Vulcano Workshop 2014, Vulcano, May 20, 2014

The Early Universe and the LHC: 2 Accelerators for 1 New Physics

Antonio Masiero
INFN and Univ. of Padova

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**?

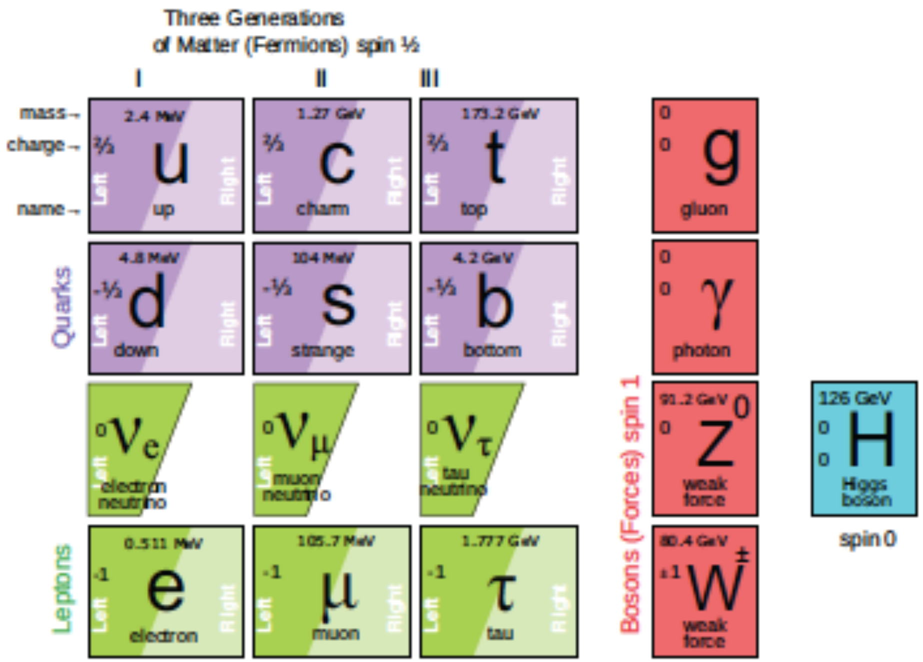
EX. **EXTRA-DIMENSIONS**
or
TeV STRING THEORY

EX.: **TECHNICOLOR** or
SUSY with ELW RAD. BREAKING

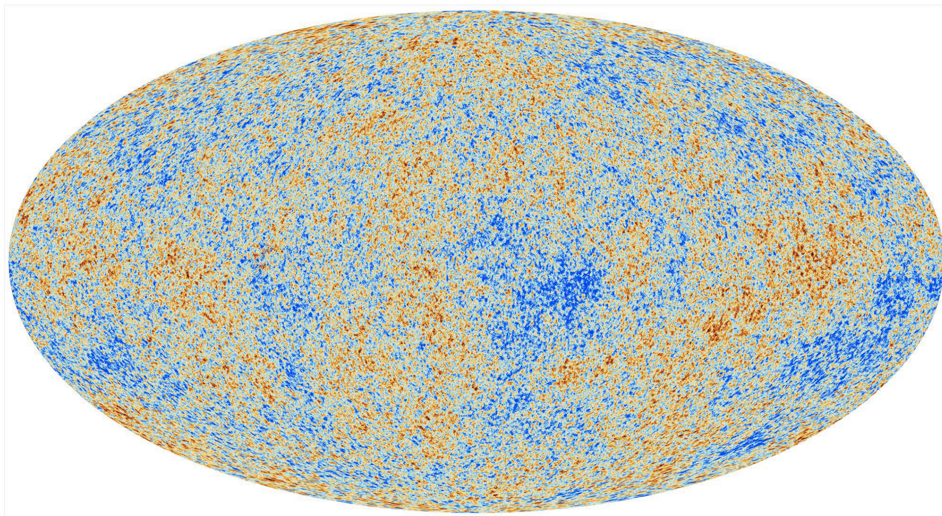
NEW PARTICLES AT THE TEV SCALE?

2013: the thiumph of the **STANDARD**

- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



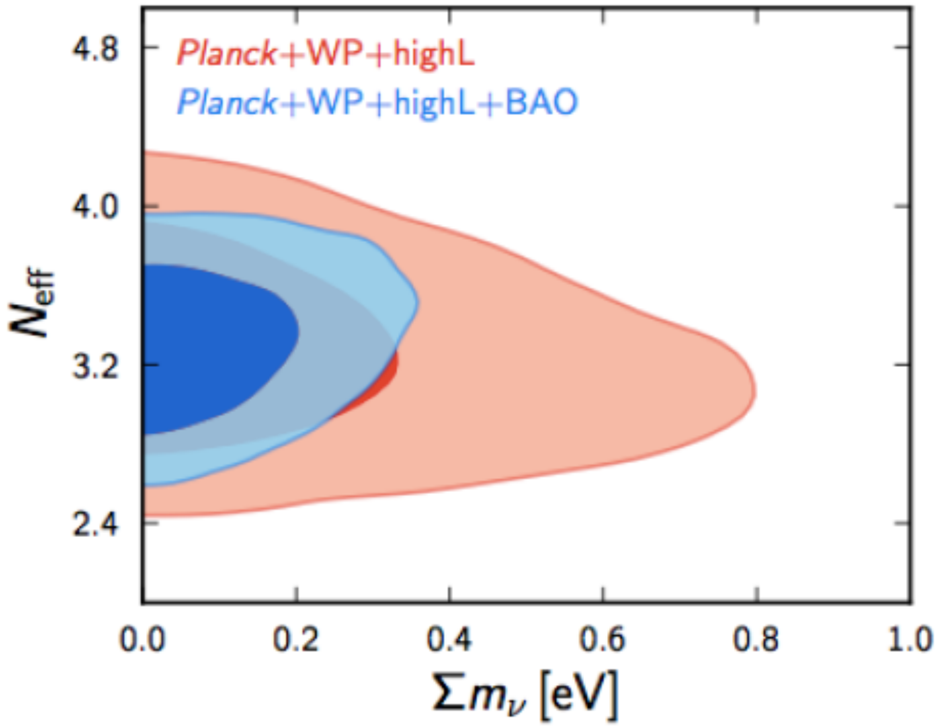
ΛCDM + "SIMPLE" INFLATION

$\Omega_\Lambda = 0.686 \pm 0.020$

$\Omega_m = 0.314 \pm 0.020$

$\Omega_b h^2 = 0.02207 \pm 0.00033$

$h = 0.674 \pm 0.014$



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

Σm_ν< 0.23- 0.8 eV

Recent **BICEP2** results: 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)

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

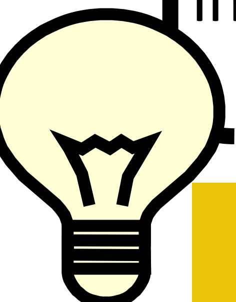
OBSERVATIONAL EVIDENCE OF NEW PHYSICS

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

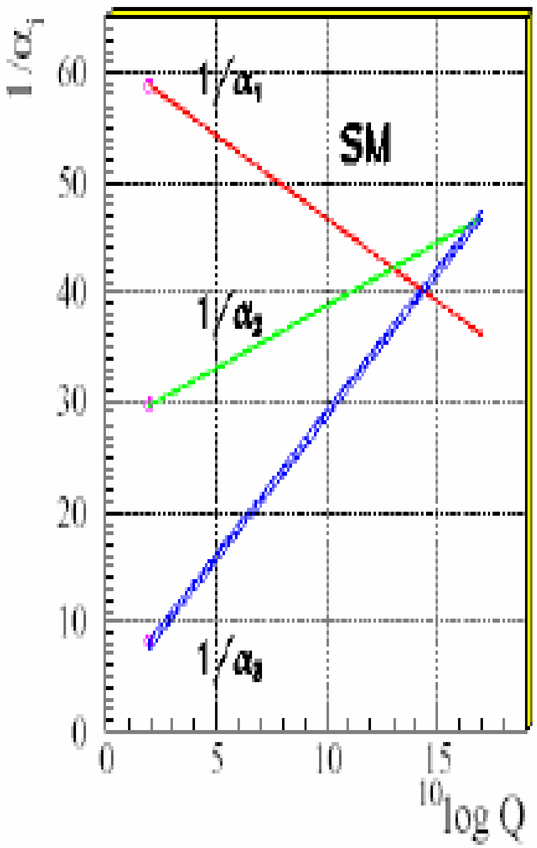


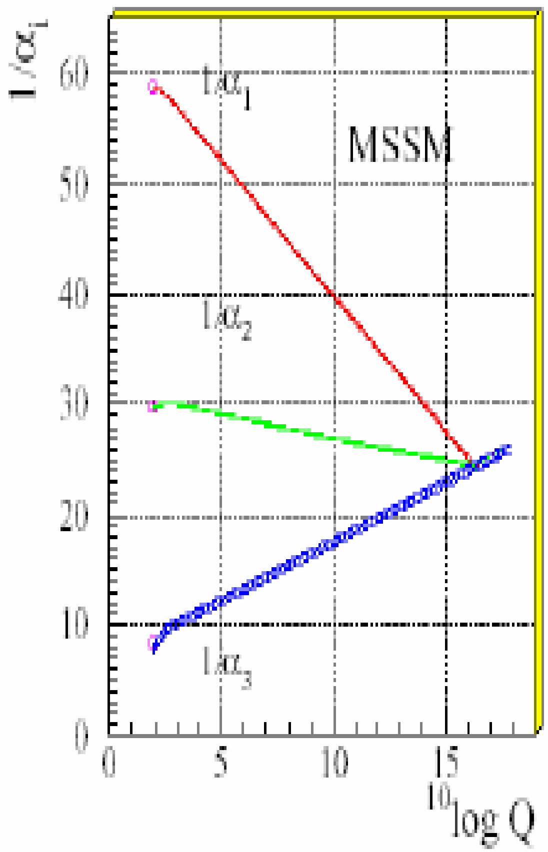
The Energy Scale from the "Theoretical" New Physics

★ ★ ★ **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

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

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

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

THE COMPREHENSION OF THE ELECTROWEAK SCALE

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

- M = O(10^{16} 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

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

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

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)

3 WAYS TO IMPLEMENT THE HIGGS MECHANISM

- **NO HIGGS PARTICLE**: **HIGGSLESS** MODEL (almost) killed by LHC (unlikely the observed scalar is an "impostor", however not impossible – ex. dilaton, radion. Possibility of mixing of an "authentic" Higgs with the "impostor"…)

- **COMPOSITE HIGGS**: PSEUDO-GOLDSTONE BOSON

- **ELEMENTARY HIGGS**

A) FINE-TUNED (unnatural Higgs – anthropic road, high-scale fundamental theory taking care of it, …)

B) NATURAL (protection mechanism: low-energy SUSY; inexistence of the scale hierarchy problem: extra dimensions, warped space, …)

3 comments on m_{NP}

ROMANINO 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 $\rightarrow$ Δ 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 ~

$$M \gg m_h$$

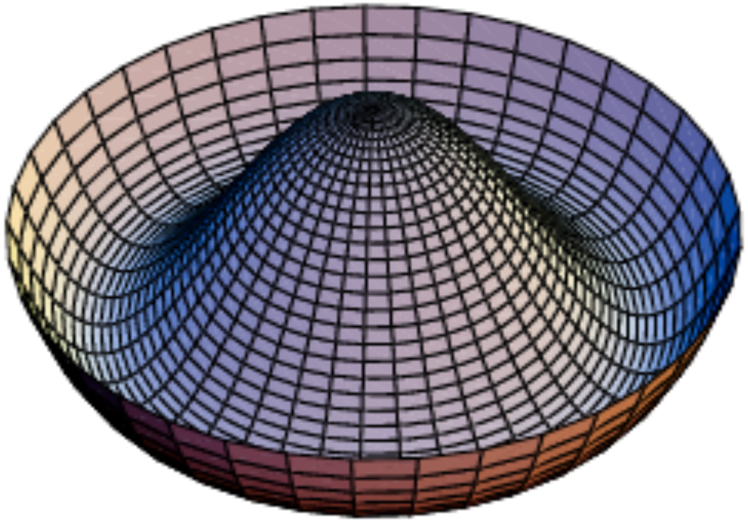
- however: it could be that there is nothing at scales ~ $M \gg m_h$ **FINITE NATURALNESS**

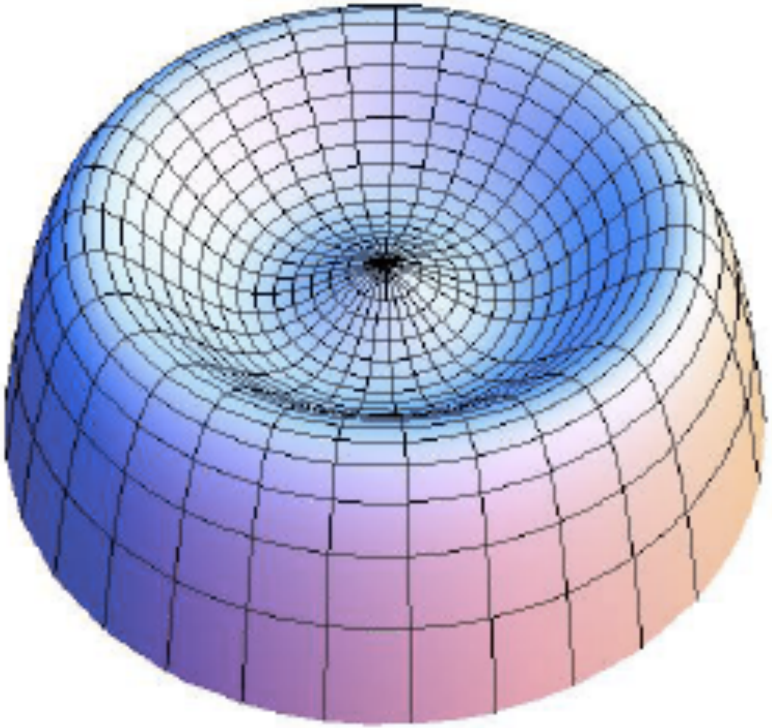
- however: it could be that there is indeed new physics at M, but **"REDUCTIONISM" DOES NOT HOLD** (**anthropic selection**) – i.e. **physics at 10^2 Gev depends on specific choices of parameters made at 10^{16} GeV !** (**unprecedented in physics**)

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

LFV ⟺ PHYSICS BSM

- LFV ⟺ NEUTRINO MASSES
- LFV ⟺ MATTER-ANTIMATTER ASYMMETRY
- LFV ⟺ GAUGE UNIFICATION
- LFV ⟺ GAUGE HIERARCHY PROBLEM

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

→ 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

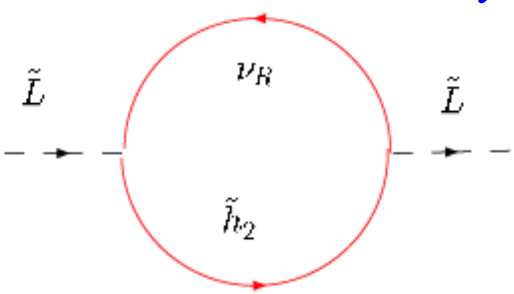
THE STRONG ENHANCEMENT OF LFV IN SUSY SEESAW MODELS CAN OCCUR

EVEN IF THE MECHANISM RESPONSIBLE FOR SUSY BREAKING IS ABSOLUTELY FLAVOR BLIND

SUSY SEESAW: *Flavor universal SUSY breaking and yet* ***large lepton flavor violation***

Borzumati, A. M. 1986 (after discussions with W. Marciano and A. Sanda)

$$L = f_l \, \overline{e}_R L h_1 + f_\nu \, \overline{\nu}_R L h_2 + M \, \nu_R \nu_R$$



$$\left(m^2_{\tilde{L}}\right)_{ij} \simeq \frac{1}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(f_\nu^\dagger f_\nu\right)_{ij} \log\frac{M}{M_G}$$

Non-diagonality of the slepton mass matrix in the basis of diagonal lepton mass matrix depends on the **unitary matrix U which diagonalizes ($f_\nu^+ f_\nu$)**

How Large LFV in SUSY SEESAW?

- 1) Size of the **Dirac neutrino couplings f_ν**
- 2) Size of the **diagonalizing matrix U**

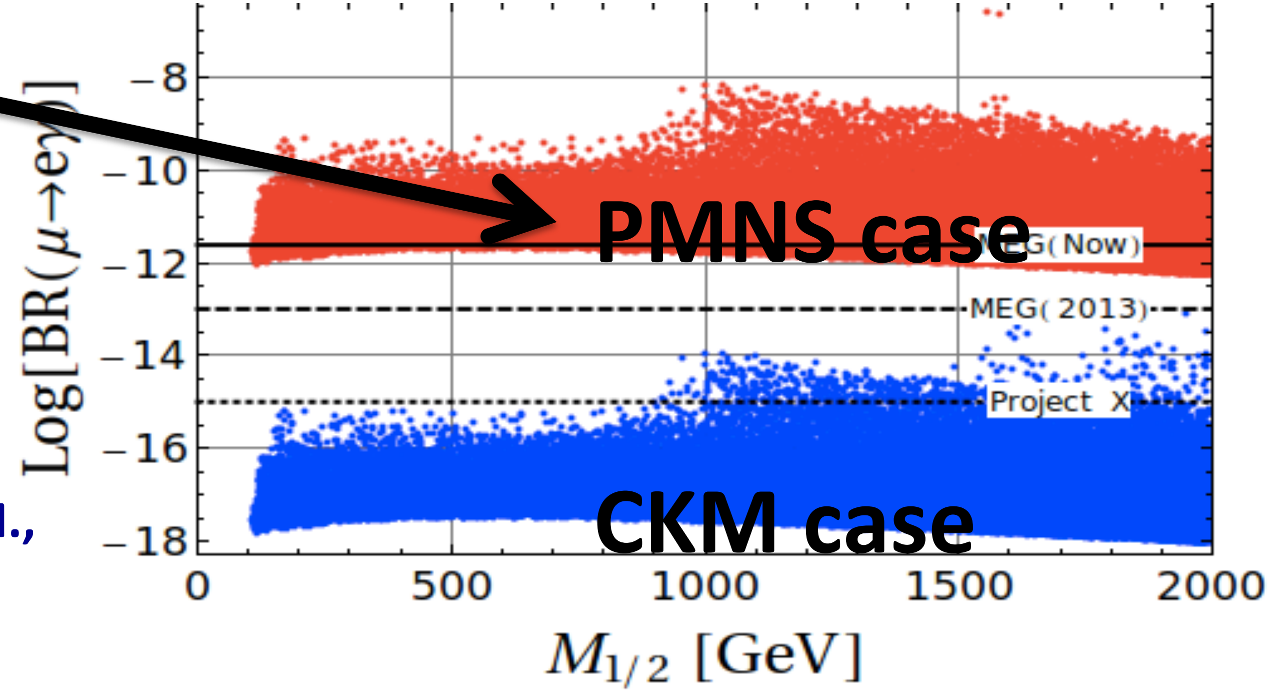
In **MSSM seesaw** or in **SUSY SU(5)** (Moroi): not possible to correlate the neutrino Yukawa couplings to know Yukawas;

In **SUSY SO(10)** (A.M., Vempati, Vives) at least one neutrino Dirac Yukawa coupling has to be of the **order of the top Yukawa coupling** one large of O(1) f_ν

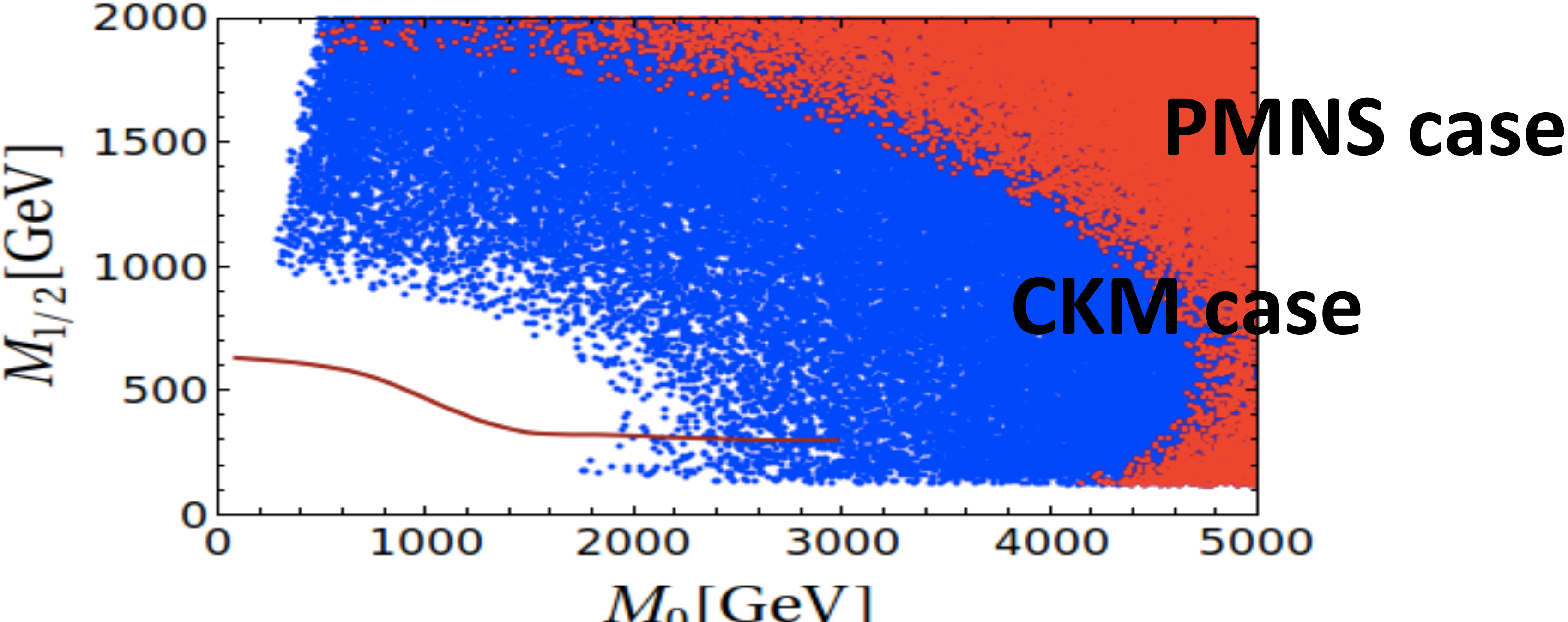
U → two "extreme" cases:

a) **U with "small" entries** → ***U = CKM***;
b) **U with "large" entries** with the exception of the 13 entry → ***U = PMNS*** matrix responsible for the diagonalization of the neutrino mass matrix

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

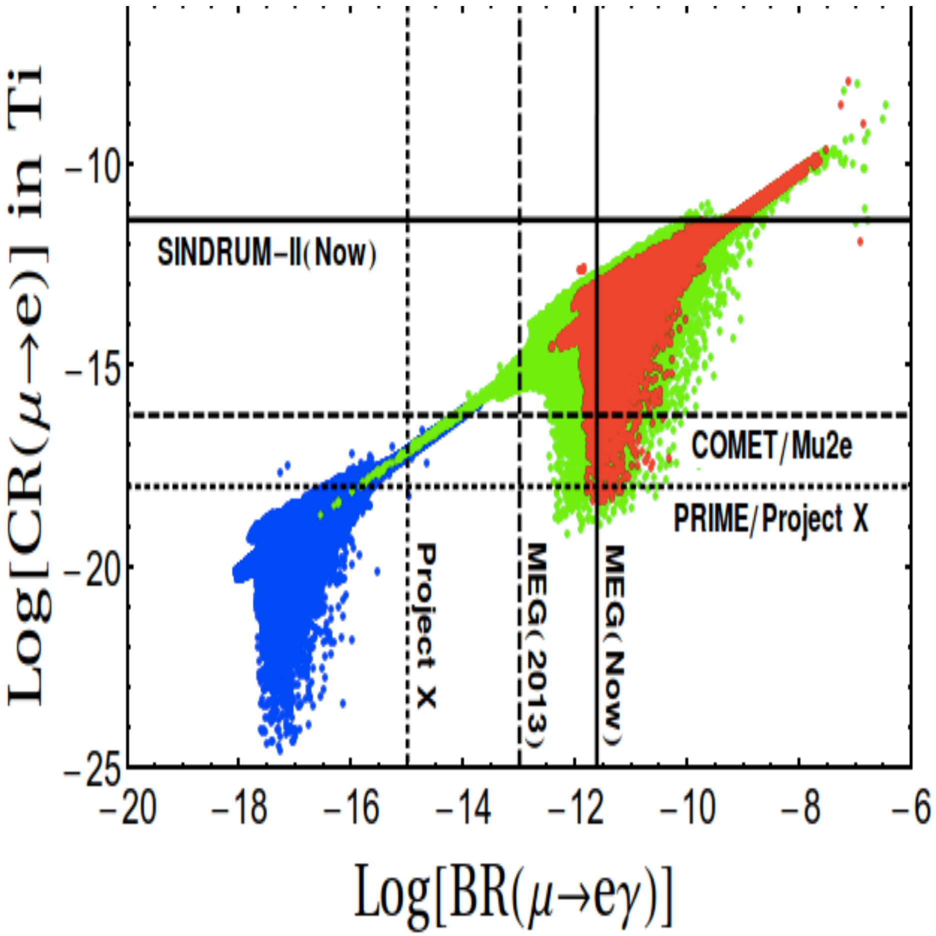


Calibbi, Chowdhuri, A. M., Patel, Vempati 2012

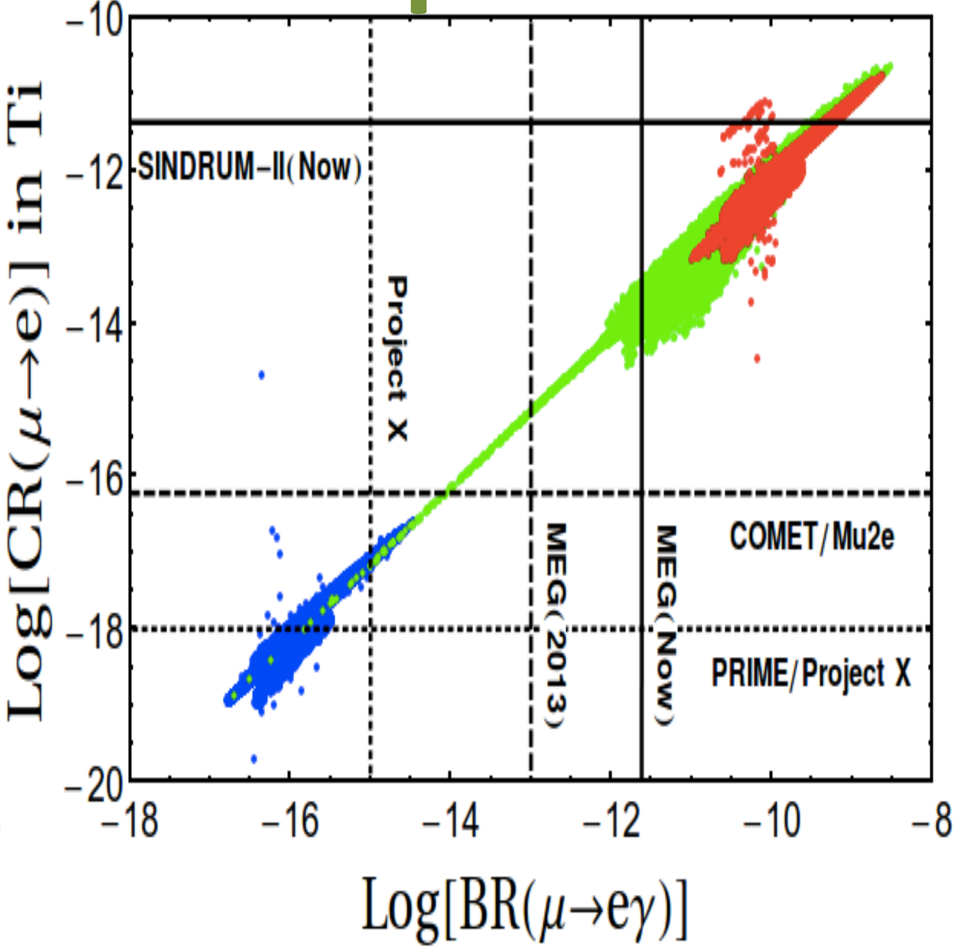


μ – e conversion vs μ → eγ

Tanβ = 10



Tanβ = 40



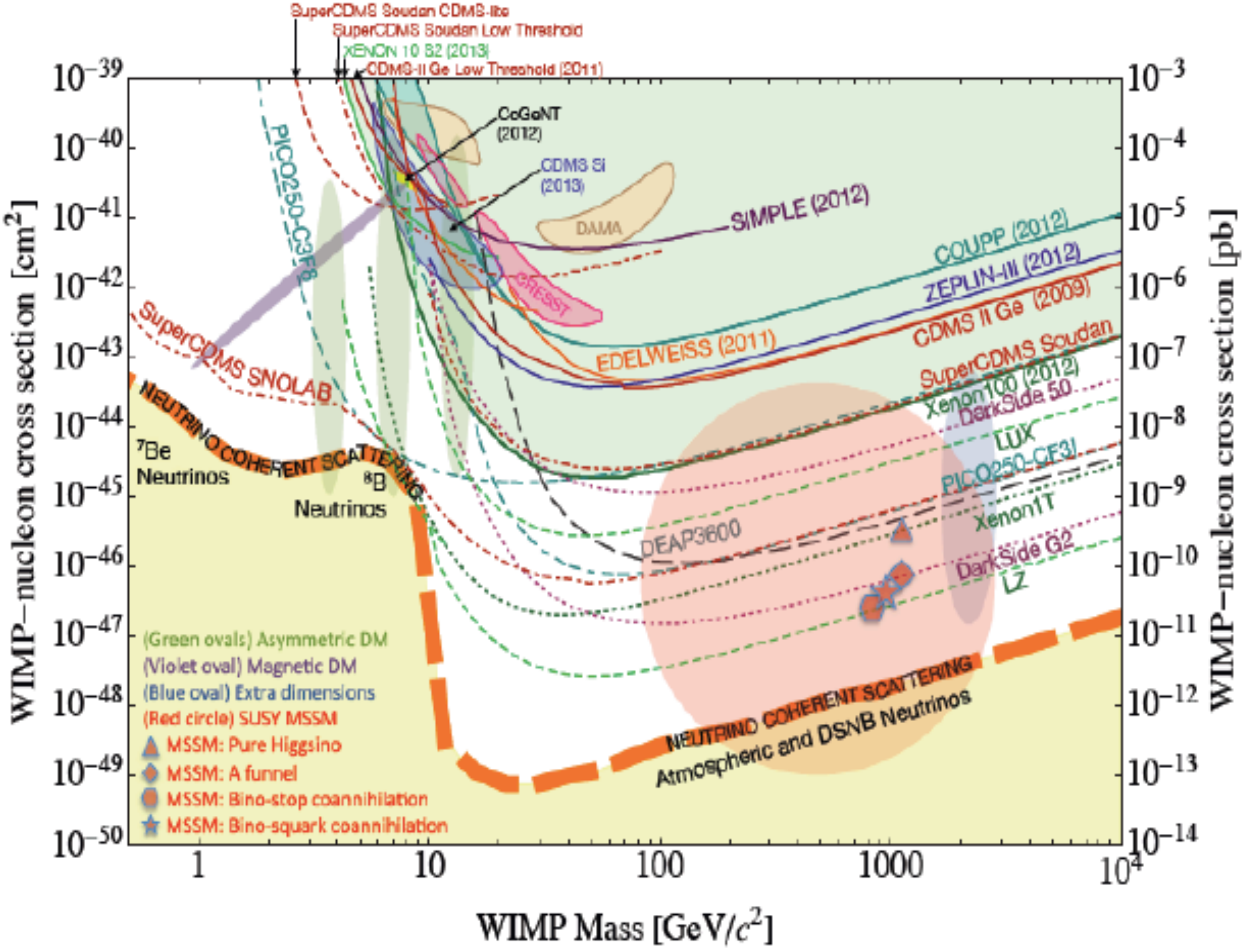
Is the DM a portal to new physics beyond the SM? (I)

- 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?

CONNECTION DM – ELW. SCALE

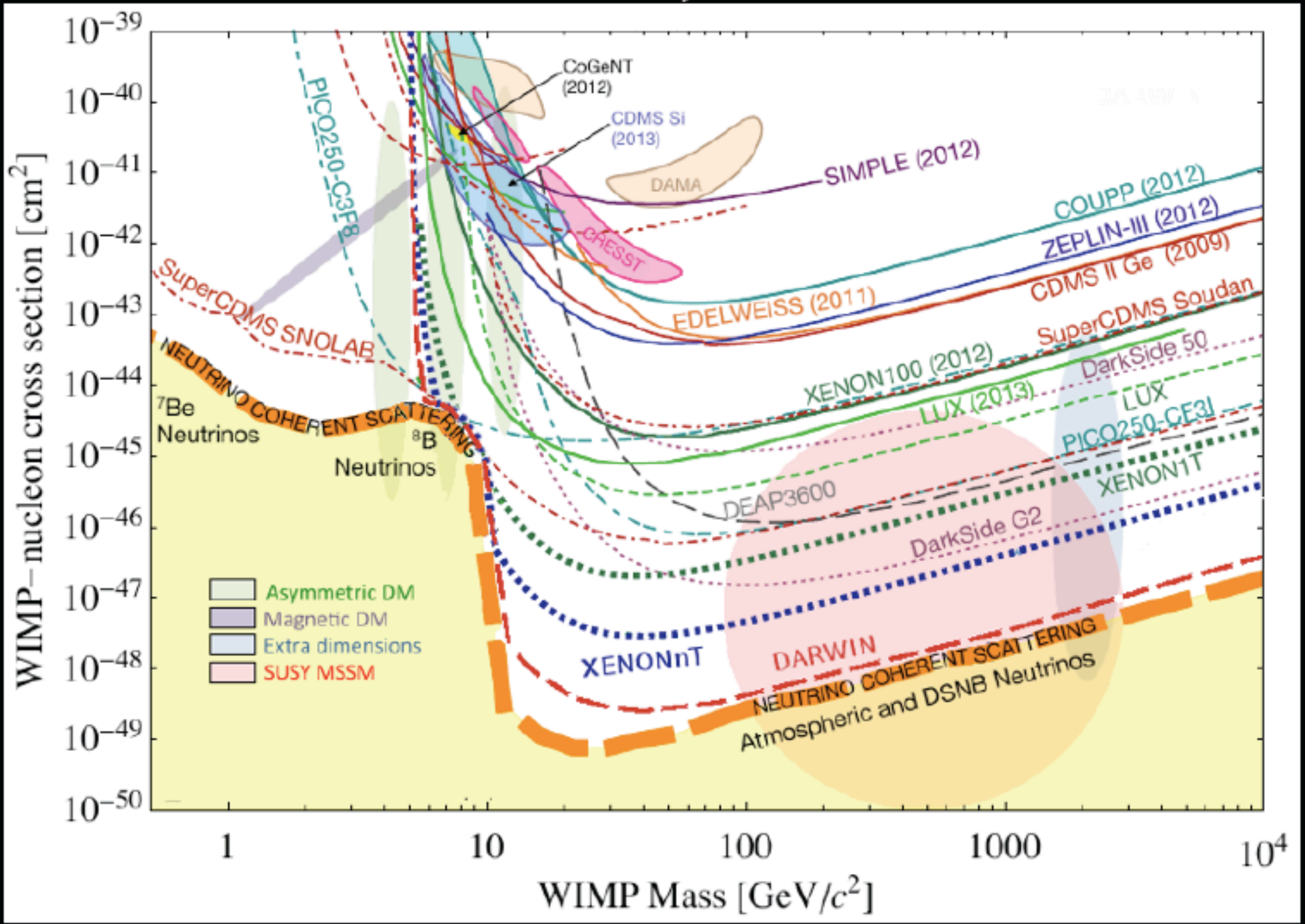
THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	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



SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
PICO250-C3F8
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
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.

2) Status / Milestones of EU Projects

Definitions:

- EU based
- non-EU based but have EU collaborators and funding
- non-EU based but have EU collaborators propose funding
- propose EU site, LOI stage

Project Name	Location	Status/Milestones
EDELWEISS	LSM	<3.3E-44 cm2 (CDMS joint), running
CRESST	LNGS	candidate signal, running
EURECA	propose DOMUS	CDR
XENON 100 / 1T	LNGS	<3.3E-45 cm2 / construction
XENON N-T	LNGS	proposed
LUX	SURF	<7.6E-46 cm2, running
LZ	SURF	proposed
DEAP	SNOLAB	construction / commissioning
DarkSide	LNGS	running
ArDM	LSC	commissioning
DARWIN	propose L/D	technical reports
DAMA/LIBRA	LNGS	candidate signal, running
ANAIS	LSC	R&D/commissioning
DM-ICE	propose LNGS	R&D/commissioning, LOI
SABRE	propose LNGS	R&D, LOI
PICO	SNOLAB	running prototype, 250L proposed
SIMPLE	LSBB	SIMPLE III done, IV proposed
CAST/IAXO	CERN	CDR, CERN LOI, TDR invited
MiMAC	LSM	running prototype
DMTPC	WIPP	running prototype
DRIFT	Boulby	running prototype

Directional Detection

A 10 Year Decision Tree

arXiv:1310.8327

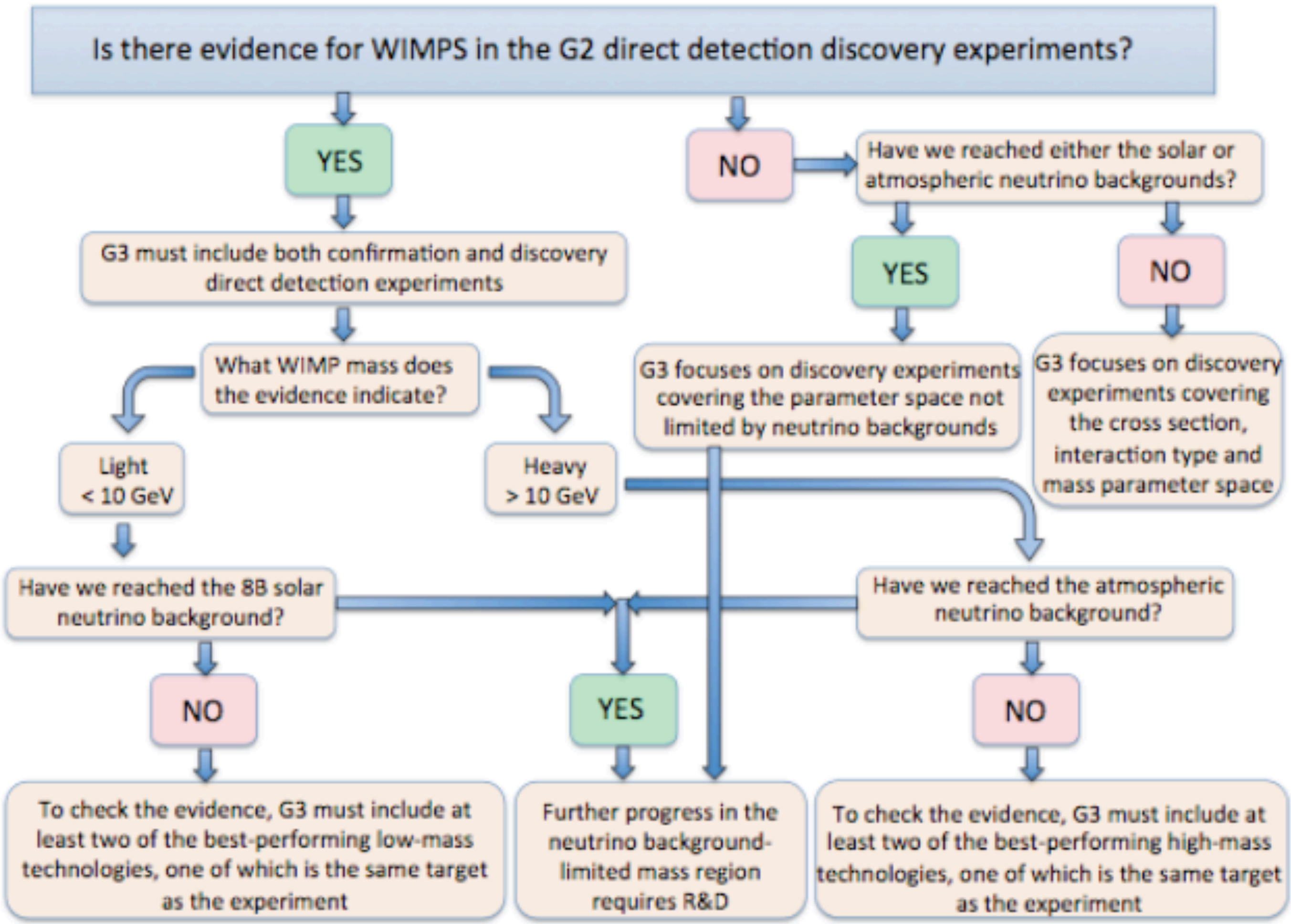
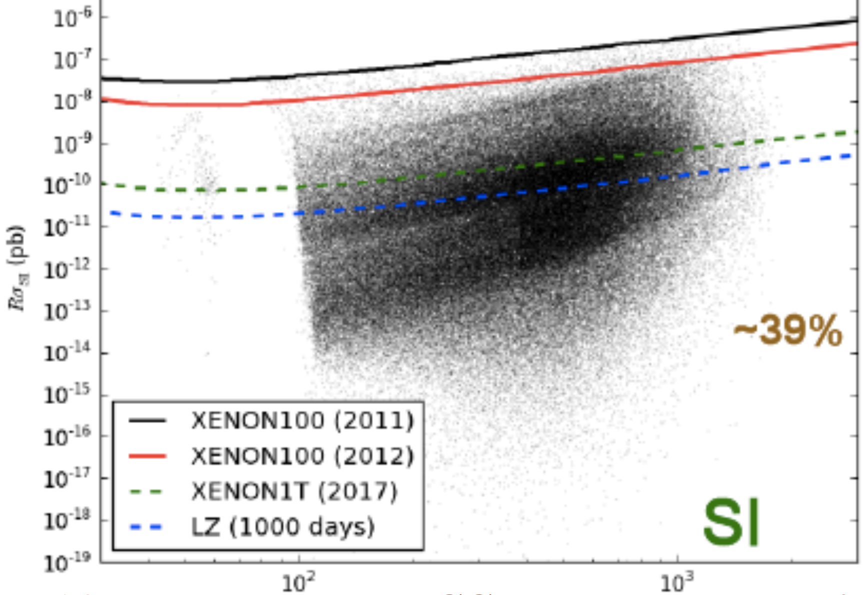
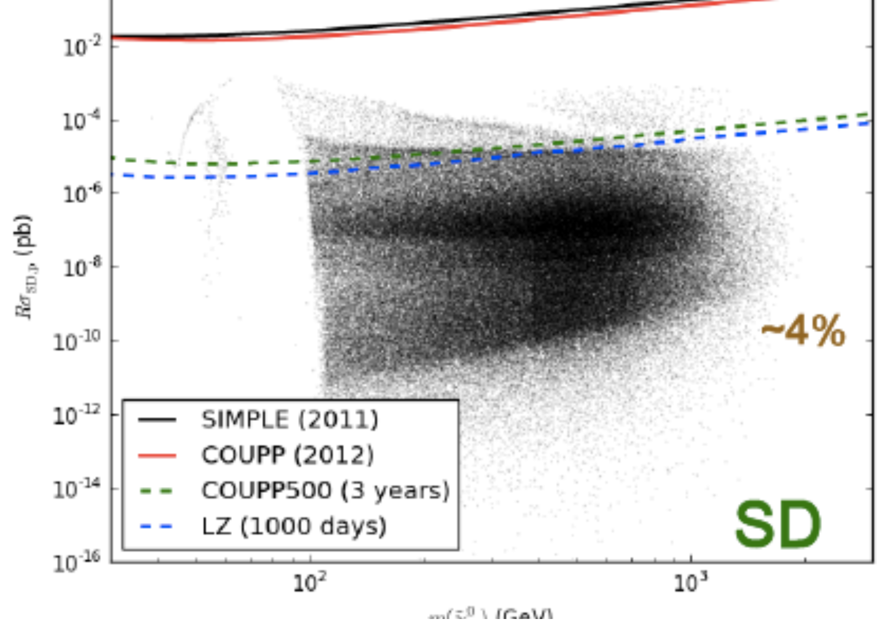


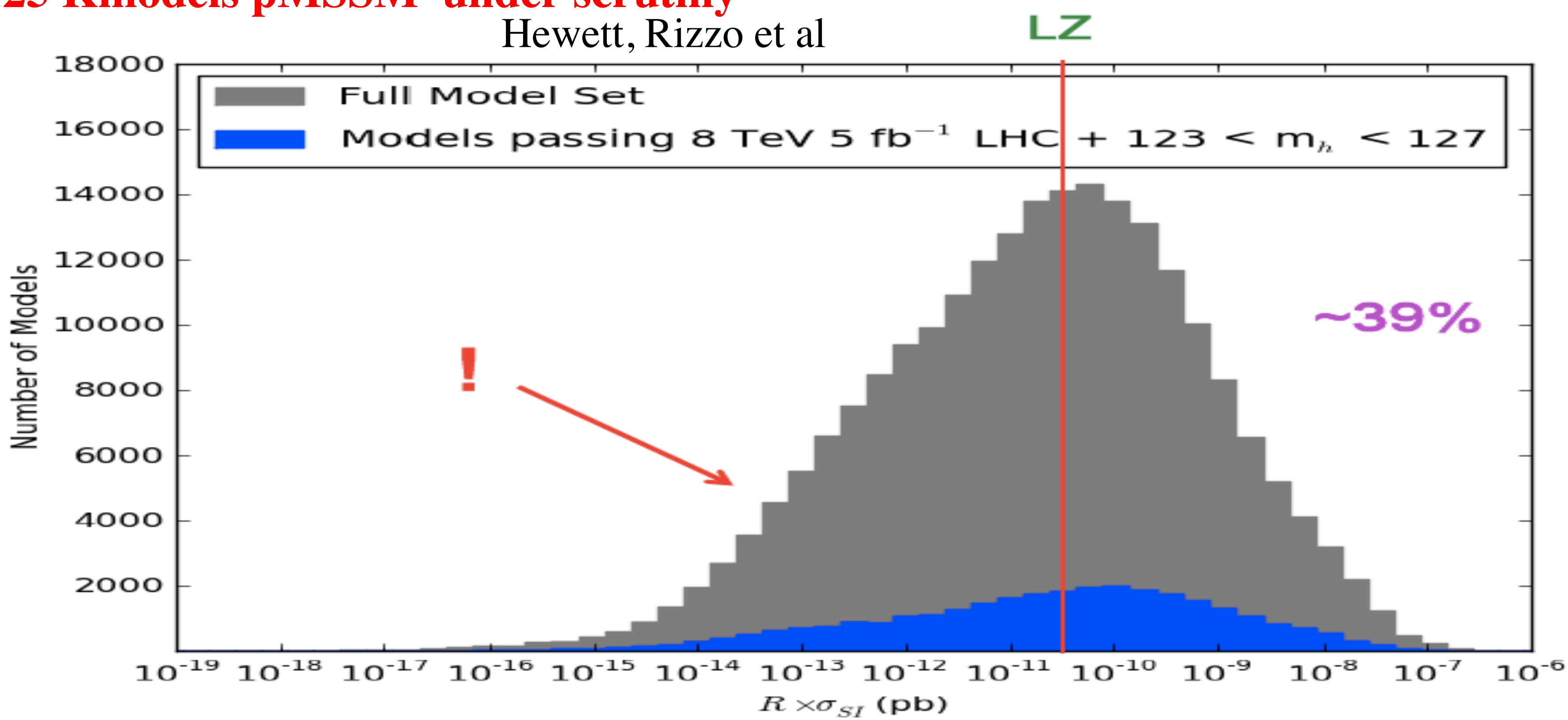
Figure 28. *Decision tree for direct detection experiments from G2 to G3.*



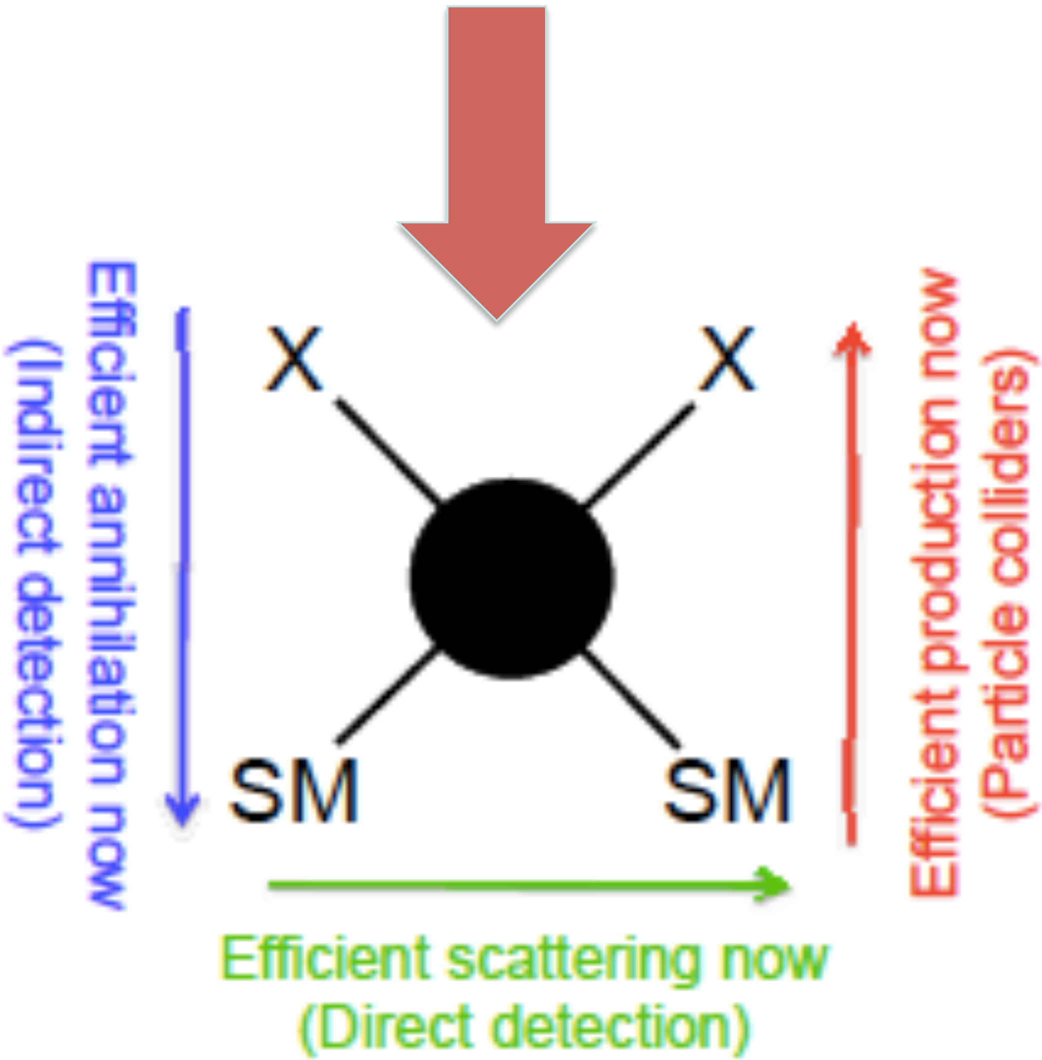


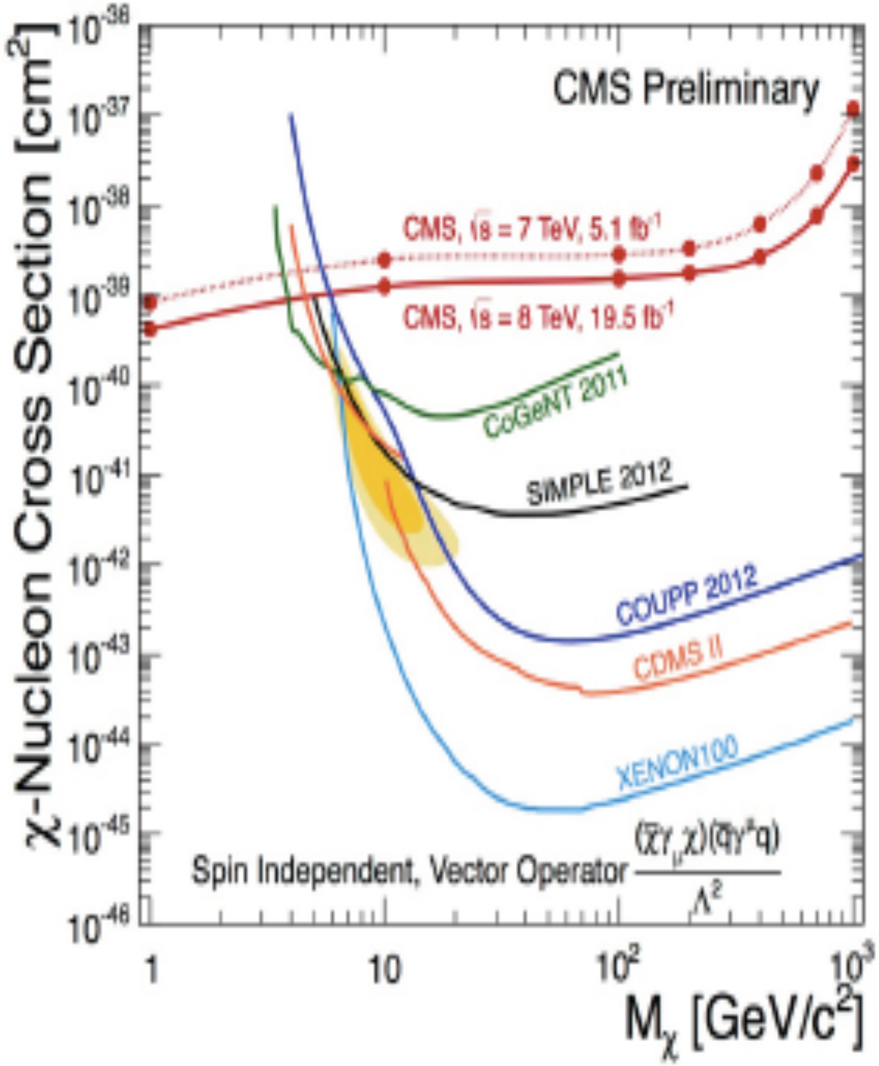
125 Kmodels pMSSM under scrutiny

Hewett, Rizzo et al

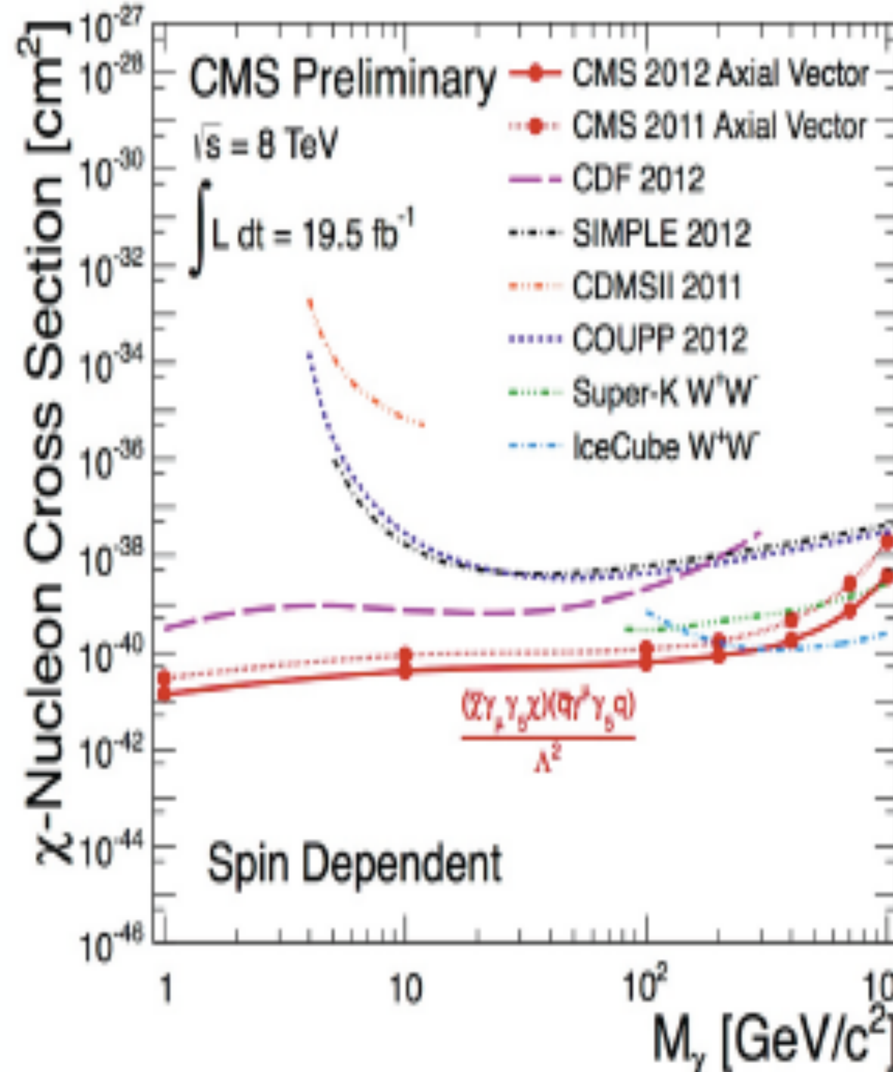


DM COMPLEMENTARITY: efficient annihilation in the early Universe implies today



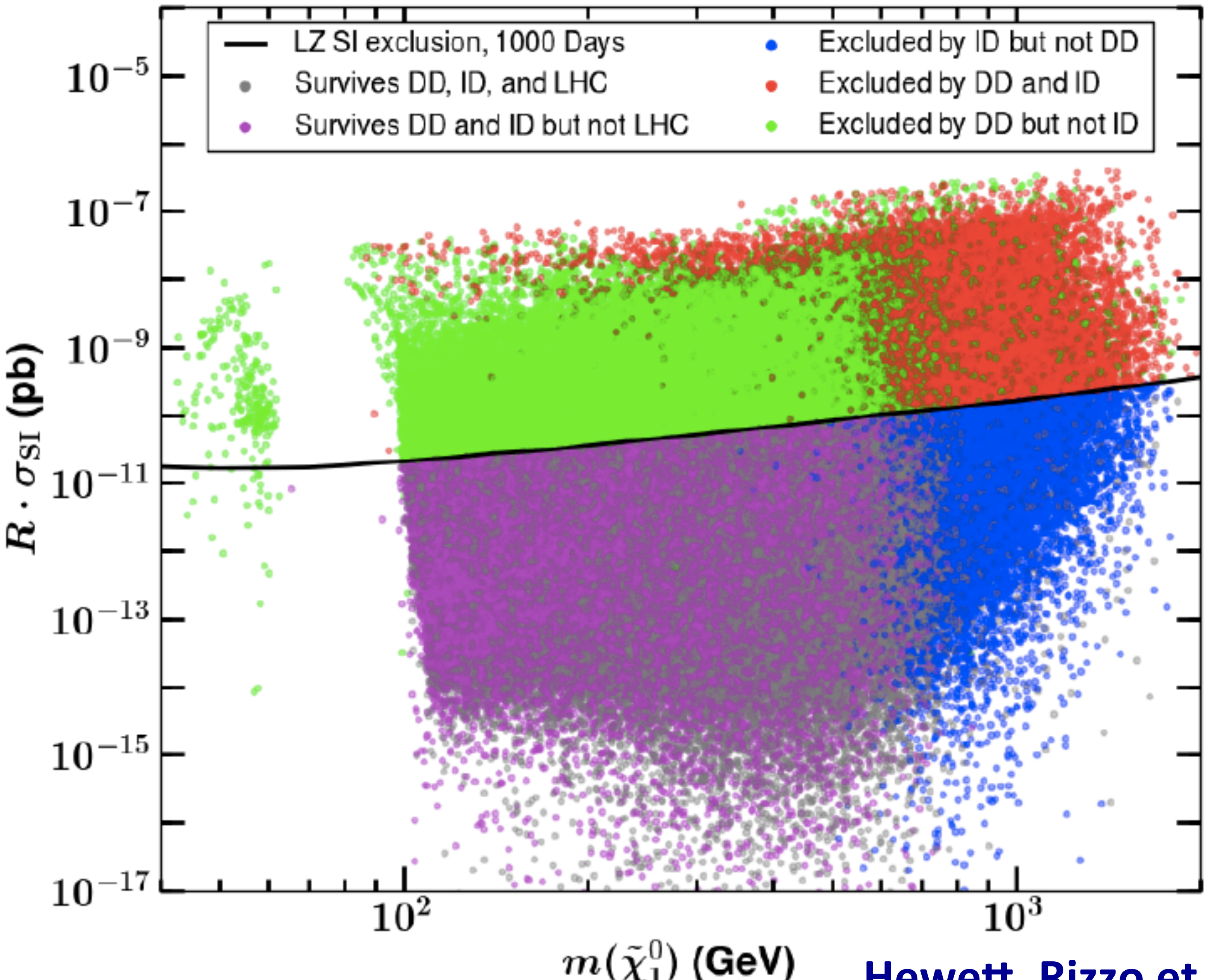


CMS Preliminary
CMS, √s = 7 TeV, 5.1 fb⁻¹
CMS, √s = 8 TeV, 19.5 fb⁻¹
CoGeNT 2011
SIMPLE 2012
COUPP 2012
CDMS II
XENON100
Spin Independent, Vector Operator $\frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$
χ-Nucleon Cross Section [cm²]
M_χ [GeV/c²]



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⁻
$\frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$
Spin Dependent
χ-Nucleon Cross Section [cm²]
M_χ [GeV/c²]

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



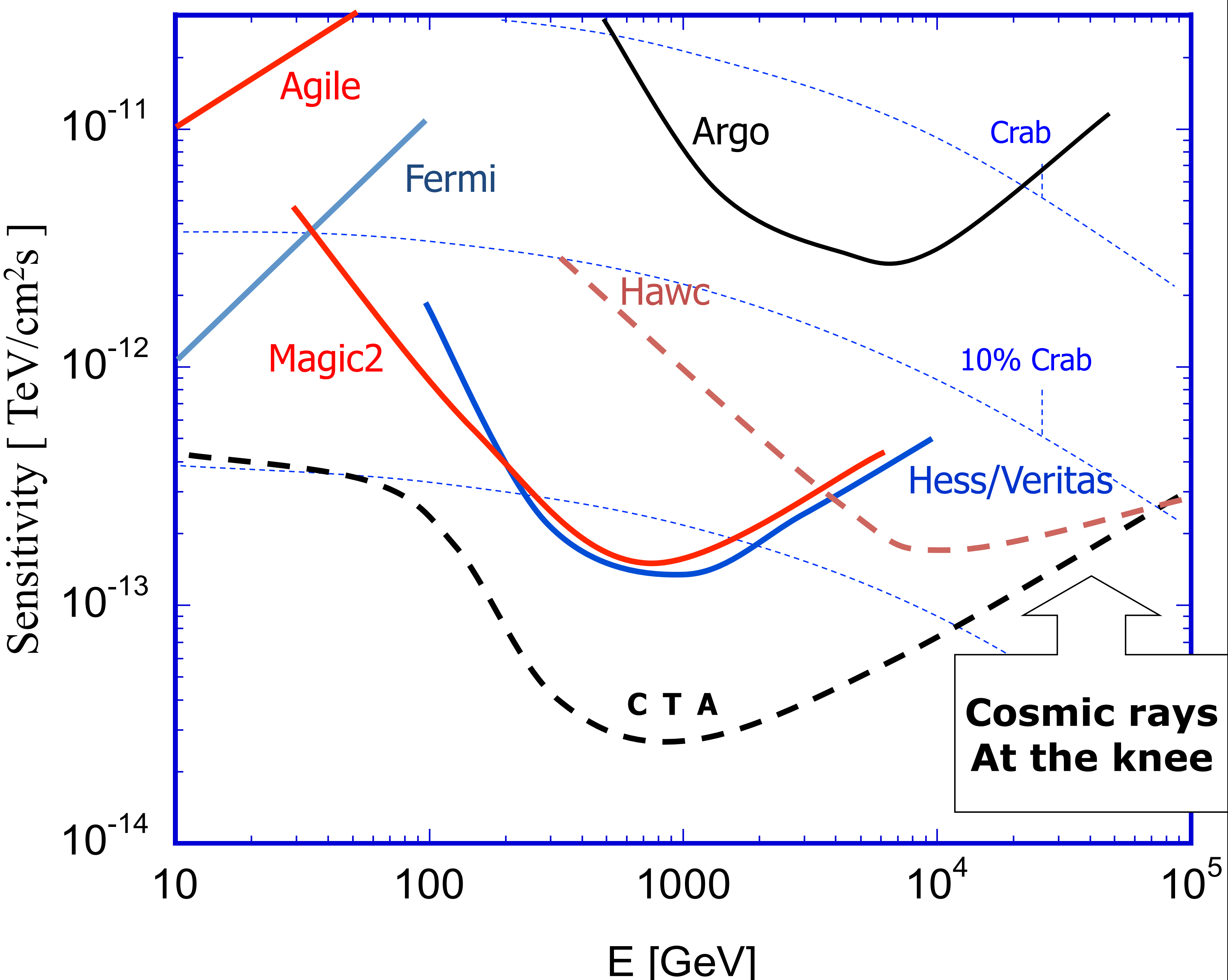
11.4%
29.2%
7.2%
27.5%
24.7%

Hewett, Rizzo et al. 2013

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

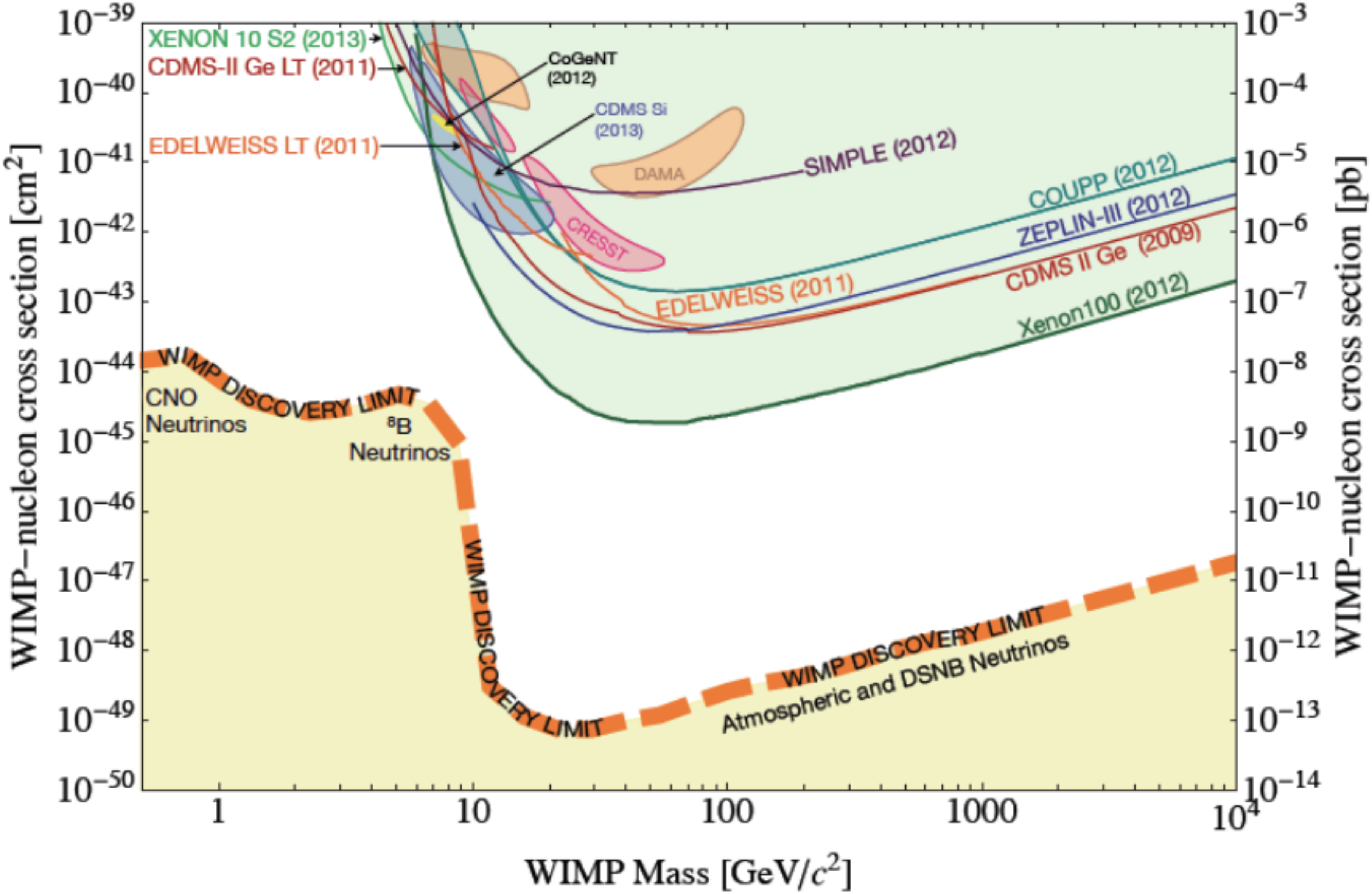
- **If the naturalness issue is indeed a relevant issue, the fact that we discovered a light higgs means that there MUST EXIST some mechanism stabilizing its mass and this mechanism NECESSARILY ENTAILS THE PRESENCE OF SOME FORM OF NEW PHYSICS AT THE ELECTROWEAK SCALE**
- Time to get ready (joint exp.-theor.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

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

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

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

LR Models?

MAJORON MODELS

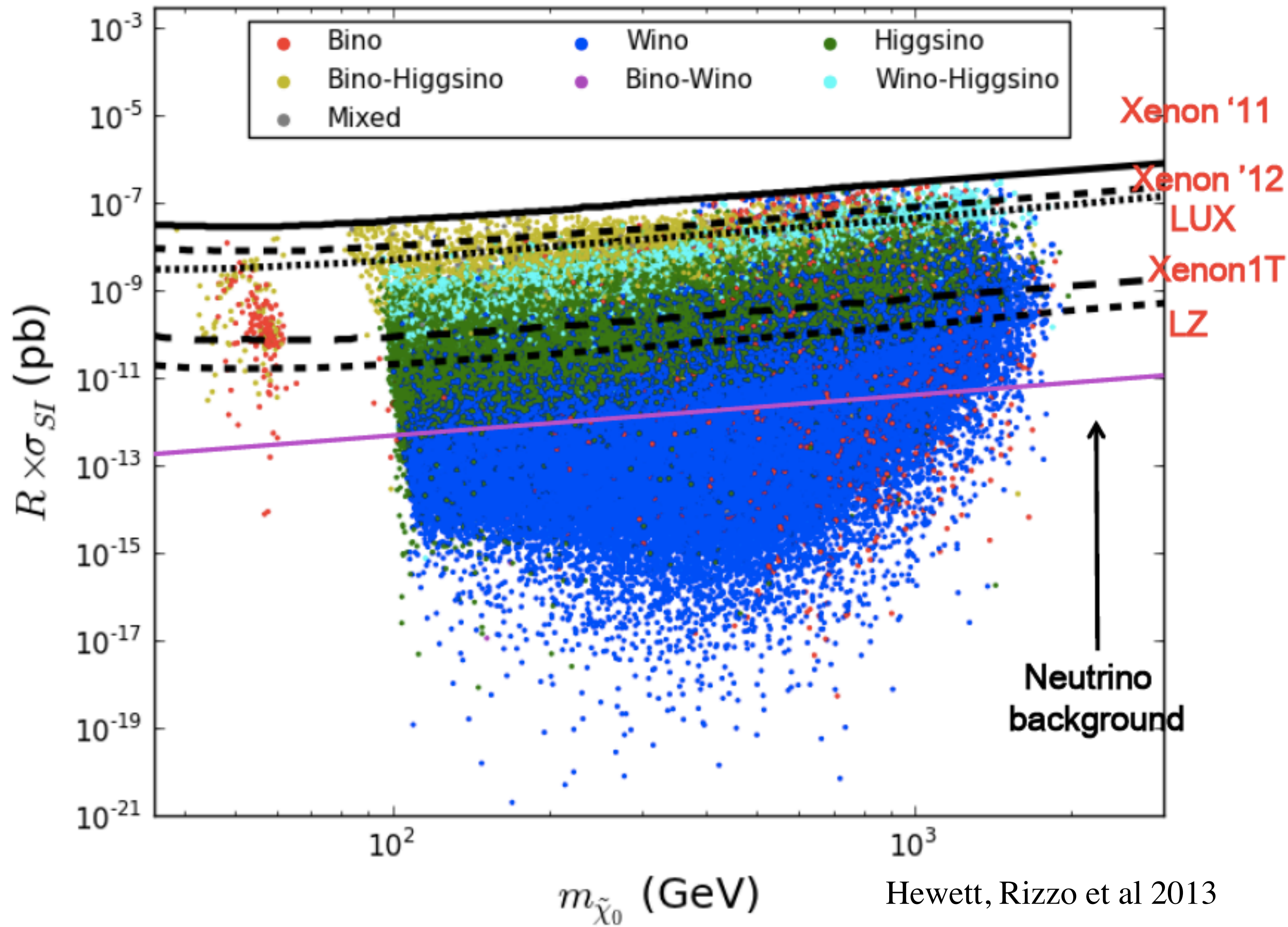
Gelmini, Roncadelli

Δ ENLARGEMENT OF THE HIGGS SCALAR SECTOR

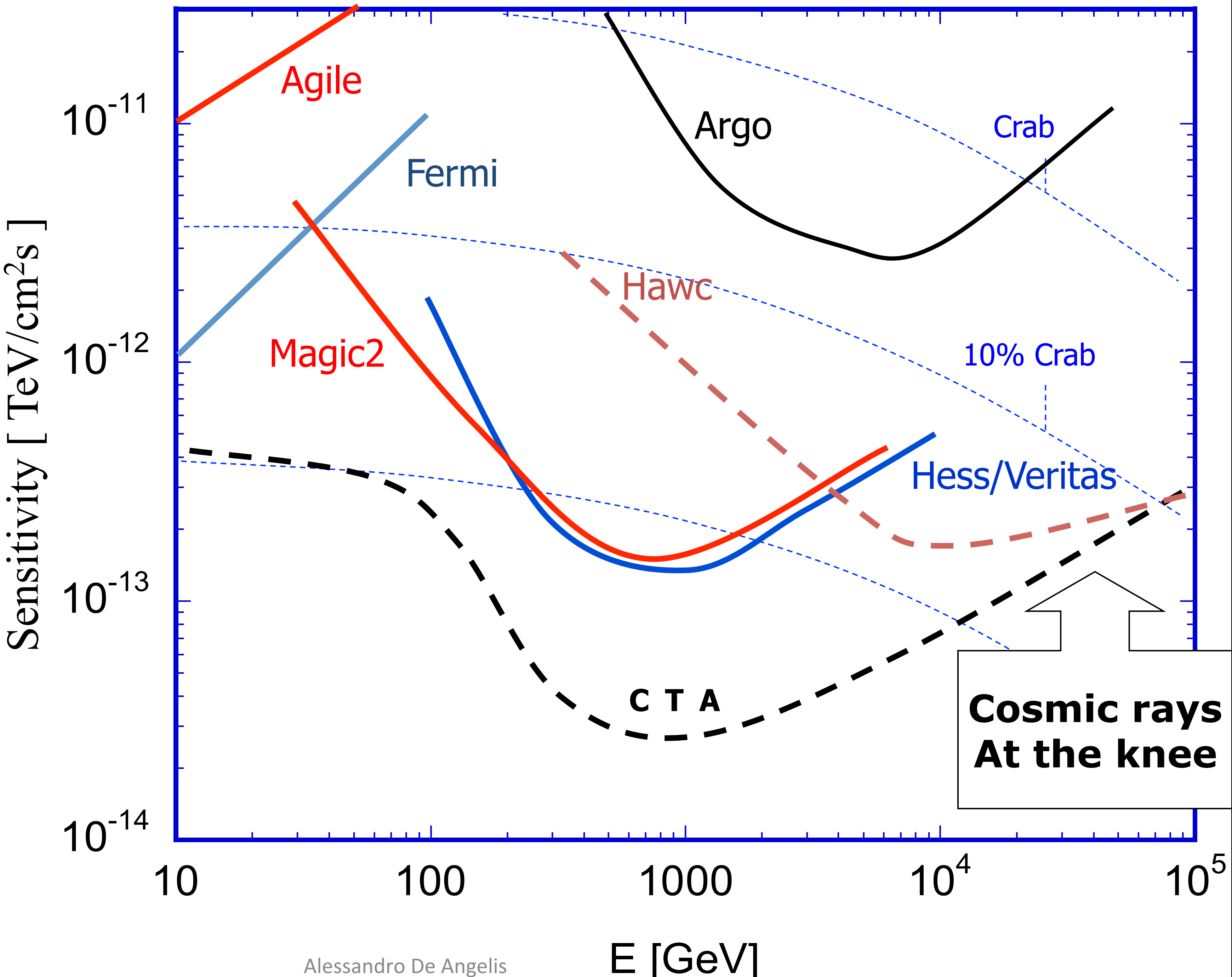
$h\, \upsilon_L \upsilon_L\, \Delta$

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

N.B.: EXCLUDED BY LEP!

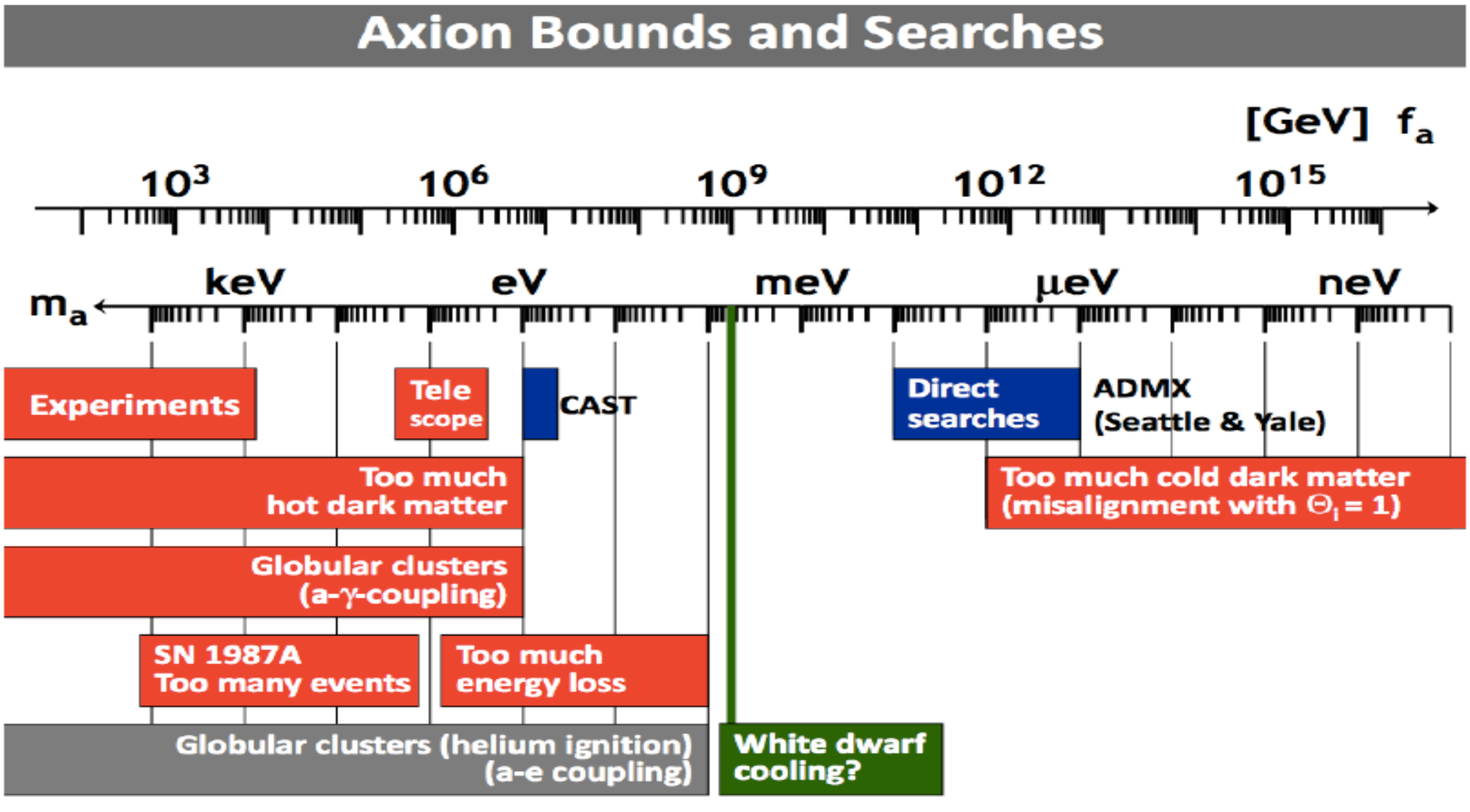


Hewett, Rizzo et al 2013

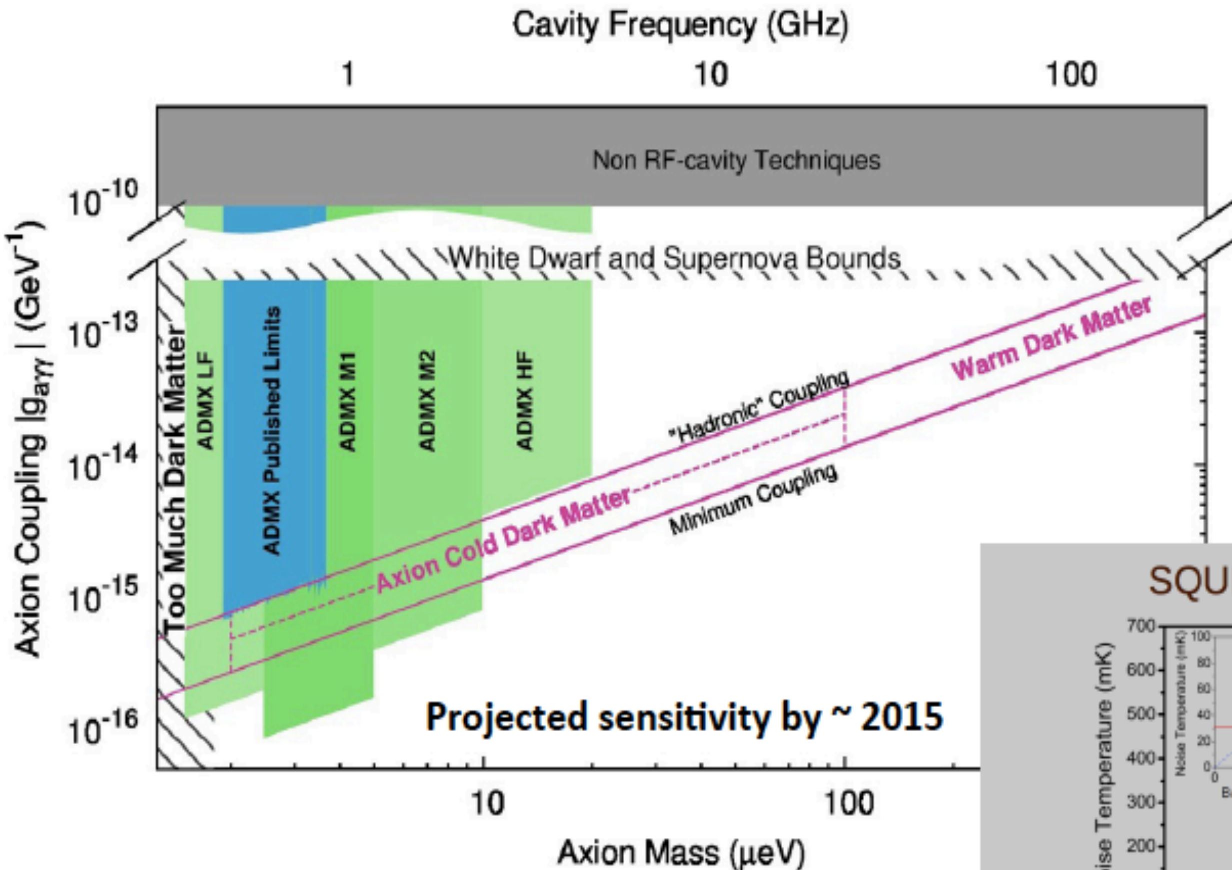


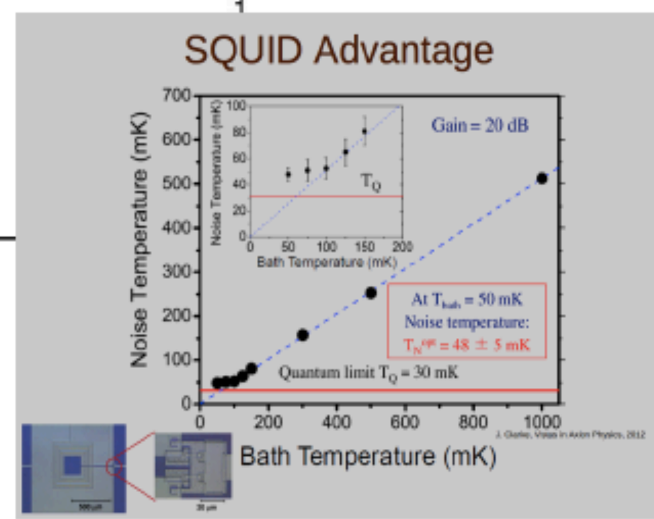
Alessandro De Angelis

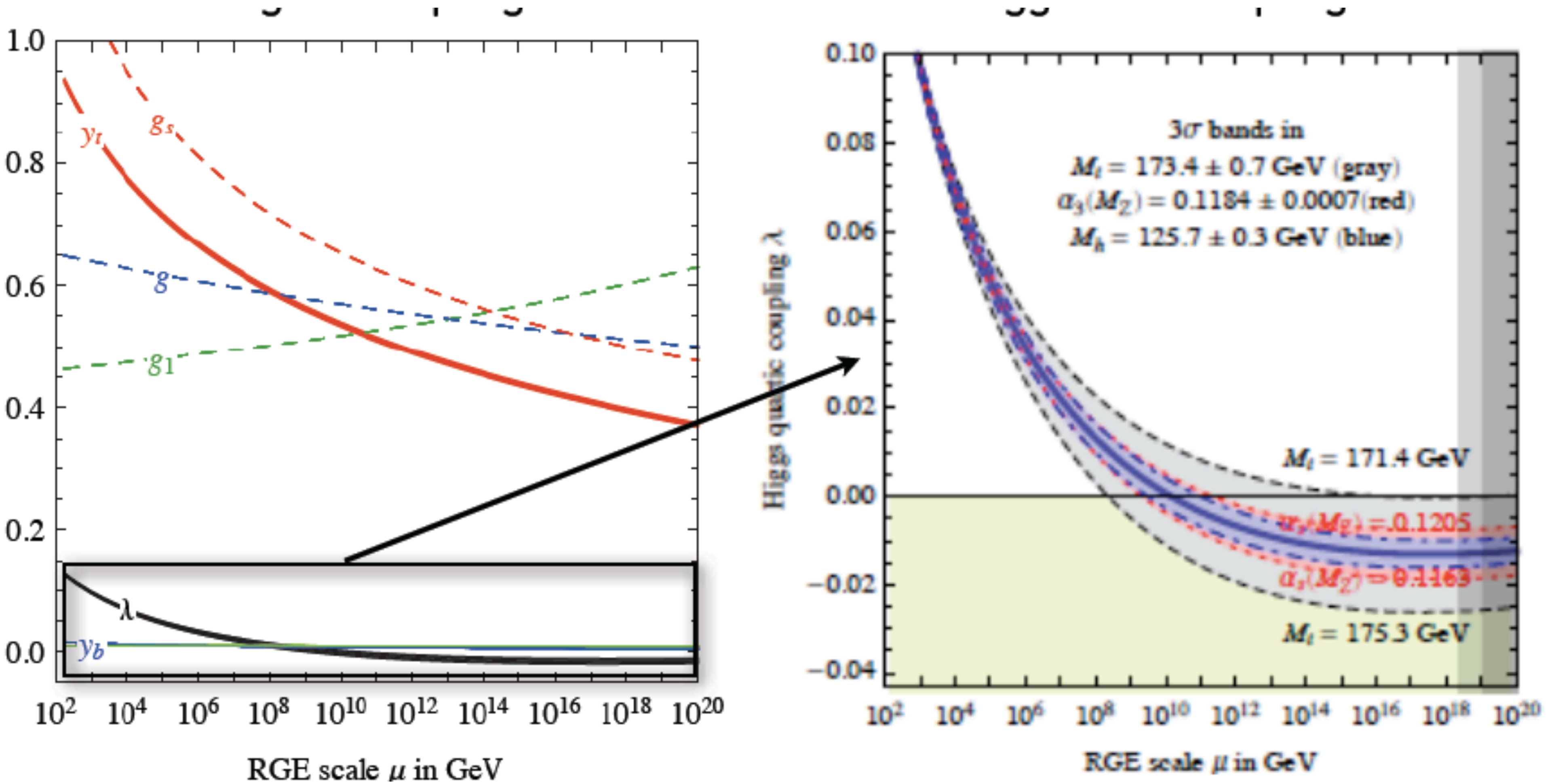
Keep in mind: we don't know at all what DM is made of ! Alternatives to WIMPs – for instance, AXIONS



ADMX achieved and projected sensitivity







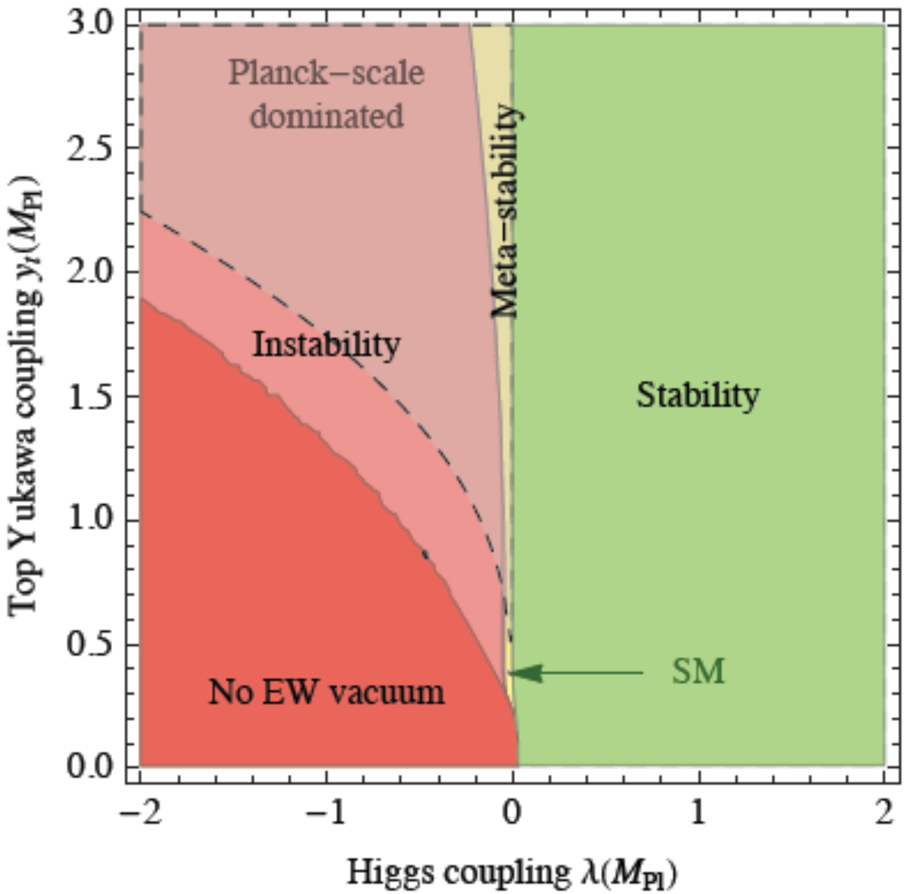
Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia 2013

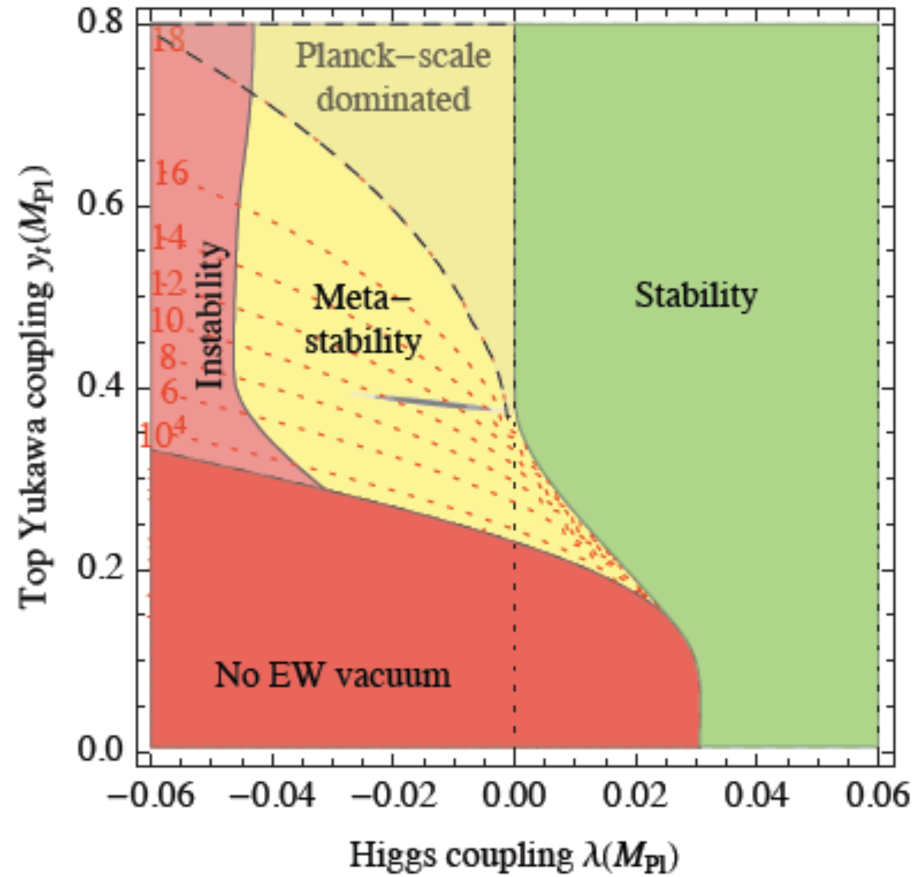
For previous works: Krive, Linde '76; Krasnikov '78; Maiani, Parisi, Petronzio '78; Cabibbo et al '79; Lindner '86; Altarelli, Isisdori '96; Ellis et al 2009; Shaposhnikov et al '12; Elias-Miro' 'et a "12; …..

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





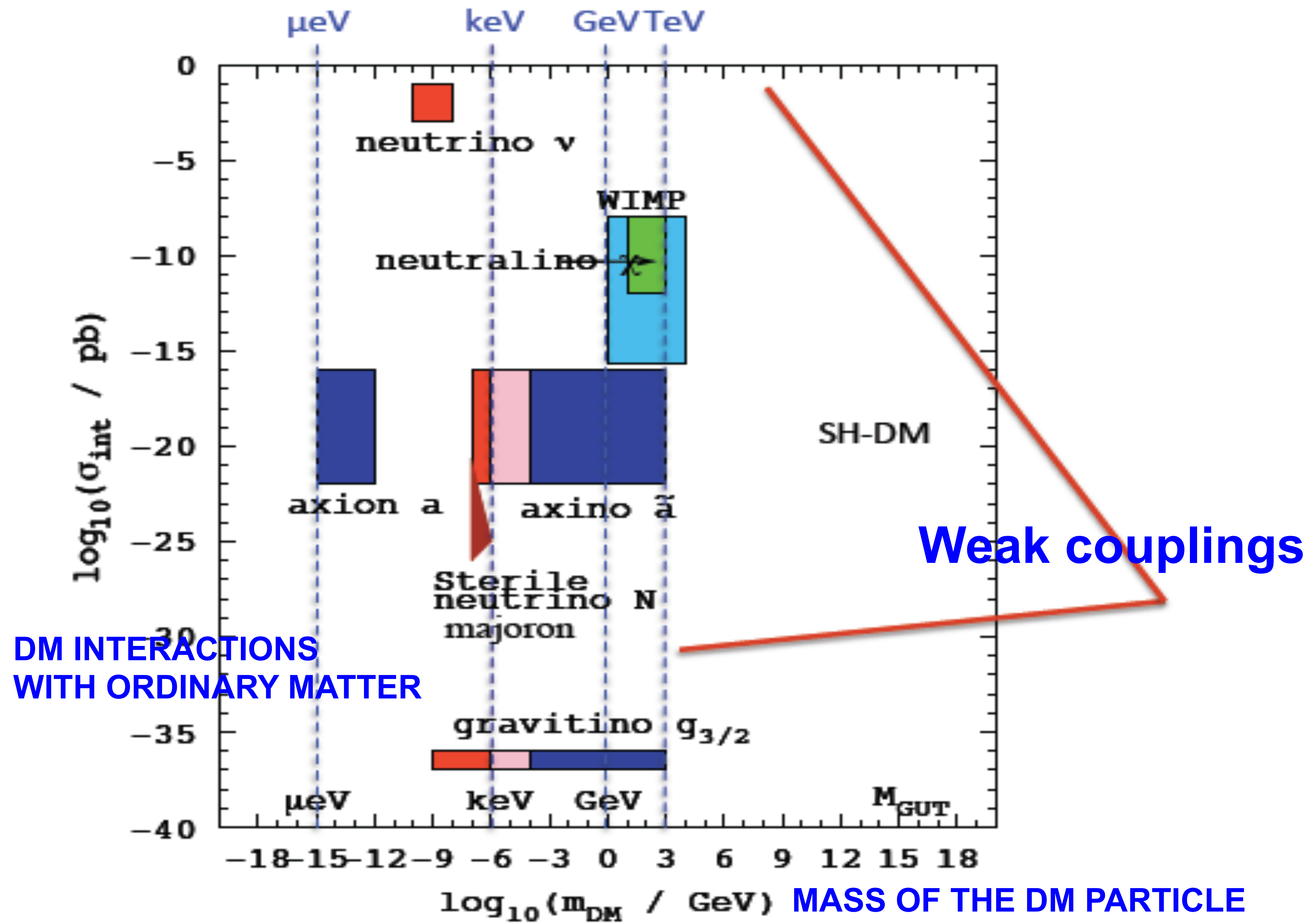
The Universe looks very close to **CRITICALITY**

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
0
−5
−10
−15
−20
−25
−30
−35
−40
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}
−18
−15
−12
−9
−6
−3
0
3
6
9
12
15
18
$\log_{10}(\sigma_{int}$ / pb)
$\log_{10}(m_{DM}$ / GeV)
MASS OF THE DM PARTICLE

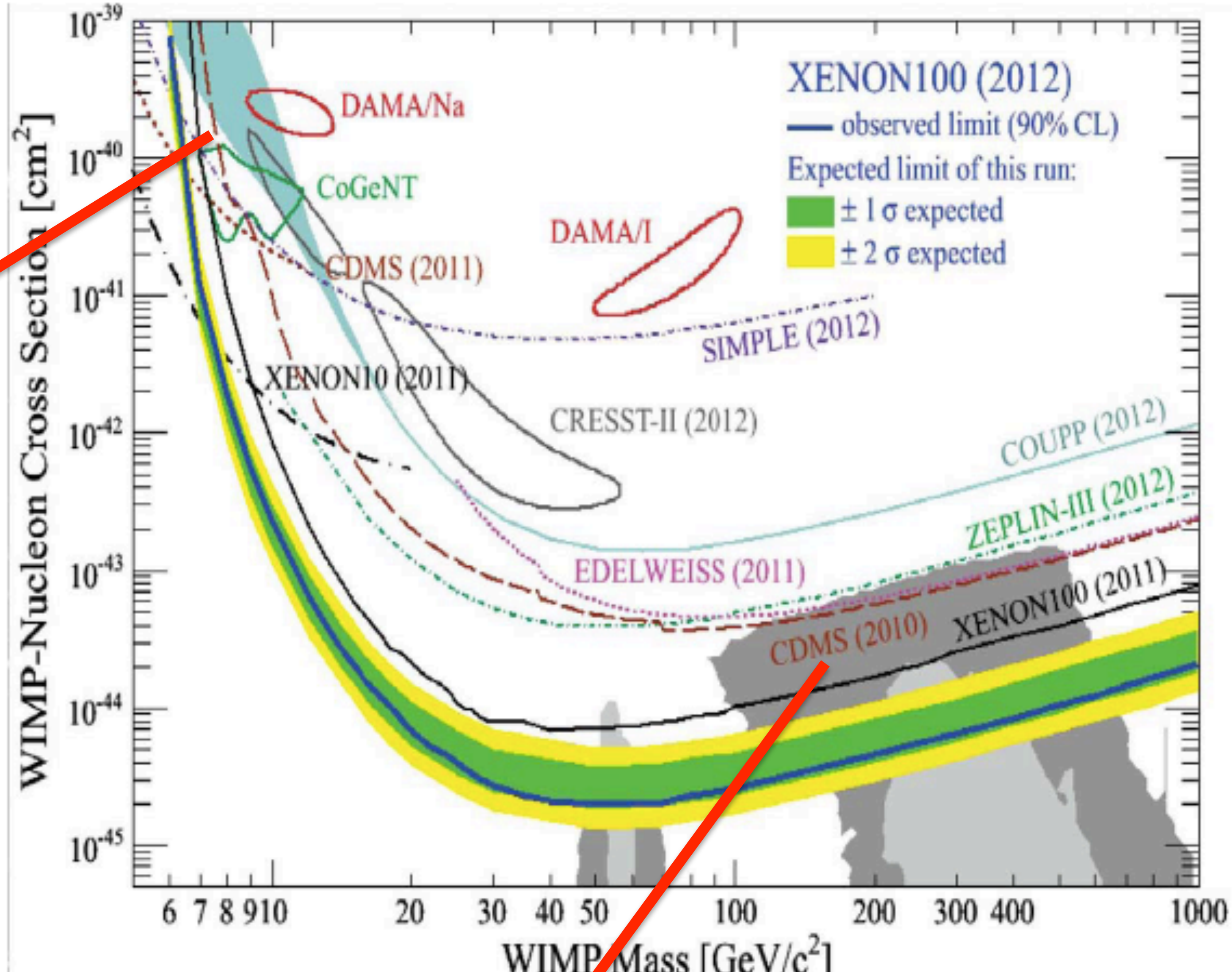
THE EDM CHALLENGE

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

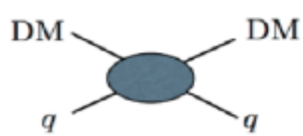
$$|d_{\rm n}| < 2.9 \times 10^{-26} e \text{ cm } (90\%\text{C.L.}),$$
$$|d_{\rm Tl}| < 9.0 \times 10^{-25} e \text{ cm } (90\%\text{C.L.}),$$
$$|d_{\rm Hg}| < 3.1 \times 10^{-29} e \text{ cm } (95\%\text{C.L.}).$$

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

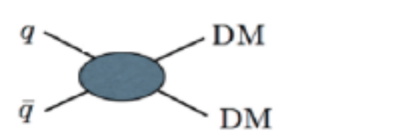
Kolb SUSY2012



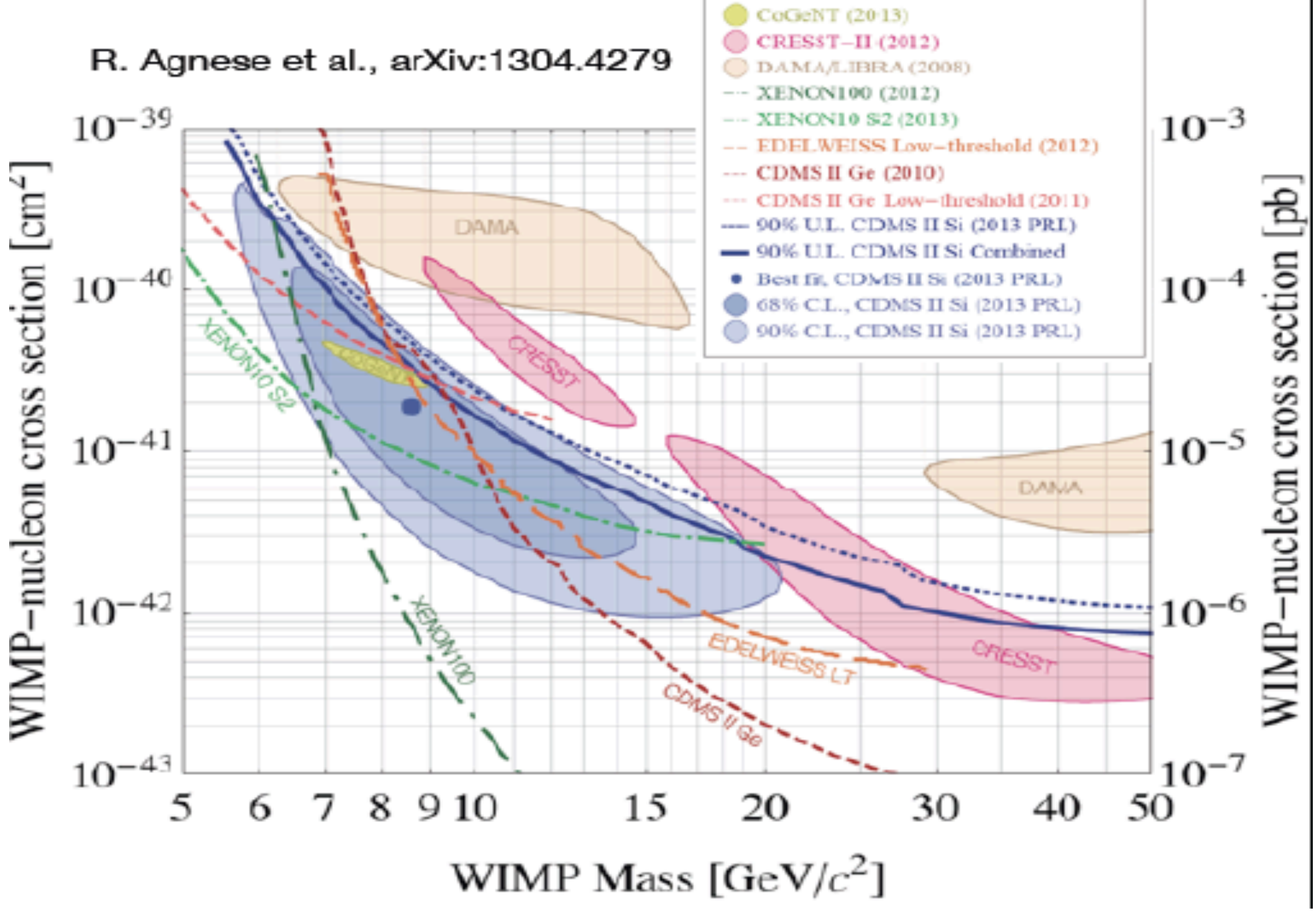
Relevant to intensify the efforts here: ex. **asymmetric DM** with **DM particles of mass~ baryon mass given that ρ_{DM} not much different from ρ_B**



Direct Detection (t-channel)

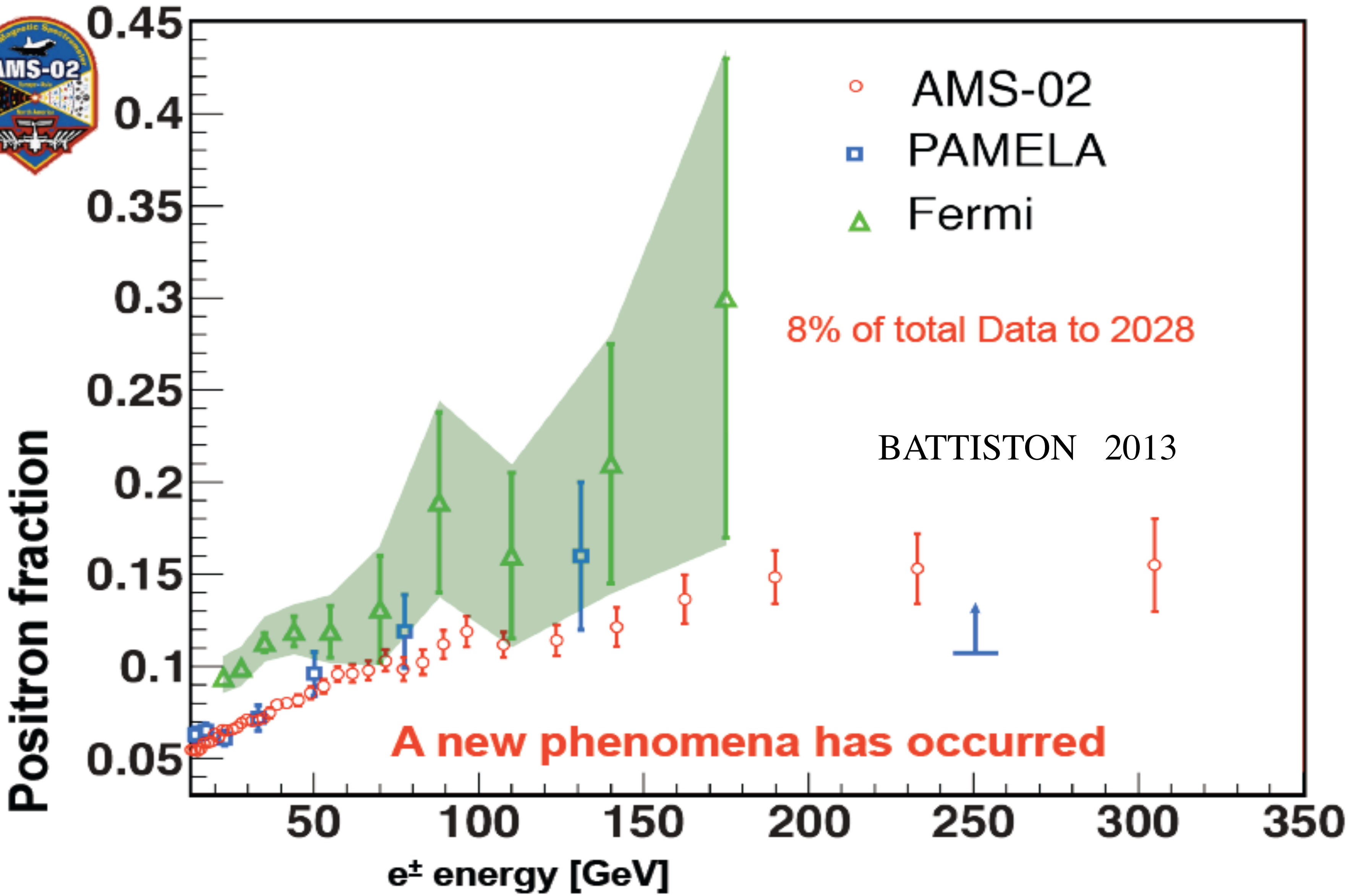


Collider Searches (s-channel)



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