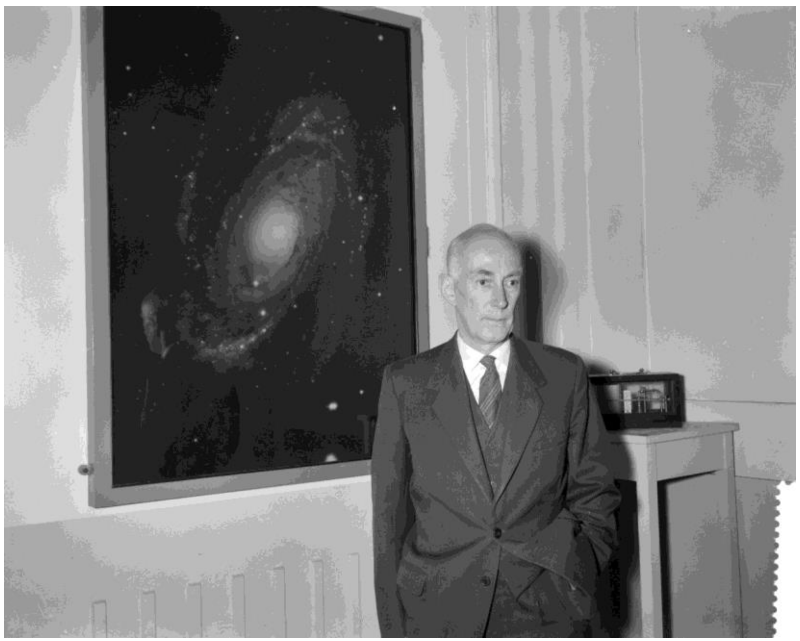
DARK MATTER (1)

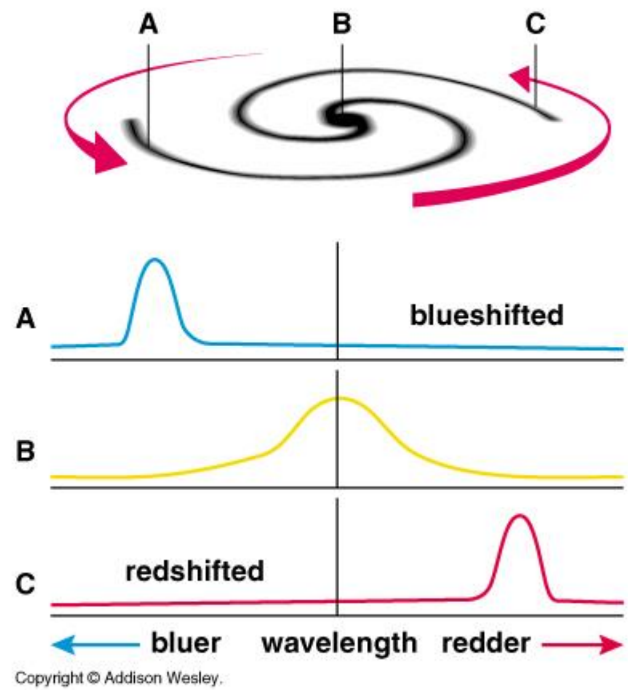
A long history, … not finished

Philippe Miné, Laboratoire Leprince-Ringuet, France

DARK MATTER EVIDENCE

Gravitation is the major interaction structuring the Universe



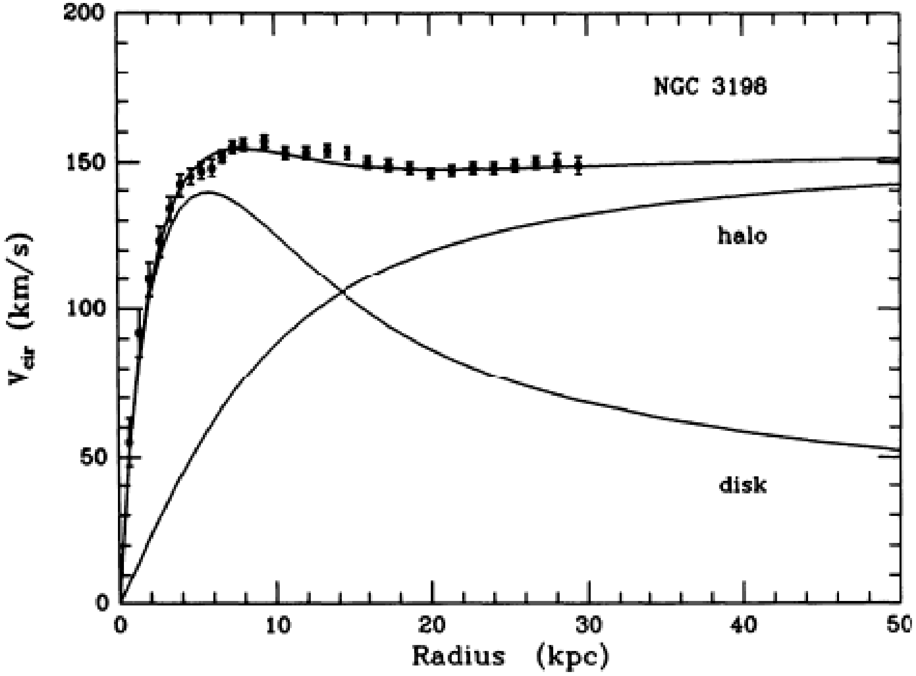


Measure of mass and rotation
of the stars of our galaxy, Milky Way
Oort 1932

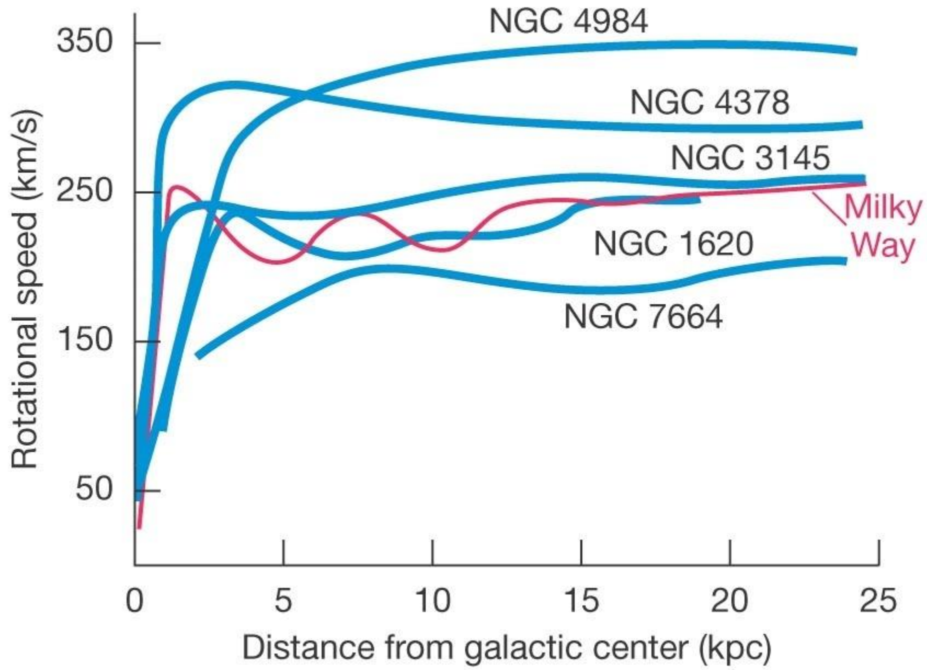
Rubin 1970 : idem
for other galaxies

$\Rightarrow$ 90% of “dark matter“

DARK MATTER EVIDENCE



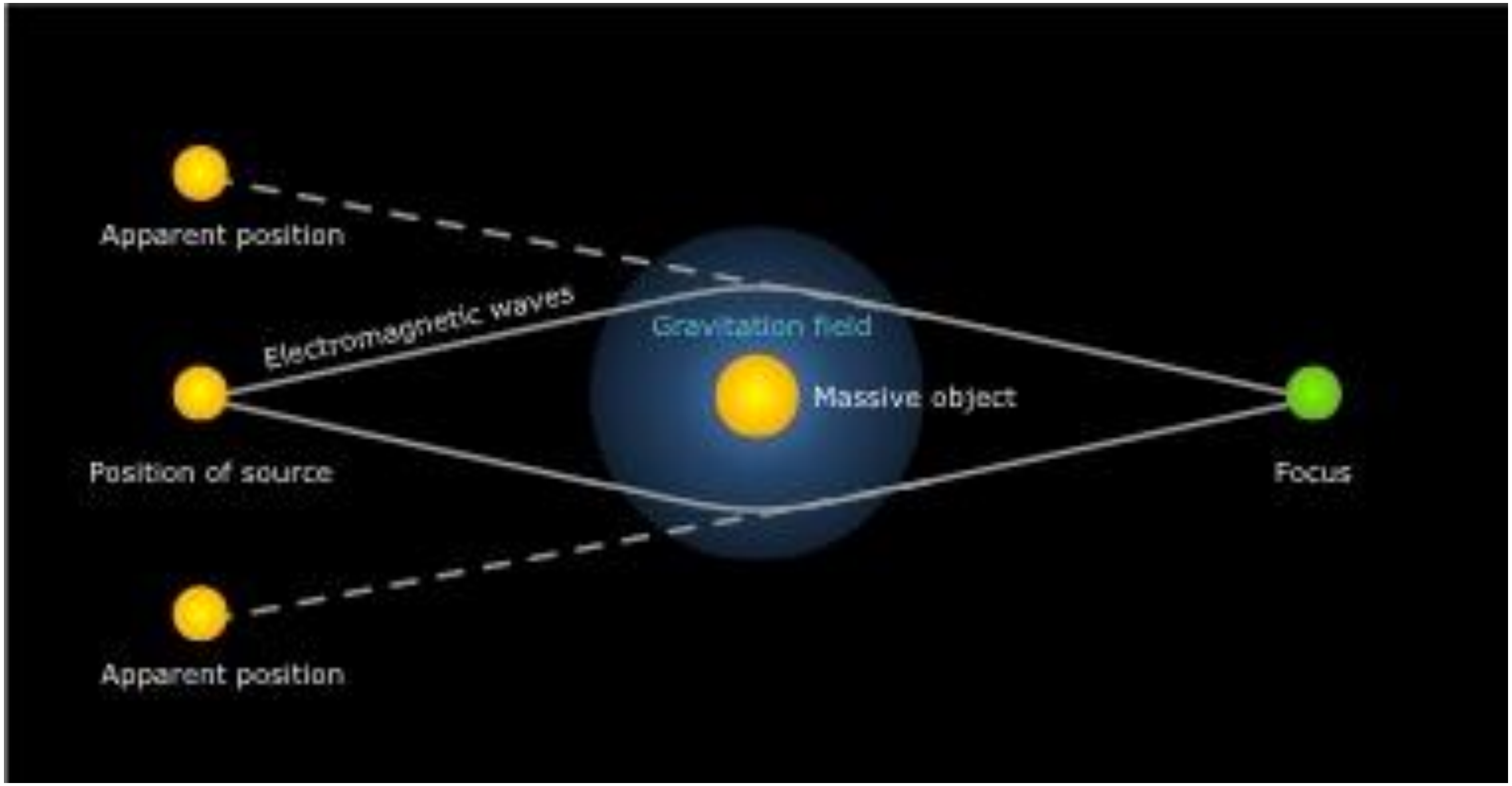
rotation curve of galaxy NGC 3198



Zwicky, same result
for galaxy clusters (1933)

DARK MATTER EVIDENCE

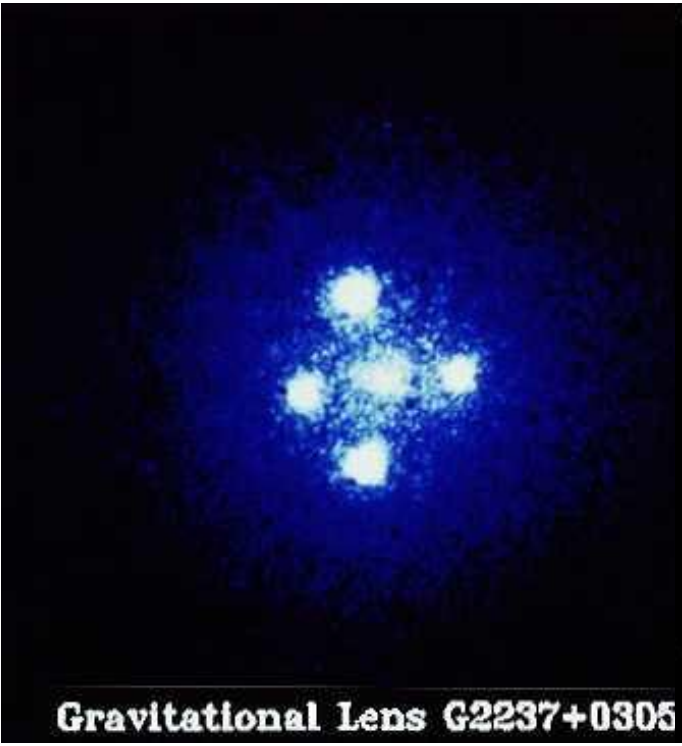
General relativity : deviation of light by gravitational force



Measure of masses for very distant objects by light gravitational deviation
⇒ dark matter

DARK MATTER EVIDENCE

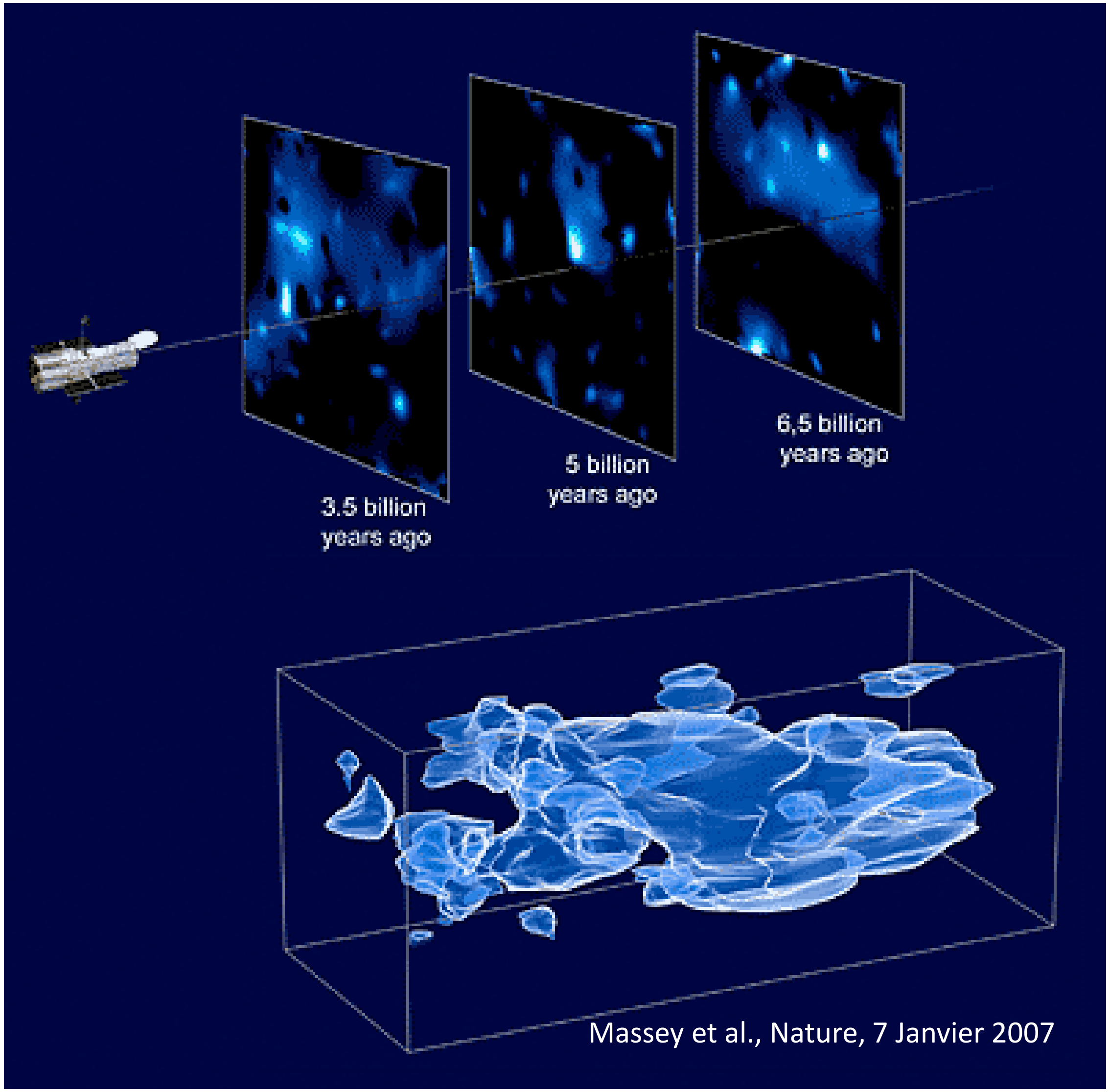
Gravitational mirages



Einstein cross

cluster of galaxies Abell 2218

DARK MATTER EVIDENCE



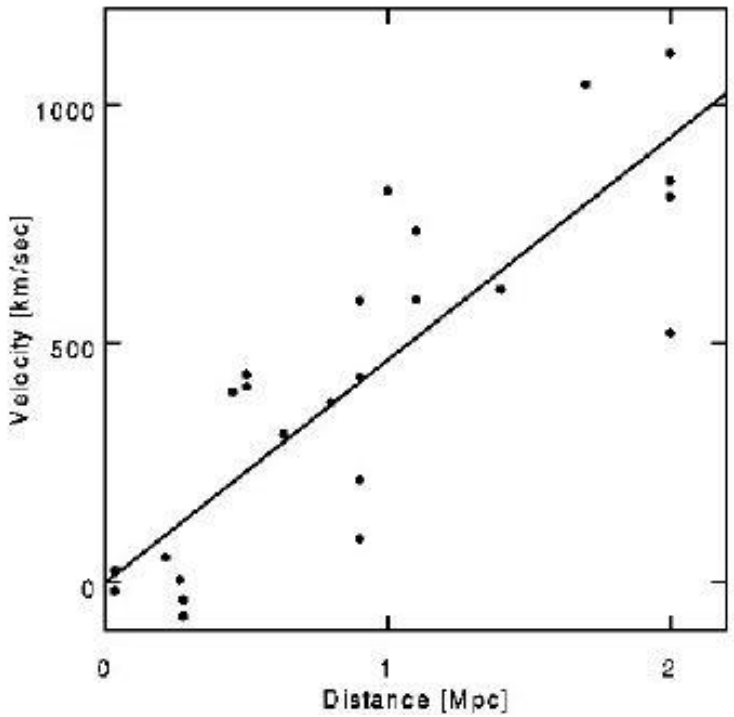
3D map of dark matter
by HST
(Hubble Space Telescope)

red shifts are measured
by terrestrial telescopes

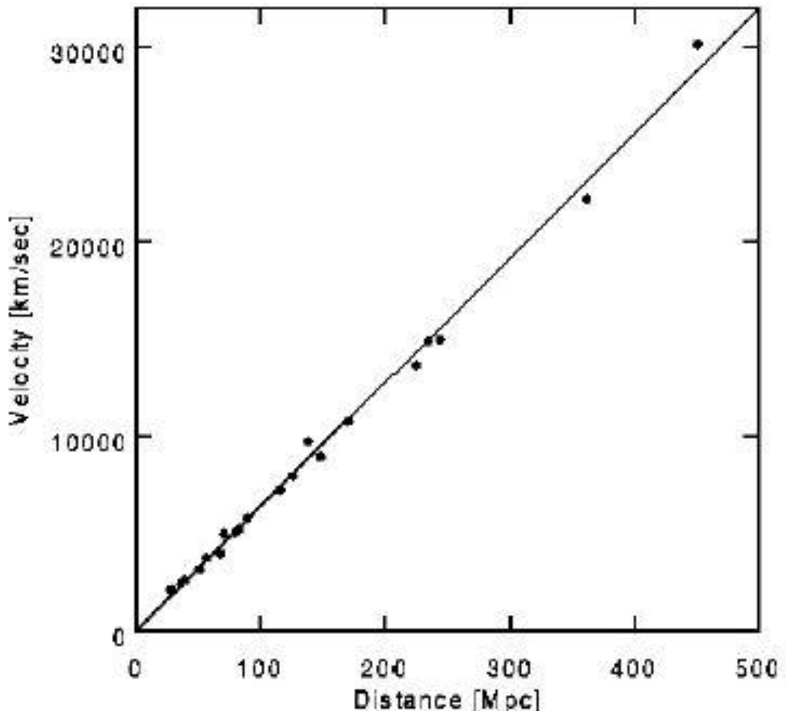
COSMOLOGY

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

Hubble constant = 67,8 ± 0.9 km s^{-1} Mpc^{-1} (Planck 2015 arXiv:1502.01589v3)



1929



1999

Freidmann-Lemaître : what is the cause of the expansion ?
static state is impossible, due to gravity of matter (could cause only contraction)

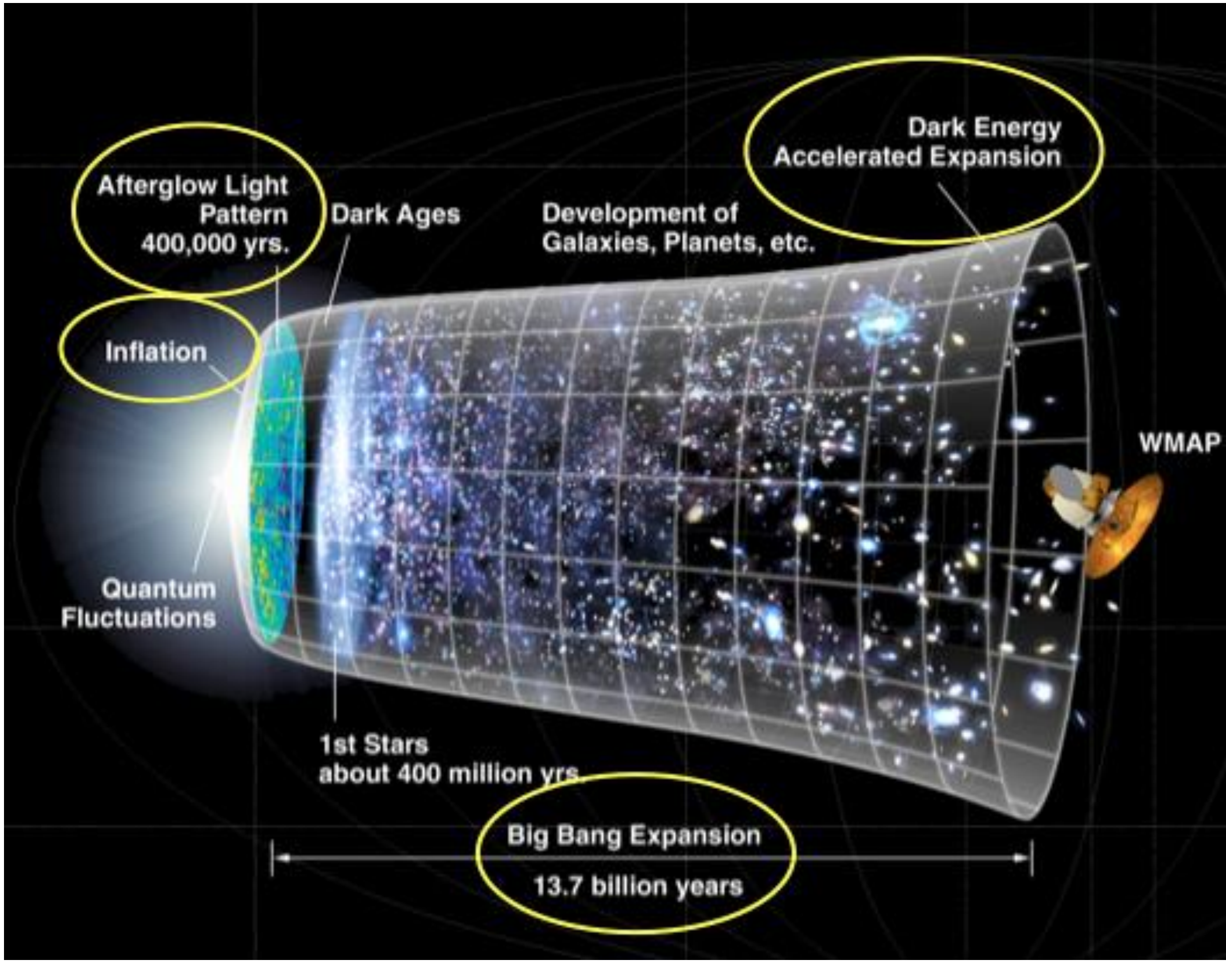
COSMOLOGY

When the Universe was much smaller

First theory by Gamow,
Alpher, Herman,
around 1940

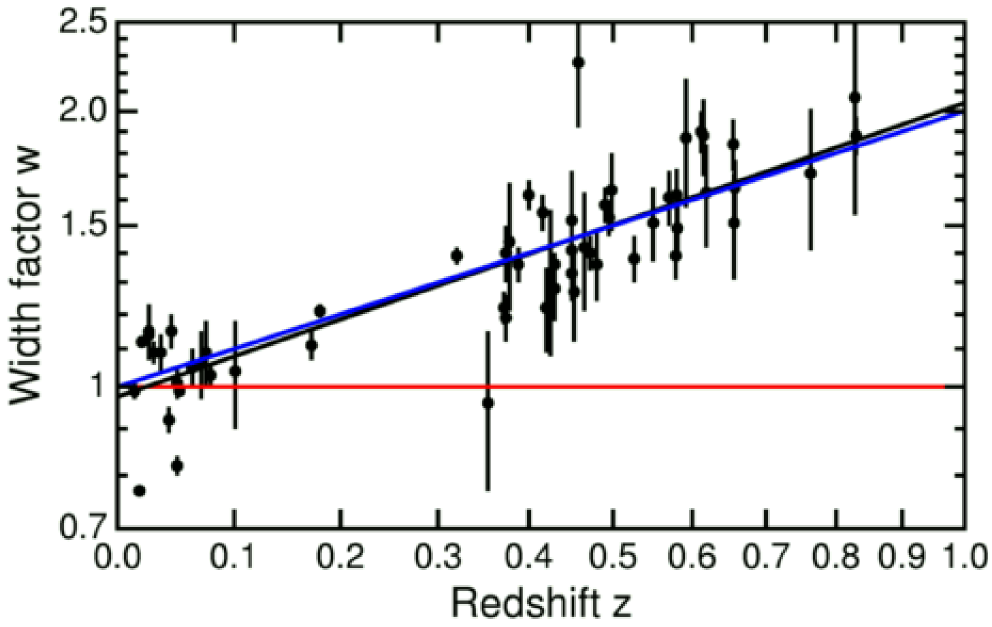
Understand stellar evolution,
application of nuclear physics,
around 1950

The initial ultra dense state
is hot, homogeneous,
like a compressed gas
application of statistical physics



ACCELERATING EXPANSION

A new method to measure very long distances : supernovae Ia



These explosive stars called "standard candles" :
- have the same characteristics everywhere (luminosity, period, …)
- are very bright,
can be seen from large distance

Periods of supernovae Ia (Supernovae Cosmology Project 2001)

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

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 $$F = -\frac{1}{3}\Lambda m r$$

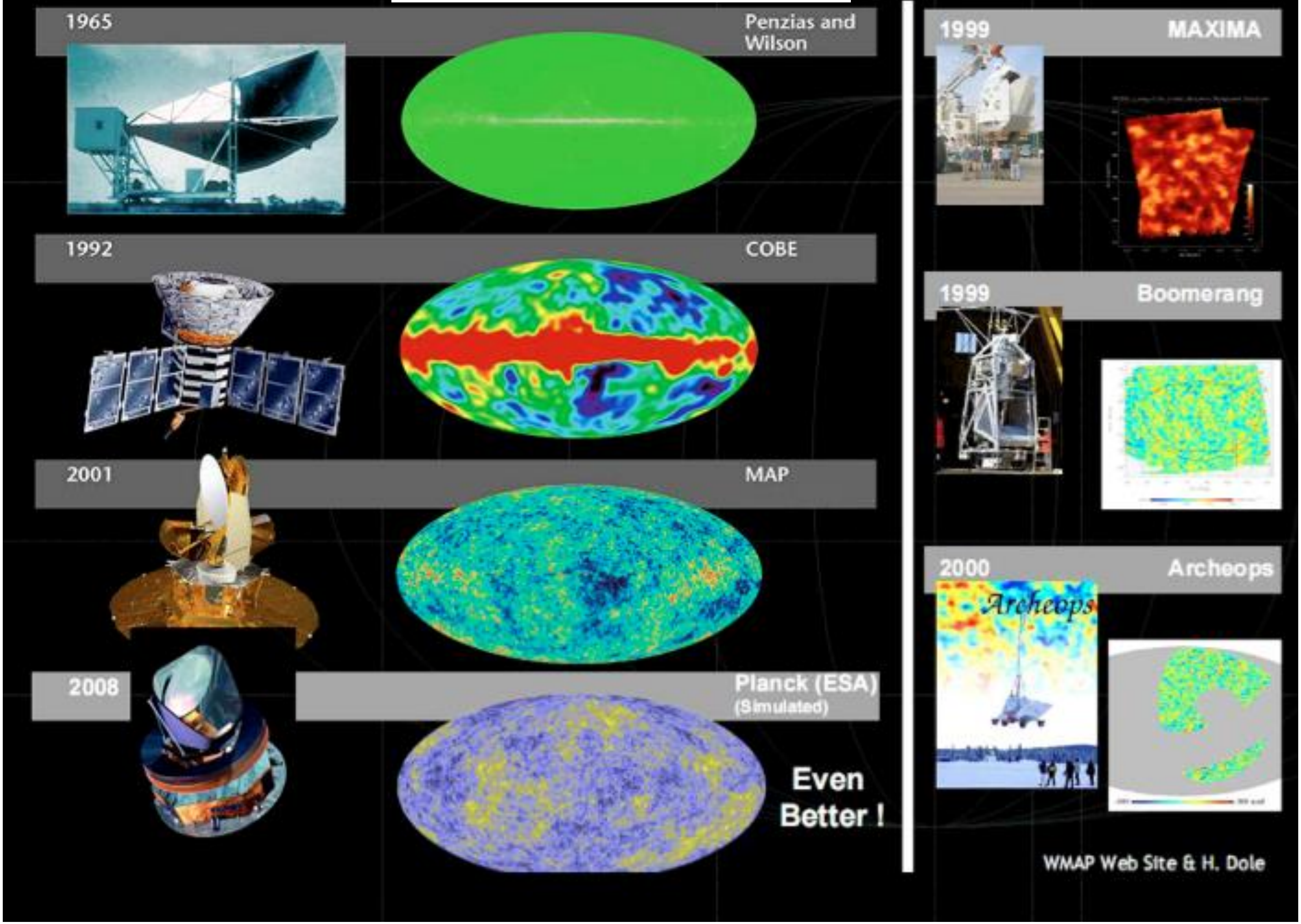
$\Rightarrow$ accelerating expansion equilibrates the self gravity of matter in the Universe

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 **"dark energy"**

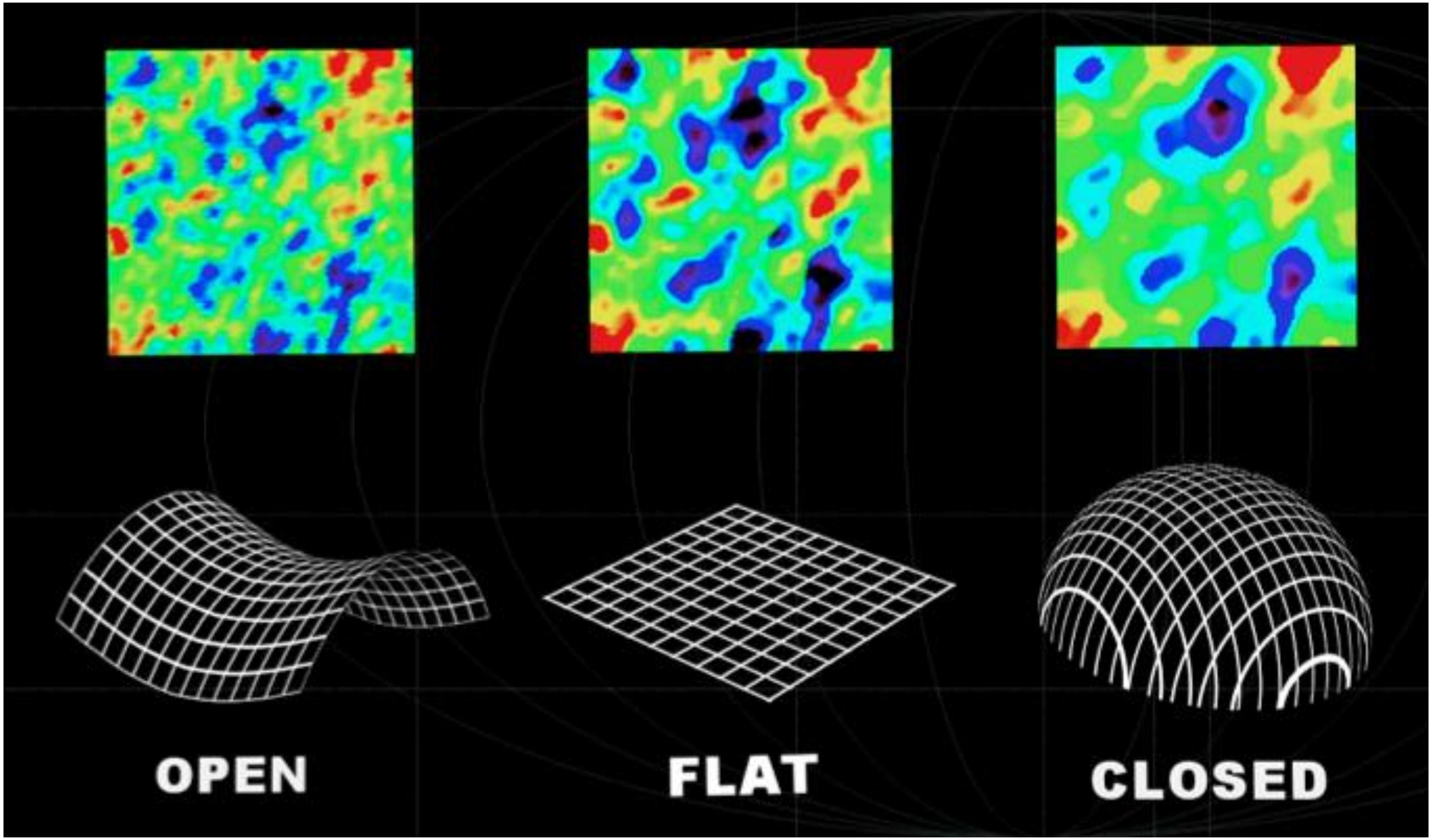
constant "vacuum density" = "negative pressure" $$\rho_v = -p_v = \frac{\Lambda}{8\pi G}$$

Cosmic Microwave Background



COSMOLOGY

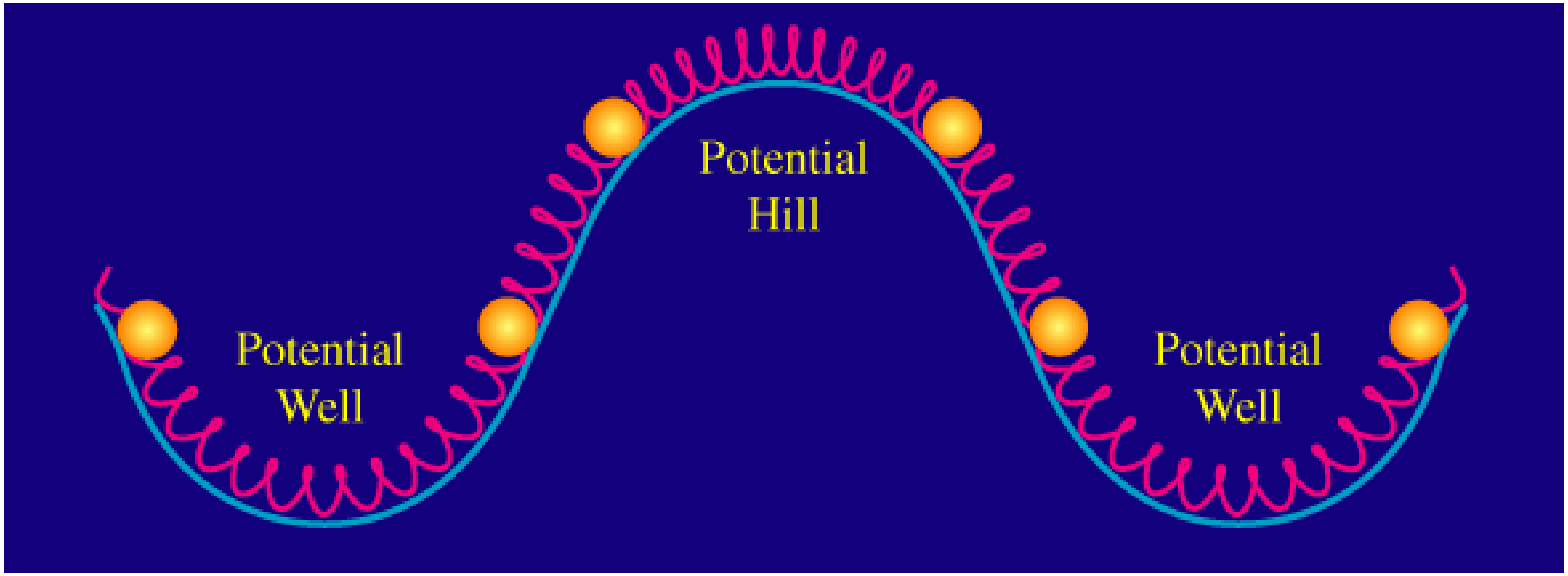
Non-Euclidian curvature of the Universe measured by CMB non-homogeneity



COSMOLOGY

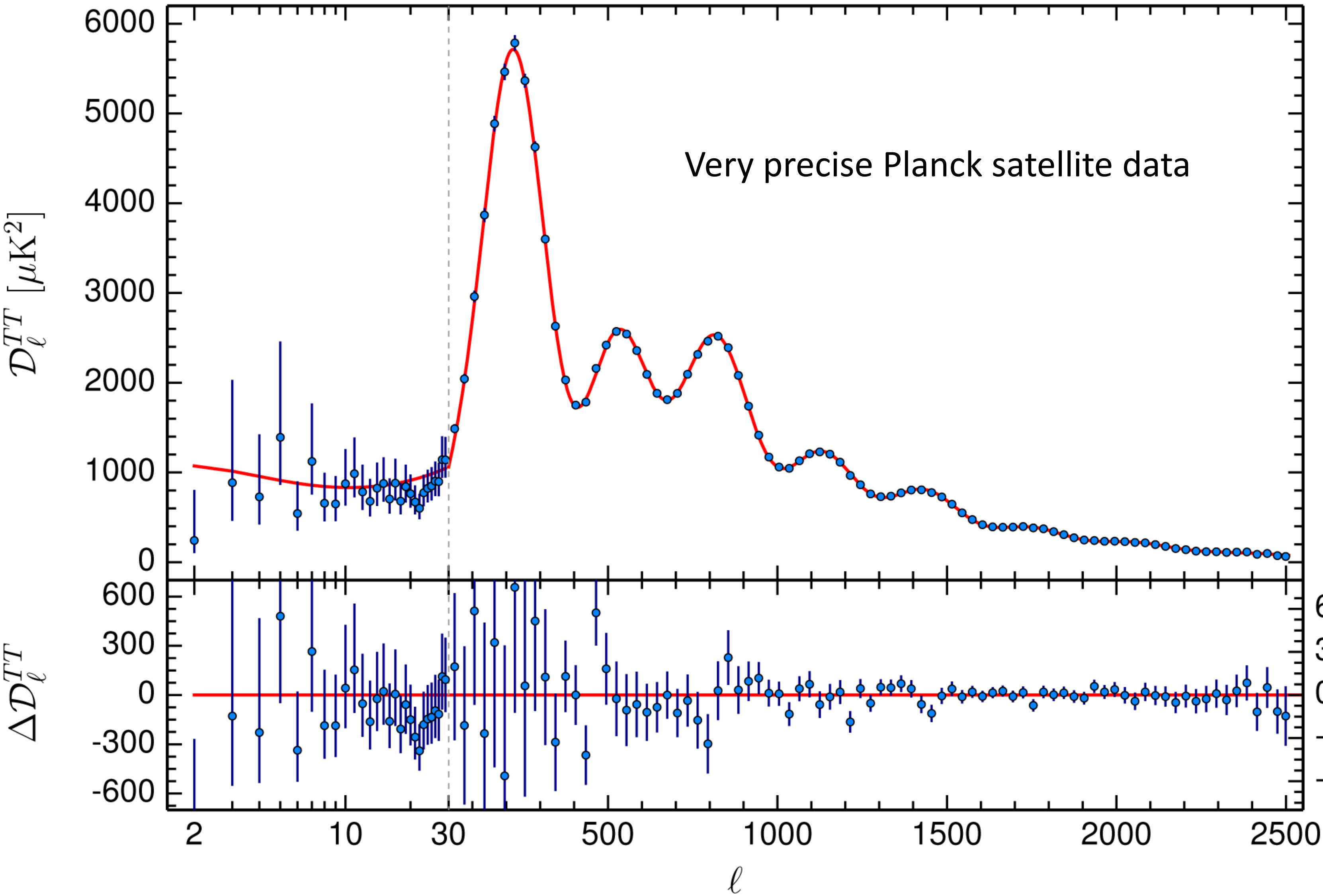
Inertia (baryons) and pressure (photons) create oscillations in photon-baryon fluid

sound waves => measure of density of baryons in early Universe



This effect does not exist for dark matter having no interaction with photons

COSMOLOGY


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}\ [\mu\mathrm{K}^2]$
Very precise Planck satellite data
600
300
0
-300
-600
60
30
0
-30
-60
$\Delta\mathcal{D}_\ell^{TT}$
2
10
30
500
1000
1500
2000
2500
ℓ

COSMOLOGY

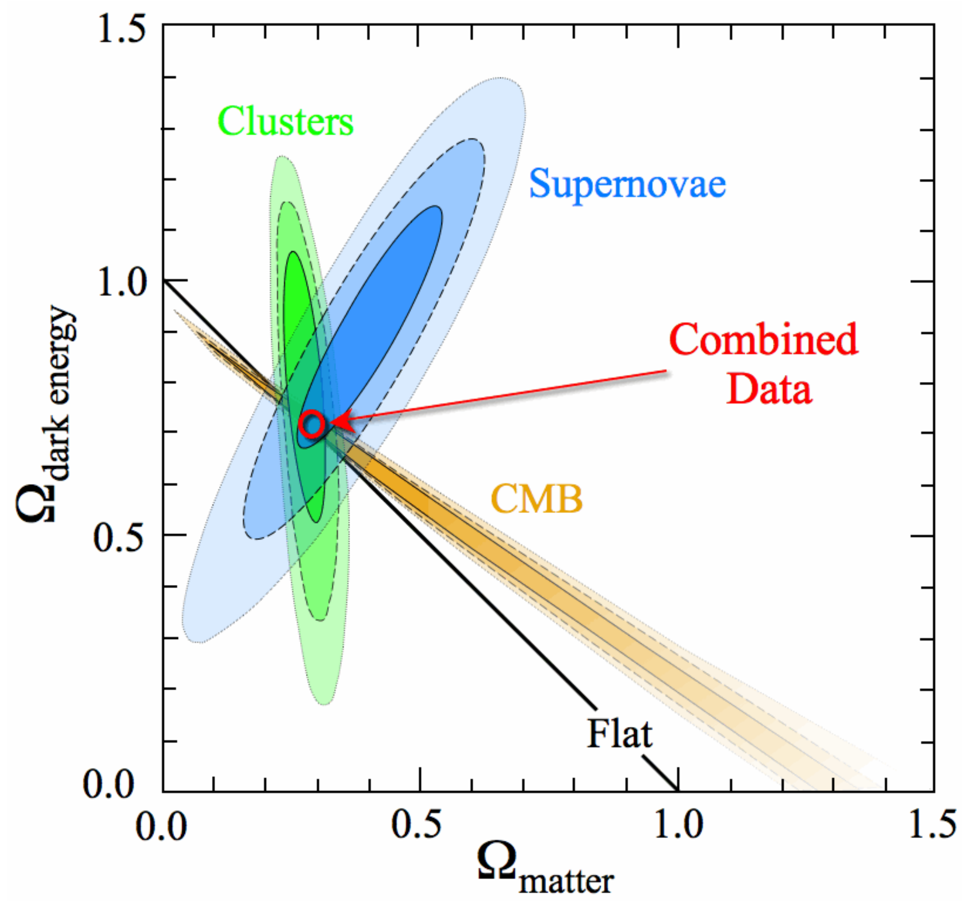
The **Λ-CDM model**
(lambda-cold dark matter)

Universe is flat

Dark energy is 70 %
$\Lambda \neq 0$

Baryonic matter is 5 %

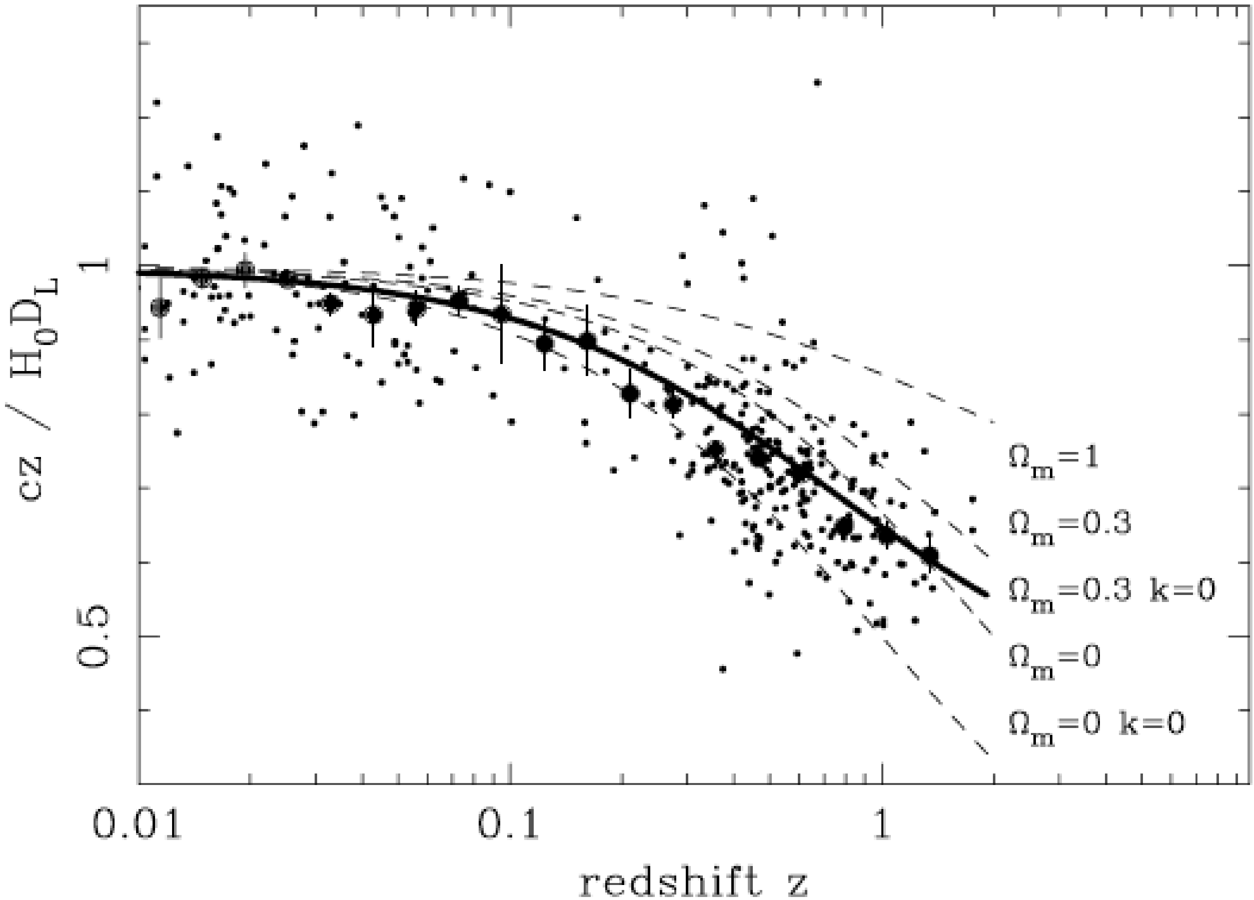
Non baryonic (cold)
dark matter is 25 %



Independent measurements give compatible parameters for the model

ACCELERATING EXPANSION

Model fits of the Universe



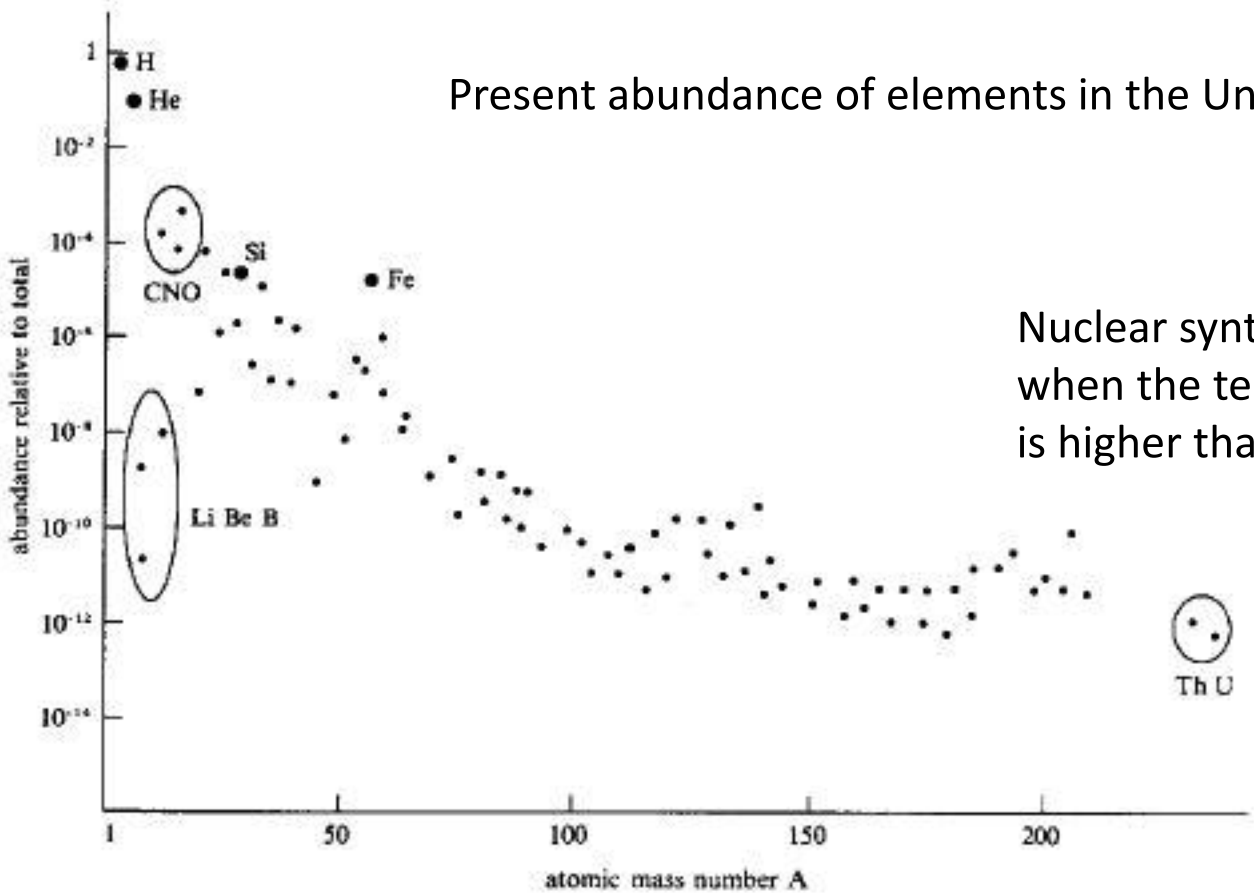
λ_e : emitted wavelength

λ_o : observed wavelength

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

k = 0 if Universe is flat

BARYONIC MATTER



Present abundance of elements in the Universe

Nuclear synthesis happens when the temperature is higher than 10^8 K

What was the abundance before stellar nucleosynthesis ?
Primordial nucleosynthesis ?

BARYONIC MATTER

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

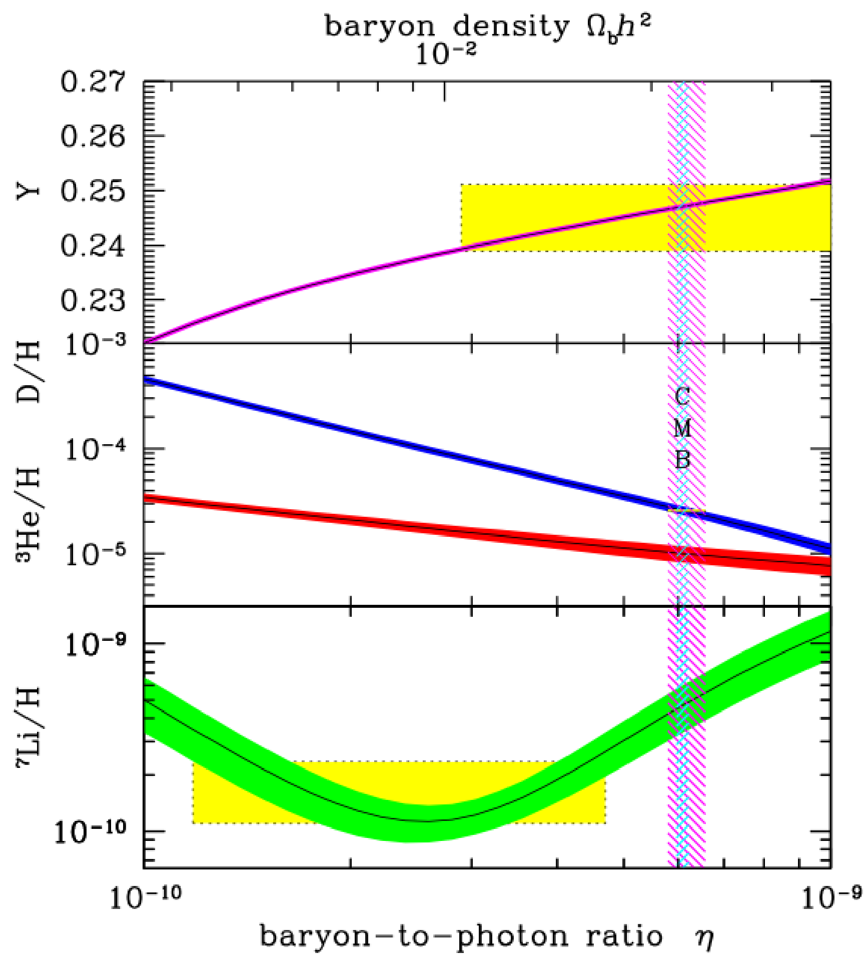
disintegration of neutrons and expansion of the Universe stops the synthesis after 3 minutes

this 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, gas) ➔ **dark baryonic matter**

total dark matter ≈ 6 times baryonic matter



BARYONIC MATTER

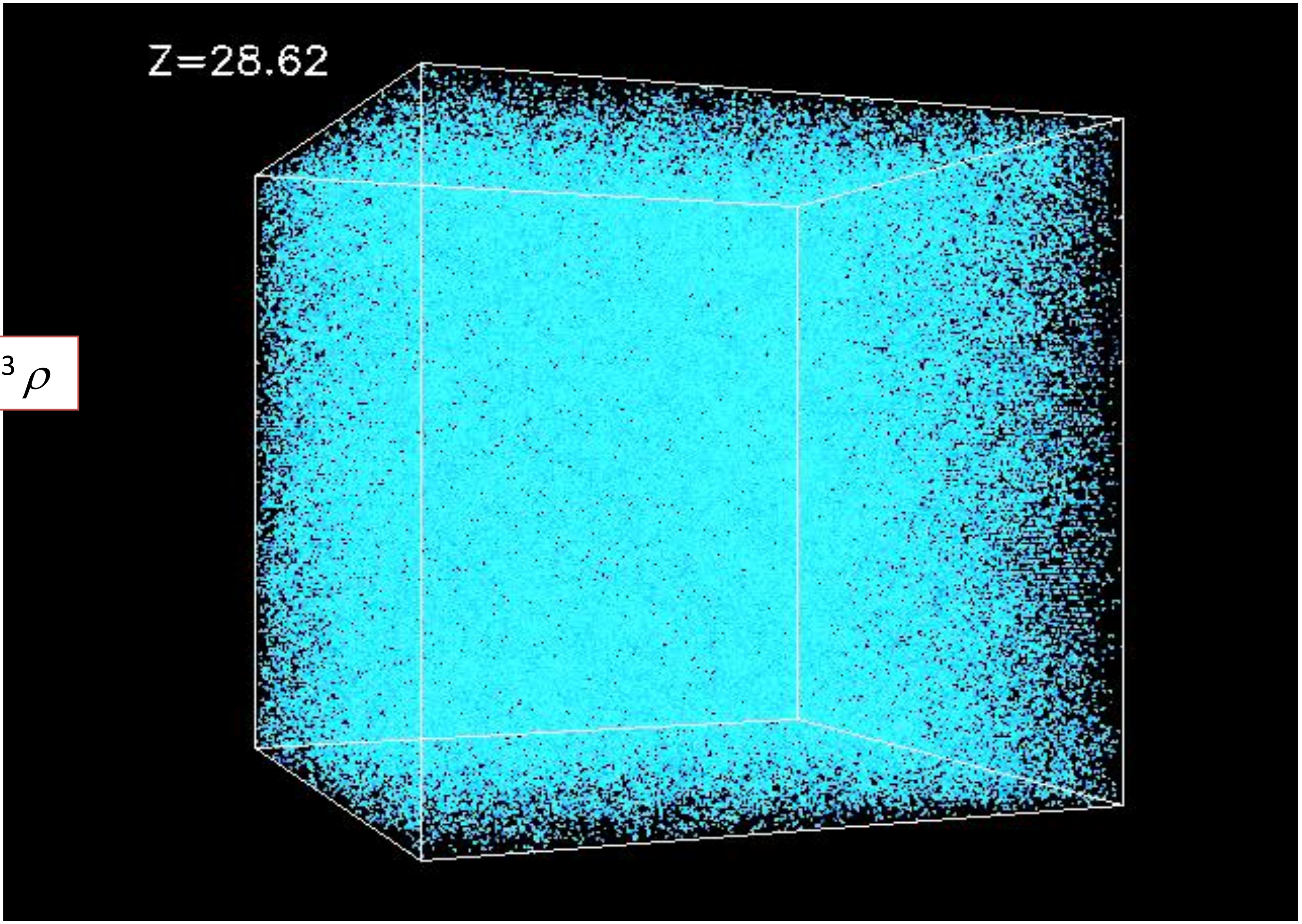
Formation of structures (galaxies, stars)

Competition between gravity and pressure
> Jeans mass

$M_J > [\, v_s / (G\rho)^{1/2} \,]^3 \rho$

$M_J \sim 10^5 \, M_\odot$

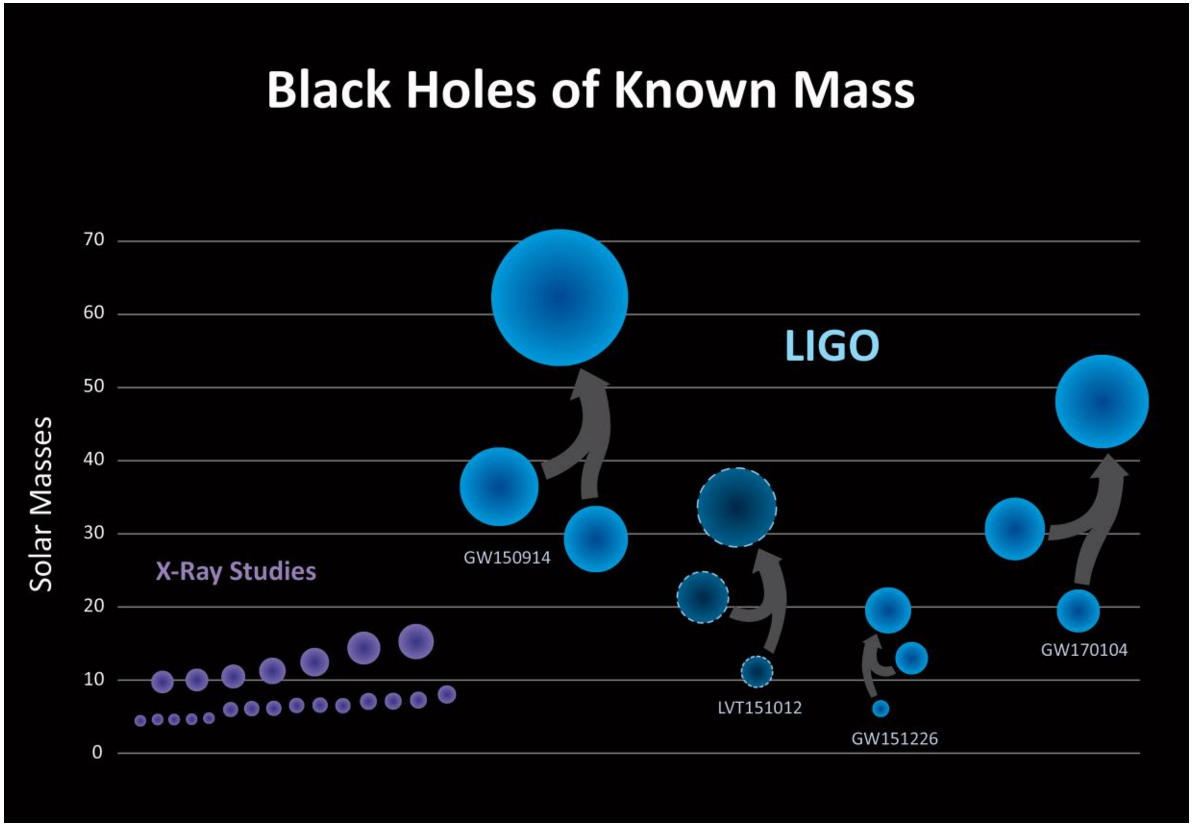
importance of non baryonic dark matter : insensitive to electromagnetism



MISSING BARYONIC MATTER

In classical physics and General Relativity, **black holes** are objects that are so dense that nothing, even light, cannot escape Schwarzschild radius $R_S = 2\,G\,M\,/\,c^2$

In astrophysics, black holes are predicted as final collapse of heavy stars, detected in 2015 by gravitational waves



Any *M* is possible
→ micro black holes can be produced in the LHC

Quantum effect :
Hawking radiation evaporation (decay) of the black hole

$$t = 8.141 \times 10^{-17} \left[\frac{M}{\mathrm{kg}} \right]^3 \mathrm{s}$$

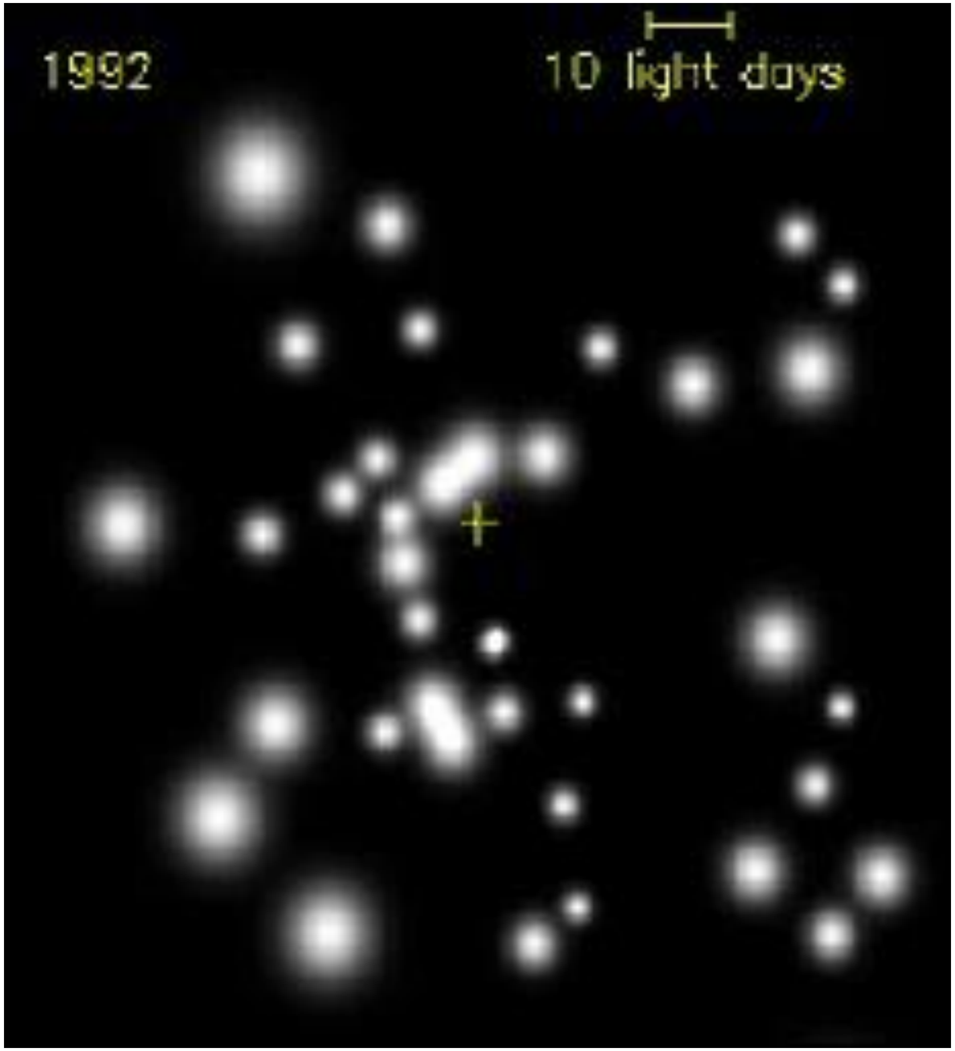
MISSING BARYONIC MATTER

In our galaxy : some candidates ?

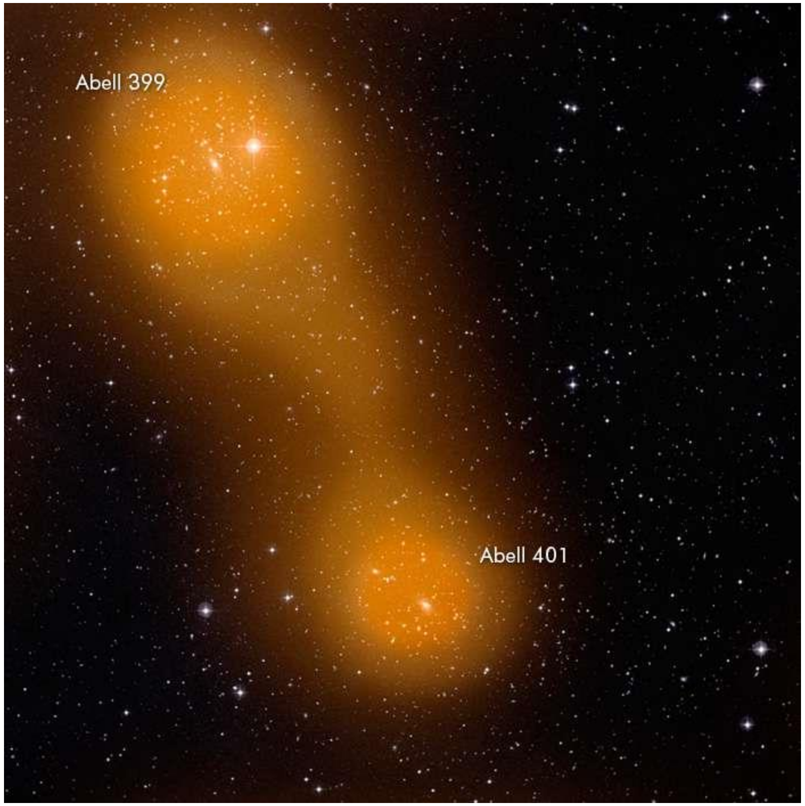
- central supermassive black hole
Sagittarius A* = $4 \times 10^6 \odot$
(as in many galaxies)

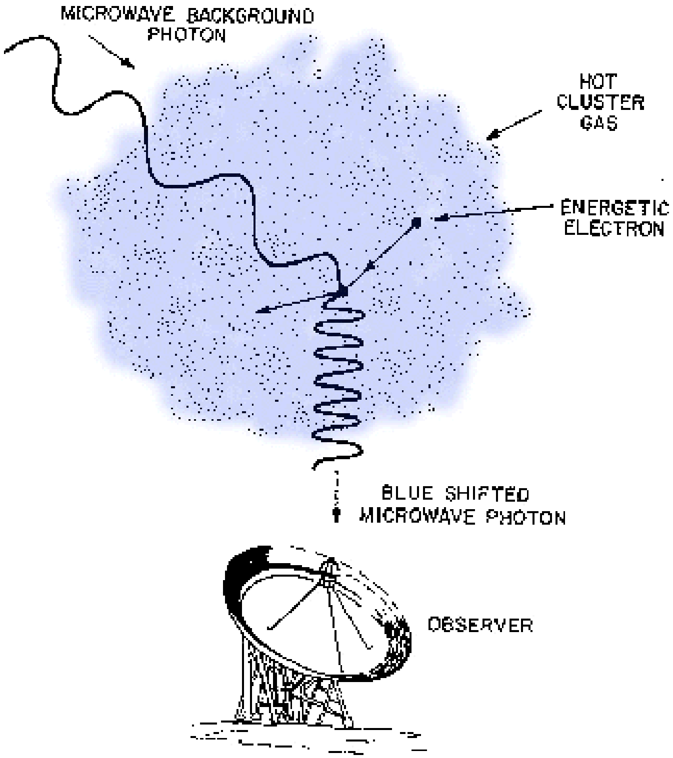
- many exoplanets have been found ≈ 2500
masses are not important compared to stars

- MACHOs (Massive Halo Objects) :
very heavy planets, brown stars,
old dwarf stars, neutron stars,
could explain the galaxy rotation pattern
some were found by light deviation,
but not enough



MISSING BARYONIC MATTER



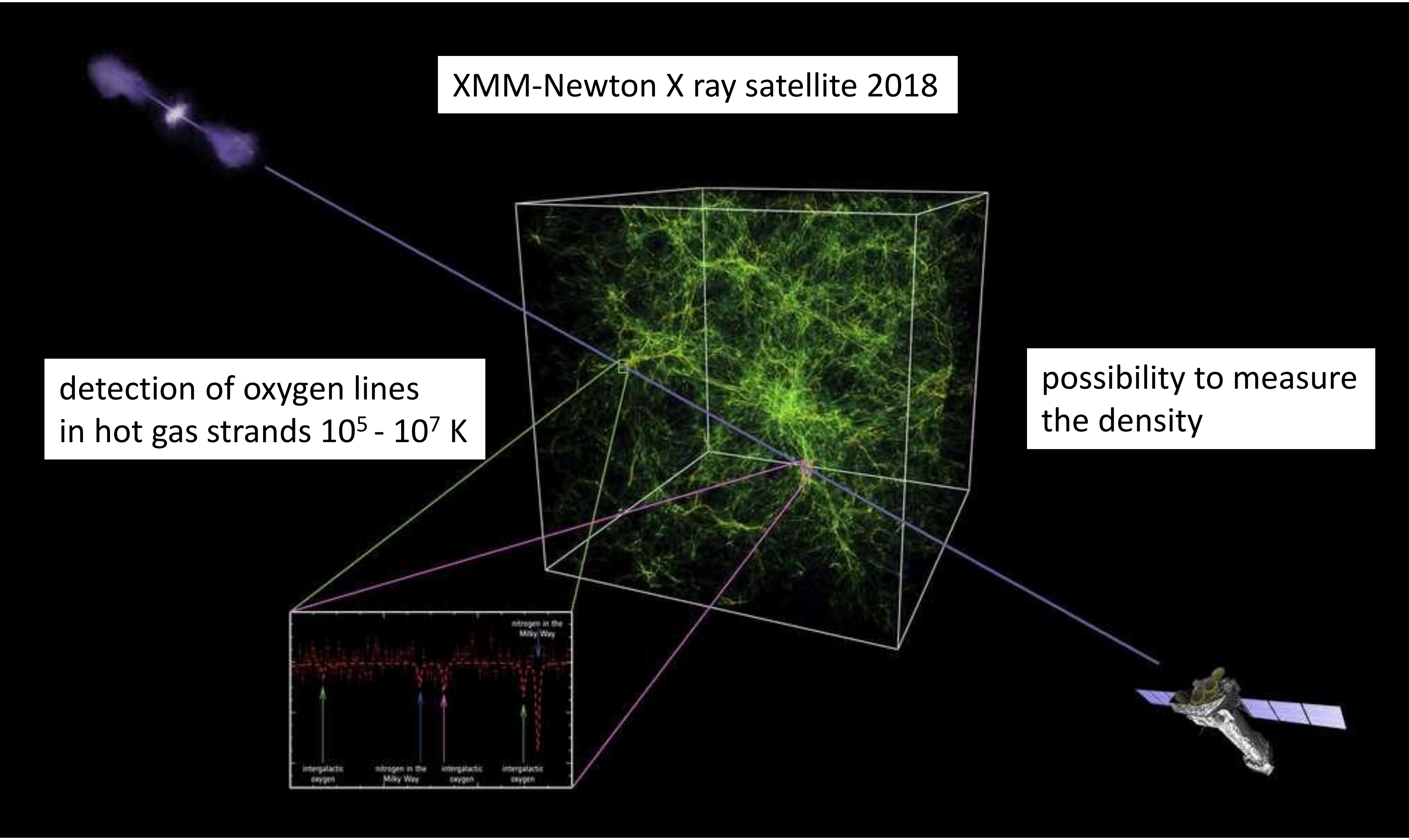


Light from CMB scattered
by electrons in diffuse strands
between galaxy clusters

Observation by Sunyaev-Zeldovich effect
Planck satellite 2017

MISSING BARYONIC MATTER

XMM-Newton X ray satellite 2018



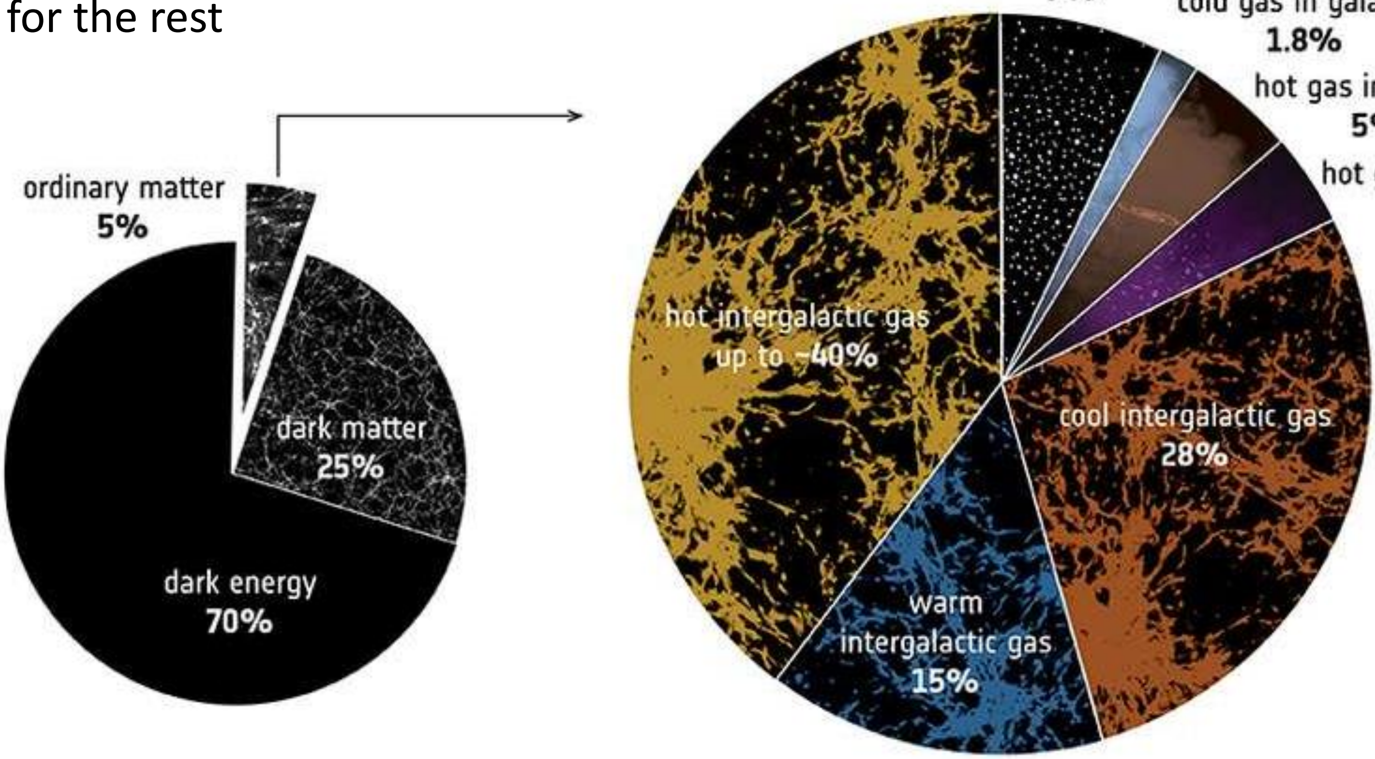
detection of oxygen lines in hot gas strands 10^5 - 10^7 K

possibility to measure the density

MISSING BARYONIC MATTER

Missing baryonic matter **problem solved**

Stars are only 7% of the "ordinary" baryonic matter
luminous or dark gas in and out of galaxies
accounts for the rest



What is non baryonic matter ?

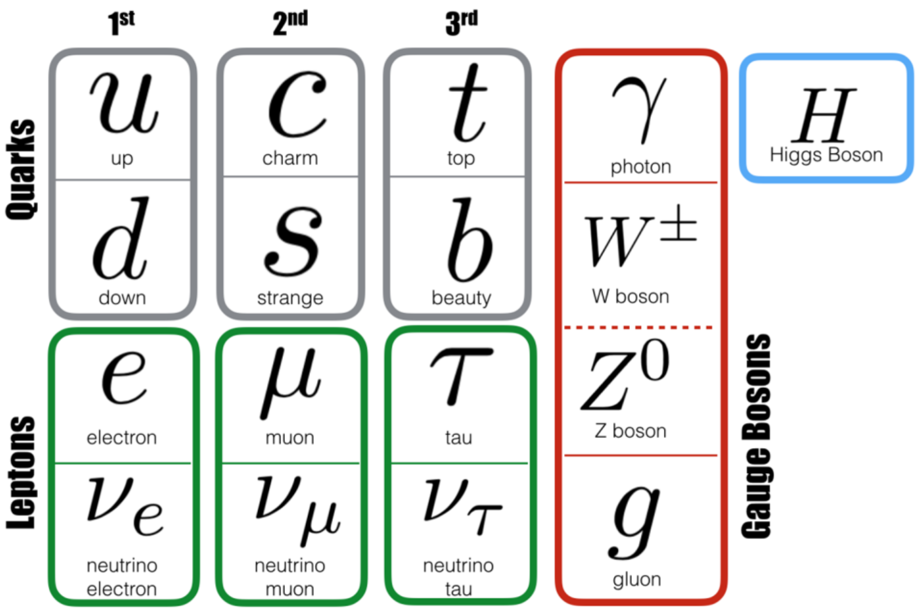
WHAT IS MATTER ?

Standard Model of particle physics

Matter is quarks and leptons, in 3 generations
fermions spin ½, all massive
first generation (u, d, e) is stable
“ordinary matter” proton, neutron, electron

3 interactions carried by gauge bosons spin 1
W and Z massive, γ and g zero mass

quarks and gluons are confined
by strong interaction QCD



gauge symmetries are spontaneously broken by the Brout-Englert-Higgs mechanism,
which gives **non zero mass** to matter fermions, increasing with generation number
and to W and Z bosons, which are unstable

the BEH mechanism is carried by the Higgs boson, massive, spin 0

WHAT IS MATTER ?

Neutrinos have very specific properties

they are electrically neutral and sensitive only to weak interaction

their masses are so low that we have only experimental upper limits
(Particle data group 2018)

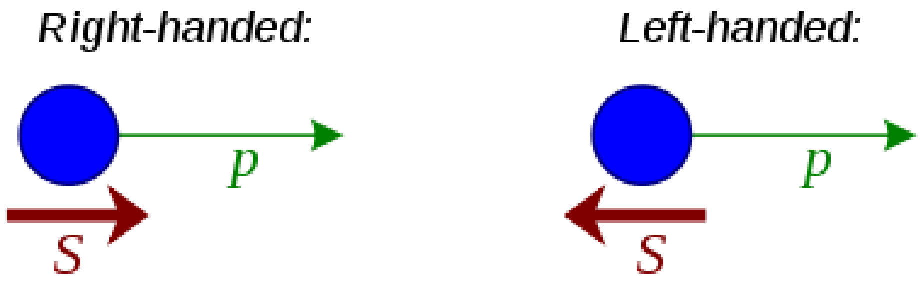
ν_e 2 eV beta decay
ν_μ 0.19 MeV muon decay
ν_τ 18.2 MeV tau decay

Z decay width measured at LEP indicates that there are only 3 generations of neutrinos
whose masses are lower than m_Z / 2 = 45 GeV

neutrinos have only chirality left (and antineutrino right) : the way they respond to weak interaction uses a term $P_L = ½(1 - \gamma^5)$ in the SM Lagrangian

WHAT IS MATTER ?

Chirality is equivalent to helicity **p.σ** only for a massless particle
helicity is not Lorentz invariant for a massive particle



neutrino eigenstates of the weak interaction differ from mass eigenstates
they are related by the Pontecorvo-Maki-Nakagawa-Sakata 3 × 3 unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

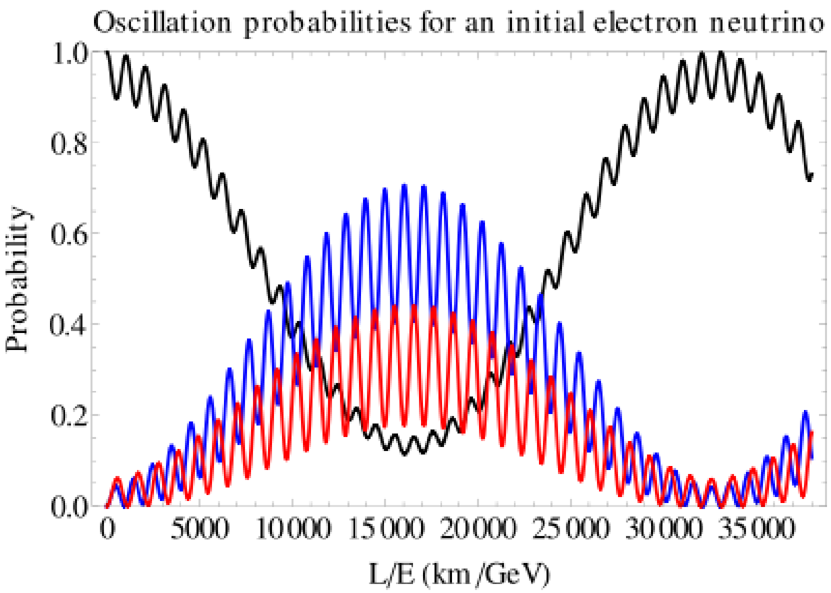
neutrinos are produced by decay, and named by the corresponding charged lepton

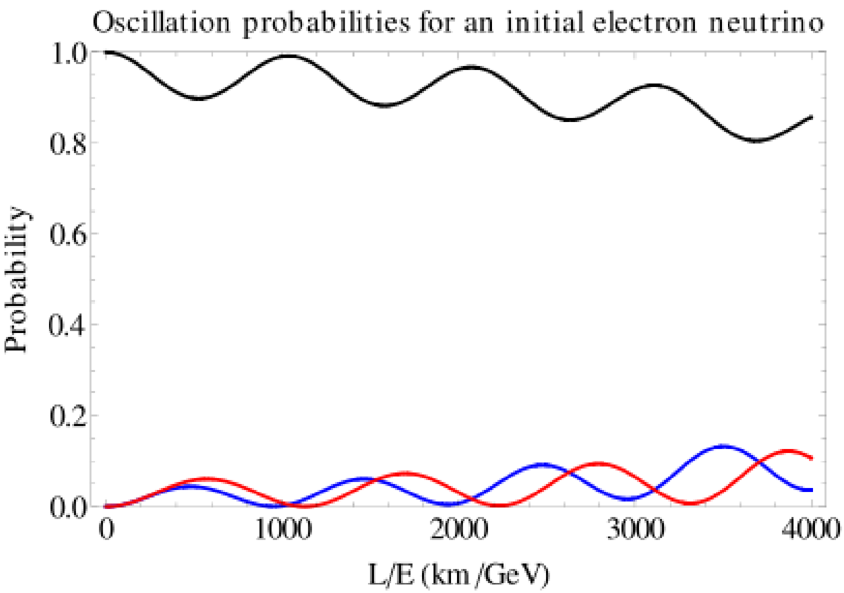
WHAT IS MATTER ?

Neutrinos are stable, but when they travel, they transform into each other because the speeds of the 3 different mass states are different : **oscillation**

solution of the “solar neutrino mystery” (1960 -1990)
1/3 of the expected ν_e were detected

experiments on accelerators and nuclear reactors





WHAT IS MATTER ?

Cosmic neutrinos : neutrinos and antineutrinos from supernova 1987

In the minimal SM the neutrinos have **zero mass**

Right-handed chirality neutrinos can exist Beyond Standard Model (GUT, …)

Their mass can be anything between 1 eV and 10^{15} GeV,

The mass is different from their SM left-handed partner (seesaw mechanism)

light neutrino

heavy neutrino

WHAT IS MATTER ?

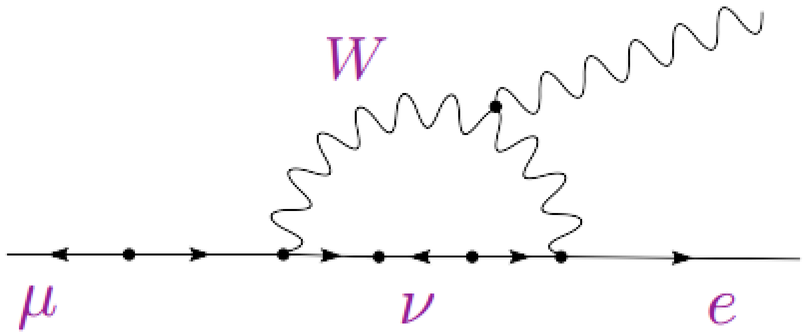
Being sensitive only to gravitation they are **sterile neutrinos**

They can by produced by oscillation from their partner, but not detected

Majorana neutrinos: neutrino is identical to antineutrino ≠ Dirac neutrinos
Some experiments still search for Majorana neutrinos (double beta decay)

$$B_{\mathrm{SM}}(\mu \to e\gamma) \sim O(10^{-52})$$

Violation of the lepton number
due to oscillation
has very low branching ratio



SUPERSYMMETRY

Extension of the Standard Model with a new symmetry

Each particle of the SM has a “superpartner” whose spin differs by ½

boson <-> fermion
electron <-> selectron   quark <-> squark
photon <-> photino   gluon <-> gluino   Higgs <-> higgsino   Z <-> zino

neutralino is a combination of photino, zino, higgsino
neutral, lightest ➔ candidate for dark matter (if R-parity is conserved)

The symmetry is broken : mass of partner ≠ mass of SM particle

Expected at LHC in 2009, but no superparticle found yet !

AXION

Particle introduced in 1977 to solve a "mystery" :
there is no CP violation in QCD, like in Electroweak sector of the Standard Model

Very weakly coupled, very low mass ➔ good candidate for DM

Can be converted into photon by a strong magnetic field : detection on Earth

Can be produced in the Sun by X rays interacting with matter and solar magnetic field

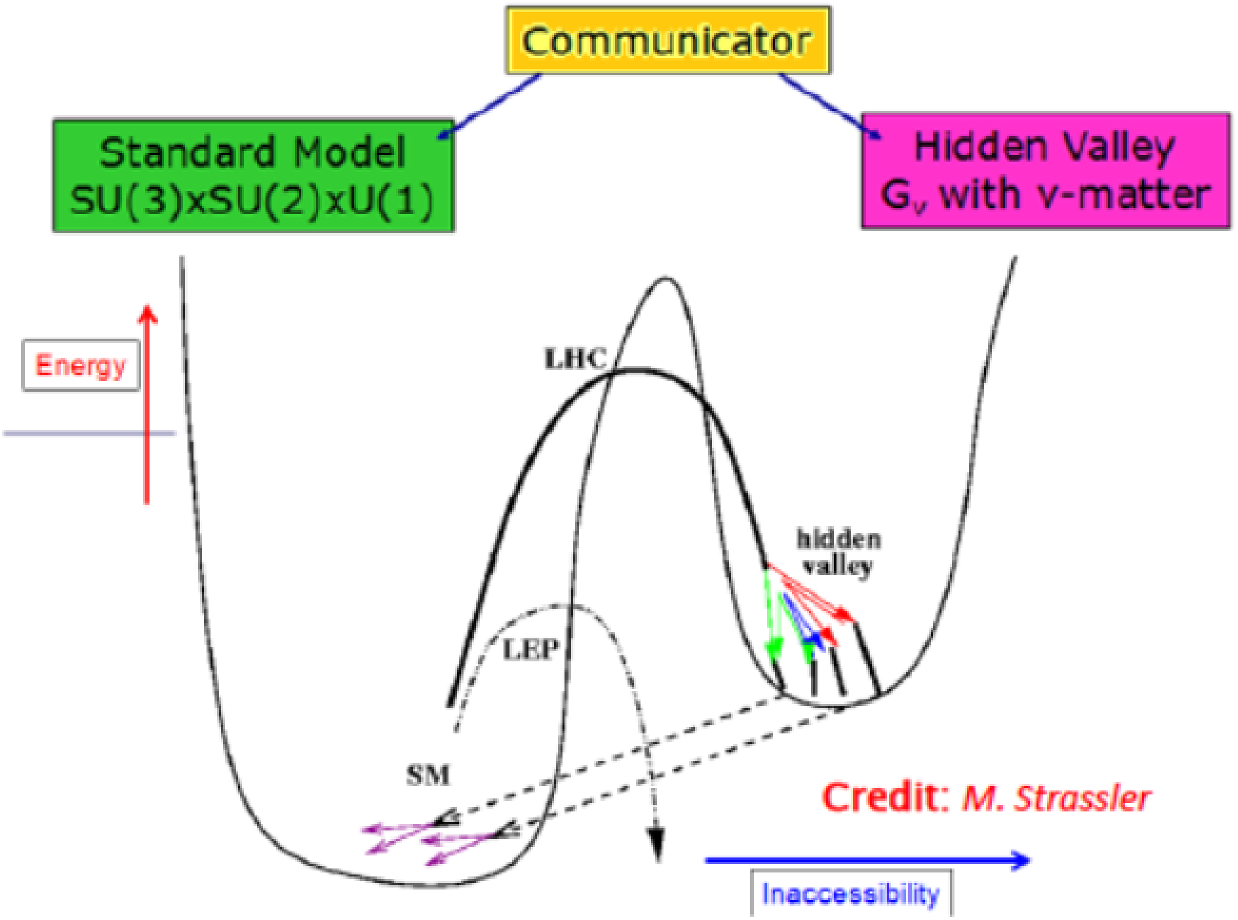
Can be produced in the early universe, and still exist (primordial axions)
because their low mass prevent them from disintegration

Looked for in large range of masses μeV to meV

HIDDEN VALLEY

Hidden Valley models imagine a hidden sector

weakly coupled to SM through a communicator (Z', Higgs, sterile neutrino, …)



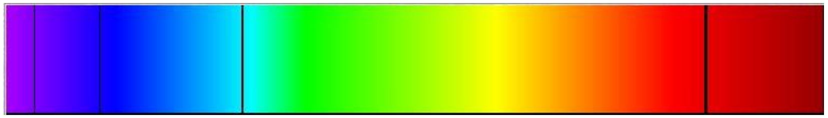
EXTRA SLIDE

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

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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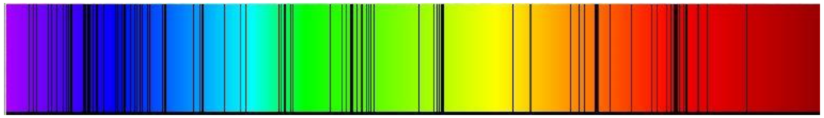

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different interpretation in General Relativity (expansion of Universe)