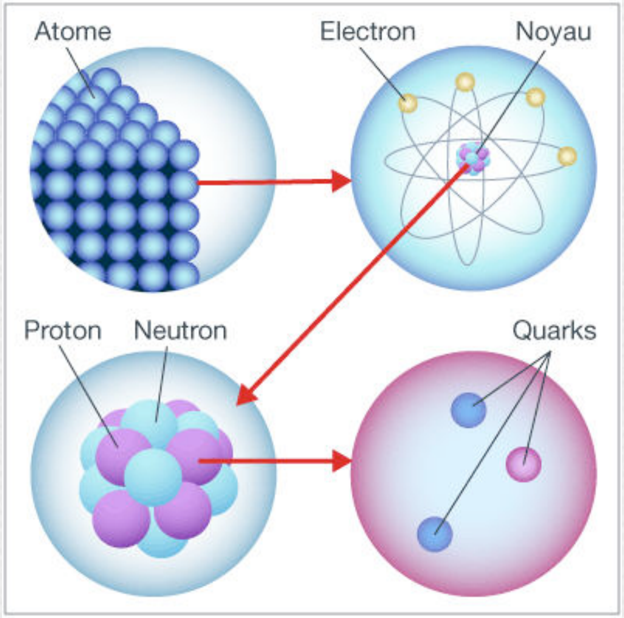
The Particle Physics-Cosmology connection



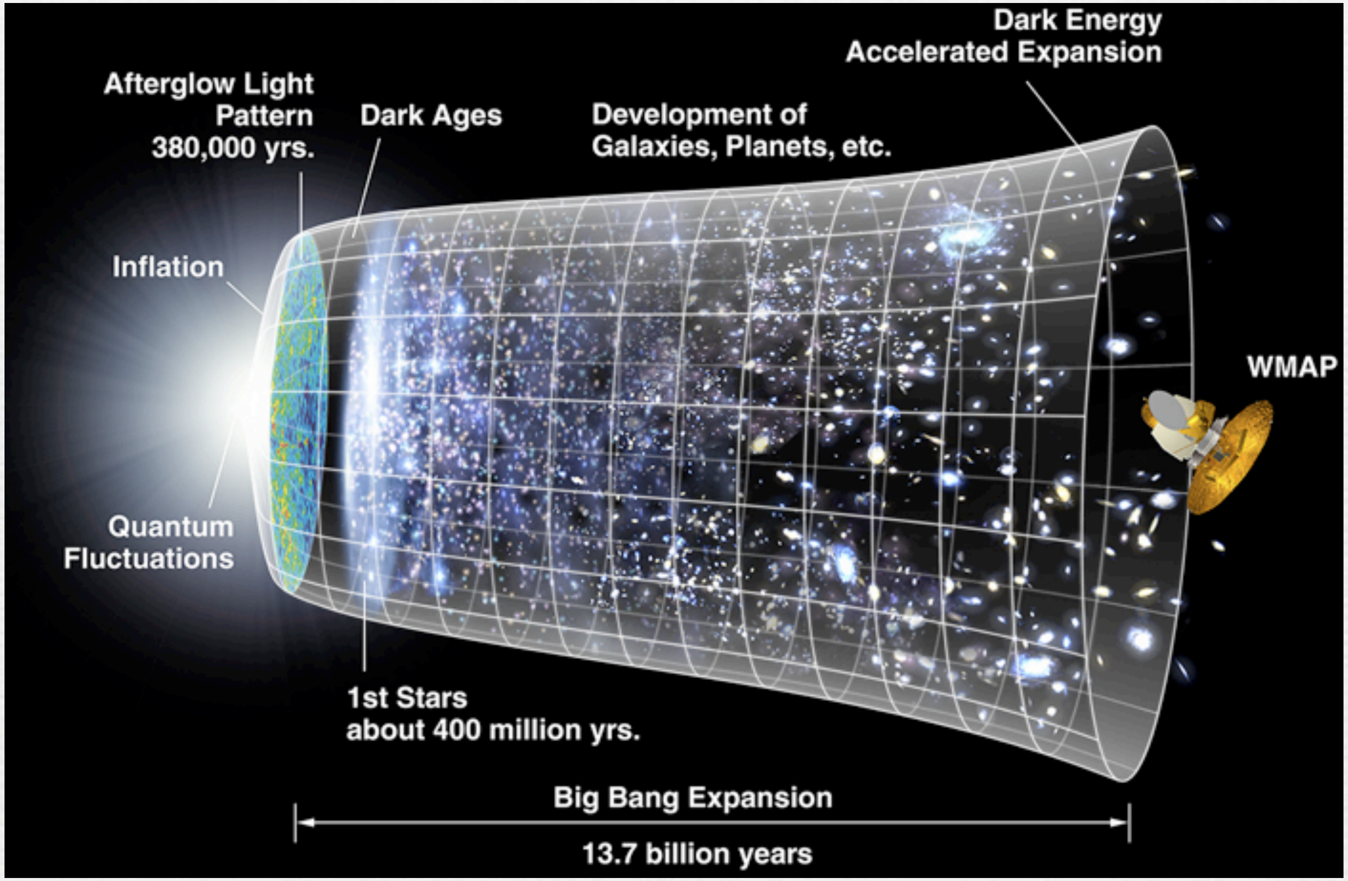
Géraldine SERVANT, CERN & IPhT CEA Saclay

Goal of cosmology: explain the structure and the evolution of the universe

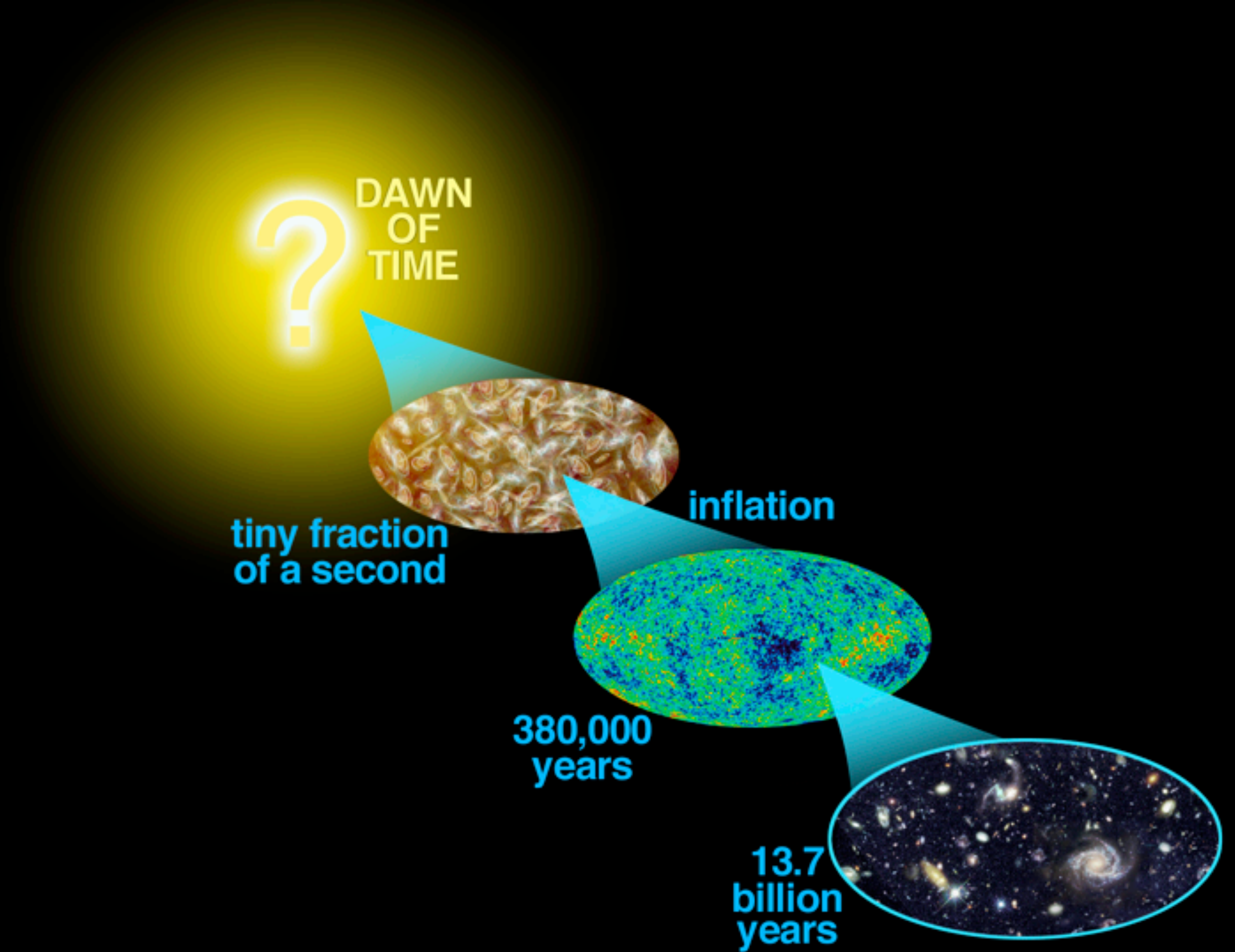
What is it made of?

How did large scale structures form ?

What are the laws controlling its evolution ?



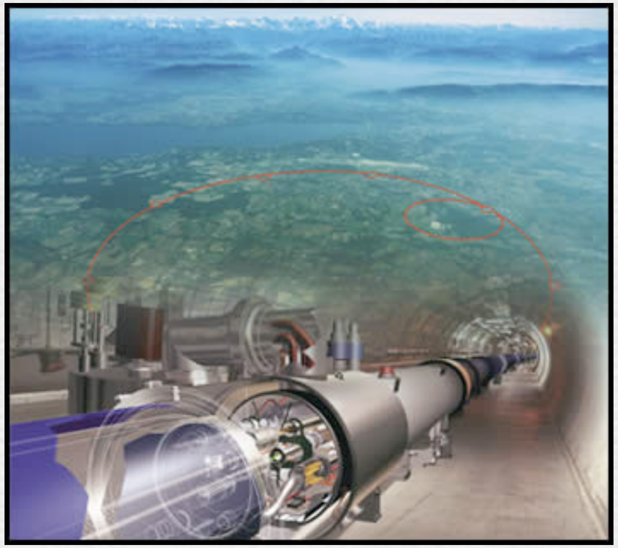
During the 20th century, we moved from a period of quasi ignorance about our universe to the establishment of a "standard cosmological model"


DAWN
OF
TIME
inflation
tiny fraction
of a second
380,000
years
13.7
billion
years

The Large Hadron Collider (LHC)

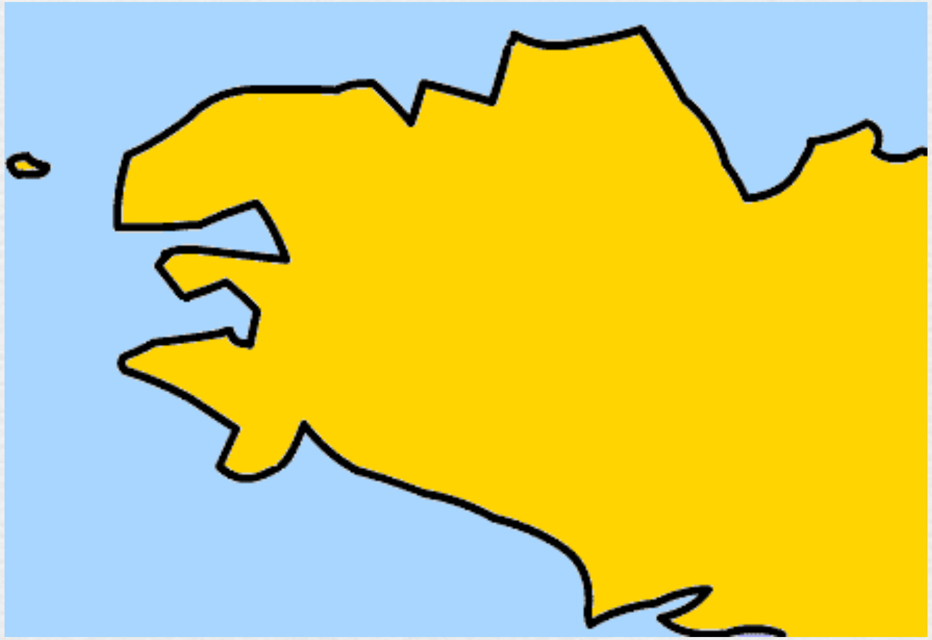
At the LHC, we collide protons at an unprecedented energy of 14×10^{12} electron-Volt

By studying the products of these collisions, we hope to discover new particles and push our understanding of the laws of physics to the smallest distant scales

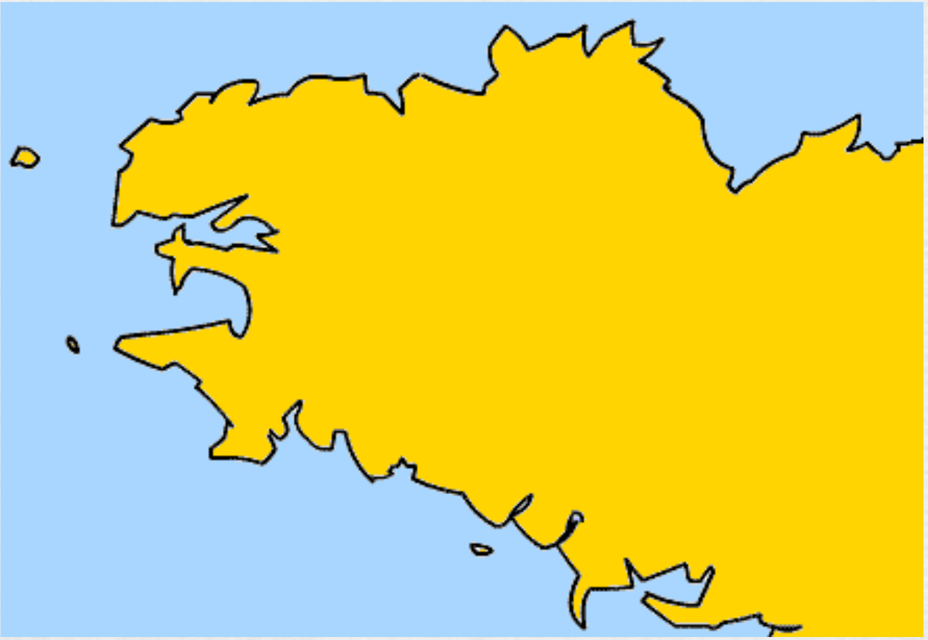


➔ The LHC: A gigantic microscope

Going to higher energies
⇛ allows to study finer details



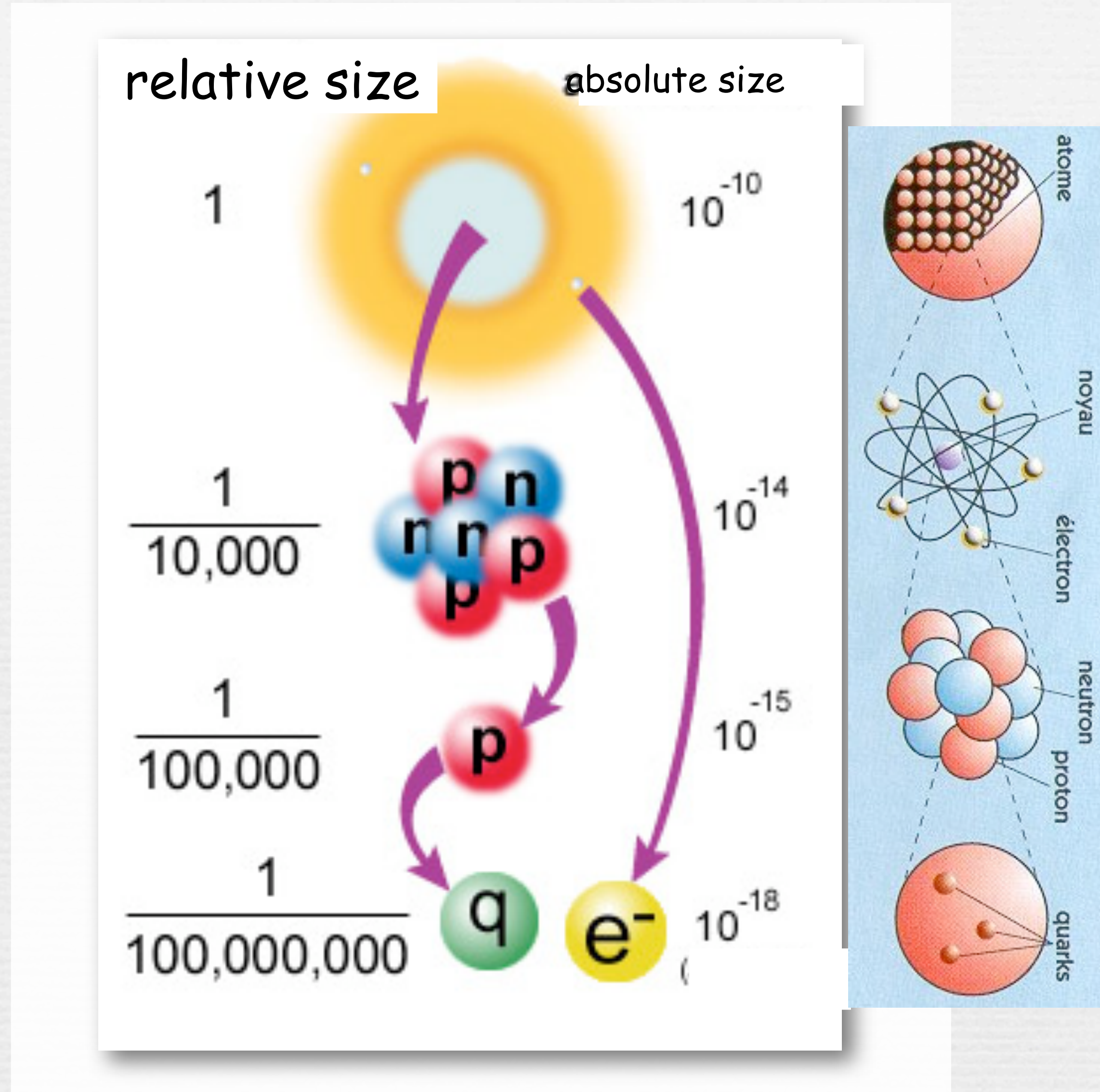
L = 400 km



L = 800 km

The elementary blocks of matter

- Matter is made of molecules ...
- Molecules are made of atoms ...
- Atoms are made of a nuclei and electrons ...
- Nuclei are made of protons and neutrons ...
- Protons and neutrons are made of quarks ...



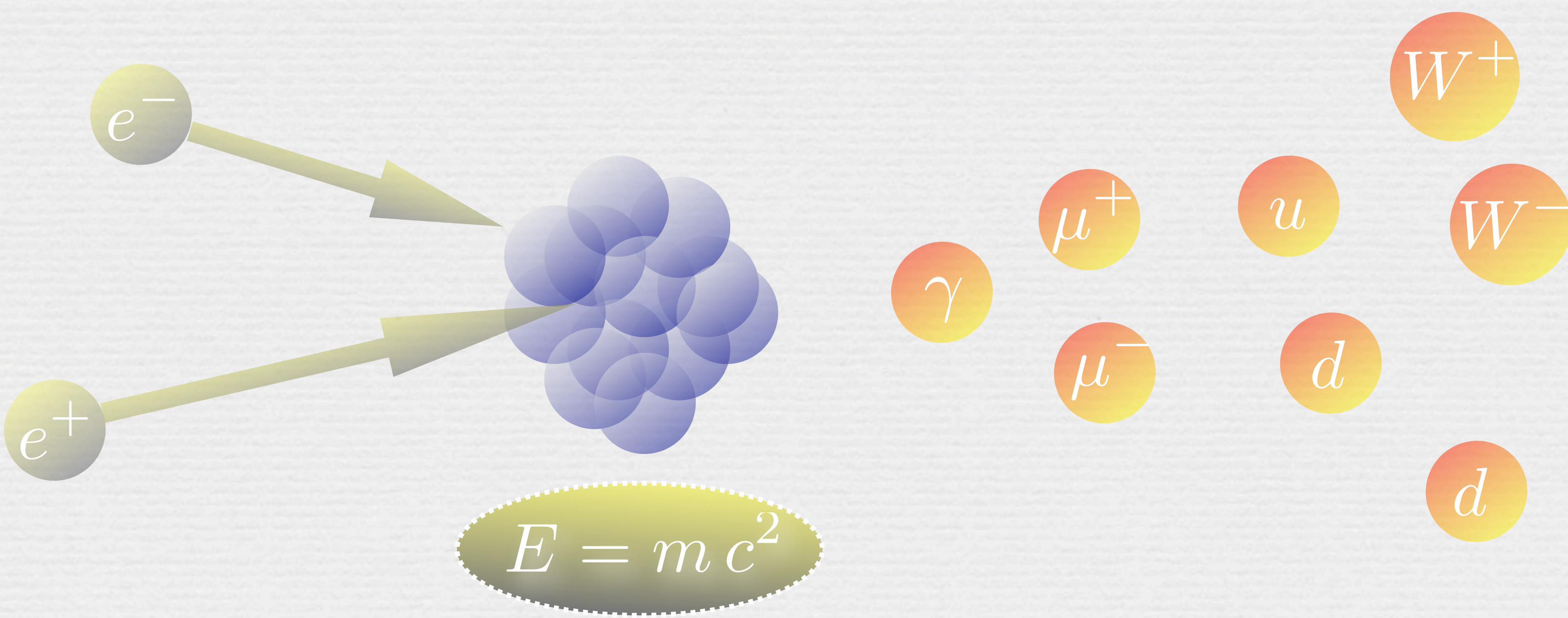
Creation of matter from energy

- ***Chemistry : rearrangement of matter***

  the different constituents of matter reorganize themselves

$$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O$$

- ***Particle physics : transformation energy ↔ matter***



electron volt eV

The energy of an electron accelerated by an electric potential difference of 1 volt. One electron-volt is thus equal to ... $1.6\,10^{-19}\,\mathrm{J}$

How heavy is this?

energies involved at CERN: 1 TeV = 1000 billions of eV= $10^{-24}\mathrm{kg}$

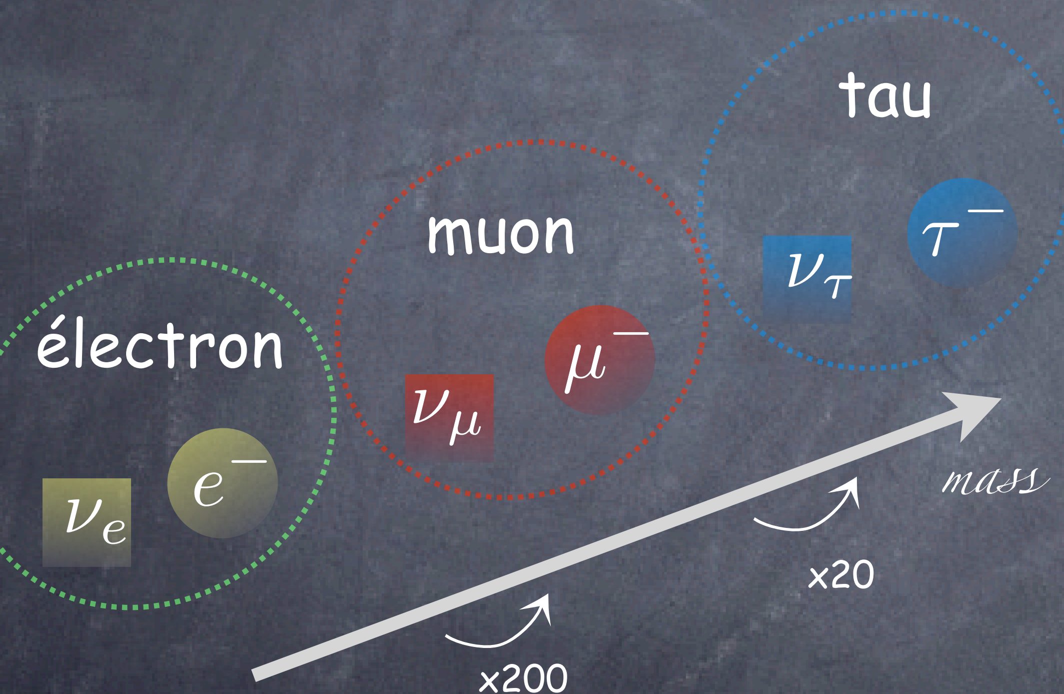
...however, in terms of energy density... this corresponds to the mass of the Earth concentrated in a 1 mm^3 cube !

the kinetic energy of a mosquito $10^{-3}\,J \sim 10^{16}\,\mathrm{eV} \sim 10^{4}\mathrm{TeV}$

The Standard Model: matter

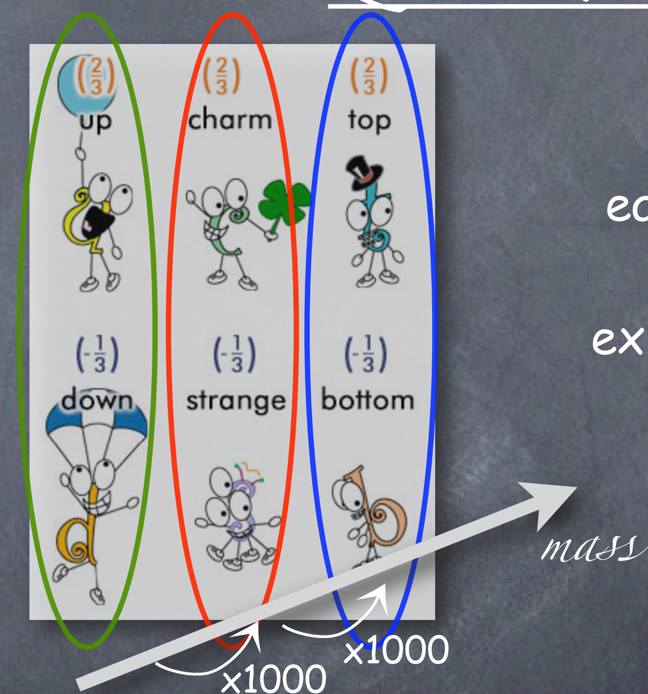
the elementary blocks:

LEPTONS



→ no composite states made of leptons

QUARKS



each of the 6 quarks exists in three colors

→ composite states (white objects

- baryons — proton $p = (u, u, d)$, neutron $n = (u, d, d)$
- mesons

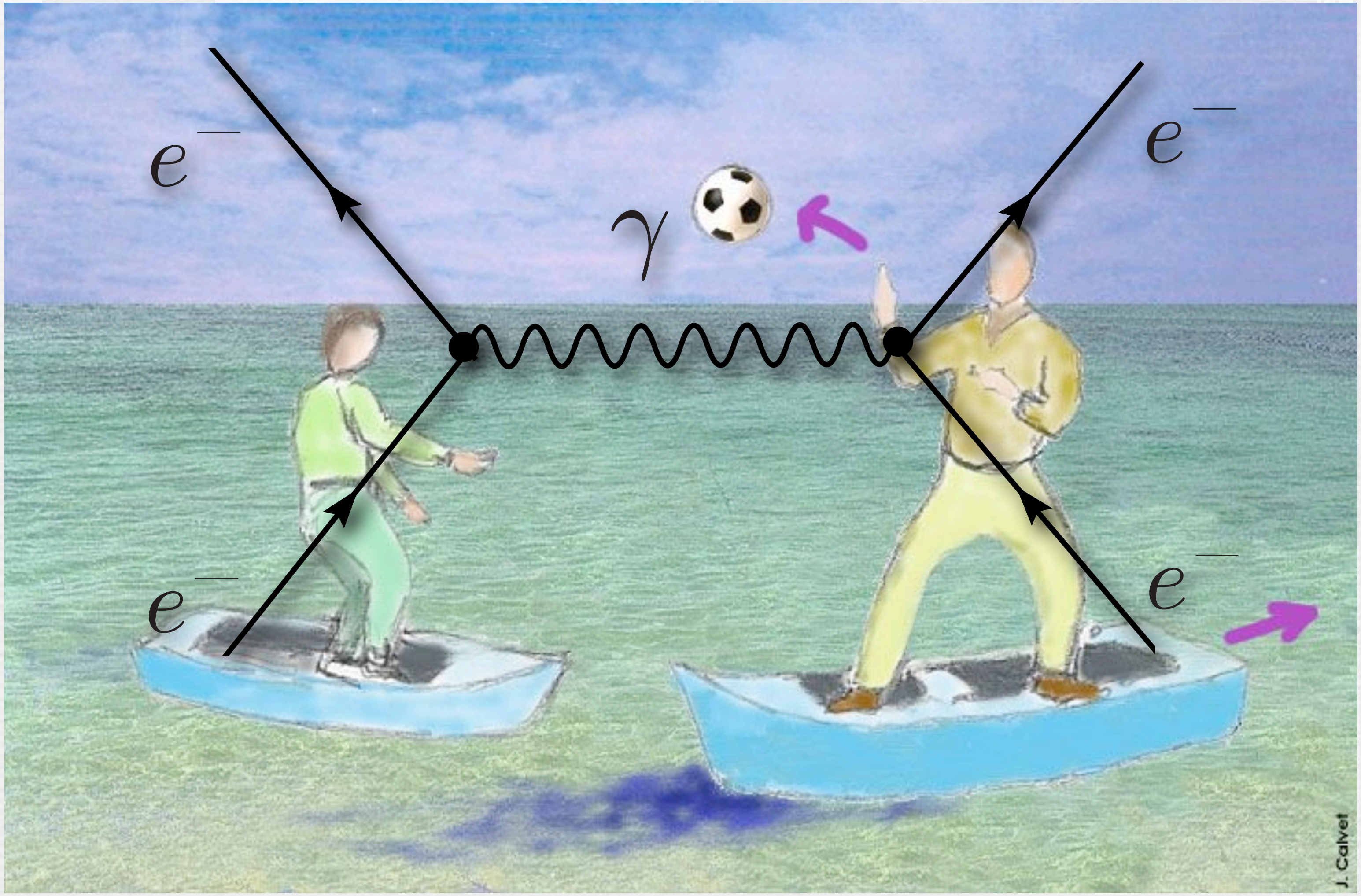
+ antiparticles

The Standard Model : interactions

- $U(1)_Y$ — *electromagnetic interactions* → Photon γ
  - light
  - atoms
  - molecules
  - intensity: 10^{-6}
- $SU(2)_L$ — *weak interactions* → bosons $W^{\pm}, Z^0$
  - β decay
  - $n \xrightarrow{W^{\pm}} p + e^- + \bar{\nu}_e$
  - intensity: 10^{-2}
- $SU(3)_C$ — *strong interactions* → gluons g^a
  - atomic nuclei
  - α decay
  - ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$
  - intensity: 1

intensity

Interactions between particles



Elementary particles interact with each other by exchanging gauge bosons

The Standard Model of Particle Physics

Forces — **Matter** — **Background**

$$\mathcal{L}_{\text{Standard Model}} = - F^a_{\mu\nu} F^{a\mu\nu} + (\lambda_{ij}\, \Psi_i \Psi_j\, h + h.c) + N_i M_{ij} N_j + |D_\mu h|^2 - V(h)$$

gauge sector

flavour sector

neutrino mass sector (if Majorana)

(spontaneous) electroweak symmetry breaking sector

$SU(3)_C \times SU(2)_L \times U(1)_Y$

- one century to develop it
- tested with impressive precision
- accounts for all data in experimental particle physics

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The Higgs is the only remaining unobserved piece

and a portal to new physics hidden sectors

(it is the only fondamental *scalar* particle)

At the LHC, the direct exploration of the Fermi scale has started

i.e distances < 10^{-15} cm

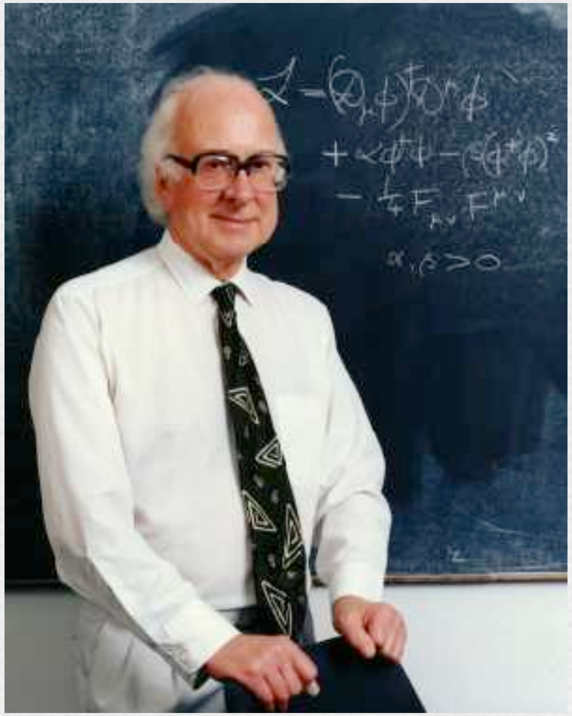
main physics goal
at the LHC:

What is the mechanism of Electroweak Symmetry breaking ?

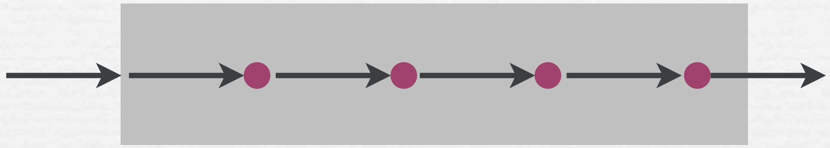
in other words:

what is the origin of the mass of elementary particles

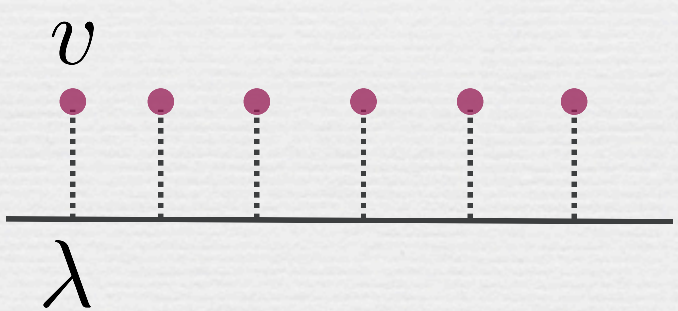
→ search for the Higgs Boson



Light propagating in a medium is slowed down by its continuous interaction with the medium itself



Think of the Higgs field as being a continuum medium embedding the whole universe. Particles interacting with it will undergo a similar "slow-down" phenomenon. Rather than slowing down however the interaction with the higgs medium gives them inertia -> mass.



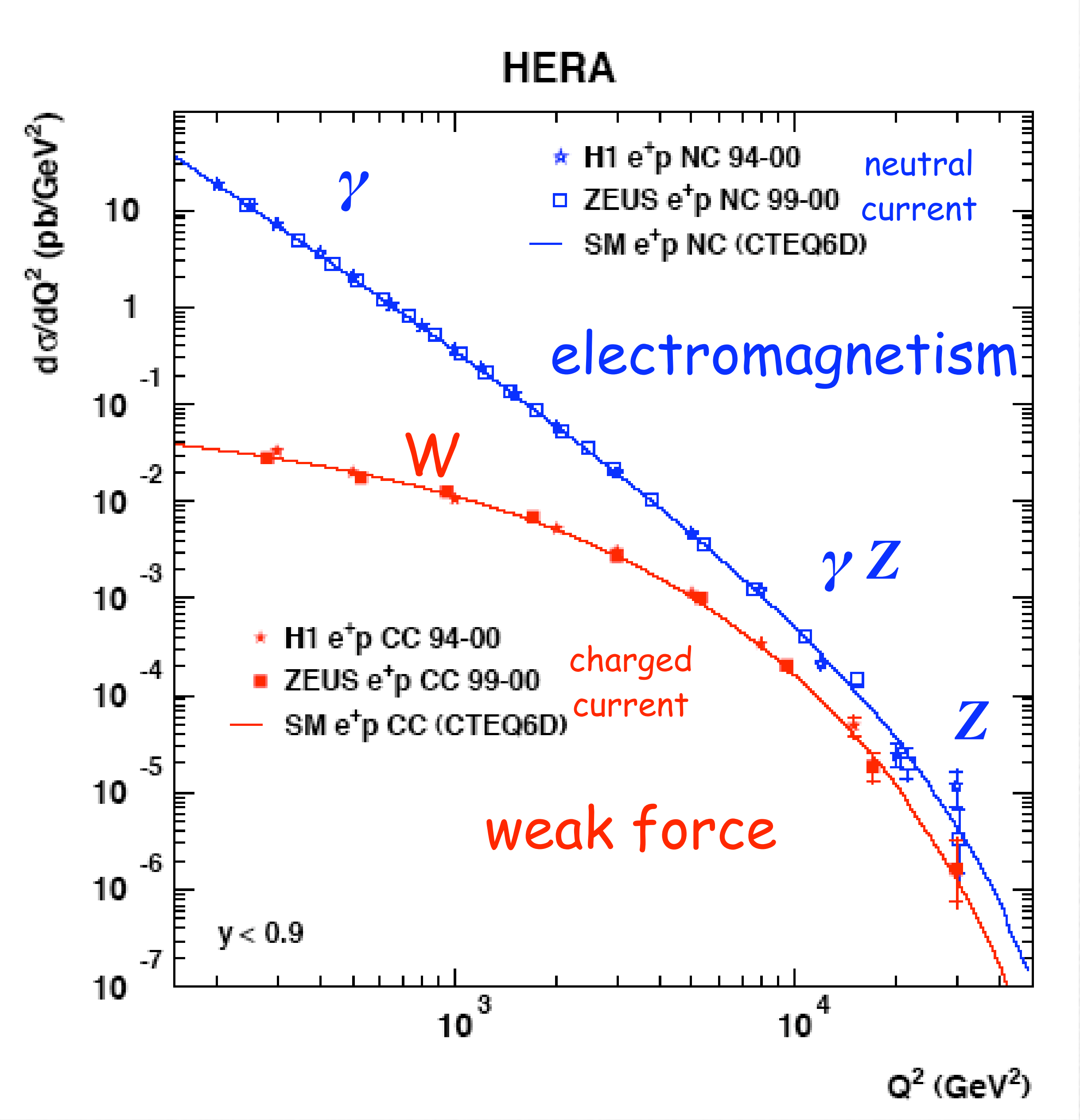
$$m \propto \lambda v$$

The number"v" is a universal property of the higgs field background. The quantity λ is a characteristic of a particle moving in the higgs field. Particles which have a large λ will have a large mass.

[M. Mangano]

A common analogy to understand the Higgs mechanism

Electroweak Unification



Detecting the Higgs Boson

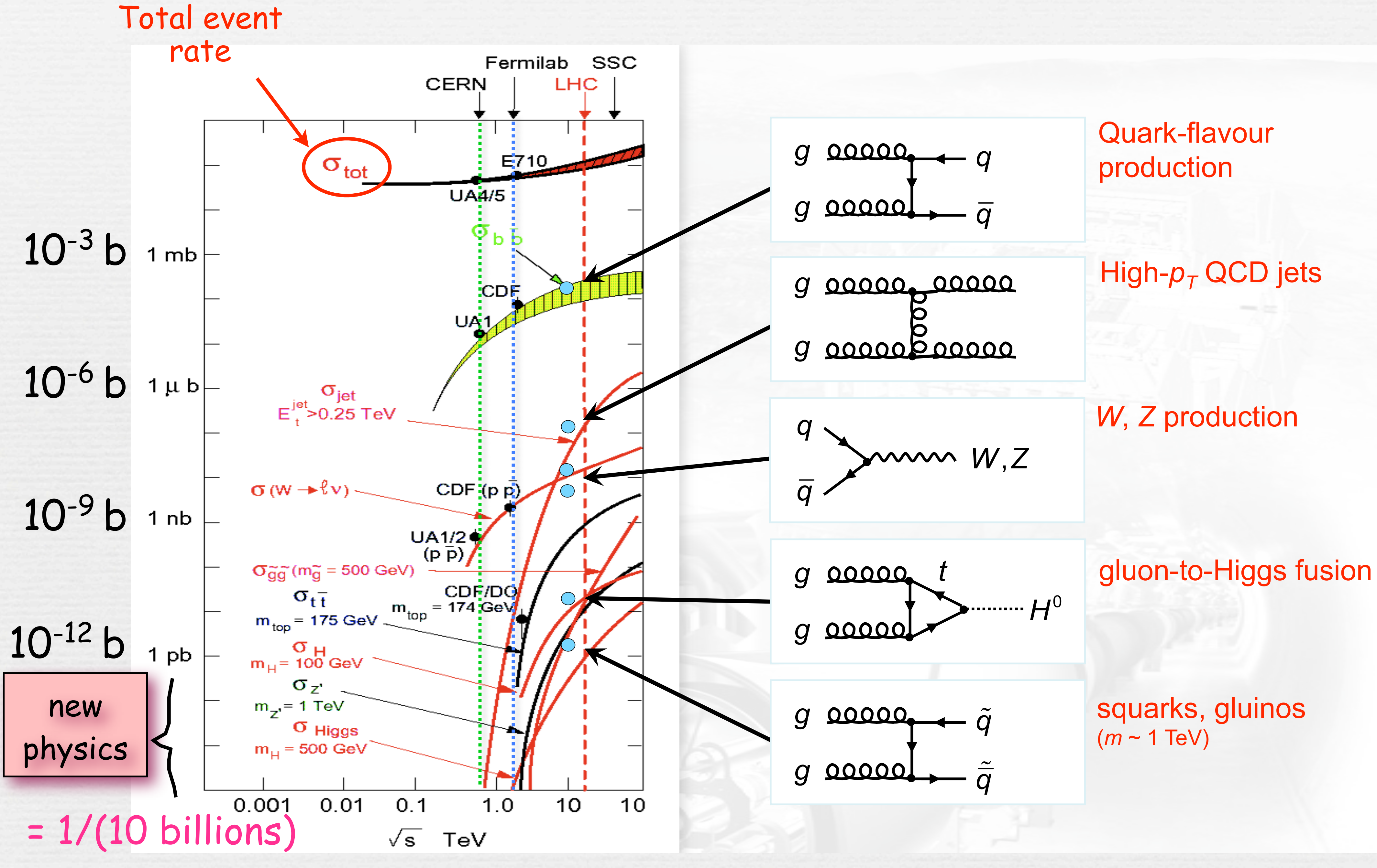
Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens when we bang on a table, creating sound waves, if we "bang" on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate "Higgs waves", which manifest themselves as particles, the so-called Higgs bosons.

Condition: the energy available should be larger than the Higgs mass.

⇒ LHC

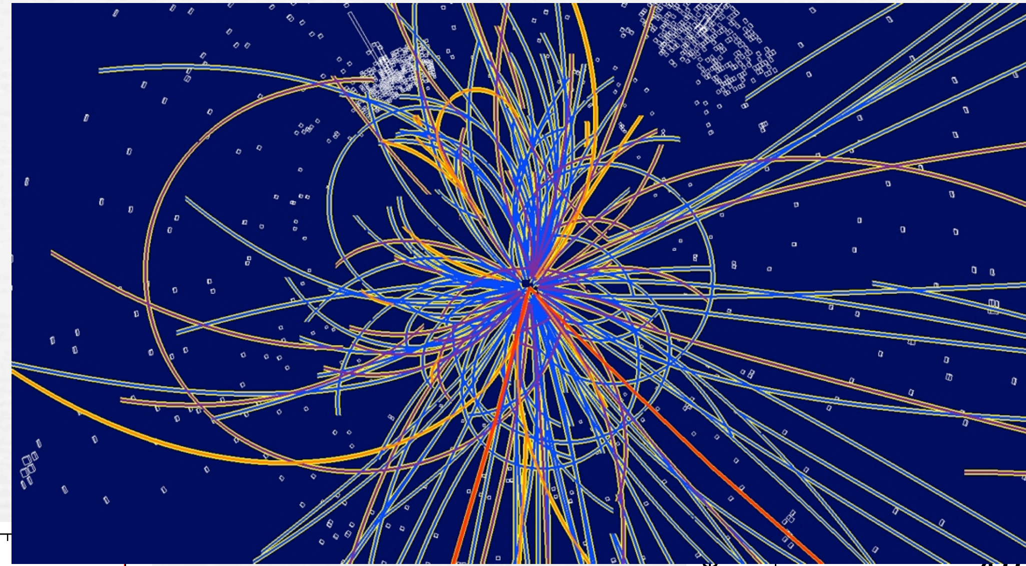
[M. Mangano]

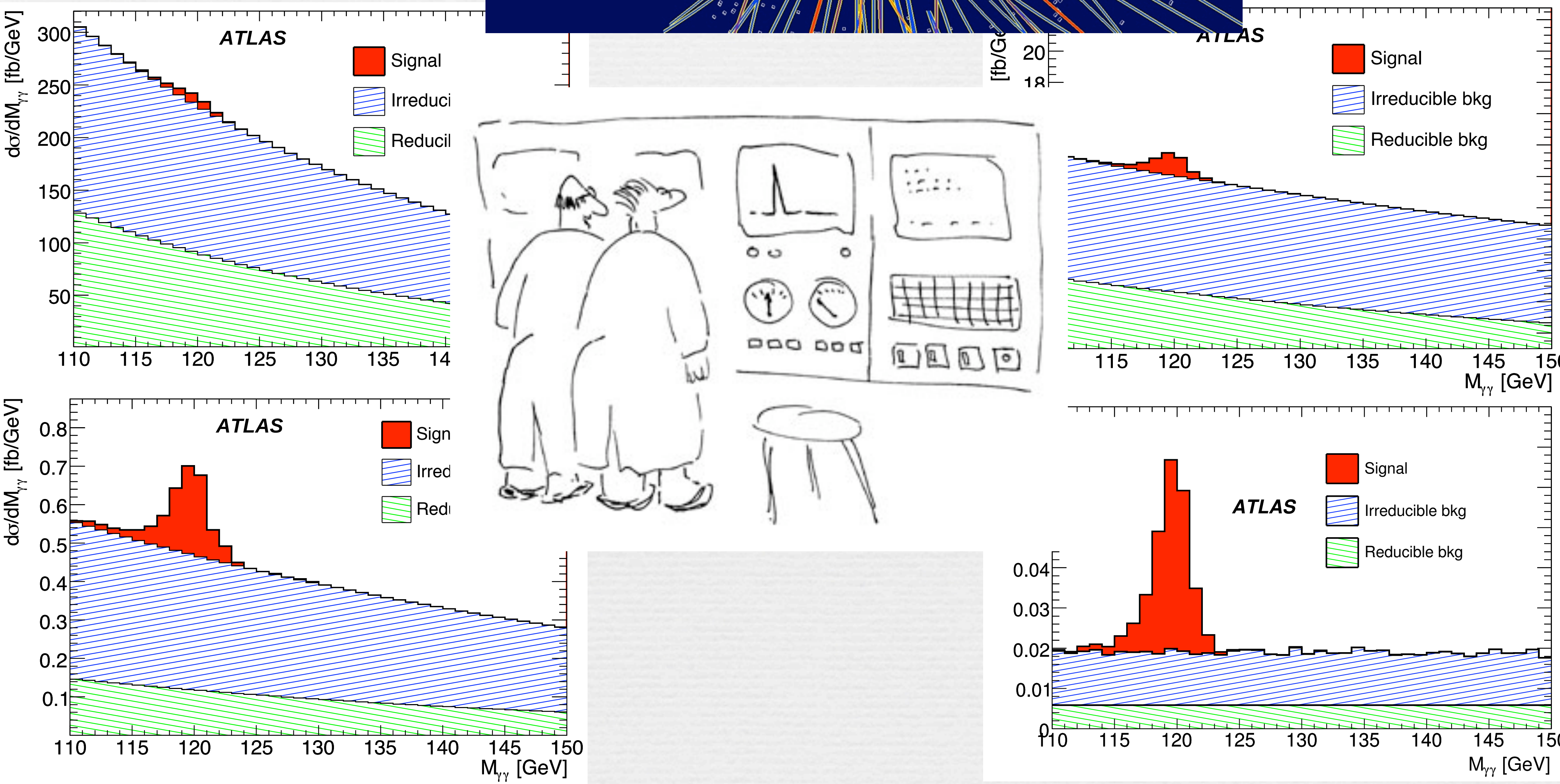
Event rate in hadron colliders



Searching for the Higgs is like searching a corn seed among 10 billions ...

In practise:




ATLAS
Signal
Irreducible bkg
Reducible bkg
dσ/dM$_{\gamma\gamma}$ [fb/GeV]
M$_{\gamma\gamma}$ [GeV]

Imagine what our universe would look like if electroweak symmetry was not broken

- quarks and leptons would be massless

- mass of proton and neutron (the strong force confines quarks into hadrons) would be a little changed

- proton becomes heavier than neutron (due to its electrostatic self energy) ! no more stable

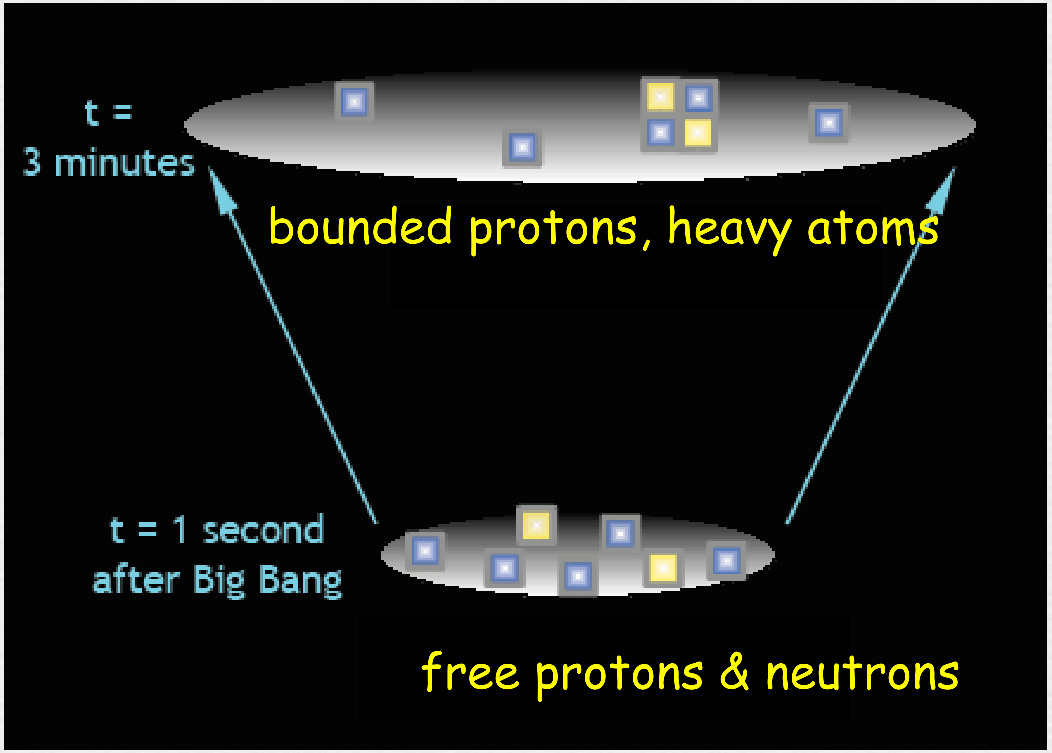
-> no hydrogen atom

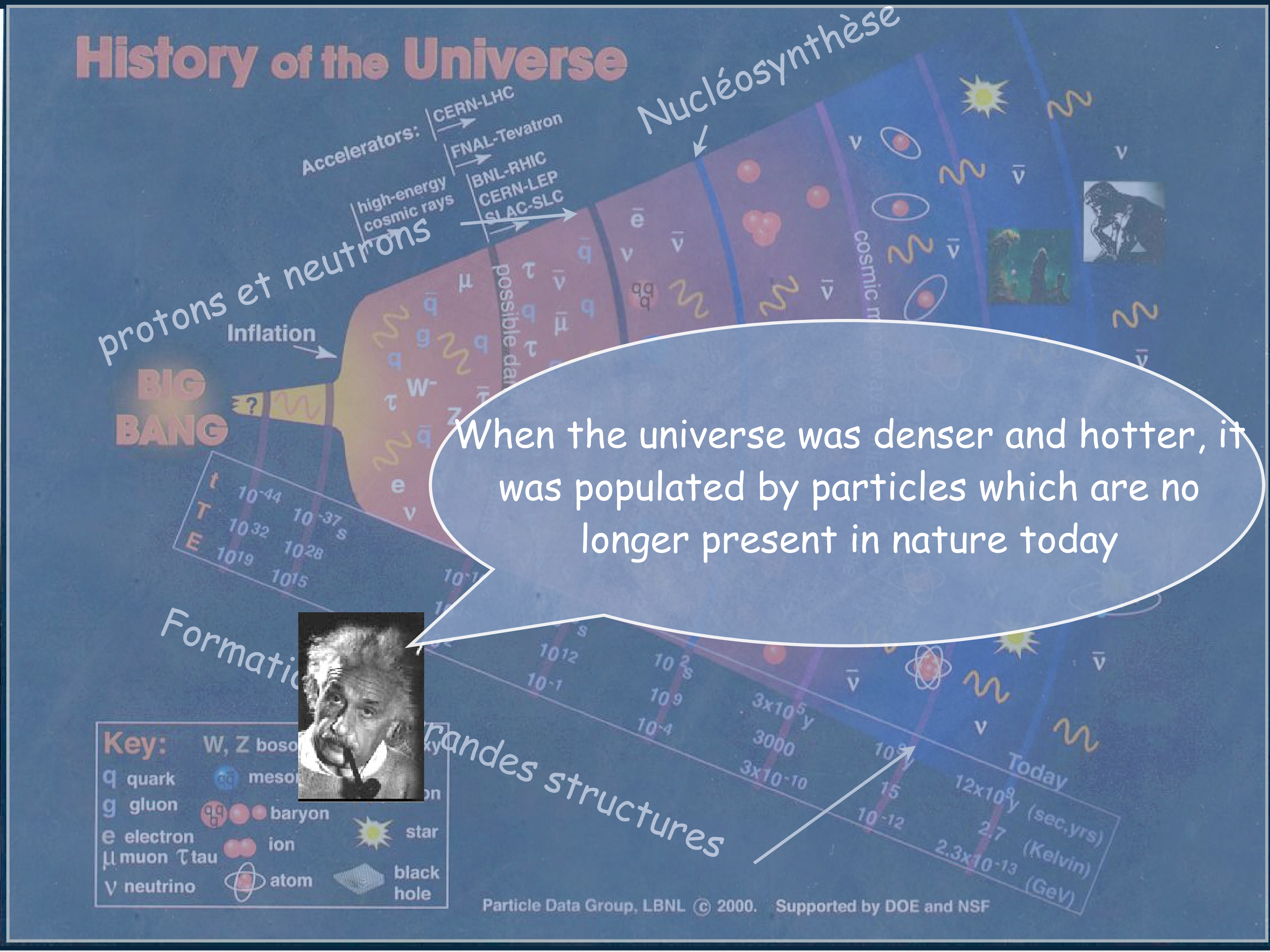
-> very different primordial nucleosynthesis

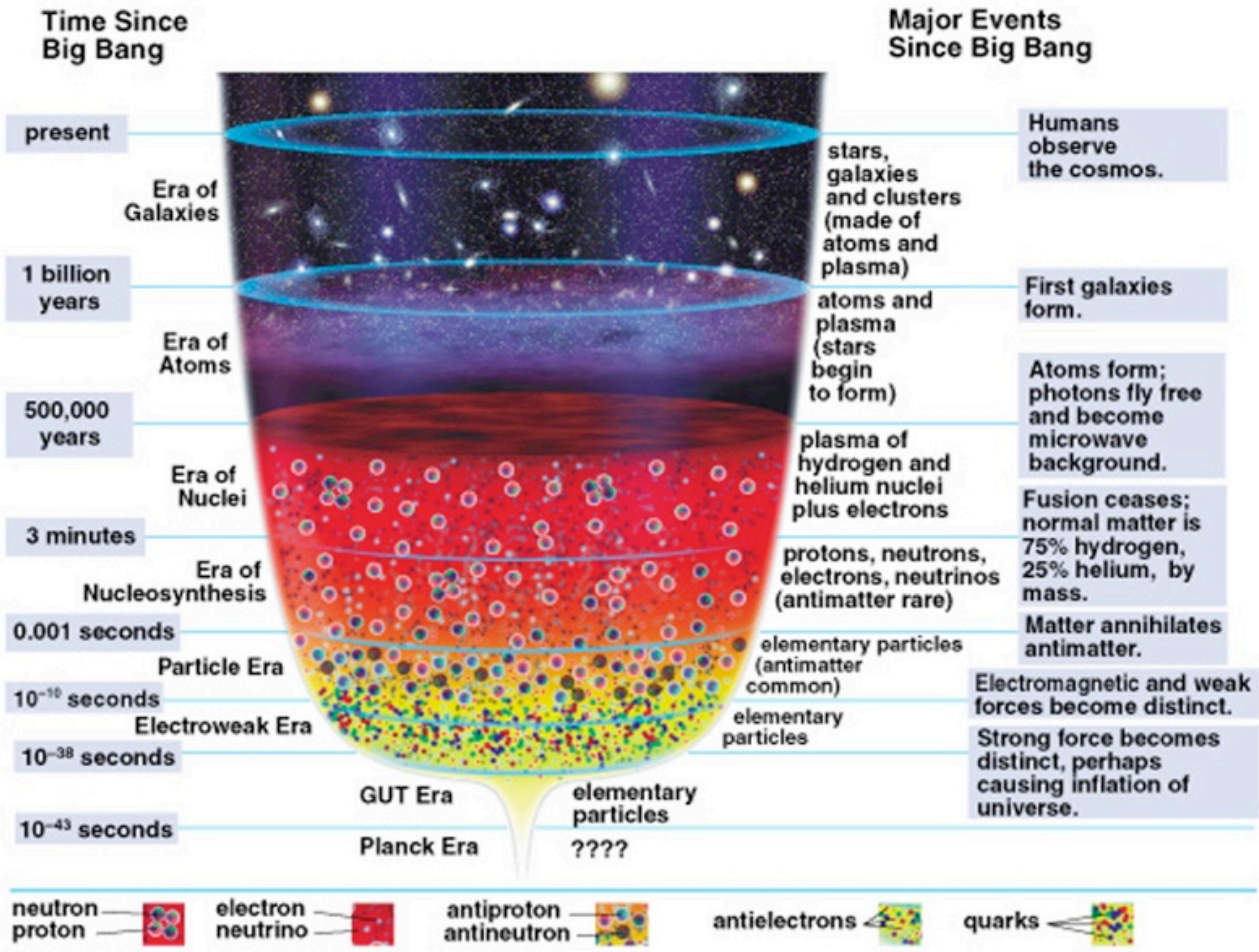
-> a profoundly different (and terribly boring) universe

From the laboratory to the first minutes of the Universe

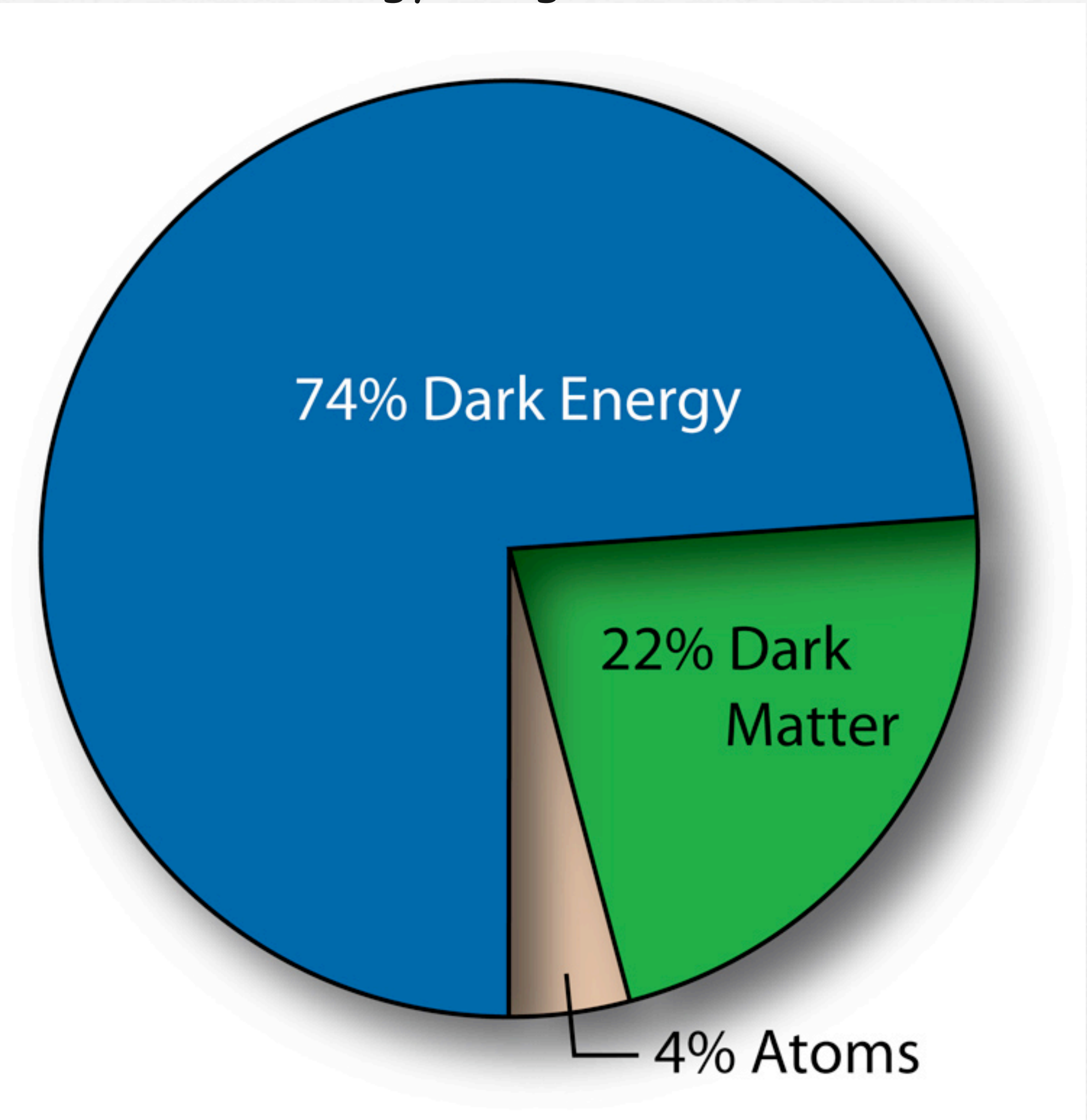
The Standard Model of particle physics enables us to explain the very first minutes in the history of the universe. For instance, it explains how the atomic nuclei were formed.




History of the Universe
Nucléosynthèse
protons et neutrons
Formation des grandes structures
When the universe was denser and hotter, it was populated by particles which are no longer present in nature today
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
Today
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z boson
meson
baryon
ion
atom
star
black hole
Particle Data Group, LBNL © 2000. Supported by DOE and NSF


Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
stars, galaxies and clusters (made of atoms and plasma)
Era of Galaxies
1 billion years
First galaxies form.
atoms and plasma (stars begin to form)
Era of Atoms
500,000 years
Atoms form; photons fly free and become microwave background.
plasma of hydrogen and helium nuclei plus electrons
Era of Nuclei
3 minutes
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
protons, neutrons, electrons, neutrinos (antimatter rare)
Era of Nucleosynthesis
0.001 seconds
Matter annihilates antimatter.
elementary particles (antimatter common)
Particle Era
10^-10 seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10^-38 seconds
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles
10^-43 seconds
Planck Era
????
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks

We don't understand 96 % of the energy budget of the universe



Precision Cosmology

WMAP Cosmological Parameters

Model: lcdm+sz+lens

Data: wmap7

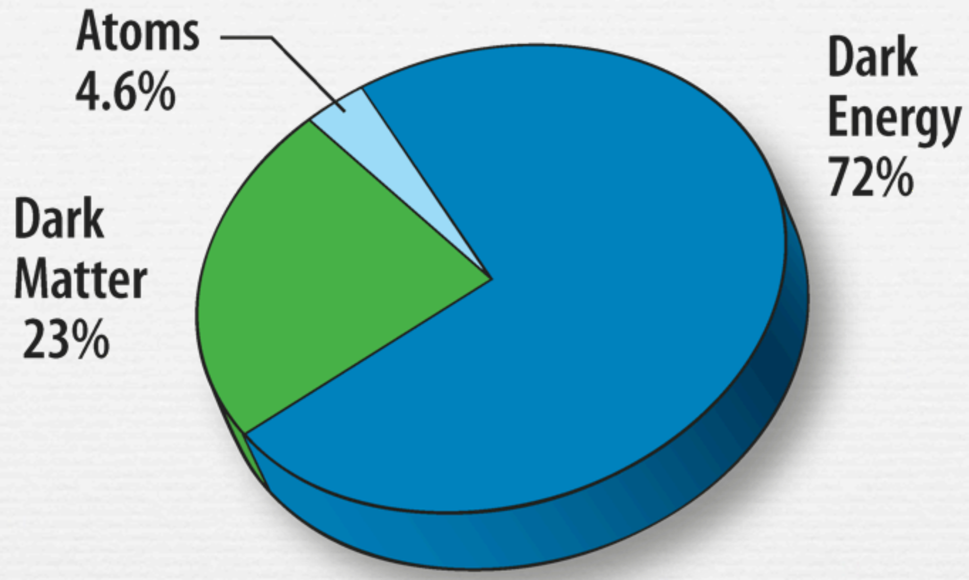
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1-n_s$	0.037 ± 0.014
$1-n_s$	$0.0079 < 1-n_s < 0.0642$ (95% CL)	$A_{\rm BAO}(z=0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$
h	0.710 ± 0.025	H_0	71.0 ± 2.5 km/s/Mpc
$k_{\rm eq}$	$0.00974^{+0.00041}_{-0.00040}$	$\ell_{\rm eq}$	137.5 ± 4.3
ℓ_*	302.44 ± 0.80	n_s	0.963 ± 0.014
Ω_b	0.0449 ± 0.0028	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$
Ω_c	0.222 ± 0.026	$\Omega_c h^2$	0.1109 ± 0.0056
Ω_Λ	0.734 ± 0.029	Ω_m	0.266 ± 0.029
$\Omega_m h^2$	$0.1334^{+0.0056}_{-0.0055}$	$r_{\rm hor}(z_{\rm dec})$	285.5 ± 3.0 Mpc
$r_s(z_d)$	153.2 ± 1.7 Mpc	$r_s(z_d)/D_v(z=0.2)$	$0.1922^{+0.0072}_{-0.0073}$
$r_s(z_d)/D_v(z=0.35)$	$0.1153^{+0.0038}_{-0.0039}$	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc
R	1.719 ± 0.019	σ_8	0.801 ± 0.030
$A_{\rm SZ}$	$0.97^{+0.68}_{-0.97}$	t_0	13.75 ± 0.13 Gyr
τ	0.088 ± 0.015	θ_*	0.010388 ± 0.000027
θ_*	0.5952 ± 0.0016 °	t_*	379164^{+5187}_{-5243} yr
$z_{\rm dec}$	1088.2 ± 1.2	z_d	1020.3 ± 1.4
$z_{\rm eq}$	3196^{+134}_{-133}	$z_{\rm reion}$	10.5 ± 1.2
z_*	$1090.79^{+0.94}_{-0.92}$		

fraction of the total energy density in "dark energy" (→ Ω_Λ)

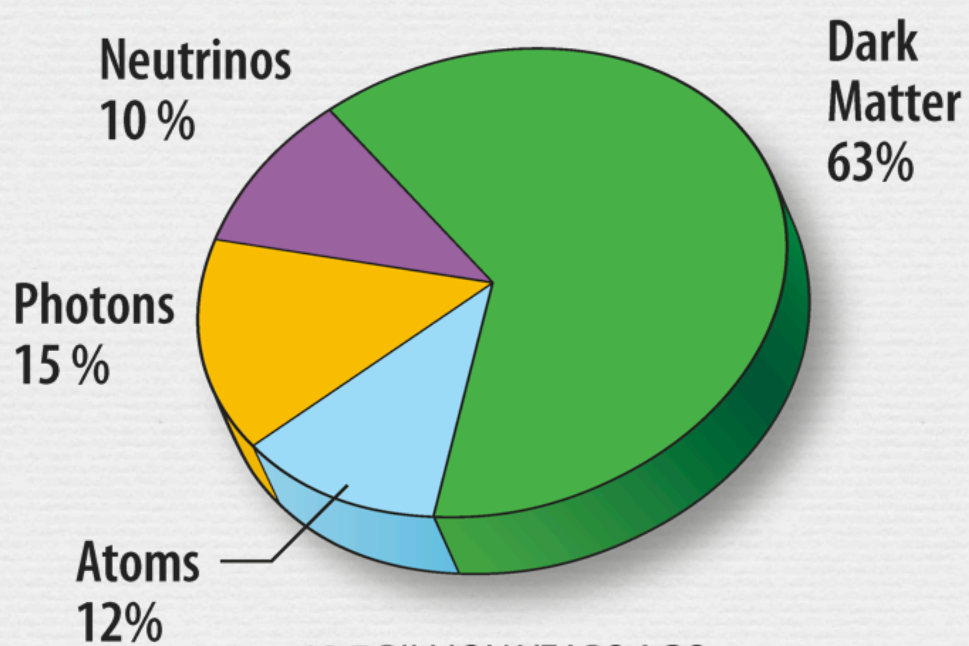
expansion rate (→ H_0)

fraction of the total energy density in matter (→ Ω_m)

age of the universe (→ t_0)



TODAY



13.7 BILLION YEARS AGO

(Universe 380,000 years old)

2 major observations unexplained by the Standard Model

- the Dark Matter of the Universe

Some invisible transparent matter (that does not interact with photons) which presence is deduced through its gravitational effects

15% baryonic matter (1% in stars, 14% in gas)

85% dark unknown matter

- the (quasi) absence of antimatter in the universe

baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

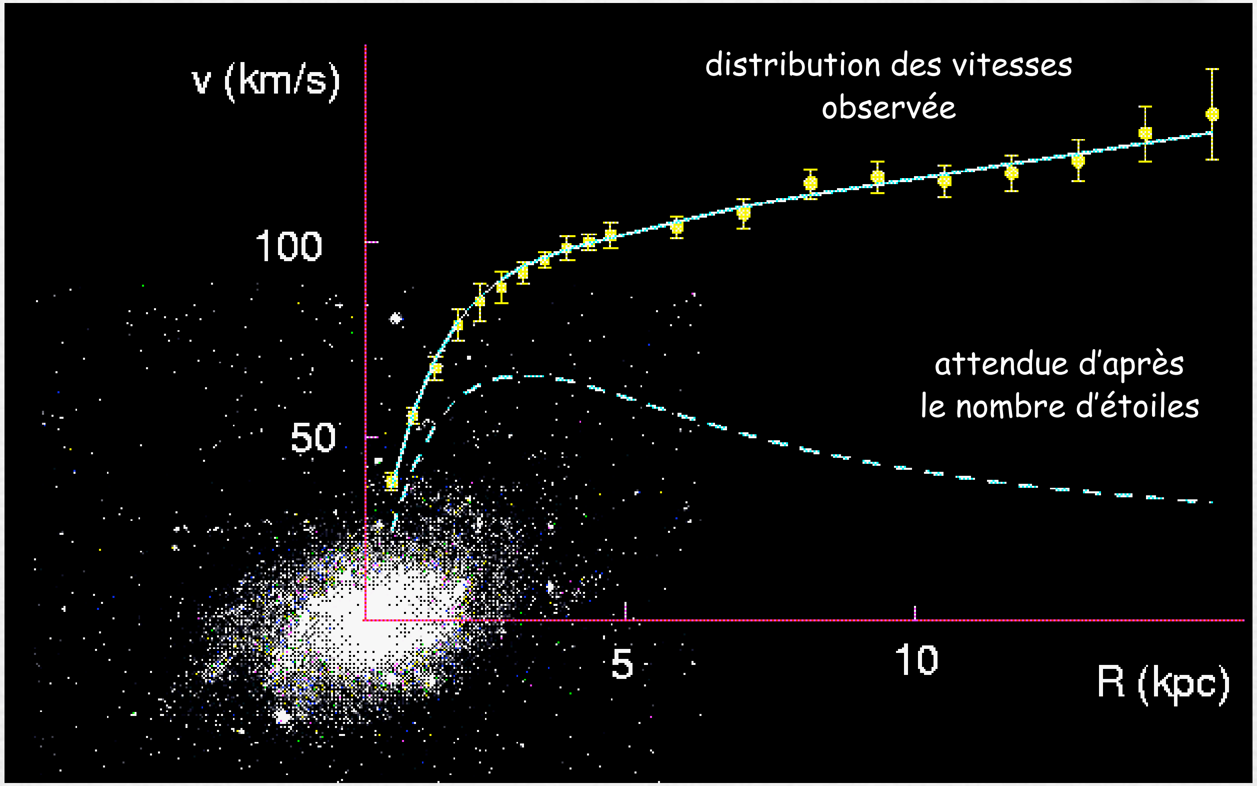
→ observational need for new physics

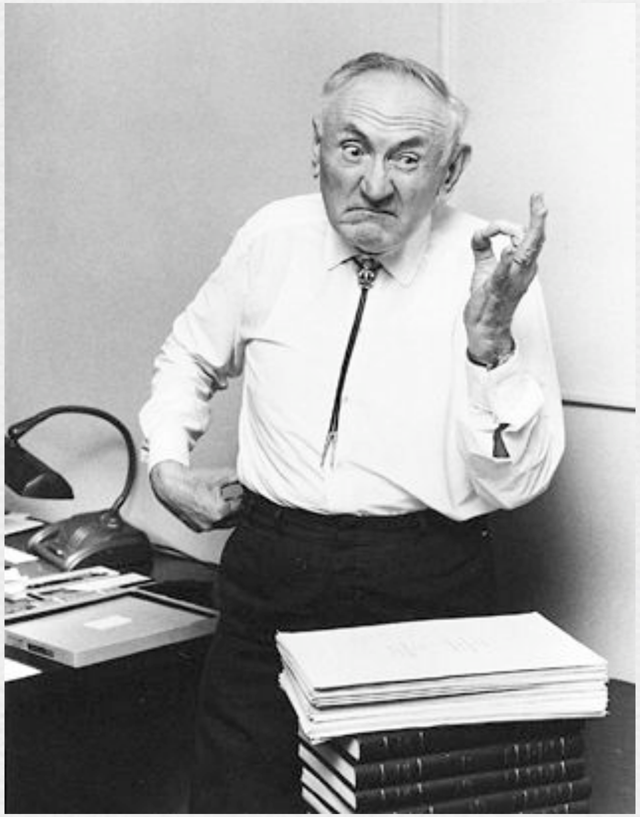
→ what does this have to do with the electroweak scale?

galaxy rotation curves

$$M(r) \propto \frac{v^2 r}{G_N}$$

At large distances from the center, beyond the edge of the galaxy, the velocity would be expected to fall as 1/sqrt(r) if most of the matter is contained in the optical disk while it was observed to remain constant, implying the existence of an extended dark halo

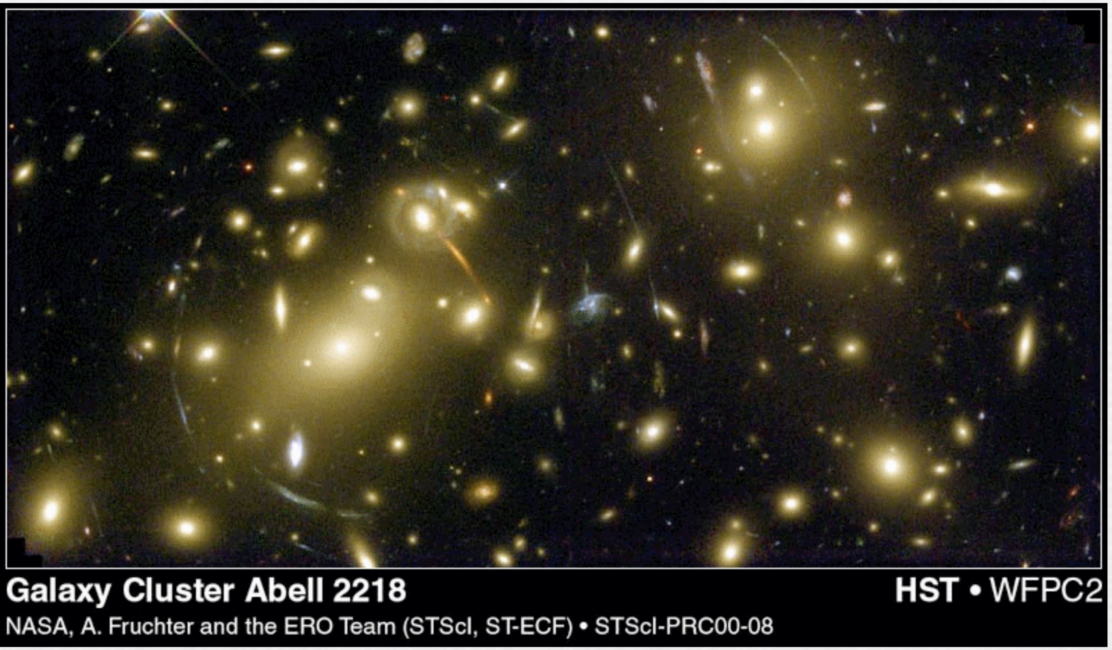


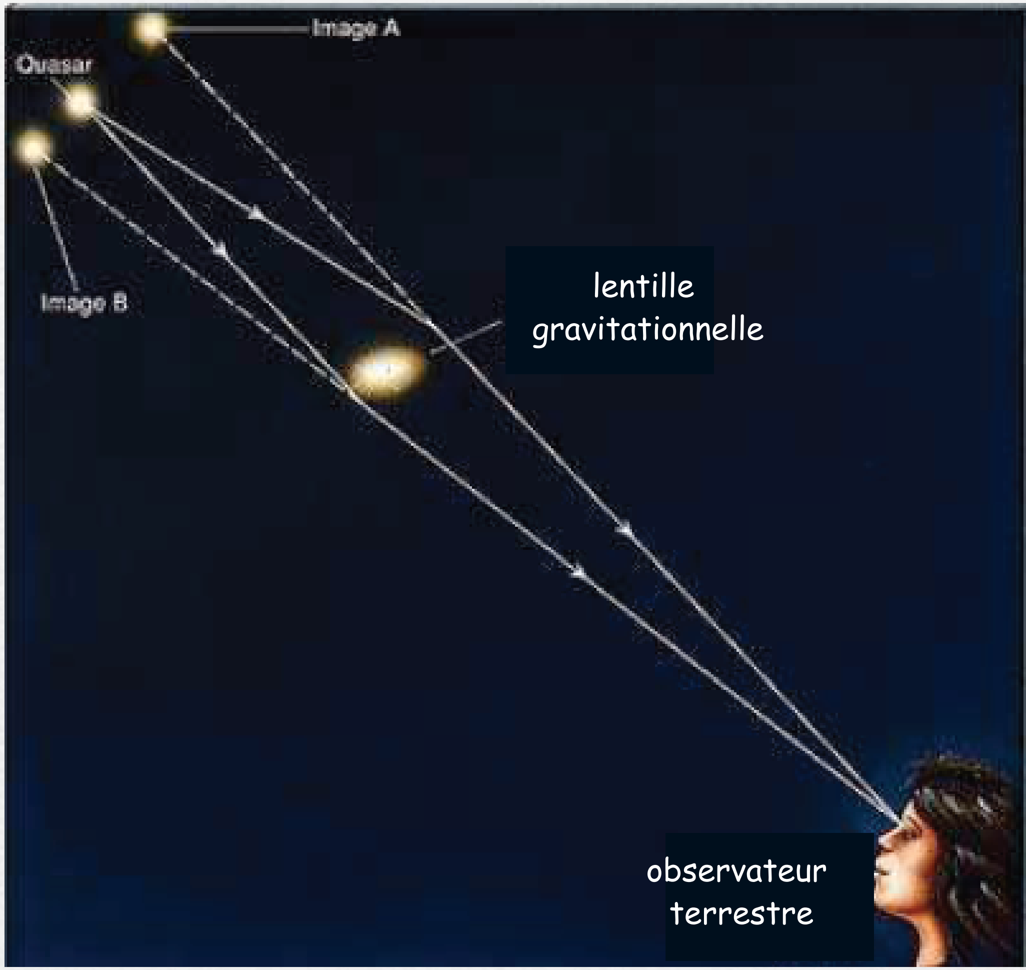


Zwicky

In 1933, Zwicky uses velocities of galaxies inside clusters to estimate the mass of clusters. The mass he obtains is much larger than the mass of stars contained in the galaxies

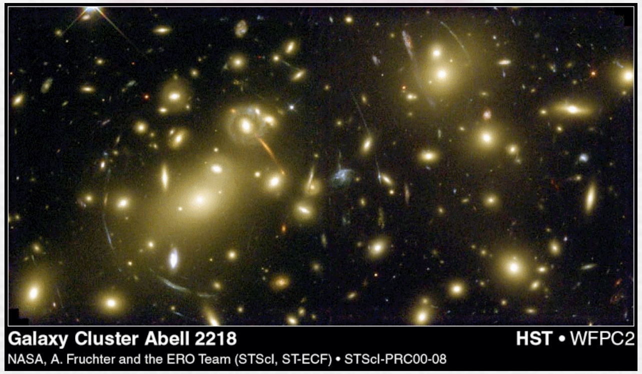
gravitational lensing



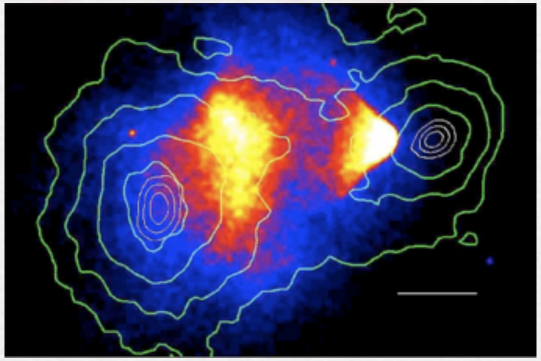


The existence of (Cold) Dark Matter has been established by a host of different methods; it is needed on all scales

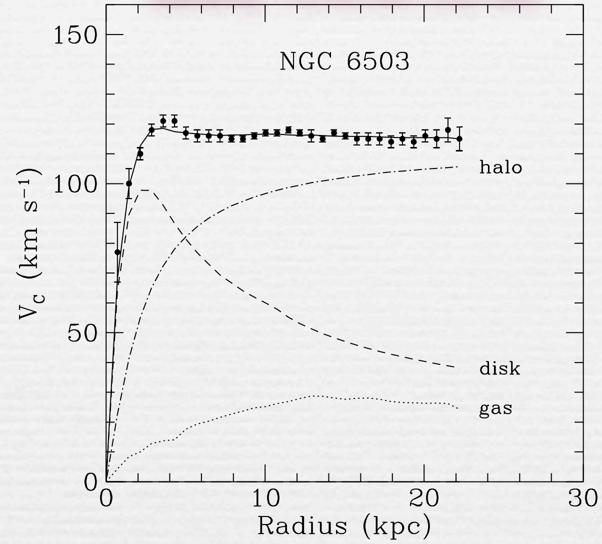
Gravitational lensing



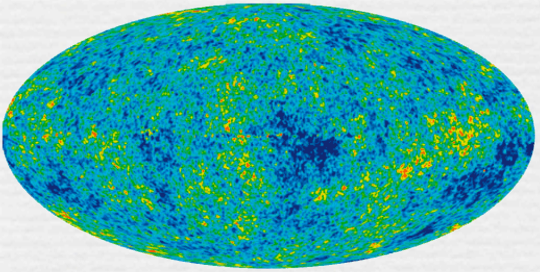
The "Bullet cluster": lensing map versus X-ray image

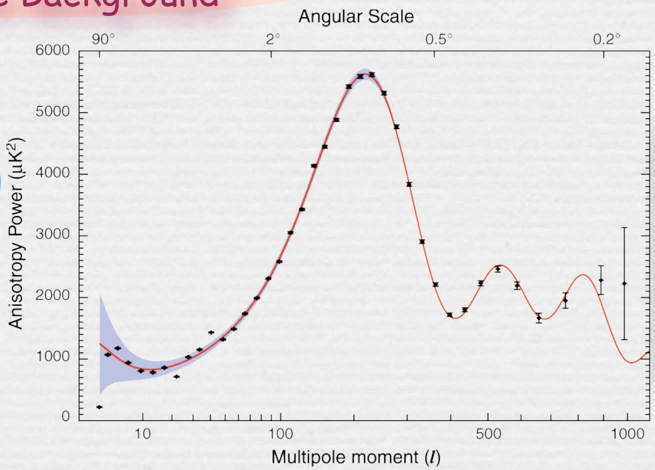


Galaxy rotation curves



Cosmic Microwave Background





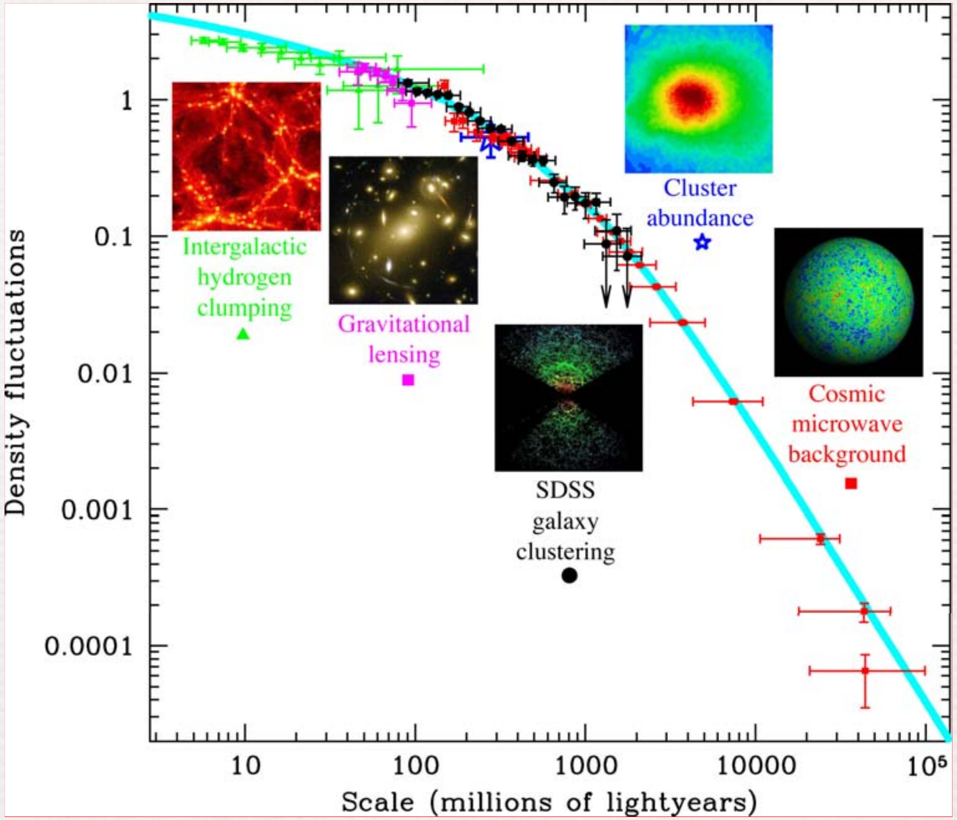
... etc

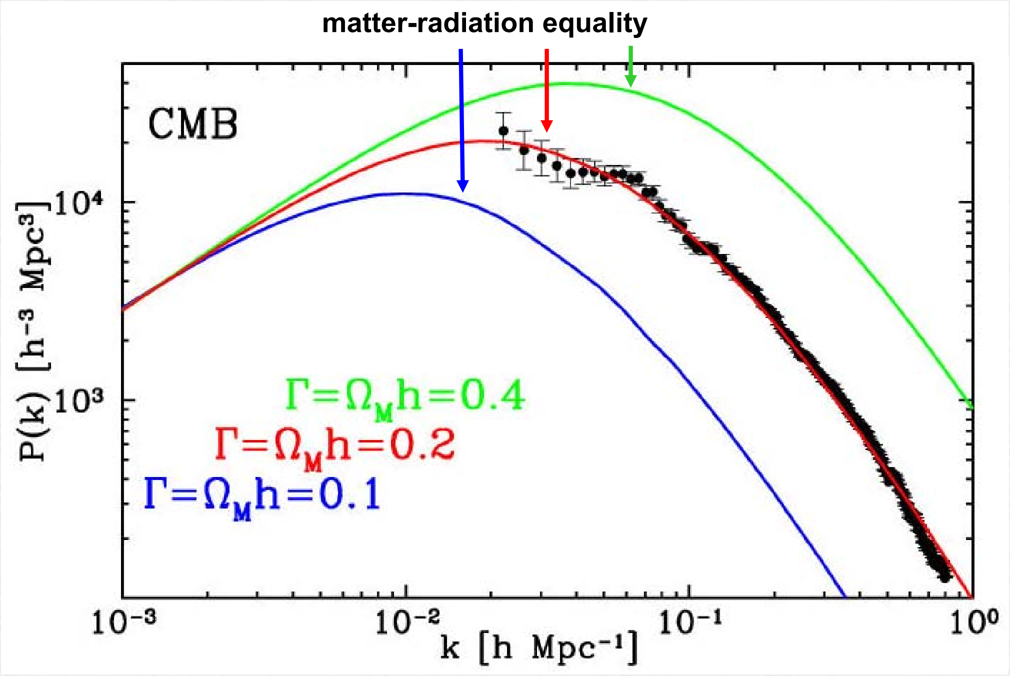
-> Fraction of the universe's energy density stored in dark matter : $\Omega_{DM} \approx 0.22$

The picture from astrophysical and cosmological observations is getting more and more focussed

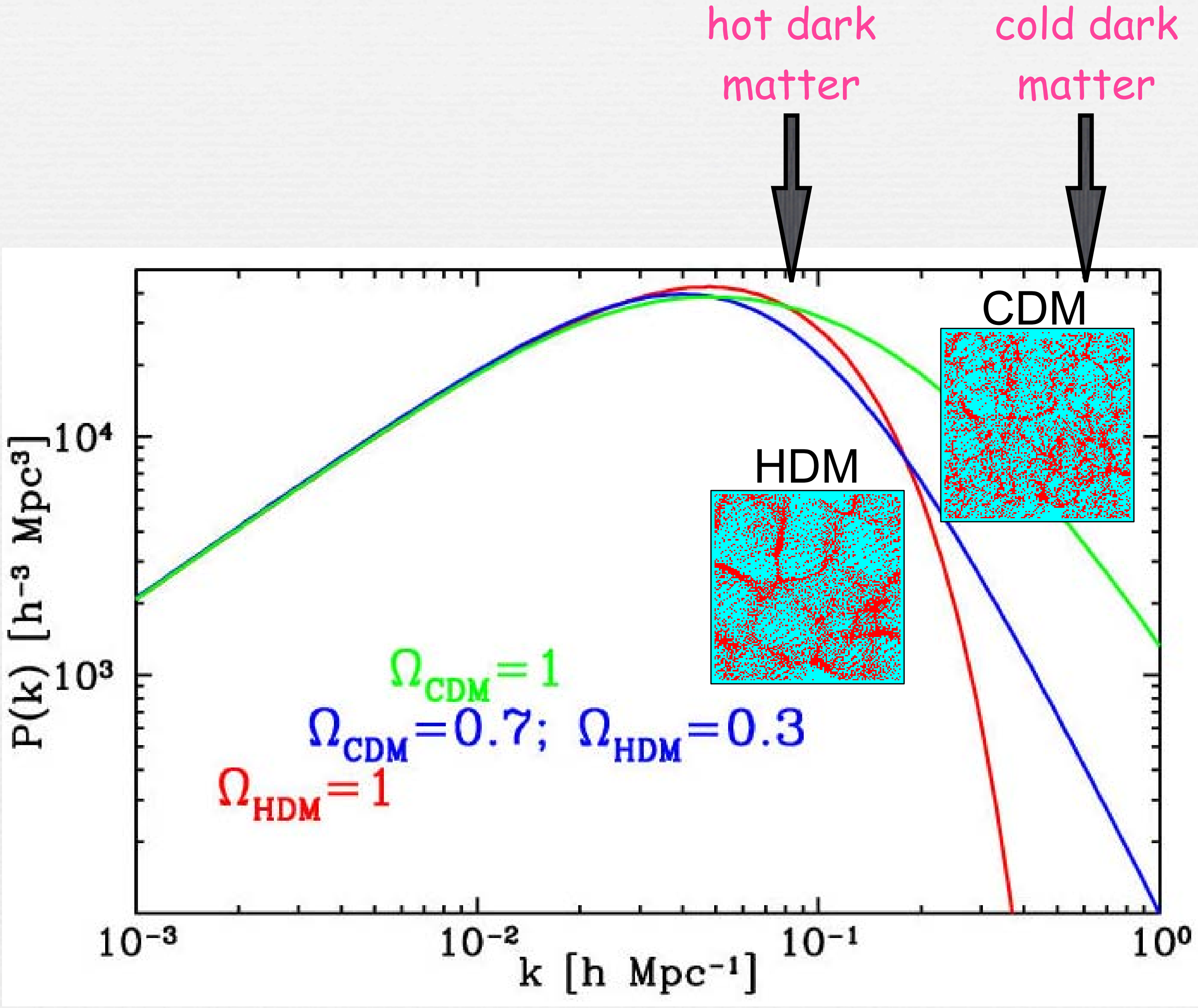
DM properties are well-constrained (gravitationally interacting, long-lived, not hot, not baryonic) but its identity remains a mystery

Matter power spectrum

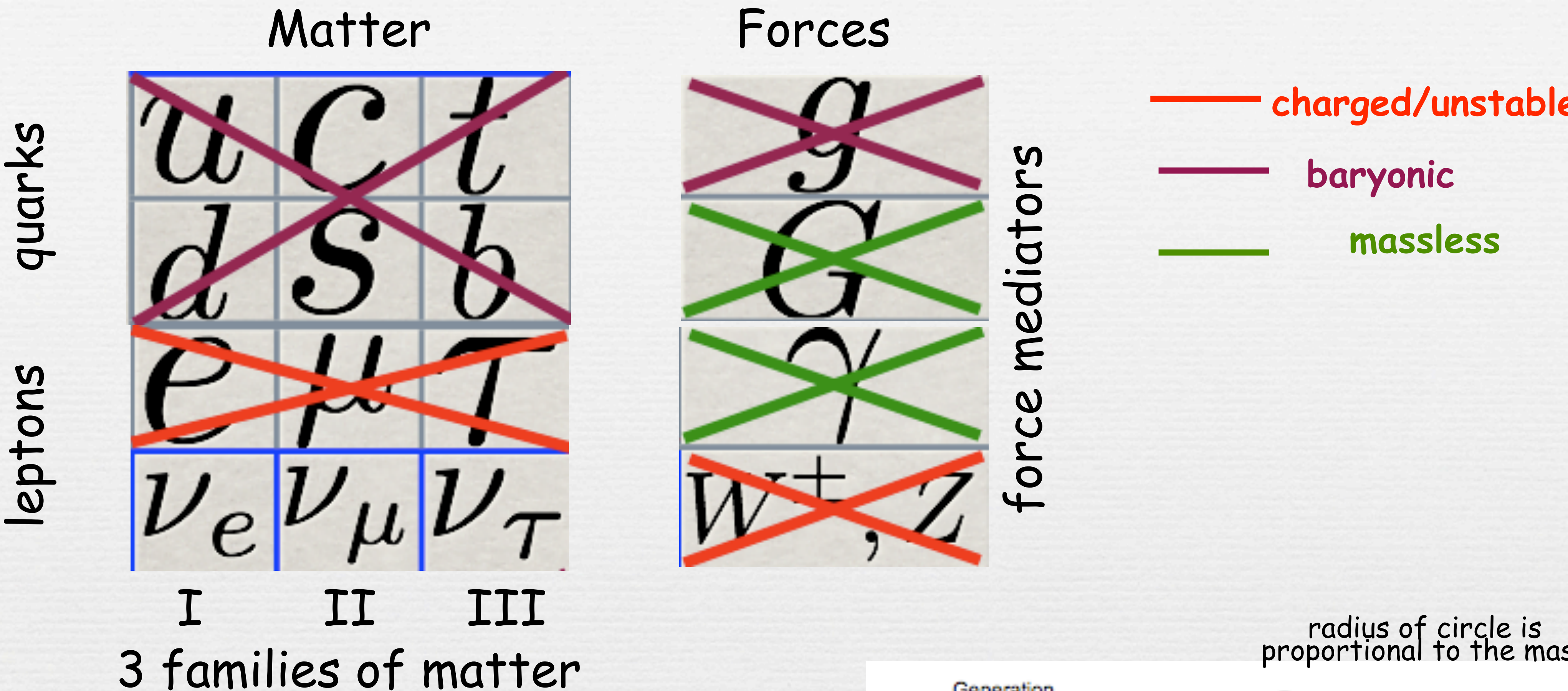




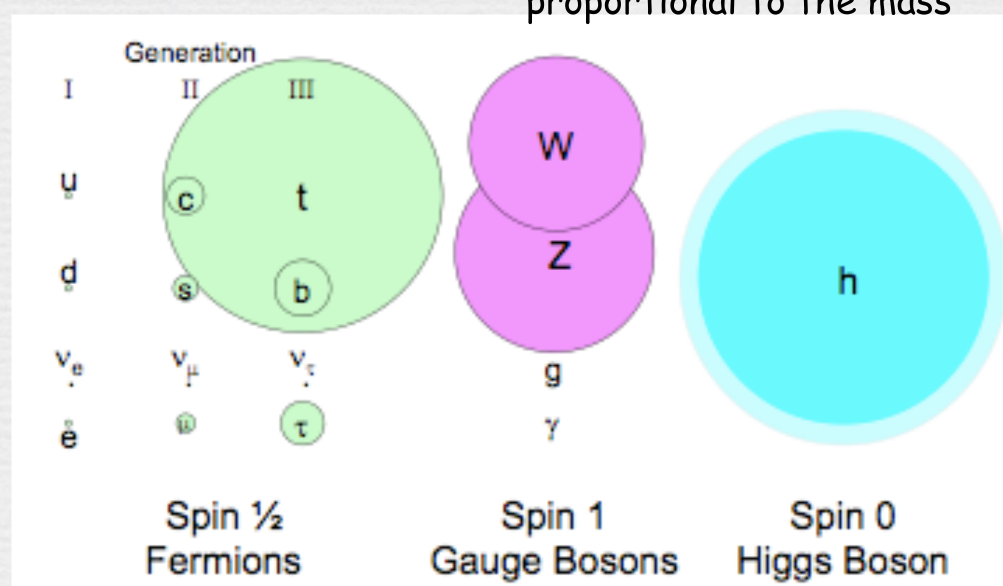
Neutrinos


hot dark matter
cold dark matter
CDM
HDM
$\Omega_{CDM}=1$
$\Omega_{CDM}=0.7;\ \Omega_{HDM}=0.3$
$\Omega_{HDM}=1$
P(k) [h^{-3} Mpc^3]
k [h Mpc^{-1}]
10^4
10^3
10^{-3}
10^{-2}
10^{-1}
10^0

Why can't dark matter be explained by the Standard Model?



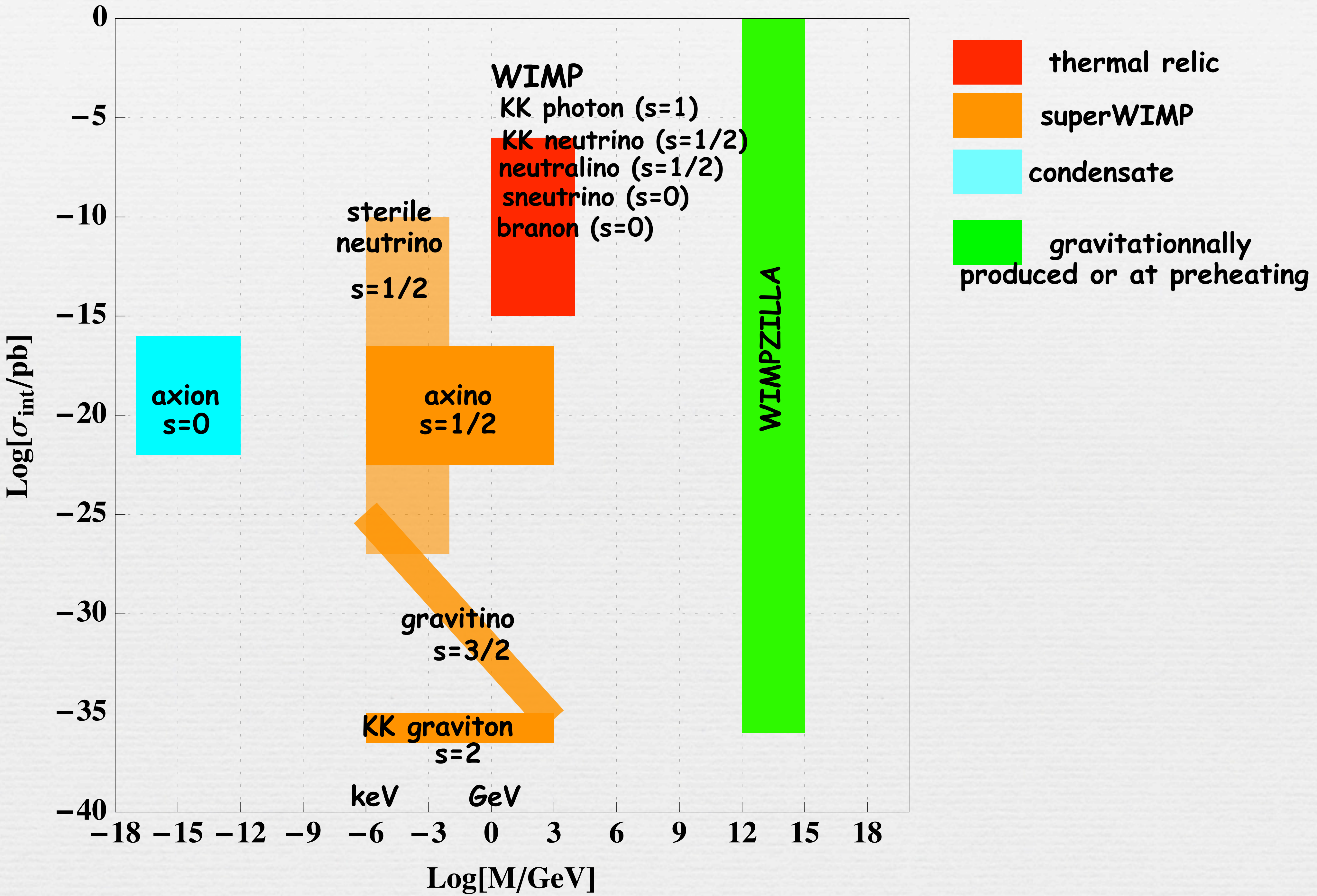
radius of circle is proportional to the mass



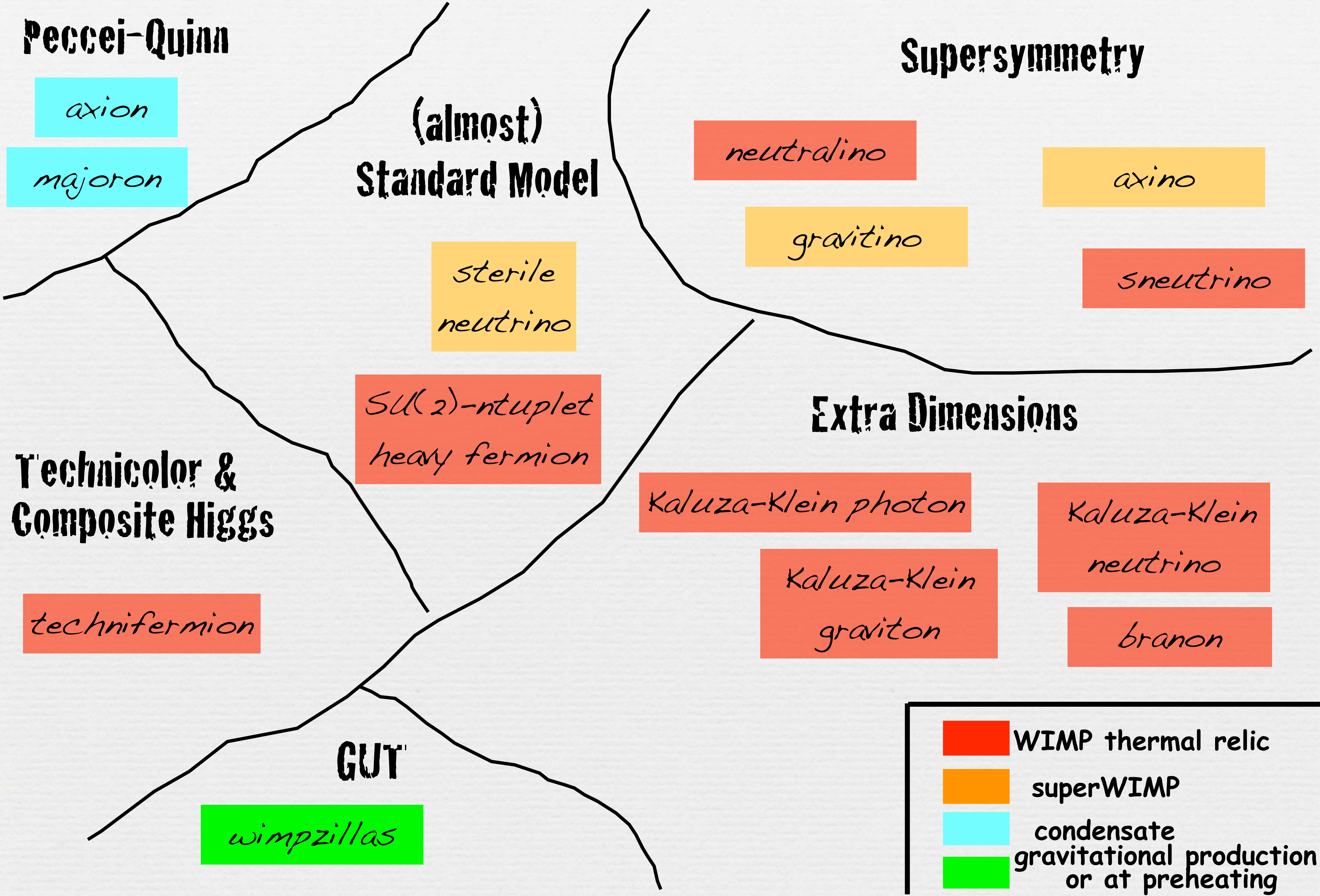
contribution to the energy budget of the universe

Particle	Ω	type
Baryons	4 - 5 %	cold
Neutrinos	< 2 %	hot
Dark matter	20 - 26 %	cold

Dark Matter Candidates Ω~1



In Theory Space



How to detect Dark Matter?

Direct detection: We can "touch" dark matter

Indirect detection: We can "catch" the particles emmitted by dark matter

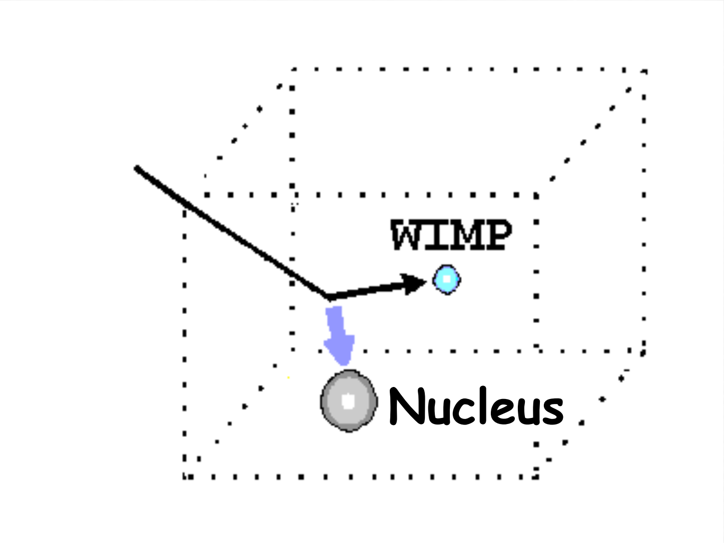
WIMP direct detection

Because they interact so weakly, Wimps drifting through the Milky Way pass through the earth without much harm.

Just a few Wimps are expected to collide elastically upon terrestrial nuclei, partially transferring to them their kinetic energy.

Direct detection consists in observing the recoiled nuclei.

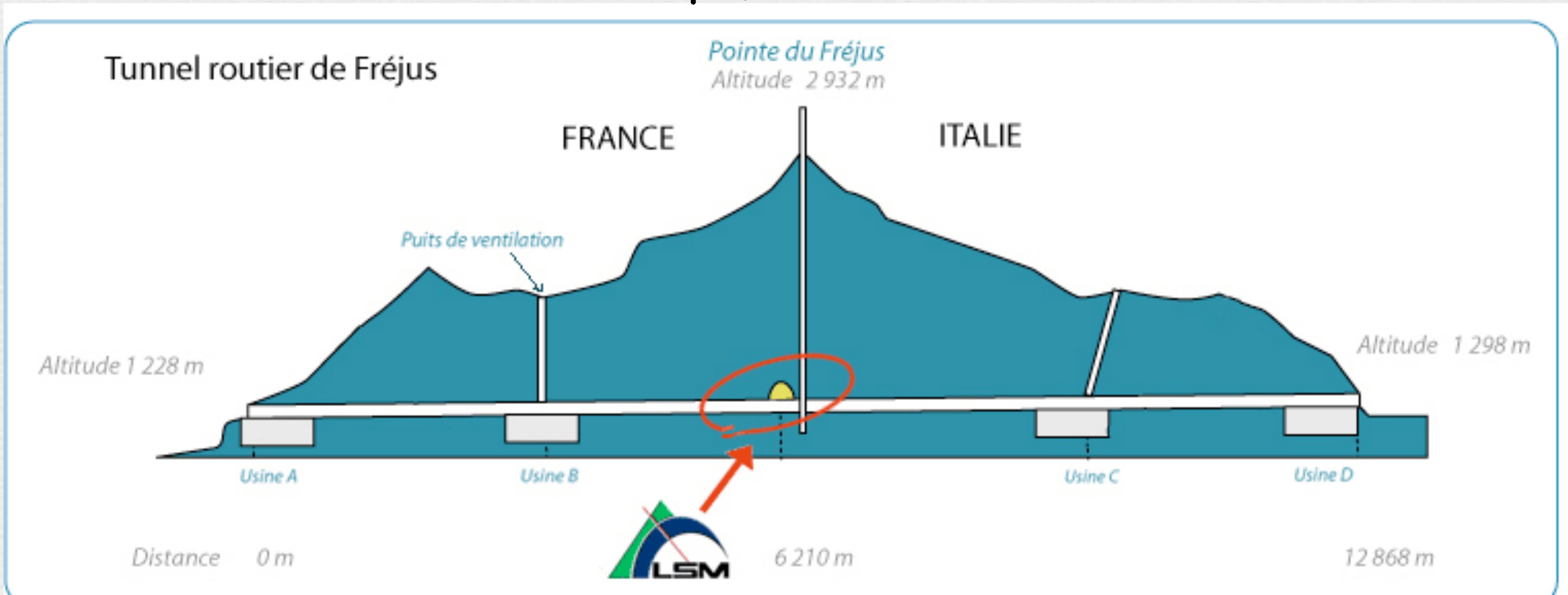
Direct detection



The earth feels a “wind of WIMPS”

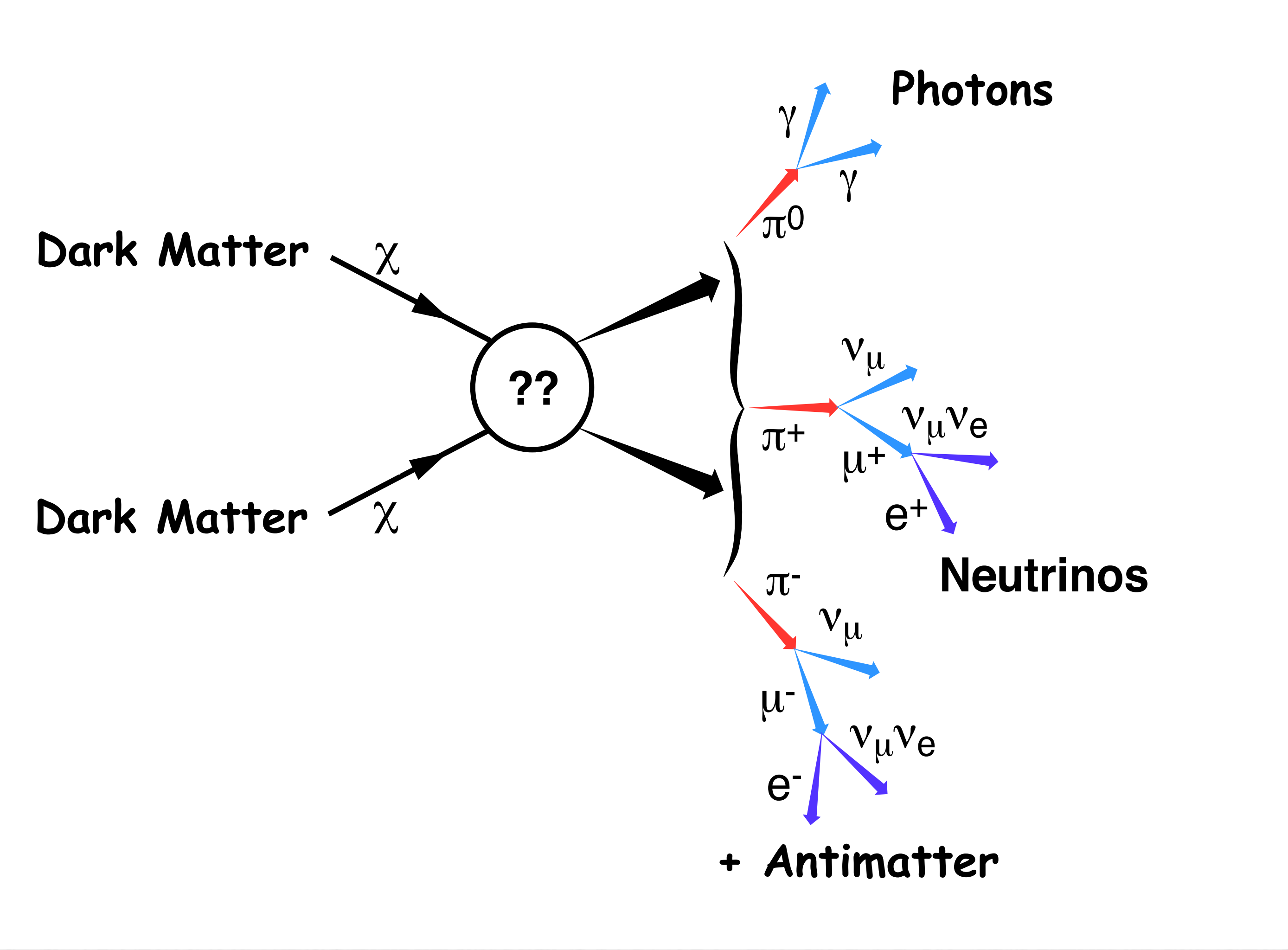
A vary large number of experiments (underground) try to detecter WIMPS by measuring the recoil motion of nuclei due to their collision with a WIMP.

for example, “EDELWEISS”:



Indirect Detection

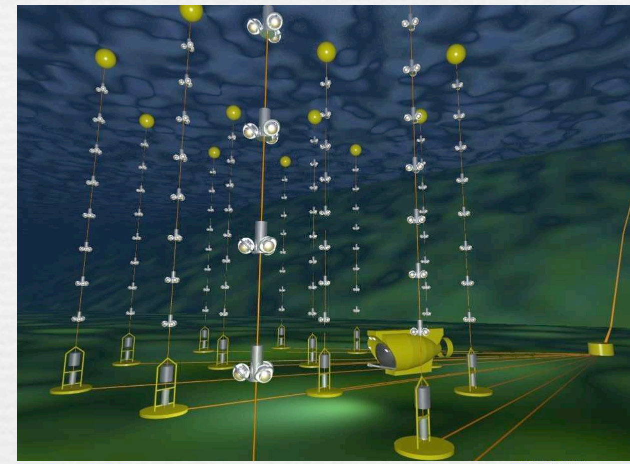
Dar Matter can produce
photons, electrons, protons, neutrinos, antiprotons, positrons :



Indirect Detection

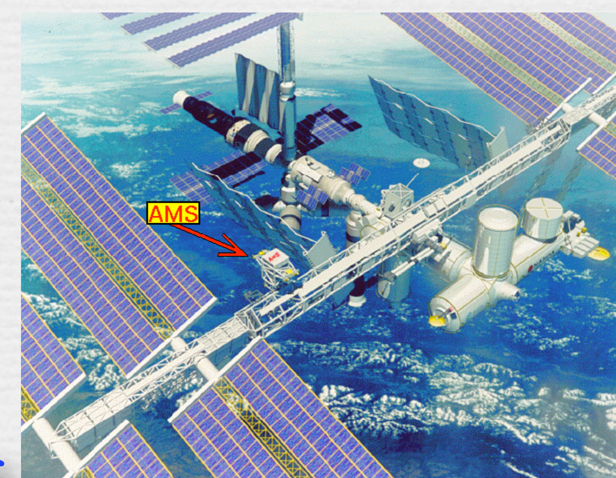
search for neutrinos in the South Pole

in the Mediterranean sea..



Antarès

Search for antiprotons in space...



AMS

Indirect Detection

Search for photons on earth

Hess

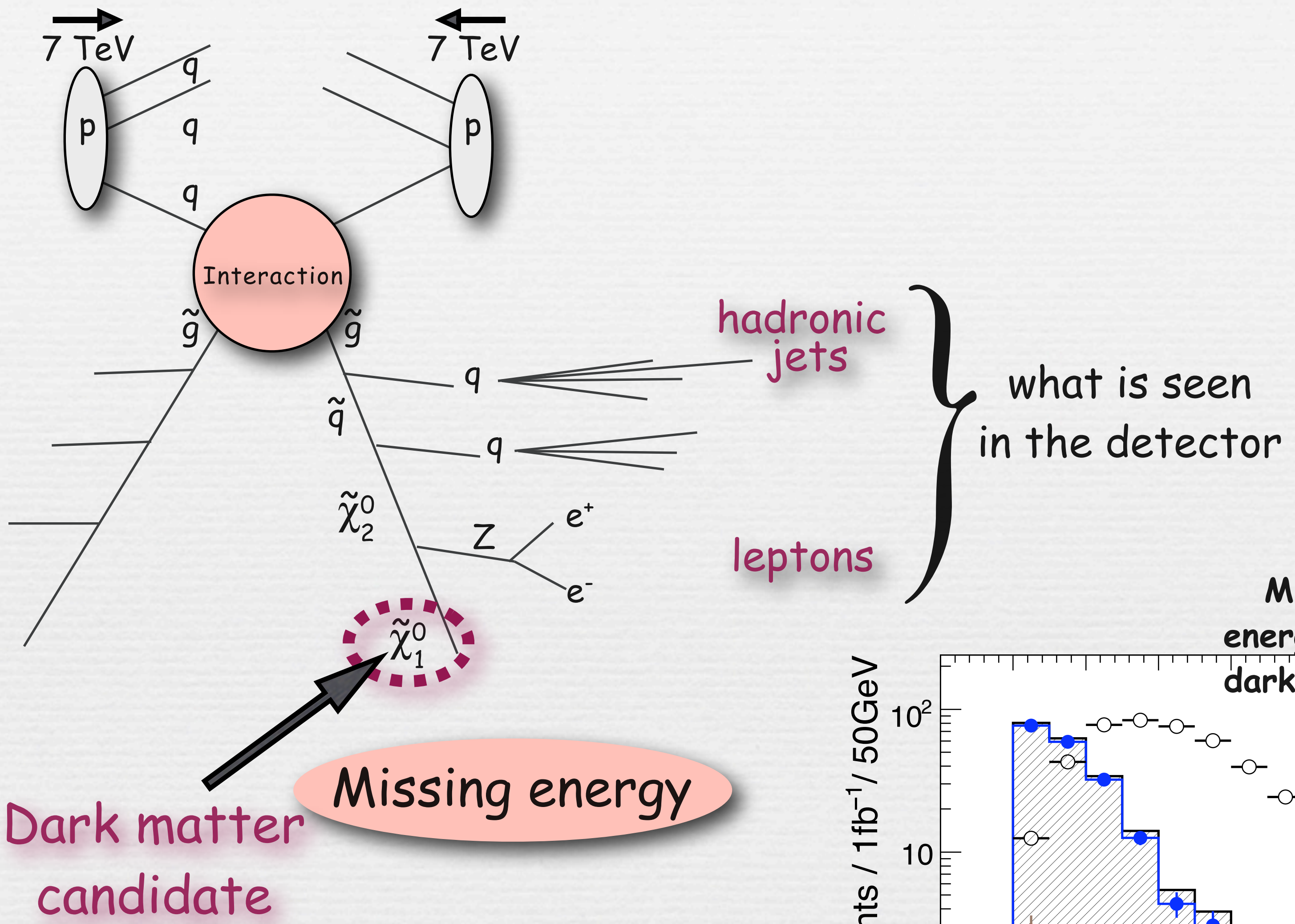
and in space ...

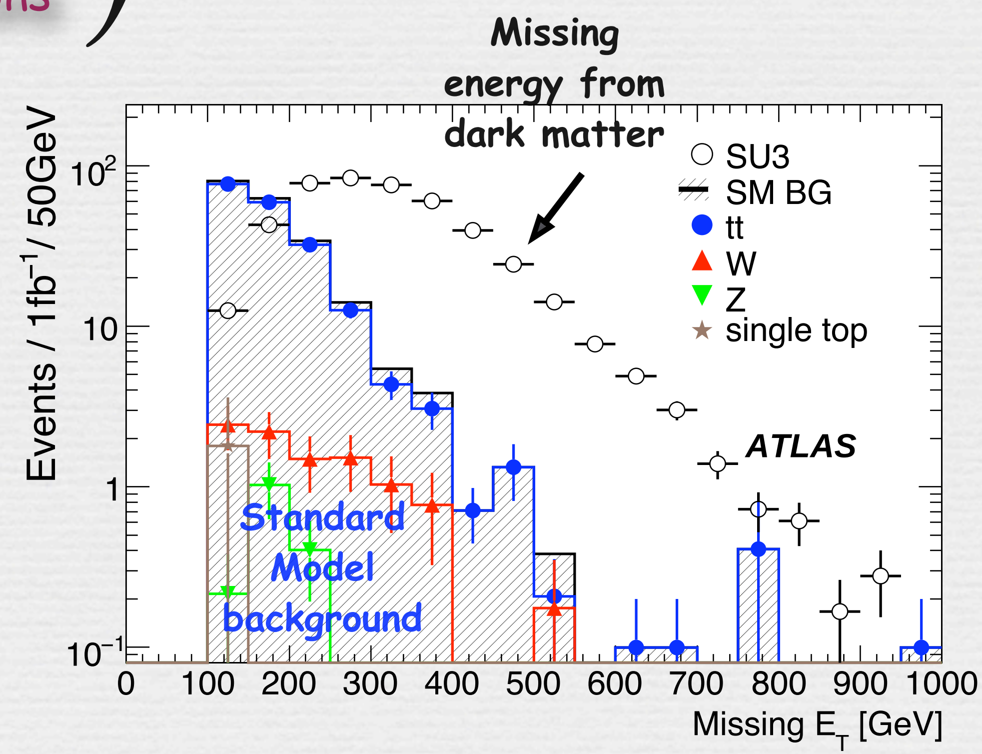
Fermi

Seeing the light from Dark Matter

- photons travel undeflected and point directly to source
- photons travel almost unattenuated and don't require a diffusion model
- detected from the ground (ACTs) and from above (FERMI)

Producing Dark Matter at LHC = "Missing Energy" events

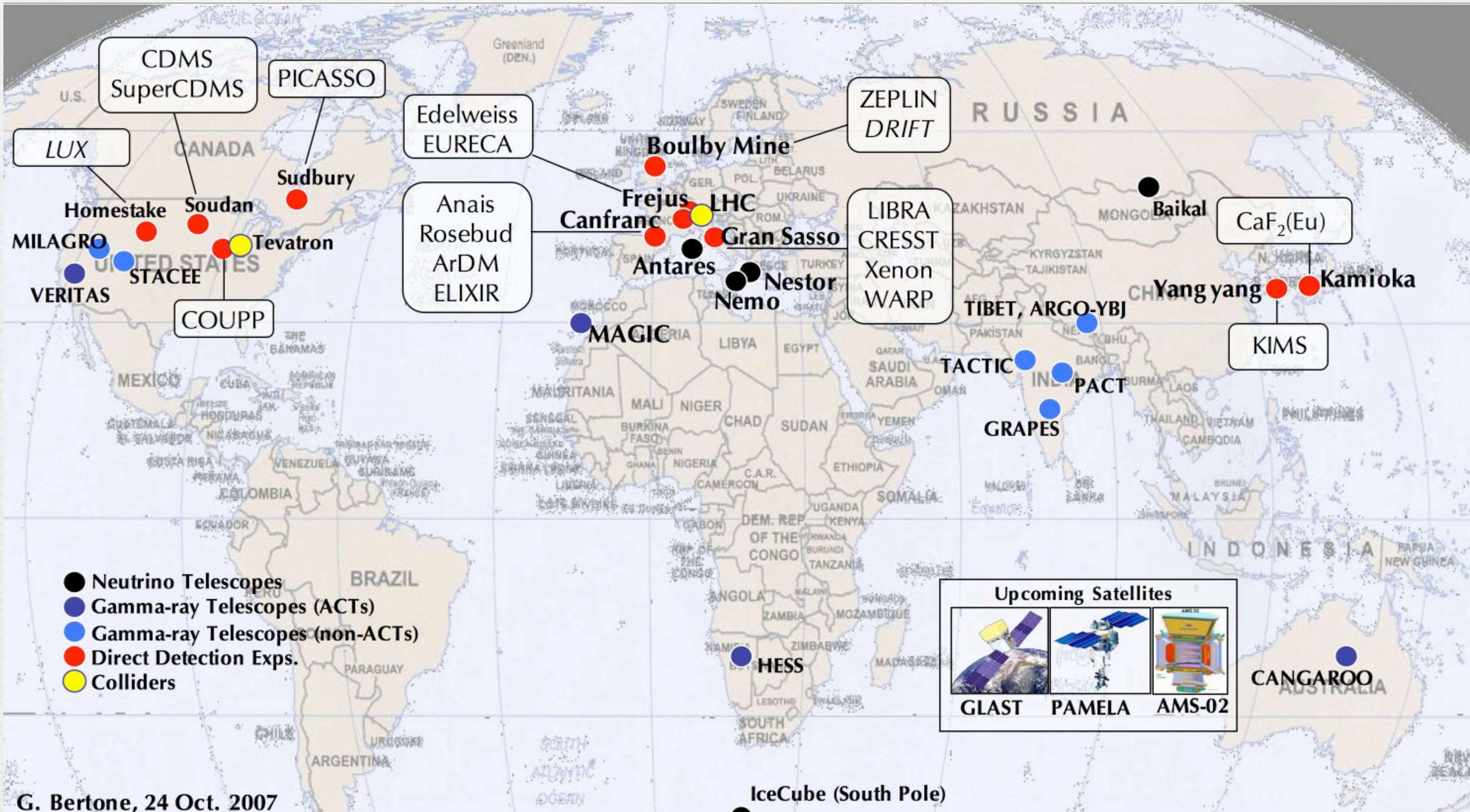




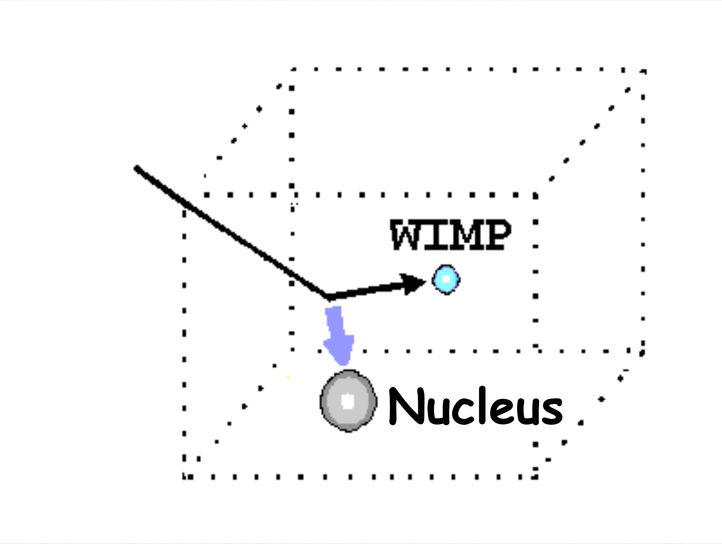
The Dark Matter Decade

Huge experimental effort towards the identification of Dark Matter

Indirect		Direct	Collider experiments
Antimatter Neutrinos Gamma Rays	Signature of Annihilation in space	Elastic Scattering signature in underground labs	Missing Energy signature in high energy accelerators



Back to Direct detection



The earth feels a "wind of WIMPS"

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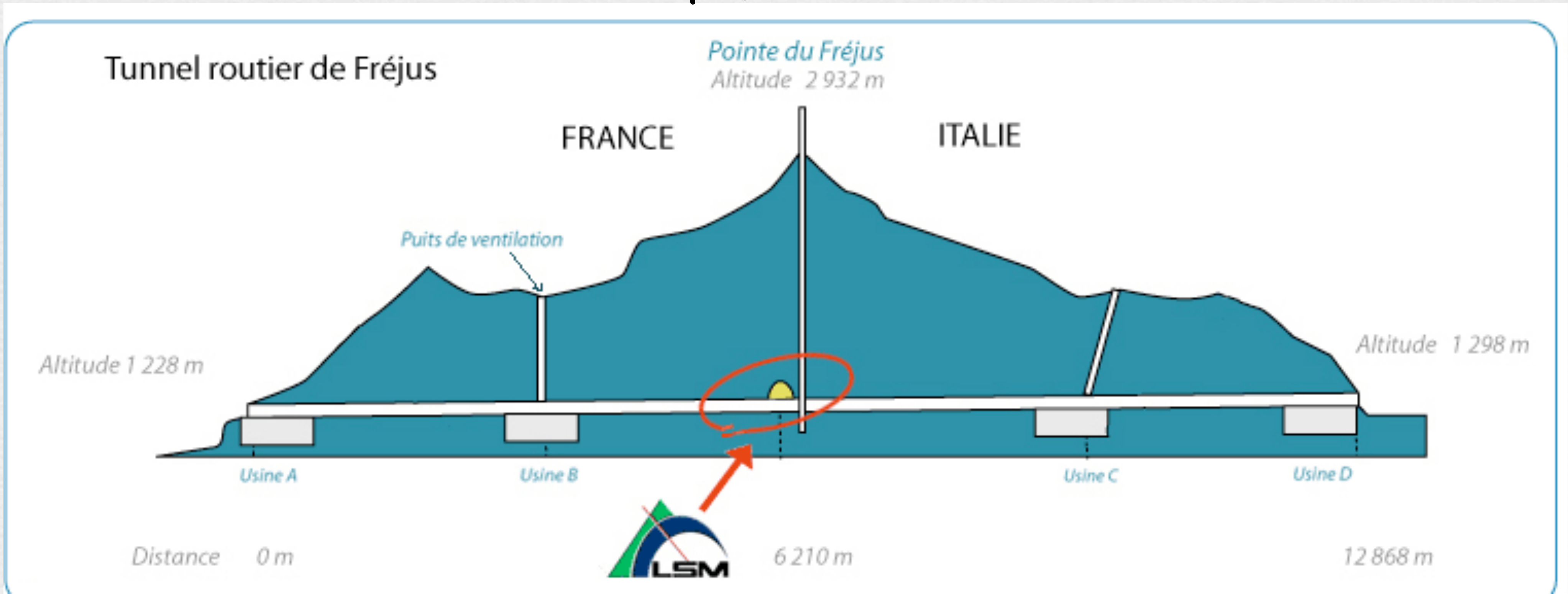


Dark Matter Direct detection

cnts / keV recoil energy E_R:

$$\frac{dN}{dE_R}(t) \propto \frac{\rho_\chi}{m_\chi} \int_{v>v_{\min}} d^3v \, \frac{d\sigma}{dE_R} \, v \, f_\oplus(\vec{v}, t)$$

ρ_χ DM energy density, default: 0.3 GeV cm^{-3}

$v_{\min}$: minimal DM velocity required to produce recoil energy E_R

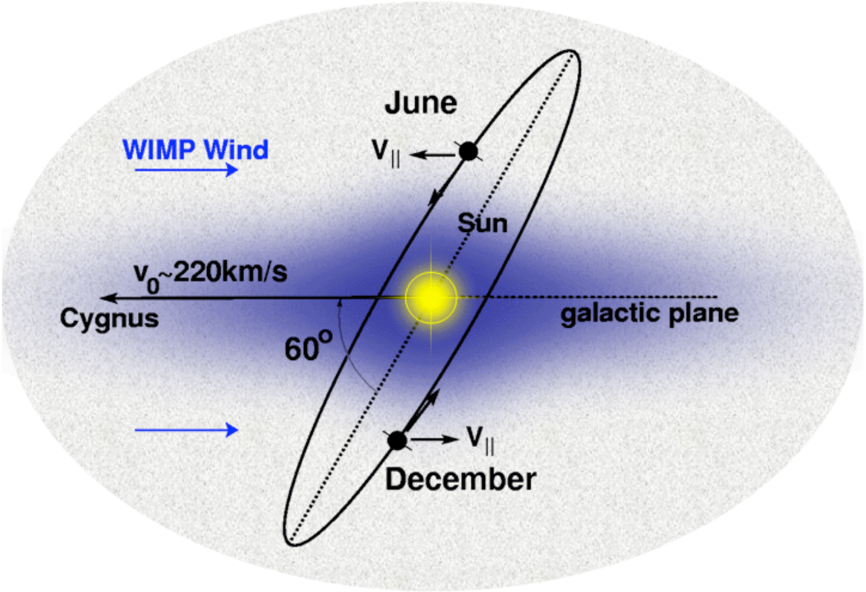
DM velocity distribution

$$f_\oplus(\vec{v}, t) = f_{\text{gal}}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t)) \qquad f_{\text{gal}}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\text{esc}} \\ 0 & v > v_{\text{esc}} \end{cases}$$

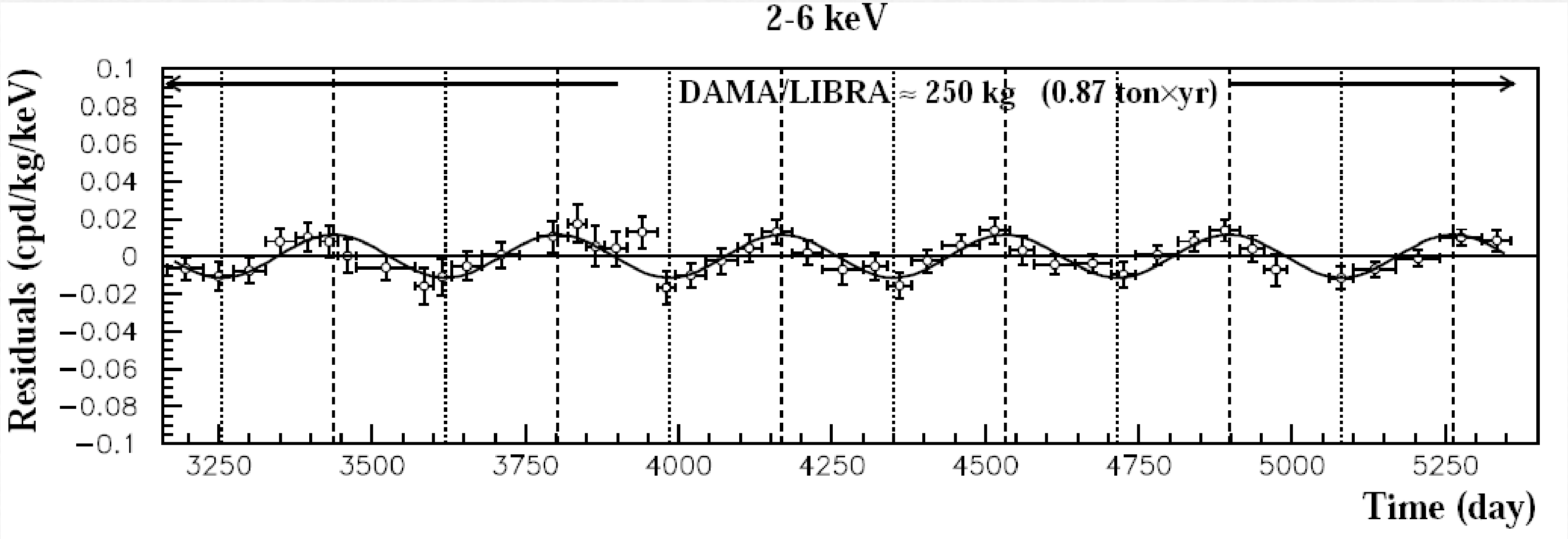
$\bar{v} \simeq 220\,\text{km/s}$ $\quad v_{\text{esc}} \simeq 550\,\text{km/s}$

sun velocity: $\vec{v}_\odot = (0, 220, 0) + (10, 13, 7)\,\text{km/s}$

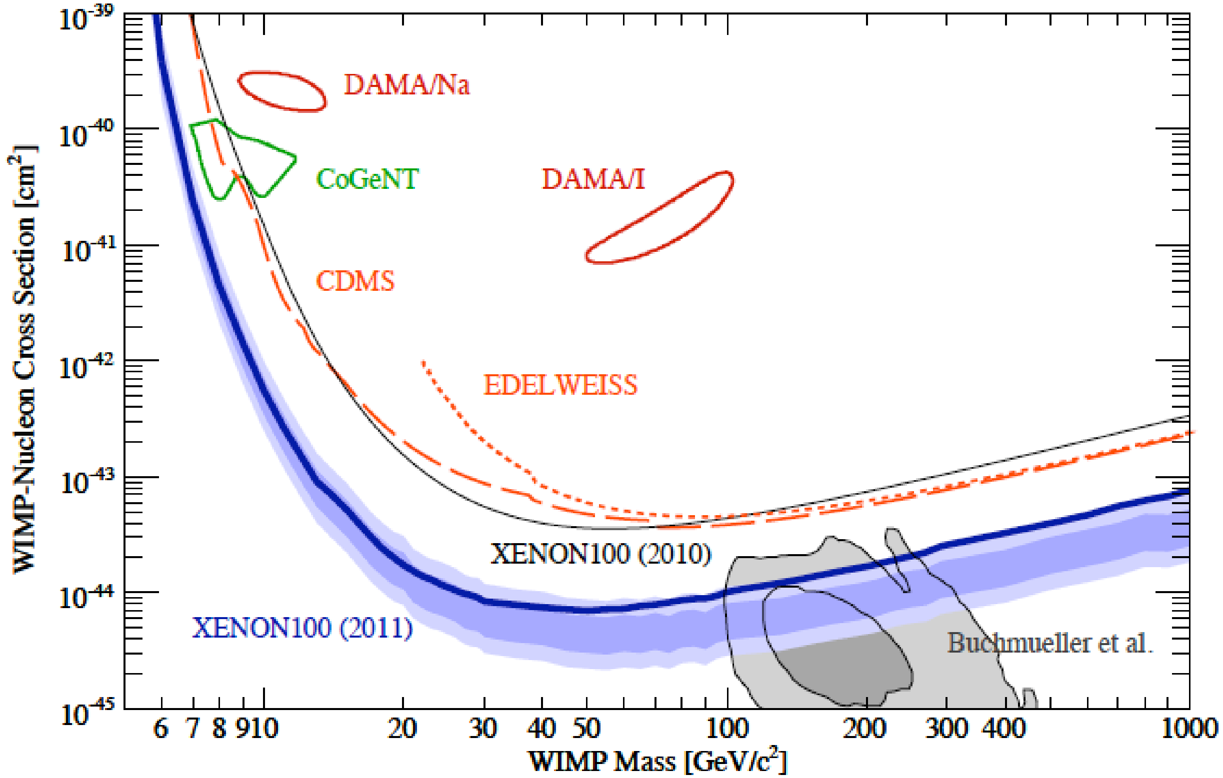
earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\text{km/s}$



DAMA/LIBRA annual modulation signal



However not seen by other experiments ...



XENON100, 1104.2549

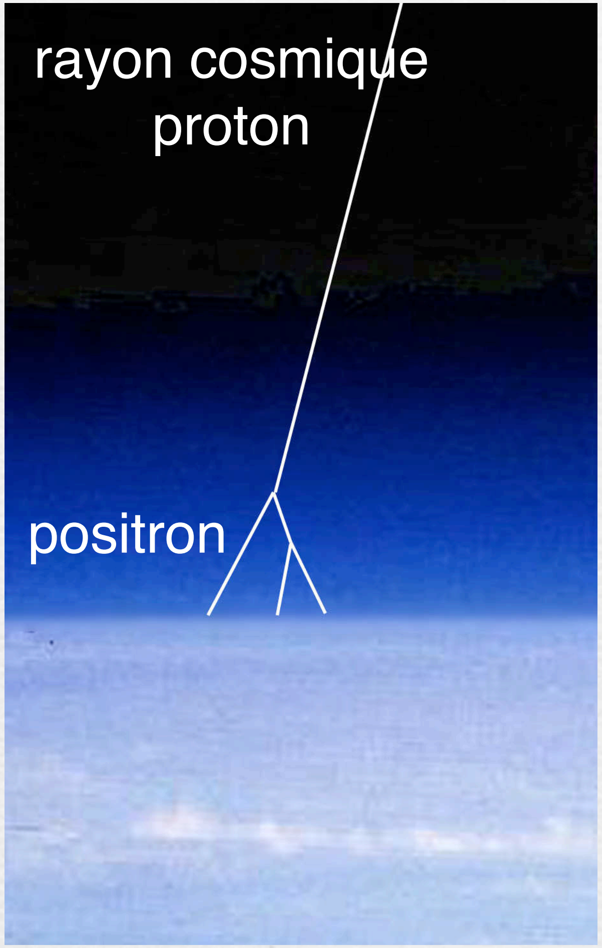
The Matter Anti-matter asymmetry

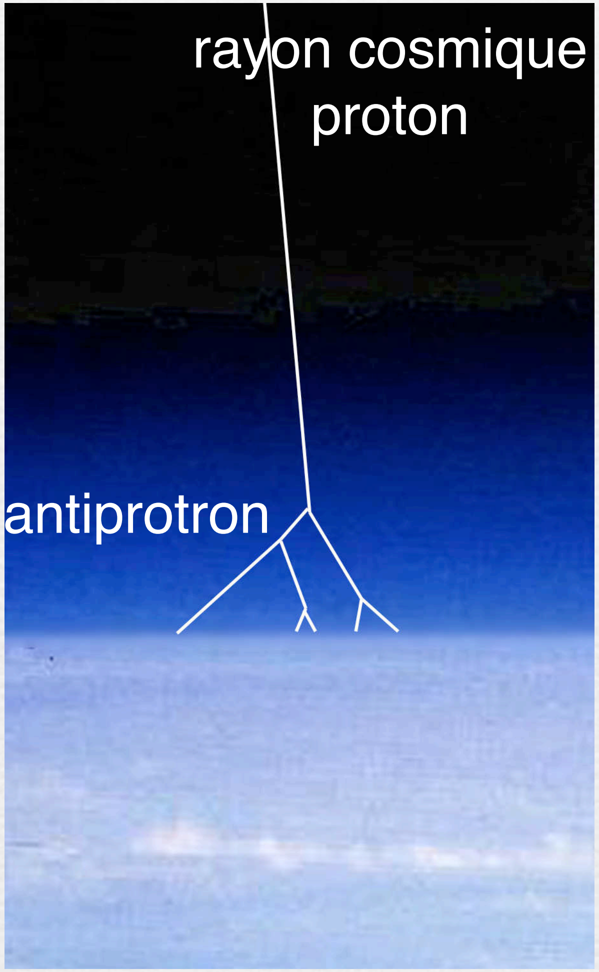
Antimatter

Each particle species has its antiparticle, carrying an opposite electric charge

électron		positron
proton		antiproton
neutron		antineutron
muon	⟷	antimuon
neutrino		antineutrino
quarks		antiquarks

Antiparticles are produced by cosmic rays entering the atmosphere





No concentration of antimatter in our observable universe

Otherwise, we would have detected the radiation coming from the annihilation between matter and antimatter

$$p + \overline{p} \rightarrow \pi^0 ... \rightarrow \gamma\gamma$$

No concentration of antimatter in our observable universe

At the scale of the solar system: no concentration of antimatter otherwise its interaction with the solar wind would produce important source of γ's visible radiation

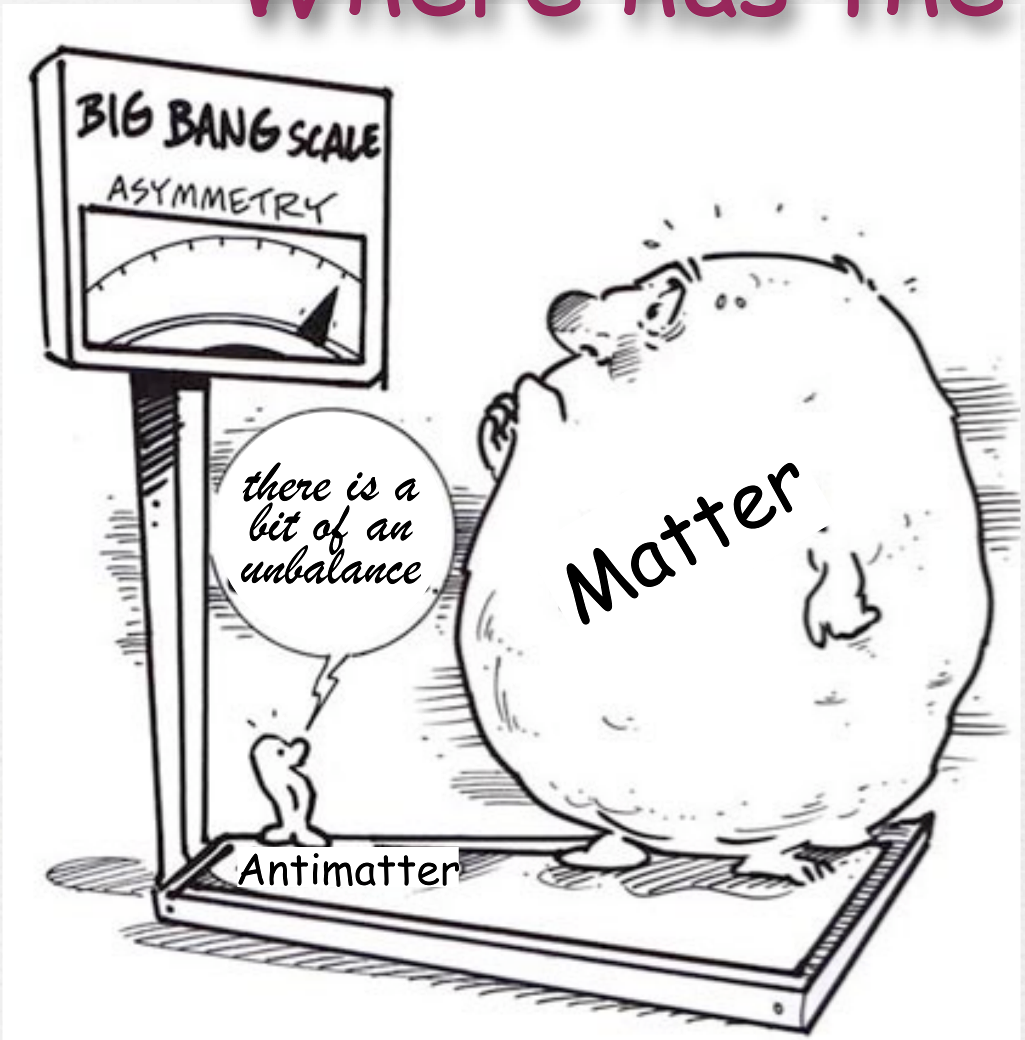
At the galactic scale: There is antimatter in the form of antiprotons in cosmic rays with ratio $n_{\overline{p}}/n_p \sim 10^{-4}$ which can be explained with processes such as

$$p + p \rightarrow 3p + \overline{p}$$

At the scale of galaxy clusters: we have not detected radiation coming from annihilation of matter and antimatter due to $p + \overline{p} \rightarrow \pi^0 ... \rightarrow \gamma\gamma$.

The universe we live in is made of matter (fortunately for us)

Where has the antimatter gone ?



Matter and antimatter should have been formed in equal quantities. However, today, there remains only matter.

baryonic asymmetry $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

characterized in terms of the baryon to photon ratio

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 6.\ 10^{-10}$$

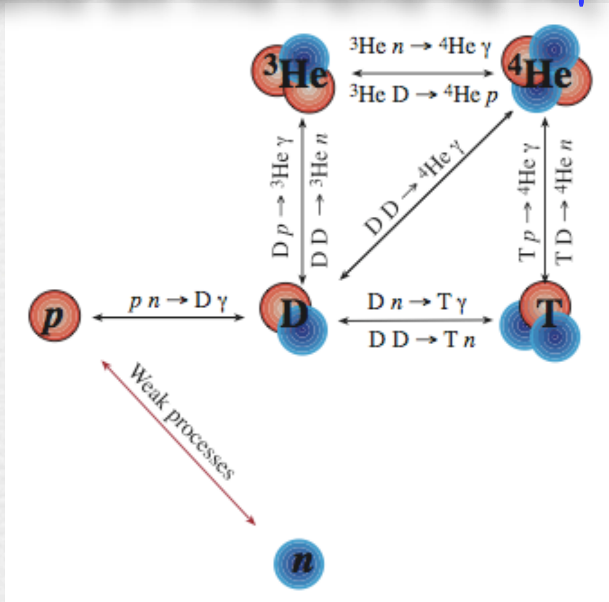
The standard model is unable to explain this matter-antimatter asymmetry

How do we measure η ?

Counting baryons is difficult because only some fraction of them formed stars and luminous objects. However, there are two indirect probes:

1) Big Bang Nucleosynthesis predictions depend on the ratio n_B / n_γ

Many more photons than baryons delays BBN by enhancing the reaction D γ →pn

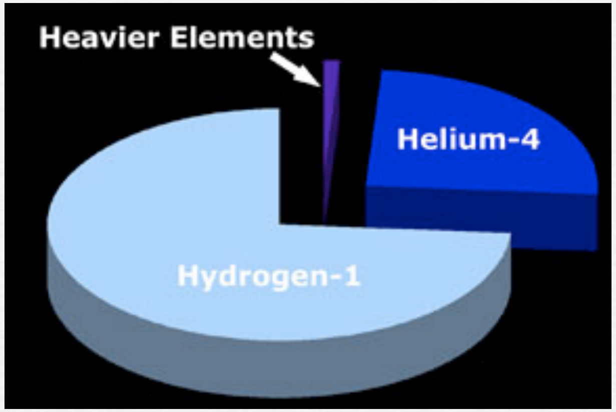


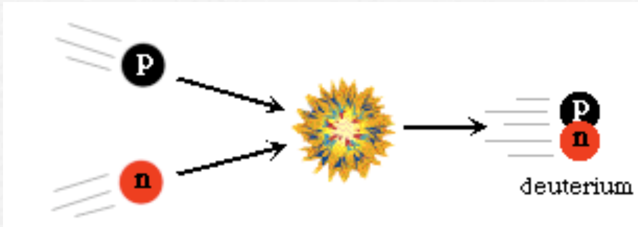
2) Measurements of CMB anisotropies

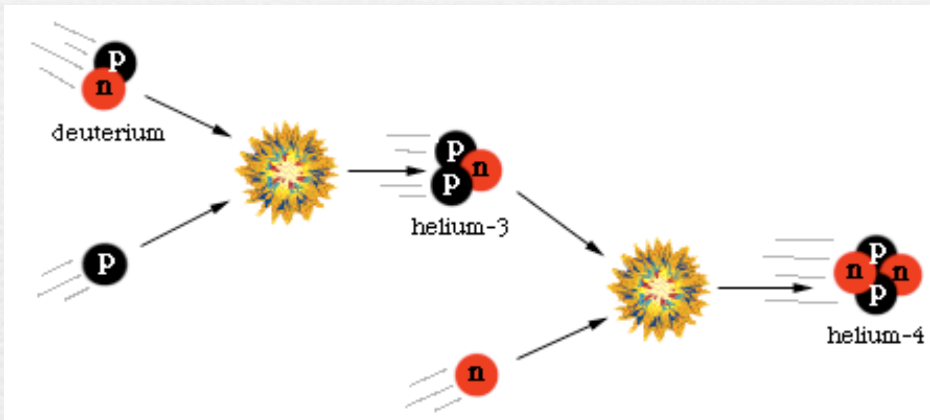
probe acoustic oscillations of the baryon/photon fluid

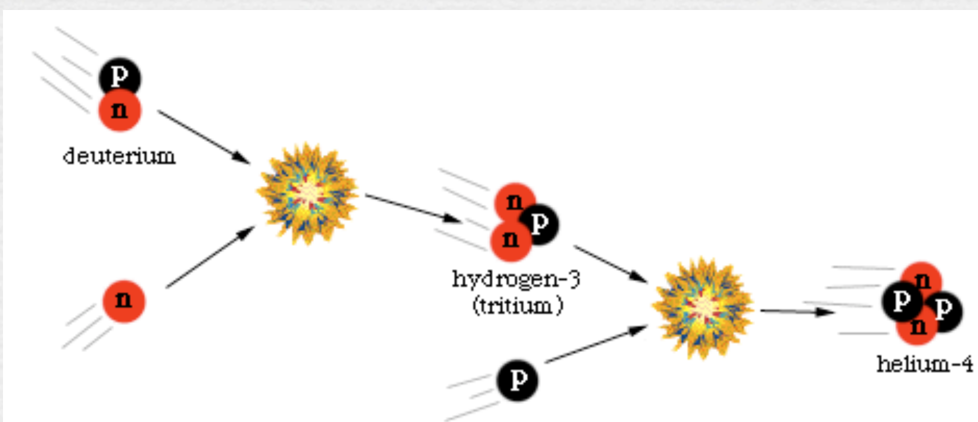
The amount of anisotropies depend on n_B / n_γ

Primordial nucleosynthesis



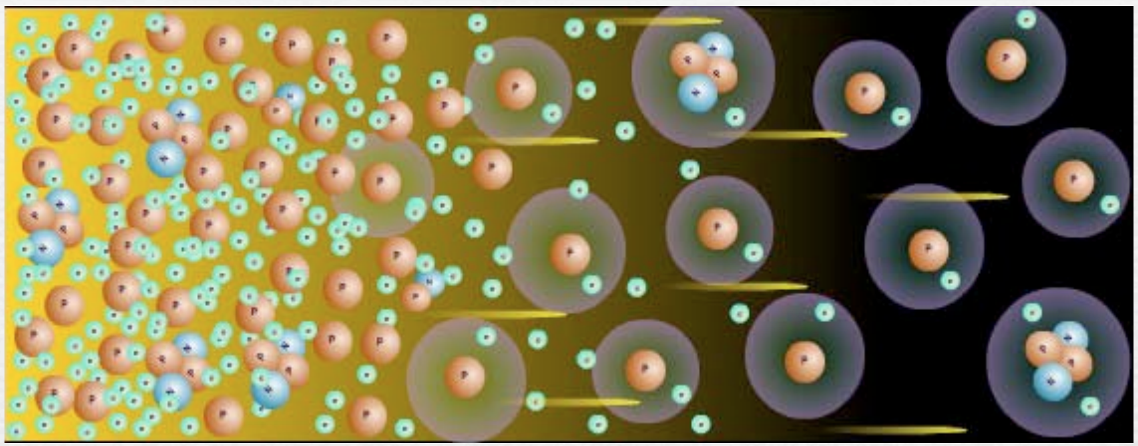


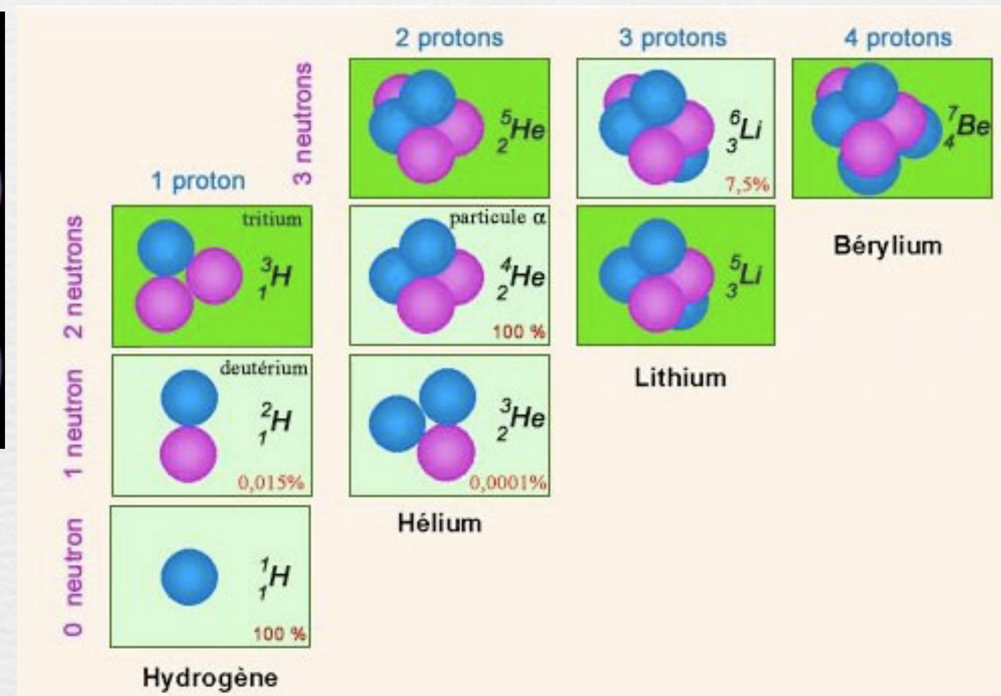




$$
\begin{aligned}
p + n &\longrightarrow D + \gamma \\
D + n &\longrightarrow {}^3H + \gamma \\
D + p &\longrightarrow {}^3He + \gamma \\
D + D &\longrightarrow {}^3H + p \\
D + D &\longrightarrow {}^3He + n \\
D + D &\longrightarrow {}^4He + \gamma \\
{}^3H + p &\longrightarrow {}^4He + \gamma \\
{}^3He + n &\longrightarrow {}^3H + p \\
{}^3He + n &\longrightarrow {}^4He + \gamma \\
{}^3H + D &\longrightarrow {}^4He + n \\
{}^3He + D &\longrightarrow {}^4He + p \\
{}^3He + {}^3He &\longrightarrow {}^4He + 2p \\
{}^4He + D &\longrightarrow {}^6Li + \gamma \\
{}^4He + {}^3H &\longrightarrow {}^7Li + \gamma \\
{}^4He + {}^3He &\longrightarrow {}^7Be + \gamma \\
{}^6Li + n &\longrightarrow {}^7Li + \gamma \\
{}^6Li + p &\longrightarrow {}^7Be + \gamma \\
{}^7Li + p &\longrightarrow {}^4He + \gamma \\
{}^7Be + n &\longrightarrow {}^7Li + p \\
{}^7Be + e^- &\longrightarrow {}^7Li + \gamma
\end{aligned}
$$

The abundance of light elements (deuterium, helium, lithium) strongly depends on the amount of protons and neutrons in the primordial universe.

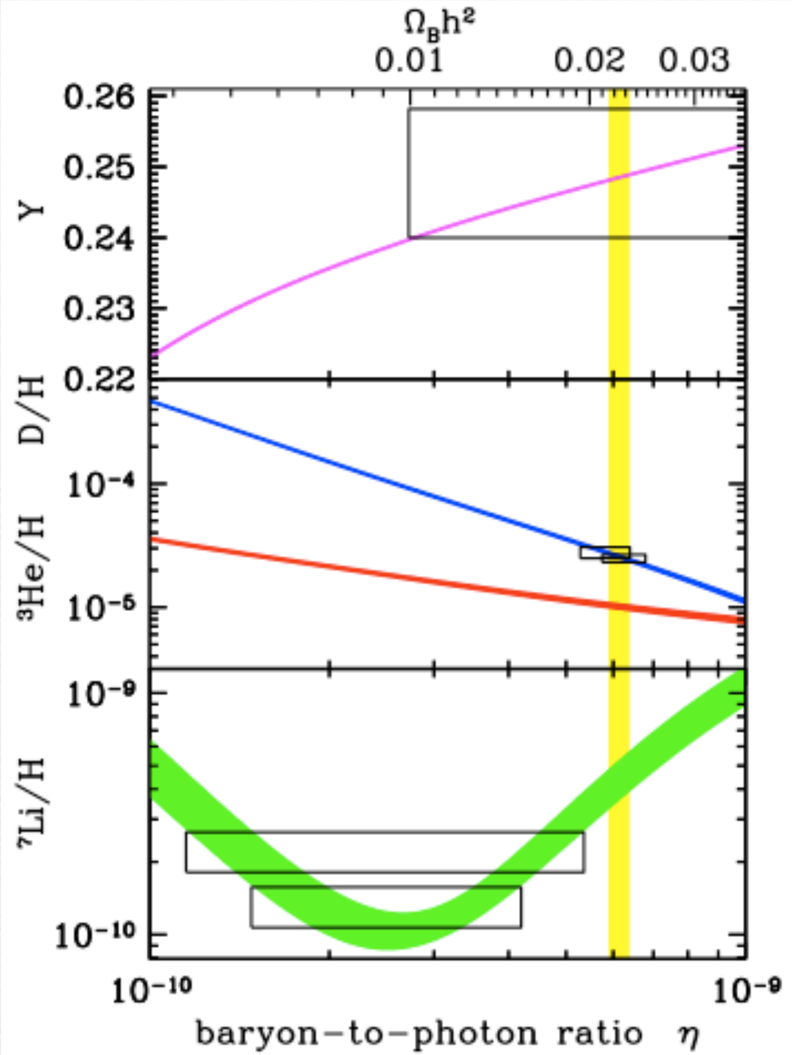




at t<1 s

$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \nu_e$$
$$n \leftrightarrow p + e^- + \overline{\nu_e}$$

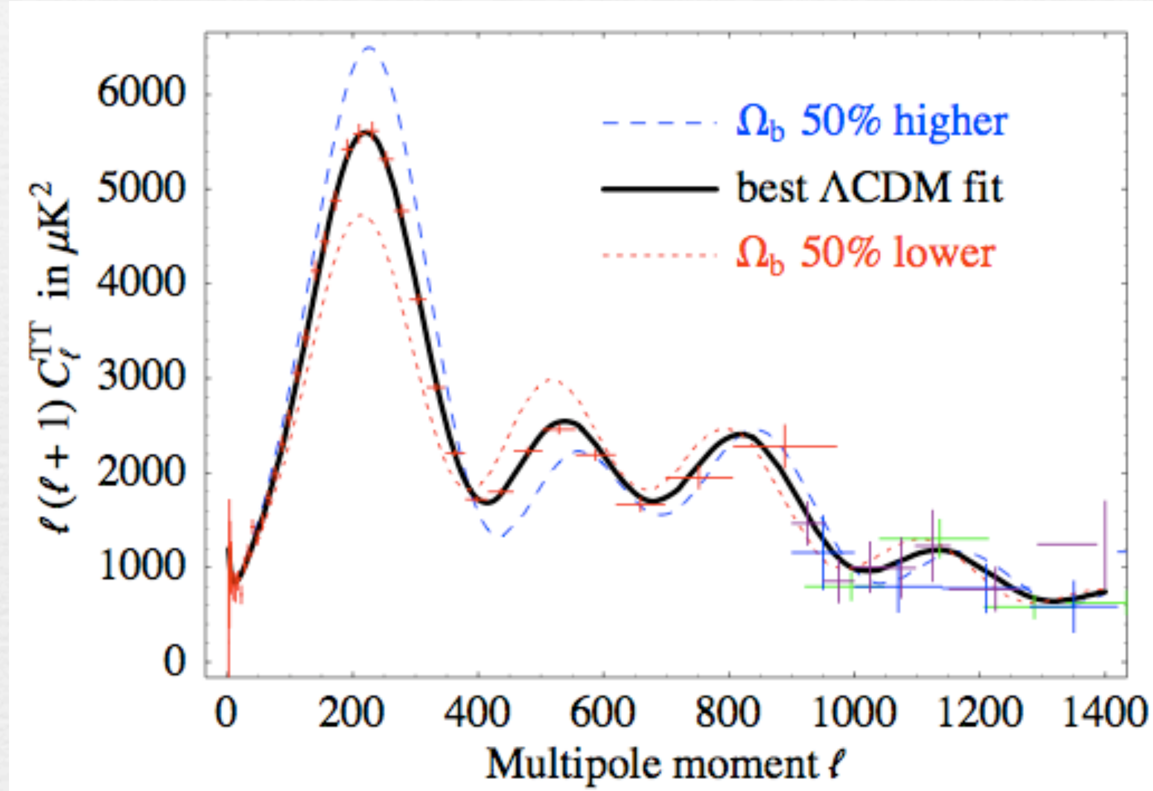
Primordial abundances versus η



$$\eta = 10^{-10} \times \begin{cases} 6.28 \pm 0.35 \\ 5.92 \pm 0.56 \end{cases}$$

Dependence of the CMB Doppler peaks on η

(CMB temperature fluctuations)



$$\eta = 10^{-10} \times (6.14 \pm 0.25)$$

$$\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$$

baryons: only a few percents of the total energy density of the universe

Matter Anti-matter asymmetry:

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ $6.\ 10^{-10}$

The great annihilation

10 000 000 001 Matter	10 000 000 000 Anti-matter

↓

1
(us)

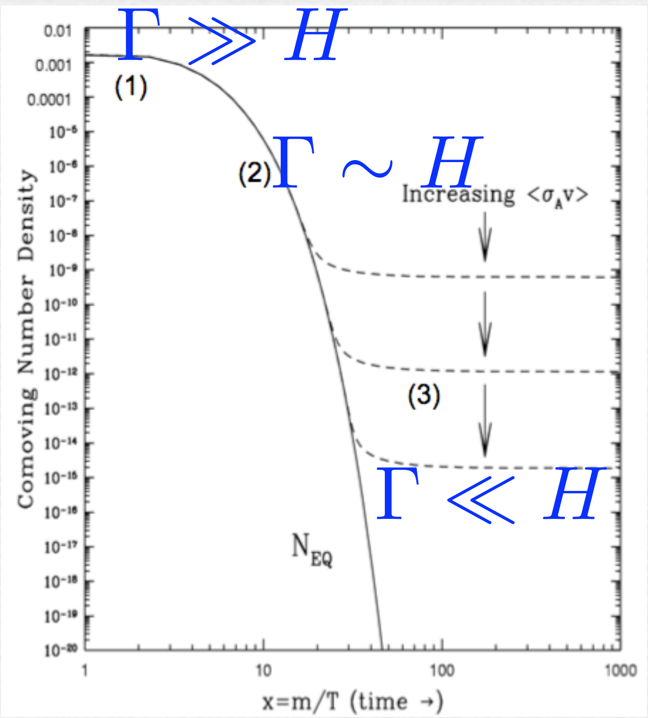
How much baryons would there be in a symmetric universe?

The great annihilation between nucleons & anti-nucleons

$$n + \bar{n} \rightarrow \pi + \pi \rightarrow \gamma + \gamma + \ldots$$

occurs when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T} / m_\pi^2 \sim H \sim \sqrt{g_*} T^2 / m_{Pl}$

corresponding to a freeze-out temperature $T_F \sim 20$ MeV



In absence of an asymmetry: $\frac{n_N}{s} \approx 7 \times 10^{-20}$

10^9 times smaller than observed,
and there are no antibaryons
-> need to invoke an initial asymmetry

10 000 000 001 Matter

10 000 000 000 Anti-matter

1 (us)

Sakharov's conditions for baryogenesis (1967)

1) Baryon number violation

(we need a process which can turn antimatter into matter)

2) C (charge conjugation) and CP (charge conjugation ×Parity) violation

(we need to prefer matter over antimatter)

3) Loss of thermal equilibrium

(we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature --particles & antiparticles have the same mass , so no asymmetry can develop)

$$\Gamma(\Delta B > 0) > \Gamma(\Delta B < 0)$$

Need to go out of equilibrium

In thermal equilibrium, any reaction which destroys baryon number will be exactly counterbalanced by the inverse reaction which creates it. Thus no asymmetry may develop, even if CP is violated. And any preexisting asymmetry will be erased by interactions

Need for

-> Long-lived particles decays out of equilibrium

-> first-order phase transitions

Why can't we achieve baryogenesis in the Standard Model?

B is violated

C and CP are violated

but which out-of-equilibrium condition?

no heavy particle which could decay out-of-equilibrium

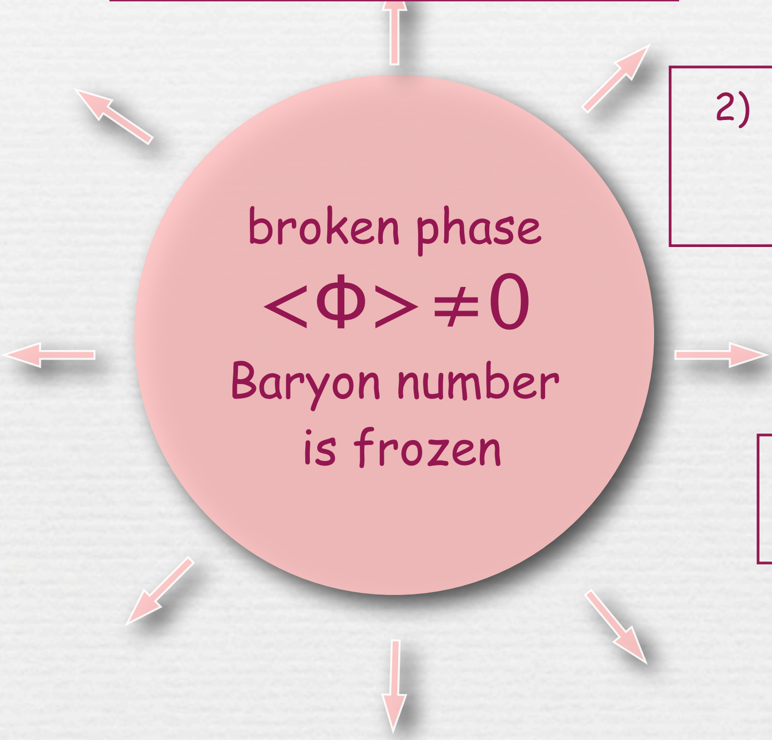
no strong first-order phase transition

Electroweak phase transition is a smooth cross over

Also, CP violation is too small (suppressed by the small quark masses, remember there is no CP violation if quark masses vanish)

Baryon asymmetry and the EW scale

1) nucleation and expansion of bubbles of broken phase



2) CP violation at phase interface responsible for mechanism of charge separation

Chirality Flux in front of the wall

3) In symmetric phase, $\langle\Phi\rangle = 0$, very active sphalerons convert chiral asymmetry into baryon asymmetry

Electroweak baryogenesis mechanism relies on a first-order phase transition

What is the nature of the electroweak phase transition?

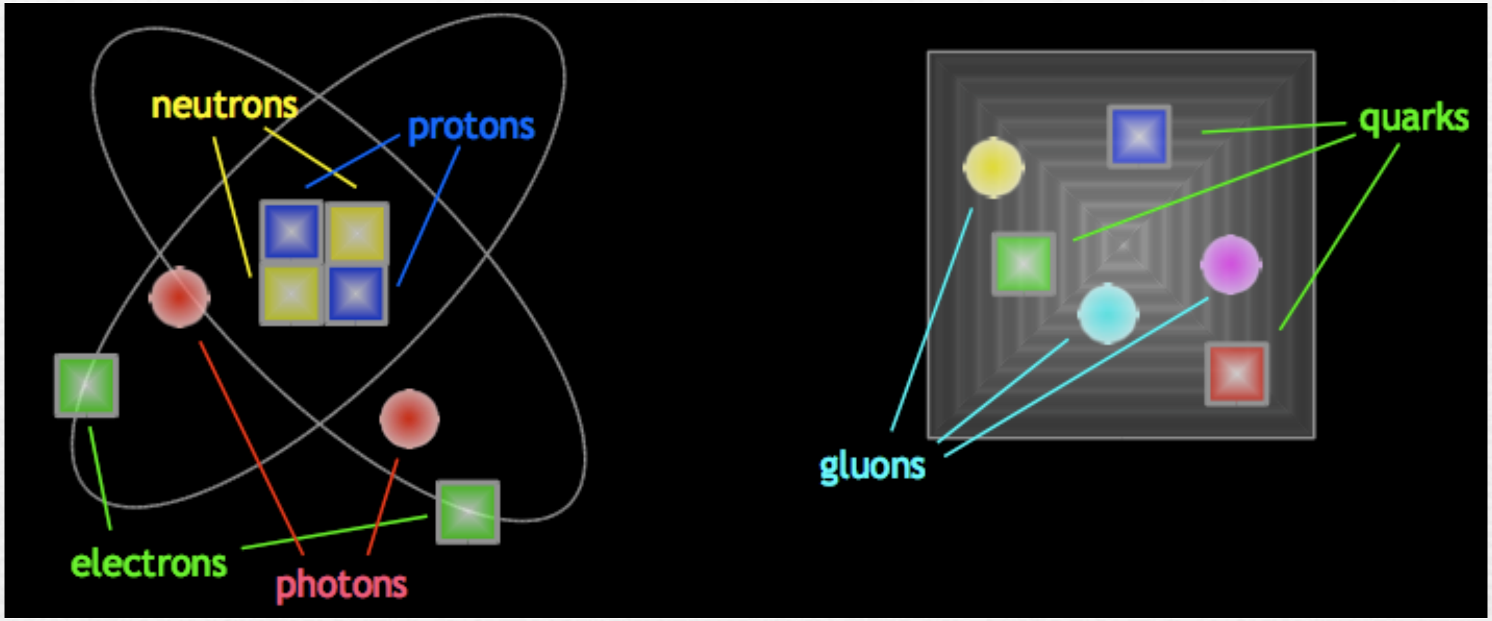
Conclusion:

The Standard model of Particle Physics is incomplete:
It cannot explain the dark Matter nor the matter-antimatter asymmetry of the universe

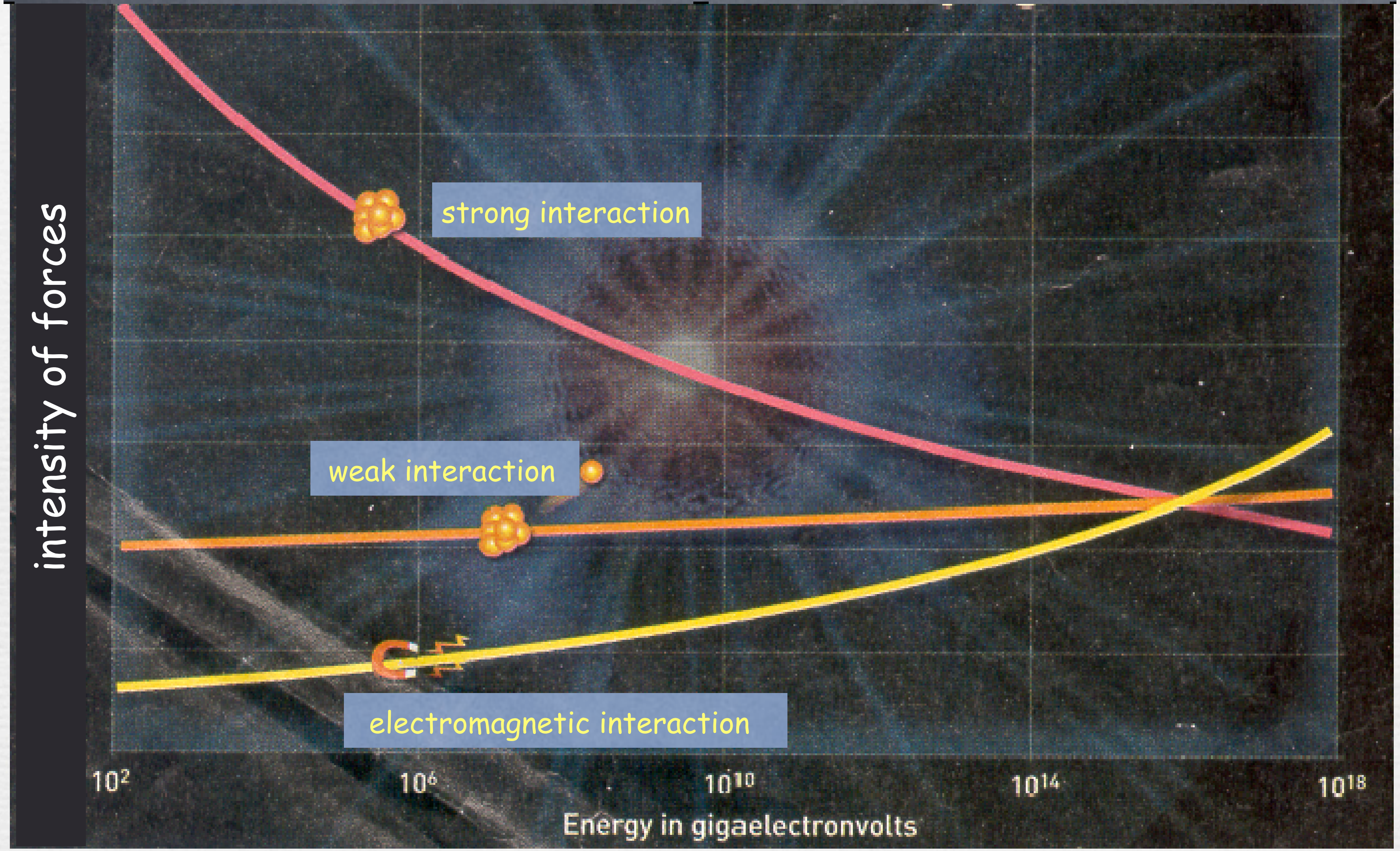
New Physics is needed!

Which physics beyond the Standard Model ?

ordinary matter is made of fermions which are tied to each other by bosons



Theories of grand unification



One single type of matter

One single fundamental interaction

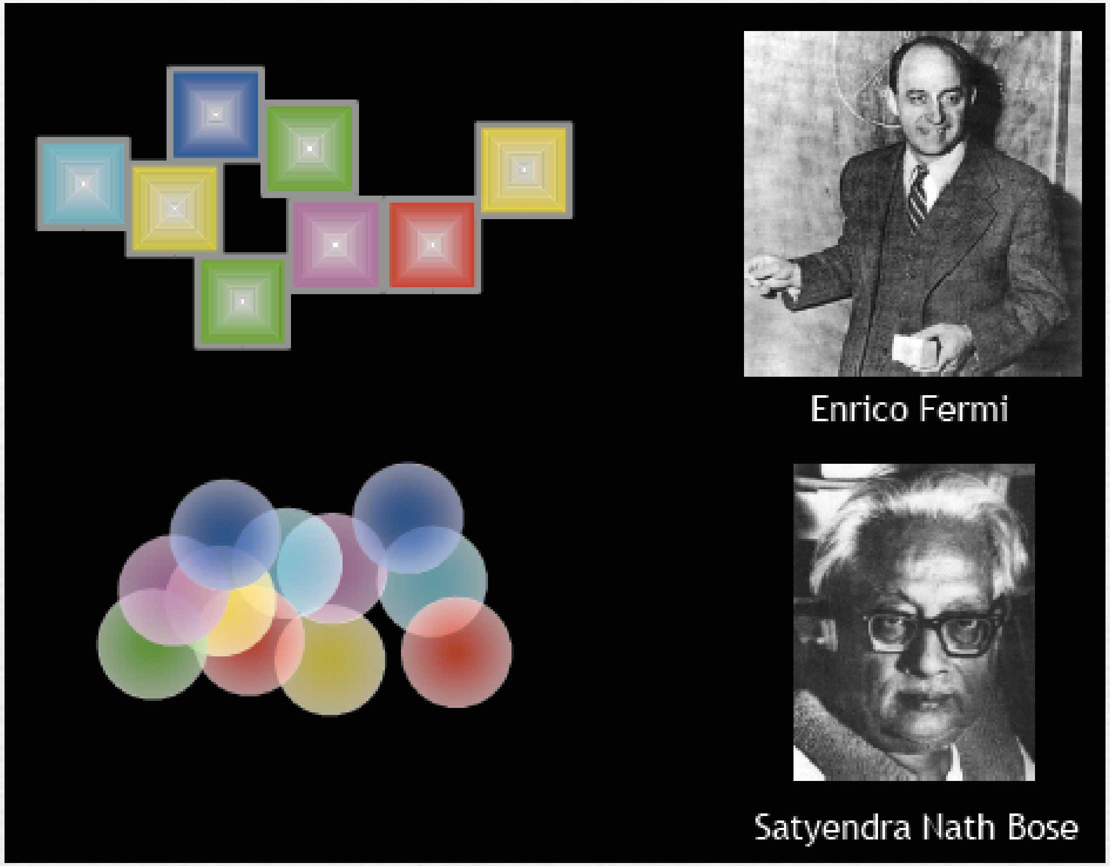
Supersymmetry

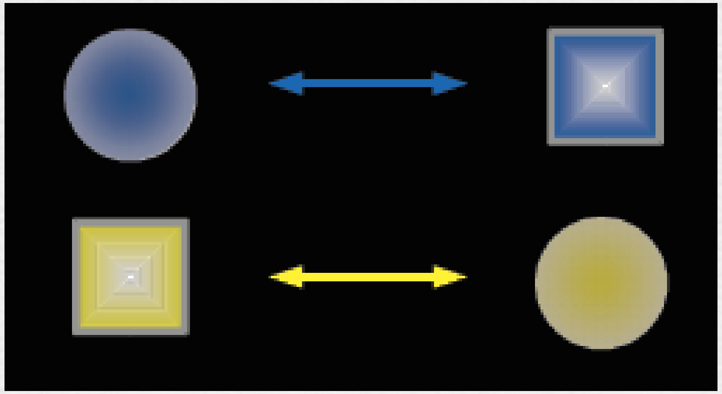
Fermions *particles of matter*

fermions repel each other

Bosons *particles of force*

bosons can pile up

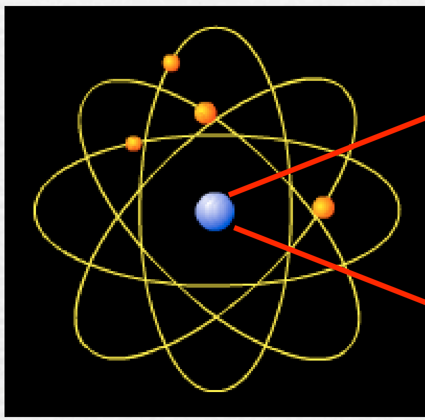




String Theory

(observable universe)

10^{-10}m

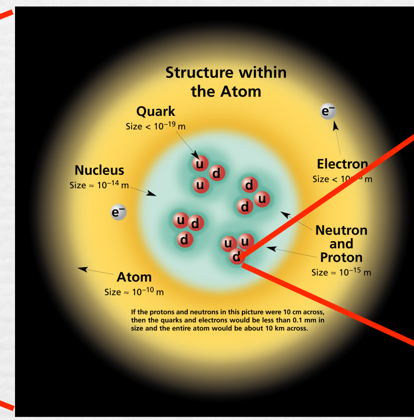


Atom

electrons + nucleus

(Earth)

10^{-17}m

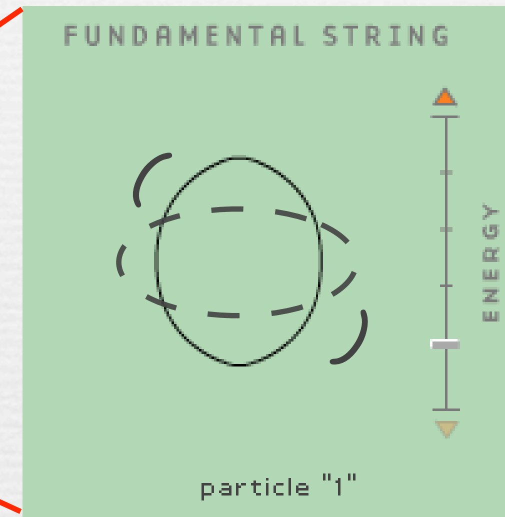


Nucleus

quarks

(Hair)

10^{-35}m

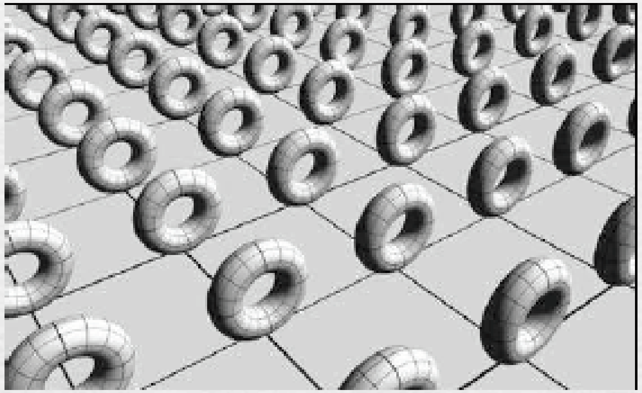


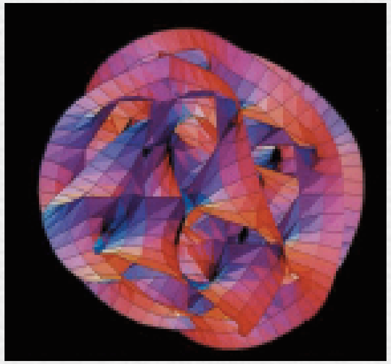
(Super)String

Extra Dimensions

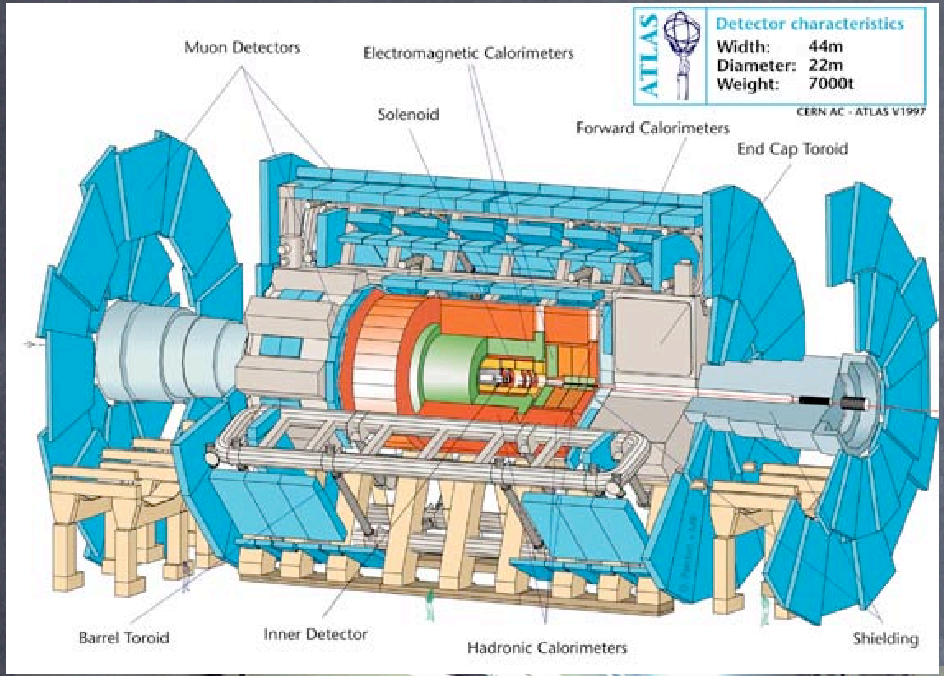
String theories are (well) defined only in spacetime with 10 or 11 dimensions

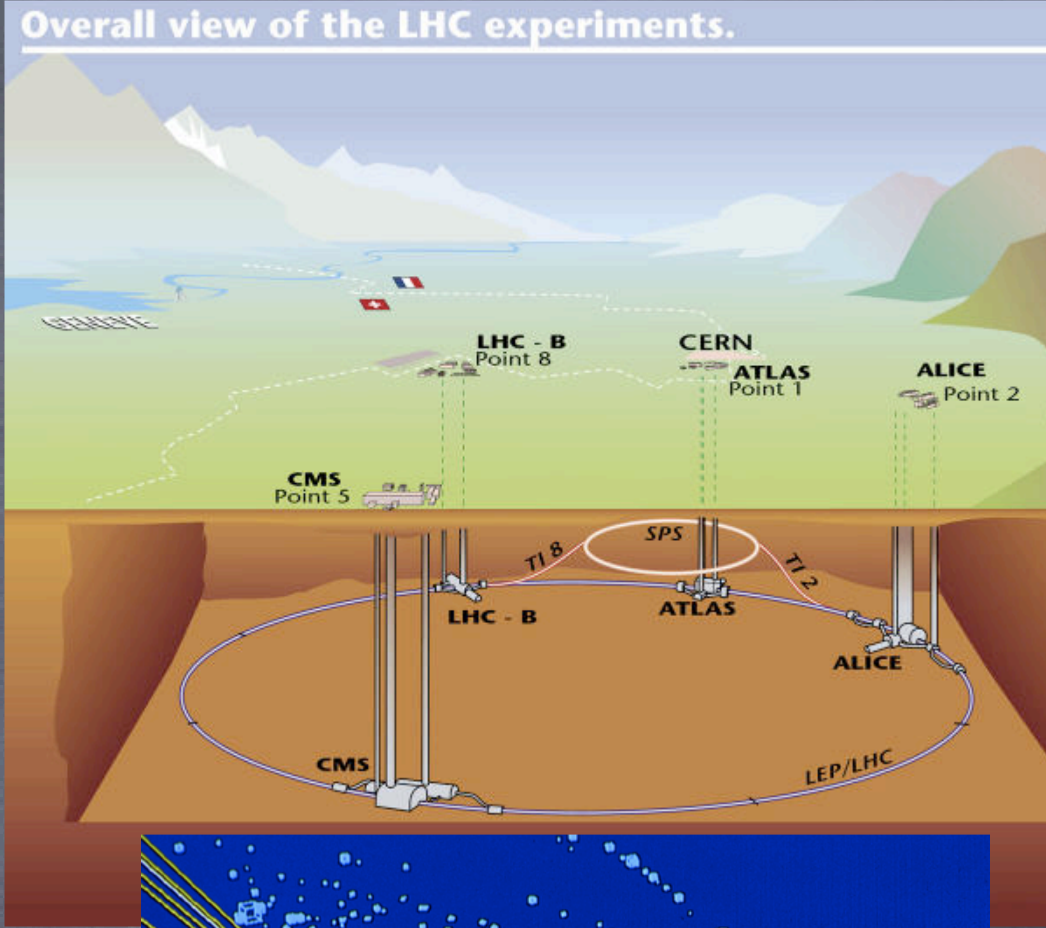
These extra dimensions are assumed to be curled up

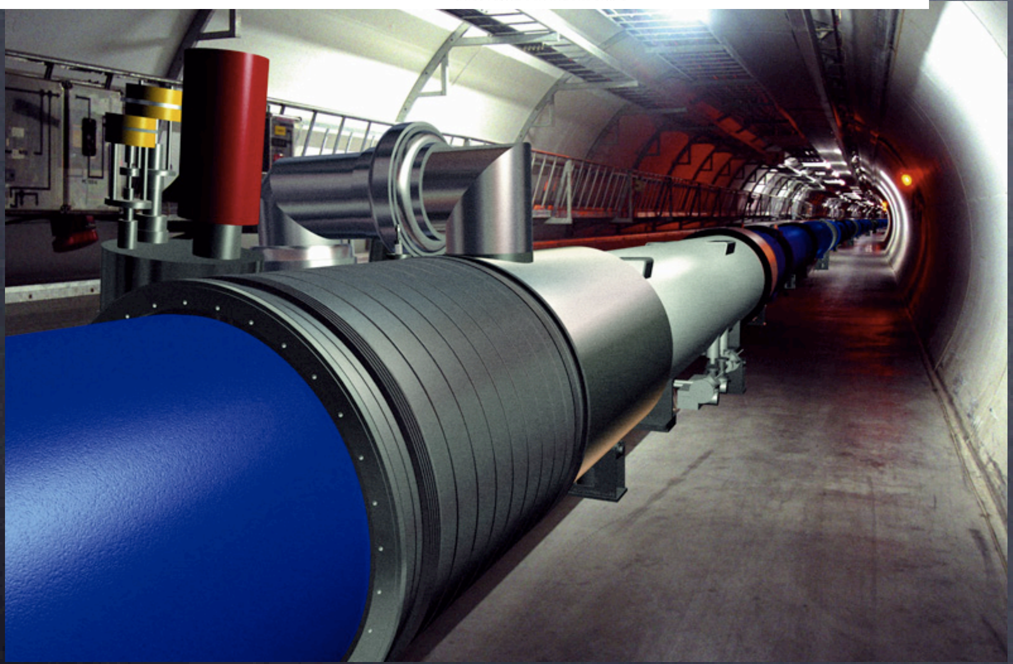


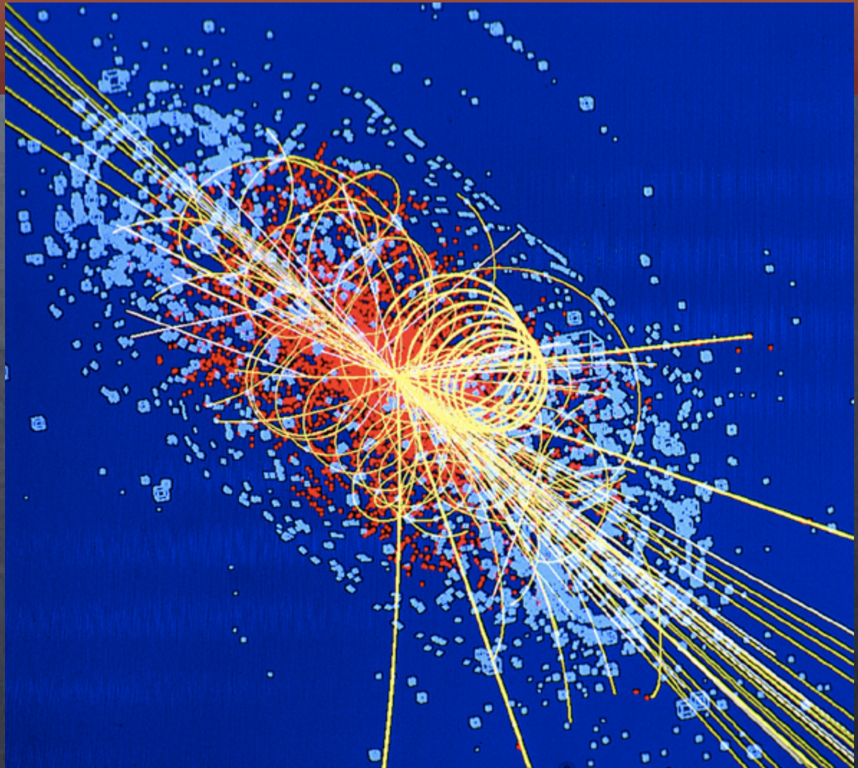


2010: A new era started for particle physicists

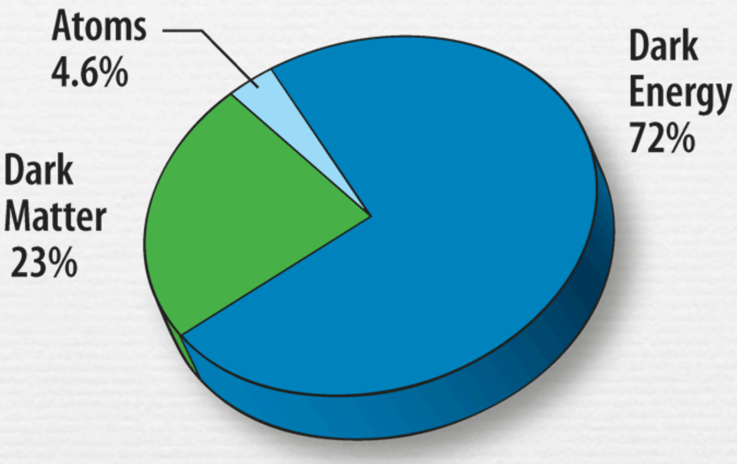




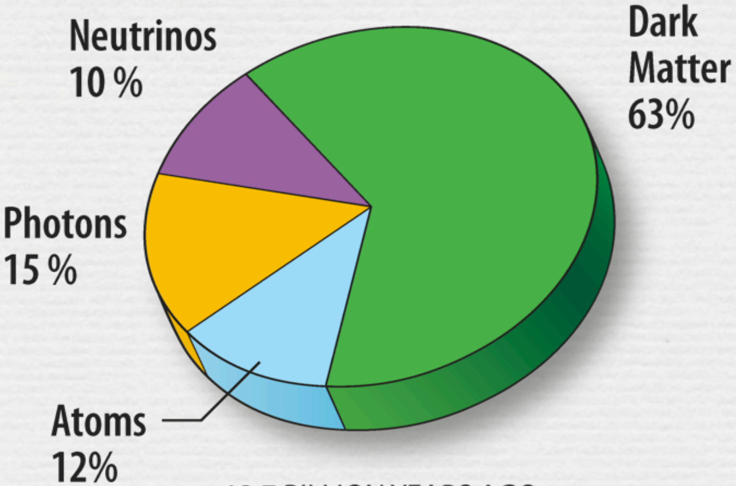




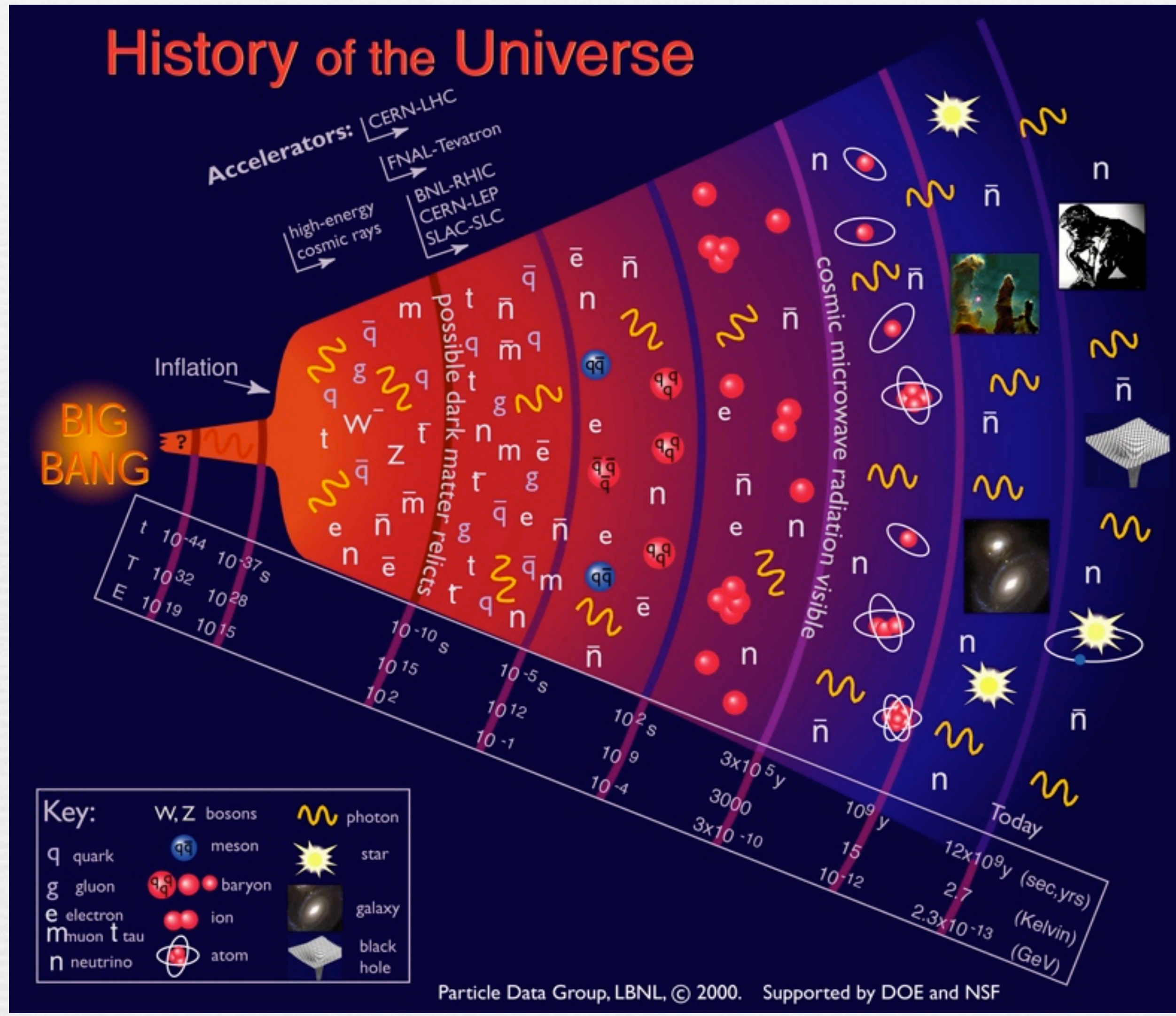
Back to the energy budget of the universe: How do we know?



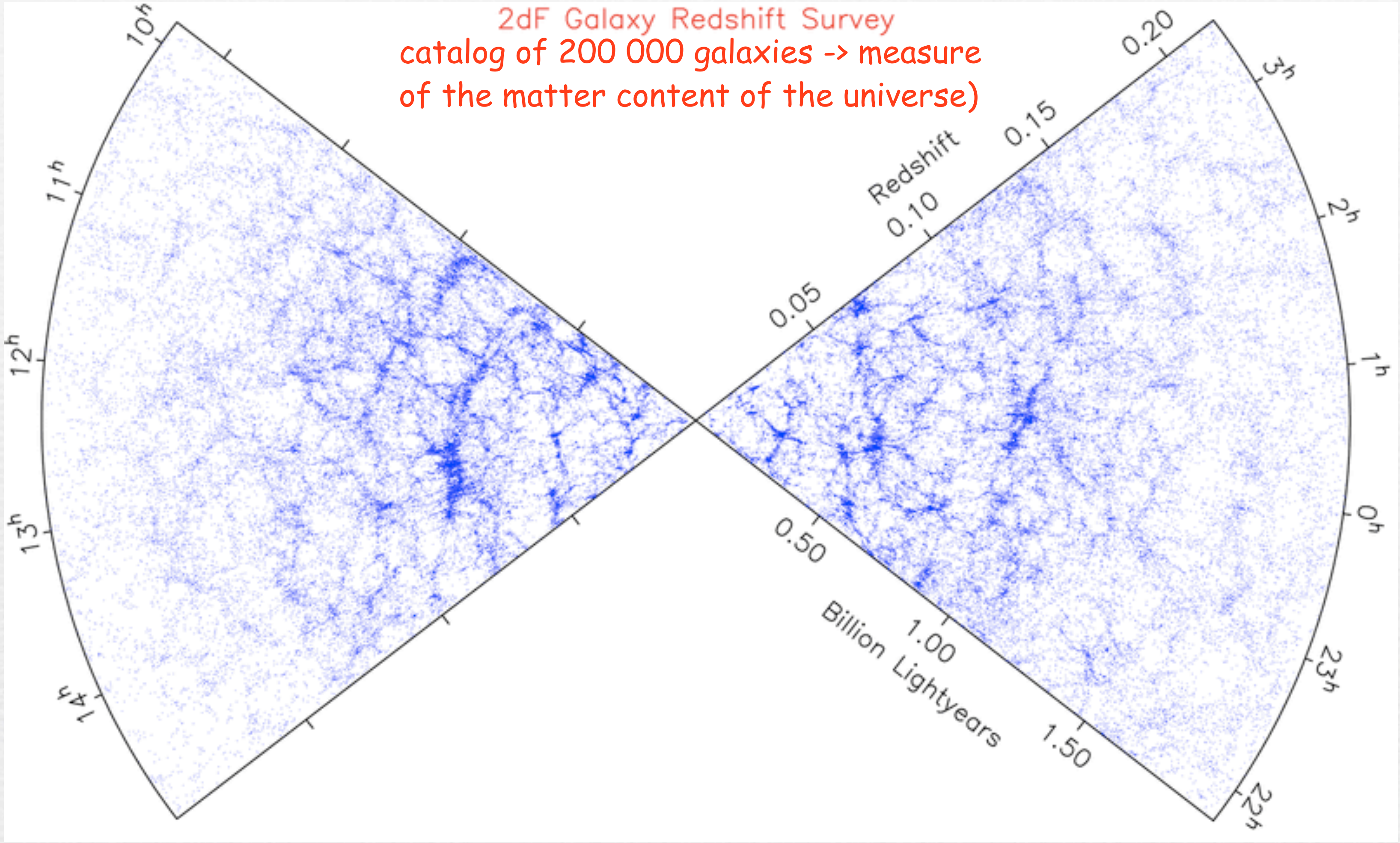
TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)



The observable universe: ~ 3000 Mpc (1 Mpc ≃ $3.26{\times}10^6$ light-years ≃ $3{\times}10^{24}$cm)



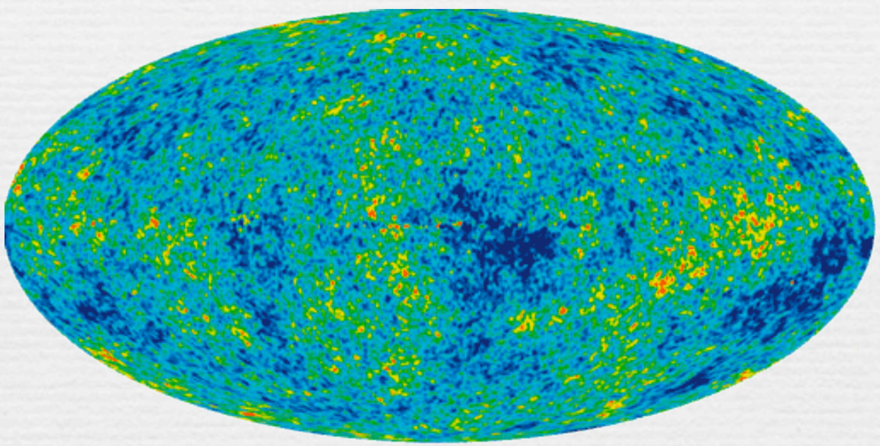
The main characteristic of our universe: homogeneous & isotropic at large scales (>100 Mpc)

at scales < 100 Mpc: very inhomogeneous structure (galaxies, clusters, super-clusters)

Property 1: Universe is homogeneous and isotropic:

It looks the same whatever the position of the observer is or whatever the direction being observed is

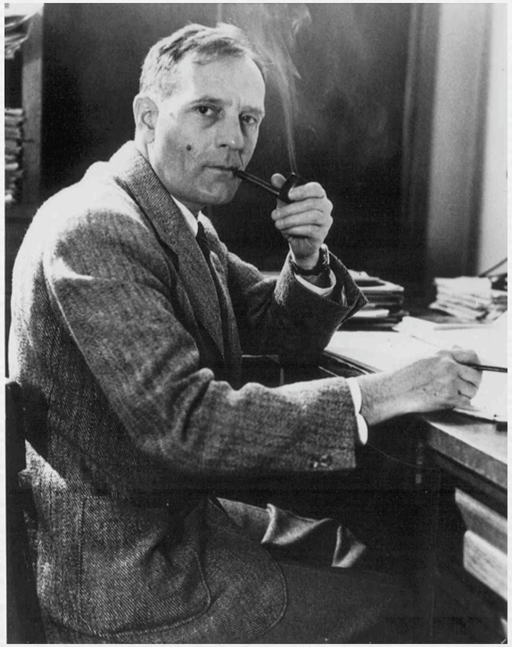
→ no preferred position, no center



cosmic microwave background anisotropies :

$$\frac{\delta T}{T} \sim 0.001\%$$

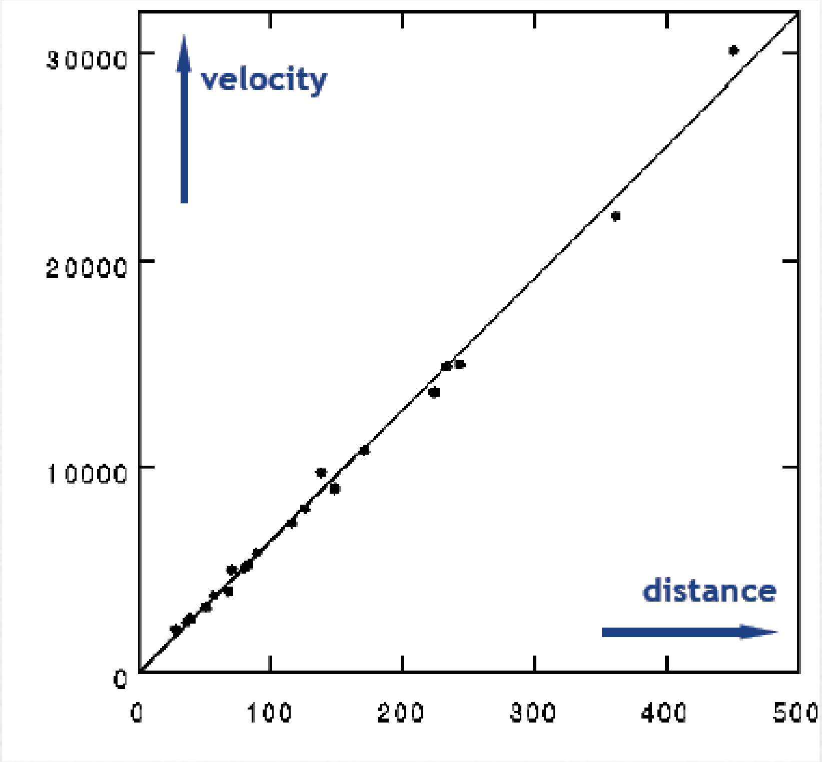
property 2: the universe is expanding



1929: Edwin Hubble

spectral lines from distant galaxies are shifted towards the red end of the spectrum

Doppler Effect $$\lambda' = \lambda \sqrt{\frac{1+v/c}{1-v/c}}$$



$v = H \times r$

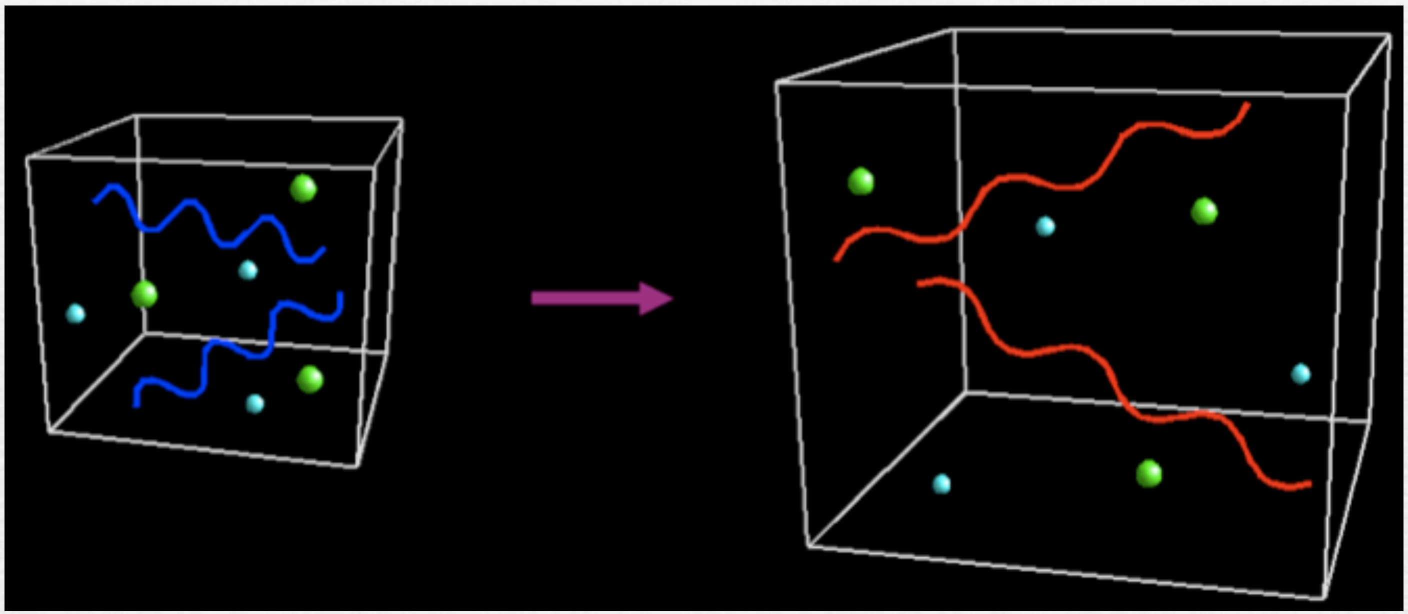
Hubble constant

The velocity of recession of a galaxy is proportional to its distance from us

The amount of shift depends on the apparent brightness and hence on the distance

The universe was denser and hotter in the past

Expansion dilutes the number of particles and "stretches" the wavelength of photons, i.e. decreases their frequency-> redshift



Big Bang theory

Einstein Equation :

$$G_{\mu\nu} = 8\pi G \; T_{\mu\nu}$$

space-time is curved by the presence of matter/energy

The Robertson-Walker metric, characterized by the "scale factor" a(t)

the energy-momentum tensor

expansion rate

$$H = \frac{\dot{a}}{a}$$

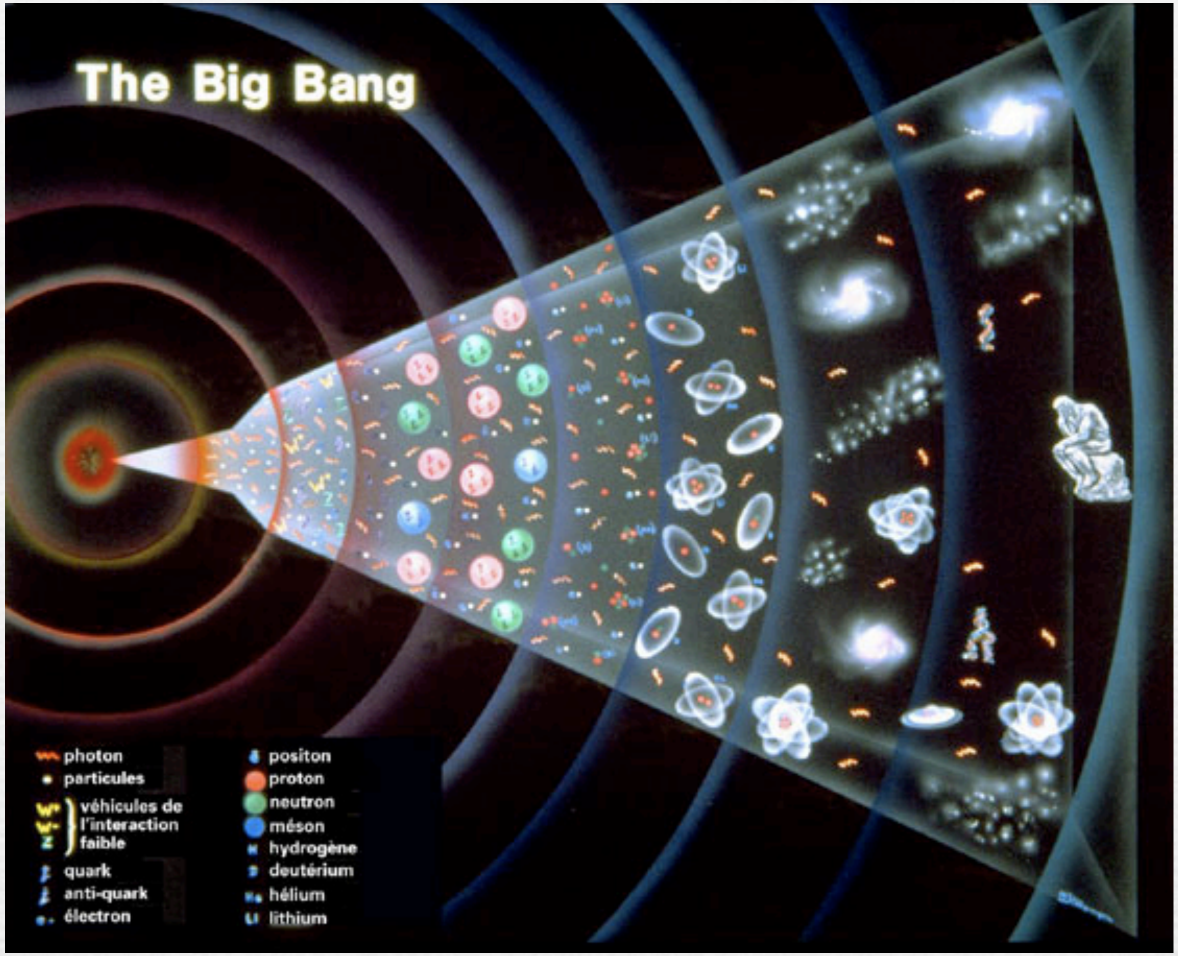
$$H = \sqrt{\frac{8\pi G \rho}{3}}$$

expansion rate

total energy density

a crucial assumption to derive the master equation, the so-called Friedman equation:

homogeneity and isotropy



Friedmann Equation:

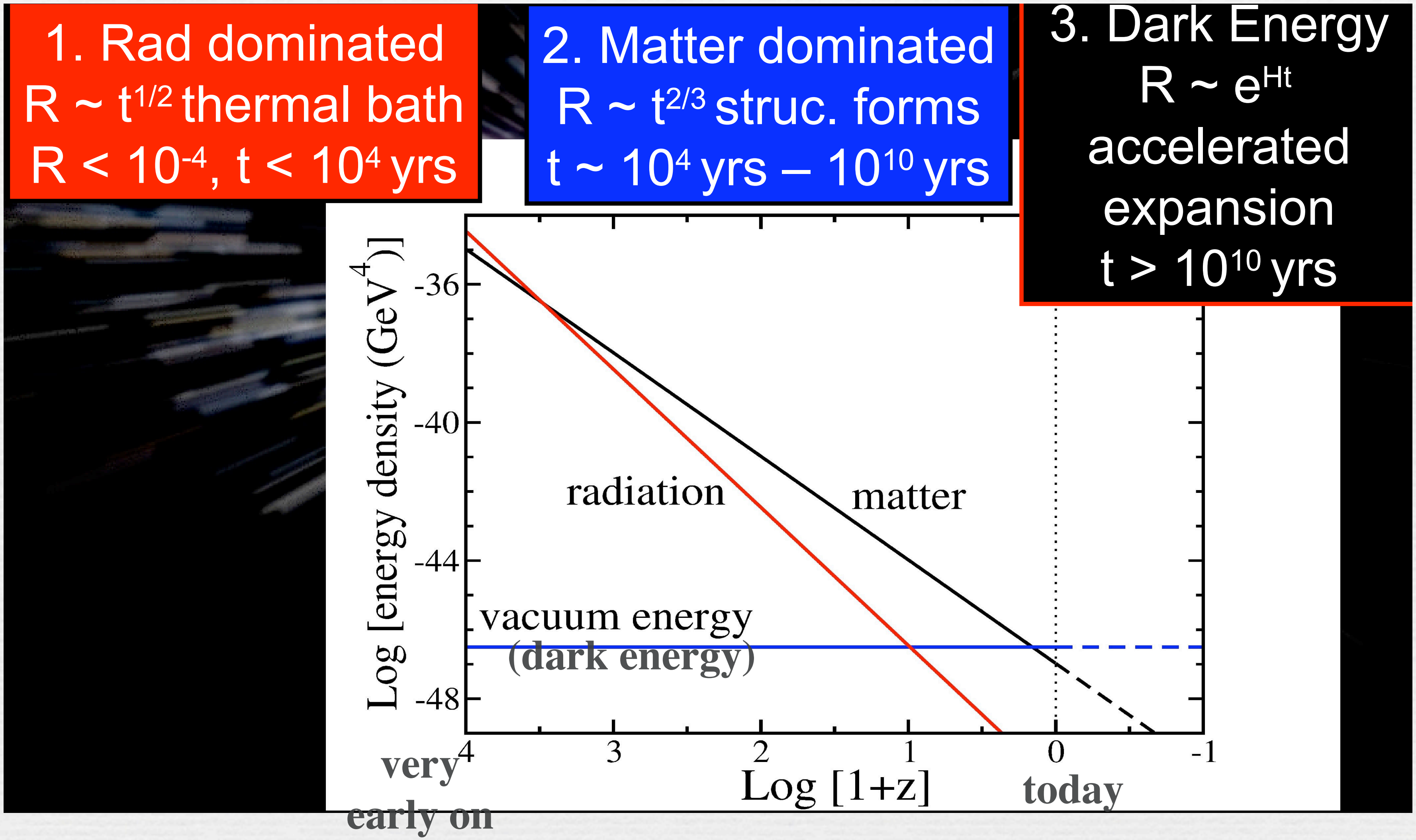
$$H = \sqrt{\frac{8\pi G \rho}{3}}$$

expansion rate

total energy density

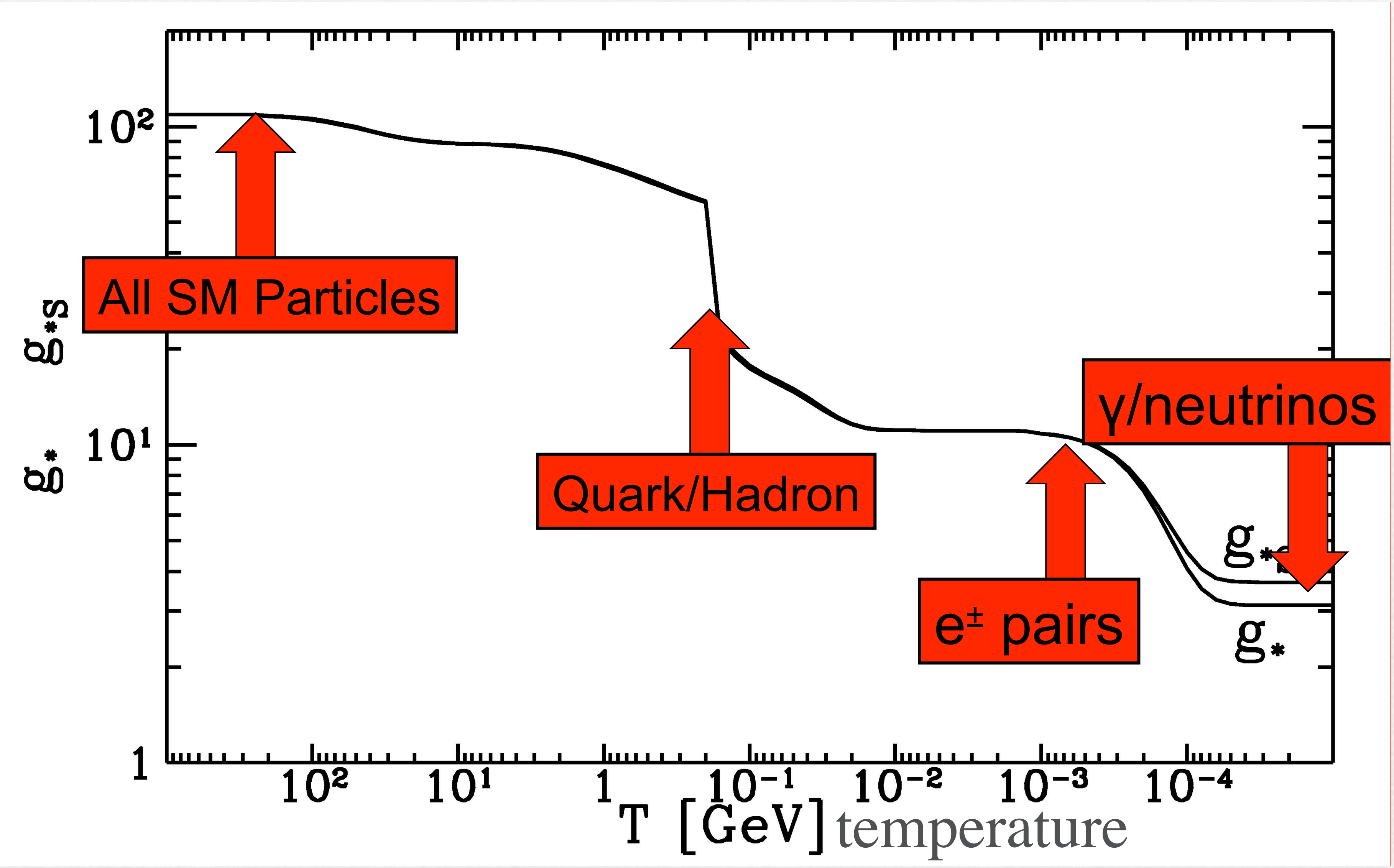
What is the value of ρ ?

3 epochs dominated by different forms of energy

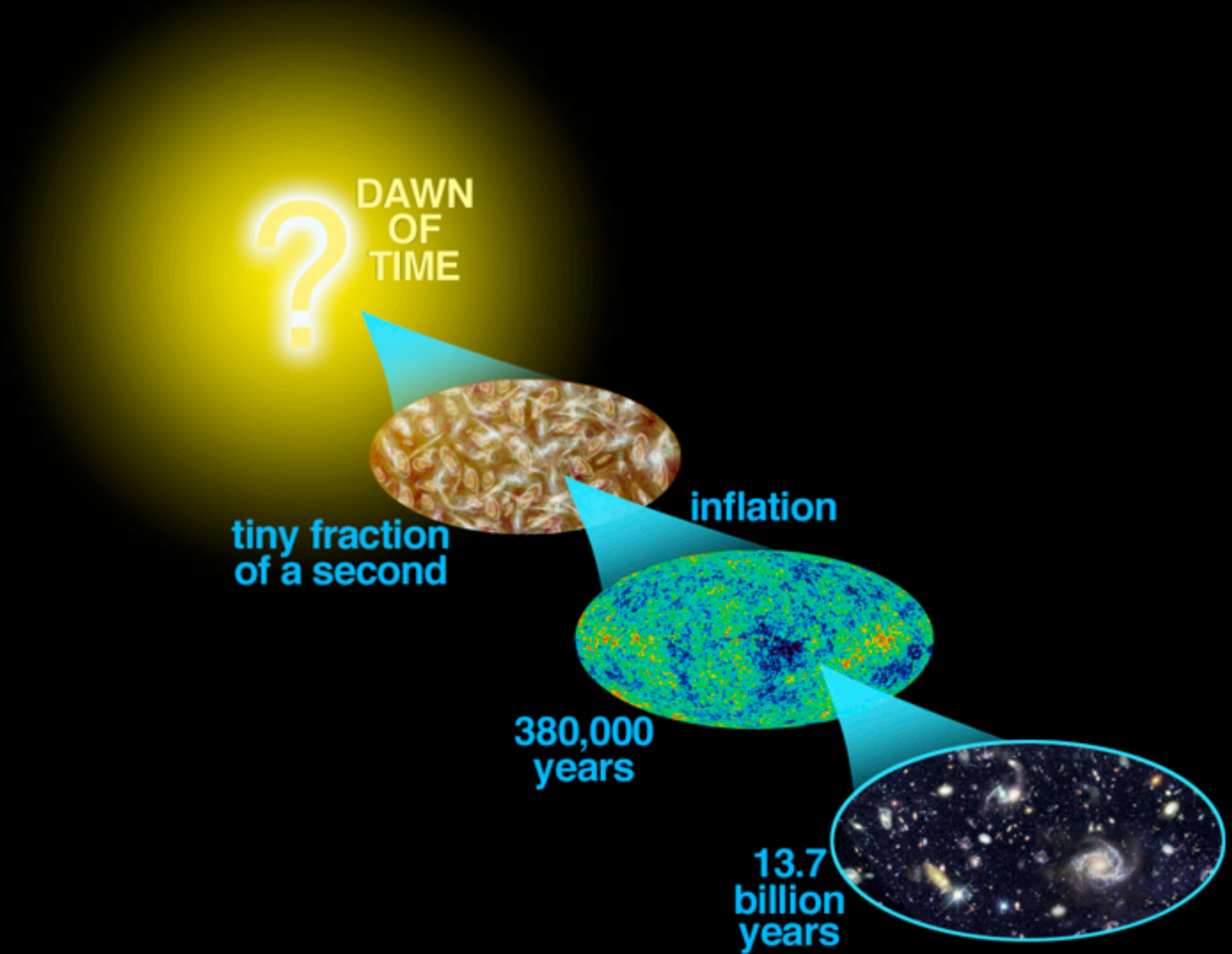


time

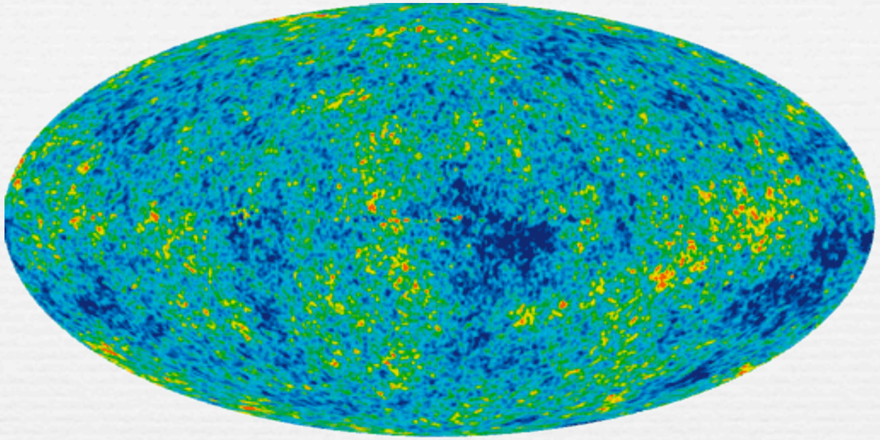
Relativistic degrees of freedom



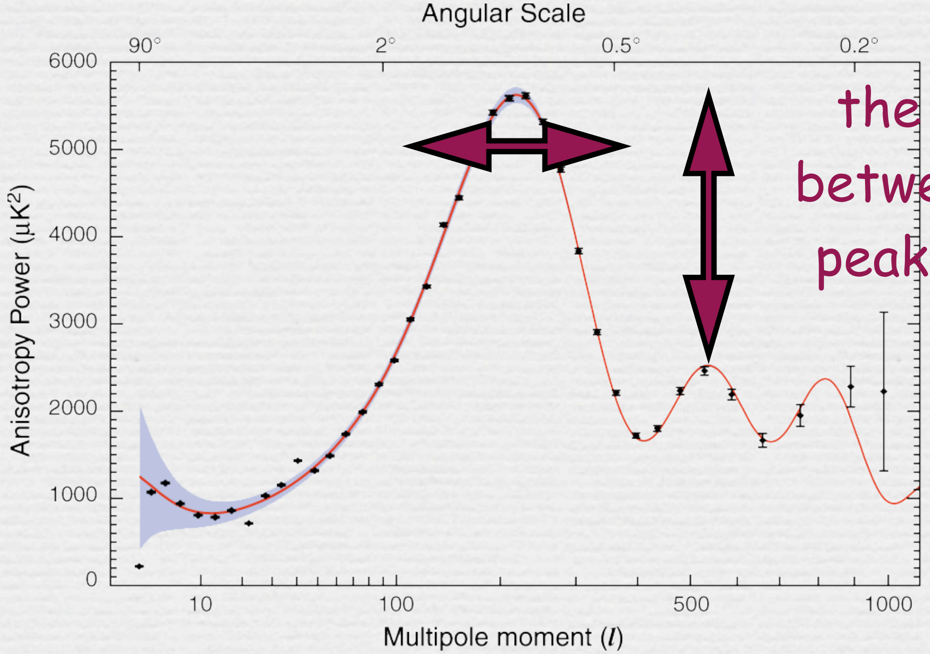
time


DAWN
OF
TIME
inflation
tiny fraction
of a second
380,000
years
13.7
billion
years

The 2.7 K Cosmic Microwave Background



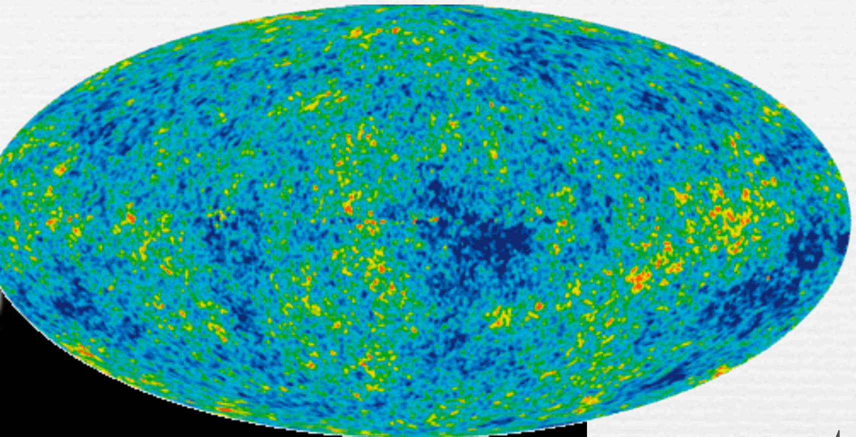
The peak position depends on Ω_{tot}



the relative height between the first two peaks depends on Ω_b

Why the same temperature everywhere?

$$\frac{\delta T}{T} \sim 0.001\%$$



- Like having found two remote islands in different parts of the world
- but the locals speak the same language
- even the same *dialect* with 10^{-5} accuracy
- we would suspect they *communicated*, must have come from the same place

particle horizon $$r_H = \int_0^t \frac{c\,dt}{R(t)}$$

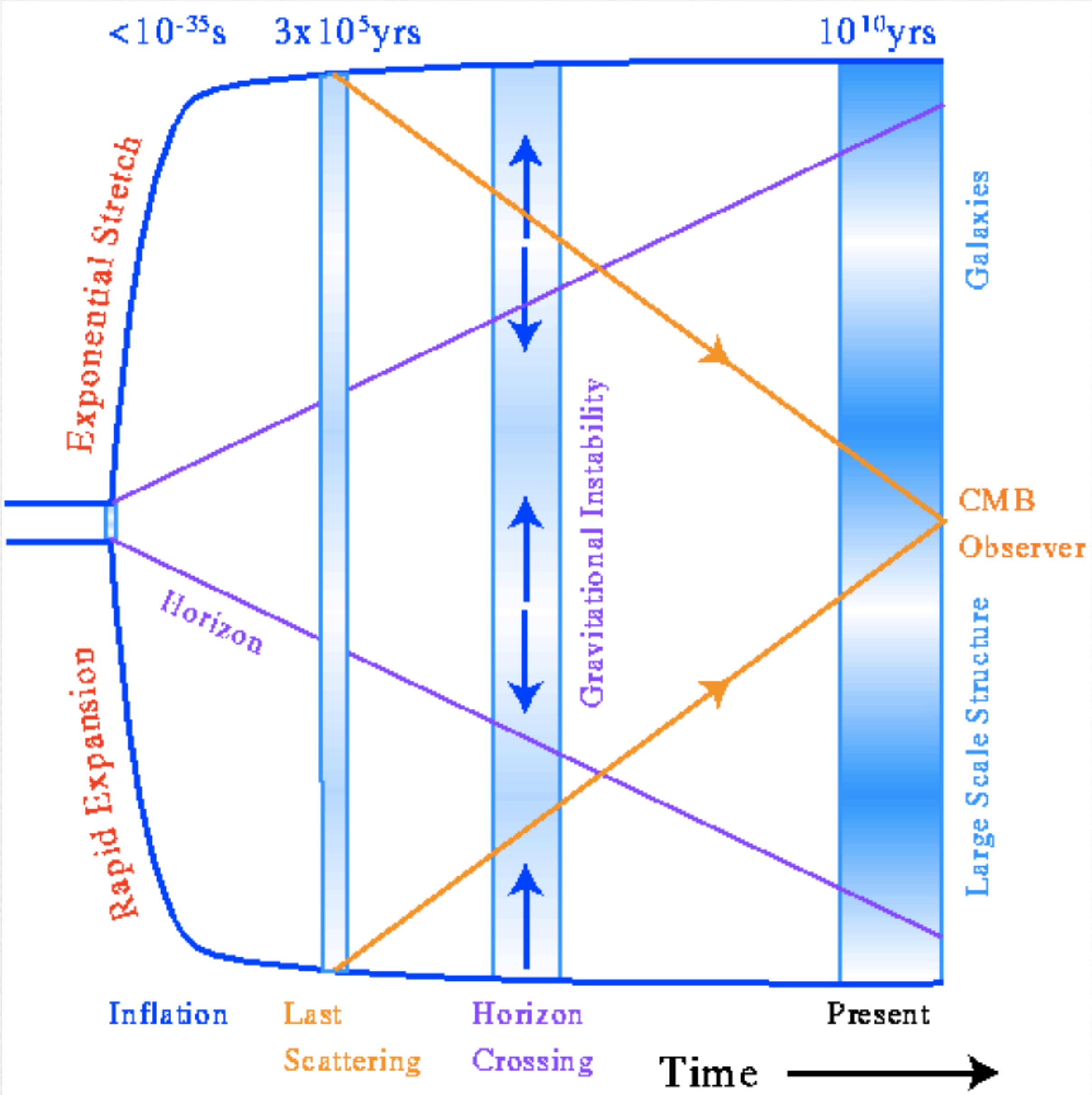
At last scattering the particle horizon was only ~ 100 Mpc, subtending an angle of about 1 degree. Why then are the large number of causally disconnected regions on the sky at the same temperature?

[H. Murayama]

To allow causal contact over the whole of the region observed at last scattering requires a universe that expanded “faster than light” near t=0

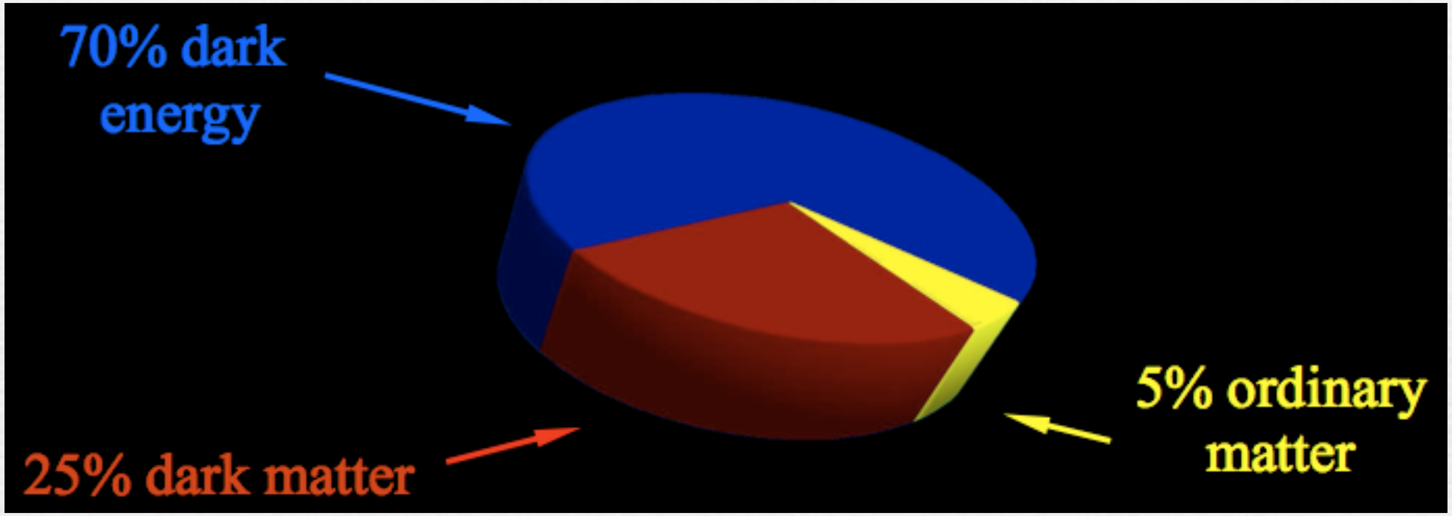
=> phase of accelerated expansion known as the inflationary universe

From inflation to structure formation



The universe is larger than our observable horizon! Regions that we see now as widely separated in oppposite directions in the sky were much closer together before inflation and could have been in direct contact, solving the horizon problem.

Back to dark Energy



How are we led to the conclusion that there is some "dark energy"?

1) Postulate a cosmological model

- Friedmann-Lemaitre-Robertson-Walker metric (Friedmann) equation

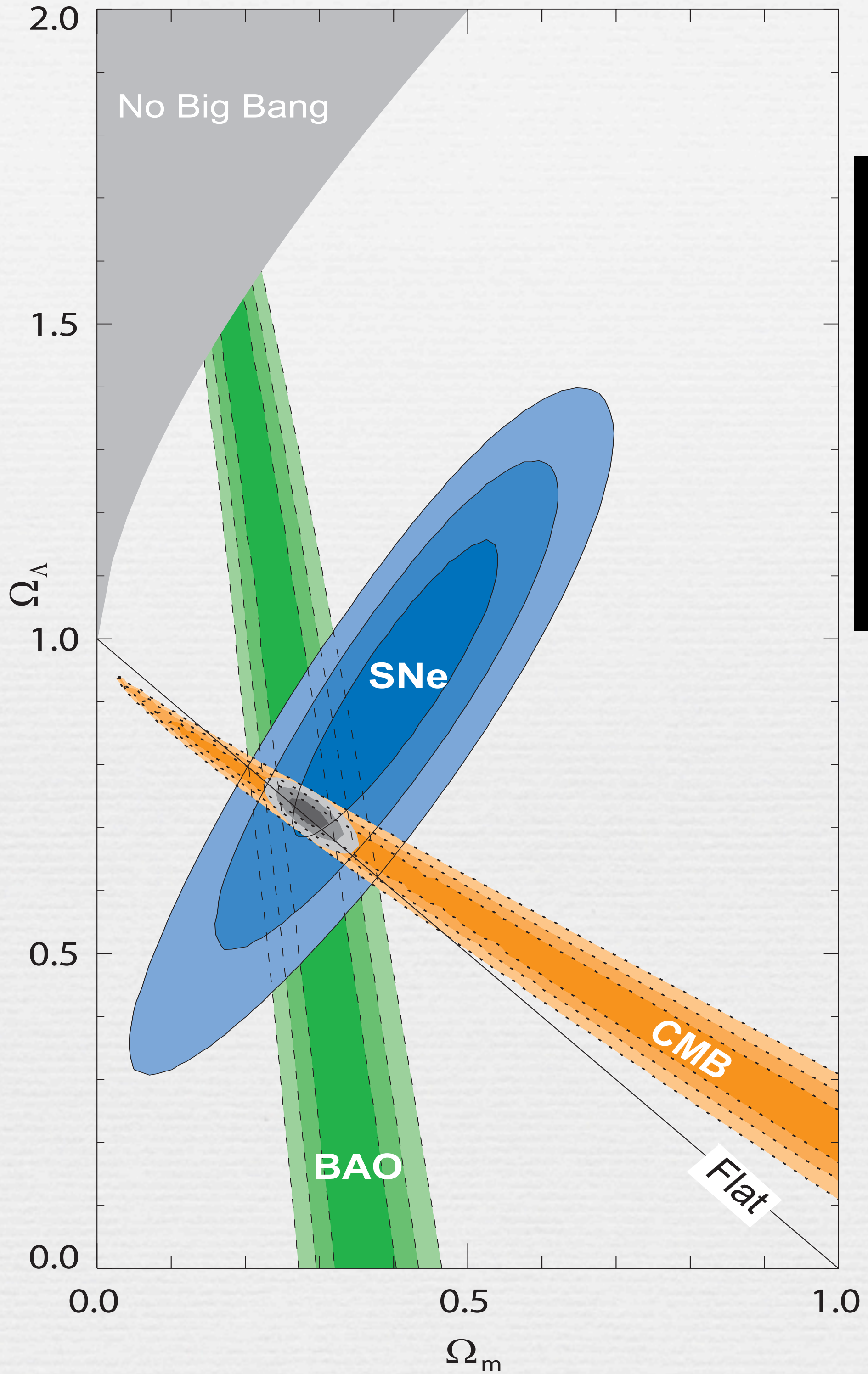
- energy content $\rho = \rho_M + \rho_R + \rho_\Lambda + ...$

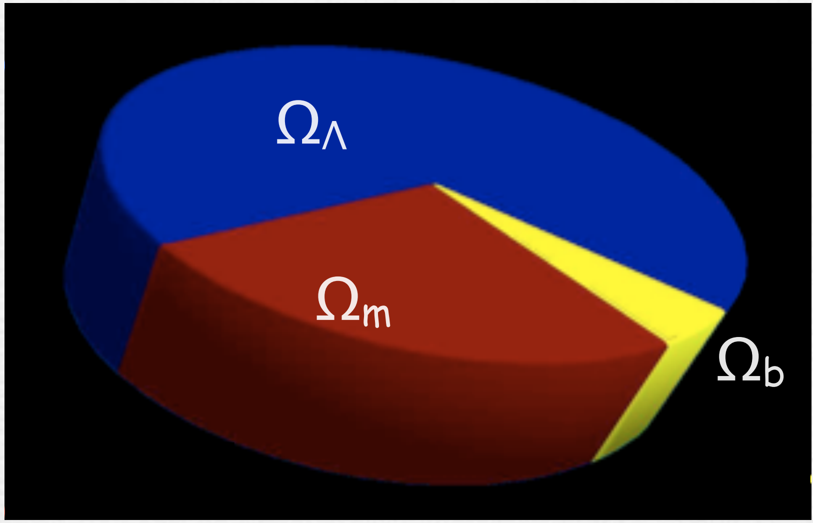
2) Calculate observables

3) compare with observations: Supernovae, *galaxies* (distribution of matter density fluctuations/power spectrum), *galaxy clusters* (mass, redshift, structure), *gravitational lensing* (measurement of deflection angles is affected by the presence of dark energy)

-> No possible "fit" of the cosmological model if $\rho_\Lambda = 0$.

-> The "fit" gives the value of the "cosmological constant" :
$\rho_\Lambda = (10^{-4}\ \mathrm{eV})^4$


2.0
1.5
1.0
0.5
0.0
No Big Bang
SNe
CMB
BAO
Flat
0.0
0.5
1.0
Ω_Λ
Ω_m


Ω_Λ
Ω_m
Ω_b

the expansion rate H is a key-quantity

Hubble's constant — curvature — matter — radiation — dark energy

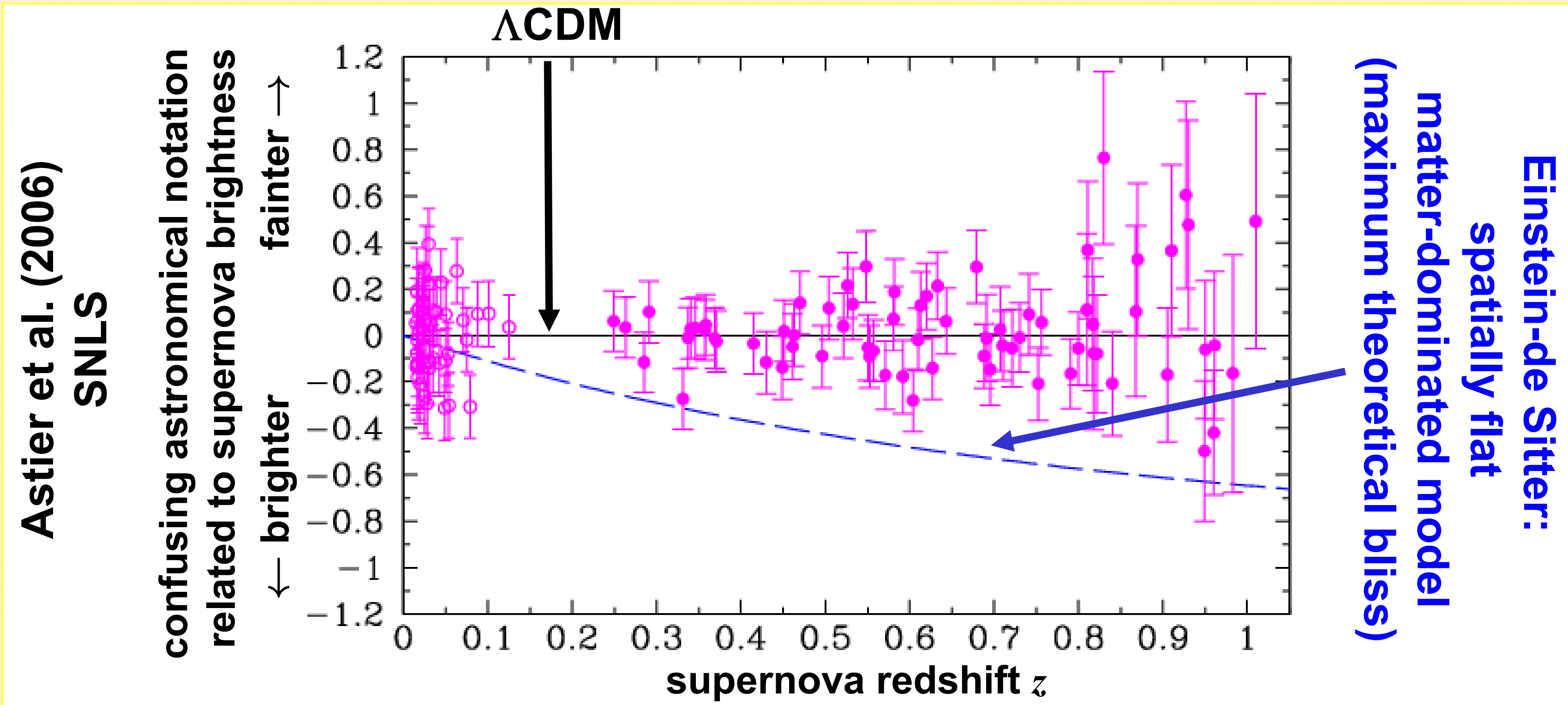
$$H^2(z) = H_0^2\left[\left(1-\Omega_{\mathrm{TOTAL}}\right)(1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_w (1+z)^{3(1+w)}\right]$$

CMB — LSS — CMB — $H(z)$

(background radiation)

(distribution of structures at large scales)

Supernovae (SNe1a)



1) Use Standard candles

2) Measure luminosity and redshift

3) make an hypothesis on the cosmological model

4) compare observations and model

-> The "fit" leads to the value of the `cosmological constant' $\rho_\Lambda = (10^{-4}\ \mathrm{eV})^4$

what an embarrassment ....

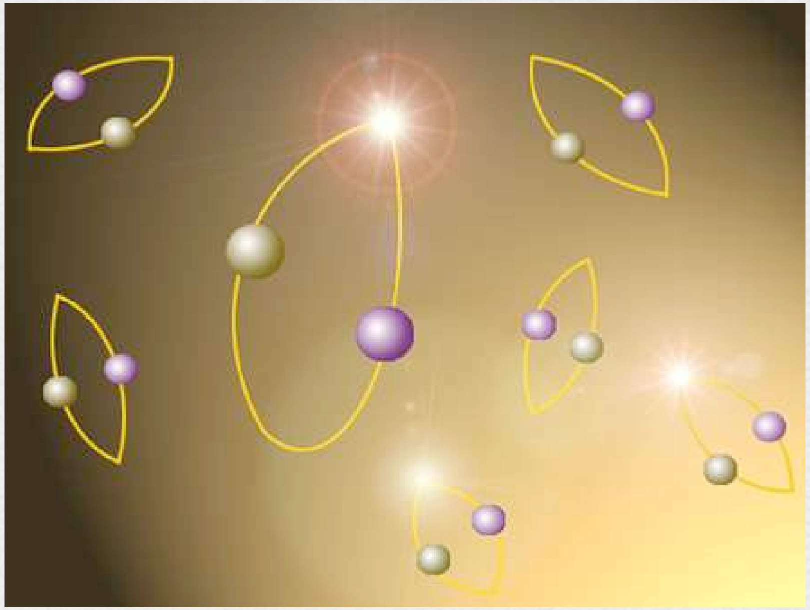
value deduced from observations:

$\rho_\Lambda = (10^{-4}\ eV)^4 = 10^{-16}\ eV^4$

expected (theoretical) value: ~ 10^{120} times the observed value

$\Lambda = M_{Planck}$ -> $\rho_\Lambda = 10^{112}\ eV^4$

$\Lambda = TeV$ -> $\rho_\Lambda = 10^{48}\ eV^4$



vacuum quantum fluctuations

Questions ?