Roma “La Sapienza”, 3 March ‘14

The Dark Matter Challenge for Particle Physics

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Introduction

The absence of new physics (in particular no WIMP's observed so far) also changed the perspective for DM

I will first summarize the demise of naturalness as a strictly reliable guiding principle (New Physics at 3, 10,...100....TeV?)

The experiments of the last years suggest to take the SM more seriously (at the extreme, the evolution of couplings shows that nothing strictly prevents the SM to be valid up to $\sim M_{Planck}$, with a metastable vacuum)

Forms of DM that only minimally enlarge the SM are now considered with more attention (axions, simplest WIMP's, keV sterile neutrinos...)

I will discuss these forms of DM together with the search for the "traditional" SUSY WIMP's

LHC 7-8 TeV

A great triumph: the 126 GeV Higgs discovery

A particle apparently just as predicted by the SM theory

The main missing block for the experimental
validation of the SM is now in place

A negative surprise: no production of new particles, no evidence of new physics which was expected on theoretical grounds

Not in ATLAS&CMS
Not in Heavy Flavour decays (LHCb, ... B-factories)
Not in $\mu \to e\gamma$ (MEG) $\mathcal{B} < 5.7 \times 10^{-13}$
Not in the EDM of the electron (ACME) $|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$
⊕........[Perhaps a deviation in $(g\text{-}2)_{\mu}$? Theoretical error?]

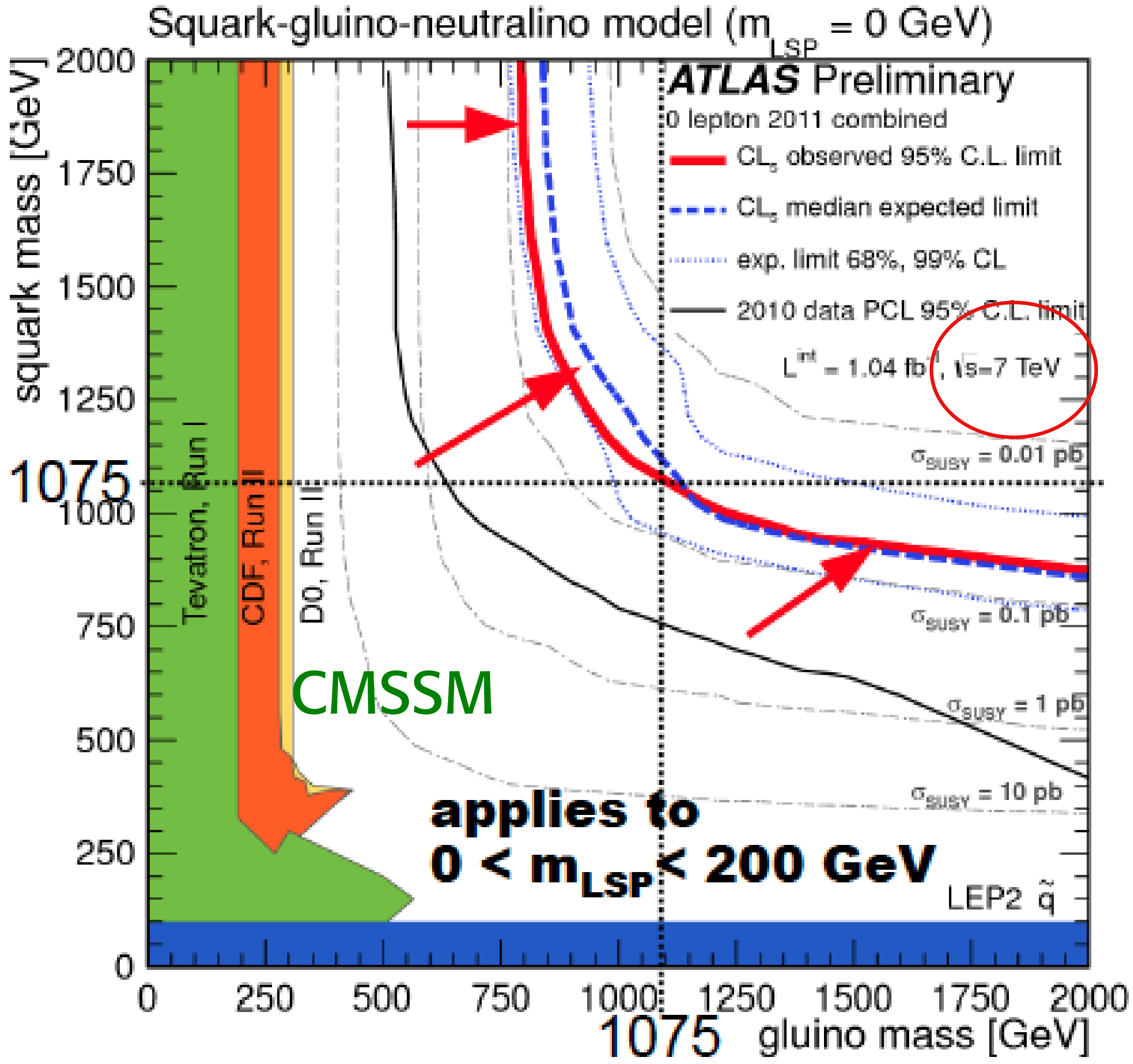
A large new territory explored at the LHC and no new physics

A big step from the
Tevatron 2 TeV
up to LHC 7-8 TeV
(-> 13-14 TeV)

This negative result
is perhaps depressing
but certainly brings
a very important input
to our field

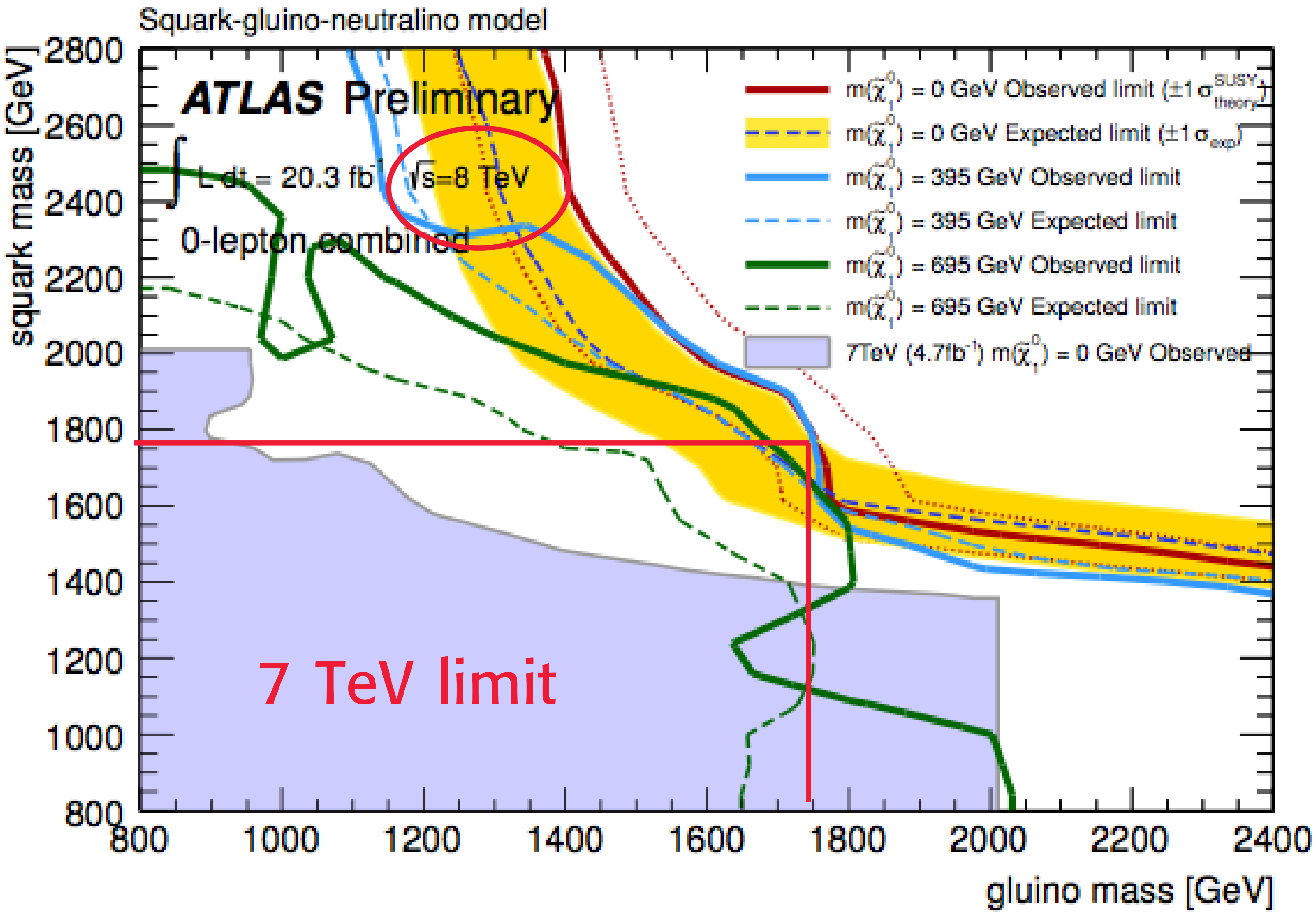
⇨ a big change
in perspective

Jets + missing E_T



CMSSM

**applies to
$0 < m_{LSP} < 200$ GeV**



degenerate squarks

~ 1700 GeV

New physics can appear at 14 TeV (we hope) but it is by now conceivable that no new physics will show up at the LHC

Naturalness? The big question mark!

Flavour is also very stringent (great new results from LHCb, CMS...)

The constraints on NP from flavour are extremely demanding: adding effective operators to SM generally leads to very large Λ

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + \boxed{c_{NP}\frac{1}{\Lambda^2}}$$

Isidori

$$c_{NP} \to \sim 1 \xrightarrow{\text{tree/strong + generic flavour}} \Lambda \gtrsim 2\times10^4 \text{ TeV [K]}$$

$$c_{NP} \to \sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavour}} \Lambda \gtrsim 2\times10^3 \text{ TeV [K]}$$

$$c_{NP} \to \sim (y_t V_{ti}{}^* V_{tj})^2 \xrightarrow{\text{tree/strong + MFV}} \Lambda \gtrsim 5 \text{ TeV [K \& B]}$$

$$c_{NP} \to \sim (y_t V_{ti}{}^* V_{tj})^2/(16\,\pi^2) \xrightarrow{\text{loop + MFV}} \Lambda \gtrsim 0.5 \text{ TeV [K \& B]}$$

For flavour the SM is very special and if there is New Physics, it must be highly non generic

eg in Minimal Flavour Violation (MFV) models

Impact of the Higgs discovery

The minimal SM Higgs:
is the simplest possible form of spont. EW symmetry breaking.

The only known example in physics of a fundamental,
weakly coupled, scalar particle with VEV

→ e.g. the quartic coupling is perturbative:

$$V = -\mu^2 \phi^\dagger \phi + \tfrac{1}{2}\lambda(\phi^\dagger\phi)^2 \qquad \phi \to v + \frac{H}{\sqrt{2}} \qquad v = 174.1 GeV$$

$$m_H{}^2 = 2\mu^2 = 2\lambda v^2 \quad \longrightarrow \quad \tfrac{1}{2}\lambda \sim 0.13$$

What was considered by many theorists just as a toy model,
a temporary addendum to the gauge part of the SM,
it is now promoted to the real thing!

Higgs, unitarity and naturalness in the SM

In the SM the Higgs provides a solution to the occurrence of unitarity violations in some amplitudes (W_L, Z_L scattering)

To avoid these violations one needed either one or more Higgs particles or some new states (e.g. new vector bosons)

Something had to happen at the few TeV scale!!

While this is a theorem, once there is the Higgs,
the necessity of new physics on the basis of naturalness
is not a theorem, although still a well motivated demand

The absence of accompanying new physics puts the issue of the relevance of our concept of naturalness at the forefront

The naturalness principle

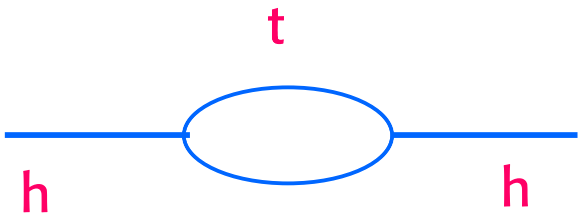
Has been and is the main motivation for new physics at the weak scale

But at present our confidence on naturalness as a guiding principle is being more and more challenged

Does Nature really care about our concept of Naturalness? Apparently not much!
Which form of Naturalness is Natural?

Quadratic sensitivity of mass in the scalar sector

$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$



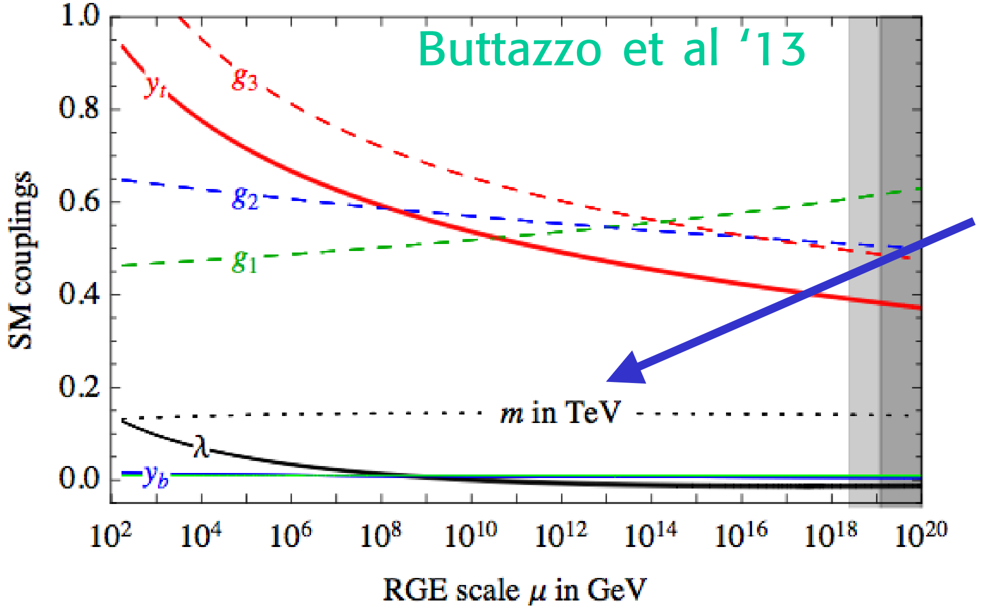
Gildener, Weinberg'76; Maiani'79; 't Hooft'79.......

If we see Λ as the scale where new physics occurs that solves the fine tuning problem, then the strong indication that Λ must be nearby follows

Actually one can formulate the naturalness requirement without reference to a cut-off but only in terms of renormalized quantities.

→

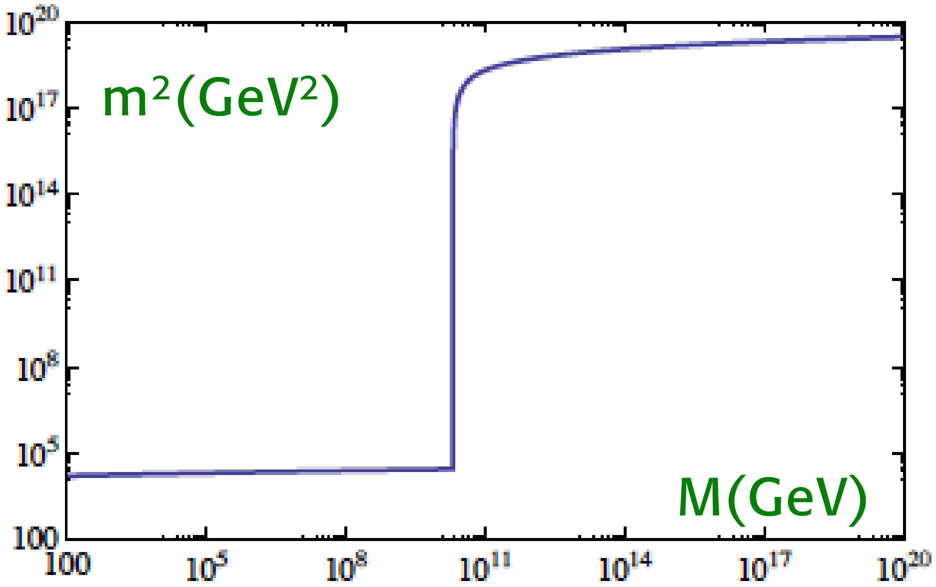
Naturalness in a more physical language



Buttazzo et al '13

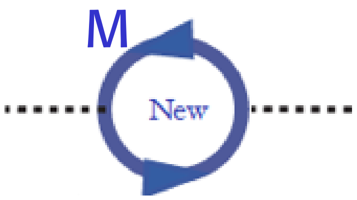
In the renormalized theory the running Higgs mass slowly evolves logaritmically

Barbieri.....



But in the presence of a threshold at M for a heavy particle coupled to the Higgs, the quadratic sensitivity produces a jump in the running mass

$M \sim 10^{10}$ GeV, $\lambda_H \sim 1$, jump: $m^2 \sim (\lambda_H M)^2/(16\pi^2)$



Fine tuning is then needed to explain the small value of m at low energy

The argument for naturalness is strong, except that it has failed so far as a guiding principle

As a consequence:
We can no more be sure that within 3 or 10 or 100 TeV.....
we are guaranteed to find the solution of the hierarchy problem --> implications for future Colliders

Moreover, it is true that the SM theory is renormalizable and completely finite and predictive

If you forget the required miraculous fine tuning you are not punished, you find no catastrophe!!

Is naturalness relevant? The multiverse alternative

- The obs. value of the cosmological constant Λ_{cosmo} poses another tremendous, unsolved naturalness problem

While natural extensions of the SM exist, no convincing natural explanation of the value of Λ_{cosmo} is known

- Yet the value of Λ_{cosmo} is close to the Weinberg upper bound for galaxy formation
- Possibly our Universe is just one of infinitely many continuously created from the vacuum by quantum fluctuations
- Different physics in different Universes according to the multitude of string theory solutions $(\sim 10^{500})$

Perhaps we live in a very unlikely Universe but one that allows our existence

Given the stubborn refusal of the SM to step aside many have turned to the anthropic philosophy also for the SM

Actually applying the anthropic principle to the SM hierarchy problem is not terribly convincing

After all, we can find plenty of models that reduce the fine tuning from 10^{14} to 10^{2}. And the added ingredients do not appear to make our existence more impossible. So why make our Universe so terribly unlikely?

But there is some similarity

Λ_{cosmo} - > a vacuum energy density in all points of space

v -> a vacuum expectation value in all points of space

With larger Λ_{cosmo} no galaxies, with larger v no nuclear physics

⊕ The anthropic way is now being kept in mind as a possibility

The other main side: stay natural and minimize the FT

- "Stealth" Naturalness: build models where naturalness is restored as close as possible to the weak scale but the related NP is arranged to be not visible so far

Fine-tuning the fine-tuning-suppression mechanism?

Two main directions

SUSY

For an orderly retreat

simplest new ingredients are

- Compressed spectra
- Heavy first 2 generations
- NMSSM (an extra Higgs singlet)

The last trench of natural SUSY!

Composite Higgs

The main idea:

H as PGB of extended symm.

a not too far compositeness scale

q and l mix with comp. ferm.

Key role of light top partners

scalar s-top

fermion t'

A revival of models that ignore the fine tuning problem

The absence of new physics appears as a paradox to us

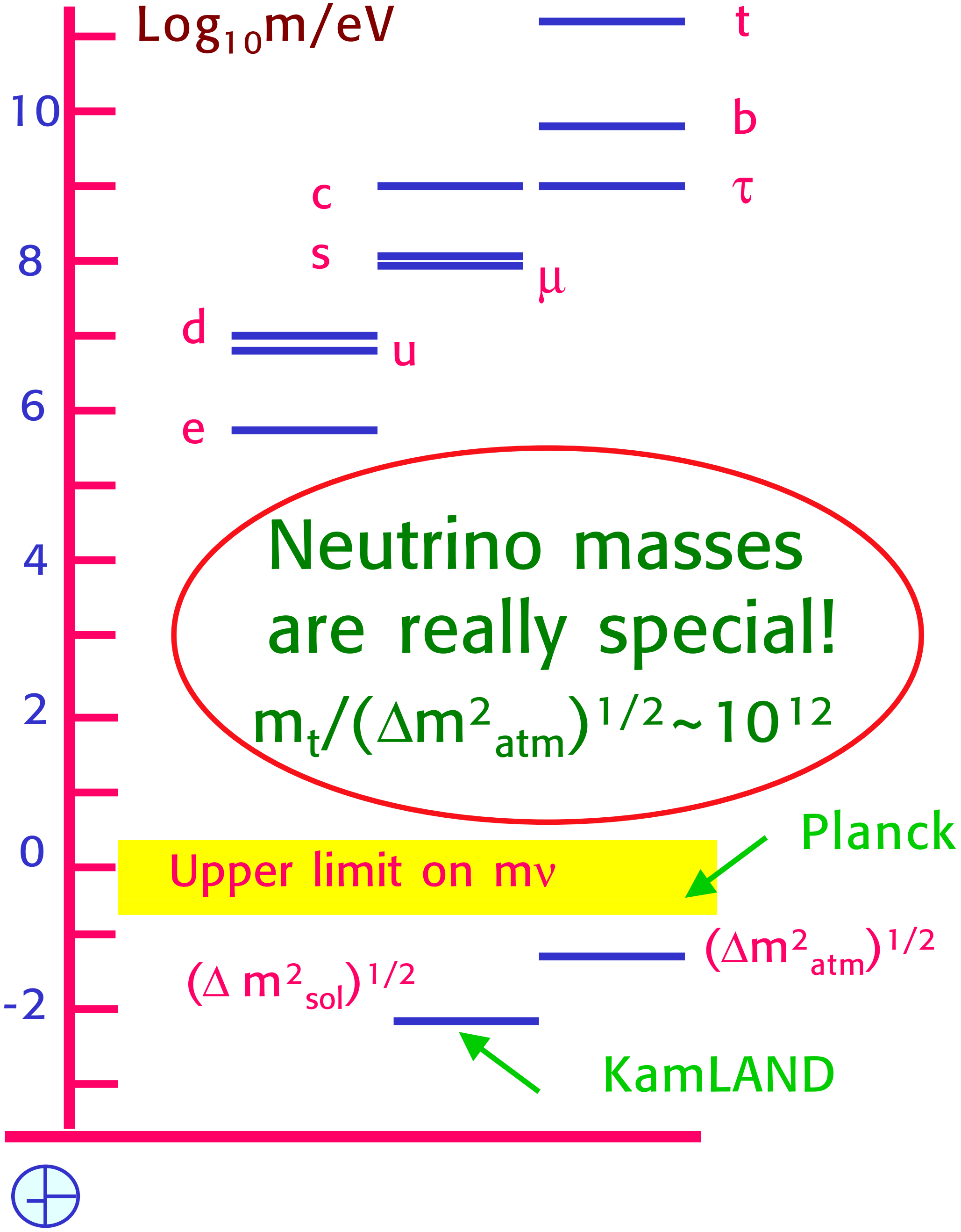
Still the picture repeatedly suggested by the data in the last ~20 years is simple and clear

Take the SM, extended to include Majorana neutrinos and some simplest form of DM, as valid up to very high energy

Neutrino masses? See-Saw mechanism
Baryogenesis? Thru leptogenesis
Dark Matter? Axions, keV sterile neutrinos...?
Coupling Unification? Some large scale scale threshold, e.g. SO(10) with an intermediate scale

GA, Meloni ‘13

Possibly Nature has a way, hidden to us, to realize a deeper form of naturalness at a more fundamental level



Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

Massless ν's?

- no ν_R
- L conserved

But ν_R can well exist and we really have no reason to expect that B and L are exactly conserved

Small ν masses?

- ν_R very heavy
- L not exactly cons.

The SM can be easily extended to include Majorana ν's

Completing the SM with ν_R

It is sufficient to introduce 3 RH gauge singlets ν_R
[each completing a 16 of SO(10) for one generation]
and not artificially impose that L is conserved

In the SM, in the absence of ν_R, B and L are "accidental" symmetries [i.e. no renormalizable gauge invariant B and/or L non-conserving vertices can be built from the fields of the theory]

But we know that non perturbative terms (instantons) break B and L (not B-L) and also non renorm. operators:

Weinberg
dim-5 operator

$$O_5 = \frac{(Hl)_i^T \lambda_{ij} (Hl)_j}{\Lambda} + \ h.c.$$

With Majorana ν_R renormalizable mass terms are allowed by gauge symmetries and break L (and B-L)

See-Saw Mechanism

Minkowski; Glashow; Yanagida;
Gell-Mann, Ramond , Slansky;
Mohapatra, Senjanovic…..

$M\nu^T{}_R\nu_R$ allowed by SU(2)xU(1)

Large Majorana mass M (as large as the cut-off)

$m_D\bar{\nu}_L\nu_R$

Dirac mass m_D from Higgs doublet(s)

$$\begin{array}{c} \\ \nu_L \\ \nu_R \end{array} \begin{array}{c} \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix} \end{array}$$

$M >> m_D$

Eigenvalues

$$|\nu_{light}| = \frac{m_D{}^2}{M} \quad , \quad \nu_{heavy} = M$$

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{GUT}$

$$m_\nu \sim \frac{m^2}{M}$$

$m: \leq m_t \sim v \sim 200$ GeV
M: scale of L non cons.

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV
$m \sim v \sim 200$ GeV

$M \sim 10^{14} - 10^{15}$ GeV

Observation of $0\nu\beta\beta$ would confirm that ν are Majorana

This is so impressive that, in my opinion, models with ν_R at the EW scale or around are strongly disfavoured

Baryogenesis by decay of heavy Majorana ν_R's

BG via Leptogenesis near the GUT scale

(after inflation)

Buchmuller,Yanagida,
Plumacher, Ellis, Lola,
Giudice et al, Fujii et al
…..

Survives as Δ(B-L) is not zero
(otherwise washed out at T_{ew} by instantons)

Main candidate: decay of lightest ν_R ($M \sim 10^{11\text{-}12}$ GeV)

L non conserv. & CP violat.'n in ν_R out-of-equilibrium decay:
B-L excess survives at T_{ew} and gives the obs. B asymmetry.

Quantitative studies confirm that the range of m_i from
ν oscill's is compatible with BG via (thermal) LG

In particular the bound
was derived for hierarchy

$m_i < 10^{-1}$ eV

Buchmuller, Di Bari, Plumacher;
Giudice et al; Pilaftsis et al;
Hambye et al

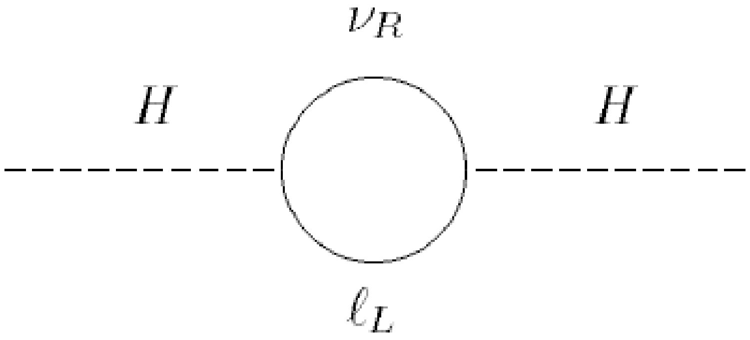
Can be relaxed for degenerate neutrinos
So fully compatible with oscill'n data!!

Heavy ν_R well match with GUT's [recall the16 of SO(10)!]

(if for naturalness SUSY is invoked, one also has the bonus that coupling unification and proton decay are OK, ...)

But so far, no SUSY or any New Physics

If only the SM + Majorana ν 's, then heavy ν_R are unnatural and require fine tuning:



for q >> M_R

$$\delta\mu^2 \approx \frac{y_\nu^2}{(2\pi)^2}\, M_R^2\, \log(q/M_R)$$
$$\approx \frac{m_\nu M_R^3}{(2\pi\, v)^2}\log(q/M_R)$$

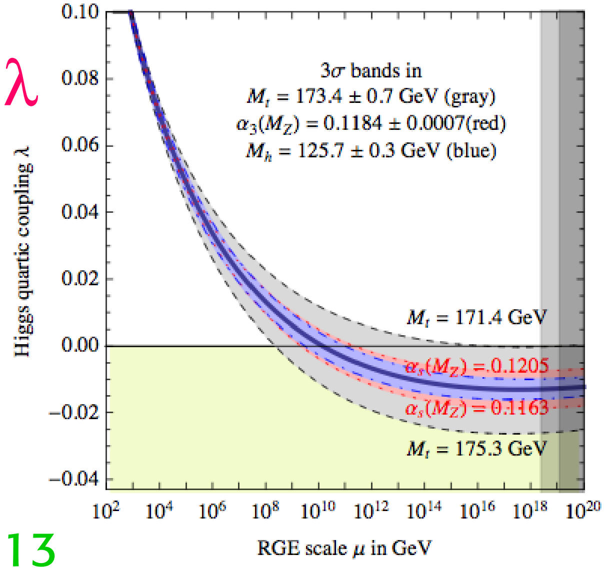
$\mu < 1$ TeV ⟶ $M_R < 10^7\text{-}10^8$ GeV

Vissani '97
Elias-Miro"11

The pure SM evolution of couplings leads to a metastable Universe

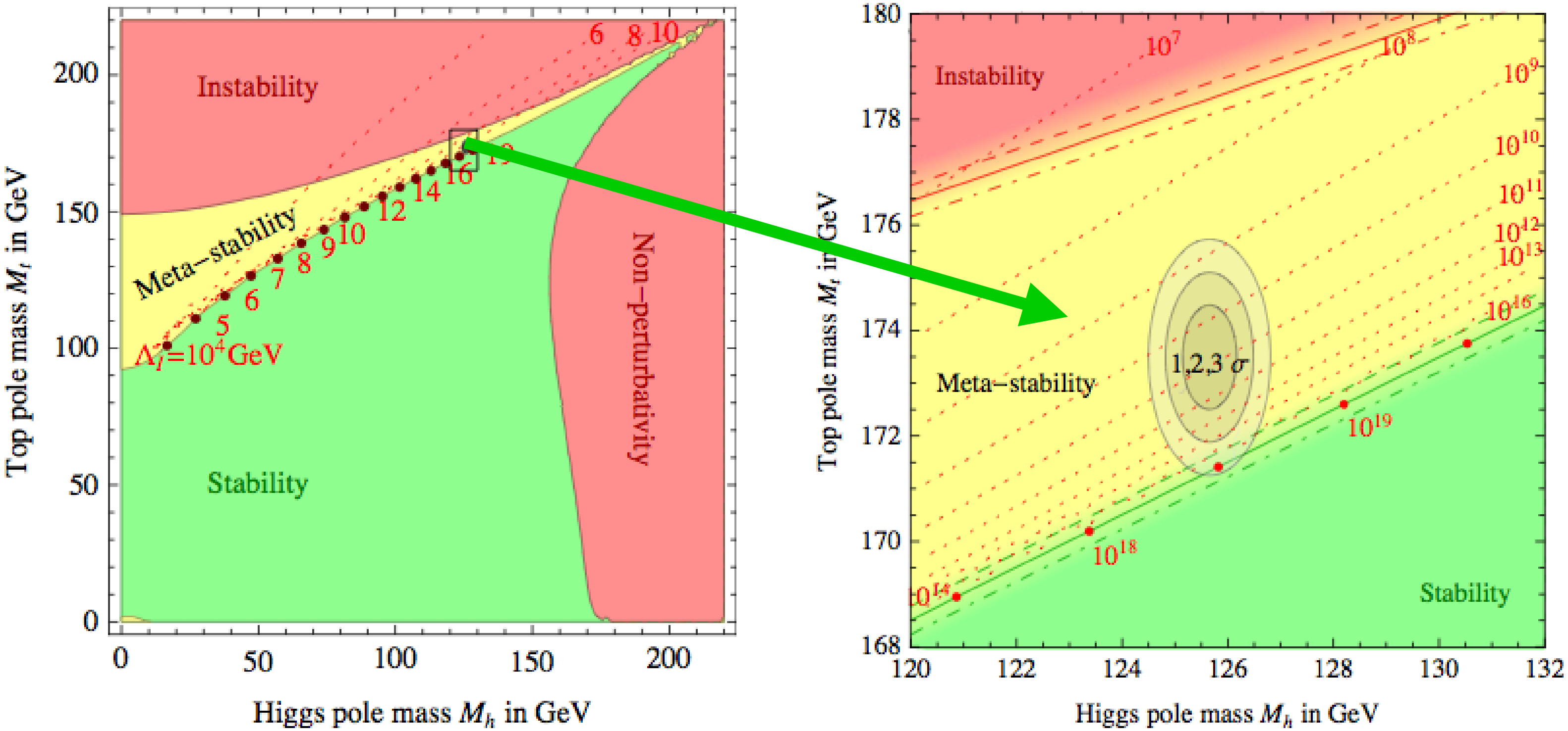
The SM evolution up to M_{Pl} leads to a narrow critical wedge: a hidden message?

λ



$\lambda\phi^4$

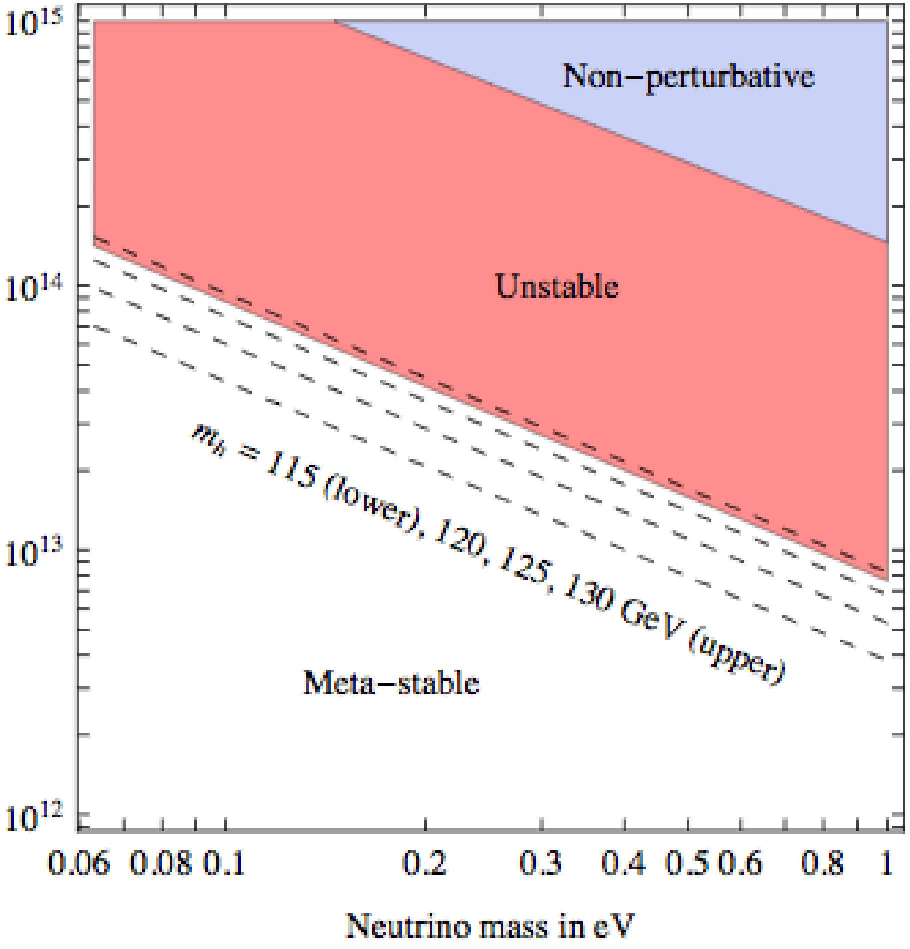
Buttazzo et al '13



Heavy ν_R's further de-stabilize the vacuum

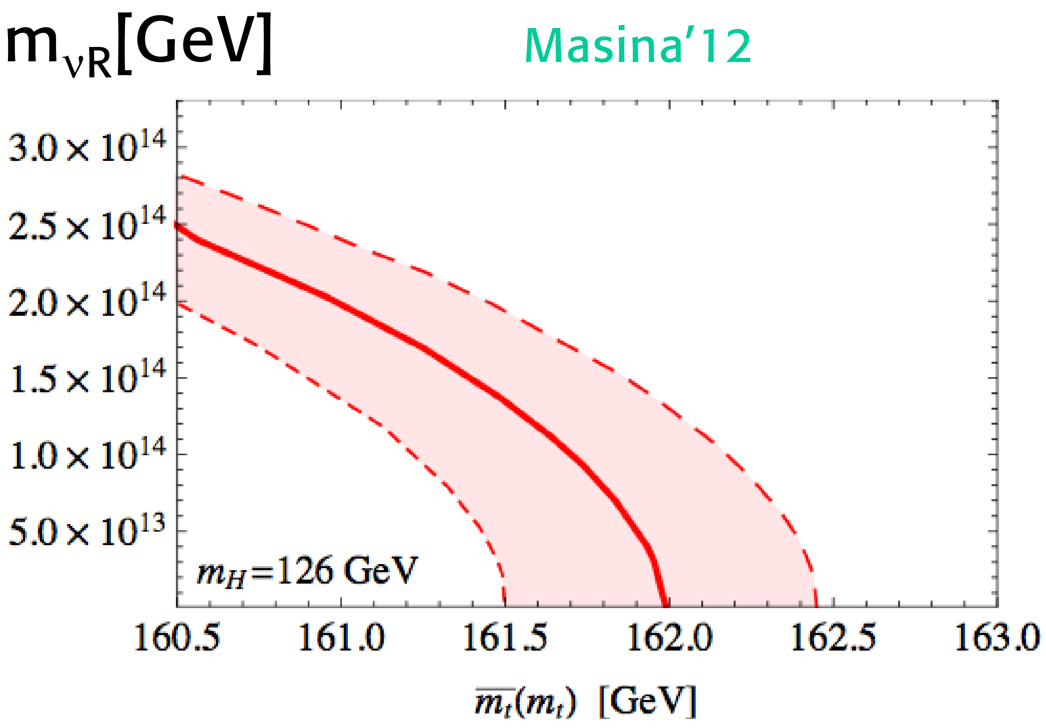
But, for $M < 10^{14}$ GeV, ν_R's do not make the vacuum unstable

J. Elias-Miro' et al '11



$m_{\nu R}$[GeV]

Masina'12



While for neutrino masses, baryogenesis... we have definite ideas on how these problems could be solved Dark Matter remains mysterious and is the most compelling argument for New Physics and the most pressing challenge for particle physics

A partial list of main candidates:

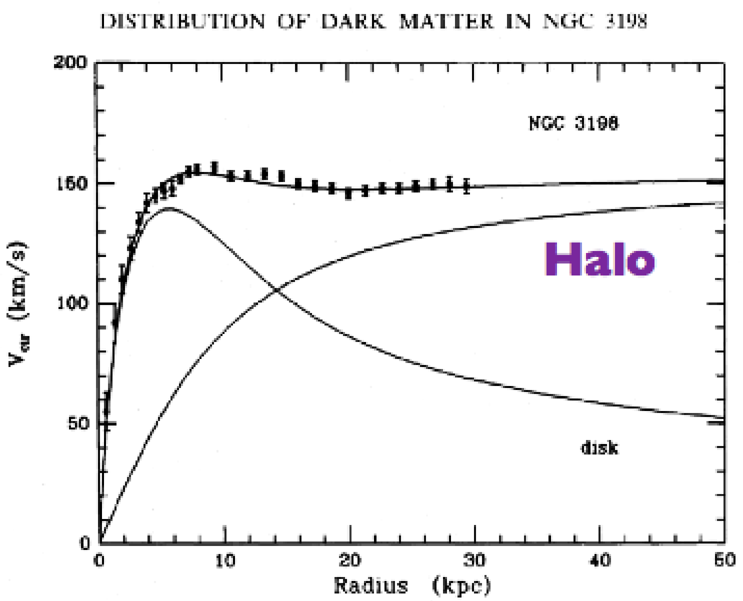
- WIMP's
- Axions
- keV sterile neutrinos

The 3 active ν's cannot make the whole of DM. Bounds:
- Dwarf Galaxies ---> m > few hundreds eV (Tremaine-Gunn)
- Galaxies ---> m > few tens eV
- Hot DM also excluded by structure formation

⊕ Nearby sterile ν's (m ~ eV) are also inadequate

A by now robust evidence for Dark matter in the Universe

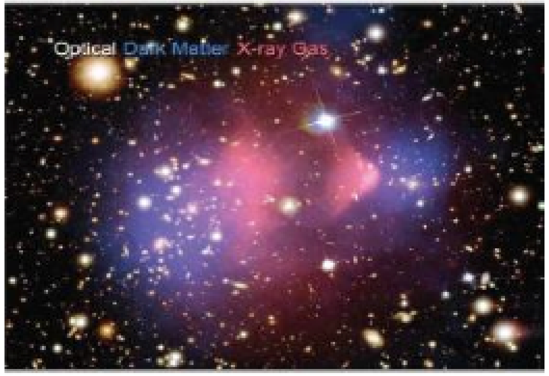
Rotation of galaxies


DISTRIBUTION OF DARK MATTER IN NGC 3198

Lensing


MACS, HST

Merging galaxies



M. Markevitch et al 2003

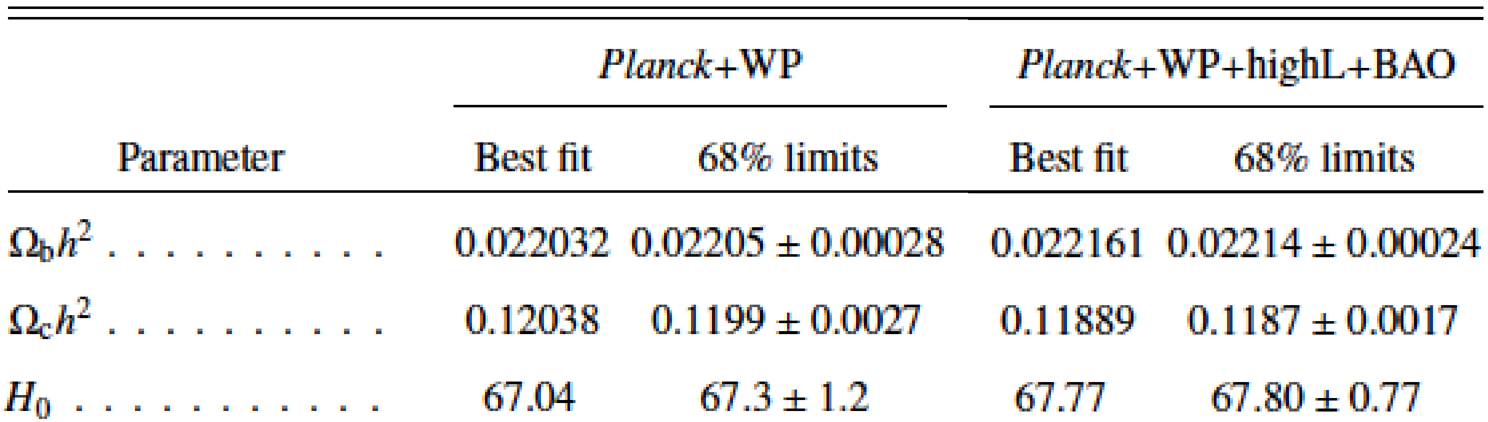
Cosmological evidence

anisotropies of Micro Wave Background Radiation
large scale structure
structure formation.....

e.g. Planck

Planck fits of DM ArXiv:1303.5076

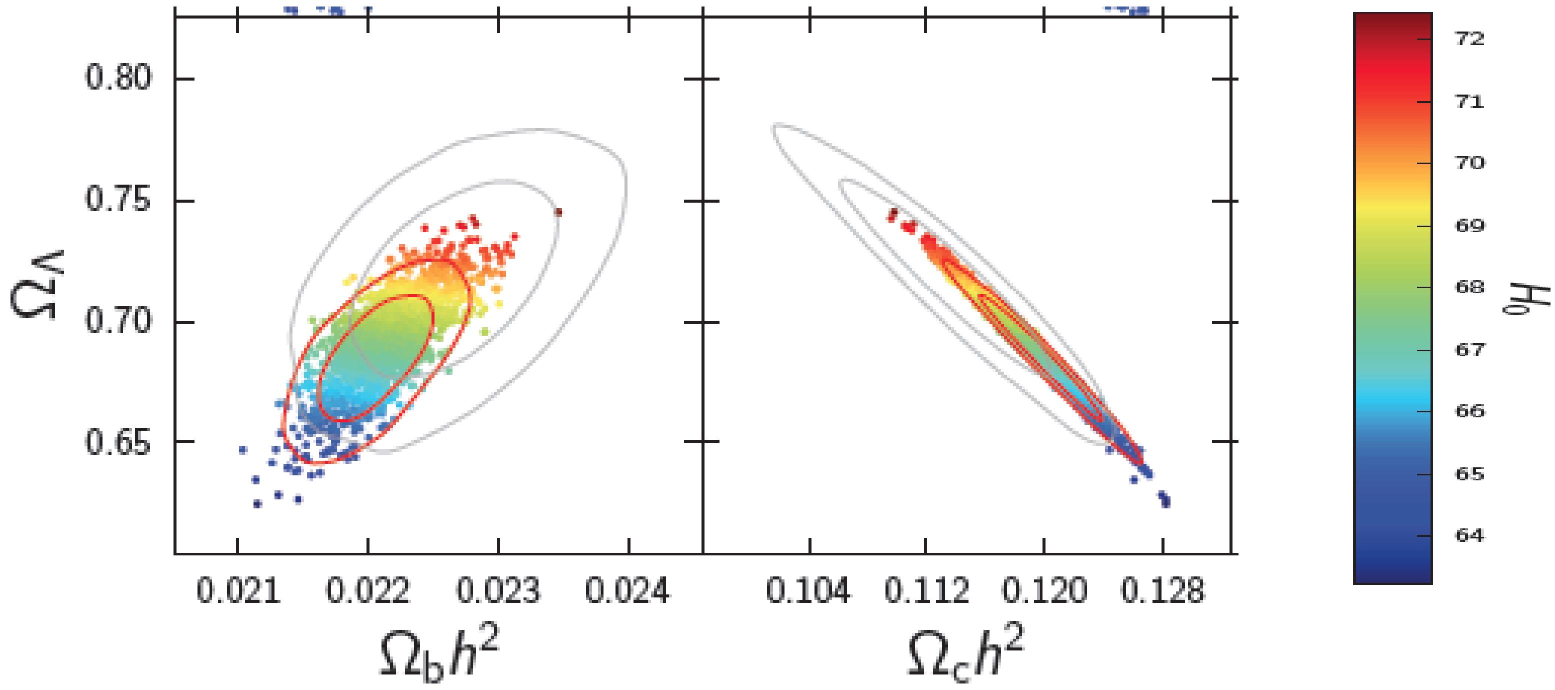
$H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$



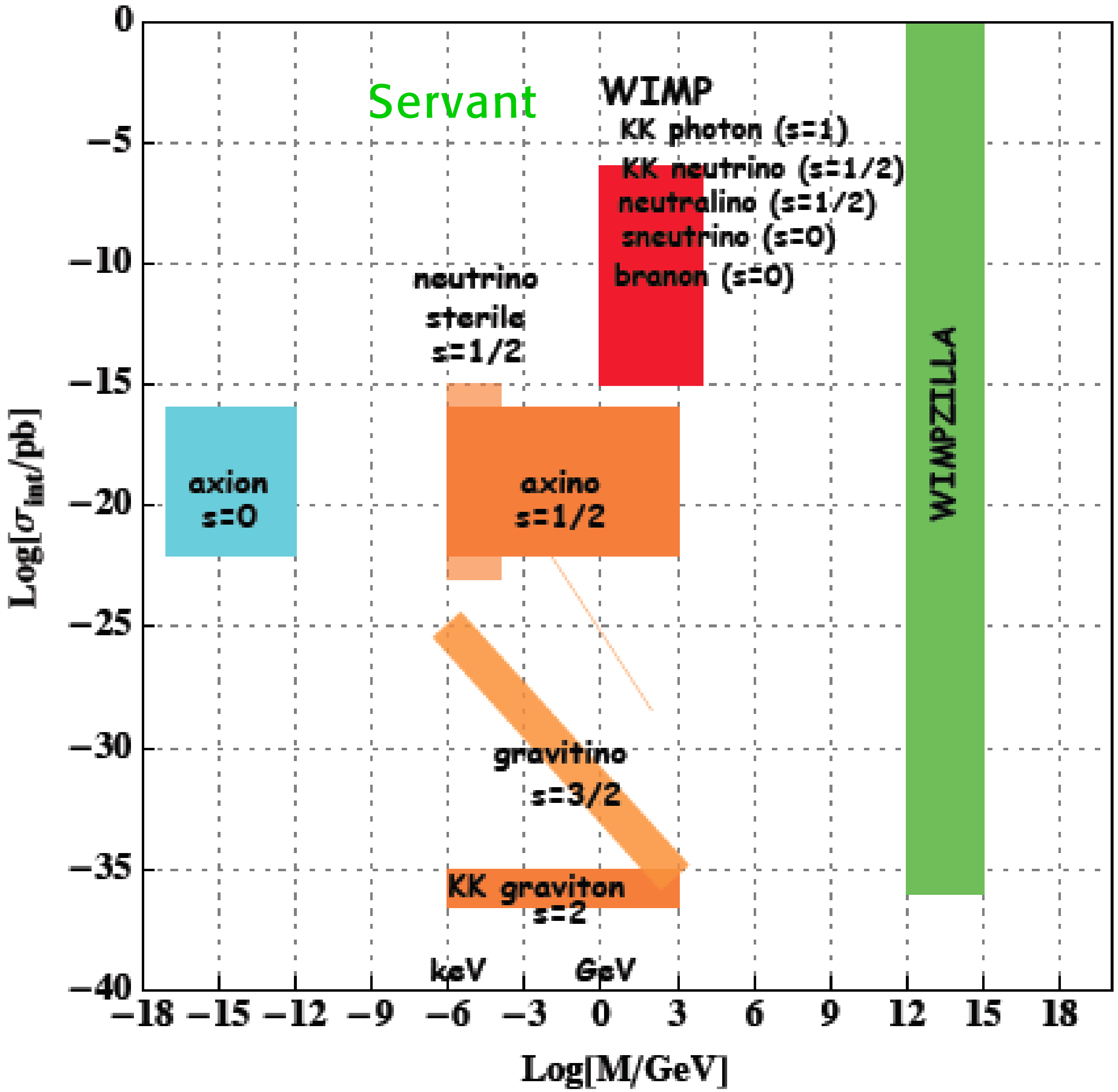
	Planck+WP		Planck+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.11889	0.1187 ± 0.0017
H_0	67.04	67.3 ± 1.2	67.77	67.80 ± 0.77

Ω_c = cold DM density

h ~ 0.67



In the literature the DM candidates span an enormous range of mass



WIMP's: Weakly Interacting Massive Particles
with m ~ 10^{-1}-10^{3} GeV

WIMP's still are optimal candidates:

LHC can reach most kinds of WIMP's

For WIMP's in thermal equilibrium after inflation the density is:

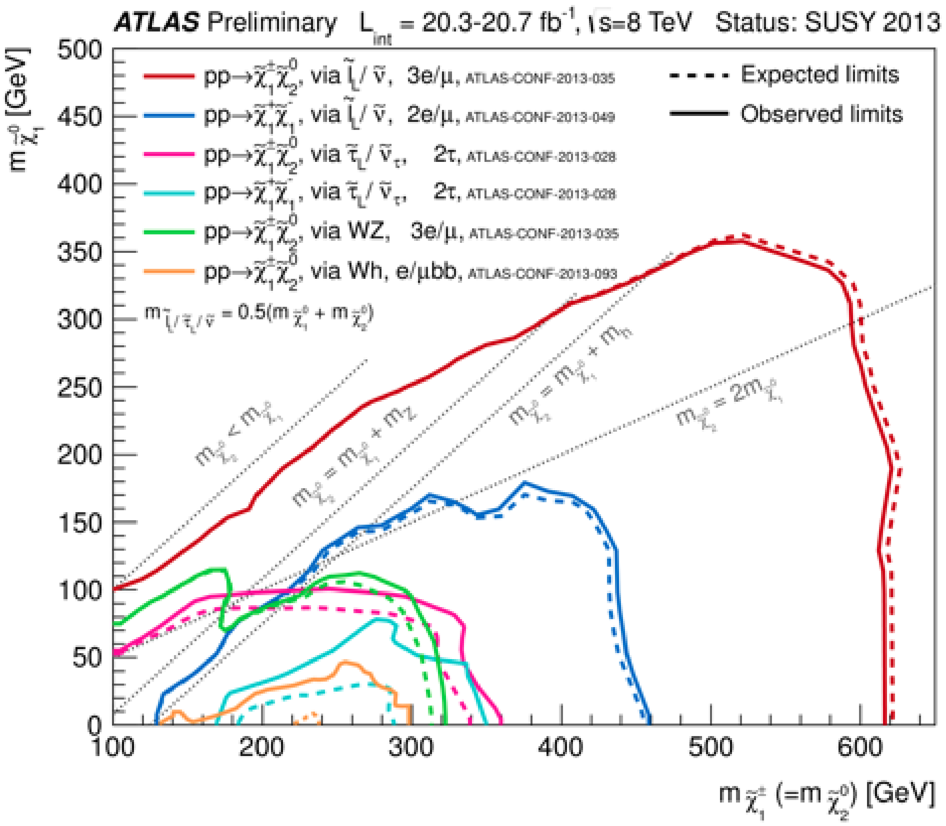
$$\boxed{\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\mathrm{Pl}}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}}$$

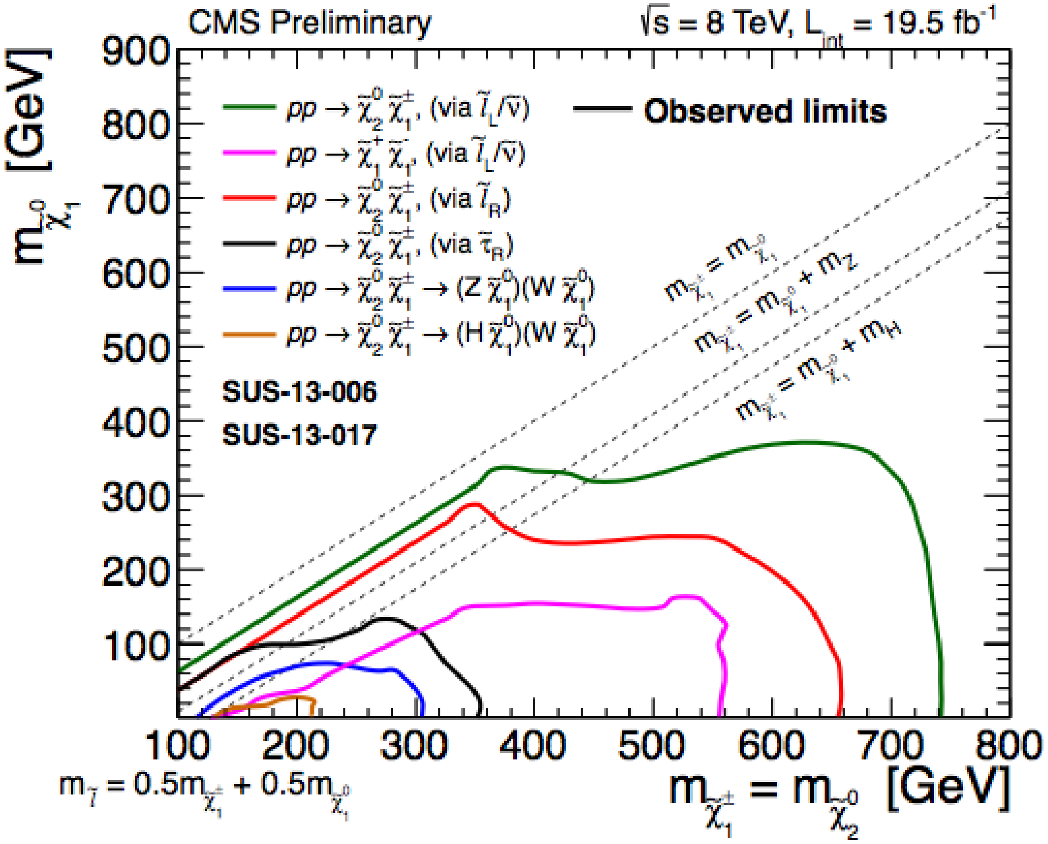
can work for typical weak cross-sections!!!

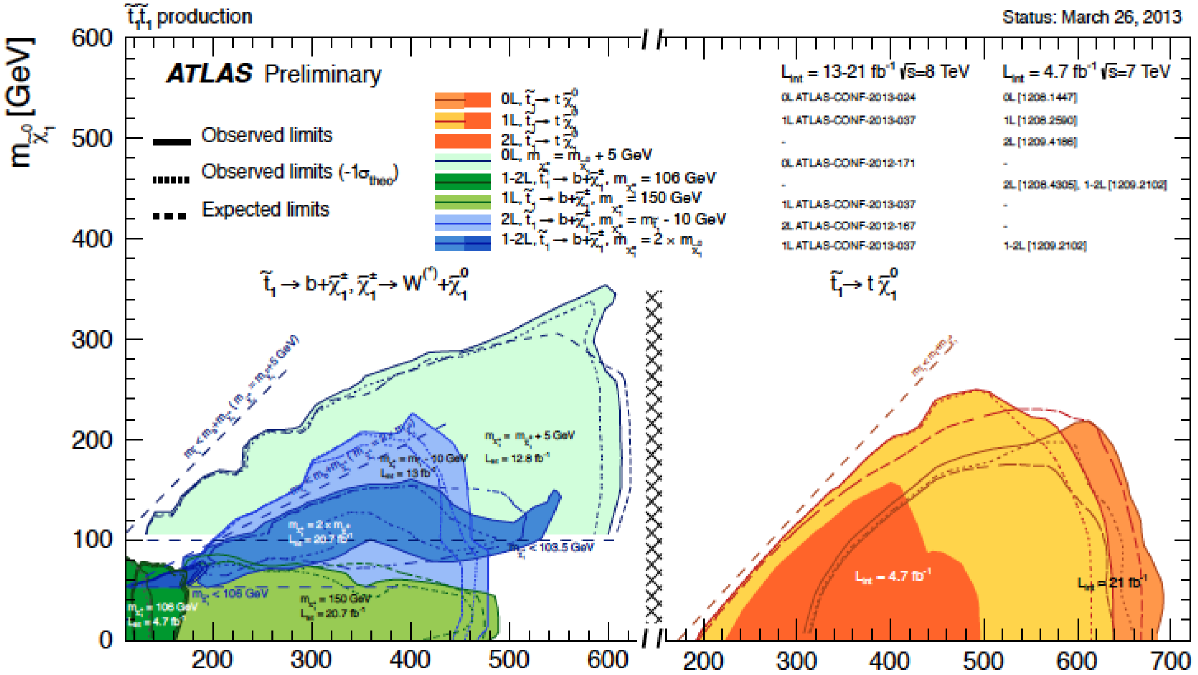
This "coincidence" is taken as a good indication in favour of a WIMP explanation of Dark Matter

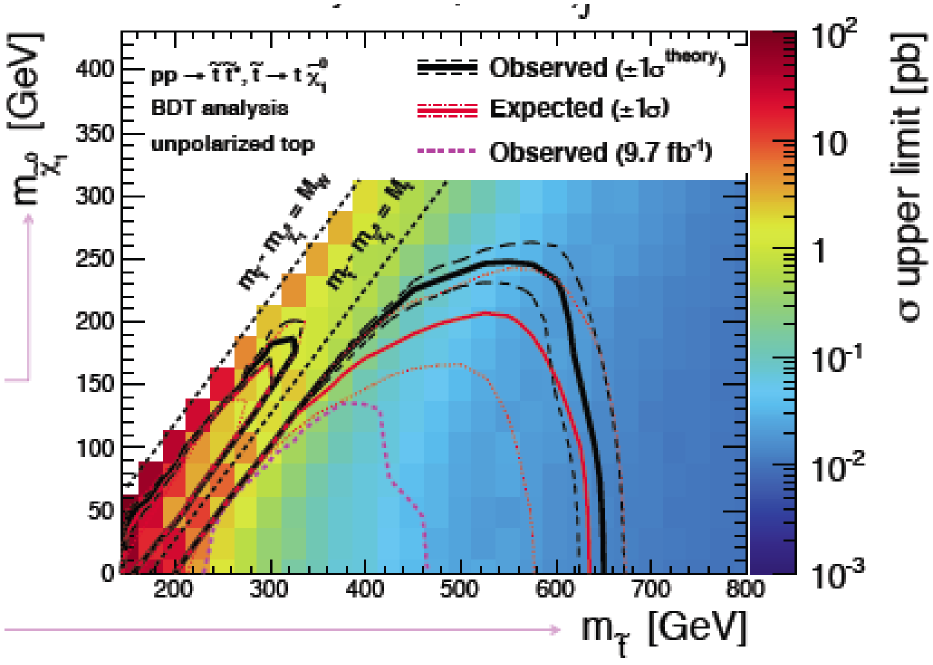
No WIMP's have been observed at the LHC

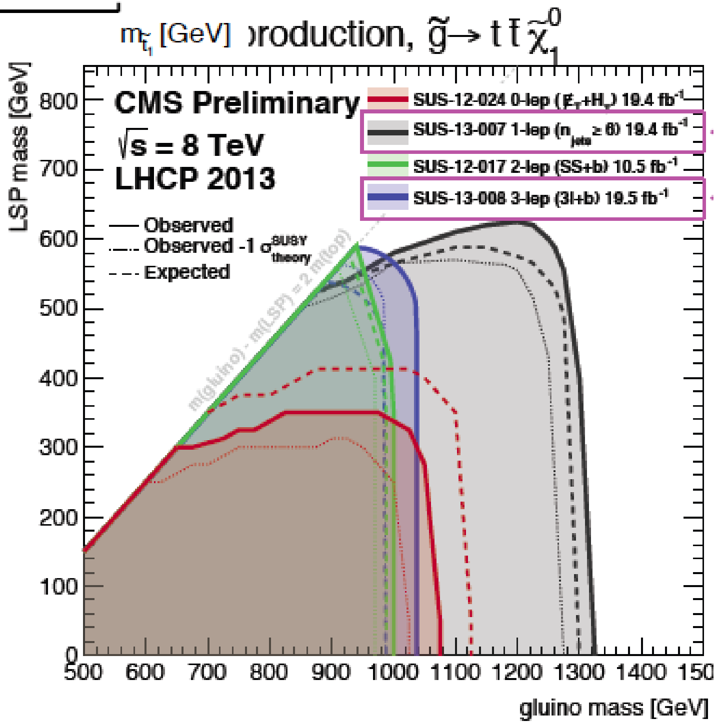
But the limits on neutralinos are not too stringent









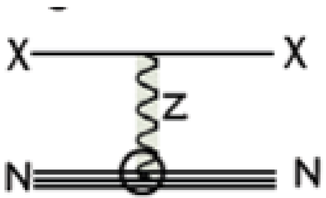


in large regions
of parameter space
$m_{\chi 0} < 350$ GeV
is allowed

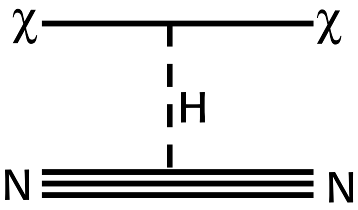
Non accelerator searches

χ N --> χ N

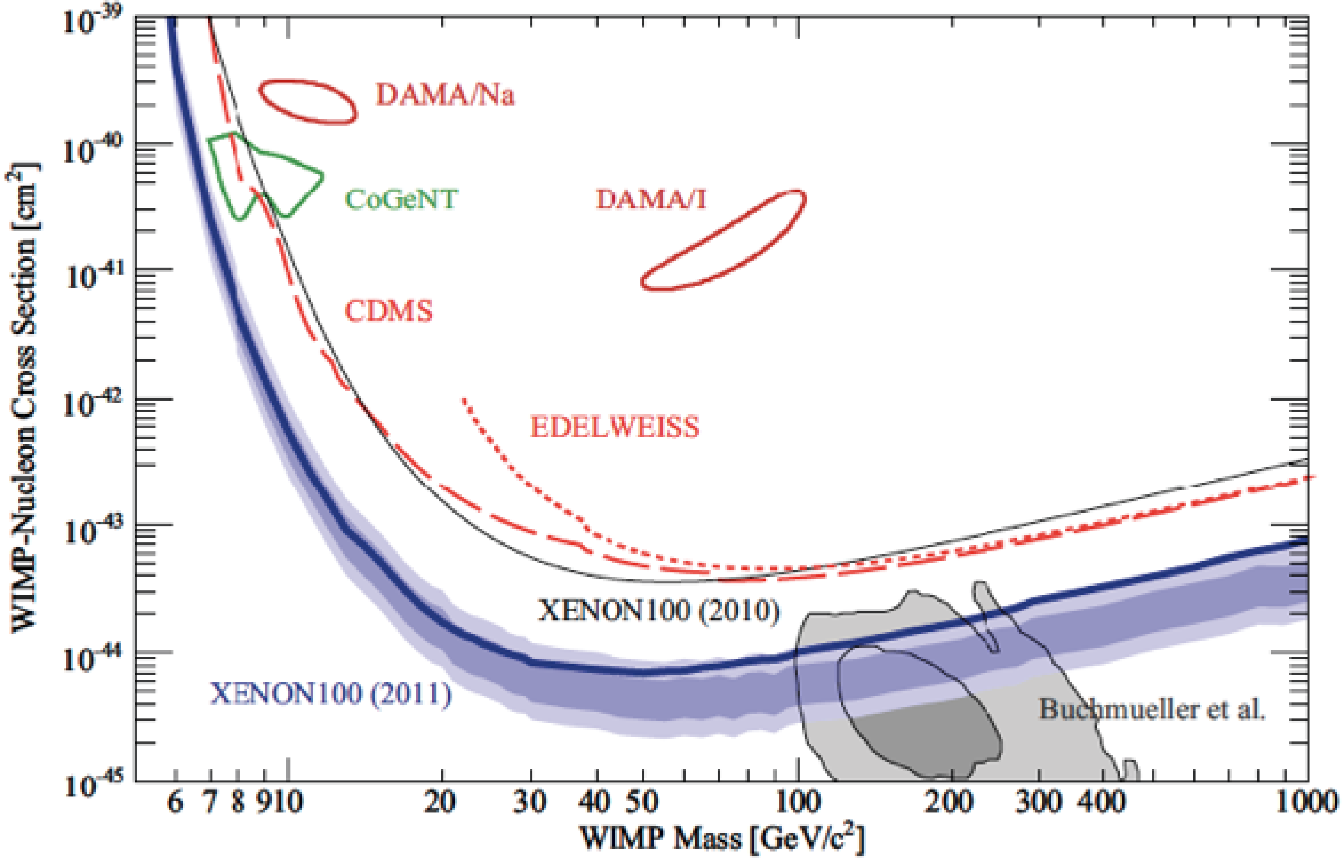
Z echange potentially large



125 GeV Higgs boson exchange being also probed now



exclusion by XENON100 (100 days x 48 kgs)



DM coupled to Z severely limited (axial couplings less constrained)

LUX constraints strongest

De Simone, Giudice, Strumia ‘14

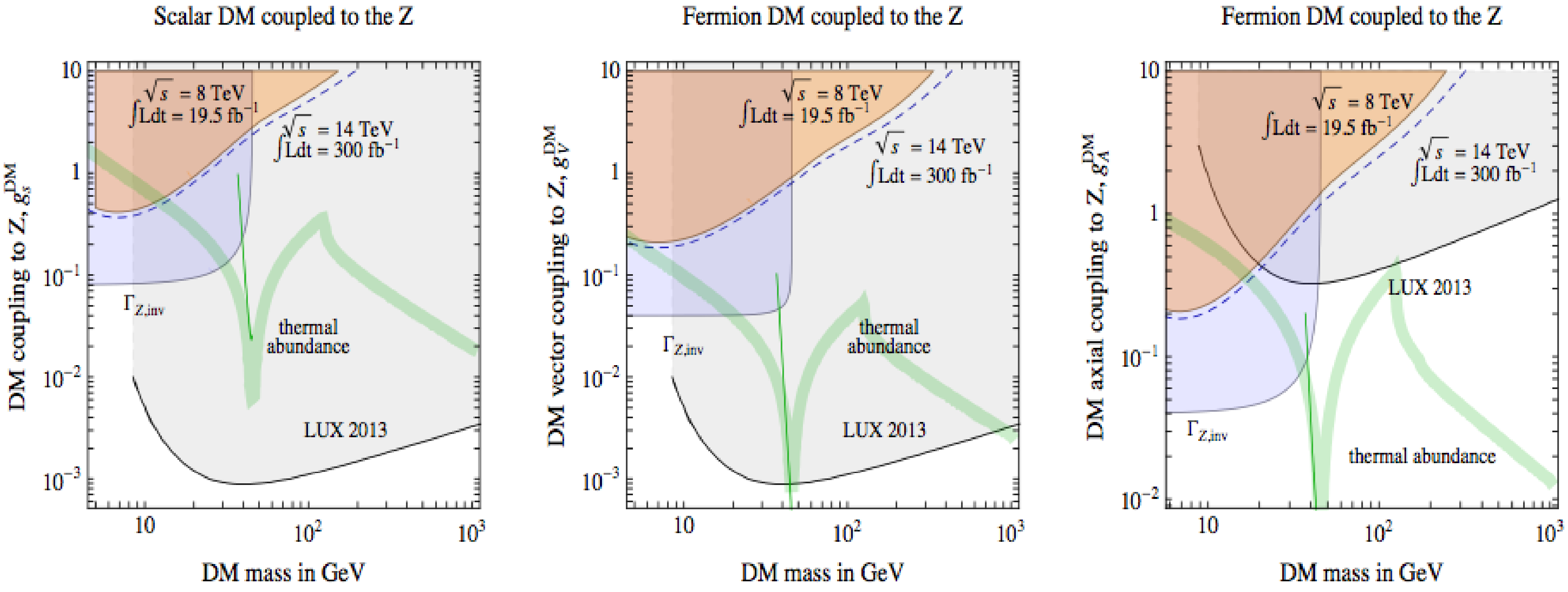
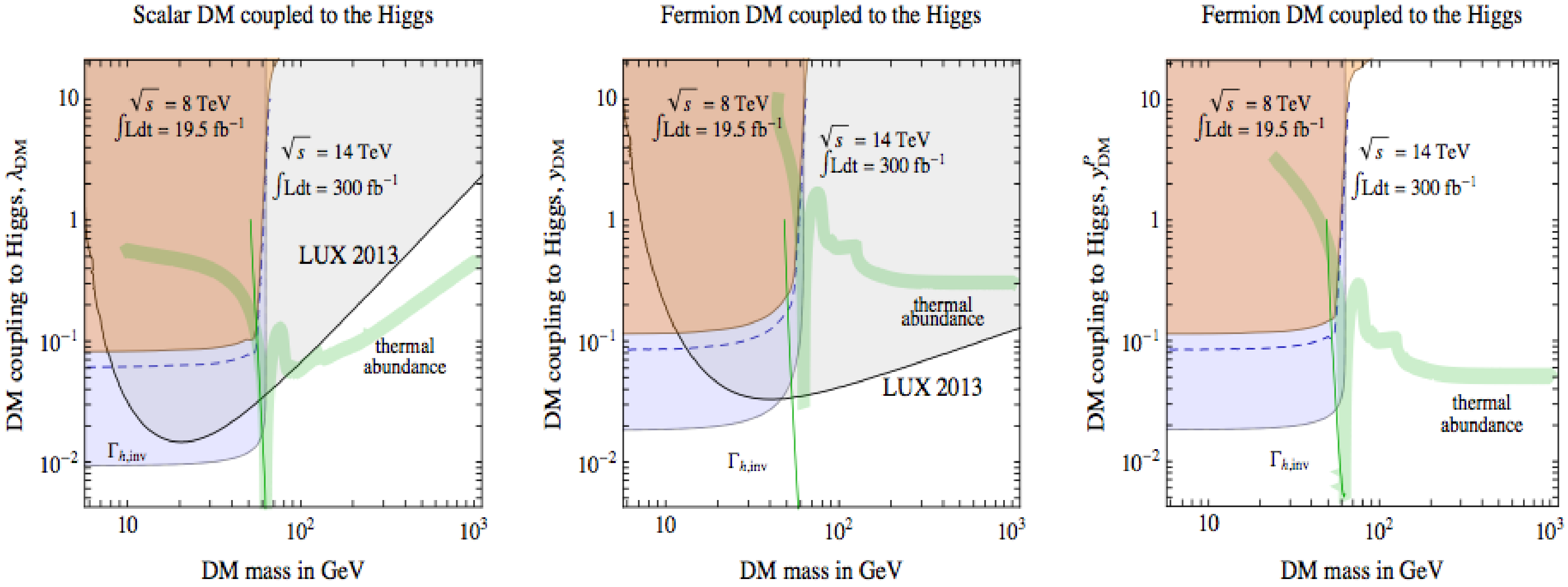


Figure 3: ***DM coupled to the Z.*** *Regions of DM mass* M_{DM} *and Z couplings* (g_s^{DM}, g_V^{DM}, g_A^{DM})*: the orange region is excluded at 90% CL by ATLAS mono-jet searches at LHC8, with forecast for LHC14 (dashed blue line); the grey region is excluded at 90% CL by LUX 2013 direct searches; the blue region is excluded by the Z-invisible width constraint* $\Gamma_{Z,\rm inv} < 2$ MeV*. The green solid curve corresponds to a thermal relic abundance via Z-coupling annihilation equal to the observed DM density (the thick curve is the off-shell estimation; the thin curve is the on-shell computation).*

DM coupled to Higgs also limited (pseudo scalar couplings less constrained)

De Simone, Giudice, Strumia '14



Scalar DM coupled to the Higgs

Fermion DM coupled to the Higgs

Fermion DM coupled to the Higgs

scalar coupling

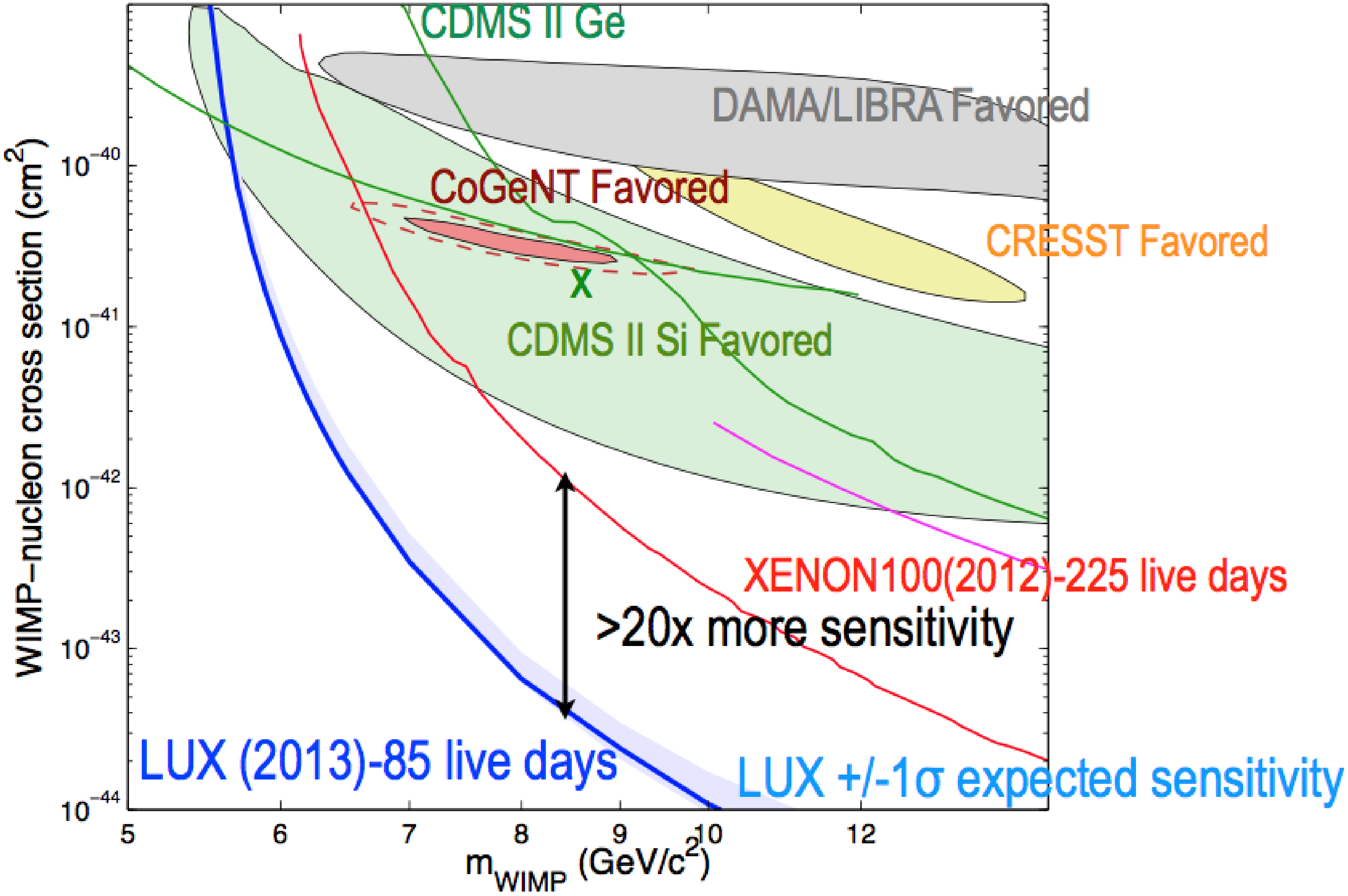
pseudoscalar coupling

Figure 4: ***DM coupled to the Higgs.*** *Regions of DM mass $M_{\rm DM}$ and Higgs couplings ($\lambda_{\rm DM}$, $y_{\rm DM}$, $y^P_{\rm DM}$): the orange region is excluded at 90% CL by ATLAS mono-jet searches at LHC8, with forecast for LHC14 (dashed blue line); the grey region is excluded at 90% CL by LUX 2013 direct searches; the blue region is excluded by the Higgs invisible width constraint $\Gamma_{h,\rm inv}/\Gamma_h < 20\%$. The green solid curve corresponds to a thermal relic abundance via Higgs-coupling annihilation equal to the observed DM density (the thick curve is the off-shell estimation; the thin curve is the on-shell computation).*

Low mass ~10 GeV WIMP's?

CDMS-Si ArXiv :1304.4279 3 events in the signal region

Now excluded by LUX ArXiv:1310.8214



However there is still plenty of room for low mass WIMP's

A heavy WIMP?

Minimal WIMP DM: just add a single EW multiplet

Cirelli, Strumia: ArXiv:0903.3381

The proposed solution is a vector-like weak-isospin-2 fermion pentaplet with Y=0, colourless, chosen on the basis of stability, on present bounds on $\sigma[\chi+N \dashrightarrow \chi+N]$ etc

Simply add

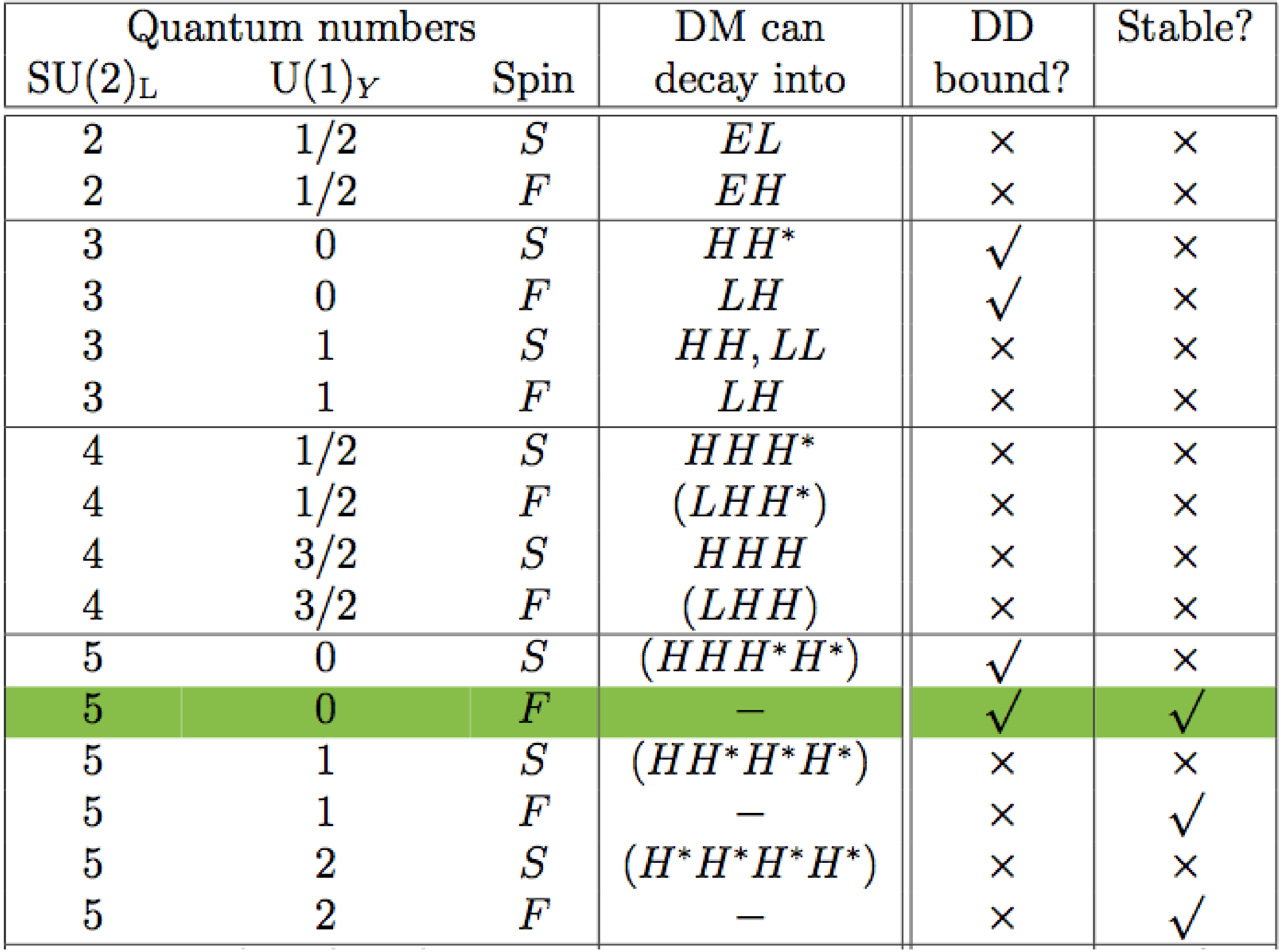
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} & \text{for fermionic } \mathcal{X} \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2 & \text{for scalar } \mathcal{X} \end{cases}$$

M is fixed by DM abundance
(taking Sommerfeld enhancement into account)

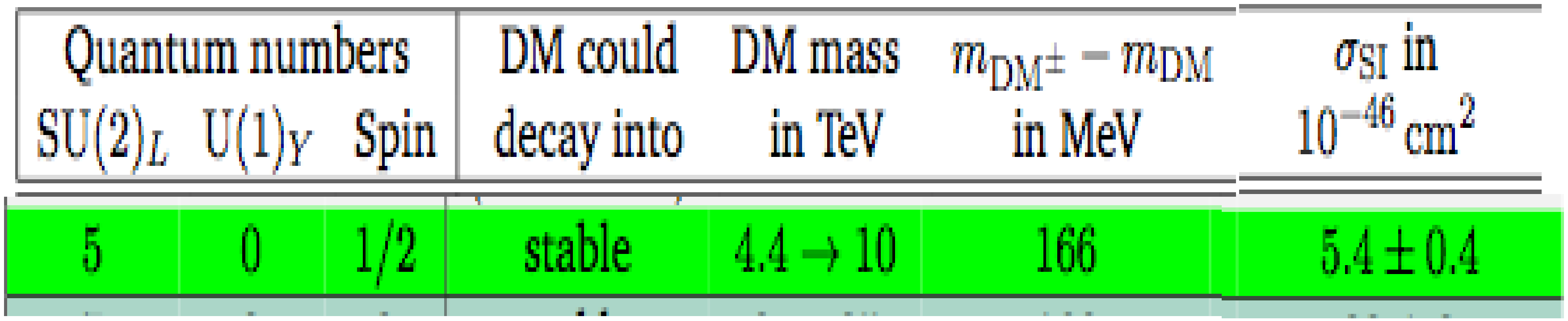
$$M = (9.6 \pm 0.2)\ \text{TeV}$$

Direct Detection

Cirelli, Strumia '09

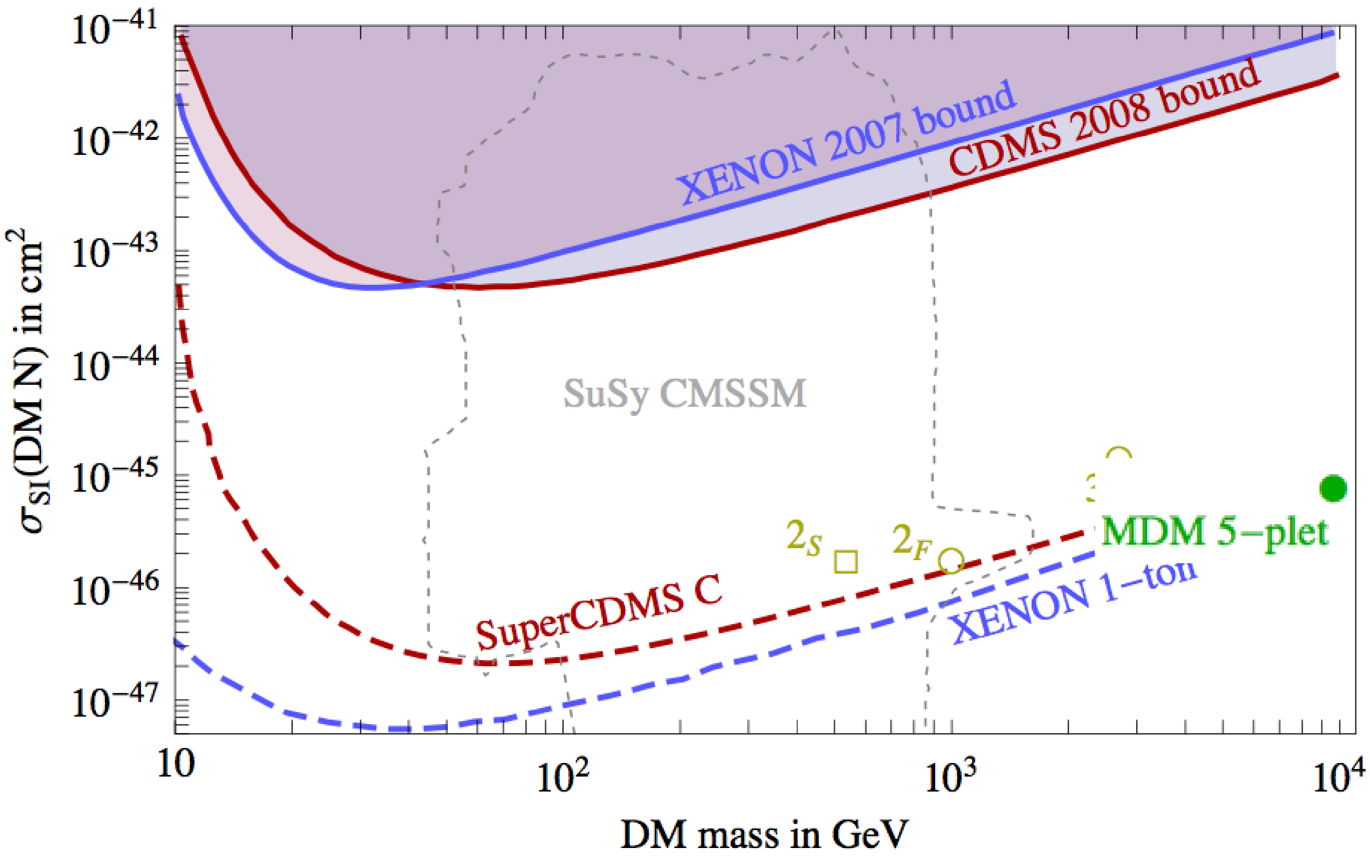


Quantum numbers			DM can decay into	DD bound?	Stable?
$SU(2)_L$	$U(1)_Y$	Spin			
2	1/2	S	EL	×	×
2	1/2	F	EH	×	×
3	0	S	HH^*	√	×
3	0	F	LH	√	×
3	1	S	HH, LL	×	×
3	1	F	LH	×	×
4	1/2	S	HHH^*	×	×
4	1/2	F	(LHH^*)	×	×
4	3/2	S	HHH	×	×
4	3/2	F	(LHH)	×	×
5	0	S	(HHH^*H^*)	√	×
5	0	F	$-$	√	√
5	1	S	$(HH^*H^*H^*)$	×	×
5	1	F	$-$	×	√
5	2	S	$(H^*H^*H^*H^*)$	×	×
5	2	F	$-$	×	√

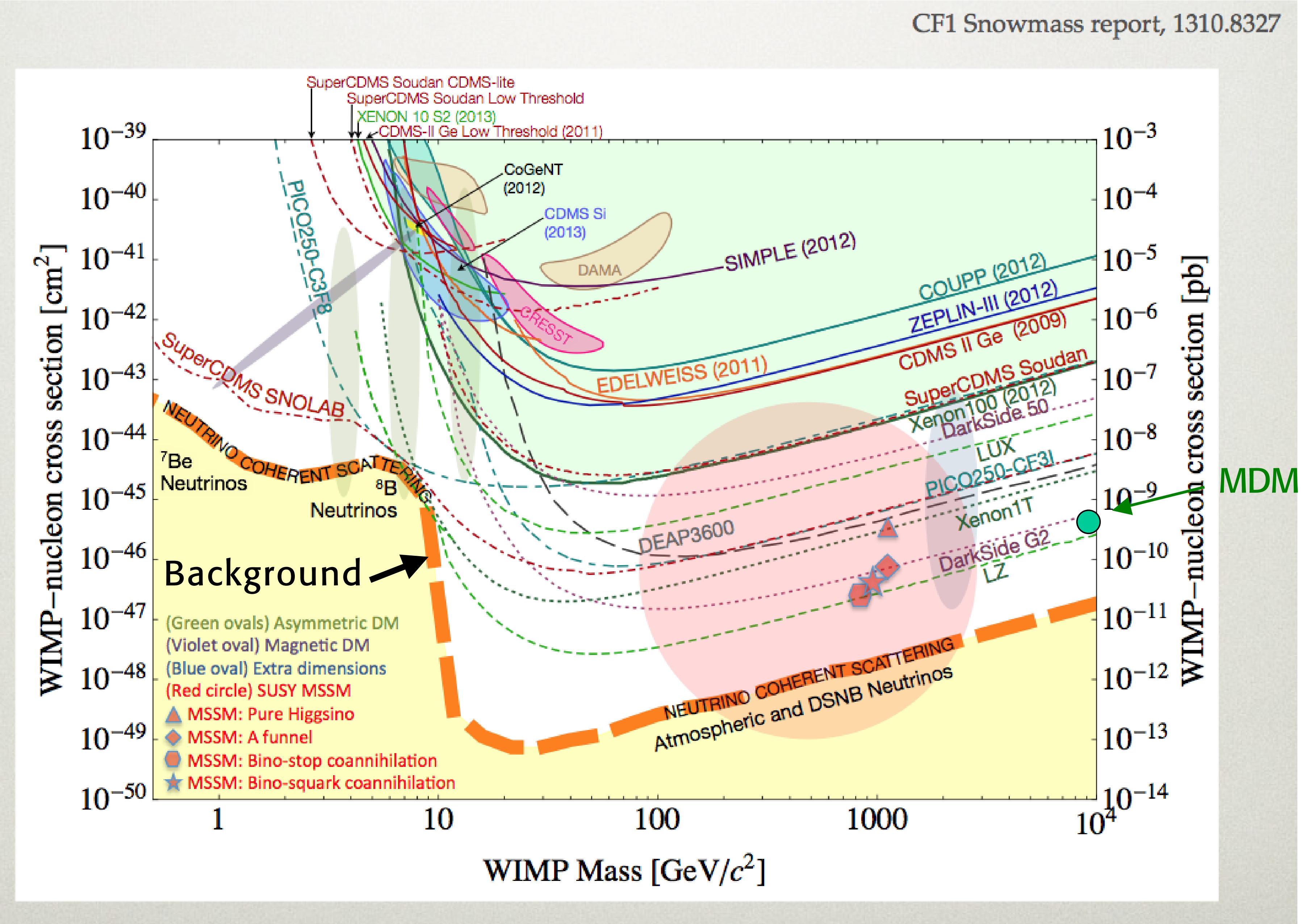


Quantum numbers			DM could decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	σ_{SI} in 10^{-46} cm^2
$SU(2)_L$	$U(1)_Y$	Spin				
5	0	1/2	stable	$4.4 \to 10$	166	5.4 ± 0.4

from ArXiv:0903.3381 updated in ArXiv:1303.7244



The WIMP non-accelerator search continues


CF1 Snowmass report, 1310.8327

The Axion [Peccei-Quinn (PQ) solution to strong CP problem]

PQ introduce a new U(1) symmetry: U(1)$_{PQ}$

Ex.: introduce new fermions ψ (charged colour triplets) and a scalar A

Kim'79, Shifman, Vainshtein, Zacharov'80 (KSVZ)

U(1)$_{PQ}$:

$$\psi' = e^{i\gamma_5 \alpha}\psi$$

$$A' = e^{-2i\alpha}A$$

No other fields are charged under U(1)$_{PQ}$

→ $M\bar{\psi}\psi$ and $H\bar{\psi}\psi$ (H=Higgs)

are forbidden, while $\lambda A\bar{\psi}\psi$ is allowed

The VEV <A> ~ f spont. breaks U(1)$_{PQ}$

The ψ mass is m ~ λ<A> ~ λ f

$A = |A| e^{i\frac{a}{f}}$ a (the axion) is the Goldstone boson

$a' = a - 2i\alpha f$ it only has derivative couplings except for the U(1)$_{PQ}$ anomaly term

$$L_{axion} = -\frac{1}{2}\partial_\mu a \partial^\mu a + L_{\text{int}}(\psi, \frac{\partial_\mu a}{f}) + [\theta + \frac{a}{f}]\frac{\alpha_s}{4\pi} Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})$$

$[\theta + \frac{a}{f}]\frac{\alpha_s}{4\pi} Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})$ the only term with a and not $\partial_\mu a$ is the potential V

The VEV <a> is fixed by $\frac{\partial V}{\partial a} = 0 \Rightarrow \frac{\alpha_s}{4\pi f}\langle Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})\rangle = 0$

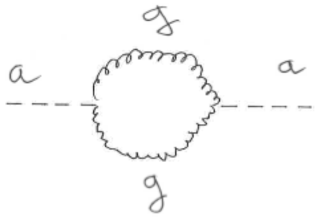
It is (not too) easy to prove that $\langle Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})\rangle \propto \sin\theta_{eff} \equiv \sin(\theta + \frac{\langle a\rangle}{f})$
so that the coefficient of the
CP violating term is put to zero!

e.g. Coleman, ‘77; Vafa, Witten ‘84……

After the shift a --> a'' + < a > (a'' is the field for perturbation theory)

we are left with the coupling $\frac{a''}{f}\frac{\alpha_s}{4\pi} Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})$ and no CP violation

This coupling also induces a mass for the axion (it would be massless if not for the anomalous breaking of $U(1)_{PQ}$)



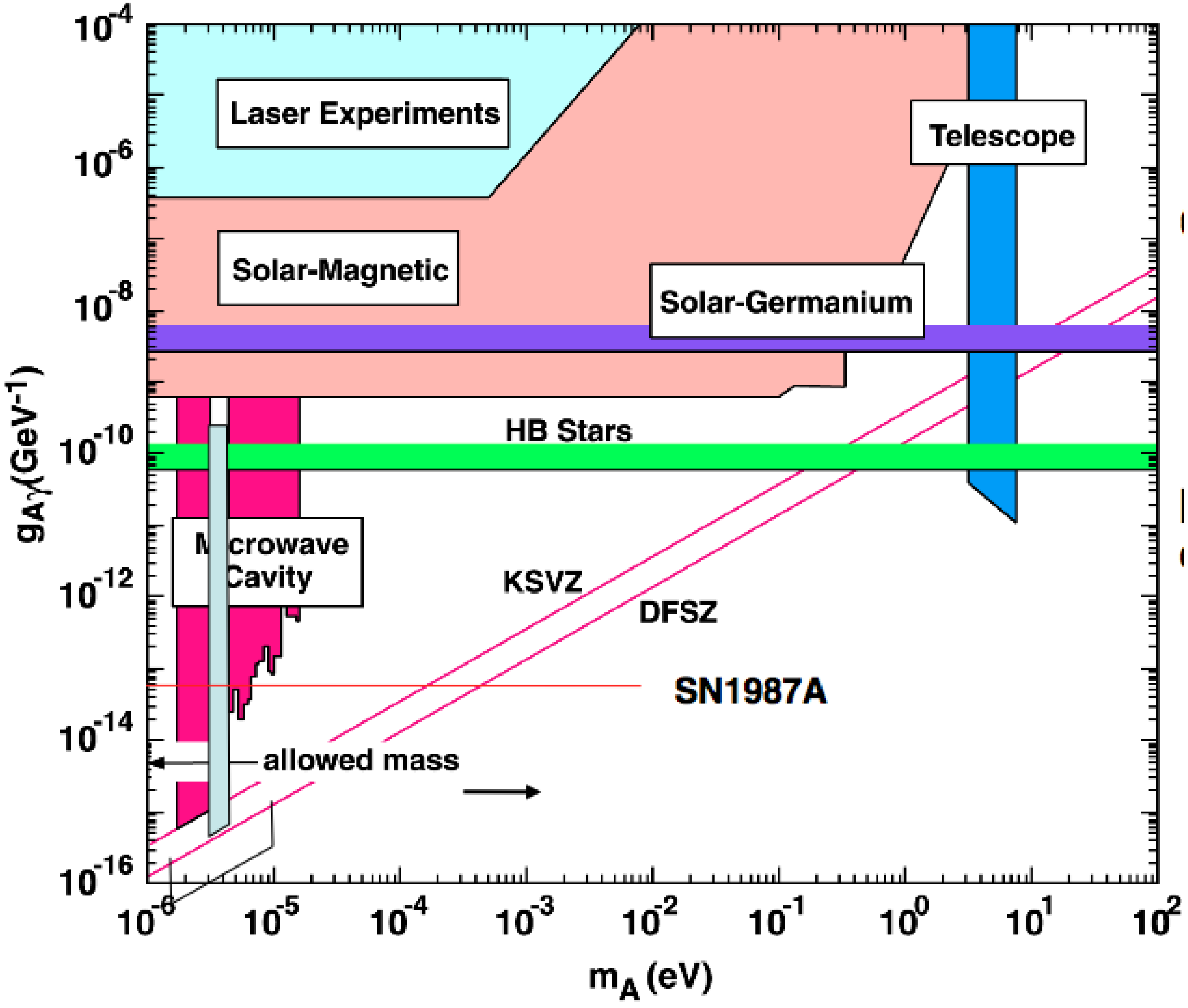
$$m_a^2 \propto \frac{\Lambda_{QCD}^4}{f^2}$$

with f large, m_a is small,
the axion coupling is small,
and the ψ mass is large

⊕ The analogous coupling to photons induces the decay a --> $\gamma\gamma$

Axion searches are very important ----> Ringwald

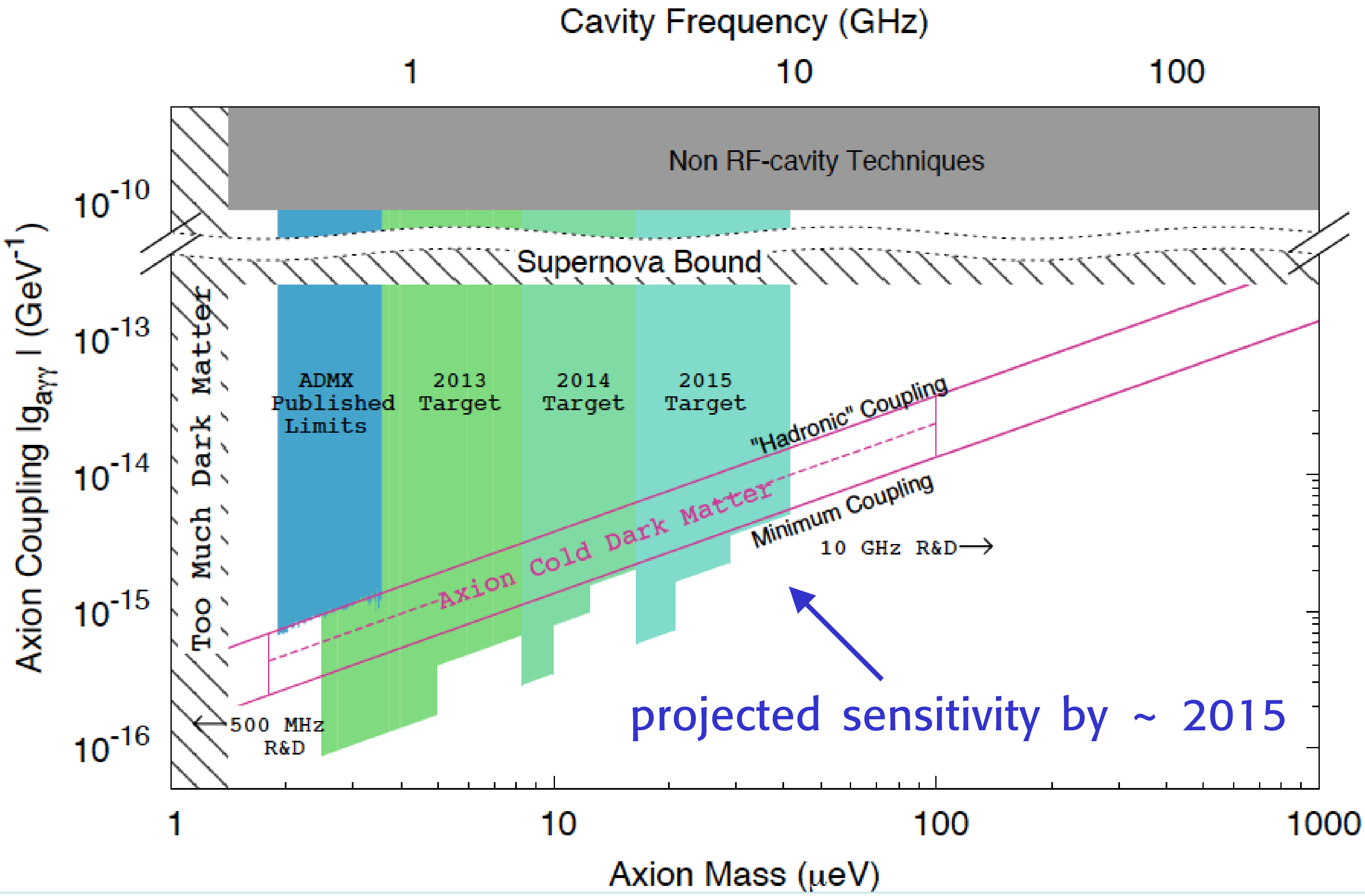
Of all DM candidates the axion is perhaps the closest to the SM (strong CP violation solved a' la Peccei-Quinn '77)



For DM
the optimal
parameters are
m ~ 10^{-5} eV
f ~ 10^{11} GeV

ADMX: the Axion Dark Matter Experiment

University of Washington at Seattle



projected sensitivity by ~ 2015

A drastic conjecture

No new thresholds between m_W and M_{Pl}?

Shaposhnikov '07--->

And hope that gravity will somehow fix the problem of fine tuning related to the M_{Pl} threshold (with many thresholds it would be more difficult for gravity to arrange the fine tuning)

Giudice EPS'13

For this, one would need to solve all problems like
Dark Matter, neutrino masses, baryogenesis....
at the EW scale

In particular no GUT's below M_{Pl}

The νMSM

Shaposhnikov et al

There are 3 RH ν's: N_1, N_2, N_3 and the see-saw mechanism

But the N_i masses are all below the EW scale

Actually N_1 ~ o(1-10) keV, and $N_{2,3}$ ~ GeV with eV splitting

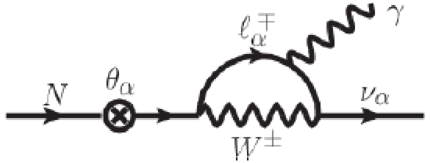
Very small Yukawa couplings are assumed to explain the small active ν masses

$$m_\nu = \frac{y_\nu^2 v^2}{M_N}$$

The phenomenology of ν oscillations can be reproduced

N_1 can explain (warm) DM

$N_{2,3}$ can explain the Baryon Asymmetry in the Universe



N_1 decay produces a distinct X-ray line

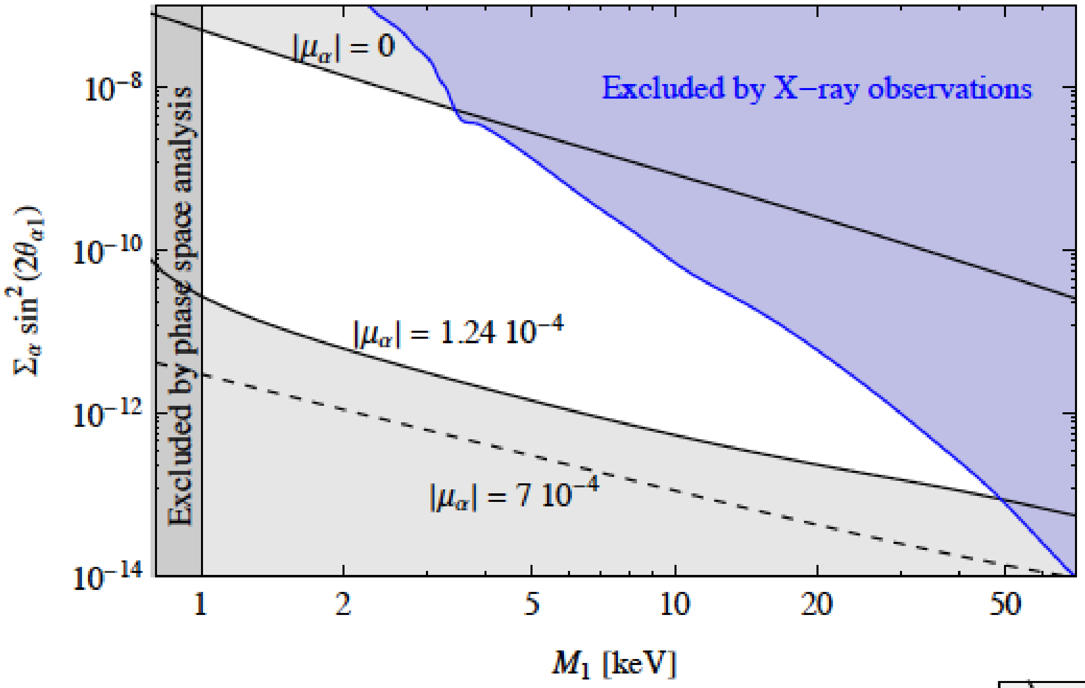
$N_1 \to \nu + \gamma$ $(E_\gamma = m_N/2)$

$$\Gamma_\gamma(m_s, \theta) = 1.38 \times 10^{-29}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

$N_{2,3}$ could be detected by dedicated accelerator experiments (eg in B decays, Br ~ 10^{-10})

A LOI for the CERN SPS has been presented

Bonivento et al, ArXiv:1310.1762



Canetti et al '12

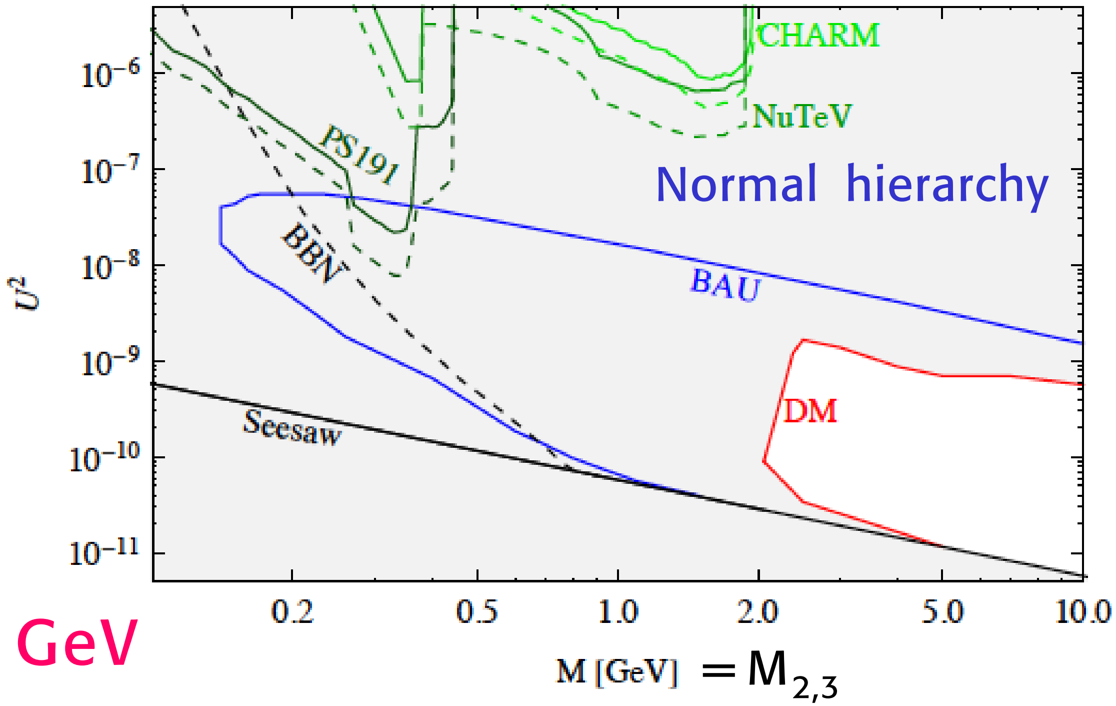
The claim is that all constraints can be satisfied

For DM one needs
$1 < M_1 < \sim 100$ keV

keV

No explanation of the mass splitting

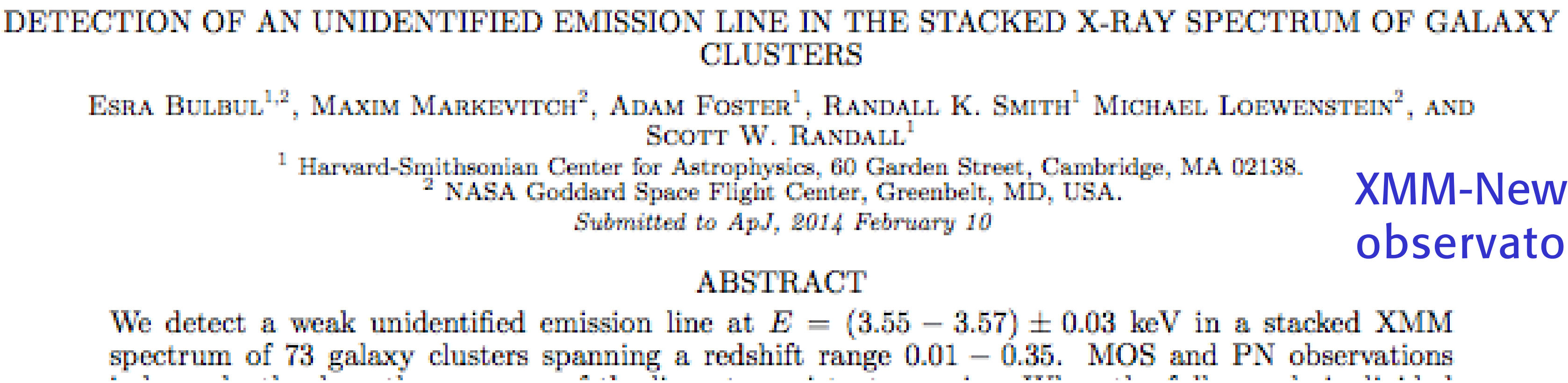
GeV



$= M_{2,3}$

A ~7 keV sterile N_1?

ArXiv:1402.2301



DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]

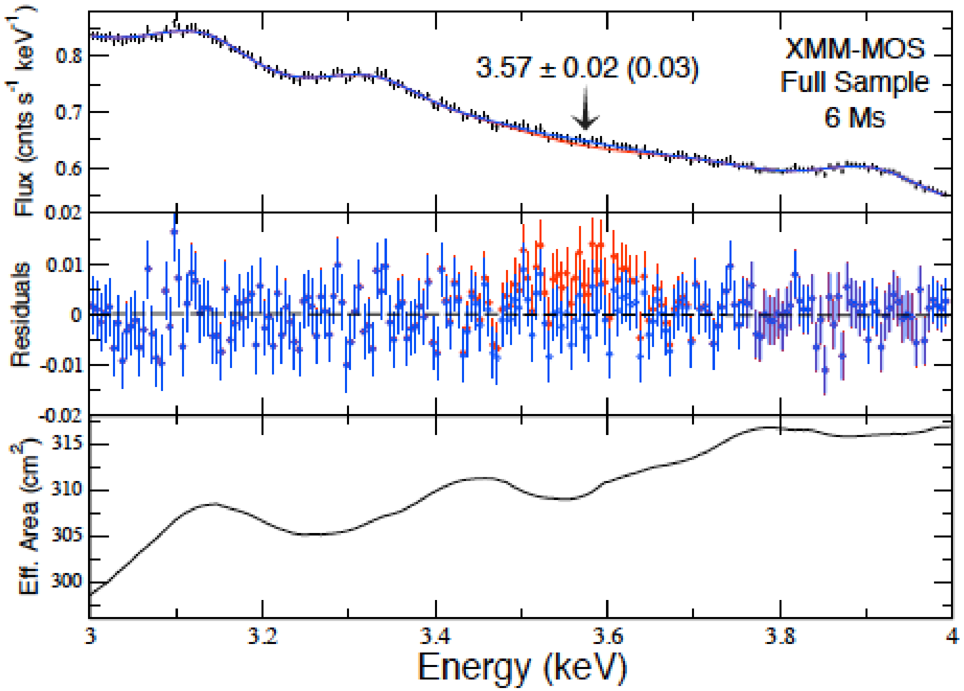
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10

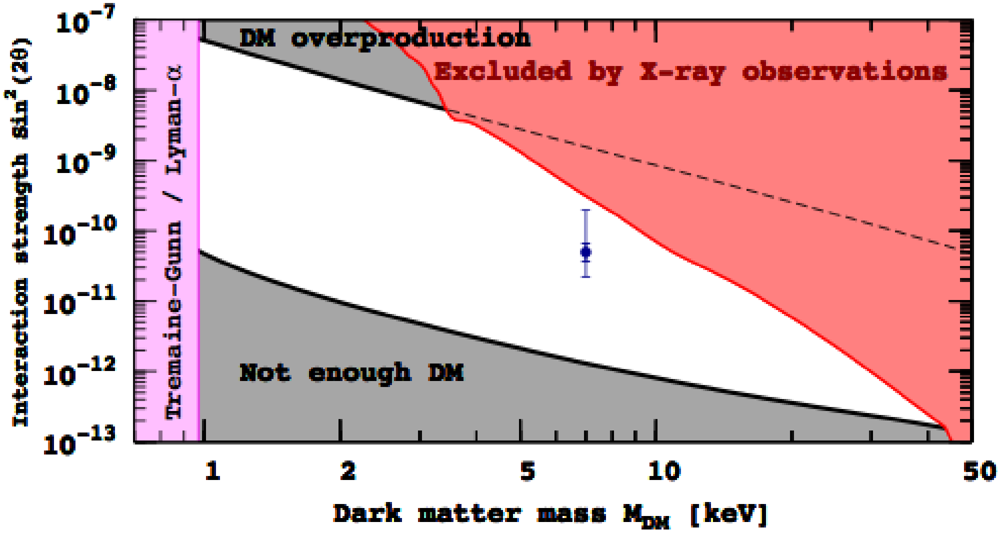
ABSTRACT

We detect a weak unidentified emission line at $E = (3.55 - 3.57) \pm 0.03$ keV in a stacked XMM spectrum of 73 galaxy clusters spanning a redshift range 0.01 – 0.35. MOS and PN observations

XMM-Newton X-ray observatory



Independent analysis by Boyarski et al
ArXiv:1402.4119



Confirmation from Chandra, Suzaku and eventually, Astro-H needed

Conclusion

The Dark Matter problem is a formidable challenge for particle physics

A great variety of solutions are still open from WIMP’s, to Axion’s, to “heavy” neutrinos and more

The observation of DM particles at the LHC is still very well possible

A great and diverse experimental effort is under way both in particle and astroparticle experiments