Observational Cosmology and Astroparticles II:

DARK ENERGY

Eusebio Sánchez – CIEMAT

SCHOOL ON HIGH ENERGY PHYSICS

"TALLER DE ALTAS ENERGÍAS" TAE 2012

Outline

1.- Introduction

Standard Model of Cosmology

Redshift

Distances

Growth of structure

2.- Cosmic Microwave background

Discovery

COBE

WMAP

Power Spectrum

3.-Dark Energy

What do we know about dark energy?

Observational Probes

How to measure

4.- Current Situation: Cosmological Parameters

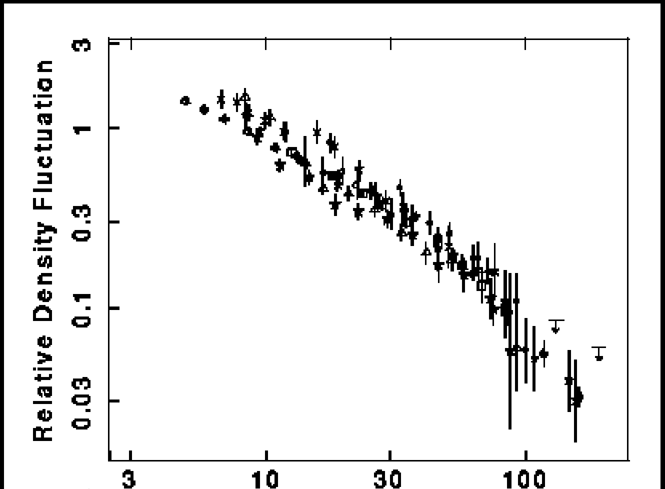
5.- Summary

Introduction

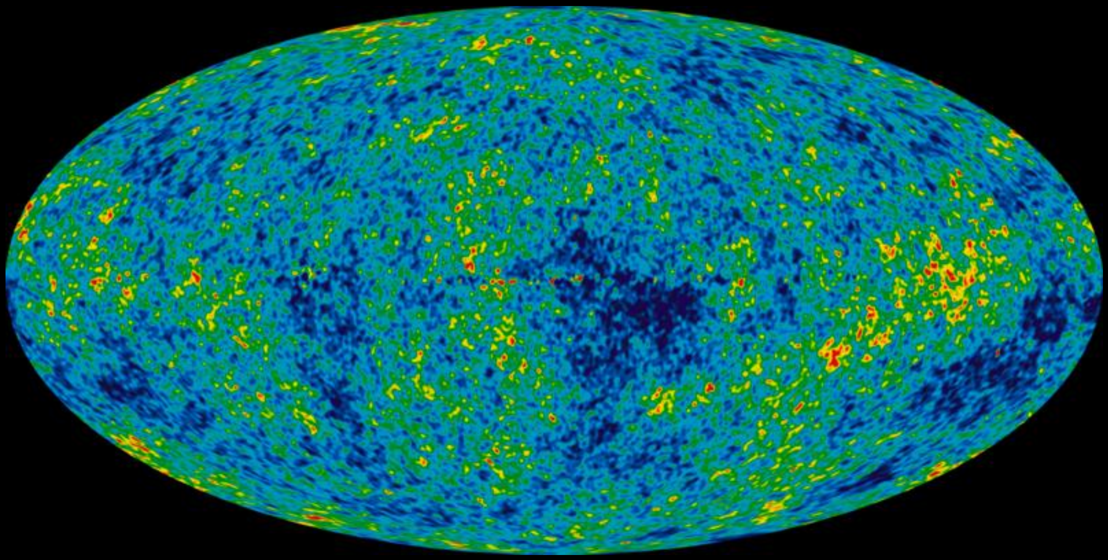
The current standard model of cosmology, LCDM, is based on

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

The cosmological principle :
The universe is HOMOGENEOUS and ISOTROPIC



Peacock & Dodds (1994)



Cosmological principle → Universal time coordinate

Galaxies at rest in **COMOVING COORDINATES**

Their collective motion is due to the expansion of space, described by the scale factor a(t); $a_0=1$ (now)

The curvature has to be constant everywhere

This leads to the LFRW (Lemaitre-Friedmann-Robertson-Walker) metric for the universe:

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

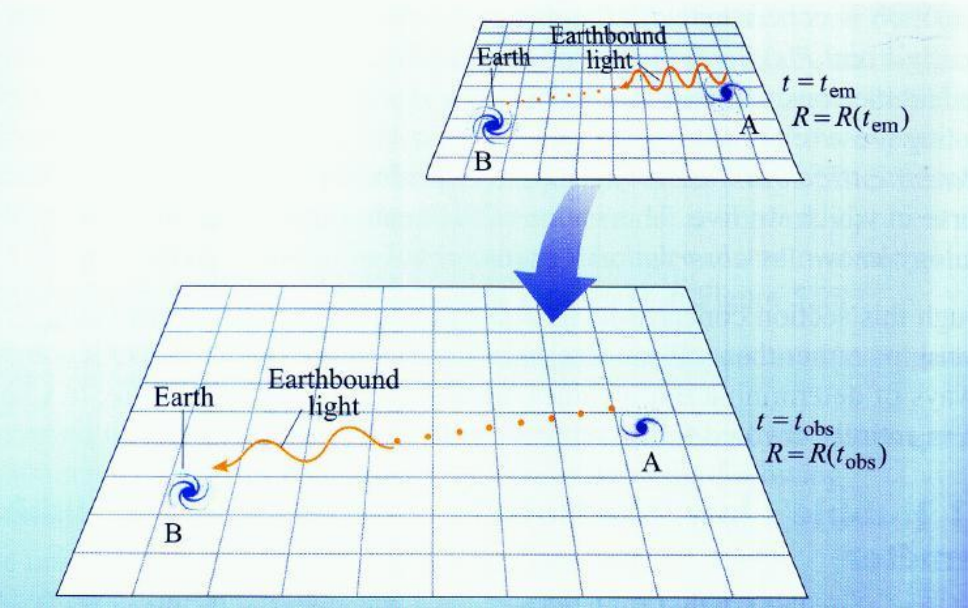
$$S_{+1}(r) = R\sin\left(r/R\right)$$

$$S_0(r) = r$$

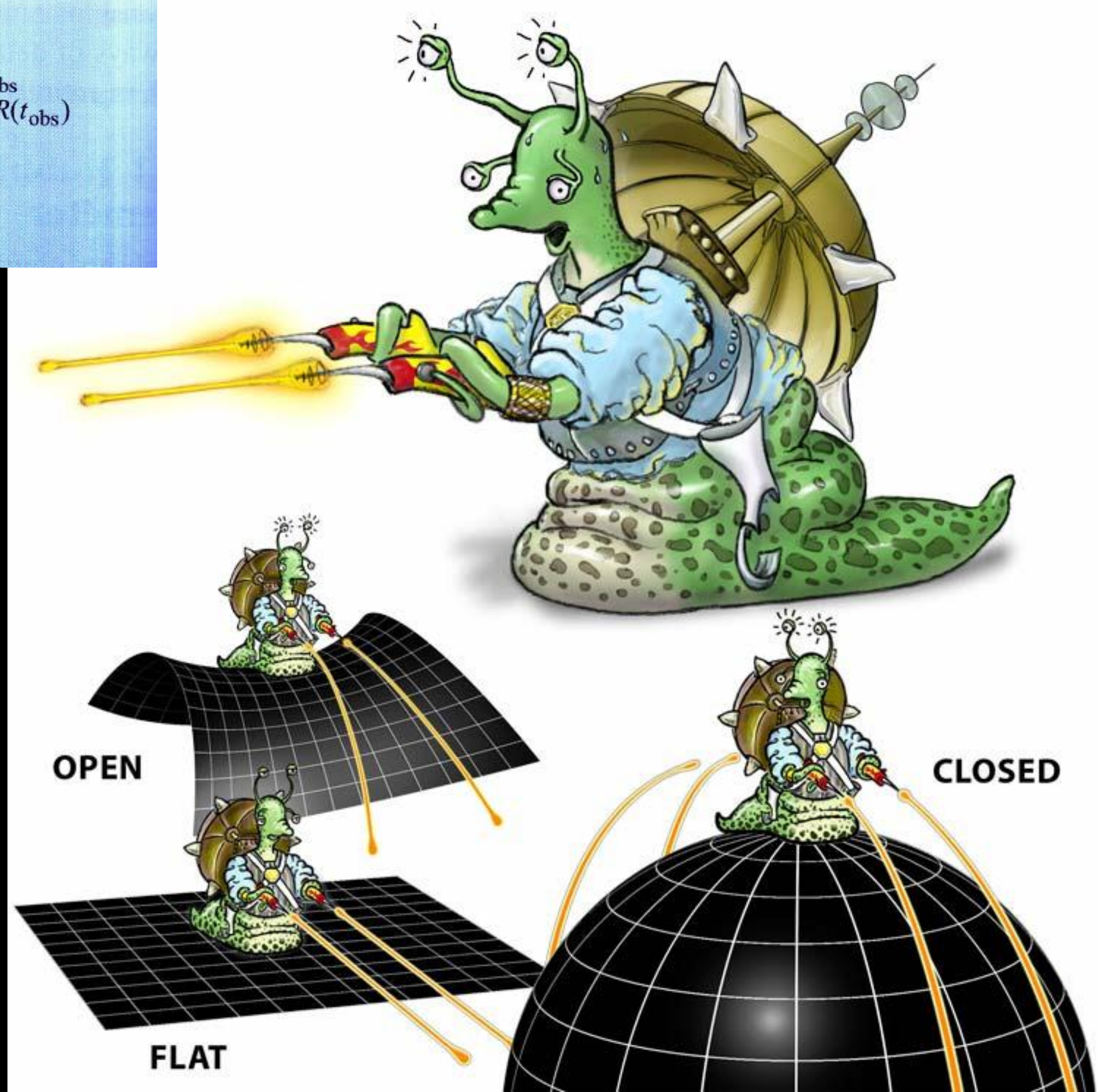
$$S_{-1}(r) = R\sinh\left(r/R\right)$$

a: scale factor of the universe
R: Radius of curvature (constant)
t: proper time
r: comoving distance

3 possible geometries for the LFRW metric



LFRW GEOMETRIES



COMOVING COORDINATES

Comoving coordinates do expand with the universe

E. Sánchez

Introducing the LFRW metric into the Einstein´s field equations of GR, we obtain the Friedmann equations:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{R^2 a^2}$$

G: Newton´s constant

ρ: energy density

p: pressure

We need to specify a equation of state for each component of the universe to solve for a(t).

The universe is filled with a homogeneus and isotropic fluid

Ideal fluid ⟹ T_{mn} = diag(-ρ,p,p,p)

Barotropic fluids, p=wρ

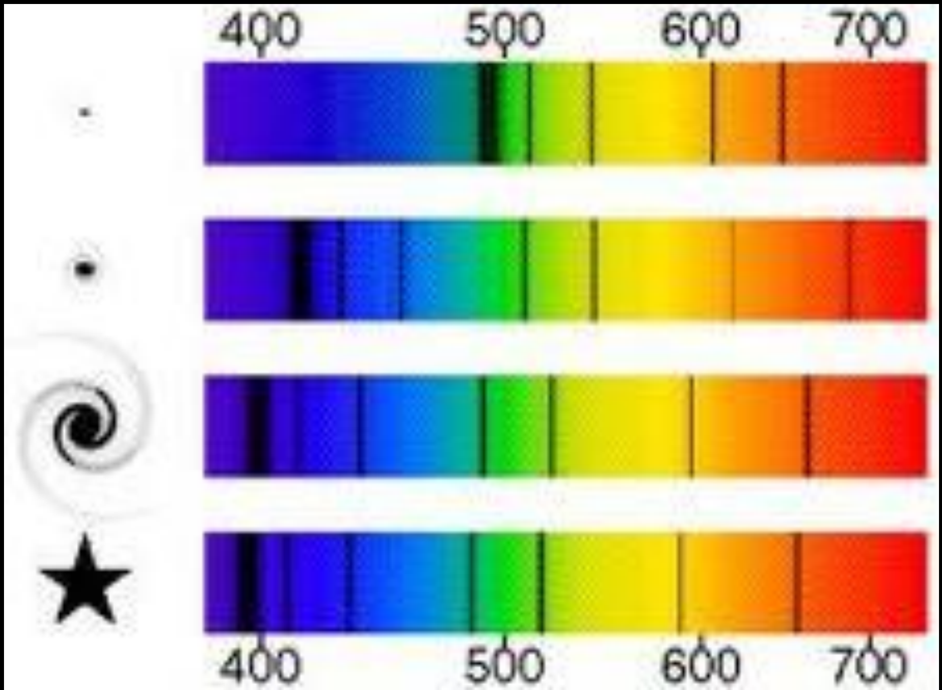
- matter (ordinary or dark): p=0, w=0
- radiation: p=r/3, w=1/3
- cosmological constant: p=-ρ, w=-1
- dark energy: w=w(t)<-1/3 (to obtain an accelerated expansion)

REDSHIFT

The light from distant sources is observed on Earth redder than it was emitted due to the expansion of the universe

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

Redshift of the source

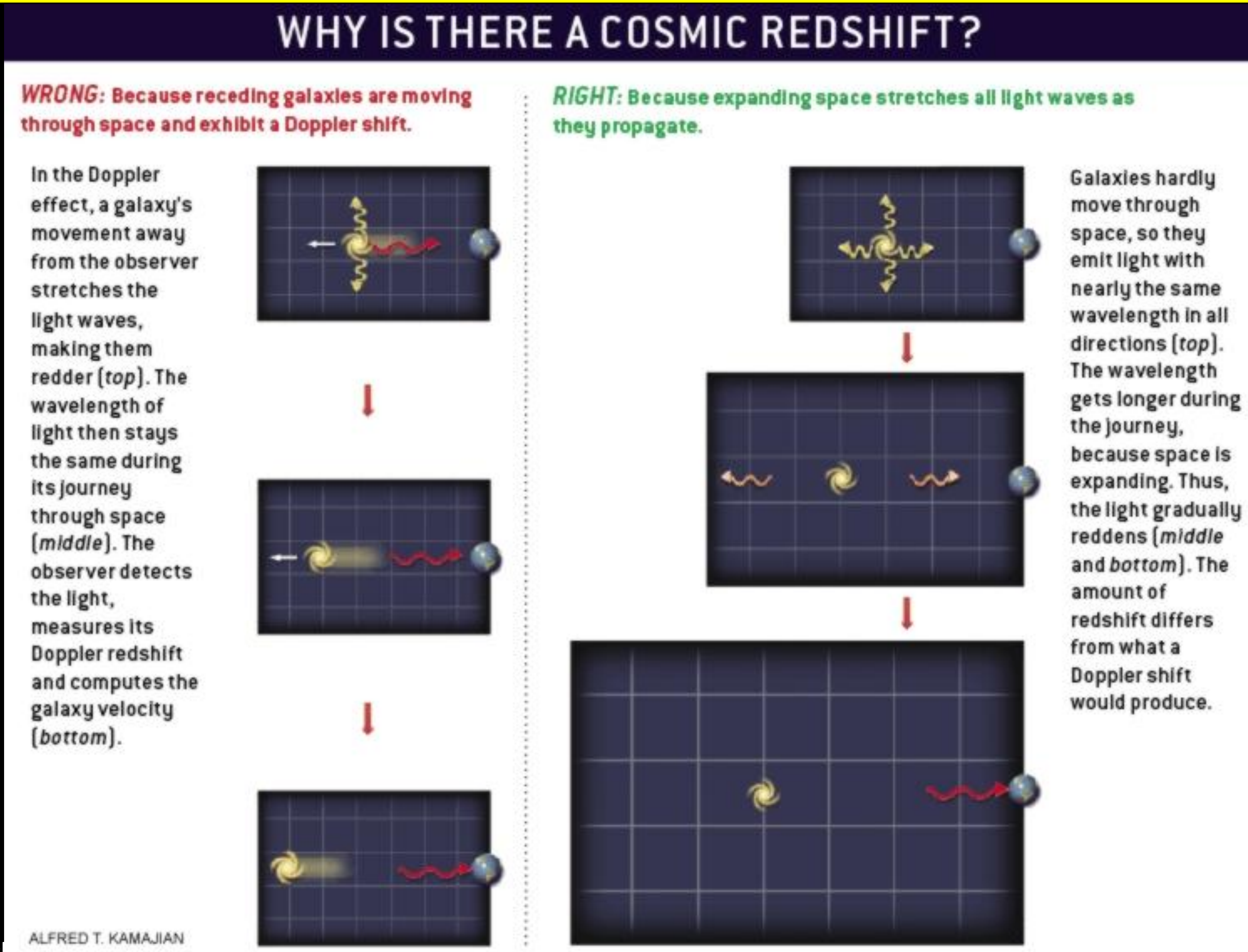


The redshift is a measurement of the scale of the universe at the time of the emission

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

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

Redshift is NOT Doppler effect



DISTANCES

The comoving distance to a source at redshift z can be computed as:

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

Several distances can be measured observationally:

– ***Luminosity distance:*** "Standard candle" with luminosity *L*

d_L *is* such that the measured flux is $\Phi = L / 4\pi d_L^2$

$d_L(z) = r(z)\,(1+z)$ (flat universe)

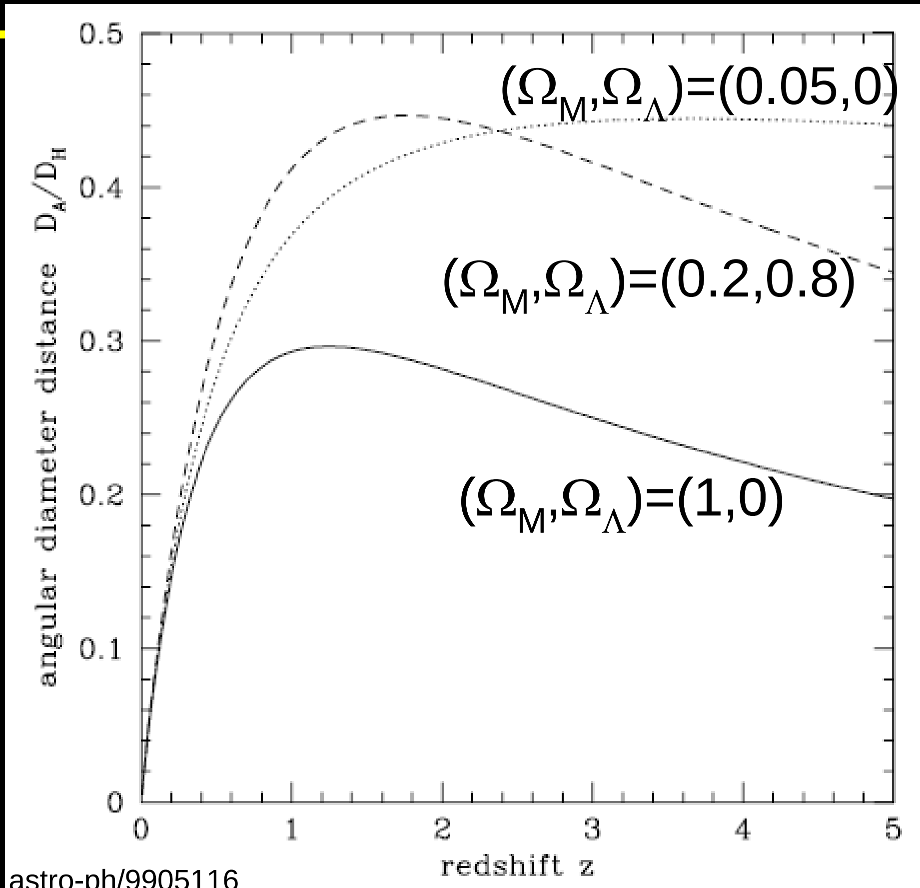
– ***Angular diameter distance***: "Standard ruler" with length l

d_A *is* such that the measured angle subtended by l is $\Delta\theta = l / d_A$

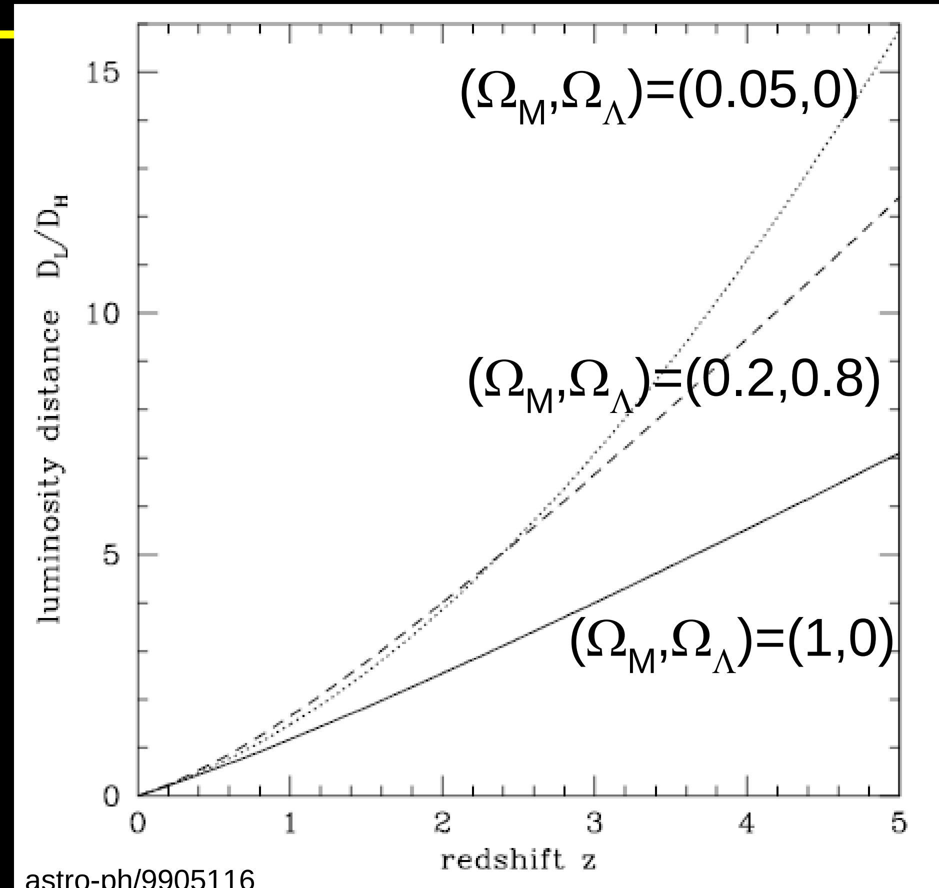
$d_A(z) = r(z) / (1+z)$ (flat universe)

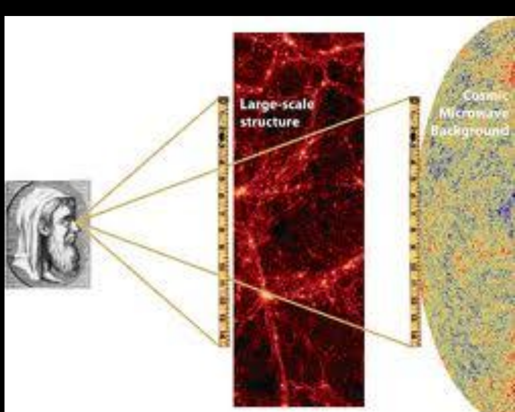
So by having a collection of either standard candles or standard rulers at different known redshifts, we will have many integrals of 1/H(z), from where one can reconstruct Ω_M, *w*, etc.

Angular diameter distance

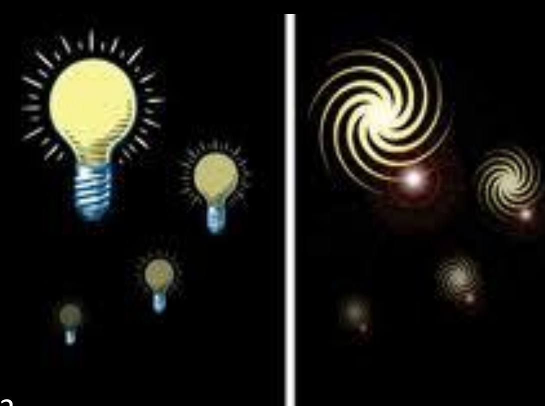


Luminosity distance





STANDARD RULERS



STANDARD CANDLES

Growth of structure

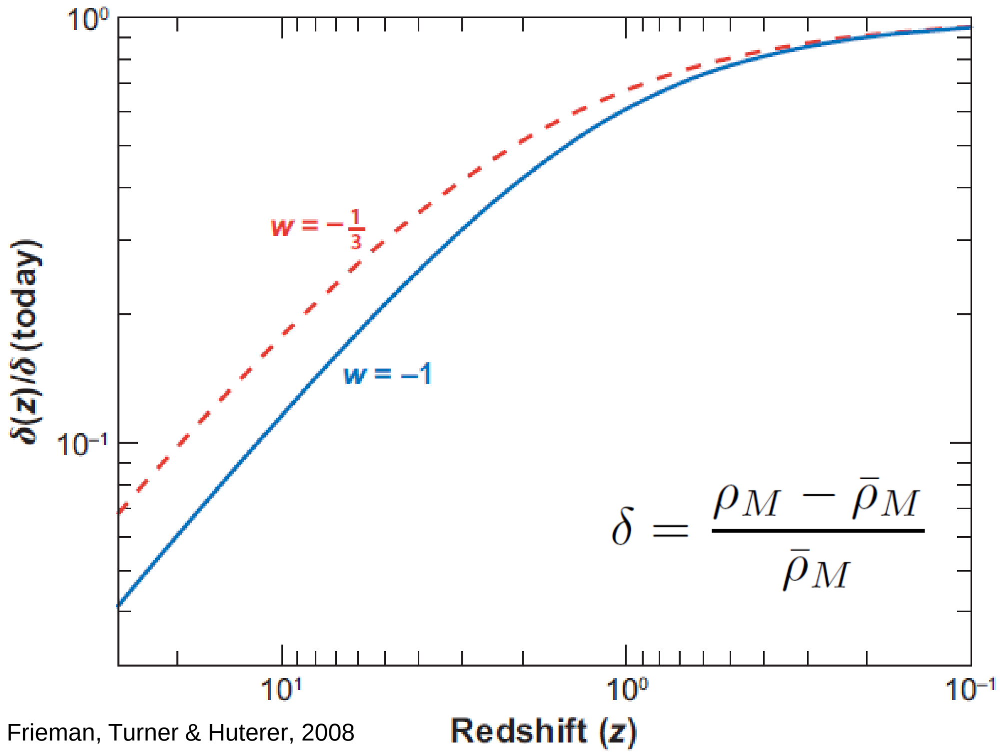
The cosmological model is able to account for the observed structure in the universe:

- 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)

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

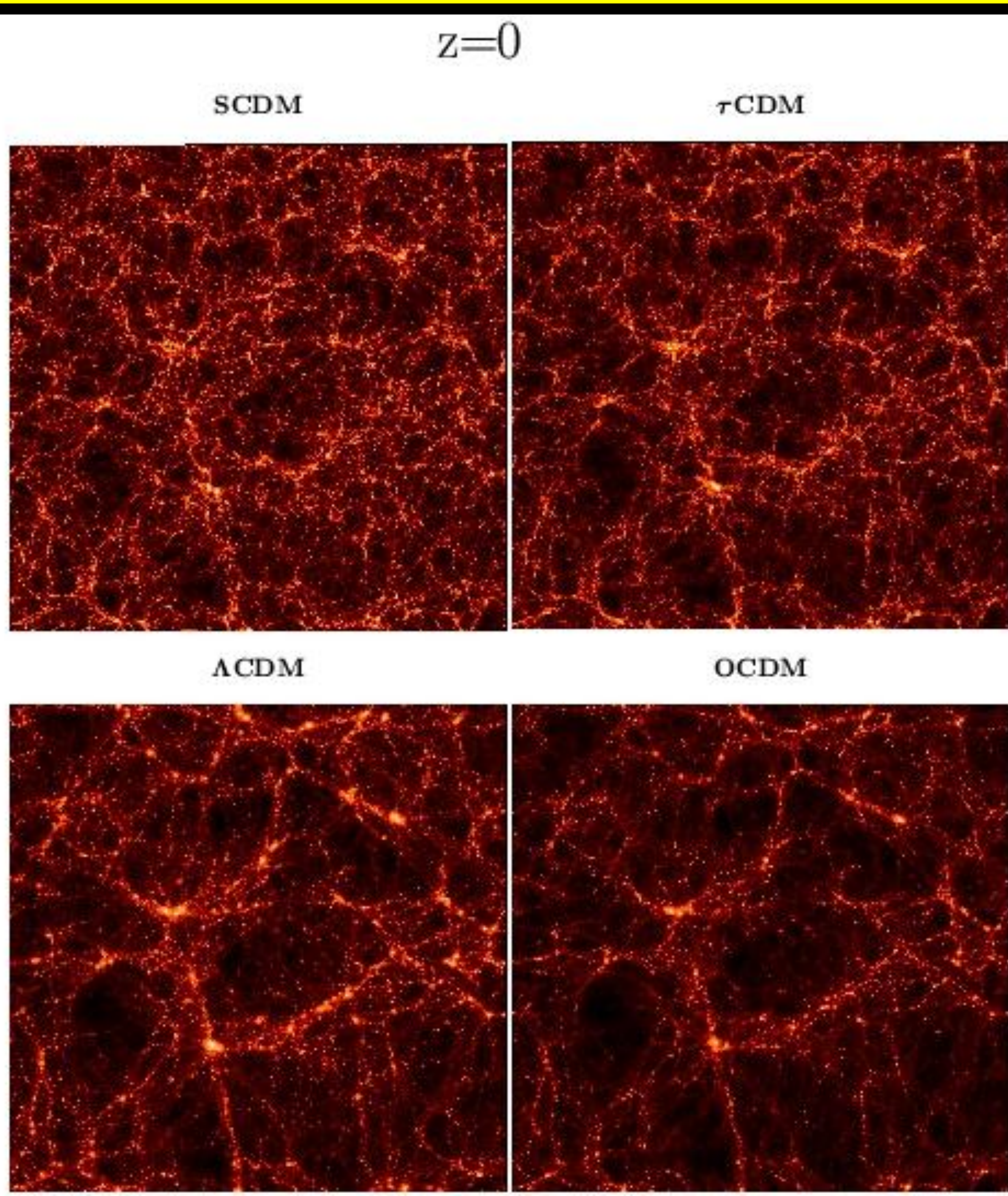
The distribution of fluctuations depends on primordial perturbations and also on the composition of the universe

<ins>COLD DARK MATTER</ins> → Hierarchical structure formation: Small structures from first



Frieman, Turner & Huterer, 2008

Different cosmological models predict different large scale structure



The VIRGO Collaboration 1996

How do yo discriminate among models?

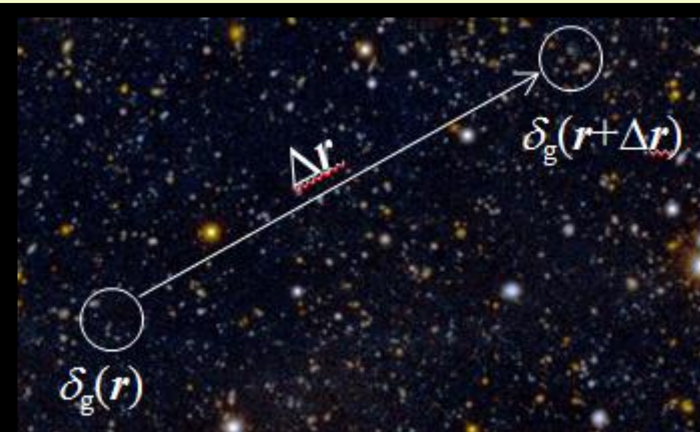
Correlation Function

$$\delta_g(r) = n_g(r)/\bar{n}_g - 1$$

$$\xi(\Delta r) = \langle \delta_g(r)\delta_g(r+\Delta r)\rangle$$

Power Spectrum

$$P(k) = \int d^3r\, e^{-ik\cdot r}\, \xi(|r|)$$



Large amount of observational evidence

From CMB → Ω_{TOT} ~1
(Universe is **<u>FLAT</u>**)

From BBN + CMB → Ω_M ~ 0.04
→ Most of the universe is **<u>non-baryonic</u>**

LSS (galaxy surveys) + DYNAMICS (rotation curves of galaxies, cluster masses, gravitational lensing) → **<u>DARK MATTER!!!!</u>** ; Ω_{DM}~ 0.22

Supernovae Ia → **<u>DARK ENERGY!!!</u>** ; Ω_{DE} ~ 0.76

- Large scale homogeneity
- Hubble diagram
- Abundances of light elements
- Existence of CMB
- Fluctuations of CMB
- LSS
- Age of stars
- Evolution of galaxies
- Time dilation in SN brightness curves
- Temperature vs redshift (Tolman test)
- Sunyaev-Zel´dovich effect
- Integrated sachs-Wolf effect
- Dark matter (rotation/dispersion velocity)
- Dark energy (accelerated expansion)
- Consistency

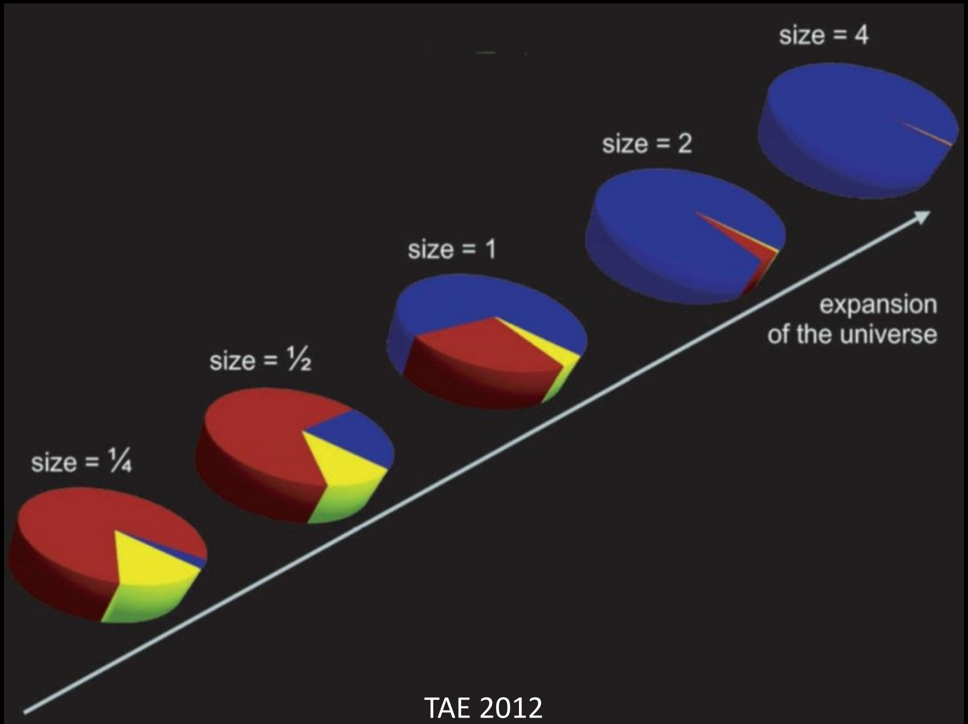
96% of the matter-energy content of the universe remains unexplained

Cosmology requires new physics beyond standard model of particle physics to understand dark matter, dark energy and inflation.

The evidence of dark energy is twofold:

Accelerated expansion of the universe, measured from SNIa

The universe is flat (from CMB) and its matter content is around 24% (from LSS, BAO), ergo, “something else” must provide the missing mass-energy. Remarkably, the same “dark energy” can also explain the accelerated expansion.



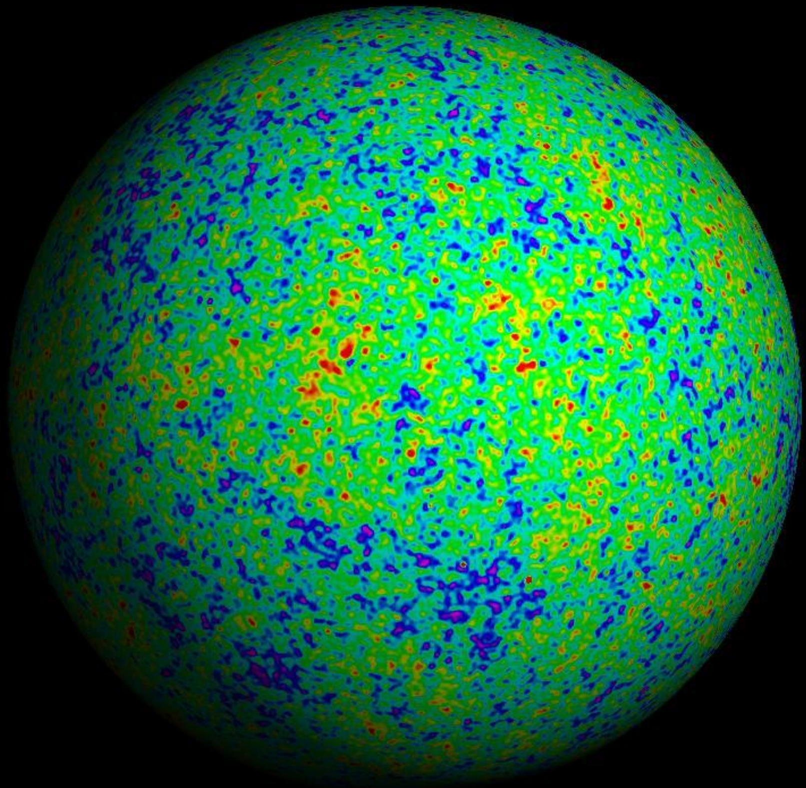
Cosmological Parameters (from PDG)

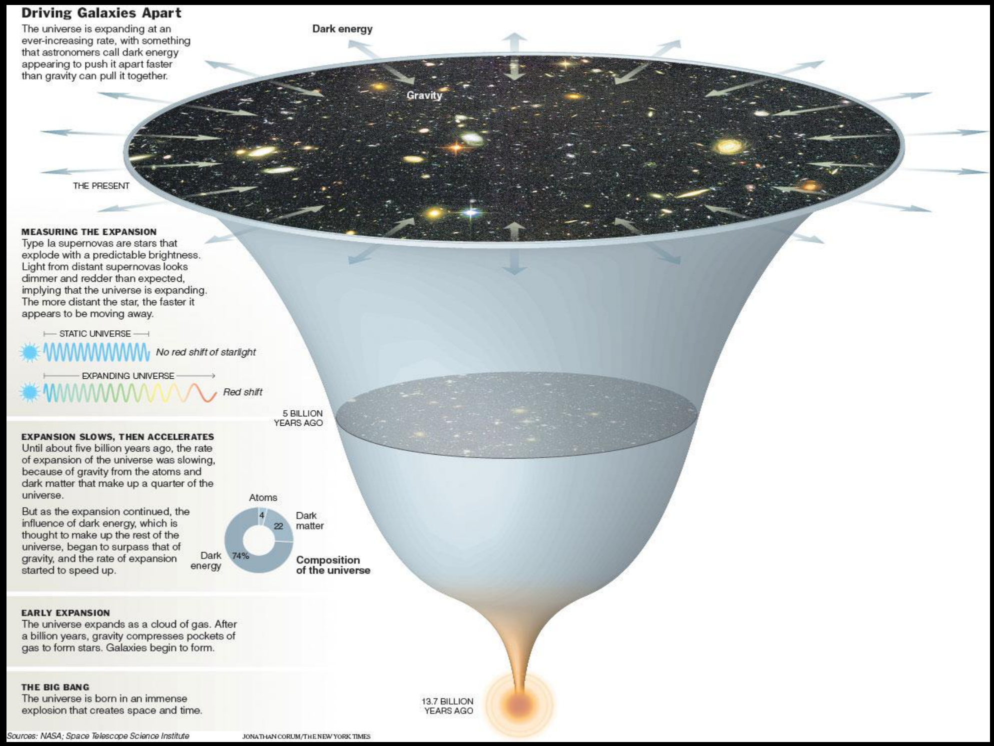
Parameter		Current Best Value
Hubble expansion rate	h	0.710(25) WMAP7
critical density	ρ_c	$1.053\,75(13)\times 10^{-5}\, h^2\, (\mathrm{GeV}/c^2)\, \mathrm{cm}^{-3}$
baryon density	Ω_b	0.045(3)
pressureless matter density	Ω_M	0.27 ± 0.03
dark energy density (LCDM)	Ω_Λ	0.73(3)
dark energy EoS parameter	w	-0.98 ± 0.05 (WMAP7+BAO+H0)
CMB radiation density	Ω_γ	$4.75(23) \times 10^{-5}$
neutrino density	Ω_ν	$0.0009 < \Omega_\nu < 0.048$
total energy density	Ω_{tot}	1.002 ± 0.011 (WMAP7+BAO+H0)
scalar spectral index	n_S	0.963(14)
age of the Universe	t_0	13.75 ± 0.13 Gyr

How do we know that? Observational Cosmology

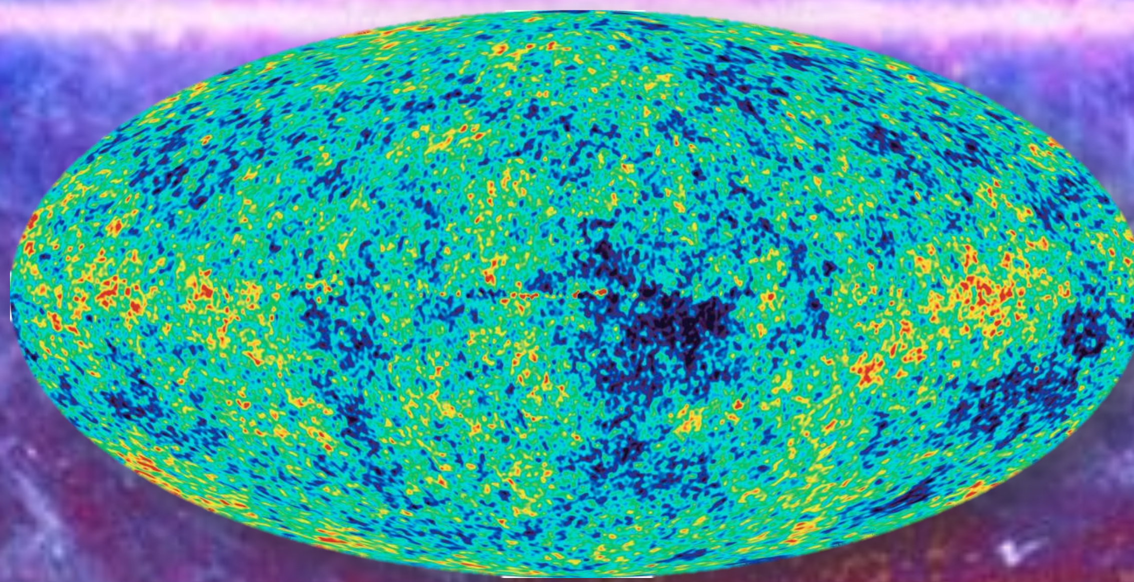
We have already seen the abundances of primordial elements and the search for dark matter.

Now we will review the other pillars of cosmology: The Cosmic Microwave Background (CMB) and the Dark energy.



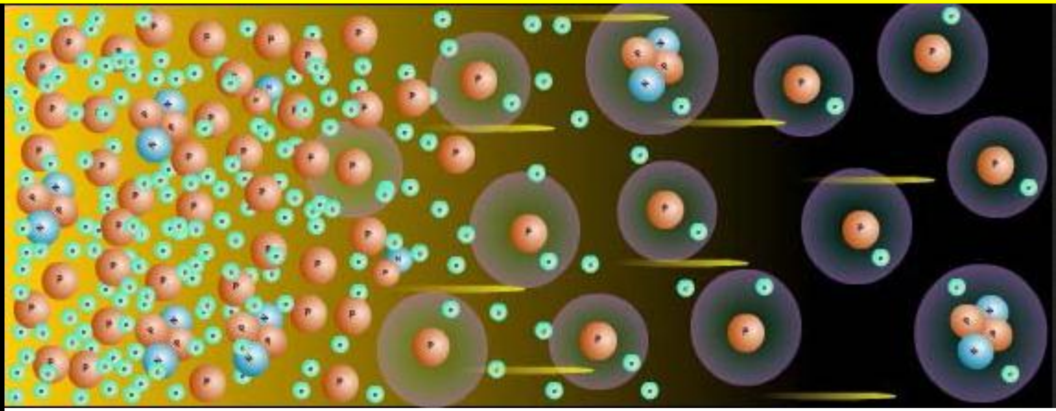


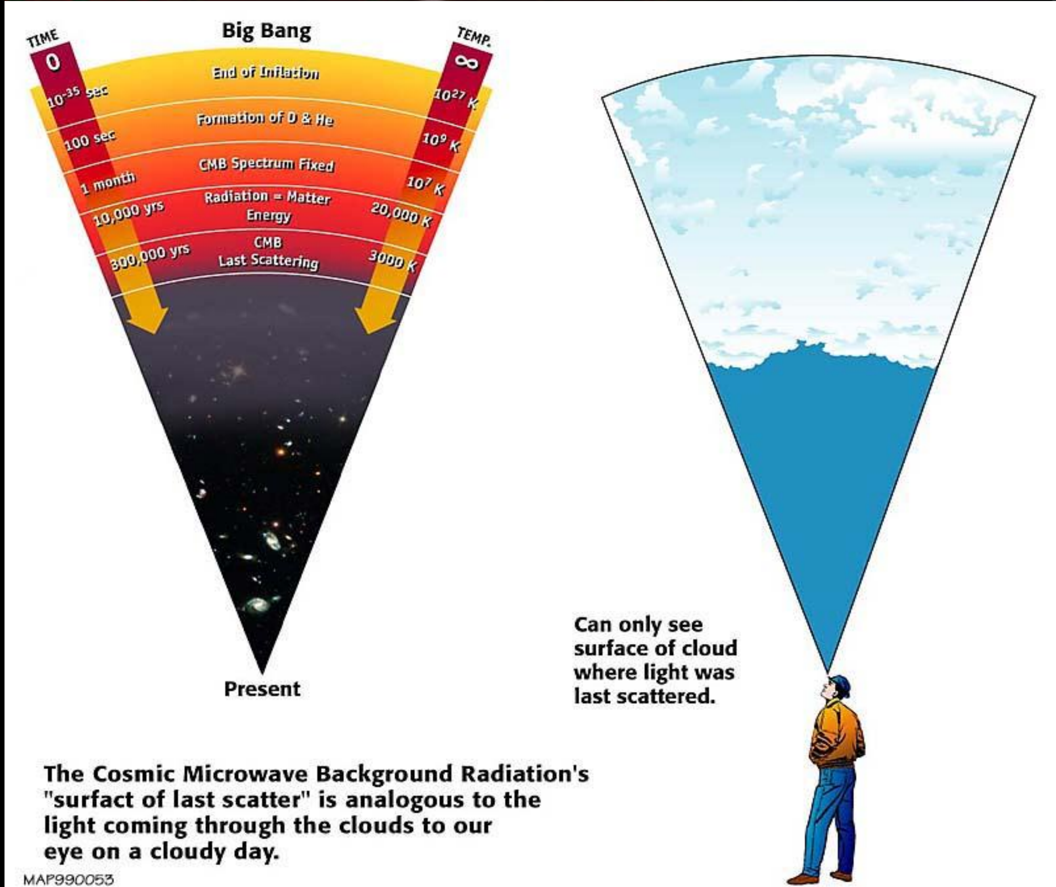
THE CMB



The Cosmic Microwave Background (CMB)

Thermal radiation from the formation of atoms ~380000 years after the big bang, or …. 13600 million years ago!!! (if the universe was a person 80 years old, CMB is a photograph when that person was 13 months old)





Discovered in 1965

In 1992 it was discovered that CMB is not fully uniform. Its small anisotropies are the seeds of all the structures we see nowadays in the universe

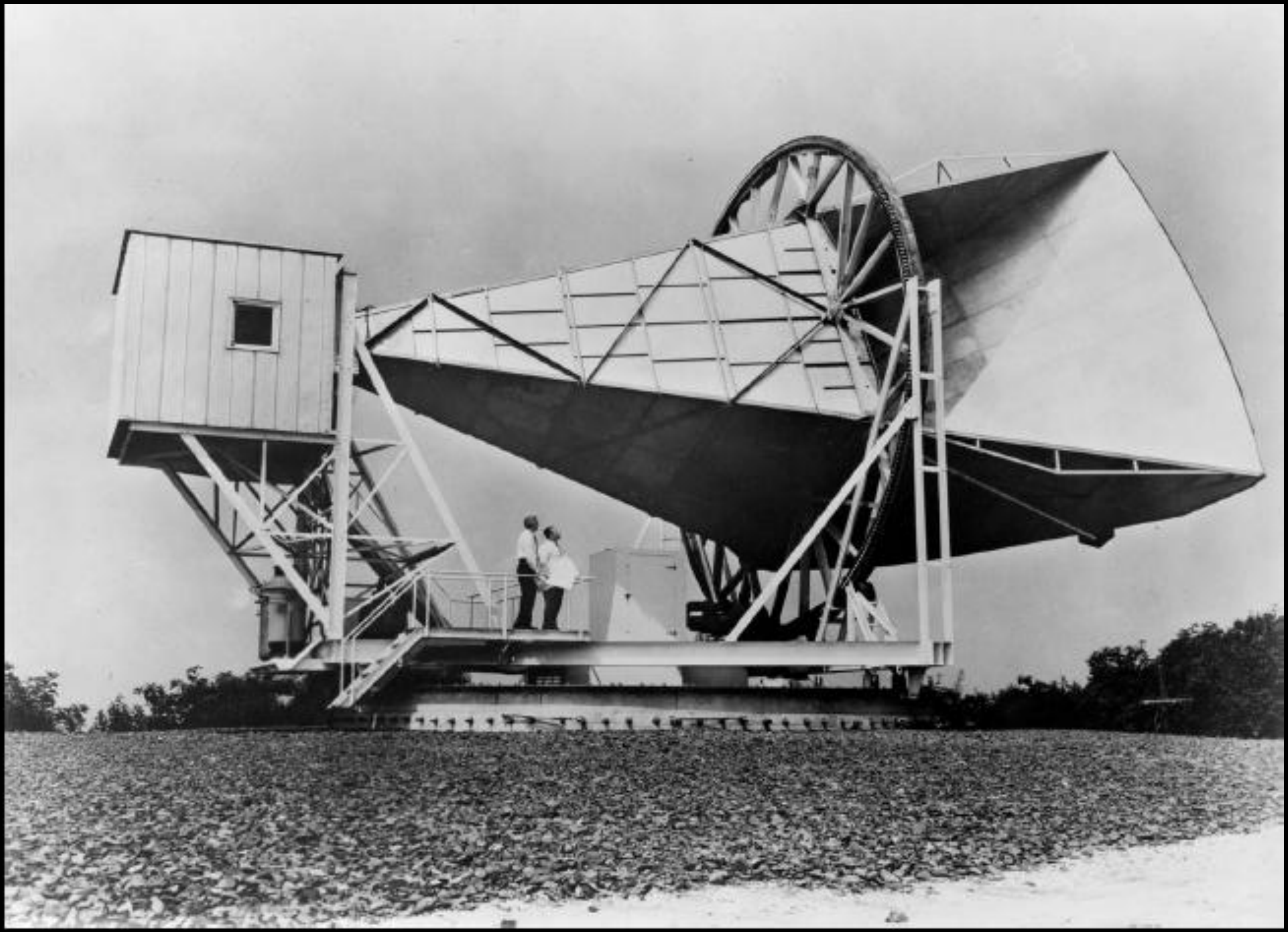
The most precise measurements of the cosmological parameters come from CMB

Discovery of CMB: Horn antenna to detect radio waves

Arno Penzias and Robert Wilson of Bell Labs (1965)

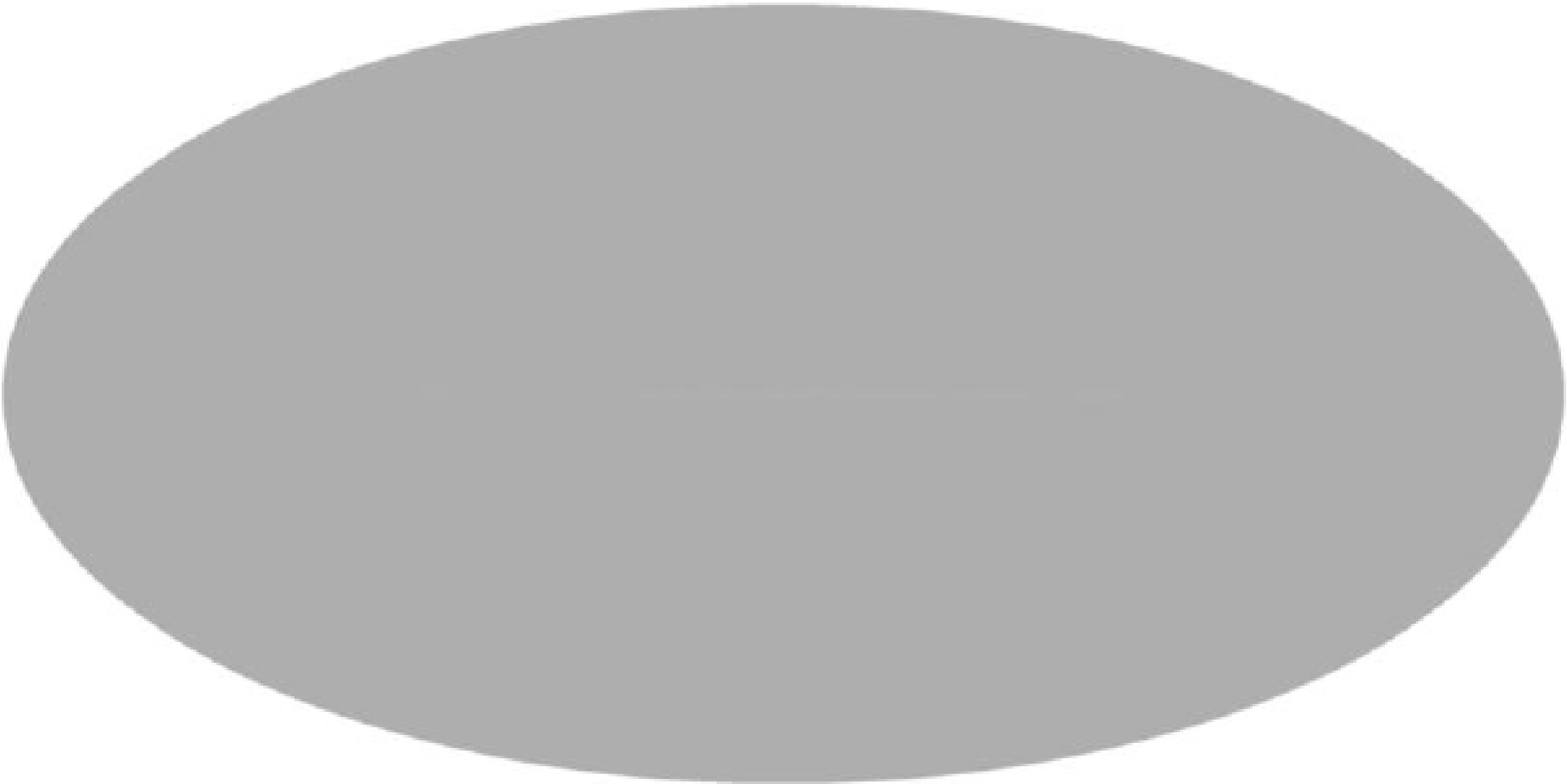
Low and steady noise persisted in the receiver

Accidental discovery



National Historic Landmark (1988)

True Contrast CMB Sky



T = 2.72548 ± 0.00057 K

33, 41 & 94 GHz as RGB, 0-4 K scale

Slide from
Ned Wright

On the CN non-discovery

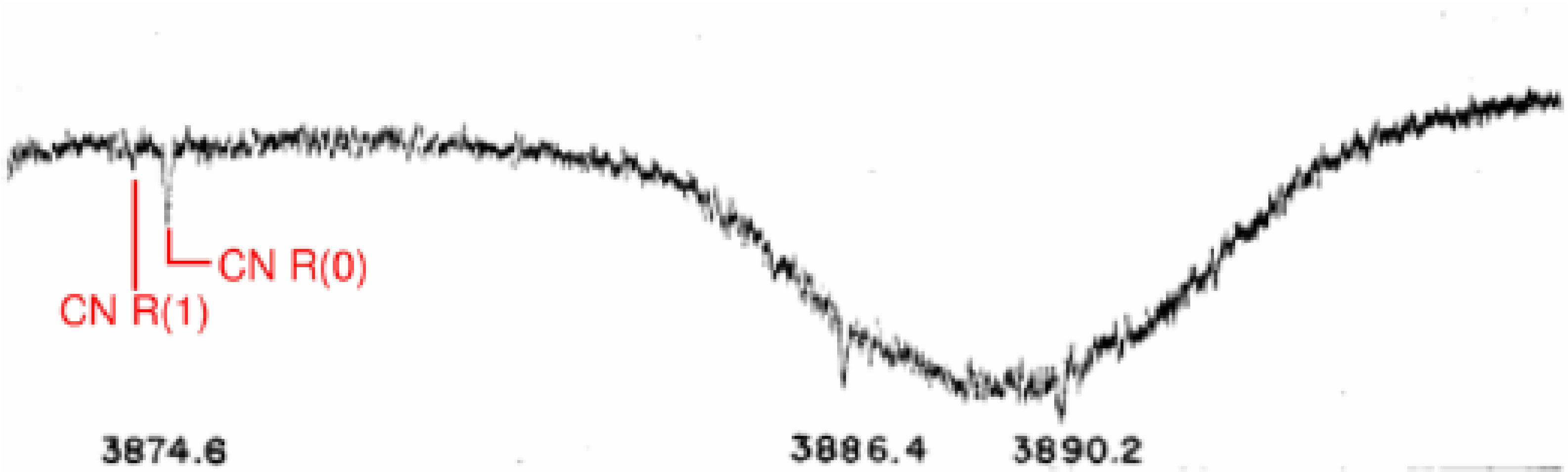


Plate 3 of Adams (1941, ApJ, 93, 11-23)

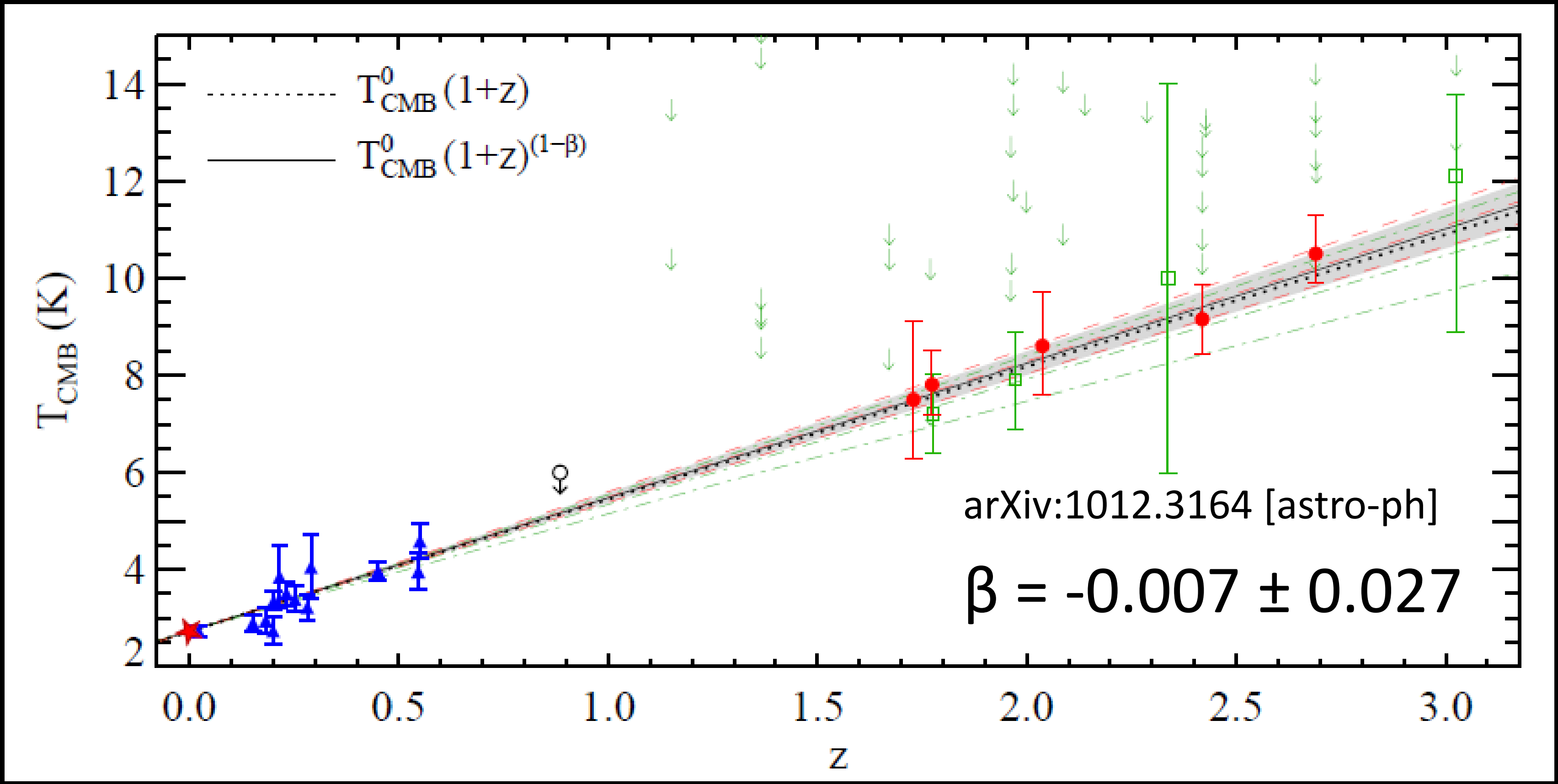
Herzberg (1950) in *Spectra of Diatomic Molecules*, p 496:

“From the intensity ratio of the lines with K=0 and K=1 a rotational temperature of 2.3º K follows, which has of course only a **very restricted meaning**.”

There went Herzberg’s [second] Nobel Prize.

Slide from Ned Wright

CMB Temperature . vs . Redshift



COBE

CO Molecule lines

SZ Effect

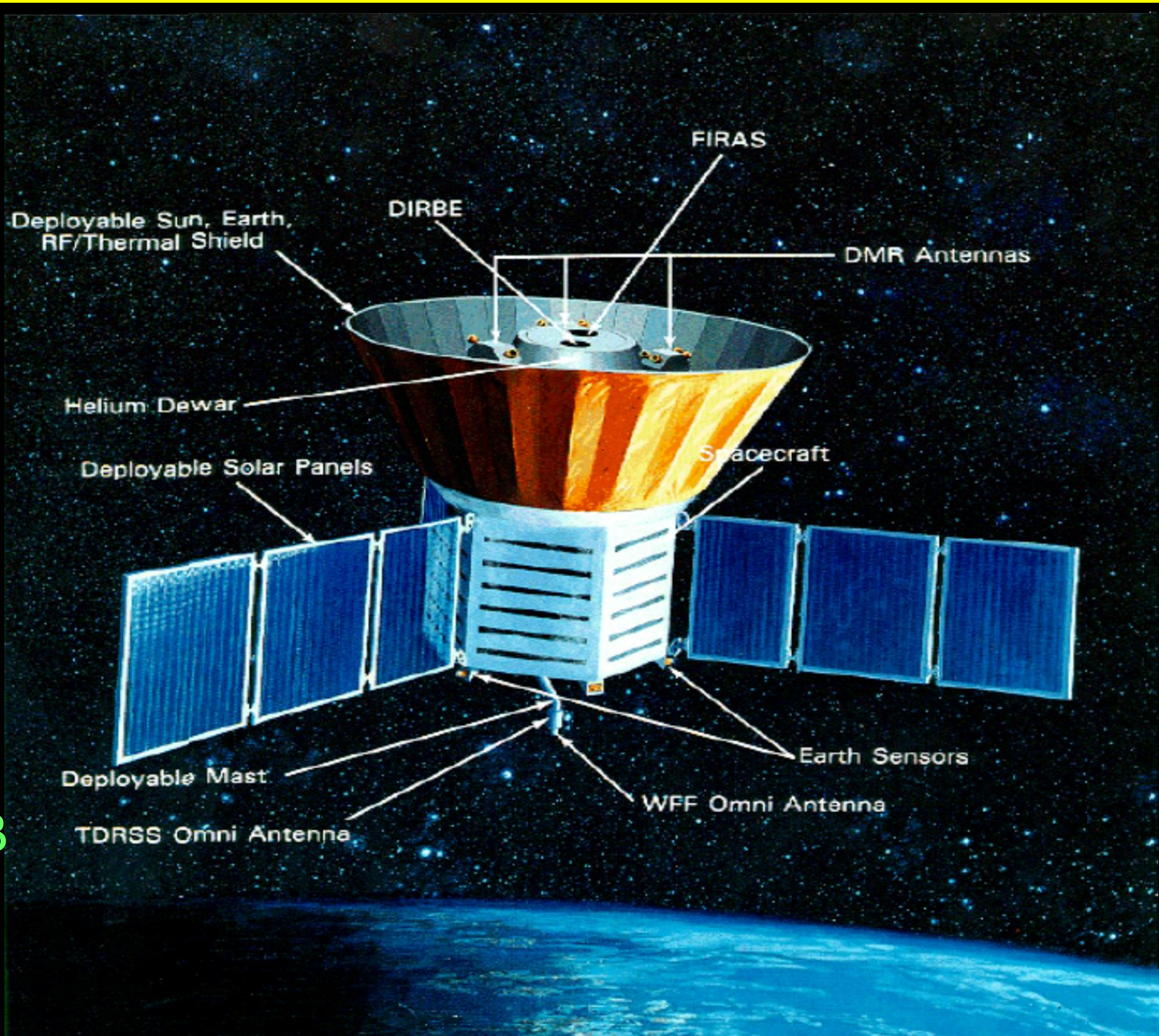
C atom lines

The COBE Satellite

Launched in 1989, 4 years mission

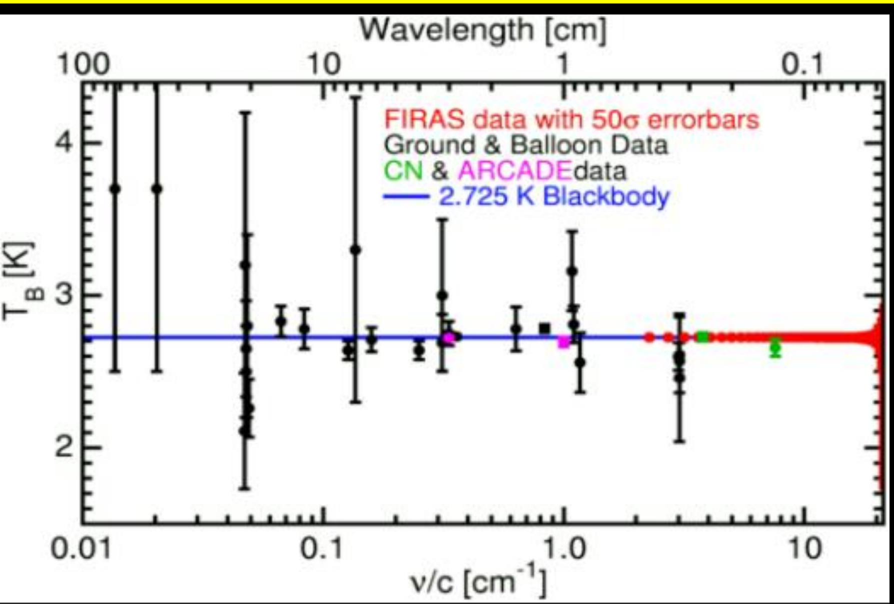
High precision measurement of the CMB temperature (1990)

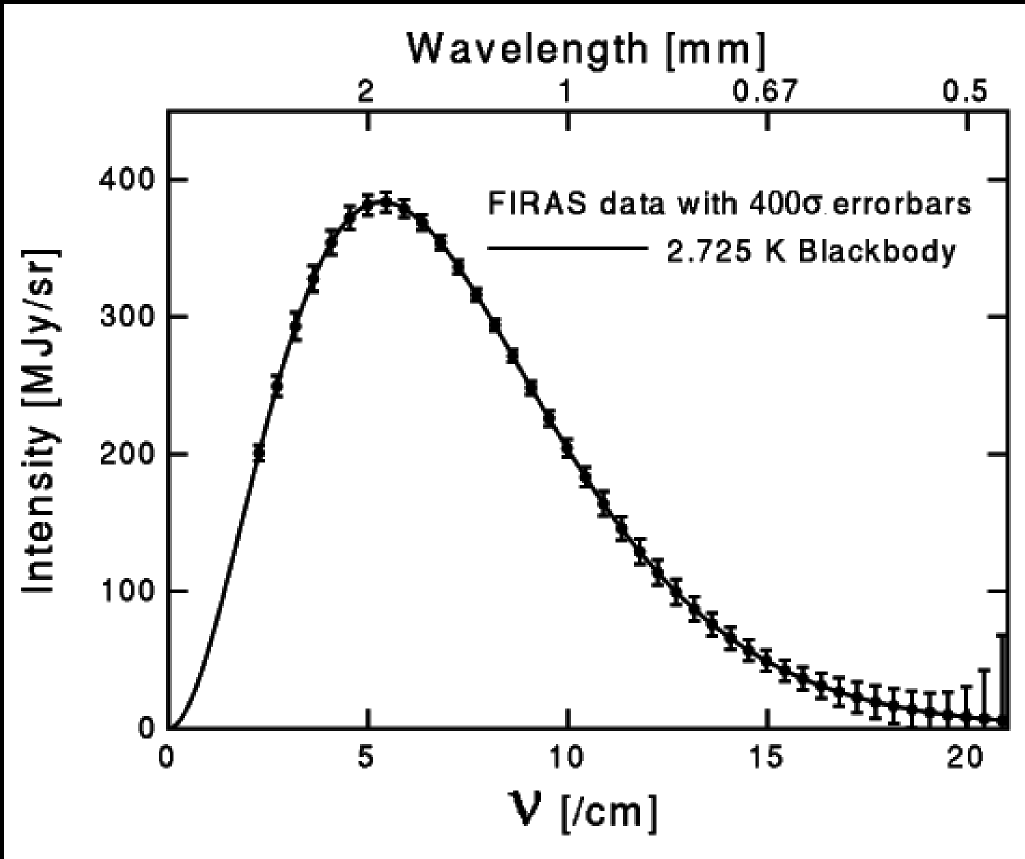
First detection of the tiny CMB anisotropies (1992)

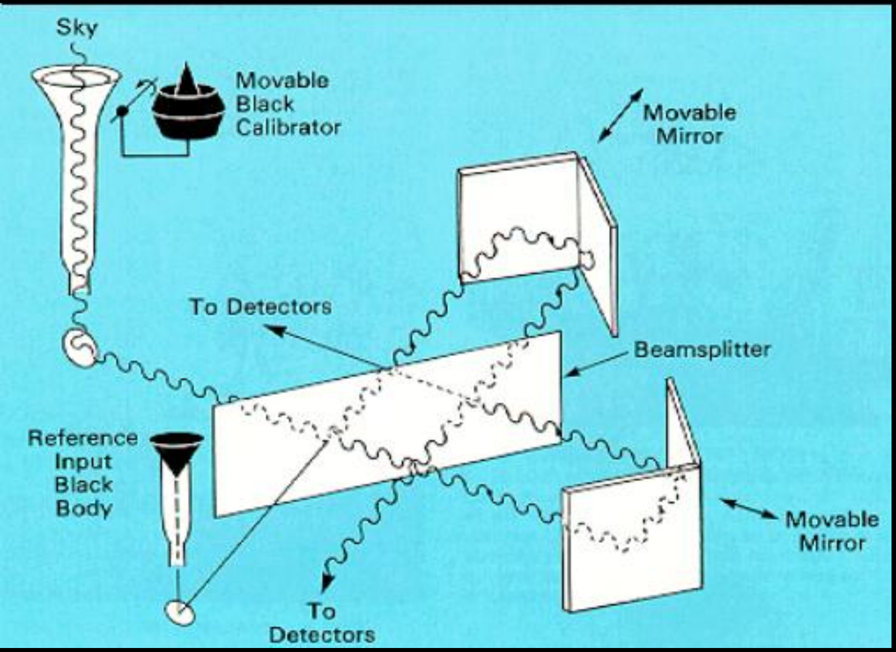


E. Sánchez

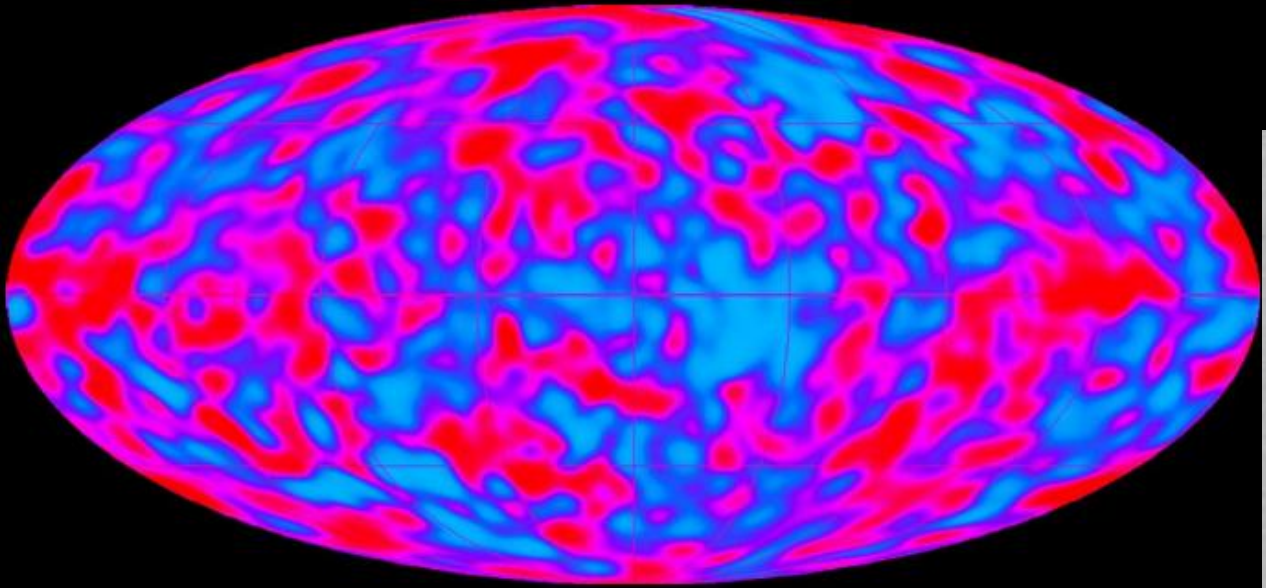
FIRAS instrument : Temperature of the CMB

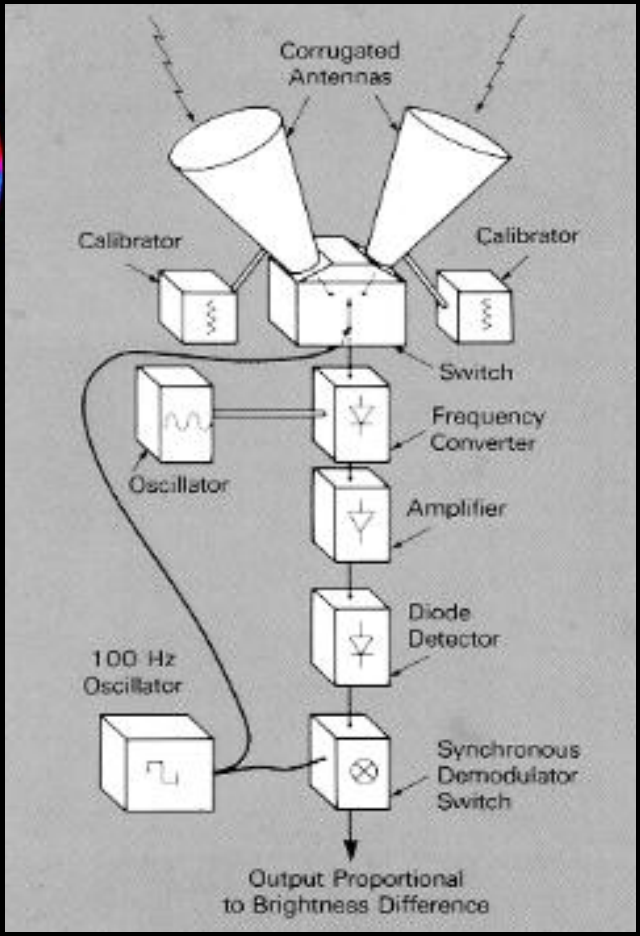


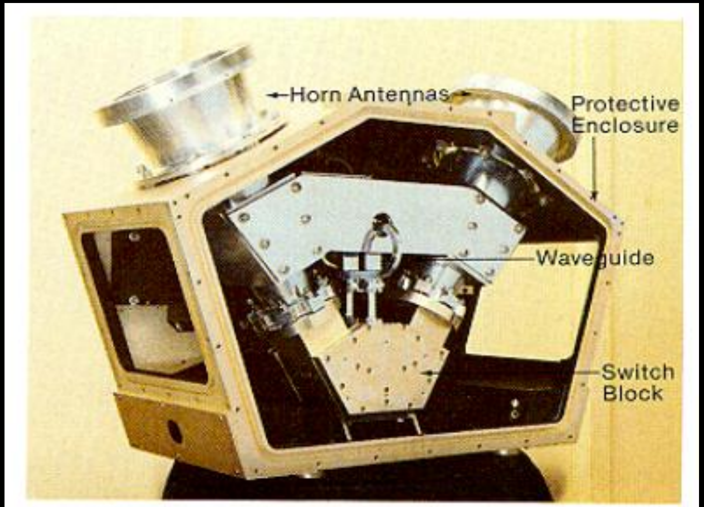




DMR instrument : Fluctuations of the CMB







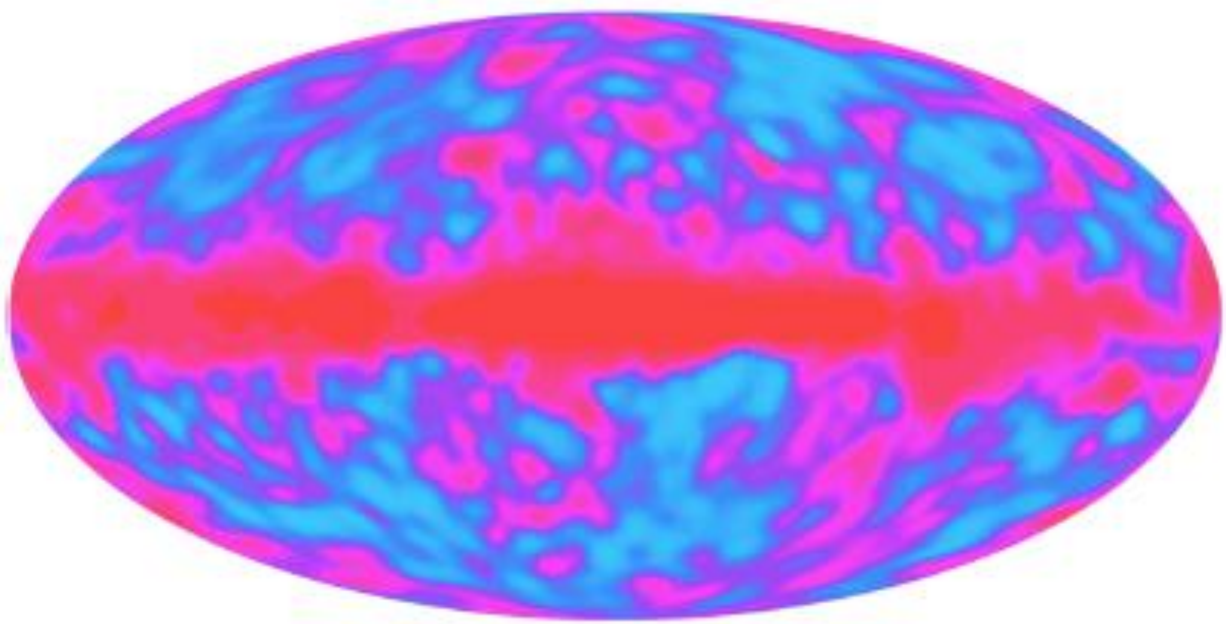
The 9.6 mm DMR receiver partially assembled. Corrugated cones are antennas.

A Big Media Splash in 1992:

THE TIMES

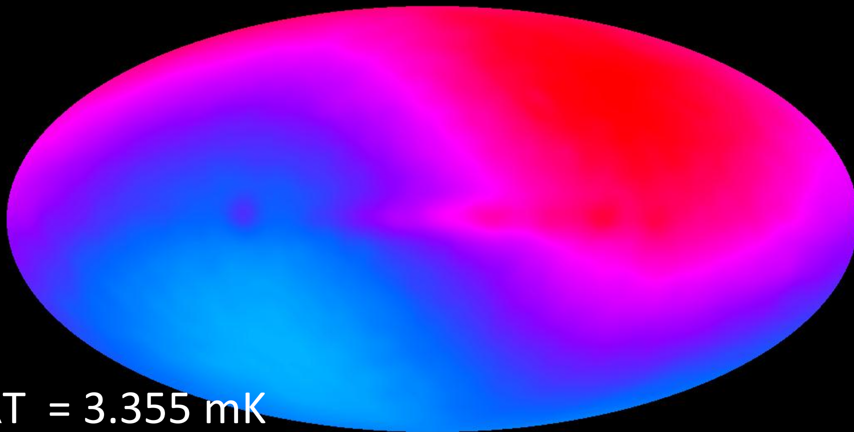
25 April 1992

Prof. Stephen Hawking of Cambridge University, not usually noted for overstatement, said: “It is the discovery of the century, if not of all time.”

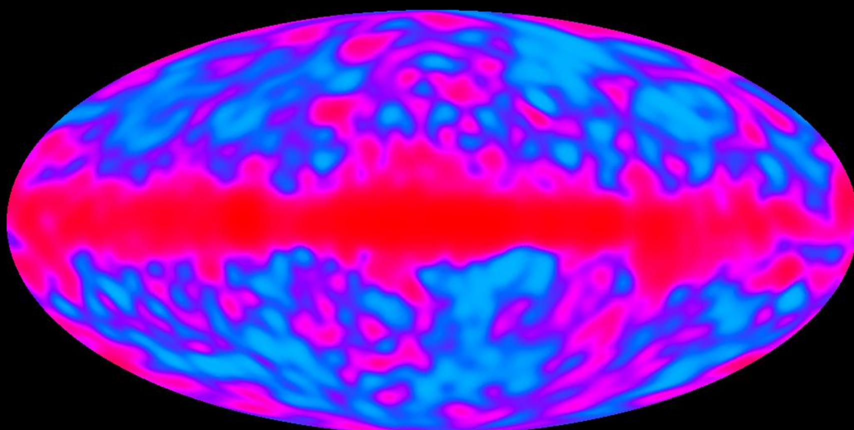


Slide from Ned Wright

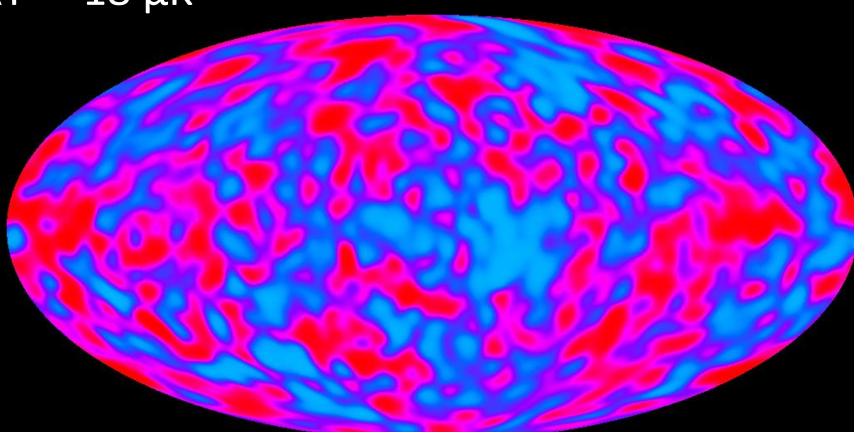
Dipole Anisotropy due to earth movement

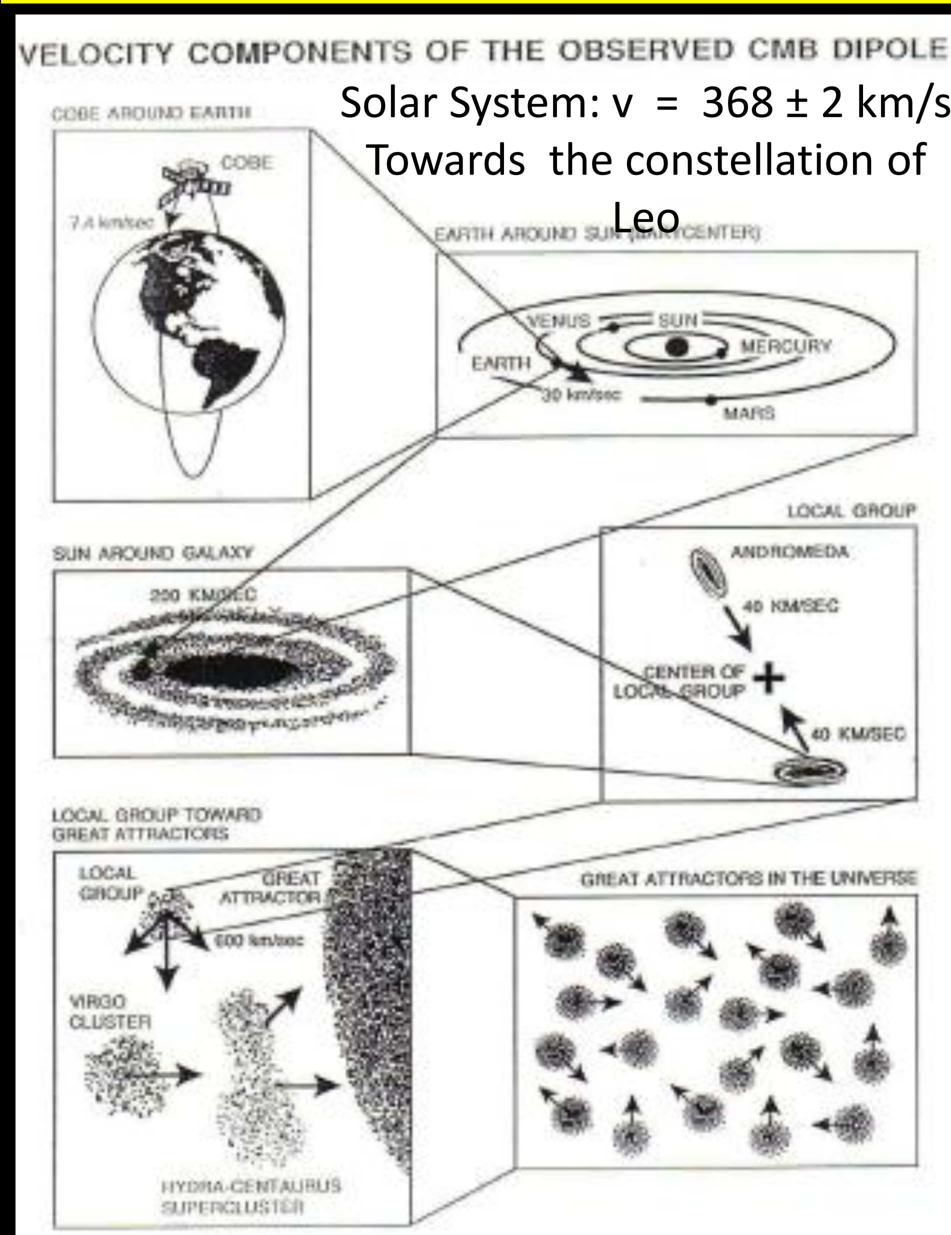


ΔT = 3.355 mK



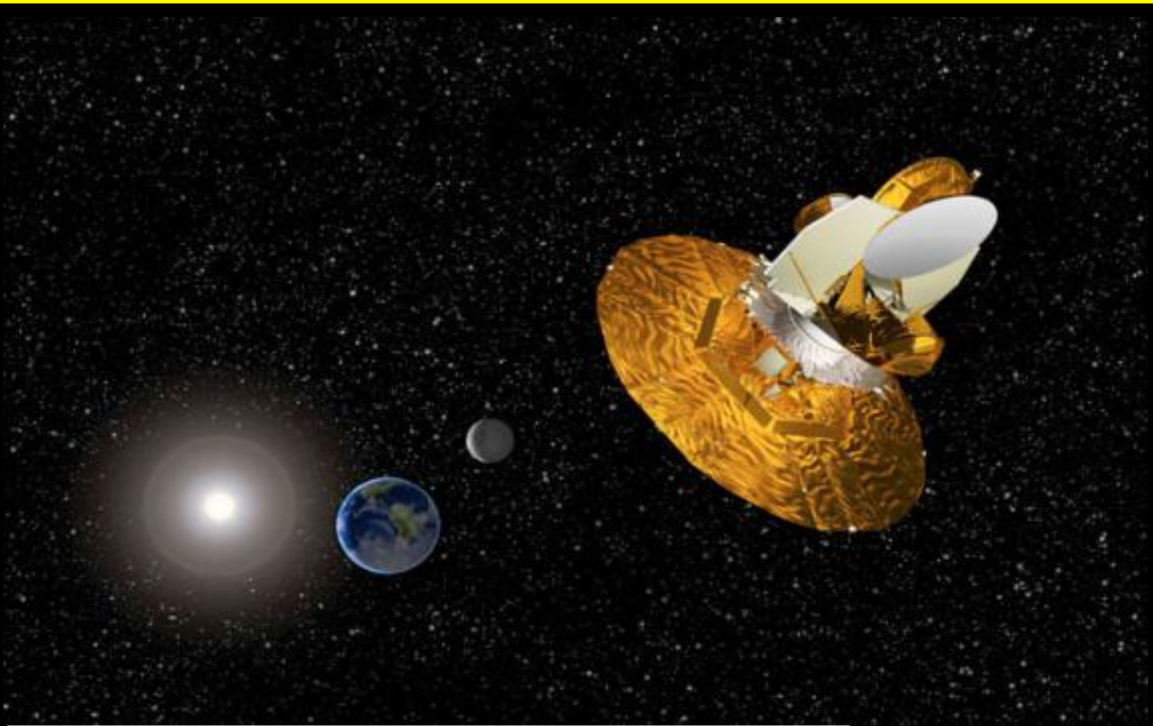
ΔT = 18 μK



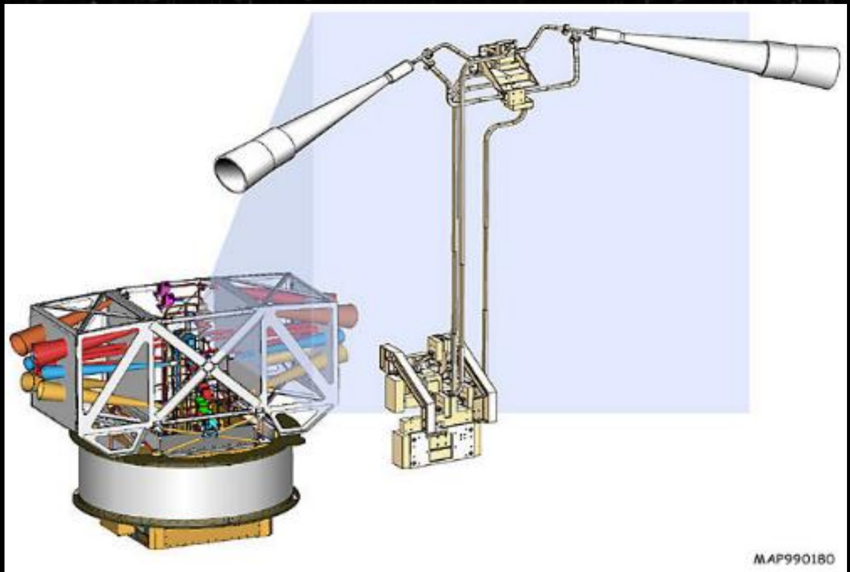


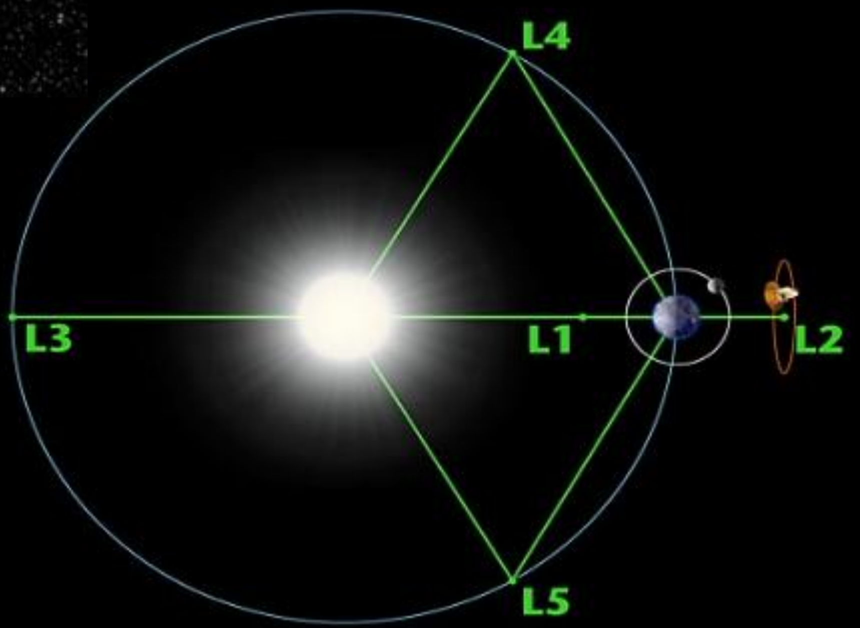
Solar System: v = 368 ± 2 km/s
Towards the constellation of Leo

WMAP : Launched in 2001 (ended august 2010)

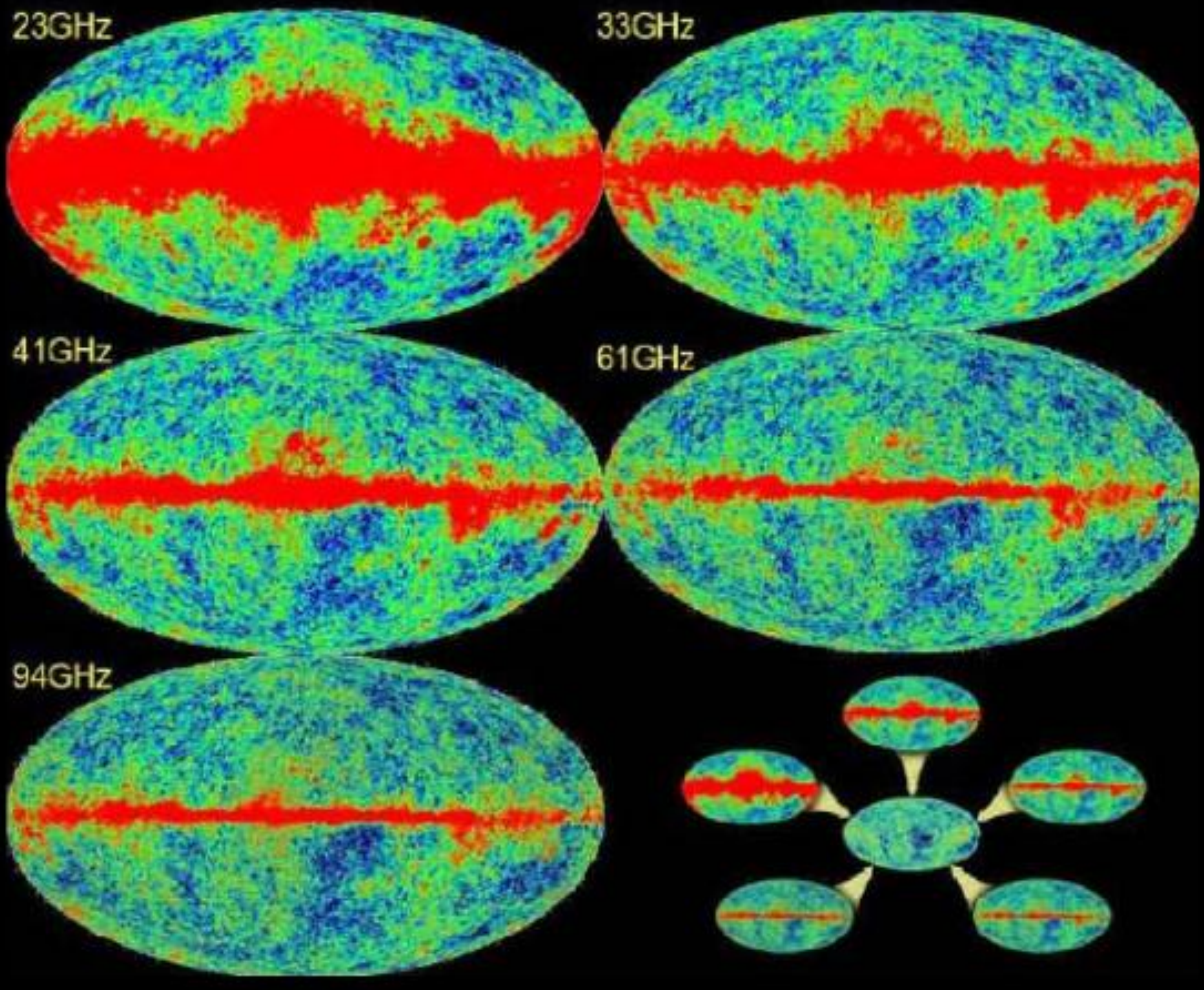


The most precise measurements up to date in cosmology, which have placed it on solid observational basis

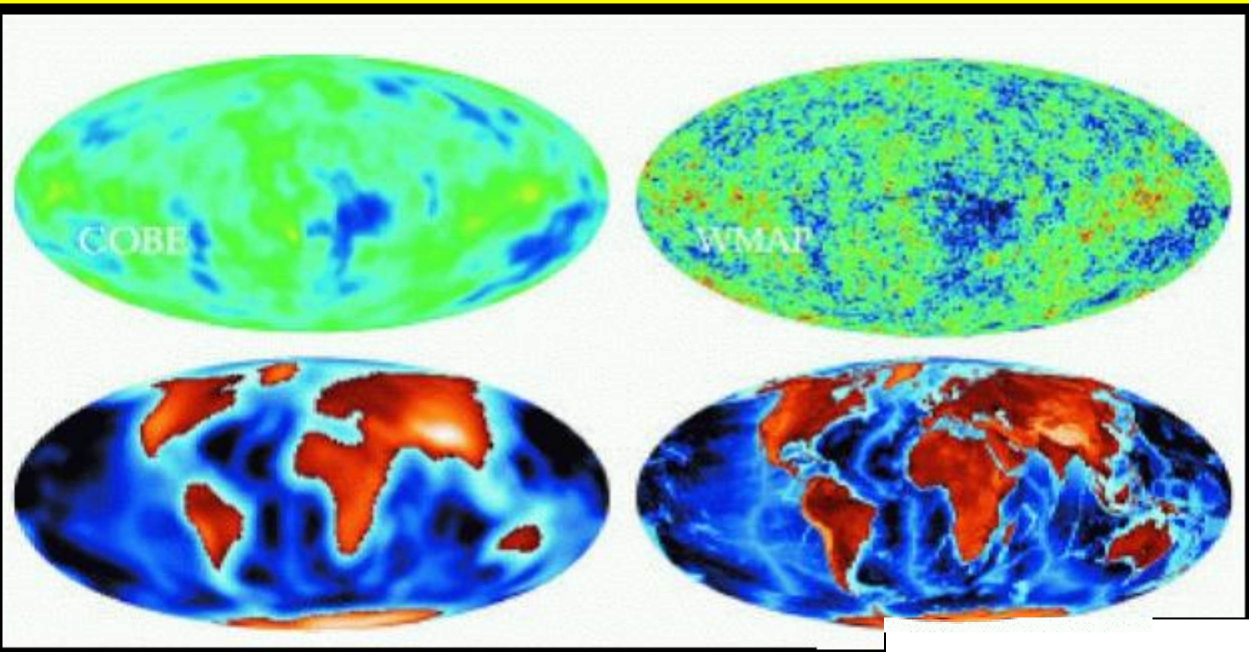




WMAP

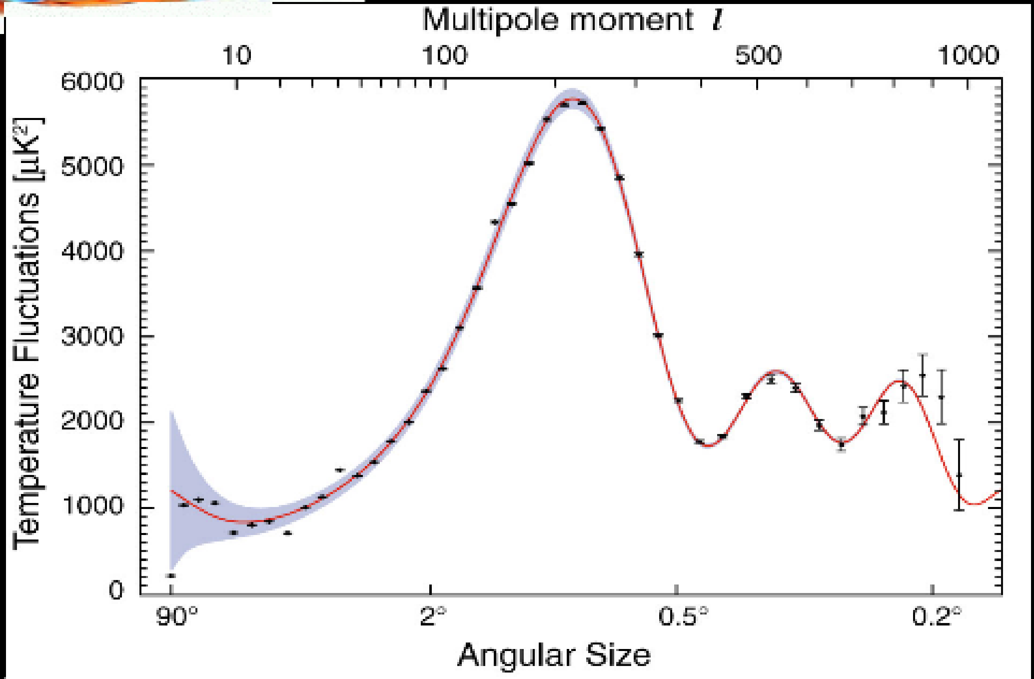


WMAP



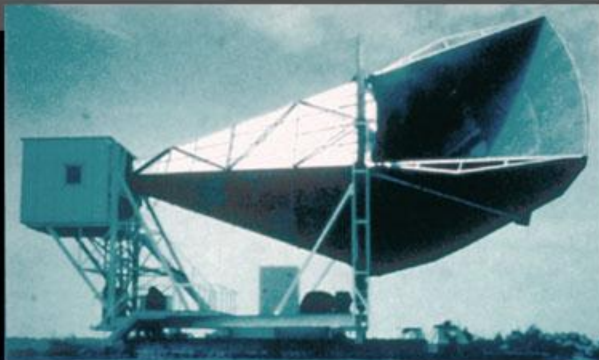
WMAP´s angular resolution is much better than COBE´s, what allows to extract more information from CMB fluctuations

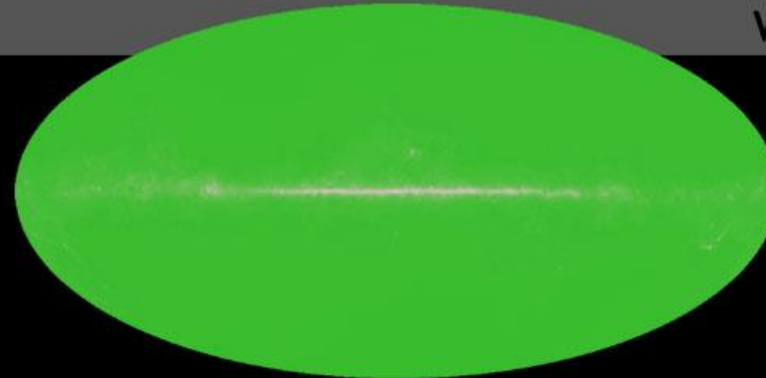
The CMB power spectrum from WMAP measurements. Red line is the cosmological model fit and the gray band is the error



1965

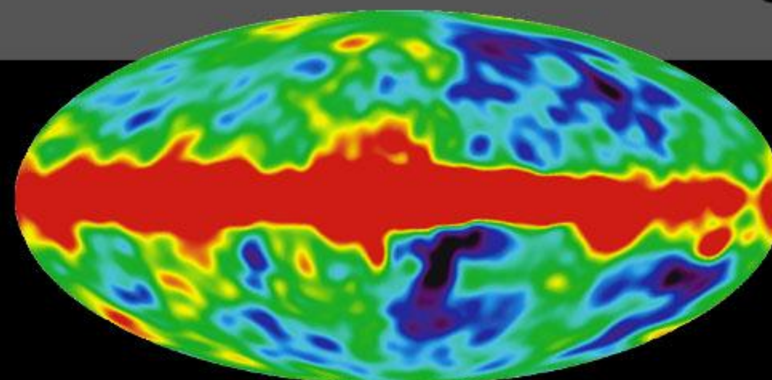
Penzias and Wilson





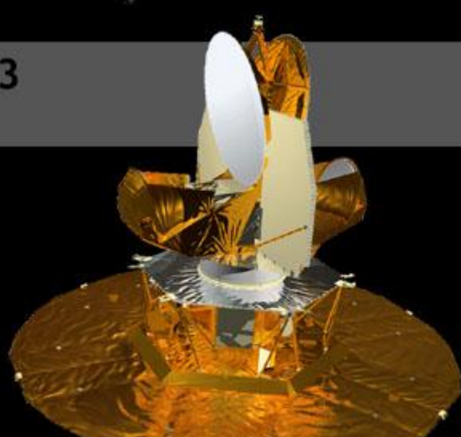
1992

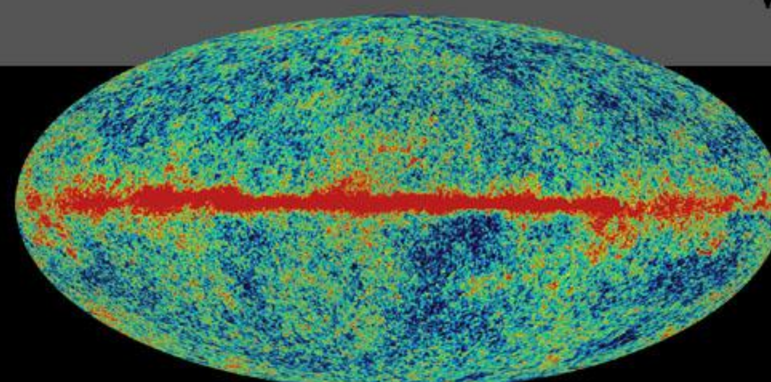
COBE



2003

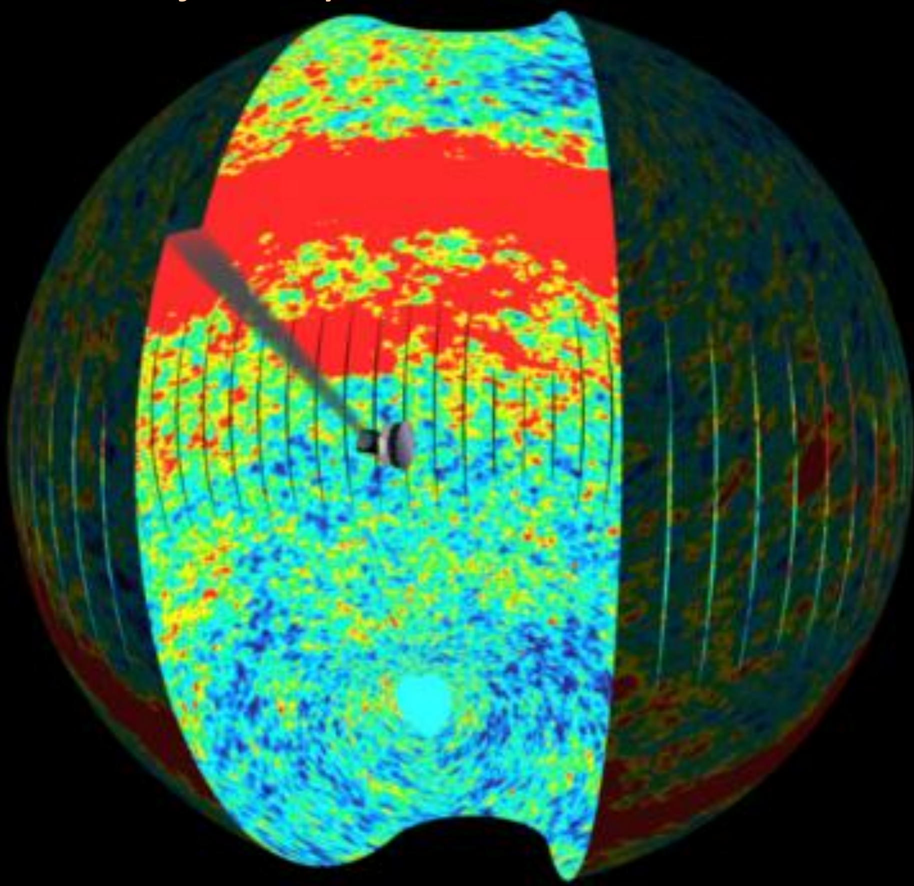
WMAP





Planck: The next generation

Arrived to Lagrangian Point 2 in july 2009. More precise than WMAP and measurement of polarization. High frequency ended taking data on january 2012. First cosmological results in january 2013



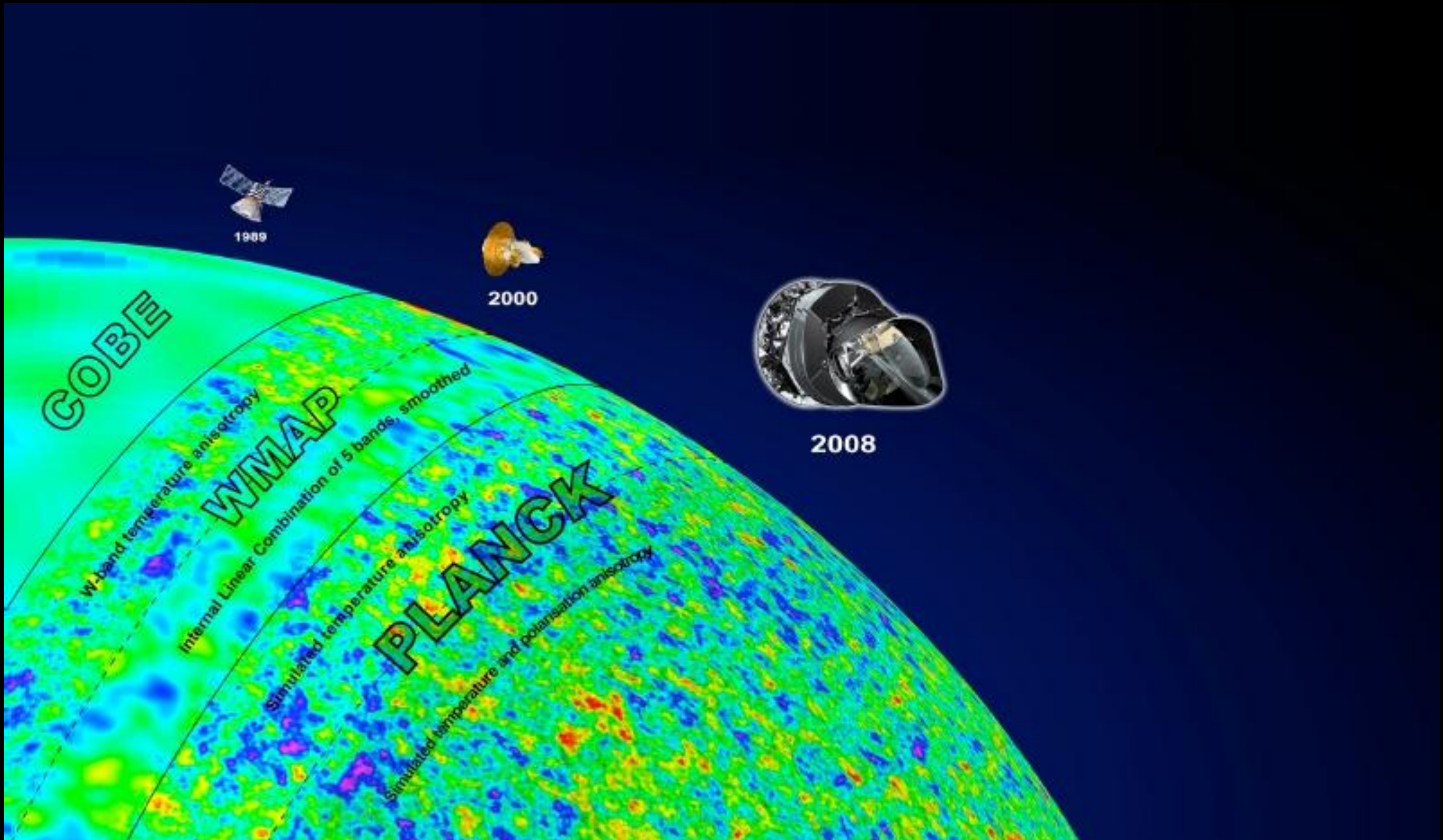
Cosmology from CMB

Measure temperature distribution (fluctuations)

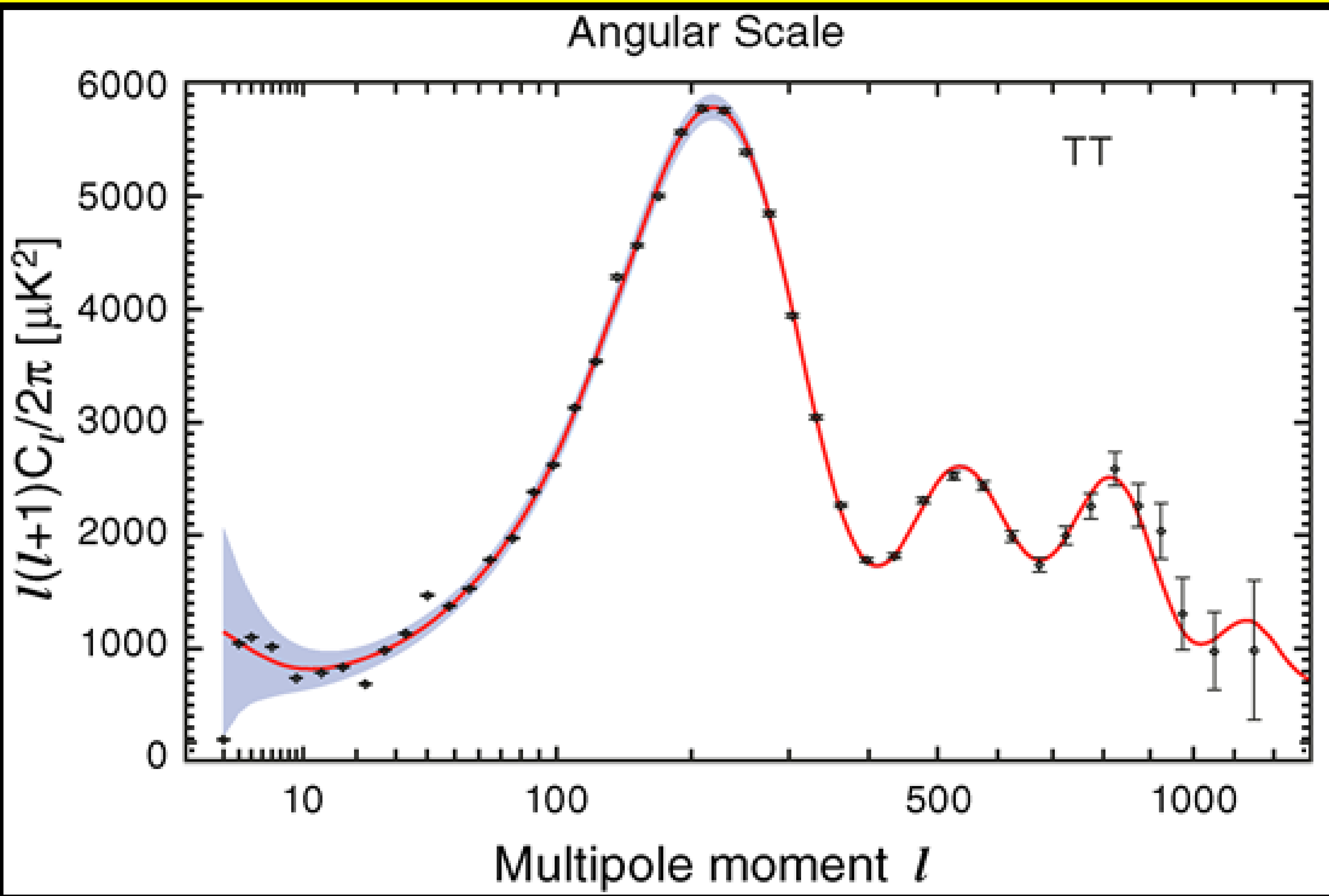
Build a map of the anisotropies

Obtain power spectrum from the map

Fit cosmological parameters to the measured power spectrum



WMAP 7 Power Spectrum and LCDM prediction



DARK ENERGY


Science
18 December 1998
Vol. 282 No. 5397
Pages 2141–2336 $7
THE ACCELERATING UNIVERSE
Breakthrough of the Year
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE


Science
19 December 2003
Vol. 302 No. 5653
Pages 2017–2172 $10
Breakthrough of the Year
Cosmic Convergence
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

What do we mean by dark energy?

The discovery of the accelerated expansion of the universe (1998) was a huge surprise, since gravity acting on matter slows down the expansion, so we expect a deccelerating expansion, not an accelerating one

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

– Einstein's cosmological constant?

– Some new dynamical field ("quintessence")?

– Modifications to General Relativity?

WHAT DO WE KNOW ABOUT DARK ENERGY?

1) **It emits no electromagnetic radiation**
2) **It has large and negative pressure**
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 densisty (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 dark energy.

No well-motivated theoretical explanations for dark energy

Very likely, progress will come from improving observational constraints

The Cosmological Constant Case

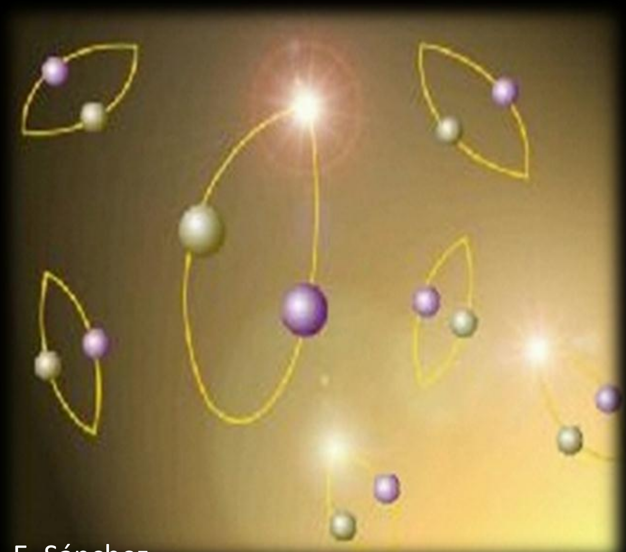
All current observations are compatible with dark energy being the cosmological constant. This is the most plausible and the most puzzling dark energy candidate.

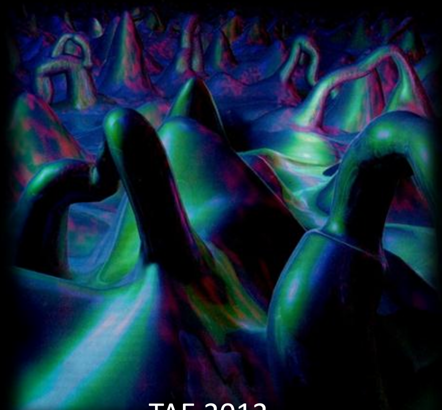
w= -1 with ~10% precision assuming flat universe and constant w

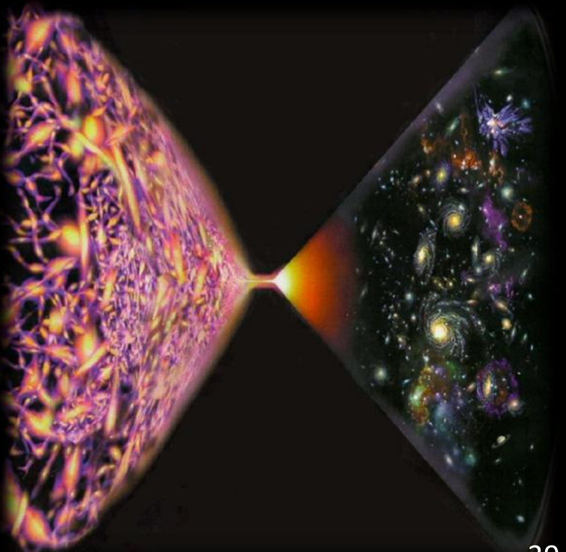
There is no physical explanation for Λ from the particle theory. If it is the vacuum energy

$$\Omega_\Lambda \sim 0.7 \longrightarrow \rho_\Lambda \sim (10\ \text{meV})^4$$

While the estimate from QFT is $\rho_\Lambda \sim M^4_{Planck} \sim 10^{120} \times (10\ \text{meV})^4$







Observational Probes of Dark energy

A phenomenological way to parametrise the dark energy properties:
Use the parameter w of the equation of state.

$$w=p/\rho$$

Main features to be tested observationally: **Is w=-1? Is dw/dz not null?**

Standard Candles: Measure $d_L=(1+z)\ r(z)$
Standard Rulers: Measure $d_A=r(z)/(1+z)$
Number Counts: Measure $dV/dz\ d\Omega = r^2(z)/\sqrt{(1-k\ r^2(z))}$
Growth of structure: A more complicated function of H(z)

DETF parametrizes $w(z) = w_0 + w_a\ (1-a)$; a(t)=scale factor=D(t)/D(0)

The DETF figure-of-merit (FoM) is the inverse of the area of the error ellipse enclosing the 95% confidence limit in the w_0-w_a plane. Larger figure-of-merit indicates greater accuracy. It is the standard way to compare measurements of dark energy

Observational Probes of Dark energy

The practical implementation of those observables can be done in many ways:

Distance probes: CMB acoustic peaks, SNIa, BAO, SZ+X-ray+Optical clusters, strong lensing statistics, Ly-alpha forest correlations, Alcock-Pazynski test, galaxy counts…

Growth of structure probes: CMB, weak lensing, galaxy clusters, Ly-alpha forest, ISW effect, …

Many tests to attack the problem of dark energy, with different sensitivities, different systematics and different levels of practical difficulty. **The study of dark energy must be done using multiple techniques.**

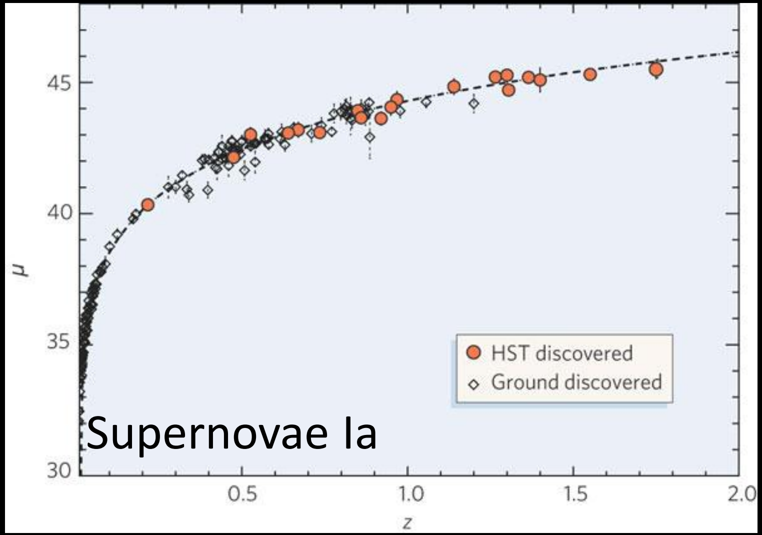
No single technique is sufficiently powerful to improve the knowledge of dark energy at the level of one order of magnitude.

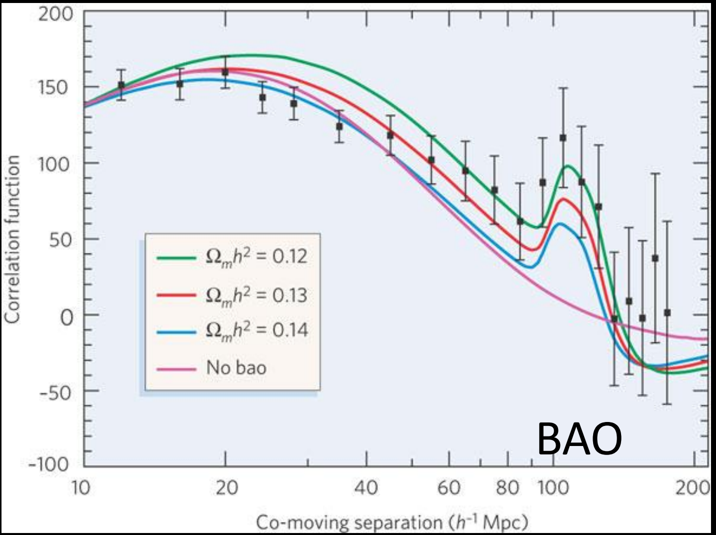
Combinations of techniques: substantially more statistical power, much more ability to discriminate among dark energy models, and more robustness to systematic errors than any single technique.

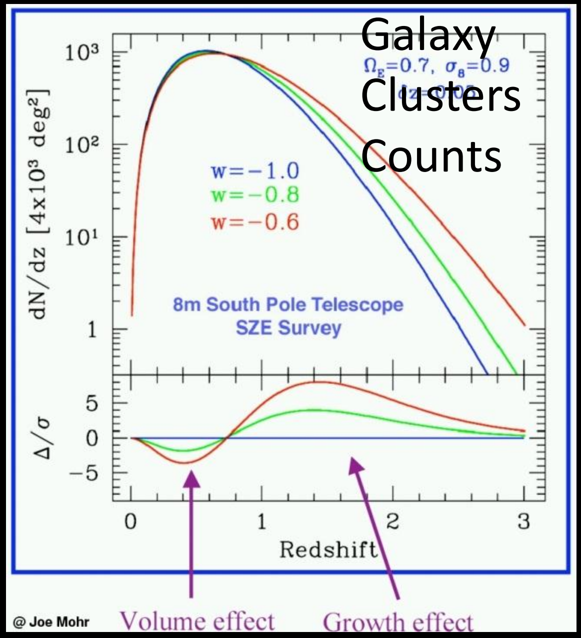
Also, the confirmation of results from any single method

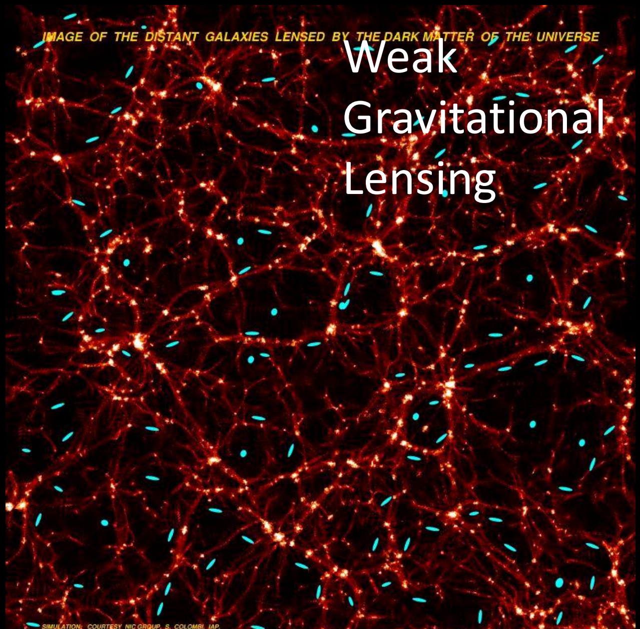
Observational Probes of Dark energy

Four methods are identified by the DETF as the most promising:







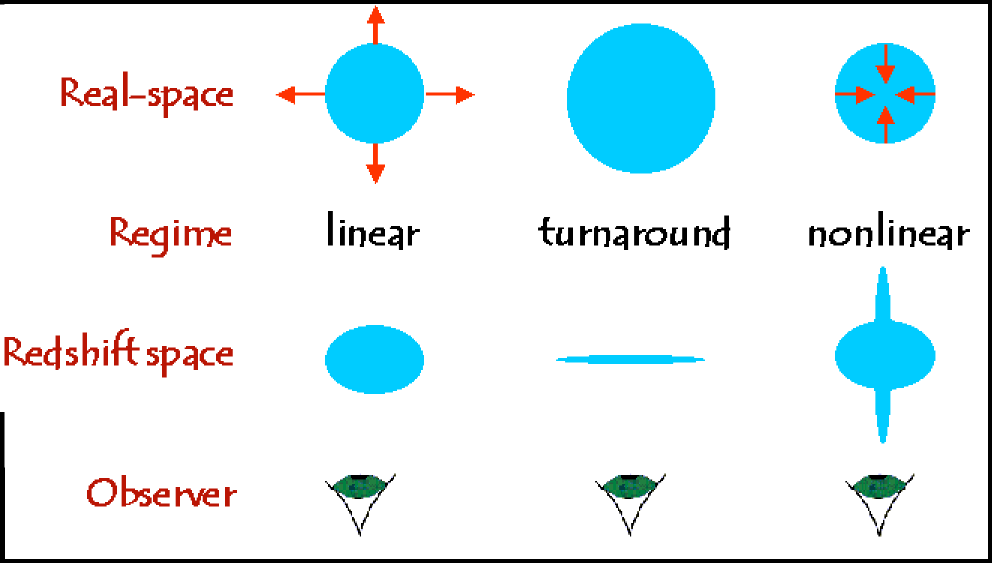


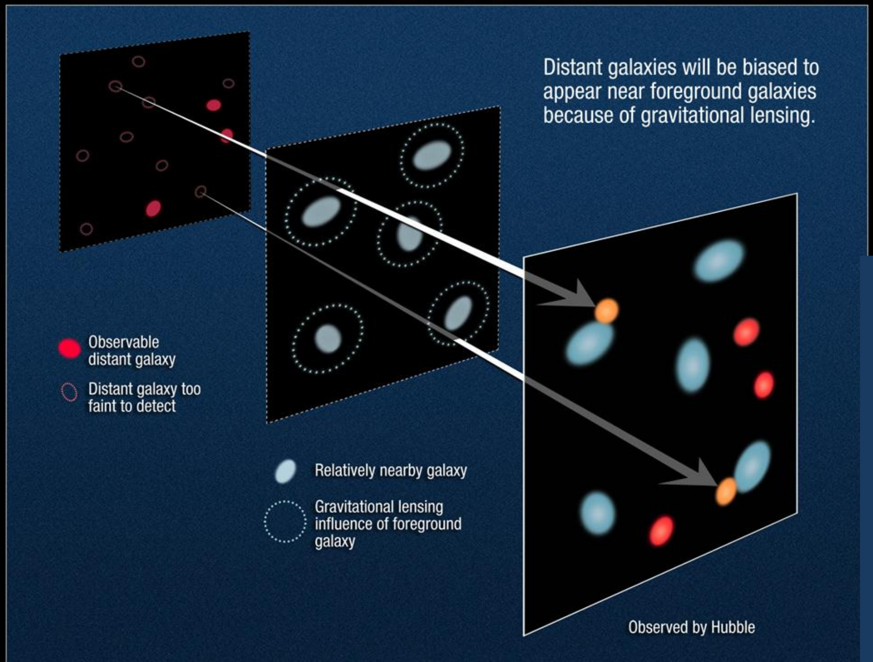
Observational Probes of Dark energy

And 2 more that have become important in recent years:

Redshift Space Distortions

Change the distribution of matter along the line of sight. The size of the effect is related to cosmology





NASA, ESA, and Z. Levay and A. Feild (STScI)

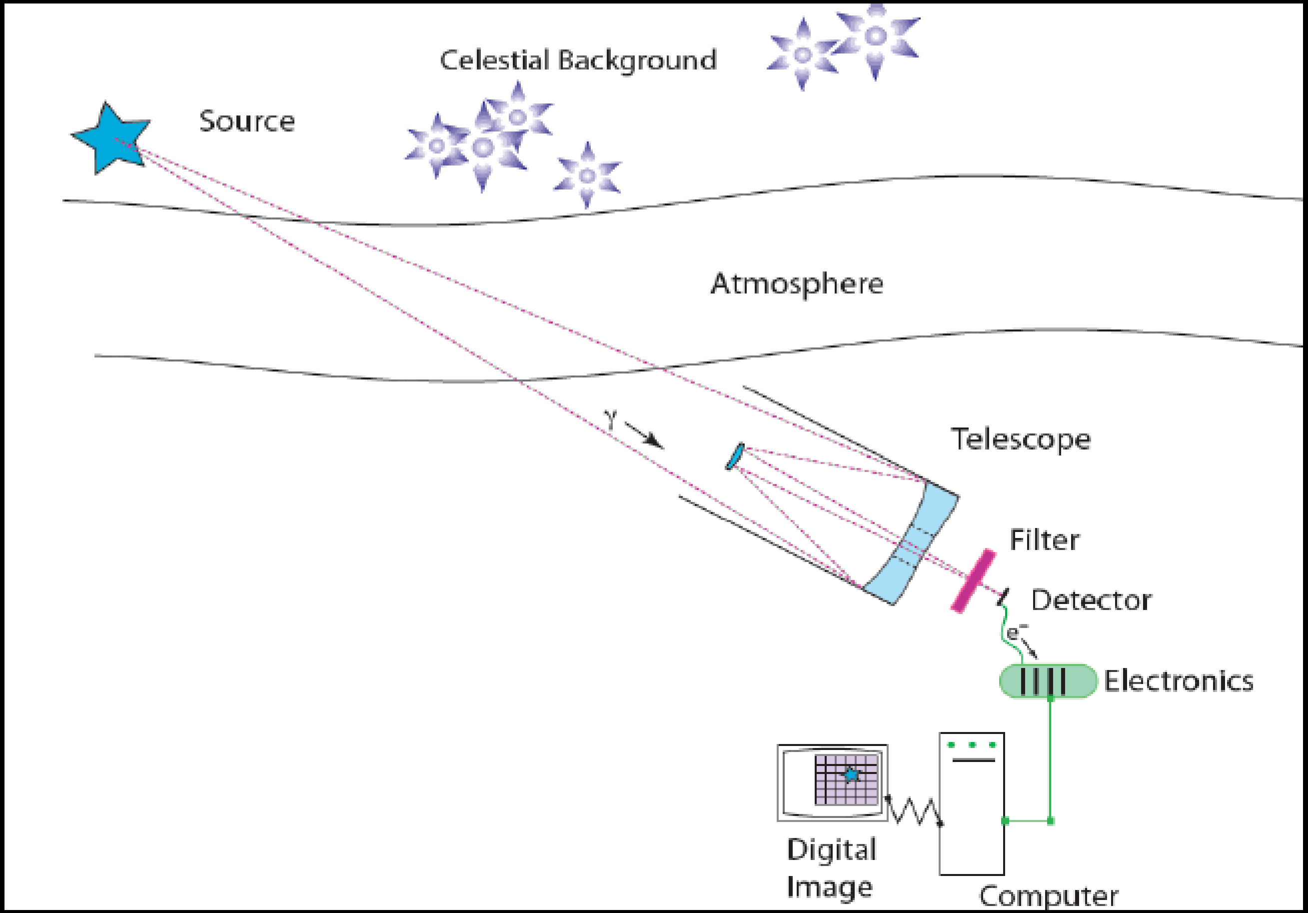
STScI-PRC11-04

Weak Lensing Magnification

The gravitational lensing effect can change the distribution of observed galaxies. Correlated with spatial distribution and therefore cosmology

How to measure these probes

In order to obtain scientific results, we need to take into account all the effects from the emission of light by the source to its translation into cosmological parameters



The source

Atmosphere: Seeing…

Telescope+optics: PSF…

Camera+Electronics+ DaQ

Pipeline for data Reduction

Scientific analysis

Types of observations

The information we obtain about the universe arrives in the form of particles: Photons, cosmic rays, neutrinos (…and dark matter, gravitational waves, anything else?)

Main body of cosmology observations uses photons (visible or NIR)
Several types of observations: Images, spectroscopy, sky background, calibration…
Main observables are: Number of photons as a function of energy, position, time, polarization…

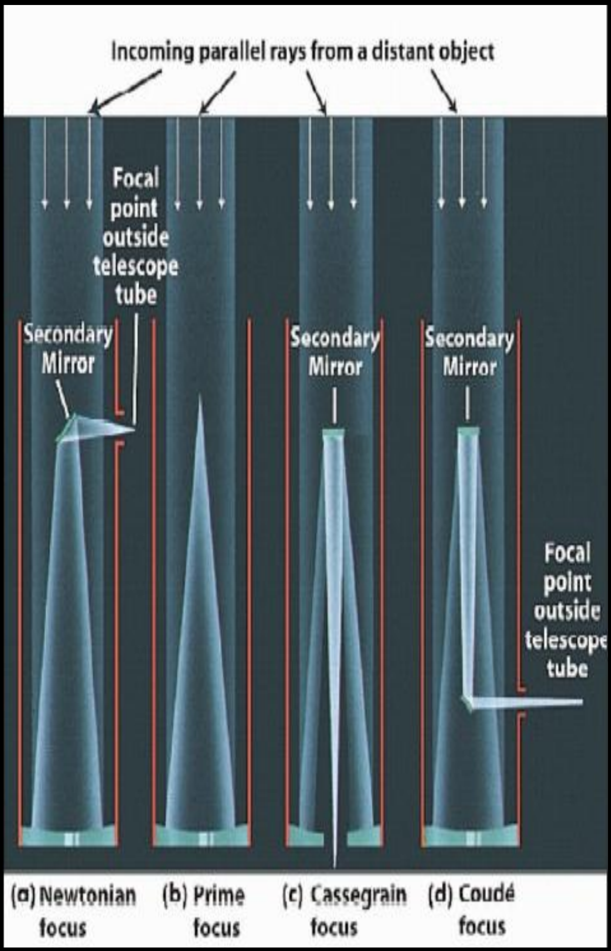
Signal in the detector → Photons properties → Source properties → Cosmological parameters

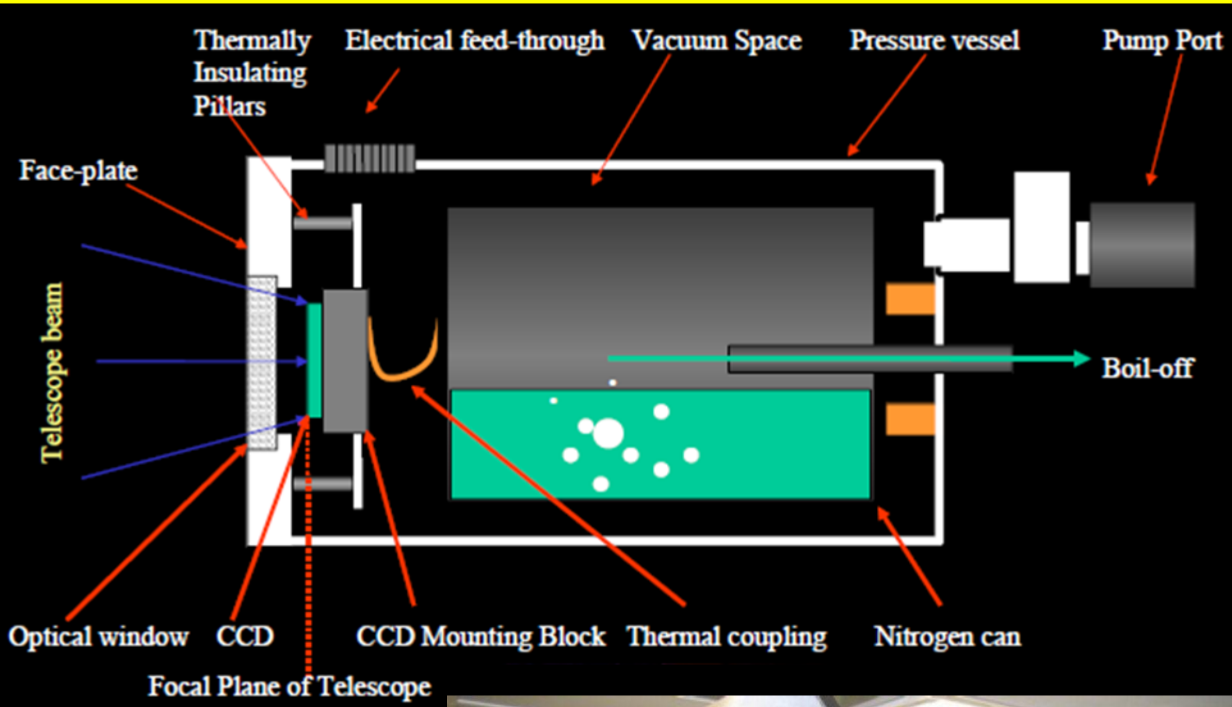
Example of Telescope

Light is measured with huge telescopes, located where the best sky observing conditions are available

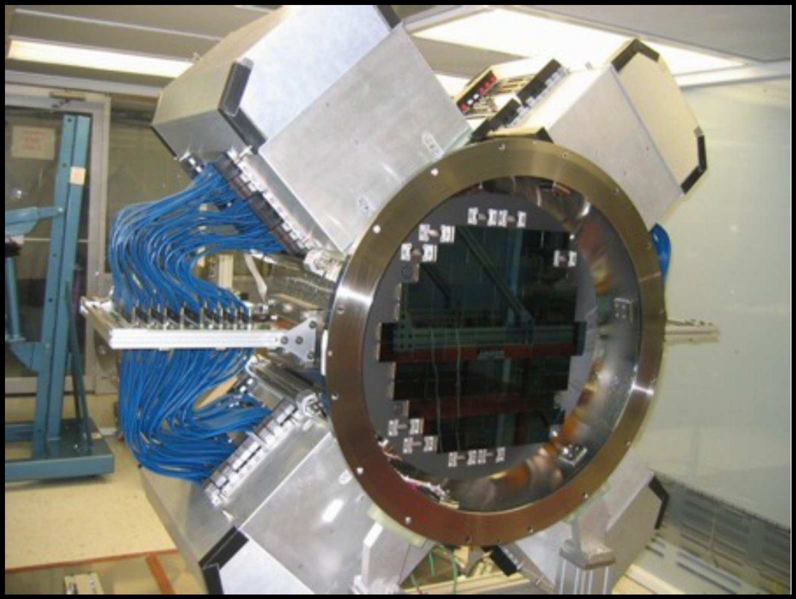
Blanco Telescope (4 m) at Cerro Tololo (Chile)

Astronomical Cameras



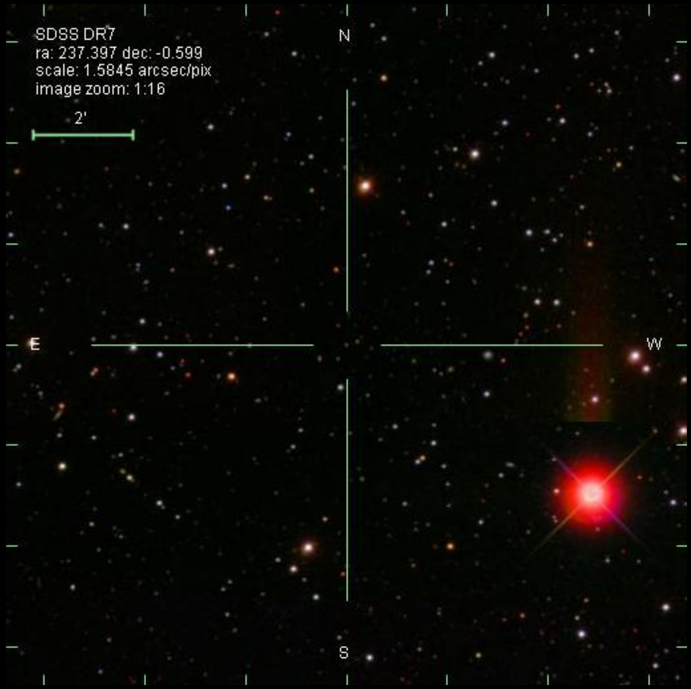


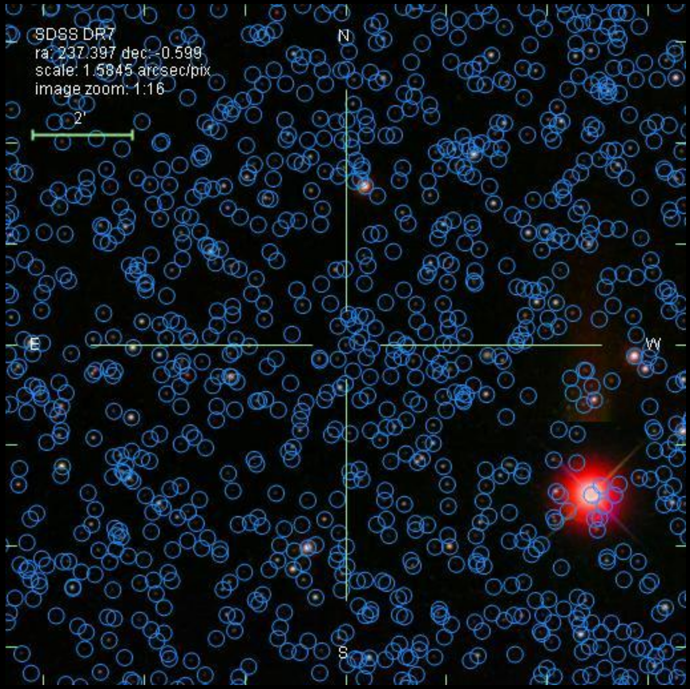
Example: Dark Energy Camera (DECam) @ Blanco Telescope



Obtaining Results from images

2 fundamental types of observations: Obtaining the full spectrum (need huge telescopes and large times. Only for selected targets) or obtaining colors from wide wavelength bands (for all objects, but less information)





To obtain cosmology from images:

Measure objects positions on the sky: From calibrated images (doable)

Classify objects: From spectrum (doable) or colors (difficult)

Measure the redshift: Doable from spectra, difficult from colors

Redshift Measurement

Spectroscopic Redshift:

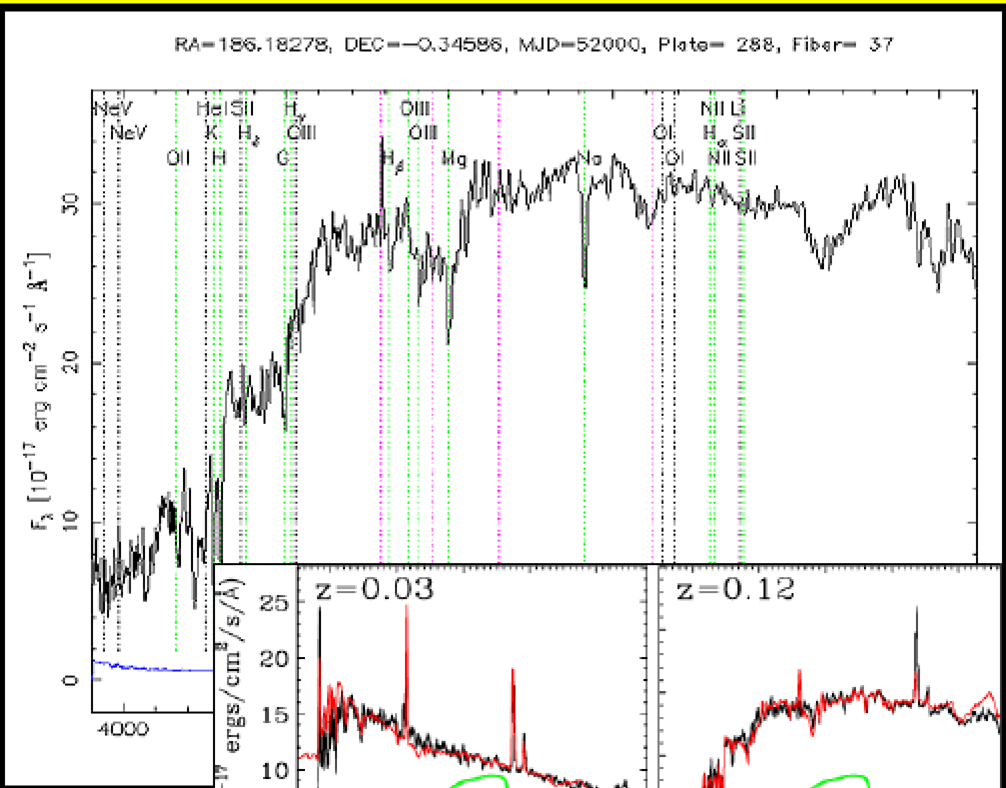
-Very precise through line identificcation

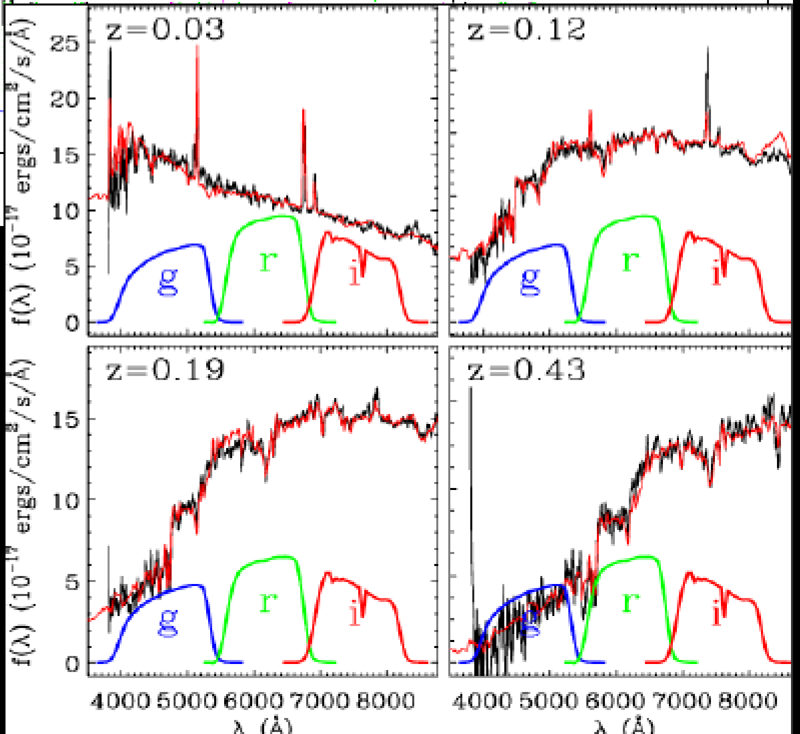
- Extremely hard: >45 minutes per object

Photometric Redshift:

-Less precise, measure flux within filters

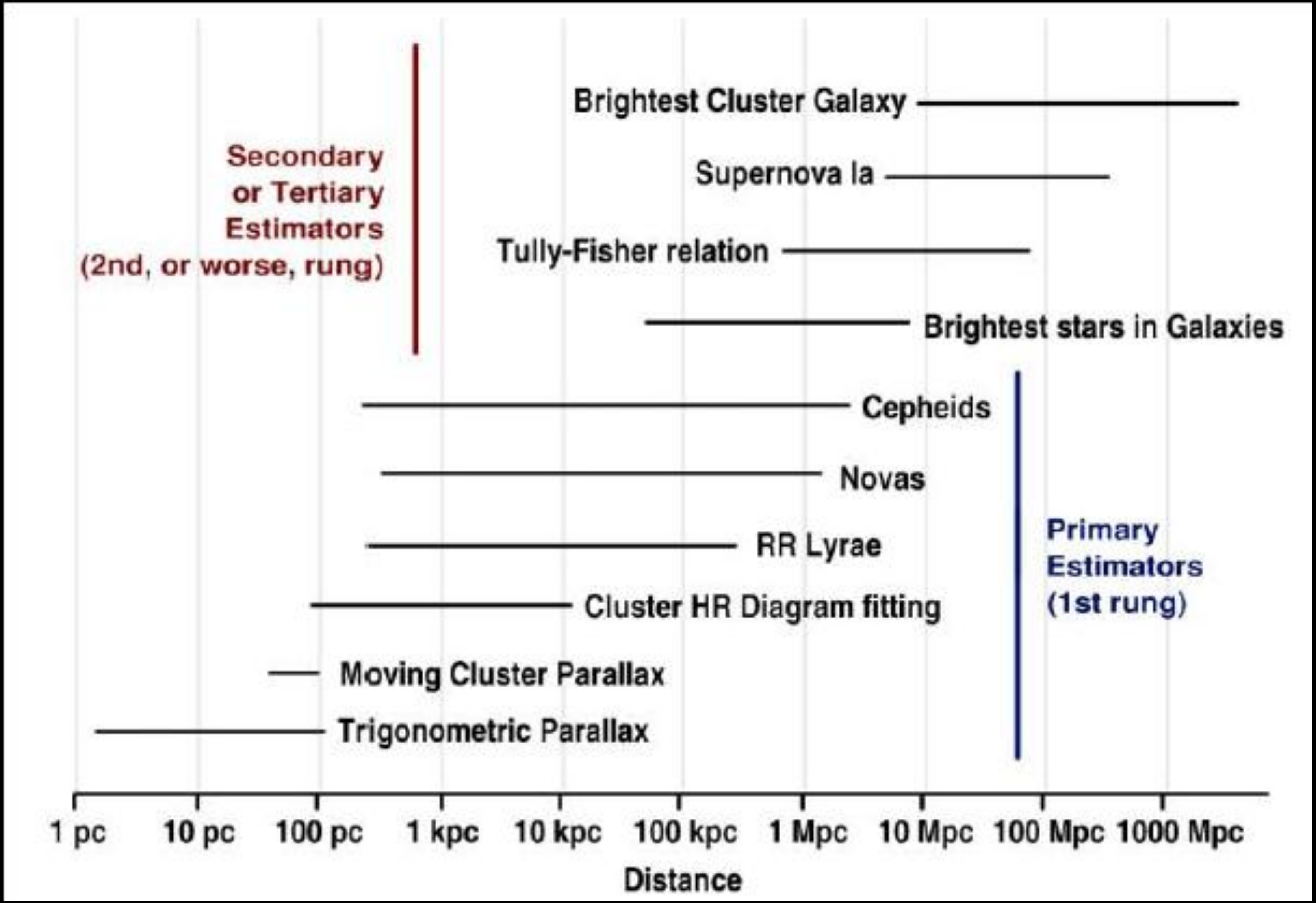
- Doable for all objects within an image in a few minutes





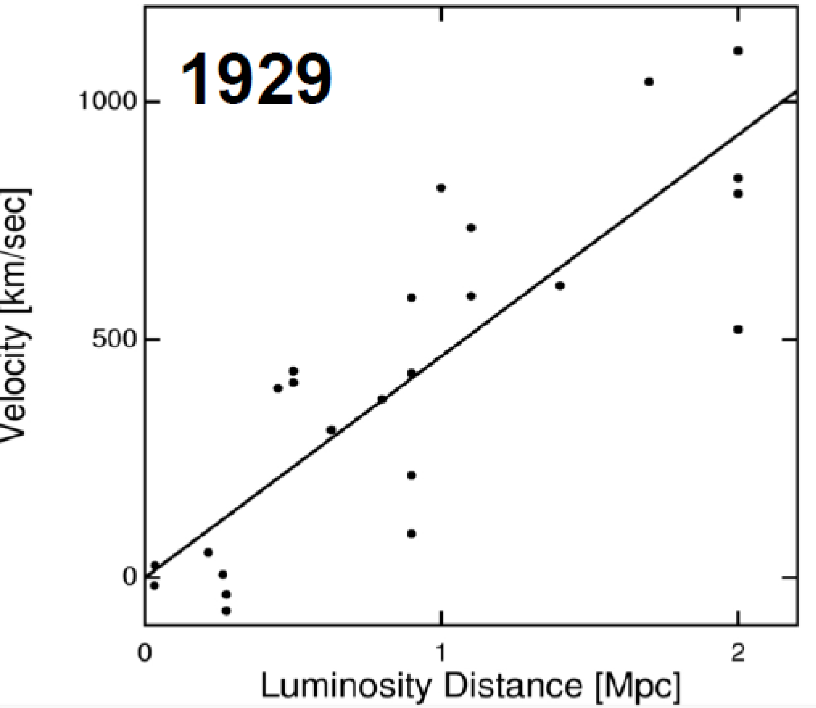
The Cosmic Distance Ladder

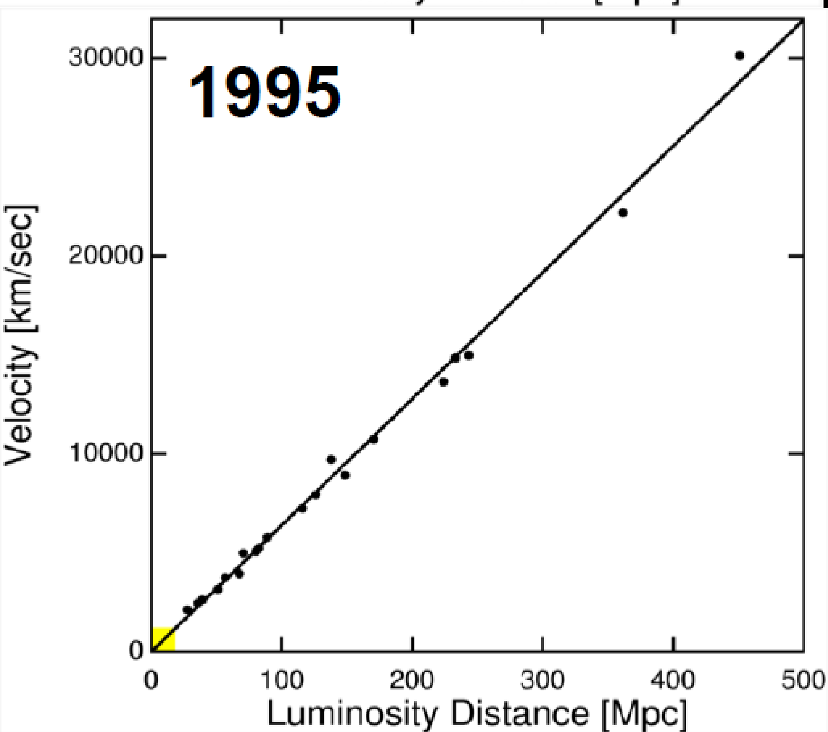
Each method is used to calibrate the next one



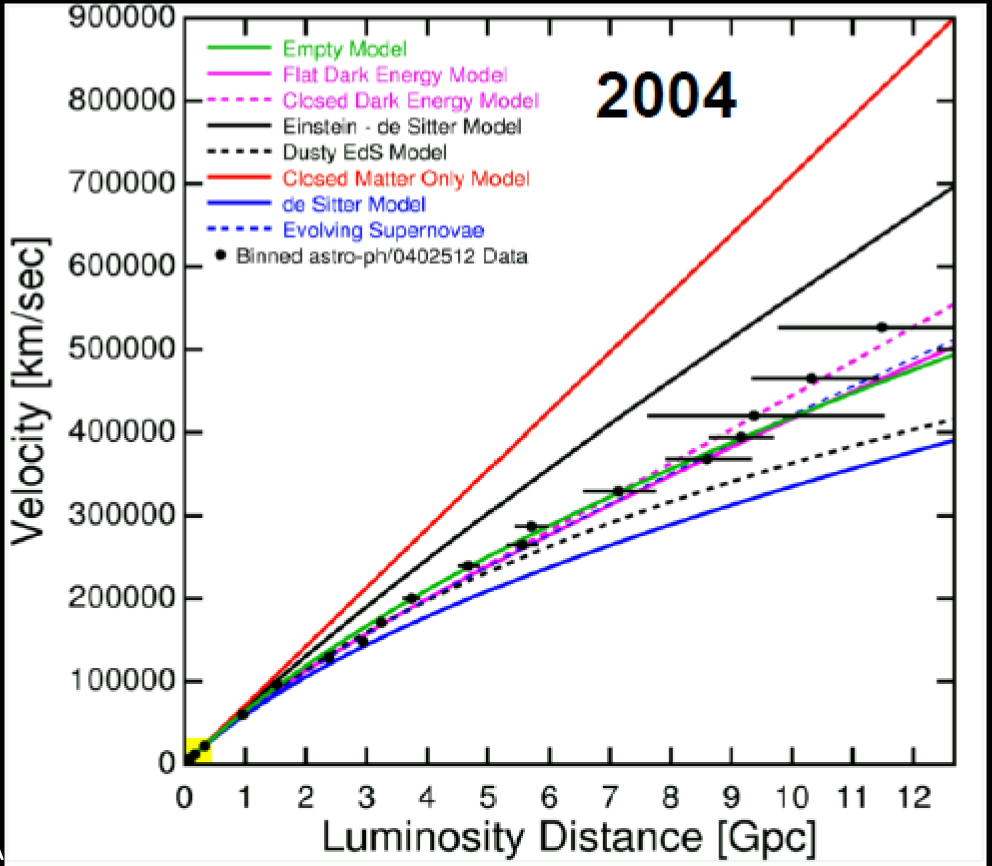
The Hubble Constant

The Hubble constant gives the expansion rate of the universe today. Its determination has become more and more precise. The current best value (2009) is **h0=74.2 ± 3.6 km/s/Mpc**





TA



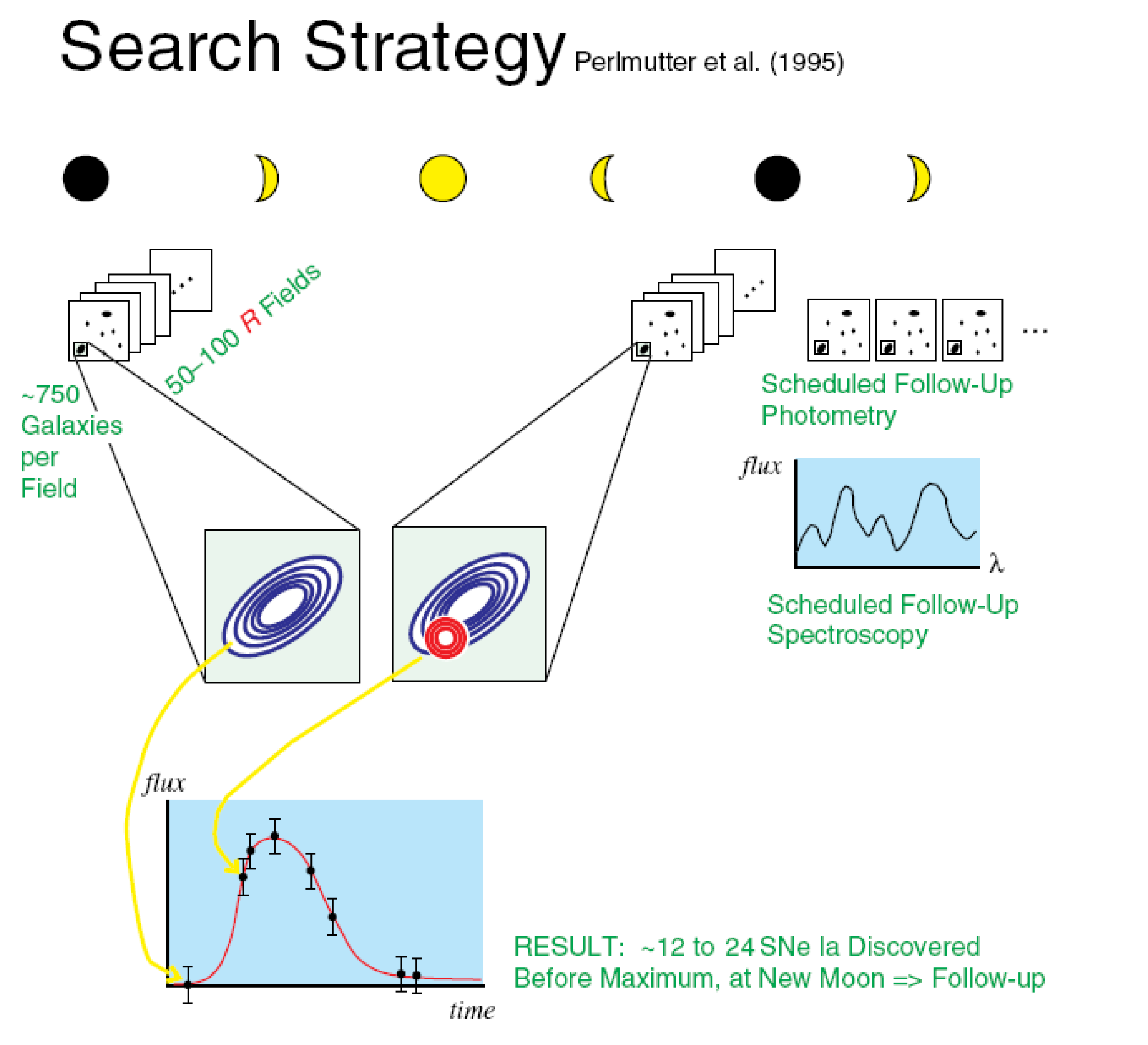
DARK ENERGY PROBES AND RESULTS

Supernovae Ia

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

The most mature technique to date

SN Ia are GOOD DISTANCE INDICATORS



Search strategy

- Rolling search
- Look systematically to the same part of the sky

Classification

- Obtain spectra and colors of all the supernovae

Obtain the light curves

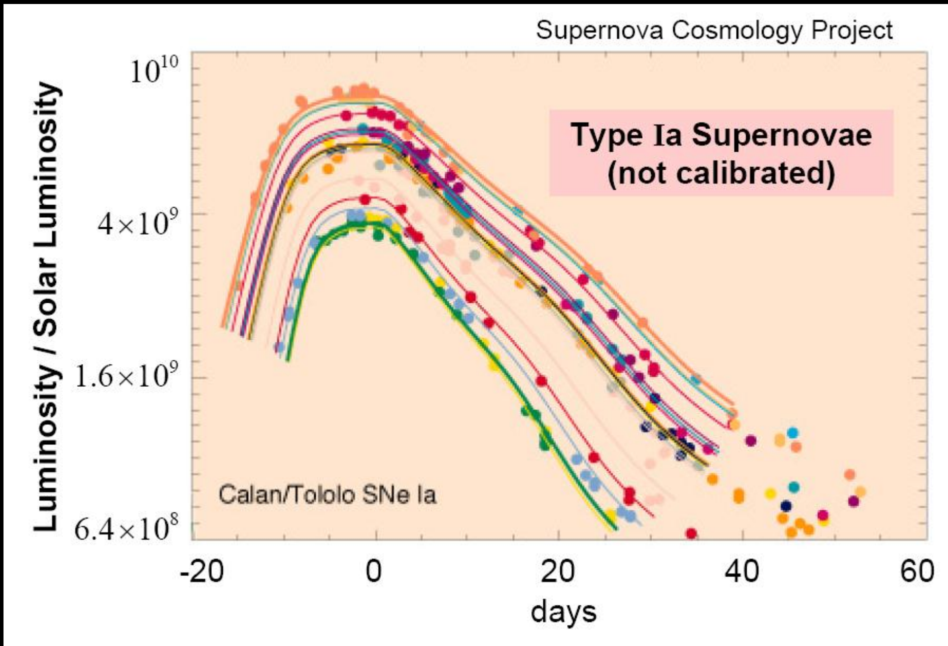
- In many colors

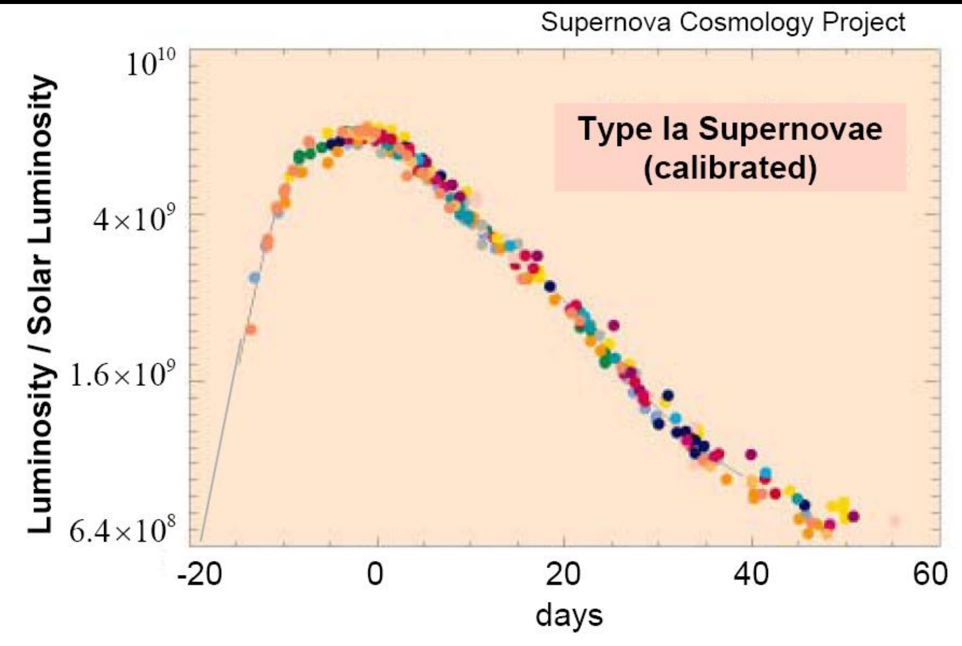
Supernovae Ia

SN Ia are GOOD DISTANCE INDICATORS

Not standard candles, but standarizable

Calibrated using nearby sne, cepheids and phenomenological models





Relate light curve shape to luminosity: Several precise phenomenological models have been developed, SALT2, MLCS2k2. More precise than the initial corrections Δm_{15} or the stretch factor.

Supernovae Ia

Once the magnitudes are measured, build the Hubble diagram

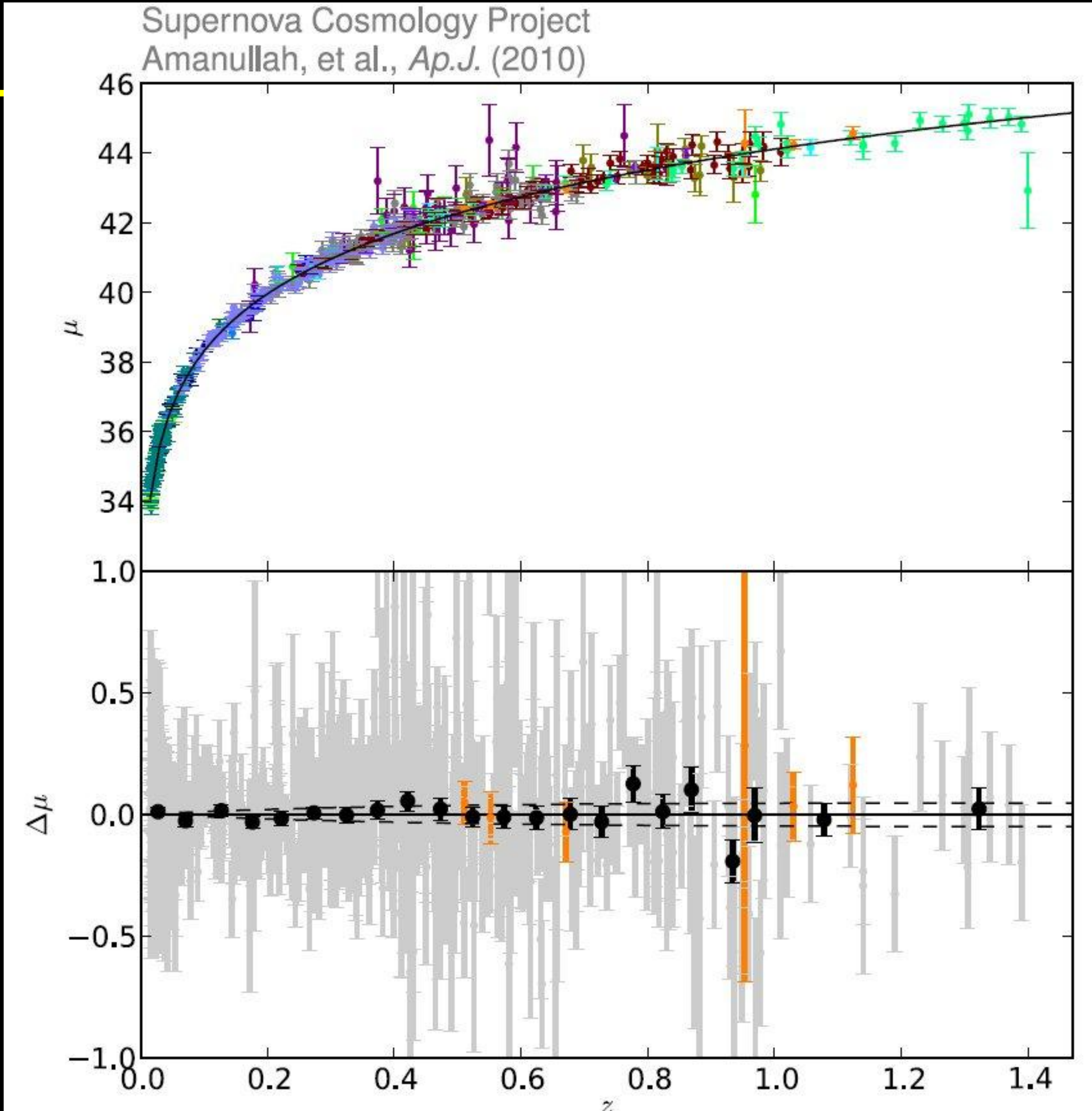
$\mu = m - M = 5\log_{10}(d_L/10pc)$
→distance modulus

and fit the cosmological parameters using a chi-square

M = Absolute magnitude (known for standard candles),

m = apparent magnitude (measured for each sn)

$$magnitude = -2.5\log_{10}\left(\phi_{SN}/\phi_0\right)$$



Supernovae Ia: Systematics from Union2 data set

Source	Error on w
Zero point	0.037
Vega	0.042
Galactic extinction normalization	0.012
Rest-frame U band	0.010
Contamination	0.021
Malmquist bias	0.026
Intergalactic extinction	0.012
Light-curve shape	0.009
Color correction	0.026
Quadrature sum (not used)	0.073
Summed in covariance matrix	0.063

Table from Amanullah et al 2010, ApJ, 716, 712

Baryon Acoustic Oscillations

- **Each initial overdensity (in DM & baryons) is an overpressure that launches a spherical sound wave (at 57% of the speed of light).**

- **Photons, that provided the pressure, decouple at recombination.**

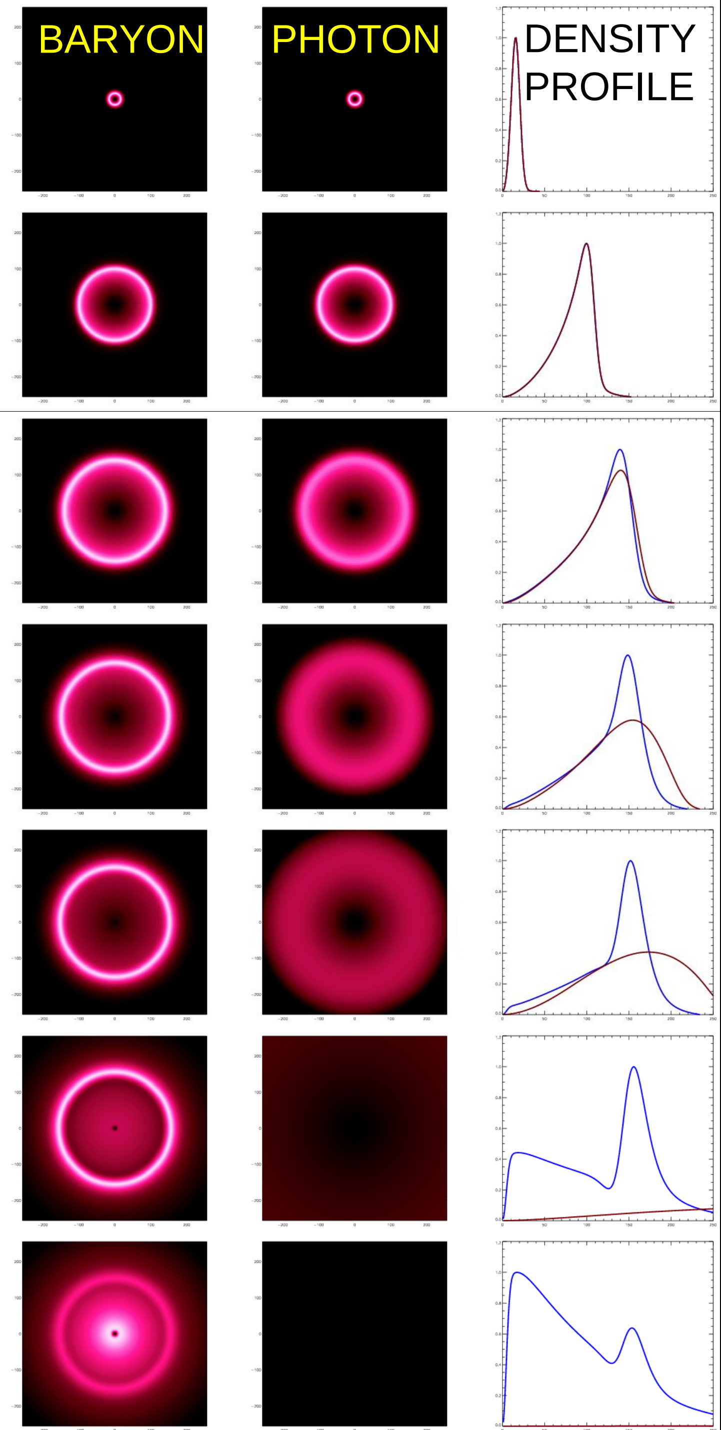
- **Sound speed drops very sharply and waves got frozen at a radius of 150 Mpc.**

- **An overdensity in baryons at 150 Mpc and at the origin (DM) both seed the formation of galaxies. More galaxies separated by this distance.**

- The scale of the acoustic oscillations depends on Ω_M and Ω_B.

- The CMB anisotropies measure these quantities and fix the oscillation scale at a redshift of ~1100.

- In a redshift survey, we can measure this scale both along the line of sight and perpendicular to the line of sight. These measurements give $H(z)$ and $DA(z)$ respectively!



At $z \gg 1000$ the universe was made of dark matter (DM), neutrinos and a highly-coupled relativistic photon-“baryon” (protons and electrons) gas.

Any initial over-density (in DM, neutrinos and gas) creates an overpressure that launches a spherical pressure (sound) wave in the gas.

This wave travels outwards at the speed of sound in the gas, $cs = c / \sqrt{3}$

At $z \sim 1100$ ($t \sim 350\,000$ yr), temperature drops enough ($T \sim 3000$ K) for protons and electrons to combine into neutral hydrogen atoms. Pressure providing photons decouple and free-stream to us (CMB)

Sound speed of baryons plummets. Wave stalls at a radius of ~150 Mpc, fixed by CMB measurements.

Over-density in the original center (DM) and in the shell (gas) both seed the formation of galaxies

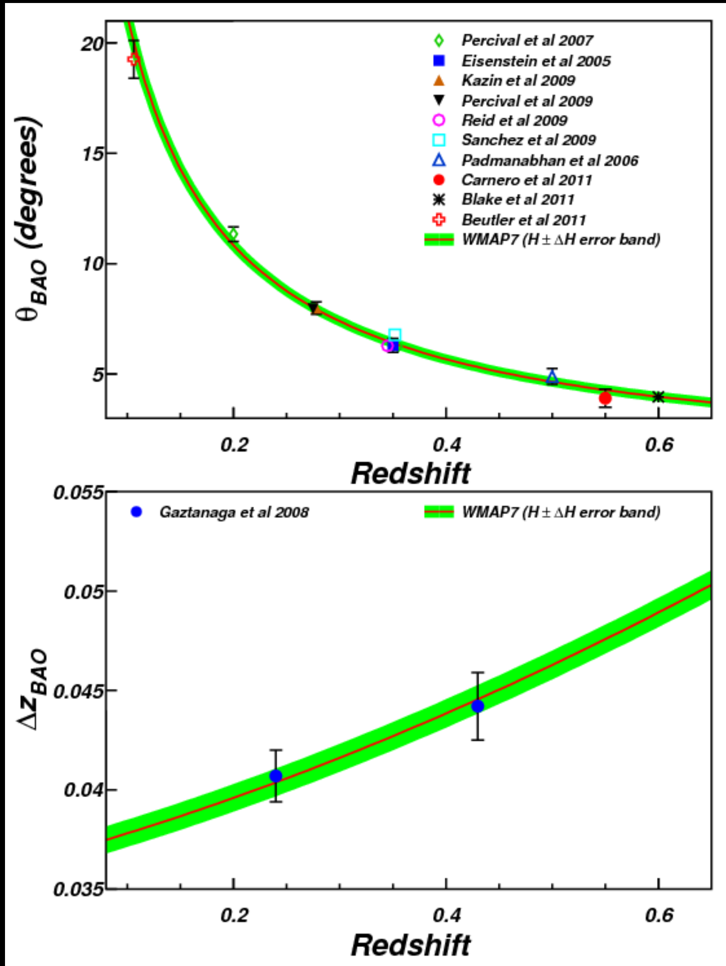
Preferred separation of galaxies at 150 Mpc:
STANDARD RULER

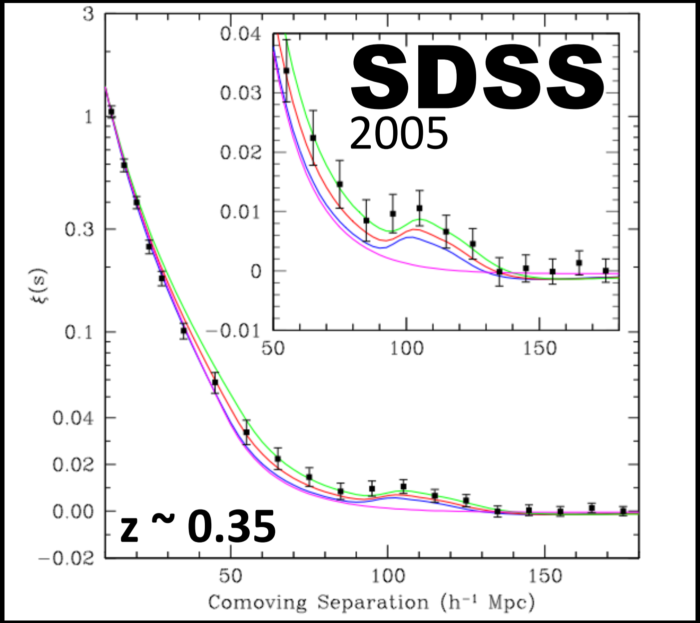
http://astro.berkeley.edu/~mwhite/bao/

Baryon Acoustic Oscillations

Measure the position and redshift of galaxies and compute the correlation function (or the power spectrum).

This is an emerging technique. Less affected by systematic errors than the other probes of dark energy.





Main Systematics:

Galaxy Bias

Redshift Space distortions

Non-linearities

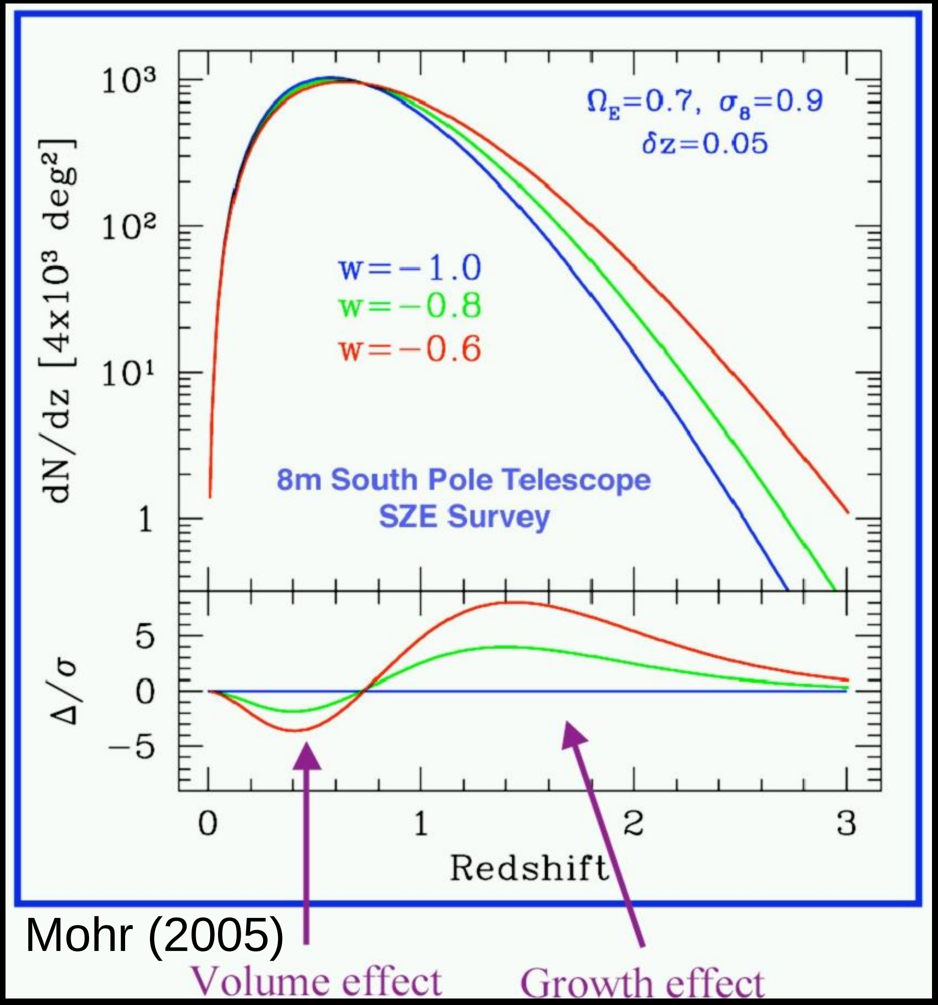
Photo-z

Number Counts of Clusters of Galaxies

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

Sensitivity comes from the volume element and from the growth of structure as a function of the redshift

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

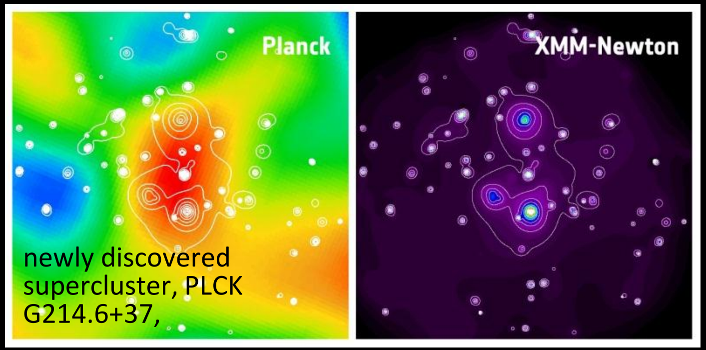


Number Counts of Clusters of Galaxies

To obtain cosmology from clusters of galaxies, first we have to identify them. Several methods have been proposed:

Sunyaev Zel'dovich effect
X-ray emission from cluster gas
Optical data
Weak lensing

PLANCK Data release (16/01/2011)

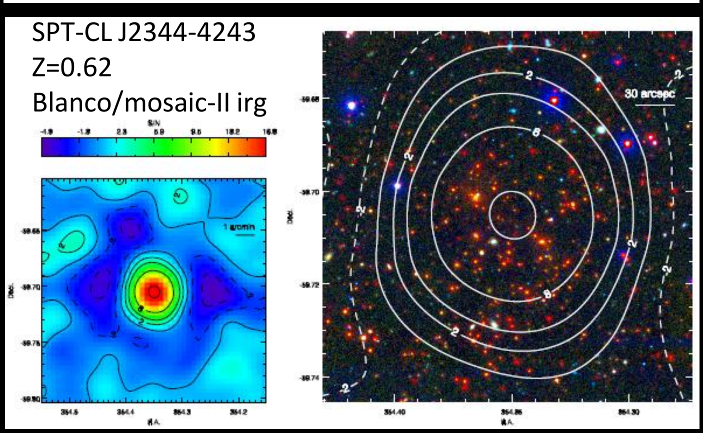


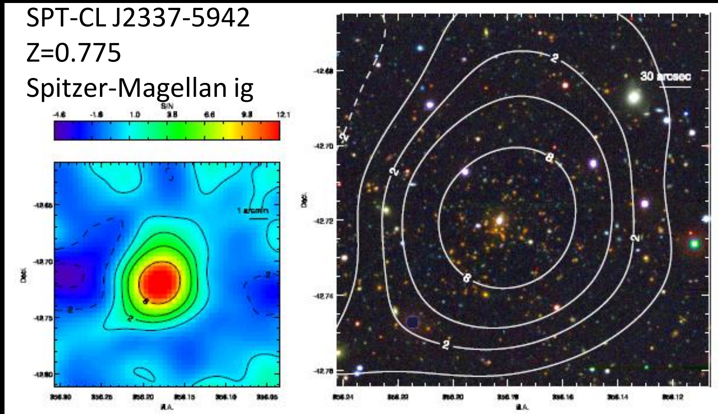
Second, measure mass and redshift

Mass from SZ, X-ray or lensing

Redshift from optical

SPT Results
R. Williamson et al., arXiV:1101.1290 astro-ph (2011)





Number Counts of Clusters of Galaxies

This is an emergent and very promising method, but not has been probed yet. Its final sensitivity will be fixed by the systematic errors

SYSTEMATICS:

Observable-mass relation: X-ray, SZ and weak lensing calibration

Sample selection, contamination

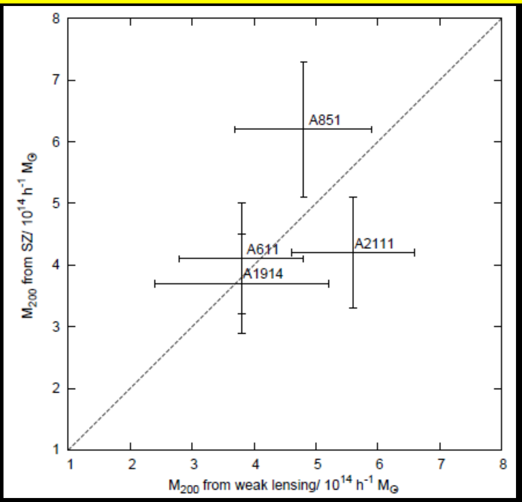
Photometric redshift

Needs:

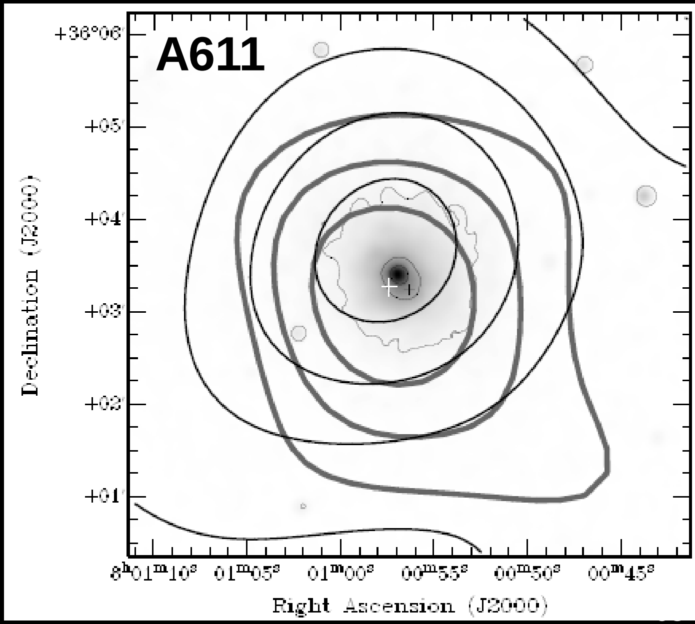
Clean way of selecting a large number of clusters

Redshift of each cluster

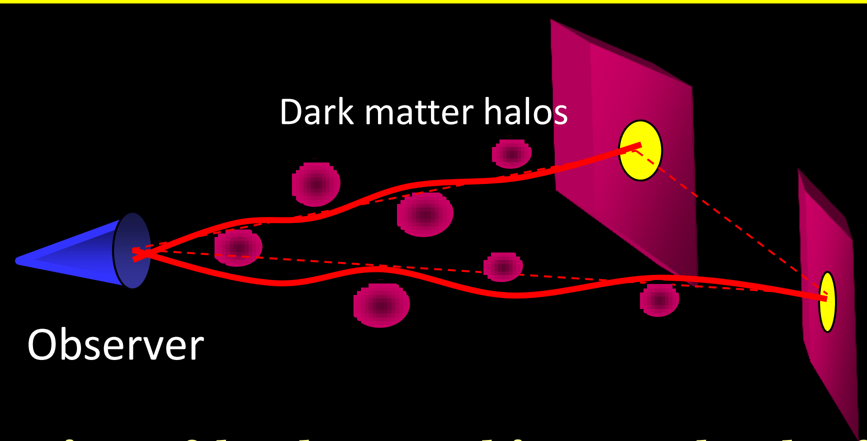
Observables that can be used as mass estimators



First mass estimations from weak lensing
AMI consortium
ArXiv:1101.5912 [astro-ph] (2011)

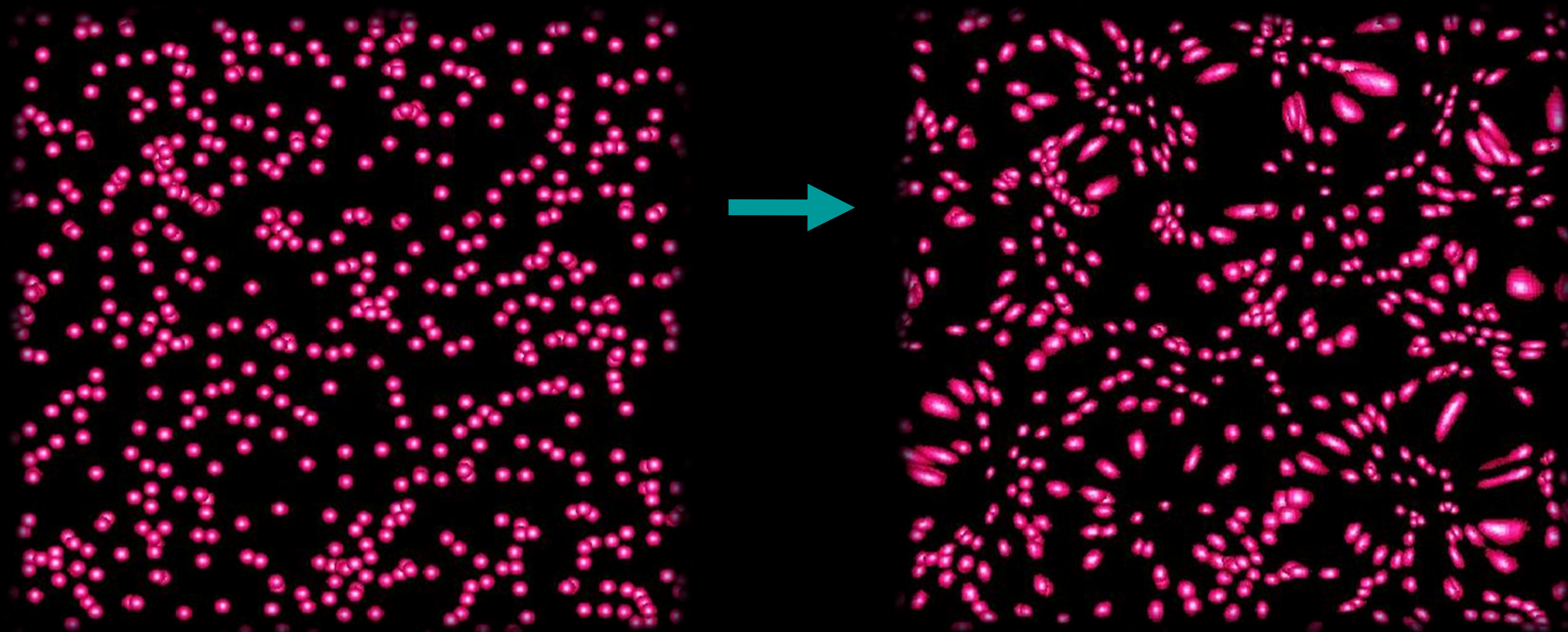


Weak Gravitational Lensing



Measure the distortion of background images by the foreground matter

Weak lensing effects of the order of 1%



UNLENSED LENSED

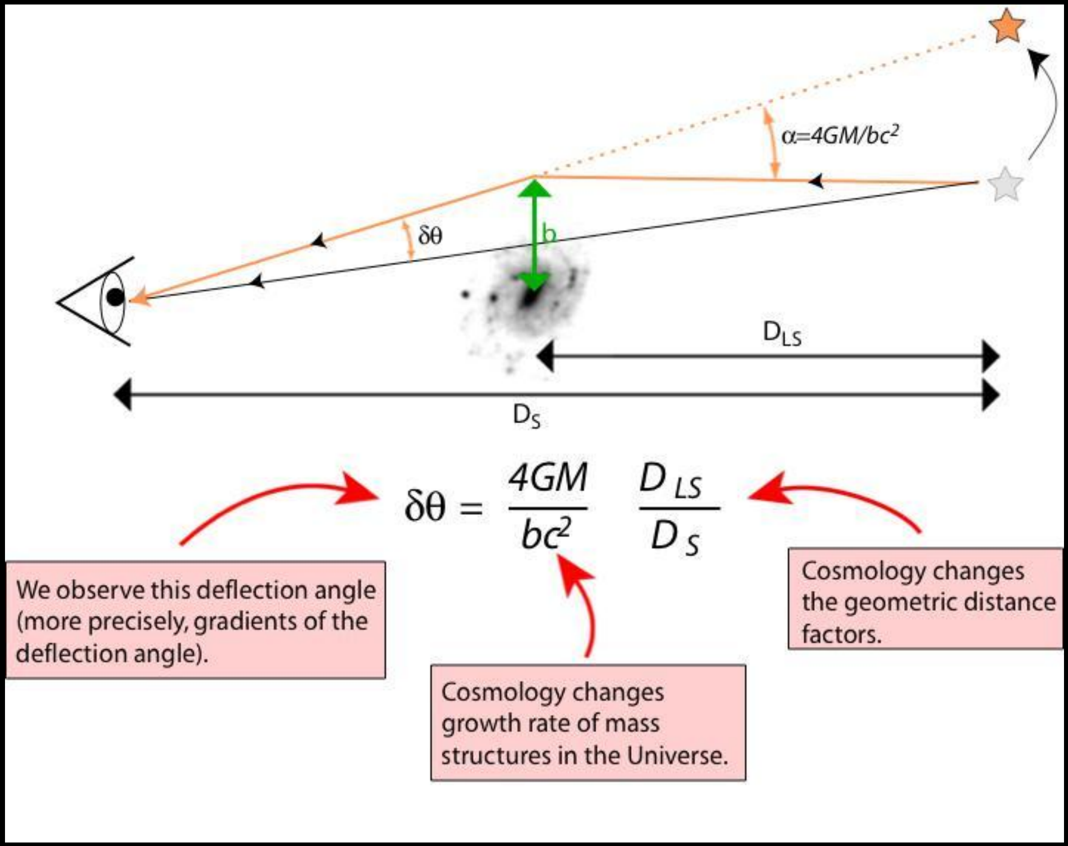
Weak Gravitational Lensing

Magnification and distortion effects due to weak lensing can be used to probe the statistical properties of the matter distribution between the observer and the distant sources.

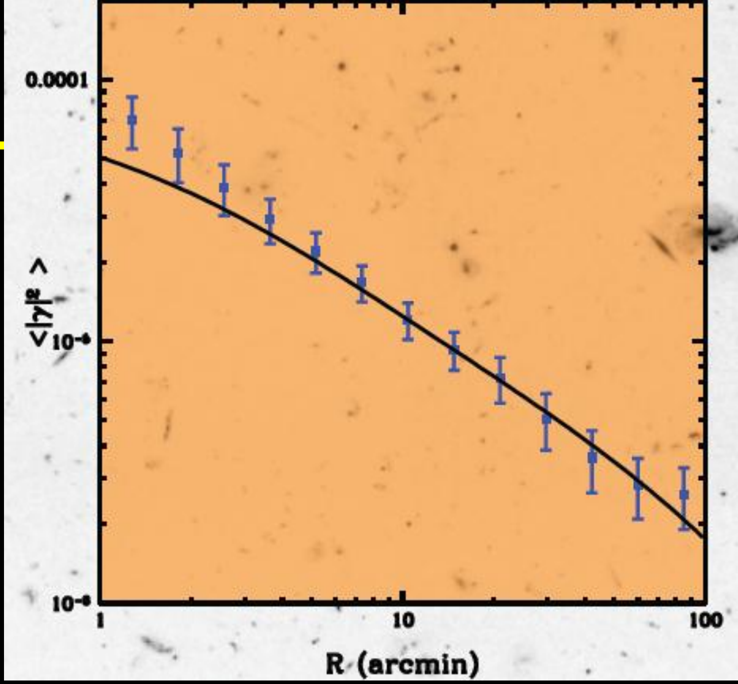
Assume that galaxies are intrinsically randomly oriented . Then, any coherent alignment of images signals the presence of an intervening tidal gravitational field.

The positions on the sky of galaxies at different distances should be independent. A statistical association of foreground galaxies with background galaxies can indicate the magnification.

Weak lensing is sensitive to cosmology through distances and the growth factor.



Weak Gravitational Lensing



CTIO Lensing Survey
75 square degrees
~2 million galaxies
Jarvis et al.,
ApJ 644 (2006) 71
astro-ph/0502243

Systematics:

Theory: Small scale power spectrum

Galaxy shape measurement

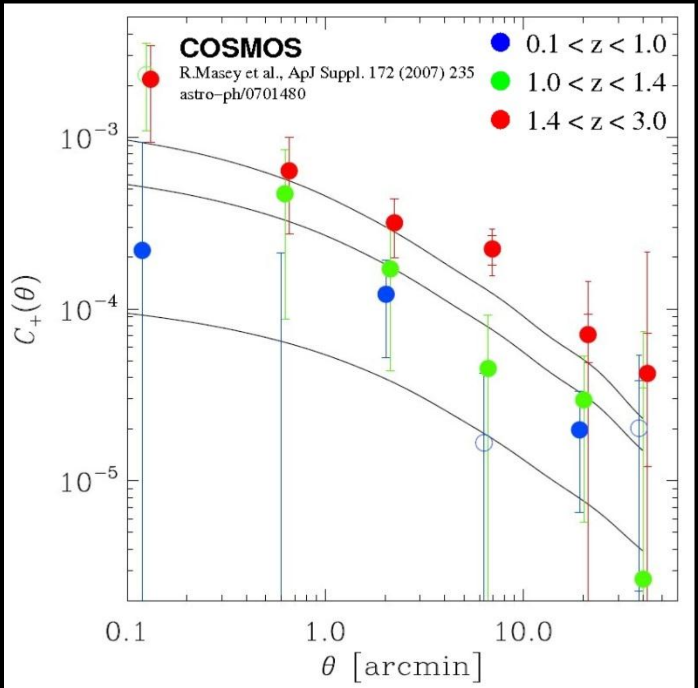
Redshift measurement

Intrinsic alignment

False detections shear

Control the PSF and instrumental effects very carefully.

COSMOS from HST
1.64 square degrees up to
Magnitude 26.6
R. Massey et al.
ApJ Suppl. 172 (2007) 235
astro-ph/0701480



CURRENT SITUATION: COSMOLOGICAL PARAMETERS

Current Situation: CLUSTERS AND WEAK LENSING

NO SIGNIFICANT CONSTRAINTS ON DARK ENERGY YET

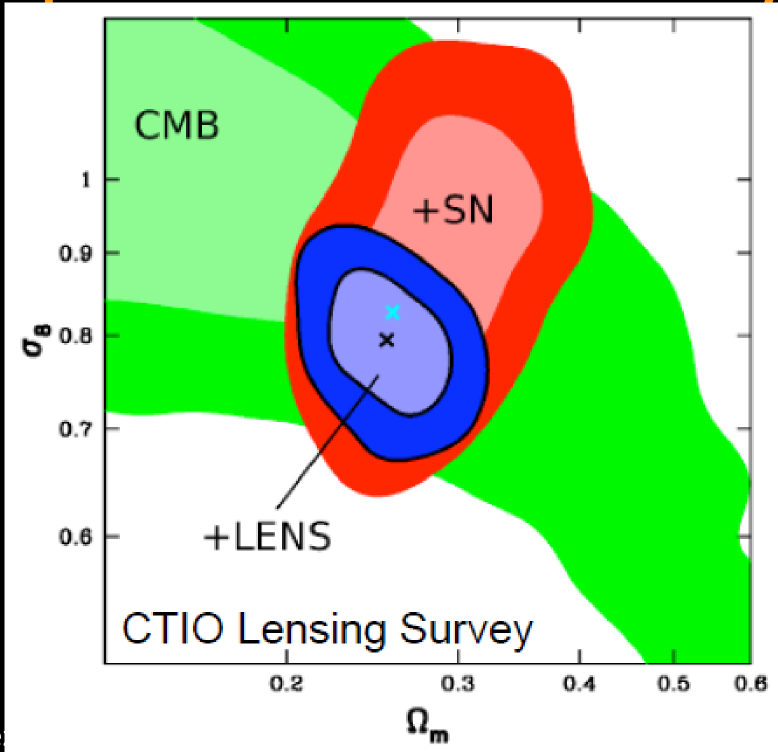
CLUSTERS:

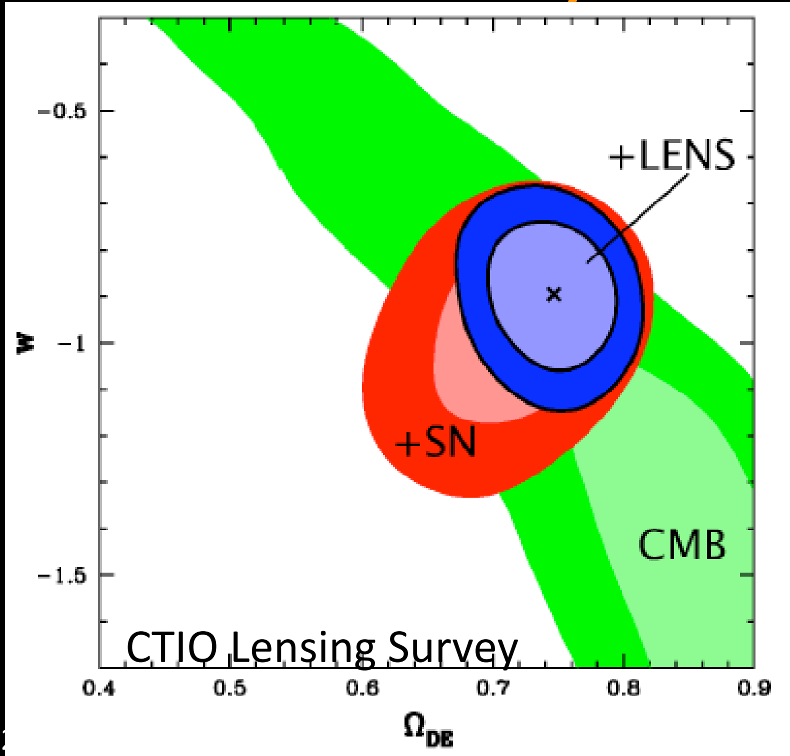
SZ effect measured (SPT, ACT, Planck…)

No dark energy constraints

WEAK LENSING:

Shear signal has been measured in many small surveys: Proof of concept. Results still limited by the size of the surveys

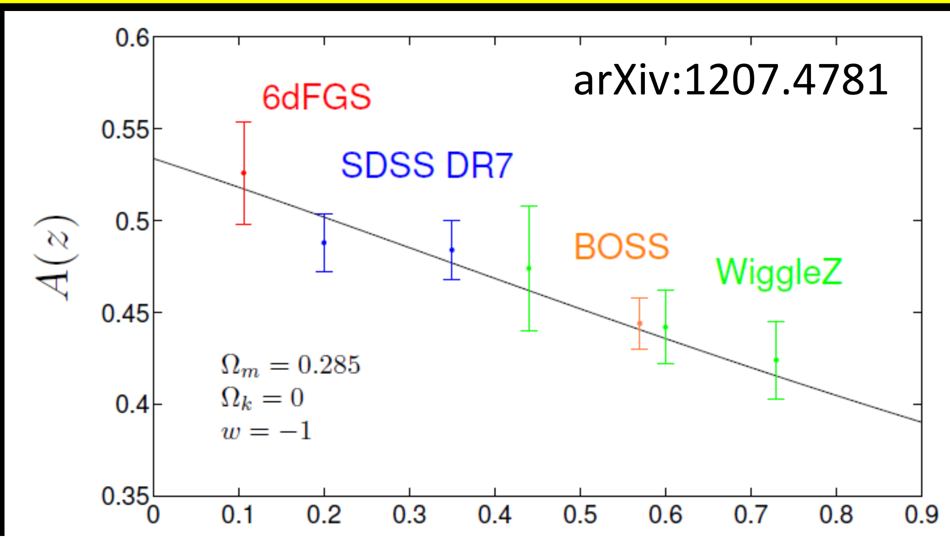




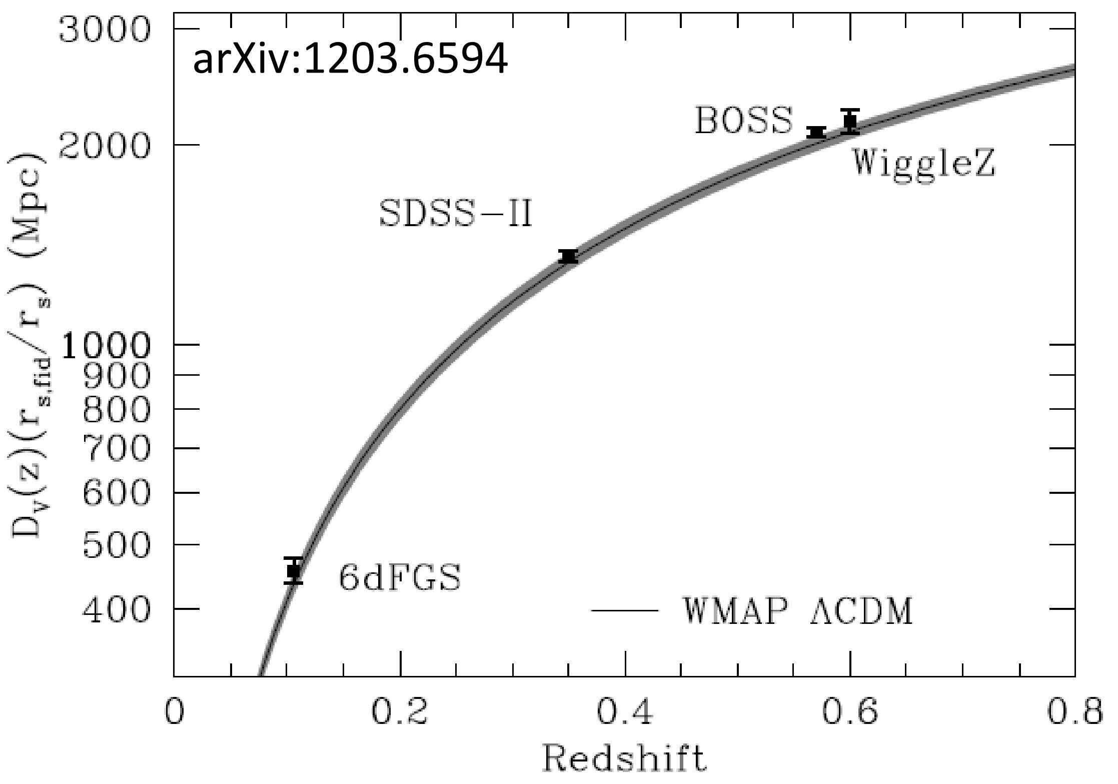
Current Situation: BAO

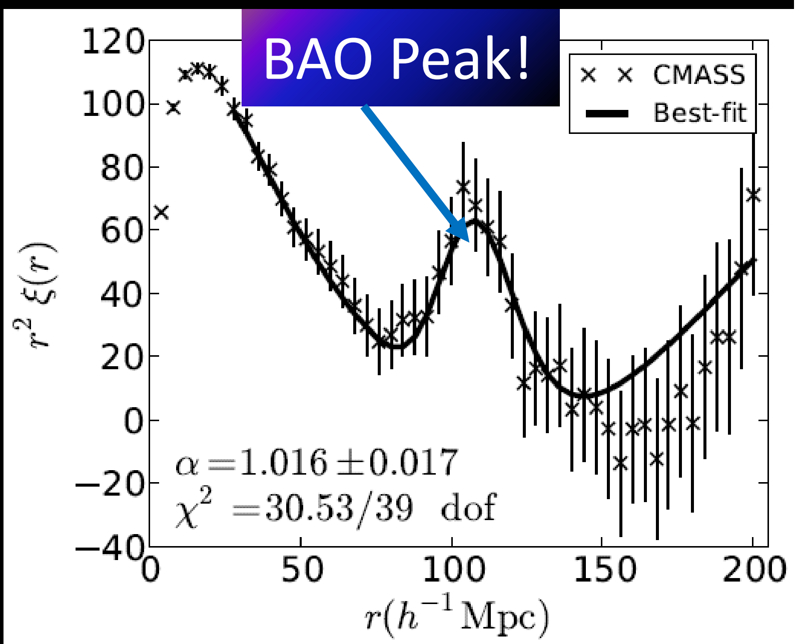
Current results from SDSS,2dF, WIGGLEz and BOSS Start to constrain the properties of the dark energy

BAO is a geometric constraint: A combination of angular diameter distance and Hubble parameter is used



Latest Results from BOSS Survey (03/2012) BAO peak observed at 6 sigma significance

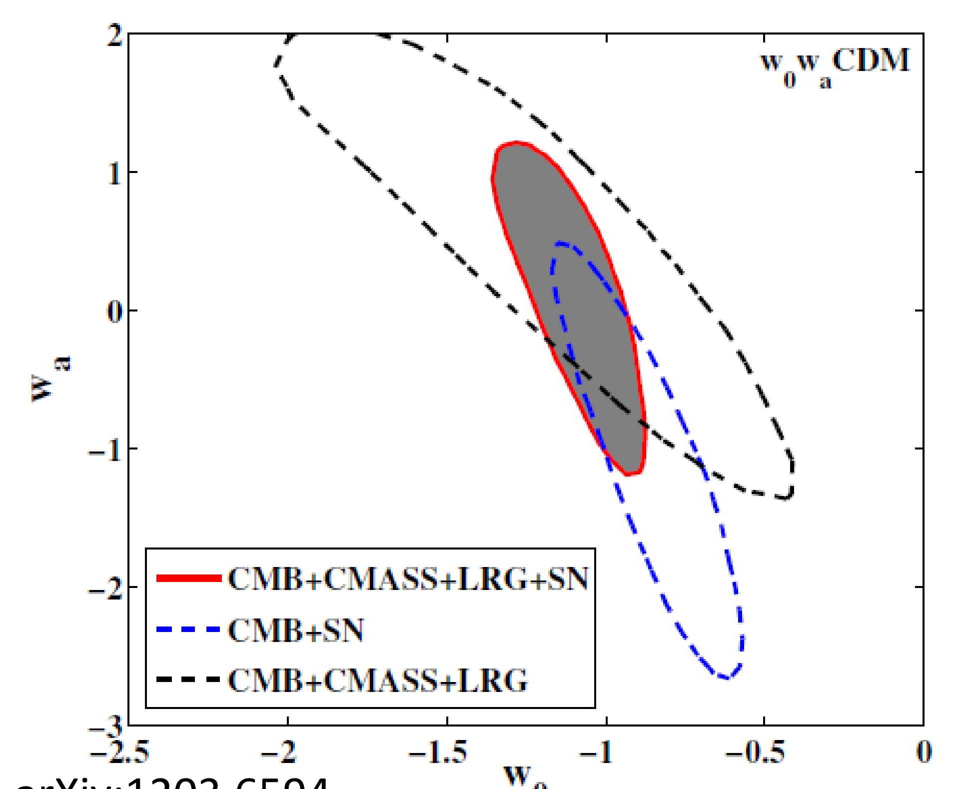




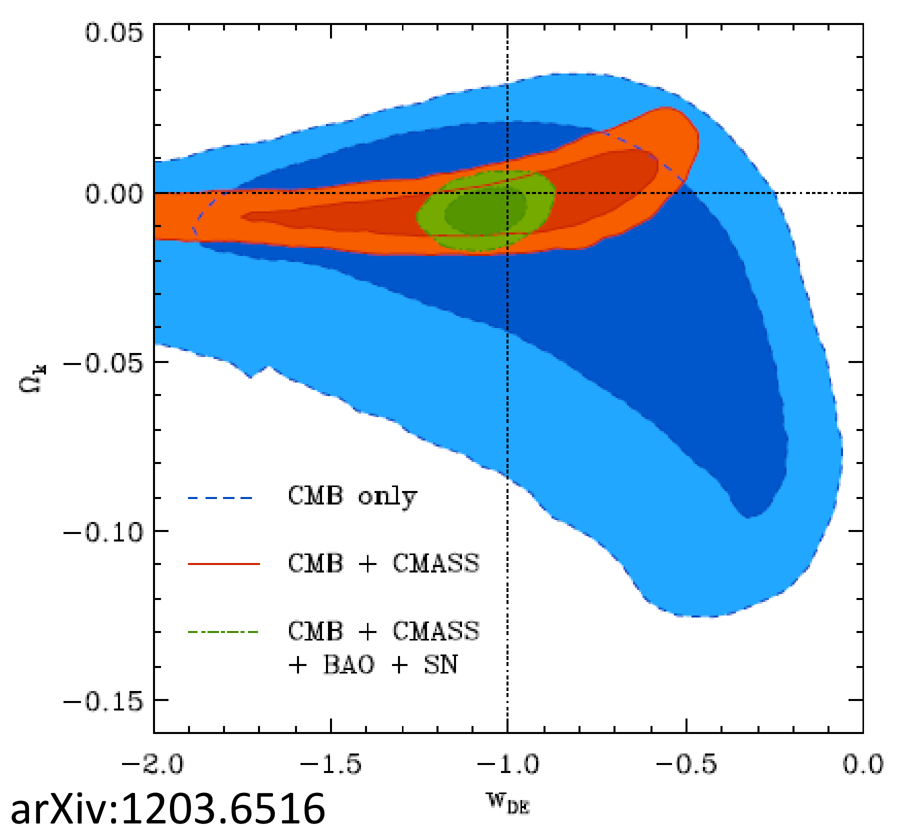
Current Situation: BAO

BAO data are compatible with dark energy being a cosmological constant

BAO used up to redshift 0.6. Still a large room for improvements

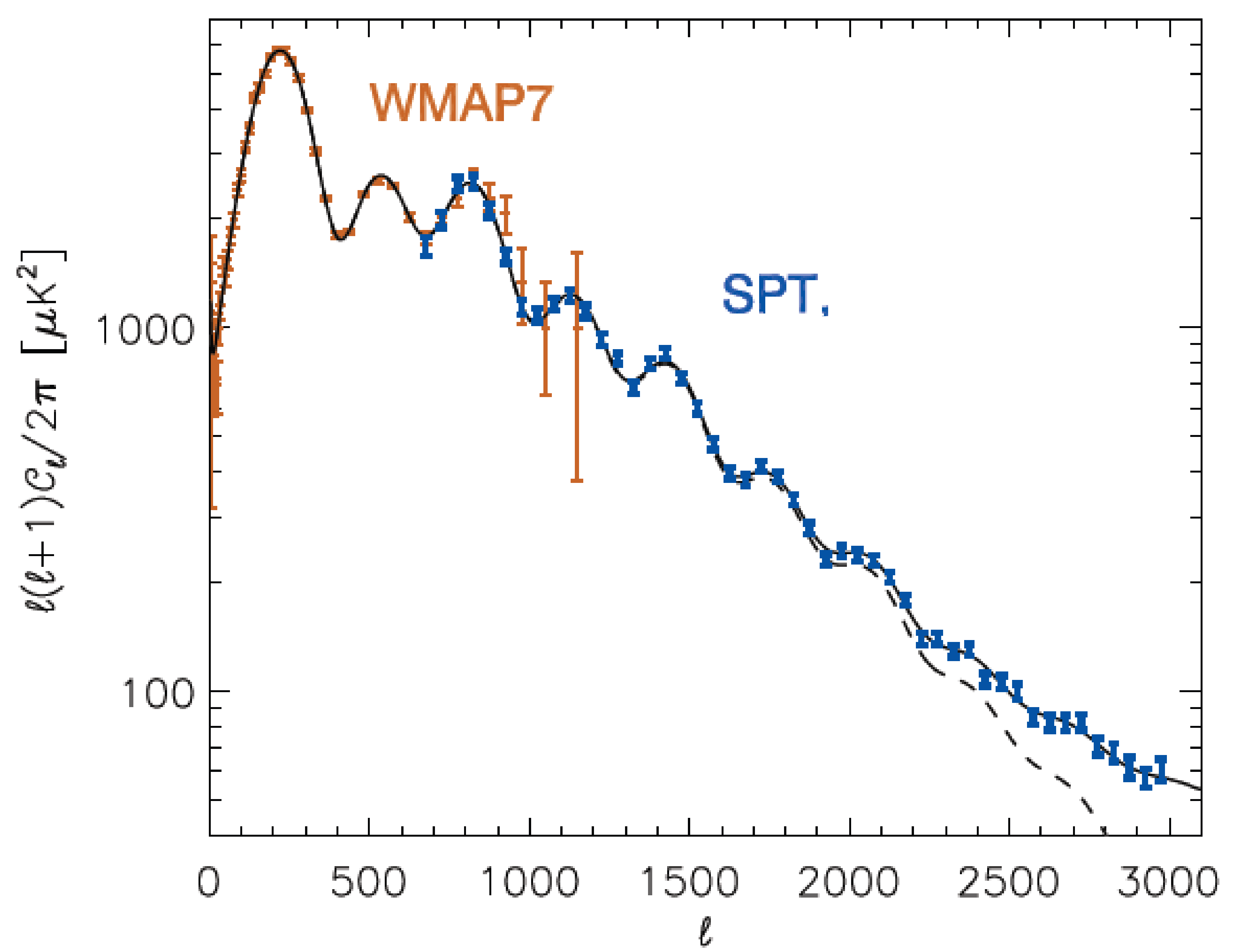


arXiv:1203.6594

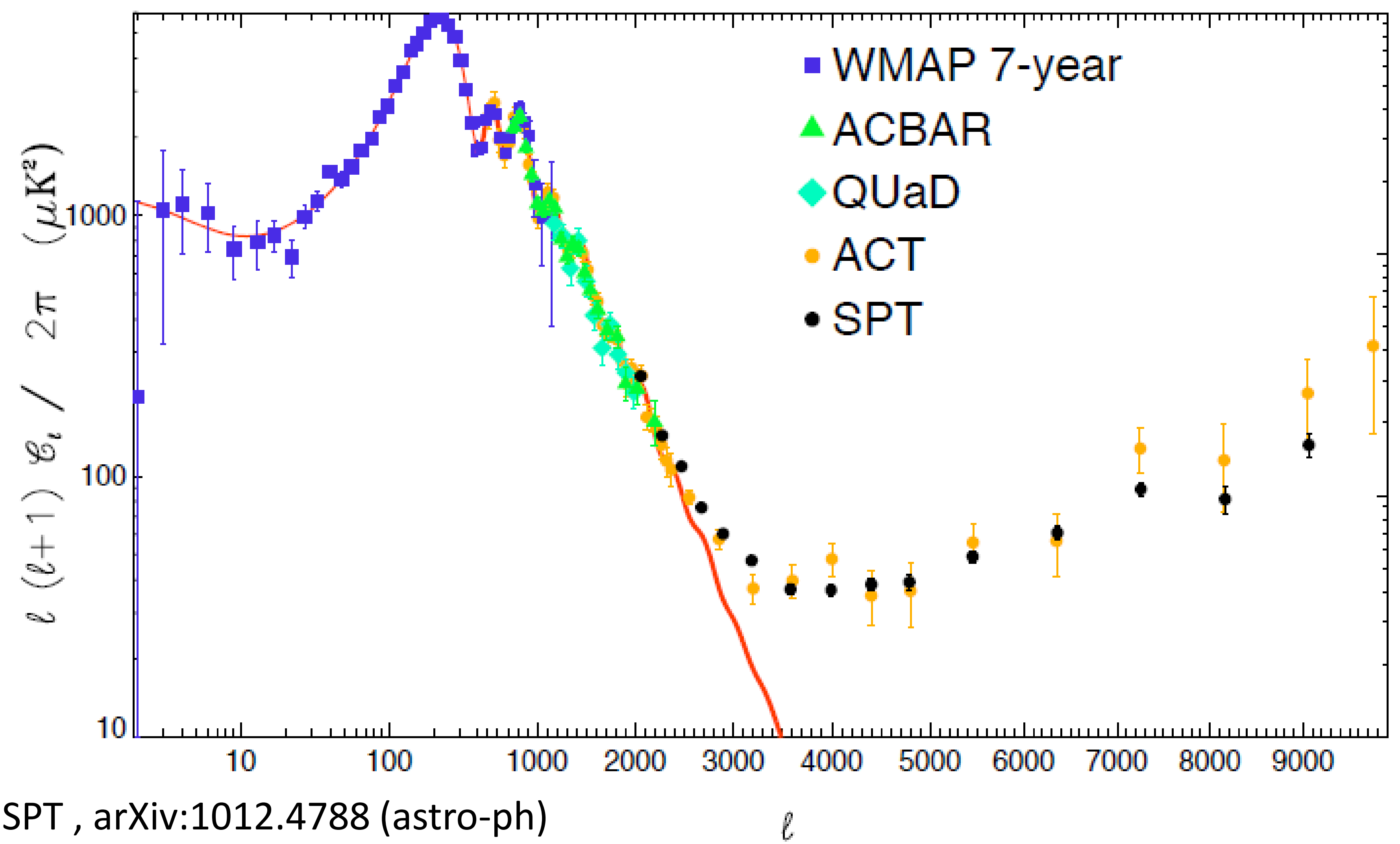


arXiv:1203.6516

Current Situation: CMB



Current Situation: CMB



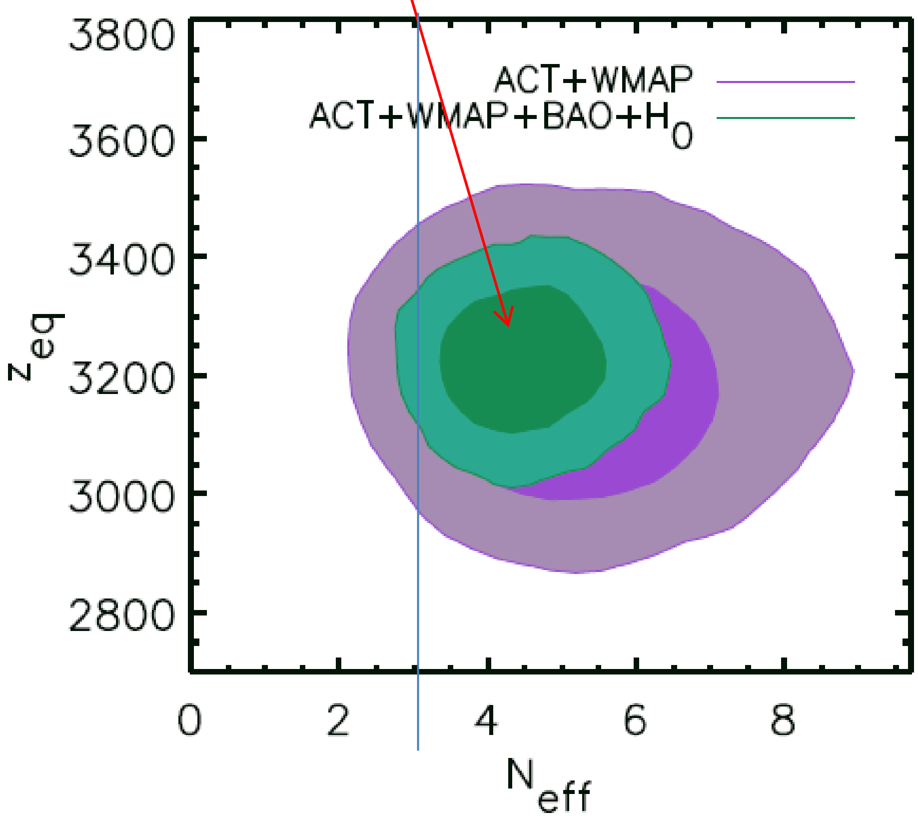
SPT , arXiv:1012.4788 (astro-ph)

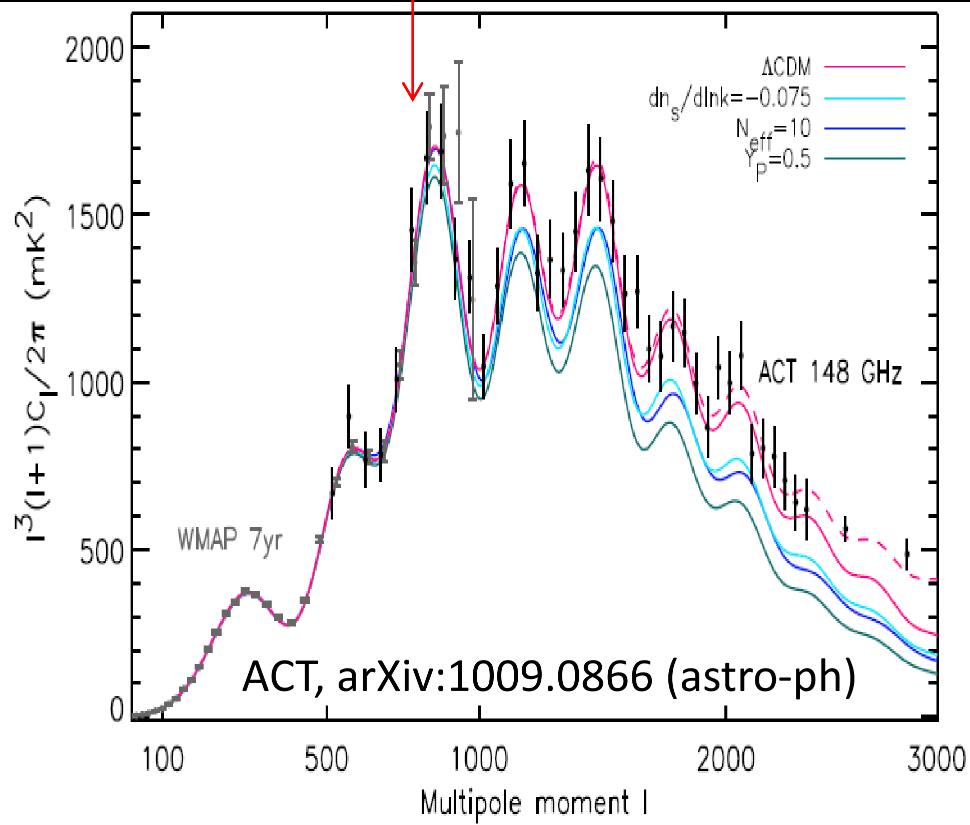
WMAP (2001-2009), current data release 7 years + ACBAR + QUAD + ACT + SPT up to l~10000, SZ effect PLANCK (2009-2012) No cosmology yet

Current Situation: CMB

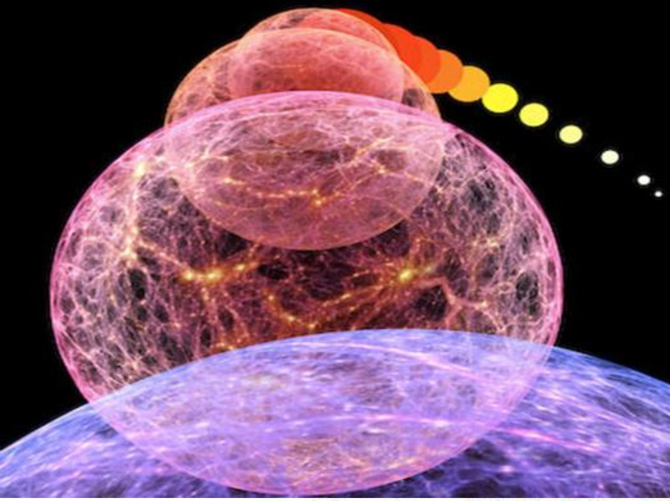
Hint of new physics???
More than 3 relativistic species is favored

7 acoustic peaks already measured in the power spectrum

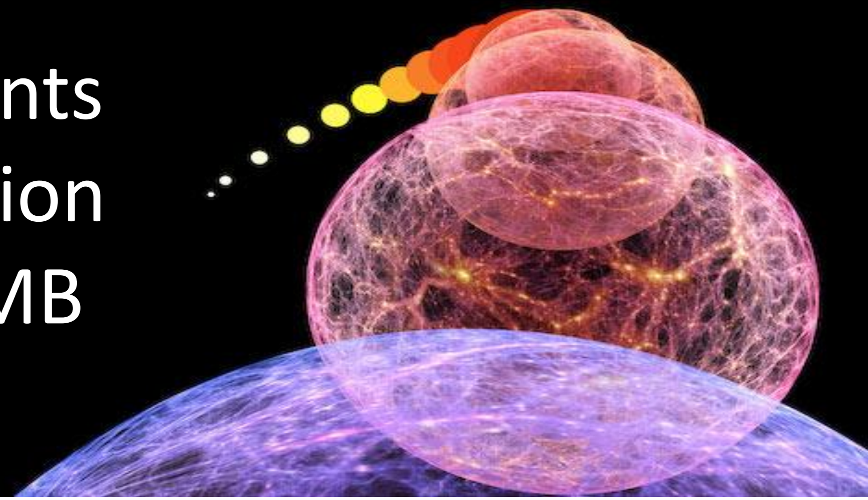


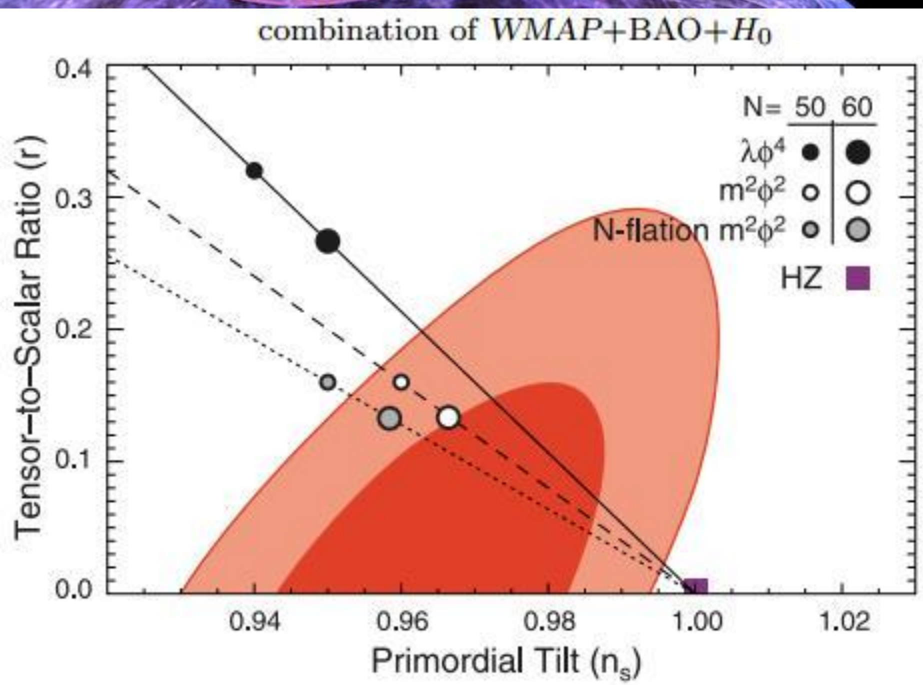


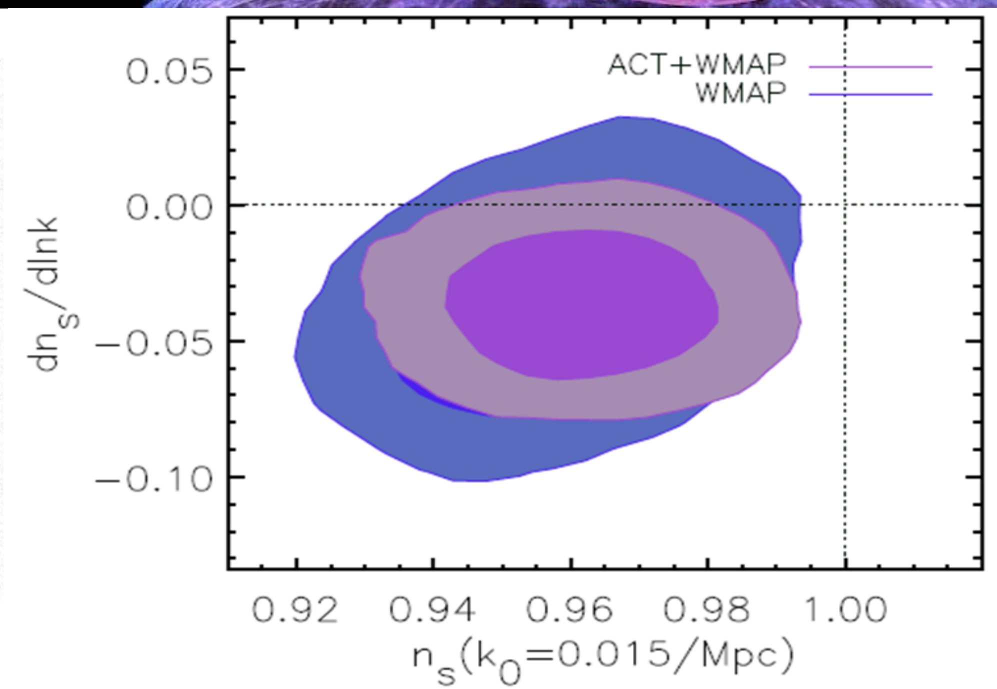
Current Situation: CMB



Constraints on inflation from CMB







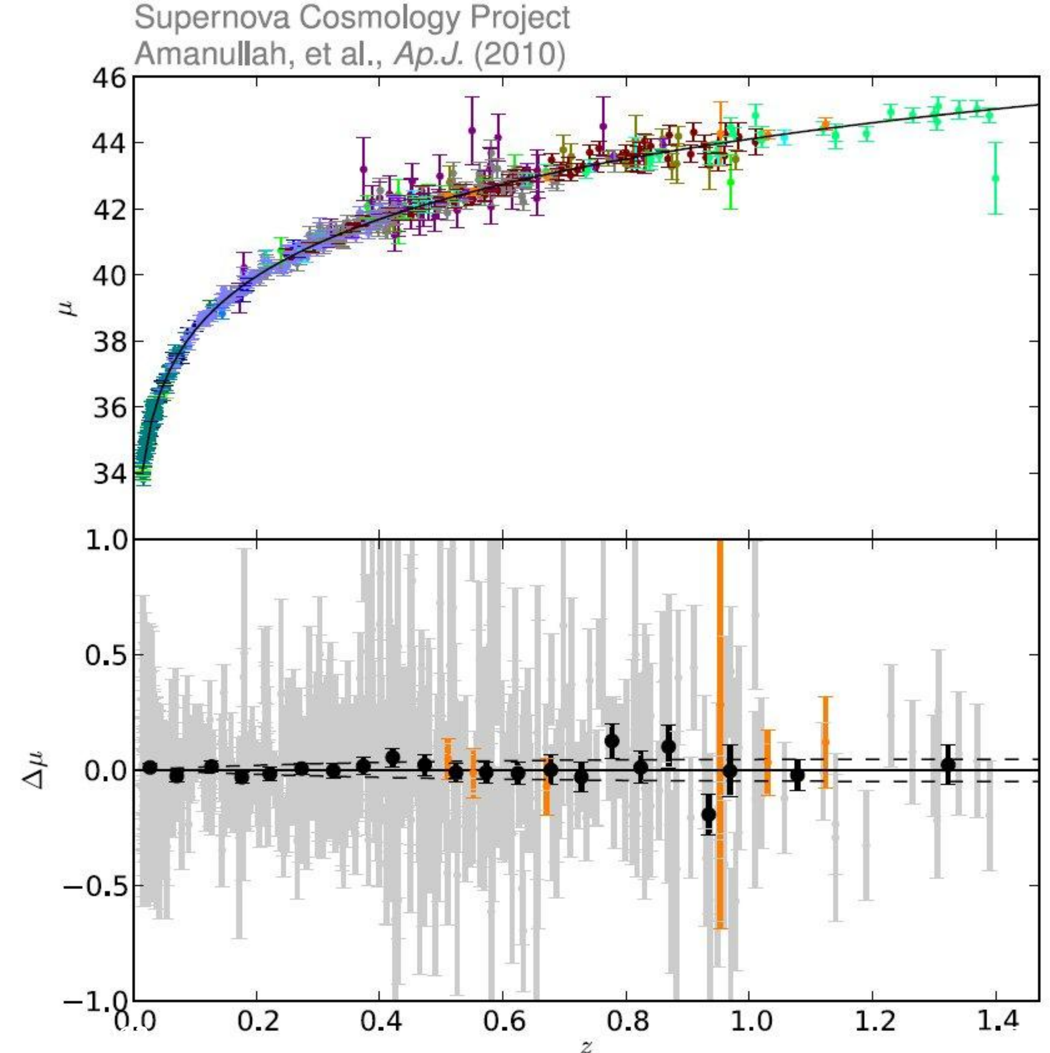
Current Situation: Supernovae

Most recent results from Union2 supernovae set (Amanullah et al. ApJ 716 (2010) 712)
557 supernovae Ia uniformly analyzed
Best constraints to date. LCDM good fit to the data

No constrain for z>1

Systematic errors are now of the same size than statistical errors

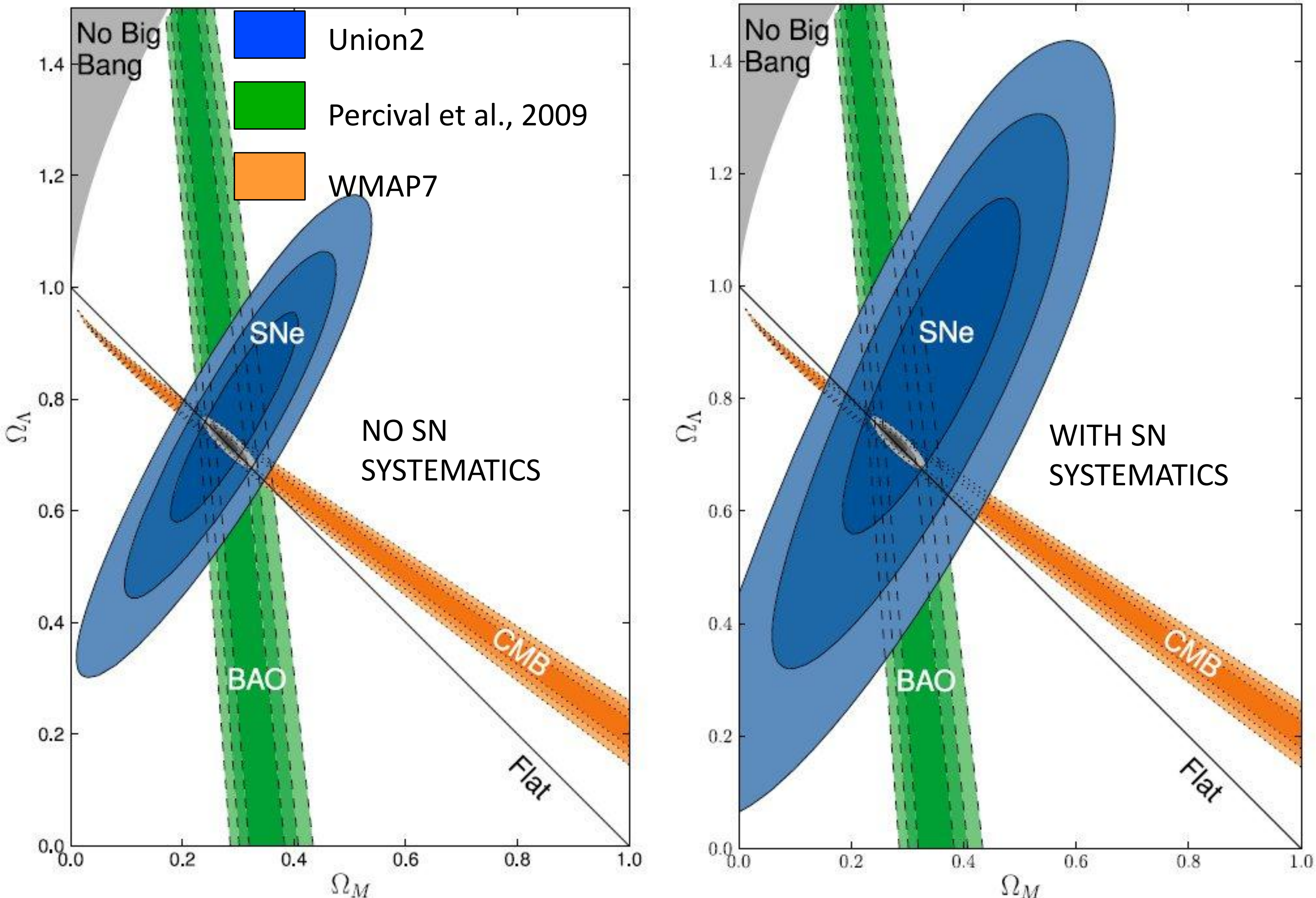
Zero-point uncertainties



E. Sánchez

Current Situation. Cosmology constraints

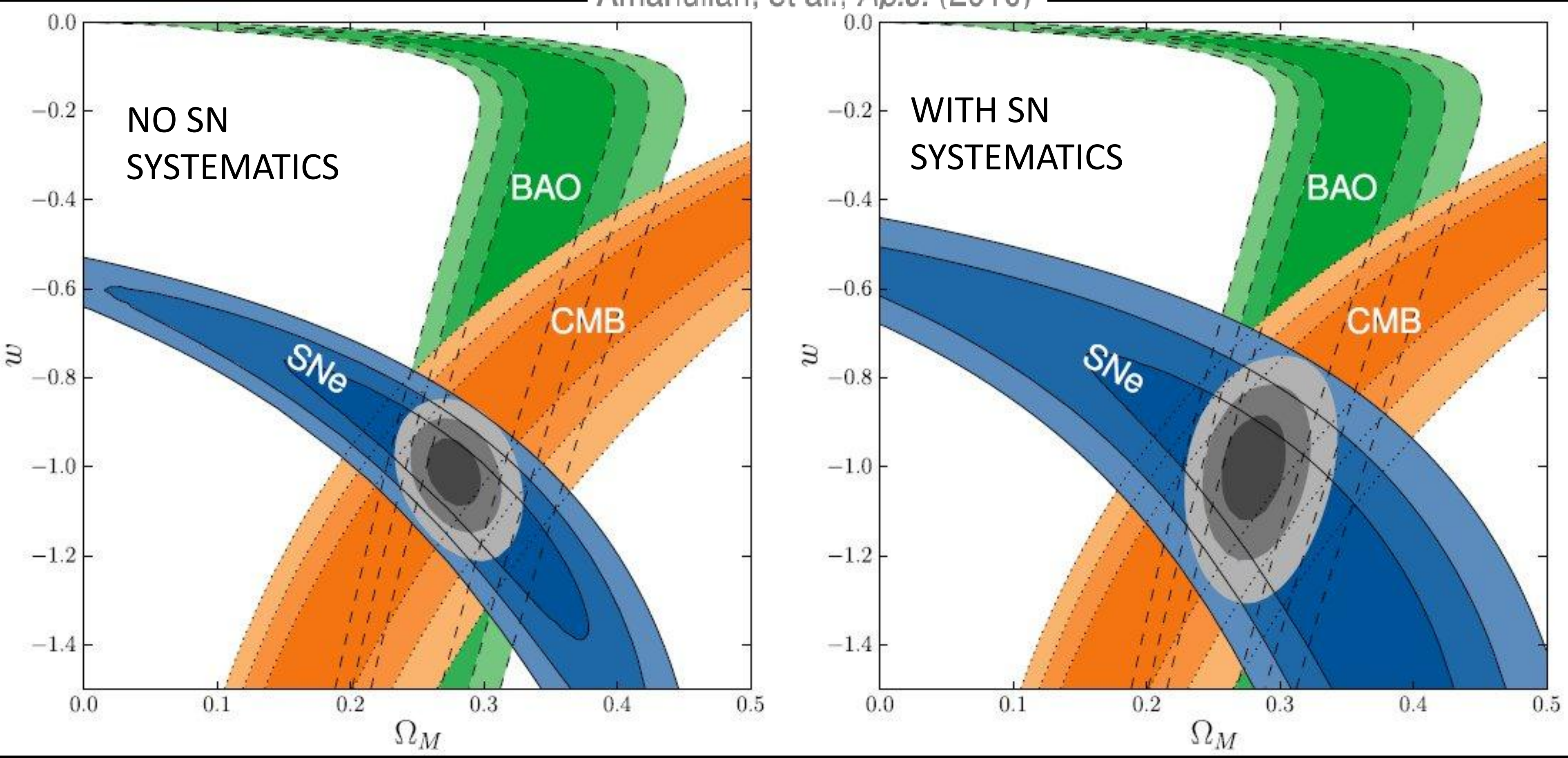
Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)



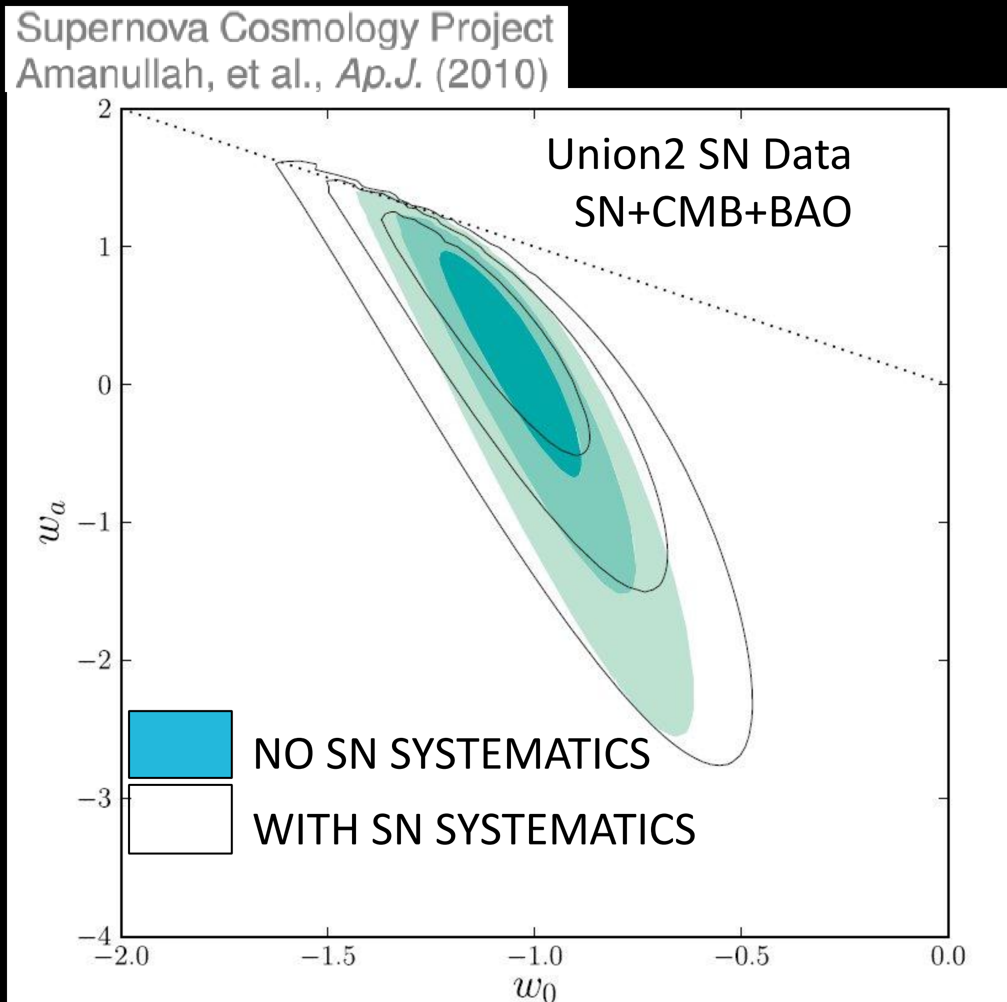
Current Situation: Cosmology Constraints

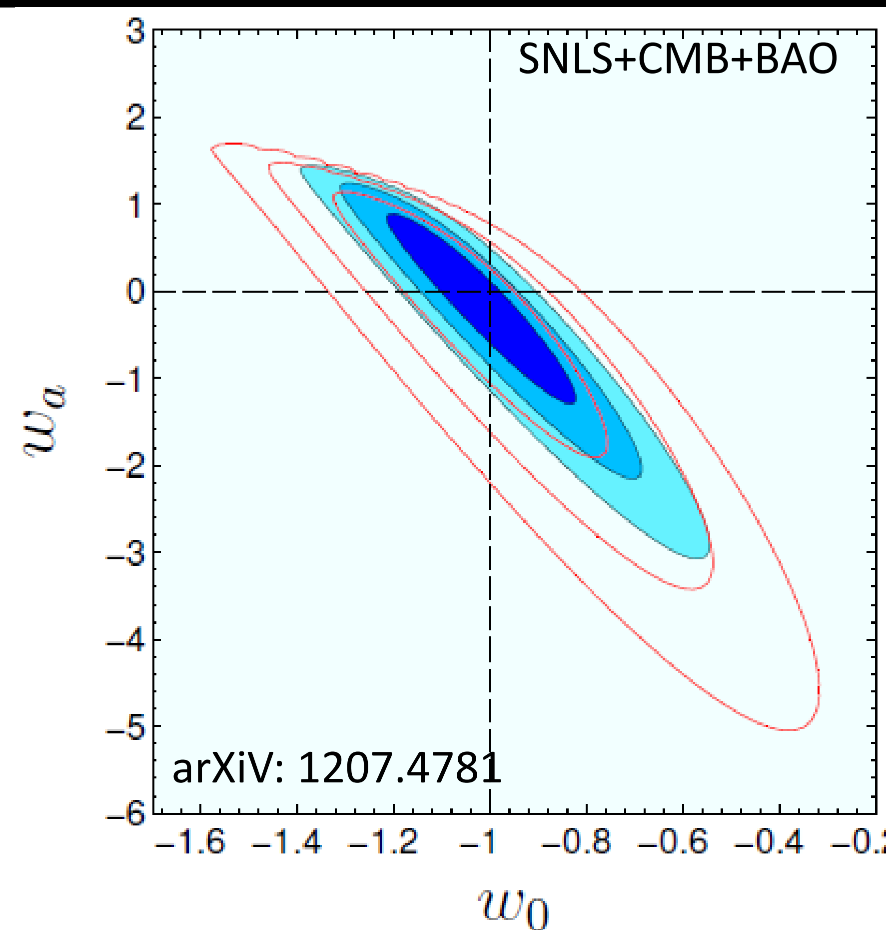
Combined data compatible with dark energy being a cosmological constant. Good consistency among different data sets.
Only combined probes get sensitivity to dark energy

Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)



Current Situation: Cosmology Constraints





CURRENT SITUATION

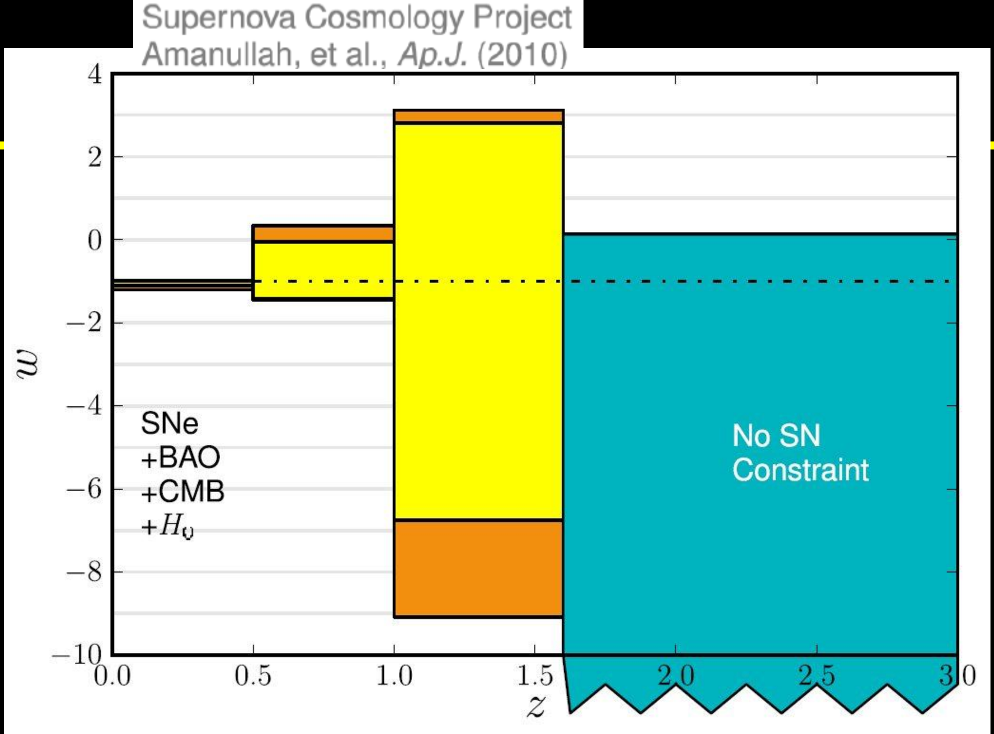
Dark energy detected with high statistical significance for z<1

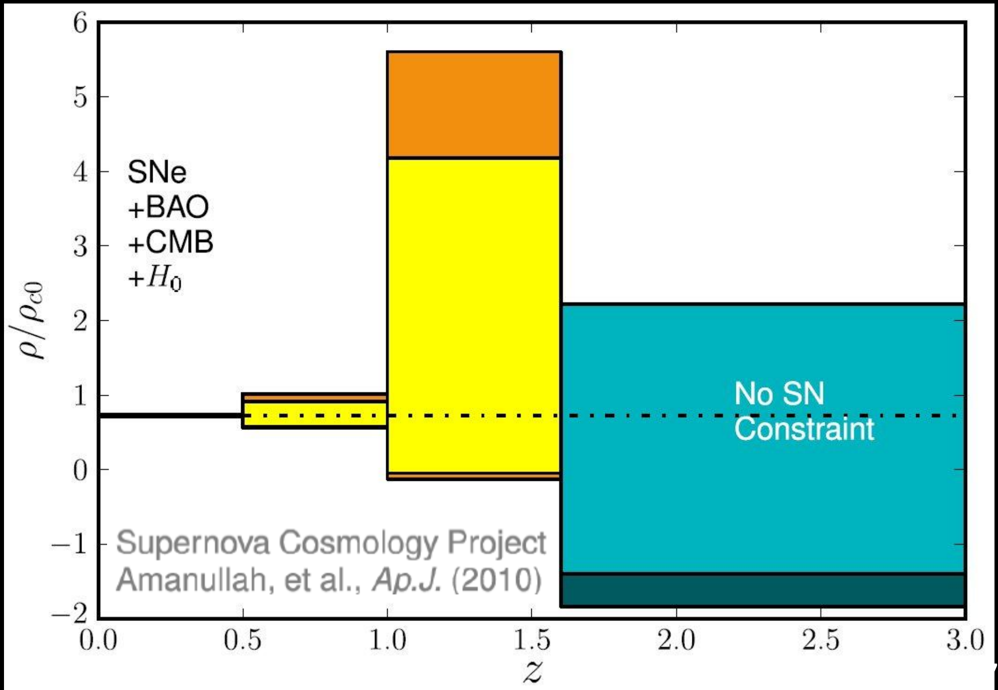
Current data do not constrain dark energy at z>1

ΛCDM remains an excellent fit to the data.

There is still large room for possible evolution of dark energy wit redshift

NEW and MORE PRECISE DATA are NEEDED: LARGE GALAXY SURVEYS





SOME GALAXY SURVEYS 2010-2020

Photometric surveys:

DES, Pan-STARRS, HSC, Skymapper, PAU, LSST, Euclid (EIC)...

Spectroscopic surveys:

WiggleZ, BOSS, BigBOSS, HETDEX, WFMOS/Sumire, Euclid (NIS)...

Summary

The existence of dark energy has been very well stablished below z~1

LCDM describes all data up to now

Dark Energy is compatible with a cosmological constant

Not enough sensitivity yet to its variation with time (redshift)

Several methods to measure dark energy properties have been proposed and verified

- Supernovae Ia
- BAO
- Weak Lensing
- Clusters
- RSD
- Magnification

They will be applied in the coming years