The Particle Physics-Cosmology connection

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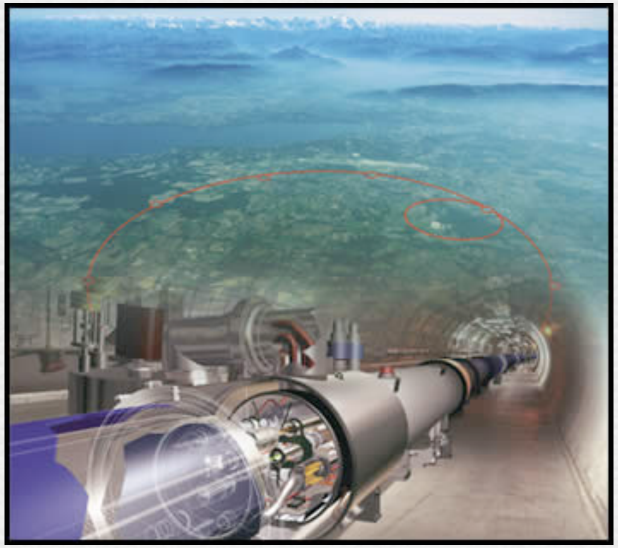
November 2009: First collisions at the Large Hadron Collider (LHC)

The LHC: The Largest (27 km) & most powerful particle accelerator on earth

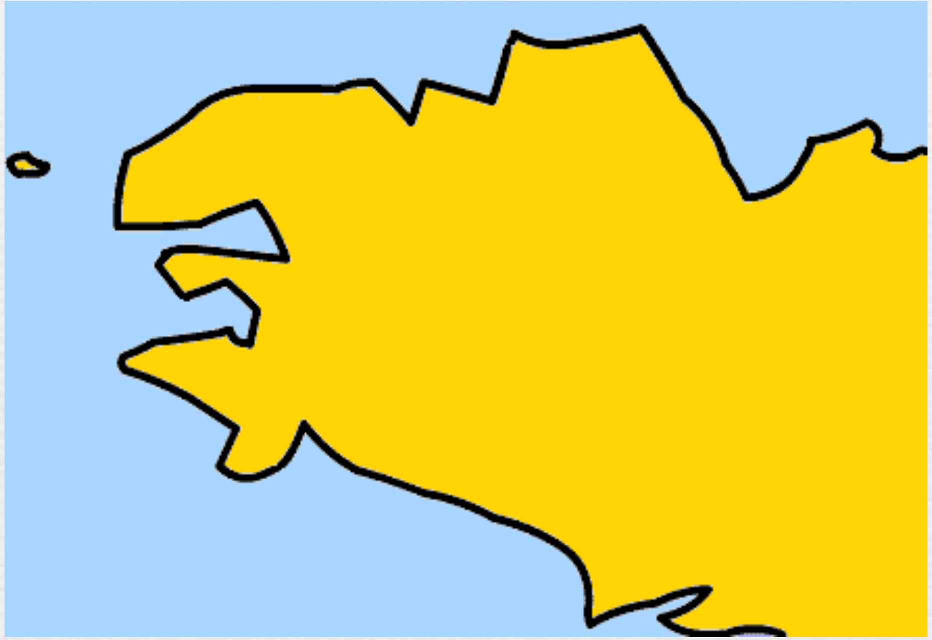
At the LHC, we collide protons at an unprecedented energy of 14×10^{12} electron-Volt

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

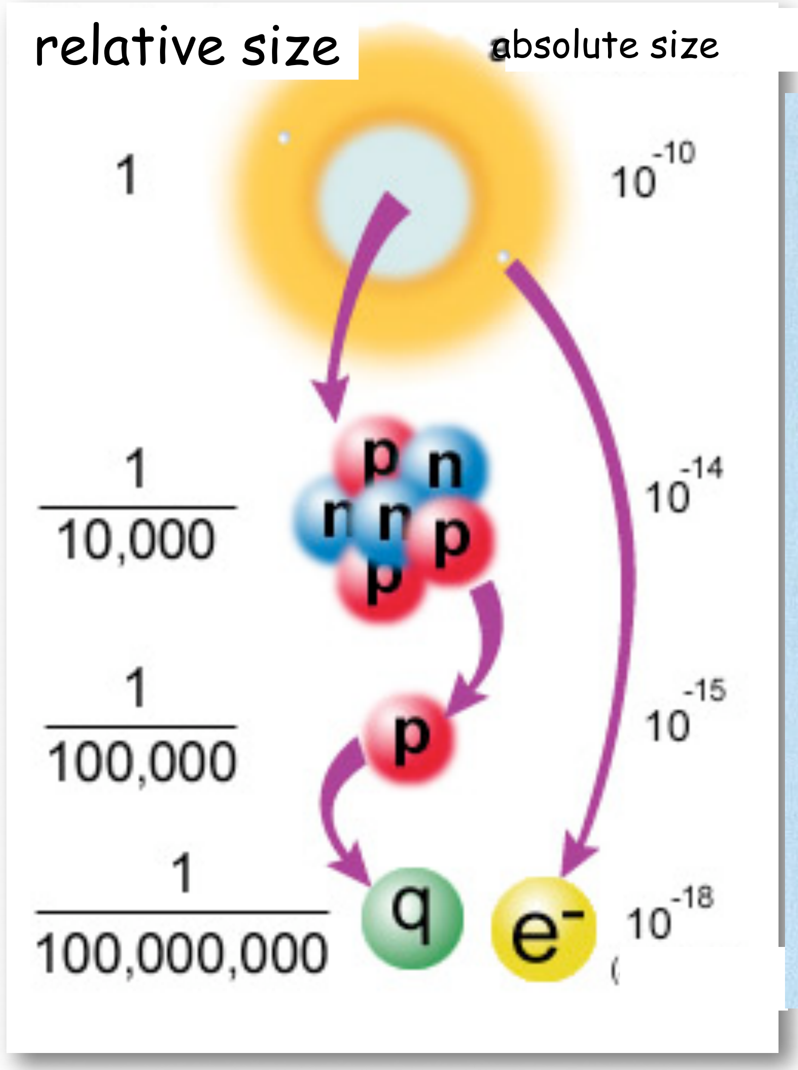


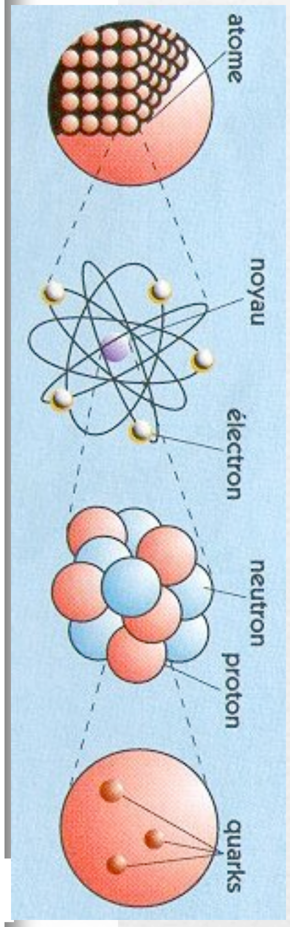
L = 400 km

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 ...





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

The Standard Model of Particle Physics

Forces **Matter** **Background**

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

gauge sector

flavour sector

neutrino mass sector (if Majorana)

(spontaneous) electroweak symmetry breaking sector

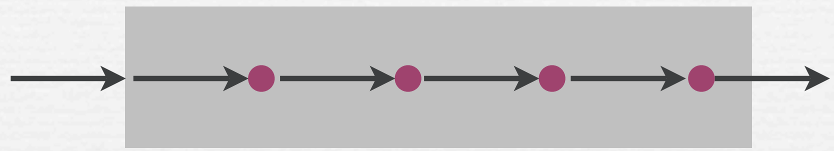
$SU(3)_C \times SU(2)_L \times U(1)_Y$

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

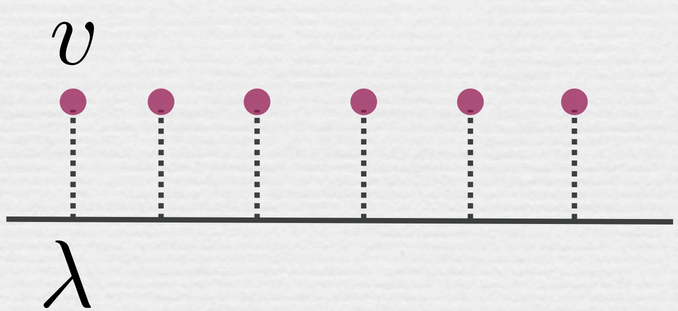
The Higgs is the only remaining unobserved piece

and a portal to new physics hidden sectors

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.

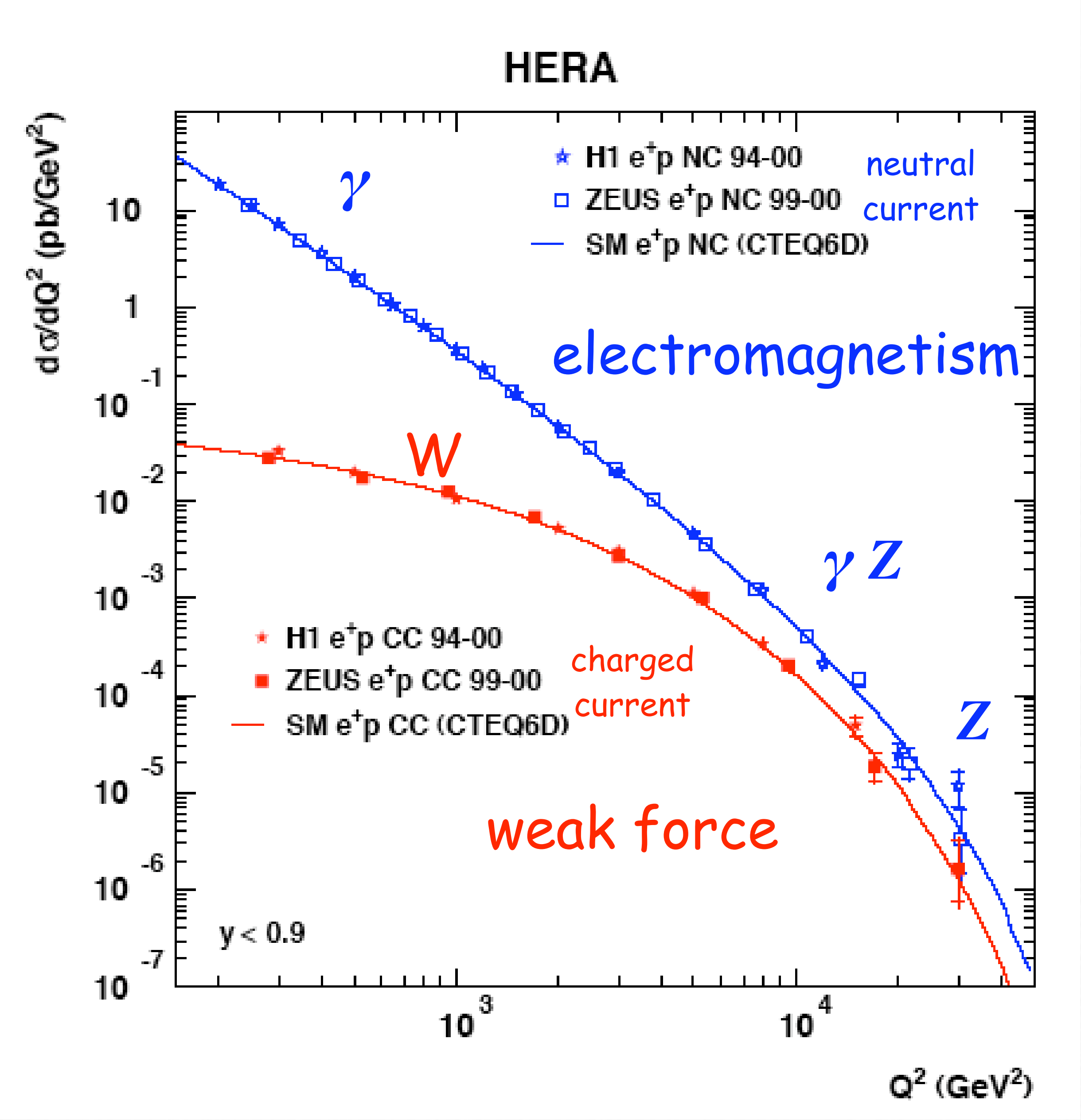


$$m \propto \lambda v$$

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.

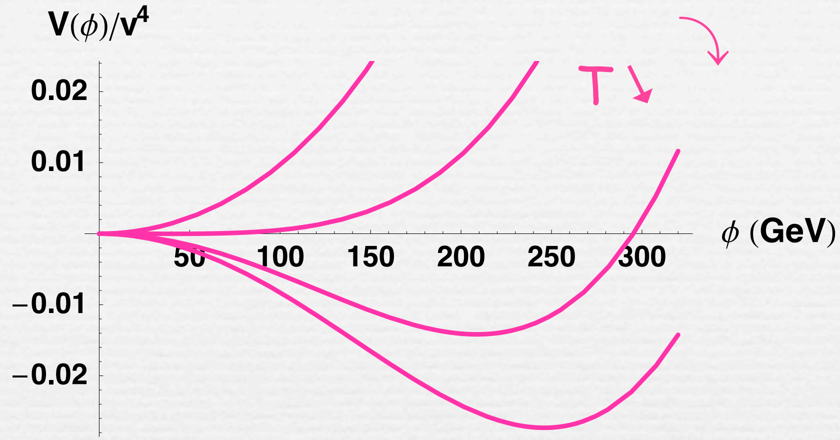
[M. Mangano]

Electroweak Unification

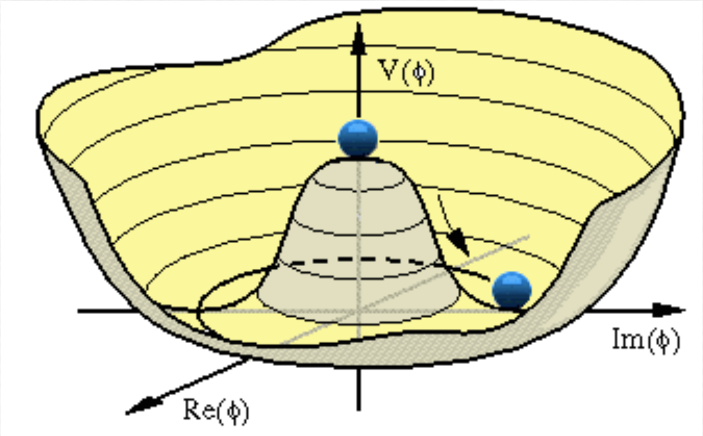


Higgs Mechanism

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



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.



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.

Which Higgs ?

- 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 ?

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

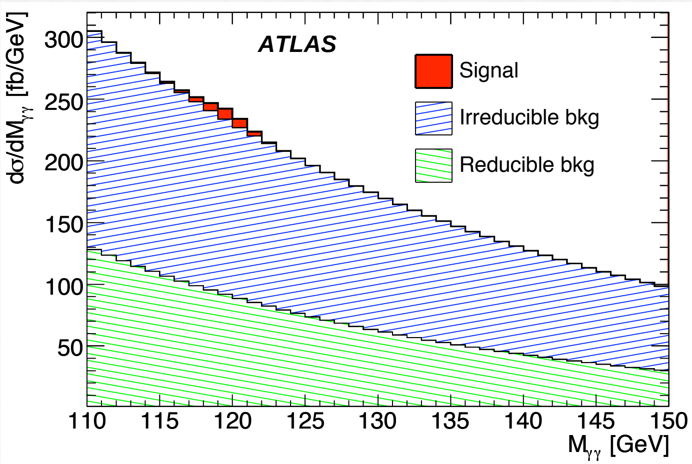
-> no hydrogen atom

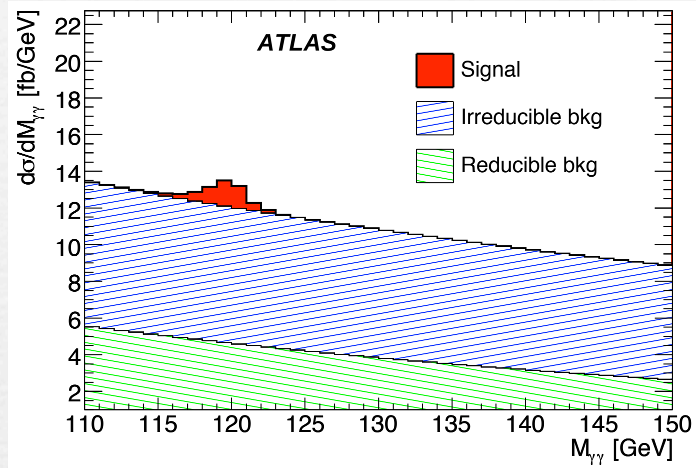
-> very different primordial nucleosynthesis

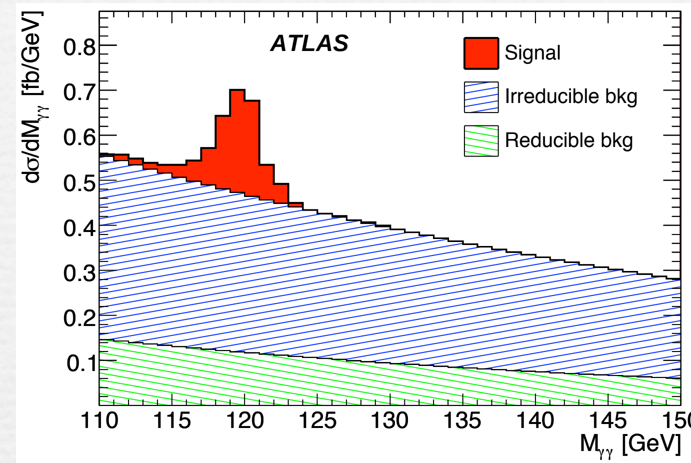
-> a profoundly different (and terribly boring) universe

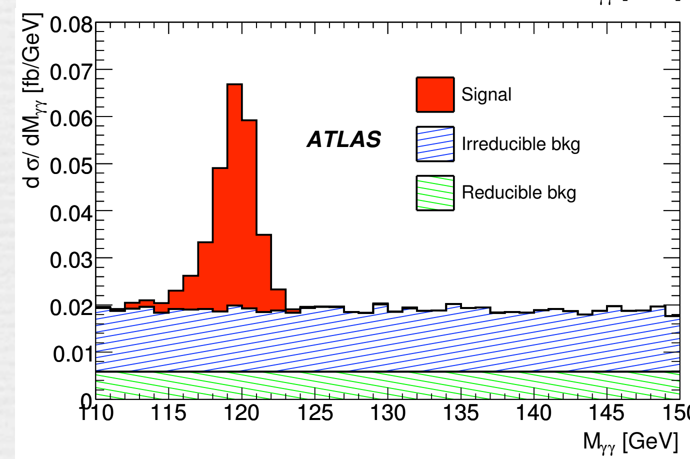
What questions the LHC experiments will try to answer :

Does a Higgs boson exist ?









If yes :

- is there only one ?
- what are its mass, width, quantum numbers ?
- does it generate EW symmetry breaking and give mass to fermions too as in the Standard Model or is something else needed ?
- what are its couplings to itself and other particles
- Spin determination
- CP properties

If no :

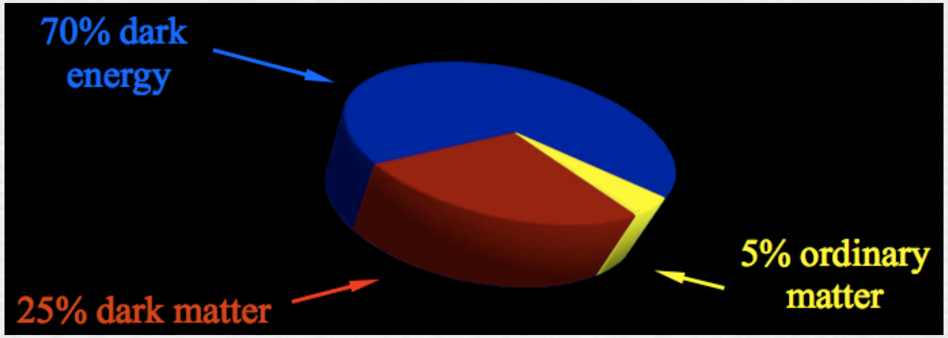
be ready for

- very tough searches at the (S)LHC (VLVL scattering, ...) or
- more spectacular phenomena such as W’, Z’ (KK) resonances, technicolor, etc...

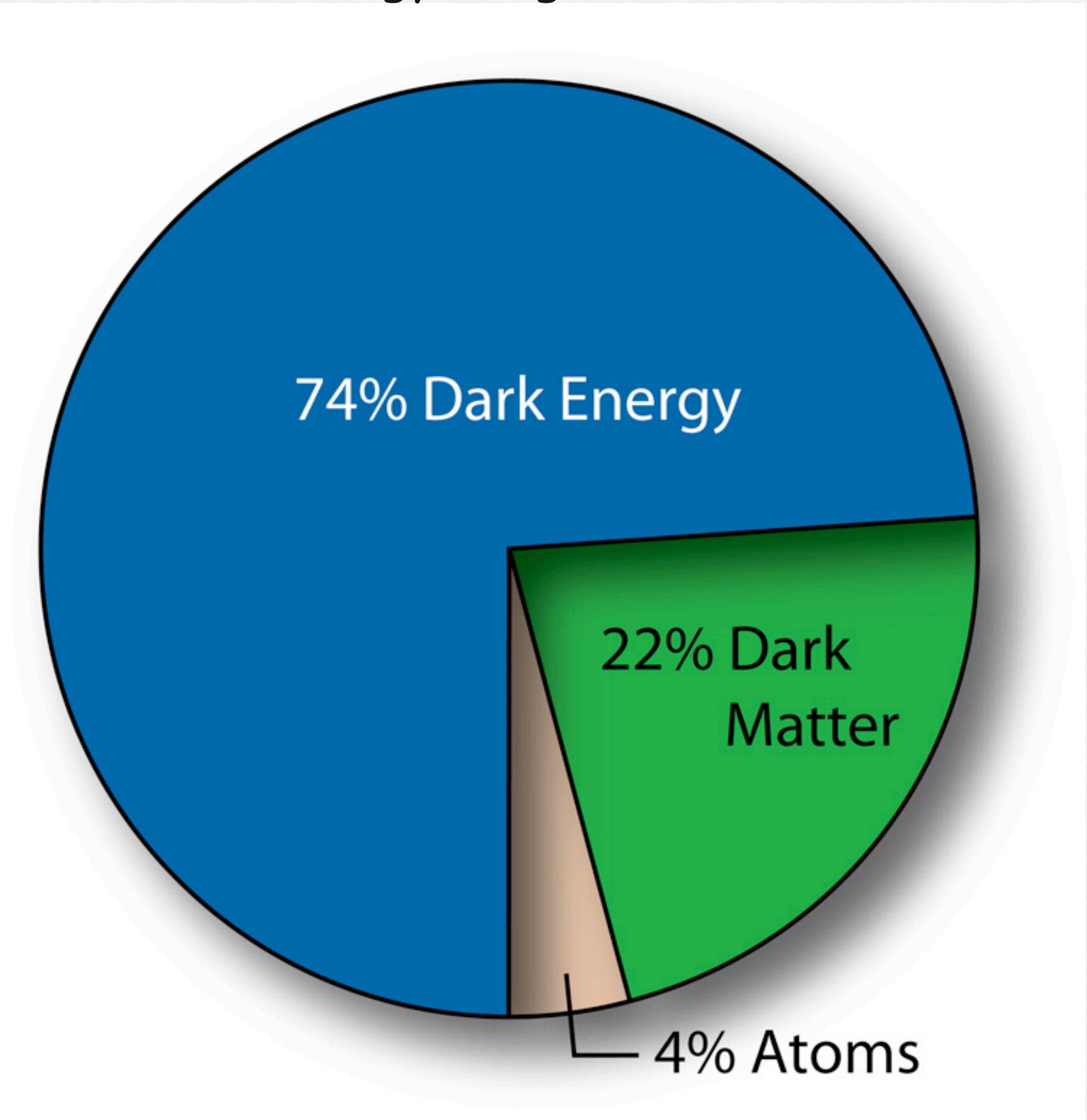
Most recent experimental successes in particle physics

- top quark discovery
- Solar, atmospheric & terrestrial neutrino oscillations
- Direct CP violation in K mesons
- CP violation in B mesons
- Validation of quantum properties of Standard Model
- Observation of accelerated expansion of the universe
- Determination of the energy/matter content of the universe

Nevertheless:
We're lacking the understanding of 95 % of the energetic content of the universe



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



Precision Cosmology

WMAP Cosmological Parameters

Model: lcdm+sz+lens

Data: wmap7

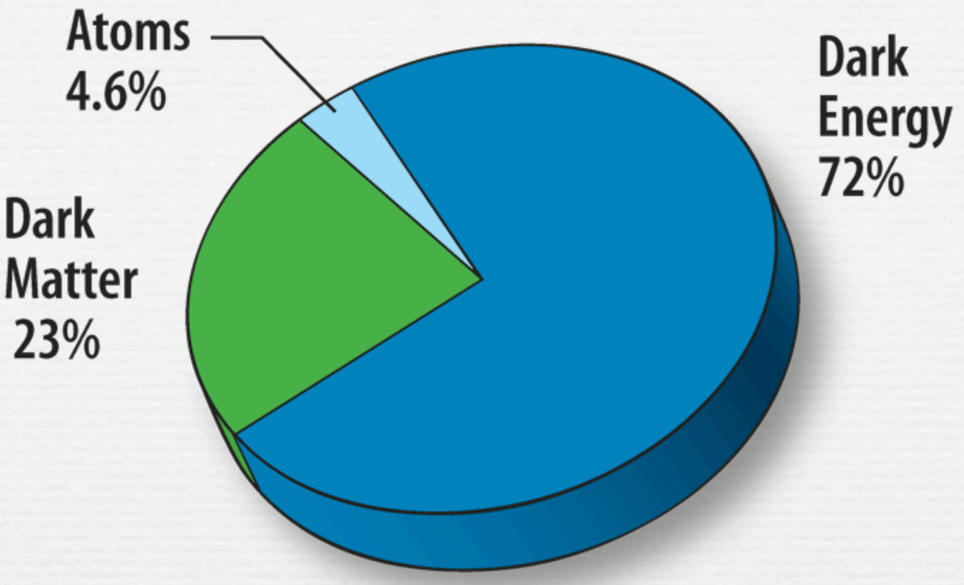
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1 - n_s$	0.037 ± 0.014
$1 - n_s$	$0.0079 < 1 - n_s < 0.0642$ (95% CL)	$A_{\rm BAO}(z = 0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm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

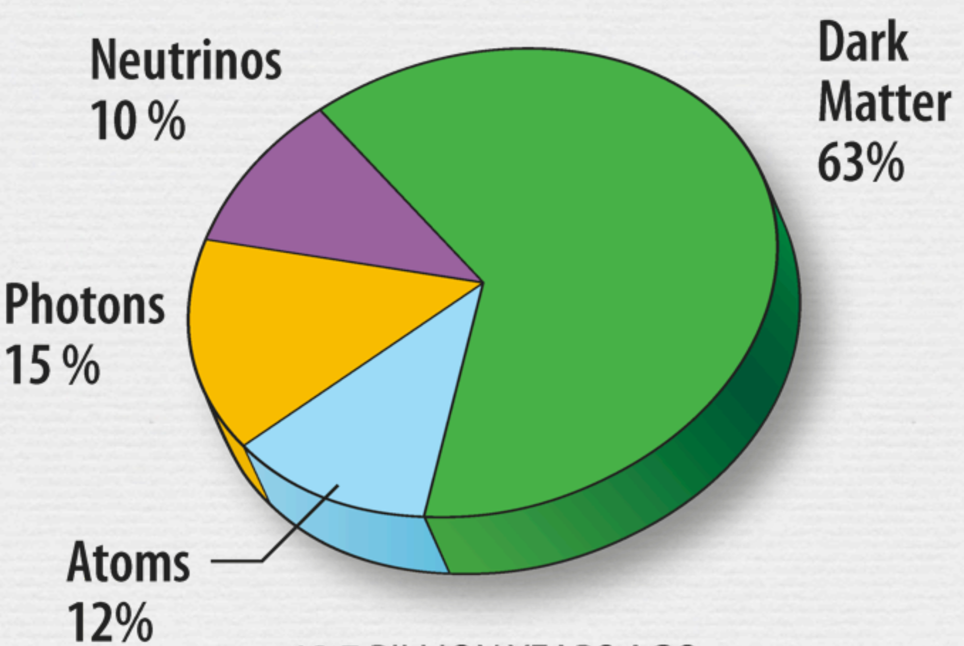
expansion rate

fraction of the total energy density in matter

age of the universe

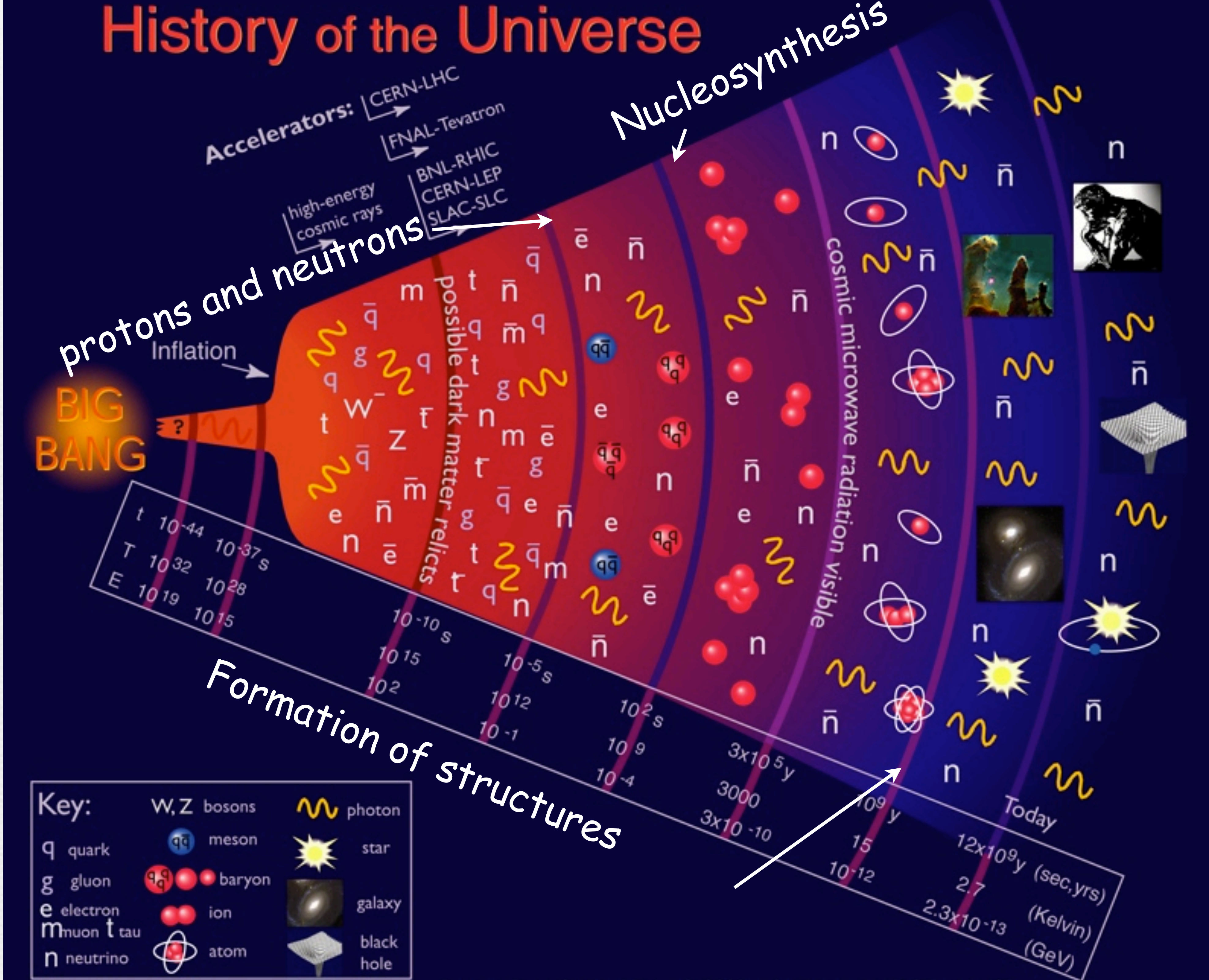


TODAY

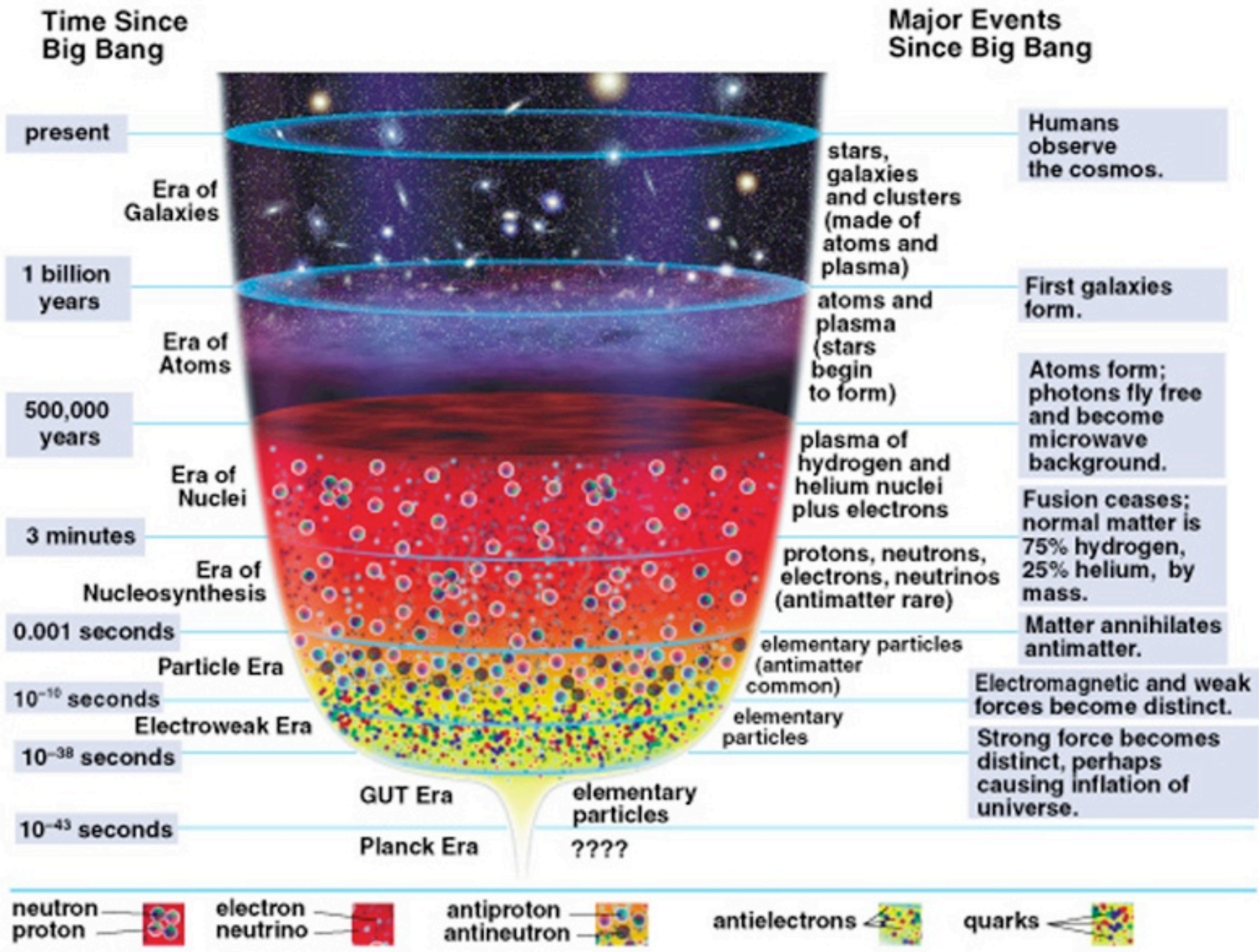


13.7 BILLION YEARS AGO

(Universe 380,000 years old)



History of the Universe
Nucleosynthesis
protons and neutrons
Formation of structures
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole



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

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

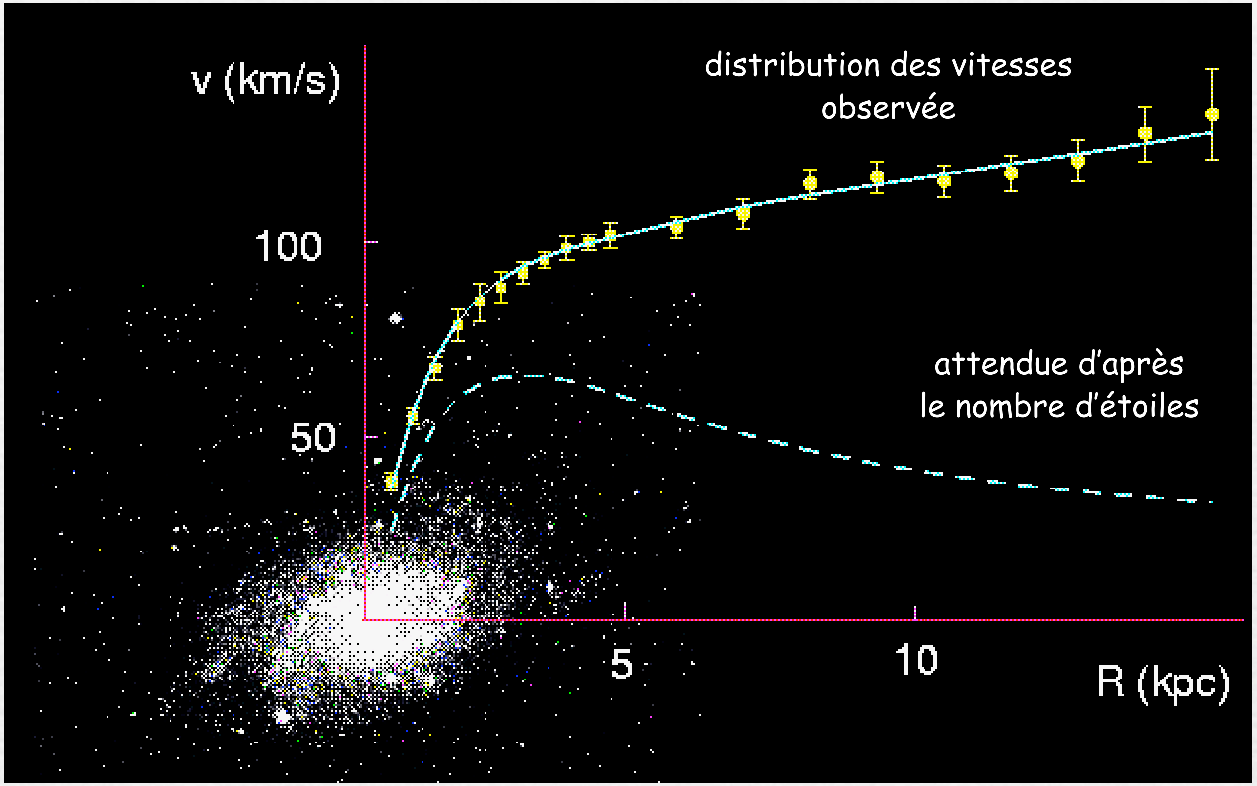
- the (quasi) absence of antimatter in the universe

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

→ observational need for new physics

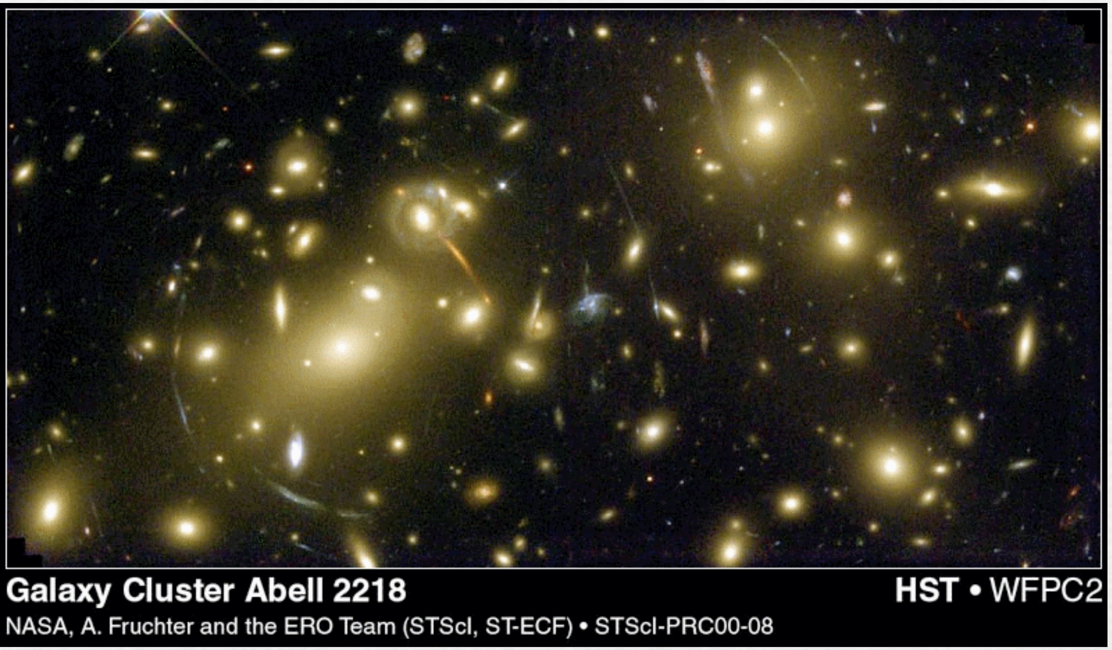
→ what does this have to do with the electroweak scale?

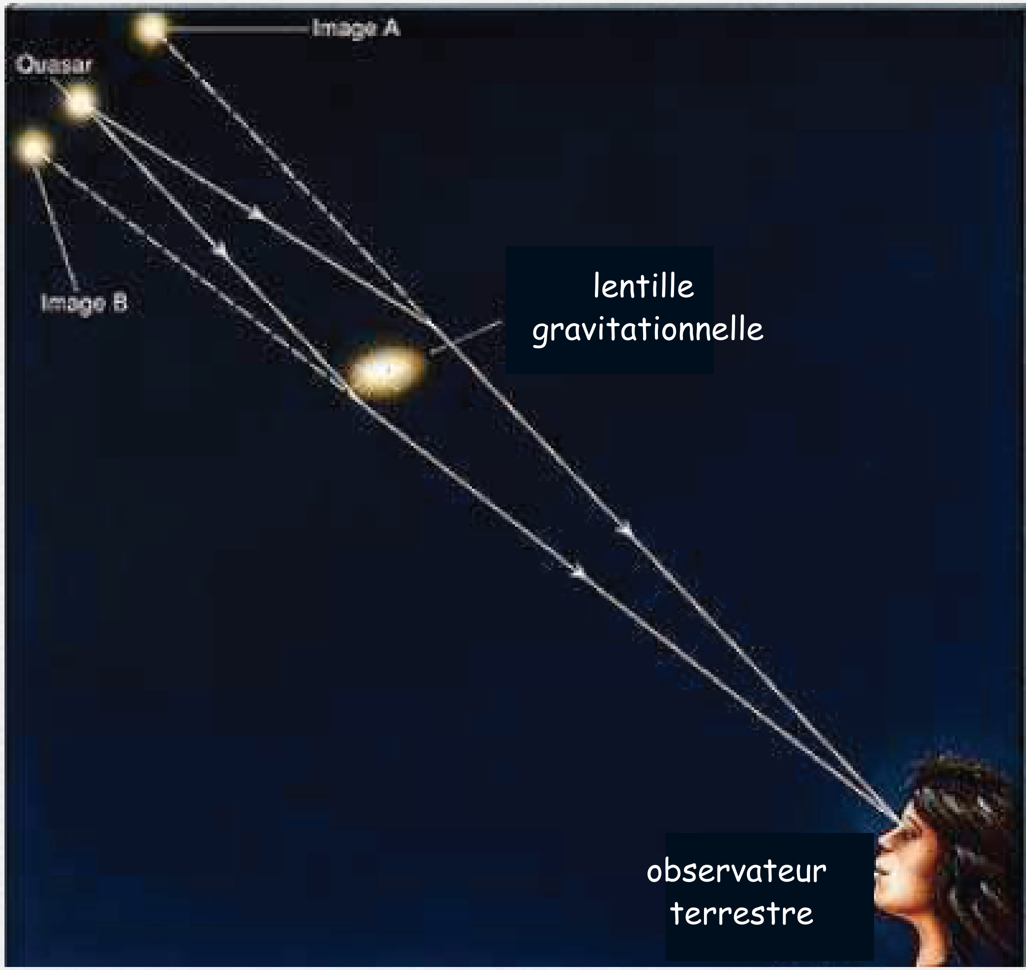
galaxy rotation curves



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

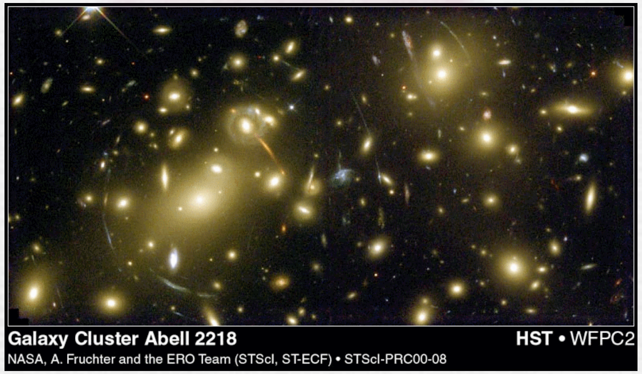
gravitational lensing



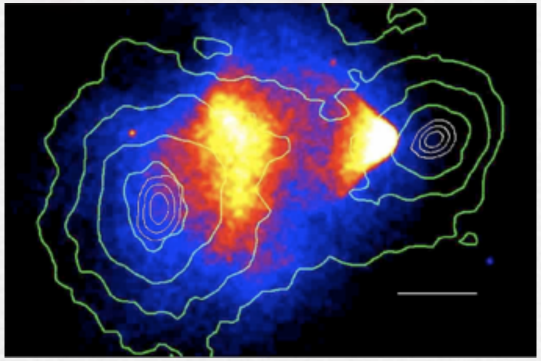


The existence of (Cold) Dark Matter has been established by a host of different methods; it is needed on all scales

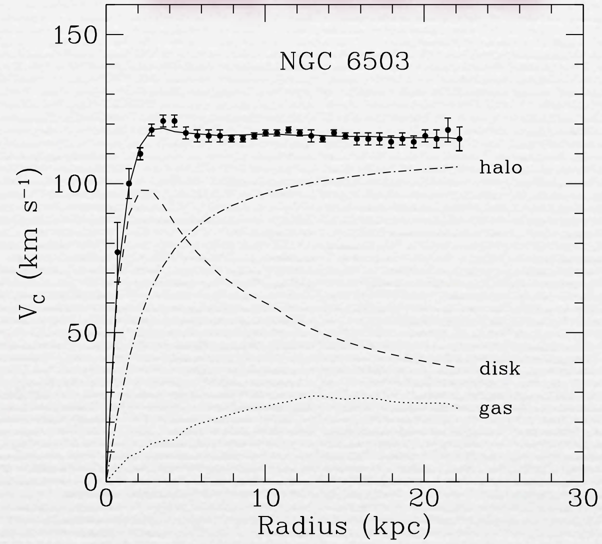
Gravitational lensing



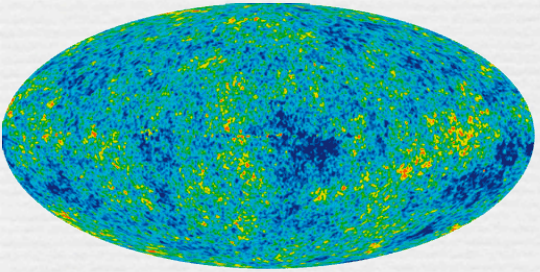
The "Bullet cluster": lensing map versus X-ray image

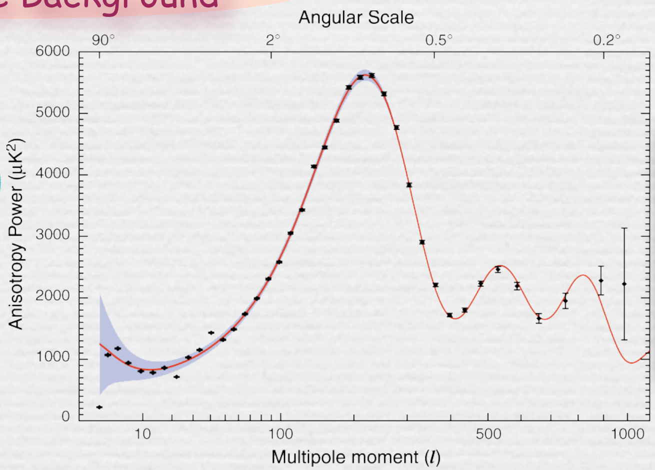


Galaxy rotation curves



Cosmic Microwave Background





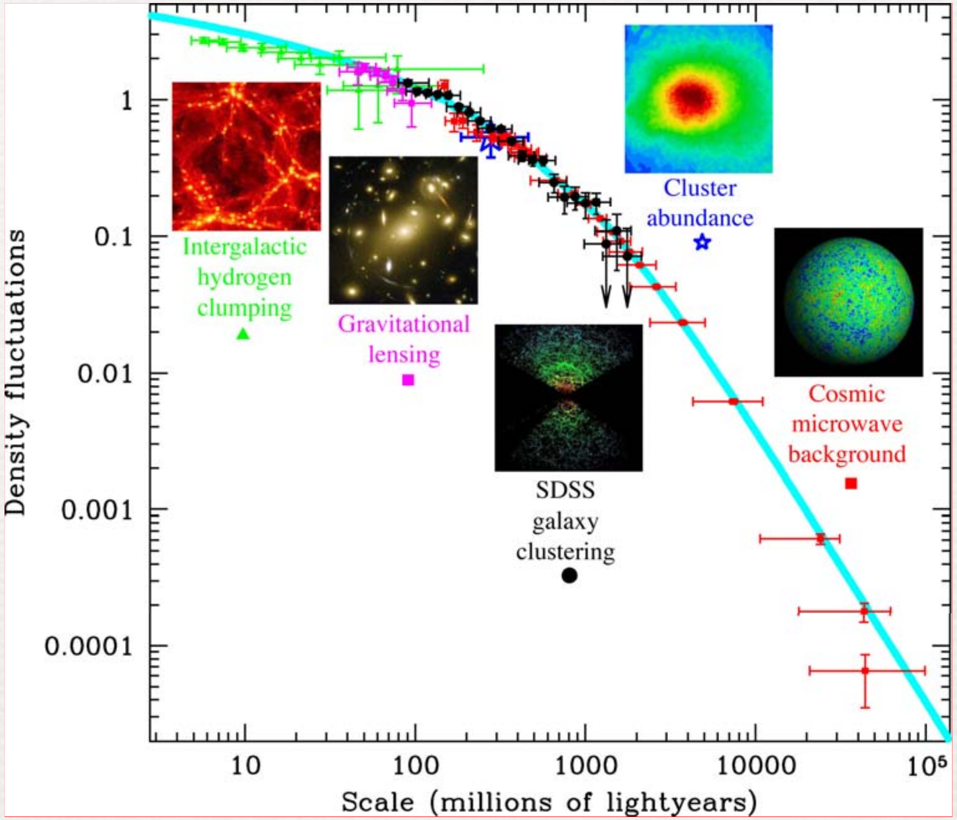
... etc

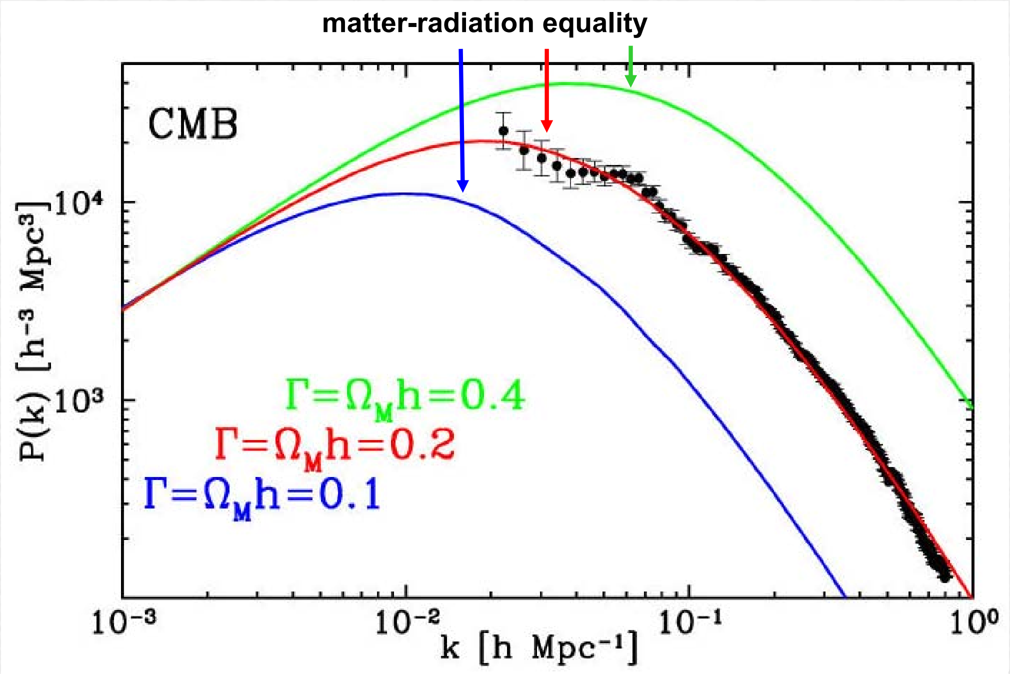
-> Fraction of the universe's energy density stored in dark matter : $\Omega_{DM} \approx 0.22$

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

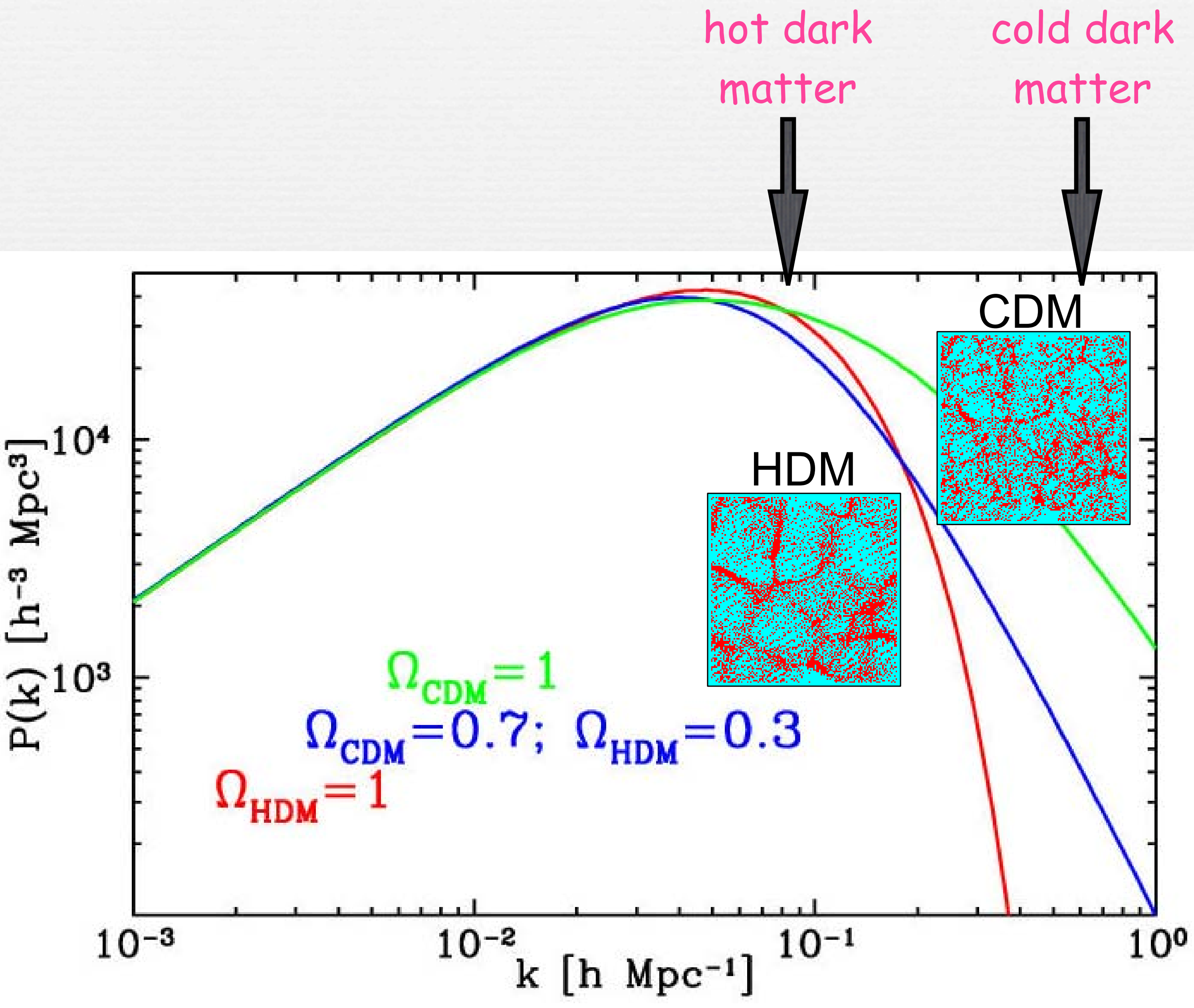
DM properties are well-constrained (gravitationally interacting, long-lived, not hot, not baryonic) but its identity remains a mystery

Matter power spectrum





Neutrinos



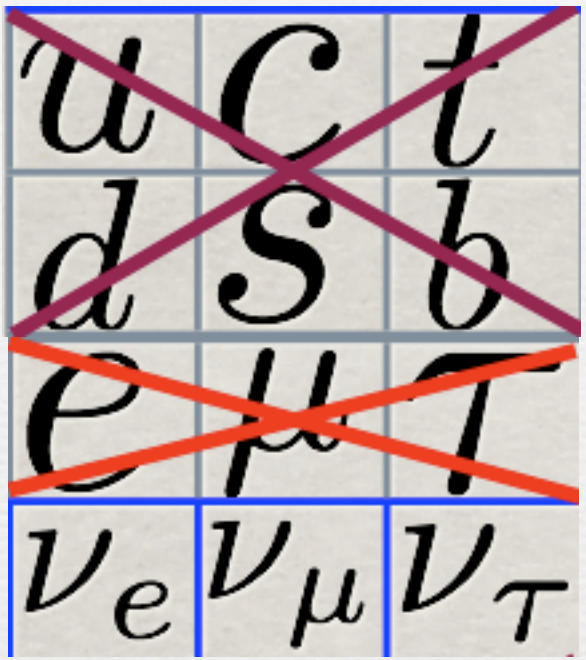
hot dark matter
cold dark matter
CDM
HDM
$\Omega_{CDM}=1$
$\Omega_{CDM}=0.7;\ \Omega_{HDM}=0.3$
$\Omega_{HDM}=1$
P(k) [h^{-3} Mpc^3]
10^4
10^3
10^{-3}
10^{-2}
10^{-1}
10^0
k [h Mpc^{-1}]

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

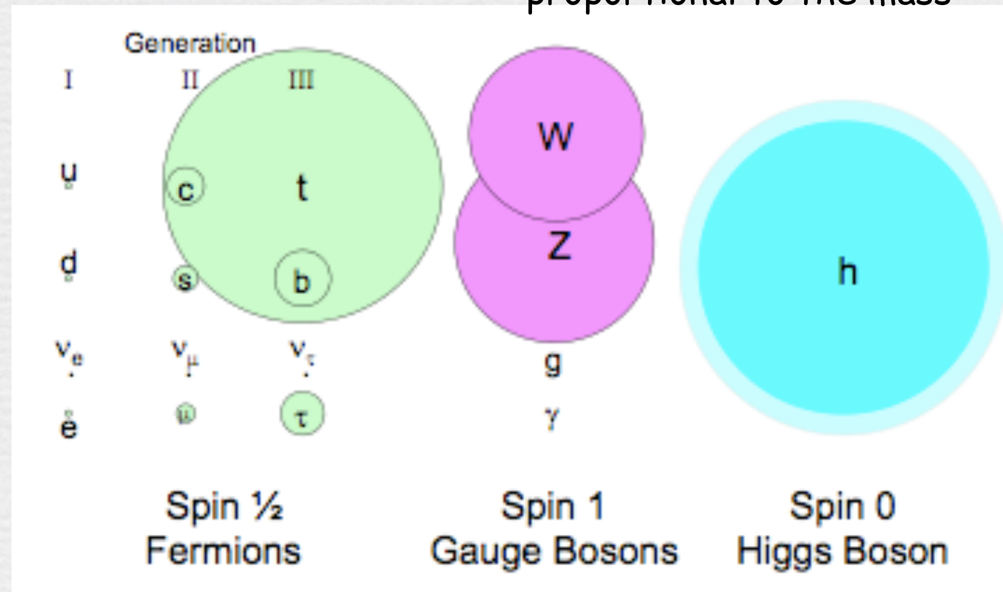
baryonic

massless

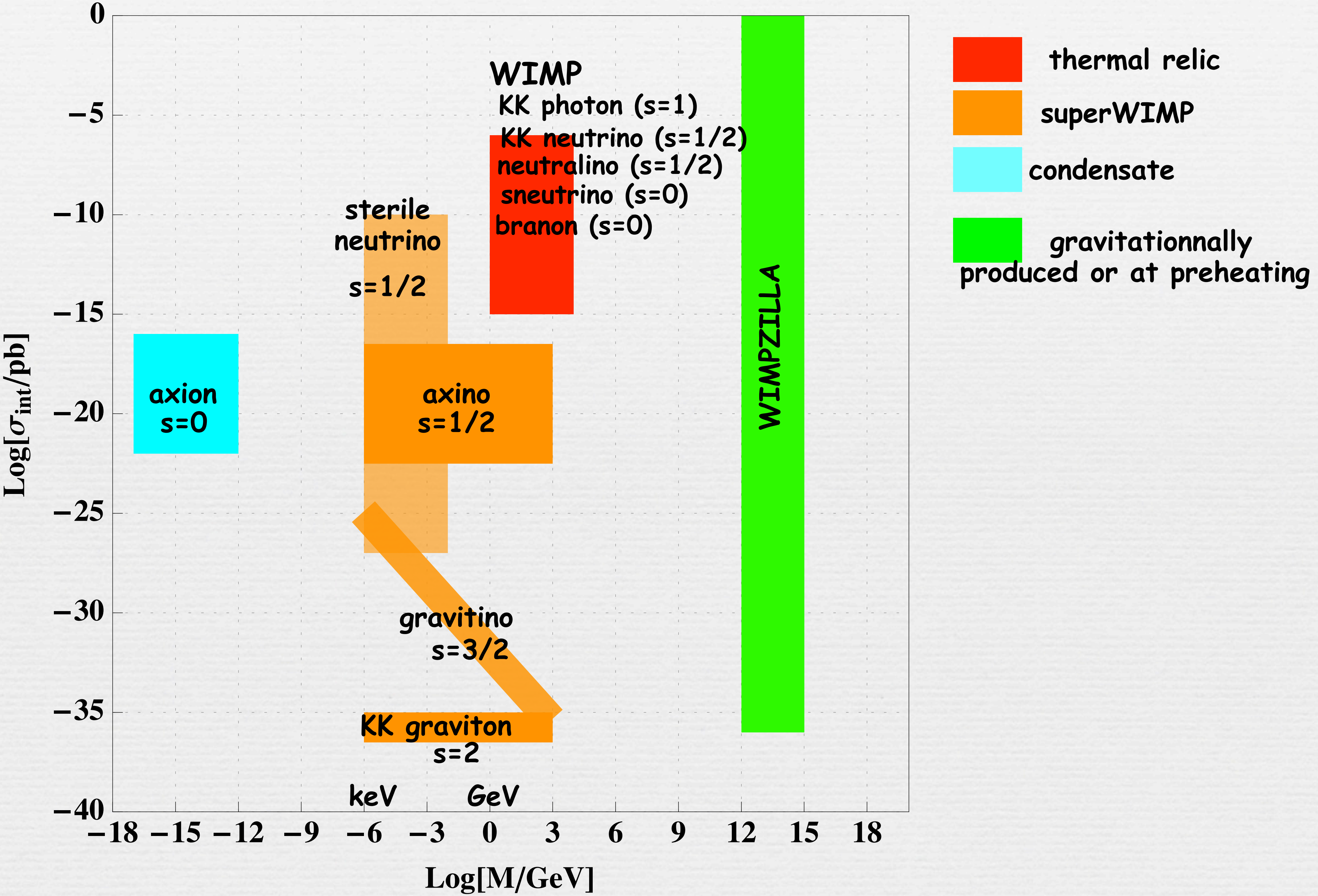
contribution to the energy budget of the universe

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

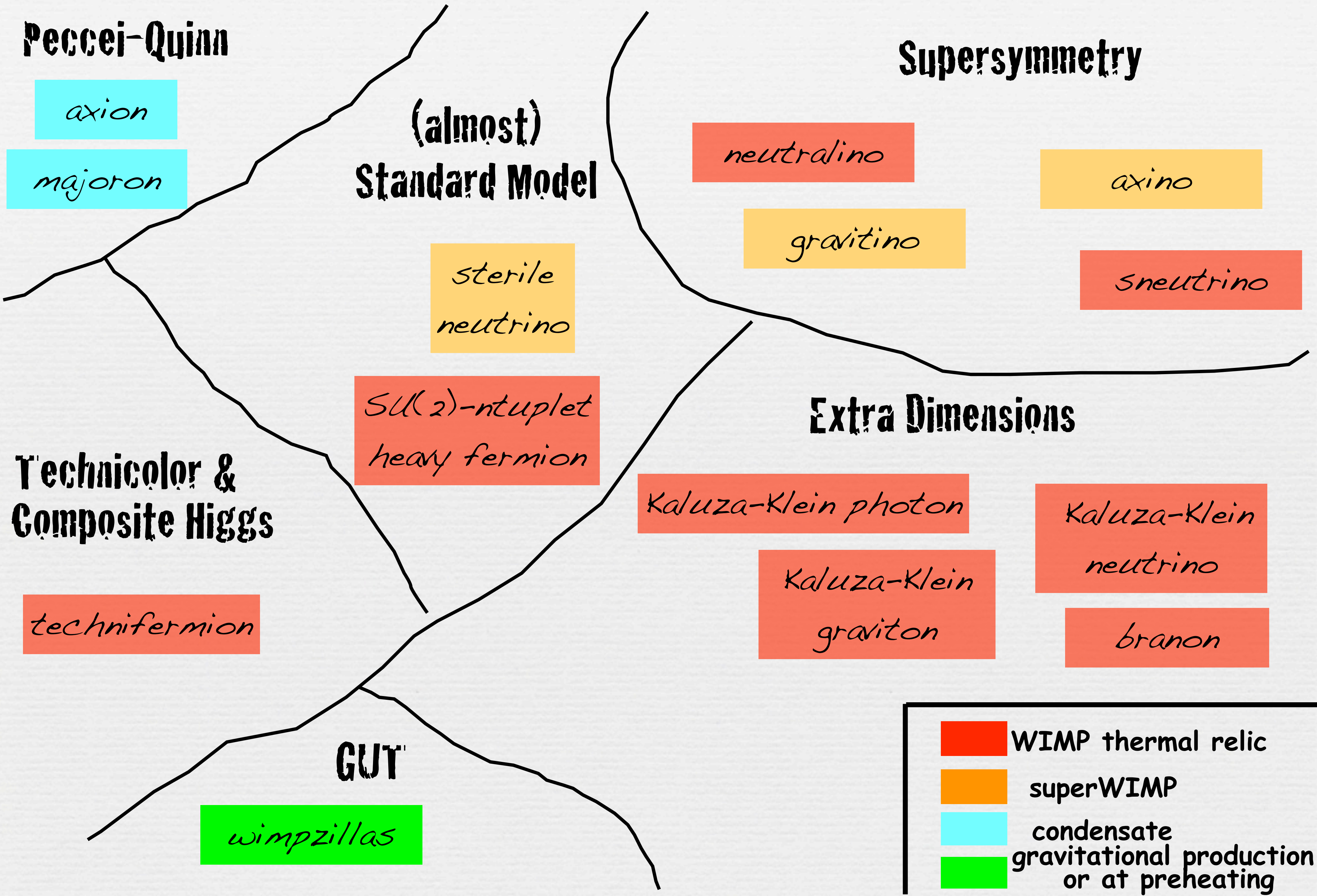
radius of circle is proportional to the mass



Dark Matter Candidates Ω~1



In Theory Space

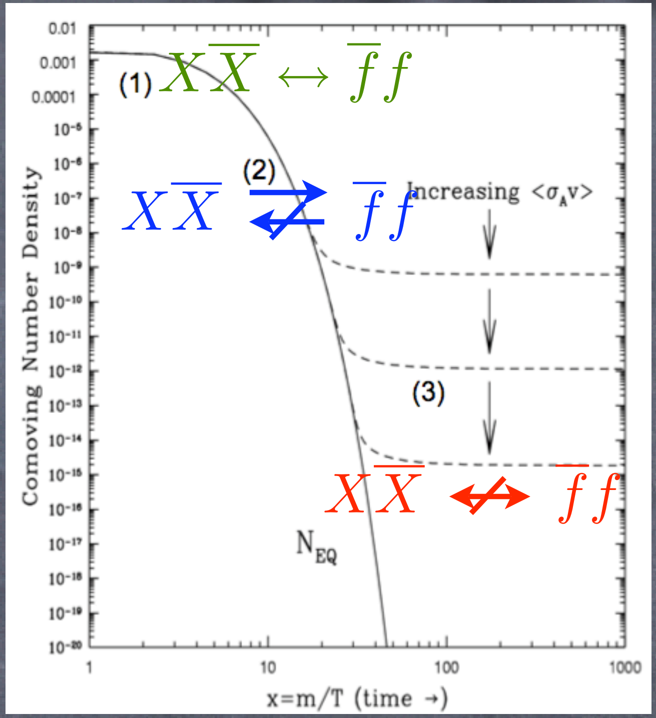


Dark matter candidates: two main possibilities

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

sizable (but not strong) couplings to the SM -> symmetry needed to guarantee stability

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



$\Rightarrow <\sigma_{anni}\ v> = 0.1$ pb

The "WIMP miracle"

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

$\Rightarrow m \sim 100$ GeV

Production mechanism is model-dependent, depends on early-universe cosmology

ex: meV scalar with $1/M_{Pl}$ couplings (radion)

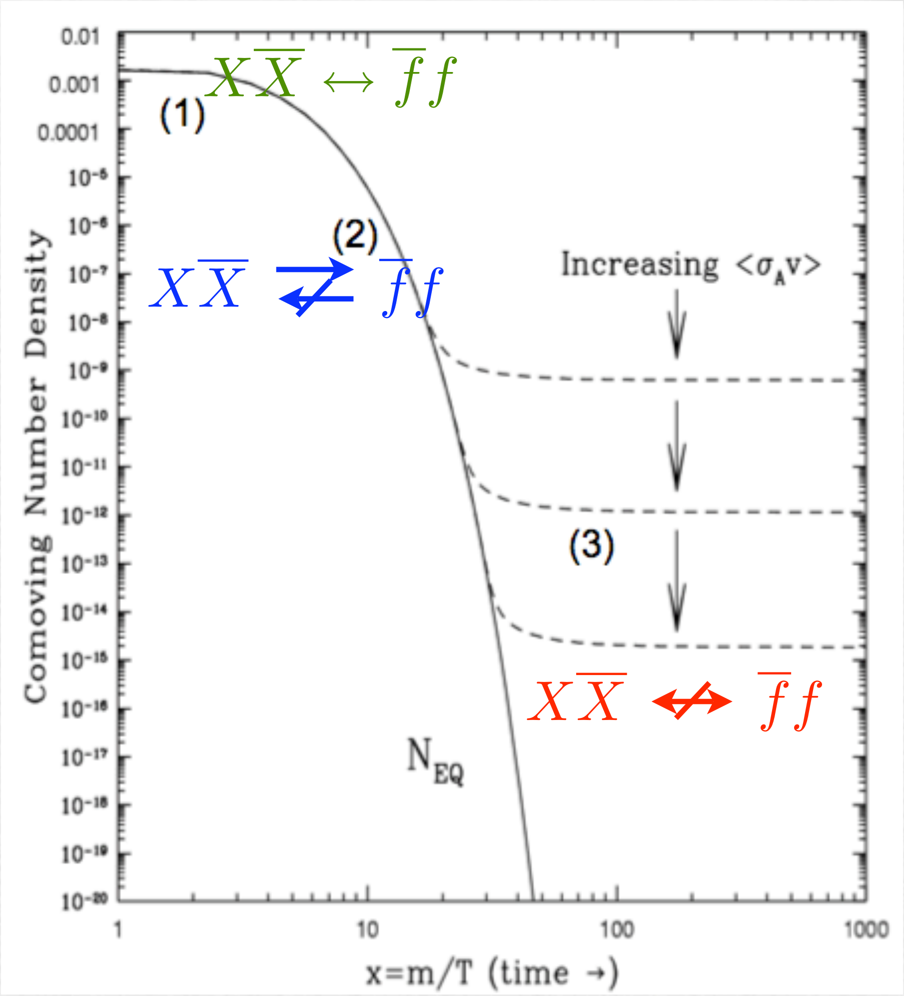
Very general, does not depend on early universe cosmology, only requires the reheat temperature to be $\gtrsim m/25$ (= weak requirement)

an alternative: superWIMPs (where most often the above calculation is still relevant since SuperWIMPs are produced from the WIMP decay)

ex: gravitino, KK graviton

Dependence on reheat temperature

The "WIMP miracle"



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

$\Rightarrow \langle\sigma_{anni} v\rangle = 0.1$ pb

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

$\Rightarrow m \sim 100$ GeV

Dark Matter and the Fermi scale

Fraction of the universe's energy density stored in a stable massive thermal relic:

$$\boxed{\Omega_{DM} \approx \frac{0.2\text{ pb}}{\sigma_{anni}}}$$

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

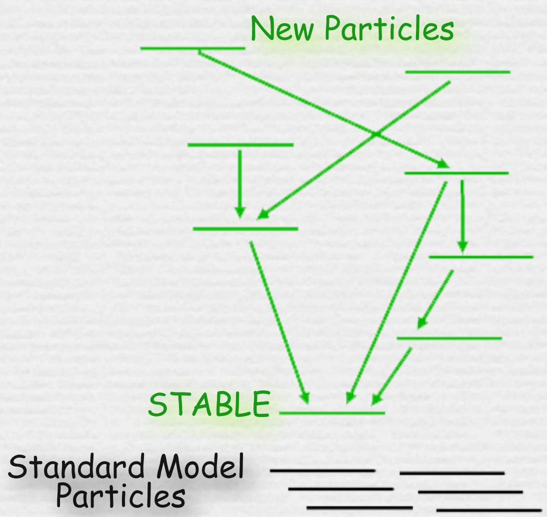
a compelling coincidence (the "WIMP miracle")

Work out properties of new degrees of freedom

The stability of a new particle is a common feature of many models

mass spectrum, interactions

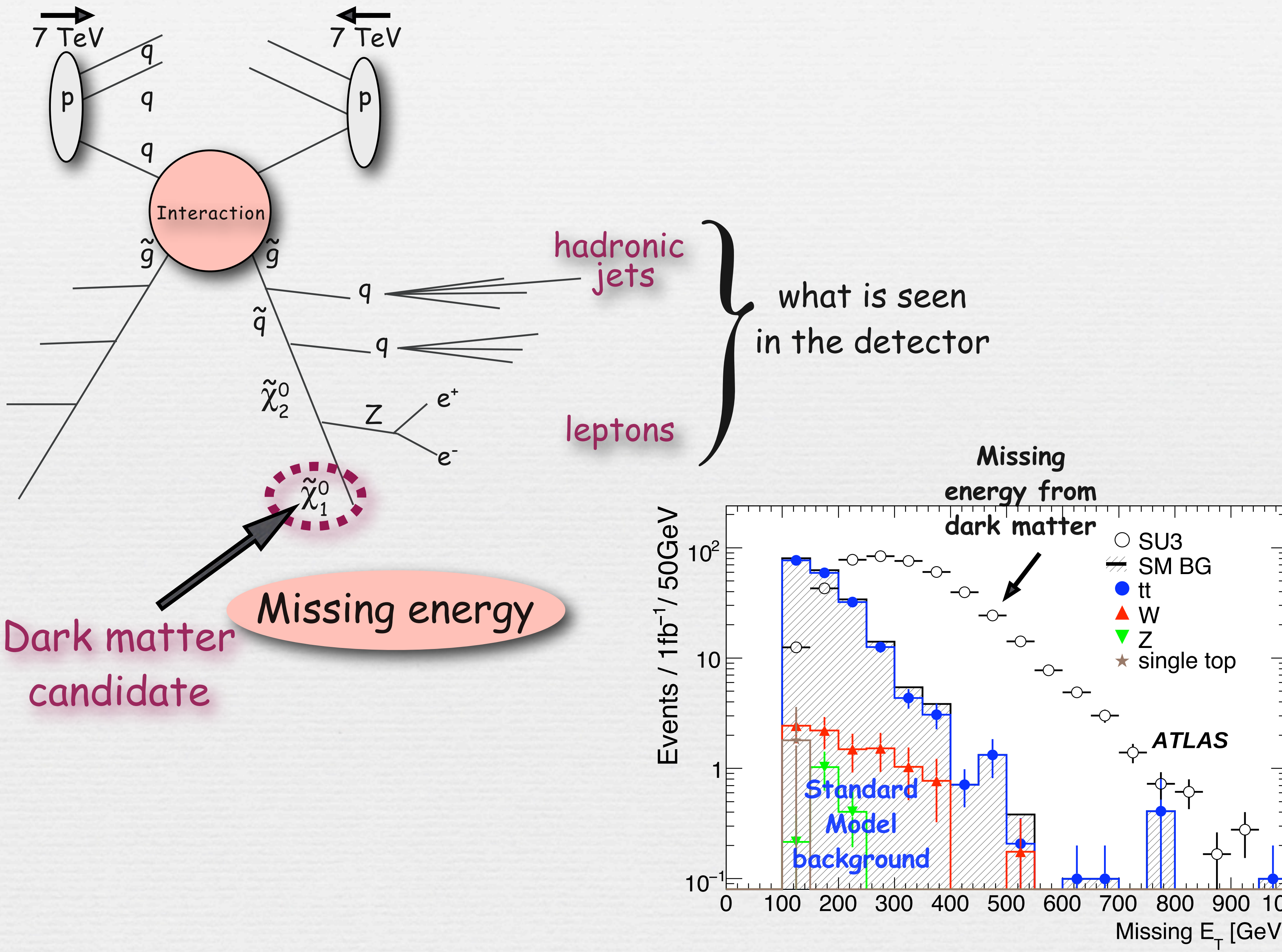
dark matter candidates



relic abundance

detection signatures & rates

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

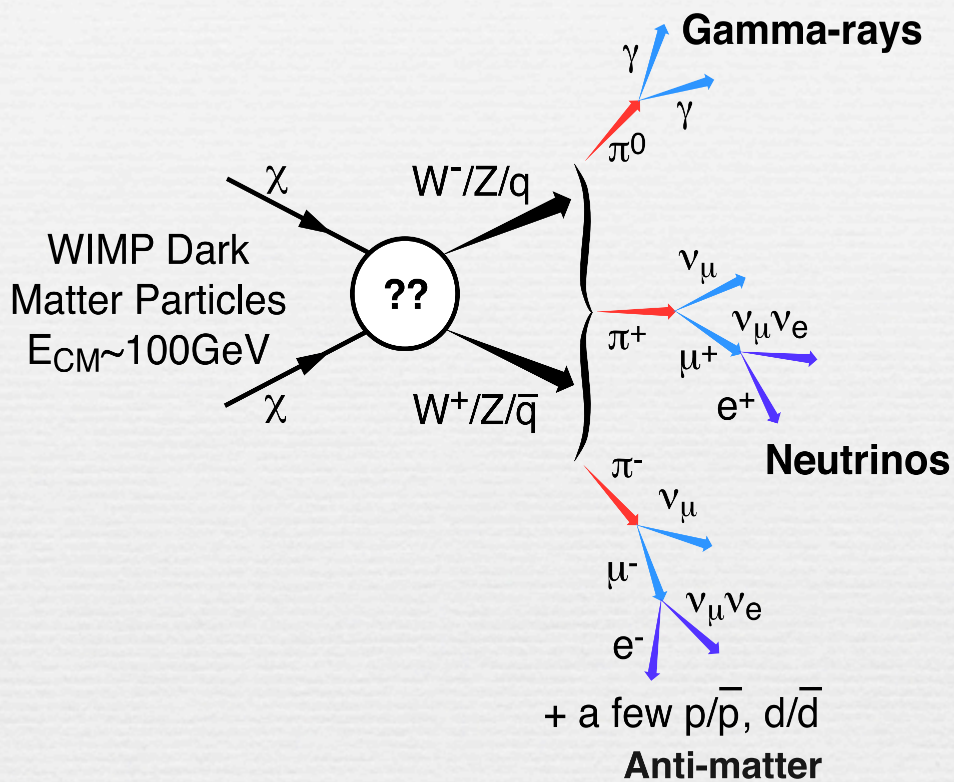
WIMP direct detection

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

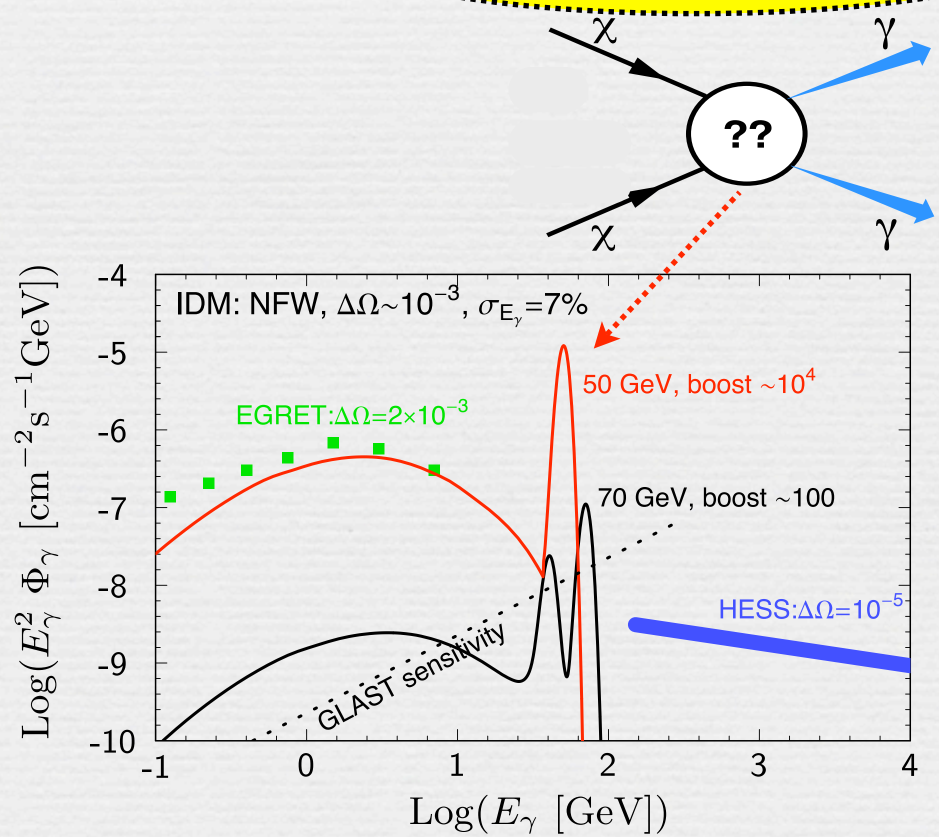
Just a few Wimps are expected to collide elastically upon terrestrial nuclei, partially transferring to them their kinetic energy.

Direct detection consists in observing the recoiled nuclei.

WIMP indirect detection



smoking gun: gamma-ray line from direct anni into γγ or γZ



gamma-ray spectra
(Inert doublet model)

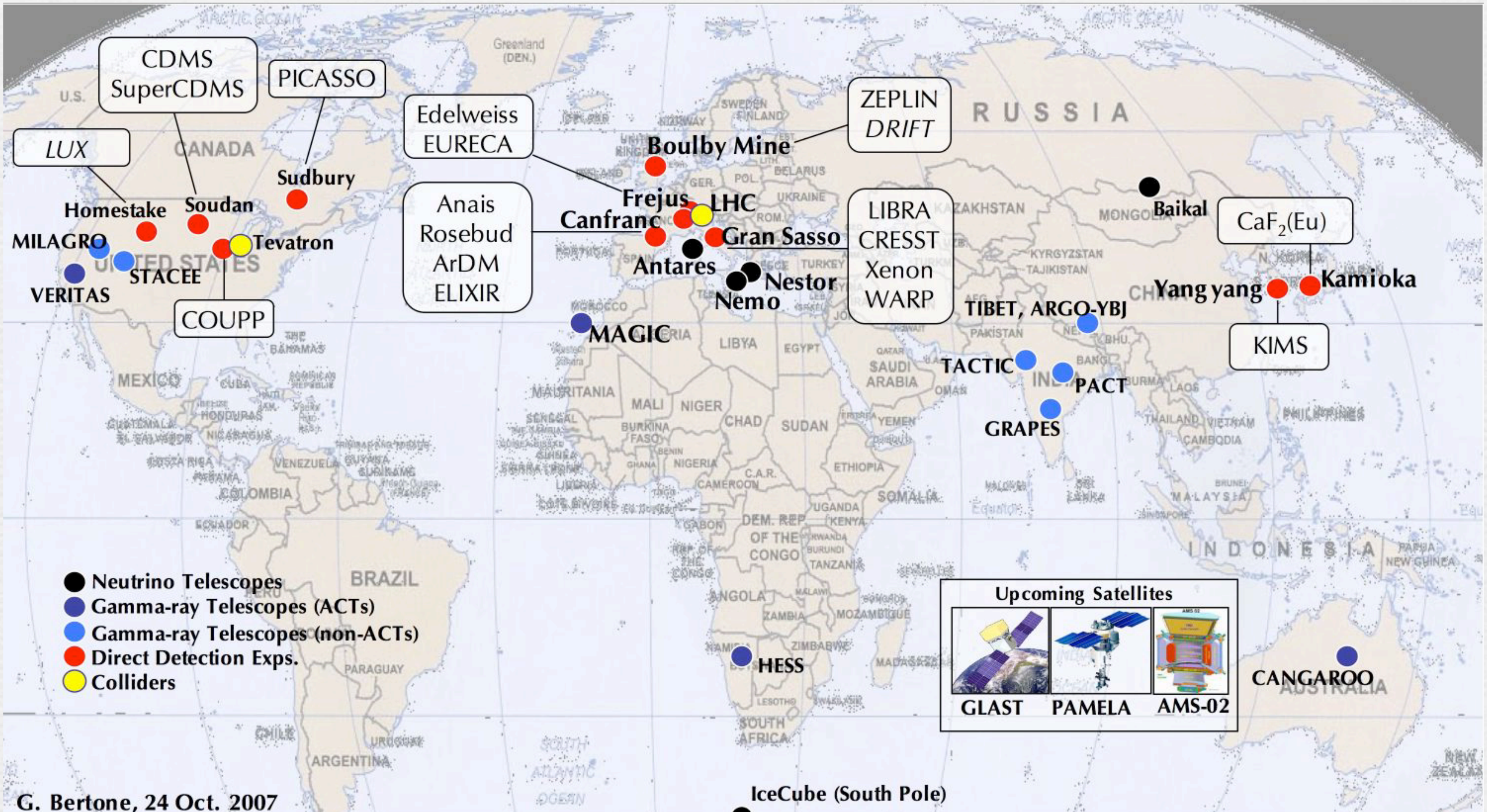
Seeing the light from Dark Matter

- 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)

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



Matter Anti-matter asymmetry:

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

Where has the antimatter gone?

Matter Anti-matter asymmetry: Observational evidence

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 asymmetry between matter and antimatter is characterized in terms of the baryon to photon ratio

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

The number of photons is not constant over the universe evolution. At early times, it is better to compare the baryon density to the entropy density since the n_B/s ratio takes a constant value as long as B is conserved and no entropy production takes place. Today, the conversion factor is

$$\frac{n_B - n_{\overline{B}}}{s} = \frac{\eta}{7.04}$$

Matter Anti-matter asymmetry:

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

10 000 000 001
Matter

10 000 000 000
Anti-matter

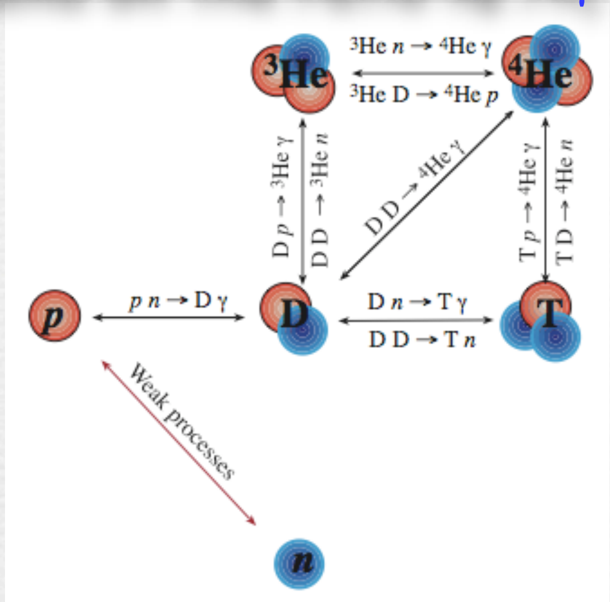
1
(us)

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

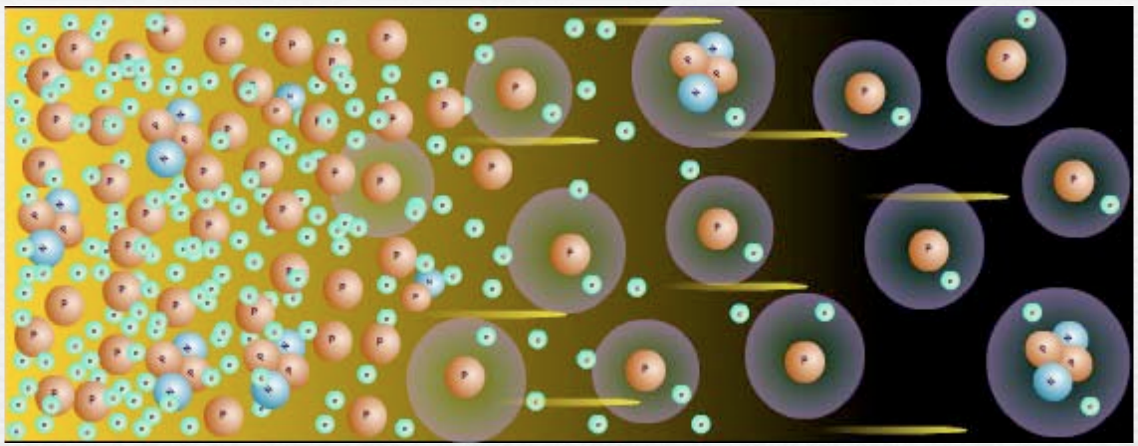


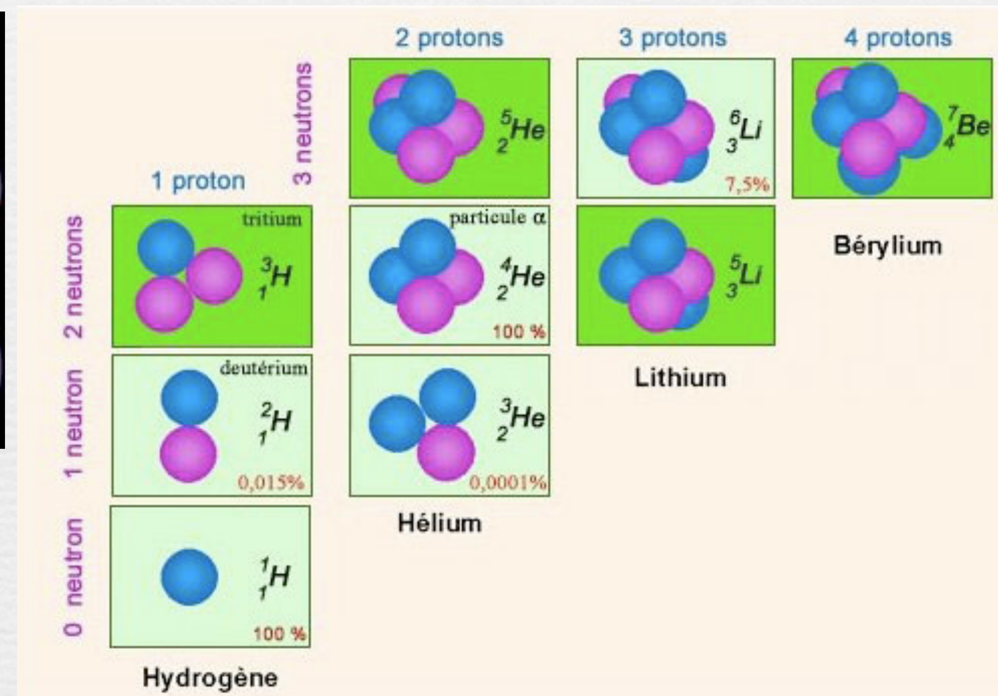
2) Measurements of CMB anisotropies

probe acoustic oscillations of the baryon/photon fluid

The amount of anisotropies depend on n_B / n_γ

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

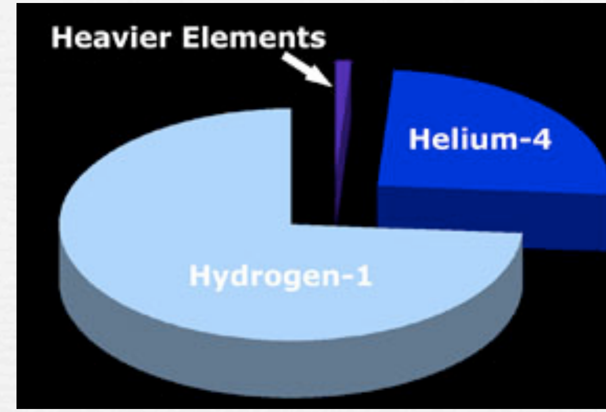


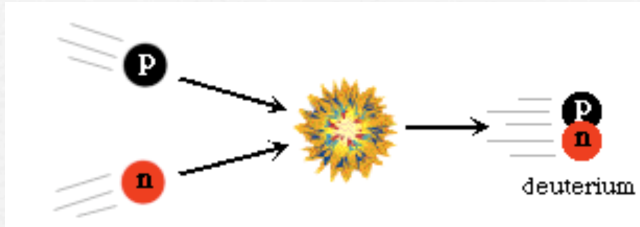


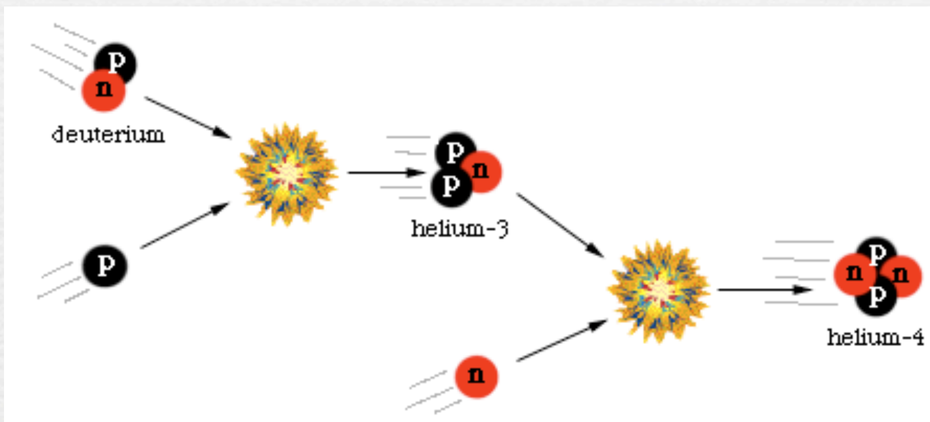
at t<1 s

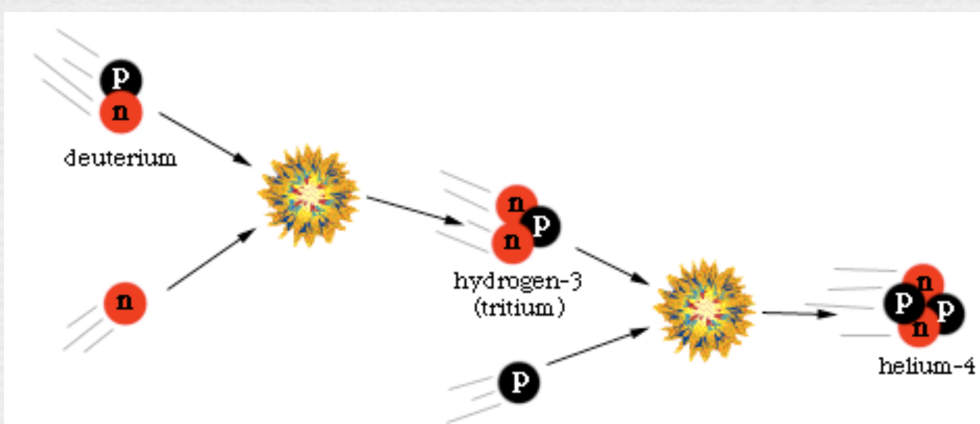
$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \nu_e$$
$$n \leftrightarrow p + e^- + \overline{\nu_e}$$

Primordial nucleosynthesis







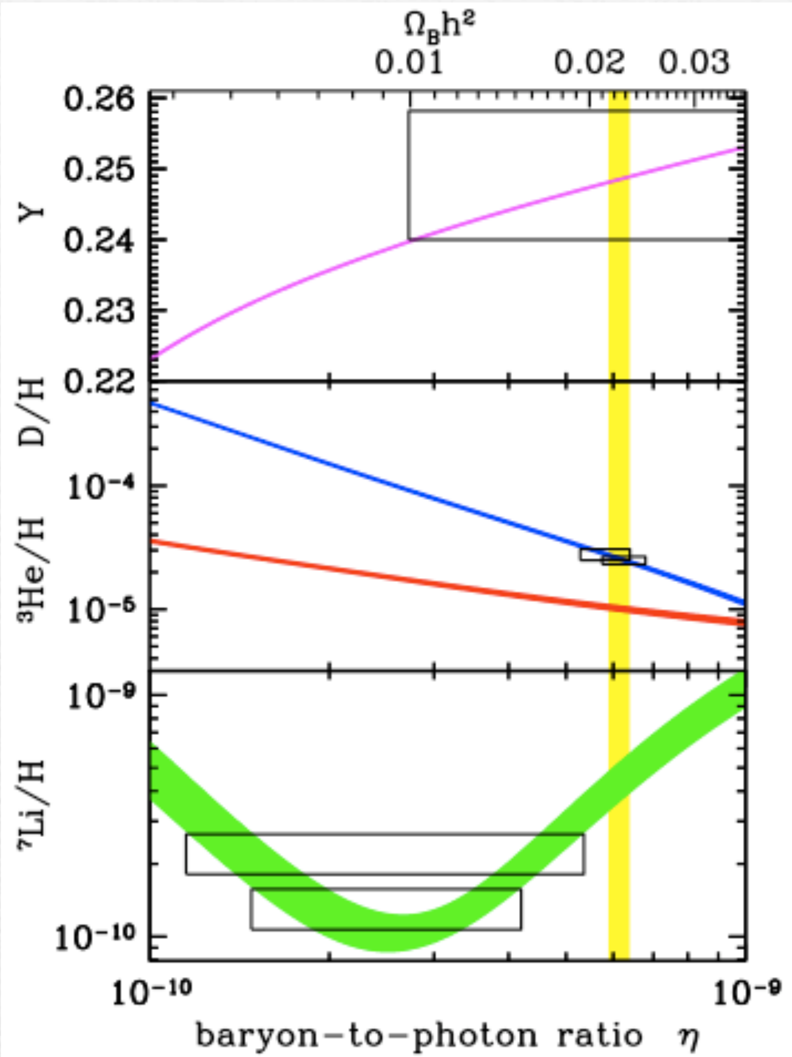


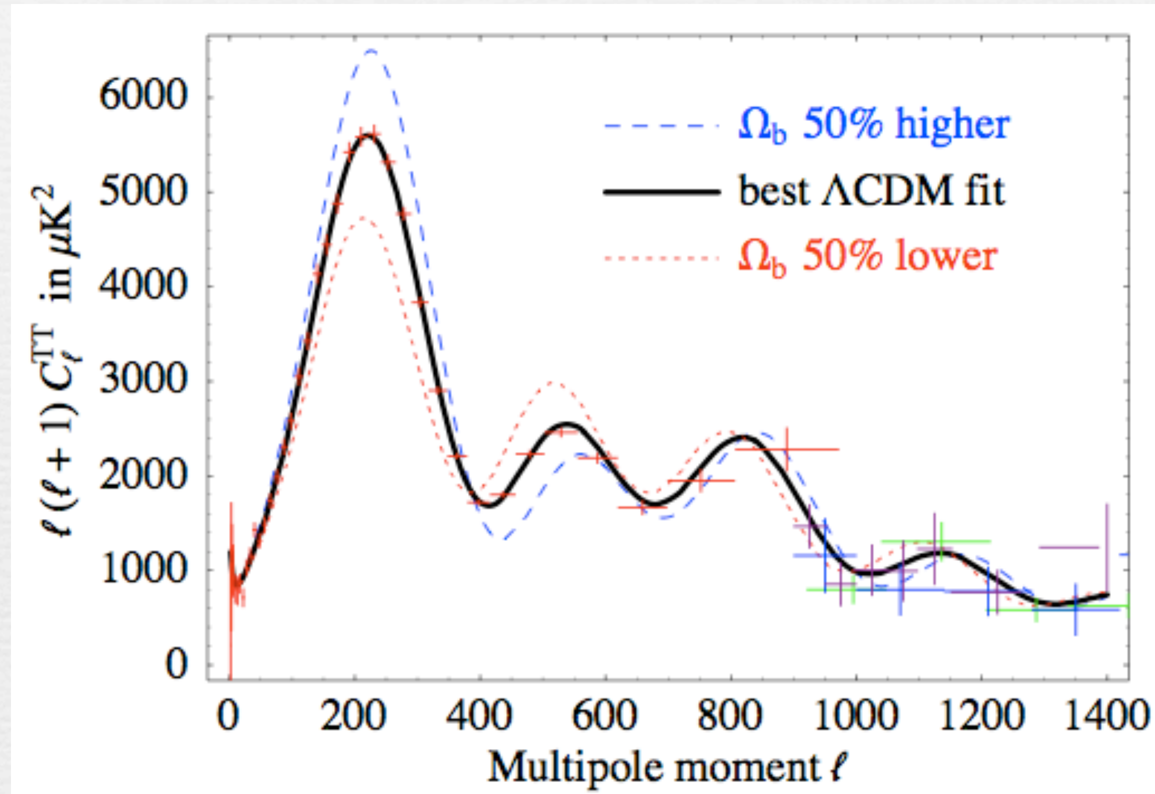
$$
\begin{array}{rcl}
\mathrm{p}+\mathrm{n} & \longrightarrow & \mathrm{D}+\gamma \\
\mathrm{D}+\mathrm{n} & \longrightarrow & {}^{3}\mathrm{H}+\gamma \\
\mathrm{D}+\mathrm{p} & \longrightarrow & {}^{3}\mathrm{He}+\gamma \\
\mathrm{D}+\mathrm{D} & \longrightarrow & {}^{3}\mathrm{H}+\mathrm{p} \\
\mathrm{D}+\mathrm{D}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

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

How much baryons would there be in a symmetric universe?

nucleon and anti-nucleon densities are maintained by annihilation processes

$$n + \overline{n} \longleftrightarrow \pi + \pi \longleftrightarrow \gamma + \gamma + \ldots$$

which become ineffective when

$$\Gamma \sim n_N / m_\pi^2 \sim H$$

leading to a freeze-out temperature

$$T_F \sim 20 \text{ MeV}$$

$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

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)

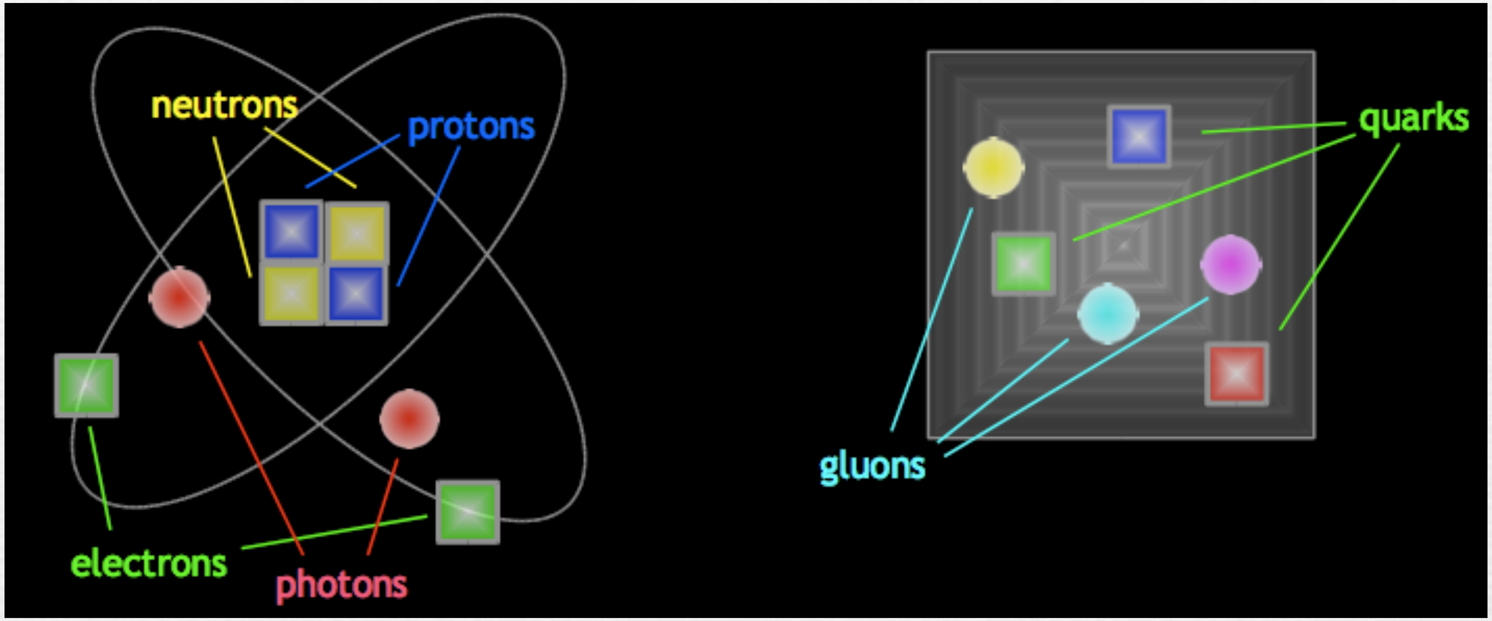
Conclusion:

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

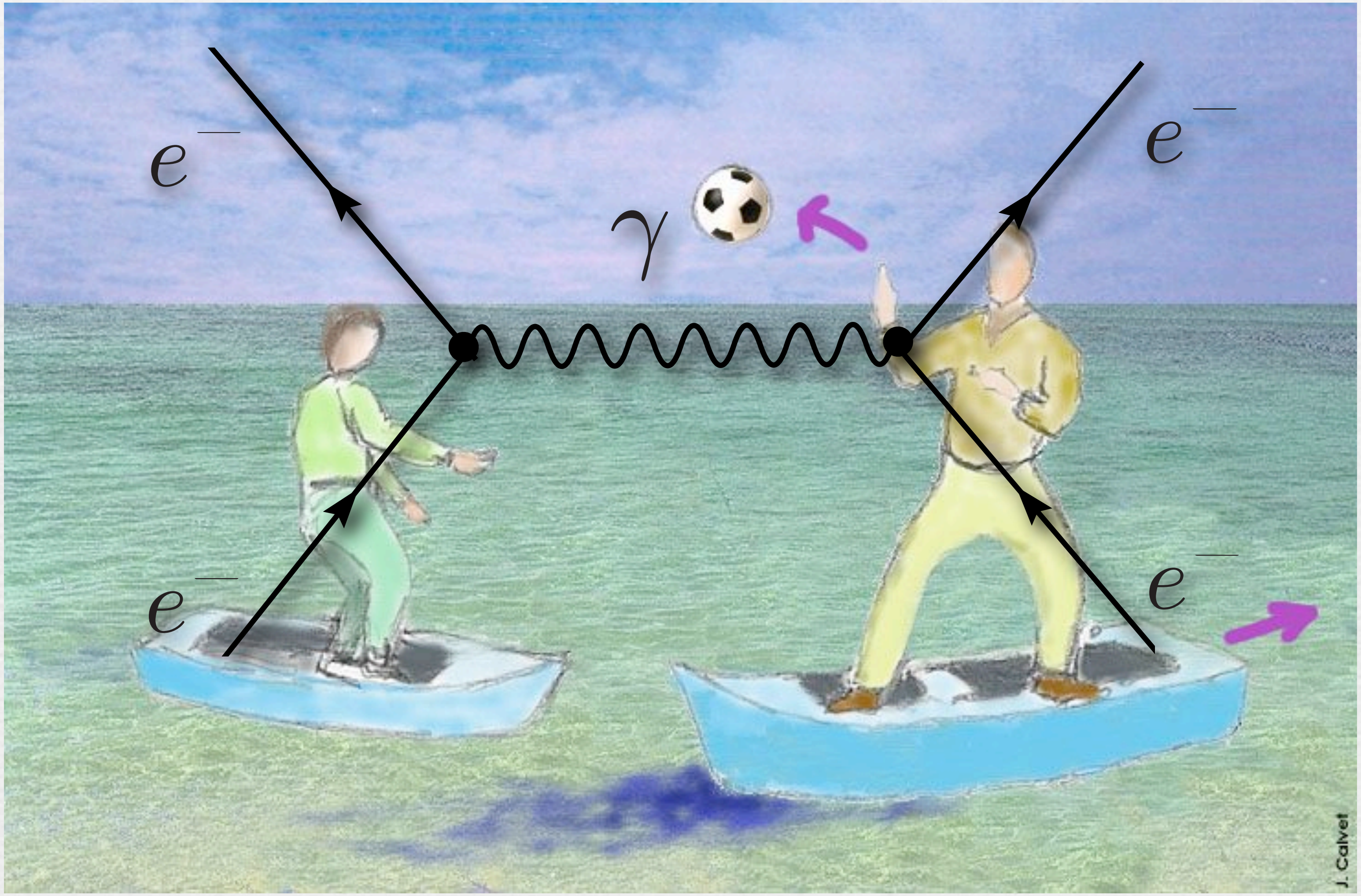
New Physics is needed!

Which physics beyond the Standard Model ?

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

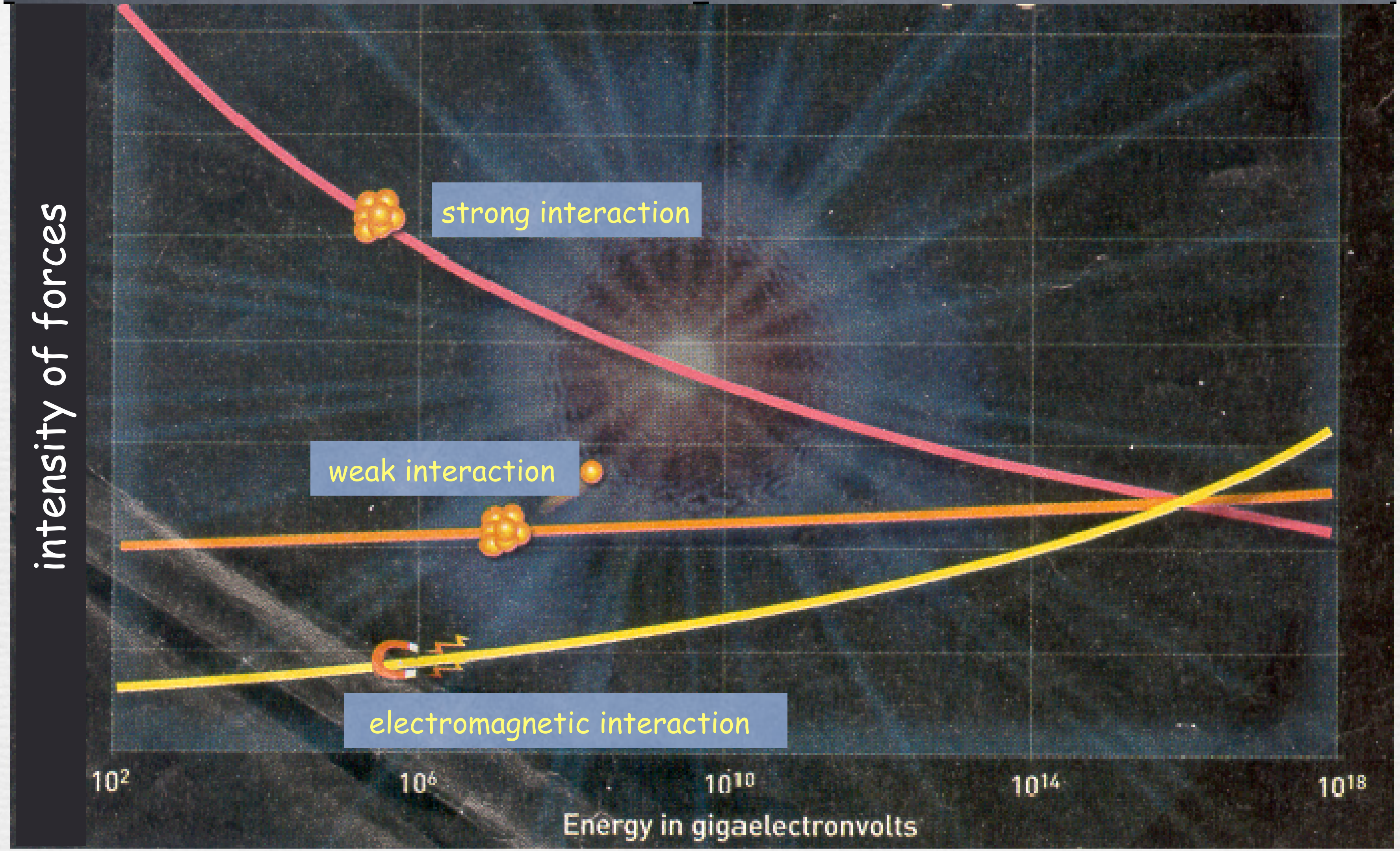


Interactions between particles



Elementary particles interact with each other by exchanging gauge bosons

Theories of grand unification



One single type of matter

One single fundamental interaction

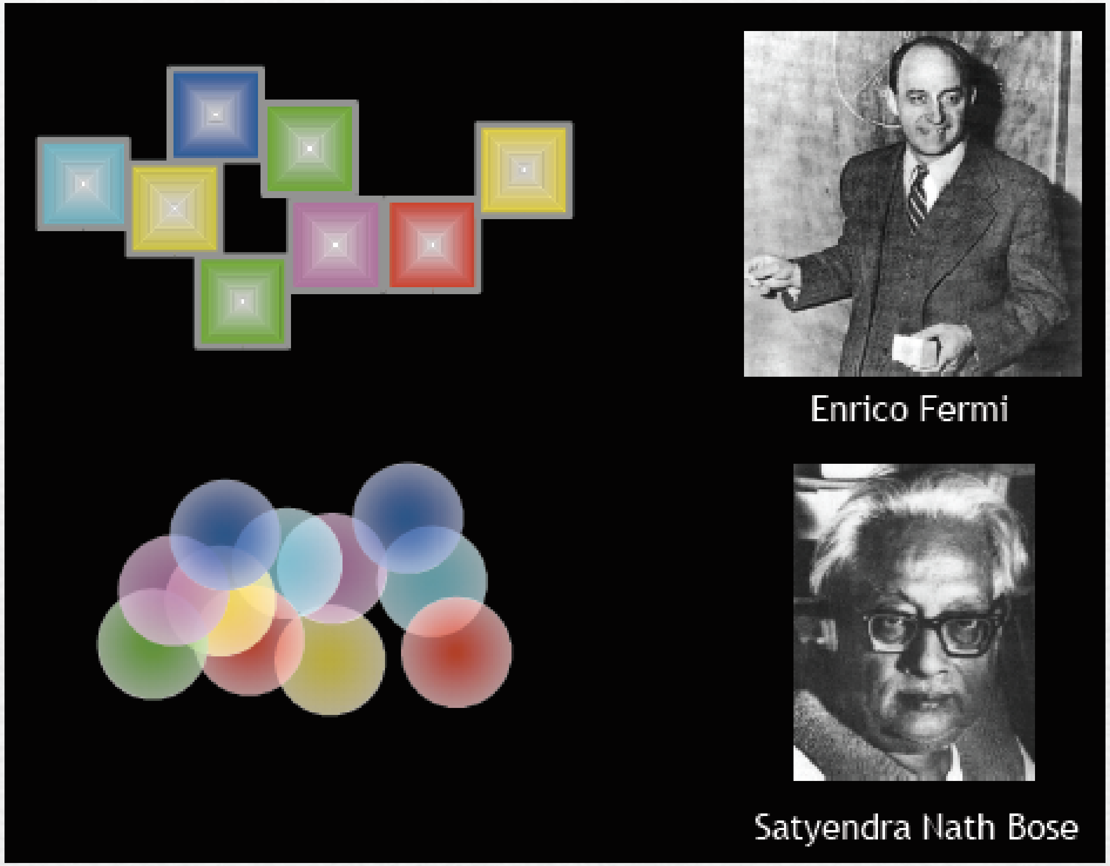
Supersymmetry

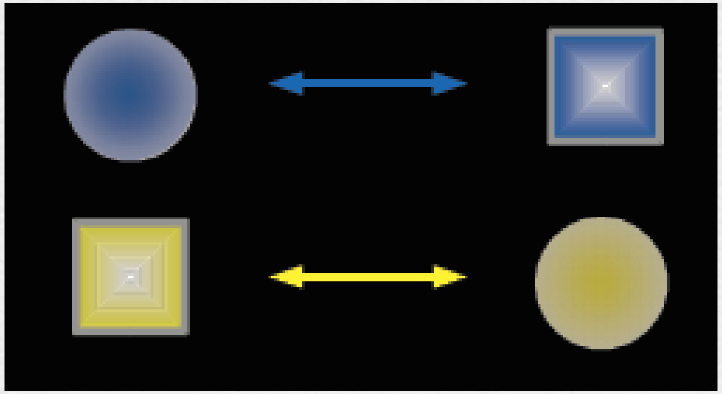
Fermions *particles of matter*

fermions repel each other

Bosons *particles of force*

bosons can pile up

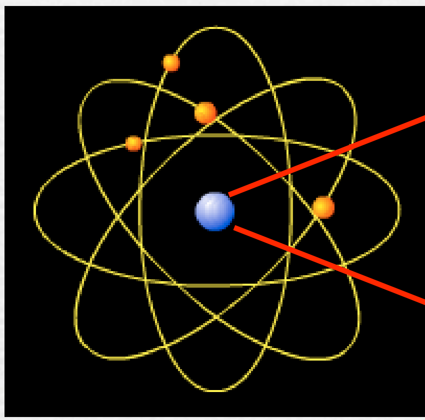




String Theory

(observable universe)

10^{-10}m

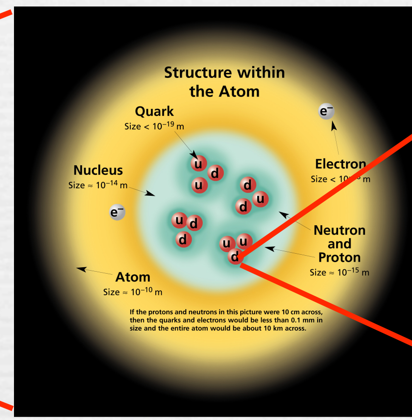


Atom

electrons + nucleus

(Earth)

10^{-17}m

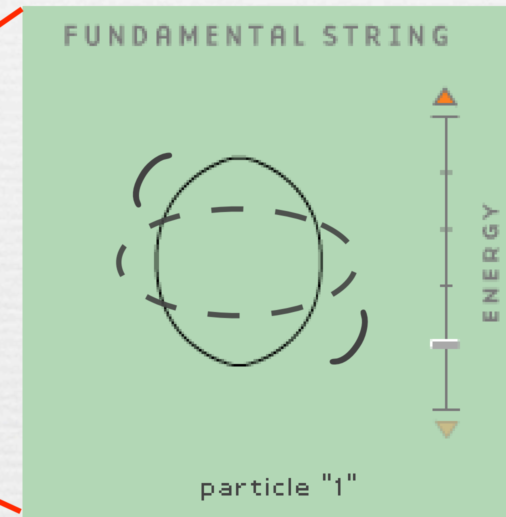


Nucleus

quarks

(Hair)

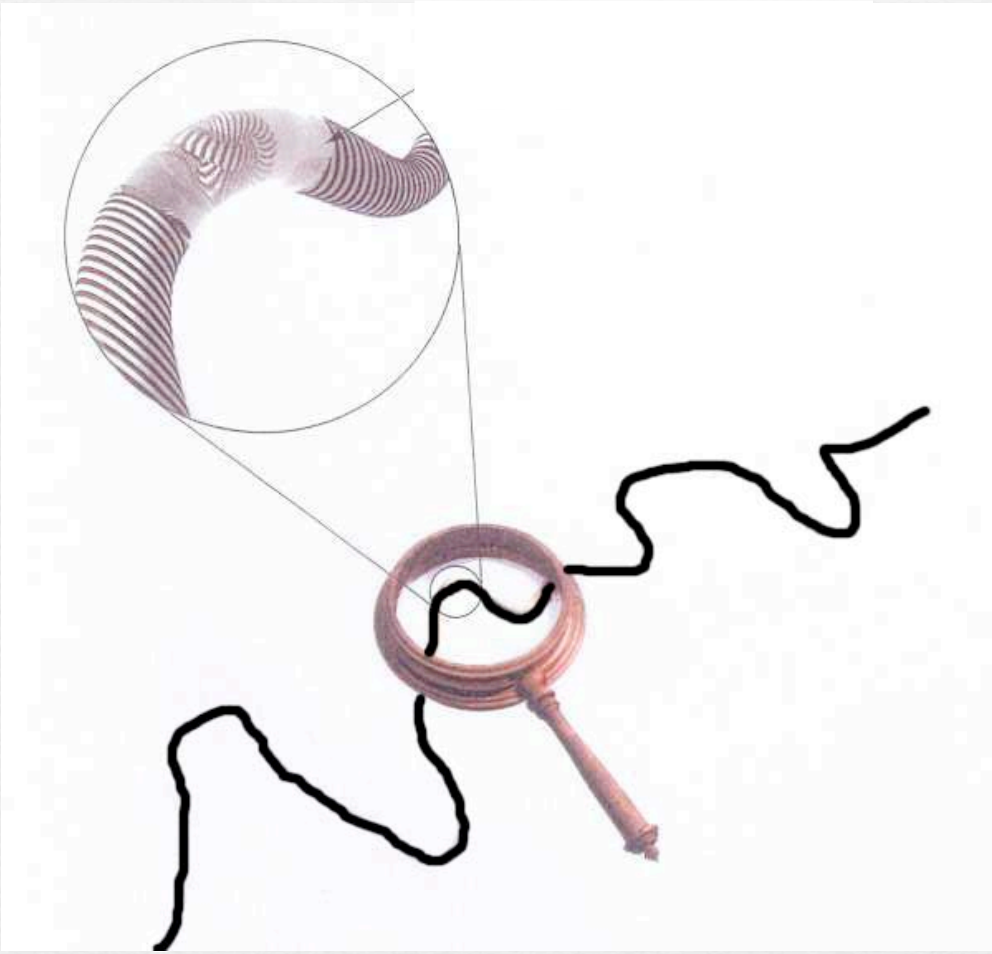
10^{-35}m

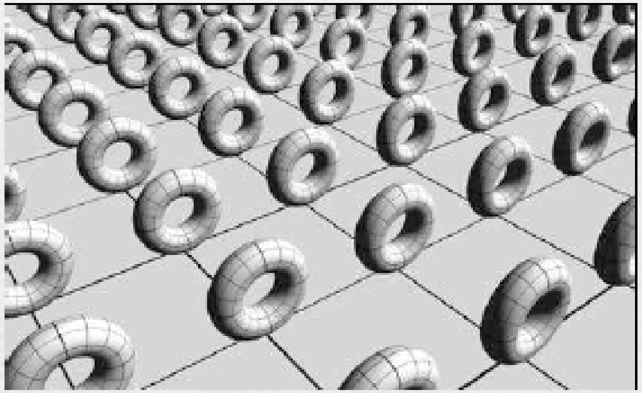


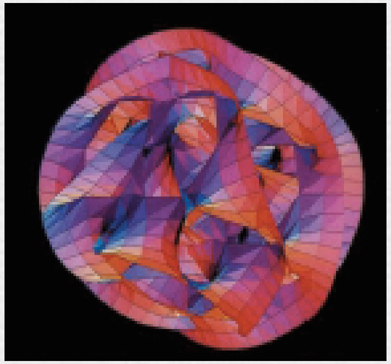
(Super)String

Extra Dimensions

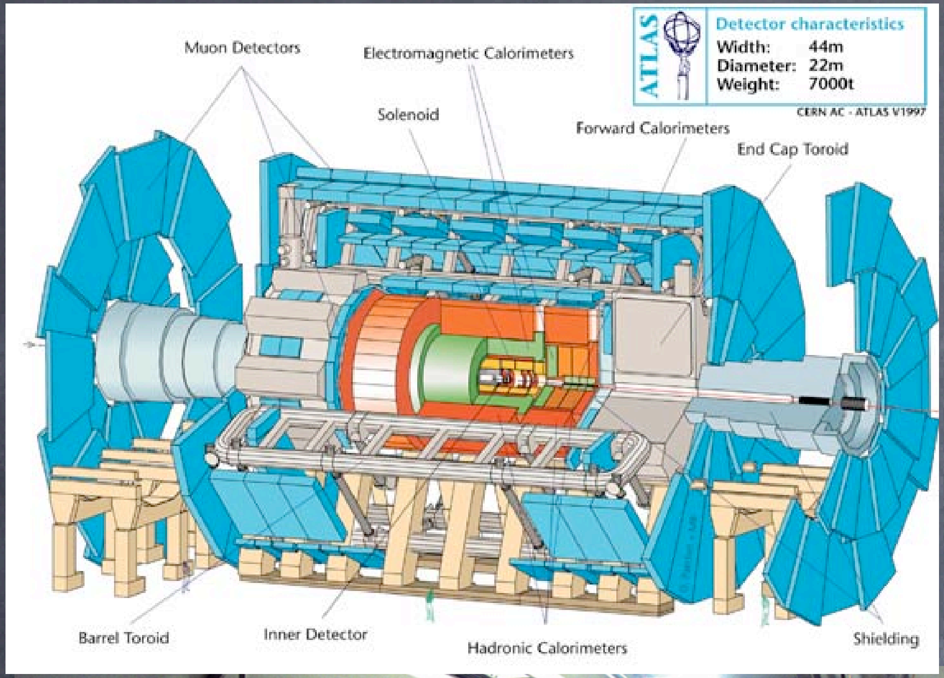
String theories are (well) defined only in spacetime with 10 or 11 dimensions
These extra dimensions are assumed to be curled up

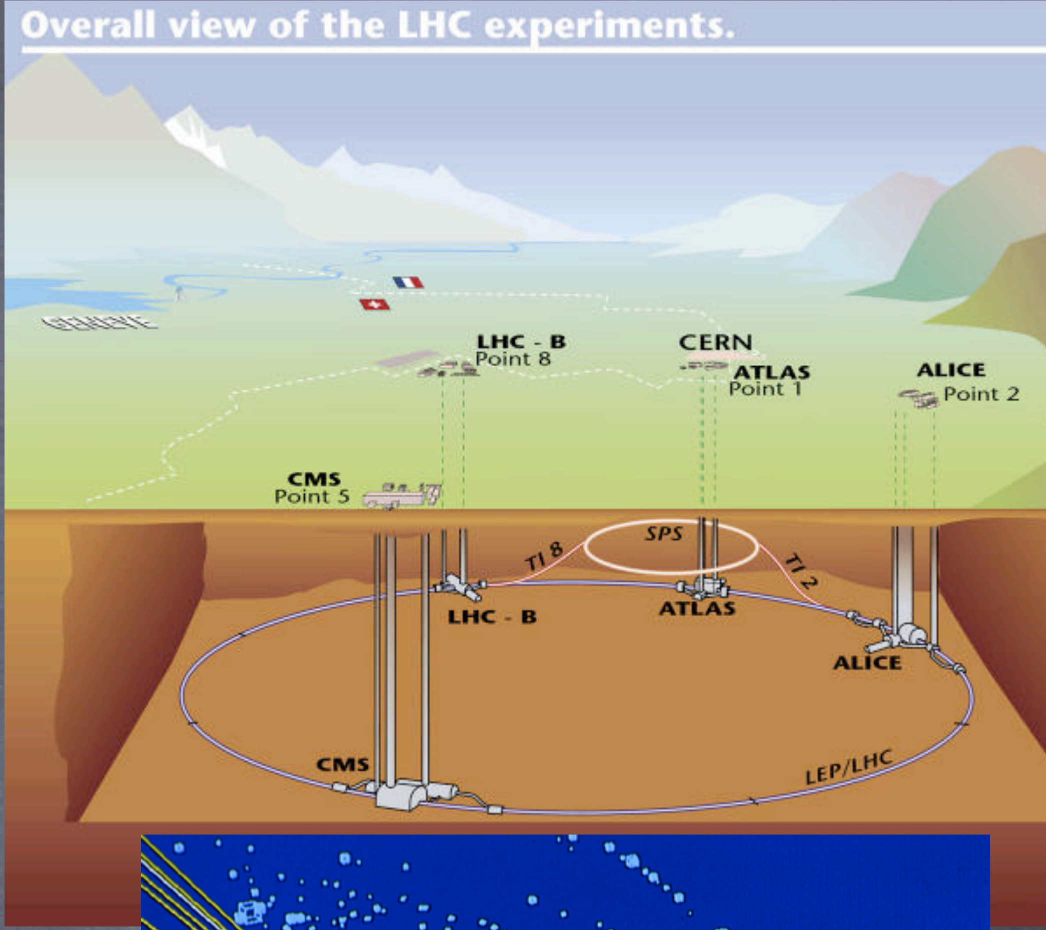


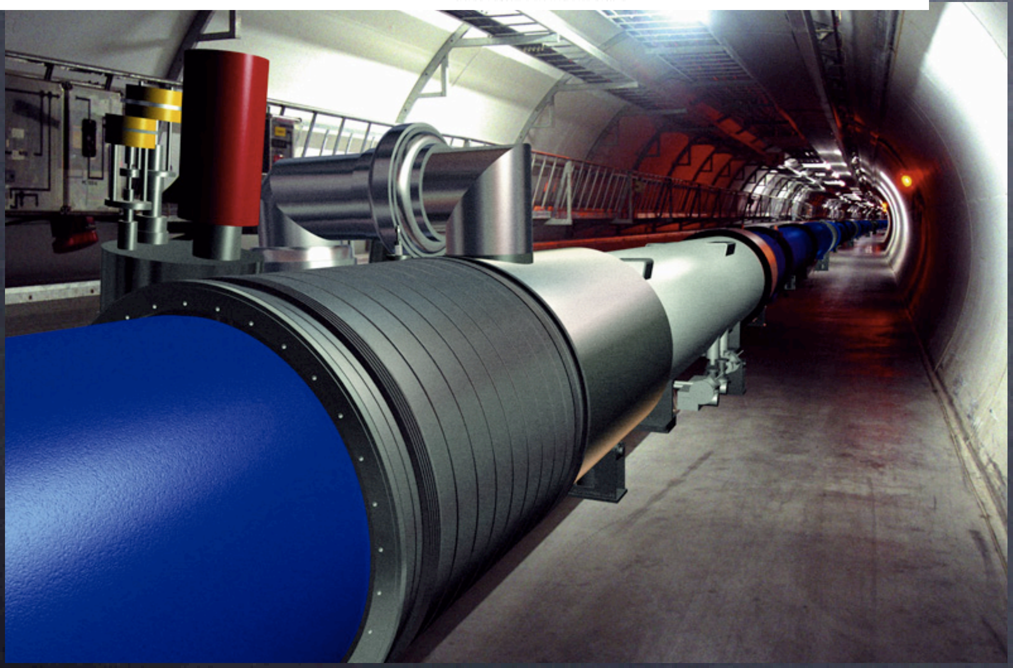


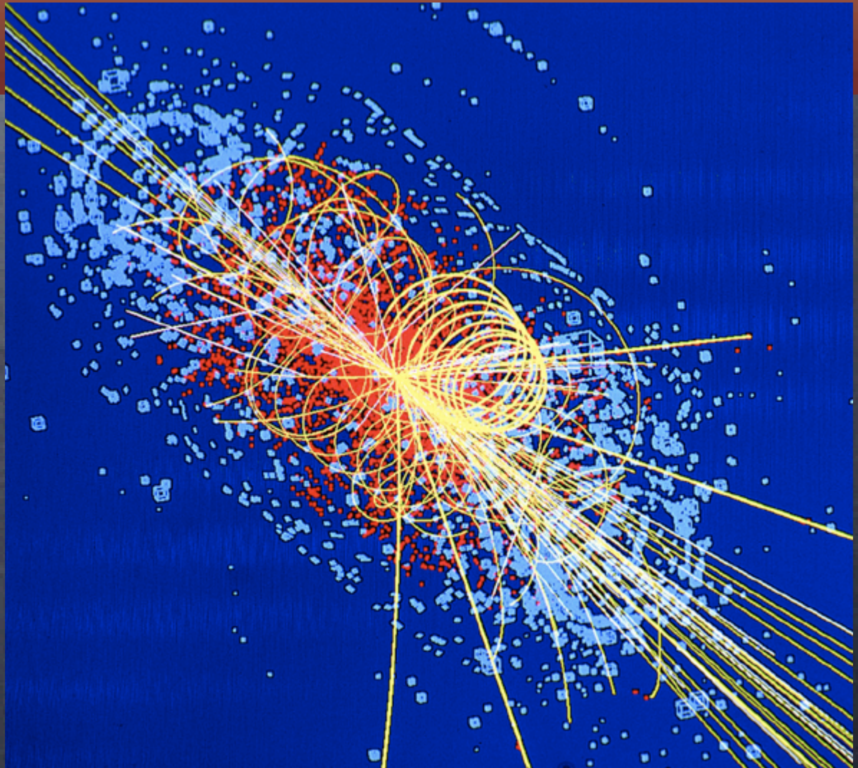


2010: A new era starts for particle physicists

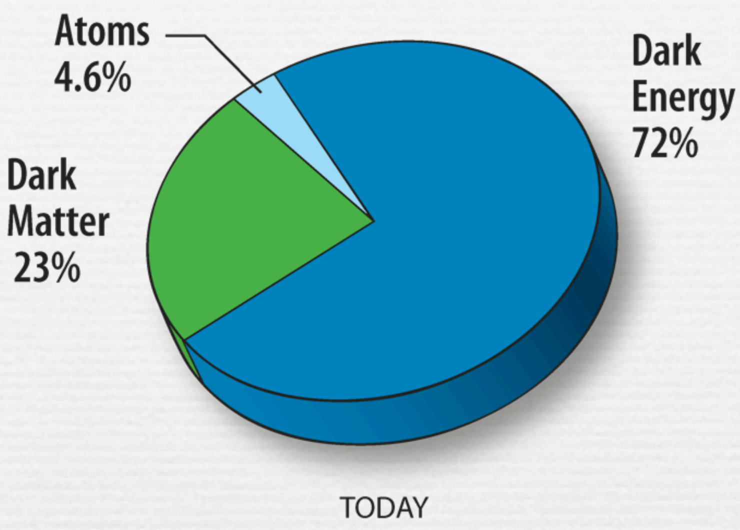


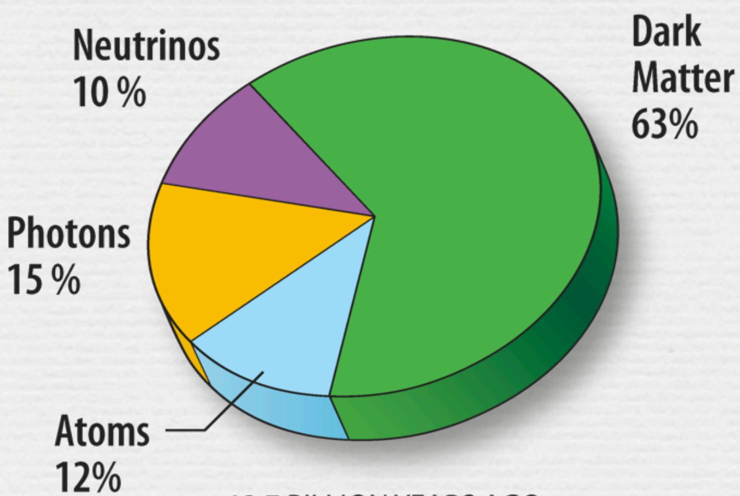




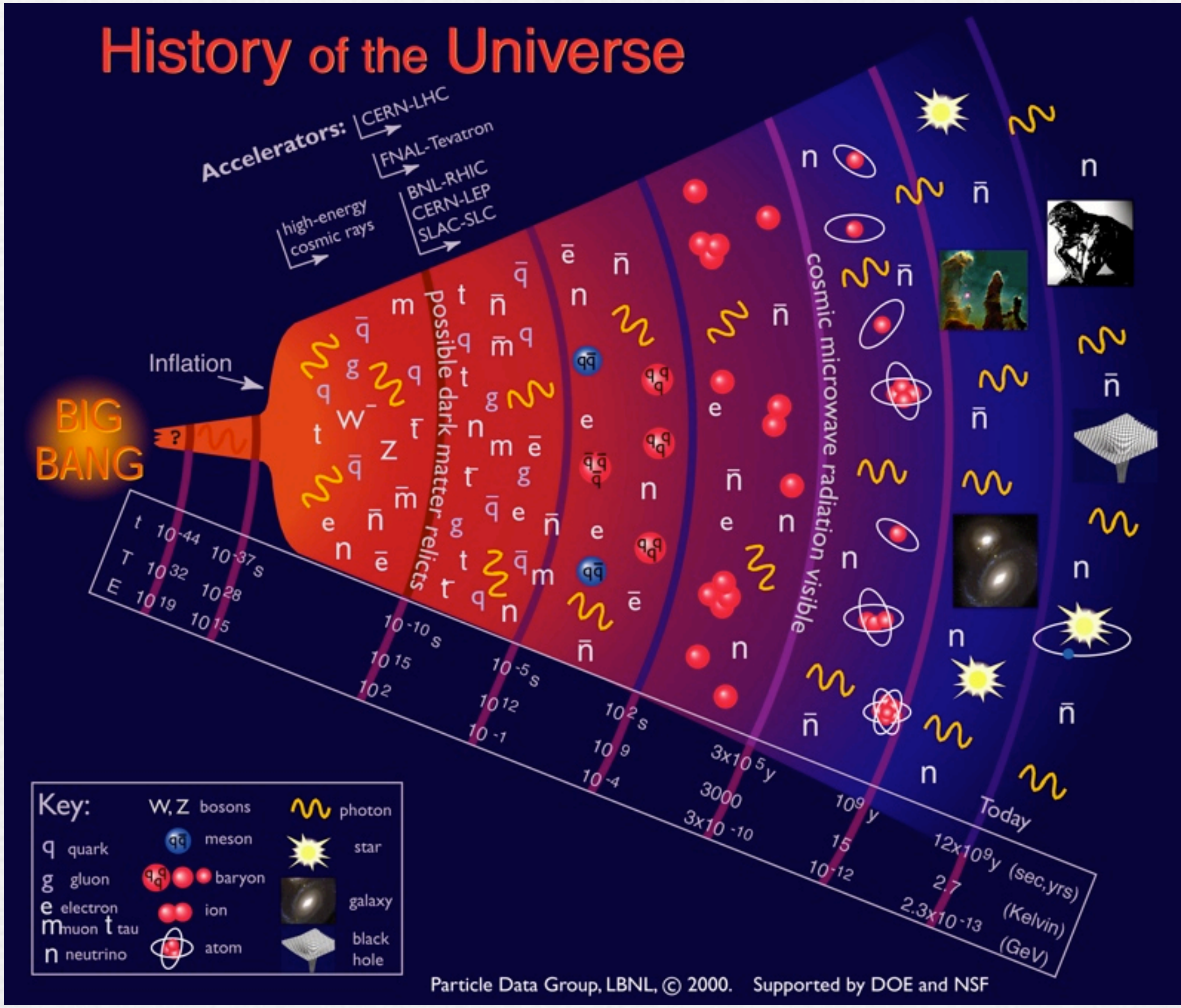


Back to Mick's question: "How do we know?"

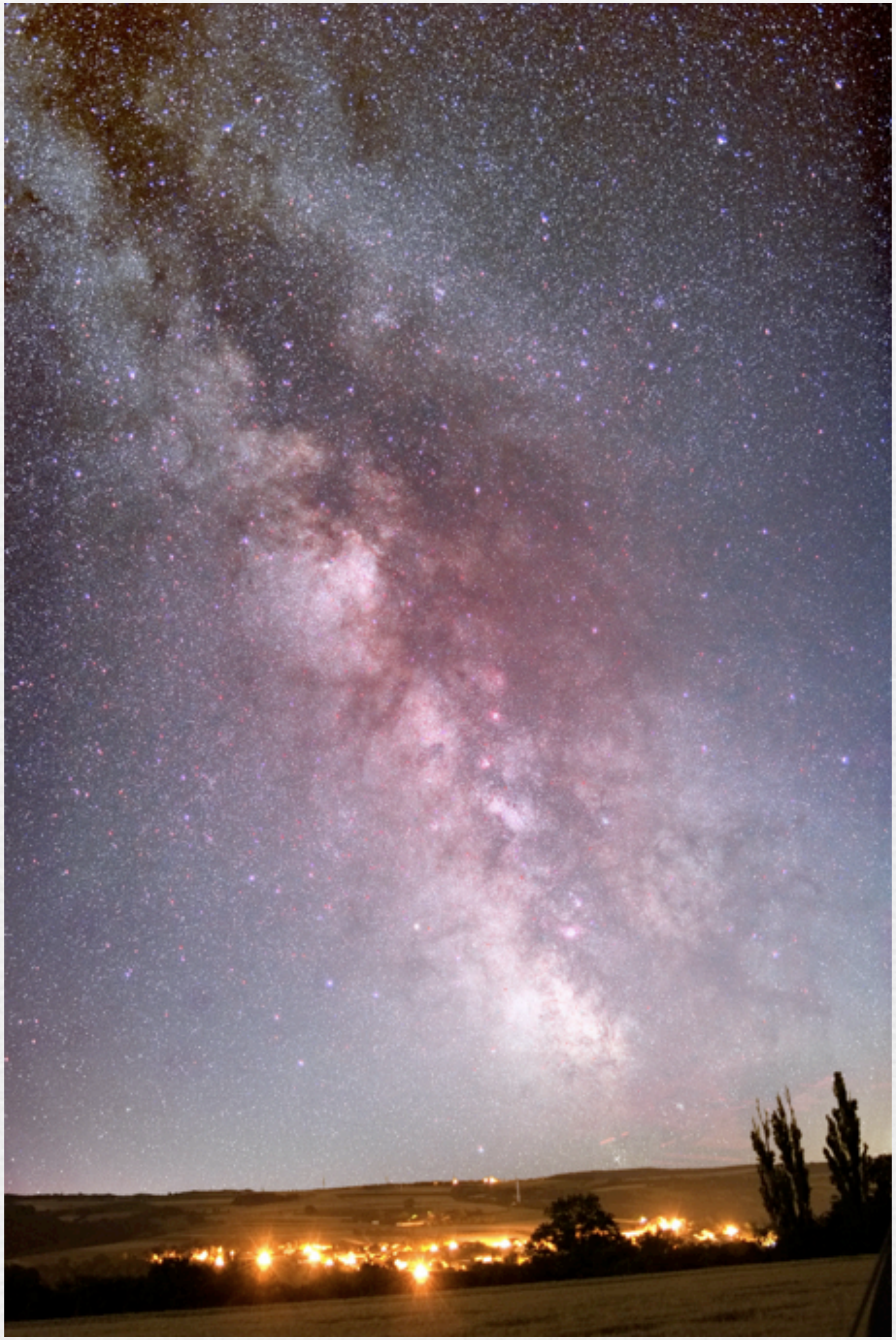




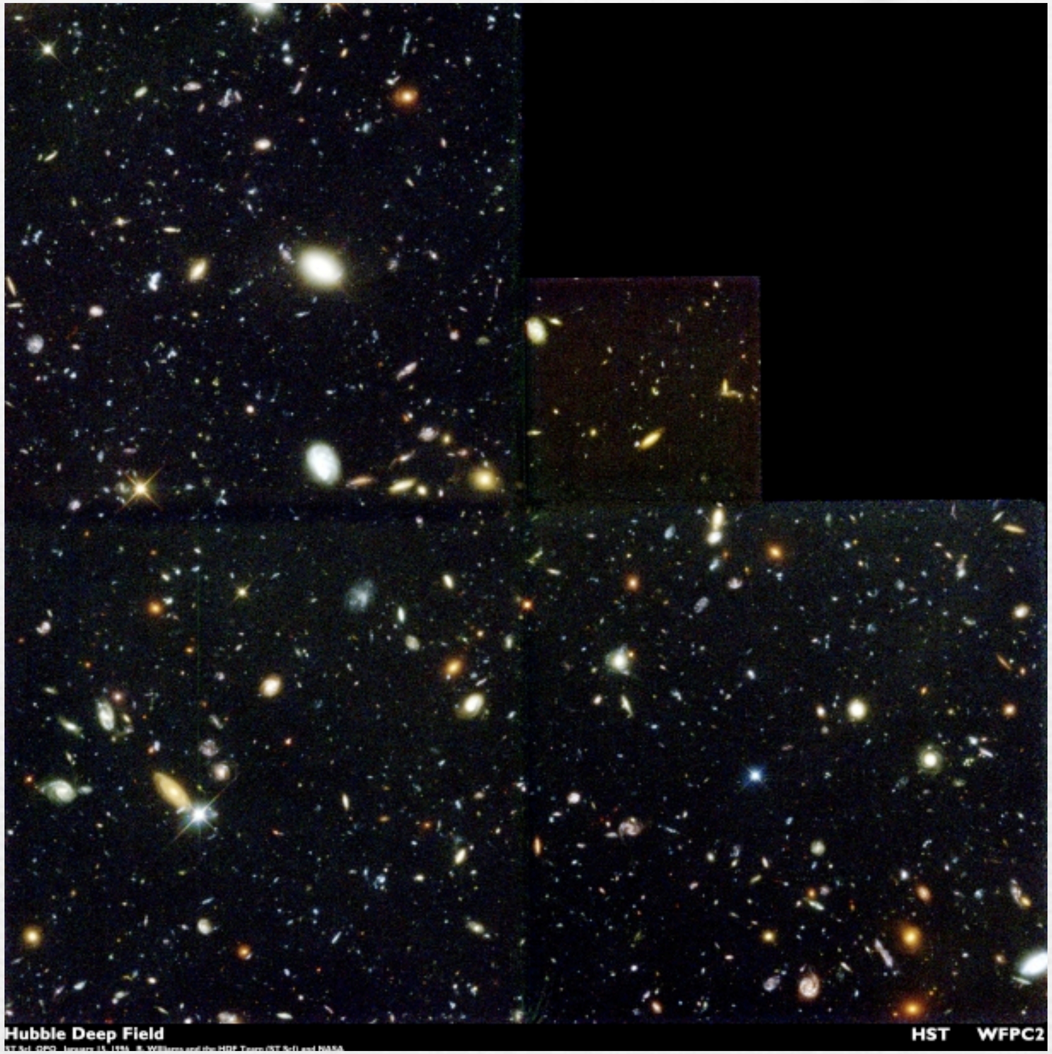
13.7 BILLION YEARS AGO
(Universe 380,000 years old)



The Milky Way: One galaxy among hundreds of billions of galaxies in our universe



Our universe: some hundreds of billions of galaxies

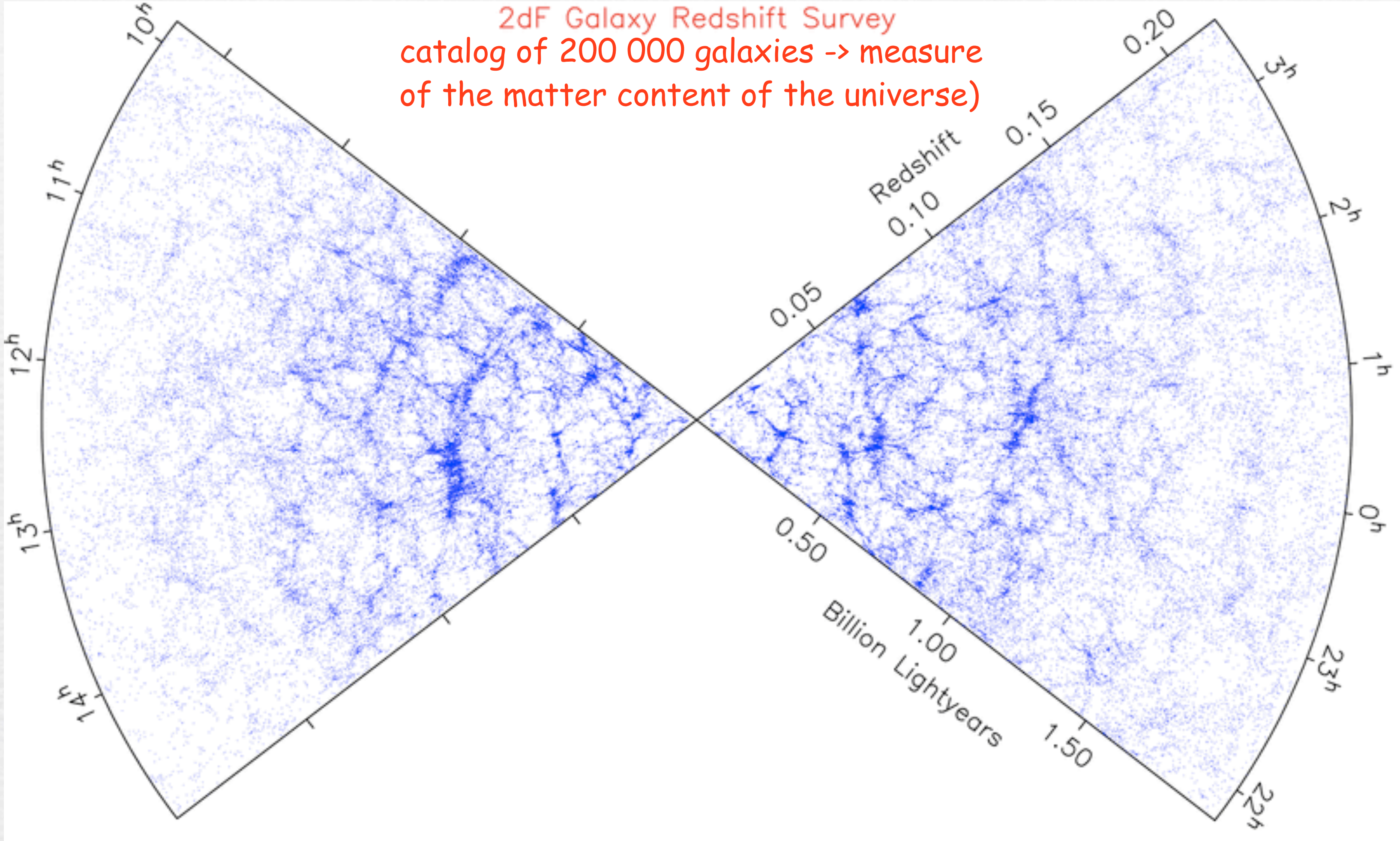


A distribution which reflects the effect of gravity

stars ⊂ galaxies ⊂ galaxy groups ⊂ galaxy clusters ⊂ superclusters

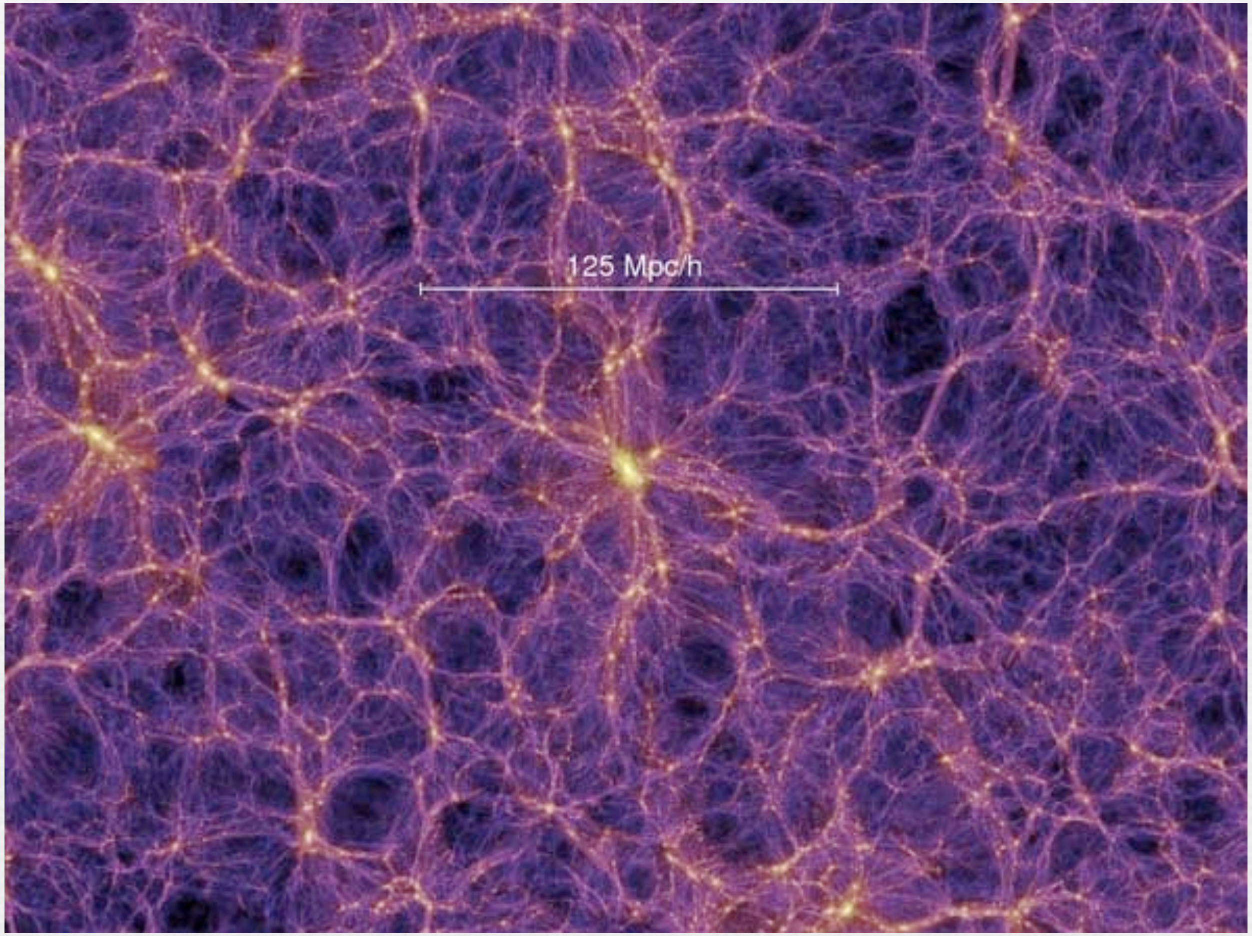
the largest known structures

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)



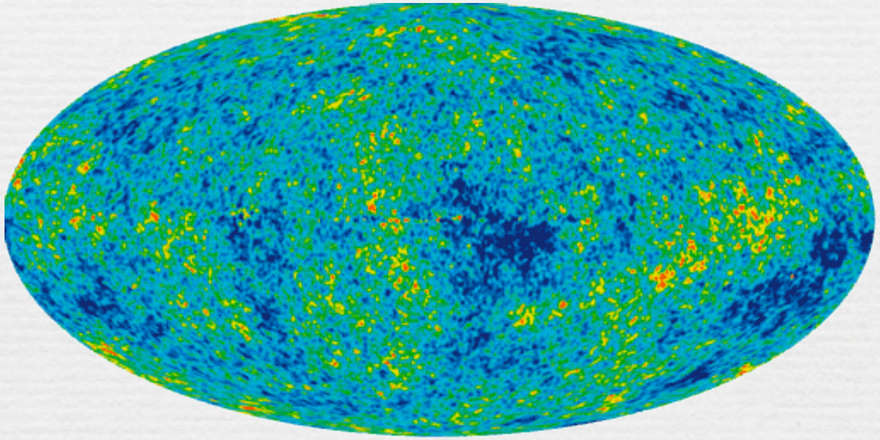
The material of the universe is not distributed at random but there is a structure on the very largest scales

Matter has condensed into filaments, super-clusters , and clusters of galaxies.
Numerical simulations of the evolution of the primordial evolution of matter enable to determine the history of some 20 millions of galaxies

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

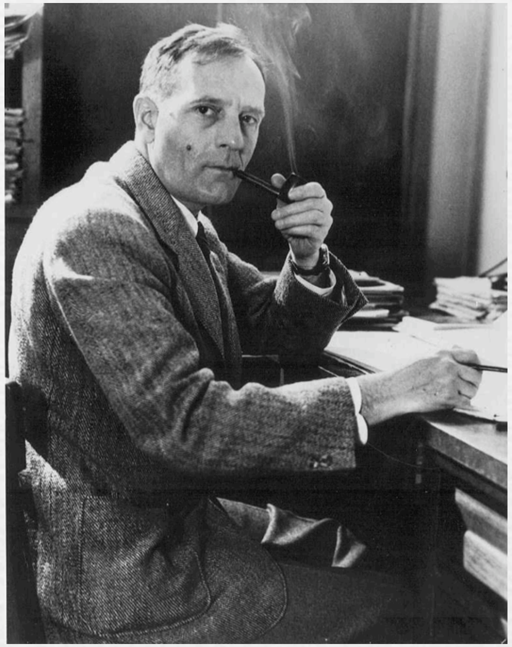
→ no preferred position, no center



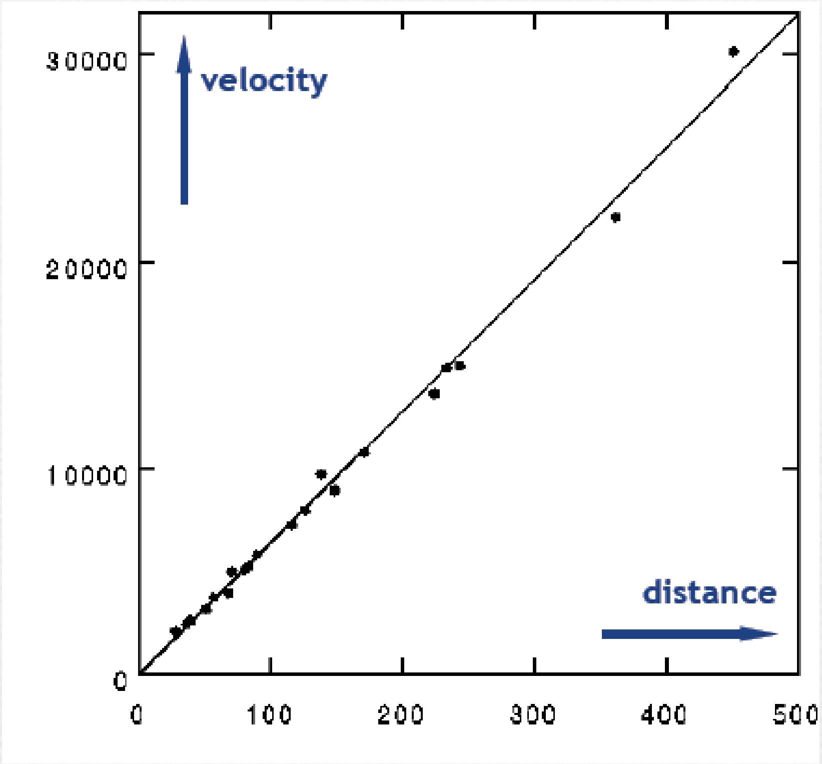
cosmic microwave background anisotropies :

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

property 2: the universe is expanding



1929: Edwin Hubble



$v = H \times r$

Hubble constant

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

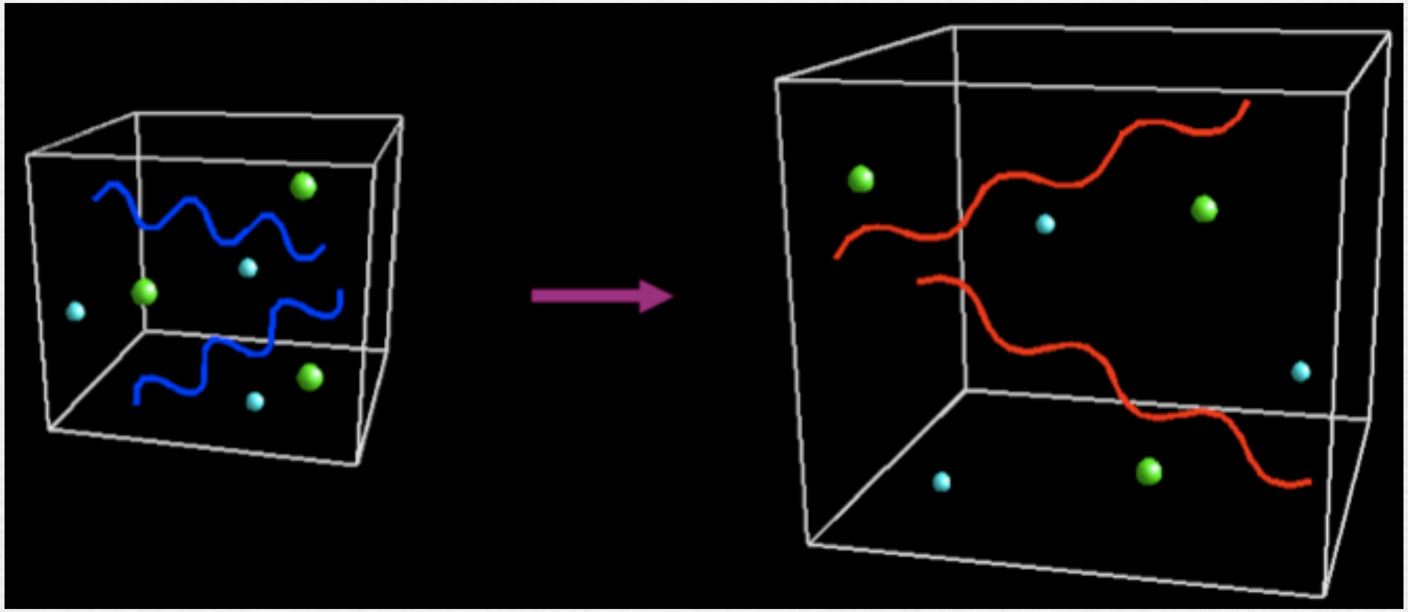
The velocity of recession of a galaxy is proportional to its distance from us

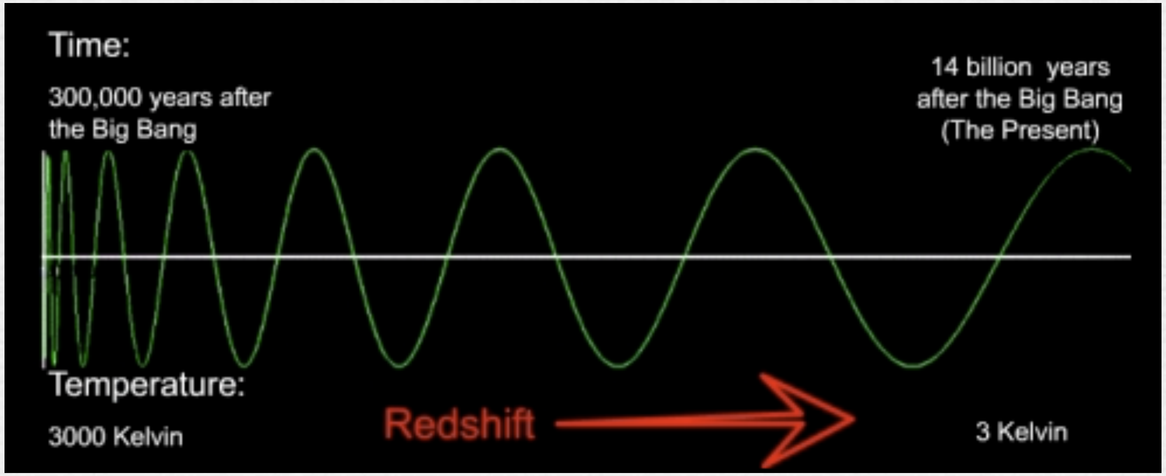
Doppler Effect $$\lambda' = \lambda \sqrt{\frac{1+v/c}{1-v/c}}$$

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 :

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

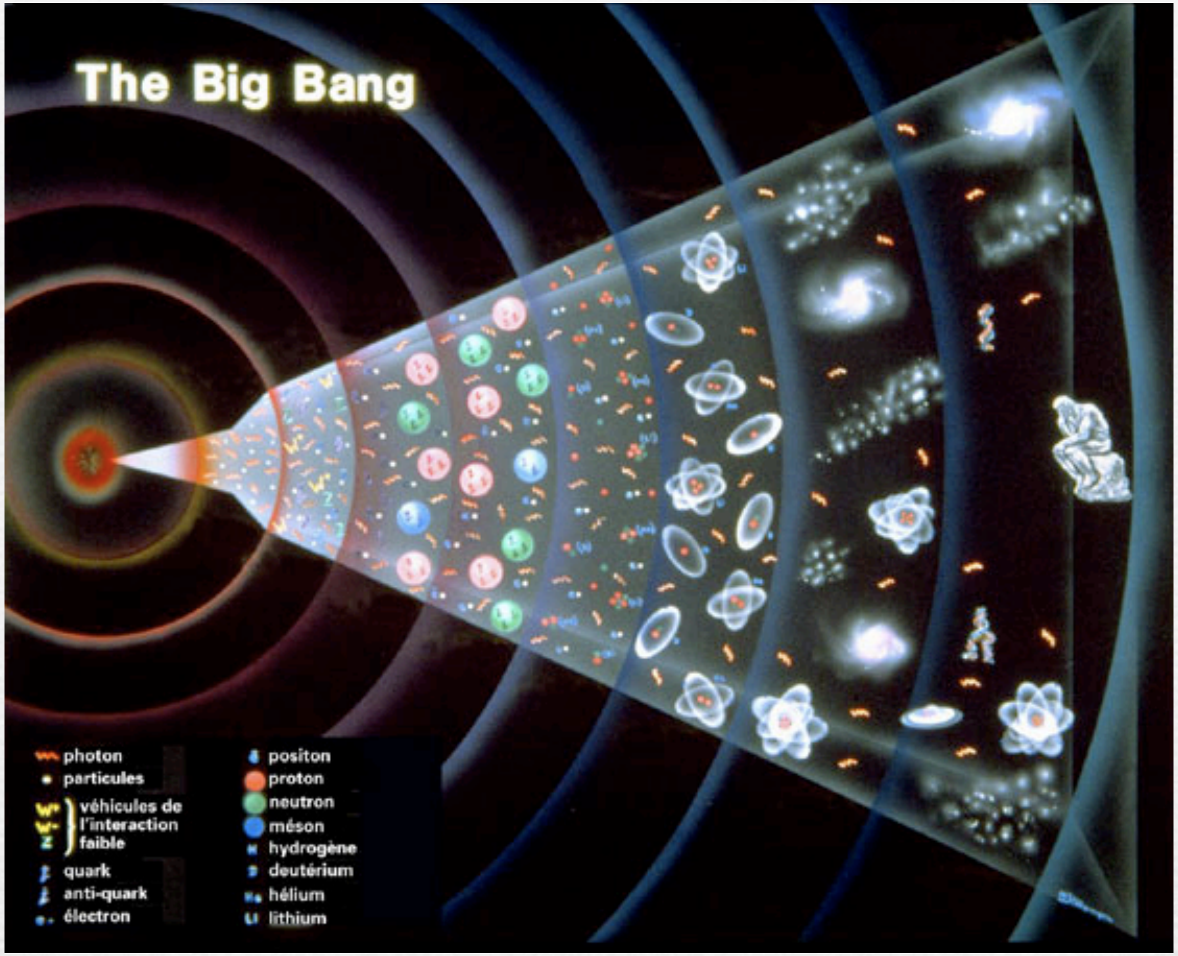
space-time is curved by the presence of matter/energy

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

the energy-momentum tensor

expansion rate

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



Friedmann Equation:

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

expansion rate

total energy density

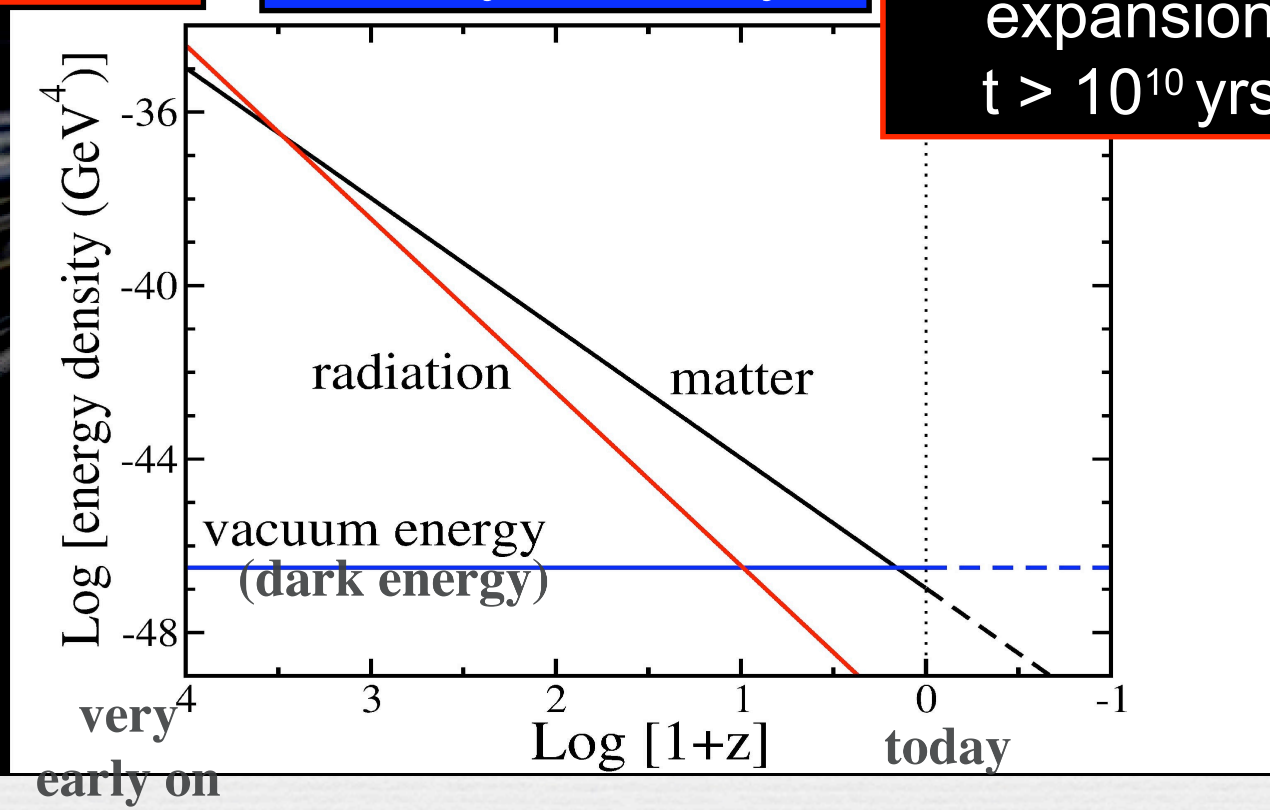
What is the value of ρ ?

3 epochs dominated by different forms of energy

1. Rad dominated
$R \sim t^{1/2}$ thermal bath
$R < 10^{-4}$, $t < 10^{4}$ yrs

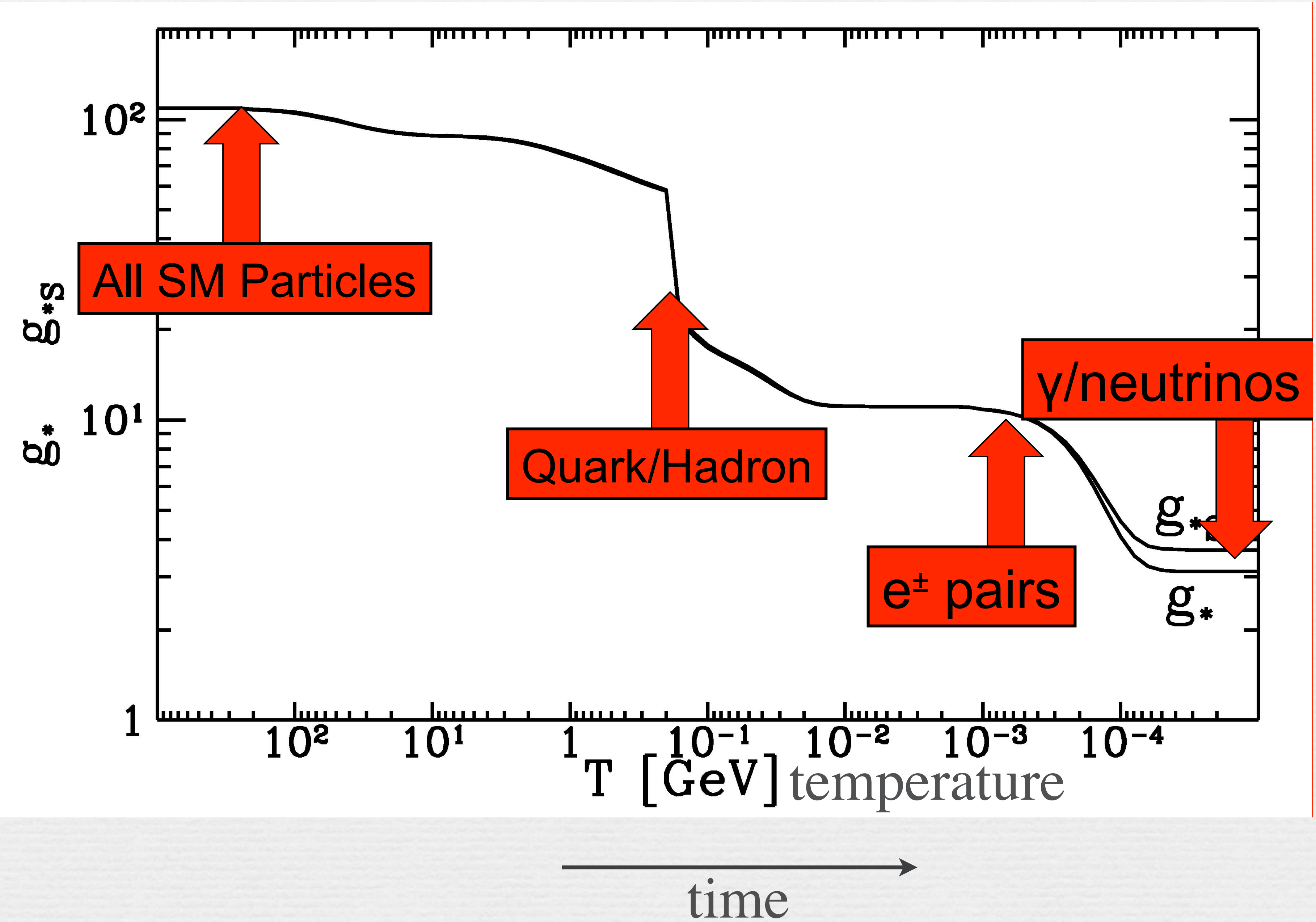
2. Matter dominated
$R \sim t^{2/3}$ struc. forms
$t \sim 10^{4}$ yrs – 10^{10} yrs

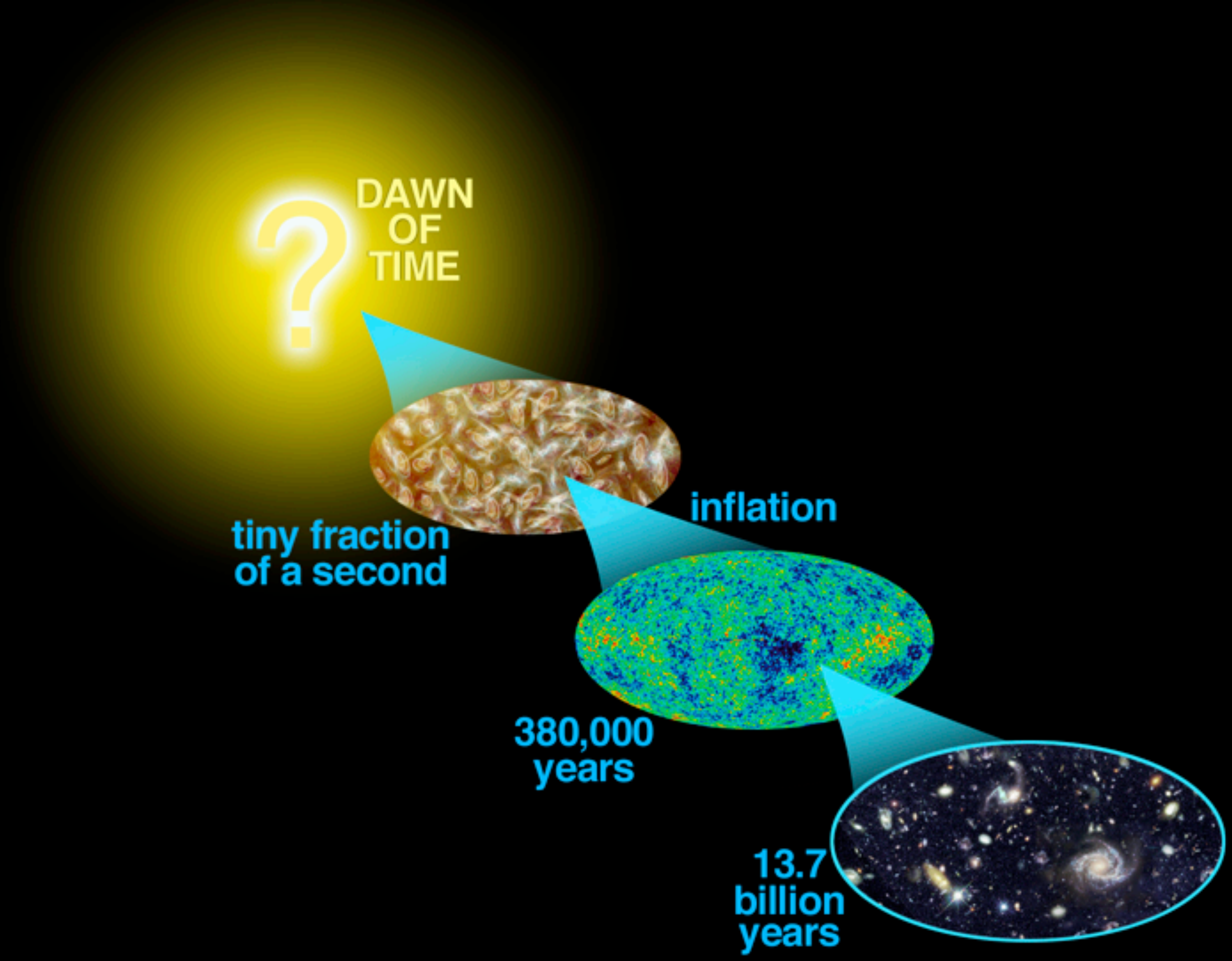
3. Dark Energy
$R \sim e^{Ht}$
accelerated
expansion
$t > 10^{10}$ yrs



time

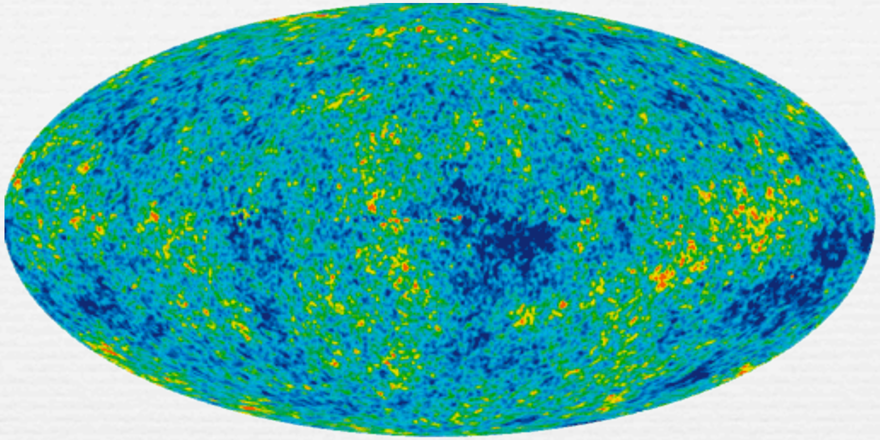
Relativistic degrees of freedom



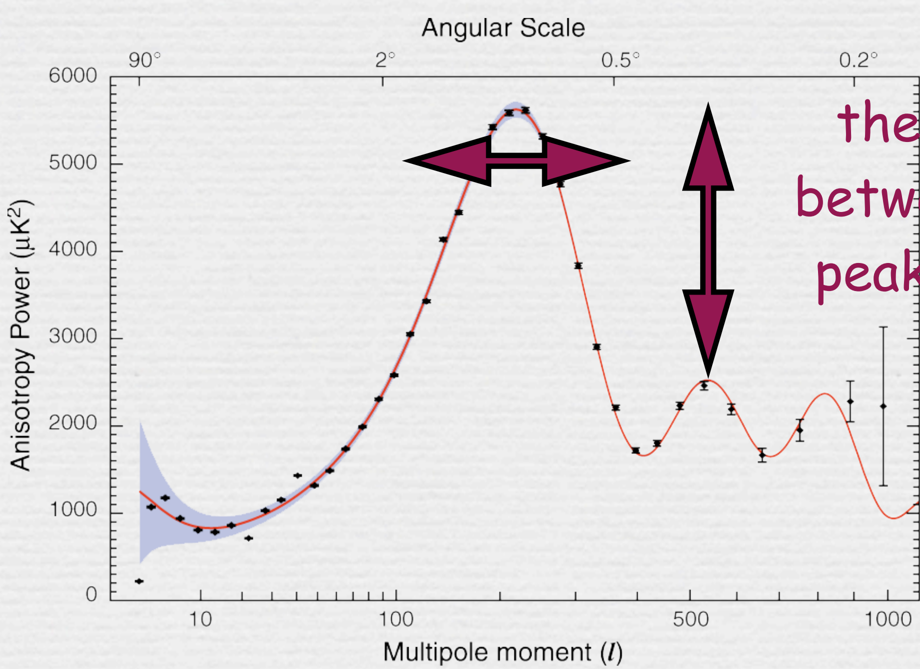


DAWN OF TIME
?
inflation
tiny fraction of a second
380,000 years
13.7 billion years

The 2.7 K Cosmic Microwave Background



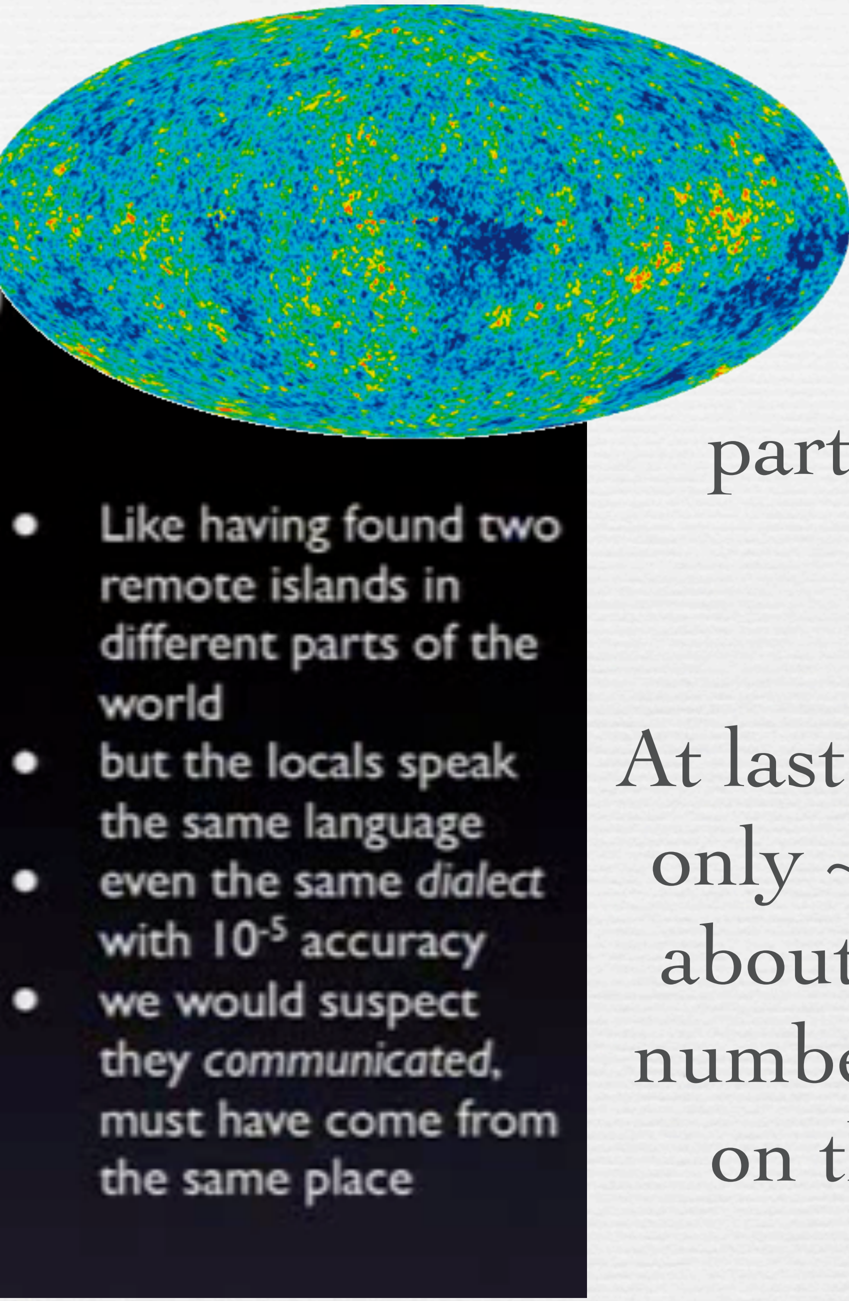
The peak position
depends on Ω_{tot}



the relative height
between the first two
peaks depends on Ω_b

Why the same temperature everywhere?

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



[H. Murayama]

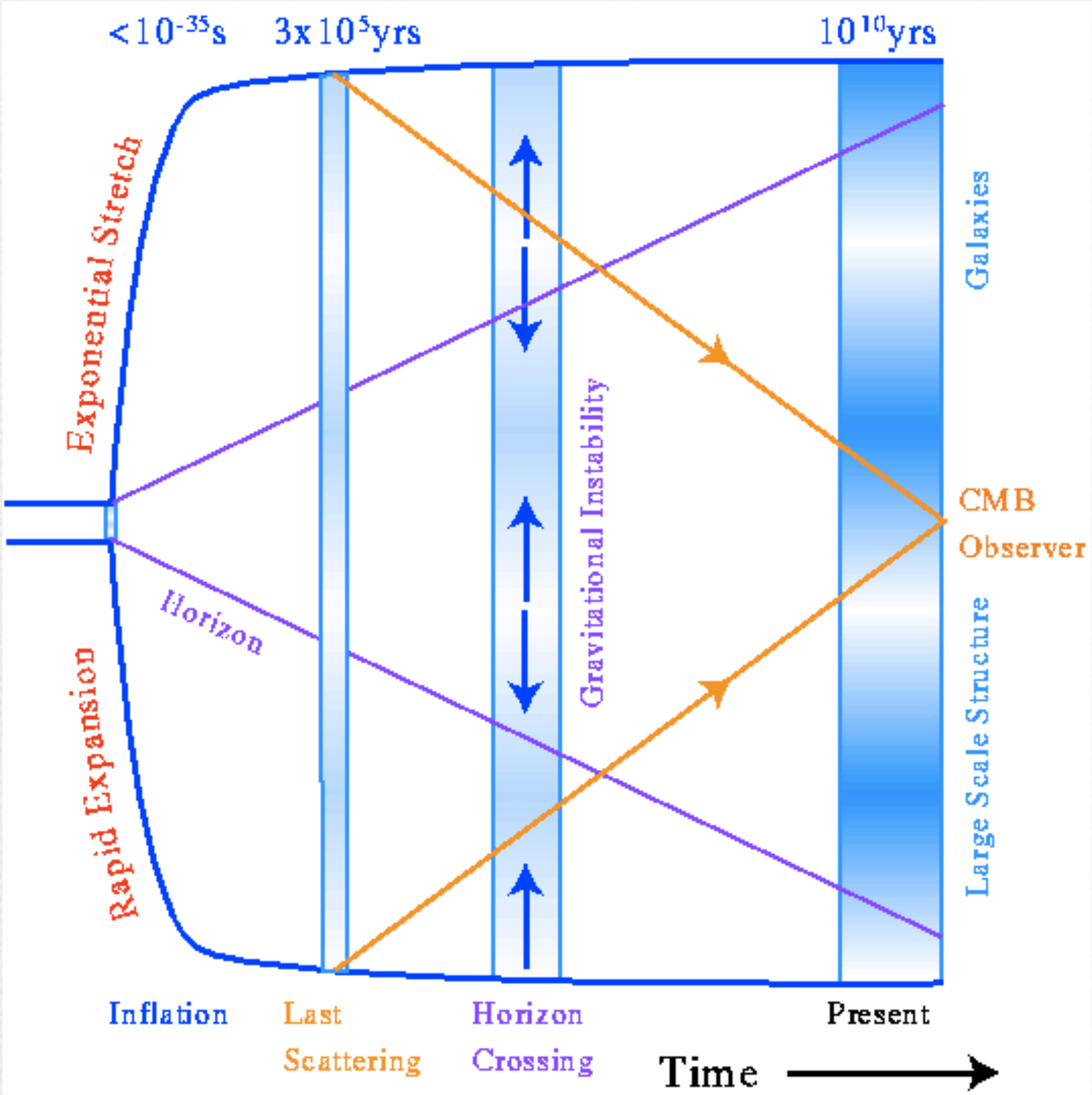
particle horizon $\quad r_H = \int_0^t \frac{c\,dt}{R(t)}$

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?

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

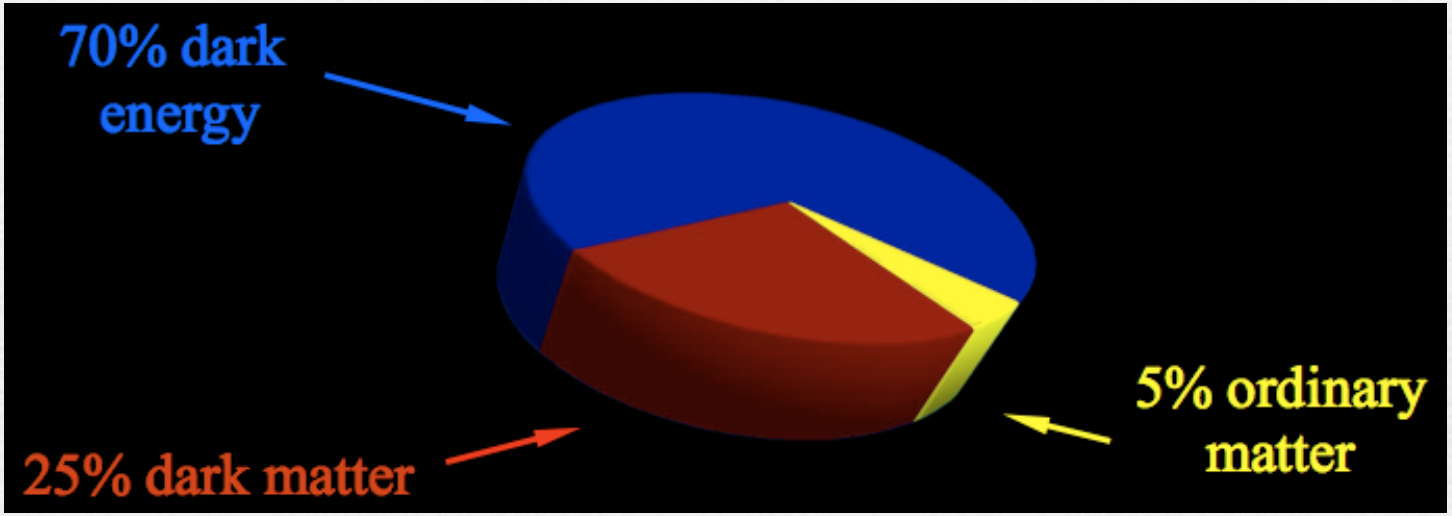
=> phase of accelerated expansion known as the inflationary universe

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 $\rho = \rho_M + \rho_R + \rho_\Lambda + \ldots$

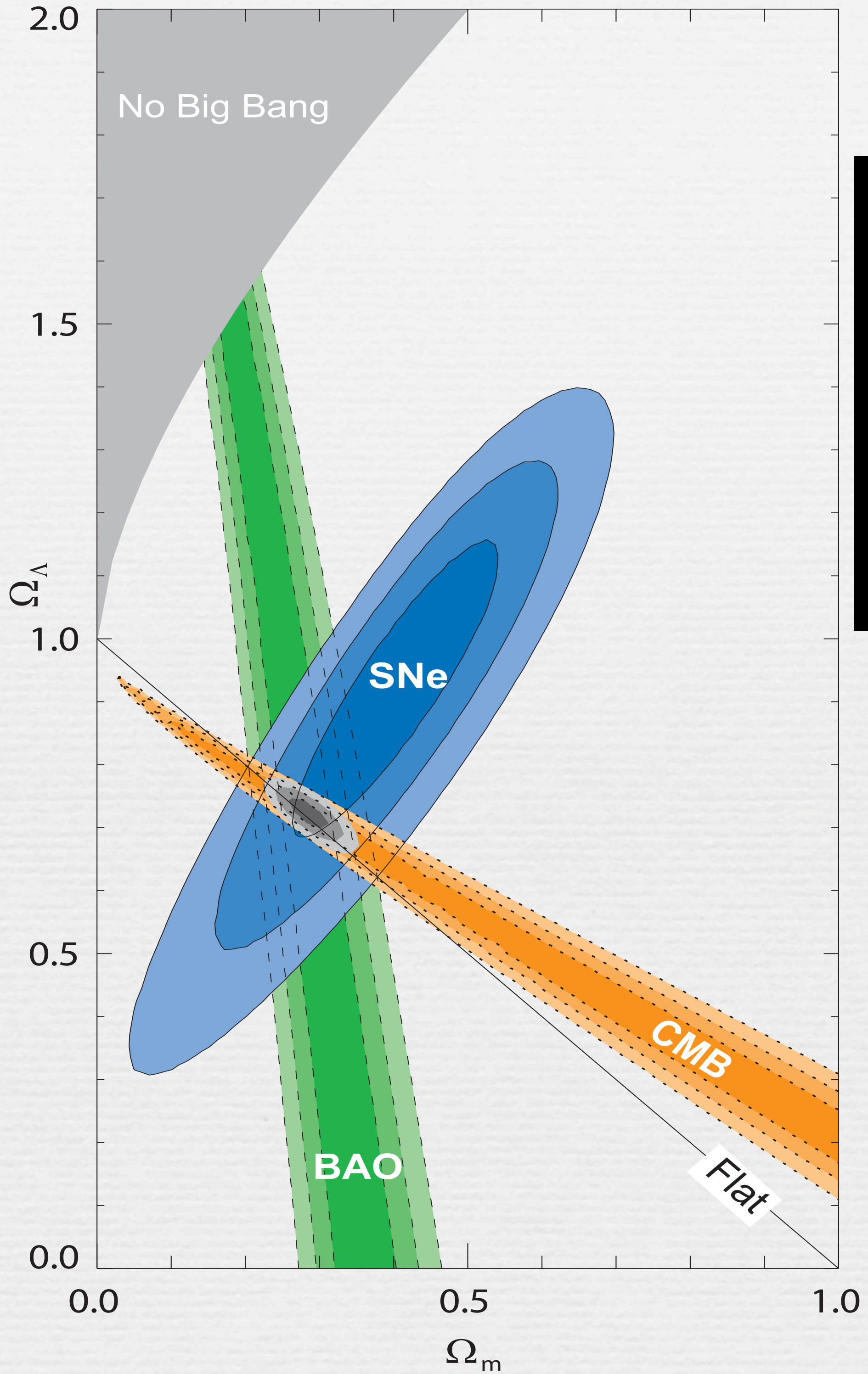
2) Calculate observables

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)

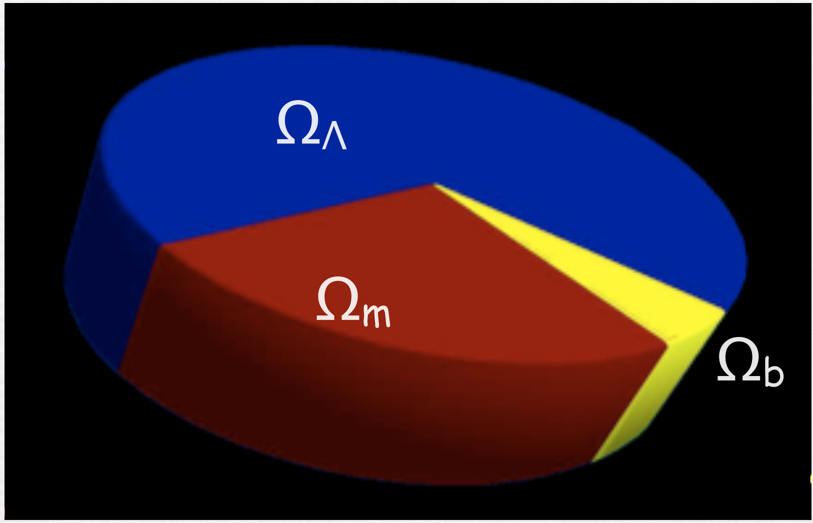
-> No possible "fit" of the cosmological model if $\rho_\Lambda = 0$.

-> 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
0.0
0.5
1.0
Ω_m
Ω_Λ
No Big Bang
SNe
CMB
BAO
Flat



Ω_Λ
Ω_m
Ω_b

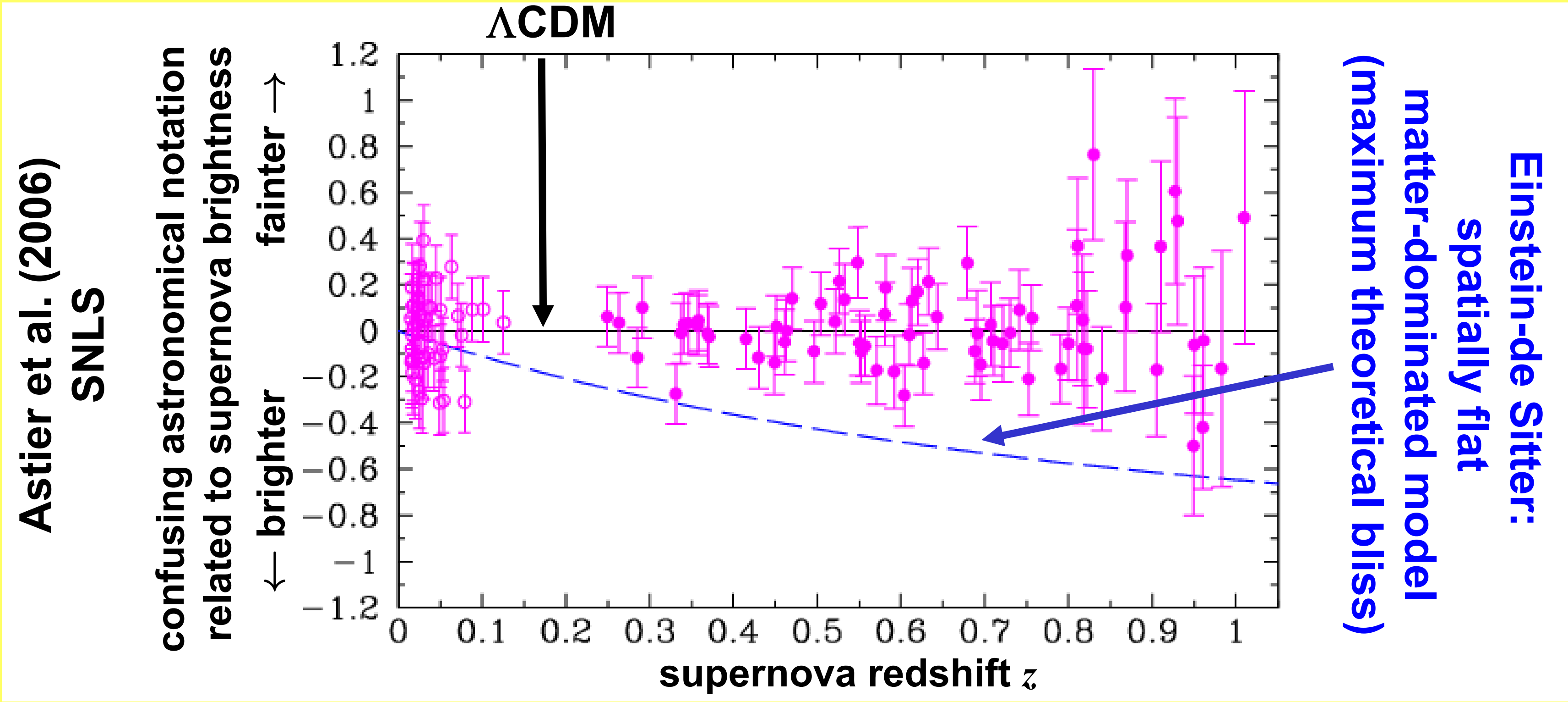
the expansion rate H is a key-quantity

$$H^2(z) = \overset{\text{Hubble's constant}}{H_0^2}\left[\overbrace{\underbrace{\left(1-\Omega_{\mathrm{TOTAL}}\right)}_{\text{CMB}}(1+z)^2}^{\text{curvature}} + \overbrace{\underbrace{\Omega_M}_{\text{LSS}}(1+z)^3}^{\text{matter}} + \overbrace{\underbrace{\Omega_R}_{\text{CMB}}(1+z)^4}^{\text{radiation}} + \overbrace{\underbrace{\Omega_w}_{H(z)}(1+z)^{3(1+w)}}^{\text{dark energy}}\right]$$

(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 ....

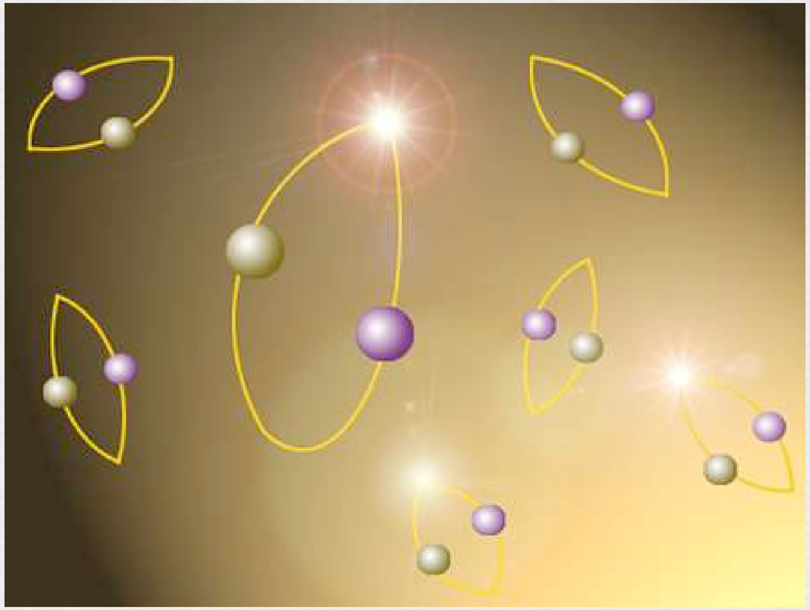
value deduced from observations:

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

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

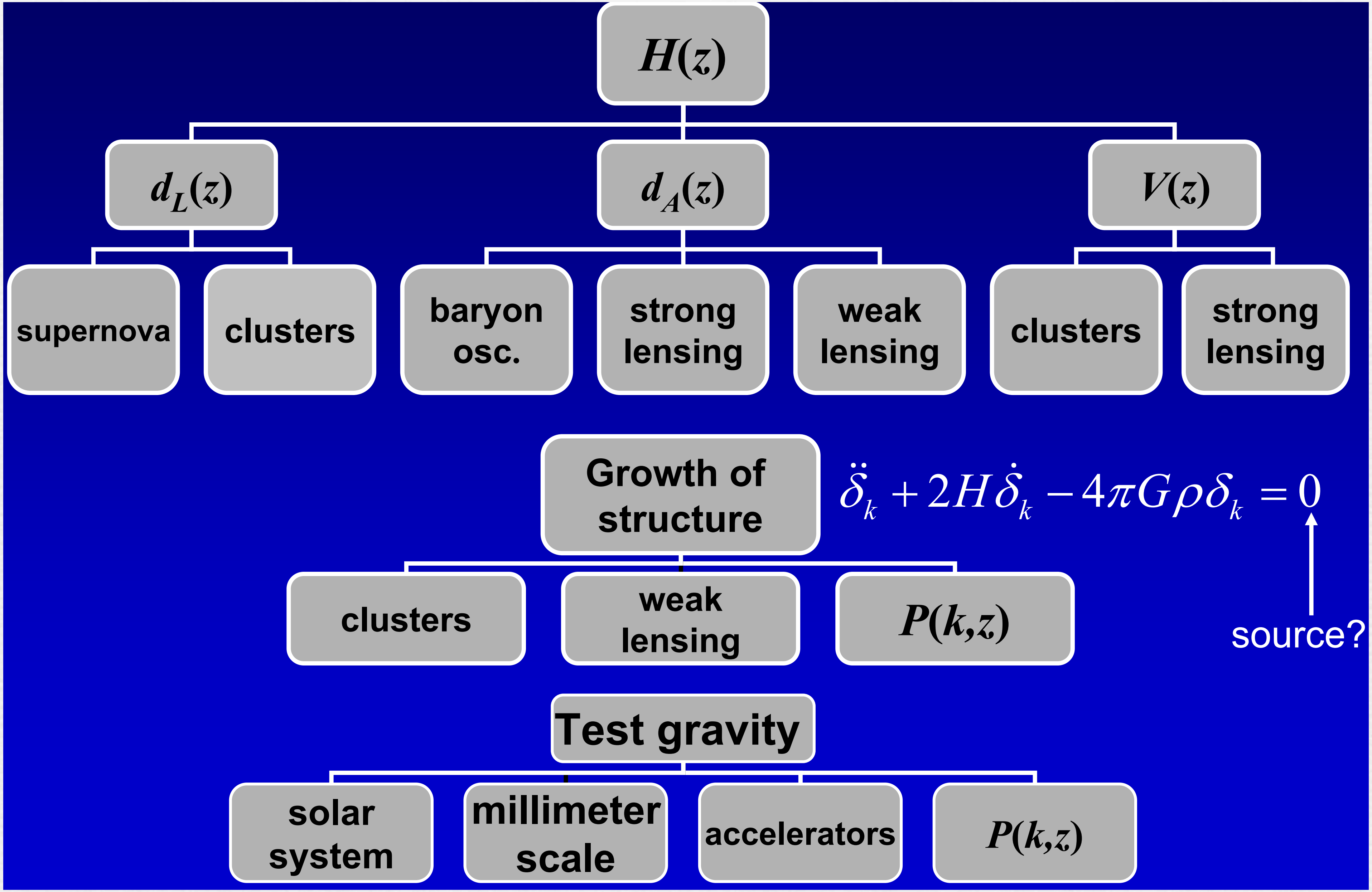
$\Lambda = M_{Planck}$ -> $\rho_\Lambda = 10^{112}\ eV^4$

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

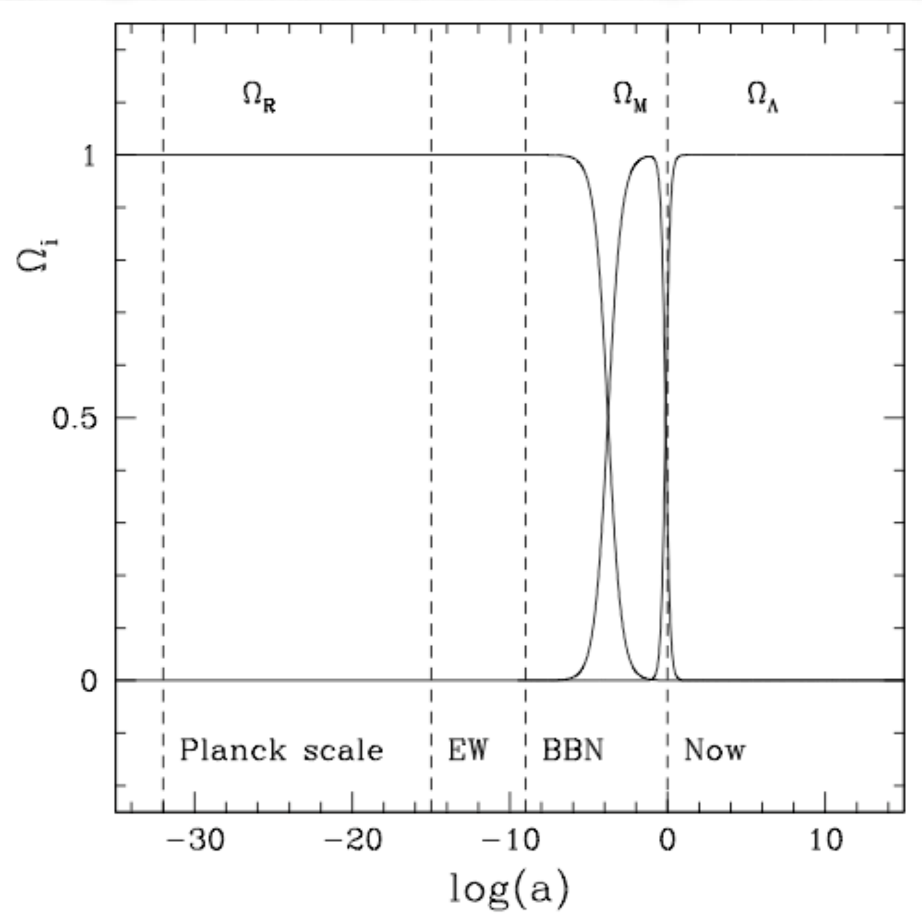


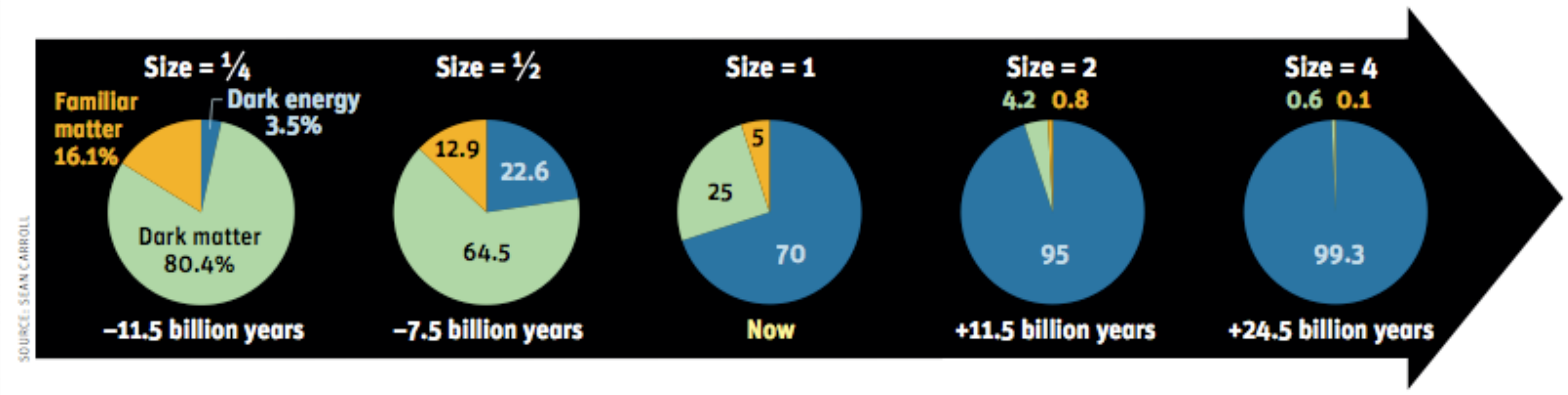
vacuum quantum fluctuations

Future plans

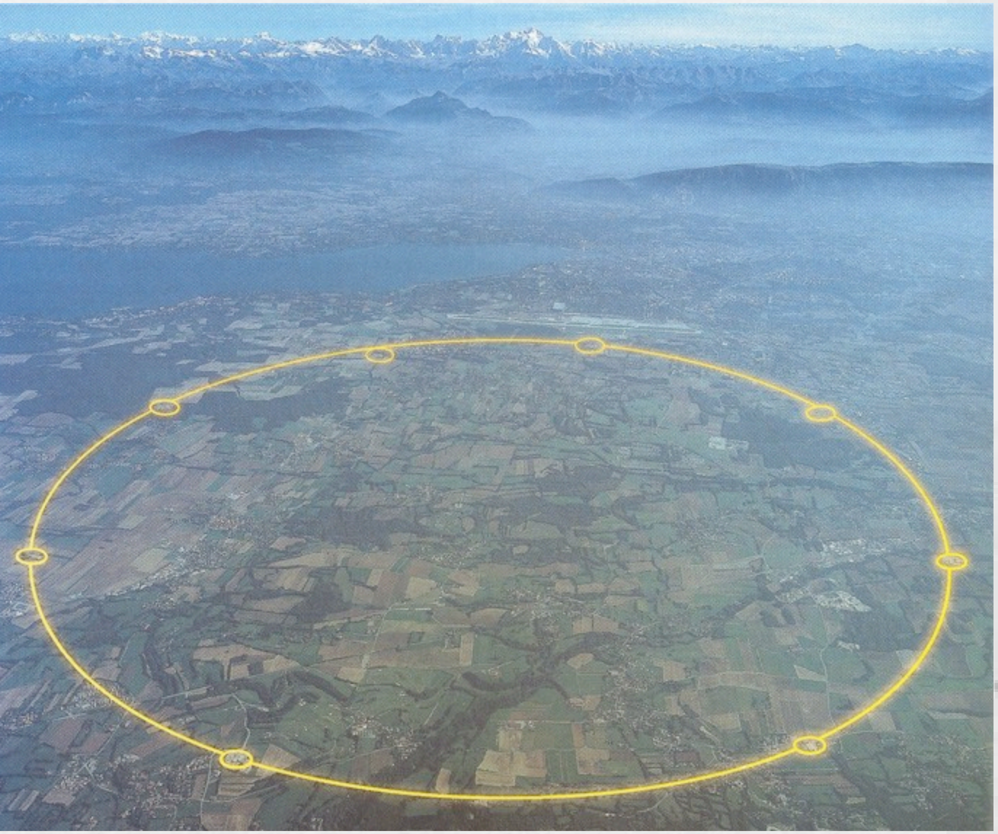


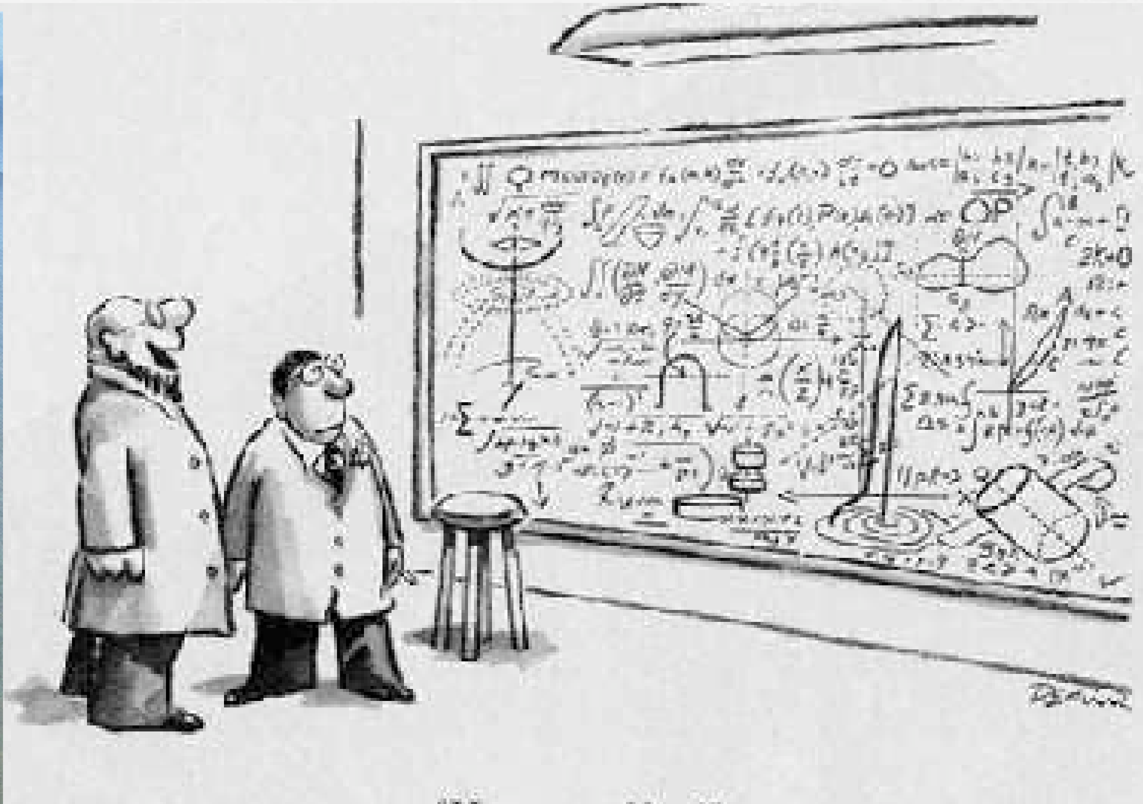
The coincidence problem (the "why now?" problem)





Questions ?





"Hey, no problem!"

Some web sites

http://www.universeadventure.org/

http://map.gsfc.nasa.gov/universe/index.html

http://www.aip.org/history/cosmology/