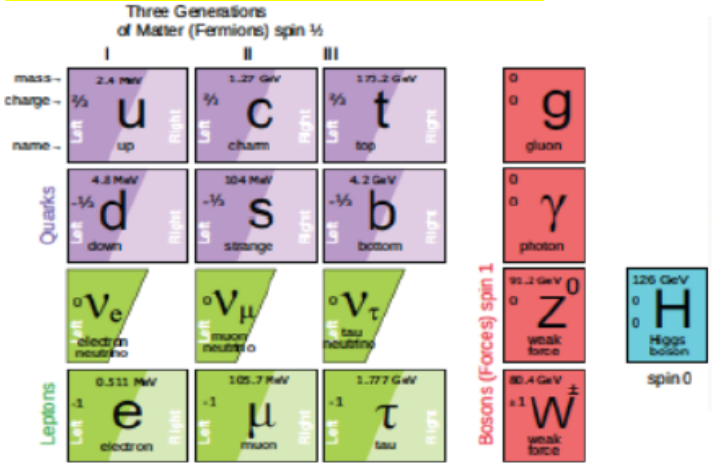
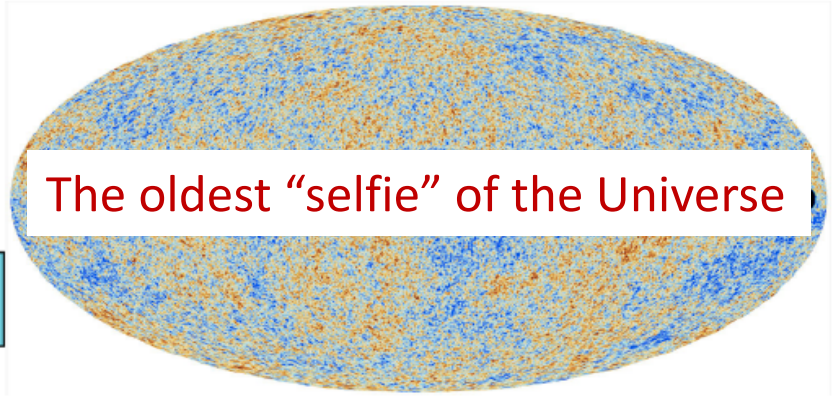
XXXII Int. Seminar of Nuclear and Subnuclear Physics “Francesco Romano”, 7-11 June 2021

MICRO-COSMOS



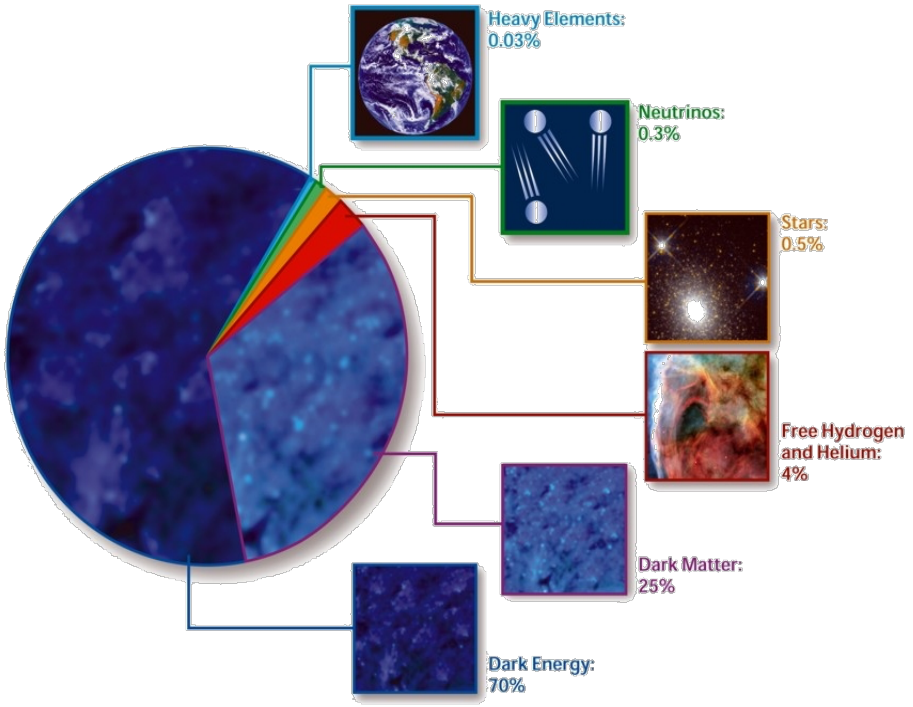
MACRO-COSMOS



BSM PHYSICS

New Physics

Beyond the Standard Model



Antonio Masiero

University of Padua and INFN

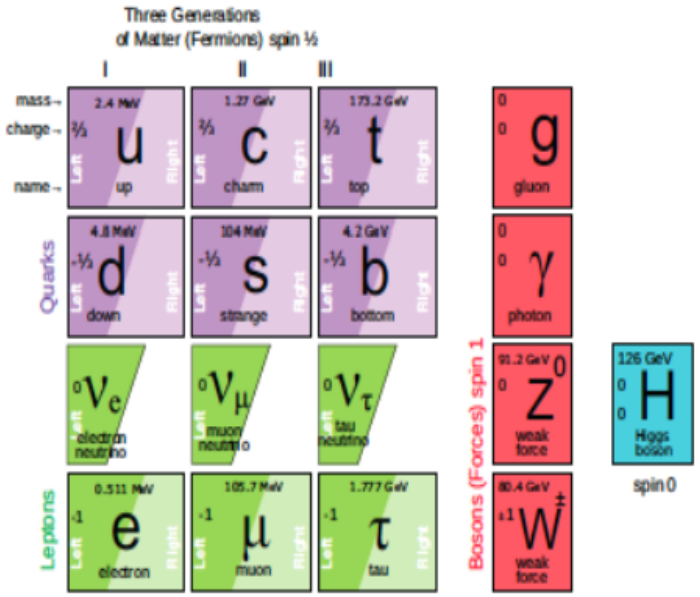
LECTURE I

- **The Standard Models of Micro- and Macro-Cosmos**
- **Critical assessment of the Standard Model (SM)of Elementary Particles and their Fundamental Interactions**
- **WHY and HOW to go Beyond the SM (BSM physics): the need of BSM PHYSICS (new particles and new interactions) and the THREE ROADS to go BSM (the High-Energy, High-Intensity and Astroparticle Physics roads)**

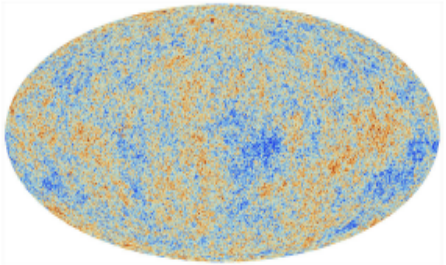
In this last decade → the triumph of the

STANDARD

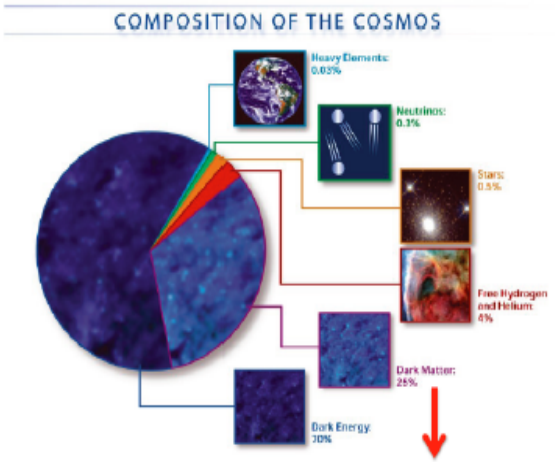
- **PARTICLE STANDARD MODEL**



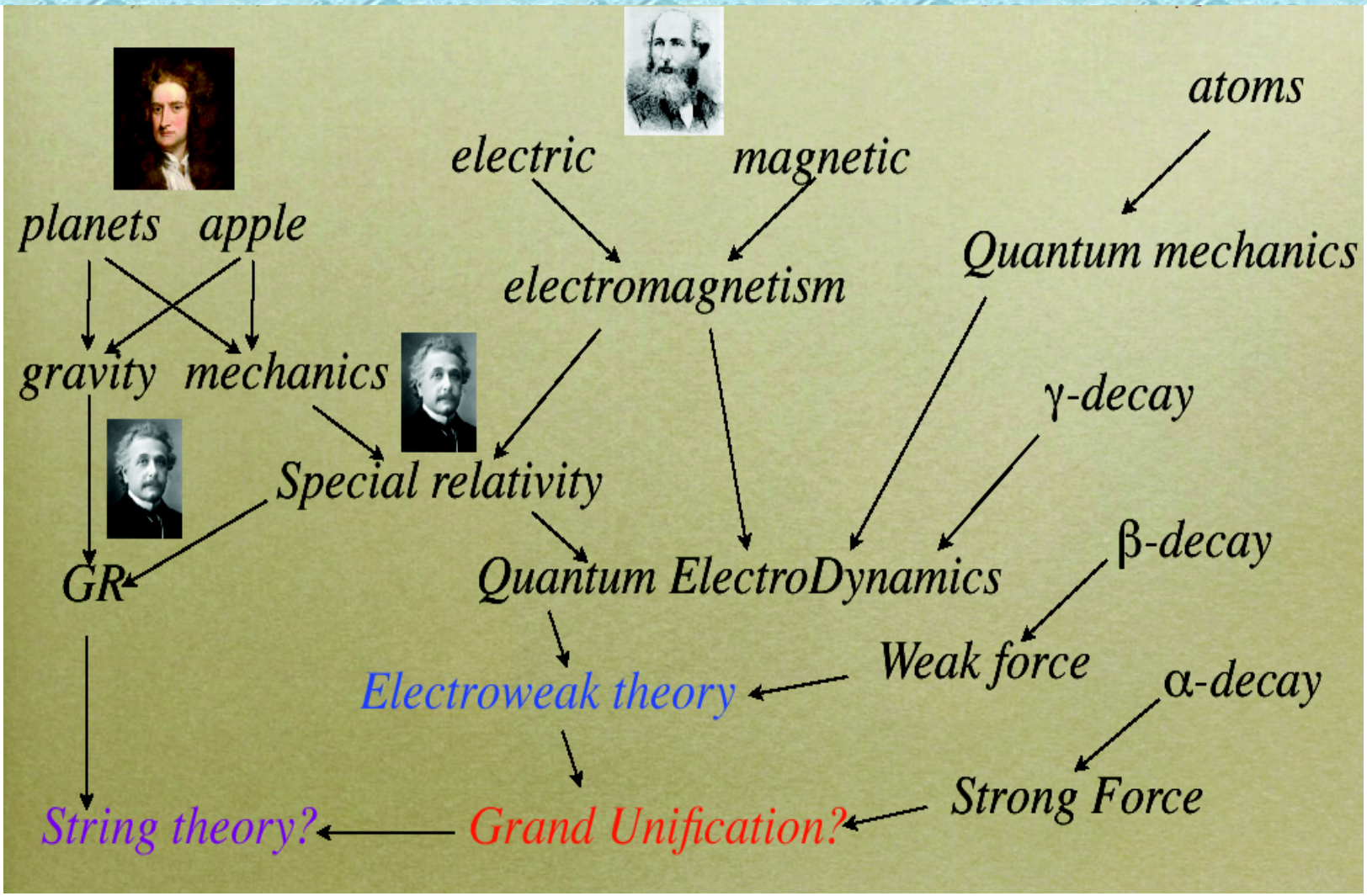
- **COSMOLOGY STANDARD MODEL**



ΛCDM + "SIMPLE" INFLATION

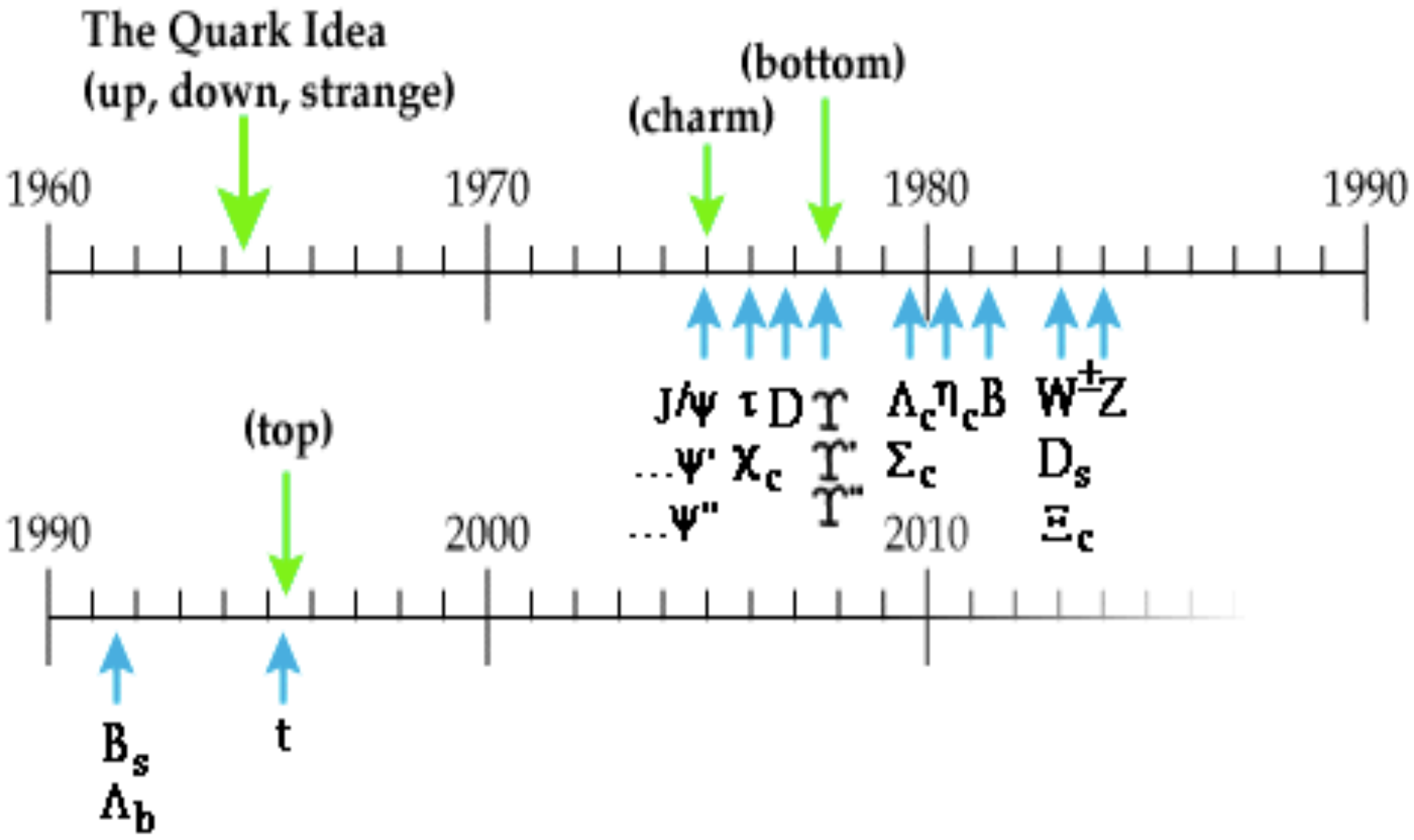


UNIFICATION of FUNDAMENTAL INTERACTIONS



Courtesy of H. Murayama

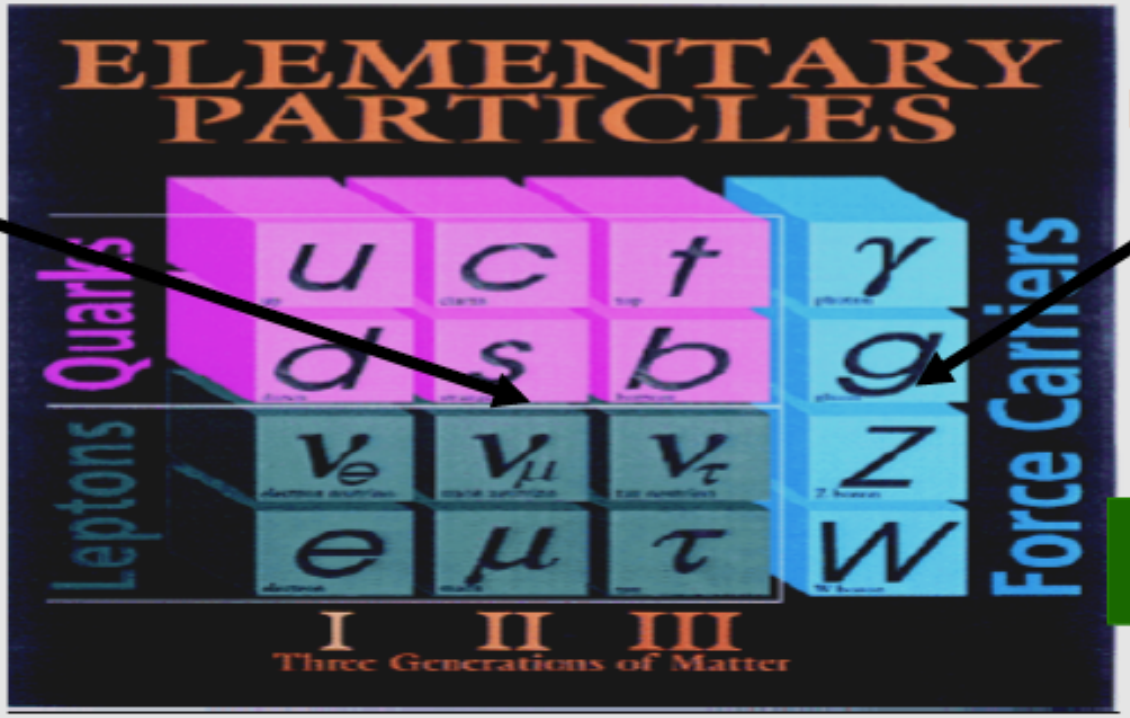
HUNTING FOR THE QUARKS



STANDARD MODEL OF ELEMENTARY PARTICLES AND THEIR INTERACTIONS

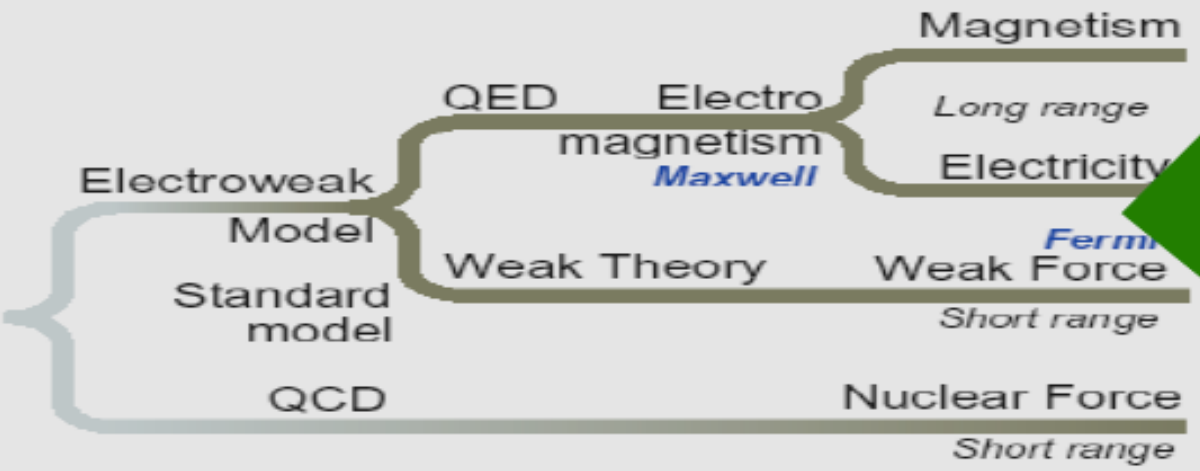
MATERIA

RADIAZIONE

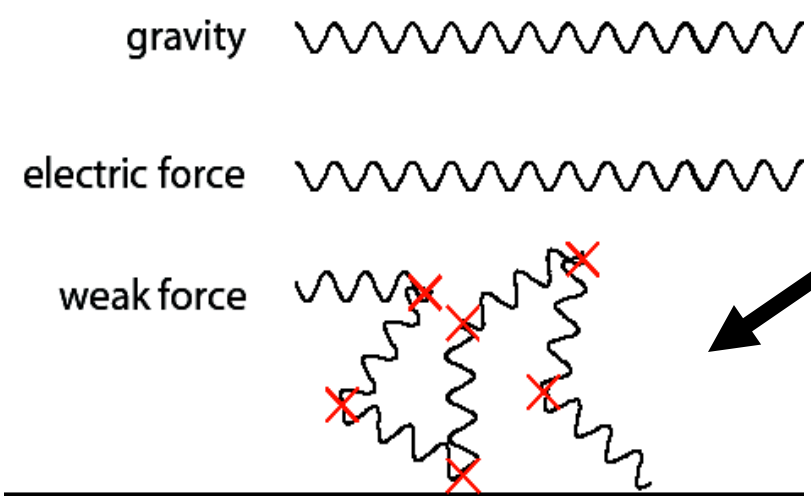


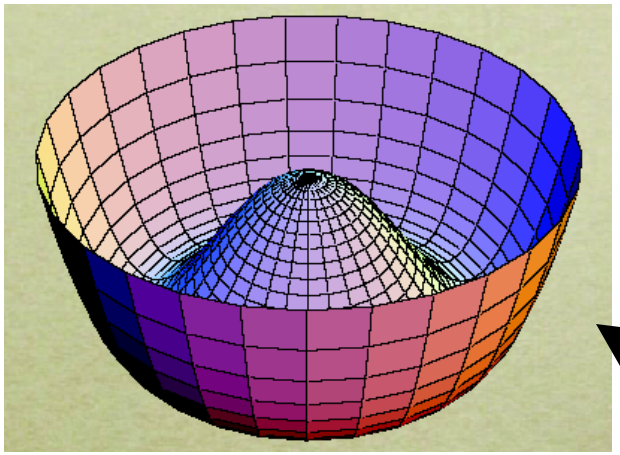
Grand Unified Theory

GUT



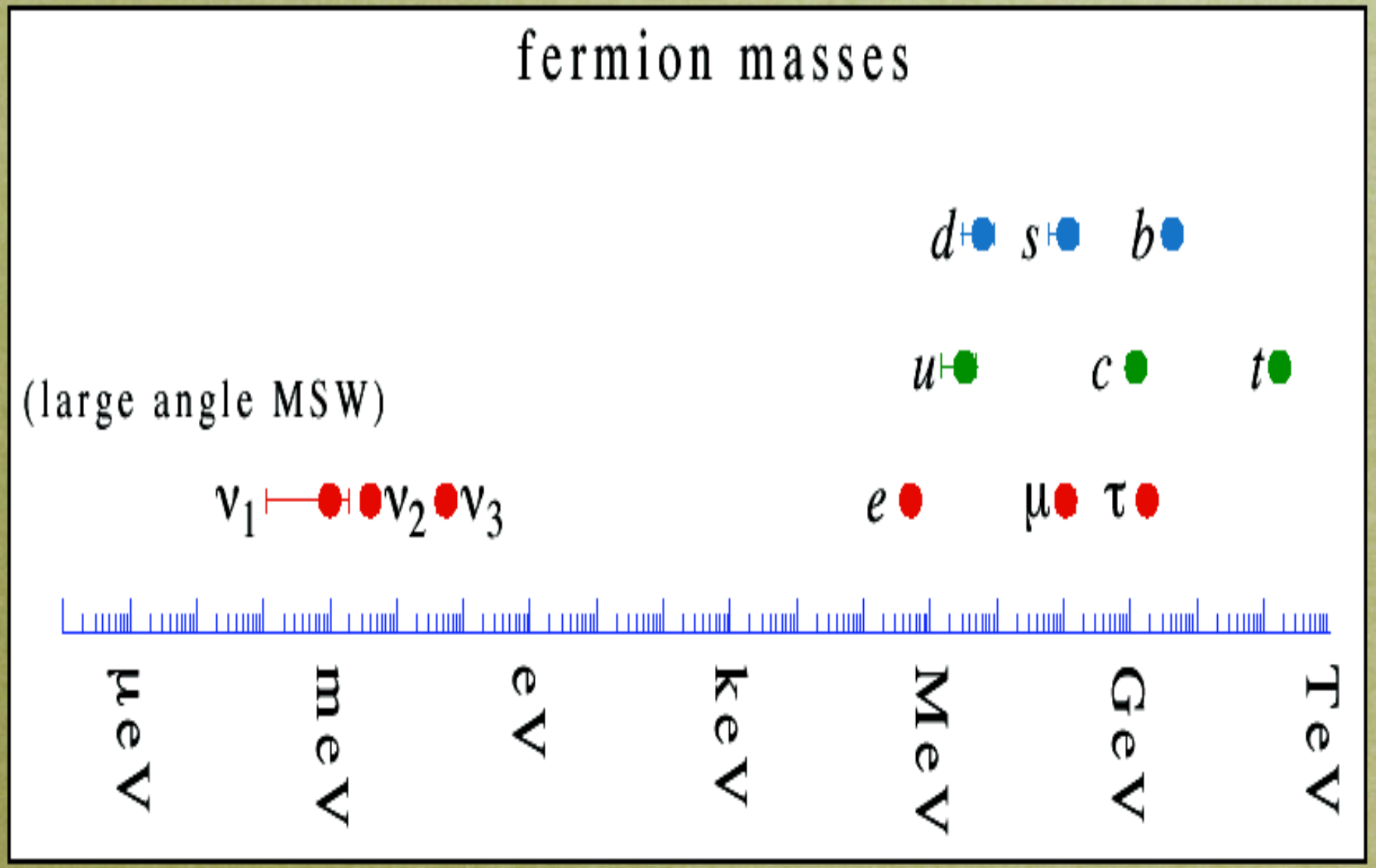
The HIGGS BOSON CONDENSATE



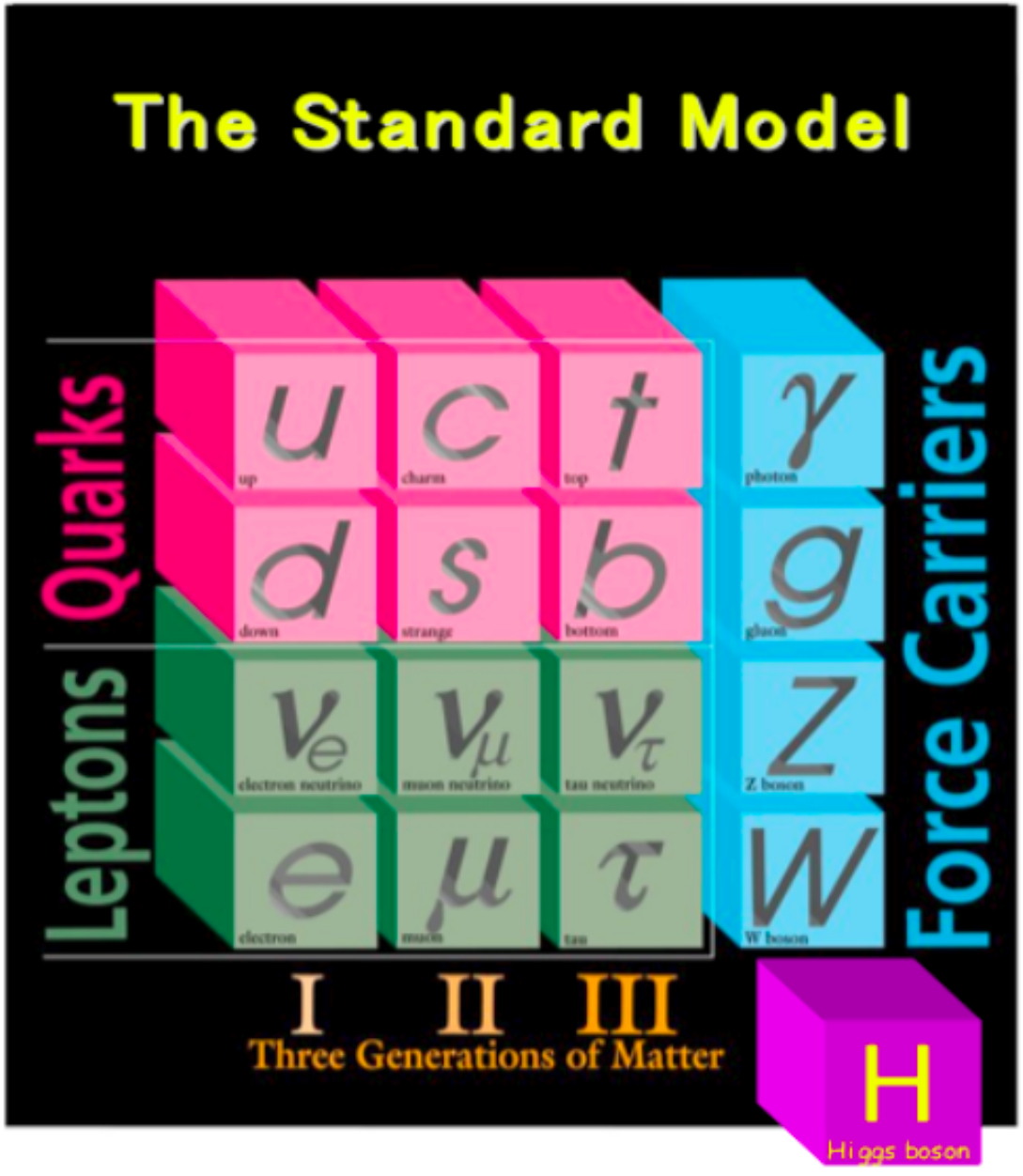


- "SOMETHING" fills the Universe: it "disturbs" Weak interactions making them SHORT-RANGED, while it does NOT affect gravity or electromagnetism.
- WHAT IS IT?
- Analogy with SUPERCONDUCTIVITY: in a superconductor the magnetic field gets repelled (Meissner effect) and penetrates only over the "penetration length", i.e. the magnetic field is short-ranged ⟶ source which disturbs are the boson condensates, Cooper pairs.
- We are "swimming" in Higgs Boson Condensates ⟶ its value at the minimum of its potential determines the masses of all particles!

THE FERMION MASS PUZZLE



Gravity
?



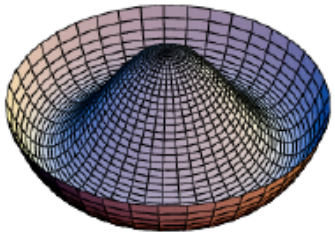
? → EXP. 2012

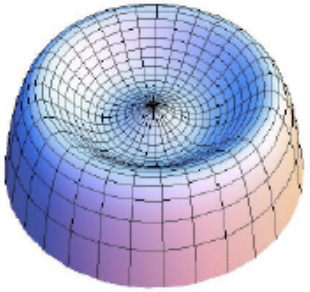
MICRO-COSMOS

- PARTICLE STANDARD MODEL

The Higgs boson and the destiny of the Universe

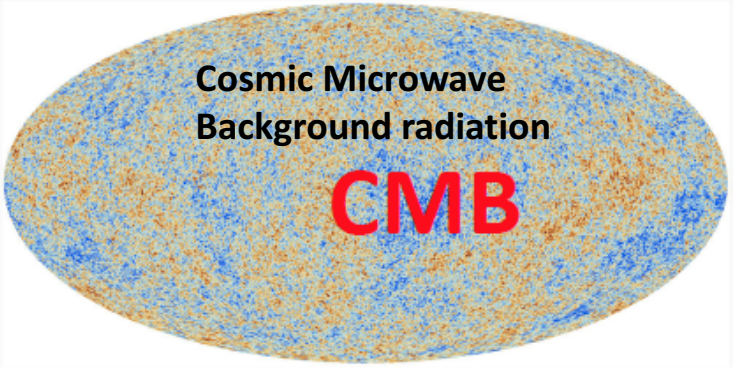
STABILITY ⟺ INSTABILITY

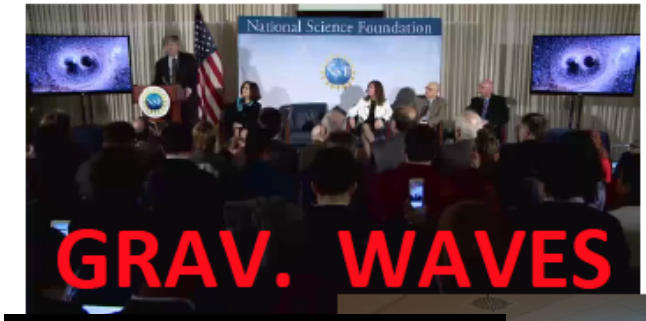


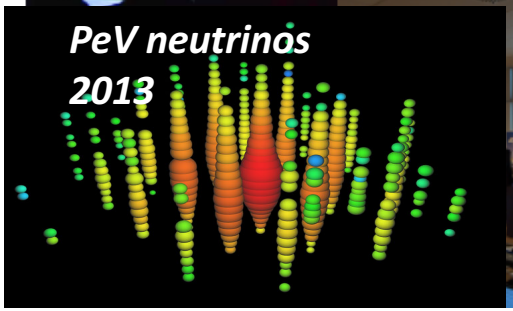


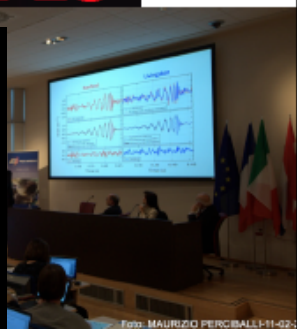
MACRO-COSMOS

- COSMOLOGY STANDARD MODEL



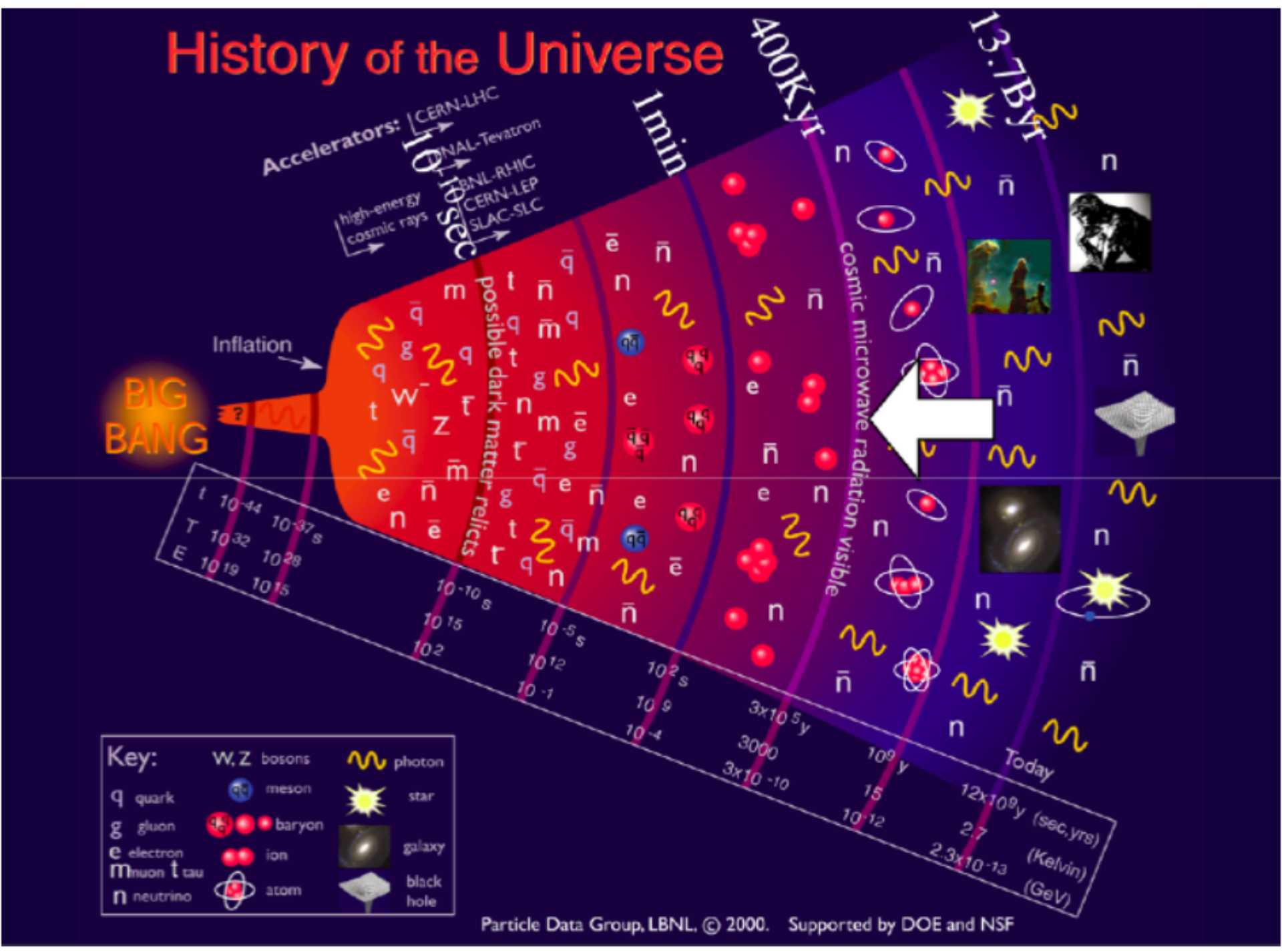


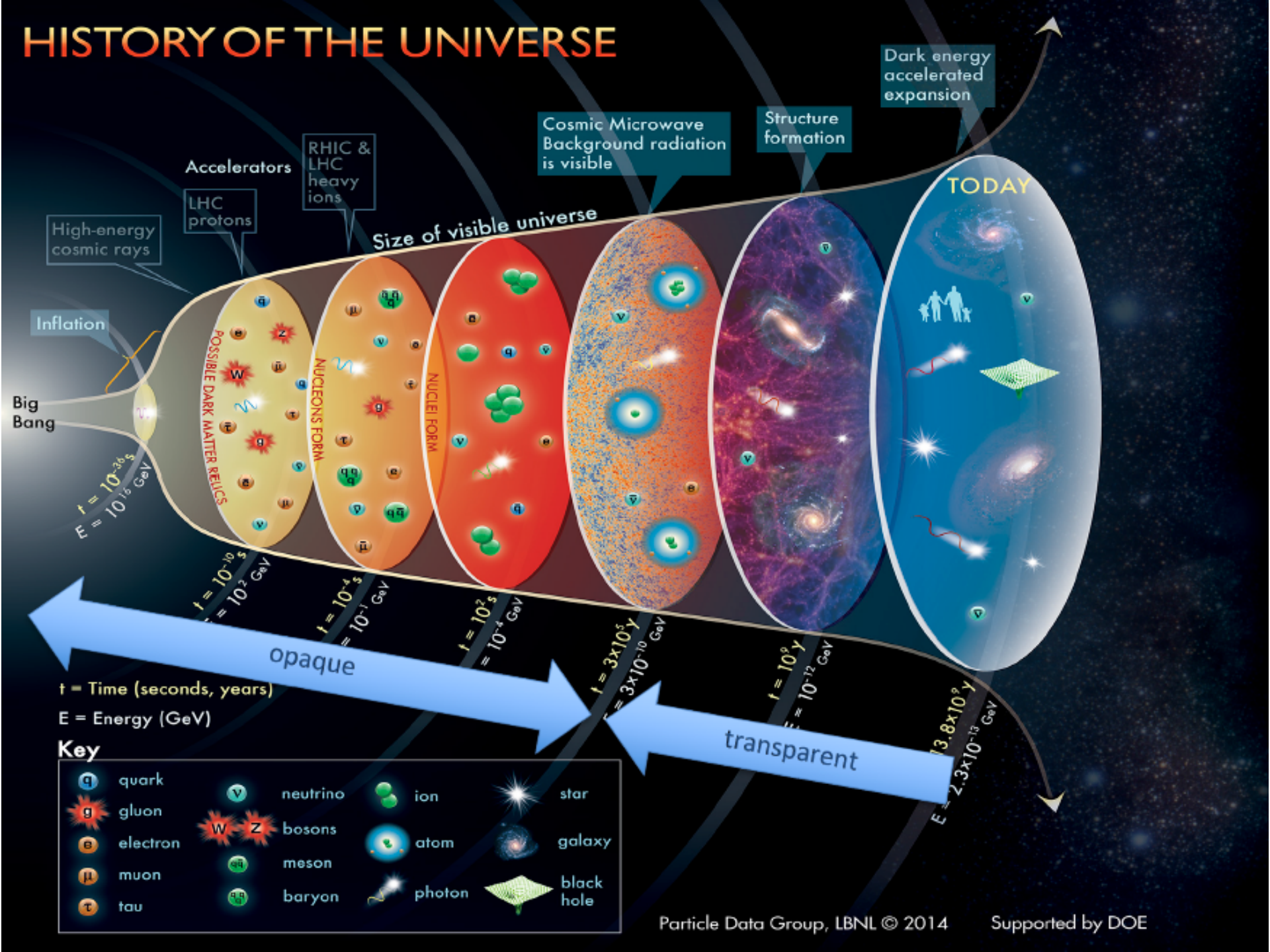


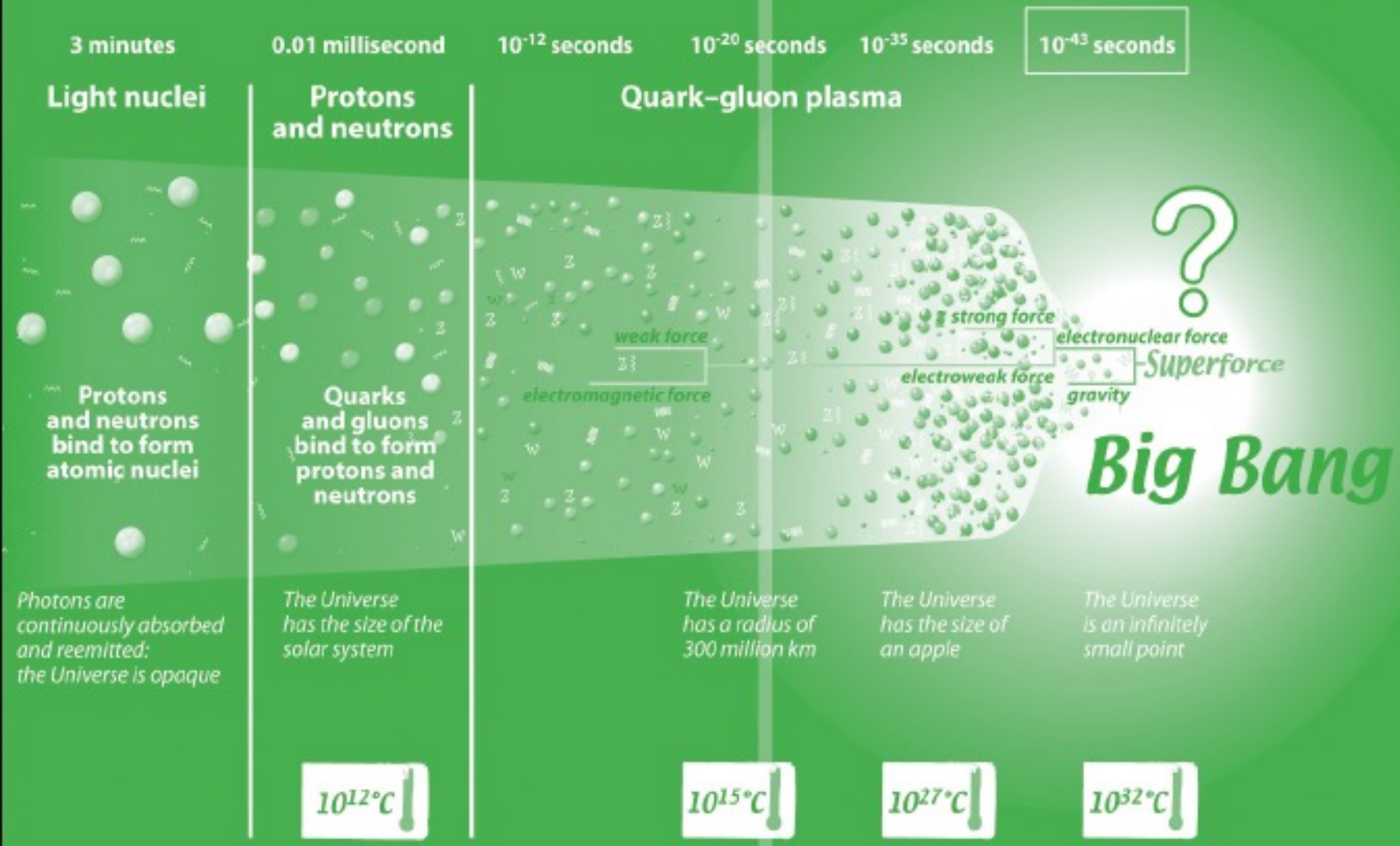


- By the end of the 20th century …
  we have a comprehensive, fundamental theory of all observed forces of nature which has been tested and might be valid from the Planck length scale [10^{-33} cm.] to the edge of the universe [10^{+28} cm.]

D. Gross 2007


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
10 10sec
1min
400Kyr
13.7Byr
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
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
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^15 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
opaque
transparent
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE


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
Quarks and gluons bind to form protons and neutrons
weak force
electromagnetic force
strong force
electronuclear force
electroweak force
gravity
Superforce
?
Big Bang
Photons are continuously absorbed and reemitted: the Universe is opaque
The Universe has the size of the solar system
The Universe has a radius of 300 million km
The Universe has the size of an apple
The Universe is an infinitely small point
10^{12}°C
10^{15}°C
10^{27}°C
10^{32}°C
2 protons + 2 neutrons = Helium nucleus
1 proton = Hydrogen nucleus
Proton
Neutron
Meson
Quark
Electron
Neutrino
Photon
Weak force
Strong force

The Evolution of the Universe

13.7 billion years

Today

Today, at CERN, we are going back in time to study the origins of matter

-270°C

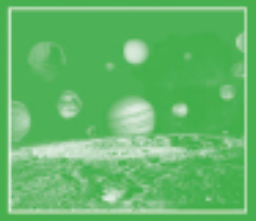
10 billion years

Life on Earth

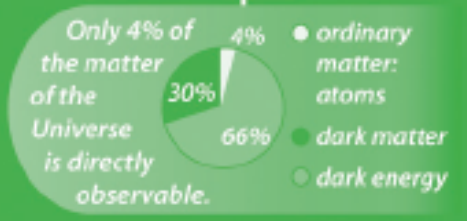
A soup of organic molecules appears on Earth, a small blue planet lost in the immense Universe

9.2 billion years

Solar system

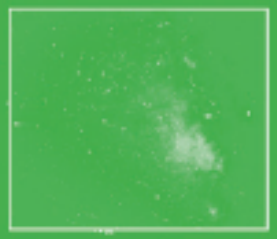


Gravity gathers the debris of stars into planets



200 million years

Stars and galaxies



Gravity gathers clouds of atoms into stars

Heavy atoms, the building blocks of life, are synthesized in the hearts of stars

4000°C

380 000 years

Light atoms

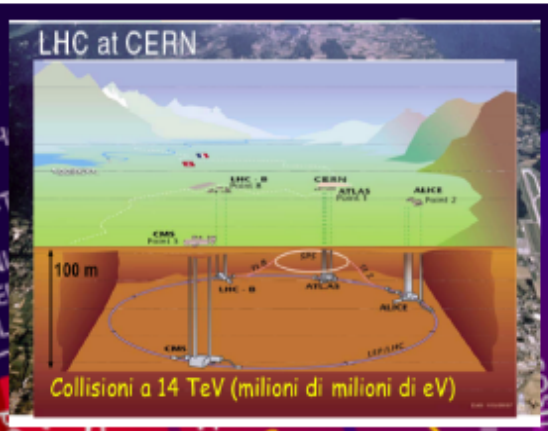
Electrons bind to atomic nuclei to form hydrogen and helium atoms

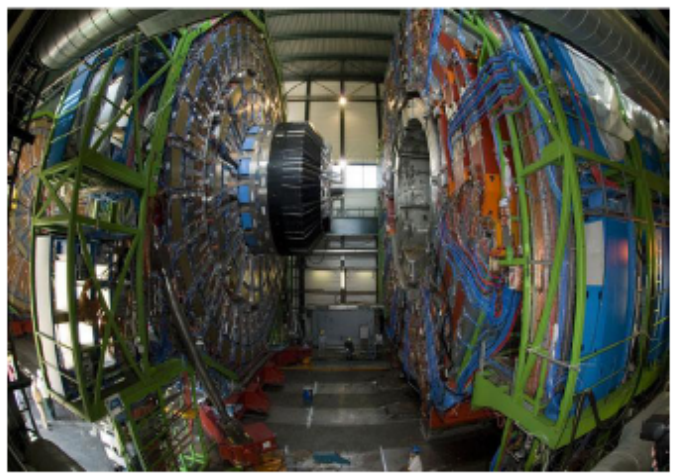
Photons no longer interact with electrons: the Universe becomes transparent and illuminates

Helium atom

Hydrogen atom

History of the





CMS

Accelerators:

high-energy cosmic rays

Inflation

BIG BANG

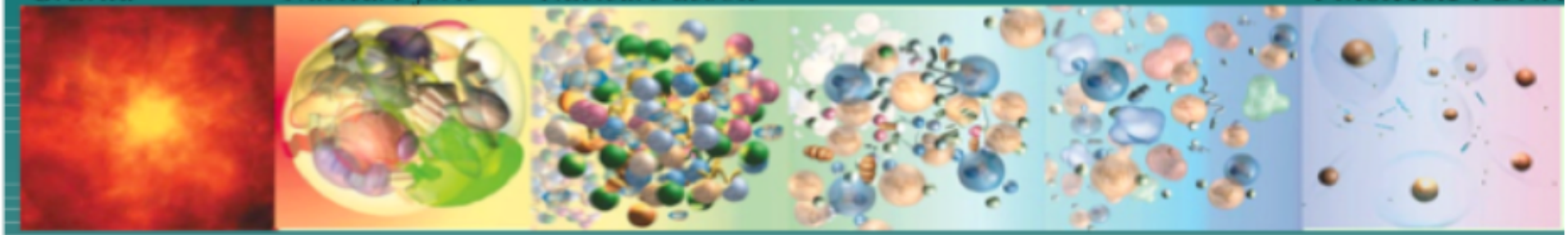
possible dark matter relic

13.7 Byr

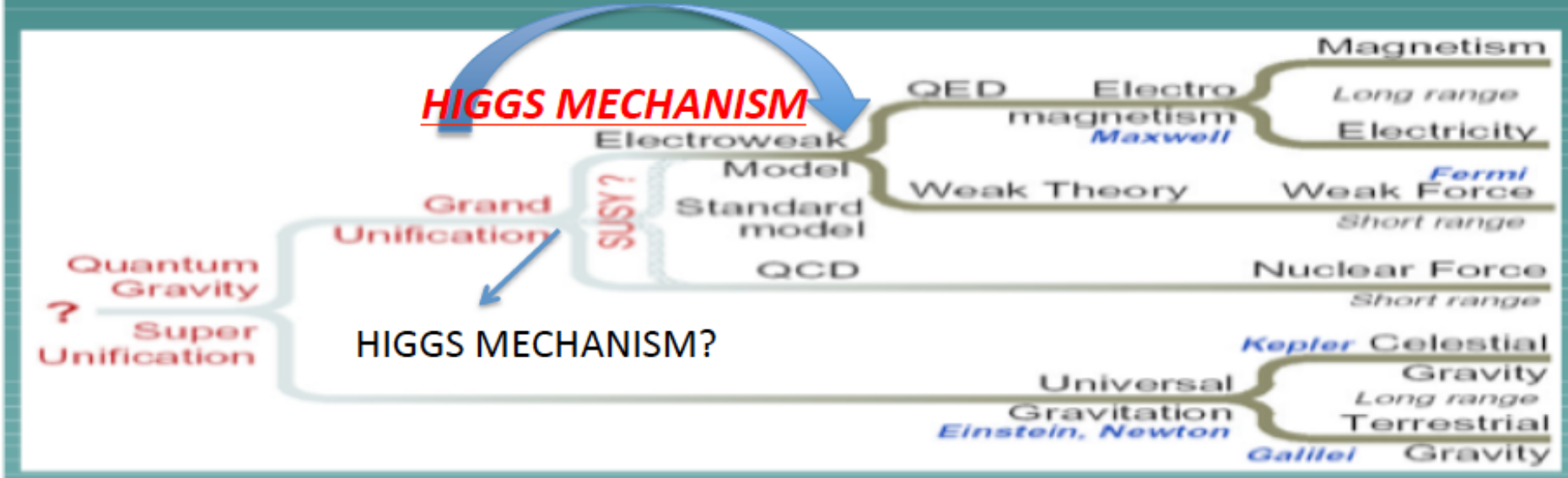
Today

Key: W, Z bosons; q quark; g gluon; e electron; m muon; t tau; n neutrino; meson; baryon; ion; atom; photon; star; galaxy; black hole

Big Bang	Quark-Gluon Plasma		Protoni e neutroni	Protoni e Nuclei leggeri	Atomi →Galassie →Molecole→DNA
Gravità	*Nucleare forte*	*Nucleare debole*			

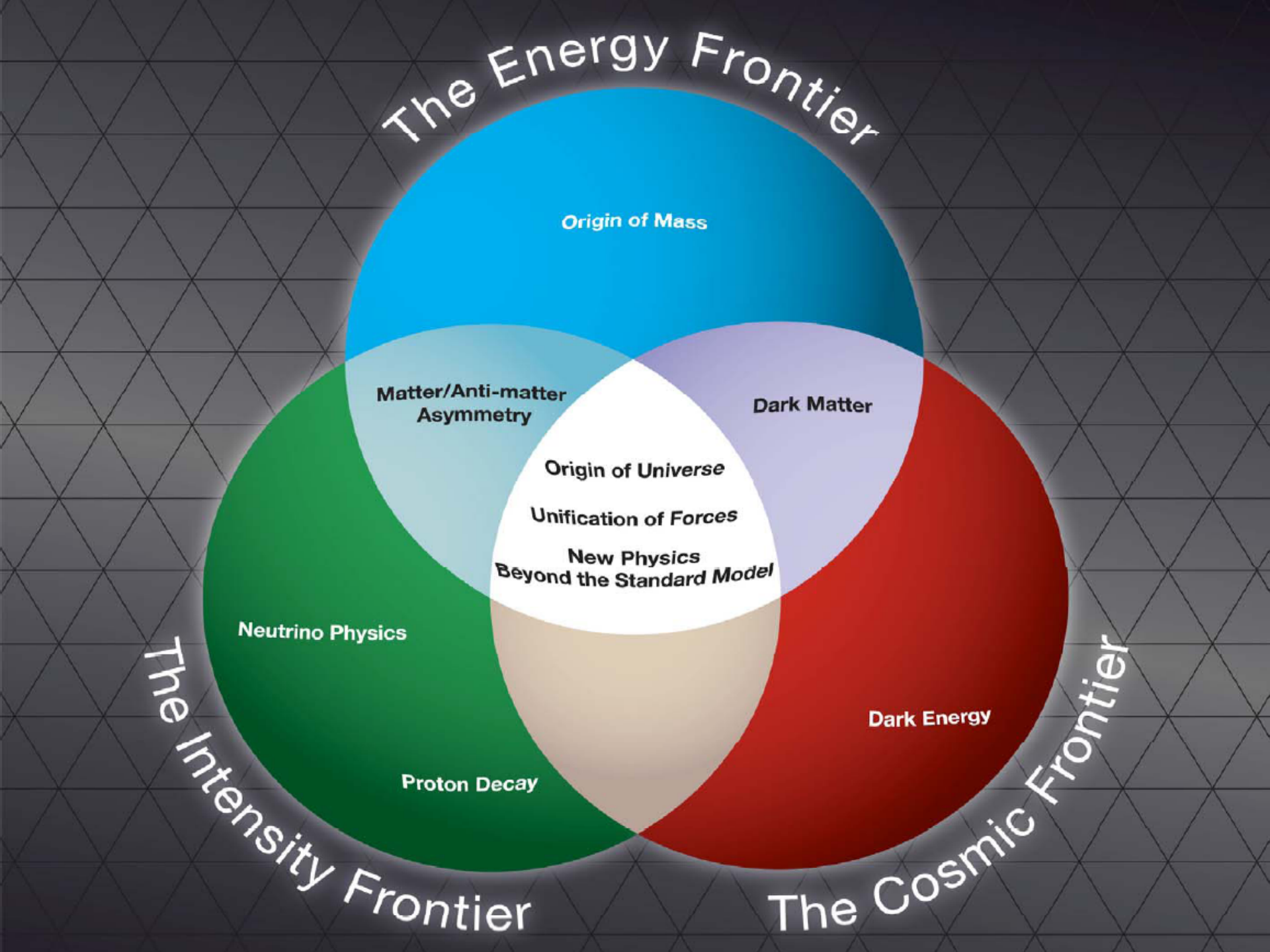


10^{-43} sec	10^{-32} sec	10^{-10} sec	10^{-4} sec	100 sec	300KY → 15GY
10^{-35} m	10^{-32} m	10^{-18} m	10^{-16} m	10^{-15} m	10^{-10} m
10^{19} GeV	10^{16} GeV	10^{2} GeV	1 GeV	1 Mev	10 eV
???	LHC	LEP			Astronomia→

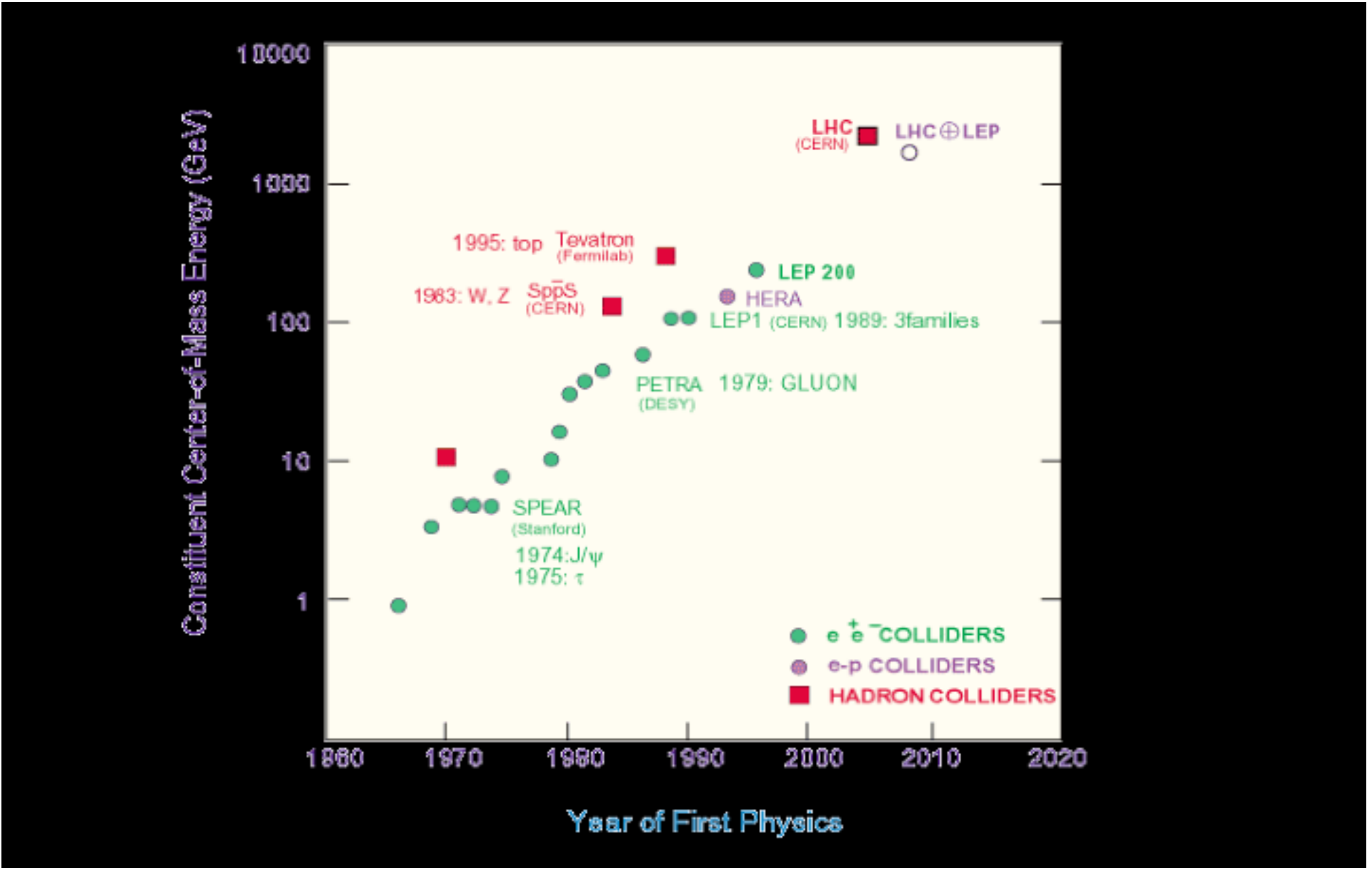


Theories:

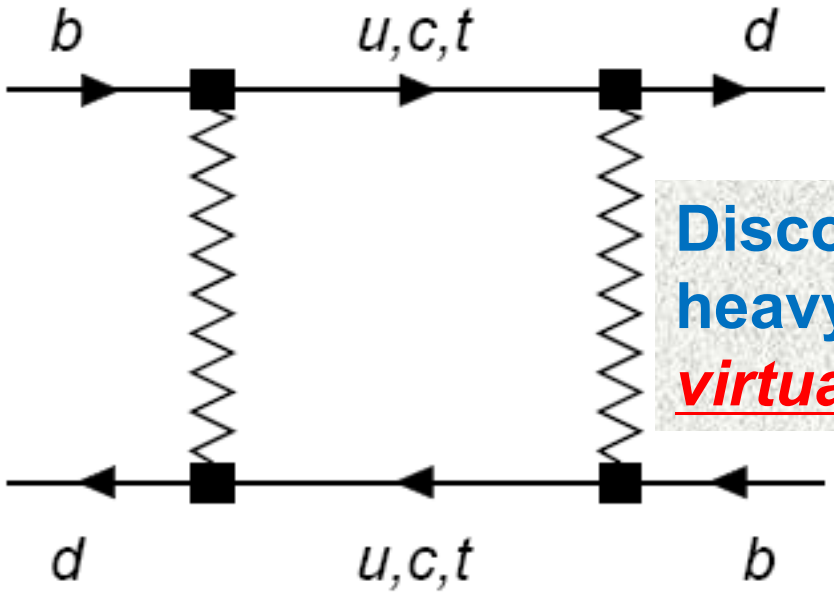
STRINGS? RELATIVISTIC/QUANTUM CLASSICAL


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
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

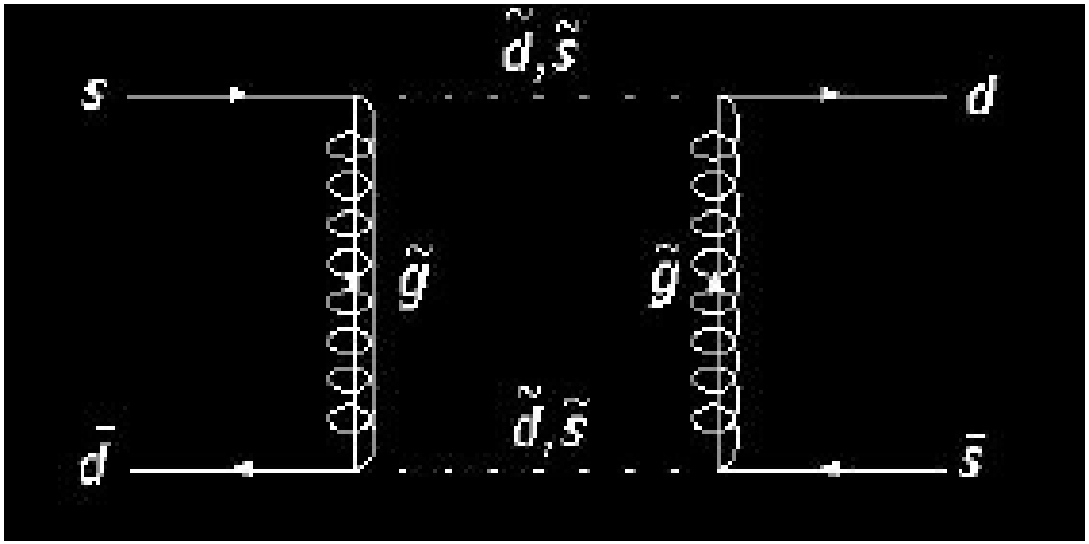
THE HIGH-ENERGY ROAD



THE HIGH-INTENSITY ROAD



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

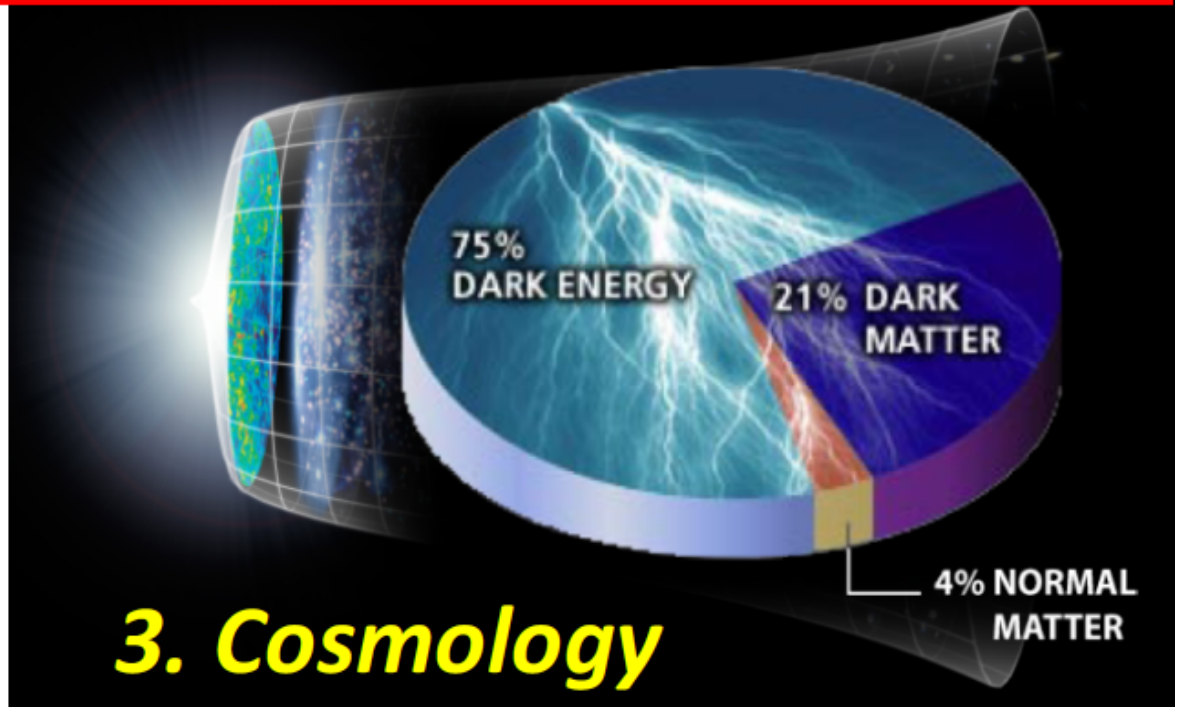


Looking for NEW PARTICLES through their virtual effects → discrepancies w.r.t. the SM predictions

THE ASTRO-PARTICLE PHYSICS ROAD

1. High-energy Universe: multi-messengers

2. Neutrino's

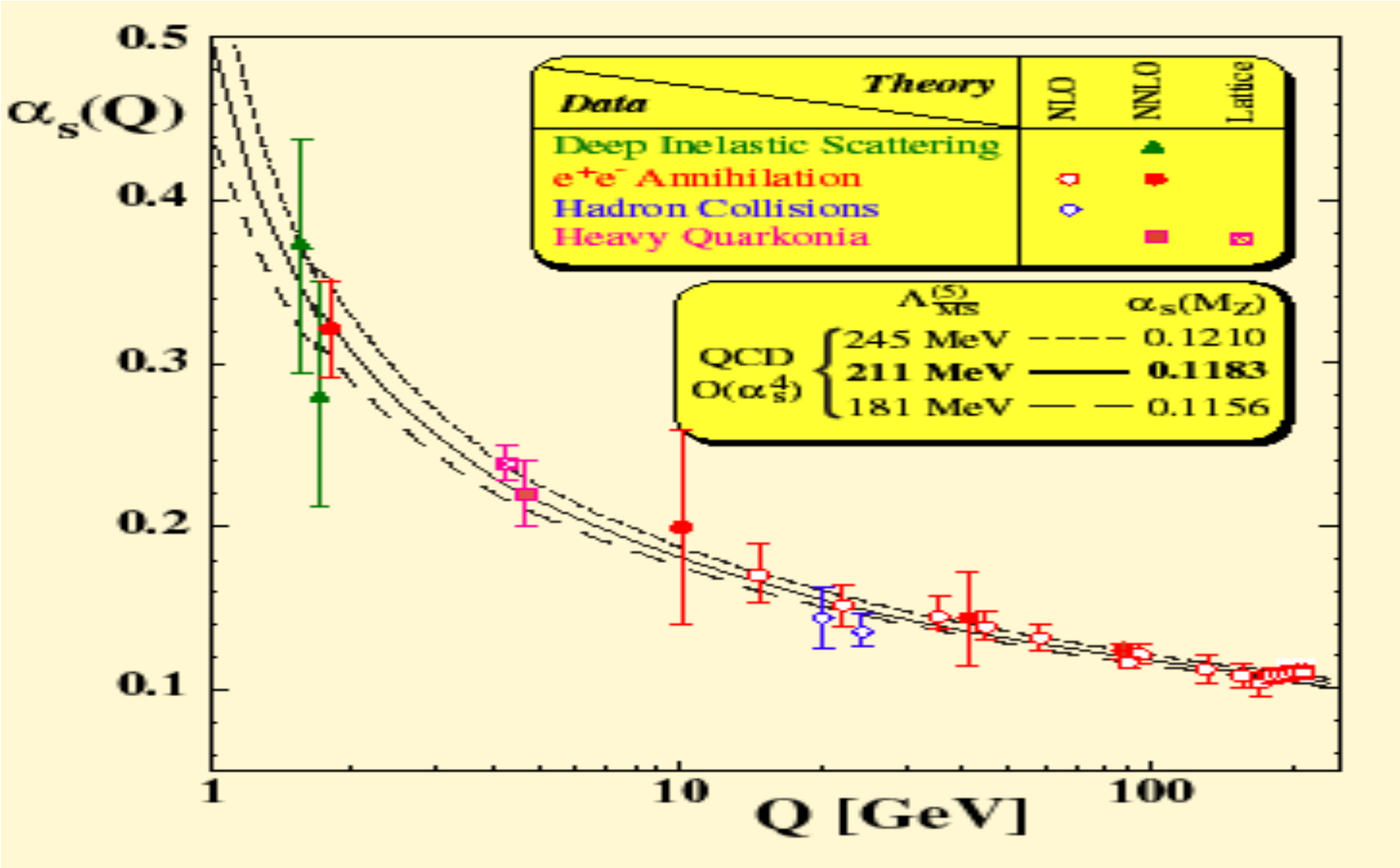


3. Cosmology

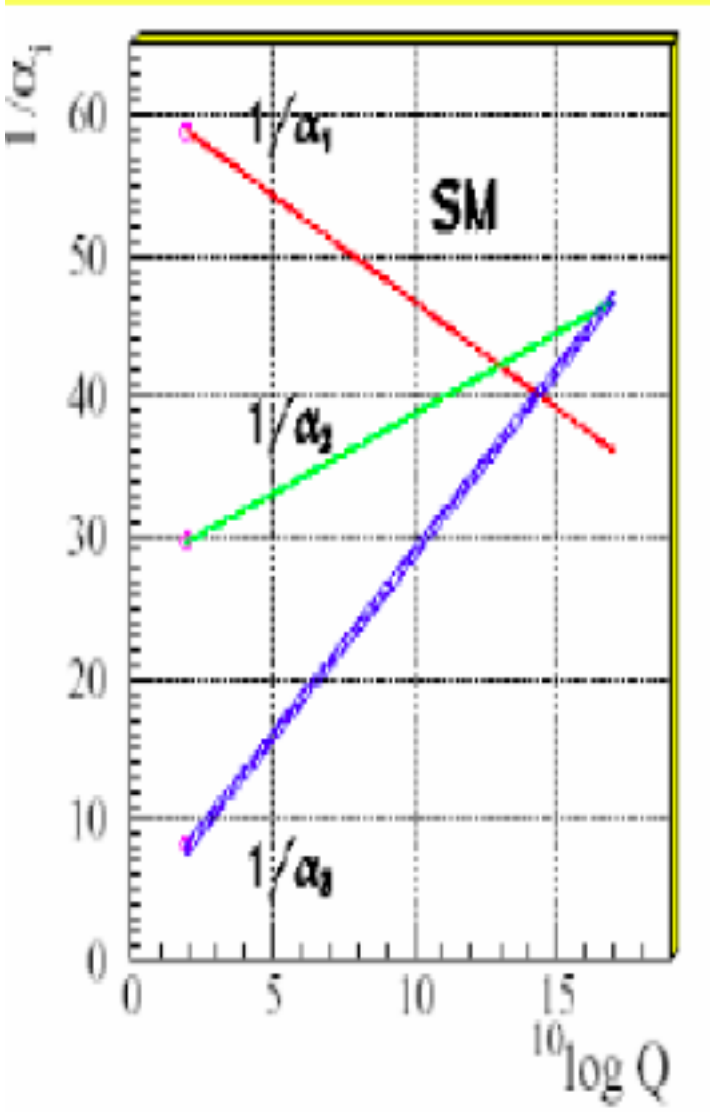
J. de Kleuver

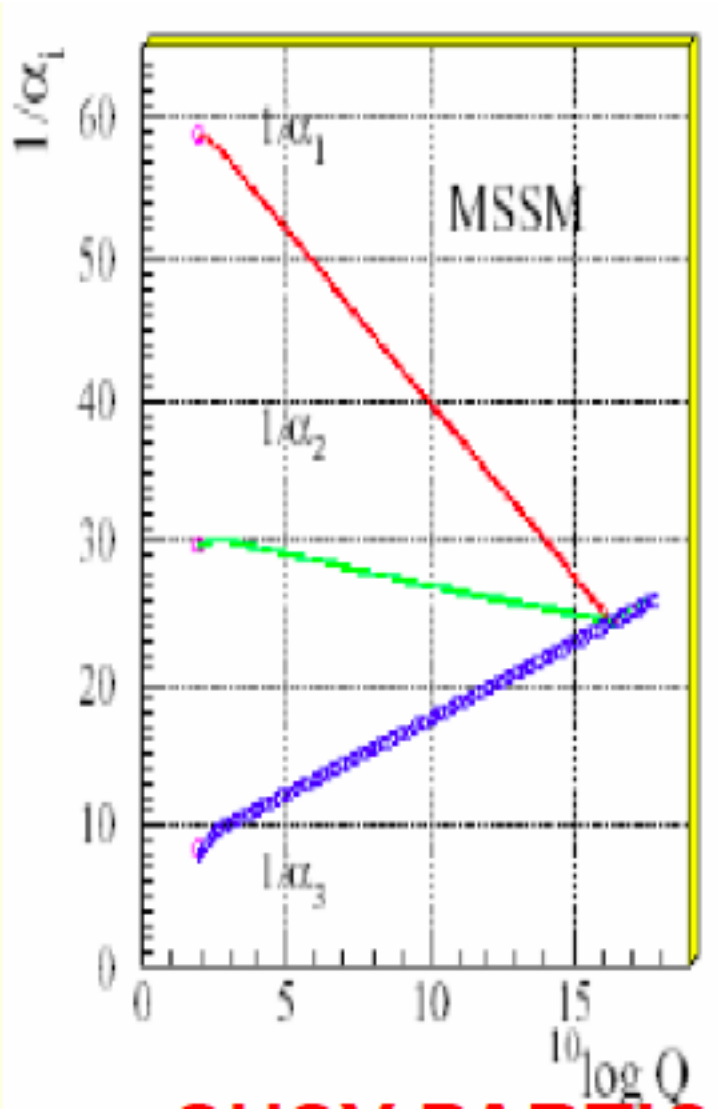
The **COUPLING CONSTANTS** of fundamental interactions are **NOT** constant, but

RUNNING COUPLING CONSTANTS



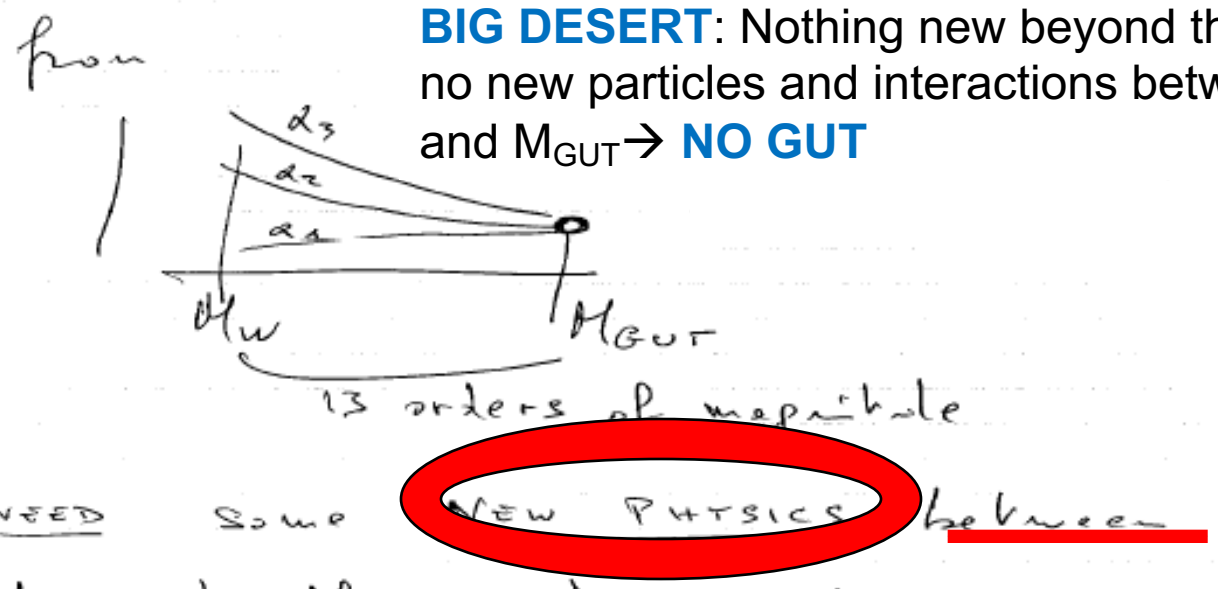
Only one fundamental interaction?





Grand Unified Theories - GUTs

BIG DESERT: Nothing new beyond the SM, i.e. no new particles and interactions between M_W and M_{GUT} → **NO GUT**



Are the SMs really STANDARD?

G-W-S SM

- **All the experimental results** of both **high-energy particle physics** and **high-intensity flavor physics** are surprisingly (and embarrassingly) in **very good agreement** with the predictions of the GSW SM

- Only (possible) exceptions:

  -- **the anomalous magnetic moment of the muon** (> 4σ **discrepancy w.r.t. the SM prediction);**

  -- **hints of violation of the lepton flavor universality in semileptonic B decays**(??)

ΛCDM SM

- **All the cosmic observations are in agreement** with the ~25% CDM, ~70% cosmological constant **Λ** , ~5% ordinary matter of the **ΛCDM SM**

- (Possible) exception: **troubles with pure Cold DM** from absence proto-galaxies, non-existence of spikes in DM density at the centre of the galaxies

- ...**Value of the Hubble constant** measured today or inferred from the Planck results on the CMB

MICRO

GWS STANDARD MODEL

MACRO

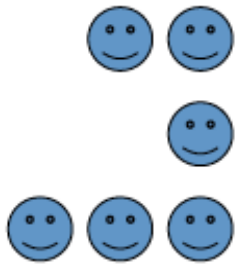
HOT BIG BANG STANDARD MODEL

UNIVERSE EXPANSION +
WEAK INTERACTIONS **NUCLEOYINTHESIS**
1 sec. after BB

NUMBER OF BARYONS and OF NEUTRINO SPECIES → CONFIRMED FROM CMB **350000 YEARS** AFTER BB

Independent confirmation from the study of the CMB

BUT ALSO



New source(s) of CP violation

-COSMIC MATTER-ANTIMATTER ASYMMETRY

-INFLATION ??? New scalar potential

- DARK MATTER + DARK ENERGY New particles and interactions

OBSERVATIONAL EVIDENCE OF NEW PHYSICS

BEYOND THE STANDARD

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 ~ equal, today $n_{baryons}/n_{photons} \sim 10^{-9}$

- **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

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 → 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_{planck} >>> M_W; stabilization of the higgs mass at M_W at any order in perturbation theory

What the SM does not account for...

neutrino masses
dark matter
baryogenesis
inflation

OBSERVATIONAL REASONS

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

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

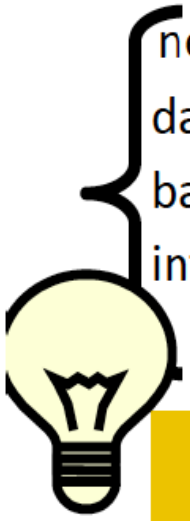
$\Theta_{CPV\ in\ STRONG\ INTERAC.} < 10^{-9}$

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 Energy Scale from the "Observational" New Physics



neutrino masses

dark matter

baryogenesis

inflation

NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE

The Energy Scale from the "Theoretical" New Physics

★ ★ ★ **Stabilization of the electroweak symmetry breaking at M_W calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale** **+**

★ **CORRECT GRAND UNIFICATION "CALLS" FOR NEW PARTICLES AT THE ELW. SCALE**

LECTURE II

- **Lepton and Baryon numbers in the SM and in GUTs**
- **The NEUTRINO MASS problem**
- **The GAUGE HIERARCHY problem**
- **Natural and unnatural solutions to the gauge hierarchy problem**
- **Low-energy Supersymmetry (SUSY)**
- **Theories with EXTRA-DIMENSIONS**

LEPTON NUMBER and ***LEPTON FLAVOR NUMBERS*** ***CONSERVATION*** in the ***SM***

- *BARYON (B) AND LEPTON (L) numbers are **AUTOMATICALLY** conserved in the SM* (at all orders of the perturbation expansion), i.e. with the fields of the SM particle spectrum it is not possible to write any **operator of dim. ≤ 4** which respects the SM gauge symmetry and violates B or L

but *B and L are NOT conserved at the QUANTUM LEVEL in the SM*

- **B and L are NOT conserved at the quantum (non-perturbative) level.**
- **no visible implications (like proton decay) at zero (or low – like the Universe today)) temperature**
- **But at** early epochs when such temperature exceeded the electroweak energy scale (i.e. T > 100 GeV) the "tunneling toll" could be avoided so that **B and L violating transitions could proceed at large rates possibly larger than the expansion rate of the Universe at that time.**

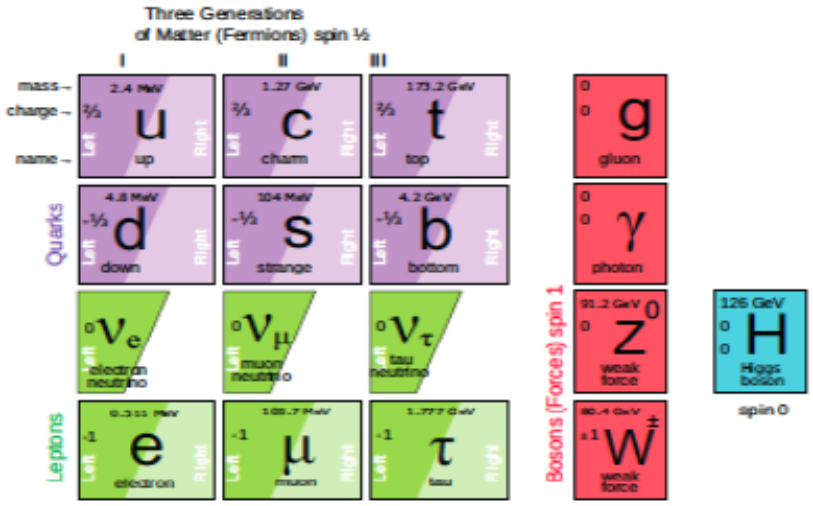
ν mass in the

SM as an **EFFECTIVE** low-energy **theory**

LLHH dim 5 → $\mathbf{M^{-1}}$LL<H><H>

$\mathbf{m_\nu \rightarrow \langle H \rangle^2 / M}$

$m_\nu < 100$ meV → $\mathbf{M > 10^{14}\ GeV}$



- No DIRAC mass

$$\overline{\nu}_L \nu_R + \overline{\nu}_R \nu_L$$

Need of a new particle: the RH neutrino ν_R

NO MAJORANA mass

$$\nu^T_R \nu_R \text{ or } \nu^T_L \nu_L$$

To obtain a neutrino mass in the renormalizable SM

--> need of new particles (ν_R, Δ scalar triplet of $SU(2)_L$)

THE FATE OF LEPTON NUMBER

L VIOLATED → υ Majorana ferm.

L CONSERVED → υ Dirac ferm. (dull option)

SMALLNESS of m_υ → PRESENCE OF A NEW PHYSICAL MASS SCALE

$h\,\bar{\upsilon}_L H\,\upsilon_R \longrightarrow m_\upsilon = h\langle H\rangle$ $\qquad$ $M_\upsilon < 5$ eV $\rightarrow h < 10^{-11}$

EXTRA-DIM. ν_R in the bulk: small overlap?

NEW HIGH SCALE / NEW LOW SCALE

SEE - SAW MECHAN.

Minkowski; Gell-Mann, Ramond, SlansKy, Vanagida

ν_R ENLARGEMENT OF THE FERMIONIC SPECTRUM

$M\upsilon_R\,\upsilon_R + h\,\bar{\upsilon}_L\,\phi\,\upsilon_R$

	υ_L	υ_R
υ_L	$\sim O$	$h\langle\phi\rangle$
υ_R	$h\langle\phi\rangle$	M

LR Models?

MAJORON MODELS

Gelmini, Roncadelli

Δ ENLARGEMENT OF THE HIGGS SCALAR SECTOR

$h\,\upsilon_L\,\upsilon_L\,\Delta$

$m\upsilon = h\langle\Delta\rangle$

N.B.: EXCLUDED BY LEP!

NEUTRINO MASSES and a "NON-TRIVIAL" NEW PHYSICS

- **If no RH neutrino** → enlargement of the SM scalar sector (Higgs triplet) + introduction of a NEW ENERGY SCALE (some new mass parameter of the enlarged Higgs potential must give rise to a VEV of the higgs triplet several orders of magnitude smaller than the VEV responsible for the electroweak symmetry breaking
- **If RH neutrinos** are introduced
- A) **pure neutrino DIRAC mass** (add to the gauge symmetry also a **global U(1) symmetry**, L, and then introduce Yukawa couplings 5-6 orders of magnitude smaller than the electron Yukawa coupling
- B) **Dirac mass + Majorana mass of the RH neutrino** (**new parameter with dimension of a mass in the Lagrangian**; most natural choice **M>> electroweak scale** since neutrino masses come from LLHH/M effective terms

"*MASS PROTECTION*"

For FERMIONS, VECTOR (GAUGE) and SCALAR BOSONS

SIMMETRY PROTECTION

- -FERMIONS → chiral symmetry
  f_L f_R not invariant under SU(2)x U(1)
- -VECTOR BOSONS → gauge symmetry

→ FERMIONS and W,Z VECTOR BOSONS can get a mass only when the elw. symmetry is broken m_f, $m_W \leq \langle H \rangle$

NO SYMMETRY PROTECTION FOR SCALAR MASSES

POSSIBLE SOLUTION

"INDUCED MASS PROTECTION"

→ Create a symmetry (SUPERSIMMETRY)
Such that FERMIONS ⟷ BOSONS

So that the fermion mass "protection" acts also on bosons as long as SUSY is exact

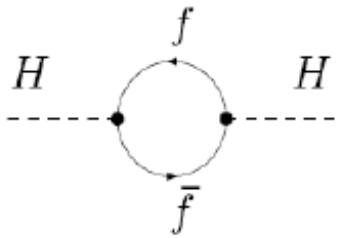
⇨ SUSY BREAKING ~ SCALE OF 0 (10^2-10^3 Gev)

→ LOW ENERGY SUSY

ON THE RADIATIVE CORRECTIONS TO THE SCALAR MASSES

Free propagation: 

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections: 

inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

$$\Sigma_H^f \sim N_f \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

$$\text{for } \Lambda \to \infty : \quad \Sigma_H^f \sim N_f \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

Notice that, on the contrary, for **fermion masses** the **radiative corrections are only logarithmically divergent**

DESTABILIZATION OF THE ELW. SYMMETRY BREAKING SCALE

For $\Lambda = M_{\rm Pl}$:

$$\Sigma_H^f \approx \delta M_H^2 \sim M_{\rm Pl}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

SCALAR MASSES ARE "UNPROTECTED" AGAINST LARGE CORRECTIONS WHICH TEND TO PUSH THEM UP TO THE LARGEST ENERGY SCALE PRESENT IN THE FULL THEORY

EX: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\rm GUT}^2$

SYMMETRY ⟶ MASS = 0 LIMIT

NO NEW SYMMETRY IN THE LIMIT $M_H = 0$

On the contrary, in the limit of massless electron one recovers the chiral symmetry, i.e. the invariance under a separate rotation of the LH and RH components of the electron

FERMION AND GAUGE BOSON MASSES ⟶

WHEN SENT TO ZERO THE THEORY ACQUIRES A NEW SYMMETRY OR, EQUIVALENTLY, THEY ARISE ONLY WHEN A CERTAIN SYMMETRY IS BROKEN, i.e. **THEIR VALUE CAN NEVER EXCEED THE SCALE AT WHICH SUCH SYMMETRY IS BROKEN**

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) → new interaction getting strong at $m_{NP} \ll M$

- **The scale at which the electroweak symmetry is spontaneously broken by <H> results from COSMOLOGICAL EVOLUTION**

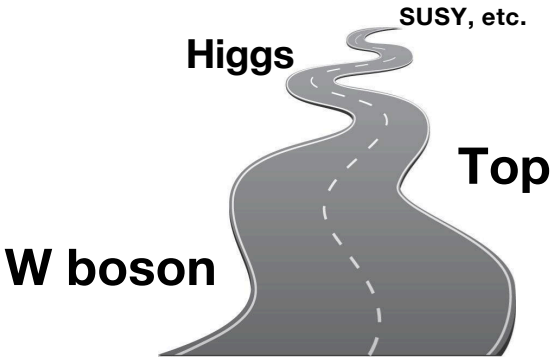
- **H is a fundamental (elementary) particle → we live in a universe where the fine-tuning at M arises (anthropic solution, multiverse, Landscape of string theory)**

or the SM cannot be considered an EFFECTIVE THEORY

- In physics **properties at an energy scale m << M do not strictly depend on the detailed knowledge (of the parameters) at M** where a "more fundamental" theory sets in (for instance, **to study atomic physics you don't need a detailed knowledge of the nuclear physics inside the nucleus of the atom**, or to explore nuclear physics you don't need a detailed knowledge of the QCD (Quantum Chromo-Dynamics) ruling the dynamics of the quarks, etc.) → at each energy scale we consider the effective theory holding at that scale removing all the degrees of freedom related to the physics at a much larger scale (or much smaller distance)
- On the contrary, **the dynamics of the SM**, in particular the scale at which the electroweak symmetry breaking occurs, **would strictly depend on the relations of parameters of a fundamental theory setting in at a scale 16 orders of magnitude larger than the elw. energy scale !**

Ideology

HEP before the LHC



HEP before the F.C.

Ideology

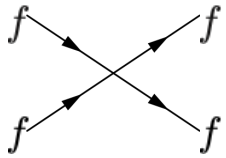
HEP before the LHC

HEP before the F.C.

SUSY, etc.

Higgs

W boson

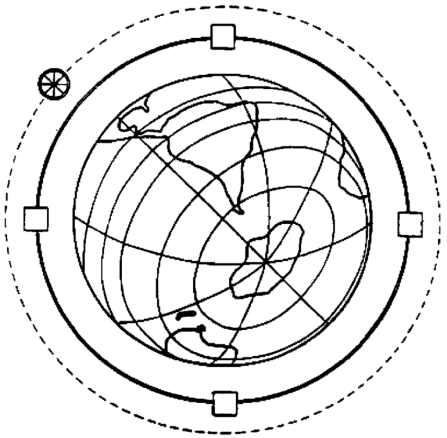


$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \rightarrow m_W < 4\pi v$$

Ultimate Accelerator.

Drawn by Fermi in the ’50 to reach 3 TeV.

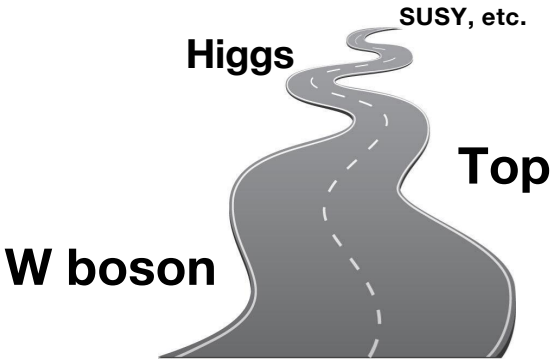
The manifesto of HEP!



A. Wulzer 2019 at the Town Meeting of EU Particle Strategy in Granada, 13-16 May 2019

High Energy Physics before and after the LHC

HEP before the LHC



HEP after the LHC

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories**

This is **good:**

next discovery will be **revolutionary**

This is **bad:**

F.C. potential cannot be evaluated on few uniquely identifiable benchmarks (e.g., Higgs for LHC). Selection made in what follows.

A. Wulzer 2019 at the Town Meeting of EU Particle Strategy in Granada

ROADS TO GO BEYOND THE STANDARD MODEL (I)

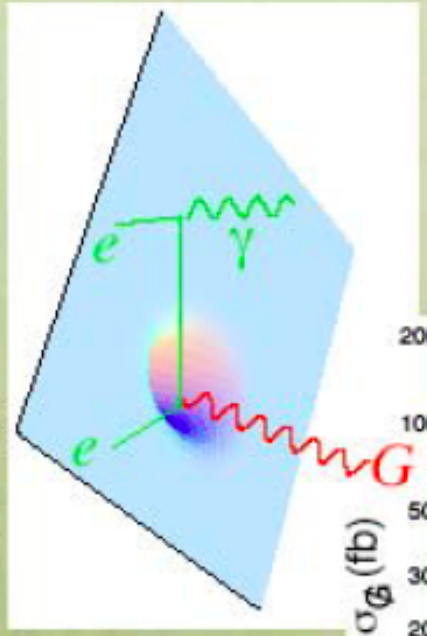
1) **THERE EXISTS NO NEW PHYSICAL ENERGY SCALE ABOVE THE ELW. SCALE**: gravity is an extremely weak force not because of the enormous value of the Planck scale, but because of the existence of **NEW DIMENSIONS** beyond the usual 3+1 space-time where (most of) the gravity flux lines get "dispersed"

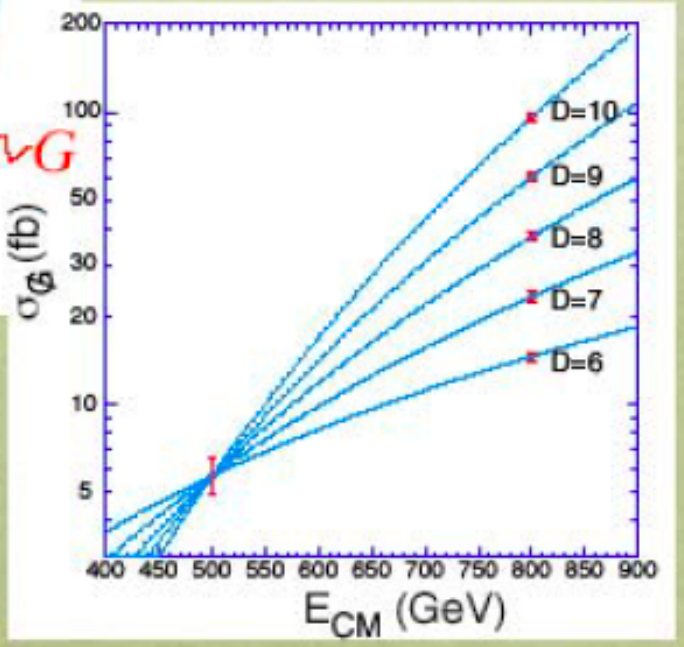
→ **VISIBILITY AT LHC**: there exist "excited" states of the ordinary particles (**Kaluza-Klein states**) and some of them are accessible at LHC (the lightest KK state may be a stable particle and it can constitute the DM)

Hidden Dimensions

- *Hidden dimensions*
- *Can emit graviton into the bulk*
- *Events with apparent energy imbalance*

How many extra dimensions are there?





ROADS TO GO BEYOND THE STANDARD MODEL (II)

- **2) NO NEED TO "PROTECT" THE HIGGS MASS AT THE ELW. SCALE: THE HIGGS IS A COMPOSITE OBJECT (for instance, a fermion condensate) WHOSE COMPOSITENESS SCALE IS THE ELW. SCALE (cfr. the pion mass case)**

  → **VISIBILITY AT LHC: THERE EXIST NEW (STRONG) INTERACTIONS AT THE ELW. SCALE WHICH PRODUCE THE HIGGS CONDENSATE** (new resonances,, new bound states, a new rescaled QCD at 1 TeV)

ROADS TO GO BEYOND THE STANDARD MODEL (III)

- **3) THE MASS OF THE ELEMENTARY HIGGS BOSON IS "PROTECTED" AT THE ELW. SCALE BECAUSE OF THE PRESENCE AT THAT ENERGY OF A NEW SYMMETRY, THE SUPERSYMMETRY (SUSY)**

  → **VISIBILITY AT LHC**: WE'LL SEE (SOME OF) THE **SUSY PARTICLES AND THEIR INTERACTIONS**. THE LIGHTEST SUSY PARTCILE (**LSP**) IS LIKELY TO BE STABLE AND PROVIDE THE **DM**. **AT THE SAME TIME, WE COULD DISCOVER SUSY AND THE SOURCE OF 90% OF THE ENTIRE MATTER PRESENT IN THE UNIVERSE.**

THE SUSY PATH

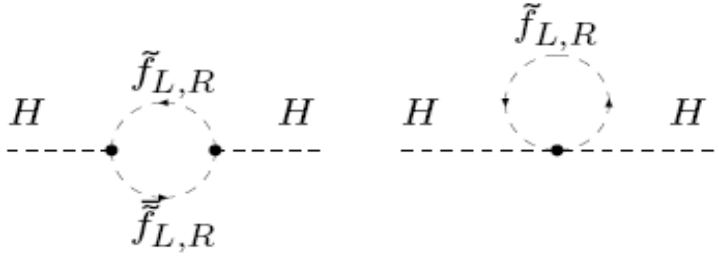
$$Q\,|\,boson>=|\,fermion> \qquad Q\,|\,fermion>=|\,boson>$$

$$[b,b]=0,\quad \{f,f\}=0 \;\Rightarrow$$

$$\{Q^i_\alpha, \overline{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu$$

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)

SUSY: additional contributions from scalar fields:



$$\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\,\lambda_{\tilde{f}}^2 \int d^4k \left(\frac{1}{k^2 - m^2_{\tilde{f}_L}} + \frac{1}{k^2 - m^2_{\tilde{f}_R}} \right) + \text{terms without quadratic div.}$$

for $\Lambda \to \infty$: $\quad \Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\,\lambda_{\tilde{f}}^2\,\Lambda^2$

$\Rightarrow$ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} = N_f$$

$$\lambda_{\tilde{f}}^2 = \lambda_f^2$$

complete correction vanishes if furthermore

$$m_{\tilde{f}} = m_f$$

Soft SUSY breaking: $m_{\tilde{f}}^2 = m_f^2 + \Delta^2, \quad \lambda_{\tilde{f}}^2 = \lambda_f^2$

$$\Rightarrow \Sigma_H^{f+\tilde{f}} \sim N_f \, \lambda_f^2 \, \Delta^2 + \ldots$$

$\Rightarrow$ correction stays acceptably small if mass splitting is of weak scale

$\Rightarrow$ realized if mass scale of SUSY partners

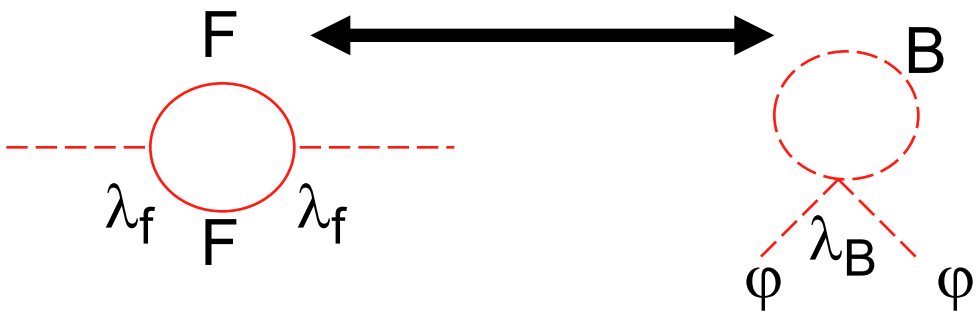
$$M_{\text{SUSY}} \lesssim 1\,\text{TeV}$$

$\Rightarrow$ SUSY at TeV scale provides attractive solution of hierarchy problem

HIERARCHY PROBLEM: THE SUSY WAY

SUSY HAS TO BE BROKEN AT A SCALE CLOSE TO 1TeV ⟶ LOW ENERGY SUSY

$m_\varphi^2 \propto \Lambda^2$ ⟶ Scale of susy breaking



$$Sm^2_{\varphi} \sim \frac{(\lambda_B - \lambda^2_f)\ \Lambda^2}{16\ \pi^2}$$

⟶ $[m^2_B - m^2_F]^{1/2} \sim 1/\sqrt{G_F}$

$\begin{pmatrix} B \\ F \end{pmatrix}$ In SUSY multiplet

SPLITTING IN MASS BETWEEN B and F of O (ELW. SCALE)

ON THE WAY TO SUPERSYMMETRIZE THE SM

SUSY Multiplets

Chiral multiplet $N=1,\ \lambda=0$

helicity	-1/2	0	1/2
# of states	1	2	1

scalar spinor

(φ, ψ)

Vector multiplet $N=1,\ \lambda=1/2$

helicity	-1	-1/2	1/2	1
# of states	1	1	1	1

(λ, A_μ)

spinor vector

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

(φ, ψ) (λ, A_μ) $(\tilde{g}, g)$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

D. KAZAKOV

Particle Content of the MSSM

Superfield	Bosons	Fermions	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
G^a	gluon g^a	gluino $\tilde{g}^a$	8	1	0
V^k	Weak $W^k(W^\pm, Z)$	wino, zino $\tilde{w}^k(\tilde{w}^\pm, \tilde{z})$	1	3	0
V'	Hypercharge $B(\gamma)$	bino $\tilde{b}(\tilde{\gamma})$	1	1	0
Matter					
L_i	sleptons $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons $L_i = (\nu, e)_L$	1	2	−1
E_i	sleptons $\tilde{E}_i = \tilde{e}_R$	leptons $E_i = e_R$	1	1	2
Q_i	squarks $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks $Q_i = (u, d)_L$	3	2	1/3
U_i	squarks $\tilde{U}_i = \tilde{u}_R$	quarks $U_i = u_R^c$	3^*	1	−4/3
D_i	squarks $\tilde{D}_i = \tilde{d}_R$	quarks $D_i = d_R^c$	3^*	1	2/3
Higgs					
H_1	Higgses H_1	higgsinos $\tilde{H}_1$	1	2	−1
H_2	Higgses H_2	higgsinos $\tilde{H}_2$	1	2	1

$$\mathcal{L}_{SM} = \underbrace{m_d \bar{Q}_L H d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \tilde{H} u_R}_{\text{u-quark mass}}$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \tilde{H} = i\sigma_2 H^\dagger, \quad H \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \tilde{H} \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term $\bar{Q}_L H^\dagger$ not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on φ_i, not on φ_i^*

IN SUSY WE NEED TO INTRODUCE AT LEAST TWO HIGGS DOUBLETS IN ORDER TO PROVIDE A MASS FOR BOTH THE UP- AND DOWN- QUARKS

SPONTANEOUS BREAKING OF SUSY

- FIRST ATTEMPT: **SPONTANEOUS BREAKING OF SUSY** (letting history teach: since spontaneous breaking of the electroweak symmetry was so successful, try to repeat it in the SUSY case) ⟶
  PROBLEM: **NO phenomenologically viable model** results from spontaneously broken SUSY (ex: one of the two selectrons remains lighter than the electron…)

2nd ATTEMPT TO BREAK SUSY: THE EXPLICIT BREAKING

- WISH: add to the SUSY version of the SM Lagrangian some terms which are **NOT** SUSY invariant, i.e. add an explicit breaking of SUSY, but try to PRESERVE the nice properties of having SUSY in the game (for instance, still quadratic divergences should be absent even when SUSY is explicitly broken) ⟶ special class of explicitly breaking terms called **SOFT BREAKING TERMS OF SUSY**

THE BASKET WHERE TO PICK UP THE WANTED (OR NEEDED) SUSY SOFT BREAKING TERMS

Classification of possible soft breaking terms:

[*L. Girardello, M. Grisaru '82*]

- scalar mass terms: $m^2_{\phi_i} |\phi_i|^2$
- trilinear scalar interactions: $A_{ijk}\phi_i\phi_j\phi_k + \text{h.c.}$
- gaugino mass terms: $\frac{1}{2}m\bar{\lambda}\lambda$
- bilinear terms: $B_{ij}\phi_i\phi_j + \text{h.c.}$
- linear terms: $C_i\phi_i$

$\Rightarrow$ relations between dimensionless couplings unchanged

no additional mass terms for chiral fermions

THE FATE OF B AND L IN THE SM AND MSSM

- **IN THE SM B AND L ARE "AUTOMATIC" SYMMETRIES**: NO B or L VIOLATING OPERATOR OF DIM.≤4 INVARIANT UNDER THE GAUGE SIMMETRY SU(3) X SU(2) X U(1) IS ALLOWED (B AND L ARE CONSERVED AT ANY ORDER IN PERTURBATION THEORY, BUT ARE VIOLATED AT THE QUANTUM LEVEL (ONLY B – L IS EXACTLY PRESERVED)
- **IN THE MSSM**, THANKS TO THE EXTENDED PARTICLE SPECTRUM WITH NEW SUSY PARTNERS CARRYING B AND L, **IT IS POSSIBLE TO WRITE (RENORMALIZABLE) OPERATORS WHICH VIOLATE EITHER B OR L**
- ⟶ IF BOTH B AND L VIOLATING OPERATORS ARE PRESENT, GIVEN THAT SUSY PARTNER MASSES ARE OF O(TEV), THERE IS NO WAY TO PREVENT A **TOO FAST PROTON DECAY** UNLESS THE YUKAWA COUPLINGS ARE INCREDIBLY SMALL!

ADDITIONAL DISCRETE SYMMETRY IN THE MSSM TO SLOW DOWN P - DECAY

- SIMPLEST (and nicest) SOLUTION: ADD A SYMMETRY WHICH **FORBIDS ALL B AND L VIOLATING OPERATORS**

  → **R PARITY**

- SINCE B AND L 4-DIM. OPERATORS INVOLVE 2 ORDINARY FERMIONS AND A SUSY SCALAR PARTICLE, THE SIMPLEST WAY TO ELIMINATE ALL OF THEM:

R = +1 FOR ORDINARY PARTICLES

R = - 1 FOR SUSY PARTNERS

IMPLICATIONS OF IMPOSING R PARITY:

i) The superpartners are created or destroyed in pairs;

ii) **THE LIGHTEST SUPERPARTNER IS ABSOLUTELY STABLE**

BROKEN R PARITY

- PROTON DECAY REQUIRES THE VIOLATION OF BOTH B AND L

  ⟶ NOT NECESSARY TO HAVE R PARITY TO KILL B AND L VIOLATING OPERATORS

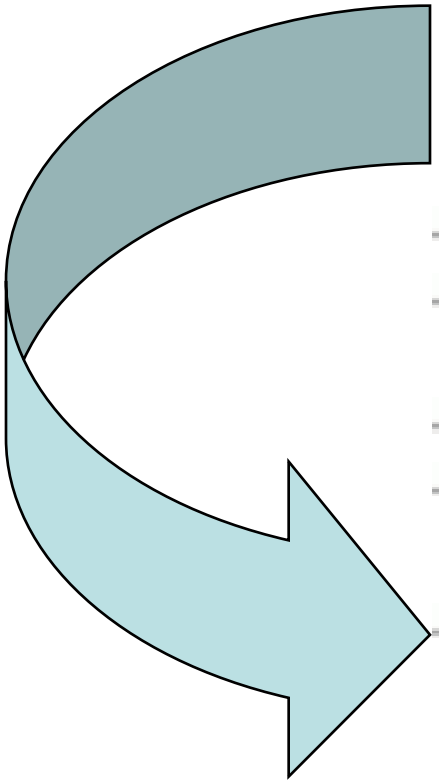
  ⟶ ENOUGH TO IMPOSE AN **ADDITIONAL DISCRETE SYMMETRY TO FORBID EITHER B OR L VIOLATING OPERATORS**; RESTRICTIONS ON THE YUKAWA COUPLINGS OF THE SURVIVING B OR L VIOLATING OPERATORS

FROM THE MSSM TO THE CMSSM (constrained MSSM)

PROLIFERATION OF PARAMETRS IN THE SOFT BREAKING SECTOR OF THE MSSM:

OVERALL NUMBER OF PARAM. IN THE MSSM IS

1 2 4



CMSSM

At $M_{GUT} \simeq 2 \times 10^{16}$ GeV:

- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- scalars $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m^2_0$
- 3–linear soft terms $A_b = A_t = A_0$
- radiative EWSB $\mu^2 = \frac{m^2_{H_b} - m^2_{H_t} \tan^2\beta}{\tan^2\beta - 1} - \frac{m_Z^2}{2}$
- five independent parameters:

$$m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)$$

$$m_{\tilde{\tau}_1} \simeq \sqrt{0.15 m^2_{1/2} + m^2_0}$$

bino: $m_\chi \simeq 0.4 m_{1/2}$

gluino $\tilde{g}$: $m_{\tilde{g}} \simeq 2.7 m_{1/2}$

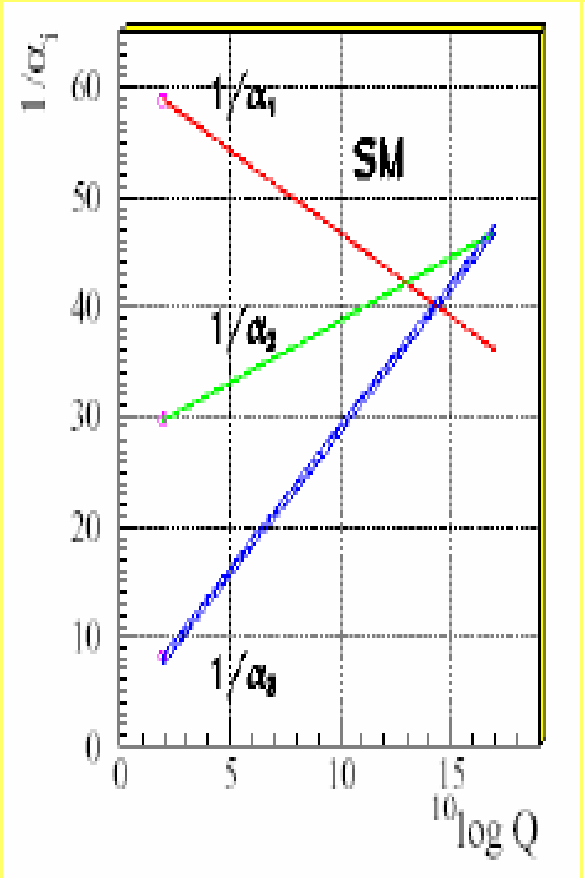
CMSSM + RADIATIVE ELW. BREAKING: A 4 – PARAMETER WORLD

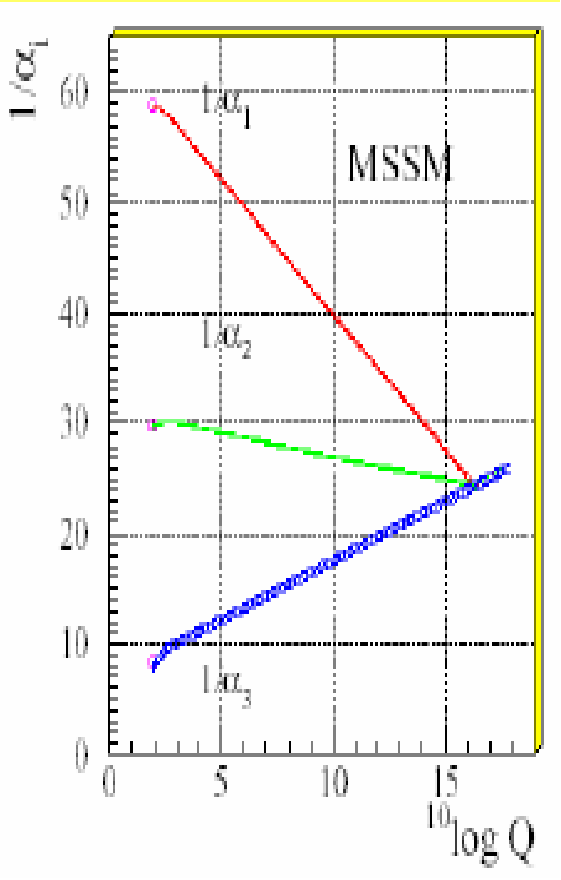
- FREE PARAM. IN THE CMSSM :

$$A,\ m_0,\ M_{1/2},\ B \leftrightarrow \tan\beta = v_2 / v_1 \quad \text{and} \quad \mu$$

IMPOSING THE RAD. BREAKING OF THE ELW. SYMMETRY ONE ESTABLISHES A RELATION BETWEEN THE ELW. BREAKING SCALE AND THE SOFT SUSY PARAMETERS **FURTHER REDUCING THE NUMBER OF THE FREE PARAM. IN THE CMSSM TO FOUR** , FOR INSTANCE THE FIRST FOUR PARAM. ABOVE + THE SIGN OF μ (THE ELW. SYMM. BREAKING FIXES ONLY THE SQUARE OF μ

LOW-ENERGY SUSY AND UNIFICATION





Input

$\alpha^{-1}(M_Z) = 128.978 \pm 0.027$

$\sin^2\theta_{\overline{MS}} = 0.23146 \pm 0.00017$

$\alpha_s(M_Z) = 0.1184 \pm 0.0031$

Output

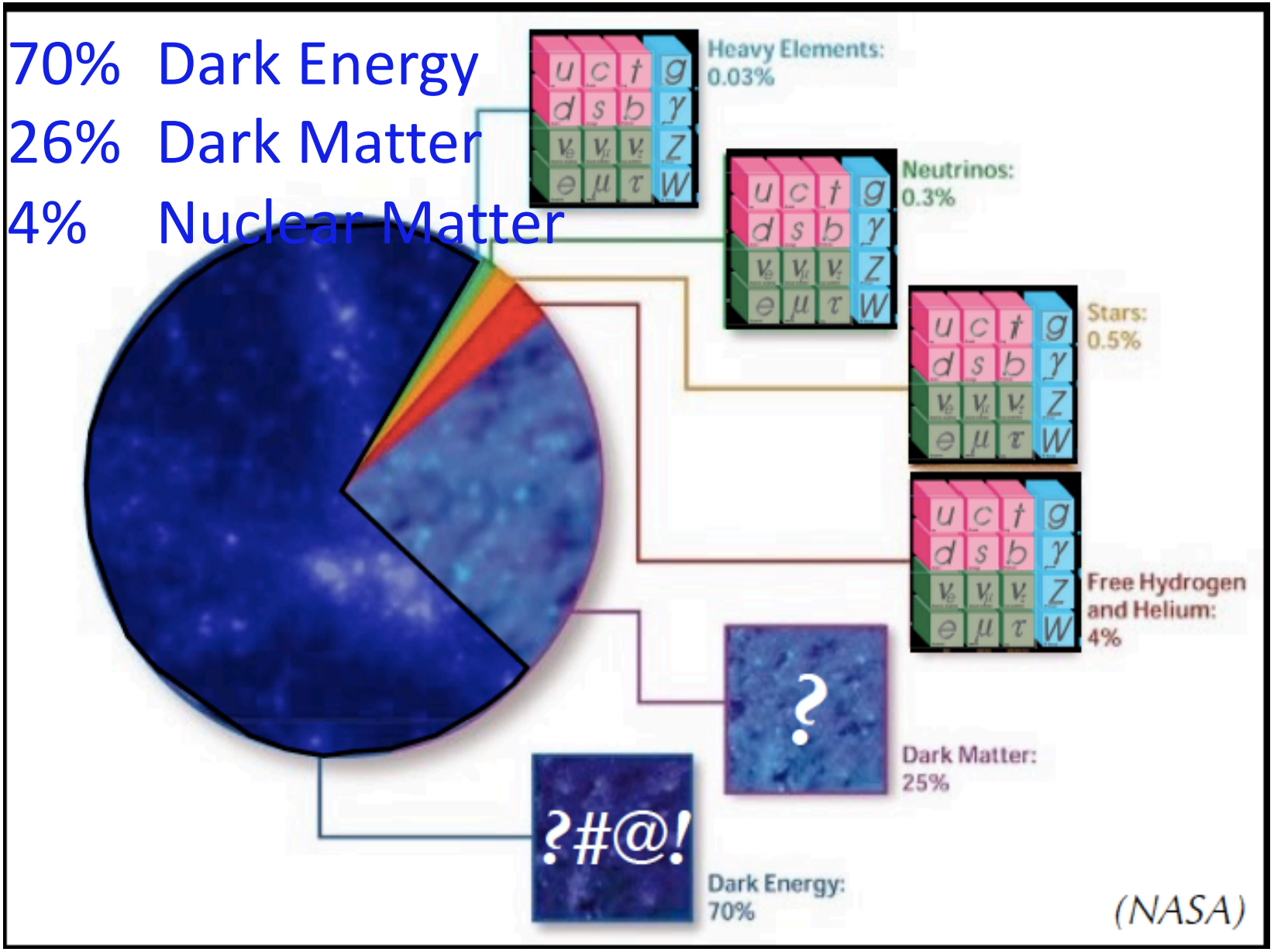
$M_{SUSY} = 10^{3.4 \pm 0.9 \pm 0.4}$ GeV

$M_{GUT} = 10^{15.8 \pm 0.3 \pm 0.1}$ GeV

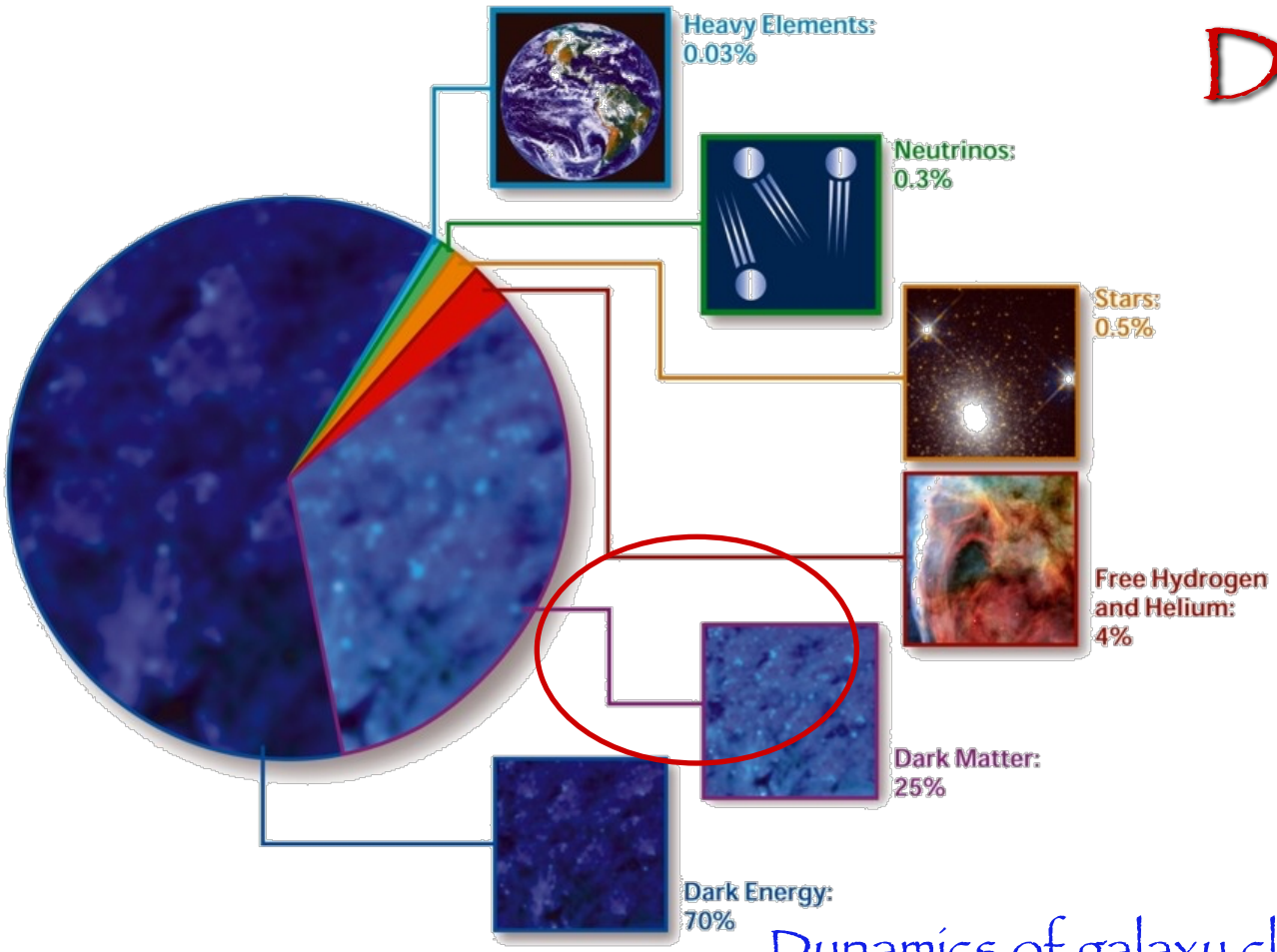
$\alpha_{GUT}^{-1} = 26.3 \pm 1.9 \pm 1.0$

Lecture III

- The DARK SIDE OF THE UNIVERSE: DARK MATTER AND DARK ENERGY
- HOW COME THAT WE EXIST: THE MYSTERY OF THE COSMIC MATTER – ANTIMATTER ASYMMETRY
- UNIverse or MULTIverse


70% Dark Energy
26% Dark Matter
4% Nuclear Matter
Heavy Elements:
0.03%
Neutrinos:
0.3%
Stars:
0.5%
Free Hydrogen
and Helium:
4%
?
Dark Matter:
25%
?#@!
Dark Energy:
70%
(NASA)

Dark Matter

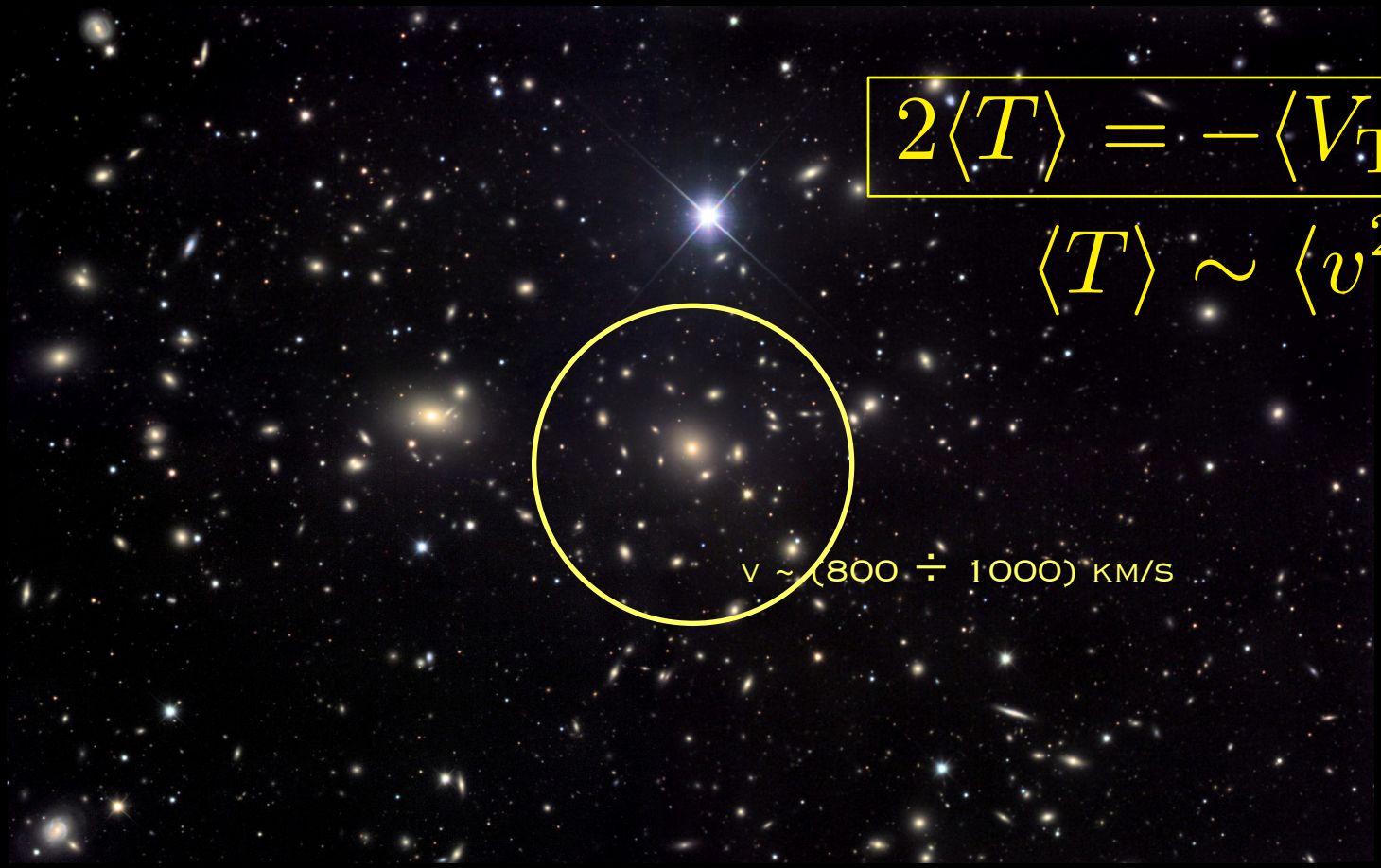


- Dynamics of galaxy clusters
- Rotational curves of galaxies
- Gravitational lensing
- Structure formation from primordial density fluctuations
- Energy density budget

N. Fornengo, Grav. Waves and Cosmology, Varenna, 2017

Galaxy cluster

Zwicky (1933)



$$2\langle T\rangle = -\langle V_{\rm TOT}\rangle$$

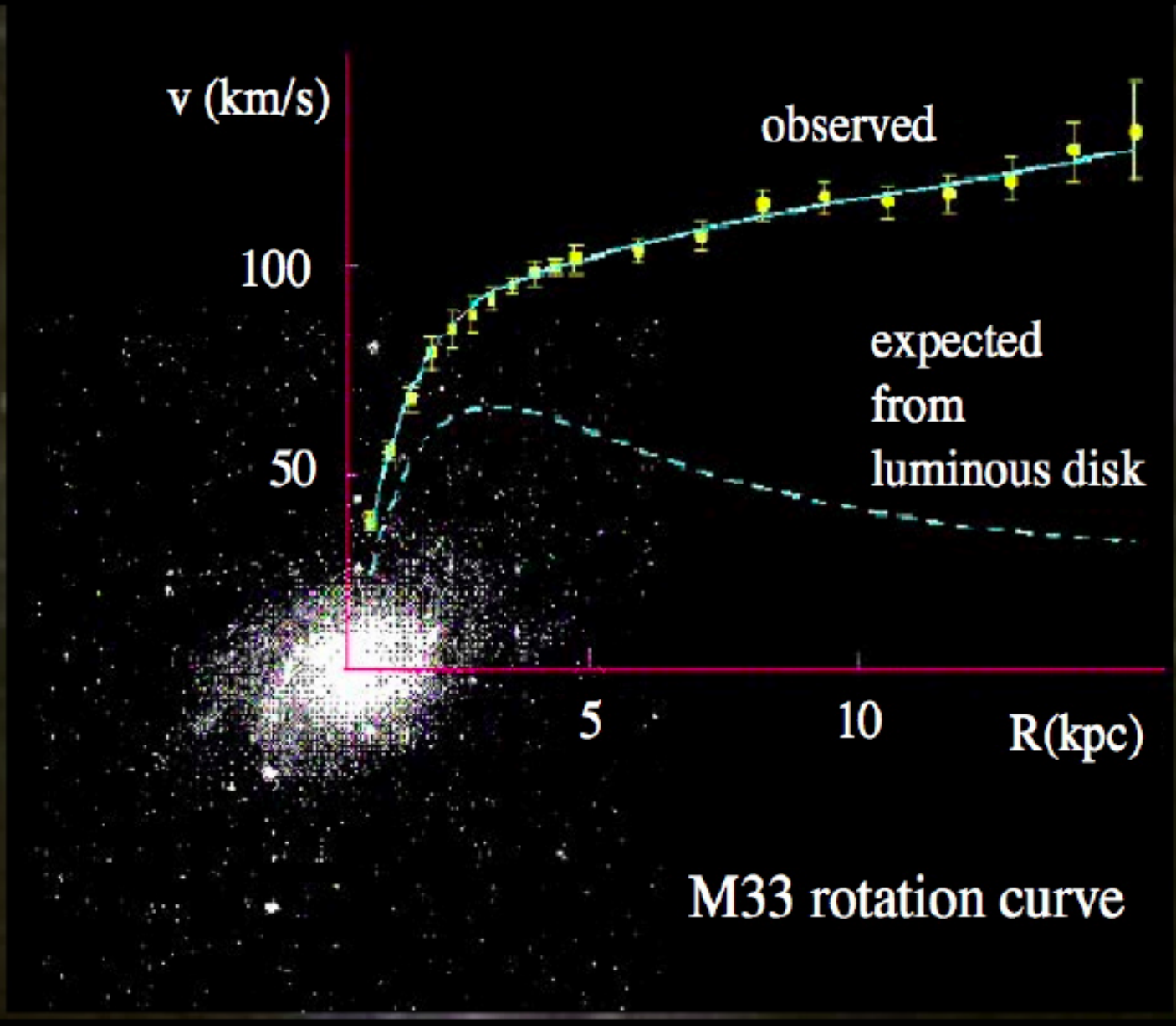
$$\langle T\rangle \sim \langle v^2\rangle$$

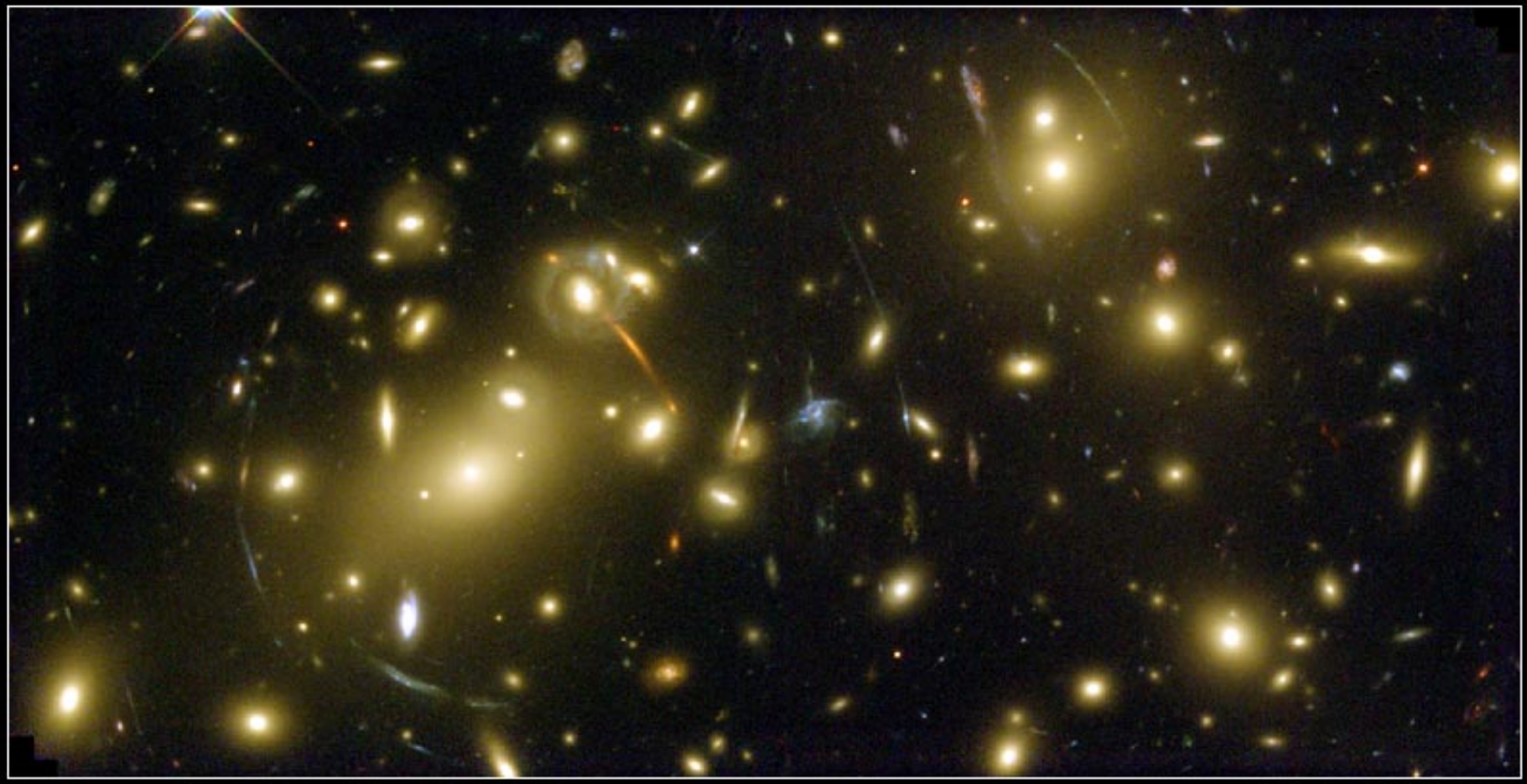
Velocity dispersion of galaxies in the cluster is too large: the cluster should "evaporate"

Much more mass than the visible one is needed

N. Fornengo, Grav. Waves and Cosmology, Varenna, 2017

Di cosa è fatto l'Universo?



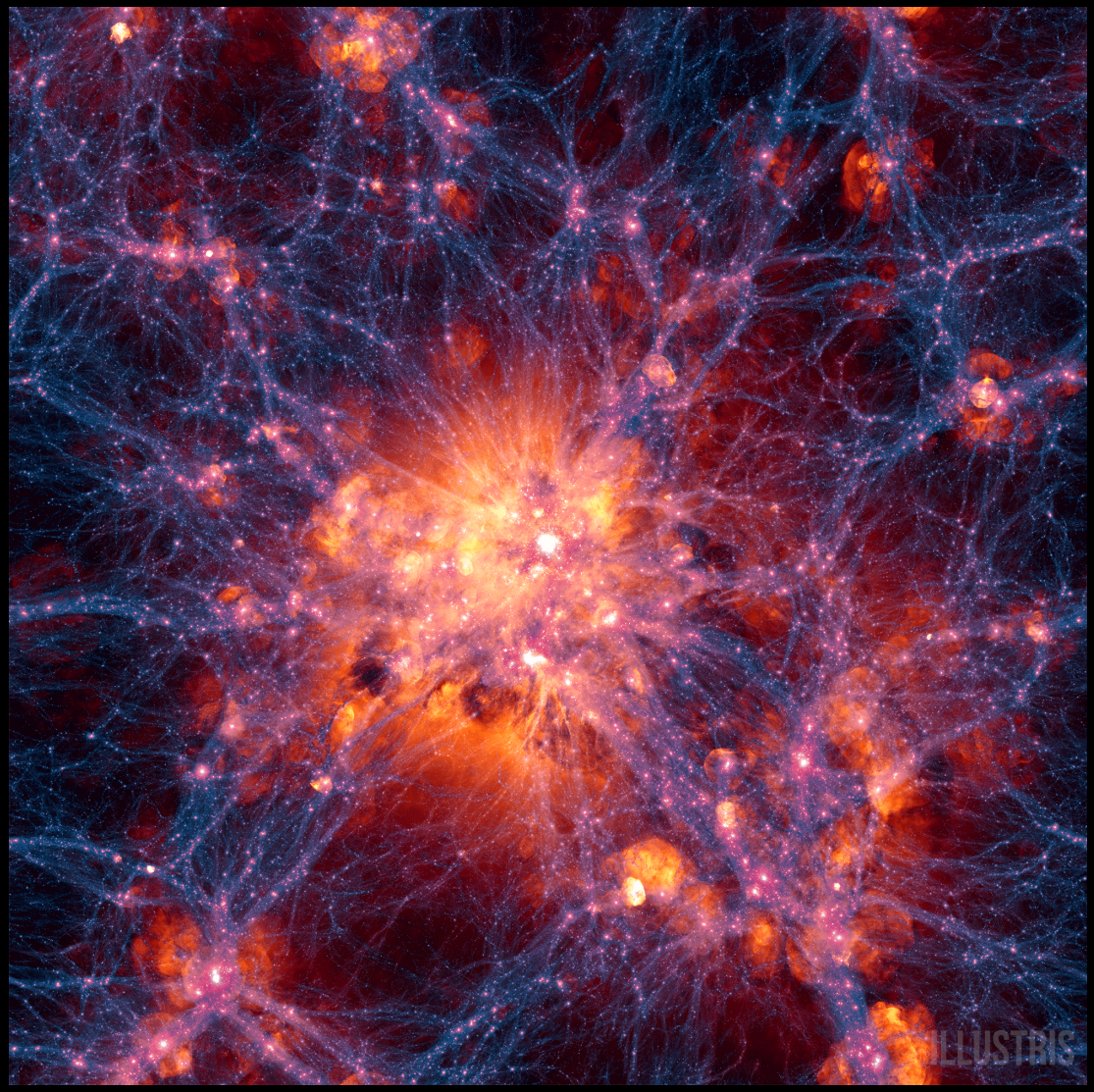


Gravitational lensing

A large amount of mass between the background galaxies and us can be inferred by the lensing effect

N. Fornengo, Grav. Waves and Cosmology, Varenna, 2017

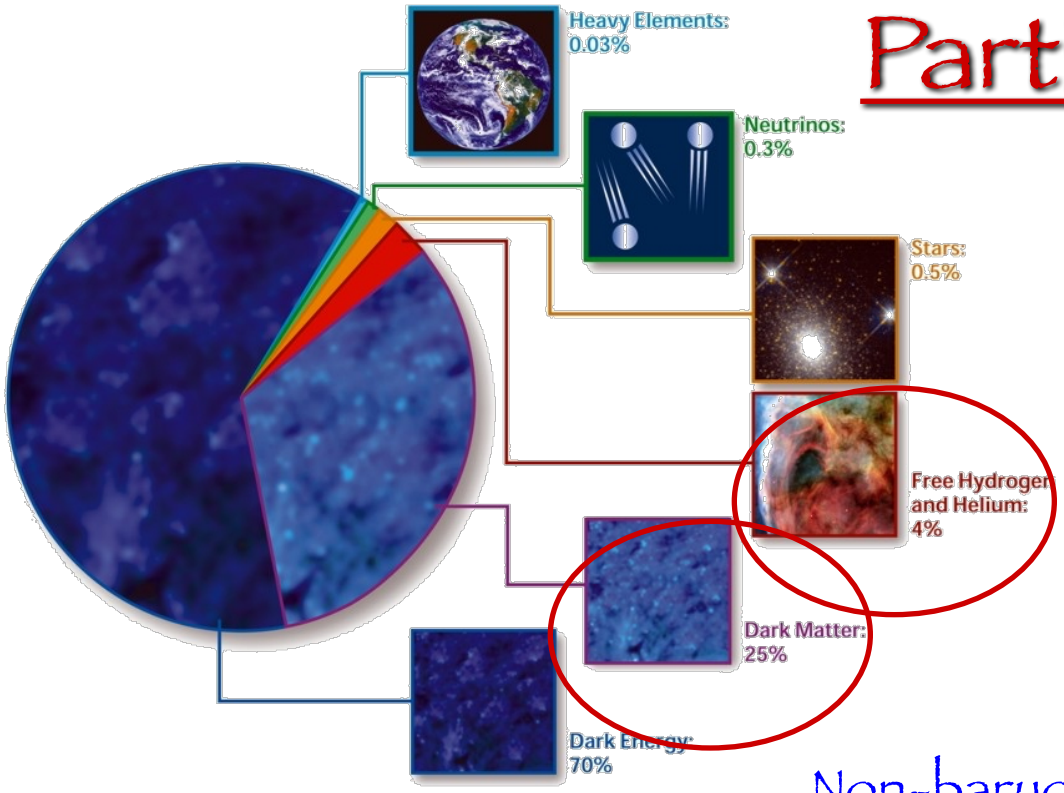
Structures in LCDM



Illustris simulation

Simulated Universe

Particle Dark Matter



Non-baryonic (cold) dark matter is needed
No candidate in the Standard Model(*)
New fundamental Physics

Dynamics of galaxy clusters
Rotational curves of galaxies
Gravitational lensing
Structure formation from primordial density fluctuations
Energy density budget

(*) Standard neutrino:
Too light: act as HDM (not CDM)

N. Fornengo, Grav. Waves and Cosmology, Varenna, 2017

DARK MATTER

the Baryon budget:

Ω_B from high-redshift Universe

- nucleosynthesis ($z \sim 10^9$): $\Omega_B^{BBN} = 0.04 \pm 0.02$
- CMB ($z \sim 10^3$): $\Omega_B^{CMB} \sim \Omega_B^{BBN} \rightarrow 5\%$
- Lyman alpha forest of the IGM ($z \sim 3$) $\rightarrow$ again 5%

Ω_B from $z \sim 0$ Universe (today) $\rightarrow$ from galaxy clusters

baryons ~ 15% : in massive clusters fraction

$\rightarrow \Omega_B \sim 0.05$ for $\Omega_M \sim 0.26$

Summary:

$\Omega_B^{luminous} \rightarrow \rho_{lum} = 9 \times 10^{-29}\ kg\ m^{-3}$

$\Omega_{lum} \sim 1\%$

$\Omega_B^{TOT} \rightarrow \rho_b = 4.0 \times 10^{-28}\ kg\ m^{-3}$ $(0.26\ baryons/m^3)$

$\Omega_B \sim 5\%$

How much MATTER in the Universe?

from gravitational potential energy deduced from galactic rotation curves or mass distribution in a cluster (obtained by the method of gravitational lensing)

→ $\rho_M \sim 2 \times 10^{-27}$ Kg m^{-3}

$\Omega_M \sim 1/4$

⟹ latest results:

$\Omega_{DM} \sim 26.4\%$ (84.4% of Ω_{matter})

($\Omega_M \sim 0.3$ $\Omega_\Lambda \sim 0.7$)

$\Omega_B h^2 = 0.022$ → $\Omega_B \sim 4-5\%$

$\Omega_\nu = \frac{\rho_\nu^0}{\rho_{crit}} = \frac{\sum m_\nu}{h^2 \cdot 93.14\ eV}$ $n_\nu^0 = 339.5$ cm^{-3}

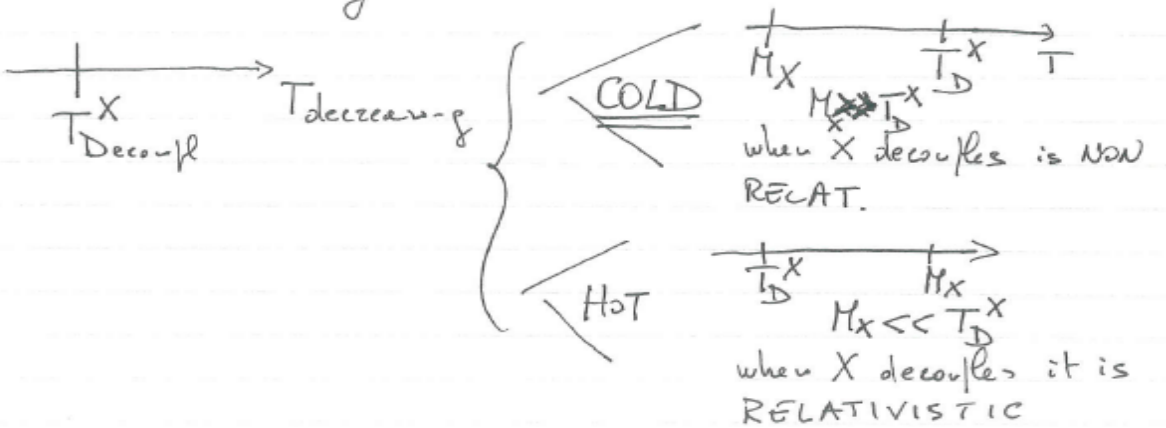
$h^2 \sim \frac{1}{2}$ → $\Omega_\nu \simeq \frac{\sum m_\nu}{50\ eV}$ → even if all 3 ν mass degenerate $\sim 1-2$ eV

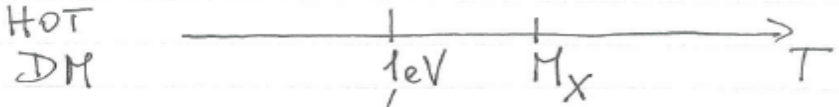
$\sum m_\nu < 3-6$ eV

→ $\Omega_\nu < 10^{-1}$ too small for $\Omega_{DM} \sim 1/4$

COLD, HOT and WARM DM

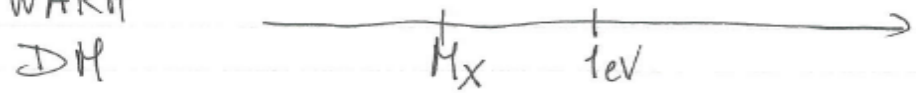
DM: X assume X in kinetic equilibrium with ordinary matter





X relativistic at matter-radiation equality

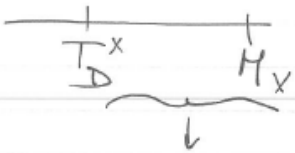
ex. $\Rightarrow$ ($M_X < 1eV$



density perturbations (seeds of structures formation) grow differently at radiation dominance or matter dominance

$\rightarrow$ their growth strongly depends on whether DM — hot or warm

relativistic particles X



X free streaming

underdense region

X hot DM ⇒ fill in underdense regions

→ DM density perturbations washed out

free streaming terminates at $T \sim M_X$

particle X gets non-relat.

WARM case : $M_X > 1\,eV$ X non-relativ. at radiation dominance

but HOT DM $M^X_{\text{HOT DM}} < 1\,eV$ X non-relativ. at matter dominance

density perturbations cannot grow as long as X non-relativ.

→ largest structures (superclusters of galaxies) form first and then they fragment into smaller structures, clusters of galaxies, galaxies etc.

This dynamics of the growth of density perturbations is in strong disagreement with our Universe structure

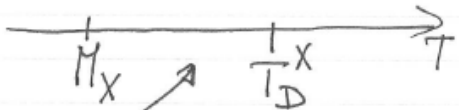
from large structures $\Longrightarrow$ strong bounds on the hot component of DM $\Rightarrow$ most of the DM must be COLD

HOT DM can be only a small component of the whole DM $\rightarrow$ ν cannot be the dominant source of DM !

THERMAL X (in thermal equil.)

case of STABLE HEAVY PARTICLE X

COMPUTATION OF $\Omega_X h^2$ under the assumption



at $T < M_X$ $\quad n_X^{eq} = g_X \left(\frac{M_X T}{2\pi}\right)^{3/2} e^{-M_X/T}$

number of X (in a comoving volume) changes only because of pair annihilations $\rightarrow$ light part.

or viceversa $\leftarrow$ pair creations

$X\bar{X} \rightarrow$ light part. $\qquad$ light part $\rightarrow X\bar{X}$

What's dark matter?

"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

DM: the most impressive evidence at the "quantitative" and "qualitative" levels of New Physics beyond SM

- QUANTITATIVE: Taking into account the latest WMAP data which in combination with LSS data provide stringent bounds on Ω_{DM} and Ω_B → **EVIDENCE FOR NON-BARYONIC DM AT MORE THAN 10 STANDARD DEVIATIONS!! THE SM DOES NOT PROVIDE ANY CANDIDATE FOR SUCH NON-BARYONIC DM**

- QUALITATIVE: it is NOT enough to provide a mass to neutrinos to obtain a valid DM candidate; LSS formation requires DM to be COLD → **NEW PARTICLES NOT INCLUDED IN THE SPECTRUM OF THE FUNDAMENTAL BUILDING BLOCKS OF THE SM !**

TEN COMMANDMENTS TO BE A "GOOD" DM CANDIDATE

BERTONE, A.M., TAOSO

- TO MATCH THE APPROPRIATE RELIC DENSITY
- TO BE COLD
- TO BE NEUTRAL
- TO BE CONSISTENT WITH BBN
- TO LEAVE STELLAR EVOLUTION UNCHANGED
- TO BE COMPATIBLE WITH CONSTRAINTS ON SELF – INTERACTIONS
- TO BE CONSISTENT WITH DIRECT DM SEARCHES
- TO BE COMPATIBLE WITH GAMMA – RAY CONSTRAINTS
- TO BE COMPATIBLE WITH OTHER ASTROPHYSICAL BOUNDS
- "TO BE PROBED EXPERIMENTALLY"

DM: the most impressive evidence at the "quantitative" and "qualitative" levels of New Physics beyond SM

- QUANTITATIVE: Taking into account the latest WMAP data which in combination with LSS data provide stringent bounds on Ω_{DM} and Ω_B → **EVIDENCE FOR NON-BARYONIC DM AT MORE THAN 10 STANDARD DEVIATIONS!! THE SM DOES NOT PROVIDE ANY CANDIDATE FOR SUCH NON-BARYONIC DM**

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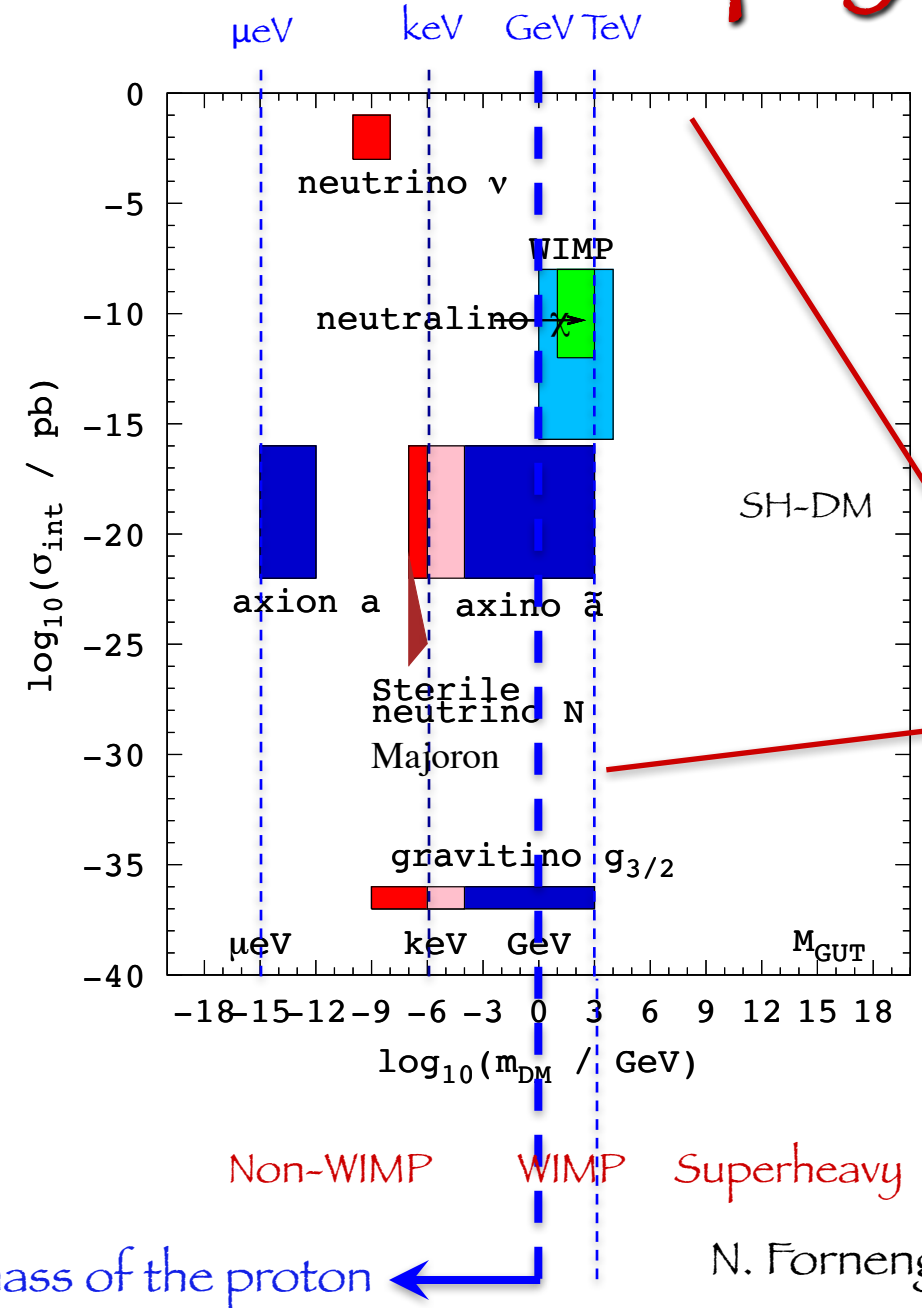
DM and ELW. SYMMETRY BREAKING

THE DM ROAD TO NEW PHYSICS BEYOND THE SM:

IS **DM** A PARTICLE OF THE ***NEW PHYSICS AT THE ELECTROWEAK ENERGY SCALE*** ?

Particle physics scales



N. Fornengo, Varenna School, 2017

"Strong (-ish)"

Self-interacting
Technicolor DM
…

"EM (-ish)"

Millicharged DM
Electric/magnetic dipole
…

Weak

WIMP

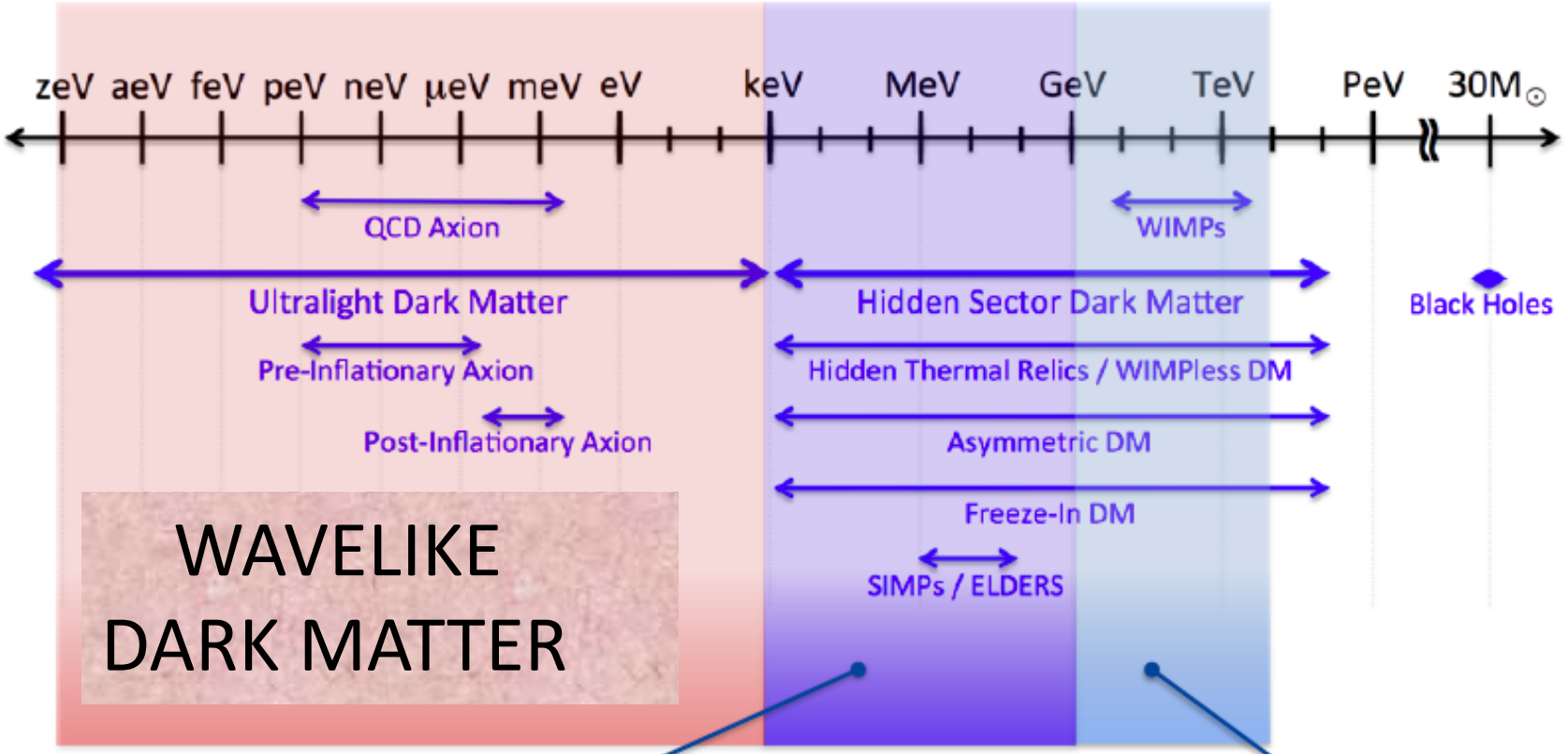
Gravitational

Relic from the early Universe
- Thermal
- Non thermal

Dynamically: non relativistic (cold)
collisionless

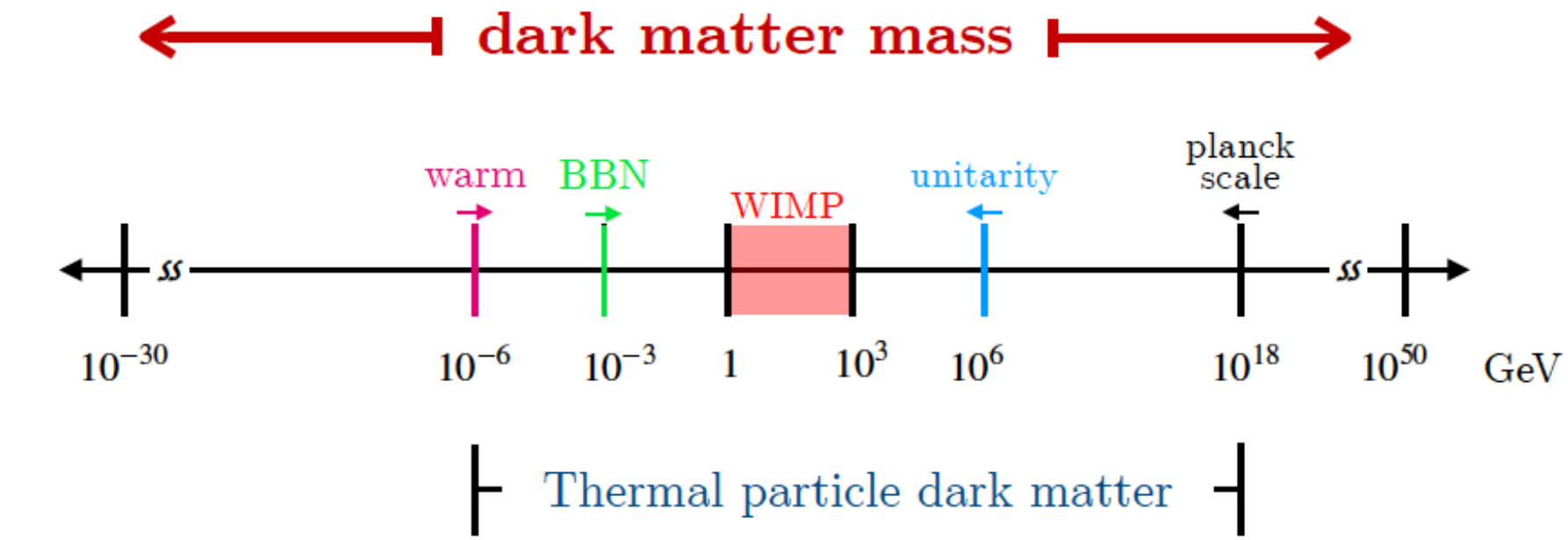
Dark Matter Candidates

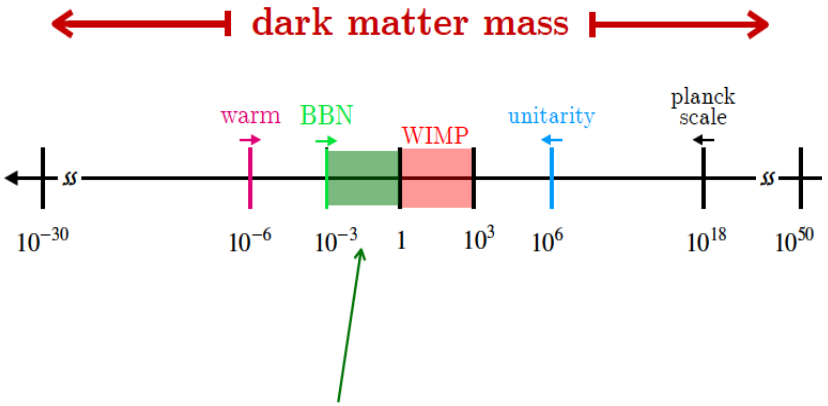
There is a wide range of possible dark matter candidates and an equally broad range of masses that dark matter may have

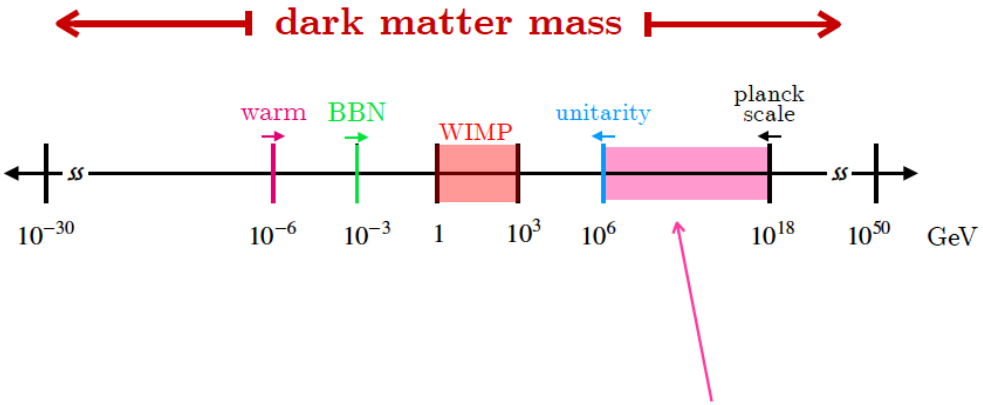


"Low Mass Dark Matter" - New ideas in direct detection and accelerator-based experiments will push into this range

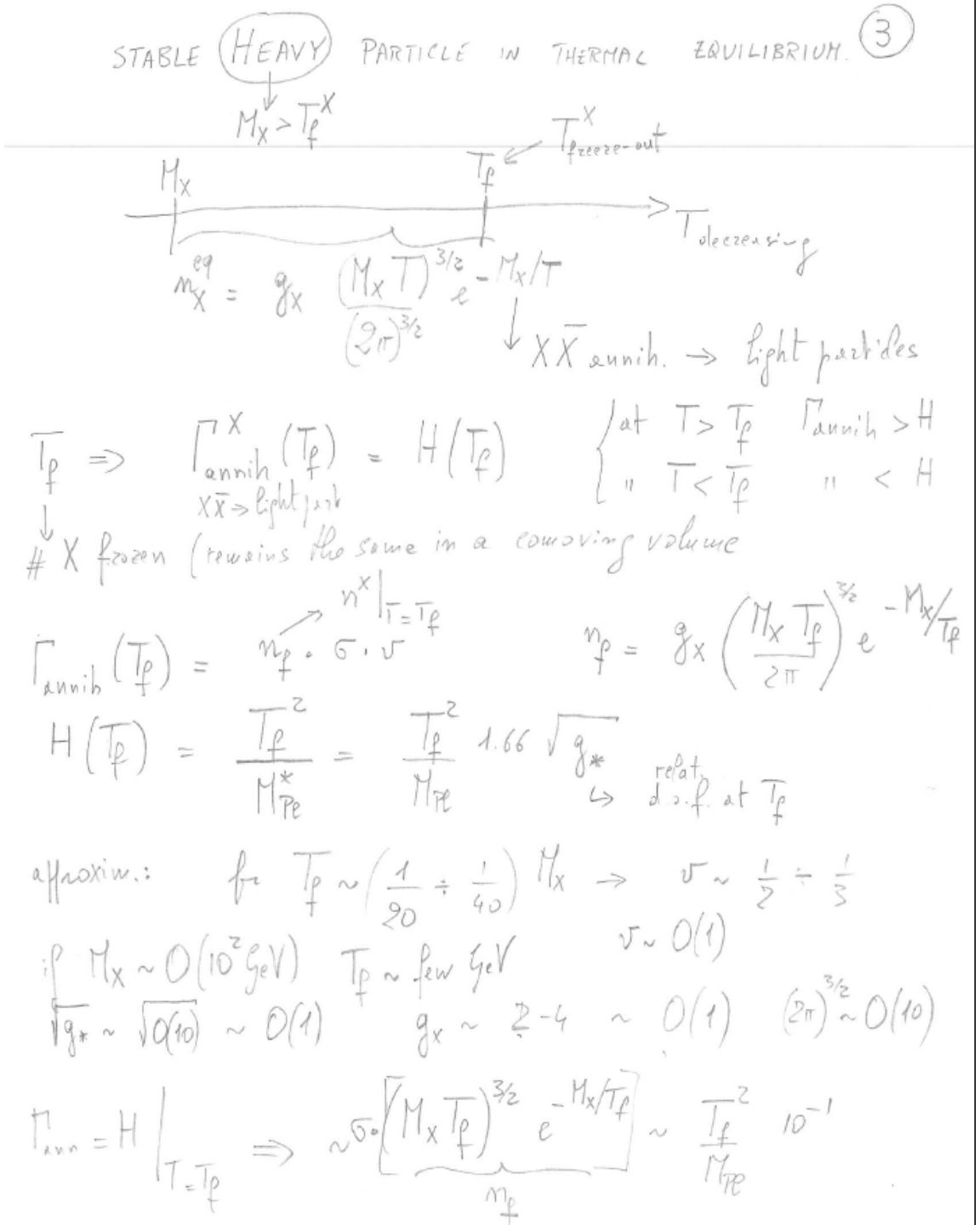
"High Mass Dark Matter" Traditional focus of direct detection experiments looking for nuclear recoils







L. Hsu, ICHEP 2020

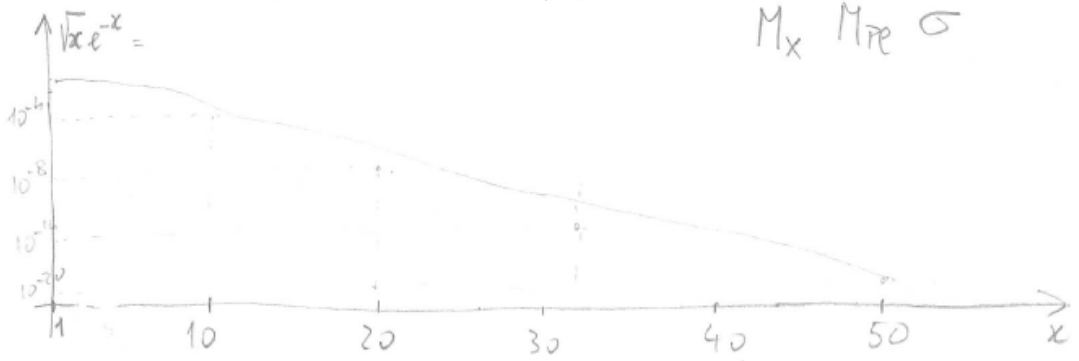


The following 6 slides contain a brief review of the computation of the **number density today of relic massive, stable particles (DM candidates**) which were **in THERMAL equilibrium** in the primordial plasma of elementary particles (the computation leads to their number density at the moment the number of such relic particles could not change any more - **FREEZE-OUT TEMPERATURE**)

$x \equiv \frac{M_X}{T_f} \rightarrow x \gg 1$ ↑ COLD REGIME $\quad M_X \gg T_f$

$n_f \cdot \sigma \simeq H \Big|_{T=T_f} \Rightarrow \frac{M_X^3 e^{-x}}{x^{3/2}} = \frac{M_X^2}{x^2 \cdot M_{Pl} \cdot \sigma}$

$M_X \sqrt{x}\, e^{-x} \simeq \frac{1}{M_{Pl} \cdot \sigma} \Rightarrow \sqrt{x}\, e^{-x} \simeq \frac{1}{M_X\, M_{Pl}\, \sigma}$



$x \sim 10 \Rightarrow \sqrt{x}\, e^{-x} \sim 10^{-4}$

$x \sim 20 \Rightarrow \;\; " \;\; \sim 10^{-8}$

$x \sim 35 \Rightarrow \;\; " \;\; \sim 10^{-14} - 10^{-15}$

$x \sim 50 \Rightarrow \;\; " \;\; \sim 10^{-21}$

$\sigma|_{\text{evaluated at } E \sim T_f}$

Ex: $M_X = 10^2\,\text{GeV} \quad \sigma \sim G_f^2 T_f^2 \sim (10^{-5}\,\text{GeV}^{-2})^2 \cdot (10^2\,\text{GeV})^2 \sim 10^{-8}\,\text{GeV}^{-2}$

$\sqrt{x}\, e^{-x} = \frac{1}{10^2\,\text{GeV}\; 10^{19}\,\text{GeV}\; 10^{-8}\,\text{GeV}^{-2}} \sim 10^{-13} \rightarrow x \sim 30$

$T_f \sim \frac{1}{35} \cdot 10^2\,\text{GeV} \sim 3\,\text{GeV}$

M_X

$$\Omega_X = \frac{\rho_X^{(today)}}{\rho_c} = \frac{m_X\, n_X^{today}}{\rho_c}$$

$n_X|_{T_f} \leftrightarrow n_X|_{T_0}$?

$T_0 = 2.7\ ^\circ K \simeq 10^{-4}\ eV$

$n_f \leftrightarrow n_0$

$$\frac{n_f}{n_0} \simeq \frac{T_f^3}{T_0^3} \qquad (a\,T \sim const \text{ in an iso-entropic universe})$$

$$\Omega_X = \frac{m_X}{\rho_c}\frac{n_0}{T_0^3}T_0^3 \simeq \frac{m_X}{\rho_c}\frac{n_f}{T_f^3}T_0^3 = \frac{T_0^3}{\rho_c}\frac{n_f}{T_f^2}\left(\frac{m_X}{T_f}\right)^x$$

$$\simeq \frac{T_0^3}{\rho_c}\frac{x}{\sigma}\frac{1}{M_{PL}\,n_f} \simeq \left(\frac{T_0^3}{\rho_c M_{PL}}\right)\frac{x}{\sigma} \qquad \sigma n_f \sim \frac{T_f^2}{M_{PL}} \quad T_f^2 \sim \sigma n_f M_{PL}$$

$$x_f \equiv \frac{m_X}{T_f} \qquad \Omega_X \sim \left(\frac{T_0^3}{\rho_c M_{PL}}\right) \times \frac{x_f}{\sigma}$$

$$\rightarrow \frac{10^{-12}\,eV^3}{5\times10^{-6}\,\frac{GeV}{cm^3}\;10^{19}\,GeV}$$

$$\frac{x}{\sigma} \sim \left(\frac{x_f}{20}\right)\cdot\left(\frac{10^{-6}\,GeV^{-2}}{\sigma}\right)\cdot 35\cdot 10^6\,GeV^2$$

$$\frac{\Omega_X}{0.25} \simeq \left(\frac{1}{0.25}\cdot 30\ 10^8\,GeV^2\right)\left(\frac{x_f}{30}\right)\left(\frac{10^{-8}\,GeV^{-2}}{\sigma}\right)\frac{10^{-12}\,eV^3}{5\times10^{-6}\,\frac{GeV}{cm^3}\;10^{19}\,GeV}$$

$$\simeq \left(\frac{x_f}{35}\right)\left(\frac{10^{-6}\,GeV^{-2}}{\sigma}\right)\ 10^2\cdot 10^8\,GeV^2\cdot\frac{10^{-39}\,GeV^3}{10^{-46}\,GeV^4\;10^{19}\,GeV} \sim$$

WIMP "MIRACLE"

$$\sqrt{x}\, e^{-x} \simeq \frac{1}{M_X M_{Pl} \sigma} \qquad e^x = \sqrt{x}\, M_X M_P \sigma$$

$$x = \ln L \qquad L = \sqrt{x}\, M_X M_P \sigma \qquad x \simeq \ln(M_X M_P \sigma)$$

$$\Omega_X \simeq \left(\frac{T_0^3}{\rho_c M_{Pl}}\right) \frac{x}{\sigma} \simeq \frac{10^{-12}\,eV^3}{10^{-46}\,GeV^4}\,\frac{x/\sigma}{10^{19}\,GeV} \simeq \frac{10^{-39}}{10^{-27}}\,GeV^{-2}\,\frac{x}{\sigma}$$

$$\simeq \left(10^{-12}\,GeV^{-2}\right)\frac{x}{\sigma} \qquad x = \frac{M_X}{T_f}$$

to have $\Omega_X \sim \frac{1}{4}$ $\quad \left(\frac{10^{-12}\,GeV^{-2}}{\sigma}\right) 4x \simeq 1 \quad \sigma \sim \frac{10^{-12}\,GeV^{-2}}{\sigma}\, 4 \ln L$

[correct expression for Ω_X using Boltzmann eq. + $\langle \sigma v \rangle$ ...

$$\Omega_X h^2 \simeq 10^{-10}\,\frac{GeV^{-2}}{\langle \sigma^{ann} v \rangle}\,\frac{1}{\sqrt{g_*(T_f)}}\,\ln\left[\frac{g_X M_X M_{Pl} \langle \sigma v \rangle}{(2\pi)^{3/2}\sqrt{g_*(T_f)}}\right] \sim O(10)$$

for heavy relic $M_X \gg T_f$ $\quad g_X^{weak} \sim g_W^4$

for $\langle \sigma^{ann} v \rangle \sim \frac{\alpha_W^2}{M_X^2} \rightarrow 10^{-7} - 10^{-8}\,GeV^{-2}$

$\Omega_X h^2 \simeq 10^{-10}\,(10^{+7} \div 10^{+8})\,10 \sim O(10^{-1})$ $\quad O(10^2\,GeV) \longrightarrow h^2 \sim \frac{1}{2}$ $\quad \Omega_{DM} \sim \frac{1}{4}$!

UPPER BOUND ON $M_X \to M_{DM}$ stable heavy particle

TO AVOID DM OVERPRODUCTION

↳ WIMP

i.e. to have $\Omega_{DM} \lesssim 0.25 - 0.30$

$$\Omega_X h^2 \sim 10^{-9}\ \text{GeV}^{-2}\ \frac{1}{\langle \sigma^{ann} v \rangle} \quad \text{in L}$$

$$\langle \sigma^{ann} v \rangle \simeq \frac{10^{-9}\ \text{GeV}^{-2}}{\Omega_X} \qquad \Omega_X < 0.3 \Rightarrow \sigma^{ann} > 10^{-9}\ \text{GeV}^{-2}$$

ex: $M_X \sim 10\ \text{TeV} = 10^4\ \text{GeV}$ $\quad \sigma \sim \frac{\alpha_{DM}^2}{10^8\ \text{GeV}^2}$ → if α_{DM} instead of being $O(\alpha_W)$ is $O(1)$

$\sigma \sim 10^{-8}\ \text{GeV}^{-2}$ (marginally?) ok

but if $M_X \sim 100\ \text{TeV}$ $\quad \sigma \sim \frac{\alpha_{DM}^2}{10^{10}\ \text{GeV}^2}$ → maximal value

if $\alpha_{DM} \sim O(1)$ $\Rightarrow \sigma \sim 10^{-10}\ \text{GeV}^{-2}$

$\Omega_X \sim \frac{10^{-9}}{10^{-10}} \sim O(10)$ too large!

[more precise computation: unitarity ↗ $\sigma \lesssim \frac{4\pi}{M_X^2}$] $\Rightarrow \Omega_X h^2 > 10^{-8}\ \text{GeV}^{-2}\ \frac{M_X^2}{4\pi}$

$M_X < 120\ \text{TeV}$

LOWER BOUND ON M_{DM}

↳ heavy relic cold DM

WIMP case $\alpha_{DM} \sim \alpha_W$

ex. massive ν : $\sigma \sim G_F^2 m_X^2$ $\quad x_f \sim 20$

$$\Omega_X h^2 \sim 10^{-9}\,\text{GeV}^{-2}\,\frac{1}{10^{-10}\,\text{GeV}^{-4}\,m_X^2} \sim \frac{10\,\text{GeV}^2}{m_X^2}$$

if $m_X \sim O(10\,\text{GeV}) \Rightarrow \Omega_X h^2 \sim \frac{10}{100} \sim 10^{-1}$

$\Rightarrow m_X \gtrsim O(10\,\text{GeV})$ to have $\Omega_X h^2 < 10^{-1}$

($m_X \sim 100\,\text{GeV} \Rightarrow \Omega_X h^2 \sim O(10)$ too large)

N.B. but if release of entropy after WIMP freeze-out

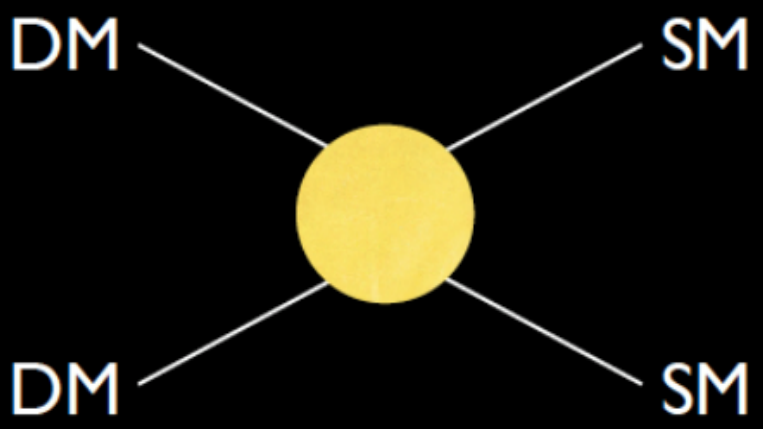
$s \to \alpha s \quad \alpha > 1$ (e.g. because decay of relics ....)

$\Rightarrow$ then $m_{WIMP} >$ 20 - 50 MeV !

✓ if $m_{WIMP} < 20$-50 MeV $\Rightarrow$ release of entropy too close to BBN ~ 1 MeV !

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10}\ {\rm GeV}\ \frac{}{m_{\rm DM}}$$

WIMP Miracle



$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300\ {\rm GeV}$$

"weak" coupling
"weak" mass scale

correct abundance

We want new particles for naturalness anyway

Miracle^2

N. Fornengo, Grav. Waves and Cosmology, Varenna, 2017

CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	SUSY	**EXTRA DIM.**	**LITTLE HIGGS.**
1) **ENLARGEMENT OF THE SM**	(x^μ, θ) Anticomm. Coord.	$(x^\mu, j^{(i)})$ New bosonic Coord.	SM part + new part to cancel Λ^2 at 1-Loop
2) **SELECTION RULE**	***R-PARITY LSP***	***KK-PARITY LKP***	***T-PARITY LTP***
→ **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

SUSY & DM : a successful marriage

- Supersymmetrizing the SM does not lead necessarily to a stable SUSY particle to be a DM candidate.
- However, the mere SUSY version of the SM is known to lead to a too fast p-decay. Hence, necessarily, the SUSY version of the SM has to be **supplemented with some additional (ad hoc?) symmetry to prevent the p-decay catastrophe.**
- Certainly the simplest and maybe also the most attractive solution is **to impose the discrete R-parity** symmetry
- MSSM + R PARITY ⟶ LIGHTEST SUSY PARTICLE (LSP) IS STABLE .
- The LSP can constitute an interesting DM candidate in several interesting realizations of the MSSM (i.e., with different SUSY breaking mechanisms including gravity, gaugino, gauge, anomaly mediations, and in various regions of the parameter space).

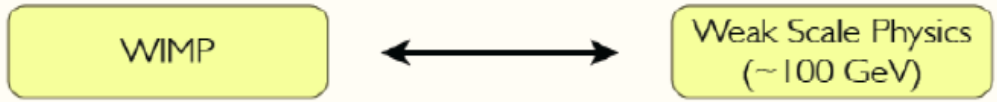
WHO IS THE LSP?

- **SUPERGRAVITY** (transmission of the SUSY breaking from the hidden to the obsevable sector occurring via gravitational interactions): best candidate to play the role of LSP:

  NEUTRALINO (i.e., the lightest of the four eigenstates of the 4x4 neutralino mass matrix)

In **CMSSM**: the LSP neutralino is almost entirely a BINO

For the last ~30 years we have been focusing on the WIMP scenario



Our experimental effort is strongly focused on the WIMP!

New production mechanisms and mediation schemes often imply a hidden dark sector. Possibly with complex dynamics.

DARK PHOTON ?

Such hidden sectors often include low scale particles, below the GeV scale.

Very different from the WIMP paradigm!!

Or **very light axions**, or axion-like particles (**ALPs**) or **very heavy**, macroscopic objects DM, for instance **primordial Black Holes**

European Strategy Update

Dark Sectors

What is meant by a dark sector ?
A Hidden sector, with Dark matter, that talks to us through a Portal

Portal can be the Higgs boson itself or New Messenger/s

Dark sector has dynamics which is not fixed by Standard Model dynamics
→ New Forces and New Symmetries
→ Multiple new states in the dark sector, including Dark Matter candidates

Interesting, distinctive phenomenology
Long-Lived Particles
Feebly interacting particles (FIP's)

Summary talk by Asai and Catena of the DM WG at the EU Strategy Granada Symposium

Further models and candidates

Models with additional scalars [GeV-TeV, WIMP]

- Singlet
- Doublet (e.g.: 2 higgs doublet model)
- Triplet

Models based on extended symmetries [GeV-TeV, WIMP]

- GUT inspired
- Discrete symmetries

Mirror dark matter

Sterile neutrinos [keV, non WIMP, warm]

Axion [μeV, non WIMP, cold]

ALP (axion-like-particles, light scalars)
[$> 10^{-22}$ eV, non WIMP, cold (BE condensate)]

Axion

- Axions arise as a dynamical way to solve the strong-CP problem

- Being particles, they can have a cosmological role

- They can be:
  - Thermally produced: hot dark matter
  - Non-thermally produced: born as nonrelativistic, classical field oscillations - very small mass, yet cold dark matter

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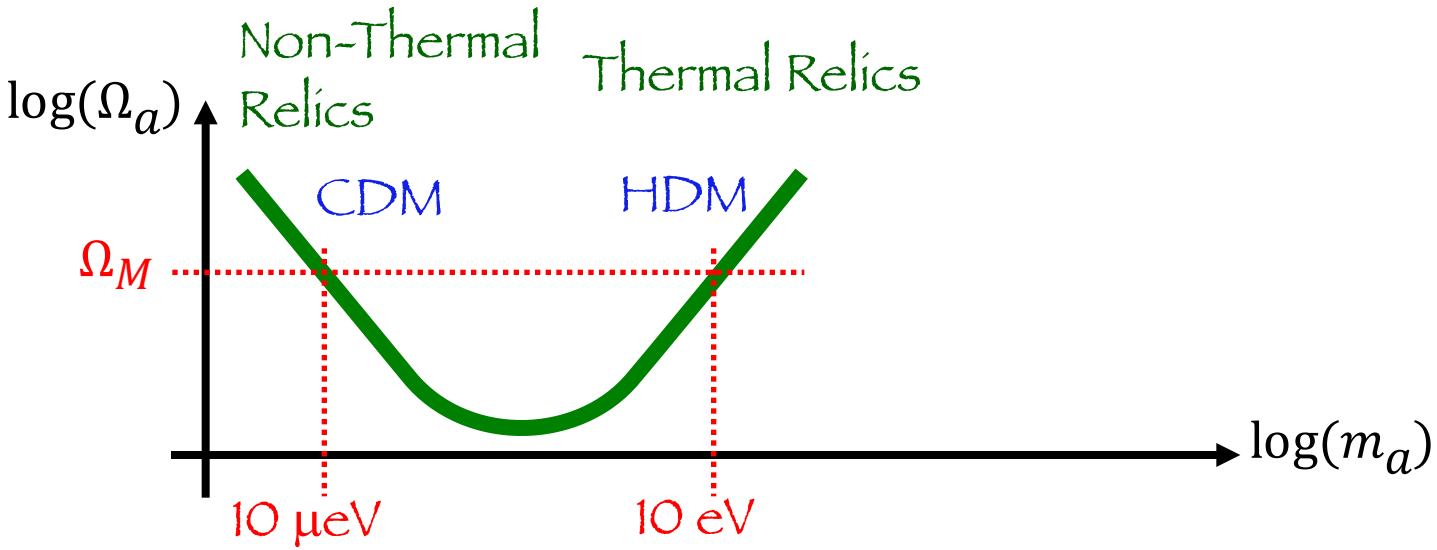
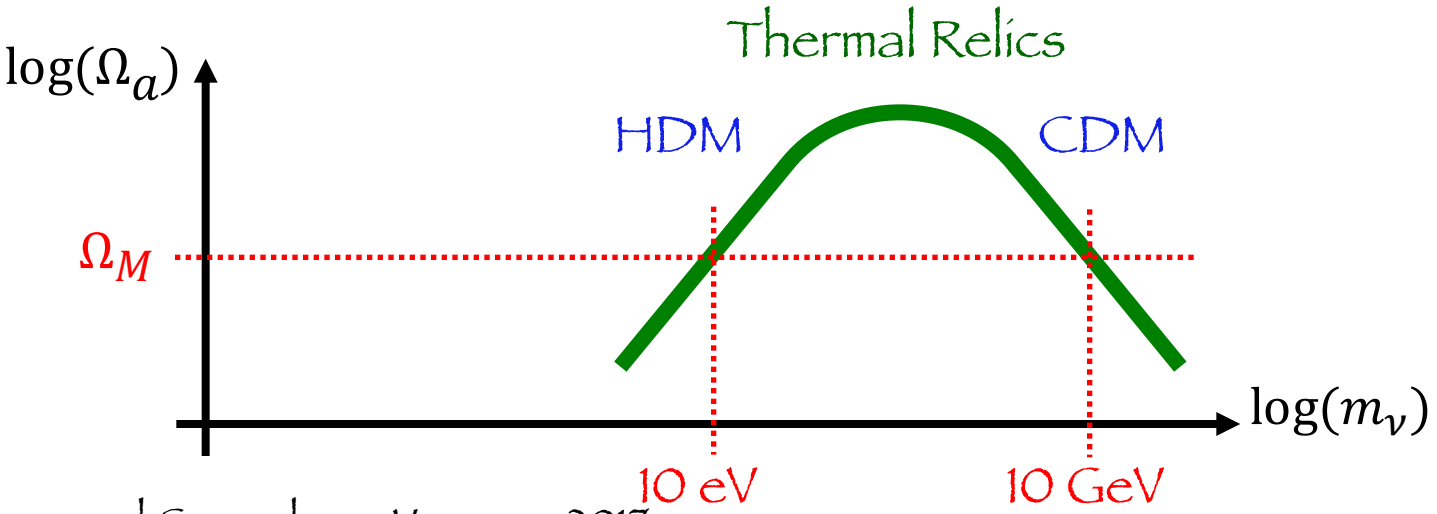
Relic abundance curves

Axions



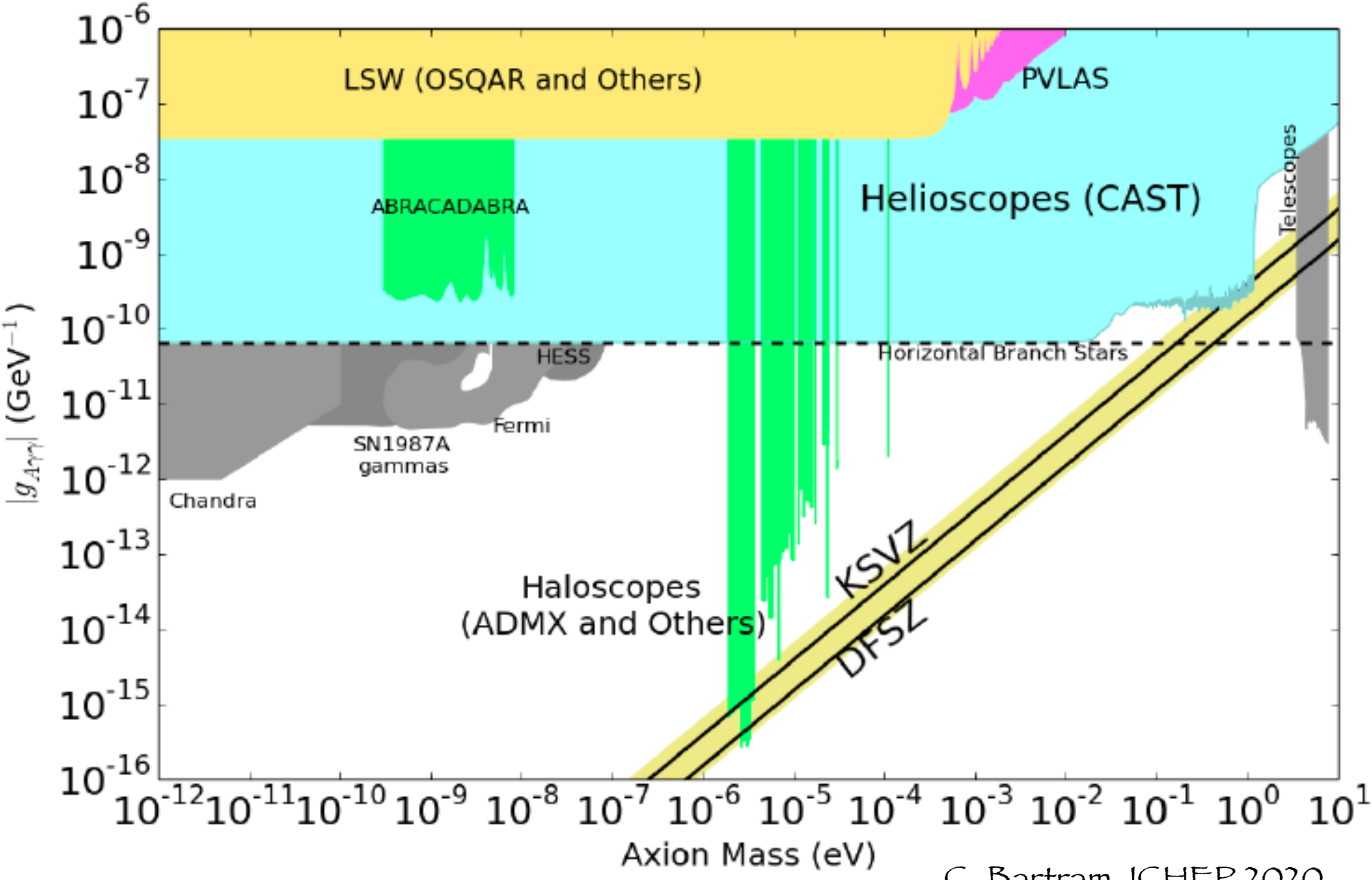
Neutrinos

WIMPs



N. Fornengo, Grav. Waves and Cosmology, Varenna, 2017

AXION-LIKE PARTICLES (ALPs) Exclusion Plot



C. Bartram, ICHEP 2020

AXION

$$\tilde{G}^{\mu\nu a} = \frac{1}{2}\,\varepsilon^{\mu\nu\lambda\rho}\,G^a_{\lambda\rho}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\alpha_s}{8\pi}\,\vartheta_0\,G^a_{\mu\nu}\,\tilde{G}^{\mu\nu a} \qquad \alpha_s \equiv \frac{g_s^2}{4\pi}$$

$\uparrow \neq P$ and CP

at the perturbative level: $G\tilde{G} \to \partial_\mu V^\mu$

$\uparrow$

$S \to \int dt\, d^3x\, \mathcal{L} \to$ surface integral

but at the non-perturbative level: configurations like instantons → does not vanish

$CP\not$ in QCD at the NON-PERTURBATIVE LEVEL

$$\partial_\mu J^\mu_A \sim \frac{\alpha_s}{2\pi}\,G^a_{\mu\nu}\,\tilde{G}^{\mu\nu a}$$

$\hookrightarrow \bar{f}\gamma^\mu\gamma^5 f$

$$\Delta\mathcal{L}_\vartheta = \Delta\mathcal{L}_{\vartheta_0} + \Delta\mathcal{L}_{\det M_q}$$

$\swarrow$

$$\frac{\alpha_s}{8\pi}\,\mathrm{Arg}\left(\det M_q\right) G^a_{\mu\nu}\,\tilde{G}^{\mu\nu a}$$

$$\Delta\mathcal{L}_\vartheta = \frac{\alpha_s}{8\pi}\underbrace{\left(\vartheta_0 + \mathrm{Arg}\det M_q\right)}_{\bar{\vartheta}} G^a_{\mu\nu}\,\tilde{G}^{\mu\nu a}$$

$d_n < 10^{-26}$ e cm $\theta < 10^{-10} - 10^{-9}$

PQ: GLOBAL symmetry

$q_{Ln} \to e^{i q^n_{PQ} \beta/2} q_{Ln}$; $q_{Rn} \to e^{-i q^n_{PQ} \beta/2} q_{Rn}$

$\hookrightarrow 1 \dots 6$
$u\ d\ s \dots t$

ex: $q^n_{PQ} = \frac{1}{6}$ $\forall n$ $\bar{q}_L H q_R$ $(\bar{u}\ \bar{d})_L \phi^0 d_R$

$\phi^0 \to e^{i q_{PQ} \beta} \phi^0$ PQ charge 1/6

but $\bar{u}_L \phi^{0\,t} u_R$
↑ charge $-1/6$ not invariant

2nd Higgs doublet $H_1 \to e^{i\beta/6} H_1$ $H_2 \to e^{-i\beta/6} H_2$

$\langle H_1^0 \rangle \neq 0$ $\langle H_2^0 \rangle \neq 0$ $\Rightarrow$ broken $U(1)_{PQ}$

$\to$ massless Goldstone boson $\to$ AXION

but $U(1)_{PQ}$ broken explicitly by quantum effects of QCD

$\to$ AXION PSEUDO-Goldstone boson

$m_{axion} \simeq 0.5 \dfrac{m_\pi f_\pi}{f_{PQ}}$ if $\langle H_1 \rangle \sim v_1$, $\langle H_2 \rangle \sim v_2$

$f_{PQ} \sim \sqrt{v_1^2 + v_2^2} = v$ $v \sim 240$ GeV

$m_a \sim 150\,\mathrm{keV}$ Weinberg - Wilczek axion

excluded experimentally

INVISIBLE AXION $f_{PQ} \gg$ EW scale

$m_a \sim 0.6\,\mathrm{eV}\left(\frac{10^7\,\mathrm{GeV}}{f_{PQ}}\right)$

$\tau_a \simeq 4\cdot 10^{24}\,s\left(\frac{eV}{m_a}\right)^5$

$\tau_a > \tau_{Univ}$ (f_a axion is no DM)

$m_a \lesssim 25\,eV$

strongest upper bound from astrophysical bound

$f_{PQ} > 10^5\,\mathrm{GeV}$ $\quad m_a < 10^{-2}\,eV$

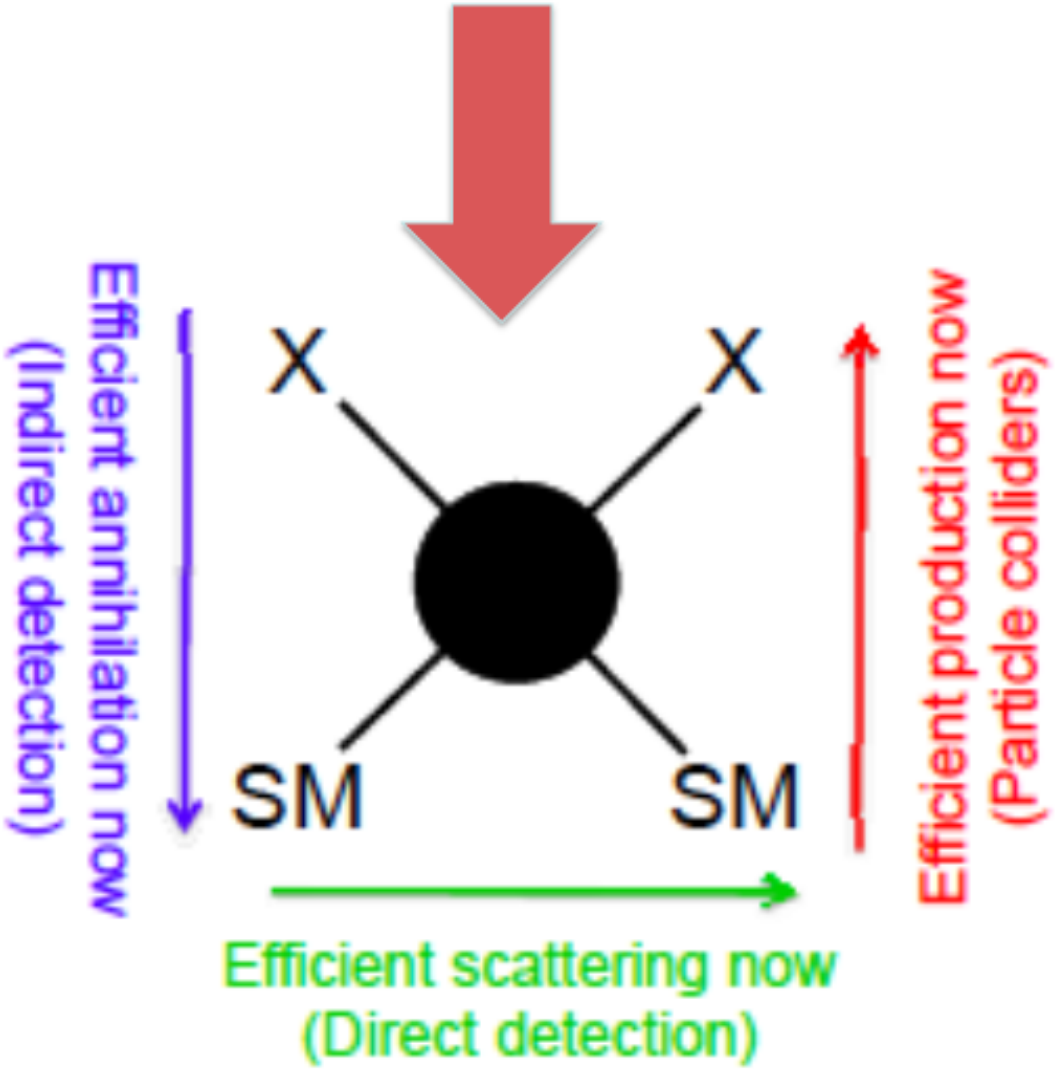
lower bound from cosmology

$\rho_a \sim \frac{1}{m_a}$

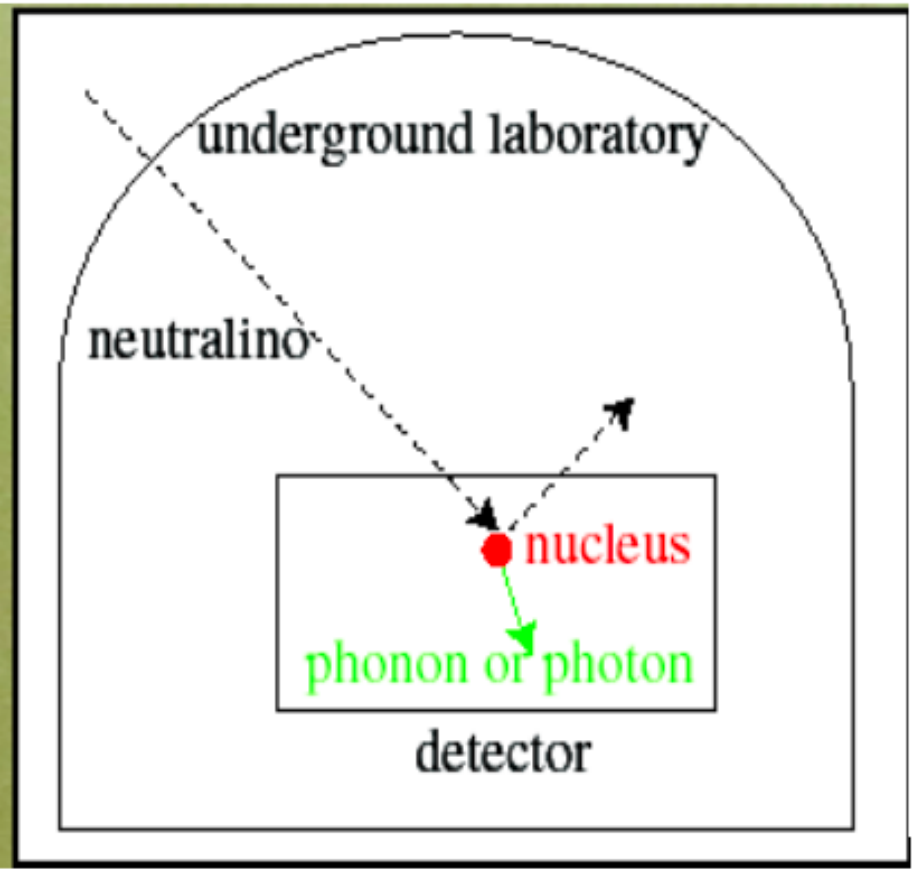
$f_{PQ} \sim \frac{1}{m_a}$ $\quad \left\{ m_a \sim 10^{-5} - 10^{-7}\,eV \right.$ good DM candidate

$\Omega_a = \frac{\rho_{a,0}}{\rho_{c,0}} \sim \left(10^{-6}\,eV\right)\theta_i^2$ $\quad \theta_i < 1$ $\quad m_a > 10^{-22}\,eV$

DM COMPLEMENTARITY: efficient annihilation in the early Universe implies today

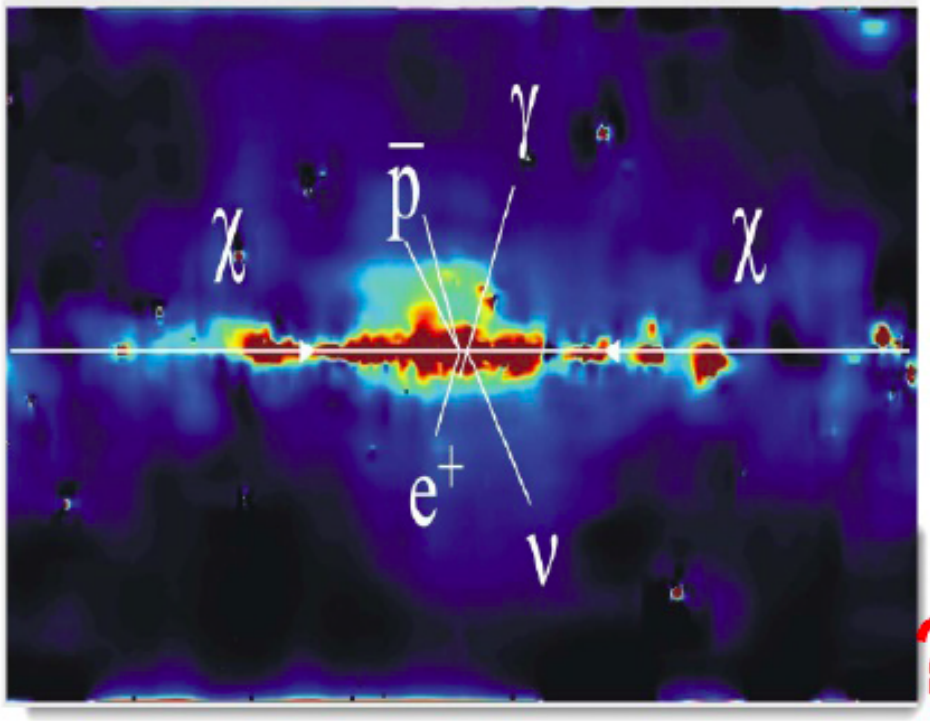


Hunting for DM

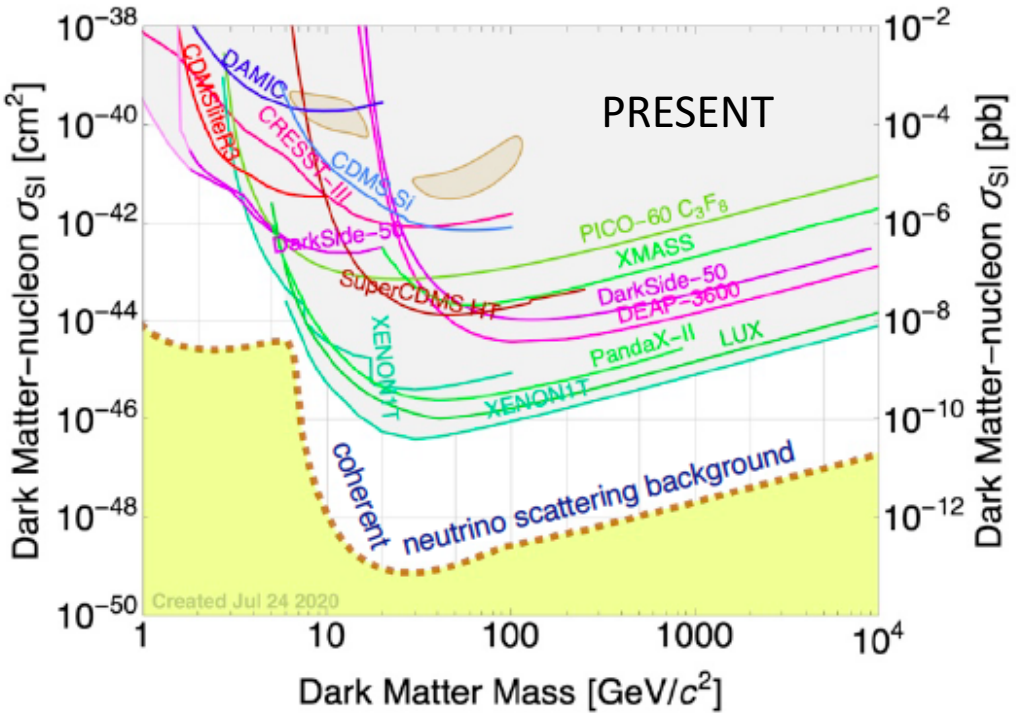


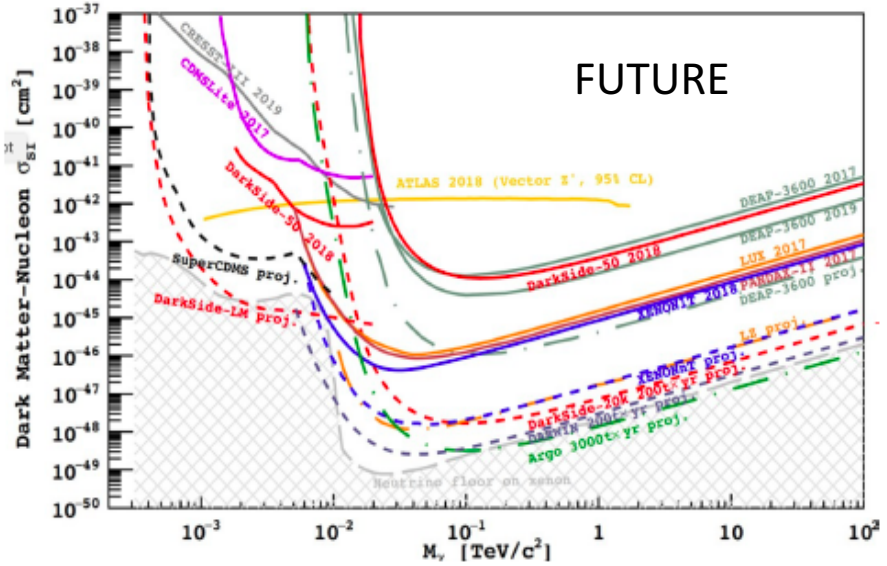
DIRECT SEARCHES

■ WIMP-WIMP annihilation in the galactic halos may be detected through production of γ, neutrinos, anti-matter.

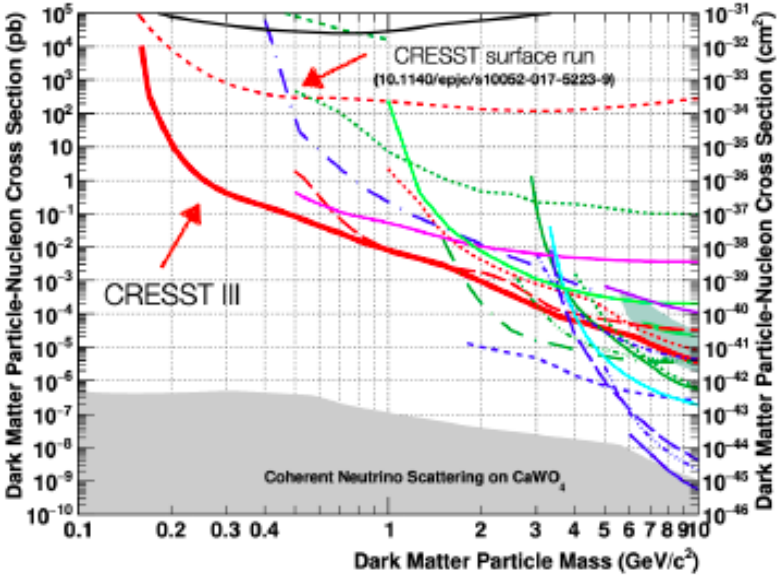


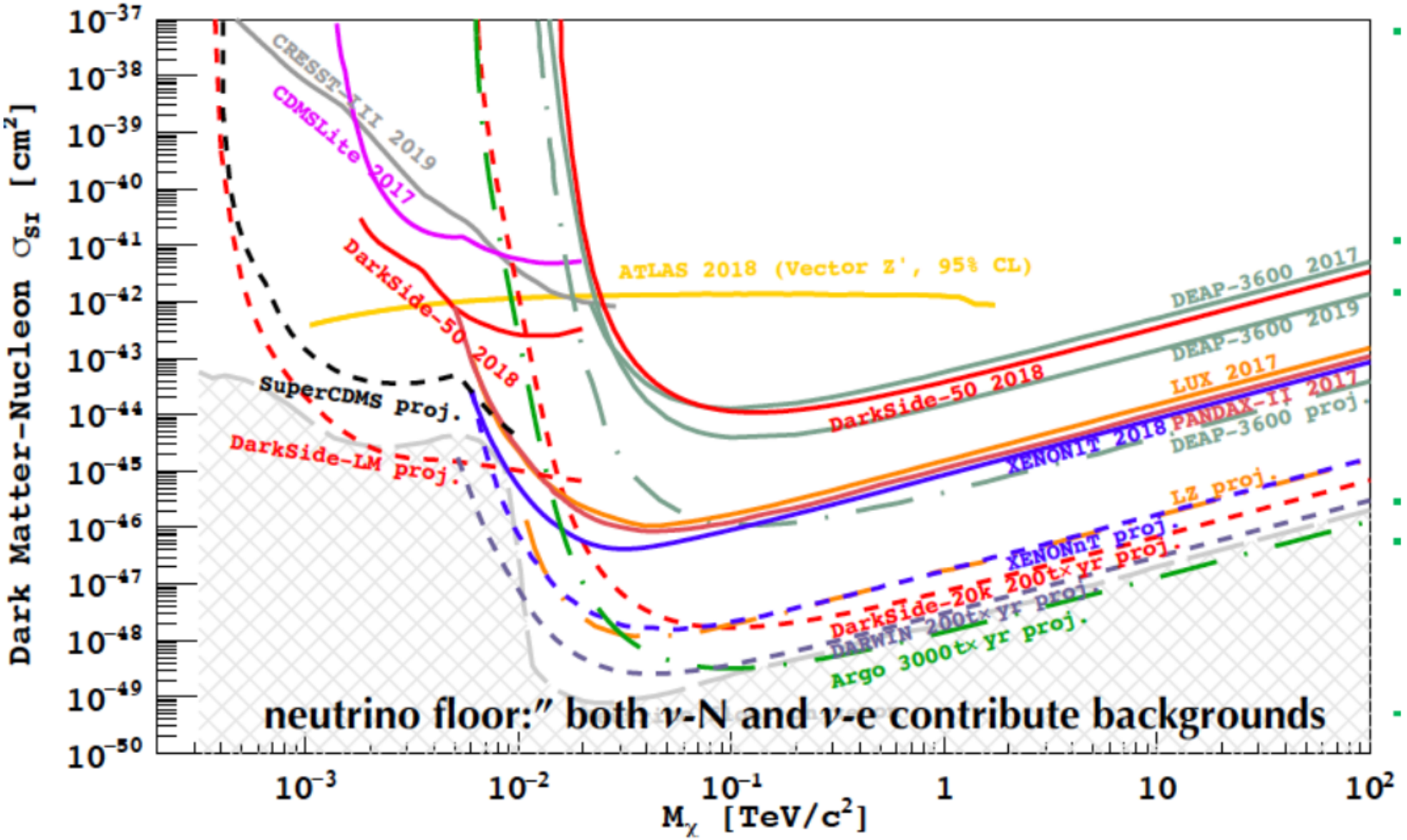
INDIRECT SEARCHES





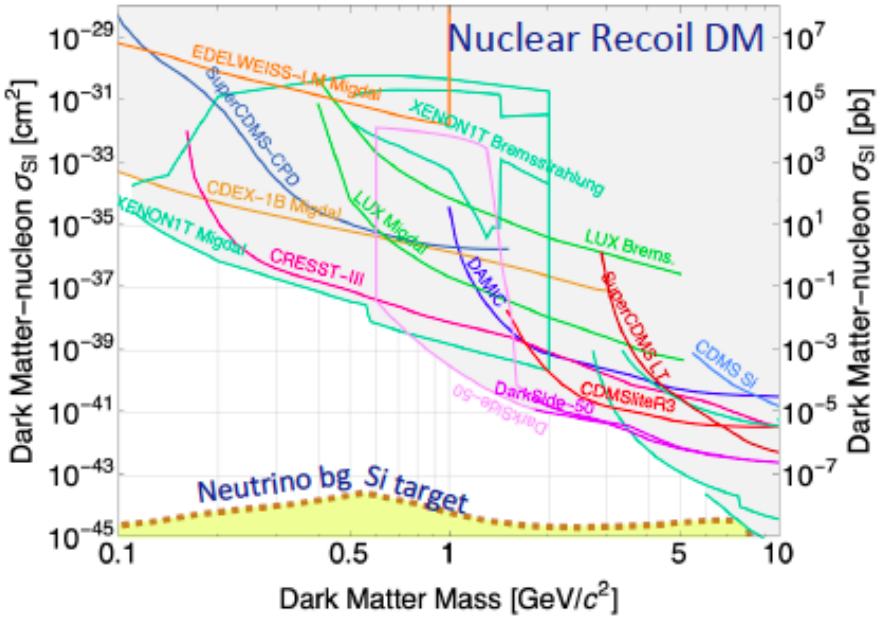
LIGHT (M < few GeVs) DM

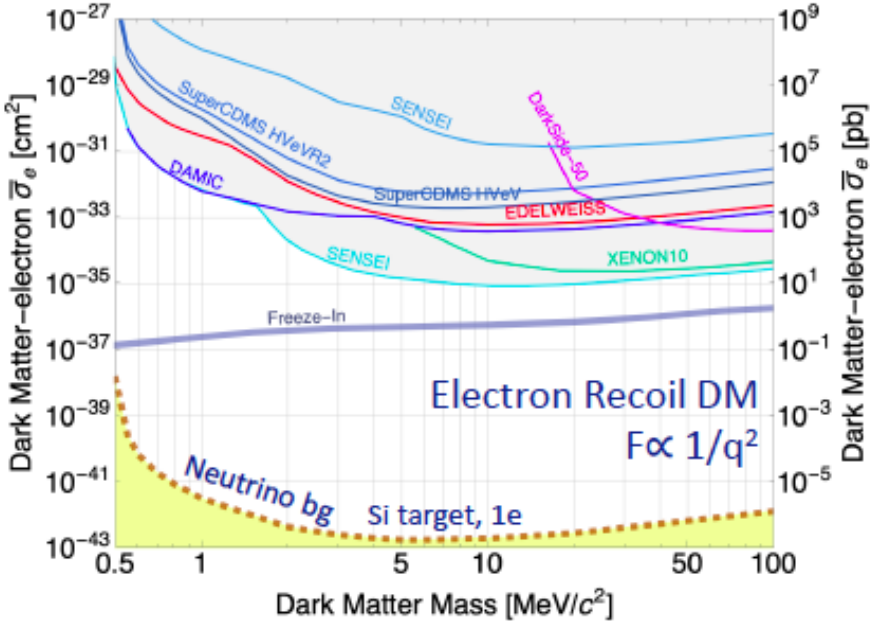



Dark Matter-Nucleon σ_{SI} [cm^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
M_χ [TeV/c^2]
CRESST-III 2019
CDMSLite 2017
DarkSide-50 2018
ATLAS 2018 (Vector Z', 95% CL)
SuperCDMS proj.
DarkSide-LM proj.
DEAP-3600 2017
DEAP-3600 2019
DarkSide-50 2018
LUX 2017
PANDAX-II 2017
XENON1T 2018
DEAP-3600 proj.
LZ proj.
XENONnT proj.
DarkSide-20k 200t×yr proj.
DARWIN 200t×yr proj.
Argo 3000t×yr proj.
neutrino floor:" both ν-N and ν-e contribute backgrounds

Current Status: Dark Matter with Mass < 10 GeV/c²

- Many well-motivated light particles outside standard "WIMP paradigm"; Large unexplored space!
- Optimal targets not necessarily nuclei and SM interaction may be through a mediator. *Signal could be DM scattering off electrons, absorption of dark photons or another inelastic process.*
- Energy threshold is key; recent detector R&D advances enable enormous progress w/ thresholds <<1 keV
- High relic number densities → competitive w/ gram-days of exposure (not ton-years)
- Radiogenic and cosmogenic backgrounds still problematic but also many new backgrounds (IR radiation, dark currents, trapped charges, vibrational noise, etc.)





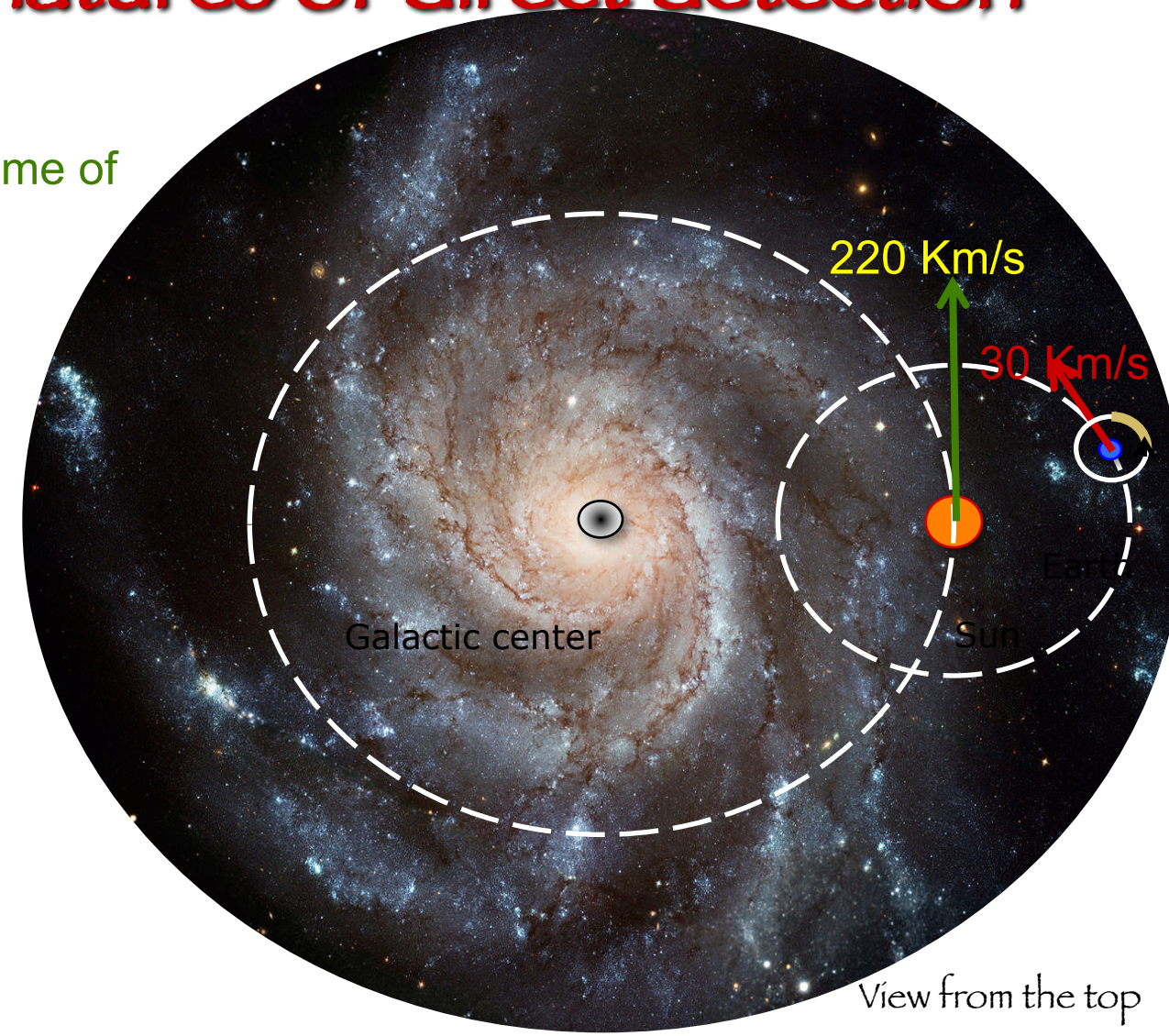
Typical signatures of direct detection

- Stationary over the lifetime of an experiment
  Directional boost

  Directionality
- Period: 1 year

  Annual modulation

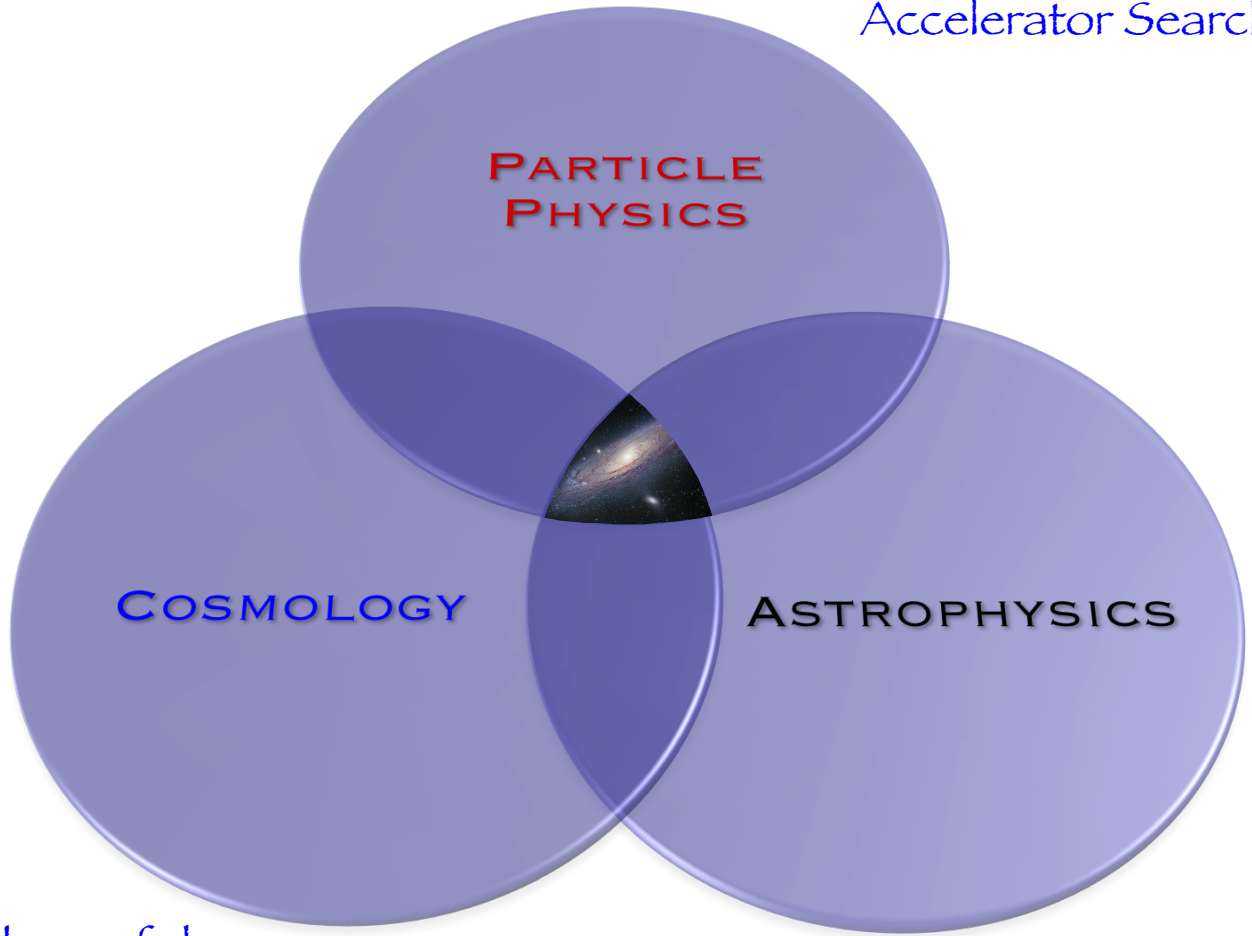
DAMA /NaI + DAMA/LIBRA at LNGS report evidence at > 10σ of an annual modulation of the signal – no other explanation present, but only DM could cause such modulation!



$$\frac{dR}{dE_R} = \frac{\xi_{\mathcal{N}}}{m_{\mathcal{N}}} \frac{\rho_\odot}{m_\chi} \int_{v_{\min}(E_R)}^{v_{\rm esc}} d^3v \, v \, f_E(\vec{v}) \frac{d\sigma_{\mathcal{N}}}{dE_R}(v, E_R)$$

The Particle Dark Matter Crossroad

Particle Candidate: Models of New Physics
(Superymmetry, Extra-dimensions, …)
Accelerator Searches

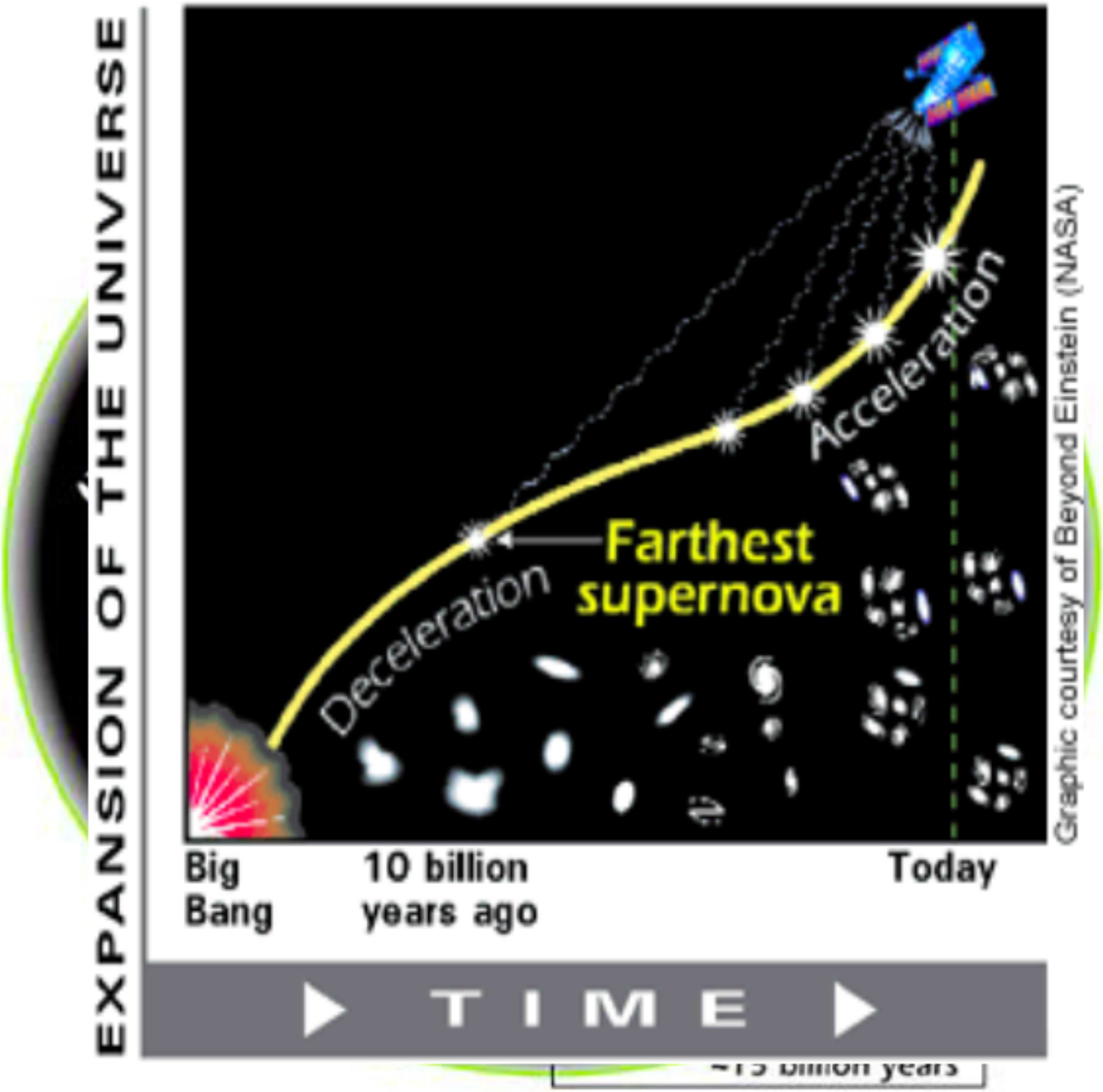


Cosmology of the
Dark Matter Particle

Astrophysical Signals of the
Dark Matter Particle

The “unbearable” acceleration of the expansion of the Universe

- Until the end of the past century the debate was if the universe was **open** (matter energy density < critical energy density) or **closed**, hence whether the universe would never end to expand or if its expansion was to stop at some point with the universe collapsing into a Big Crunch. **But no “reasonable” physicist was doubting that in any case the attractive force of gravity had to slow down the expansion of the universe** (indeed, a de-acceleration parameter was introduced to measure such slow down).
- **But**, on the contrary …


EXPANSION OF THE UNIVERSE
Farthest supernova
Deceleration
Acceleration
Big Bang
10 billion years ago
Today
TIME
Graphic courtesy of Beyond Einstein (NASA)

DARK ENERGY

- What is causing the acceleration of the expansion of the universe?
  - Einstein's cosmological constant Λ?
  - Some new dynamical field ("quintessence," Higgs-like)?
  - Modifications to General Relativity?

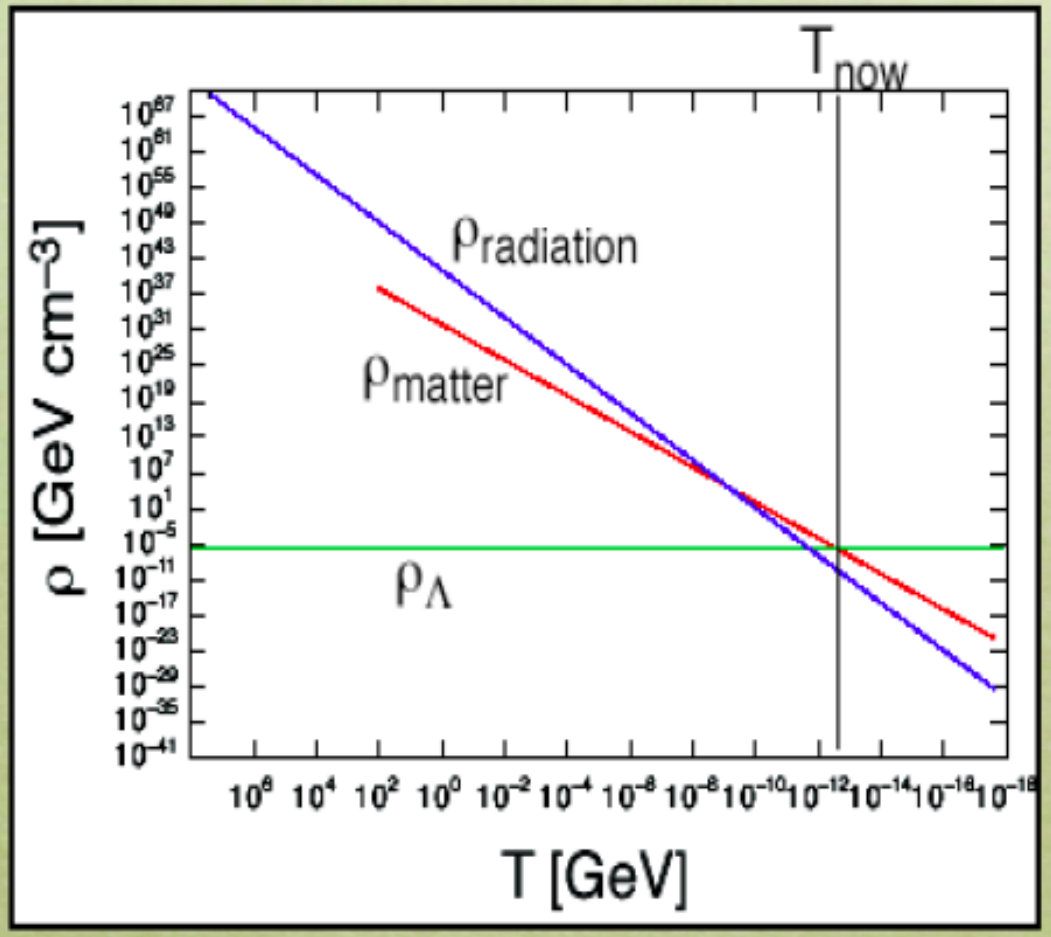
  } "Dark Energy"

- Dark energy effects can be studied in two main cosmological observables:
  - The history of the expansion rate of the universe: supernovae, weak lensing, baryon acoustic oscillations (BAO), cluster counting, etc.
  - The history of the rate of the growth of structure in the universe: weak lensing, large-scale structure, cluster counting, redshift-space distortions, etc.
- For all probes other than SNe, **large galaxy surveys are needed**:
  - **Spectroscopic**: 3D (redshift), medium depth, low density, selection effects
  - **Photometric**: "2.5D" (photo-z), deeper, higher density, no selection effects

Ramon Miquel

THE "WHY NOW" PROBLEM

- *Why do we see matter and cosmological constant almost equal in amount?*
- *"Why Now" problem*
- *Actually a triple coincidence problem including the radiation*
- *If there is a deep reason for* $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{Pl})^4$, *coincidence natural*



Arkani-Hamed, Hall, Kolda, HM

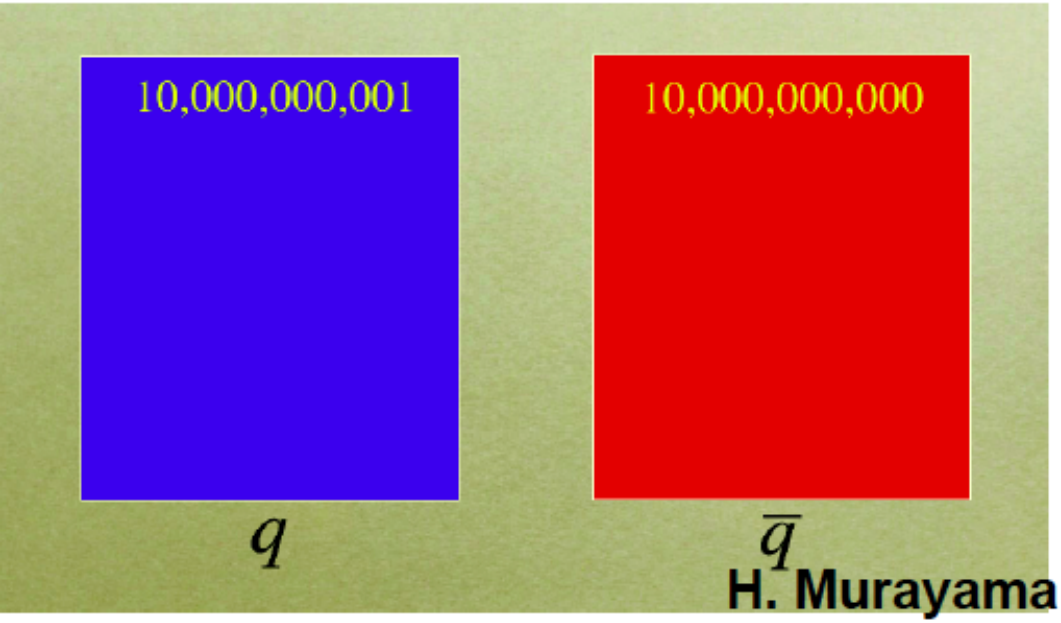
THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:
-why only baryons
-why $N_{baryons}/N_{photon} \sim 10^{-10}$

- NO EVIDENCE OF ANTIMATTER WITHIN THE SOLAR SYSTEM
- ANTIPROTONS IN COSMIC RAYS: IN AGREEMENT WITH PRODUCTION AS SECONDARIES IN COLLISIONS
- IF IN CLUSTER OF GALAXIES WE HAD AN ADMIXTURE OF GALAXIES MADE OF MATTER AND ANTIMATTER → THE PHOTON FLUX PRODUCED BY MATTER-ANTIMATTER ANNIHILATION IN THE CLUSTER WOULD EXCEED THE OBSERVED GAMMA FLUX
- IF $N_{ba.} = N_{antibar}$ AND NO SEPARATION WELL BEFORE THEY DECOUPLE WE WOULD BE LEFT WITH $N_{bar.}/N_{photon} << 10^{-10}$
- IF BARYONS-ANTIBARYONS ARE SEPARATED EARLIER → DOMAINS OF BARYONS AND ANTIBARYONS ARE TOO SMALL SMALL TODAY TO EXPLAIN SEPARATIONS LARGER THAN THE SUPERCLUSTER SIZE

↓

- ONLY MATTER IS PRESENT
- HOW TO DYNAMICALLY PRODUCE A BARYON-ANTIBARYON ASYMMETRY STARTING FROM A SYMMETRIC SITUATION

THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:
-why only baryons
-why $N_{baryons}/N_{photon} \sim 10^{-10}$



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_{HIGGS} > 80 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 NEUTRINO MASSES

MATTER-ANTIMATTER ASYMMETRY ⟷ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

- Key-ingredient of the SEE-SAW mechanism for neutrino masses: **large Majorana mass for RIGHT-HANDED neutrino**
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

VANILLA LEPTOGENESISIS !

→ it is possible to create a lepton-antilepton asymmetry at the moment RH neutrinos decay. Since SM interactions preserve Baryon and Lepton numbers at all orders in perturbation theory, but violate them at the quantum level, such **LEPTON ASYMMETRY** can be converted by these purely quantum effects into a BARYON-ANTIBARYON ASYMMETRY (**Fukugita-Yanagida mechanism for leptogenesis**)

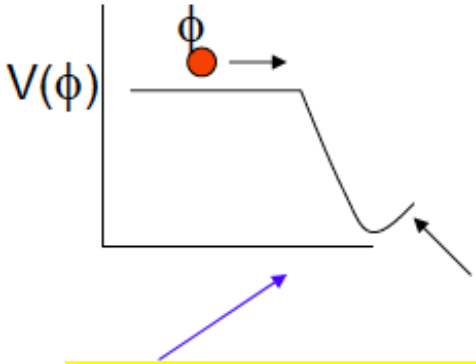
INFLATION

SEVERE COSMOGICAL PROBLEMS

- **CAUSALITY** (isotropy of CMBR)
- **FLATNESS** (Ω close to 1 today)
- **AGE OF THE UNIV.**
- **PRIMORDIAL MONOPOLES**

COMMON SOLUTION FOR THESE PROBLEMS

VERY FAST (EXPONENTIAL) EXPANSION IN THE UNIV.



VACUUM ENERGY → Ω dominated by vacuum en.

TRUE VACUUM

For some inflationary models → large amount of primordial gravitational wave

NO WAY TO GET AN INFLATIONARY SCALAR POTENTIAL IN THE SM, UNLESS THERE EXIXTS A NON-MINIMAL COUPLING OF THE SM HIGGS FIELD TO GRAVITY

UNI- or MULTI- VERSE?

- Gauge hierarchy, cosmological constant, DE – DM – Ordinary Matter energy densities, values of the running coupling constants, neutron-proton mass difference, … **FINE-TUNING of Fundamental Parameters**, a **Fundamental Theory** accounting for such apparent fine-tuning (maybe the Theory of Everything (**TOE**)), **Anthropic Principle** or ...?

- **String Theory Landscape**: many (infinite?) **DEGENERATE VACUA** → each vacuum corresponds to a different universe, i.e. a universe with different values of the fundamental parameters → we live and study the ONLY universe where our life is allowed, i.e. just "OUR" universe where the fundamental parameters take the particular values allowing for our existence;

- In the **ETERNAL INFLATION** theory some regions of space stop stretching , form distinct bubbles – with different SSB and hence different physical constants

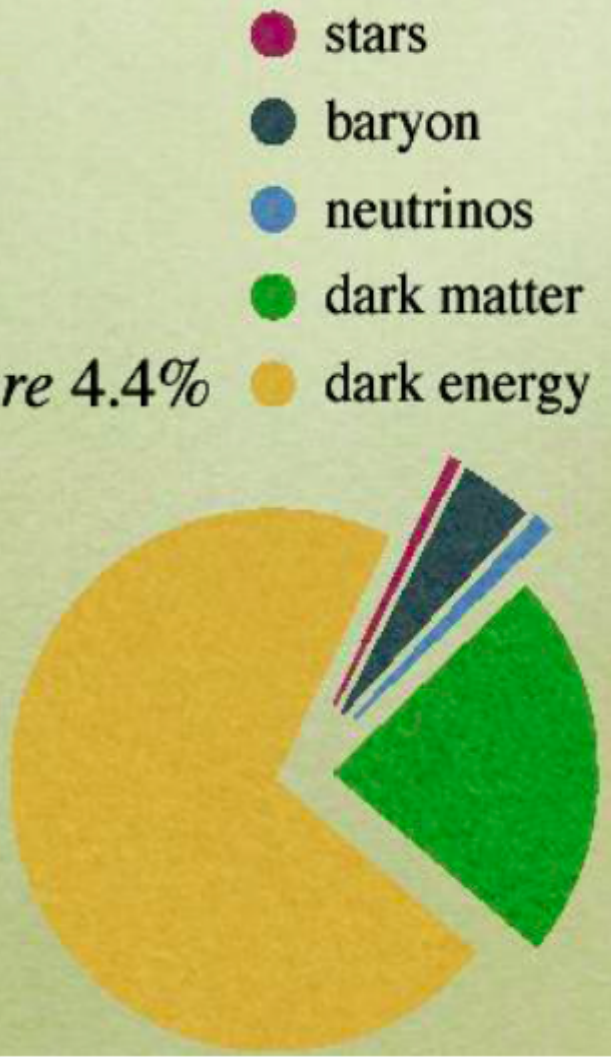
- **Weinberg's anthropic explanation** of the small (but not exactly zero) value of **the cosmological constant** (his paper was written in 1987 long before the exp. discovery of the accelerated expansion of the universe).

5 numbers, 5 indications of physics beyond the Standard Models of Particle Physics and Cosmology: **NEUTRINO MASSES**, **DARK MATTER**, **DARK ENERGY**, **ANTIMATTER** and **VACUUM ENERGY**

- *Stars and galaxies are only* ~0.5%
- *Neutrinos are* **> 0.1 %**
- *Rest of ordinary matter*

  (electrons, protons & neutrons) are 4.4%
- *Dark Matter* **~ 27%**
- *Dark Energy* **~ 68 %**
- *Anti-Matter* **0 %**
- *Higgs Bose-Einstein condensate*

  ~ **10^{62} %** **??**



thanks to H. Murayama

We are living in an extraordinarily exciting time for our comprehension of the Universe from

its smallest to its largest space and time scales

- the two traditional particle physics roads:

ENERGY frontier → produce and observe new particles

INTENSITY frontier → precision tests of the SM → discover new particles through their virtual effects

The "new" road to access new physics beyond the SM:

ASTROPARTICLE frontier → new phenomena at the interface between particle physics, cosmology and astrophysics unexplained within the SM → demand for new physics beyond the two SMs