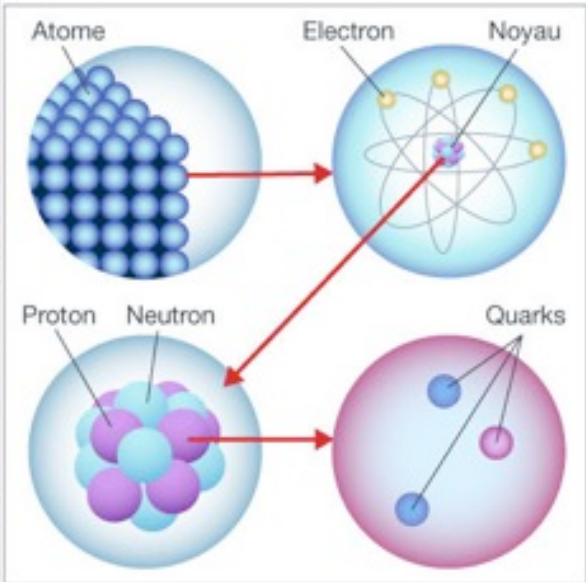
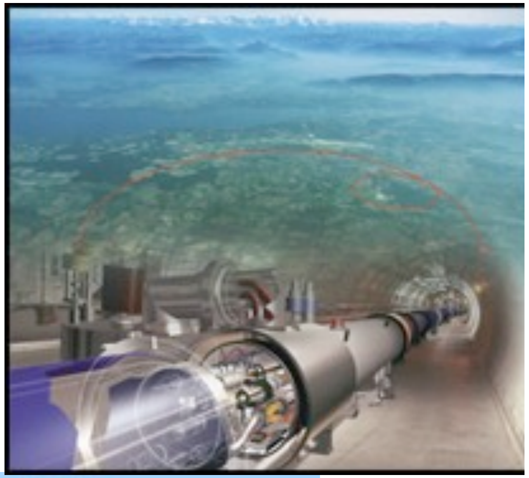
The Particle Physics-Cosmology connection



CERN Teacher's Programme, July 18th 2012

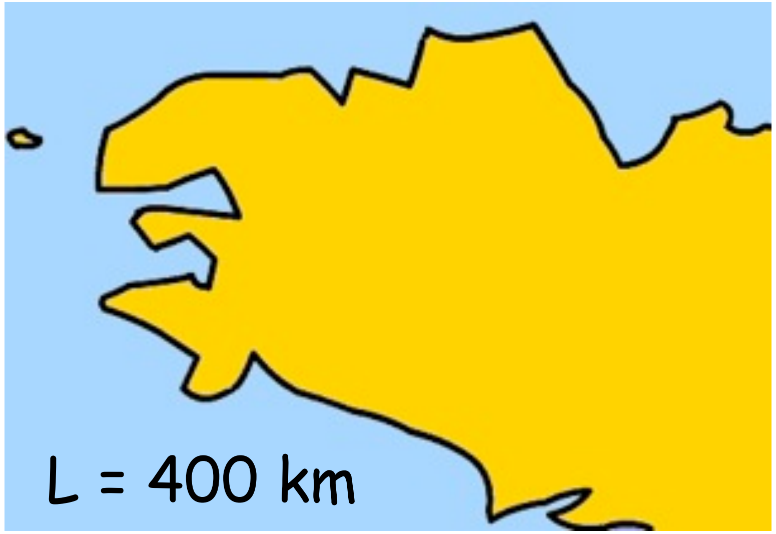
Géraldine SERVANT, CERN & IPhT CEA Saclay

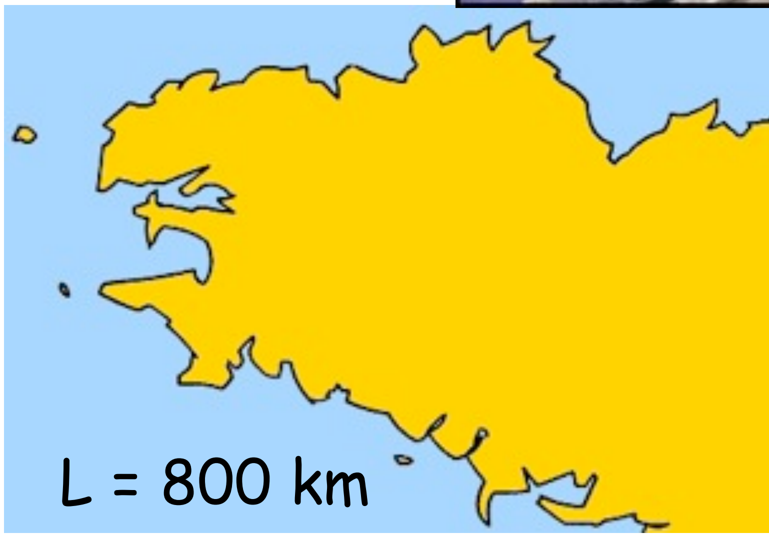
The Large Hadron Collider



➜ The LHC: the most gigantic microscope ever built

Going to higher energies ⇛ allows to study finer details





Particle Physics:
study of short distances

resolution limited by the de Broglie wavelength $\lambda = h/p$

High energy physics

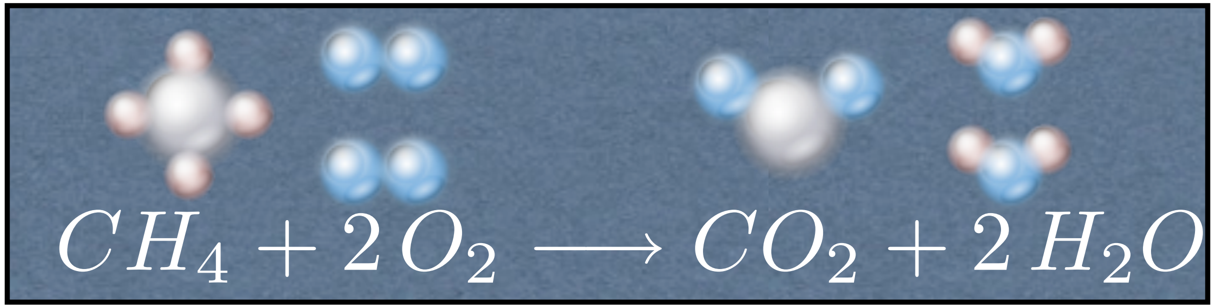
high resolution necessitates large p

p>>m
relativistic regime

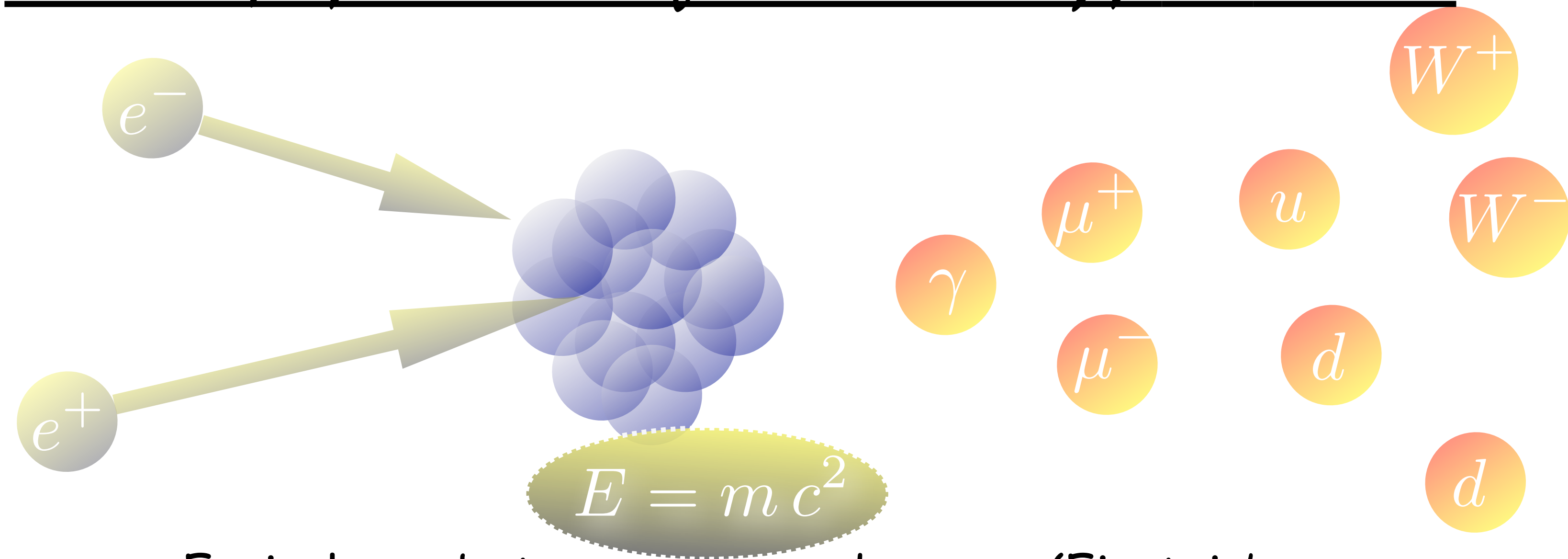
Creation of matter from energy

- *Chemistry : rearrangement of matter*

the different constituents of matter reorganize themselves



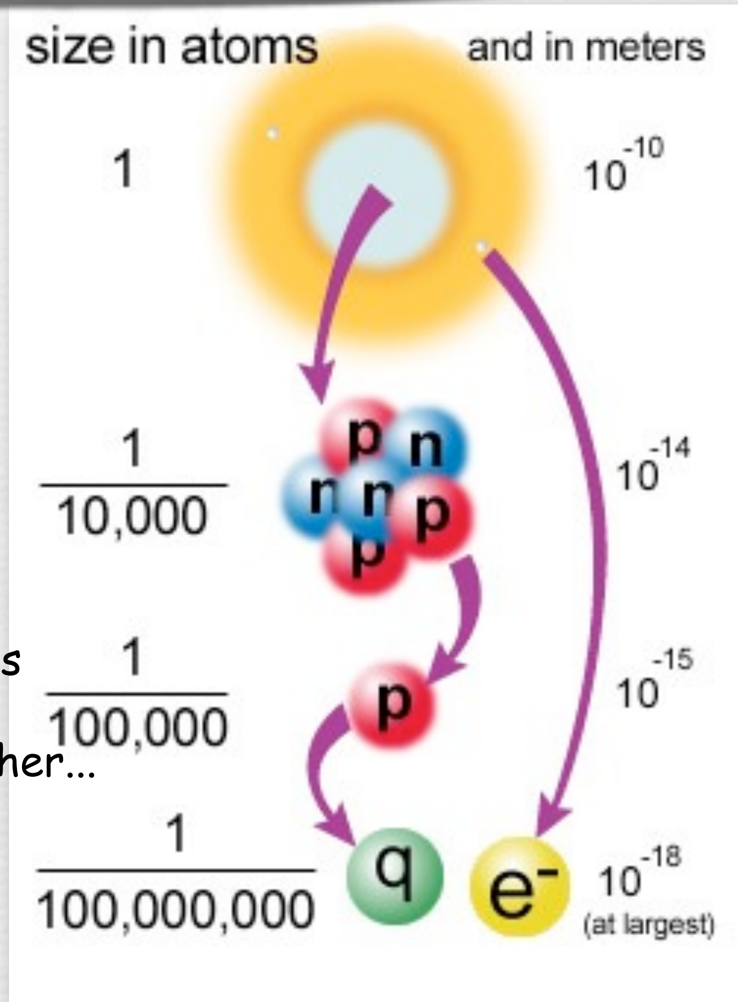
- *Particle physics : transformation energy ↔ matter*

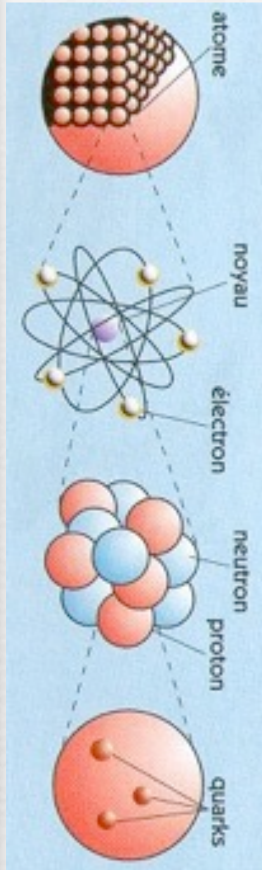


Equivalence between mass and energy (Einstein's idea) plays a very fundamental role in particle physics

The elementary blocks of matter

- Matter is made of molecules
- Molecules are built out of atoms
- Atoms are made of nuclei and electrons
- Nuclei are assemblies of protons and neutrons
- Protons and neutrons are quarks bound together...





The volume of an atom corresponds to 10^{24} times the volume of an electron

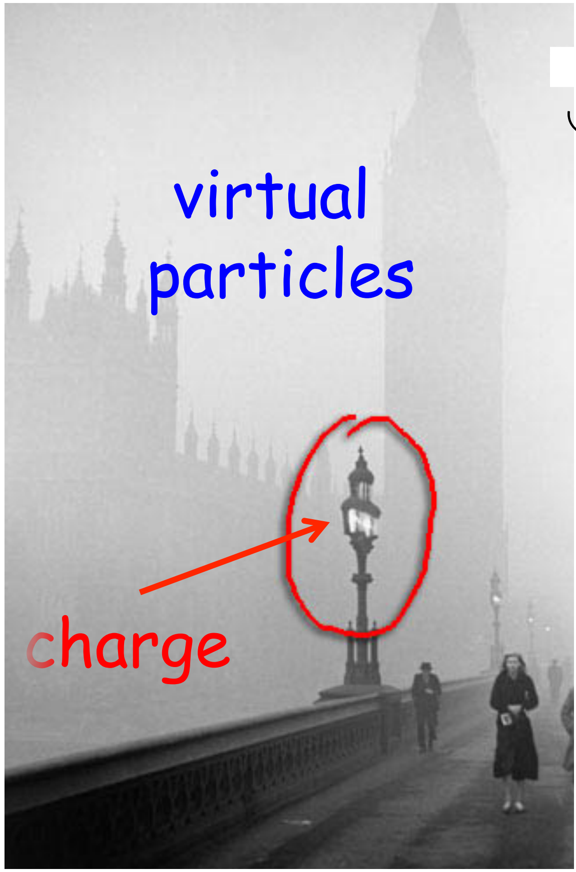
Classically, matter contains a lot of void

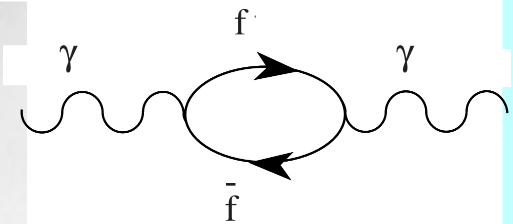
Quantum mechanically, this void is populated by pairs of virtual particles

Evolution of coupling constants

Classical physics: the forces depend on distances

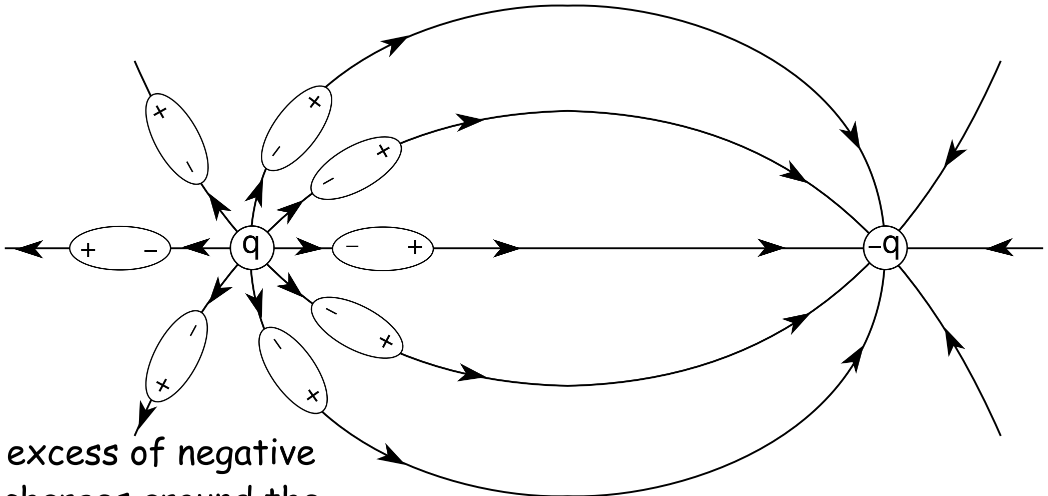
Quantum physics : the charges depend on distances





The electromagnetic coupling decreases at large distances.
Charge screening (vacuum polarization) due to virtual fermion-antifermion pairs

The vacuum behaves as a polarized dielectric medium



excess of negative charges around the positron: screening

An opposite effect for the strong coupling

because of the **non-abelian** nature of the underlying SU(3) gauge symmetry: the gauge boson self-interactions generate an **anti-screening** effect through gauge boson loops. This effect is larger than the one from fermion loops --> the strong coupling decreases at short distances

$$\frac{\partial \alpha_s}{\partial \log E} = \beta(\alpha_s) = \frac{\alpha_s^2}{\pi}\left(-\frac{11N_c}{6} + \frac{N_f}{3}\right)$$

$\alpha_s \nearrow$ when $d \nearrow$

$$\alpha_s = g_s^2/4\pi$$

property of 'asymptotic freedom'

quarks behave as free particles when the energy becomes very large

Evolution of gauge couplings

The evolution of gauge couplings is controlled by the renormalization group equations

$$\frac{d\alpha(\mu)}{d\log\mu} \equiv \beta(\alpha(\mu))$$

At one loop:

$$\beta(\alpha) \equiv \frac{d\alpha(\mu)}{d\log\mu} = \frac{-b}{2\pi}\,\alpha^2 + \mathcal{O}(\alpha^3)$$

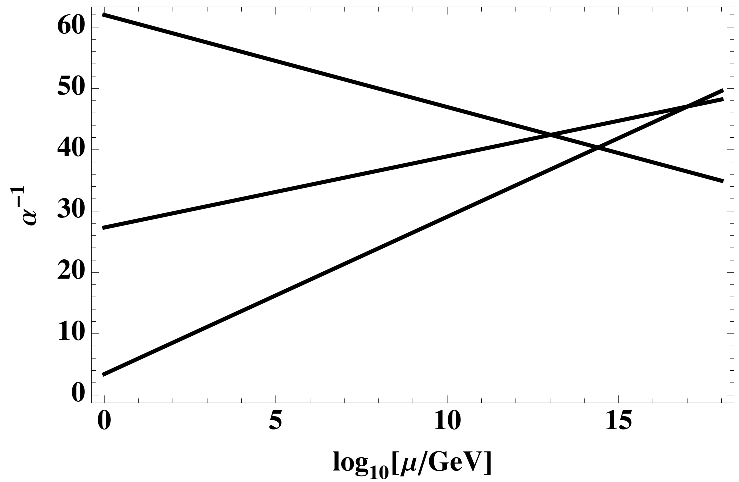
So couplings vary logarithmically as a function of the energy scale:

$$\frac{1}{\alpha_i(\mu)} = \frac{1}{\alpha_i(\mu_0)} + \frac{b_i}{2\pi}\log\frac{\mu}{\mu_0}$$

$$\alpha_i = g_i^2/4\pi \qquad i = SU(3), SU(2), U(1)$$

b_i : defined by the particle content

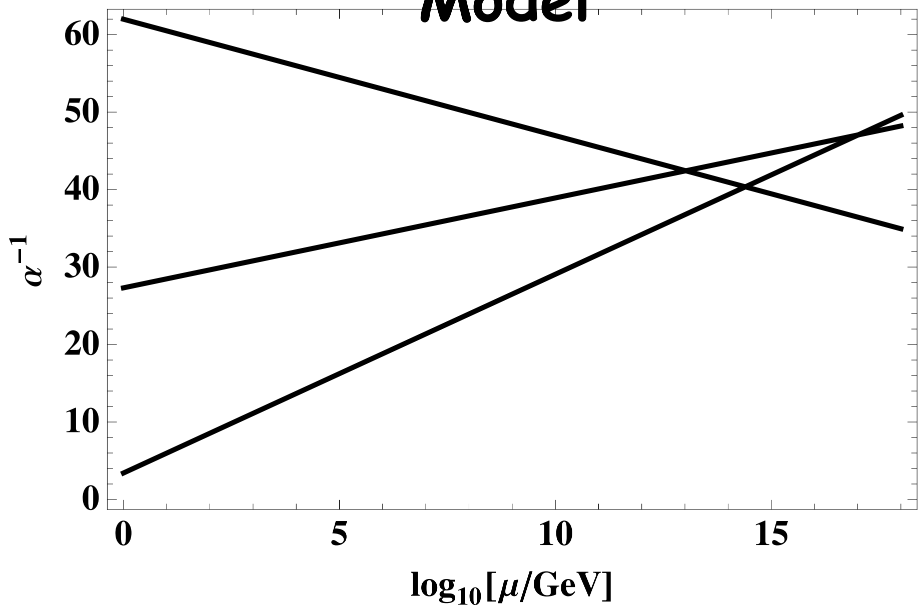
we observe different couplings but it looks like a low energy artefact



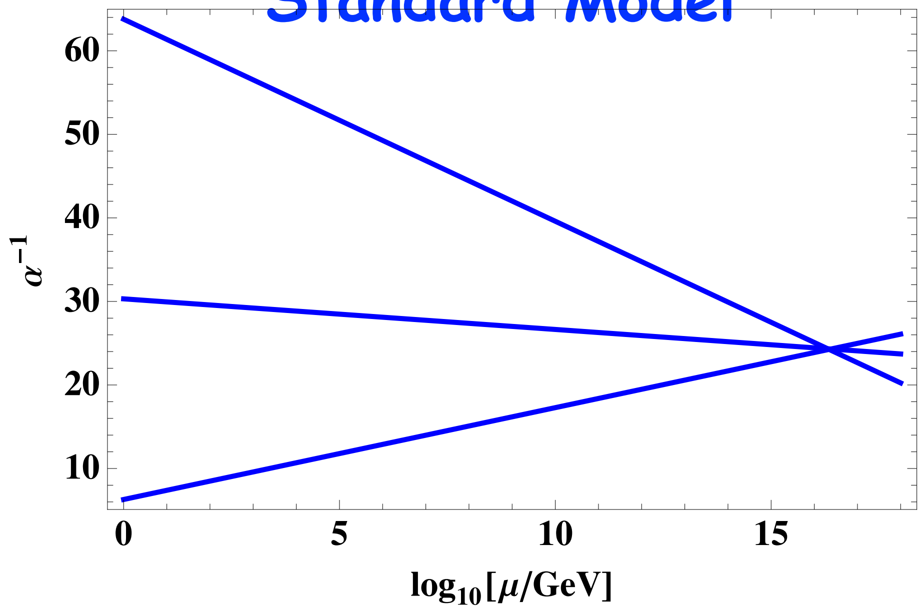
Comparison

1-loop evolution of gauge couplings

Standard Model



Supersymmetric Standard Model



The Standard Model: matter

the elementary blocks:

LEPTONS

électron: ν_e e^-

muon: ν_μ μ^-

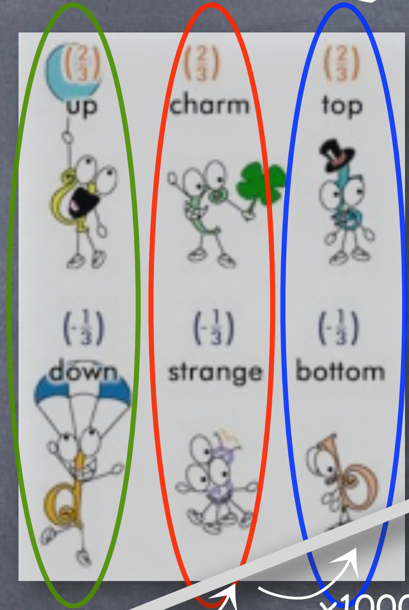
tau: ν_τ τ^-

mass

x200 x20

➡ no composite states made of leptons

QUARKS



mass

x1000 x1000

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

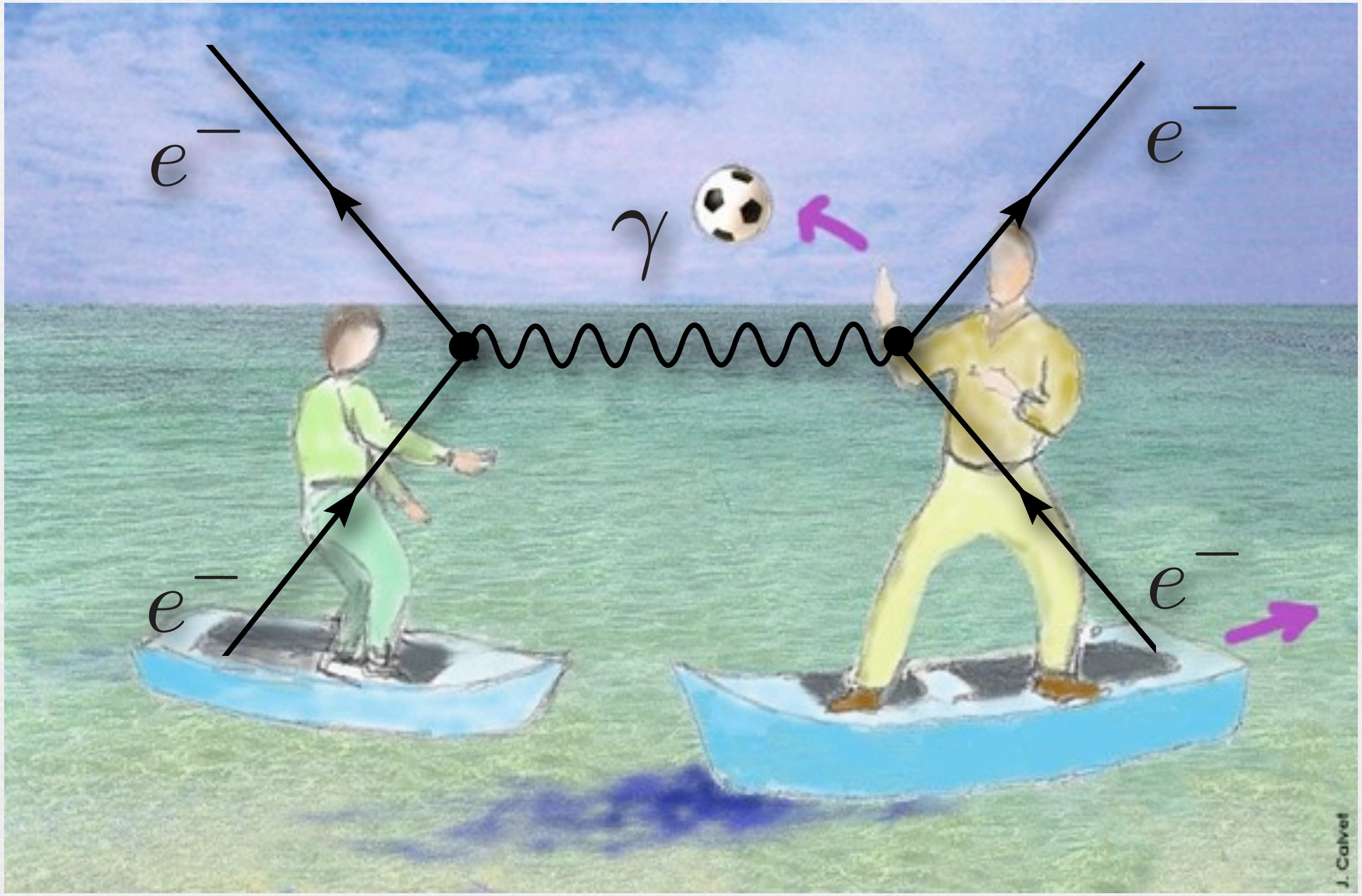
+ antiparticles

The Standard Model : interactions

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

intensity

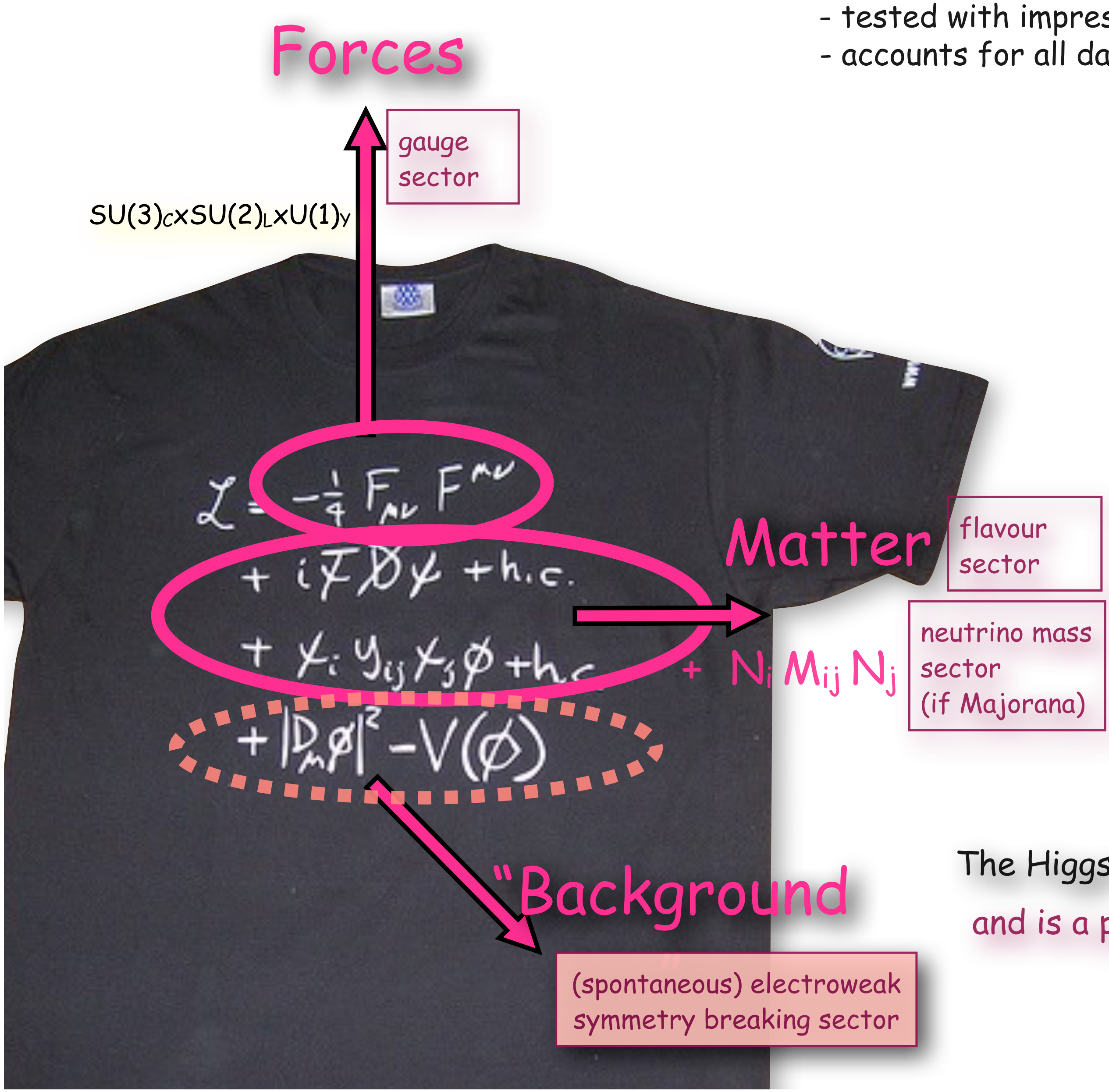
Interactions between particles

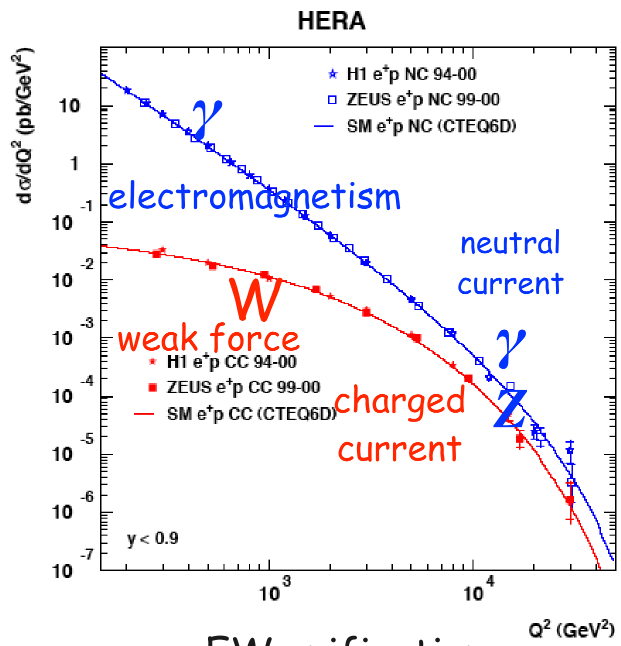


Elementary particles interact with each other by exchanging gauge bosons

The Standard Model of Particle Physics

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





EW unification

The Higgs was the only remaining unobserved piece

and is a portal to new physics hidden sectors

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

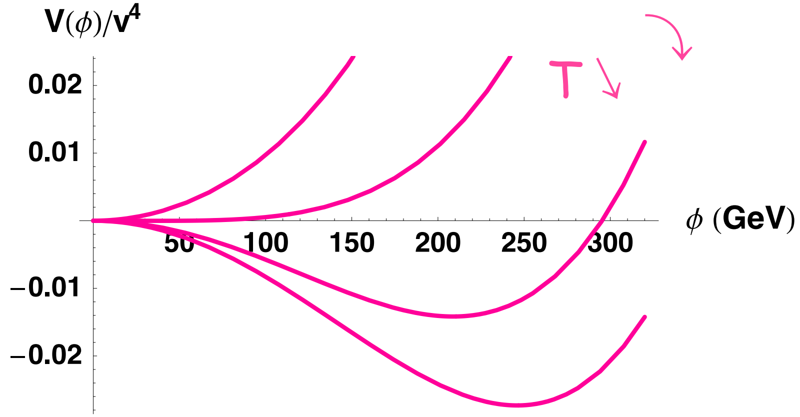
i.e distances < 10^{-15} cm

main physics goal at the LHC:

What is the mechanism of Electroweak Symmetry breaking ?

The (adhoc) Higgs Mechanism (a model without dynamics)

EW symmetry breaking is described by the condensation of a scalar field

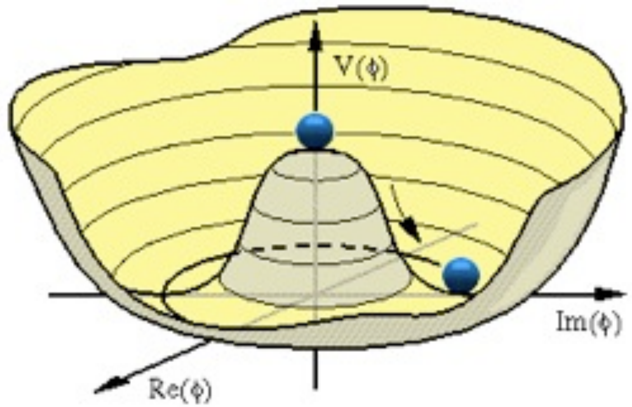


$$\Phi = \begin{bmatrix} \phi^+ \\ \frac{v + H + i\varphi_Z}{\sqrt{2}} \end{bmatrix}$$

Background value, Higgs medium

Higgs boson: excitation of the higgs medium

The Higgs selects a vacuum state by developing a non zero background value. When it does so, it gives mass to SM particles it couples to.



$$V(\Phi) = \frac{\mu^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}\Phi^\dagger\Phi$$

Why is μ^2 negative ?

the puzzle:

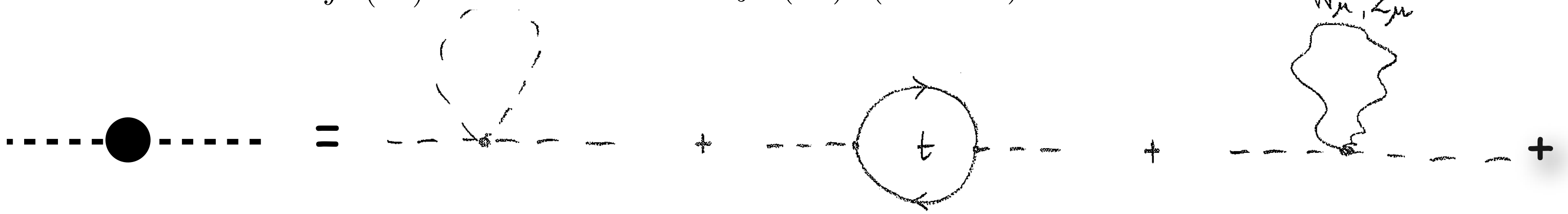
We do not know what makes the Higgs condensate.
We ARRANGE the Higgs potential so that the Higgs condensates but this is just a parametrization that we are unable to explain dynamically.

The hierarchy problem

As soon as we introduce a fundamental scalar field in the theory (the Higgs),
this generates a puzzle: the so-called “hierarchy problem”.

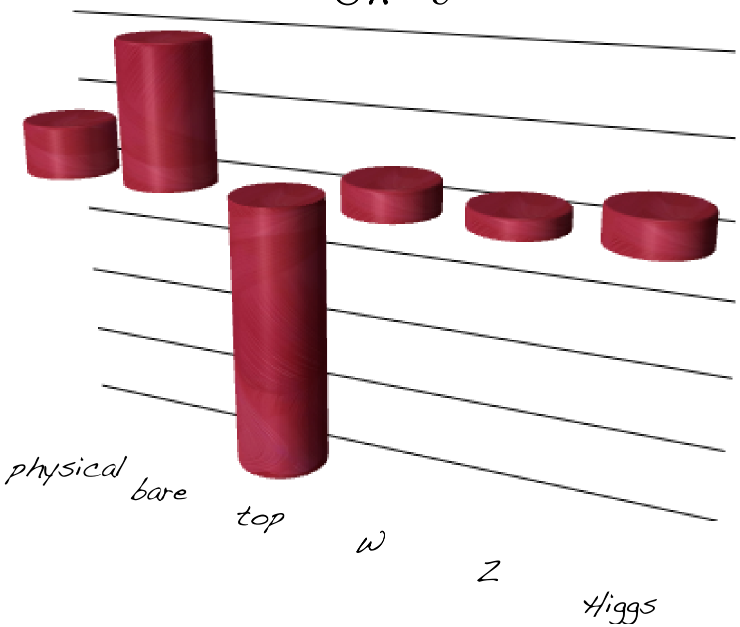
= the fact that the Higgs self-energy receives radiative contributions that are quadratically divergent.

$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2$$



+ Higher loops
Smaller Yukawa

$$\delta m_H^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \sim -(0.23\ \Lambda)^2$$



strong sensitivity on high energy unknown physics

Λ , the maximum mass scale that the theory describes

To stabilise the Higgs mass at the EW scale against the Planck scale, we need to adjust the parameter of the Higgs potential at a level of 10^{-32}.

History repeats itself?

There are examples in physics where unexpected and precise parameter cancellations were actually the signal of the existence of new particles.

For instance, the electron self energy has a power divergence that can be cured only by the introduction of the positron.

Similarly, the extreme sensitivity of the Higgs self energy with respect to physics at high momentum can be naturally reduced by introducing new symmetries and new degrees of freedom, such as supersymmetry, or extra spacial dimensions or additional global symmetries.

Classical/Quantum Electromagnetism & Antimatter

an electron makes an electric field which carries an energy

$$\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

electric charge (e^2)

classical size of the electron (r_e)

and interacts back to the electron and contributes to its mass $\delta m c^2 = \Delta E_{\text{Coulomb}}$

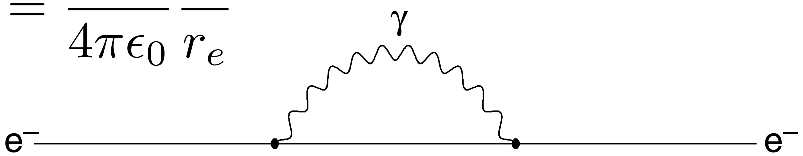
$$\delta m \sim m_e \quad \Rightarrow \quad r_e \sim \frac{e^2}{4\pi\epsilon_0 m_e c^2} \sim 10^{-13}\ \text{m}$$

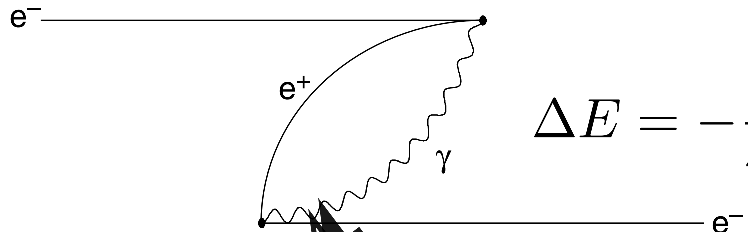
The electron repels itself due to its charge, how to keep electric charge in a small pack?

electron point like!

antimatter comes to rescue the 19th century "electron crisis"

$$\Delta E = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$





$$\Delta E = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

$$\Delta E = \frac{3\alpha}{4\pi} m_e c^2 \log\frac{\hbar}{r_e m_e c}$$

Weisskopf '39

new states ≈ softer UV behavior, small correction to the mass

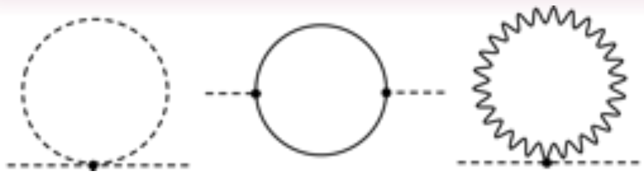
The hierarchy problem: What is keeping the Higgs boson light?

we need new degrees of freedom to cancel Λ^2 divergences
and ensure the stability of the weak scale

a problem that arises for any elementary SCALAR particle

does not arise for fermions (protected by chiral symmetry) or
gauge bosons (protected by the gauge symmetry)

What is cancelling the divergent diagrams?



$\Rightarrow \delta M_H^2 \propto \Lambda^2$

A light Higgs calls for New Physics at the TeV scale

the "hierarchy problem": the main motivation for building the LHC

Addressing the hierarchy problem

($\delta m_h^2|_{1-loop} \sim -\frac{y_t^2}{8\pi^2}\Lambda_{UV}^2$)

with a new symmetry

Supersymmetry

fermion

$$\Psi \rightarrow e^{i\theta\gamma_5}\ \Psi$$

Ψ massless:

protected by chiral symmetry

$\Psi \overset{\text{SUSY}}{\longleftrightarrow} H$

Extra dimensions

vector

$$A_\mu \rightarrow A_\mu + \partial\theta$$

A_μ massless:

protected by gauge invariance

In 5 dimensions: $H=A_5$

new global symmetry

scalar

$$H \rightarrow H + \theta$$

H massless:

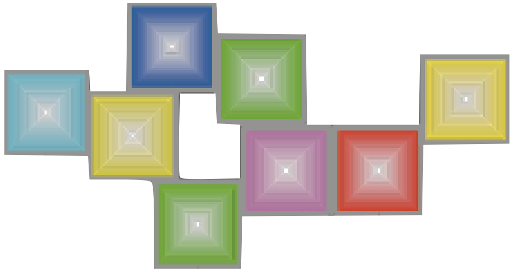
protected by a global symmetry

An elegant solution to the hierarchy pb: Supersymmetry

2 categories of particles:

Fermions *matter particles*

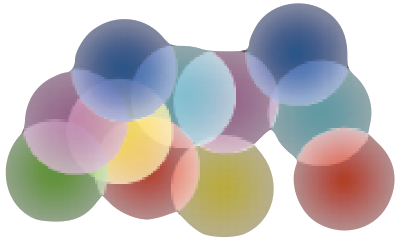
fermions repel
each other



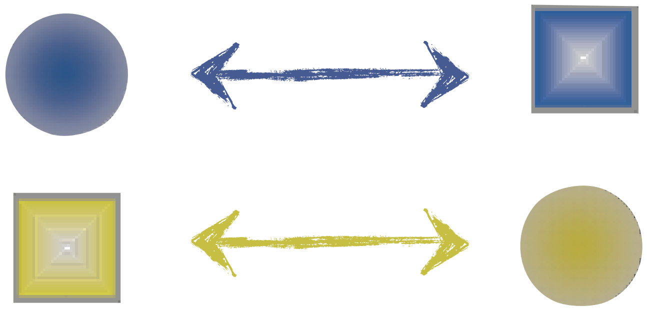
[Enrico Fermi 1901-1954]

Bosons *force carriers*

bosons can pile up



[Satyendra Bose 1894-1974]

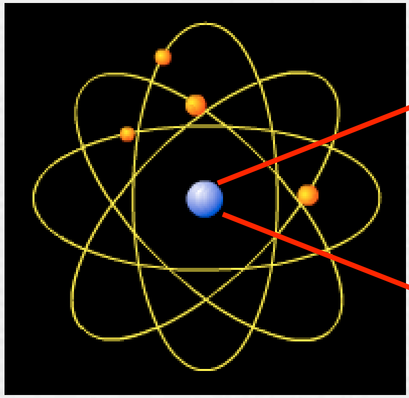


String Theory

unification of the Standard Model forces with gravity

(observable universe)

$10^{-10}\mathrm{m}$

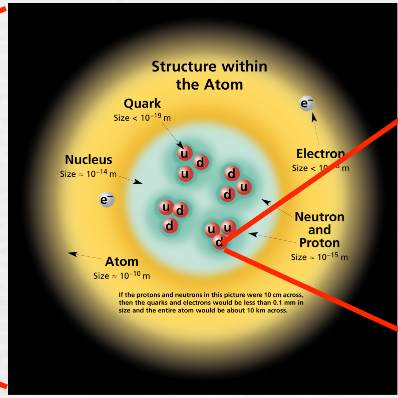


Atom

electrons + nucleus

(Earth)

$10^{-17}\mathrm{m}$

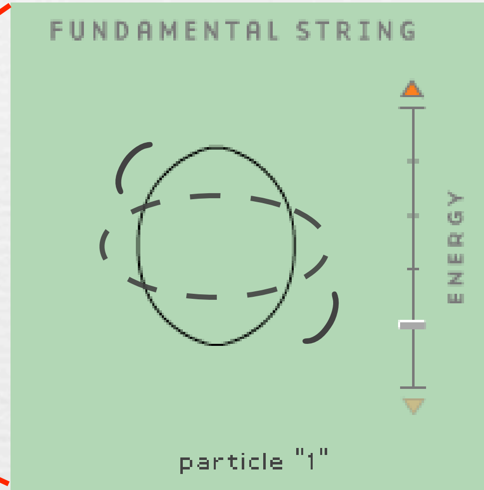


Nucleus

quarks

(Hair)

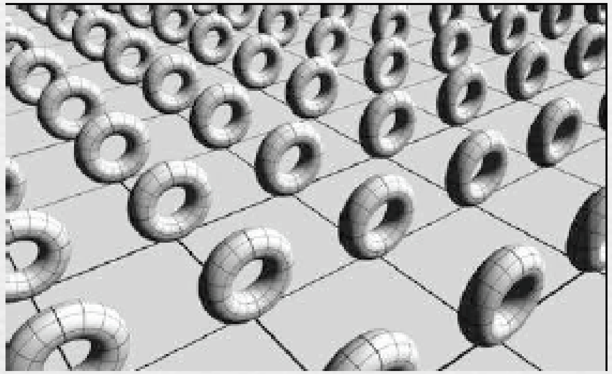
$10^{-35}\mathrm{m}$

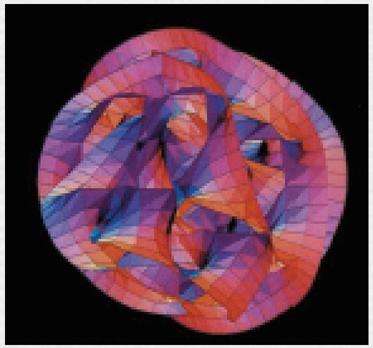


(Super)String

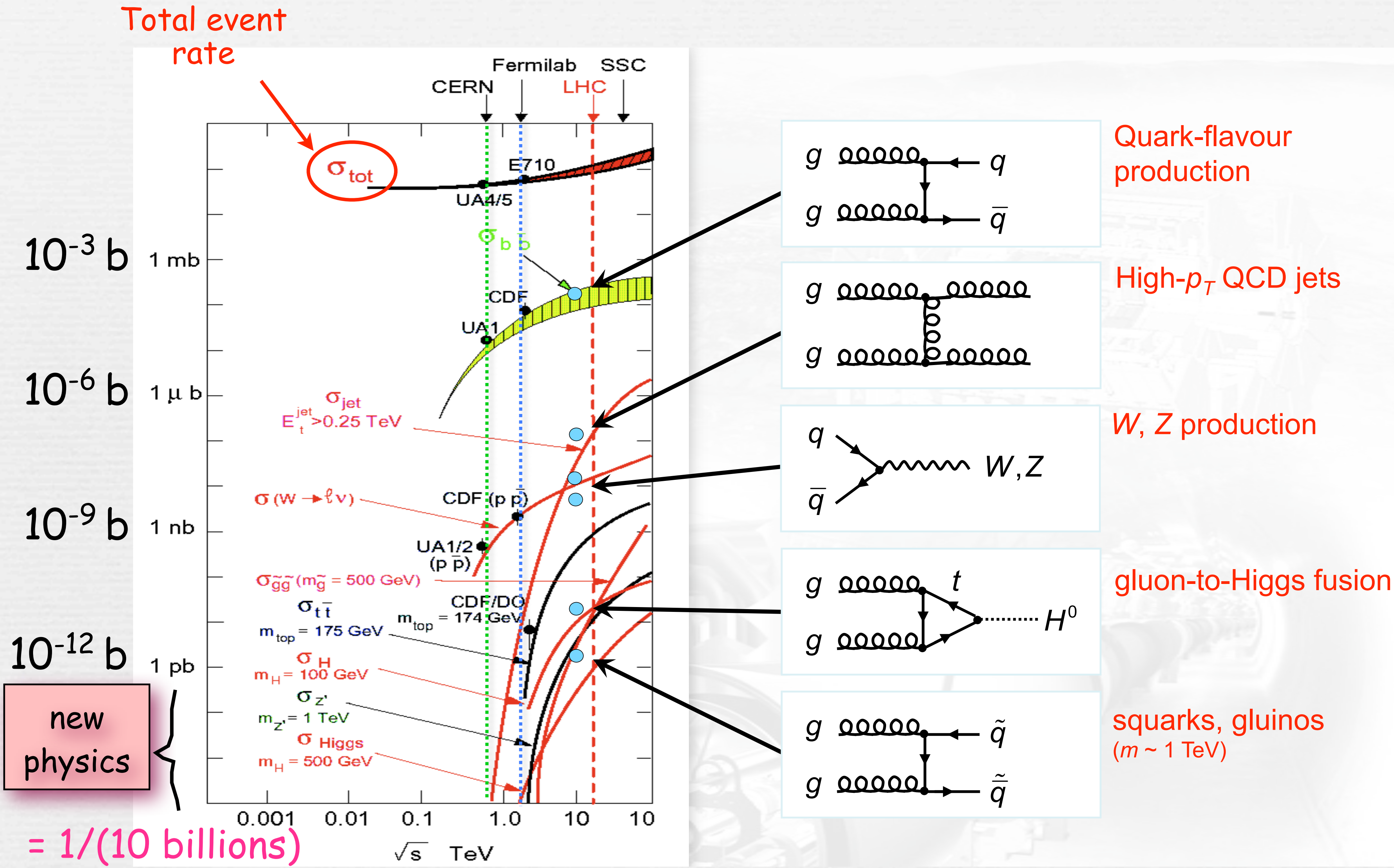
Extra Dimensions

String theories are (well) defined only in spacetime with 10 or 11 dimensions
These extra dimensions are assumed to be curled up





Event rate in hadron colliders



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

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

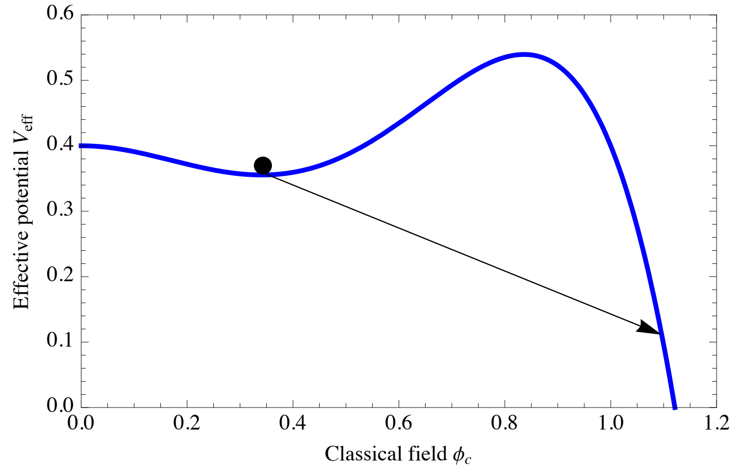
-> very different primordial nucleosynthesis

-> a profoundly different (and terribly boring) universe

Cosmological implications of Standard Model Higgs mass measurement

At large field values, the Higgs potential is $V_{eff} \approx \lambda_{eff}(\phi)\phi^4$

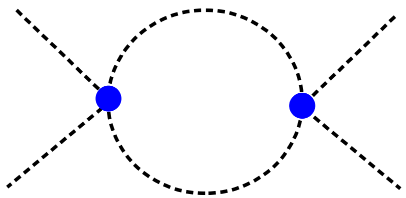
If at some scale $\lambda_{eff} < 0$ the electroweak minimum is unstable



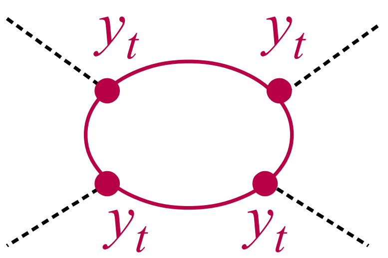
question: Can the SM be ruled if there is a minimum deeper than the EW minimum?

λ_{eff} determined by the "running" of the Higgs self coupling

controlled by two main competitive effects



makes λ grow

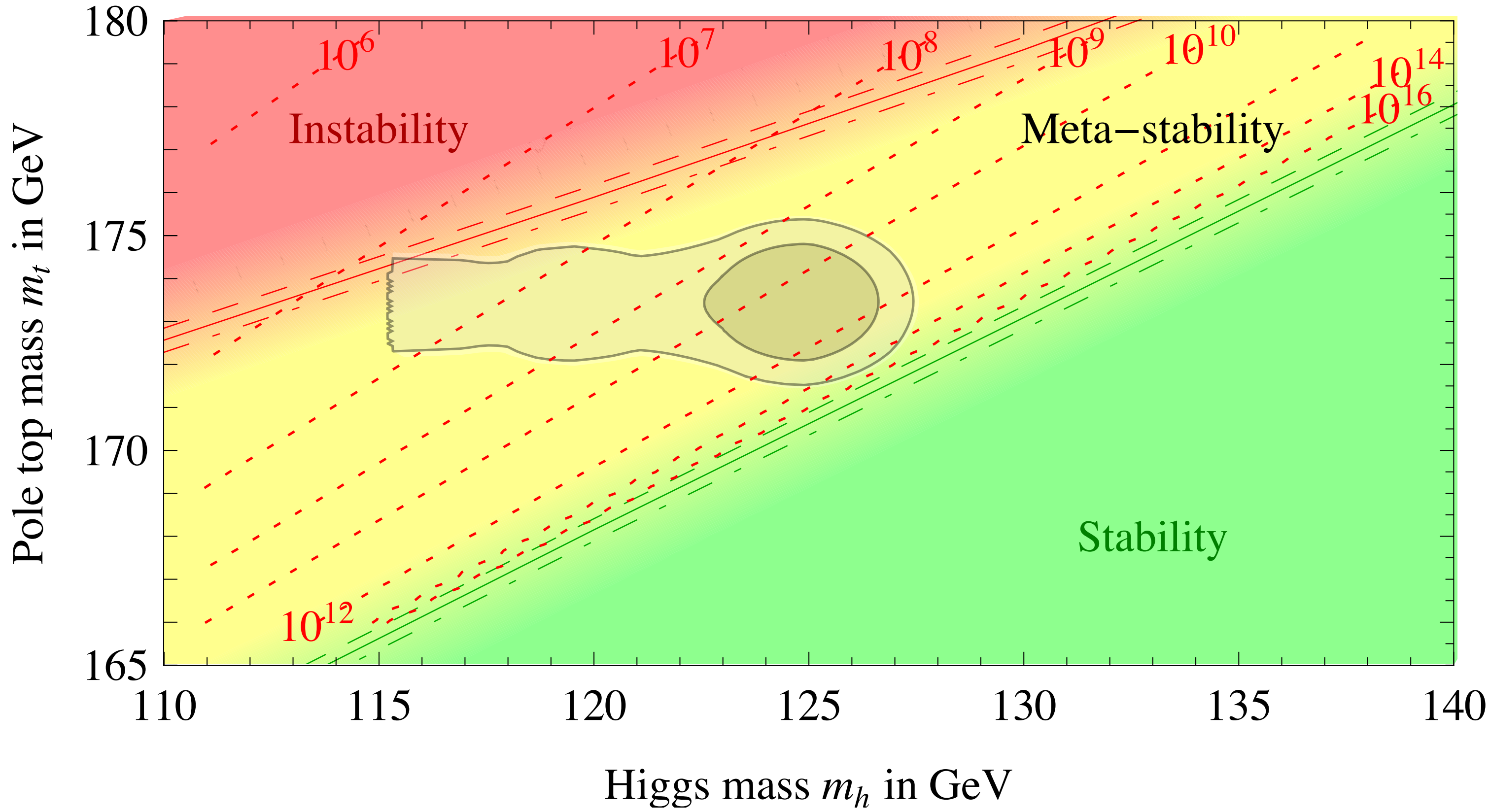


makes λ decrease

answer: No, if the lifetime of the unstable EW vacuum is longer than the age of the universe (metastability)

Cosmological implications of Standard Model
Higgs mass : we are safe!

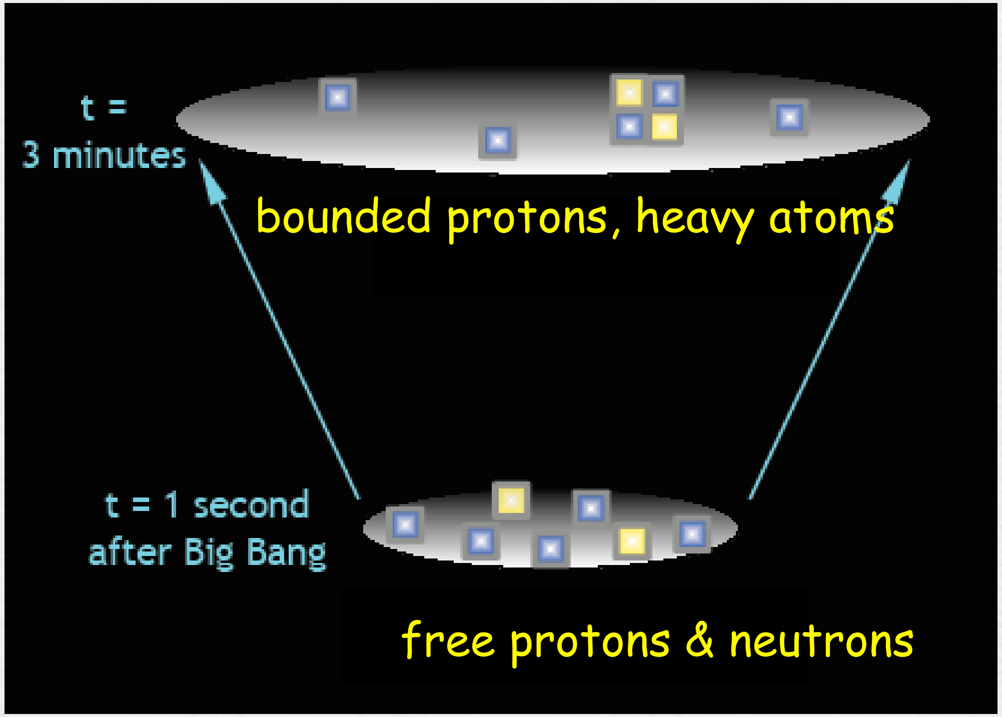
Elias-Miro et al, 1112.3022

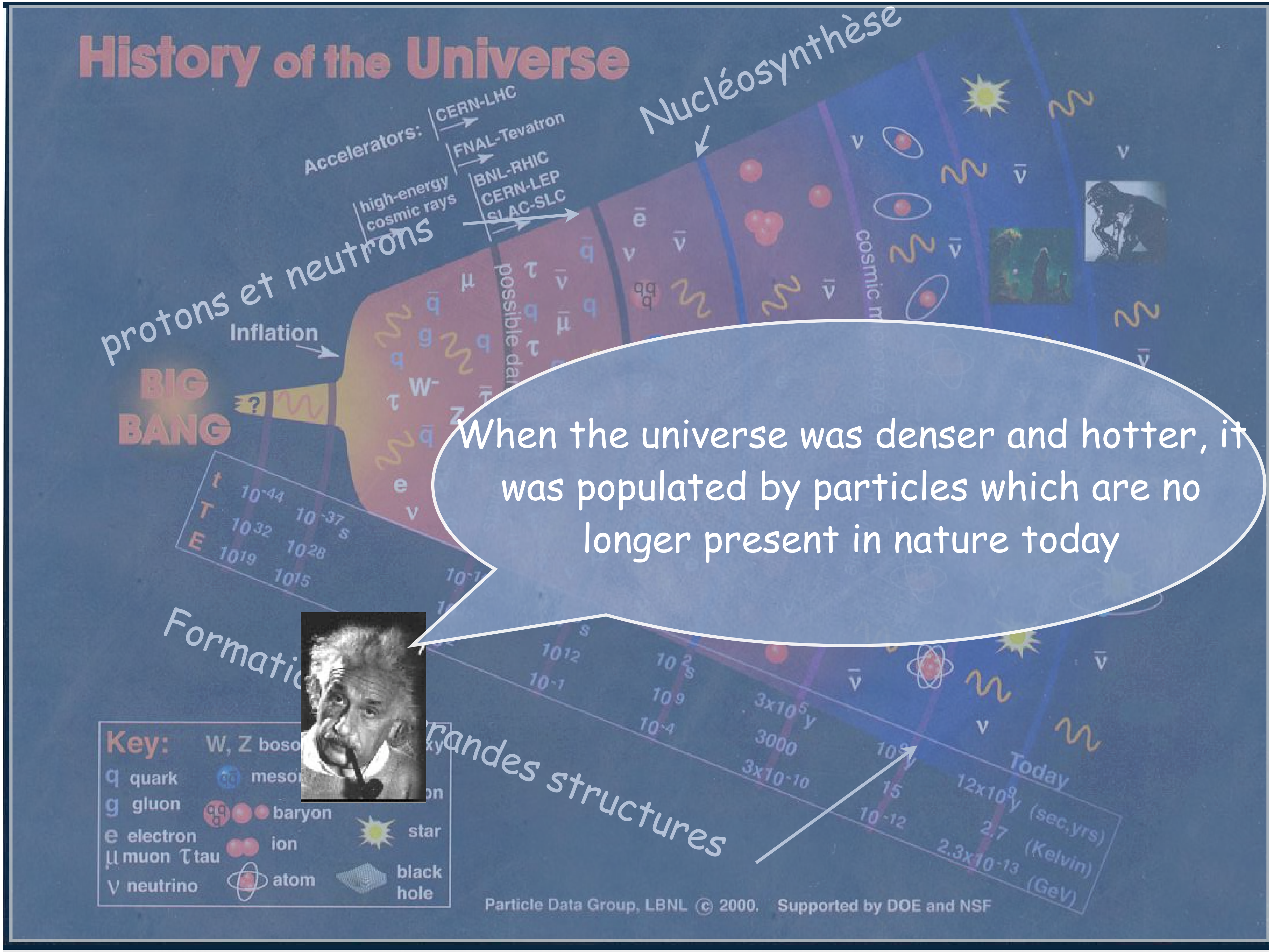


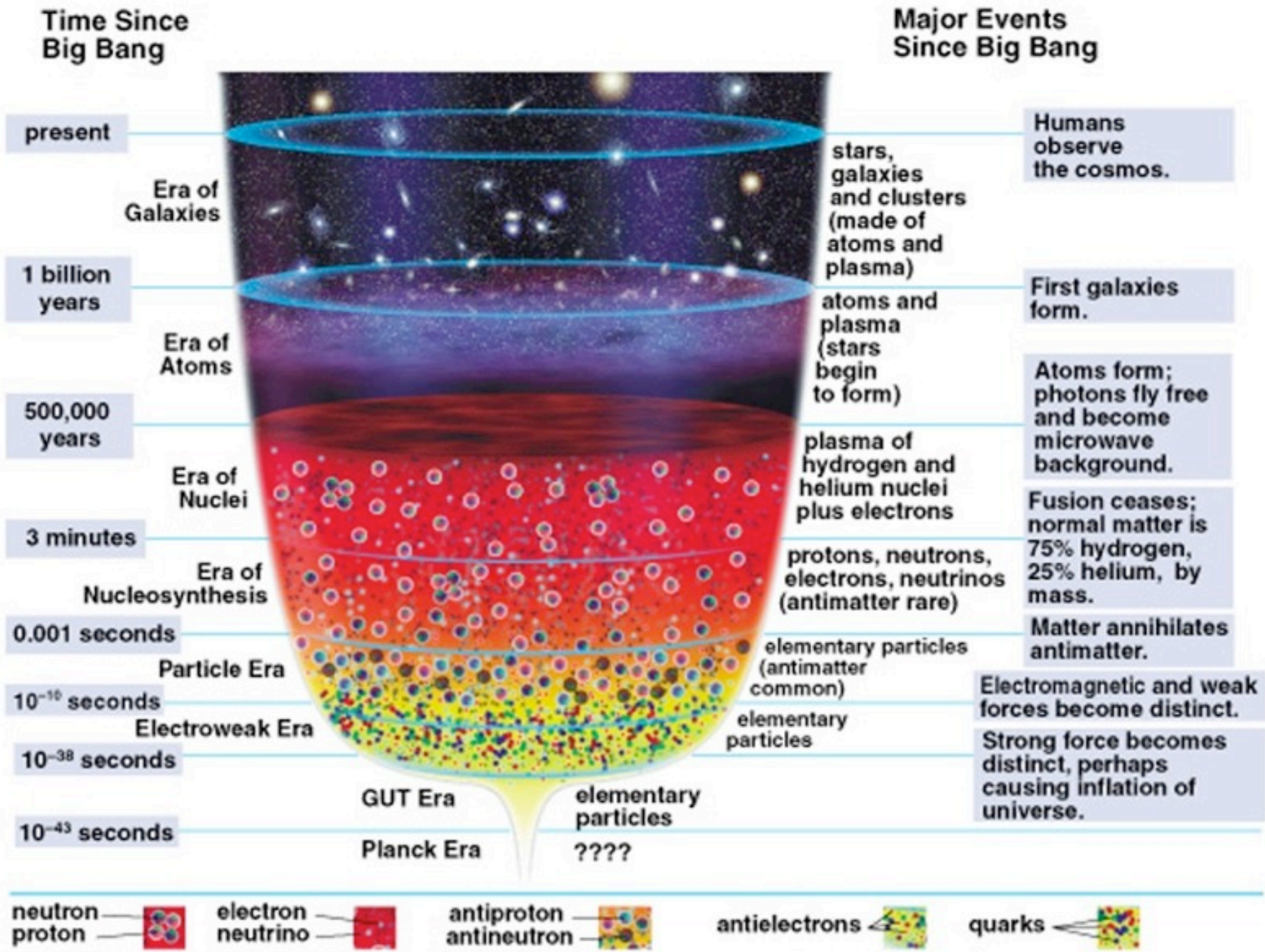
A SM ~ 125 GeV Higgs does not imply a strict upper bound on the scale of new physics. The Higgs potential is unstable but our vacuum is sufficiently long-lived

From the laboratory to the first minutes of the Universe

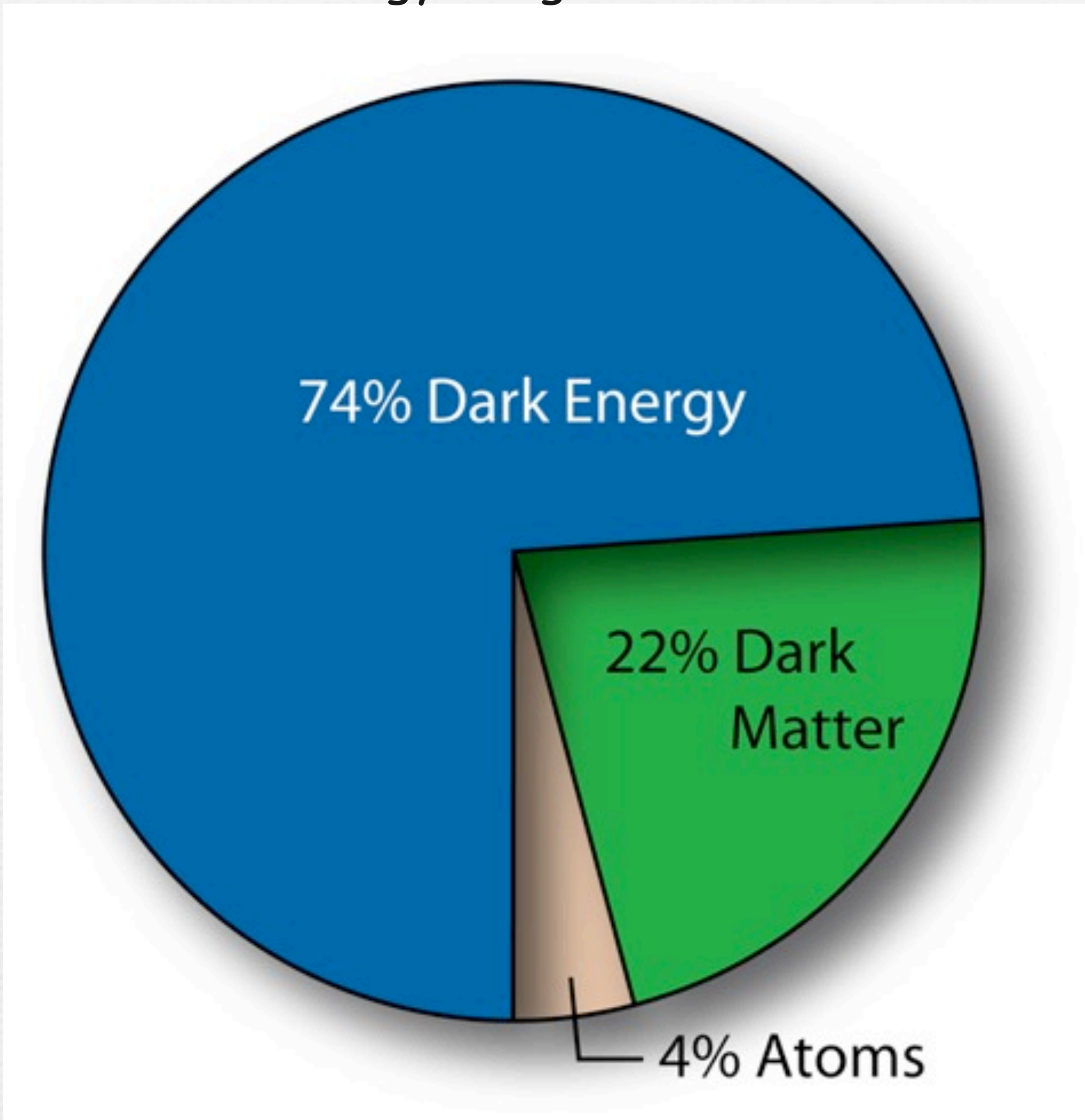
The Standard Model of particle physics enables us to explain the very first minutes in the history of the universe. For instance, it explains how the atomic nuclei were formed.




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
possible dark matter
cosmic microwave
When the universe was denser and hotter, it was populated by particles which are no longer present in nature today
Formation des grandes structures
t
T
E
Today
(sec, yrs)
(Kelvin)
(GeV)
Key:
W, Z bosons
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
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.
Era of Galaxies
stars, galaxies and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
500,000 years
Atoms form; photons fly free and become microwave background.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Era of Nucleosynthesis
protons, neutrons, electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
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

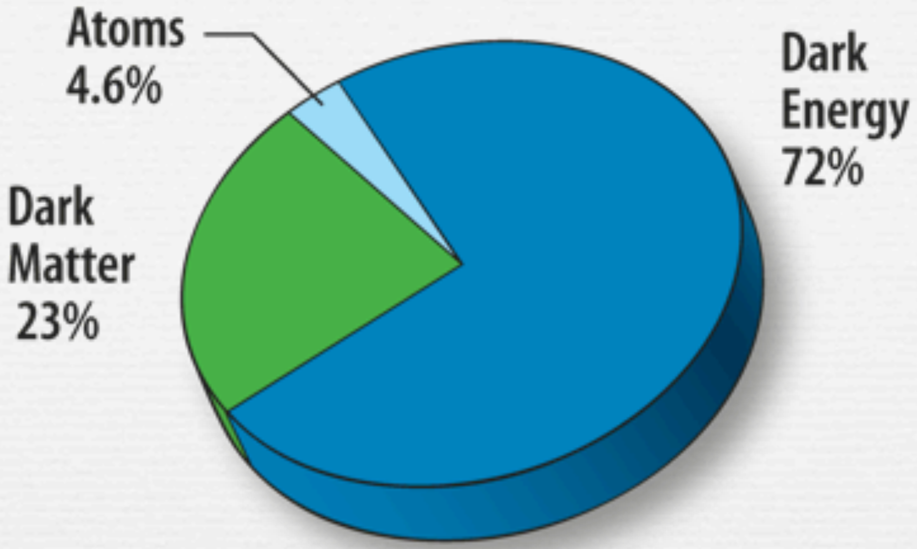
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1 - n_s$	0.037 ± 0.014
$1 - n_s$	$0.0079 < 1 - n_s < 0.0642$ (95% CL)	$A_{\rm BAO}(z = 0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm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

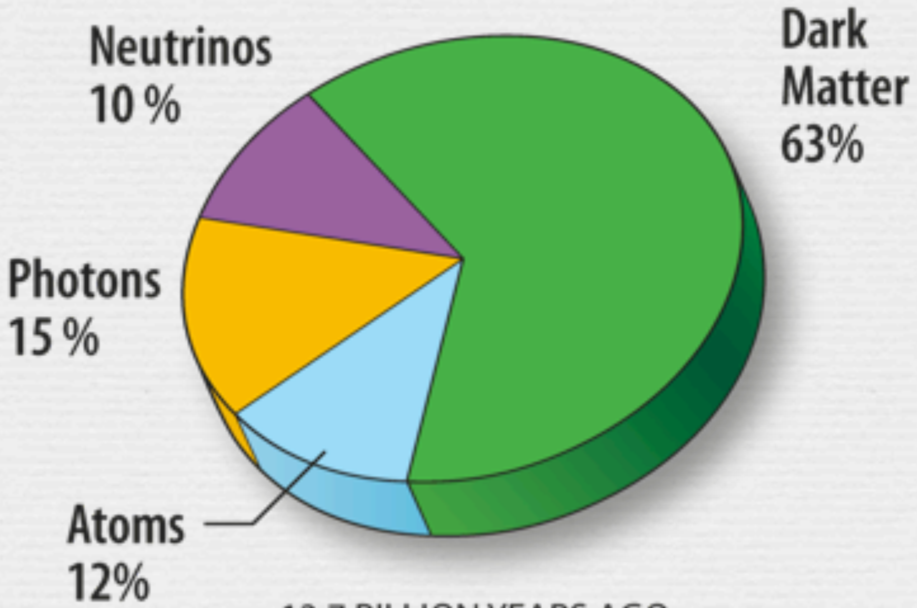
expansion rate ← H_0

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?

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

$$\Omega_{DM} = \frac{\text{energy density of the universe stored in dark matter}}{\text{total energy density of the universe}} \sim 25\ \%$$

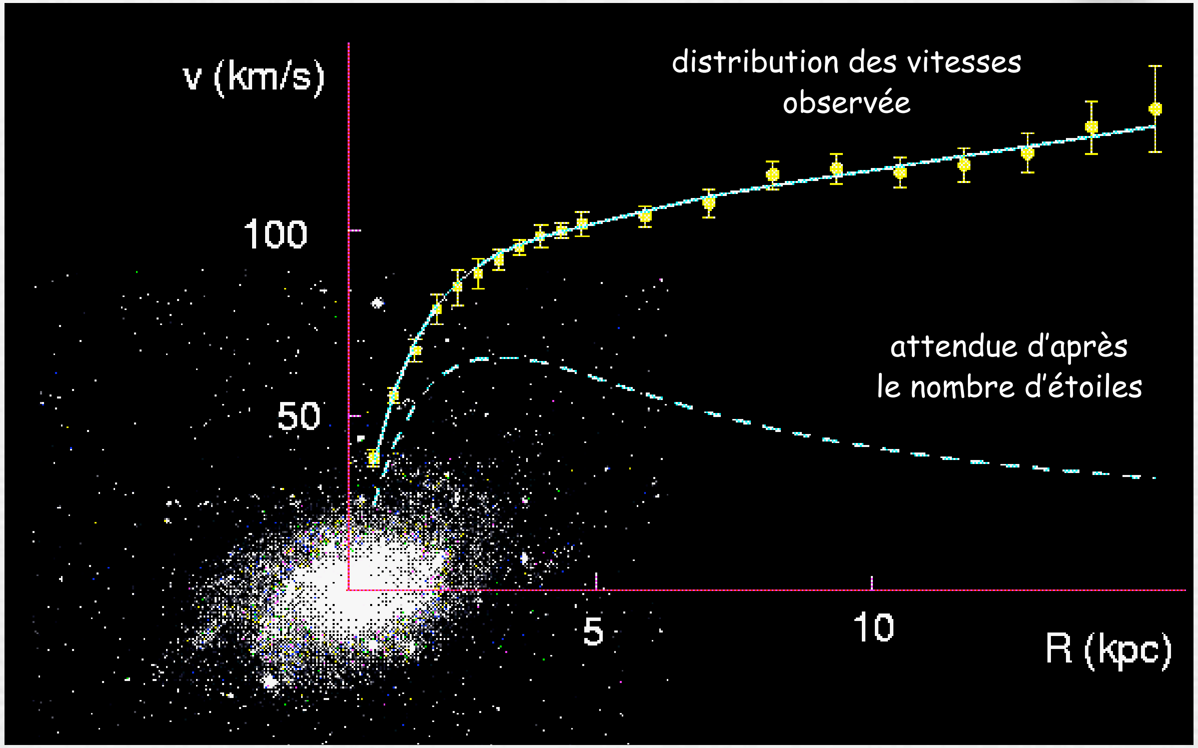
$\Omega_{\text{dark energy}} \sim 70\ \%$

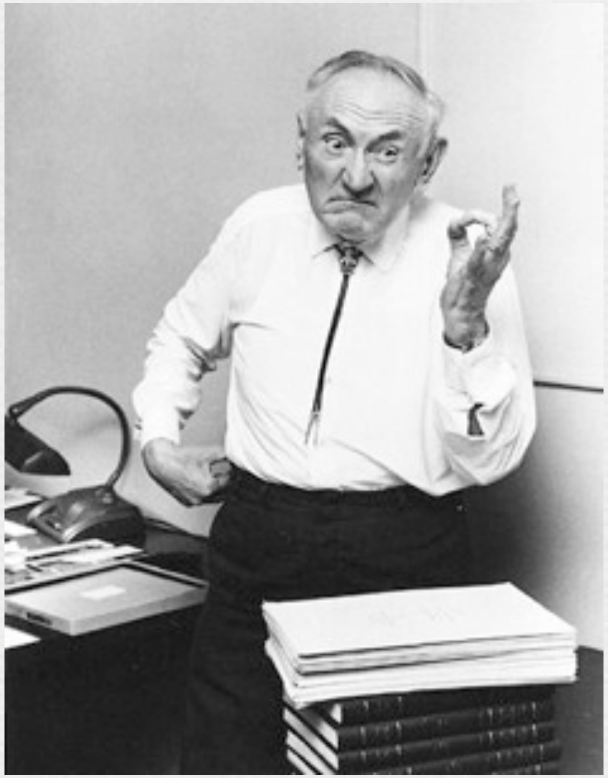
$\Omega_{SM} = \ \sim 5\ \%$

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

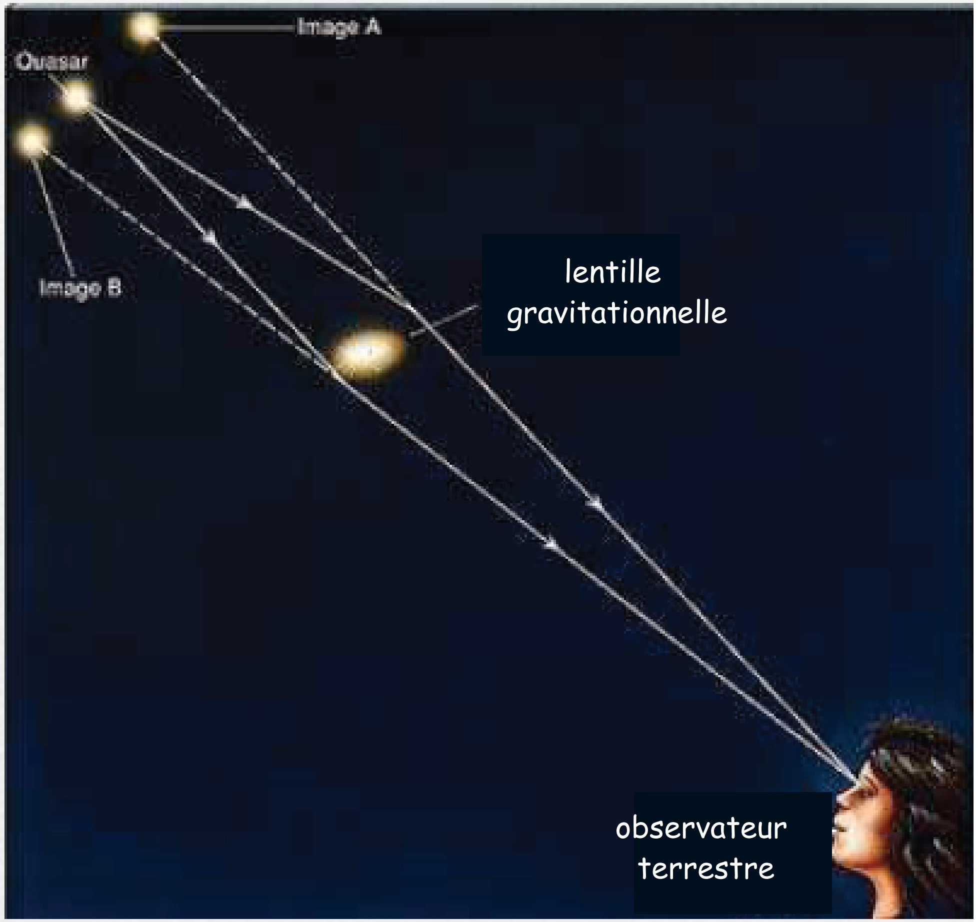




Zwicky

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

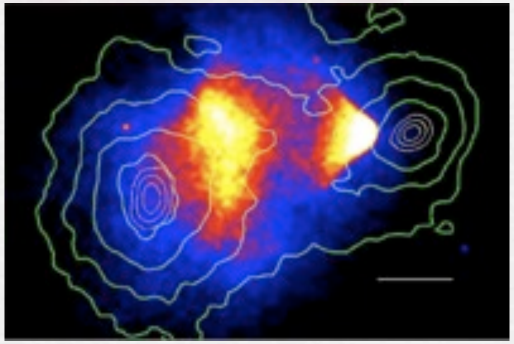
gravitational lensing



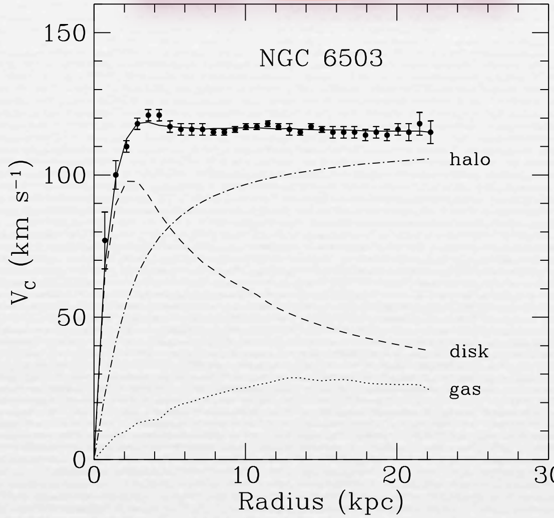
The existence of (Cold) Dark Matter has been established by a host of different methods; it is needed on all scales

Gravitational lensing

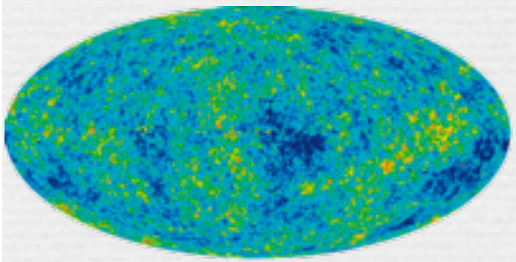
The "Bullet cluster": lensing map versus X-ray image

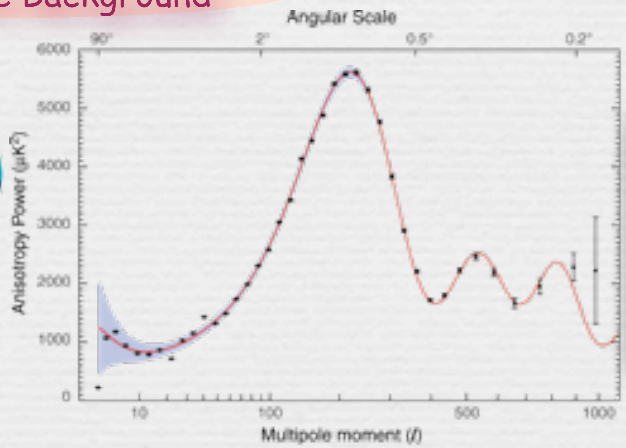


Galaxy rotation curves



Cosmic Microwave Background





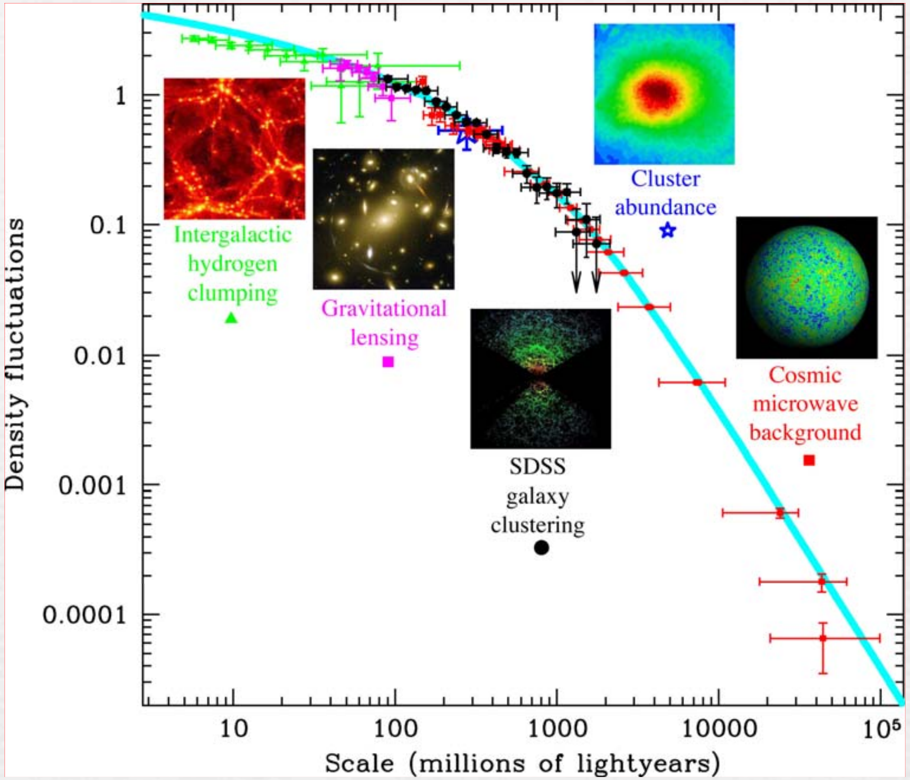
... etc

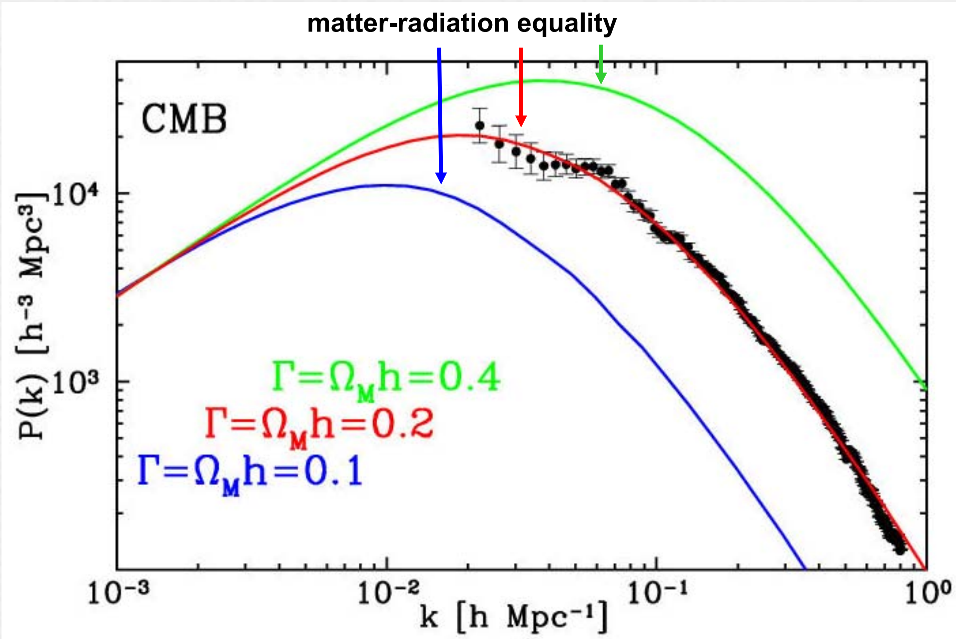
-> Fraction of the universe's energy density stored in dark matter : $\Omega_{DM} \approx 0.22$

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

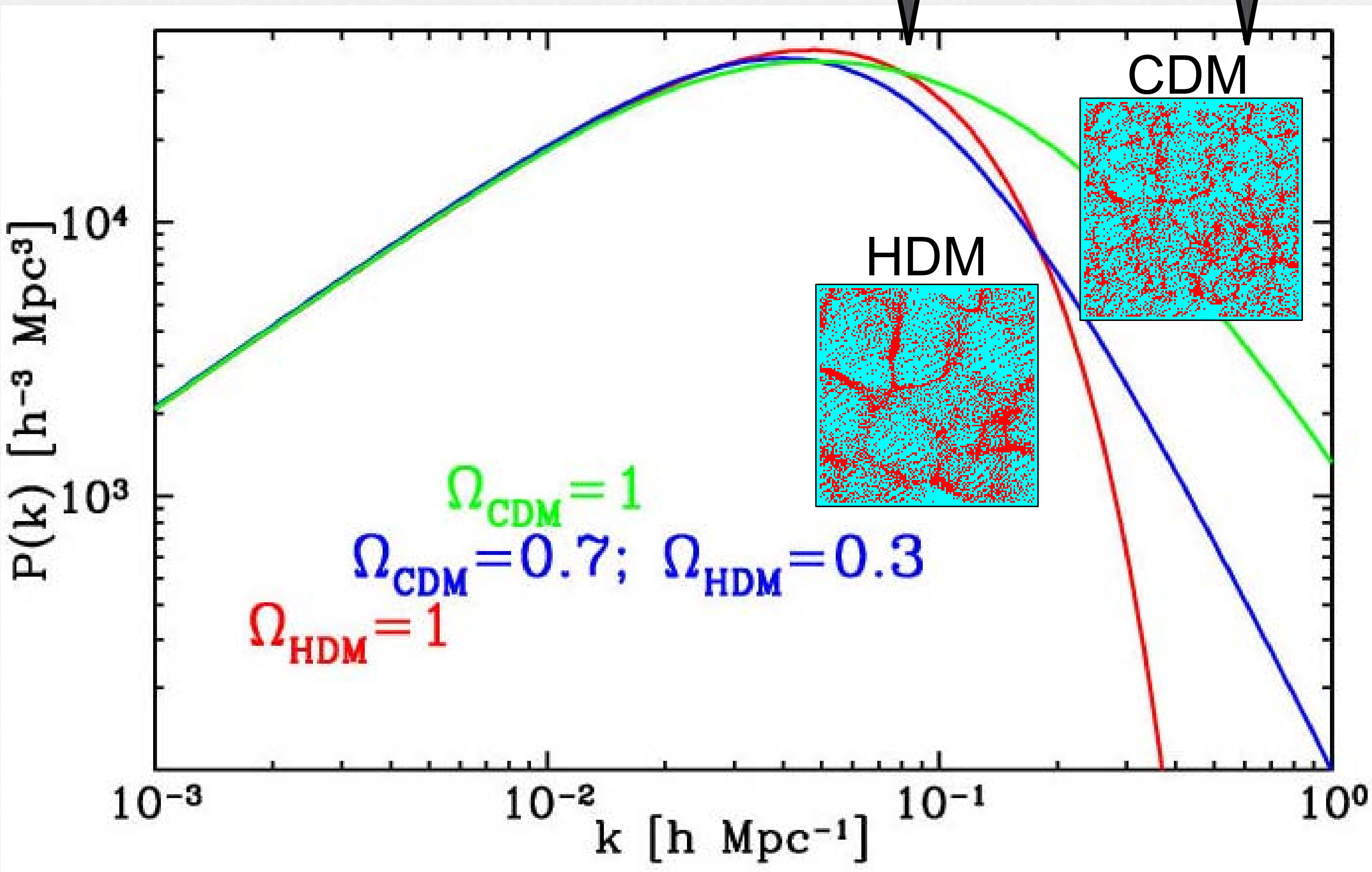




Neutrinos

hot dark matter

cold dark matter

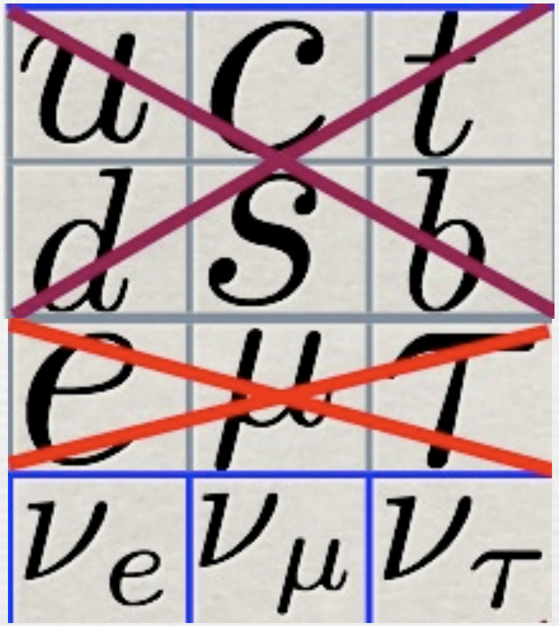


Why can't dark matter be explained by the Standard Model?

Matter

quarks

leptons



I II III

3 families of matter

Forces

force mediators

charged/unstable

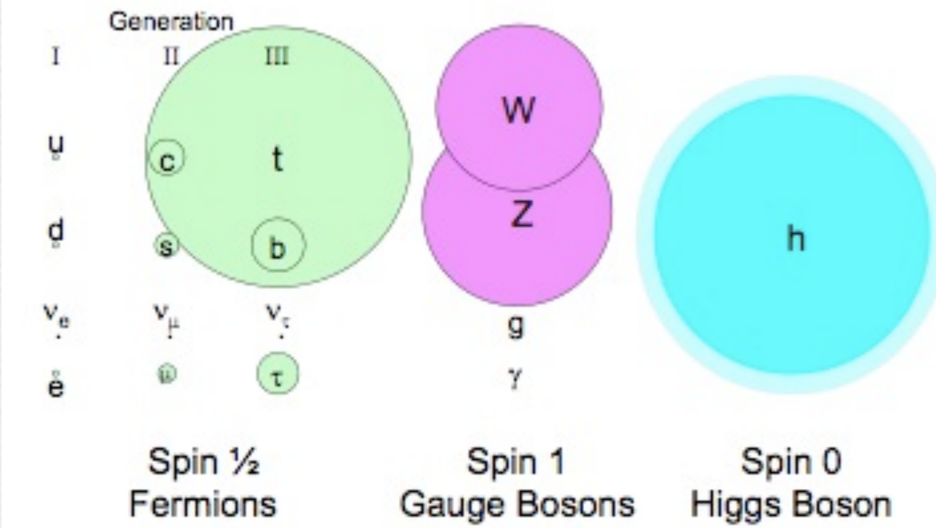
baryonic

massless

contribution to the energy budget of the universe

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

radius of circle is proportional to the mass



Dark Matter candidates

Two main possibilities:

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

Long-lived
(stable on cosmological scales)

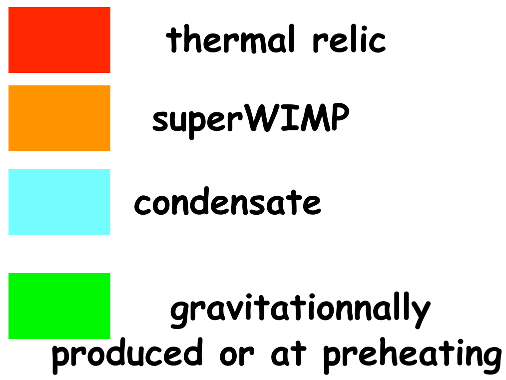
$\tau_{DM} > \tau_{universe} \sim 10^{18}\ s$

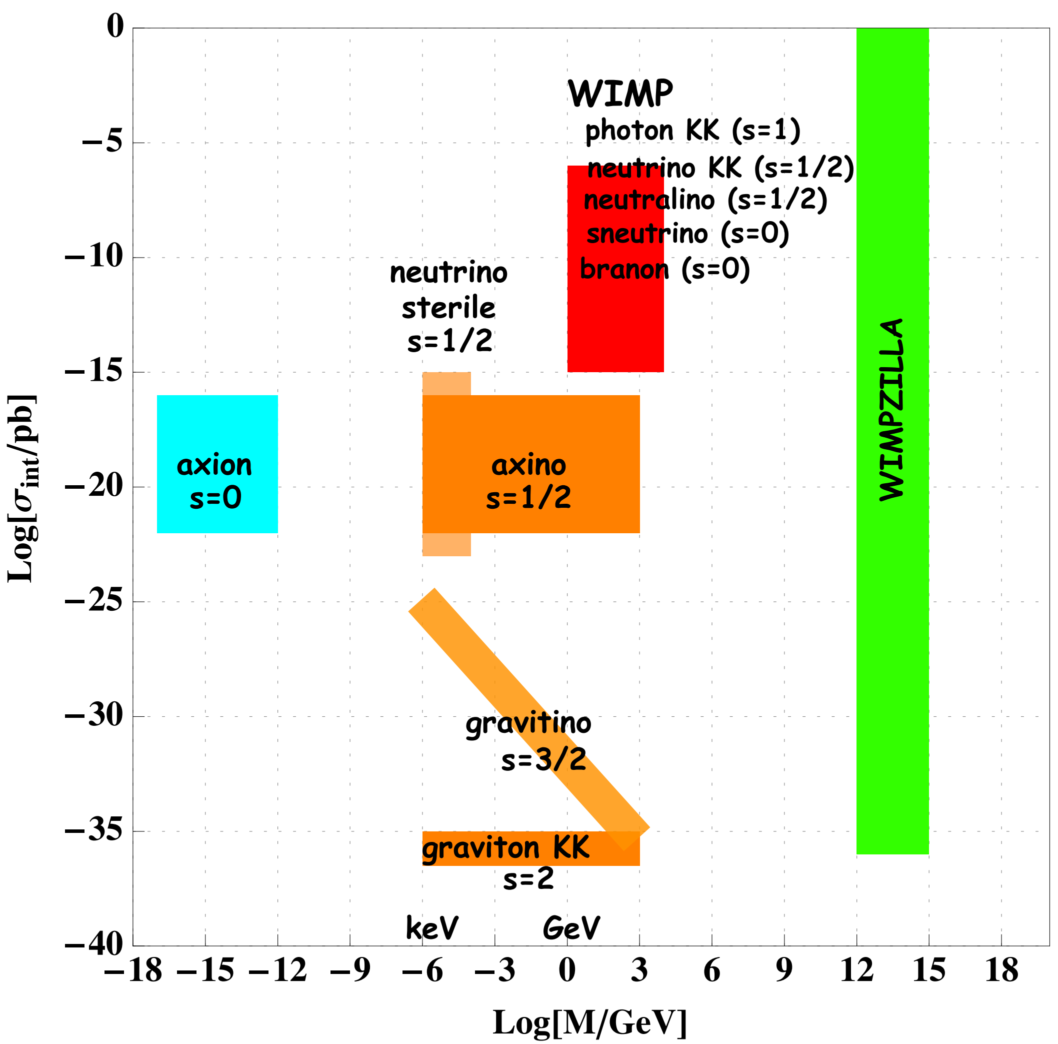
sizably interacting (but not strongly) with the SM -> symmetry needed to guarantee stability

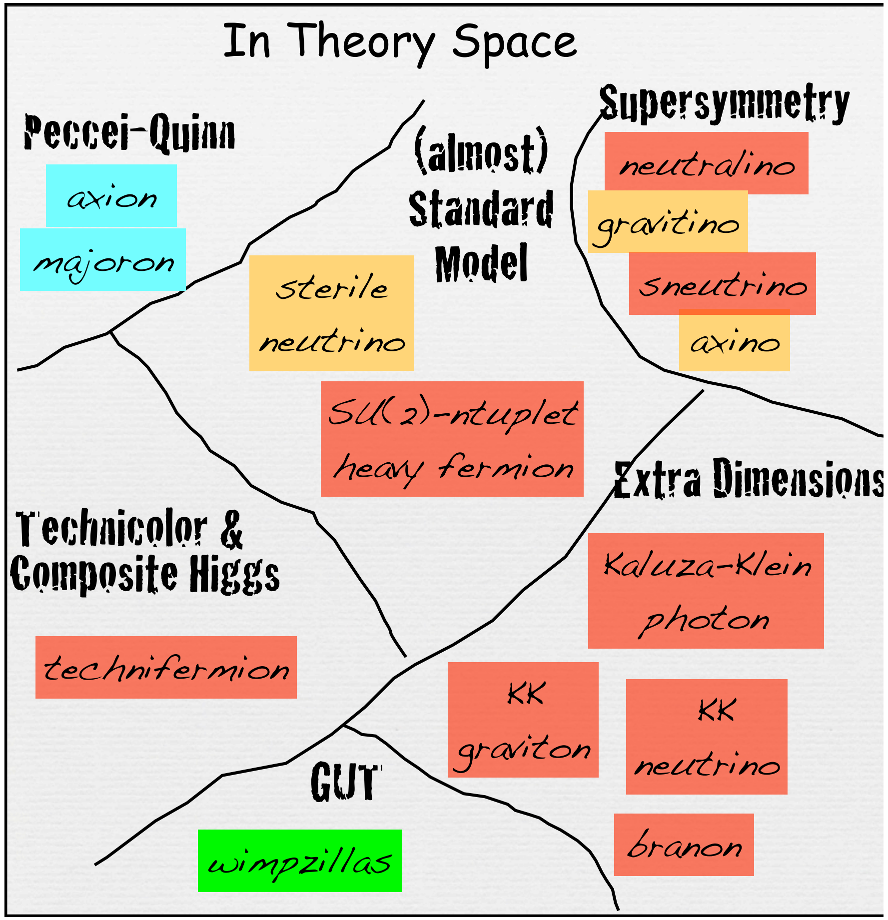
stable by a symmetry

-> WIMP

Dark Matter Candidates with $\Omega_{DM} \sim 1$



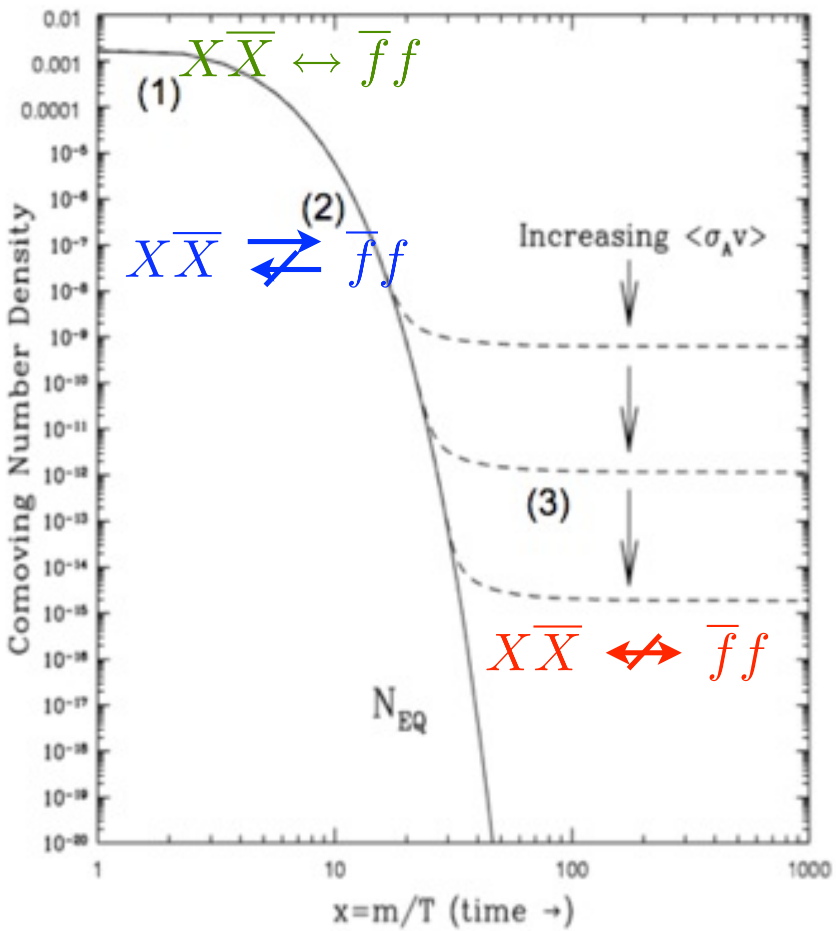




good to keep in mind if no sign of wimp detection within the next decade ...

The relic abundance of a stable particle follows from the generic thermal freeze-out mechanism in the expanding universe

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



expansion rate of universe

freese-out :

annihilation rate of particle

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

Thermal relic: $\Omega_{DM} \propto 1/\sigma_{anni}$

$\Rightarrow \sigma_{anni} \approx 1$ pb

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

$\Rightarrow m \sim 100$ GeV

The "WIMP miracle"

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

→ a particle with a typical EW-scale cross section

$\sigma_{anni} \approx 1$ pb leads to the correct dark matter abundance.

How to detect Dark Matter?

Direct detection: We can “touch” dark matter

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

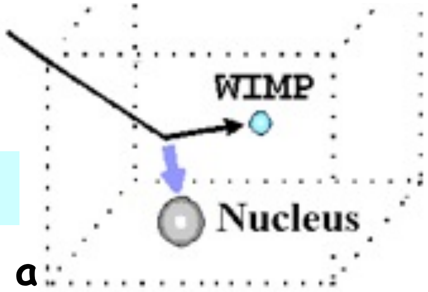
WIMP direct detection

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.

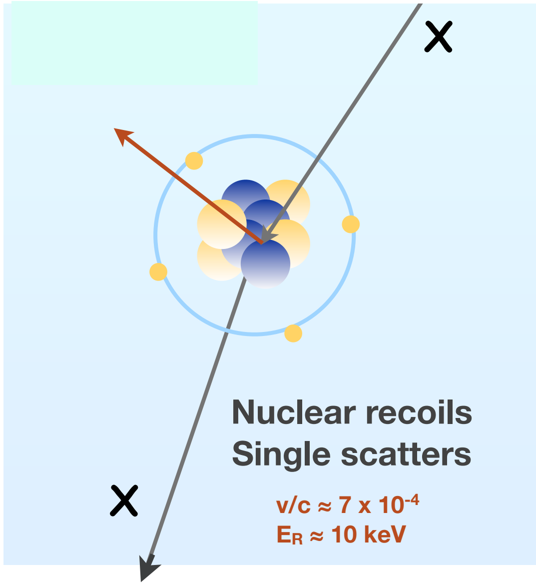
Direct detection consists in observing the recoiled nuclei.

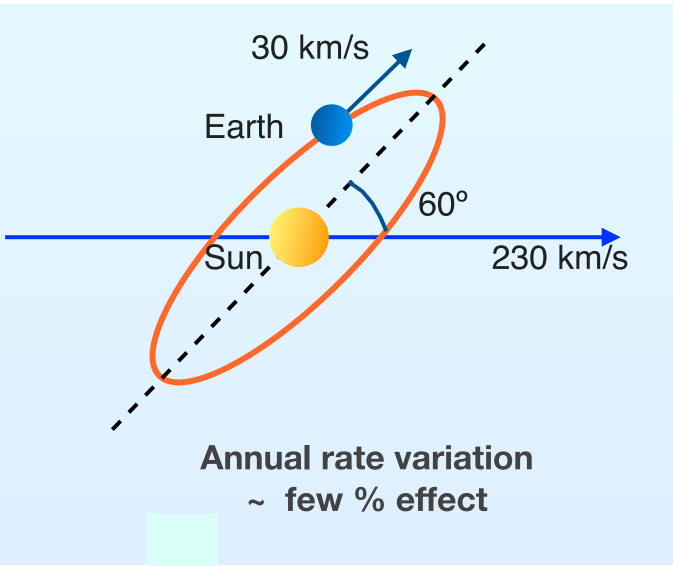
Direct Detection

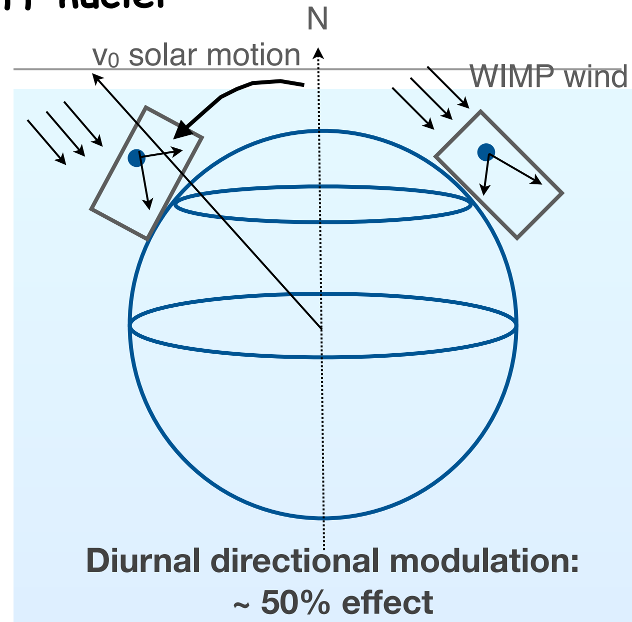


WIMP flux on Earth: ~ 10^5 $cm^{-2}s^{-1}$ (for a 100 GeV WIMP)

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



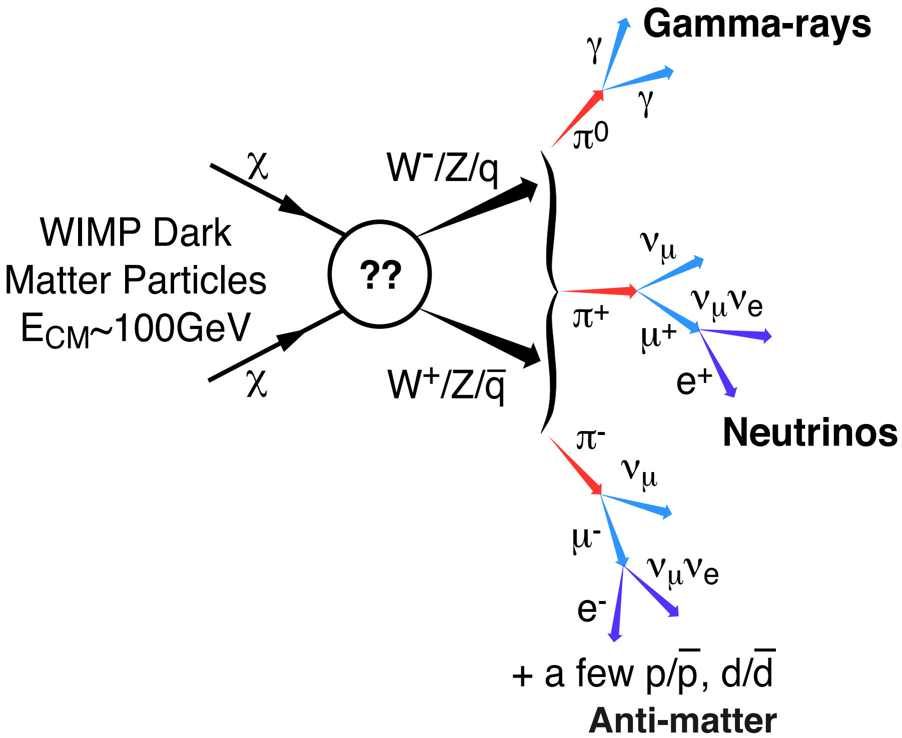




for example, "EDELWEISS":

WIMP indirect detection

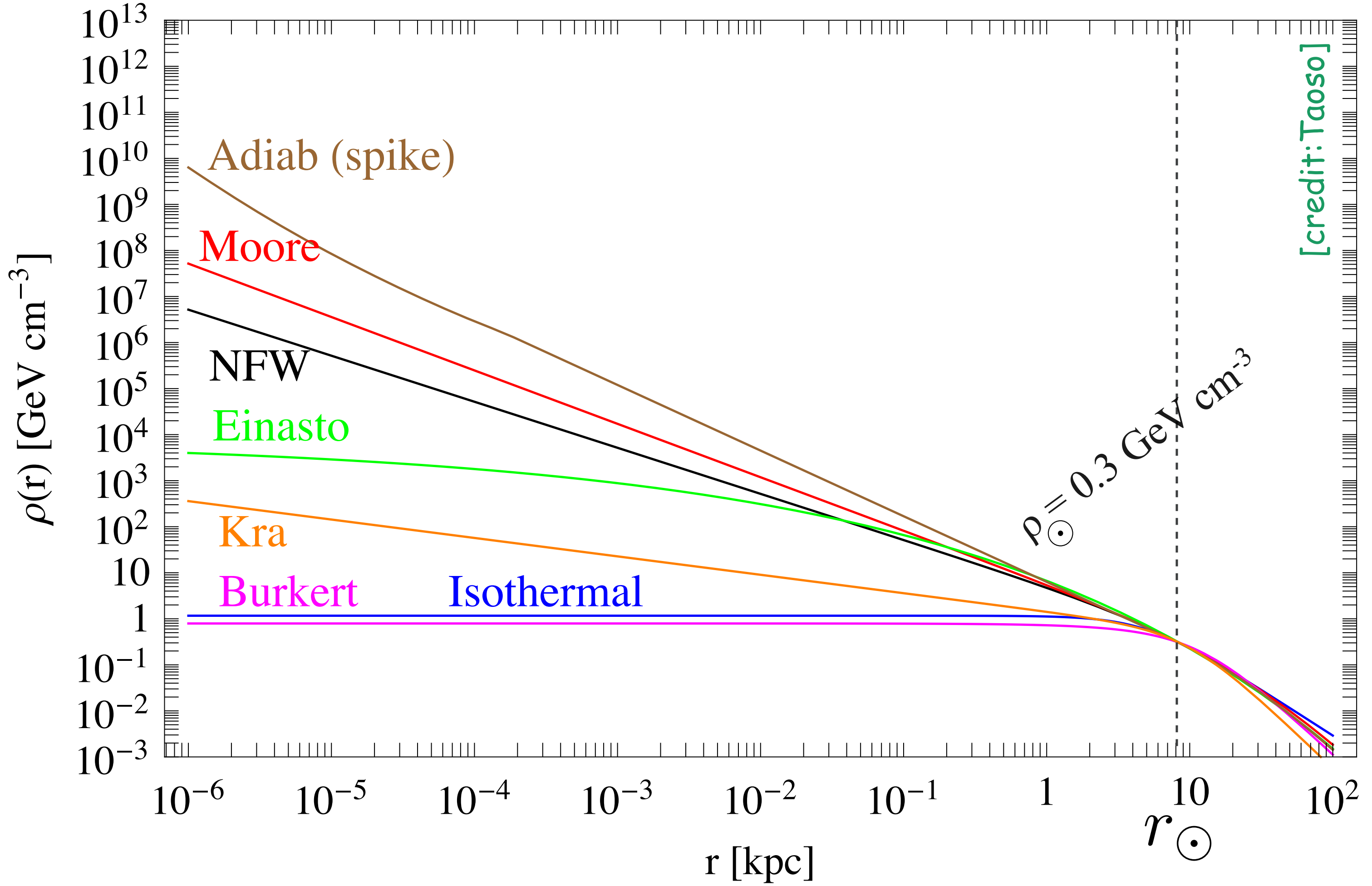
Dar Matter can produce
photons, electrons, protons, neutrinos, antiprotons, positrons :



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

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

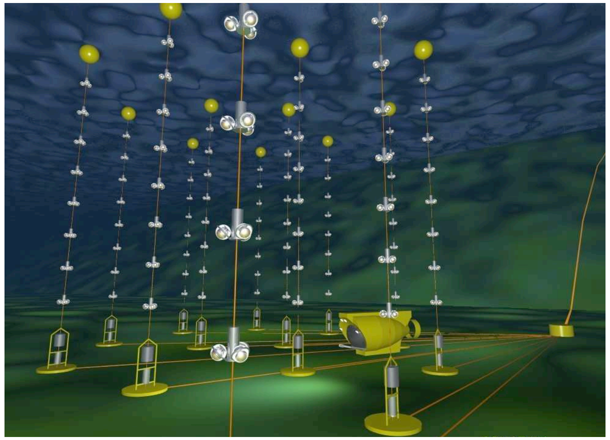
Astrophysical uncertainties on the DM density profile



Indirect Detection

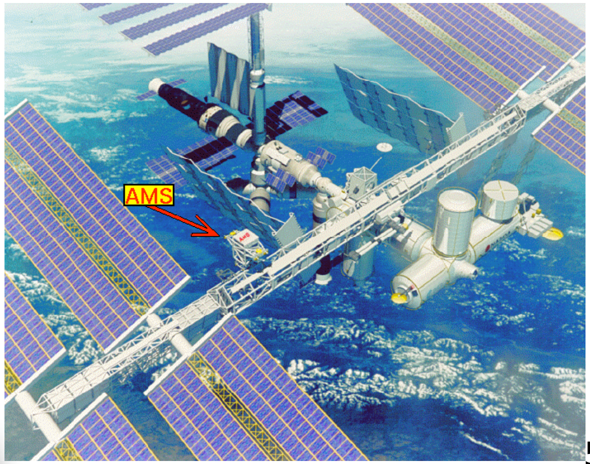
Search for neutrinos in the South Pole

In the Mediterranean



Antarès

Search for antiprotons in space



AMS

Indirect Detection

Search for dark matter photons on Earth

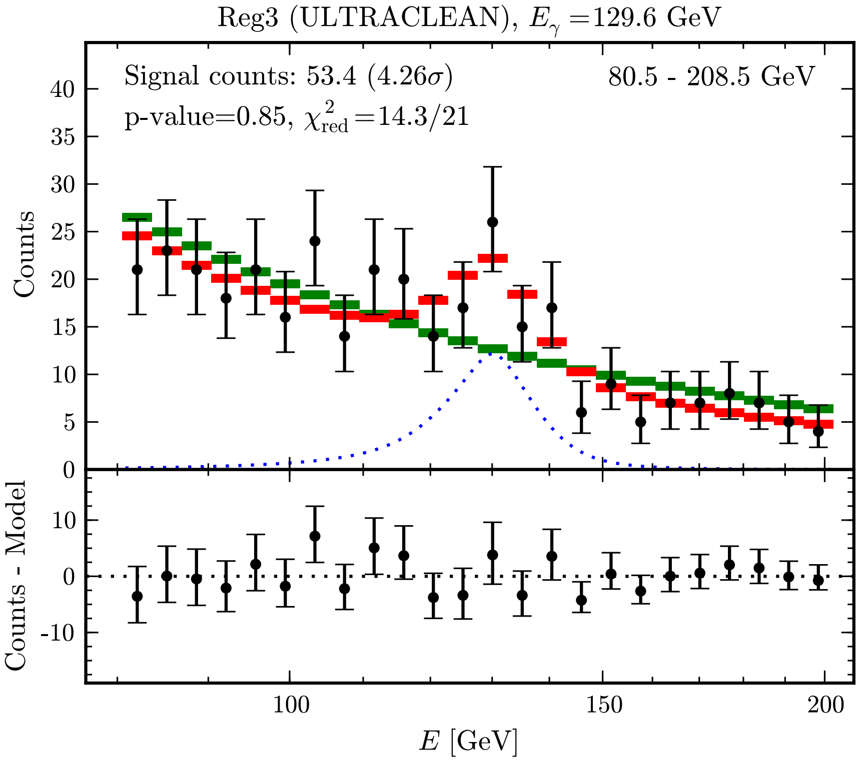
Hess

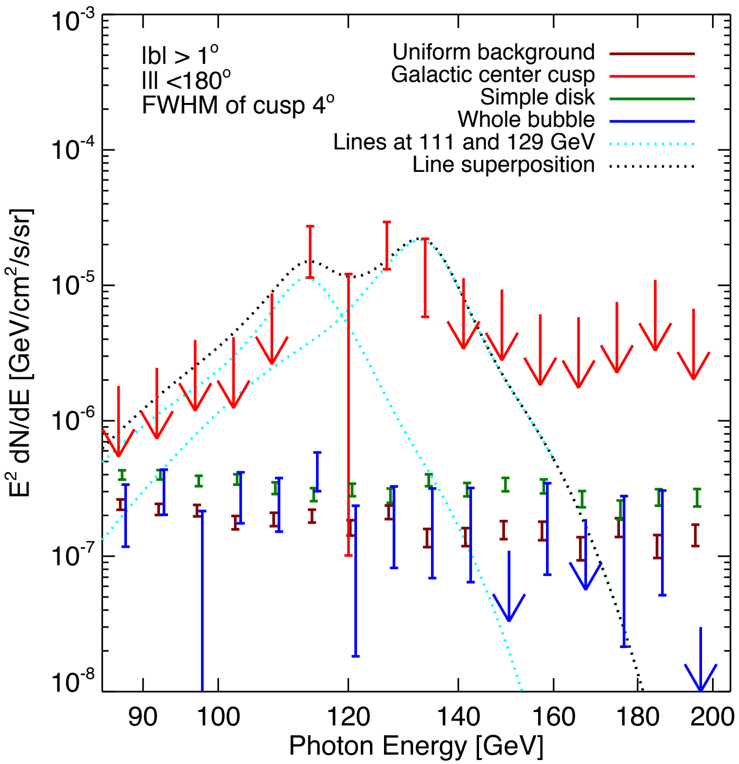
and in space

Fermi

A ~130 GeV gamma ray line (in Fermi data) from the galactic center?

Spring 2012
hot topic

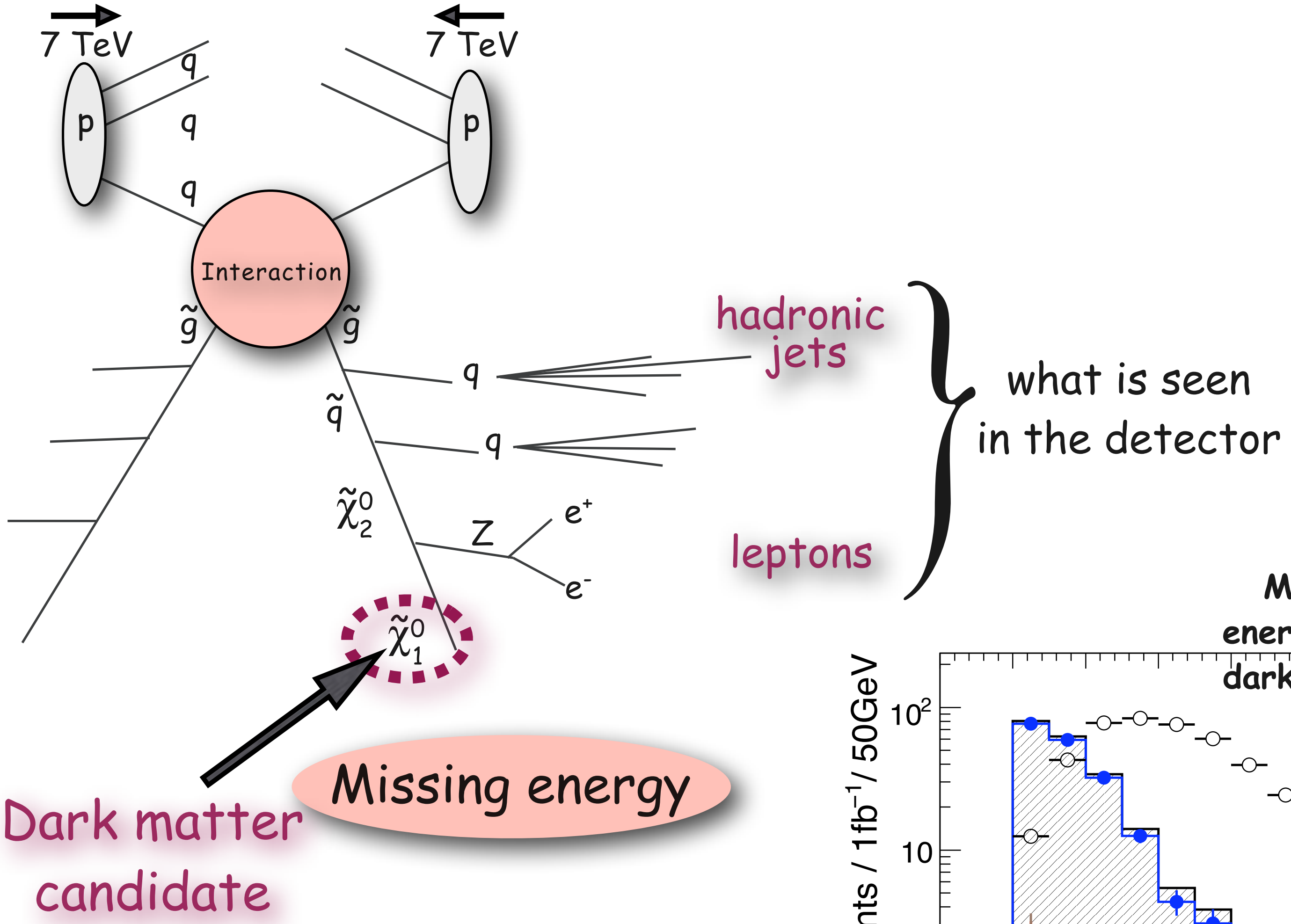


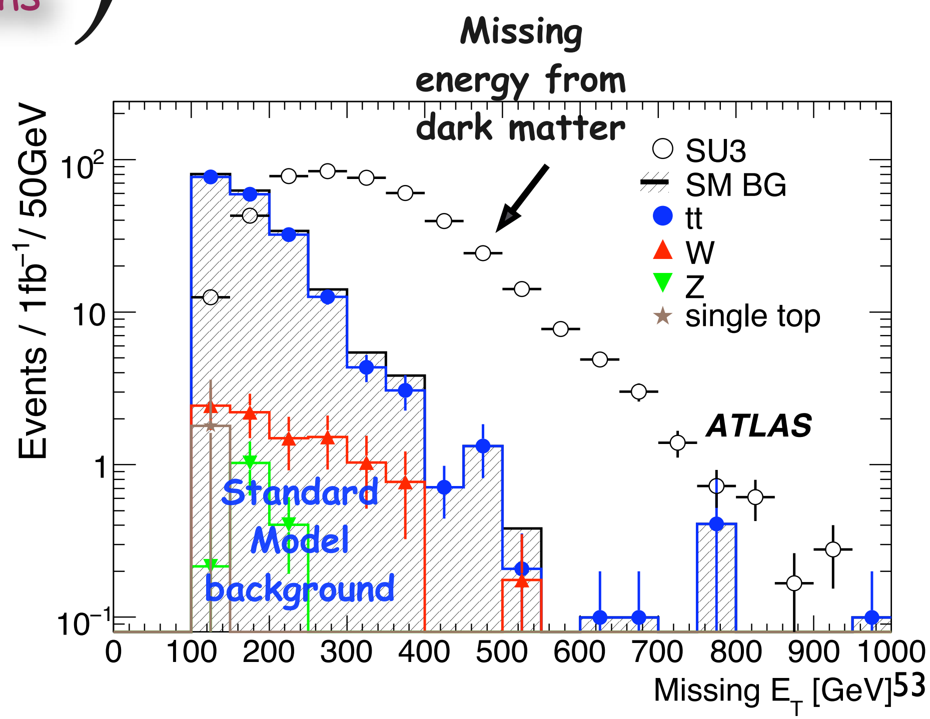


Weniger,1204.2797

Su & Finkbeiner,1206.1616

Producing Dark Matter at LHC = "Missing Energy" events





LHC: not sufficient to provide all answers

LHC sees missing energy events and measures mass for new particles

but what is the underlying theory?

Spins are difficult to measure (need for $e^+ e^-$ Linear Collider)

Solving the Dark Matter problem requires

1) detecting dark matter in the galaxy (from its annihilation products)

2) studying its properties in the laboratory

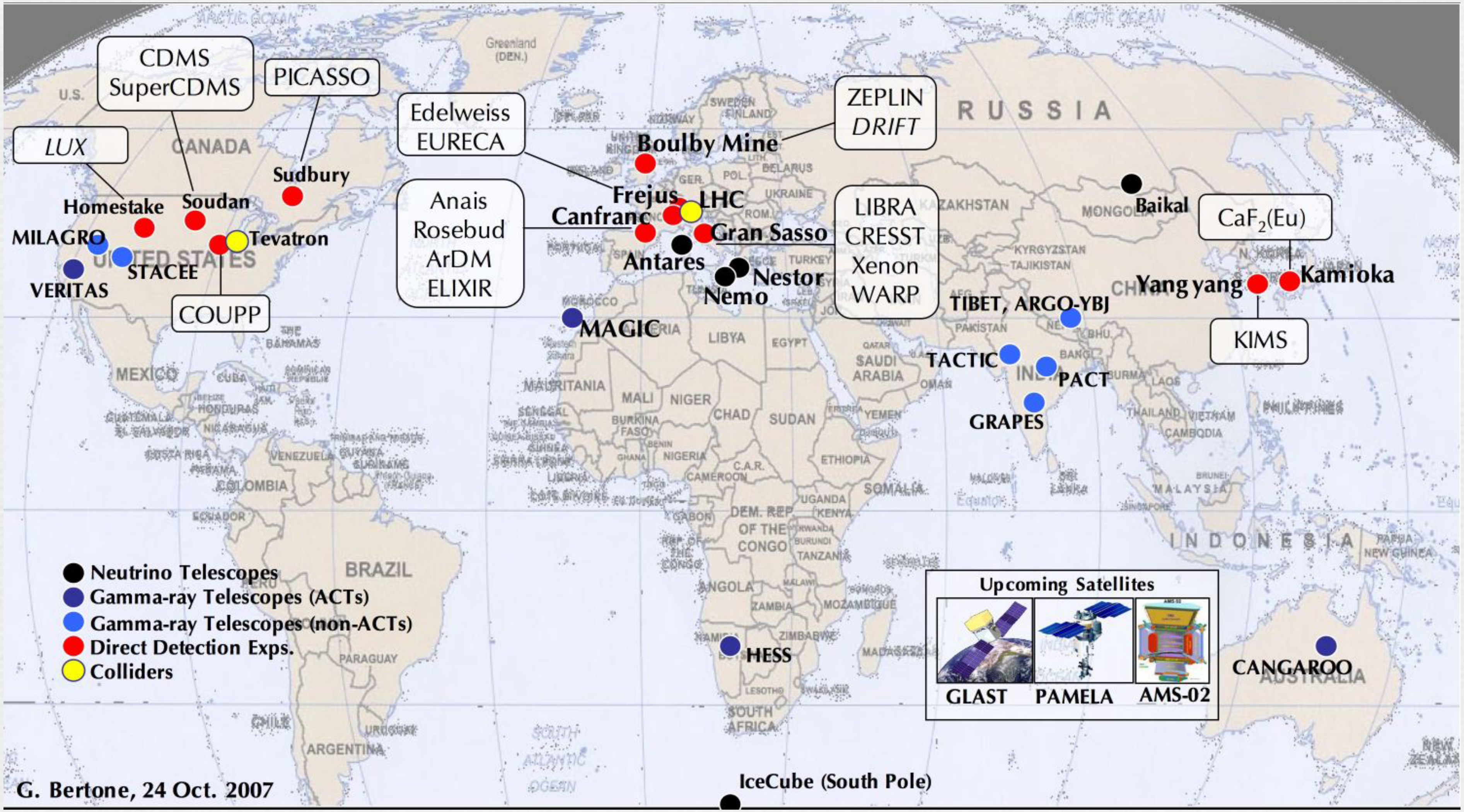
3) being able to make the connection between the two

Need complementarity of particle astrophysics (direct/indirect experiments) to identify the nature of the Dark Matter particle

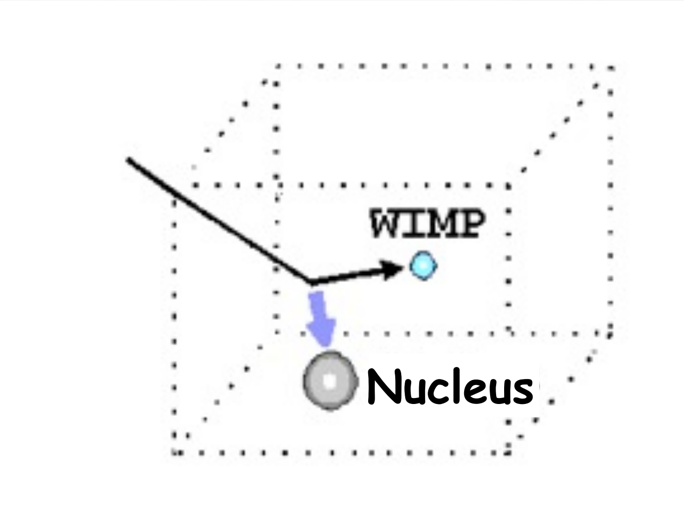
The Dark Matter Decade

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



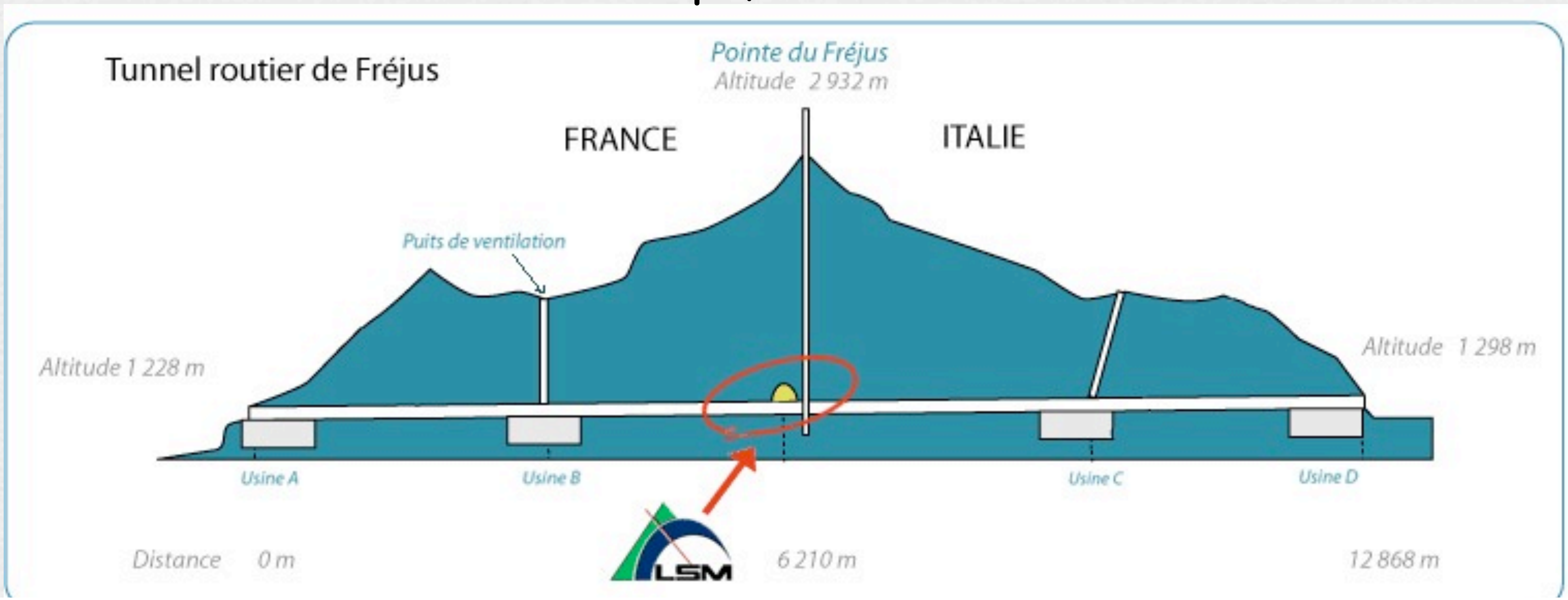
Back to Direct detection



The earth feels a "wind of WIMPS"

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":



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

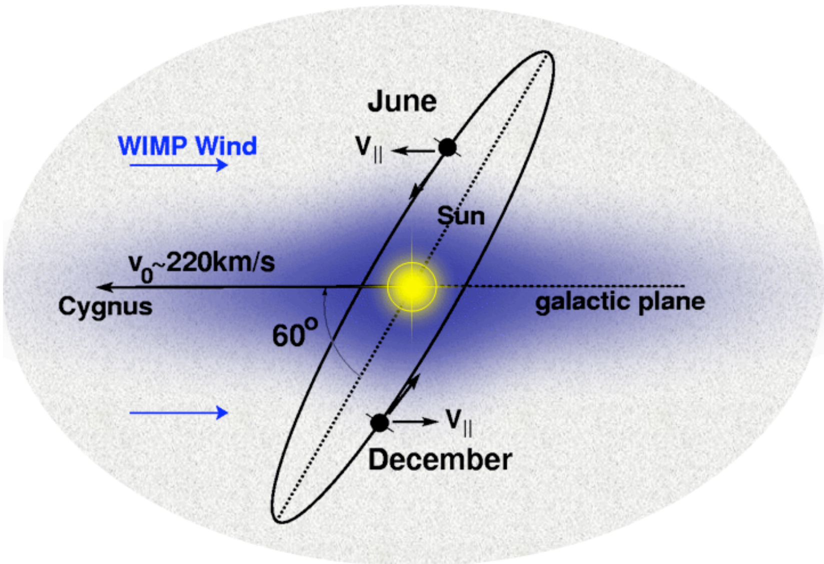
DM velocity distribution

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

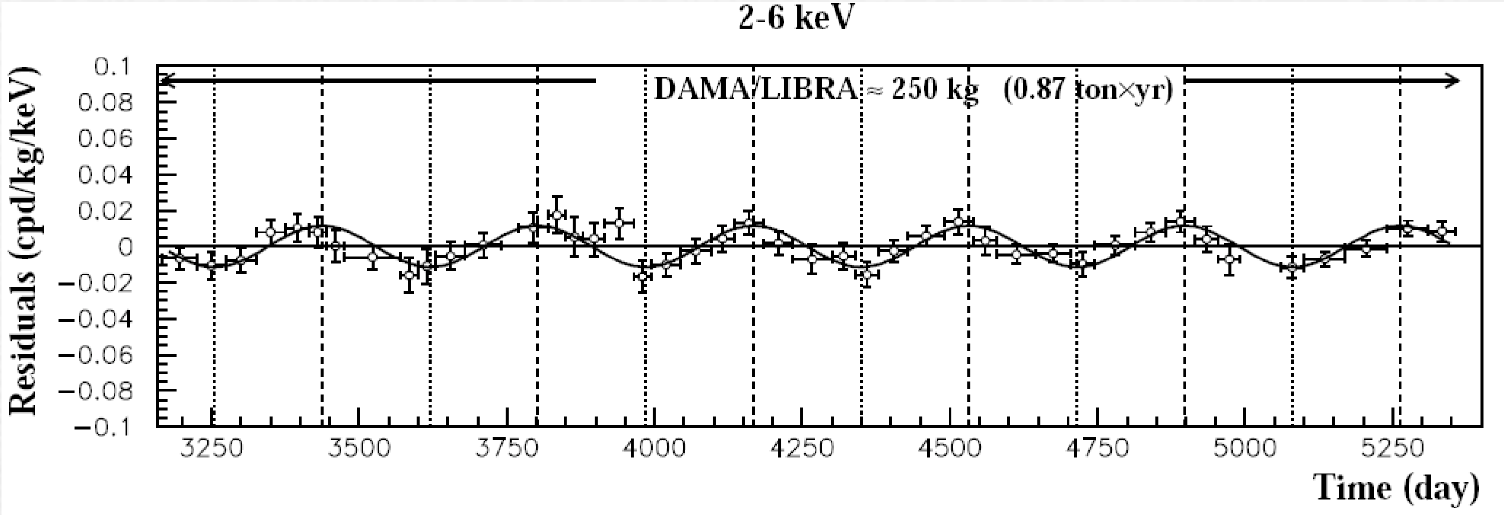
$\bar{v} \simeq 220\,{\rm km/s}$ $\qquad v_{\rm esc} \simeq 550\,{\rm km/s}$

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

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

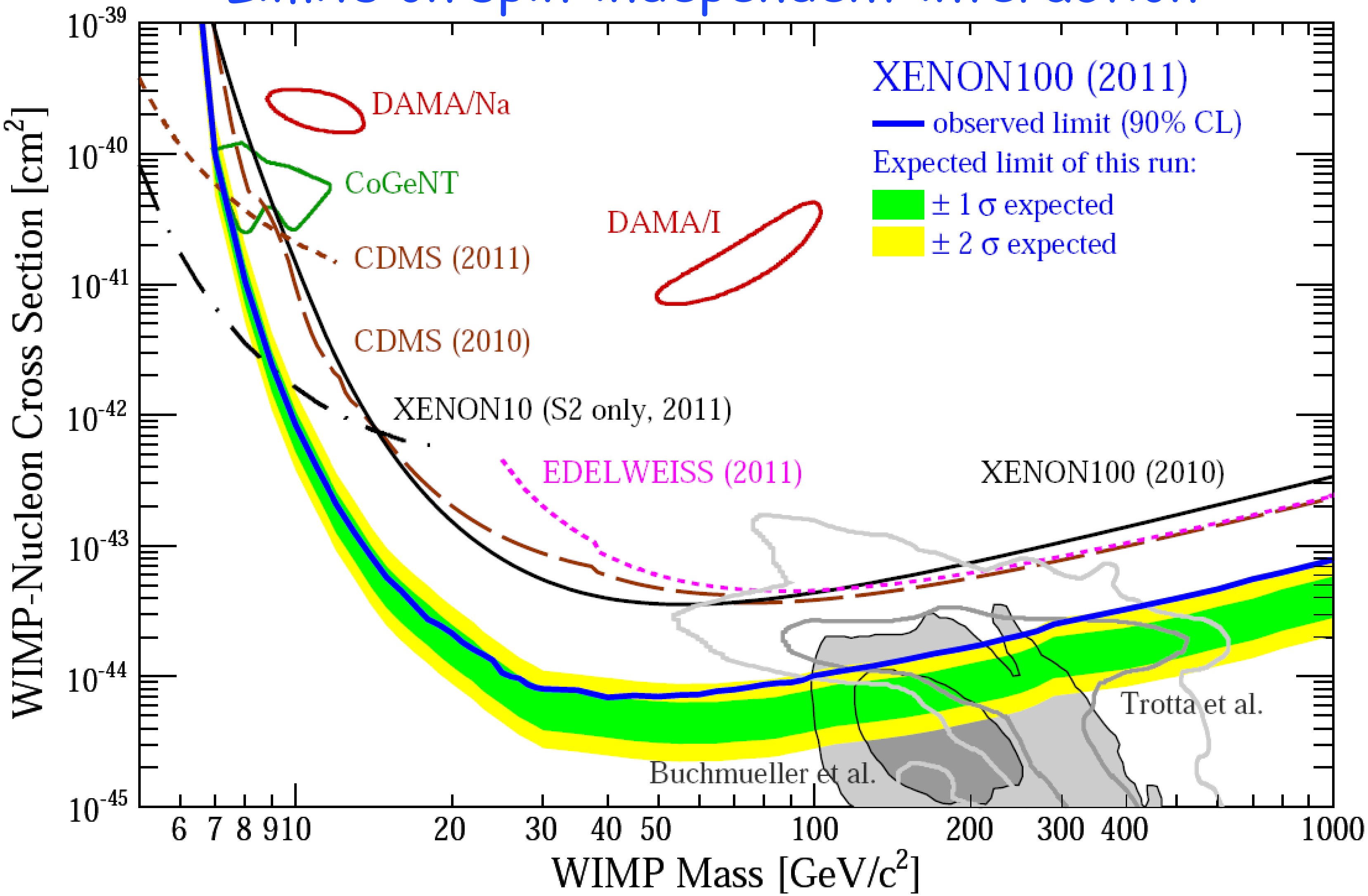


DAMA/LIBRA annual modulation signal



However not seen by other experiments ...

Limits on spin-independent interaction



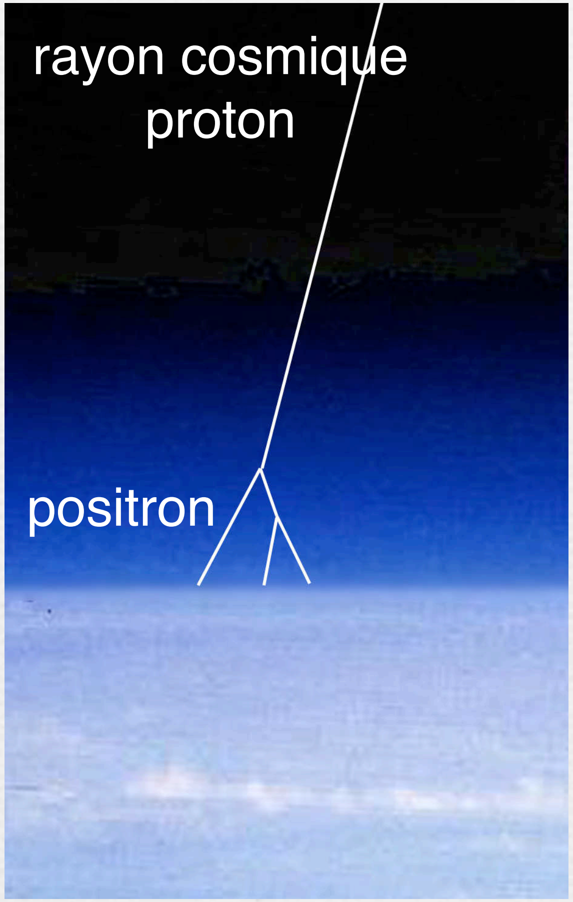
The Matter Anti-matter asymmetry

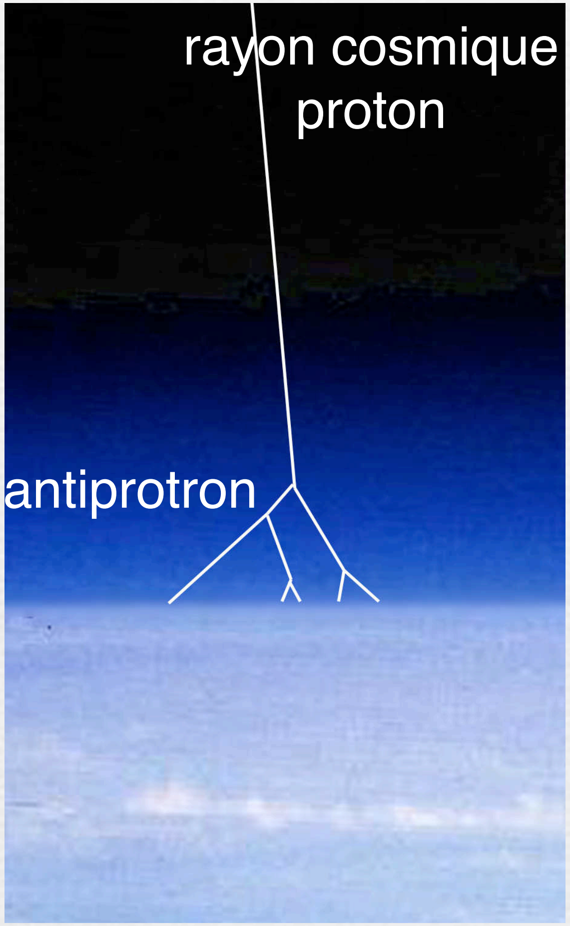
Antimatter

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

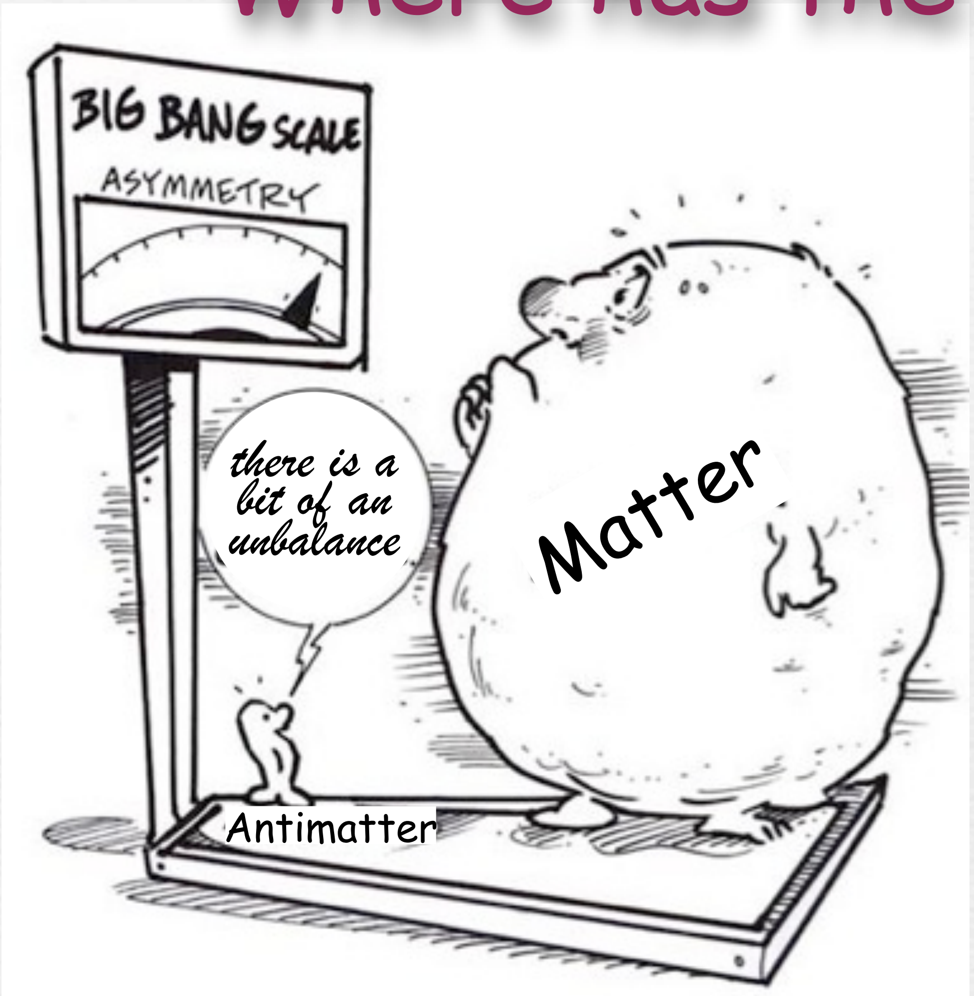
At the galactic scale: There is antimatter in the form of antiprotons in cosmic rays with ratio $n_{\overline{p}}/n_p \sim 10^{-4}$ which can be explained with processes such as

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

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

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

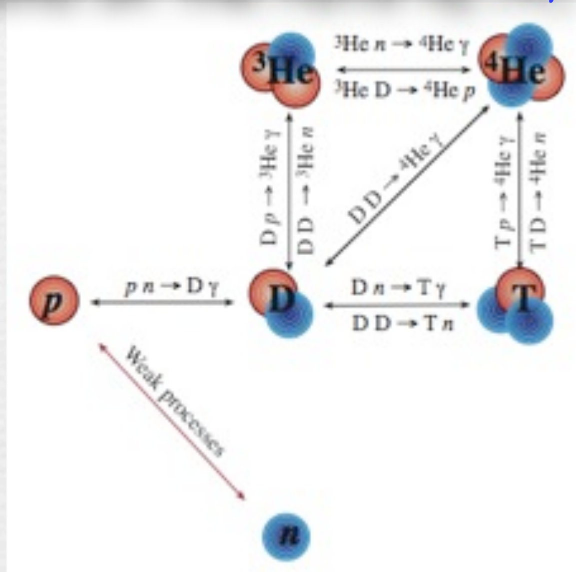
The standard model is unable to explain this matter-antimatter asymmetry

How do we measure η ?

Counting baryons is difficult because only some fraction of them formed stars and luminous objecs. 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 $\gamma \rightarrow$ pn

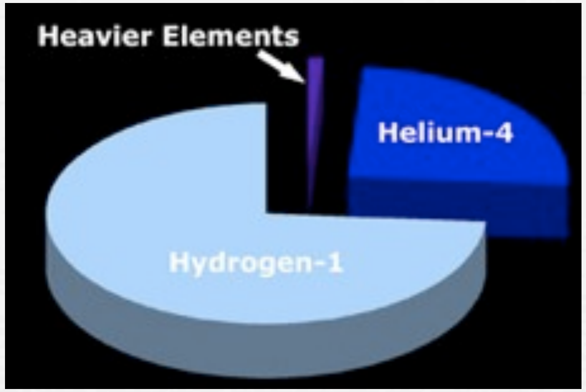


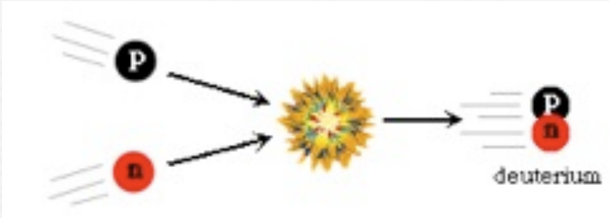
2) Measurements of CMB anisotropies

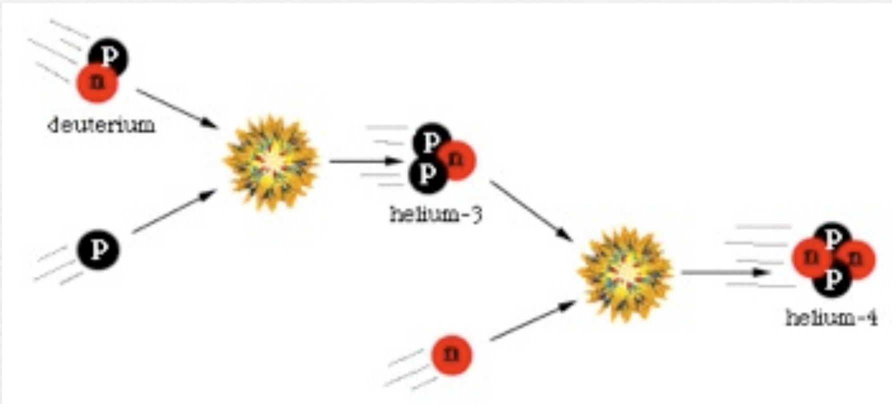
probe acoustic oscillations of the baryon/photon fluid

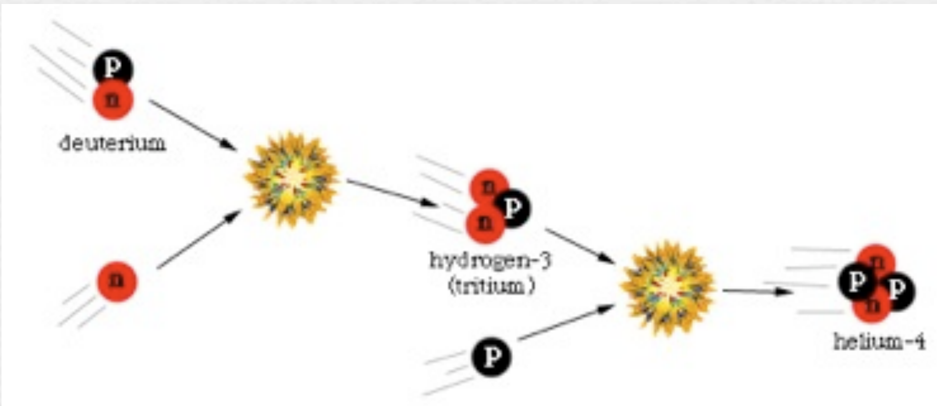
The amount of anisotropies depend on n_B / n_γ

Primordial nucleosynthesis



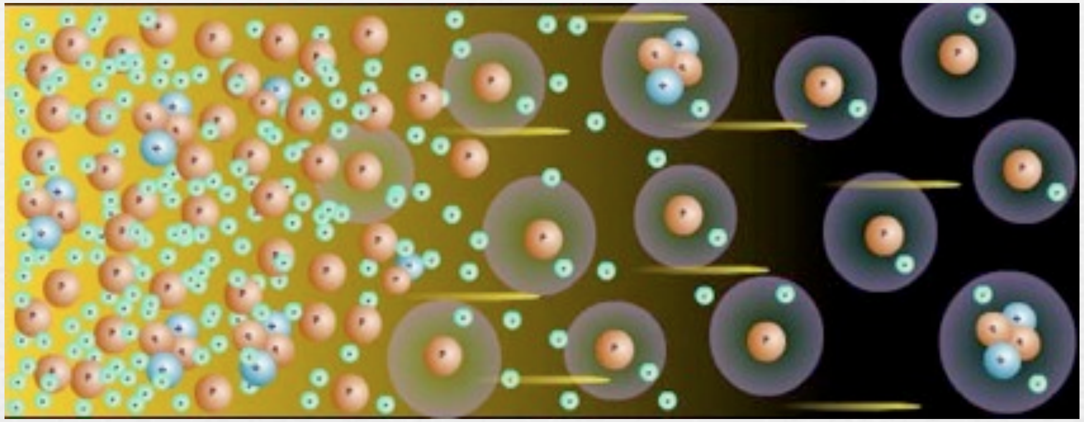


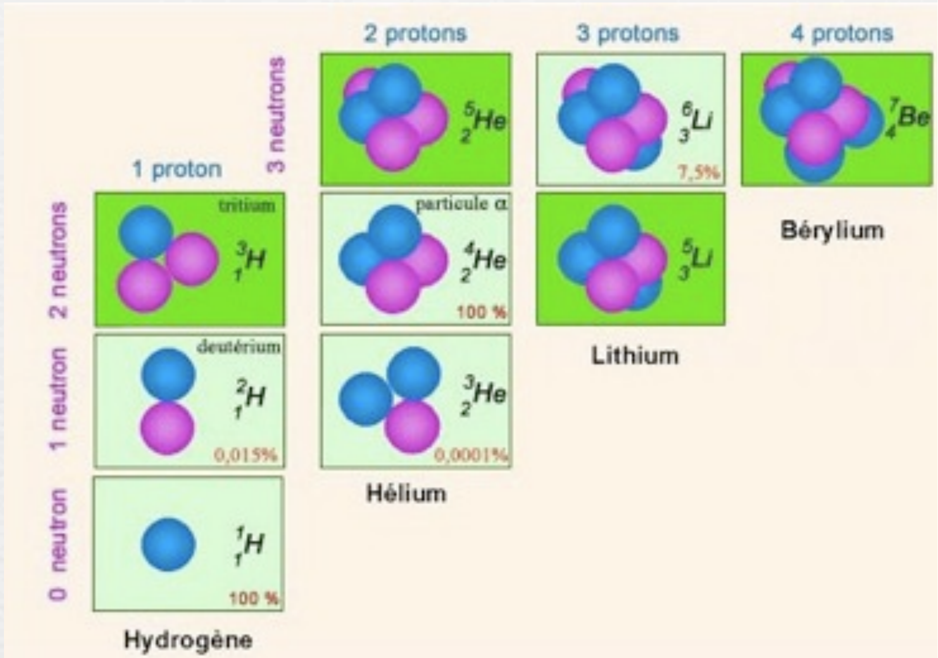




$\mathrm{p}+\mathrm{n}$	$\rightarrow$	$\mathrm{D}+\gamma$
$\mathrm{D}+\mathrm{n}$	$\rightarrow$	${}^3\mathrm{H}+\gamma$
$\mathrm{D}+\mathrm{p}$	$\rightarrow$	${}^3\mathrm{He}+\gamma$
$\mathrm{D}+\mathrm{D}$	$\rightarrow$	${}^3\mathrm{H}+\mathrm{p}$
$\mathrm{D}+\mathrm{D}$	$\rightarrow$	${}^3\mathrm{He}+\mathrm{n}$
$\mathrm{D}+\mathrm{D}$	$\rightarrow$	${}^4\mathrm{He}+\gamma$
${}^3\mathrm{H}+\mathrm{p}$	$\rightarrow$	${}^4\mathrm{He}+\gamma$
${}^3\mathrm{He}+\mathrm{n}$	$\rightarrow$	${}^3\mathrm{H}+\mathrm{p}$
${}^3\mathrm{He}+\mathrm{n}$	$\rightarrow$	${}^4\mathrm{He}+\gamma$
${}^3\mathrm{H}+\mathrm{D}$	$\rightarrow$	${}^4\mathrm{He}+\mathrm{n}$
${}^3\mathrm{He}+\mathrm{D}$	$\rightarrow$	${}^4\mathrm{He}+\mathrm{p}$
${}^3\mathrm{He}+{}^3\mathrm{He}$	$\rightarrow$	${}^4\mathrm{He}+2\mathrm{p}$
${}^4\mathrm{He}+\mathrm{D}$	$\rightarrow$	${}^6\mathrm{Li}+\gamma$
${}^4\mathrm{He}+{}^3\mathrm{H}$	$\rightarrow$	${}^7\mathrm{Li}+\gamma$
${}^4\mathrm{He}+{}^3\mathrm{He}$	$\rightarrow$	${}^7\mathrm{Be}+\gamma$
${}^6\mathrm{Li}+\mathrm{n}$	$\rightarrow$	${}^7\mathrm{Li}+\gamma$
${}^6\mathrm{Li}+\mathrm{p}$	$\rightarrow$	${}^7\mathrm{Be}+\gamma$
${}^7\mathrm{Li}+\mathrm{p}$	$\rightarrow$	${}^4\mathrm{He}+\gamma$
${}^7\mathrm{Be}+\mathrm{n}$	$\rightarrow$	${}^7\mathrm{Li}+\mathrm{p}$
${}^7\mathrm{Be}+\mathrm{e}^-$	$\rightarrow$	${}^7\mathrm{Li}+\gamma$

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





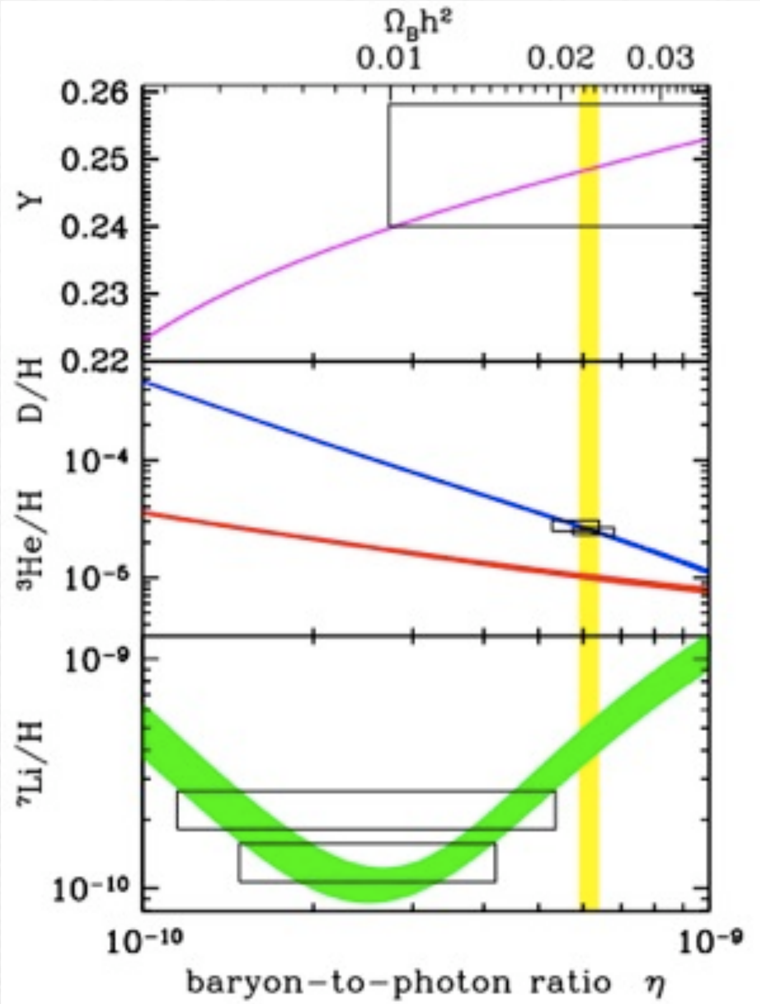
at t<1 s

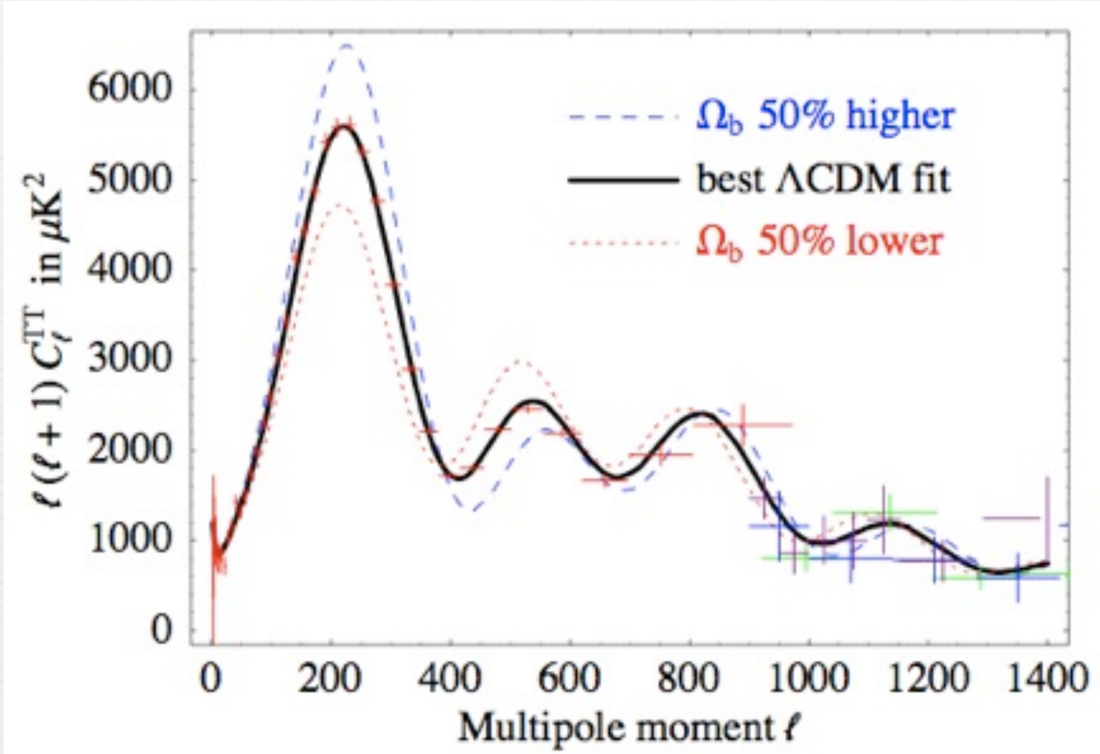
$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \nu_e$$
$$n \leftrightarrow p + e^- + \overline{\nu}_e$$

Primordial abundances versus η

Dependence of the CMB Doppler peaks on η

(CMB temperature fluctuations)





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

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

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

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)

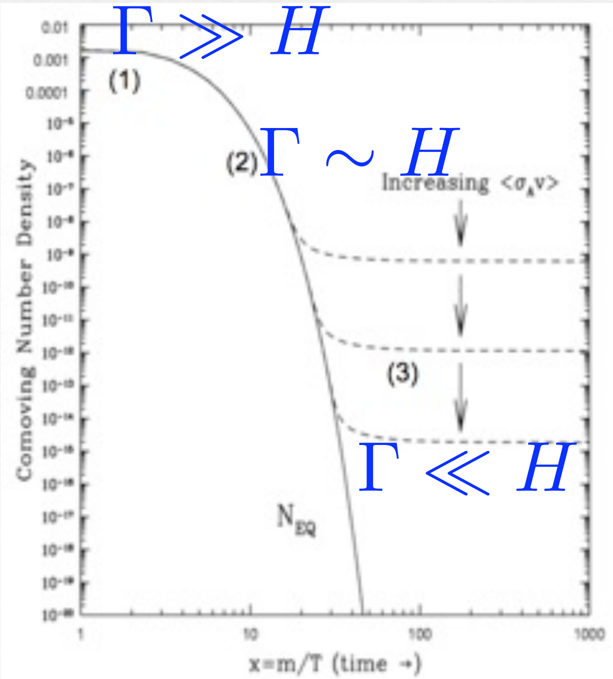
How much baryons would there be in a symmetric universe?

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)

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

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

B is violated

C and CP are violated

but which out-of-equilibrium condition?

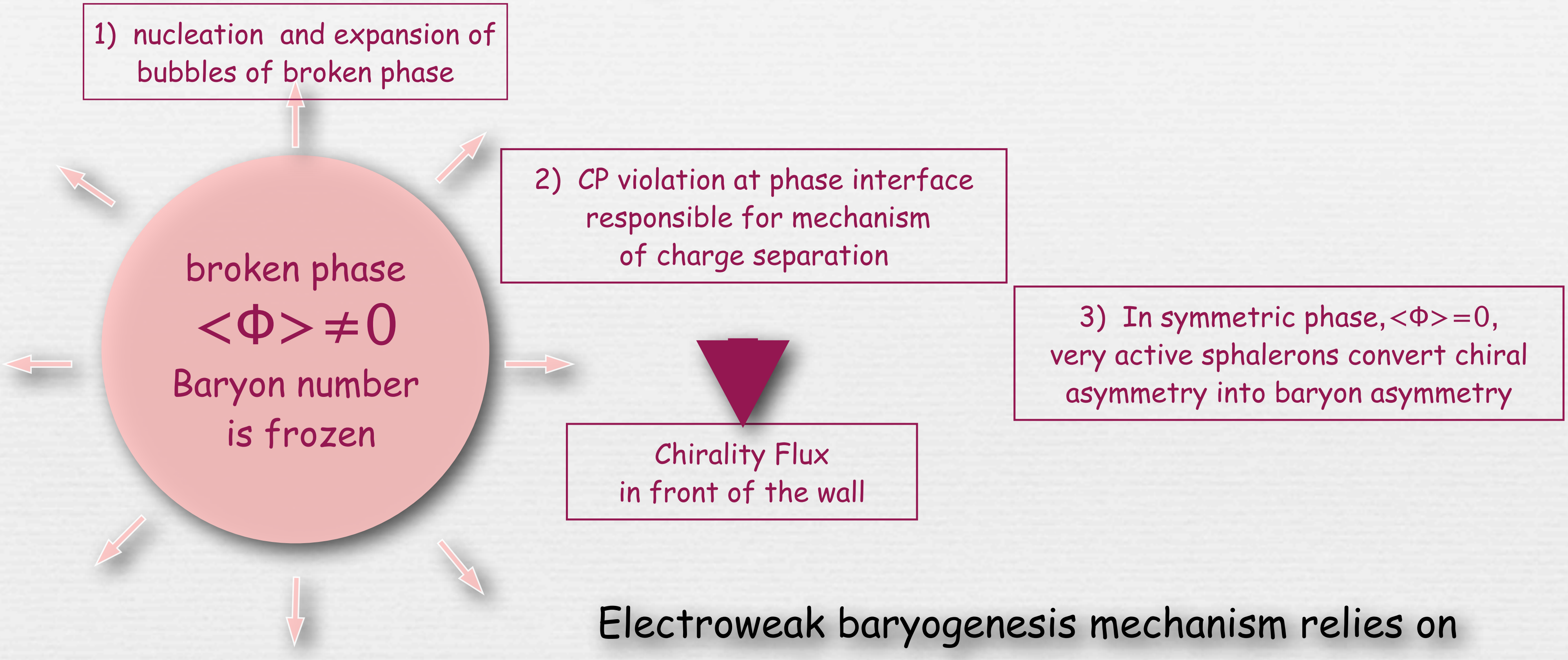
no heavy particle which could decay out-of-equilibrium

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

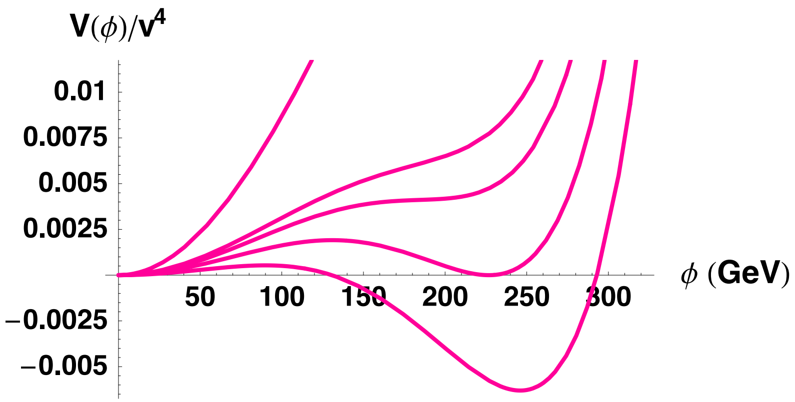


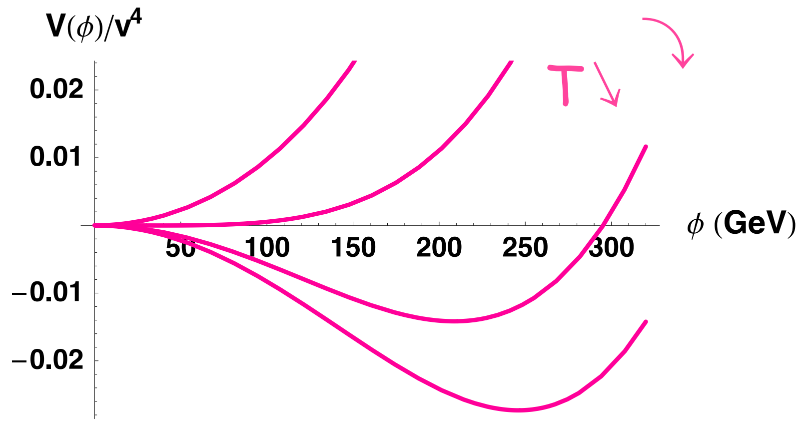
Electroweak baryogenesis mechanism relies on a first-order phase transition

What is the nature of the electroweak phase transition?

What is the nature of the electroweak phase transition ?

first-order or second-order?





LHC will provide insight as it will shed light on the Higgs sector

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!