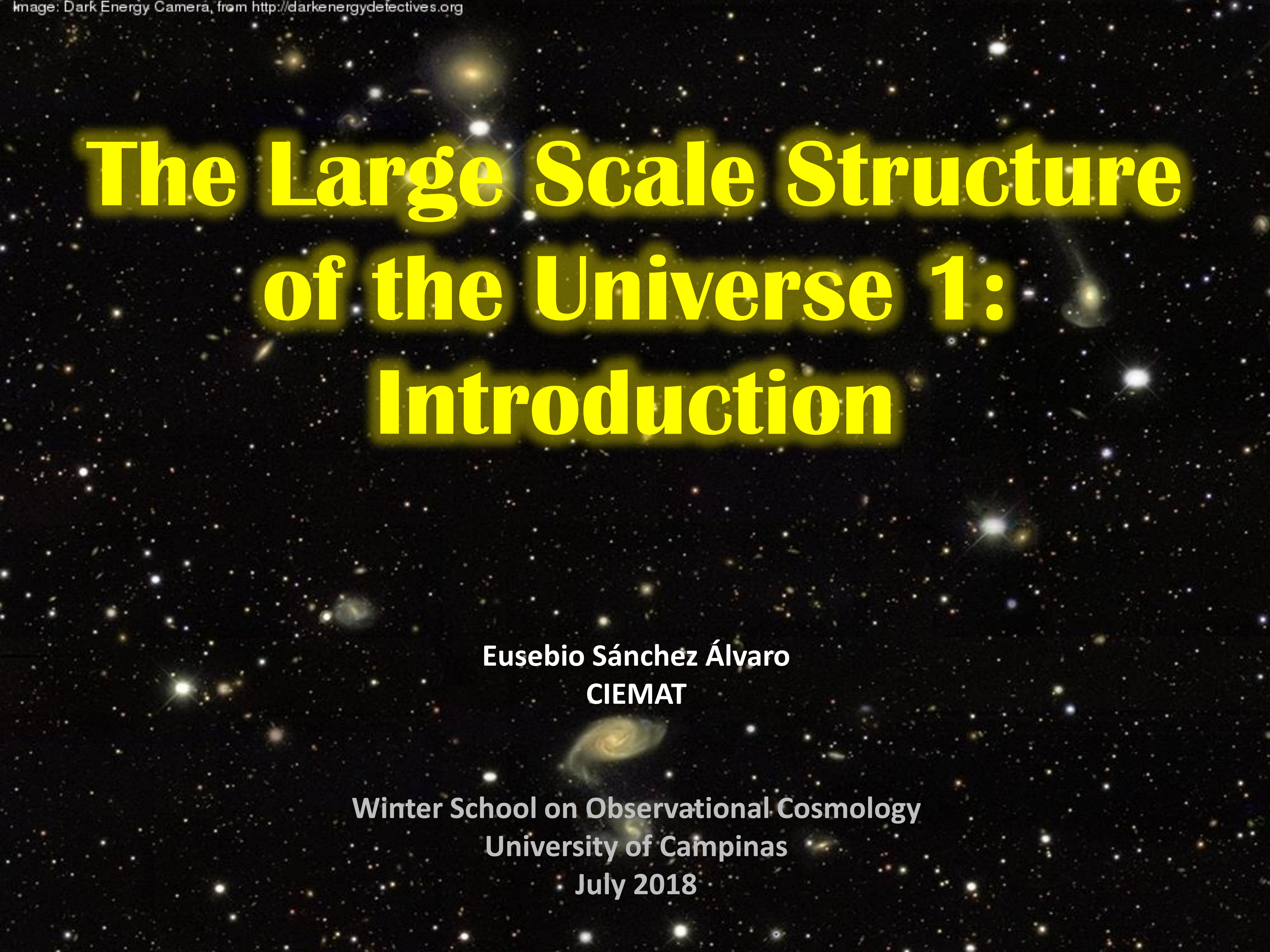

The Large Scale Structure of the Universe 1: Introduction

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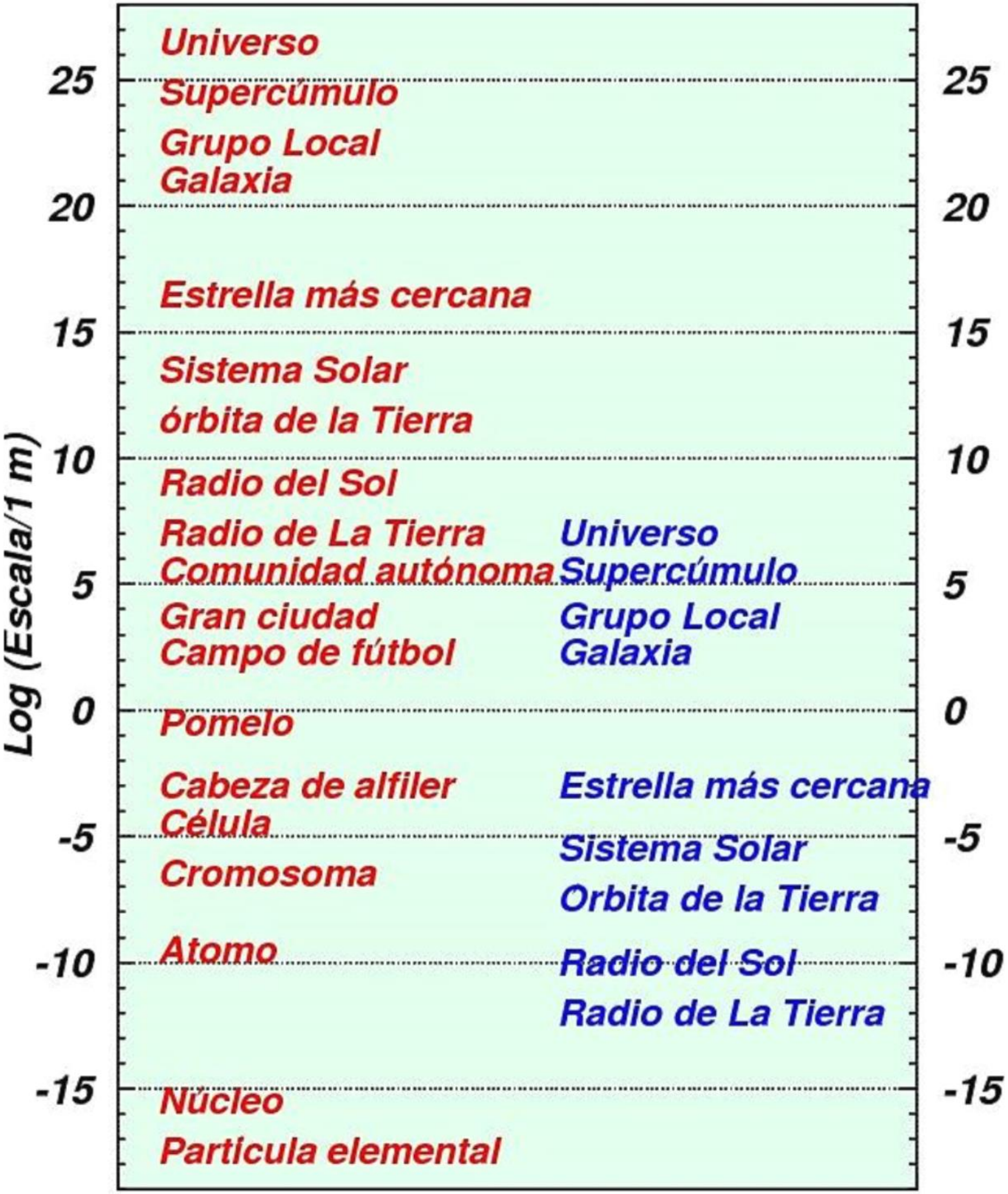
CIEMAT

Winter School on Observational Cosmology
University of Campinas
July 2018

General Introduction to ΛCDM

Basis of cosmology
FLRW Metric, comoving coordinates
Redshift and scale factor. Friedmann equations
Distances: Angular diameter distance and standard rulers
Common misunderstandings about the big bang
Observational basis of ΛCDM
Universe History and Composition
What do we know about dark matter and dark energy?
Cosmic inflation in 1 minute

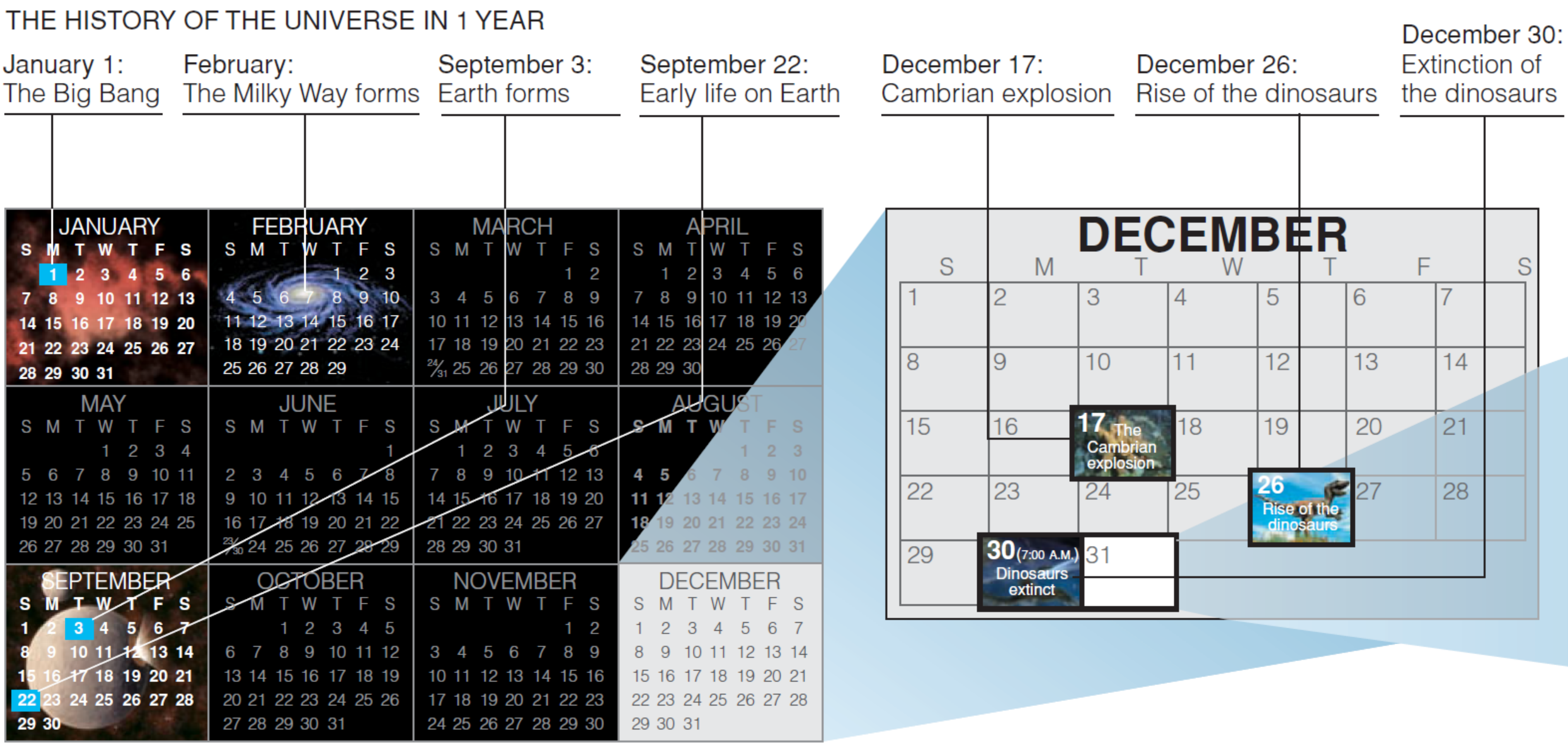


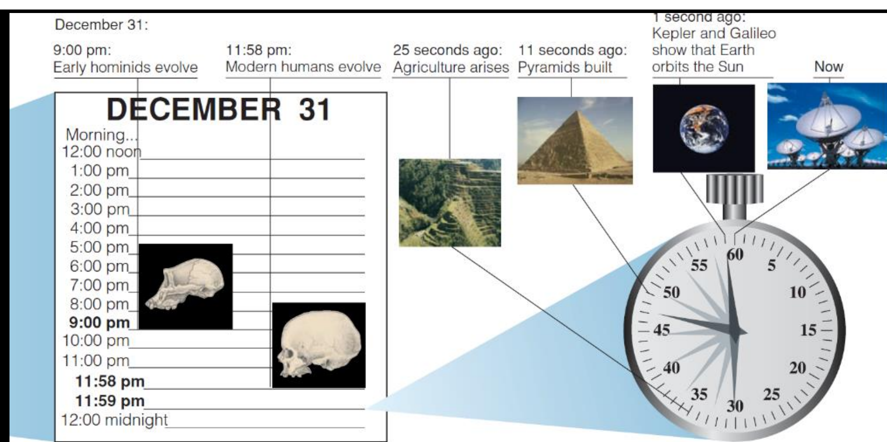
Cosmology is about the largest distance scales, the whole visible Universe

The Universe contains hierarchically ordered structures

Observations at these huge distances are also observations at early times because of the finite speed of light

The history of the Universe in 1 year





Based in Carl Sagan´s idea

Taken from “The Cosmic Perspective”

Previous: How to measure celestial objects

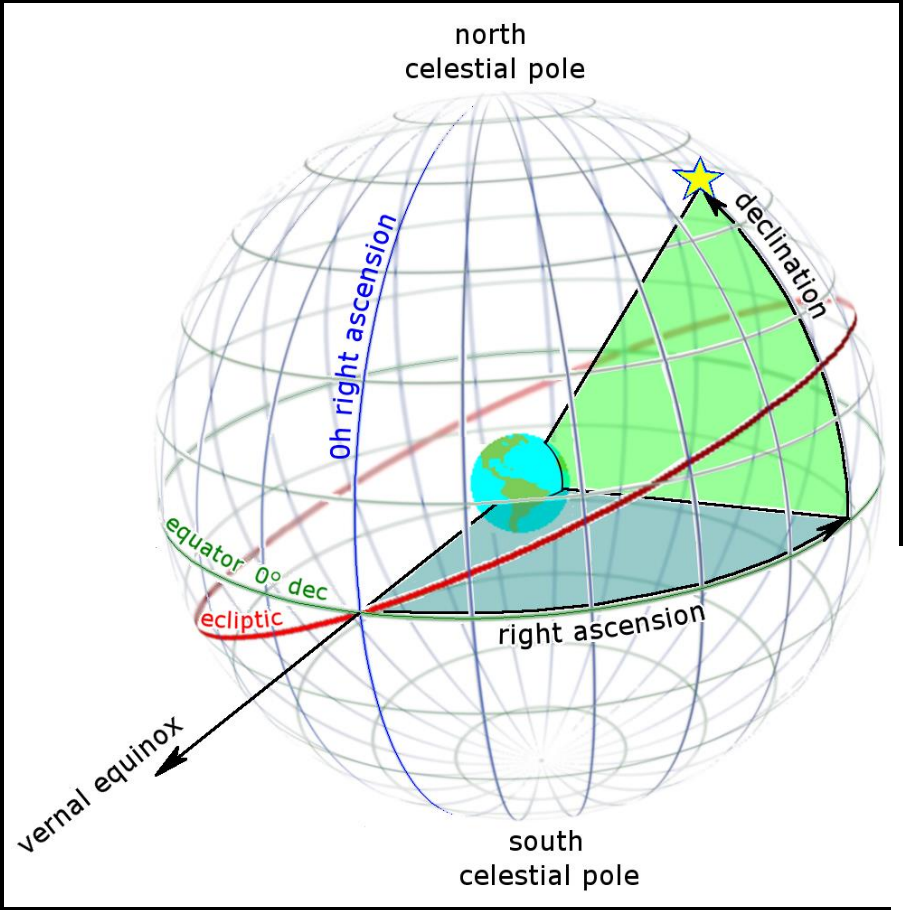
Position in the sky

Distance

Recession velocity

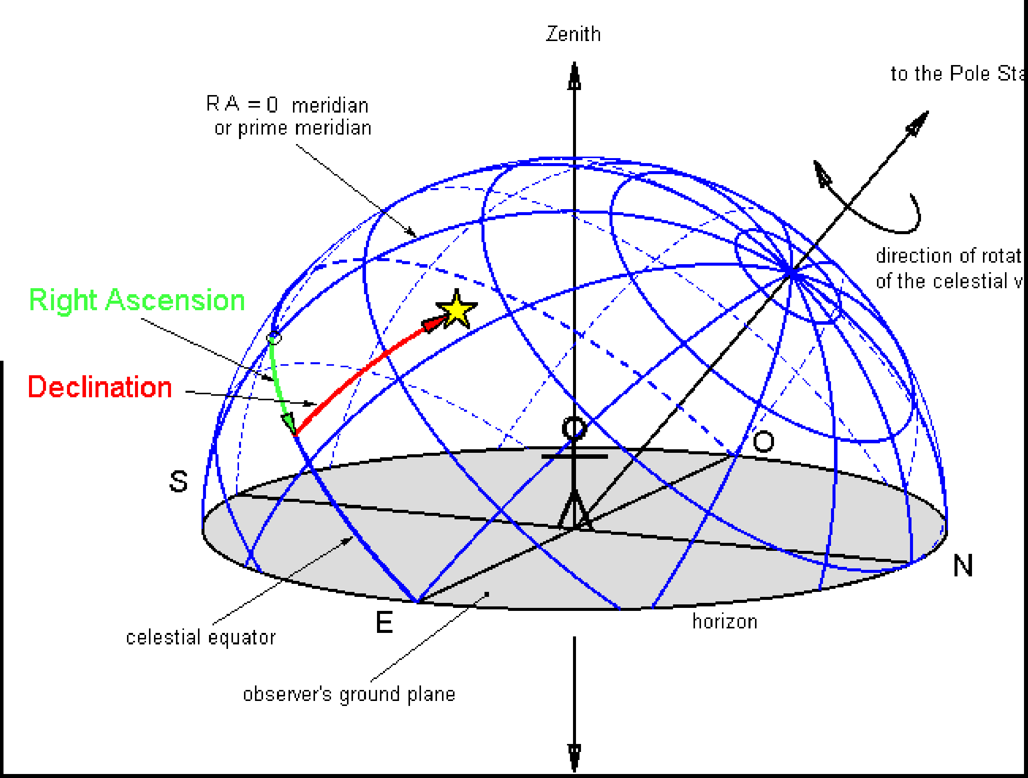
Other properties: *Temperature, density, chemical composition…*

Equatorial coordinates: right ascension, declination

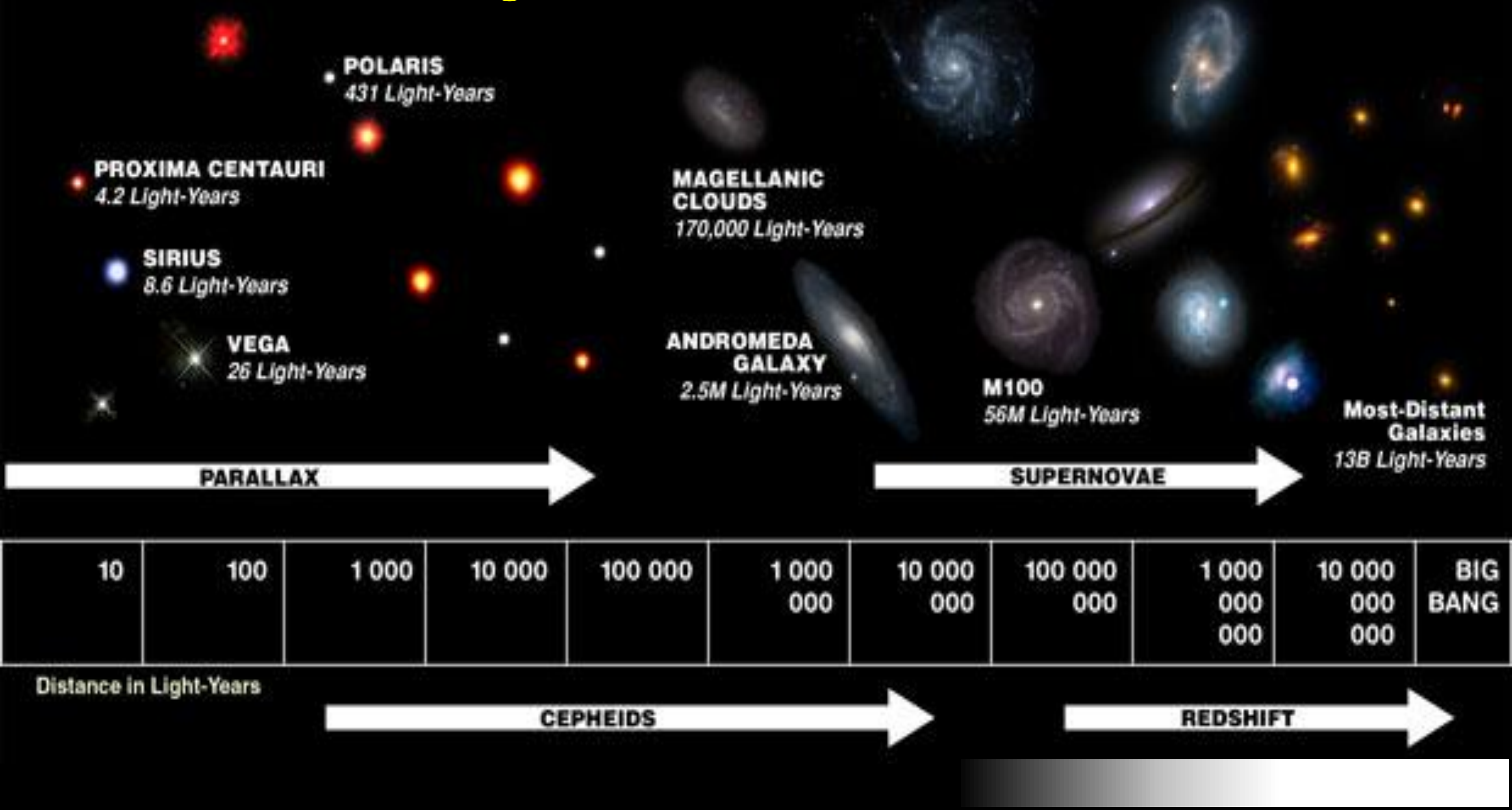


The large cosmological projects do use equatorial cordinates to locate objects in the sky

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



Measuring Distances: The Cosmic ladder



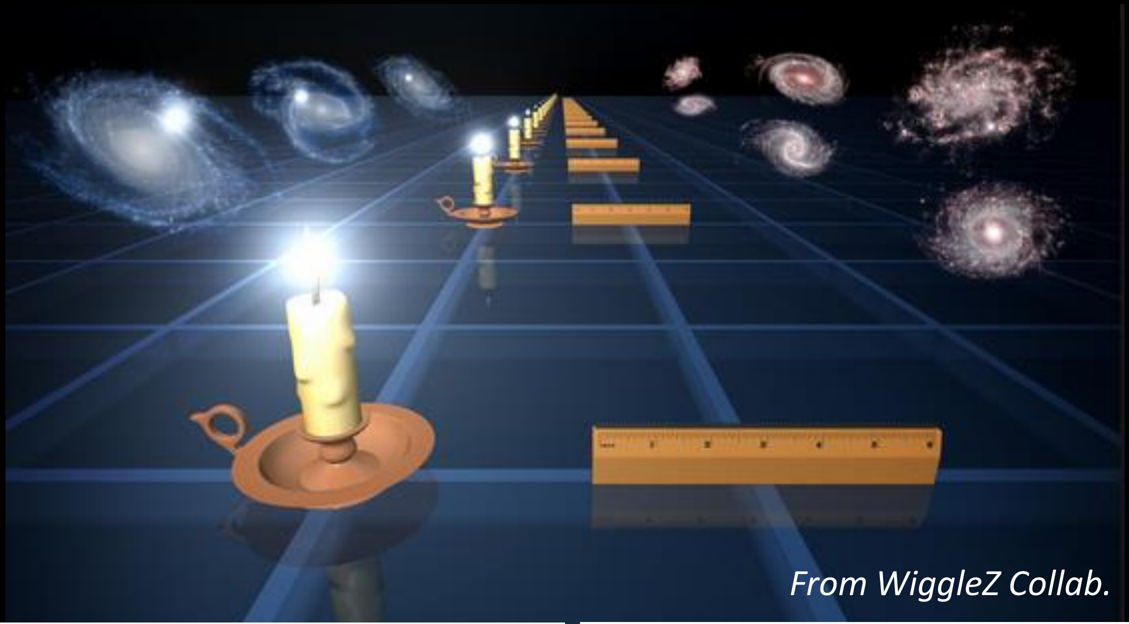
The different methods are chained

COSMOLOGY

Cosmic Distances: Standard Candles and Standard Rulers

Luminosity Distance

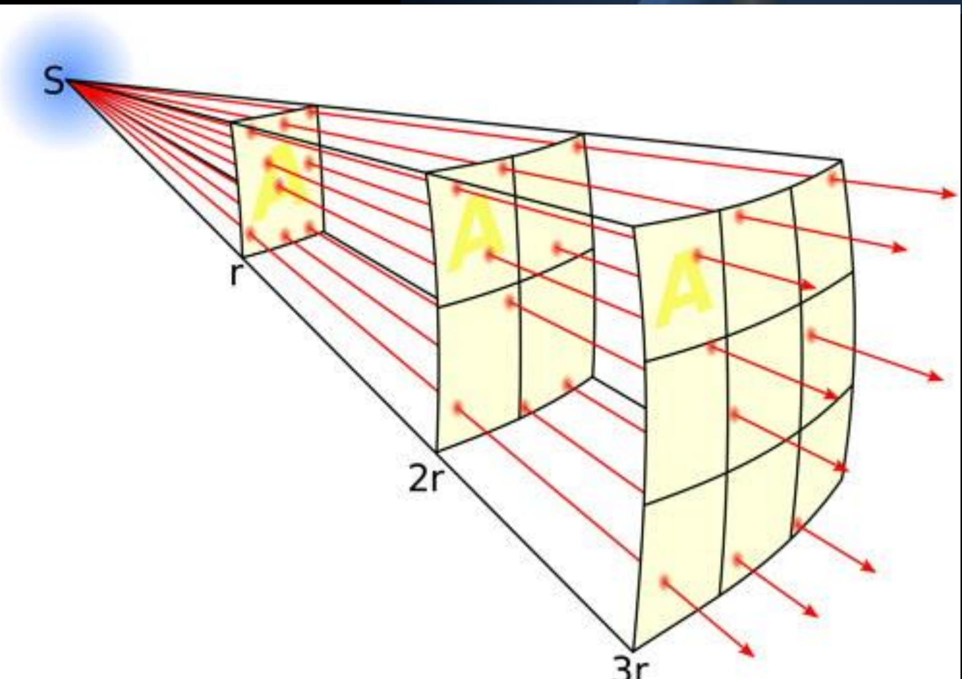
$$F = \frac{L}{4\pi D_L^2}$$

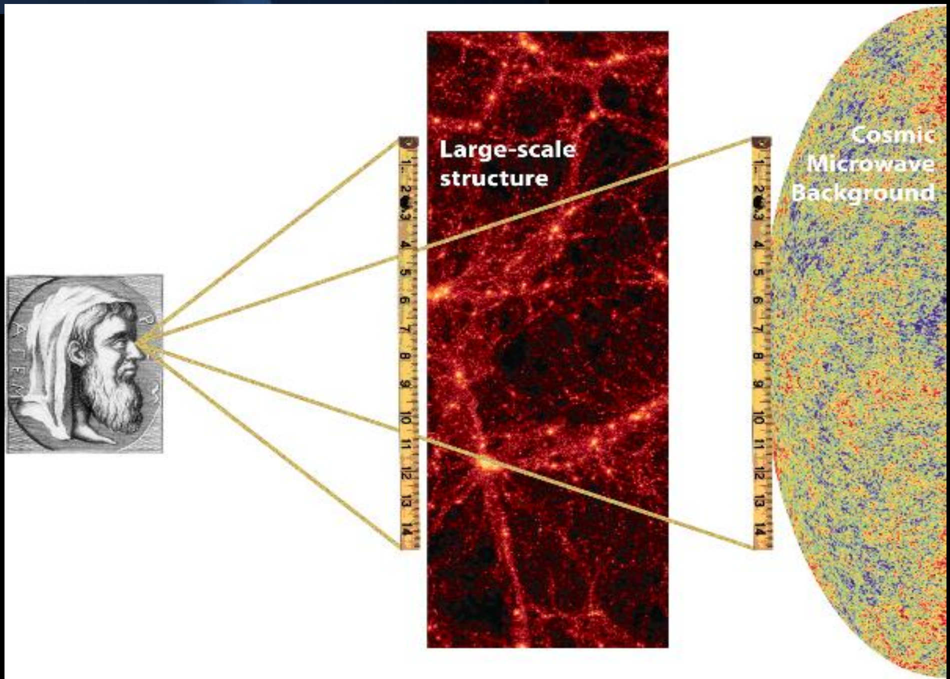


From WiggleZ Collab.

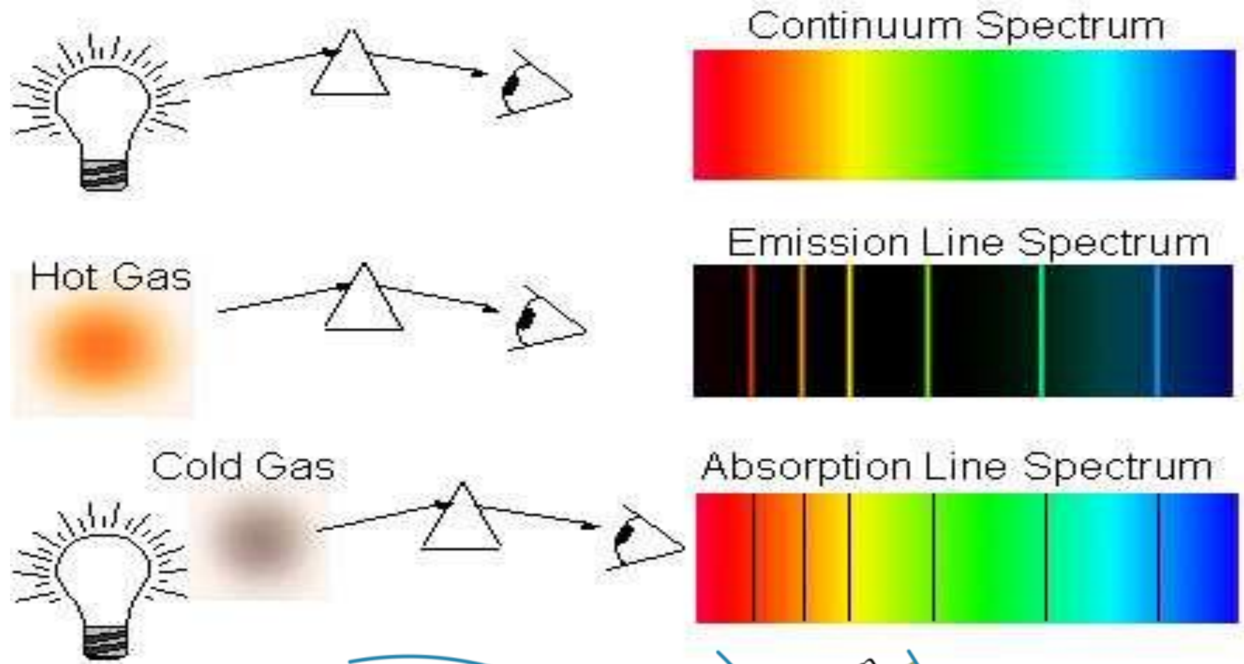
Angular Diameter Distance

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



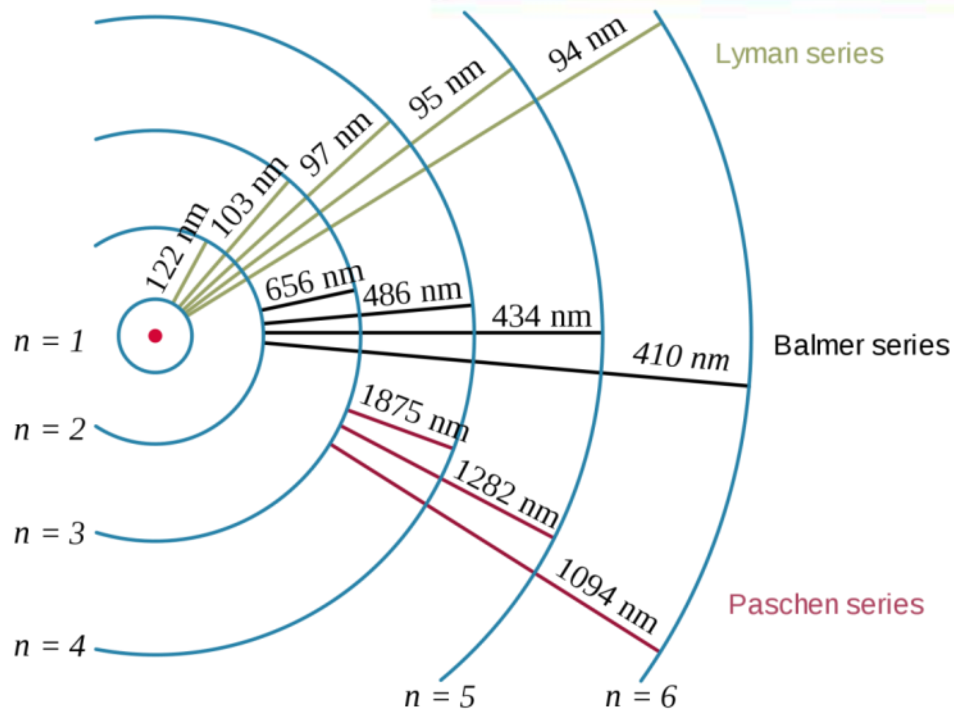


Velocity: Atomic Spectra



Atoms absorb or emit photons only with some energies, that are fixed by its electronic structure

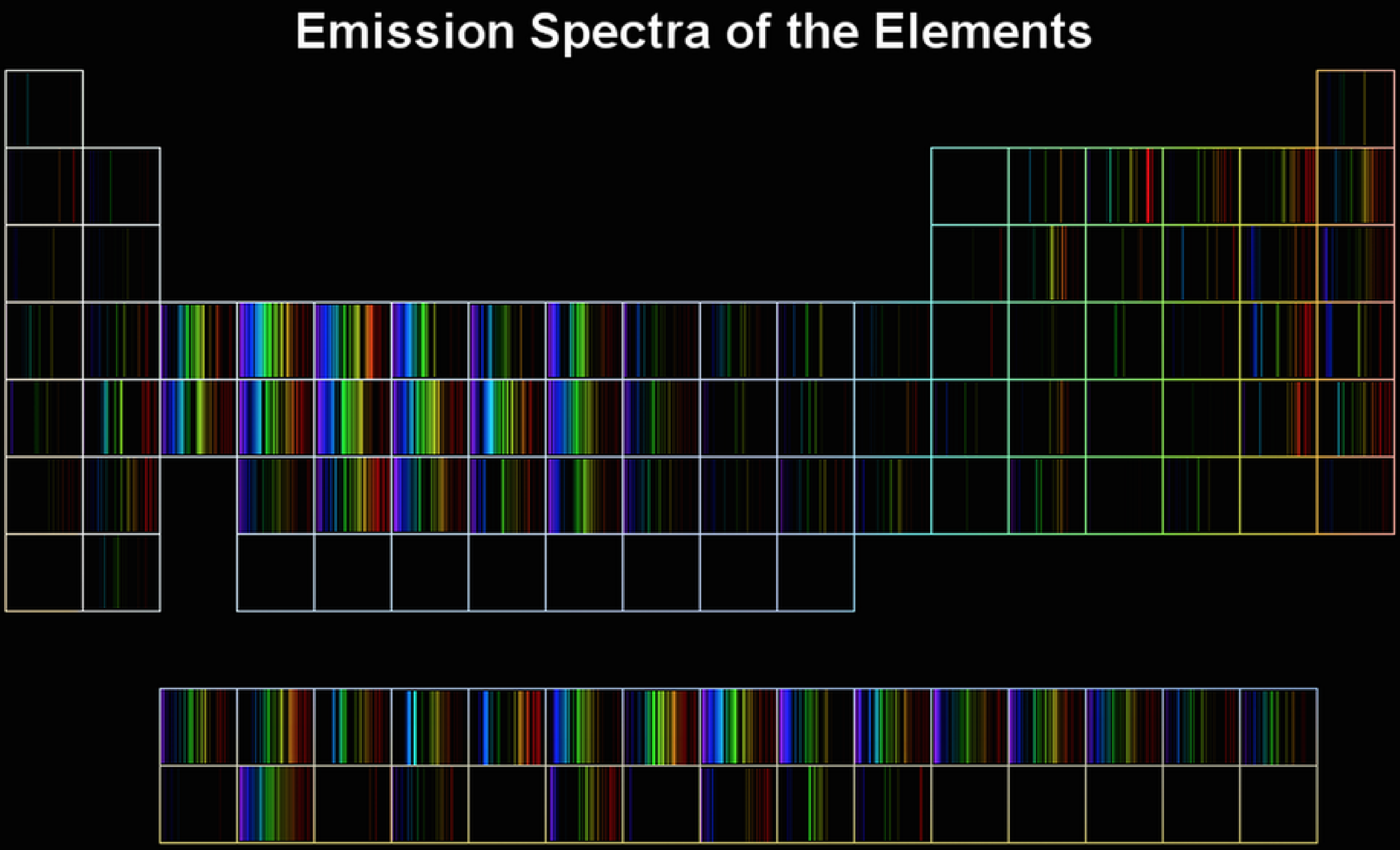
These energies are observed as bright or dark lines when light passes through a prism that disperses it in wavelengths



Bohr Model:

$$E = 13.6 \, [(1/n_1^2) - (1/n_2^2)] \text{ eV}$$

Spectra are atoms´ signature



Spectra tell us the recession velocity of celestial objects

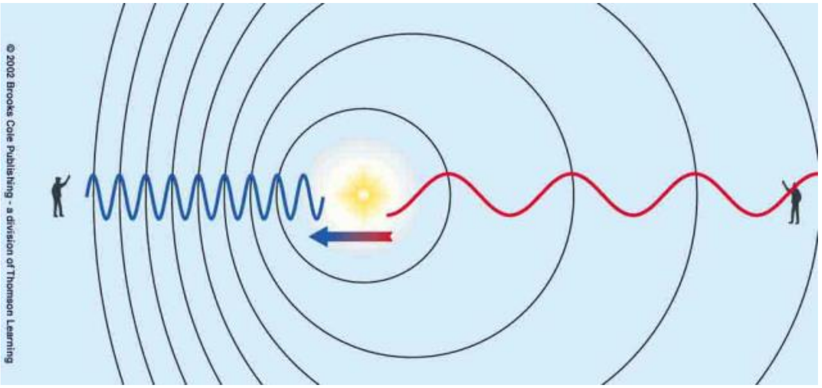
Spectral lines change their positions when the source is moving

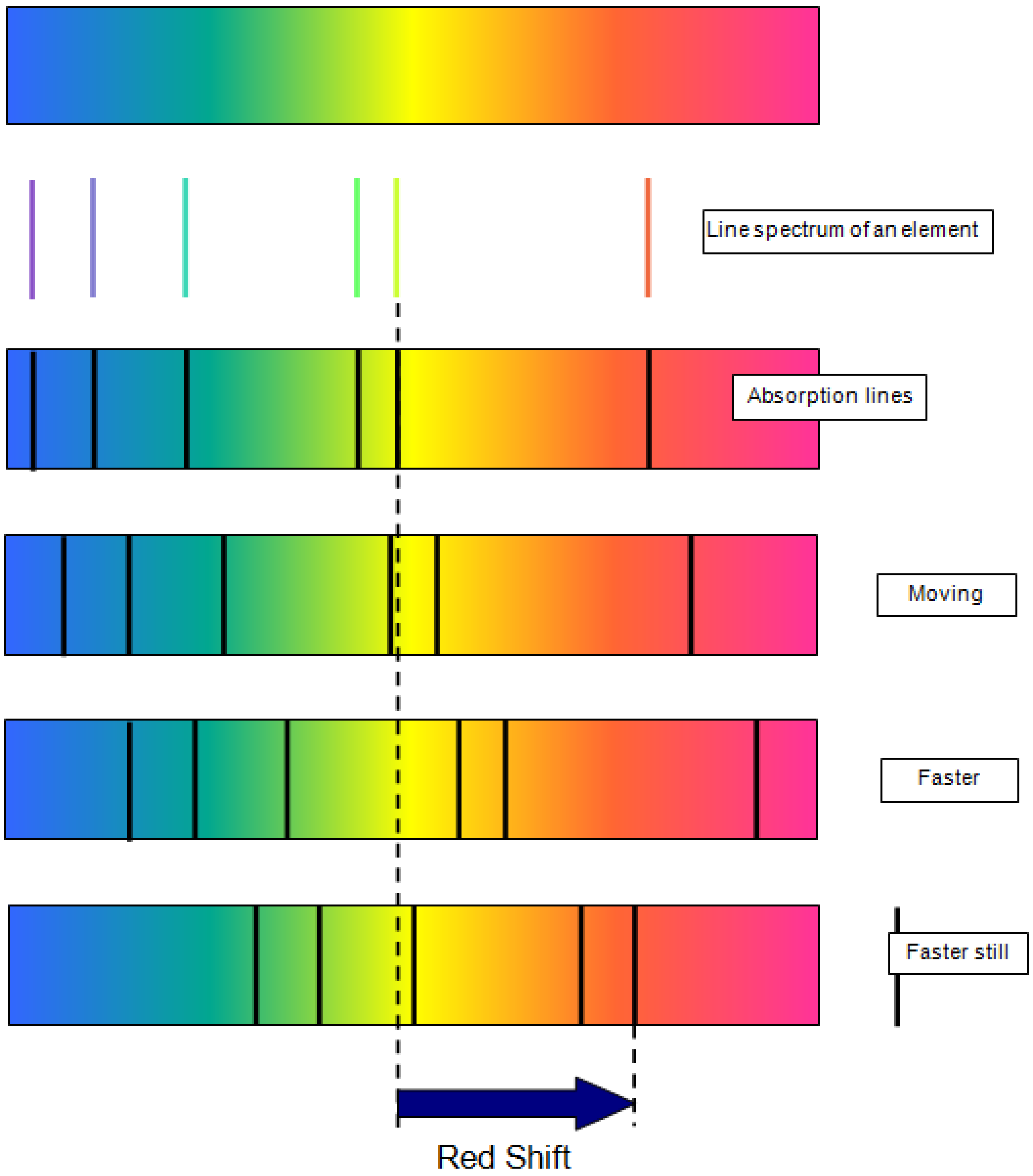
The measurement of line´s displacement allows to obtain the recession velocity of the source.

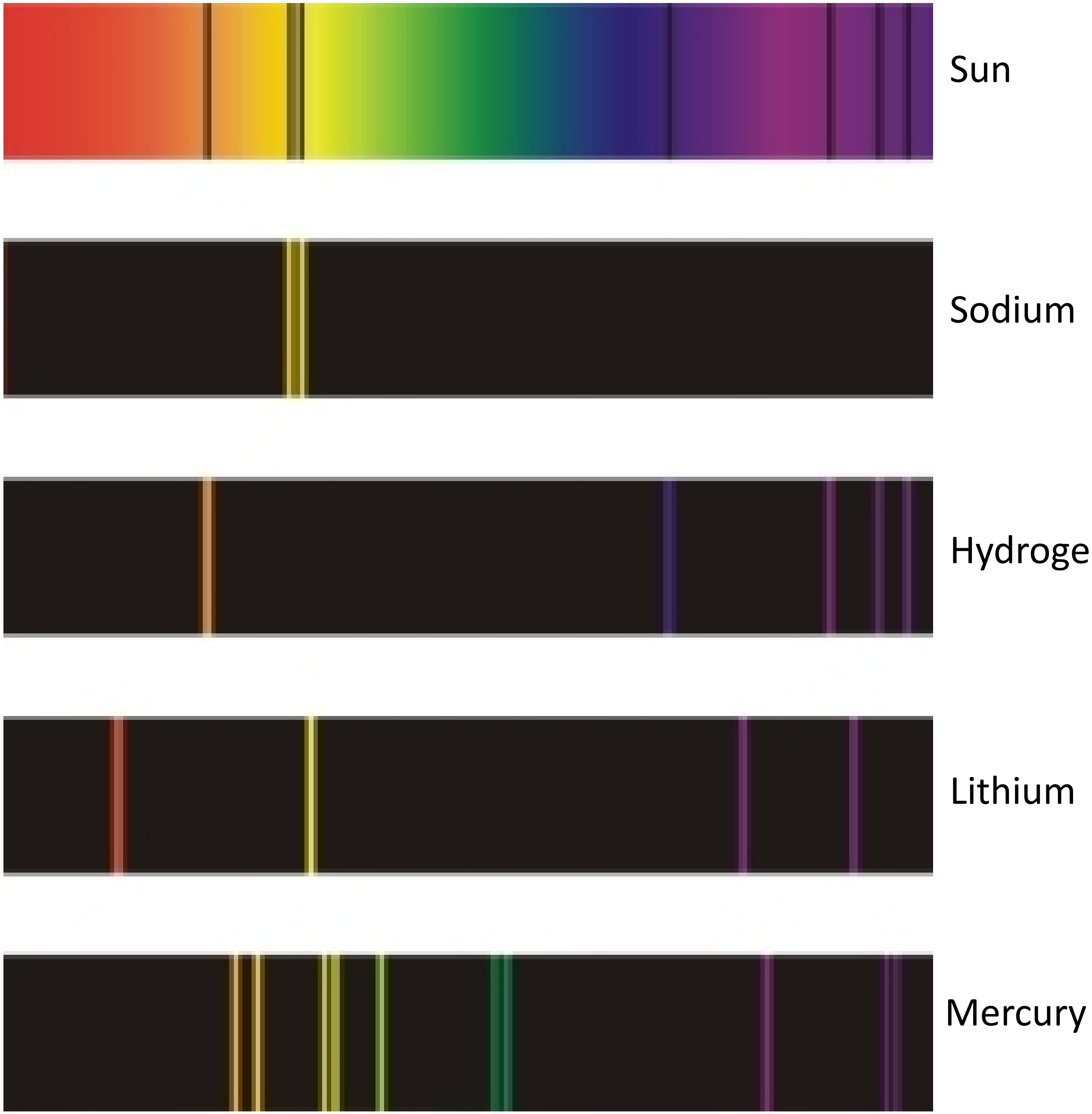
$$\mathbf{z = (\lambda-\lambda_0)/\lambda_0}$$

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

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







Chemical Composition from the spectrum

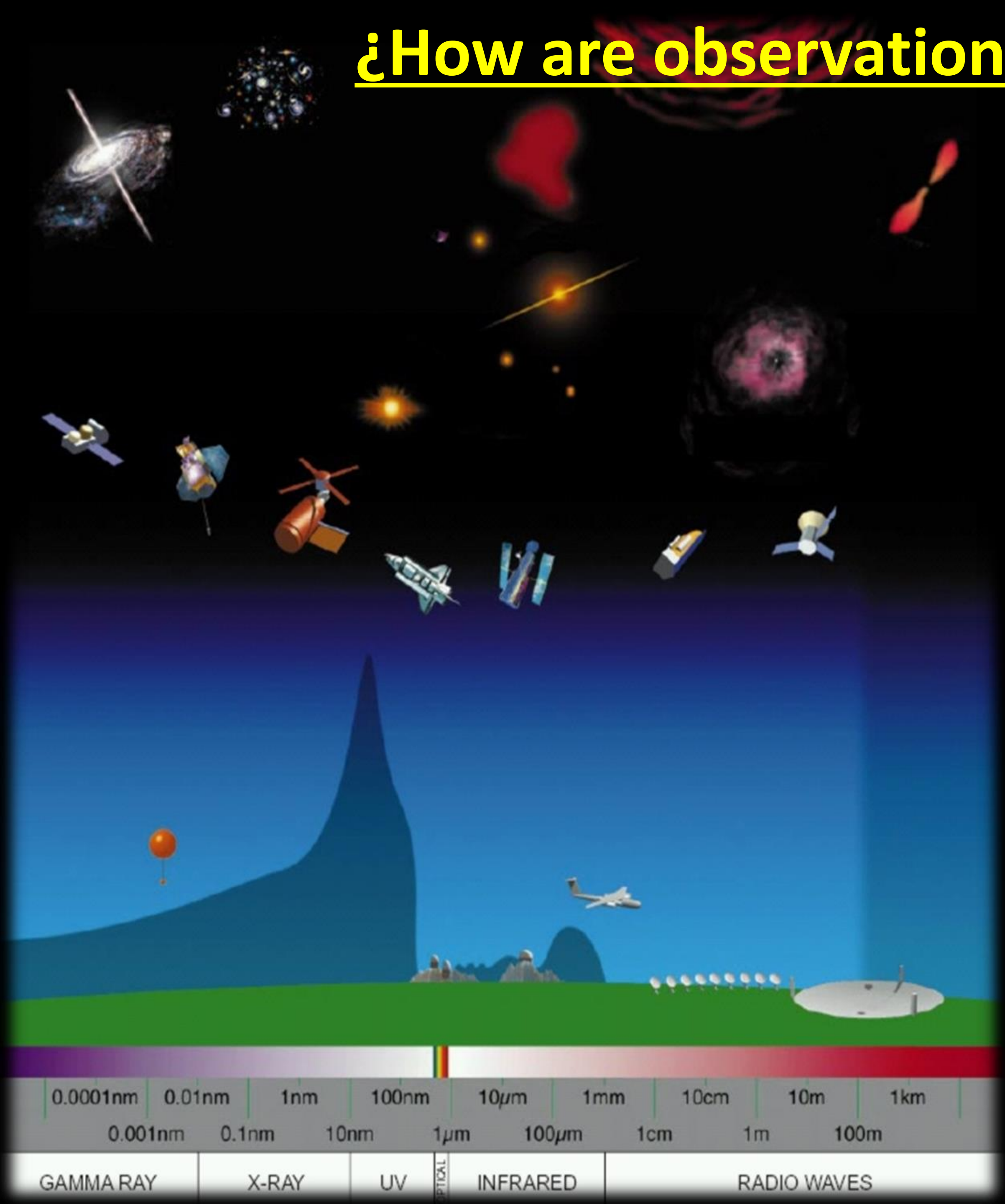
In this case, we can see that the Sun contains hydrogen and sodium, but neither lithium nor mercury

2 main measurements for Cosmology:

Distance as a function of z (BAO)

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

¿How are observations made?



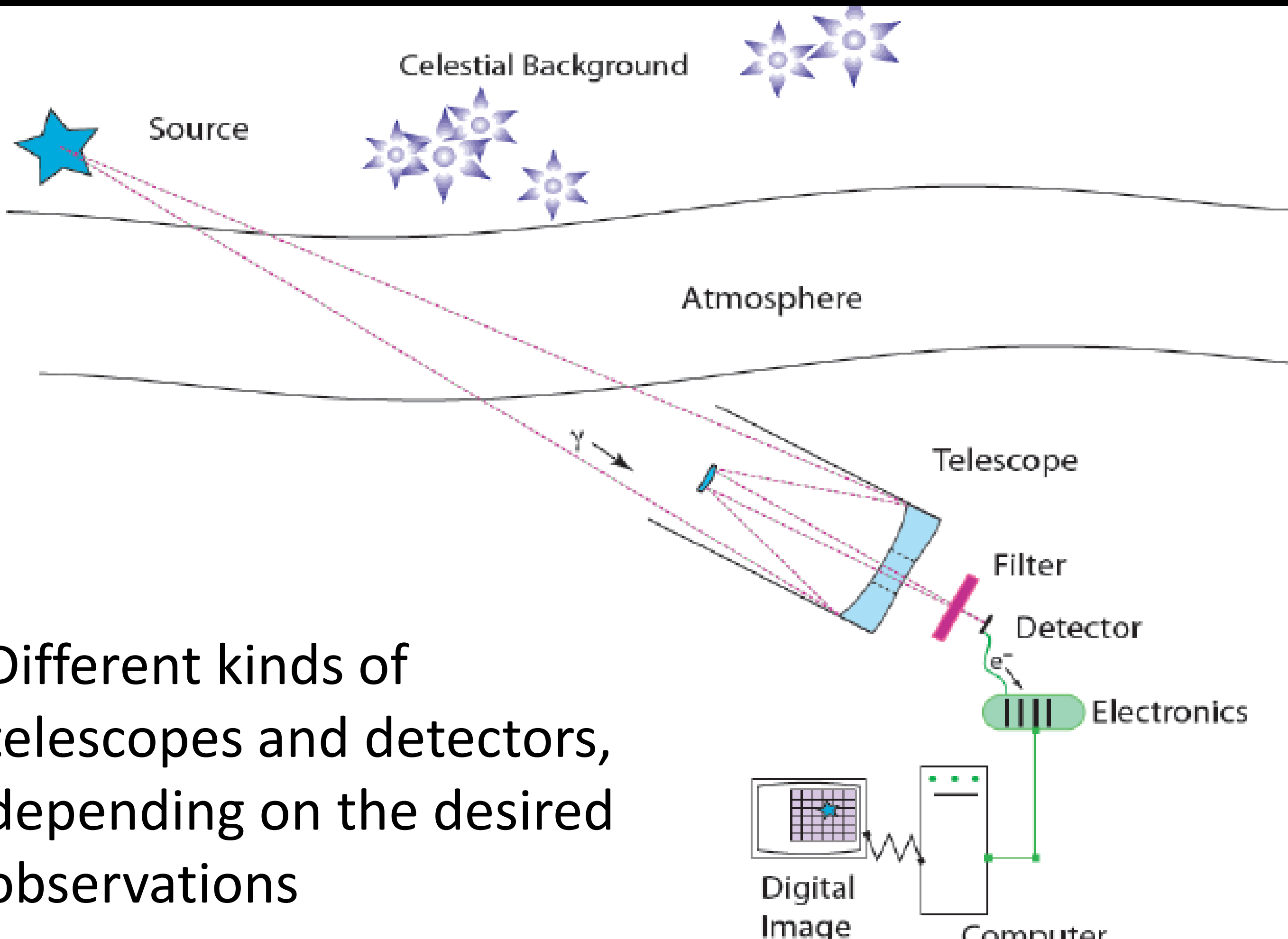
Powerful telescopes on earth and in space

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

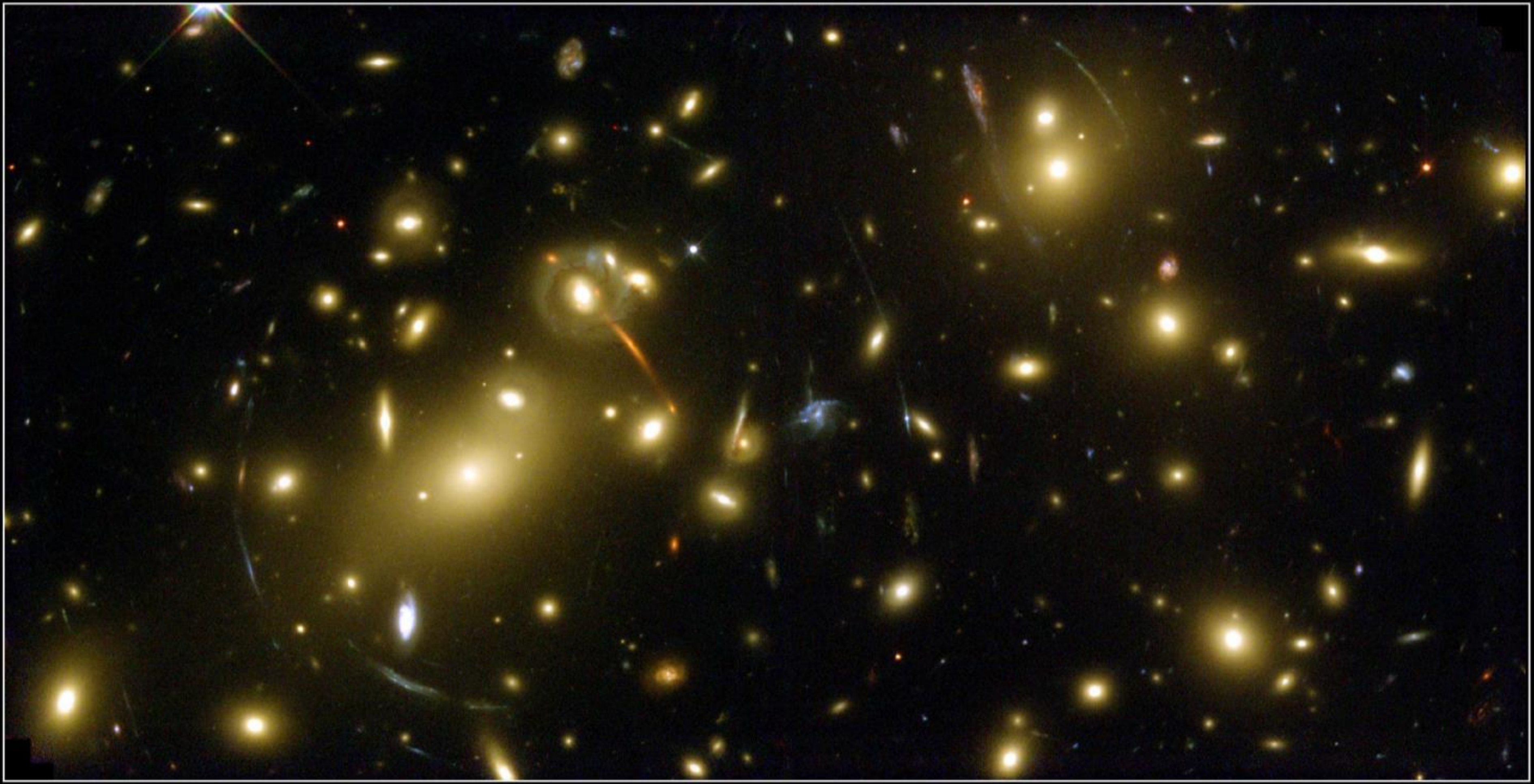
- Light source
- The atmosphere
- Telescope and optical system
- Camera
- Electronics+DaQ
- Data processing and calibration
- Scientific analysis

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

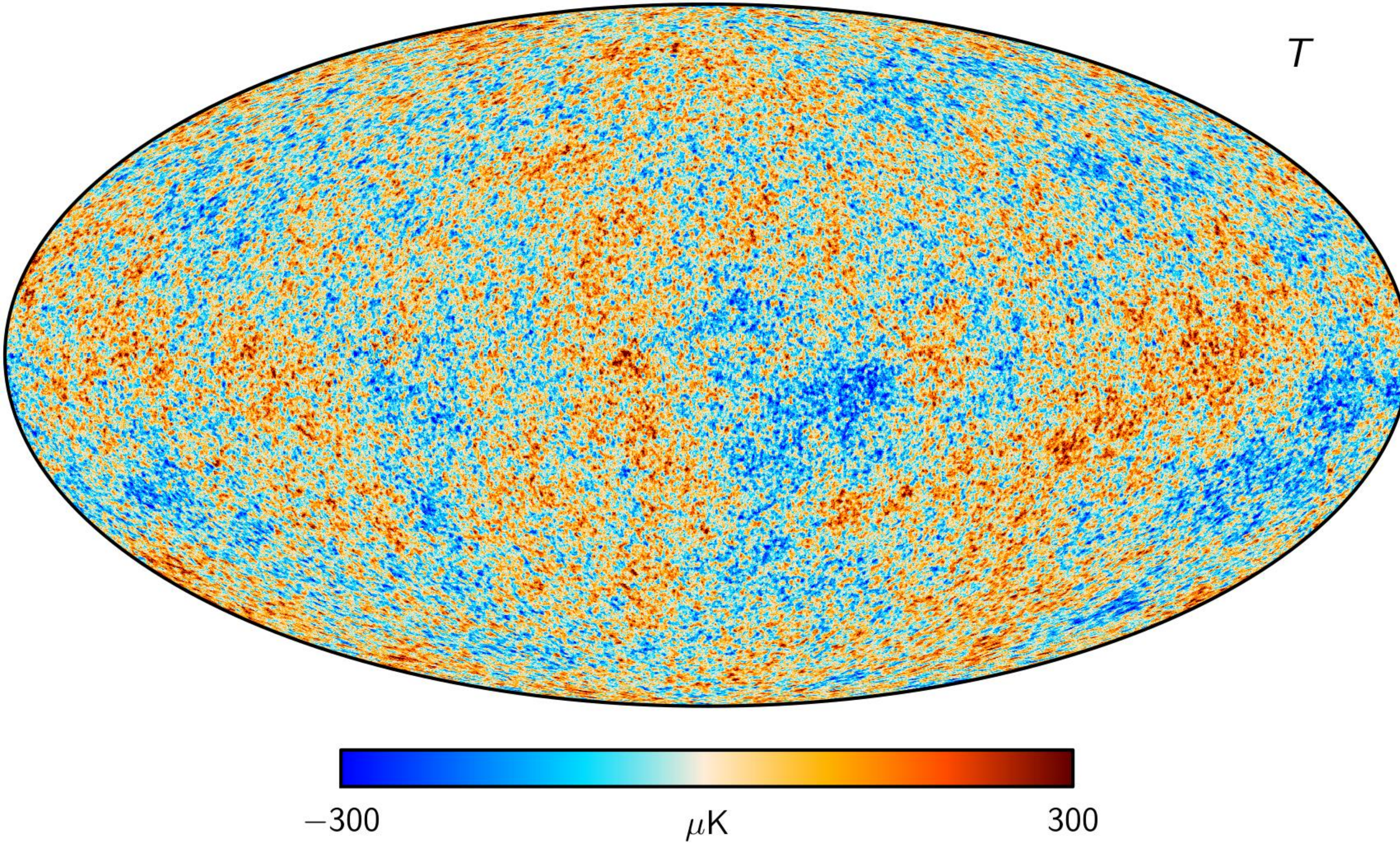


Galaxy Cluster Abell 2218

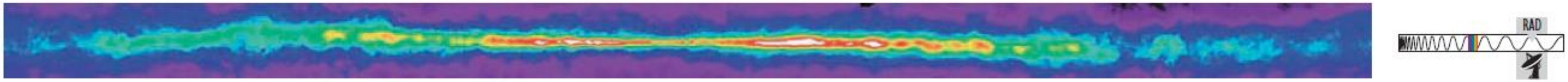
Hubble Space Telescope • WFPC2

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

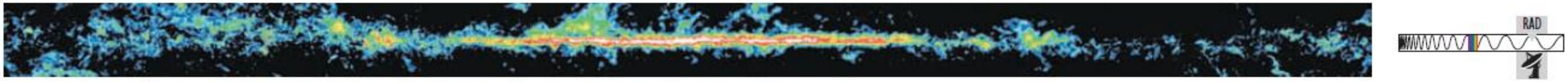
Map of the CMB from the space telescope Planck



The Milky Way in different wavelengths lof the electromagnetic radiation



a 21-cm radio emission from atomic hydrogen gas.



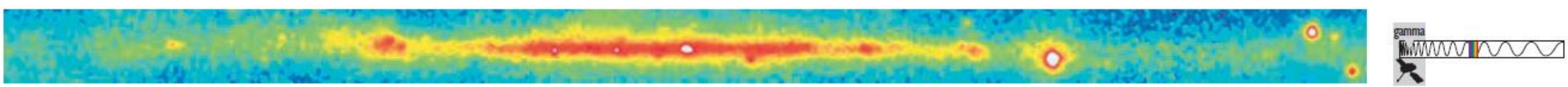
b Radio emission from carbon monoxide reveals molecular clouds.

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.

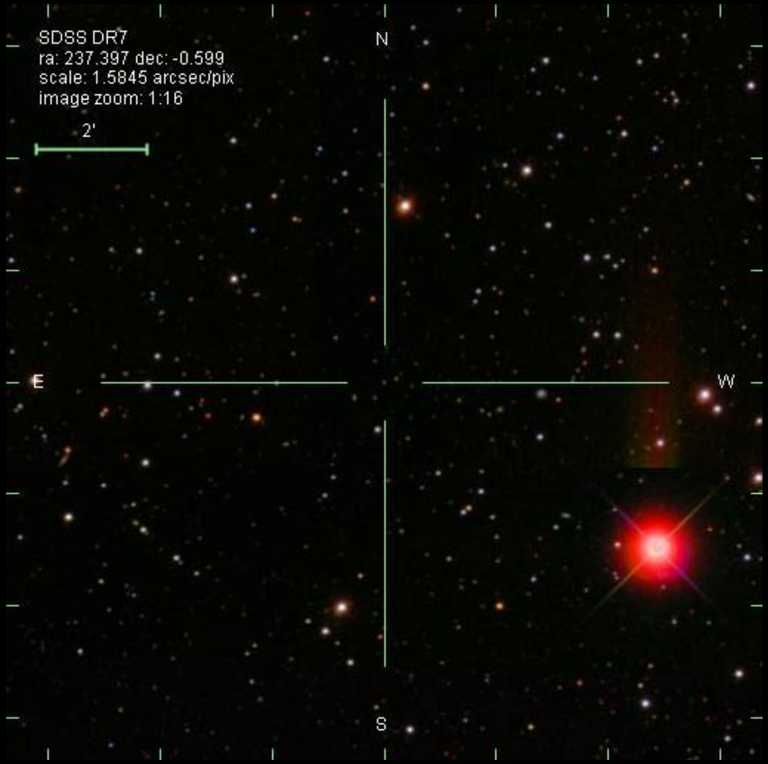
f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).

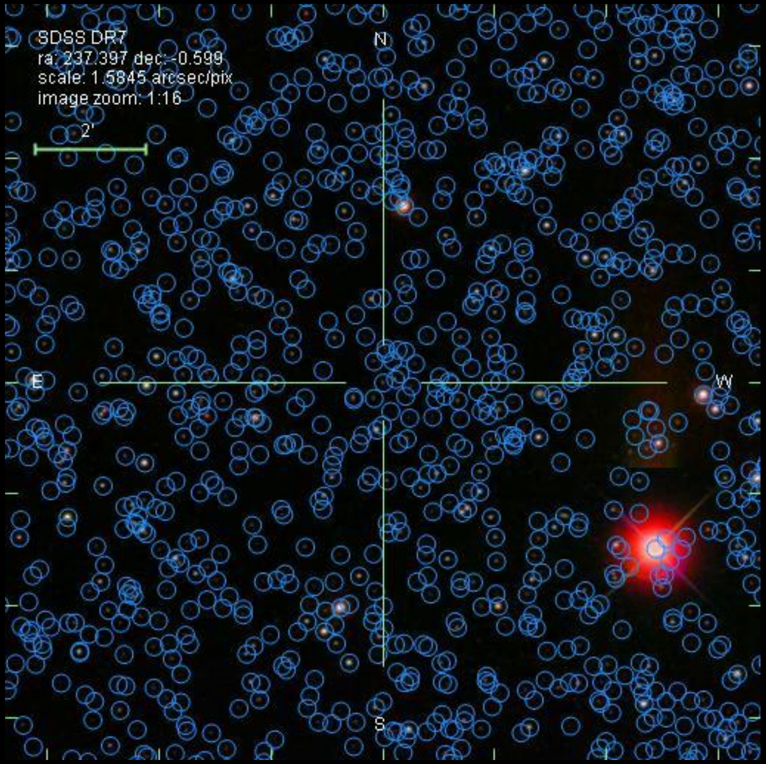


g Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

From images to results

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

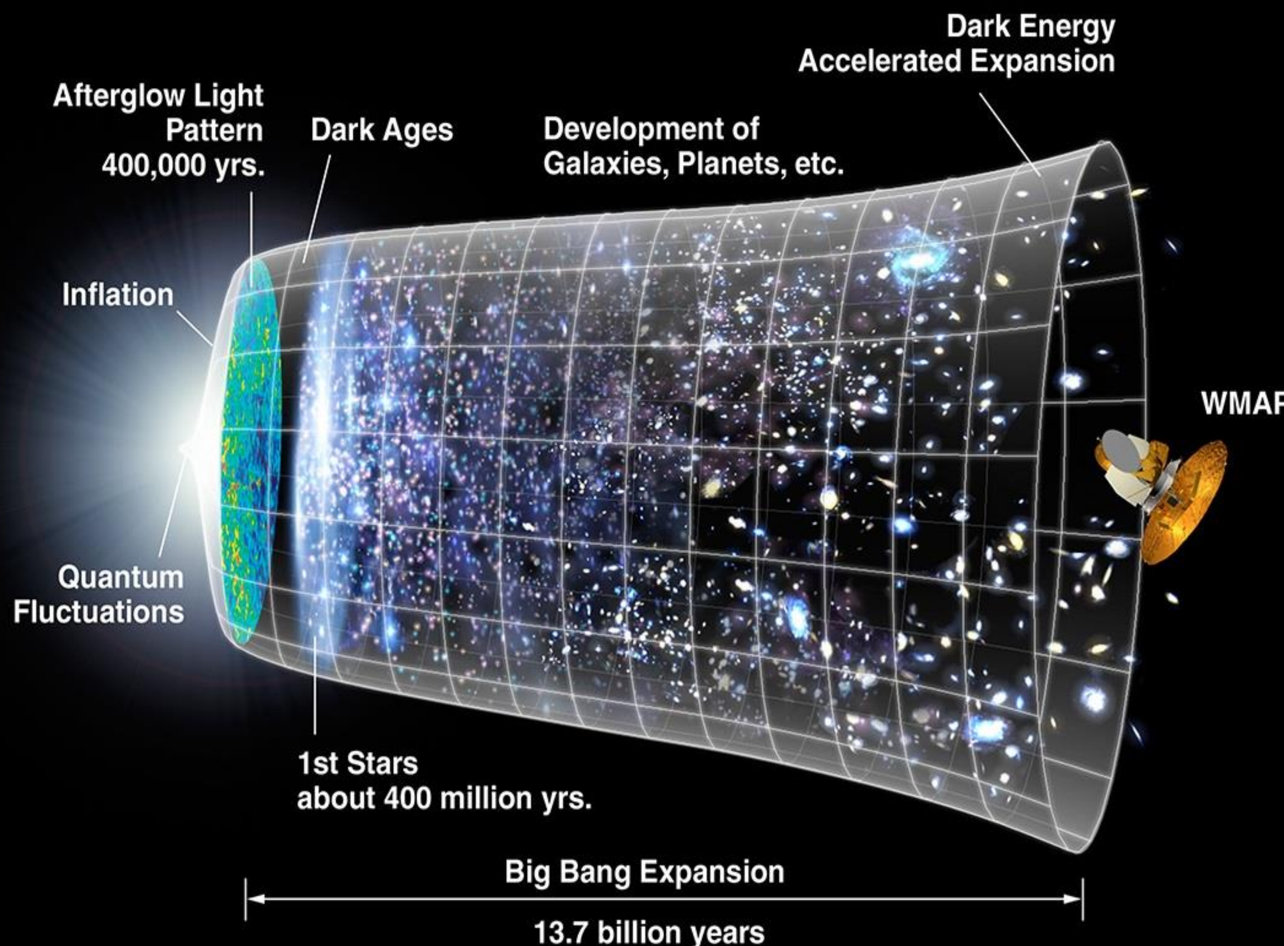




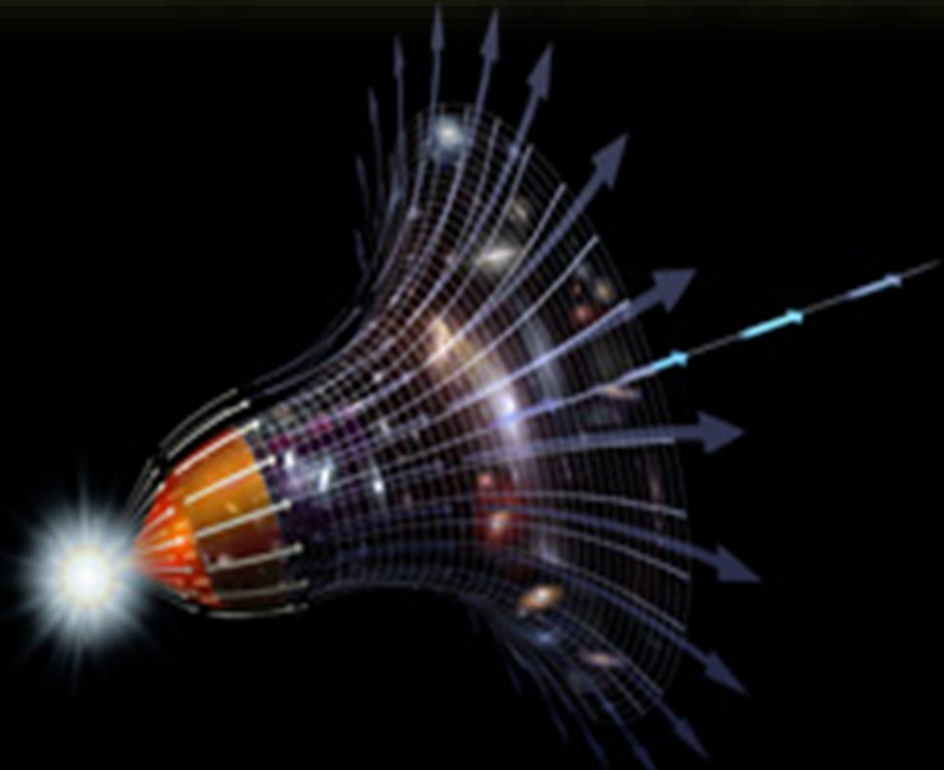
To obtain cosmological results:

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

COSMOLOGY: THE SCIENCE OF THE UNIVERSE

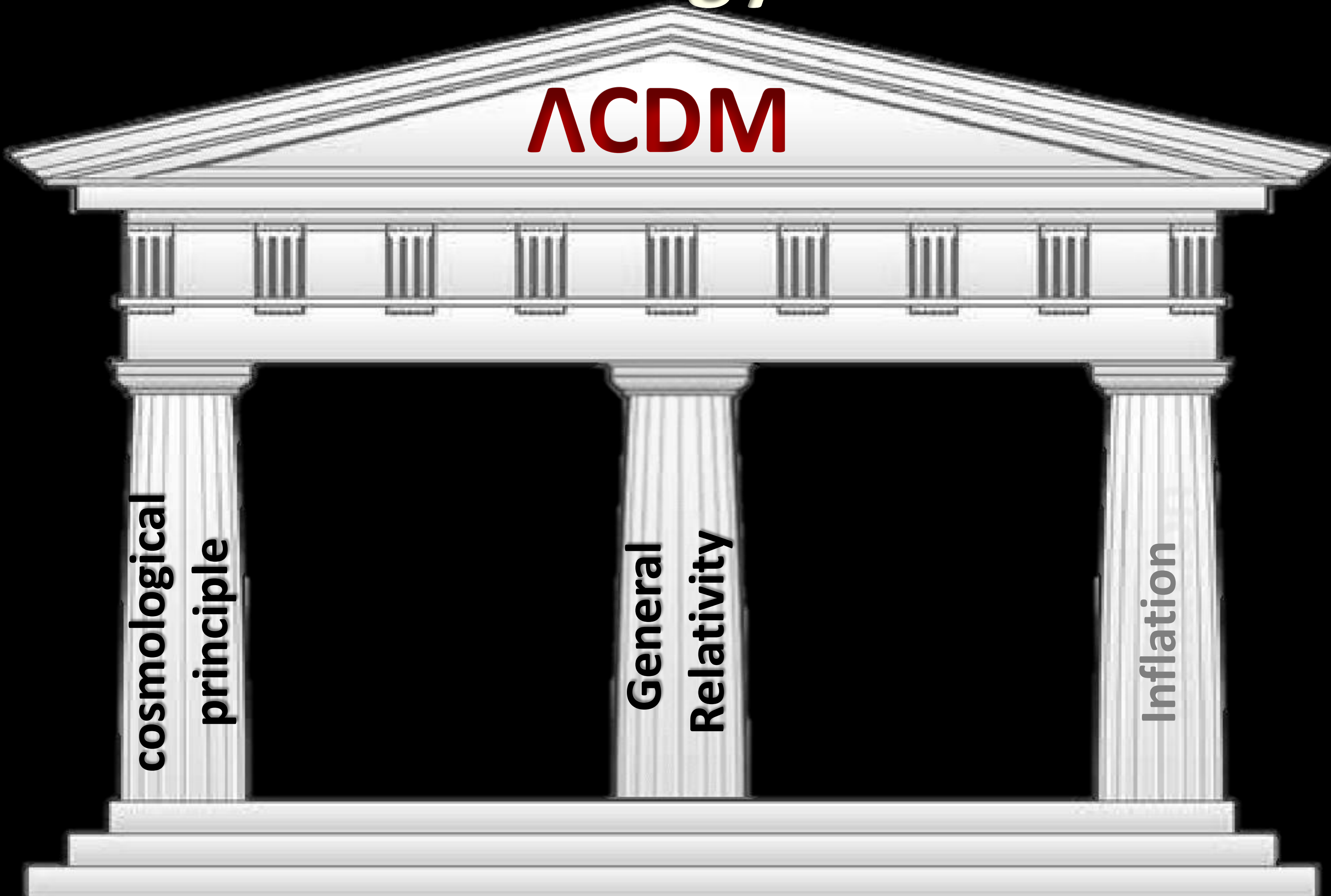


THE BIG BANG



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

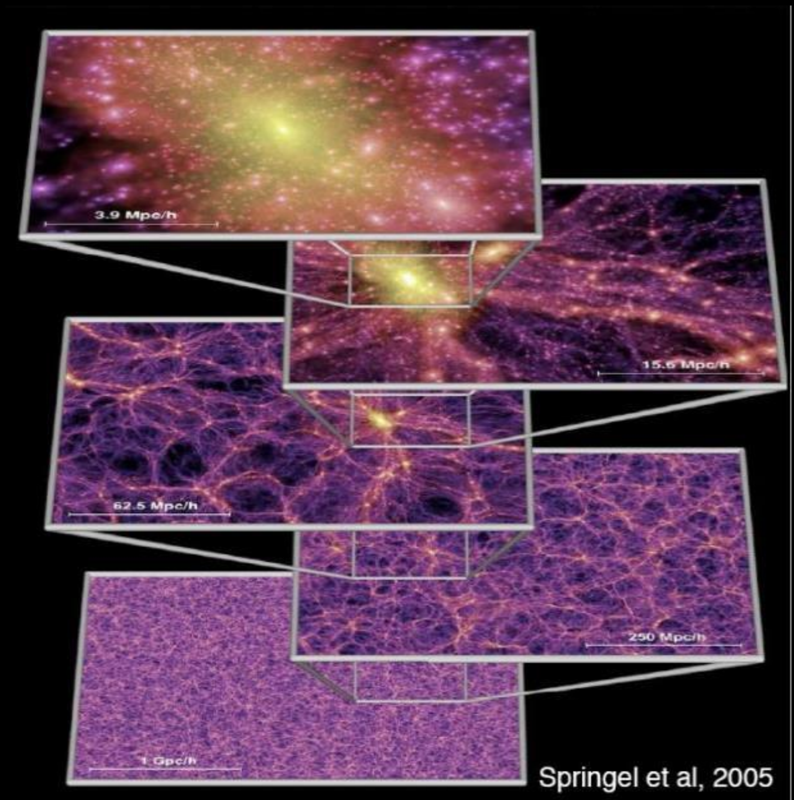
Cosmology Basis



The cosmological principle

The Universe is homogeneous and isotropic

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



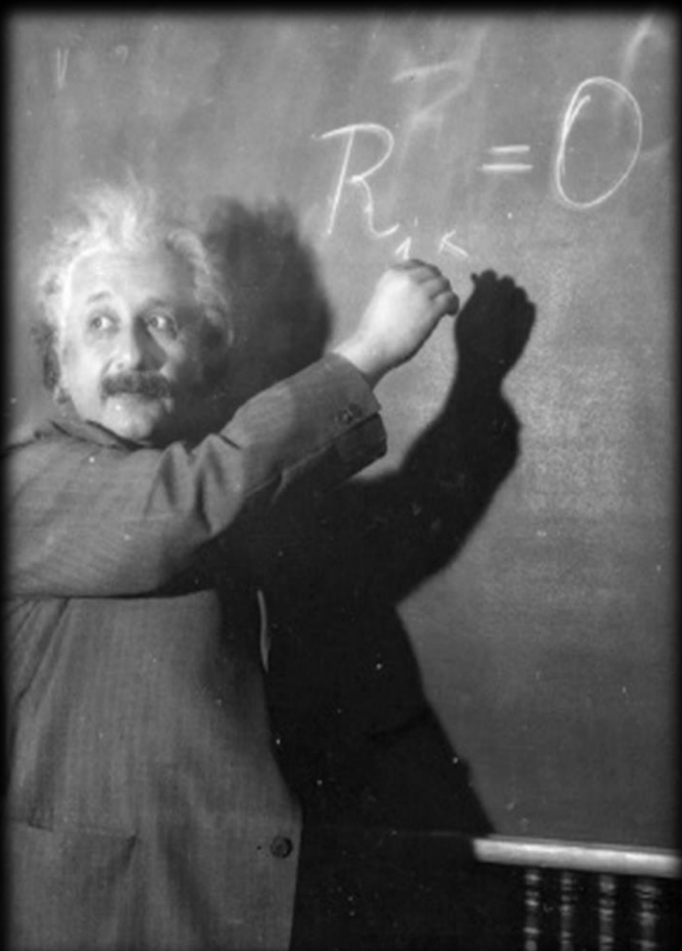
It is verified only for regions with a size around 100 Mpc or larger

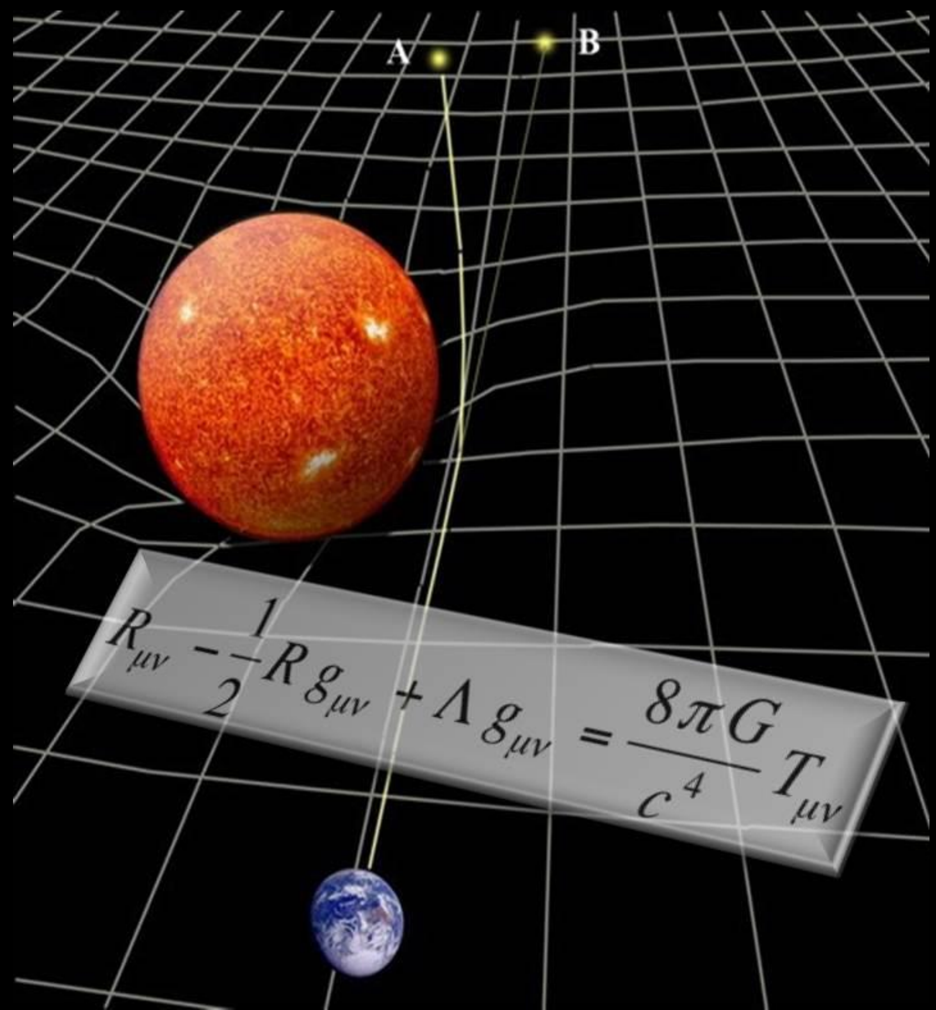
The Big Bang theory is able to explain why this happens. It describes how structures that we observe in the Universe are formed.

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

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

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

$$S_0(r) = r$$

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

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

The General Relativity predicts an expanding (or contracting) Universe

3 possible geometries:

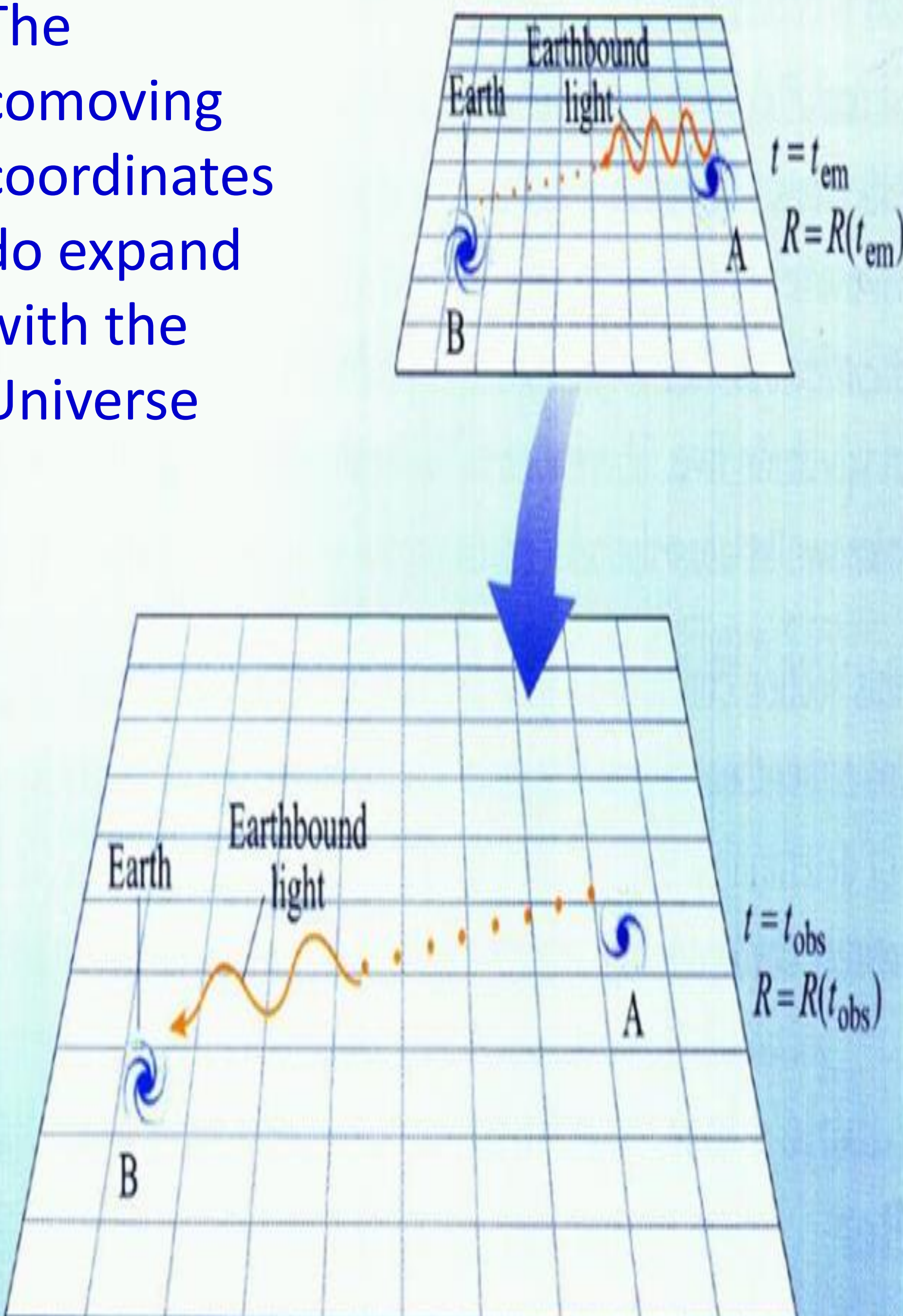
$\rho < \rho_C$ → open (hyperbolic)
$\rho = \rho_C$ → flat (euclidean)
$\rho > \rho_C$ → closed (eliptic)

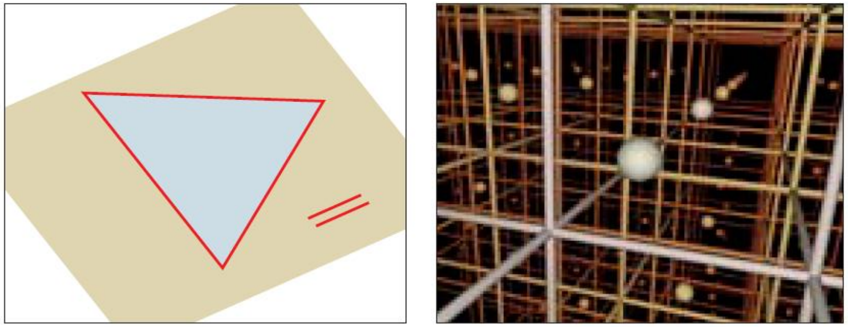
Scale Factor: How distances grow with time

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

Comoving Coordinates: They expand with the Universe

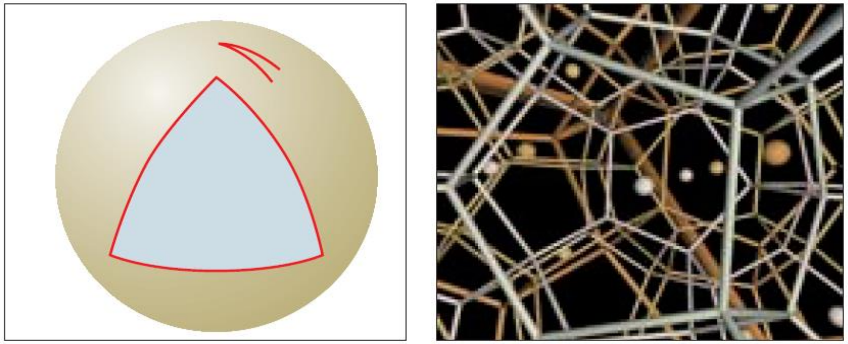
The comoving coordinates do expand with the Universe



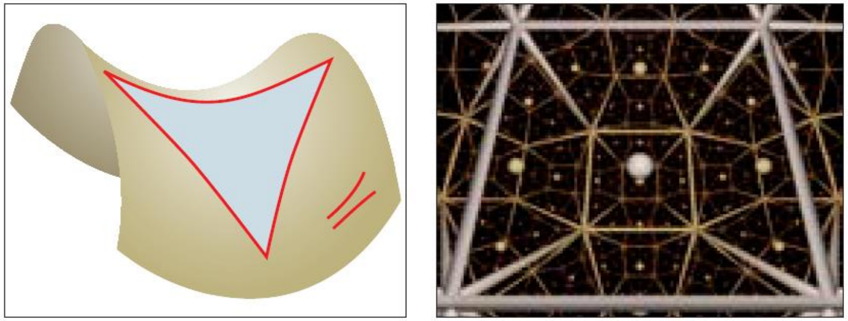


Flat space obeys the familiar rules of Euclidean geometry. The angular size of identical spheres is inversely proportional to distance—the usual vanishing-point perspective taught in art class.

3 possible geometries



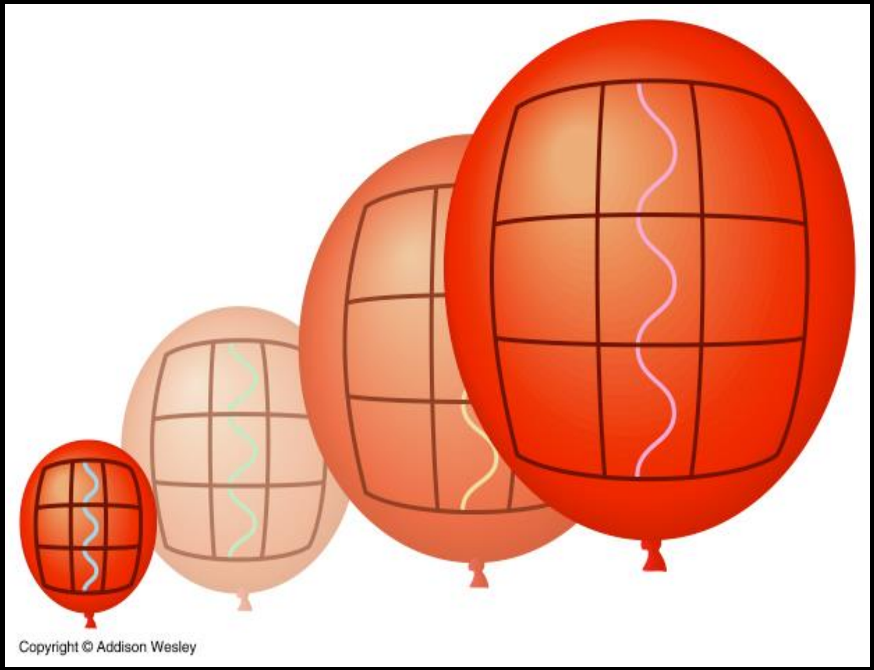
Spherical space has the geometric properties of a globe. With increasing distance, the spheres at first seem smaller. They reach a minimum apparent size and subsequently look larger. (Similarly, lines of longitude emanating from a pole separate, reach a maximum separation at the equator and then refocus 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 light of the galaxies is observed redshifted beacuse 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 halotropic 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 deifferent way with the scale factor:

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

Matter: a^{-3}

Radiation: a^{-4}

Cosmological Constant: Constant!!!

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

$$d(\rho a^3) = -P da^3 = -w\rho da^3$$

$$a^3 d\rho + \rho 3a^2 da = -3w\rho a^2 da$$

$$a^3 d\rho = -3(1+w)a^2 \rho da$$

$$\frac{d\rho}{\rho} = -3(1+w)\frac{da}{a}$$

$$d(ln\rho) = -3(1+w)d(lna)$$

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

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

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

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

$$da a^{3(1+w)/2-1} = \sqrt{\frac{8\pi G\rho_0}{3}}dt$$

$$a^{3(1+w)/2} \propto t$$

$$a \propto t^{2/3(1+w)}$$

We will use these equations later, when treating with perturbations

Distancies

The comoving distance to a source of redshift z is:

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

For a Euclidean Universe

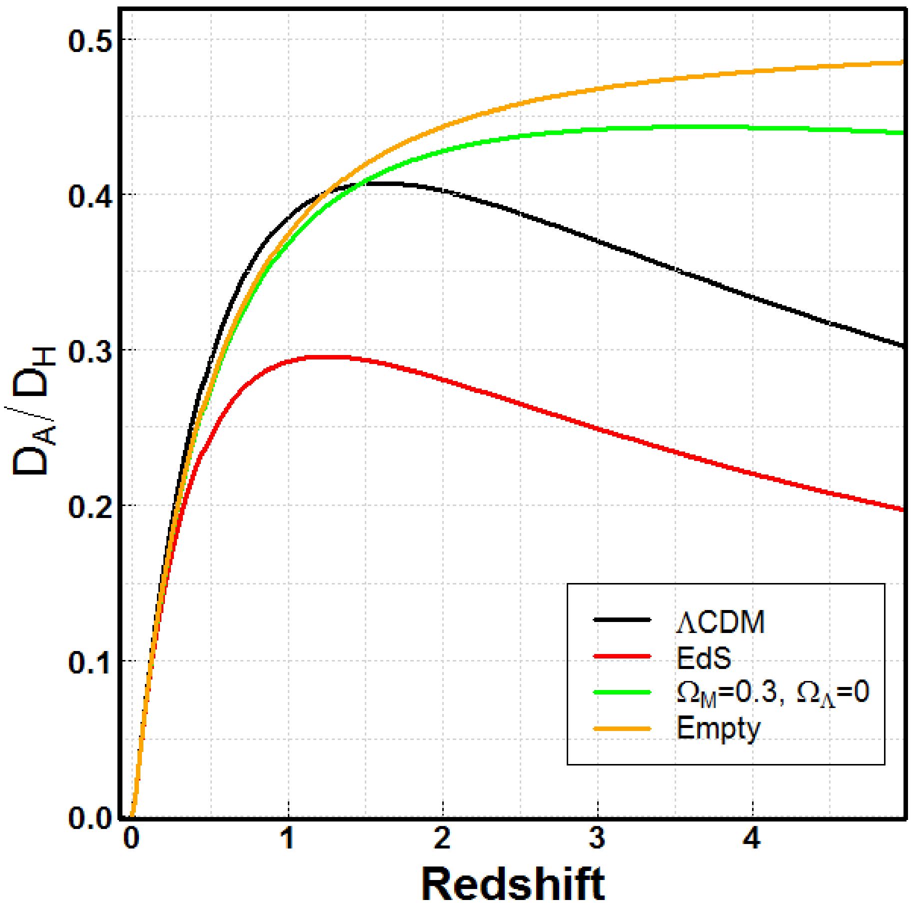
Luminosity distance: $d_L = r(z)\,(1+z)$

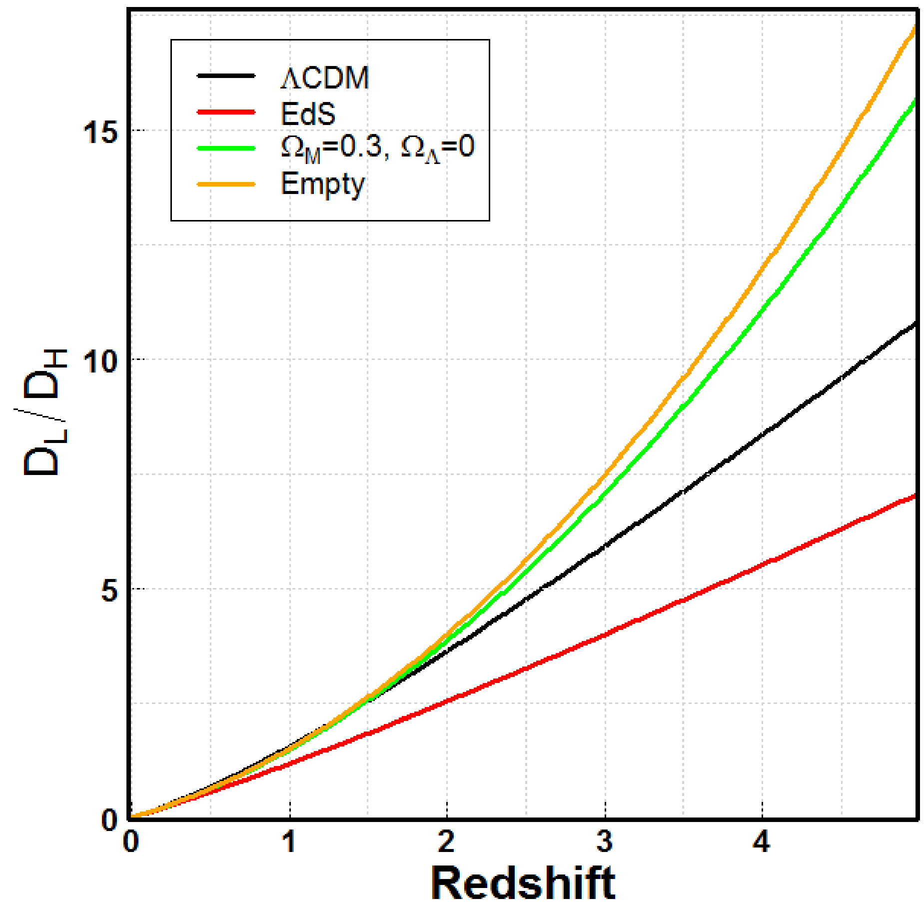
Angular diameter distance: $d_A = r(z)/(1+z)$

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.

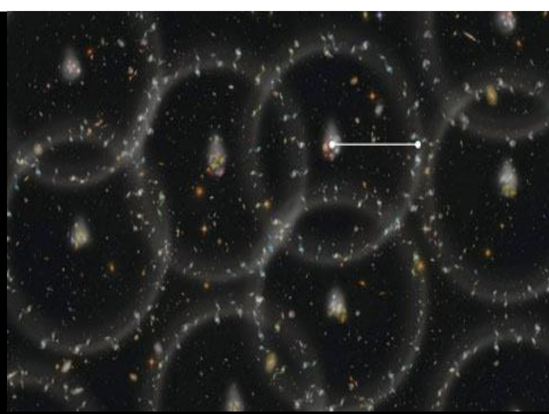
Angular Diameter Distance

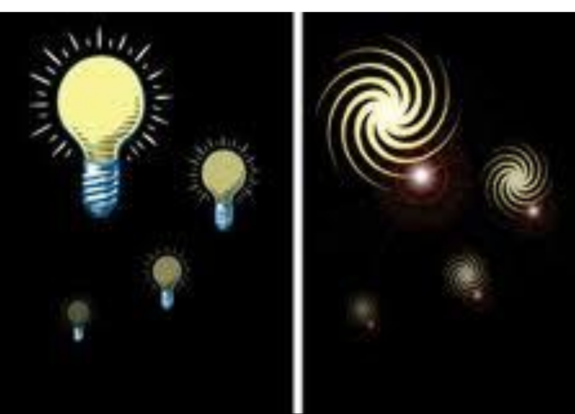
Luminosity Distance





STANDARD
RULERS



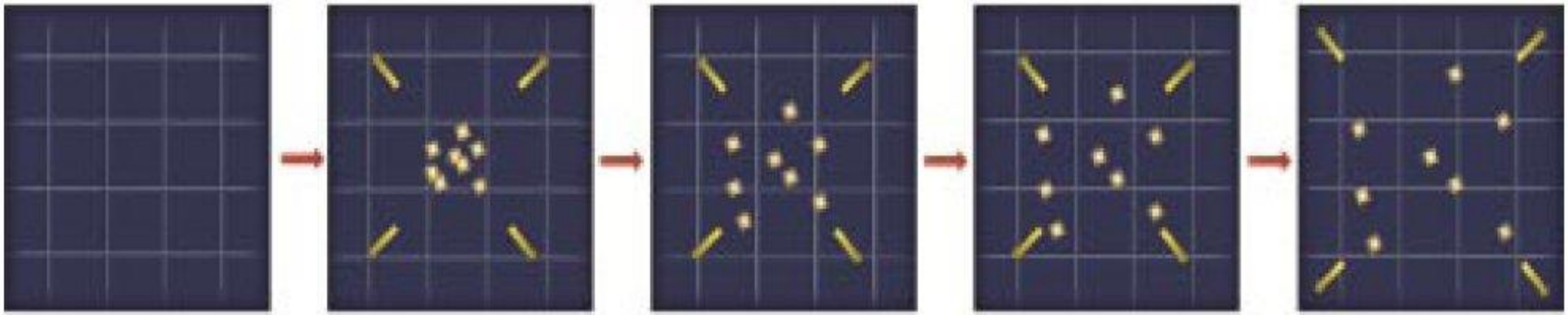


STANDARD
CANDLES

WHAT KIND OF EXPLOSION WAS THE BIG BANG?

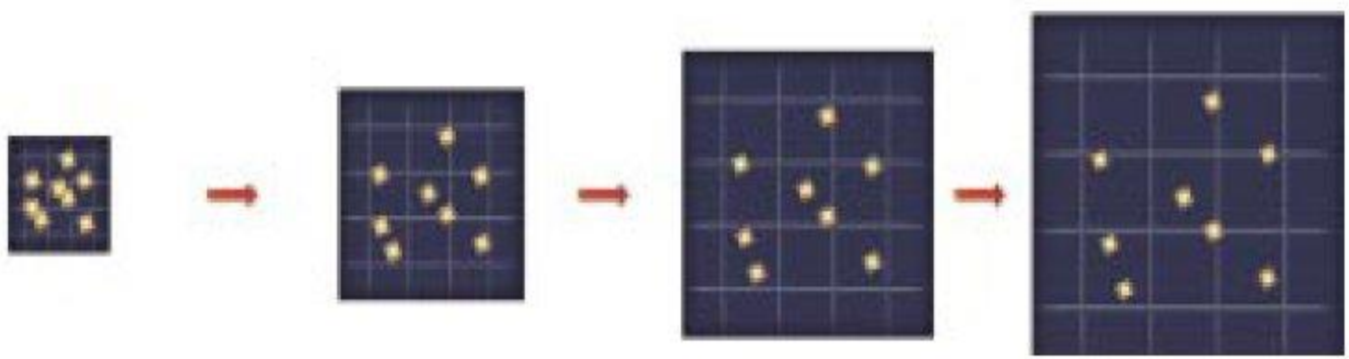
WRONG: **The big bang was like a bomb going off at a certain location in previously empty space.**

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.

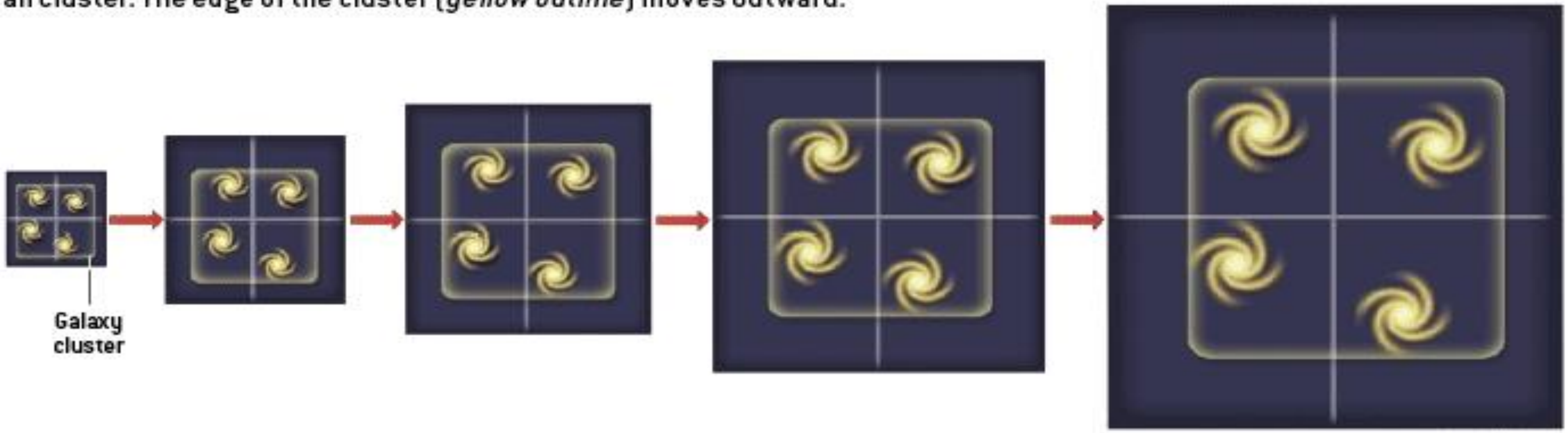


From Scientific American

DO OBJECTS INSIDE THE UNIVERSE EXPAND, TOO?

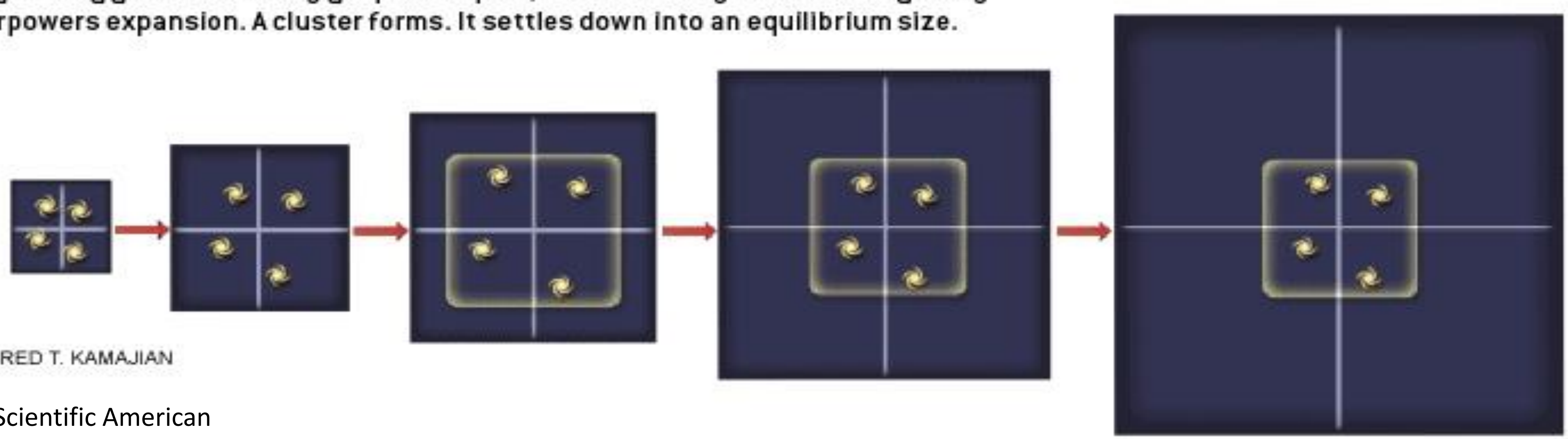
***WRONG*: Yes. Expansion causes the universe and everything in it to grow.**

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.



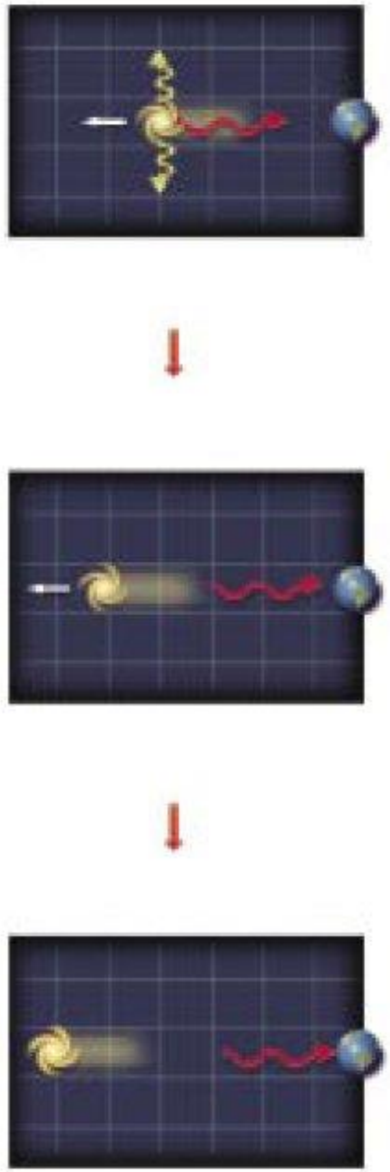
ALFRED T. KAMAJIAN

From Scientific American

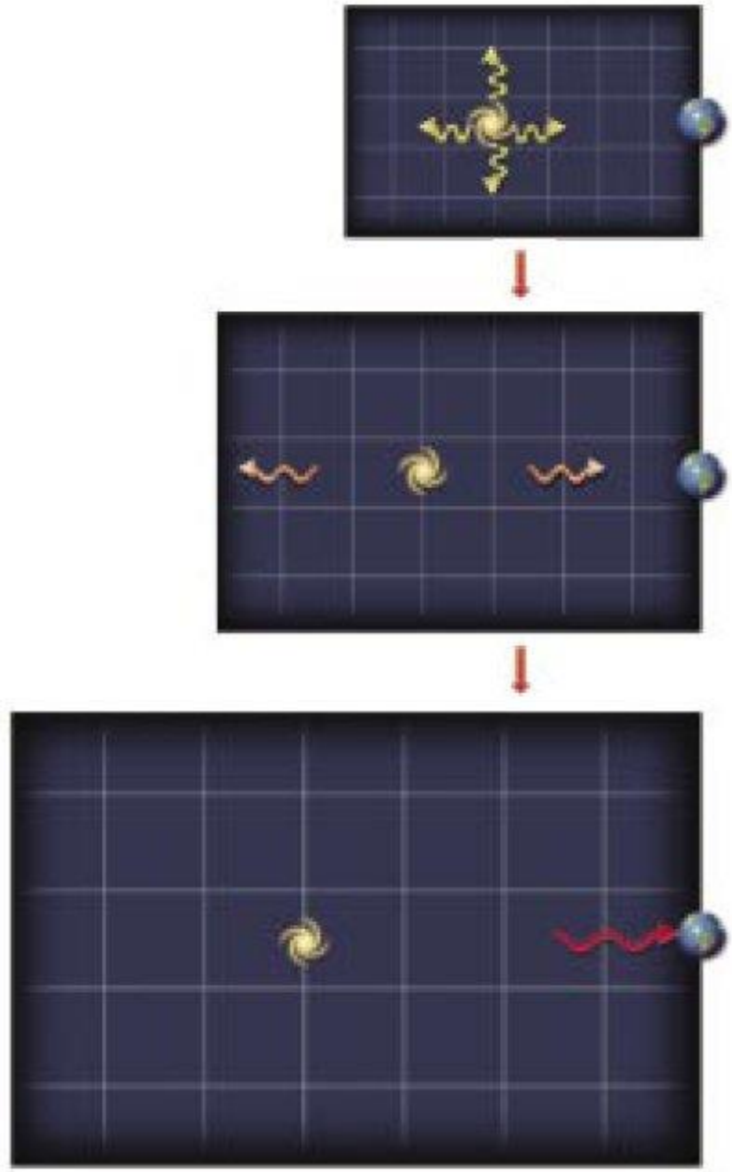
WHY IS THERE A COSMIC REDSHIFT?

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.**



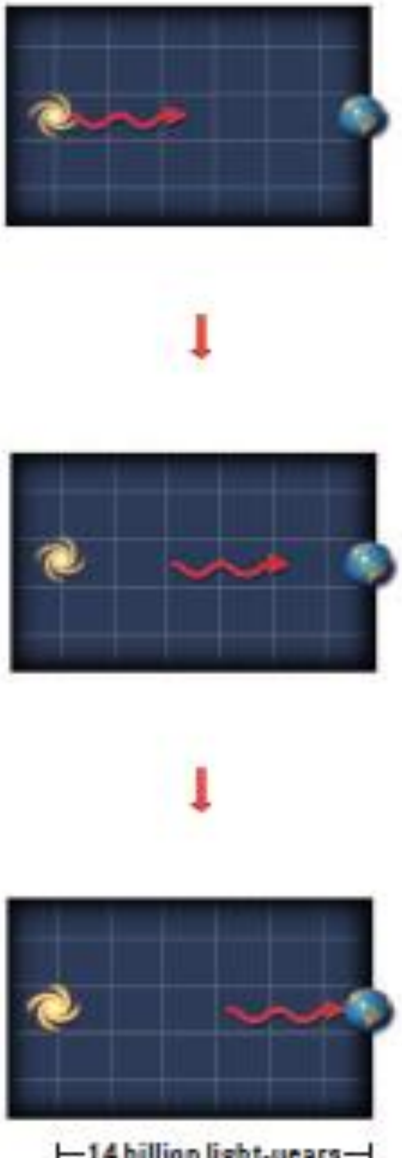
Galaxies hardly move through space, so they emit light with nearly the same wavelength in all directions (*top*). The wavelength gets longer during the journey, because space is expanding. Thus, the light gradually reddens (*middle* and *bottom*). The amount of redshift differs from what a Doppler shift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

From Scientific American

HOW LARGE IS THE OBSERVABLE UNIVERSE?

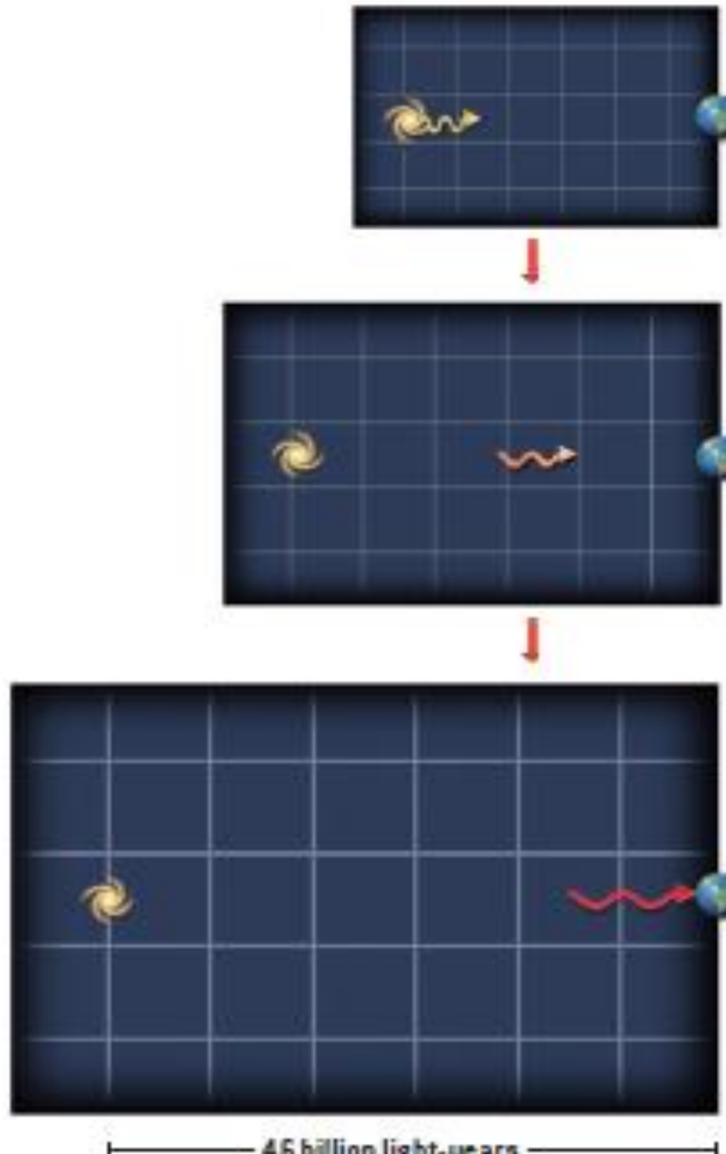
WRONG: **The universe is 14 billion years old, so the radius of the observable part is 14 billion light-years.**

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.

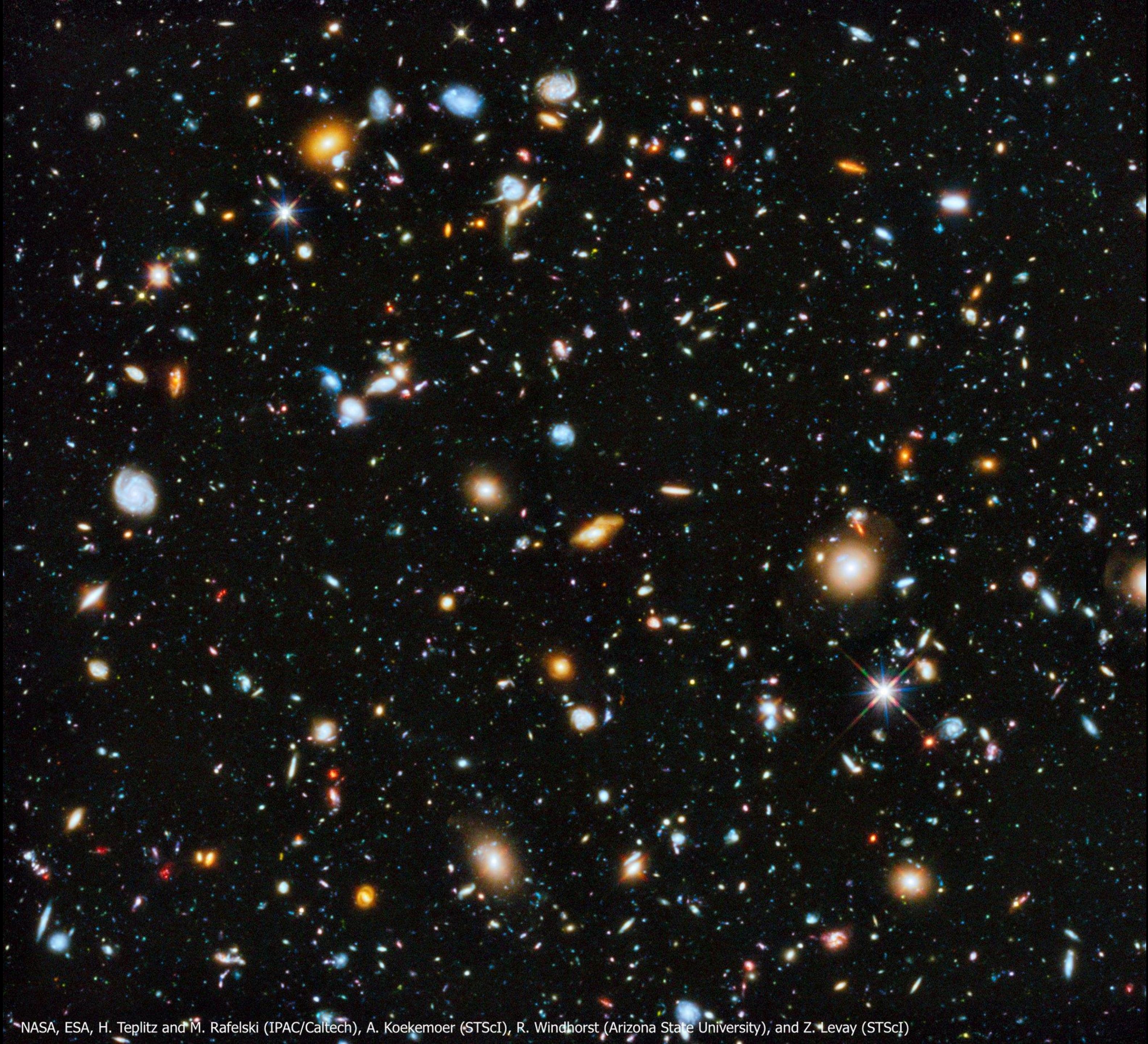


From Scientific American

The observable Universe is finite

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

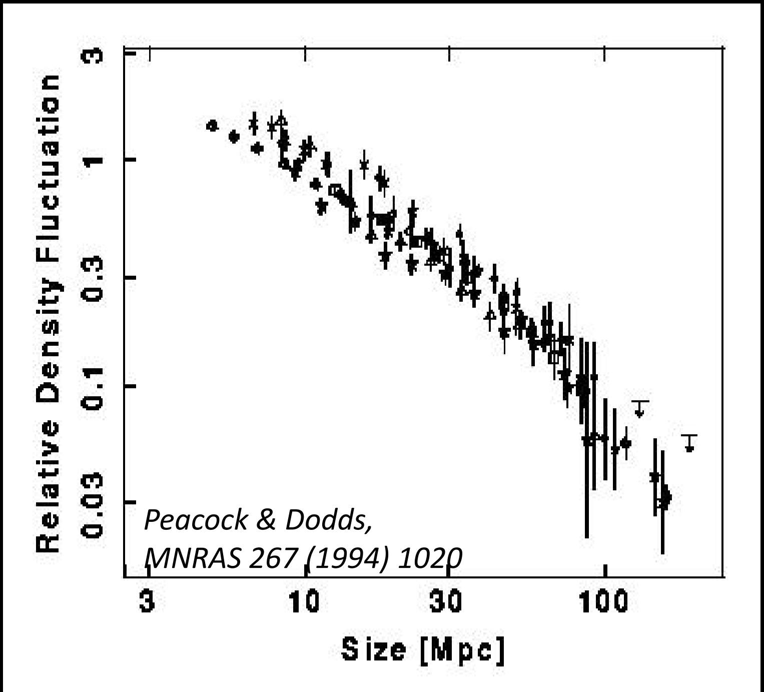
<u>The light they are emitting now will never reach the Earth!!!</u>



NASA, ESA, H. Teplitz and M. Rafelski (IPAC/Caltech), A. Koekemoer (STScI), R. Windhorst (Arizona State University), and Z. Levay (STScI)

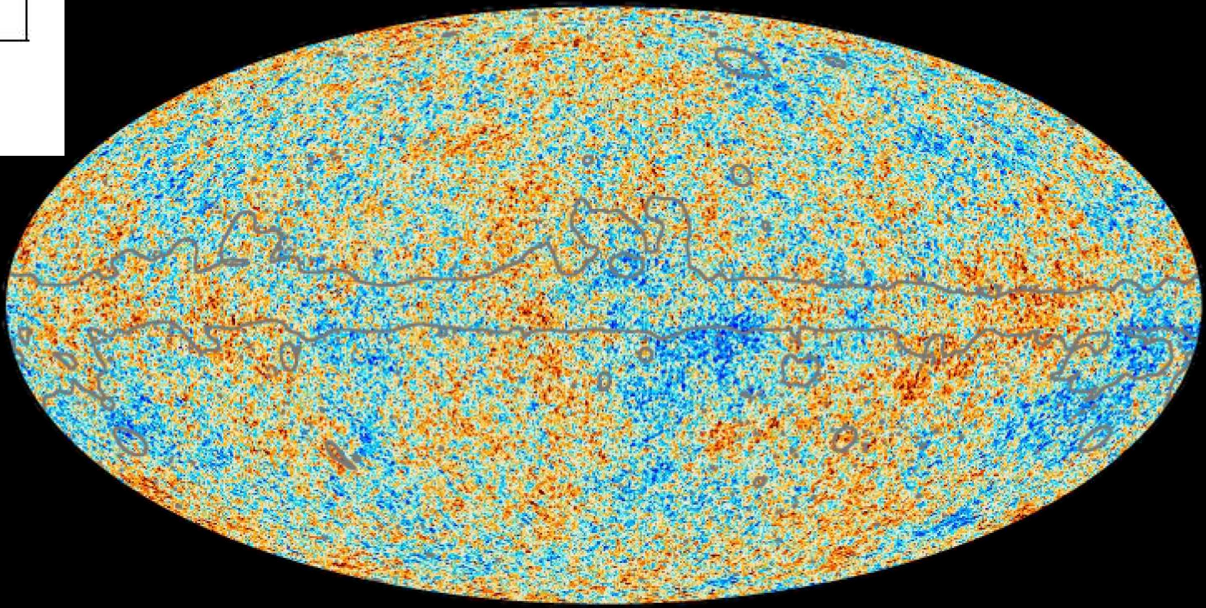
OBSERVATIONAL BASIS

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



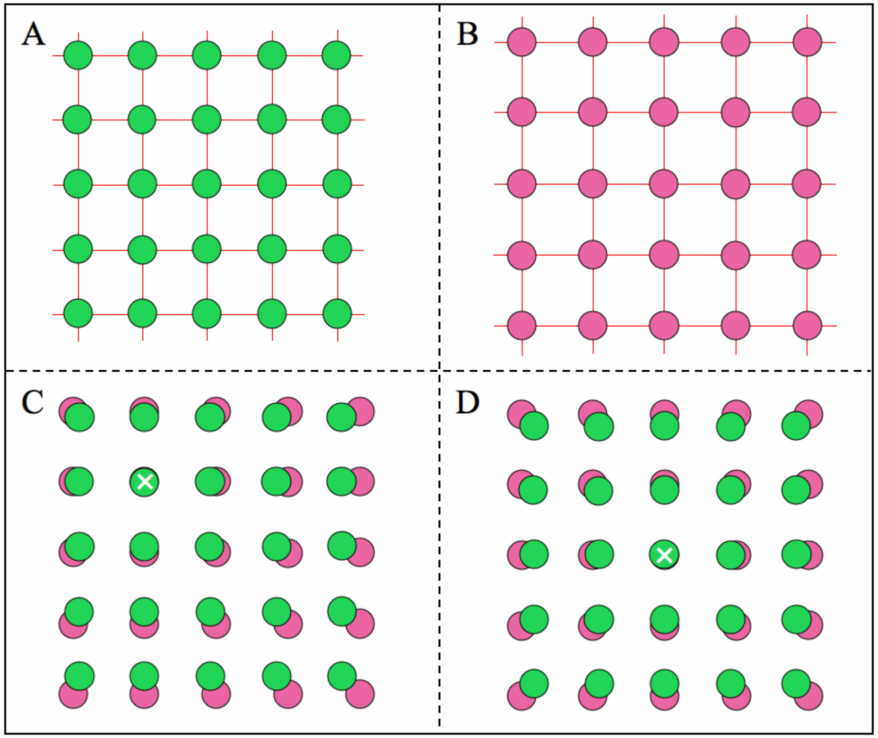
Planck Collaboration 2018

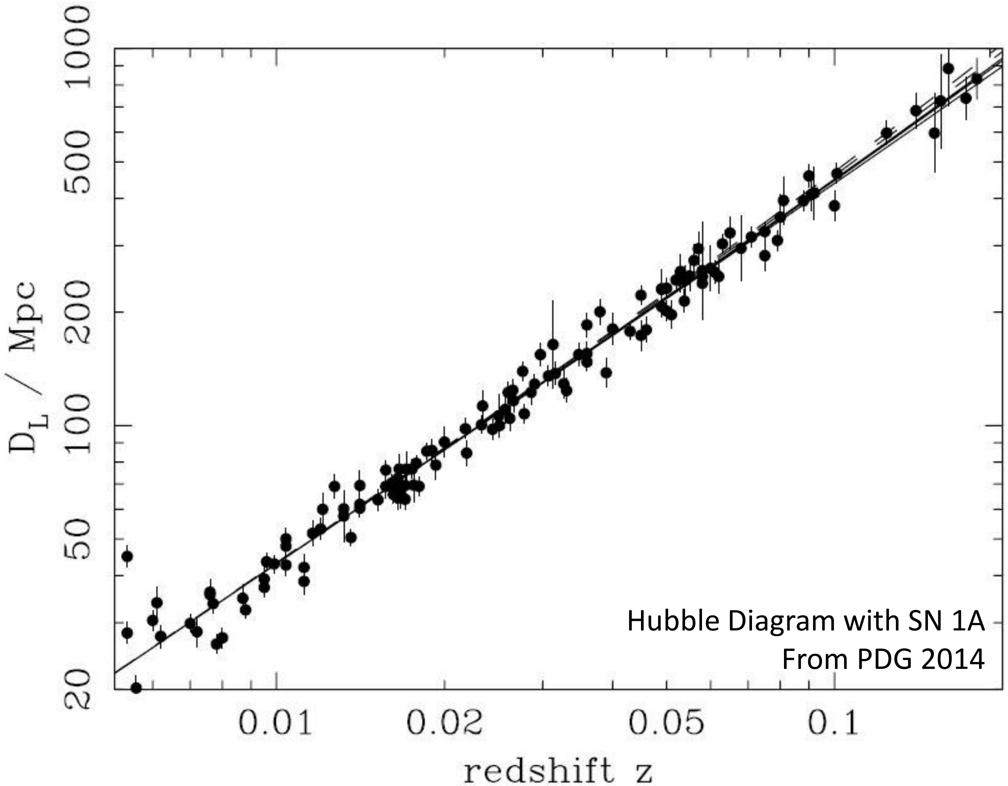
Expansion: The Hubble Law

Galaxias 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

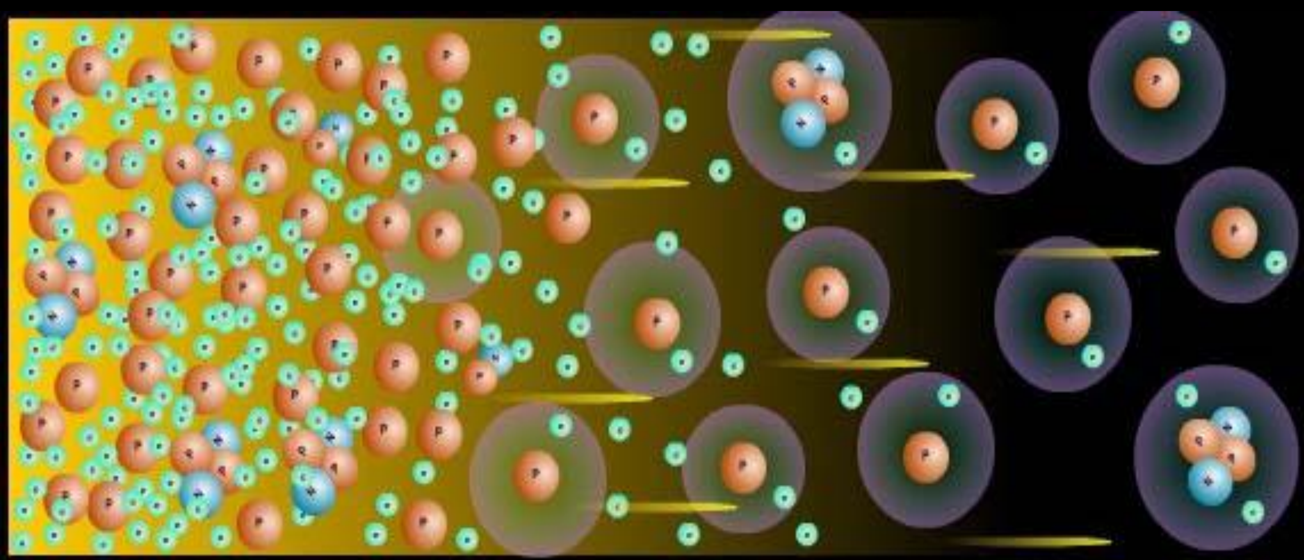




THE COSMIC MICROWAVE BACKGROUND

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!!!)**

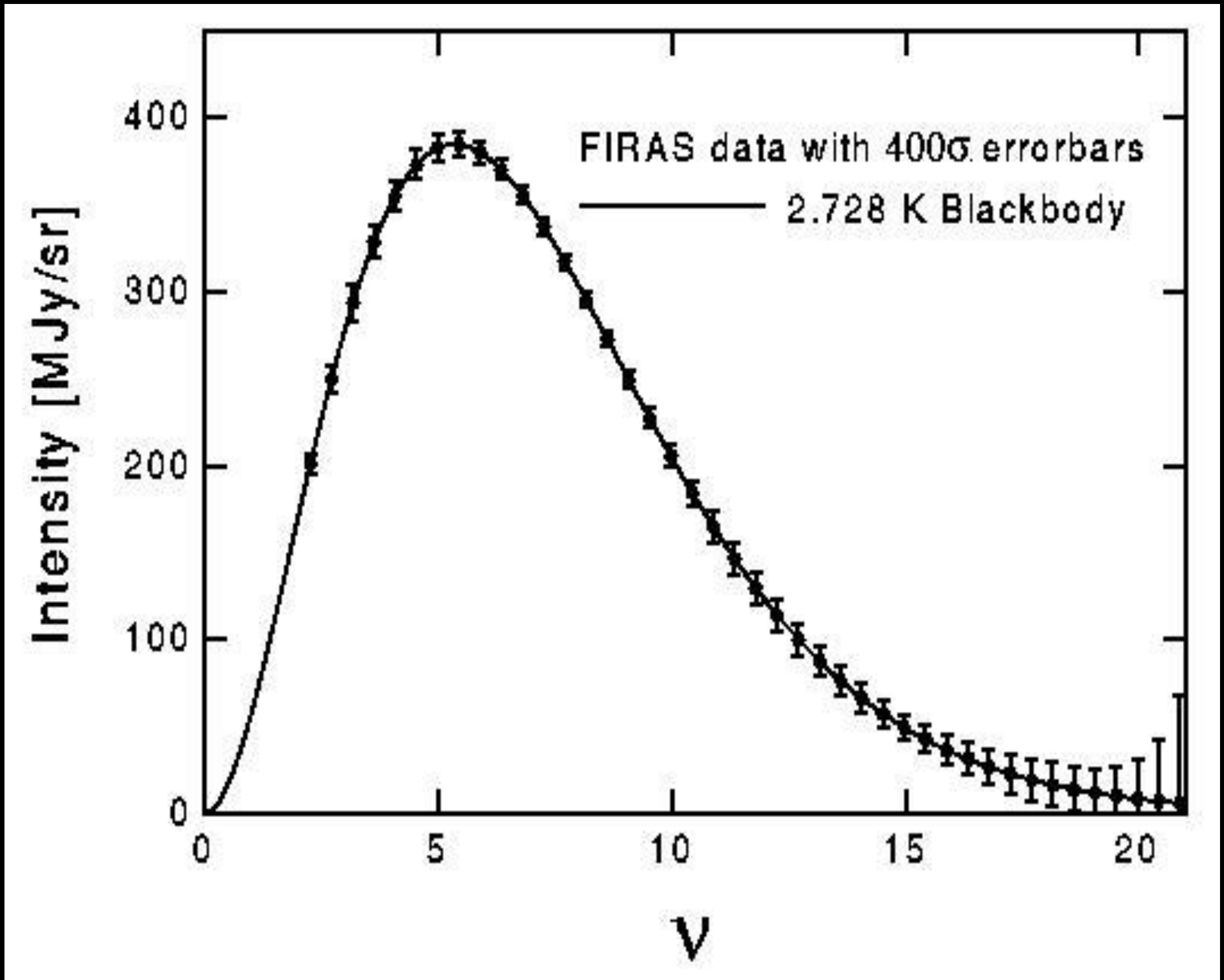


The confirmation that the CMB is not completely uniform was done in 1992. Its small anisotropies are the imprint of the origin of all the structures we see today (clusters, galaxies…)

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

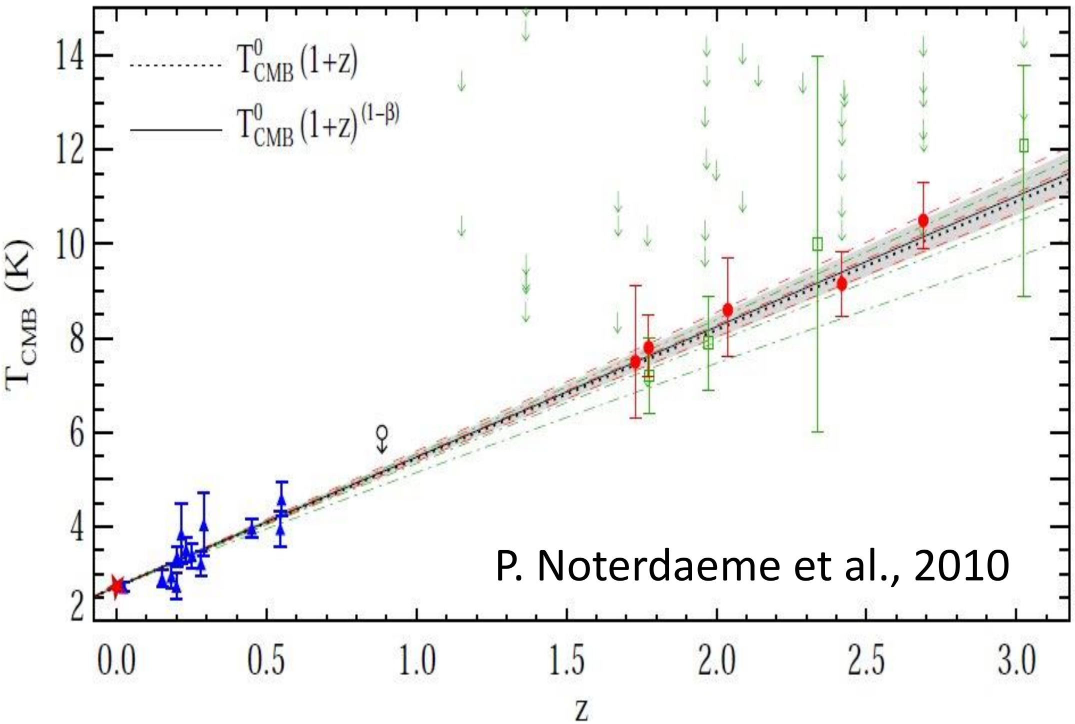
Black Body Spectrum at 2.72548 ± 0.00057 K

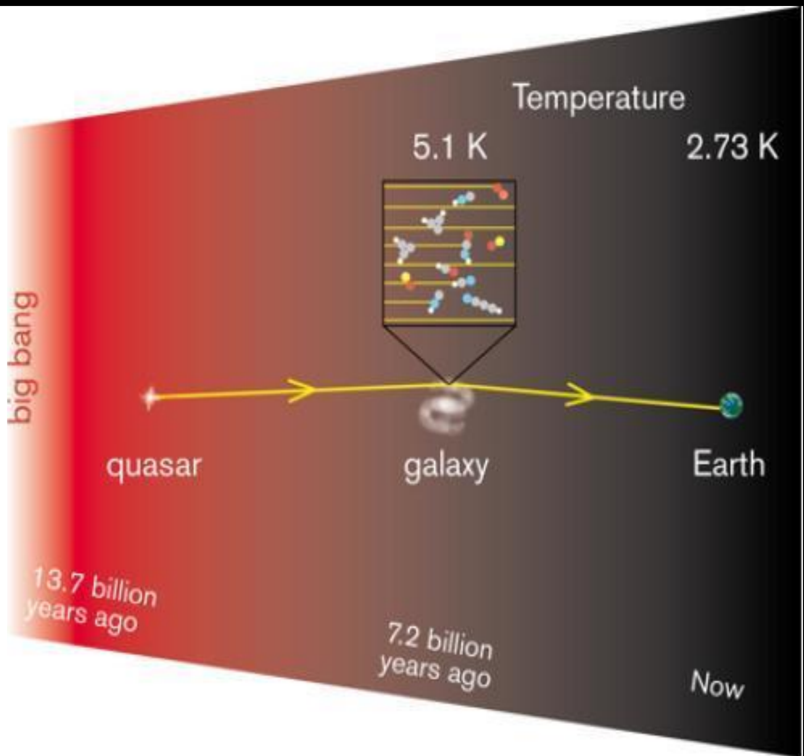


The Cosmic Microwave Background (CMB)

The Universe was hotter in the past

The cooling rate is exactly predicted by the Big Bang theory

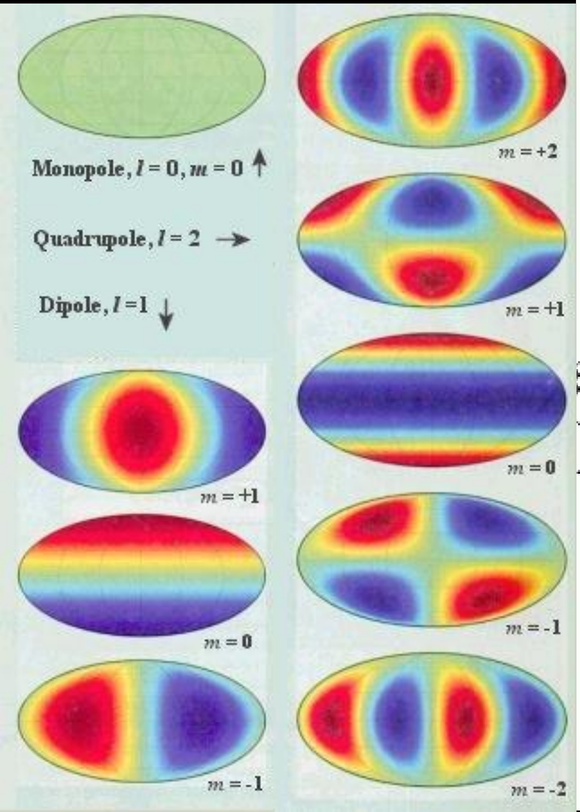


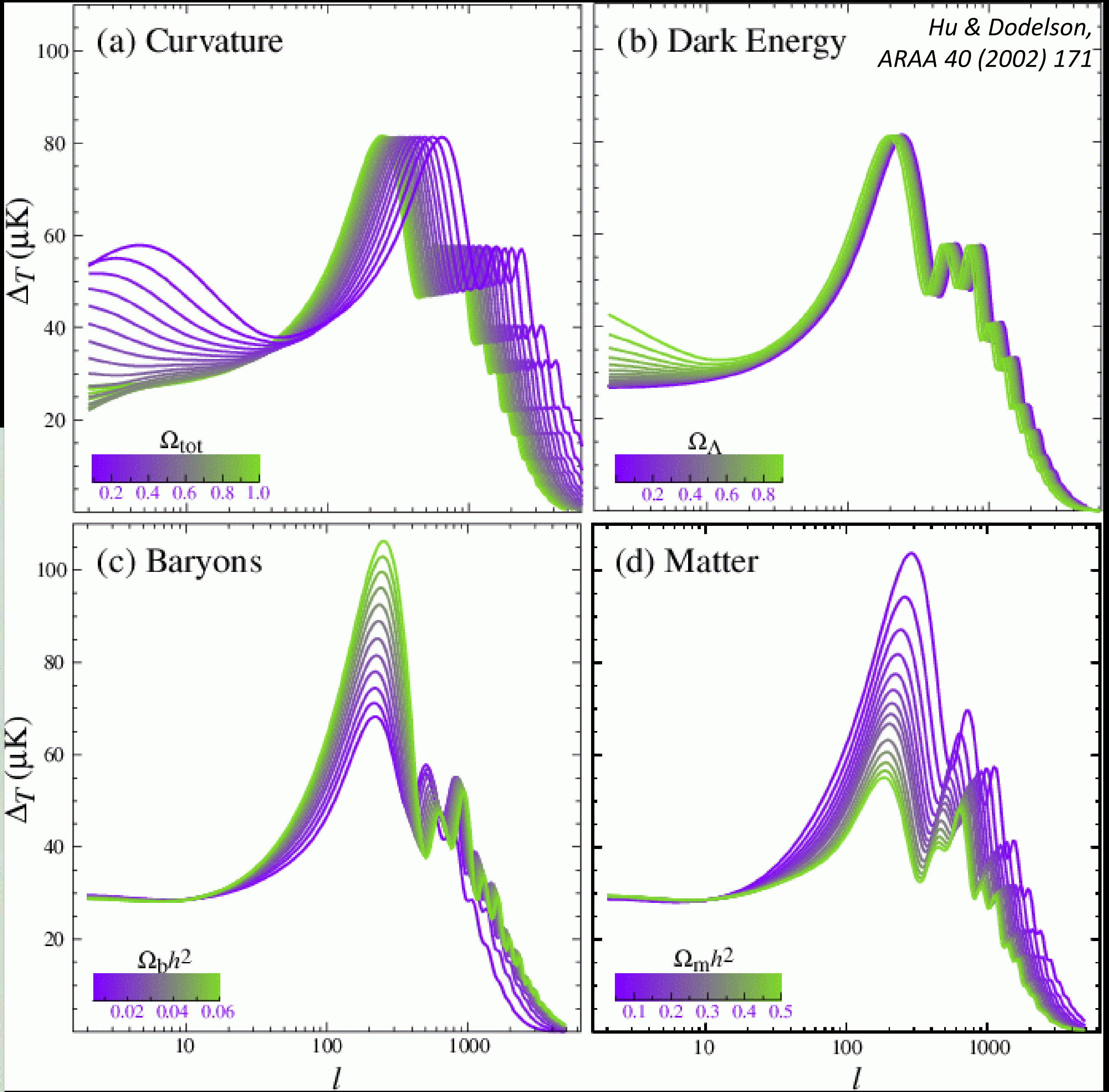


The Cosmic Microwave Background (CMB)

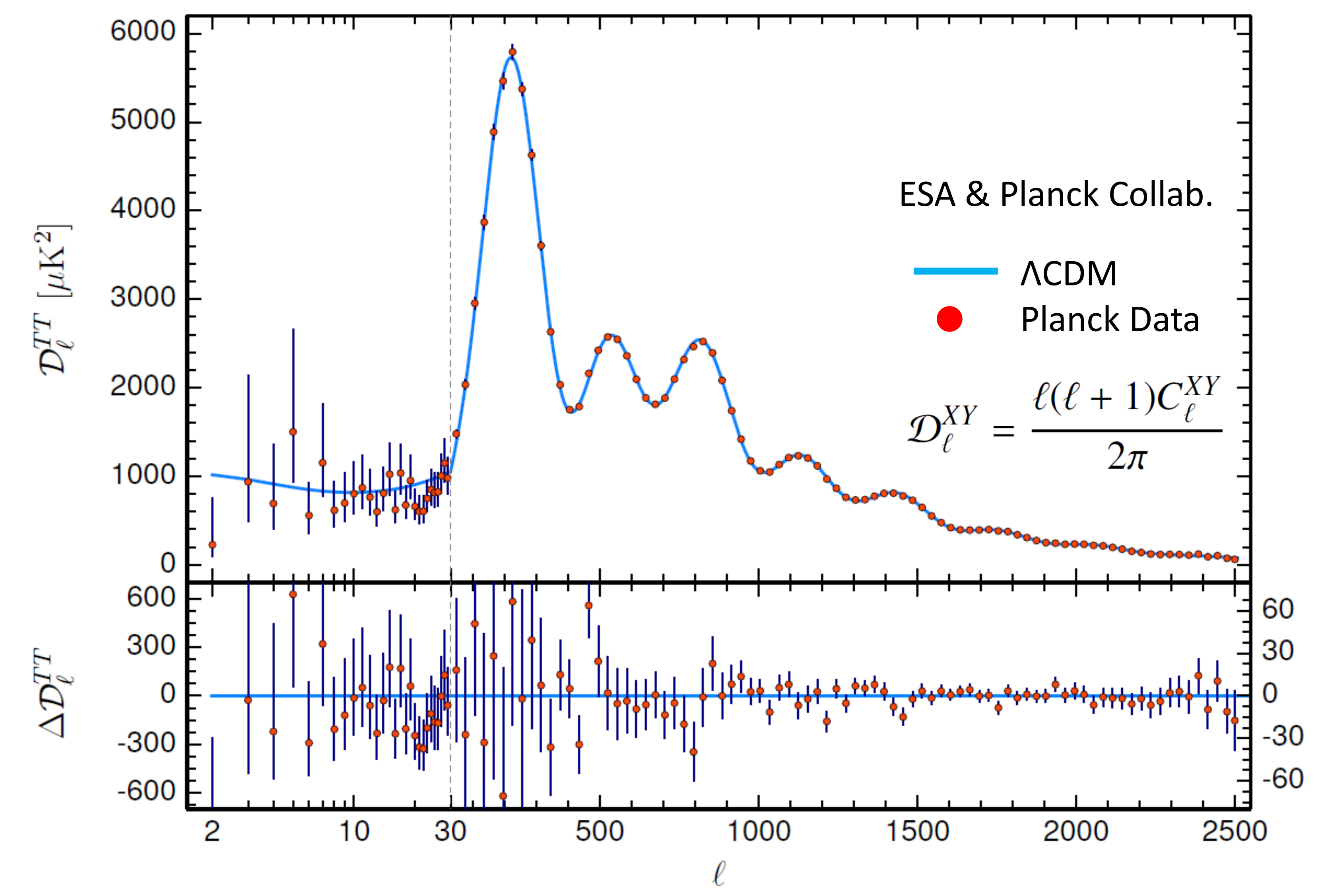
The power spectrum of the CMB depends on the cosmological parameters

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





The Cosmic Microwave Background (CMB)

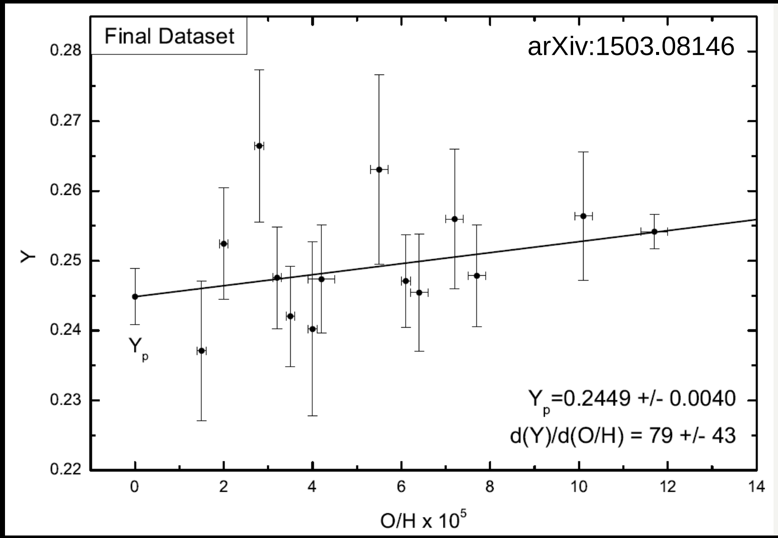


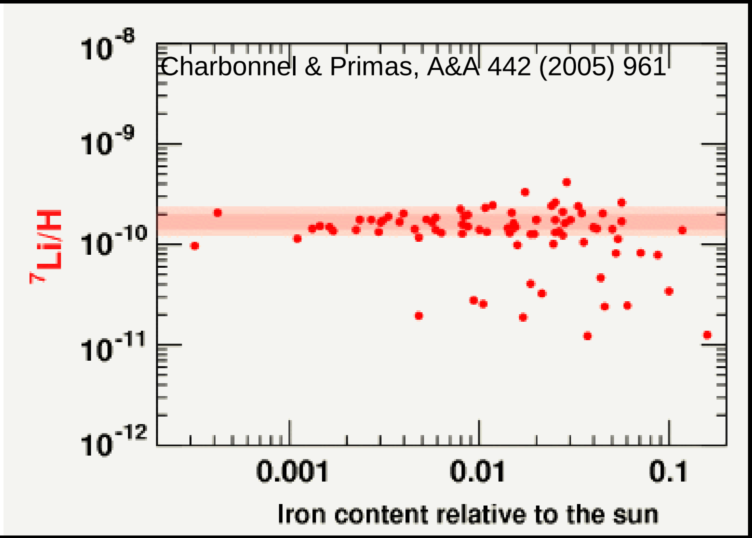
Extraordinary agreement between ΛCDM and data

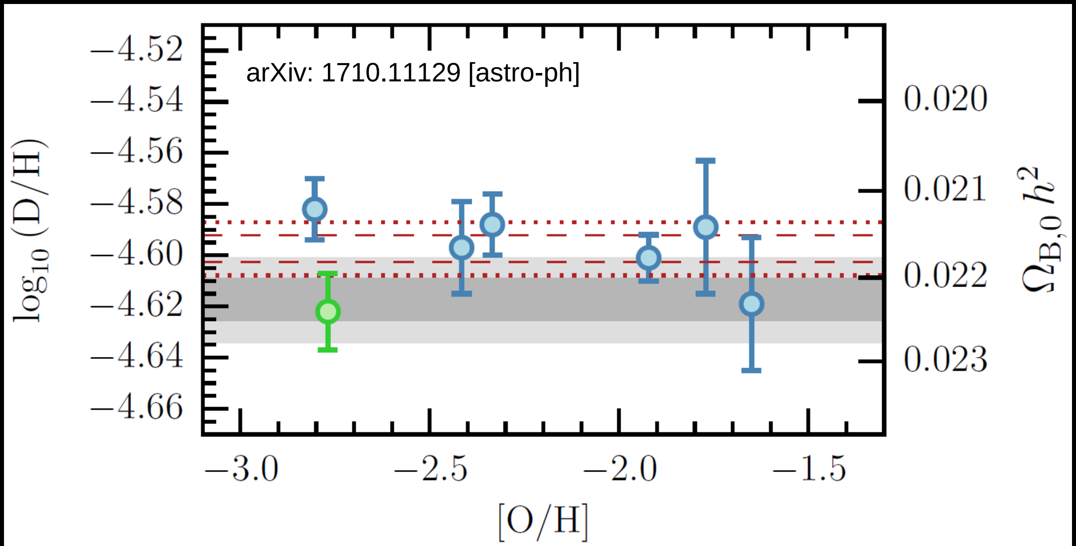
The spatial geometry of the Universe is Euclidean

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)







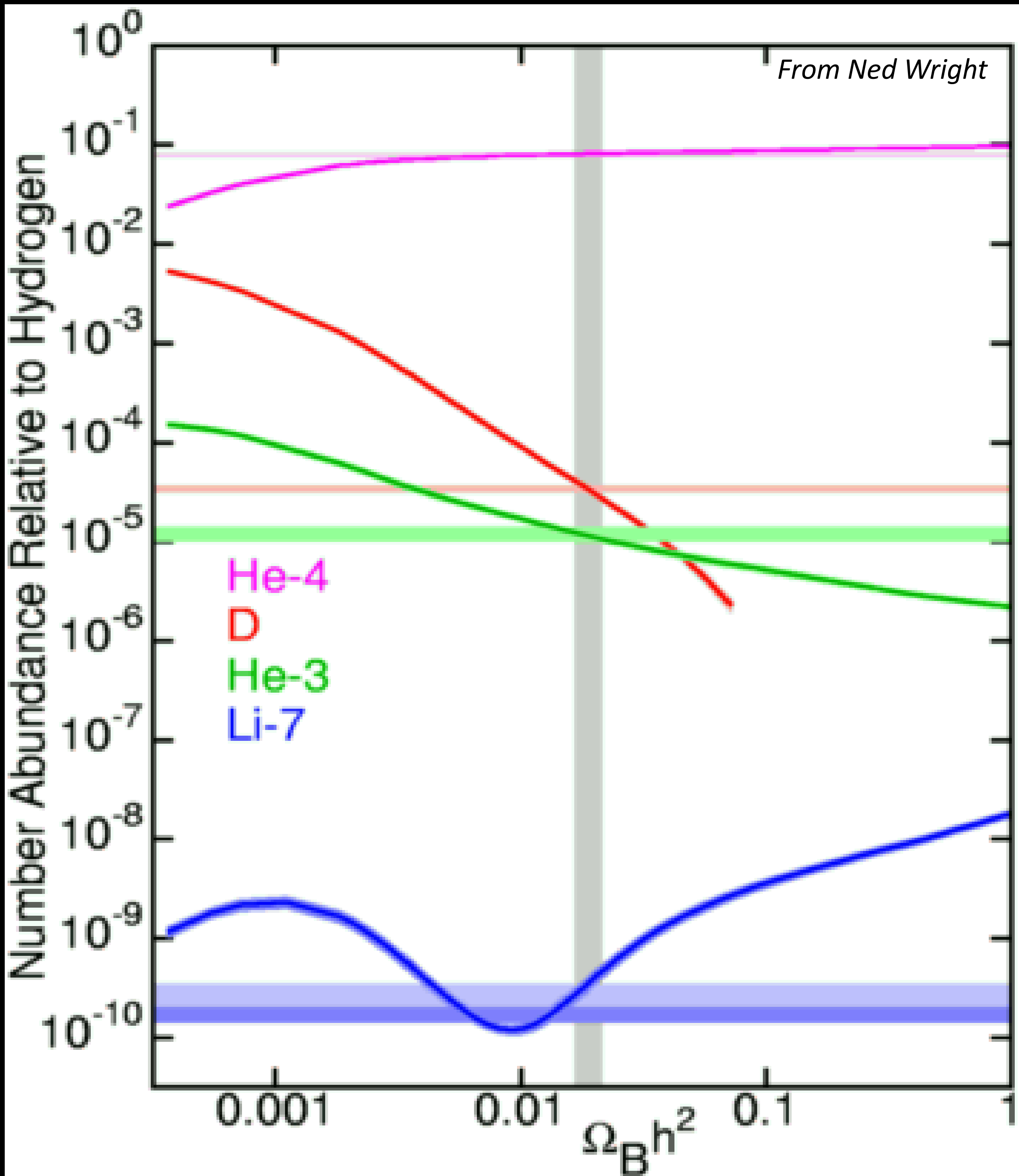
Measure their abundancies:

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

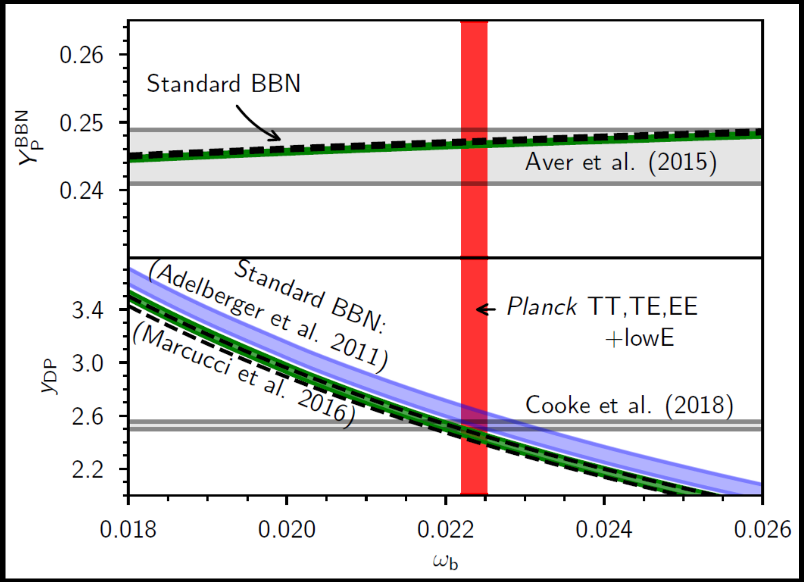


Abundancies measure the number of baryons (protons and neutrons, this is, normal matter)

Is a well-known physics (atoms)

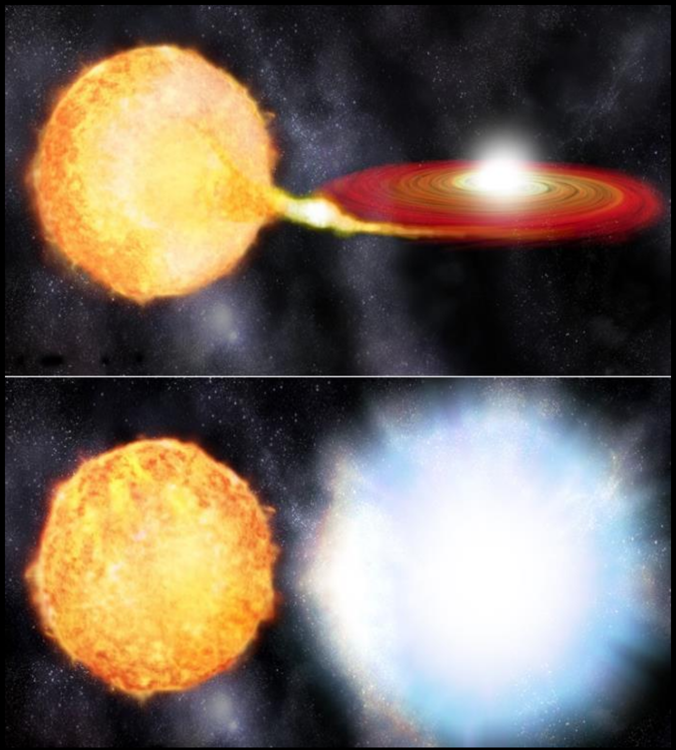
The number of photons per baryon is measured in the CMB. In perfect agreement with the abundances!

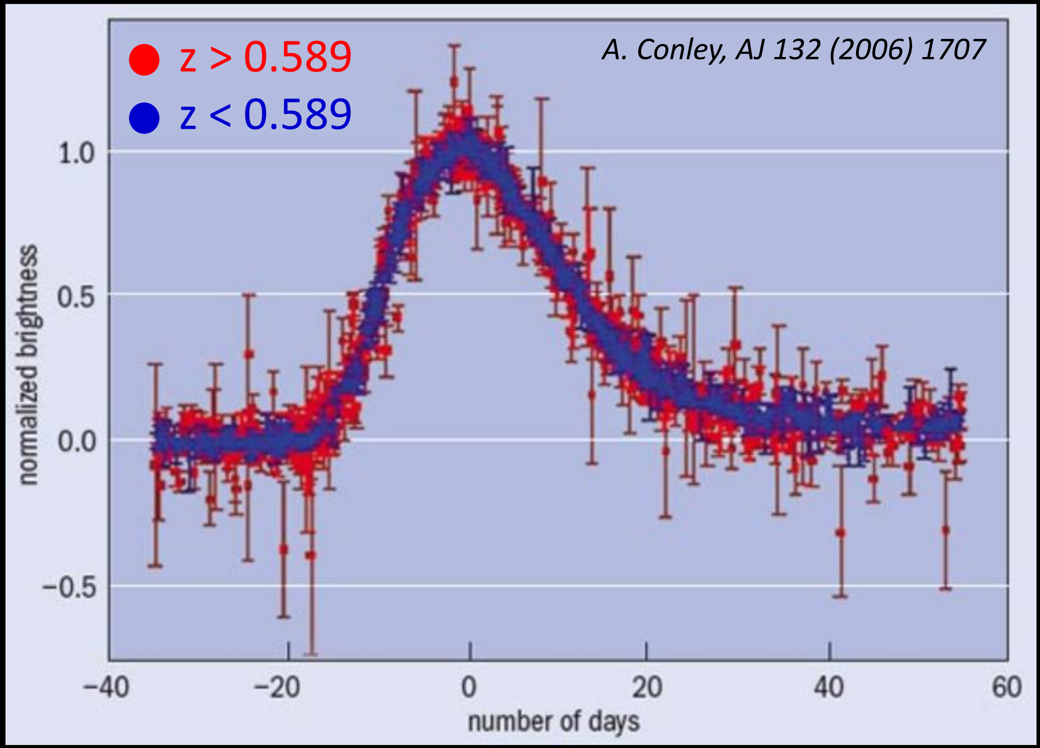
THERE IS NON-BARYONIC DARK MATTER!



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



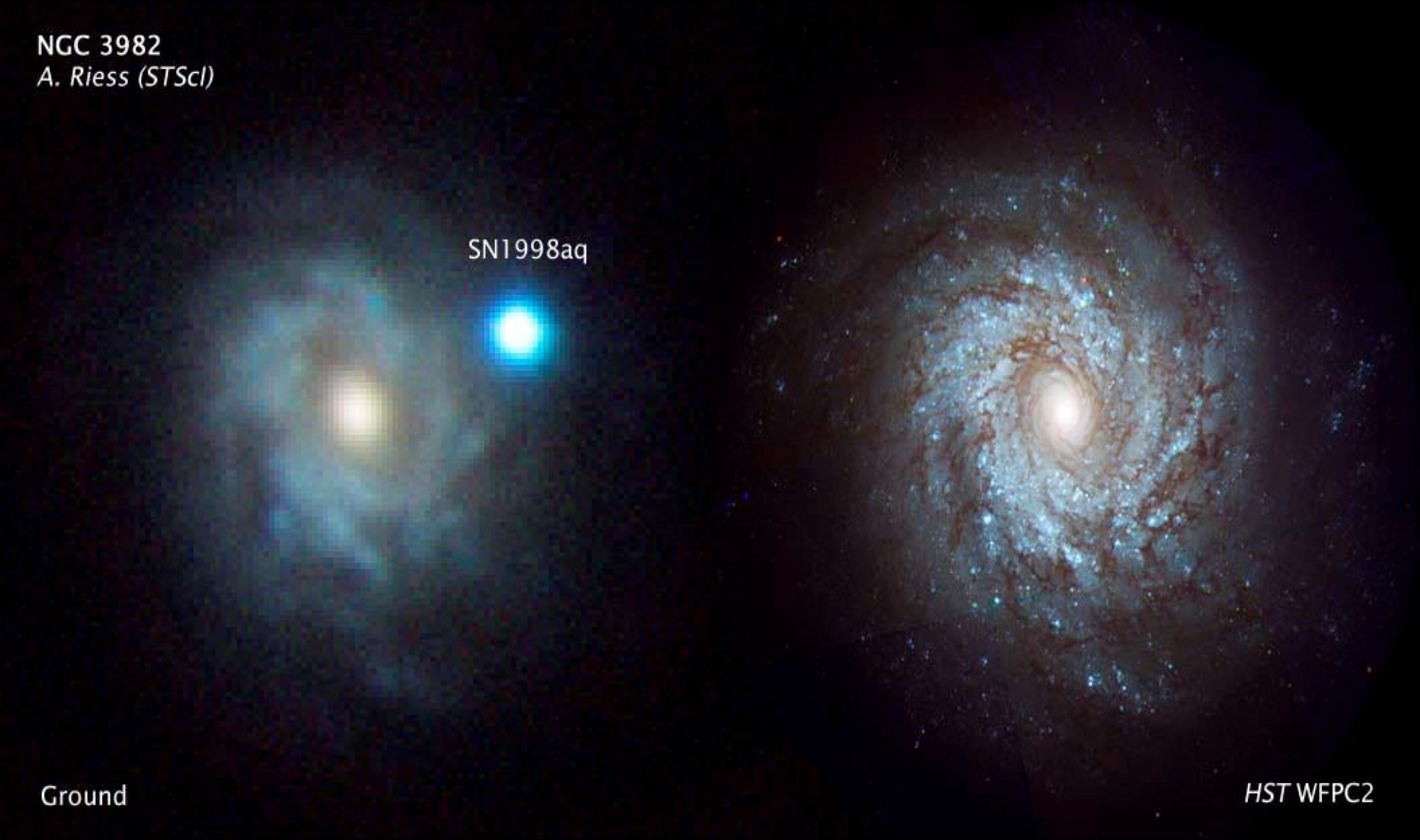


SN1a: Binary systems red giant-white dwarf

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



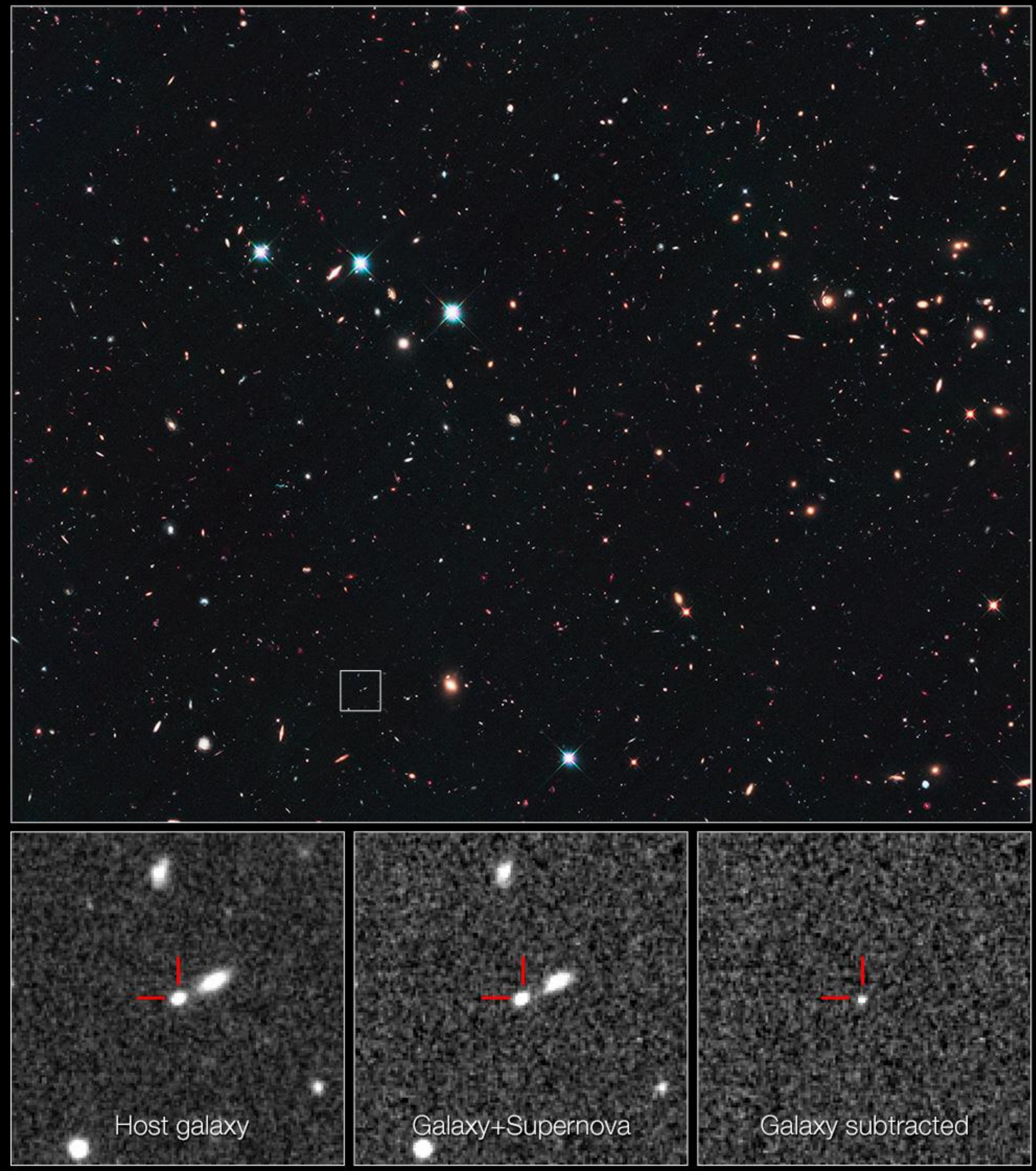
SN UDS10WiL

The farthest known SN 1a

z=1.914

5.02 Gpc (comoving)

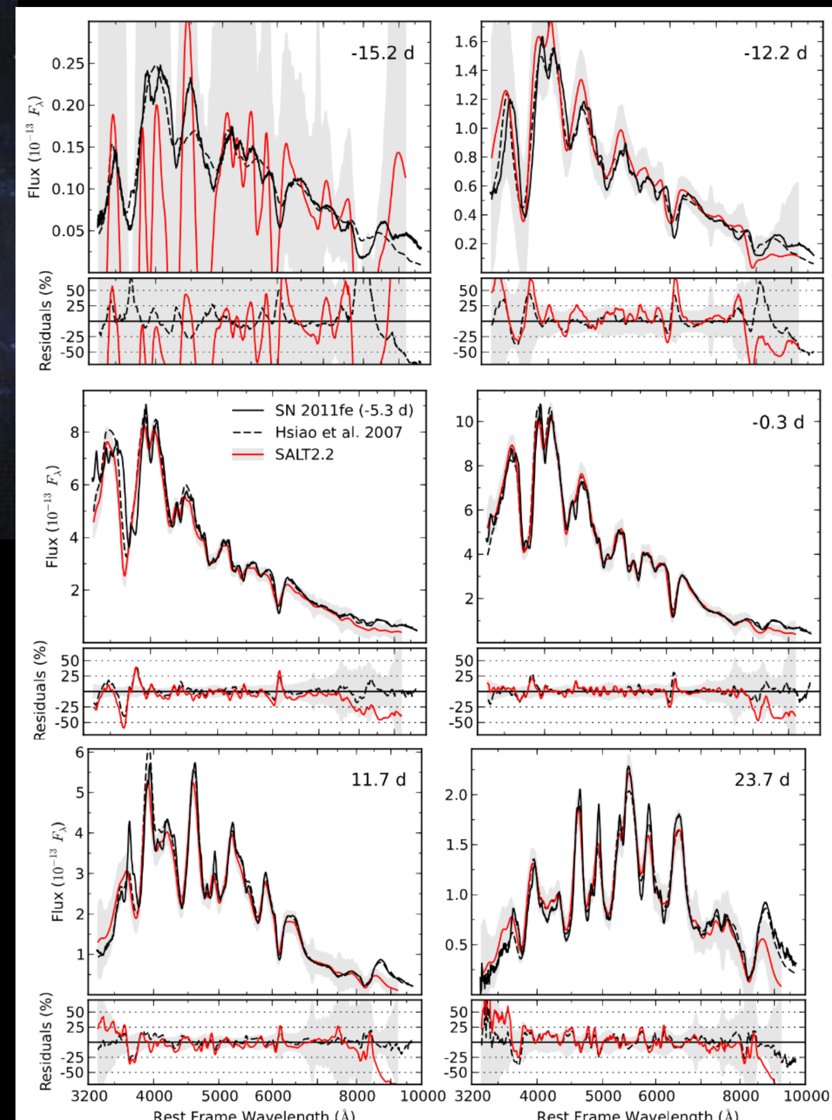
April 2013 with the Hubble



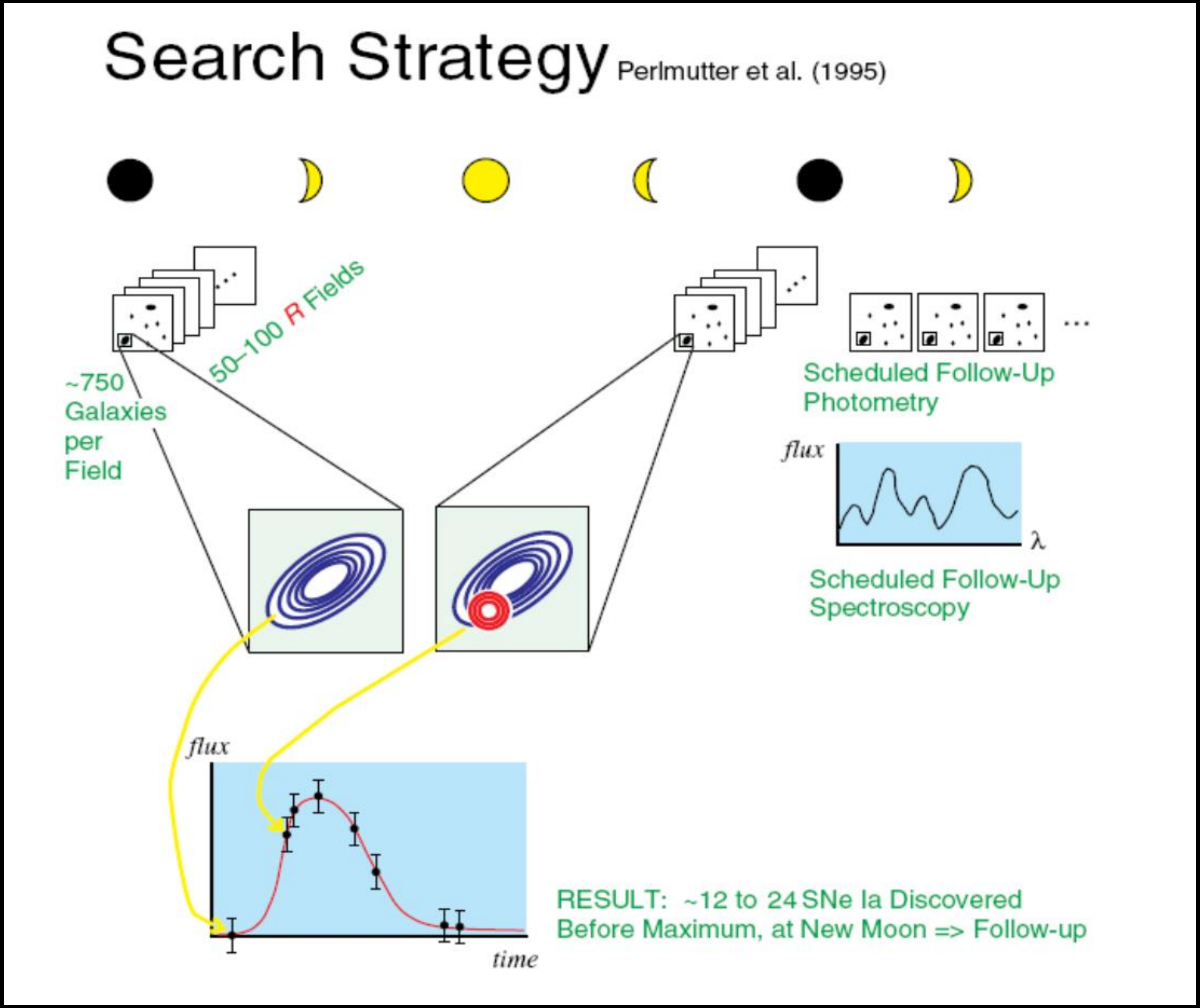
SN2011ef

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

arXiv:1302.1292 [astro-ph]



Estrategy to search for supernovae



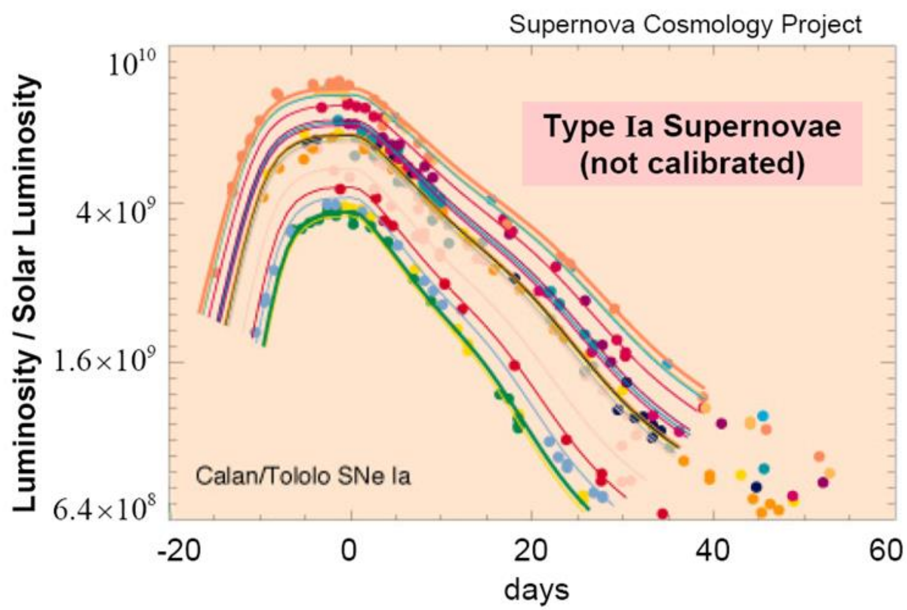
Rolling Search: Observing systematically the same sky región

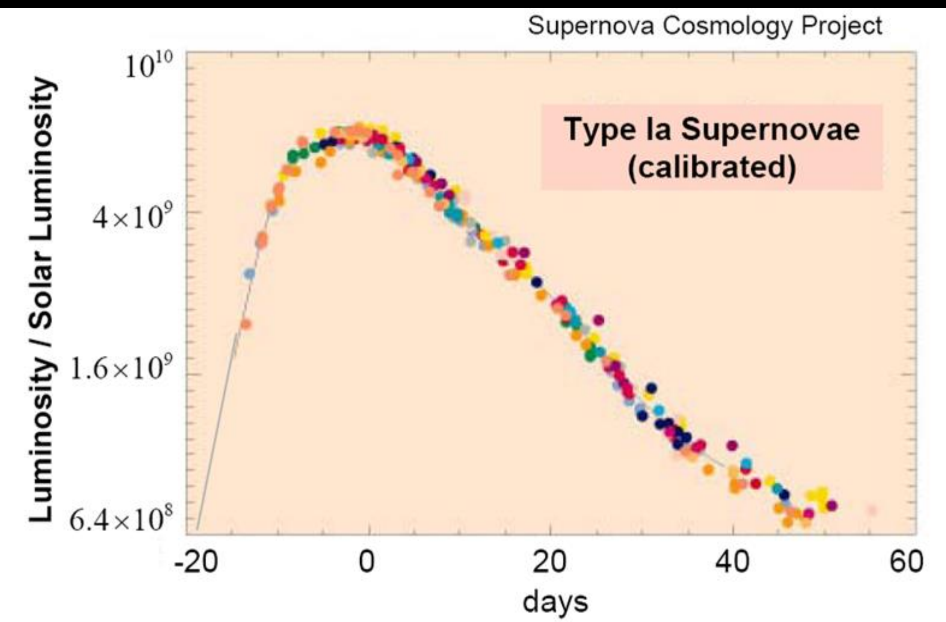
Clasification: Spectrum and colors

Measurement of light curves: In many colors

Supernovae brightness calibration

They are not standard candles, but stadarizable candles. Calibration through close supernovae (2011ef), cepheids and phenomenological models





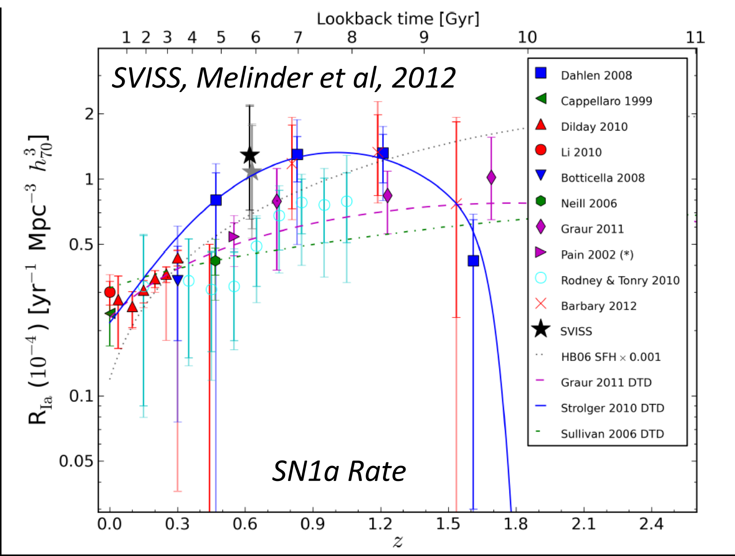
M~-19.5 (~5x10^{9} M⊙)

duration ~ 50 días (comoving!)

Universal specta and light curves

In every Galaxy type

~1 SN1a per Mpc^{3} and century



Systematic Errors

- Dust: Far supernovae can be dimmed by the presence of dust
- **Evolution:** The supernovae properties could change with time or the environment. Study Hubble diagrams for every Galaxy type.
- **Selection bias and k-correction:** The far supernovae thend to be brighter
- **Calibration and extinction:** Use nearby supernovae
- **Contamination:** How many non-1ª supernovae are selected?
- **Gravitational lensing:** The lensing effect can change the bright of the supernova

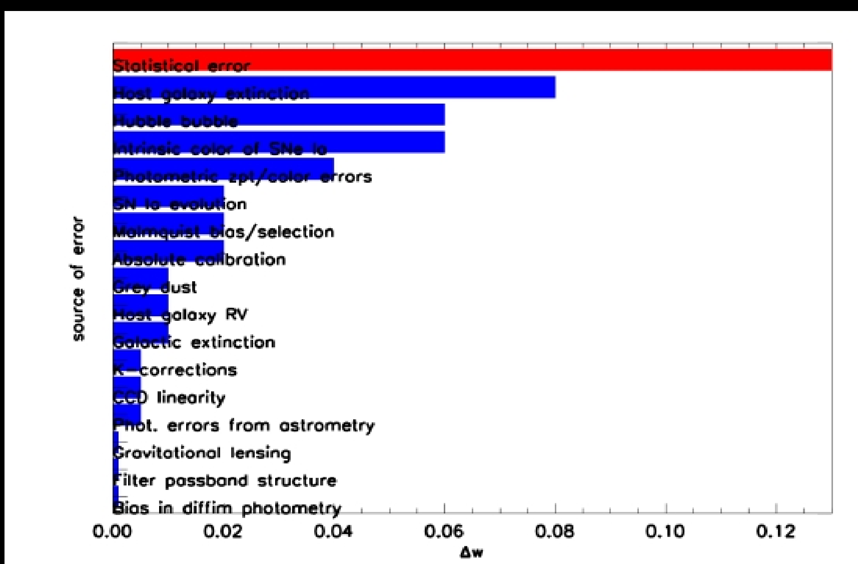


Table 6. Summary of uncertainties in the derived cosmological parameters. The dominant systematic uncertainty arises from the photometric calibration, itself dominated by the i_M and z_M band contributions.

Source	$\sigma(\Omega_M)$ (flat)	$\sigma(\Omega_{tot})$	$\sigma(w)$	$\sigma(\Omega_M)$ (with BAO)	$\sigma(w)$ (with BAO)
Zero-points	0.024	0.51	0.05	0.004	0.040
Vega spectrum	0.012	0.02	0.03	0.003	0.024
Filter bandpasses	0.007	0.01	0.02	0.002	0.013
Malmquist bias	0.016	0.22	0.03	0.004	0.025
Sum (*sys*)	0.032	0.55	0.07	0.007	0.054
Meas. errors	0.037	0.52	0.09	0.020	0.087
$U - B$ color (*stat*)	0.020	0.10	0.05	0.003	0.021
Sum (*stat*)	0.042	0.53	0.10	0.021	0.090

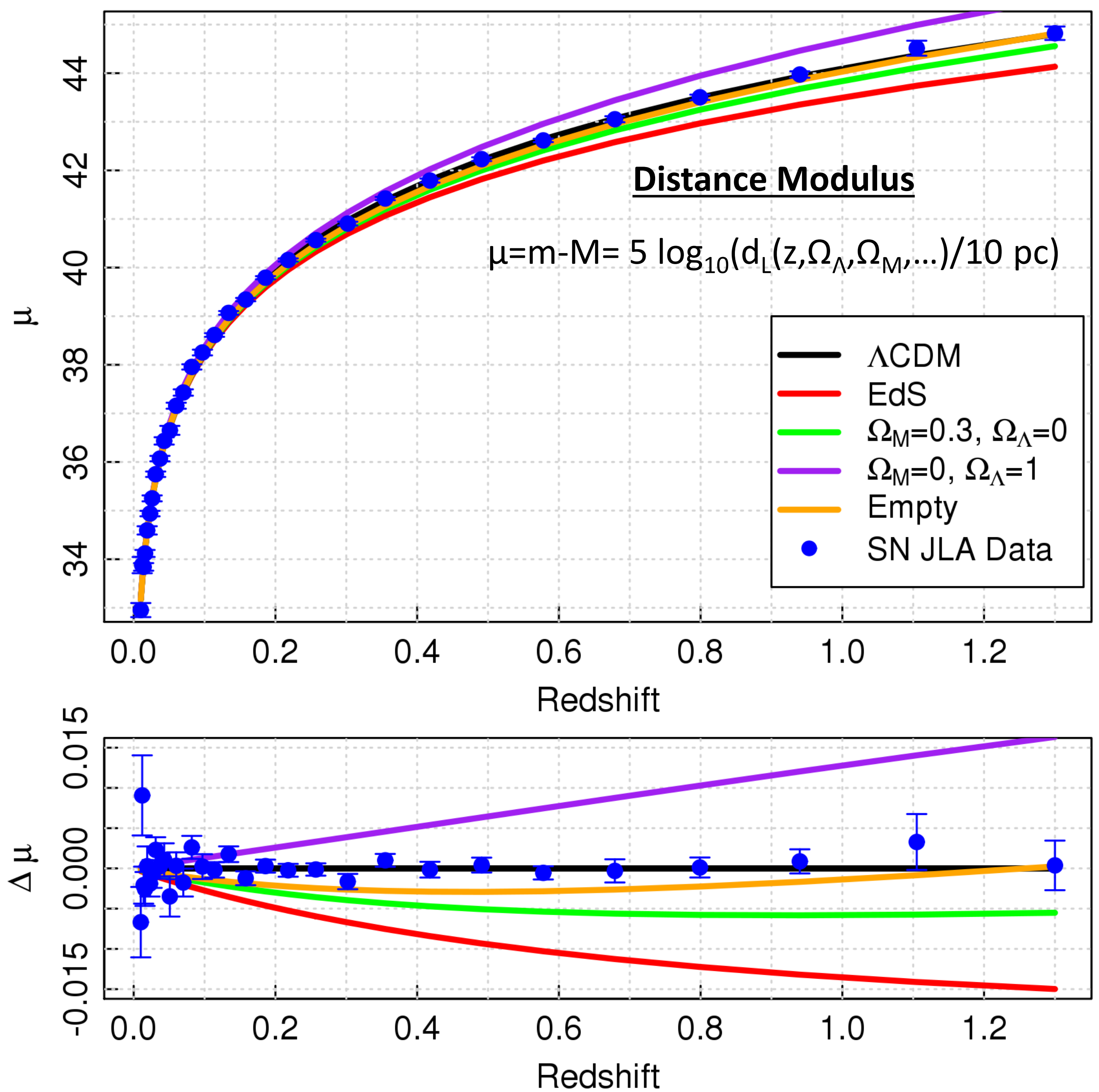
ESSENCE

SNLS

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

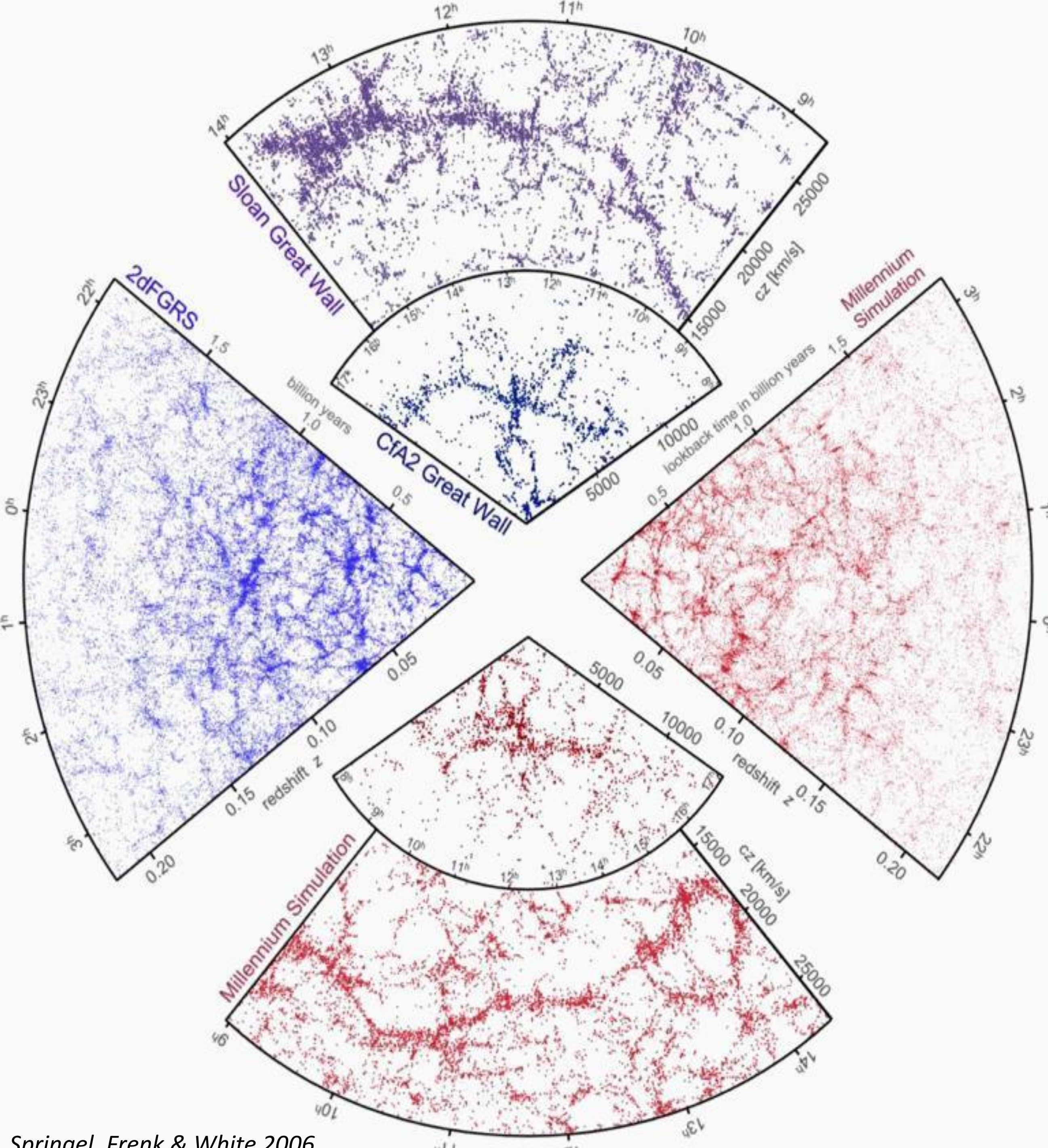
THE EXPANSION OF THE UNIVERSE IS ACCELERATING:

¡¡¡¡DARK ENERGY!!!!



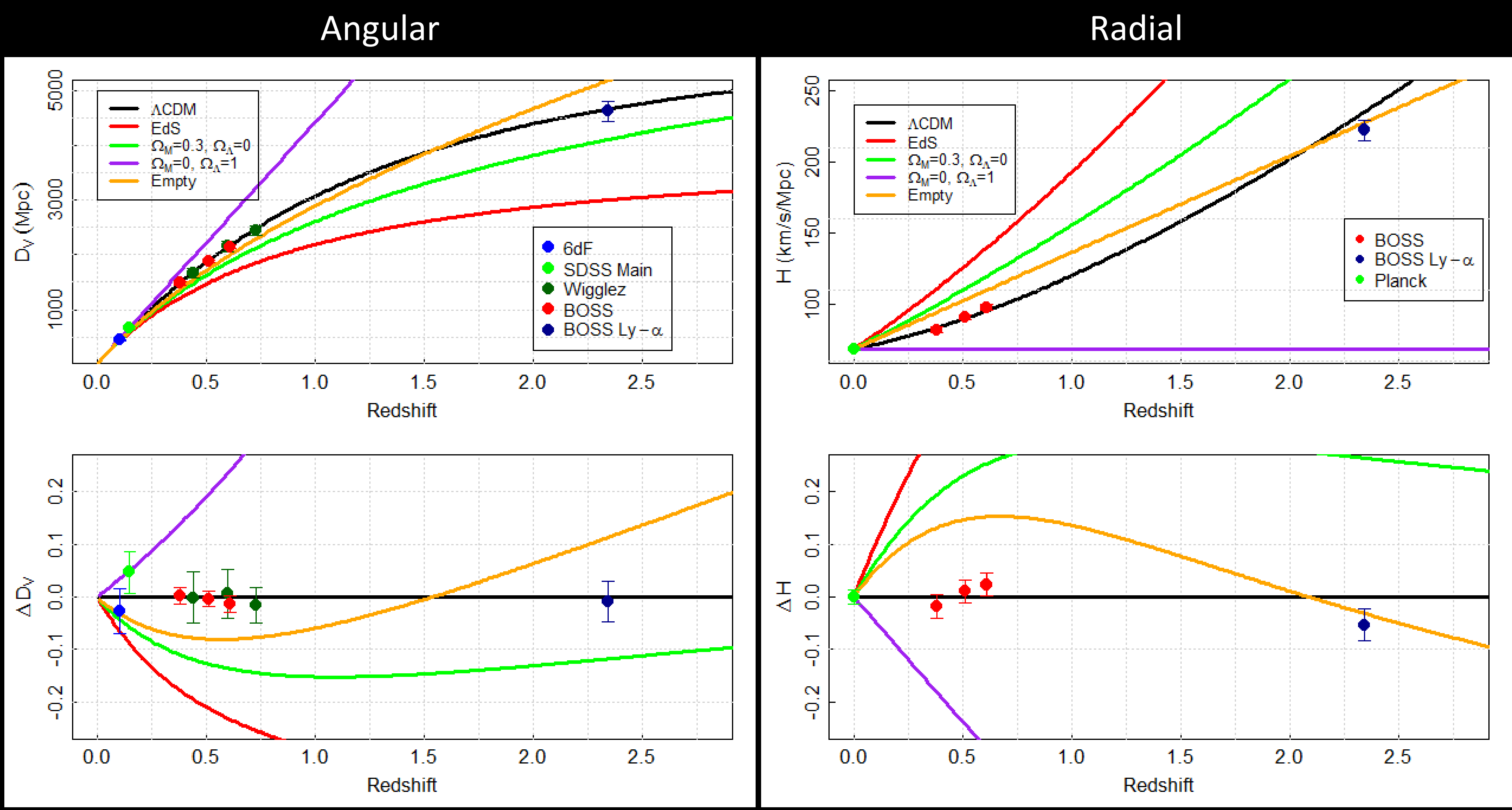
The Large Scale Structure (LSS) of the Universe

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



Springel, Frenk & White 2006

BAO as a standard ruler



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

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**

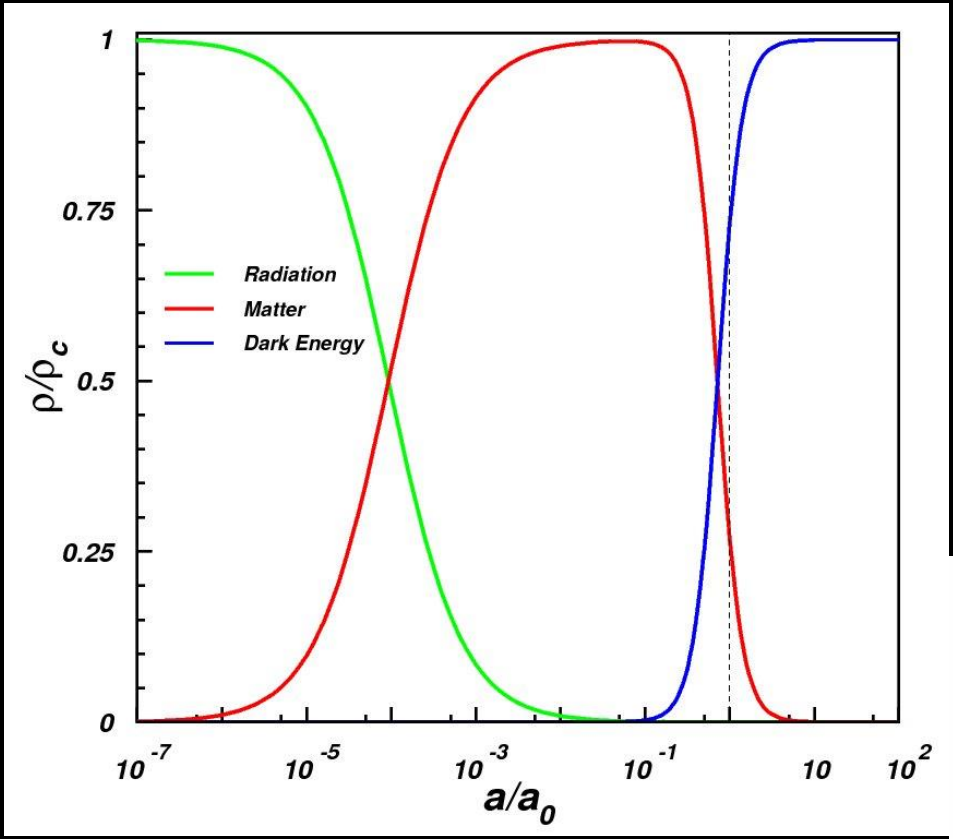
LSS+DYNAMICS → **DARK MATTER!** ; Ω_{DM} ~ 0.27

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

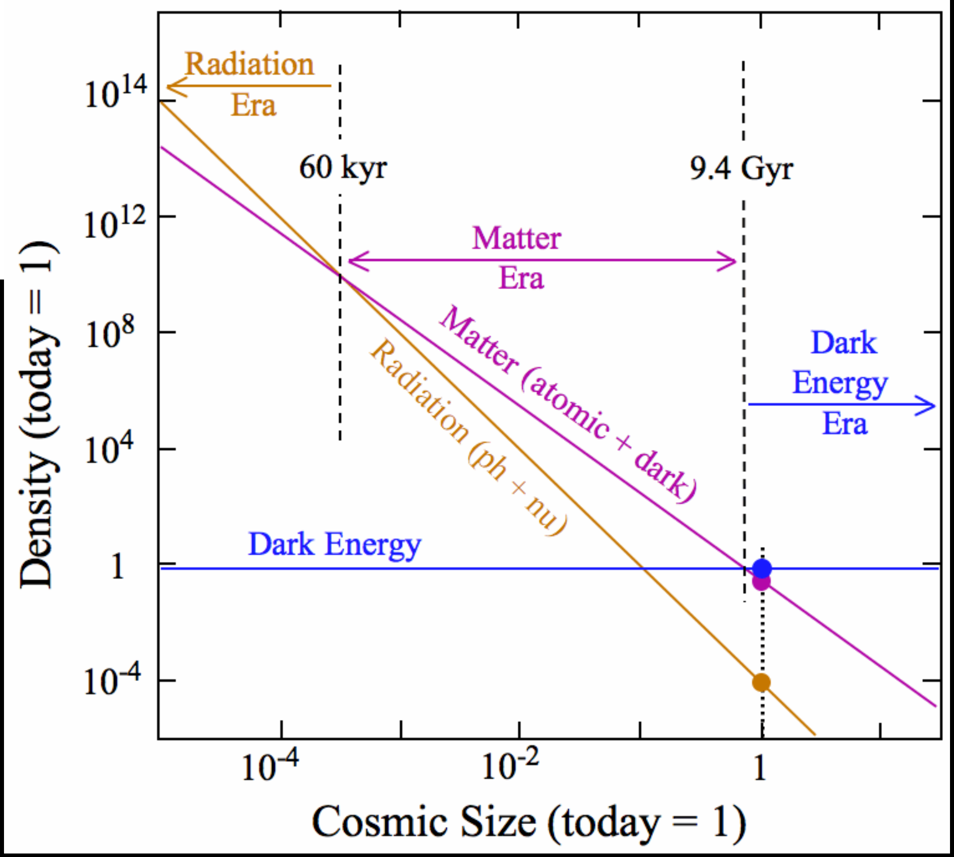
- Large scale homogeneity
- Hubble Law
- Light elements abundances
- Existence of the CMB
- Fluctuations of the CMB
- LSS
- Stars ages
- Galaxy evolution
- Time dilation of the SN brightness
- Temperature vs redshift (Tolman test)
- Sunyaev-Zel´dovich Effect
- Integrated Sachs-Wolf effect
- Galaxies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

Universe History

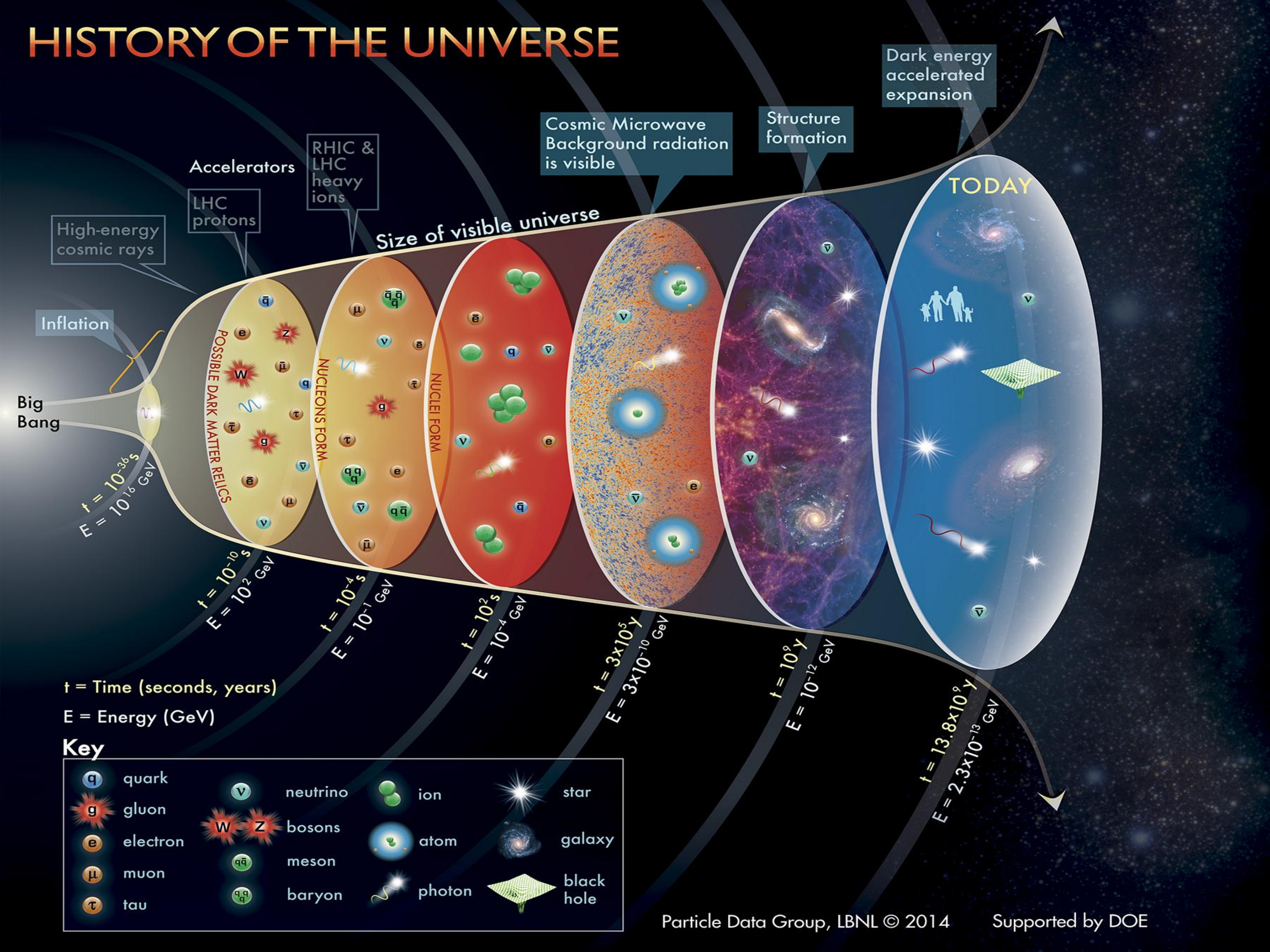
Era	Physics Processes	t	z	T	Radius
Planck	Quantum Gravity	$<10^{-43}$ s			
Inflation	Inflation, baryogenesis				
Radiation	EW phase transition	$\sim10^{-12}$ s	10^{15}	100 GeV	5×10^{-5} ly (asteroids)
	QCD phase transition	$\sim10^{-6}$ s	10^{12}	150 MeV	0.04 ly
	Neutrino Decoupling	1 s	6×10^{9}	1MeV	8 ly (Sirius)
	e+ e- annihilation	6 s	2×10^{9}	500 keV	23 lyr
	BBN	3 min	4×10^{8}	100 keV	115 lyr
	matter-radiation equality	60000 yr	3200	0.75 keV	15 Mlyr
Matter	Recombination	260 kyr	1400	0.33 eV	33 Mlyr
	CMB Decoupling	380 kyr	1100	0.25 eV	42 Mlyr
	Reionization	~250 Myr	~20	~5 meV	3 Glyr
	matter-dark energy equality	9 Gyr	0.4	0.33 meV	33 Gly
Dark Energy	today	13.8 Gyr	0	0.24 meV	46 Gyr



relative densities



absolute densities


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
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meson
baryon
ion
atom
photon
star
galaxy
black hole
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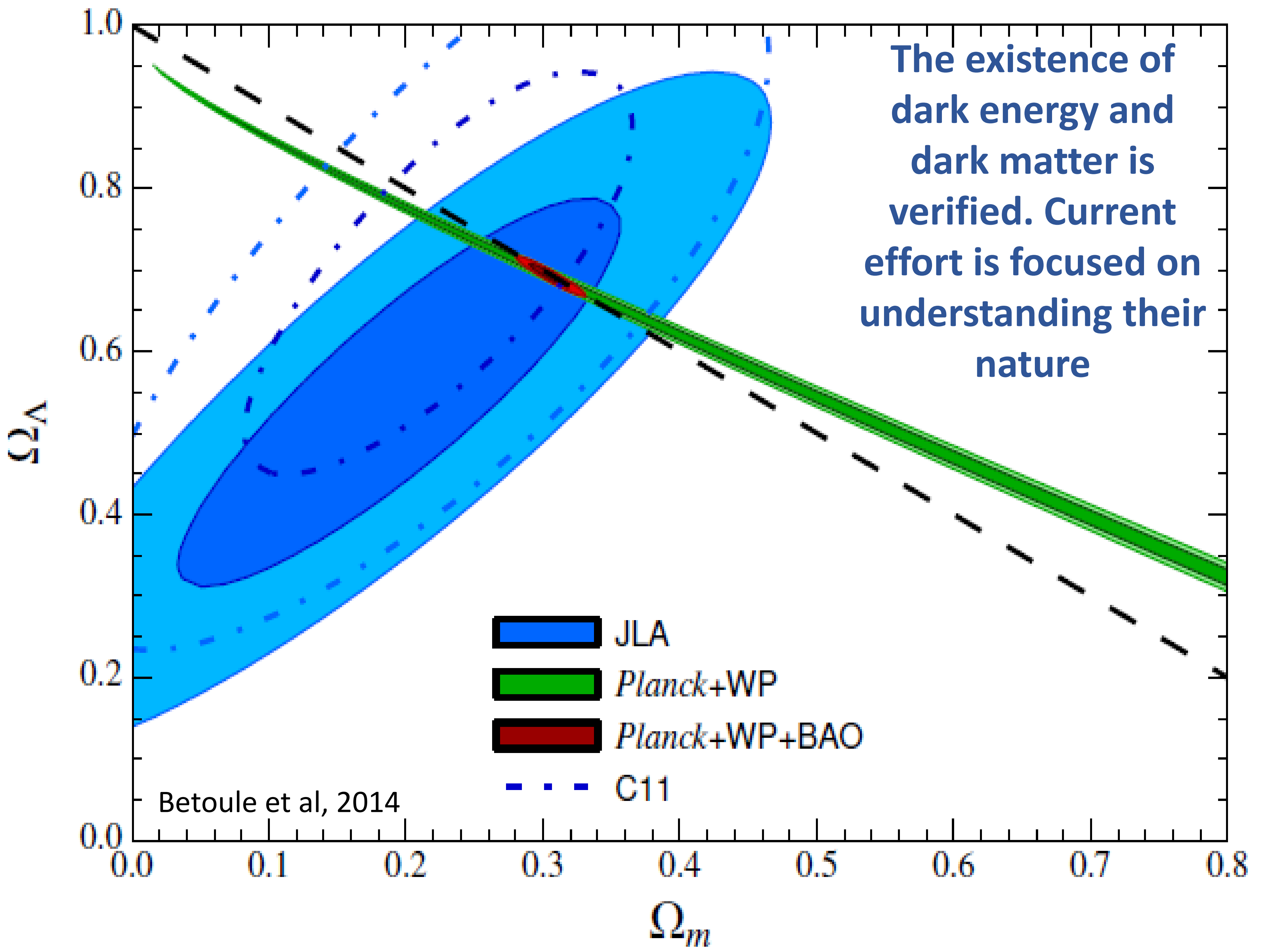
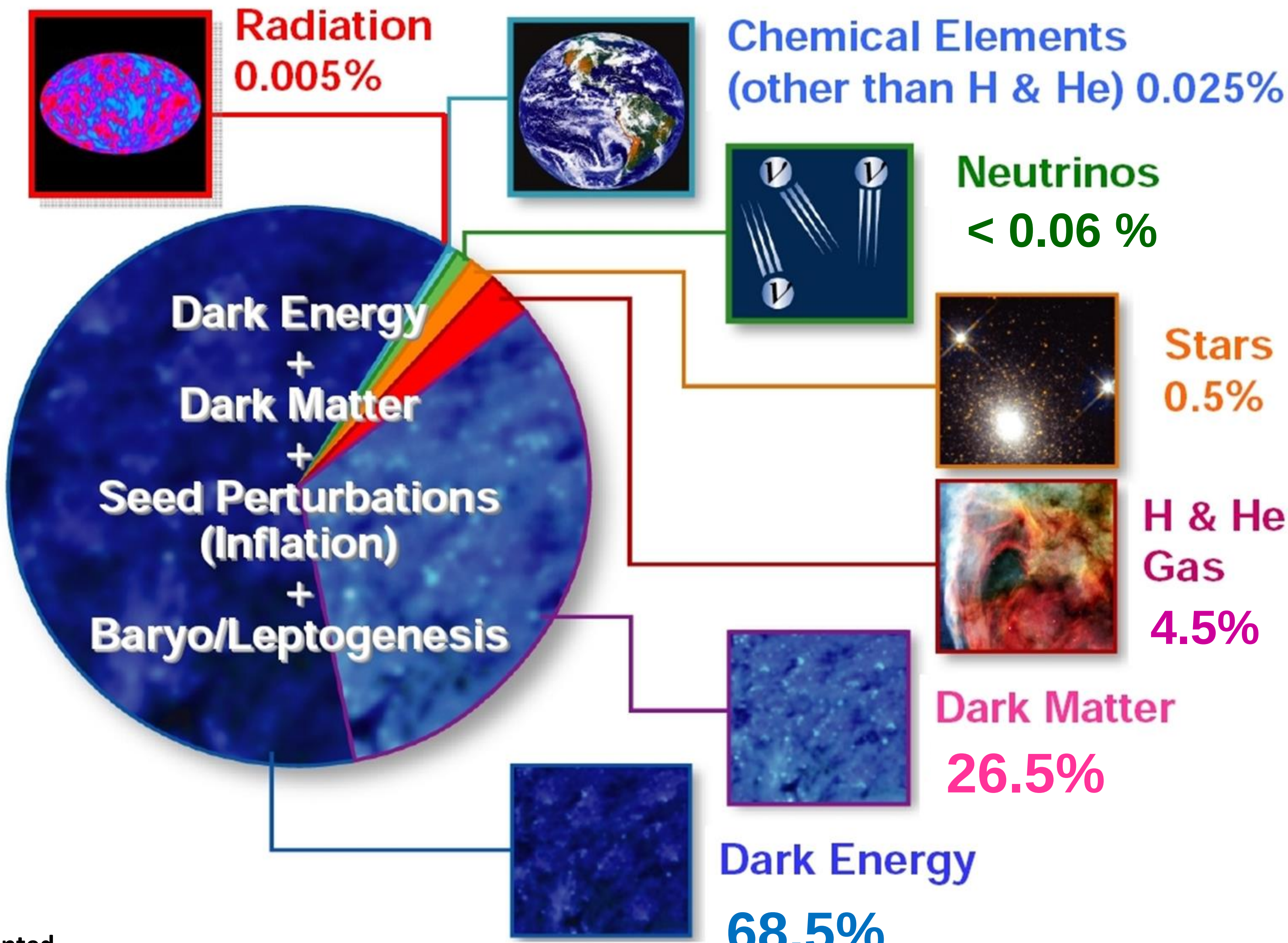
Supported by DOE



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
1.0
0.8
0.6
0.4
0.2
0.0
Ω_Λ
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Ω_m



Adapted
From Rocky Kolb

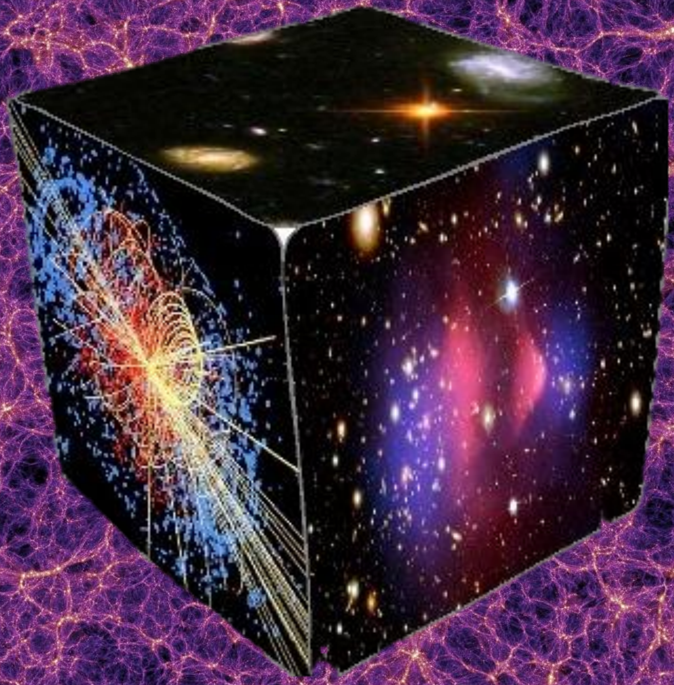
The Big Bang today: ΛCDM

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 beyond the standard model physics

DARK MATTER



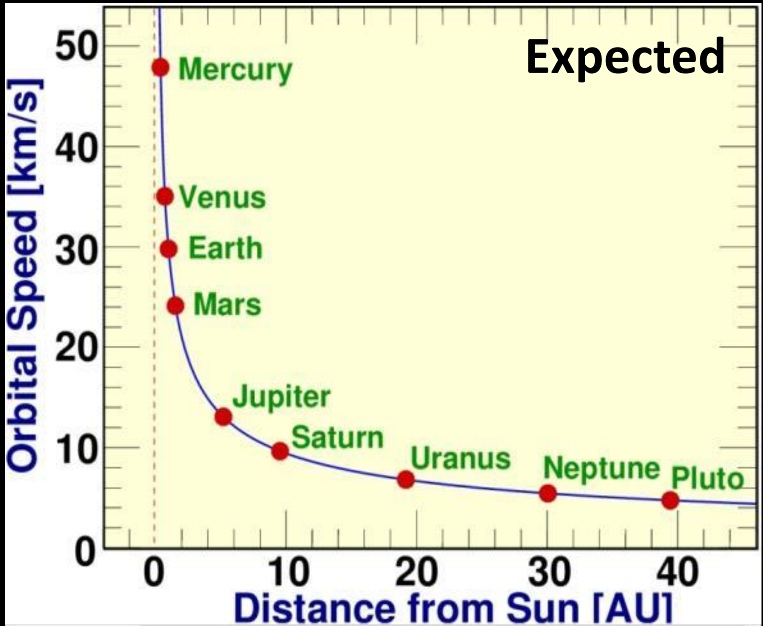
Observational Evidence

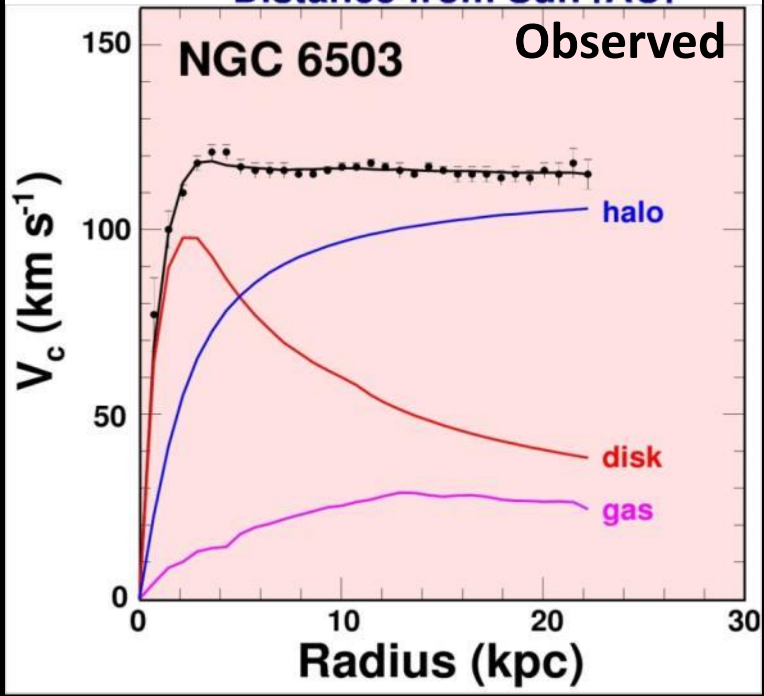
The existence of the dark matter is deduced from many different observations

The first evidence was obtained in the 30s, and since then it has only grown. Some of the main measurement that show the existence of dark matter are:

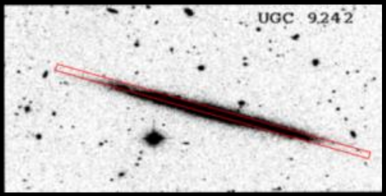
- **The rotation curves of spiral galaxies and the velocity dispersions of elliptical galaxies.**
- **The mass-luminosity ratio for Galaxy clusters**
- **Gravitational lenses**
- **The large scale structure of the Universe**
- **The primordial abundances**

Rotation Curves





Measuring the redshift for different zones of the Galaxy. One of the extremes recedes and the other approaches, and we can measure the rotation velocity

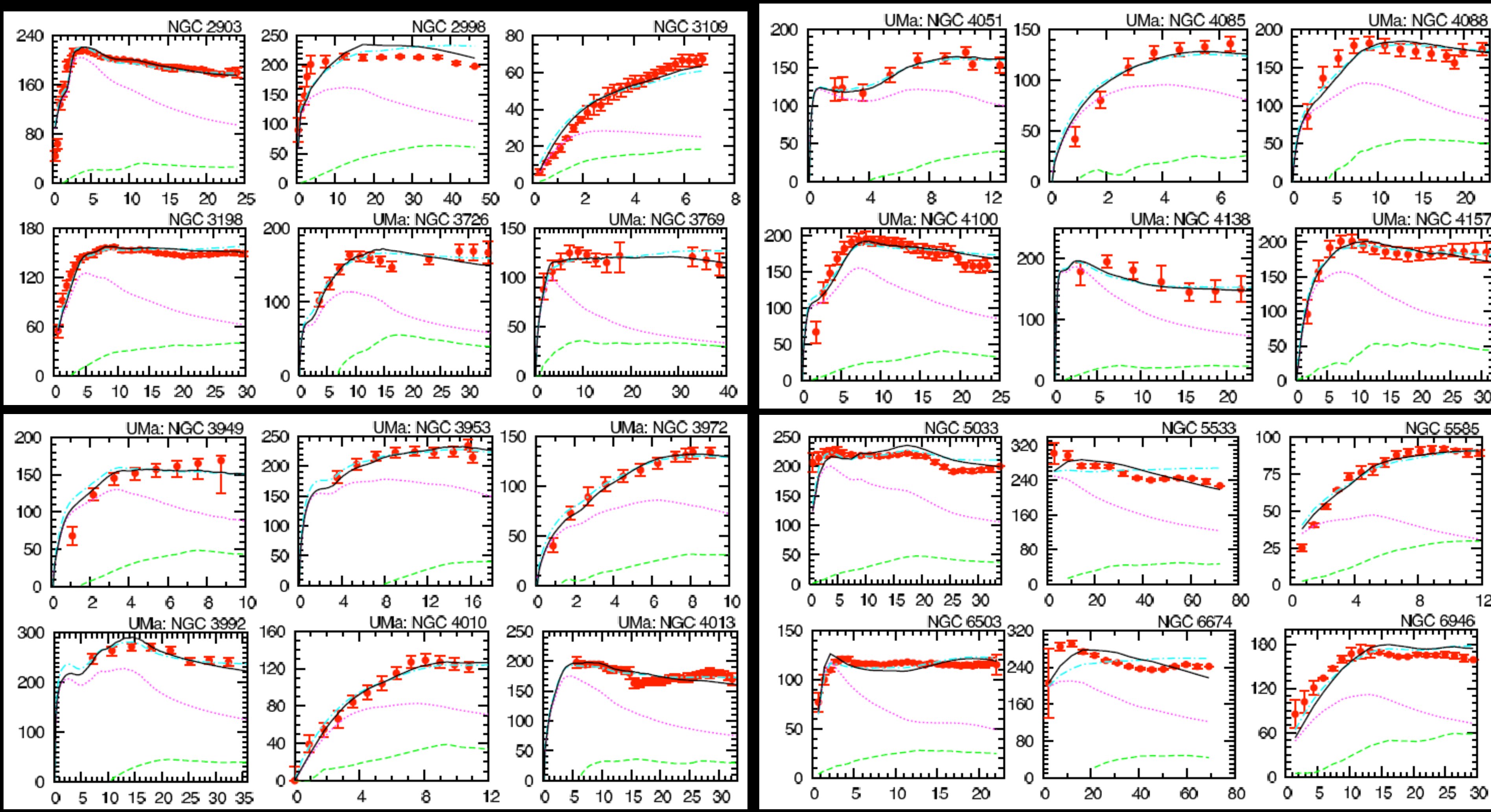


Galaxies do not follow the expected Newtonian (or Einstenian) gravity prediction from only their stars.

More (invisible) matter is needed in order to maintain the rotation speed

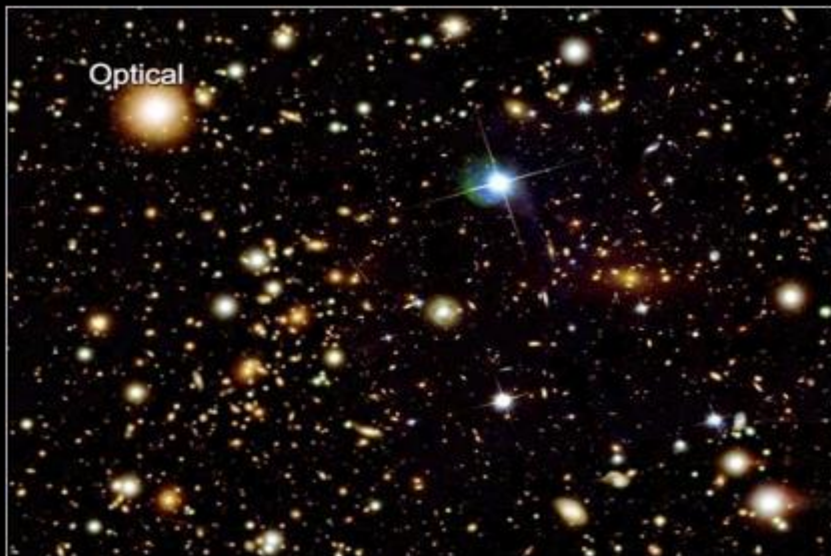
DARK MATTER!

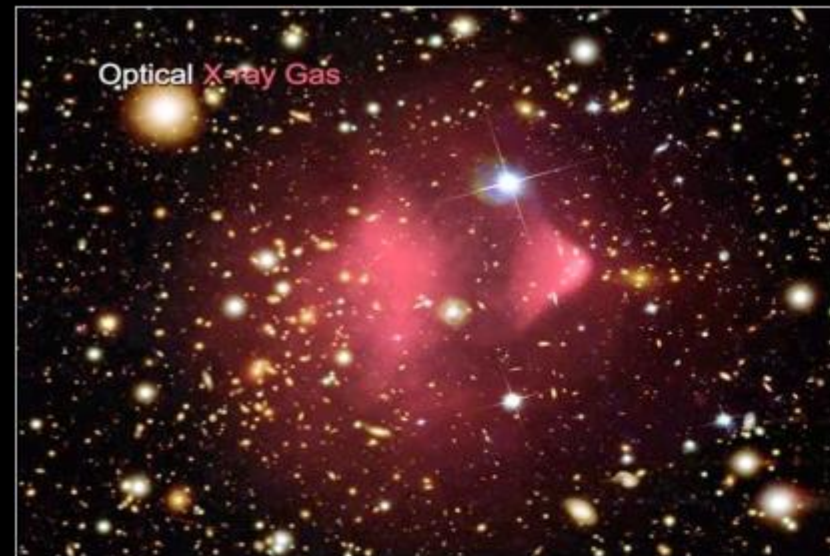
Rotation Curves



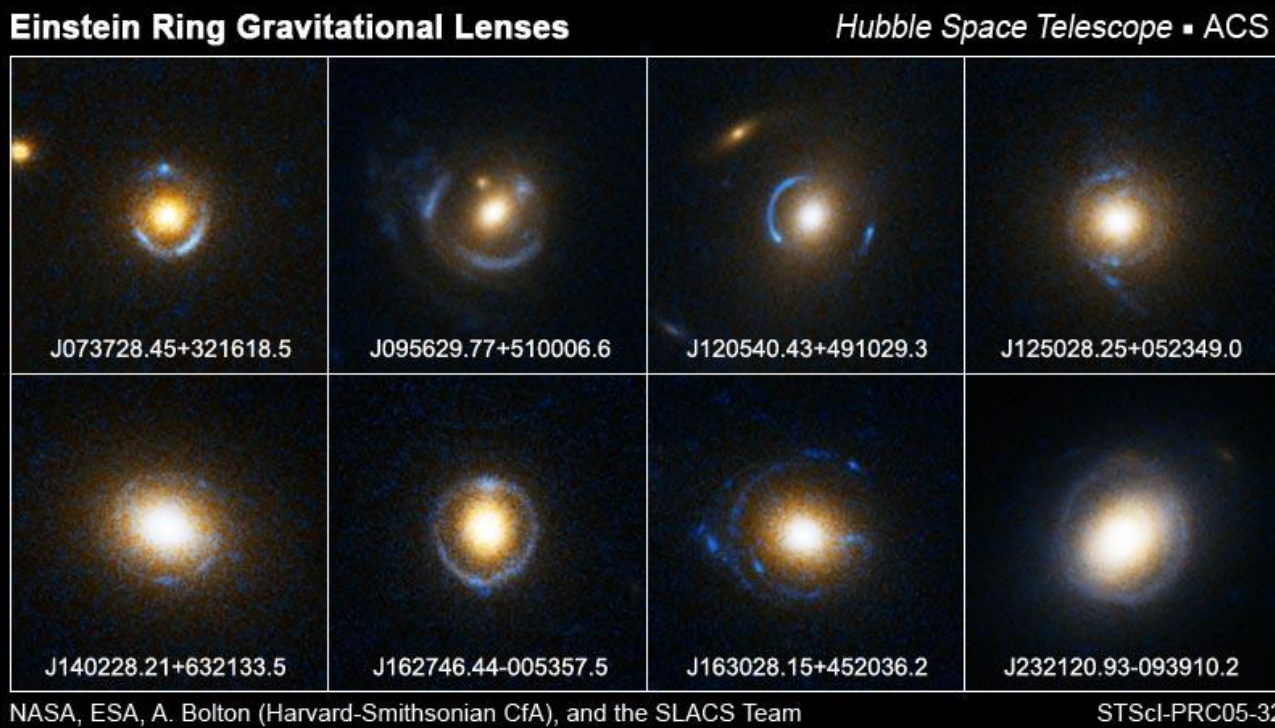
DARK MATTER!!!!

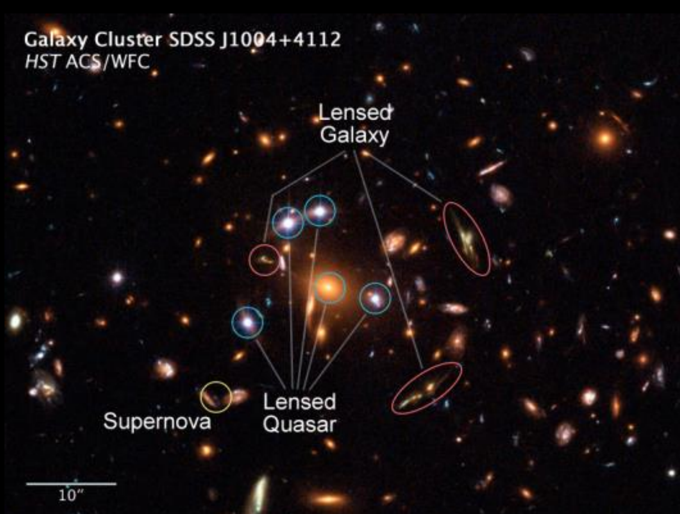
Total Mass >> Visible Mass

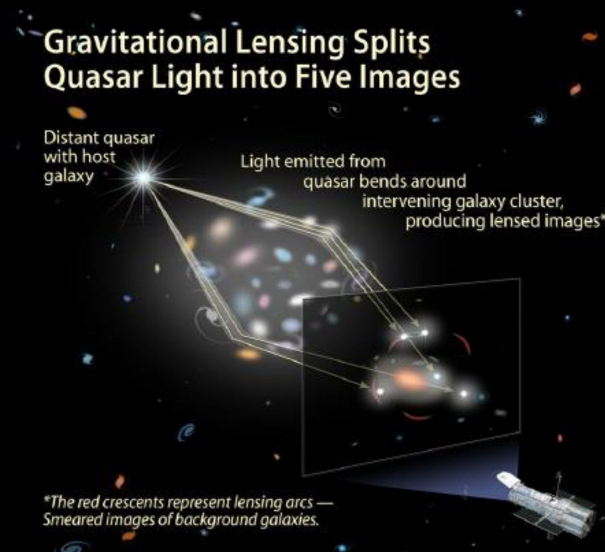




Gravitational Lensing

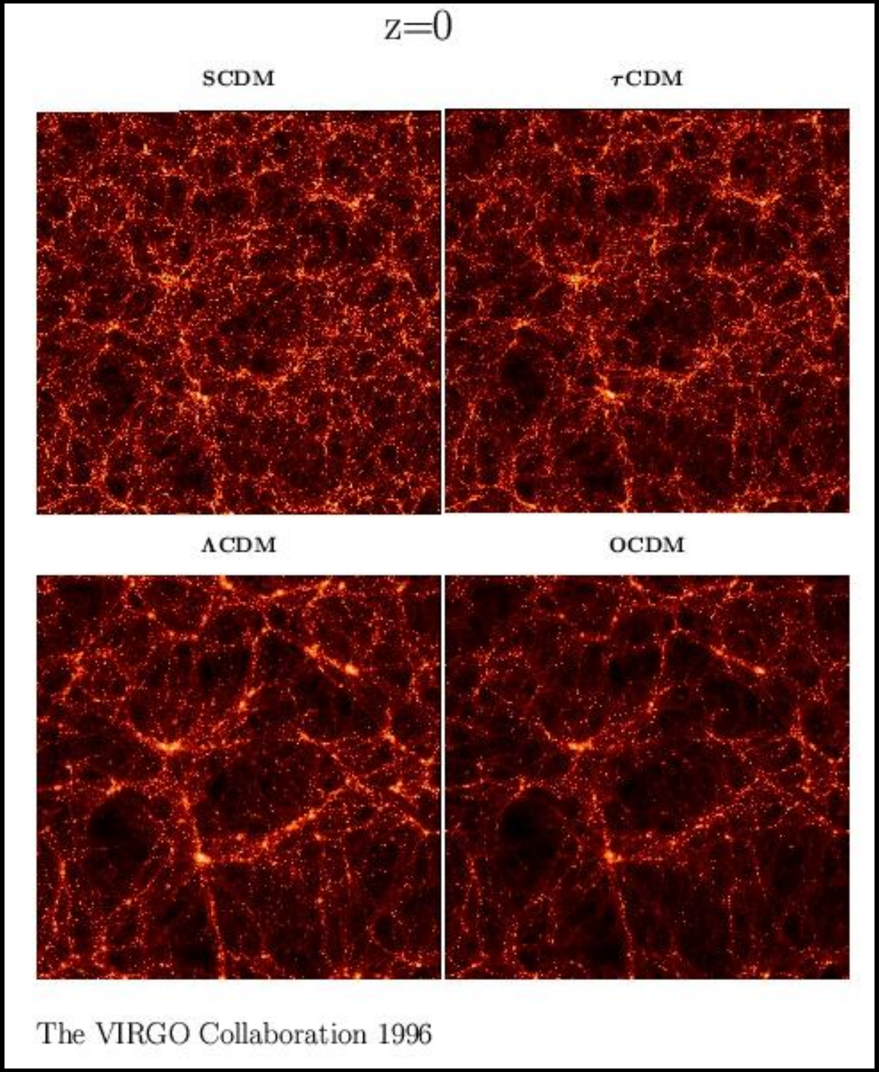


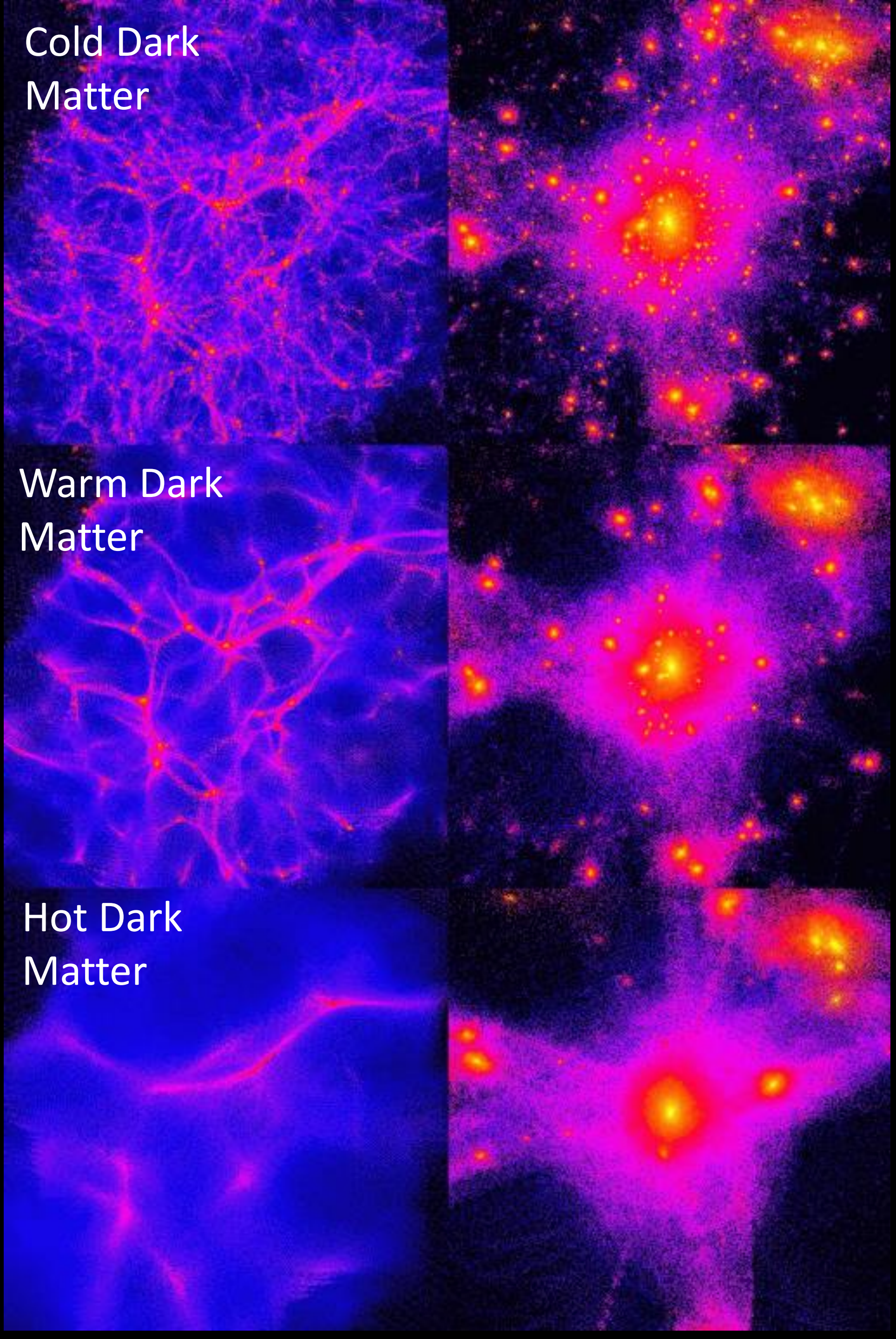




LSS

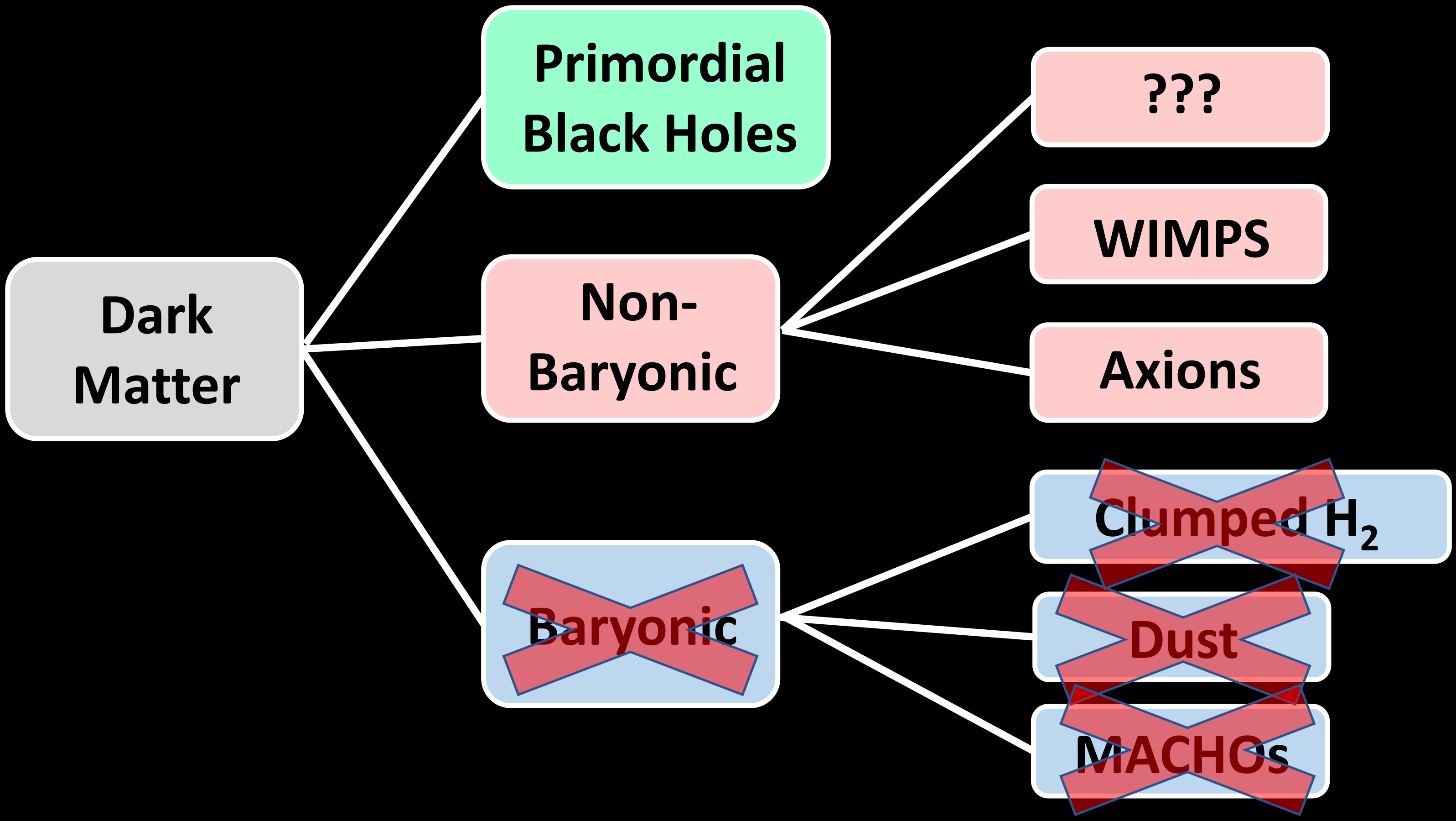
Different matter contents produce different structure properties



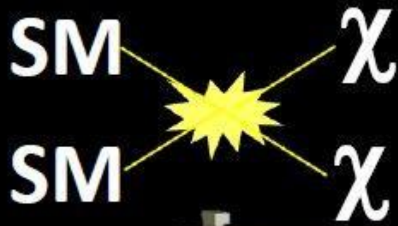


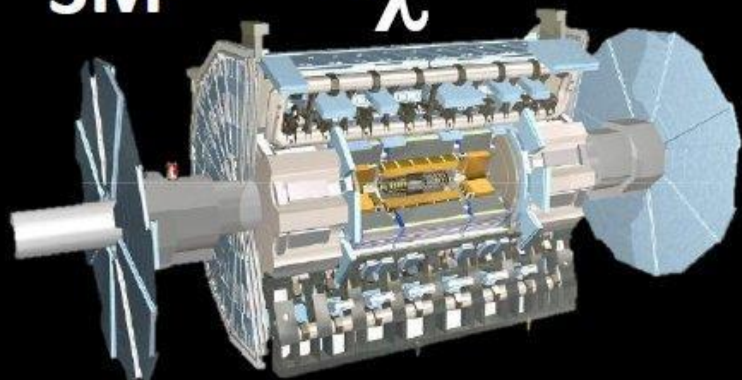
¿What do we know about dark matter?

The structure growth is bottom-up (clusters and superclusters are still forming), **THE DARK MATTER IS COLD**: ***non-relativistic, stable, neutral and very weakly interacting***



How to detect dark matter





INDIRECT DETECTION:

Measure gamma rays, neutrinos, positrons, antiprotons, anti-deuterons, etc from DM annihilation

PRODUCTION:

Produce and measure DM from partcle colliders

DIRECT DETECTION:

Measure DM scattering off targets in detectors on Earth

Current Situation

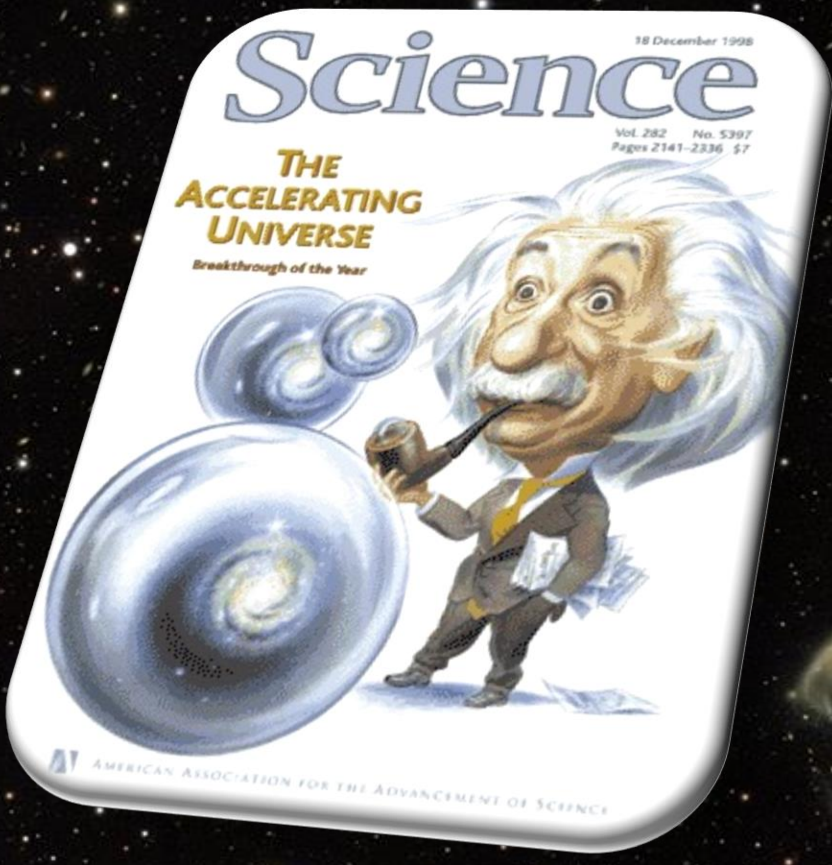
There is evidence of the existence of **COLD DARK MATTER**: Stable, neutral and non-relativistic. It Forms ~25% of the Universe density

If they are WIMPs, the local abundance is ~0.4 GeV/cm^3
For m_{WIMP}~100 GeV, around 10 WIMPs per year do interact with a human body
For m_{WIMP}~10 GeV, around 10^5 WIMPs per year do interact with a human body

There is a huge international scientific effort to detect dark matter in the lab, but no signal has been observed

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

DARK ENERGY



What is dark energy?

The Discovery of the accelerated expansión of the Universe (1998) was a huge surprise, since the expectation was exactly the opposite due to the gravity action (attractive and non repulsive)

The dark energy is the mechanism that causes the accelated cosmic expansión

The Einstein´s Cosmological Constant

(A new field of force (“quintaessence”), 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.

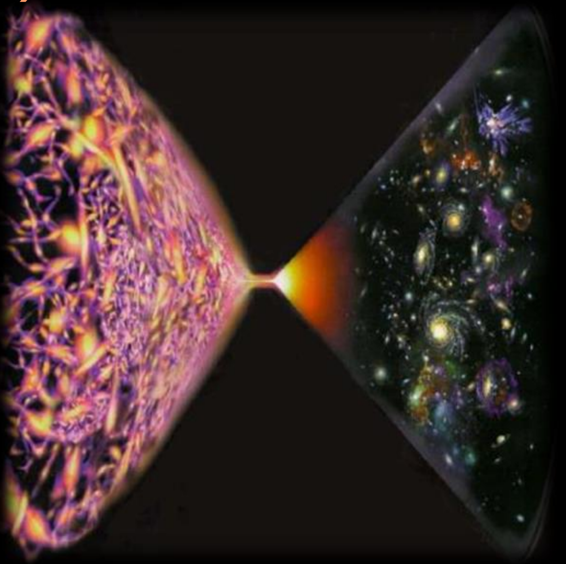
w= -1 with ~10% precision assuming flat universe and constant w

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

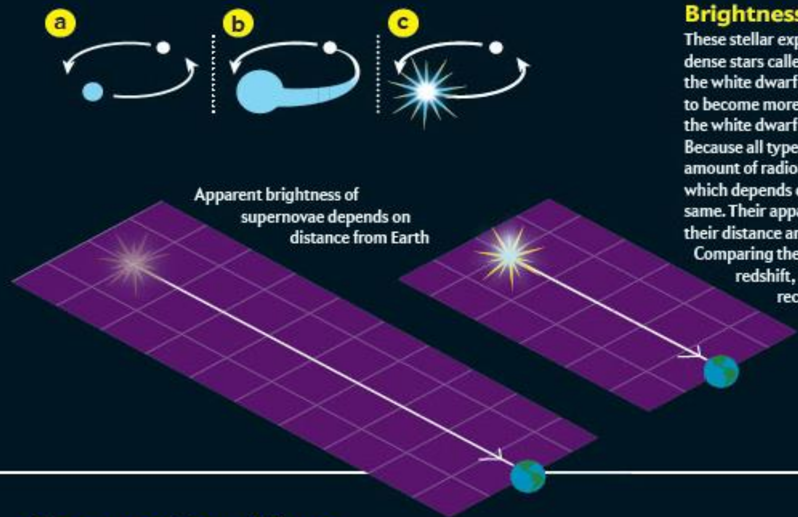
$$\rho_\Lambda \sim M^4_{Planck} \sim 10^{120} \text{ x } (10 \text{ meV})^4$$



Methods to study dark energy

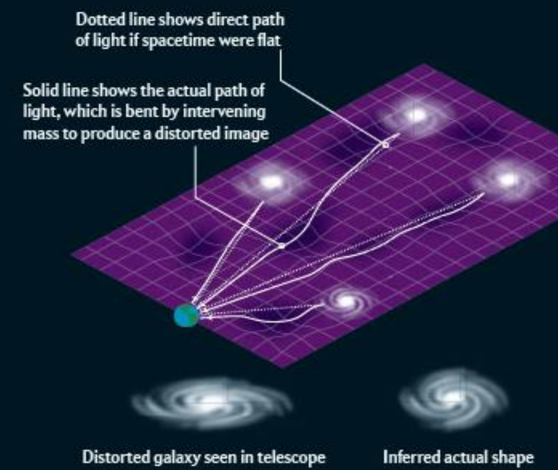
Brightness of Type Ia Supernovae

These stellar explosions result from particular types of dense stars called white dwarfs. In one possible scenario the white dwarf pulls matter off a companion star (a) to become more and more massive (b), until it reaches the white dwarf mass limit, triggering a supernova (c). Because all type Ia supernovae produce nearly the same amount of radioactive material, their intrinsic brightness, which depends on that material, is nearly always the same. Their apparent brightness, then, depends only on their distance and thus reveals how far away they are. Comparing the distances of supernovae with their redshift, a measurement of how fast they are receding from us, reveals how fast the universe was expanding at different cosmic epochs.



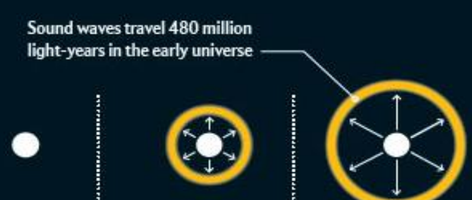
Extent of Gravitational Lensing

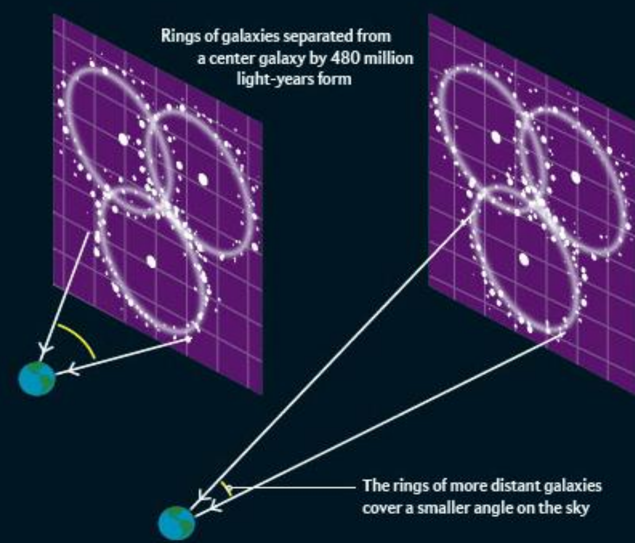
The light from distant galaxies will bend when it passes massive objects—such as galaxy clusters—on its way to Earth. This bending—an effect called gravitational lensing—causes the galaxies' shapes to appear distorted in the telescope. The experiment will measure the slight distortions of many galaxies to create a map of how mass is spread through space. The degree to which galaxies at different distances from us are gravitationally lensed will reveal the clumpiness of matter at different epochs of the universe.



Signatures of Sound Waves

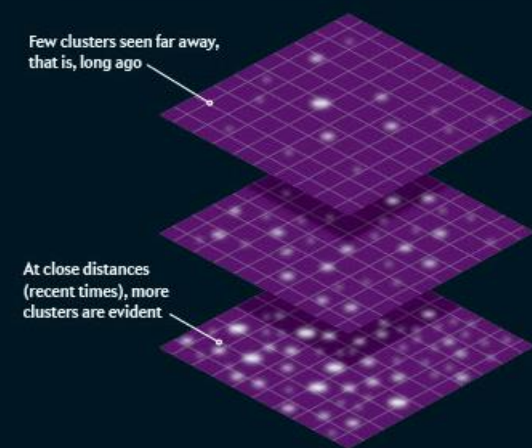
Sound waves emitted in the early universe traveled through space at nearly the speed of light until the cosmos had cooled enough for atoms to form. The distance covered by the waves up to that point—which corresponds to 480 million light-years today—made it slightly more likely that two galaxies would form with just that much space between them. This effect shows up as a slight excess of galaxies in a spherical shell with a radius of 480 million light-years from a given galaxy. On the sky, we see an overdensity of galaxies in an angular ring around the central galaxy. Because astronomers know the absolute radius of the ring, they can measure the angle on the sky the ring covers to infer the distance to the galaxies—the farther away they are, the smaller the angle. These distances, in turn compared with the galaxies' redshifts, map out the expansion history of the universe.





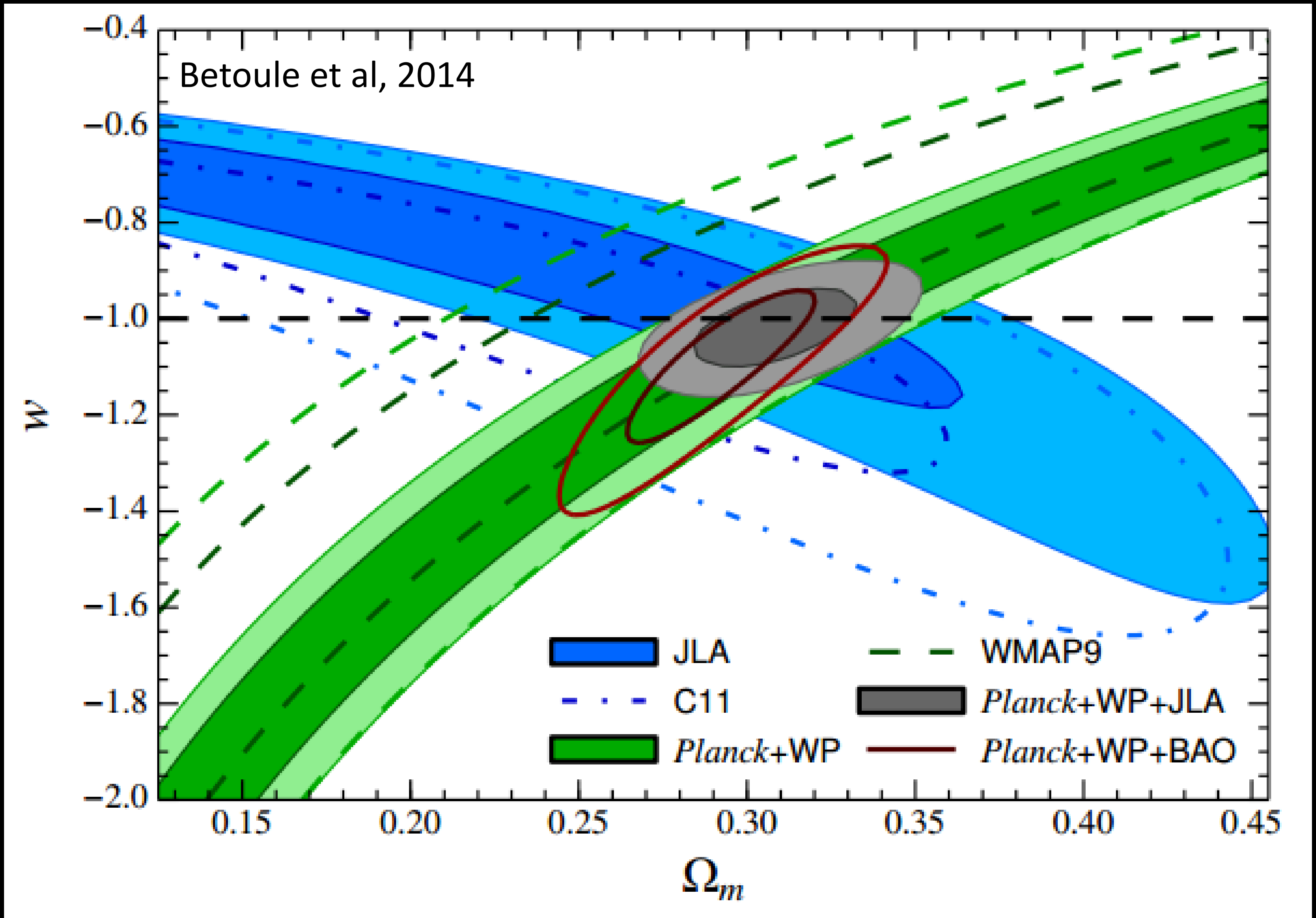
Clusters of Galaxies

Over time gravity pulls galaxies together into clusters, against the push of whatever is causing cosmic expansion to accelerate. The DES will hunt for tens of thousands of clusters out to billions of light-years away and compare the numbers of clusters seen nearby, corresponding to recent times, and far away, corresponding to long ago, to learn how fast galaxies have clumped together over time.



Current Situation

All observations are compatible with the dark energy being the cosmological constant, i. e., the vacuum energy



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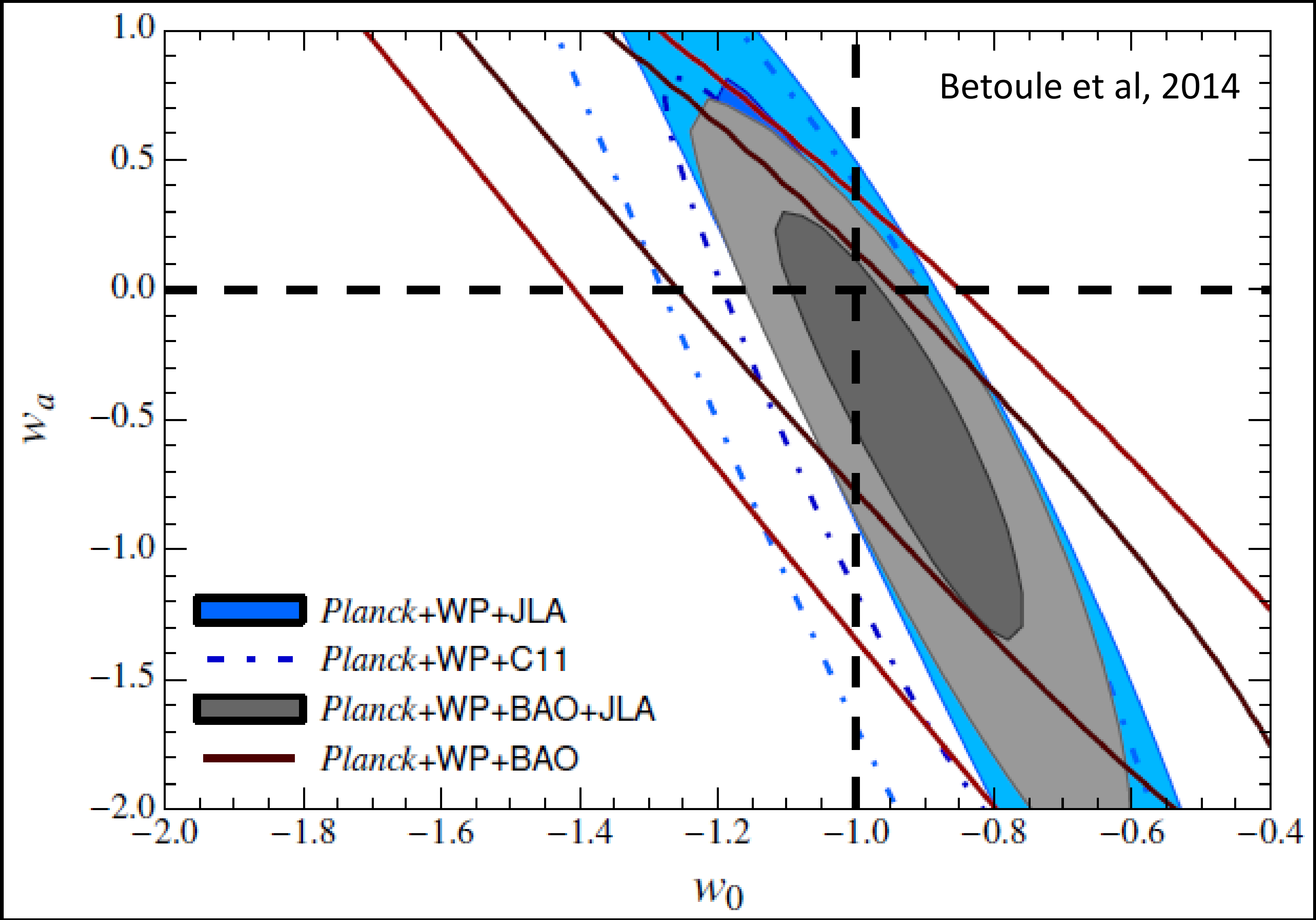
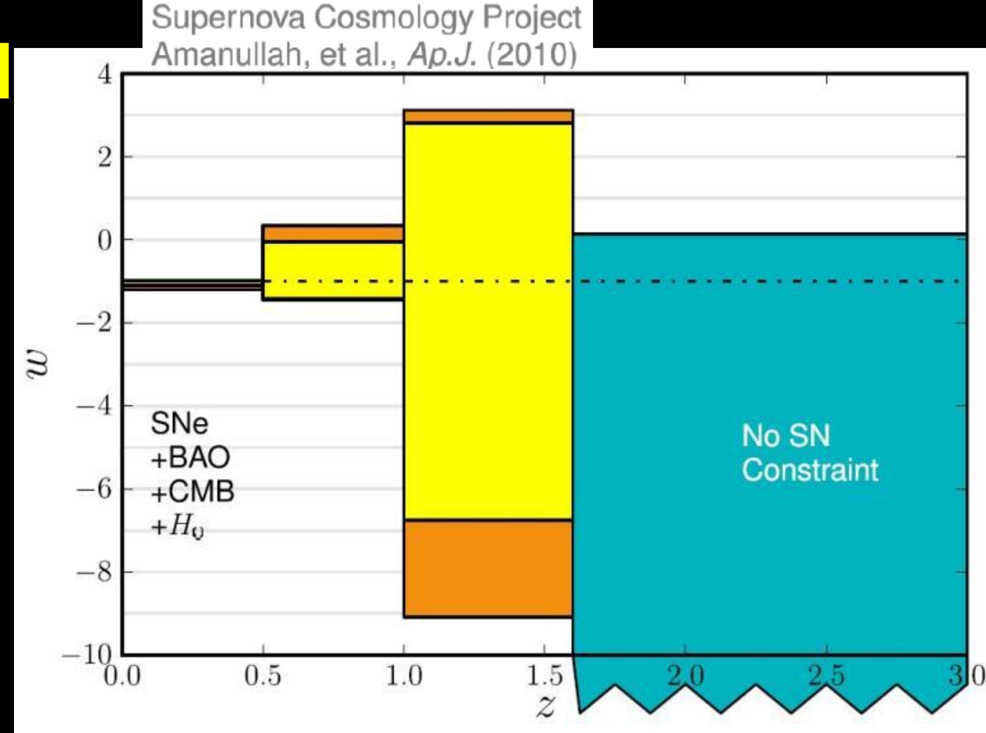


CURRENT SITUATION

Dark energy has been unequivocally detected for z<1

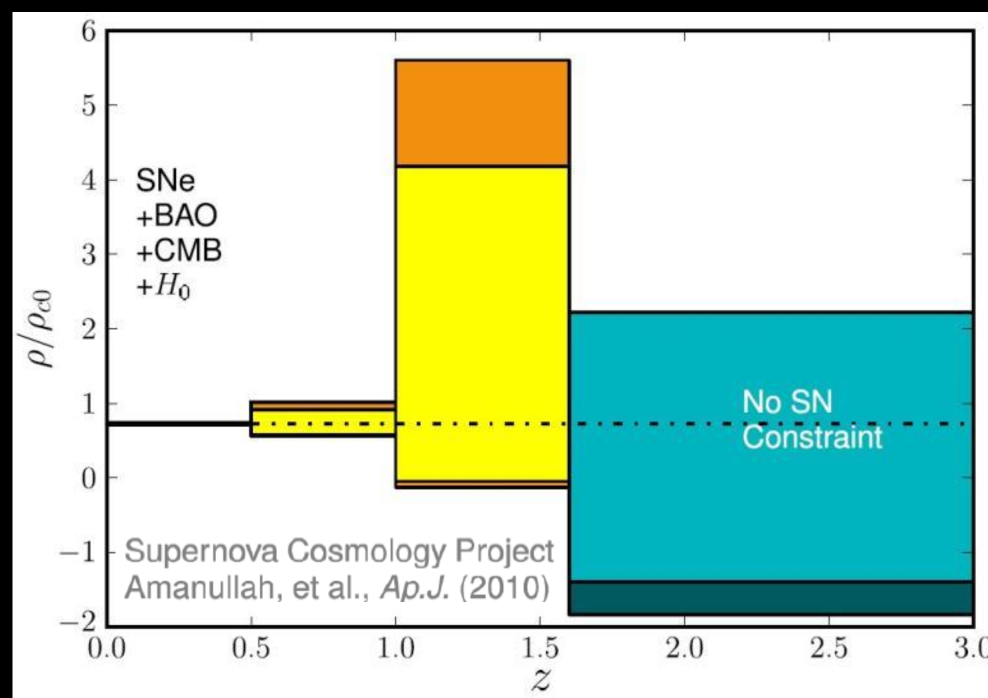
Current data are not sensitive for z>1



ΛCDM is an excellent description of all data.

There is still a long way to study the evolution with the redshift

WE NEED NEW AND MORE PRECISE DATA: HUGE GALAXY SURVEYS



The origin of the Universe

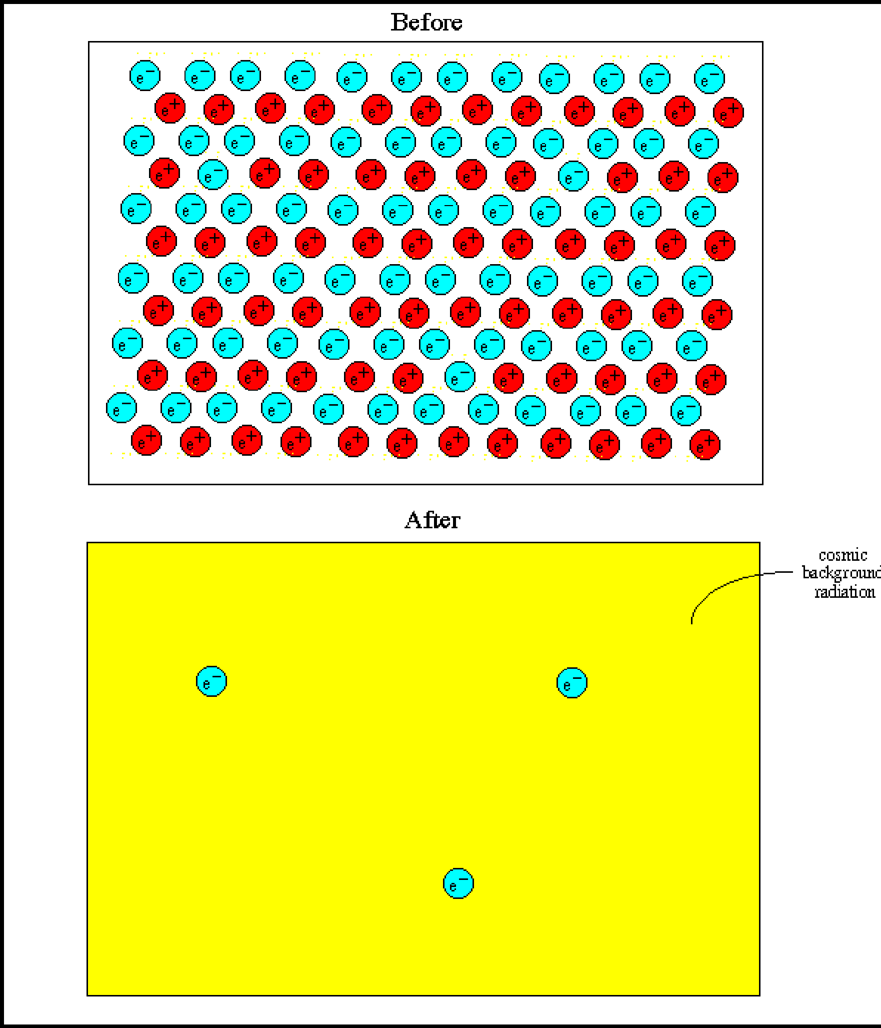
Baryogenesis: Why there is no antimatter?

The Universe is made of matter. Why there is no antimatter?

The number of baryons in the Universe, from BBN, is much smaller than the number of photons in the CMB,

$$n_B/n_\gamma = (6.1 \pm 0.3)\text{x}10^{-10} \text{ (measured)}$$

$$n_B/n_\gamma \sim 10^{-20} \text{ (Expected in the SM)}$$



Baryons are a small excess after annihilation with antibaryons

Sakharov Conditions:

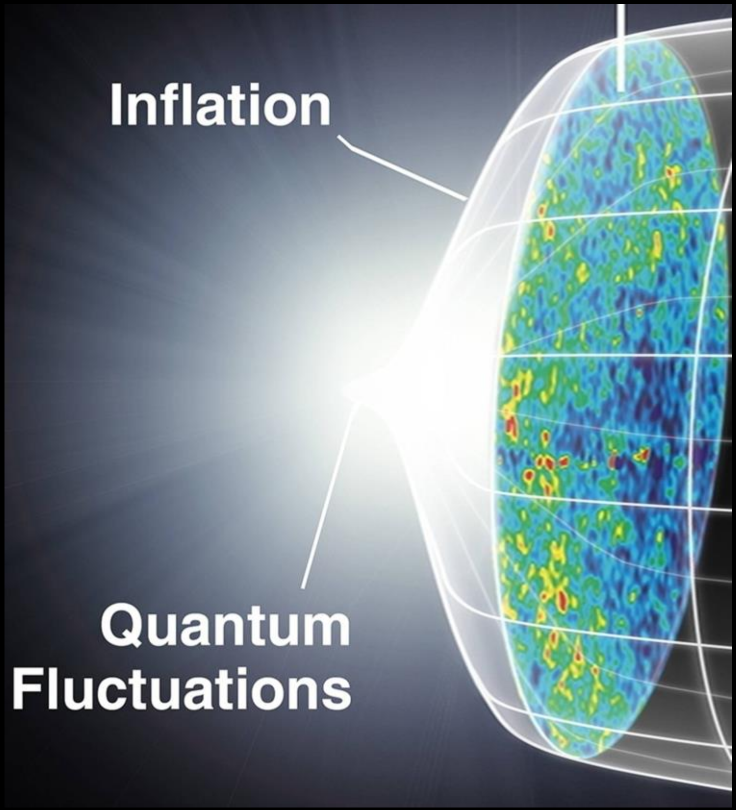
Violation of the Baryon number conservation

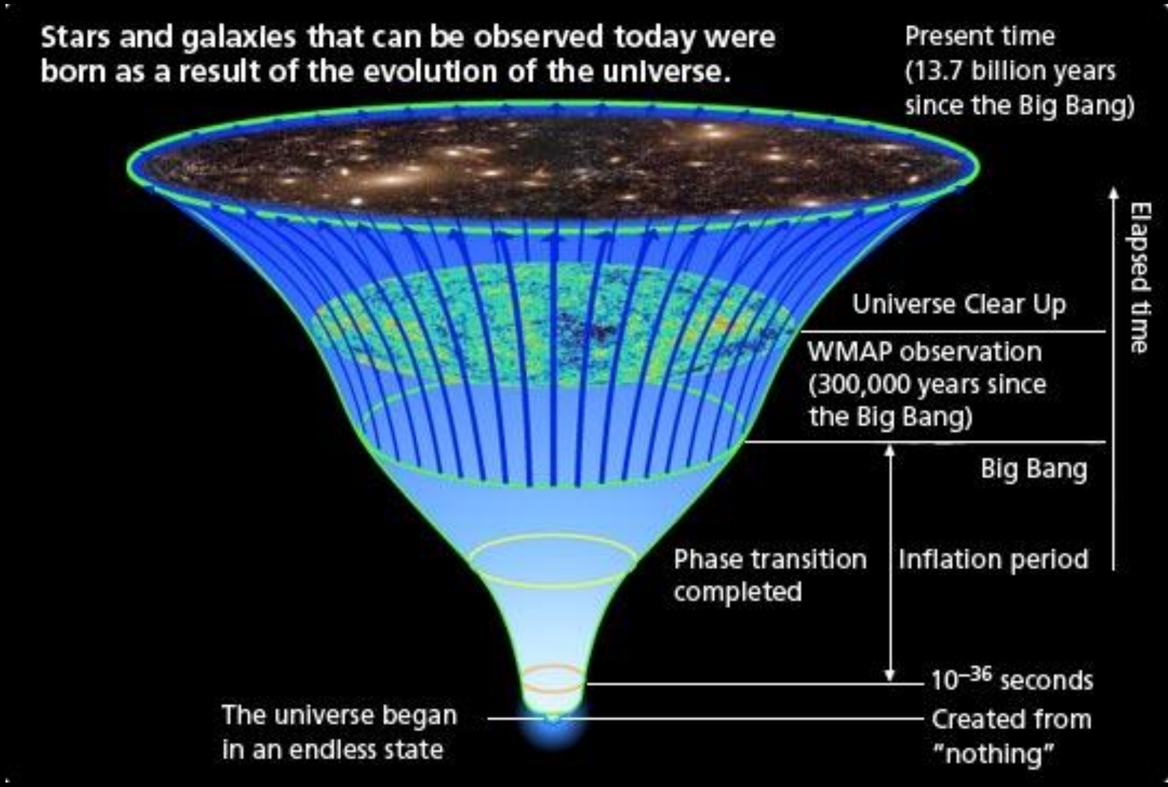
Violation of C and CP

No thermodynamical equilibrium

These conditions are verified by the Standard Model. But the CP violation is not enough. The baryogenesis requires new physics.

The cosmic inflation: the bang of the big bang

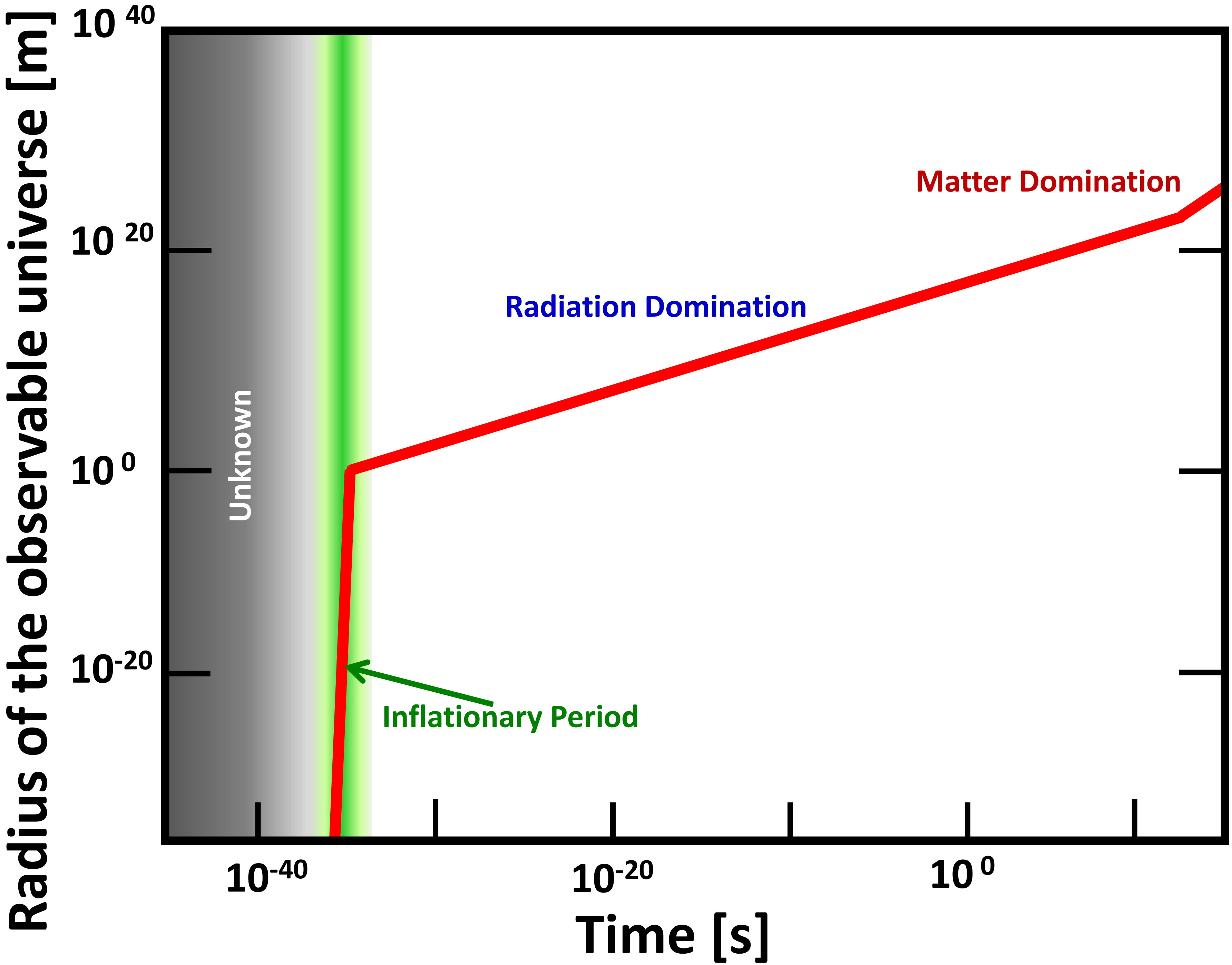




The third pillar of cosmology is the cosmic inflation

It solves some of the classical big bang problems: Homogeneity and flatness

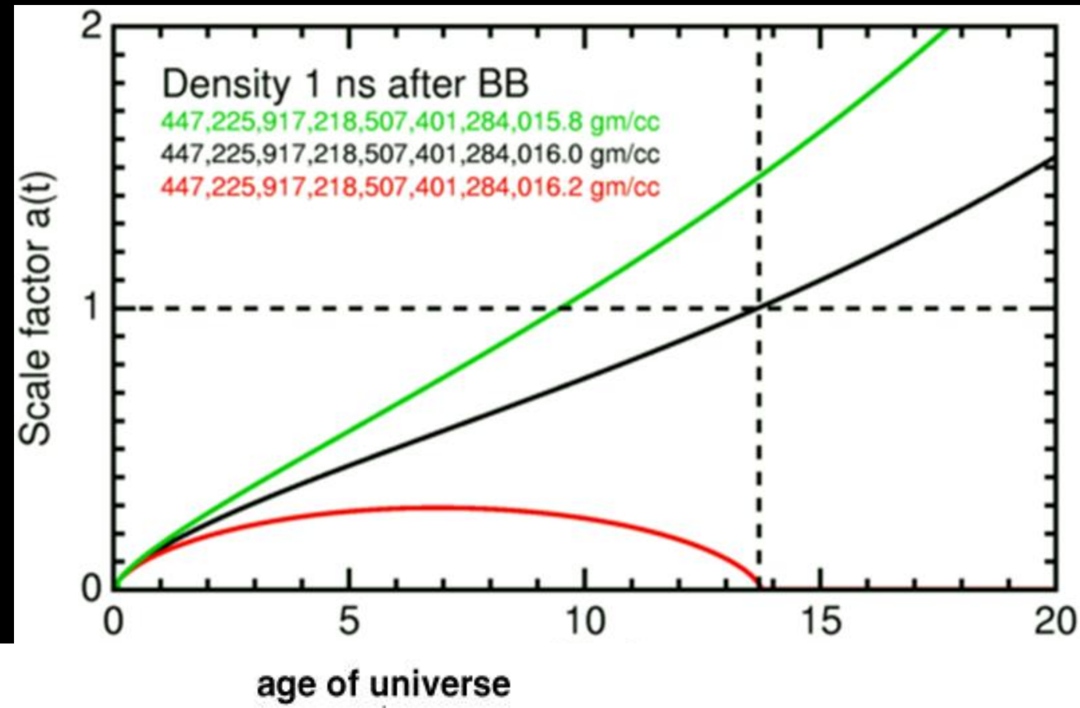
Its details are still unknown, but it is our best description of the early Universe



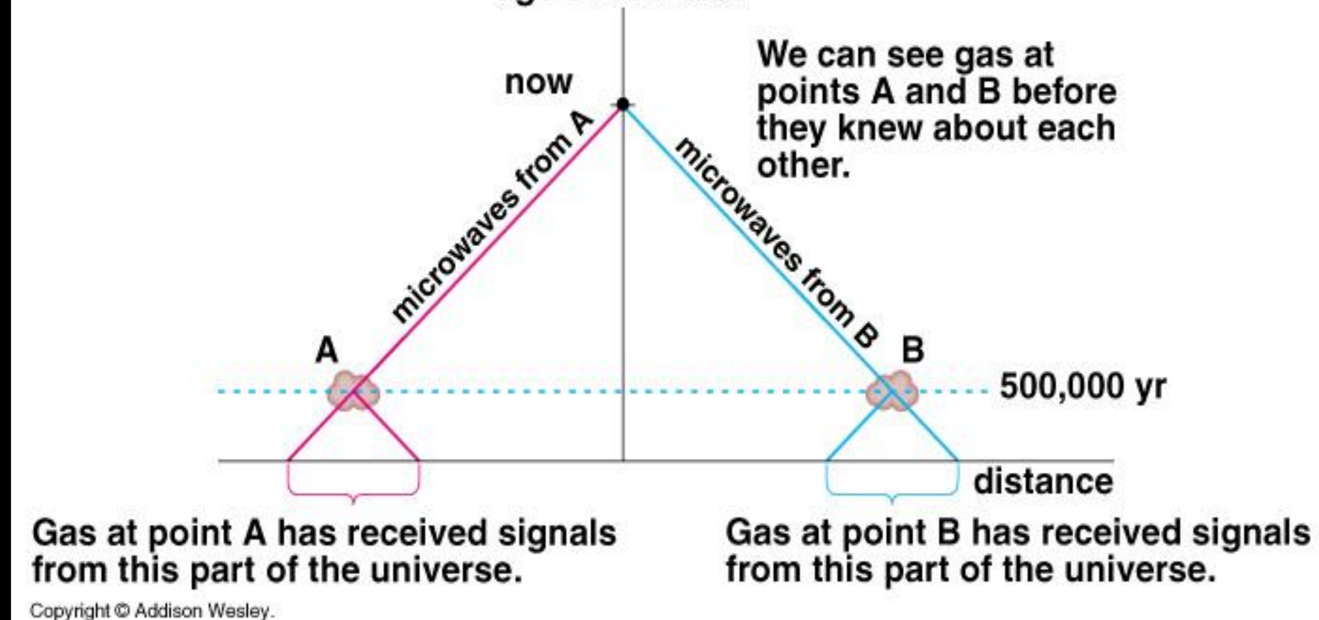
Radius of the observable universe [m]
10 40
10 20
10 0
10-20
Unknown
Matter Domination
Radiation Domination
Inflationary Period
10-40
10-20
10 0
Time [s]

The horizon and flatness problems

Why is the Universe Euclidean?
This is an unstable value that requires an unbelivable fine-tunning at the beginning of the Universe

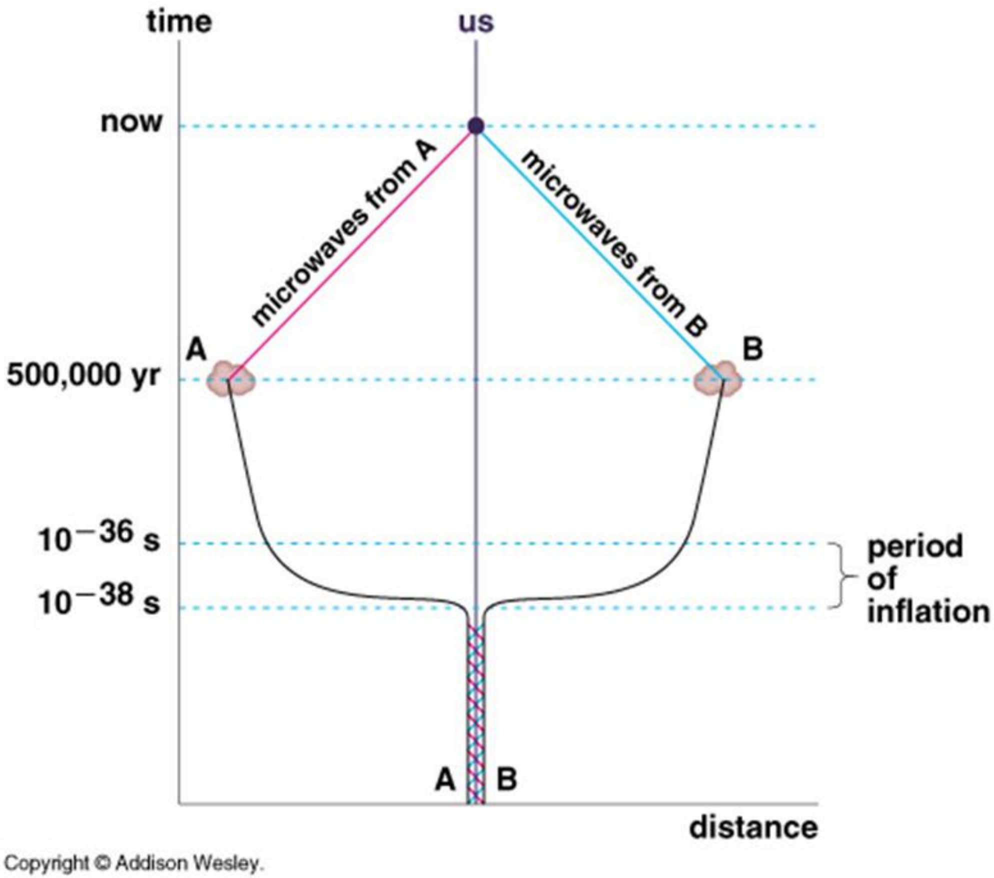


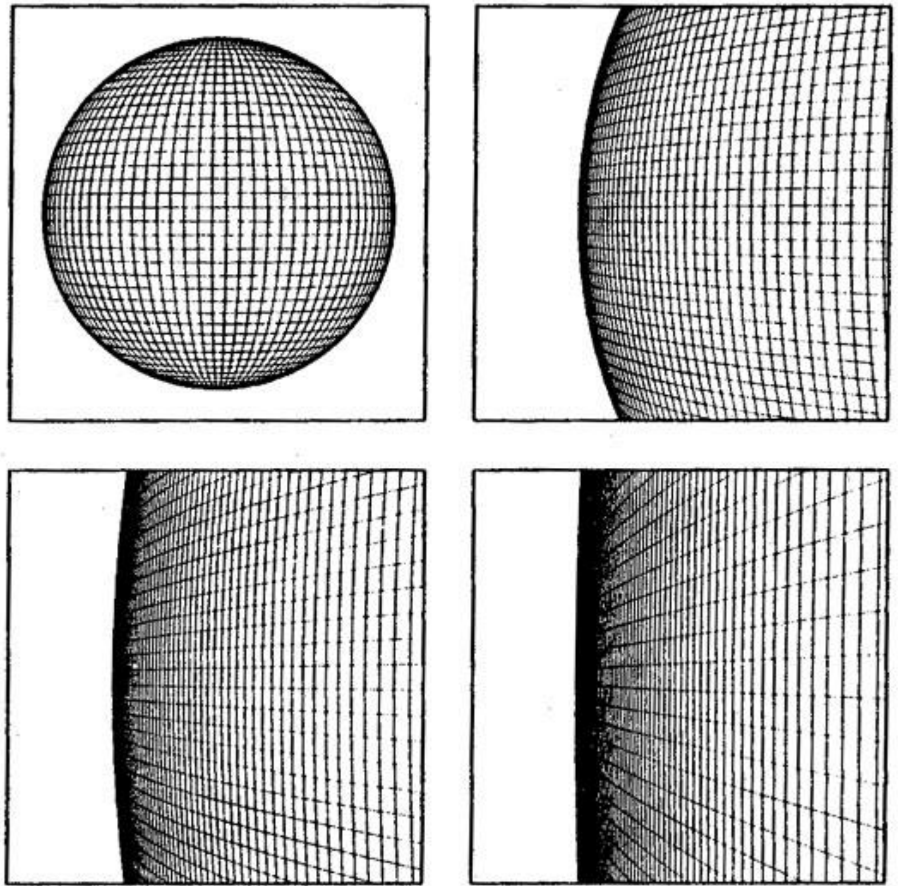
Why is the Universe so homogeneous?
Distant regions were never in causal contact, how can they be at the same temperature?



Inflation to the rescue

An initial period of exponential grow (the inflation) solves both problems and in addition, gives some predictions about the Universe that can be observationally verified





Inflation in one minute

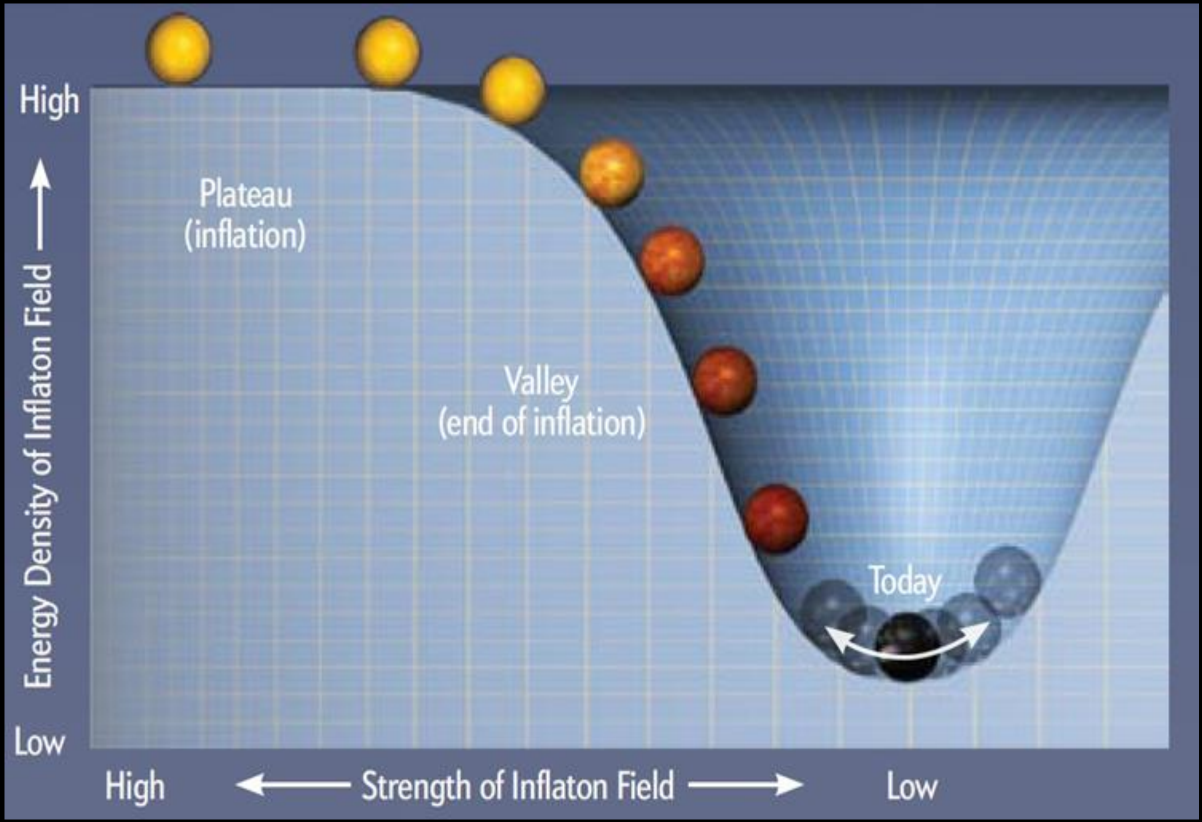
The universo begins very small… Perhaps as a quantum fluctuation in the spacetime foam.

An unstable field (the inflaton), fills the whole space

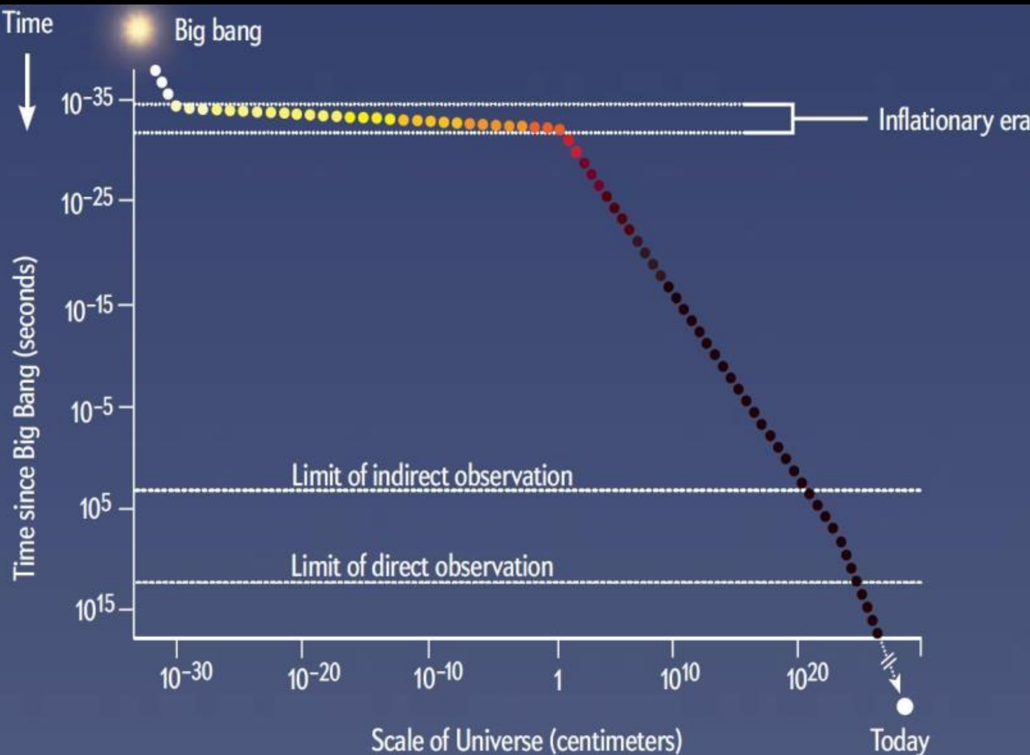
It produces gravitational repulsión! Explosion.

The field is unstable and decays. Inflation ends after 10^{-35} s

The inflaton energy is released during the oscillations around the minimum, and produces all matter that we see today in the Universe as a very hot and dense plasma

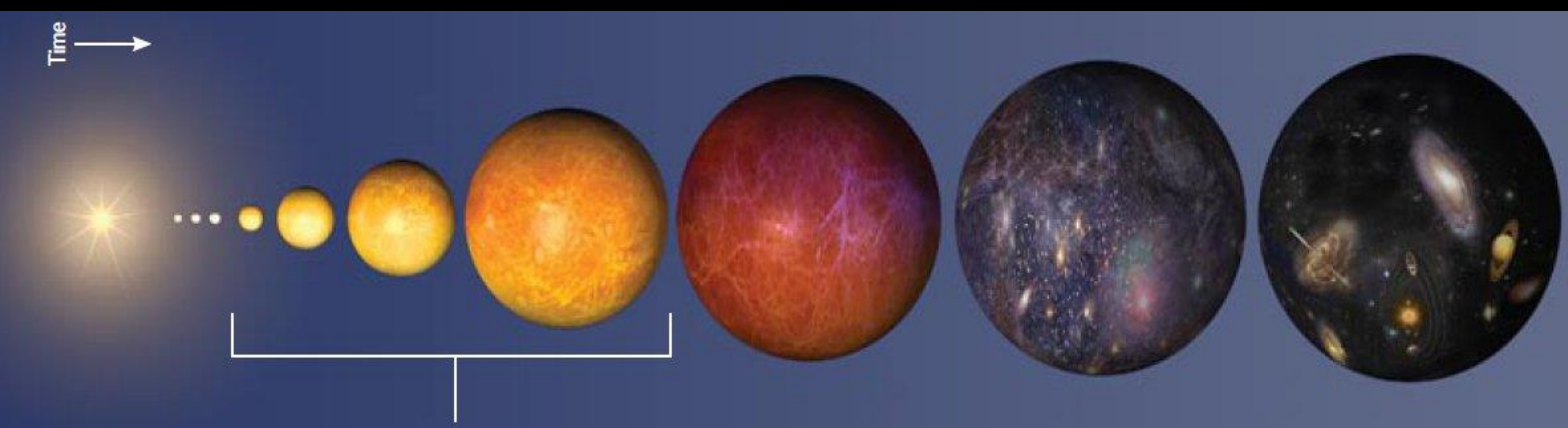


Inflación in one minute

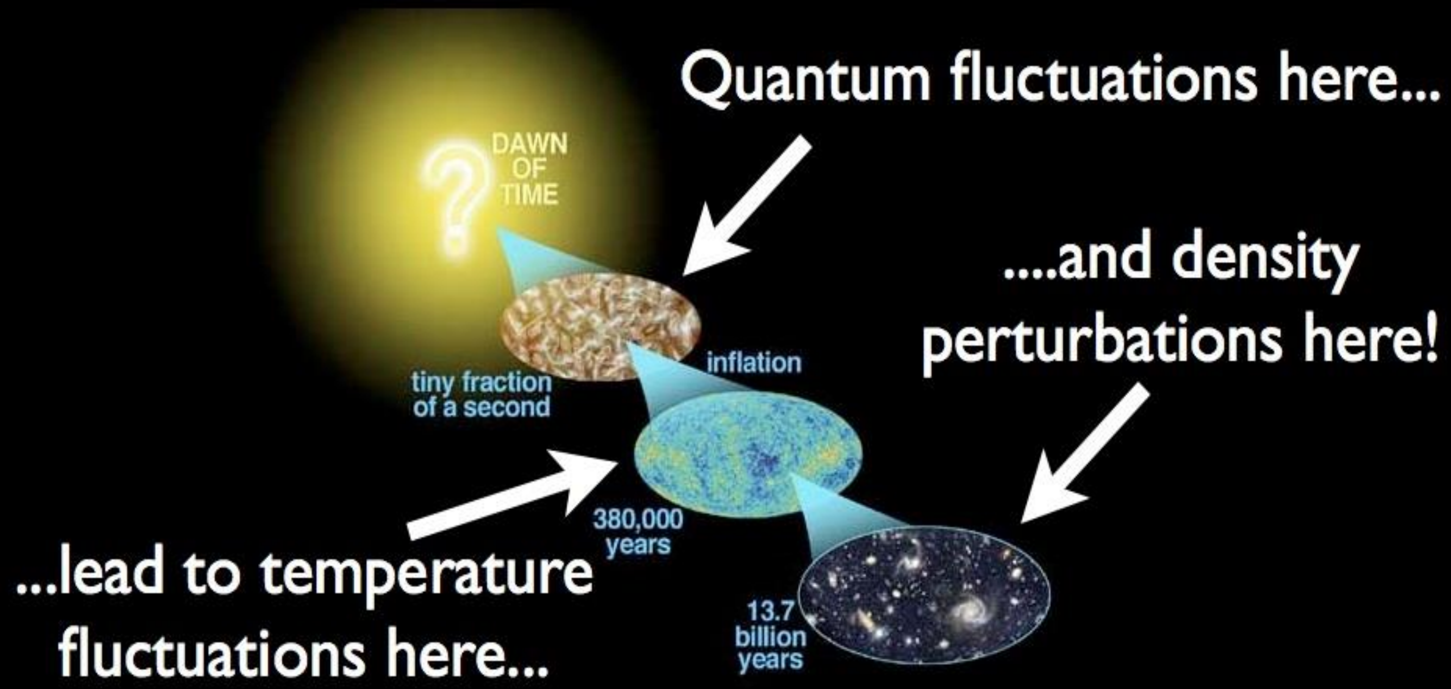


When inflation ends, the observable Universe has a size like a ball

The "primordial soup" is the starting point of the classical big bang. From this momento on, the Universe expands and cools up to today.



Inflación in one minute



Inflation explains the structure formation in the Universe. The initial inhomogeneities are due to the quantum fluctuations during the inflationary period, amplified by the wild expansion.

The largest structures we observe today are the result of quantum fluctuations that happened on microscopic scales!

Conclusions

ΛCDM, the current big bang theory, has been confirmed by a huge amount of observations. It is based on:

- The General Relativity Theory
- The Cosmological Principle
- The particle physics in the early Universe

It requires new physics, both to explain the dark side and the early Universe.

- *Dark Energy (68%)*
- *Dark Matter(27%)*
- *Inflation, baryogenesis and the cosmic origin*