The HIGGS
and the
EXCESSIVE success
of the SM

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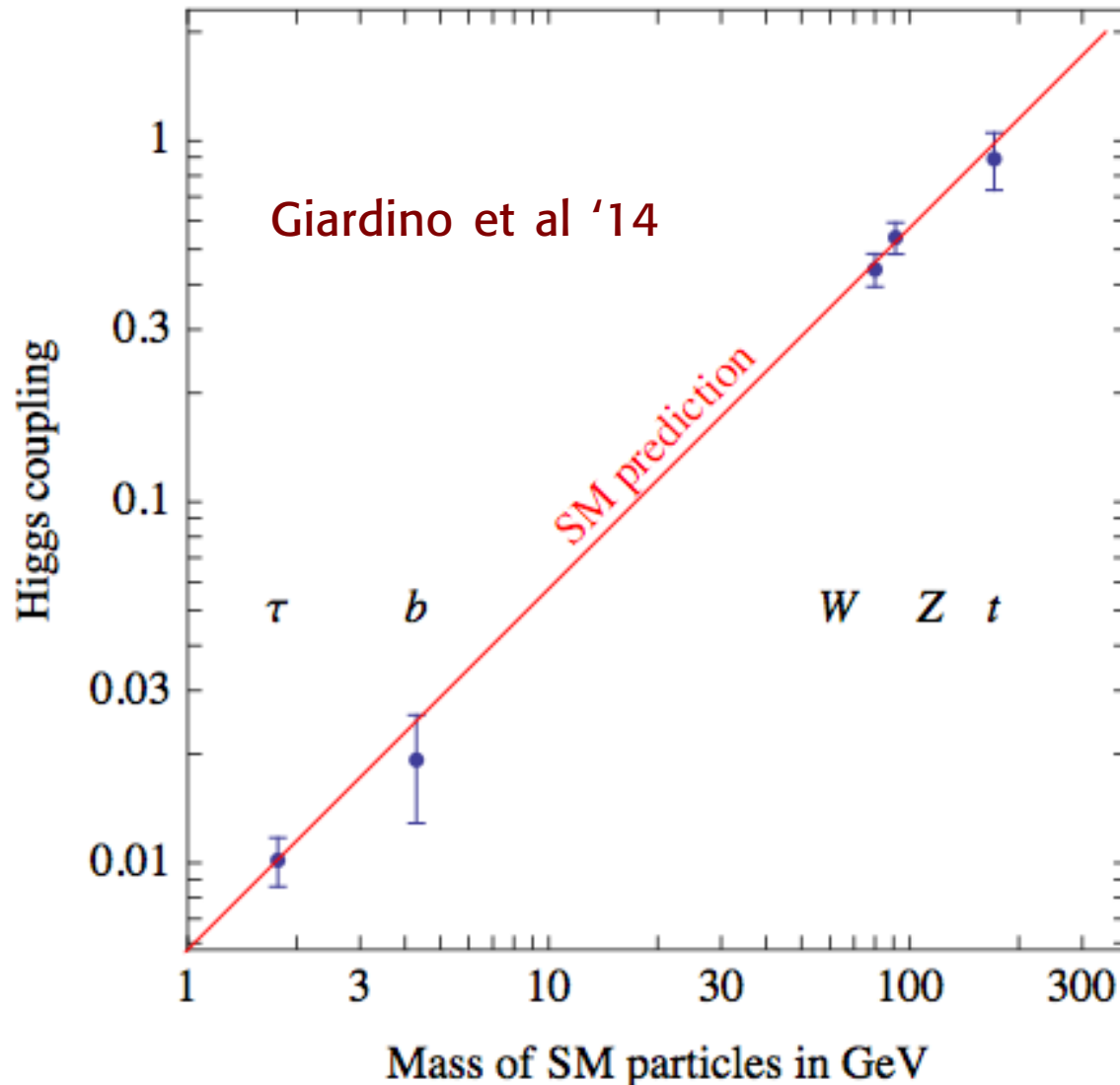
Not in ATLAS&CMS
Not in Heavy Flavour decays (LHCb, …….. B-factories)
Not in μ -> eγ (MEG) $\mathcal{B} < 5.7 \times 10^{-13}$
Not in the EDM of the electron (ACME) $|d_e| < 8.7 \times 10^{-29} \ e \ \mathrm{cm}$
⊕ ……..[Perhaps a deviation in (g-2)$_\mu$?]

The Higgs couplings are in proportion to masses: a striking signature [plus specified, gg, $\gamma\gamma$, $Z\gamma$ eff. couplings]

Giardino et al '14

Nearly impossible to reproduce by accident

Agrees with a SM doublet: no Clebsch or mixing distortions detected

The spin-parity 0^+ also looks OK

It really appears as the SM Higgs particle!!!

The precise measurements of Higgs couplings are crucial to determine to what extent it is SM

eg Alonso et al
Giudice et al
Csaki et al
Contino
Keren-zur et al
Falkowski et al
Elias-Miro et al
Pomarol, Riva…..

It would really be astonishing if no deviation from the SM is seen!

General effective lagrangians are being studied by adding higher dim ops or introducing eff. couplings

Almeida et al

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$

$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$

$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2 \theta_W Z_{\mu\nu} Z^{\mu\nu} + 2 W_{\mu\nu}^+ W^{-\mu\nu} \right) H$$

$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$

Rates: $\mu = \sigma Br / (\sigma Br)^{SM}$

19.03.14

E. Gross

$\mu_{\gamma\gamma}$ — $\mu = 1.57^{+0.33}_{-0.28}$

μ_{ZZ} — $\mu = 1.44^{+0.40}_{-0.35}$

μ_{WW} — $\mu = 1.00^{+0.32}_{-0.29}$

$\mu_{\tau\tau}$ — $\mu = 1.4^{+0.5}_{-0.4}$

μ_{bb} — $\mu = 0.2^{+0.7}_{-0.6}$

Combined fit — $\mu = 1.30^{+0.18}_{-0.17}$

ATLAS

$[m_H = 125.5 \text{ GeV}]$

$\mu_{\gamma\gamma}$ — $\mu = 0.77^{+0.27}_{-0.27}$

μ_{ZZ} — $\mu = 0.92^{+0.28}_{-0.28}$

μ_{WW} — $\mu = 0.68^{+0.2}_{-0.2}$

$\mu_{\tau\tau}$ — $\mu = 1.10^{+0.41}_{-0.41}$

μ_{bb} — $\mu = 1.15^{+0.62}_{-0.62}$

Combined fit — $\mu = 0.80^{+0.14}_{-0.14}$

CMS

$[m_H = 125.7 \text{ GeV}]$

-2   -1.5   -1   -0.5   0   0.5   1   1.5

It really looks like the SM Higgs!

19.03.14

λ_{WZ}	$\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$	ATLAS
λ_{WZ}	[0.73-1.0]	CMS
κ_F	$\kappa_F = 0.99^{+0.17}_{-0.15}$	ATLAS
κ_F	[0.71-1.11]	CMS
κ_V	$\kappa_V = 1.15^{+0.08}_{-0.08}$	ATLAS
κ_V	[0.81-0.97]	CMS
λ_{FV}	$\lambda_{FV} = 0.86^{+0.14}_{-0.12}$	ATLAS
κ_g	$\kappa_g = 1.08^{+0.15}_{-0.13}$	ATLAS
κ_g	[0.73-0.94]	CMS
κ_γ	$\kappa_\gamma = 1.19^{+0.15}_{-0.12}$	ATLAS
κ_γ	[0.79-1.14]	CMS
λ_{du}	[0.78-1.15]	ATLAS
λ_{du}	[1.0-1.6]	CMS
$|\lambda_{lq}|$	[0.99-1.5]	ATLAS
λ_{lq}	[0.89-1.62]	CMS
B_{iu}	$B_{iu}<0.55$	ATLAS
B_{iu}	$B_{iu}<0.64$	CMS

Coupling scale factor
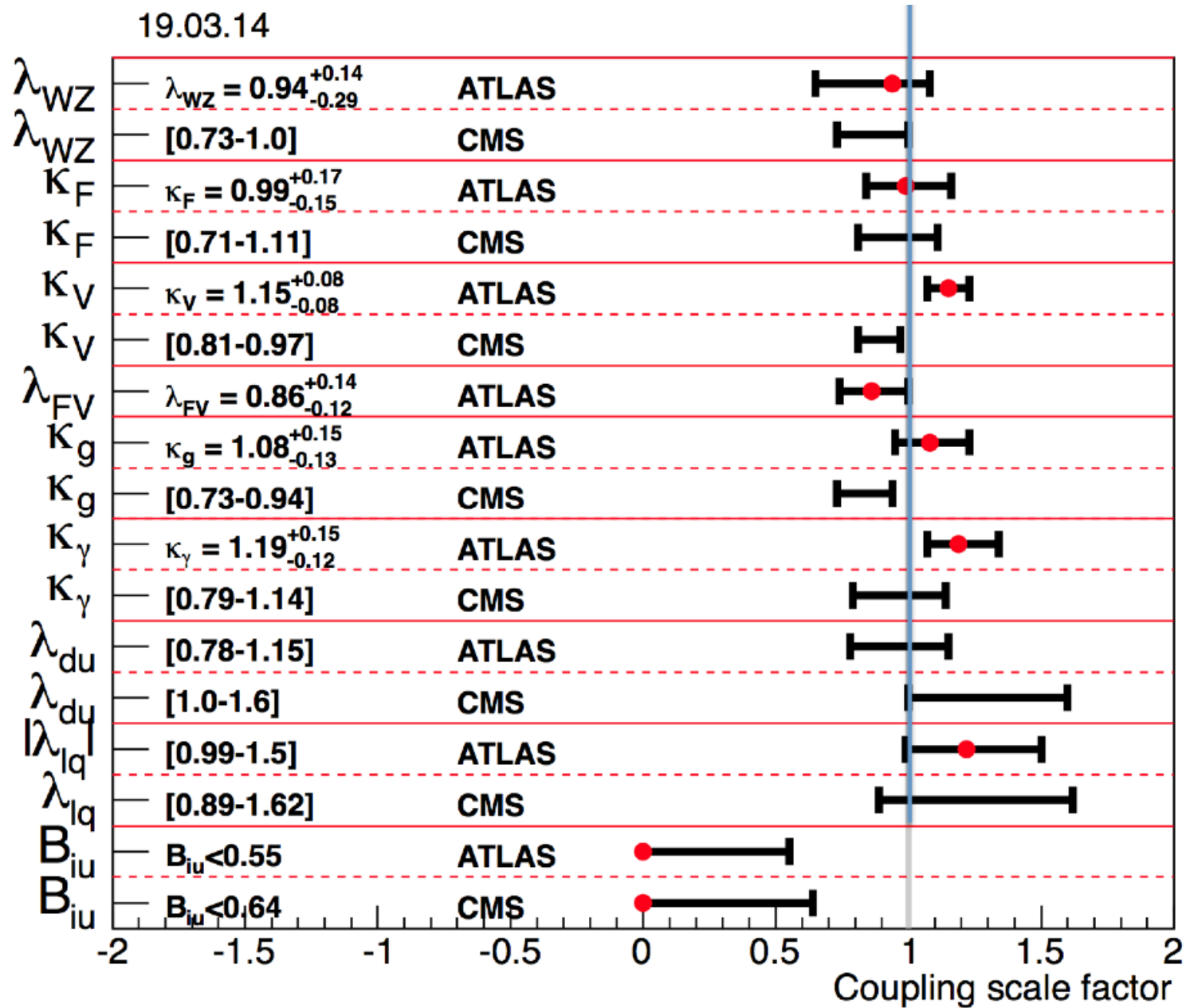
For example:

MSSM: separate u and d couplings and | a=hVV| < 1

Tree level formulae
Radiative corrections
important

$$\tan 2\alpha = \tan 2\beta \frac{m_A^2 - m_Z^2}{m_A^2 + m_Z^2}$$

$$a = hVV = \sin(\beta - \alpha)$$

$$c_u = huu = \frac{\cos\alpha}{\sin\beta}$$

$$c_d = hdd = -\frac{\sin\alpha}{\cos\beta}$$
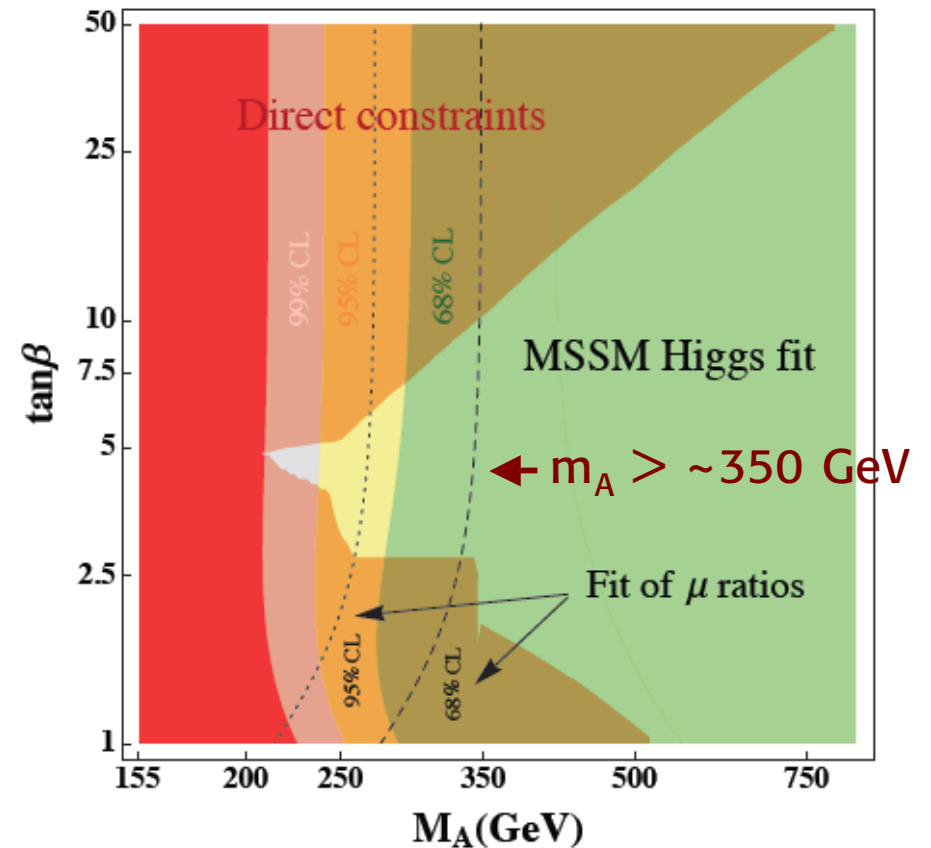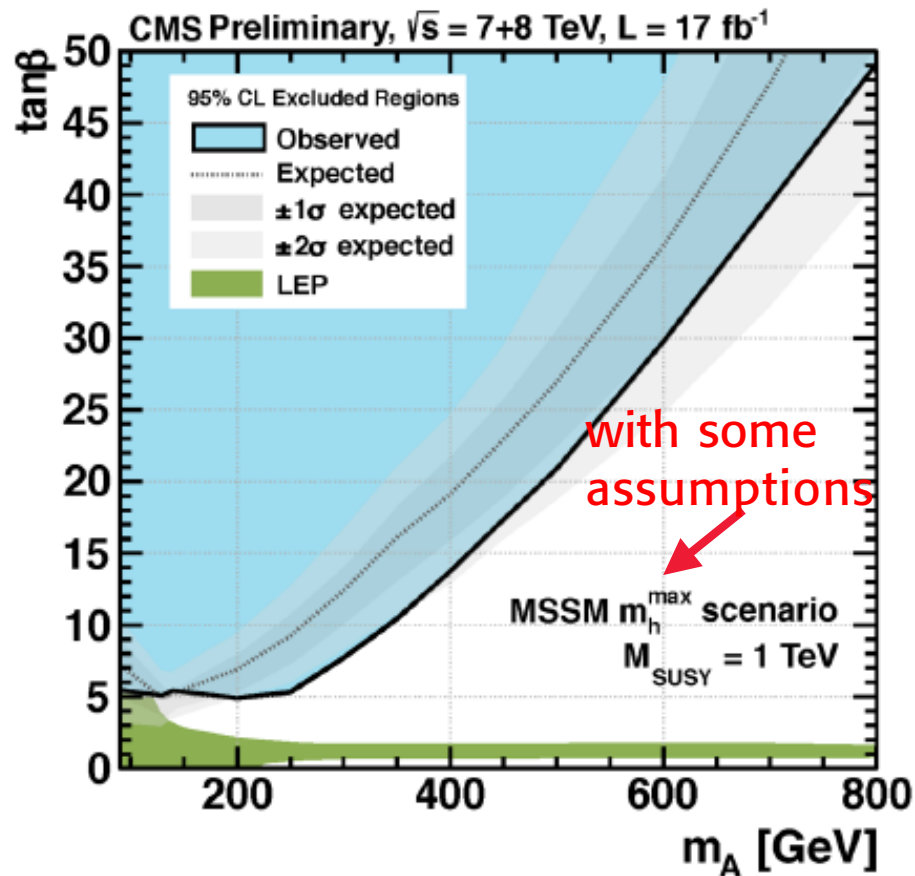
If $c_u > 1$ then $c_d < 1$
and viceversa

Azatov, Galloway'13

Up–Suppressed
[Type II]

Down–
Suppressed
[Type II]

68, 95, 99% CL
—— LHC
-- -- w/ Tevatron

Best Fits (LHC)
⊕ Global
★ Type II

c_b

c_t
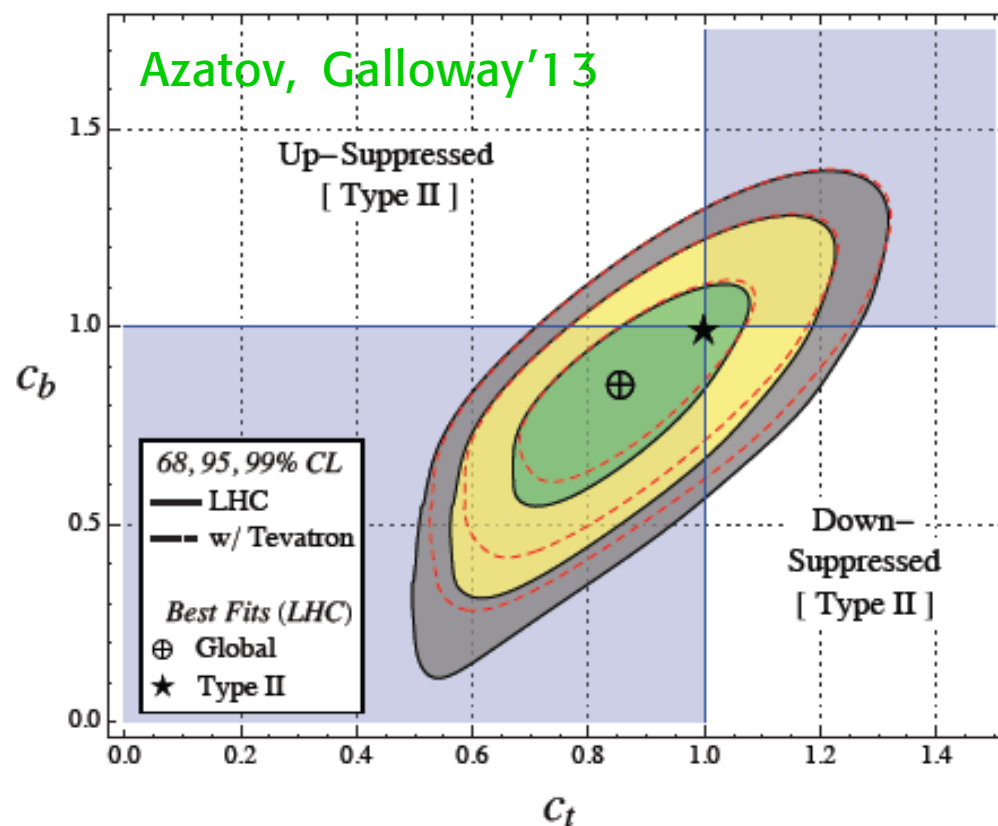
A very important open question:
Are there more Higgs particles?
Here we focus on MSSM

Theorists analysis

Djouadi, Maiani et al '13

CMS Preliminary, $\sqrt{s}$ = 7+8 TeV, L = 17 fb^{-1}

95% CL Excluded Regions
Observed
Expected
±1σ expected
±2σ expected
LEP

with some assumptions

MSSM m_h^{max} scenario
M_{SUSY} = 1 TeV

Direct constraints

99% CL   95% CL   68% CL

MSSM Higgs fit

← m_A > ~350 GeV

Fit of μ ratios

95% CL   68% CL

M_A(GeV)

$\tau\tau$

this limit has now been improved

Now a better limit is obtained

$$m_A > 400 \; GeV \; \text{for} \; \text{tg}\beta > 2$$
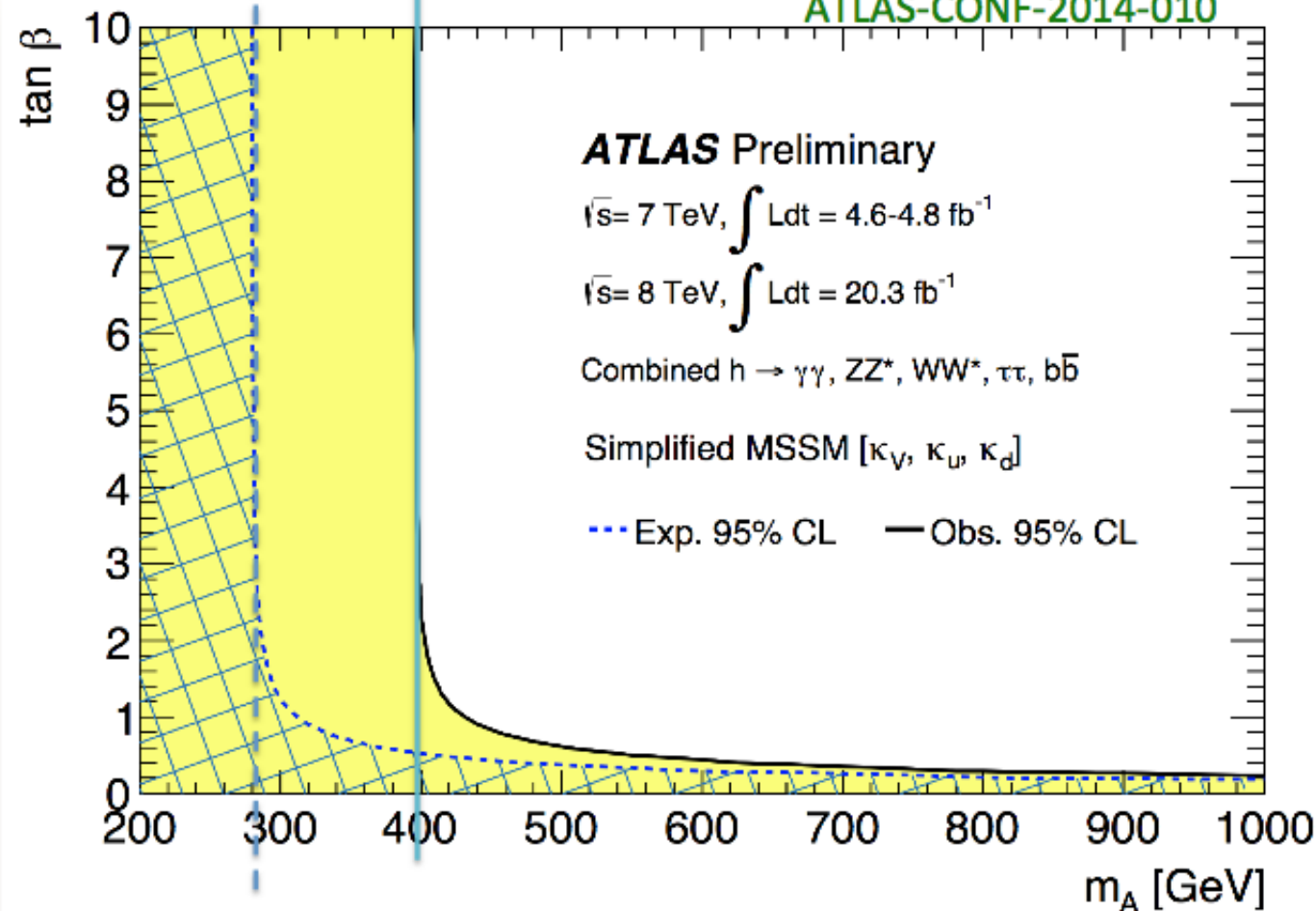
Bottom line:

The issue of extra Higgs (doublets and/or singlets) is a clear priority

ATLAS-CONF-2014-010

ATLAS Preliminary

$\sqrt{s} = 7$ TeV, $\int$ Ldt = 4.6-4.8 fb^{-1}

$\sqrt{s} = 8$ TeV, $\int$ Ldt = 20.3 fb^{-1}

Combined h → $\gamma\gamma$, ZZ*, WW*, $\tau\tau$, b$\bar{b}$

Simplified MSSM [κ_V, κ_u, κ_d]

- - - Exp. 95% CL   —— Obs. 95% CL

tan β m_A [GeV]

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

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

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

e.g. the quartic coupling is perturbative:

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

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

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 but 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

No indirect evidence of new physics (is g-2 really solid?)
No direct evidence of new physics at the LHC

Manifestly some amount of fine tuning is imposed on us by the data. More so now after the LHC7-8 results

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

The argument for naturalness is really 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.....
the solution of the hierarchy problem must be found
--> 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!!

The naturalness argument for new physics at the EW scale is often expressed in terms of the quadratic cut-off dependence in the scalar sector

$$\delta m^2_{h\,|top} = -\frac{3G_F}{2\sqrt{2}\pi^2}m_t^2\Lambda^2 \sim -(0.2\Lambda)^2$$
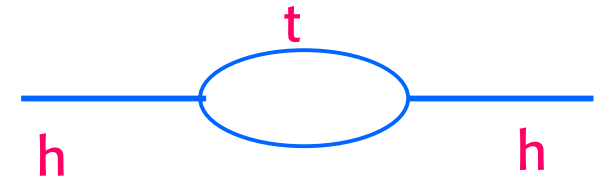
If we see the cut-off Λ as the scale where new physics occurs that solves the fine tuning problem, then the new physics must be nearby

The argument can be formulated in terms of renormalized quantities with no reference to a cut-off --->
quadratic sensitivity to thresholds at high energy

Naturalness in a more physical language

Buttazzo et al '13
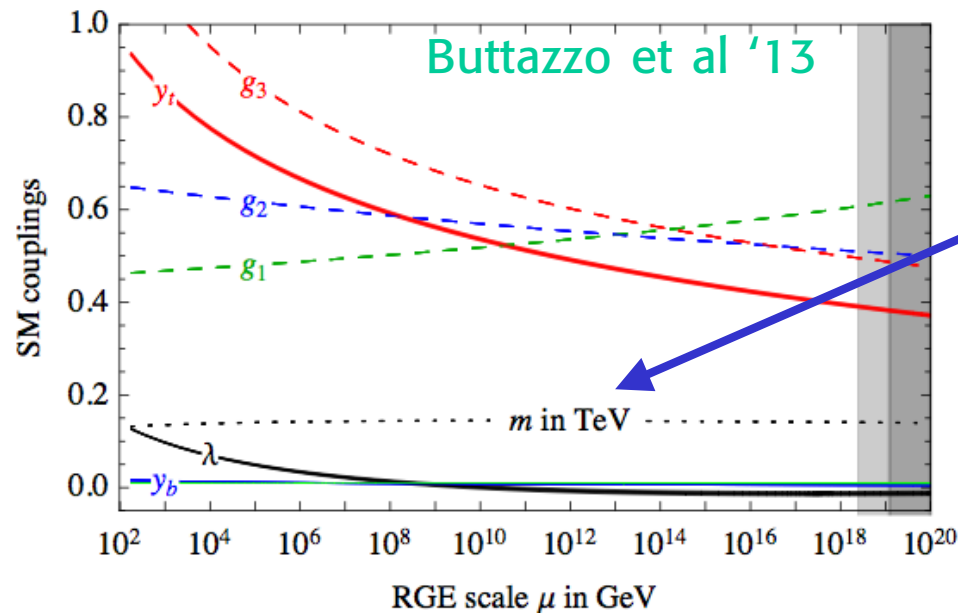
In the renormalized theory the running Higgs mass slowly evolves logaritmically

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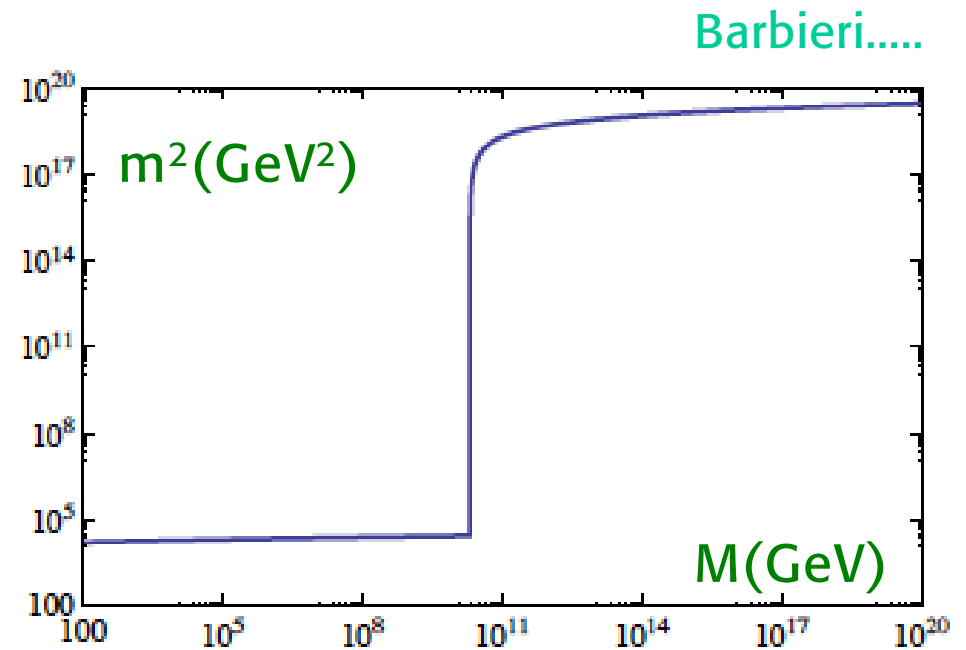
But in the presence of a threshold at M for a heavy particle coupled to the Higgs, the quadratic sensitivity produces a jump in the running mass

$M \sim 10^{10}$ 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
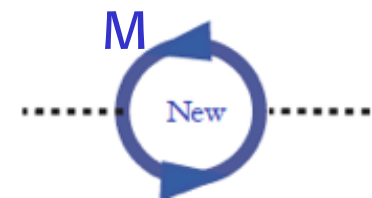
No no-go theorem for the SM at large energies

The pure SM evolution of couplings leads to a metastable Universe

λ

$\lambda\phi^4$

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

Buttazzo et al '13   see also Branchina '13
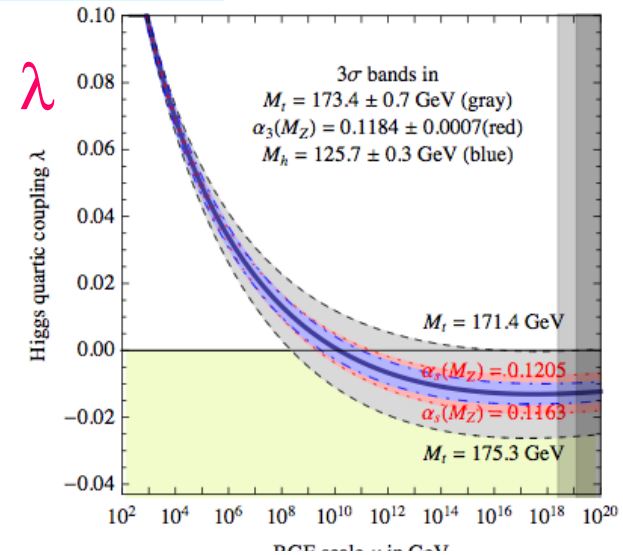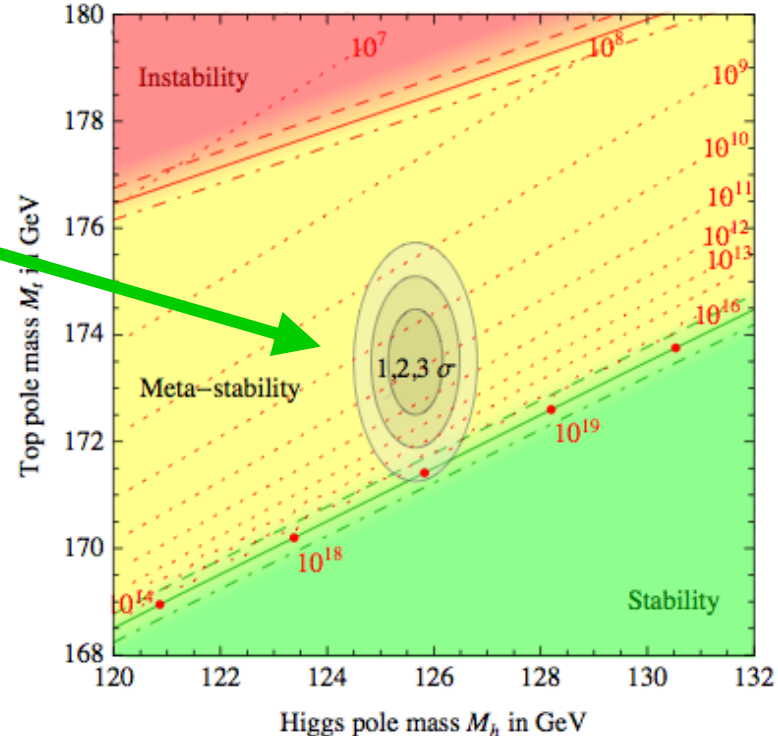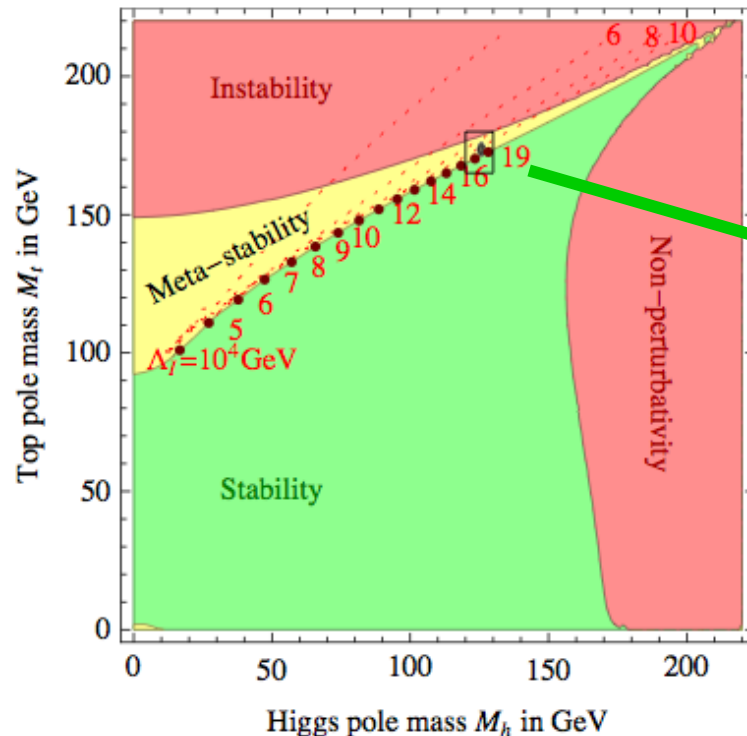
The absence of new physics appears as a paradox to us

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 form of DM, as valid up to some very high energy

Thus, ignoring the FT, minimal modifications to the SM are being considered

Neutrino masses? See-Saw mechanism
Baryogenesis? Thru leptogenesis
Dark Matter? Simple WIMPs, Axions, keV sterile ν's.....
Coupling Unification? Some large scale threshold,
e.g. non-SUSY 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

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)

A very natural and appealing explanation (see-saw):

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale M ~ 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 ~ v ~ 200 GeV
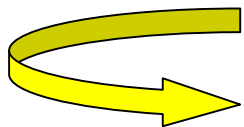
M ~ 10^{14} - 10^{15} GeV

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

A great extra bonus of see-saw with heavy Majorana ν_R's

Baryogenesis via Leptogenesis near the GUT scale

(after inflation)

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

Only survives if Δ(B-L) is not zero
(otherwise is washed out at T_{ew} by instantons)

.....

Decays of lightest ν_R (M~10^{11-12} GeV) satisfy Sacharov conditions

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

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

$\oplus$

Heavy ν_R well match with GUT's [recall the 16 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:
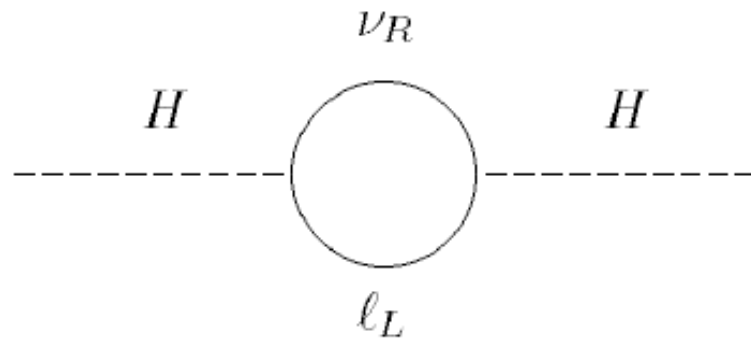
for q >> M_R

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

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

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

Vissani '97; Elias-Miro et al '11;
Farina et al '13; De Gouvea et al '14

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
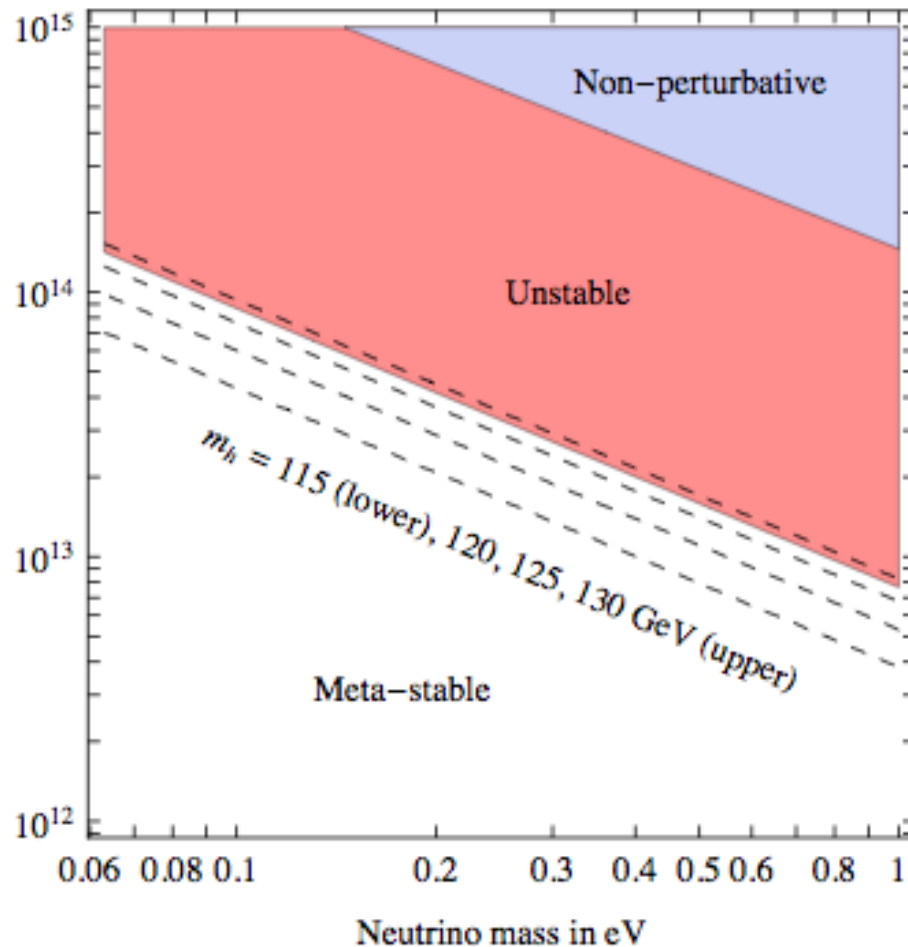
Masina'12
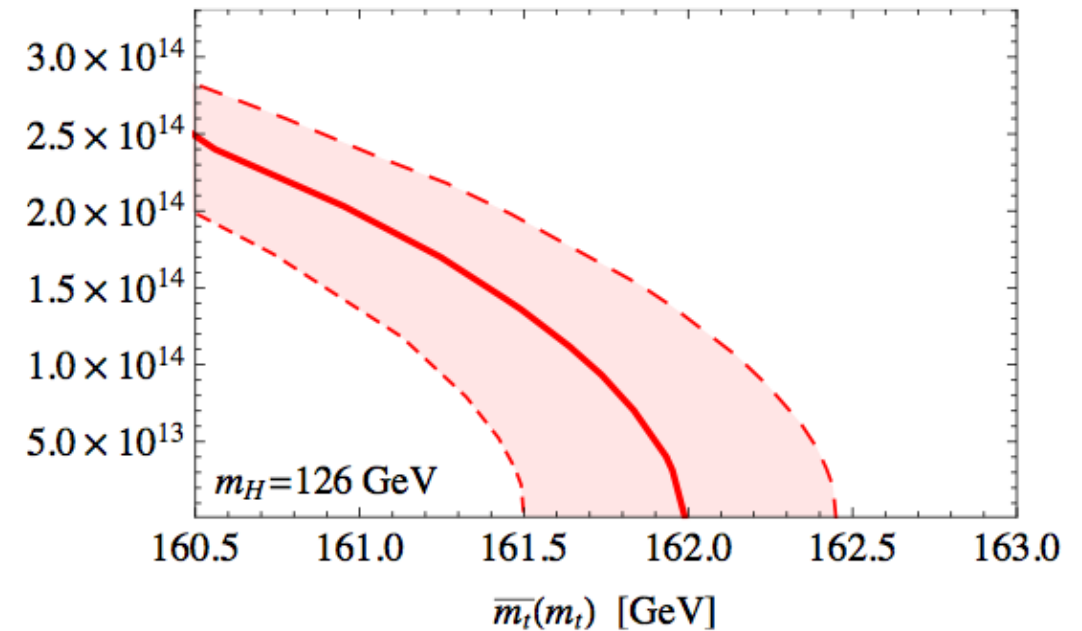
At present Dark Matter is THE crucial problem in particle physics

A by now robust evidence for Dark Matter in the Universe

Rotation of galaxies
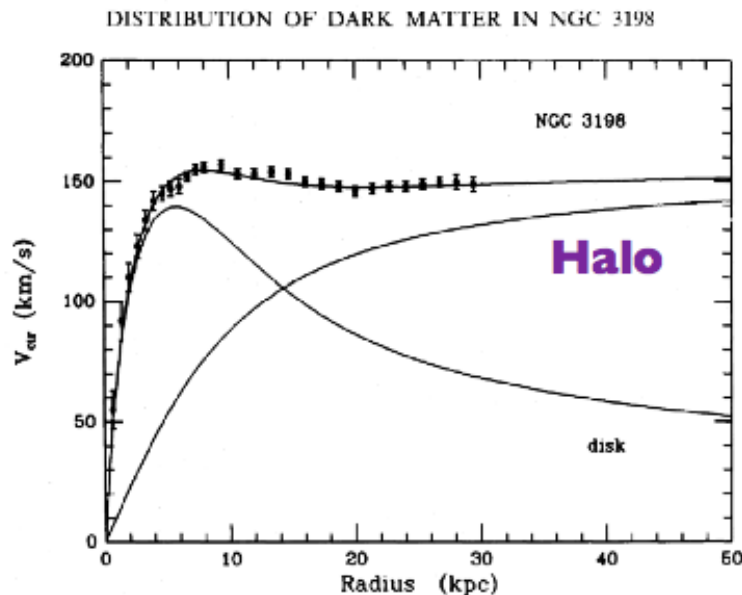
Lensing

Merging clusters of galaxies

DISTRIBUTION OF DARK MATTER IN NGC 3198

NGC 3198

Halo

disk

MACS, HST

Optical Dark Matter X-ray Gas

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

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

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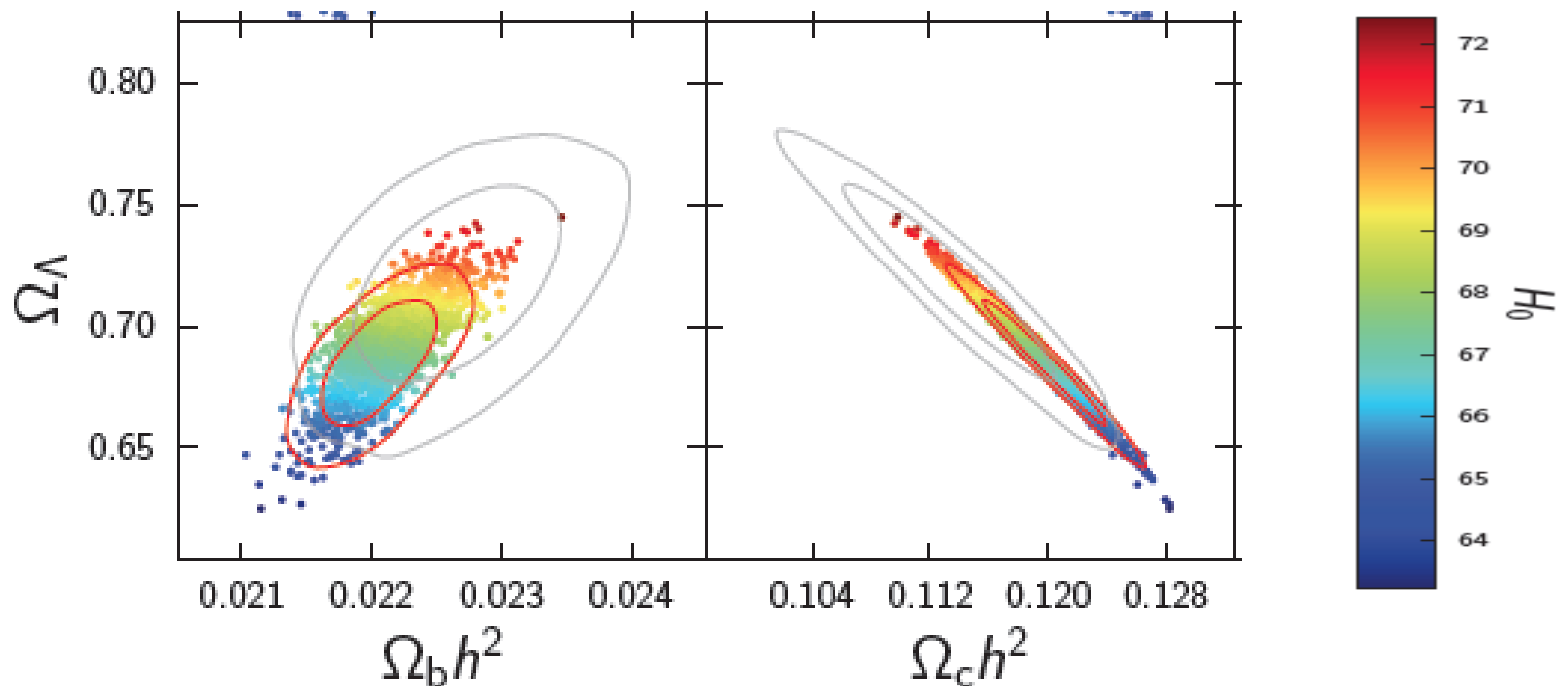
While for neutrino masses, baryogenesis... we have
definite ideas on how these problems could be solved
Dark Matter remains mysterious and is a very
compelling argument for New Physics and the most pressing
challenge for particle physics

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

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

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

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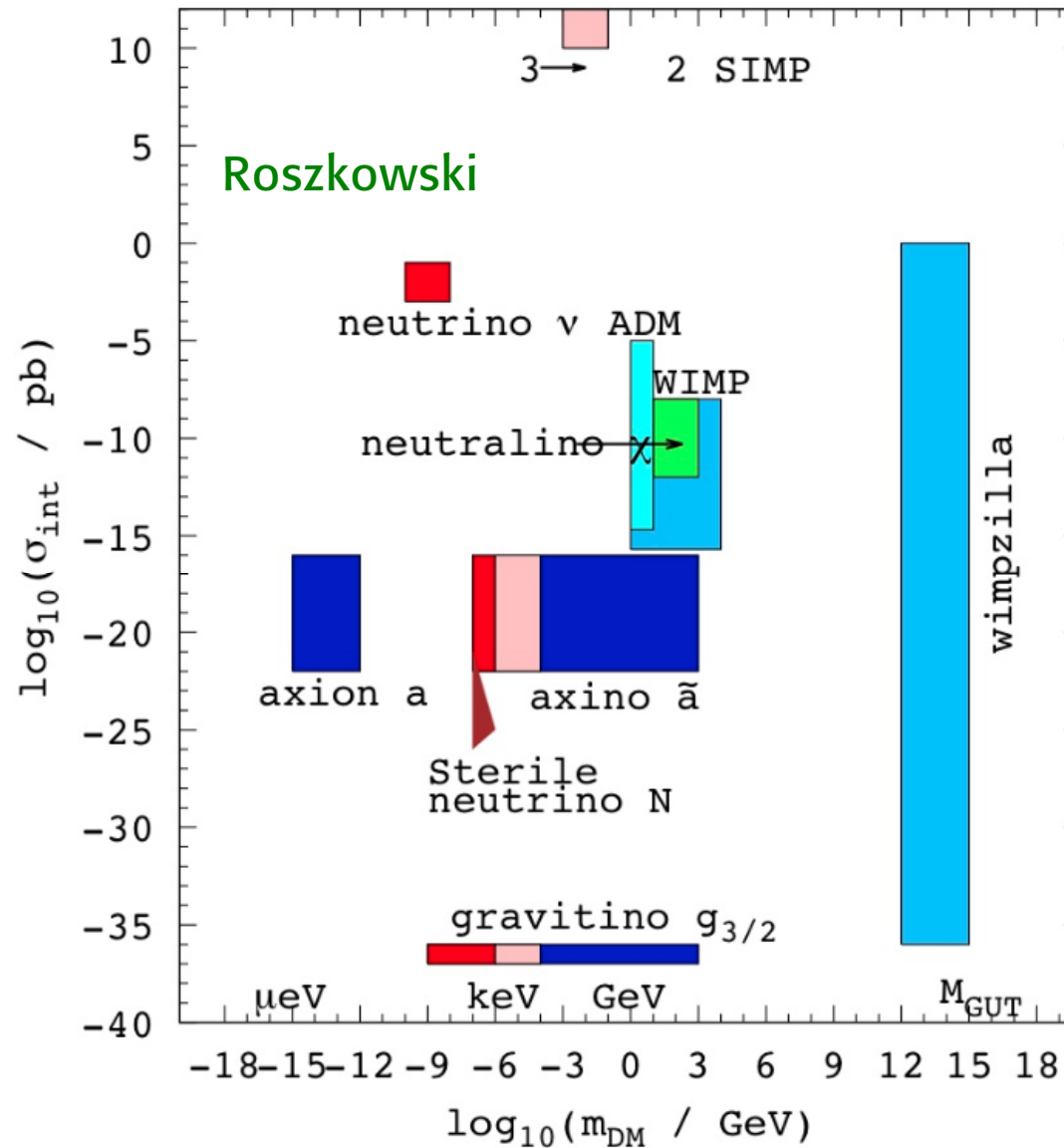
WIMP's: Weakly Interacting Massive Particles
with m ~ 10^{-1}-10^3 GeV

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:

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

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 SUSY WIMPS (neutralinos) are not too stringent

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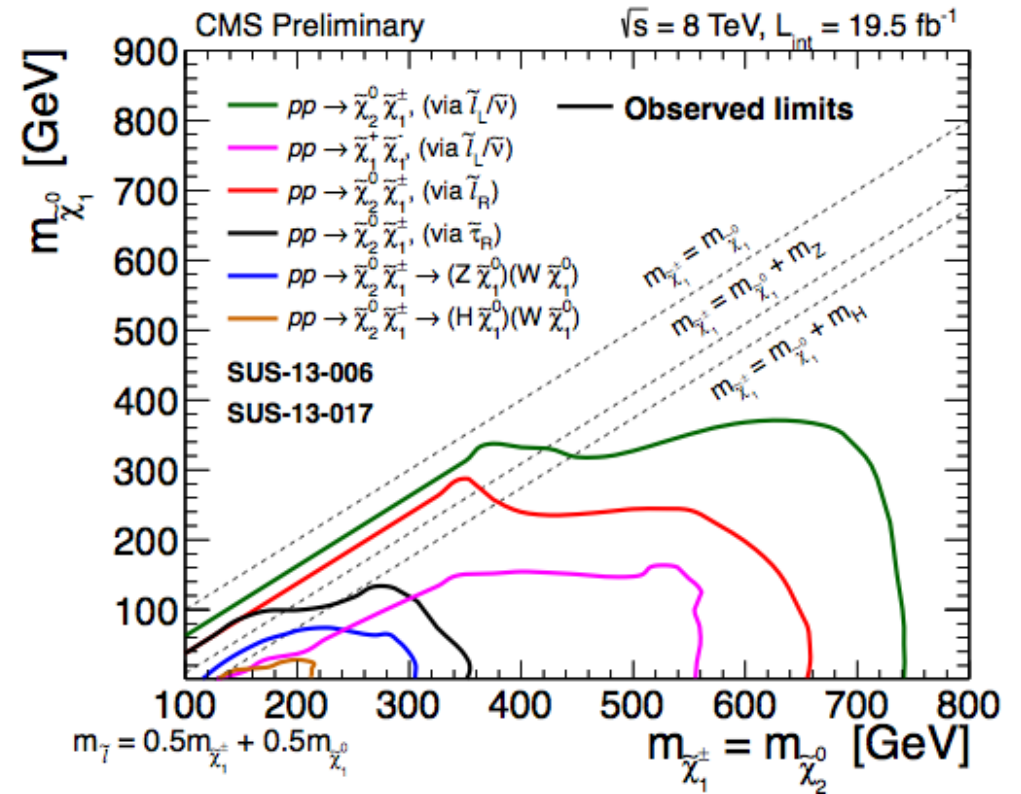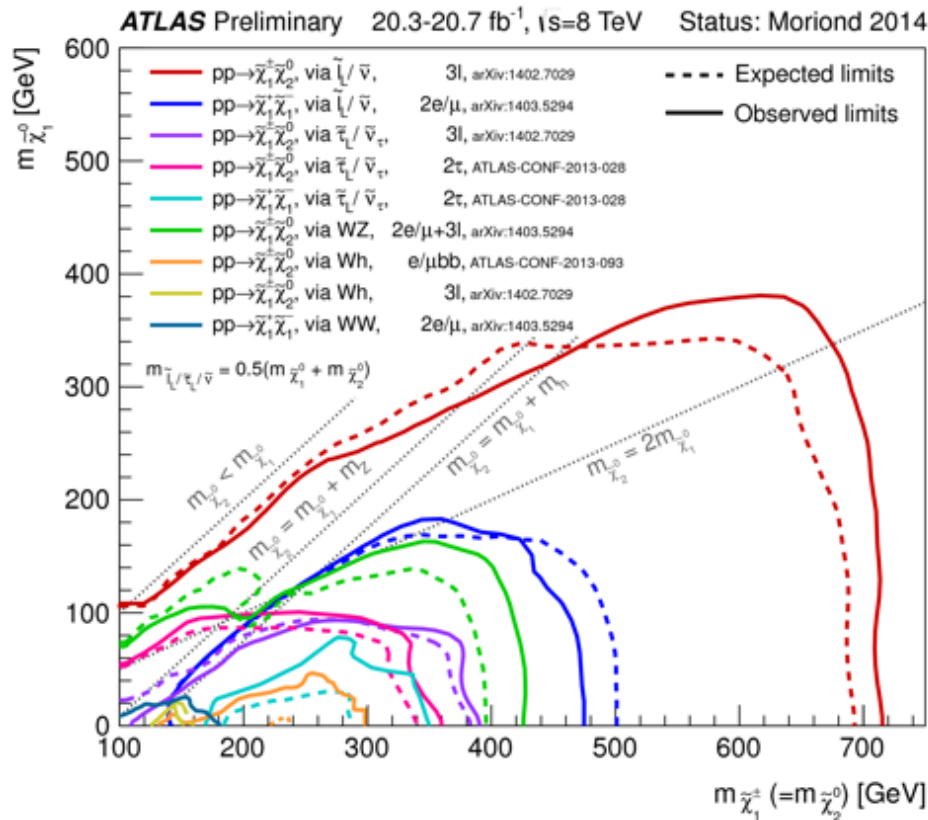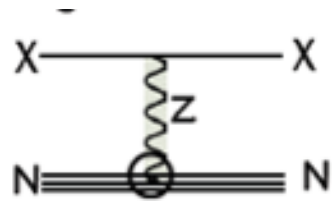

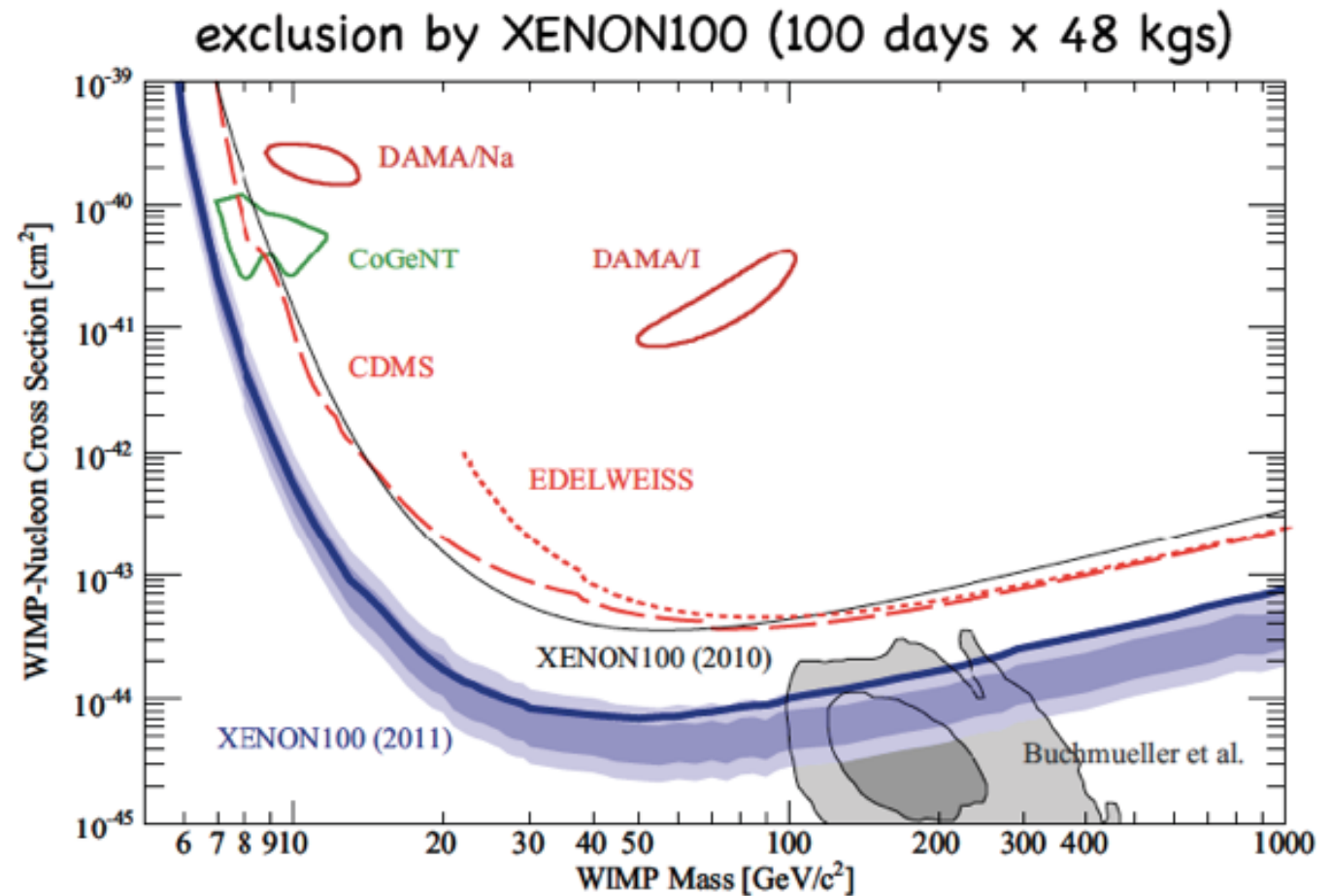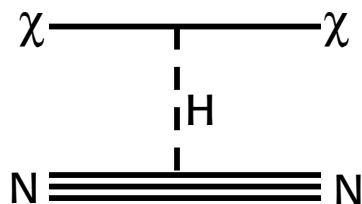A strict bound is very low: $m_{\chi^0} > 25$ GeV (light s-taus and higgsinos)

Calibbi et al'13

Non accelerator searches

$\chi\, N \to \chi\, N$

Z echange
potentially
large

125 GeV Higgs
boson exchange
being also
probed now

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

LUX constraints strongest
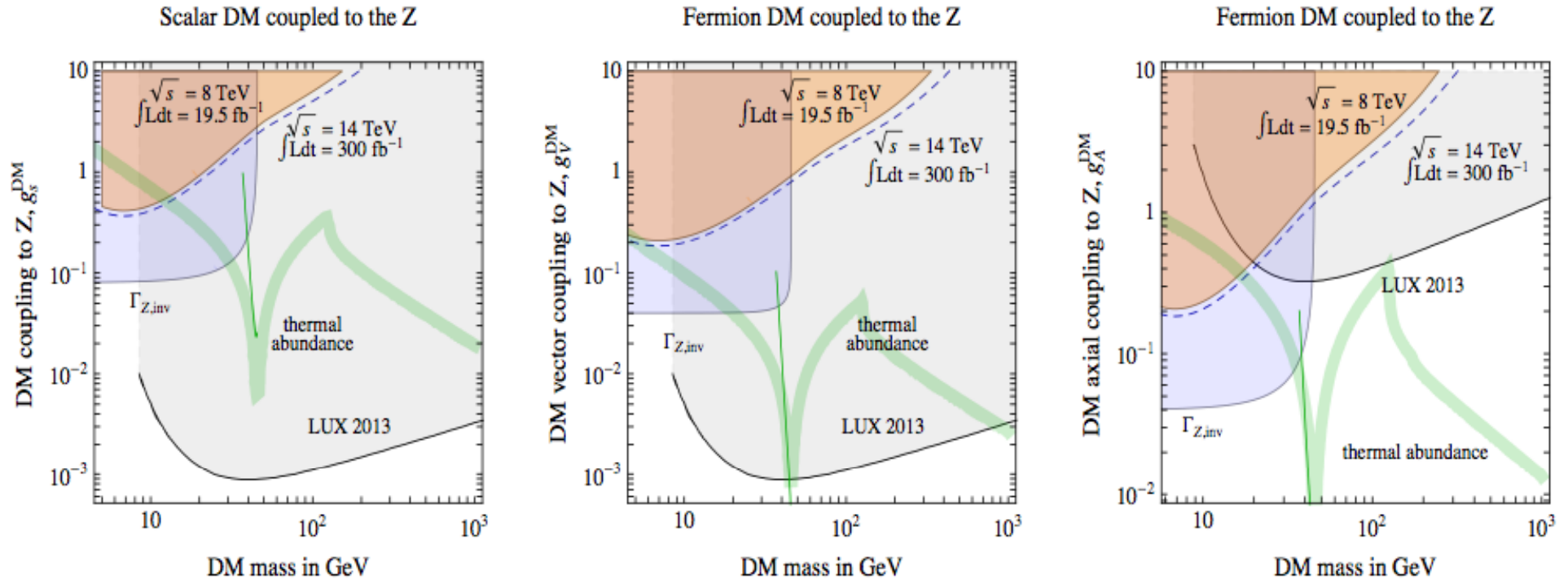
De Simone, Giudice, Strumia '14

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 $\Gamma_{Z,inv} < 2$ 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)
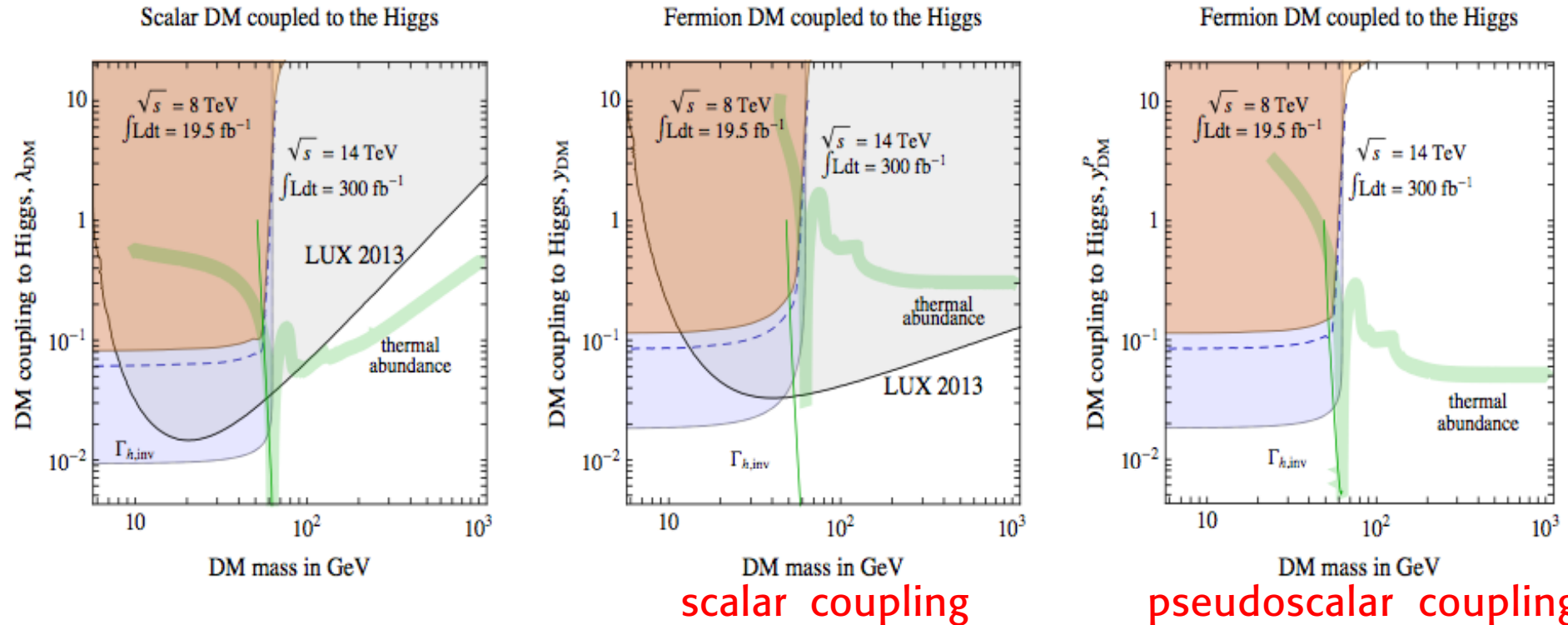
De Simone, Giudice, Strumia '14

scalar coupling   pseudoscalar coupling

Figure 4: **DM coupled to the Higgs.** Regions of DM mass M_{DM} and Higgs couplings (λ_{DM}, y_{DM}, y_{DM}^P): 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 $\Gamma_{h,inv}/\Gamma_h < 20\%$. 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**
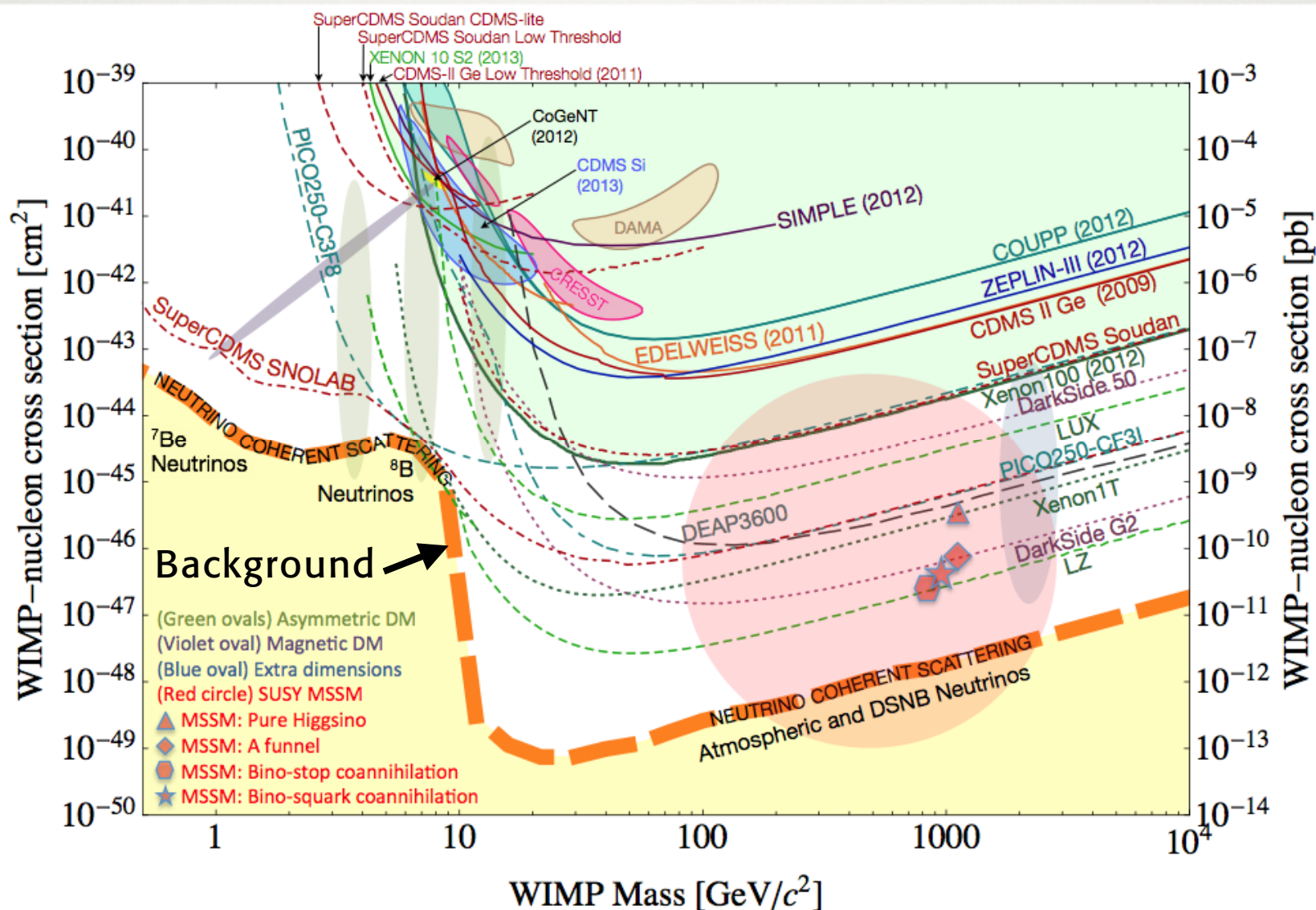**Now excluded by LUX   ArXiv:1310.8214**
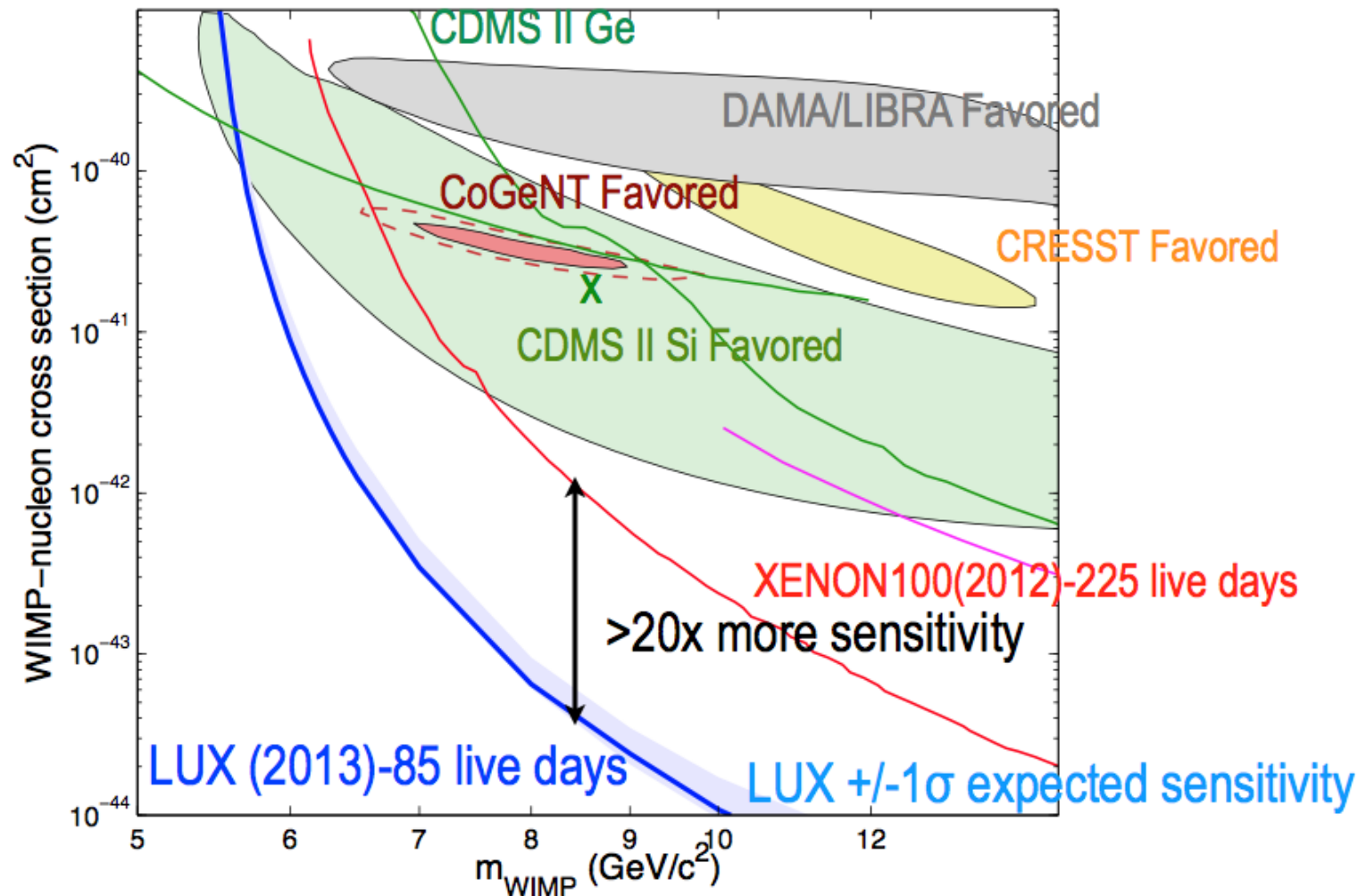
However
there is
still plenty of
room
for low mass
WIMP's

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 $U(1)_{PQ}$

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

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

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

The ψ mass is m $\sim \lambda<A> \sim \lambda f$ $\longrightarrow$ new particles at scale f!

$$A = |A| e^{i\frac{a}{f}}$$

a (the axion) is the Goldstone boson

$a' = a$ -2iαf

it only has derivative couplings except for the $U(1)_{PQ}$ anomaly term

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

The only term with a and not $\partial_\mu a$ is the potential V

$$V = [\theta + \frac{a}{f}]\frac{\alpha_s}{4\pi}Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})$$

The VEV $<a>$ is fixed by

$$\frac{\partial V}{\partial a} = 0 \Rightarrow \frac{\alpha_s}{4\pi f}\langle Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})\rangle = 0$$
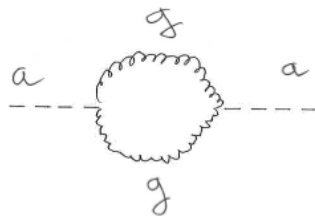
It is (not too) easy to prove that $\langle Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})\rangle \propto \sin\theta_{eff} \equiv \sin(\theta + \frac{\langle a\rangle}{f})$

so that the coefficient of the CP violating term is put to zero!

e.g. Coleman, '77; Vafa, Witten '84......

After the shift $a \dashrightarrow a'' + <a>$ (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 $U(1)_{PQ}$)
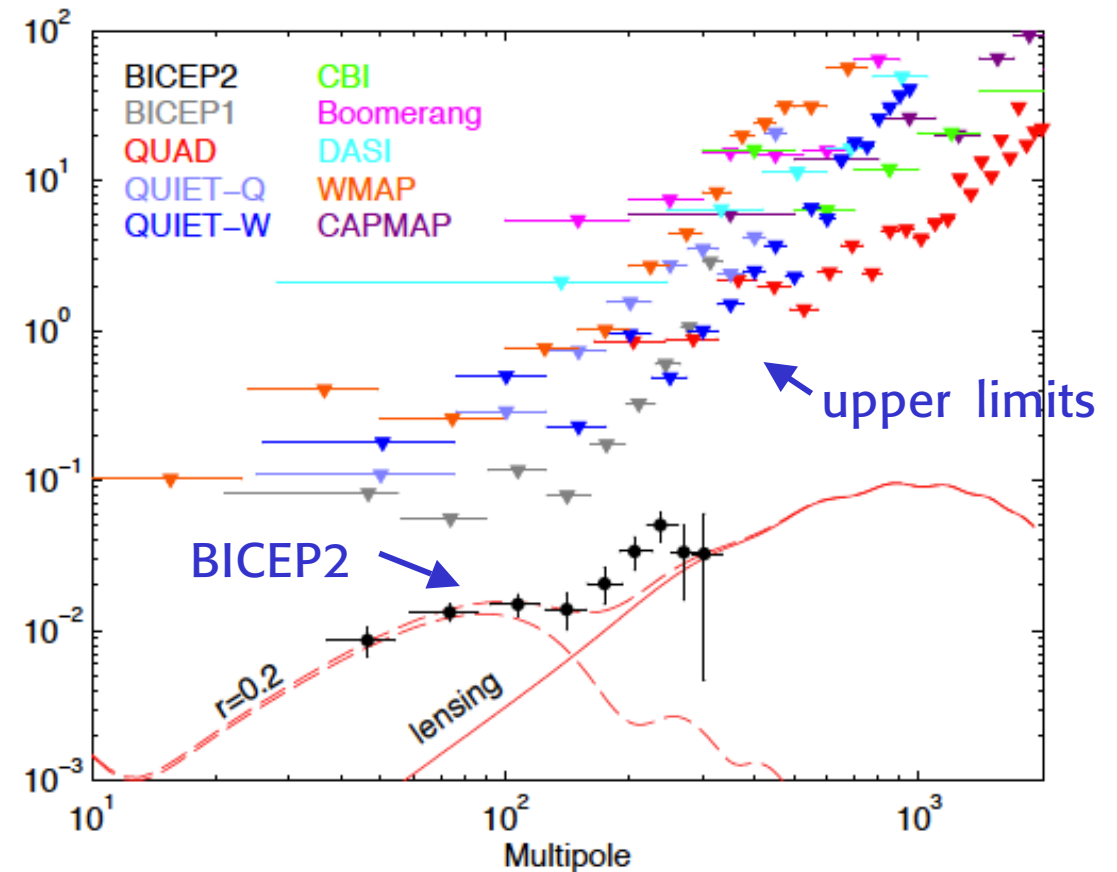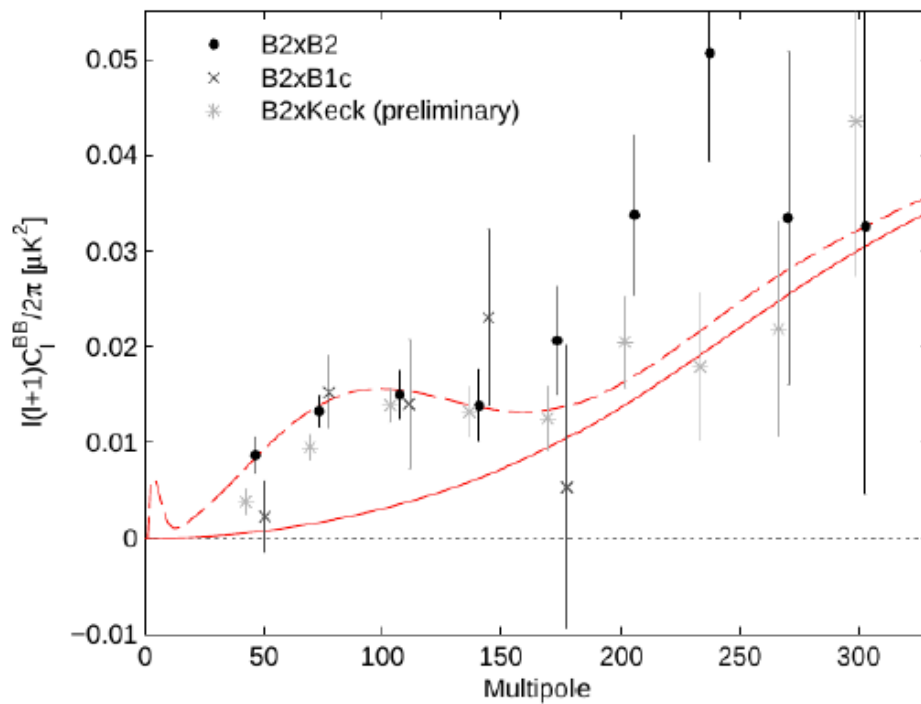

$$m_a^2 \propto \frac{\Lambda_{QCD}^4}{f^2}$$

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

$\oplus$ The analogous coupling to photons induces the decay $a \dashrightarrow \gamma\gamma$

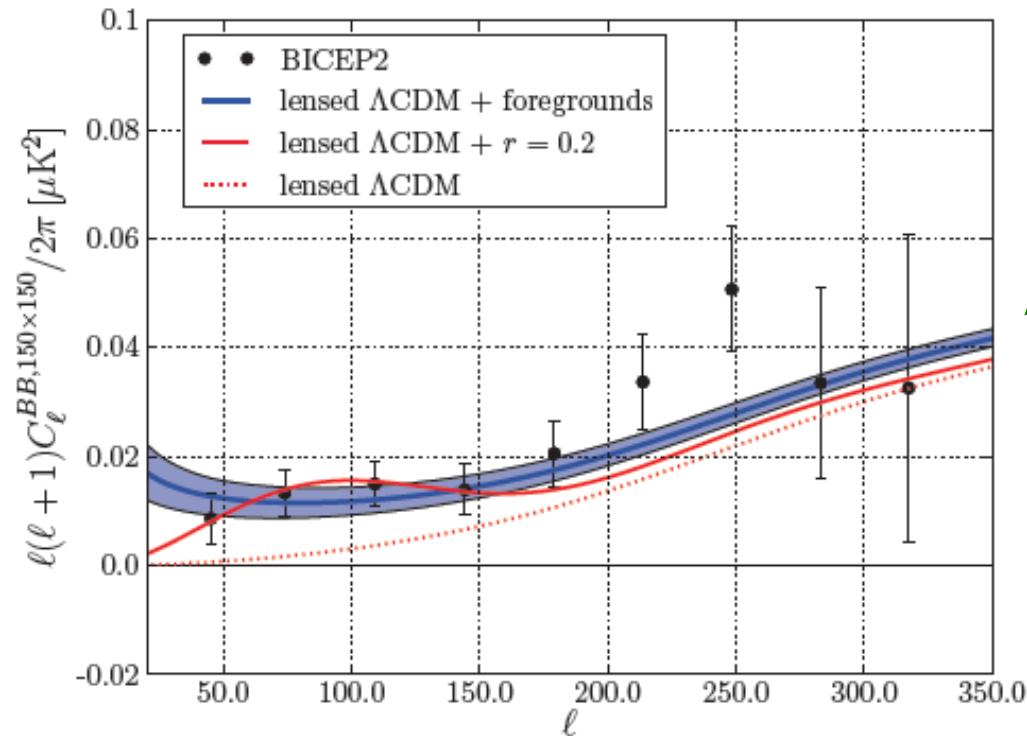# Sensational news from cosmology

The BICEP2 Data

A large value of $r = A_T/A_s \sim 0.2$ is found

Caution: it could be that it all comes from dust!

Flauger, Hill, Spergel '14

A model of foreground dust polarized emission

Planck data (released in October ?)
and/or measurements at different frequencies
can tell the difference

To be confirmed by other experiments
Planck, POLARBEAR, ACTPole, KecK Array...
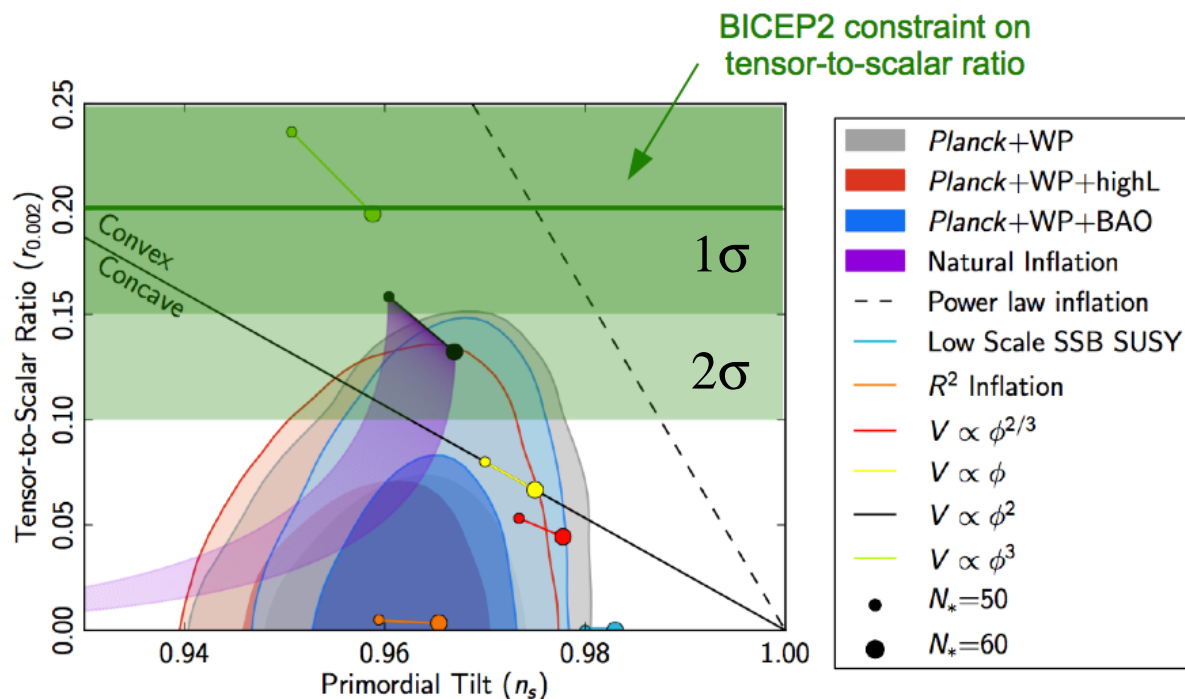
Great impact on Inflation

$$r = 0.20\ ^{+0.07}_{-0.05}$$
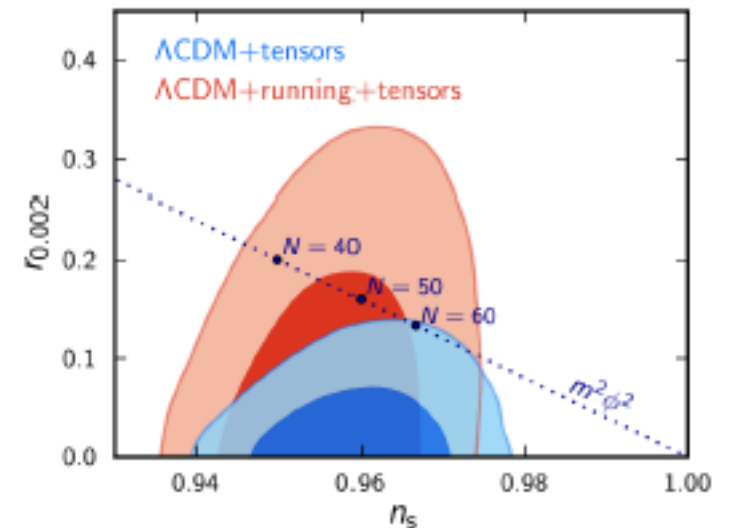
Energy scale of inflation:

$$V_{\text{inf}}^{1/4} \approx 2.2 \cdot 10^{16} \left(\frac{r}{0.2}\right)^{1/4} \text{GeV}$$

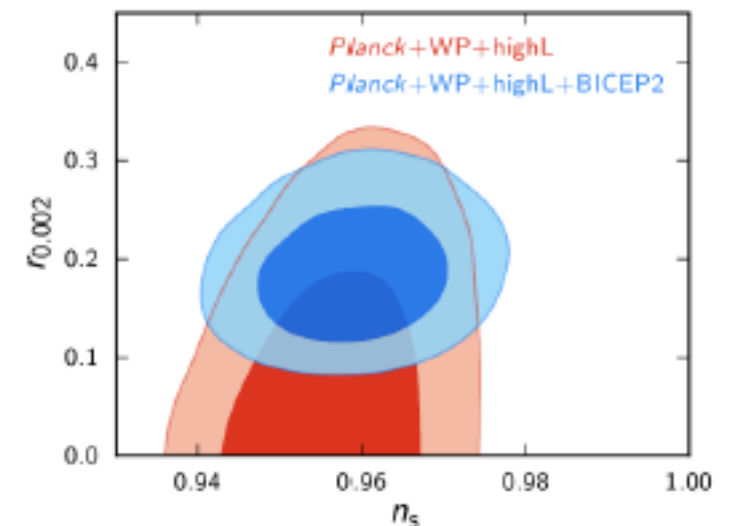## Tantalizing close to M_{GUT}!

Evidence of a scale below M_{Pl}?

BICEP2 constraint on
tensor-to-scalar ratio

Planck 2013

- ΛCDM+tensors
- ΛCDM+running+tensors

$N = 40$
$N = 50$
$N = 60$
$m^2\phi^2$

Moderate tension with Planck

Bicep2 2014

| Planck+WP |
| Planck+WP+highL |
| Planck+WP+BAO |
| Natural Inflation |
| Power law inflation |
| Low Scale SSB SUSY |
| R^2 Inflation |
| $V \propto \phi^{2/3}$ |
| $V \propto \phi$ |
| $V \propto \phi^2$ |
| $V \propto \phi^3$ |
| $N_* = 50$ |
| $N_* = 60$ |

Tensor-to-Scalar Ratio ($r_{0.002}$)

Primordial Tilt (n_s)

Convex
Concave

1σ
2σ

Planck+WP+highL
Planck+WP+highL+BICEP2

$r_{0.002}$

n_s

Implications of BICEP2 on axions

Visinelli, Gondolo '14

window of
opportunity
after inflation
$f_a \sim 10^{10} - 10^{11}$ GeV
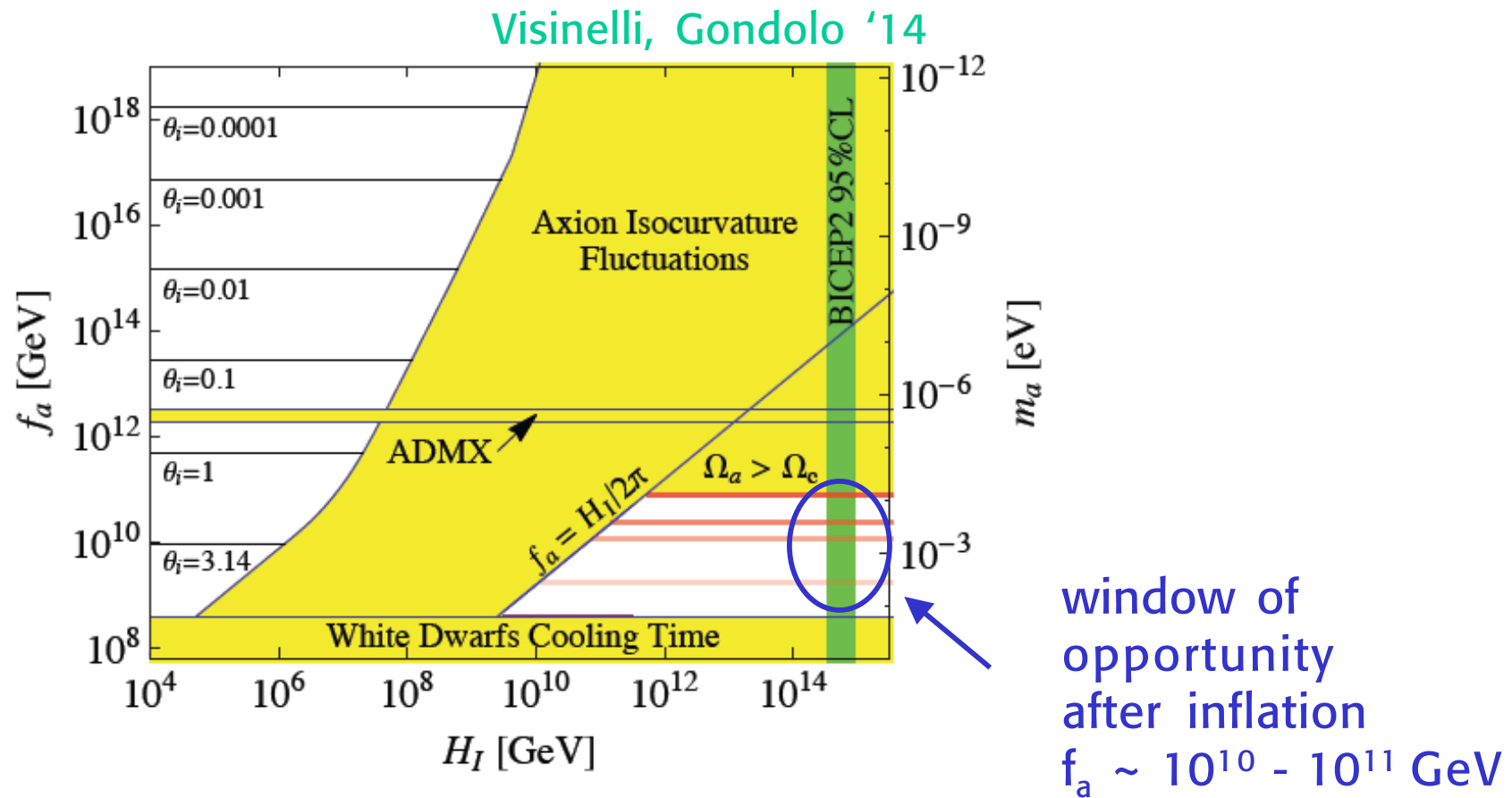
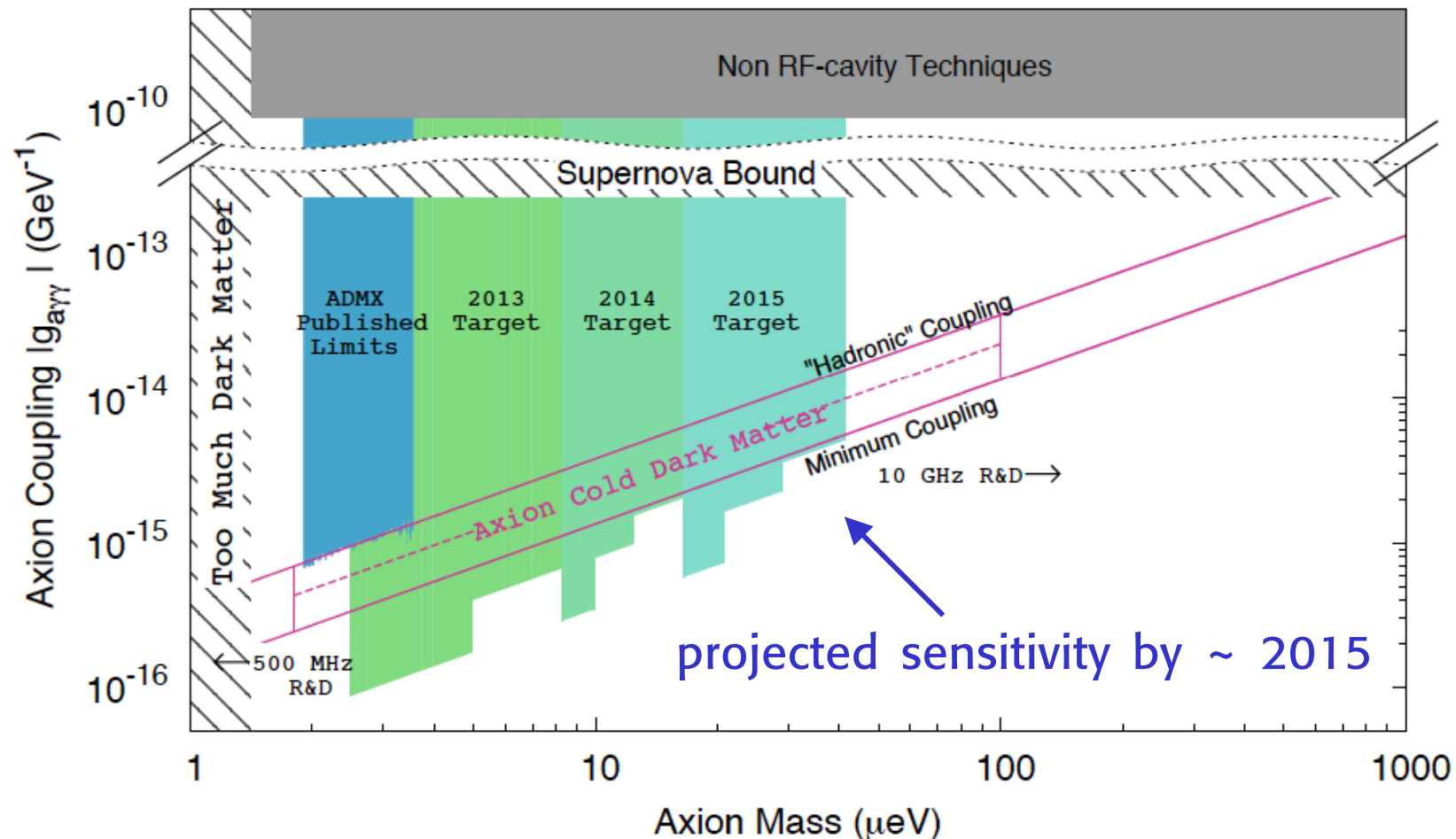# Axion searches are very important

ADMX: the Axion Dark Matter Experiment
University of Washington at Seattle

projected sensitivity by ~ 2015

To cope with the naturalness riddle different lines of thought have emerged

- Insist on minimizing the fine tuning: immagine suitable forms of new physics around the corner

- Opt for a total acceptance of fine tuning: the anthropic philosophy

- Accept fine tuning only up to an intermediate scale: e.g. split SUSY

- Argue that possibly there is no fine tuning: the no new threshold (up to M_{Pl}) conjecture

One line: insisting on minimizing the FT

- "Stealth" Naturalness: build models where naturalness is restored not too far from 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 ← → Composite Higgs

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!

H as PGB of extended symm.
q and l mix with comp. ferm.

Key role of light top partners

Going beyond the MSSM: an extra singlet Higgs

In a promising class of models a singlet Higgs S is added
and the μ term arises from the S VEV (the μ problem is solved)

additional term

$$\lambda \, SH_uH_d$$

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$

Mixing with S can modify the Higgs mass and couplings
at tree level

Hall et al '11, King et al '12, Barbieri et al '13.....

NMSSM: $\lambda < \sim 0.7$ the theory remains perturbative up to M_{GUT}
(no need of large stop mixing, less fine tuning)

λ SUSY: $\lambda \sim 1 - 2$ for $\lambda > 2$ theory non pert. at ~10 TeV

It is not completely excluded that at 126 GeV the second heaviest
is seen while the lightest escaped detection at LEP

Ellwanger '11, Belanger et al '12

- Going beyond the MSSM:
Natural SUSY ⟶

Minimum for MSSM to be natural

$$m_{\tilde{g}}, m_{\tilde{t}}, m_{\tilde{b}}, m_{\tilde{h}} \quad < \sim 1 \text{ TeV}$$

Heavy 1st, 2nd generation scalars

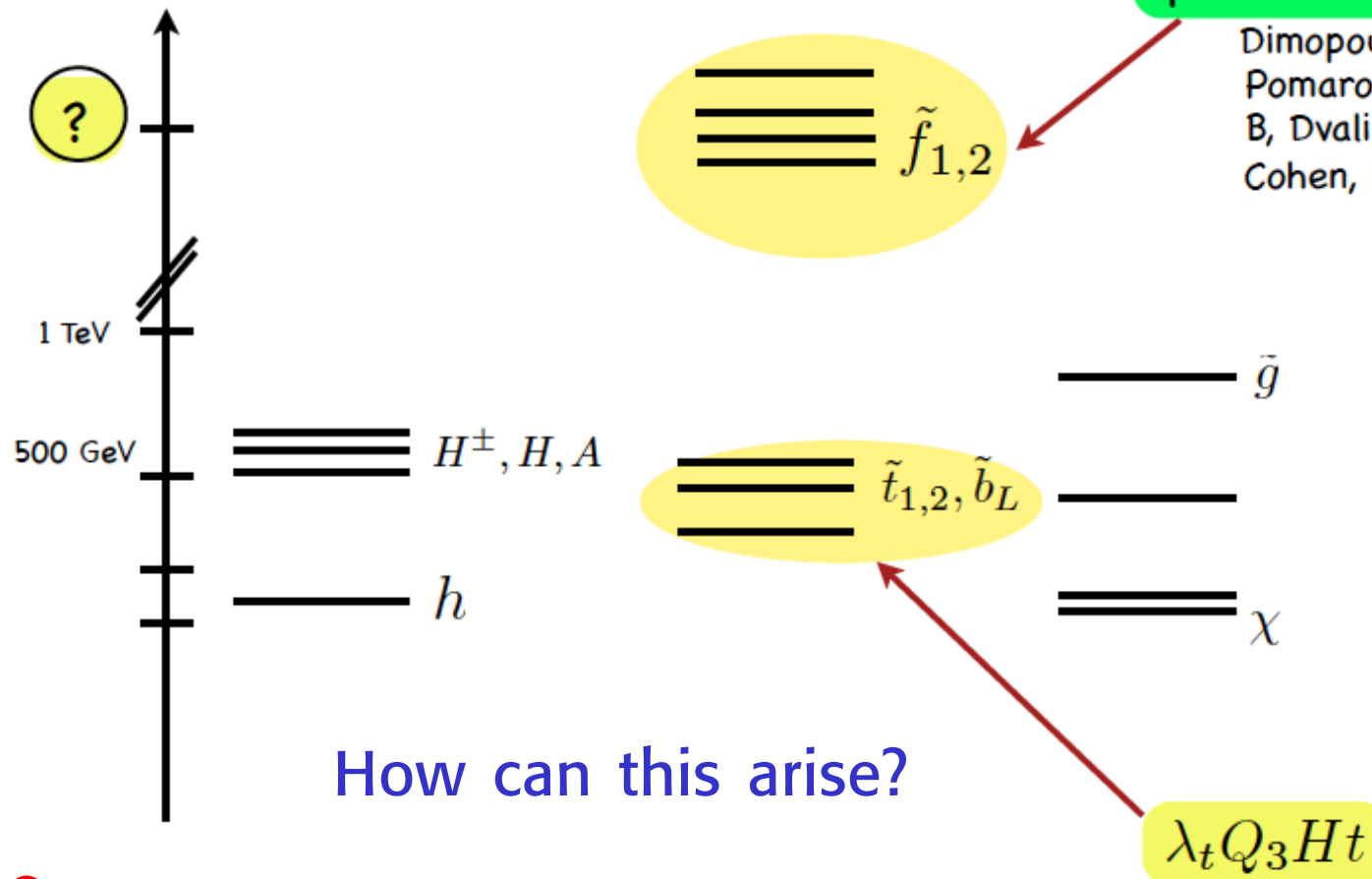Flavour and CP problems improved

Dimopoulos, Giudice 1995
Pomarol, Tommasini 1995
B, Dvali, Hall 1995
Cohen, Kaplan, Nelson 1996

pioneer papers

recent papers, e.g.

Papucci et al '11
Brust et al '11
Essig et al '11
Katz et al '11
Larsen et al '12
Csaki et al '12
.....

?

1 TeV

500 GeV

$H^{\pm}, H, A$

h

$\tilde{f}_{1,2}$

$\tilde{g}$

$\tilde{t}_{1,2}, \tilde{b}_L$

χ

$\lambda_t Q_3 H t$
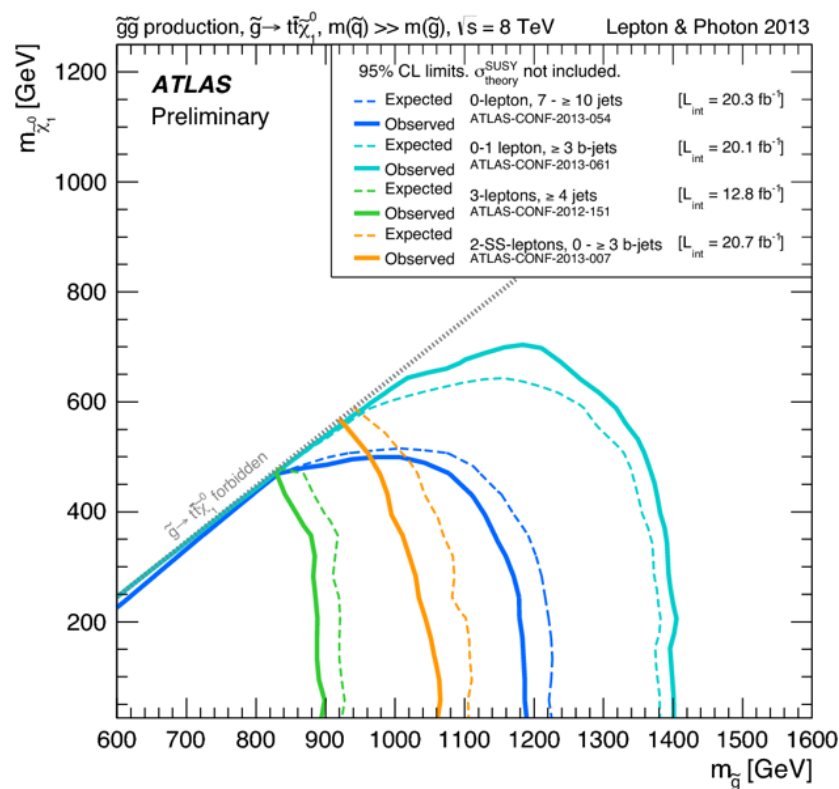
How can this arise?

Barbieri

For g-2
light sleptons
welcome

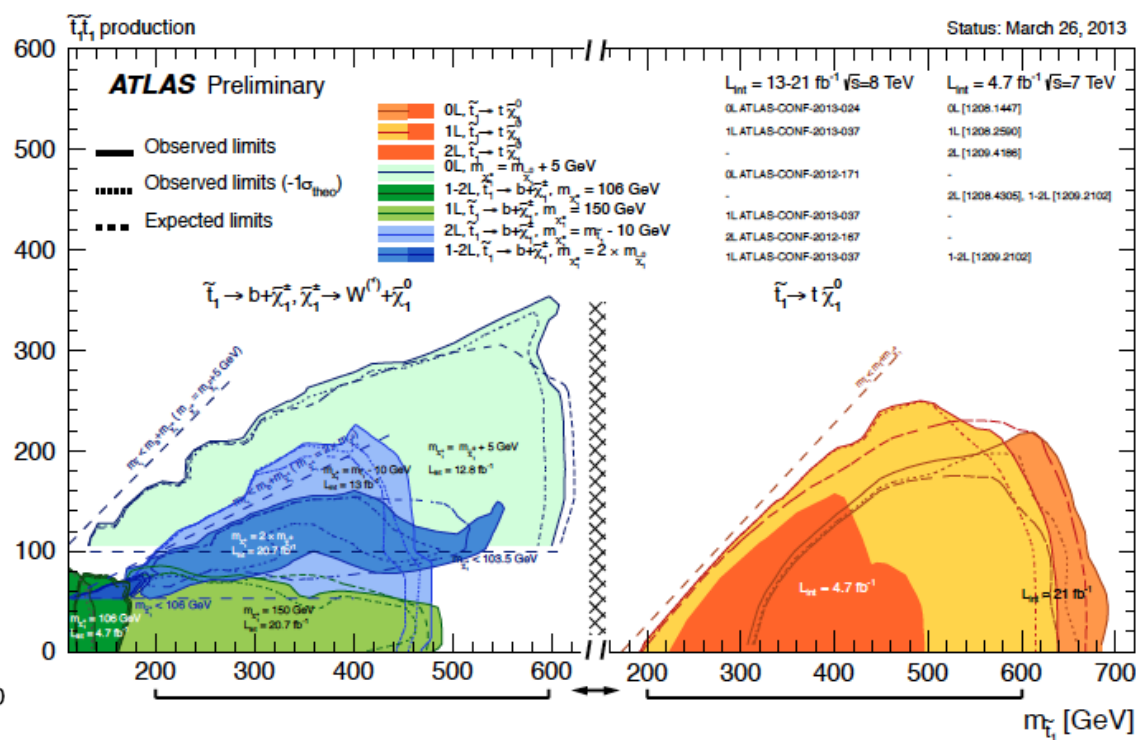# Searches of light gluinos, s-top, s-bottom: already biting hard

Gluino mediated s-top production: $m_g < 1.4$ TeV excluded with some assumptions on BRs.

Direct s-top production: $m_{stop} < 0.60$-0.65 TeV excluded assuming 100% BR for either $b\chi^+$ or $t\chi^0$
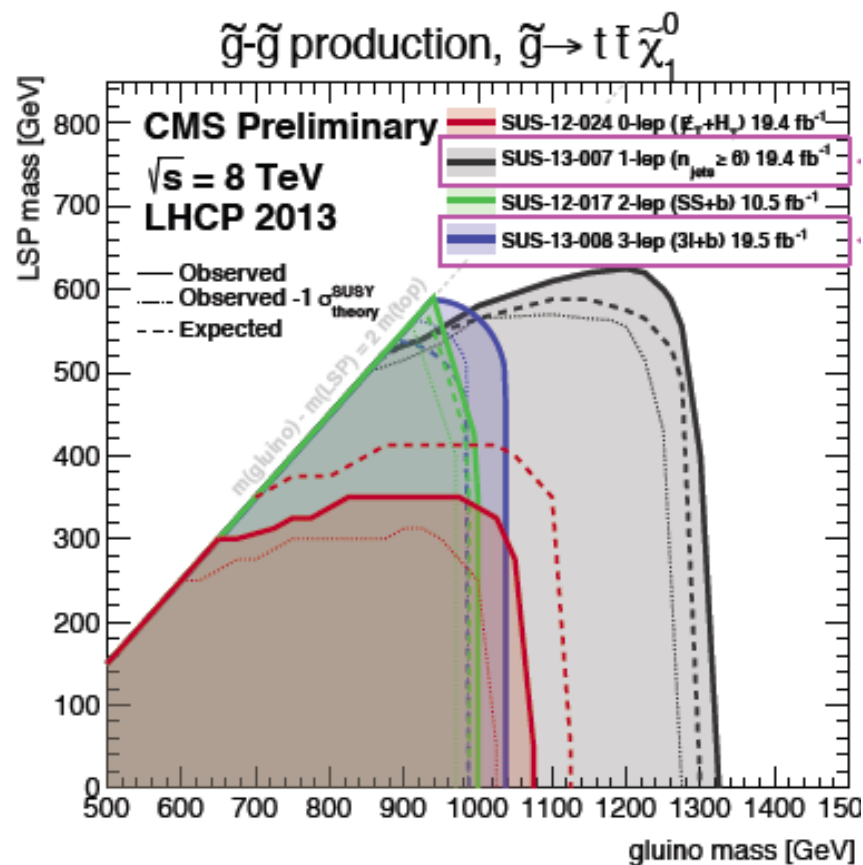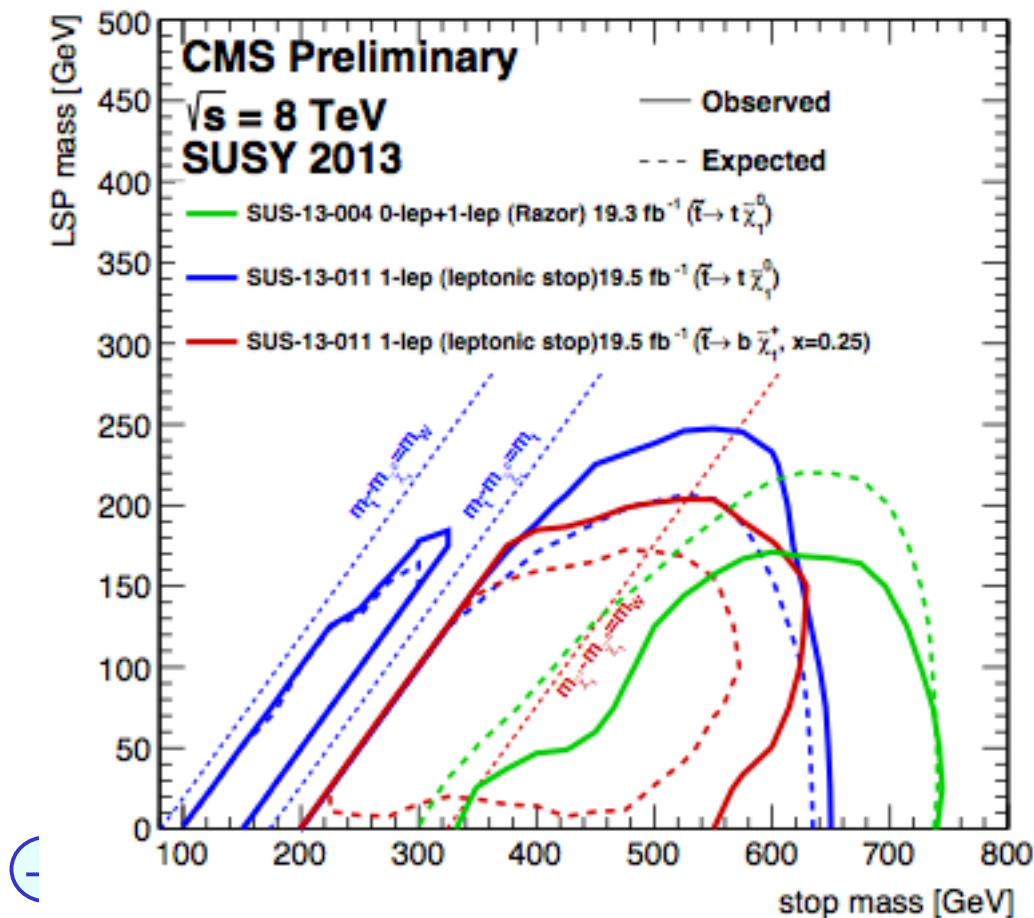
ATLAS

gluino

s-top

Searches for stops, gluinos, sbottoms target natural SUSY

- Probe stops up to ~650 GeV
- Probe gluinos up to ~1.3 TeV
- Probe sbottoms up to ~600 GeV

$\tilde{t}$-$\tilde{t}$ production

CMS

- **Composite Higgs** Georgi, Kaplan '84; Kaplan '91; Agashe, Contino, Pomarol '05; Agashe et al '06; Giudice et al '07; Contino et al '07; Csaki, Falkowski, Weiler '08; Contino, Servant '08; Mrazek, Wulzer '10; Panico, Wulzer '11; De Curtis, Redi, Tesi '11; Marzocca, Serone, Shu '12; Pomarol, Riva'12; De Simone et al '12.........

The light Higgs is a bound state of a strongly interacting sector and a pseudo-Goldstone boson of an enlarged symmetry. eg. SO(5)/SO(4). Can be set up in a holographic ED context.

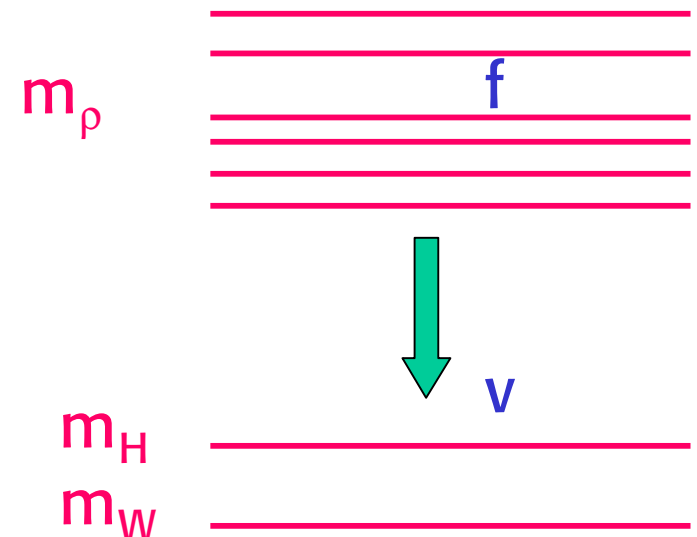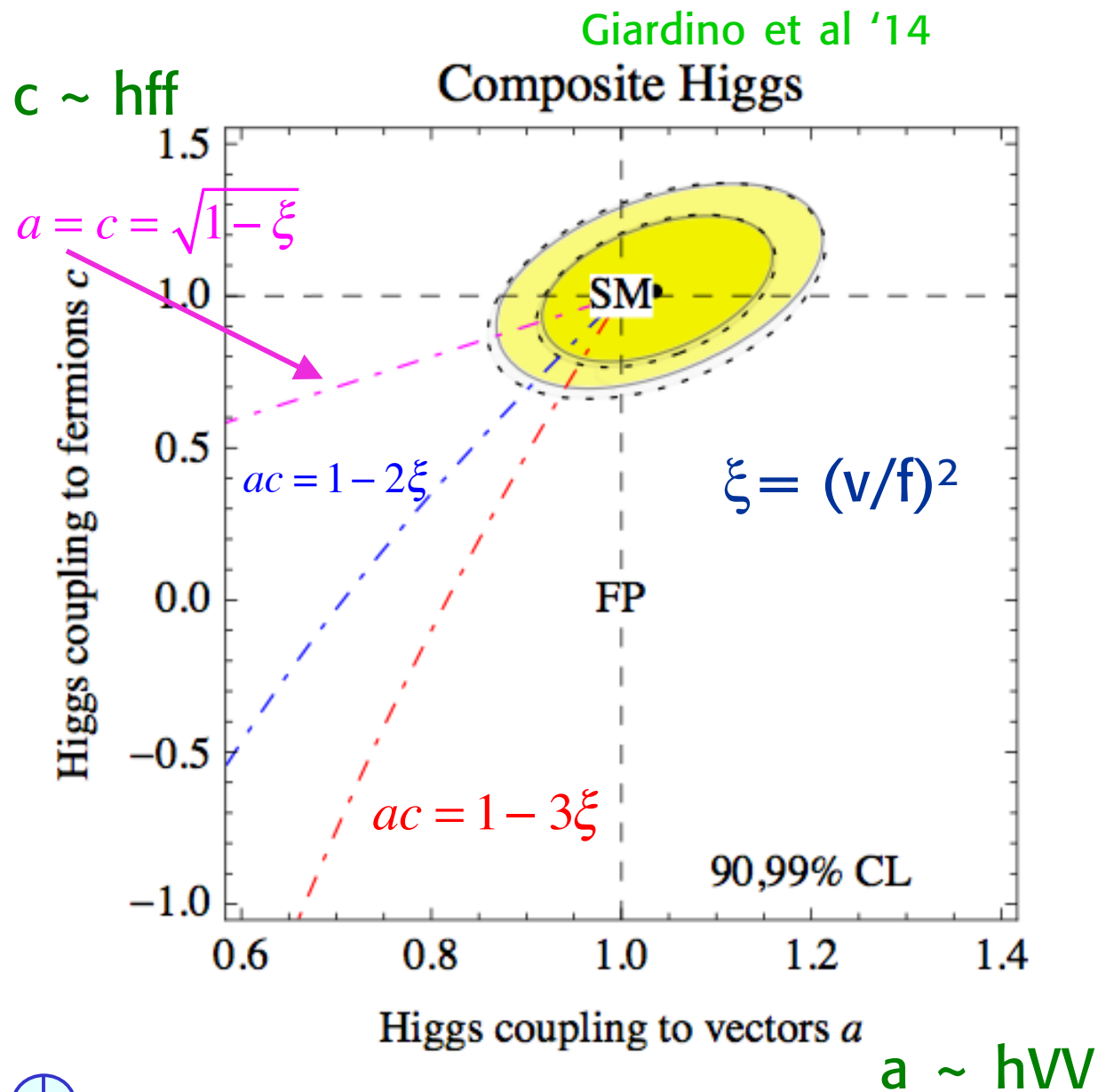$v \sim$ EW scale $\quad f \sim$ SI scale

$\sim f < m_\rho <\sim 4\pi f$

$\xi = (v/f)^2$

ξ interpolates between SM [$\xi \sim 0$] and some degree of compositeness

$\xi \sim 1$ similar to Technicolor

[ξ severely limited by precision EW tests $\xi < \sim 0.2$]

m_ρ

f

v

m_H

m_W

c ~ hff

$a = c = \sqrt{1 - \xi}$

Higgs coupling to fermions c

$ac = 1 - 2\xi$

$ac = 1 - 3\xi$

Giardino et al '14

Composite Higgs

SM

$\xi = (v/f)^2$

FP

90, 99% CL

Higgs coupling to vectors a

a ~ hVV

ξ severely limited by precision EW tests $\xi < \sim 0.2$

m_ρ

f

v

m_H

m_W
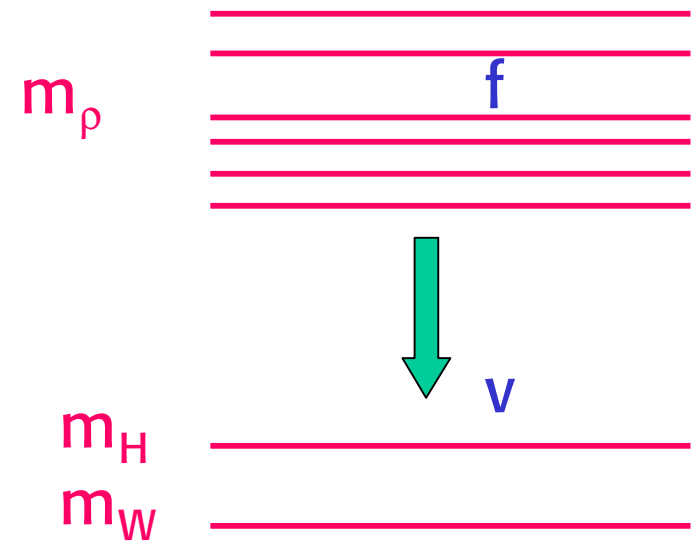
In general composite models are more vulnerable than SUSY from EW precision tests
(for SUSY, Higgs couplings are more effective than EWPT)

No clear UV completion, no connection to GUTs

Composite models can be tested by:

- Searching for fermions of charges 2/3 or 5/3 ... that quench the bad top loop behaviour

- Measurable deviations can be expected in channels
  pp -> tth, gg -> hh and in decays h-> $\mu\mu$, h -> Zγ
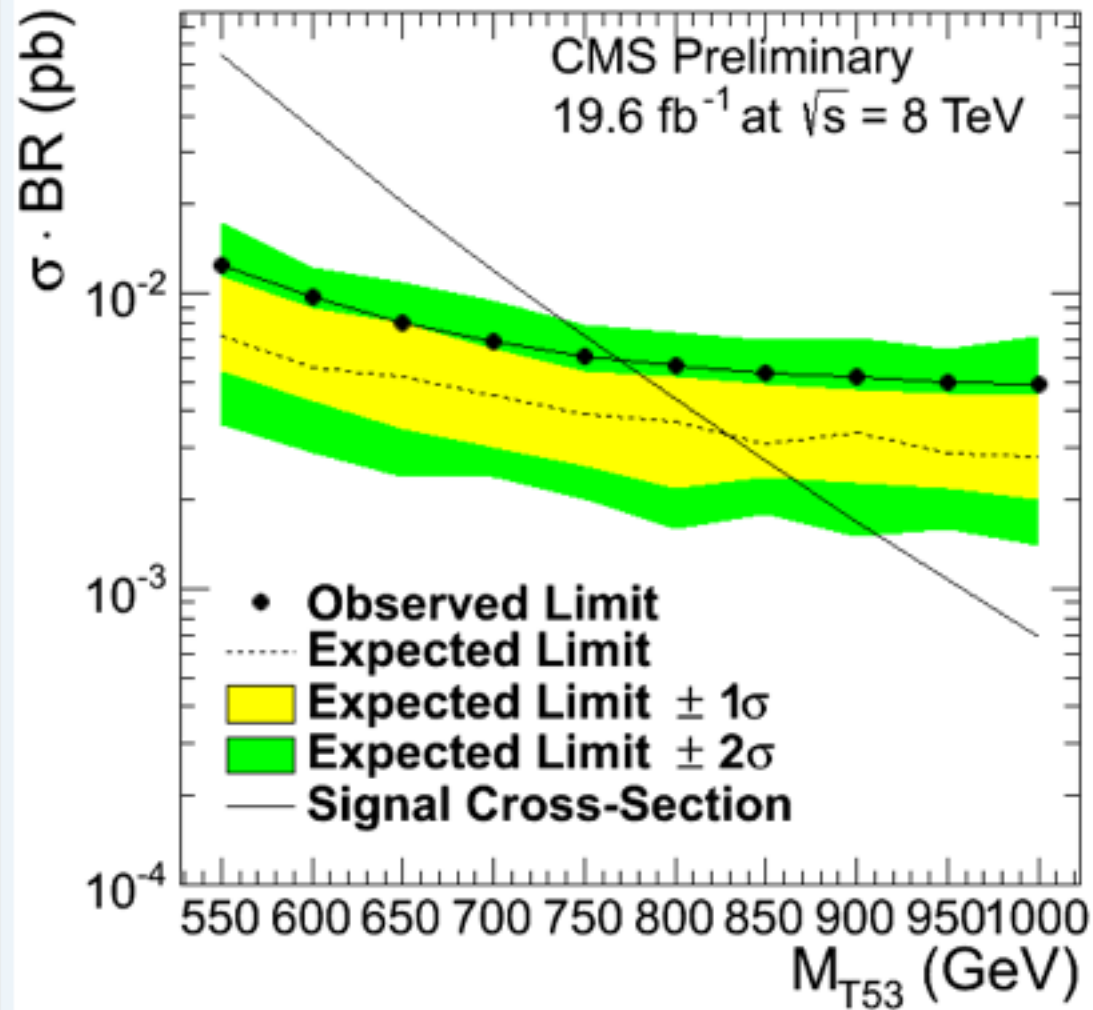
Some recent papers:
Azatov et al '13
Contino et al '13
Jenkins et al '13
Grojean et al '13......

Searches for t partners

In composite models the top loop bad behaviour is quenched by a new fermion

CMS Preliminary
19.6 fb^{-1} at $\sqrt{s}$ = 8 TeV

- **Observed Limit**
- ------ **Expected Limit**
- **Expected Limit ± 1σ**
- **Expected Limit ± 2σ**
- —— **Signal Cross-Section**

y-axis: $\sigma \cdot$ BR (pb)

x-axis: M_{T53} (GeV)

Expected and observed 95% C.L. limits on the $T_{5/3}$ production cross section. The 1-sigma and 2-sigma combined statistical and systematic expected variation is shown as a yellow (light) and green (dark) band, respectively.

A 5/3 charged fermion cannot mix and is not pushed up

- The empirical value of the cosmological constant Λ_{cosmo} poses a tremendous, unsolved naturalness problem

  While natural extensions of the SM exist, no 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 (multiverse)

- 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
$\Lambda_{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

$\oplus$ The anthropic way is now being kept in mind as a possibility

A revival of models that accept some fine tuning

Examples:

Split SUSY
heavy scalars, light gauginos and higgsinos (DM and Unification)

High scale SUSY
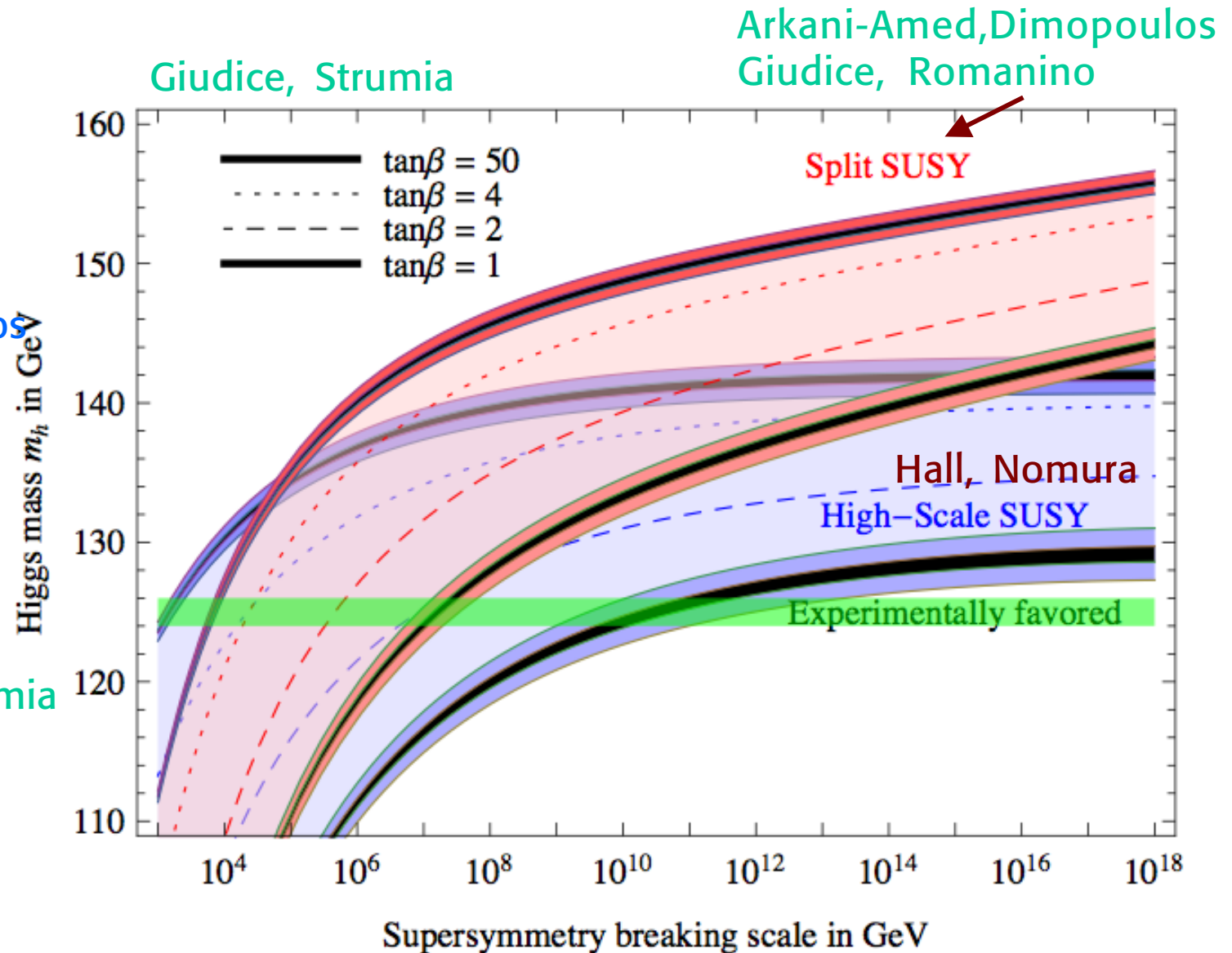all sparticles heavy λh^4 fixed by gauge

Non SUSY GUT's
Unificaxion
Giudice, Rattazzi, Strumia
Non SUSY SO(10)
GA, Meloni
••••••••

Giudice, Strumia

Arkani-Amed, Dimopoulos
Giudice, Romanino

Split SUSY

$\tan\beta = 50$	
$\tan\beta = 4$	
$\tan\beta = 2$	
$\tan\beta = 1$	

Hall, Nomura
High–Scale SUSY

Experimentally favored

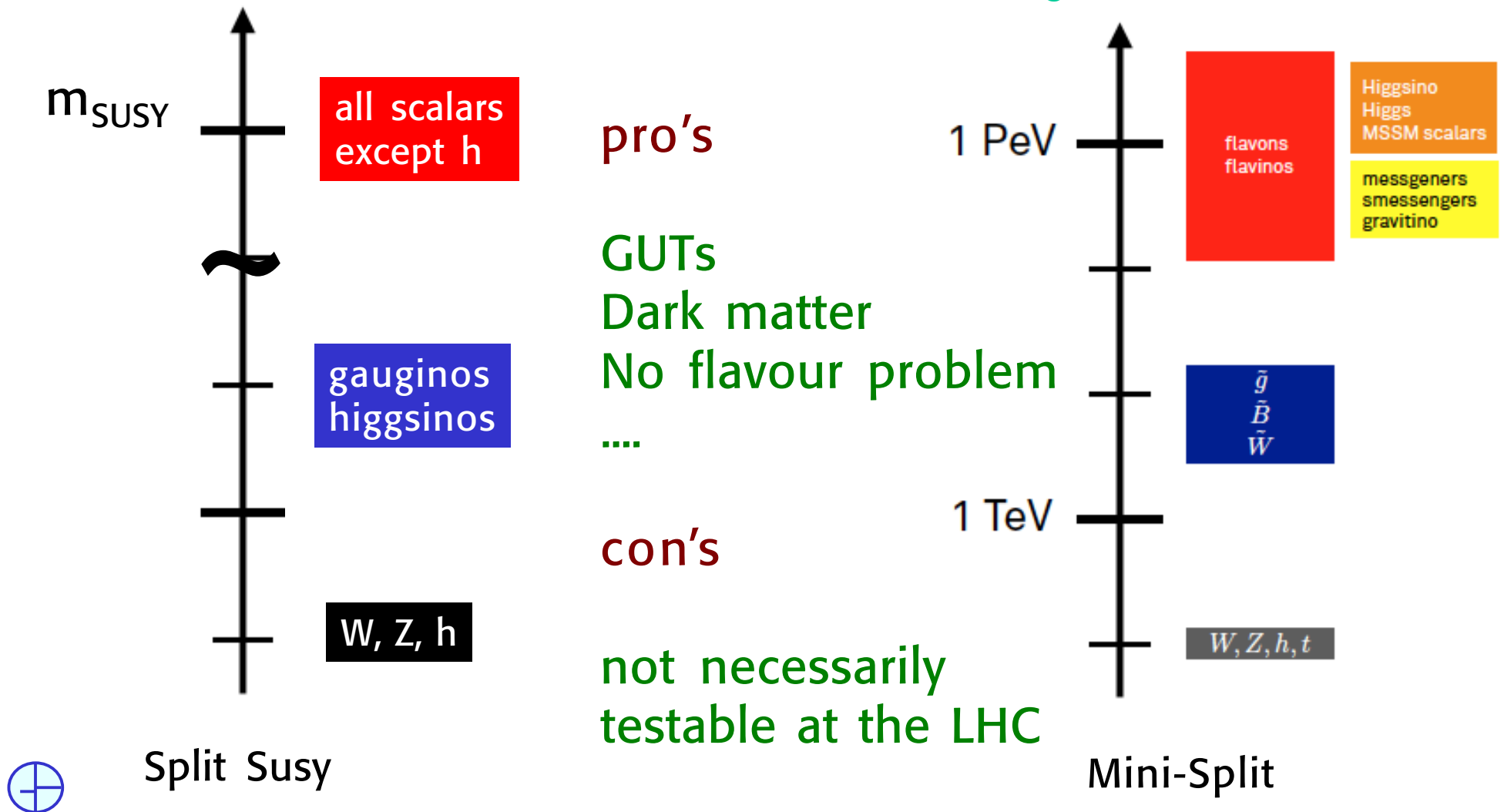Higgs mass m_h in GeV

Supersymmetry breaking scale in GeV

Split or Mini-Split SUSY could be a compromise: accept fine tuning but up to a point

Arkani-Hamed, Dimopoulos '04
Giudice, Romanino ' 04

Baumgart, Stolarski, Zorawski '14

m_{SUSY}

all scalars
except h

gauginos
higgsinos

W, Z, h

Split Susy

pro's

GUTs
Dark matter
No flavour problem
....

con's

not necessarily
testable at the LHC

1 PeV

flavons
flavinos

Higgsino
Higgs
MSSM scalars

messgeners
smessengers
gravitino

$\tilde{g}$
$\tilde{B}$
$\tilde{W}$

1 TeV

W, Z, h, t

Mini-Split

Remove the FT problem: 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 needs to solve all problems like
Dark Matter, neutrino masses, baryogenesis....
at the EW scale

In particular no GUTs, no heavy RH neutrinos, no
WIMPs..... below M_{Pl}. A big loss!!

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
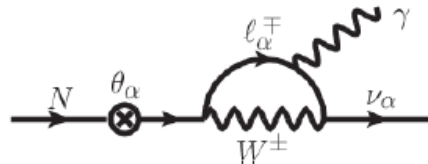Actually $N_1 \sim o(1\text{-}10)$ keV, and $N_{2,3} \sim$ GeV with eV splitting
Very small Yukawa couplings are assumed to explain the
small active ν masses

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

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

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

$$\Gamma_\gamma(m_s, \theta) = 1.38 \times 10^{-29} \ \text{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1 \ \text{keV}}\right)^5$$
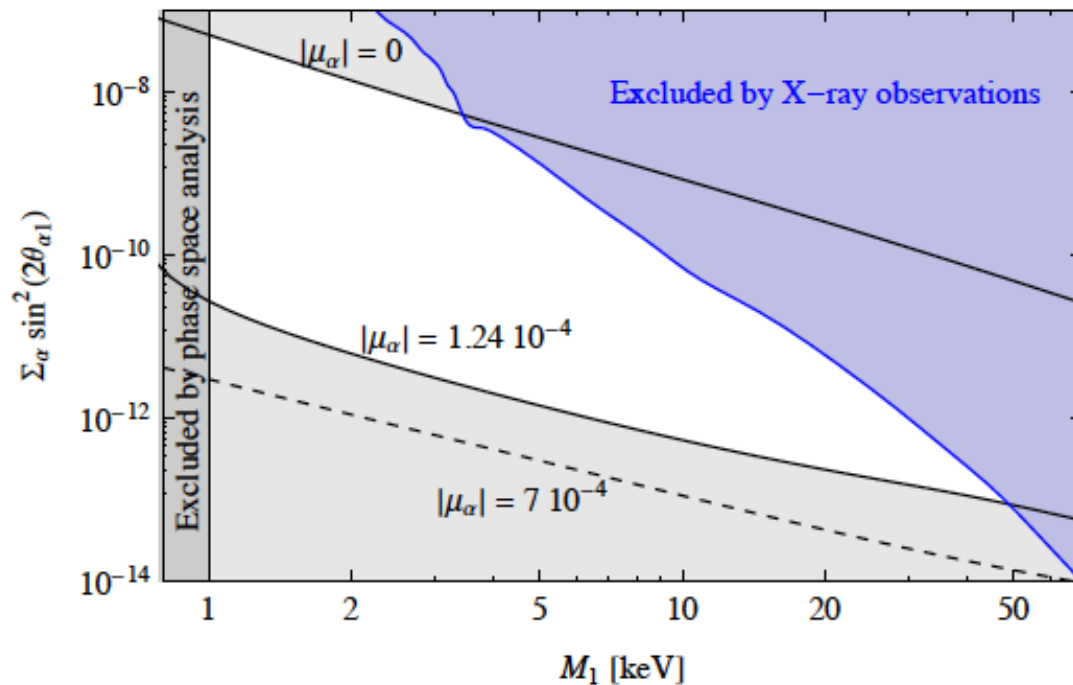
$N_{2,3}$ could be detected by dedicated accelerator experiments
(eg in B decays, Br $\sim 10^{-10}$)
A LOI for the CERN SPS has been presented
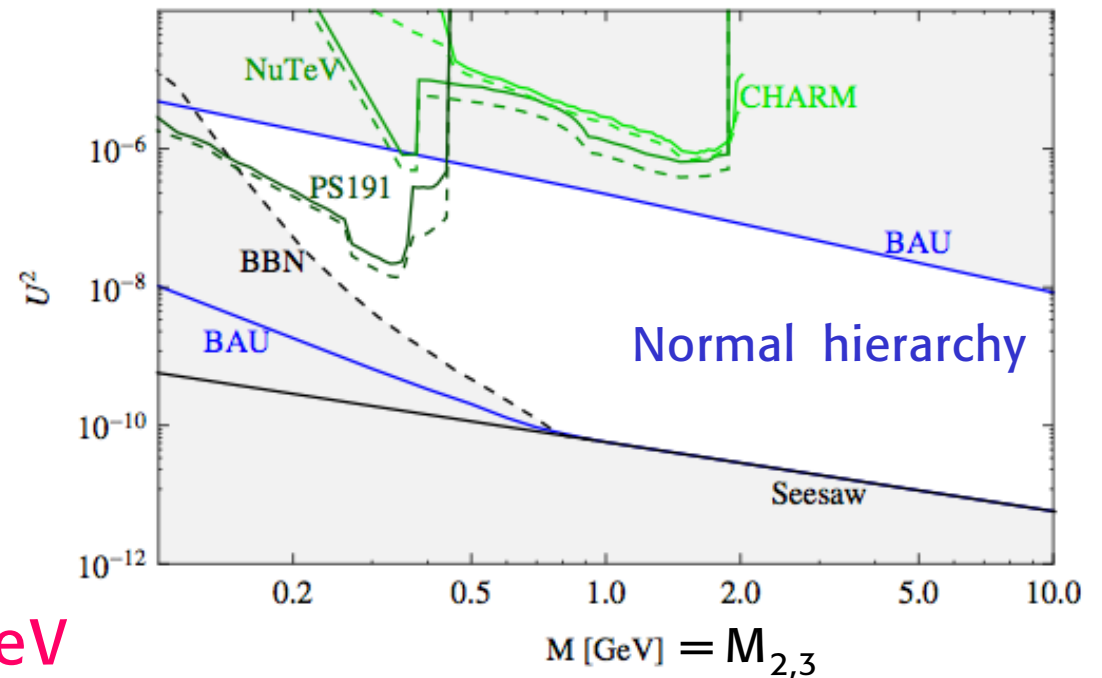Bonivento et al, ArXiv:1310.1762

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

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]

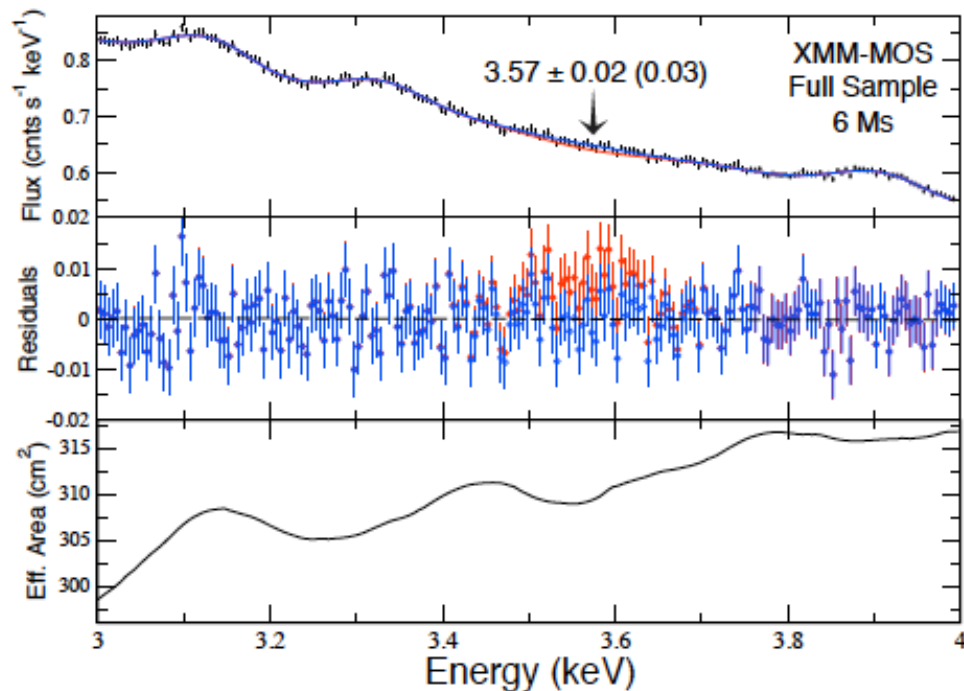[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

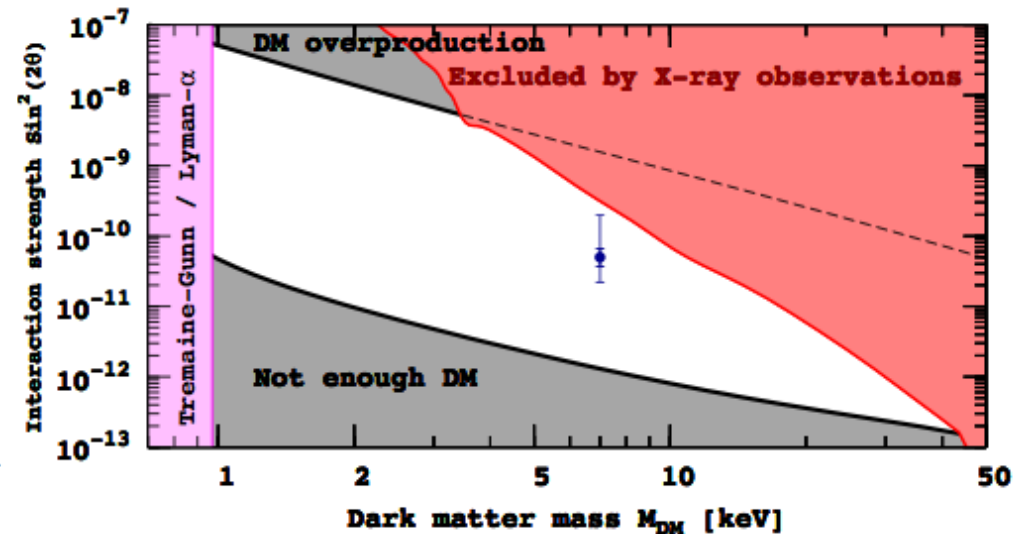XMM-Newton X-ray observatory

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

Independent analysis by Boyarski et al
ArXiv:1402.4119

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

The "evidence" for the 3.5 keV line has been questioned

Questioning a 3.5 keV dark matter emission line

Signe Riemer-Sørensen[1,*]

[1]Institute of Theoretical Astrophysics, University of Oslo, PO 1029 Blindern, 0315 Oslo, Norway

Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line

Tesla Jeltema[1]* and Stefano Profumo[1]†

[1]Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA

but also supported: the debate is open

Checking the dark matter origin of 3.53 keV line with the Milky Way center

A. Boyarsky[1], J. Franse[1,2], D. Iakubovskyi[3], and O. Ruchayskiy[4]

[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands
[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
[4]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

Summary

- Higgs, minimal, elementary, standard

- No new physics. Naive naturalness failed

  We expected complexity, we found simplicity

- The SM could hold up to M_{Pl}

  Minimal completions of SM

  Majorana ν's, see-saw, leptogenesis ....

- Today the most crucial problem is Dark Matter

  WIMPS, Axions, keV ν's....

- Different theoretical avenues

  Insist on as minimal as possible Fine Tuning (FT)

  Stealth SUSY, nearby compositeness.....

  Accept some FT

  e.g. Split-SUSY

  Total acceptance of FT: the Anthropic metaphysics

- Denial of FT: the no-threshold philosophy

  the νMSM, scale invariant theories

  price: no GUTs, no heavy ν_R ....

  But BICEP2 now makes the GUT scale to reappear!