INTRODUCTION TO COSMOLOGY

(1) From Hubble to Planck : 1929 - 2015

BEFORE HUBBLE

Aristarque of Samos	–310, -230	heliocentrism
Copernic	1473, 1543	heliocentrism

The Earth is NOT the center of the Universe

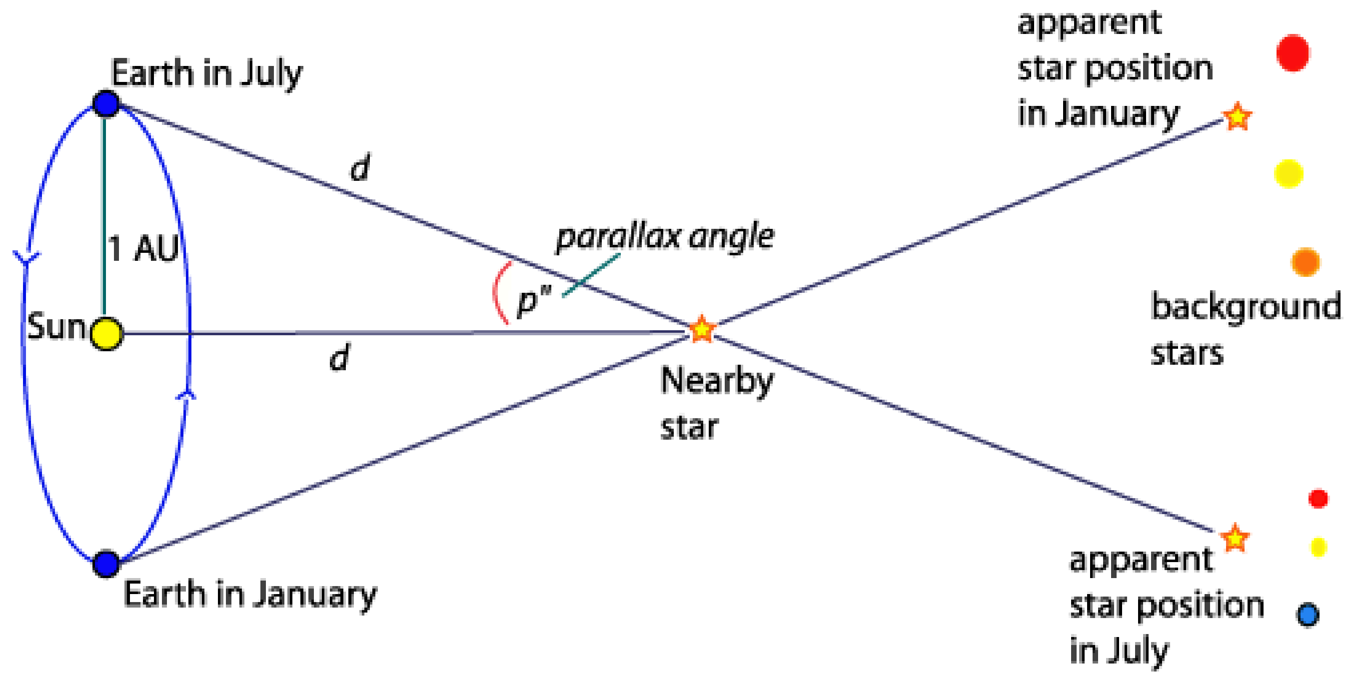
Rømer	1676	finite speed of light
Newton	1687	gravitation law

No distance of stars, no galaxies

Universe is eternal and infinite

Bessel	1838	distance of stars by parallax
Einstein	1905	special relativity
	1916	general relativity (relativistic gravitation)
Eddington	1919	deviation of light by gravitation
Hubble	1924	galaxy Andromeda measure of distance by Cepheids stars

BEFORE HUBBLE



Parallax of nearby star

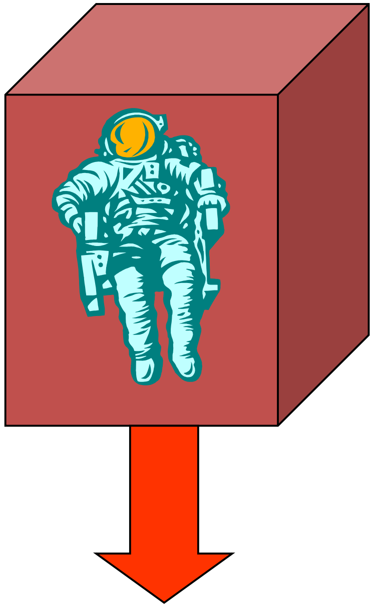
1 parsec (1'' arc) = 3.867×10^{13} km = 3.262 light years

Hipparcos satellite (1990) up to 100 pc

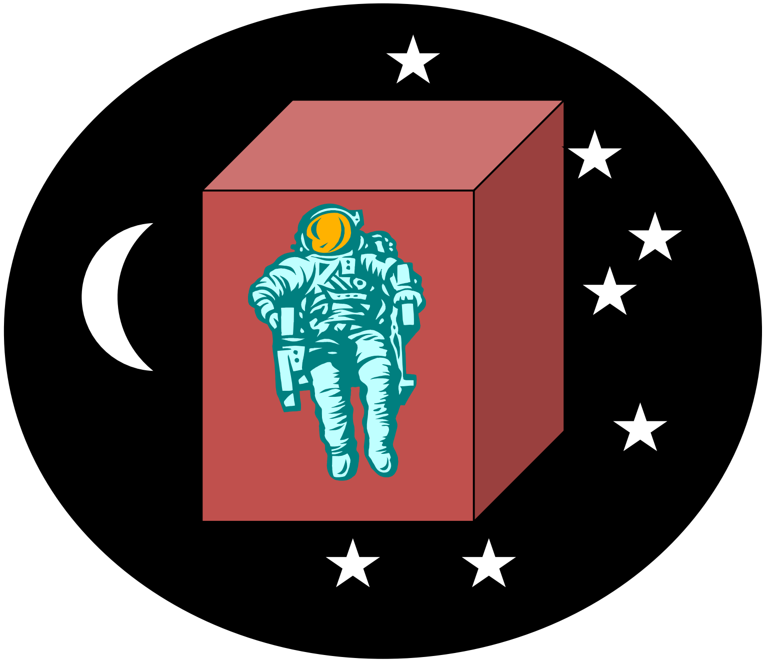
Cepheids 2 Mpc

BEFORE HUBBLE

General Relativity is based on principle of equivalence



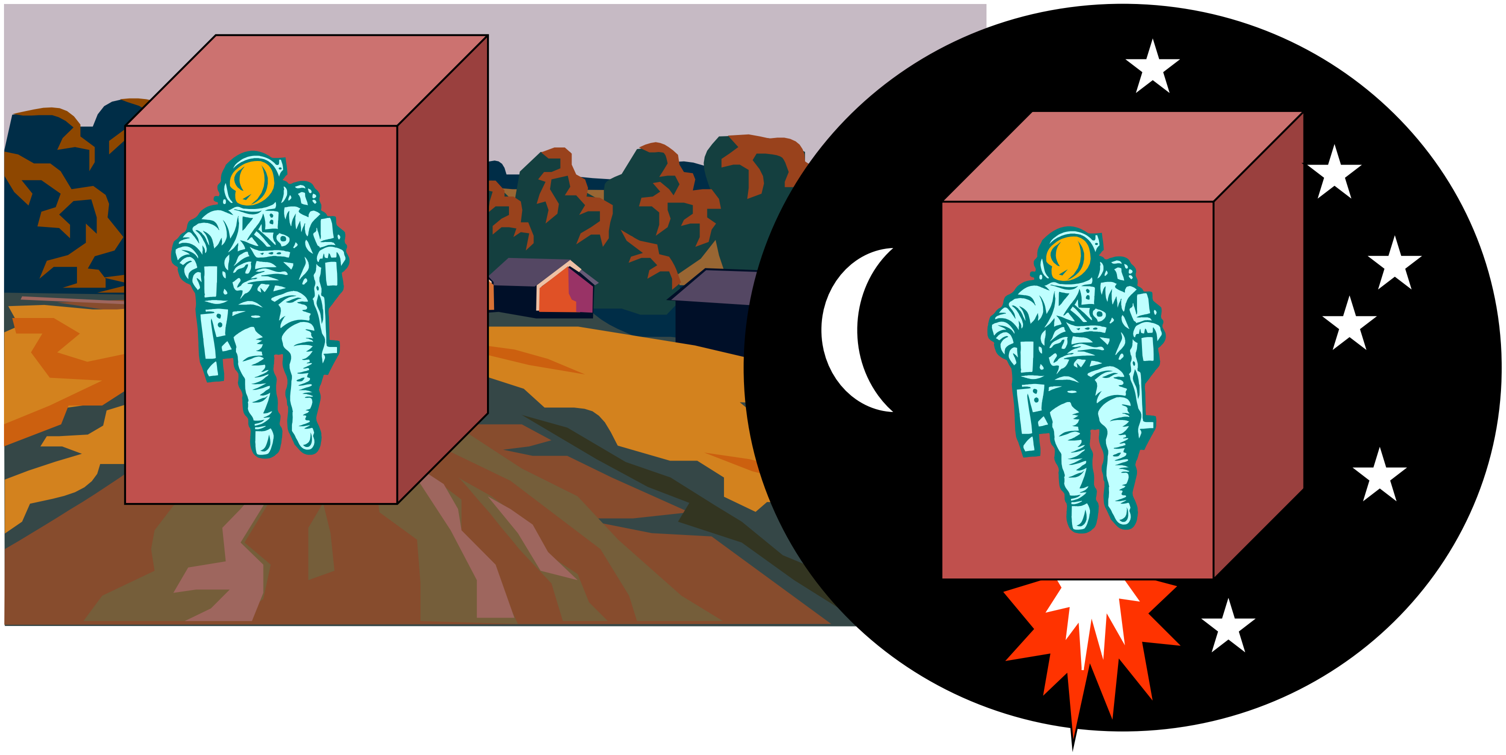
astronaut in freefall



astronaut in inertial frame

frame falling freely in a gravitational field
"looks like" inertial frame

BEFORE HUBBLE



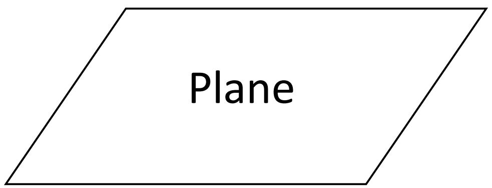
astronaut under gravity astronaut in accelerating frame

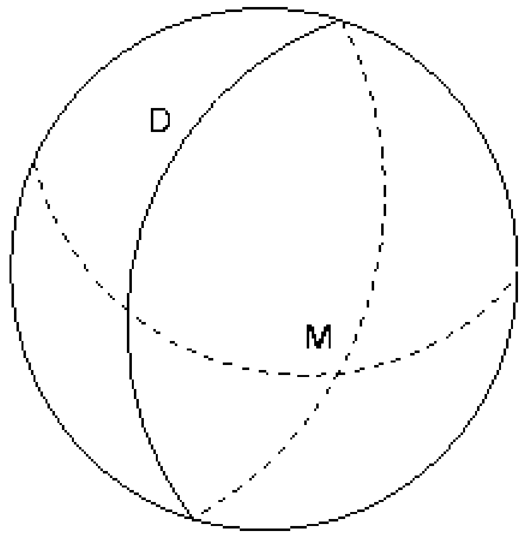
gravity looks like acceleration
(gravity appears to be a “kinematic force”)

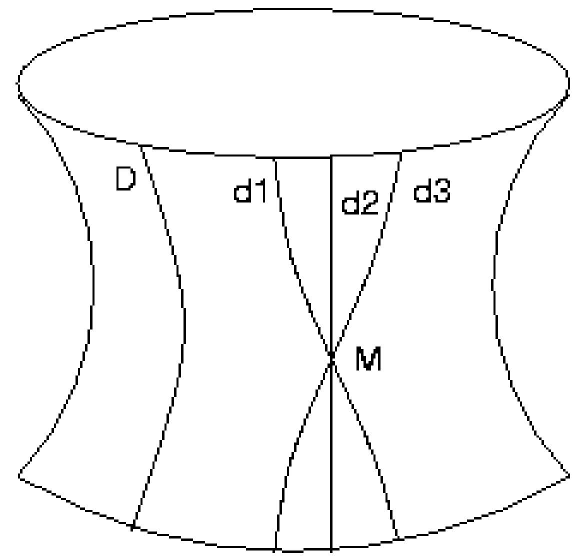
BEFORE HUBBLE

non Euclidian geometries

XIX^{e} century : surfaces (Gauss), parallels postulate (Bolyai, Lobatchevski), manifold differentiation (Riemann), tensor calculus (Christoffel, Ricci)







Géodésics
= straight lines

circles

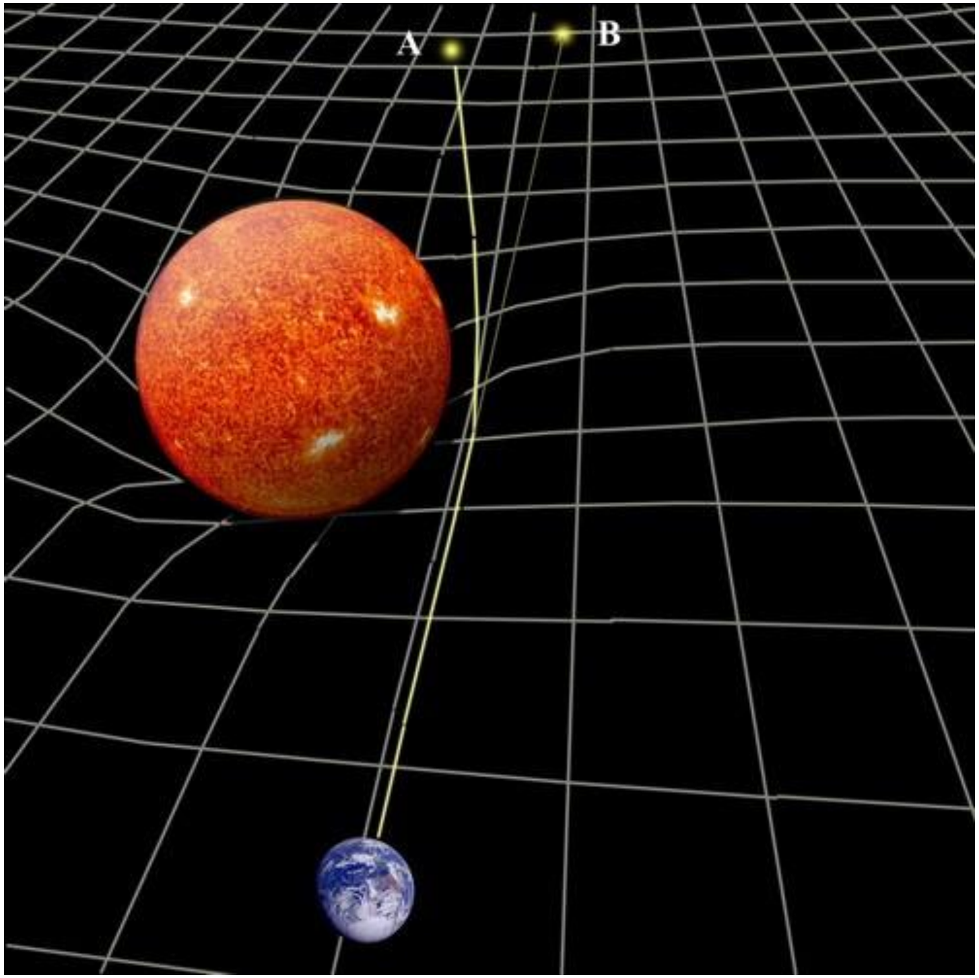
1 parallel

no //

∞ number of //

BEFORE HUBBLE

local curvature of space
caused by gravity



Universe can be
- finite if positive curvature
- infinite if negative
or zero curvature

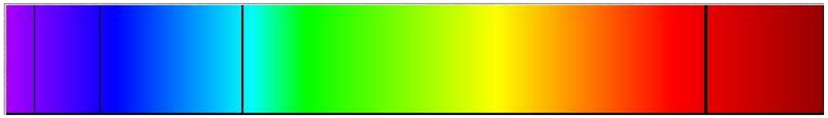
EXPANSION OF THE UNIVERSE

$$z = \frac{\Delta\lambda}{\lambda} = \frac{\lambda_o - \lambda_e}{\lambda_e}$$

small speed $v = c\,z$

in Special Relativity $\beta = \frac{v}{c}$ $1 + z = \frac{\lambda_o}{\lambda_e} = \sqrt{\frac{1+\beta}{1-\beta}}$

spectroscopy lines : measure of radial speed by Doppler effect,



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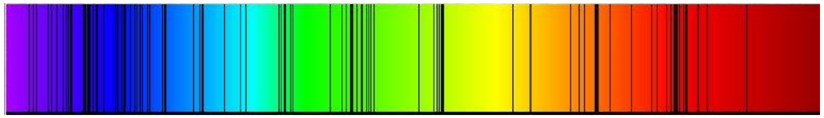
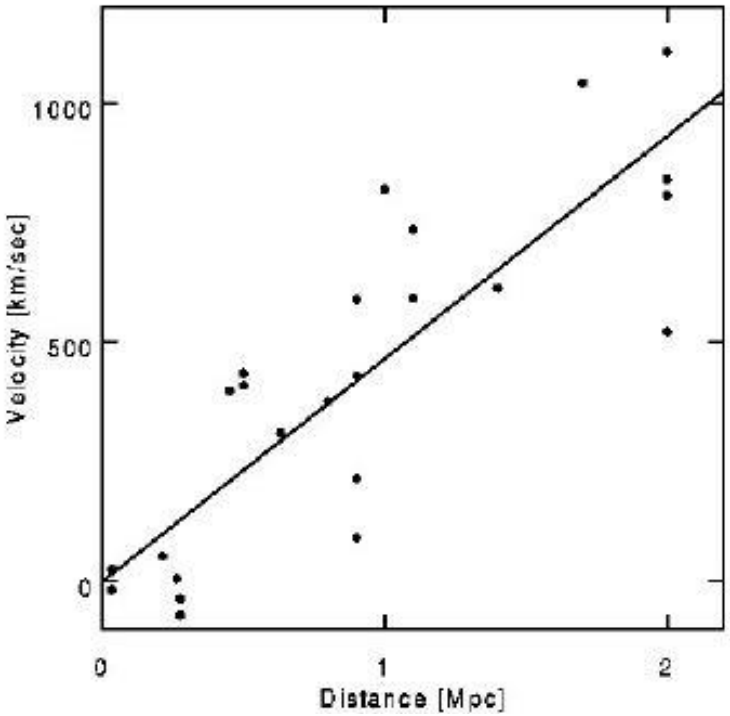


Ca

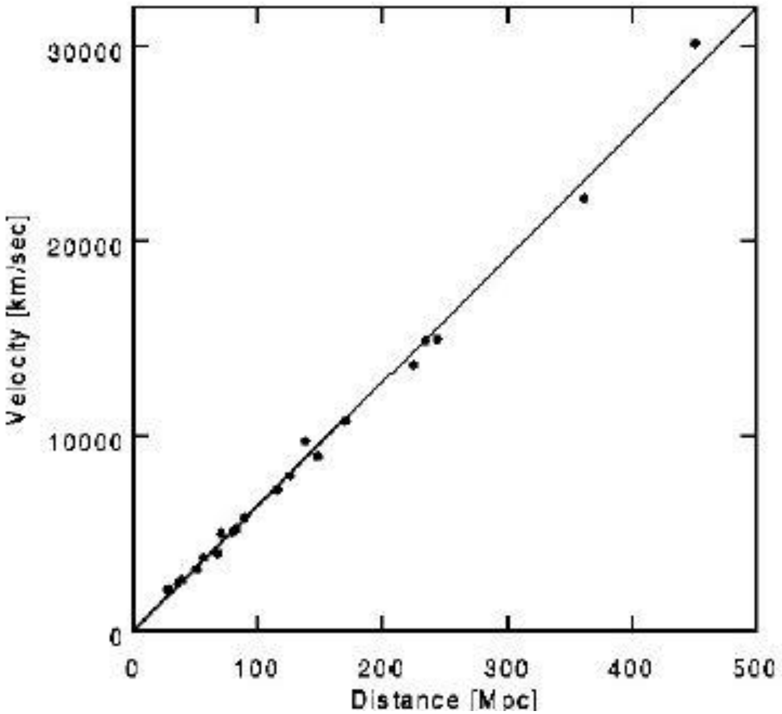
different interpretation in General Relativity (expansion of Universe)

EXPANSION OF THE UNIVERSE

Hubble constant = 70 km s^{-1} Mpc^{-1}



1929

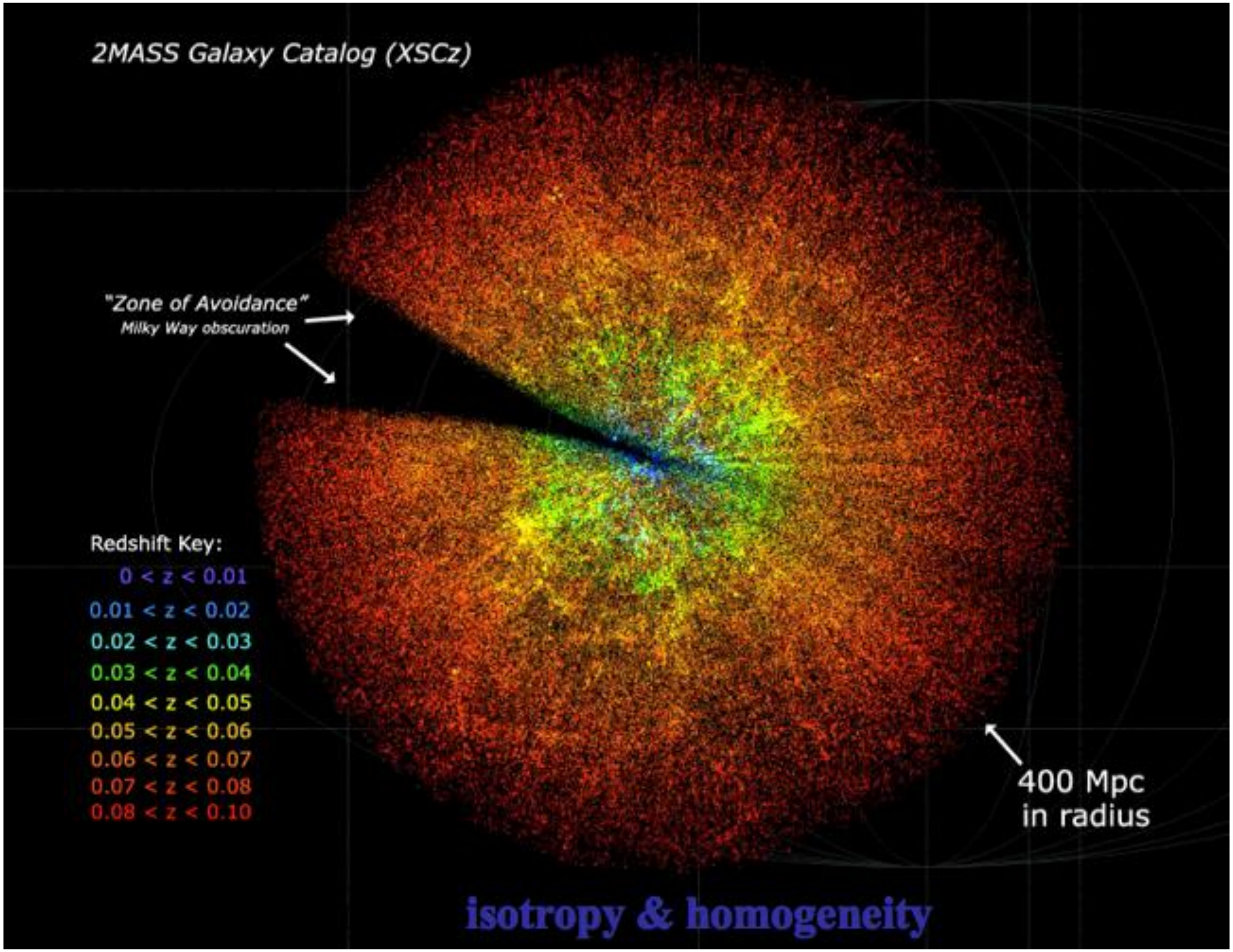


1999

A new paradigm : Universe is NOT eternal, Universe is AGING

Postulate of Standard Model of cosmology : homogeneity and isotropy

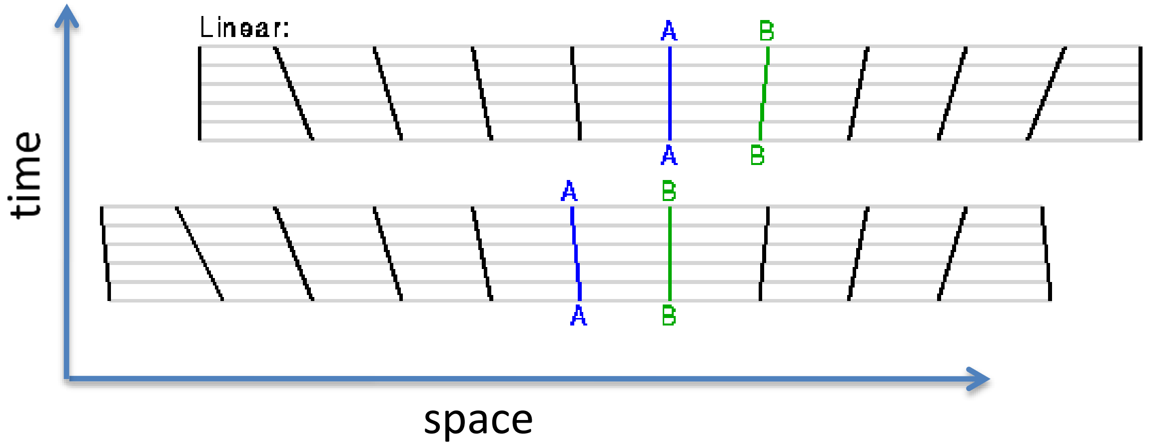
EXPANSION OF THE UNIVERSE



EXPANSION OF THE UNIVERSE

universality of Hubble "constant" H_0 in space, not in time

expansion is homolog, nobody is at the center of the Universe

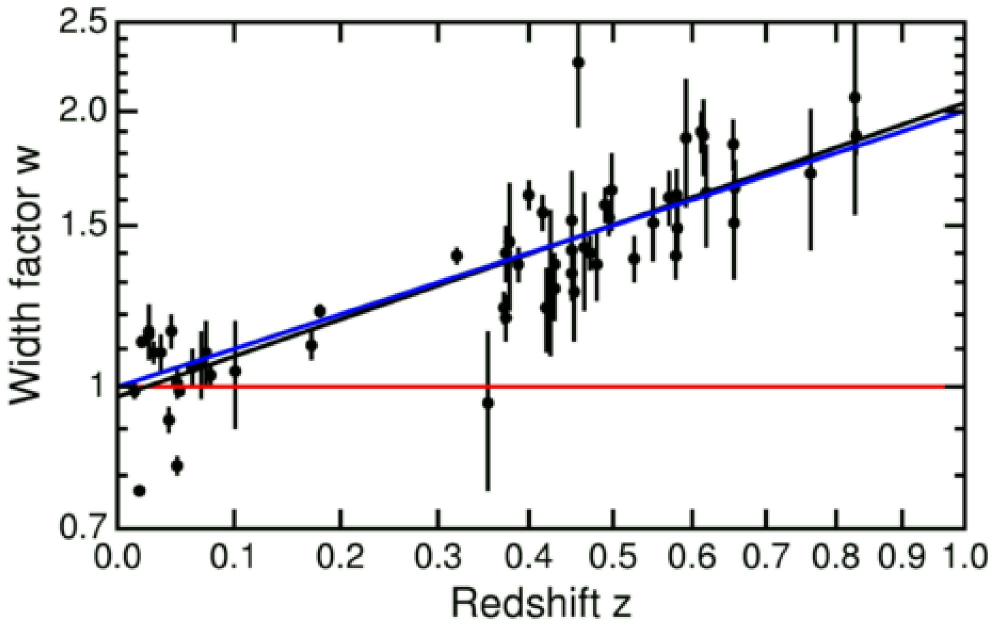


galaxies are motionless in comoving coordinates, except random individual motion

there is a universal scale factor $R(t)$

ACCELERATING EXPANSION

A new method to measure very long distances : supernovae Ia

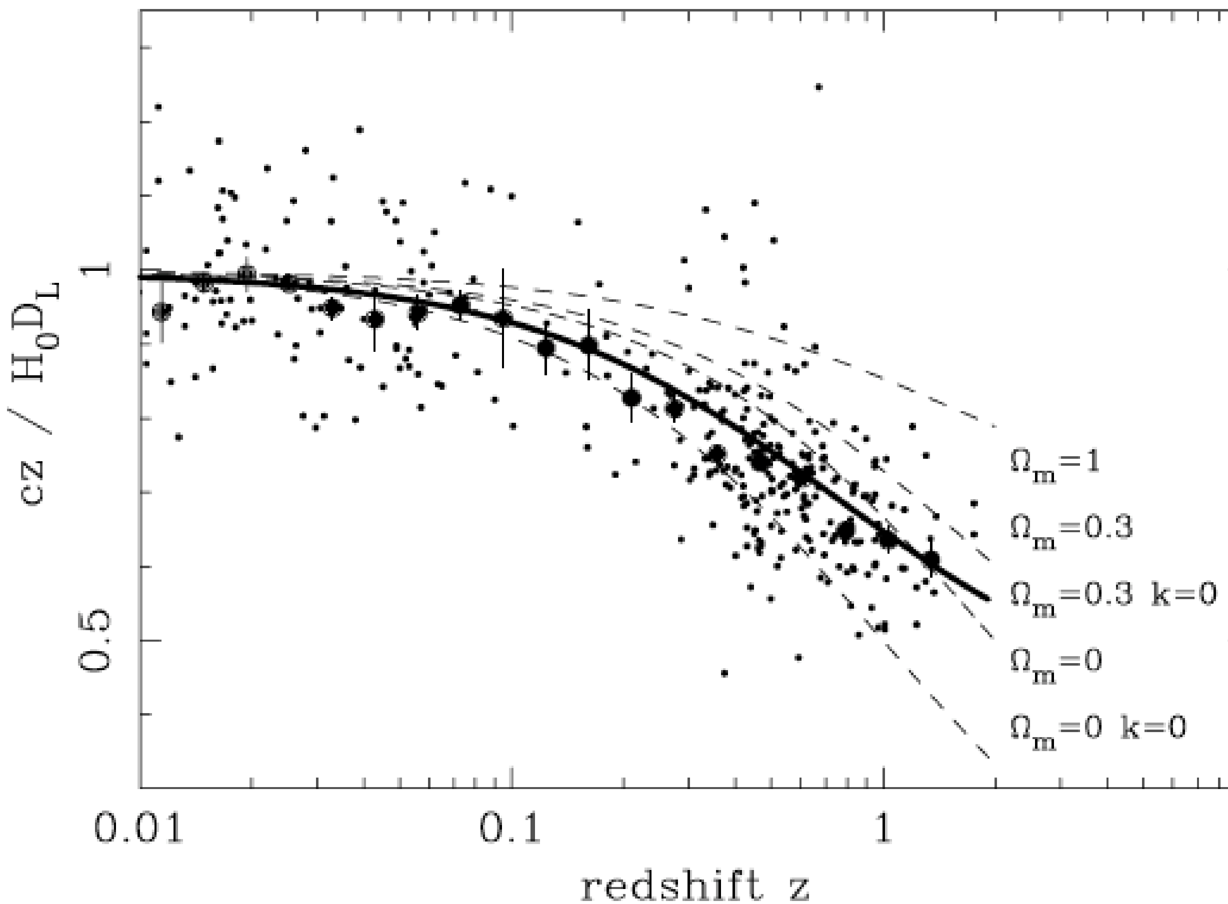


These explosive stars
- have the same characteristics (luminosity, period) everywhere
- are very bright,
can be seen from very far

Periods of supernovae Ia (Supernovae Cosmology Project 2001)

dilatation of time : an independent proof of the expansion of the Universe !

ACCELERATING EXPANSION



z/*D* is not constant in time

ACCELERATING EXPANSION

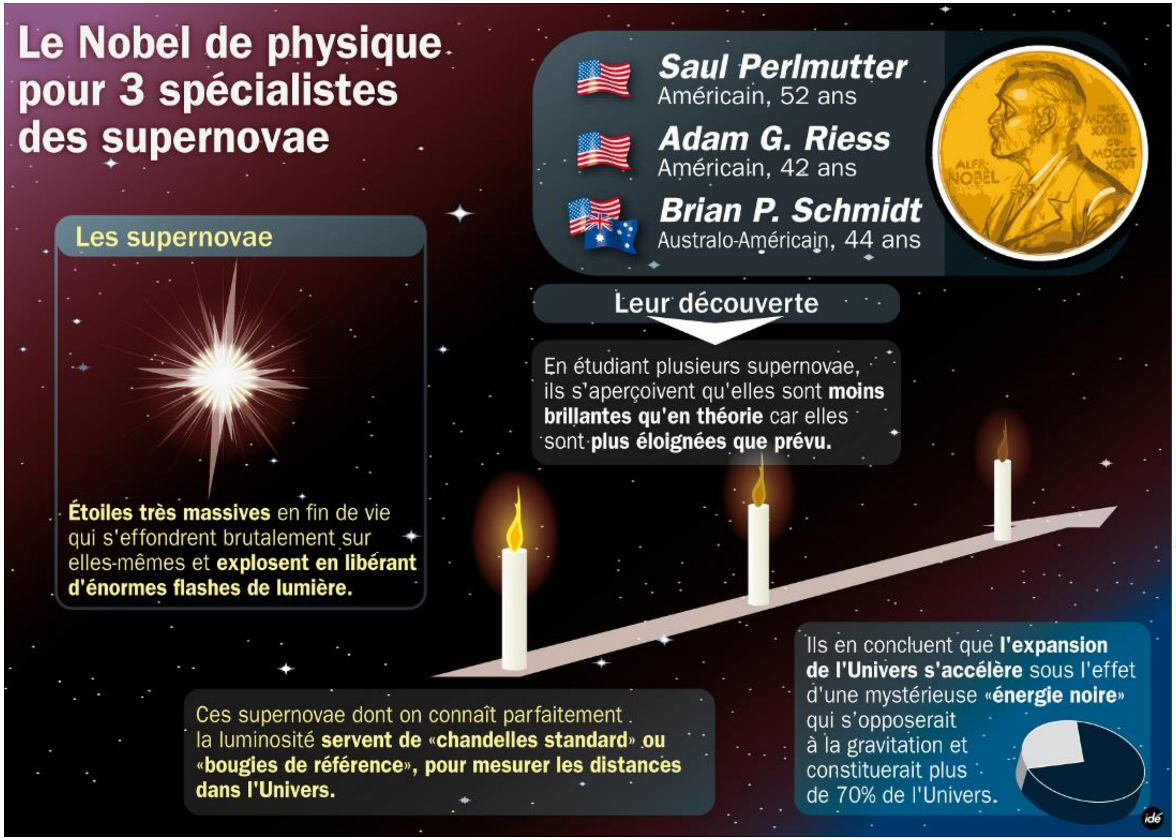


Photo: Ariel Zambelich, Copyright © Nobel Media AB

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

Nobel prize 2011

Nobel prize 2006 John Mather & George Smoot

ACCELERATING EXPANSION

Cosmological constant introduced by Einstein in General Relativity so that Universe is static

$\Rightarrow$ modification of gravitation law

Can be interpreted as a repulsive force proportional to distance $F = -\frac{1}{3}\Lambda m r$

$\Rightarrow$ accelerating expansion equilibrates the self gravity of matter in the Universe

BUT Hubble discovers expansion: Universe is NOT static

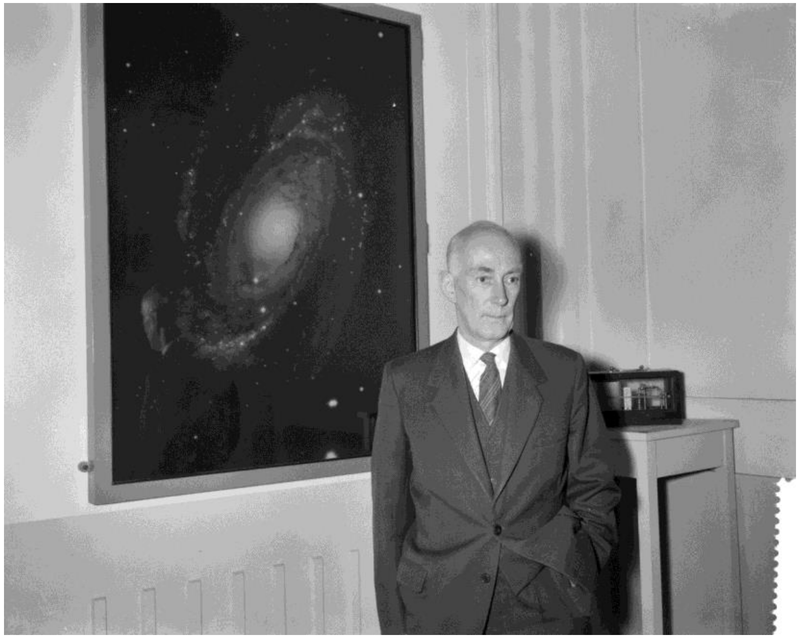
The biggest mistake in my life (*Einstein*)

BUT now there is an accelerating expansion $\Rightarrow$ Λ comes back

constant "vacuum density" = "negative pressure" $\rho_v = -p_v = \frac{\Lambda}{8\pi G}$

DARK MATTER

What is the cause of the expansion ?
static state is impossible, due to gravity of matter (could cause only contraction)

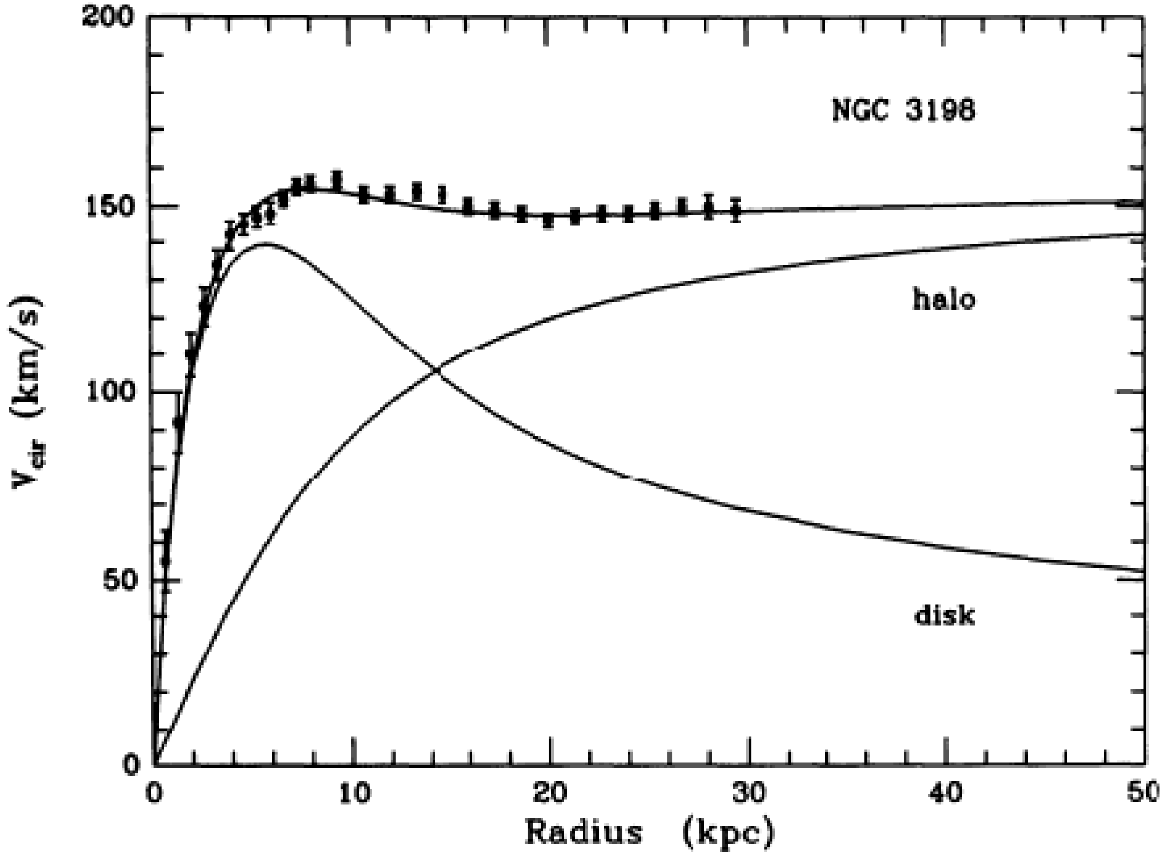


Measure of mass in our galaxy
Milky Way Oort 1932

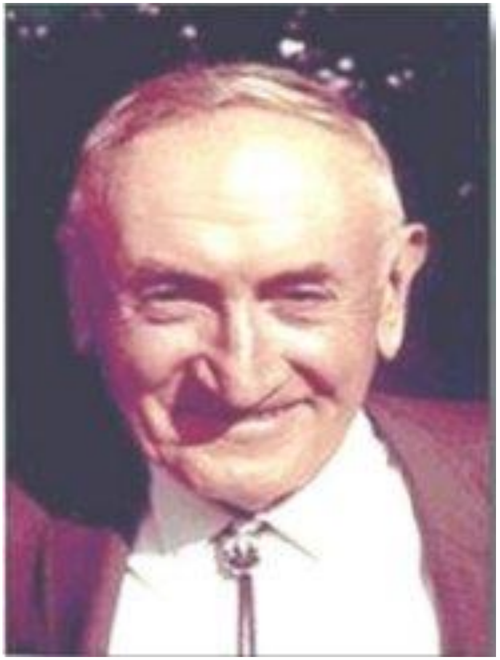
Rubin 1970 : idem
for other galaxies

$\Rightarrow$ 90% of "dark matter"

DARK MATTER

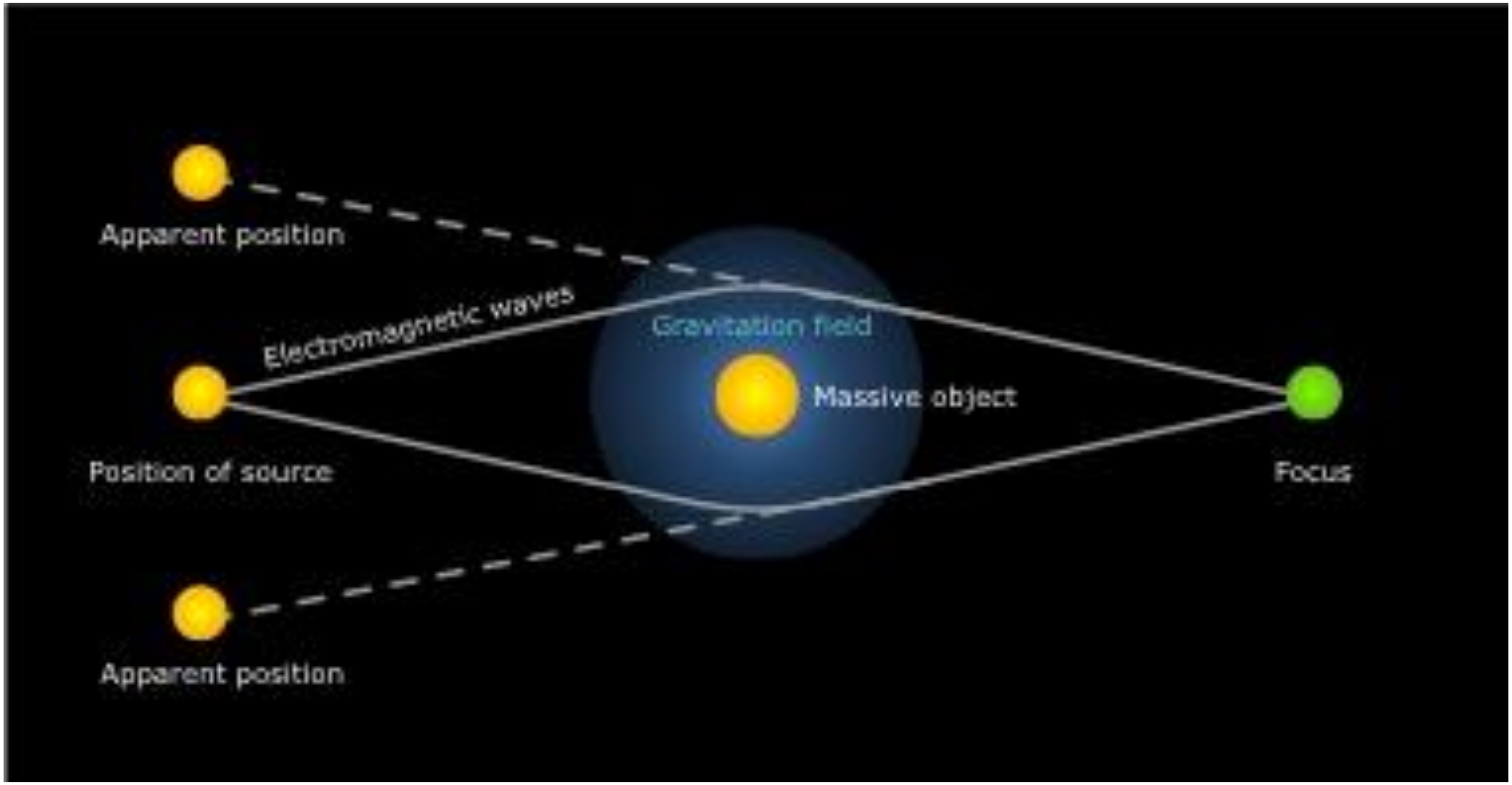


rotation curve of galaxy NGC 3198



Zwicky, idem for galaxy clusters (1933)

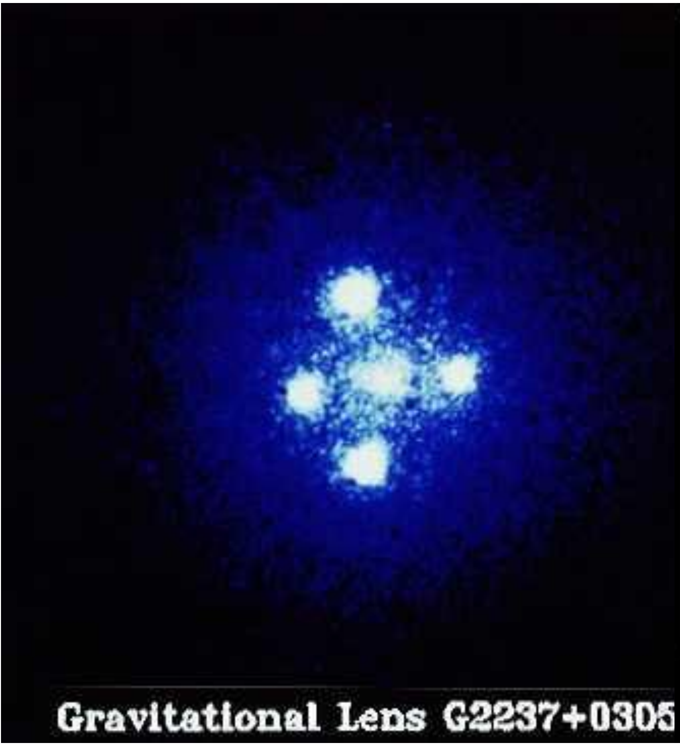
DARK MATTER



Measure of masses for very distant objects by light gravitational deviation
$\Rightarrow$ dark matter

DARK MATTER

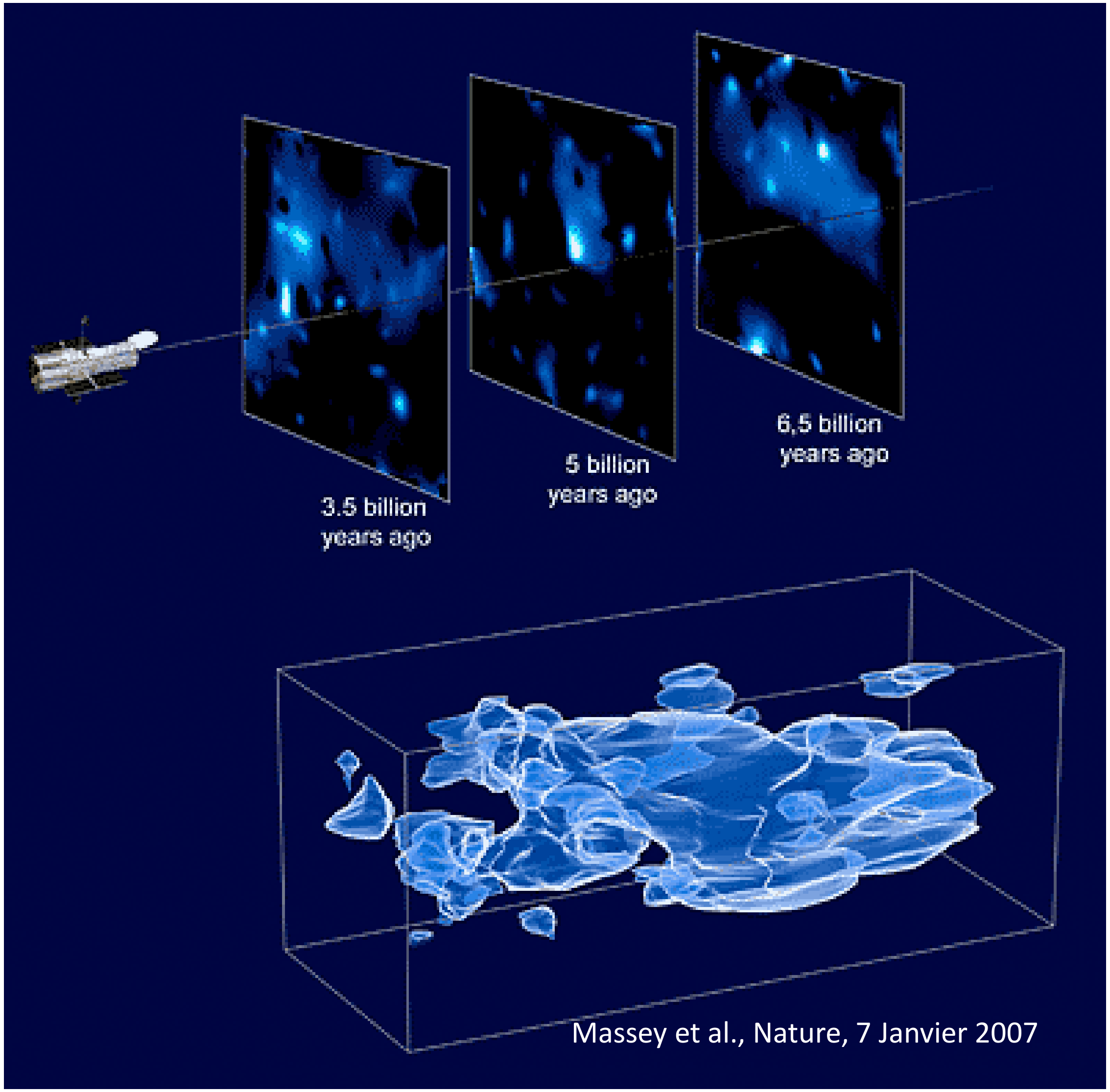
Gravitational mirages



Einstein cross

cluster of galaxies Abell 2218

DARK MATTER



3D map of dark matter by HST (Hubble Space Telescope)

red shifts measured by terrestrial telescopes

HOT BIG BANG

When the Universe was much smaller

First theory by George Gamow, Ralph Alpher, Robert Herman, around 1940

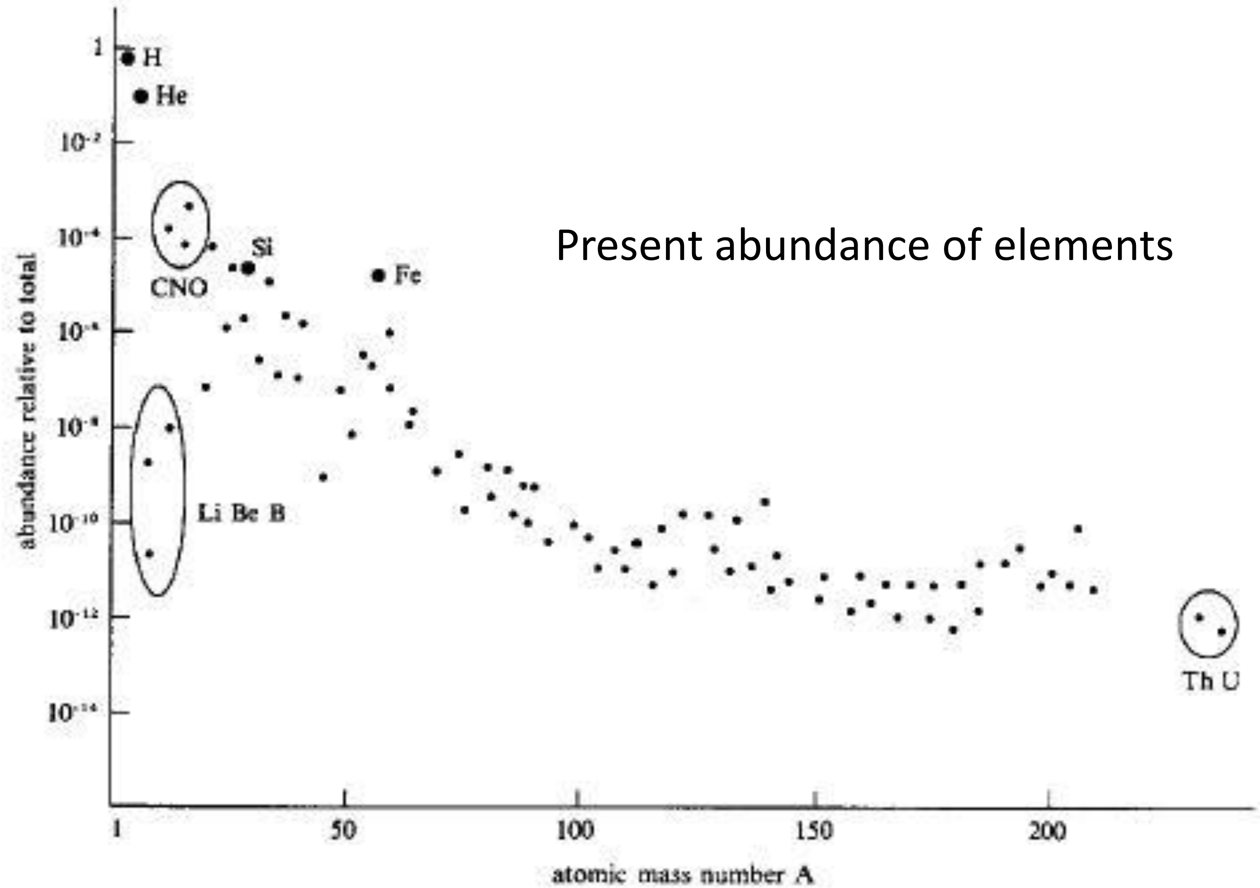
Understand stellar evolution, with the help of nuclear physics, around 1950

Assume the initial ultradense state is hot, like a compressed gas : application of statistical physics

- nuclear synthesis when the temperature is higher than 10^8 K

- thermal equilibrium of matter and light when $T > 3000$ K

HOT BIG BANG



Present abundance of elements

What was the abundance in the Universe before stellar nucleosynthesis ?

Primordial nucleosynthesis ?

HOT BIG BANG

production of deuterium, helium 3, helium 4, lithium 7 => 4 independent measurements

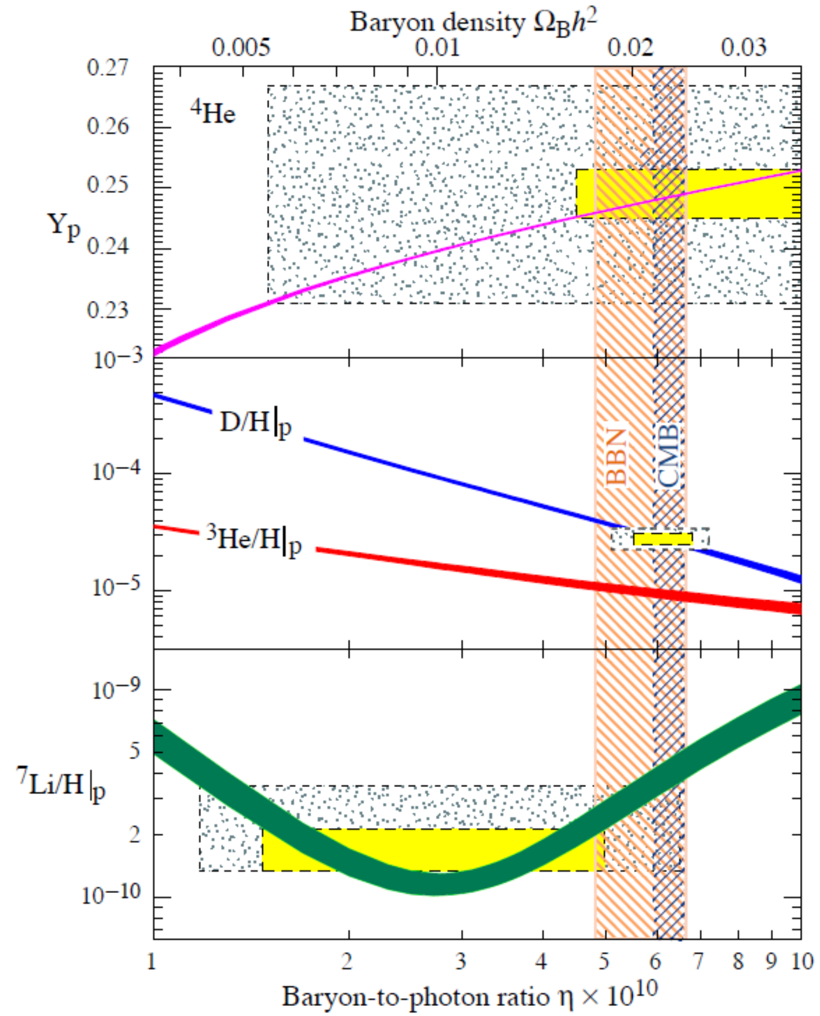
disintegration of neutrons and expansion of the Universe stops the synthesis after 3 minutes

is a measure of the density of Universe by the ratio :
baryon (neutron + proton) / photon

BBN (Big Bang Nucleosynthesis)

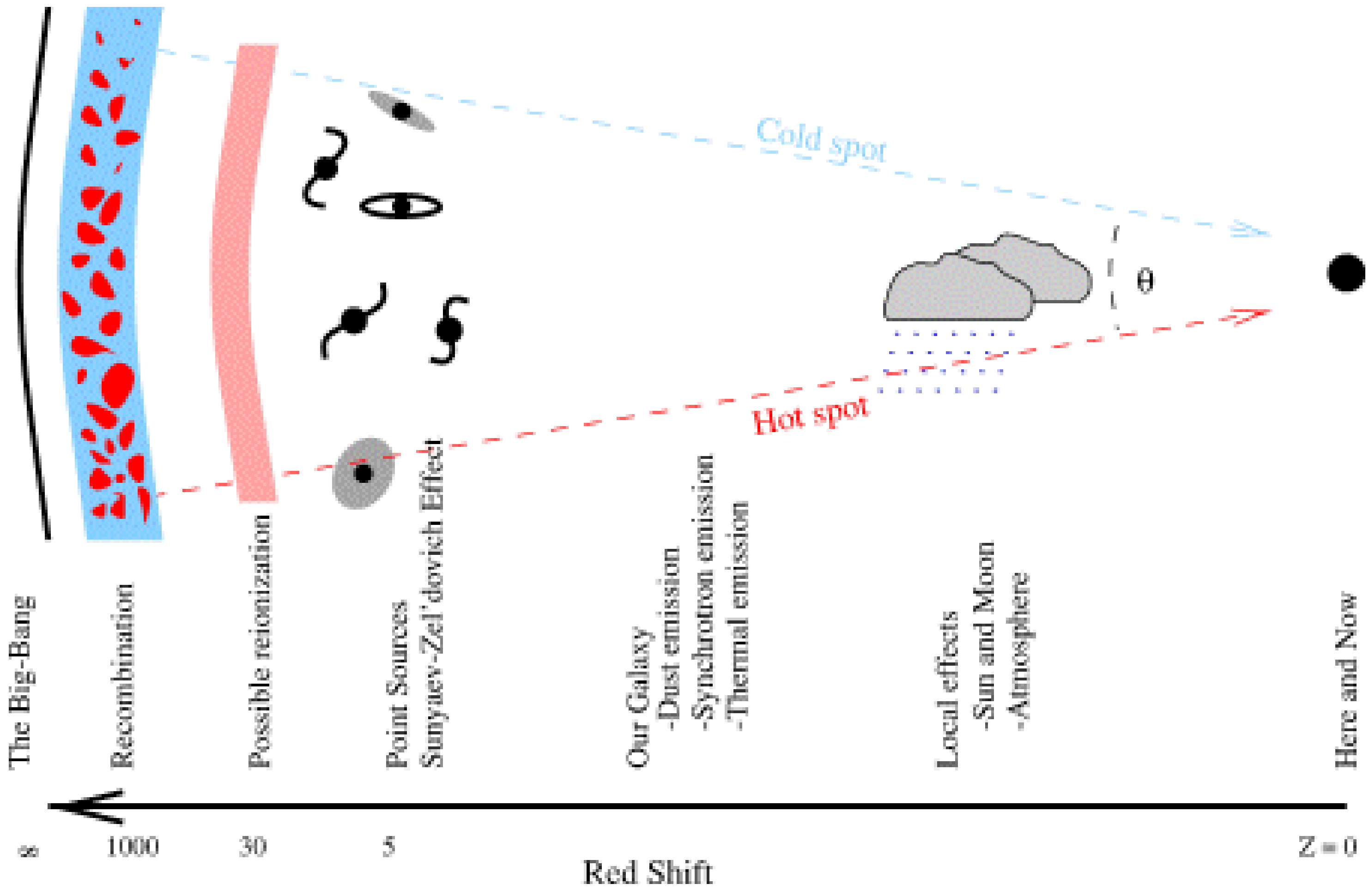
Baryonic matter ≈ 4 times luminous matter (stars)

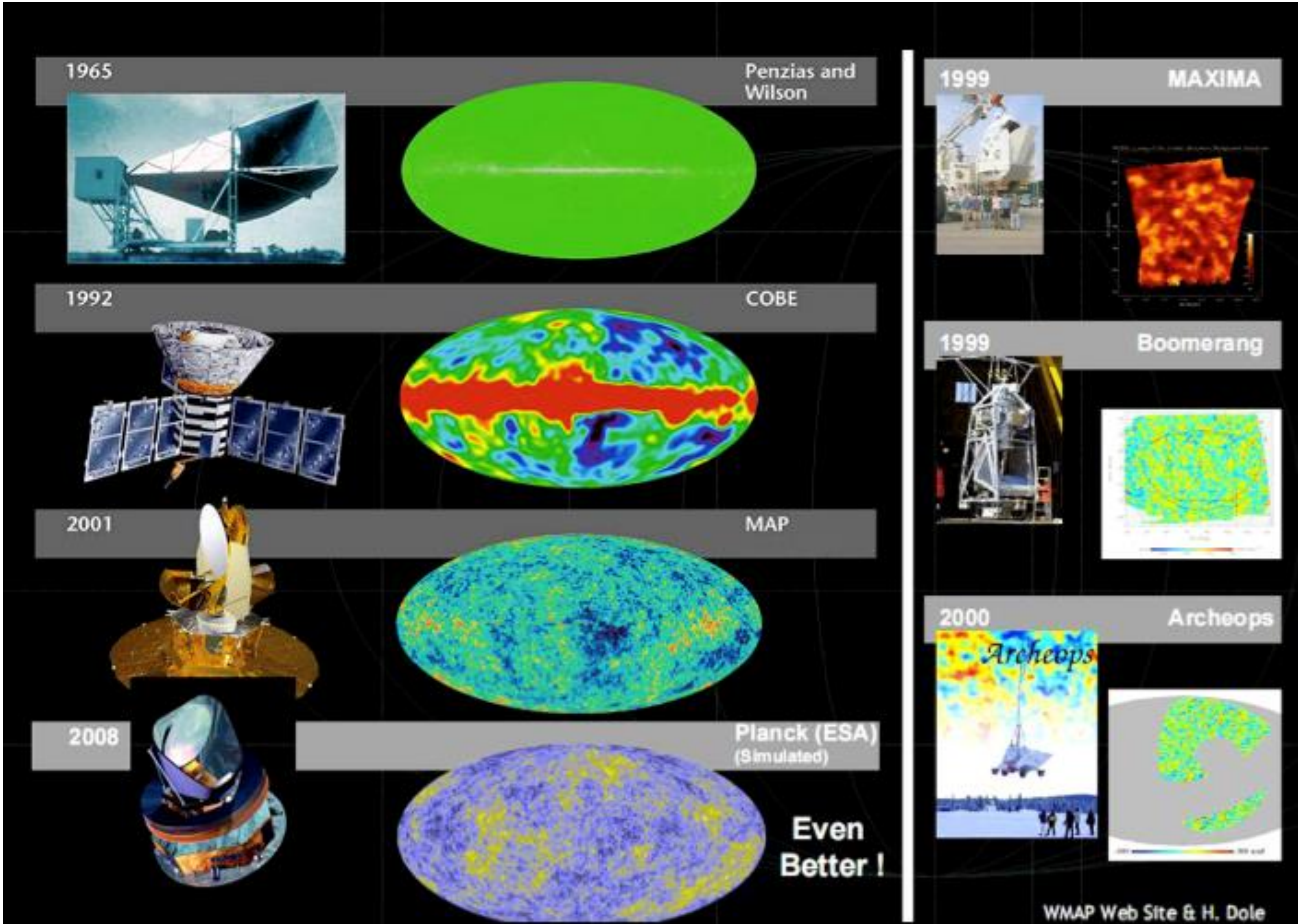
Total dark matter ≈ 6 times baryonic matter



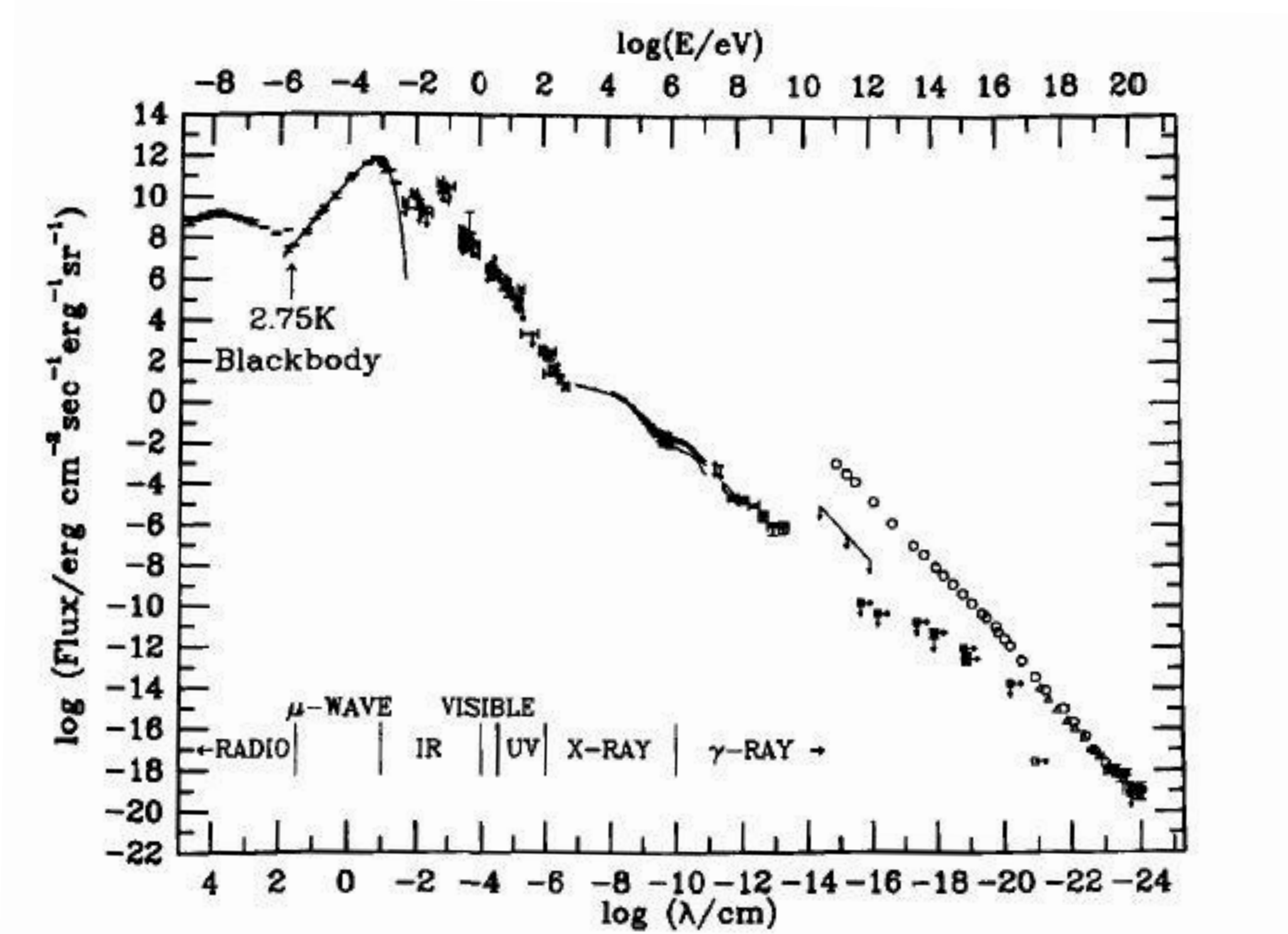
THE FIRST LIGHT

Main prediction of the hot big bang model




1965
Penzias and Wilson
1992
COBE
2001
MAP
2008
Planck (ESA)
(Simulated)
Even Better !
1999
MAXIMA
1999
Boomerang
2000
Archeops
Archeops
WMAP Web Site & H. Dole

THE FIRST LIGHT



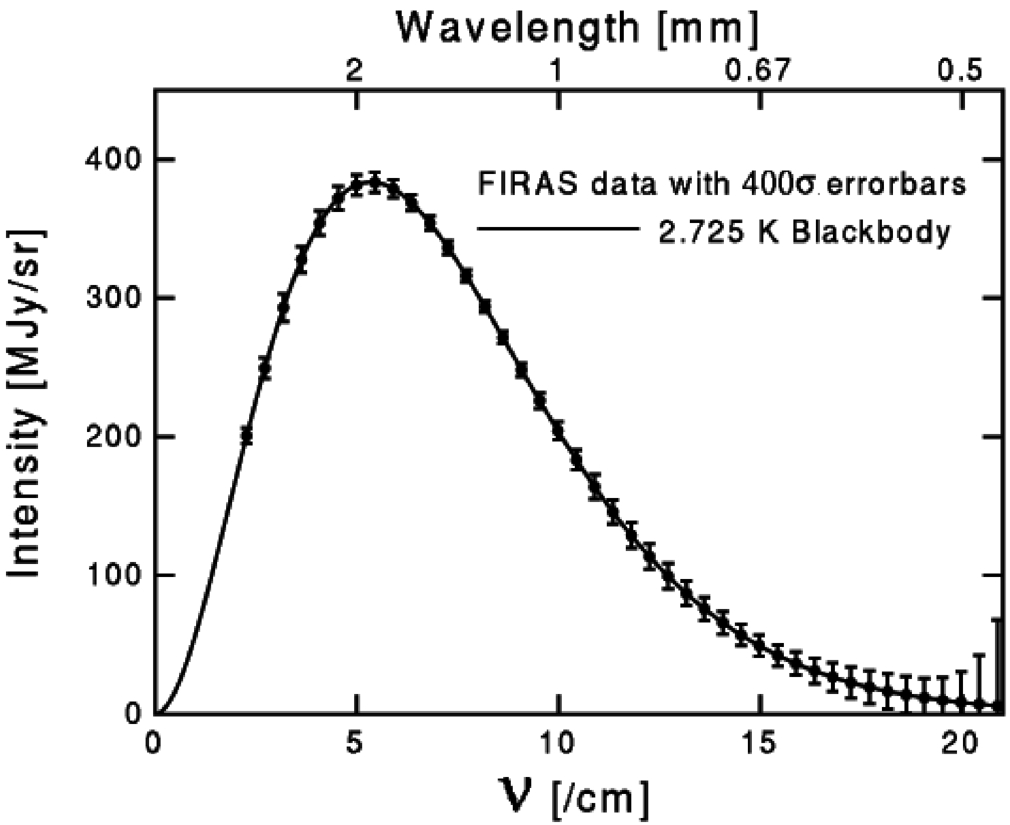
THE FIRST LIGHT

millimetric radiation,   isotropic at 10^{-5}
(after correction due to Earth movement)

perfect black body spectrum

Cosmic Microwave Background (CMB)

(satellite COBE 1992)



THE FIRST LIGHT

Predicted by Gamow a early as 1946 (nucleosynthesis) at 10 kelvins,
almost seen by McKellar en 1941
and by Dicke, Peebles, Roll, Wilkinson en 1965

Measured on Earth par Penzias et Wilson at 7.35 cm

energy density divided by λ
(Planck law)

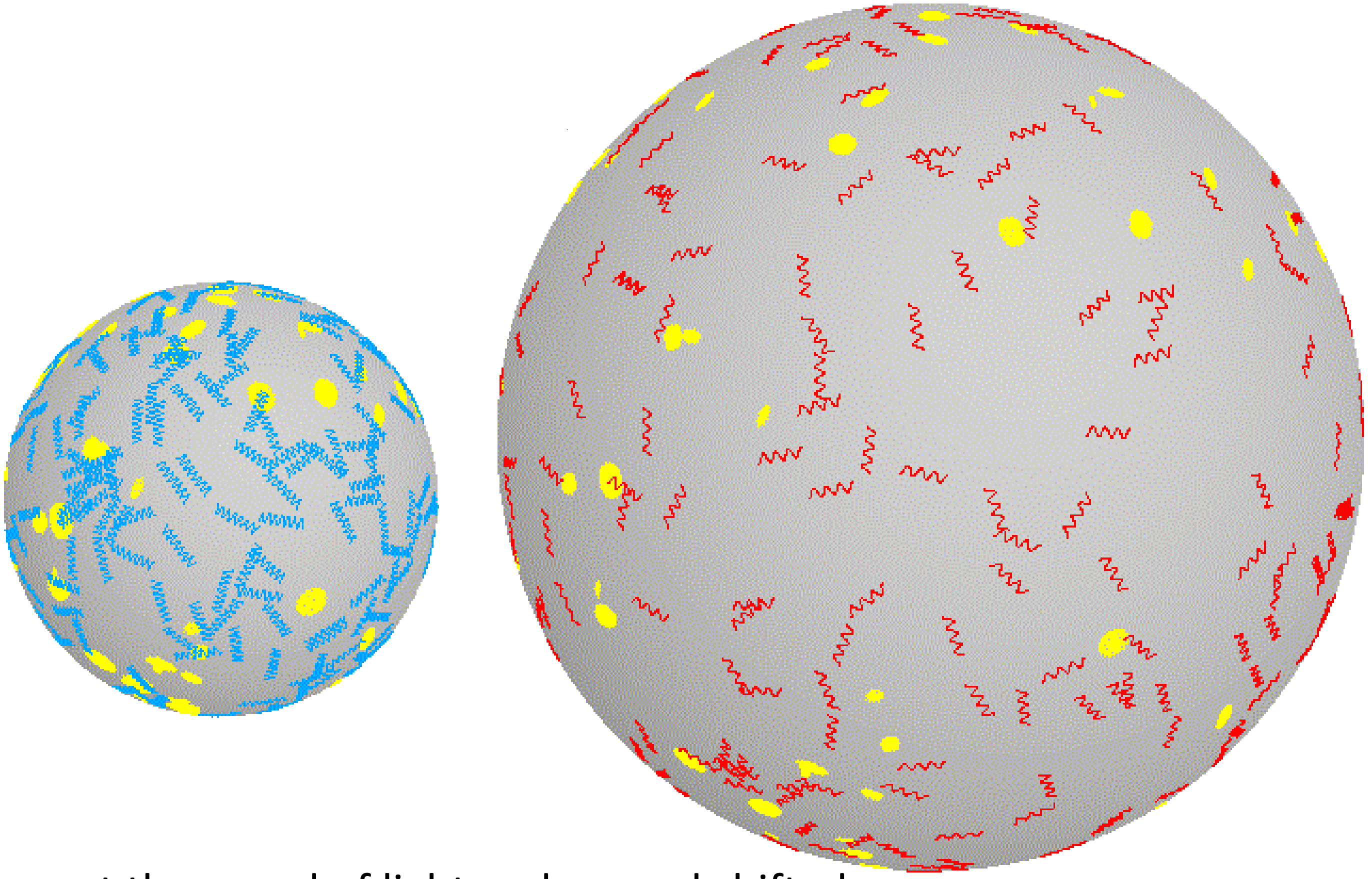
$$\frac{du}{d\lambda} = \frac{8\pi h\,c}{\lambda^5\left(\exp\left(\frac{h\,c}{\lambda\,k\,T}\right)-1\right)}$$

If the spatial dimensions and the wavelength are multiplied by a scale factor

$$f = \frac{\lambda'}{\lambda}$$

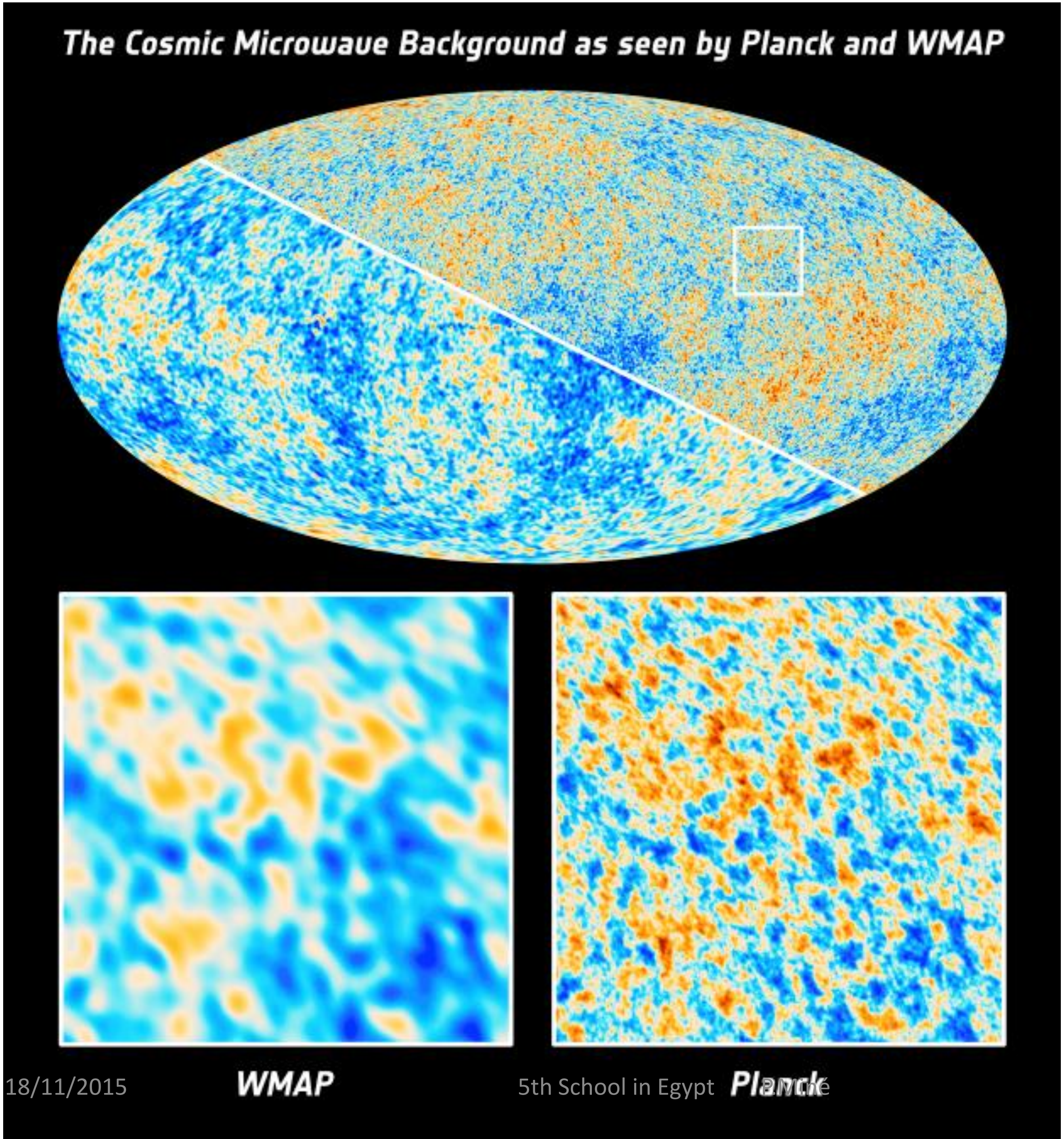
the spectral shape is not modified, number of photons is constant
($E = h\,c\,/\,\lambda$), but T becomes T'

THE FIRST LIGHT



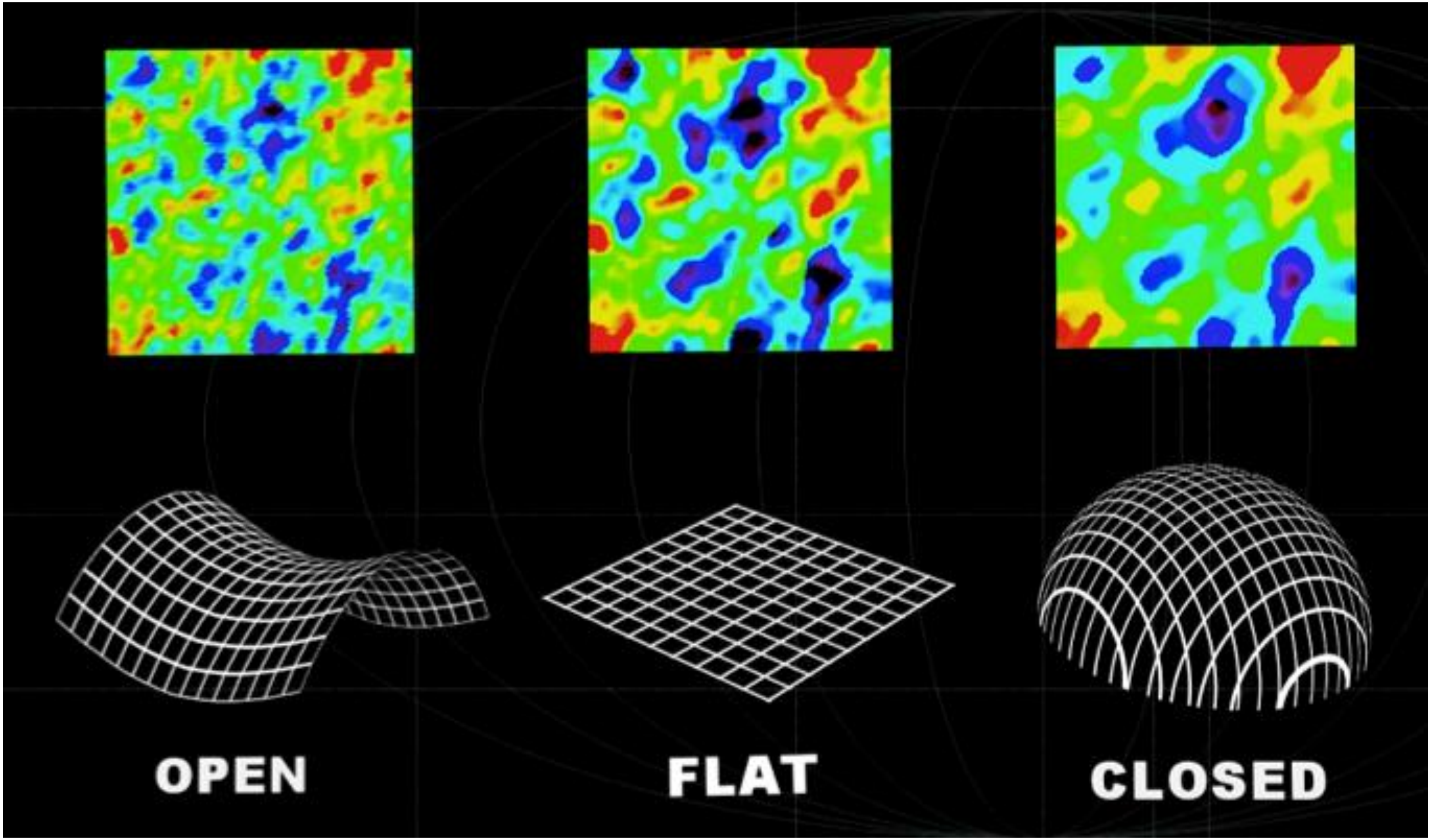
photons run at the speed of light and are red shifted
galaxies are scattered while keeping their size

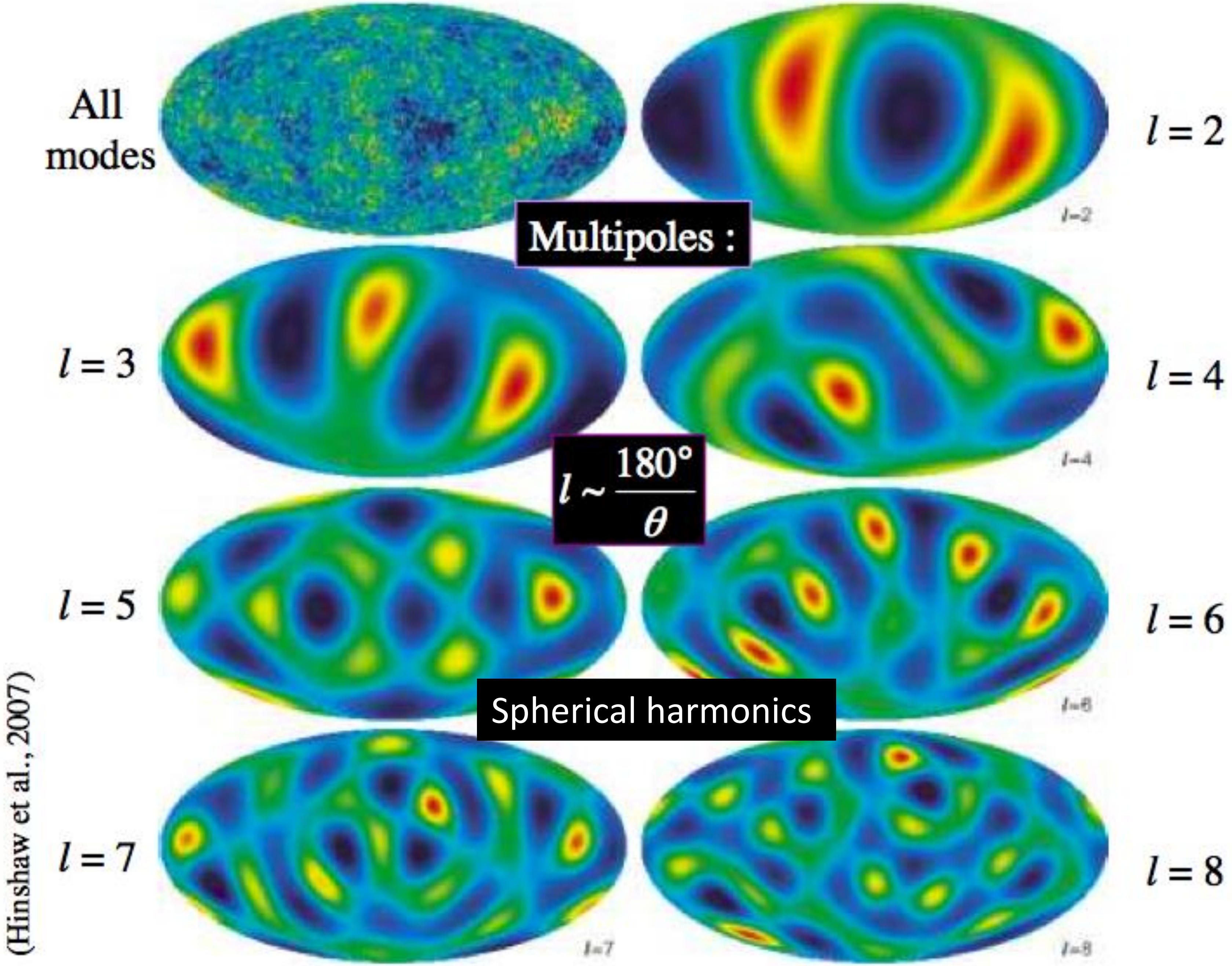
analogy of an inflated balloon (2D finite universe)



What can we learn from CMB non homogeneities ?

THE FIRST LIGHT

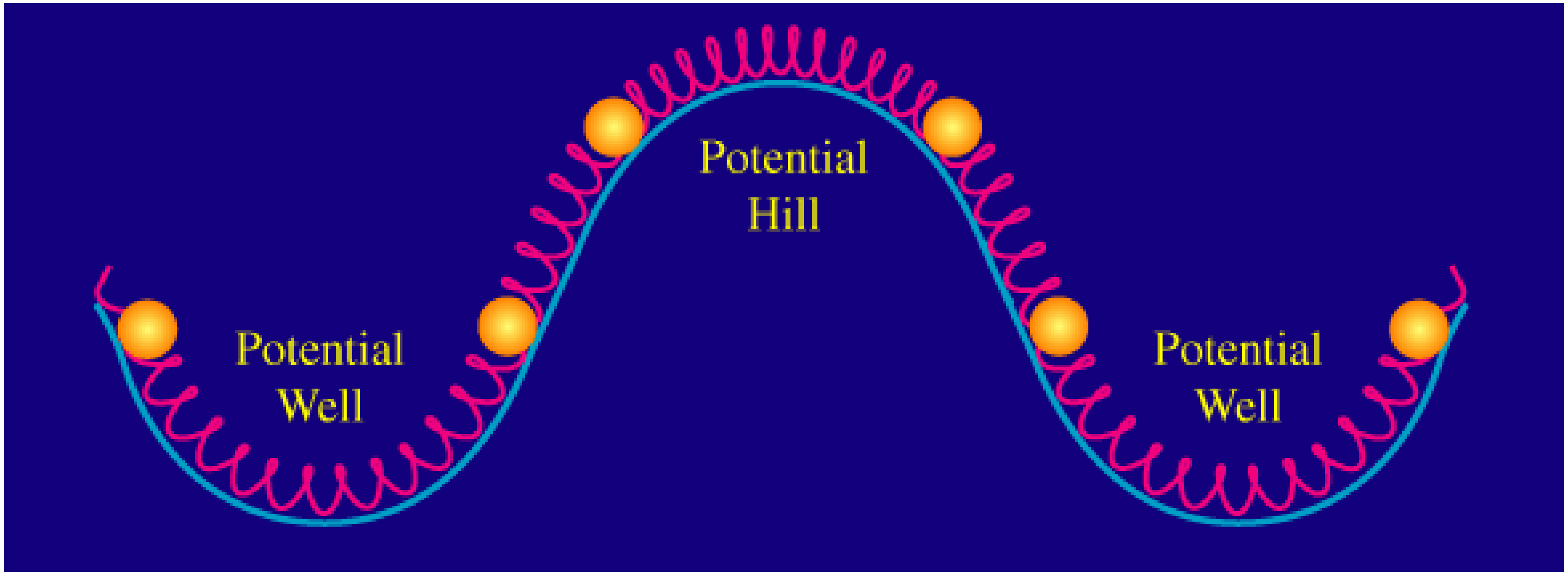



All modes
l = 2
Multipoles :
l = 3
l = 4
$l \sim \frac{180°}{\theta}$
l = 5
l = 6
Spherical harmonics
l = 7
l = 8
(Hinshaw et al., 2007)

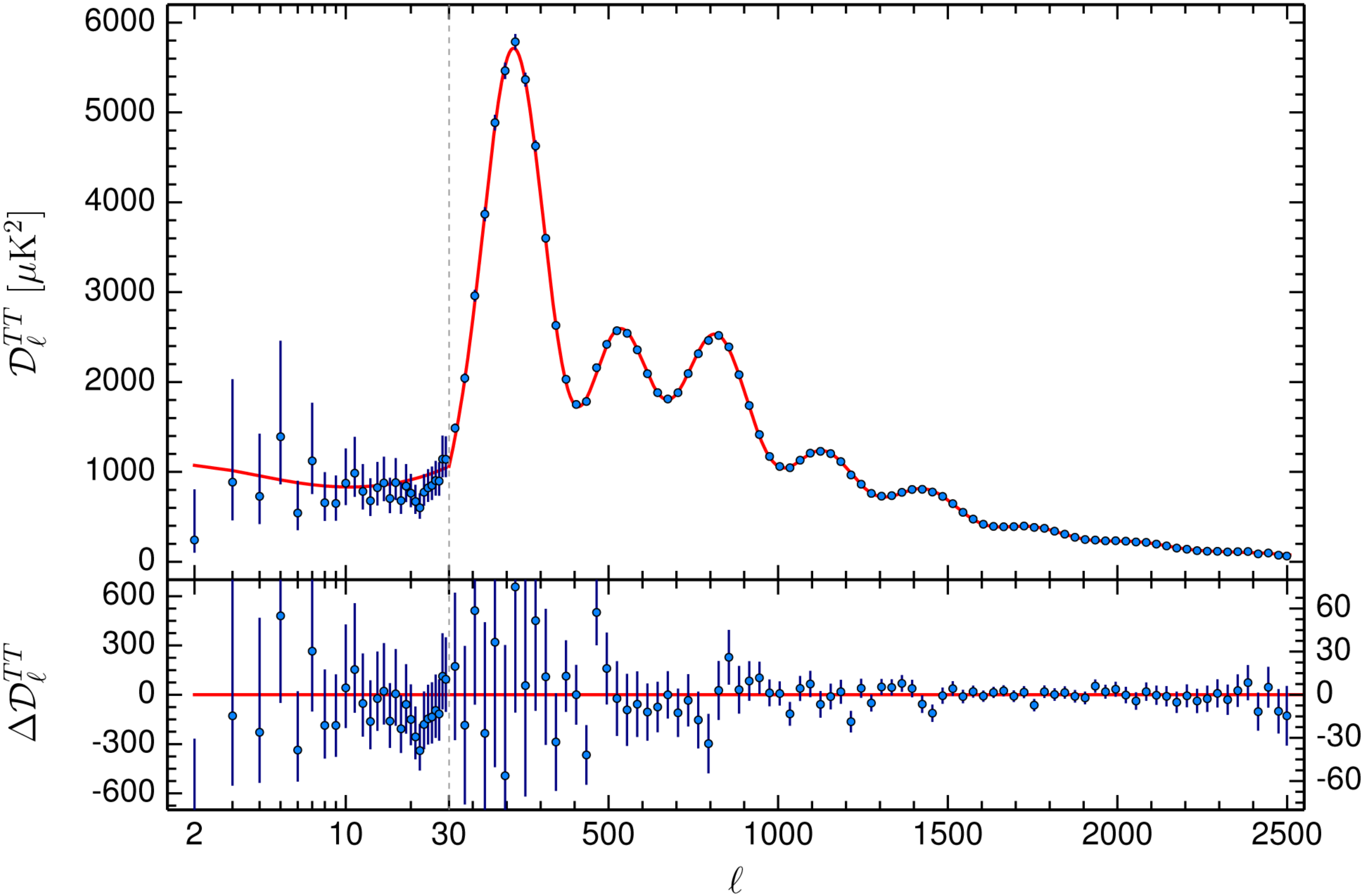
THE FIRST LIGHT

gravity (baryons) and pressure (photons) create oscillations in photon-baryon fluid

sound waves



THE FIRST LIGHT



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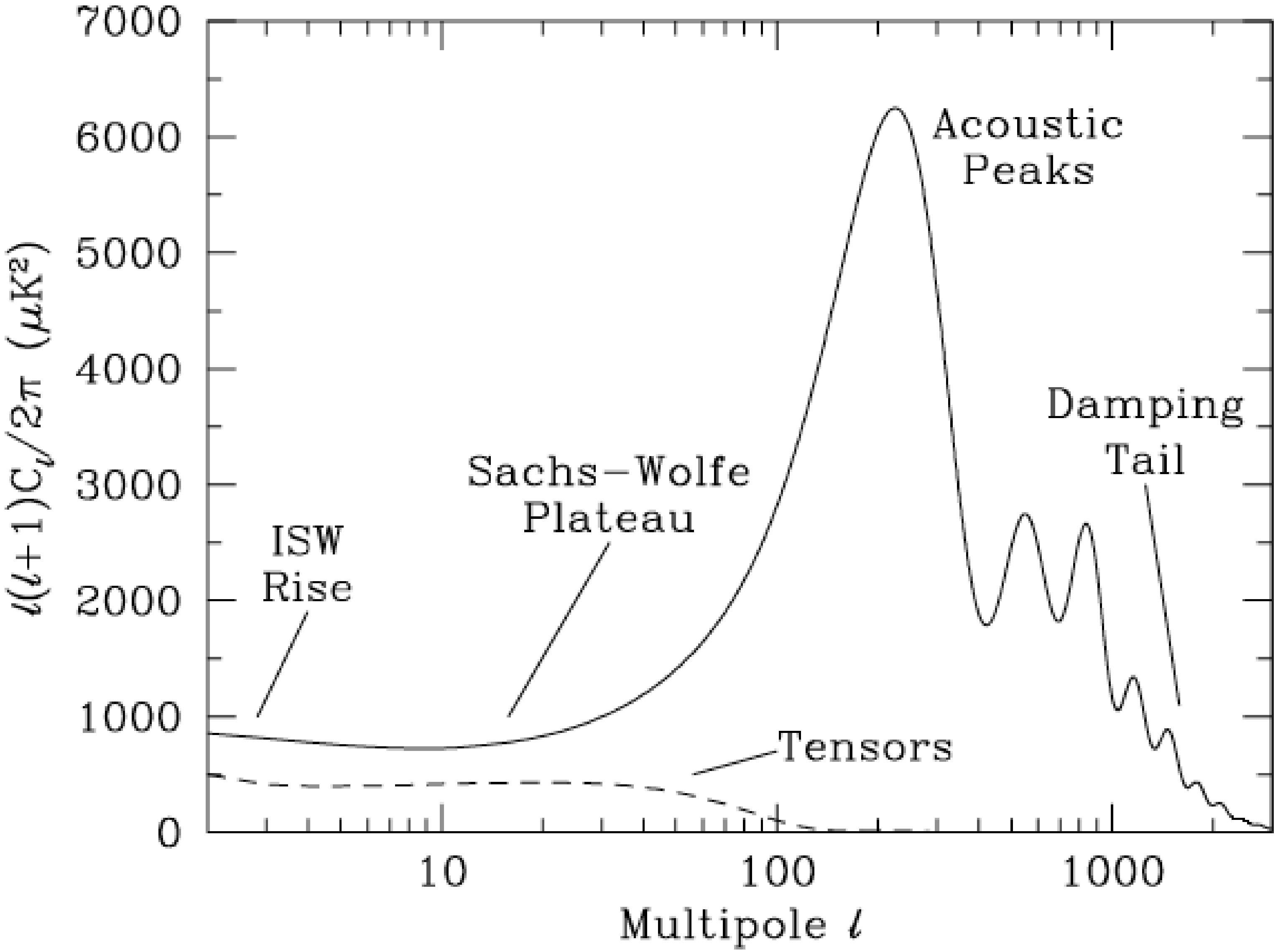
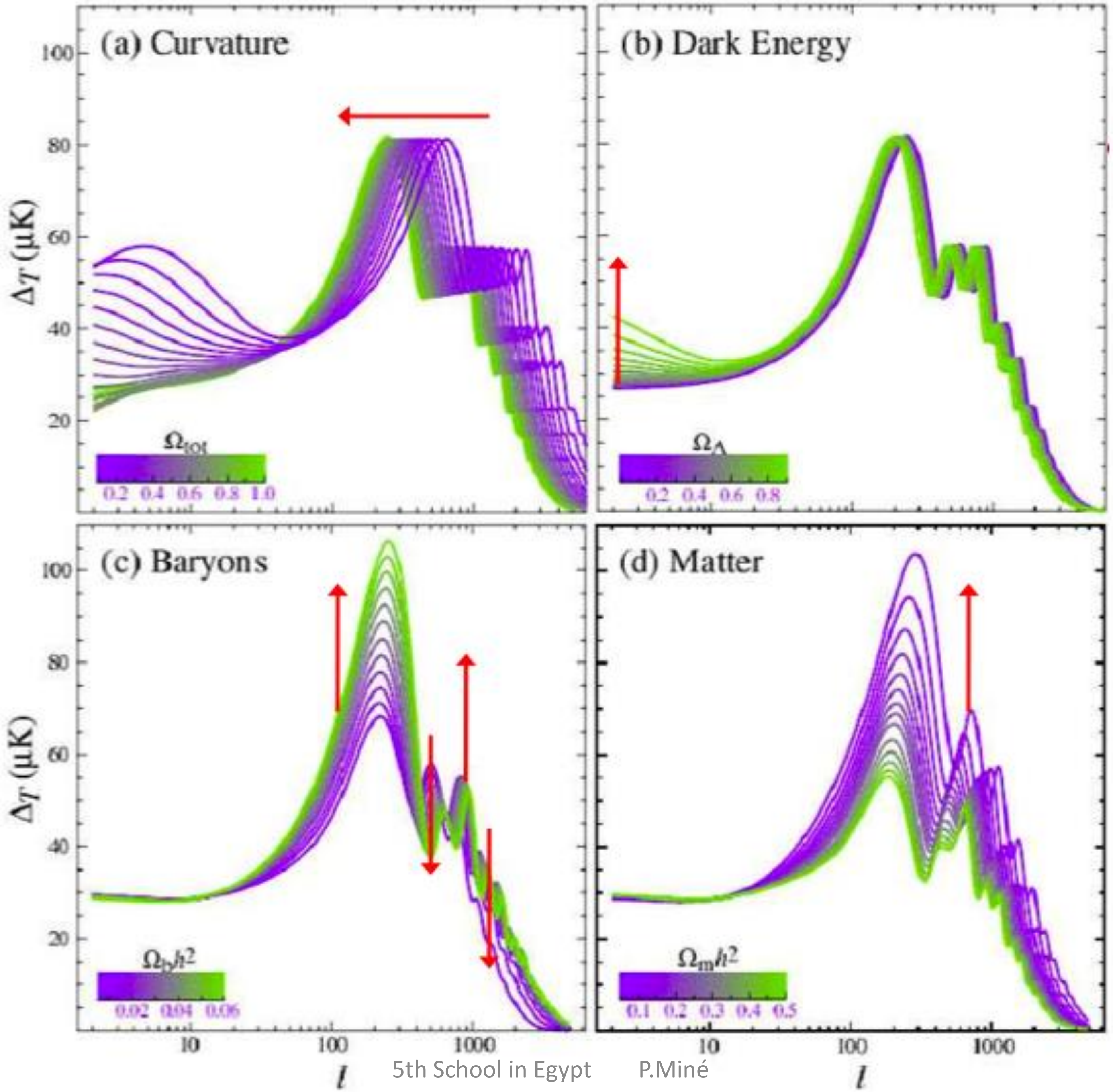
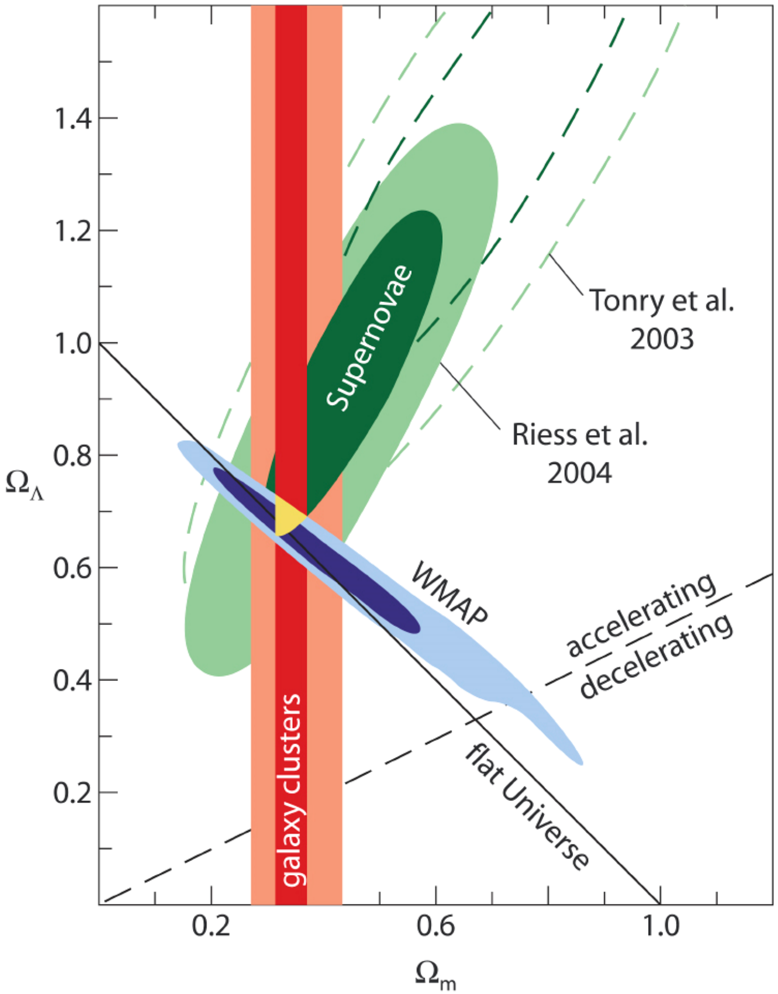




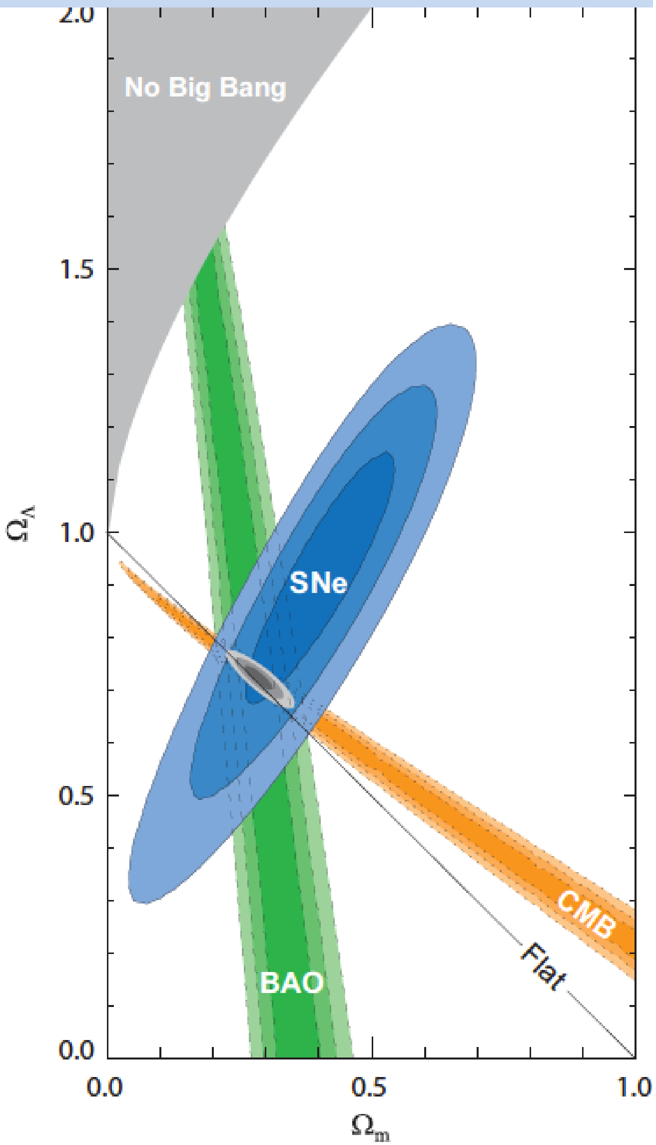
(a) Curvature
(b) Dark Energy
(c) Baryons
(d) Matter
Δ_T (μK)
Δ_T (μK)
Ω_{tot}
0.2 0.4 0.6 0.8 1.0
Ω_Λ
0.2 0.4 0.6 0.8
$\Omega_b h^2$
0.02 0.04 0.06
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5
l
l

THE FIRST LIGHT

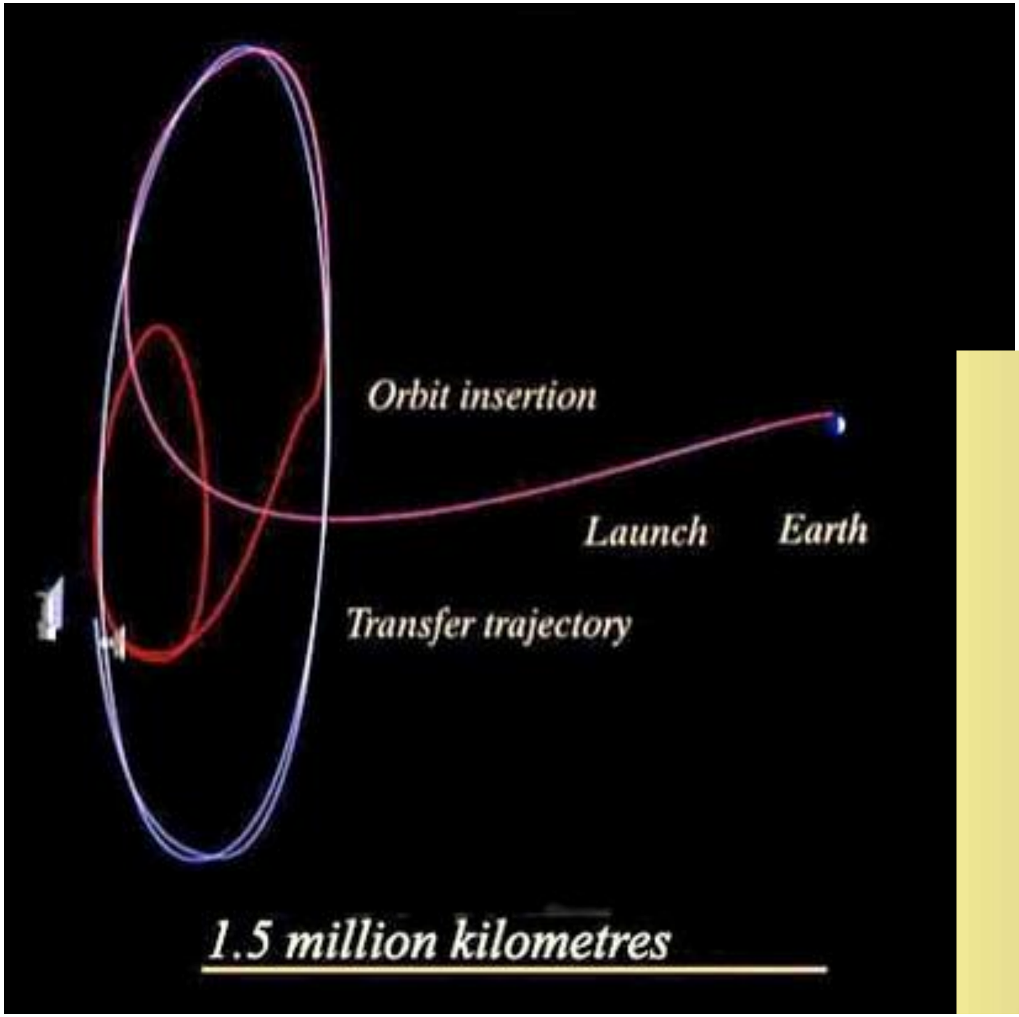


Constraining the Cosmological Parametres

ESO PR Photo 18d/04 (3 June 2004)

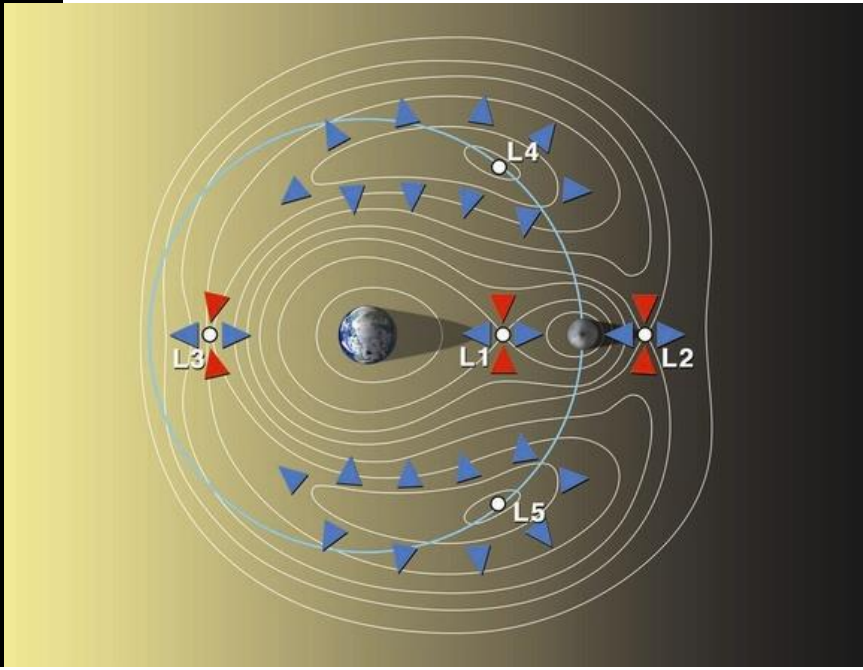


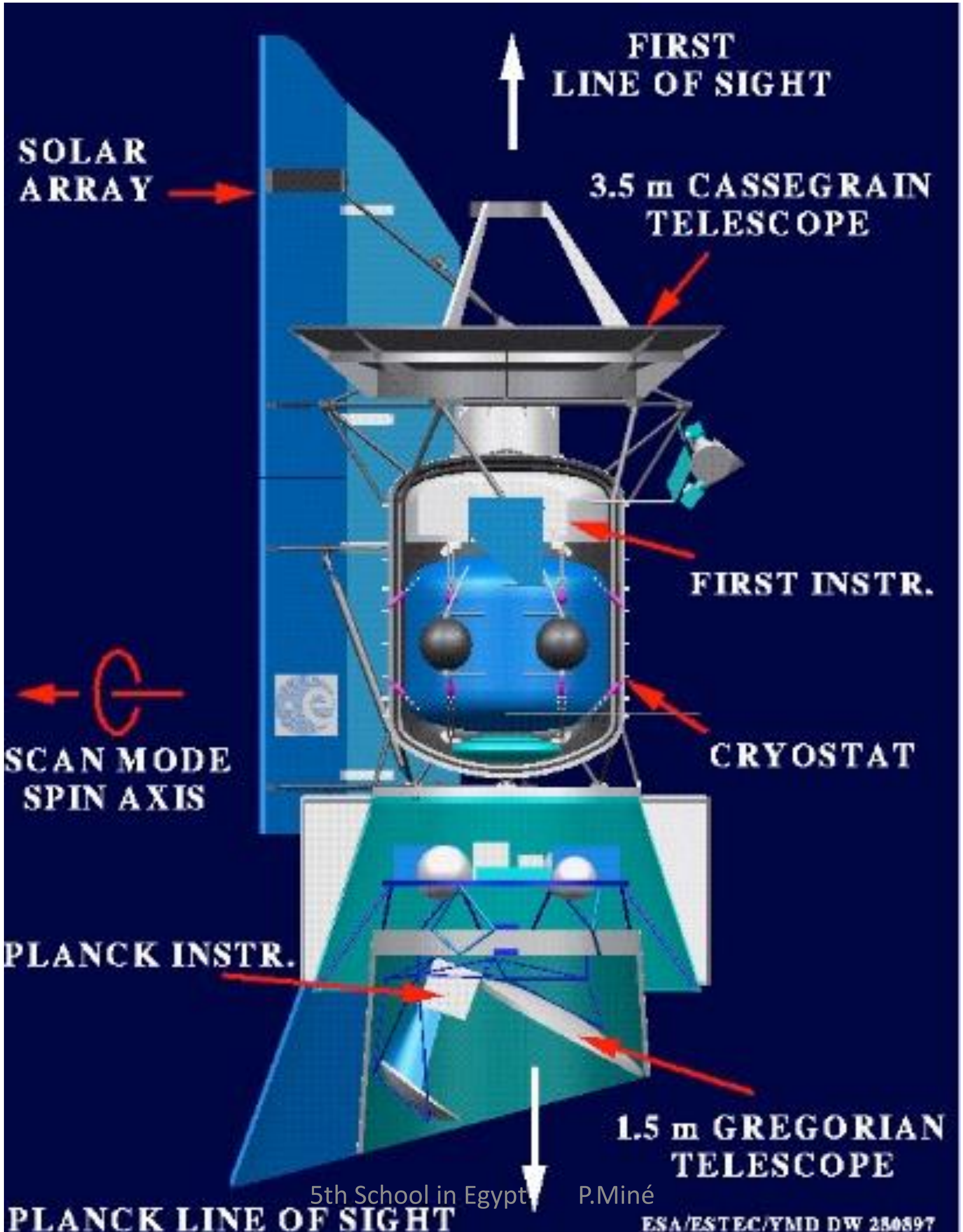
PLANCK MISSION



Lagrange point L2

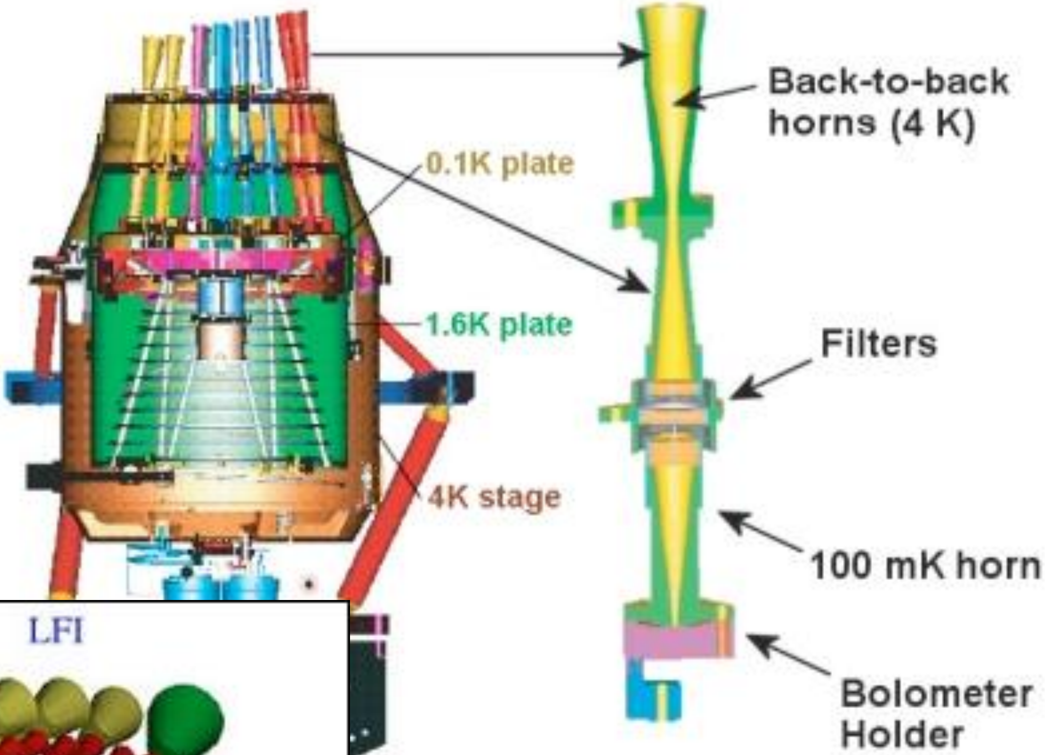
protected of Sun light and background

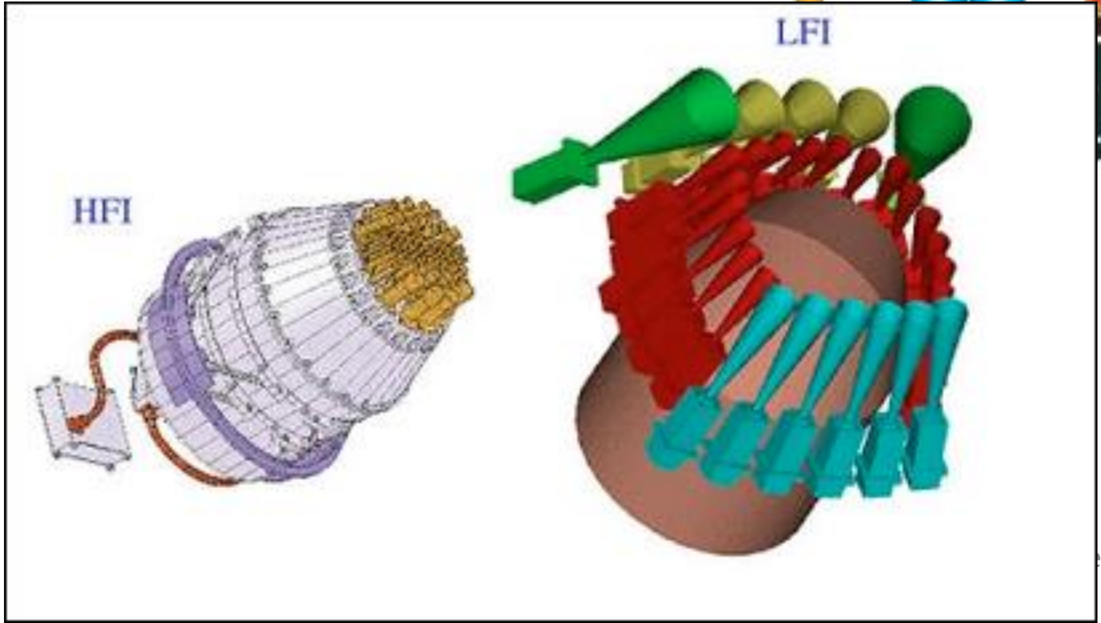



FIRST
LINE OF SIGHT
SOLAR
ARRAY
3.5 m CASSEGRAIN
TELESCOPE
FIRST INSTR.
CRYOSTAT
SCAN MODE
SPIN AXIS
PLANCK INSTR.
1.5 m GREGORIAN
TELESCOPE
PLANCK LINE OF SIGHT
ESA/ESTEC/YMD DW 280897

PLANCK MISSION

bolometers measure
the thermal power

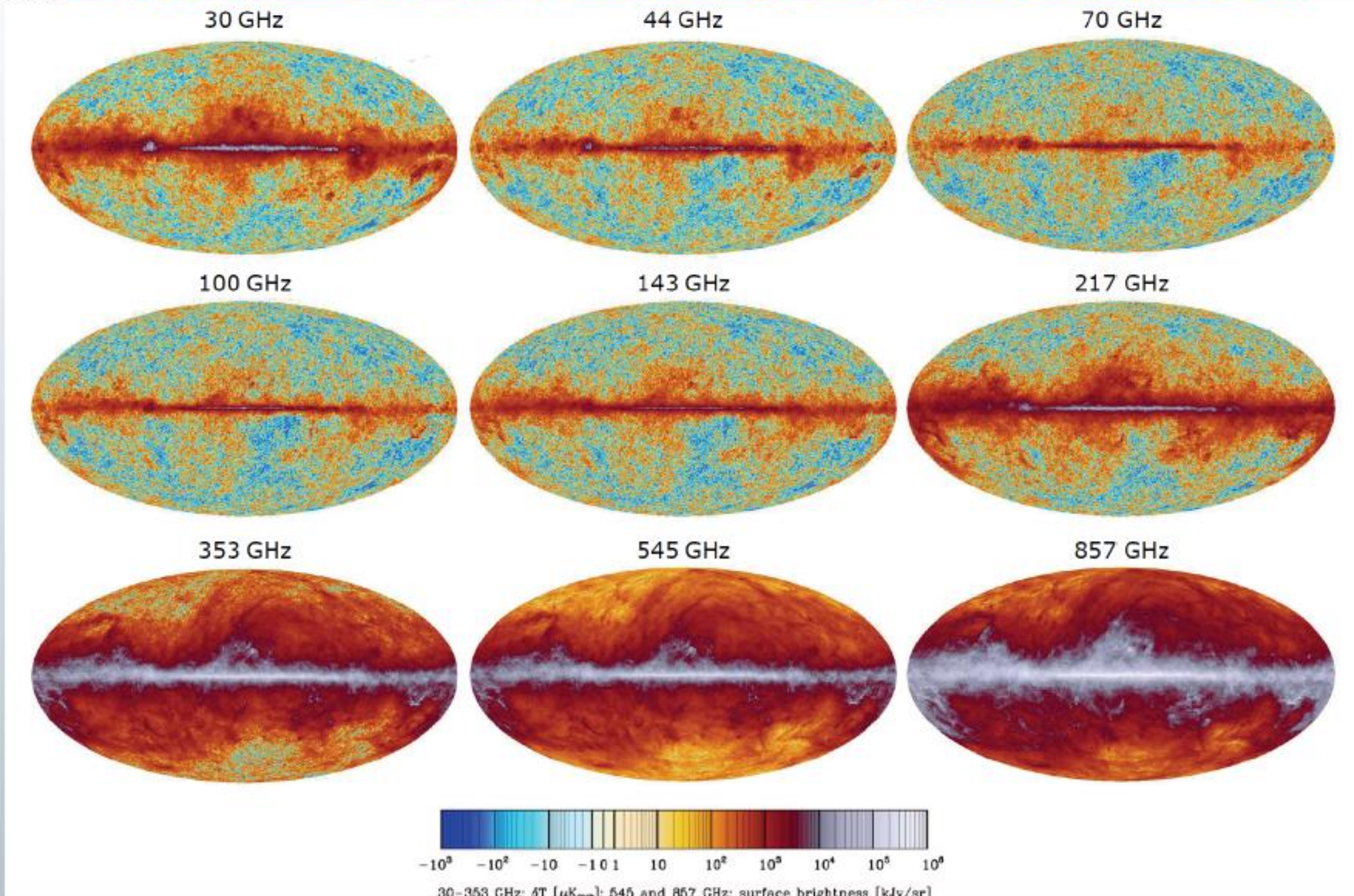




High Frequency Instrument

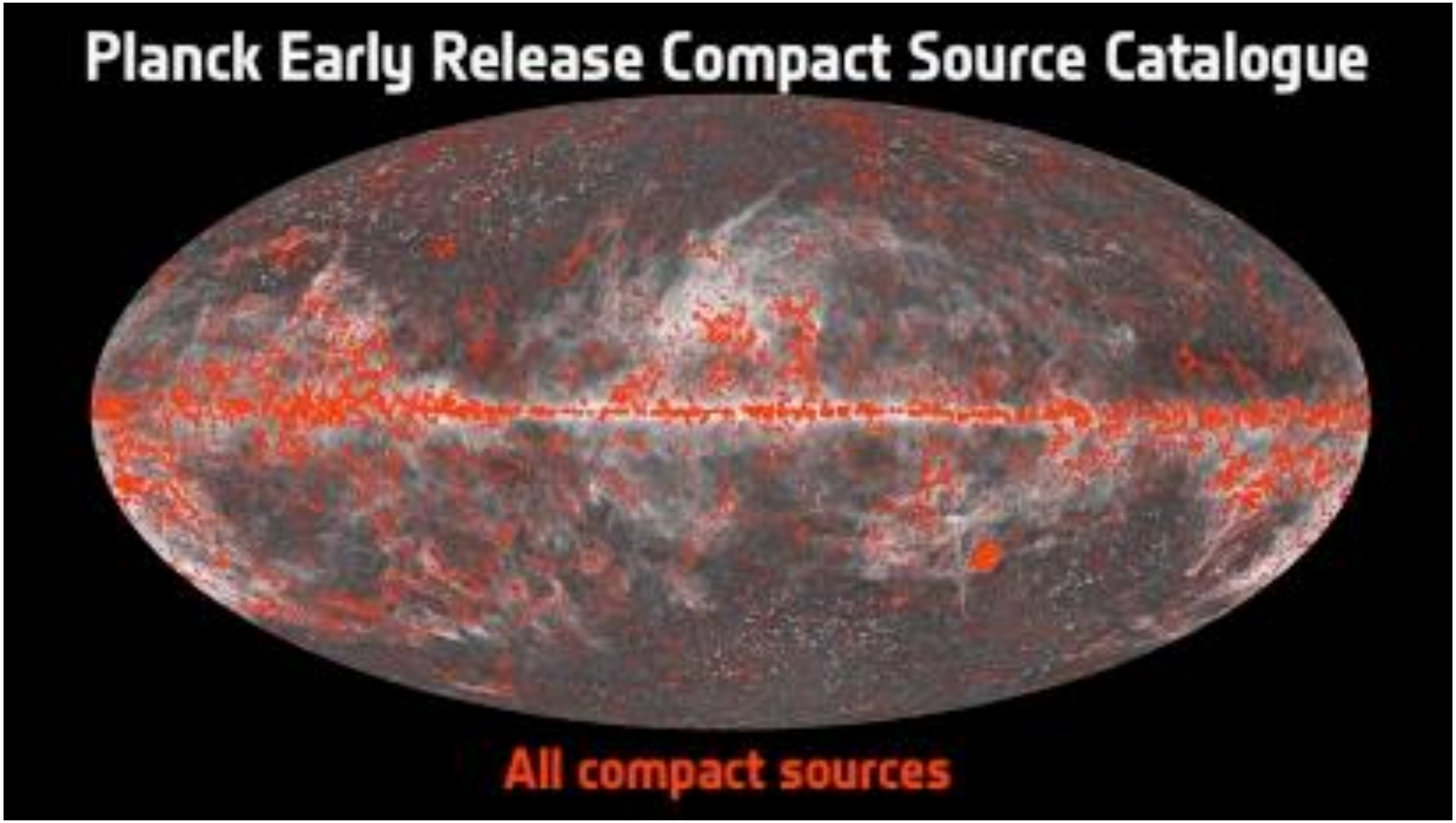
Low Frequency Instrument

Planck 2015 temperature maps

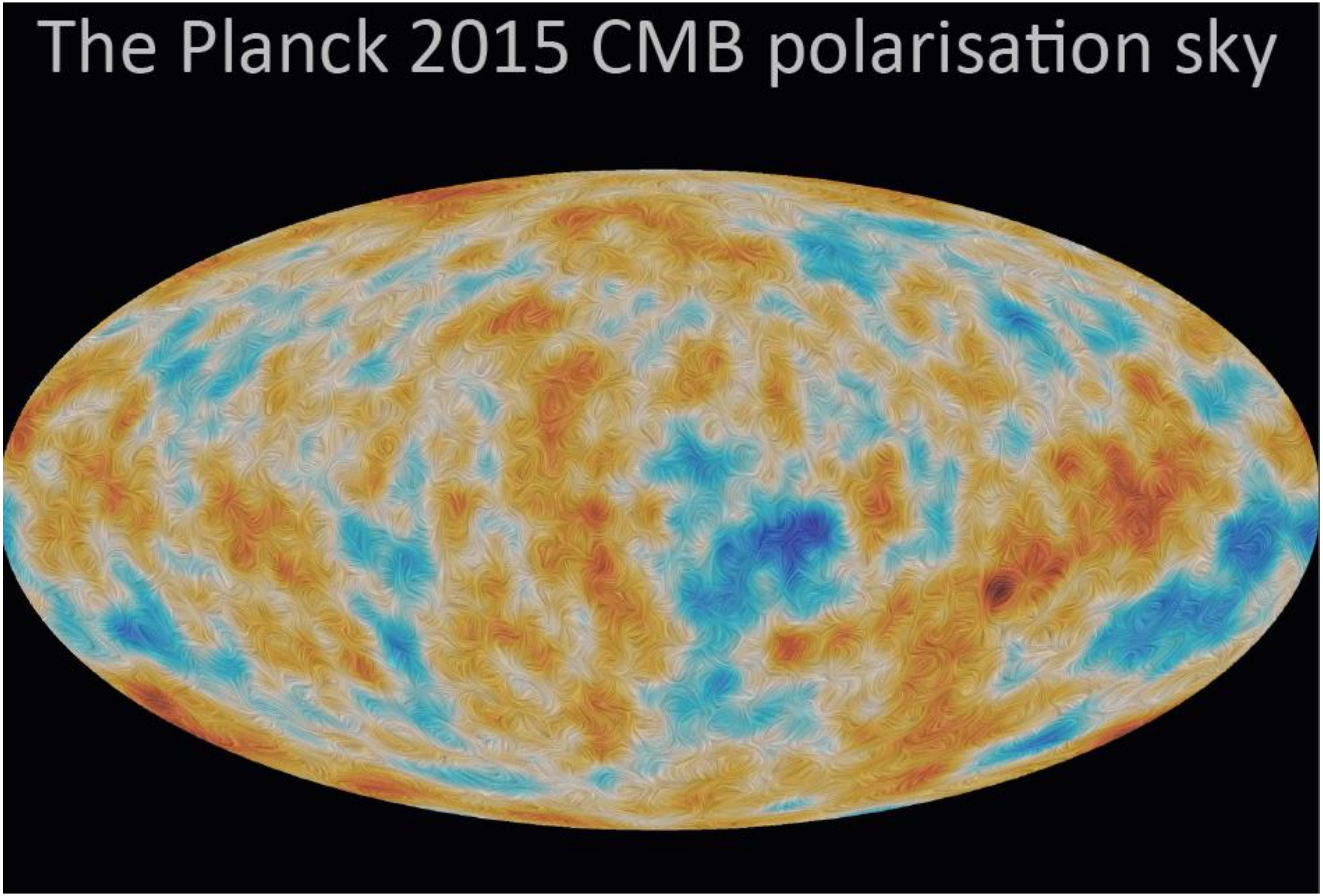


PLANCK MISSION

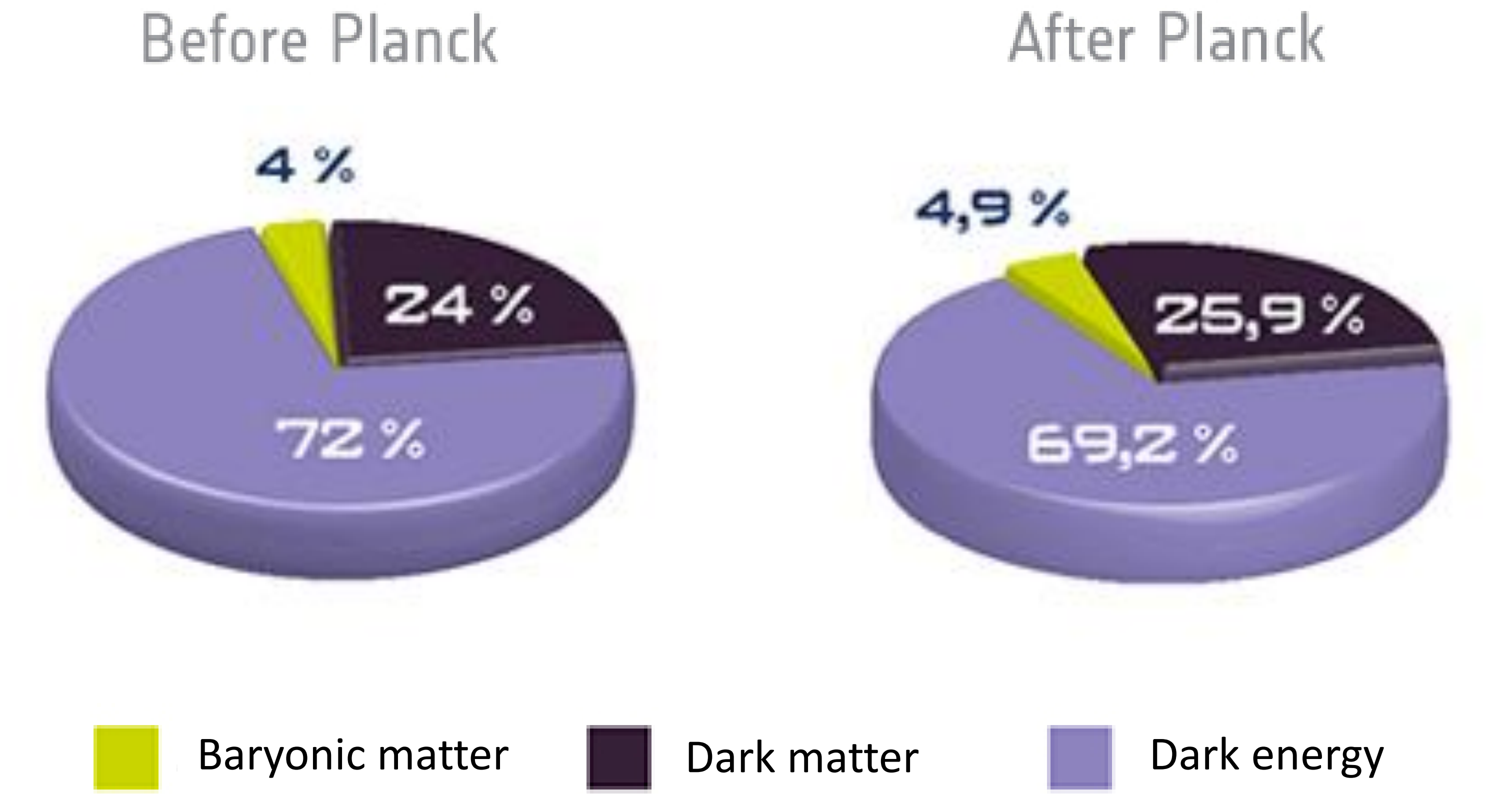
Filtering the data



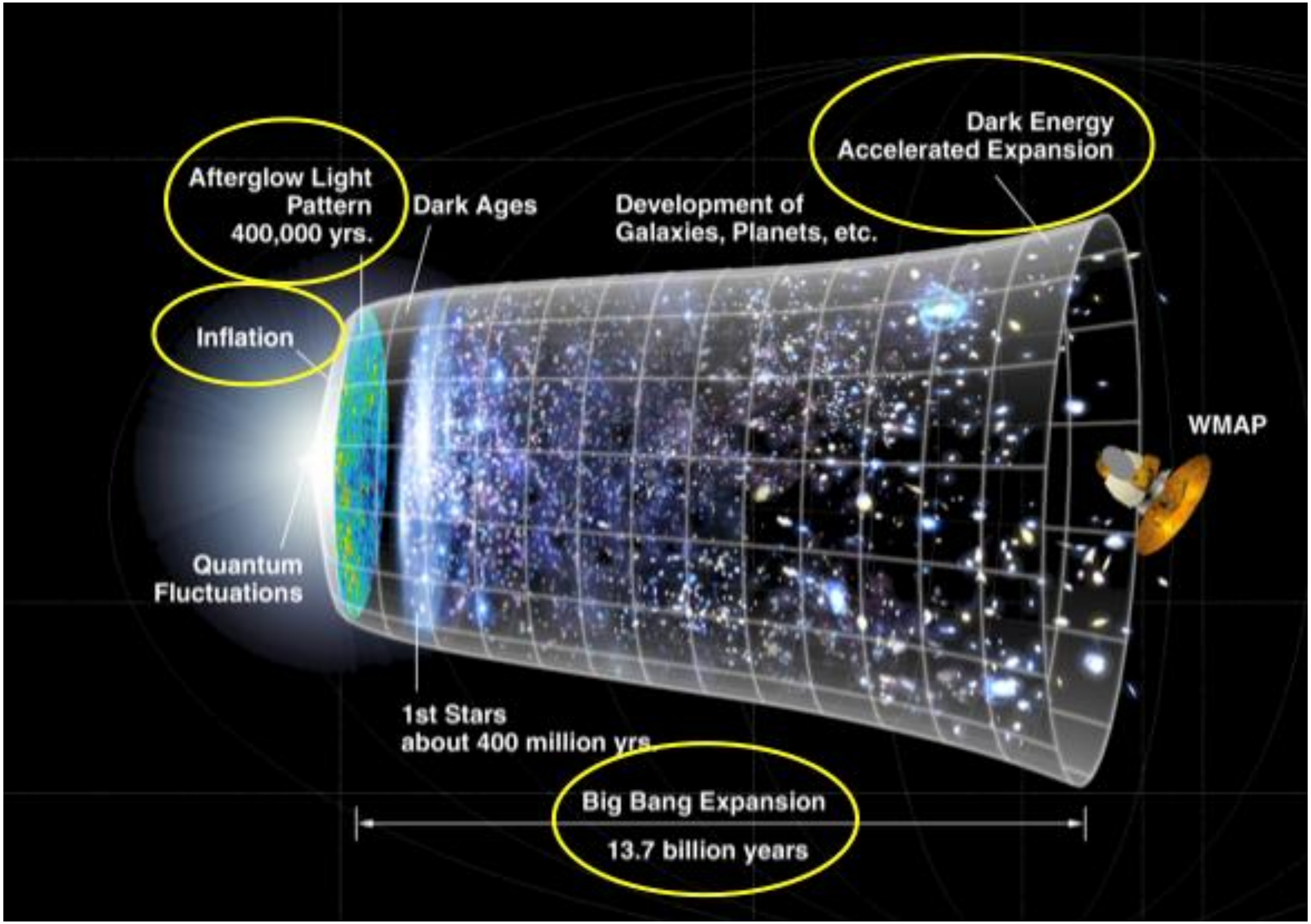
PLANCK MISSION



WHAT WE KNOW (AND DON'T)



WHAT WE KNOW (AND DON'T)



WHAT WE KNOW (AND DON'T)

What are the constituents of the baryonic dark matter ?

What are the constituents of the non baryonic dark matter ?
Can we explain it by new particles, can we produce them in laboratory ?

Is dark energy due to a cosmological constant ?
or is this "constant" variable ?

How did a uniform universe became non uniform (structure formation) ?

How an exponential dilatation happened at the beginning "inflation" ?

What theory can we use for instant zero (Planck era)
when quantum effect cannot be neglected in gravitation ?

BACKUP

Results (March 2014) from BICEP2 at the South Pole
Background Imaging of Cosmic Galactic Polarization

BACKUP

Generated in thermal equilibrium, the CMB is not polarized

In General Relativity, gravitational waves are tensors → polarized
If produced by inflation 10^{-35} s after the Big Bang, they distort the CMB

2015 Planck results in the whole sky invalidate BICEP2 polarization data