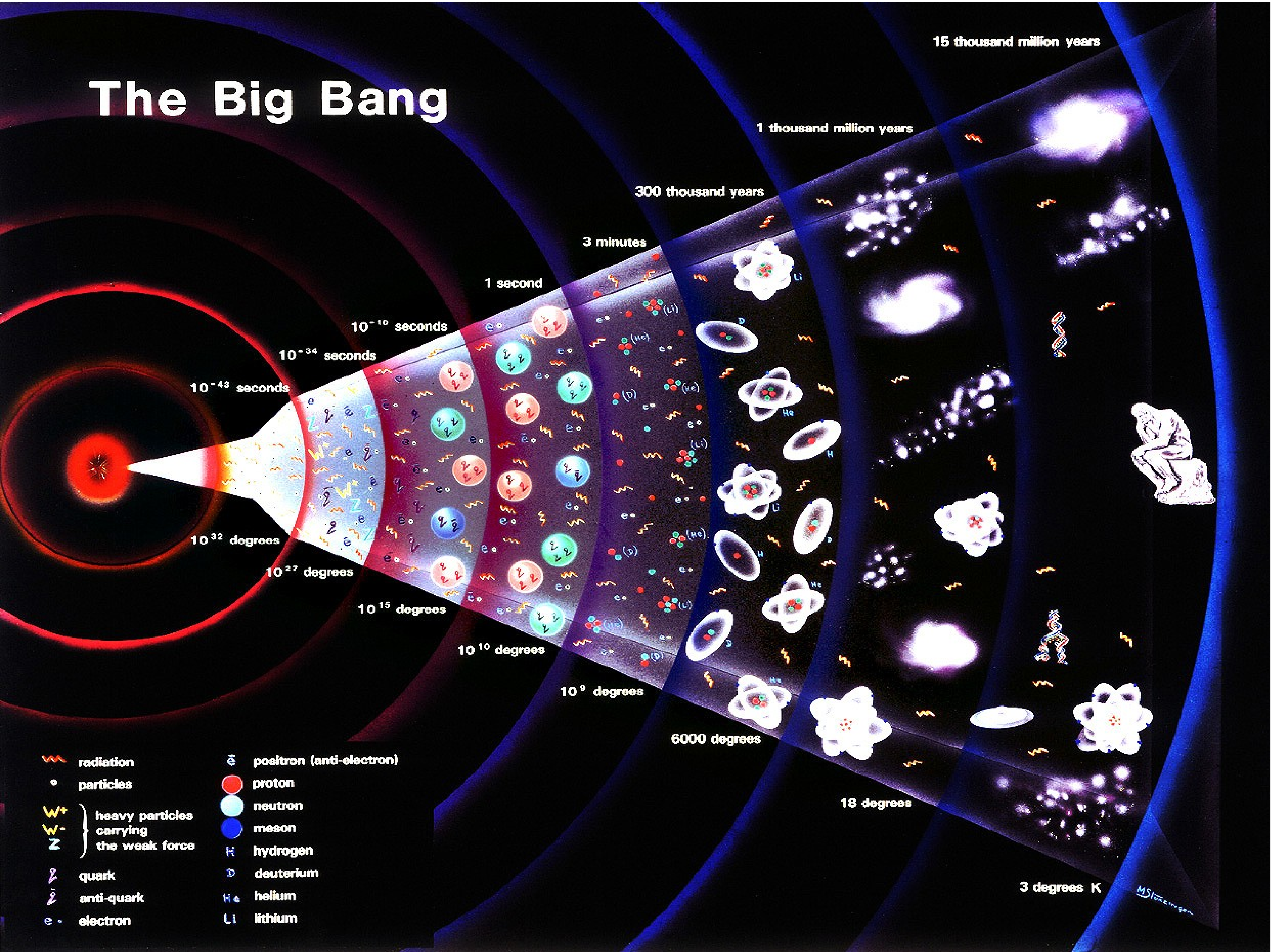
Beyond the standard model

- Why do we think there is something beyond?
  - Cosmological known issues
  - Theoretical known issues

Cosmology


COSMOLOGY MARCHES ON
Where the hell did it all come from?
Where the hell did it all come from?


The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
e electron
ē positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

The first problem

- The gravitational force is:

$$F_g = -G\frac{m_1 m_2}{r^2}$$

- Where $G = 6.67384 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$ is the gravitational constant
- What are natural scales: mass and length for gravity?

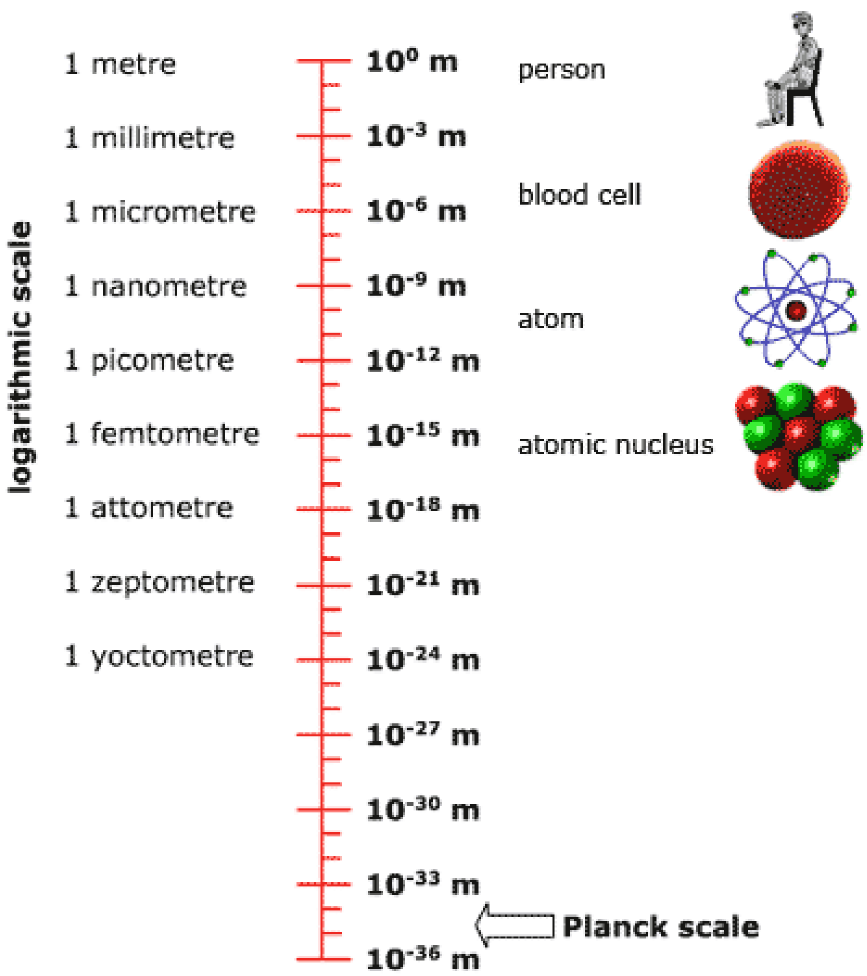
The first problem

- The Universe is governed by general relativity
- There is no quantum theory of gravity!
- The scale where quantum gravity becomes important is the Planck scale

$$m_{planck} = \sqrt{\frac{\hbar c}{G}} \approx 10^{19}\, GeV$$

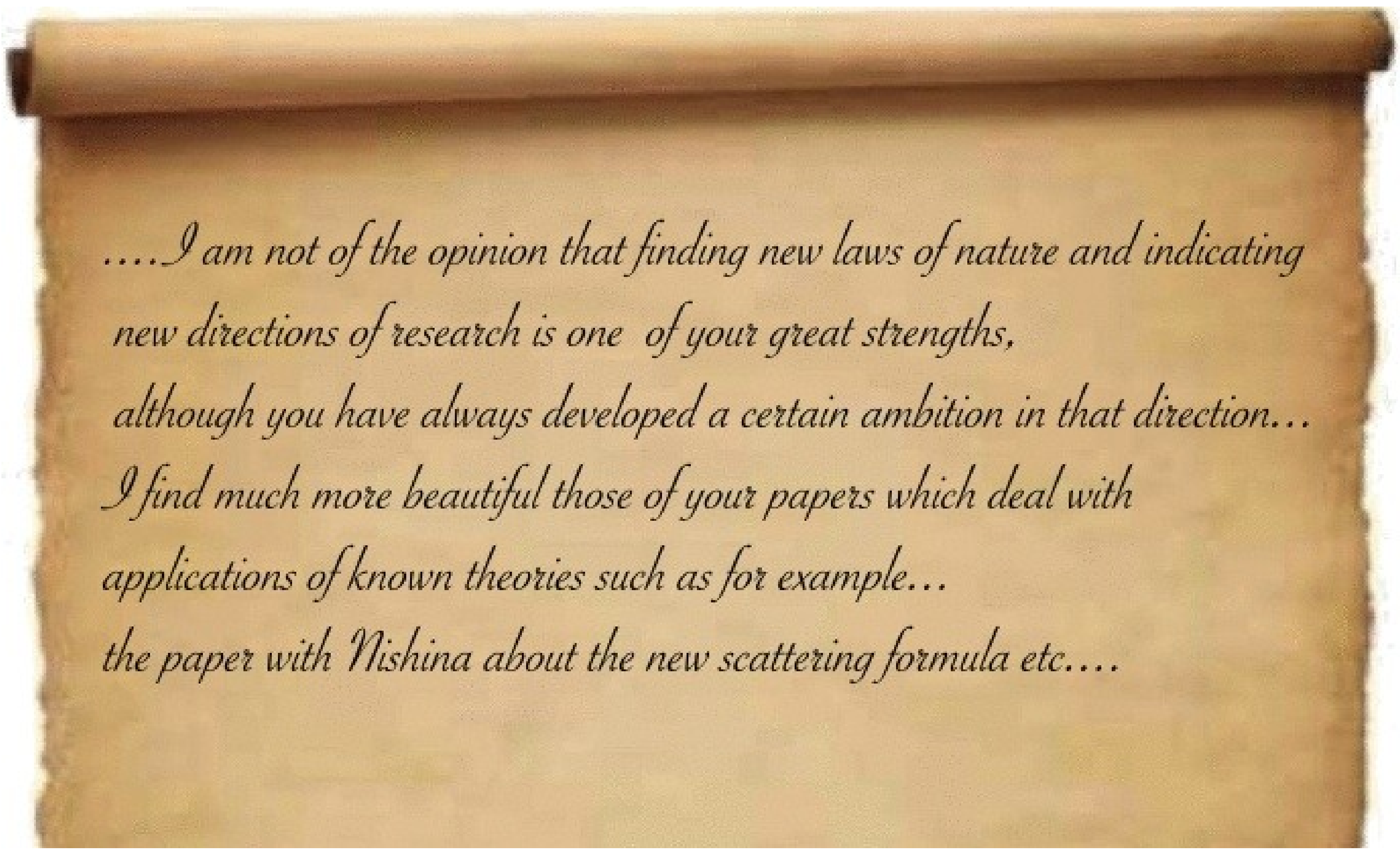
$$l_{planck} = \sqrt{\frac{\hbar G}{c^3}} \approx 10^{-20}\, fm$$

We expect a new unified theory to become important at this scale



- Problem: planck scale is so small/large that it cannot be probed experimentally yet
- Theoretical solutions exist: string theory!
- Next slides mainly taken from Eliezer Rabinovici's talk in the Nobel symposium on LHC results 2013

Shortly Before arriving in Stockholm, Klein received a letter from his good friend Pauli which reads in part:



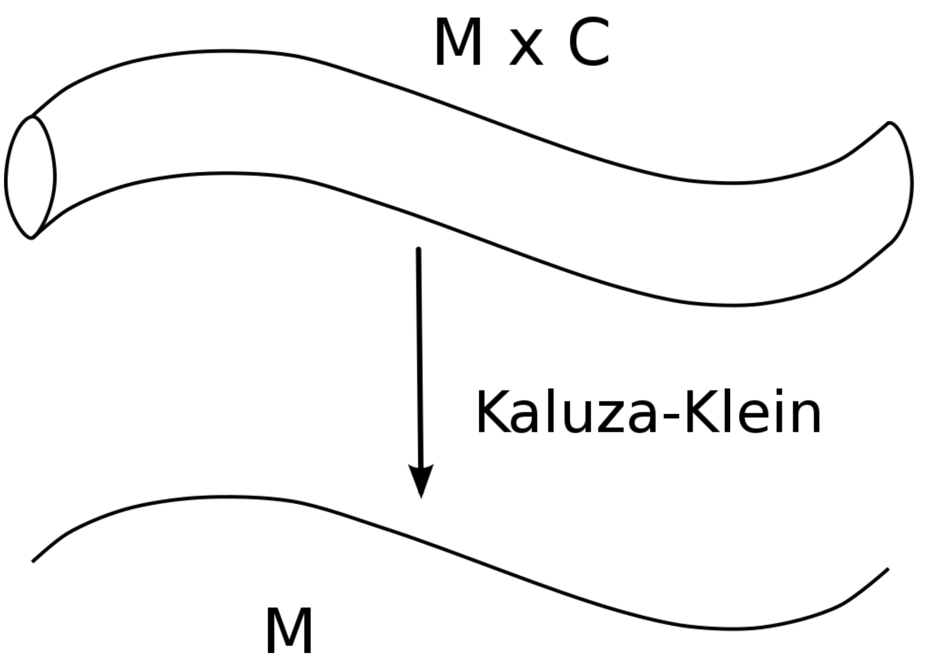
....I am not of the opinion that finding new laws of nature and indicating new directions of research is one of your great strengths, although you have always developed a certain ambition in that direction... I find much more beautiful those of your papers which deal with applications of known theories such as for example... the paper with Nishina about the new scattering formula etc....

Kaluza–Klein theory

(http://en.wikipedia.org/wiki/Kaluza-Klein_theory)

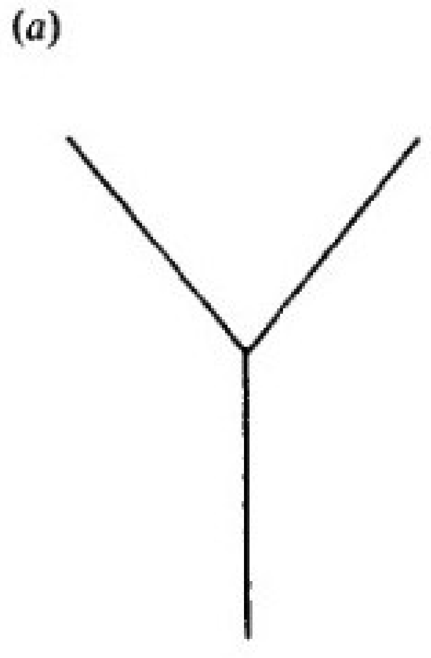
- In physics, Kaluza–Klein theory (KK theory) is a model that seeks to unify the two fundamental forces of gravitation and electromagnetism.
- The theory was first published in 1921. It was proposed by the mathematician Theodor Kaluza who extended general relativity to a five-dimensional spacetime.
- In 1926, Oskar Klein (Swedish theoretical physicist) proposed that the fourth spatial dimension is curled up in a circle of a very small radius, so that a particle moving a short distance along that axis would return to where it began.

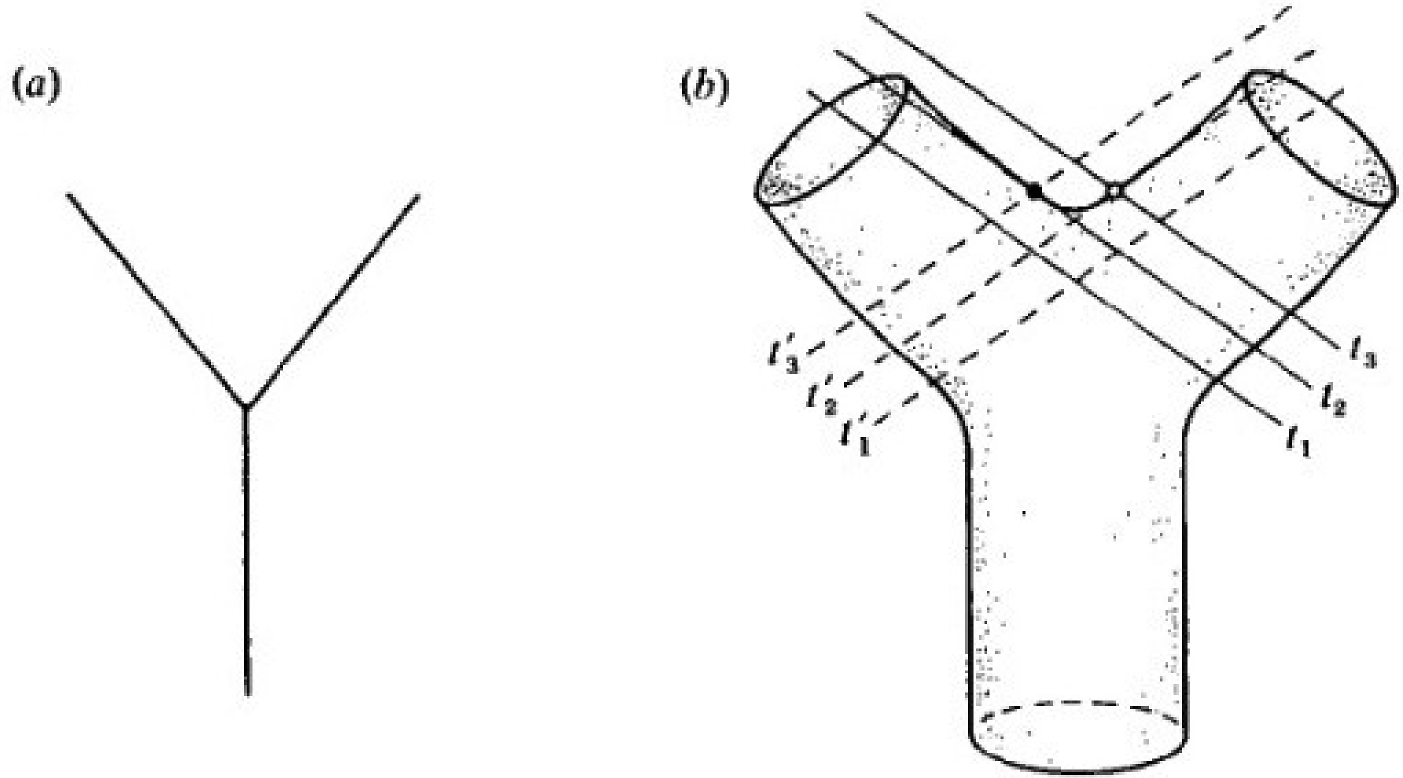
Compact extra dimensions
Basis of string theory



- The extra dimension(s) gives rise to new physics
- Original idea: "geometric" description of electromagnetism
- Modern: excitations of the compact dimension

Particle scattering vs string scattering




(a)
(b)
l'_3
l'_2
l'_1
l_3
l_2
l_1

Bohr correspondence principle

Open
string

$$\int -\frac{1}{4}\mathrm{Tr}F_{\mu\nu}^2\, d^4x$$

(Quantum Field Theory)

Bohr correspondence principle

Open string

$$\int -\frac{1}{4}\mathrm{Tr}F_{\mu\nu}^2\, d^4x$$

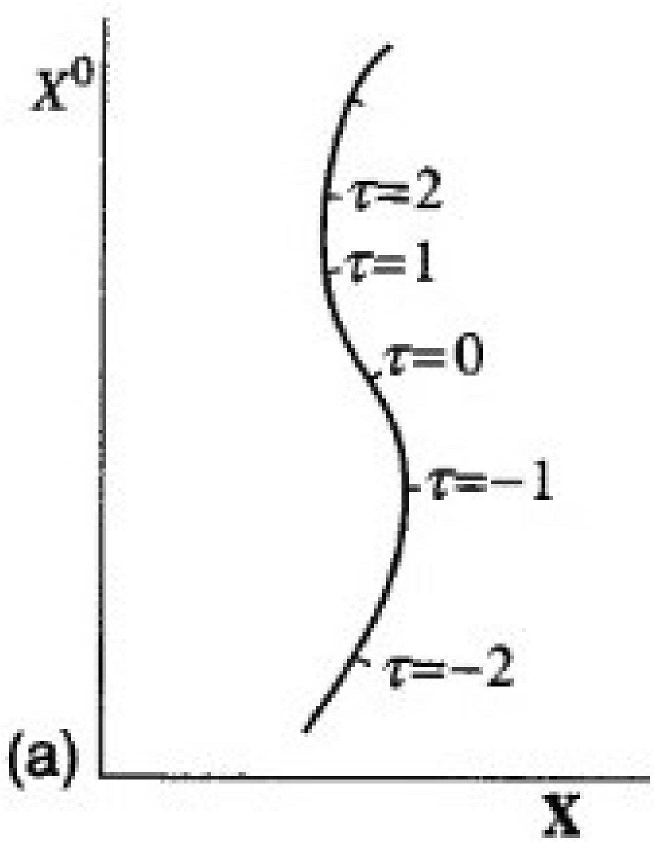
(Quantum Field Theory)

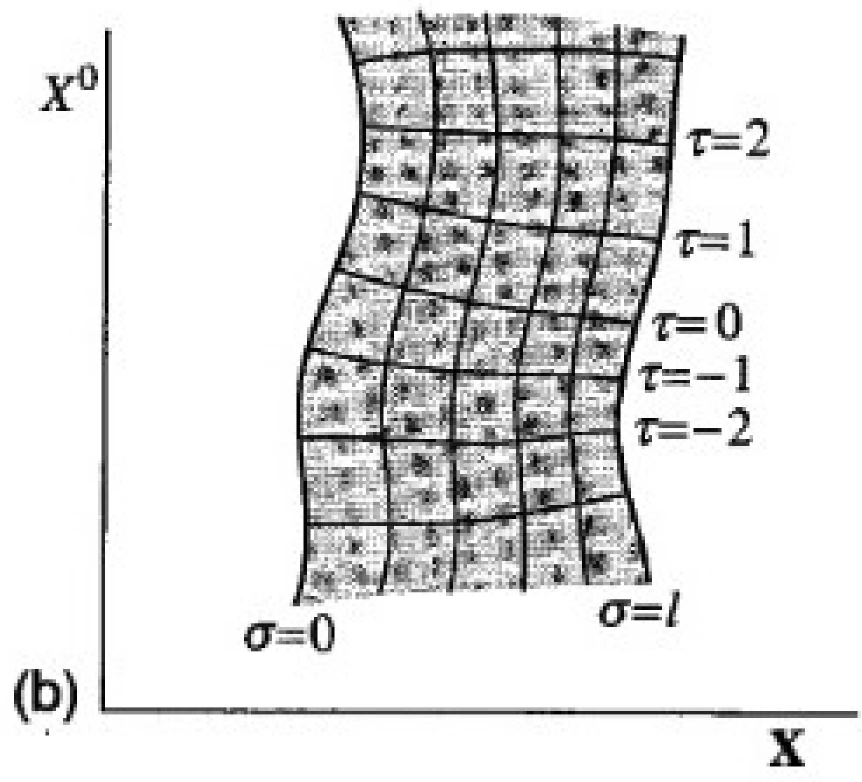
Closed string

$$\int R\sqrt{-g}\, d^4x$$

(Gravity)

Worldline vs Worldsheet





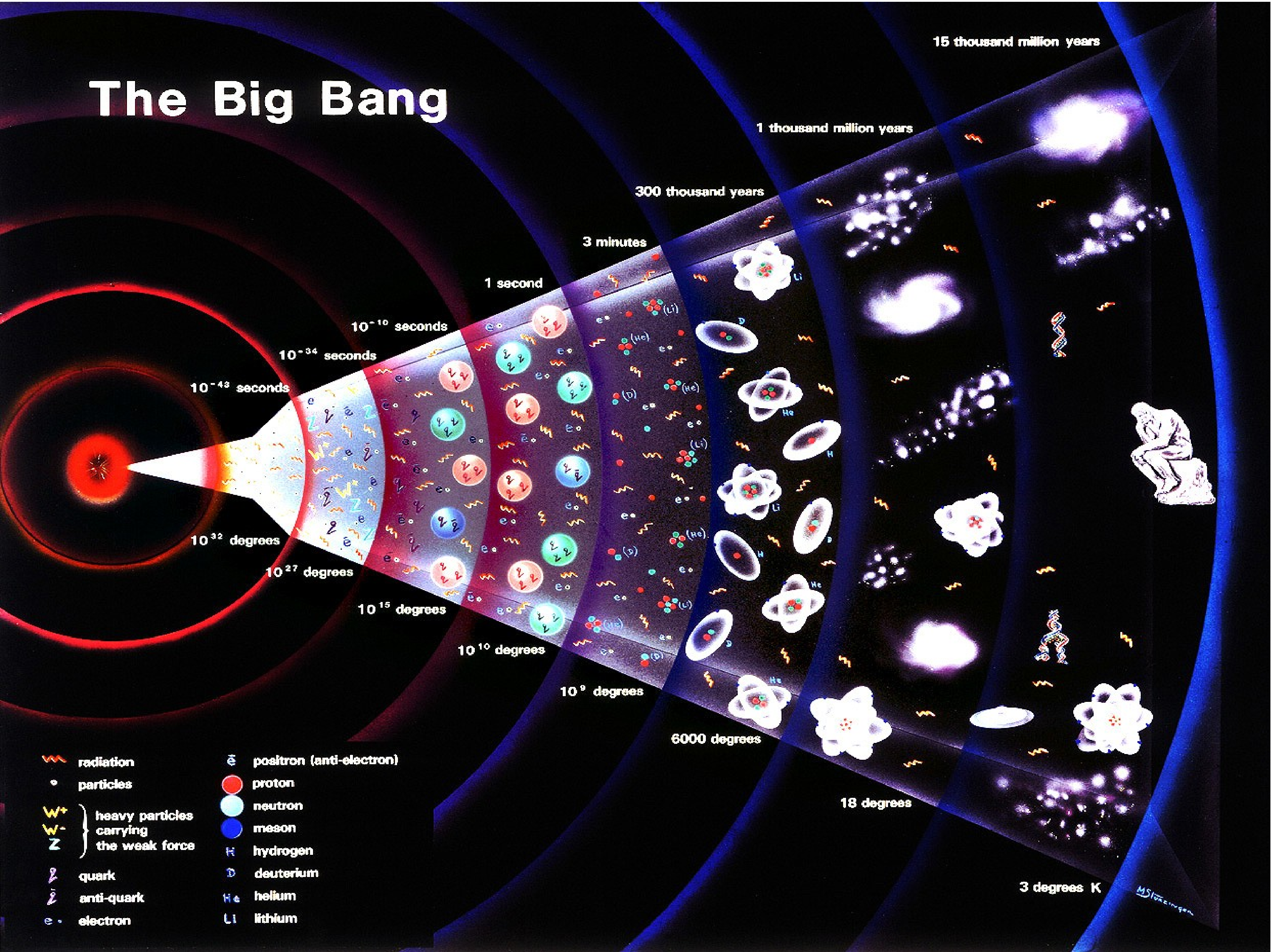
String Theory: number of dimensions

- What must be the “dimension” becomes a scientific question : Central charge=26,15 sometimes means dimensions= 26 or =10 (condensed matter systems classified) N.K.K was already there but the number of dimensions are obtained bottom up by the known interactions

- Important that this is a mathematical requirement. The theory only works mathematically if Ndimensions is e.g. 26

Leaving string theory

- The problem with string theory is that in addition to being extremely difficult from a mathematical point of view it has not lead to testable predictions



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heavy particles carrying the weak force
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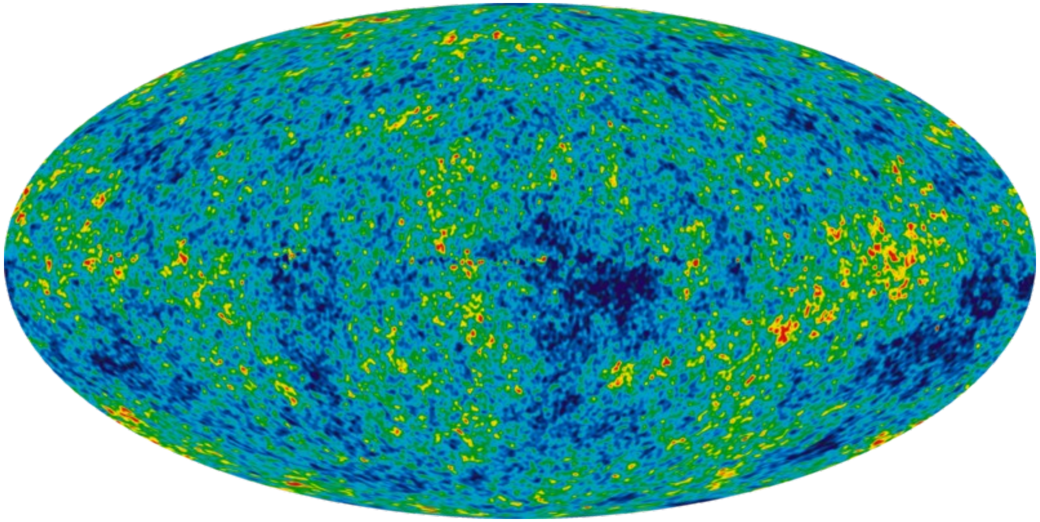
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

What is the evidence for the big bang?

What is the evidence for the big bang?

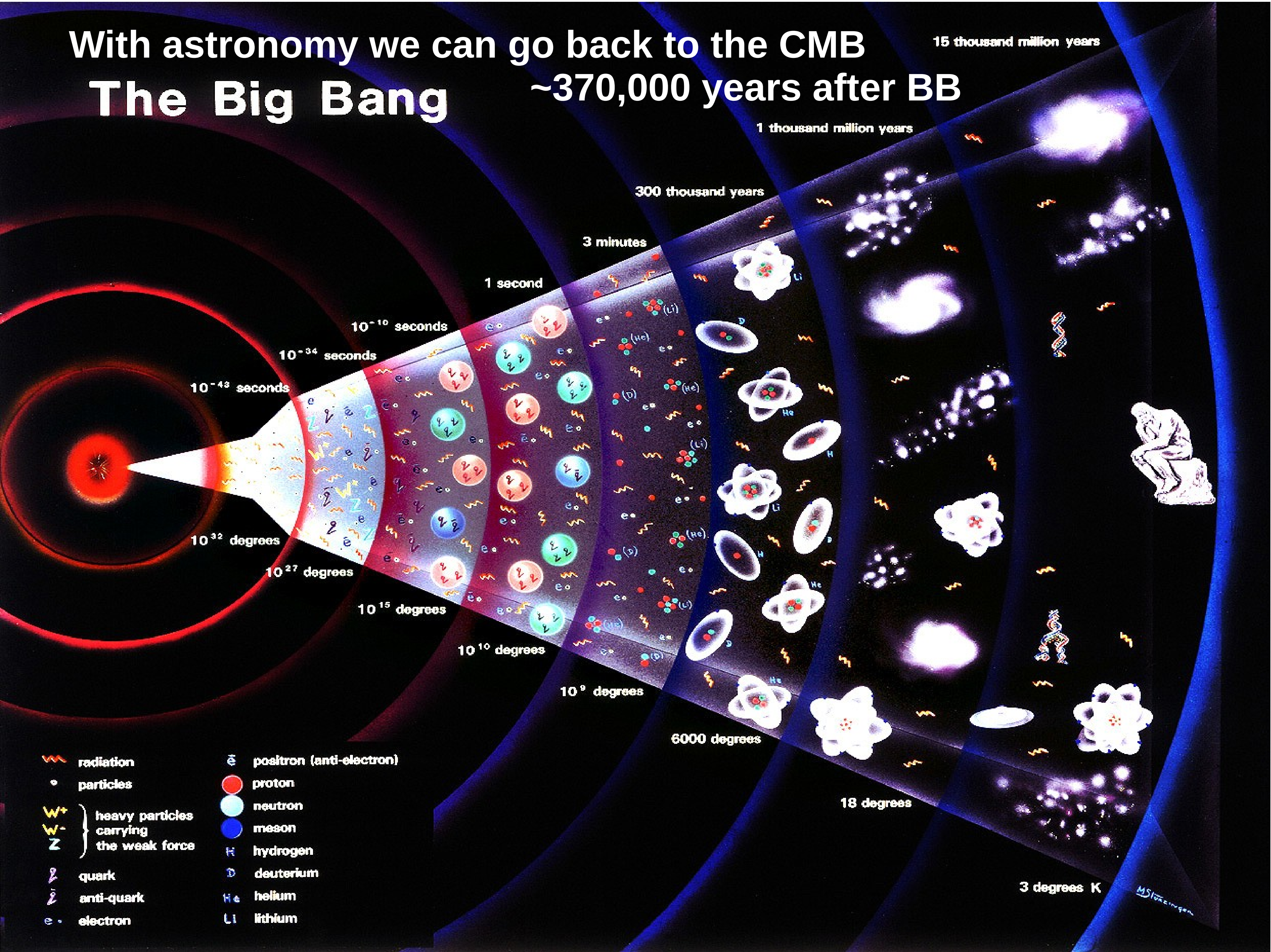
- All galaxies seems to be moving away from us (redshift) = Hubble law
- The abundances of hydrogen and helium in the Universe is close to what one would expect from statistical thermal production (Nucleosynthesis)
- The cosmic microwave background (T~2.7 K)

Cosmic Microwave Background

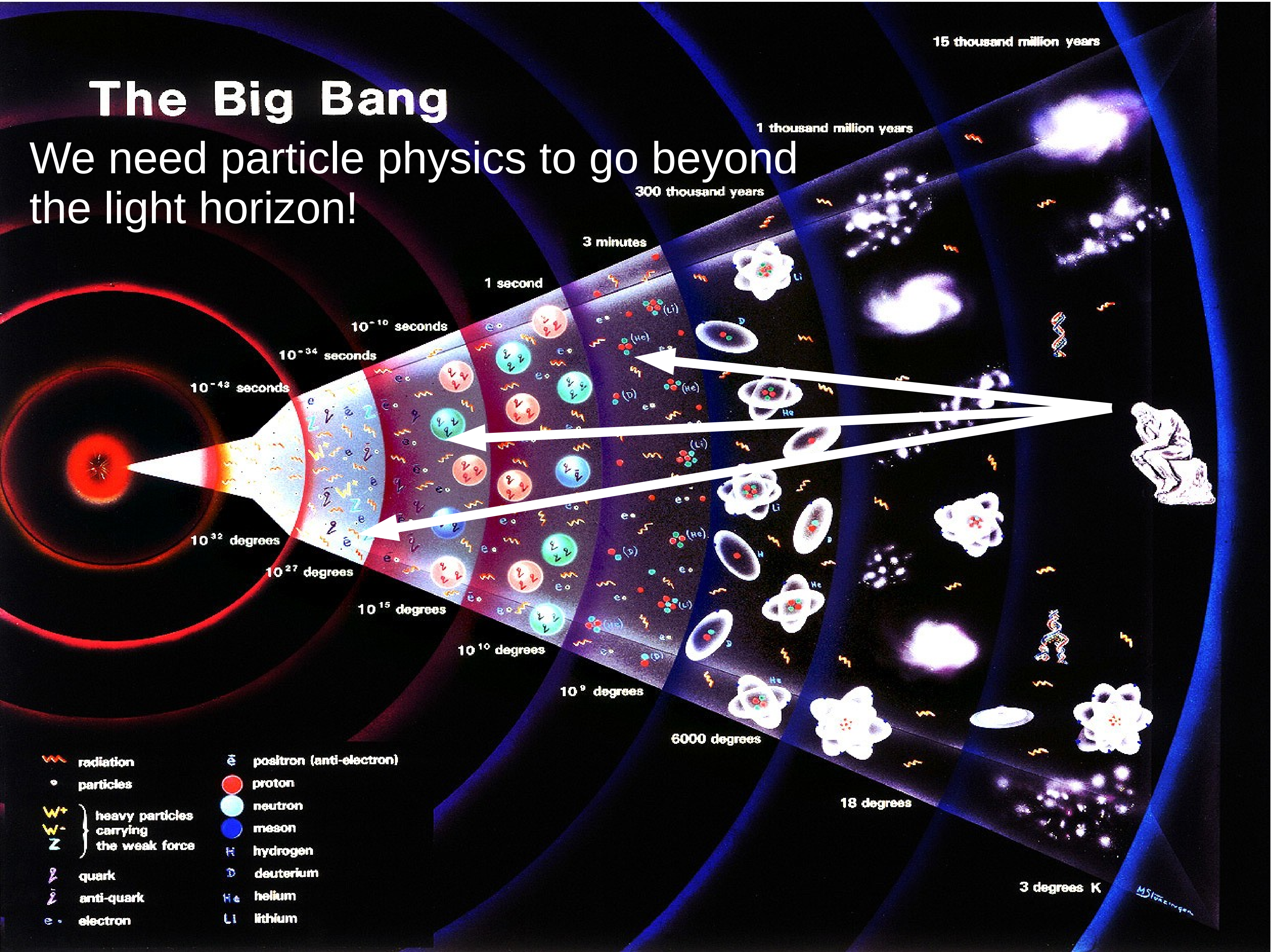


- Nine Year Microwave Sky
- The detailed, all-sky picture of the infant universe created from nine years of WMAP data. The image reveals 13.77 billion year old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become the galaxies. The signal from our galaxy was subtracted using the multi-frequency data. This image shows a temperature range of ± 200 microKelvin.
- Credit: NASA / WMAP Science Team

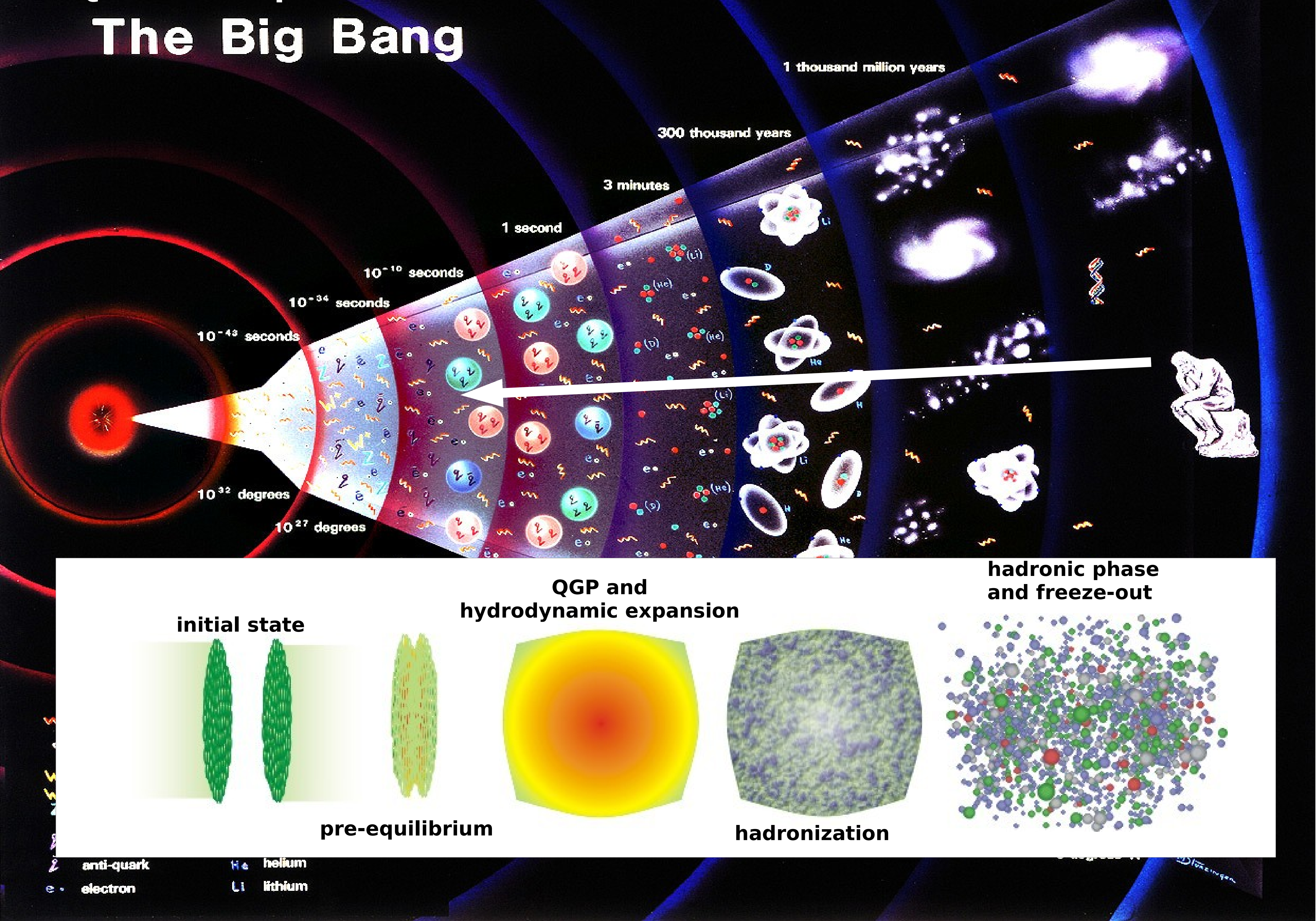
With astronomy we can go back to the CMB ~370,000 years after BB



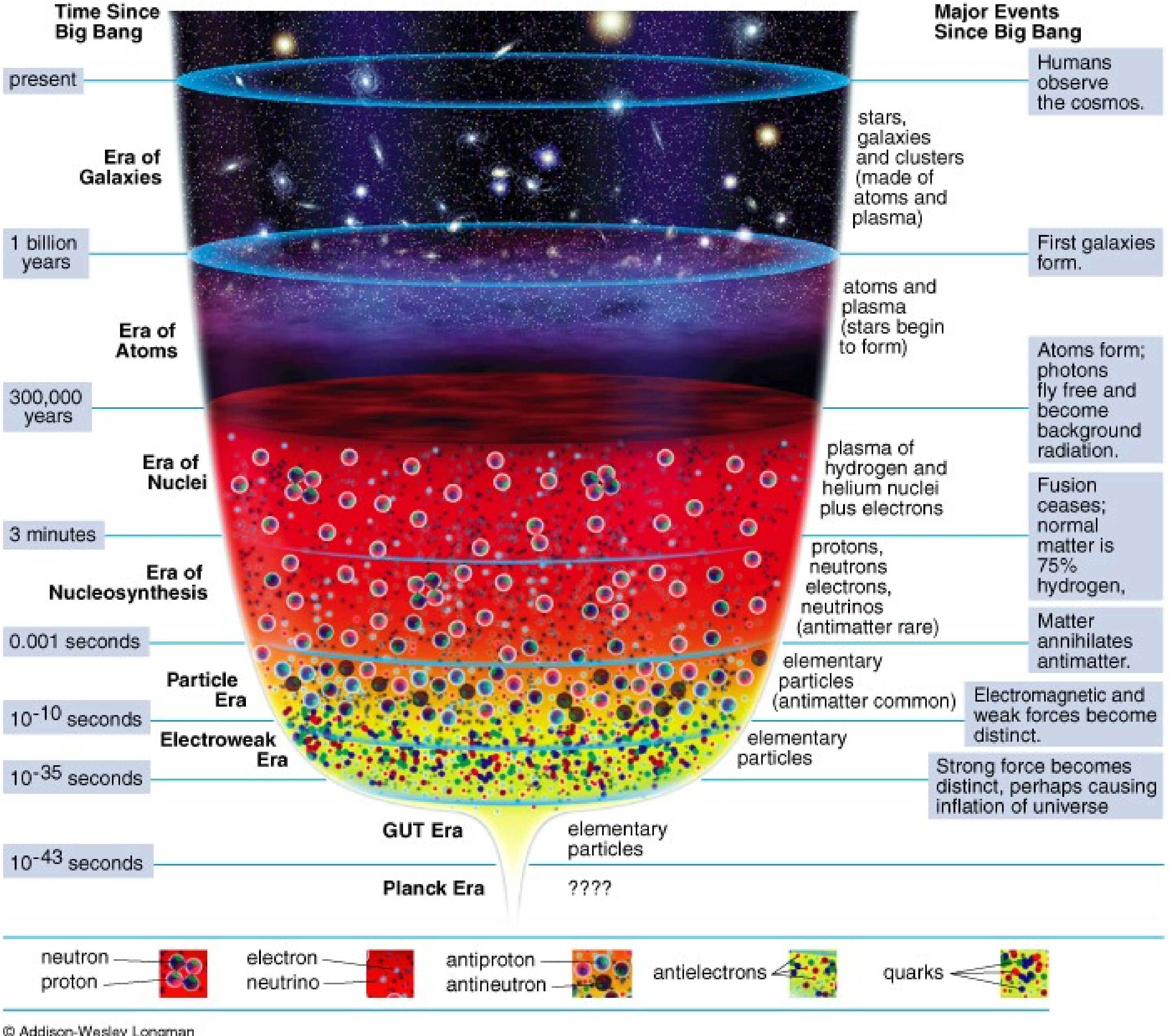
We need particle physics to go beyond the light horizon!



QGP – the phase of the universe 1 micro second after



A particle physics view of the evolution of the Universe



How do we know that we do not live in a matter anti-matter symmetric Universe?

- How could one test this?

How do we know that we do not live in a matter anti-matter symmetric Universe?

- "When matter and antimatter meet, they annihilate each other and the mass is converted into energy--specifically, into gamma-rays. If a distant galaxy were made of antimatter, it would constantly be producing gamma-rays as it encountered the matter in the intergalactic gas clouds that exist throughout galaxy clusters.

- "We do not see any steady stream of gamma-rays coming from any source in the sky. Therefore, astronomers conclude that there are not occasional 'rogue' galaxies made of antimatter. If there is any large amount of antimatter in the universe, it must encompass at least an entire galaxy cluster, and probably a supercluster. Once might postulate the existence of such antimatter superclusters, but then one would be faced with the problem of coming up with a mechanism that, shortly after the big bang, would have separated these now-gigantic clumps of antimatter from the neighboring clumps of mater. No such mechanism has yet been envisioned."

- Taken from: http://www.scientificamerican.com/article.cfm?id=how-do-we-know-that

Matter anti-matter asymmetry

- For some reason which we do not understand there seems to have been a matter anti-matter asymmetry so that when the Universe hadromized after roughly 1 microsecond there was 1 extra baryon for each roughly 1 billion baryon and anti-baryon pair

Sakharov criteria

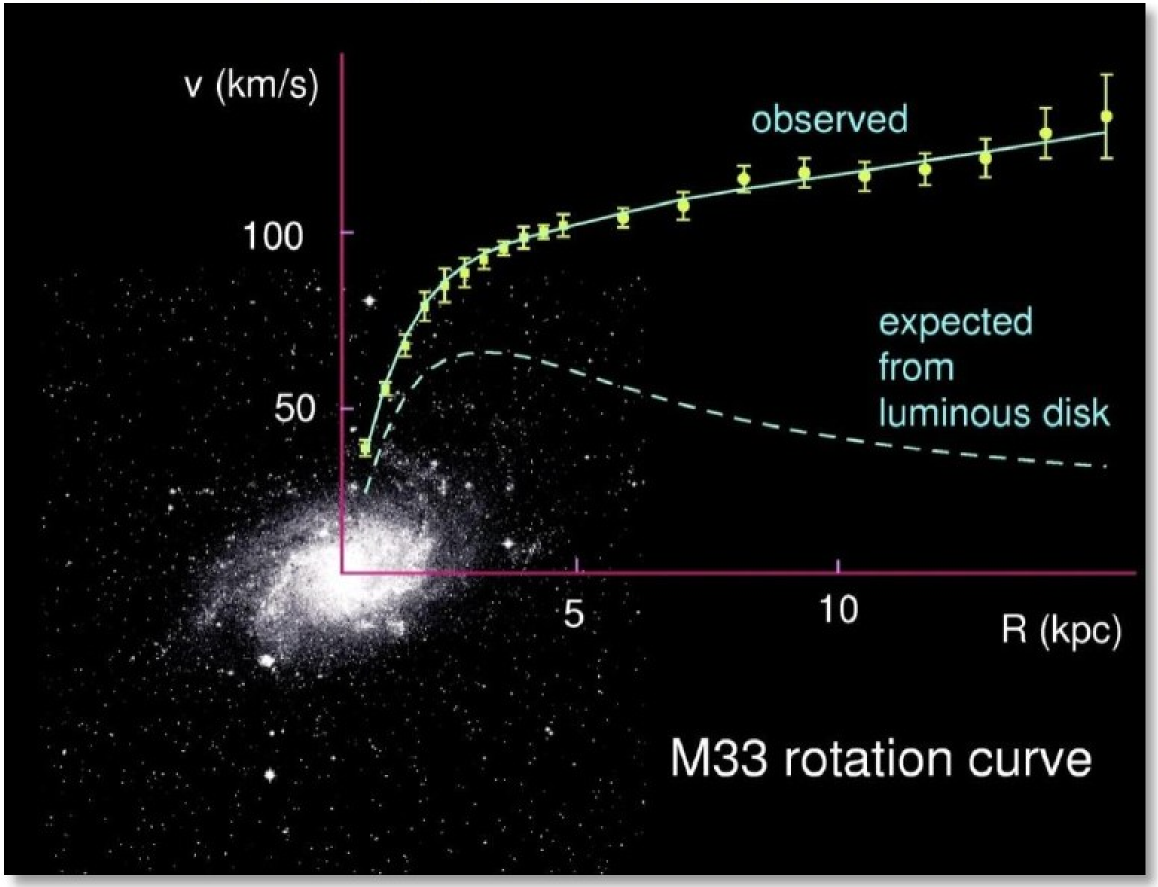
- Sakharov conditions from http://en.wikipedia.org/wiki/Baryogenesis
- In 1967, Andrei Sakharov proposed a set of three necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter at different rates.
- Baryon number B violation.
- C-symmetry and CP-symmetry violation.
- Interactions out of thermal equilibrium.
- Baryon number violation is obviously a necessary condition to produce an excess of baryons over anti-baryons. But C-symmetry violation is also needed so that the interactions which produce more baryons than anti-baryons will not be counterbalanced by interactions which produce more anti-baryons than baryons. CP-symmetry violation is similarly required because otherwise equal numbers of left-handed baryons and right-handed anti-baryons would be produced, as well as equal numbers of left-handed anti-baryons and right-handed baryons. **Finally, the interactions must be out of thermal equilibrium, since otherwise CPT symmetry would assure compensation between processes increasing and decreasing the baryon number.**

Dark matter

- ”If this over-density is confirmed we would arrive at the astonishing conclusion that dark matter is present with a much greater density than luminous matter.” Zwicky 1933

Indirect detection

Galaxy rotation curves

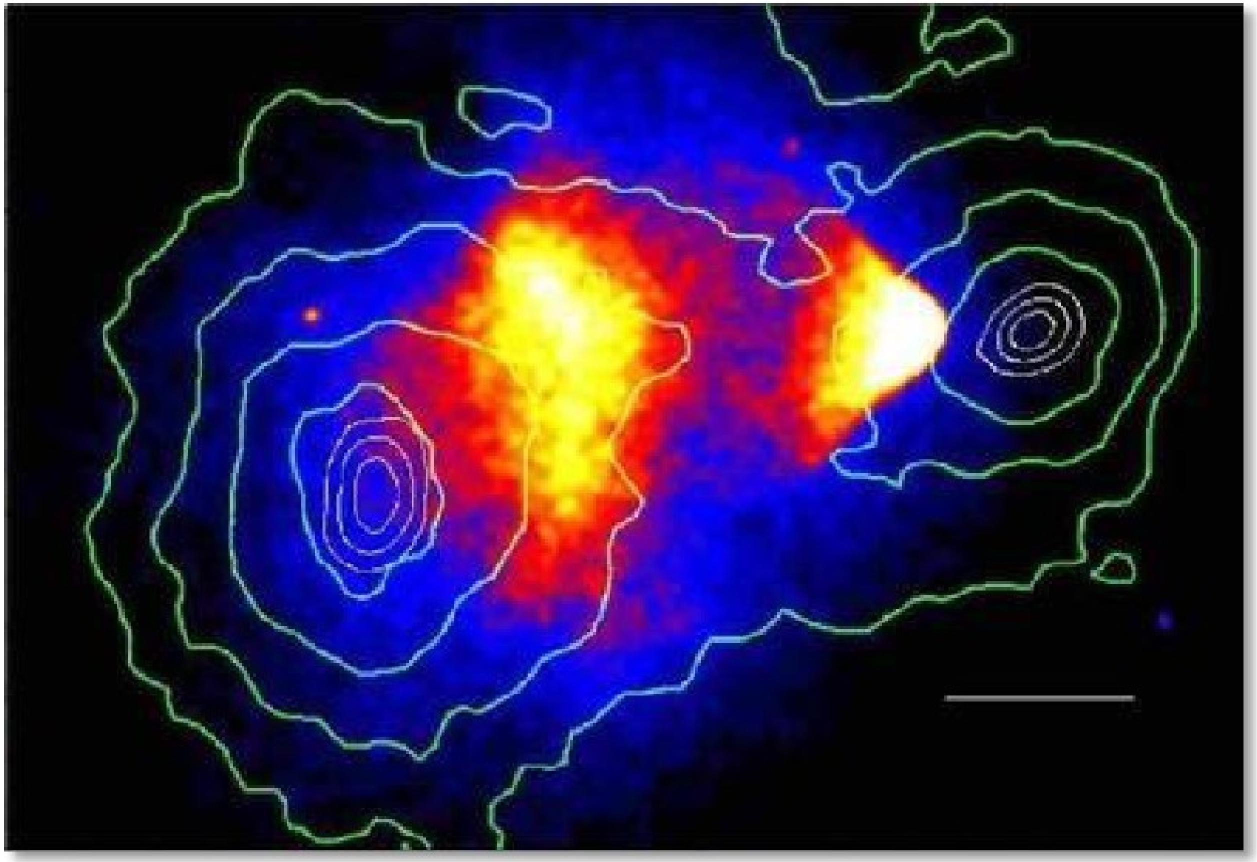


L.B., Rep. Prog. Phys. 2000

MOdified Newtonian Dynamics (MOND)

- These indirect rotation curves can be explained by alternative gravitational forces where the 1/radius^2 for some reason does not work everywhere
- An experiment to look for MOND will be shown at DESY

Direct detection



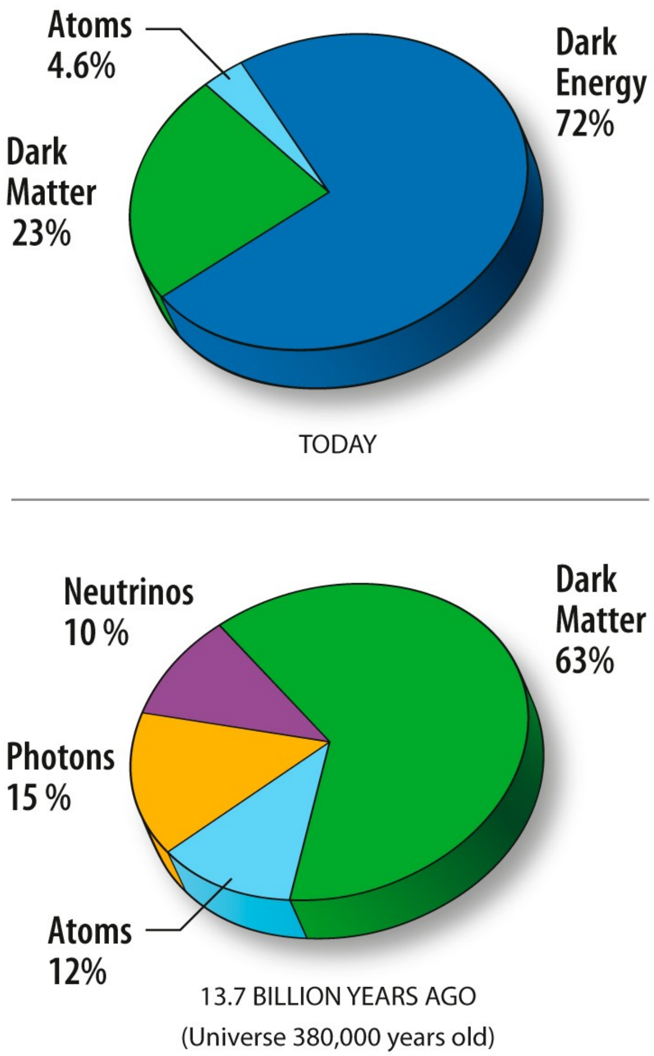
The bullet cluster, D. Clowe et al., 2006

8

What do we know about dark matter?

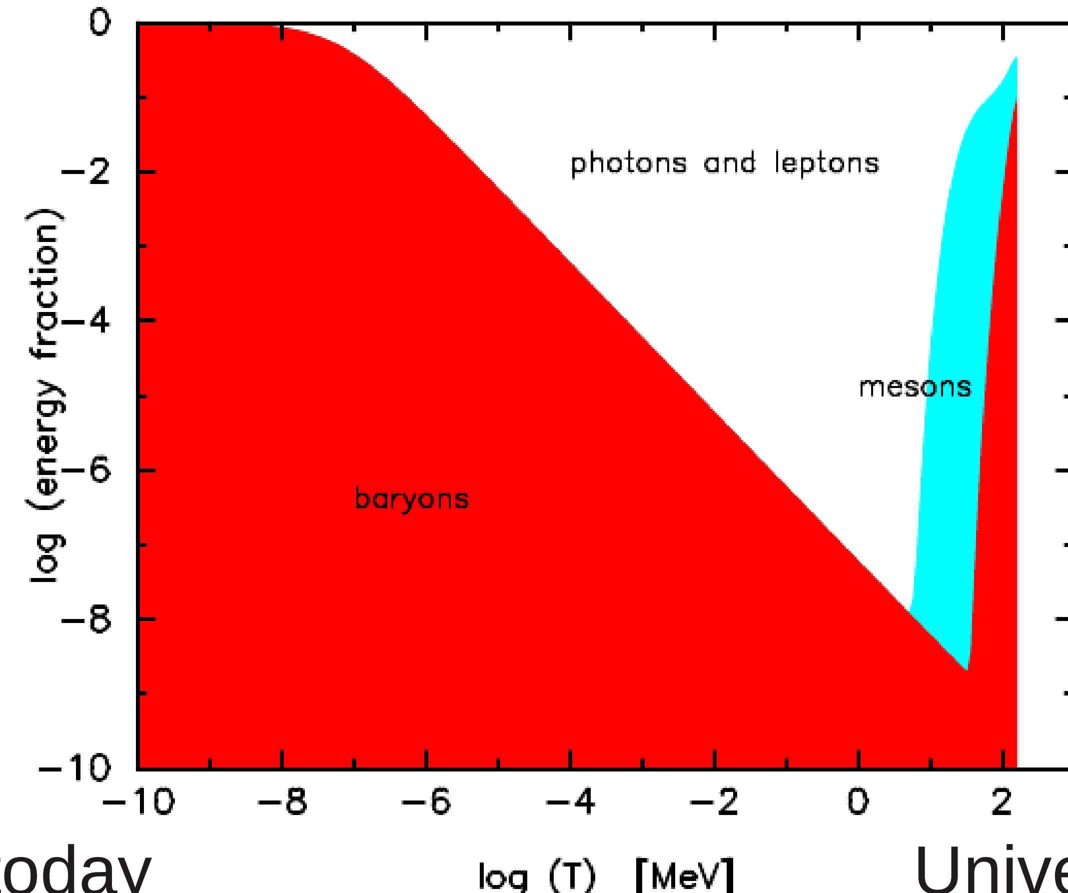
- Non luminous = dark
- Interacts via gravitation
- Electric neutral
- Has very small cross section to interact with normal matter
  - Depending on the origin one can infer a weak like scale => Ideas like WIMP (Weakly Interacting Massive Particles)

How much dark matter is there?



- From standard cosmological fits to astronomical measurements we know that there is roughly 5 times more dark matter than matter ever since the universe became transparent

Does the Universe prefer dark matter and energy?



Matter and anti-matter annihilates

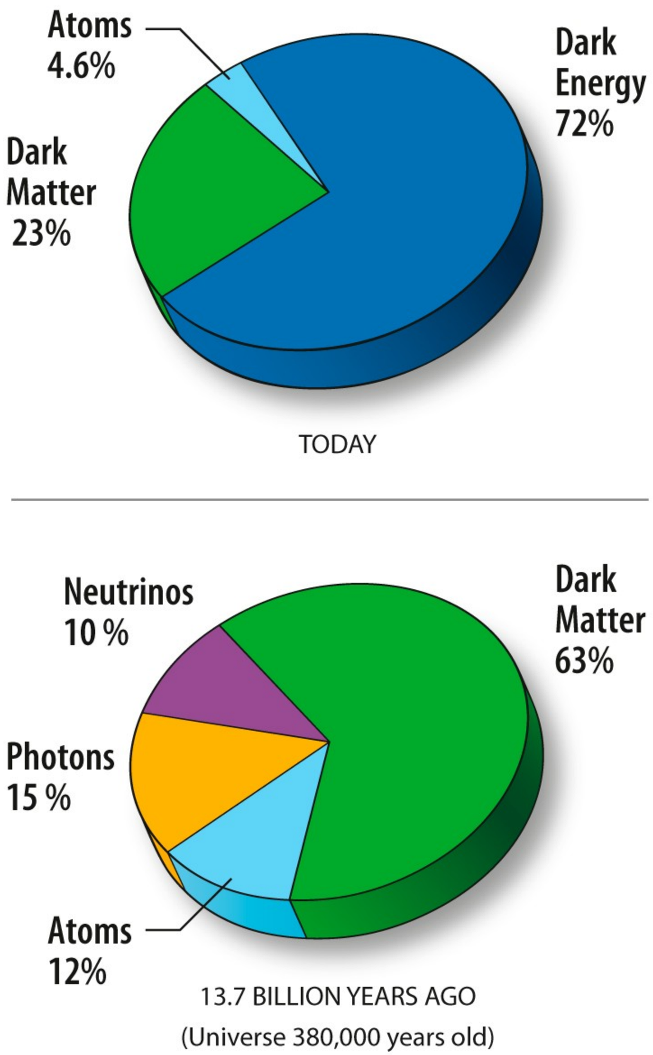
Universe today

Universe hadronizes

Fig. 4. The fraction of the luminous energy in light particles (photons and leptons), mesons and baryons. Note that temperature decreases from right to left.

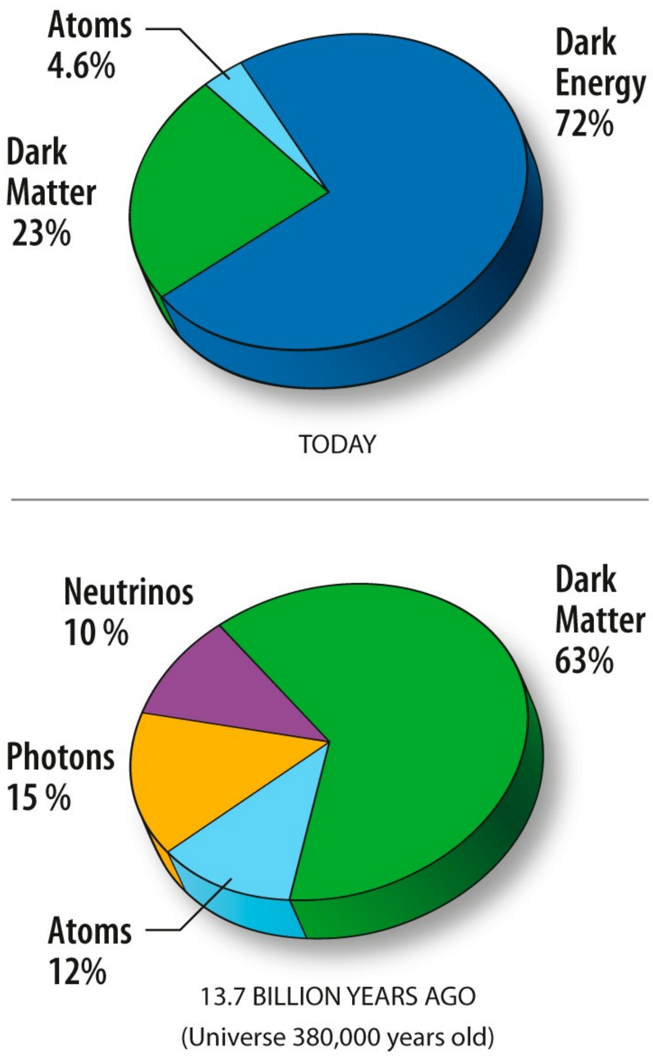
Time

Does the Universe prefer dark matter and energy?



- That is also a question about at what time you measure!
- Most normal matter annihilates with anti-matter producing eventually photons and neutrinos
- The relative density of relativistic matter (photons and in the early Universe neutrinos) decreases with time

What about dark energy?



- The gravitational pull of both matter and dark matter decelerate the Universe
- The dark energy is "something" that makes the Universe accelerate
- Unclear even at theoretical level what this could be

Big cosmological questions for particle physics

- Clear
  - What is dark matter?
  - Why is there an asymmetry between matter and antimatter?

- Unclear
  - How to unify general relativity and Quantum Field Theory?
  - What is dark energy?

Theoretical questions

- Easy to formulate:
  - Why are the parameters of the SM like they are?
    - Charges, masses
  - Why are there only 3 spatial dimensions and 1 time dimensions?
  - Why are there 3 generations?

- Problem:
  - How to formulate testable theories?
  - Can the questions be answered by new physics theories or are they given? We do not know.

Focus on 2 issues that seems very promising

- Higgs stability and mass
- Grand unification (tomorrow)

Higss mass has 2 issues

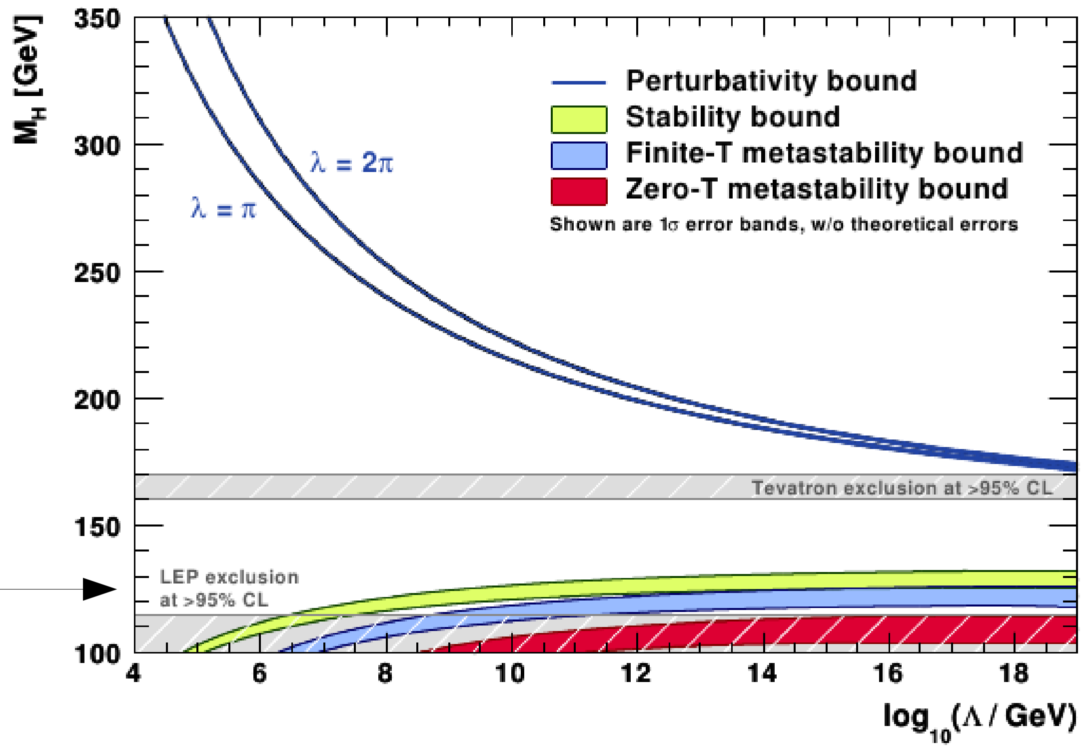
- Stability of Higgs vacuum
- Why is the mass so small?

Stability of Higgs vacuum

- From: arXiv:0906.0954v2
- Extrapolating the Standard Model to high scales using the renormalisation group, three possibilities arise, depending on the mass of the Higgs boson:
  - if the Higgs mass is large enough the Higgs self-coupling may blow up, entailing some new non-perturbative dynamics;
  - if the Higgs mass is small the effective potential of the Standard Model may reveal an instability;
  - or the Standard Model may survive all the way to the Planck scale for an intermediate range of Higgs masses.
- This latter case does not necessarily require stability at all times, but includes the possibility of a metastable vacuum which has not yet decayed.

Stability of the Higgs vacuum (2009)

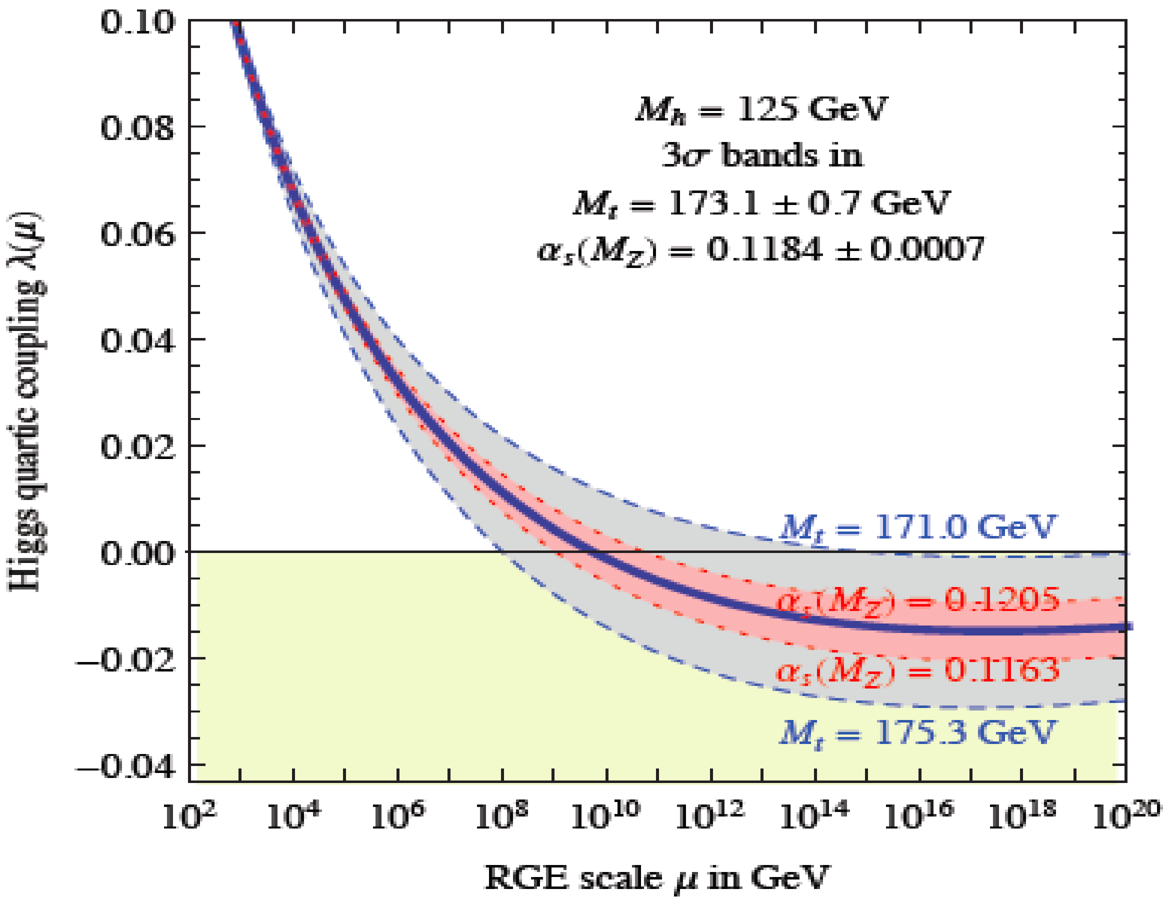
Higgs mass



Scale of new physics

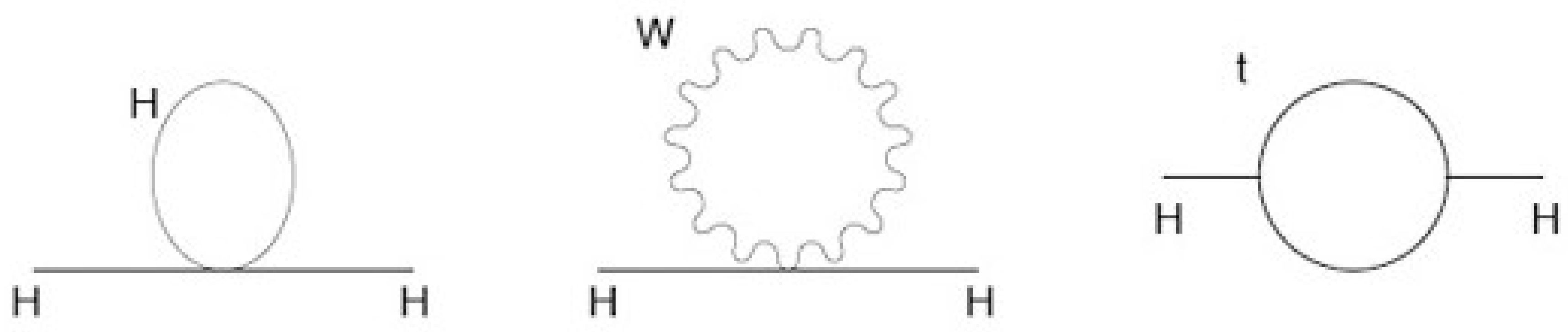
Figure 2: *The scale Λ at which the two-loop RGEs drive the quartic SM Higgs coupling non-perturbative, and the scale Λ at which the RGEs create an instability in the electroweak vacuum ($\lambda < 0$). The width of the bands indicates the errors induced by the uncertainties in m_t and α_s (added quadratically). The perturbativity upper bound (sometimes referred to as 'triviality' bound) is given for $\lambda = \pi$ (lower bold line [blue]) and $\lambda = 2\pi$ (upper bold line [blue]). Their difference indicates the size of the theoretical uncertainty in this bound. The absolute vacuum stability bound is displayed by the light shaded [green] band, while the less restrictive finite-temperature and zero-temperature metastability bounds are medium [blue] and dark shaded [red], respectively. The theoretical uncertainties in these bounds have been ignored in the plot, but are shown in Fig. 3 (right panel). The grey hatched areas indicate the LEP [1] and Tevatron [2] exclusion domains.*

Stability of the Higgs vacuum (Today)



The vacuum is meta-stable

Higgs mass corrections are large!

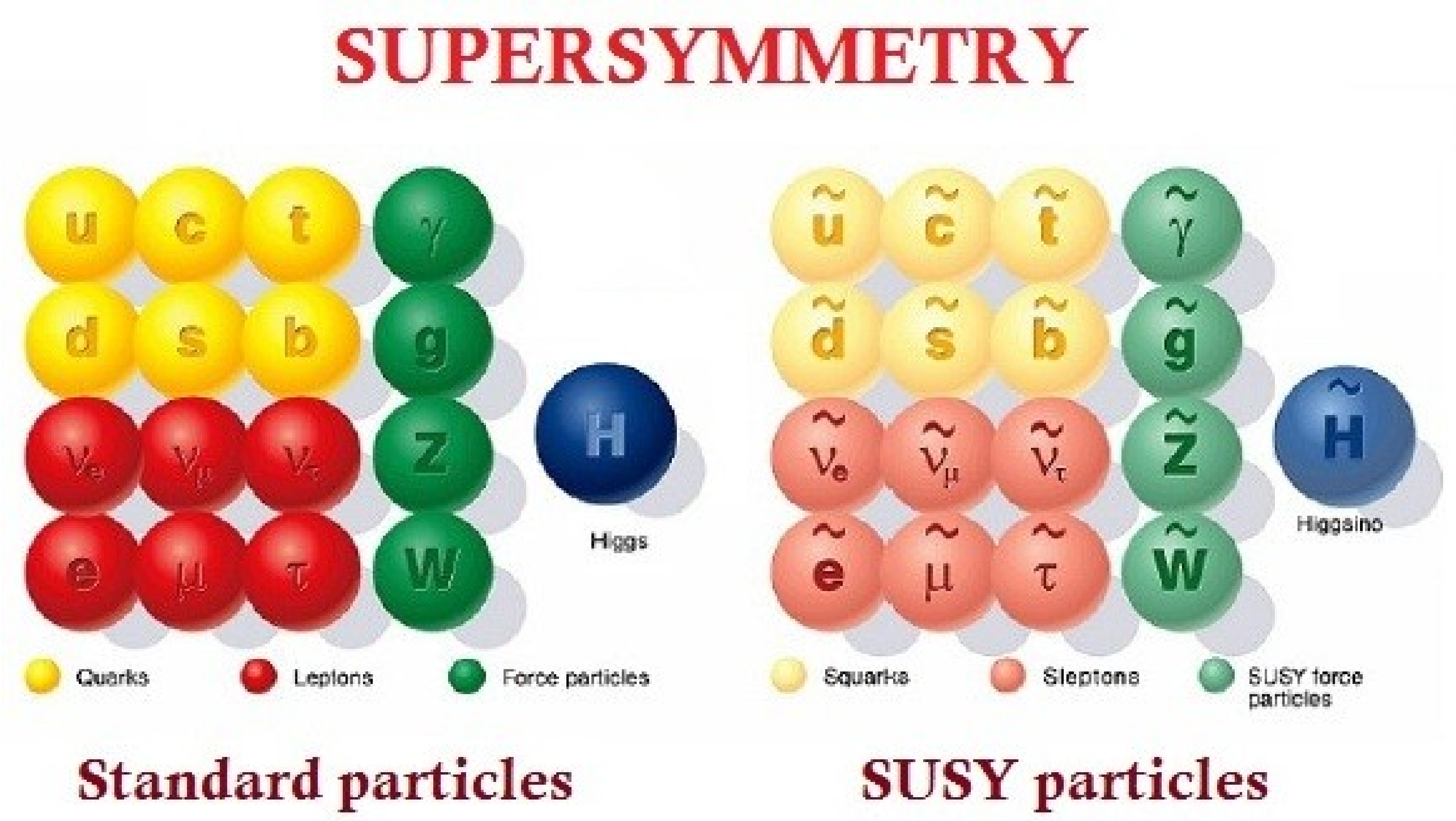


- One obtains for 1 loop:

$$m_{h_{\rm SM}}^2 = \mu^2 + \frac{3\Lambda^2}{32\pi^2 v^2}(2m_W^2 + m_Z^2 + m_{h_{\rm SM}}^2 - 4m_t^2)$$

- So the corrections are larger than the Higgs mass but with opposite signs!?

Solution? Supersymmetry!

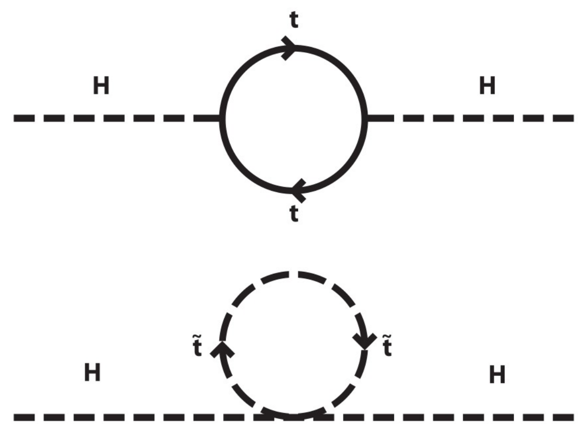


The special things are the spins (Note also additional Higgses!)

FERMIONS			BOSONS		
spin	Name	Symbols	Name	Symbols	spin
½	leptons	e, ν_{eL}	sleptons	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_{eL}$	0
		$\mu, \nu_{\mu L}$		$\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_{\mu L}$	
		$\tau, \nu_{\tau L}$		$\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_{\tau L}$	
½	quarks	u, d	squarks	$\tilde{u}_L, \tilde{d}_L, \tilde{u}_R, \tilde{d}_R$	0
		c, s		$\tilde{c}_L, \tilde{s}_L, \tilde{c}_R, \tilde{s}_R$	
		t, b		$\tilde{t}_L, \tilde{b}_L, \tilde{t}_R, \tilde{b}_R$	
½	gluinos	$\tilde{g}$	gluons	g	1
½	charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	EW bosons	$\gamma, Z^0, W^\pm$	1
½	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	higgs	$h^0, H^0, A^0, H^\pm$	0

SM particles (observed)	SM particles (not yet observed)	Super Partners (not yet observed)

SUSY offers some explanation

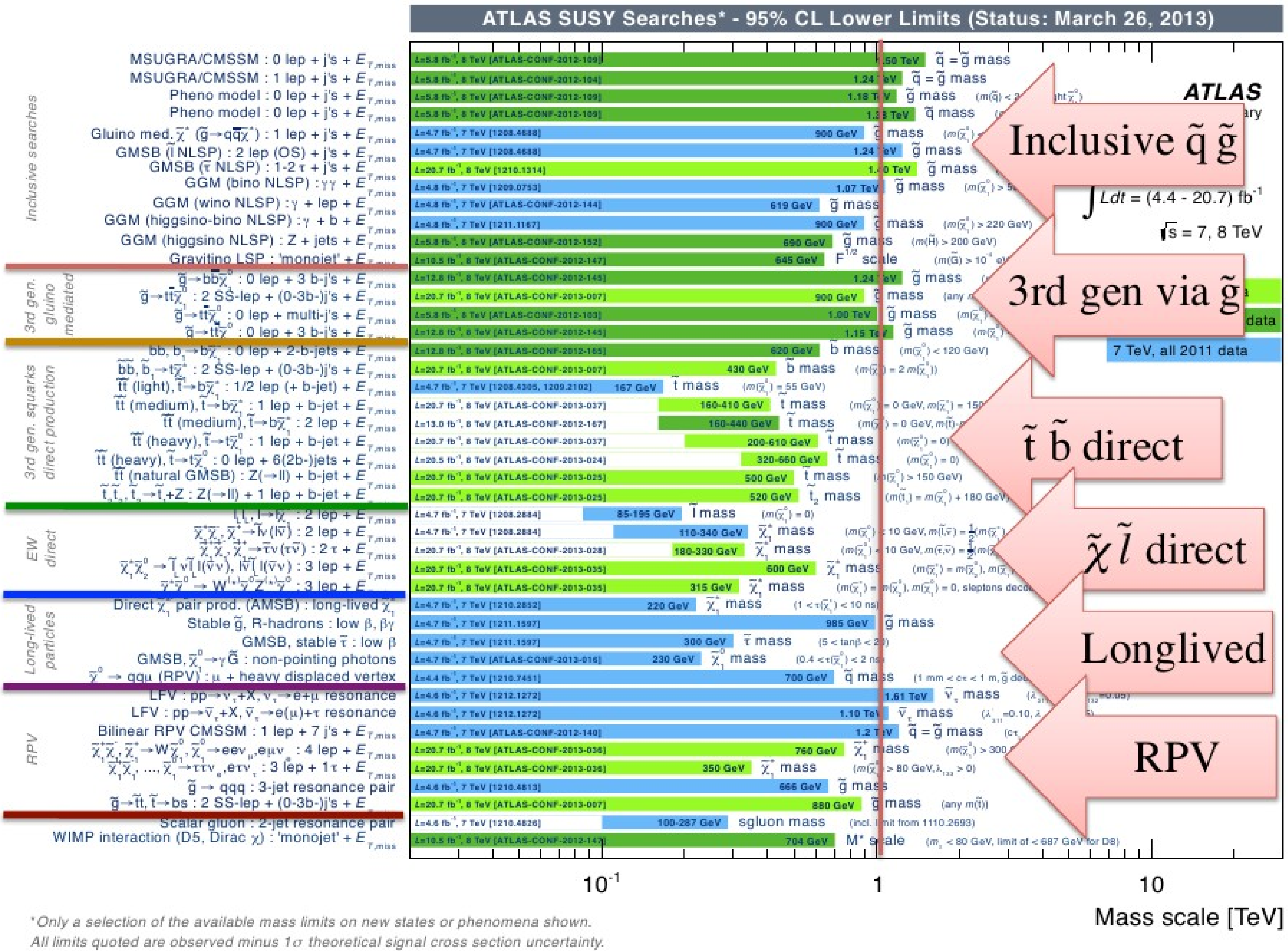


- The corrections to the mass for the particle and SUSY partner has opposite signs → cancels!
- Similarly this stabilizes the Higgs vacuum

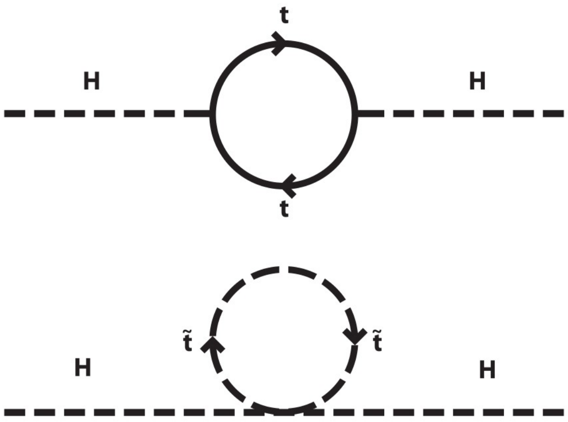
SUSY can provide dark matter candidates

- The lightest neutral SUSY particle can be stable if there is a special conserved SUSY quantum number (typical taken to be R-parity)
- This SUSY particle will be stable and can be very heavy
- SUSY can provide a reasonable dark matter candidate

Problem: Not seen so far at LHC



Problem: SUSY is only really beautiful when it is natural



- The cancellation only works easily (naturally) if the masses of the top and stop (SUSY top) is similar