Image: Dark Energy Camera, from http://darkenergydetectives.org

Introduction to Cosmology
1: ΛCDM

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Previous: How to measure celestial objects

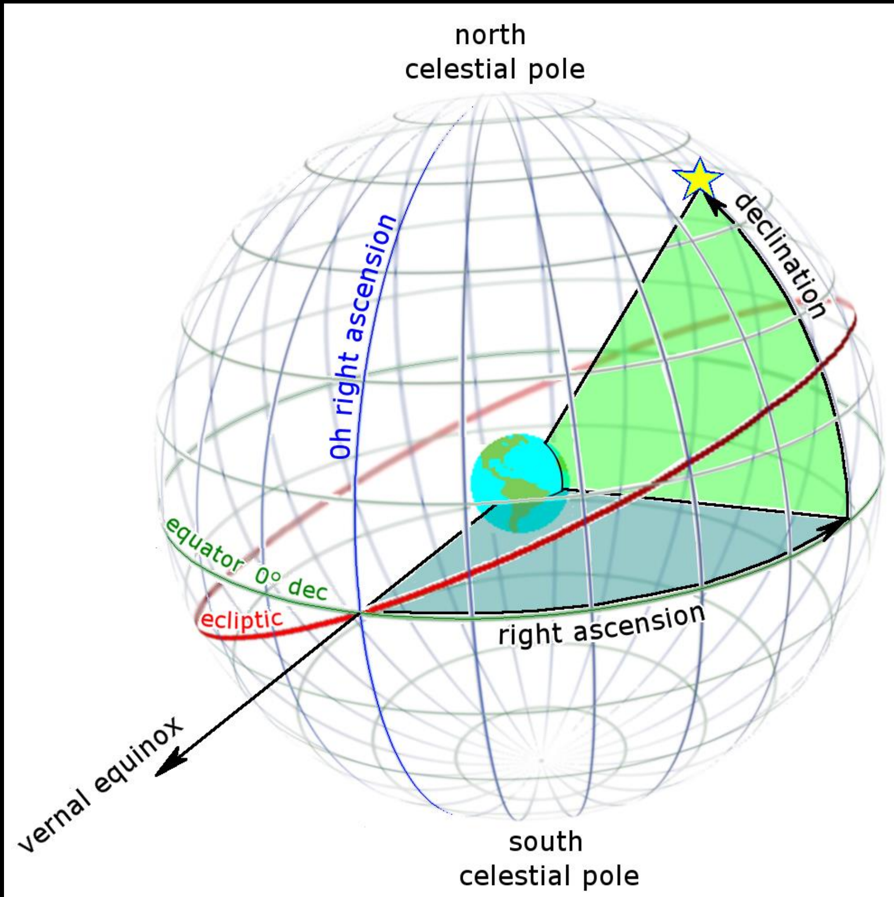
Position in the sky

Distance

Recession velocity

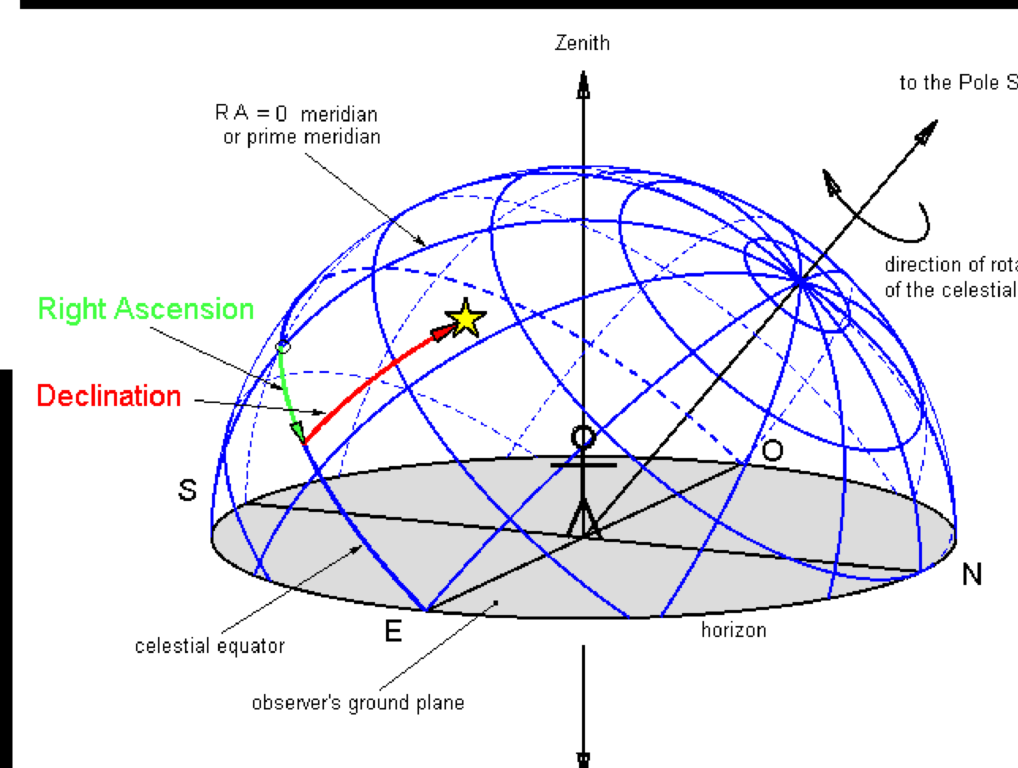
Other properties: *Temperature, density, chemical composition…*

Equatorial coordinates: right ascension, declination

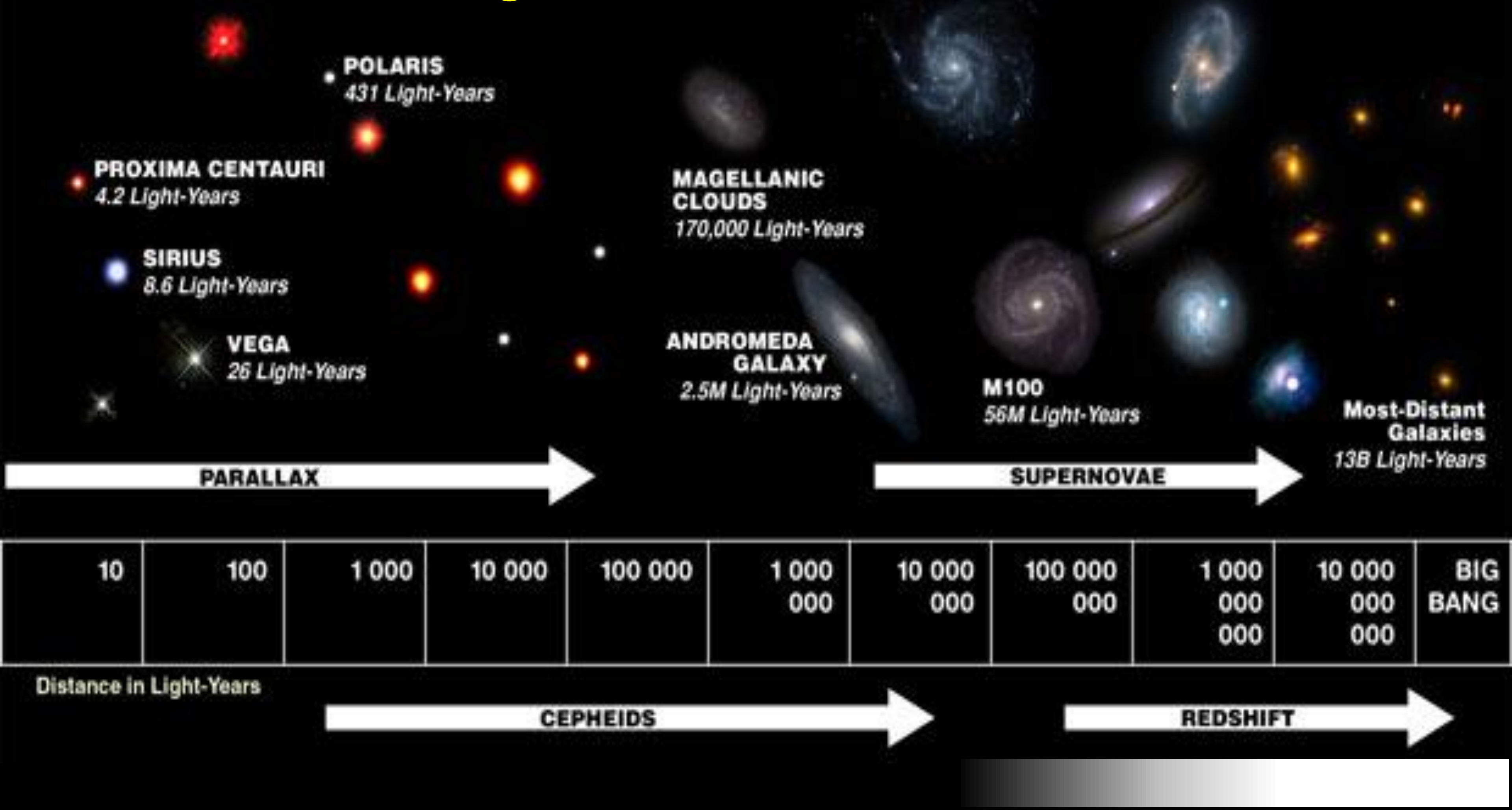


The large cosmological projects do use equatorial cordinates to locate objects in the sky

The third dimension (distance) is much more difficult to measure



Measuring Distances: The Cosmic ladder



The different methods are chained

COSMOLOGY

Spectra tell us the recession velocity of celestial objects

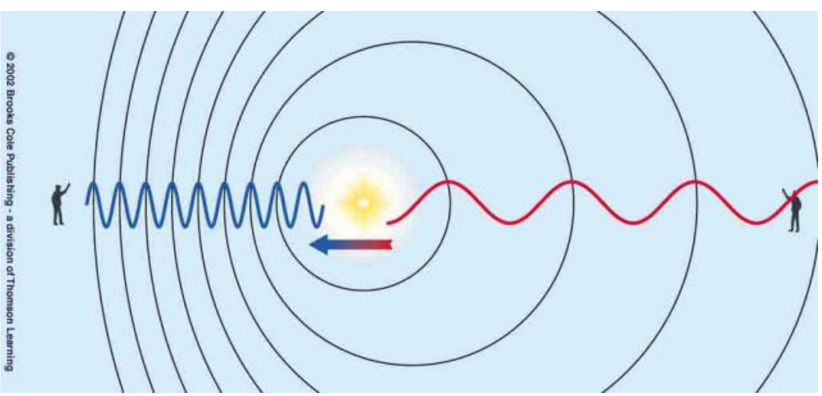
Spectral lines change their positions when the source is moving

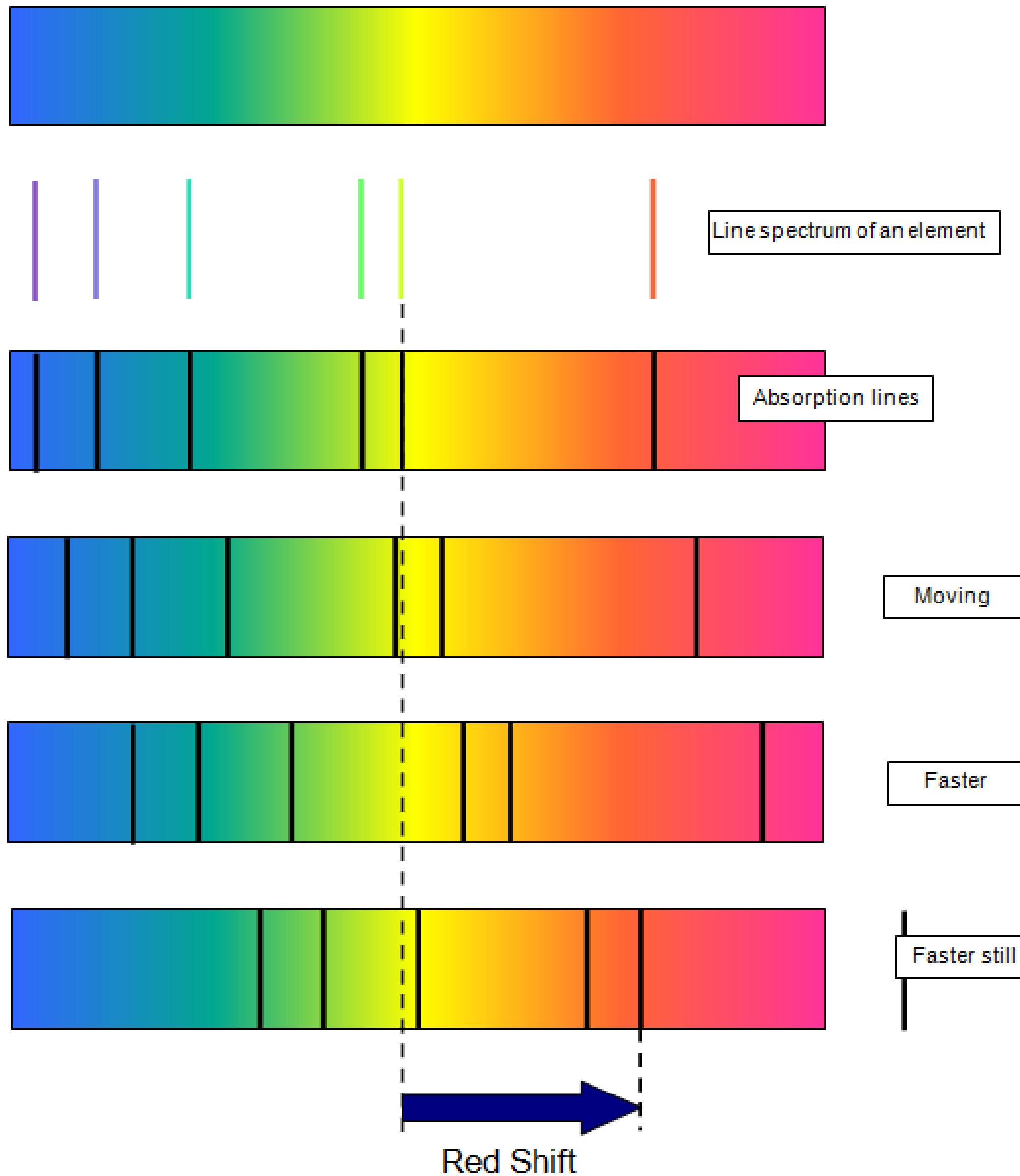
The measurement of line´s displacement allows to obtain the recession velocity of the source.

$$\mathbf{z = (\lambda - \lambda_0)/\lambda_0}$$

For small z, $\mathbf{v \sim cz}$

λ = measured ; λ_0 = at rest ; c = light





2 main measurements for Cosmology:

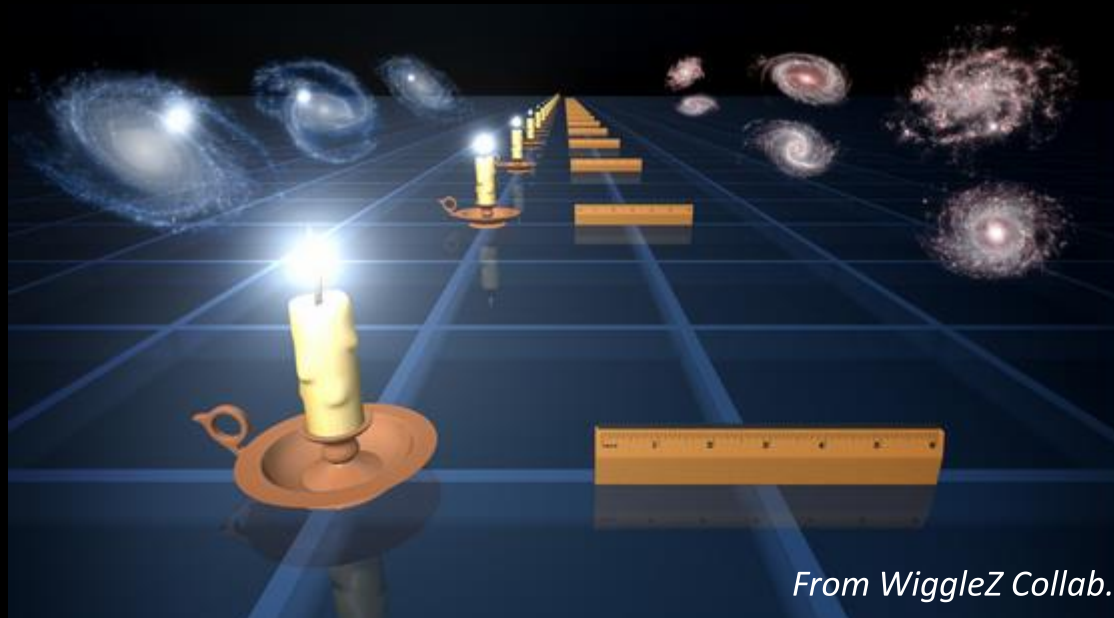
Distance as a function of z

The formation and evolution of cosmic structures (superclusters, clusters, galaxies…)

Cosmic Distances: Standard Candles and Standard Rulers

Luminosity Distance

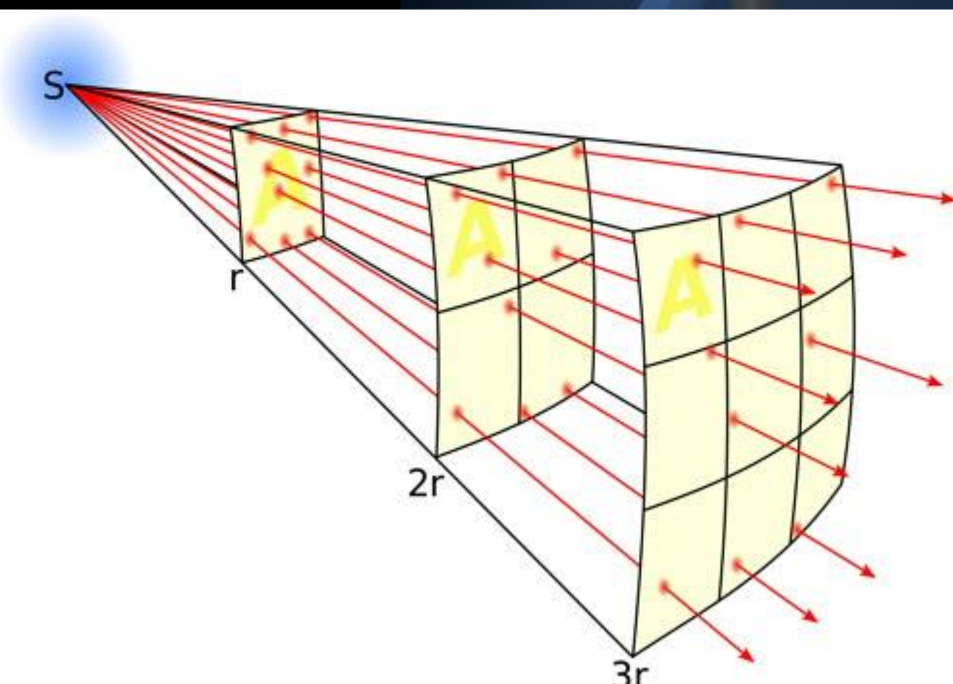
$$F = \frac{L}{4\pi D_L^2}$$

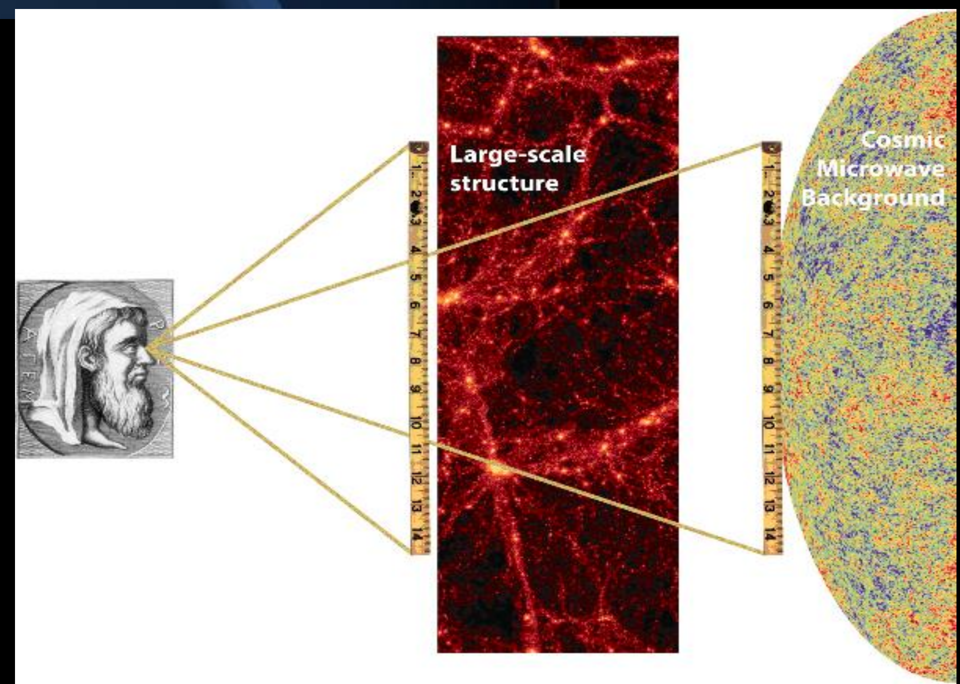


From WiggleZ Collab.

Angular Diameter Distance

$$D_A = \frac{R}{\theta}$$





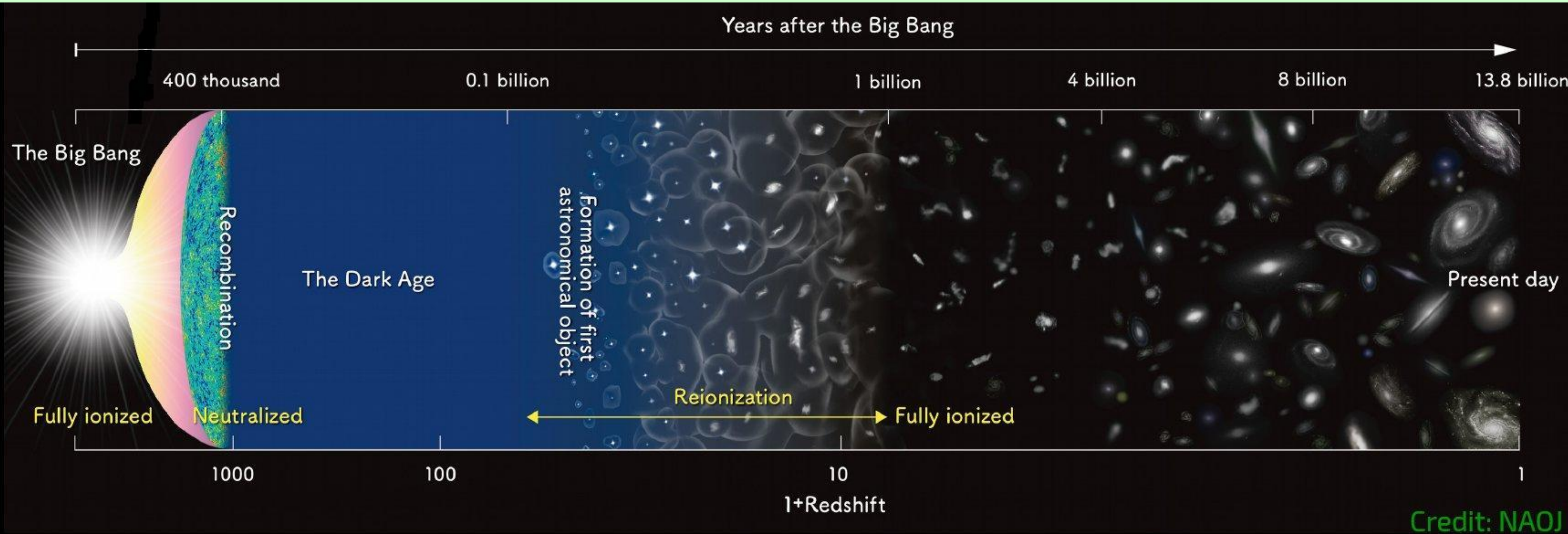
LSS Formation and Evolution: General Idea

Generation of fluctuations: Quantum fluctuations of the inflaton become classic due to the wild inflationary expansión. At the end of inflation the inflaton field decays into particles

Quantum fluctuations of the field → fluctuations in the number of particles → fluctuations in the energy density

Inflation generates initial conditions, (Gaussian) i. e. seeds for the LSS:

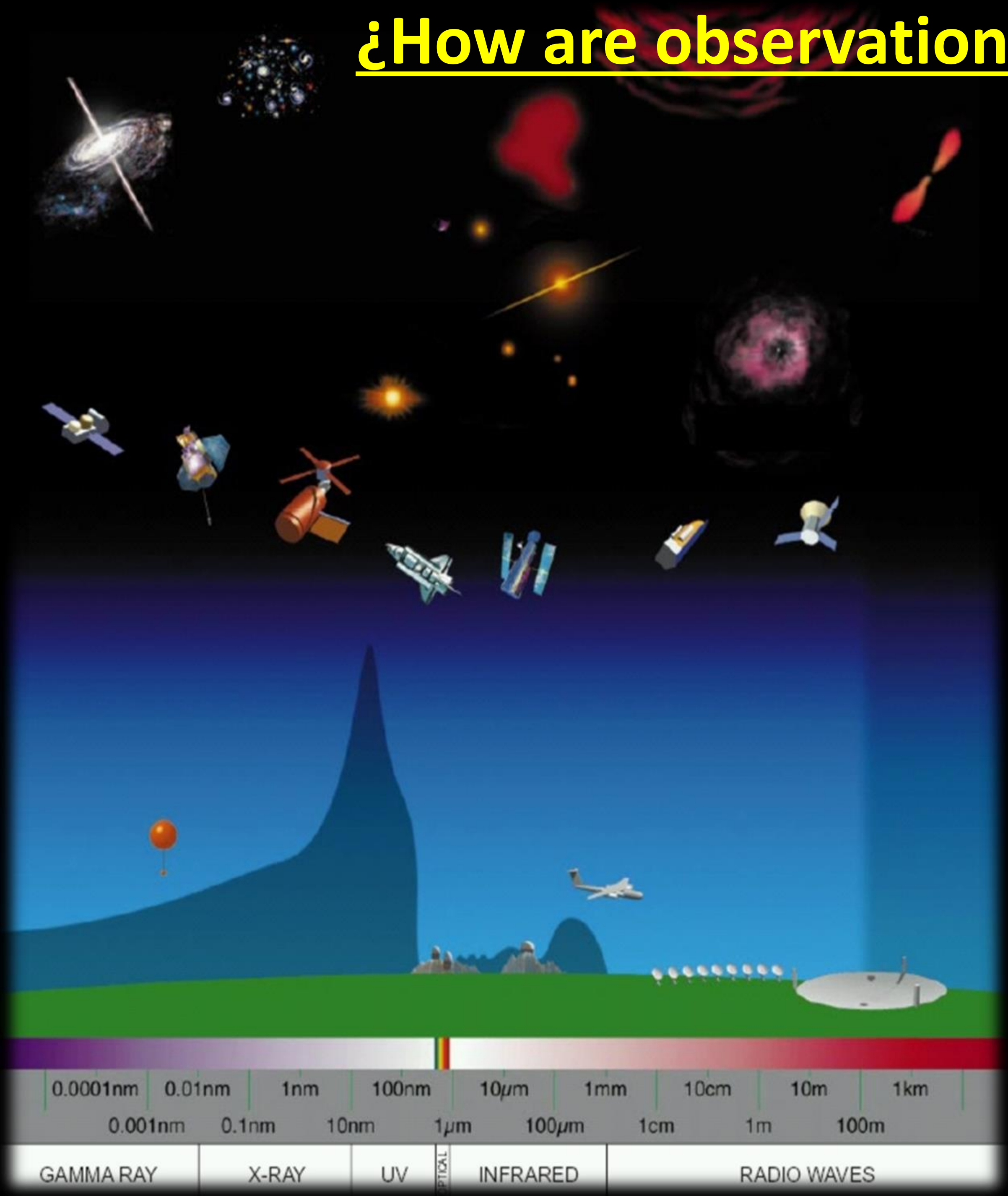
Gravity does the rest



The properties of the initial fluctuations determine the properties of the LSS

Important point: Inflaton is a quantum field → We cannot predict the specific value of the fluctuations, but only their statistical properties → Our predictions for the LSS are statistical

¿How are observations made?



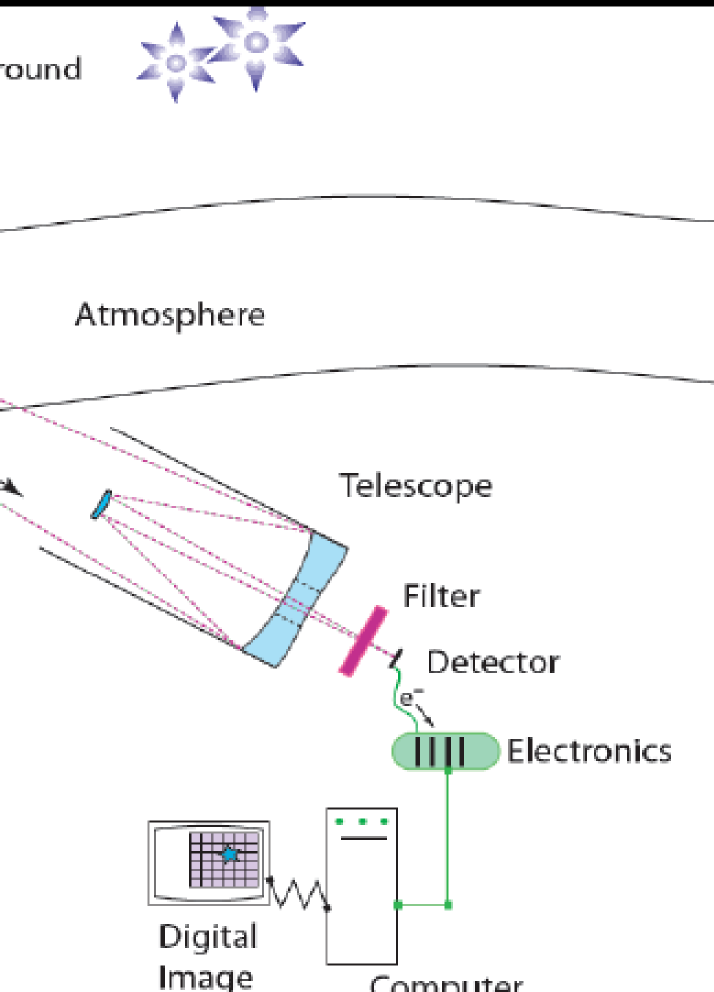
Powerful telescopes on earth and in space

In many wavelengths

Also other signals (besides of light) are observed (cosmic rays, neutrinos, gravitational waves...)

How observacions are done

Many observational effects in the measurement



Different kinds of telescopes and detectors, depending on the desired observations

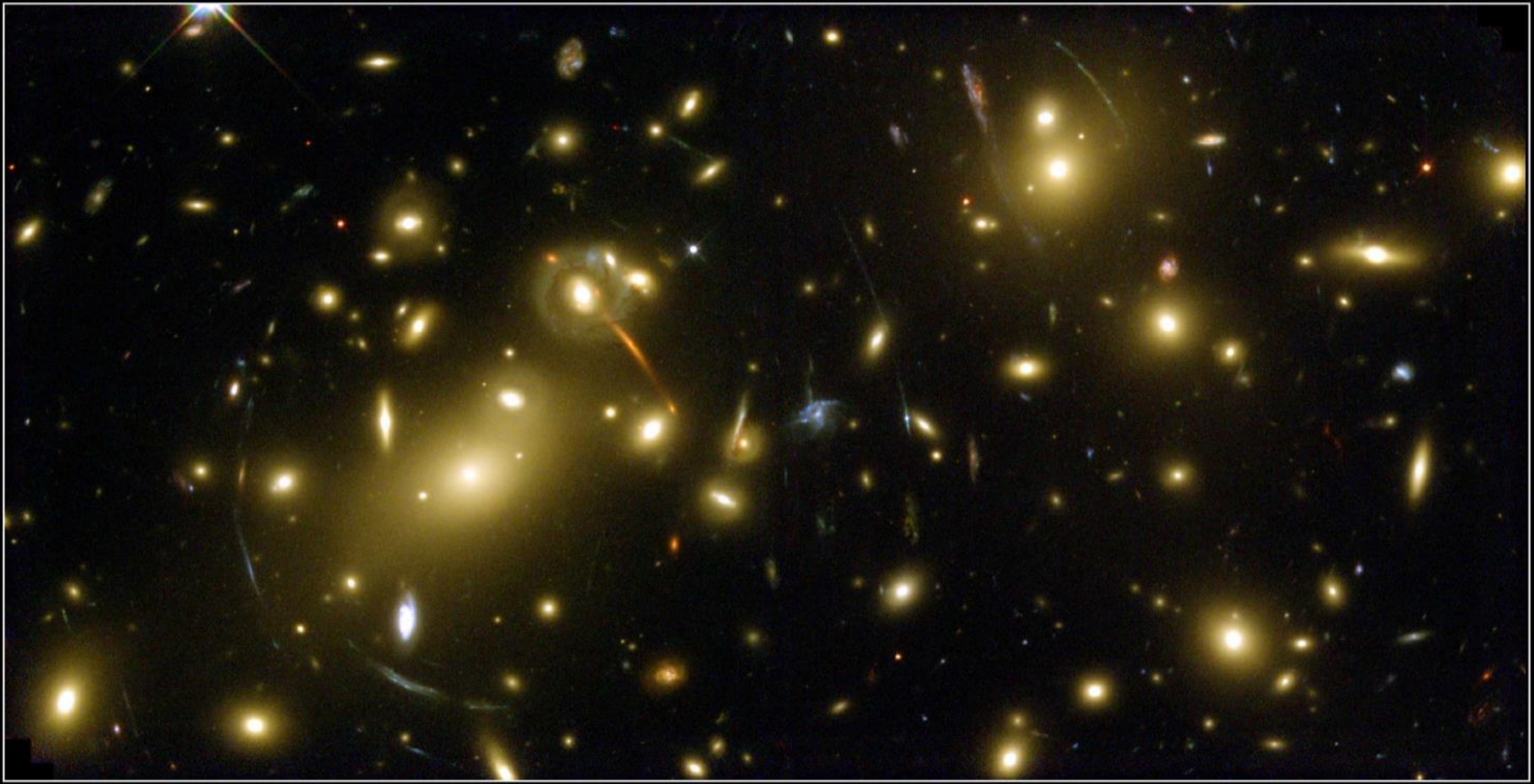
- Light source
- The atmosphere
- Telescope and optical system
- Camera
- Electronics+DaQ
- Data processing and calibration
- Scientific analysis

The Blanco Telescope in Chile

Its mirror has a diameter of 4m (the largest are ~10m)

The Blanco Telescope, in Chile

Image from darkenergydetectives.org

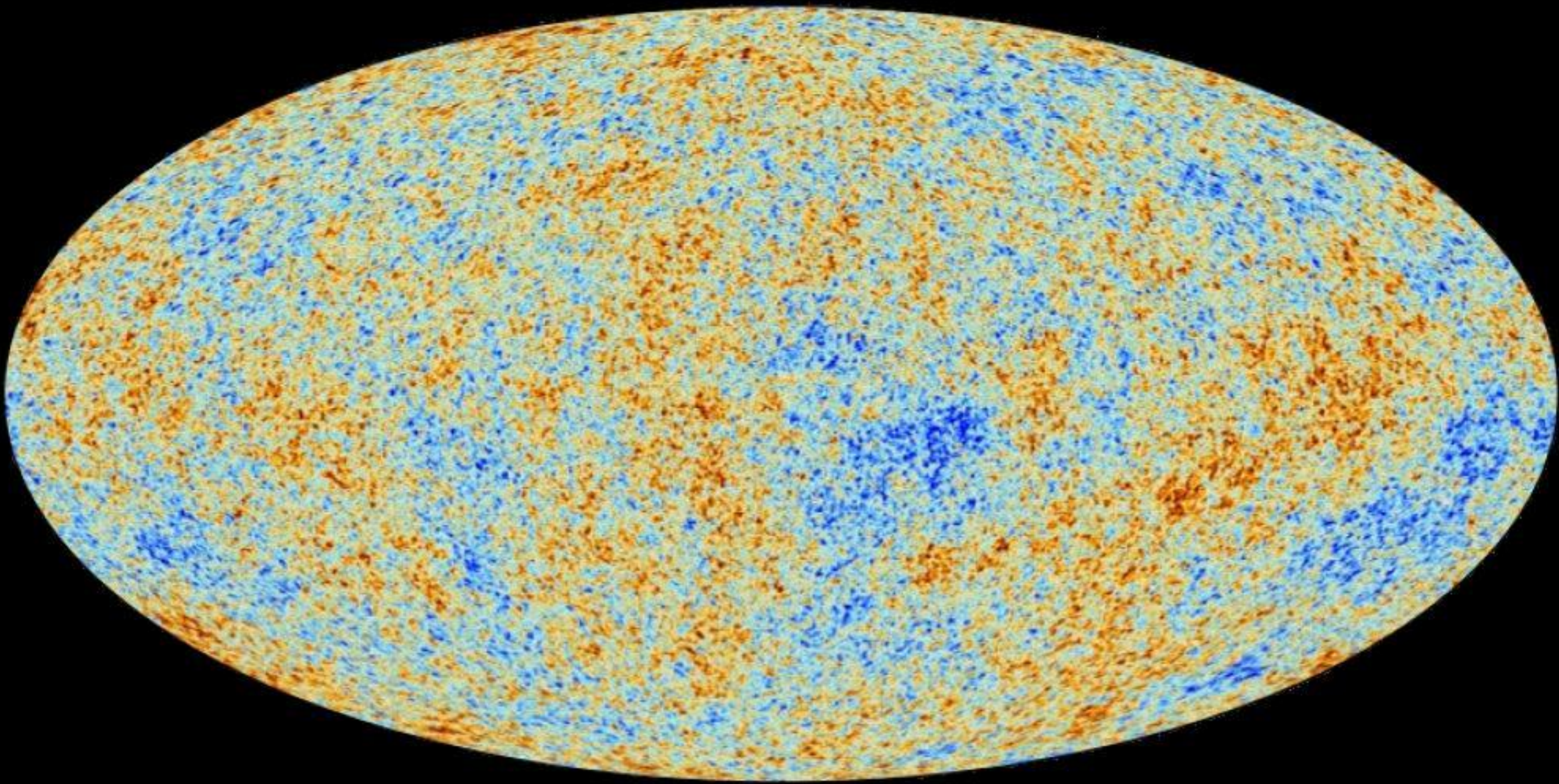


Galaxy Cluster Abell 2218

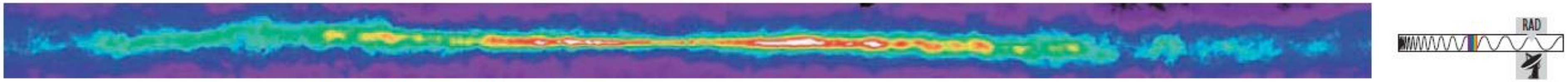
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

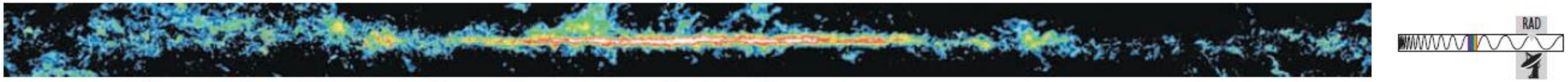
Map of the CMB from the space telescope Planck



The Milky Way in different wavelengths lof the electromagnetic radiation



a 21-cm radio emission from atomic hydrogen gas.



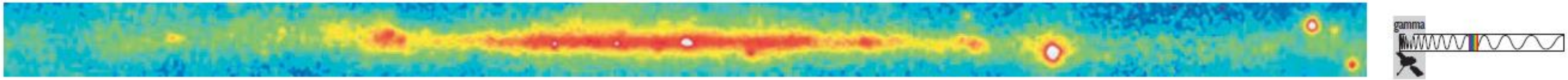
b Radio emission from carbon monoxide reveals molecular clouds.

c Infrared emission from interstellar dust (wavelength 60 to 100 μm).

d Infrared emission from stars that penetrates most interstellar material (wavelength 1 to 4 μm).

e Visible light emitted by stars is scattered and absorbed by dust.

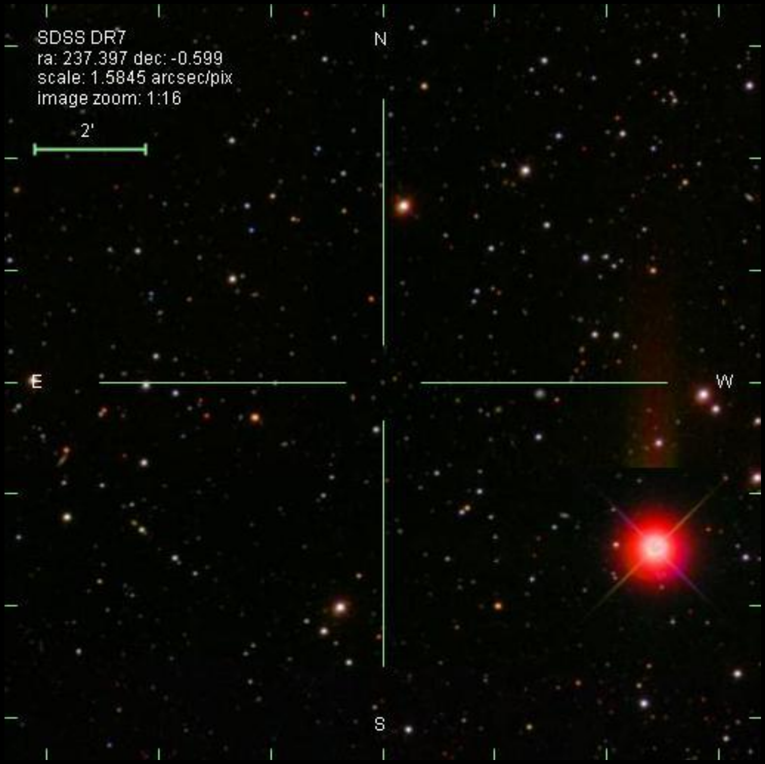
f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).

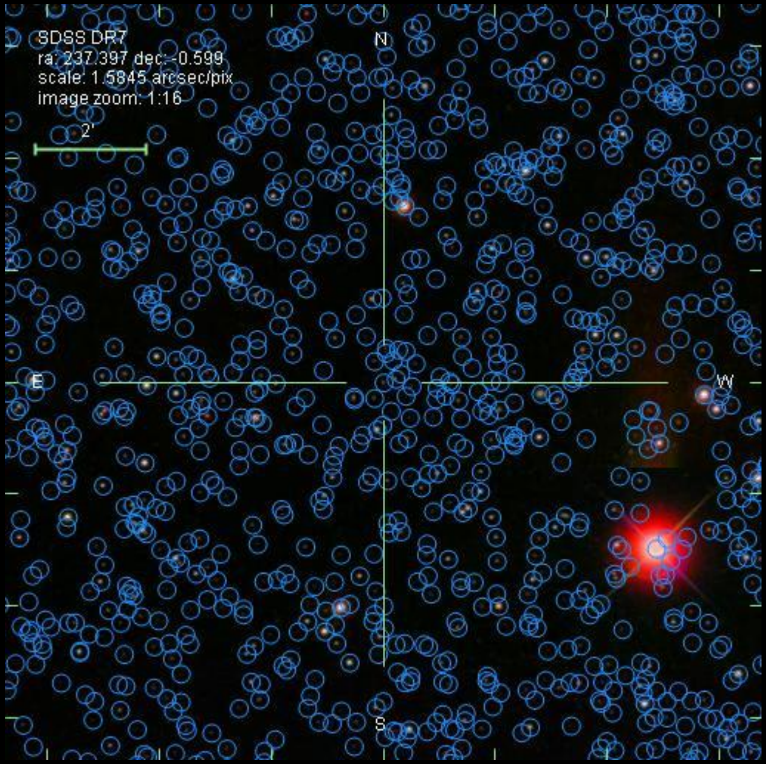


g Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

From images to results

The objects (usually galaxies) are detected using dedicated computing programs

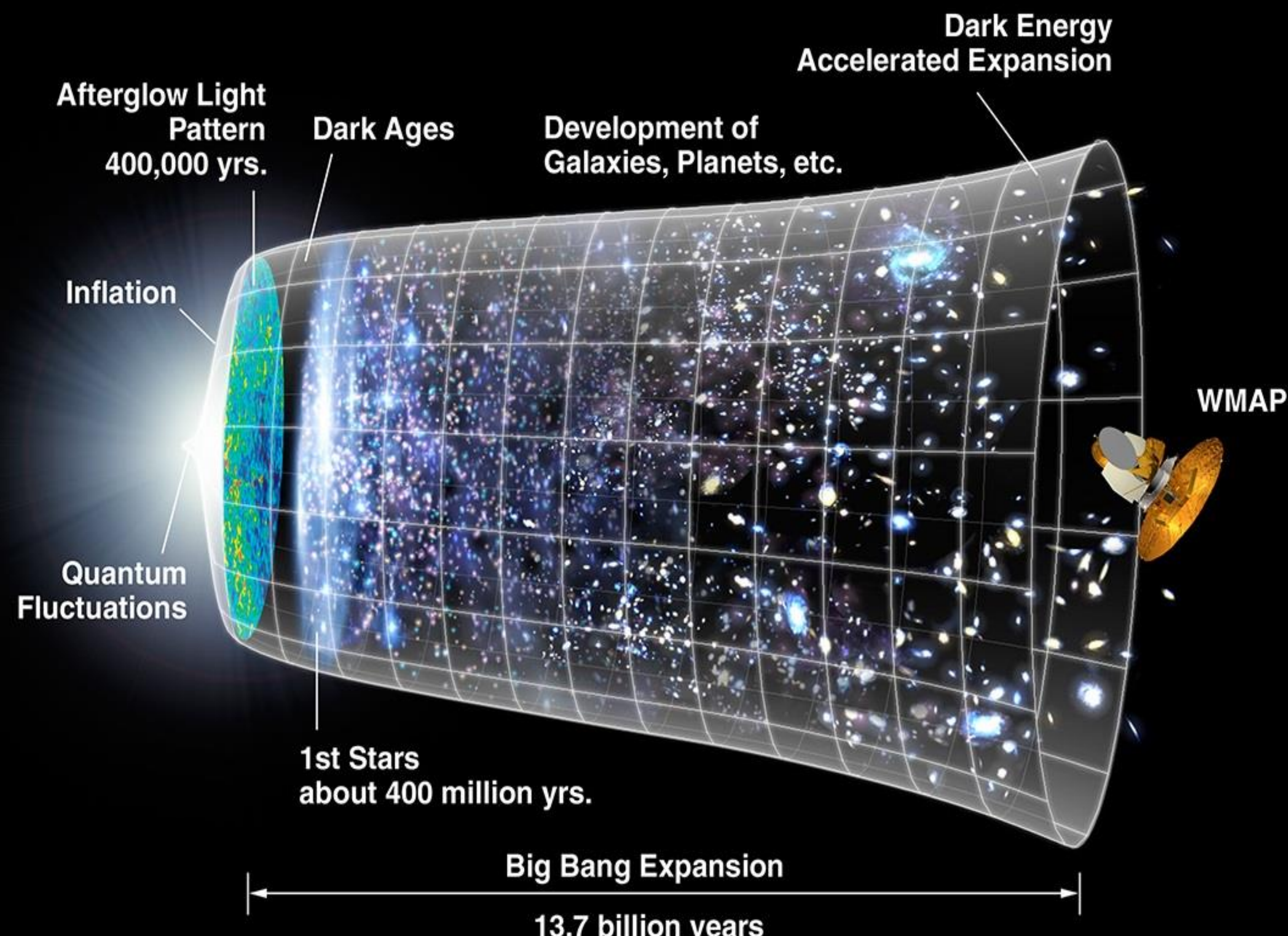




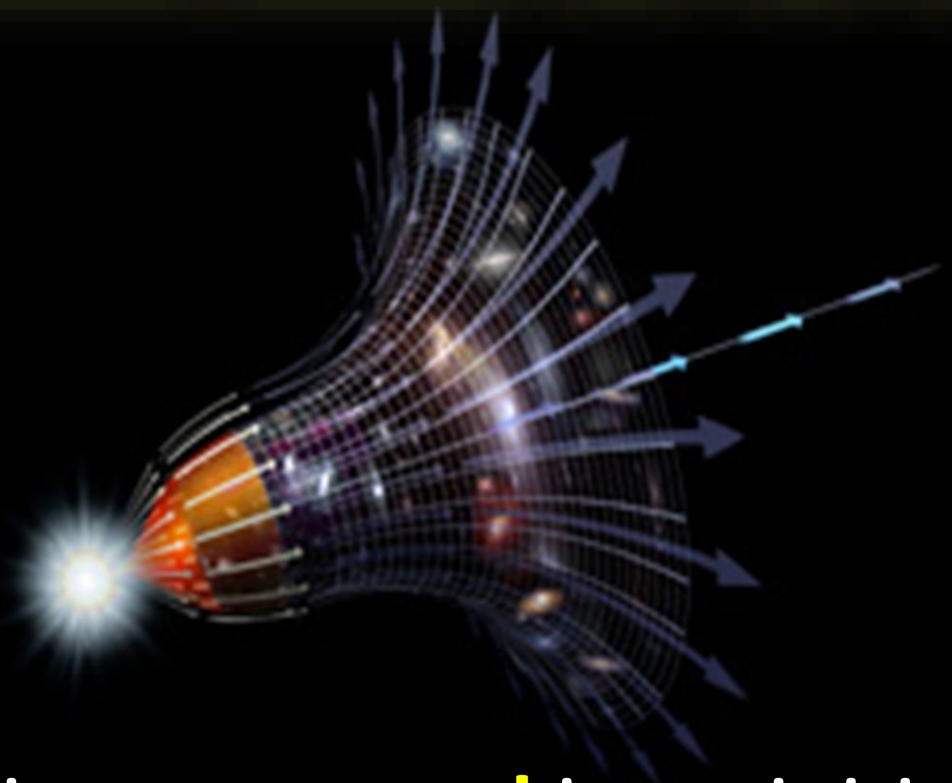
To obtain cosmological results:

- Measure object´s position in the sky
- Clasify objets: Stars, galaxiaјes, quasars…?
- Measure z

COSMOLOGY: THE SCIENCE OF THE UNIVERSE

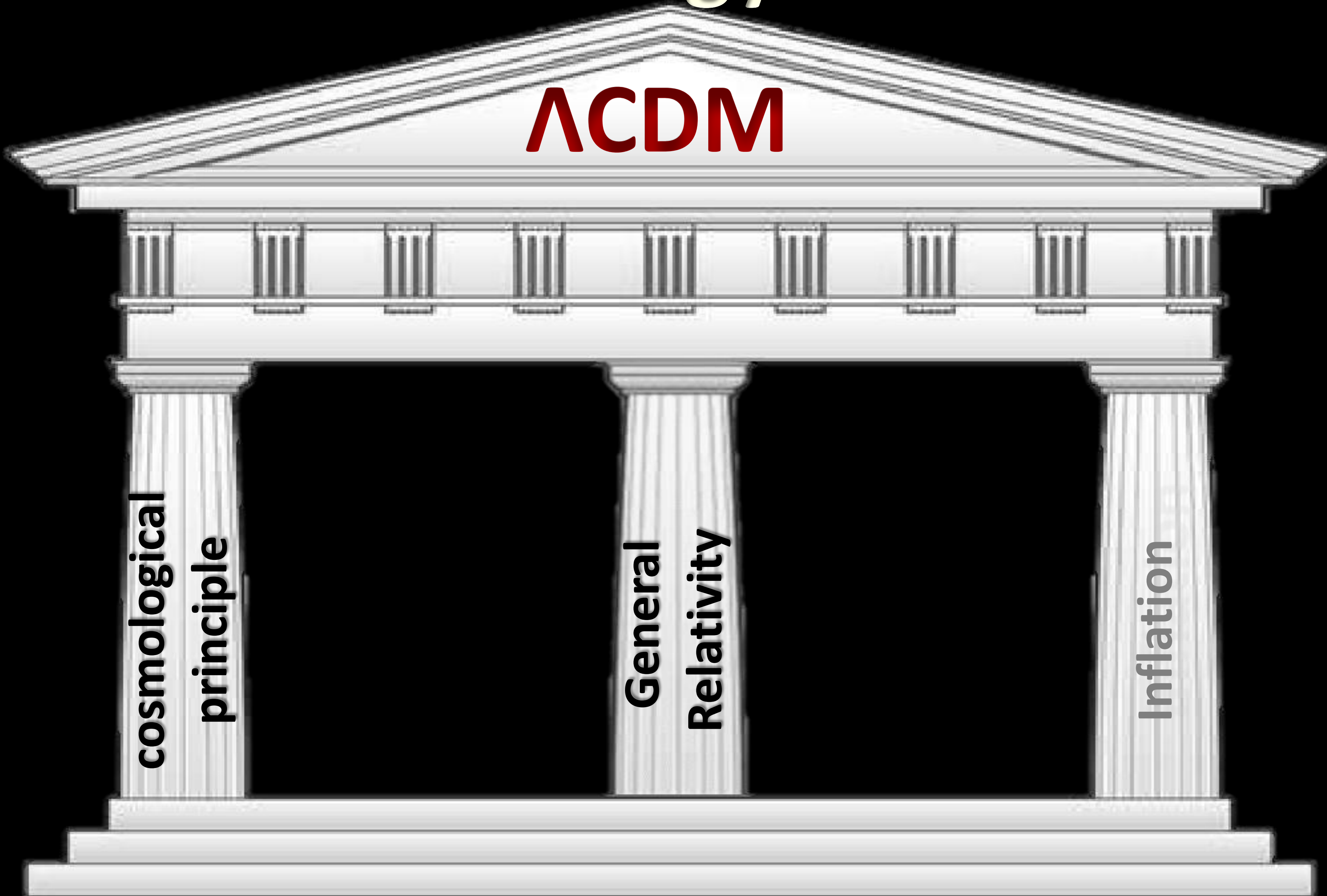


THE BIG BANG



The Universe **started** in an initial state extremely dense and hot, and since then it is **expanding and cooling**

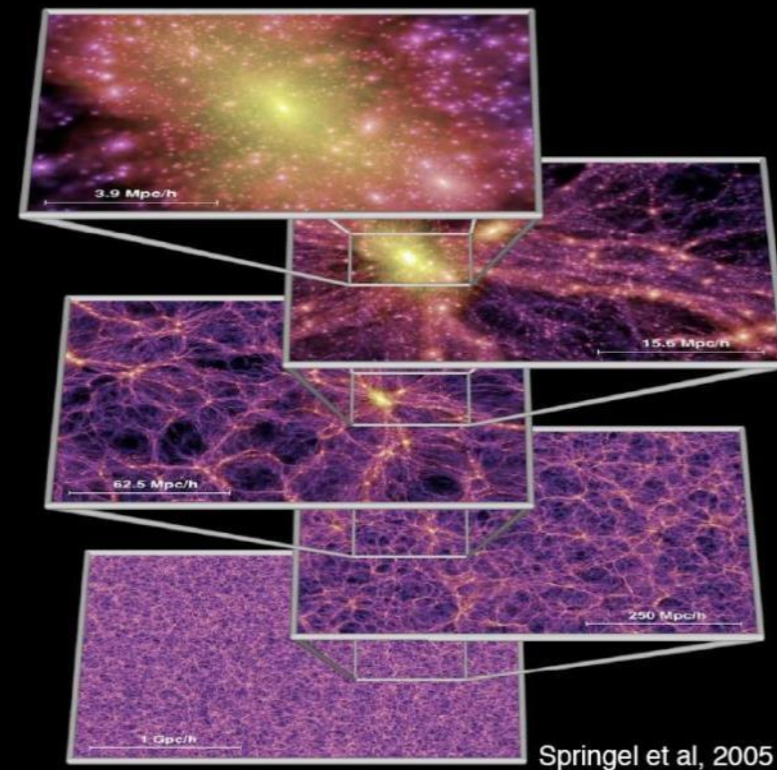
Cosmology Basis



The cosmological principle

The Universe is homogeneous and isotropic

The universe properties are independent of the position and of the direction.



Springel et al, 2005

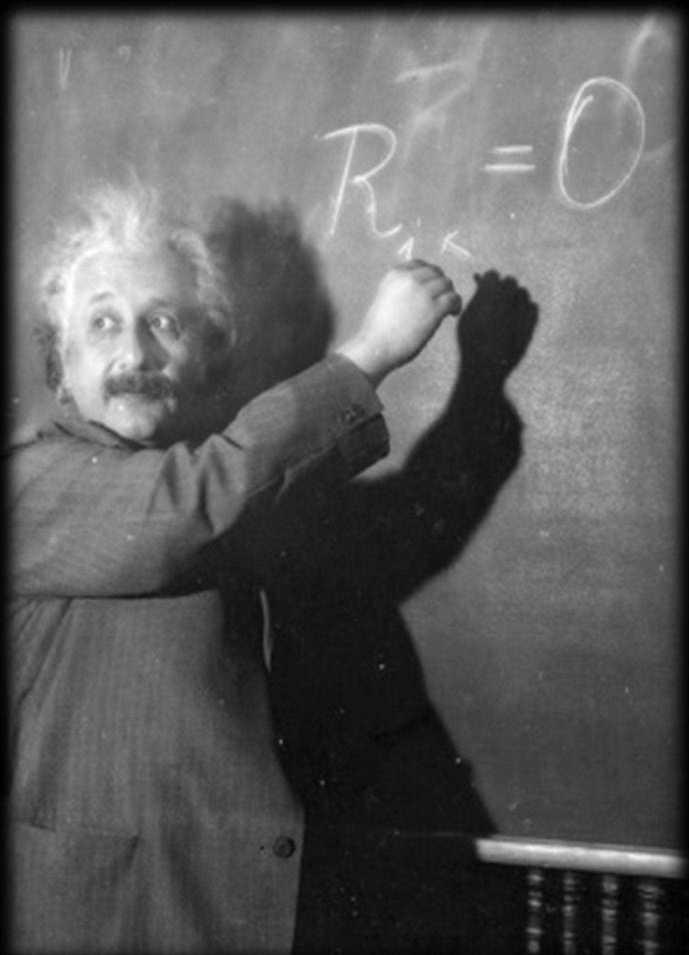
It is verified only for regions with a size around 100 Mpc or larger

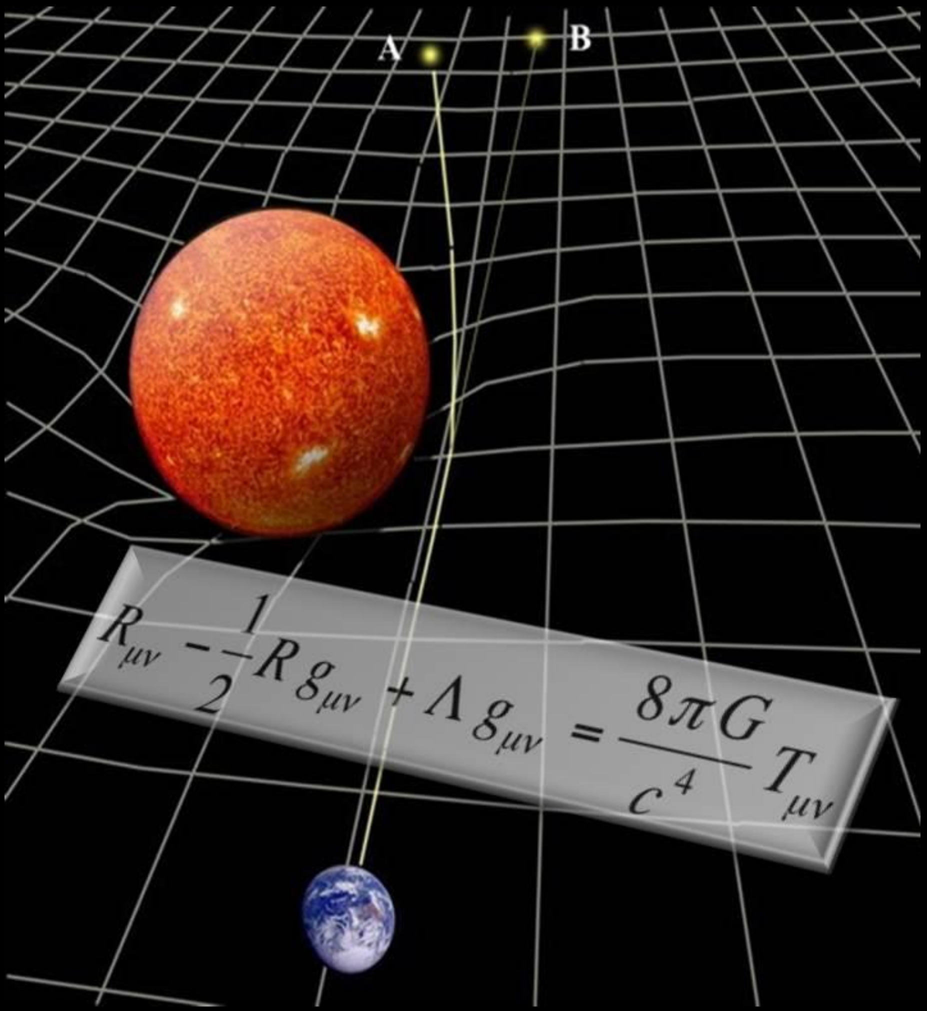
The Big Bang theory is able to explain why this happens. It describes how structures that we observe in the Universe are formed.

General Relativity Theory

Gravity is spacetime curvature

"Spacetime tells matter how to move; matter tells spacetime how to curve.", *J. A. Wheeler*





The metric is a consequence of the cosmological principle

FLRW Metric

Friedmann-Lemaitre-Robertson-Walker

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

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

$$S_0(r) = r$$

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

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

The General Relativity predicts an expanding (or contracting) Universe

3 possible geometries:

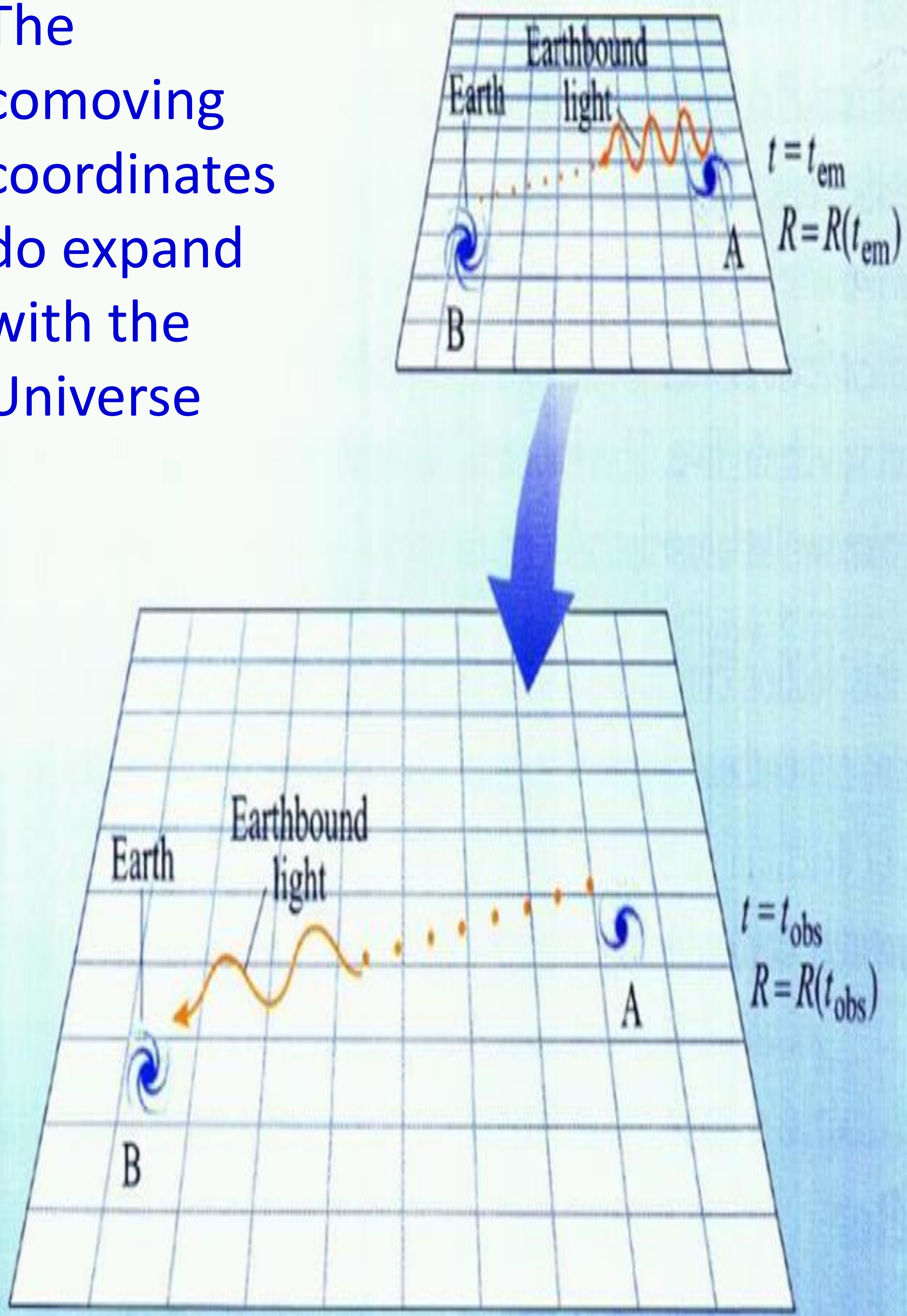
$\rho < \rho_C$ → open (hyperbolic)
$\rho = \rho_C$ → flat (euclidean)
$\rho > \rho_C$ → closed (eliptic)

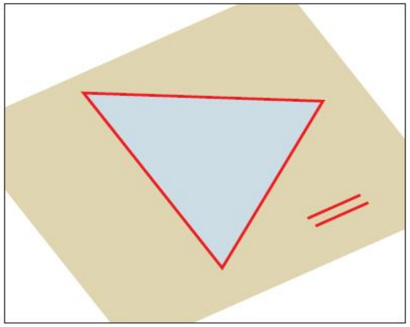
Scale Factor: How distances grow with time

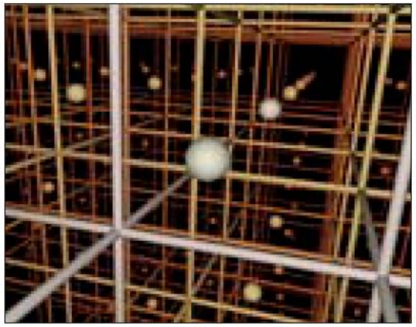
Cosmic time: The time measured by a comoving observer (follows the expansión)

Comoving Coordinates: They expand with the Universe

The comoving coordinates do expand with the Universe

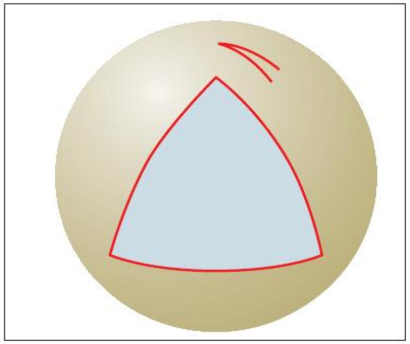




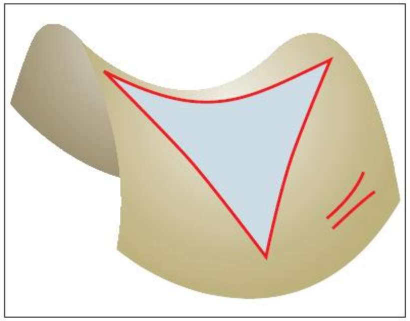


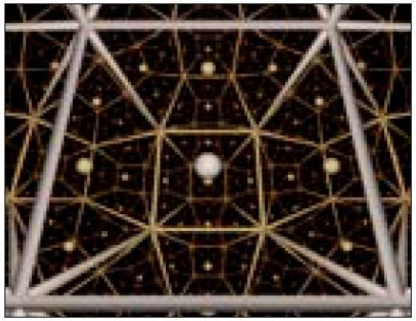
Flat space obeys the familiar rules of Euclidean geometry. The angular size of identical spheres is inversely proportional to distance—the usual vanishing-point perspective taught in art class.

3 possible geometries



Spherical space has the geometric properties of a globe. With increasing distance, the spheres at first seem smaller. They reach a minimum apparent size and subsequently look larger. (Similarly, lines of longitude emanating from a pole separate, reach a maximum separation at the equator and then refocus onto the opposite pole.) This framework consists of dodecahedra.

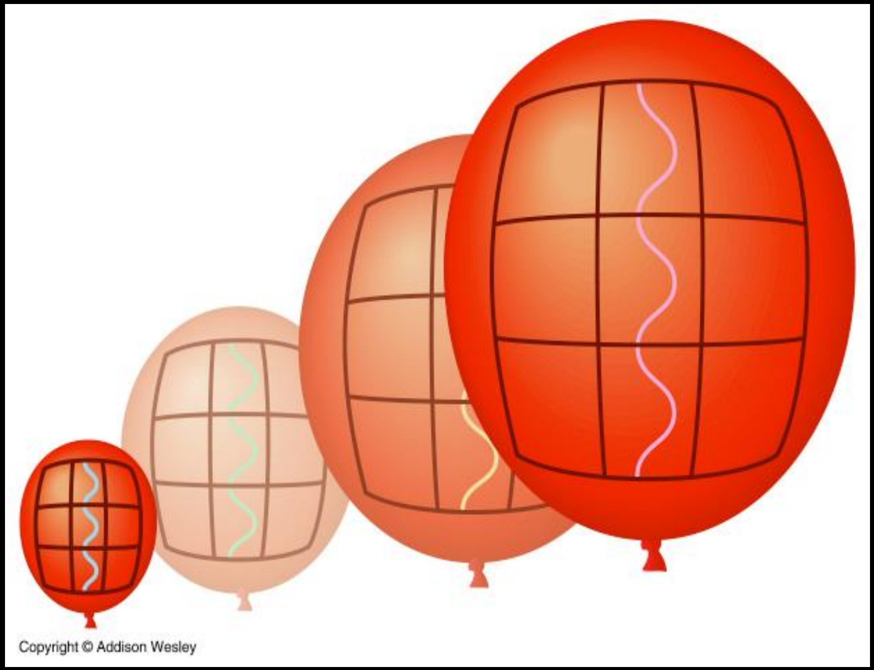




Hyperbolic space has the geometry of a saddle. Angular size shrinks much more rapidly with distance than in Euclidean space. Because angles are more acute, five cubelike objects fit around each edge, rather than only four.

From Scientific American

The oberved light of the galaxies is redshifted because the Universe is expanding



The expansión of the space pulls the light and increases its wavelength → Redshift

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

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

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

Substituting the FLRW metric in the Einstein Eqs., we obtain the Friedmann eqs.:

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

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

G = Newton´s Constant
ρ = *Energy Density*
p = Pressure
Λ = Cosmological Constant

We need to specify the matter species that the Universe contains to solve the equations

Equation of State for perfect barotropic fluids: $p = w\rho$

$$T_{\mu\nu} = (\rho + p/c^2)u_\mu u_\nu + p g_{\mu\nu}$$

Energy-momentum tensor for a perfect fluid

In addition to Friedmann eqs., the continuity equation

$$\dot{\rho} + 3(\rho + \frac{P}{c^2})\frac{\dot{a}}{a} = 0$$

Given the EoS, it relates the density with the scale factor

The Universe contains a mix of fluids, with p=wρ

- matter (both ordinary or dark): p=0, w=0
- radiation: $P=\rho/3$, $w=1/3$
- Cosmological Constant: $p=-\rho$, $w=-1$
- Dark Energy $w=w(t)<-1/3$ (to have accelerated expansion)

For each matter type, the density changes in a different way with the scale factor:

$$\rho \propto a^{-3(1+w)}$$

Matter: a^{-3}

Radiation: a^{-4}

Cosmological Constant: Constant!!!

$$d(\rho a^3) = -P da^3 = -w\rho da^3$$
$$a^3 d\rho + \rho 3a^2 da = -3w\rho a^2 da$$
$$a^3 d\rho = -3(1+w)a^2 \rho da$$
$$\frac{d\rho}{\rho} = -3(1+w)\frac{da}{a}$$
$$d(ln\rho) = -3(1+w)d(lna)$$
$$\rho \propto a^{-3(1+w)}$$

How densities and scale factor evolve for the different matter/energy species in the cosmos

The expansión rate of the Universe depends on the EoS of its components

$$(\frac{\dot{a}}{a})^2 = \frac{8\pi G\rho_0}{3}a^{-3(1+w)}$$
$$\frac{\dot{a}}{a} = \frac{8\pi G\rho_0}{3}a^{-3(1+w)/2}$$
$$\dot{a} = \frac{8\pi G\rho_0}{3}a^{-3(1+w)/2-1}$$
$$daa^{3(1+w)/2-1} = \frac{8\pi G\rho_0}{3}dt$$
$$a^{3(1+w)/2} \propto t$$
$$a \propto t^{2/3(1+w)}$$

Distances

The comoving distance to a source of redshift z is:

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

Several distances can be measured observationally

Luminosity distance: "Standard Candle" with luminosity L

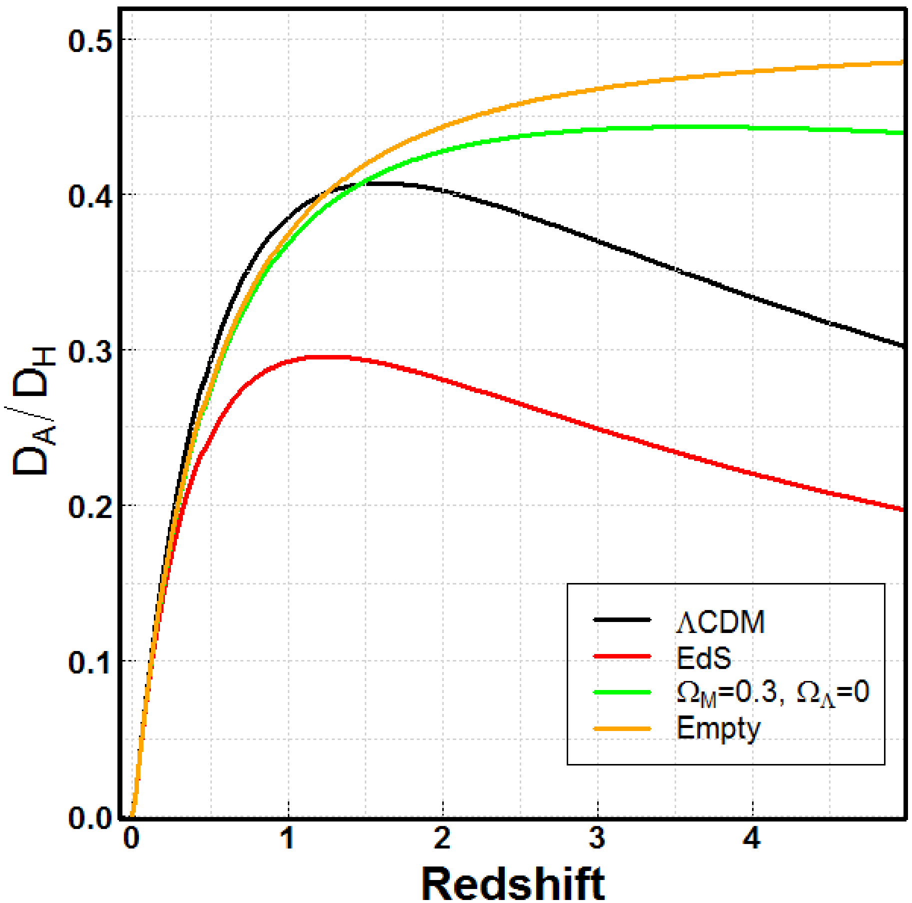
$\phi = L/4\pi d_L^2$; $d_L = r(z)(1+z)$ (flat Universe)

Angular diameter distance: "Standard Ruler" with length l

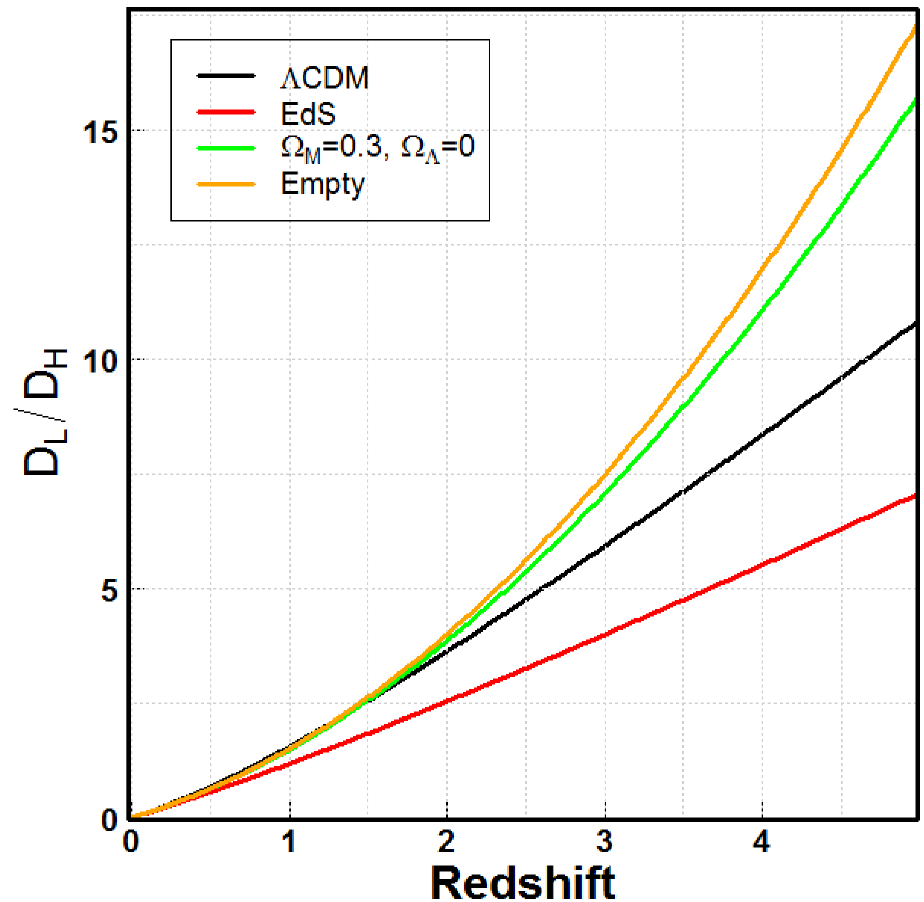
$\Delta\theta = l/d_A$; $d_A = r(z)/(1+z)$ (flat Universe)

Therefore, from a set of standard rulers or standard candles with different redshifts, we will have many values of *r(z)*, from which we can obtain Ω_m, w, etc.

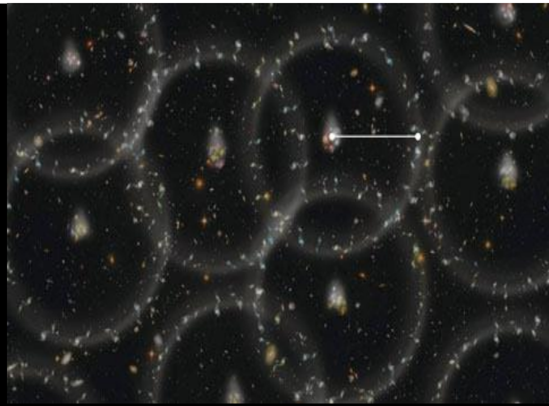
Angular Diameter Distance

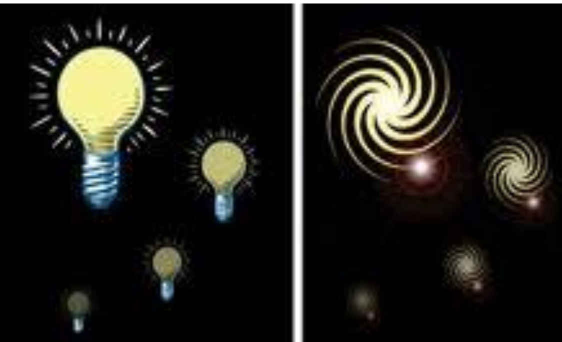


Luminosity Distance



STANDARD RULERS



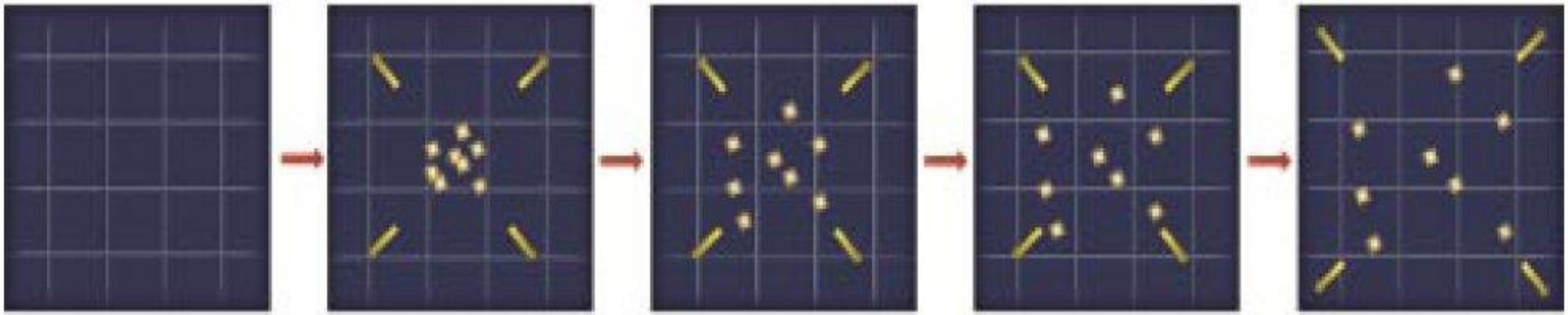


STANDARD CANDLES

WHAT KIND OF EXPLOSION WAS THE BIG BANG?

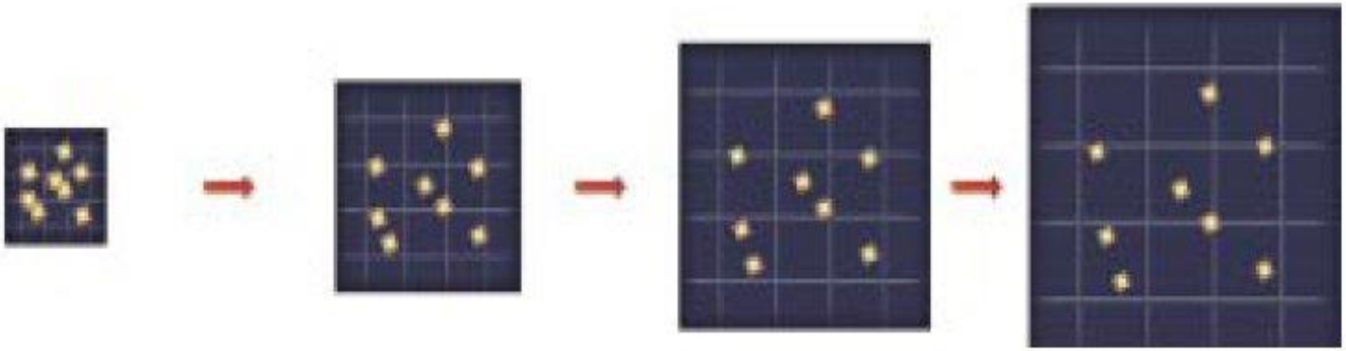
WRONG: The big bang was like a bomb going off at a certain location in previously empty space.

In this view, the universe came into existence when matter exploded out from some particular location. The pressure was highest at the center and lowest in the surrounding void; this pressure difference pushed material outward.



RIGHT: It was an explosion of space itself.

The space we inhabit is itself expanding. There was no center to this explosion; it happened everywhere. The density and pressure were the same everywhere, so there was no pressure difference to drive a conventional explosion.

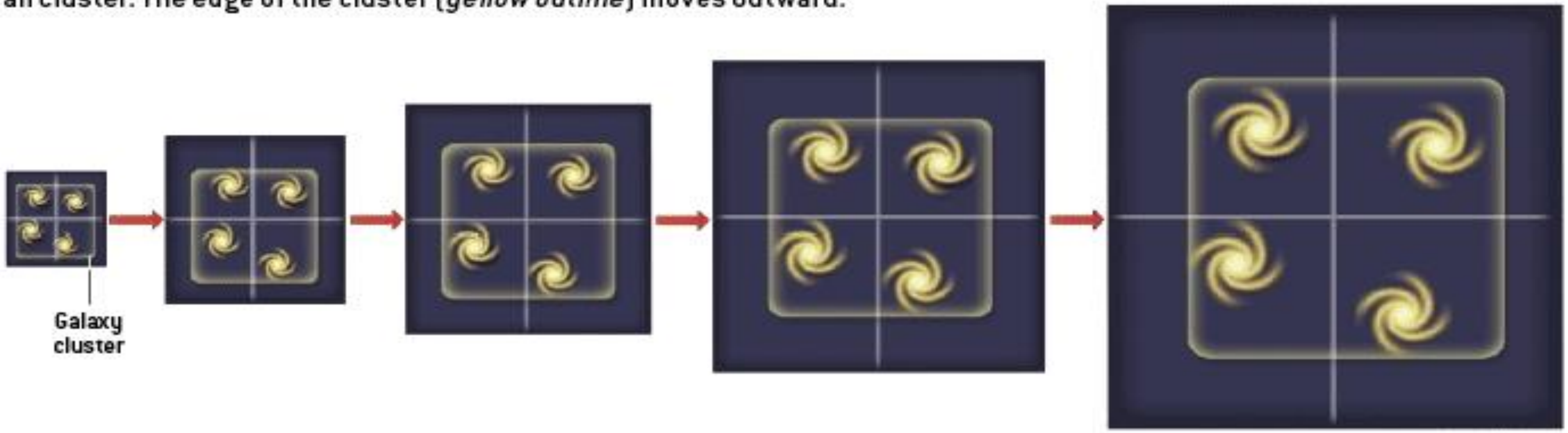


From Scientific American

DO OBJECTS INSIDE THE UNIVERSE EXPAND, TOO?

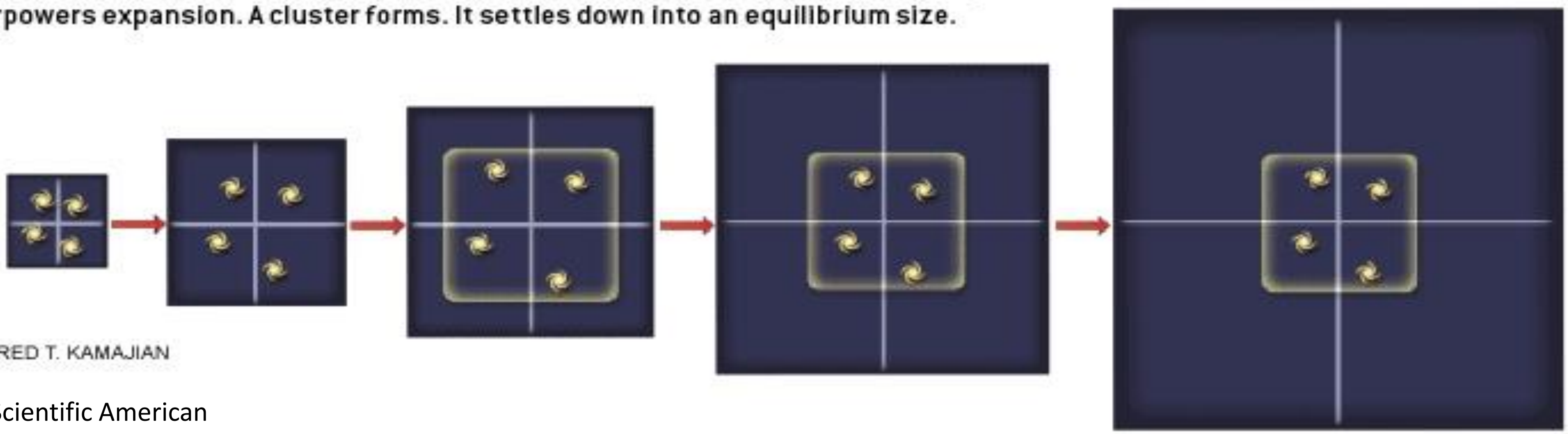
WRONG: Yes. Expansion causes the universe and everything in it to grow.

Consider galaxies in a cluster. As the universe gets bigger, so do the galaxies and the overall cluster. The edge of the cluster (*yellow outline*) moves outward.



RIGHT: No. The universe grows, but coherent objects inside it do not.

Neighboring galaxies initially get pulled apart, but eventually their mutual gravity overpowers expansion. A cluster forms. It settles down into an equilibrium size.



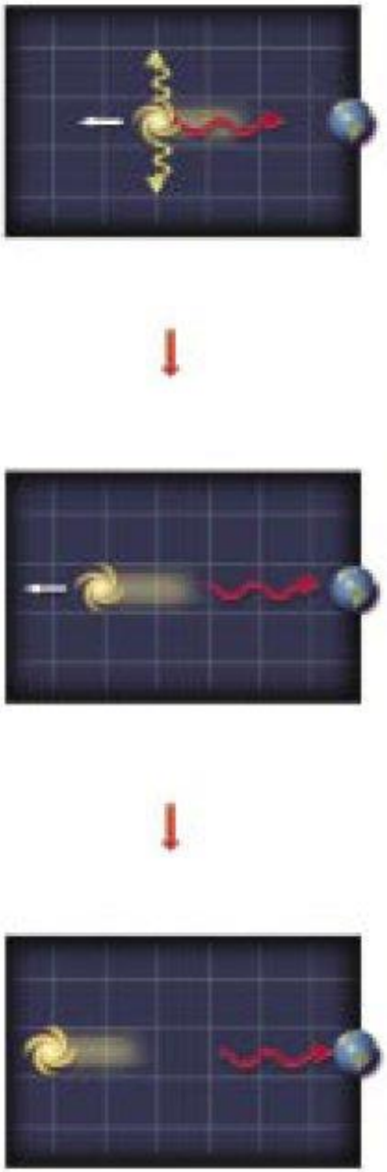
ALFRED T. KAMAJIAN

From Scientific American

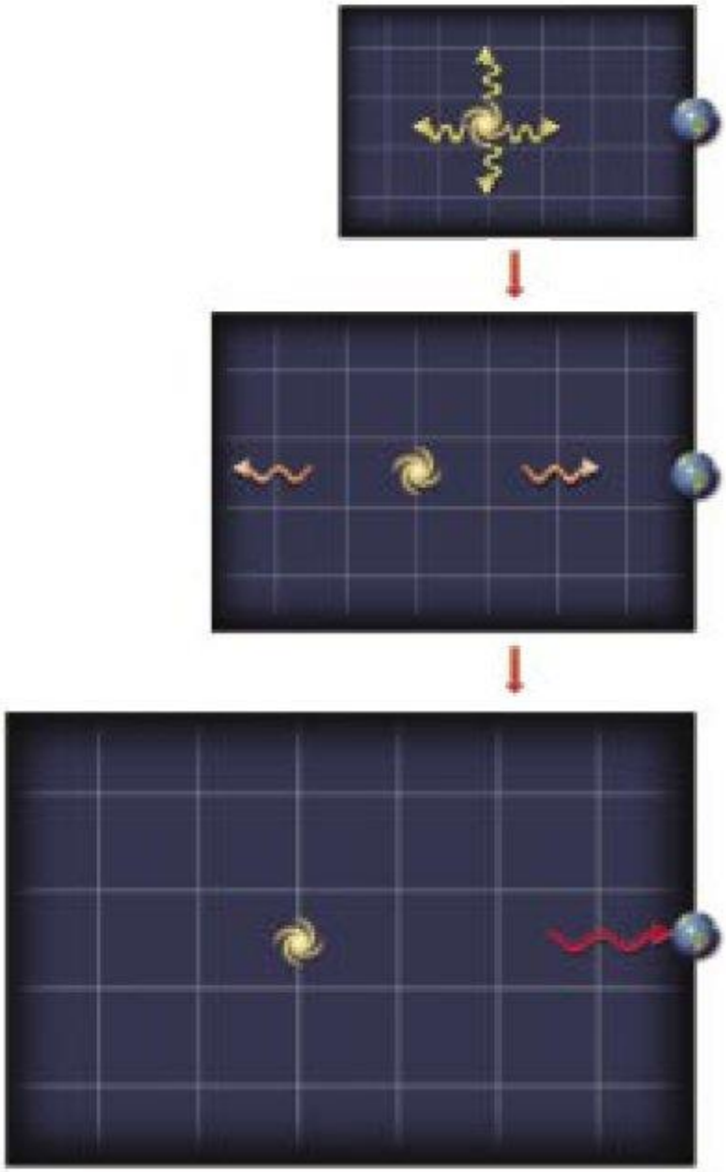
WHY IS THERE A COSMIC REDSHIFT?

WRONG: **Because receding galaxies are moving through space and exhibit a Doppler shift.**

In the Doppler effect, a galaxy's movement away from the observer stretches the light waves, making them redder (*top*). The wavelength of light then stays the same during its journey through space (*middle*). The observer detects the light, measures its Doppler redshift and computes the galaxy velocity (*bottom*).



RIGHT: **Because expanding space stretches all light waves as they propagate.**



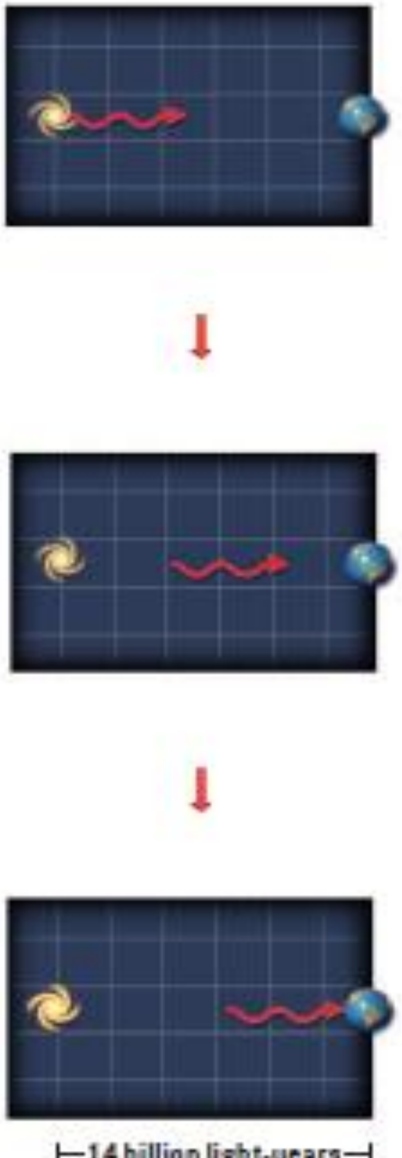
Galaxies hardly move through space, so they emit light with nearly the same wavelength in all directions (*top*). The wavelength gets longer during the journey, because space is expanding. Thus, the light gradually reddens (*middle* and *bottom*). The amount of redshift differs from what a Doppler shift would produce.

From Scientific American

HOW LARGE IS THE OBSERVABLE UNIVERSE?

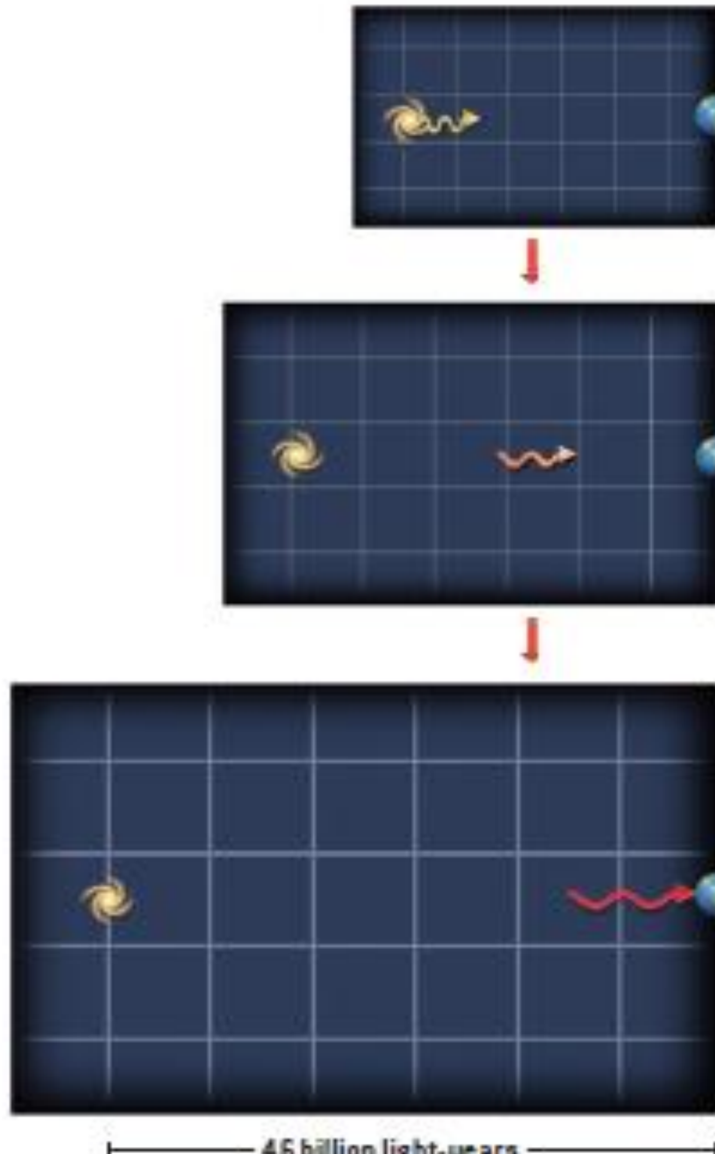
WRONG: **The universe is 14 billion years old, so the radius of the observable part is 14 billion light-years.**

Consider the most distant observable galaxy—one whose photons, emitted shortly after the big bang, are only now reaching us. A light-year is the distance photons travel in one year. So a photon from that galaxy has traveled 14 billion light-years.



RIGHT: **Because space is expanding, the observable part of our universe has a radius of more than 14 billion light-years.**

As a photon travels, the space it traverses expands. By the time it reaches us, the total distance to the originating galaxy is larger than a simple calculation based on the travel time might imply—about three times as large.

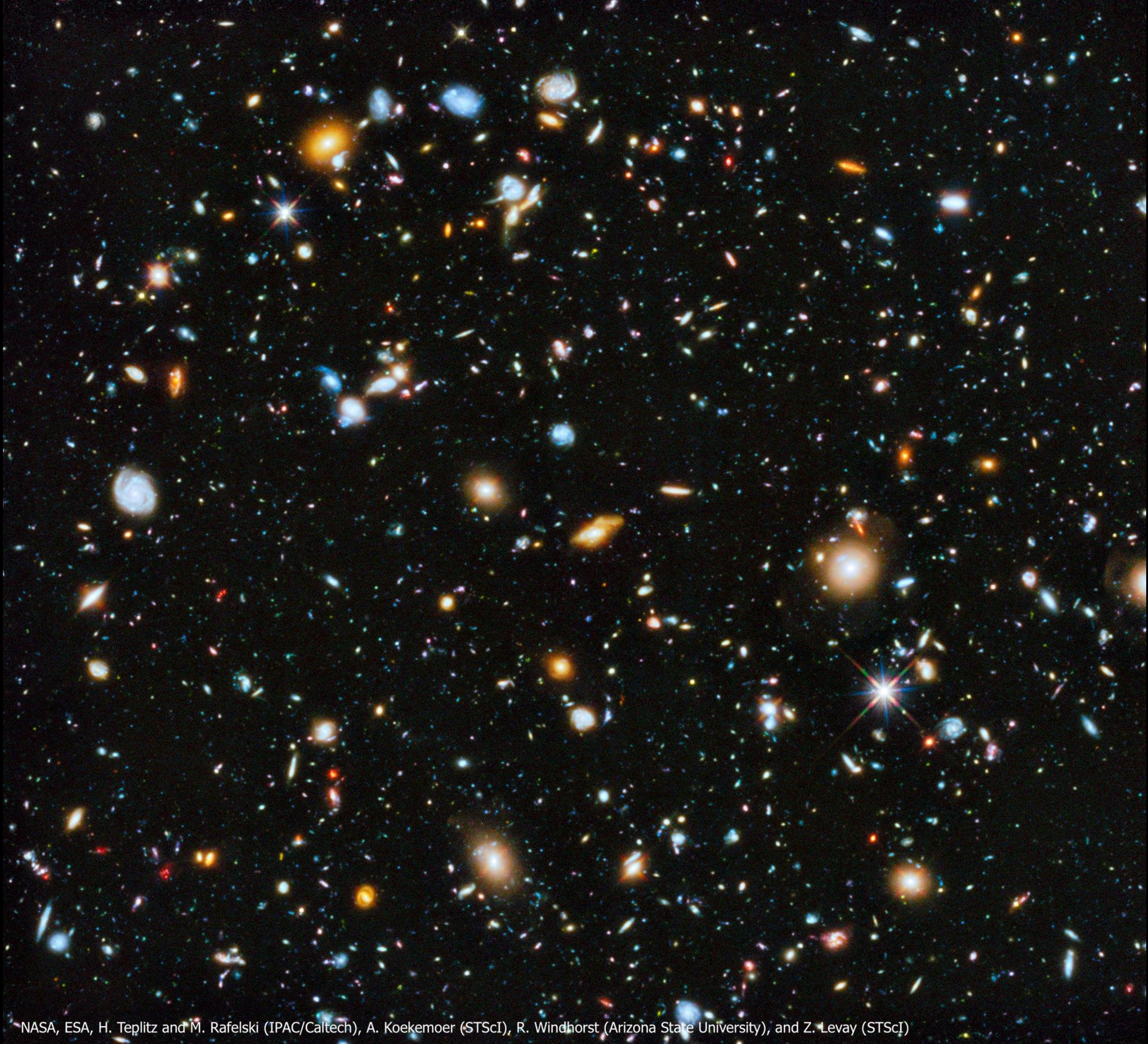


From Scientific American

The observable Universe is finite

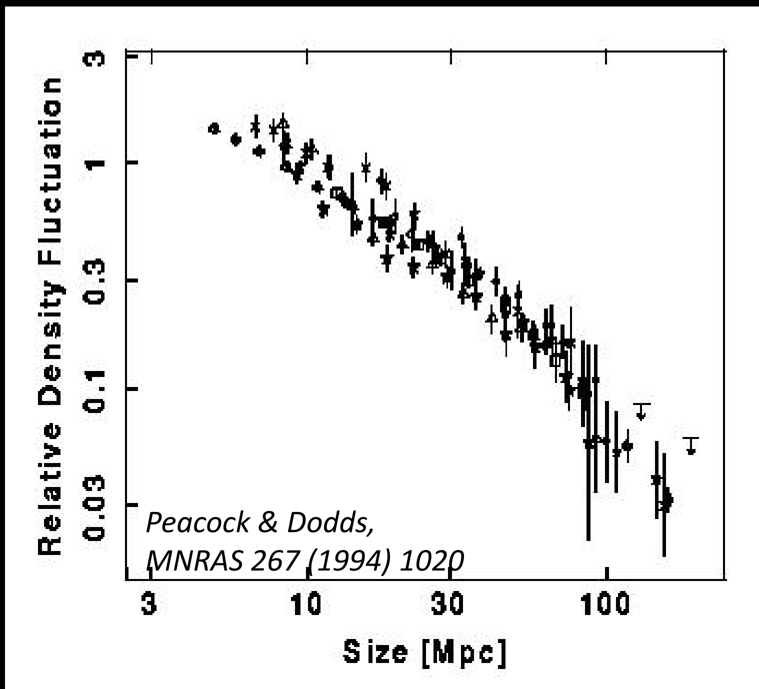
Around half of the galaxies in this image of the HUDF are beyond the cosmological event horizon.

The light they are emitting now will never reach the Earth!!!



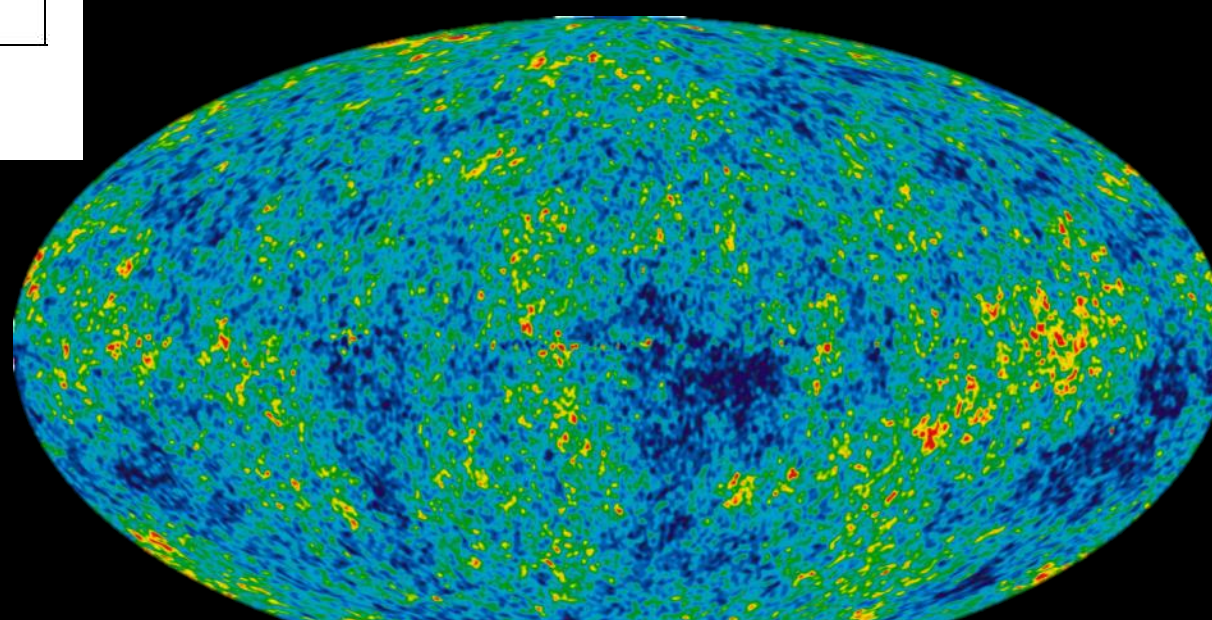
OBSERVATIONAL BASIS

Observational verification of the cosmological principle



Homogeneity: Very difficult to observe. Confirmed that Galaxy distribution tends to uniformity with a few percent precisión for distances of the order of 100 Mpc

Isotropy: Verified with a precisión of 1 part in 10^5 using the CMB



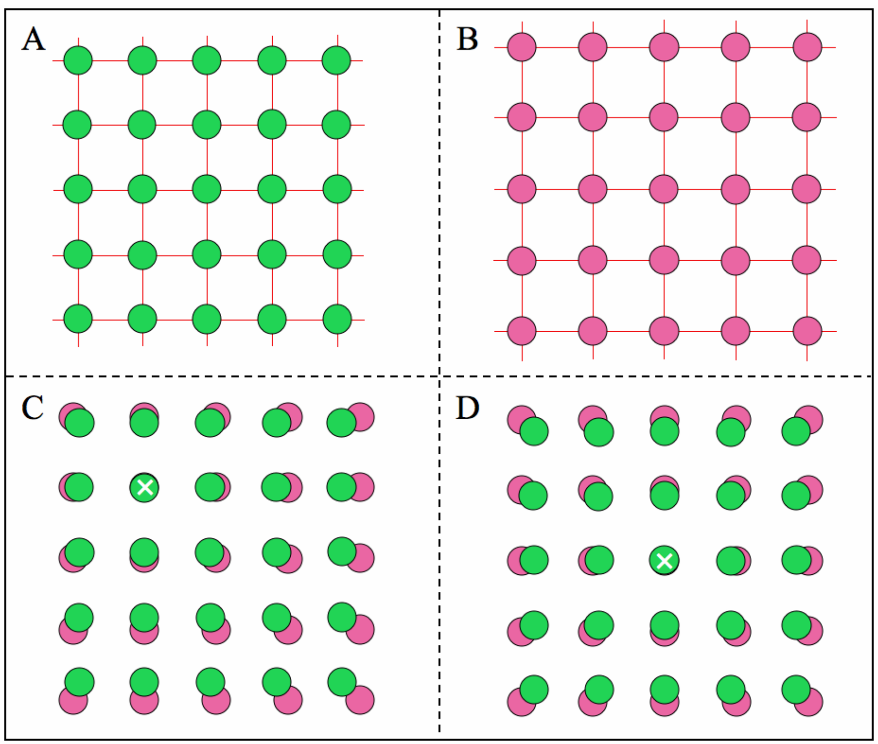
WMAP Collaboration

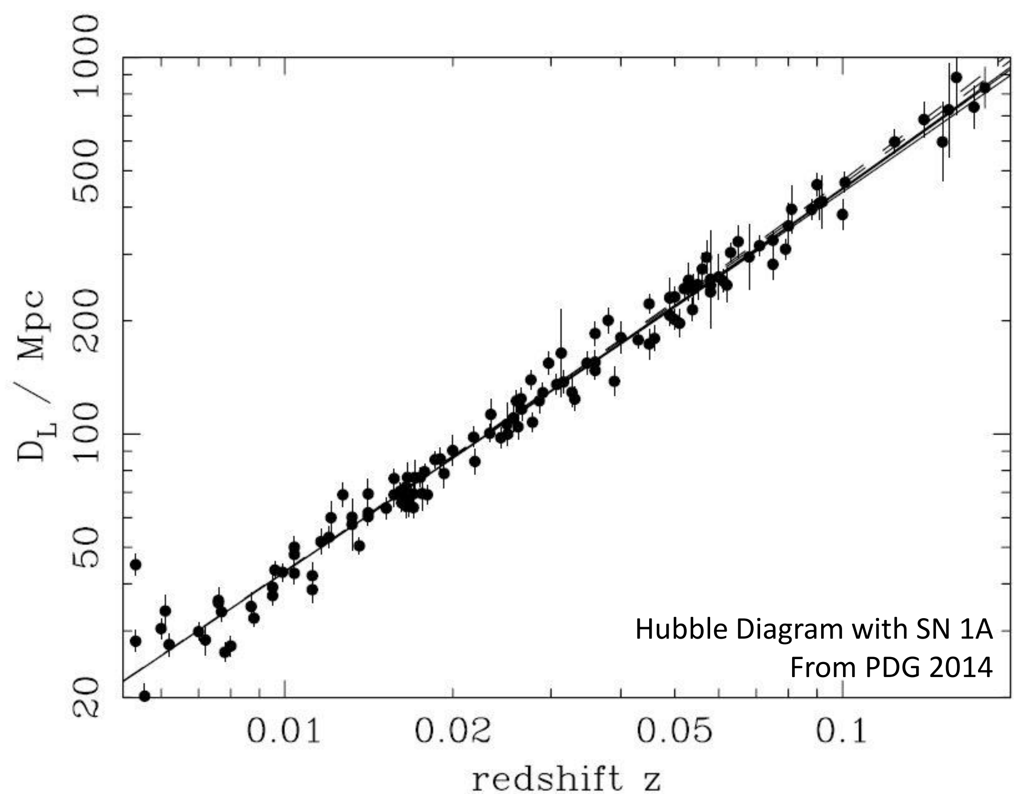
Expansion: The Hubble Law

Galaxies recede from the Earth with a velocity that is proportional to the distance. The Universe expands as expected from the cosmological principle

$$cz \sim v = H\, d = \frac{\dot{a}}{a} d$$

H= Hubble constant (km/s/Mpc), v=velocity, d=distance

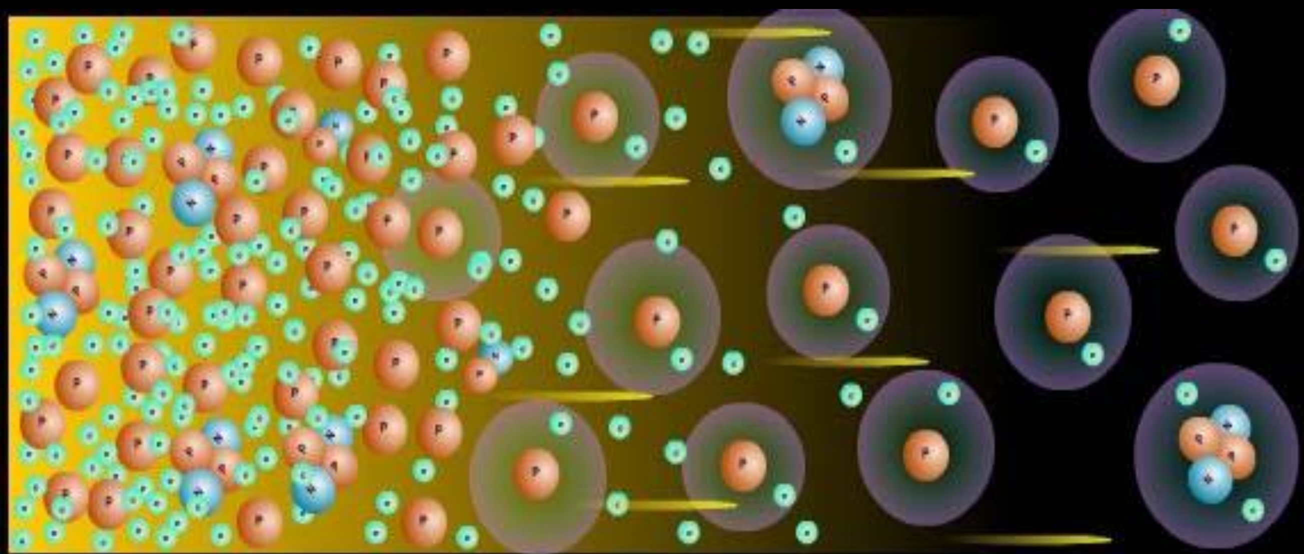




THE COSMIC MICROWAVE BACKGROUND

One of the decisive predictions of the Big Bang

Comes from the matter-radiation decoupling, **when the Universe had 380000 years. That means from...13800 million years ago!!! (If the Universe is a 80 years old person, the CMB is a picture when was 13 months old!!!)**

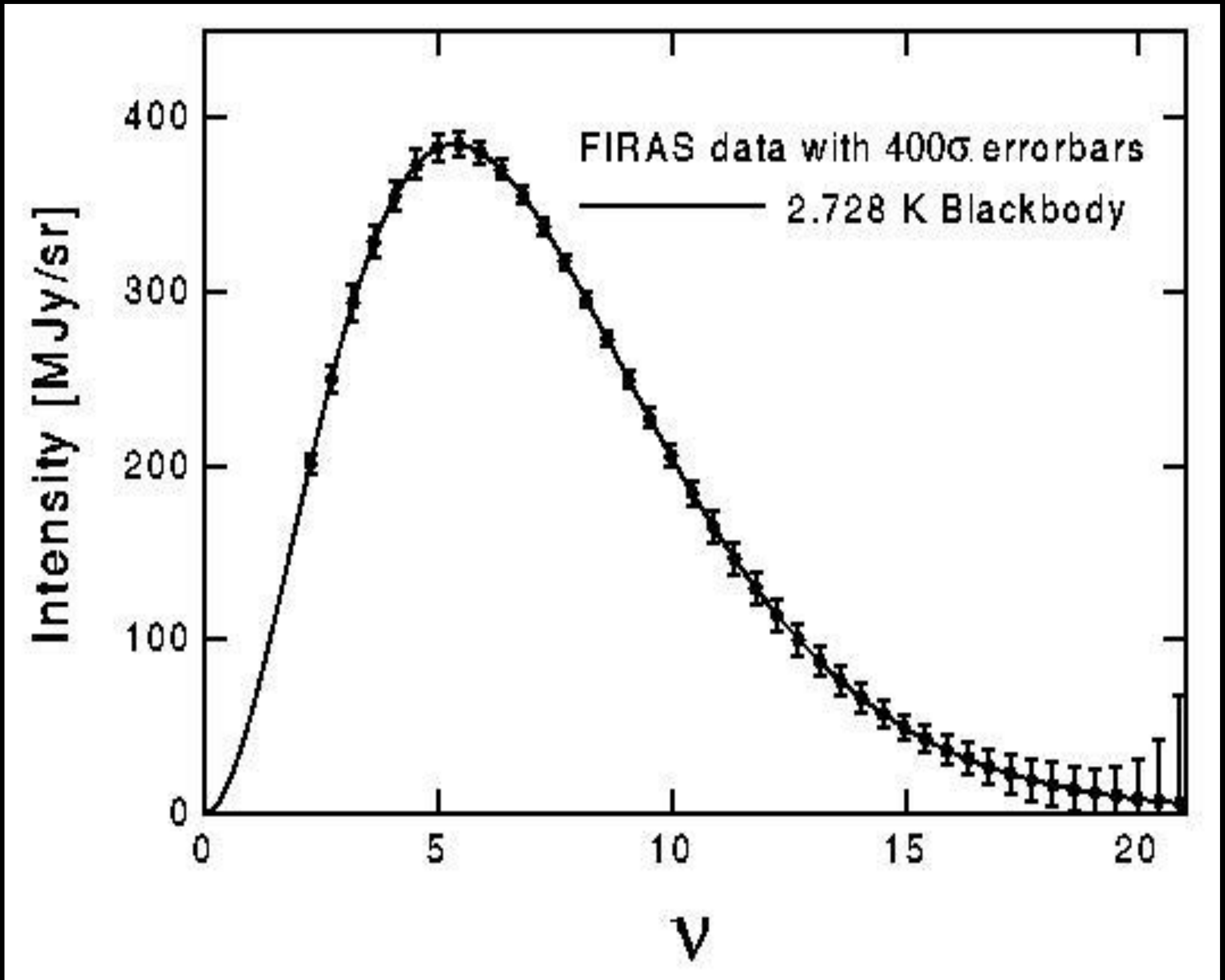


The confirmation that the CMB is not completely uniform was done in 1992. Its small anisotropies are the imprint of the origin of all the structures we see today (clusters, galaxies, stars,...)

The Cosmic Microwave Background (CMB)

It was produced at a temperature of 3000 K, when the Universe was cold enough to form atoms, and it has been cooling since then because of the cosmic expansion

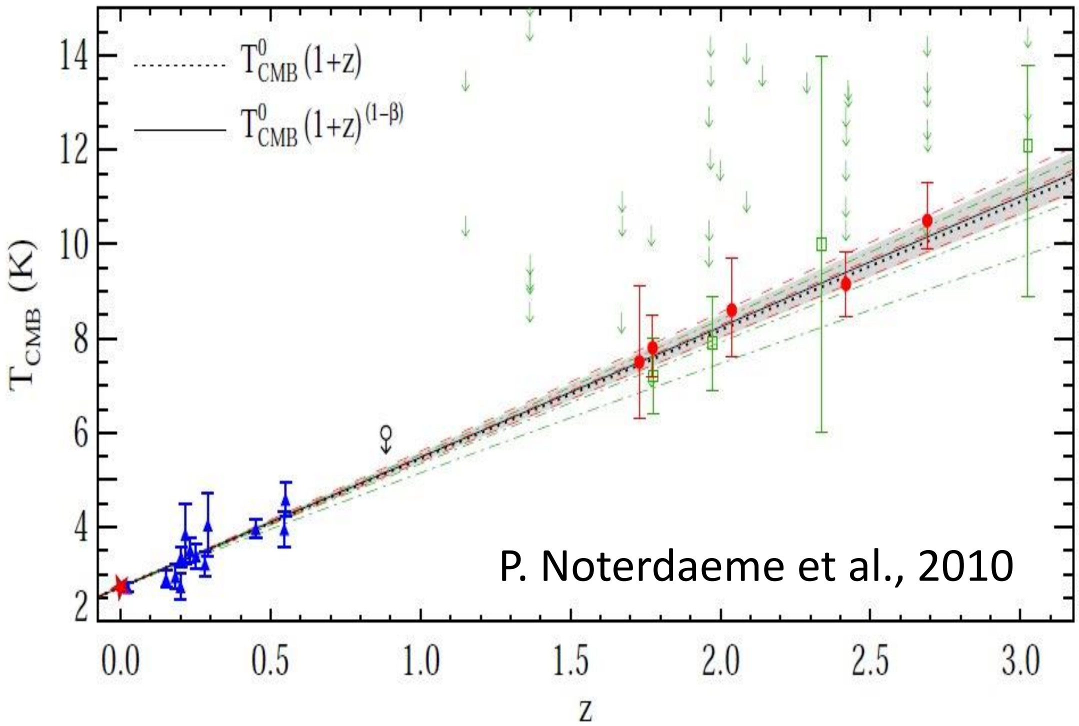
Black Body Spectrum at 2.72548 ± 0.00057 K

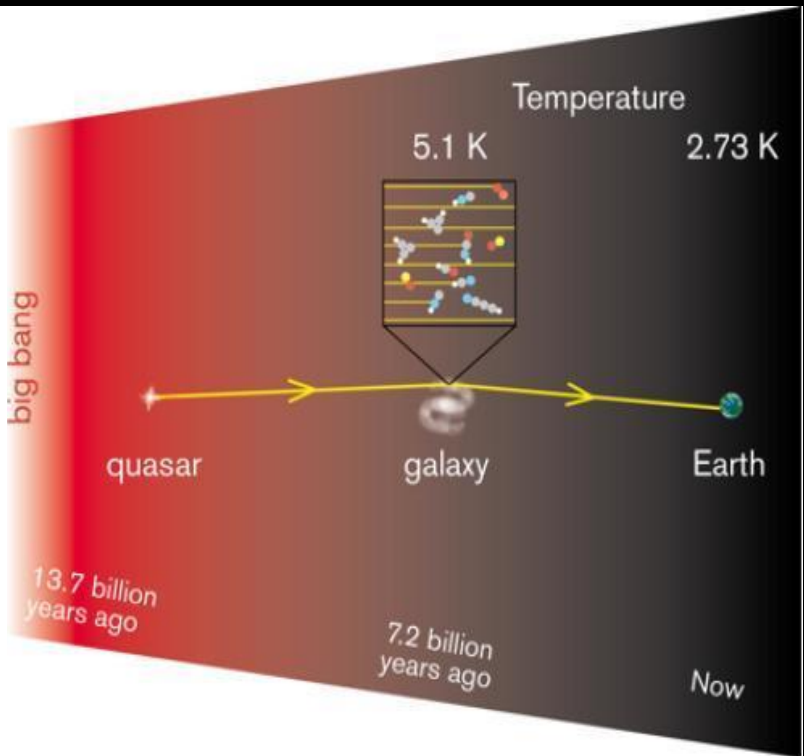


The Cosmic Microwave Background (CMB)

The Universe was hotter in the past

The cooling rate is exactly predicted by the Big Bang theory

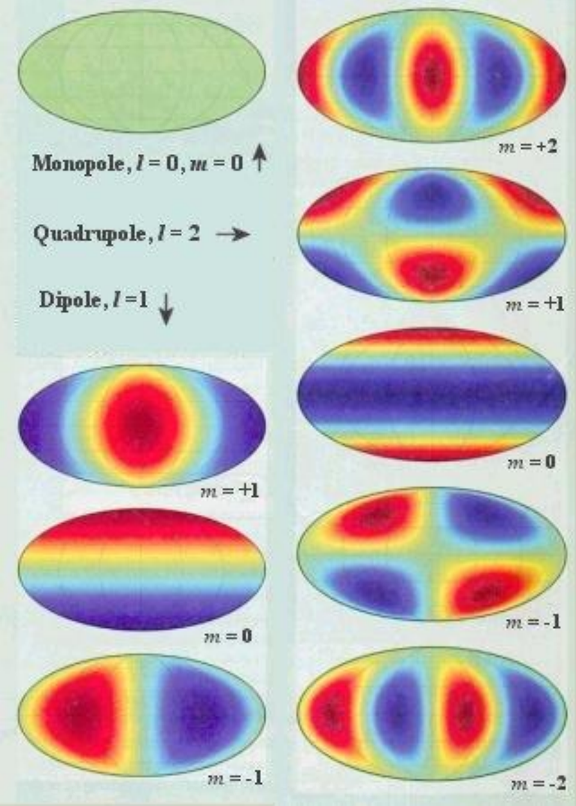


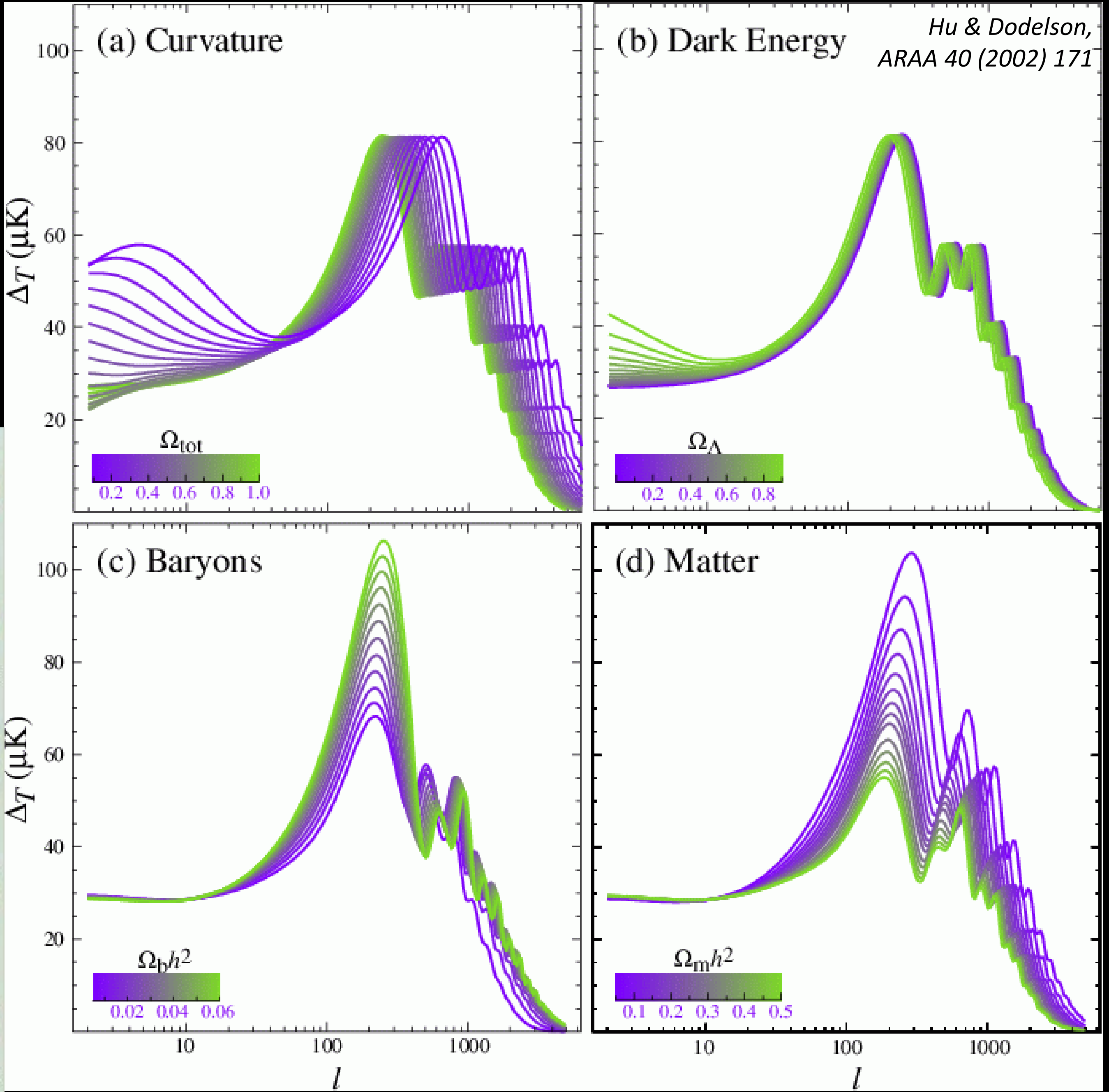


The Cosmic Microwave Background (CMB)

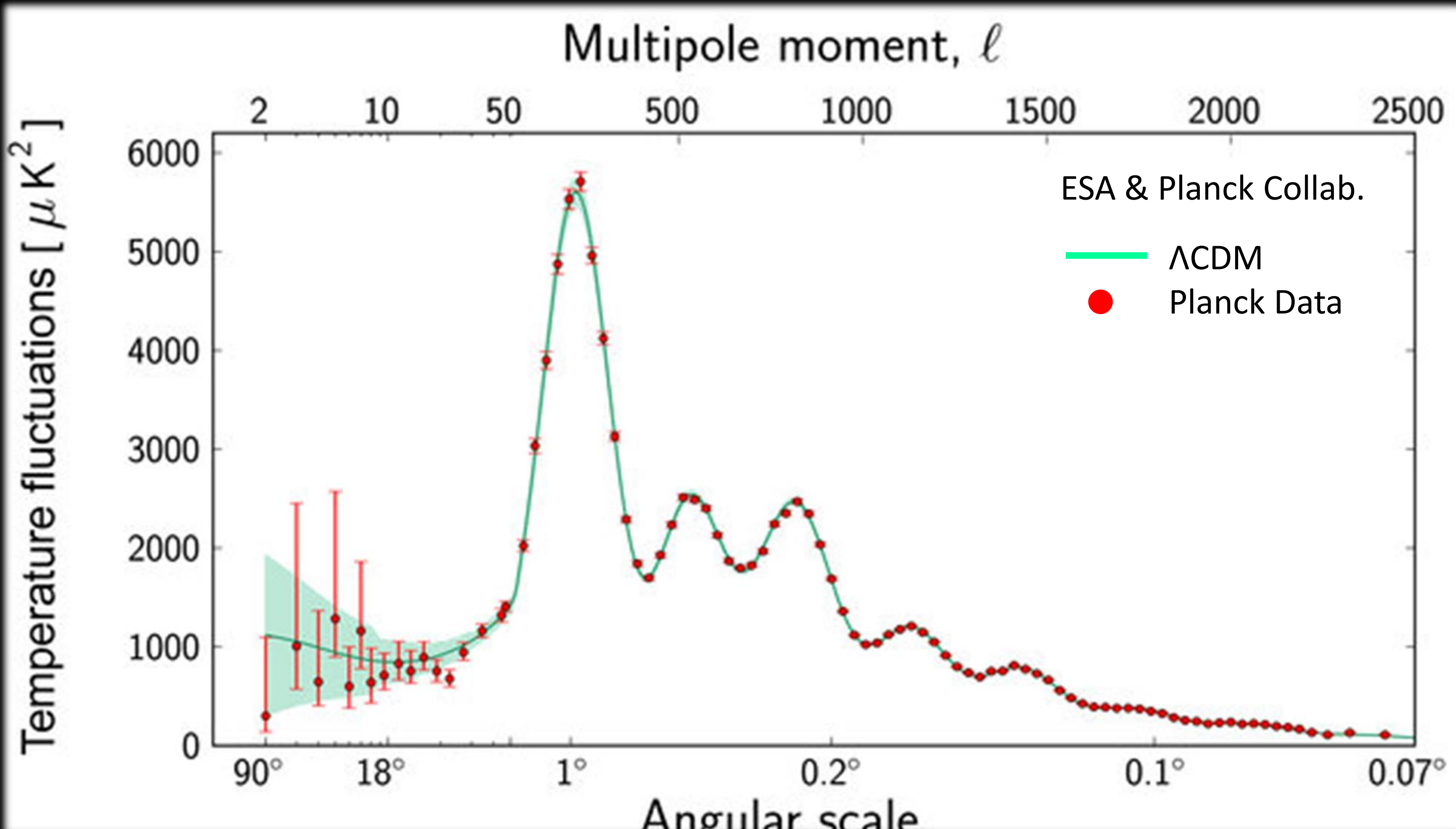
The power spectrum of the CMB depends on the cosmological parameters

The power spectrum describes the size of fluctuations as a function of the size





The Cosmic Microwave Background (CMB)

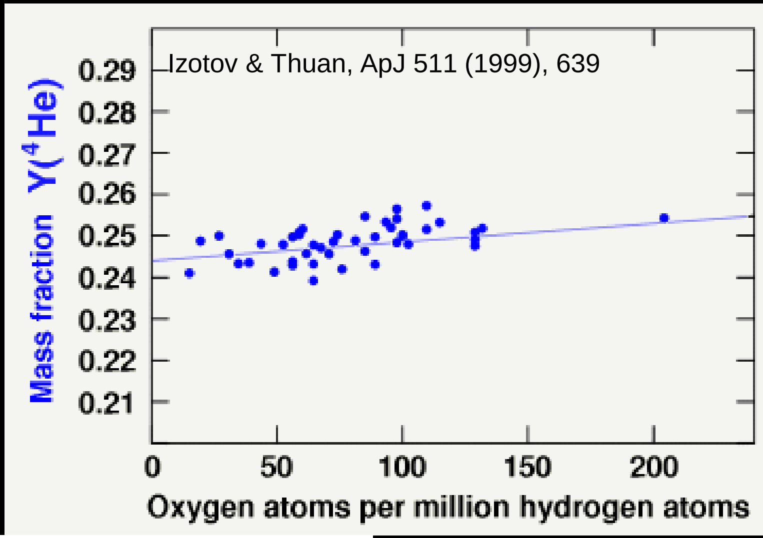


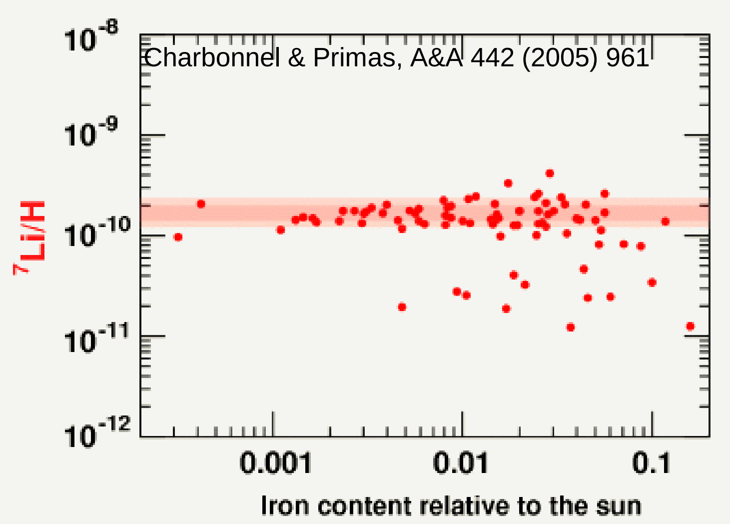
Extraordinary agreement between ΛCDM and data

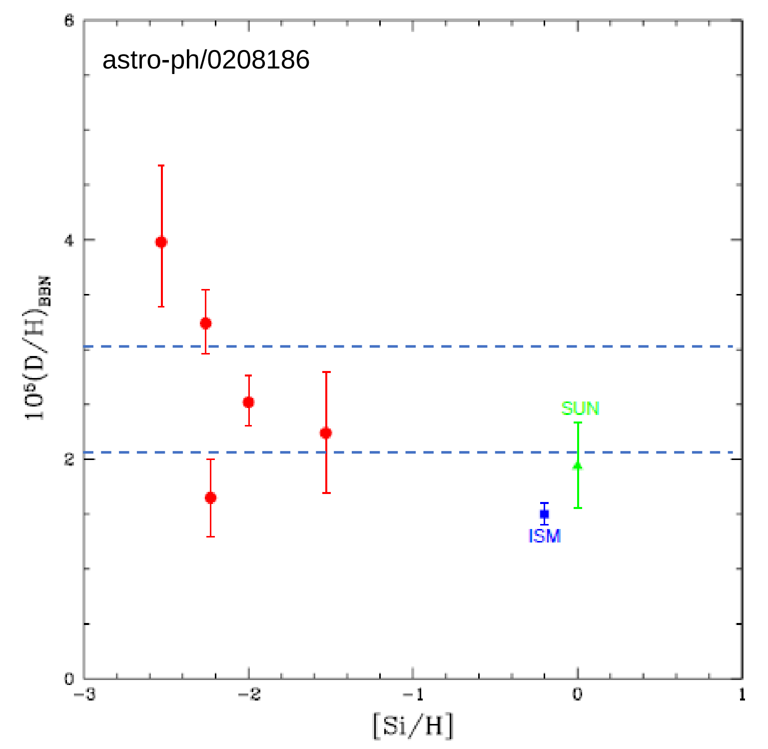
The spatial geometry of the Universe is Euclidean

The primordial nucleosynthesis

The lightest atomic nuclei formed in the first quarter of hour of the Universe (from ~3 minutes to ~20 minutes after the BB)







Measure their abundancies:

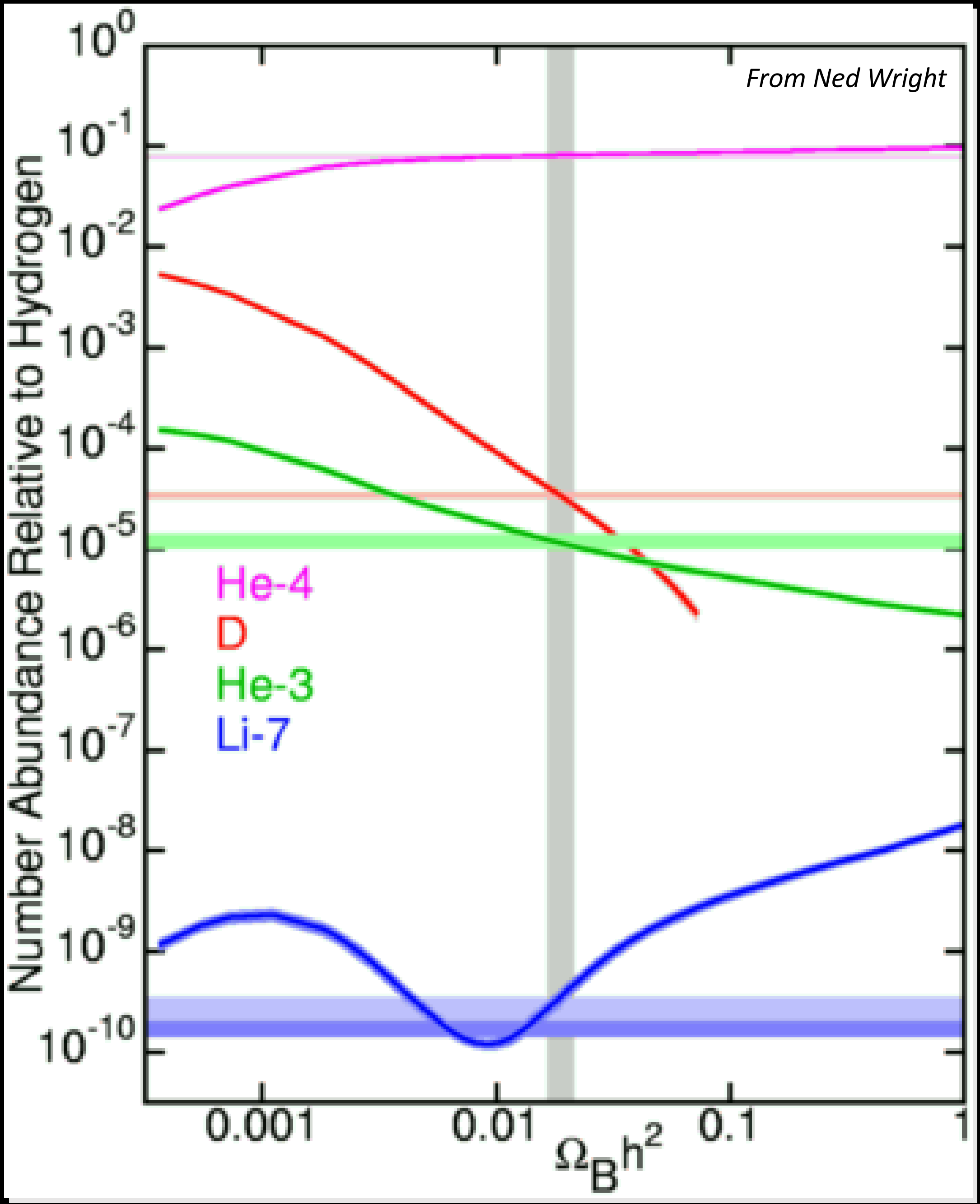
D→ absorption lines in QSOs

^{4}He→ Extragalactic HII regions of low metallicity (O/H).

^{7}Li→ Dwarf stars in the galactic halo.

Large systematic errors.

Nucleosynthesis: non-baryonic dark matter



Abundancies of primordial elements measure the number of baryons

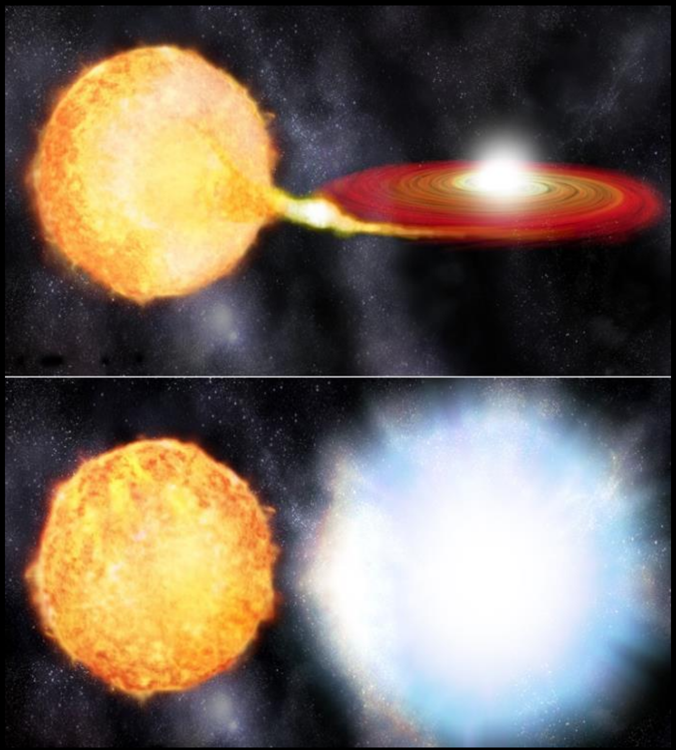
Is a well-known physics (atoms)

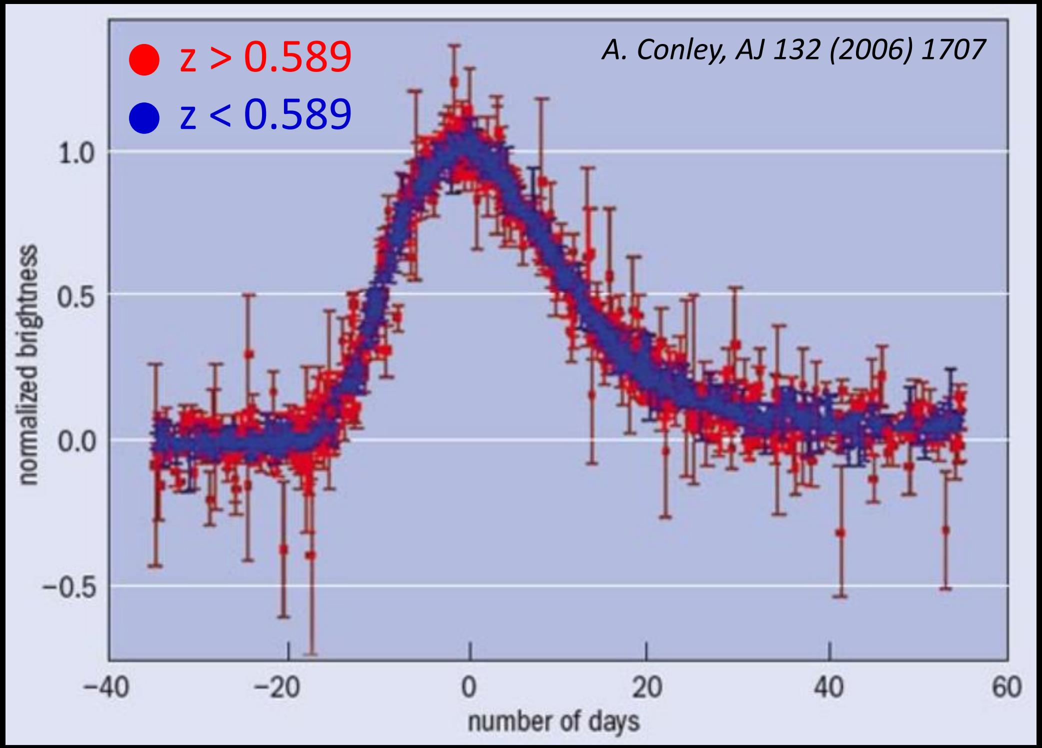
The number of photons per baryon is measured in the CMB. In perfect agreement with the abundances!

THERE IS NON-BARYONIC DARK MATTER!

Supernovae Ia: dark energy

Supernovae are the result of the violent death of massive stars. They are extremely bright, therefore, can be seen up to huge distances



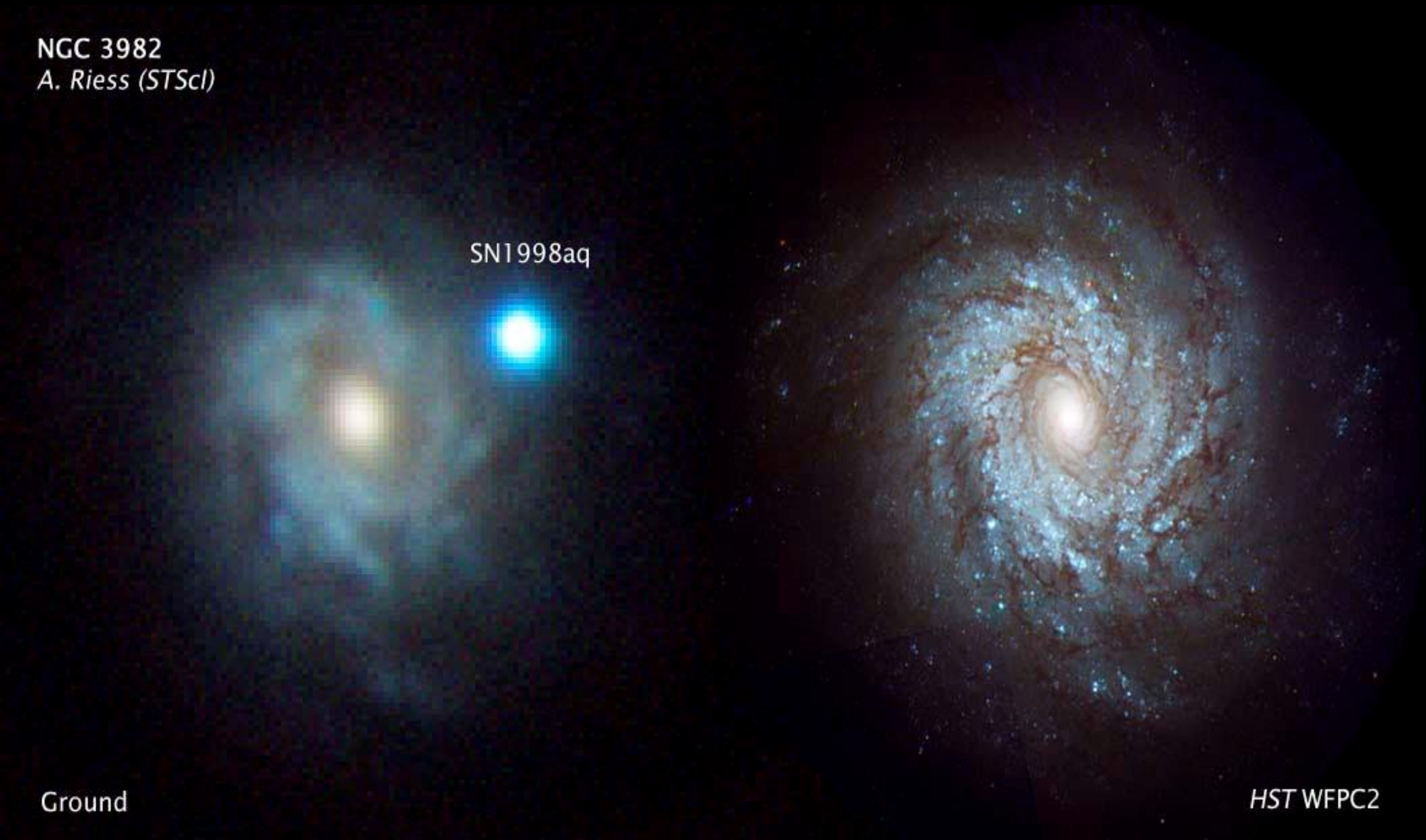


SN1a: Binary systems red giant-White dwarf

The white dwarf gets mass from the red giant

When it reaches the Chandrashekar limit, it explodes. All are identical, since they explode when the limit is reached (stellar amnesia)

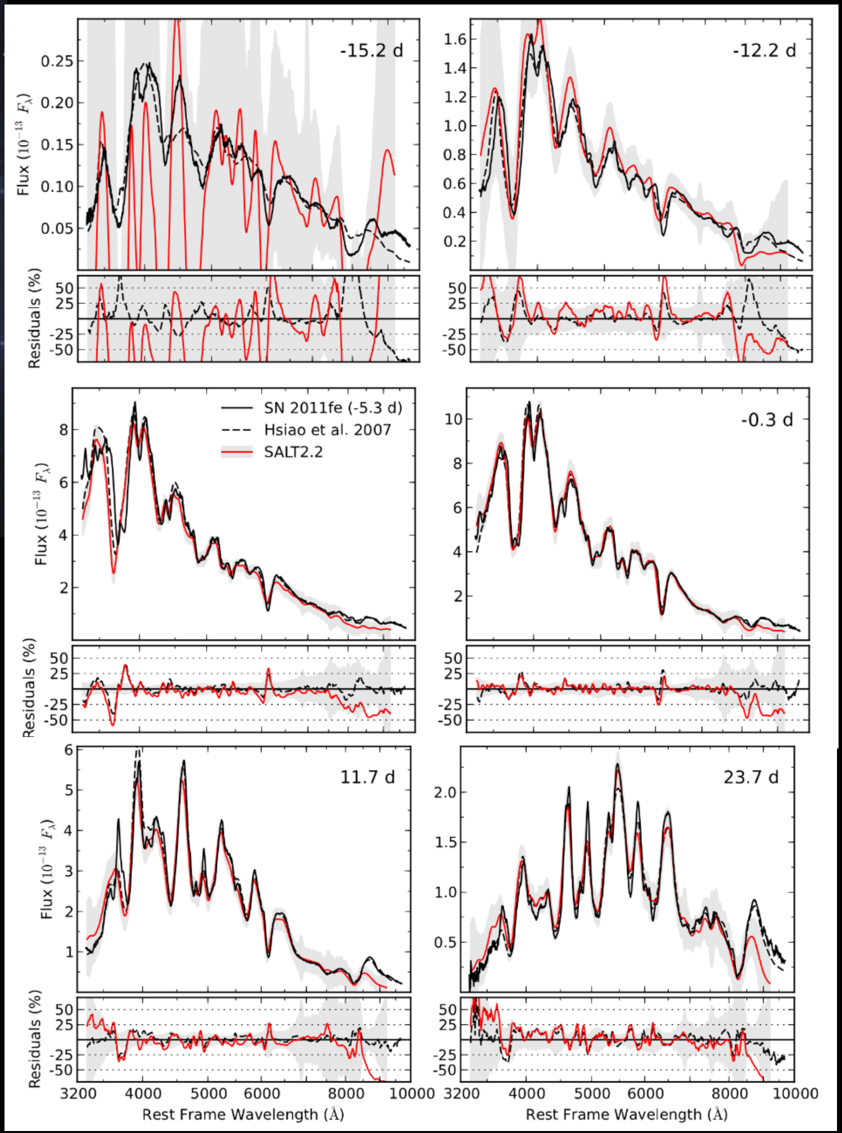
SN 1998aq



SN2011ef

The closest and brightest known 1a. In the M101 galaxy, at z=0.000804, or 6.4 Mpc.

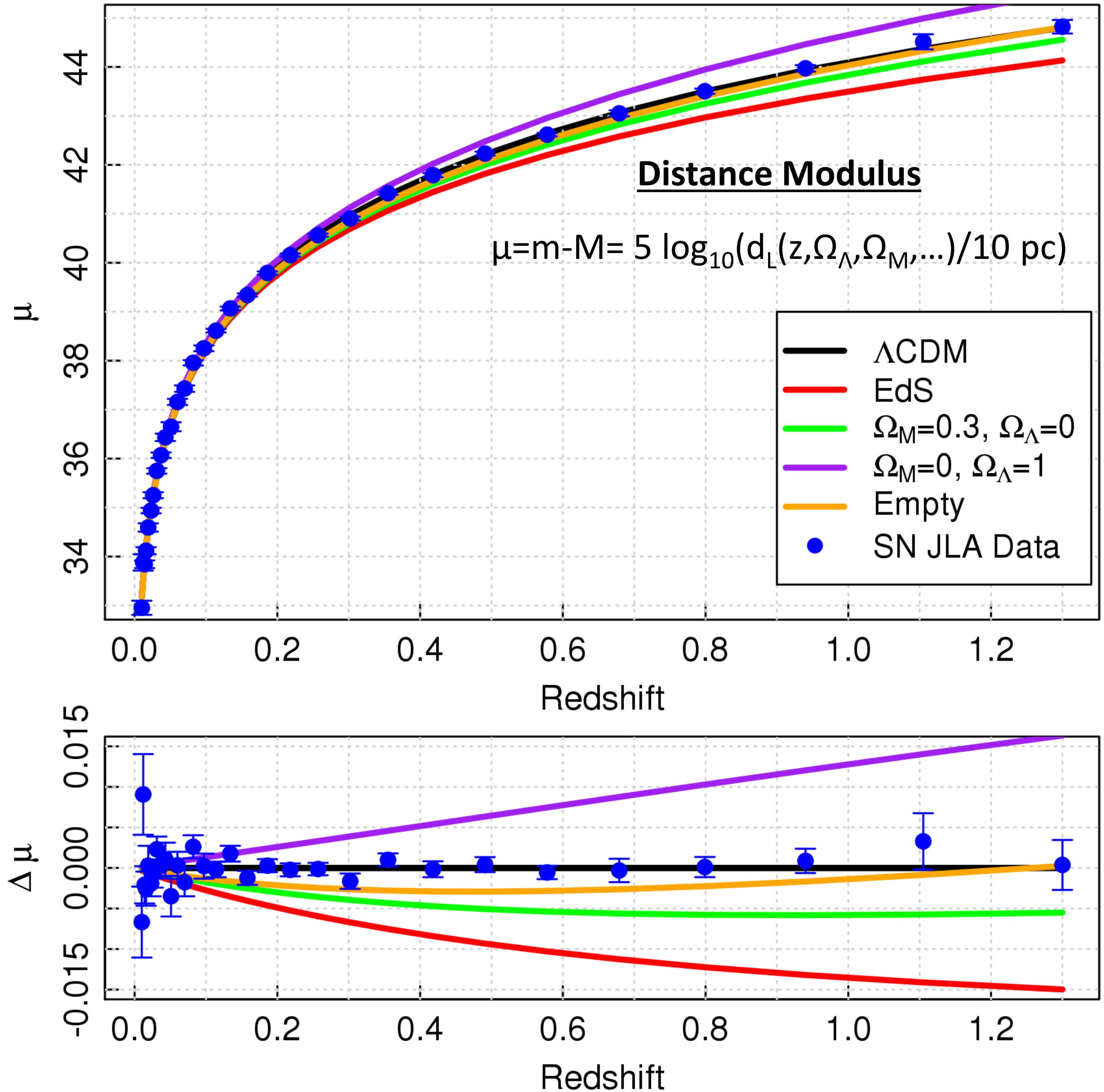
arXiv:1302.1292 [astro-ph]

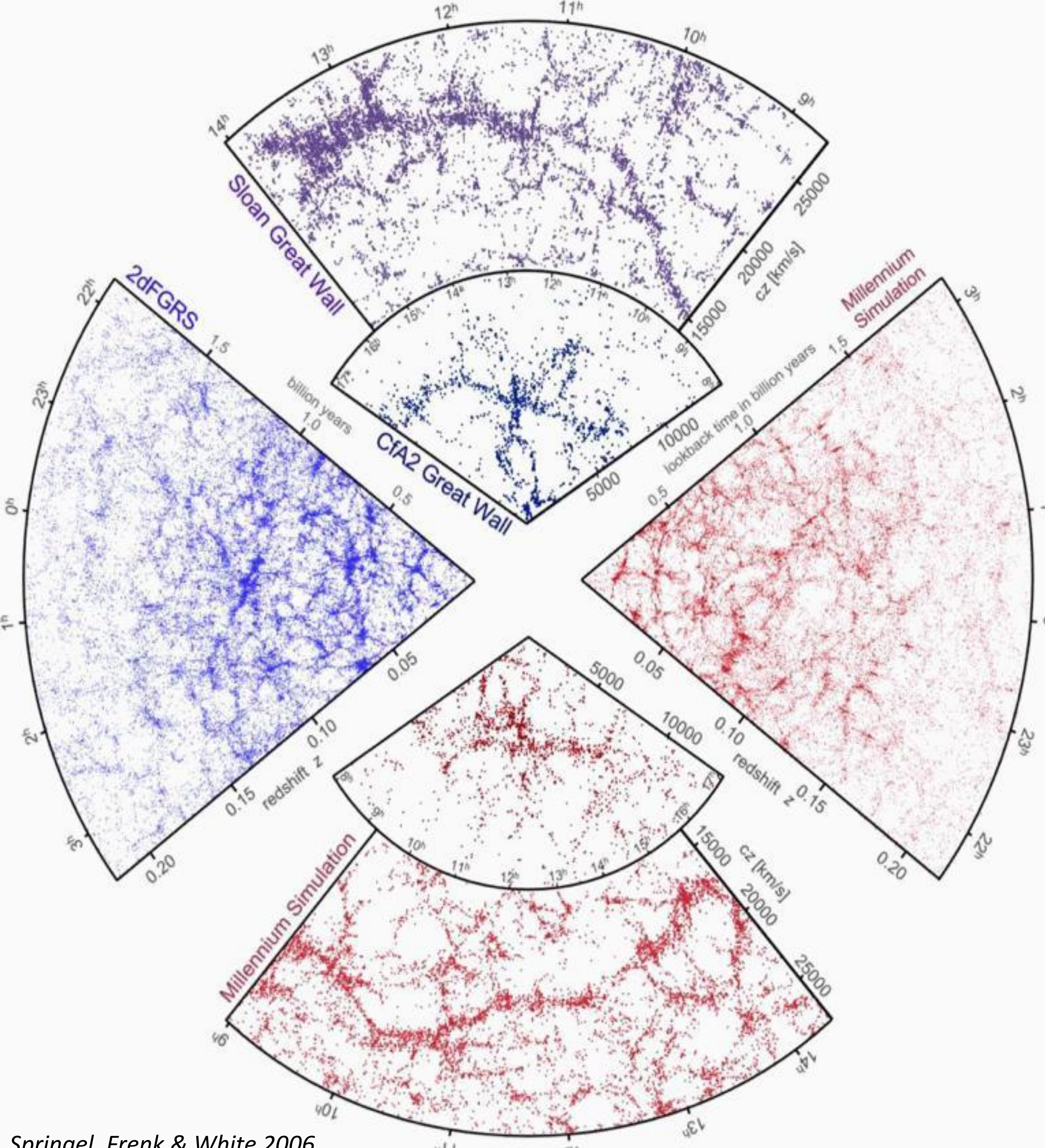


Once we have the luminosities, we can build the Hubbble diagram and fit the cosmological parameters

<u>THE EXPANSION OF THE UNIVERSE IS ACCELERATING:</u>

¡¡¡¡DARK ENERGY!!!!





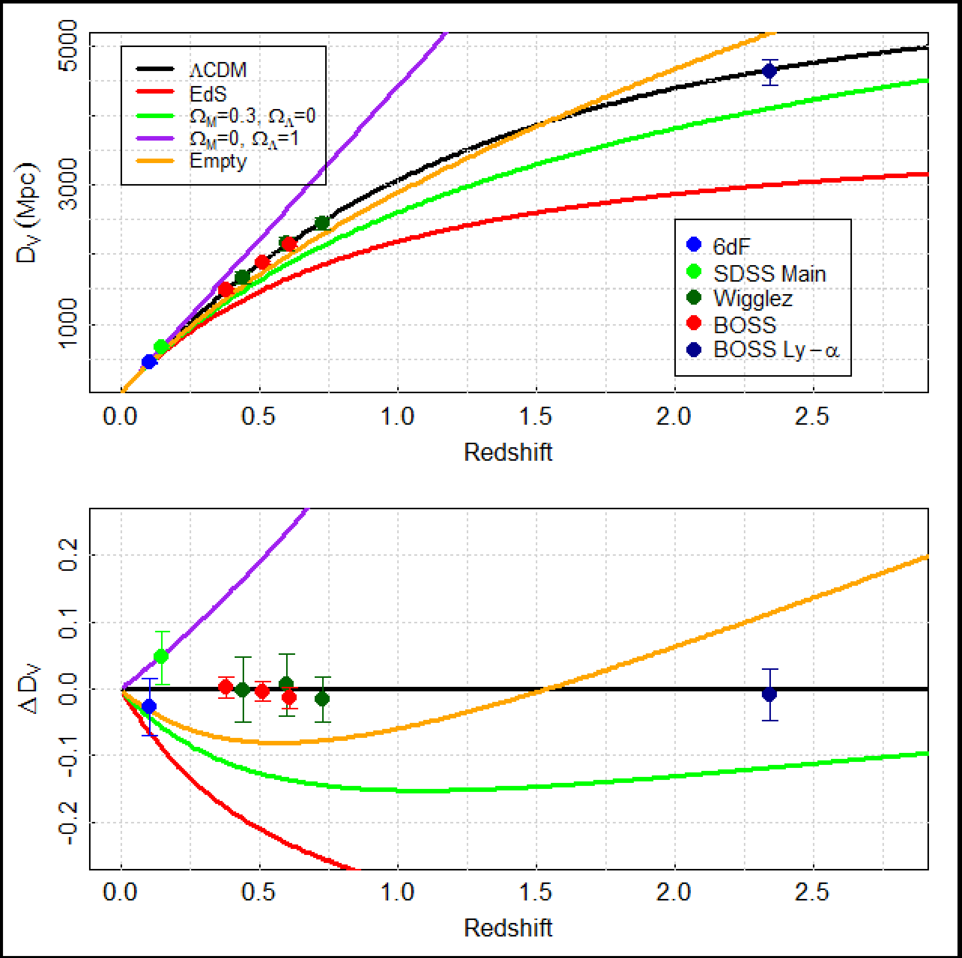
Springel, Frenk & White 2006

The Large Scale Structure (LSS) of the Universe

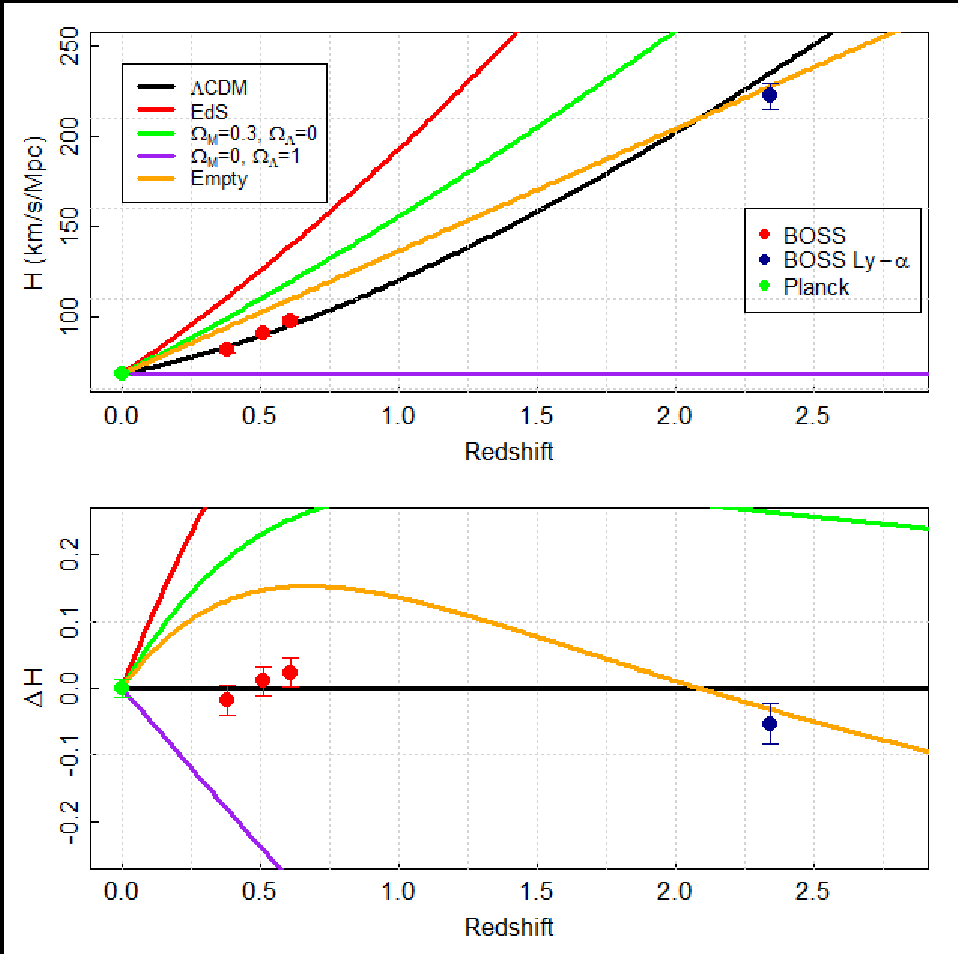
The Big Bang with a ~70% of dark energy and a ~30% of matter (normal plus dark), is able to describe the structure formation in the Universe

BAO as a standard ruler

Angular



Radial



Again, we need ~70% of dark energy and ~30% of matter (25% dark and 5% baryonic)

The Big Bang today: ΛCDM

It is not speculation anymore. Based on a huge quantity of precise observations

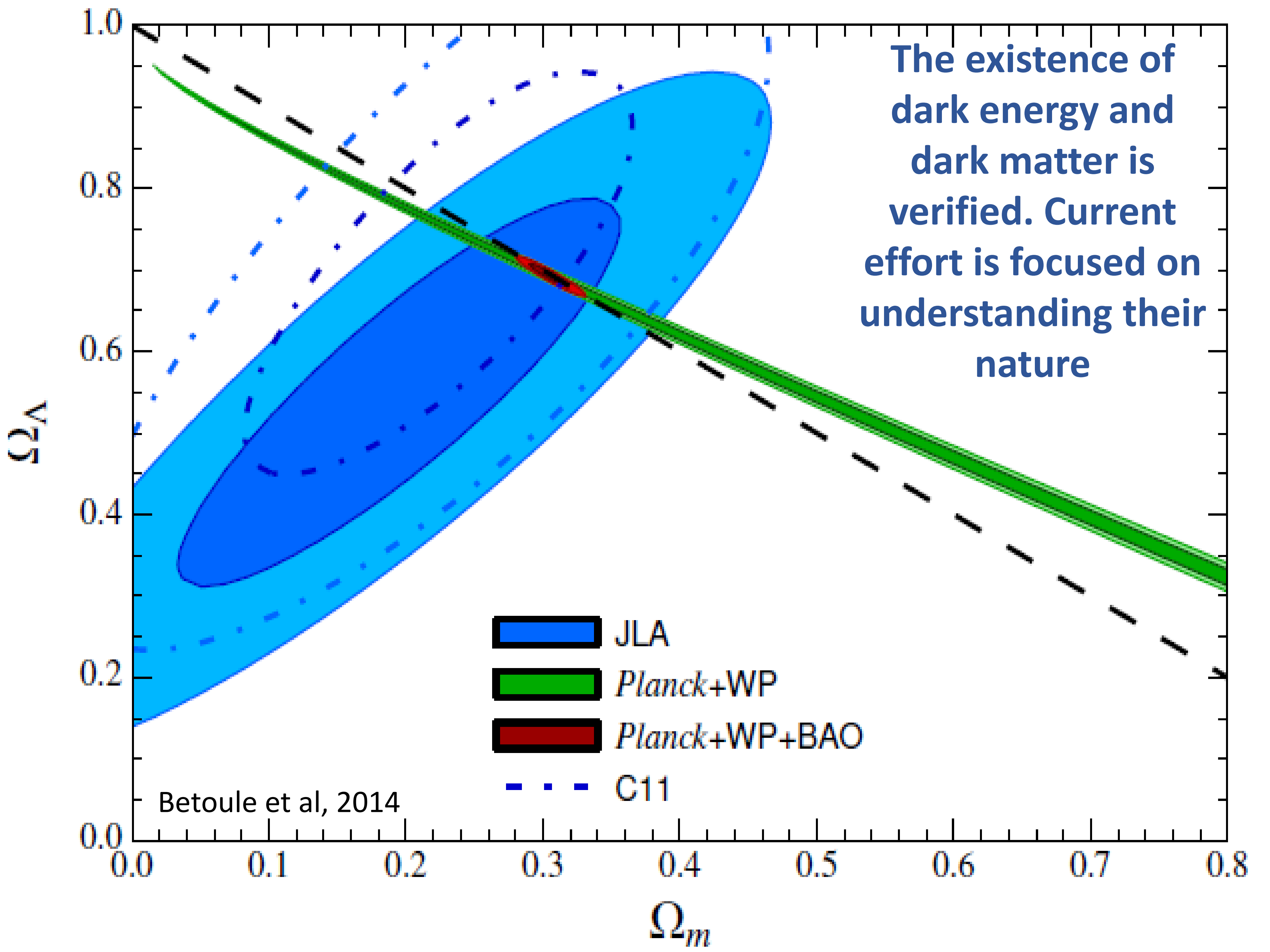
CMB → Ω_{TOT} ~1 (the Universe is **FLAT**)

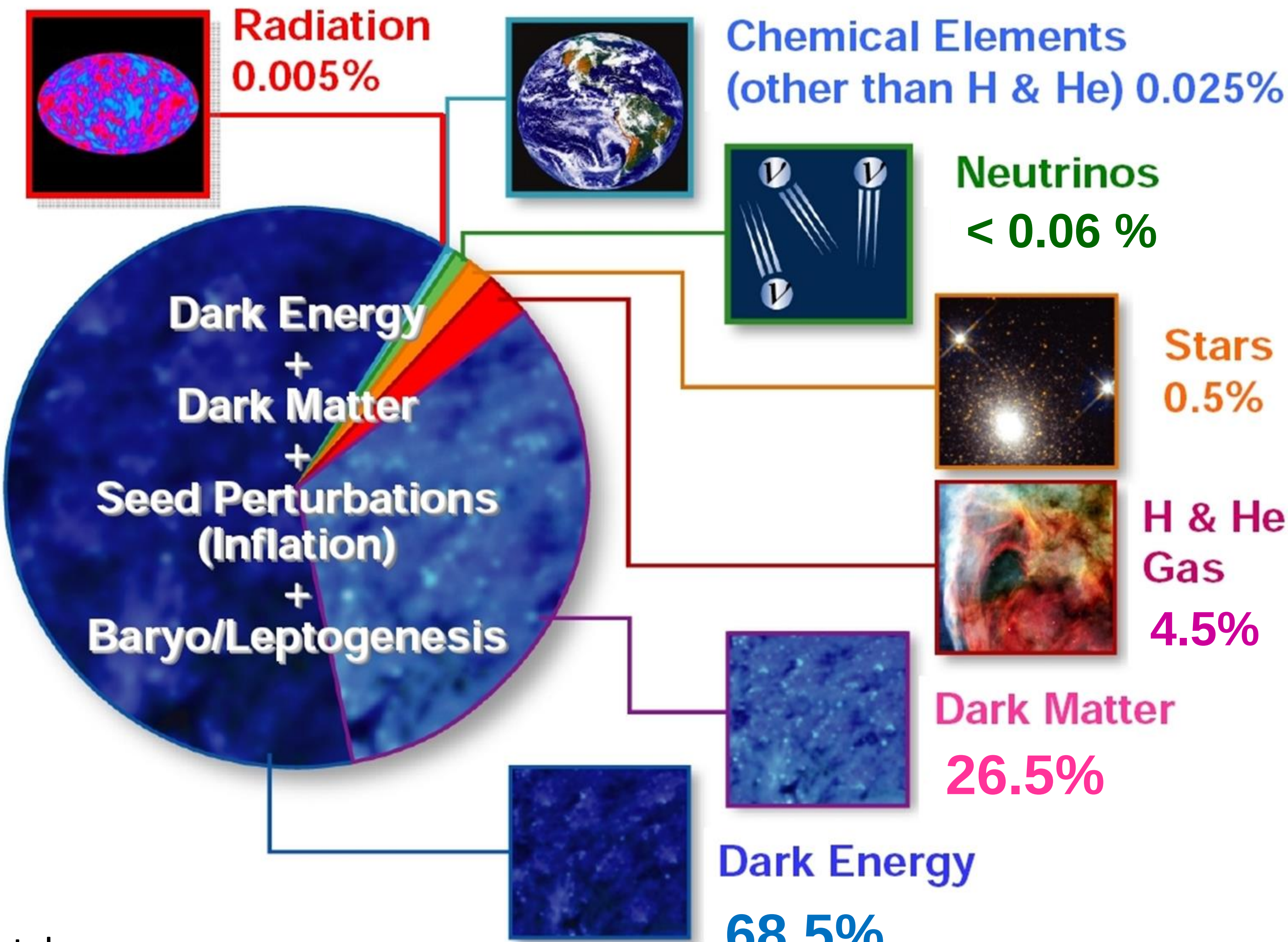
BBN+CMB → Ω_B ~ 0.05 → most of the universe is **NON-BARYONIC**

LSS+GALAXY DYNAMICS → **DARK MATTER!** ; Ω_{DM} ~ 0.27

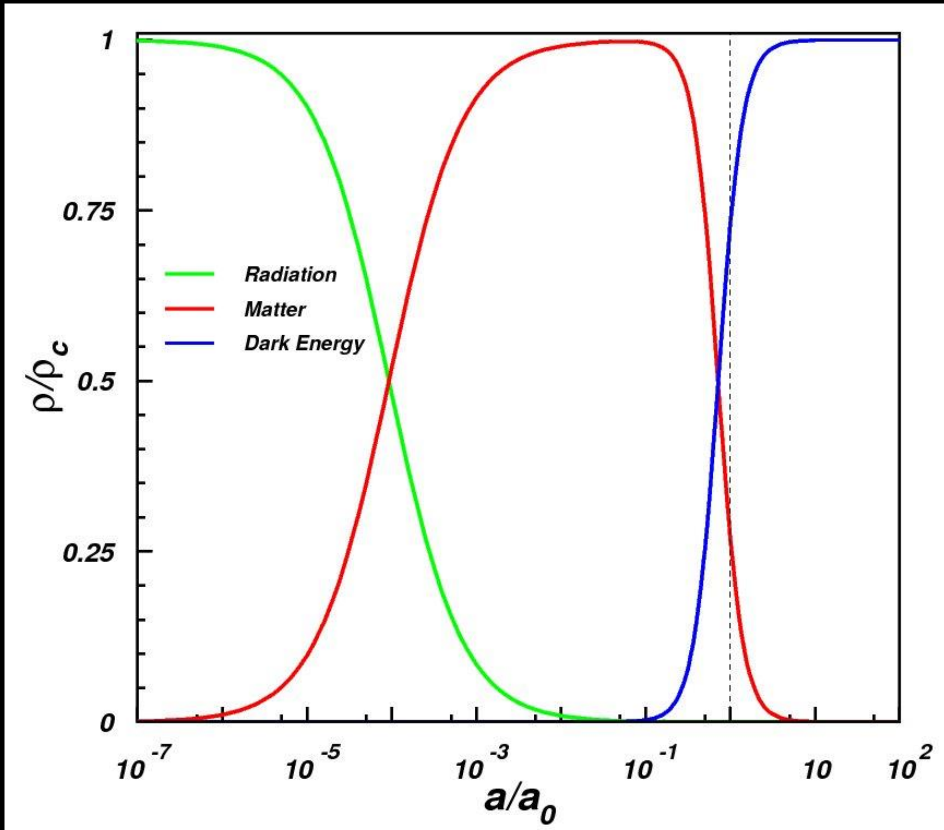
Supernovae Ia+LSS+CMB → **DARK ENERGY!** ; Ω_{DE} ~ 0.68

- Large scale homogeneity
- Hubble Law
- Light elements abundances
- Existence of the CMB
- Fluctuations of the CMB
- LSS
- Stars ages
- Galaxy evolution
- Time dilation of the SN brightness
- Temperature vs redshift (Tolman test)
- Sunyaev-Zel´dovich Effect
- Integrated Sachs-Wolf effect
- Galaxies (rotation/dispersion)
- Dark Energy (accelerated expansin)
- Gravitacional lenses (weak/strong)
- Consistency of all observacions


The existence of dark energy and dark matter is verified. Current effort is focused on understanding their nature
JLA
Planck+WP
Planck+WP+BAO
C11
Betoule et al, 2014
Ω_Λ
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8



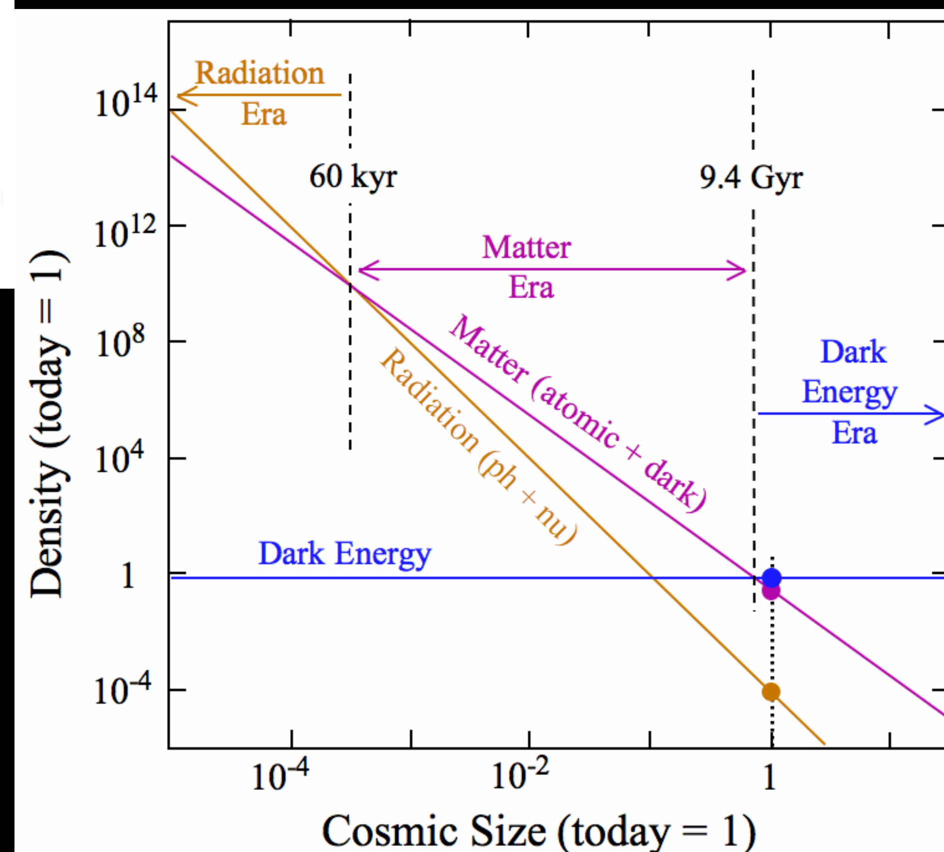
Adapted
From Rocky Kolb



relative densities

3 epochs in the Universe history:

Radiation Dominated
Matter Dominated
Lambda Dominated



absolute densities

The Big Bang today: ΛCDM

The Big Bang theory is an excellent description of the observed Universe

A 25% of the Universe content (the dark matter) is of unknown nature

ΛCDM requires physics beyond the Standard Model