IFAE 2015, ROMA TOR VERGATA, 8-10 aprile 2015

# E dopo l'Higgs?


**Antonio Masiero**

**INFN and Univ. of Padova**

- 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**

# WHY BSM

"**OBSERVATIONAL**" **REASONS**:

- **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**

# 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 → "vurria, ma non posso…")
- **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 *

# Is gauge hierarchy a "fictitious" problem?

- * Notice: gauge hierarchy is not a problem of the SM in itself; indeed, it arises when the **SM particles come in touch with much more massive particles** probably related to a new, large energy scale in physics

- But, how about having the SM as the final theory ("forever") of all the interactions, but for gravity whose quantization has its own story independently from the SM of electroweak+ strong interactions? – **softened gravity** (Giudice, Isidori, Salvio, Strumia 2014)

# 2012: the conquest of a new energy scale in physics

- ~1900 ATOMIC SCALE $10^{-8}$ cm. $1/(\alpha m_e)$
- ~1970 STRONG SCALE $10^{-13}$ cm. $M e^{-2\Pi/\alpha_s b}$
- ~2010 WEAK SCALE $10^{-17}$ cm. $TeV^{-1}$

FUNDAMENTAL OR DERIVED SCALE?

EX. EXTRA-DIMENSIONS
**or**
TeV STRING THEORY

EX.: TECHNICOLOR or
SUSY with ELW RAD. BREAKING

## NEW PARTICLES AT THE TEV SCALE?

MICRO

MACRO

GWS STANDARD MODEL

HOT BIG BANG
STANDARD MODEL

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

# NUCLEOYINTHESIS

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

BUT ALSO

FRICTION POINTS

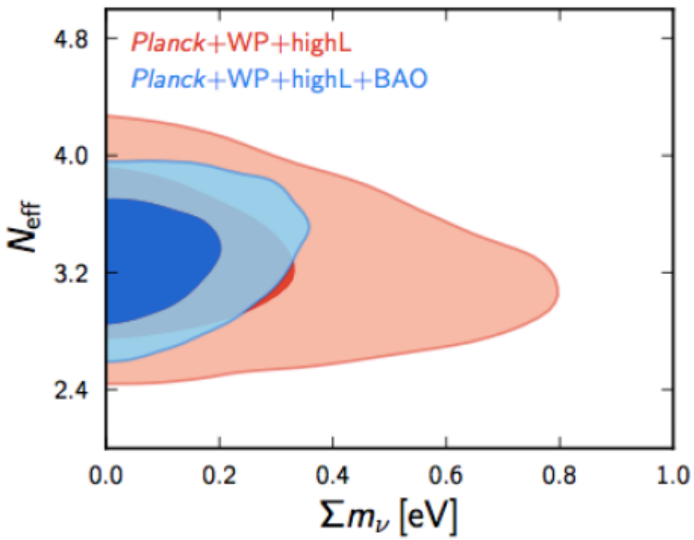
**-COSMIC MATTER-ANTIMATTER ASYMMETRY**

**-INFLATION ???**

**- DARK MATTER + DARK ENERGY**

**OBSERVATIONAL EVIDENCE OF NEW PHYSICS**

**BEYOND THE STANDARD**




$N_{eff}$=3.36±0.34

The extracted value of $N_{eff}$ depends whether one makes use of the value of the Hubble parametr from the Planck data or from independent observations

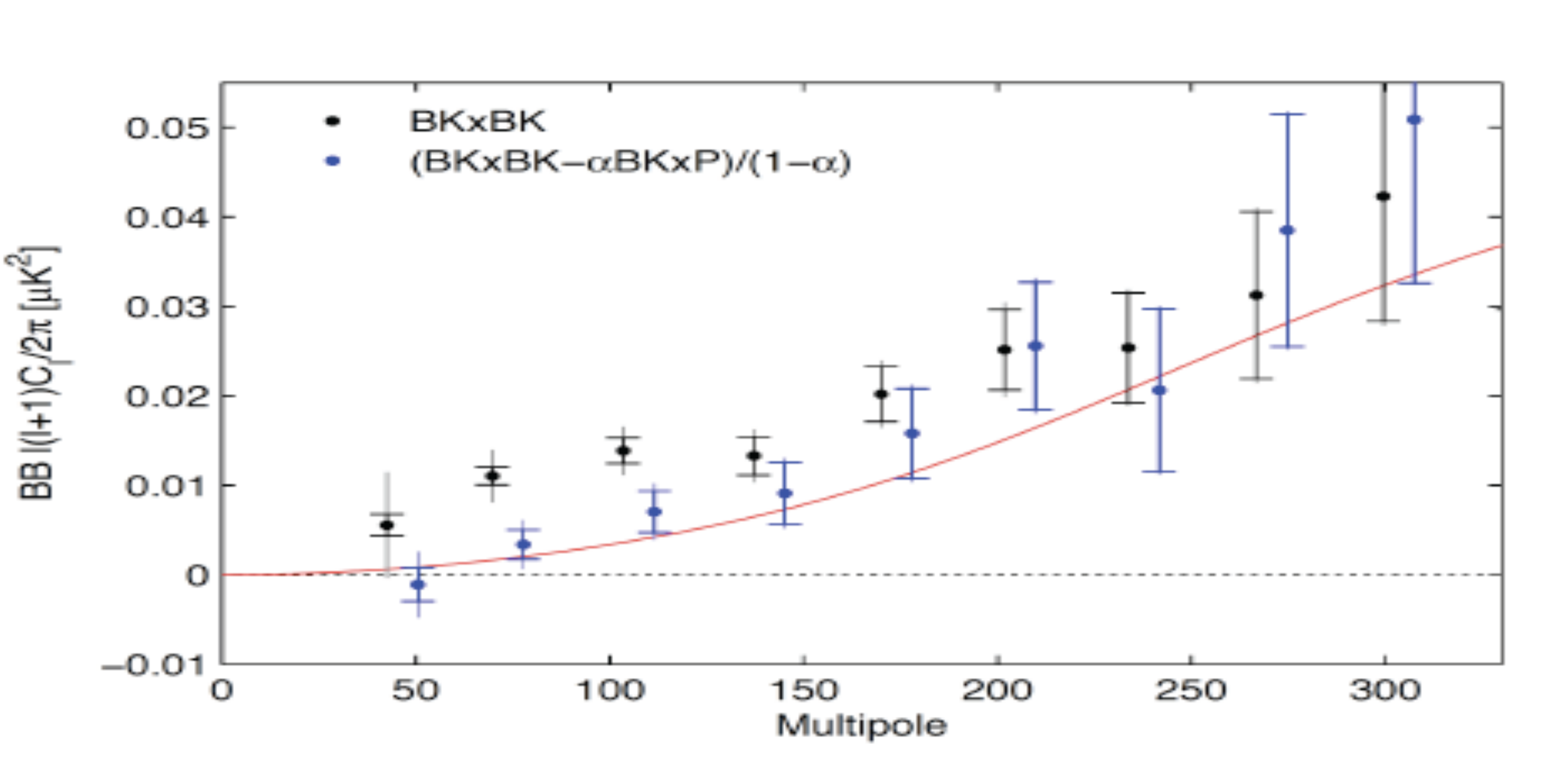
$\Sigma m_\nu$< 0.23- 0.8 eV

Recent (and controversial!) **BICEP2** results :
from the measurement of the B-mode polarization of the CMB photons
→ initial **inflationary epoch** at energies ~ **$V^{1/4}$ = 1.94 x $10^{16}$ GeV $(r/0.12)^{1/4}$ ;** r= ratio of the CMB tensorial/scalar components – from BICEP2 r ~0.2 , r≠0 at ~6 σ

**INFLATON at ~ $10^{16}$ GeV**, not standard Higgs inflation (see, however, Bezrukov and Shaposhnikov)

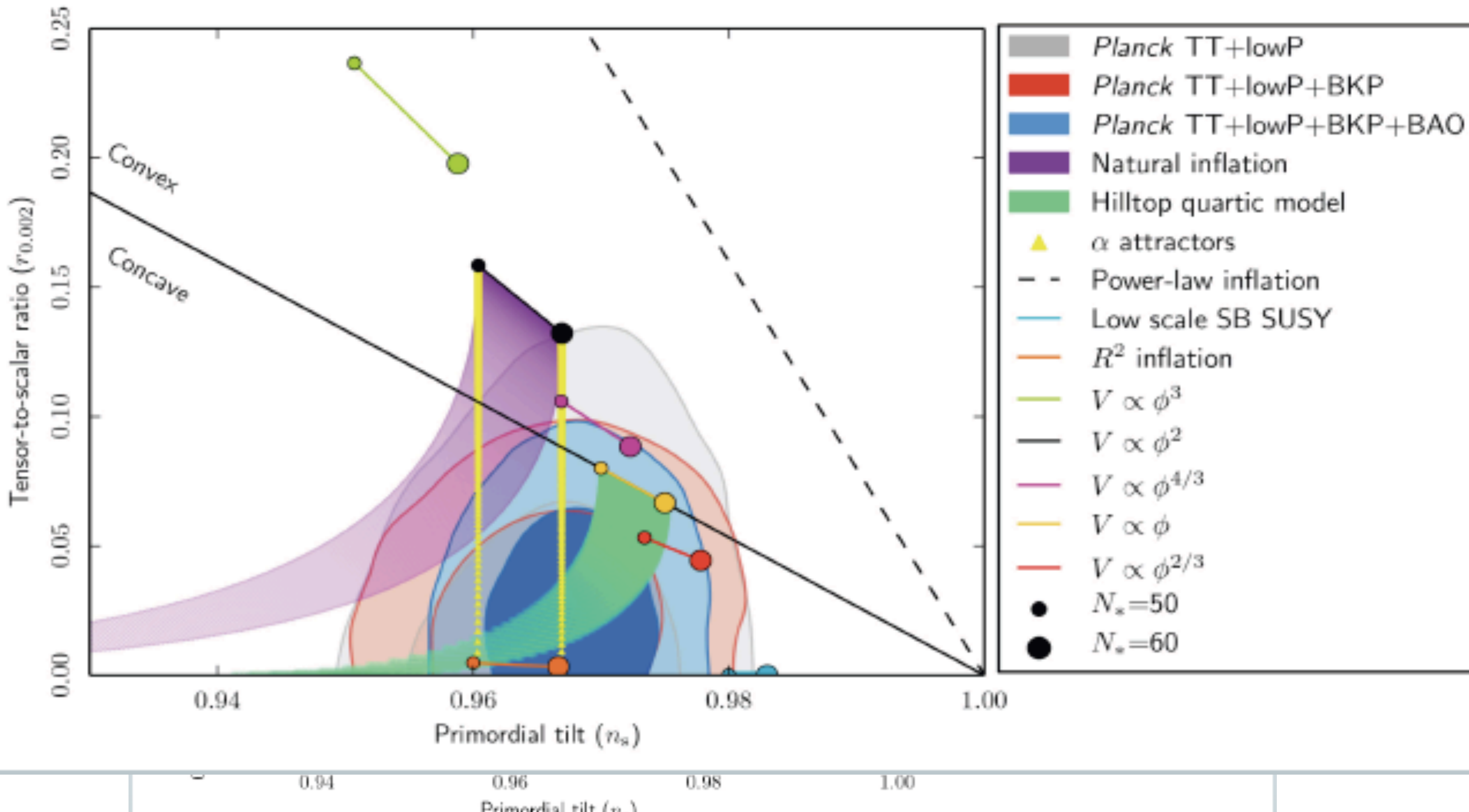
A.M. IPA **Sept. 2014**

# Subtracting PLANCK "dust" from BICEP2 results




r<0.12 @95% CL

# THE INFLATON SCALAR POTENTIAL




$$V^{1/4} = 1.94 \times 10^{16} \left(\frac{r}{0.12}\right)^{1/4} \text{GeV}$$

# Info from Planck: Neutrino # and mass

$\Sigma m_\nu < 0.23$ eV (95% CL)

$N_{eff} = 3.15 \pm 0.23$

Planck + Lyman alpha

$\Sigma m_\nu < 0.14$ eV (C.L)

**Prospects for PLANCK + EUCLID**

$\Delta m_\nu \sim 0.03$ eV & $\Delta N_\nu \sim 0.08$

# What the combined BICEP2 +PLANCK analysis is telling us

- Only upper limit on r → **no hint for the presence of a large energy scale (related to primordial inflation)**
- Most **inflationary scalar potentials** still allowed
- Strong constraints on the **number of neutrino-like particles** present at the photon decoupling and on the **sum of the neutrino masses**

# Going beyond the SM:
# the NEUTRINO MASS

**A. GIULIANI**, SAC APPEC 2013

**Cosmology**, **single** and **double β decay** measure different combinations of the neutrino mass eigenvalues, constraining the **neutrino mass scale**

In a standard three active neutrino scenario:

$$\Sigma \equiv \sum_{i=1}^{3} M_i$$

**cosmology**
simple sum
pure kinematical effect

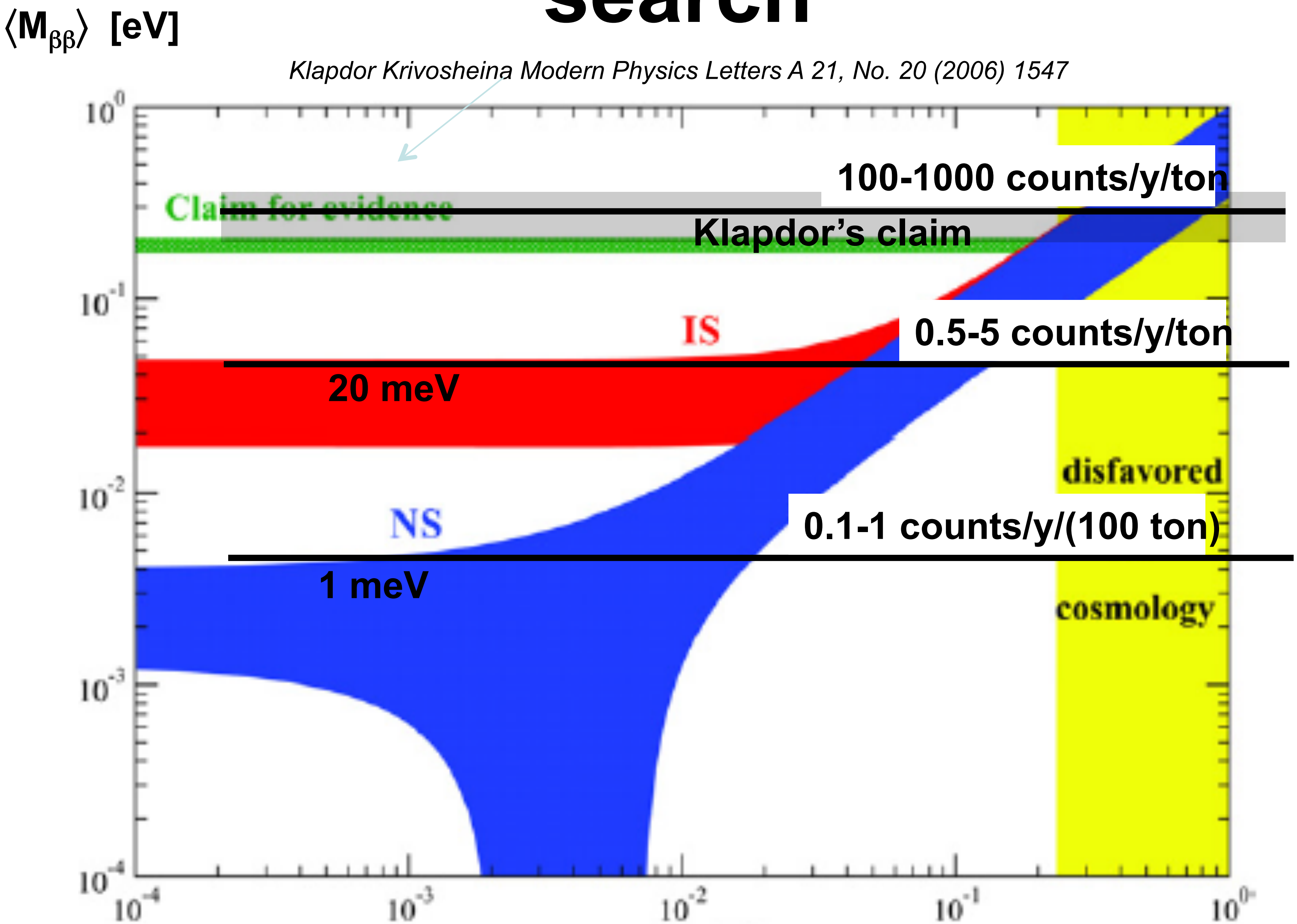
$$\langle M_\beta \rangle \equiv \left( \sum_{i=1}^{3} M_i^2 \, |U_{ei}|^2 \right)^{1/2}$$

**β decay**
incoherent sum
real neutrino

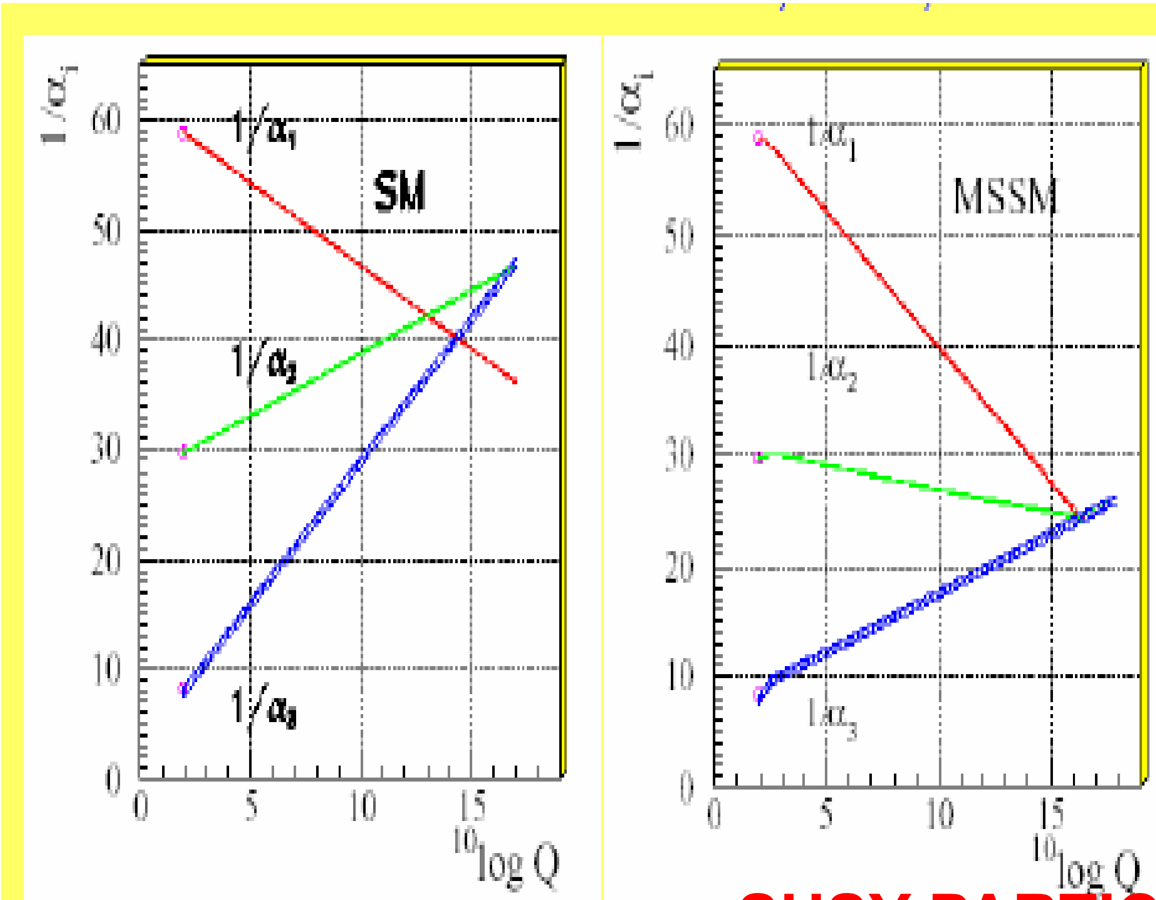
$$\langle M_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} M_i \, |U_{ei}|^2 \, e^{i\alpha_i} \right|$$

**double β decay**
coherent sum
virtual neutrino
Majorana phases

# Three challenges for 0ν-DBD search



# 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**

$M_{SUSY} = 10^{3.4\pm0.9\pm0.4}$ GeV

$M_{GUT} = 10^{15.8\pm0.3\pm0.1}$ GeV

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

**SUSY PARTICLES AT THE TEV SCALE !**

# THE "COMPREHENSION" OF THE ELECTROWEAK SCALE

$$V = \mu^2 |H|^2 + \lambda |H|^4$$ **$\mu \sim 10^2$ GeV**

- $M = O(10^{16}\ \text{GeV})$

| | SU(3) | SU(2) | U(1) |
|---|---|---|---|
| L | 1 | 2 | -1/2 |
| e | 1 | 1 | 1 |
| Q | 3 | 2 | 1/6 |
| u | 3* | 1 | -2/3 |
| d | 3* | 1 | 1/3 |

→ SO(10): 16

$$m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2} M^2$$

**ONLY FOR SCALARS; SM FERMIONS AND GAUGE BOSON MASSES ARE PROTECTED BY THE SU(2) × U(1) SYMMETRY !**

**To comprehend (i.e. stabilize) the elw. scale need NEW PHYSICS (NP) to be operative at a scale** $m_{NP} \ll M$

# 3 comments on $m_{NP}$

ROMANINO at WHAT NEXT 2014

- Any upper bound on $m_{NP}$ is subjective: any value of $m_{NP}$ acceptable provided one accepts a cancellation

$$\Delta \gtrsim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

$m_{NP} > 1.5$ TeV $\leftrightarrow$ $\Delta > 10$

$m_{NP} > 5$ TeV $\leftrightarrow$ $\Delta > 100$

**$m_{NP}$ x 2 $\rightarrow$ $\Delta$ x 4**

- The bound on Δ is model-dependent:

"supersoft" $$\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

"soft" $$\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 \times \log\left(\frac{M^2}{m_{\rm NP}^2}\right)$$

- The argument assumes that the electroweak scale can be understood in terms of physics at a scale ~

$$M \gg m_h$$

- **Alternative 1** : it could be that there is nothing at scale $M \gg m_h$ **FINITE NATURALNESS**

- **Alternative 2**: it could be that there is indeed new physics at M, but **"REDUCTIONISM" DOES NOT HOLD** (**anthropic selection**) – i.e. **physics at $10^2$ Gev depends on specific choices of parameters made at $10^{16}$ GeV !** (**unprecedented in physics**)

$$m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2} M^2$$

- **UNNATURAL or FINE-TUNING SOLUTION** tuning of parameters at the scale M with precision O( $m_H/M)^2$

- **NATURAL SOLUTION**
  Dynamics or symmetries or space-time modifications giving rise to a UV cut-off ~ $(m_H)^2$

- **SYMMETRY vs. MULTIVERSE**

# The BIG and the SMALL- dim[m] ≠ 0

- $V = \mu^2|H|^2 + \lambda|H|^4$ what is the value of the energy of its vacuum, i.e. the SM **vacuum energy**?
  → $V_o = \mu^2 <H>^2 + \lambda <H>^4 \sim (100\ \text{GeV})^2$

observed vacuum energy, i.e. dark energy accelerating the expansion of the Universe O($10^{-3}$ eV)

- V defined up to a constant → choose such constant to **cancel** the O $(100\ \text{GeV})^2$ contribution
- **$10^{-3}$ eV $10^{2}$ GeV $10^{16}$ GeV $10^{19}$ GeV**

- **Why** so different mass scales ?

- **How** to guarantee their separation → symmetry vs. multiverse

# The BIG and the SMALL – dim[m]=0

- $h_t - h_e$ **flavour** issue
- $L_{SM}$ no symmetry prevents to add a term violating **CP in the strong interactions** whose size depends on a **dimensionless** parameter θ → the bound on the neutron EDM → $\theta < 10^{-10}$
- **The θ – problem** : the symmetry solution

Axion from breaking of global chiral symmetry; axion field acts as dynamical theta para-meter, [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \underbrace{\frac{A}{f_A}}_{\bar{\theta}} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

spontaneously relaxing to zero, $\langle A \rangle = 0$ (thus CP conserved)

- mass due to chiral symmetry breaking $m_A \sim m_\pi f_\pi / f_A$
- has universal coupling to photons, $\mathcal{L} \supset -\frac{\alpha}{8\pi} C_0 \frac{A}{f_A} F_{\mu\nu} \tilde{F}^{\mu\nu}$

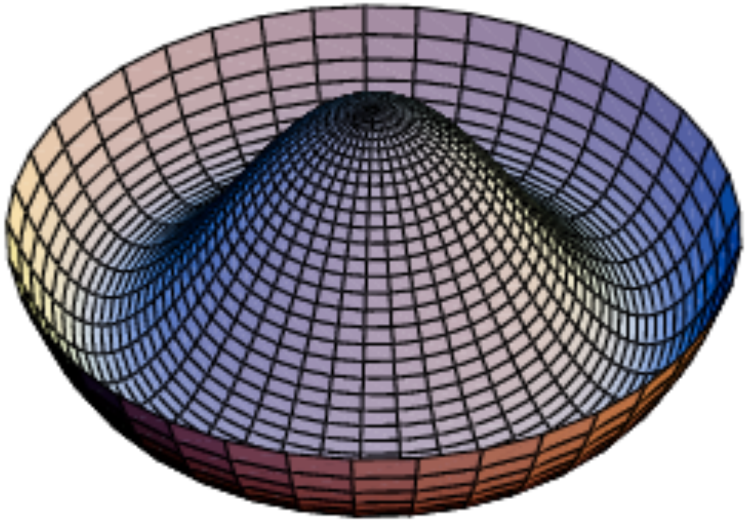
**Ringwald**

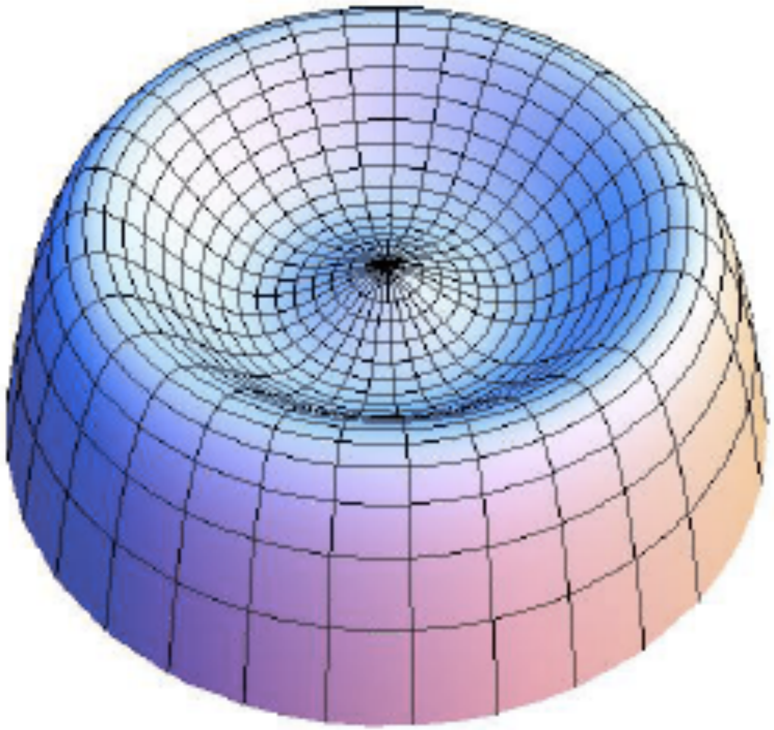
# LOW-ENERGY SIGNATURES OF UNIFICATION AT $10^{16}$ GeV

- **PROTON DECAY** mediated by new particles (scalars or gauge bosons) related to the unified physics at $10^{16}$ GeV which DOES NOT respect the BARYON and LEPTON NUMBER SYMMETRIES → for a mediator of mass ~ $10^{16}$ GeV we expect a proton lifetime in the ballpark of ~ $10^{34}$ years → exp. accessible

- **NEUTRON-ANTINEUTRON OSCILLATION** if the unified symmetry (ex. SO(10)) breaks down to an intermediate symmetry subsequently spontaneously broken at ~ $10^6$ GeV with the breaking of Baryon number of two units (ex. $SO(10) \rightarrow SU(4)_{PS} \times SU(2)_L \times SU(2)_R \rightarrow SU(3) \times SU(2)_L \times U(1)_Y$) → exp. accessible (for instance , at the ESS)

STABILITY ⟷ INSTABILITY





ON THE IMPORTANCE OF PRECISELY MEASURING HIGGS and TOP MASSES

# 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"**

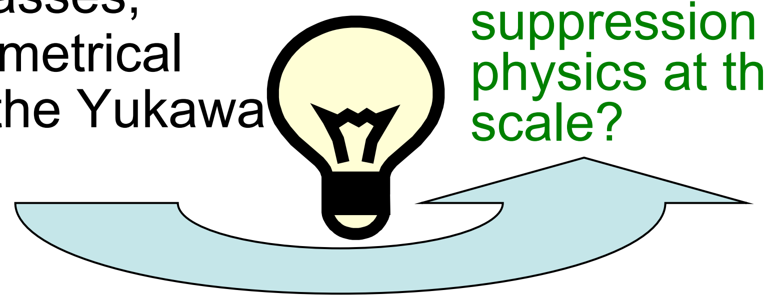
( new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, …?)

## 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.**

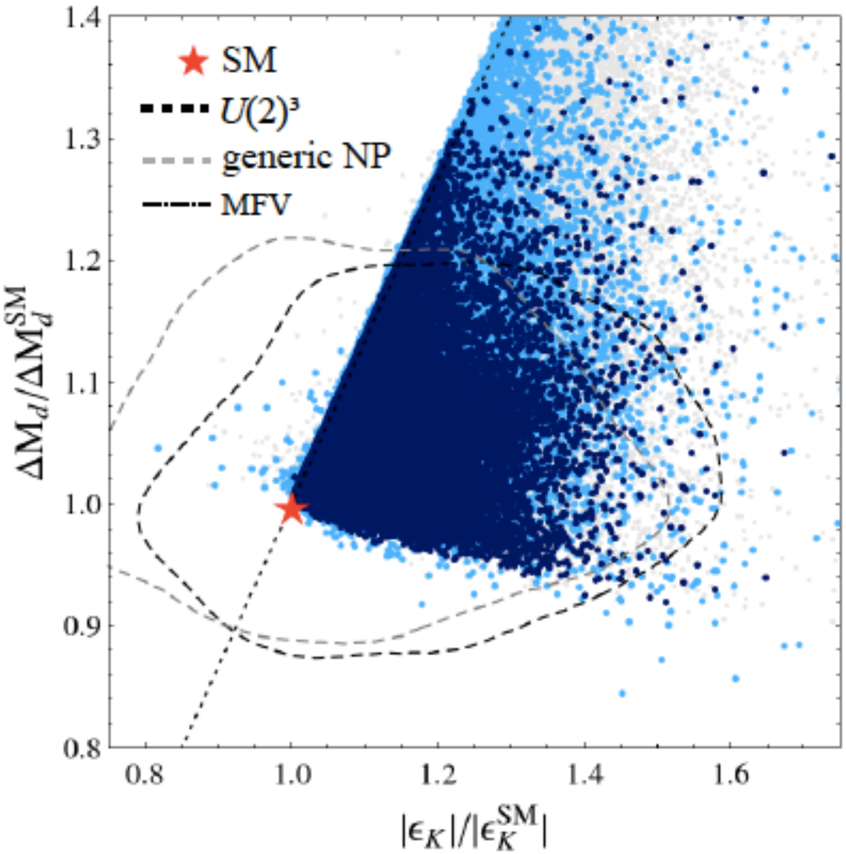
How to cope with such delicate suppression if the there is new physics at the electroweak scale?



# LHC (real NP particles) – FCNC (virtual NP particles)
# CONSTRANING New Physics

D. STRAUB

## Numerical results for $\Delta F = 2$ observables




- All blue points fullfil collider bounds
- Dashed lines: $\Delta F = 2$ constraints (black: $U(2)^3$, gray: generic)
- Direct bounds almost as constraining as flavour, except for compressed spectra

[Barbieri et al. 1402.6677]

# 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** )

# LFV IN SUSY SEE-SAW

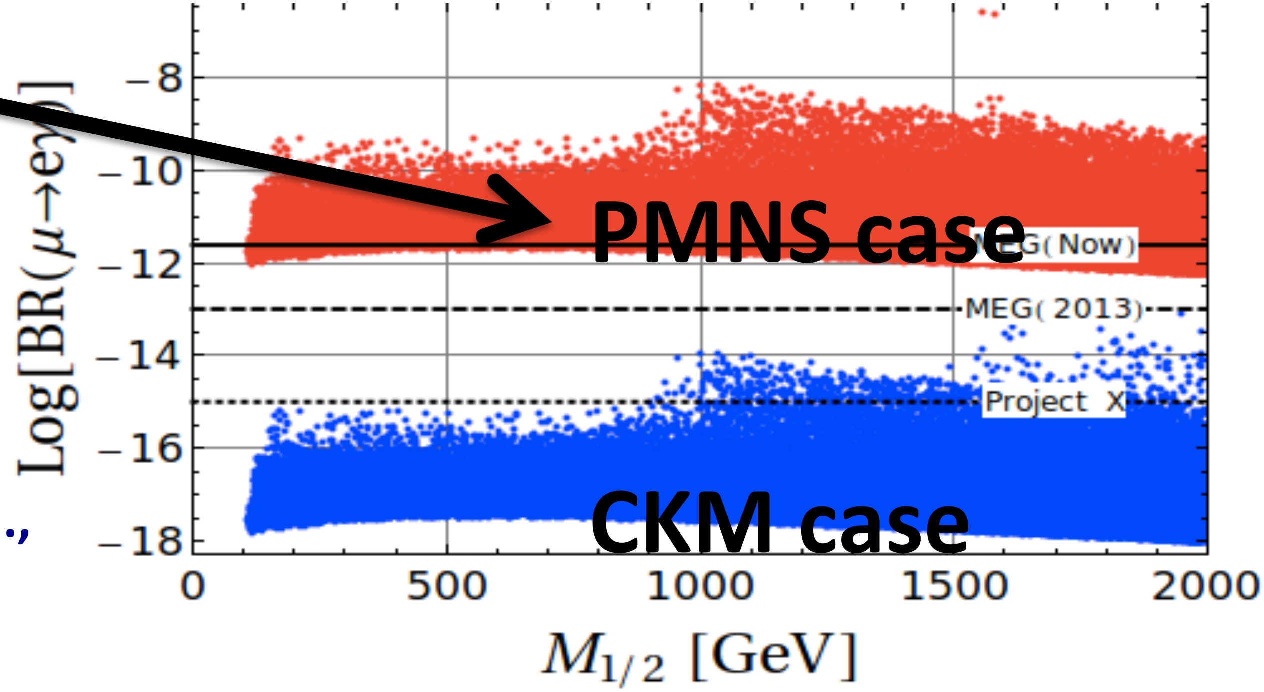
**SEE- SAW (type 1)** **LOW-ENERGY SUSY**

**New source of (leptonic) flavor:**

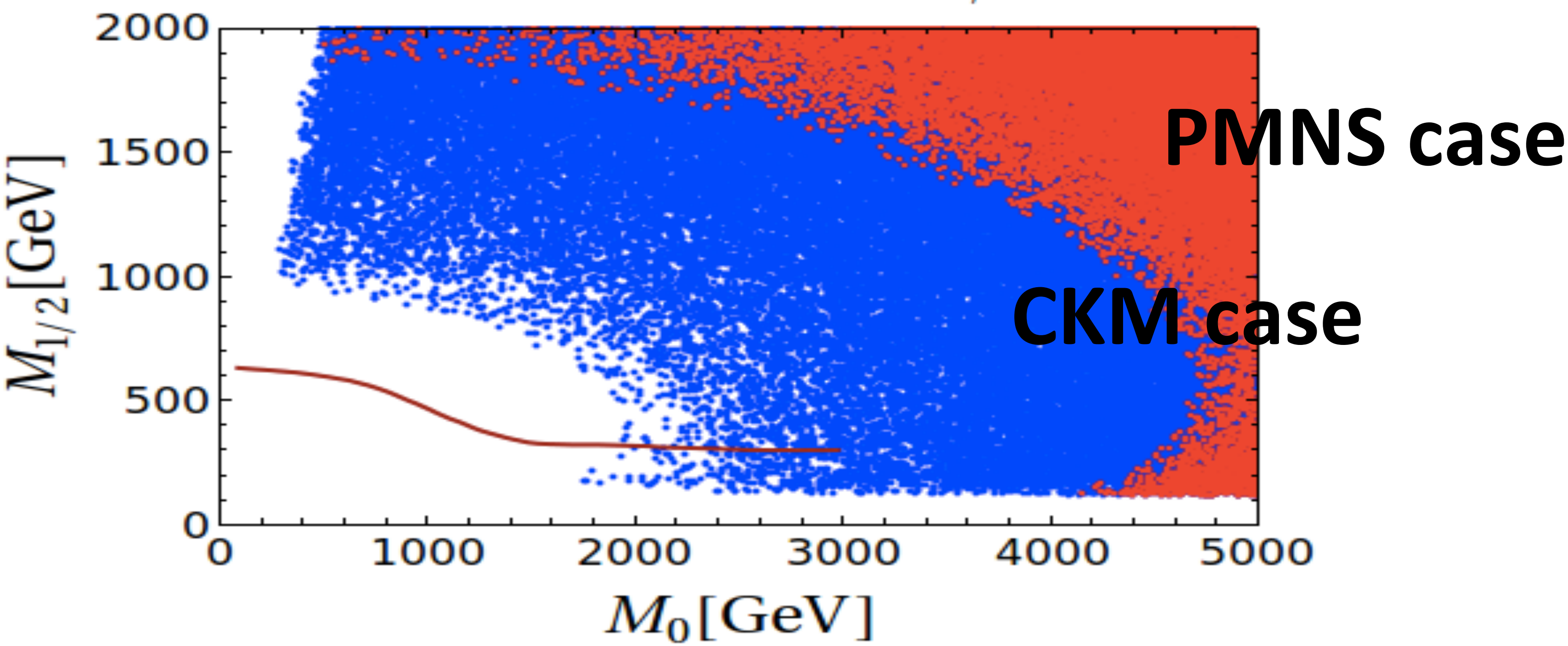
YUKAWA COUPLINGS OF THE NEUTRINO DIRAC MASS CONTRIBUTIONS, i.e. **THE YUKAWAs** of the **HIGGS couplings to the LETF- and RIGHT – HANDED NEUTRINOS**

**The scalar lepton masses through their running bring memory of those new sources of leptonic flavor at the TeV scale, i.e. at energies much below the (Majorana) mass of the RH neutrinos**

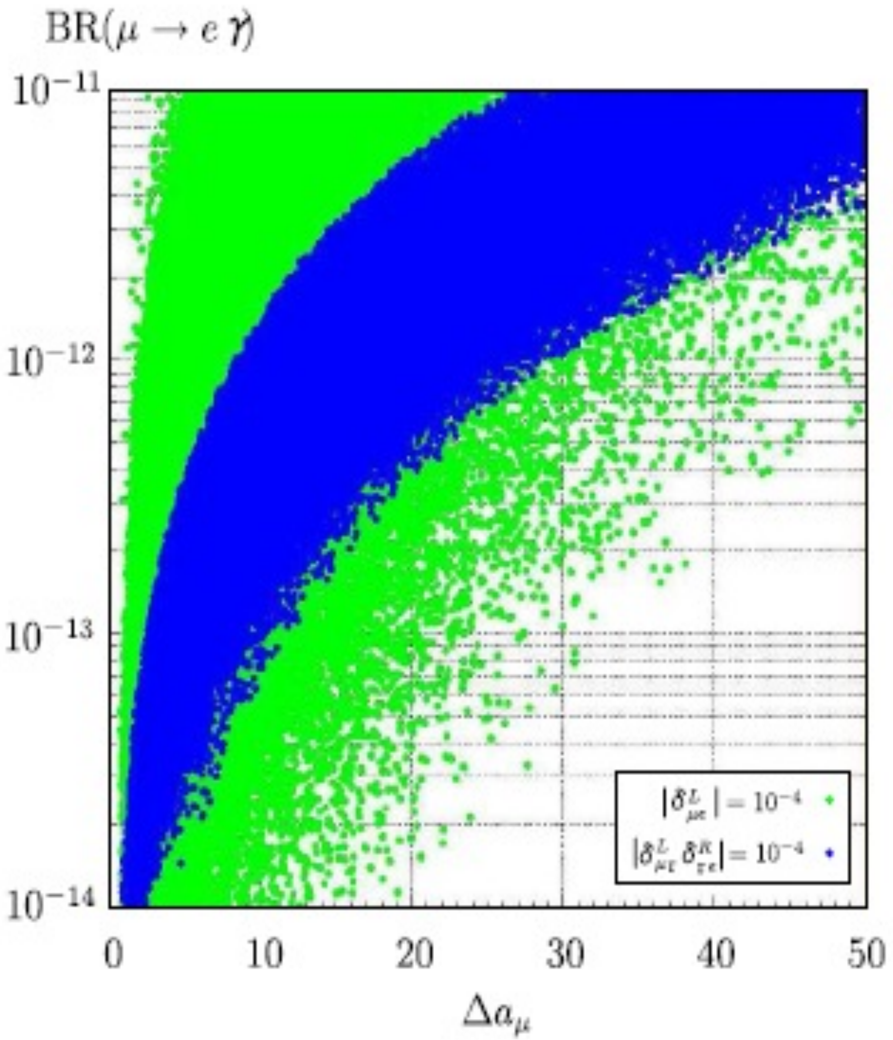
PMNS case in mSUGRA with $\tan\beta = 10$

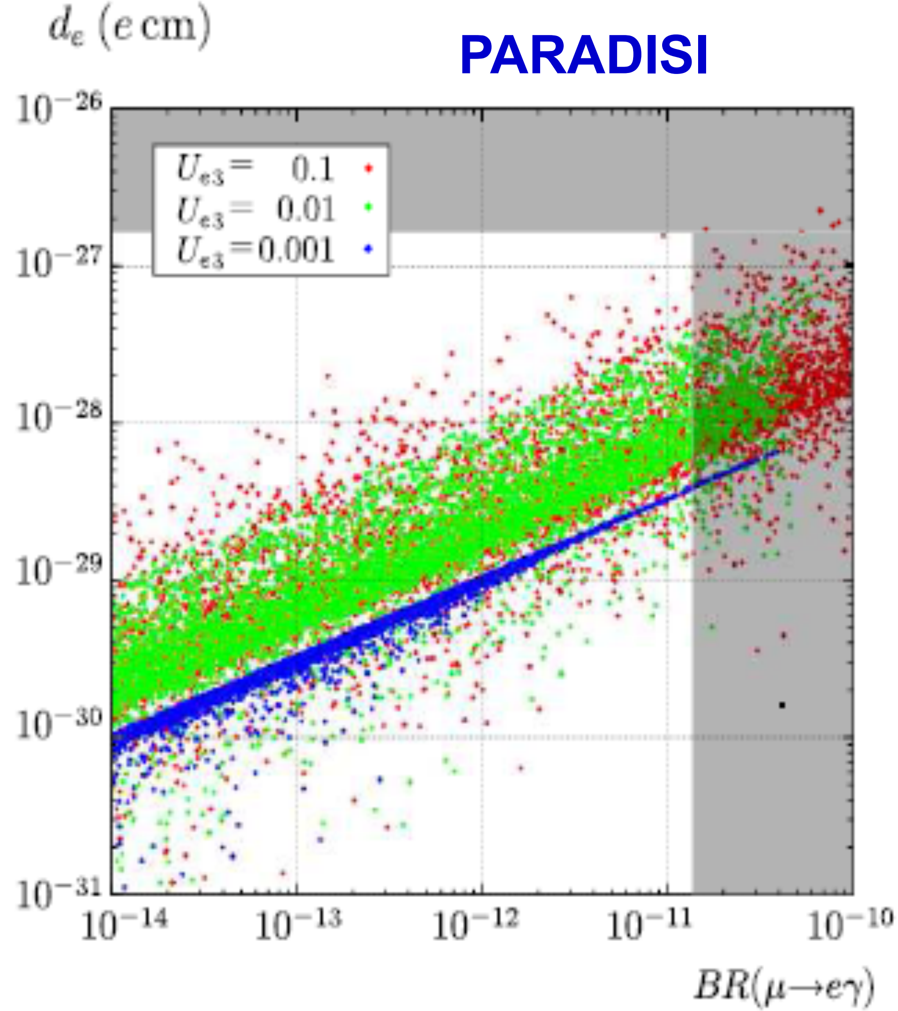



Calibbi, Chowdhuri, A. M., Patel, Vempati 2012



# *LFV, g – 2, EDM*: a promising correlation in SUSY SEESAW



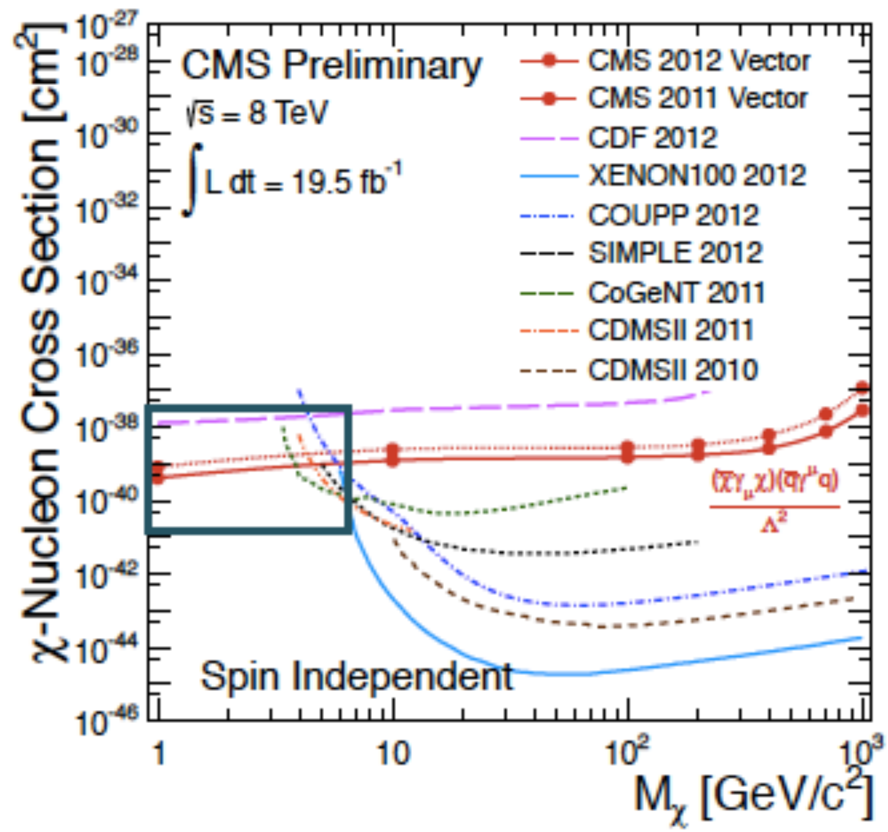
# CONNECTION DM – ELW. SCALE

## ***THE WIMP MIRACLE*** :STABLE ELW. SCALE WIMPs

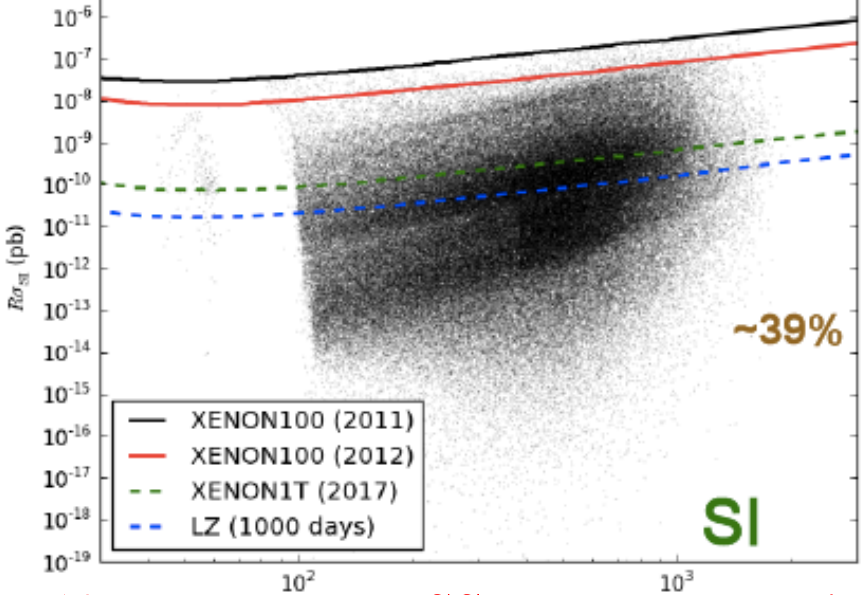
| | SUSY | EXTRA DIM. | LITTLE HIGGS. |
|---|---|---|---|
| 1) **ENLARGEMENT OF THE SM** | $(x^{\mu}, \theta)$ | $(x^{\mu}, j^{i})$ | SM part + new part |
| | Anticomm. Coord. | New bosonic Coord. | to cancel $\Lambda^2$ at 1-Loop |
| 2) **SELECTION RULE** | ***R-PARITY LSP*** | ***KK-PARITY LKP*** |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

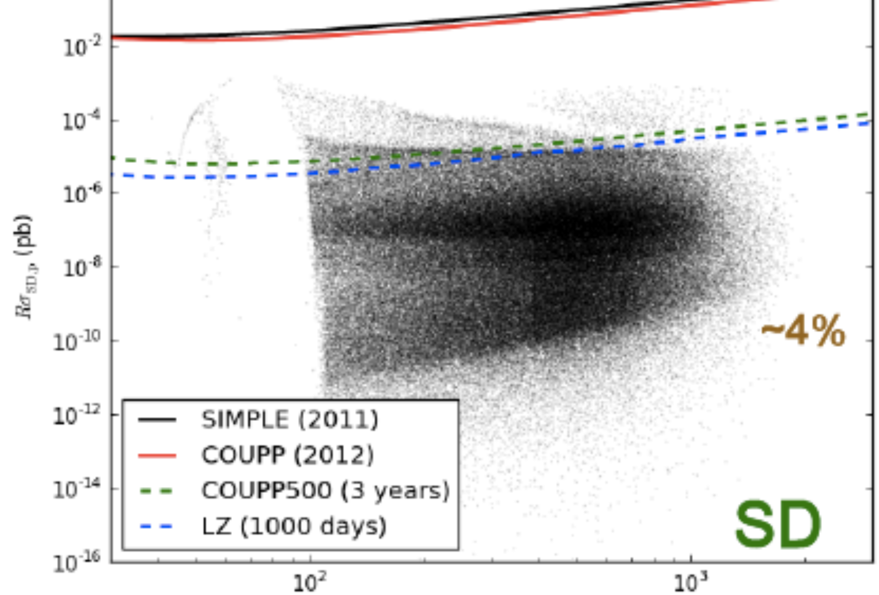
# “Collider-friendly” Dark Matter [DM]

- È possibile vedere un segnale di DM (non solo per M < 10 GeV) a LHC?
  - interazione prevalentemente spin dependent: Majorana DM
  - interazione significativamente inelastica: pDirac DM



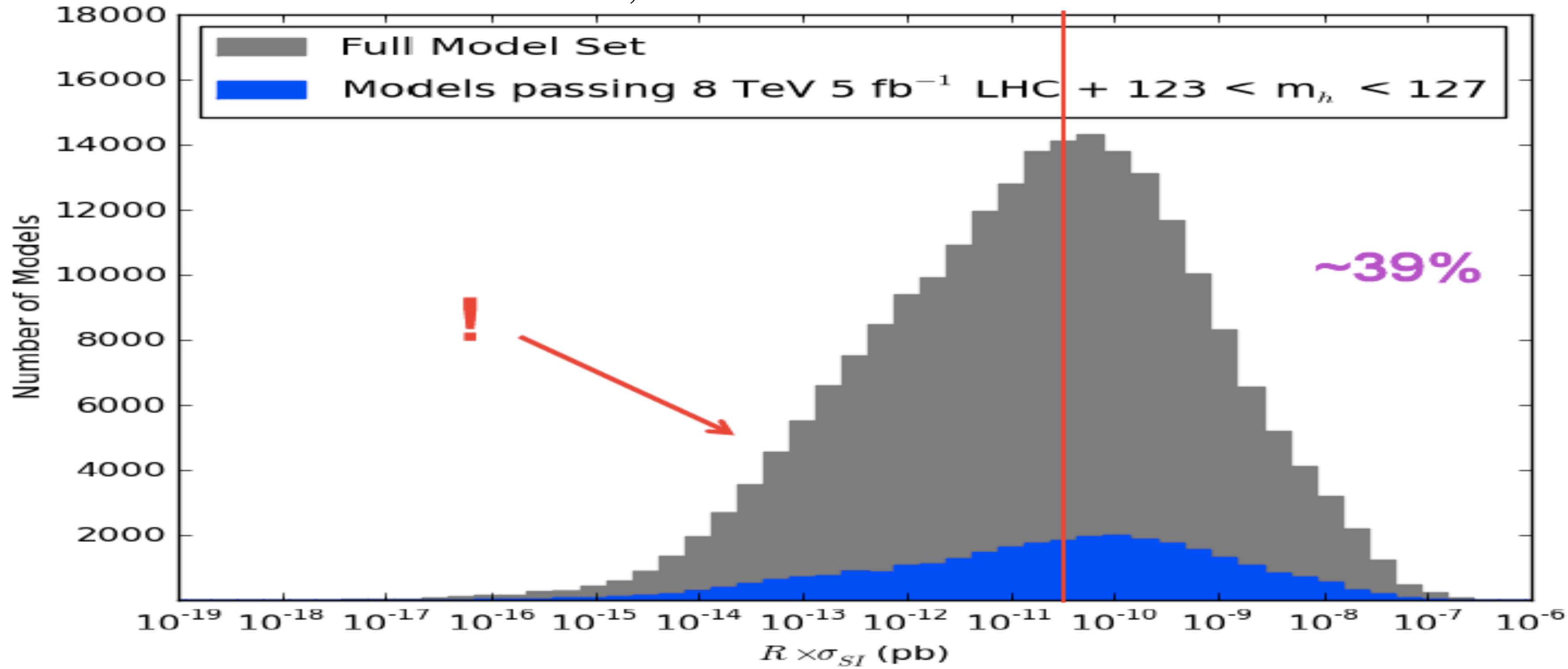

Romanino, What Next, LNF 2015



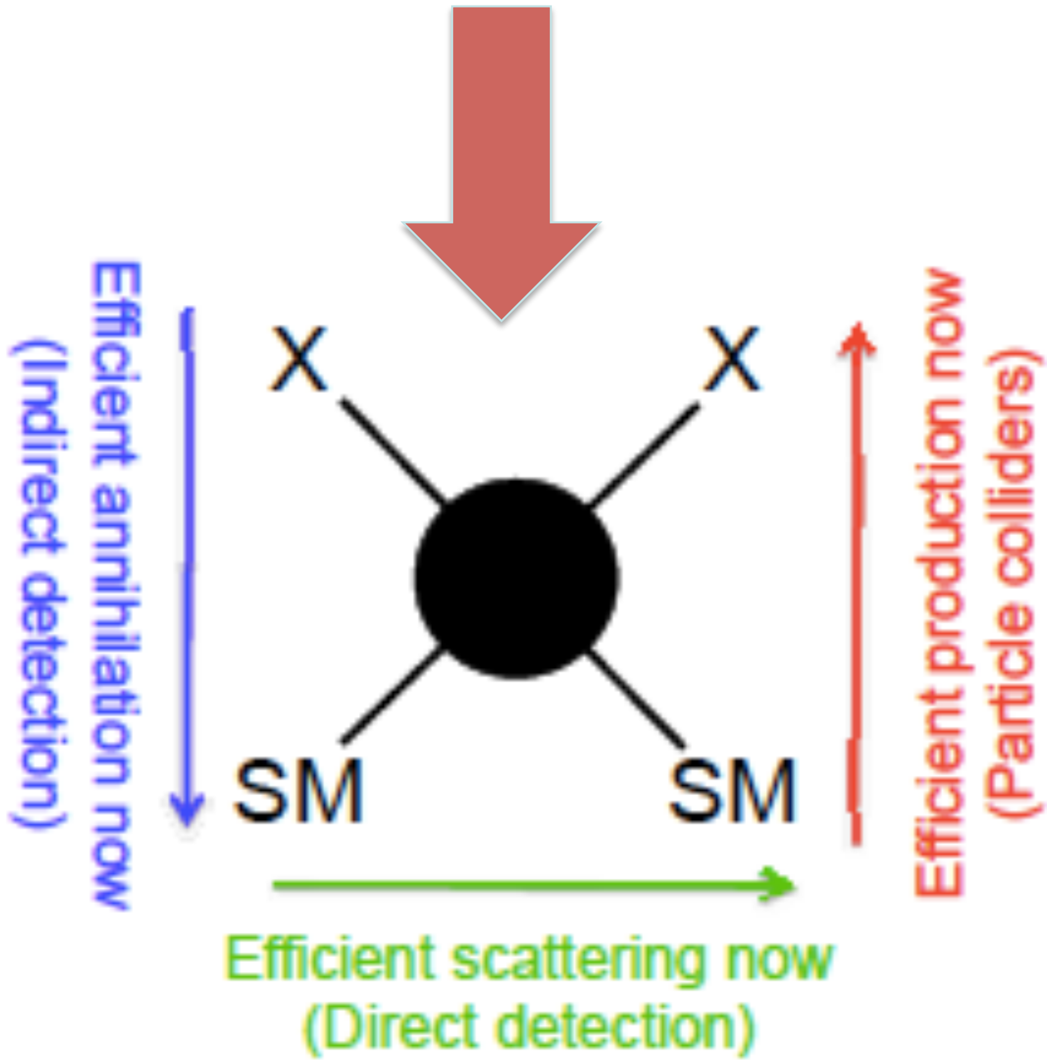

**125k models pMSSM under scrutiny**

Hewett, Rizzo et al



# *DM COMPLEMENTARITY*: efficient annihilation in the early Universe implies today

**R. Poettgen (ATLAS), E. Torassa (CMS)**

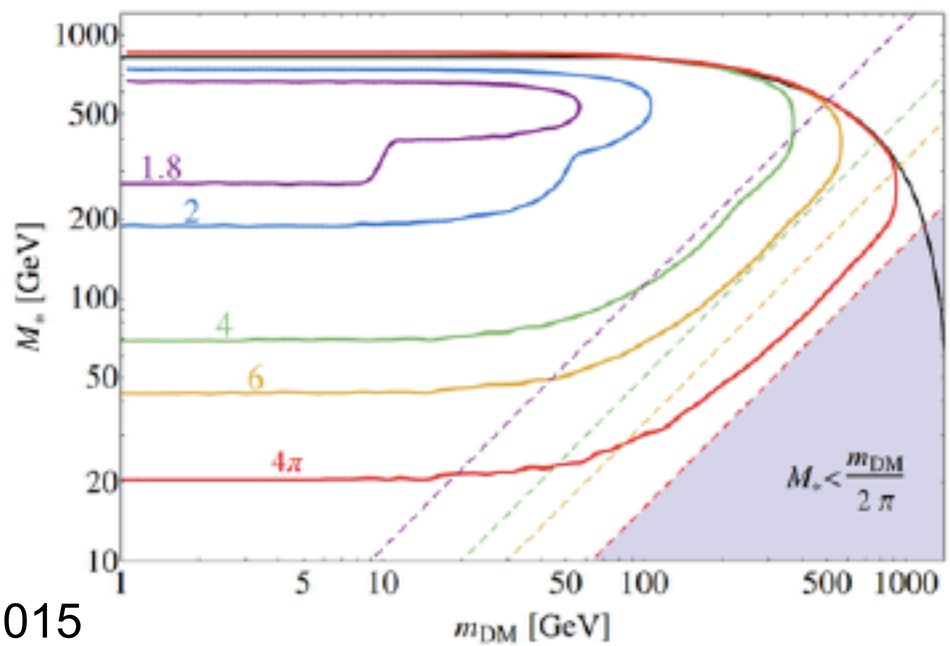


# DM: approccio EFT al collider

- $\frac{1}{M_*^2}(\overline{X}\gamma^\mu\gamma^5 X)(\overline{q}\gamma_\mu\gamma^5 q)$

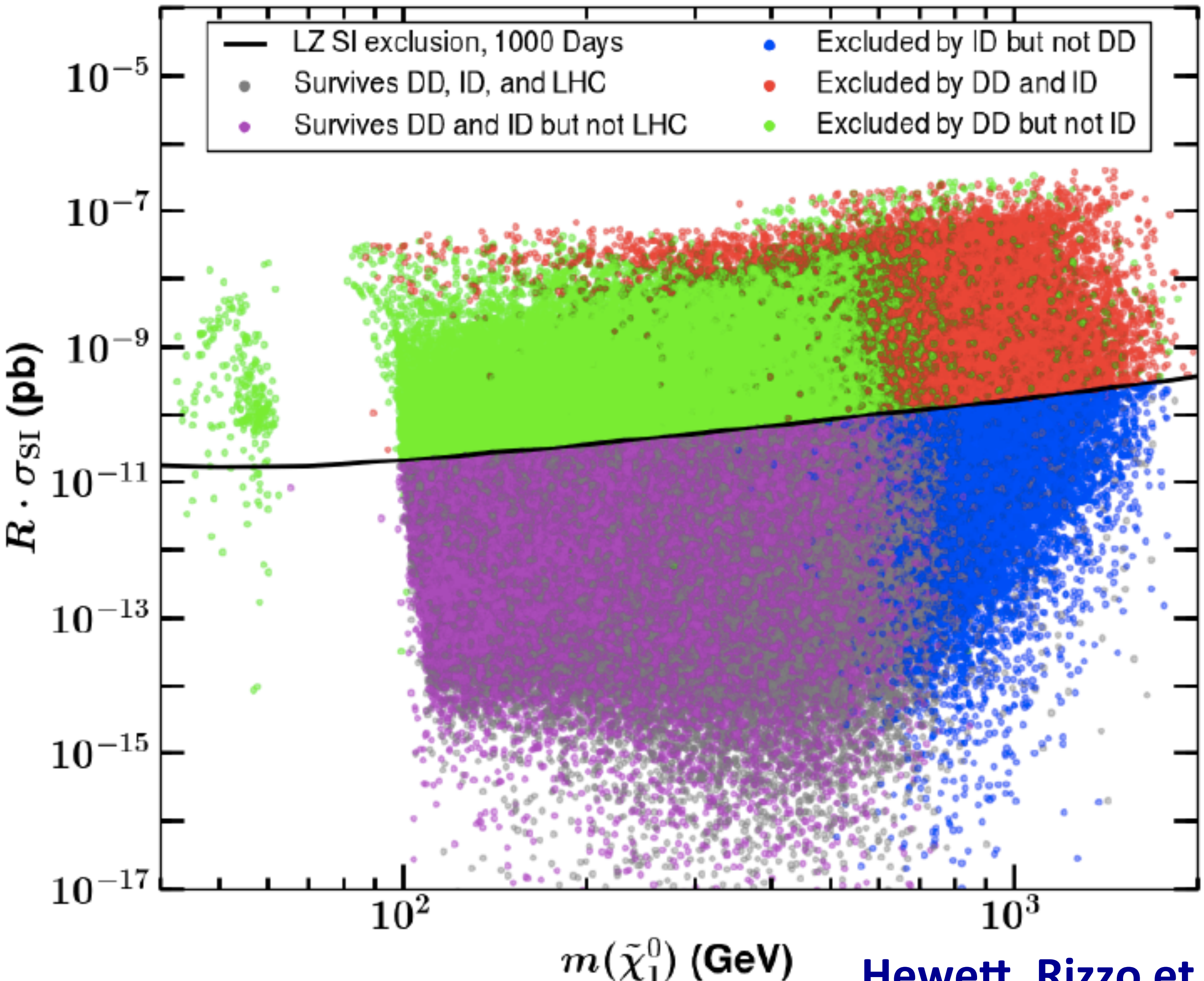
Racco, Wulzer, Zwirner 2015;
De Simone, Giudice, Strumia 2014

- La EFT vale sotto il cutoff $M_{\rm cut} \sim M_{\rm mess} = g_* M_*$
- Approccio rigoroso $\sigma^S_{EFT}\Big|_{E_{\rm cm}<M_{\rm cut}} \leq \sigma^S_{\rm true} < \sigma_{\rm exc}$
- Reinterpretazione conservativa dei limiti




Romanino, What Next, LNF 2015

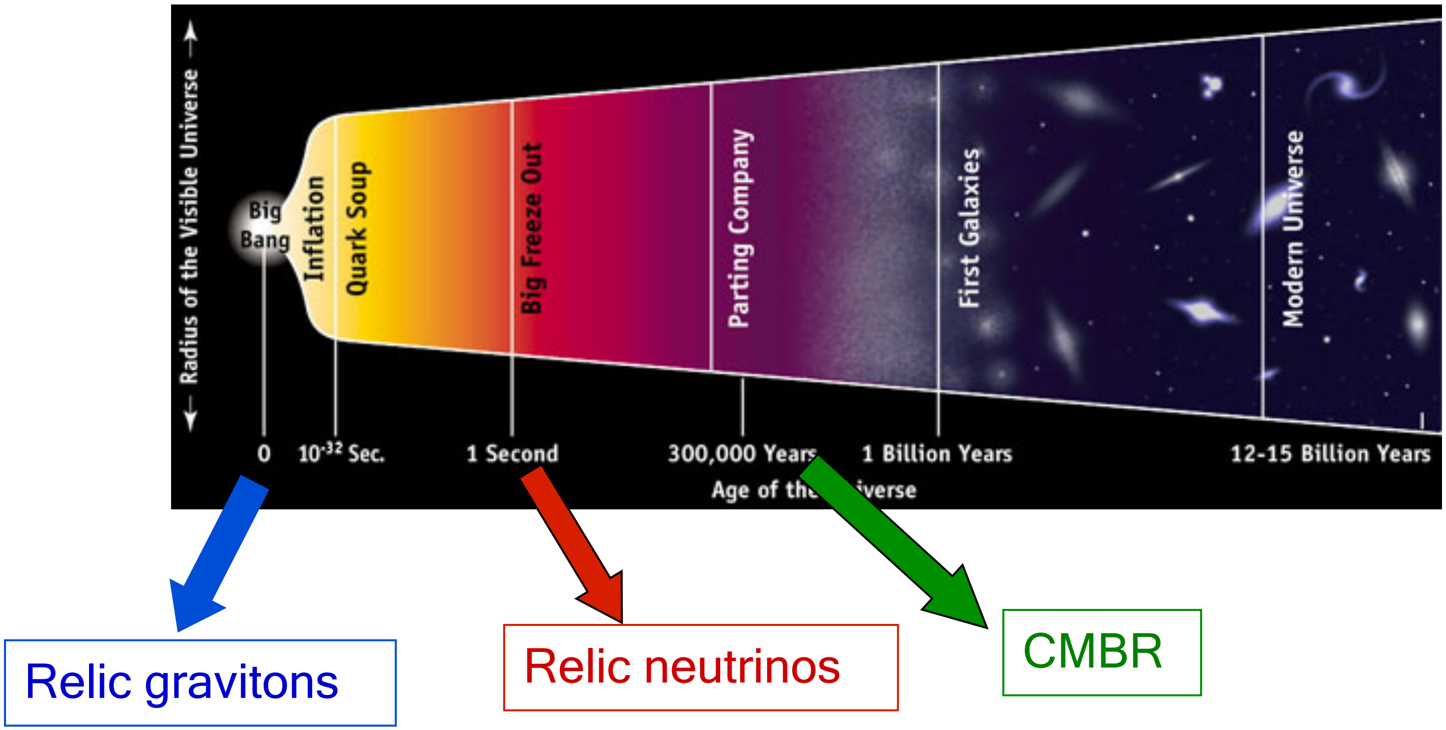
# pMSSM models DD = LZ both SI + SD ID = FERMI + CTA




11.4%
29.2%
7.2%
27.5%
24.7%

Hewett, Rizzo et al. 2013

# Relic Stochastic Background




- Imprinting of the early expansion of the universe
- Correlation of at least two detectors needed

- 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

- **We know nothing**. Right now we are standing in a tiny circle of light around our feet, and every thousand years we push that circle out just a little bit. Every time someone sticks his toe out beyond that circle, it opens up whole worlds of inquiry –

J Ellenberg 2010

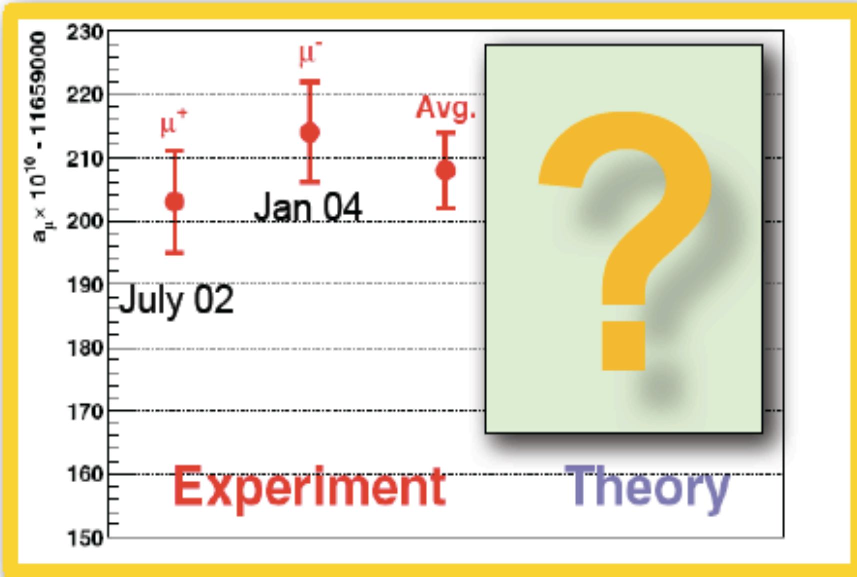
# WHAT NEXT

In view of the complex landscape we have to confront, INFN has recently started a process to identify the most important research themes that we should focus on amongst those that in this moment do not receive enough attention (people, funding). FERRONI


**HIGH ENERGY, HIGH-INTENSITY, ASTROPARTICLE PHYSICS COMPLEMENTARY ATTACK TO THE NEW PHYSICS FORTRESS**

# BACKUP SLIDES

# The muon g-2: the experimental result




- **Today:** $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys})\times10^{-11}$ [0.5ppm].
- **Future:** new muon g-2 experiments proposed at:
  - Fermilab E989, aiming at $\pm 16\times10^{-11}$, ie 0.14ppm ← Sep 2012: CD0 approval! Data in (late) 2016?
  - J-PARC aiming at 0.1 ppm

  See B. Lee Roberts & T. Mibe @ Tau2012, September 2012
- **Are theorists ready for this (amazing) precision?** No(t yet)

# The muon g-2: SM vs. Experiment

**Adding up all contributions, we get the following SM predictions and comparisons with the measured value:**

$a_\mu^{EXP} = 116592089\ (63) \times 10^{-11}$

E821 – Final Report: PRD73 (2006) 072 with latest value of $\lambda = \mu_\mu/\mu_p$ from CODATA'06

| $a_\mu^{SM} \times 10^{11}$ | $\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$ | $\sigma$ |
|---|---|---|
| 116 591 794 (66) | $295\ (91) \times 10^{-11}$ | 3.2 [1] |
| 116 591 814 (57) | $275\ (85) \times 10^{-11}$ | 3.2 [2] |
| 116 591 840 (58) | $249\ (86) \times 10^{-11}$ | 2.9 [3] |

with the "conservative" $a_\mu^{HHO}(lbl) = 116\ (39) \times 10^{-11}$ and the LO hadronic from:


[1] Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1

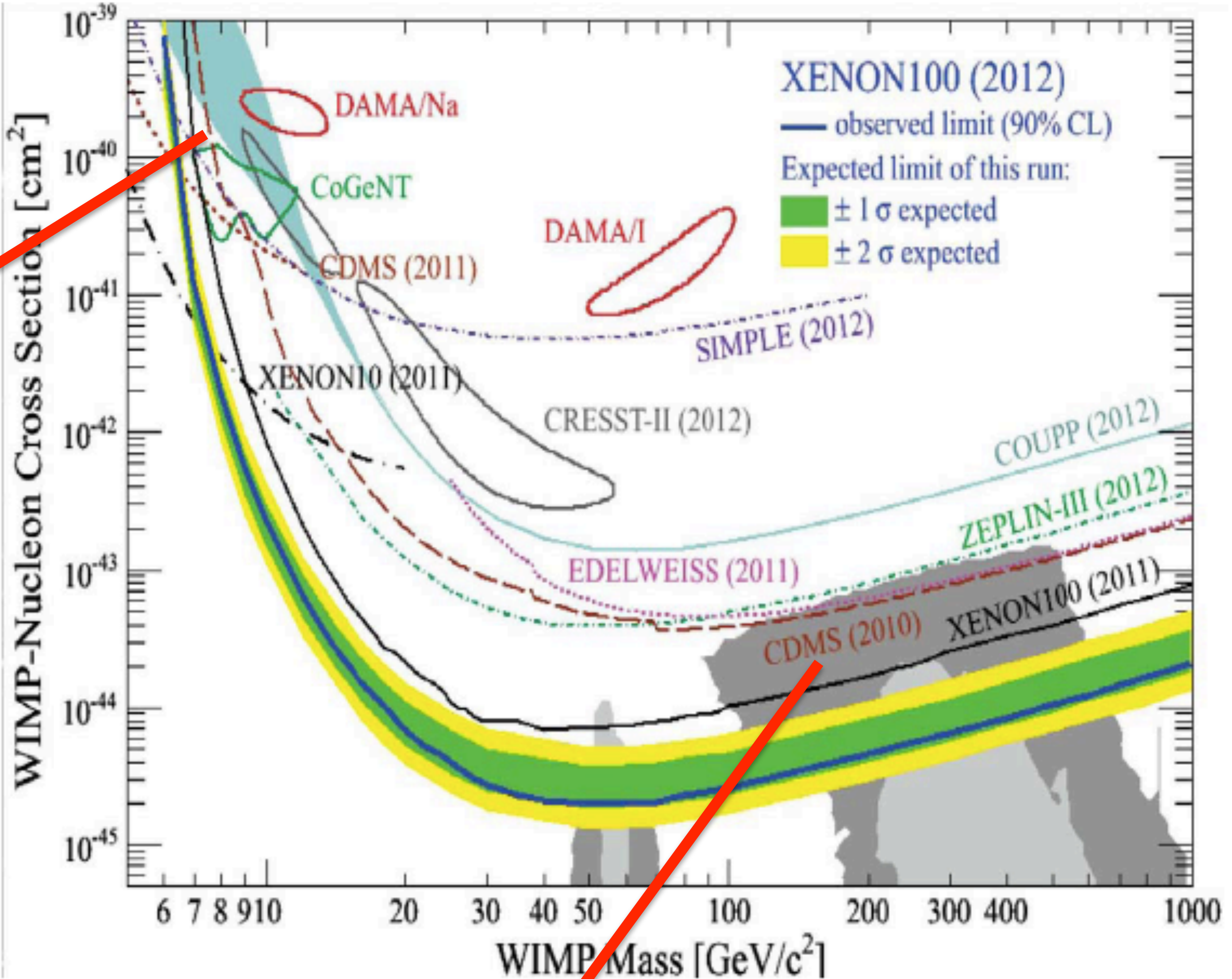
[2] Davier et al, EPJ C71 (2011) 1515 (includes BaBar & KLOE10 2π)

[3] Hagiwara et al, JPG38 (2011) 085003 (includes BaBar & KLOE10 2π)

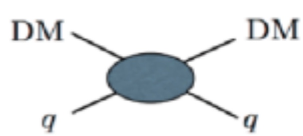

**Note that the th. error is now about the same as the exp. one**

Low-mass region:
either unexplained backgrounds in DAMA, CoGeNT, and CRESST-II, …
or
… other experiments do not understand low recoil energy calibration, …
or
… can't compare different experiments

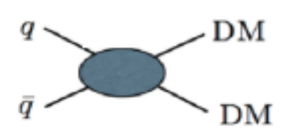
**Kolb SUSY2012**



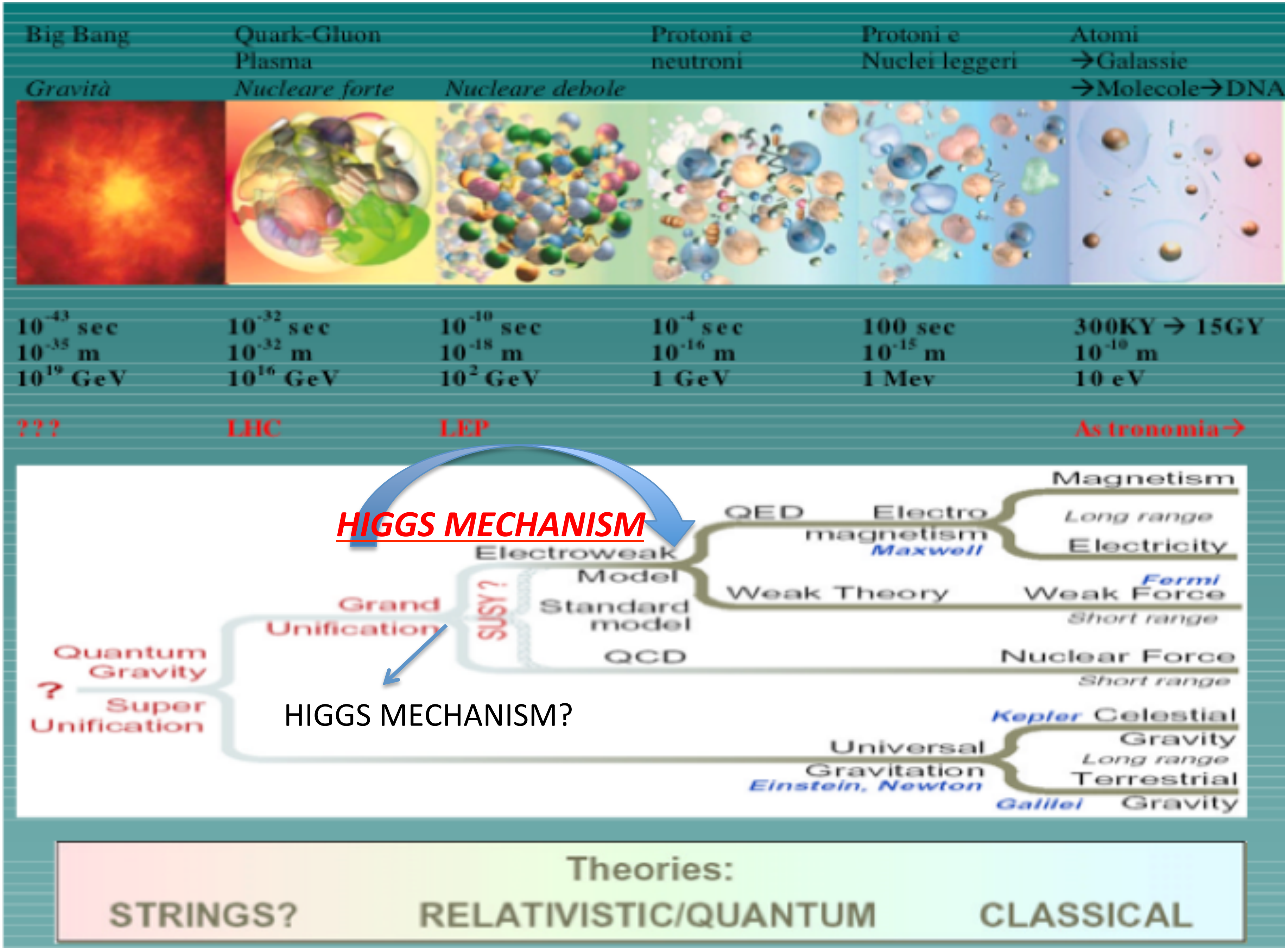

Relevant to intensify the efforts here: ex. **asymmetric DM** with **DM particles of mass~ baryon mass given that $\rho_{DM}$ not much different from $\rho_B$**




*Direct Detection (t-channel)*




*Collider Searches (s-channel)*



Big Bang
Gravità
Quark-Gluon Plasma
Nucleare forte
Nucleare debole
Protoni e neutroni
Protoni e Nuclei leggeri
Atomi →Galassie →Molecole→DNA
10^-43 sec
10^-35 m
10^19 GeV
10^-32 sec
10^-32 m
10^16 GeV
10^-10 sec
10^-18 m
10^2 GeV
10^-4 sec
10^-16 m
1 GeV
100 sec
10^-15 m
1 Mev
300KY → 15GY
10^-10 m
10 eV
???
LHC
LEP
Astronomia→
HIGGS MECHANISM
Magnetism
QED
Electro magnetism
Maxwell
Long range
Electricity
Electroweak Model
Grand Unification
SUSY ?
Standard model
Weak Theory
Fermi
Weak Force
Short range
Quantum Gravity
QCD
Nuclear Force
Short range
?
Super Unification
HIGGS MECHANISM?
Kepler
Celestial Gravity
Universal Gravitation
Einstein, Newton
Long range
Terrestrial Gravity
Galilei
Theories:
STRINGS?
RELATIVISTIC/QUANTUM
CLASSICAL