Warsaw, 7 Avril '14

The HIGGS and the EXCESSIVE success of the SM

Guido Altarelli
Roma Tre/CERN

LHC 7-8 TeV

A great triumph: the 126 GeV Higgs discovery  

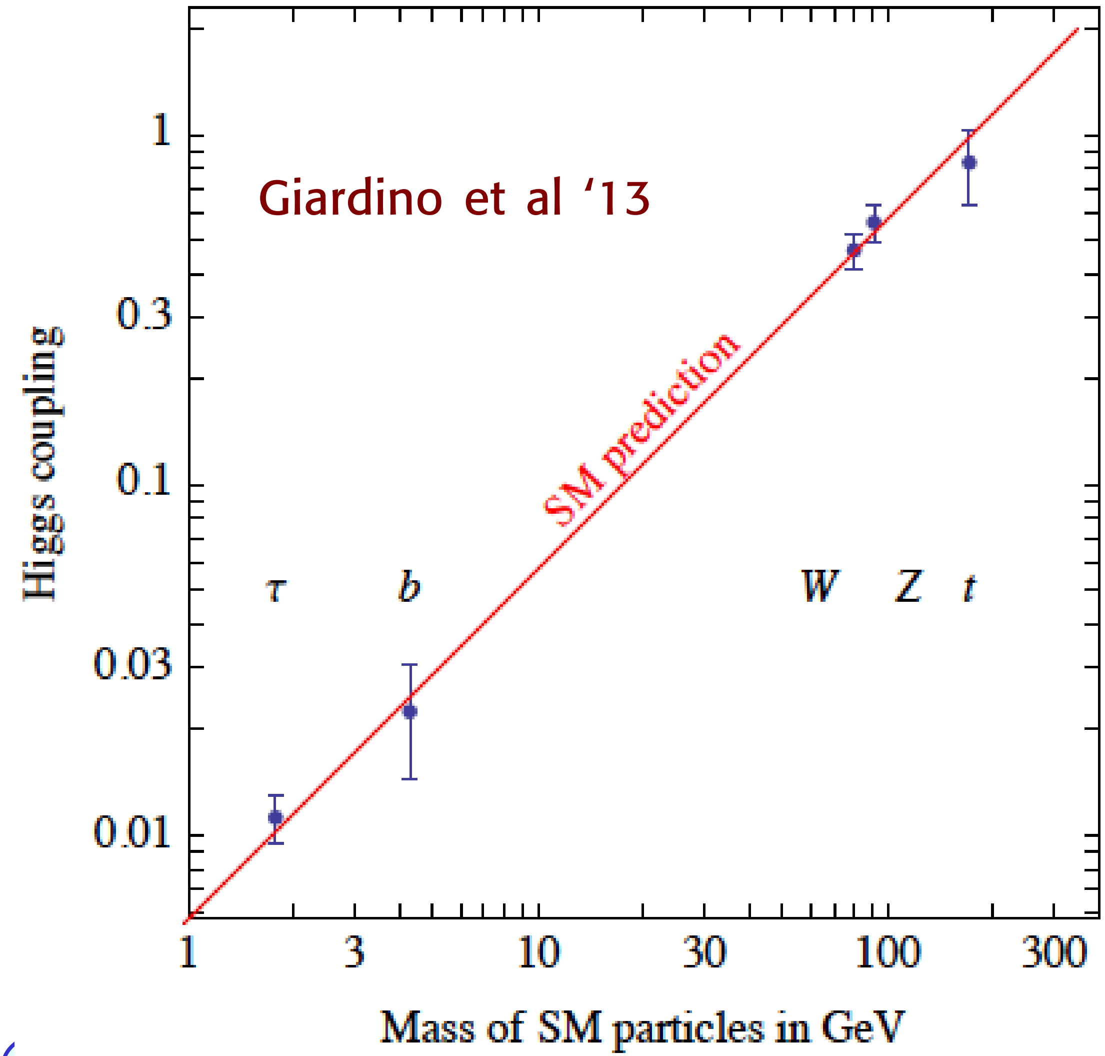
A particle apparently just as predicted by the SM theory

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 $(g-2)_\mu$?]

The Higgs couplings are in proportion to masses: a striking signature [plus specified, gg, γγ, Zγ eff. couplings]



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

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

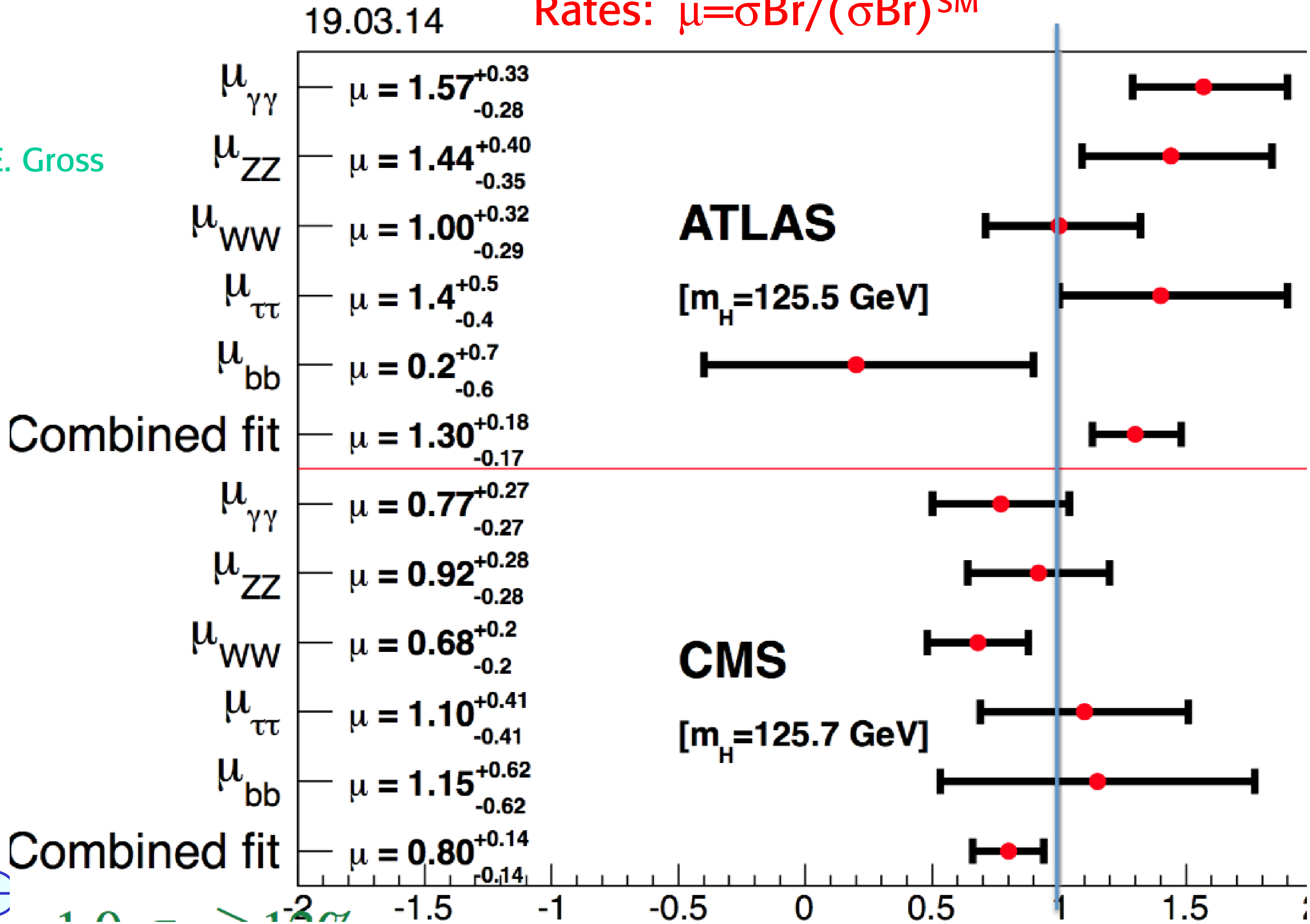
eg Alonso et al
Giudice et al
Csaki et al
Contino
Keren-zur et al
Falkowski et al
Elias-Miro et al
Pomarol, Riva.....

Almeida et al

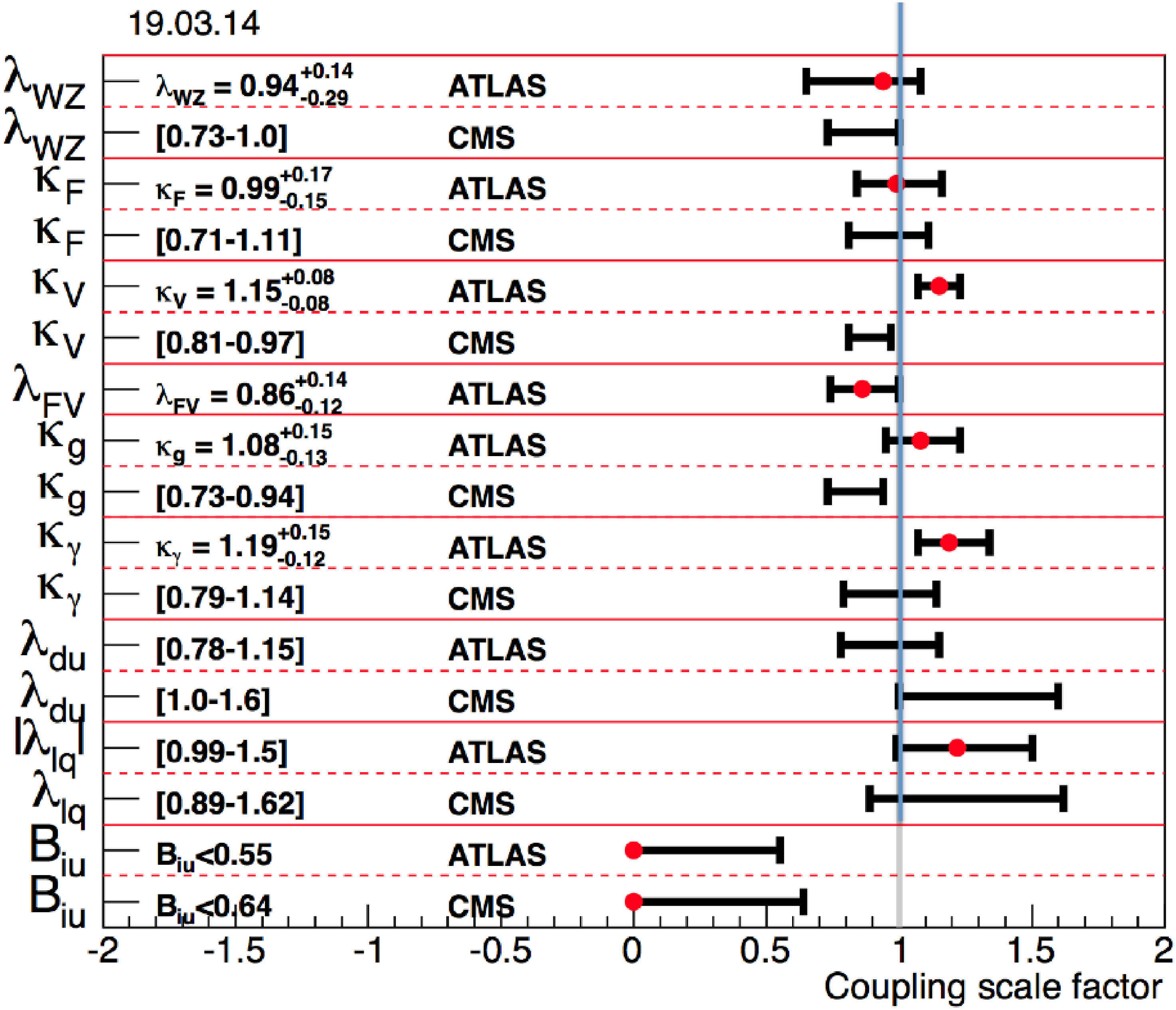
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W^+_{\mu\nu} W^{-\mu\nu}\right) H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$

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

E. Gross



It really looks like the SM Higgs!



For example:

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

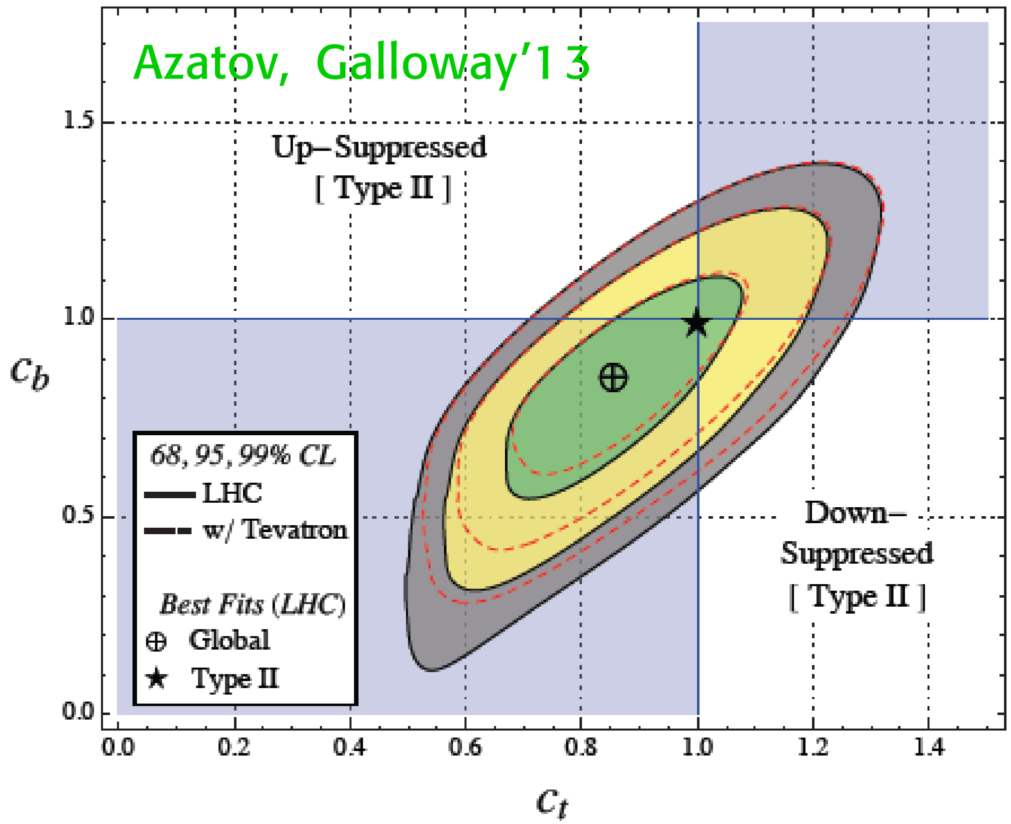
Tree level formulae
Radiative corrections
important

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

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

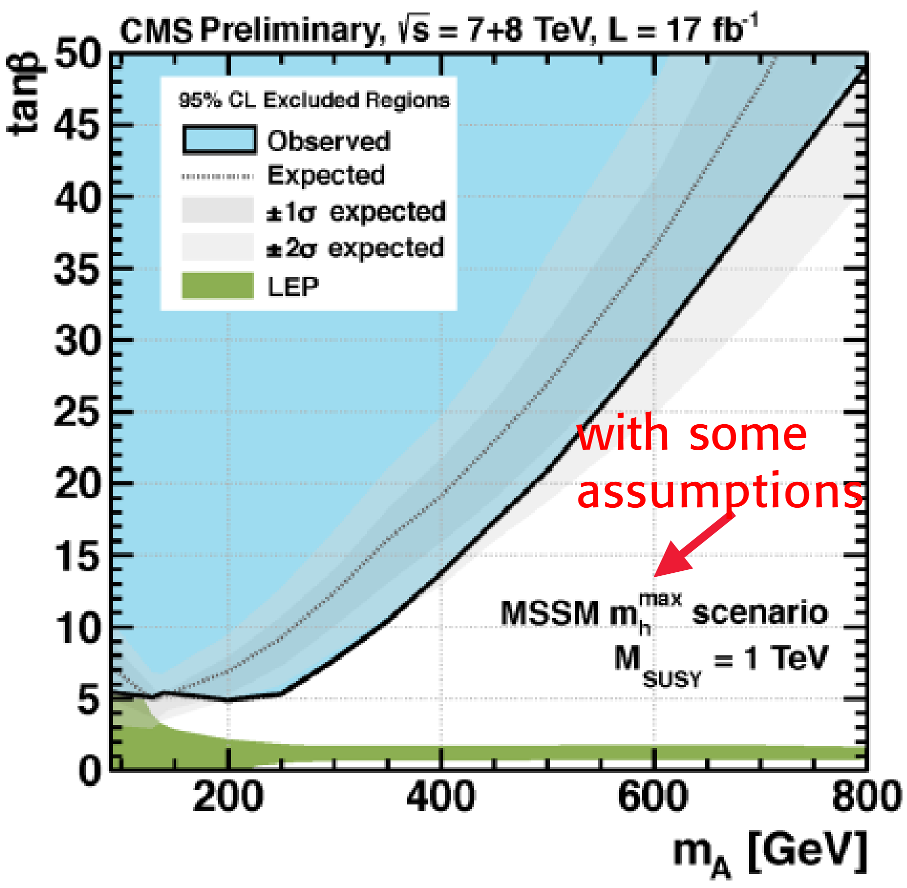
$$c_u = huu = \frac{\cos\alpha}{\sin\beta}$$

$$c_d = hdd = -\frac{\sin\alpha}{\cos\beta}$$



If $c_u > 1$ then $c_d < 1$
and viceversa

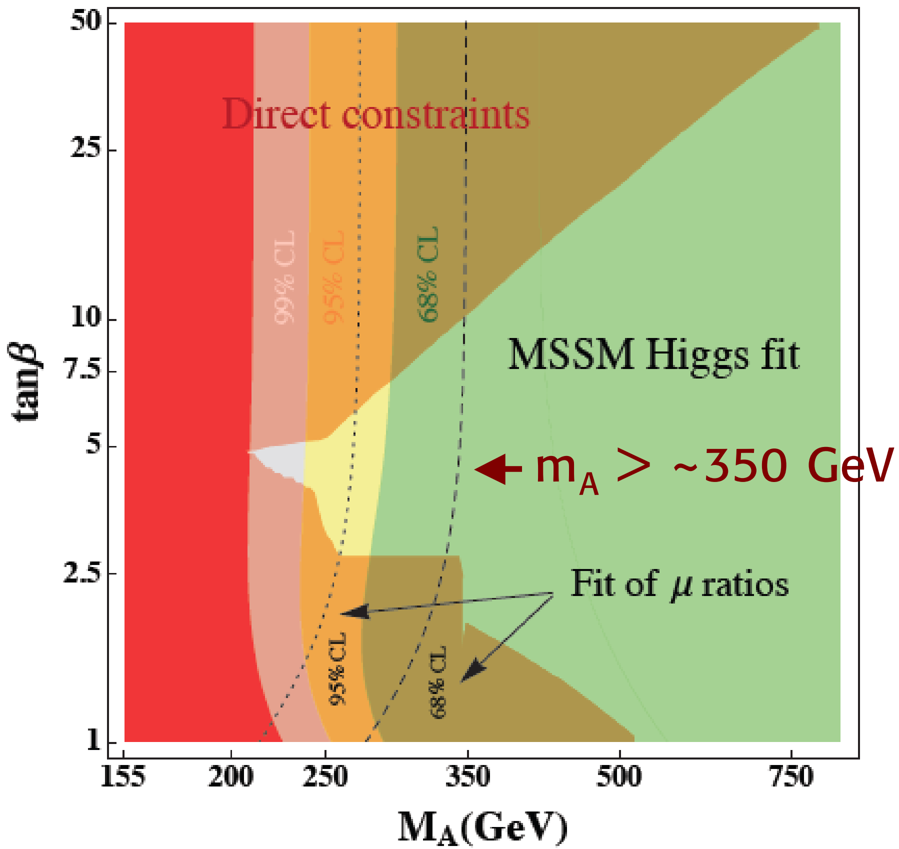
A very important open question:
Are there more Higgs particles?
Here we focus on MSSM



$\tau\tau$

Theorists analysis

Djouadi, Maiani et al '13

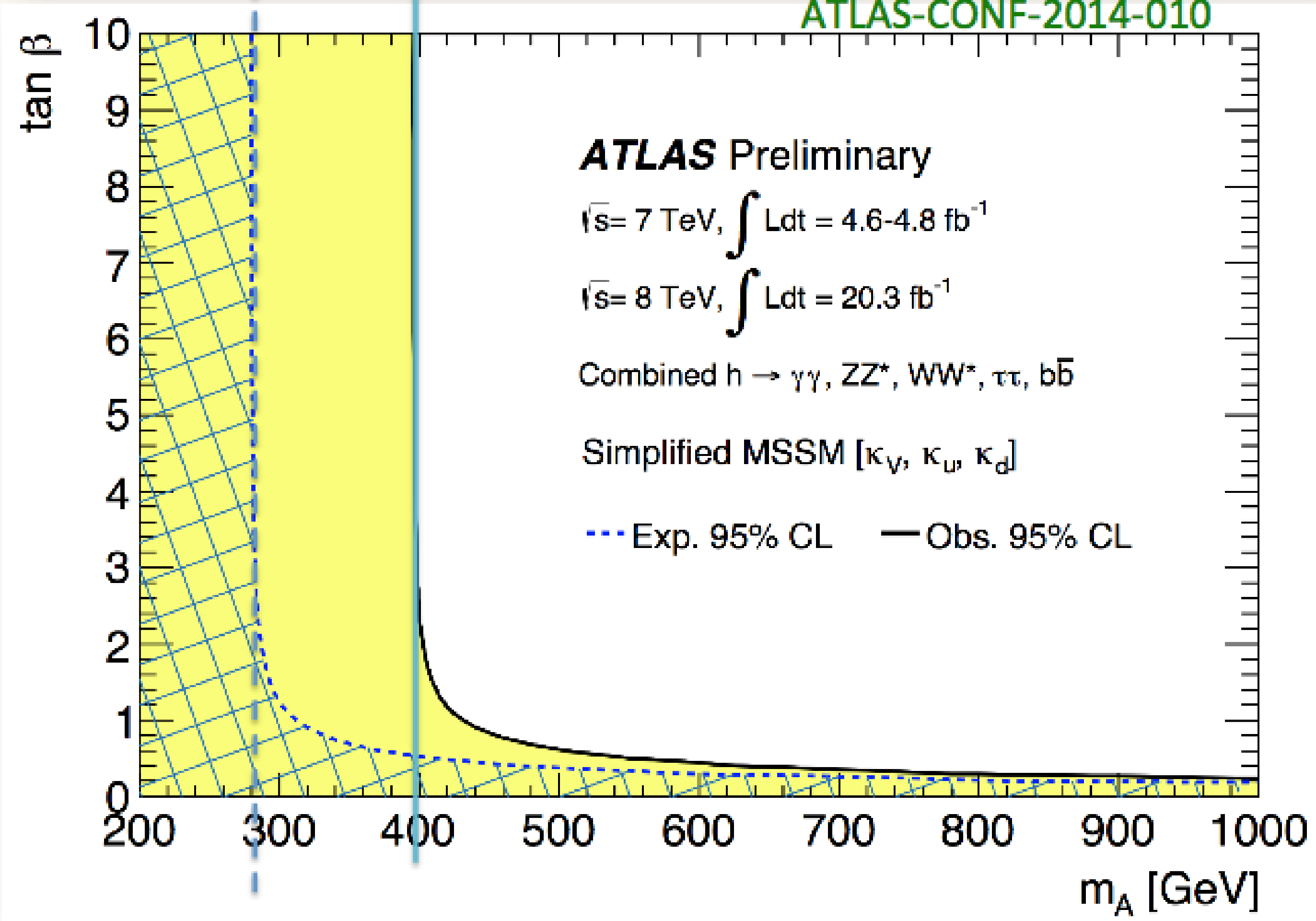


this limit has now been improved

Now a better limit is obtained

E. Gross, Moriond EW '14

$$m_A > 400\ GeV \text{ for } \mathrm{tg}\beta > 2$$



Bottom line:

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

Impact of the Higgs discovery

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:

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

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

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

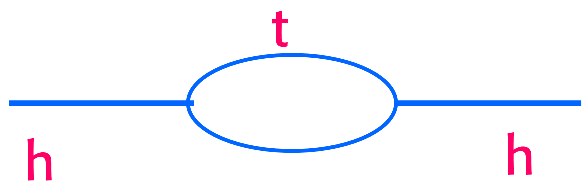
As a consequence:
We can no more be sure that within 3 or 10 or 100 TeV.....
the solution of the hierarchy problem must be found
--> implications for future Colliders

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

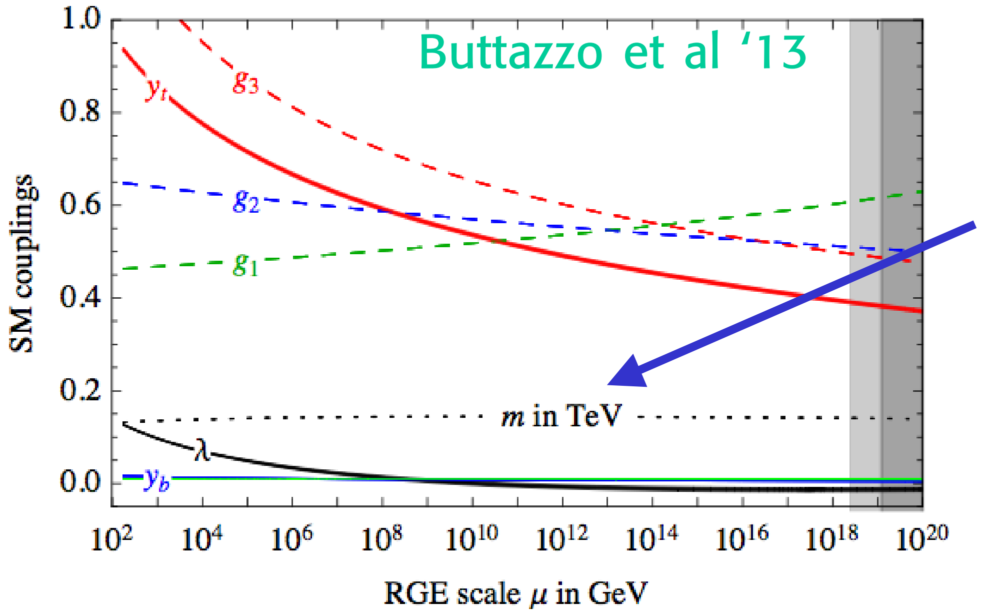
$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$



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

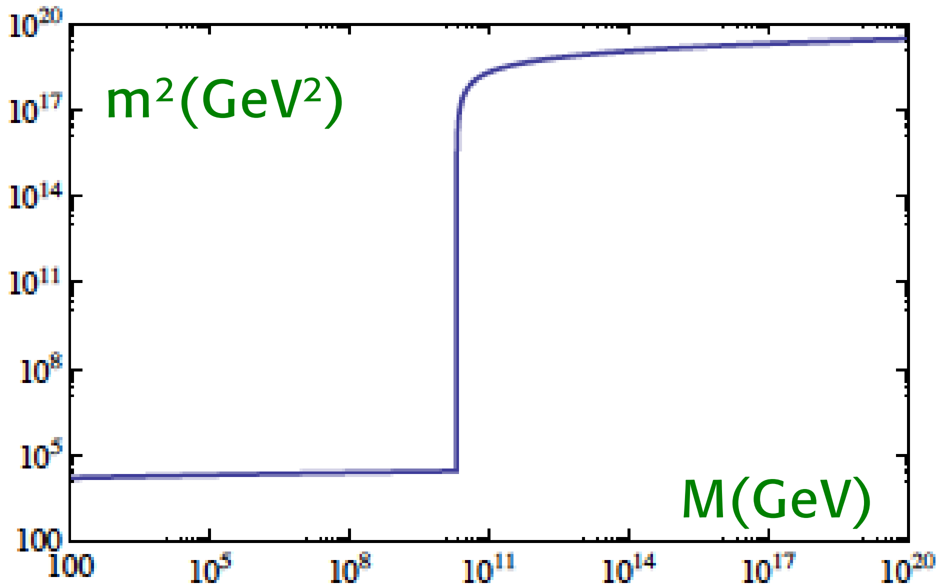
The argument can be formulated in terms of renormalized quantities with no reference to a cut-off ---> quadratic sensitivity to thresholds at high energy

Naturalness in a more physical language



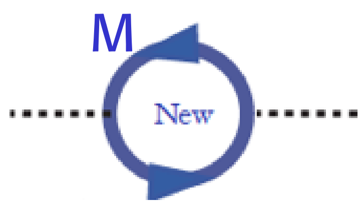
In the renormalized theory the running Higgs mass slowly evolves logaritmically

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

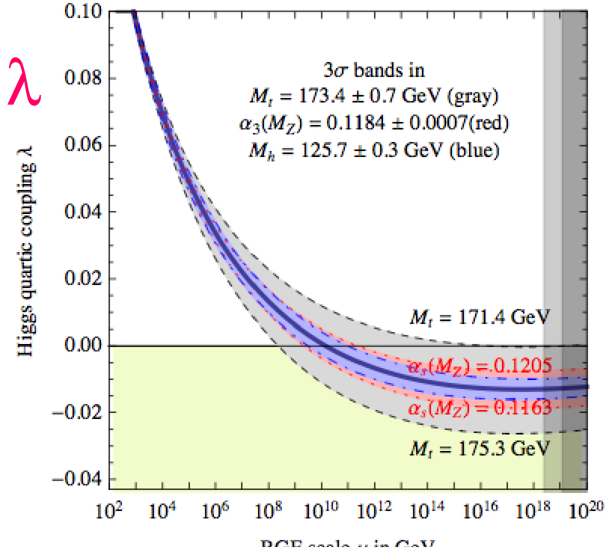
$M \sim 10^{10}$ GeV, $\lambda_H \sim 1$, jump: $m^2 \sim (\lambda_H M)^2/(16\pi^2)$



- 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

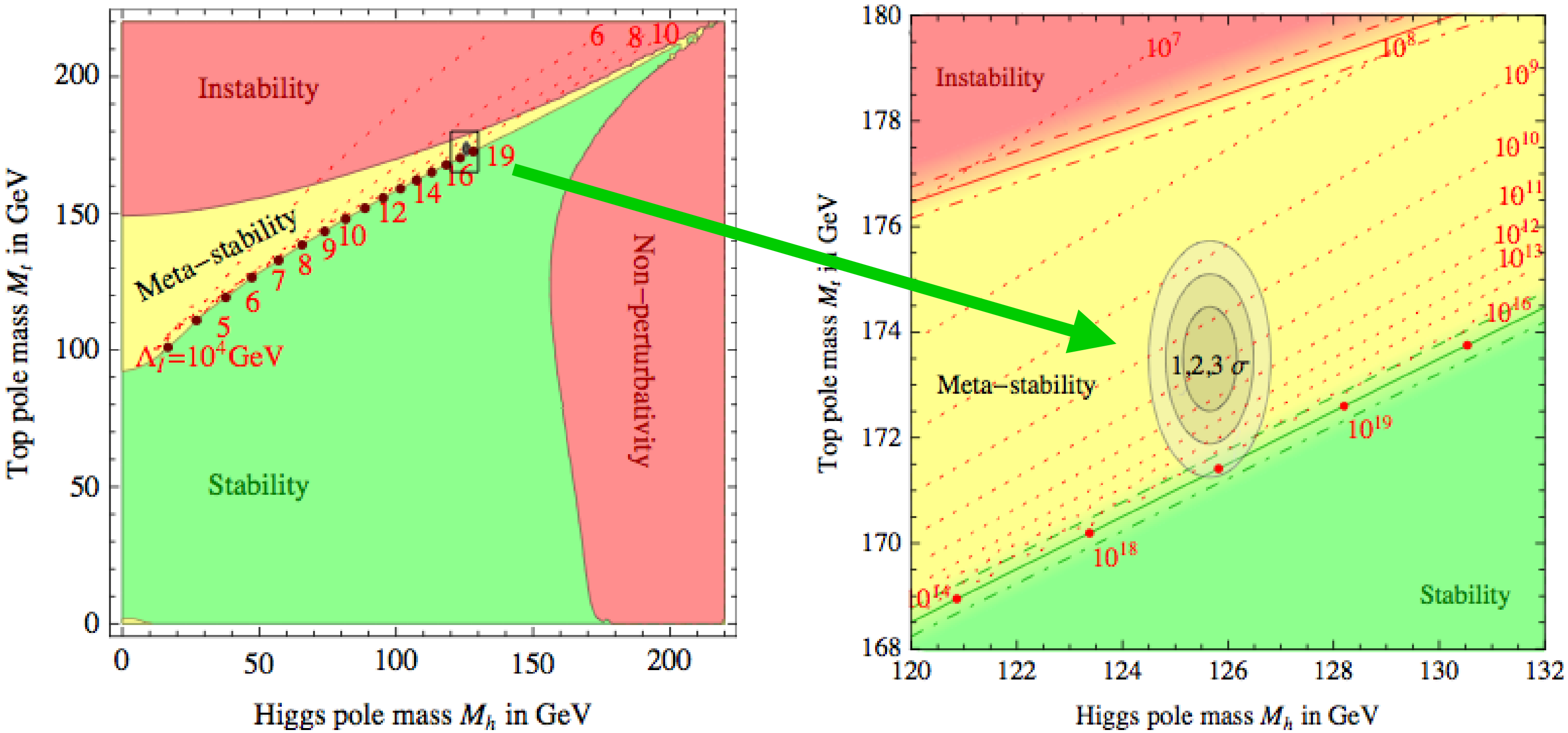
The pure SM evolution of couplings leads to a metastable Universe



$\lambda\phi^4$

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

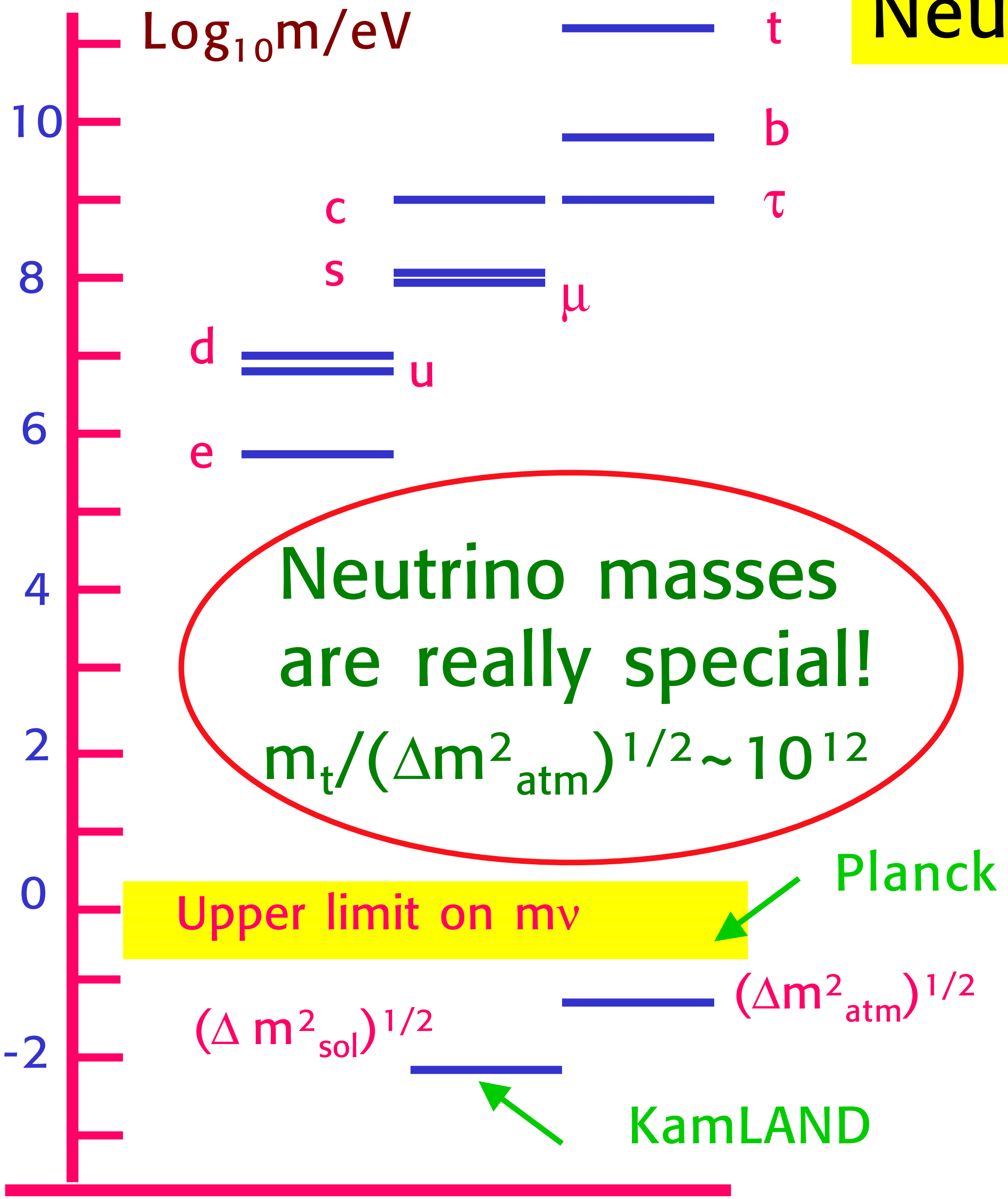
Thus, ignoring the FT, minimal modifications to the SM are being considered

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

Neutrinos



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)

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

$M >> m_D$

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

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 ($M \sim 10^{11-12}$ GeV) satisfy Sacharov conditions

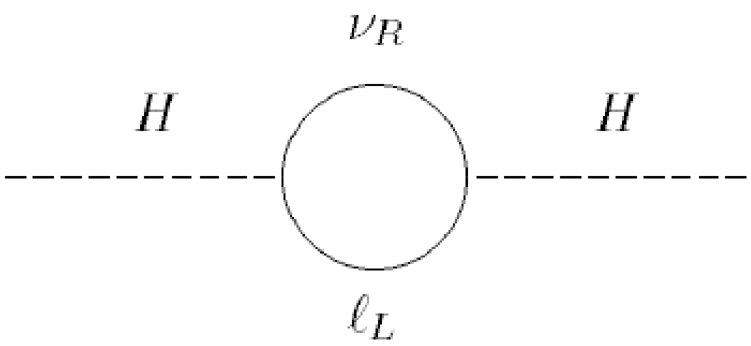
L non conserv. & CP violat.'n in ν_R out-of-equilibrium decay:
B-L excess survives at T_{ew} and gives the obs. B asymmetry.

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

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

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

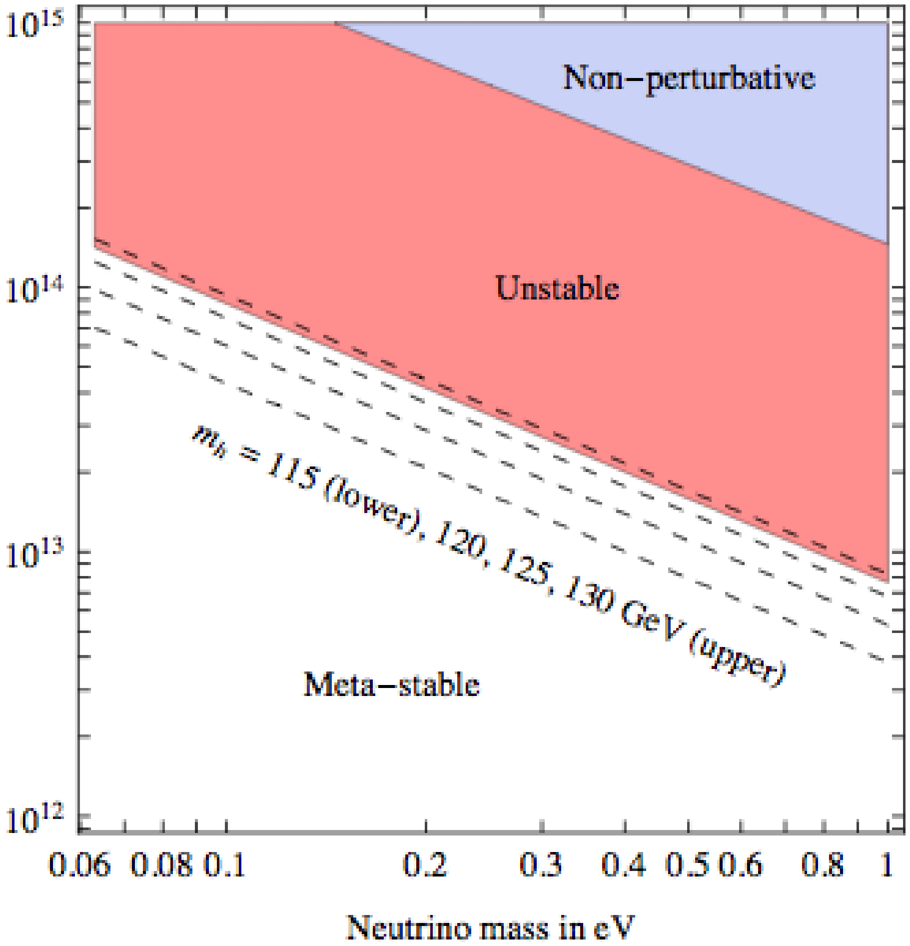
$\mu < 1$ TeV ⟶ $M_R < 10^7$-10^8 GeV

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

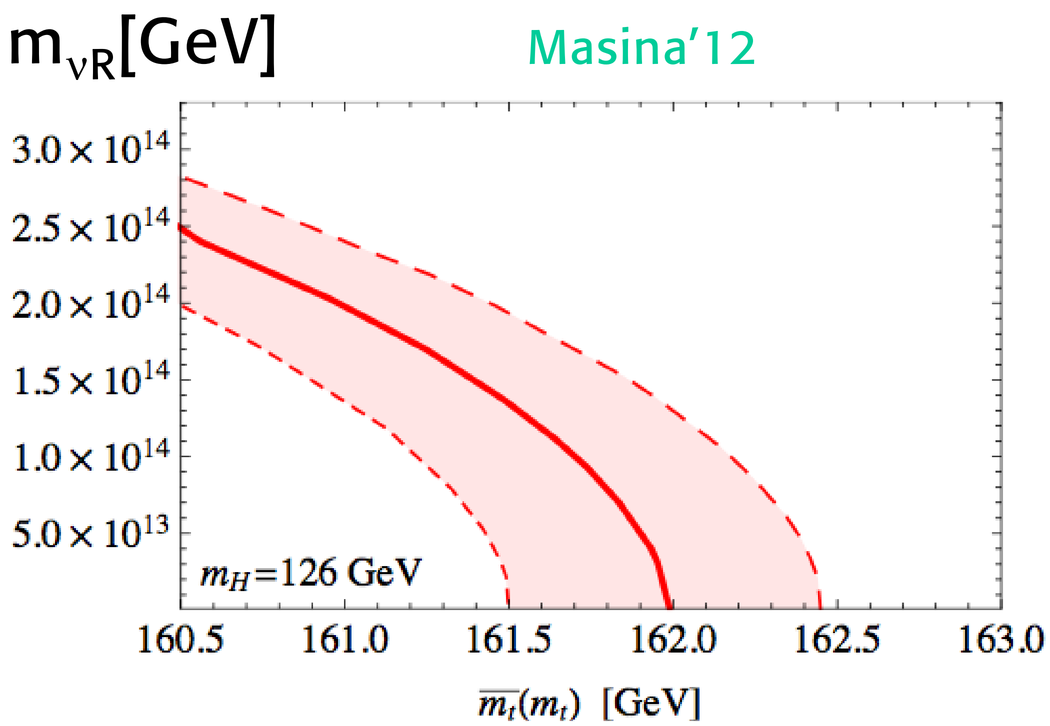
Heavy ν_R's further de-stabilize the vacuum

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

J. Elias-Miro' et al '11



Masina'12



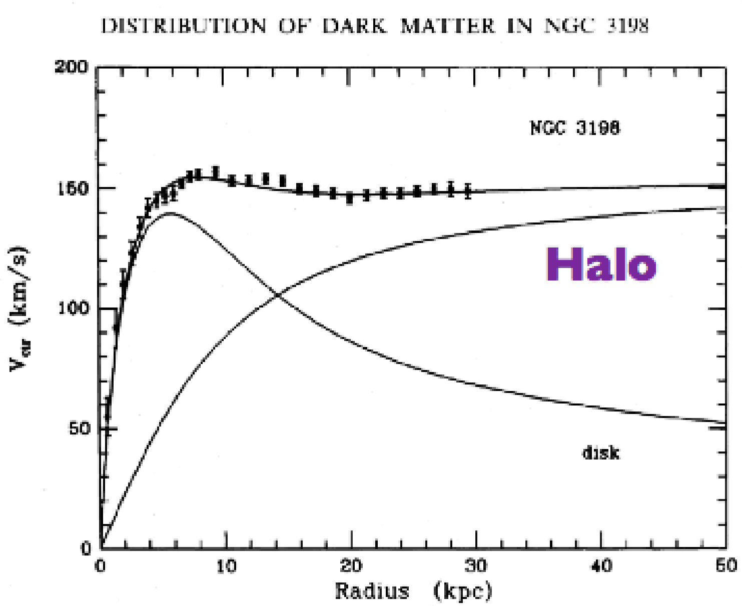
At present Dark Matter is THE crucial problem in particle physics

A by now robust evidence for Dark Matter in the Universe

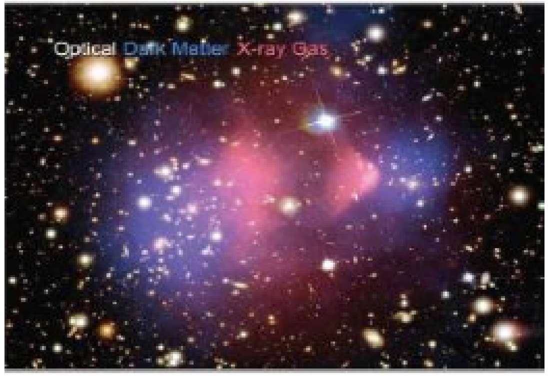
Rotation of galaxies

Lensing

Merging clusters of galaxies



MACS, HST



M. Markevitch et al 2003

Cosmological evidence

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

e.g. Planck

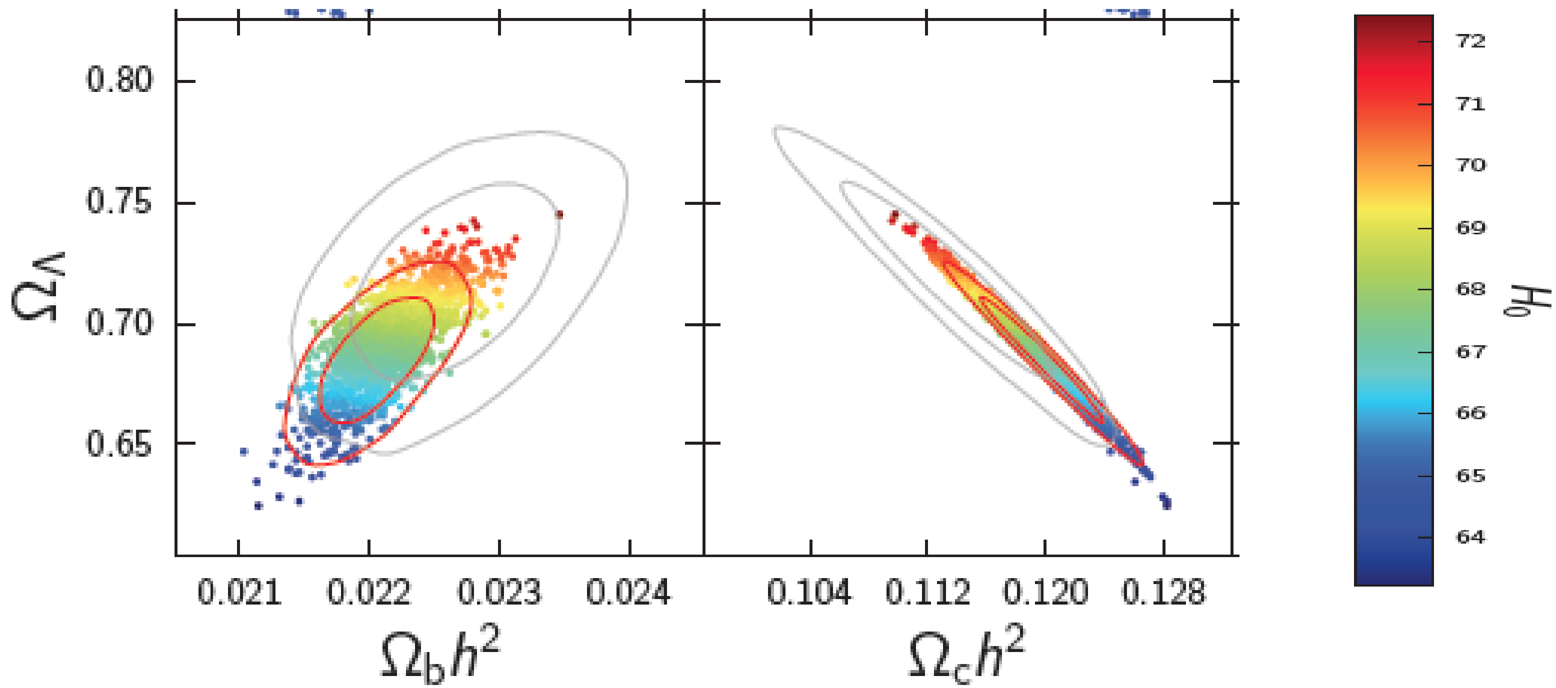
Planck fits of DM ArXiv:1303.5076

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

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 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

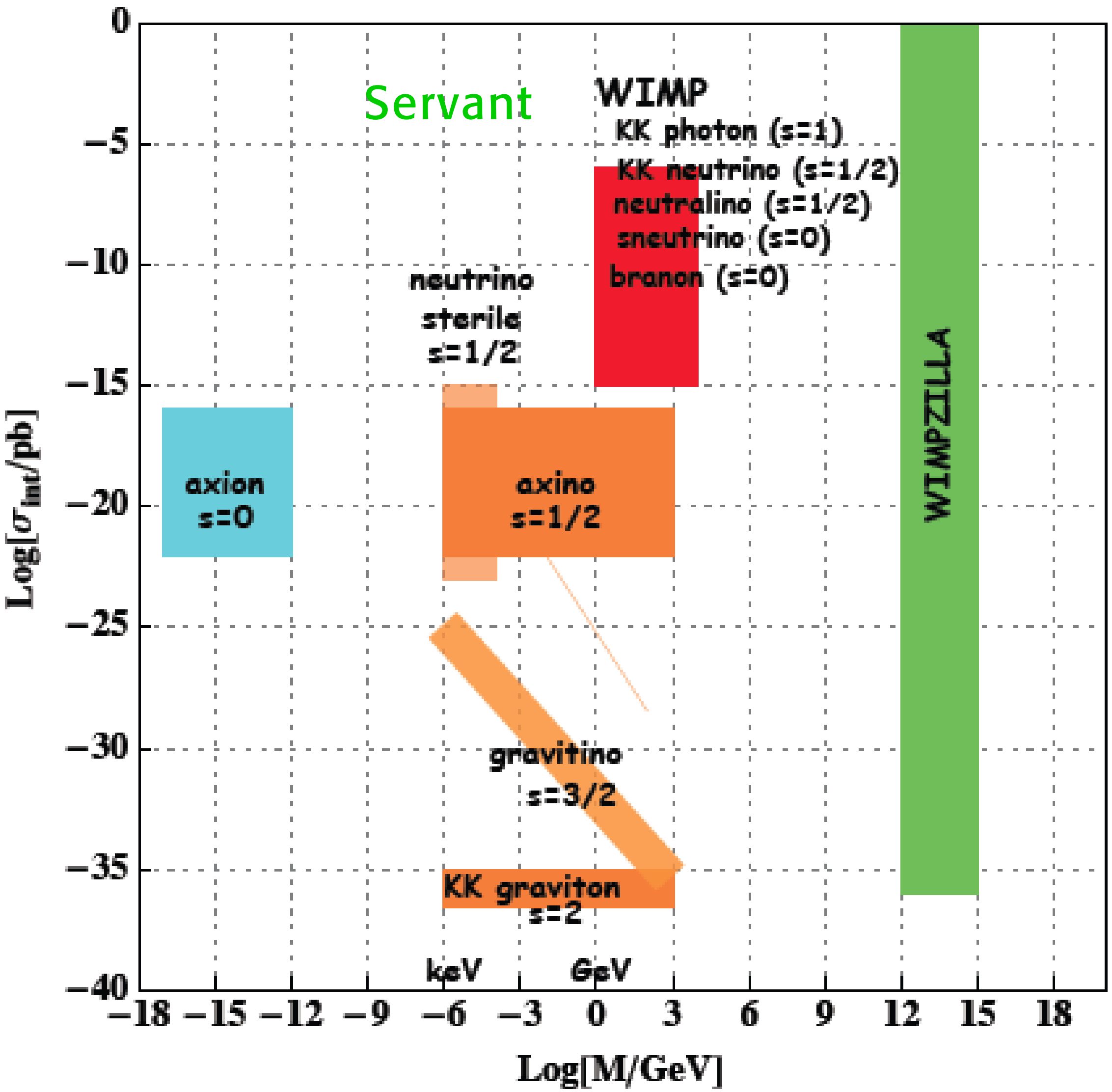
A partial list of main candidates:

- 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

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

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:

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

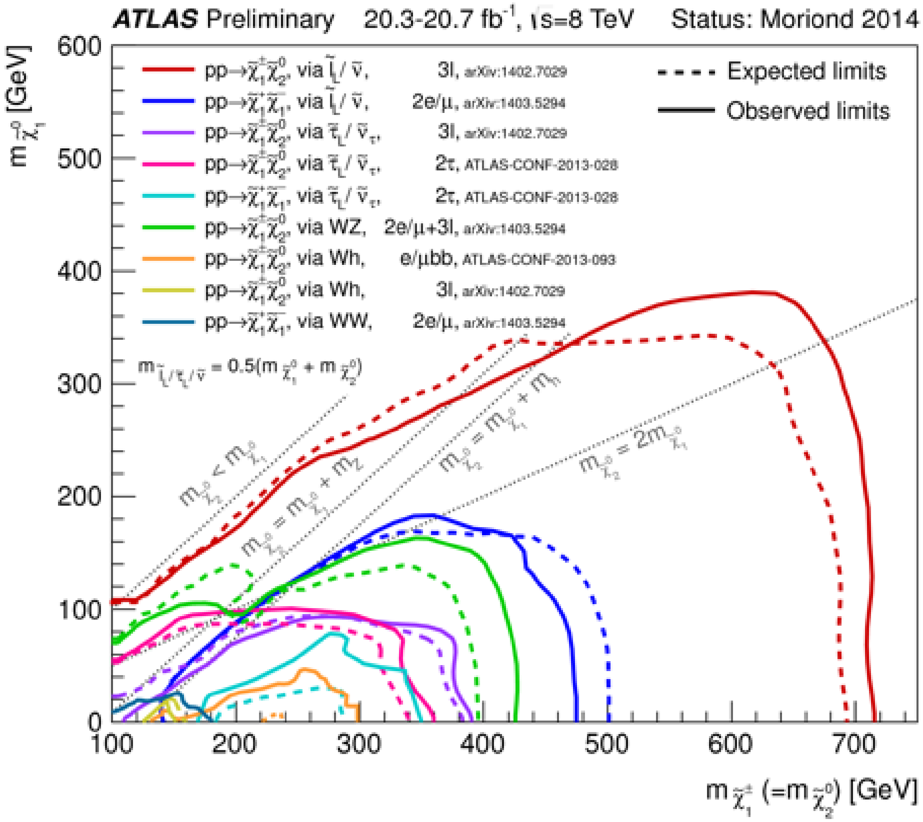
can work for typical weak cross-sections!!!

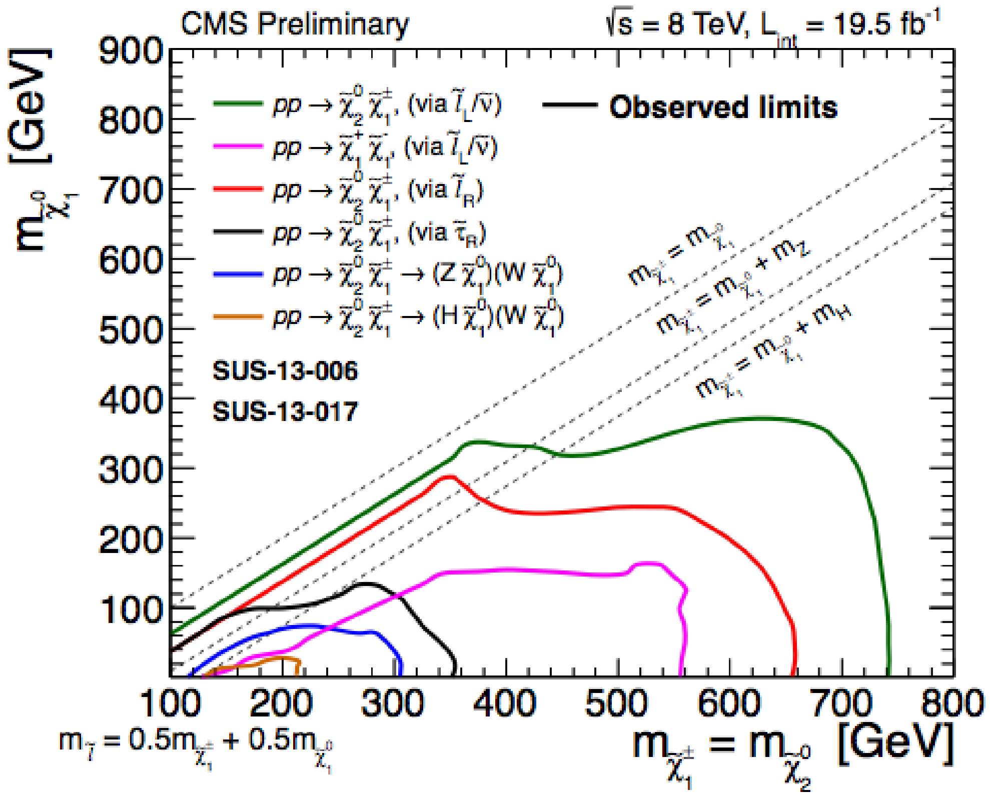
This "coincidence" is taken as a good indication in favour
of a WIMP explanation of Dark Matter

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





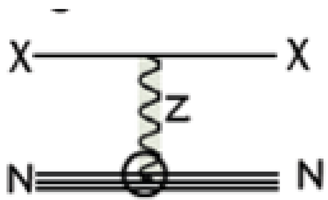
A strict bound is very low: $m_{\chi 0} > 25$ GeV (light s-taus and higgsinos)

Calibbi et al'13

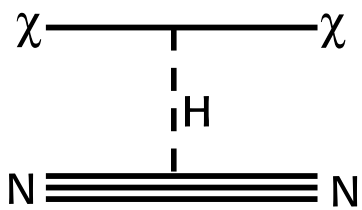
Non accelerator searches

$\chi N \to \chi N$

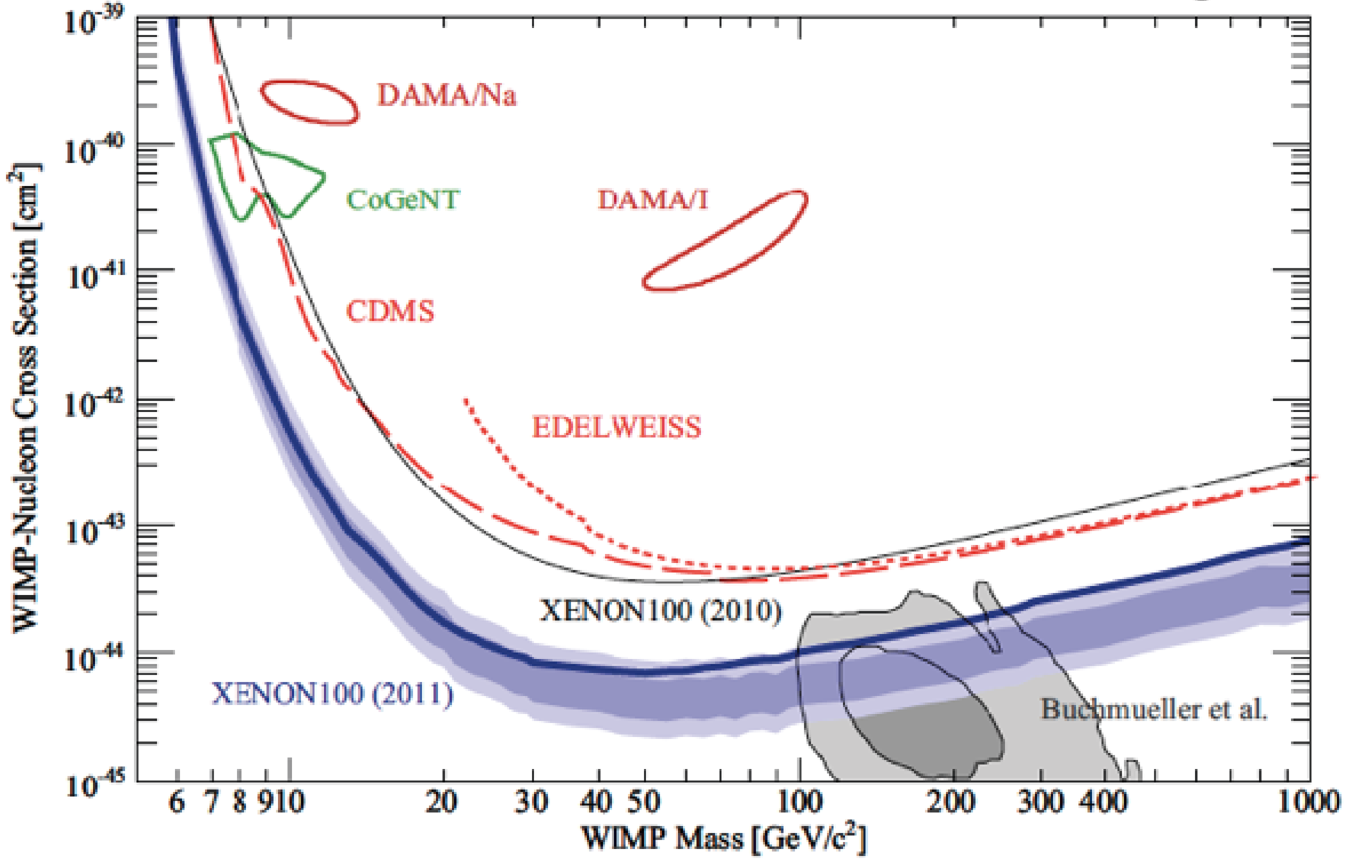
Z echange potentially large



125 GeV Higgs boson exchange being also probed now



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

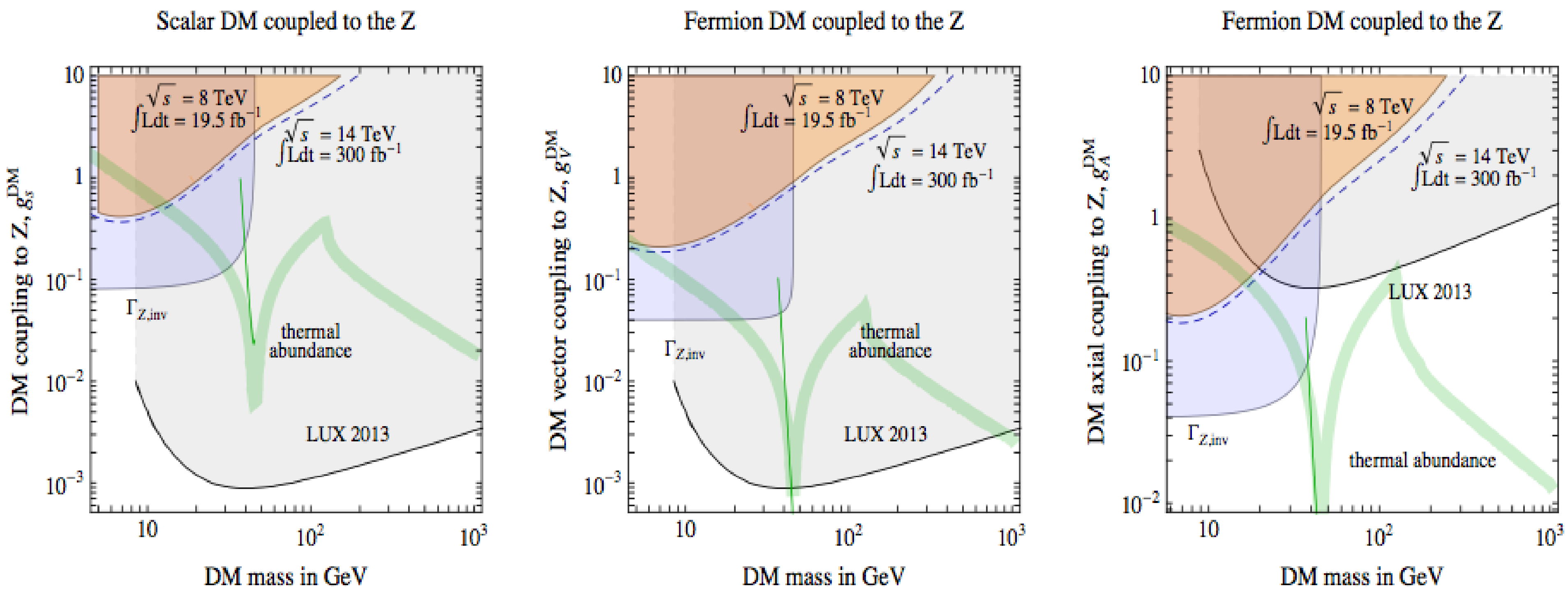
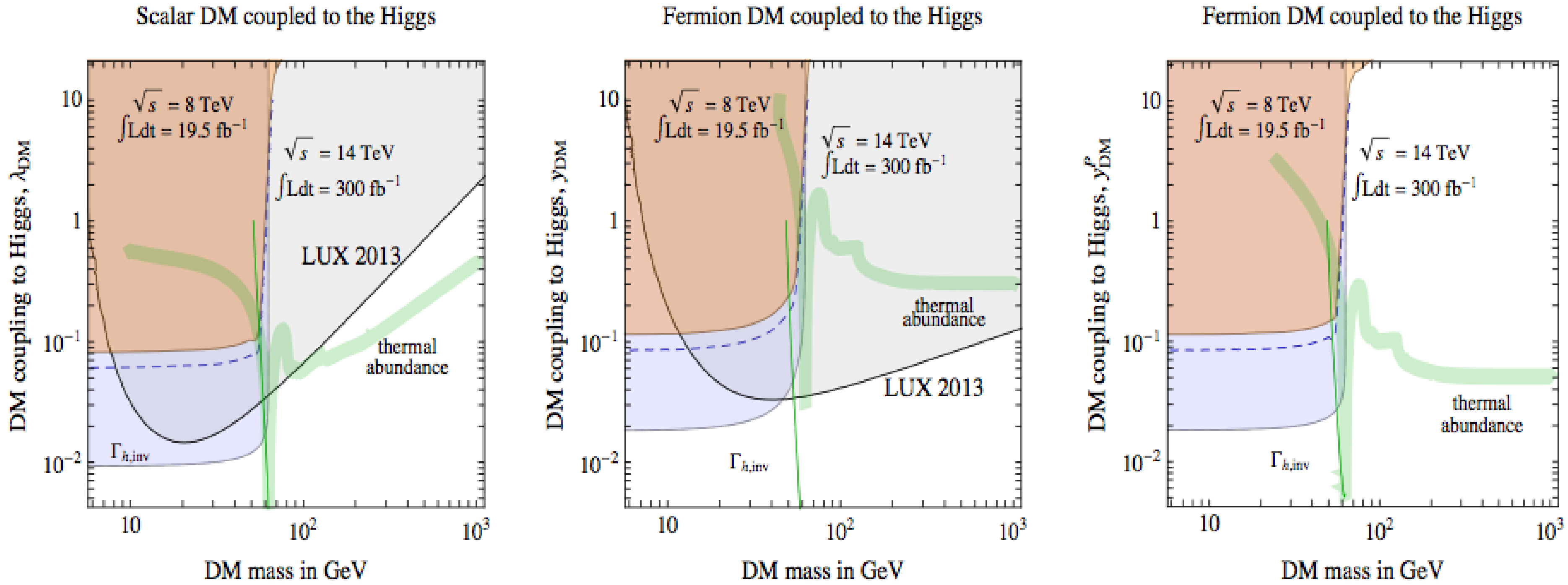


Figure 3: ***DM coupled to the Z.*** *Regions of DM mass* $M_{\rm DM}$ *and Z couplings* ($g_s^{\rm DM}$, $g_V^{\rm DM}$, $g_A^{\rm DM}$)*: the orange region is excluded at 90% CL by ATLAS mono-jet searches at LHC8, with forecast for LHC14 (dashed blue line); the grey region is excluded at 90% CL by LUX 2013 direct searches; the blue region is excluded by the 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 coupling

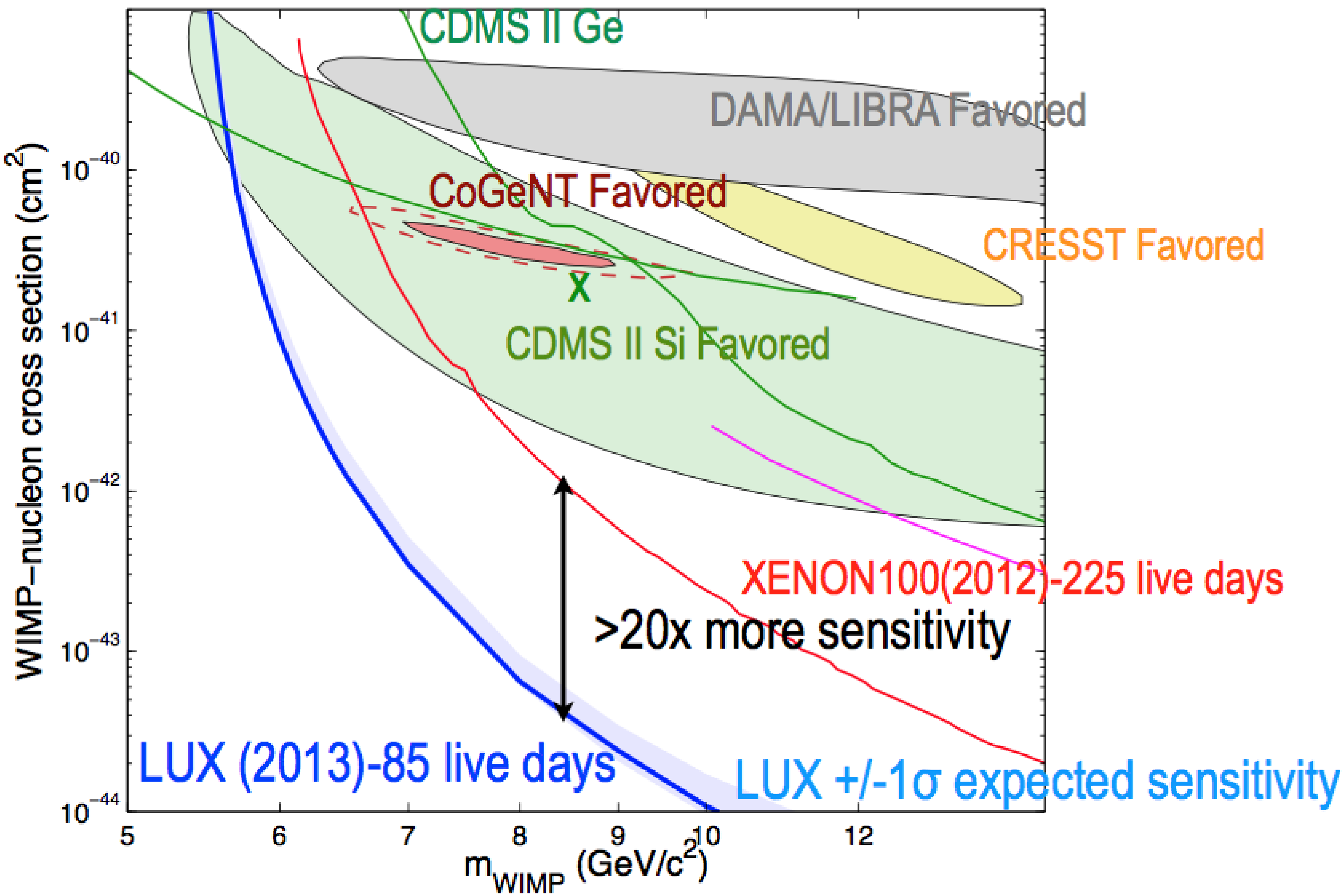
pseudoscalar coupling

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?

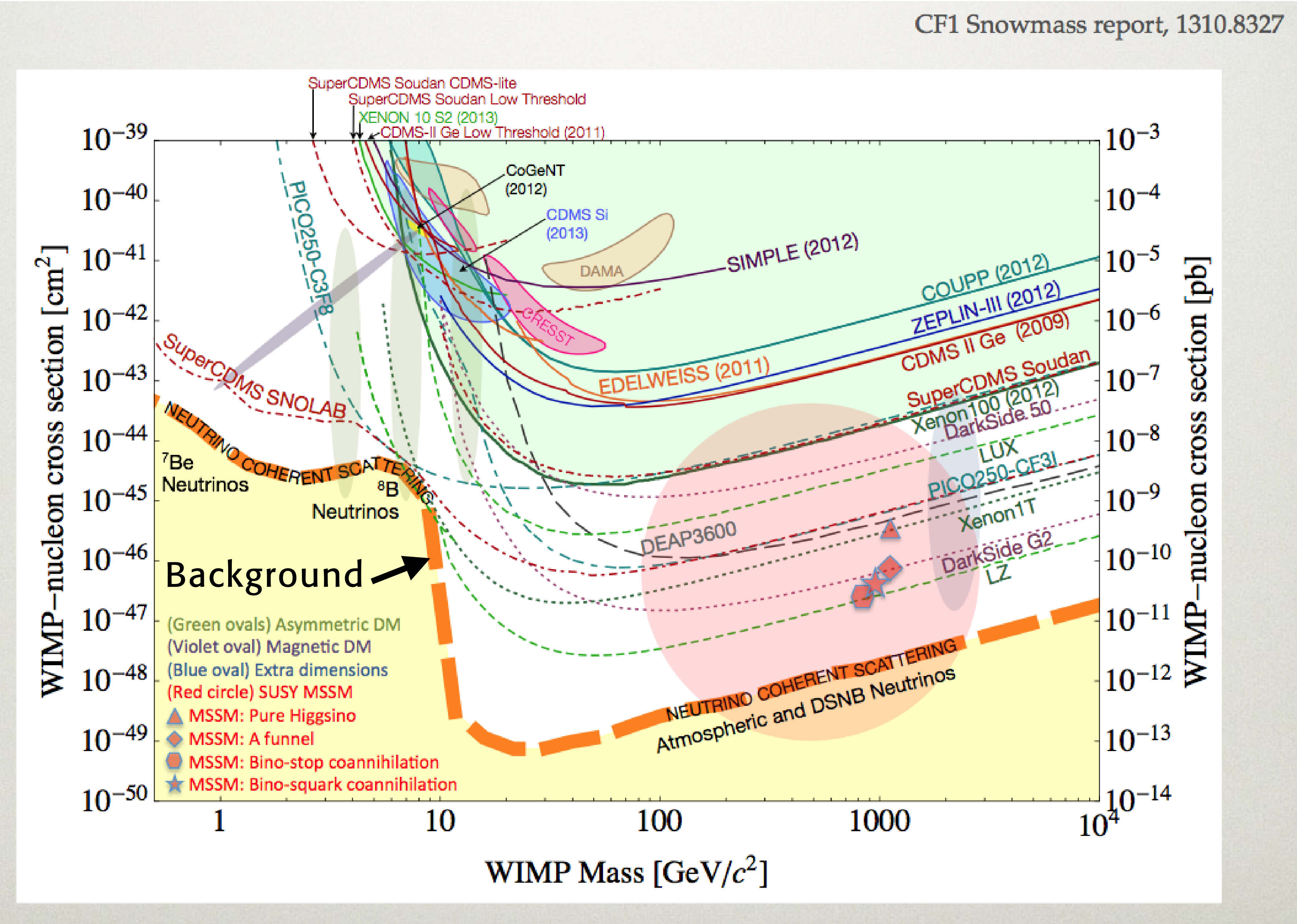
CDMS-Si ArXiv :1304.4279 3 events in the signal region

Now excluded by LUX ArXiv:1310.8214



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

The WIMP non-accelerator search continues



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 $\langle A\rangle \sim f$ spont. breaks $U(1)_{PQ}$

The ψ mass is $m \sim \lambda\langle A\rangle \sim \lambda f$ → new particles at scale 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

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

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 $\frac{\partial V}{\partial a} = 0 \Rightarrow \frac{\alpha_s}{4\pi f}\langle Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})\rangle = 0$

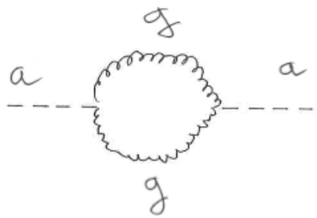
It is (not too) easy to prove that $\langle Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})\rangle \propto \sin\theta_{eff} \equiv \sin(\theta + \frac{\langle a\rangle}{f})$
so that the coefficient of the
CP violating term is put to zero!

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

After the shift a --> 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 $U(1)_{PQ}$)



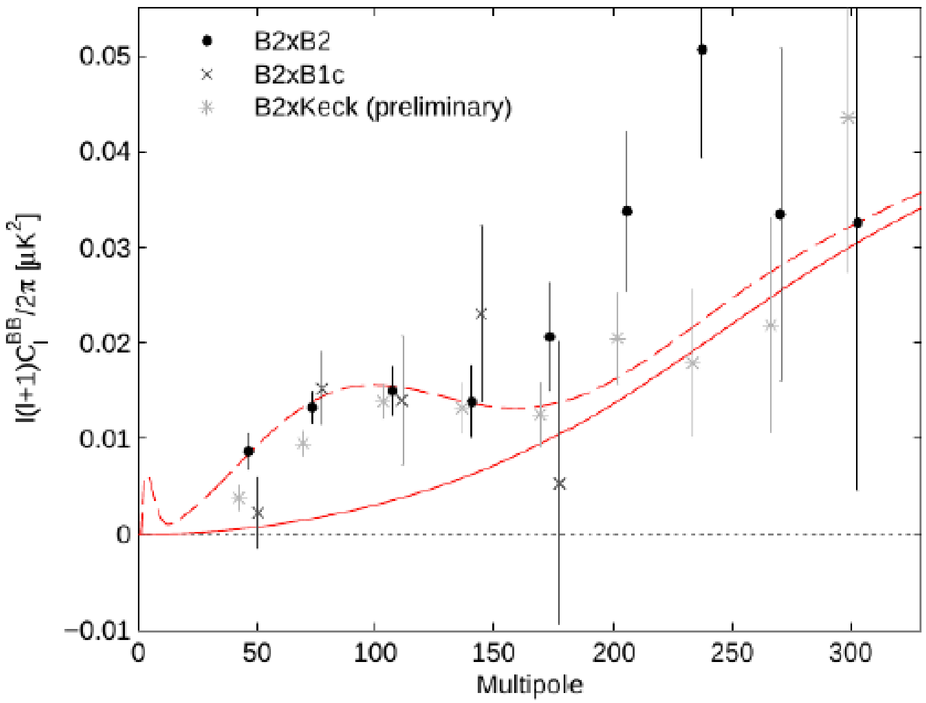
$$m_a^2 \propto \frac{\Lambda_{QCD}^4}{f^2}$$

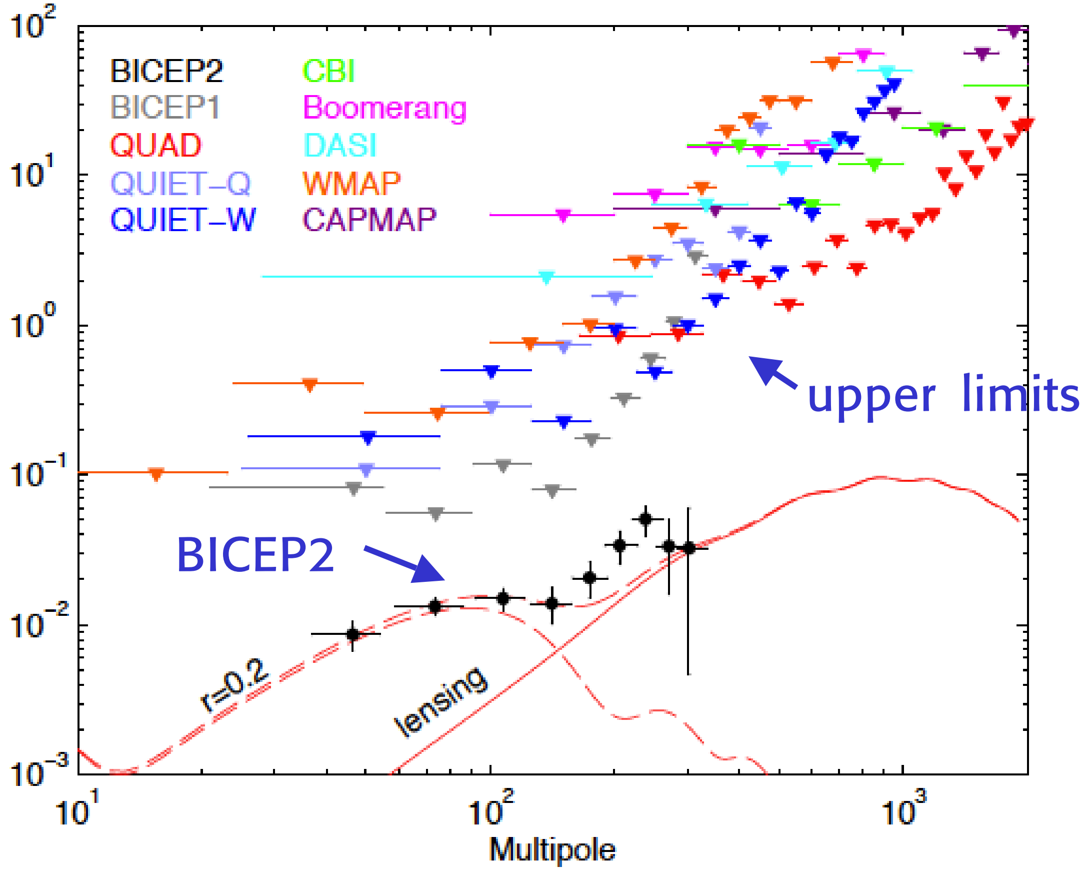
with f large, m_a is small,
the axion coupling is small,
and the ψ mass is large

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

Sensational news from cosmology

The BICEP2 Data





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

Great impact on Inflation

$r = 0.20\ ^{+0.7}_{-0.5}$

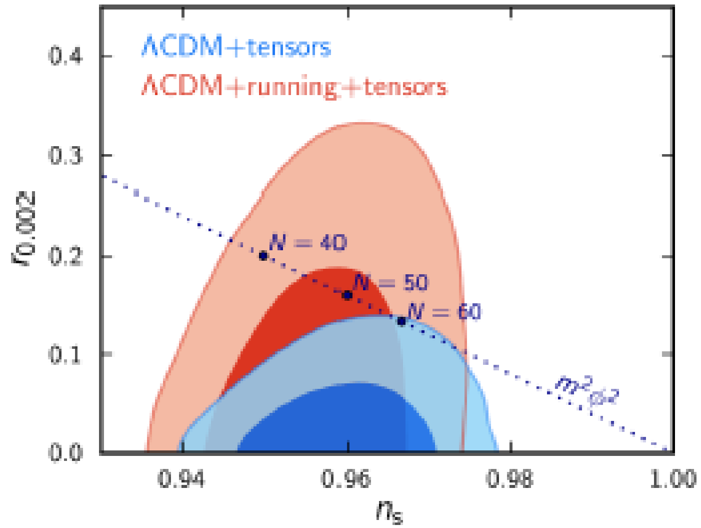
Energy scale of inflation:

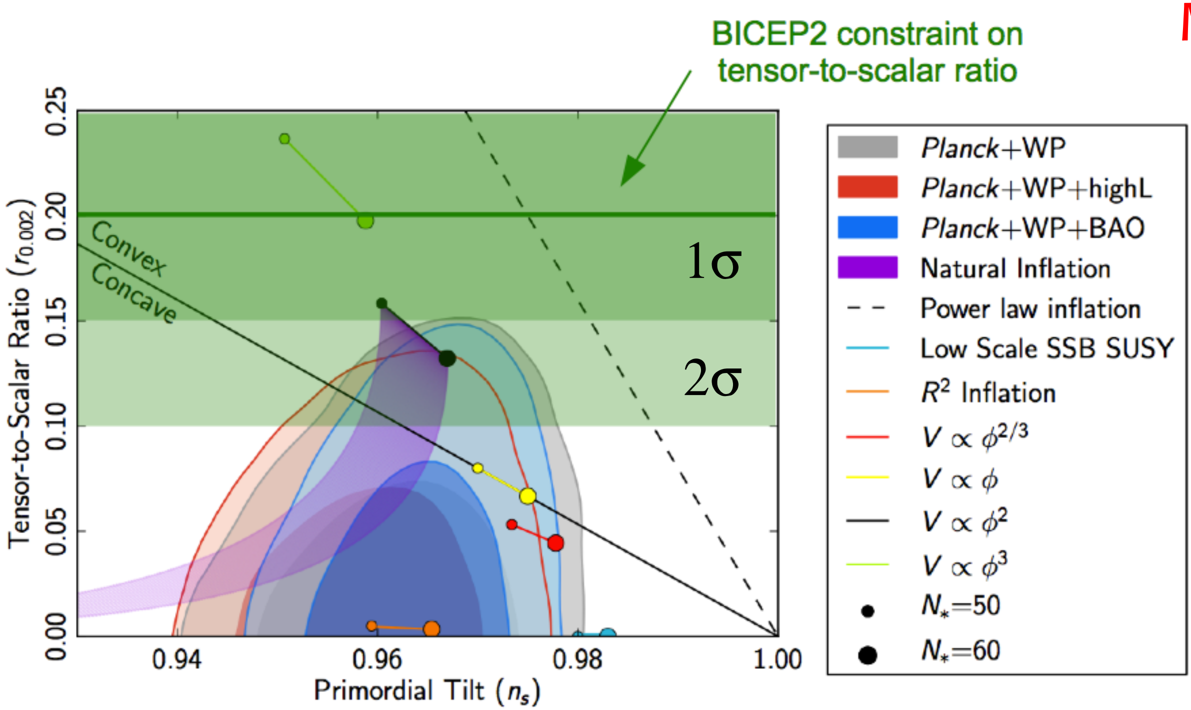
$$V_{\rm inf}^{1/4} \approx 2.2 \cdot 10^{16} \left(\frac{r}{0.2}\right)^{1/4} \ {\rm GeV}$$

Tantalizing close to M_{GUT}!

Evidence of a scale below M_{Pl}?

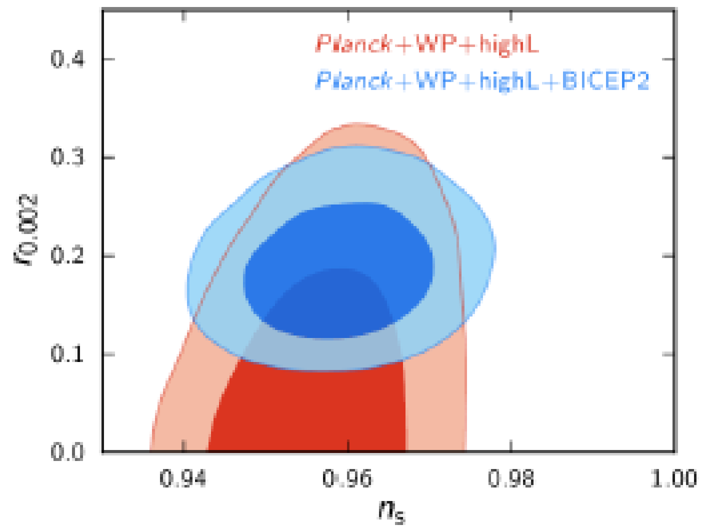
Planck 2013





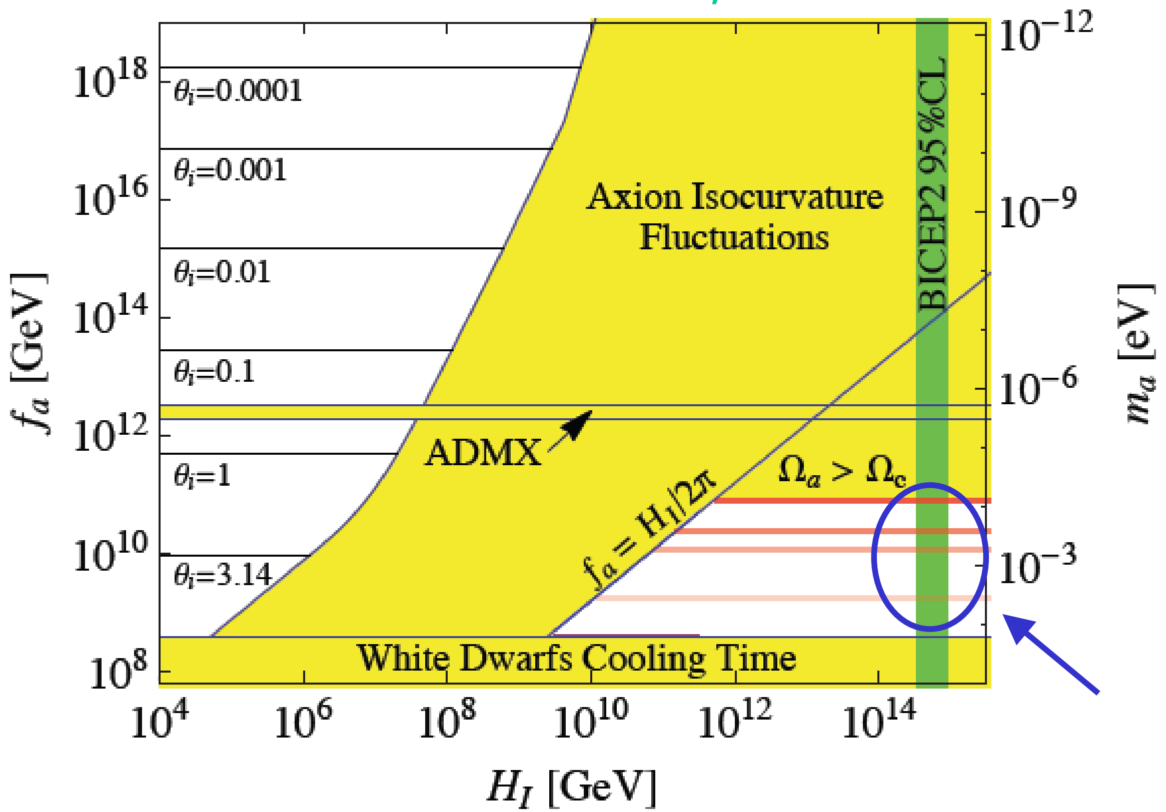
Moderate tension with Planck

Bicep2 2014



Implications of BICEP2 on axions

Visinelli, Gondolo '14

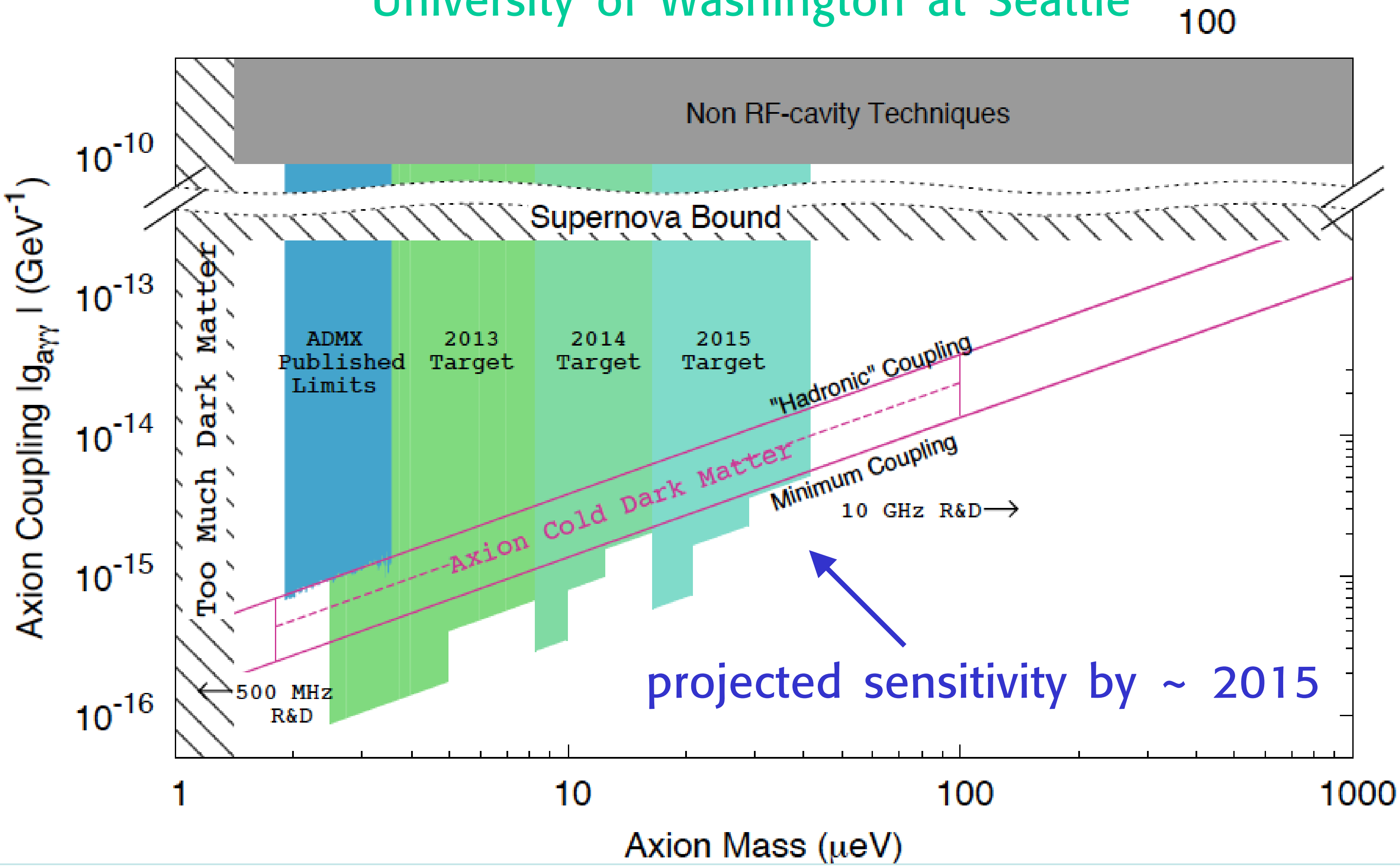


window of opportunity after inflation $f_a \sim 10^{10}$ - 10^{11} GeV

Axion searches are very important

ADMX: the Axion Dark Matter Experiment

University of Washington at Seattle



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

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

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)

$\lambda \, SH_uH_d$

additional term

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

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: **Minimum for MSSM to be natural**

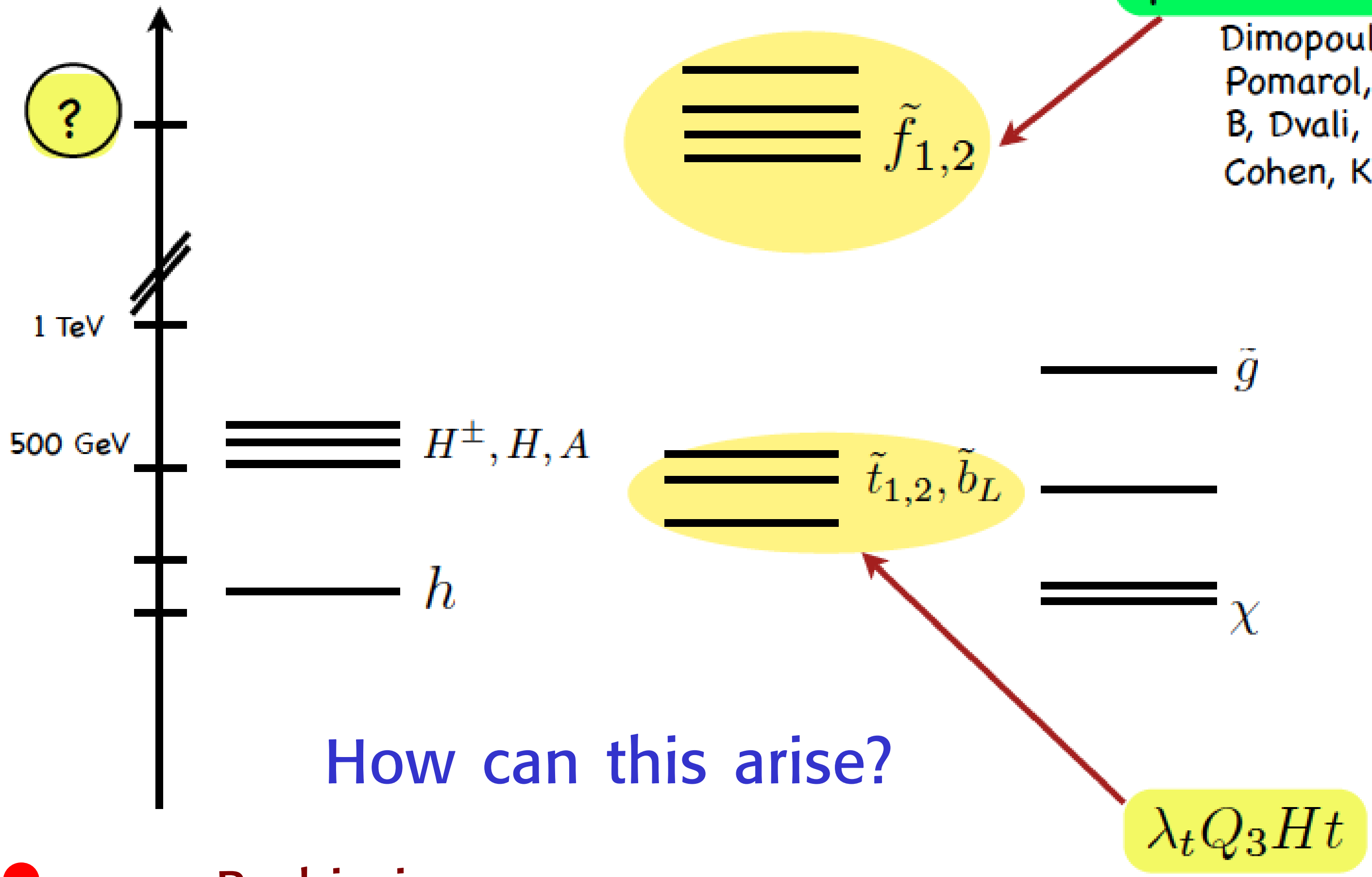
Natural SUSY → $m_{\tilde{g}}, m_{\tilde{t}}, m_{\tilde{b}}, m_{\tilde{h}}$ < ~1 TeV

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



How can this arise?

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
.....

For g-2 light sleptons welcome

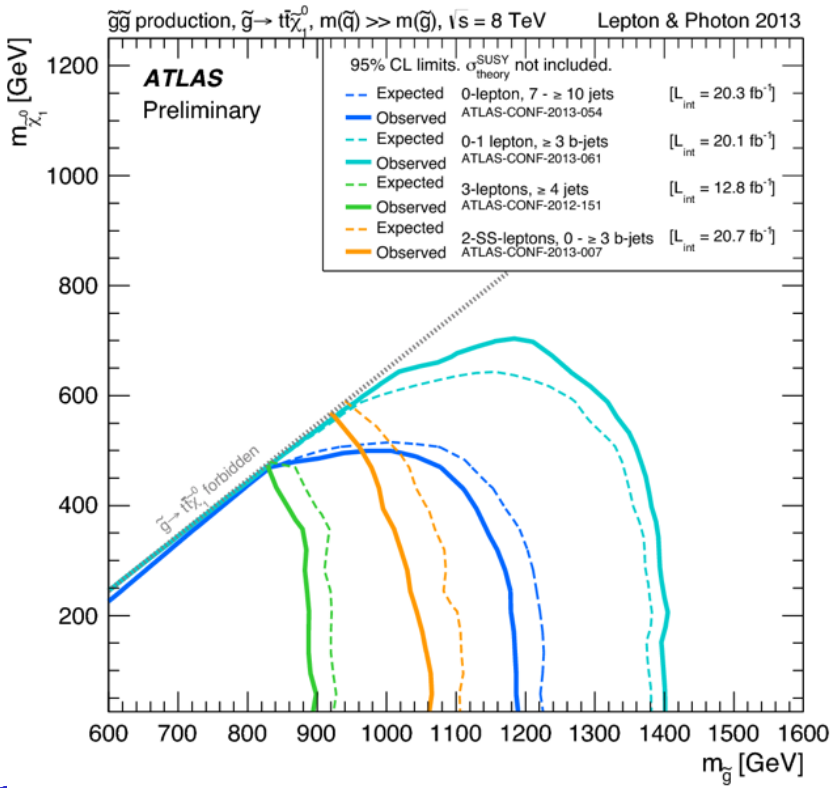
• Barbieri

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

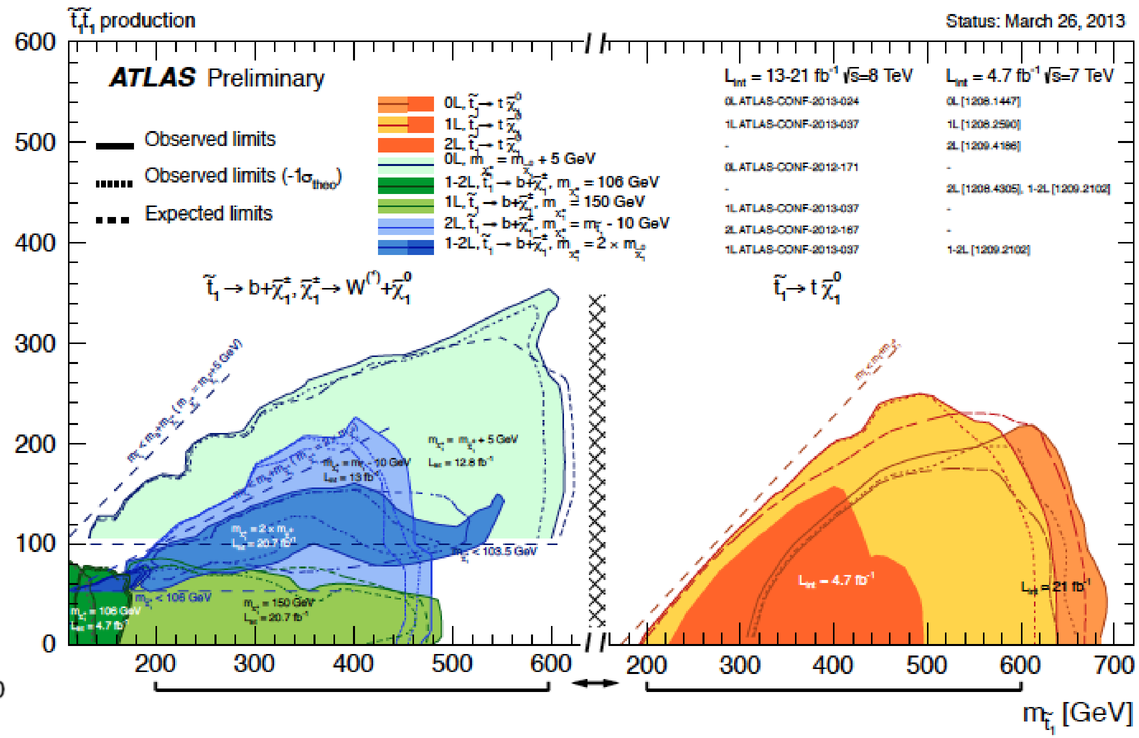
Gluino mediated s-top production: $m_{\tilde{g}} < 1.4$ TeV excluded with some assumptions on BRs.

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



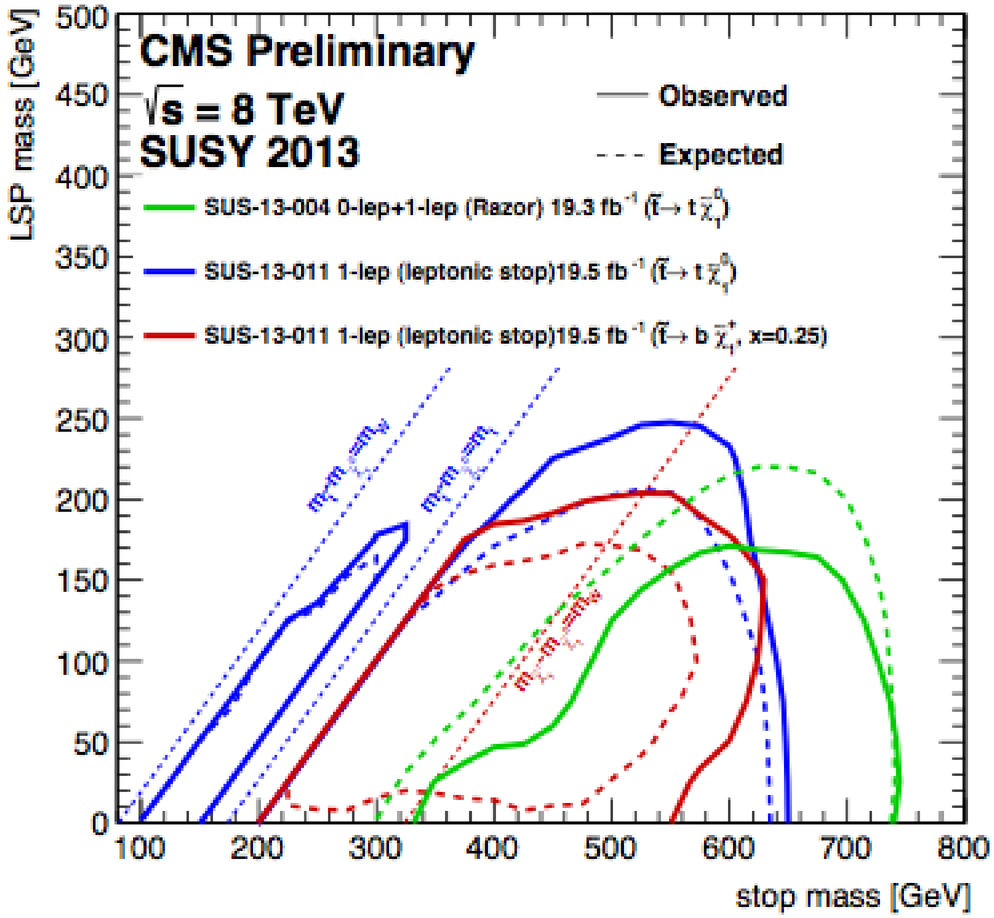
s-top

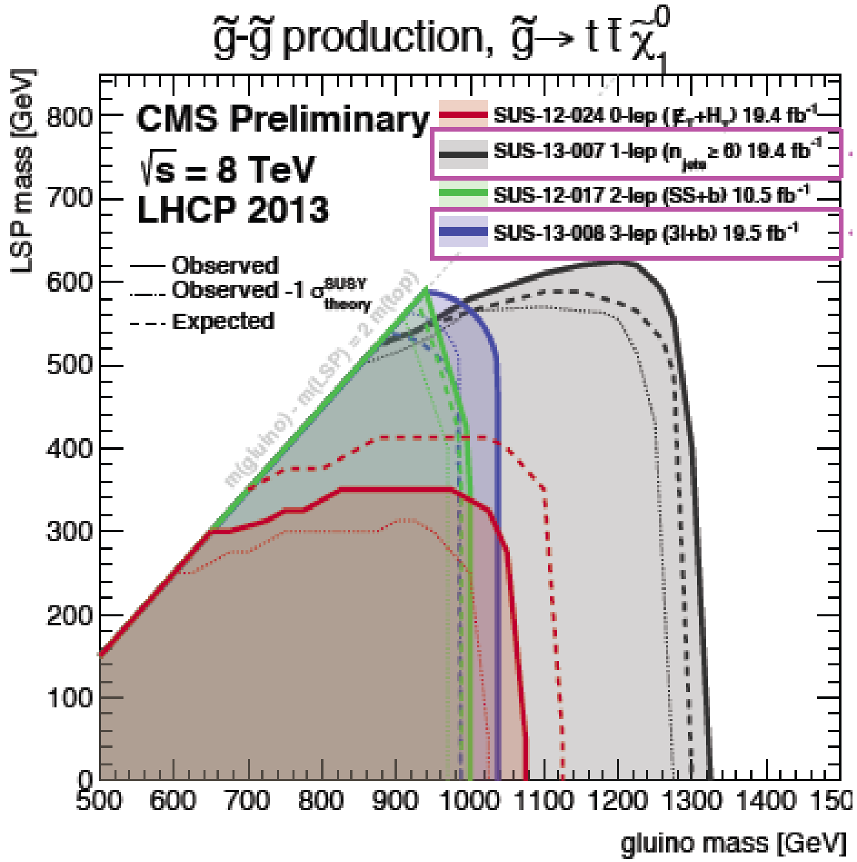
Searches for stops, gluinos, sbottoms target natural SUSY

- 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 ~ EW scale f ~ SI scale

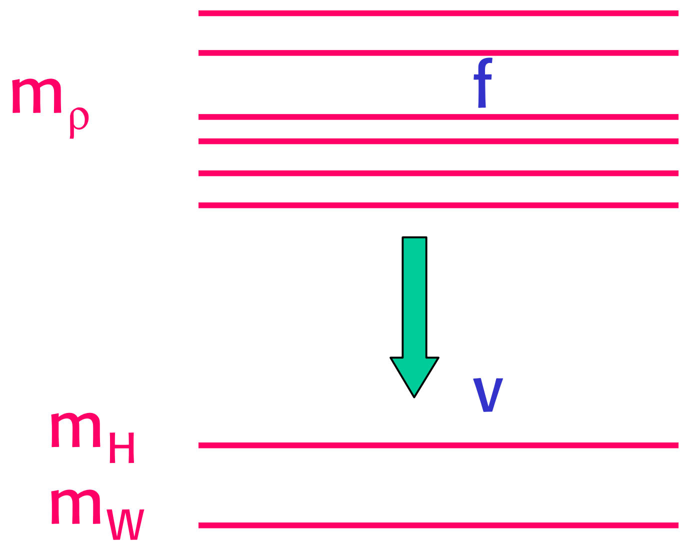
$\sim f < m_\rho <\sim 4\pi f$

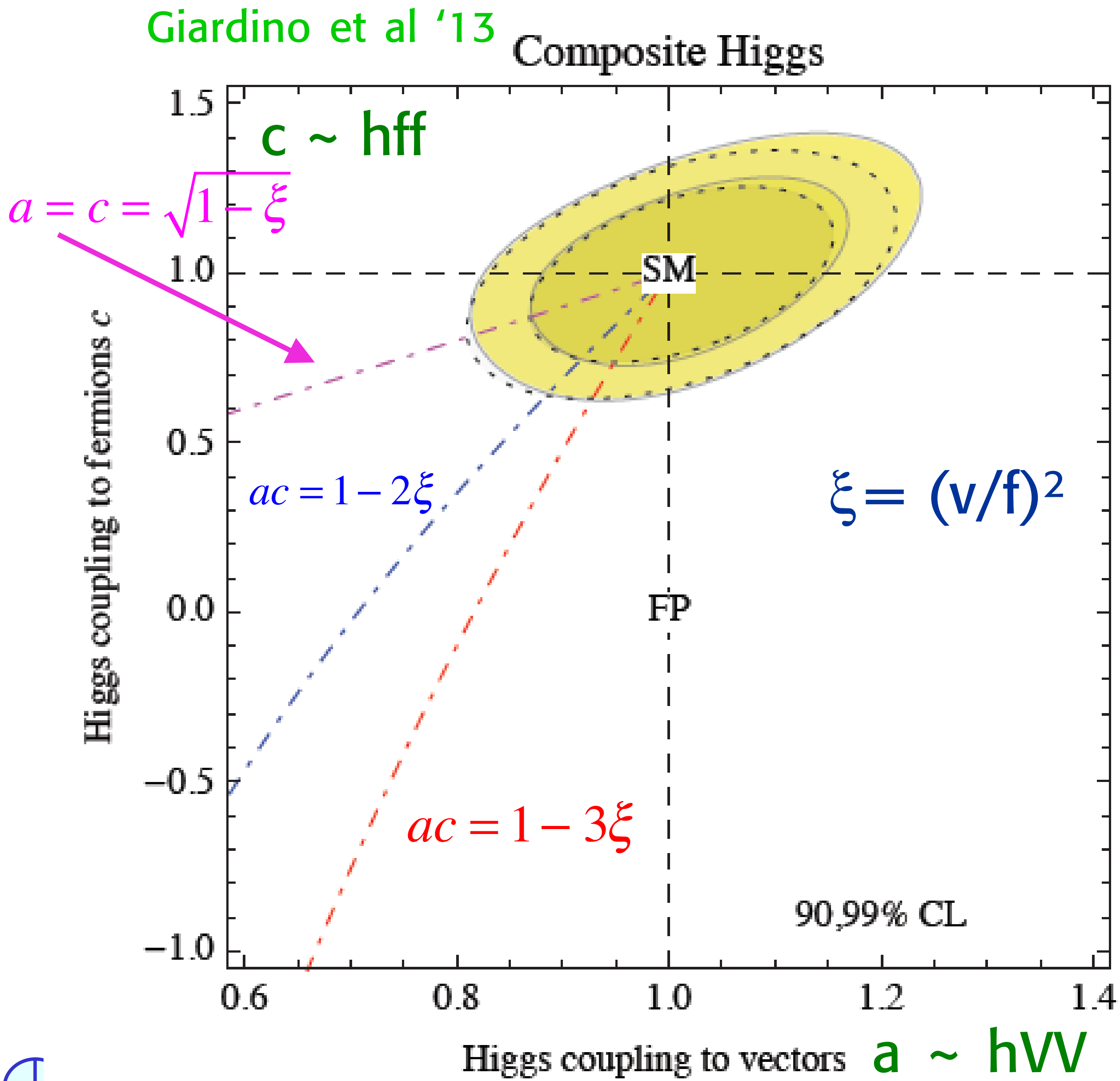
$\xi = (v/f)^2$

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

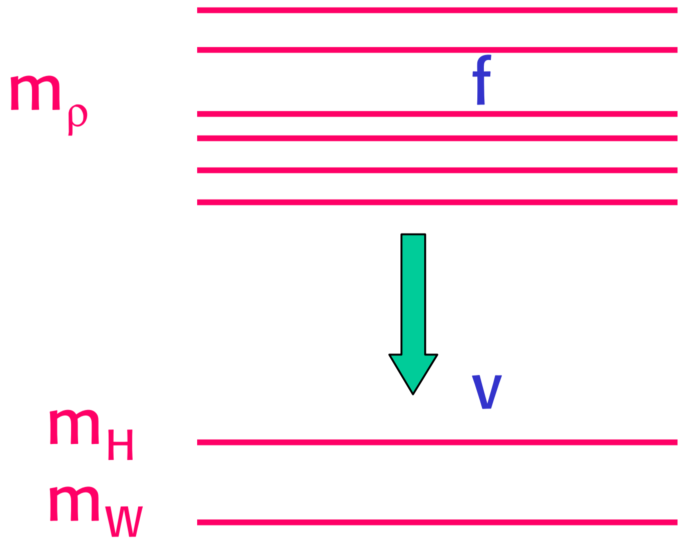
$\xi \sim 1$ similar to Technicolor

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





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



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:

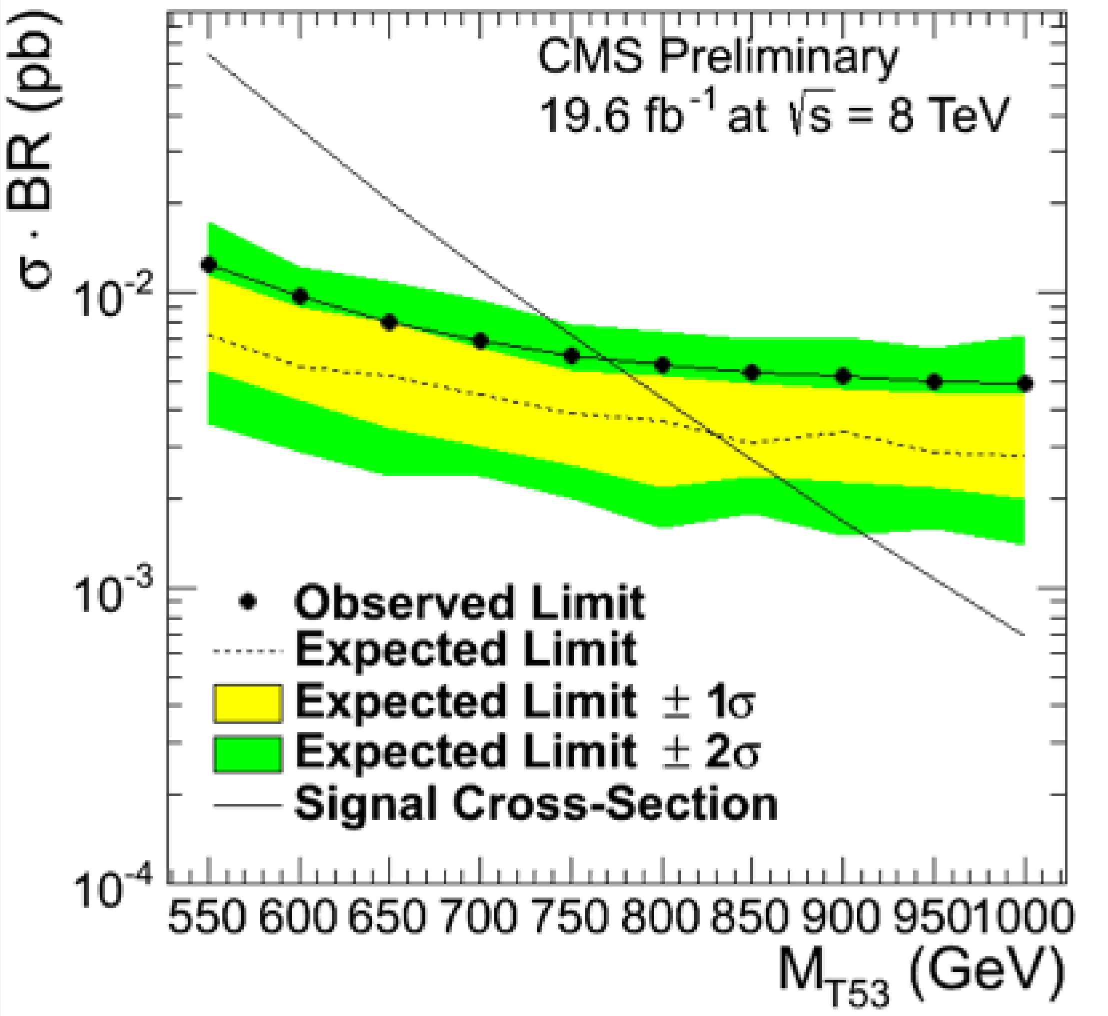
- Searching for fermions of charges 2/3 or 5/3 ... that quench the bad top loop behaviour

- Measurable deviations can be expected in channels $pp \to tth$, $gg \to hh$ and in decays $h \to \mu\mu$, $h \to Z\gamma$

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



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

At the other extreme: the anthropic multiverse

- 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

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

A revival of models that accept some fine tuning

Examples:

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

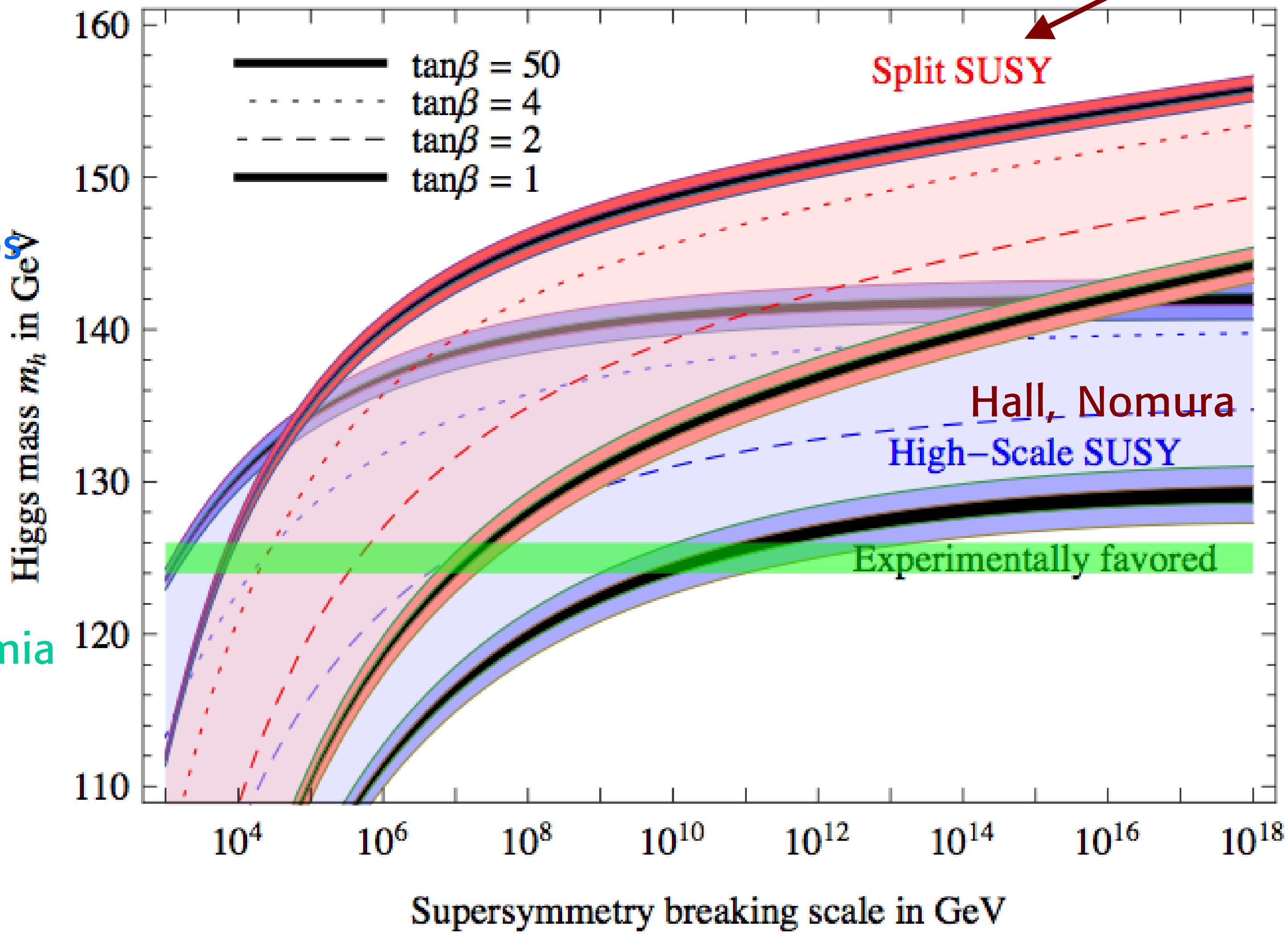
High scale SUSY
all sparticles heavy
λh^4 fixed by gauge

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

Giudice, Strumia

Arkani-Amed, Dimopoulos
Giudice, Romanino

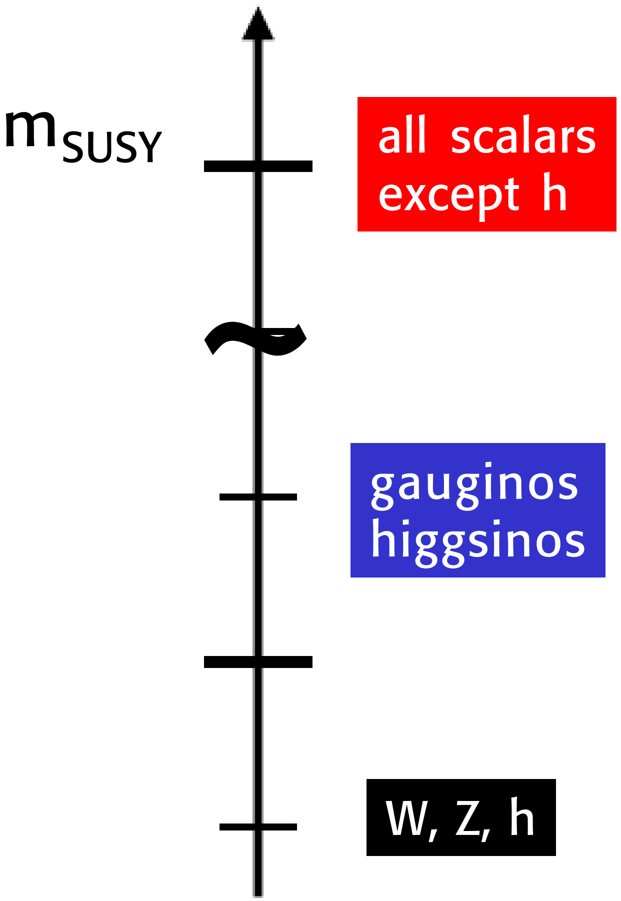
Hall, Nomura



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



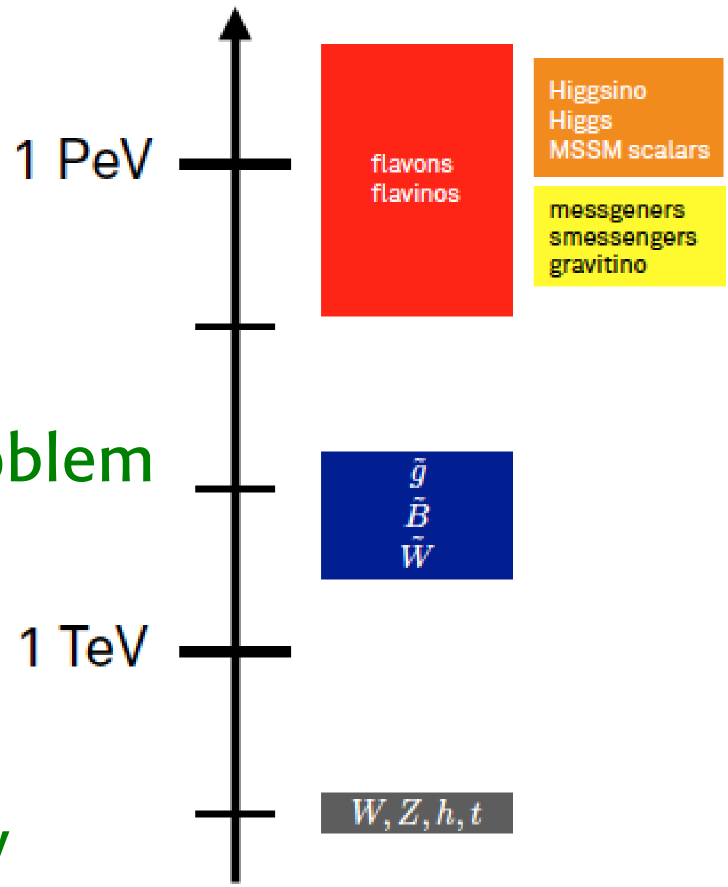
Split Susy

pro's

GUTs
Dark matter
No flavour problem
....

con's

not necessarily testable at the LHC



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

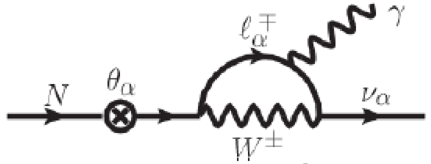
Very small Yukawa couplings are assumed to explain the small active ν masses

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

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

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

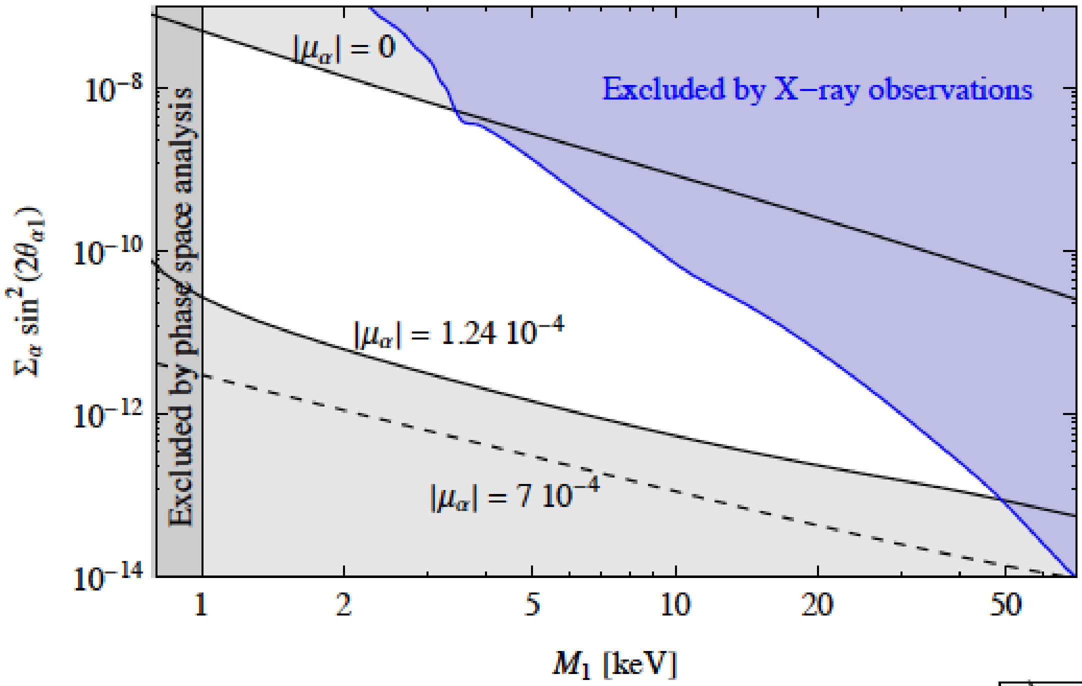
$$\Gamma_\gamma(m_s, \theta) = 1.38 \times 10^{-29}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

$N_{2,3}$ 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

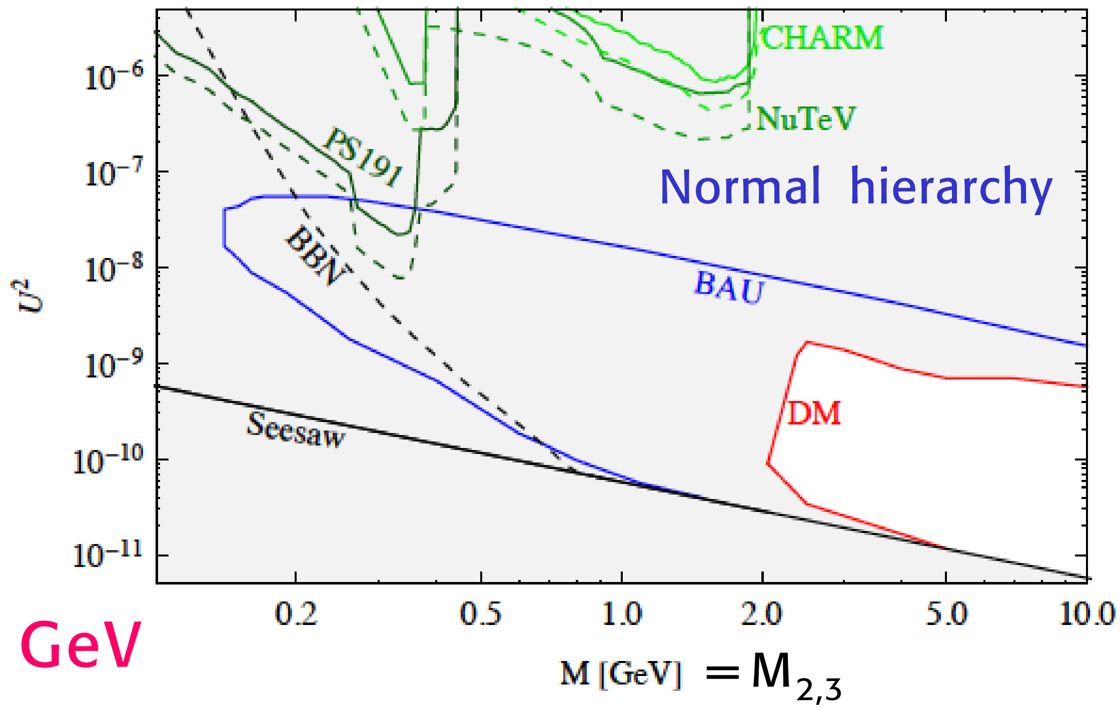


The claim is that all constraints can be satisfied

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

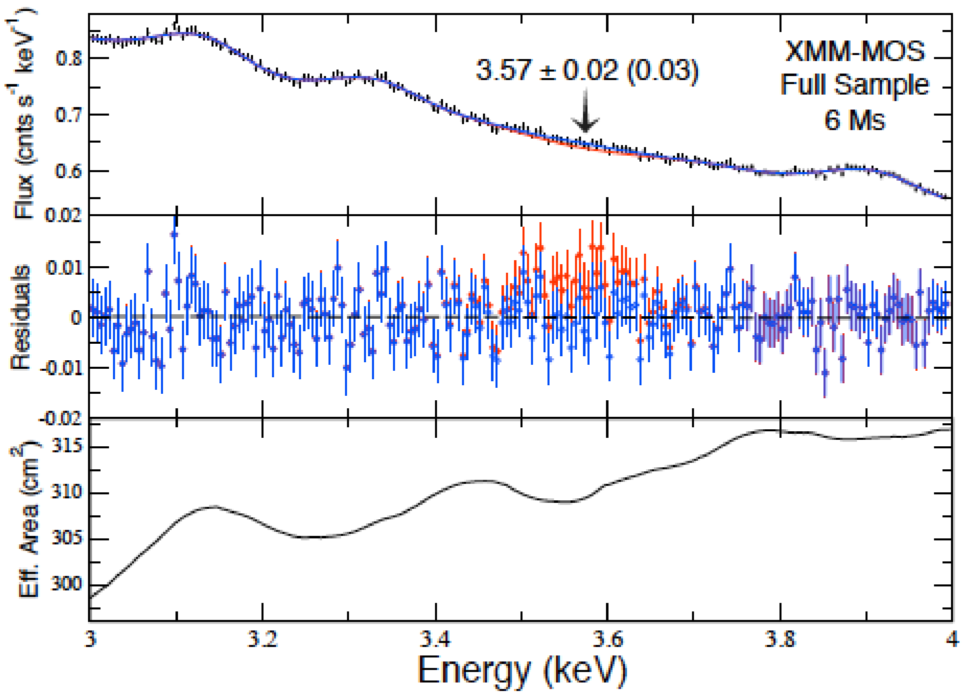
DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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

XMM-Newton X-ray observatory

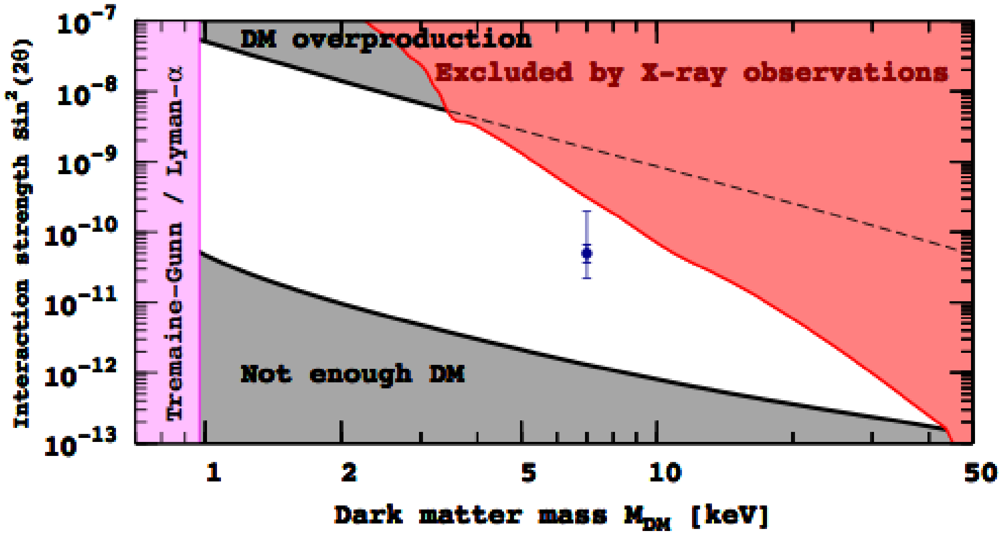
ABSTRACT

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

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!