Vulcano, 21 May '14

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
Precision tests of couplings mandatory to look for deviations

A negative surprise: no production of new particles, no evidence of New Physics (NP) 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 $(g\text{-}2)_\mu$?]

Most of the evidence for NP comes from the sky: Dark Energy, Dark Matter, Baryogenesis and also neutrino oscill'ns

Impact of the Higgs discovery

The main missing block for the experimental validation of the SM was finally put in place after a long hunt

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:

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

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

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

Manifestly a substantial 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 remains 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
--> negative implication for the design of future Colliders

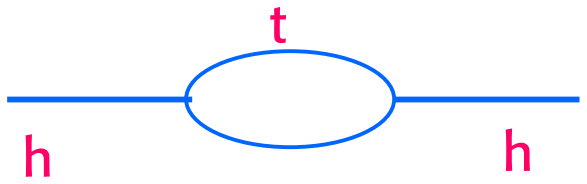
Moreover, it is true that the SM theory is renormalizable
and completely finite and predictive

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

The possibility that the SM holds well beyond the EW scale
must now be seriously considered

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

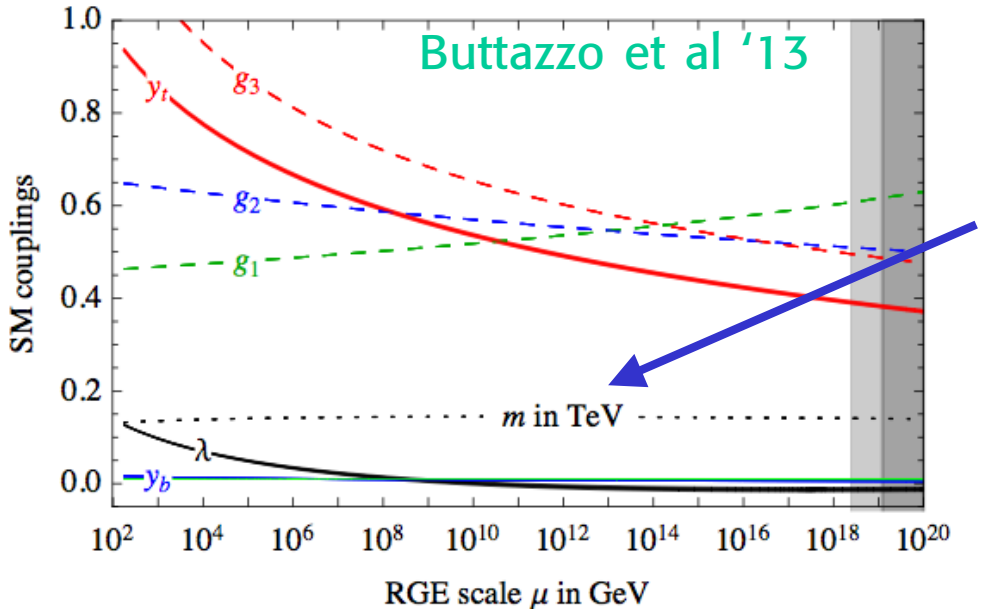
$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$



Then, 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

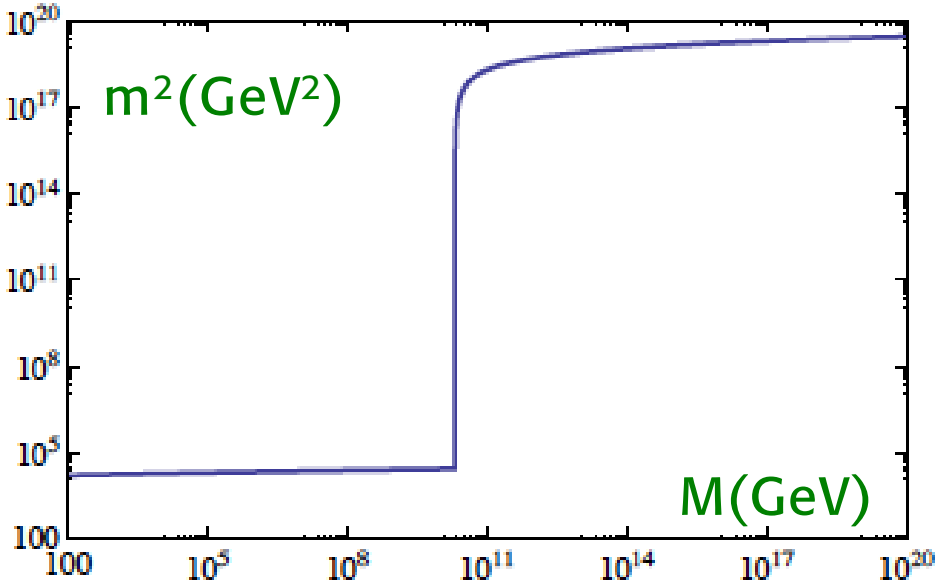
The argument can be formulated in terms of renormalized quantities with no reference to a cut-off --->
quadratic sensitivity to thresholds at high energy

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

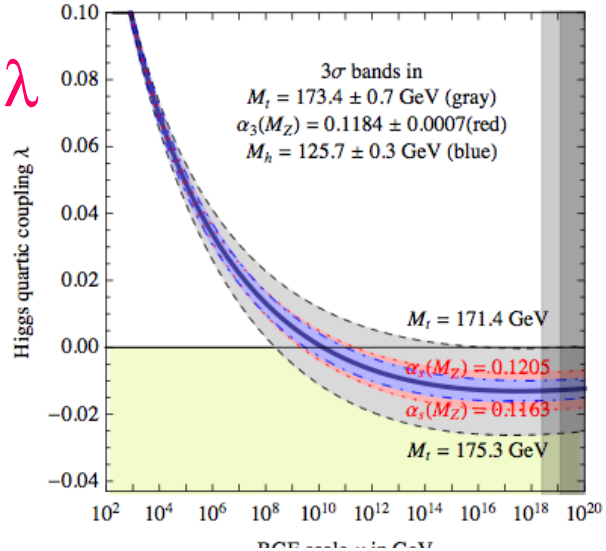
$M \sim 10^{10}$ GeV, $\lambda_H \sim 1$, jump: $m^2 \sim (\lambda_H M)^2/(16\pi^2)$

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

No no-go theorem for the SM at large energies

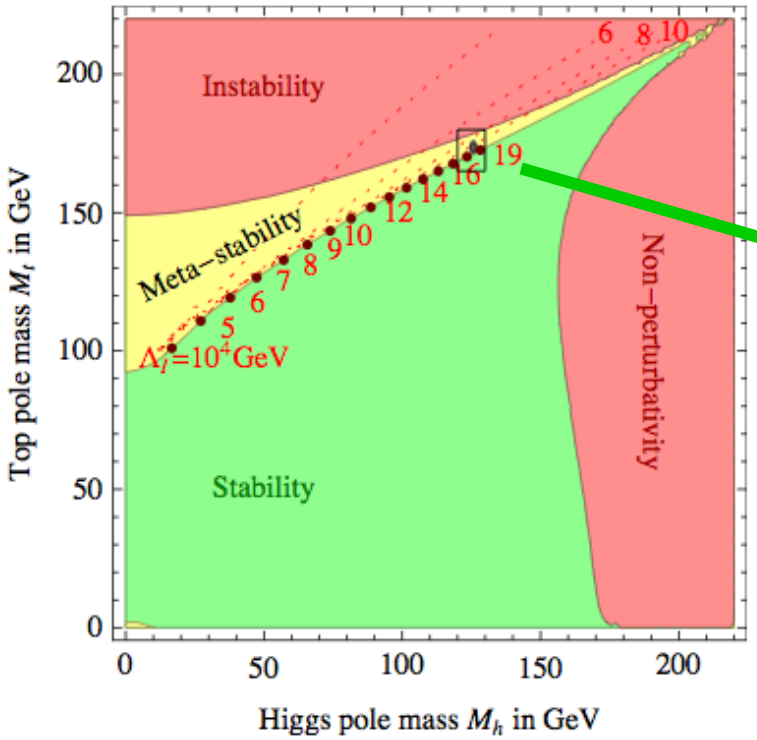
The pure SM evolution of couplings leads to a metastable Universe

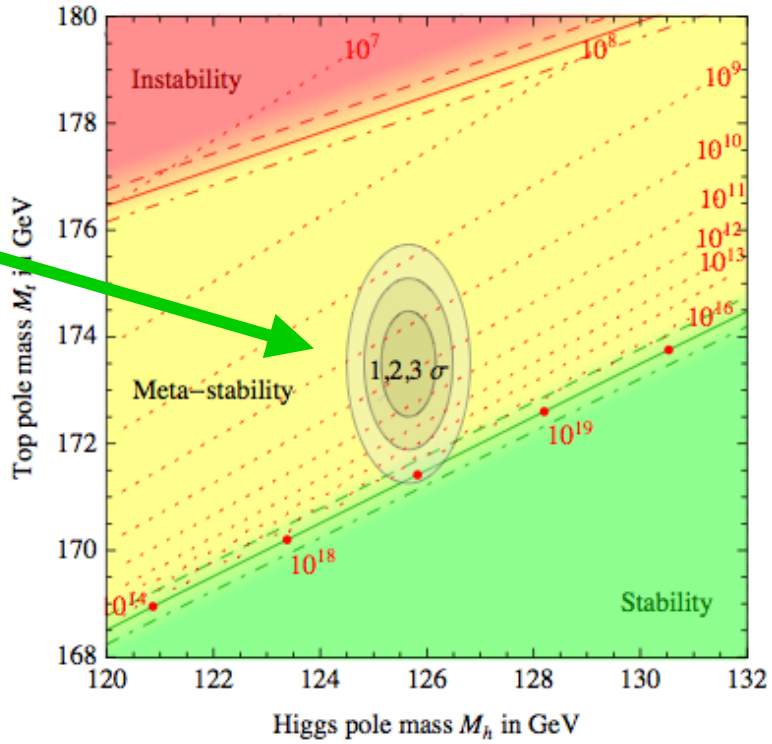
The SM evolution up to M_{Pl} leads to a narrow critical wedge: a hidden message?



$\lambda\phi^4$

Buttazzo et al '13 but 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

ν mass: 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 neutrinos $M\nu^T_R\nu_R$ is allowed by SU(2)xU(1) (ν_R is a gauge singlet) and breaks 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 $M \sim M_{GUT}$

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

$m: \leq m_t \sim v \sim 200$ 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 ($M \sim 10^{11\text{-}12}$ 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.

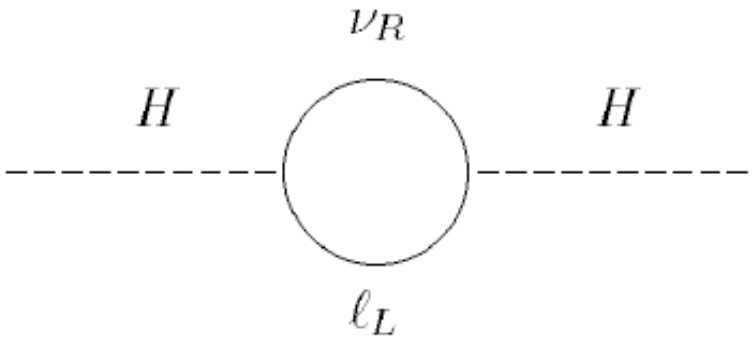
Quantitative studies confirm that the range of m_i from ν oscill's is compatible with BG via (thermal) LG

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 $q \gg M_R$

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

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

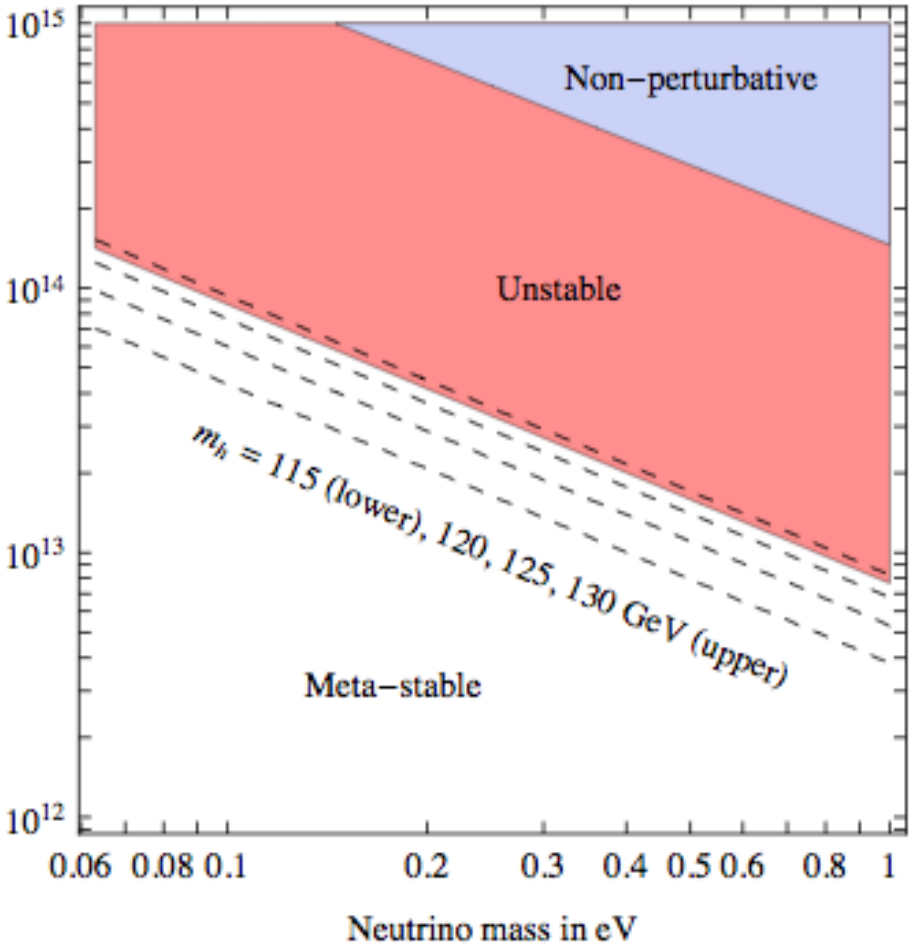
$\mu < 1$ TeV $\longrightarrow$ $M_R < 10^7$-10^8 GeV

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

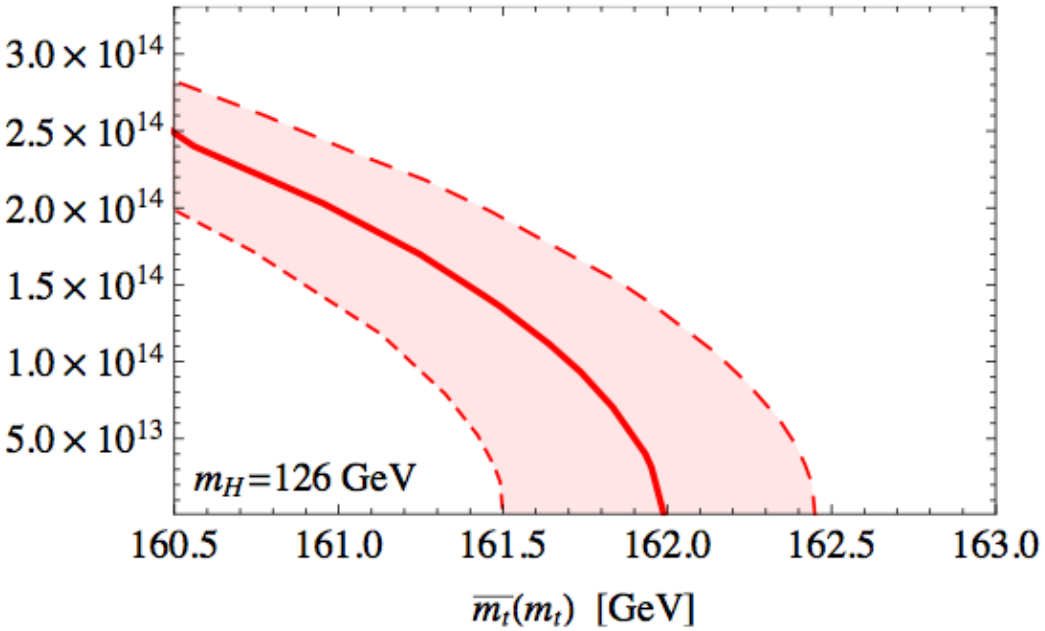
But, for $M < 10^{14}$ GeV, ν_R's do not make the vacuum unstable

J. Elias-Miro' et al '11



$m_{\nu R}$[GeV]

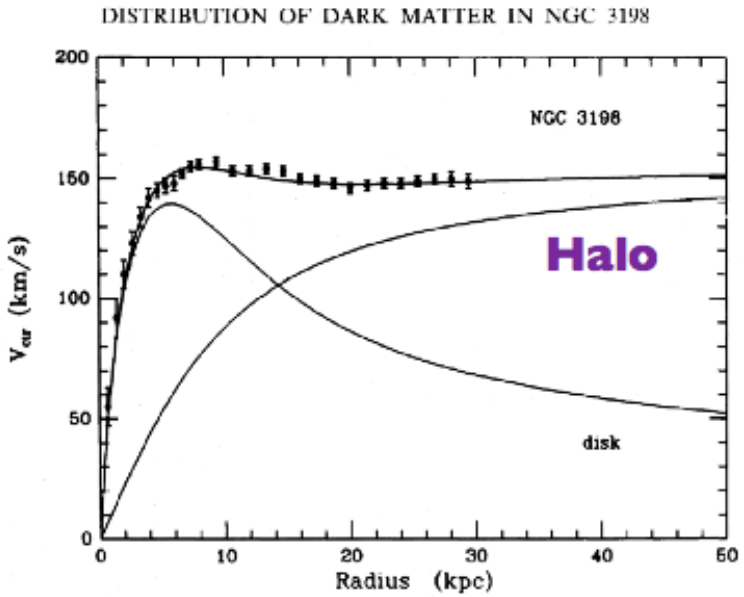
Masina'12



At present Dark Matter is THE crucial problem

A by now robust evidence for Dark Matter in the Universe

Rotation of galaxies



Lensing

MACS, HST

Merging clusters of galaxies

M. Markevitch et al 2003

Cosmological evidence

anisotropies of Micro Wave Background Radiation

large scale structure

structure formation.....

e.g. Planck

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

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:

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

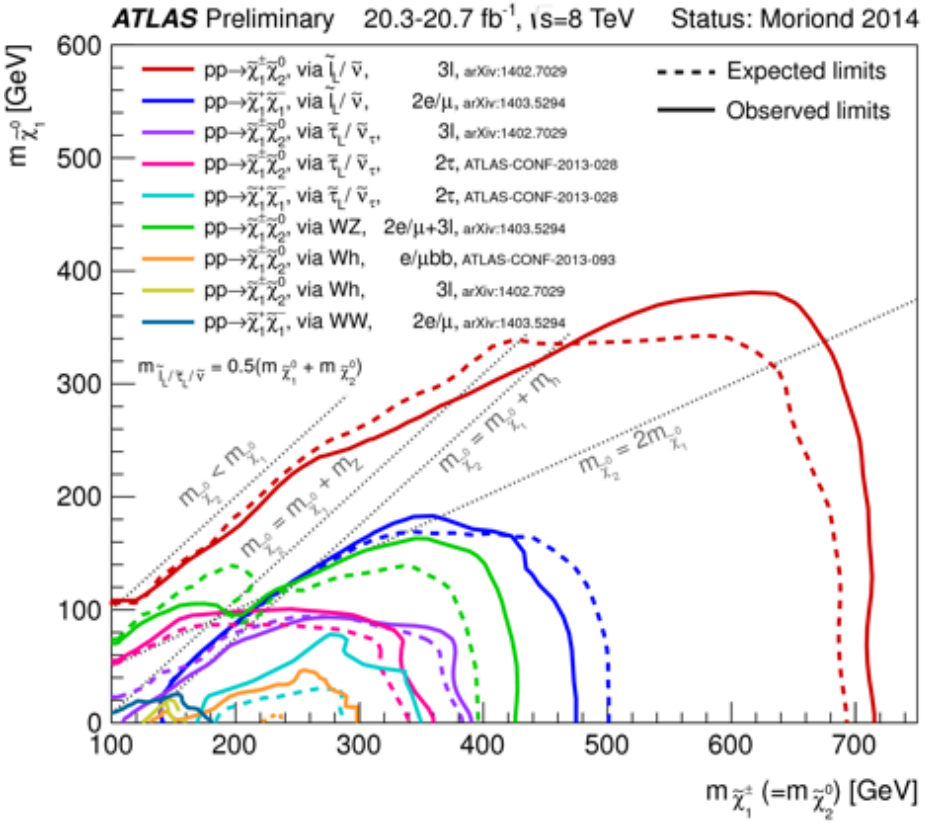
can work for typical weak cross-sections!!!

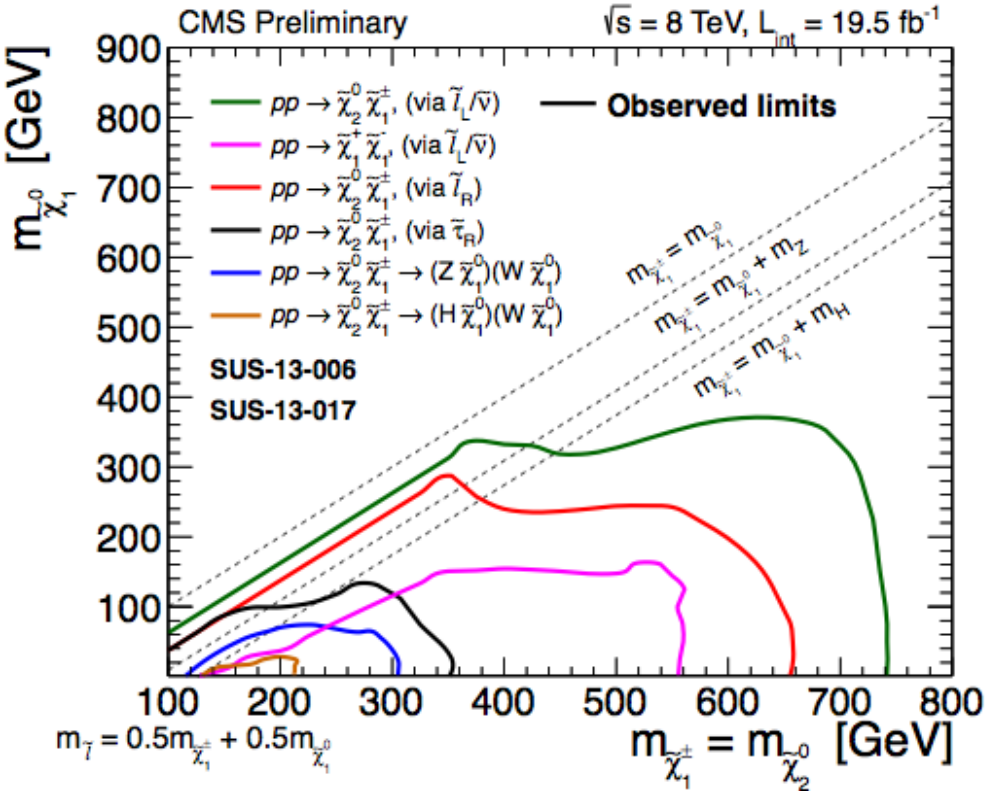
This "coincidence" is taken as a good indication in favour of a WIMP explanation of Dark Matter

No WIMP's have been observed at the LHC

But the LHC limits on SUSY WIMPS (neutralinos) are not stringent

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





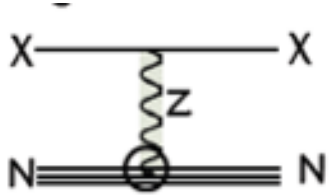
A strict bound is very low: $m_{\chi 0} > 25$ GeV (light s-taus and higgsinos)

Calibbi et al'13

The WIMP non-accelerator searches are very powerful

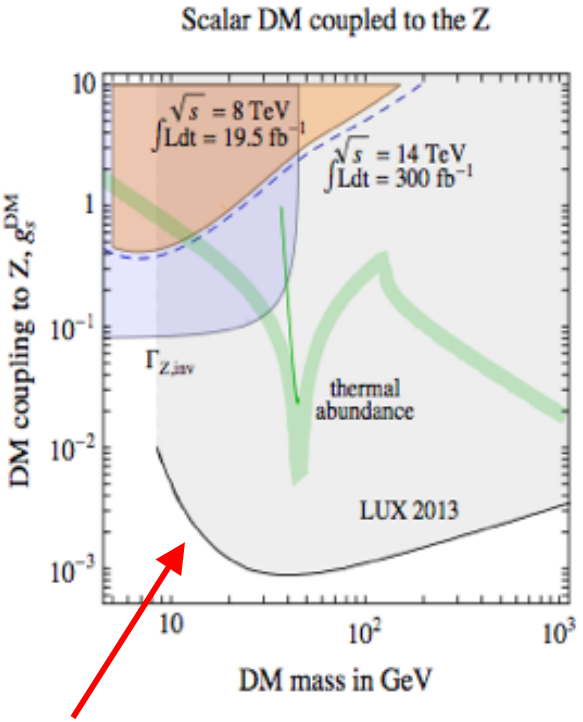
eg χ N --> χ N
or $\chi\,\chi$ --> N N

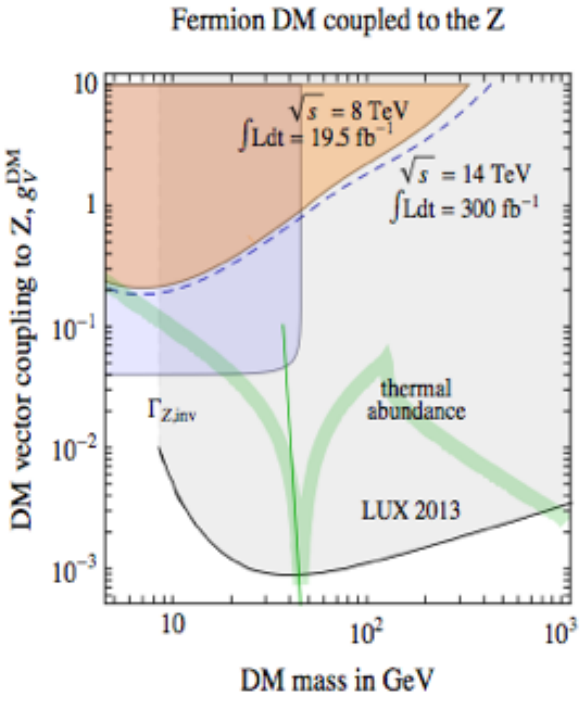
Z echange potentially large

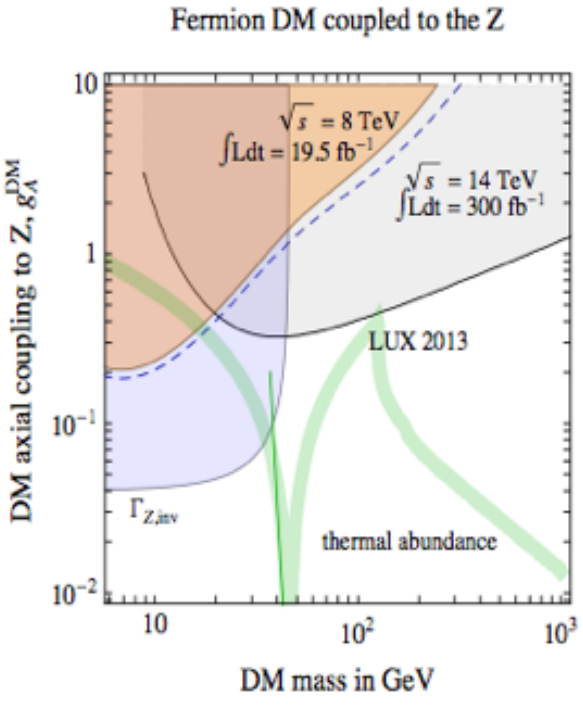


DM coupled to Z severely limited (axial couplings less constrained)

De Simone, Giudice, Strumia '14







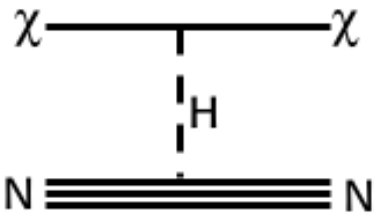
LUX constraints

Still plenty of room for low mass WIMP's

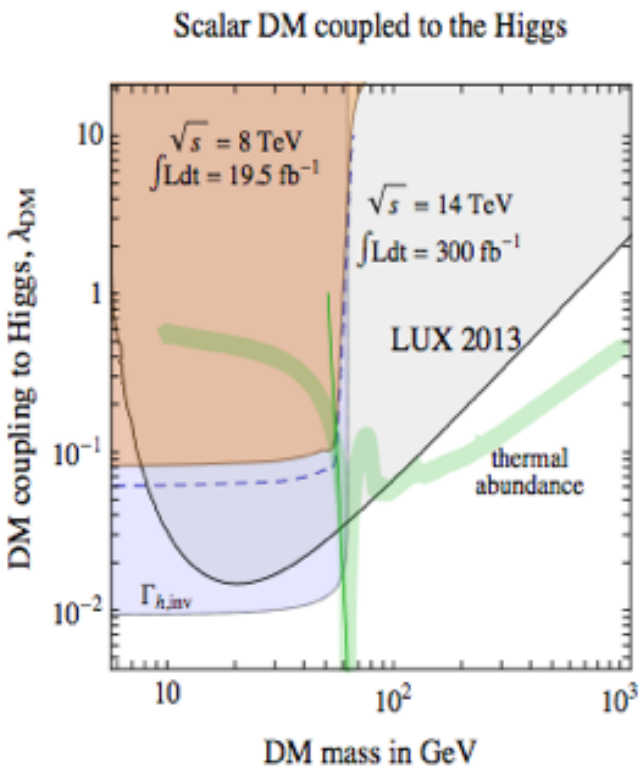
DM coupled to Higgs also limited (pseudo scalar couplings less constrained)

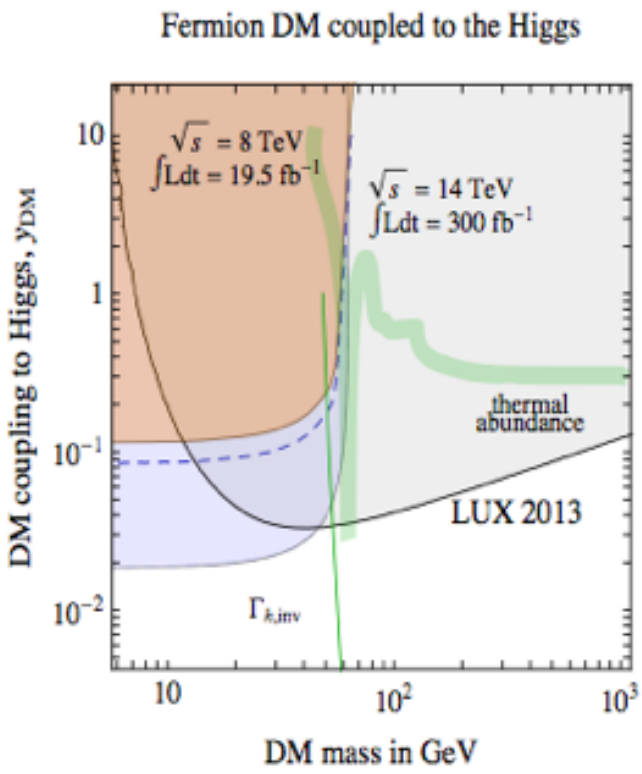
eg χ N --> χ N
or $\chi\,\chi$ --> N N

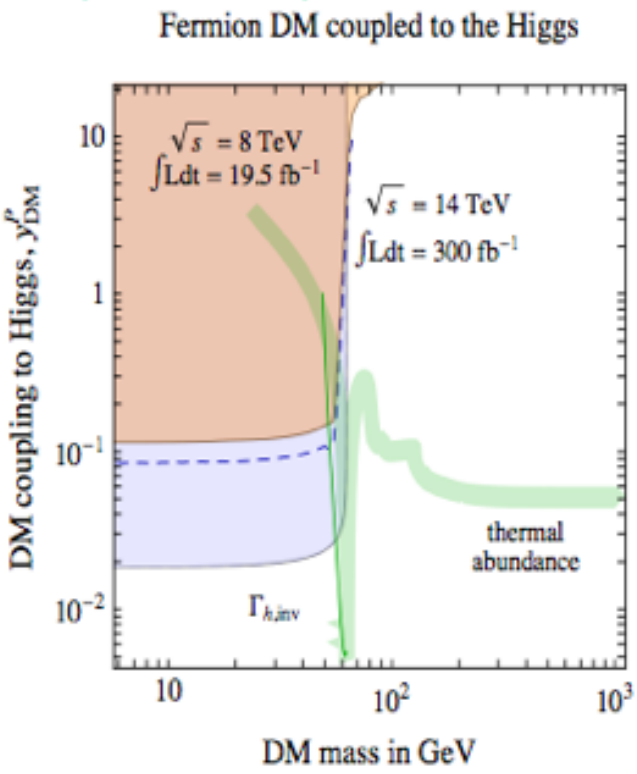
125 GeV Higgs boson exchange being also probed now



De Simone, Giudice, Strumia '14







scalar coupling

pseudoscalar coupling

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 $U(1)_{PQ}$

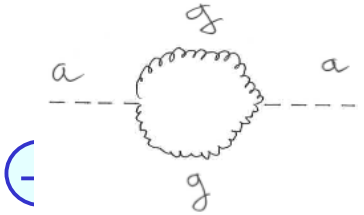
The ψ mass is m ~ λ<A> ~ λ f → new particles at scale f!

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

a (the axion) is the Goldstone boson it only has derivative couplings but for the $U(1)_{PQ}$ anomaly term

$a' = a - 2i\alpha f$

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



→ mass for the axion

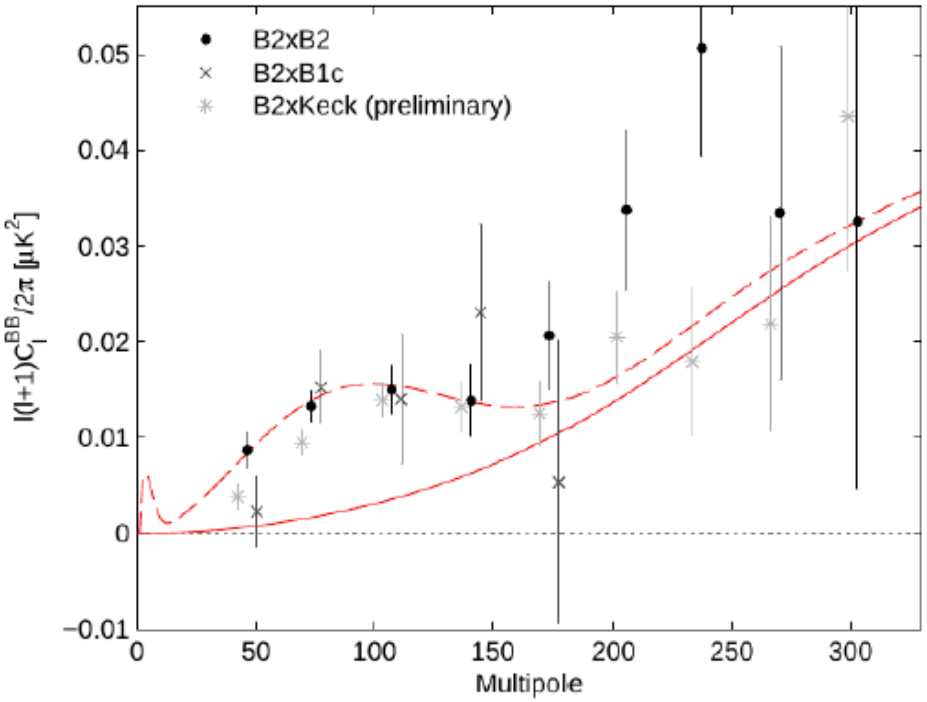
$$m_a^2 \propto \frac{\Lambda_{QCD}^4}{f^2}$$

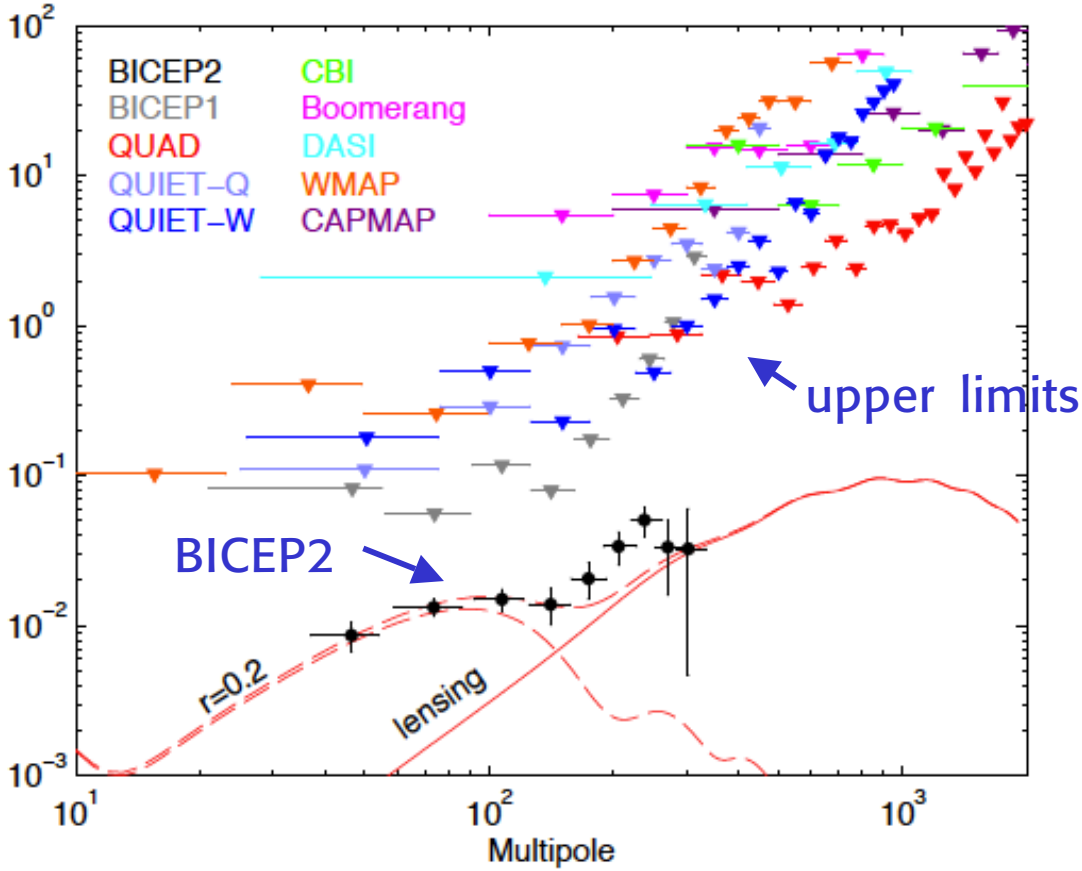
The analogous coupling to photons induces the decay $a \to \gamma\gamma$

Sensational news from cosmology

The BICEP2 Data

To be confirmed by other experiments
Planck, POLARBEAR, ACTPole, KecK Array...





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

Great impact on Inflation

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

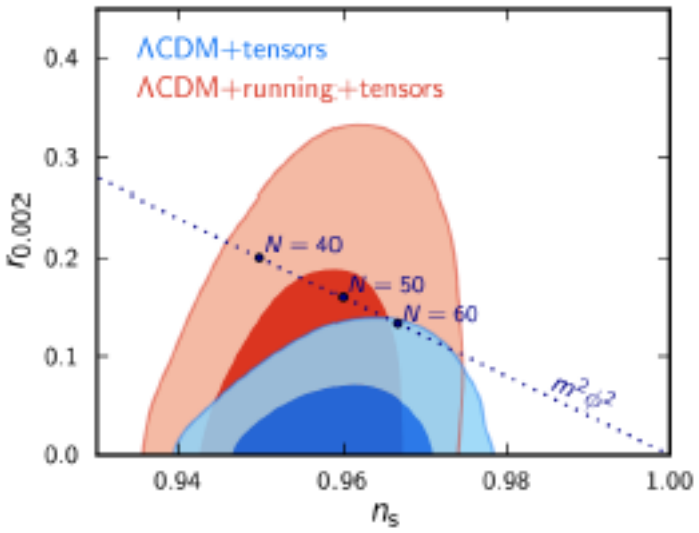
Energy scale of inflation:

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

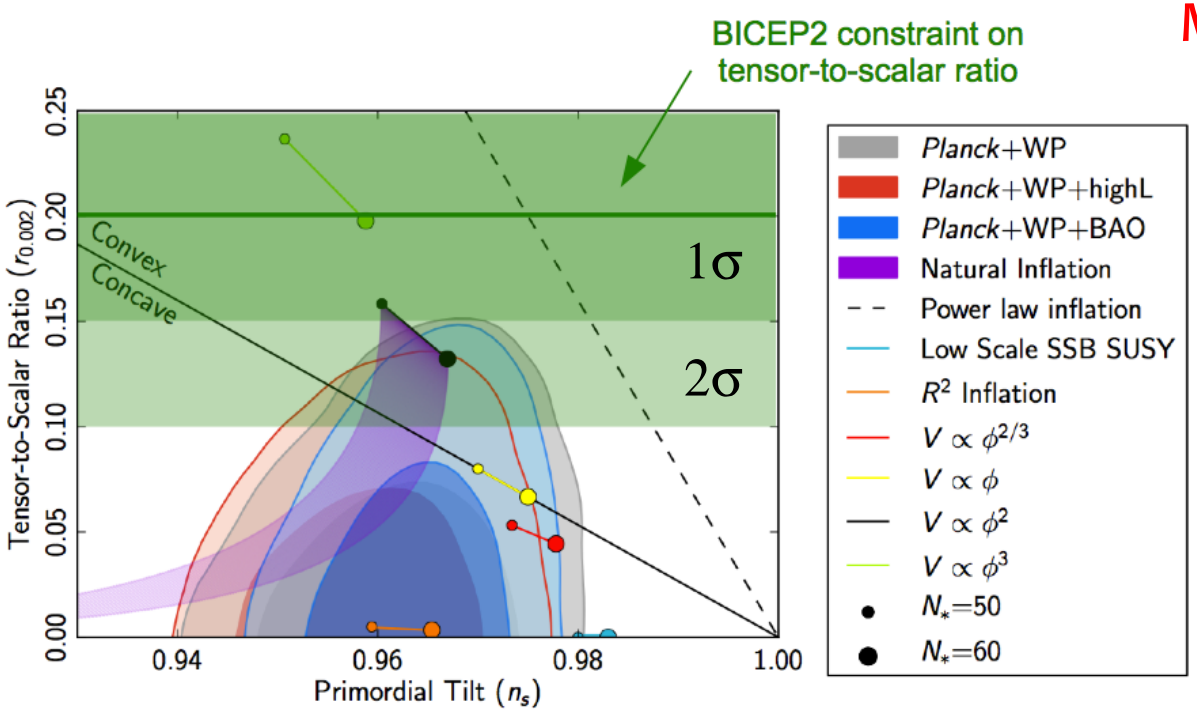
Tantalizing close to M_{GUT}!

Evidence of a scale below M_{Pl}?

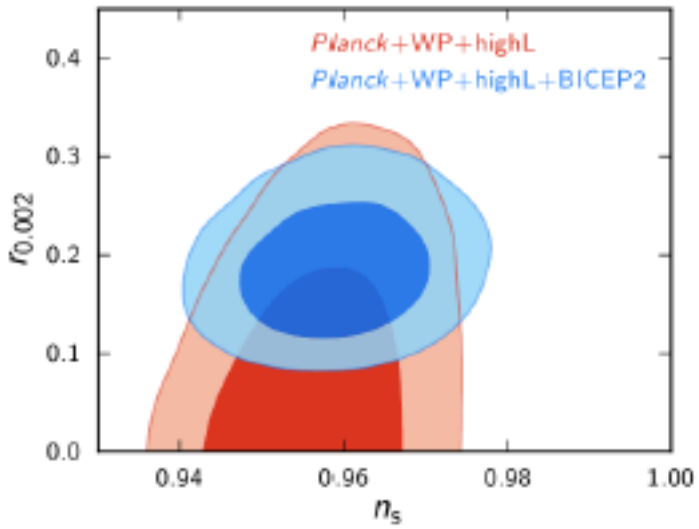
Planck 2013



Moderate tension with Planck

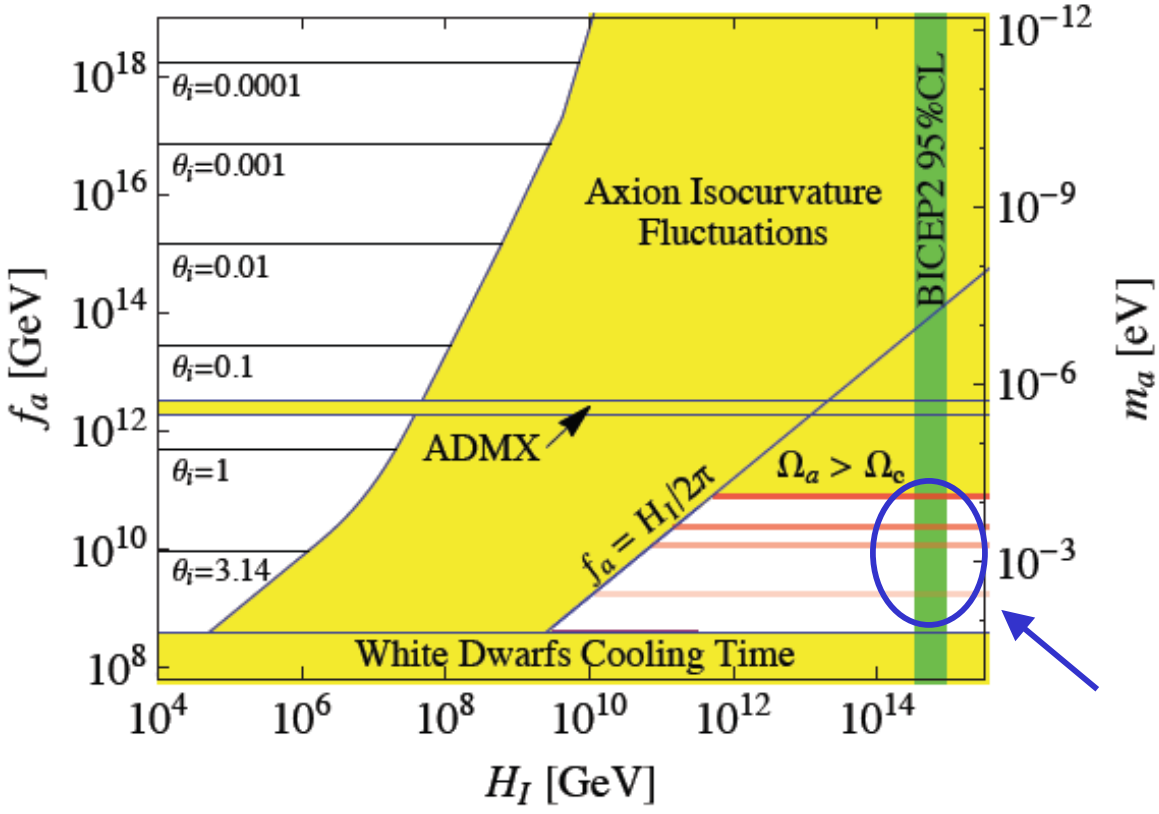


Bicep2 2014



Implications of BICEP2 on axions

Visinelli, Gondolo '14



window of opportunity after inflation

$f_a \sim 10^{10} - 10^{11}$ GeV

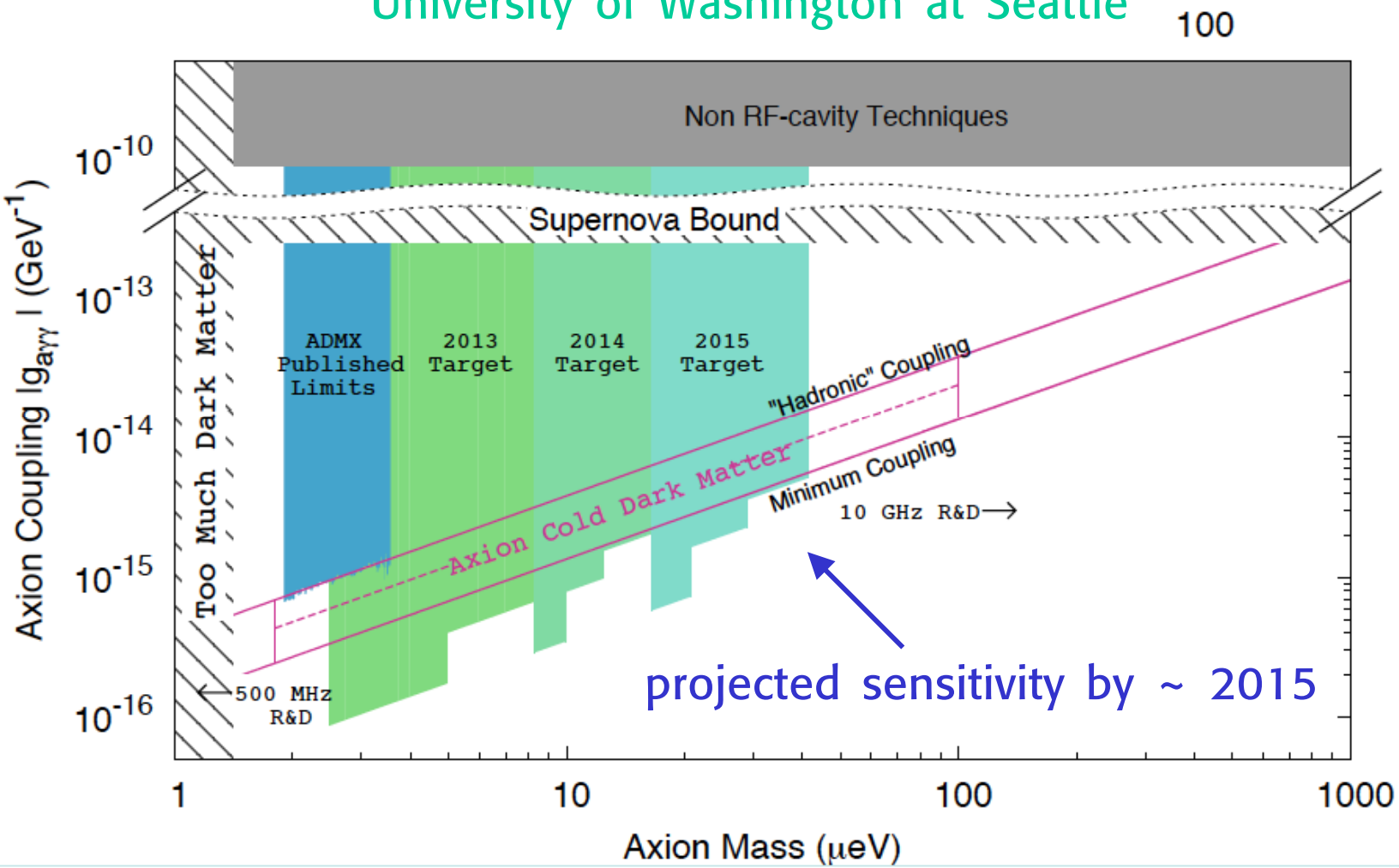
$ma \sim 10^{-4} - 10^{-5}$ eV

Di Valentino et al '14

Axion searches are very important

e.g 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 (LHC14?)
- 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

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

The best scenarios for the next LHC runs!!

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 substantial 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
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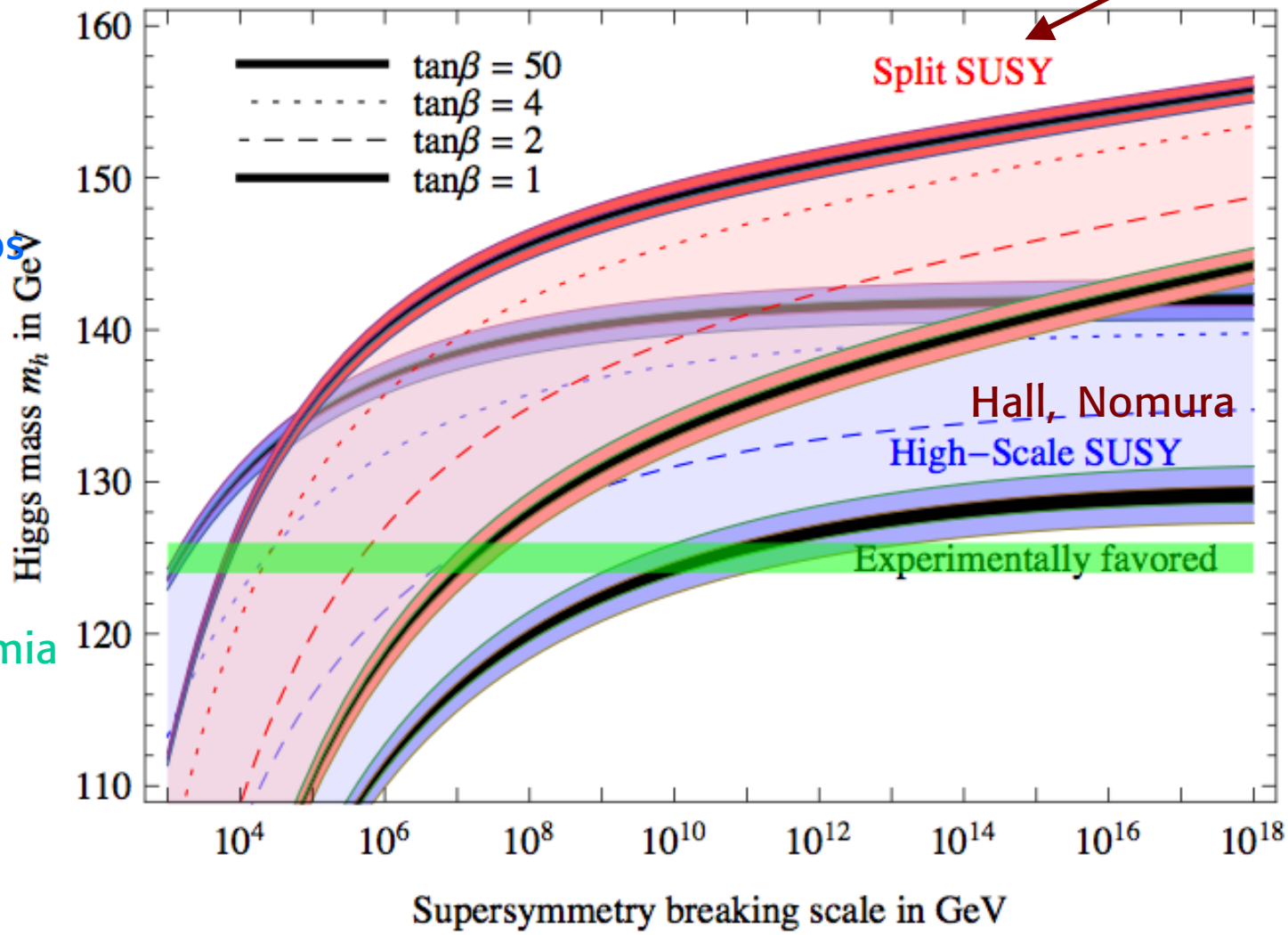
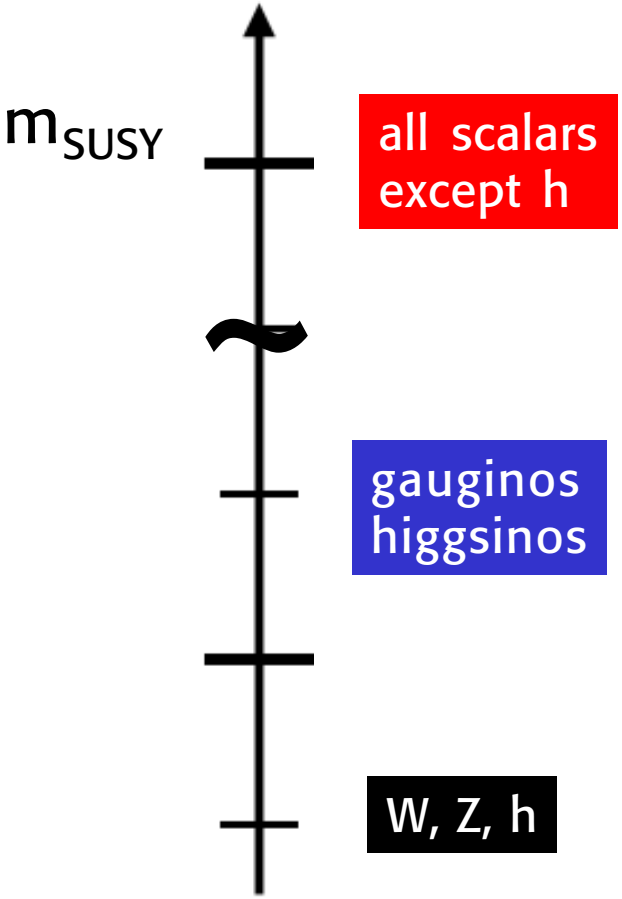
Giudice, Strumia

Arkani-Amed,Dimopoulos
Giudice, Romanino



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

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



Split Susy

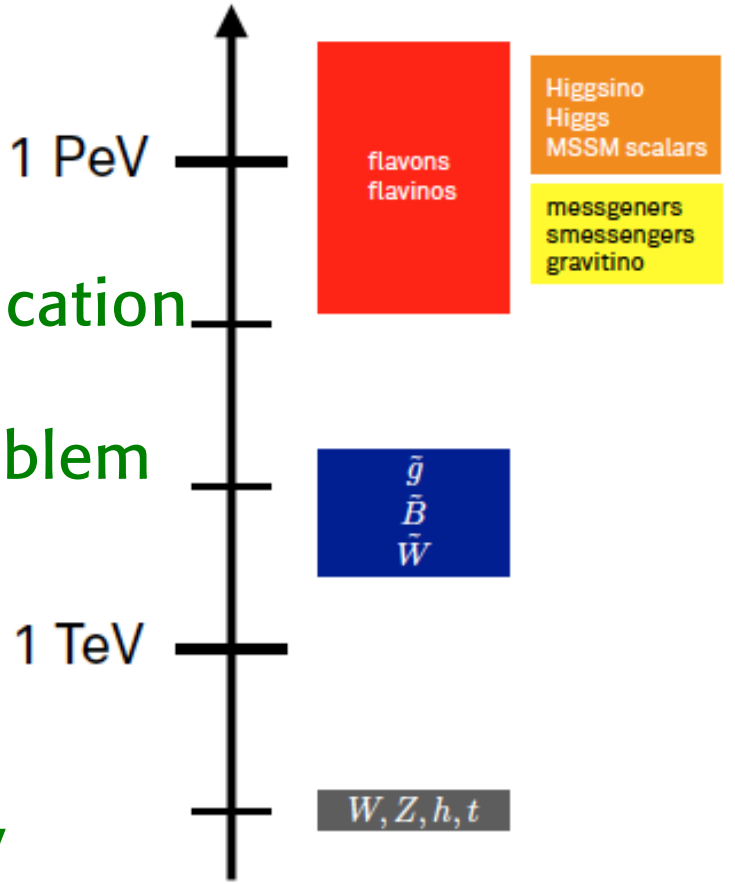
pro's

Coupling Unification
Dark matter
No flavour problem
....

con's

not necessarily testable at the LHC

Baumgart, Stolarski, Zorawski '14



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!!

A more restrictive variant: scale invariant theories possibly including gravity (A-gravity): only a-dimensional couplings exist.

⊕ Spont. breaking of scale invariance

e.g. Racioppi et al '13
Khoze '13
Hill '14
Salvio,Strumia '14

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

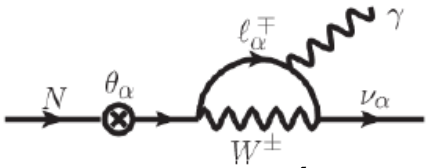
Very small Yukawa couplings are assumed to explain the small active ν masses

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

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



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

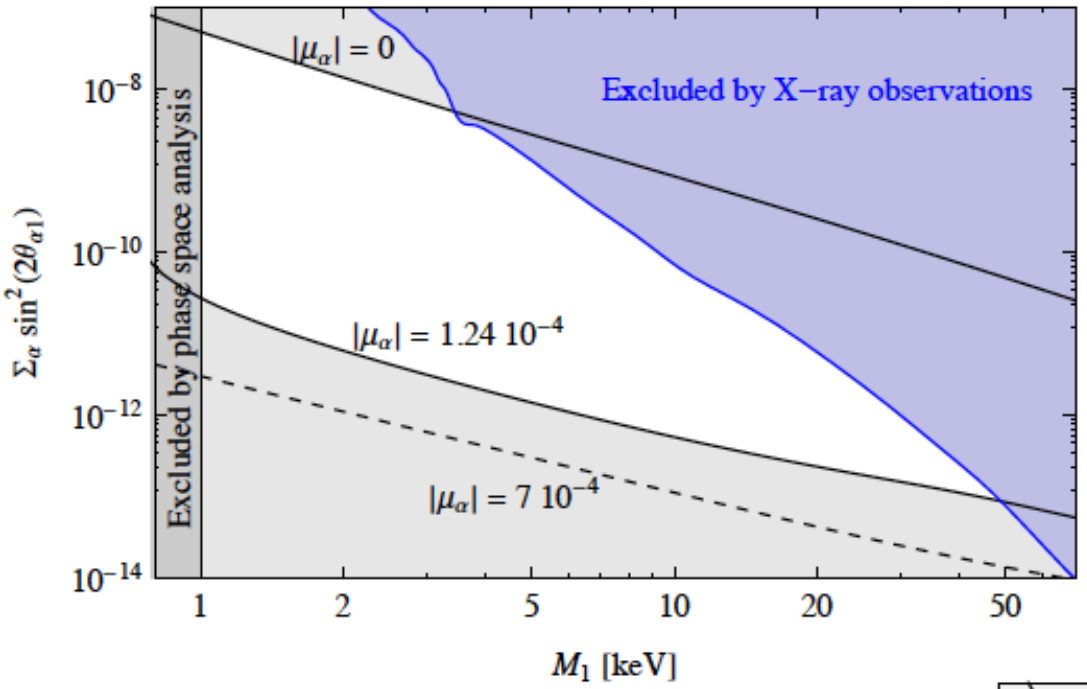
N_1 decay produces a distinct X-ray line

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

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

A LOI for the CERN SPS has been presented (SHIP)

Bonivento et al, ArXiv:1310.1762



Canetti et al '12

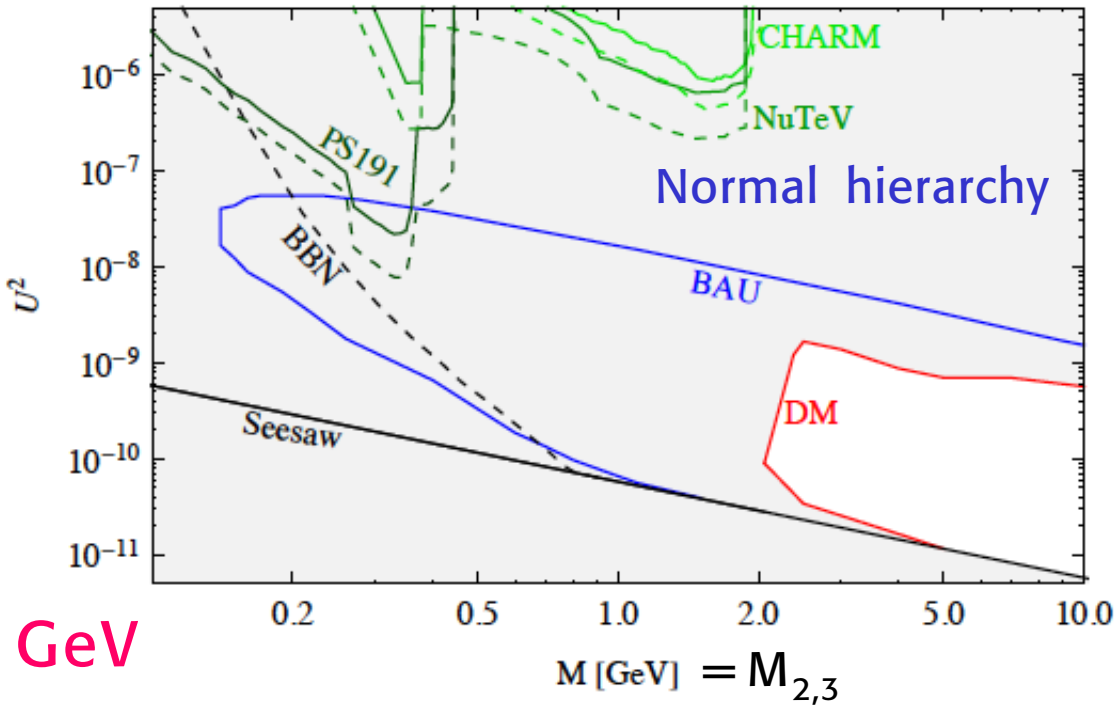
The claim is that all constraints can be satisfied

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]

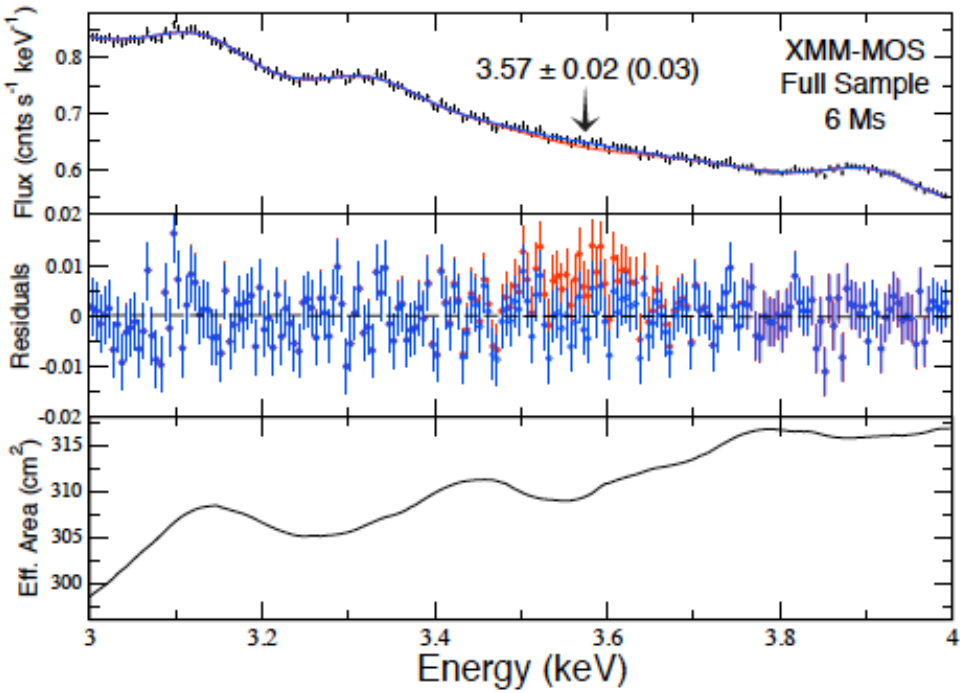
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10

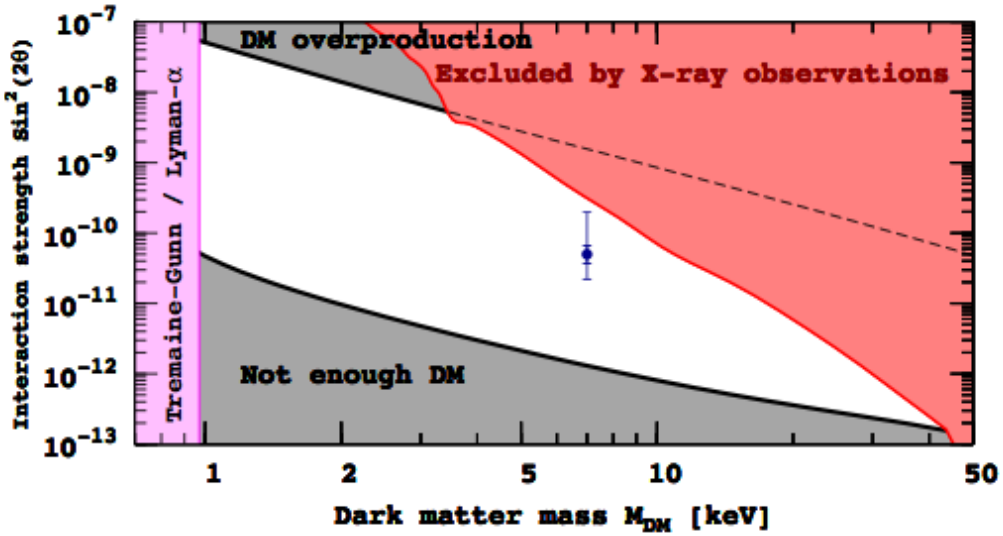
XMM-Newton X-ray observatory

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 exp. 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 substantial FT

  e.g. Split-SUSY

  Total acceptance of FT: the Anthropic metaphysics
- Demise of FT: the no-threshold conjecture

  the νMSM, scale invariant theories

  price: no GUTs, no heavy ν_R ....

  But BICEP2 now makes the GUT scale to reappear!