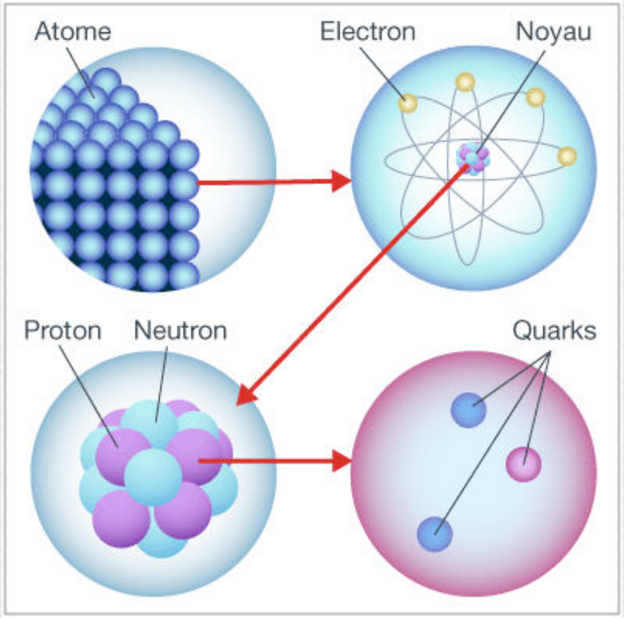
The Particle Physics-Cosmology connection



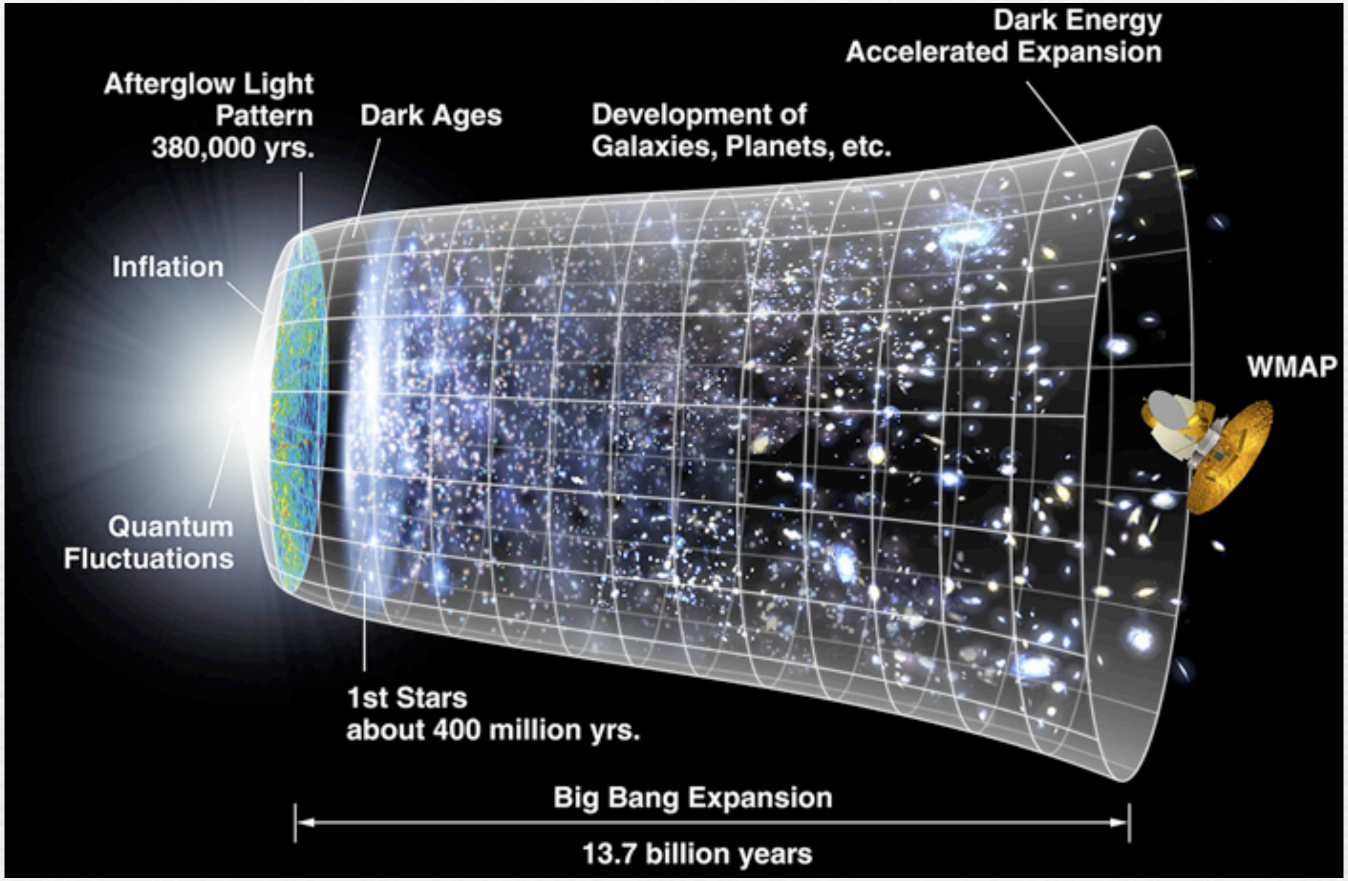
Géraldine SERVANT, CERN & IPhT CEA Saclay

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

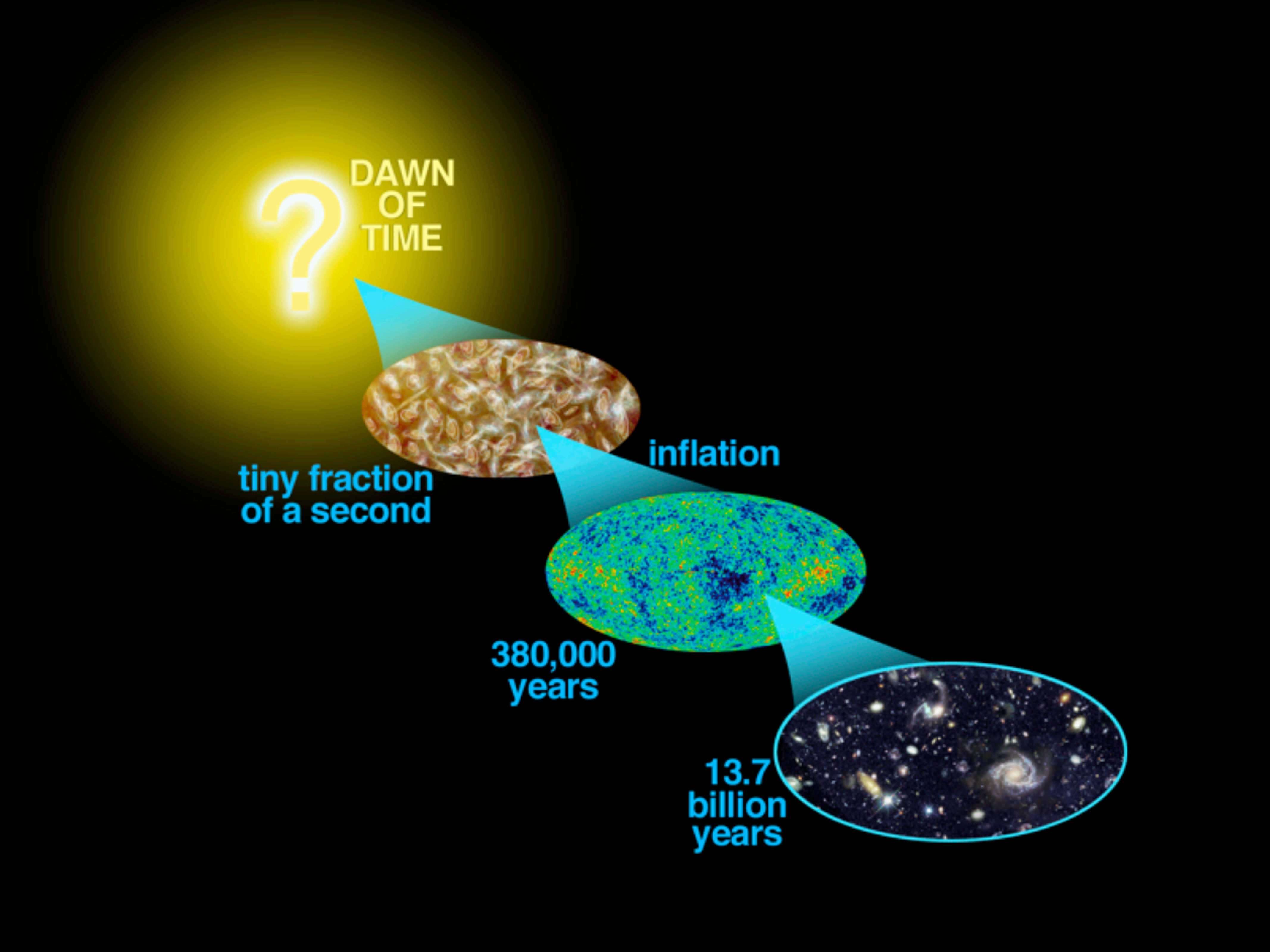
What is it made of?

How did large scale structures form ?

What are the laws controlling its evolution ?



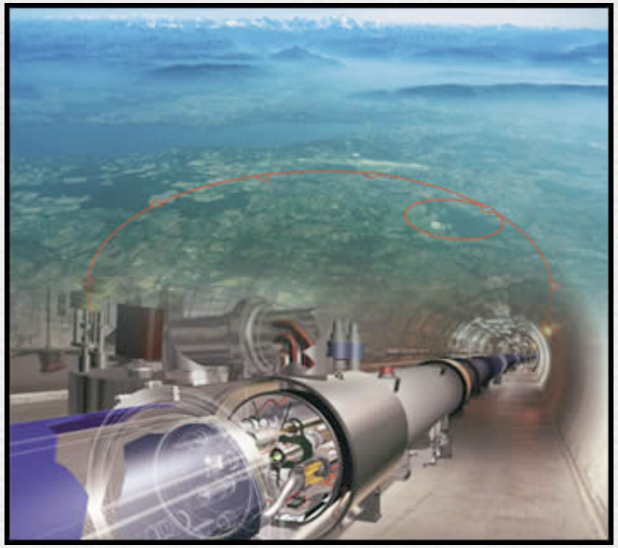
During the 20th century, we moved from a period of quasi ignorance about our universe to the establishment of a "standard cosmological model"


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

The Large Hadron Collider (LHC)

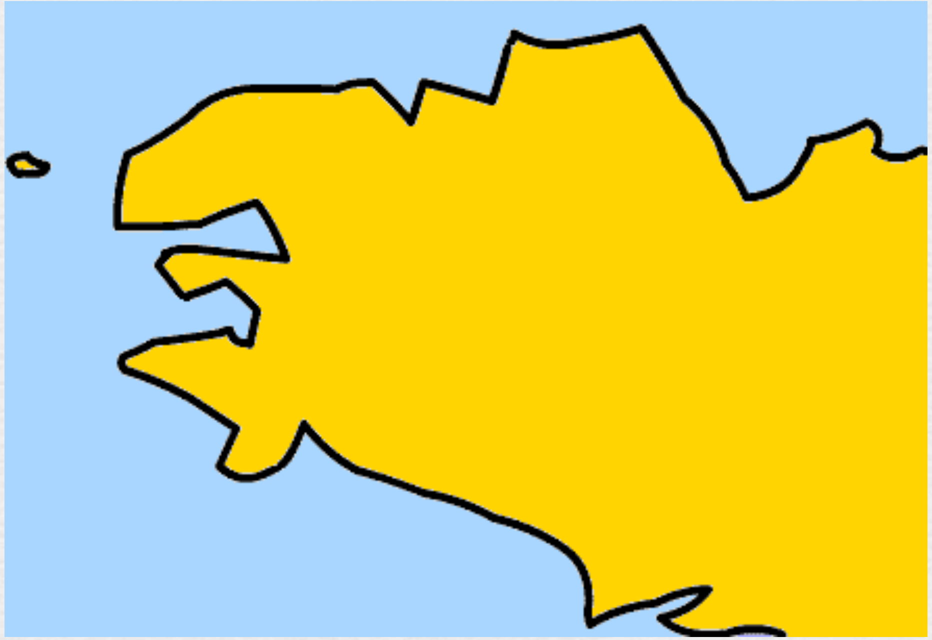
At the LHC, we collide protons at an unprecedented energy of 14 $\times 10^{12}$ electron-Volt

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

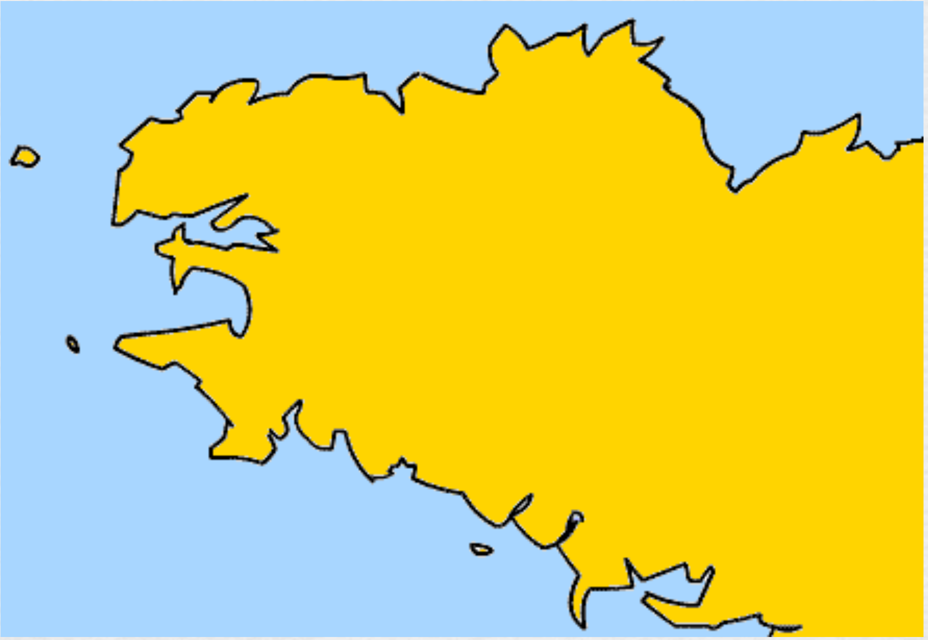


➔ The LHC: A gigantic microscope

Going to higher energies
⇛ allows to study finer details



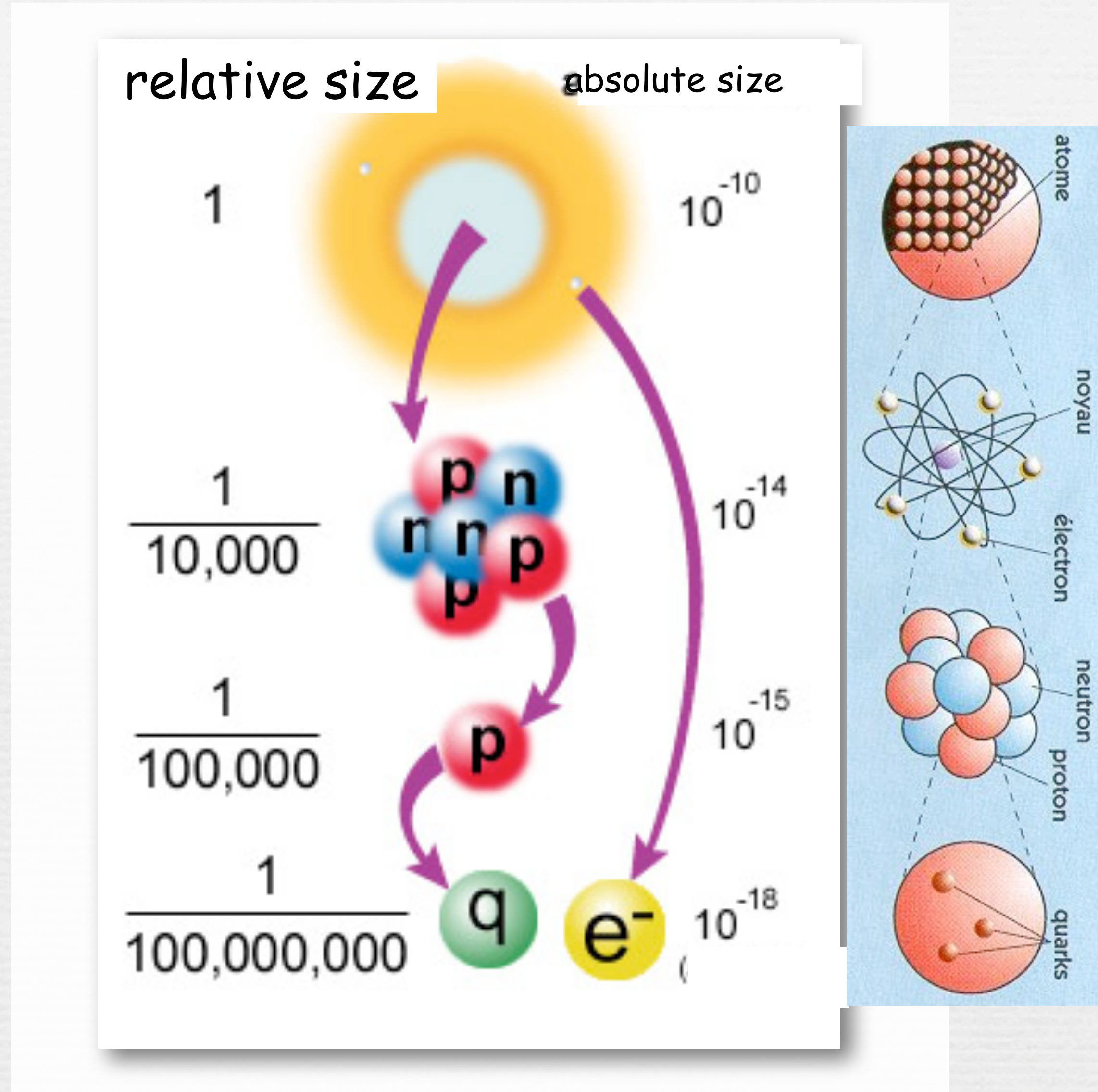
L = 400 km



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 ...



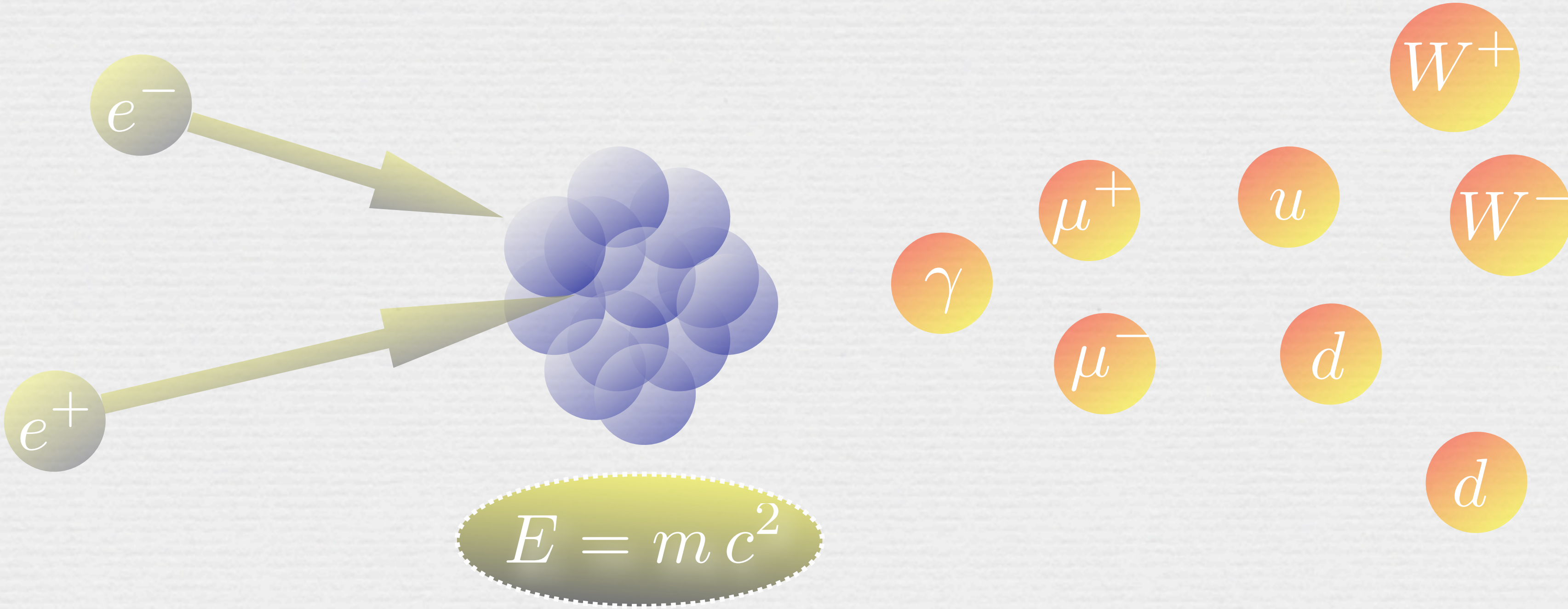
Creation of matter from energy

- ***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= $10^{-24}\mathrm{kg}$

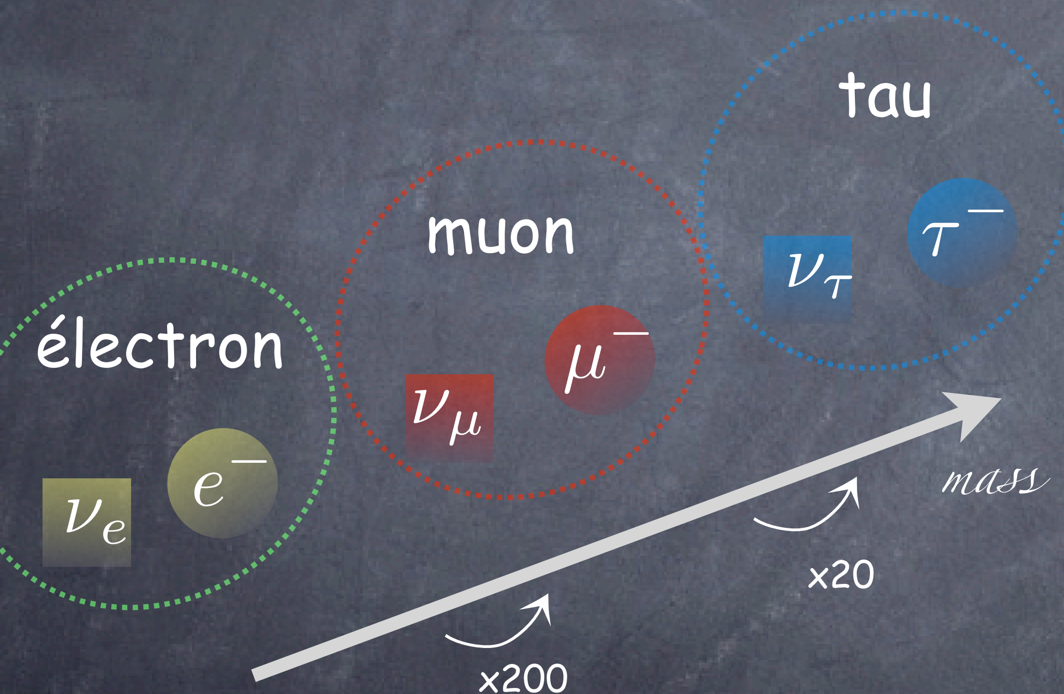
...however, in terms of energy density... this corresponds to the mass of the Earth concentrated in a 1 mm³ cube !

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

The Standard Model: matter

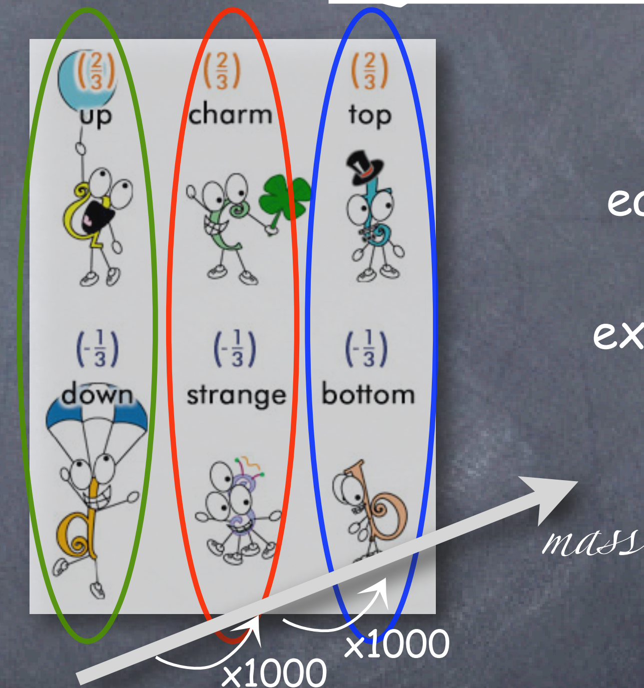
the elementary blocks:

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

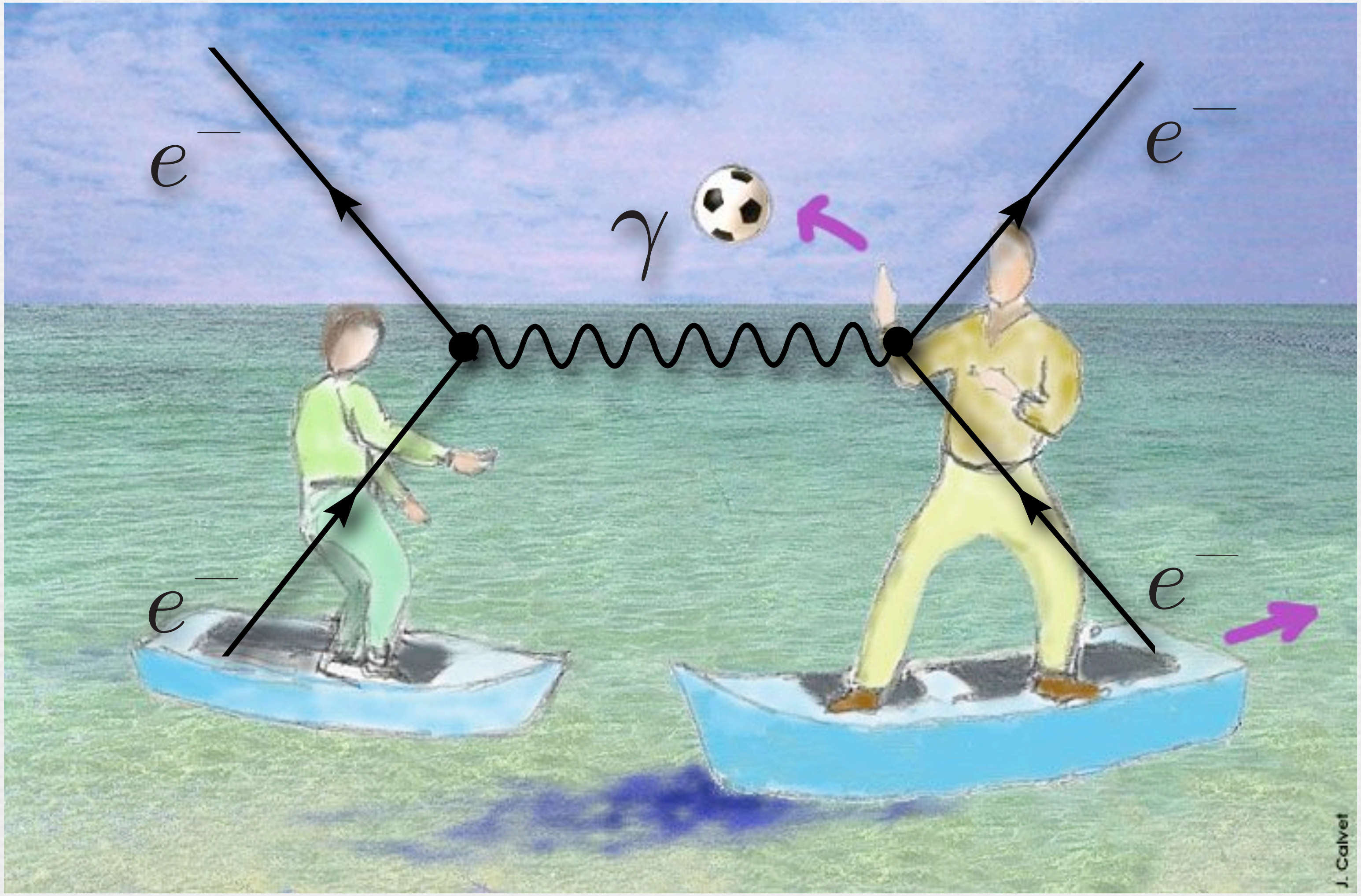
- $U(1)_Y$ — ***electromagnetic interactions*** → Photon γ
  - light
  - atoms
  - molecules

- $SU(2)_L$ — ***weak interactions*** → bosons $W^{\pm}, Z^0$
  - β decay
  - $n \xrightarrow{W^{\pm}} p + e^- + \bar{\nu}_e$

- $SU(3)_C$ — ***strong interactions*** → gluons g^a
  - atomic nuclei
  - α decay
  - ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$

intensity: 10^{-6} (electromagnetic), 10^{-2} (weak), 1 (strong)

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

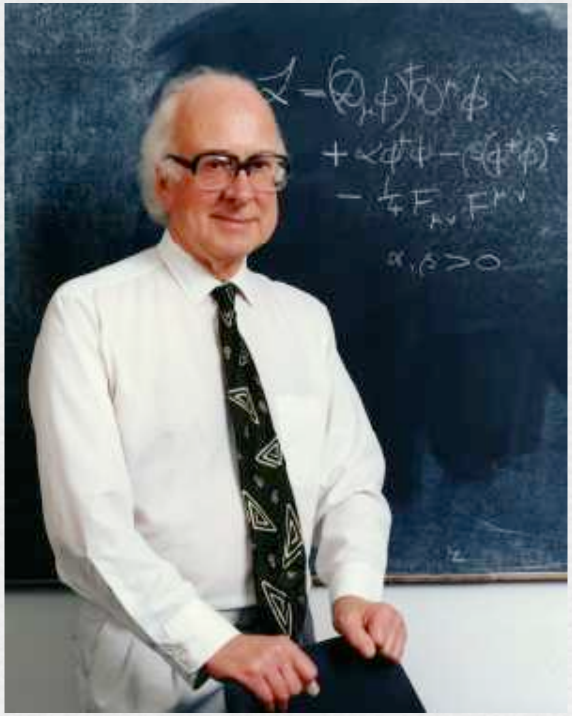
main physics goal
at the LHC:

What is the mechanism of Electroweak Symmetry breaking ?

in other words:

what is the origin of the mass of elementary particles

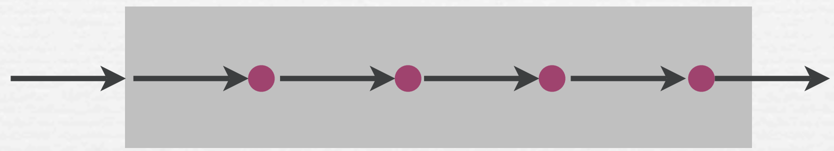
→ search for the Higgs Boson



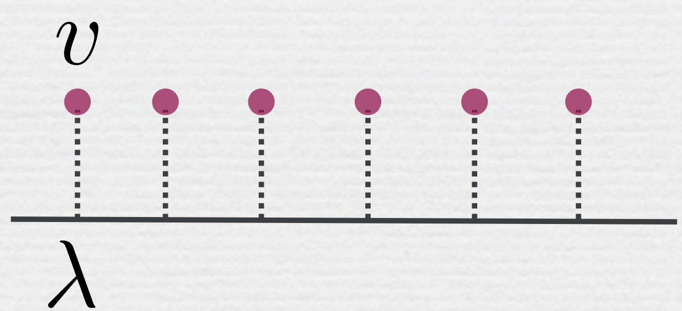
and other variants ...

- Composite Higgs ?
- Little Higgs ?
- Littlest Higgs ?
- Intermediate Higgs ?
- Slim Higgs ?
- Fat Higgs ?
- Gauge-Higgs ?
- Holographic Higgs ?
- Gaugephobic Higgs ?
- Higgsless ?
- UnHiggs ?
- Portal Higgs ?
- Simplest Higgs ?
- Private Higgs ?
- Lone Higgs ?
- Phantom Higgs ?

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

Detecting the Higgs Boson

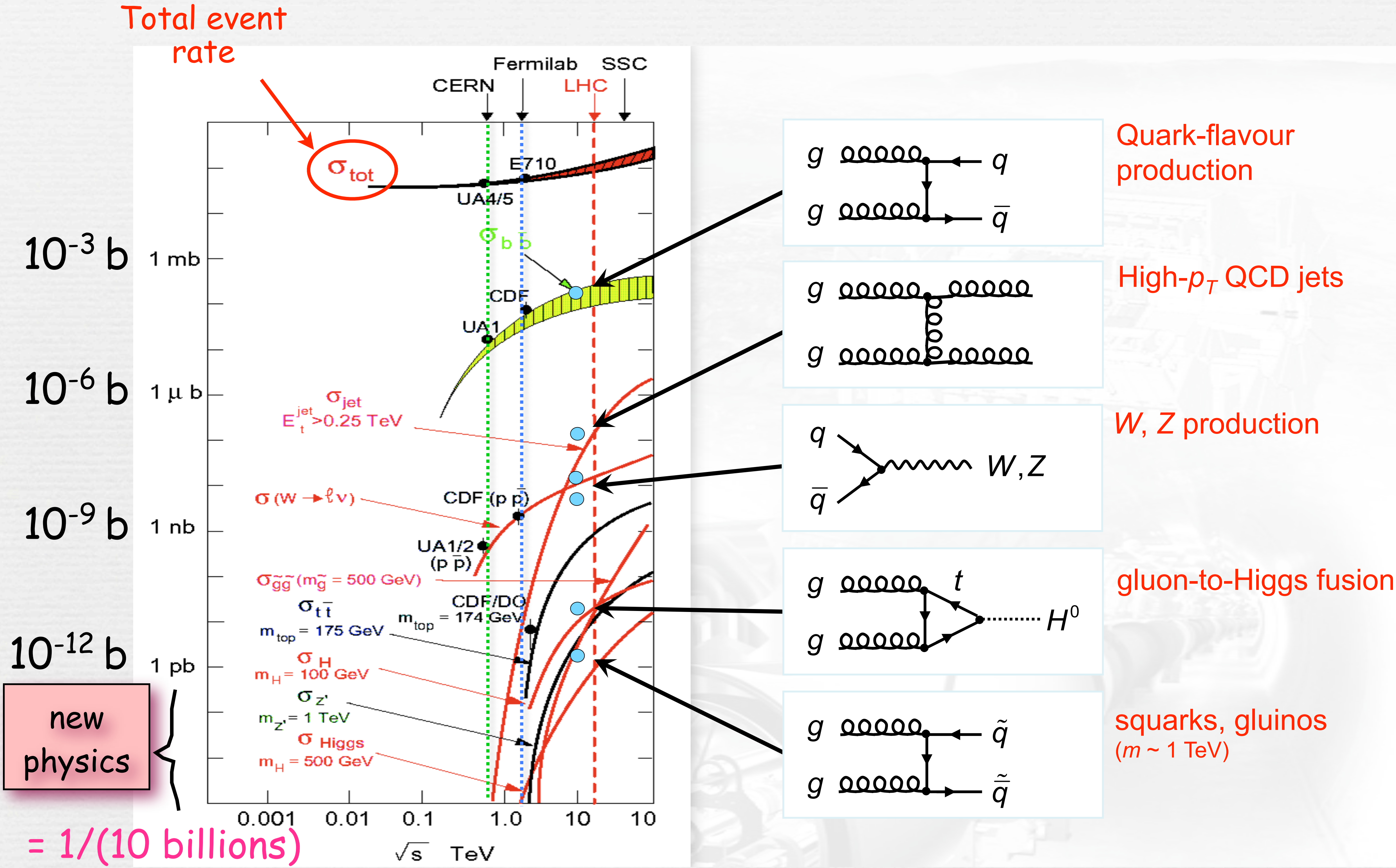
Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens when we bang on a table, creating sound waves, if we “bang” on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate “Higgs waves”, which manifest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

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

$\Rightarrow$ LHC

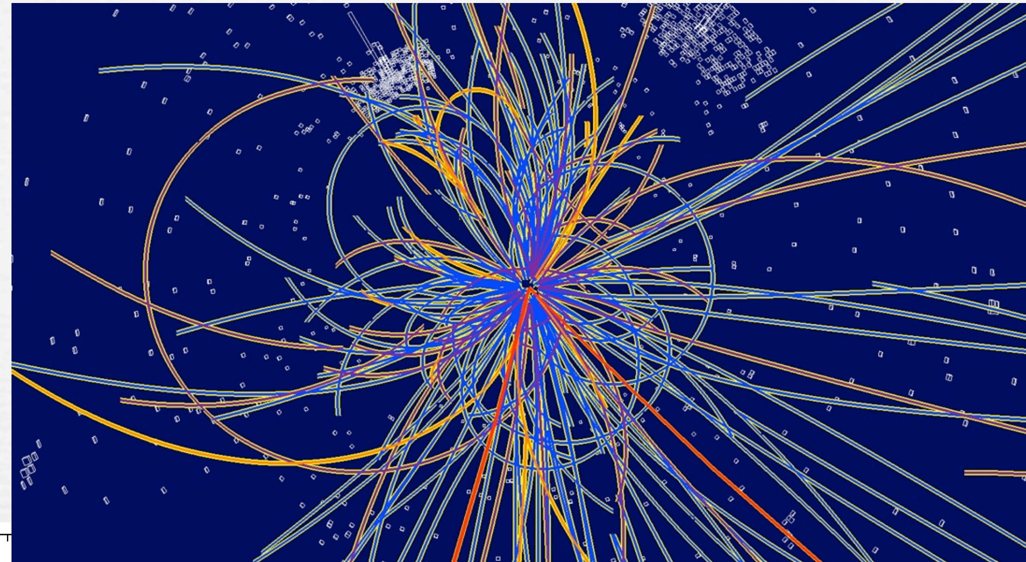
[M. Mangano]

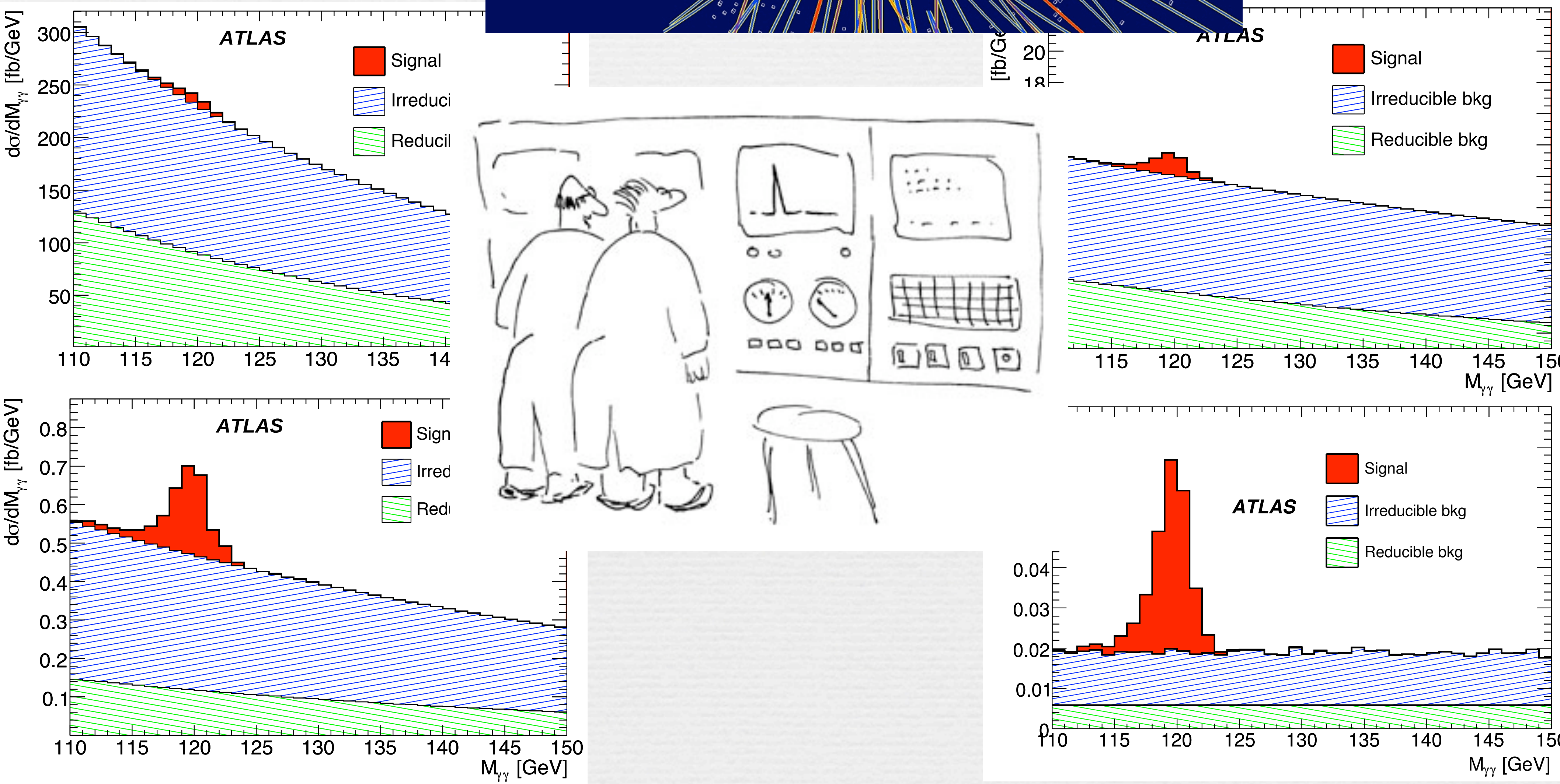
Event rate in hadron colliders



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

In practise:




ATLAS
Signal
Irreducible bkg
Reducible bkg
dσ/dMγγ [fb/GeV]
Mγγ [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

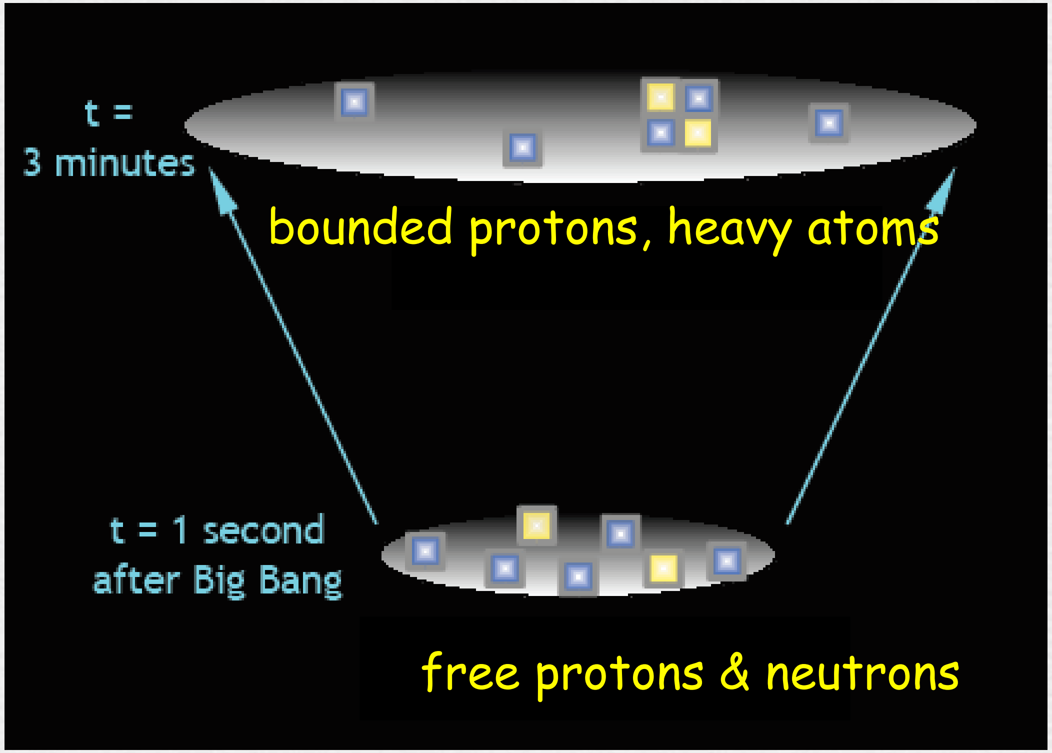
-> no hydrogen atom

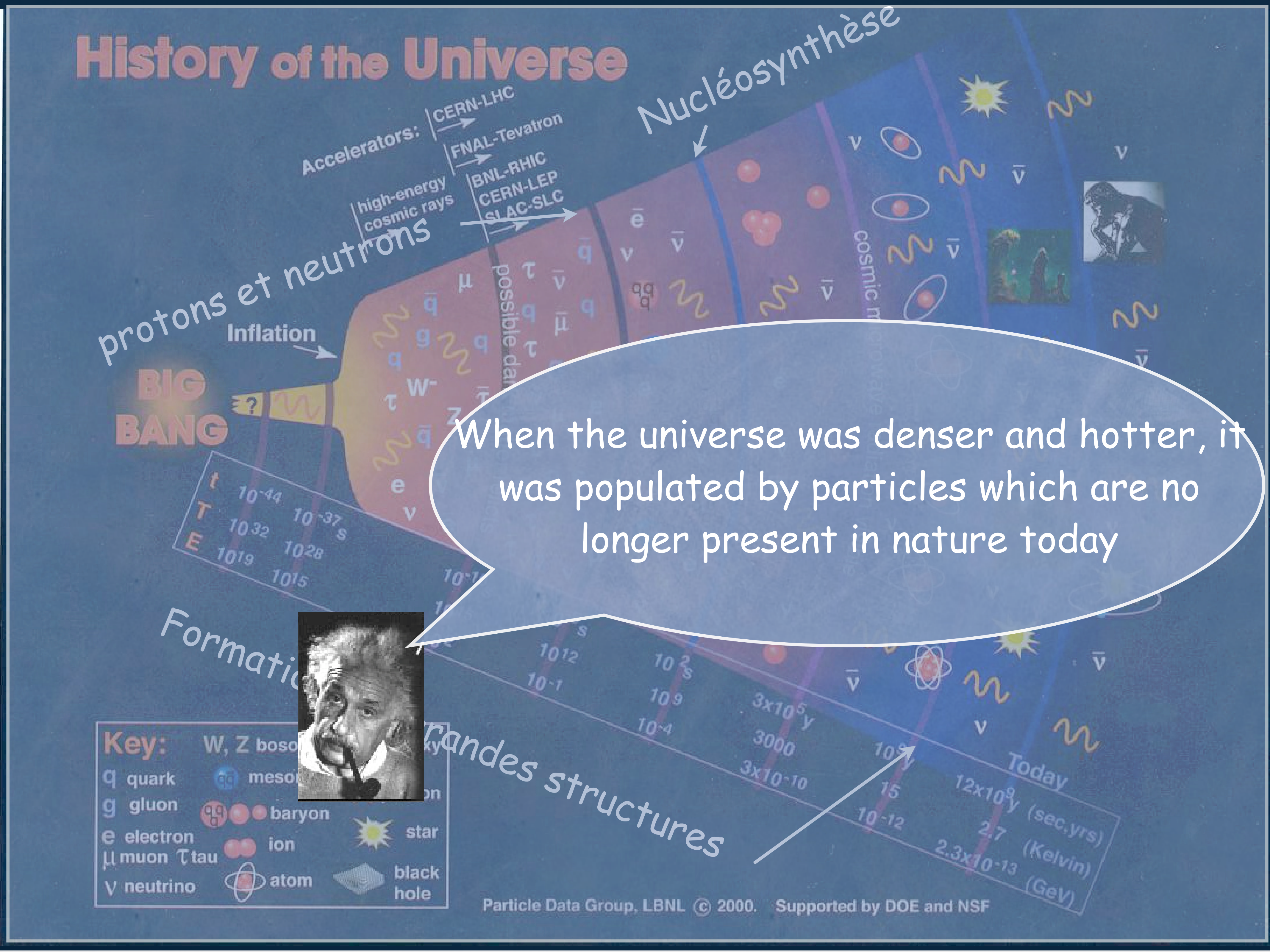
-> very different primordial nucleosynthesis

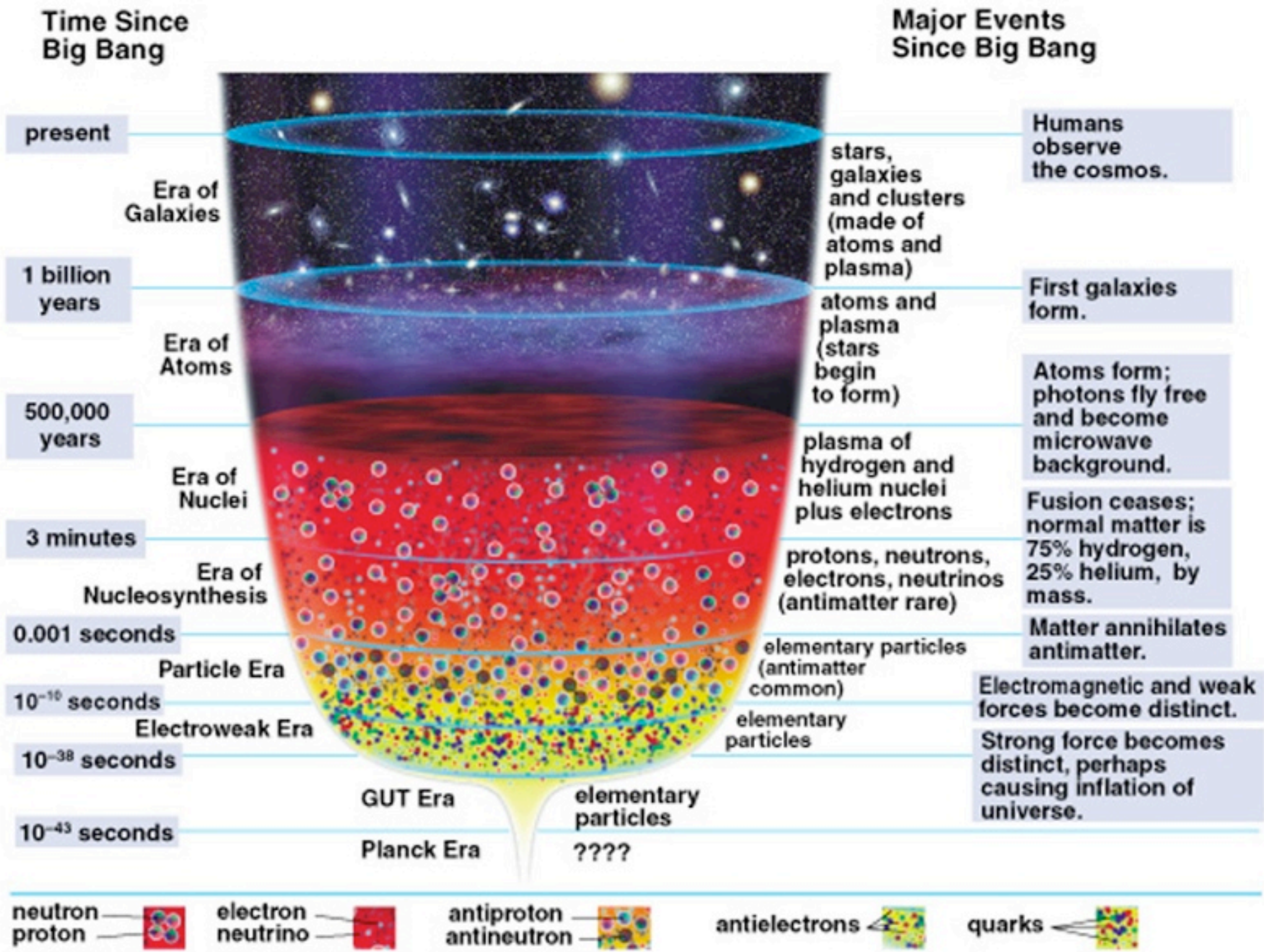
-> a profoundly different (and terribly boring) universe

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.



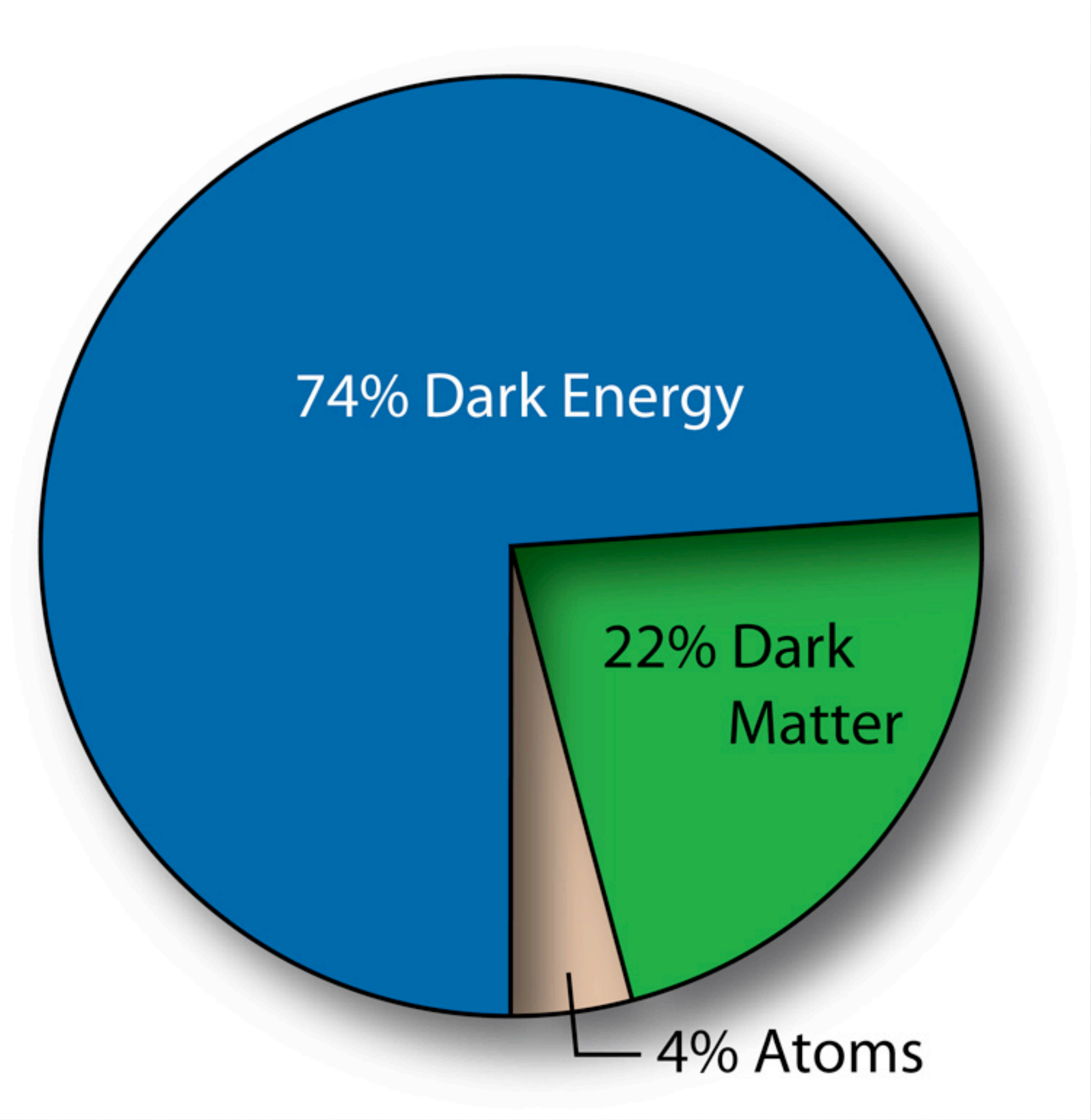

History of the Universe
Nucléosynthèse
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
protons et neutrons
Inflation
BIG BANG
When the universe was denser and hotter, it was populated by particles which are no longer present in nature today
Formation des grandes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

Despite all these successes...

We don’t understand 96 % of the energy budget of the universe !



Precision Cosmology

WMAP Cosmological Parameters

Model: lcdm+sz+lens

Data: wmap7

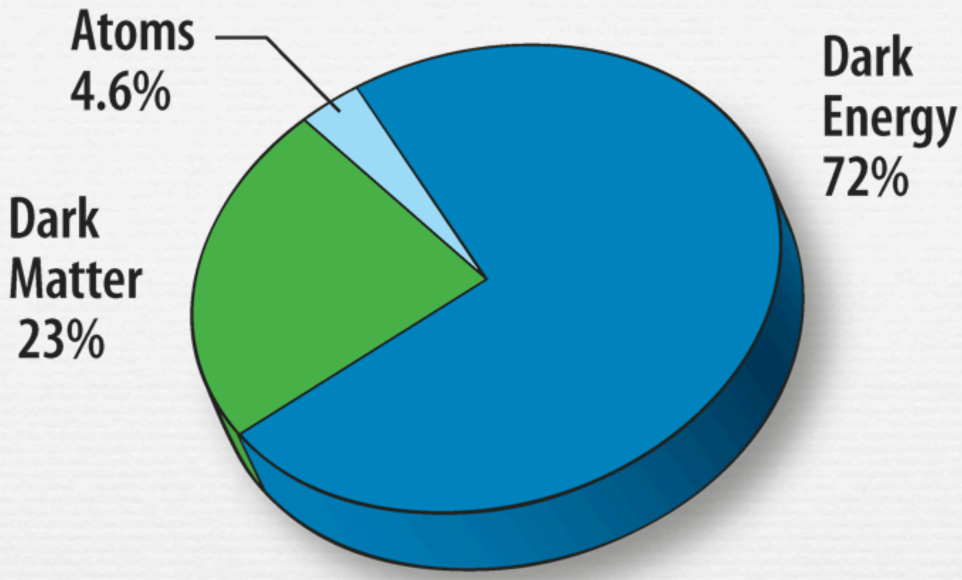
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1 - n_s$	0.037 ± 0.014
$1 - n_s$	$0.0079 < 1 - n_s < 0.0642$ (95% CL)	$A_{\rm BAO}(z = 0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$
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

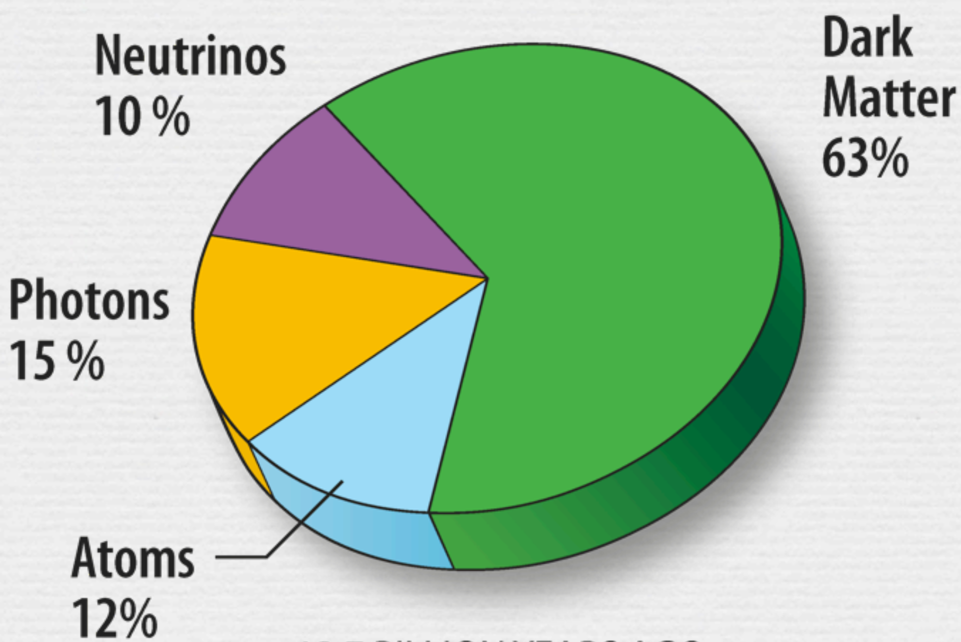
H_0 ← expansion rate

Ω_m ← fraction of the total energy density in matter

t_0 ← age of the universe



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

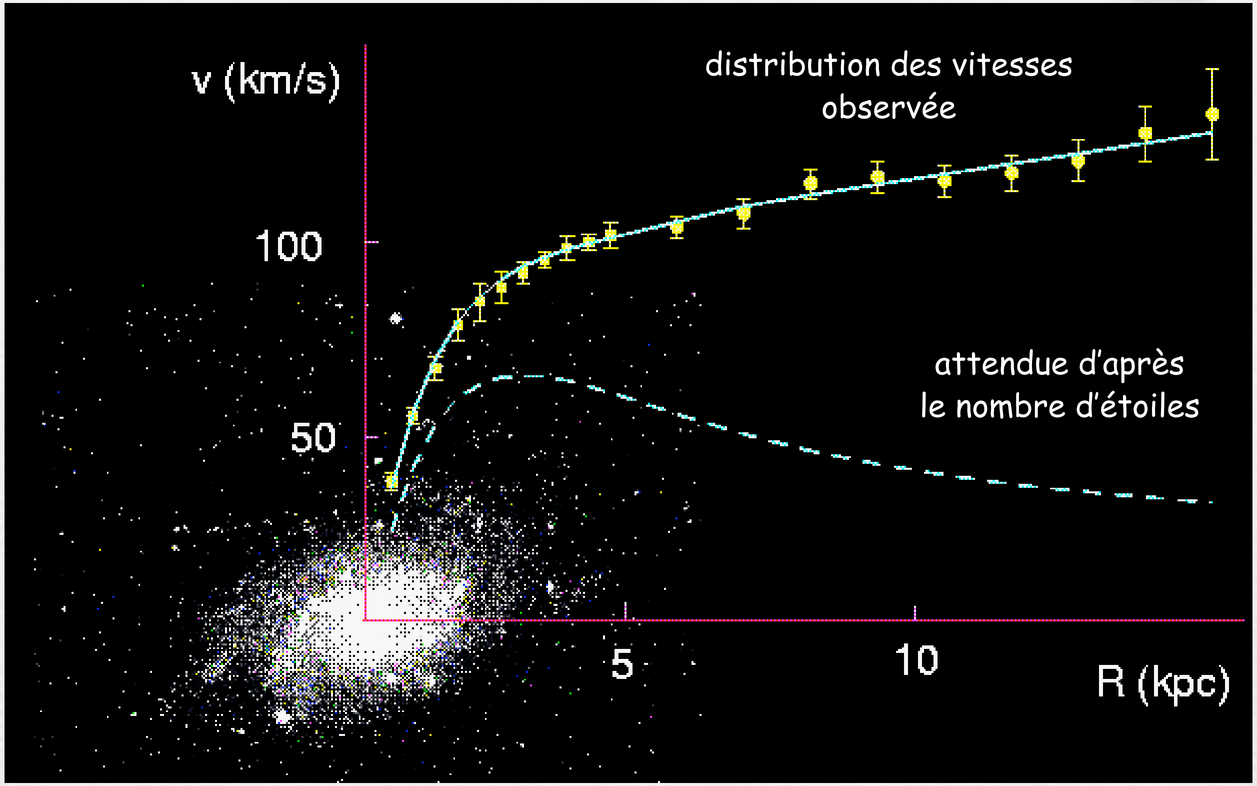
→ observational need for new physics

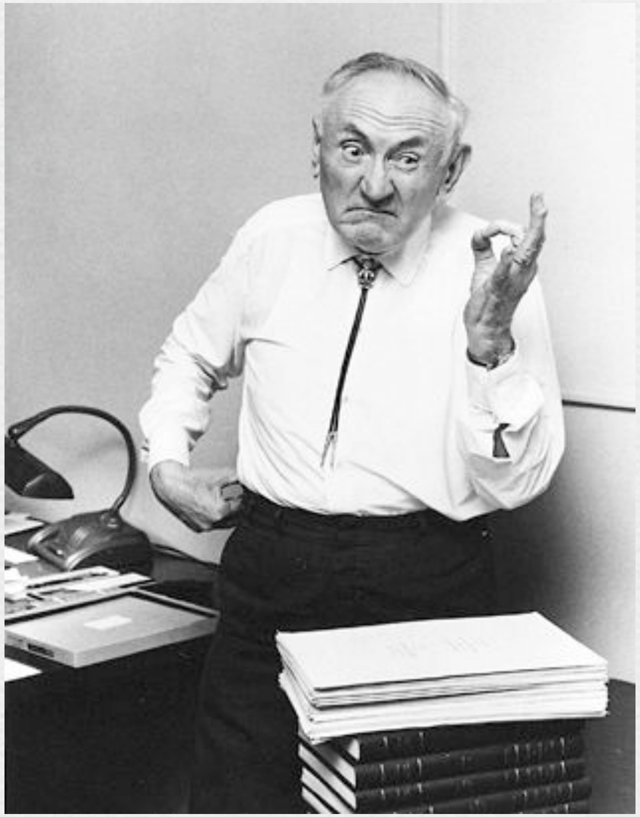
→ what does this have to do with the electroweak scale?

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

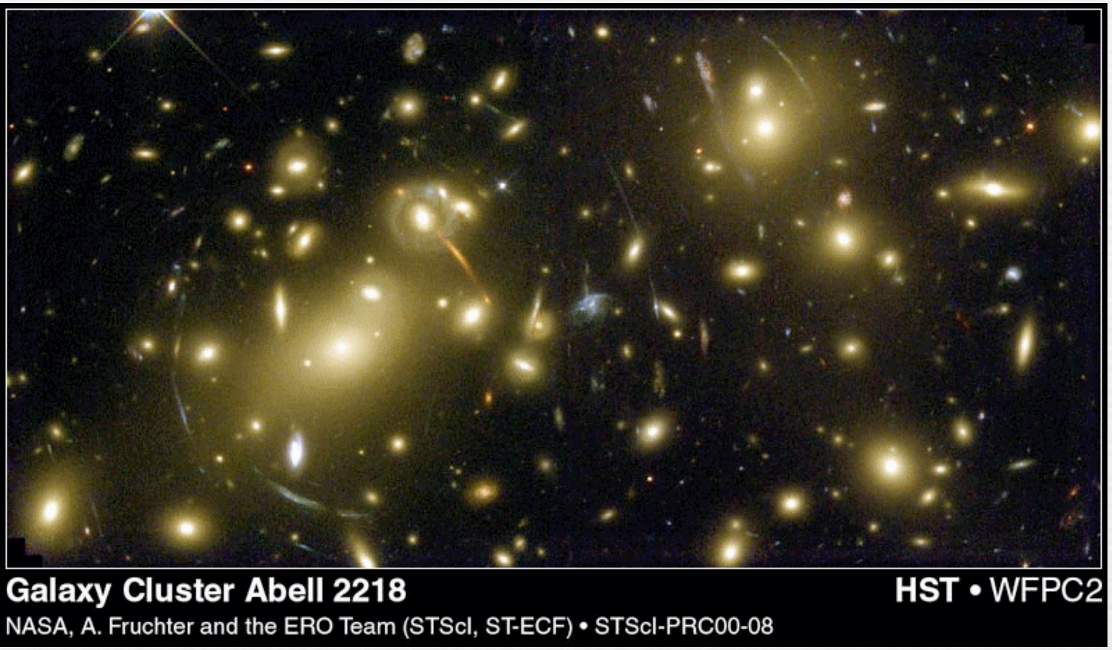


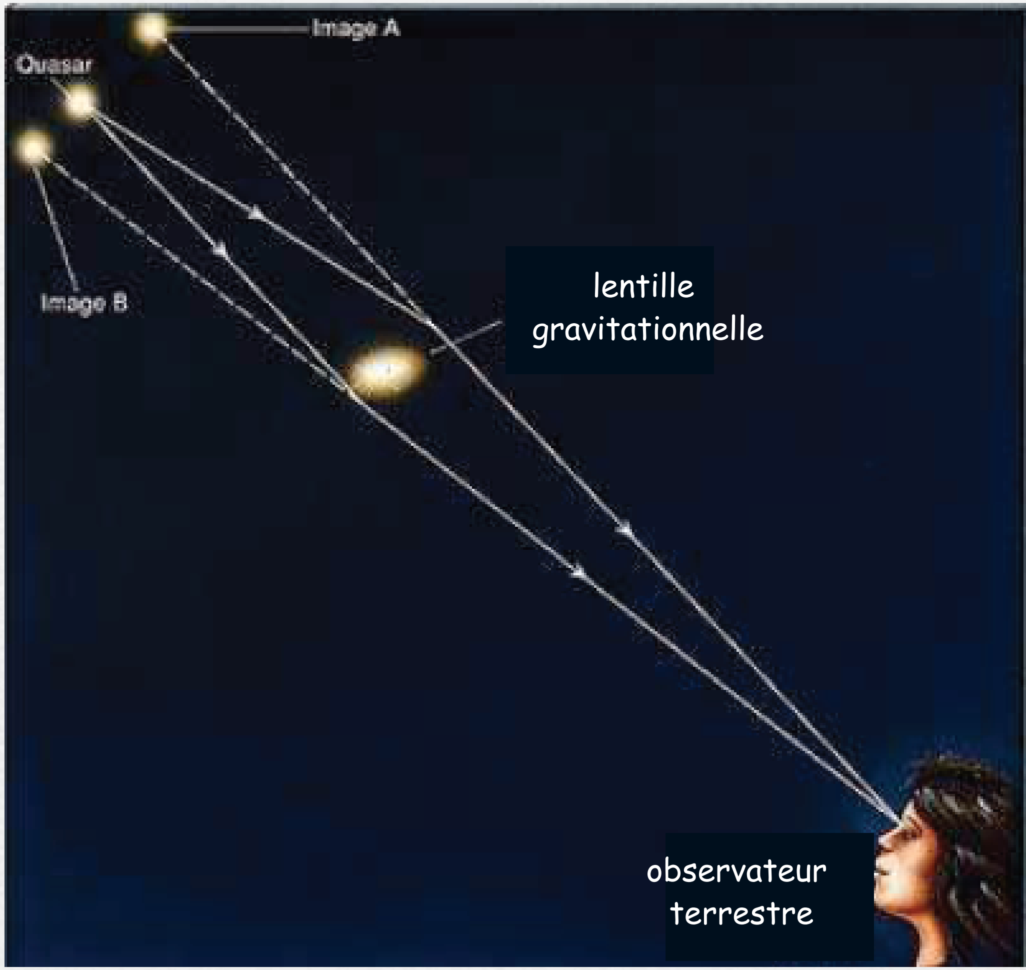


Zwicky

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

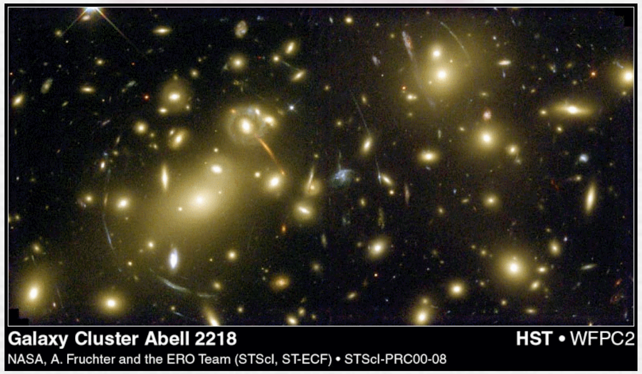
gravitational lensing



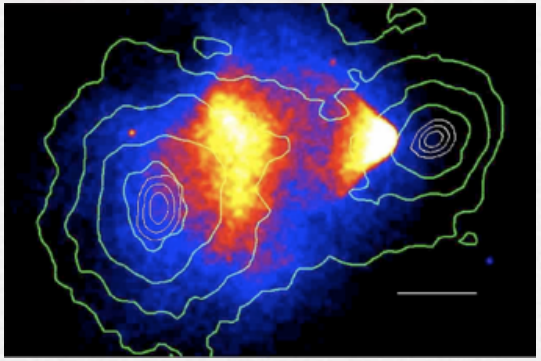


The existence of (Cold) Dark Matter has been established by a host of different methods; it is needed on all scales

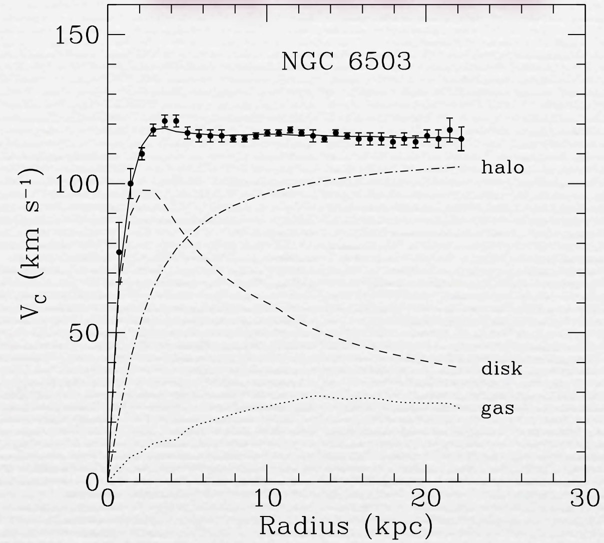
Gravitational lensing



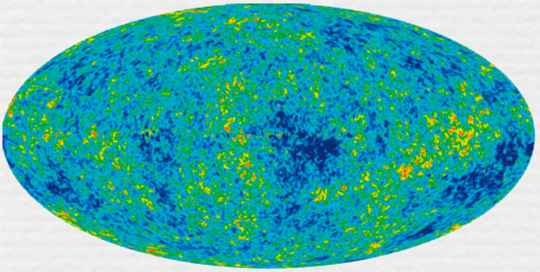
The "Bullet cluster": lensing map versus X-ray image

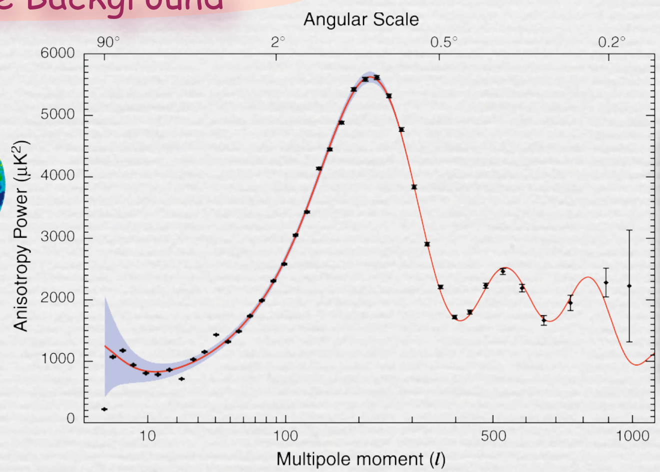


Galaxy rotation curves



Cosmic Microwave Background





... etc

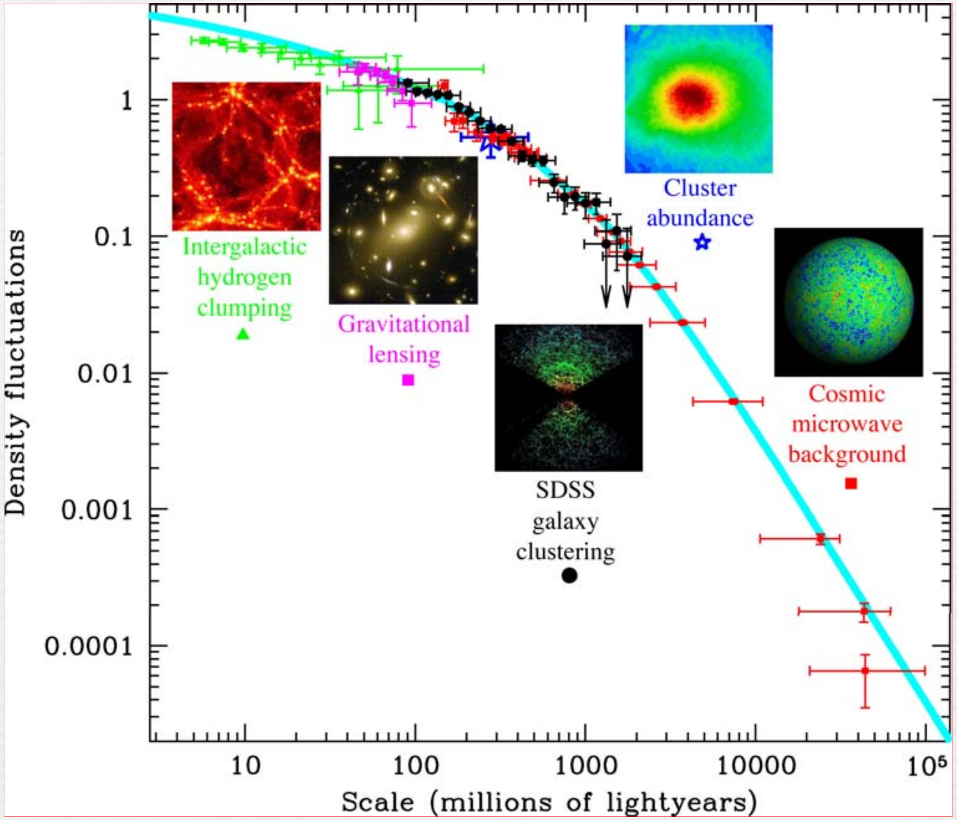
-> Fraction of the universe's energy density stored in dark matter :

$\Omega_{DM} \approx 0.22$

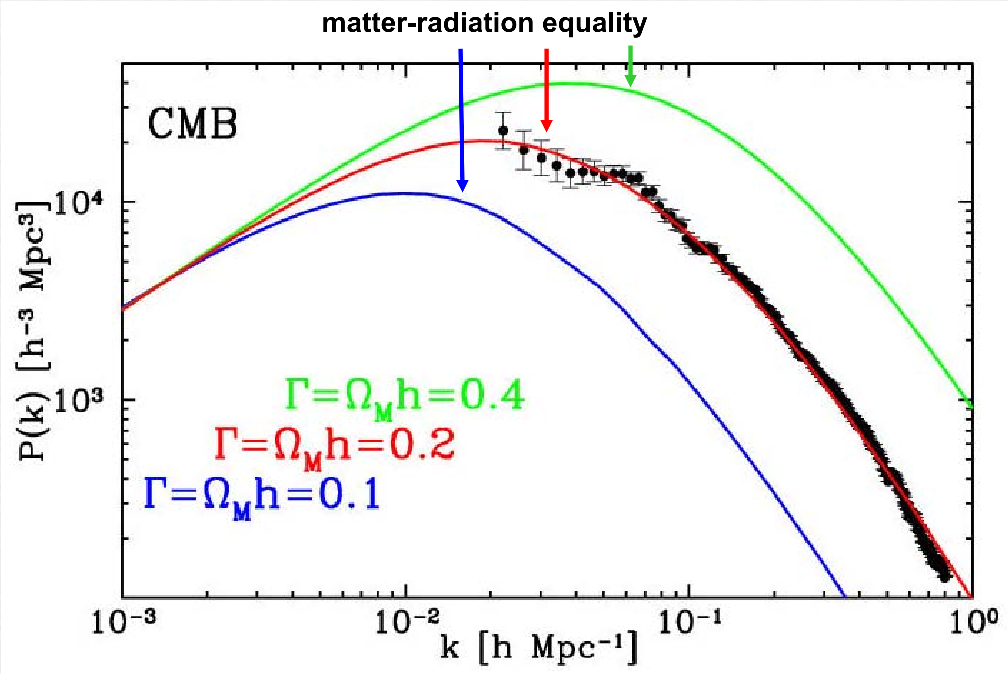
The picture from astrophysical and cosmological observations is getting more and more focussed

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

Matter power spectrum

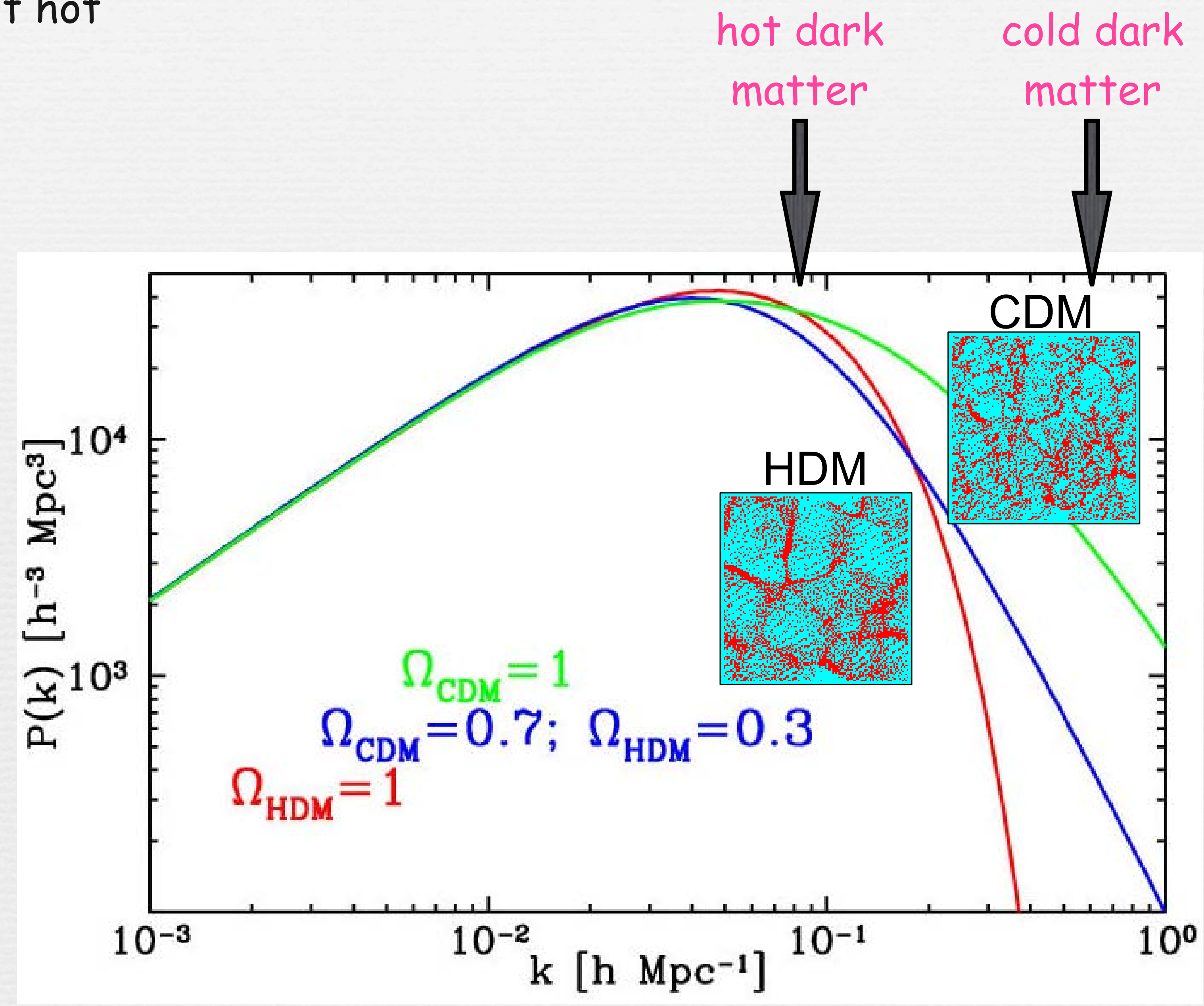


--> DM is not baryonic



Neutrinos

DM is not hot

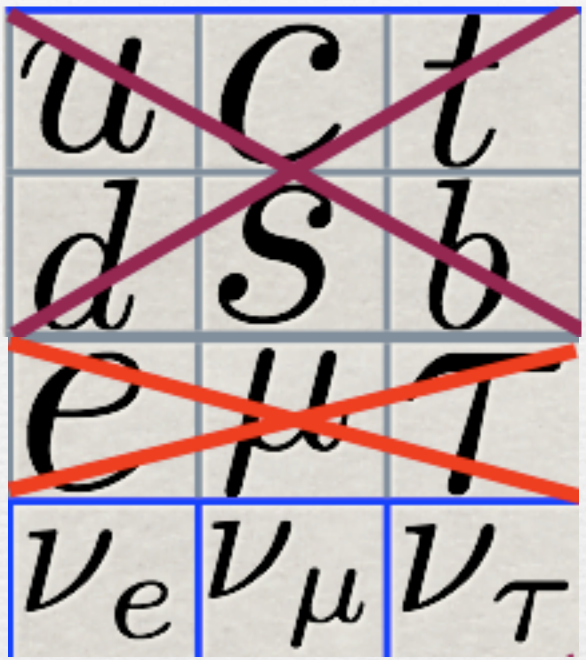


Why can't dark matter be explained by the Standard Model?

Matter

quarks

leptons



I II III

3 families of matter

Forces

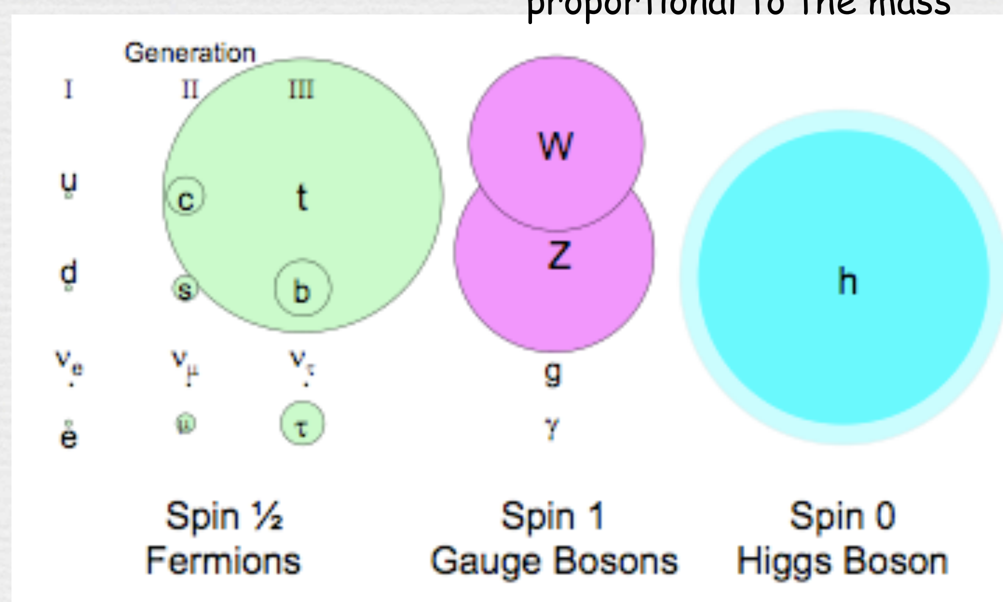
force mediators

charged/unstable

baryonic

massless

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

Two possibilities:

very light & only gravitationally coupled (or with equivalently suppressed couplings) -> stable on cosmological scales

Long-lived
(stable on cosmological scales)

$$\tau_{DM} > \tau_{universe} \sim 10^{18}\ s$$

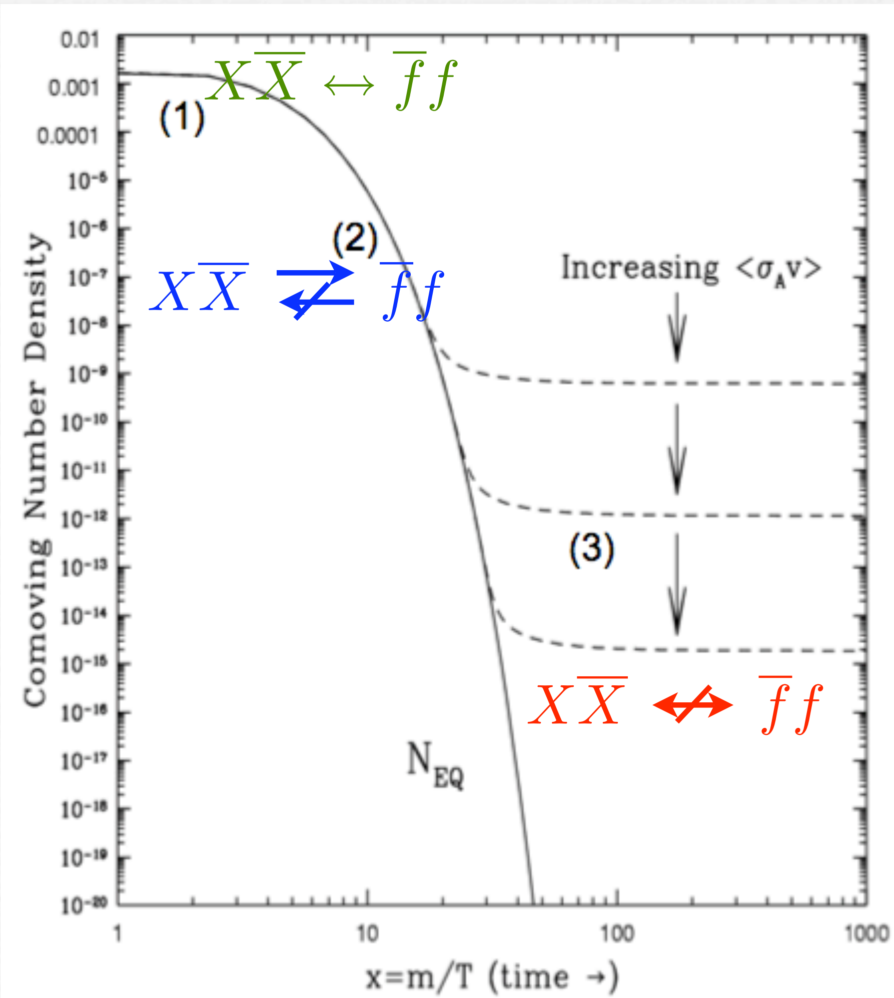
sizably interacting (but not strongly) with the SM -> symmetry needed to guarantee stability

stable by a symmetry

-> WIMP

The WIMP relic abundance follows from the generic thermal freeze-out mechanism in the expanding universe

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{T}}^2)$$



freese-out :

$$H \sim \frac{\sqrt{g}T^2}{M_{\mathrm{P}}} \sim \Gamma = n\sigma v$$

Thermal relic: $\Omega h^2 \propto 1/\langle\sigma_{anni} v\rangle$

$\Rightarrow \langle\sigma_{anni} v\rangle \approx 1$ pb

$\sigma \sim \alpha^2/m^2$

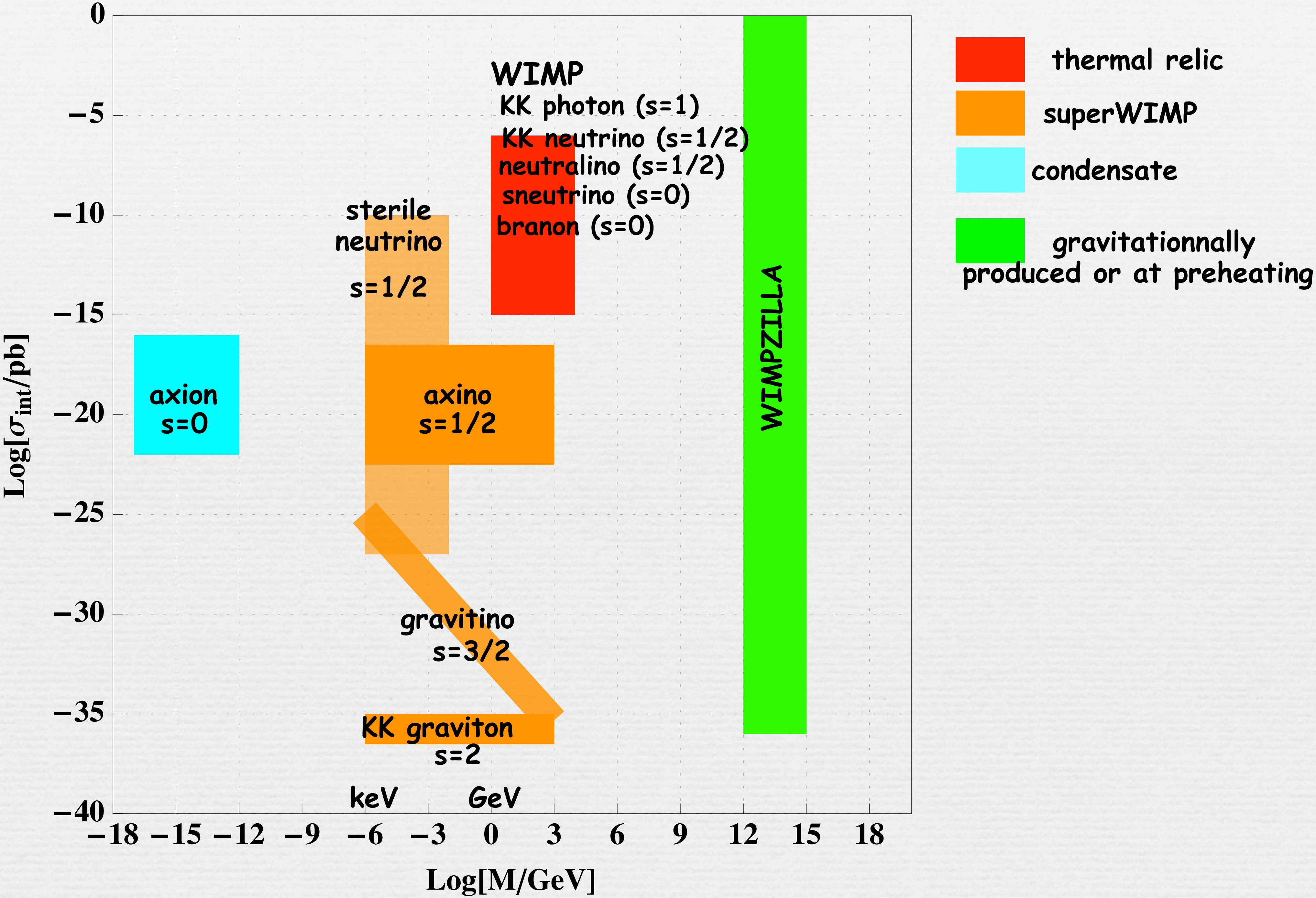
$\Rightarrow m \sim 100$ GeV

The "WIMP miracle"

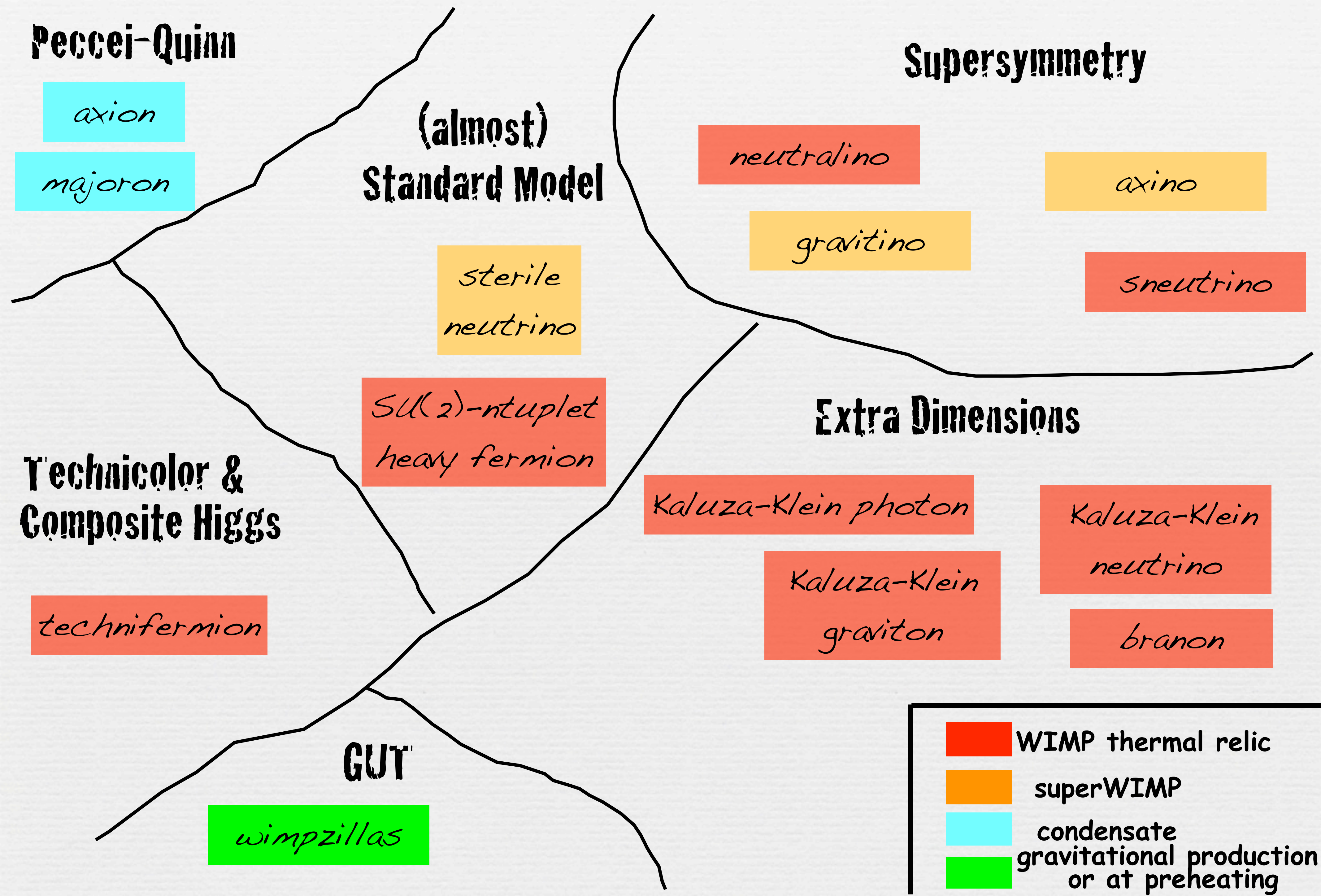
$$\Omega_{DM} \approx \frac{O(1)\ \mathrm{pb}}{\sigma_{anni}}$$

→ a particle with a typical EW-scale cross section $\sigma_{anni} \approx 1$ pb leads to the correct dark matter abundance.

Dark Matter Candidates Ω~1



In Theory Space



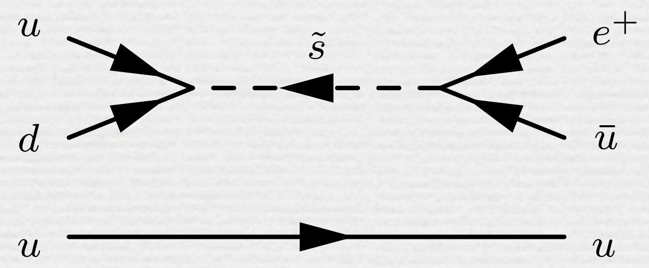
Supersymmetric Dark Matter

The lightest supersymmetric particle is stable due to R-parity, a symmetry distinguishing partners and super-partners, originally **assumed** to avoid proton decay

R-parity: $$R_p = (-1)^{3B+L+2s}$$

under which SM particles are even and superpartners are odd

Primarily introduced to prevent fast proton decay in supersymmetry:



-> The Lightest Supersymmetric Particle (odd) is thus stable

How to detect Dark Matter?

Direct detection: We can "touch" dark matter

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

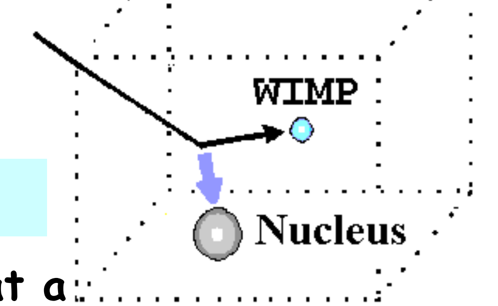
WIMP direct detection

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.

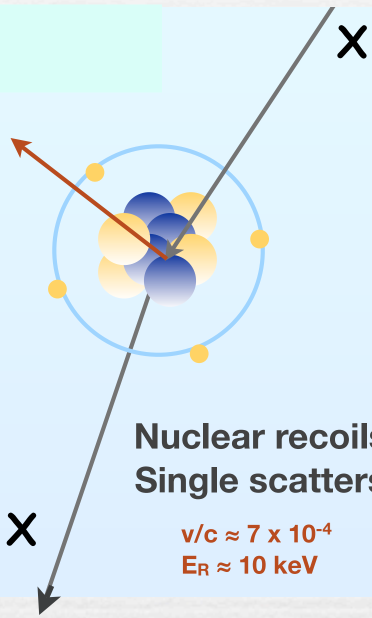
Direct detection consists in observing the recoiled nuclei.

Direct Detection



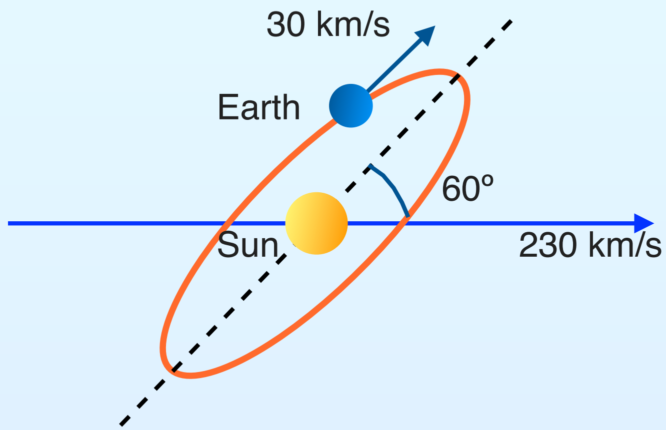
WIMP flux on Earth: ~ 10^5 $cm^{-2}s^{-1}$ (for a 100 GeV WIMP)

even though WIMPs are weakly interacting, this flux is large enough so that a potentially measurable fraction will elastically scatter off nuclei

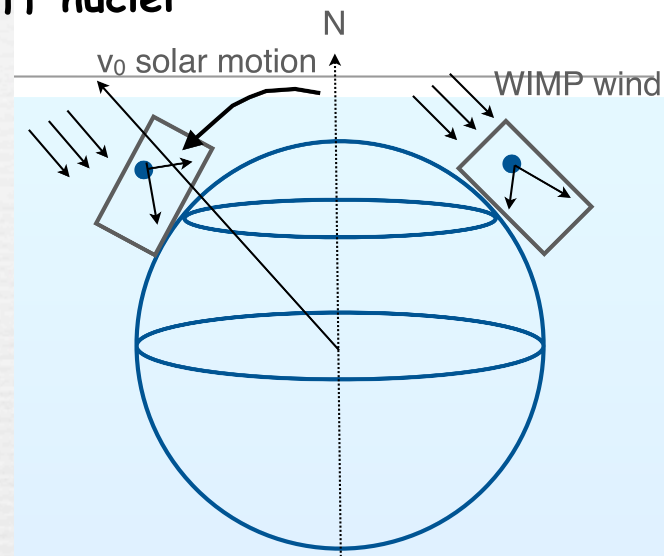


Nuclear recoils
Single scatters

$v/c \approx 7 \times 10^{-4}$
$E_R \approx 10$ keV

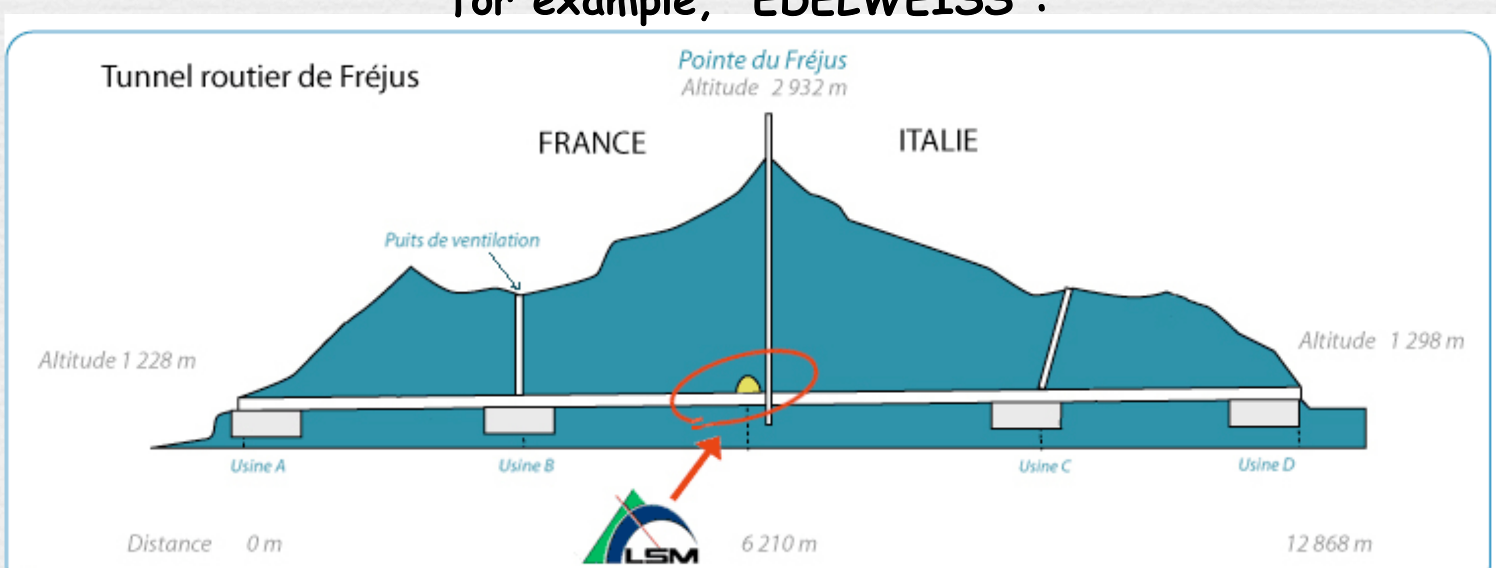


Annual rate variation
~ few % effect



Diurnal directional modulation:
~ 50% effect

for example, "EDELWEISS":



Dark Matter Direct detection

cnts / keV recoil energy E_R:

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

ρ_χ DM energy density, default: 0.3 GeV cm^{-3}
$v_{\rm min}$: minimal DM velocity required to produce recoil energy E_R

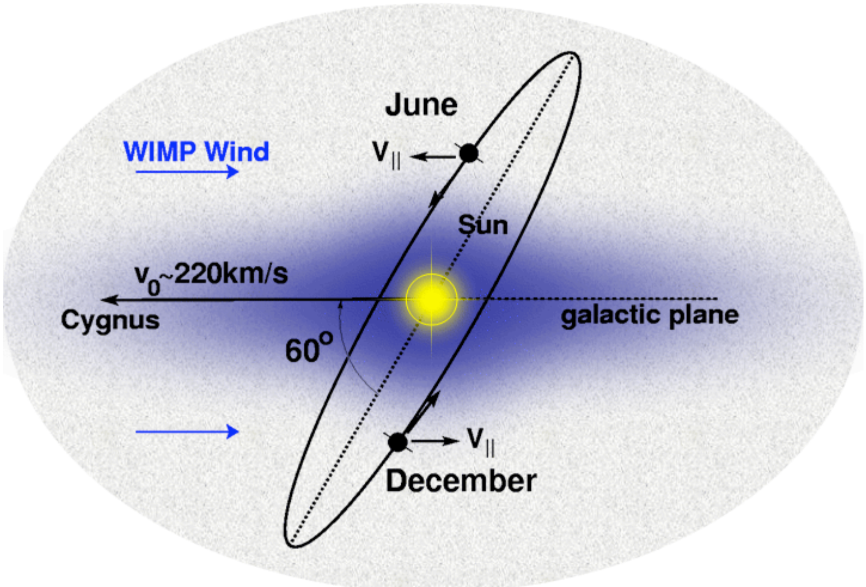
DM velocity distribution

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

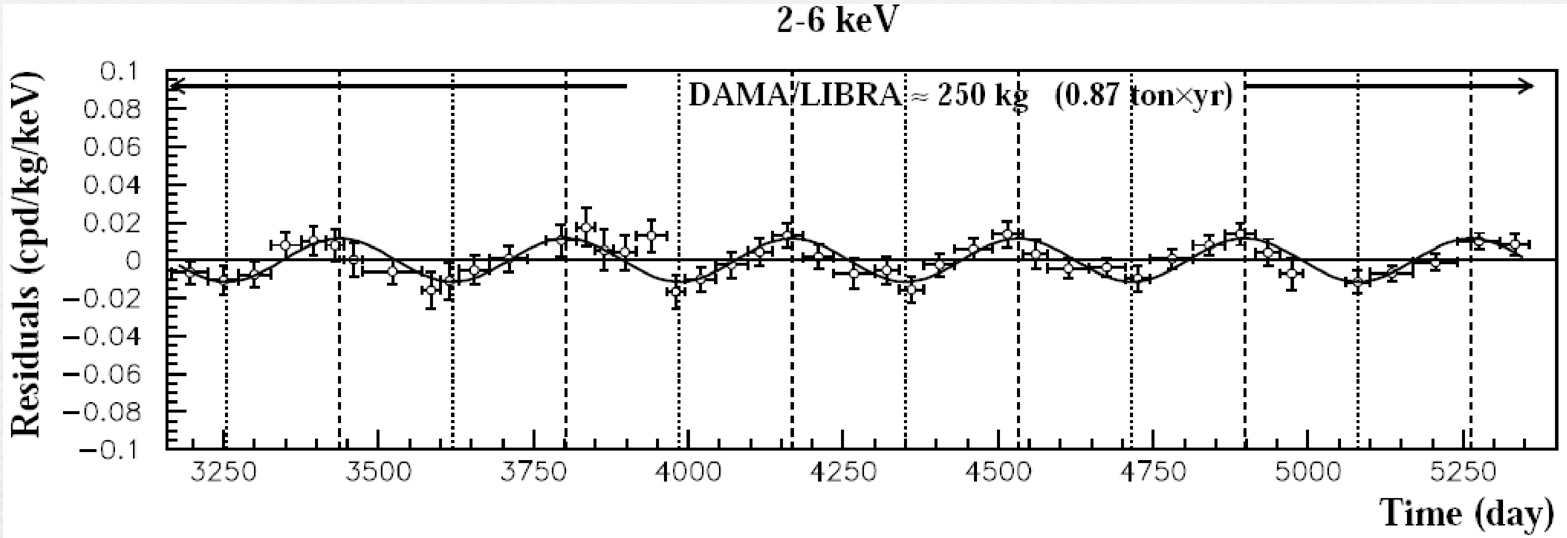
$\bar{v} \simeq 220\,\mathrm{km/s}$ $\quad v_{\rm esc} \simeq 550\,\mathrm{km/s}$

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

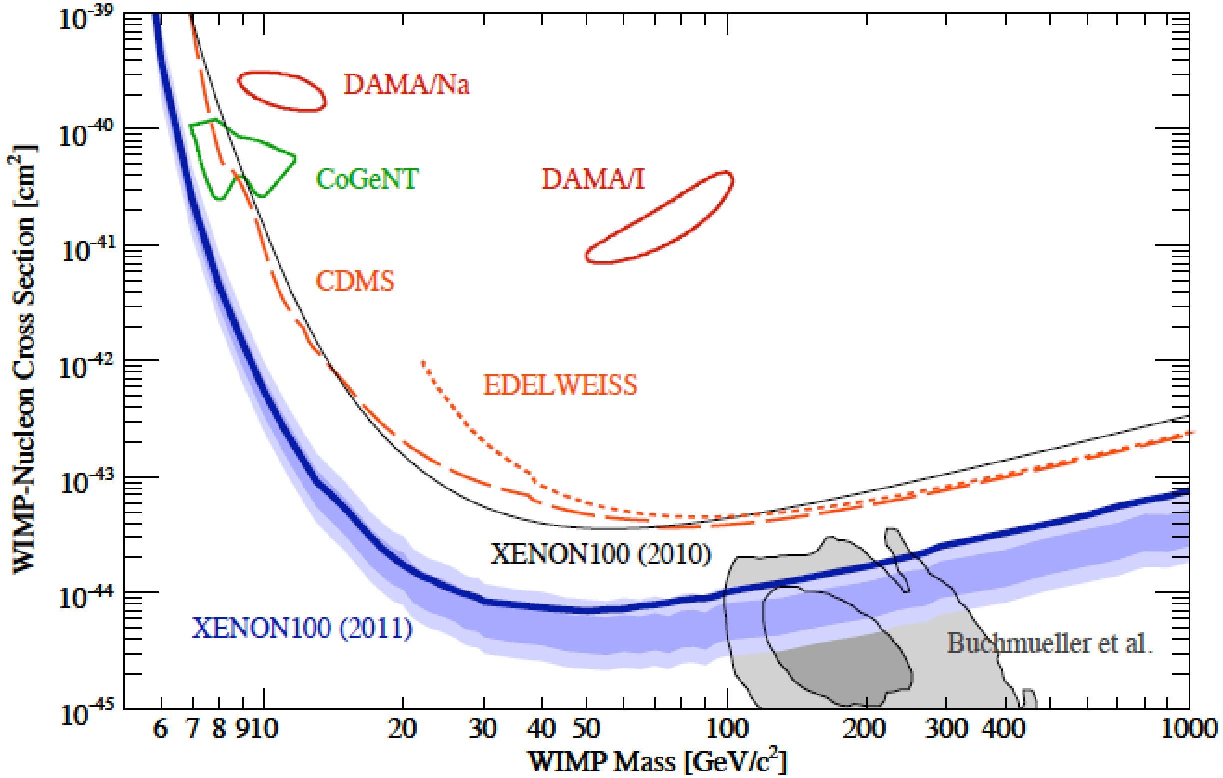
earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\mathrm{km/s}$



DAMA/LIBRA annual modulation signal



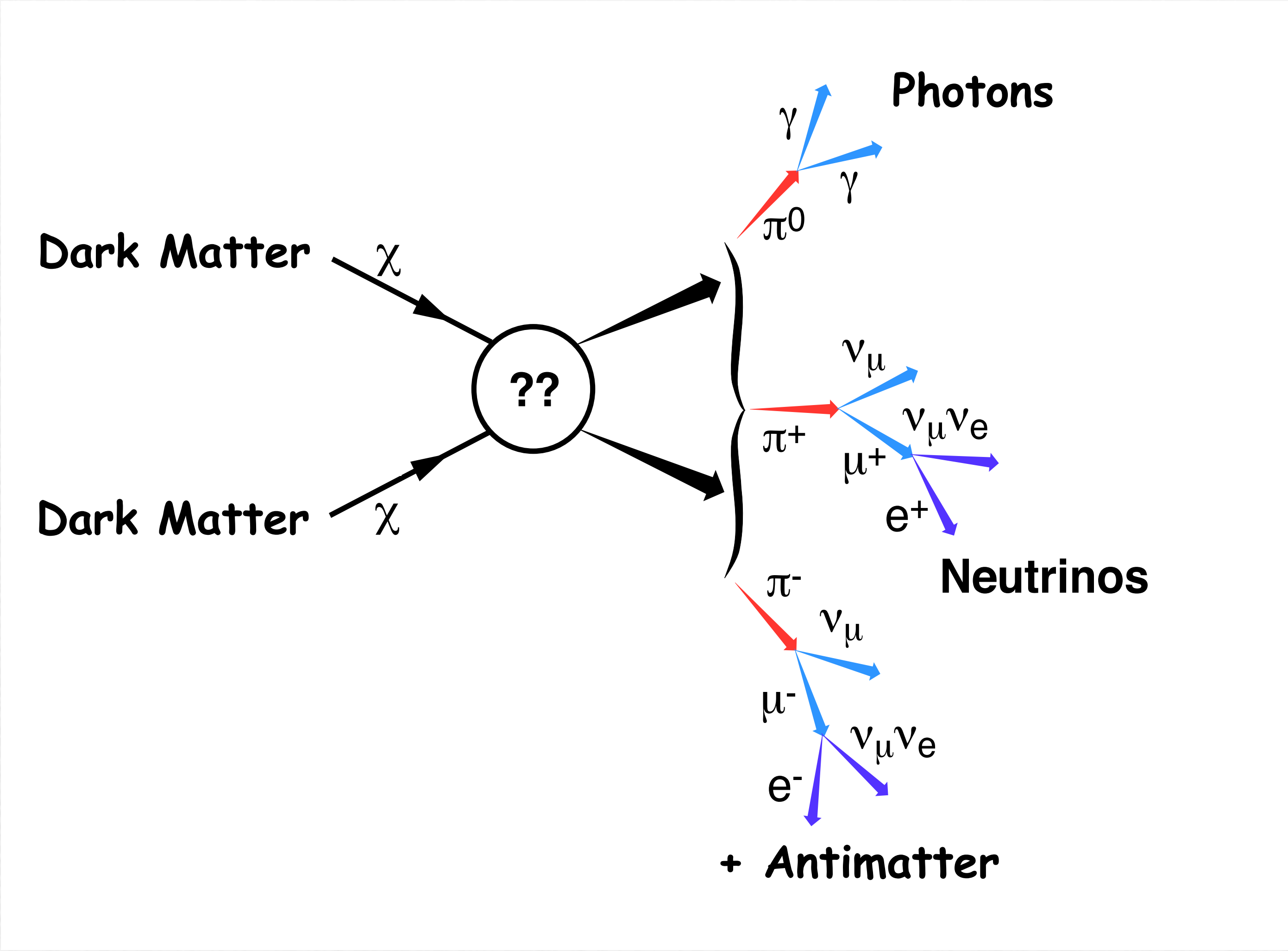
However not seen by other experiments ...



XENON100, 1104.2549

Indirect Detection

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

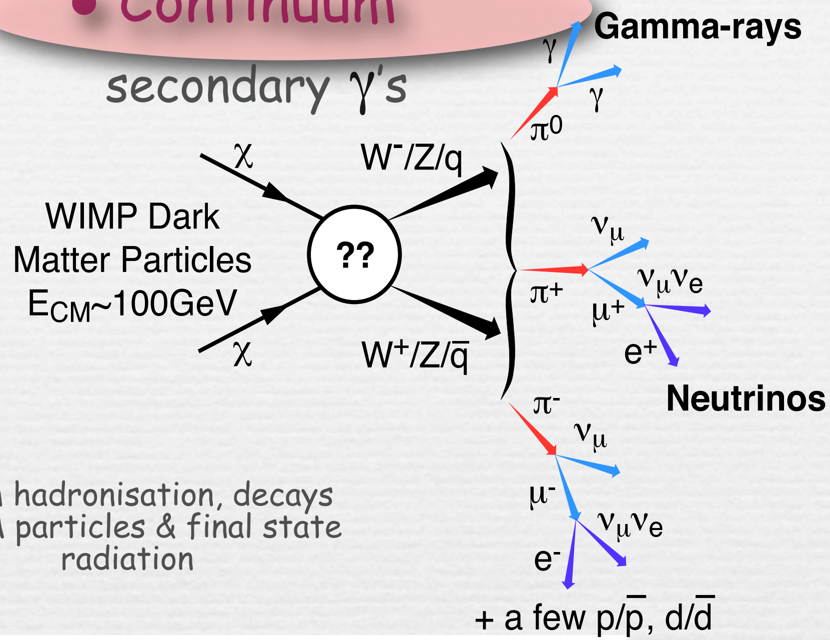


Seeing the light from Dark Matter

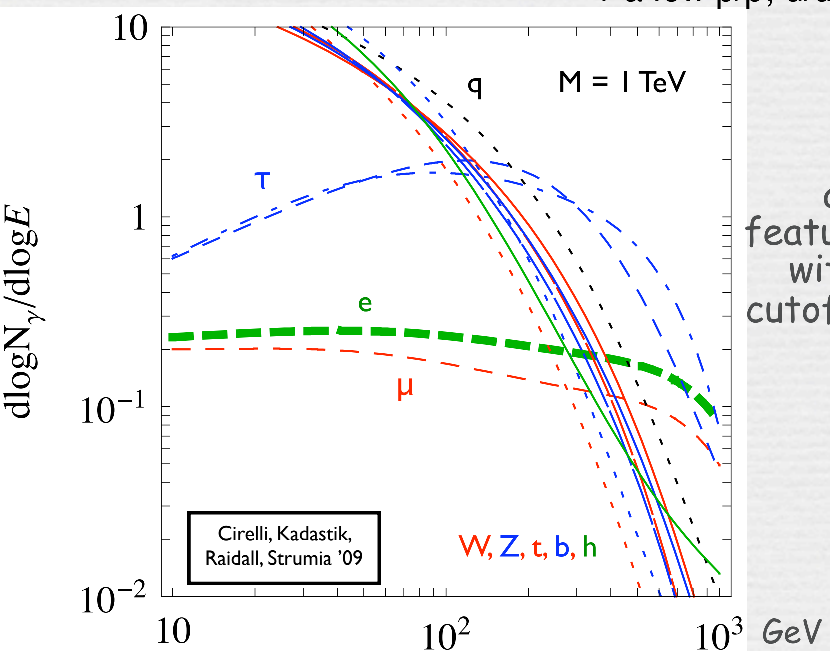
γ's from DM annihilations consist of 2 components

• Continuum

secondary γ's



from hadronisation, decays of SM particles & final state radiation

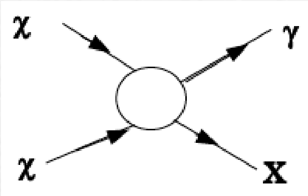


almost featureless but with sharp cutoff at Wimp mass

• Lines

primary γ's

loop-level annihilation into γ+X



-> mono energetic lines superimposed onto continuum at

$$E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)$$

☺ -> striking spectral feature, SMOKING GUN signature of Dark Matter

☹ lines are usually small (loop-suppressed) compared to continuum

Bergstrom, Ullio, Buckley '98

WIMP indirect detection

number of annihilation events between two wimps from the local halo

$$N \sim n^2 \sigma v \,.\, V .\, T$$

$$n \approx 3\ 10^{-3}\ cm^{-3} \quad \text{if } m \approx 100\ GeV$$

$$\sigma v \sim 1\ pb\ .\ 10^{-3} \sim 10^{-12}\ GeV$$

-> $N/\text{year} \sim 10^{14}\ cm^{-3}\ (GeV.cm)^{-3}\ .\ V$

($1\ s \sim 10^{24}\ GeV^{-1}$ and $GeV.cm \sim 10^{14}$)

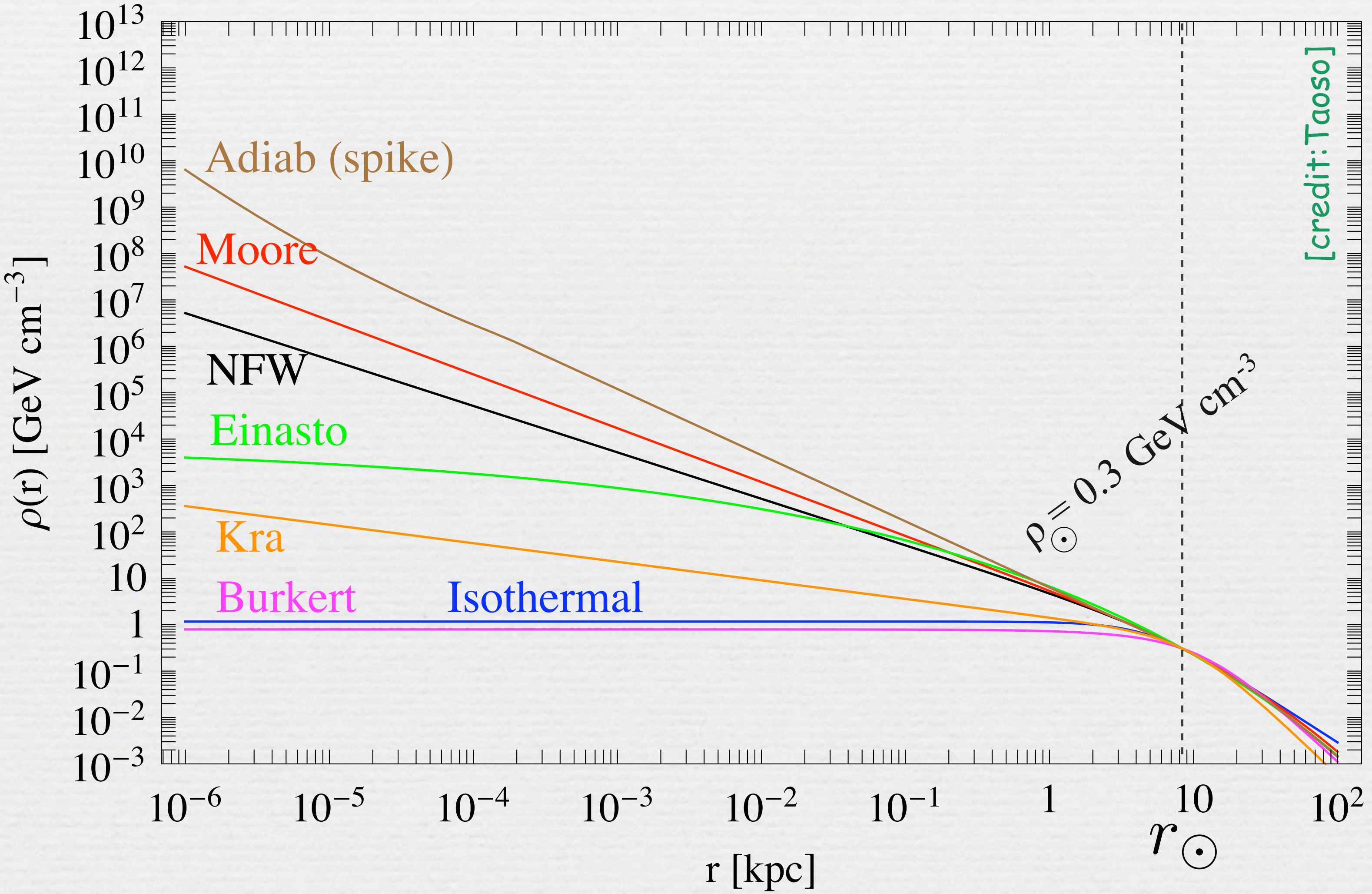
-> $N/\text{year}/km^3 \sim 10^{-13}$

--> look at regions where n is enhanced
and probe large regions of the sky

$$\frac{d\Phi}{dE} \propto \int \rho^2$$

Searches focus on regions of the sky where DM clumps: Galactic Center, dwarf galaxies...

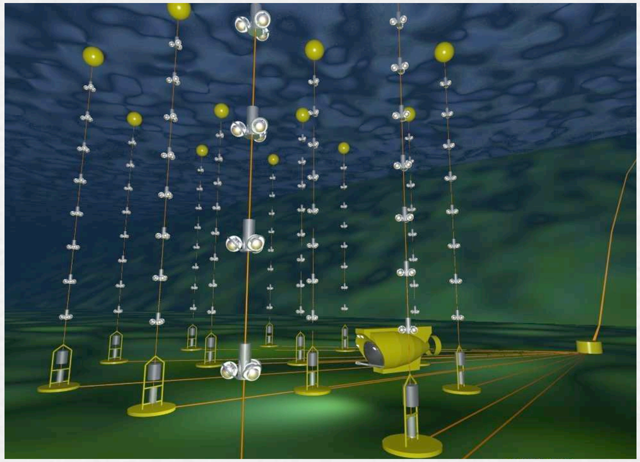
Astrophysical uncertainties on the DM density profile



Indirect Detection

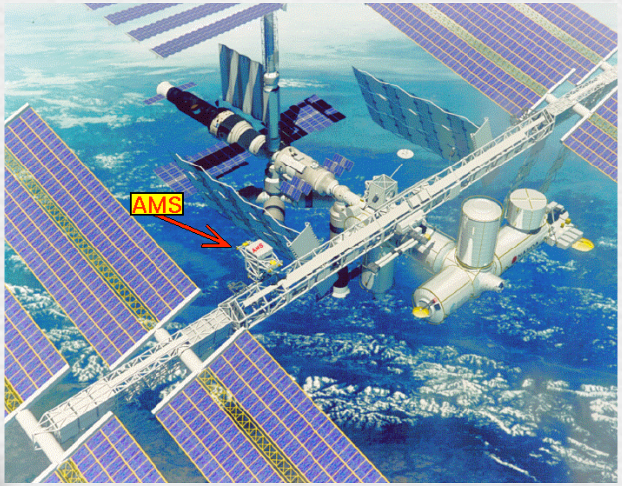
search for neutrinos in the South Pole

in the Mediterranean sea..



Antarès

Search for antiprotons in space...



AMS

Indirect Detection

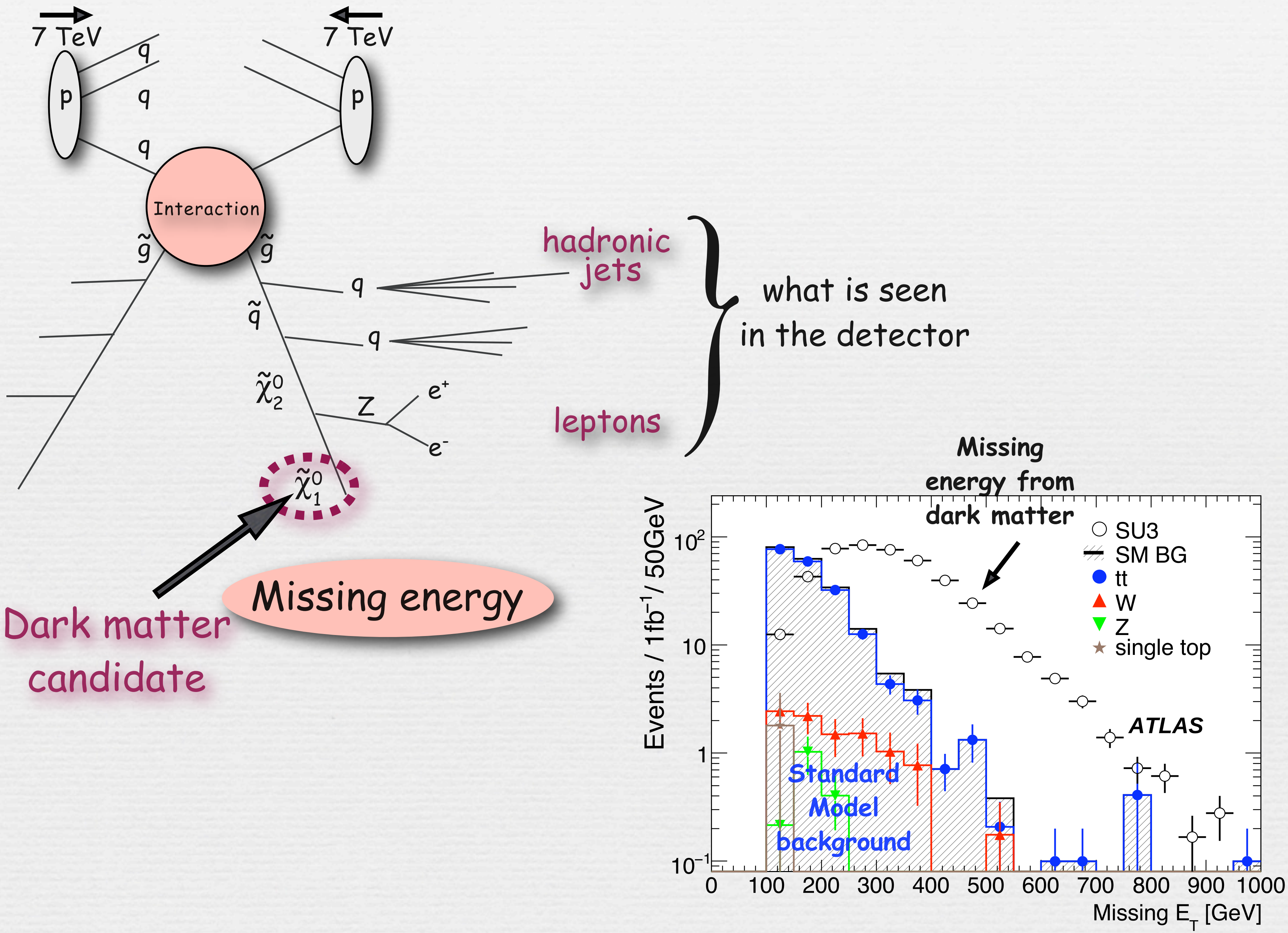
Search for photons on earth

Hess

and in space ...

Fermi

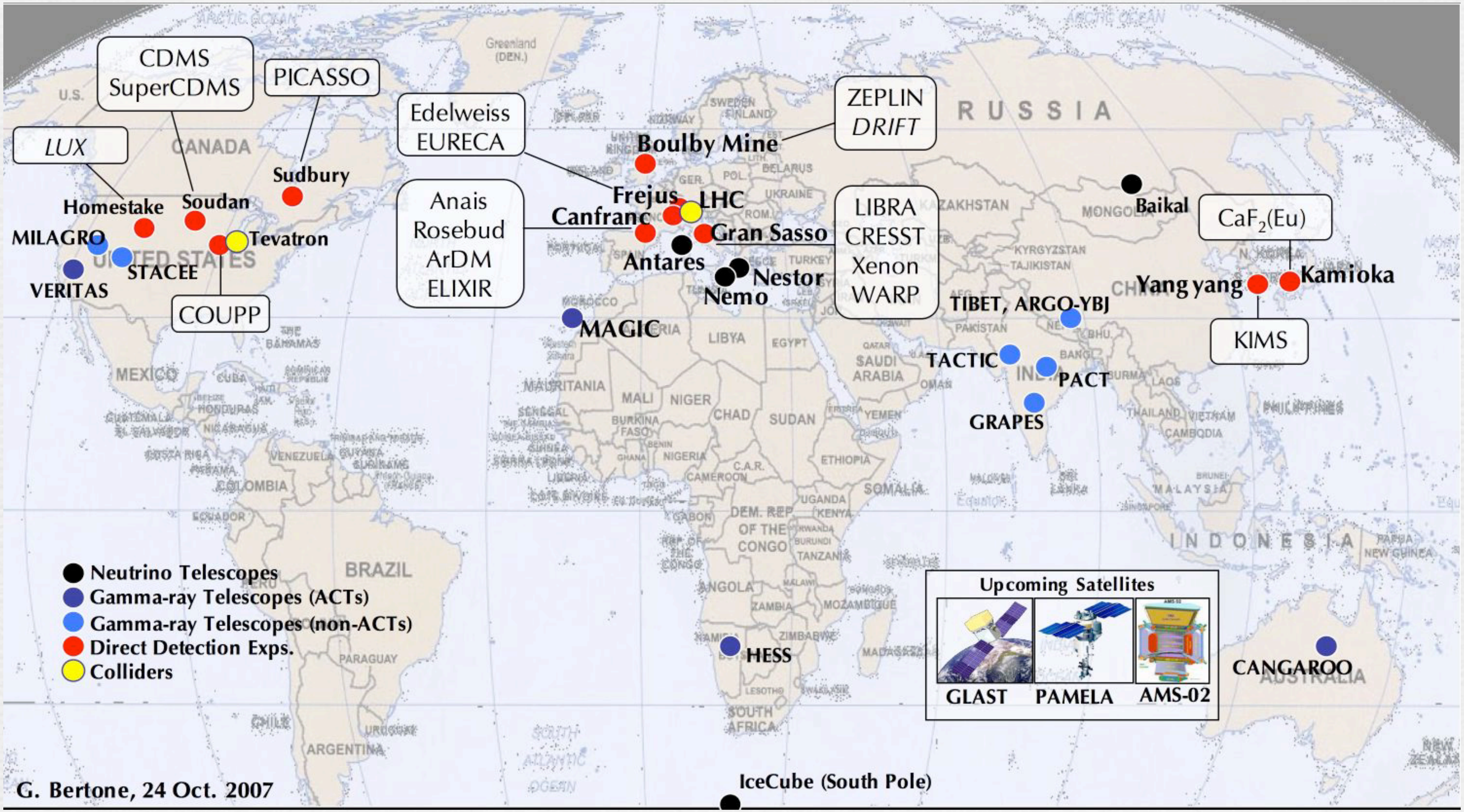
Producing Dark Matter at LHC = "Missing Energy" events



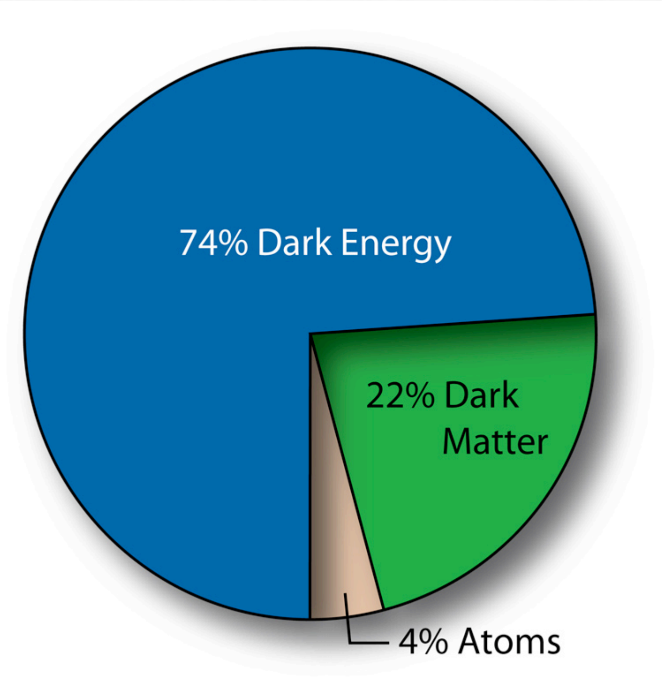
The Dark Matter Decade

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



Are the Dark Matter and baryon abundances related ?



$\Omega_{DM} \approx 5\text{-}6\ \Omega_{baryons}$

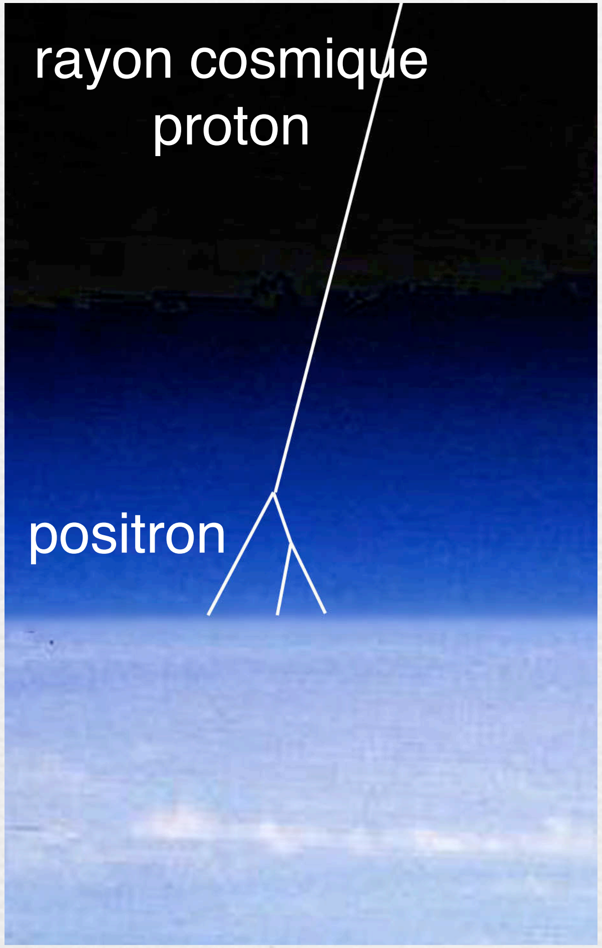
The Matter Anti-matter asymmetry

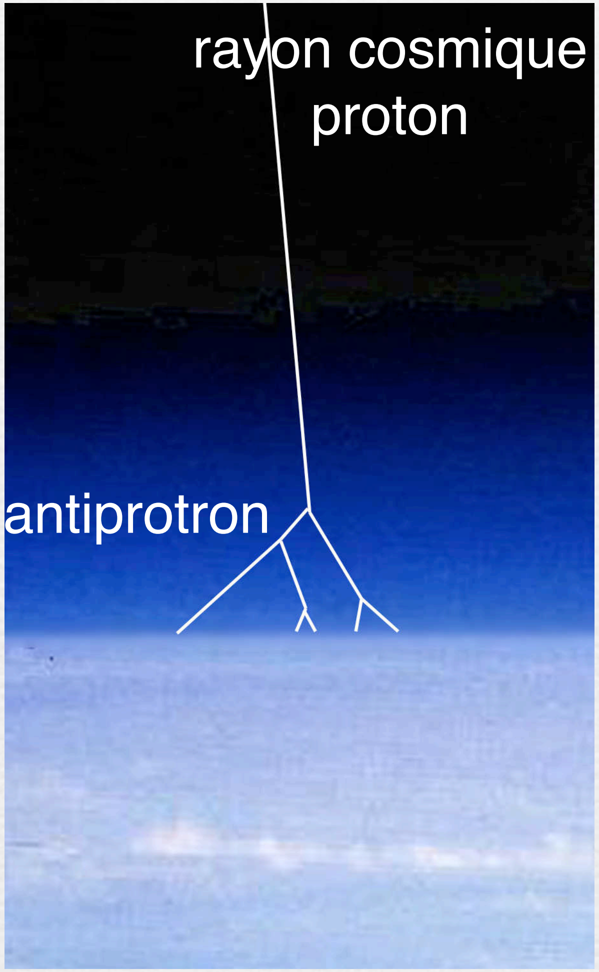
Antimatter

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

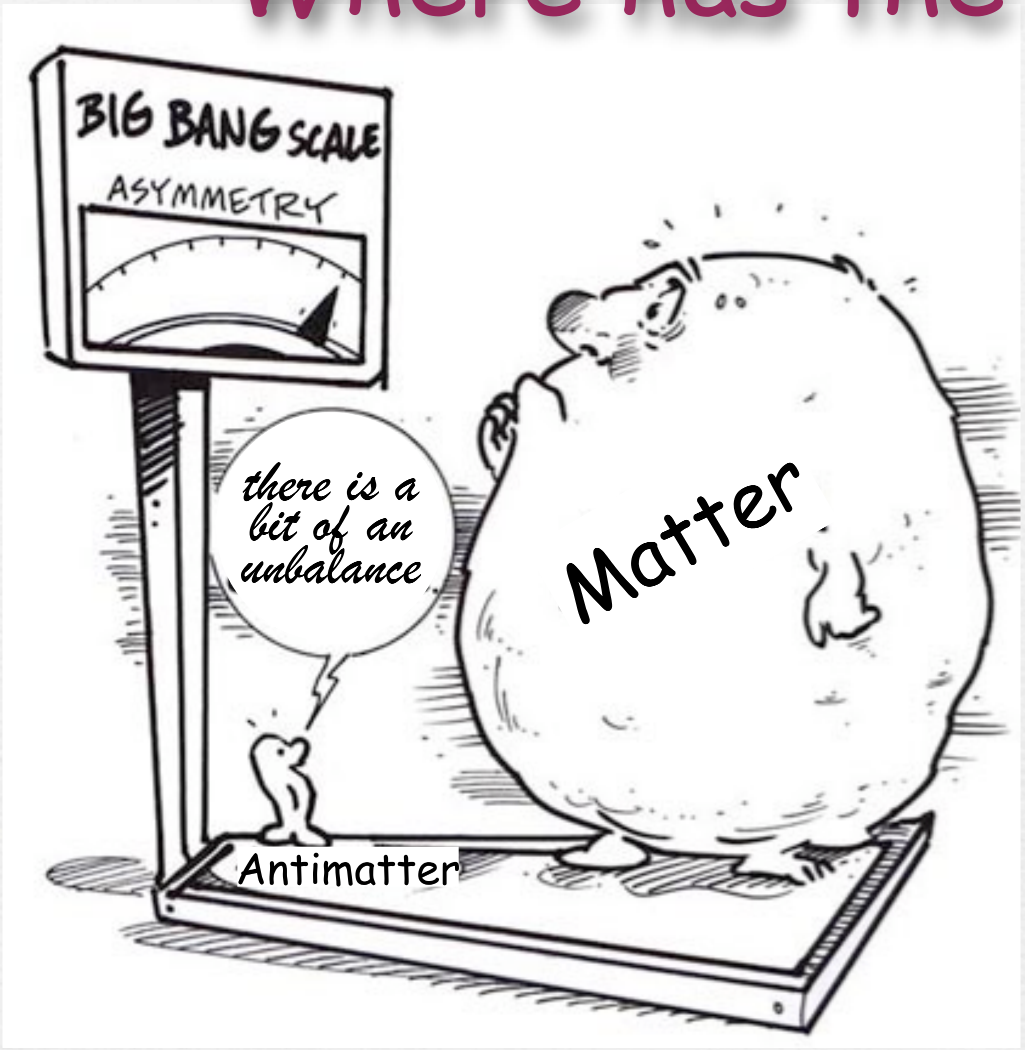
At the galactic scale: There is antimatter in the form of antiprotons in cosmic rays with ratio $n_{\overline{p}}/n_p \sim 10^{-4}$ which can be explained with processes such as

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

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

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

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)

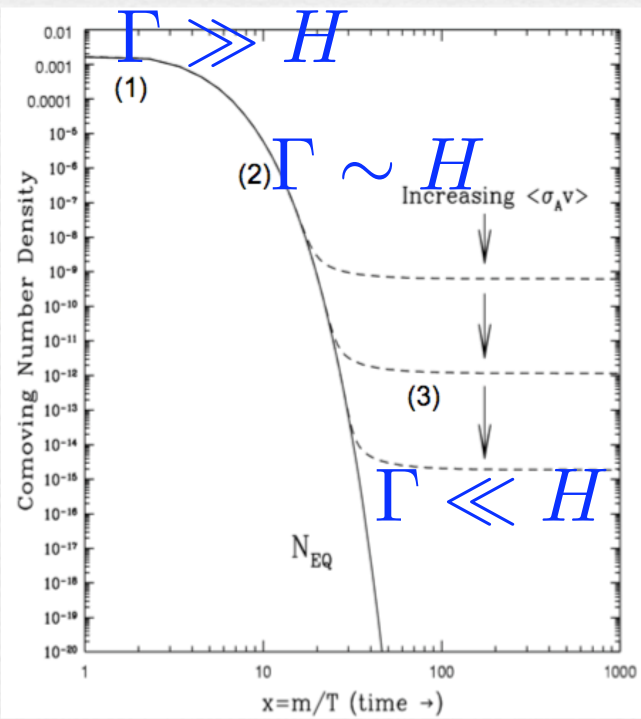
How much baryons would there be in a symmetric universe?

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)

Matter Anti-matter asymmetry of the universe:

characterized in terms of the baryon to photon ratio

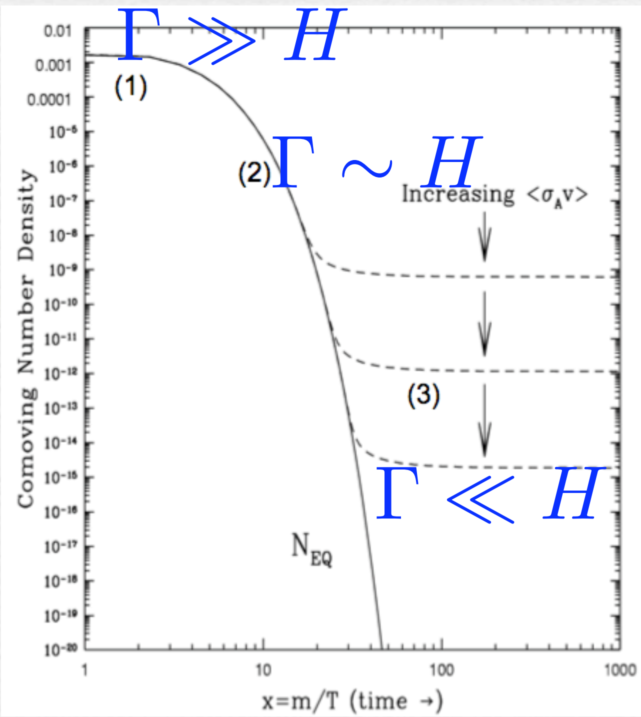
$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ 6. 10^{-10}

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)

Similarly, Dark Matter may be asymmetric

$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

Does this indicate a common dynamics?

If $n_{dm} - \overline{n}_{dm} \propto n_b - \overline{n}_b$

then $$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{(n_{dm} - \overline{n}_{dm}) m_{dm}}{(n_b - \overline{n}_b) m_b} \sim C \frac{m_{dm}}{m_b}$$

conservation of global charge: $$Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\bar{b}})$$

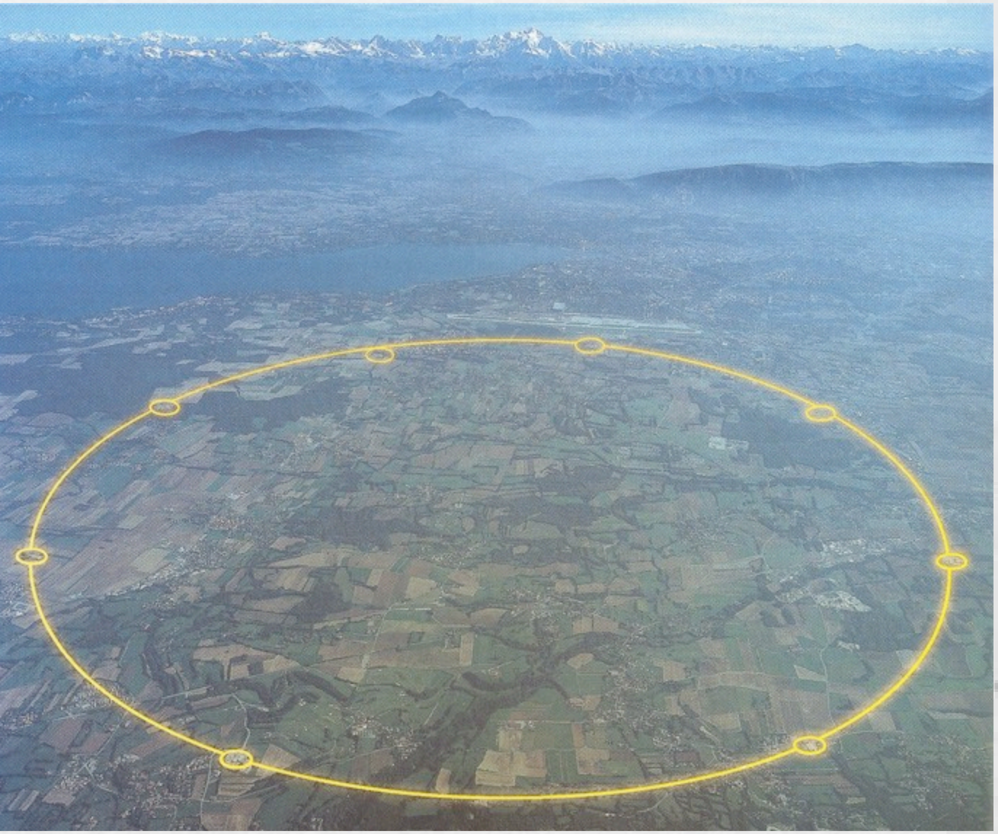
if efficient annihilations: $$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{Q_b}{Q_{dm}} \frac{m_{dm}}{m_b} \longrightarrow$$ typical expected mass ~ GeV

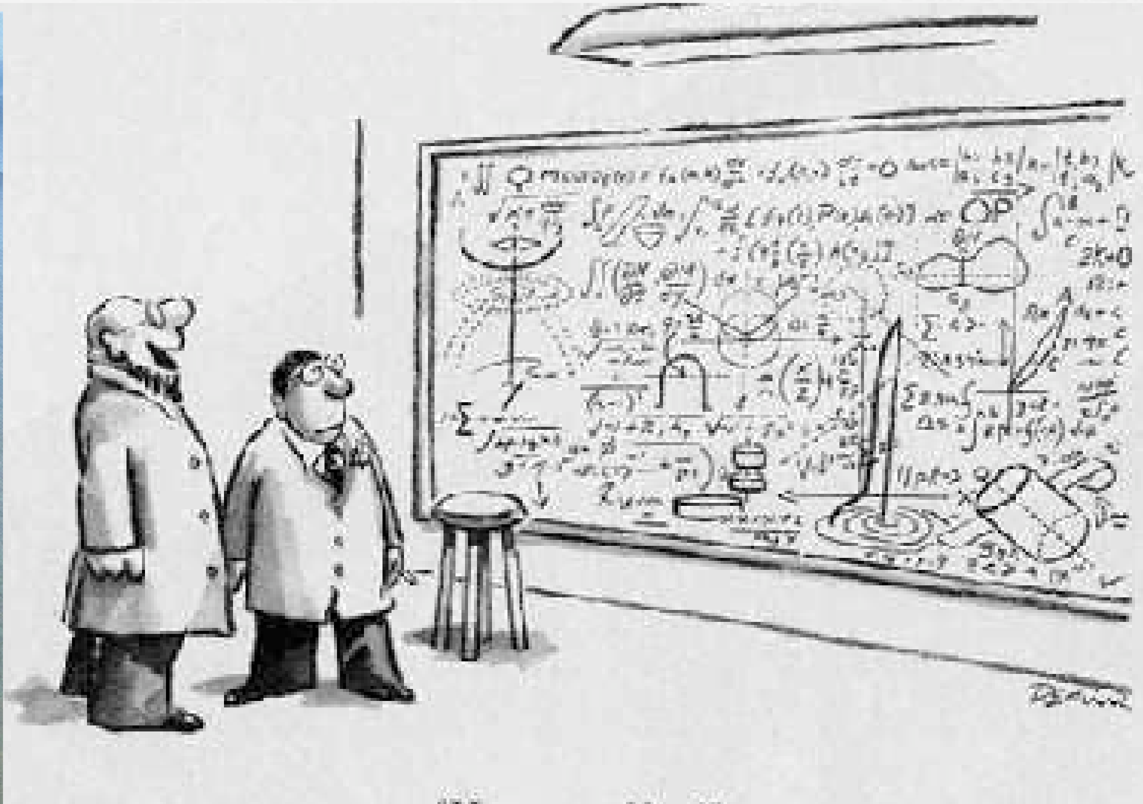
two possibilities:

1) asymmetries in baryons and in DM generated simultaneously

2) a pre-existing asymmetry (either in DM or in baryons) is transferred between the two sectors

Questions ?





"Hey, no problem!"