

NA62 Collaboration meeting, Ferrara, Sept. 1 – 5, 2014

Accelerator and Non-accelerator Roads to New Physics



**or WHY it ain't to be so
in the next few years !!!**

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?

2013: the triumph of the **STANDARD**

- **PARTICLE STANDARD MODEL**
- **COSMOLOGY STANDARD MODEL**

The diagram illustrates the Standard Model of particle physics, organized into three generations of matter (fermions) and a section for bosons.

Three Generations of Matter (Fermions) spin 1/2

I

mass → 2.4 MeV	1.27 GeV	173.2 GeV
charge → 2/3	2/3	2/3
name → Left u Right up	Left c Right charm	Left t Right top

Quarks

mass → 4.8 MeV	104 MeV	4.2 GeV
charge → -1/3	-1/3	-1/3
name → Left d Right down	Left s Right strange	Left b Right bottom

Leptons

mass → 0.511 MeV	105.7 MeV	1.777 GeV
charge → -1	-1	-1
name → Left e Right electron	Left μ Right muon	Left τ Right tau

Neutrinos

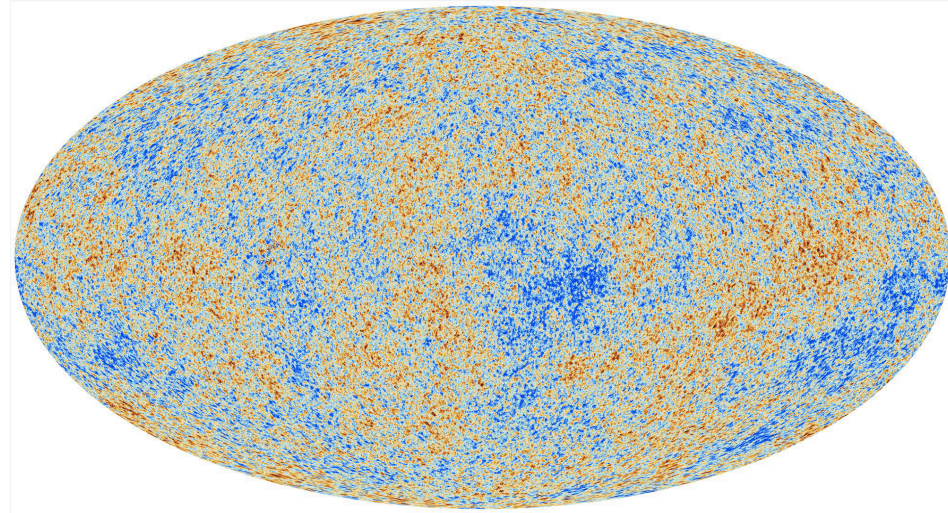
mass → 0 ν_e electron neutrino	0 ν_μ muon neutrino	0 ν_τ tau neutrino
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Bosons (Forces) spin 1

mass → 0	91.2 GeV	80.4 GeV
charge → 0	0	±1
name → g gluon	Z weak force	W[±] weak force

spin 0

mass → 126 GeV
charge → 0
name → H Higgs boson



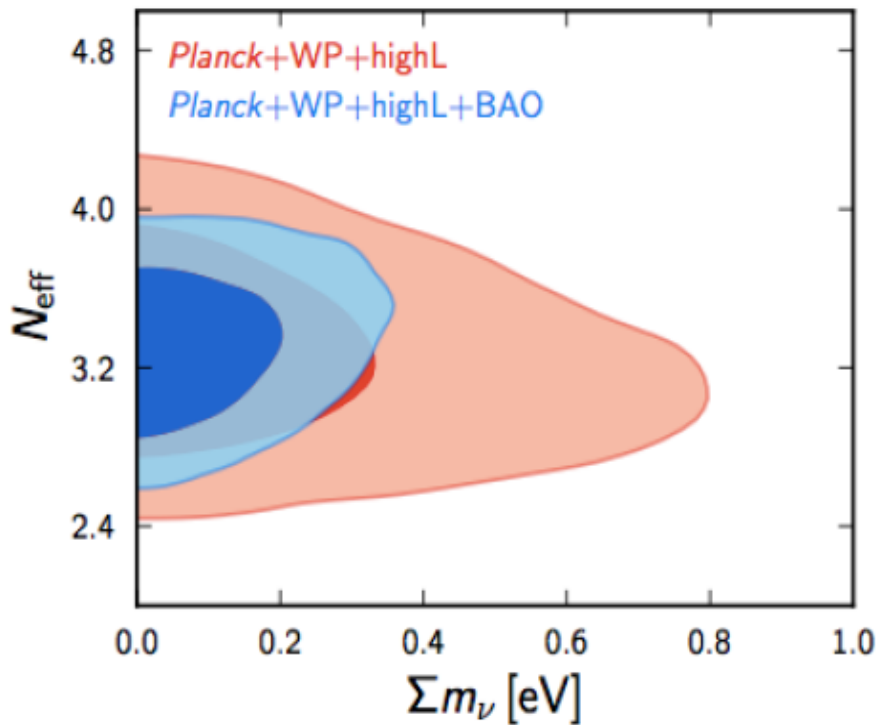
Λ CDM + “SIMPLE” INFLATION

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

$$\Omega_m = 0.314 \pm 0.020$$

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

$$h=0.674\pm0.014$$



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

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 (and controversial!) **BICEP2** results:
 from the measurement of the B-mode polarization of the CMB photons
 → 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**

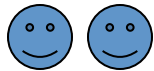
1 sec. after BB

NUMBER OF BARYONS and OF
NEUTRINO SPECIES →

CONFIRMED FROM CMB **350000**
YEARS AFTER BB

BUT ALSO

FRICTION POINTS



-COSMIC MATTER-ANTIMATTER ASYMMETRY

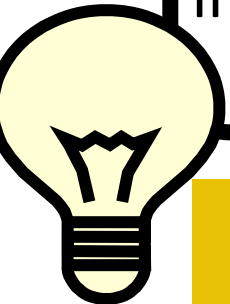
-INFLATION ???

- 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



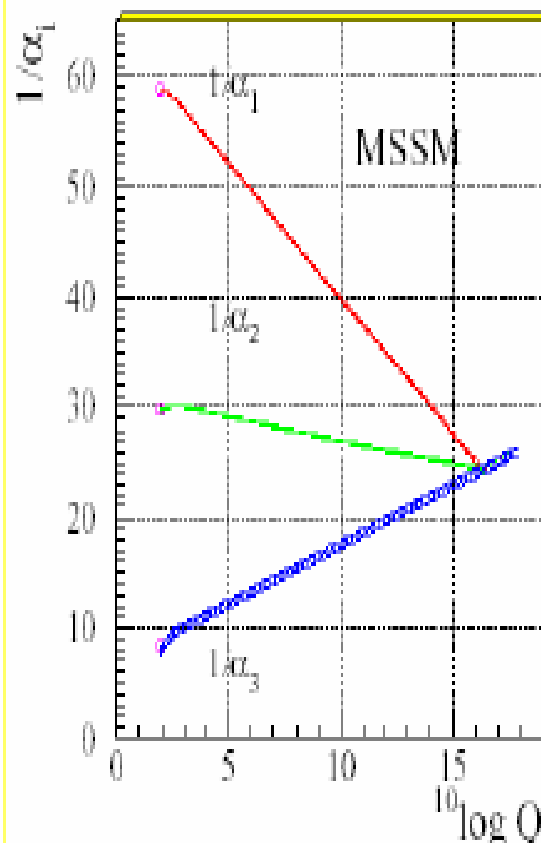
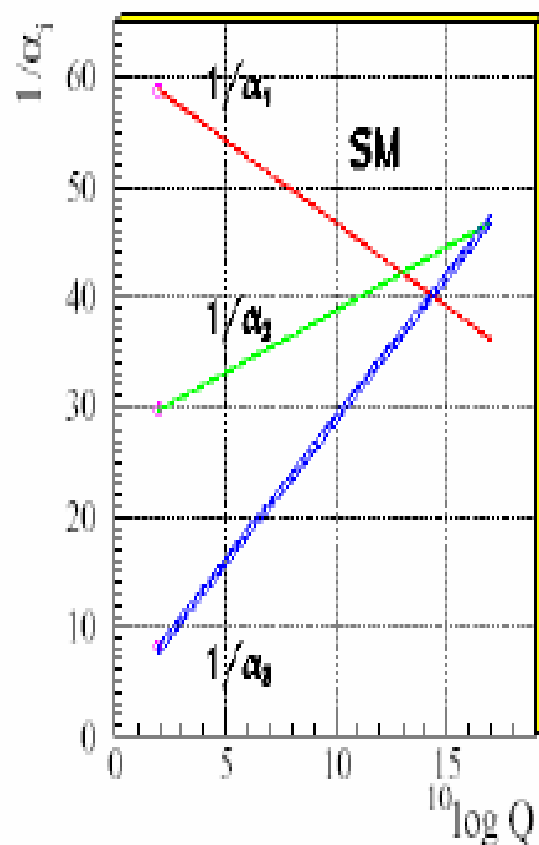
NO NEED FOR THE
NP SCALE TO BE
CLOSE TO THE
ELW. SCALE

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

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

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

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

**e.g. SUSY PARTICLES AT
THE TEV SCALE !**

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 $SU(2) \times U(1)$ 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

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

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

- 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 $\sim$

$$M \gg m_h$$

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

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

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

- **UNNATURAL or FINE-TUNING SOLUTION** tuning of parameters at the scale M with precision $O(m_H/M)^2$
- **NATURAL SOLUTION**
Dynamics or symmetries or space-time modifications giving rise to a UV cut-off $\sim (m_H)^2$
- **SYMMETRY vs. MULTIVERSE**

The BIG and the SMALL- $\dim[m] \neq 0$

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

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

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

but θ very small TODAY at $T=0 \Rightarrow$
 θ very small at $T \neq 0$ 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 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 $\rightarrow$ 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)

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**, just a single higgs doublet accomplishing a two-fold task, namely breaking the EW symmetry AND stabilizing the 5th extra dimension (Geller, Bar-Shalom, Soni)

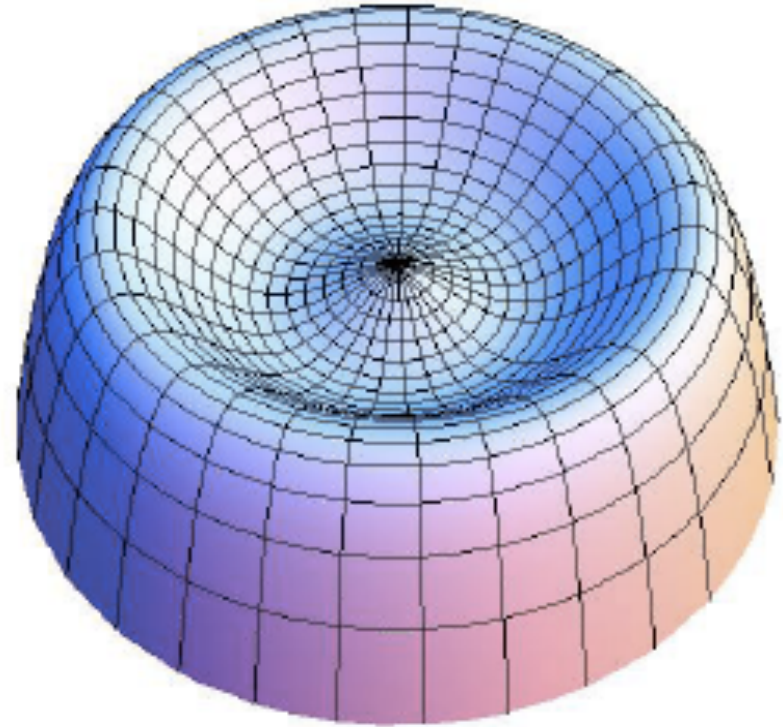
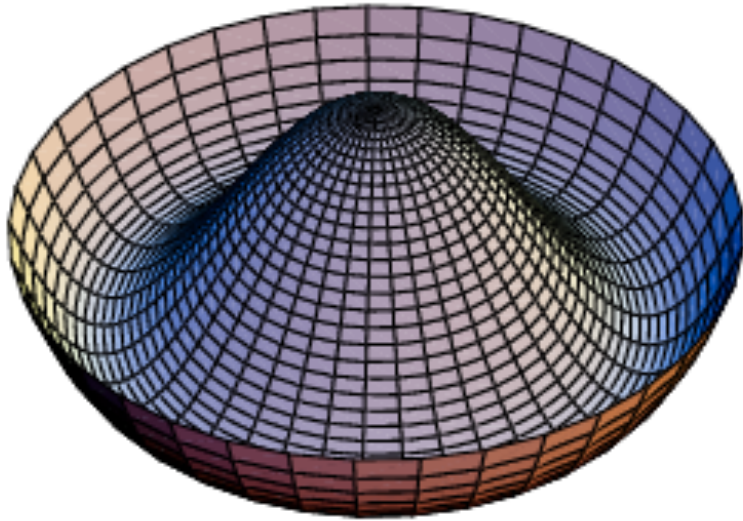
On the peculiar value of M_H

- 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 $\sim 50\%$ of the tree-level value)

STABILITY

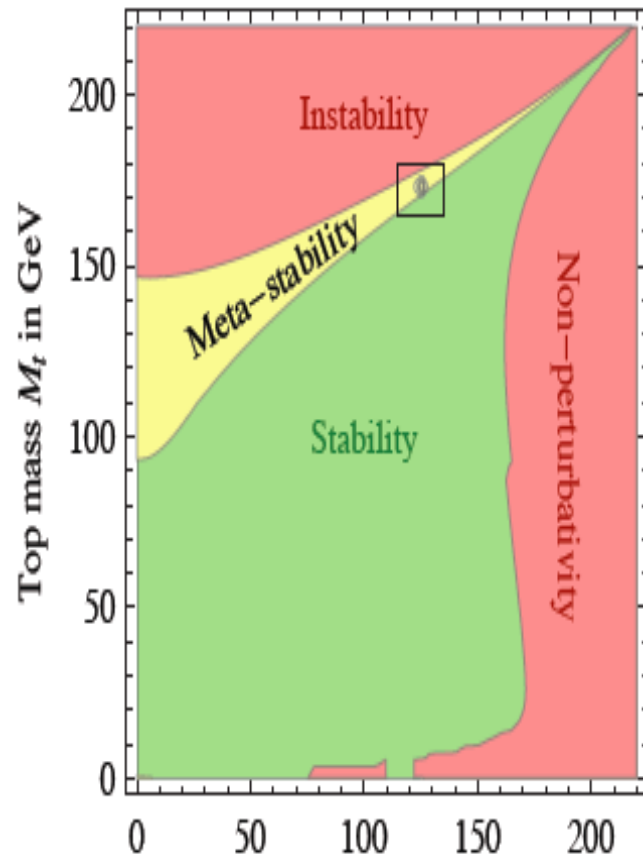


INSTABILITY

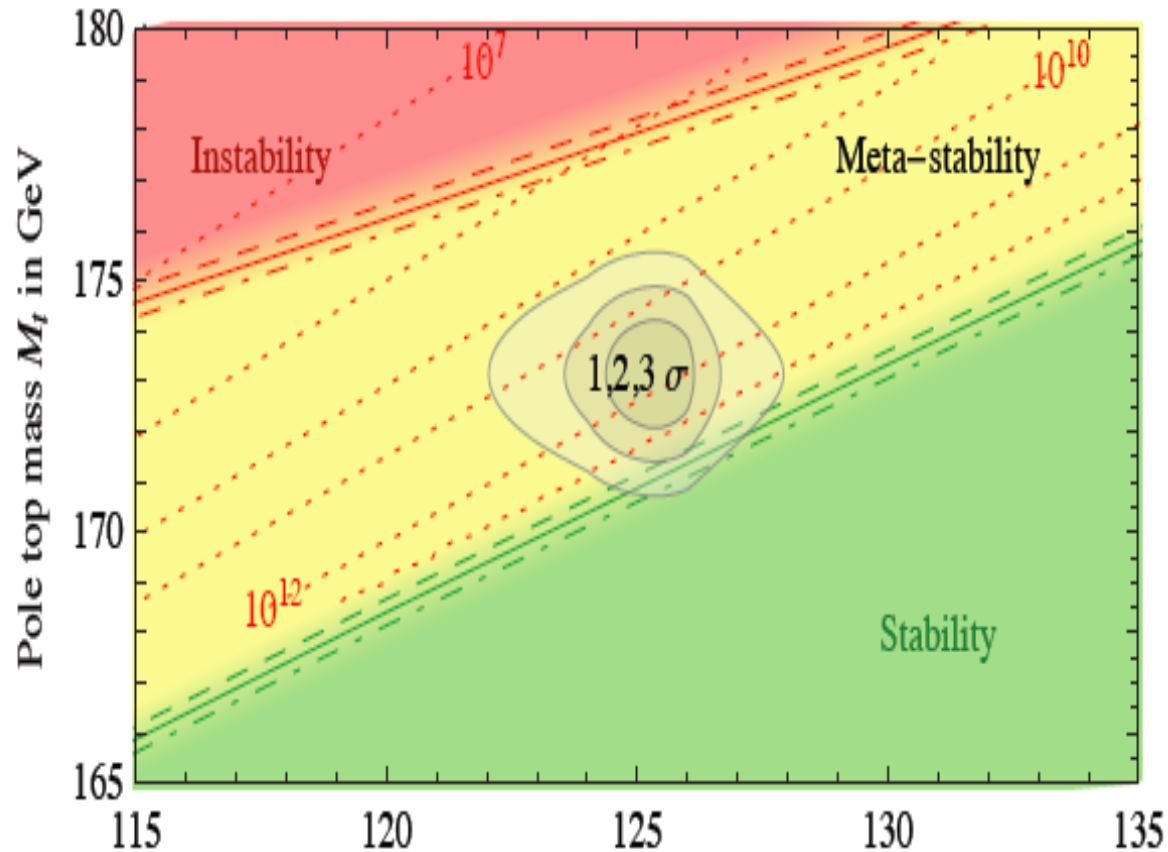


**ON THE IMPORTANCE OF PRECISELY
MEASURING HIGGS and TOP MASSES**

LIVING DANGEROUSLY IN A “PROBABLE” METASTABLE UNIVERSE



Higgs mass M_h in GeV



Higgs mass M_h in GeV

BEZRUKOV, KALMIKOV, KNIEHL, SHAPOSHNIKOV 2012;

DEGRASSI, DI VITA, ELIAS-MIRO', ESPINOSA, GIUDICE, ISIDORI, STRUMIA 2012

FIRST COMPLETE ANALYSIS NNLO OF THE SM HIGGS POTENTIAL

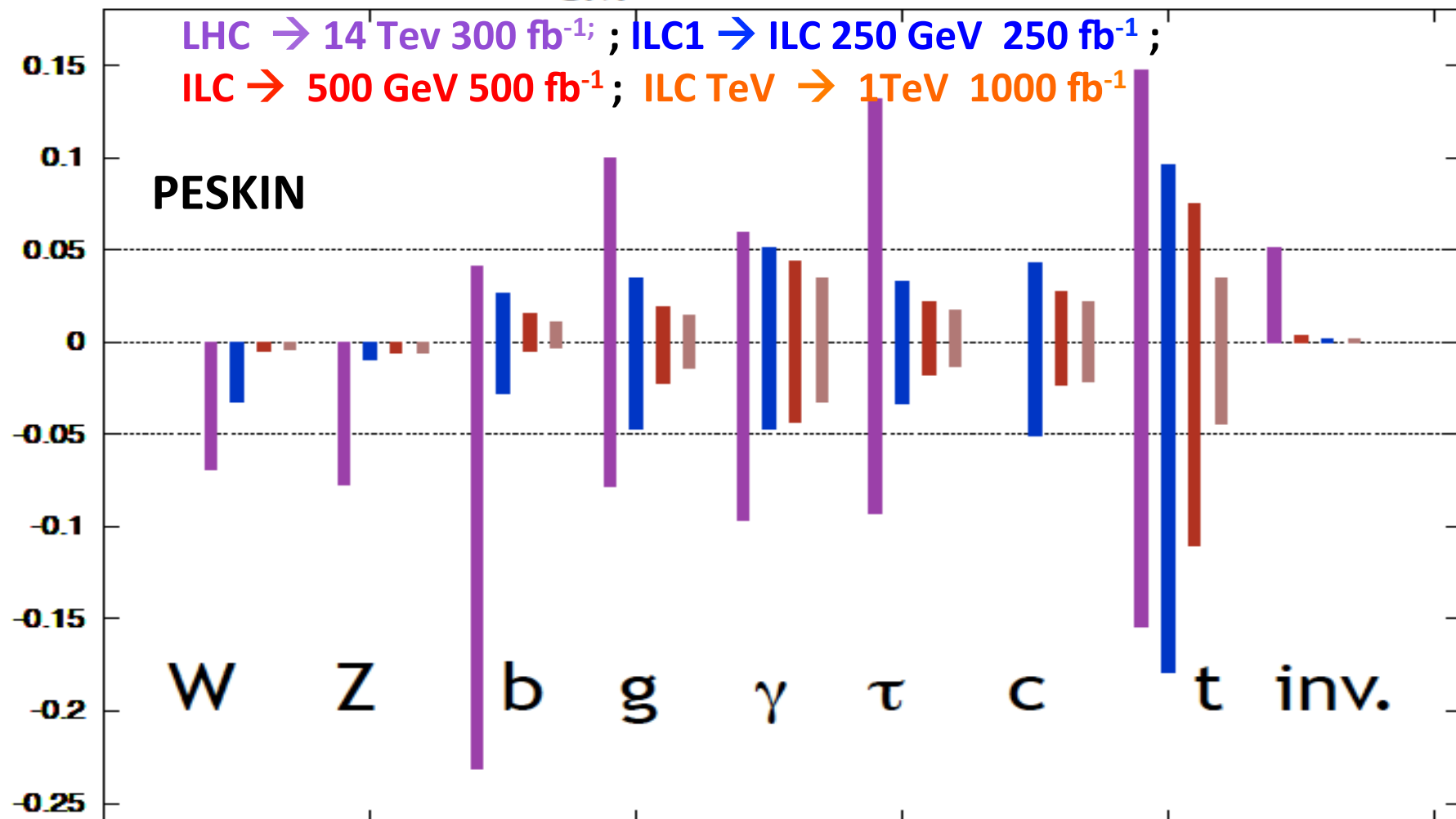
HIGGS Couplings Sensitivity at LHC and ILC

TANABE at this meeting

$g(hAA)/g(hAA)|_{SM}^{-1}$ LHC/ILC1/ILC/ILCTeV

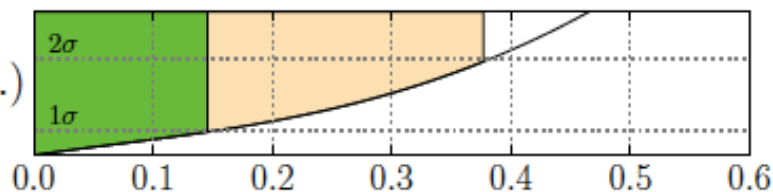
LHC $\rightarrow$ 14 TeV 300 fb $^{-1}$; ILC1 $\rightarrow$ ILC 250 GeV 250 fb $^{-1}$;
ILC $\rightarrow$ 500 GeV 500 fb $^{-1}$; ILC TeV $\rightarrow$ 1TeV 1000 fb $^{-1}$

PESKIN



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

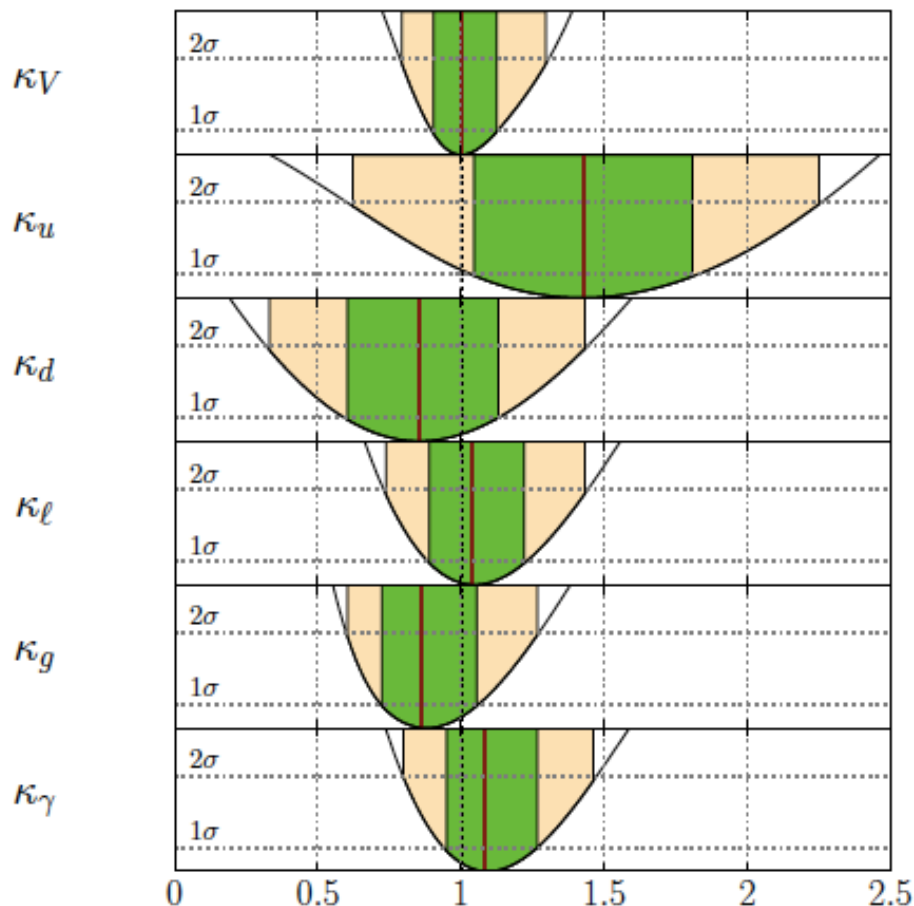
ATLAS + CMS + Tev:
 $\text{BR}(H \rightarrow \text{inv.})$



HiggsSignals

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

Seven fit parameters



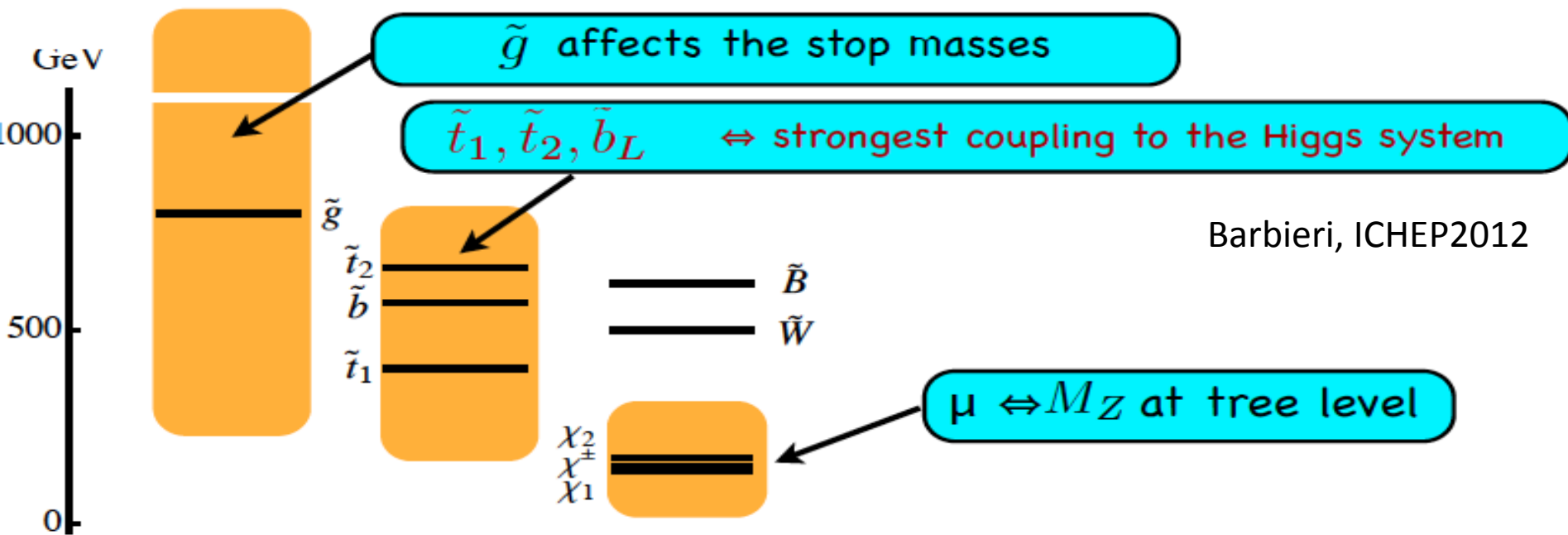
G. WEIGLEIN, IPA2014

⇒ 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”

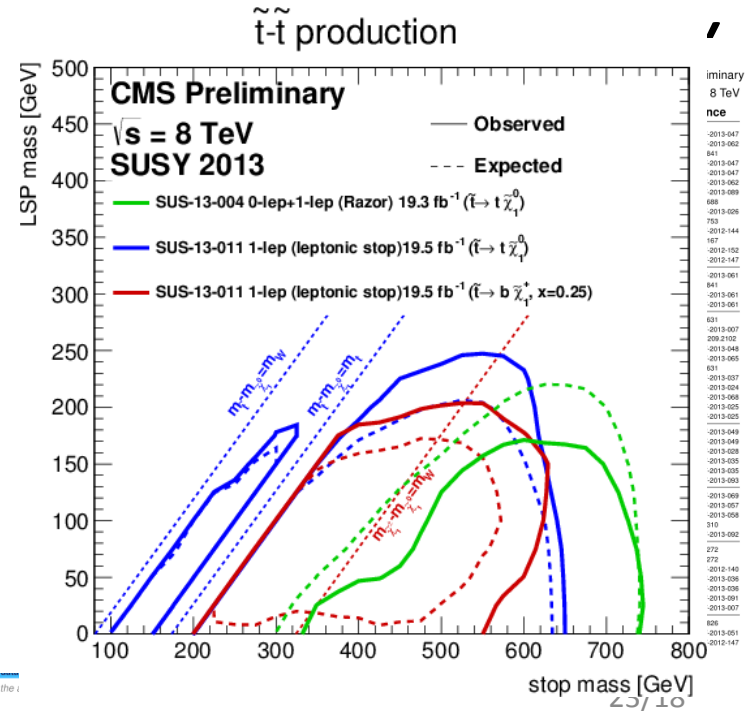
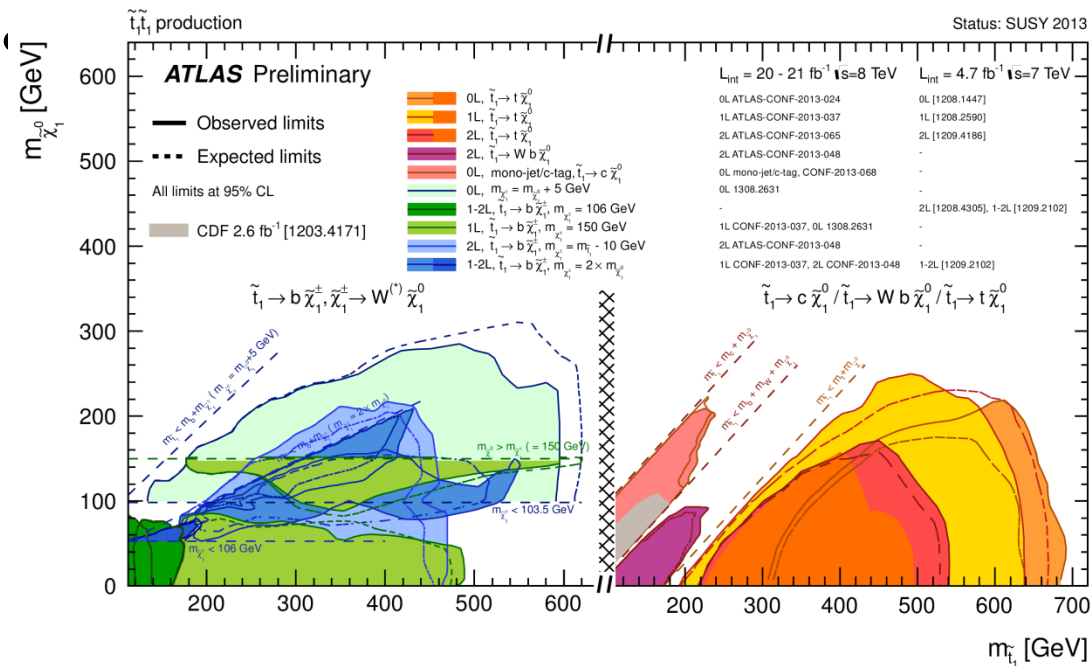


orange areas indicative and dependent on how the Higgs boson gets its mass

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

SUSY searches

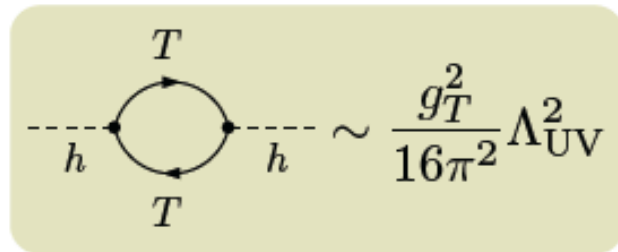
- Higgs mass value reduces SUSY parameter space
- Direct searches unsuccessful $\rightarrow$ gluinos well above 1 TeV
- Working on stop expected lighter



Higgs and flavor physics as indirect BSM probes

NEUBERT SUSY2012

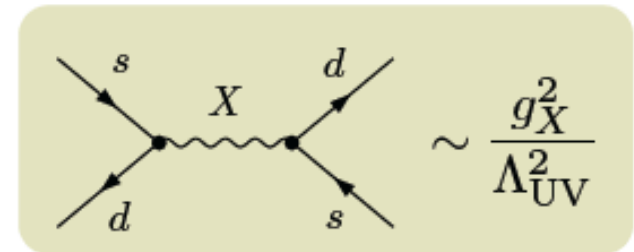
$$\mathcal{L}_{\text{EFT}} = \underbrace{\Lambda_{\text{UV}}^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2}_{\text{electroweak symmetry breaking} \quad \Downarrow \quad \text{Higgs mass}} + \mathcal{L}_{\text{SM}}^{\text{gauge}} + \mathcal{L}_{\text{SM}}^{\text{Yukawa}} + \underbrace{\frac{\mathcal{L}^{(5)}}{\Lambda_{\text{UV}}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\text{UV}}^2} + \dots}_{\Downarrow}$$



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

no fine-tuning $\Downarrow$

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



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

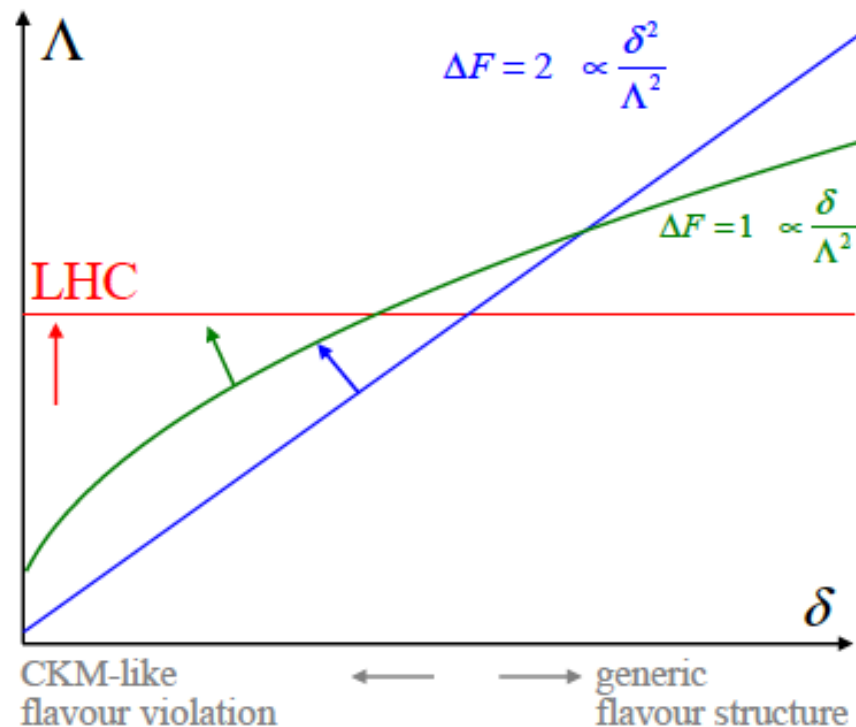
bounds on flavor mixing $\Downarrow$ assuming *generic* flavor structure

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

Possible solutions to flavor problem explaining $\Lambda_{\text{Higgs}} \ll \Lambda_{\text{flavor}}$:

- (i) $\Lambda_{\text{UV}} \gg 1 \text{ TeV}$: **Higgs fine tuned**, new particles too heavy for LHC
- (ii) $\Lambda_{\text{UV}} \approx 1 \text{ TeV}$: quark flavor-mixing protected by a **flavor symmetry**

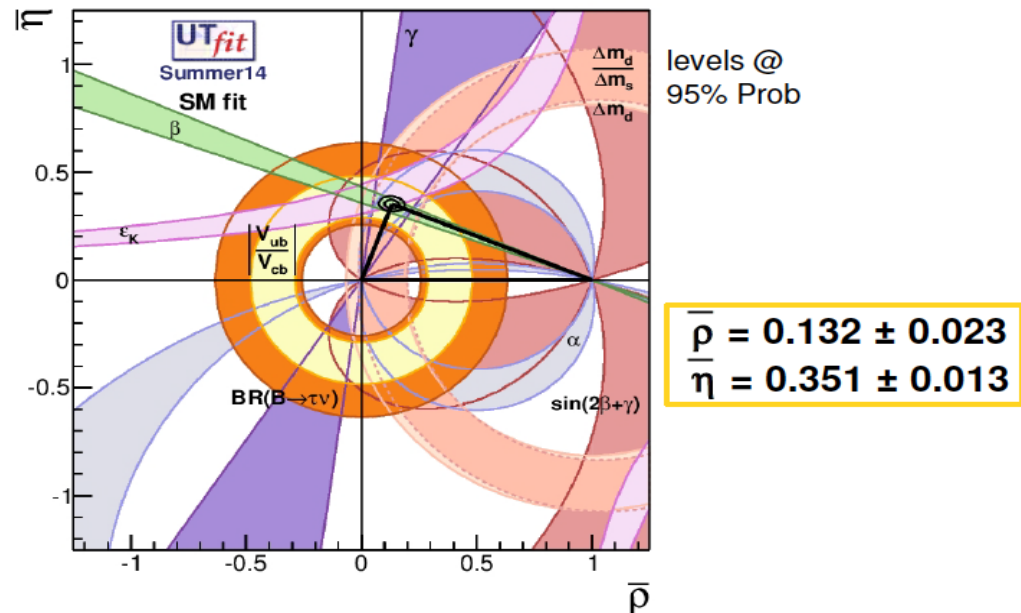
Flavour vs. collider bounds on the new physics scale Λ



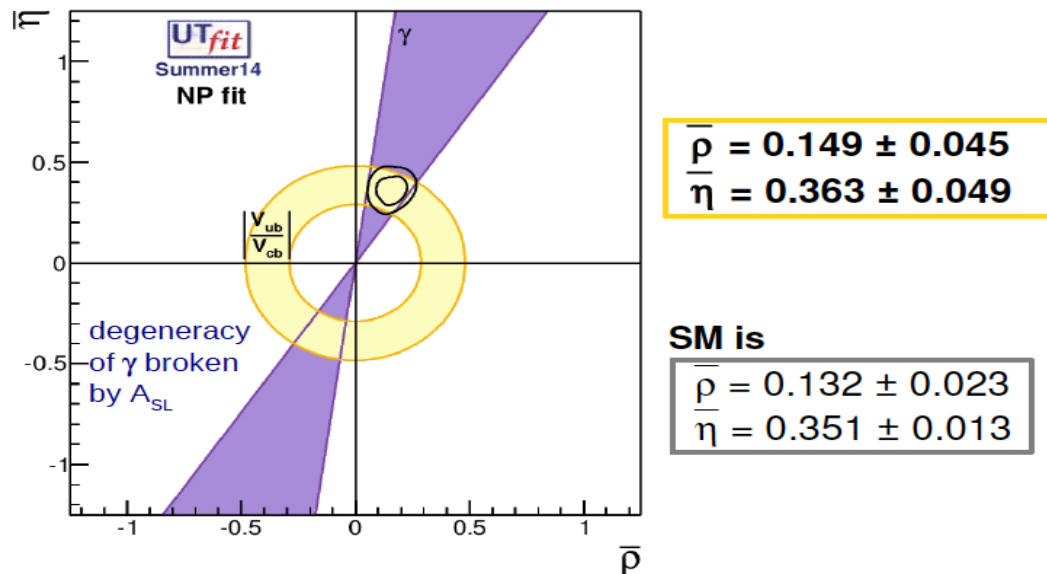
- Rare decays: much more observables, more sensitive to “small” flavour violation at “natural” scales

Unitarity Triangle analysis in the SM:

Observables	Accuracy
$ V_{ub}/V_{cb} $	$\sim 13\%$
ϵ_K	$\sim 0.5\%$
Δm_d	$\sim 1\%$
$ \Delta m_d/\Delta m_s $	$\sim 1\%$
$\sin 2\beta$	$\sim 3\%$
α	$\sim 8\%$
γ	$\sim 10\%$
$BR(B \rightarrow \tau \nu)$	$\sim 19\%$



NP analysis results



Unitarity Triangle analysis in the SM:

obtained excluding
the given constraint
from the fit

Observables	Measurement	Prediction	Pull ($\# \sigma$)
$\sin 2\beta$	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
$ V_{ub} \cdot 10^3$	3.75 ± 0.46	3.62 ± 0.12	< 1
$ V_{ub} \cdot 10^3$ (incl)	4.40 ± 0.31	—	~ 2.3
$ V_{ub} \cdot 10^3$ (excl)	3.42 ± 0.22	—	< 1
$ V_{cb} \cdot 10^3$	40.9 ± 1.0	42.1 ± 0.7	< 1
B_K	0.766 ± 0.010	0.841 ± 0.078	< 1
$\text{BR}(B \rightarrow \tau \nu)[10^{-4}]$	1.14 ± 0.22	0.81 ± 0.07	~ 1.4
$\text{BR}(B_s \rightarrow \ell \ell)[10^{-9}]$	2.9 ± 0.7	3.92 ± 0.16	~ 1.3
$\text{BR}(B_d \rightarrow \ell \ell)[10^{-9}]$	0.37 ± 0.15	0.114 ± 0.007	~ 1.7
$A_{\text{SL}}^d \cdot 10^3$	-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”

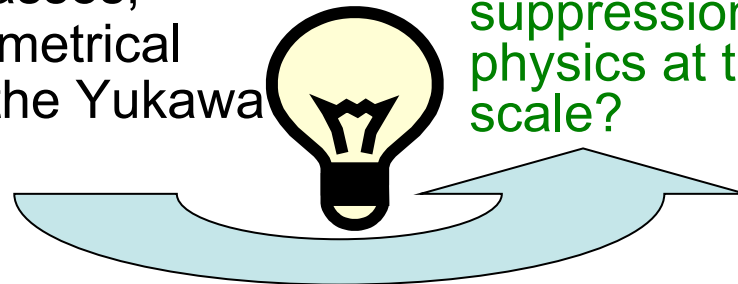
(new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, ...?)

FCNC

Flavour changing neutral current (FCNC) processes are suppressed.

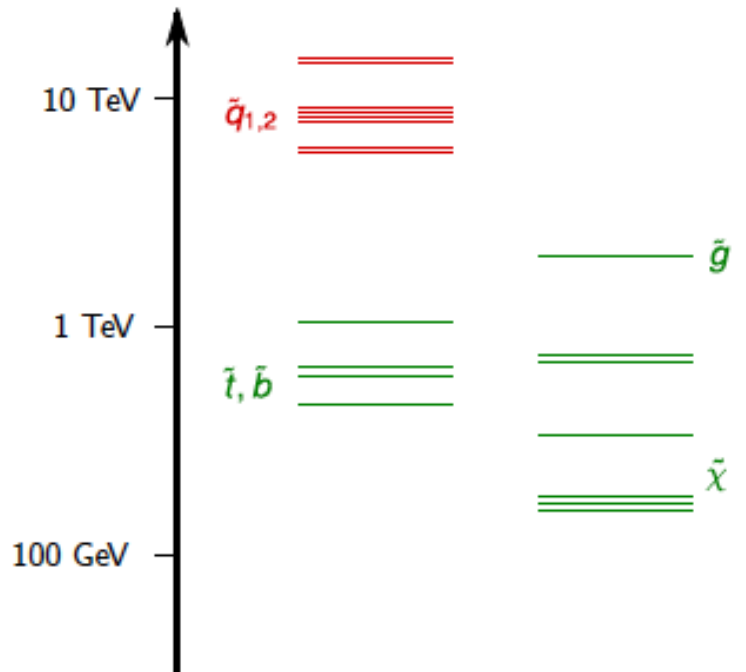
In the SM two nice mechanisms are at work: the **GIM mechanism** and the structure of the **CKM mixing matrix**.

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



Natural SUSY & $U(2)^3$

Straub 2014



- Strong LHC bounds on 1st/2nd generation squarks
- Light 3rd generation squarks to solve hierarchy problem

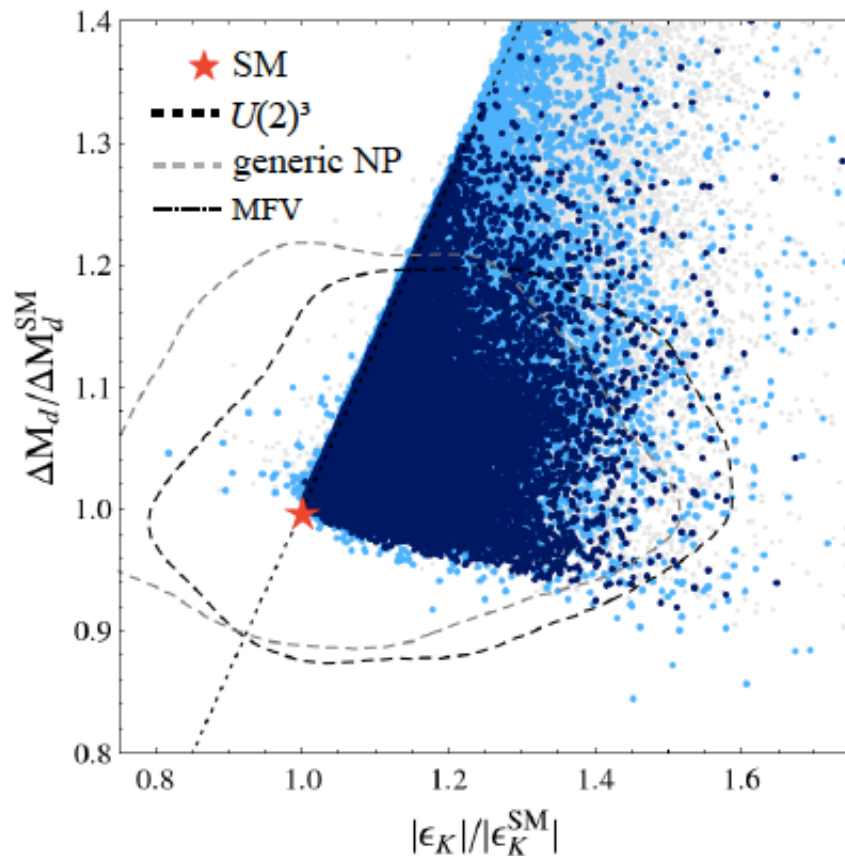
Natural SUSY with split generations + CKM-like flavour violation: approximate, minimally broken $U(2)^3$ flavour symmetry (“split MFV”)

[Barbieri et al. 1105.2296]

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

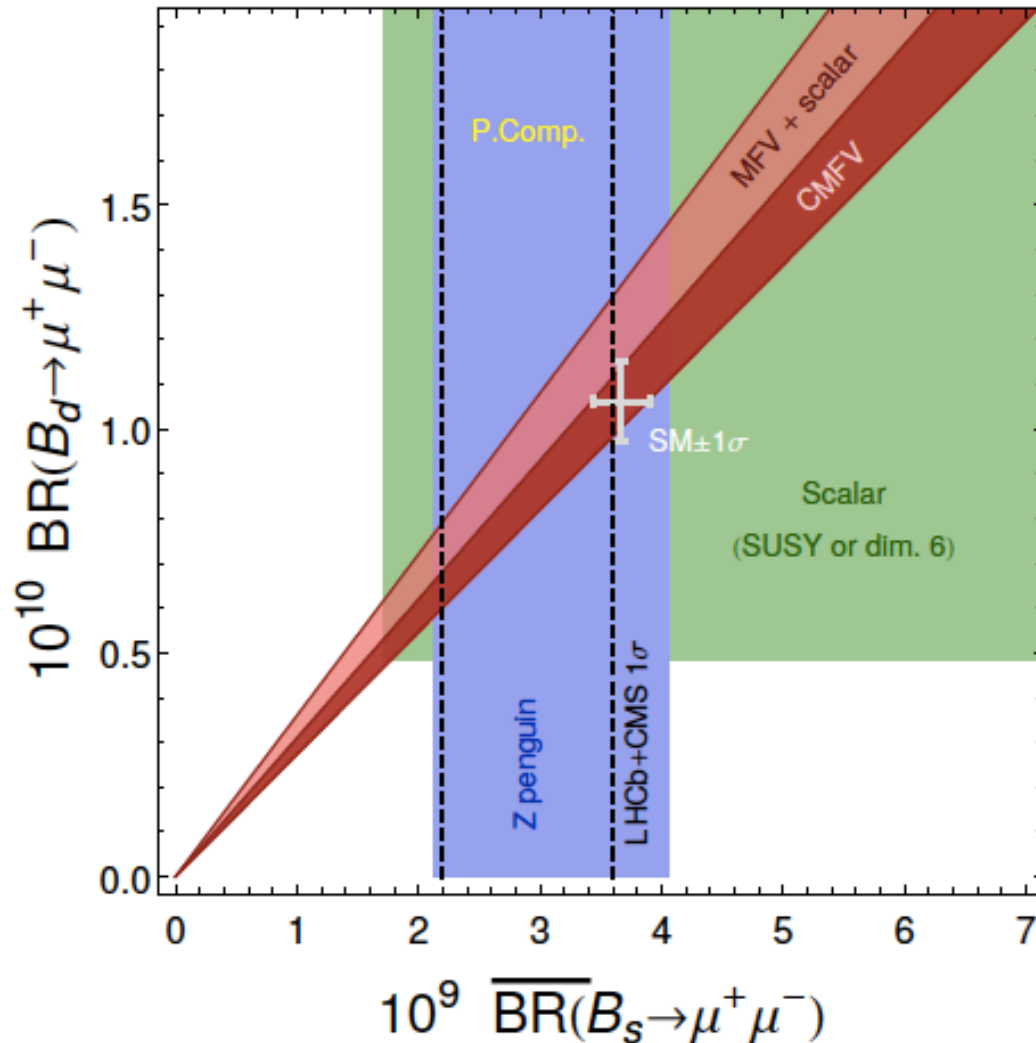
D. STRAUB, IPA2014

Numerical results for $\Delta F = 2$ observables



- All blue points fulfil 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

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

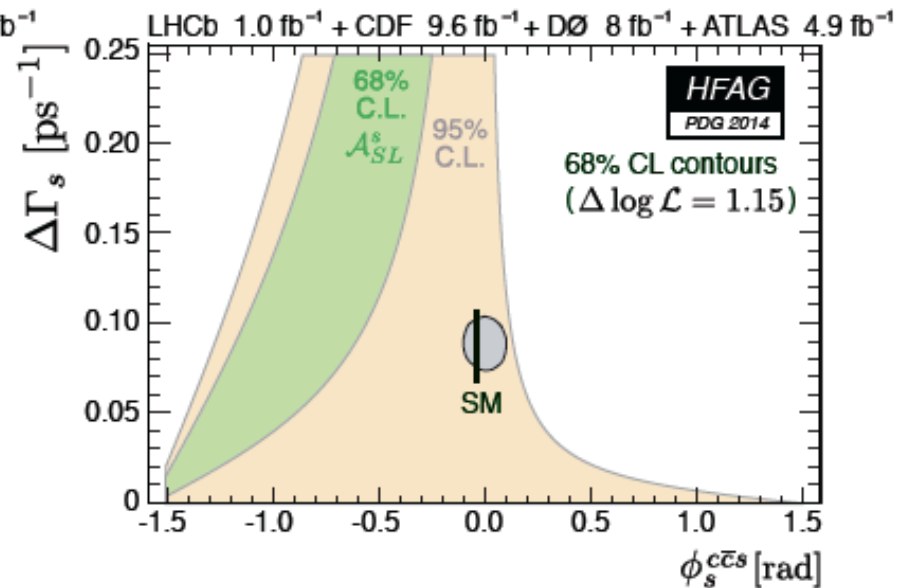
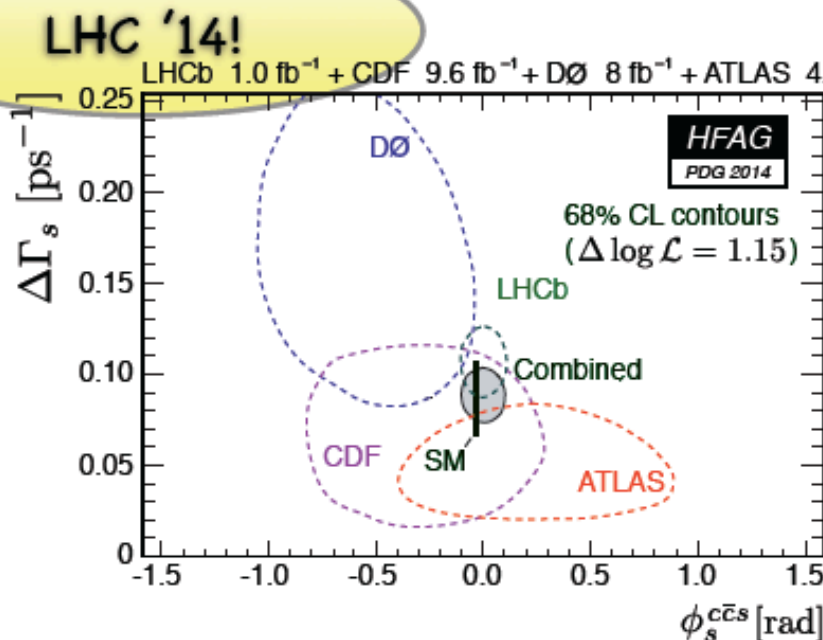


- ▶ $B_s \rightarrow \mu\mu$ vs. $B_d \rightarrow \mu\mu$: powerful test of Minimal Flavour Violation
- ▶ Beyond MFV: scalar operators (e.g. SUSY) unconstrained by other processes
- ▶ Z penguins beyond MFV: size constrained by $b \rightarrow s \ell^+ \ell^-$ processes (notably $B \rightarrow K^* \mu^+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

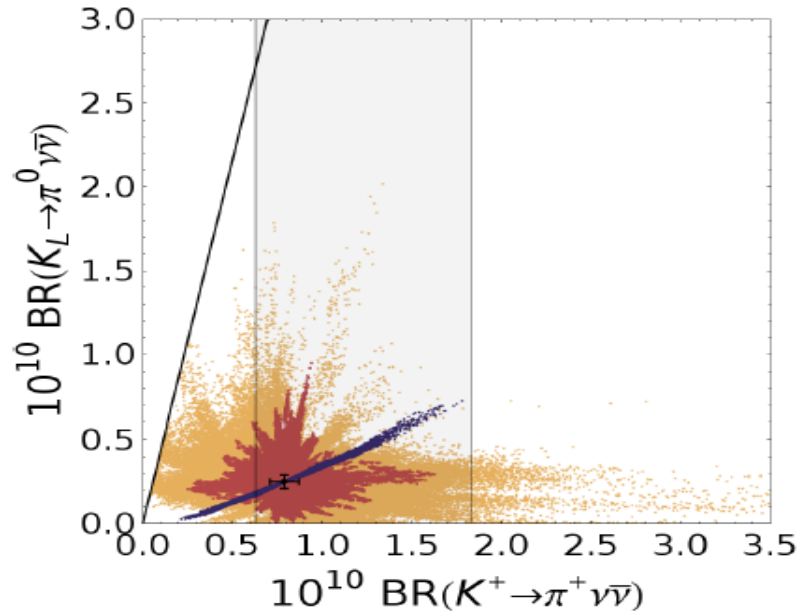
B_s mixing phase measurement

- ▶ The experimental errors are significantly reduced by the new LHCb measurement.
- ▶ The current measurement of Φ_s is consistent to SM ($= -0.0363 \pm 0.0016$):
 $\Phi_s = 0.070 \pm 0.055$
- ▶ LHCb has an ability to reach to the error down to $\delta\Phi_s = \pm 0.025$ by 2018 and the upgrade can reach to the precision of $\delta\Phi_s = \pm 0.009$.
- ▶ So it is *too early to conclude*! New physics may appear here!

E. Kou, IPA2014



$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ vs. } K_L \rightarrow \pi^0 \nu \bar{\nu}$$

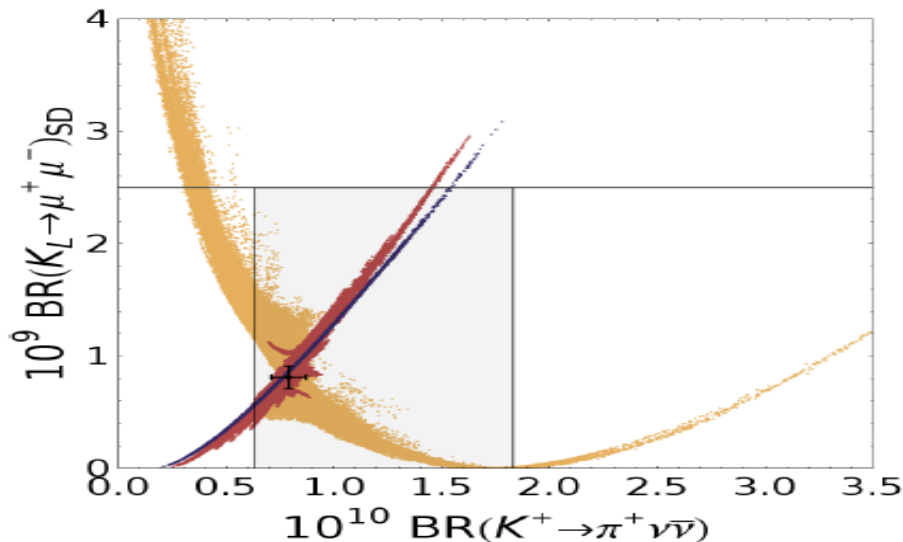


triplet + anarchy
bidoublet + anarchy
bidoublet + $U(2)^3$

- Visible effects in both modes
- $U(2)^3$: aligned in phase with the SM

[Straub 1302.4651]

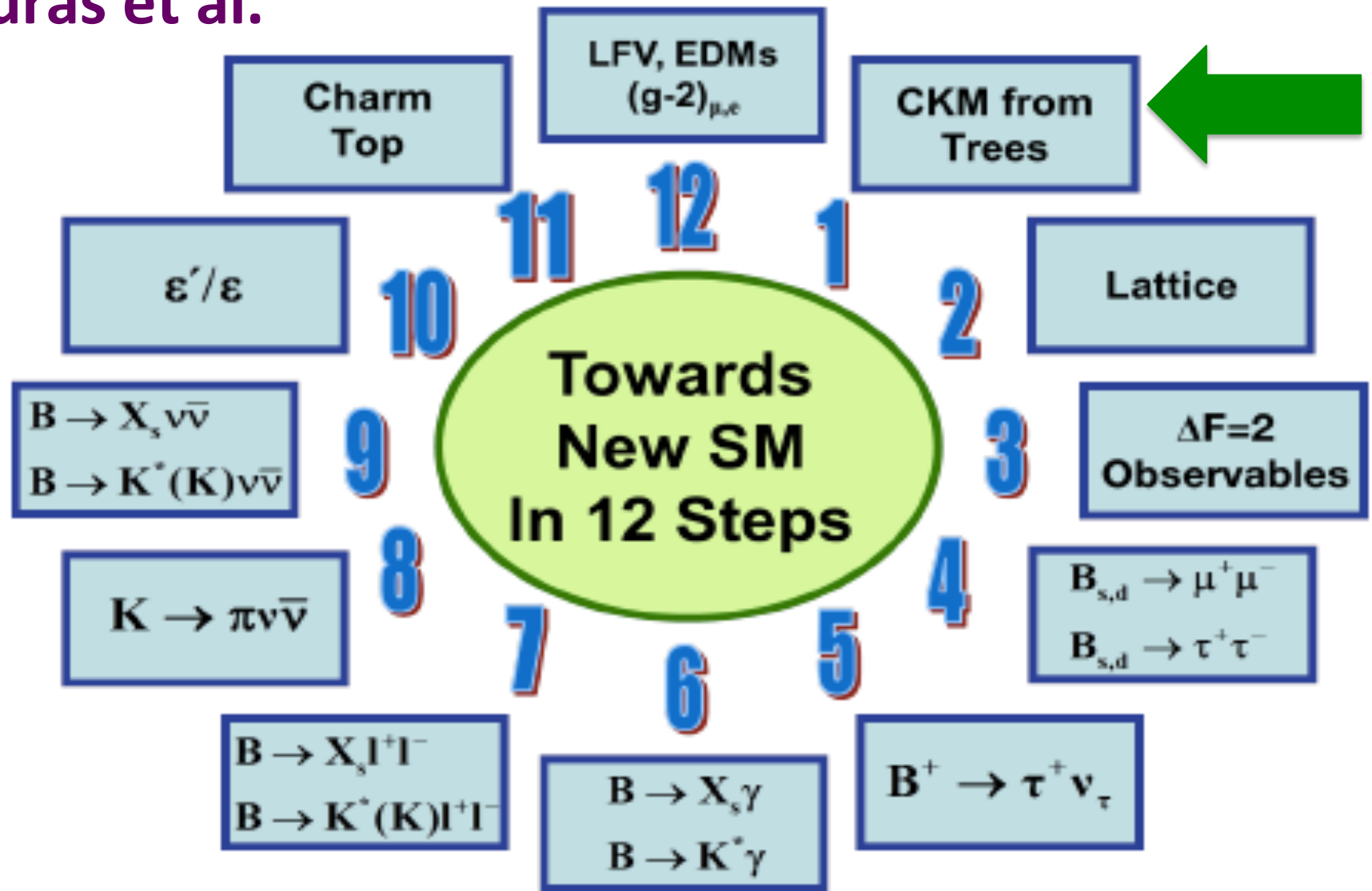
$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ vs. } K_L \rightarrow \mu^+ \mu^-$$



**STILL ROOM FOR VISIBLE NEW
PHYSICS EFFECTS FOR INSTANCE IN
FCNC KAON PHYSICS IN SPITE OF
ALL THE STRINGENT HIGH-ENERGY
AND HIGH-INTENSITY CONSTRAINTS**

The flavour clock cannot stop !!!

Buras et al.



THE FATE OF LEPTON NUMBER

L VIOLATED

ν Majorana ferm.

SMALLNESS of m_ν

PRESENCE OF A **NEW** PHYSICAL MASS SCALE

L CONSERVED

ν Dirac ferm.
(dull option)

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

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

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

NEW HIGH SCALE **NEW LOW SCALE**

SEE - SAW MECHAN.

Minkowski; Gell-Mann,
Ramond, Slansky,
Vanagida

ν_R ENLARGEMENT OF THE
FERMIONIC SPECTRUM

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

$$\begin{array}{ccc} \nu_L & \sim \frac{\nu_L}{\langle \phi \rangle} & \frac{\nu_R}{\langle \phi \rangle} \\ \nu_R & \langle \phi \rangle & M \end{array}$$

LR
Models?

MAJORON MODELS

Gelmini, Roncadelli

Δ ENLARGEMENT OF THE
HIGGS SCALAR SECTOR

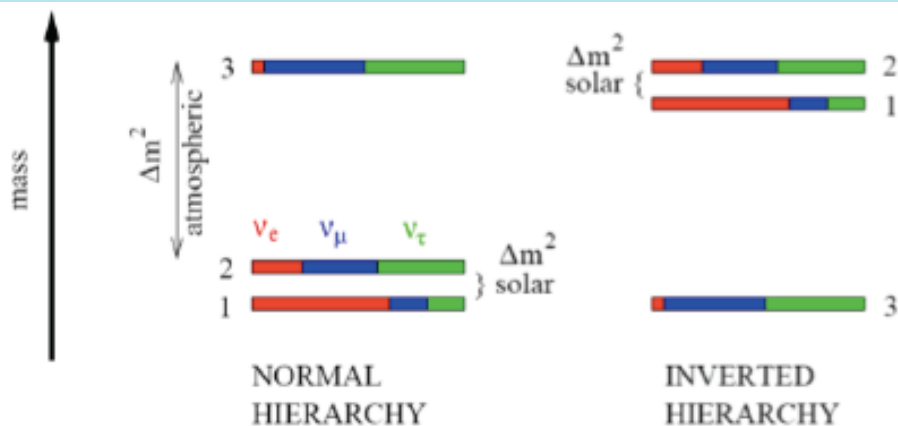
$$h \bar{\nu}_L \nu_L \Delta$$

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

N.B.: EXCLUDED BY LEP!

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**($\theta_{12}, \theta_{13} \rightarrow$ **mass hierarchy**):
 - KamLAND, Daya Bay $\rightarrow$ JUNO, Double CHOOZ, Reno,...
- **Accelerator neutrinos**($\theta_{23}, \theta_{13} \rightarrow$ **mass hierarchy, δ , ...**):
 - MINOS, **OPERA**, MiniBooNe, **T2K**, NOVA, **ICARUS**...



CPV

+ A number of anomalies:

LSND ?

Reactor neutrino flux ?

Sterile neutrinos ? MiniBoone

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

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

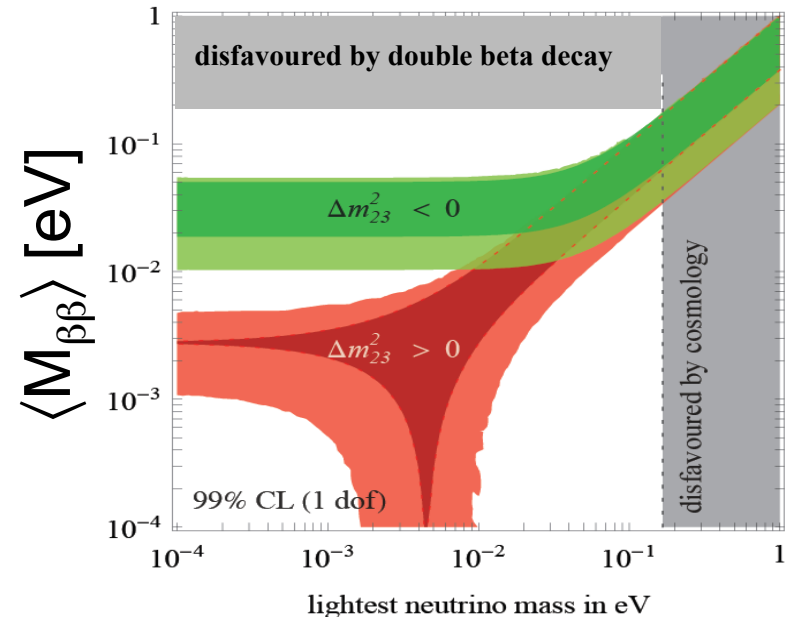
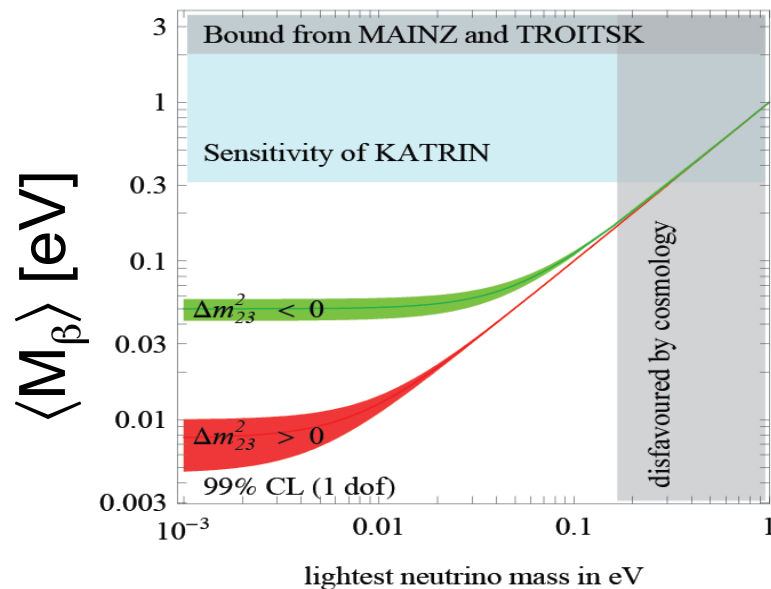
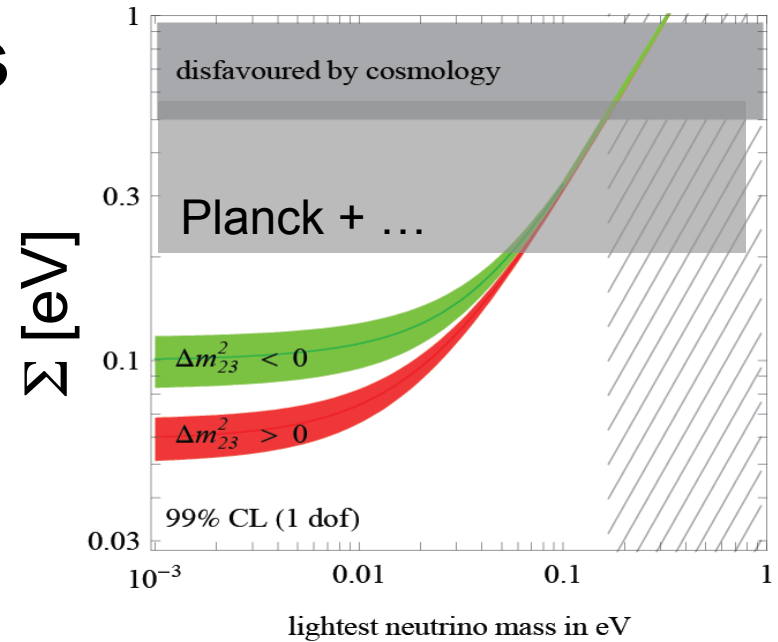
double β decay
coherent sum
virtual neutrino
Majorana phases

Status on neutrino mass

The three constrained parameters can be plotted as a function of the lightest neutrino mass

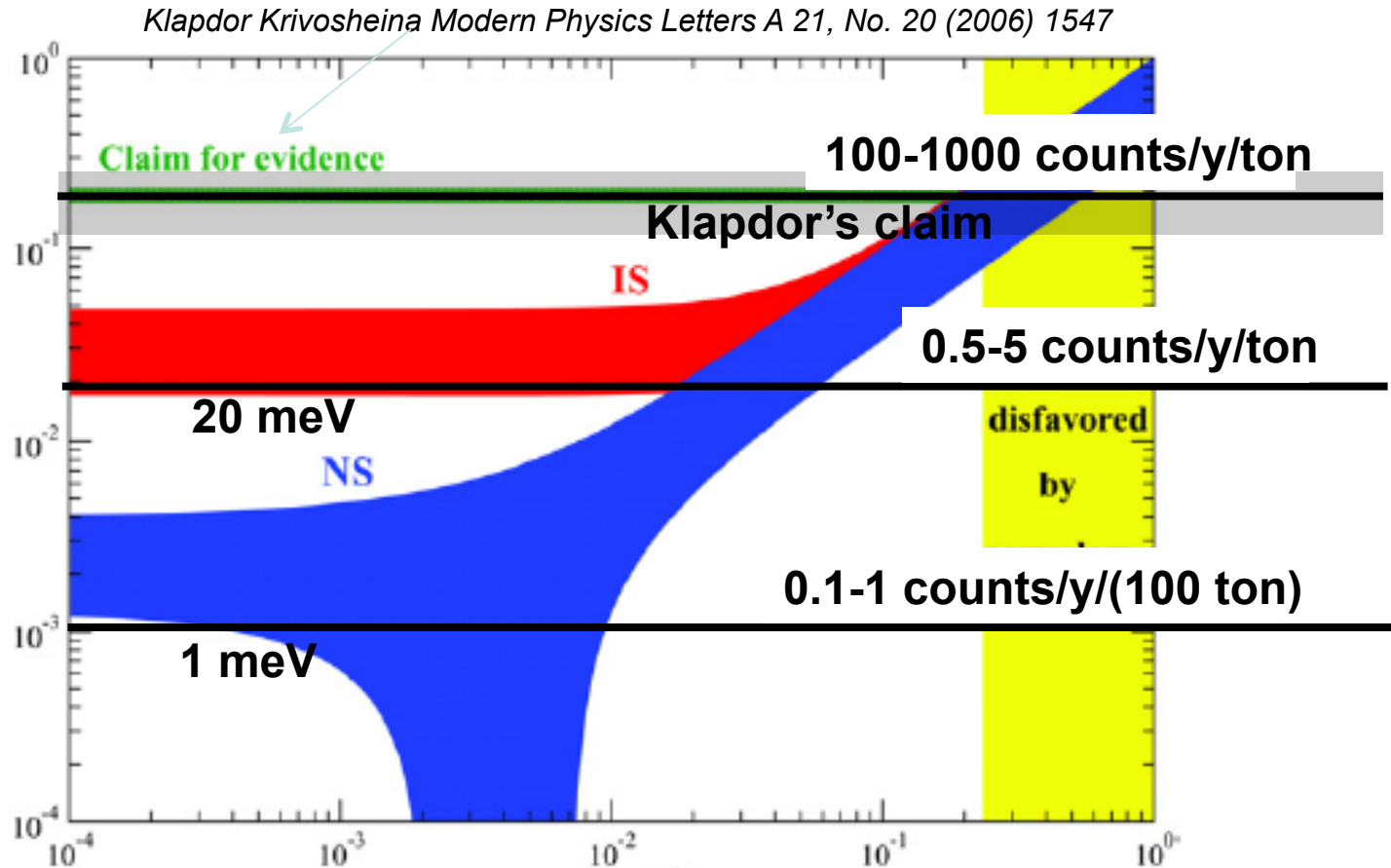
Two bands appear in each plot, corresponding to **inverted** and **direct hierarchy**

The two bands merge in the **degenerate case** (the only one presently probed)



Three challenges for 0ν -DBD search

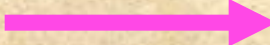
$\langle M_{\beta\beta} \rangle$ [eV]



MATTER-ANTIMATTER ASYMMETRY $\longleftrightarrow$ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

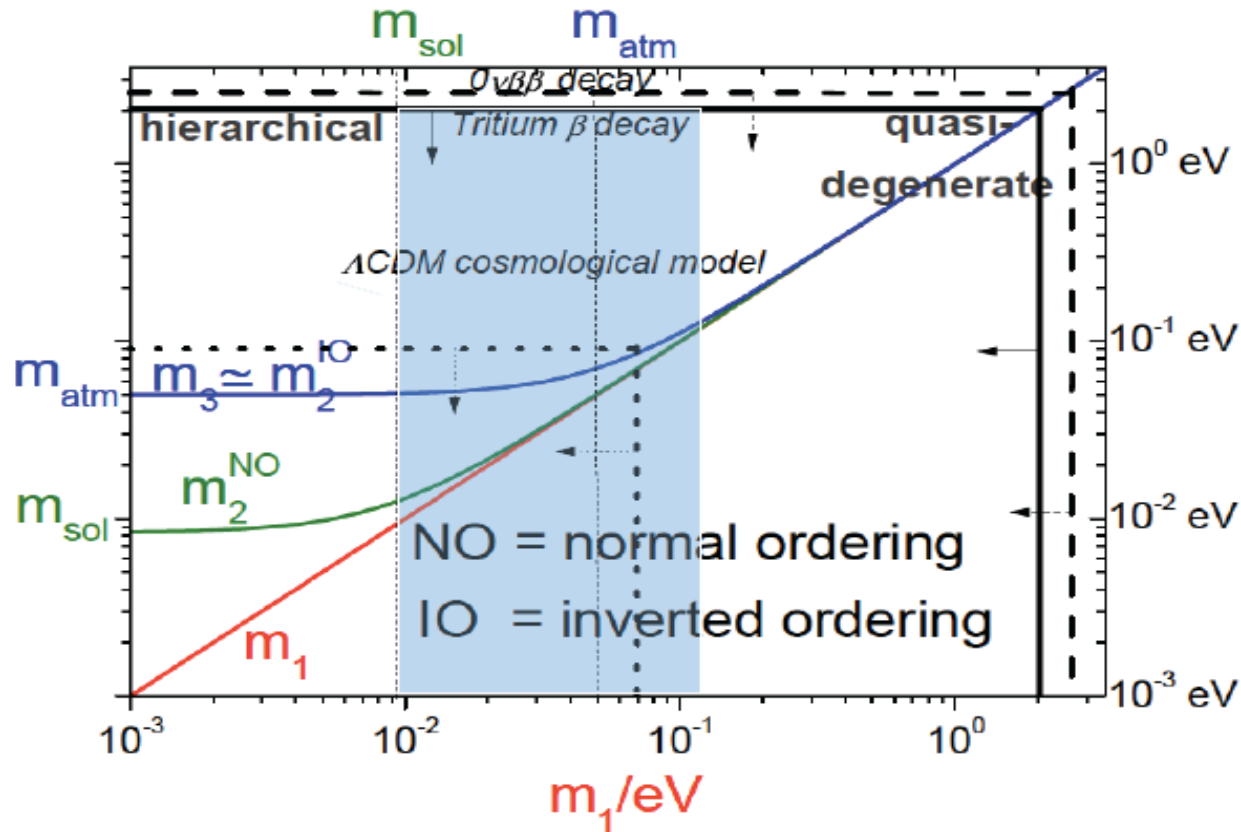
- Key-ingredient of the SEE-SAW mechanism for neutrino masses: **large Majorana mass for RIGHT-HANDED neutrino**
- In the early Universe the heavy RH neutrino decays with Lepton Number violation; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

VANILLA LEPTOGENESIS !

 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 !



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

P. Di Bari, Sophie King, M. Re Fiorentin 2014

LFV IN SUSY SEE-SAW

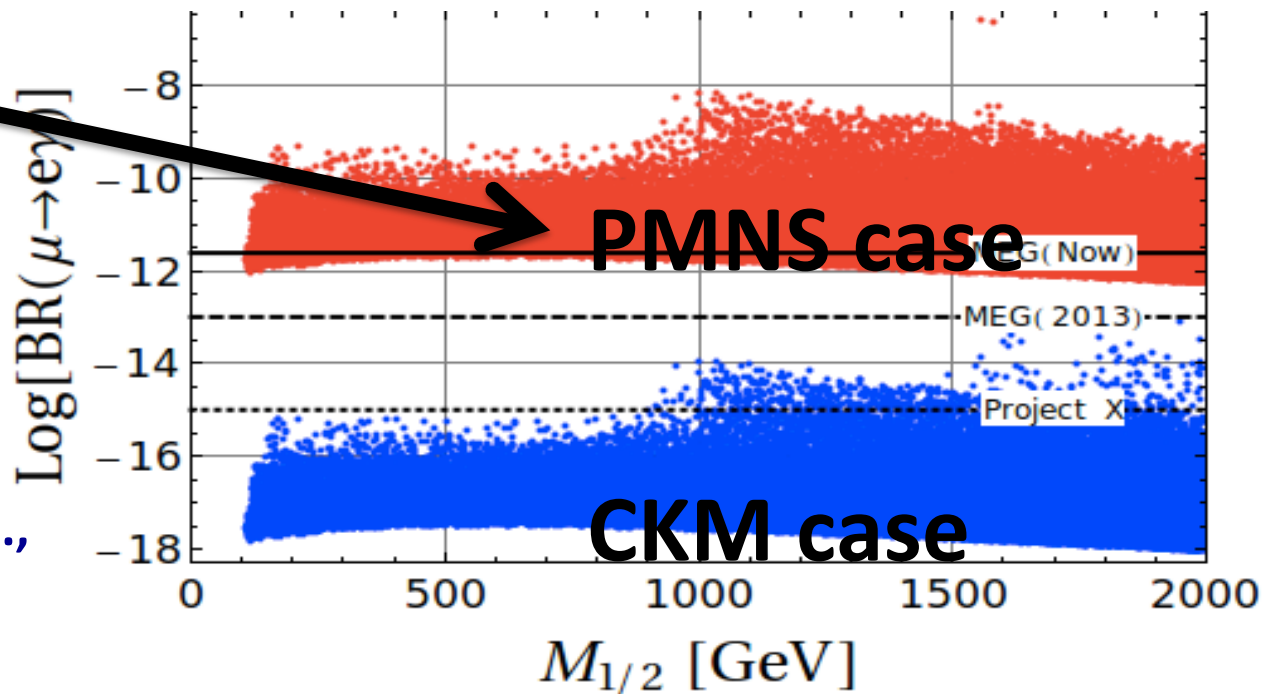
SEE- SAW (type 1) LOW-ENERGY SUSY

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

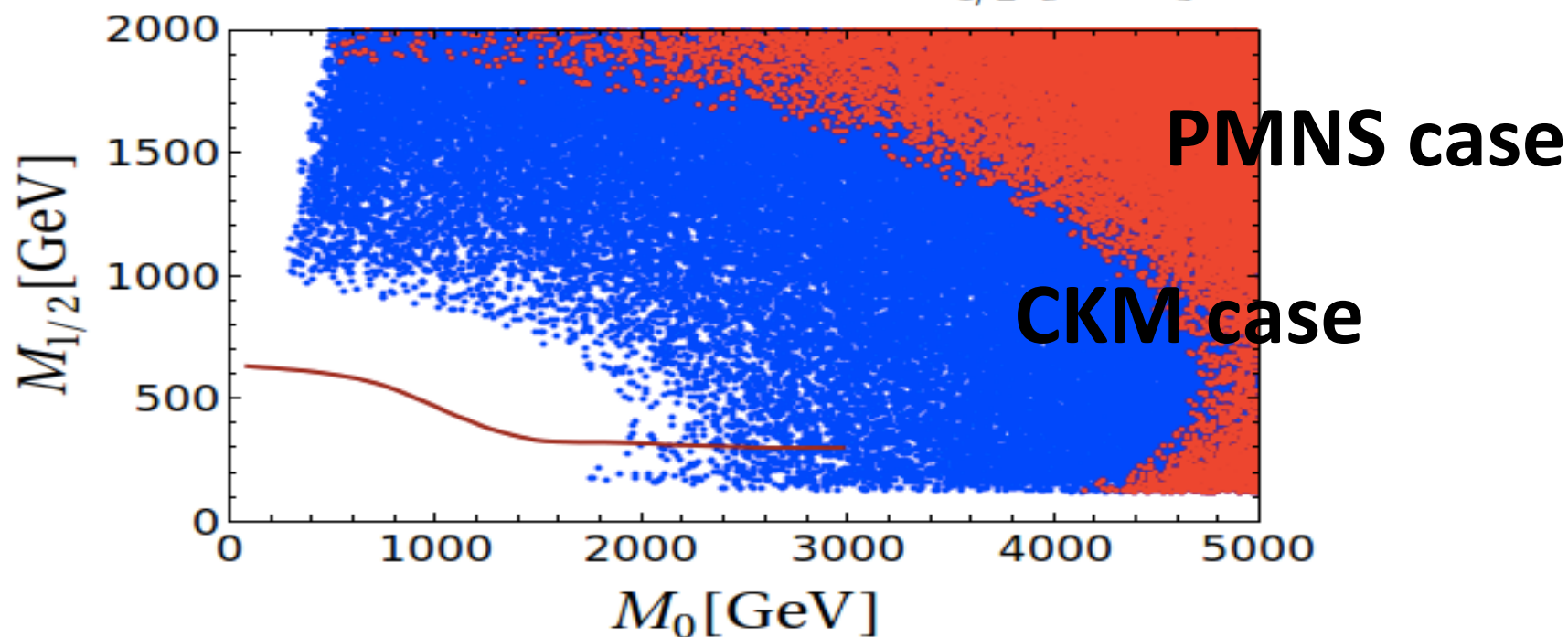
YUKAWA COUPLINGS OF THE
NEUTRINO DIRAC MASS
CONTRIBUTIONS, i.e. **THE**
YUKAWAs of the
HIGGS couplings to
the LEFT- and RIGHT –
HANDED NEUTRINOS

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

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

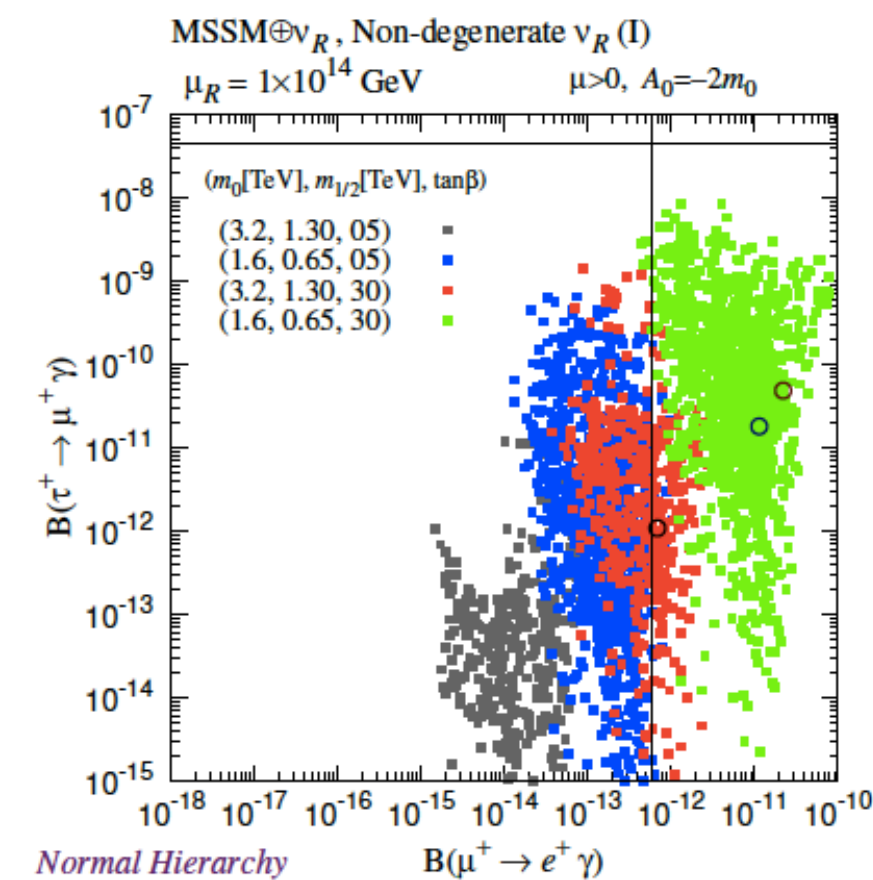


Calibbi, Chowdhuri, A. M.,
Patel, Vempati 2012

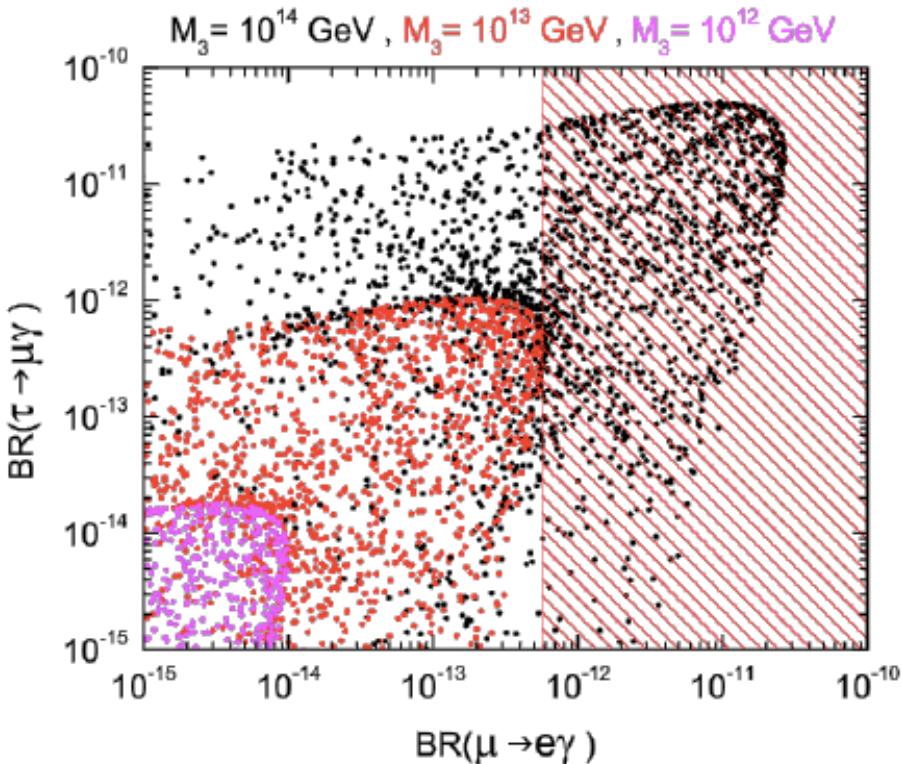


SUSY Type I seesaw model

SUSY parameters fixed, ν_R parameters varied:

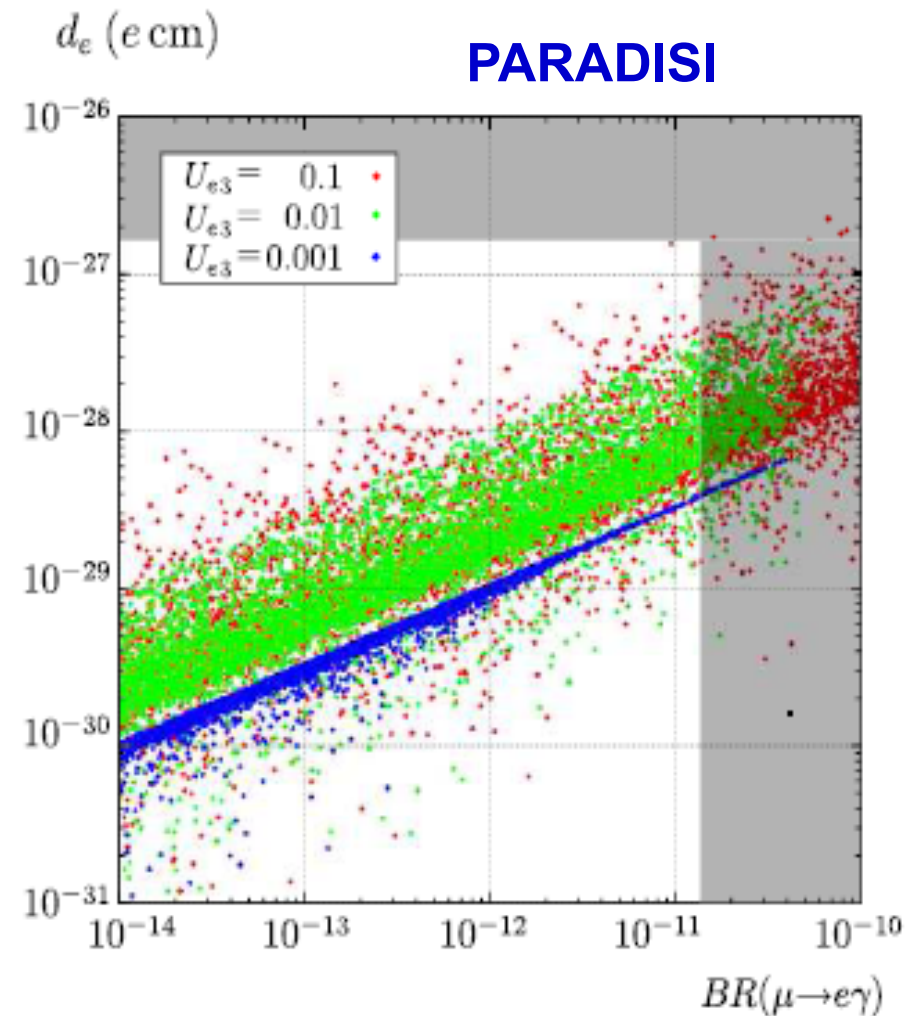
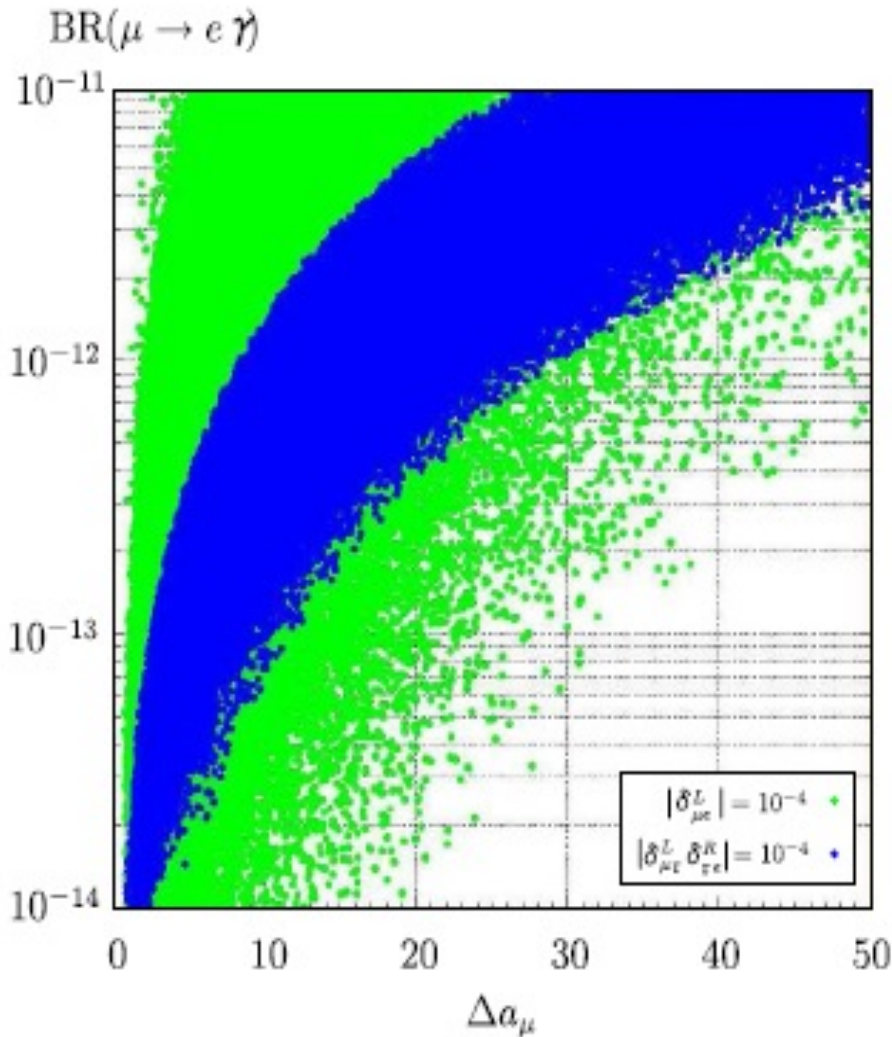


[Goto et al., FLASY2013]

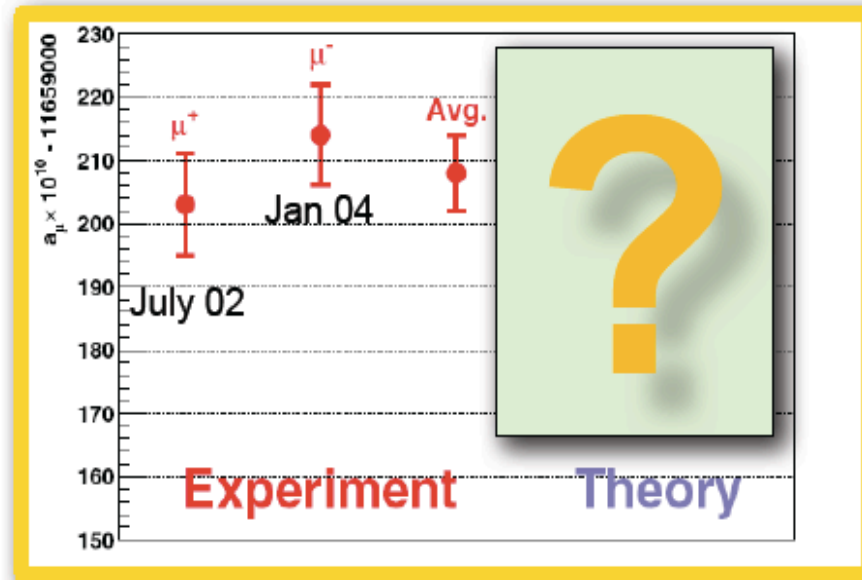


[Joaquim, ICHEP2014]

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



The muon g-2: the experimental result



● Today: $a_\mu^{\text{EXP}} = (116592089 \pm 54_{\text{stat}} \pm 33_{\text{sys}}) \times 10^{-11}$ [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

● Are theorists ready for this (amazing) precision? No(t yet)

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

The muon g-2: SM vs. Experiment

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

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

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

$a_{\mu}^{\text{SM}} \times 10^{11}$	$\Delta a_{\mu} = a_{\mu}^{\text{EXP}} - a_{\mu}^{\text{SM}}$	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” $a_{\mu}^{\text{HHO}}(|b|) = 116 (39) \times 10^{-11}$ 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

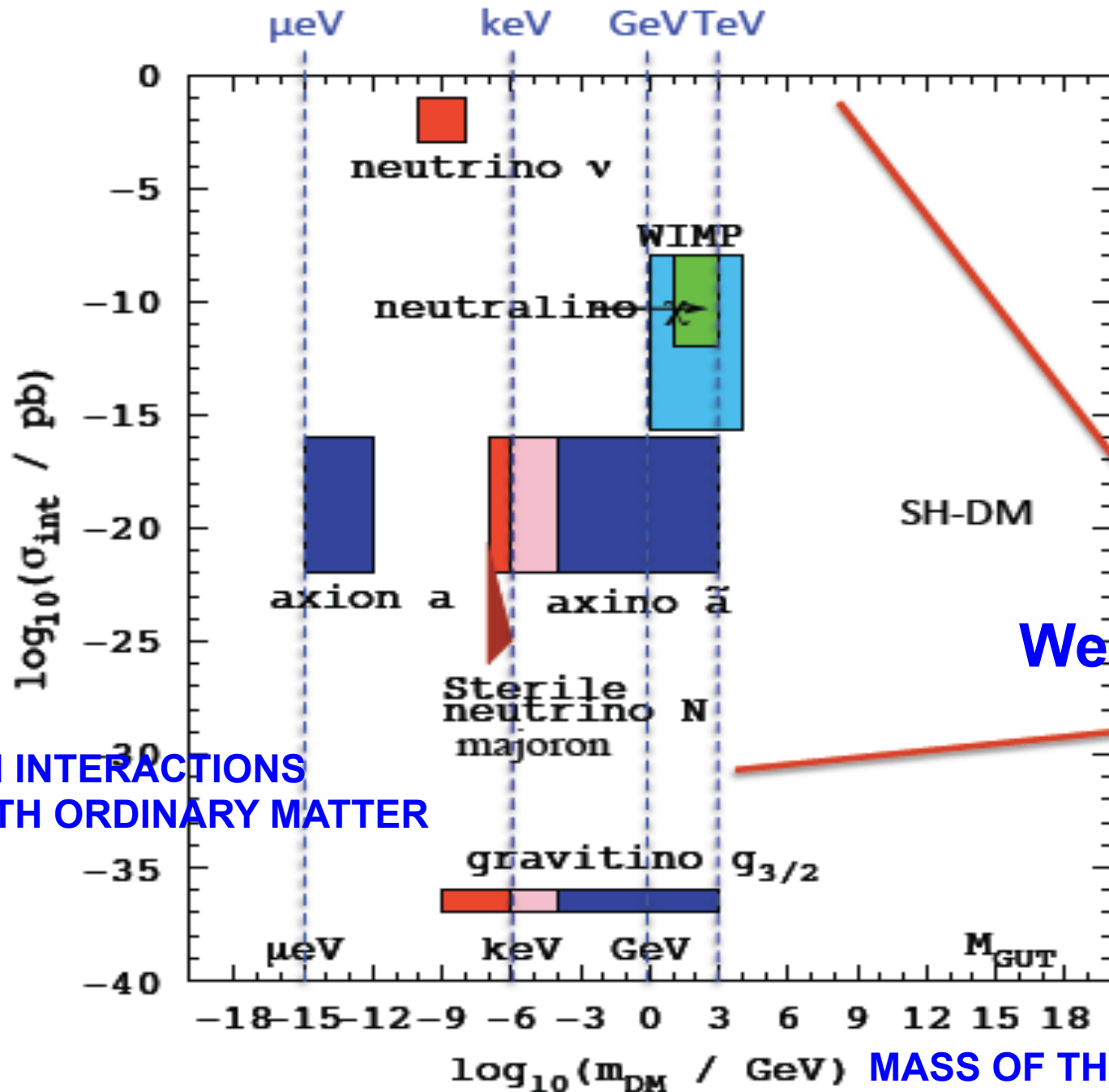
Current and projected sensitivities

C. GRIFFITH, IPA2014

	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}	$\sim 10^{-38}$
Hg	3×10^{-29}	10^{-30}	$< 10^{-35}$

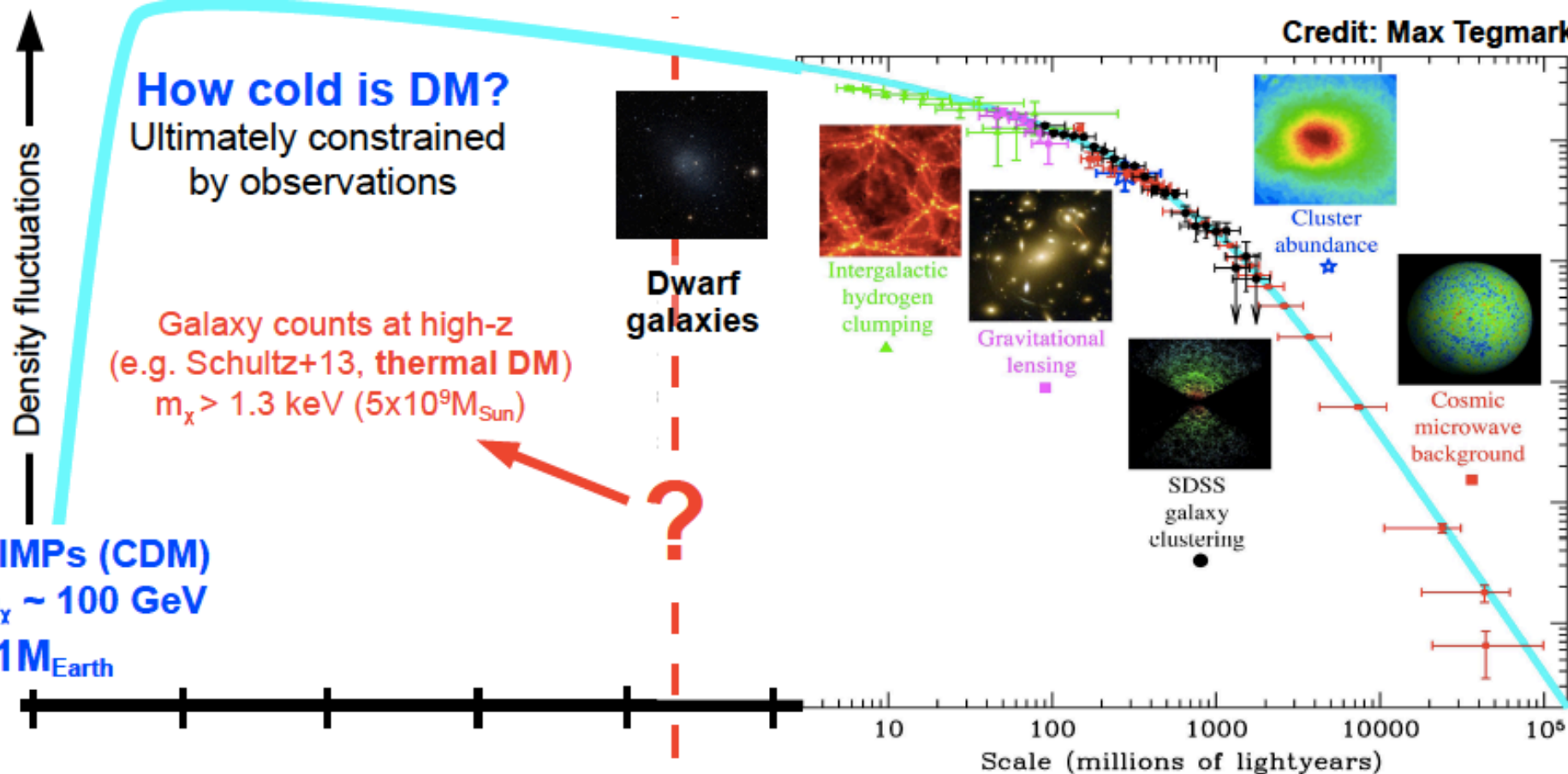
(units are in e.cm)

***THE DM ROAD TO NEW
PHYSICS BEYOND THE SM:
IS DM A PARTICLE OF
THE NEW PHYSICS AT
THE ELECTROWEAK
ENERGY SCALE ?***



MASS OF THE DM PARTICLE

Credit: Max Tegmark



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,
....



Example: $\nu\Lambda$ MDM

P. Ko and Y. Tang 2014

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

1) ENLARGEMENT OF THE SM

SUSY
(χ^μ, θ)

Anticomm.
Coord.

EXTRA DIM.
(χ^μ, j^i)

New bosonic
Coord.

LITTLE HIGGS.
SM part + new part

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

Info to extract from the direct searches

Y. Kahn, IPA2014

Kahn, McCullough, Fox 2014

$= g(v_{min})$

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

DM model

detector properties

nuclear
physics

DM halo model

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

Usual method: $\text{DM model} + \text{halo model} \rightarrow \text{limits/preferred values in } m_\chi - \sigma_n \text{ space}$

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

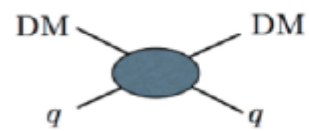
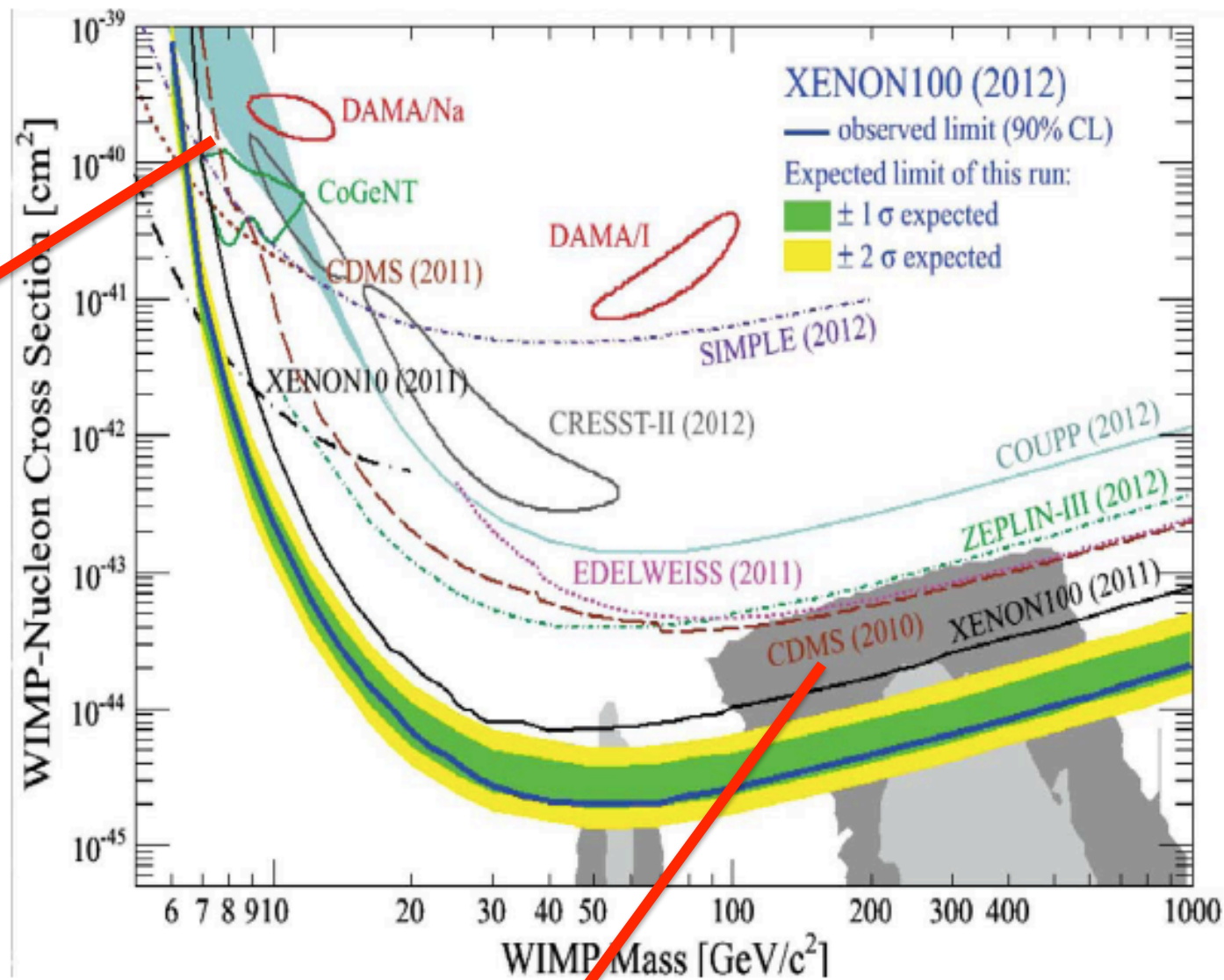
No assumptions about DM halo, easy to compare multiple experiments (esp. signal vs. exclusion)

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

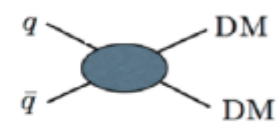
Kolb SUSY2012

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

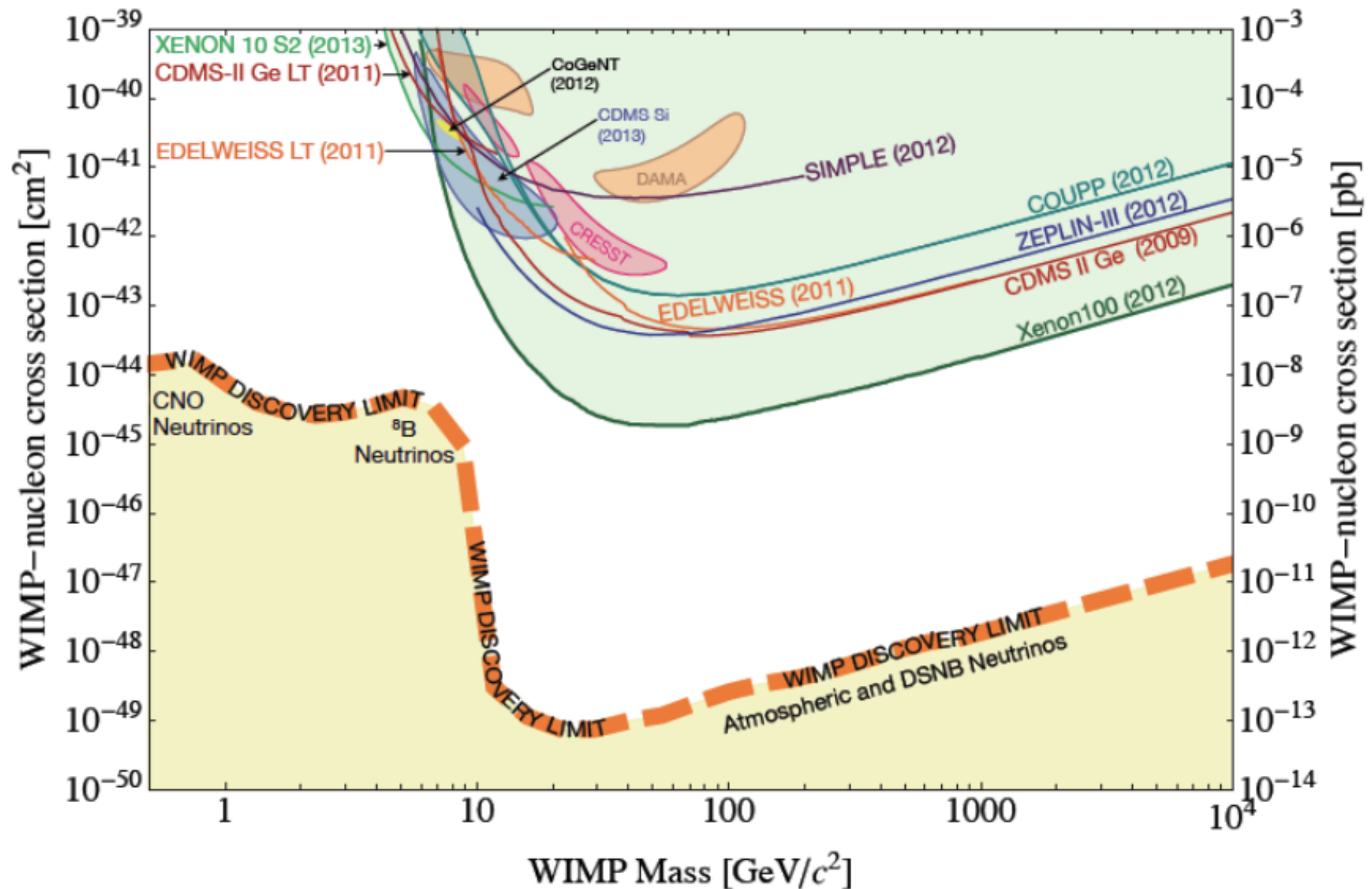


Direct Detection (t-channel)



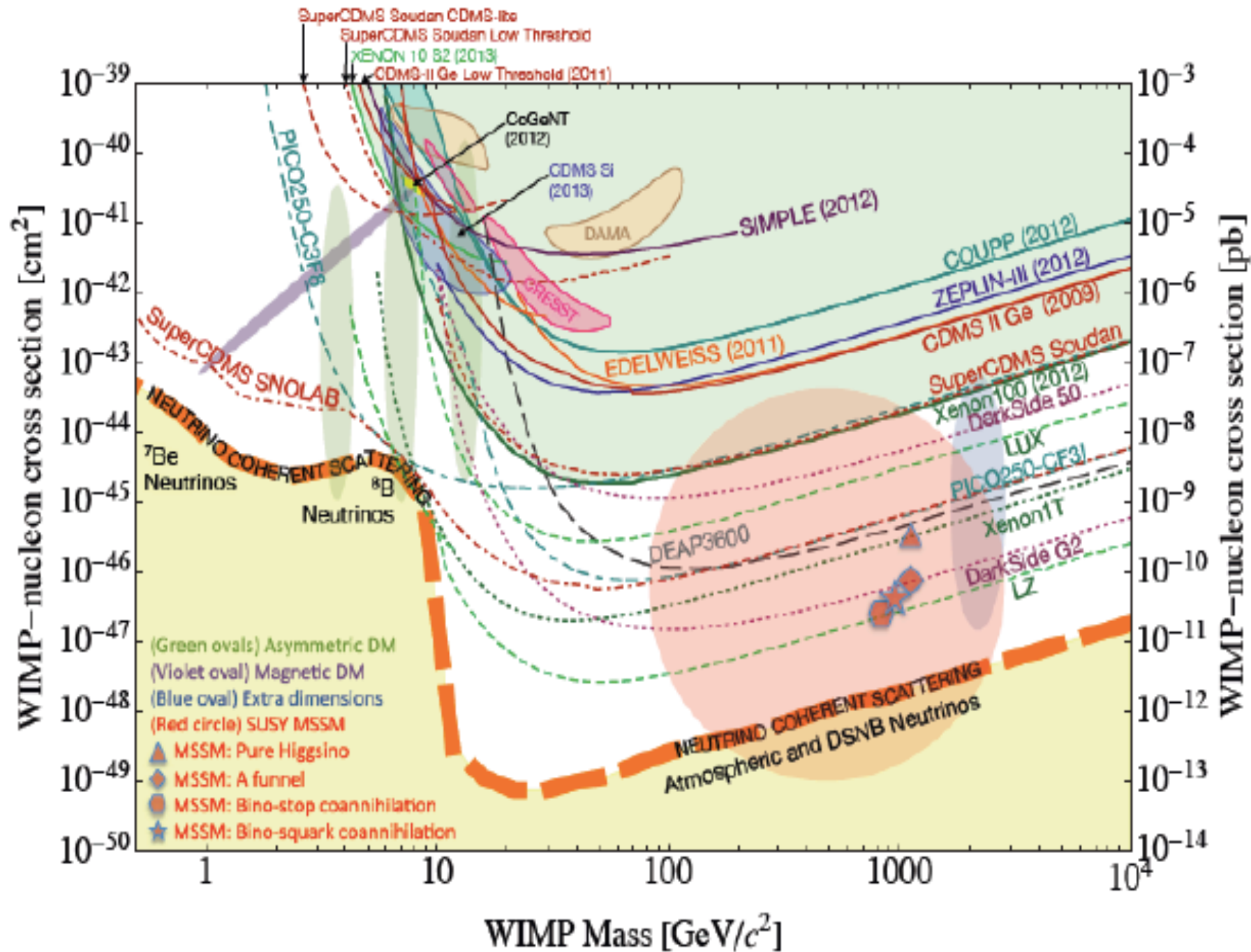
Collider Searches (s-channel)

Spin-Independent Cross Section: Current Experiment Results

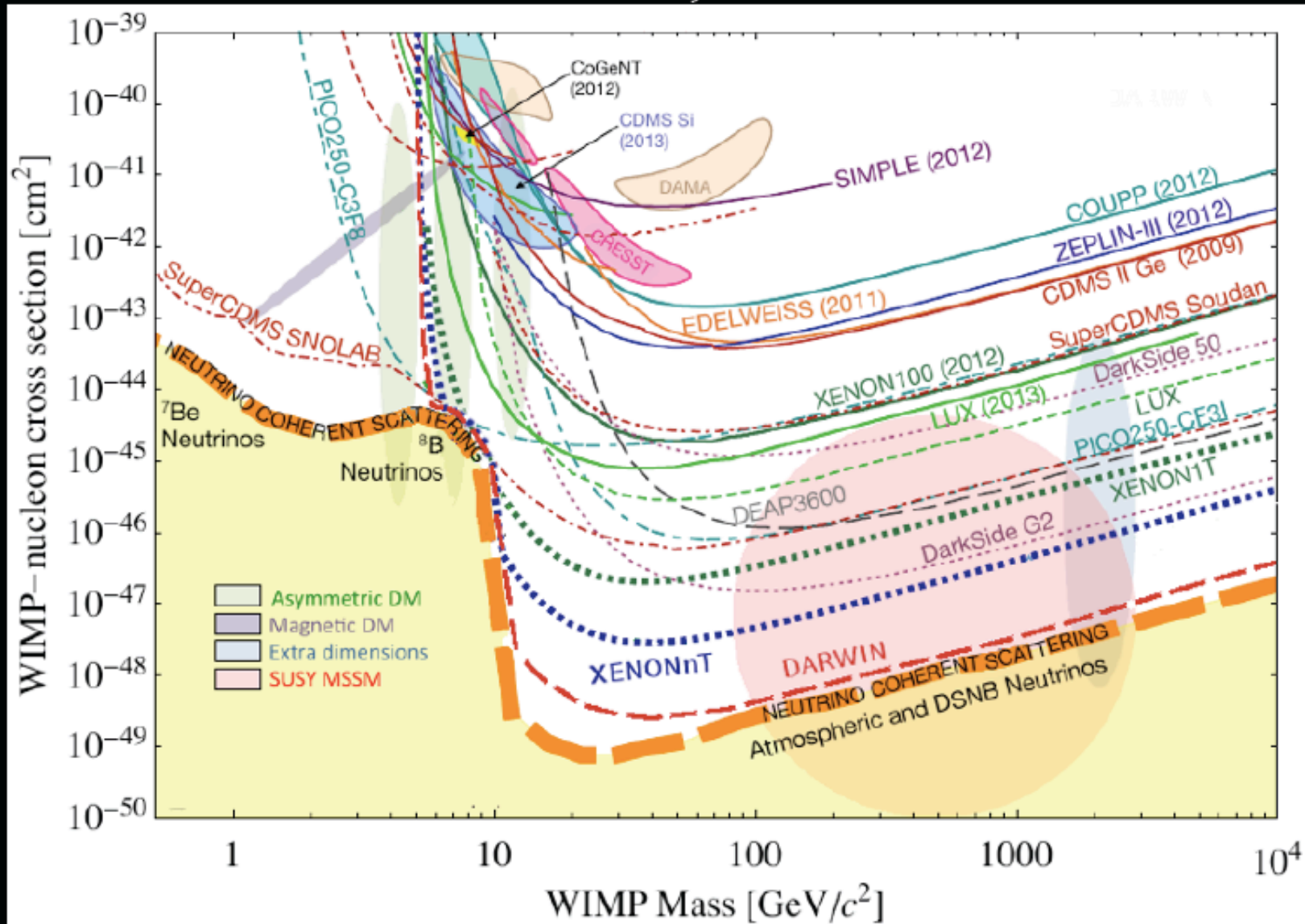


so far: ~ 3 years / order of magnitude



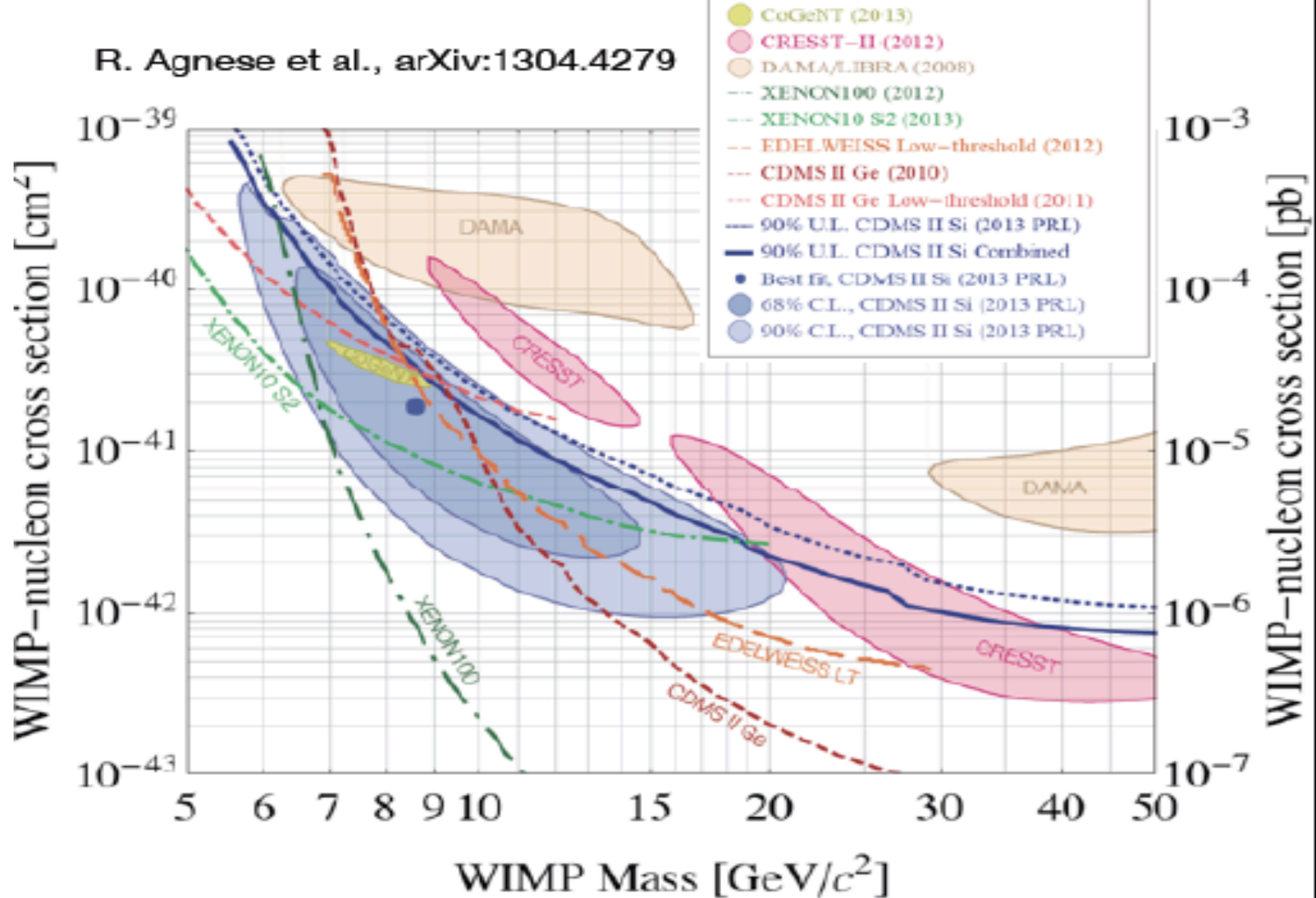


1) Science Goals: Dark Matter Projected Sensitivities

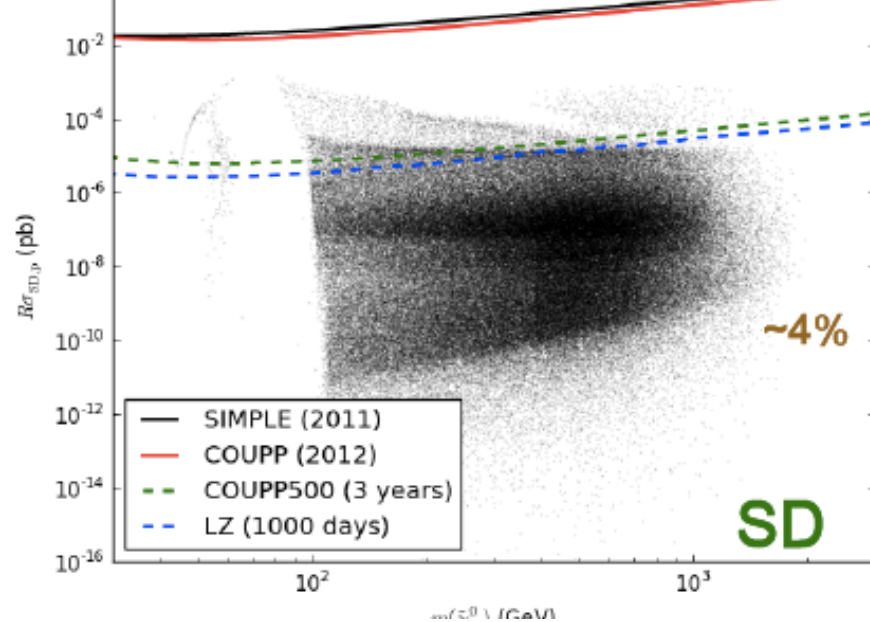
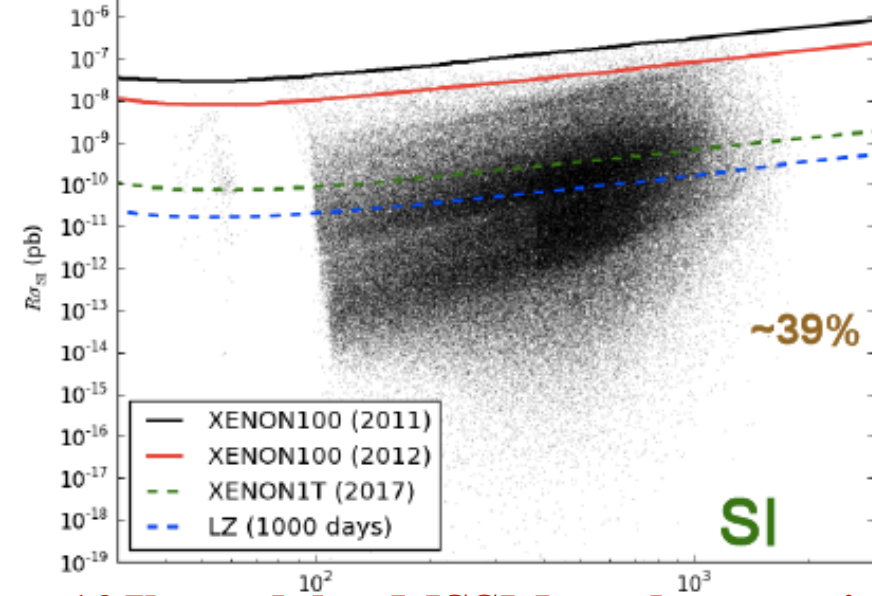


What if 2+ of these experiments observe strong candidate dark matter signals?
Build a directional detector to establish astrophysical origin.

R. Agnese et al., arXiv:1304.4279

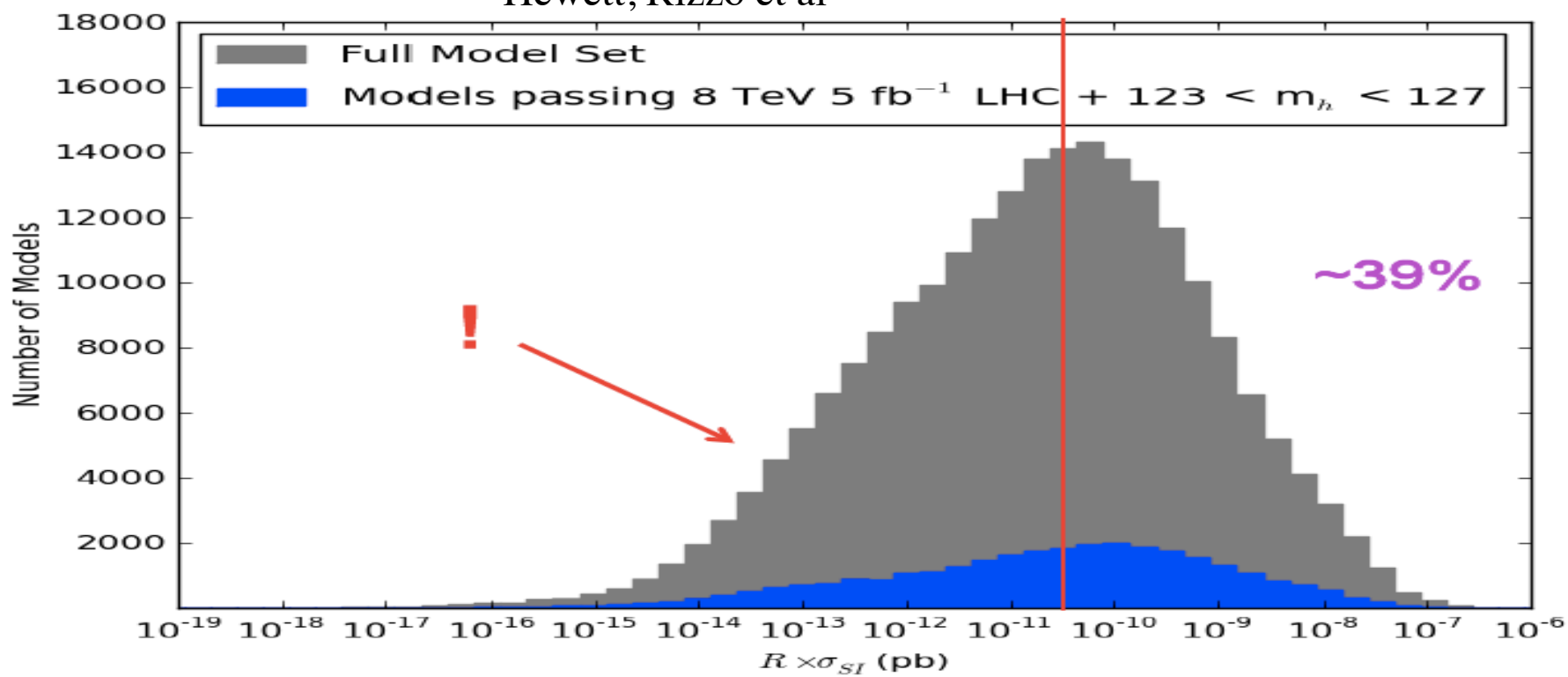


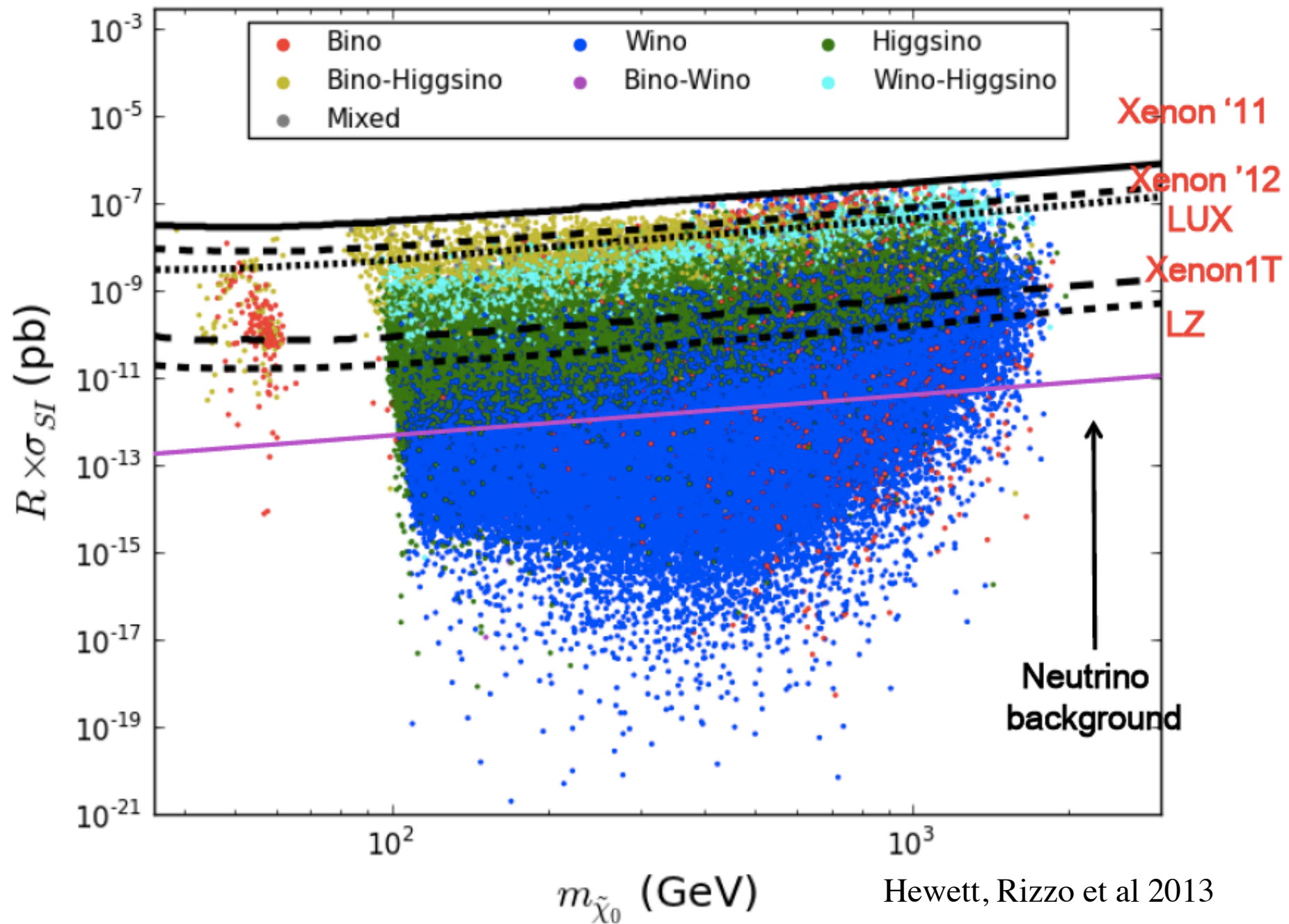
RELEVANCE OF THE DAMA-LIBRA RESULT– IMPORTANCE OF AN INDEPENDENT VERIFICATION (hard to reach the same level of sensitivity)



125k models pMSSM under scrutiny

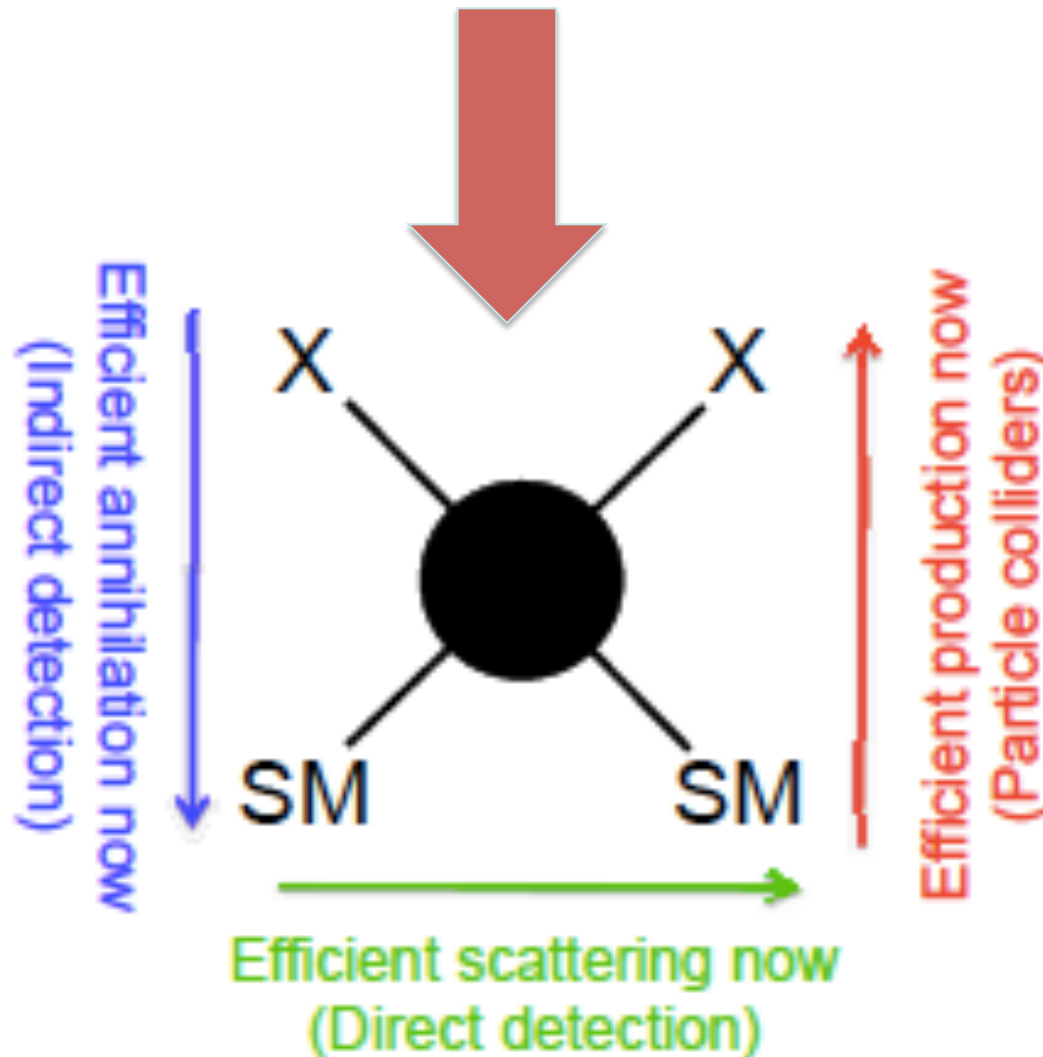
Hewett, Rizzo et al

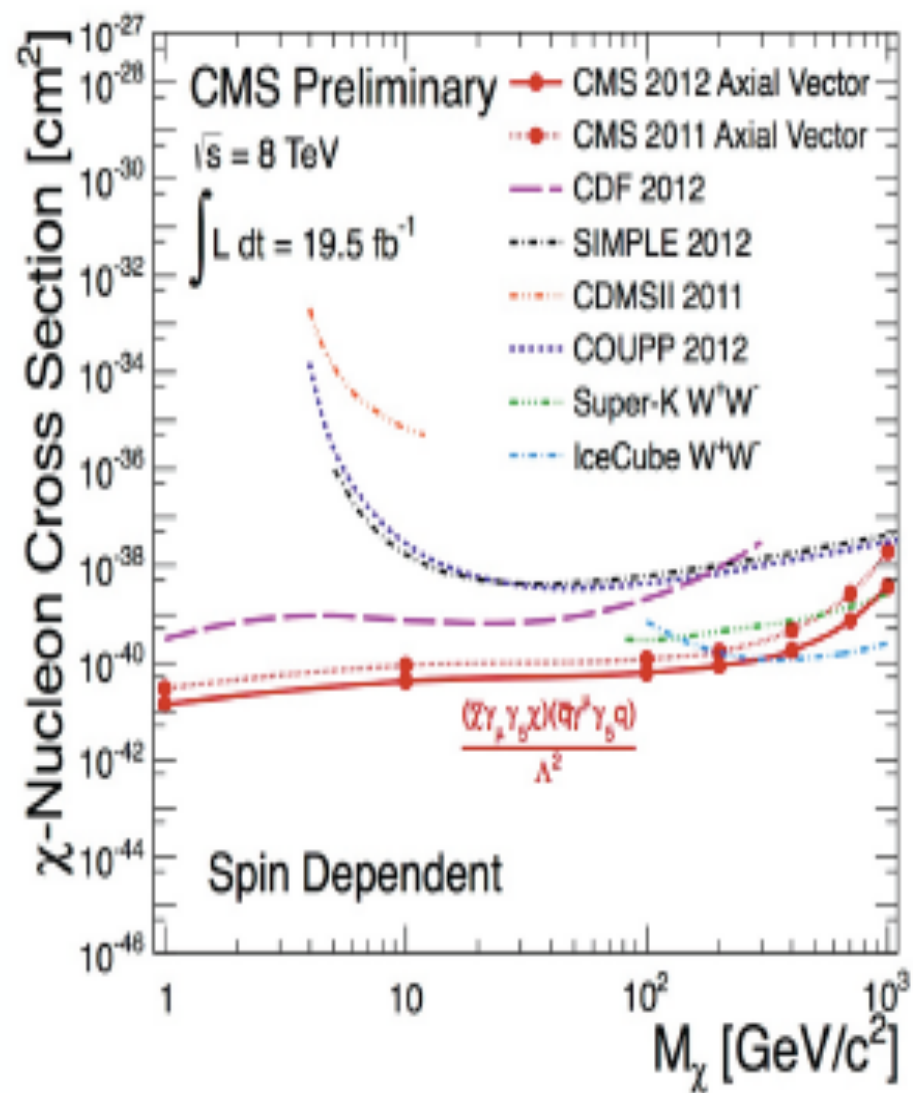
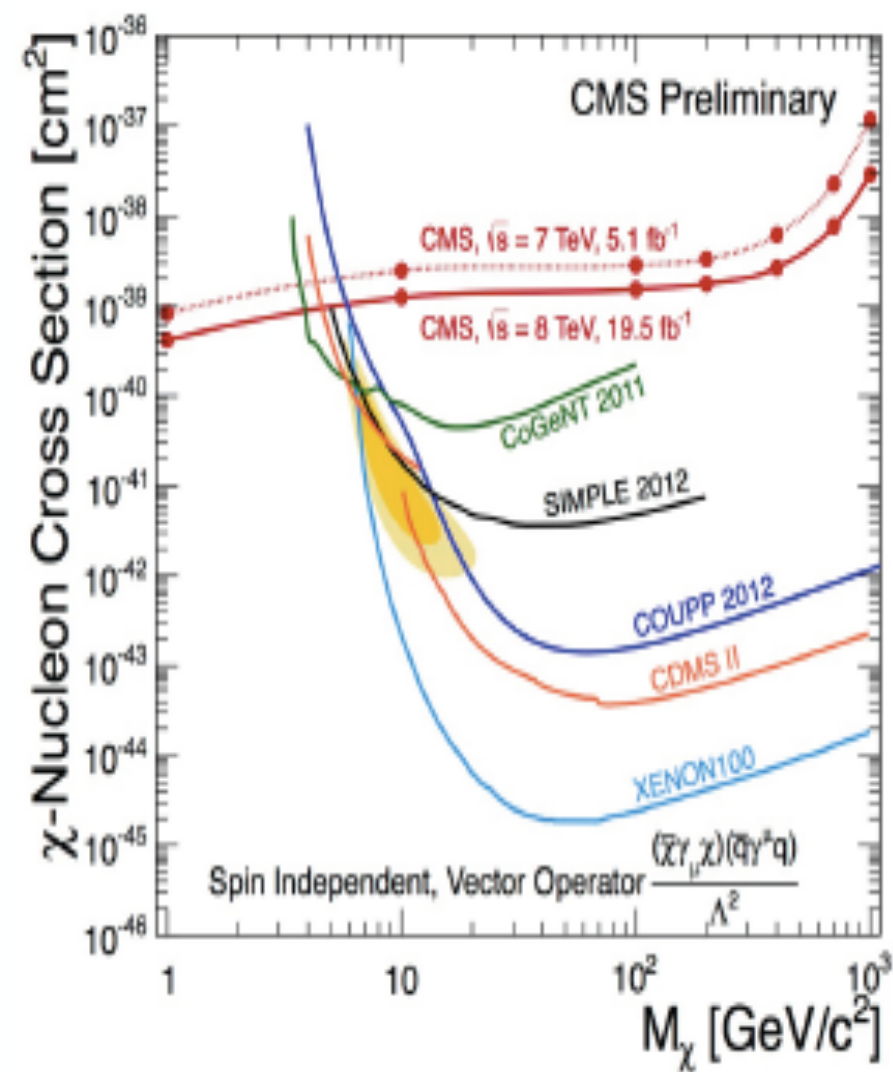


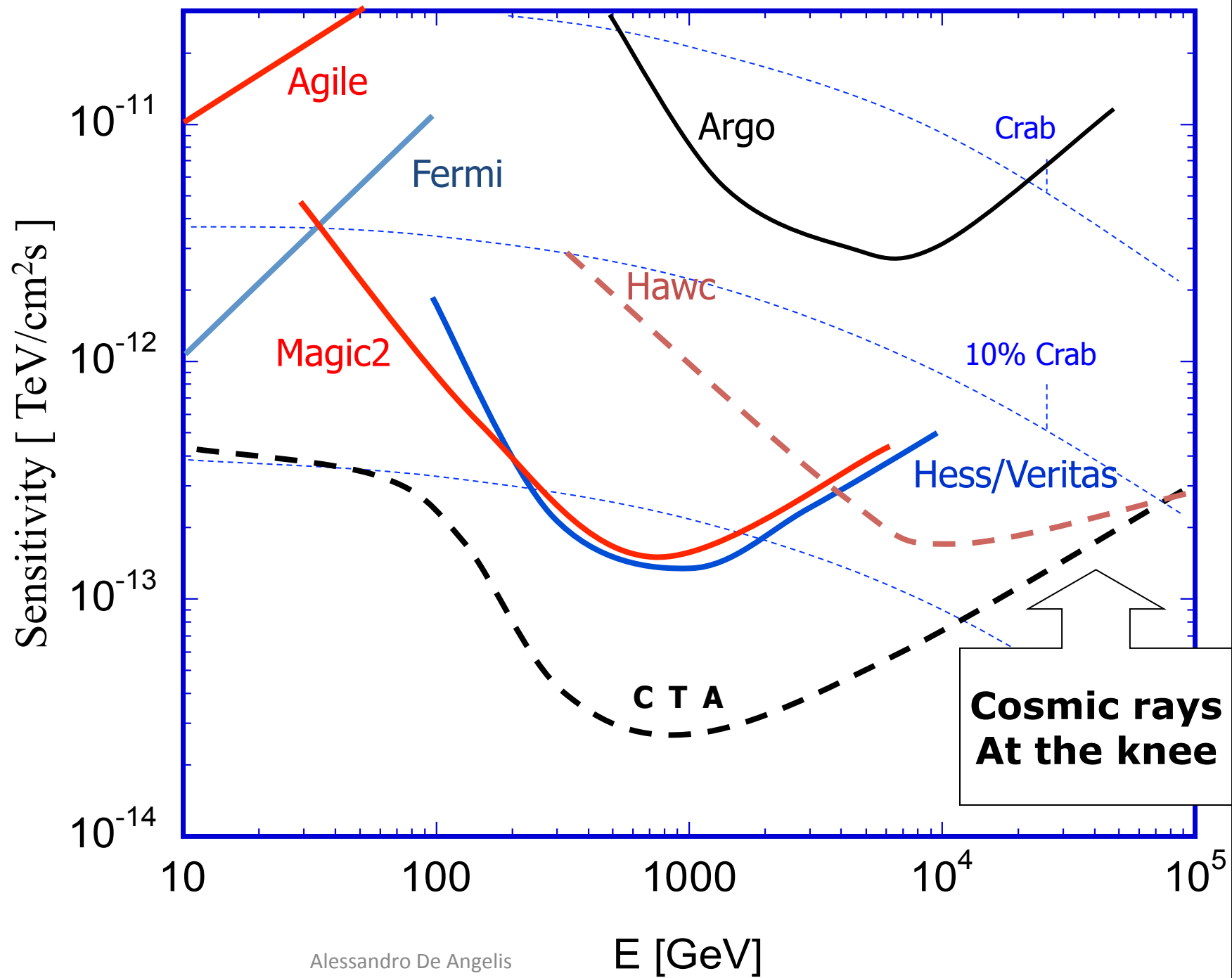


DM COMPLEMENTARITY: efficient annihilation in the early Universe implies today

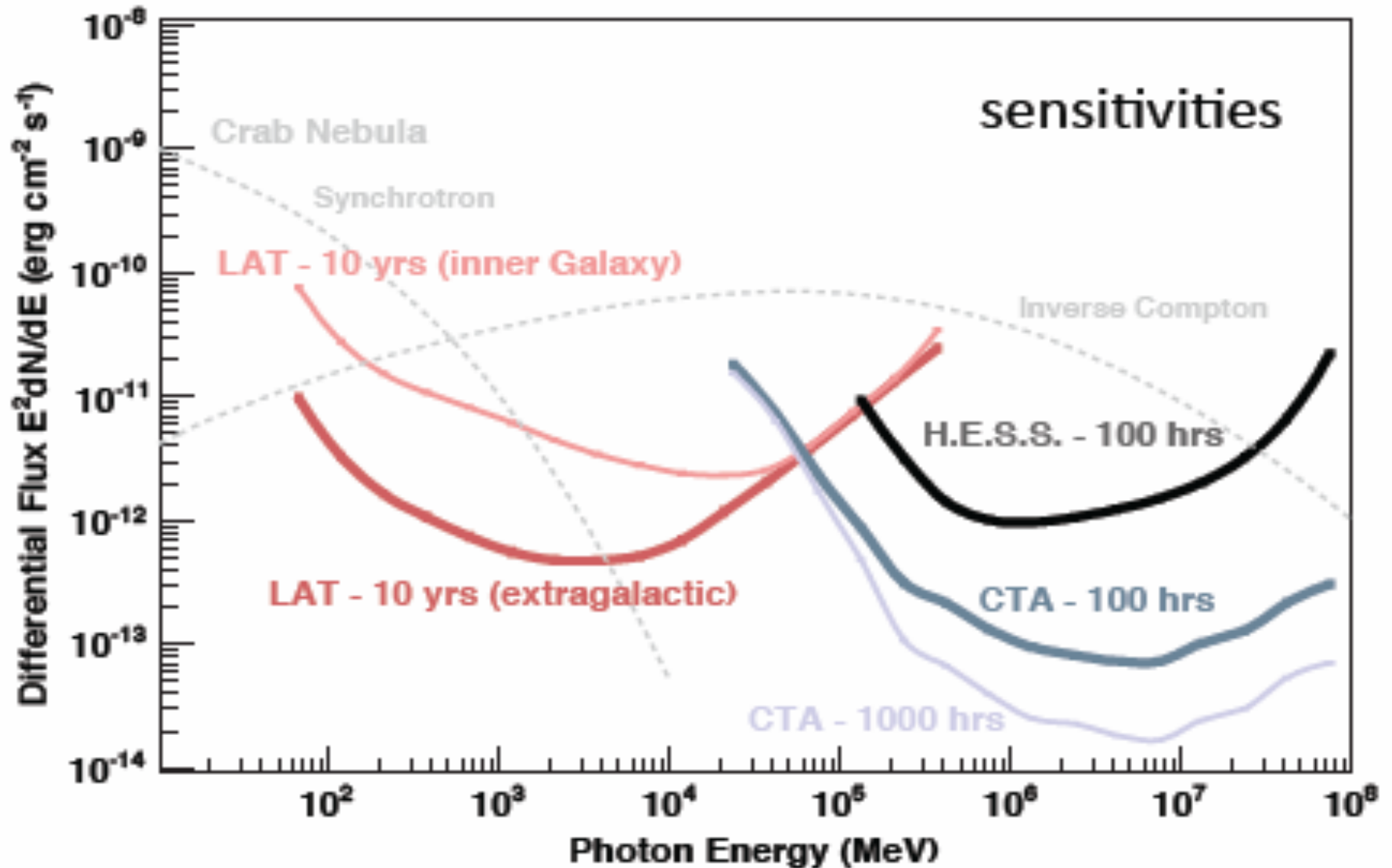
R. Poettgen (ATLAS), E. Torassa (CMS)



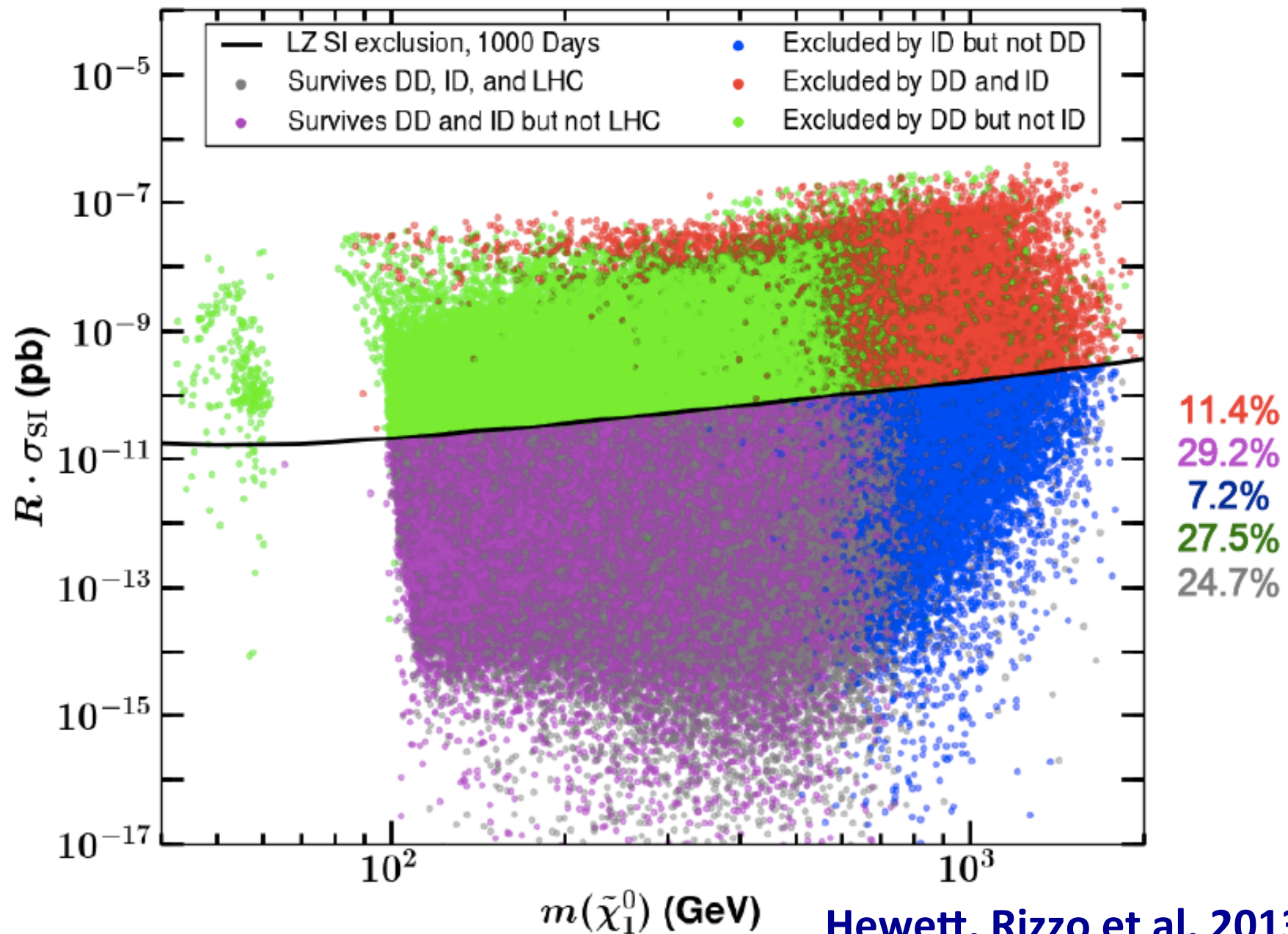




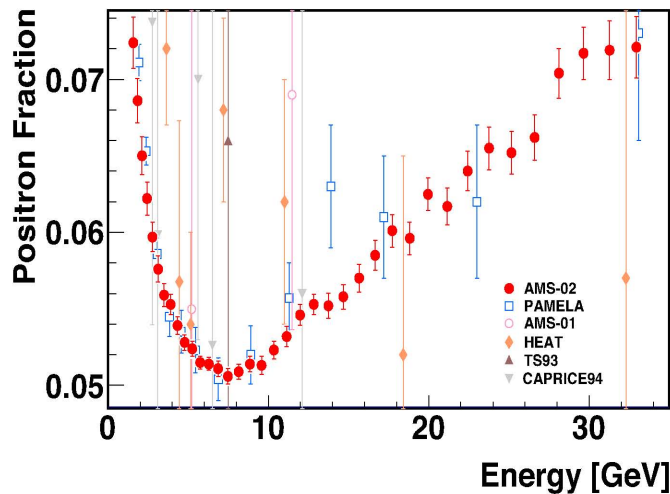
GAMMA – ASTRONOMY FROM EARTH AND SPACE



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



AMS Positron Fraction 2014 @ Low Energies



AMS Positron Fraction 2014 @ High Energies

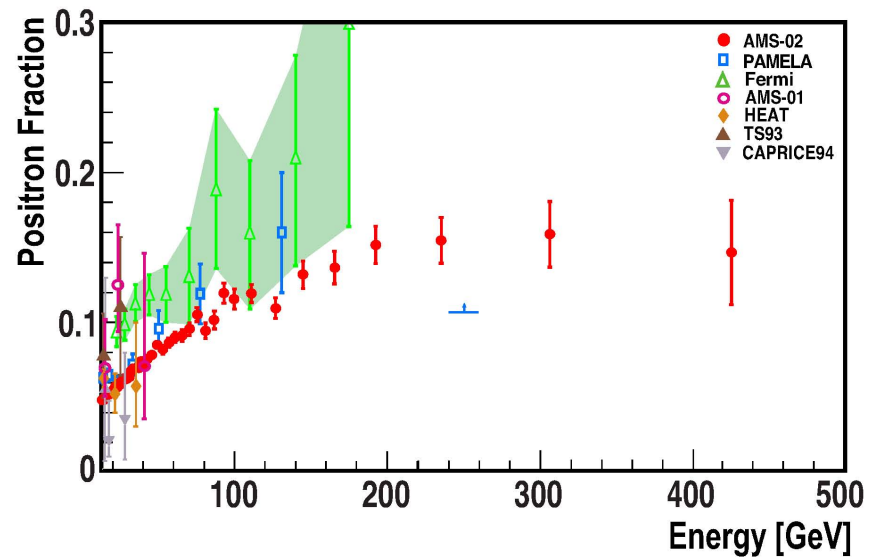
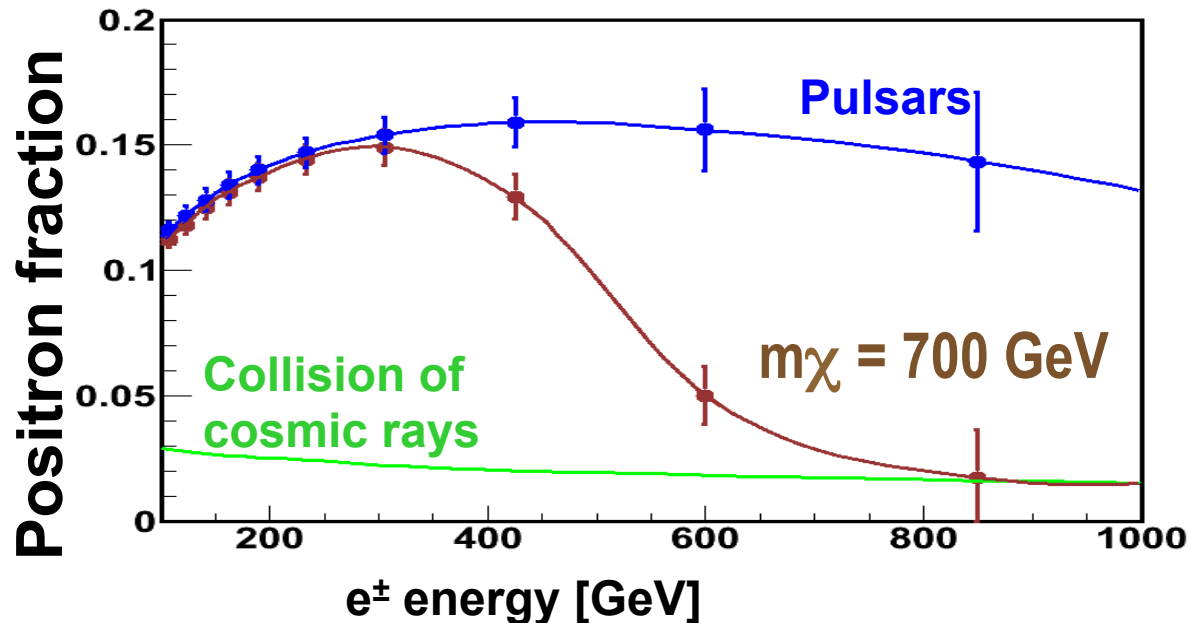


FIG. 2. The positron fraction from 1 to 35 GeV. It shows a minimum around 10 GeV followed by a steady increase. The AMS data provide accurate information on the minimum of the posi

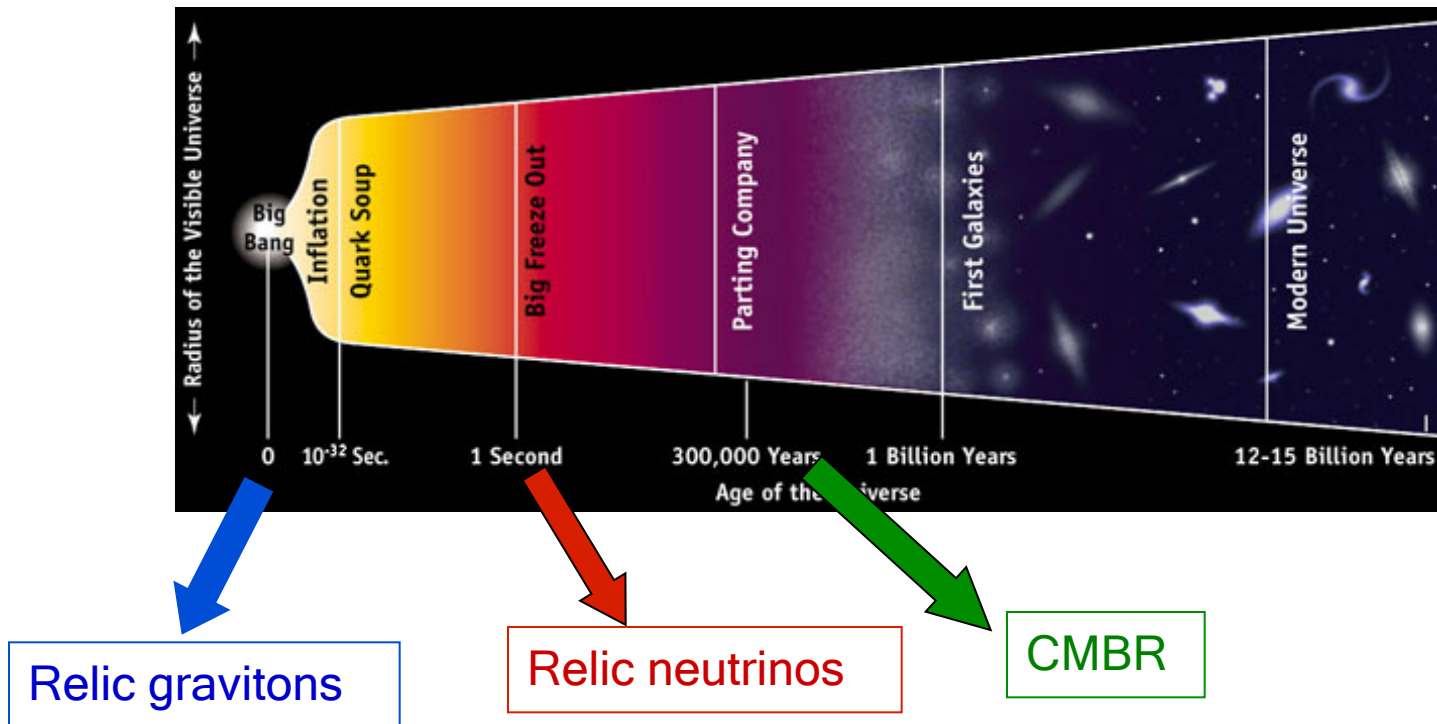
ends the energy range to 500 GeV
m PAMELA [21] (the horizontal

Origin of
Positron
Fraction:
Particle
Physics or
Astrophysics
?



M. Pohl,
IPA2014

Relic Stochastic Background

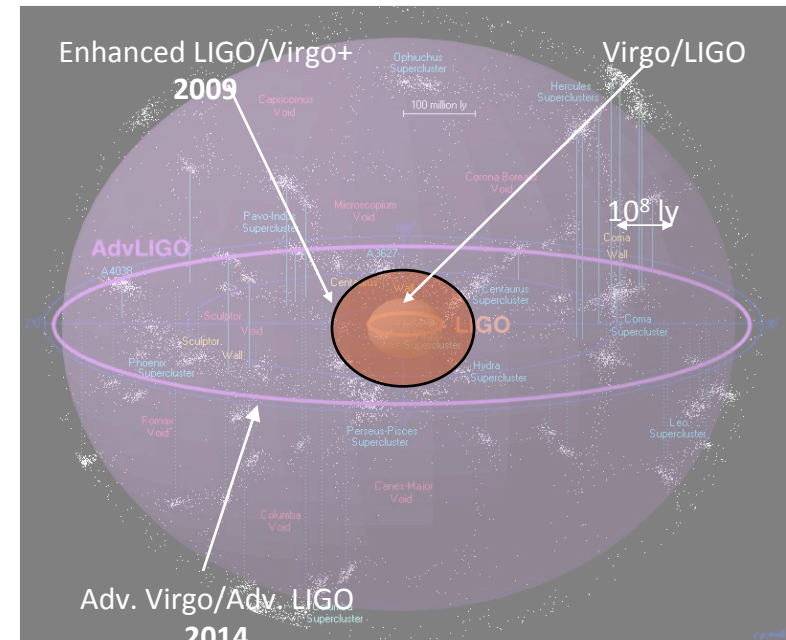


- Imprinting of the early expansion of the universe
- Correlation of at least two detectors needed

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	$E_{\text{GW}} = 10^{-2} M_{\odot} c^2$		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

PHD Syndrome

(Post Higgs Depression)?



(Savas Dimopoulos, GGI, July 2013)



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

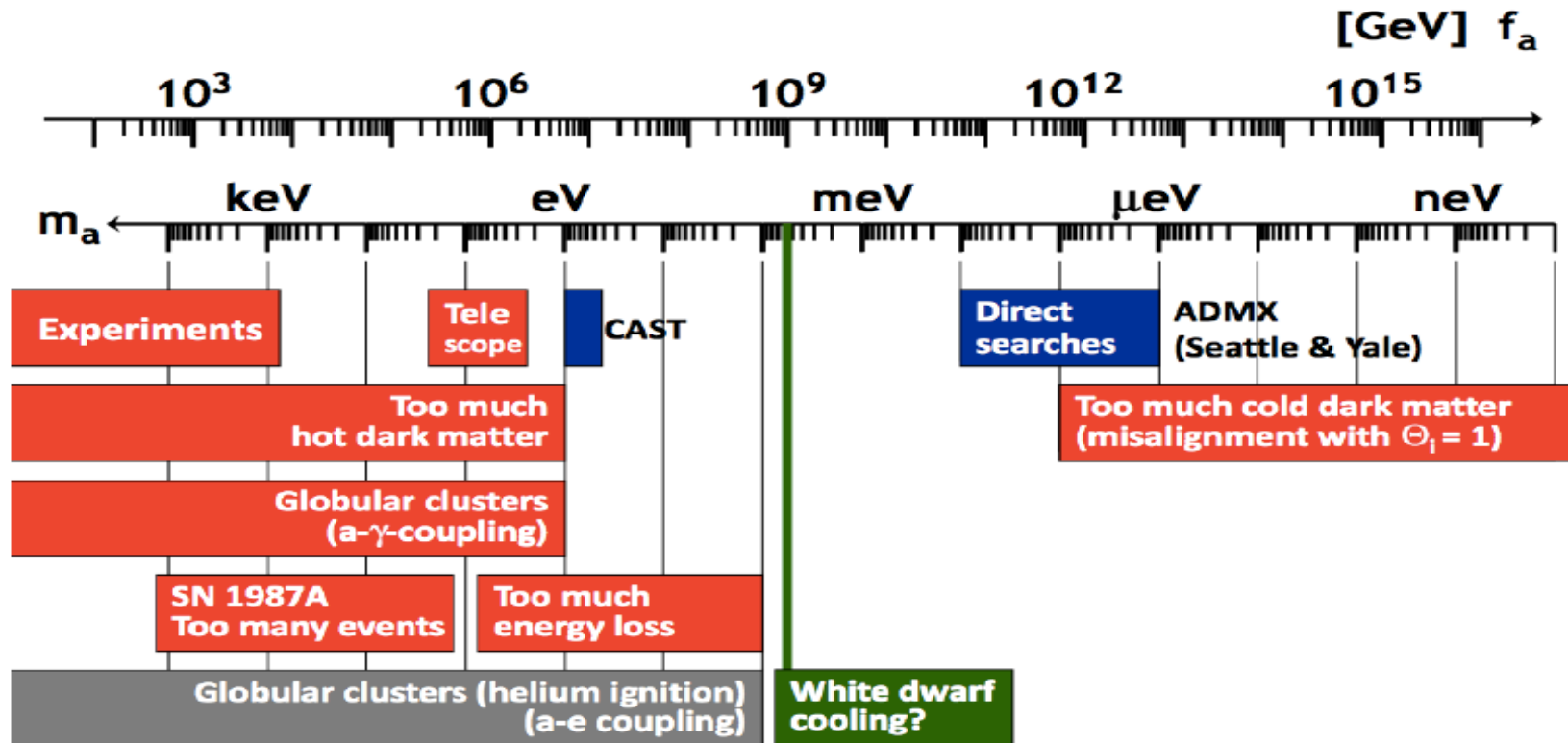
- **If** the naturalness issue is indeed a relevant issue, the fact that we discovered a light higgs means **that there MUST EXIST some mechanism stabilizing its mass and this mechanism NECESSARILY ENTAILS THE PRESENCE OF SOME FORM OF NEW PHYSICS AT THE ELECTROWEAK SCALE**
- Time to get ready (joint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



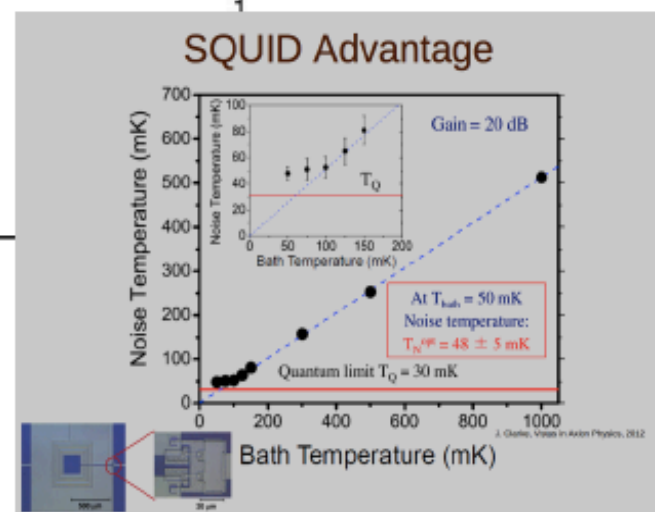
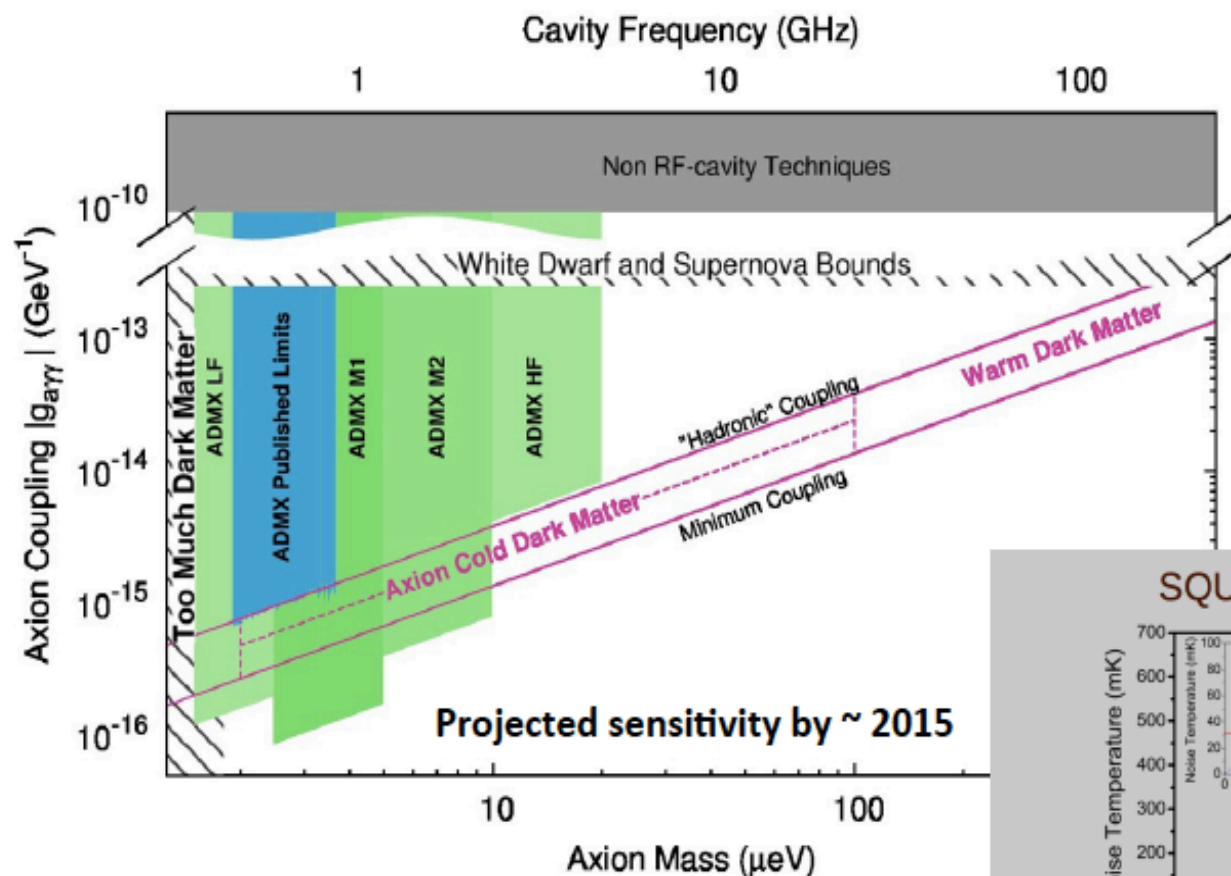
BACK-UP SLIDES

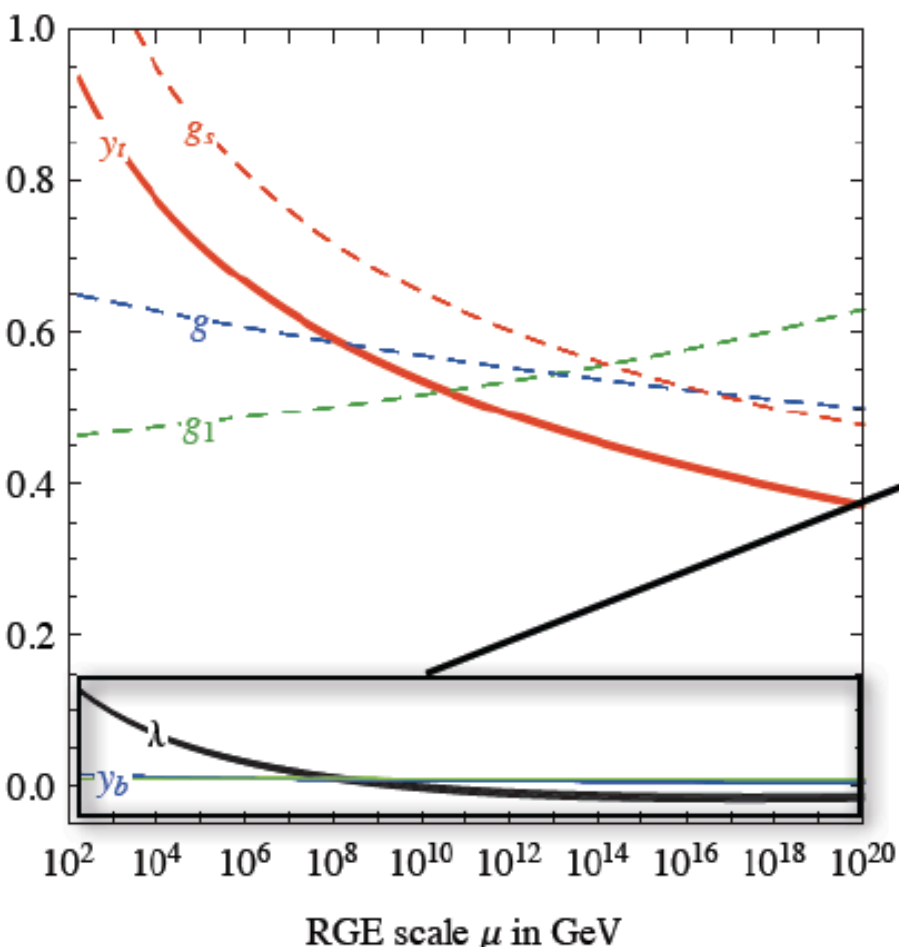
Keep in mind: we don't know at all what DM is made of ! Alternatives to WIMPs – for instance, **AXIONS**

Axion Bounds and Searches

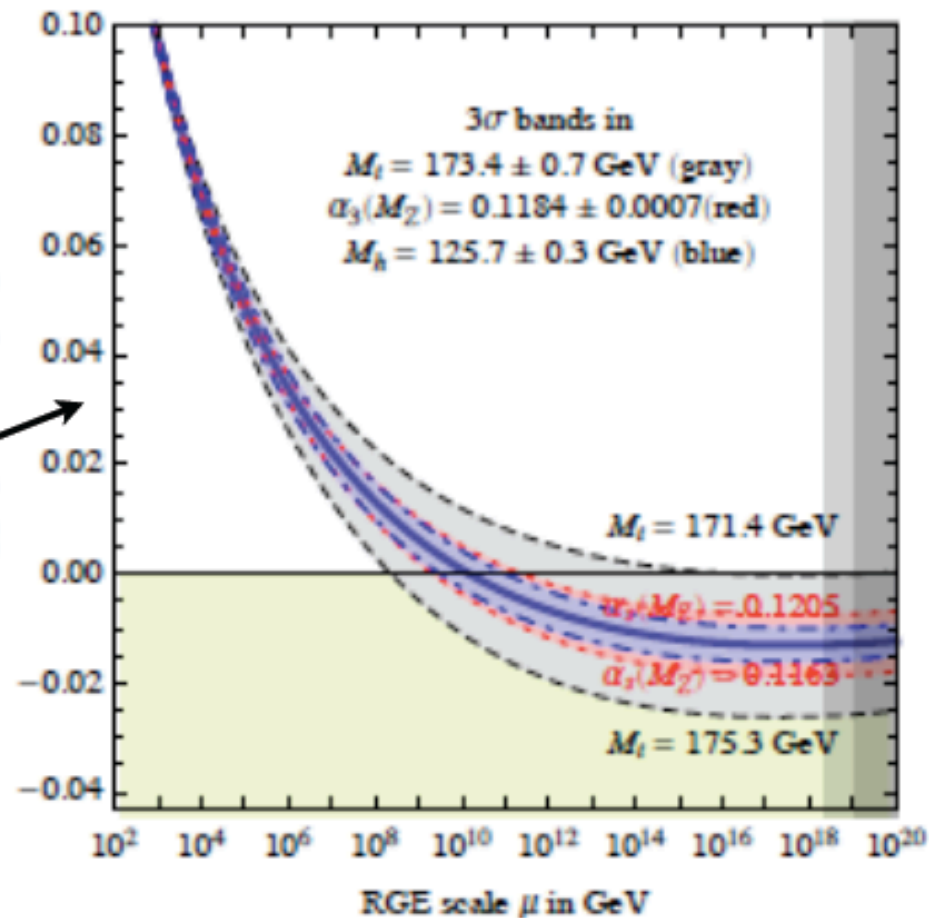


ADMX achieved and projected sensitivity





Higgs quartic coupling λ

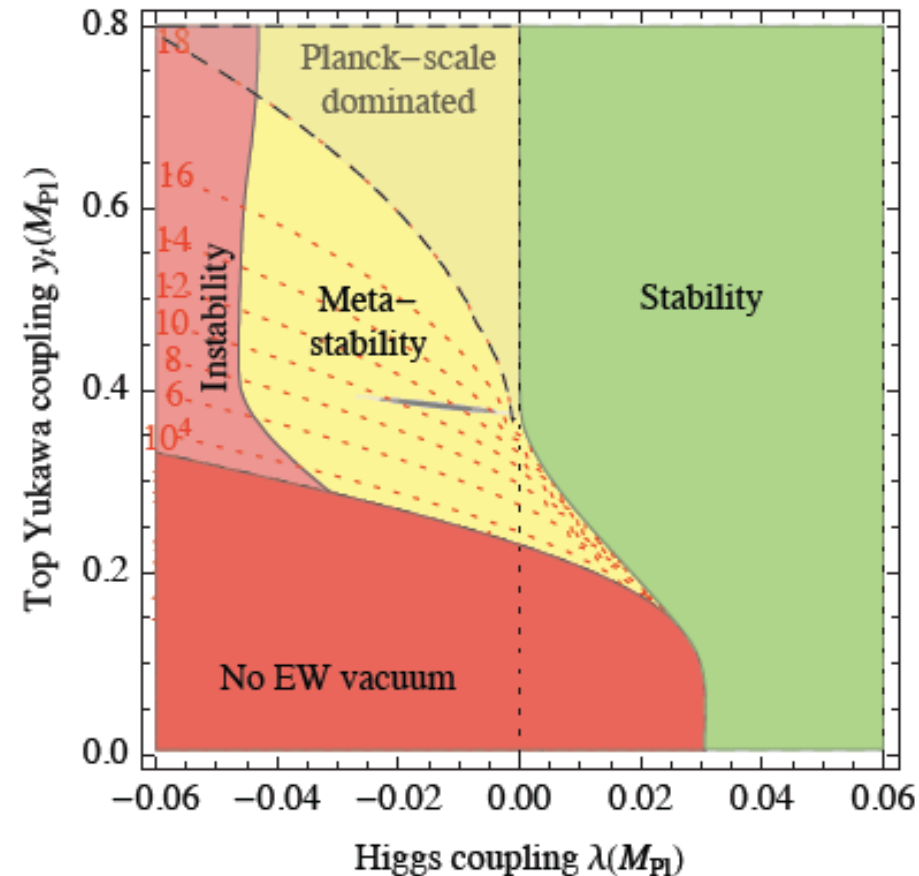
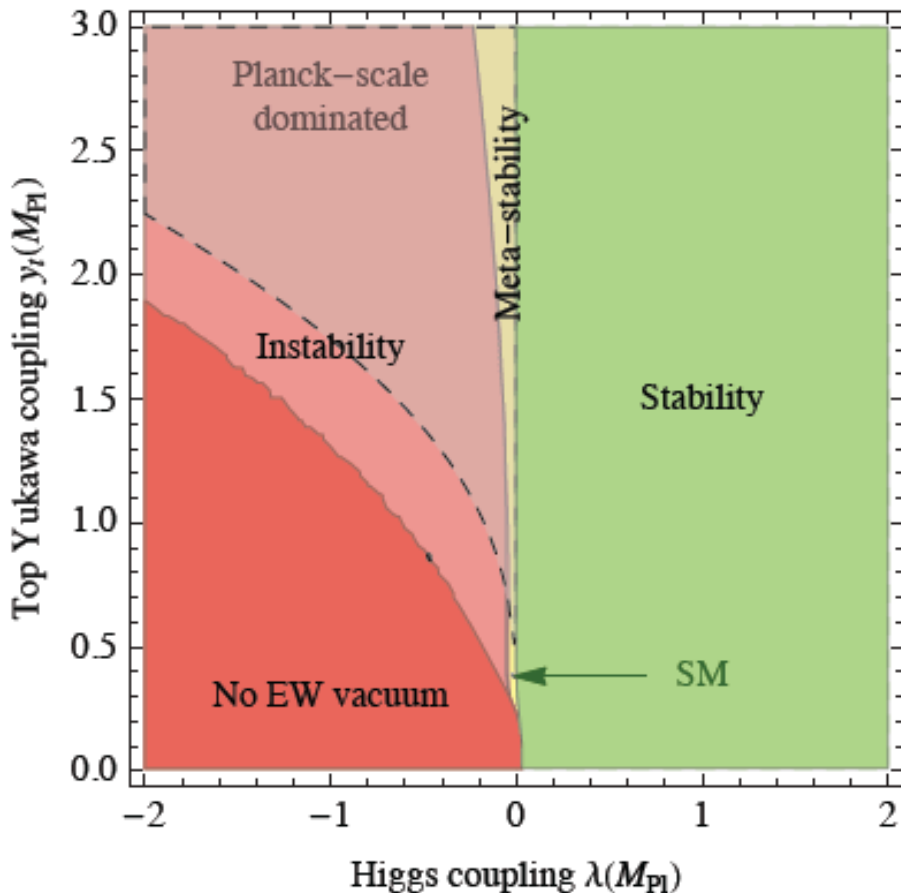


Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia 2013

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

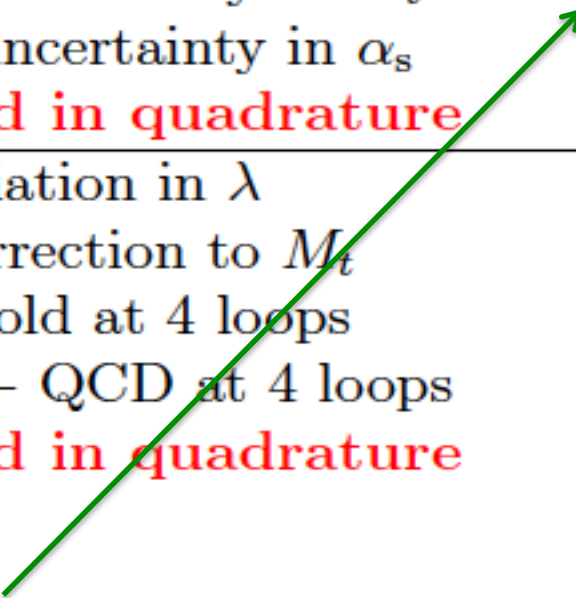


The Universe looks very close to **CRITICALITY**

ON THE IMPORTANCE OF PRECISELY MEASURING HIGGS and TOP MASSES

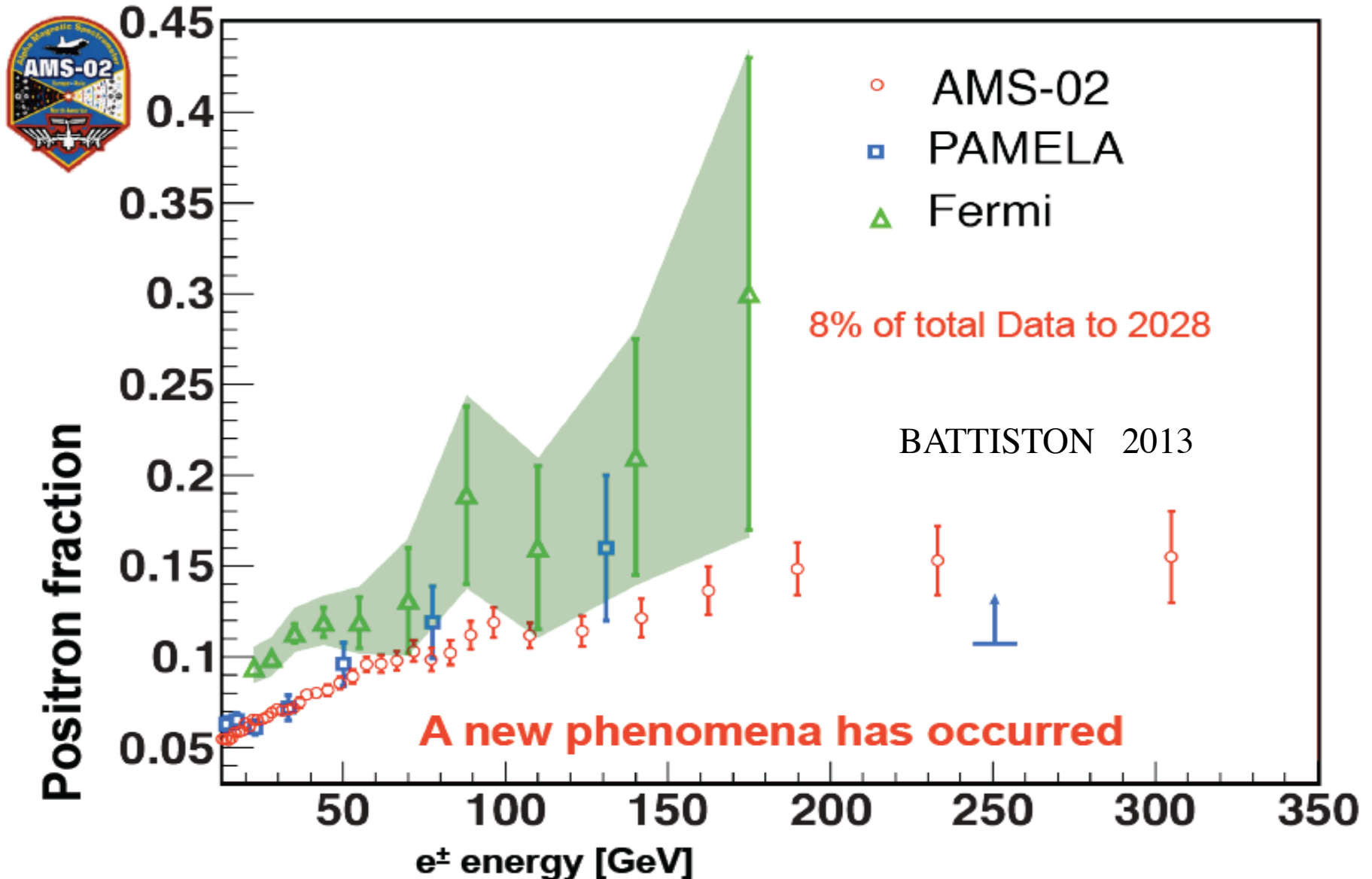
DEGRASSI ET AL

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



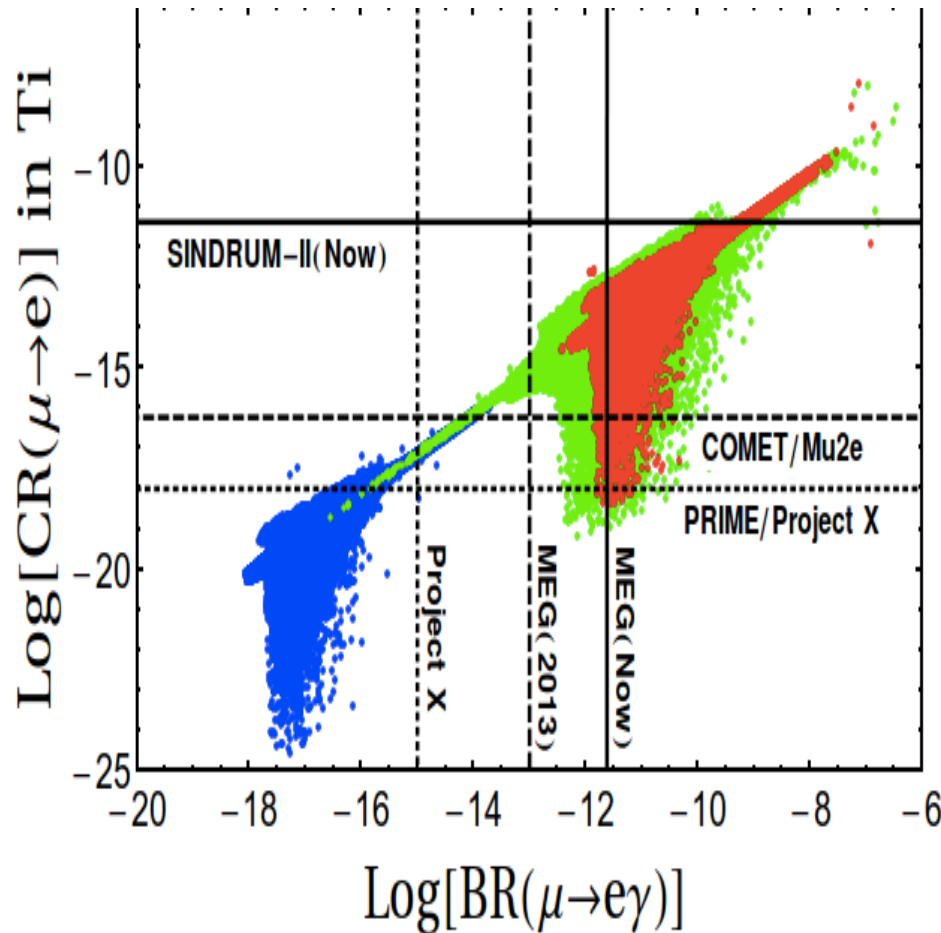
INTRINSIC DIFFICULTY TO “DEFINE” WHAT THE TOP MASS IS
AT A **HADRON COLLIDER** WITH UNCERTAINTY ≤ 1 GeV

INDIRECT SEARCHES FOR DM

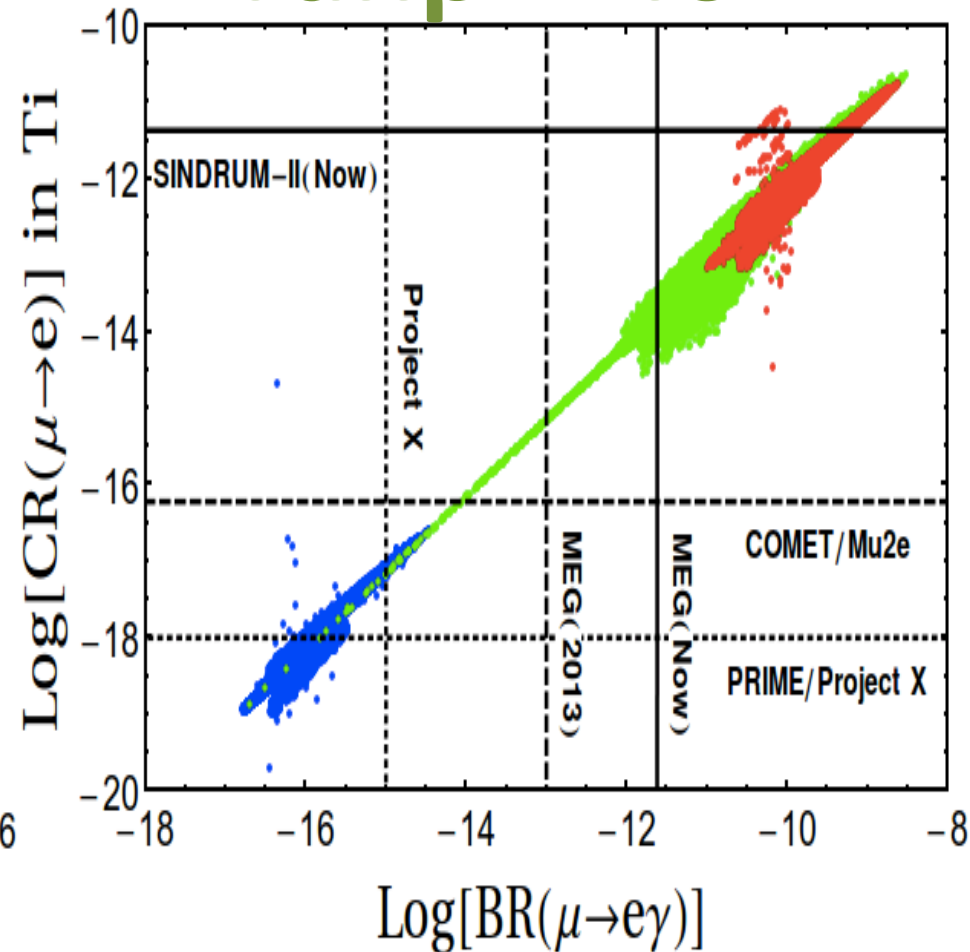


$\mu - e$ conversion vs $\mu \rightarrow e\gamma$

$\tan\beta = 10$



$\tan\beta = 40$



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?

Big Bang

Quark-Gluon
Plasma

Protoni e
neutroni

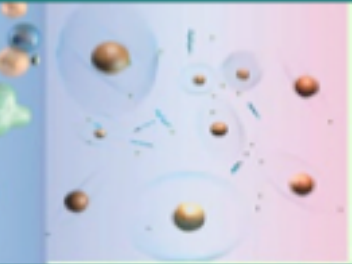
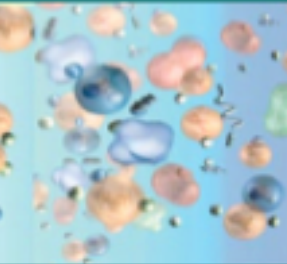
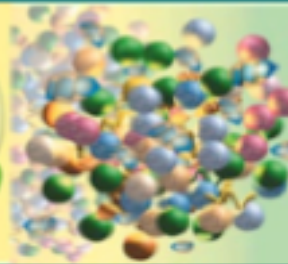
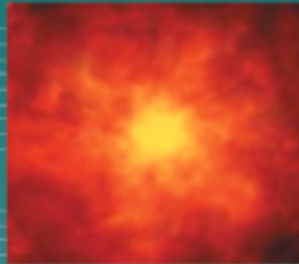
Protoni e
Nuclei leggeri

Atomi
→ Galassie
→ Molecole → DNA

Gravità

Nucleare forte

Nucleare debole



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

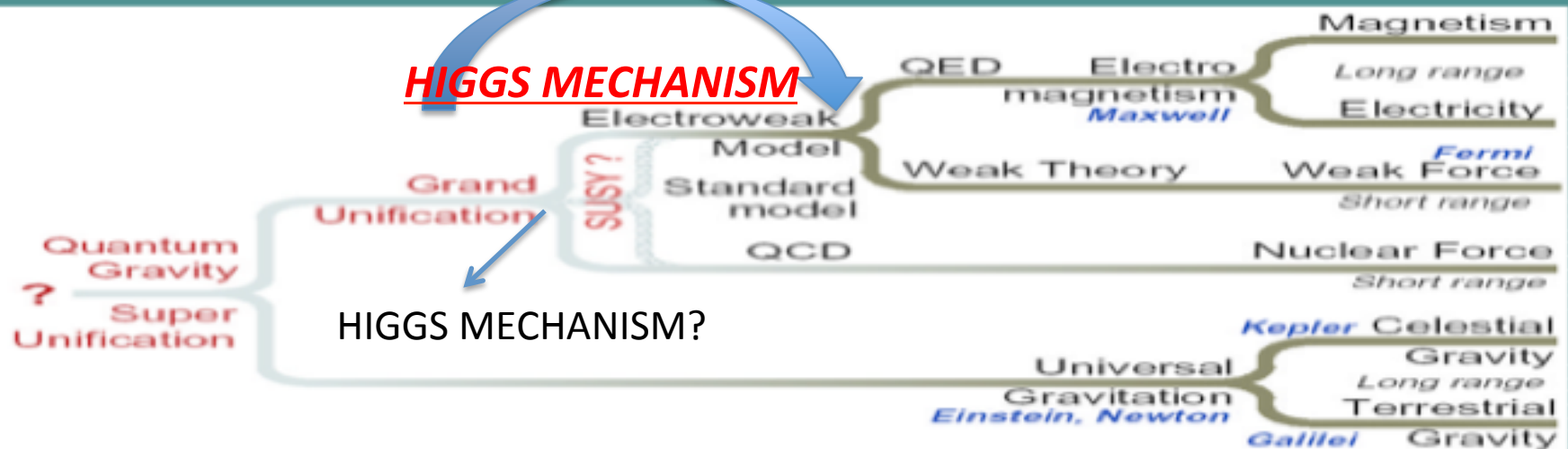
???

LHC

LEP

As tronomia →

HIGGS MECHANISM



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

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

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

⇒ Need high-precision determination of M_H to exploit the sensitivity of $\text{BR}(H \rightarrow ZZ^*)$, ... 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**

7- 8 APRILE 2014

ANGELICUM

INFN
Istituto Nazionale di Fisica Nucleare



**what
NEXT?**

Alla vigilia degli importanti input sperimentali che arriveranno da LHC a più alta energia e dai nuovi esperimenti sulla materia oscura, l'INFN si interroga sulle possibili strade da prendere per la ricerca di nuova fisica oltre il Modello Standard.

è aperto a tutta la nostra comunità INFN, per il tuo contributo iscriviti dal sito www.infn.it

Congress Centre - Aula Magna
Angelicum, 1 Roma

azioni
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The next step

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

➤ Impact of enrichment 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	~ 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?

A. Giuliani SAC APPEC 2013

Which chance do we have to get them in Europe?

EWSB: WITH OR WITHOUT A HIGGS BOSON

Bottom-Up Approach

Scenario #1
no linear regime

Scenario #2

R. CONTINO PLANCK2012

$SU(2)_L \times U(1)_Y$ linear
+ perturbativity

Scenario #3

$SU(2)_L \times U(1)_Y$ linear
+ strong dynamics

UV
strong dynamics
(new resonances $\rho, \dots$)

NO



IR
effective theory of χ^i

UV
weakly coupled theory

$[\chi^i, \phi^a]$

Higgs bosons UV

LIKELY



IR
effective theory of χ^i

UV
strong dynamics
(new resonances $\rho, \dots$)

MAYBE

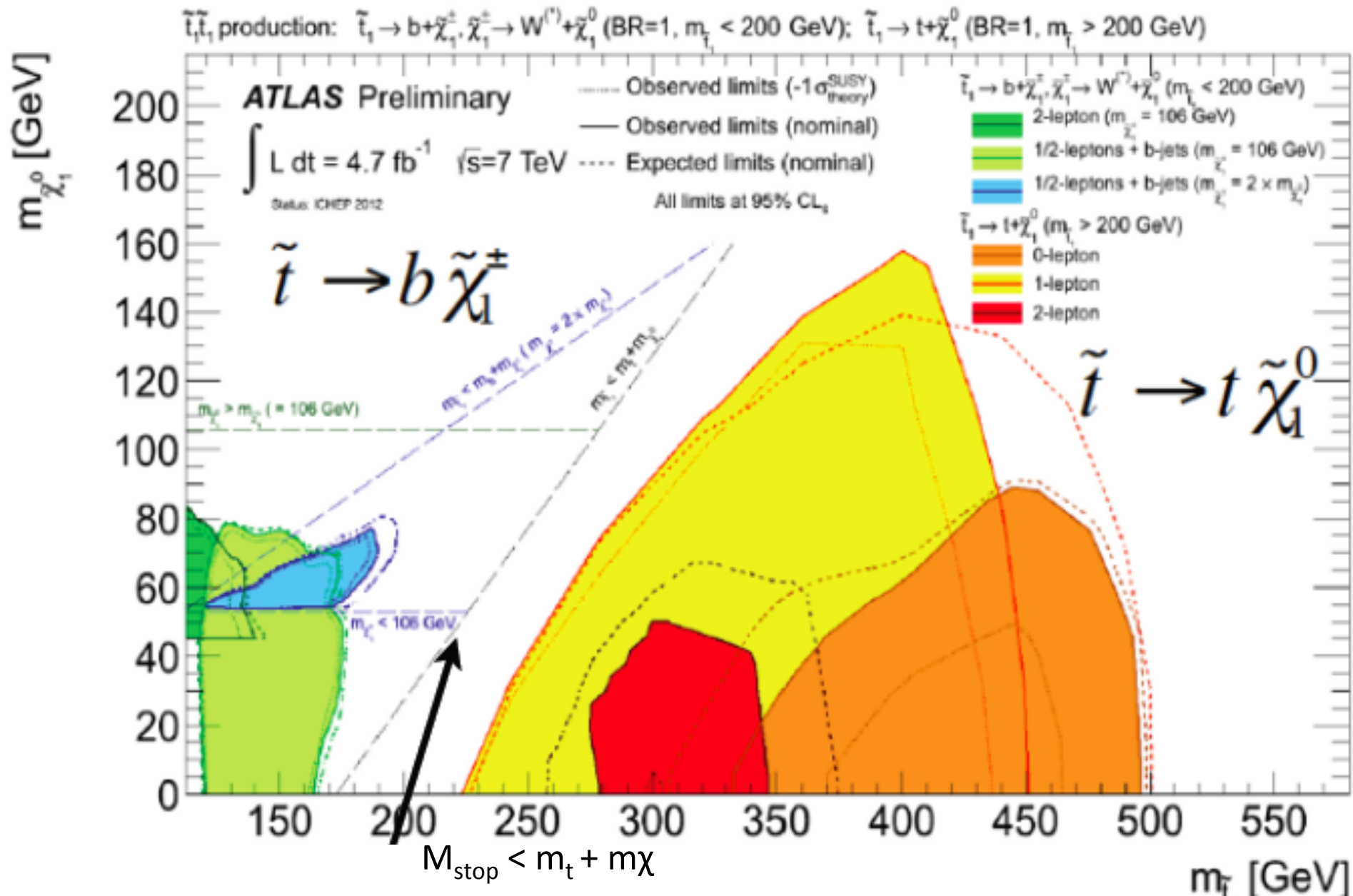


$[\chi^i, \phi^a]$

IR
effective theory of χ^i

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

Hunting for a light s-top



the (almost complete) CKM triumph

