

The fundamental building blocks

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- By the end of the 20th century ...
**we have a comprehensive,
fundamental theory of all
observed forces of nature which
has been tested and might be
valid from the Planck length
scale [10^{-33} cm.] to the edge of
the universe [10^{+28} cm.]**

D. Gross 2007

In this last decade → the triumph of the

STANDARD

- **PARTICLE STANDARD**

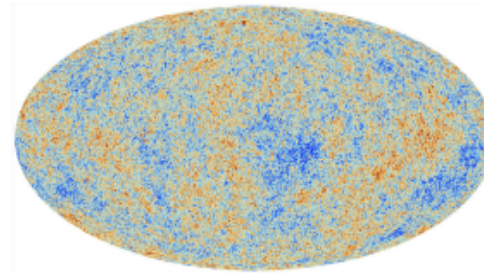
MODEL

Three Generations of Matter (Fermions) spin 1/2

	I	II	III	
mass	2.4 MeV	1.27 GeV	173.2 GeV	0
charge	2/3	2/3	2/3	0
name	u up	c charm	t top	g gluon
	Left Right	Left Right	Left Right	0
Quarks	4.8 MeV	104 MeV	4.2 GeV	0
	d down	s strange	b bottom	γ photon
	Left Right	Left Right	Left Right	0
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	91.2 GeV Z weak force
Leptons	0.511 MeV	105.7 MeV	1.777 GeV	126 GeV H Higgs boson
	e electron	μ muon	τ tau	spin 0
	Left Right	Left Right	Left Right	80.4 GeV W $^\pm$ weak force

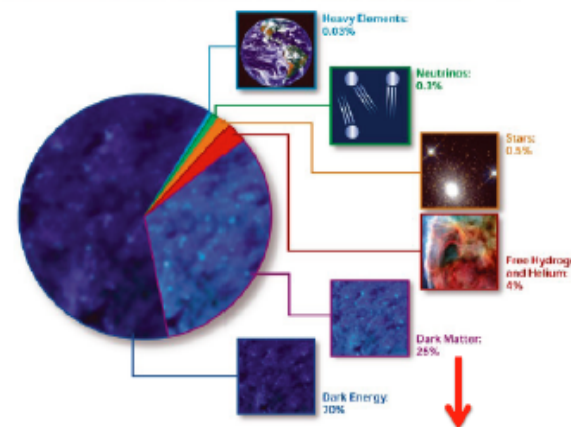
- **COSMOLOGY STANDARD**

MODEL



Λ CDM + "SIMPLE" INFLATION

COMPOSITION OF THE COSMOS



SM PREDICTS THAT NEUTRINOS ARE MASSLESS



Democritus, Abdera,
c.460-c.370 BC)

Colui che 'l mondo A CASO
pone (**He who the world
places AT RANDOM**)

Dante, Divina Commedia,
Inferno IV 136

The 25 centuries old **homework** assigned to us by

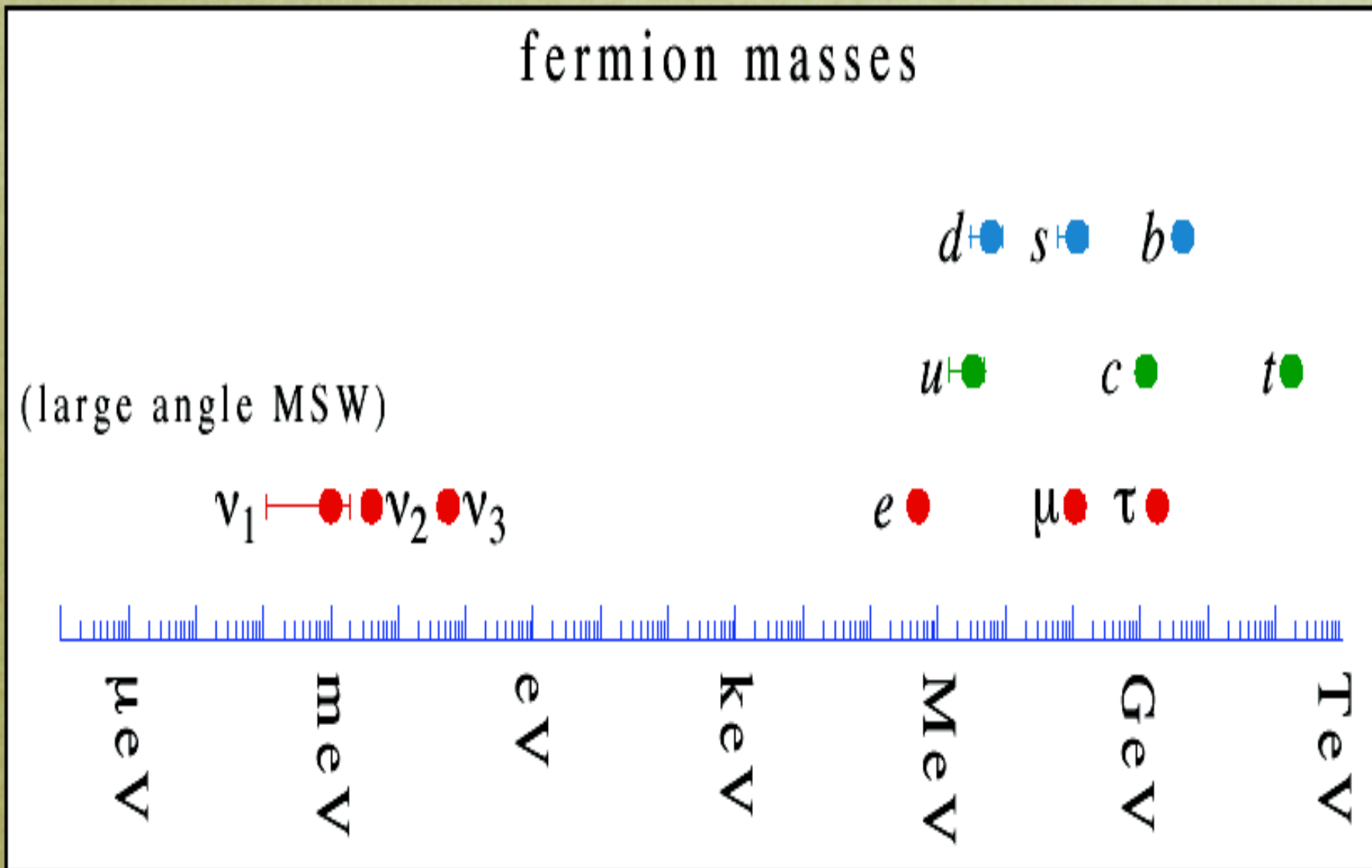
Democritus:

- Divisibility of matter coming to an end: the existence of **ATOMS** – **What are the “atoms” of the 21st century?**
- Atoms succeed to move because there exists the **VOID** between an atom and another atom - **What is the modern QUANTUM VACUUM?**
- Atoms move **AT RANDOM** in the empty space and through their collisions they give rise to all the objects in the universe --> **Randomness vs Necessity of the values of the fundamental parameters in the quantum field theories of elementary particles.**

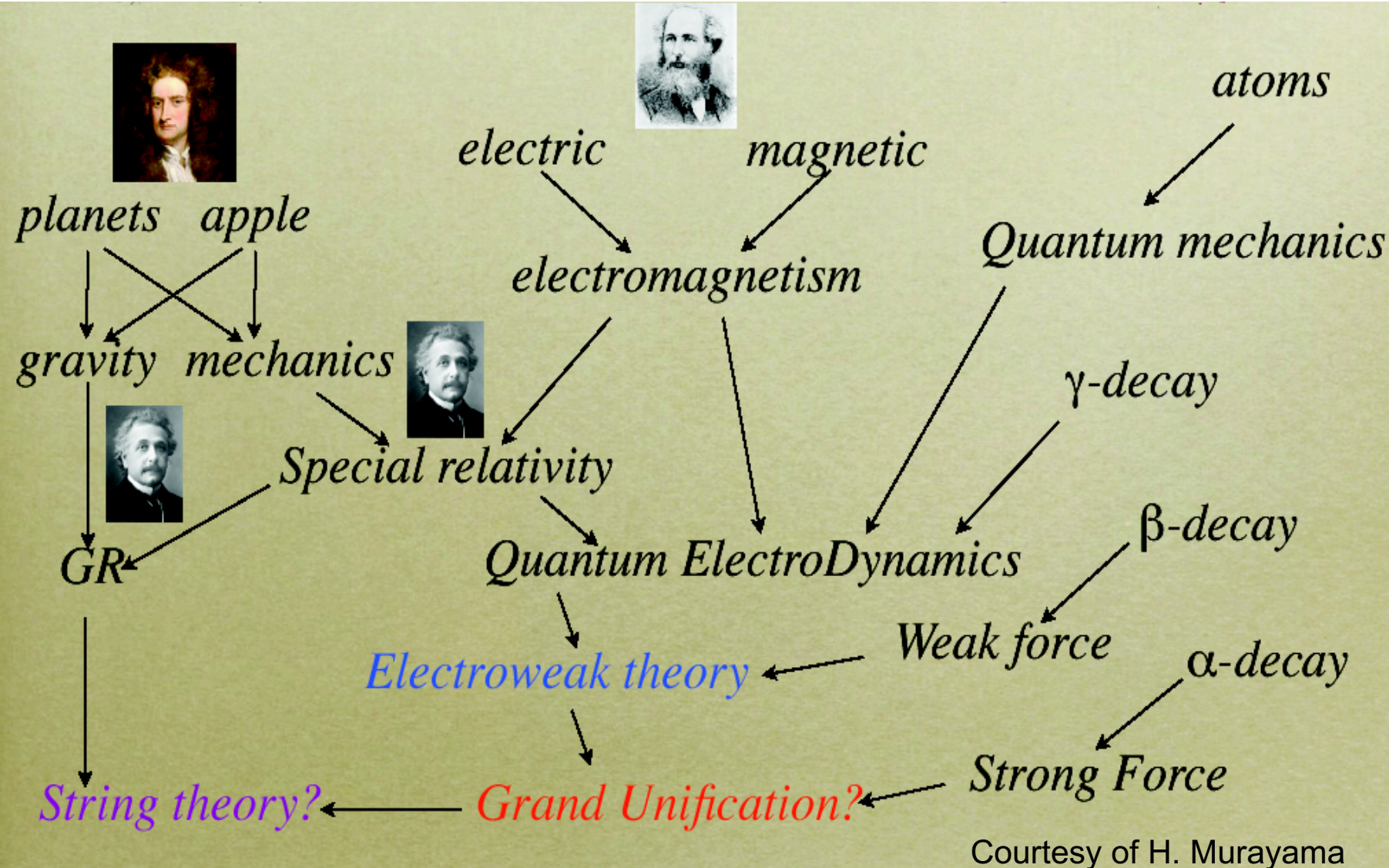
THE HIGH-ENERGY ROAD



THE FERMION MASS PUZZLE

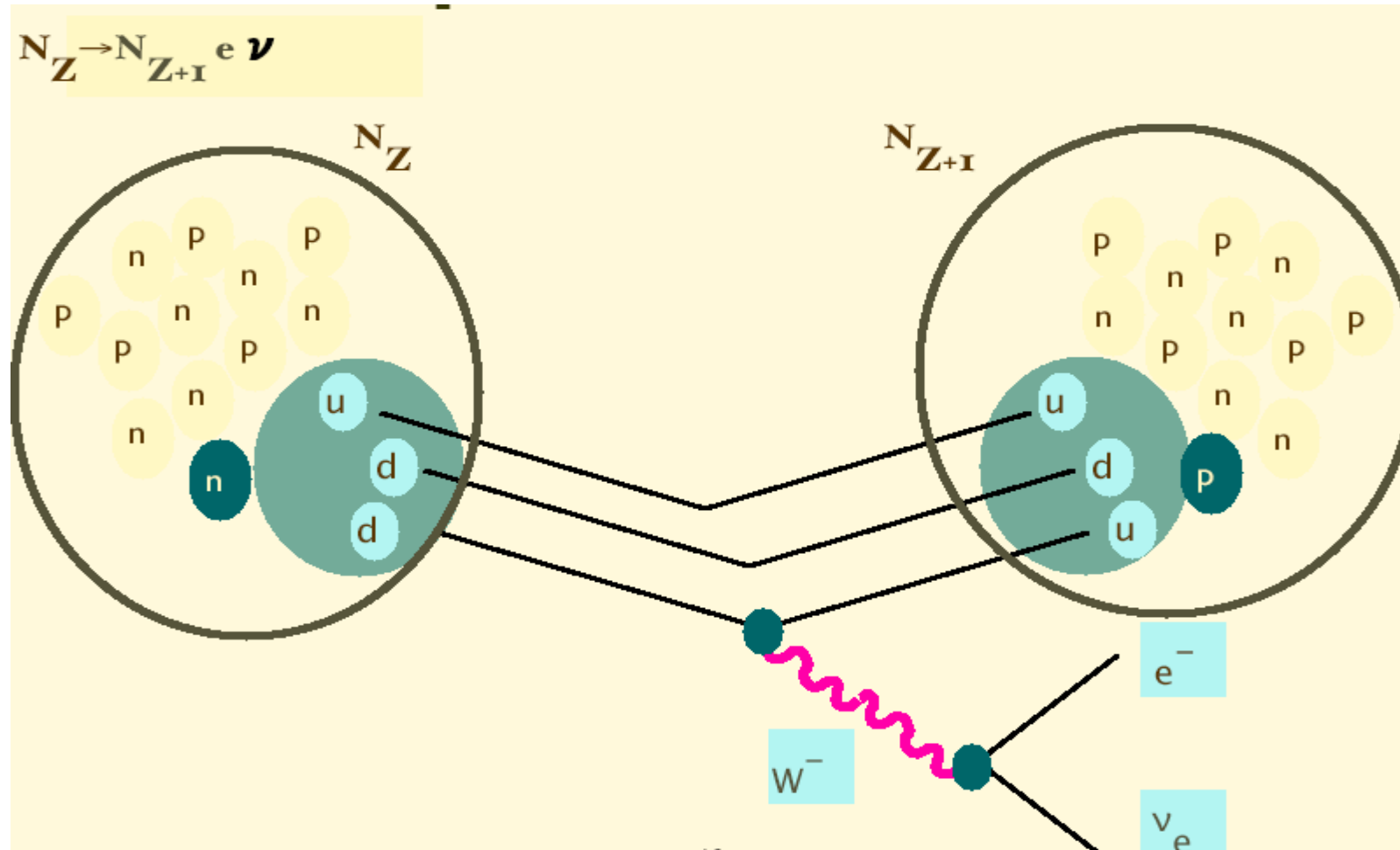


UNIFICATION of FUNDAMENTAL INTERACTIONS



NUCLEUS β -DECAY

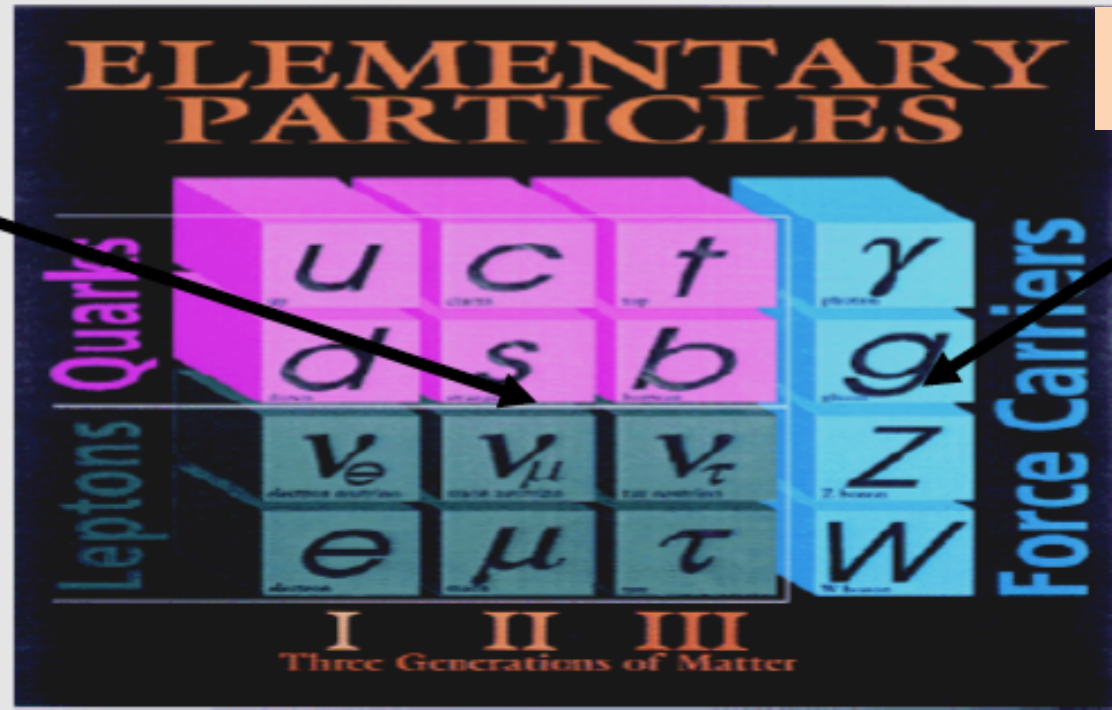
(Nuclear) **WEAK** Interactions



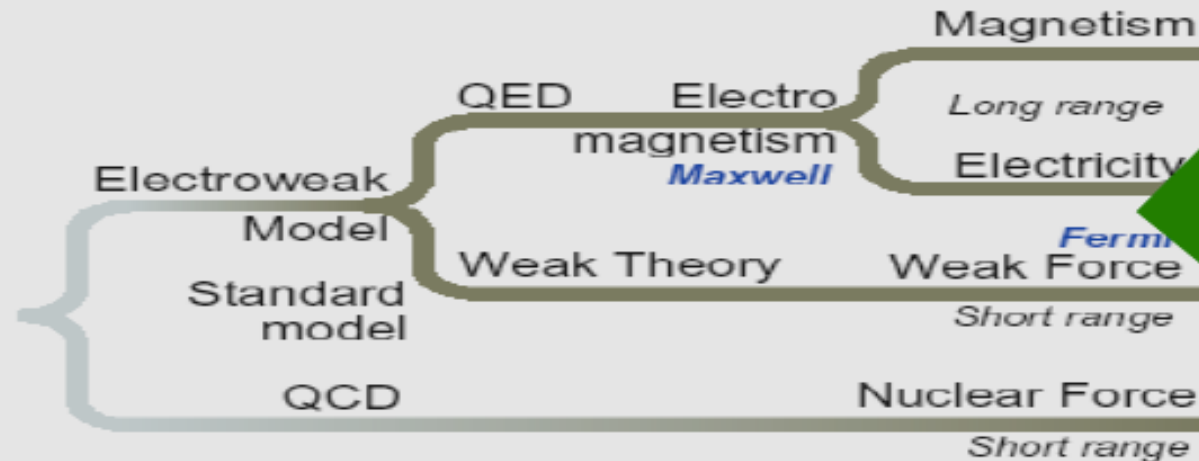
SM OF ELEMENTARY PARTICLES AND FUNDAMENTAL INTERACTIONS

MATTER

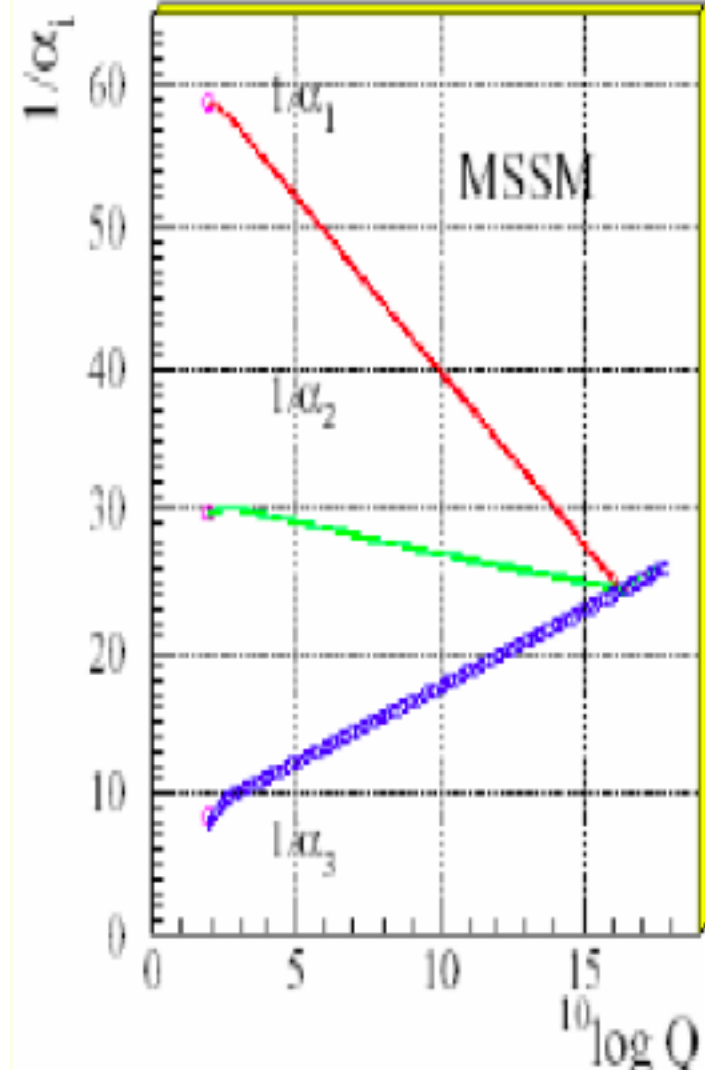
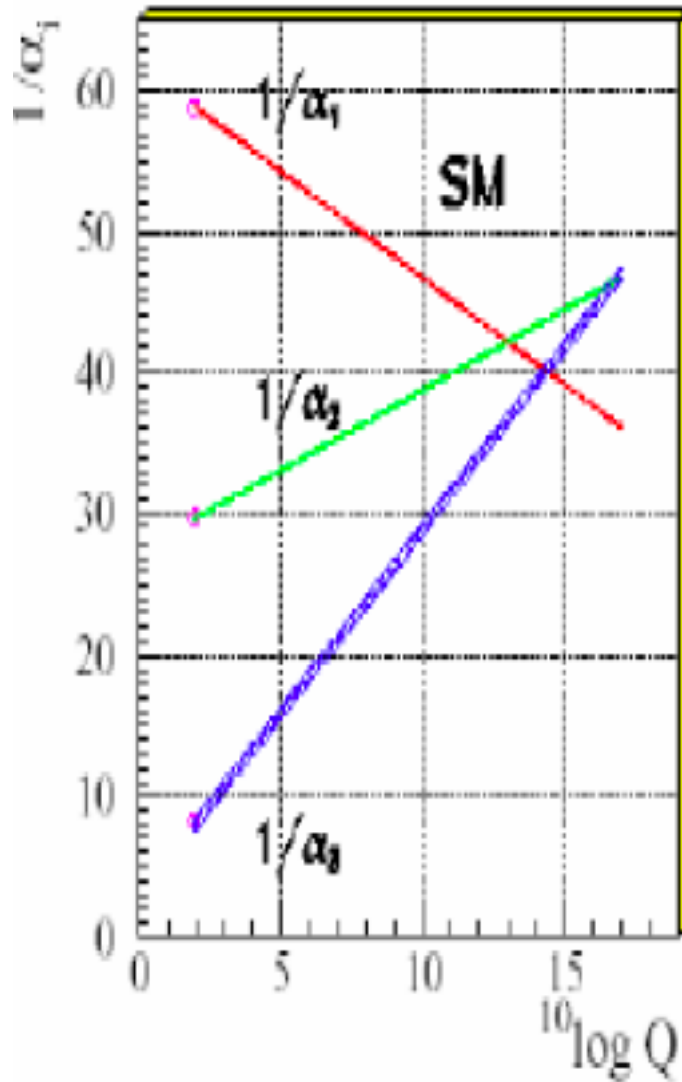
RADIATION



**Grand
Unified
Theory
GUT**



Only one fundamental interaction?

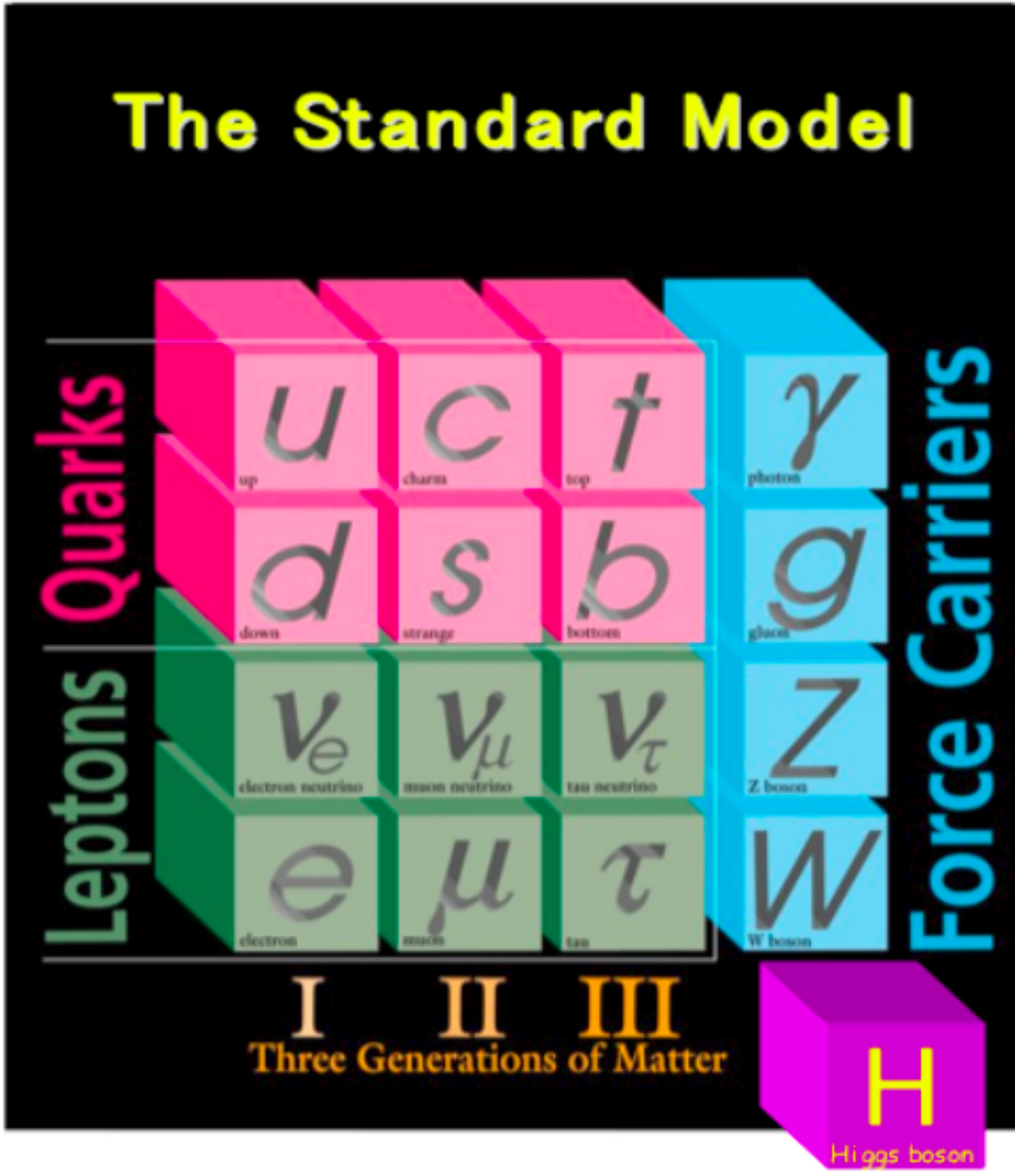


Adding new **SUPERSymmetric (SUSY) particles** (partners of the SM particles) with **masses of O (100GeV – few TeV)**

The “deus ex machina”:
the **HIGGS Boson**

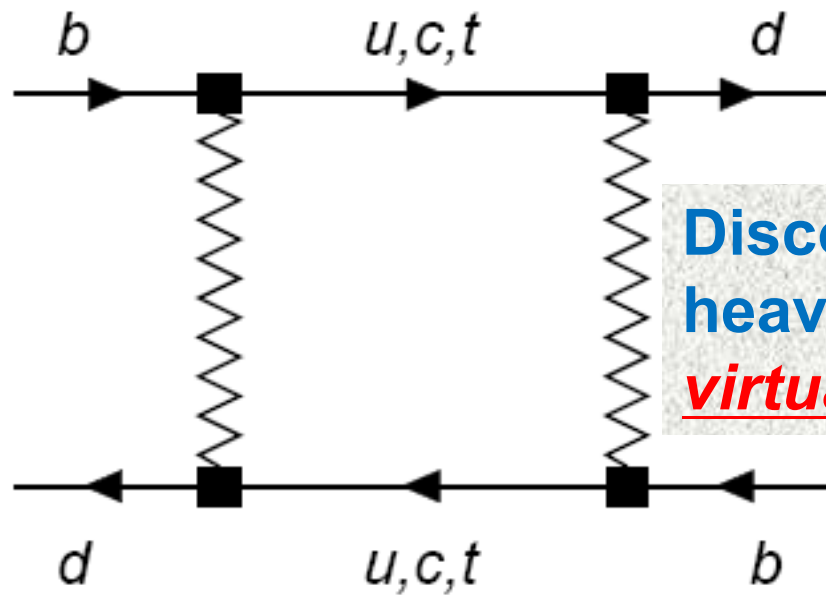
Gravity
?

From **massless** to **massive** (matter and radiation) particles → addition of a scalar field, the **HIGGS BOSON** → construction of an energy potential of H such that it is minimized by a non-vanishing value of H , i.e. the “**Higgs VACUUM expectation**” is **DIFFERENT from ZERO**.

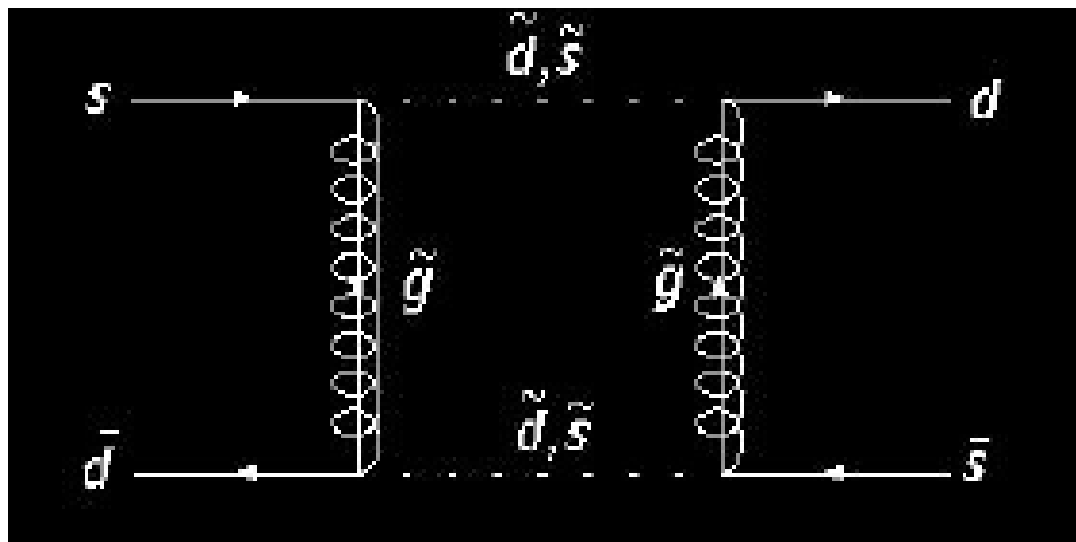


? → **EXP. 2012**

THE HIGH-INTENSITY ROAD



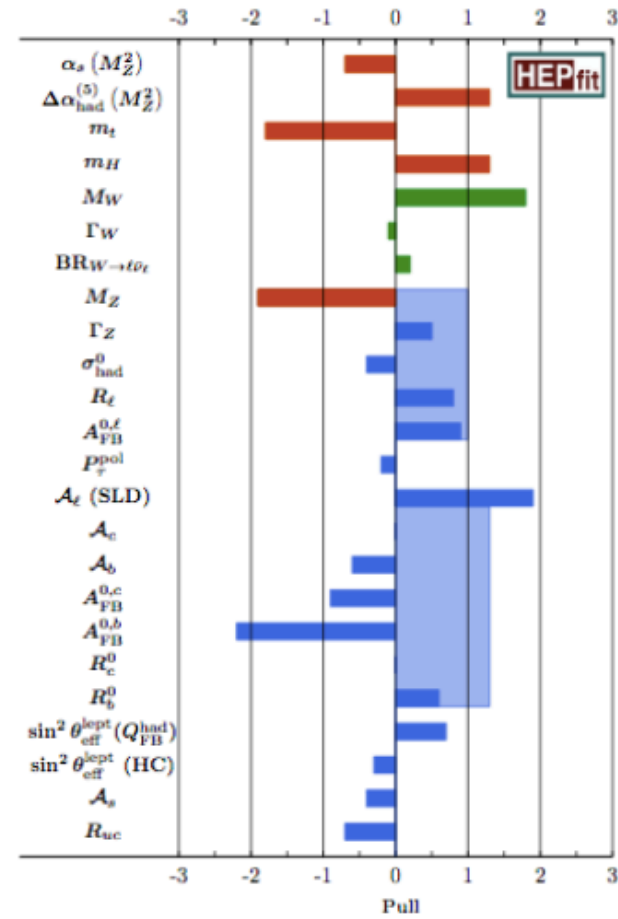
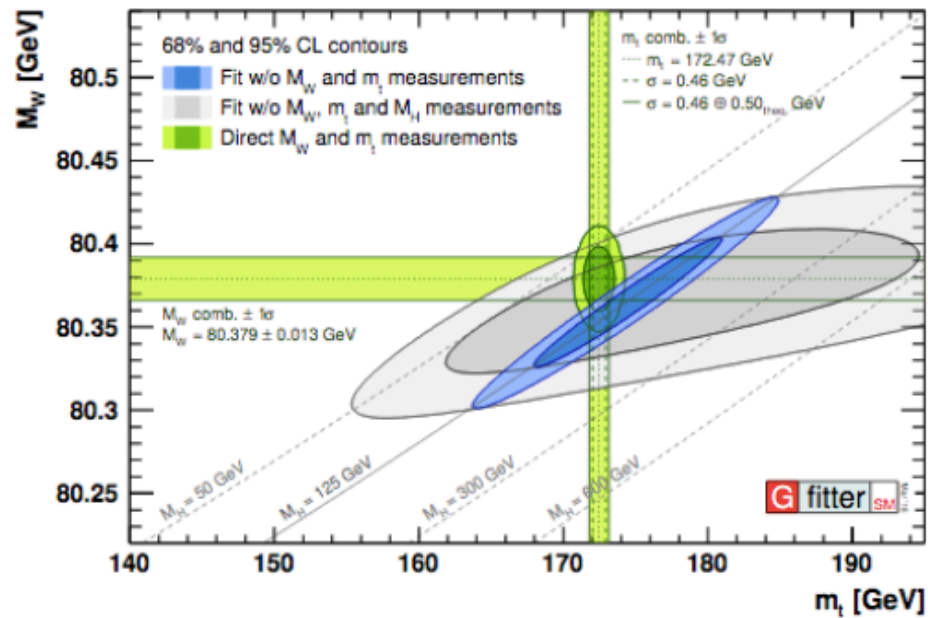
Discovering the presence of the heavy up-type quarks through their virtual effects on physical processes



Looking for **NEW PARTICLES** through their virtual effects → **discrepancies** w.r.t. the **SM predictions**

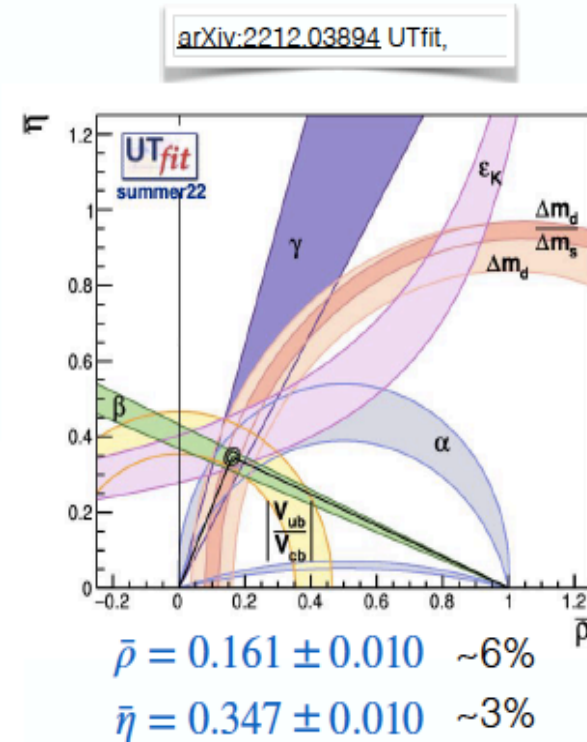
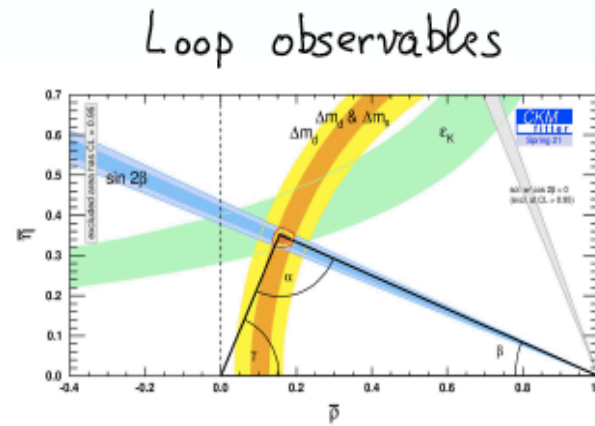
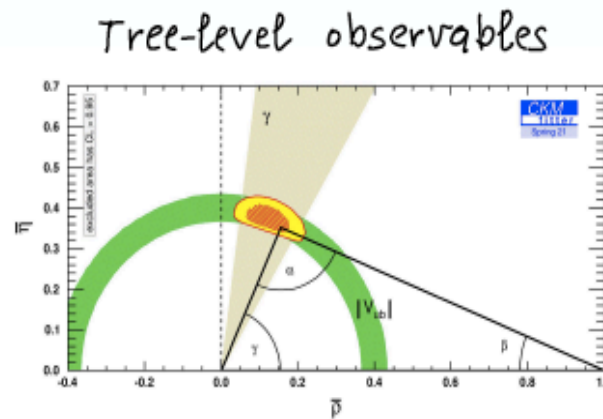
Precision Observables

ELW. PRECISION PHYSICS



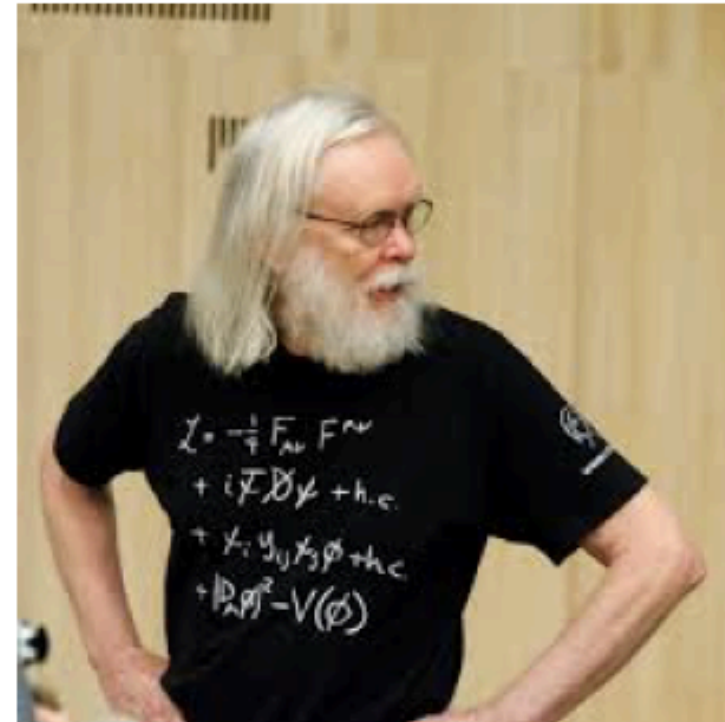
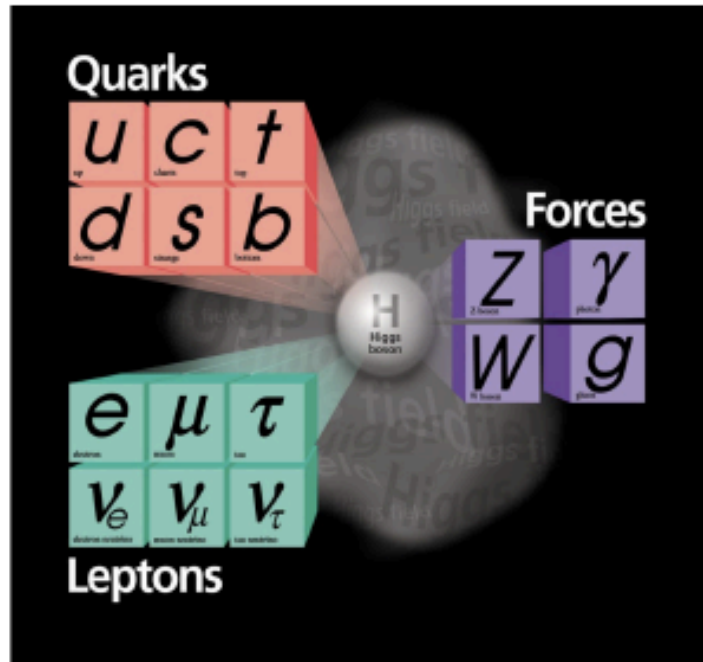
Consistency tests of the CKM matrix

- At the current level of precision ($\sim\%$), all measurements are consistent and intersect in the apex of the UT
- What is particularly noteworthy is the consistency of the tree-level determinations of CKM elements, with those obtained from meson-anti meson mixing



- New Physics effects (if there) are small!
- But... past examples show that it is unwise to think that few % is good enough

The Standard Model (**SM**) is a remarkably simple Quantum Field Theory (**QFT**) that describes well all microscopic phenomena that we observe in **Nature**

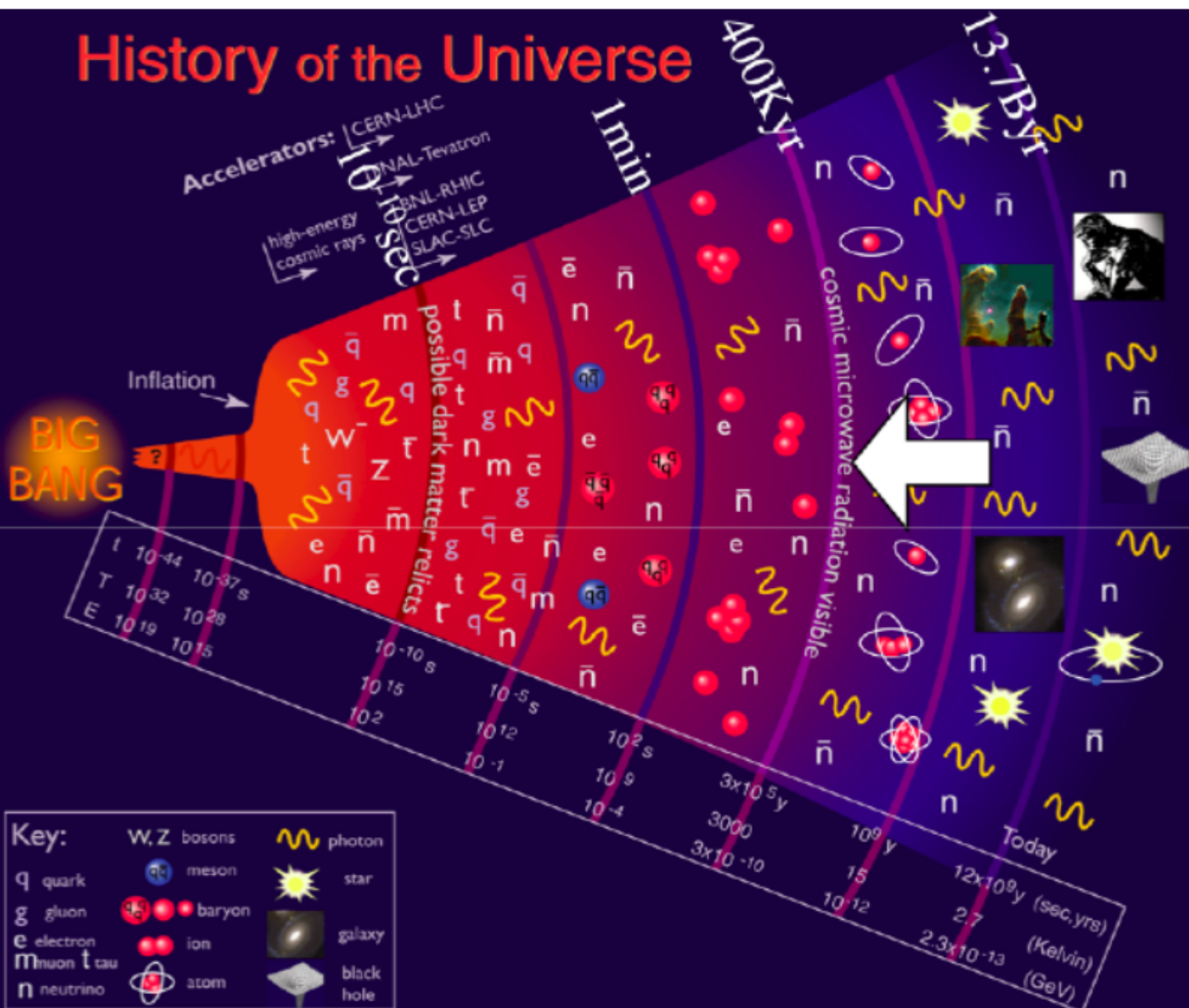


The SM describes fundamental interactions among elementary particles

“This is short enough to write on a T-shirt!”

[John Ellis]

History of the Universe



3 minutes

0.01 millisecond

10^{-12} seconds

10^{-20} seconds

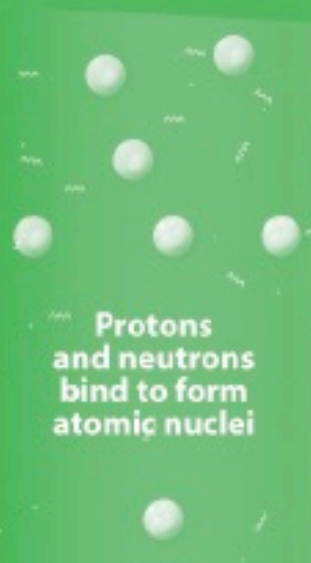
10^{-35} seconds

10^{-43} seconds

Light nuclei

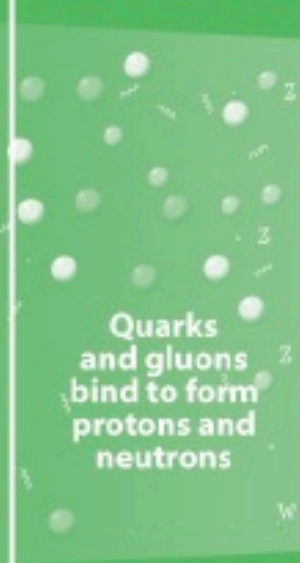
Protons and neutrons

Quark-gluon plasma



Protons and neutrons bind to form atomic nuclei

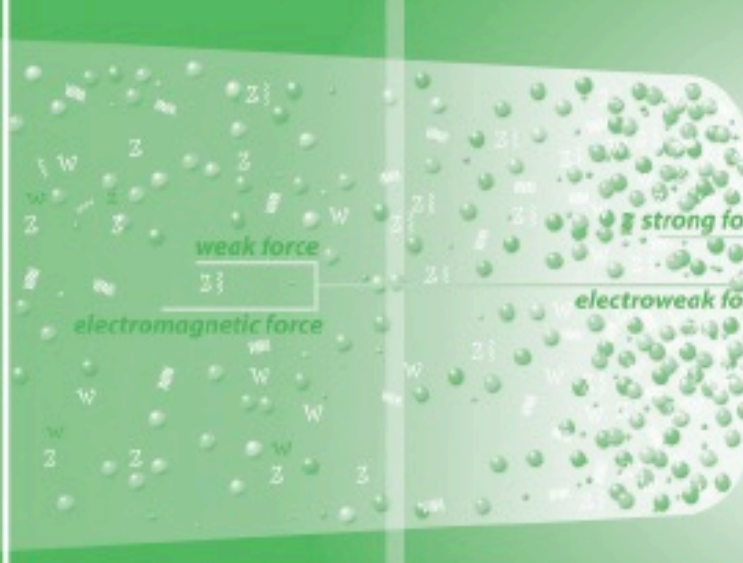
Photons are continuously absorbed and reemitted: the Universe is opaque



Quarks and gluons bind to form protons and neutrons

The Universe has the size of the solar system

10^{12}°C



weak force

electromagnetic force

strong force

electroweak force

electronuclear force

gravity

Superforce

The Universe has a radius of 300 million km

10^{15}°C

The Universe has the size of an apple

10^{27}°C

The Universe is an infinitely small point

10^{32}°C



Big Bang

- 2 protons + 2 neutrons = Helium nucleus
- 1 proton = Hydrogen nucleus

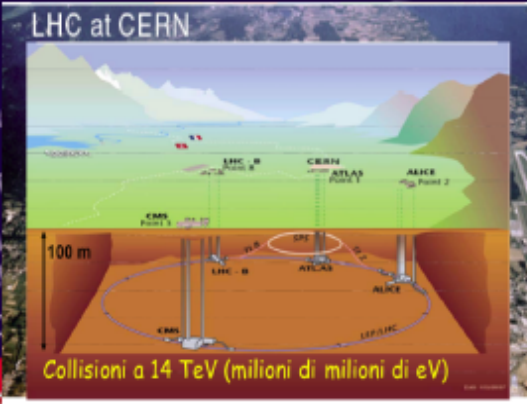
- Proton
- Neutron
- Meson

- Quark
- Electron
- Neutrino

- Photon
- Weak force
- Strong force

History of the

Accelerators: CERN-LHC



BIG BANG

Inflation

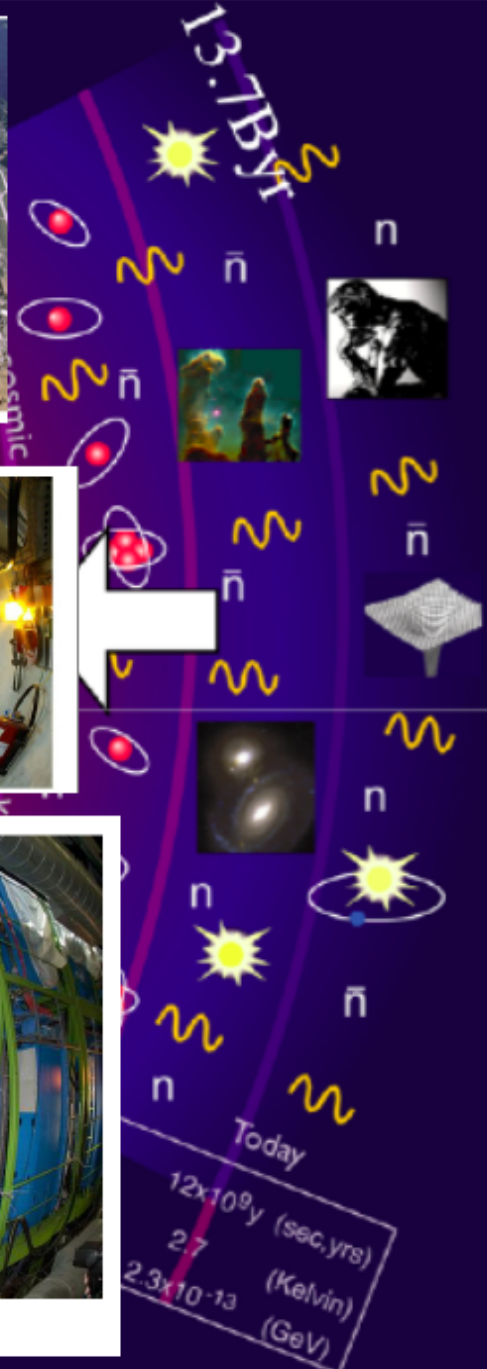
t	10^{-44}	10^{-37} s
T	10^{32}	10^{28}
E	10^{19}	10^{15}



CMS

Key:

q quark	W, Z bosons	photon
g gluon	meson	star
e electron	baryon	galaxy
μ muon	ion	black hole
τ tau	atom	
ν neutrino		



The Energy Frontier

Origin of Mass

Matter/Anti-matter
Asymmetry

Dark Matter

Origin of Universe

Unification of Forces

New Physics
Beyond the Standard Model

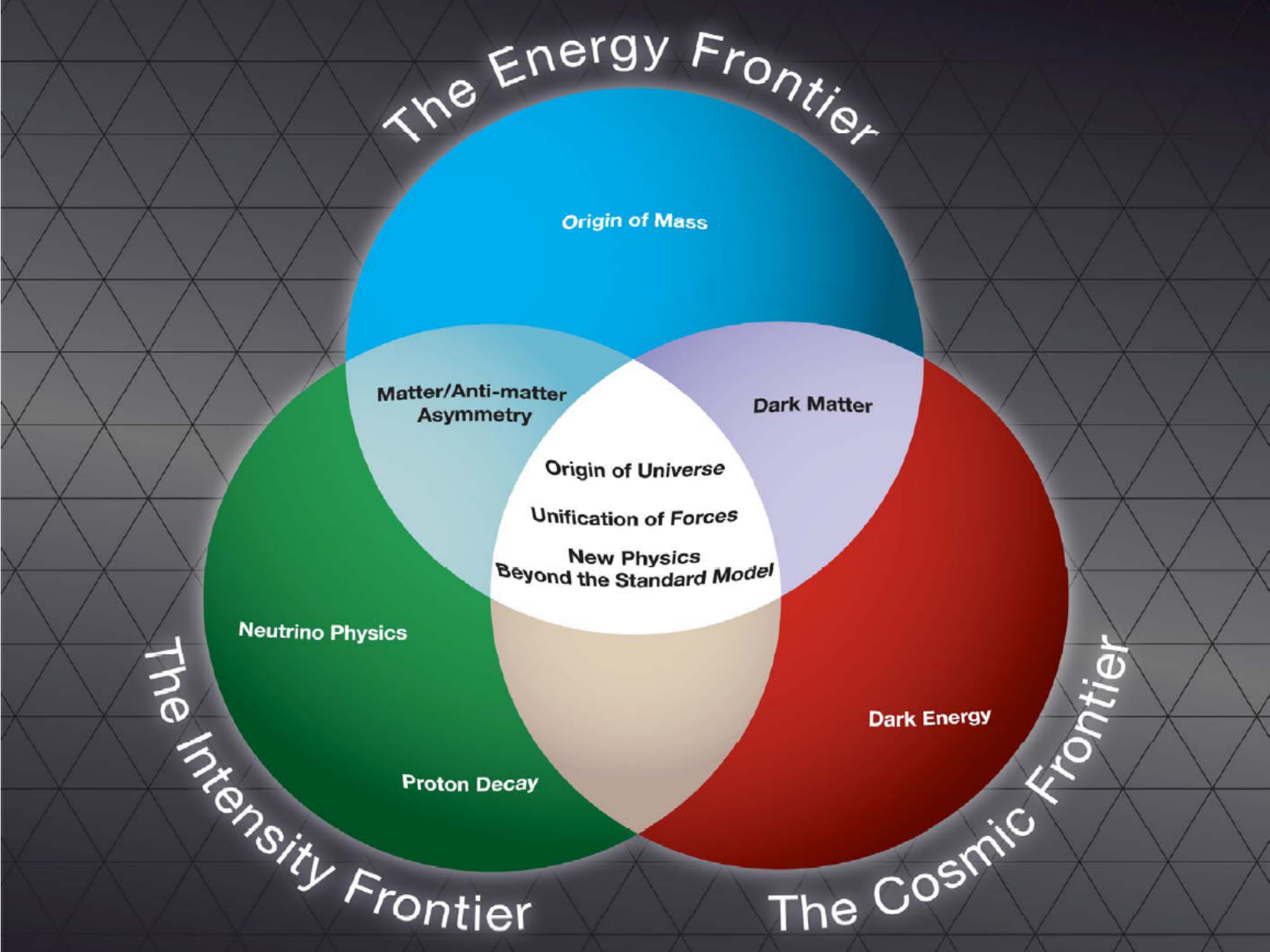
Neutrino Physics

Dark Energy

Proton Decay

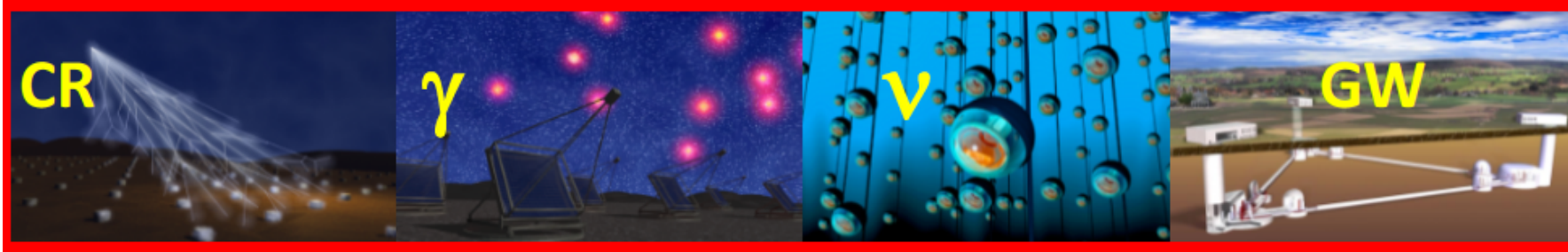
The Intensity Frontier

The Cosmic Frontier



THE ASTRO-PARTICLE PHYSICS ROAD

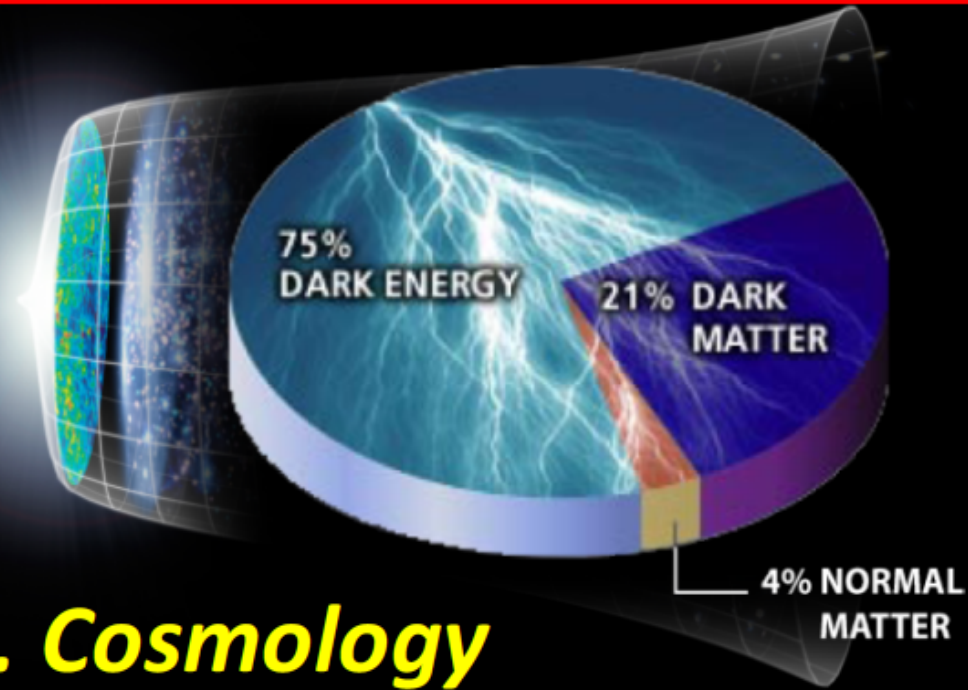
1. High-energy Universe: multi-messengers



2. Neutrino's



3. Cosmology



Beyond the SM physics

WHY BSM

Theoretical reasons (of dissatisfaction towards the SM as a “final” theory rather than actual problems for the SM)

- Lack of the theory of **Flavor** (why three fermion families, why hierarchical mass spectrum, why mixing angles so different)
- **CPV in strong interactions**, i.e. the θ -problem
- **Unification** of the fundamental interactions (running the SM gauge couplings \rightarrow clear trend for unification of the interactions, but “pure SM” fails) – gravitational interactions as an external classical field
- **Gauge hierarchy** – twofold puzzle: why M_{GUT} or $M_{\text{planck}} \gg \gg M_W$; stabilization of the higgs mass at M_W at any order in perturbation theory

How to cope with the **GAUGE HIERARCHY “PROBLEM”**

Naturalness or

Un-naturalness?

- **New SYMMETRY** giving rise to a cut-off at

$$m_{NP} \ll M$$

Low-energy **SuperSymmetry**

- **Space-time modification** (extra-dim., warped space)
- **COMPOSITE HIGGS** : the Higgs is a pseudo-Goldstone boson (pion-like) \rightarrow new interaction getting strong at

$$m_{NP} \ll M$$

- The scale at which the electroweak symmetry is spontaneously broken by $\langle H \rangle$ results from **COSMOLOGICAL EVOLUTION**
- H is a fundamental (elementary) particle \rightarrow we live in a universe where the fine-tuning at M arises (**anthropic solution, multiverse, Landscape of string theory**)

MICRO
PARTICLE PHYSICS

GWS STANDARD MODEL

UNIVERSE EXPANSION
(SM COSMOLOGY)
+
ELECTROWEAK INTERACTIONS
(SM PARTICLE PHYSICS)

MACRO
COSMOLOGY

HOT BIG BANG
STANDARD MODEL



HAPPY MARRIAGE
Ex: **NUCLEOSYNTHESIS**

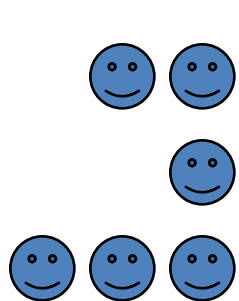
NUCLEAR
ASTROPHYSICS

n_B/n_γ from **BBN**
few minutes after BB
confirmed by **CMB**
350 kyrs after BB

BUT ALSO



NEW SOURCE OF CP VIOLATION



- **COSMIC MATTER-ANTIMATTER ASYMMETRY**

- **INFLATION** **NEW SCALAR POTENTIAL**

- **DARK MATTER + DARK ENERGY**

NEW PARTICLES AND INTERACTIONS

"OBSERVATIONAL" EVIDENCE FOR NEW PHYSICS BEYOND THE
(PARTICLE PHYSICS) STANDARD MODEL

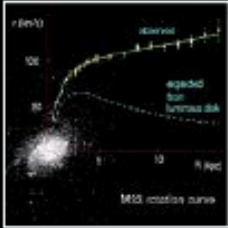
WHY to go beyond the SM of particle physics

“**OBSERVATIONAL**” REASONS calling for new particles/
interactions:

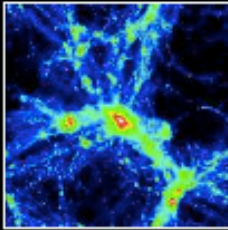
- **Dark Matter**
- **Neutrino Masses**
- **Cosmic Matter-Antimatter Asymmetry**
(twofold problem: disappearance of primordial
antimatter and extreme reduction of the number of
baryons w.r.t the number of photons – initially \sim equal,
today $n_{\text{baryons}}/n_{\text{photons}} \sim 10^{-9}$)

What is the Universe made of?

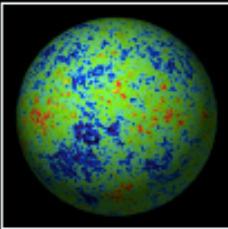
OBSERVATIONS



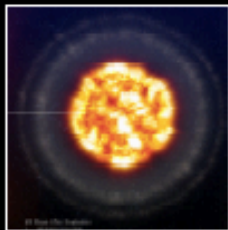
• Rotation Curves



• Clusters of galaxies

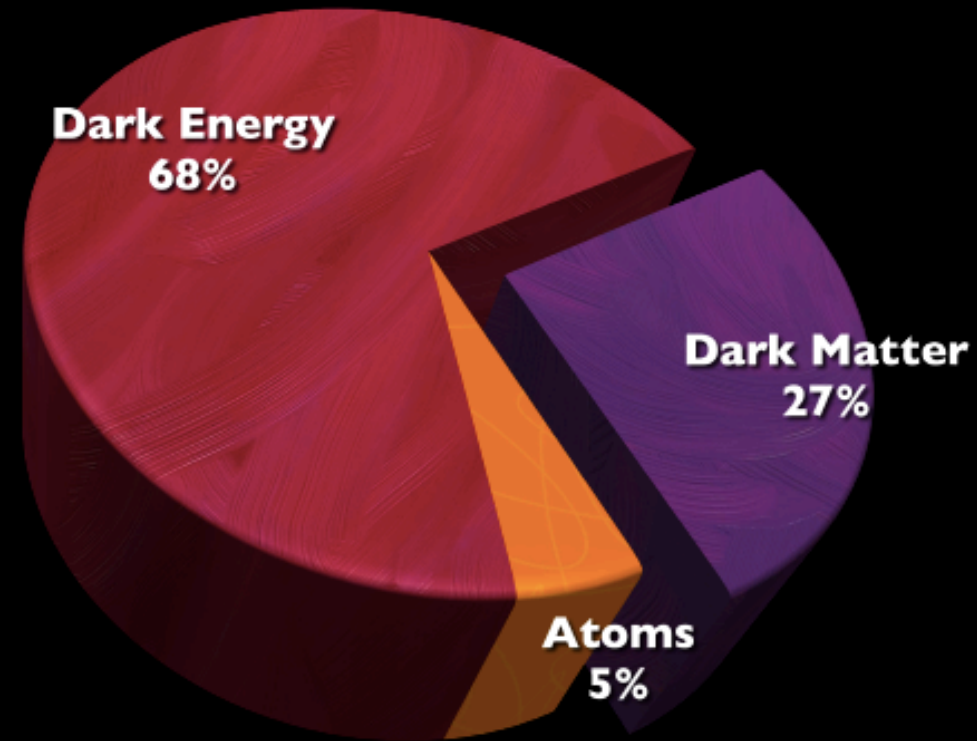


• CMB

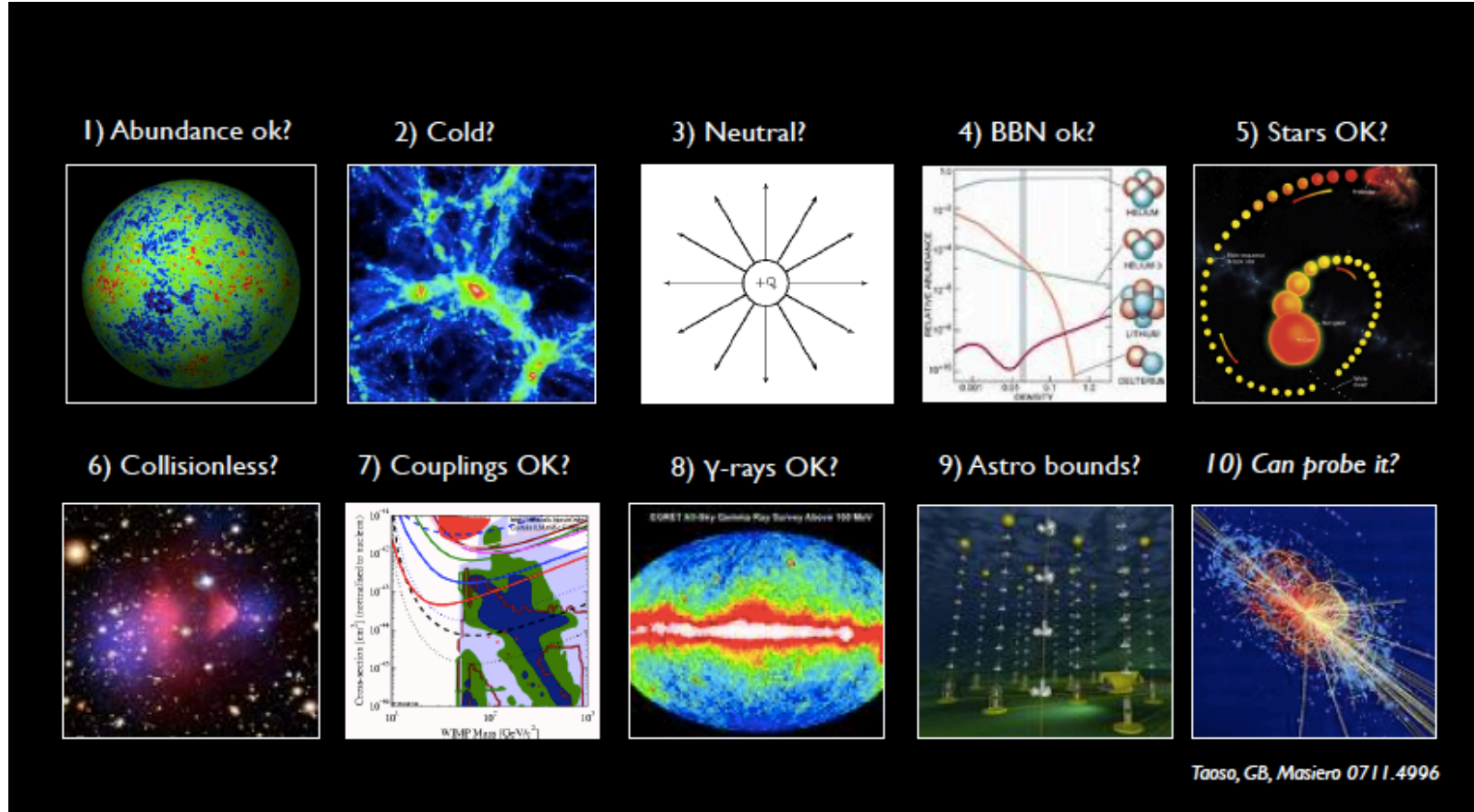


• Type Ia Supernovae

...

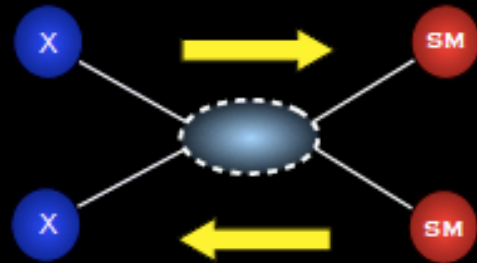


The Ten Commandments to respect to be a “good” DM candidate



NONE OF THE SM PARTICLES CAN BE A GOOD DM CANDIDATE !

The WIMP paradigm is based on a simple yet powerful idea:



$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle [n_\chi^2 - (n_\chi^{\text{eq}})^2]$$

Weak-scale cross sections can reproduce observed relic density

$$\Omega h^2 \approx \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle\sigma v\rangle}$$

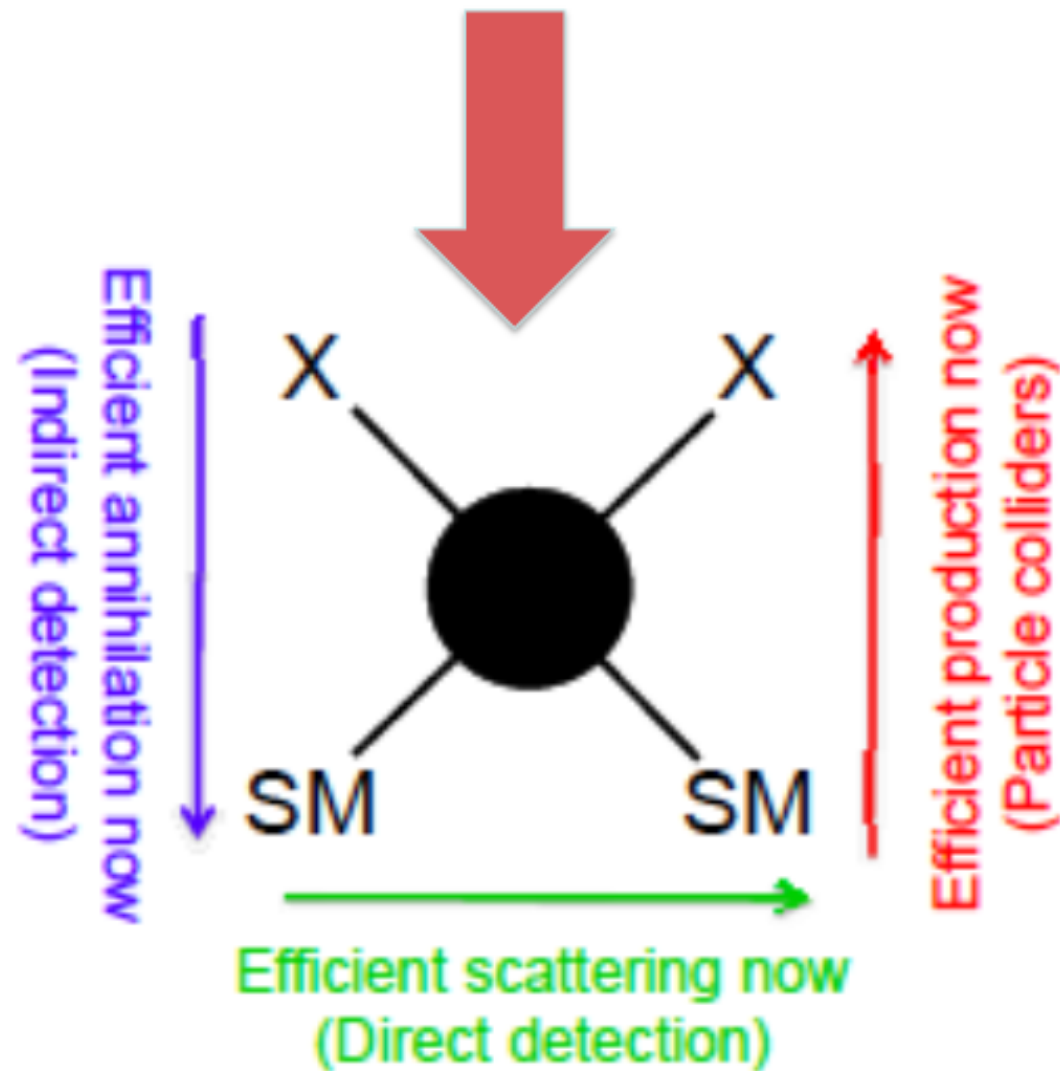
‘WIMP miracle’: new physics at $\sim 1 \text{ TeV}$ solves at same time fundamental problems of particle physics (*hierarchy problem*) AND DM

CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE : STABLE ELW. SCALE WIMPs

	SUSY (x^μ, θ)	EXTRA DIM. (x^μ, j^i)	LITTLE HIGGS. SM part + new part
1) ENLARGEMENT OF THE SM	Anticomm. Coord.	New bosonic Coord.	to cancel Λ^2 at 1-Loop
2) SELECTION RULE	<u>R-PARITY LSP</u>	<u>KK-PARITY LKP</u>	<u>T-PARITY LTP</u>
→ DISCRETE SYMM.	Neutralino spin 1/2	spin1	spin0
→ STABLE NEW PART.	↓	↓	↓
3) FIND REGION (S) PARAM. SPACE WHERE THE “L” NEW PART. IS NEUTRAL + $\Omega_L h^2$ OK	m_{LSP} ~100 - 200 GeV	m_{LKP} ~600 - 800 GeV	m_{LTP} ~400 - 800 GeV

DM COMPLEMENTARITY: efficient annihilation in the early Universe implies today



- **Primordial Inflation**

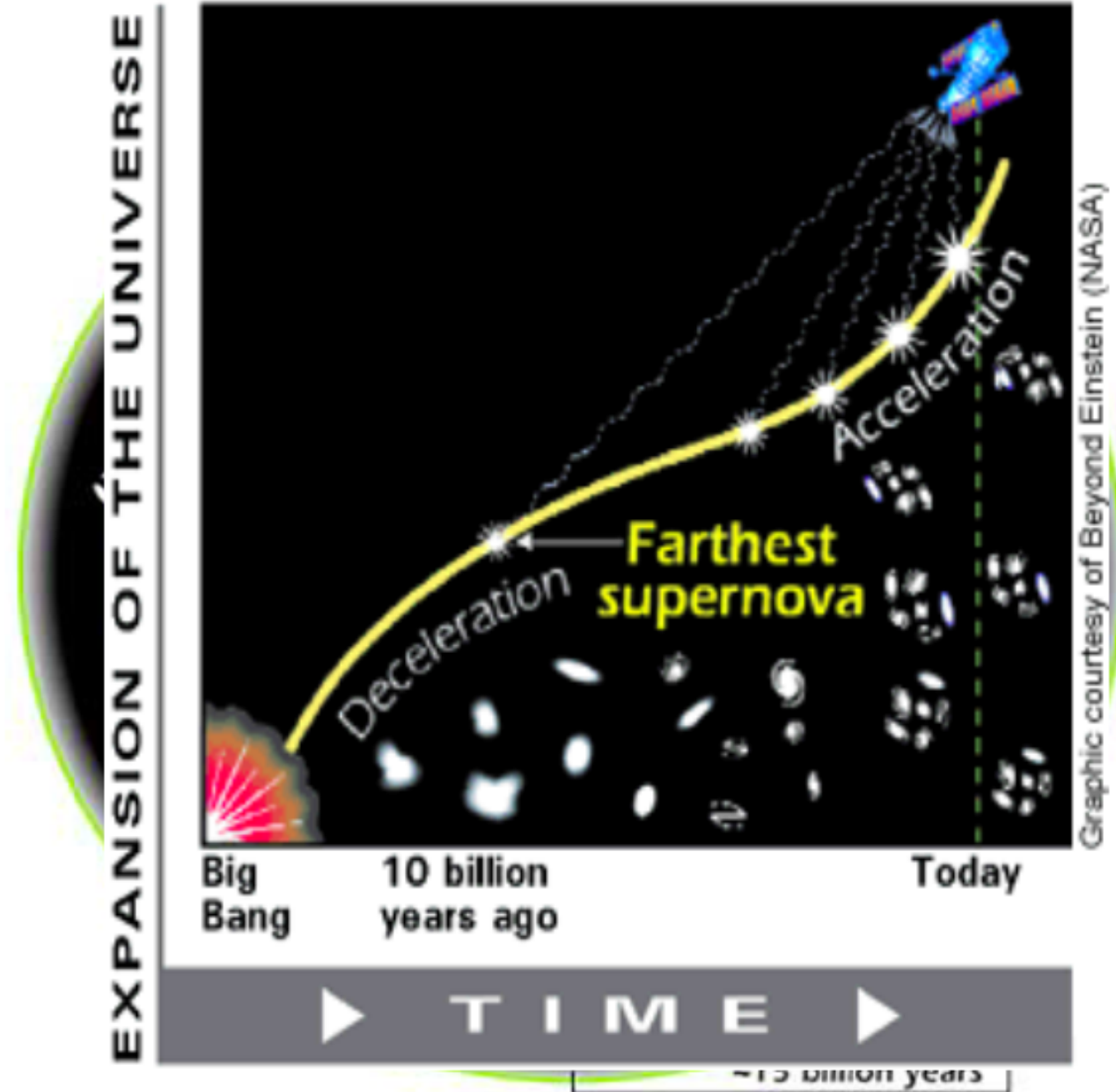
- **Dark Energy**

Possibility to go beyond the **SM of Cosmology?**

Possibility that they are linked to the **absence of GRAVITY as a quantized interaction in the Particle Physics SM?**

Not sure we have to include “**New Particles**” to tackle them – ex. using the SM Higgs as the inflaton in models where Gravity couples non minimally to H

The speed at which the universe expands **“has to decrease”** since only the attractive gravitational force is in action, and yet, **on the contrary....**



General Relativity (1915)

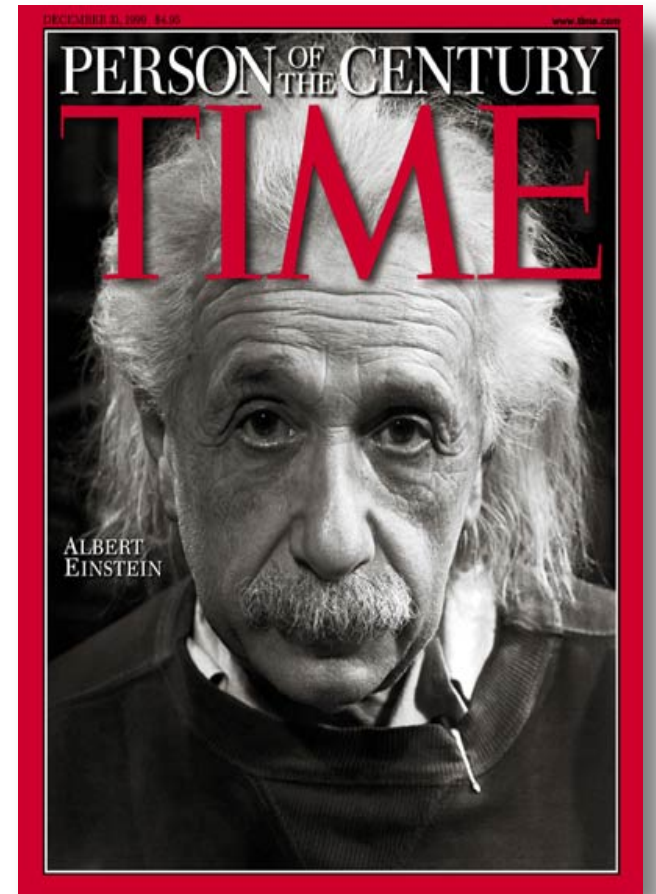
$$\mathbf{G}_{\mu\nu} = \frac{8\pi G}{c^4} \mathbf{T}_{\mu\nu}$$

Space-time **GEOMETRY** **Mass-energy content**

Einstein's GR equation predicts that the universe expands → to avoid such expansion Einstein introduces a **COSMOLOGICAL CONSTANT** + $\Lambda g_{\mu\nu}$

After Hubble experimentally discovers that the universe is actually expanding --→ Einstein comments " adding a cosmological constant to my eq. was the **GREATEST BLUNDER** of my career!

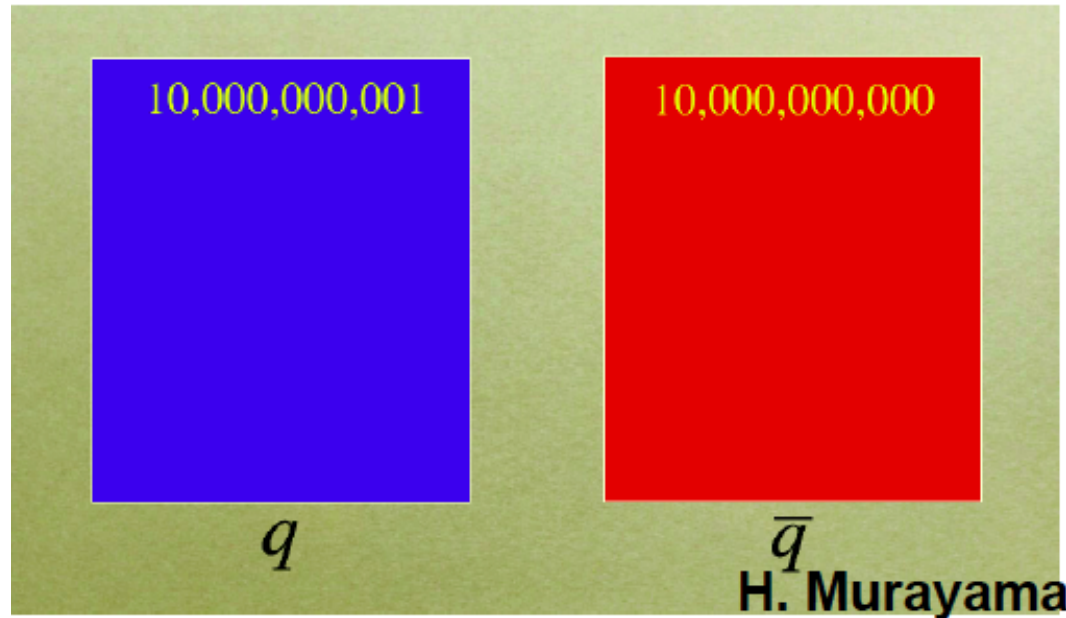
Today we reintroduce such a cosmological constant with a specific value to ensure the accelerated expansion of the universe → is such a cosmological constant related to the **Quantum Vacuum Energy** the source of the **DARK ENERGY** causing the accelerated expansion of the universe?



THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:

-why only baryons

-why $N_{\text{baryons}}/N_{\text{photon}} \sim 10^{-10}$



Peculiar initial conditions?

Or is there a **dynamics** allowing for matter to prevail over antimatter starting from a perfectly **symmetric situation in matter – antimatter** content of the plasma after inflation?

**SM FAILS TO GIVE RISE TO A SUITABLE
COSMIC MATTER-ANTIMATTER
ASYMMETRY**

- **NOT ENOUGH CP VIOLATION IN THE SM**
NEED FOR **NEW SOURCES OF CPV IN
ADDITION TO THE PHASE PRESENT IN
THE CKM MIXING MATRIX**
- FOR $M_{\text{HIGGS}} > 80 \text{ GeV}$ THE ELW. PHASE TRANSITION
OF THE SM IS A SMOOTH CROSSOVER

NEED **NEW PHYSICS BEYOND SM**. IN PARTICULAR,
FASCINATING POSSIBILITY: **THE ENTIRE MATTER IN
THE UNIVERSE ORIGINATES FROM THE
SAME MECHANISM RESPONSIBLE FOR THE
EXTREME SMALLNESS OF m_ν**

What the SM does not account for...

neutrino masses
dark matter
baryogenesis
inflation



OBSERVATIONAL REASONS

$$M_{\text{HIGGS}} / M_{\text{PLANCK}} \sim 10^{-16}$$

$$E_{\text{VACUUM (DE)}} / M_{\text{HIGGS}} \sim 10^{-14}$$

$$\Theta_{\text{CPV in STRONG INTERAC.}} < 10^{-9}$$



THEOR. REASONS

+ lack of **UNIFICATION** of the **ELW.** and strong interactions

+lack of a physical “explanation” of the (largely different) **masses and mixings** of the fermions

THE MYSTERY OF THE 5 NUMBERS THAT THE SM IS UNABLE TO EXPLAIN

- Stars and galaxies are only $\sim 0.5\%$
- Neutrinos are $\sim 0.1-1.5\%$ **NEUTRINO MASS**
- Rest of ordinary matter
(electrons, protons & neutrons) are 4.4%



- Dark Matter **27 %** **WHAT IS DM MADE OF?**
- Dark Energy **68 %** **ENERGY OF THE QUANTUM VACUUM?**
- Anti-Matter **0%** **WHAT PRODUCED THE COSMIC MATTER-ANTIMATTER ASYMMETRY**
- Higgs Bose-Einstein condensate
 $\sim 10^{62}\%??$ **COSMOLOGICAL CONSTANT PROBLEM (QUANTUM VACUUM ENERGY?)**



**There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy**

Hamlet, Act 1 Scene 5