IPA 2014, QMUL, June 18 – 22, 2014

Theoretical Summary

Proving that it's no longer so

Antonio Masiero
INFN and Univ. of Padova

EXPERIMENT THEORY

Thanks to the speakers:

Andy Bevan, Christian Stegman, James Pinfold, Emi Kou, Martin Haigh, Jesús Zavala, Jon Coleman, Qingmin Zhang, Wolfgang Rau, Chris D'Andrea, Yoni Kahn, JR Wilson,Teppei Katori, Benjamin Joachimi, Jason Koskinen, Stefano Liberati, Antonio Racioppi, M Bona, Alessandro Gaz, Andrew Brown, Ruth Poettgen, Malcolm John, Ryan Page, Niels Madsen, Mitesh Patel, Wei Wang, Ezio Torassa, Csaba Balazs, Amarjit Soni, Emanuele Santovetti, Alan Watson, Tomohiko Tanabe, Geraldine Servant, David Straub, Jan Conrad, Yong Tang, Steven Gratton, Barry Barish, Pasquale Di Bari, Georg Weiglein, Alessandro Gaz, Anže Slosar, Jocelyn Monroe, Kiyoshi Hayasaka, Martin Pohl, Lucian Stefan Ancu, Chamkaur Ghag, Nago Keiko, Thomas O'Donnel, Alexander Kuzmin, Abner Soffer, Ruban Saakyan, Phil Litchfield, Toru Goto, Hajime Nishiguch, W Clark Griffith, Jessie Shelton

COSMOLOGY -ASTROPHYSICS HIGH-ENERGY, FLAVOUR PHYSICS

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. $Me^{-2\Pi/\alpha_s b}$
- ~2010 WEAK SCALE 10^{-17} cm. TeV^{-1}

FUNDAMENTAL OR DERIVED SCALE?

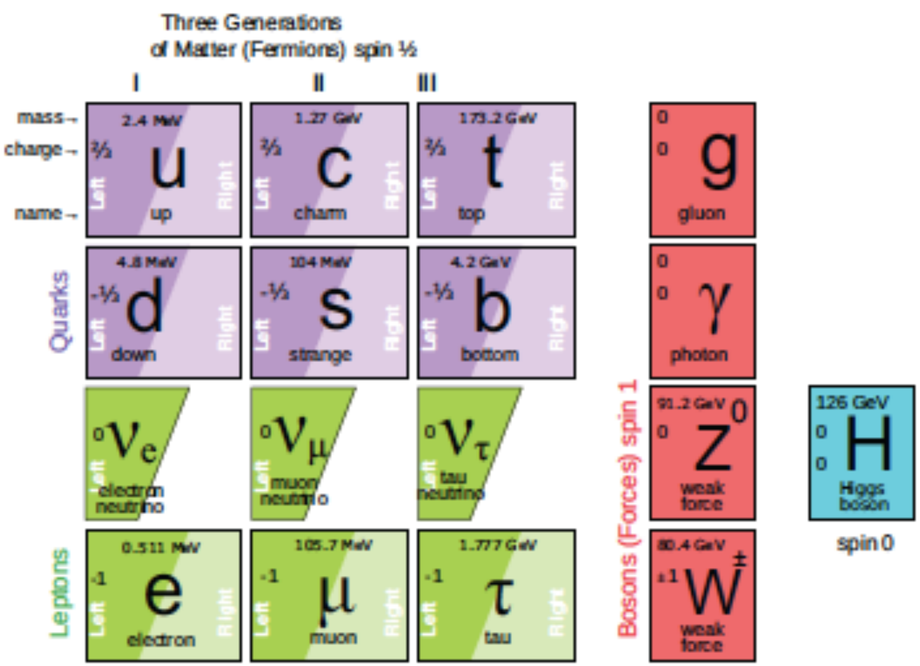
EX. EXTRA-DIMENSIONS
or
TeV STRING THEORY

EX.: TECHNICOLOR or
SUSY with ELW RAD. BREAKING

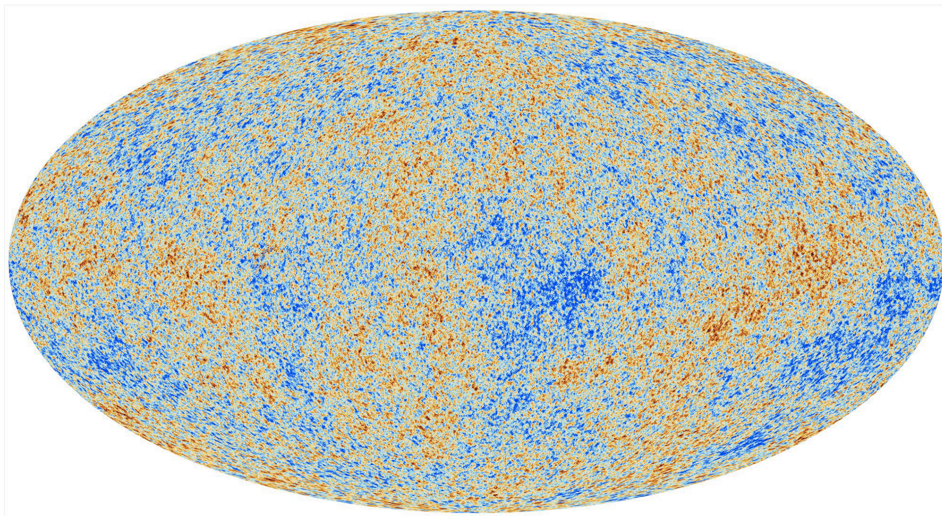
NEW PARTICLES AT THE TEV SCALE?

2013: the thiumph of the STANDARD

- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



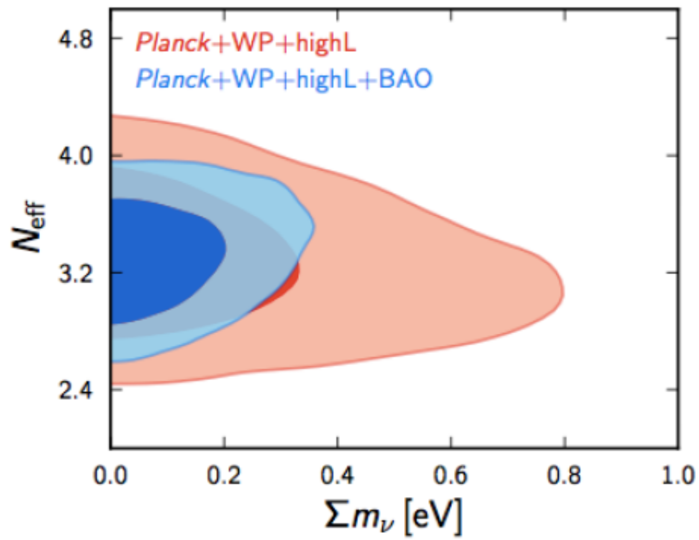
ΛCDM + "SIMPLE" INFLATION

$\Omega_\Lambda=0.686\pm0.020$

$\Omega_m=0.314\pm0.020$

$\Omega_b h^2=0.02207\pm0.00033$

$h=0.674\pm0.014$



$N_{eff}=3.36\pm0.34$

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

$\Sigma m_\nu < 0.23\text{-}\ 0.8$ eV

Recent (and controversial!) **BICEP2** results **(SLOSAR, this meeting)**: from the measurement of the B-mode polarization of the CMB photons → initial **inflationary epoch** at energies ~ $\mathbf{V^{1/4} = 1.94 \times 10^{16}}$ **GeV** $\mathbf{(r/0.12)^{1/4}}$ **;** 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)

QFT and GR classical scale invariant: M_P induced by the inflaton VEV with the inflaton non-minimally coupled to gravity (**A. RACIOPPI at this meeting**)

MICRO

GWS STANDARD MODEL

MACRO

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 ???

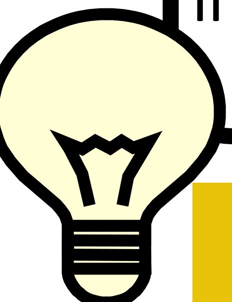
- DARK MATTER + DARK ENERGY

OBSERVATIONAL EVIDENCE OF NEW PHYSICS

BEYOND THE STANDARD

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

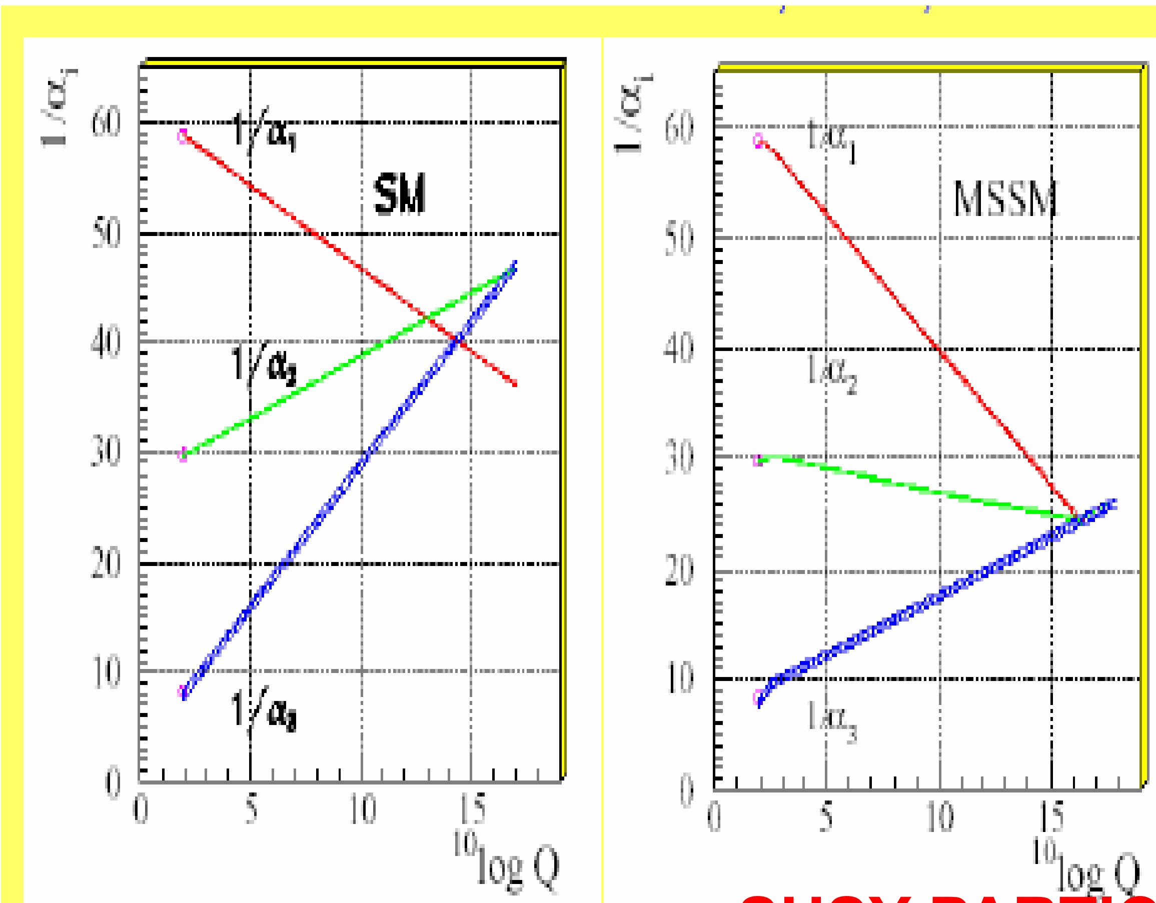
The Energy Scale from the "Theoretical" New Physics

★★★ **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**

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

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

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

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

	SU(3)	SU(2)	U(1)		SO(10)
L	1	2	-1/2		
e	1	1	1		
Q	3	2	1/6	⇒	16
u	3*	1	-2/3		
d	3*	1	1/3		

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

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

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

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

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

m_{NP} x 2 → Δ x 4

- The bound on Δ is model-dependent:

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

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

- 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 scal $M \gg m_h$ **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 $\sim (m_H)^2$

- **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**?
  → $V_o = \mu^2 \langle H\rangle^2 + \lambda \langle H\rangle^4 \sim (100\ \text{GeV})^2$

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

but **θ very small TODAY** at T=0 ≠>

θ very small at **T ≠ 0 in the early Universe**

Strong CP violation from the QCD axion can be responsible for the matter antimatter asymmetry of the universe in the context of cold baryogenesis

if the EW phase transition is delayed down to the QCD scale

G. SERVANT at IPA2014

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)

Ways to implement the BEH mechanism

- **STANDARD HIGGS:**

- **FINE-TUNED (unnatural Higgs – anthropic road, high-scale fundamental theory taking care of it, …)**
- **NATURAL (protection mechanism: low-energy SUSY; inexistence of the scale hierarchy problem: extra dimensions, warped space, …)**

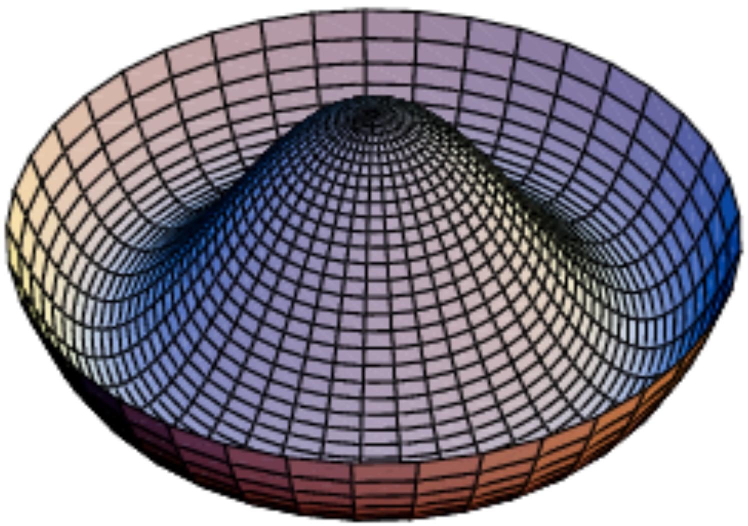
- **COMPOSITE HIGGS: Pseudo-Goldstone boson**

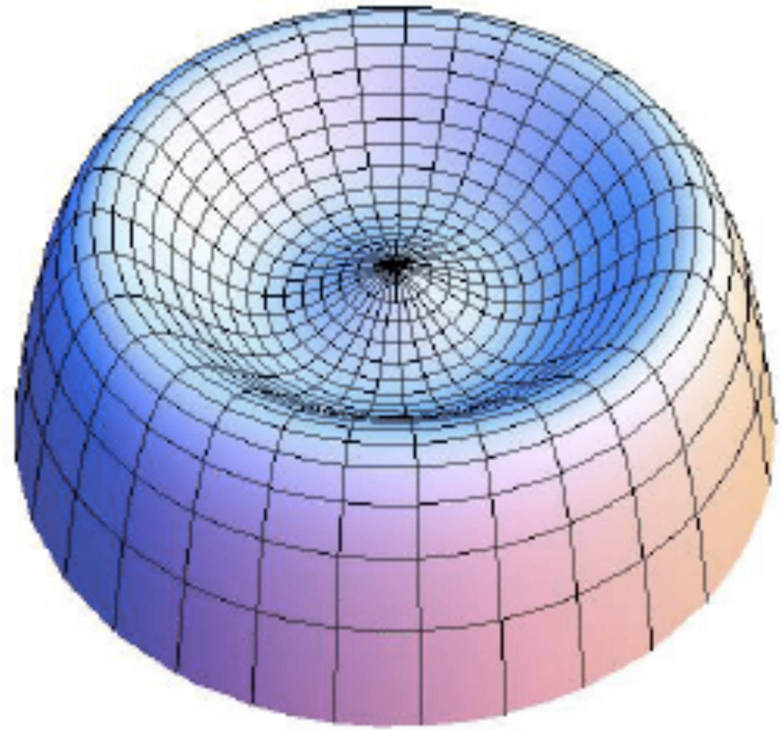
- **More EXOTIC HIGGS (SEMI-IMPOSTOR HIGGS – completely impostor higgs like in the truly higgs-less models by now indefensible) ex.: HIGGS-RADION FIELD (A. Soni at IPA2014), just a single higgs doublet accomplishing a two-fold task, namely breaking the EW symmetry AND stablizing the 5th extra dimension (Geller, Bar-Shalom, Soni)**

On the peculiar value of M_H

- **For the SM to survive up to a very large scale, M_{GUT} or M_{Planck} : M_H in the fork 125 – 180 GeV, with ~ 125 GeV just on the verge between stability and instability of the vacuum state where the SM sits**
- For the existence of a **(minimal) supersymmetric extension of the SM** at the elw. scale, the lightest SUSY Higgs must have **$M_h < 130$ GeV** (for M_h >120 GeV, the radiative correction to M_h is ~ 50% of the tree-level value)

STABILITY ↔ INSTABILITY

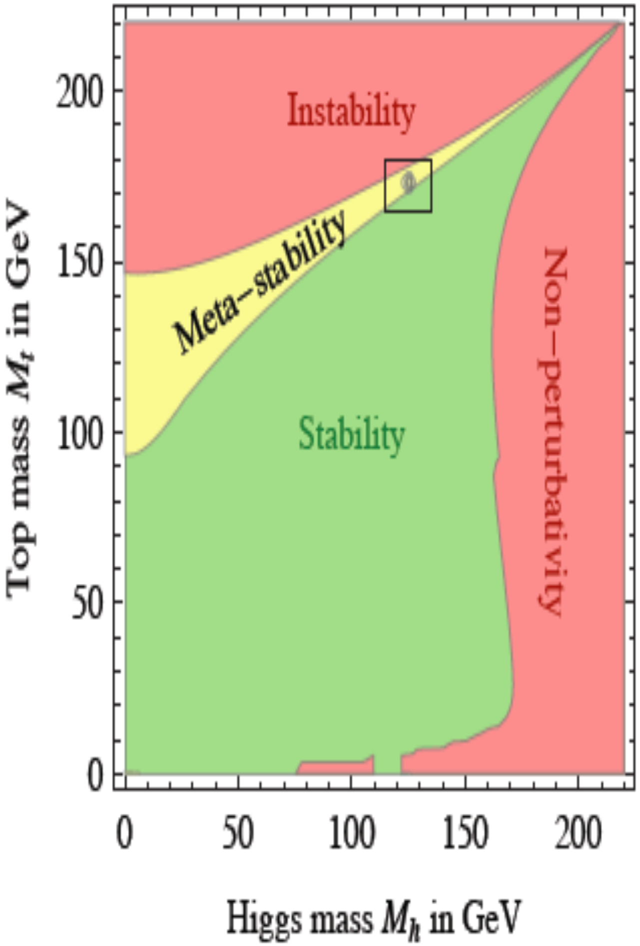


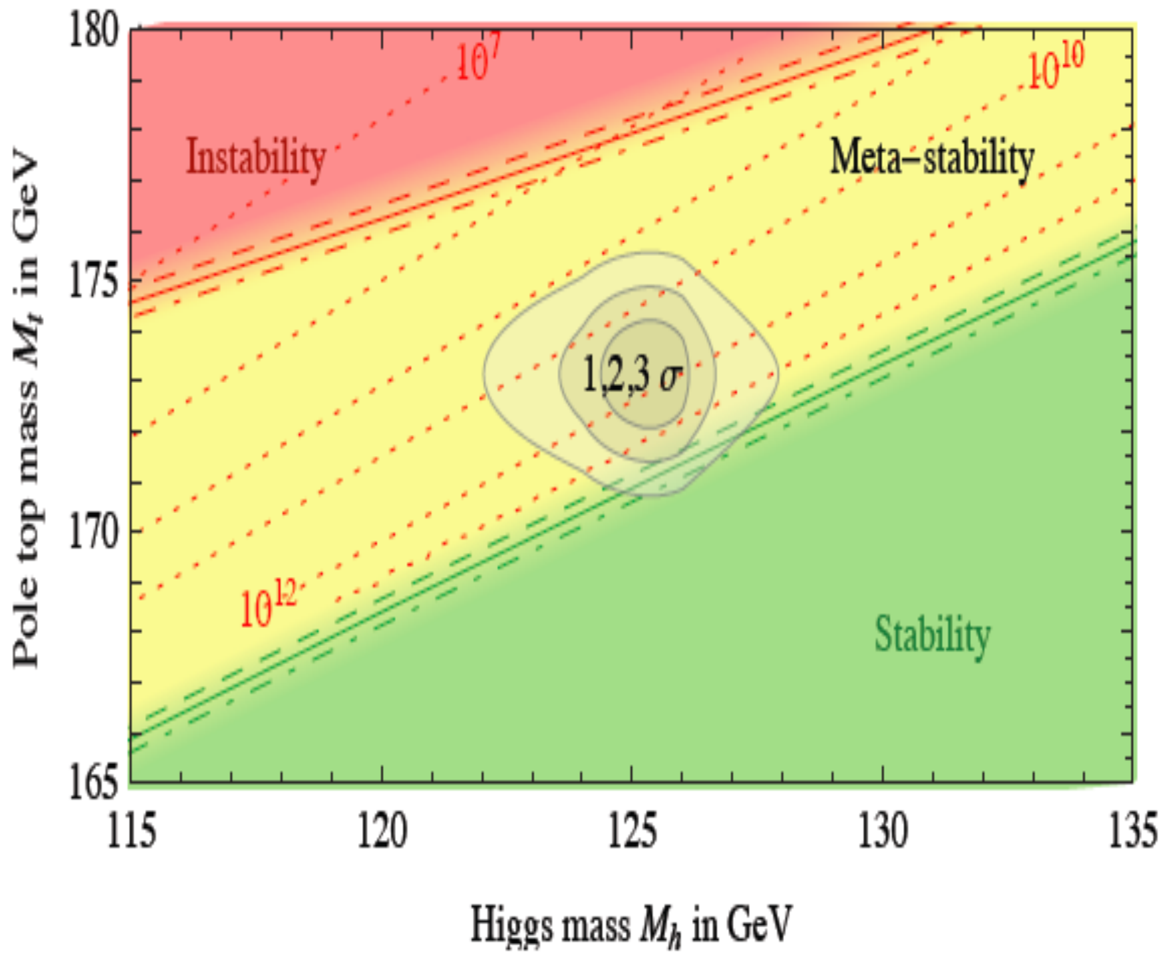


ON THE IMPORTANCE OF PRECISELY MEASURING HIGGS and TOP MASSES

WEIGLEIN at this meeting

LIVING DANGEREOUSLY IN A "PROBABLE" METASTABLE UNIVERSE



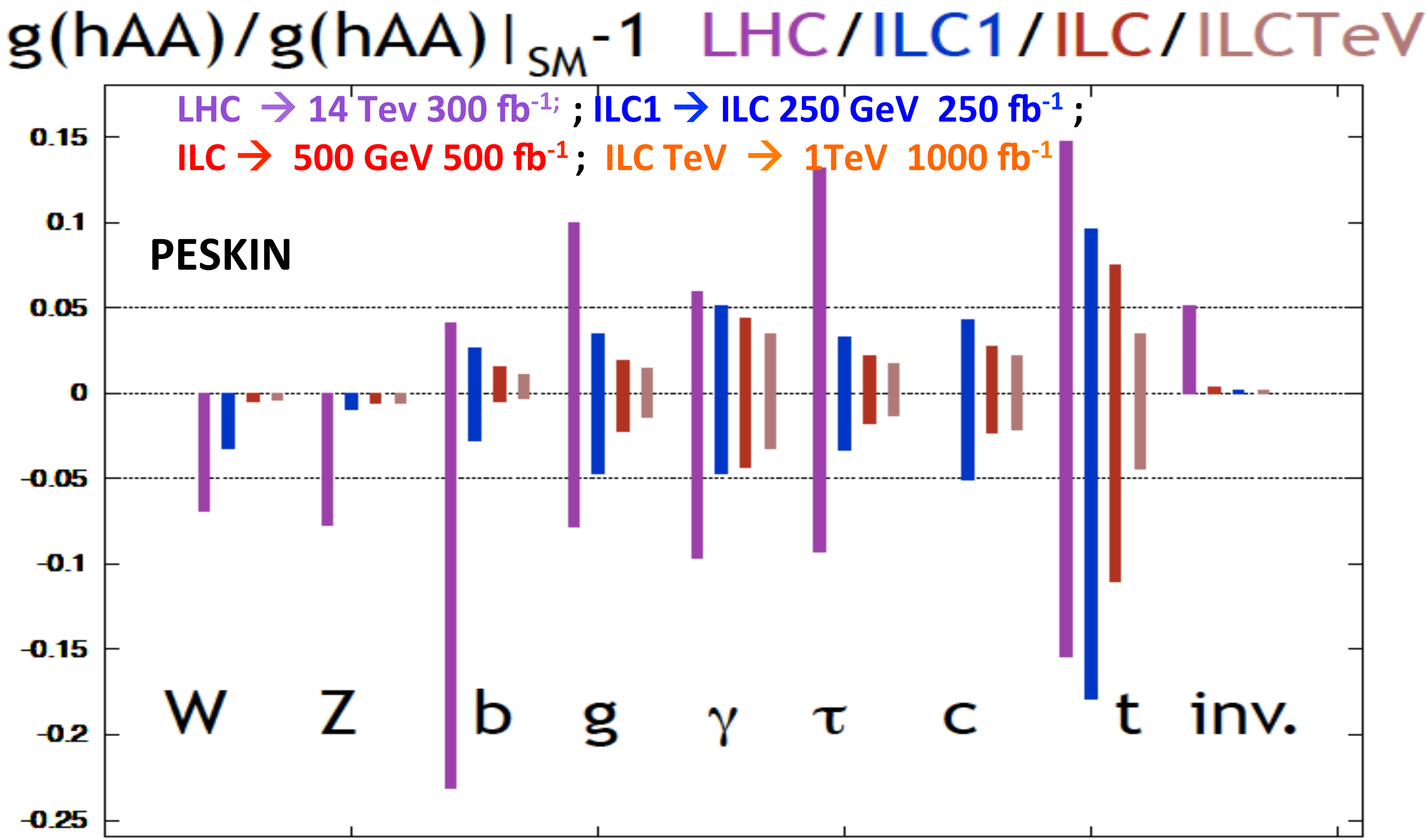


BEZRUKOV, KALMIKOV, KNIEHL, SHAPOSHNIKOV 2012;
DEGRASSI, DI VITA, ELIAS-MIRO', ESPINOSA, GIUDICE, ISIDORI, STRUMIA 2012

FIRST COMPLETE ANALYSIS NNLO OF THE SM HIGGS POTENTIAL

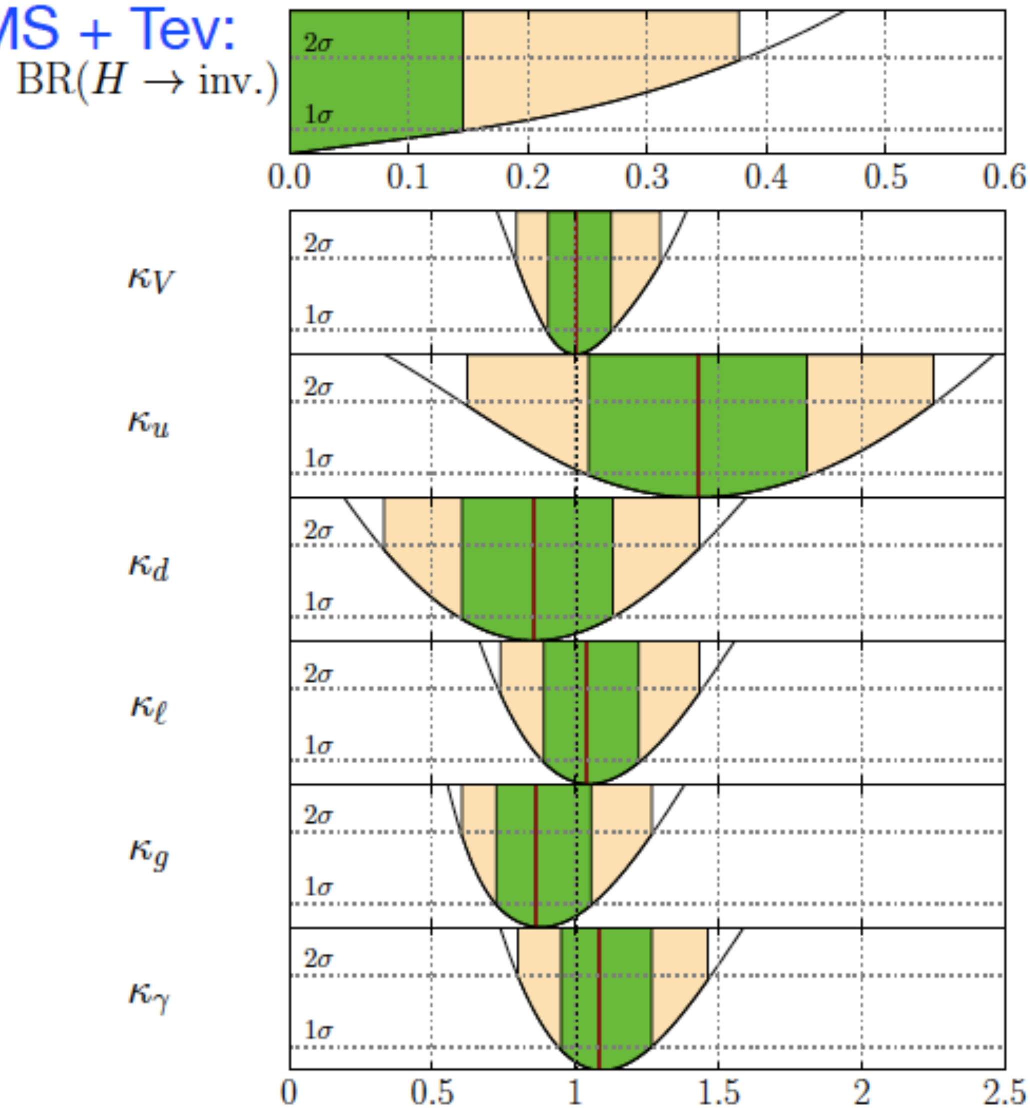
HIGGS Couplings Sensitivity at LHC and ILC

TANABE at this meeting



Constraints on coupling scale factors from ATLAS + CMS + Tevatron data

ATLAS + CMS + Tev:



Seven fit parameters

HiggsSignals

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '14]

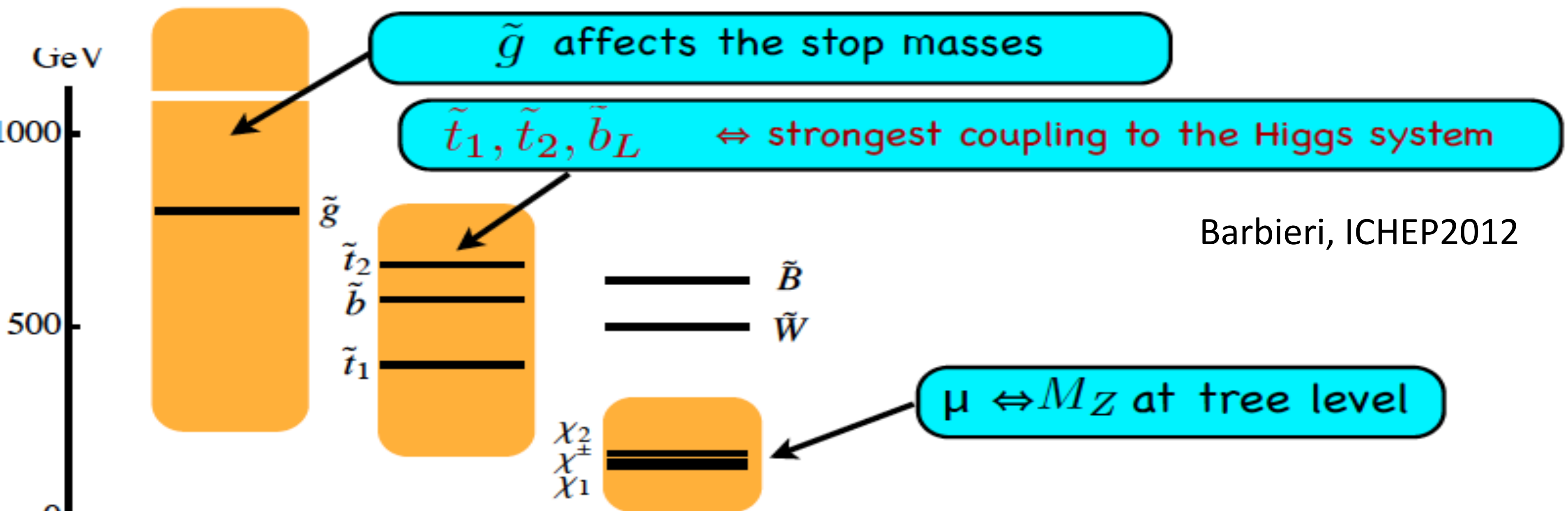
G. WEIGLEIN at this meeting

⇒ Significantly improved precision compared to ATLAS or CMS results alone

NATURAL SUSY

LOW-ENERGY SUSY to cope with the gauge hierarchy problem: only the SUSY particles involved in the cancellation of the quadratic div. to the Higgs mass have to remain "light"

"s-particles at their naturalness limit"



Barbieri, ICHEP2012

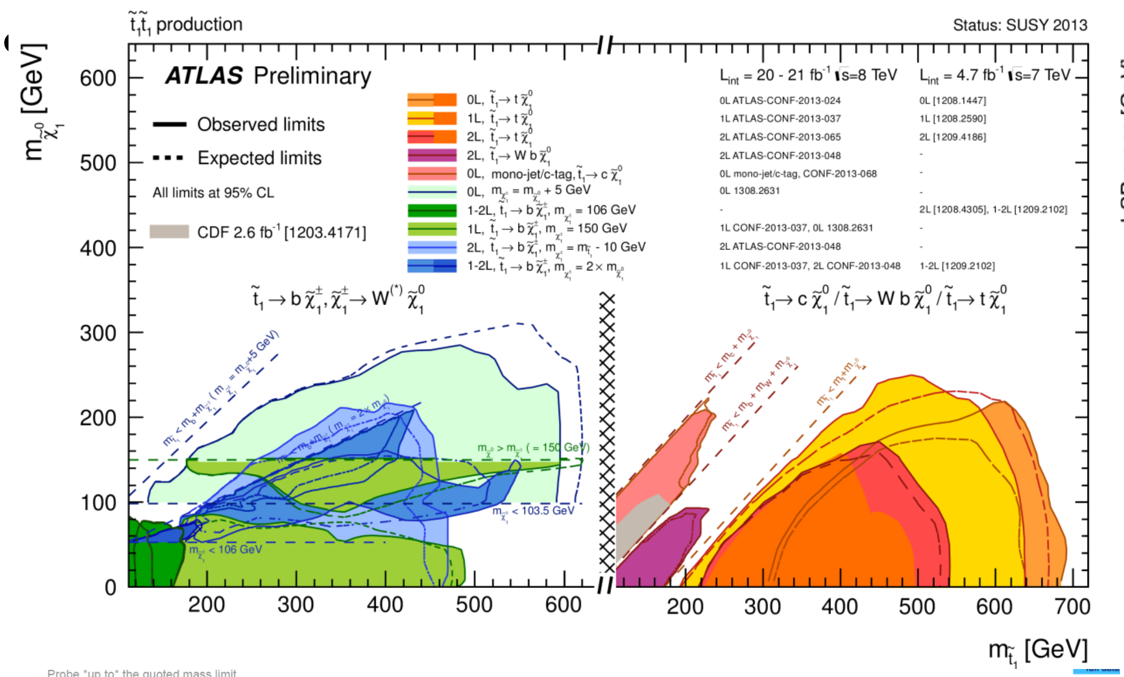
orange areas indicative and dependent on how the Higgs boson gets its mass

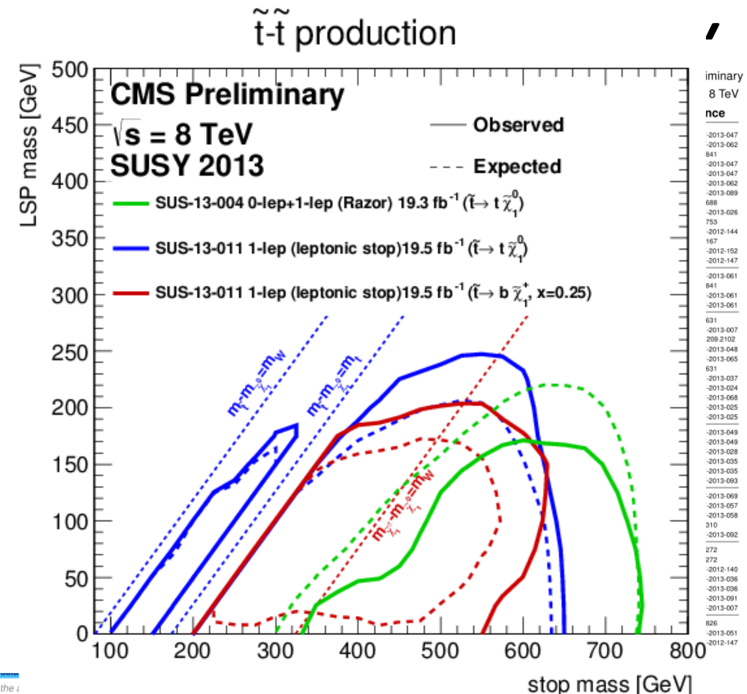
$\tilde{B}, \tilde{W}$ not much constrained but expected below $m_{\tilde{g}}$

SUSY searches

ATLAS → ANCU
CMS → GAZ
at this meeting

- Higgs mass value reduces SUSY parameter space
- Direct searches unsuccessful → gluinos well above 1 TeV
- Working on stop expected lighter



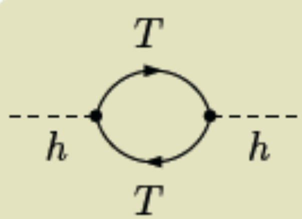


Higgs and flavor physics as indirect BSM probes

NEUBERT SUSY2012

$$\mathcal{L}_{\rm EFT} = \Lambda_{\rm UV}^2\,\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2} + \dots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass

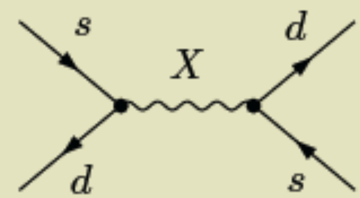


$$\sim \frac{g_T^2}{16\pi^2}\Lambda_{\rm UV}^2$$

no fine-tuning $\Downarrow$

$$\Lambda_{\rm Higgs} \lesssim 1 \text{ TeV}$$

$\Downarrow$



$$\sim \frac{g_X^2}{\Lambda_{\rm UV}^2}$$

bounds on flavor mixing $\Downarrow$ assuming *generic* flavor structure

$$\Lambda_{\rm flavor} \gtrsim 10^3 \text{ TeV}$$

Possible solutions to flavor problem explaining $\Lambda_{\rm Higgs} << \Lambda_{\rm flavor}$:

(i) $\Lambda_{\rm UV} >> 1$ TeV: **Higgs fine tuned**, new particles too heavy for LHC

(ii) $\Lambda_{\rm UV} \approx 1$ TeV: quark flavor-mixing protected by a **flavor symmetry**

Unitarity Triangle analysis in the SM:

obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.679 ± 0.024	0.753 ± 0.042	~ 1.5
γ	68.3 ± 7.5	69.5 ± 3.9	< 1
α	90.8 ± 7.0	87.2 ± 3.9	< 1
$\lvert V_{ub}\rvert \cdot 10^3$	3.75 ± 0.46	3.62 ± 0.12	< 1
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	4.40 ± 0.31	–	~ 2.3
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	3.42 ± 0.22	–	< 1
$\lvert V_{cb}\rvert \cdot 10^3$	40.9 ± 1.0	42.1 ± 0.7	< 1
B_K	0.766 ± 0.010	0.841 ± 0.078	< 1
$BR(B \to \tau\nu)[10^{-4}]$	1.14 ± 0.22	0.81 ± 0.07	~ 1.4
$BR(B_s \to ll)[10^{-9}]$	2.9 ± 0.7	3.92 ± 0.16	~ 1.3
$BR(B_d \to ll)[10^{-9}]$	0.37 ± 0.15	0.114 ± 0.007	~ 1.7
$A_{SL}^d \cdot 10^3$	-4.8 ± 5.2	0.012 ± 0.002	< 1
$A_{\mu\mu} \cdot 10^3$	-7.9 ± 2.0	-0.12 ± 0.02	~ 3.9

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"**

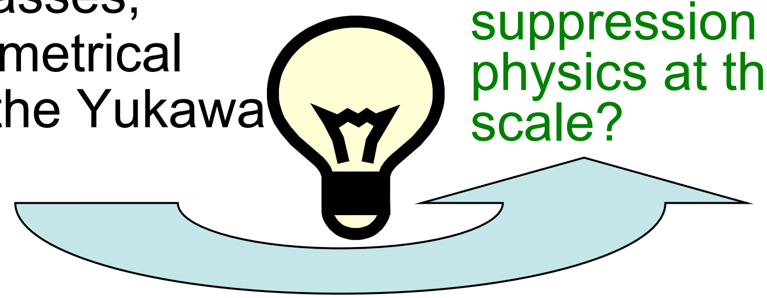
(new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, …?)

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.**

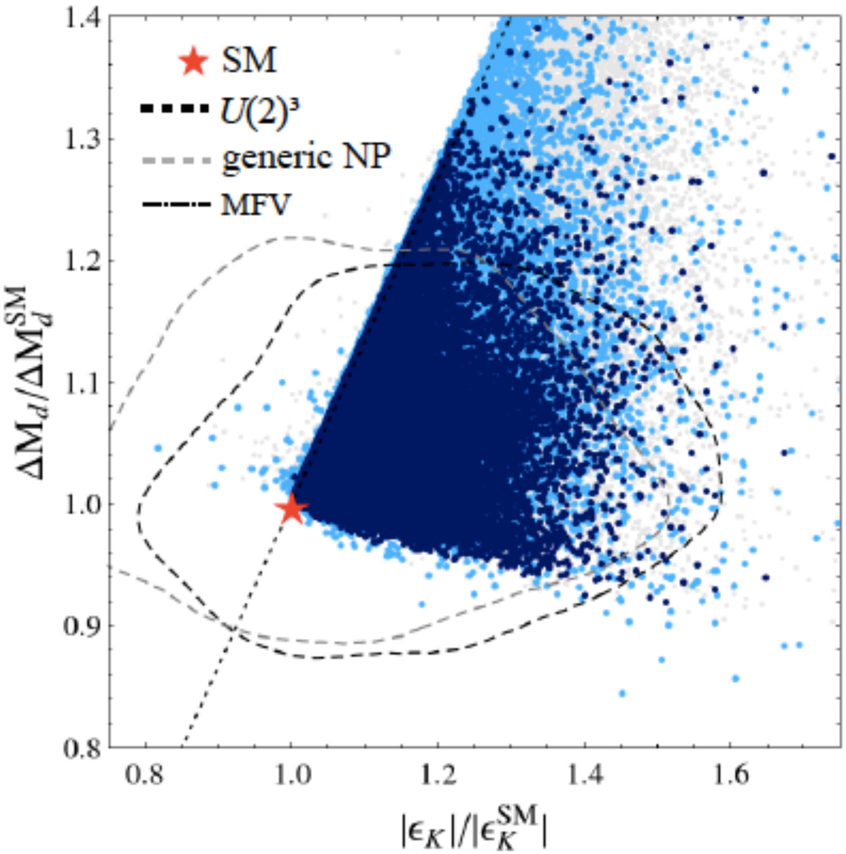
How to cope with such delicate suppression if the there is new physics at the electroweak scale?



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

D. STRAUB at this meeting

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]

B_s mixing phase measurement

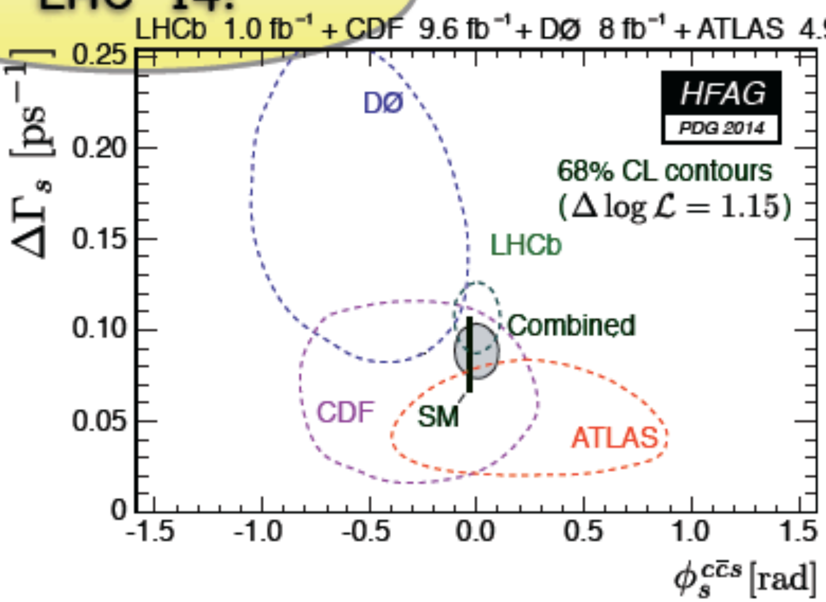
- The experimental errors are significantly reduced by the new LHCb measurement.
- The current measurement of Φs is consistent to SM (=-0.0363±0.0016):

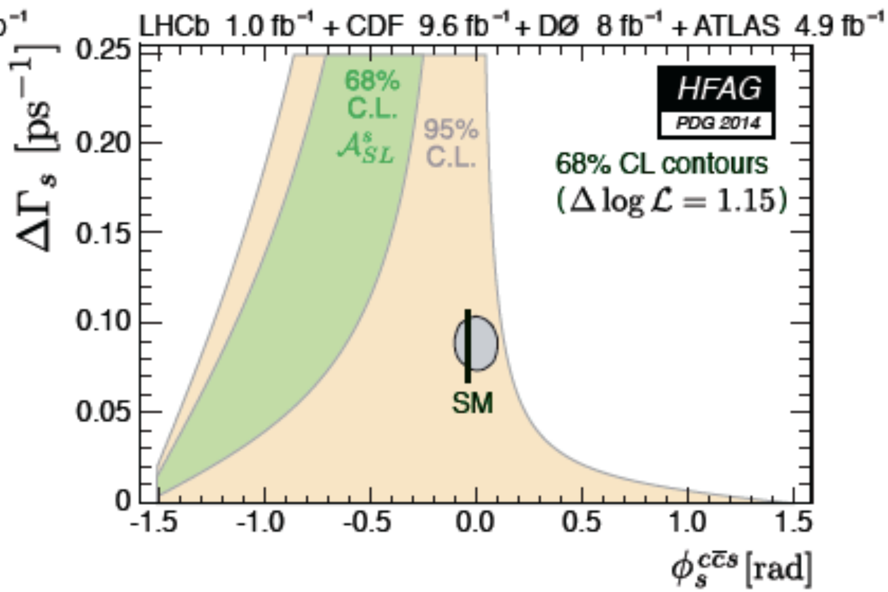
$$\Phi_s = 0.070 \pm 0.055$$

- LHCb has an ability to reach to the error down to δΦs=±0.025 by 2018 and the upgrade can reach to the precision of δΦs=±0.009.
- So it is too early to conclude! New physics may appear here!

LHC '14!

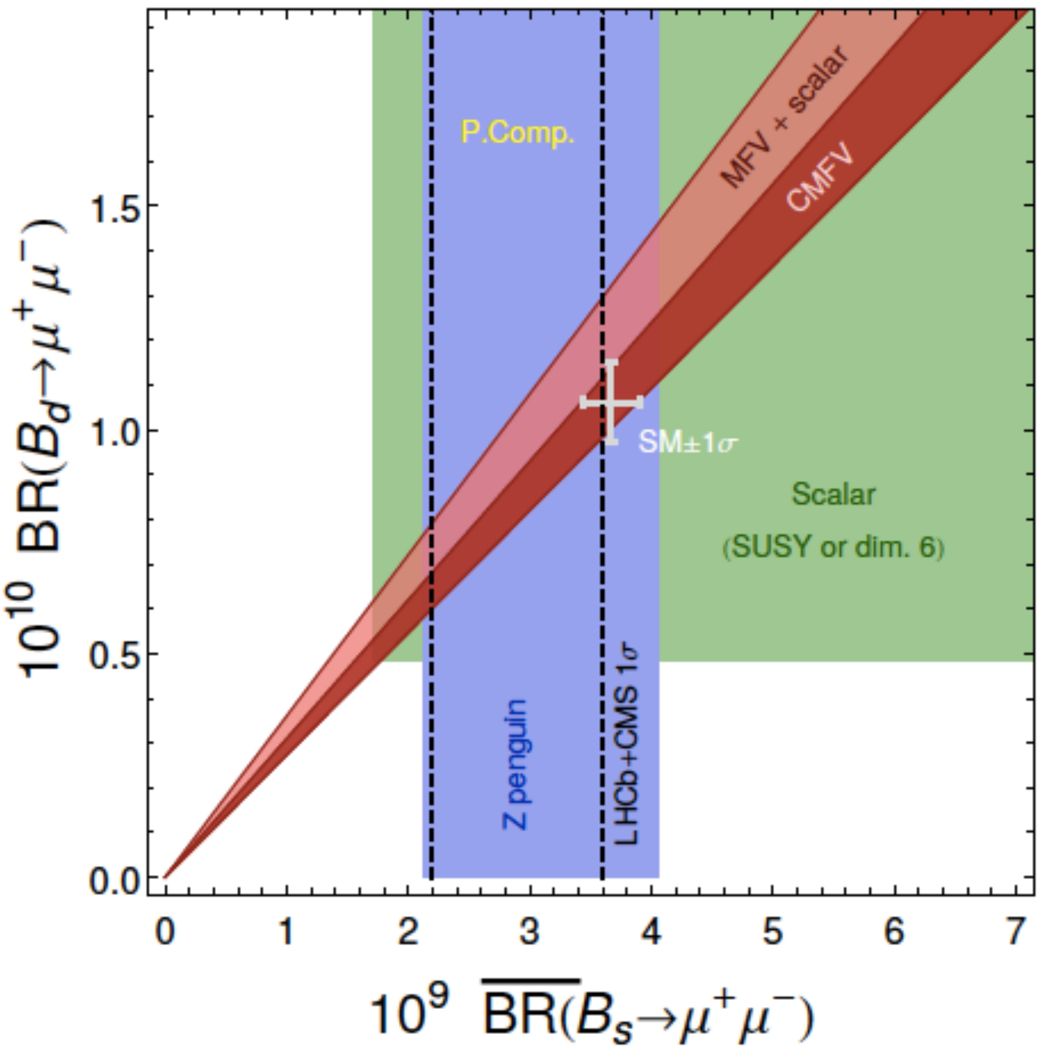
Emi KOU at this meeting





D. STRAUB at this meeting

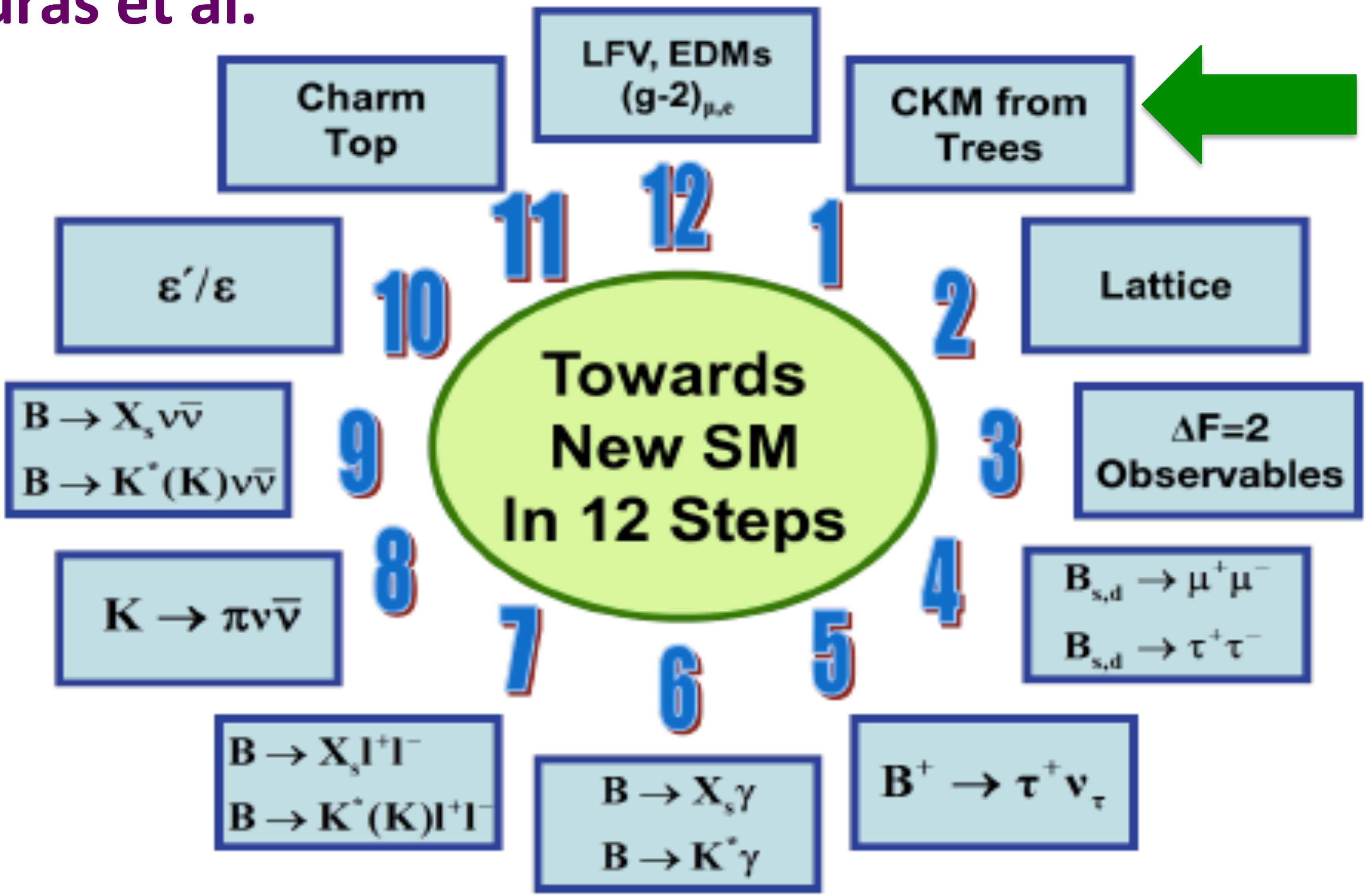
Model-independently: $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$



- $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$: powerful test of Minimal Flavour Violation
- Beyond MFV: scalar operators (e.g. SUSY) unconstrained by other processes
- Z penguins beyond MFV: size constrained by $b \to s\ell^+\ell^-$ processes (notably $B \to K^*\mu^+\mu^-$)

The flavour clock cannot stop !!!

Buras et al.



THE FATE OF LEPTON NUMBER

L VIOLATED

υ Majorana ferm.

L CONSERVED

υ Dirac ferm.
(dull option)

SMALLNESS of m_υ

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

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

Δ ENLARGEMENT OF THE HIGGS SCALAR SECTOR

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

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

N.B.: EXCLUDED BY LEP!

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

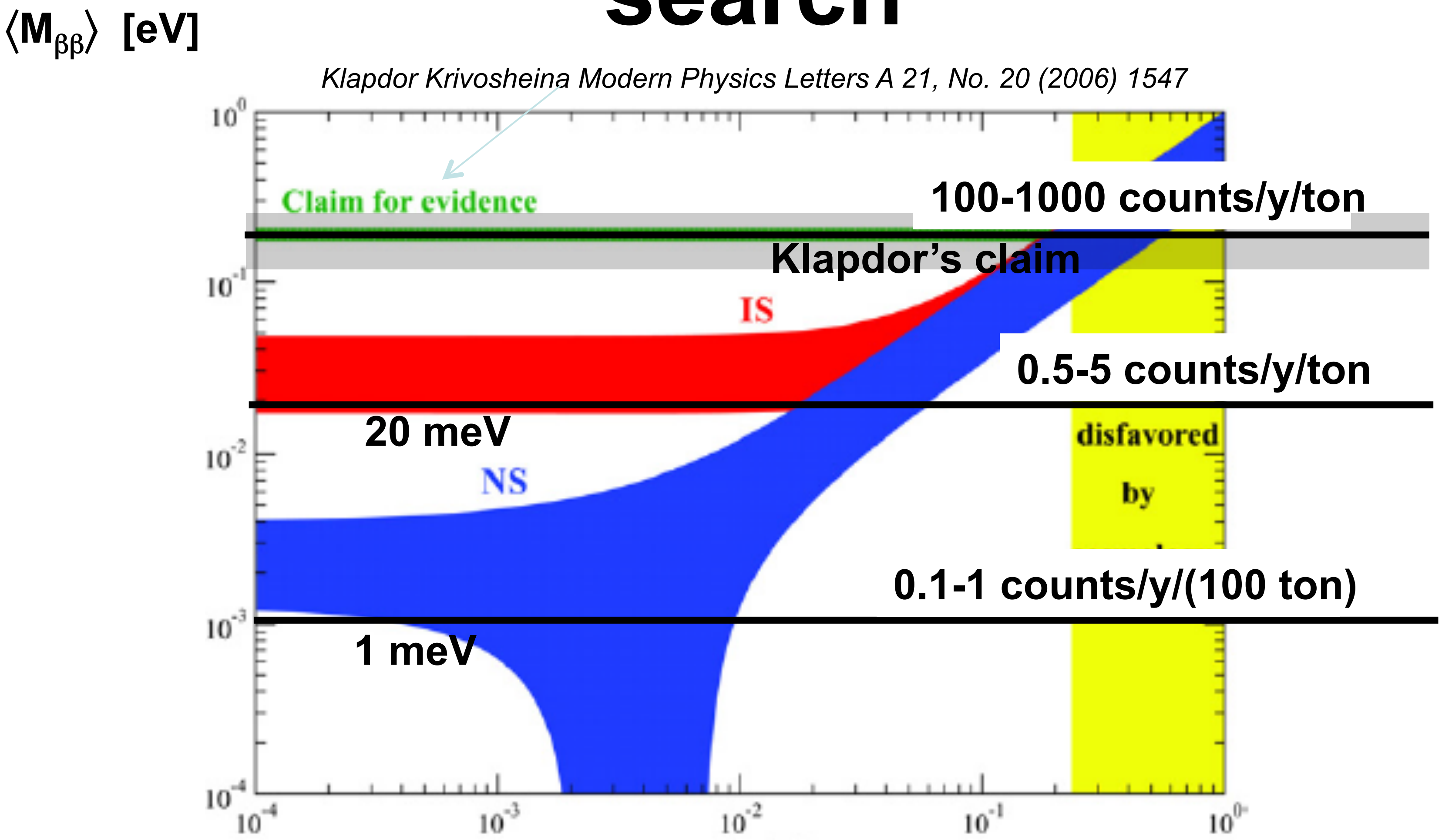
$$\langle M_\beta \rangle \equiv \left(\sum_{i=1}^{3} M_i^2 \, |U_{ei}|^2 \right)^{1/2}$$

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



Nice re-visitation of where we stay in this fundamental challenge
→ R. Saakyan at this meeting

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

For a nice review C. BALAZS at this meeting

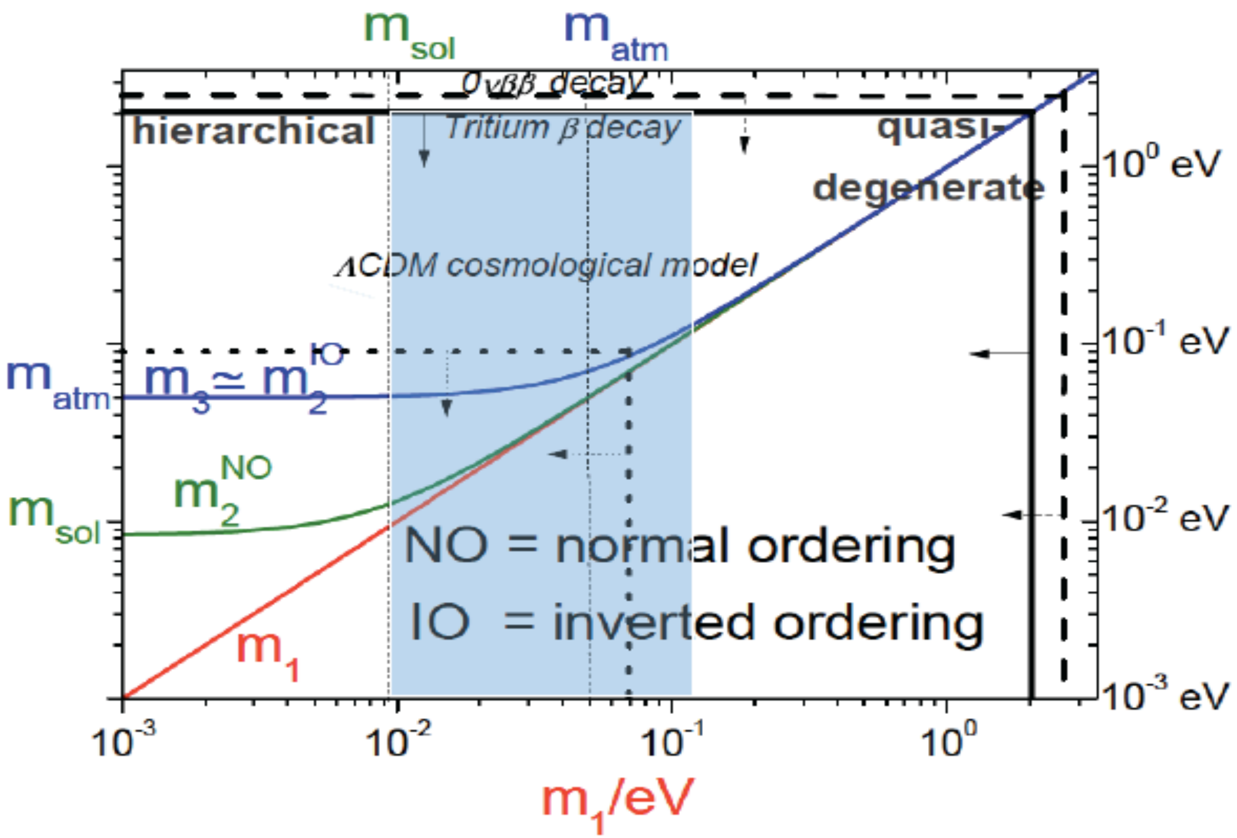
- Key-ingredient of the SEE-SAW mechanism for neutrino masses: **large Majorana mass for RIGHT-HANDED neutrino**
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

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**)

A new neutrino mass window for leptogenesis

FLAVOURED LEPTOGENESIS ! **P. Di Bari at this meeting**



$$0.01\ \text{eV} \lesssim m_1 \lesssim 0.1\ \text{eV}$$

(PDB, Sophie King, Michele Re Fiorentin 2014)

LFV IN SUSY SEE-SAW

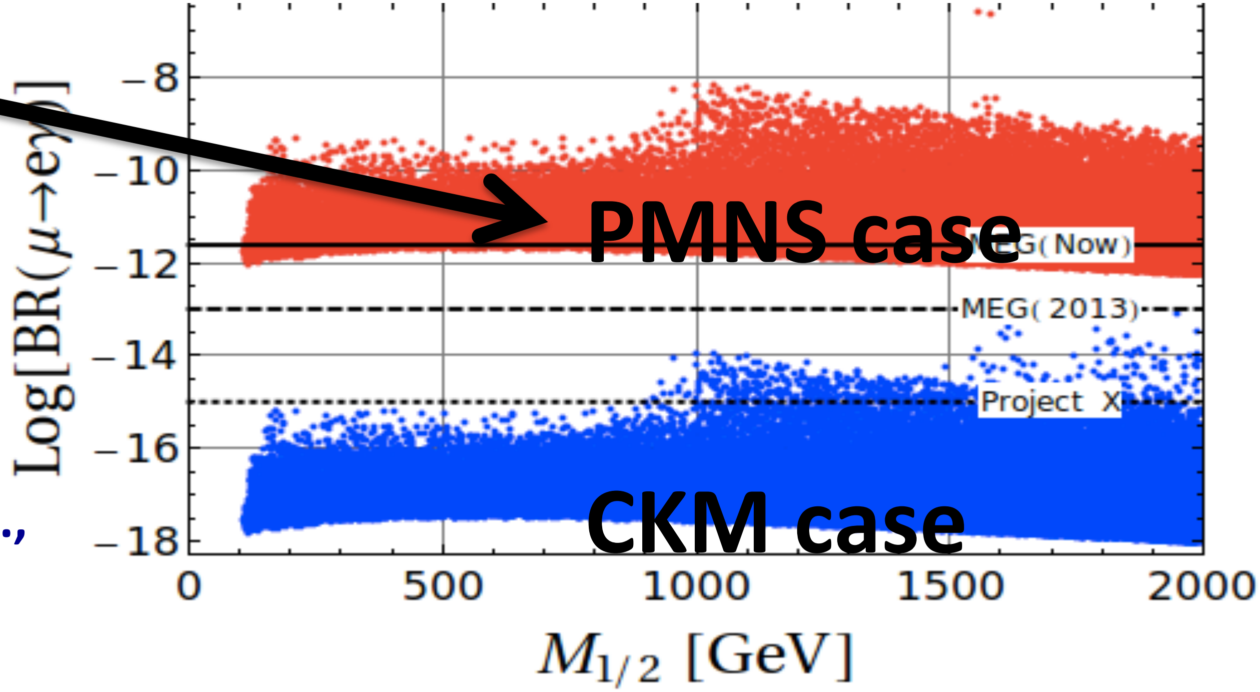
SEE- SAW (type 1) **LOW-ENERGY SUSY**

New source of (leptonic) flavor:

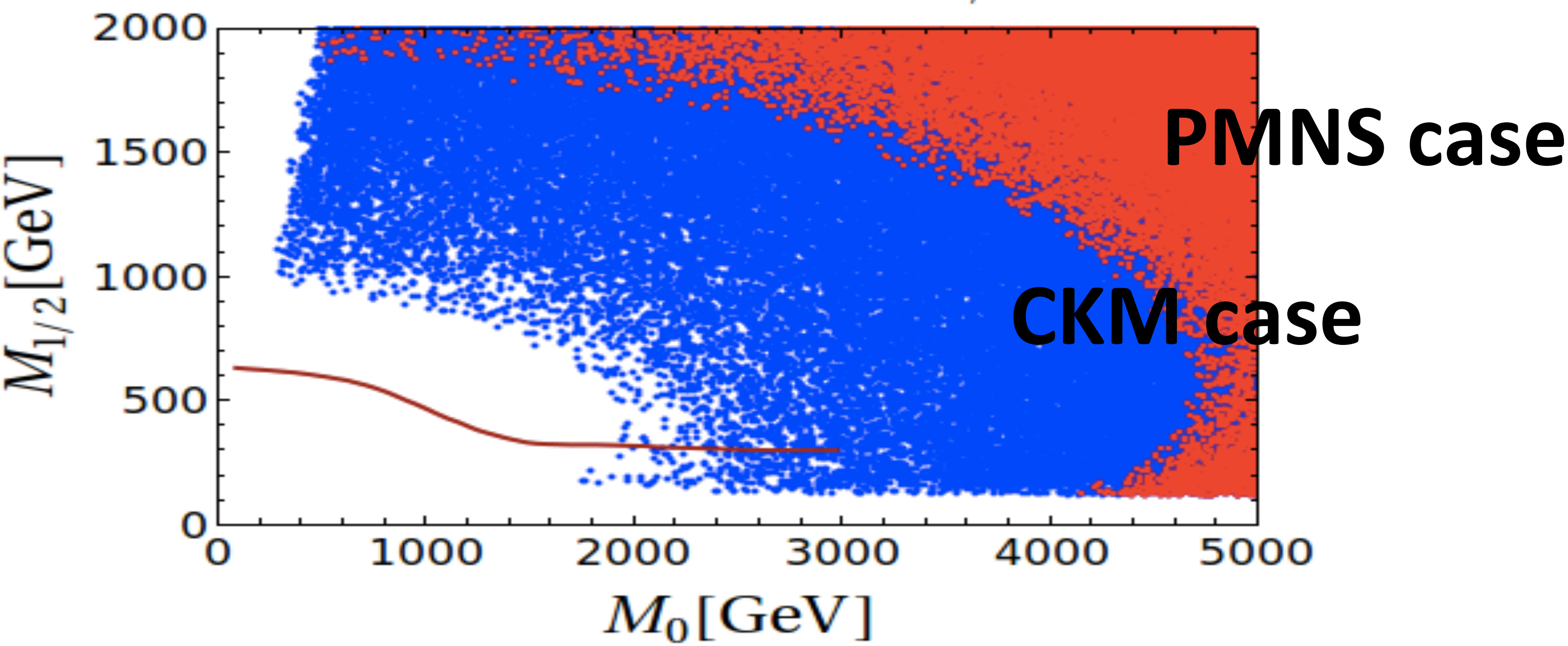
YUKAWA COUPLINGS OF THE NEUTRINO DIRAC MASS CONTRIBUTIONS, i.e. **THE YUKAWAs** of the **HIGGS couplings to the LETF- and RIGHT – HANDED NEUTRINOS**

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 tanβ = 10



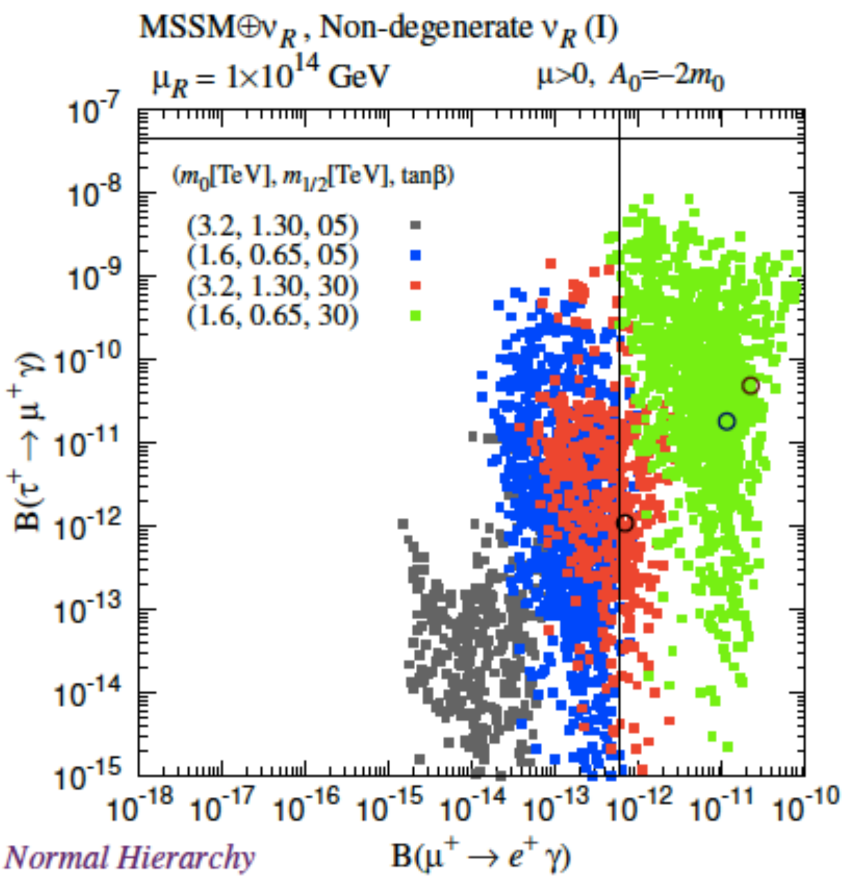
Calibbi, Chowdhuri, A. M., Patel, Vempati 2012

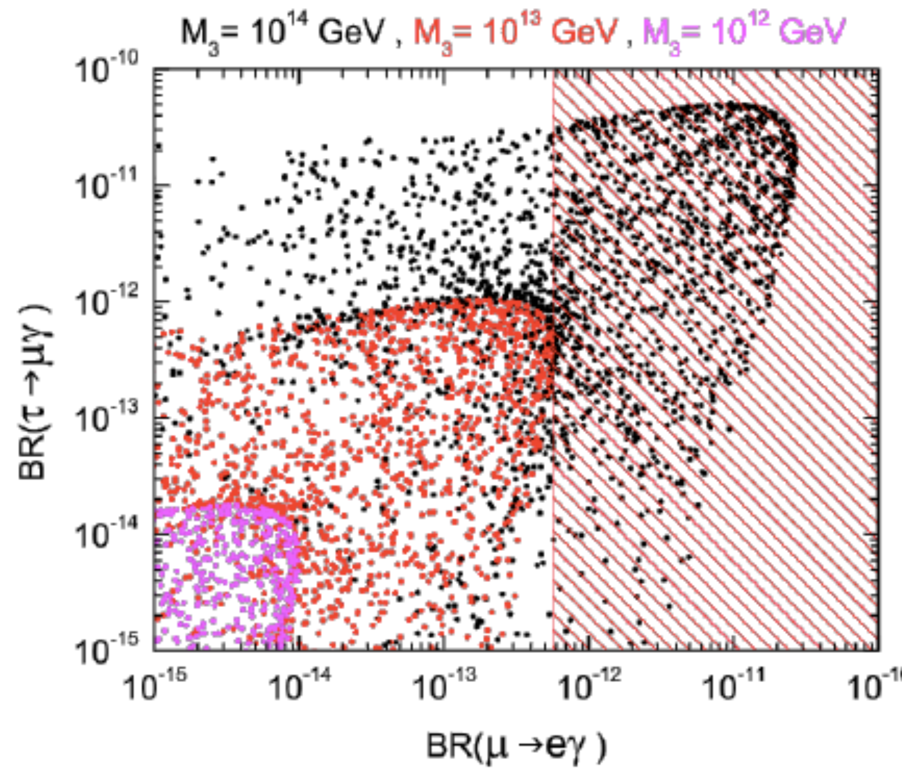


SUSY Type I seesaw model

T. GOTO at this meeting

SUSY parameters fixed, ν_R parameters varied:

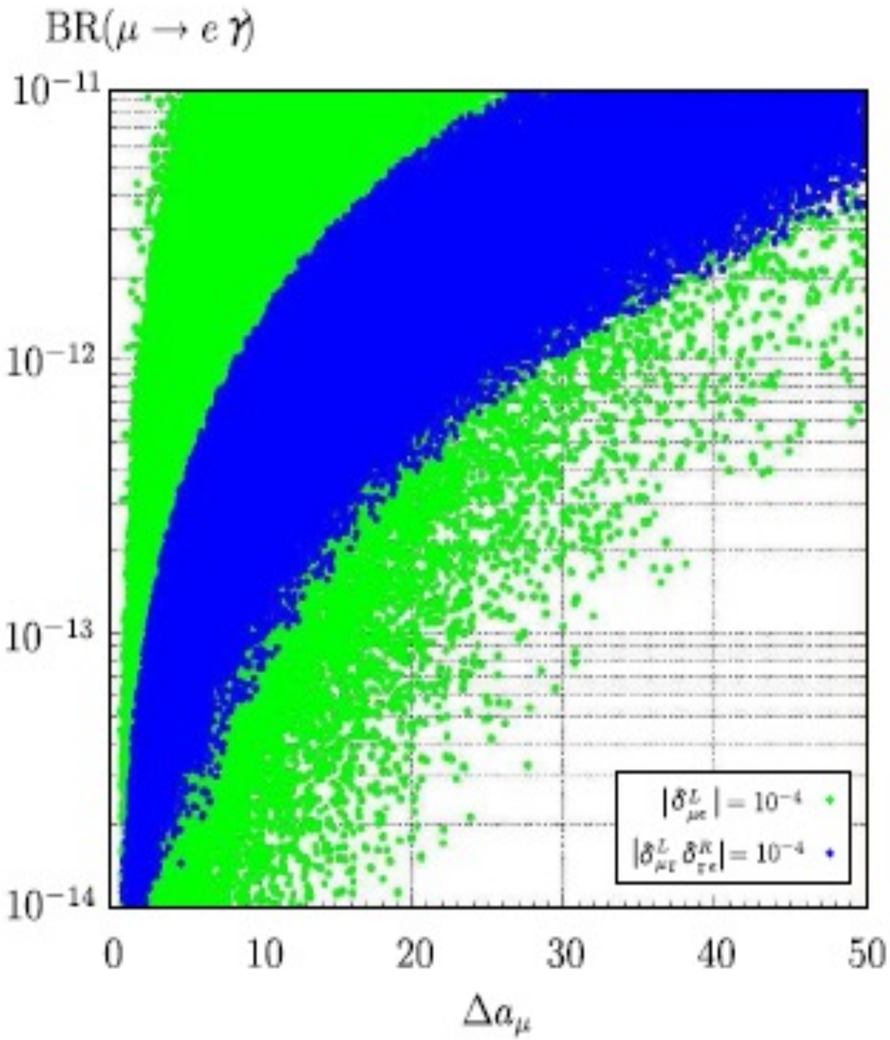


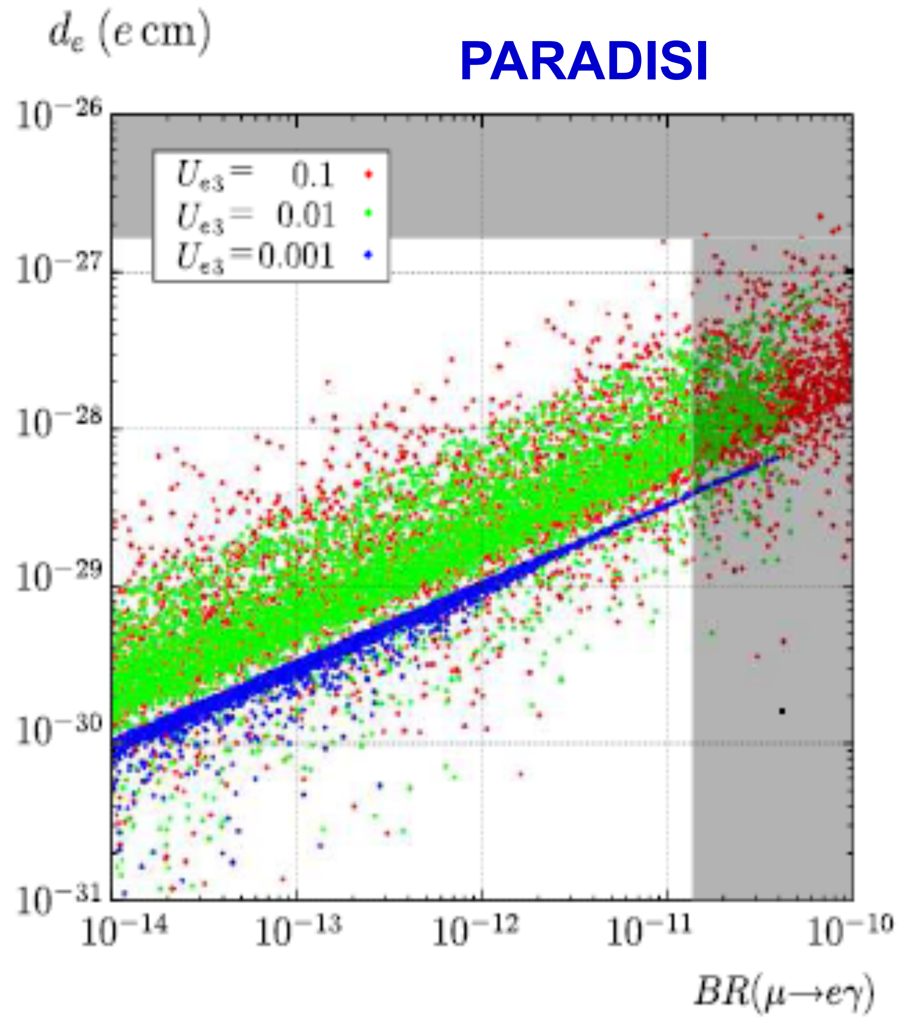


[Goto *et al.*, FLASY2013]

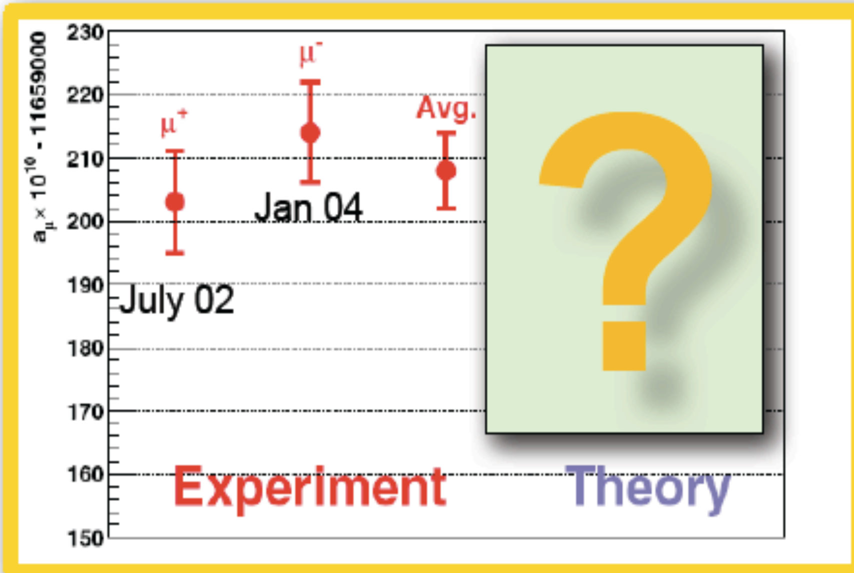
[Joaquim, ICHEP2014]

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





The muon g-2: the experimental result



- Today: $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys})\times 10^{-11}$ [0.5ppm].
- Future: new muon g-2 experiments proposed at:
  - Fermilab E989, aiming at $\pm 16\times 10^{-11}$, ie 0.14ppm
  - J-PARC aiming at 0.1 ppm

  See B. Lee Roberts & T. Mibe @ Tau2012, September 2012

Sep 2012:
CD0 approval!
Data in (late)
2016?

- 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

$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$	σ
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

THE EDM CHALLENGE

FOR **ANY** **NEW PHYSICS AT THE TEV SCALE** WITH **NEW SOURCES OF CP VIOLATION** → NEED FOR **FINE-TUNING** TO PASS THE EDM TESTS OR SOME **DYNAMICS TO SUPPRESS THE CPV** IN FLAVOR CONSERVING EDMS

Current and projected sensitivities

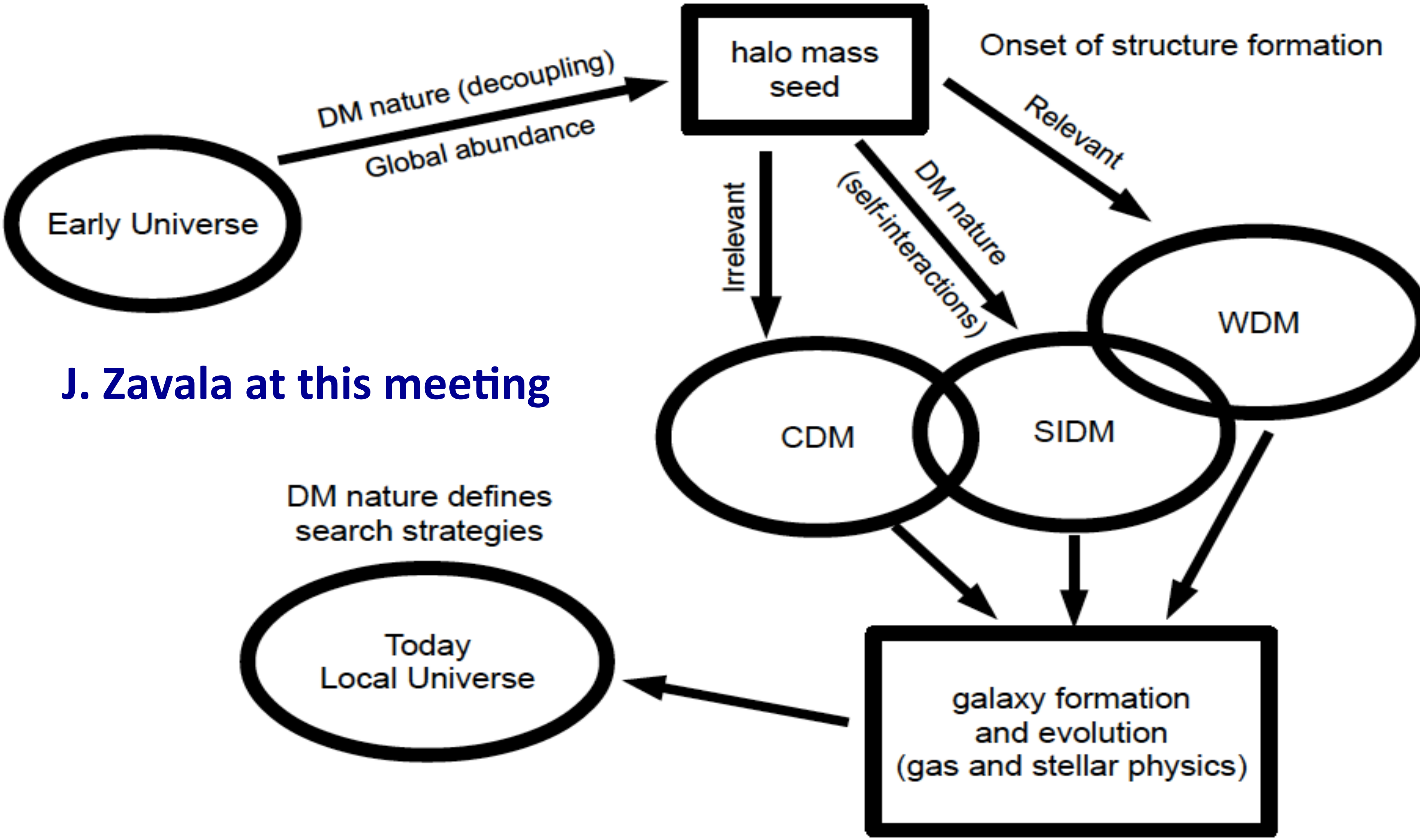
C. GRIFFITH at this meeting

	current limit	projected sens. from planned exp.	standard model CKM prediction
n	3×10^{-26}	10^{-28}	$10^{-31} - 10^{-33}$
e	9×10^{-29}	10^{-30}	$\sim10^{-38}$
Hg	3×10^{-29}	10^{-30}	$<10^{-35}$

THE DM ROAD TO NEW PHYSICS BEYOND THE SM:

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

The relevance of the DM nature across time



J. Zavala at this meeting

- astrophysical constraints are weak enough for the DM nature to play a major role in the formation and evolution of galaxies

CDM Controversies?

- Cusp-vs-Core problem
- Missing satellites problem
- To-big-to-fail problem

Possible solutions

- Baryonic physics:
  gas cooling, star formation,
  supernova feedback,…
- Dark Matter:
  warm dark matter
  Decaying DM
  Self-Interacting DM

Spergel et al, Sigurdson et al,
Boehm et al, Kaplinghat et al,
Loeb et al, Tulin et al,
van de Aarseen et al,
….

Y. TANG at this meeting

Example:νΛMDM

P. Ko, YT, 1404.0236

We introduce two right-handed gauge singlets, a dark sector with an extra $U(1)_X$ gauge symmetry,

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^{μ}, j^{i}) New bosonic Coord.	SM part + new part to cancel Λ^2 at 1-Loop
2) **SELECTION RULE** → **DISCRETE SYMM.** → **STABLE NEW PART.**	***R-PARITY LSP*** Neutralino spin 1/2	***KK-PARITY LKP*** spin1	***T-PARITY LTP*** spin0
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

Info to extract from the direct searches

Y. Kahn at this meeting
Kahn, McCullough, Fox

$$\frac{dR}{dE_R} = \frac{\rho_\chi \sigma_n}{2 m_\chi \mu_{n\chi}^2} N_A m_n C_T^2(A,Z) \int dE'_R G(E_R, E'_R) \epsilon(E'_R) F^2(E'_R) \underbrace{\int_{v_{min}(E'_R)}^{\infty} \frac{f(\mathbf{v}+\mathbf{v}_E)}{v} d^3v}_{= g(v_{min})}$$

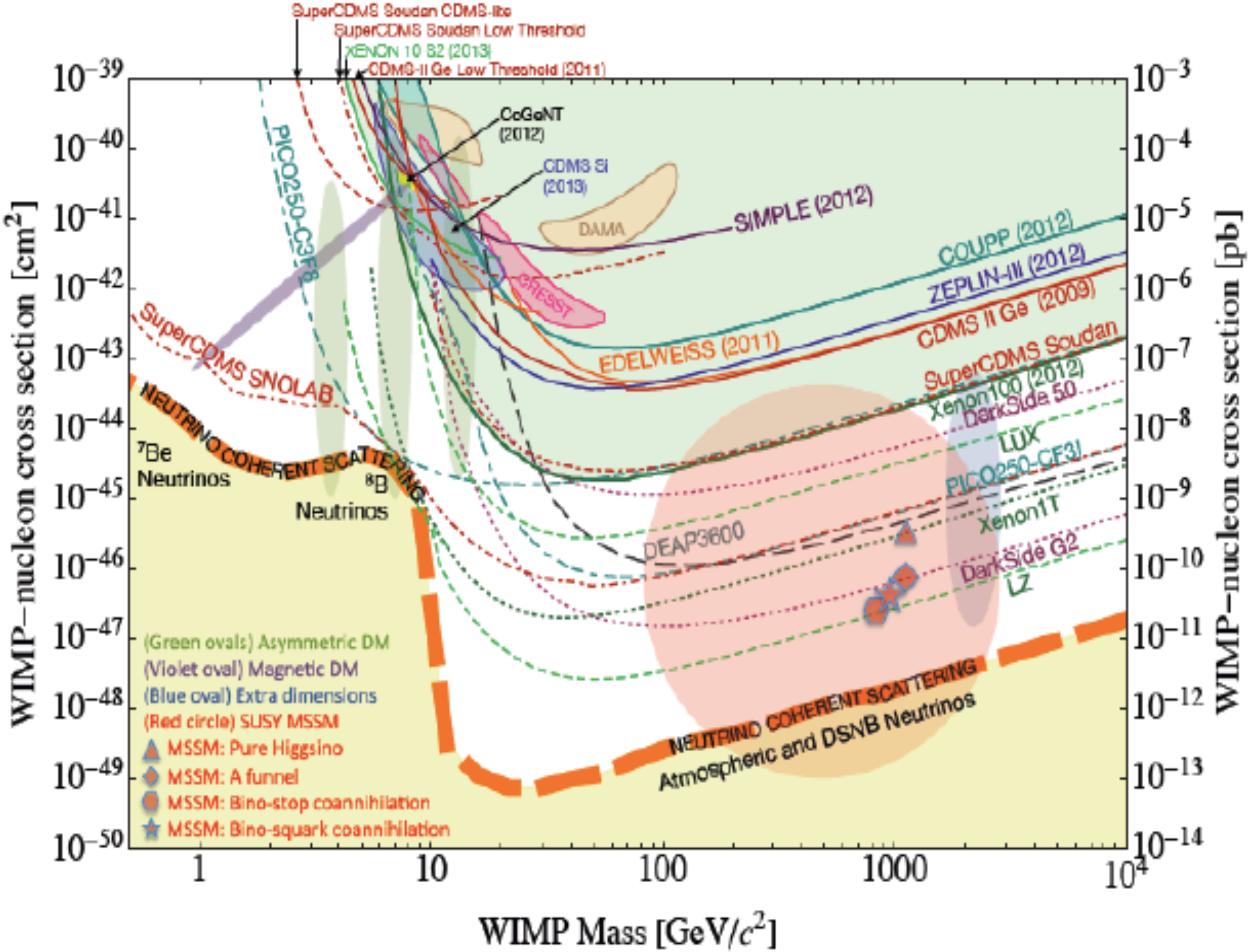
DM model — detector properties — nuclear physics — DM halo model

$v_{min}(E'_R)$: min. DM velocity required for nuclear recoil E'_R

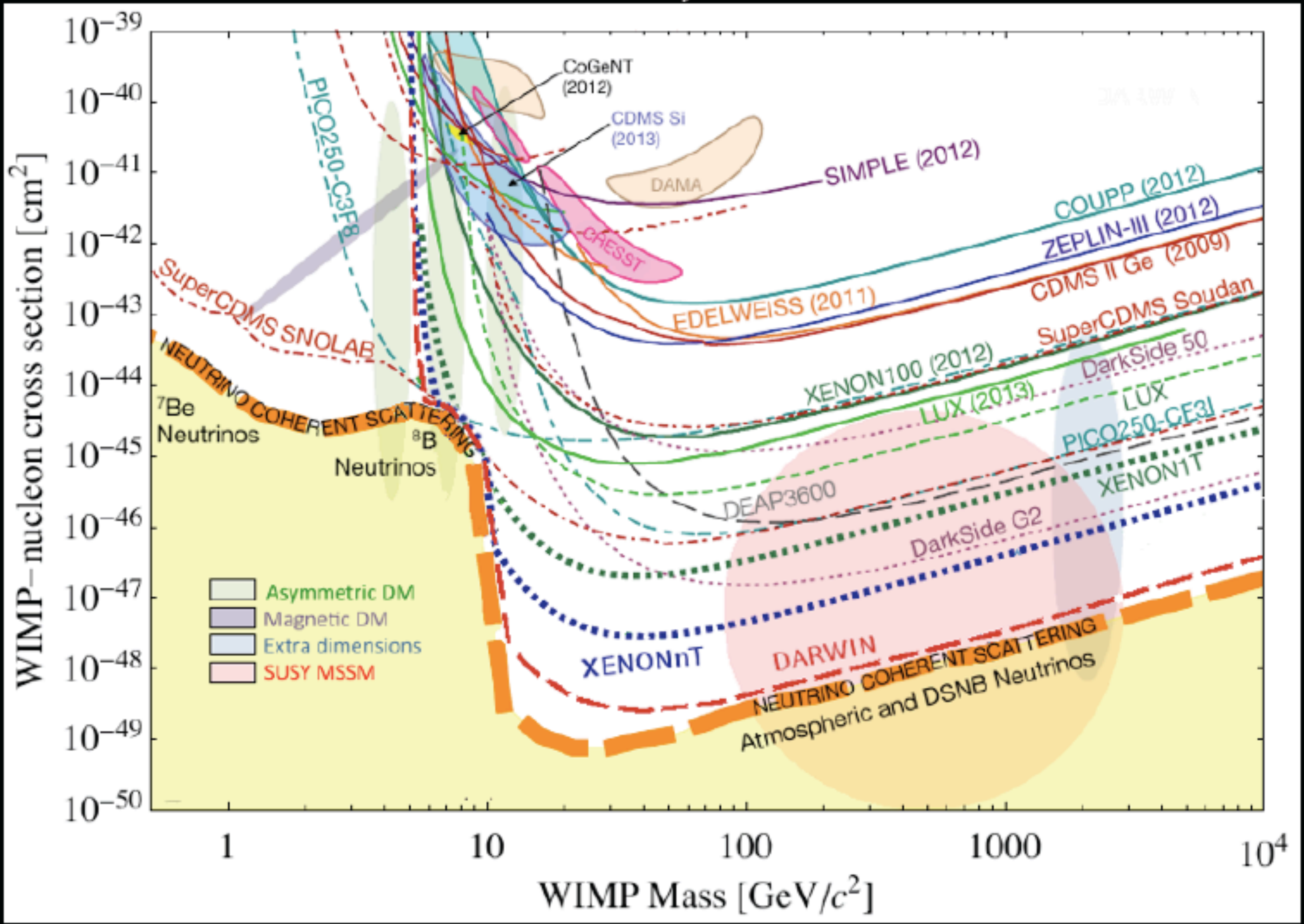
Usual method: DM model + halo model → limits/preferred values in $m_\chi - \sigma_n$ space

Halo-independent: DM model → limits/preferred values in $v_{min} - g(v_{min})$ space

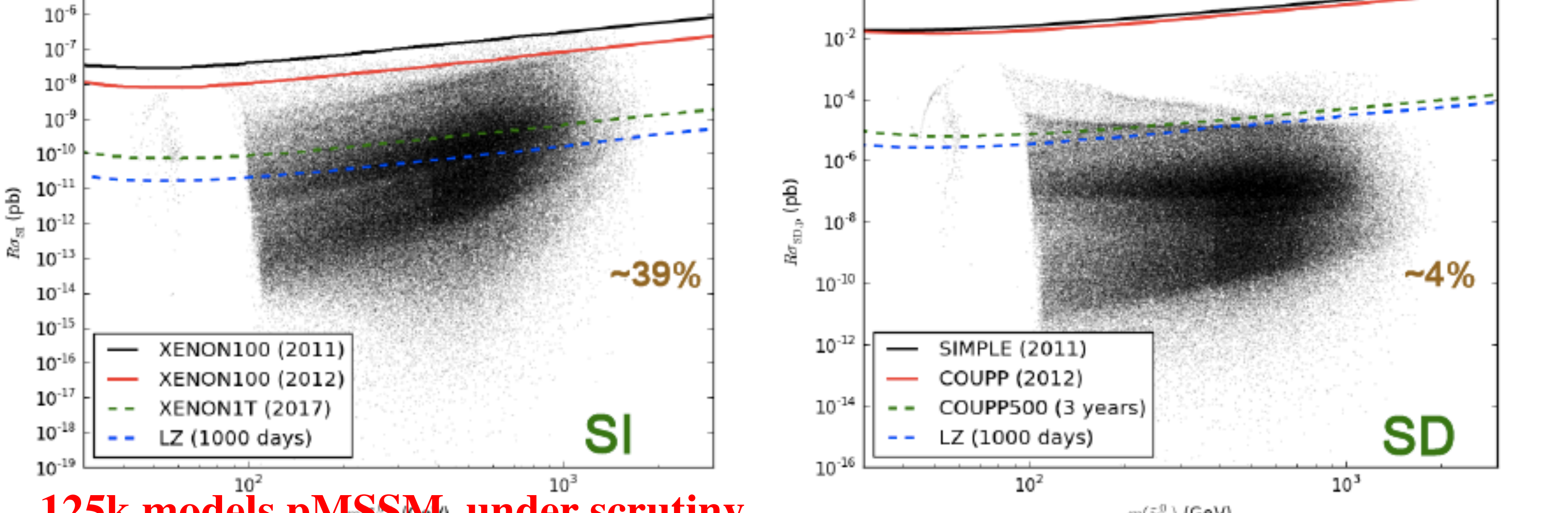
No assumptions about DM halo, easy to compare multiple experiments (esp. signal vs. exclusion)


SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]

1) Science Goals: Dark Matter Projected Sensitivities

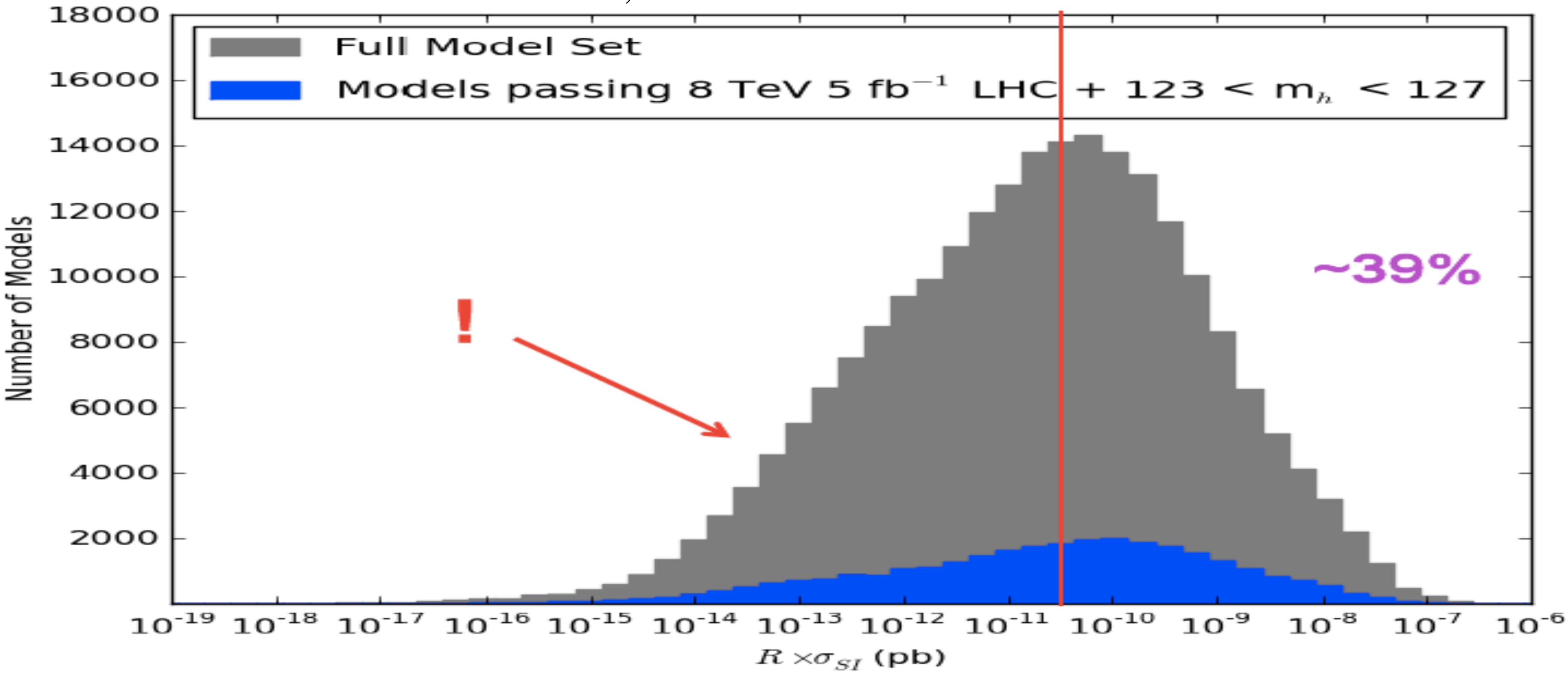


What if 2+ of these experiments observe strong candidate dark matter signals?
Build a directional detector to establish astrophysical origin.



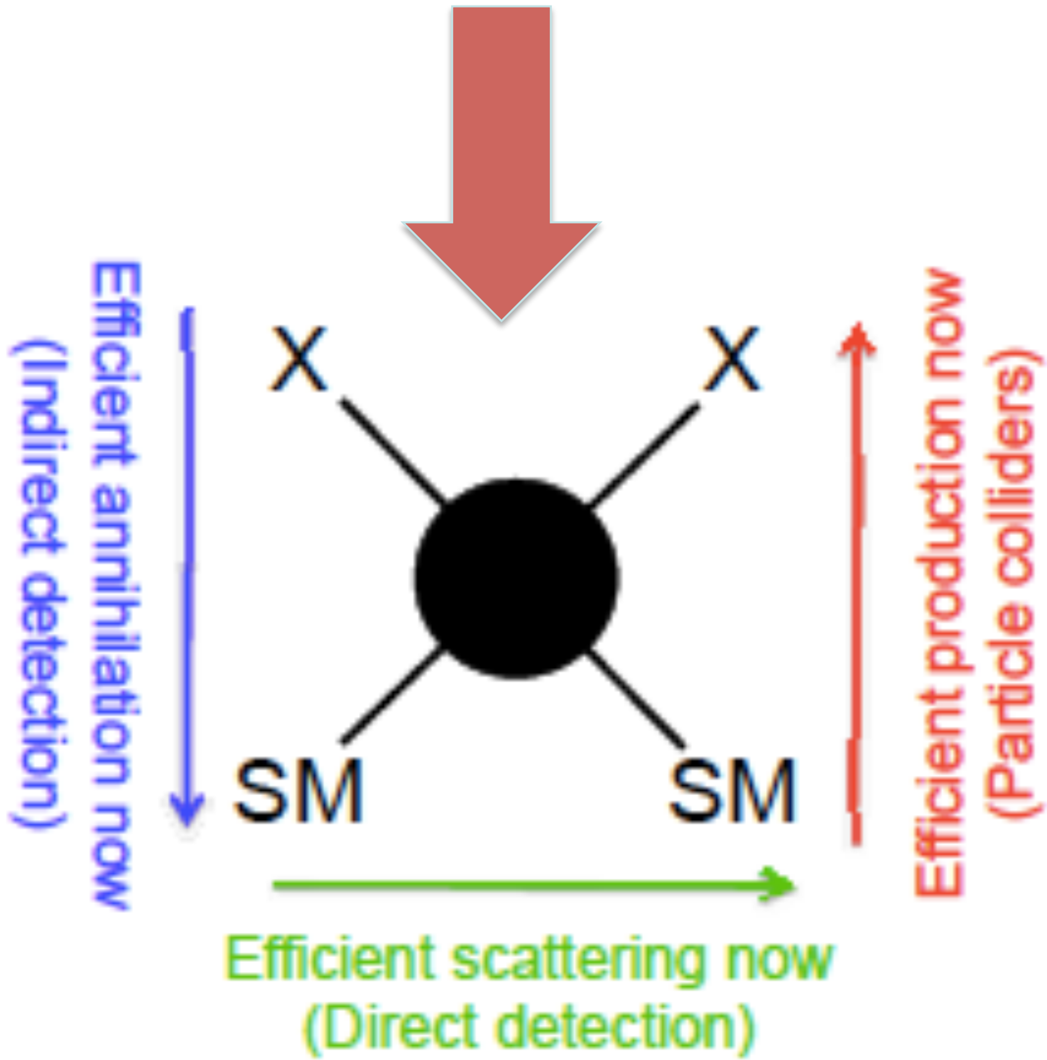
125k models pMSSM under scrutiny

Hewett, Rizzo et al

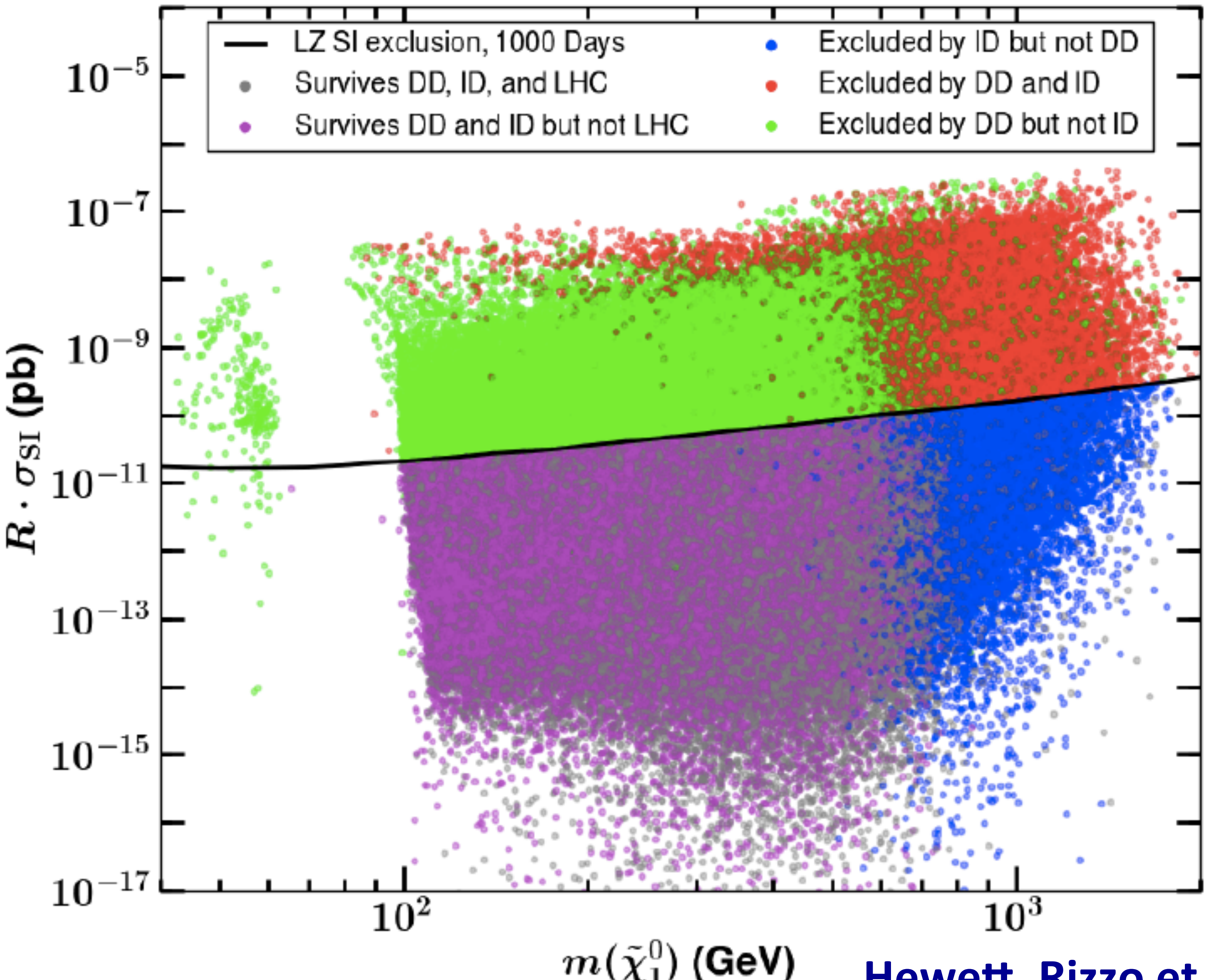


DM COMPLEMENTARITY: efficient annihilation in the early Universe implies today

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



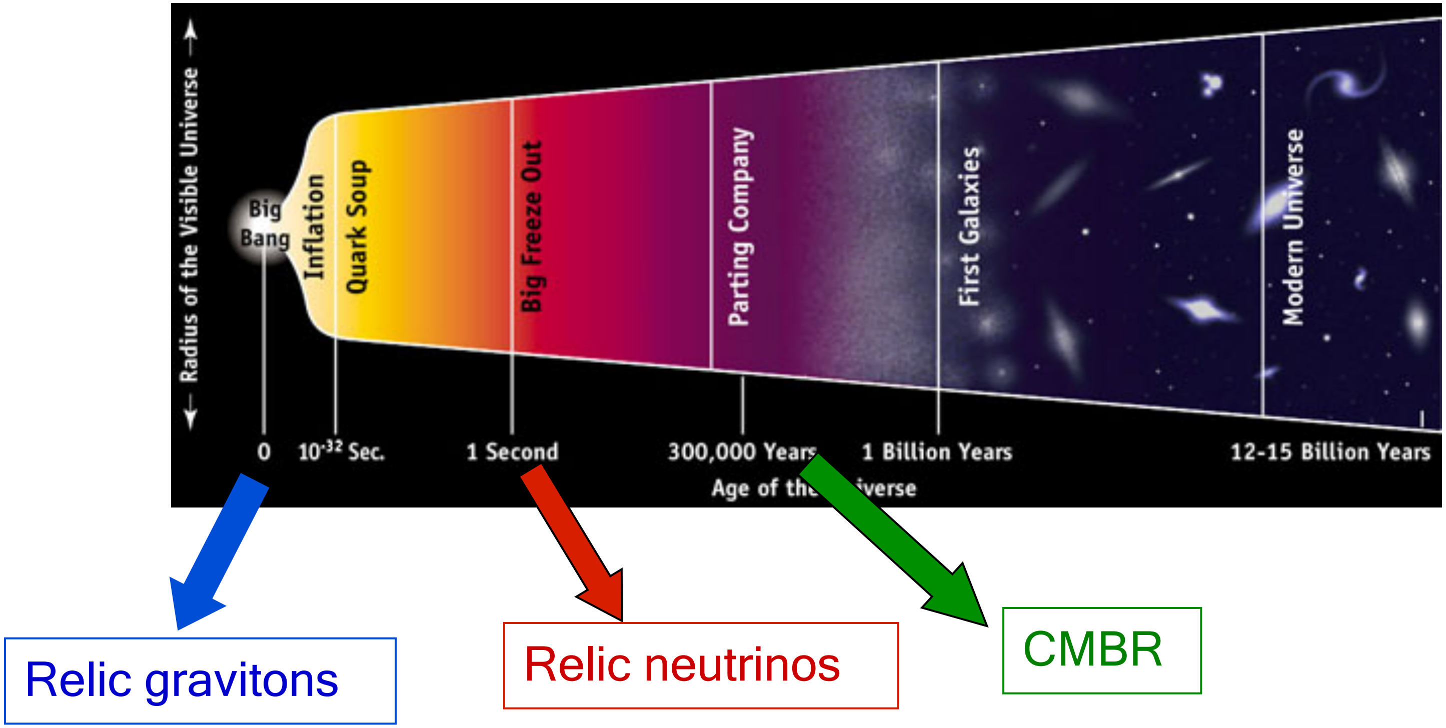
pMSSM models DD = LZ both SI + SD ID = FERMI + CTA



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

2nd GENERATION:
DISCOVERY AND ASTRONOMY

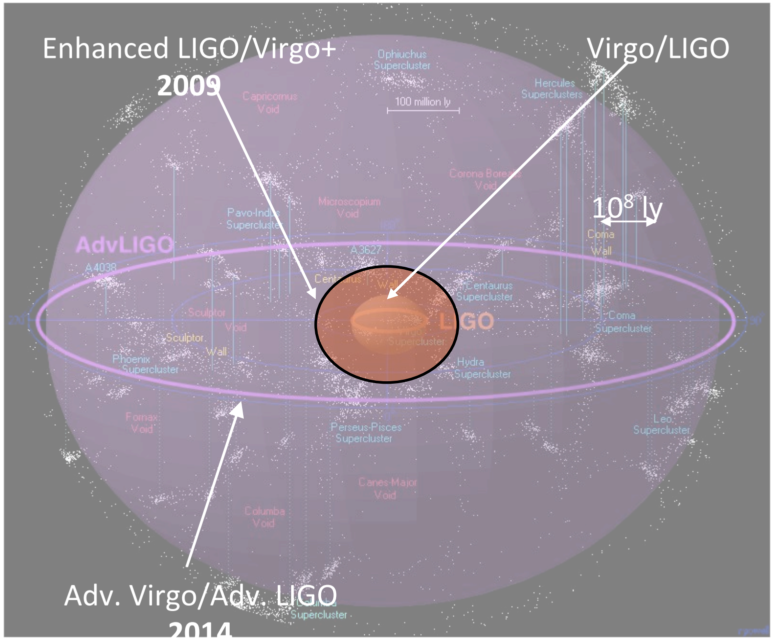
2nd generation detectors:
Advanced Virgo, Advanced LIGO

GOAL:

sensitivity 10x better →

look 10x further →

Detection rate 1000x larger



Credit: R.Powell, B.Berger

B. BARISH at this meeting

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections
		LIGO	Virgo	LIGO	Virgo	
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100

LORENTZ INVARIANCE VIOLATION

LIV PHENOMENOLOGY IN MATTER: A TOOOLKIT

S. Liberati. Topic Review CQG (2013)
Kostelecky periodic review of mSME
Recent Reviews QG phenomenology Hossenfelder and Amenilino Camelia

S. LIBERATI at this meeting

Terrestrial tests:

- Penning traps
- Clock comparison experiments
- Cavity experiments
- Spin polarized torsion balance
- Neutral mesons
- Anti-Hydrogen
- Slow atoms recoils

Astrophysical tests:

- Cosmological variation of couplings, CMB
- Cumulative effects in astrophysics
- Anomalous threshold reactions
- Shift of standard thresholds reactions with new threshold phenomenology
- LV induced decays not characterized by a threshold
- Reactions affected by "speeds limits"

This wealth of tests already severely constraints the Minimal Standard Model extension (dim 3,4 ops, boost and rotations breaking):

QED: up to $O(10^{-22})$ on dim 4,
Hadronic sector : up to $O(10^{-46})$ on dim 3, $O(10^{-27})$ on dim 4.
Neutrinos: up to $O(10^{-28})$ on dim 4 from neutrino oscillations

Hence we shall in what follow consider the higher order
LIV operators mass dimension 5 and 6 and hence mainly

PHD Syndrome
(Post Higgs Depression)?

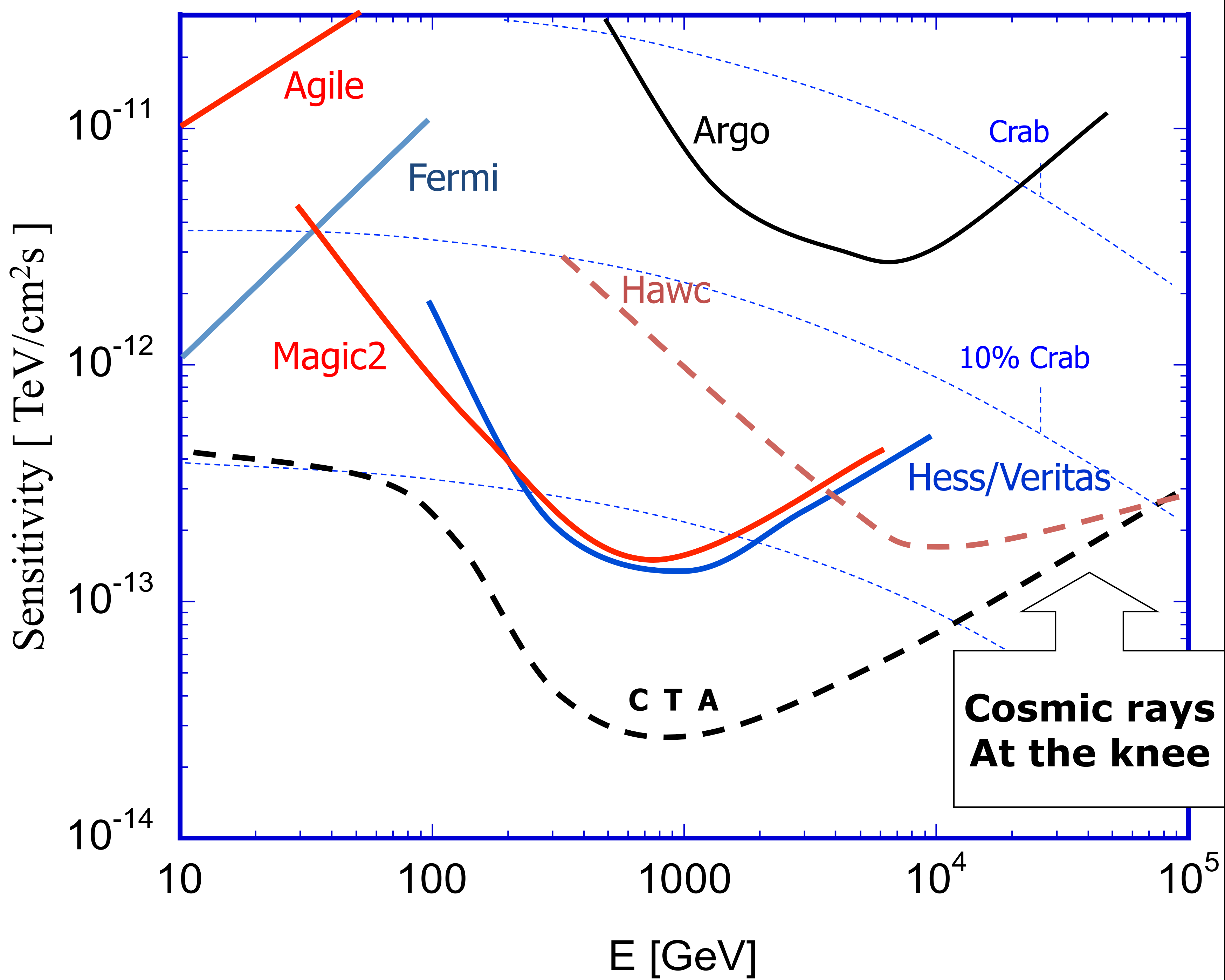
(Savas Dimopoulos, GGI, July 2013)

Post-Higgs Depression? No, thanks just the opposite....

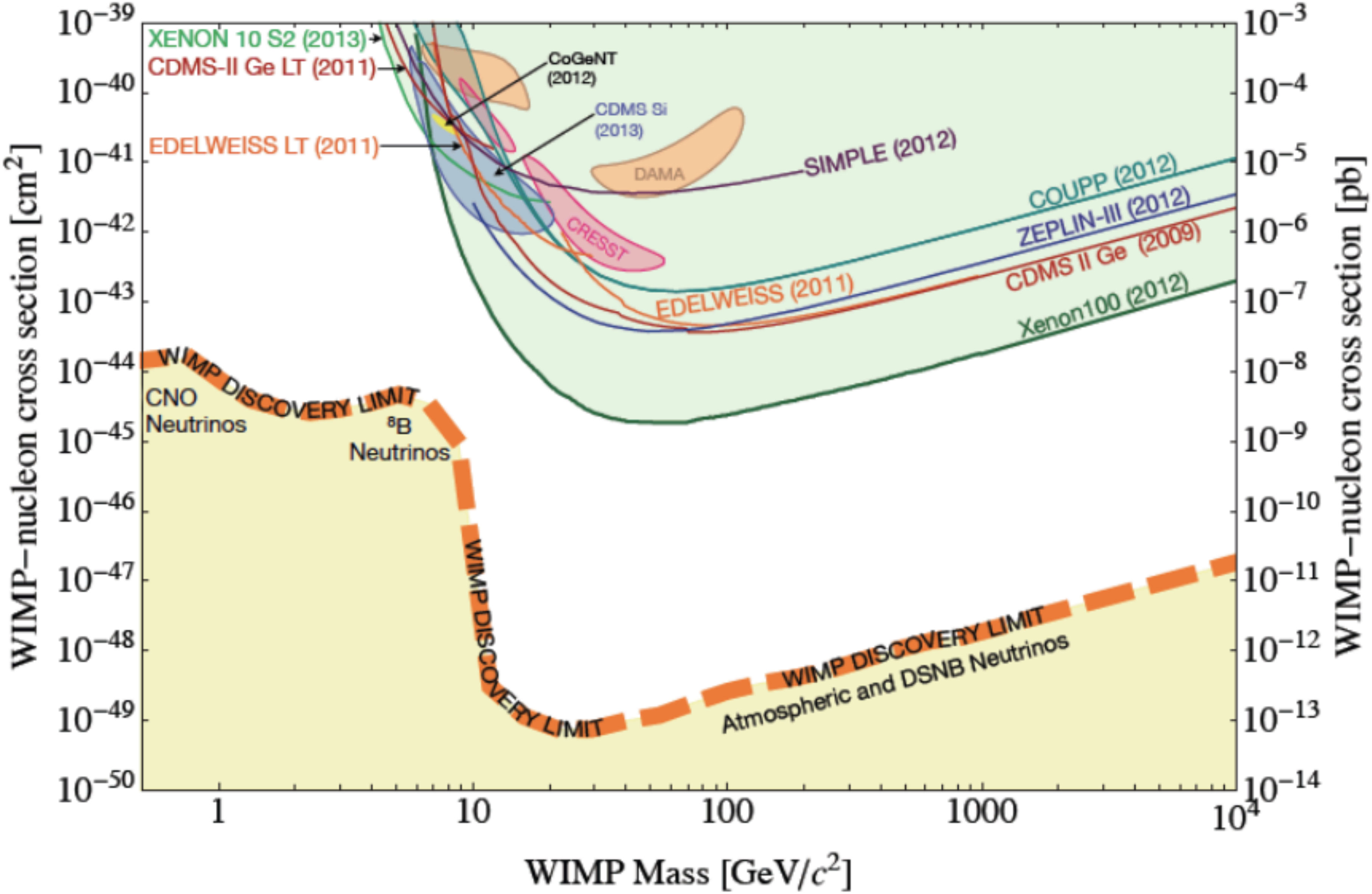
- **If the naturalness issue is indeed a relevant issue, the fact that we discovered a light higgs means that there MUST EXIST some mechanism stabilizing its mass and this mechanism NECESSARILY ENTAILS THE PRESENCE OF SOME FORM OF NEW PHYSICS AT THE ELECTROWEAK SCALE**
- Time to get ready (joint exp.-theor. effort) for the new results **in high energy, high intensity, neutrino physics, gravitational waves, cosmic radiation, dark matter and dark energy searches**


THEORIES
PROOFS
S. harris

BACK-UP SLIDES


Agile
Argo
Crab
Fermi
Hawc
Magic2
10% Crab
Hess/Veritas
C T A
Cosmic rays
At the knee
10^{-11}
10^{-12}
10^{-13}
10^{-14}
Sensitivity [TeV/cm^{2}s]
10
100
1000
10^4
10^5
E [GeV]

Spin-Independent Cross Section: Current Experiment Results



so far: ~3 years / order of magnitude

THE FATE OF LEPTON NUMBER

L VIOLATED

υ Majorana ferm.

SMALLNESS of m_{υ}

PRESENCE OF A NEW PHYSICAL MASS SCALE

L CONSERVED

υ Dirac ferm.

(dull option)

$h\,\bar{\upsilon}_L H\,\upsilon_R \rightarrow m_{\upsilon} = h\,\langle H\rangle$ $\quad M_{\upsilon} < 5$ 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	~O	$h\,\langle\phi\rangle$
υ_R	$h\,\langle\phi\rangle$	M

LR Models?

MAJORON MODELS

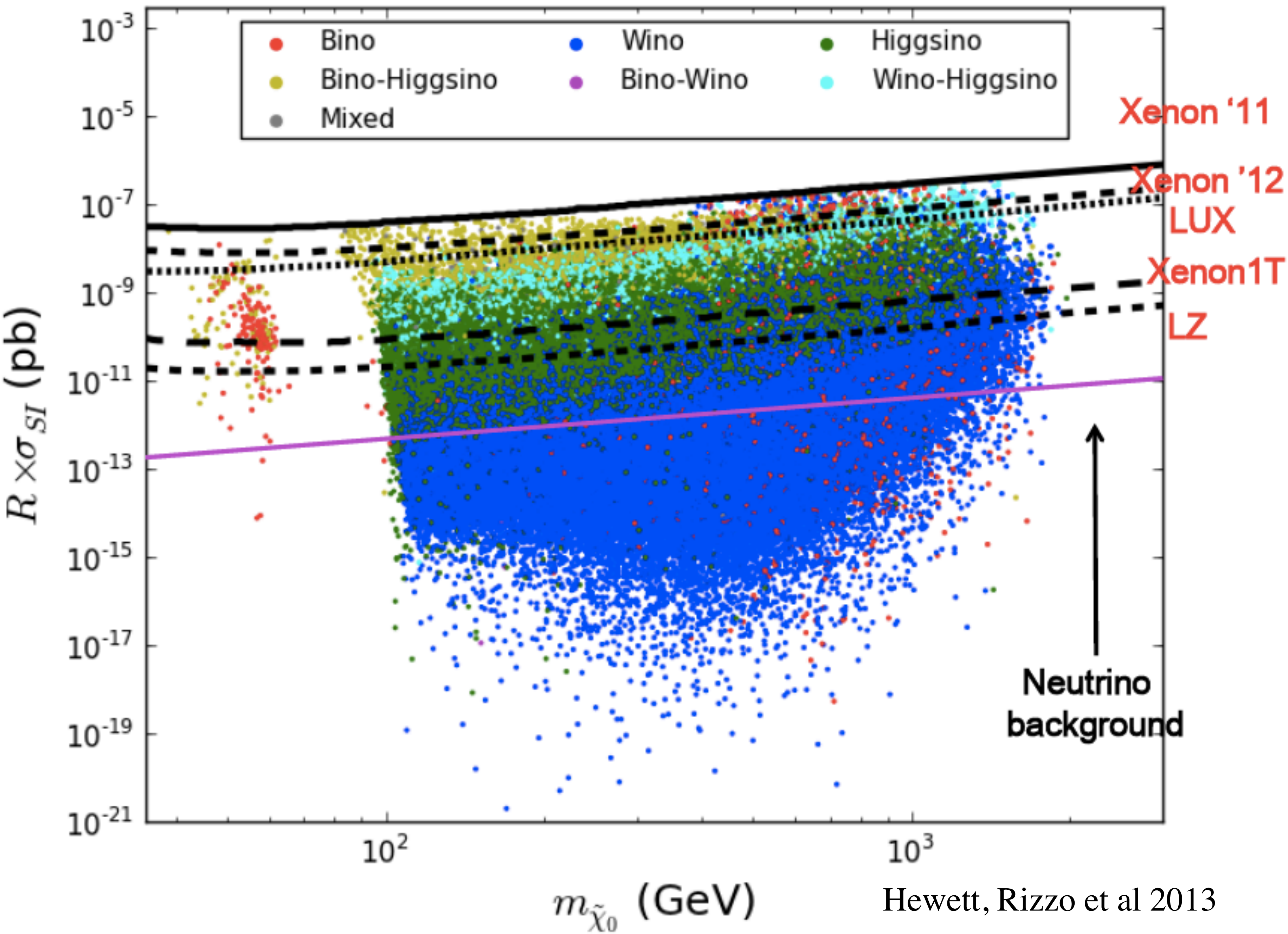
Gelmini, Roncadelli

Δ ENLARGEMENT OF THE HIGGS SCALAR SECTOR

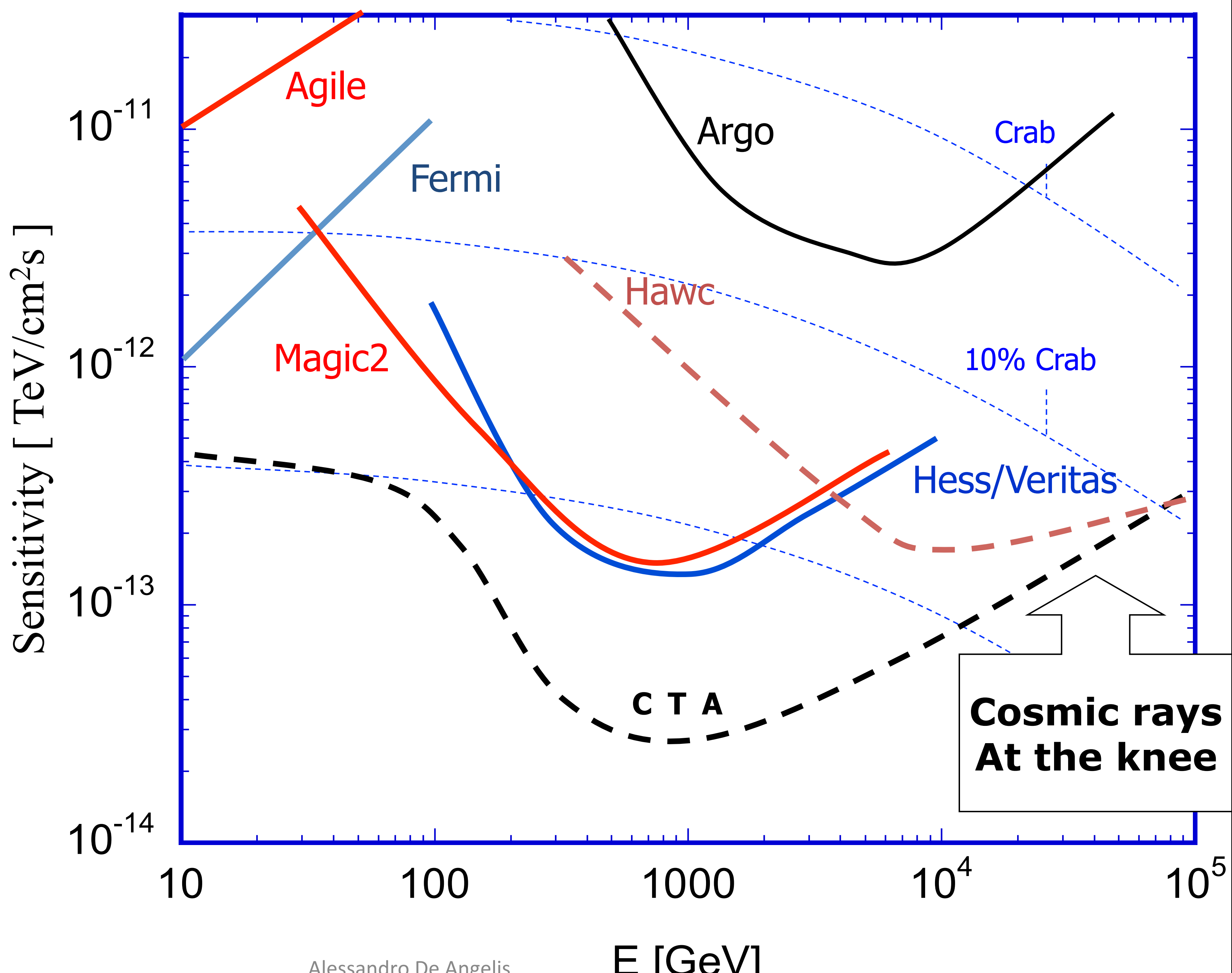
$h\,\upsilon_L\upsilon_L\,\Delta$

$m_{\upsilon} = h\,\langle\Delta\rangle$

N.B.: EXCLUDED BY LEP!

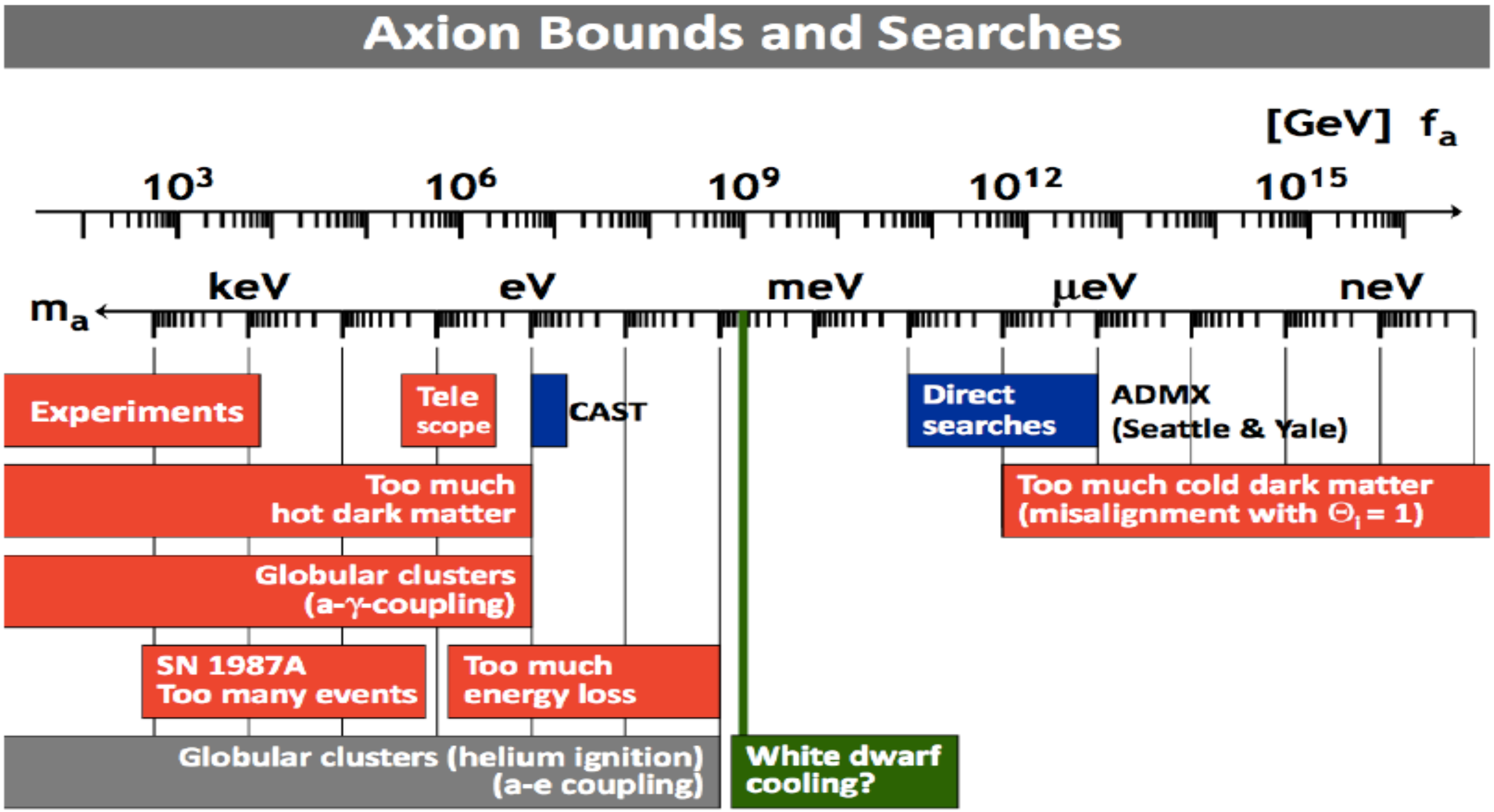


Hewett, Rizzo et al 2013

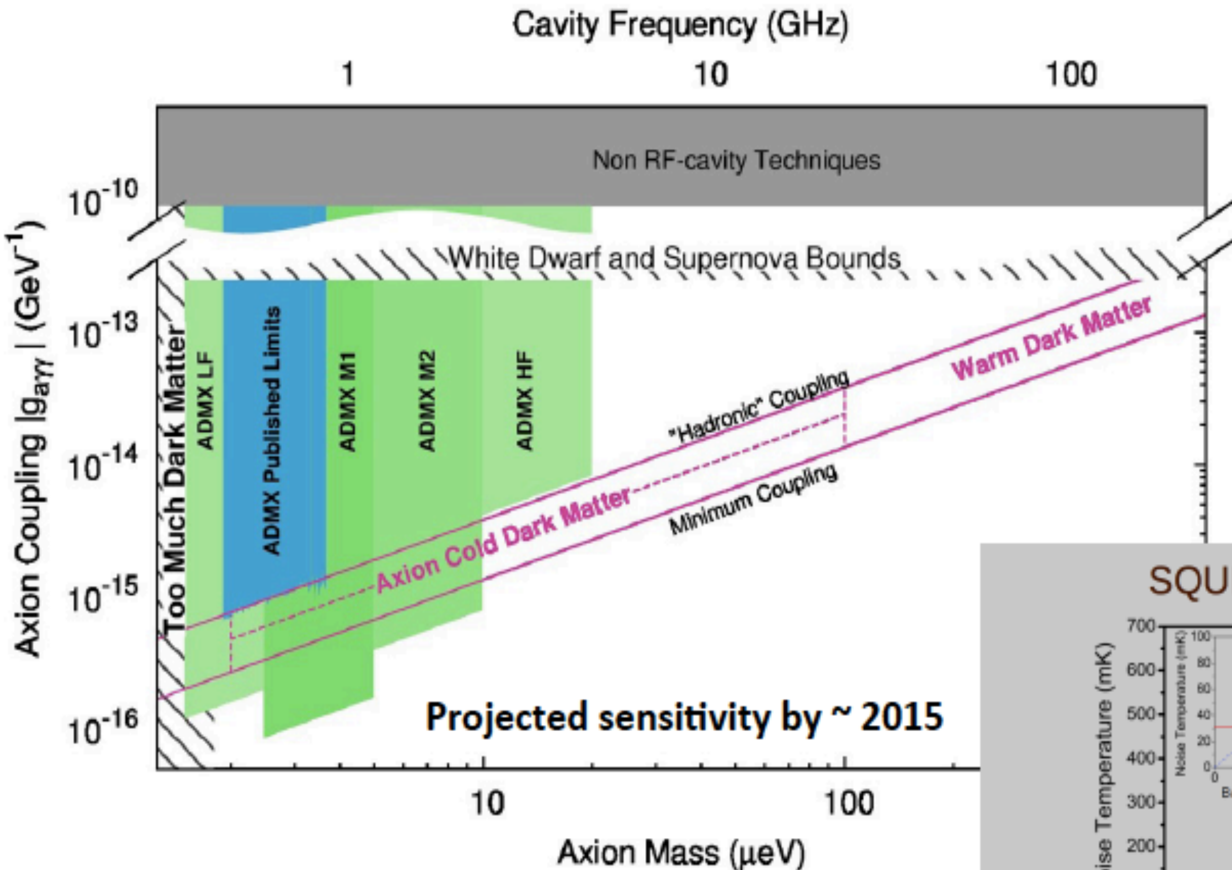


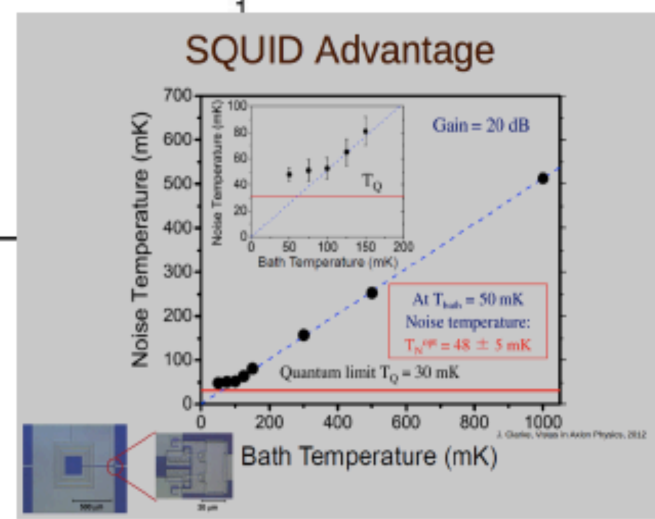
Alessandro De Angelis

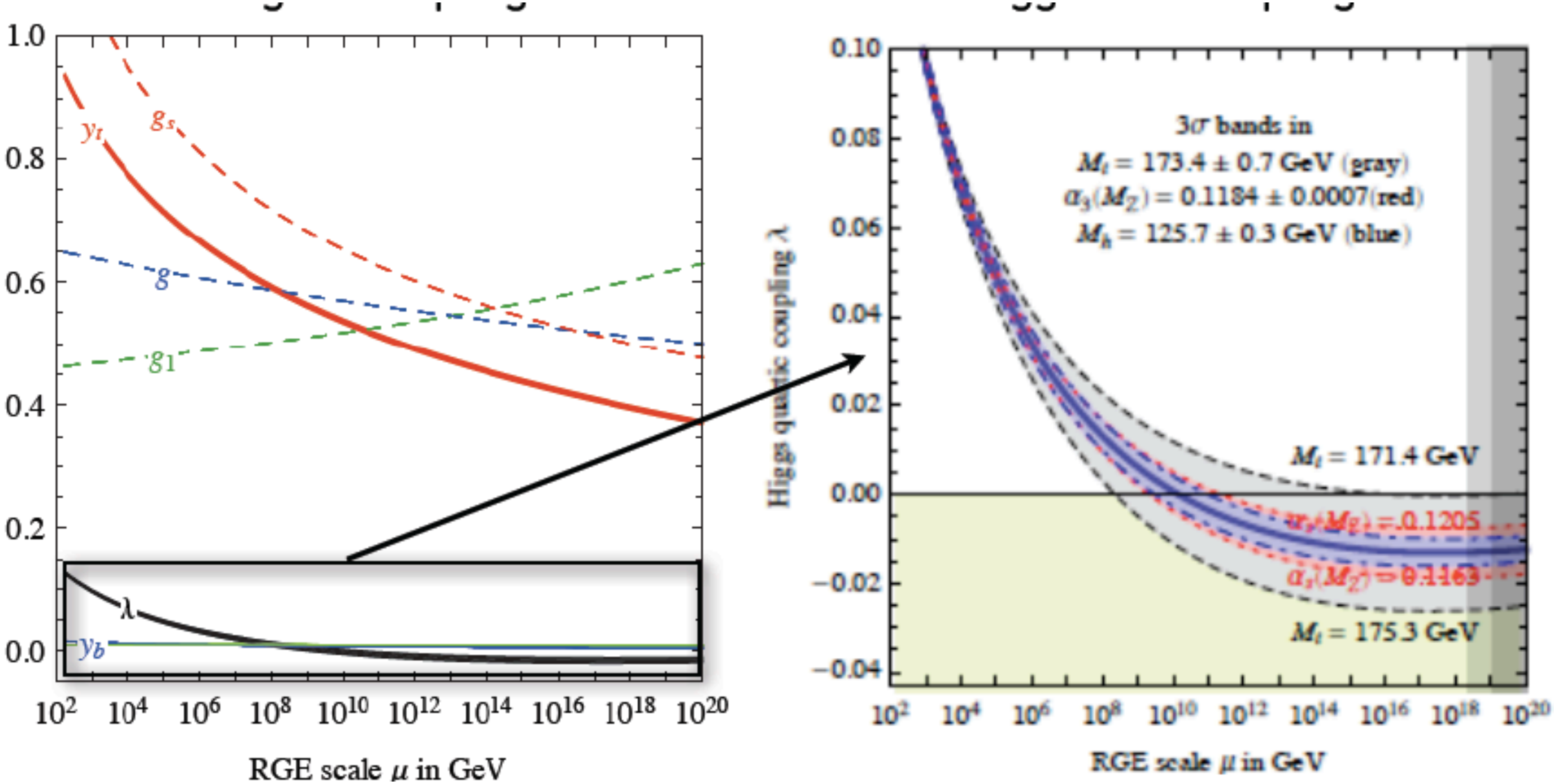
Keep in mind: we don't know at all what DM is made of ! Alternatives to WIMPs – for instance, AXIONS



ADMX achieved and projected sensitivity





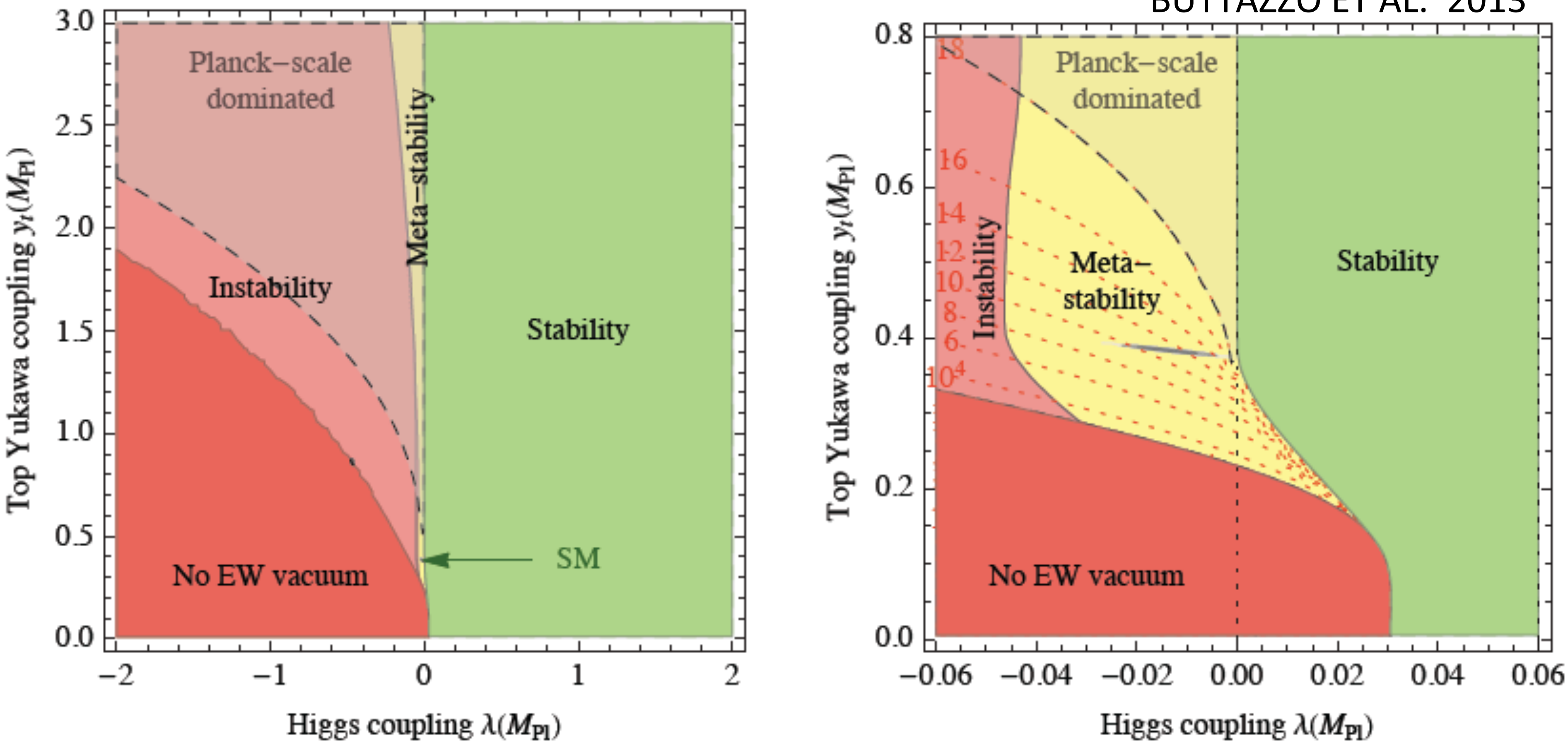


Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia 2013

For previous works: Krive, Linde '76; Krasnikov '78; Maiani, Parisi, Petronzio '78; Cabibbo et al '79; Lindner '86; Altarelli, Isisdori '96; Ellis et al 2009; Shaposhnikov et al '12; Elias-Miro' 'et a "12; …..
Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12

IF SM VALID UP TO M_{PLANCK} → **M_H formidable telescope to sneak into unexplorable energies…**

BUTTAZZO ET AL. 2013



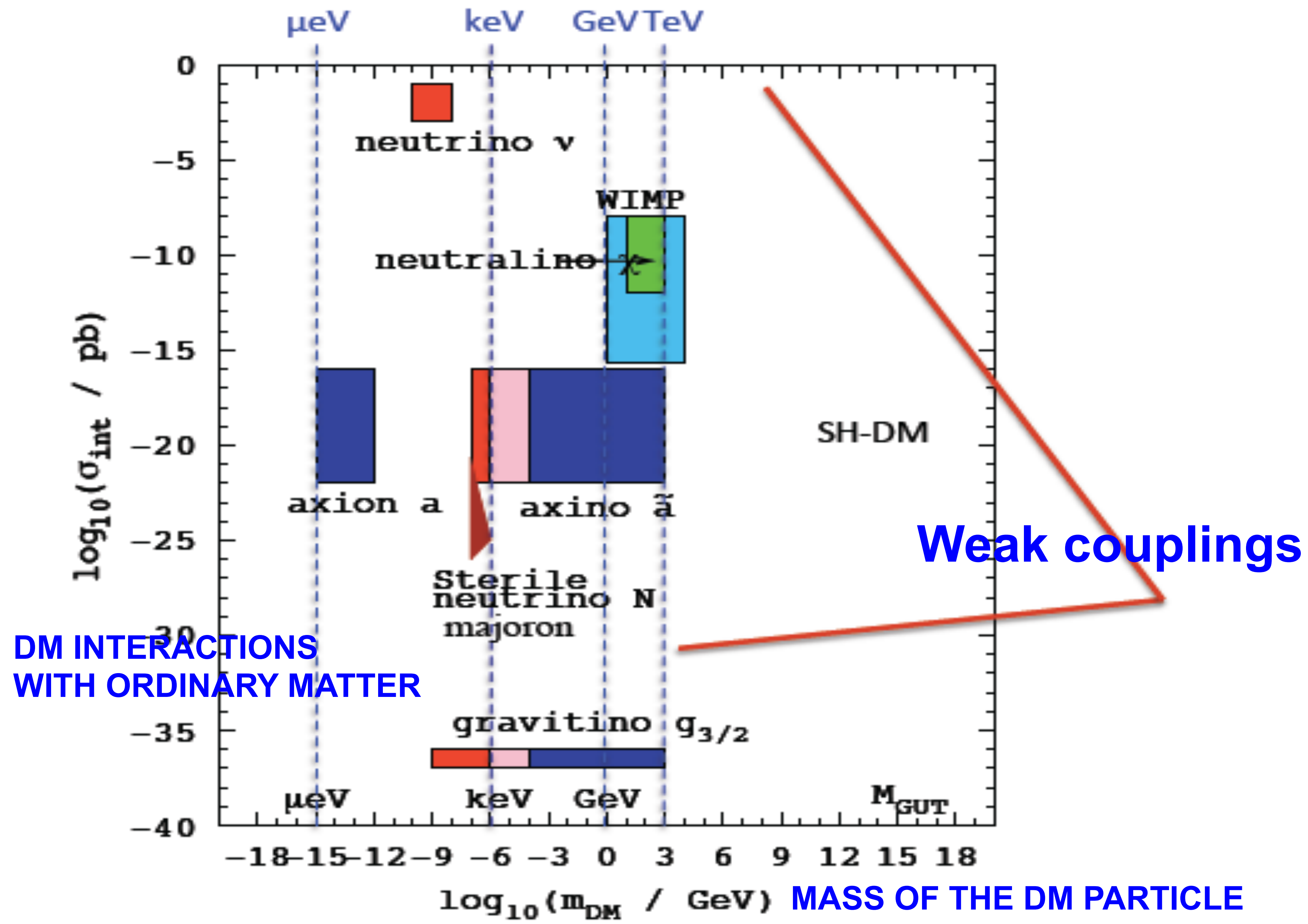
The Universe looks very close to **CRITICALITY**

ON THE IMPORTANCE OF PRECISELY MEASURING HIGGS and TOP MASSES

DEGRASSI ET AL

Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	± 1.4 GeV
α_s	experimental uncertainty in α_s	± 0.5 GeV
Experiment	Total combined in quadrature	± 1.5 GeV
λ	scale variation in λ	± 0.7 GeV
y_t	$\mathcal{O}(\Lambda_{QCD})$ correction to M_t	± 0.6 GeV
y_t	QCD threshold at 4 loops	± 0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	± 0.2 GeV
Theory	Total combined in quadrature	± 1.0 GeV

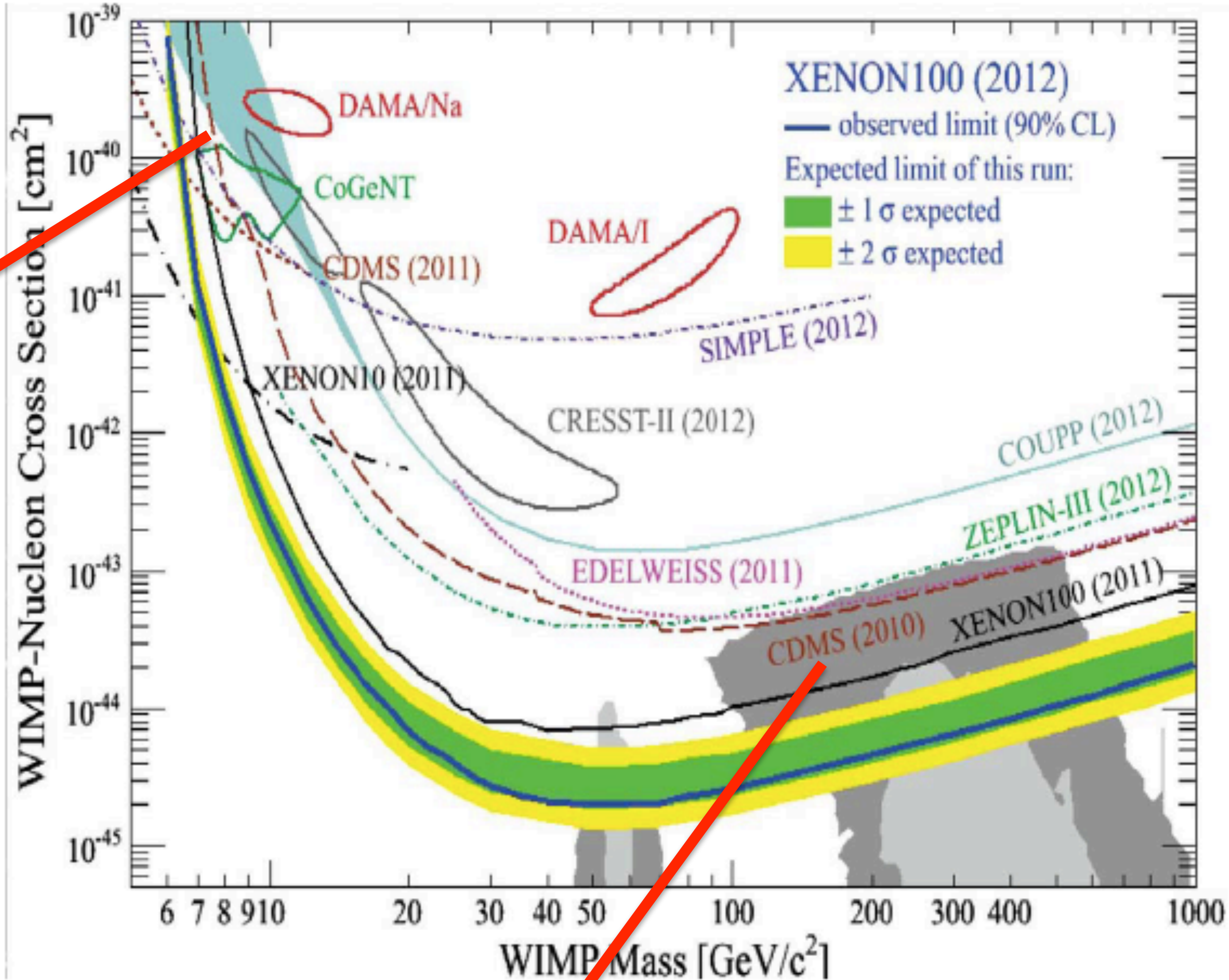
INTRINSIC DIFFICULTY TO "DEFINE" WHAT THE TOP MASS IS AT A **HADRON COLLIDER** WITH UNCERTAINTY ≤ 1 GeV

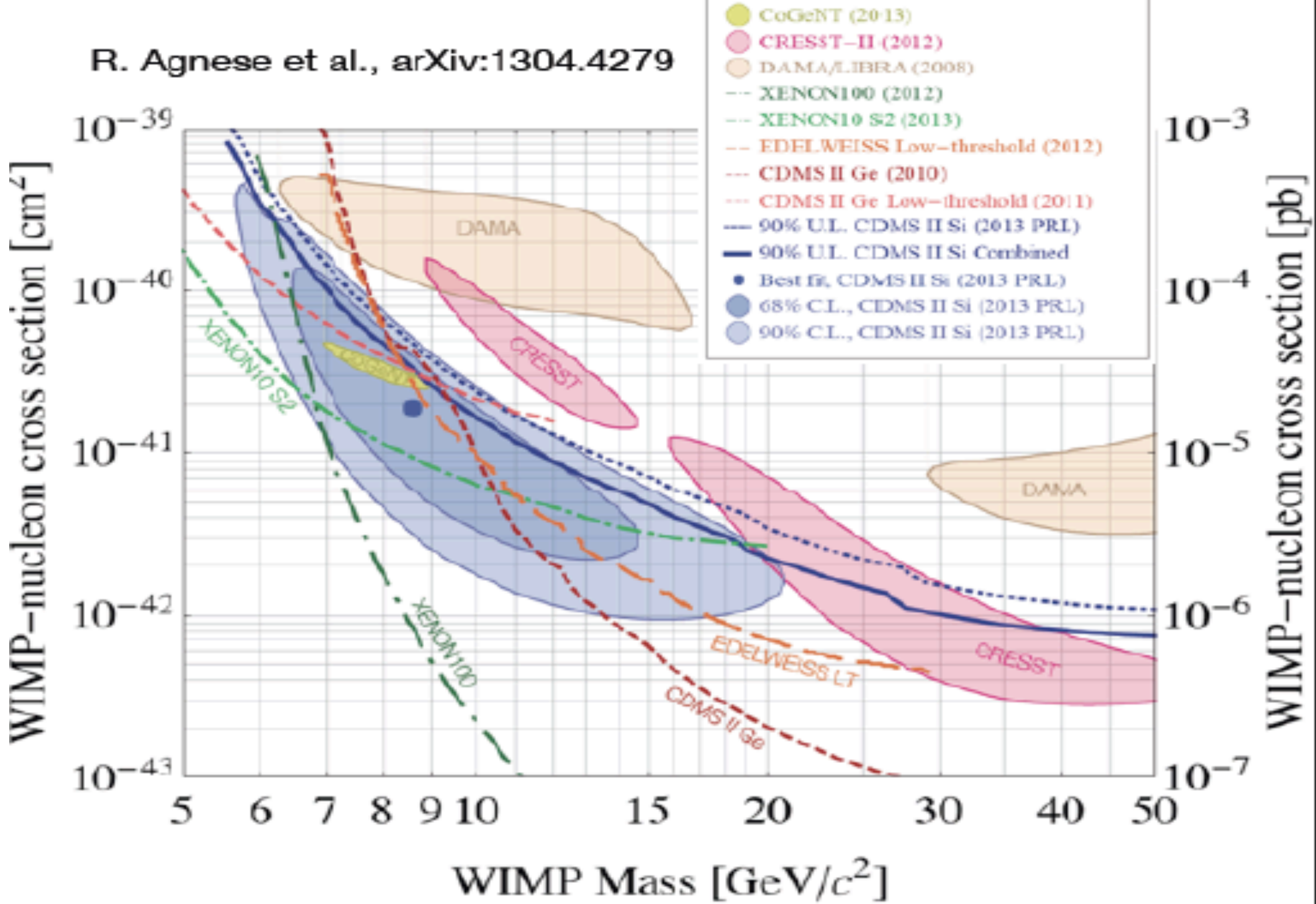

μeV
keV
GeV
TeV
neutrino ν
WIMP
neutralino χ
SH-DM
axion a
axino ã
Weak couplings
Sterile neutrino N
majoron
DM INTERACTIONS
WITH ORDINARY MATTER
gravitino $g_{3/2}$
μeV
keV
GeV
M_{GUT}
$\log_{10}(\sigma_{int}$ / pb)
0
−5
−10
−15
−20
−25
−30
−35
−40
−18
−15
−12
−9
−6
−3
0
3
6
9
12
15
18
$\log_{10}(m_{DM}$ / GeV)
MASS OF THE DM PARTICLE

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

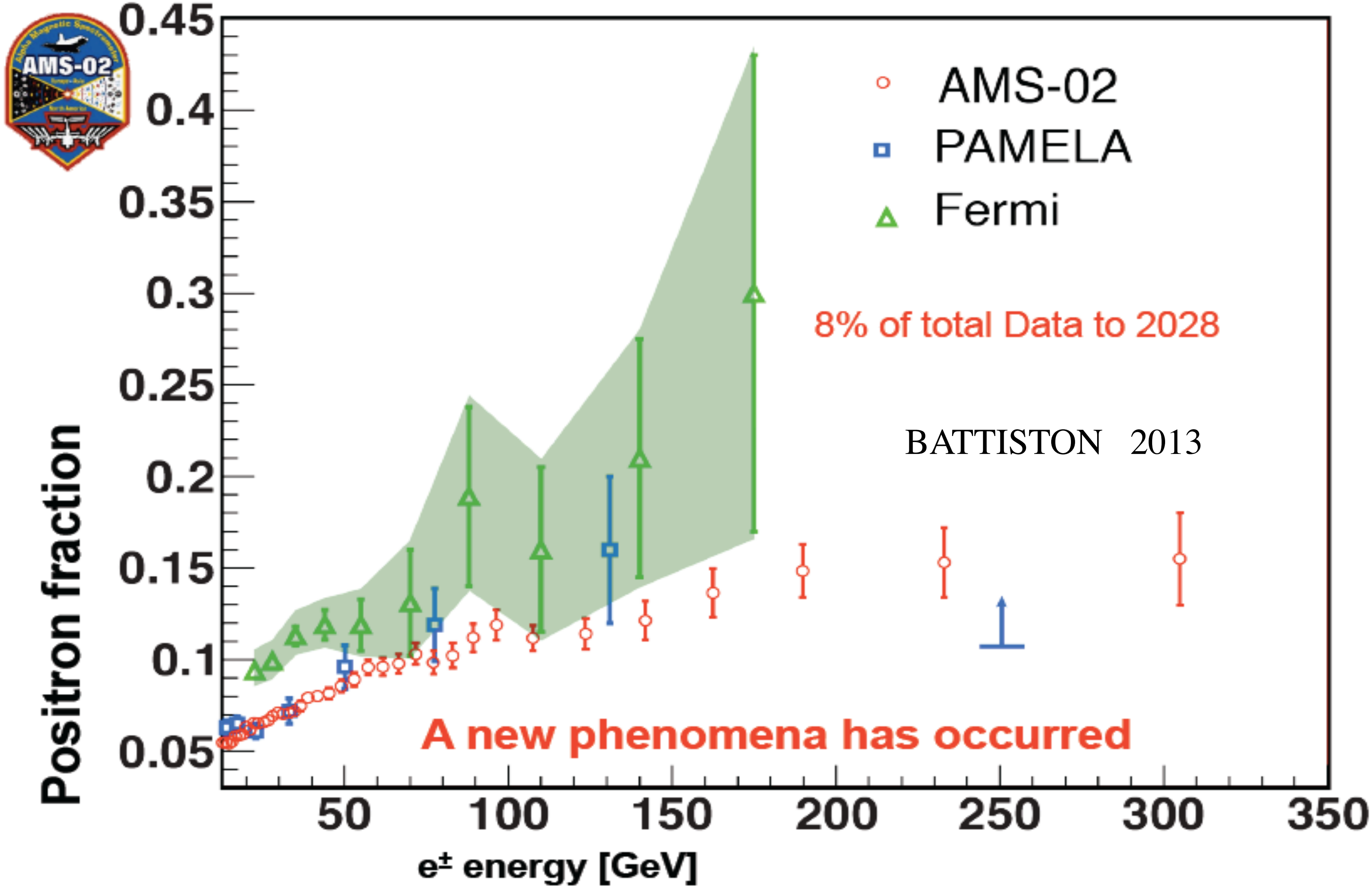
Relevant to intensify the efforts here: ex. **asymmetric DM** with **DM particles of mass~ baryon mass given that ρ_{DM} not much different from ρ_B**



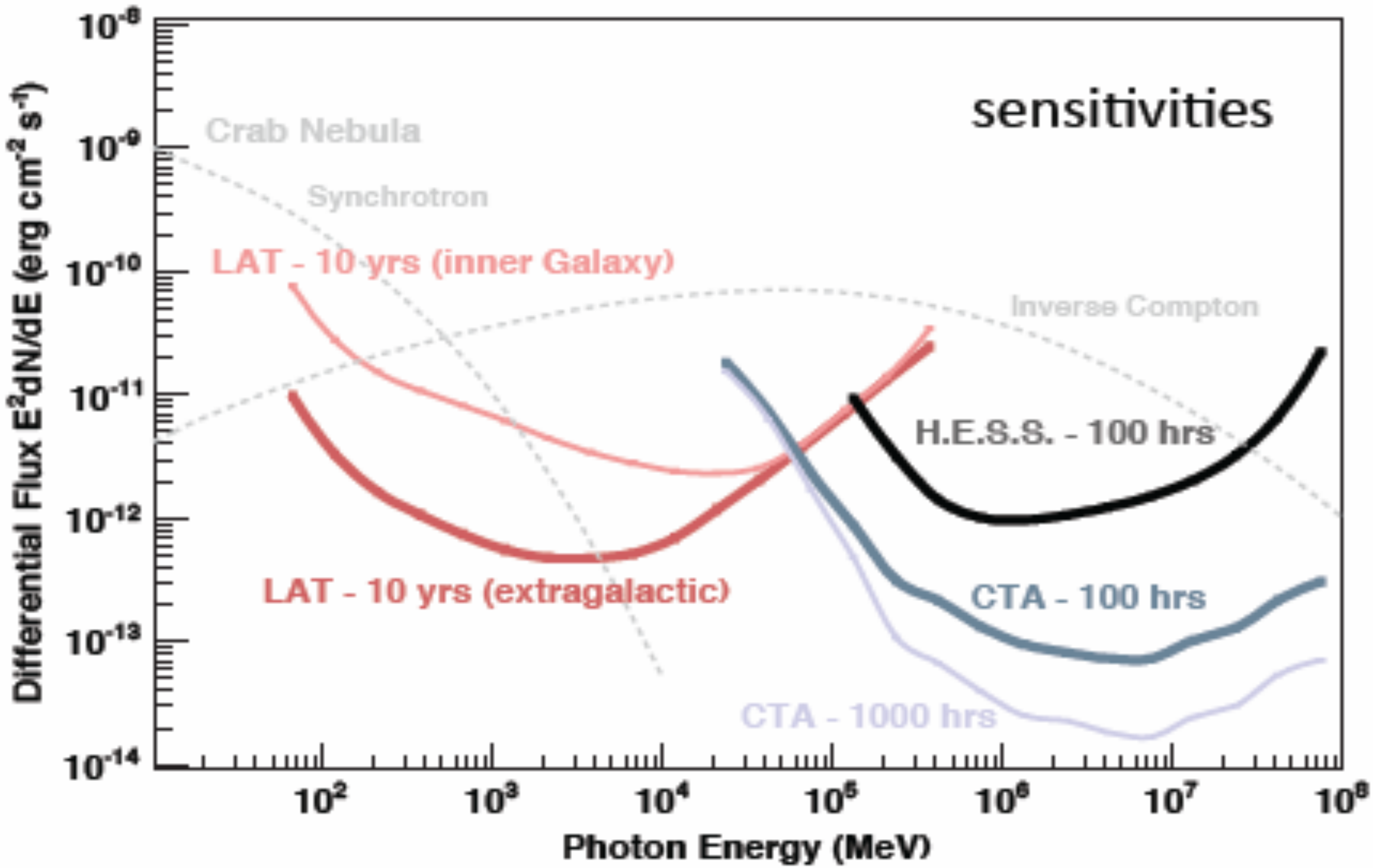


RELEVANCE OF THE DAMA-LIBRA RESULT– IMPORTANCE OF AN INDEPENDENT VERIFICATION (hard to reach the same level of sensitivity)

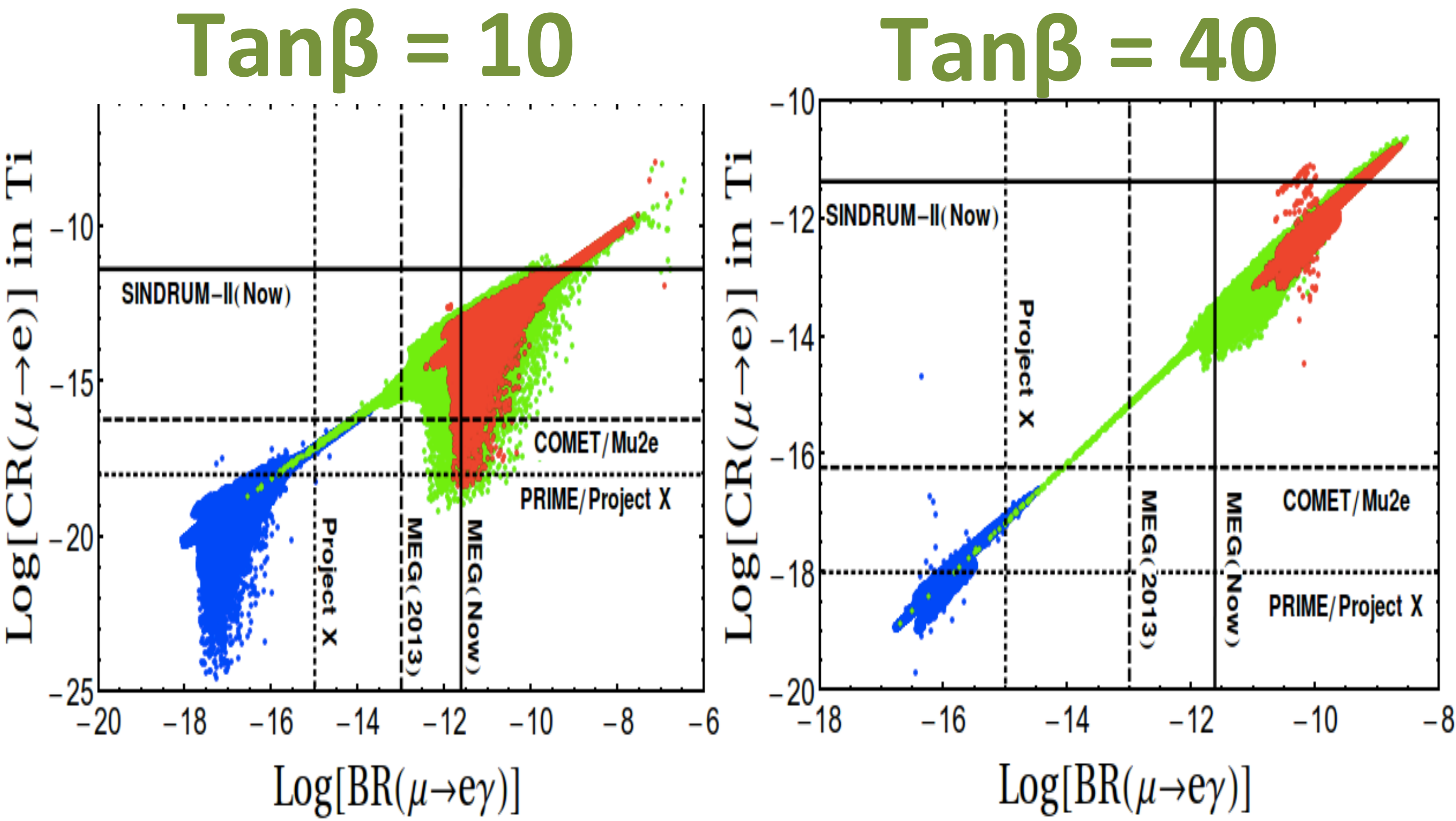
INDIRECT SEARCHES FOR DM



GAMMA – ASTRONOMY FROM EARTH AND SPACE

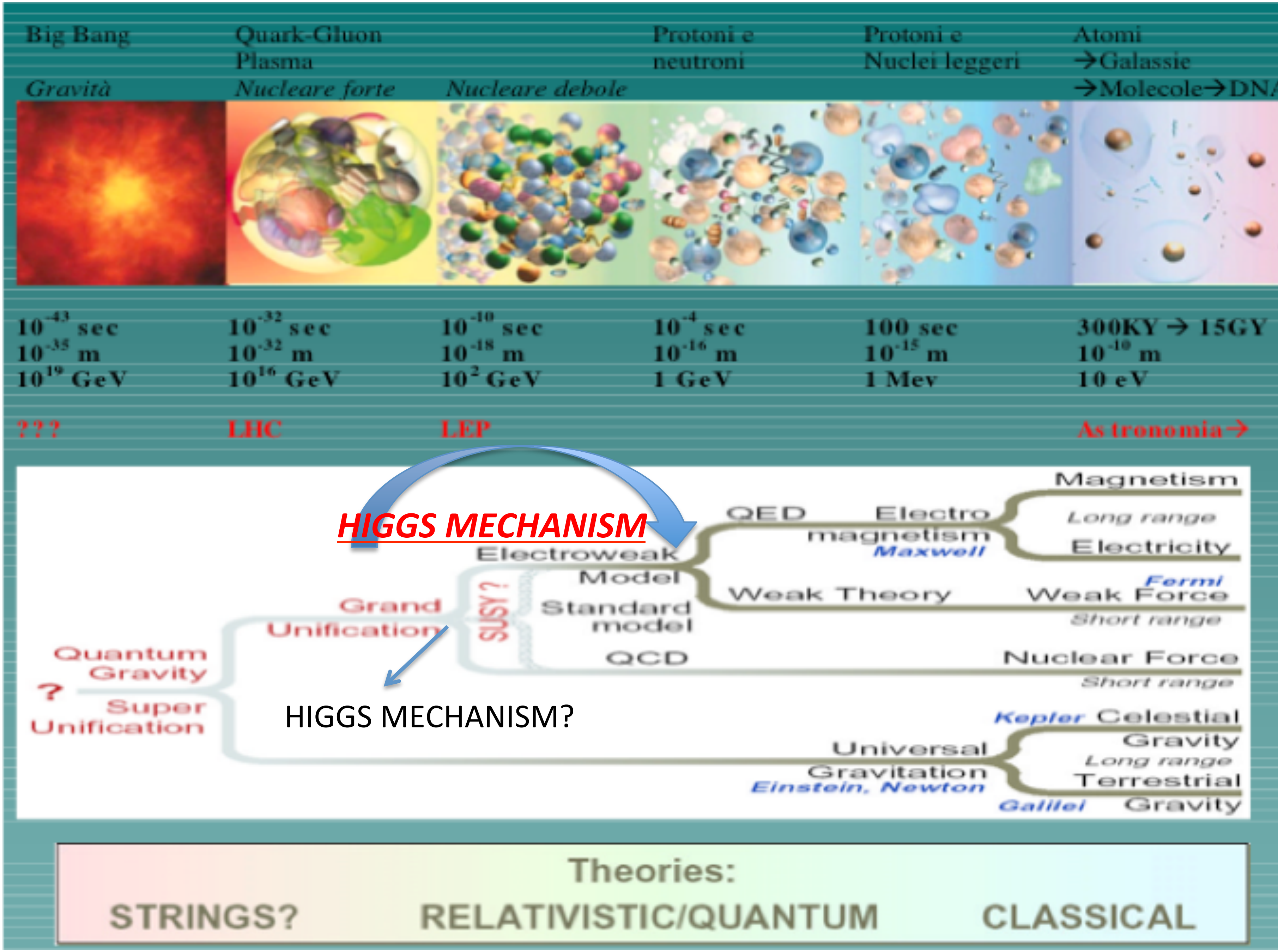


μ – e conversion vs μ → eγ



Is the DM a portal to new physics beyond the SM? (I)

- DM: most of the gravitationally clusterized form of energy of the Universe that we call MATTER is of non-baryonic nature, i.e. **non-baryonic DM exists**, and **it is by itself new physics**, i.e. it is made of particle(s) which are not present in the SM particle spectrum
- **Is (are) the mass(es) of the DM particle(s) at the electroweak scale**, i.e. of O(1TeV), or is the DM scale not correlated at all with the elw. scale?



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
As tronomia→
HIGGS MECHANISM
Magnetism
QED
Electro magnetism
Maxwell
Long range
Electricity
Electroweak
Model
Fermi
Weak Theory
Weak Force
Short range
Grand Unification
SUSY ?
Standard model
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

Higgs (and top?) physics: the importance of being precise

Higgs mass measurement: the need for high precision

Measuring the mass of the discovered signal with high precision is of interest in its own right

But a high-precision measurement has also direct implications for probing Higgs physics

M_H: crucial input parameter for Higgs physics

BR($H \to ZZ^*$), BR($H \to WW^*$): highly sensitive to precise numerical value of M_H

A change in M_H of 0.2 GeV shifts BR($H \to ZZ^*$) by 2.5%!

⇒ Need high-precision determination of M_H to exploit the sensitivity of BR($H \to ZZ^*$), ... to test BSM physics

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

The next step

It is clear that at least **1 ton isotope** is required to explore the inverted hierarchy region

- Impact of enrichement cost

Isotope	Abundance	Price/kg [k$]	Price/(10 t) [M$]
^{76}Ge	7.61	~ 80	800 (640)$^{*)}$
^{82}Se	8.73	~ 120	1200 (1000)$^{*)}$
^{100}Mo	9.63	~ 80	800 (640)$^{*)}$
^{116}Cd	7.49	~ 180	1800 (1440)$^{*)}$
^{130}Te	34.08	~ 20	200 (160)$^{*)}$
^{136}Xe	8.87	$\sim$ 5-10	50-100 (40-80)$^{*)}$
^{150}Nd (?)	5.6	> 200	> 2000

Barabash, 2013

- How many technological approaches and which ones?

- How many isotopes and which ones?

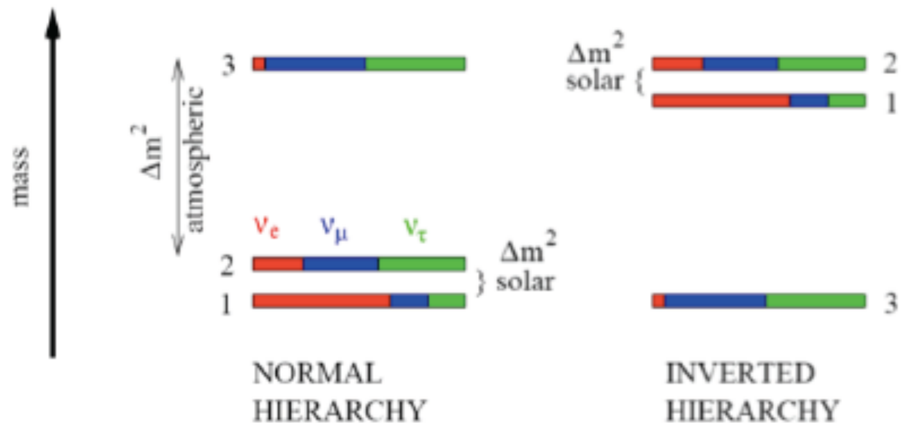
- **Which infrastructures?**

Which chance do we have to get them in Europe?

A. Giuliani SAC APPEC 2013

Neutrino oscillations & sterile neutrinos

- **Atmospheric neutrinos(θ_{23})**
  - SuperK, HyperK/UNO, INO, TITAND,...
- **Solar neutrinos(θ_{12}):**
  - GALLEX/SAGE, SuperK, SNO, Borexino, XMASS, ...
- **Reactor neutrinos(θ_{12},θ_{13} → mass hierarchy):**
  - KamLAND, Daya Bay→ JUNO, Double CHOOZ, Reno,...
- **Accelerator neutrinos(θ_{23},θ_{13} → mass hierarchy, δ, ...):**
  - MINOS, OPERA, MiniBooNe, T2K, NOVA, ICARUS...



CPV

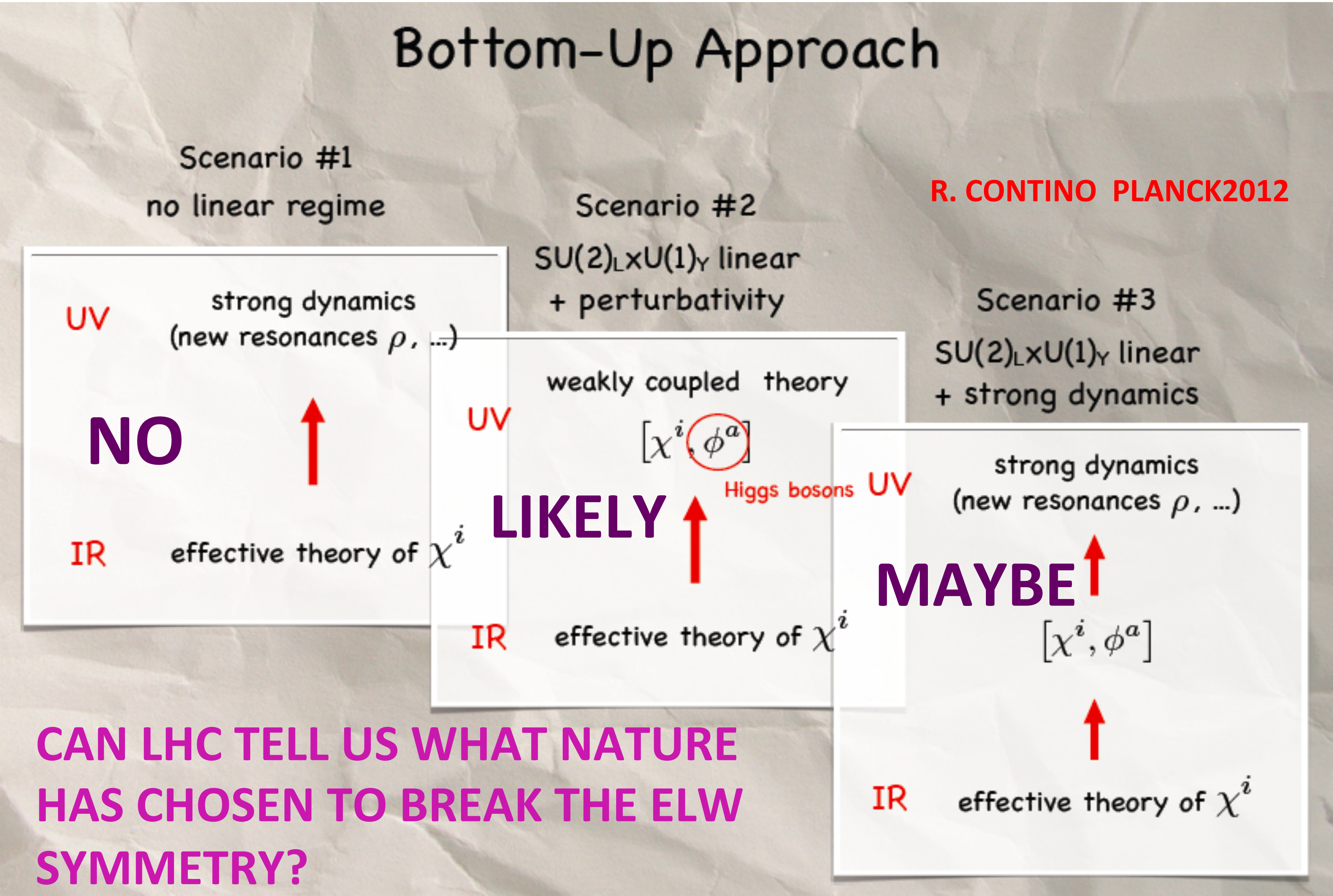
+ A number of anomalies:

LSND ?

Reactor neutrino flux ?

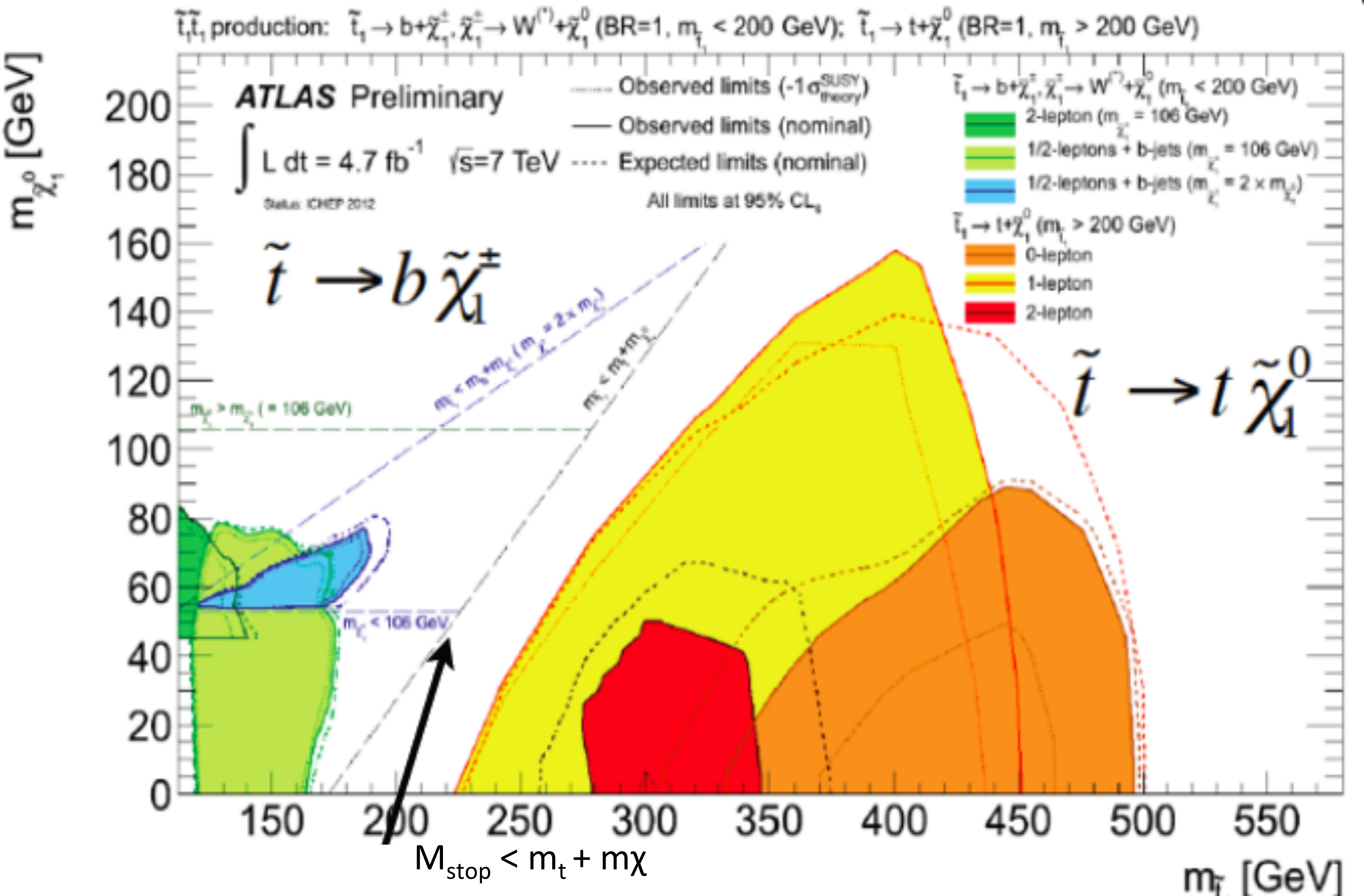
Sterile neutrinos ? MiniBoone

EWSB: WITH OR WITHOUT A HIGGS BOSON

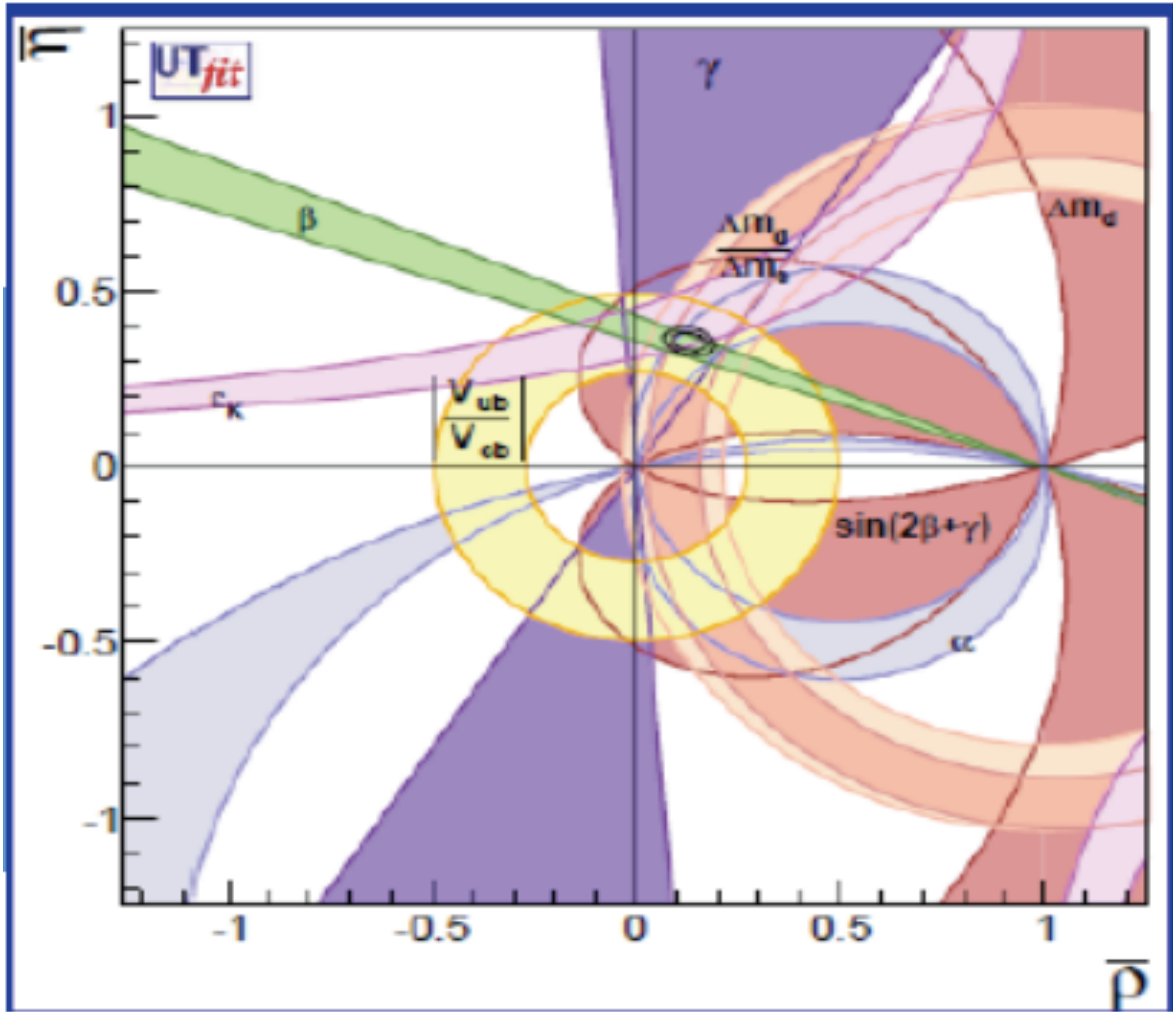


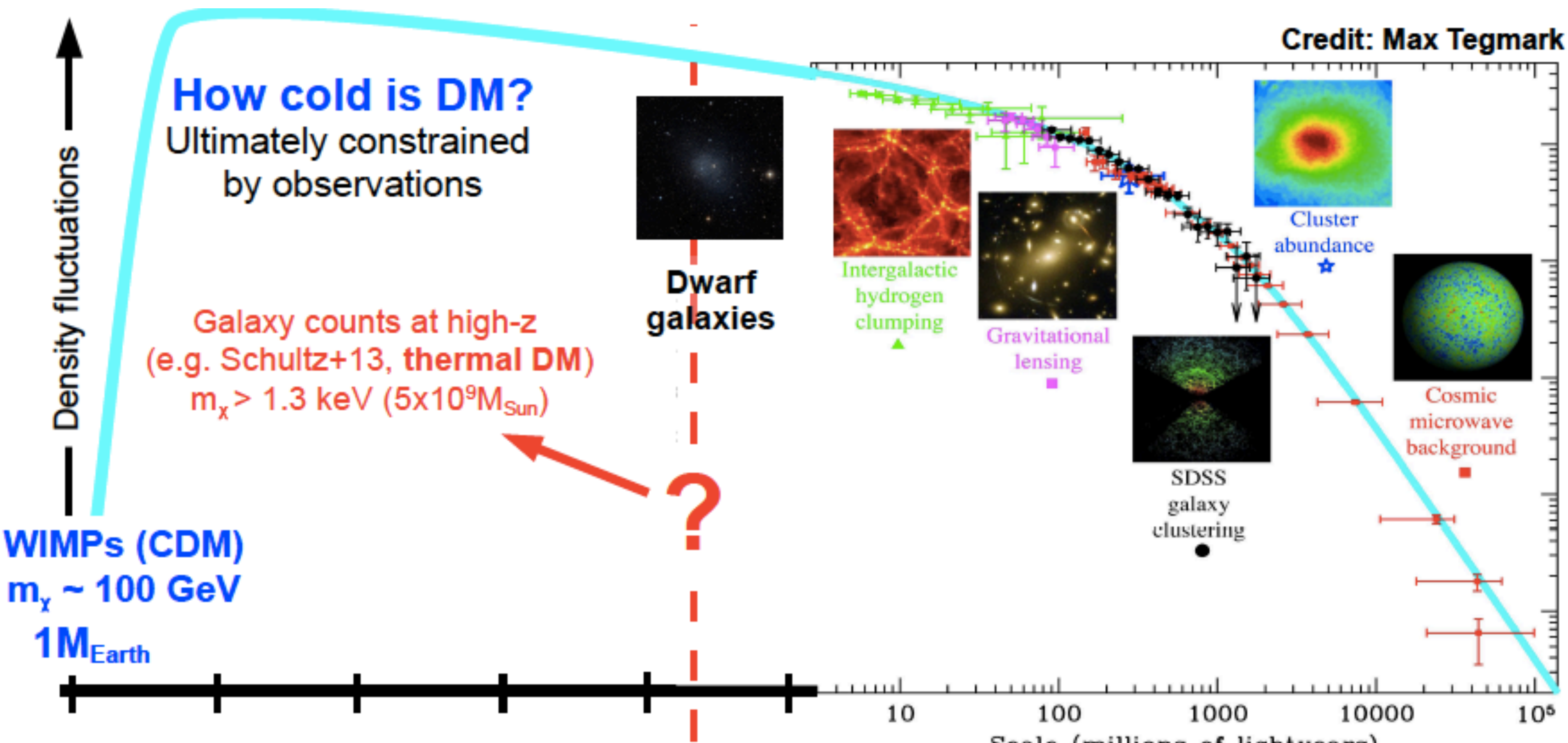
CAN LHC TELL US WHAT NATURE HAS CHOSEN TO BREAK THE ELW SYMMETRY?

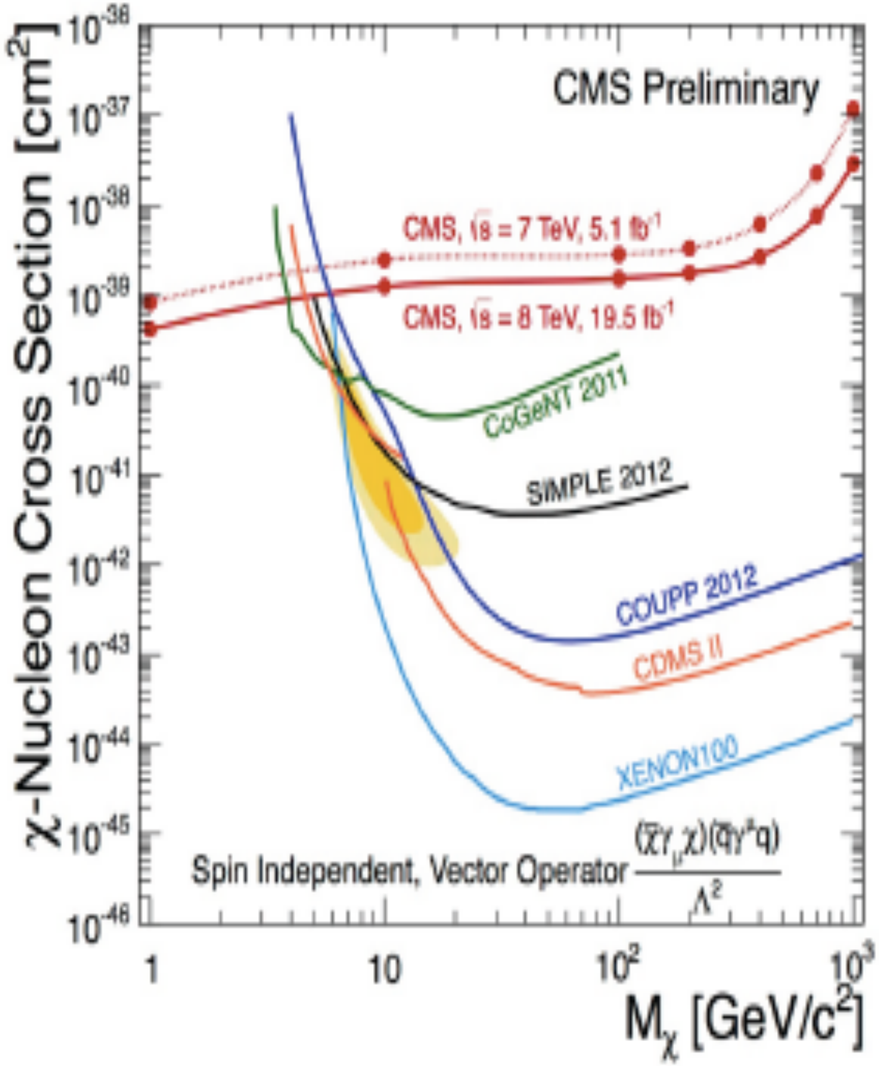
Hunting for a light s-top



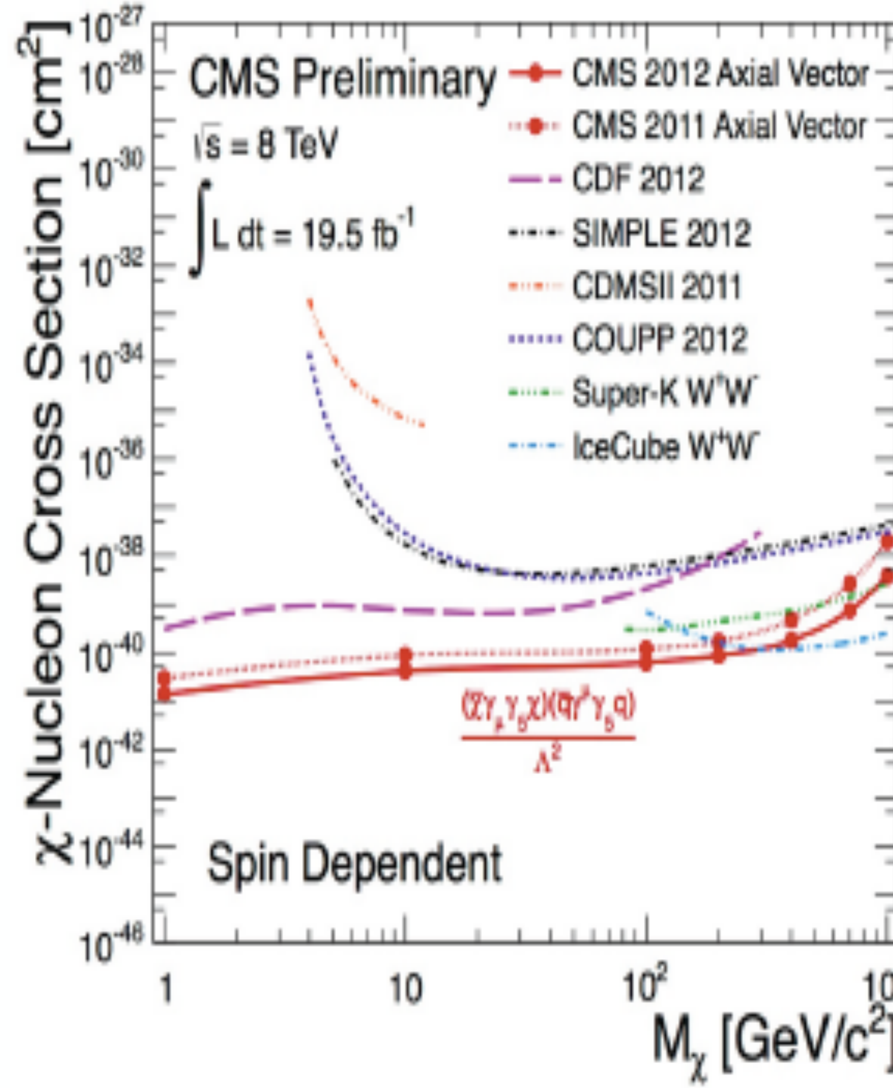
the (almost complete) CKM triumph




Credit: Max Tegmark
How cold is DM?
Ultimately constrained by observations
Density fluctuations
Galaxy counts at high-z
(e.g. Schultz+13, thermal DM)
$m_\chi > 1.3$ keV ($5\times10^9 M_{Sun}$)
?
Dwarf galaxies
WIMPs (CDM)
$m_\chi \sim 100$ GeV
$1M_{Earth}$
Intergalactic hydrogen clumping
Gravitational lensing
Cluster abundance
SDSS galaxy clustering
Cosmic microwave background
10
100
1000
10000
10^5
Scale (millions of lightyears)



CMS Preliminary
CMS, √s = 7 TeV, 5.1 fb-1
CMS, √s = 8 TeV, 19.5 fb-1
CoGeNT 2011
SIMPLE 2012
COUPP 2012
CDMS II
XENON100
Spin Independent, Vector Operator
χ-Nucleon Cross Section [cm²]
M_χ [GeV/c²]



CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb-1
CMS 2012 Axial Vector
CMS 2011 Axial Vector
CDF 2012
SIMPLE 2012
CDMSII 2011
COUPP 2012
Super-K W+W-
IceCube W+W-
Spin Dependent
χ-Nucleon Cross Section [cm²]
M_χ [GeV/c²]