

Workshop strategia futura CSN1

La Biodola, 22-24 maggio 2014

Fisica delle Interazioni Fondamentali: Prospettive

Antonio Masiero

INFN and Univ. of Padova

2012: the conquest of a new energy scale in physics

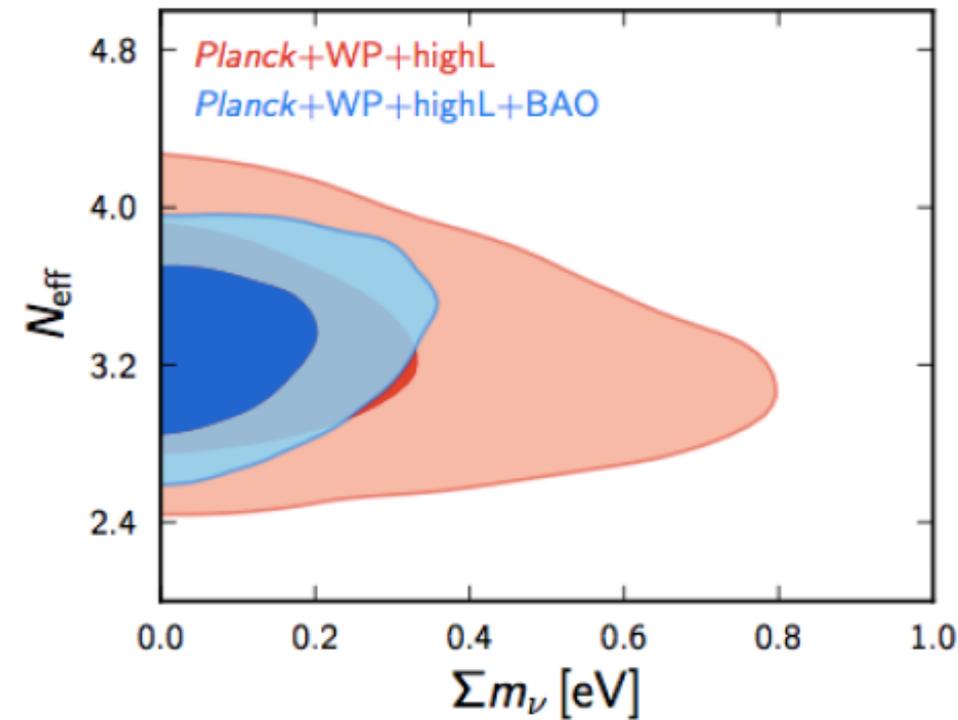
- ~1900 **ATOMIC SCALE** 10^{-8} cm. $1/(\alpha m_e)$
- ~1970 **STRONG SCALE** 10^{-13} cm. $M e^{-2\pi/\alpha_S b}$
- ~2010 **WEAK SCALE** 10^{-17} cm. TeV^{-1}

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?



$$N_{\text{eff}} = 3.36 \pm 0.34$$

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

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

Recent **BICEP2** results: from the measurement of the B-mode polarization of the CMB photons \rightarrow initial **inflationary epoch** at energies $\sim V^{1/4} = 1.94 \times 10^{16} \text{ GeV} (r/0.12)^{1/4}$
 r = ratio of the CMB tensorial/scalar components – from BICEP2 $r \sim 0.2$, $r \neq 0$ at $\sim 6 \sigma$

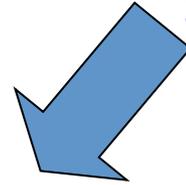
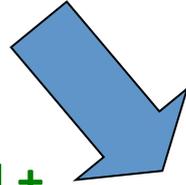
INFLATON at $\sim 10^{16} \text{ GeV}$, not standard Higgs inflation (see, however, Bezrukov and Shaposhnikov)

MICRO

MACRO

GWS STANDARD MODEL

HOT BIG BANG
STANDARD MODEL



UNIVERSE EXPANSION +
WEAK INTERACTIONS **NUCLEOSYNTHESIS**

NUMBER OF BARYONS and OF
NEUTRINO SPECIES →

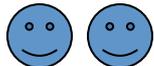
1 sec. after BB

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

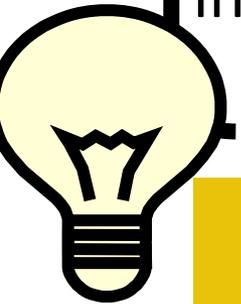
BEYOND THE STANDARD

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

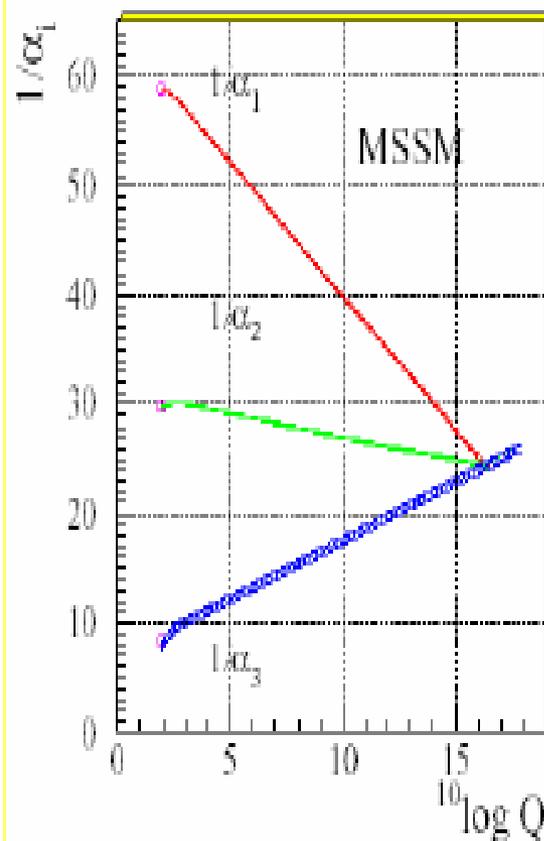
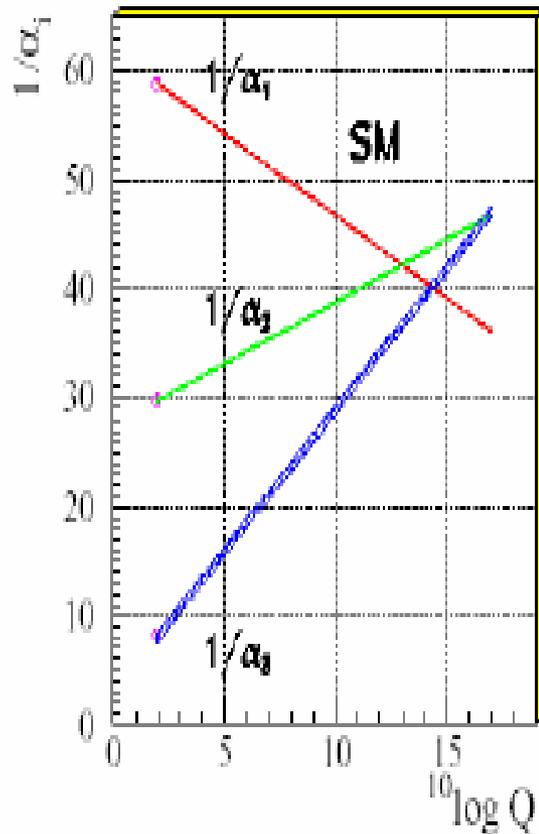


The Energy Scale from the “Theoretical” New Physics

★ ★ ★ 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

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

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

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

THE COMPREHENSION OF THE ELECTROWEAK SCALE

$$V = \mu^2 |H|^2 + \lambda |H|^4 \quad \mu \sim 10^2 \text{ GeV}$$

• $M = O(10^{16} \text{ GeV})$

	SU(3)	SU(2)	U(1)		SO(10)
L	1	2	-1/2	➔	16
e	1	1	1		
Q	3	2	1/6		
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

$$m_{NP} \ll M$$

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

- **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]

- $V = \mu^2 |H|^2 + \lambda |H|^4$ what is the value of the energy of its vacuum, i.e. the SM **vacuum energy**?
→ $V_0 = \mu^2 \langle H \rangle^2 + \lambda \langle H \rangle^4 \sim (100 \text{ GeV})^2$
- observed vacuum energy, i.e. dark energy
accelerating the expansion of the Universe $O(10^{-3} \text{ eV})$
- 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 $\theta \rightarrow$ the bound on the neutron EDM $\rightarrow \theta < 10^{-10}$
- **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]

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

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 \rightarrow for a mediator of mass $\sim 10^{16}$ GeV we expect a proton lifetime in the ballpark of $\sim 10^{34}$ years \rightarrow exp. accessible
- NEUTRON-ANTINEUTRON OSCILLATION if the unified symmetry (ex. $SO(10)$) breaks down to an intermediate symmetry subsequently spontaneously broken at $\sim 10^6$ GeV with the breaking of Baryon number of two units (ex. $SO(10) \rightarrow SU(4)_{PS} \times SU(2)_L \times SU(2)_R \rightarrow SU(3) \times SU(2)_L \times U(1)_Y$) \rightarrow 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

$$\Delta \gtrsim \left(\frac{m_{\text{NP}}}{0.5 \text{ TeV}} \right)^2 \quad m_{\text{NP}} > 1.5 \text{ TeV} \quad \leftrightarrow \quad \Delta > 10$$
$$\Delta \gtrsim \left(\frac{m_{\text{NP}}}{0.5 \text{ TeV}} \right)^2 \quad m_{\text{NP}} > 5 \text{ TeV} \quad \leftrightarrow \quad \Delta > 100$$

$$m_{\text{NP}} \times 2 \rightarrow \Delta \times 4$$

- The bound on Δ is model-dependent:

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

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

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

$$M \gg m_h$$

- however: it could be that there is nothing at scales

$$\sim M \gg m_h \quad \text{FINITE NATURALNESS}$$

- 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)

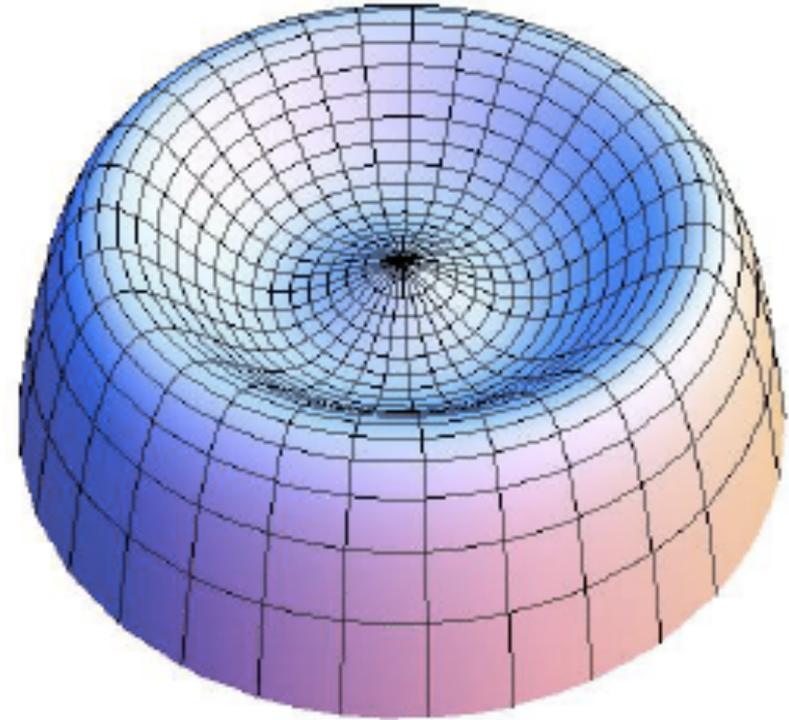
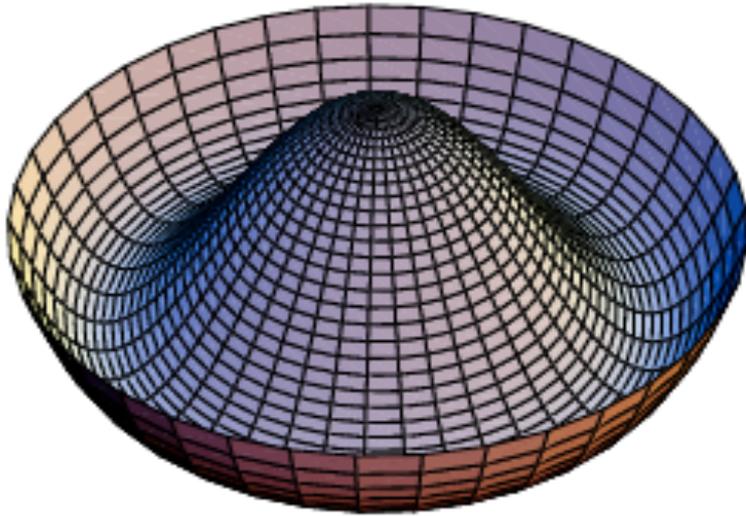
On the peculiar value of M_H

- 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 $\sim 50\%$ 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 violation; 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 LEFT- 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.

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

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

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

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 known 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 $O(1) f_\nu$

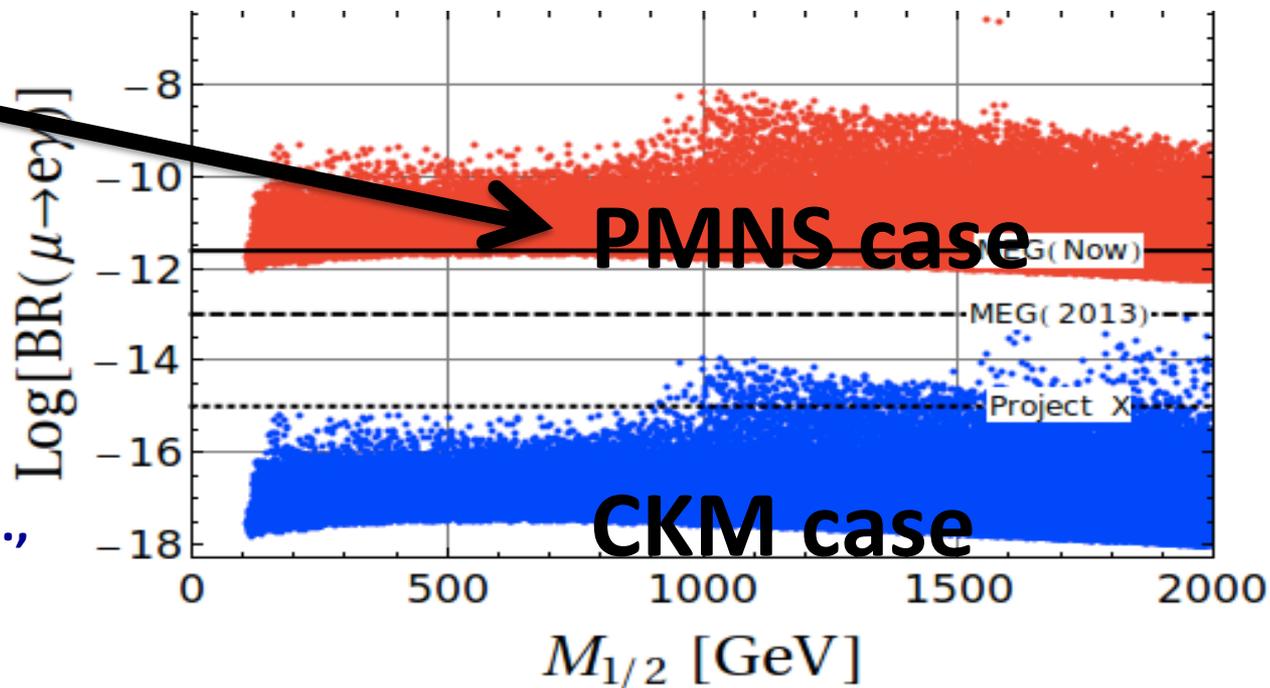
U  two “extreme” cases:

a) U with “small” entries  $U = CKM$;

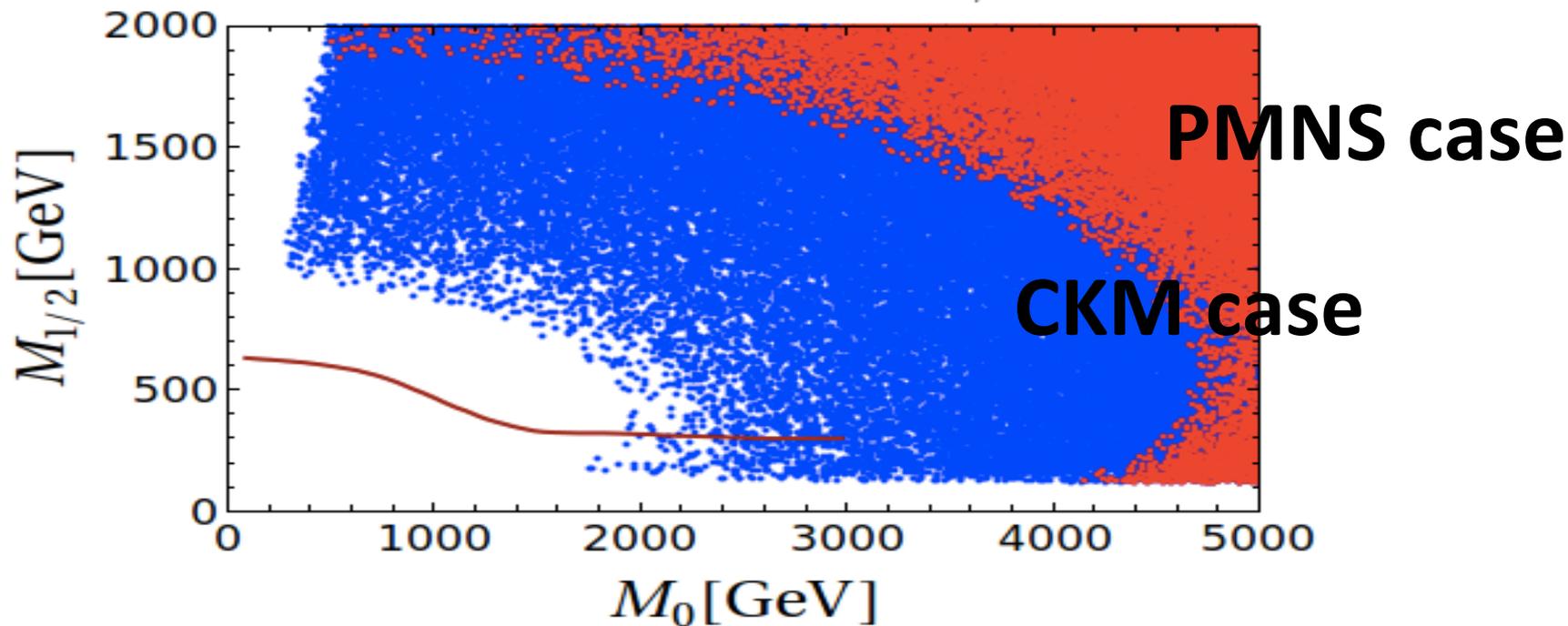
b) U with “large” entries with the exception of the 13 entry

 $U = PMNS$ 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



CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE : STABLE ELW. SCALE WIMPs

1) ENLARGEMENT OF THE SM

SUSY
(x^μ, θ)

EXTRA DIM.
(x^μ, j^i)

LITTLE HIGGS.
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}

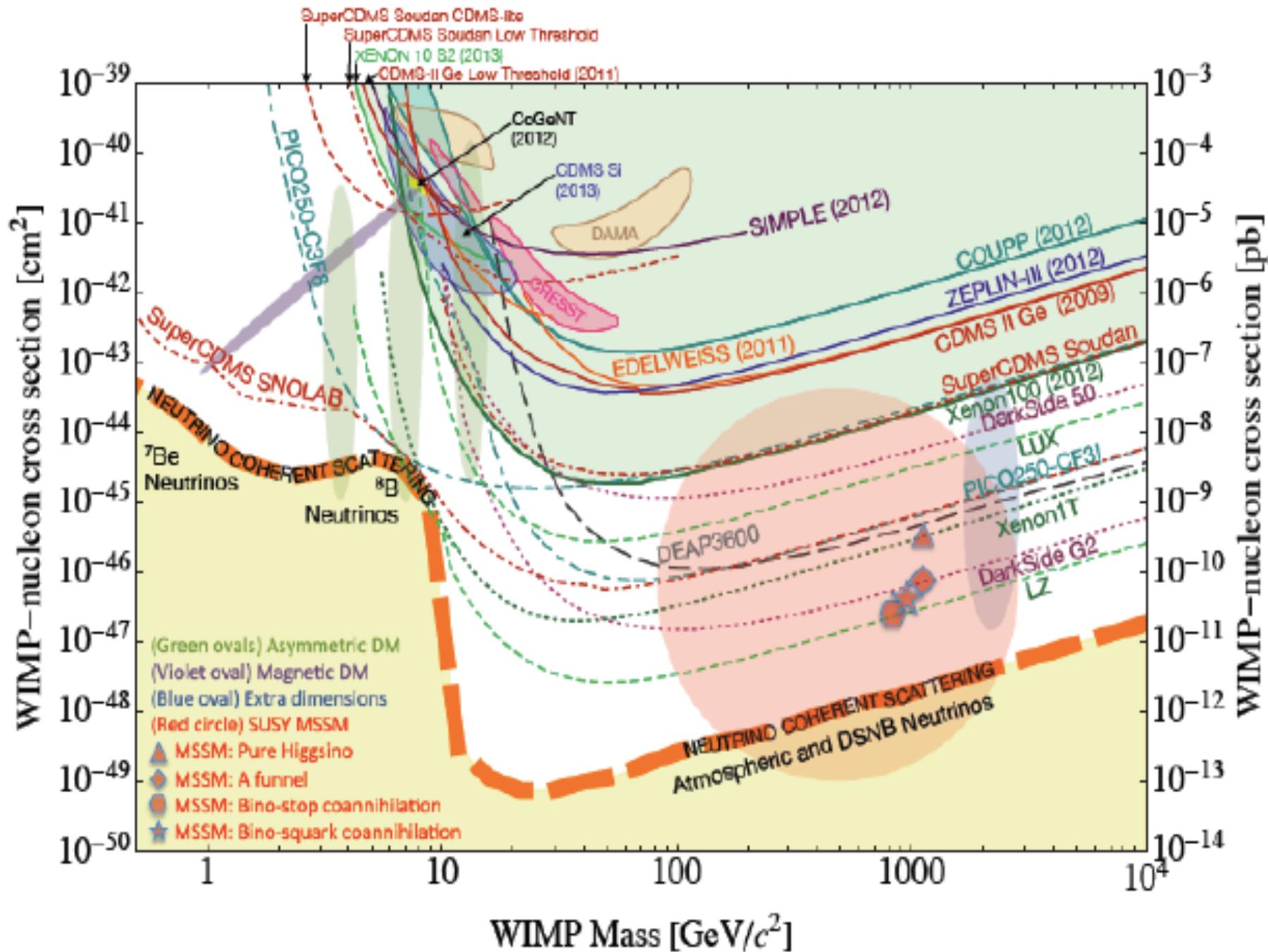
~100 - 200
GeV

m_{LKP}

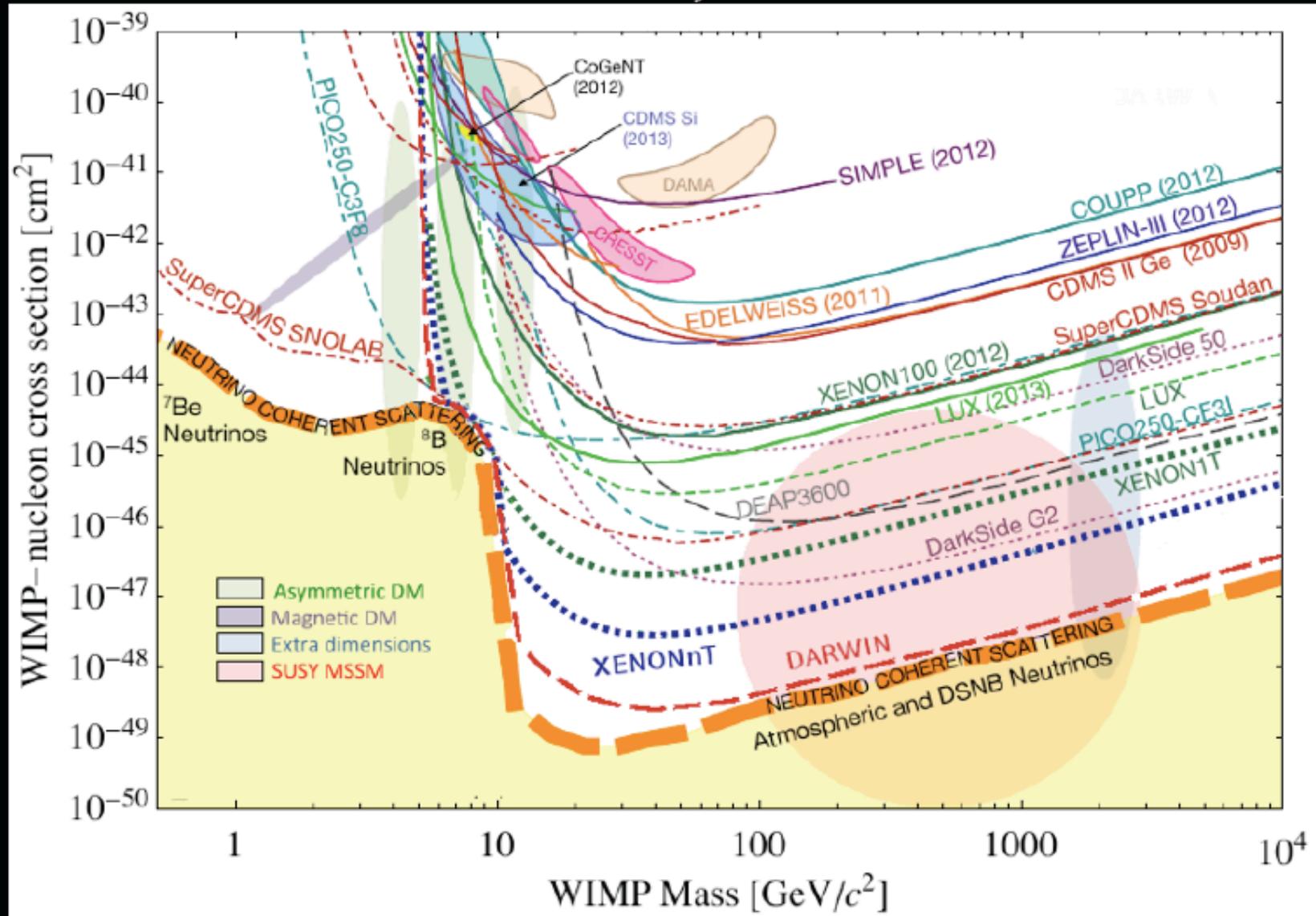
~600 - 800
GeV

m_{LTP}

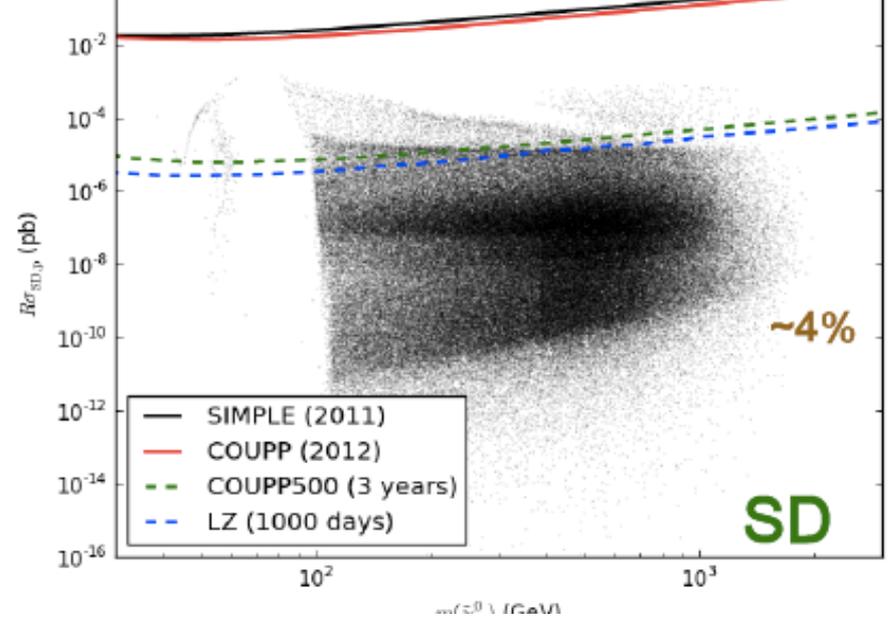
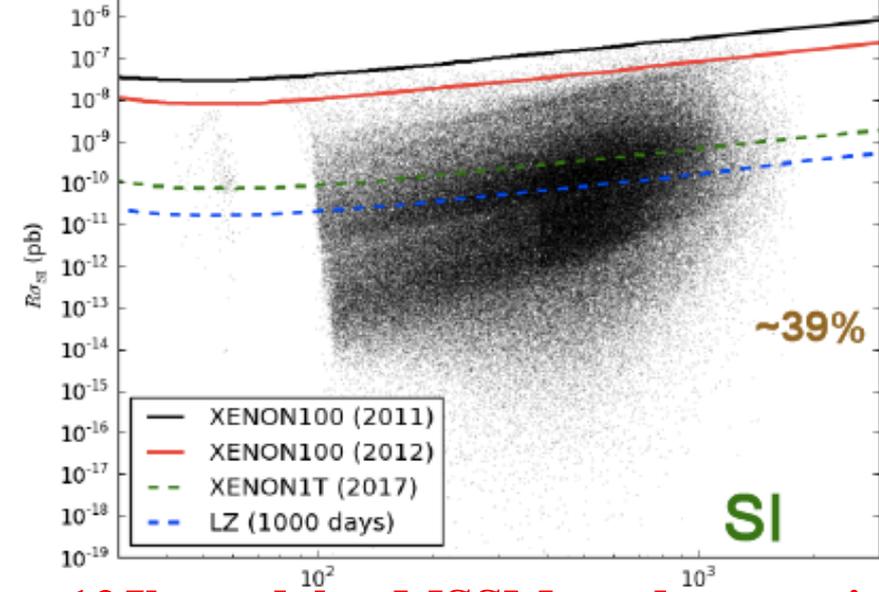
~400 - 800
GeV



1) Science Goals: Dark Matter Projected Sensitivities



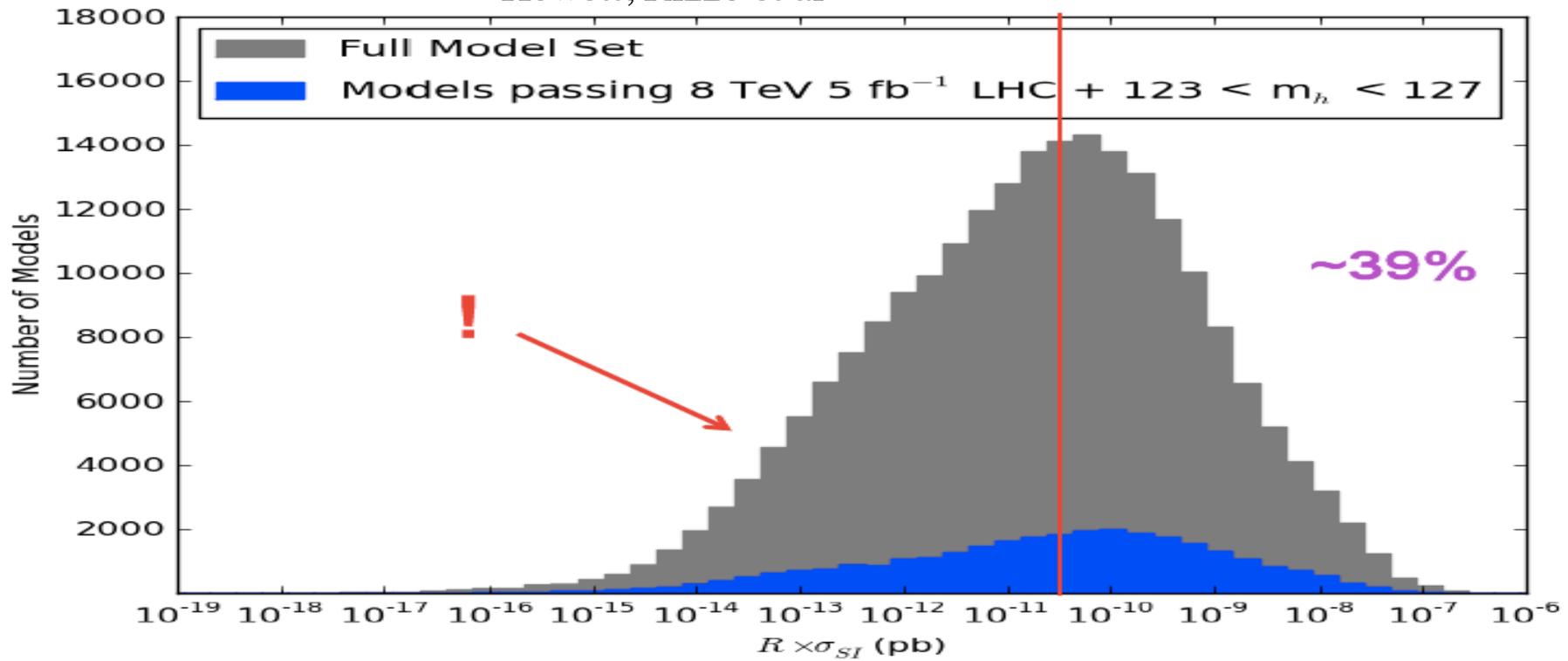
What if 2+ of these experiments observe strong candidate dark matter signals?
Build a directional detector to establish astrophysical origin.



125k models pMSSM under scrutiny

Hewett, Rizzo et al

LZ



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 cm ² (CDMS joint), running
CRESST	LNGS	candidate signal, running
EURECA	propose DOMUS	CDR
XENON 100 / 1T	LNGS	<3.3E-45 cm ² / construction
XENON N-T	LNGS	proposed
LUX	SURF	<7.6E-46 cm ² , 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

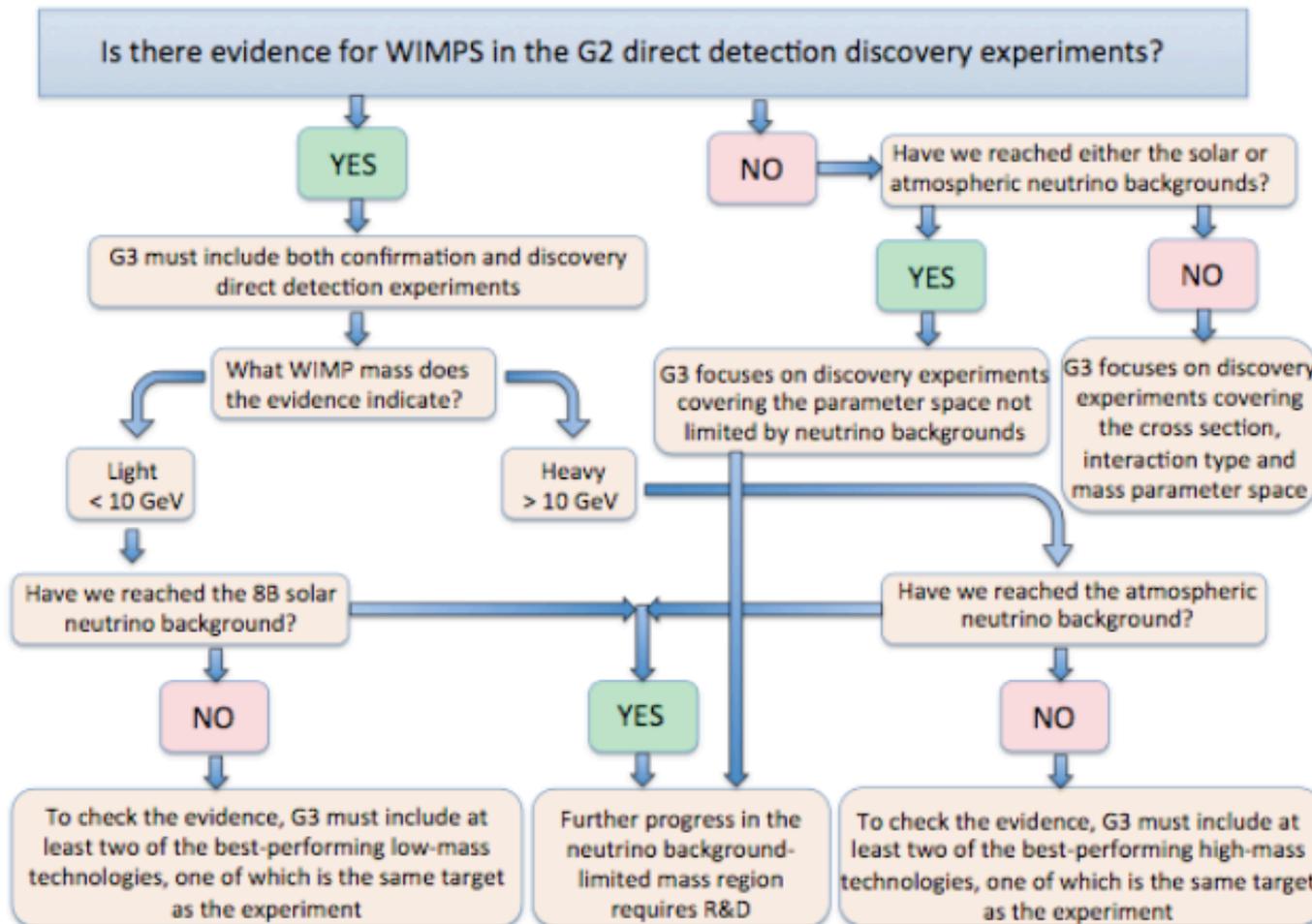
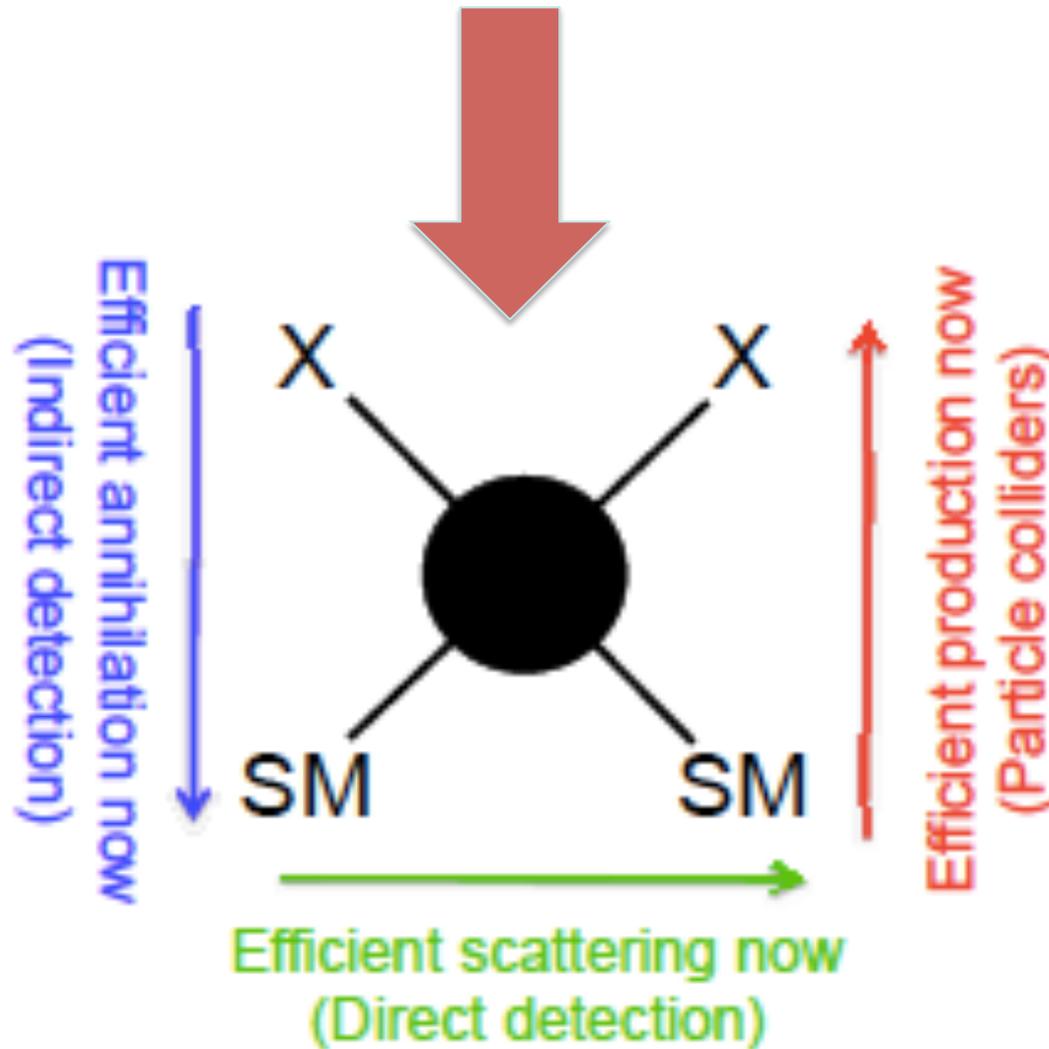
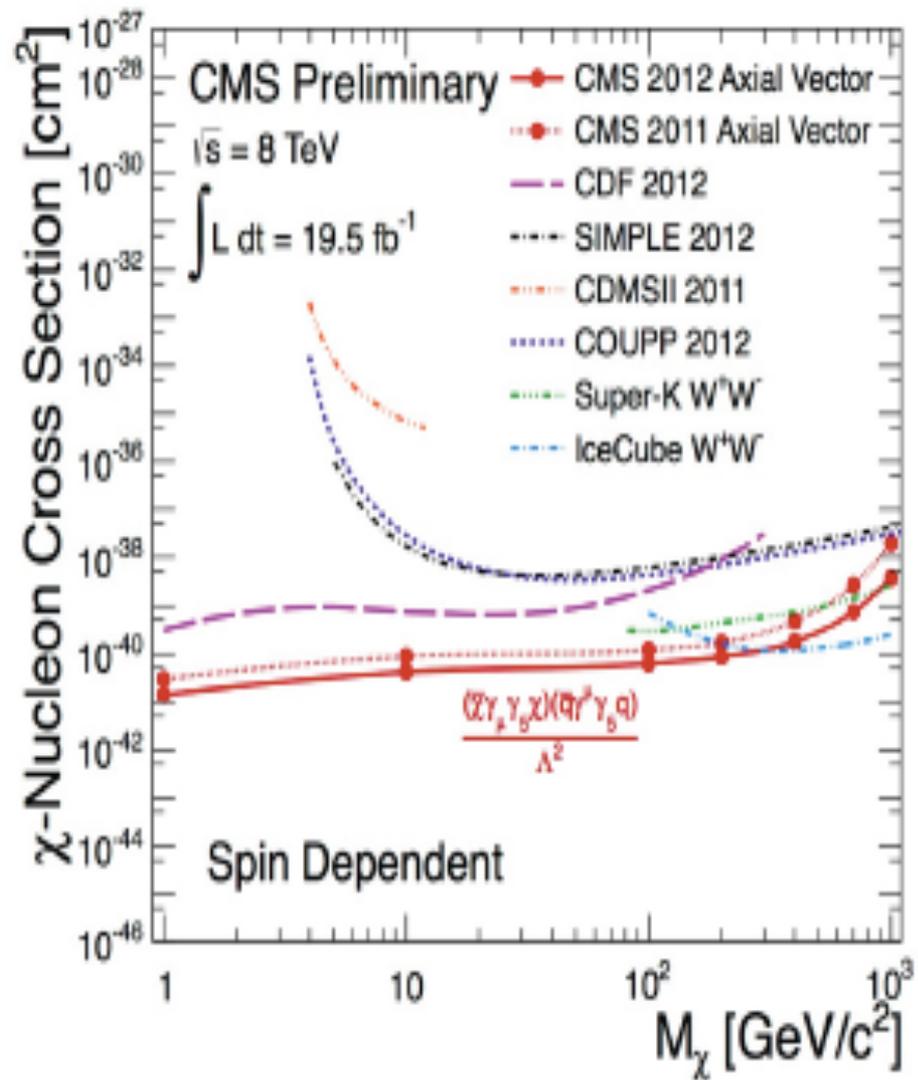
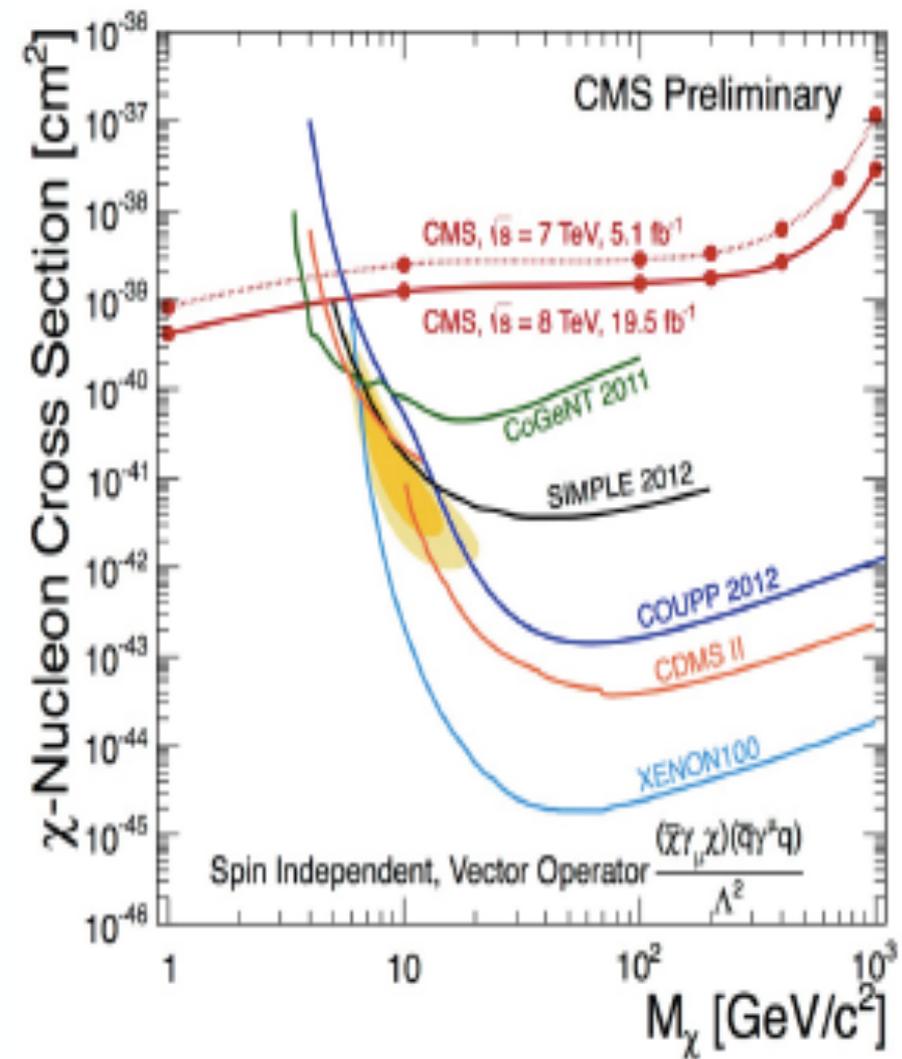


Figure 28. Decision tree for direct detection experiments from G2 to G3.

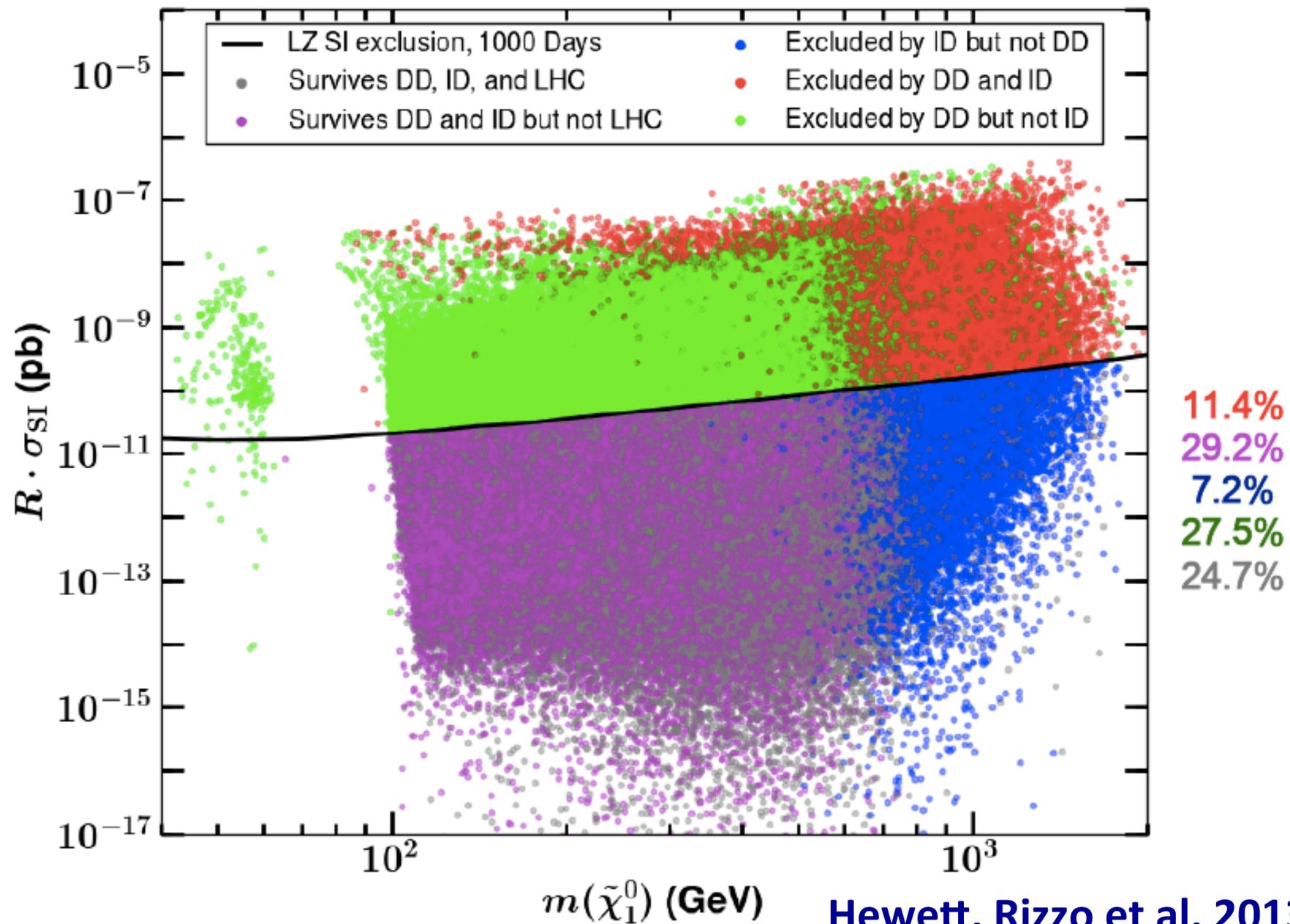


DM COMPLEMENTARITY: efficient annihilation in the early Universe implies today





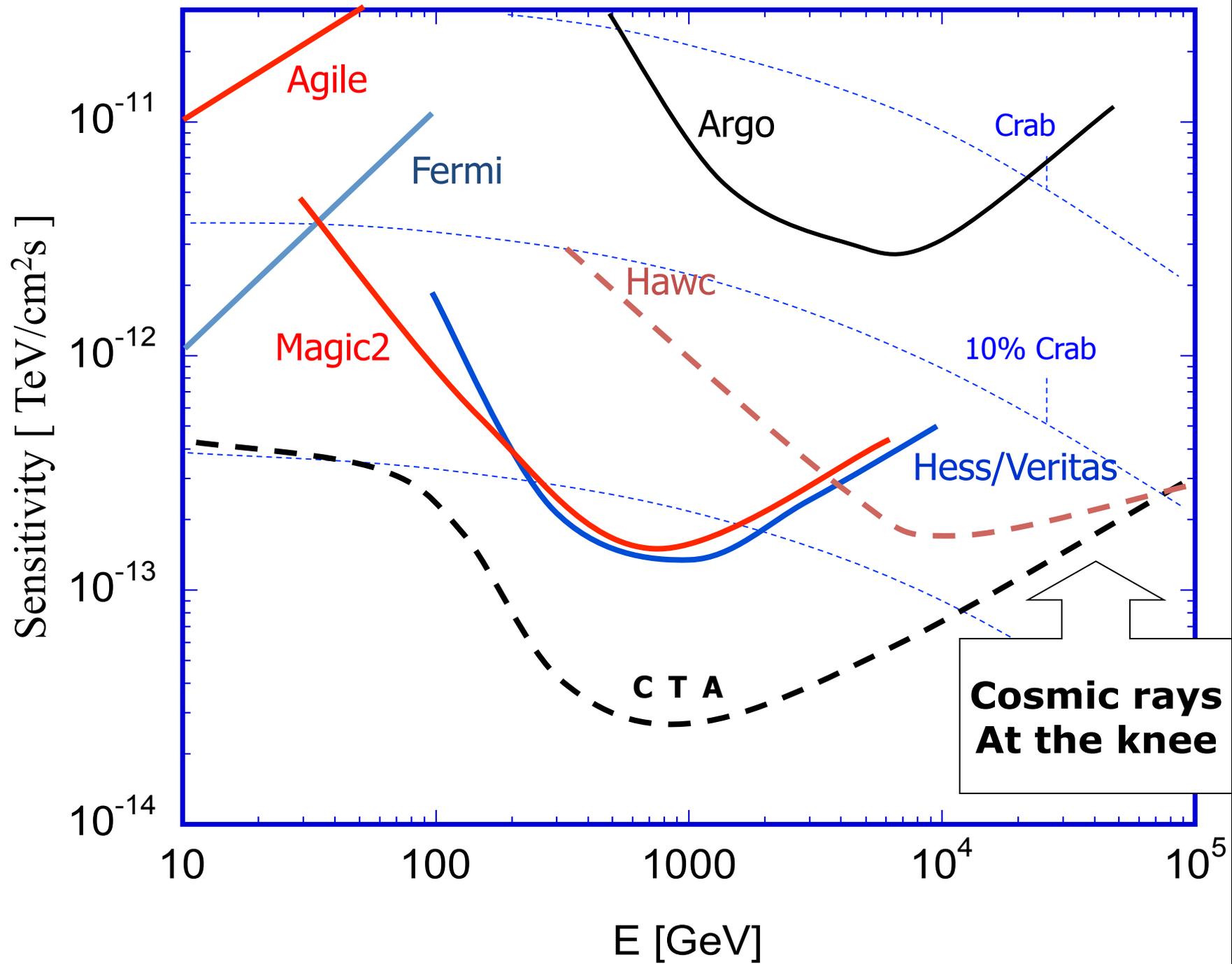
pMSSM models DD = LZ both SI + SD ID = FERMI + CTA



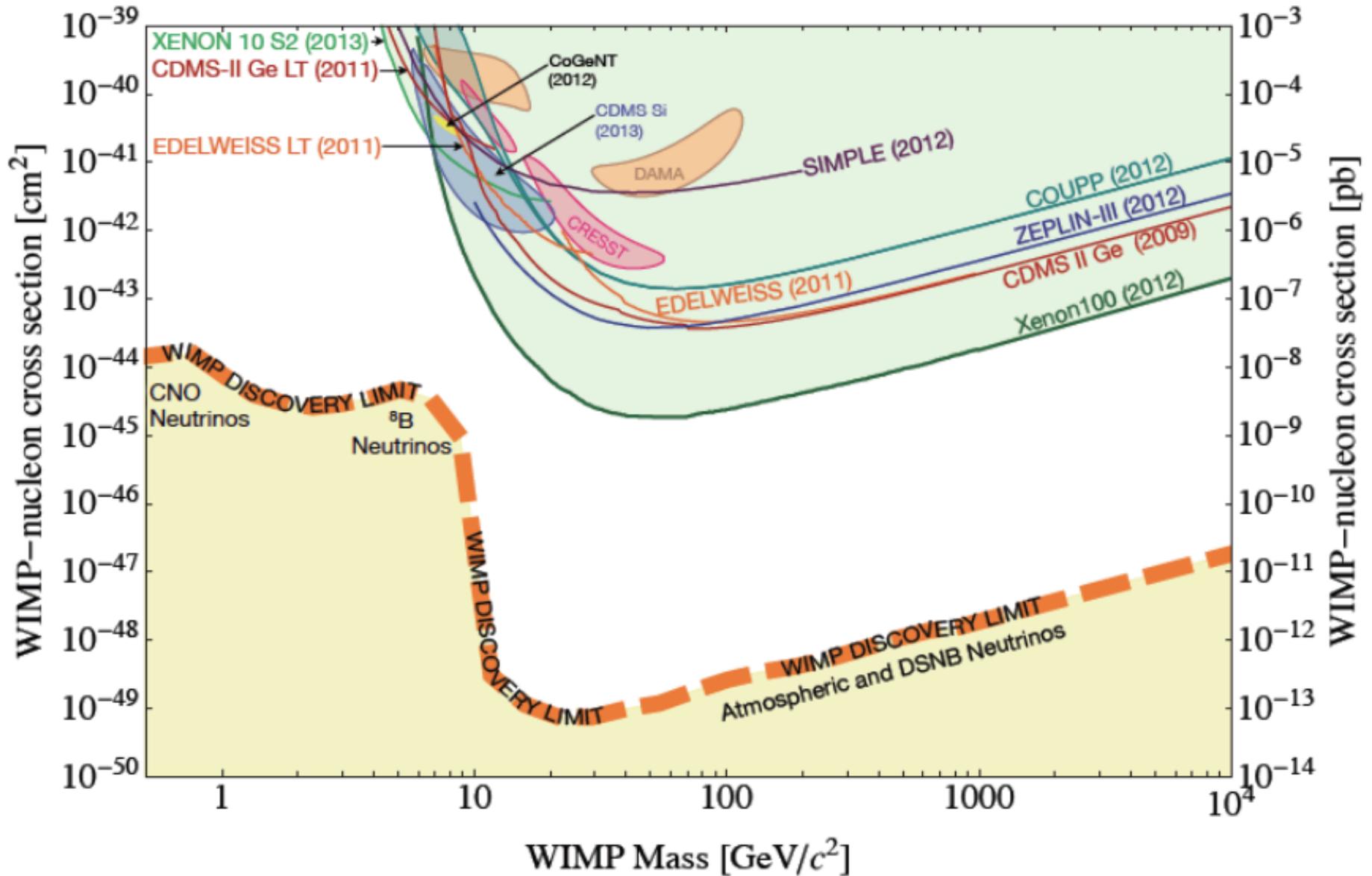
Post-Higgs Depression? No, thanks just the opposite....

- **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



Spin-Independent Cross Section: Current Experiment Results



so far: ~ 3 years / order of magnitude

THE FATE OF LEPTON NUMBER

L VIOLATED

L CONSERVED

ν Majorana ferm.

ν Dirac ferm.
(dull option)

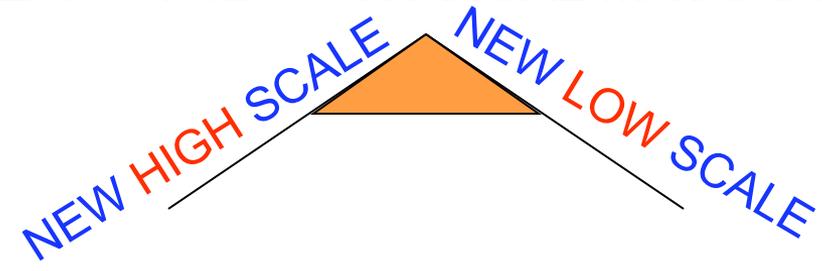
SMALLNESS of m_ν

$$h \bar{\nu}_L H \nu_R \rightarrow m_\nu = h \langle H \rangle$$

$$M_\nu < 5 \text{ eV} \rightarrow h < 10^{-11}$$

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

PRESENCE OF A **NEW** PHYSICAL MASS SCALE



SEE - SAW MECHAN.

MAJORON MODELS

Minkowski; Gell-Mann,
Ramond, Slansky,
Vanagida

Gelmini, Roncadelli

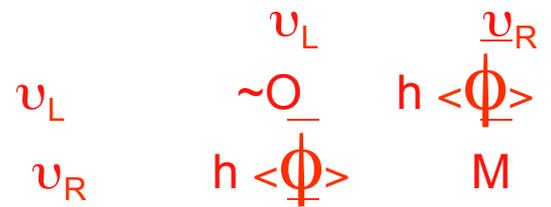
ν_R ENLARGEMENT OF THE
FERMIONIC SPECTRUM

Δ ENLARGEMENT OF THE
HIGGS SCALAR SECTOR

$$M \nu_R \nu_R + h \bar{\nu}_L \phi^- \bar{\nu}_R$$

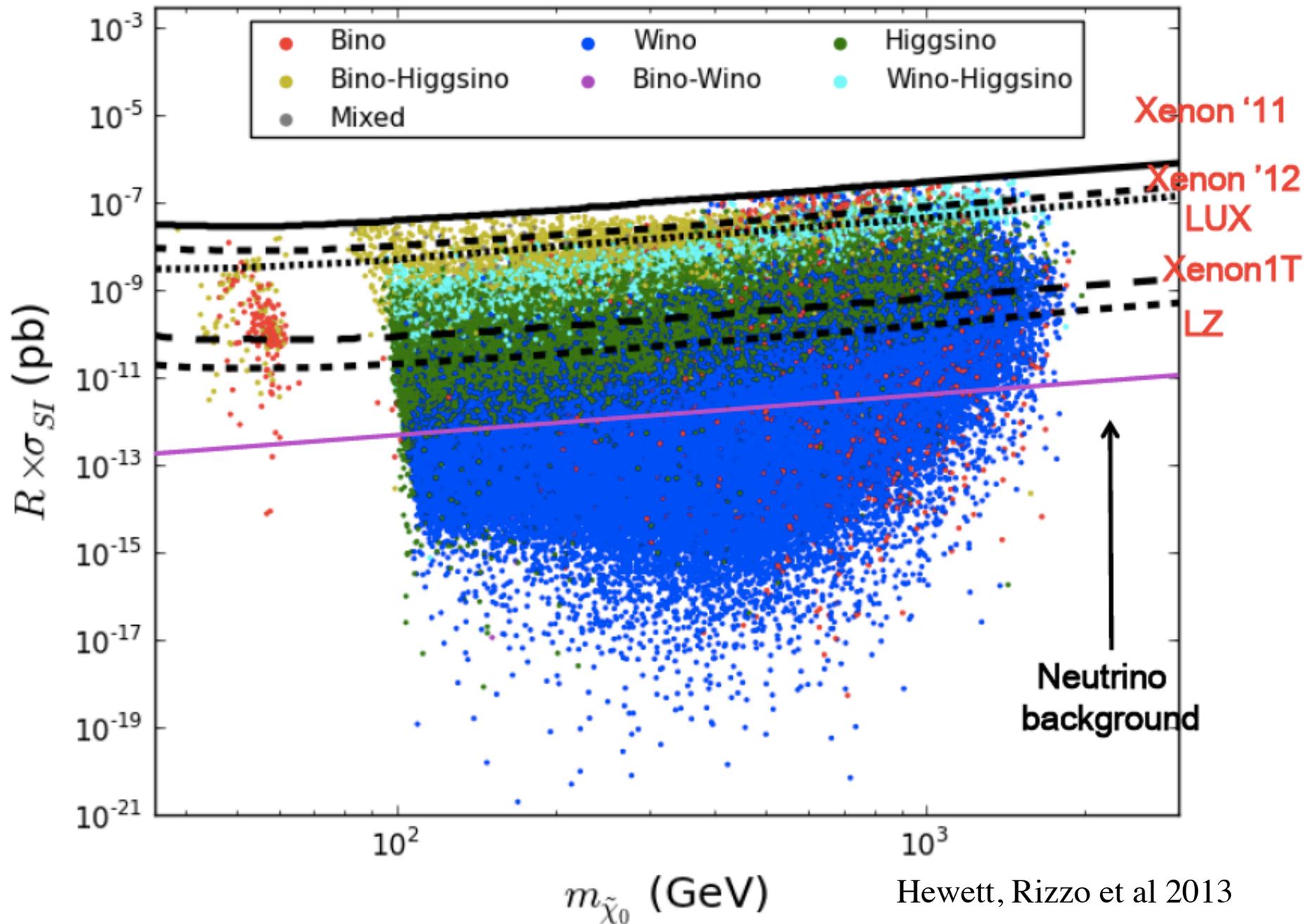
$$h \nu_L \nu_L \Delta$$

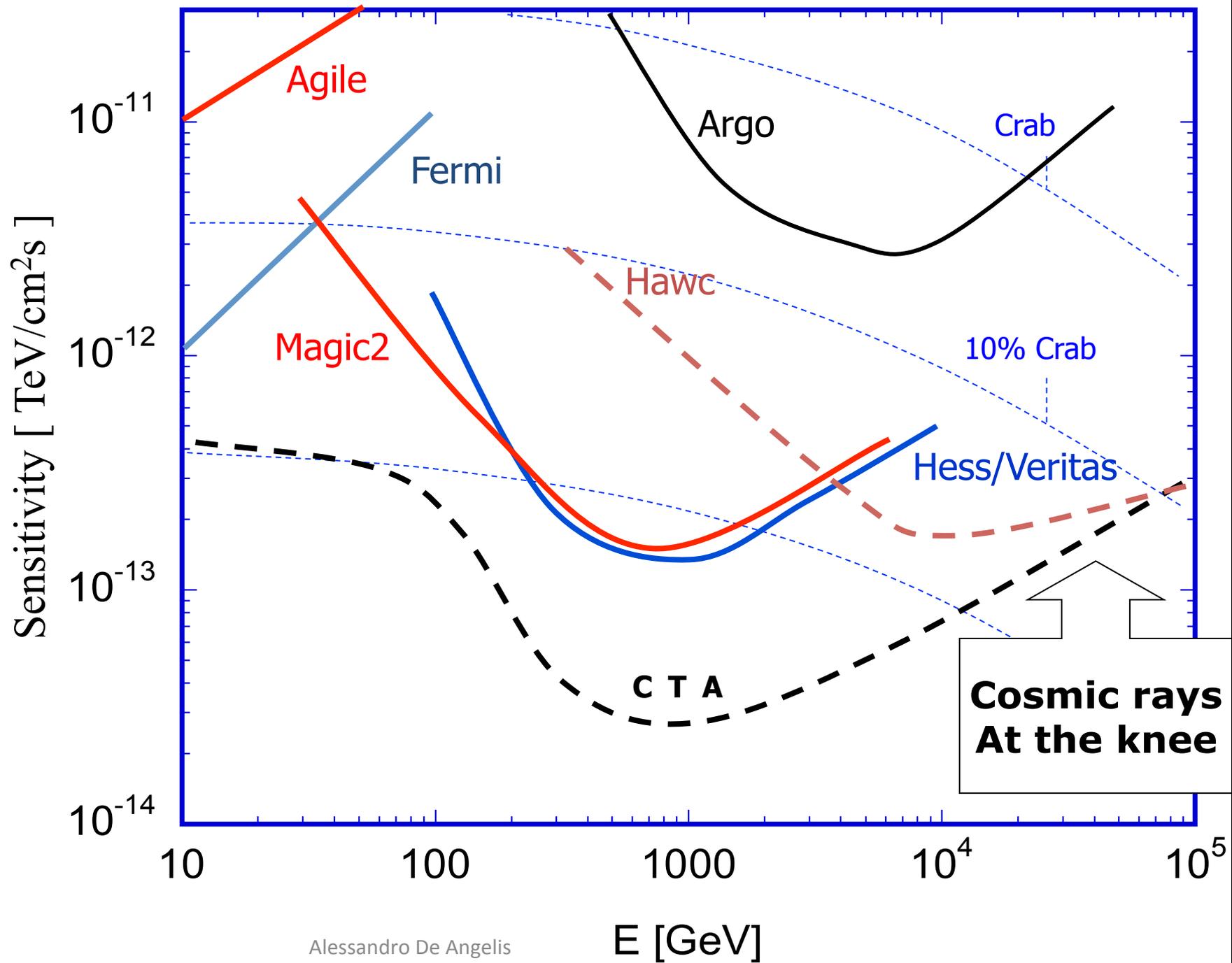
$$m_\nu = h \langle \Delta \rangle$$



LR
Models?

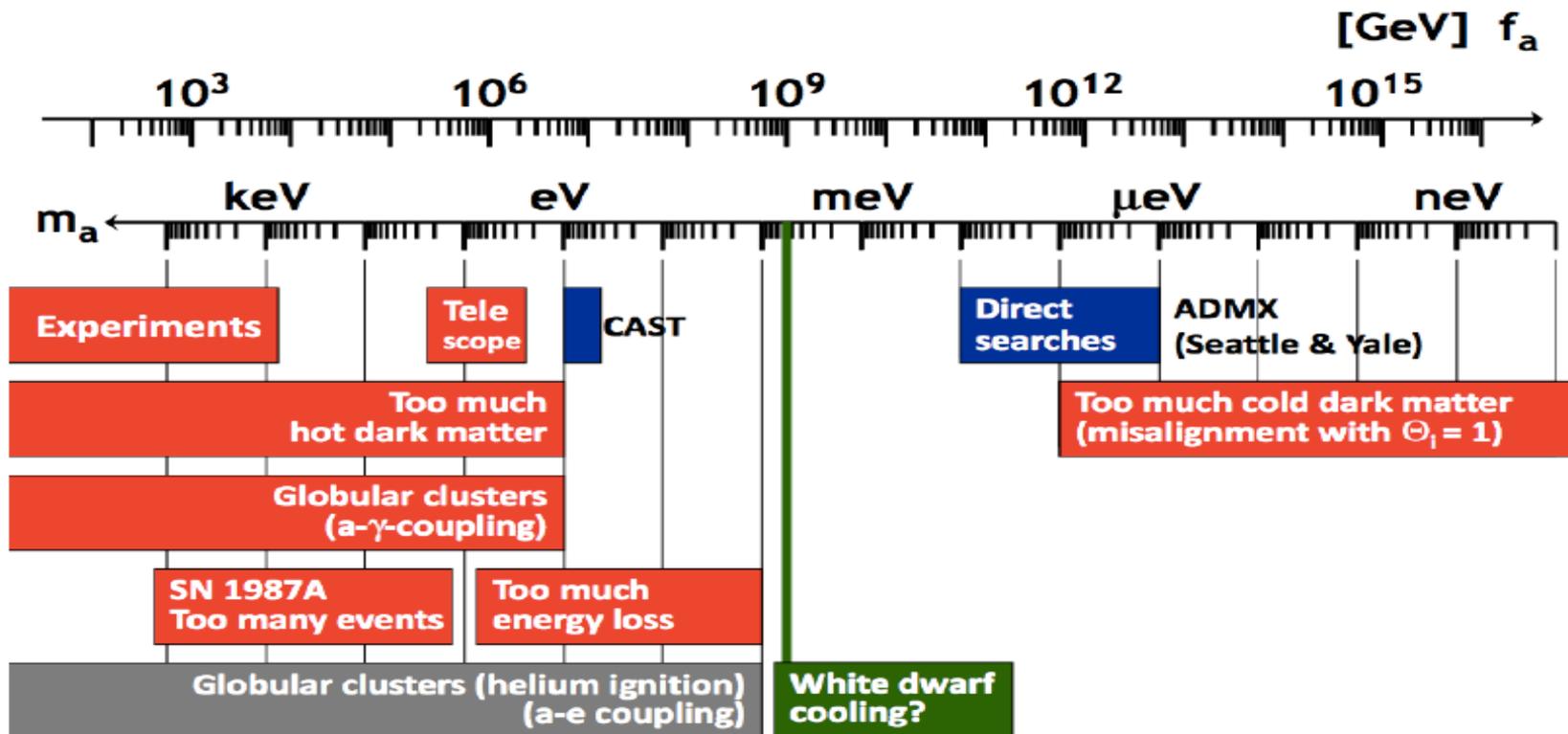
N.B.: EXCLUDED BY LEP!



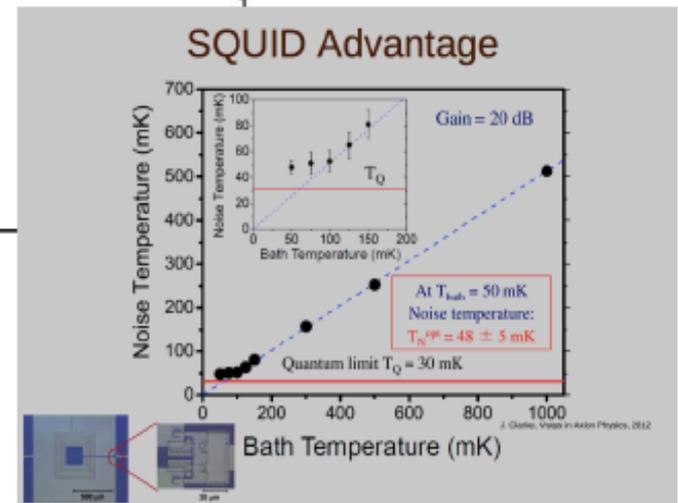
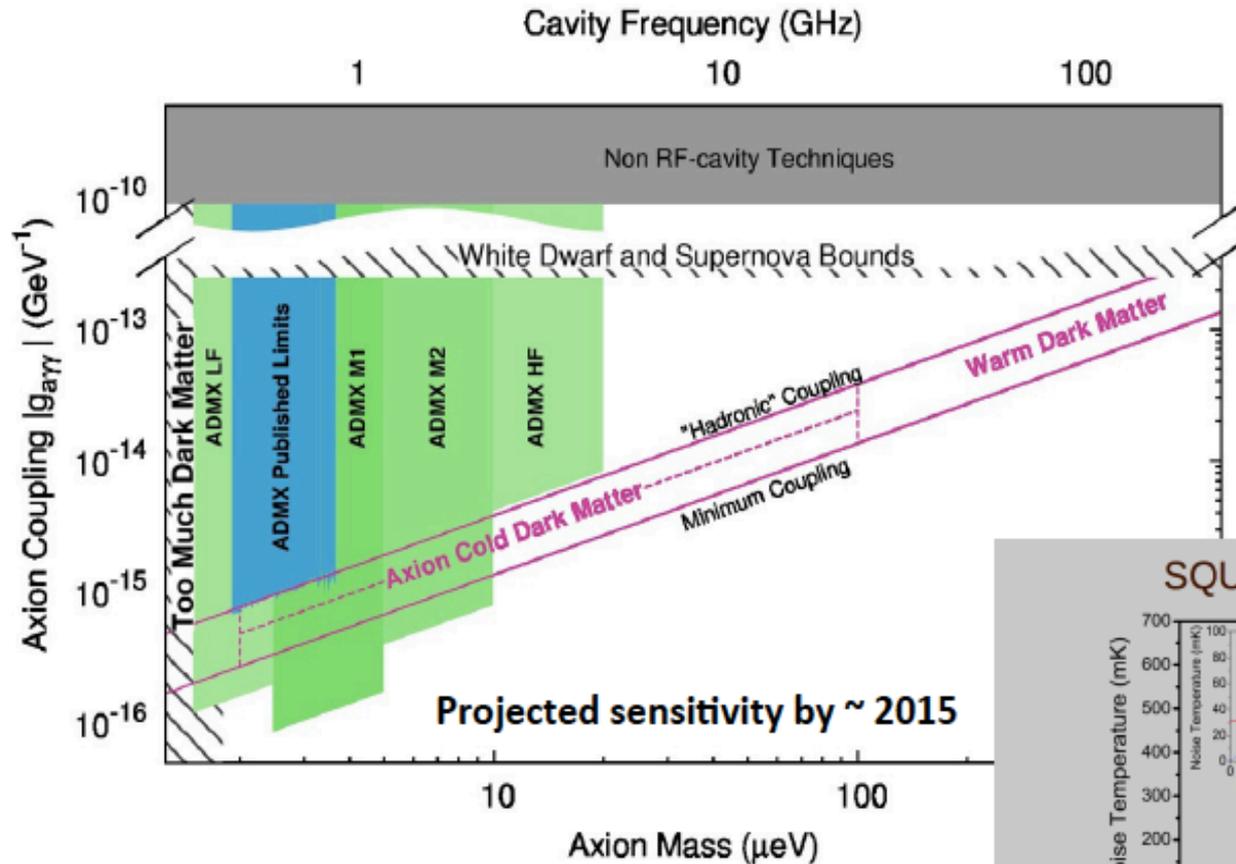


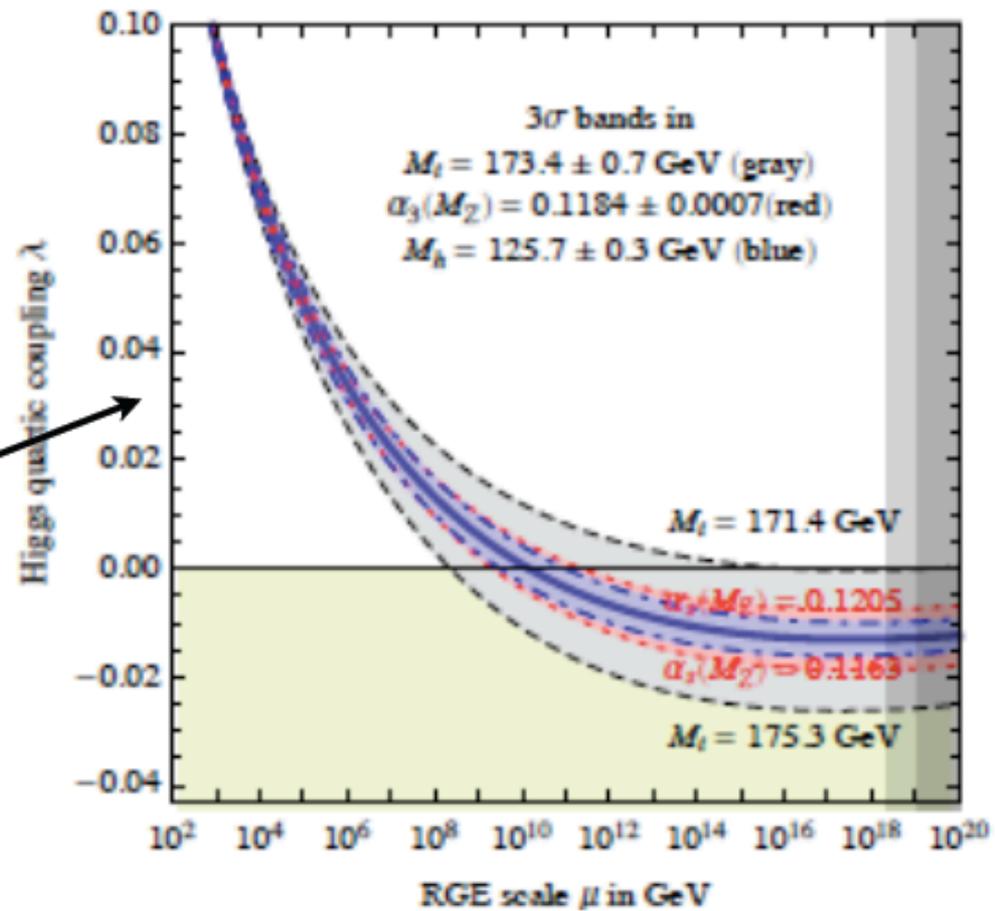
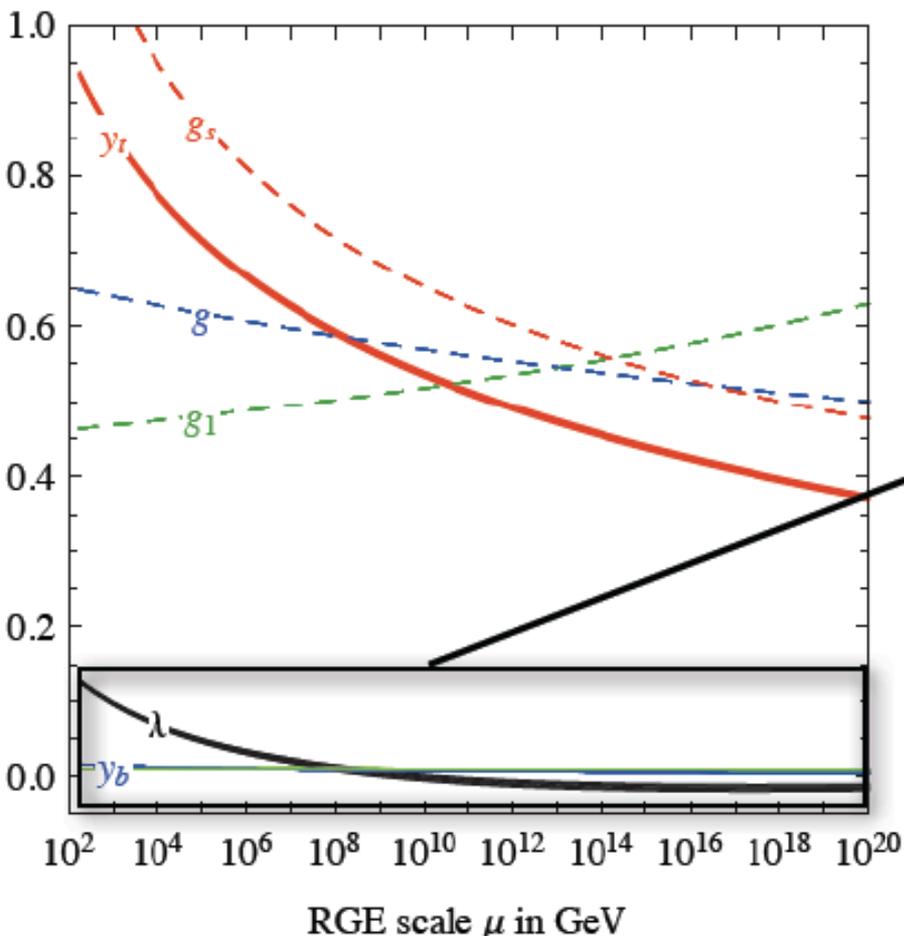
Keep in mind: we don't know at all what DM is made of ! Alternatives to WIMPs – for instance, **AXIONS**

Axion Bounds and Searches



ADMX achieved and projected sensitivity

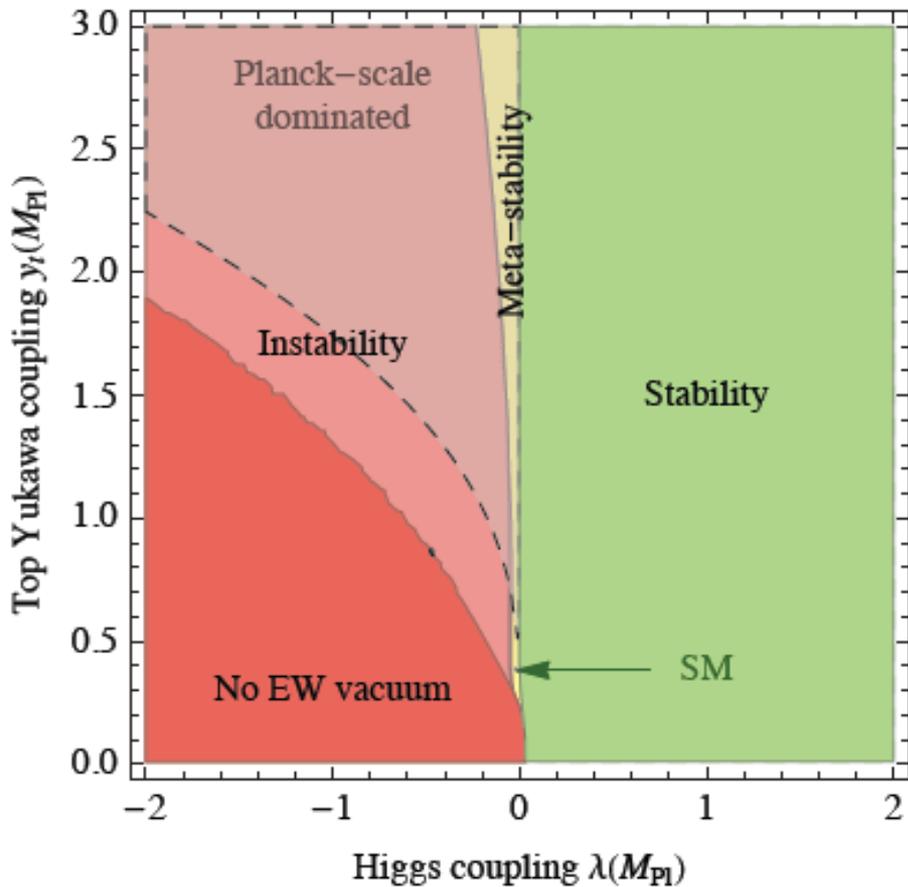




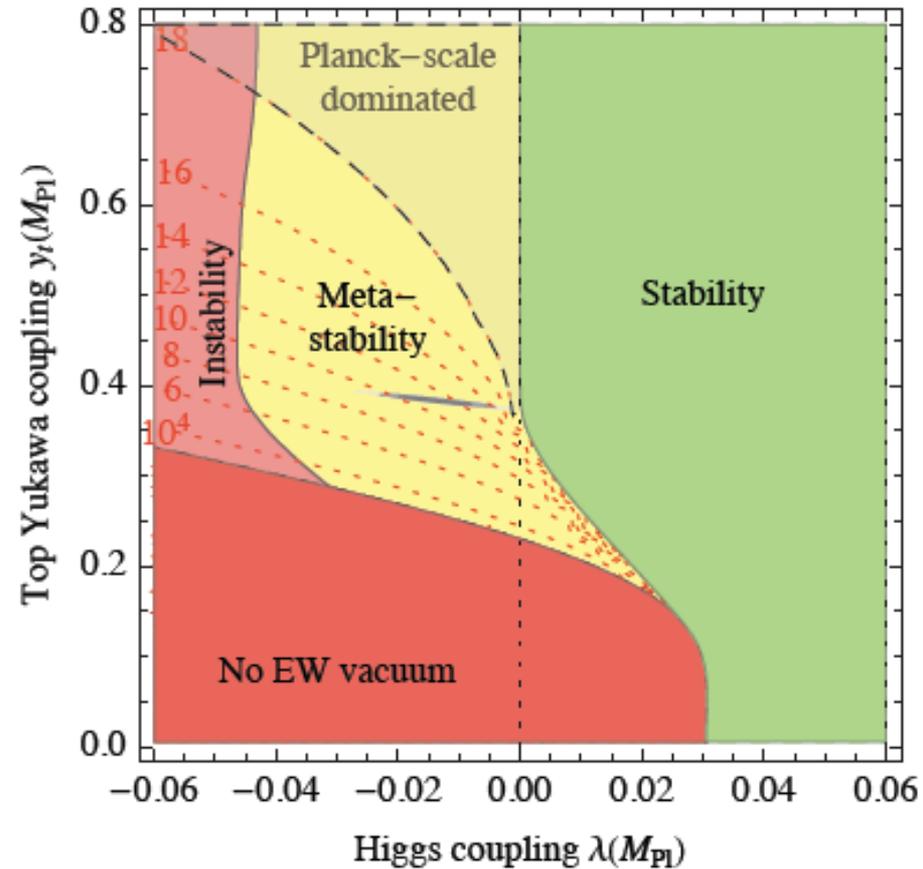
Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia 2013

For previous works: Krive, Linde '76; Krasnikov '78; Maiani, Parisi, Petronzio '78; Cabibbo et al '79; Lindner '86; Altarelli, Isidori '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 $M_{\text{PLANCK}} \rightarrow M_H$ formidable telescope to sneak into unexplorable energies...



BUTTAZZO ET AL. 2013

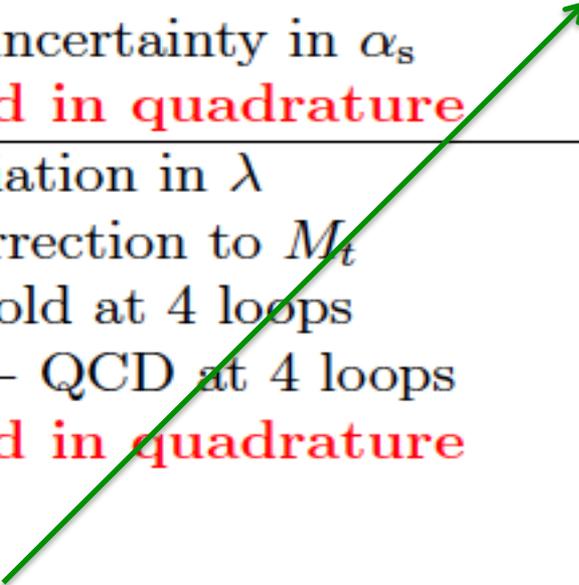


The Universe looks very close to **CRITICALITY**

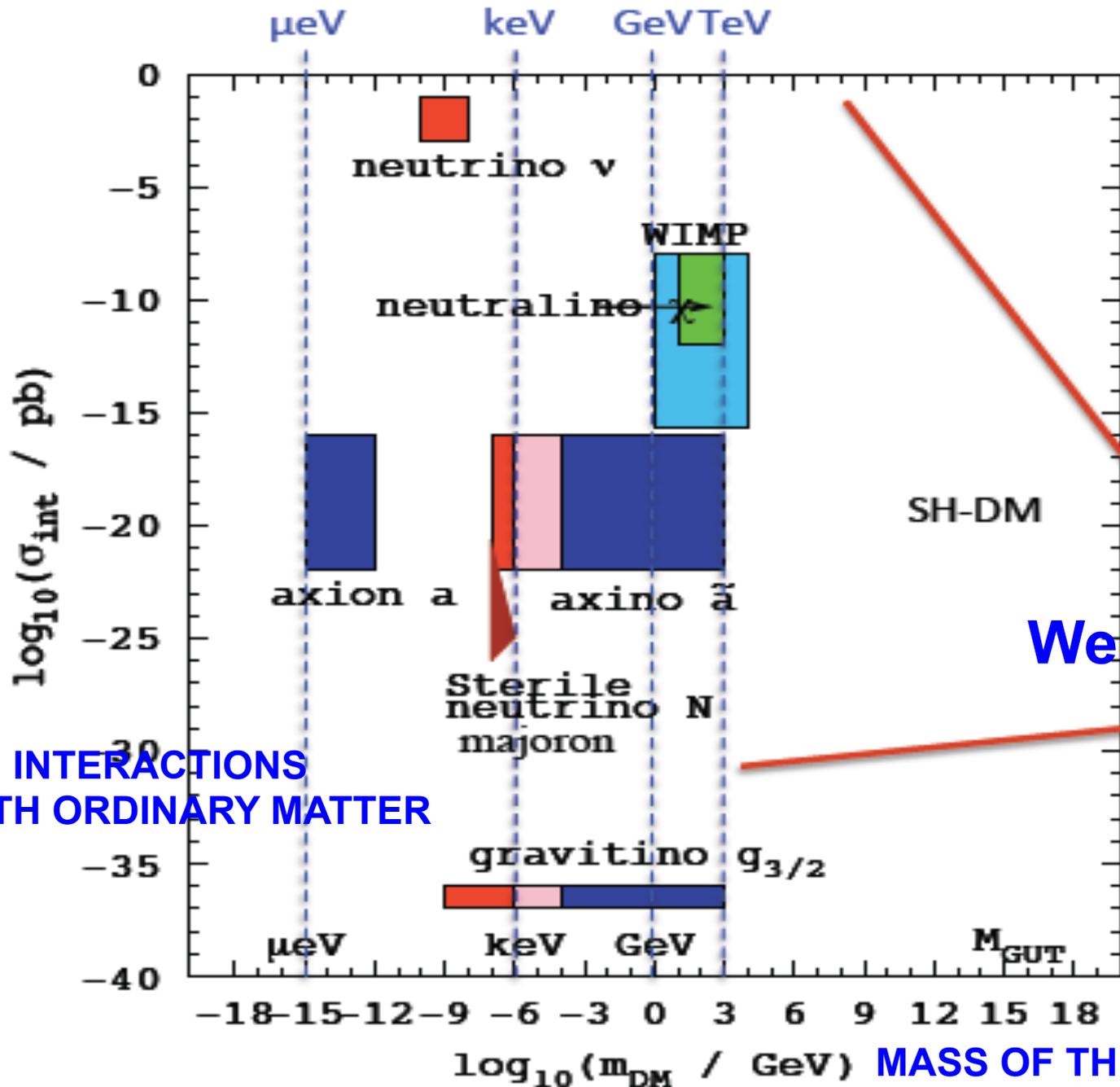
ON THE IMPORTANCE OF PRECISELY MEASURING HIGGS and TOP MASSES

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	$\mathcal{O}(\Lambda_{\text{QCD}})$ 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



Weak couplings

DM INTERACTIONS WITH ORDINARY MATTER

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

$$|d_n| < 2.9 \times 10^{-26} e \text{ cm (90\%C.L.)},$$

$$|d_{Tl}| < 9.0 \times 10^{-25} e \text{ cm (90\%C.L.)},$$

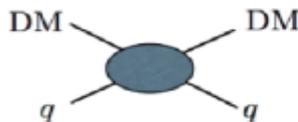
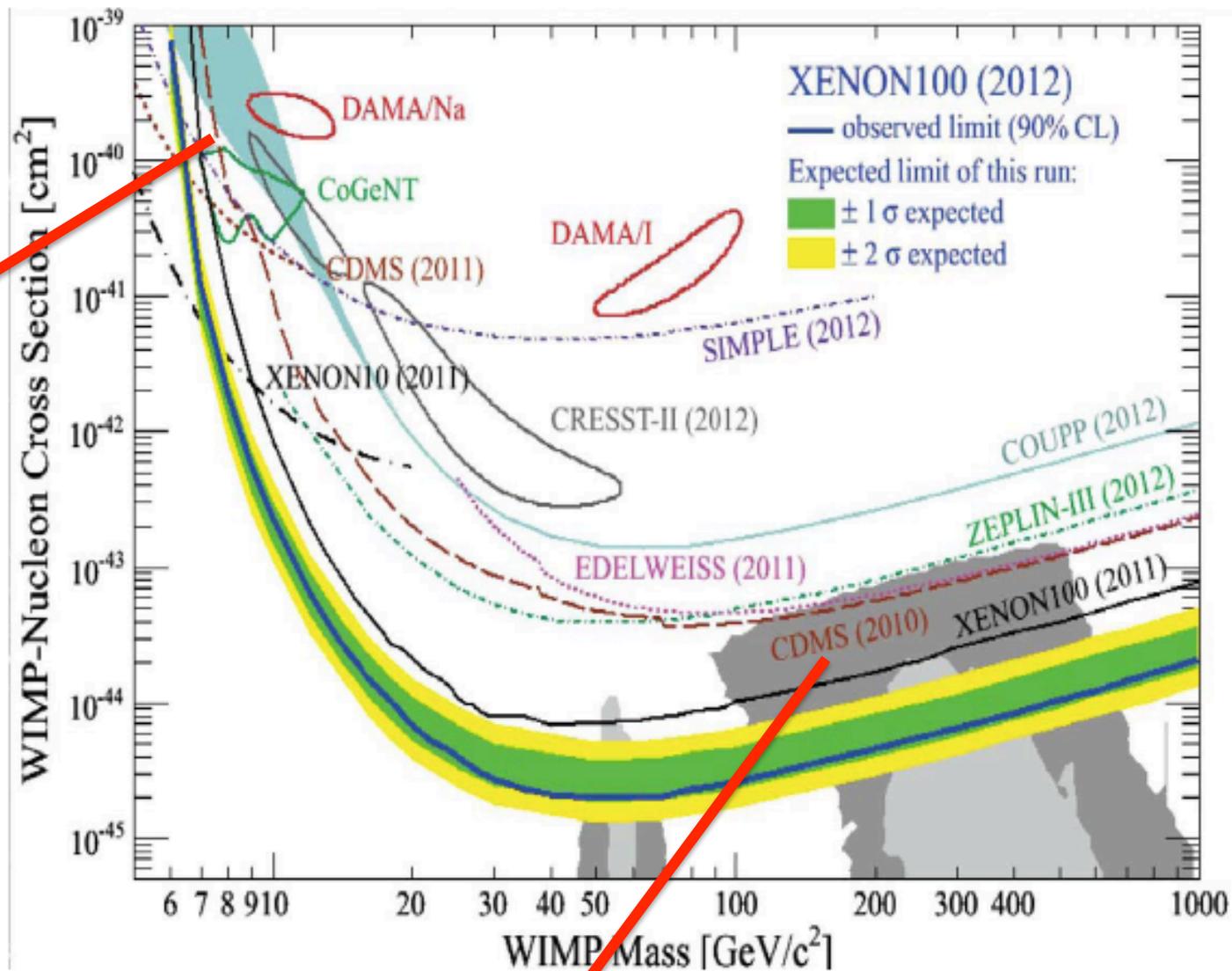
$$|d_{Hg}| < 3.1 \times 10^{-29} e \text{ cm (95\%C.L.)}.$$

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

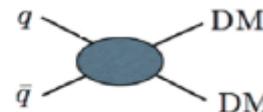
Kolb SUSY2012

Relevant to
 intensify the efforts
 here: ex.

asymmetric DM
 with **DM particles**
 of mass \sim baryon
 mass given that
 ρ_{DM} not much
 different from ρ_B

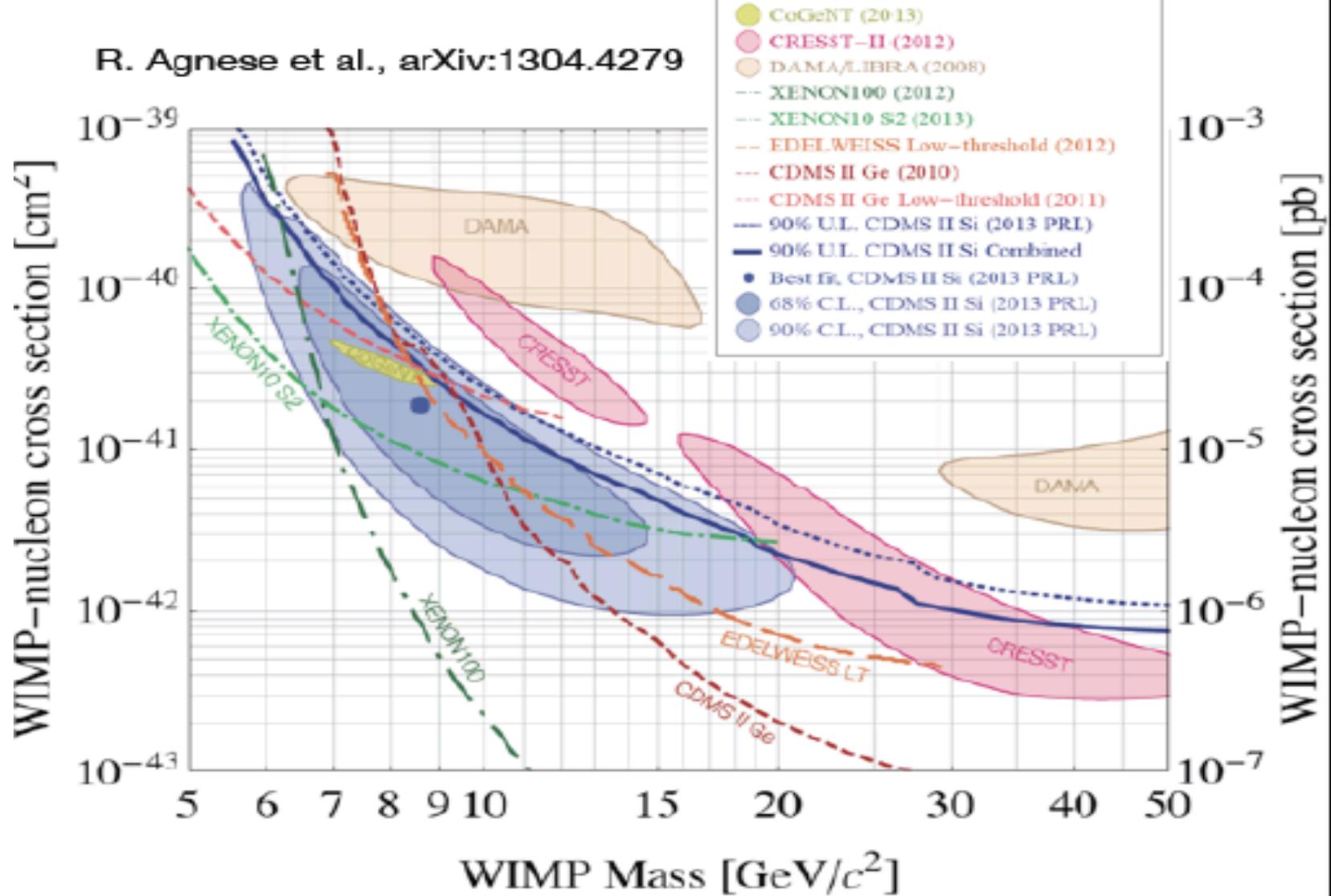


Direct Detection (t-channel)



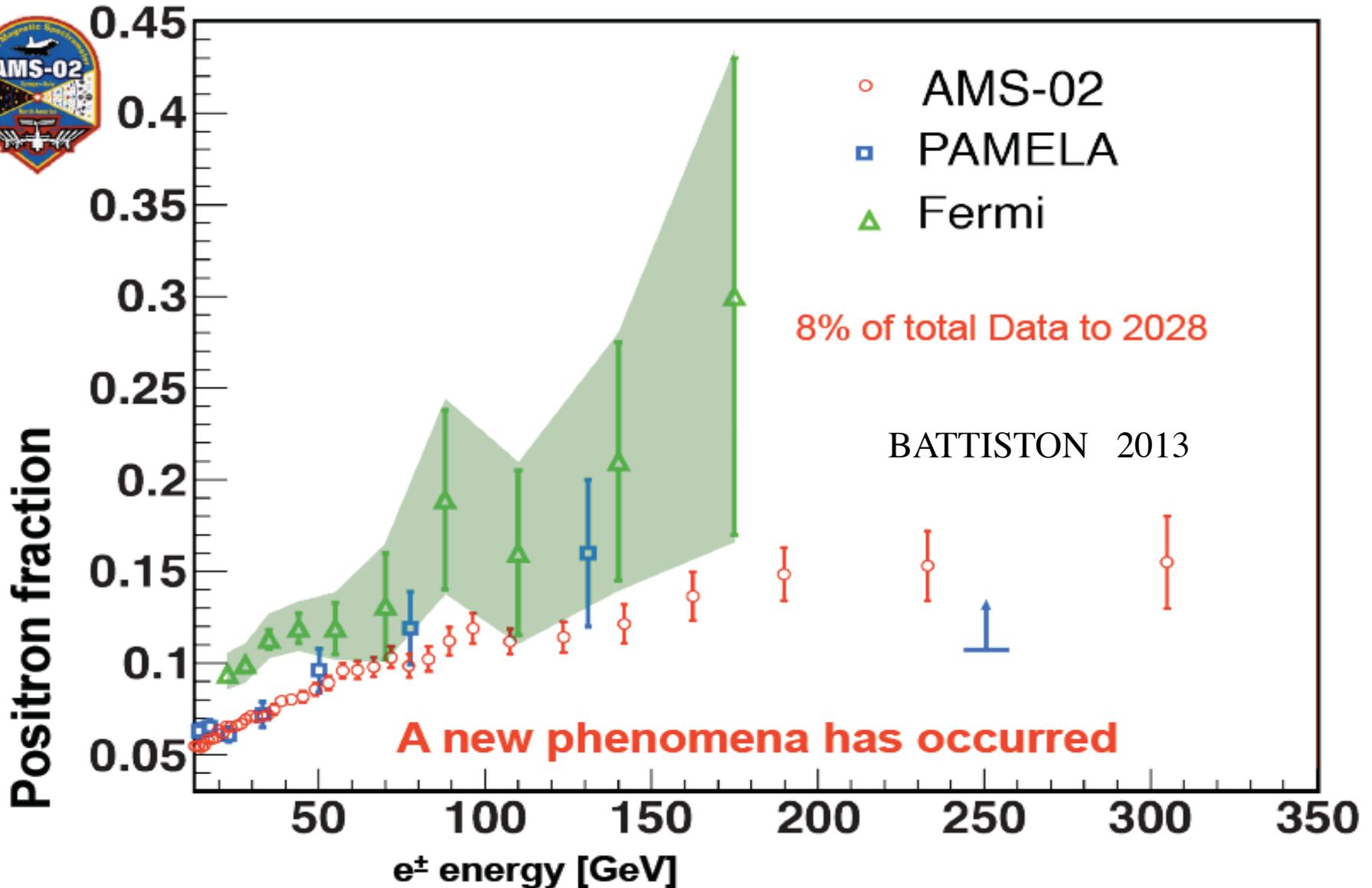
Collider Searches (s-channel)

R. Agnese et al., arXiv:1304.4279

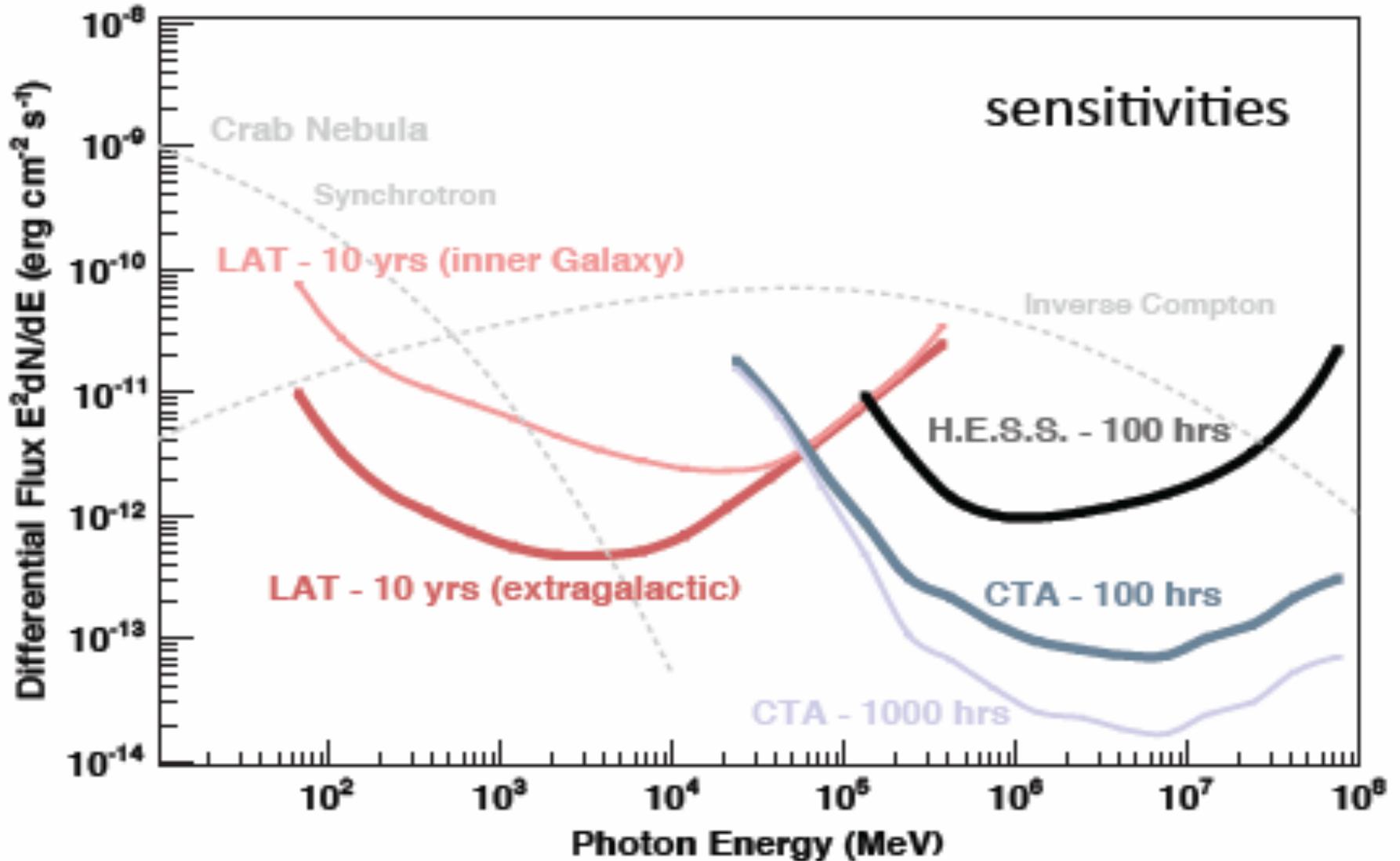


RELEVANCE OF THE DAMA-LIBRA RESULT– IMPORTANCE OF AN INDEPENDENT VERIFICATION (hard to reach the same level of sensitivity)

INDIRECT SEARCHES FOR DM

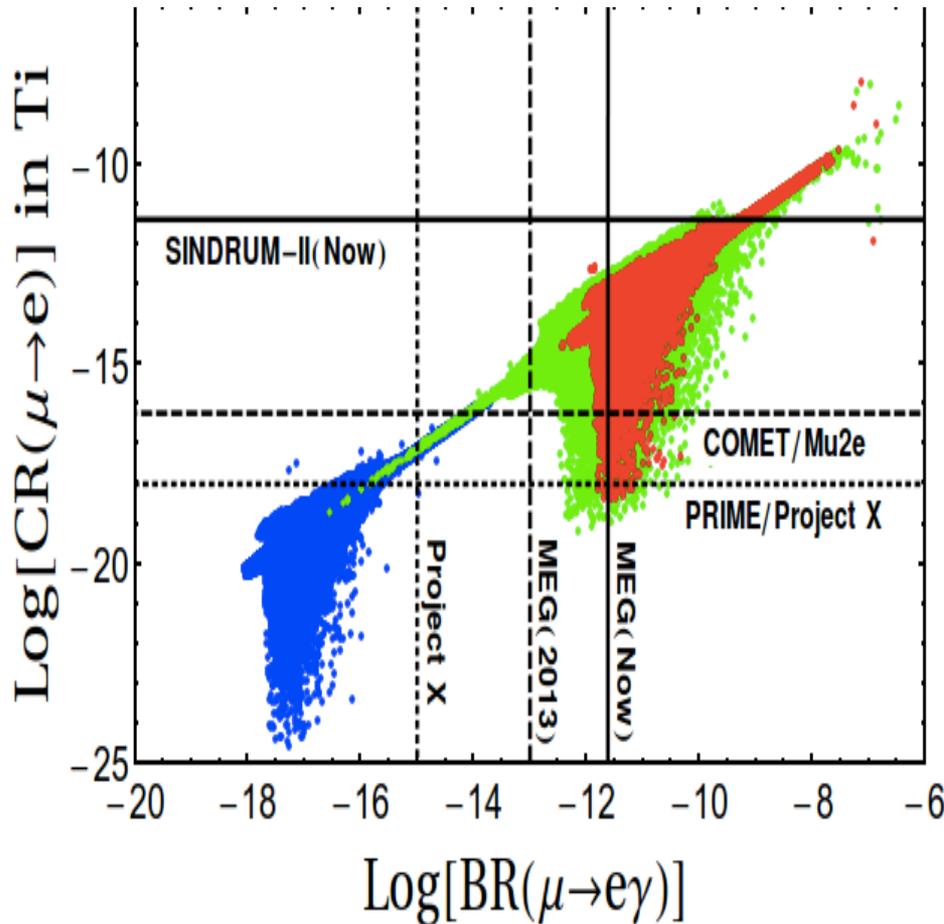


GAMMA – ASTRONOMY FROM EARTH AND SPACE

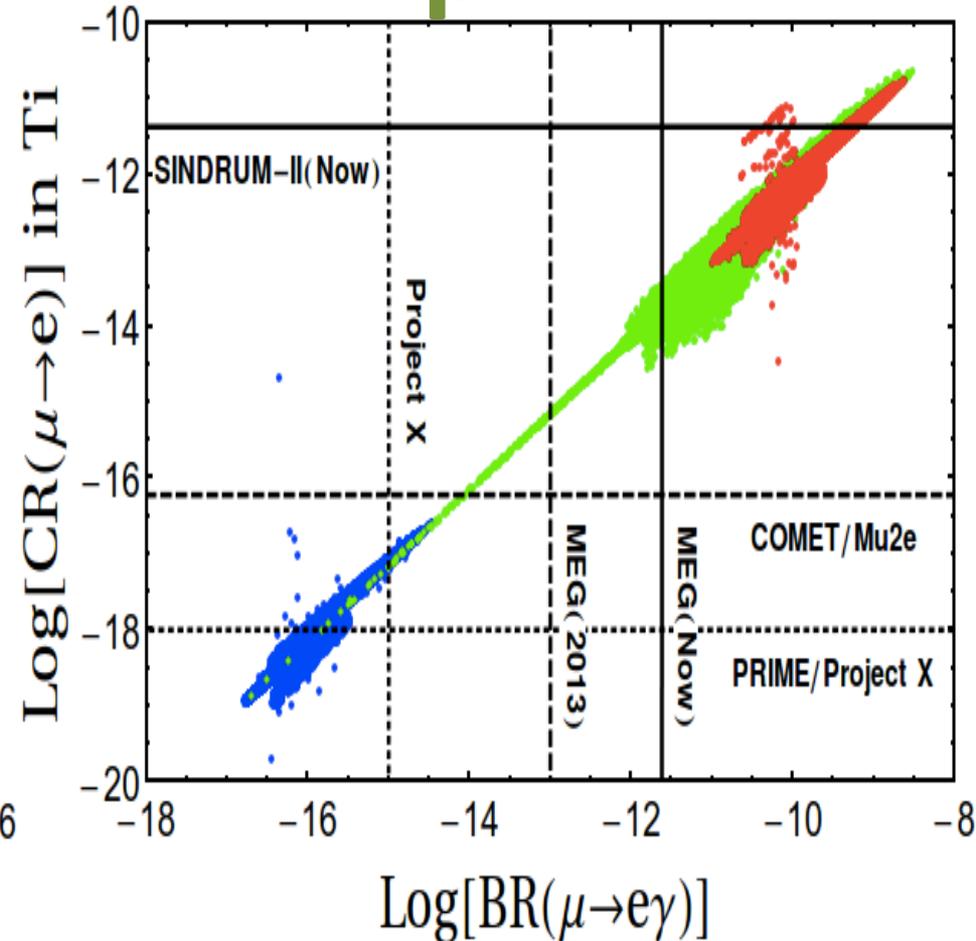


$\mu - e$ conversion vs $\mu \rightarrow e\gamma$

$\text{Tan}\beta = 10$



$\text{Tan}\beta = 40$



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 $O(1\text{TeV})$, or is the DM scale not correlated at all with the elw. scale?