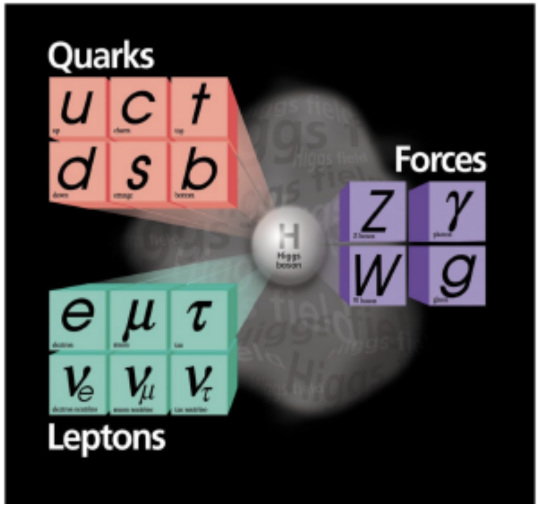
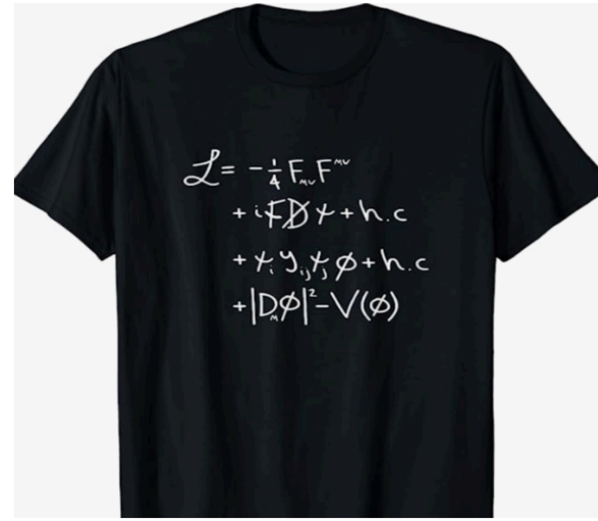
ISAPP2023: Neutrino physics , astrophysics and cosmology – SIF, Varenna, 26 June – 6 July 2023



MICRO-COSMOS

LECTURES III – IV – V



Basics on particle physics.

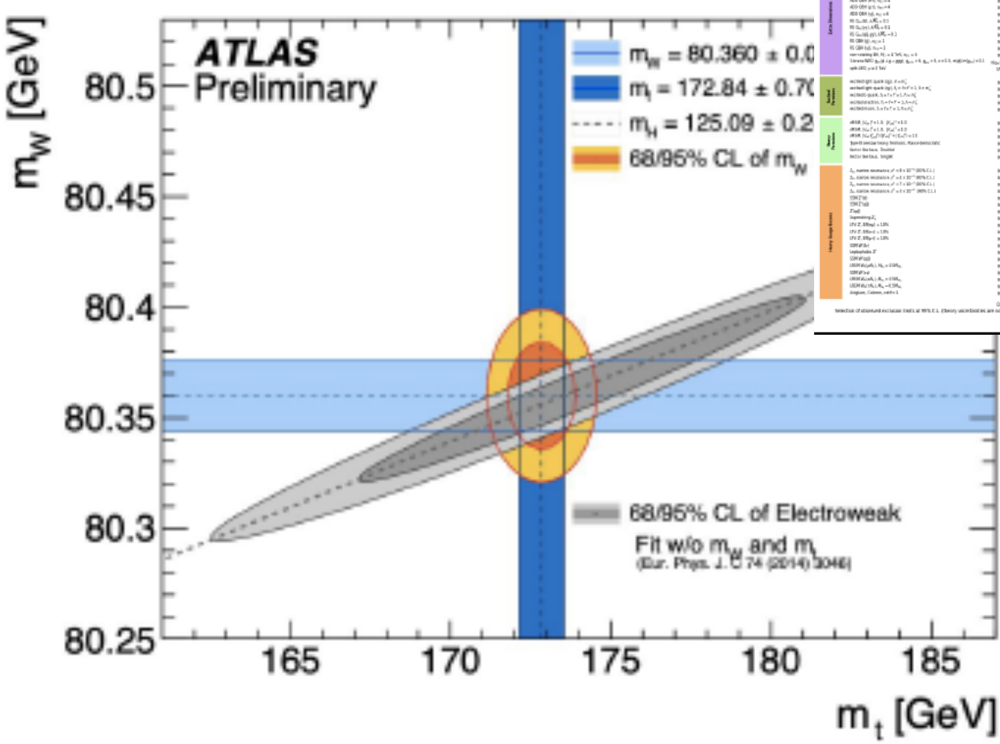
Structure of the

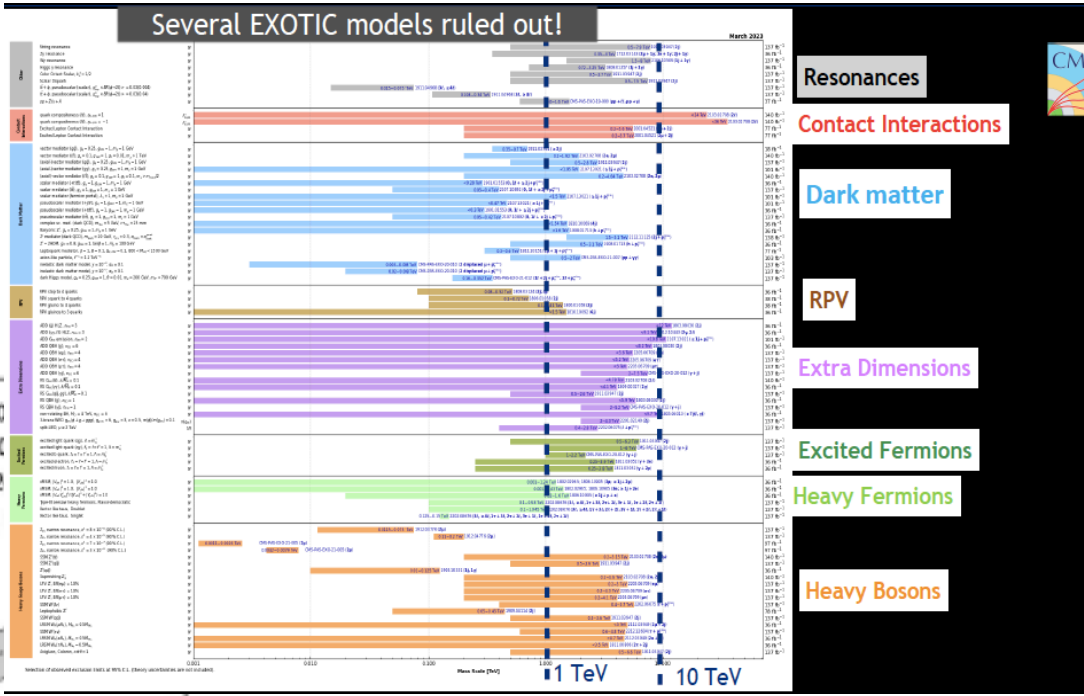
Standard Model of particle physics

Antonio Masiero

University of Padua and INFN

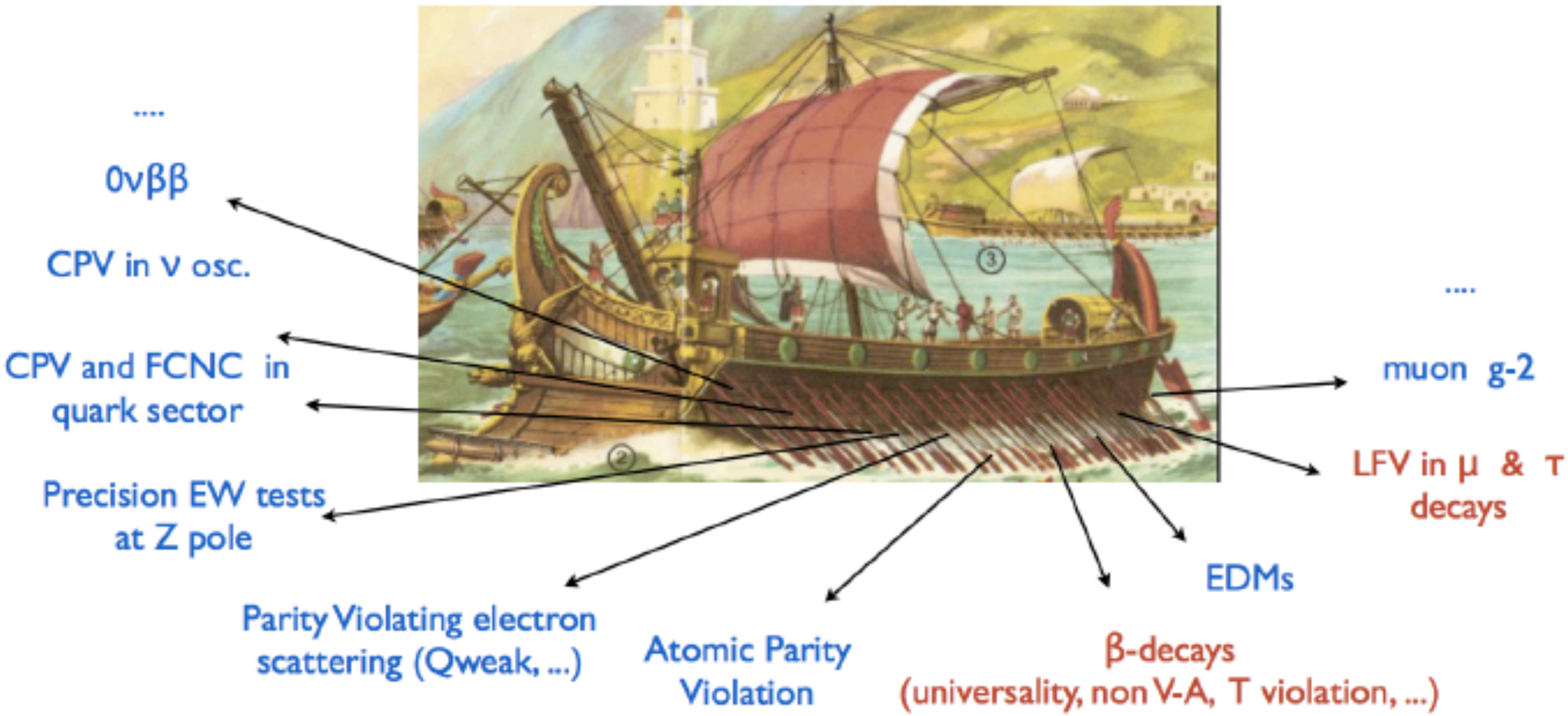
NO hints of BSM new physics from the HIGH-ENERGY FRONTIER





Where to look for New Physics at low-energy?

- **Processes very suppressed or even forbidden in the SM**
- **Processes predicted with high precision in the SM**

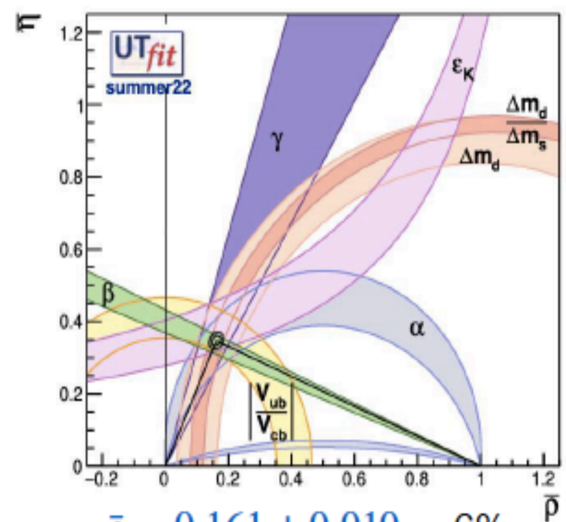


High-intensity frontier: A collective effort to determine the NP dynamics

Consistency tests of the CKM matrix

- At the current level of precision (~%), 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

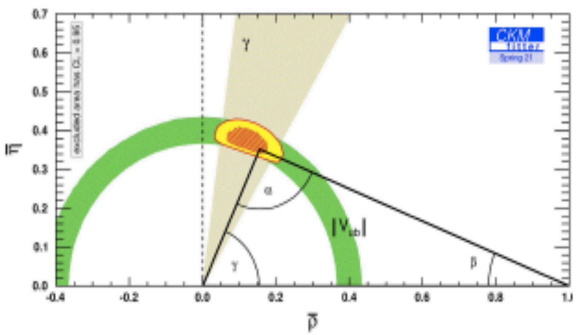
arXiv:2212.03894 UTfit,



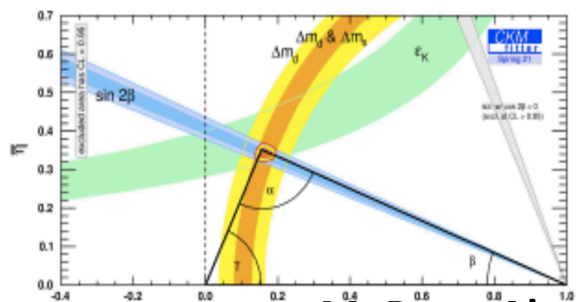
$\bar{\rho} = 0.161 \pm 0.010$ ~6%

$\bar{\eta} = 0.347 \pm 0.010$ ~3%

Tree-level observables



Loop observables



M. Pepe-Altarelli, Erice School, June 2023

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

The FLAVOR PHYSICS test passed unscathed by the SM

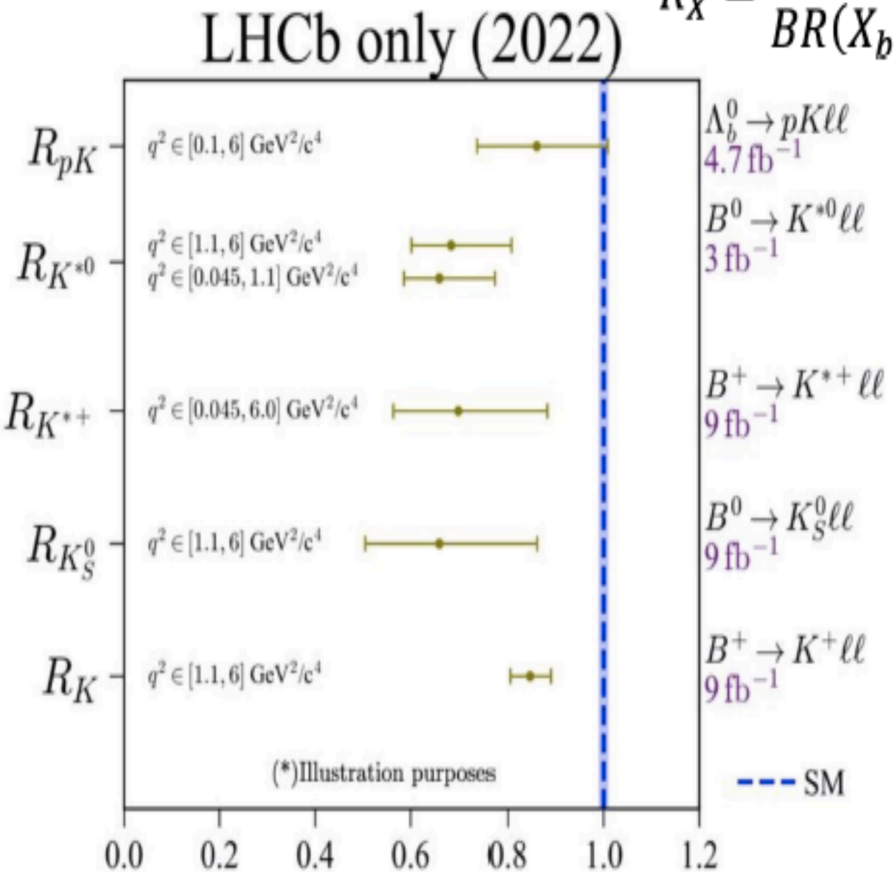
... but for the alleged "B ANOMALIES"

Tests of Lepton Flavour Universality

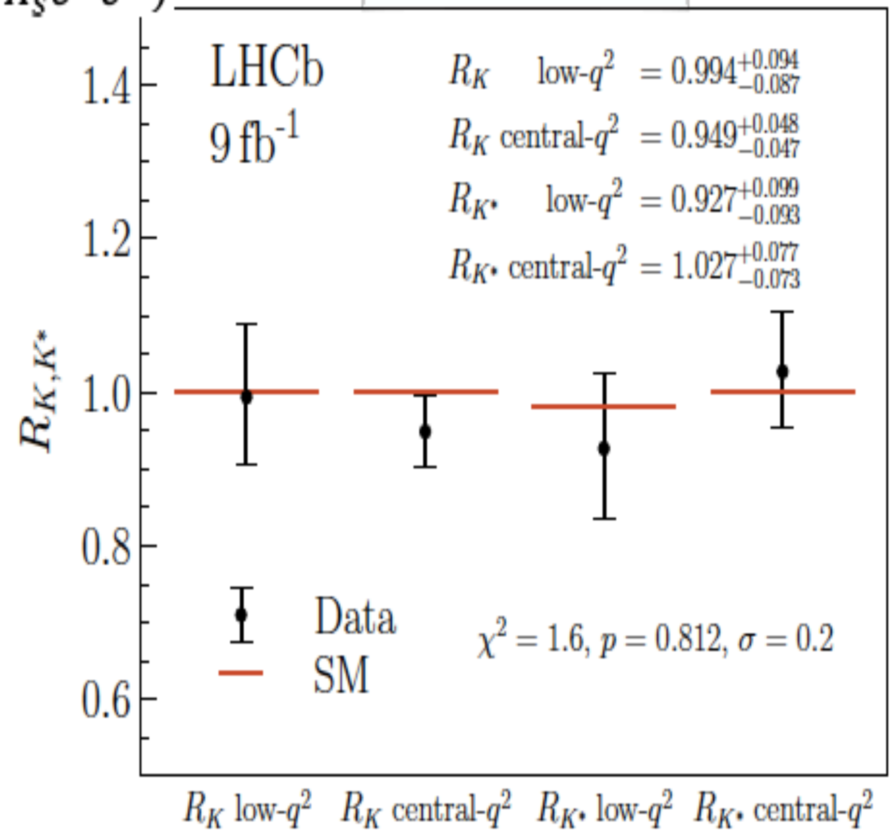
$$R_X = \frac{BR(X_b \to X_s \mu^+\mu^-)}{BR(X_b \to X_s e^+e^-)}$$

arXiv:2212.09152
arXiv:2212.09153

Pre Dec 2022



Post Dec 2022



Low q^2: $q^2 \in [0.1, 1.1]\,\mathrm{GeV}^2/c^4$

Central q^2: $q^2 \in [0.1, 1.1]\,\mathrm{GeV}^2/c^4$

M. Pepe-Altarelli, Erice School, June 2023

Tests of Lepton Flavour Universality

$$R_X = \frac{BR(X_b \to X_s \mu^+ \mu^-)}{BR(X_b \to X_s e^+ e^-)}$$

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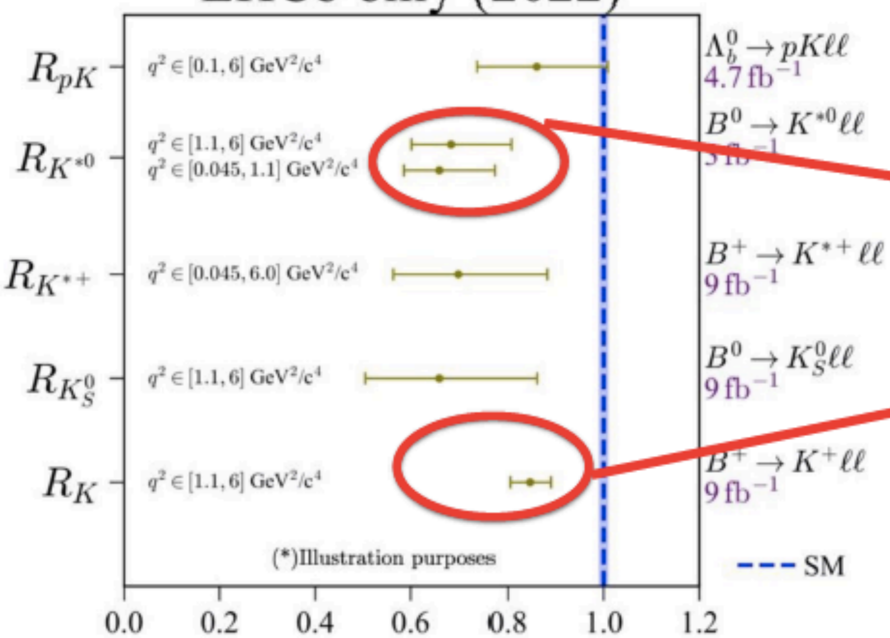
Pre Dec 2022



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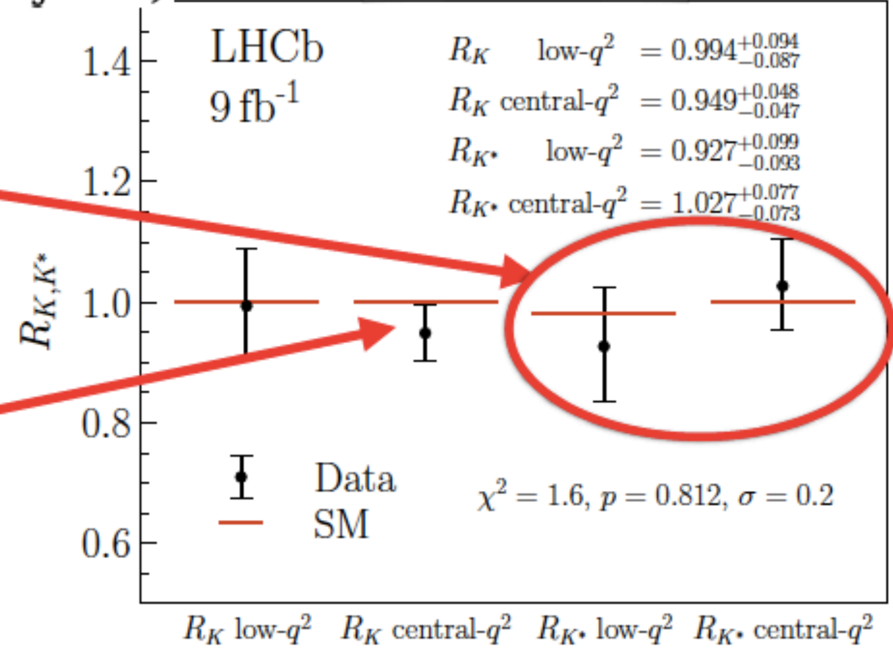

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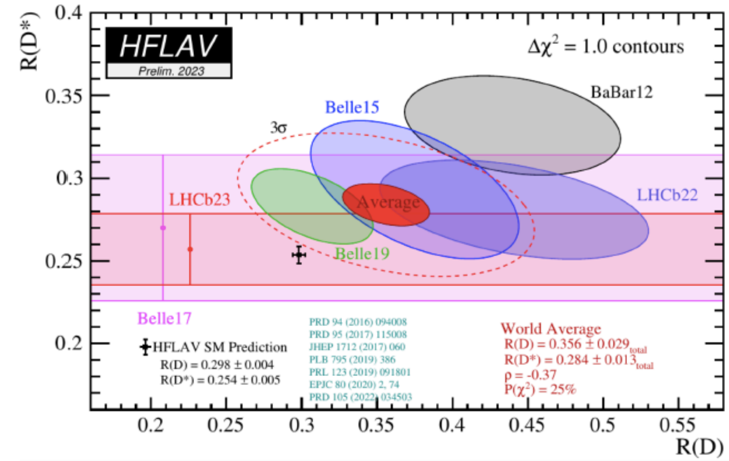
Central q^2: $q^2 \in [0.1, 1.1]\,\mathrm{GeV}^2/c^4$

A remaining flavor puzzle in B physics?

A puzzling result
in tree-level $b \to c$ transitions

$R(D)$ vs $R(D^*)$

3.2 σ tension



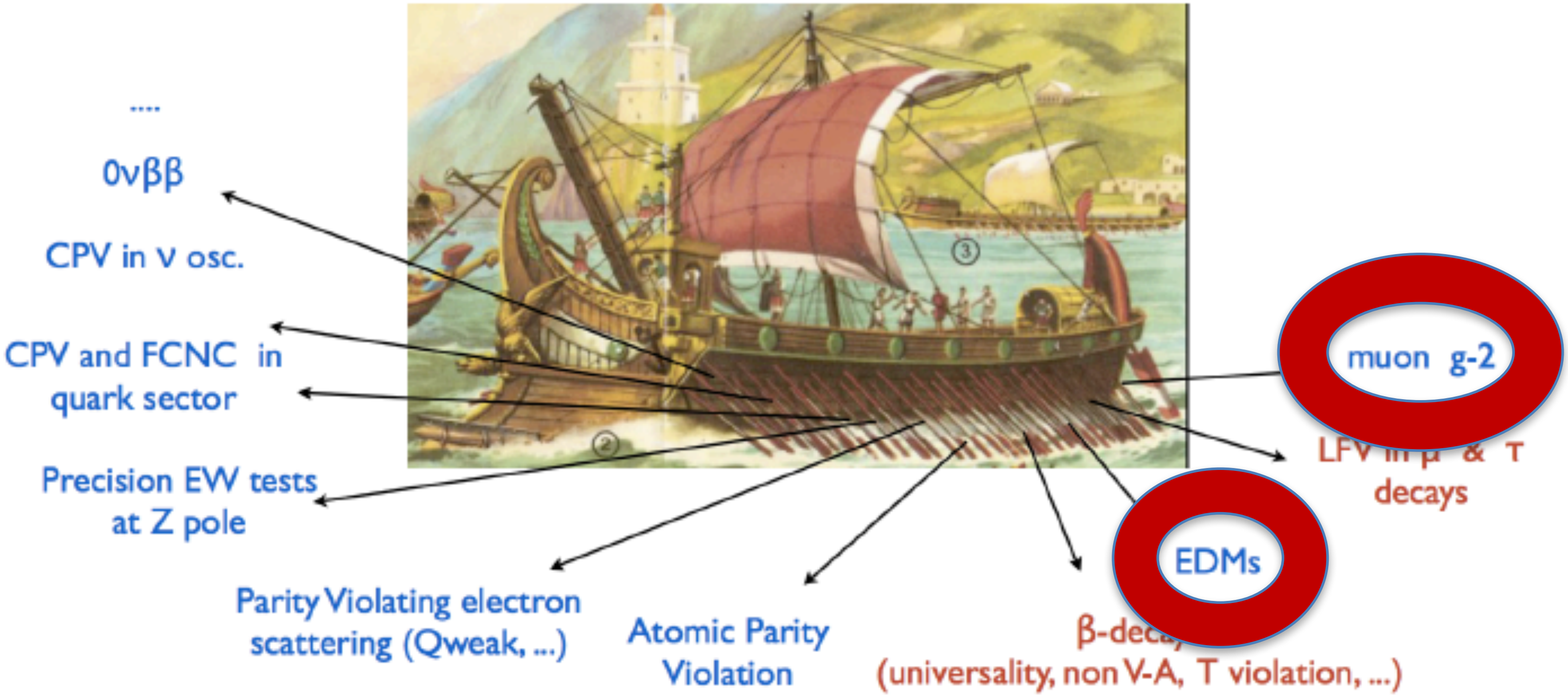
- Other recent predictions, purely lattice-based, give a higher value for $R(D^*)$ and larger uncertainties

48

In conclusion, **NO firm hints for any discrepancy between SM expectations and experimental results in the many and accurate tests in FLAVOR PHYSICS** (FCNC, lepton flavor universality in K,D, B semileptonic decays, etc.)

Where to look for New Physics at low-energy?

- Processes very **suppressed** or even **forbidden** in the SM
- Processes predicted with **high precision** in the SM



High-intensity frontier: A collective effort to determine the NP dynamics

Interaction of a fermion f with the photon field A_μ, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$-d_f \frac{\vec{S}}{|S|} \cdot \vec{E} \qquad \rightarrow \qquad d_f \frac{i}{2} (\bar{f} \sigma_{\mu\nu} \gamma_5 f) F^{\mu\nu}$$

$$-\mu_f \frac{\vec{S}}{|S|} \cdot \vec{B} \qquad \rightarrow \qquad e(\bar{f} \gamma_\mu f) A^\mu + a_f \frac{e}{4m_f} (\bar{f} \sigma_{\mu\nu} f) F^{\mu\nu}$$

the usual minimal coupling of fermions with the photon give rise to a magnetic moment with gyromagnetic factor $g = 2$

the dimension 5 operators induce an electric dipole moment d_f and an anomalous magnetic moment a_f

$$\mu_f = g_f \frac{e}{2m_f} \quad , \qquad (g_f - 2) = 2a_f$$

The $(g\text{-}2)_\mu$ puzzle
the **SM theoretical computation**

QED contribution

"$g-2$ is not an experiment: it is a way of life."

[John Adams (Head of the Proton Synchrotron at CERN (1954-1961))]

This statement also applies to many theorists! [Nyffeler '16]

$$a_\mu^{\mathrm{QED}} = (1/2)\ (\alpha/\pi)$$ [Schwinger, 1948]

$$+\ 0.765857426\ (16)\ (\alpha/\pi)^2$$

[Sommerfield; Petermann; Suura&Wichmann '57; Elend '66]

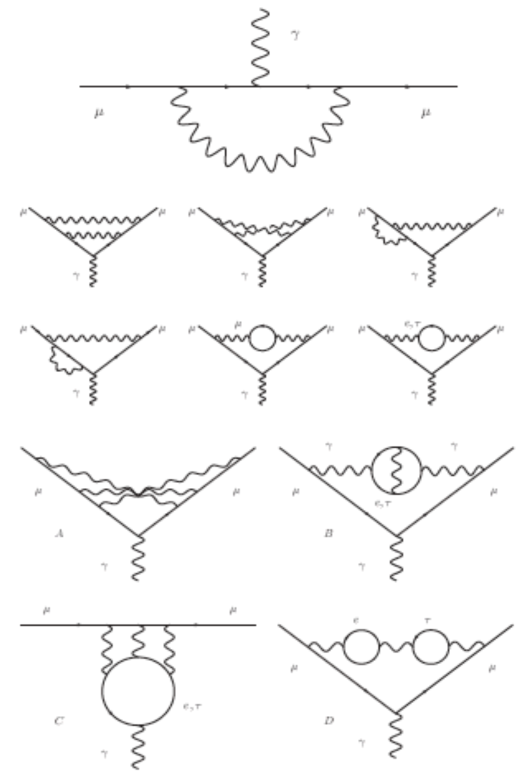
$$+\ 24.05050988\ (28)\ (\alpha/\pi)^3$$

[Remiddi, Laporta, Barbieri...; Czarnecki, Skrzypek '99]

$$+\ 130.8780\ (60)\ (\alpha/\pi)^4$$

[Kinoshita et al. '81-'15; Steinhauser et al. '13-'16; Laporta '17]

$$+\ 750.86\ (88)\ (\alpha/\pi)^5$$ [Kinoshita et al. '90-'19]



$a_\mu^{\mathrm{QED}} = 116584718.931\ (19)(100)(23) \times 10^{-11}$

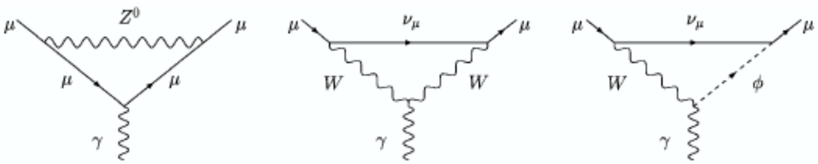
mainly from 4-loop coeff. unc. — 6-loop — from α(Cs)

$\alpha = 1/137.035999046(27)$ [0.2ppb] Parker et al 2018 — WP20 value

[WP20 ≡ T. Aoyama *et al.*, Phys. Rept. '20]

EW contribution

- **One-loop term:**



$$a_\mu^{\mathrm{EW}}(\text{1-loop}) = \frac{5G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1+\frac{1}{5}\left(1-4\sin^2\theta_W\right)^2+O\left(\frac{m_\mu^2}{M_{Z,W,H}^2}\right)\right] \approx 195\times10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda;
Studenikin et al. '80s

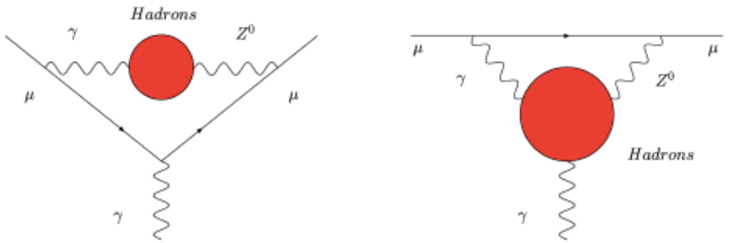
- **One-loop plus higher-order terms:**

$\boxed{a_\mu^{\mathrm{EW}} = 153.6\,(1.0) \times 10^{-11}}$

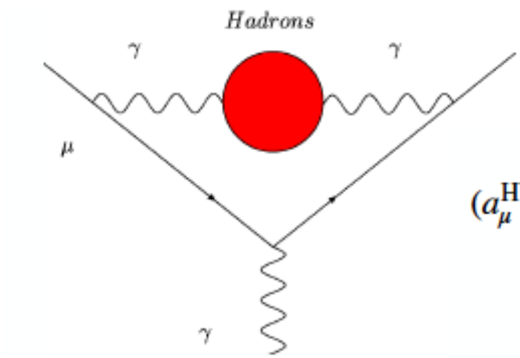
Kukhto et al. '92; Czarnecki, Krause, Marciano '95; Knecht, Peris, Perrottet, de Rafael '02; Czarnecki, Marciano and Vainshtein '02; Degrassi and Giudice '98; Heinemeyer, Stockinger, Weiglein '04; Gribouk and Czarnecki '05; Vainshtein '03; Gnendiger, Stockinger, Stockinger-Kim 2013, Ishikawa, Nakazawa, Yasui, 2019.

Hadronic loop uncertainties (and 3-loop nonleading logs).

WP20 value



Hadronic Vacuum Polarization (HVP) contribution



$\sigma(e^+e^- \to \gamma^* \to \text{hadrons})$

$$(a_\mu^{\mathrm{HVP}})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty} \frac{\mathrm{d}s}{s} K(s)\,\mathrm{Im}\,\Pi_{\mathrm{had}}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} \mathrm{d}s\, K(s)\sigma_{\mathrm{had}}(s)$$

dispersion relations

optical theorem

kernel function

$K(s) \approx m_\mu^2/3s$ for $\sqrt{s} \gg m_\mu$

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s)\, R(s) \qquad R(s) = \frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

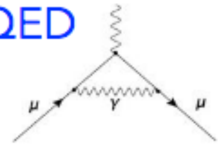
a_μ^{HLO} = 6895 (33) x 10^{-11}	F. Jegerlehner, arXiv:1711.06089
= 6939 (40) x 10^{-11}	Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921
= 6928 (24) x 10^{-11}	Keshavarzi, Nomura, Teubner, arXiv:1911.00367
= **6931 (40) x 10^{-11} (0.6%)**	WP20 value

WP20 = White Paper of the Muon g-2 Theory Initiative: arXiv:2006.04822

The 4 classes of SM contributions: **uncertainty largely dominated** by the **hadronic contributions** in **Vacuum Polarization (HVP)** and **Light-by-Light** (HLbL)

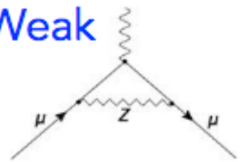
$$a_\mu(\mathrm{SM}) = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{Weak}) + a_\mu(\mathrm{Hadronic})$$

QED



$+\ldots$ $116\,584\,718.9\,(1) \times 10^{-11}$ 0.001 ppm

Weak

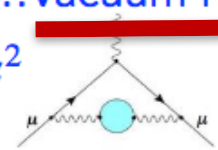


$+\ldots$ $153.6\,(1.0) \times 10^{-11}$ 0.01 ppm

Hadronic…

…Vacuum Polarization (HVP)

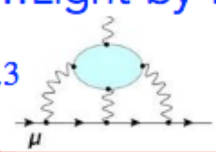
α^2



$+\ldots$ $6845\,(40) \times 10^{-11}$ [0.6%] 0.37 ppm

…Light-by-Light (HLbL)

α^3



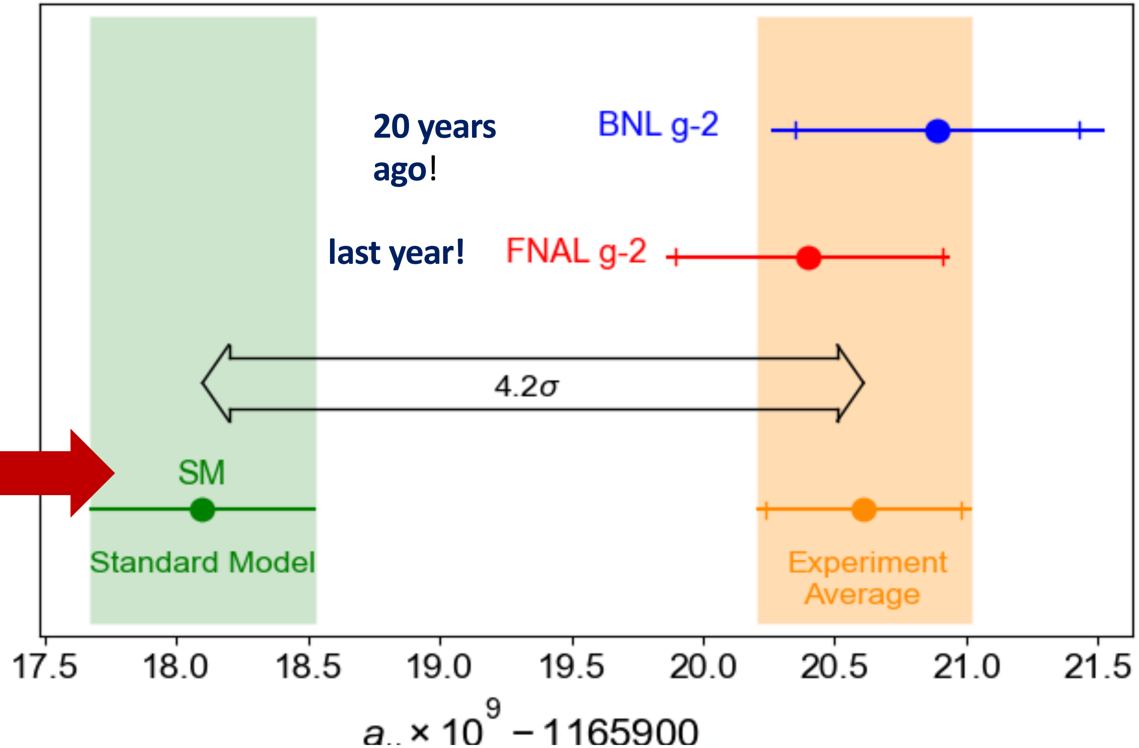
$+\ldots$ $92\,(18) \times 10^{-11}$ [20%] 0.15 ppm

Numbers from Theory Initiative Whitepaper

C. Lehner, April 8, 2021 - CERN EP Seminar

$(g-2)_\mu$ experimental vs. SM theoretical expectation

HVP contribution evaluated using the **dispersion relations** and the exp. $e^+e^- \rightarrow$ hadrons data

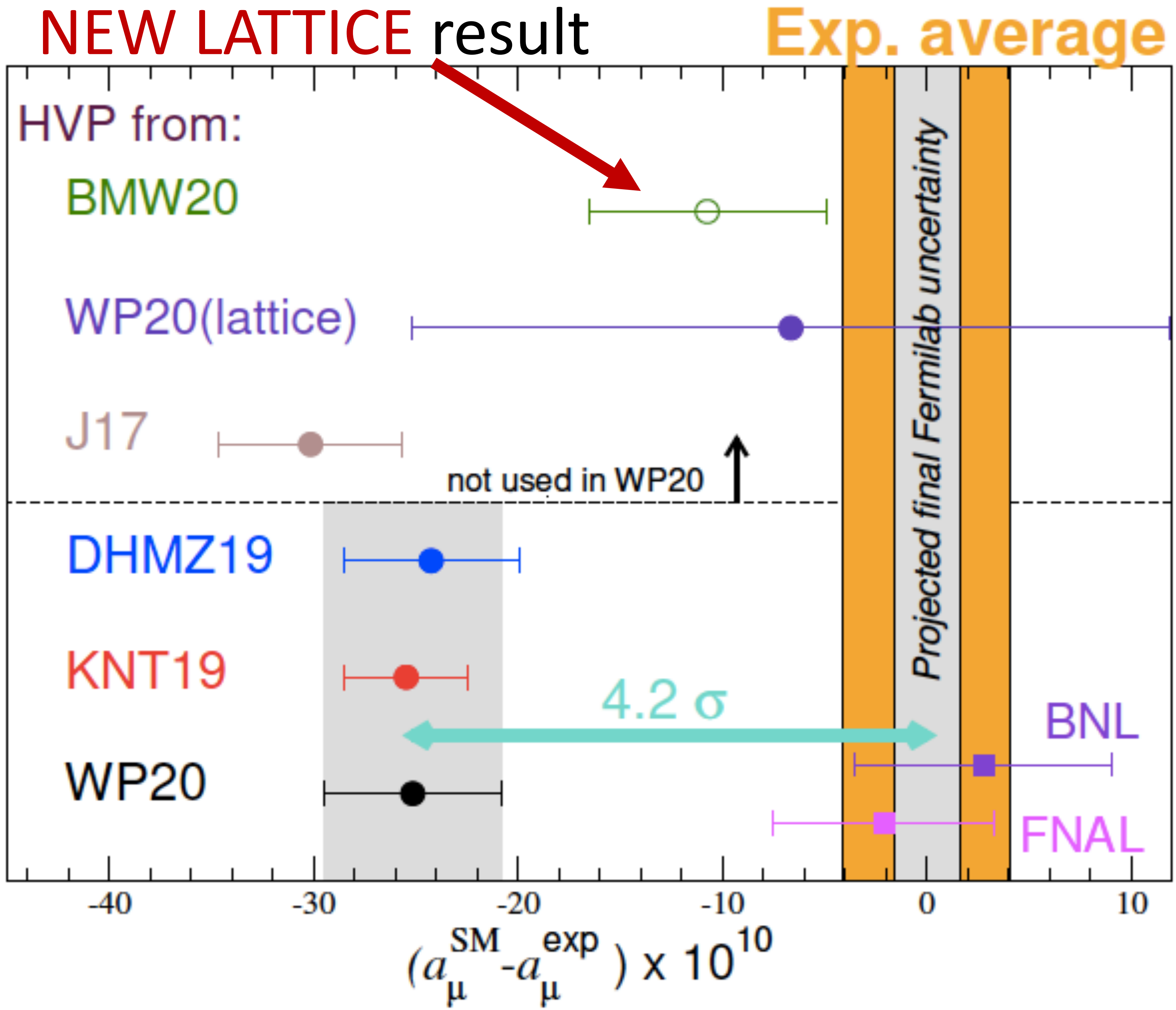


a_μ^{EXP} = (116592089 ± 63) x 10^{-11} [0.54ppm] BNL E821

a_μ^{EXP} = (116592040 ± 54) x 10^{-11} [0.46ppm] FNAL E989 Run 1

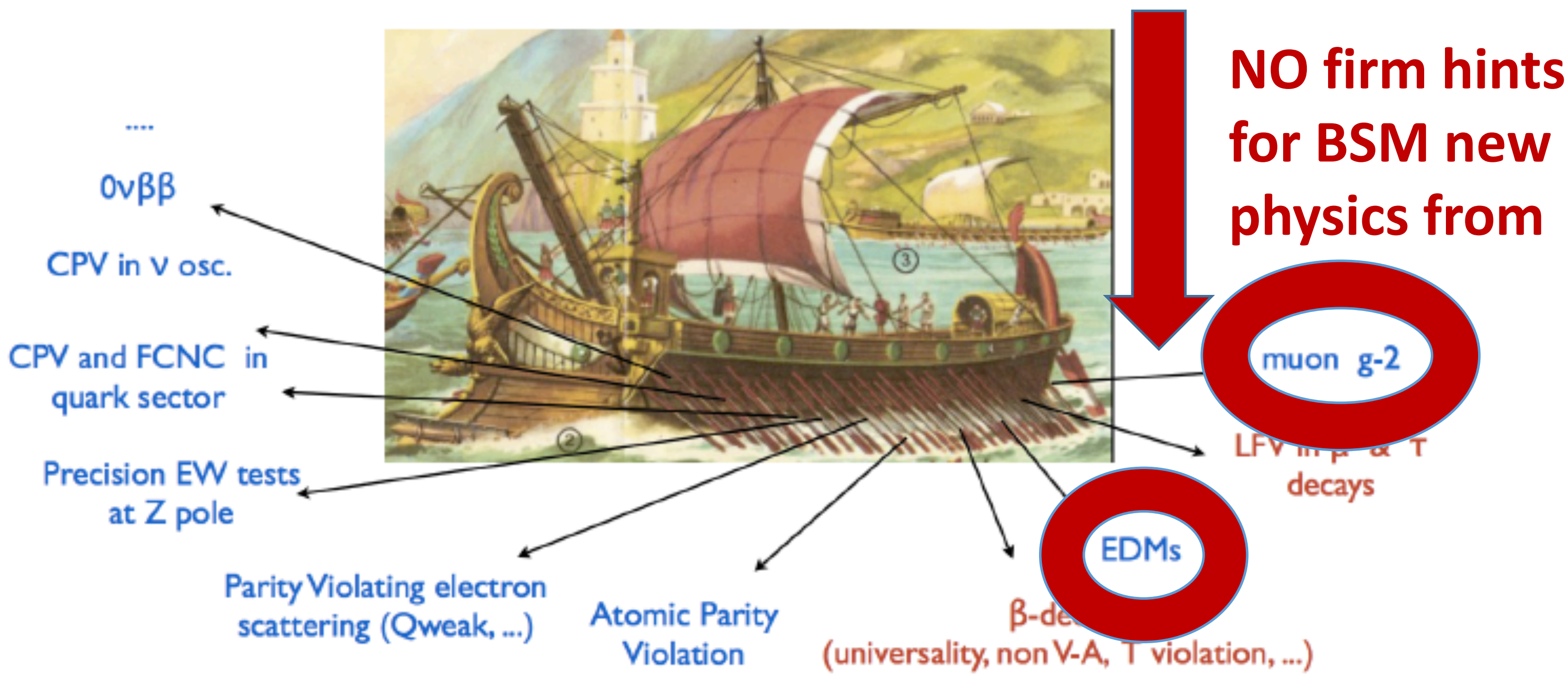
a_μ^{EXP} = (116592061 ± 41) x 10^{-11} [0.35ppm] WA

FNAL aims at 16×10^{-11}


NEW LATTICE result
Exp. average
HVP from:
BMW20
WP20(lattice)
J17
not used in WP20
DHMZ19
KNT19
WP20
Projected final Fermilab uncertainty
4.2 σ
BNL
FNAL
-40
-30
-20
-10
0
10
$(a_\mu^{SM} - a_\mu^{exp}) \times 10^{10}$

Where to look for New Physics at low-energy?

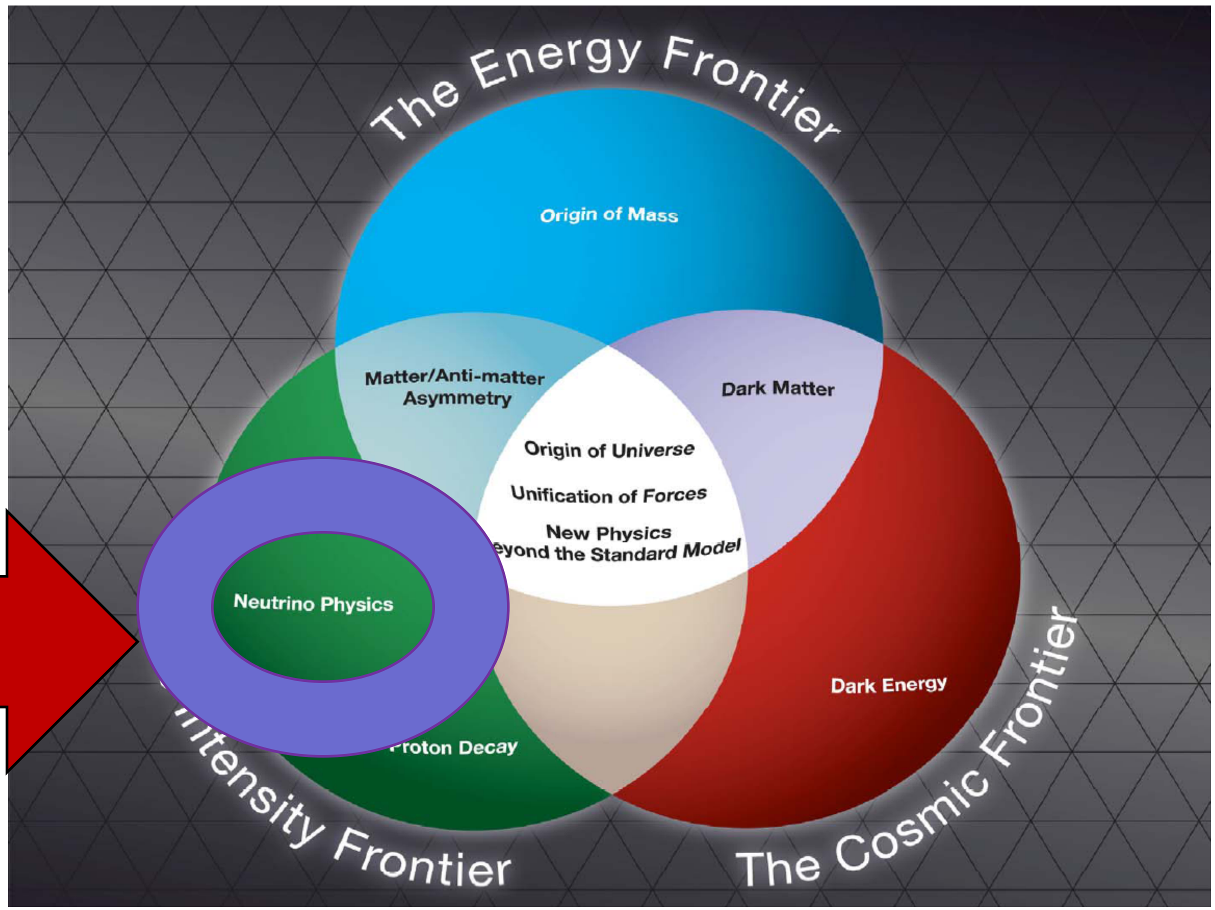
- **Processes very suppressed or even forbidden in the SM**
- **Processes predicted with high precision in the SM**



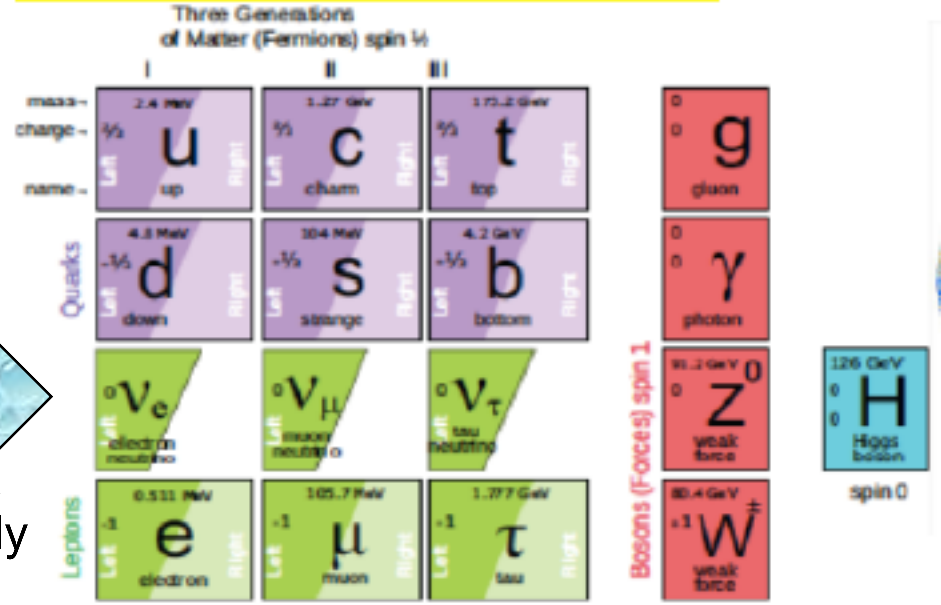
High-intensity frontier: A collective effort to determine the NP dynamics

NO (firm) HINTS **for BSM NEW PHYSICS** from the **HIGH ENERGY** and **INTENSITY frontiers,**

BUT…



MICRO-COSMOS



ν peculiarity: in the SM

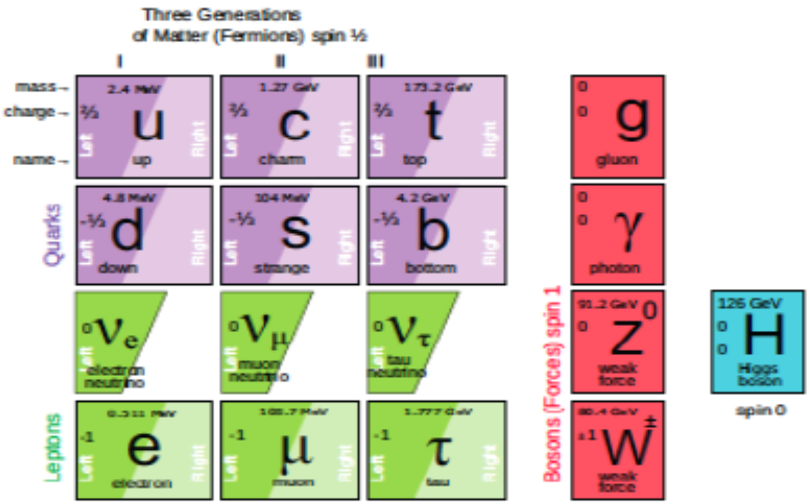
ONLY LEFT-HANDED ν

i) **V– A** structure of the charged weak currents (i.e. the W boson couples only to the **LEFT-HANDED** fermions) ;

ii) ν doesn't couple to photons (no neutral currents observed at the time the SM was proposed);

iii) In any case, even **today no hint** of the presence of a **right-handed neutrino**

iv) Before observing neutrino oscillations, this (very light) particle was widely thought to be **massless** → **no need for the presence of its right-handed component**



- No DIRAC mass

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

Need of a new particle: the RH neutrino ν_R

NO MAJORANA mass

$$\nu^T{}_R\, \nu_R \text{ or } \boxed{\nu^T{}_L\, \nu_L} \rightarrow$$

No $SU(2)_L$ and $U(1)_Y$ invariant

To obtain a neutrino mass in the renormalizable SM --> need of new particles (**ν_R**, **Δ** scalar triplet of $SU(2)_L$)

$U(1)_B$: B(q) = 1/3 ; B(all other SM fields) = 0

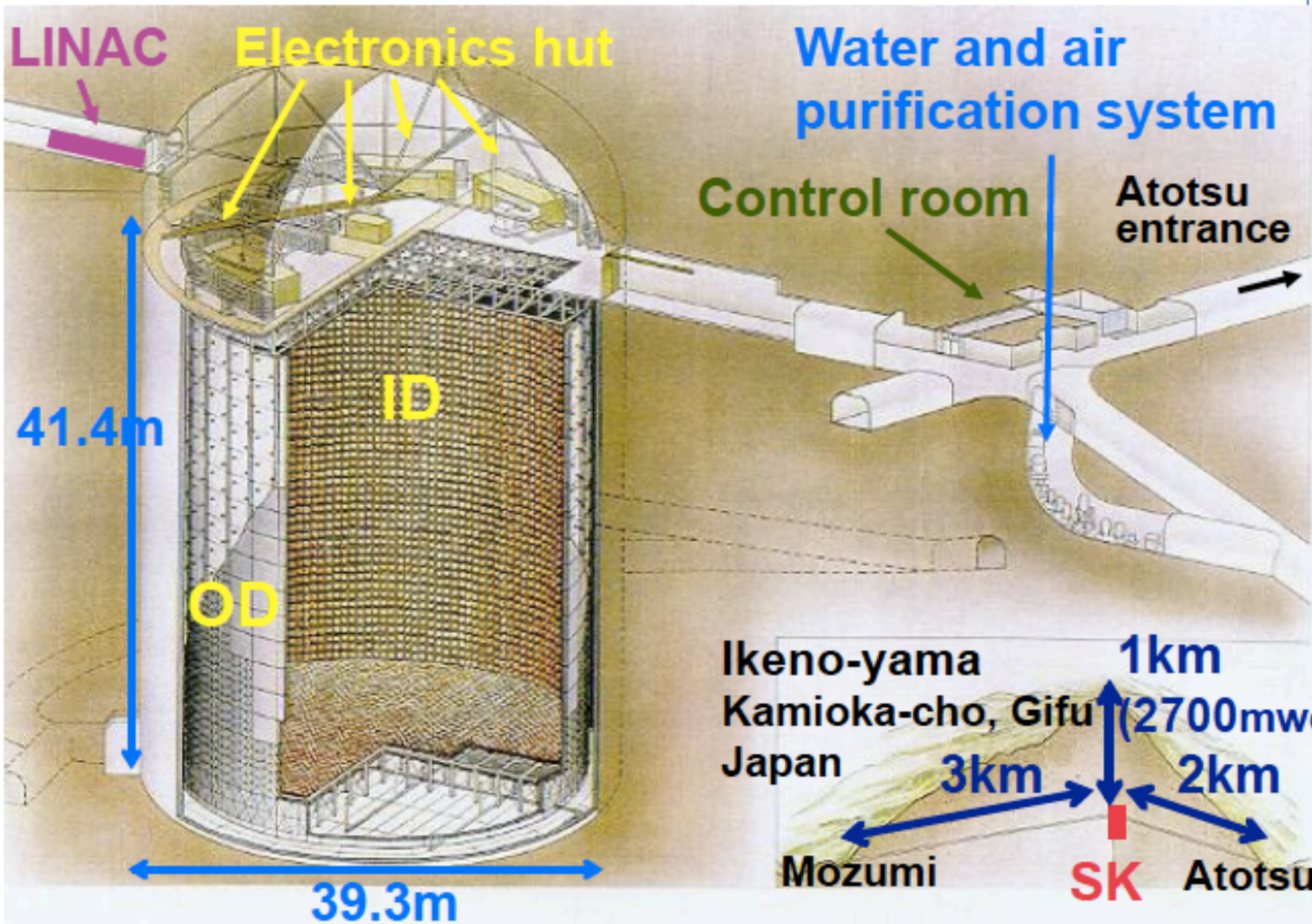
$U(1)_L$: L(leptons) = 1; L (all other SM fields) = 0

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

Super-Kamiokande detector

M. Nakahata, Erice School, 2023

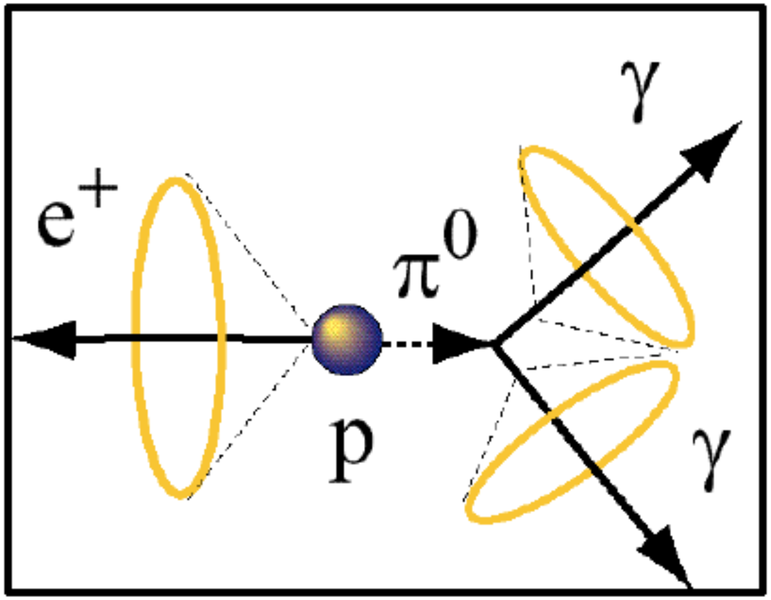


- 50 kton water Cherenkov
- 32kt photo-sensitive volume
- 22.5kt fid. vol. (2m from ID wall)
- SK-I: April 1996~
- SK-VII is running

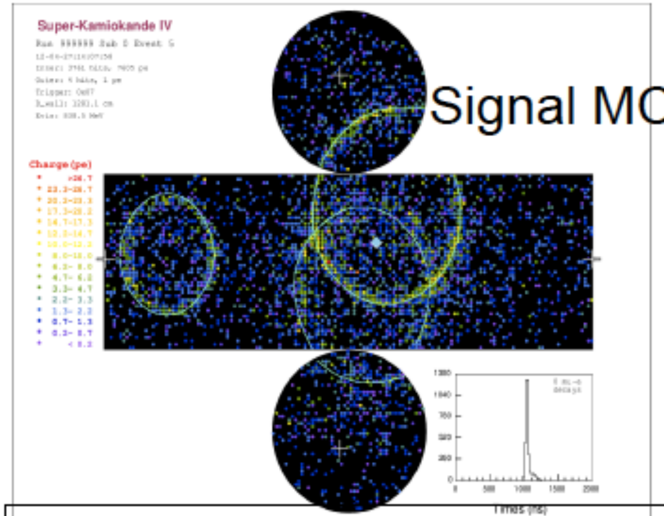
Inner Detector (ID) PMT: ~11,000 20-inch PMTs
Outer Detector (OD) PMT: 1885 8-inch PMTs

Search for Proton decays

Search for $p \rightarrow e^+\pi^0$



- **Positron and π^0 run back-to-back**
  - Momentum 459 MeV/c
- **All particles in the final stable are visible with Super-K**
  - **Able to reconstruct p mass and momentum**



- Event selection:
  - All particles are fully contained in FV
    - (New!) Expand FV (dwall >200 cm → > 100 cm)
  - 2 or 3 rings (two of them from π0)
  - All particles are e-like, w/o Michel-e
  - $85 < M_{\pi 0} < 185$ MeV/c^2
  - $800 < M_p < 1050$ MeV/c^2
  - $100 < P_{tot} < 250$ or $P_{tot} < 100$MeV/c
  - Neutron-tagging (SK-IV)
    - Further reduce bkg by ~50%

M. Nakahata, Erice School, 2023

Results on $p \rightarrow e^+\pi^0$ and $p \rightarrow \mu^+\pi^0$

	Eff(%)	Exp. BG (event)	Observed (event)
$p \rightarrow e^+\pi^0$			
Lower	18.1	0.02	0
Upper	19.5	058	0
$p \rightarrow \mu^+\pi^0$			
Lower	17.3	0.05	0
Upper	17.2	0.89	1

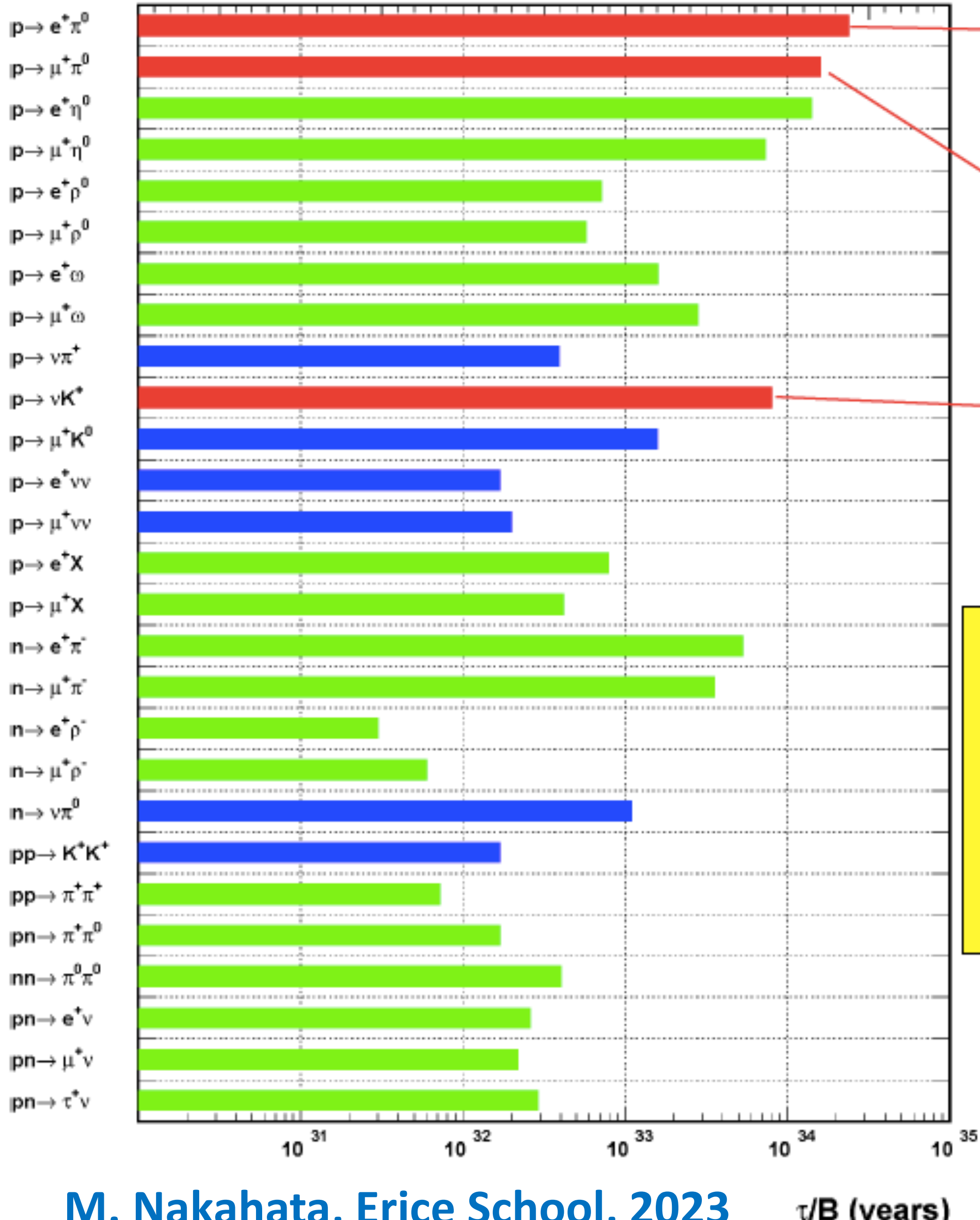
Lifetime limt (90% CL,450 kton・yrs data)

$p \rightarrow e^+\pi^0$: > 2.4×10^{34} years

$p \rightarrow \mu^+\pi^0$: > 1.6×10^{34} years

M. Nakahata, Erice School, 2023

Nucleon decay limits for various decay modes



$p \rightarrow e^+\pi^0$ (450 kt·yrs)
$\tau/Br > 2.4 \times 10^{34}$ years

$p \rightarrow \mu^+\pi^0$ (450 kt·yrs)
$\tau/Br > 1.6 \times 10^{34}$ years

$p \rightarrow \bar{\nu} K^+$ (365kt·yrs)
$\tau/Br > 8.2 \times 10^{33}$ years

- Reached around 10^{34} years for favored decay modes.
- Searched systematically also for the other modes and reached 10^{32} - 10^{34} years.
- Strictest limits in the world.

Red: analyzed with 450/365kt·yrs data
Green: analyzed with 350kt·yrs data
Blue: analyzed with SK I-III (173kt·yrs)

M. Nakahata, Erice School, 2023

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.**

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

Choice A) → in this case $U(1)_L$ is **no longer an AUTOMATIC SYMMETRY** of the theory, rather it is a **NEW GLOBAL SYMMETRY** one imposes by hand **IN ADDITION** to the SM gauge symmetry.

THE FATE OF LEPTON NUMBER

L VIOLATED

υ Majorana ferm.

L CONSERVED

υ Dirac ferm.
(dull option)

SMALLNESS of m_υ

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

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

PRESENCE OF A NEW PHYSICAL MASS SCALE

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	~O	$h \langle \phi \rangle$
υ_R	$h \langle \phi \rangle$	M

LR
Models?

MAJORON MODELS

Gelmini, Roncadelli;
Glashow et al.

Δ ENLARGEMENT OF THE HIGGS SCALAR SECTOR

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

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

ν mass in the

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

LLHH dim 5 → $M^{-1} LL\langle H\rangle\langle H\rangle$

$$m_\nu \to \langle H\rangle^2 / M$$

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

Baryon number violation in the SM as an **Effective low-energy remnant** of a more fundamental theory at a **higher mass scale M**

qqql → es. $U_R\, U_R\, D_R\, E_R$ → **$p \to e^+ \pi^o$**

B – L conserved

qqql dim 6 M^{-2} qqql

$\tau_p > 10^{34}$ years → **$M > 10^{15}$ GeV**

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 FRICTION POINTS

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

THE FLAVOUR PROBLEMS

FERMION MASSES

What is the rationale hiding behind the spectrum of fermion masses and mixing angles (our "**Balmer lines**" problem)

→ **LACK OF A FLAVOUR "THEORY"**

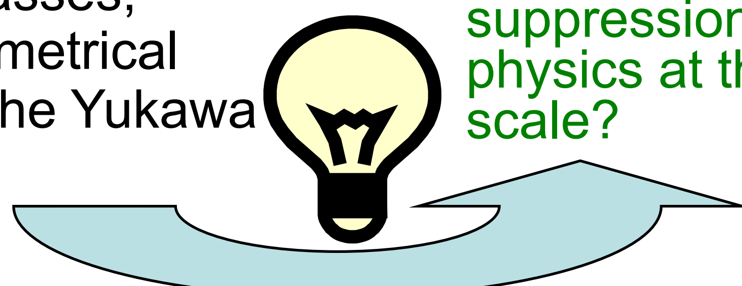
(new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, …?)

FCNC

Flavour changing neutral current (FCNC) processes are suppressed.

In the SM two nice mechanisms are at work: the **GIM mechanism** and the structure of the **CKM mixing matrix.**

How to cope with such delicate suppression if the there is new physics at the electroweak scale?



Chiral symmetry breaking

in the two flavor quark model (u,d)

$$SU_L(2) \otimes SU_R(2) \otimes U_A(1) \otimes U_V(1)$$

$$\downarrow$$

$$SU_V(2) \otimes U_V(1)$$

4 Nambu-Goldstone bosons $\pi^+ \; \pi^0 \; \pi^- \; \eta$

$$m_\eta < \sqrt{3}\, m_\pi$$ S. Weinberg

The $U_A(1)$ Problem

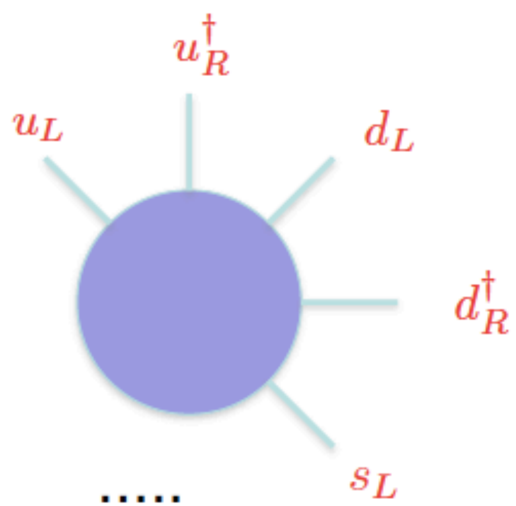
P. Sikivie, Erice School 2023

In Quantum Chromodynamics (QCD)

$U_A(1)$ has a Adler-Bell-Jackiw anomaly, and is therefore explicitly broken.

Quantum tunneling events, called instantons, produce axial charge for each flavor

't Hooft, 1976



$$\mathcal{L}_{\mathrm{QCD}} = \ \dots \ + \ \bar{\theta}\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta - \arg\left(m_u \, m_d \ \dots \ m_t\right)$$

P. Sikivie, Erice School 2023

The Strong CP Problem

$$\mathcal{L}_{\rm QCD} = \;...\; + \;\bar{\theta}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

where

$$\begin{aligned}\bar{\theta} &= \theta - \arg\left(m_u\, m_d \;\ldots\; m_t\right) \\ &= \theta - \arg\det\left(Y^u\, Y^d\right)\end{aligned}$$

The absence of P and CP violation in the strong interactions requires

$$\bar{\theta} \leq 10^{-10}$$

from upper limit on the neutron electric dipole moment

P. Sikivie, Erice School 2023

$$U_{PQ}(1)$$

- is a symmetry of the classical action

- is spontaneously broken

- has a color anomaly

Peccei and Quinn, 1977

If a $\mathrm{U_{PQ}(1)}$ symmetry is assumed,

$$\mathcal{L} = \; ... \; + \; \frac{a}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \; + \; \frac{1}{2}\partial_\mu a \partial^\mu a$$

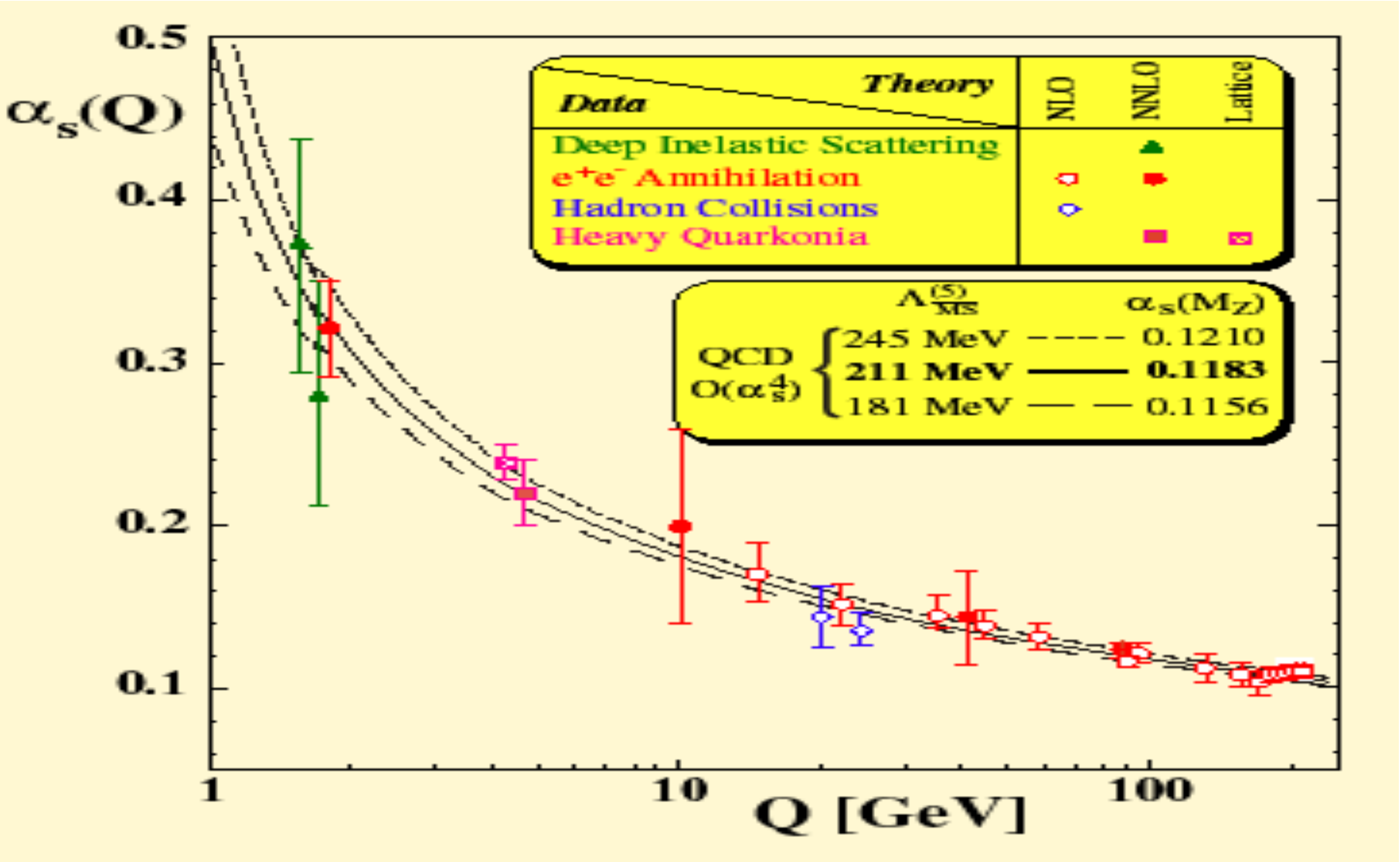
$\bar{\theta} = \dfrac{a}{f_a}$ relaxes to zero,

and a light neutral pseudoscalar particle is predicted: the axion.

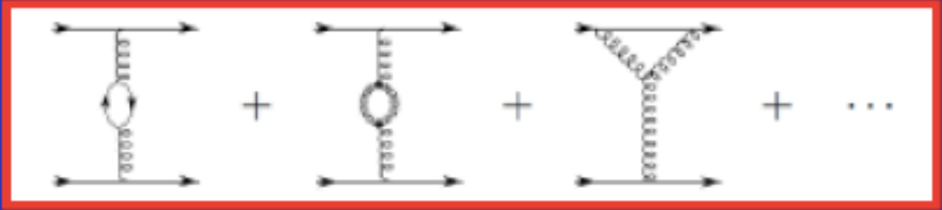
Weinberg, Wilczek 1978

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

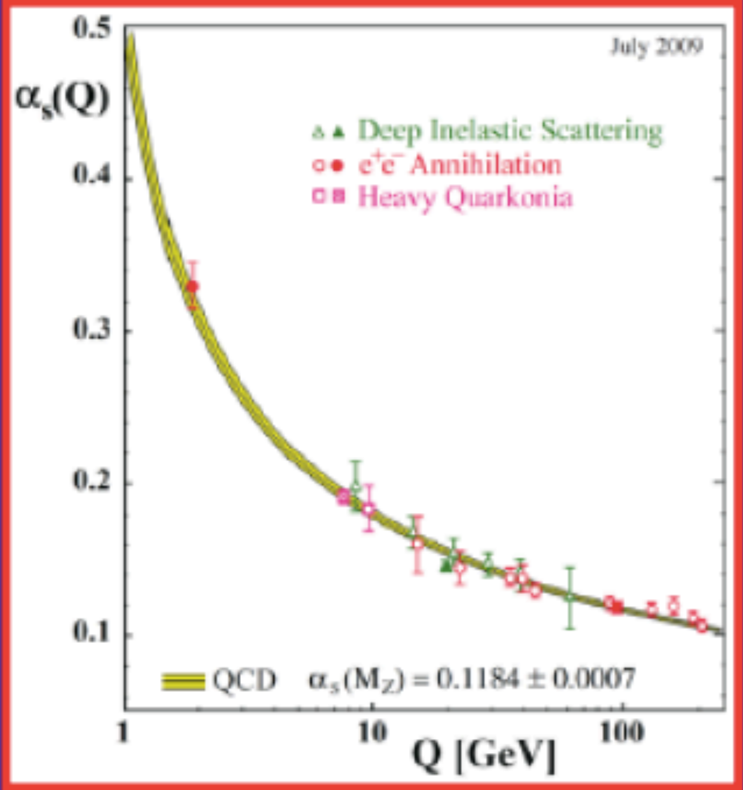
RUNNING COUPLING CONSTANTS



ASYMPTOTIC FREEDOM



$$\alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{1 - \beta_1 \frac{\alpha_s(Q_0^2)}{2\pi} \log\left(\frac{Q^2}{Q_0^2}\right)}$$



$$\beta_1 = \frac{2\,N_F - 11\,N_C}{6} < 0 \quad \Rightarrow \quad \lim_{Q^2\to\infty} \alpha_s(Q^2) = 0$$

$\alpha_s(Q^2)$ increases at low energies

$\alpha_s \sim O(1)$ at 1 GeV

Non–Perturbative Region

$\Rightarrow$ **CONFINEMENT ?**

GRAND UNIFICATION

$$\frac{d\alpha_i}{d\ln q^2} = b_i\,\alpha_i^2 + O(\alpha_i^3)$$

$$\begin{cases} b_3 = -\frac{1}{4\pi}\left[\frac{11}{3}\cdot 3 - \frac{4}{3}\,n_{gener.} + \underset{\text{+ scalars}}{\cdots}\right] \\ b_2 = -\frac{1}{4\pi}\left[\frac{11}{3}\cdot 2 - \frac{4}{3}\,n_{gener} + \cdots\right] \end{cases}$$

$$b_1 = -\frac{1}{4\pi}\left[-\frac{4}{3}\,n_{gener.} + \cdots\right]$$

with Y defined by $Q = T_3 + \sqrt{\frac{5}{3}}\,Y$

$$\frac{1}{\alpha_i(q^2)} = \frac{1}{\alpha_i(M_X^2)} + b_i \ln\left(M_X^2/q^2\right)$$

ask for: $\alpha_1(M_X^2) = \alpha_2(M_X^2) = \alpha_3(M_X^2) = \alpha_G$

unknown: α_G, M_X, $\sin^2\theta_W$ (or α_3)

$\Rightarrow$ possible to DETERMINE (predict) a LOW EN. PARAM

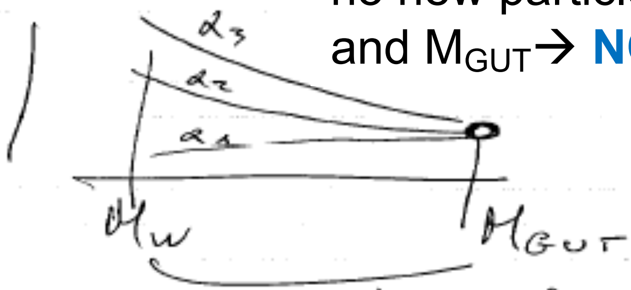
$\sin^2\theta_W \simeq 0.2$ in the right ball-park!

But with today precision: α_s predicted several standard deviations away from the correct value $\Rightarrow$ need some modification

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**

from

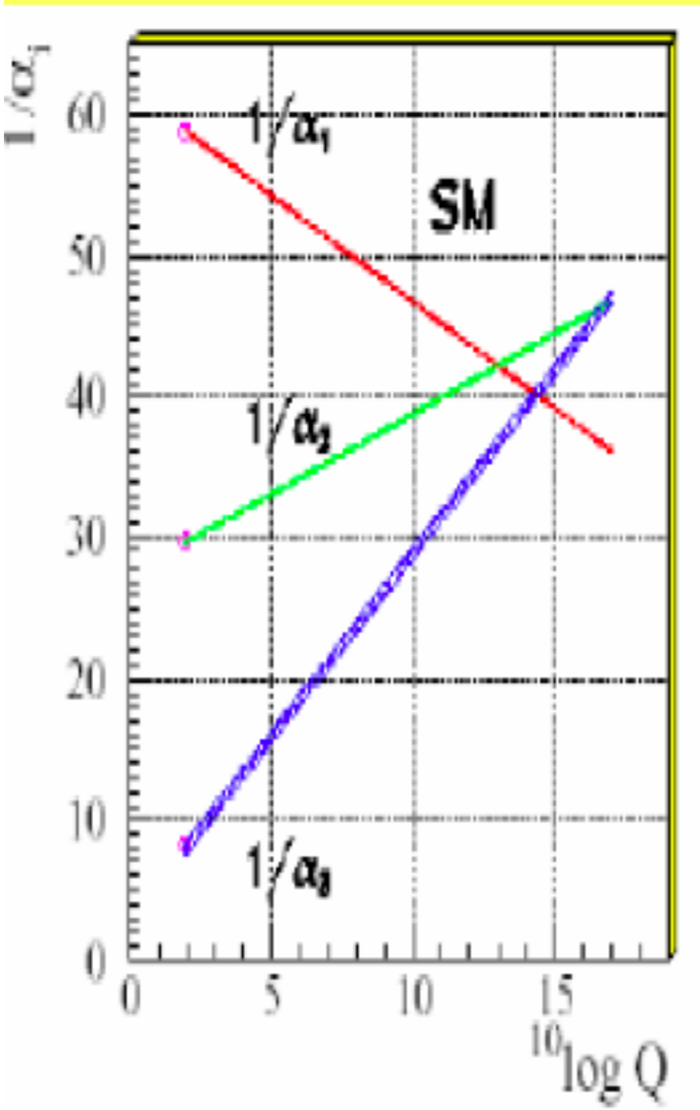


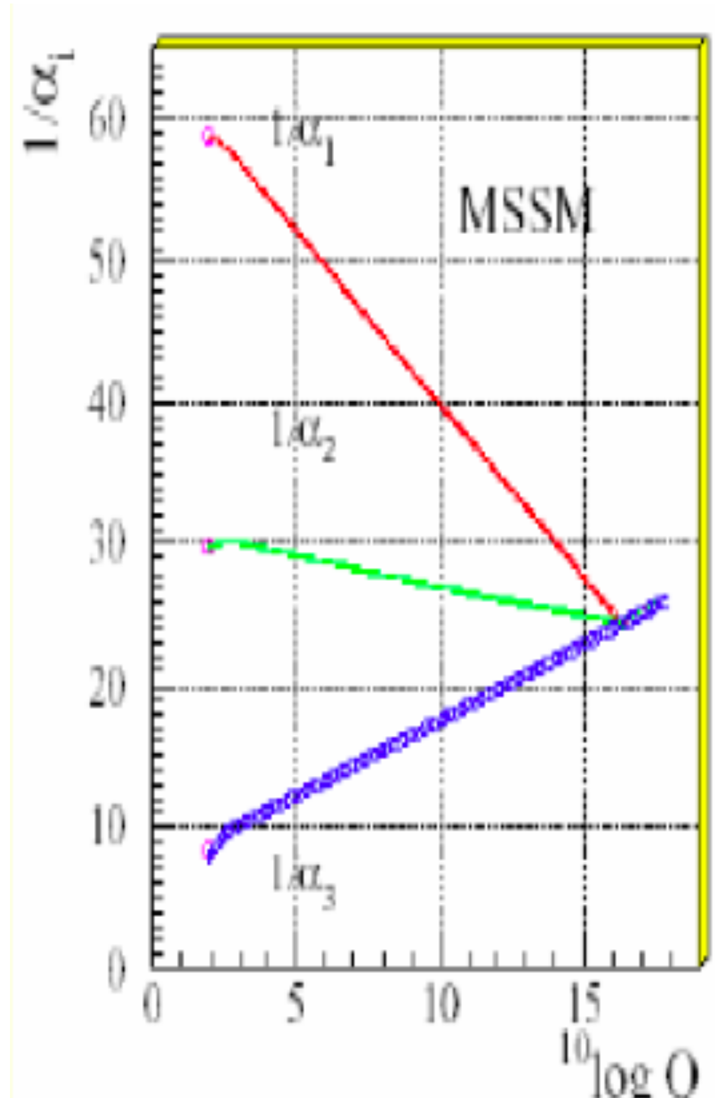
13 orders of magnitude

NEED SOME NEW PHYSICS between M_W and M_{GUT} to modify the slopes of the 3 curves to obtain the correct value of α_S (or $\sin\theta_W$) as the low-energy prediction!

Ex: new SUSY particles at ~ M_W ?

Only one fundamental interaction?





“*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, $m_W \leq$ <H>

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

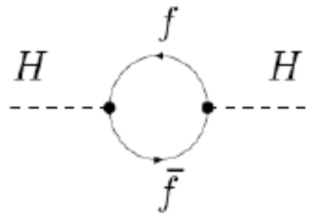
⇨ SUSY BREAKING ~ SCALE OF 0 (10^2-10^3 Gev)

→ 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: $i(p^2 - M_H^2 + \Sigma_H^f)$

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

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

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

DESTABILIZATION OF THE ELW. SYMMETRY BREAKING SCALE

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

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

(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): $\delta M_H^2 \approx M_{\text{GUT}}^2$

SYMMETRY $\longrightarrow$ 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 $\longrightarrow$

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

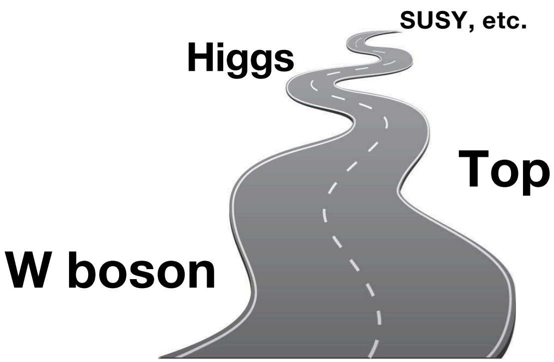
- H is a fundamental (elementary) particle → we live in a universe where the fine-tuning at M arises (anthropic solution, multiverse, Landscape of string theory)

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

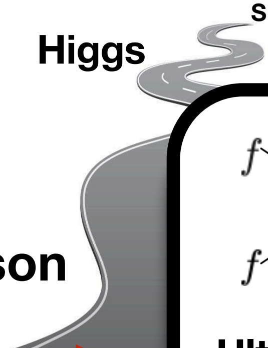
HEP before the LHC



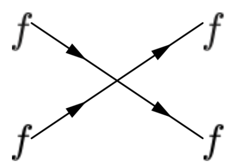
HEP before the F.C.

Ideology

HEP before the LHC | **HEP before the F.C.**



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

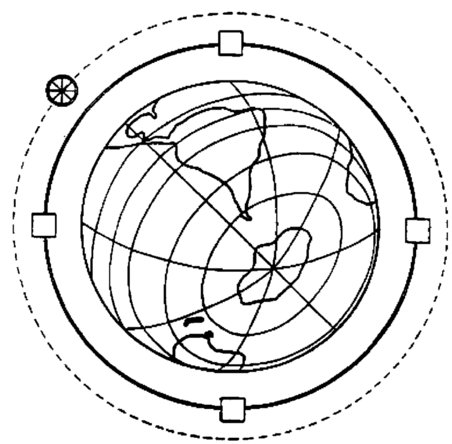


$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \longrightarrow m_W < 4\pi v$$

Ultimate Accelerator.

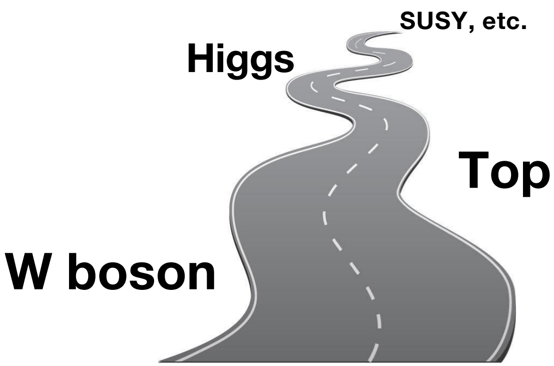
Drawn by Fermi in the ’50 to reach 3 TeV.

The manifesto of HEP!



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

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 calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale +

★★ CORRECT GRAND UNIFICATION "CALLS" FOR NEW PARTICLES AT THE ELW. SCALE (in particular few hundred GeV SUSY particles)

ELW. SYMM. BREAKING STABILIZATION VS. FLAVOR PROTECTION: THE SCALE TENSION

$$M(B_d\text{-}\bar{B}_d) \sim \; c_{SM} \frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{new} \frac{1}{\Lambda^2}$$

If $c_{new} \sim c_{SM} \sim 1$

Isidori

$\Lambda > 10^4$ TeV for $O^{(6)} \sim (\bar{s}\,d)^2$

[K^0-$\bar{K}^0$ mixing]

$\Lambda > 10^3$ TeV for $O^{(6)} \sim (\bar{b}\,d)^2$

[B^0-$\bar{B}^0$ mixing]

UV SM COMPLETION TO STABILIZE THE ELW. SYMM. BREAKING: ΛUV ~ O(1 TeV)

How large Λ NP and/or how small the "angles" of the Λ = 1 TeV NP couplings have to be to cope with the FCNC ?

Mixing	$\Lambda_{NP}^{CPC} \gtrsim$	$\Lambda_{NP}^{CPV} \gtrsim$
$K-\overline{K}$	1000 TeV	20000 TeV
$D-\overline{D}$	1000 TeV	3000 TeV
$B-\overline{B}$	400 TeV	800 TeV
$B_s-\overline{B}_s$	70 TeV	70 TeV

Y. NIR et al.

$K-\overline{K}$	8×10^{-7}	6×10^{-9}
$D-\overline{D}$	5×10^{-7}	1×10^{-7}
$B-\overline{B}$	5×10^{-6}	1×10^{-6}
$B_s-\overline{B_s}$	2×10^{-4}	2×10^{-4}

SMALLNESS OF THE NP COUPLINGS IF THE NP SCALE IS 1 TEV

$$Y_t\sim1,\quad Y_c\sim10^{-2},\quad Y_u\sim10^{-5}$$
$$Y_b\sim10^{-2},\quad Y_s\sim10^{-3},\quad Y_d\sim10^{-4}$$
$$Y_\tau\sim10^{-2},\quad Y_\mu\sim10^{-3},\quad Y_e\sim10^{-6}$$
$$|V_{us}|\sim0.2,\quad |V_{cb}|\sim0.04,\quad |V_{ub}|\sim0.004,\quad \delta_{\rm KM}\sim1$$

SMALLNESS OF THE SM COUPLINGS

What about new physics?

Effective field theory

Λ_{UV}

TeV

Simplicity 🙂

Naturalness 🙁

TeV Λ_{UV}

Naturalness 🙂

Simplicity 🙁

$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \ldots$$

$m_h^2 \simeq \Lambda^2$

$\Rightarrow \Lambda \simeq 10^3$ GeV

$m_\nu = 0$

$U(1)_L^3 \times U(1)_B$

GIM

$Y_u, Y_d, Y_l \Rightarrow$ Fla~~v~~or & $\cancel{C}\cancel{P}$

$U(\cancel{1})_L \rightarrow m_\nu \neq 0$ $\Rightarrow \Lambda \geq 10^{14}$ GeV

Fla~~v~~or $\Rightarrow \mu \rightarrow e\gamma, \Delta m_K, \ldots$ $\Rightarrow \Lambda \geq 10^6$ GeV

$\cancel{CP} \Rightarrow$ edm's

Dipoles $\Rightarrow (g-2)_\mu$

$U(1)_B \Rightarrow p \rightarrow \pi^0 e^+$ $\Rightarrow \Lambda \geq 10^{15}$ GeV

$\Rightarrow \Lambda \geq 10^3$ GeV

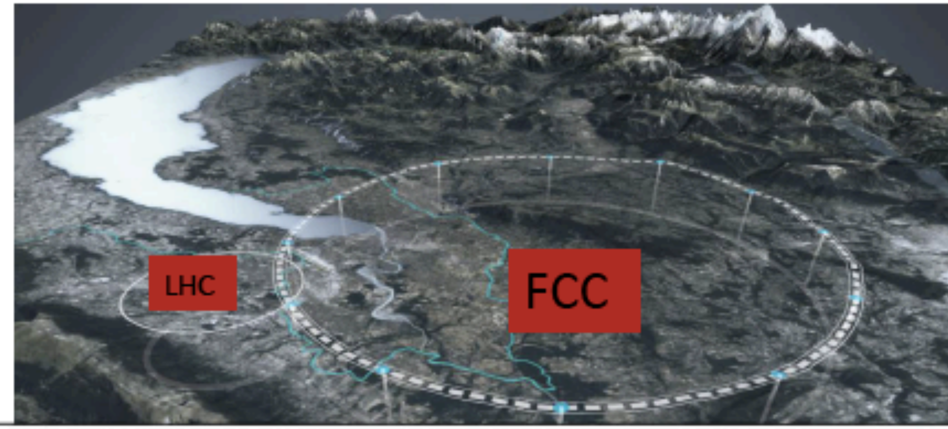
2021

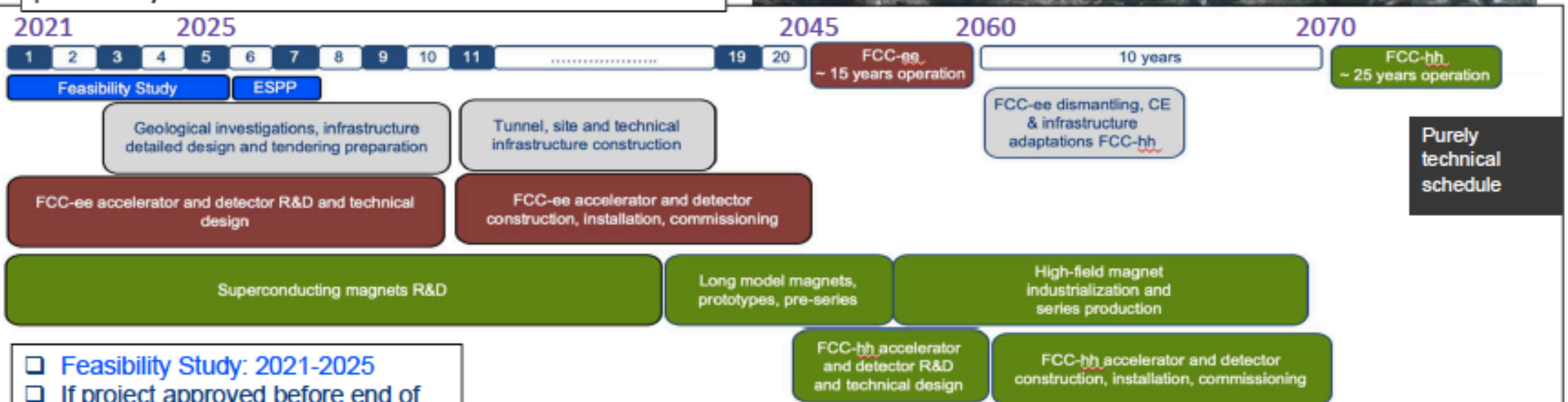
Rattazzi@GGI tea break

This leaves us with

the Future Circular Collider (e^+e^- followed by pp) – at CERN
or maybe a similar facility in China

Reference https://indico.cern.ch/event/1202105/timetable/
I have drawn particularly on discussions with and slides provided by Fabiola Gianotti and Gavin Salam





- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

For health of field:
imperative to minimise gap between Hi-Lumi LHC and FCC e^+e^-

Llewellyn Smith. Erice School 2023

Following Gavin Salam, look at Z'_{SSM} as a simple measure of progress

Tevatron

$p\bar{p}$, 1.96 TeV, 10 fb^{-1}

Exclusion limit ~ 1.2 TeV

(if they had analysed all their data in electron and muon channels; actual CDF limit 1.071 TeV, 4.7fb^{-1}, $\mu\mu$ only)

$\times 4$ →

LHC

pp, 13.6 TeV, 139 fb^{-1}

Exclusion limit ~ 5.1 TeV

(electron and muon channels, single experiment)

$\times 7.8$ →

FCC-hh

pp, 100 TeV, 20 ab^{-1}

Exclusion limit ~ 41 TeV

(based on PDF luminosity scaling, assuming detectors can handle muons and electrons at these energies)

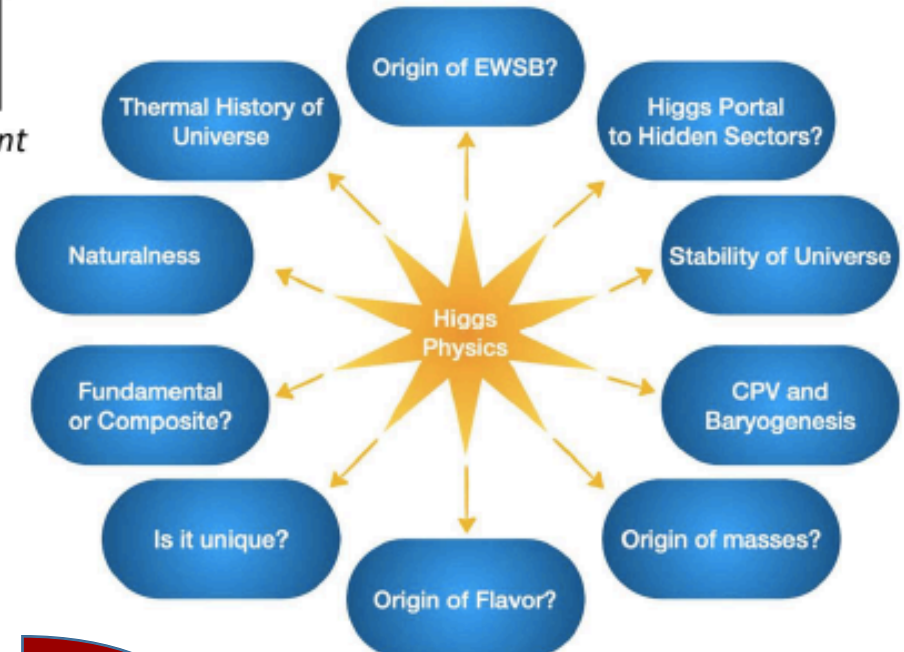
Llewellyn Smith. Erice School 2023

Many problems with the standard model related to the Higgs sector

$$\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0$$

flavour *naturalness* *stability*

cosmological constant



Apart from first term, Higgs interactions qualitatively new

$$\mathcal{L}_{SM} = \cdots + |D_\mu\phi|^2 + \psi_i y_{ij}\psi_j\phi - V(\phi)$$

Gauge interactions, structurally like those in QED, QCD, EW, **studied for many decades** (but now with a scalar)

Yukawa interactions. Responsible for fermion masses, and induces "fifth force" between fermions. **Direct study started only in 2018!**

Higgs potential → self-interaction ("sixth?" force between scalars).

Holds the SM together.

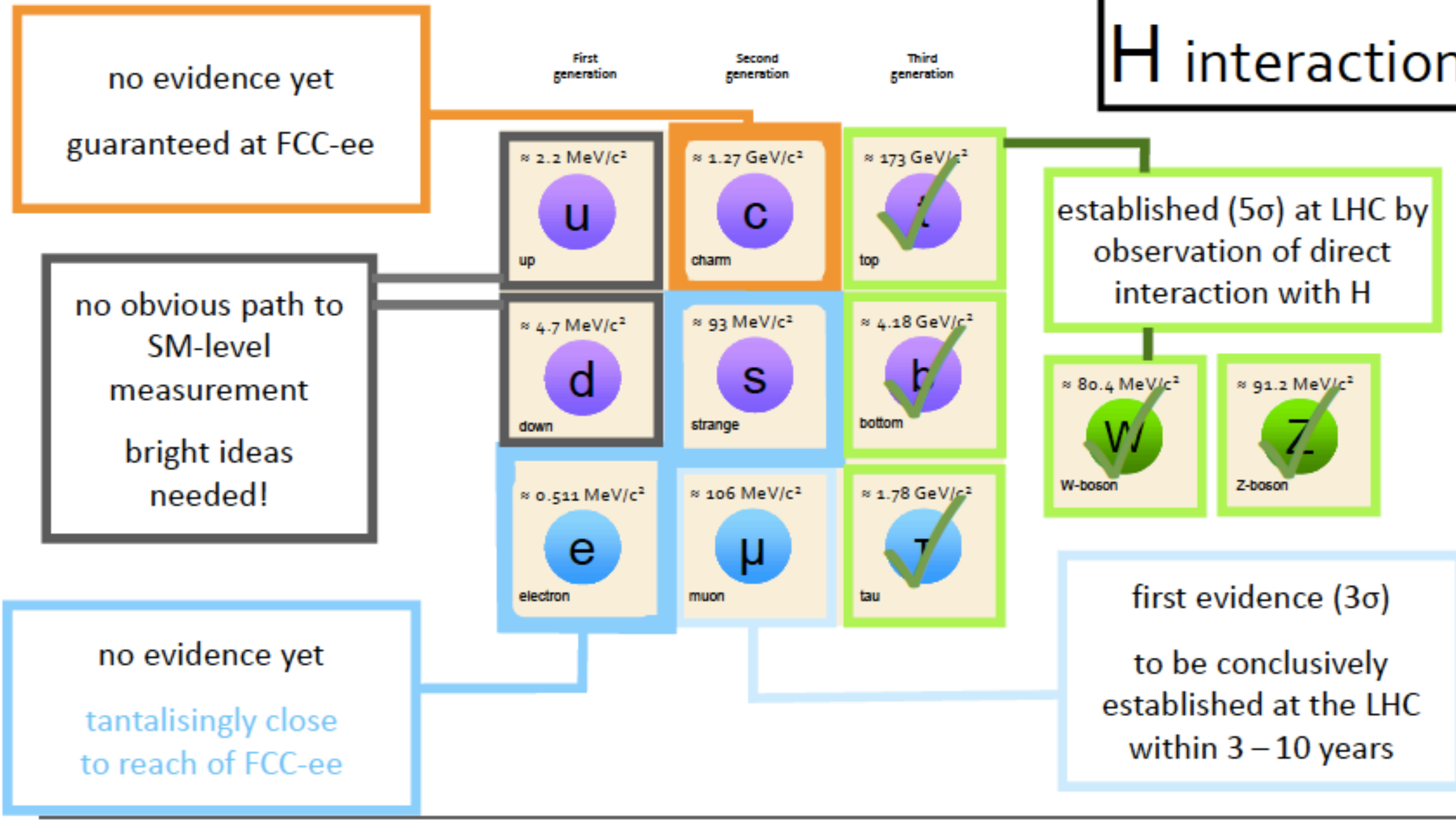
Unobserved

$$V_{min} = [-\mu^2|\phi|^2 + \lambda|\phi|^4]_{\phi_0} + V_0$$

cosmological constant

$$= -2.6 \times 10^{28}\, kg/m^3 + V_0 = \boxed{5.96 \times 10^{-27}\, kg/m^3}$$

H interactions



What the SM does not account for…

neutrino masses
dark matter
baryogenesis
inflation

OBSERVATIONAL REASONS

$M_{HIGGS} / M_{PLANCK} \sim 10^{-16}$
$E_{VACUUM} (DE) / M_{HIGGS} \sim 10^{-14}$
$\Theta_{CPV\ in\ STRONG\ INTERAC.} < 10^{-9}$

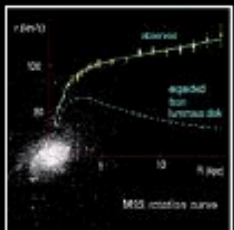
THEOR. REASONS

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

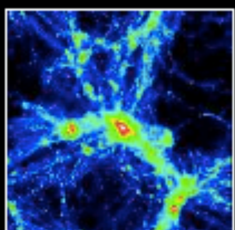
+lack of a physical "explanation" of the (largely different) **masses and mixings of the fermions**

What is the Universe made of?

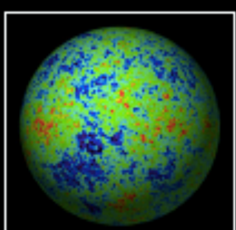
OBSERVATIONS



• Rotation Curves



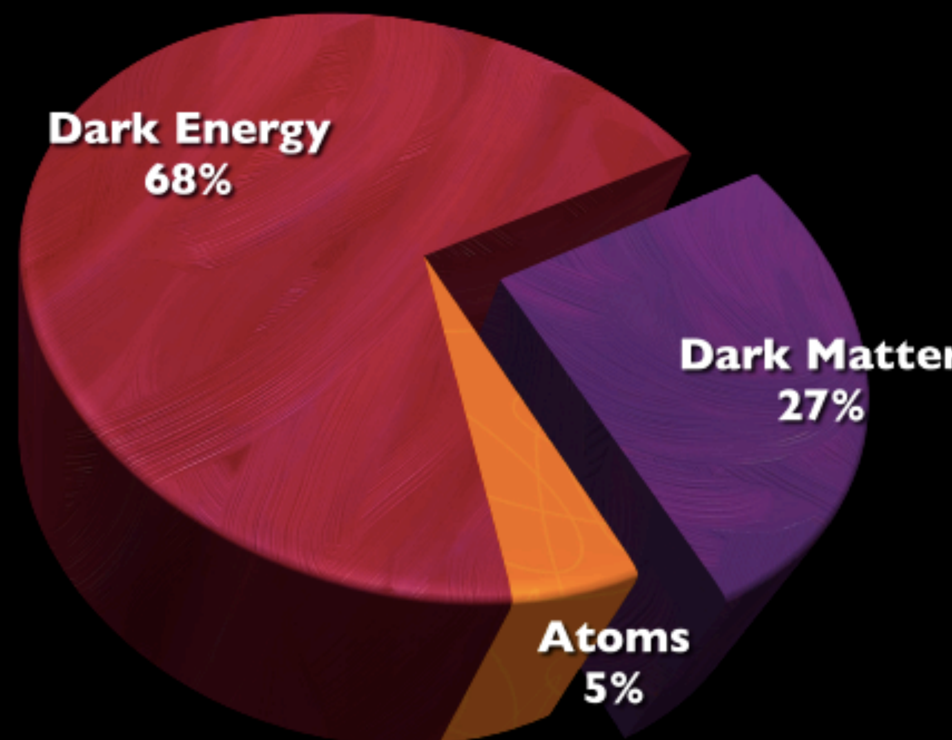
• Clusters of galaxies



• CMB

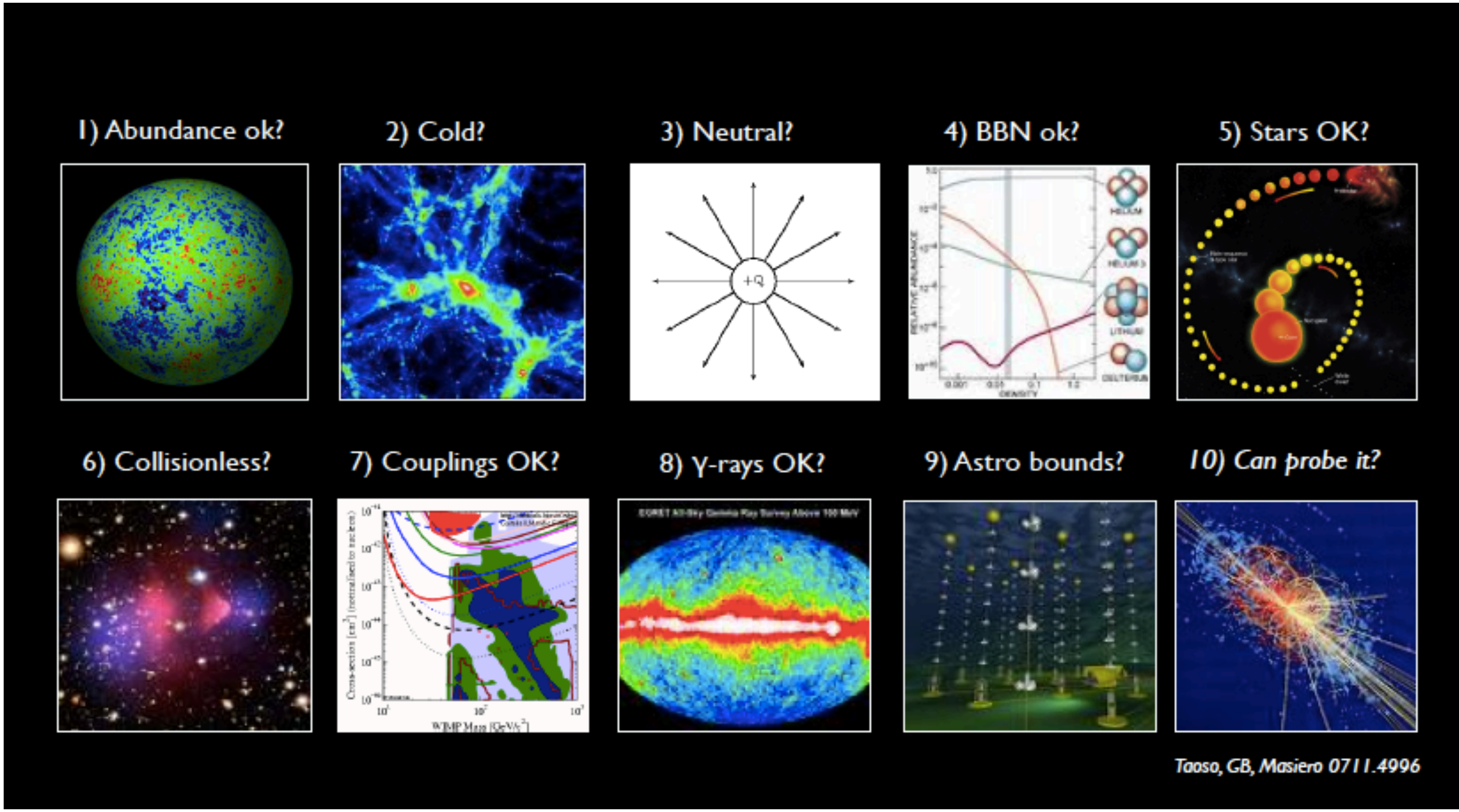
• Type Ia Supernovae

...



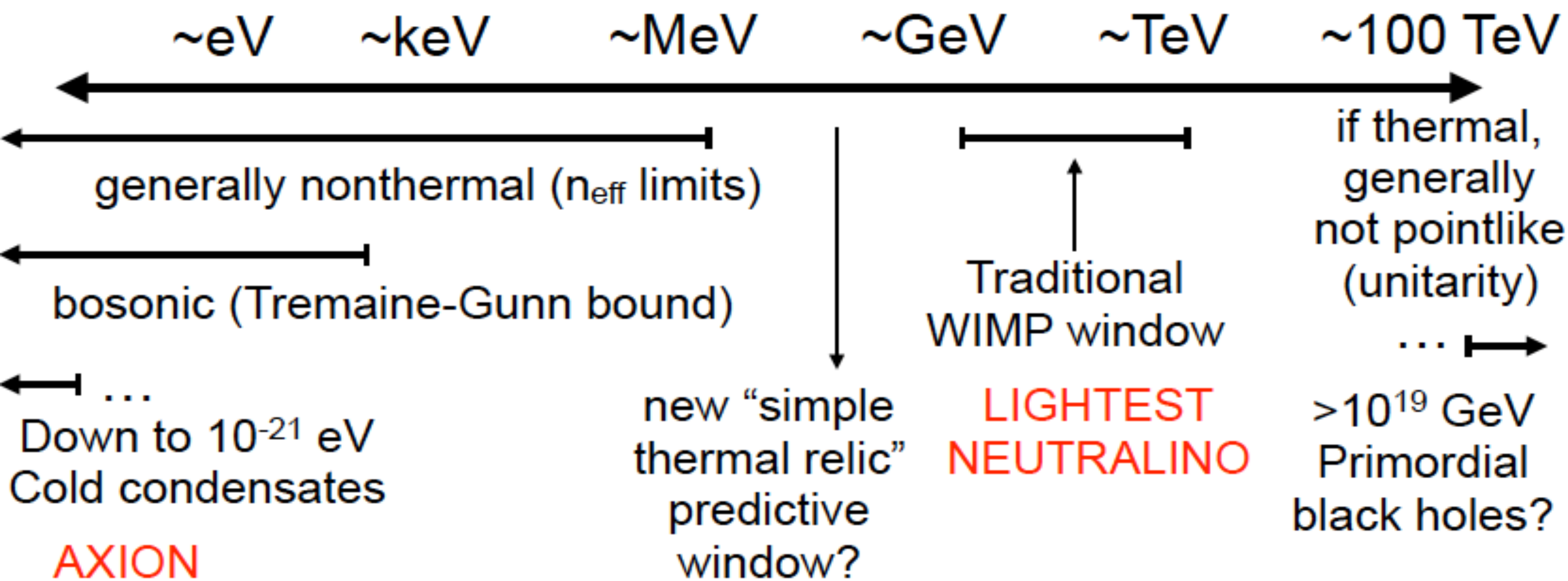
G. Bertone, Erice School, June 2023

The Ten Commadments to respect to be a "good" DM candidate



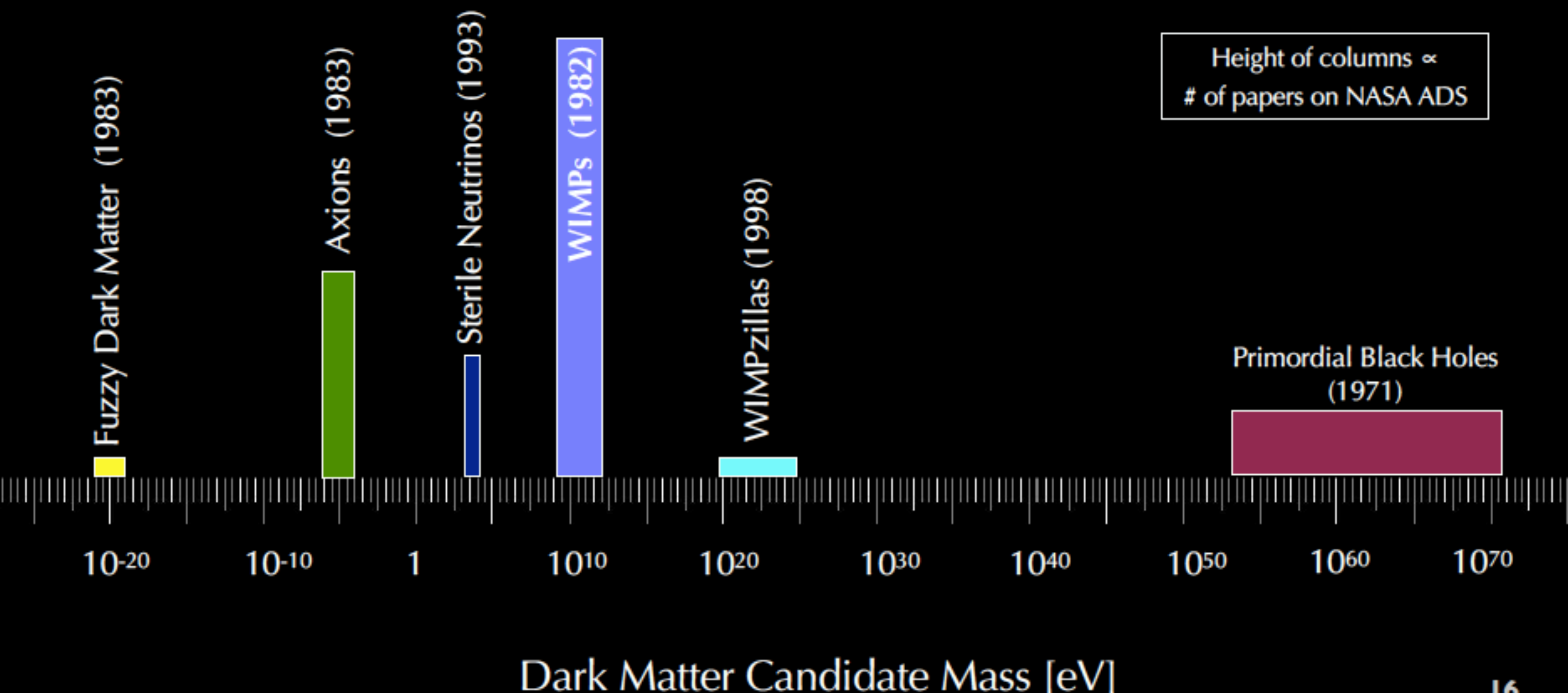
NONE OF THE SM PARTICLES CAN BE A GOOD DM CANDIDATE !

Dark matter mass scales



Candidates

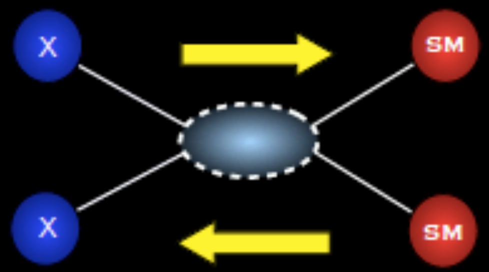
- No shortage of ideas..
- Tens of dark matter models, each with its own phenomenology
- Models span 90 orders of magnitude in DM candidate mass!



Candidates

GB, Tait, *Nature* (2018) 1810.01668

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



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

Weak-scale cross sections can reproduce observed relic density

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

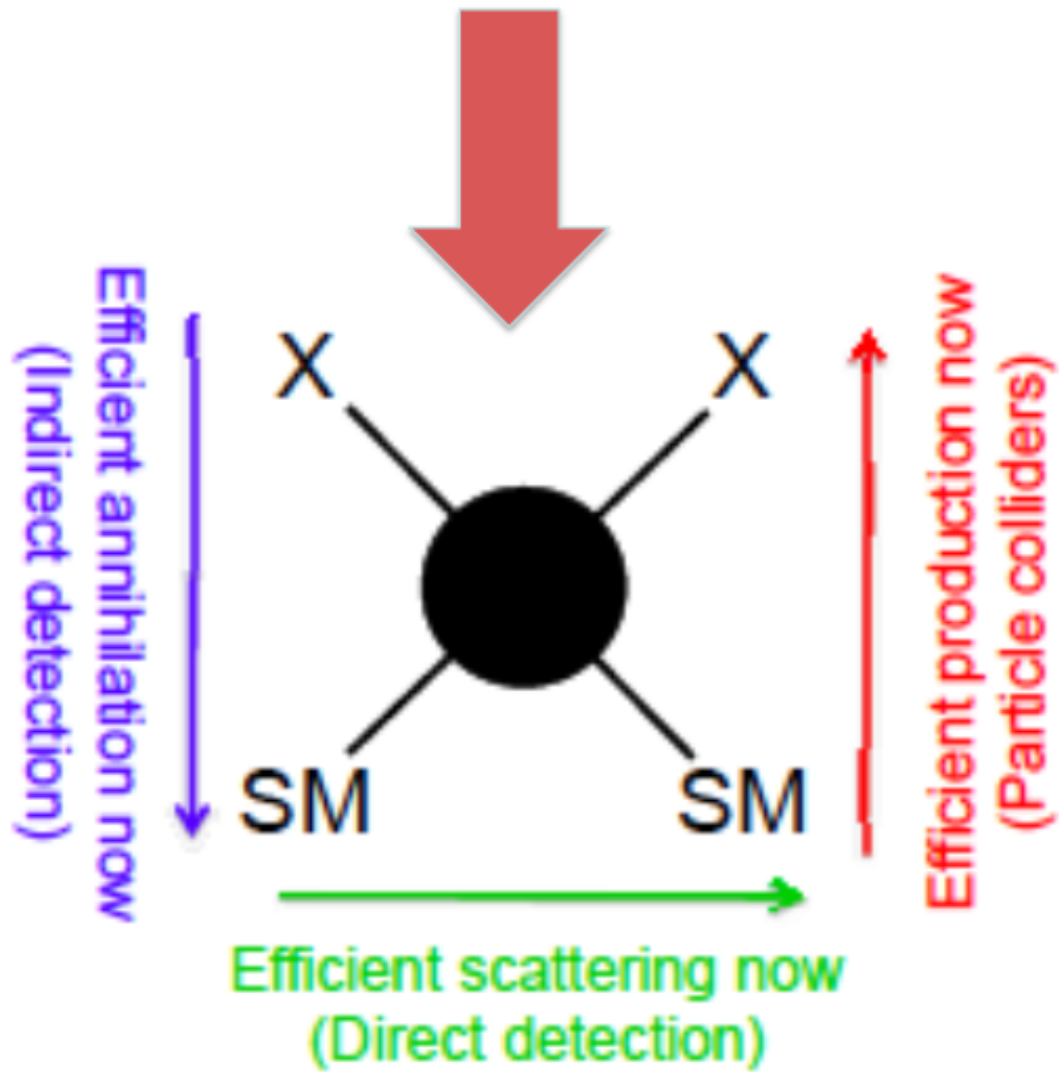
'WIMP miracle': new physics at ~1 TeV solves at same time fundamental problems of particle physics (*hierarchy problem*) AND DM

CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) **ENLARGEMENT OF THE SM**	(x^{μ}, θ)	(x^{μ}, j^{i})	SM part + new part
	Anticomm. Coord.	New bosonic Coord.	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

DM COMPLEMENTARITY: efficient annihilation in the early Universe implies today



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 $\longrightarrow$ 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

Dark Sectors

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

Standard Model → Portal → Dark Sector

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

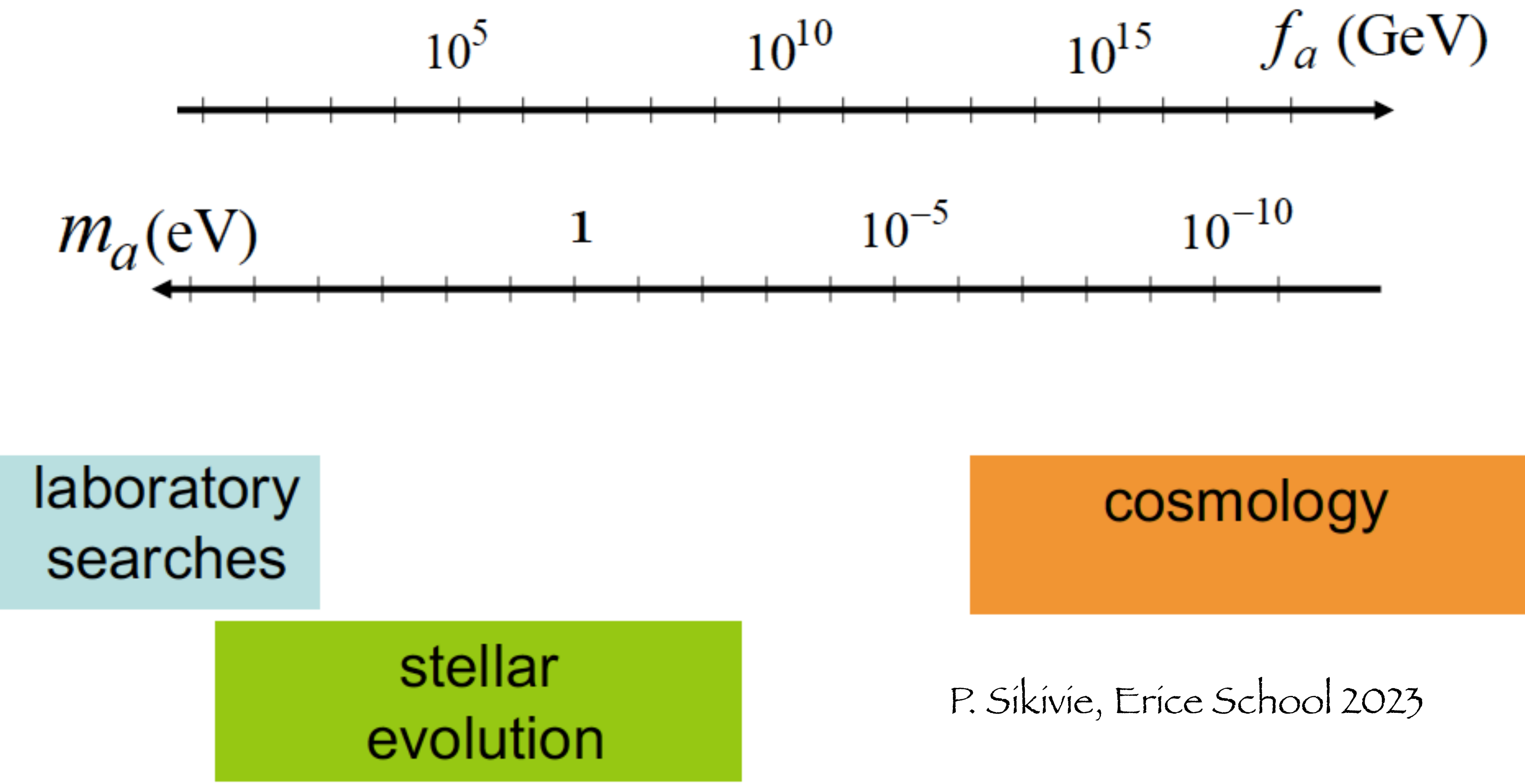
Axion

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

- Being particles, they can have a cosmological role

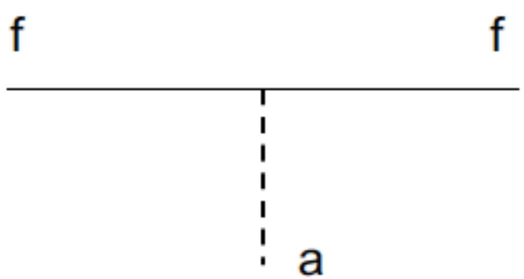
- They can be:
  - Thermally produced: hot dark matter
  - Non-thermally produced: born as nonrelativistic, classical field oscillations - very small mass, yet cold dark matter

Axion constraints

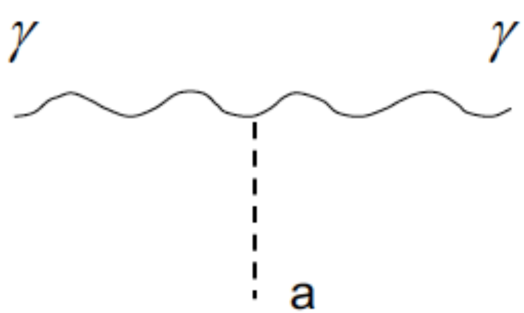


P. Sikivie, Erice School 2023

$$m_a \simeq 6 \text{ eV} \frac{10^6 \text{ GeV}}{f_a}$$



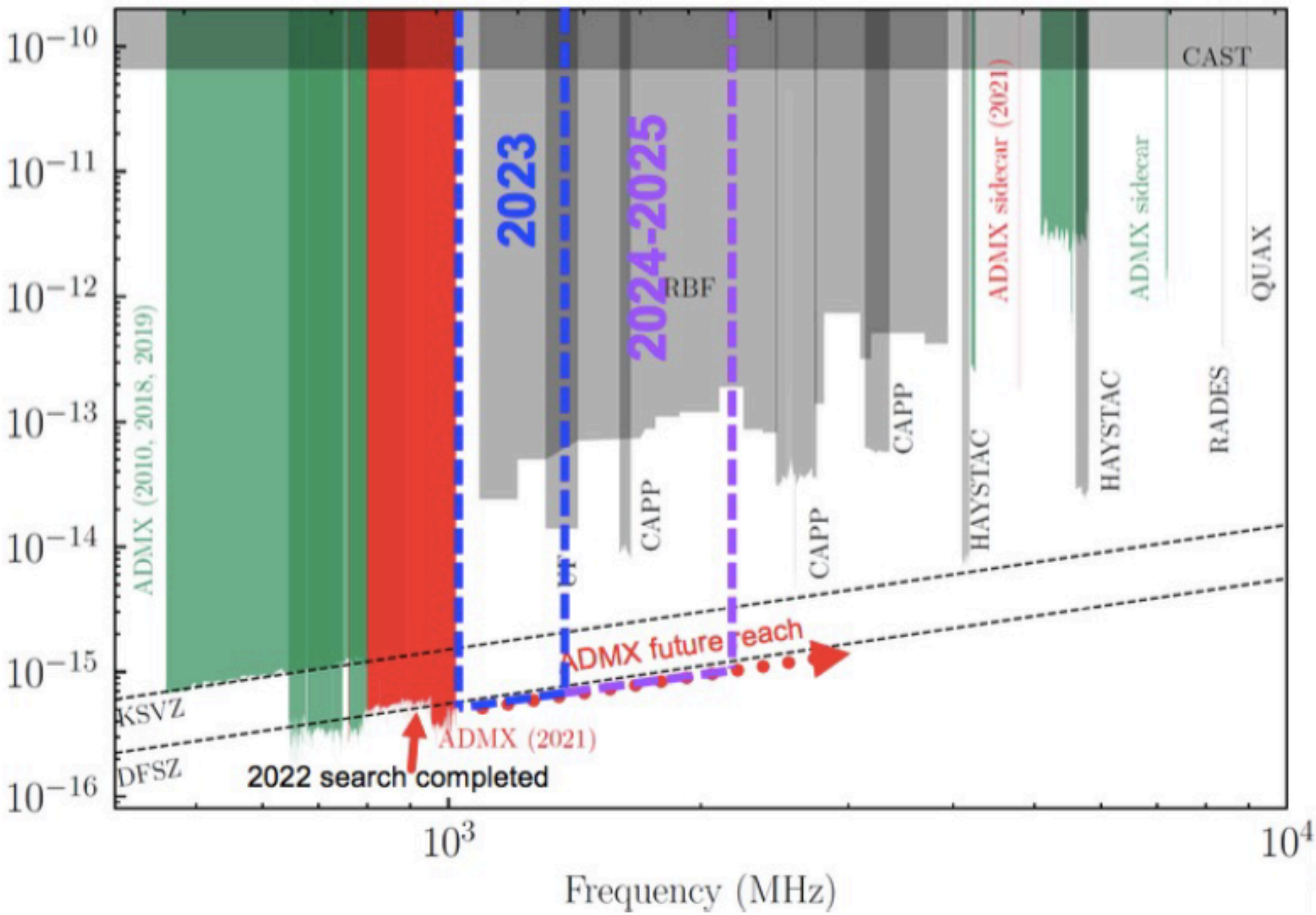
$$\mathcal{L}_{a\bar{f}f} = i g_f \frac{a}{f_a} \bar{f} \gamma_5 f$$



$$\mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

g_γ = 0.97 in KSVZ model
0.36 in DFSZ model

Axion haloscope limits



slide from G. Carosi

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

WIMP ⟷ Weak Scale Physics (~100 GeV)

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**

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 $\longrightarrow$ 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 $\longrightarrow$ DOMAINS OF BARYONS AND ANTIBARYONS ARE TOO SMALL SMALL TODAY TO EXPLAIN SEPARATIONS LARGER THAN THE SUPERCLUSTER SIZE

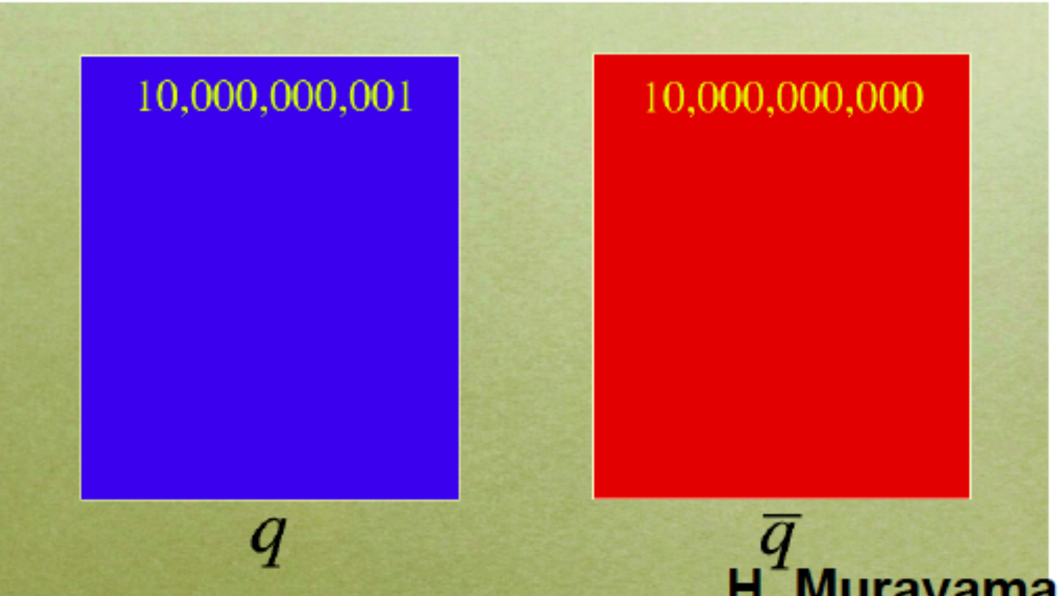
$\Downarrow$

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



H. Murayama

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 m_ν

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

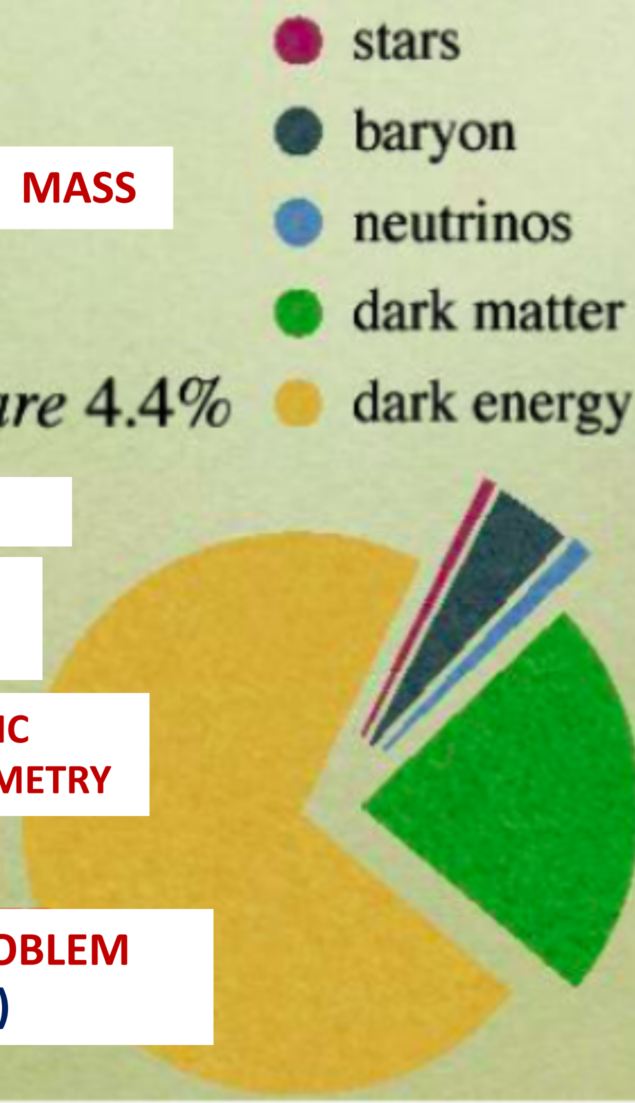
- Key-ingredient of the SEE-SAW mechanism for neutrino masses: **large Majorana mass for RIGHT-HANDED neutrino**
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

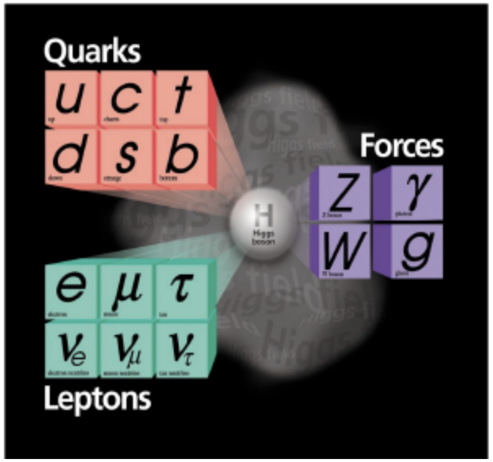
VANILLA LEPTOGENESISIS !

→ 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**)

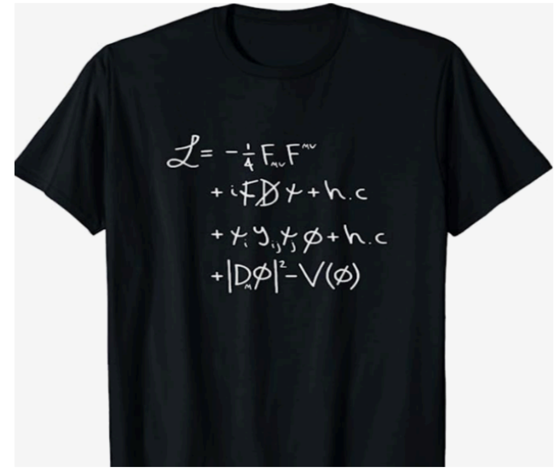
THE MISTERY OF THE 5 NUMBERS THAT THE SM IS UNABLE TO EXPLAIN

- *Stars and galaxies are only ~0.5%*
- *Neutrinos are ~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 ~10^{62}%??* **COSMOLOGICAL CONSTANT PROBLEM (QUANTUM VACUUM ENERGY?)**





MICRO-COSMOS



Up to you to prepare this new T-shirt of ISAPP 20..