 well-sampled Sne Ia to z~1



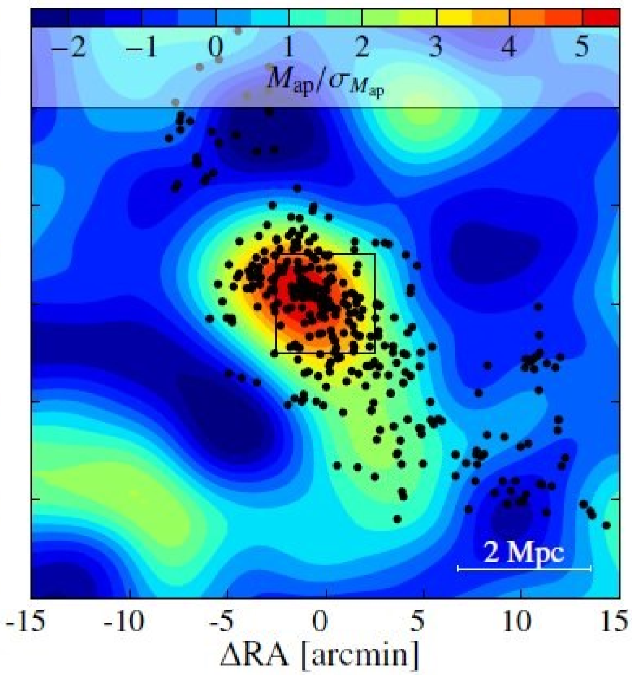
DES: First Results



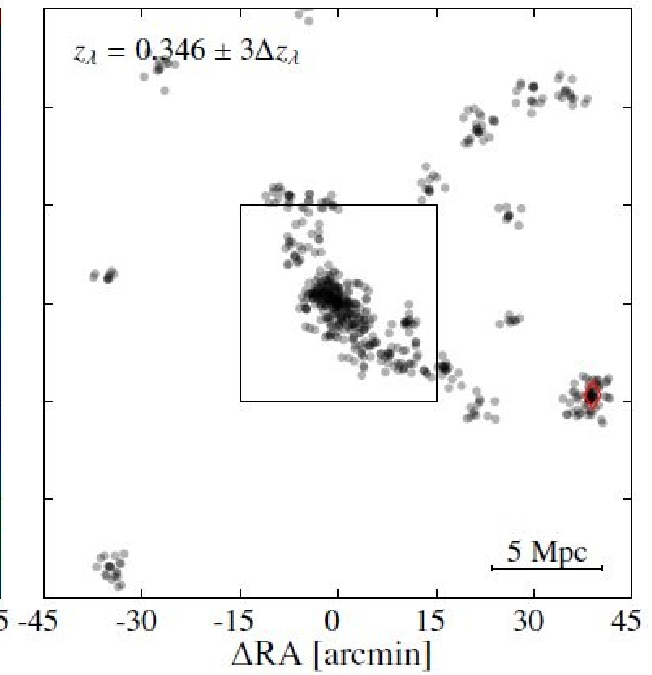
DES: First Results



Multi-color image of the inner 5 arcmin



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



The same galaxies, but for the entire useable field of view of 90 arcmin

PAU

New camera for WHT with 18 CCDs covering a **1 deg diameter field of view**

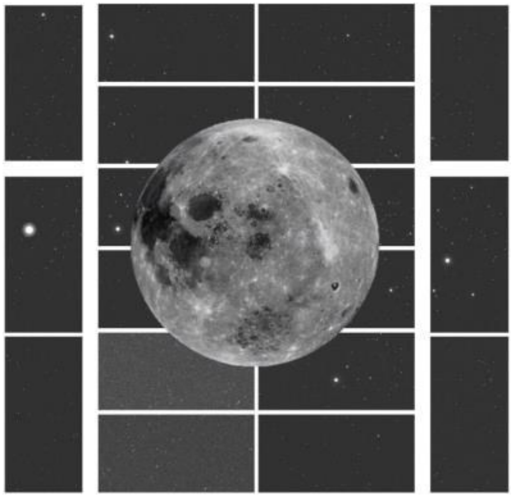
40 Narrow band filters (100 A width) and wide band (u, g. r, i , z, Y) in movable trays

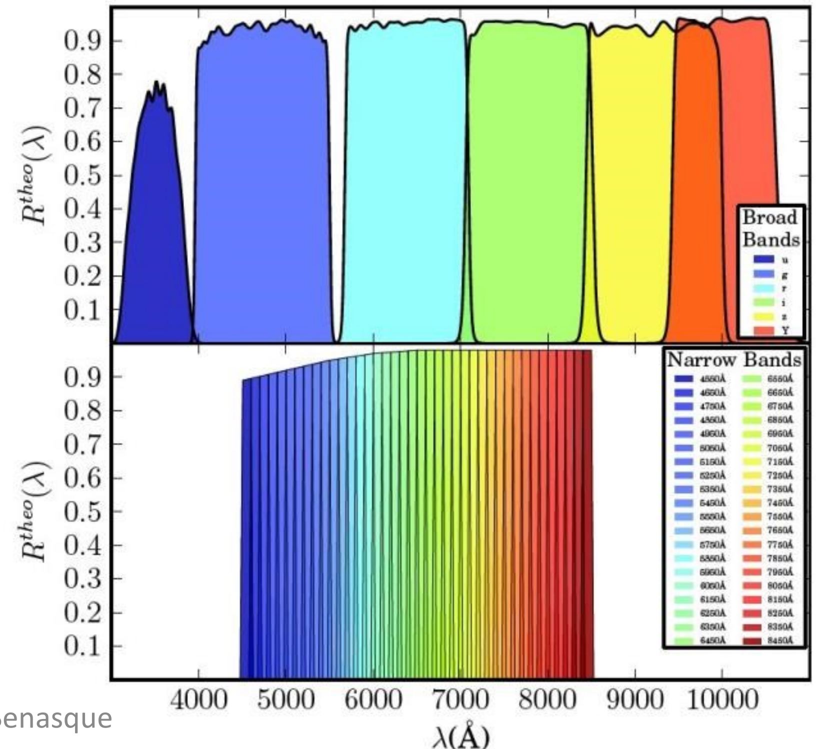
Provide low resolution spectra

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

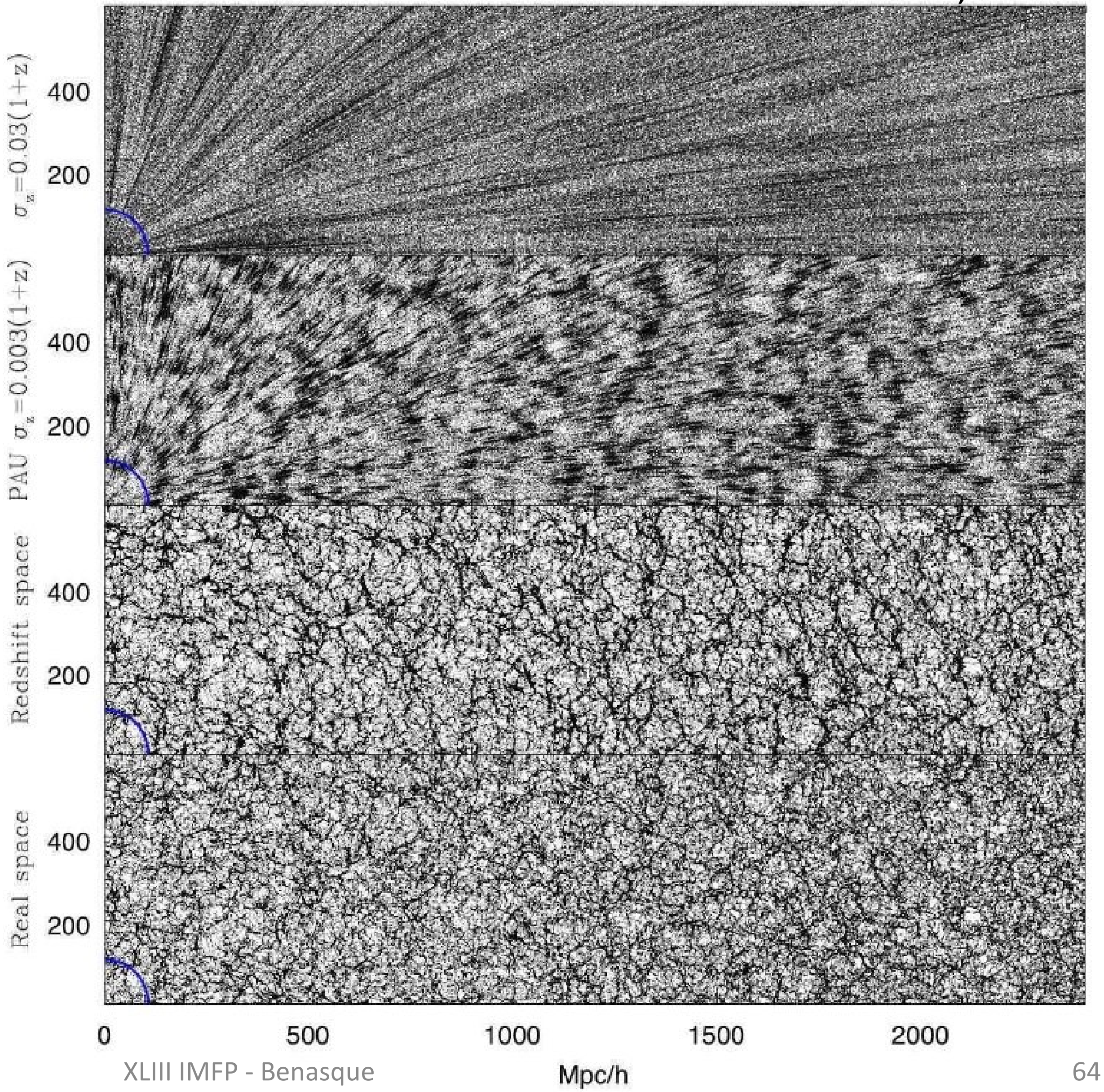
Benitez et al, 2009

z-space, Δz=0.03(1+z) + peculiar velocities (DES)

z-space, Δz=0.003(1+z) + peculiar velocities (PAU)

z-space, perfect resolution + peculiar velocities

Real space



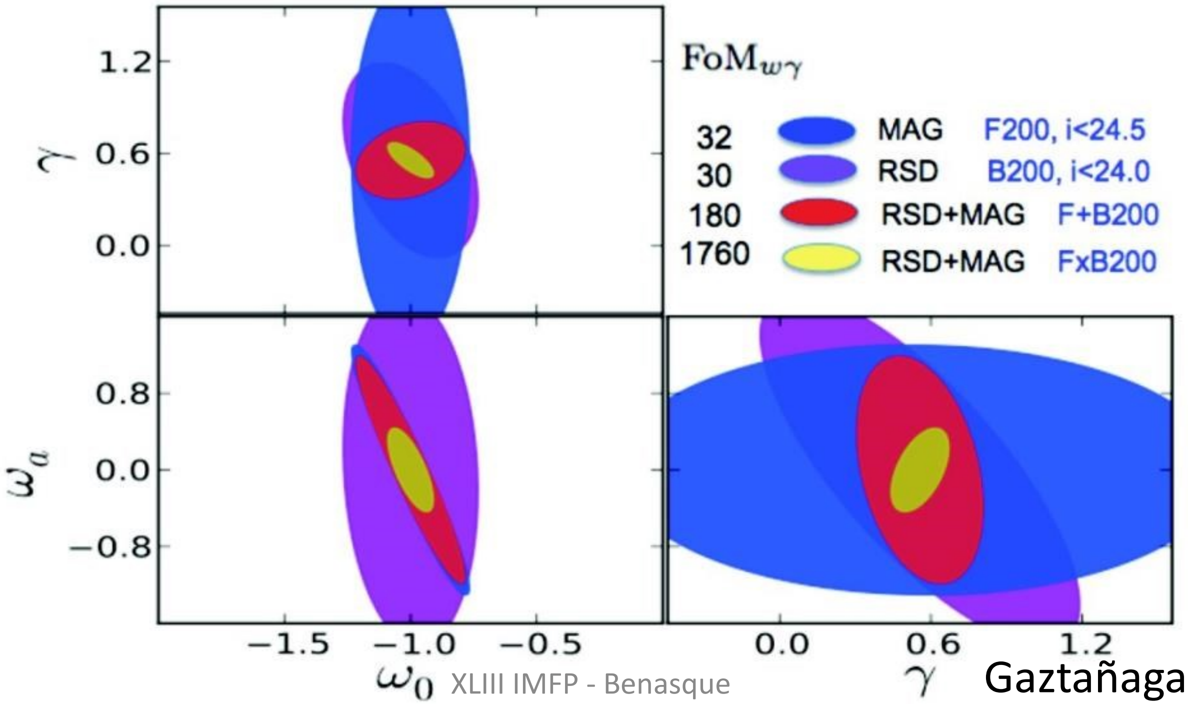
PAU:Science

The survey strategy produces 2 samples:

- "Spectroscopic" sample: Good photoz with narrow filters z≤1
- "Photometric" sample: Photoz with wide filters to z~1.4

Main science case:

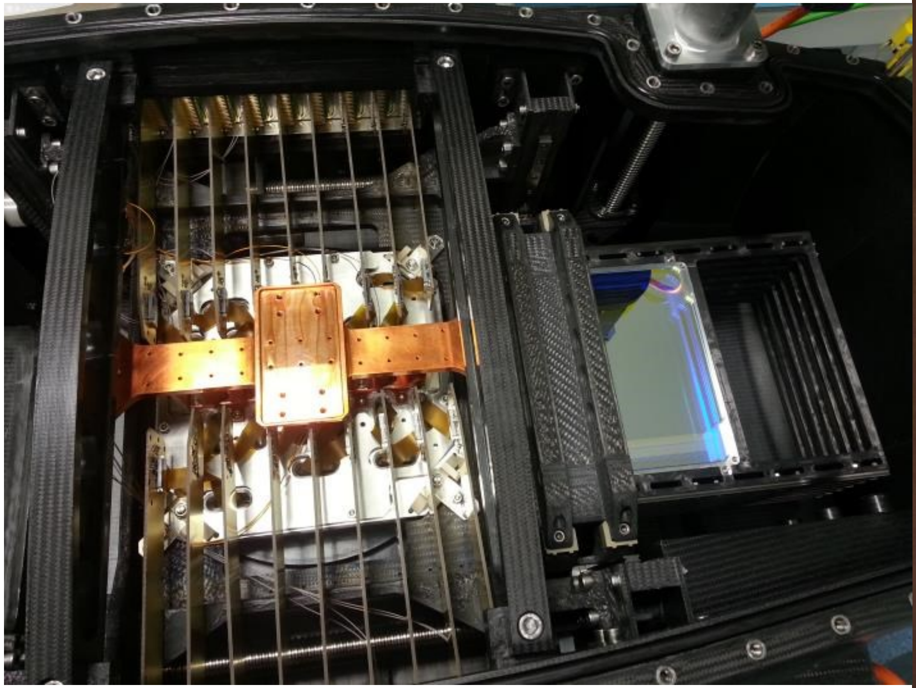
- Near sample for redshift space distortions
- Far sample for weak lensing magnification
- Combine both in the same sample→ Unique advantage of PAU

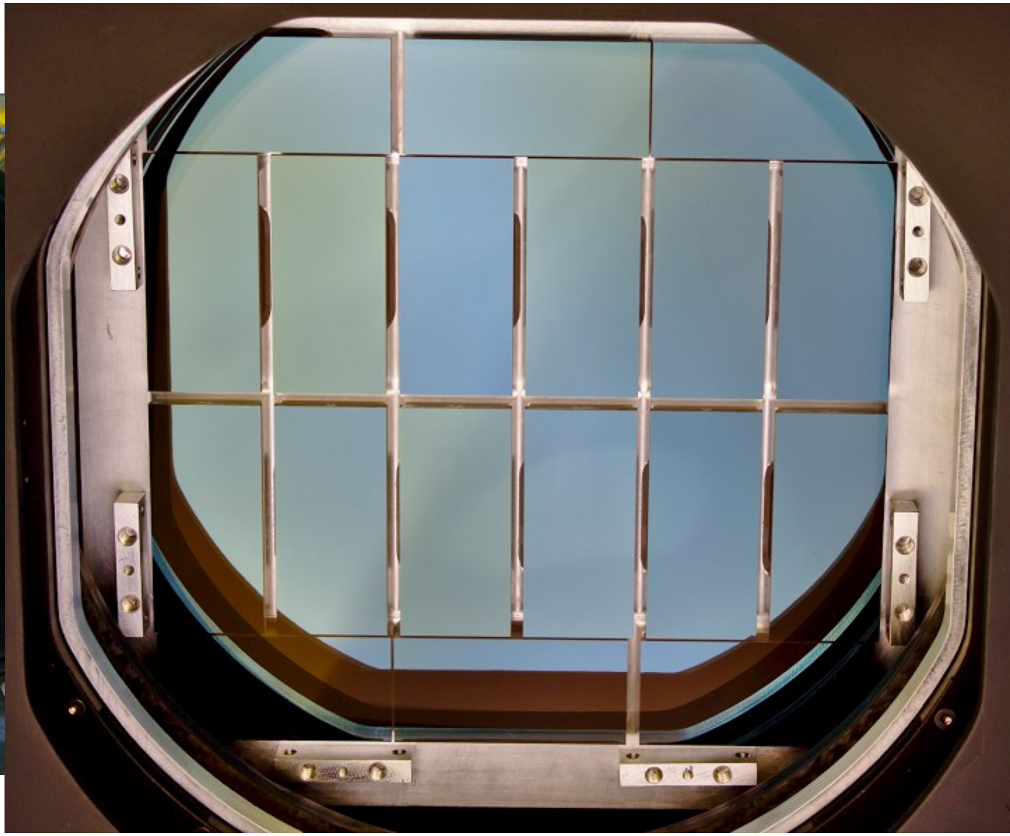


Gaztañaga et al, 2012

PAU:Status

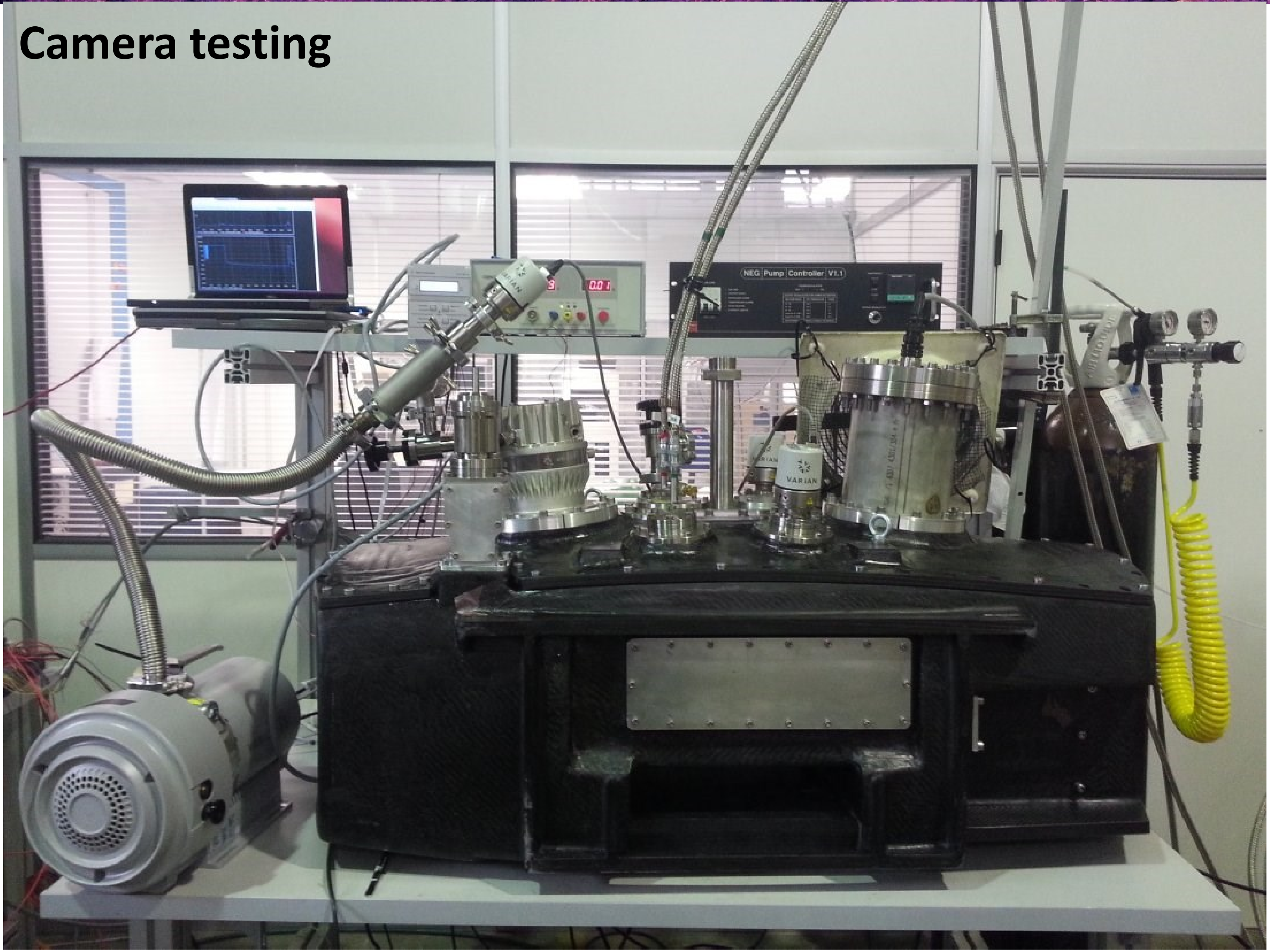
The construction of the PAU camera is basically finished
Data management system is written
PAUCam will be installed at the WHT on summer (june 2015)
Commissioning and science verification in 2015





PAU:Status

Camera testing



CONCLUSIONS

The accelerating expansion of the Universe is a firmly established observatin, but its physicsl origin remains a deep mystery

All current data are consistent with ΛCDM (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