Dark Matter and the Higgs Boson Discovery

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INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

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Outline

- ✧ Introduction – DM: evidence and general properties
- ✧ Theory frameworks for DM candidates
- ✧ SUSY neutralino as DM
- ✧ Implications of mh~126 GeV and direct limits on SUSY:

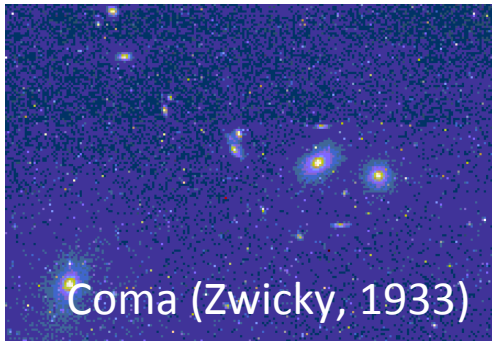
→ New DM candidate: ~1 TeV higgsino

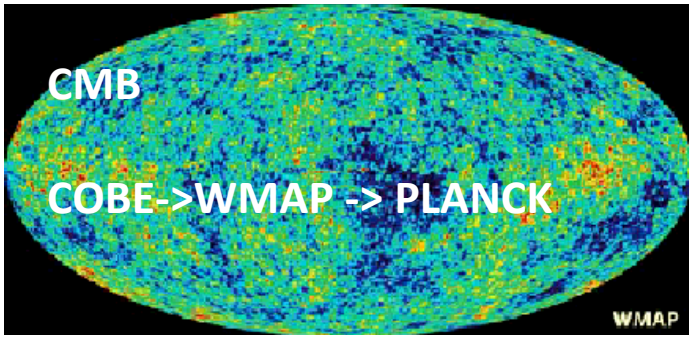
- ✧ Prospects for detection
- ✧ Other recent developments and claims
- ✧ Summary


There is more out there
than meets the eye
al. et Frenk

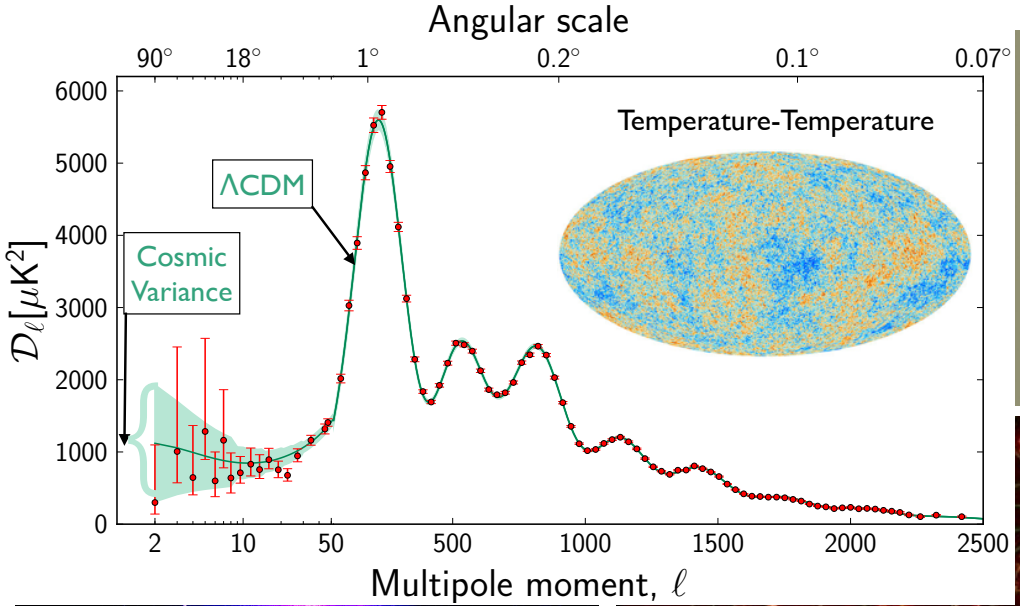

The WIMP Reigns
…but remains elusive

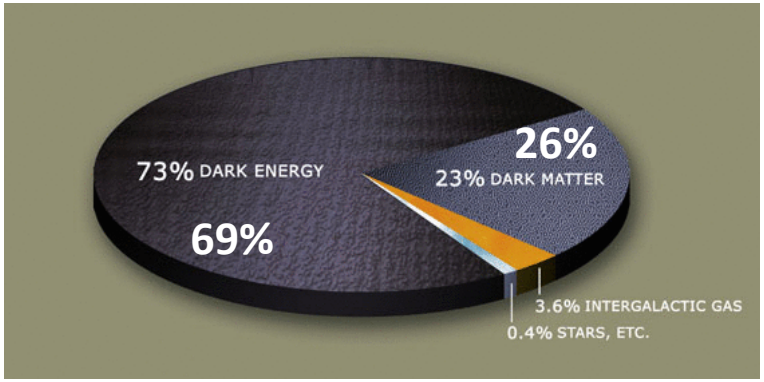
Footprints of Dark Matter

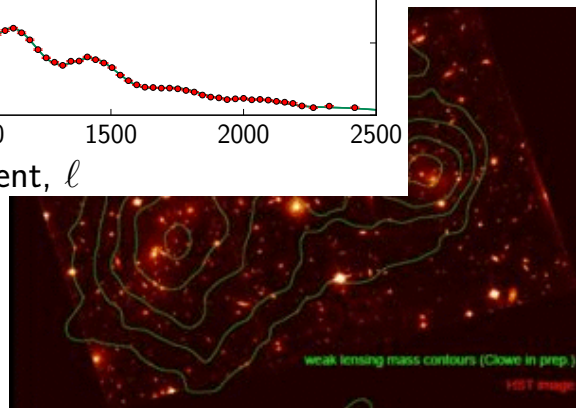


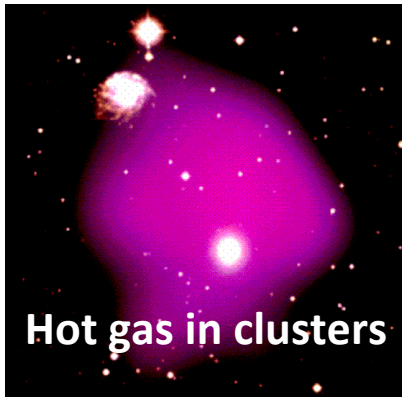


…felt but not seen









What is the DM?

- non–baryonic
- cold (CDM)

  or possibly (?) warmish
- no electric nor (preferably) color interactions
- relic from the Big Bang
- element of some sensible particle theory

plausible choice ⇒ WIMP

(weakly interacting massive particle)

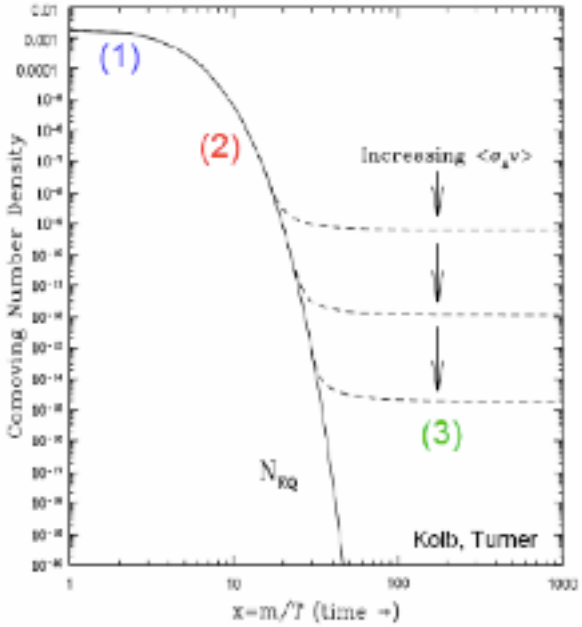
...a very broad class, not a single candidate

...How weak can weak be?

WIMP: most likely an unknown particle

A simple, persuasive argument:

- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$



WIMP relic abundance

$$\Omega h^2 \simeq \frac{1}{\left\langle \left(\frac{\sigma_{\rm ann}}{10^{-38}\,{\rm cm}^2}\right)\left(\frac{v/c}{0.1}\right)\right\rangle}$$

$\sigma_{\rm ann}$ – c.s. for WIMP pair–annihilation in the early Universe

v – their relative velocity, $\langle \ldots \rangle$– thermal average

$$\sigma_{\rm ann} \sim \sigma_{\rm weak} \sim 10^{-38}\,{\rm cm}^2 = 10^{-2}\,{\rm pb} \;\Rightarrow\; \Omega h^2 \sim 1$$

A hint? Possibly, but...

Not "WIMP Miracle" but weak int. – relic density coincidence

CDM: some theory frameworks

- ✧ SUSY <- by far most popular (and best motivated)
- ✧ DM and various extensions of the SM (portals/hidden valleys,…)
- ✧ Asymmetric DM
- ✧ Self-interacting DM
- ✧ Universal extra dim's
- ✧ …

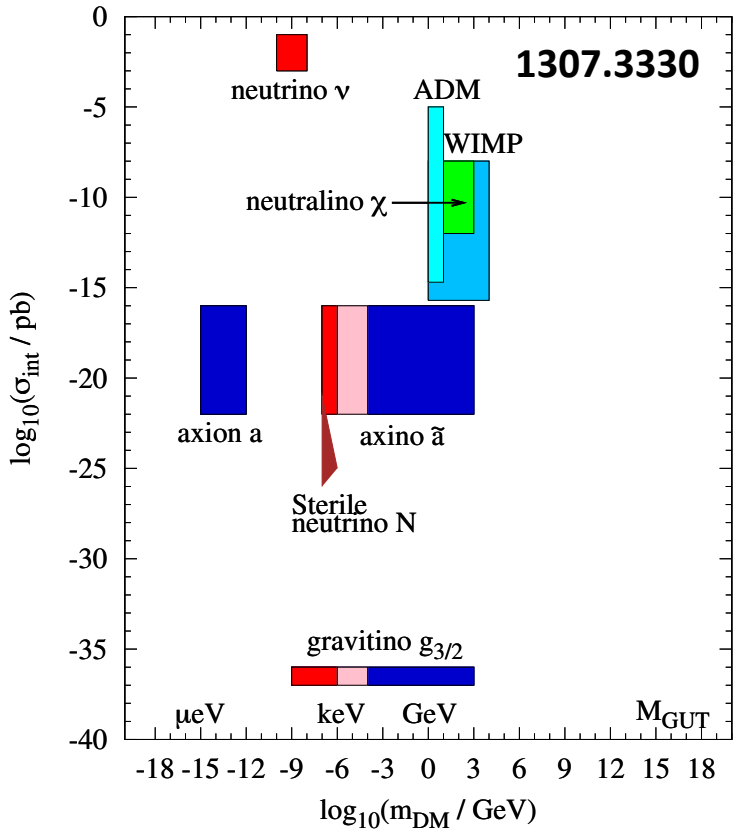
<u>SUSY frameworks:</u>

- ❖ Unified (=GUT-constrained) models (Constrained MSSM, …)
  - virtues: well-motivated, predictive, realistic
  - limitations: may miss some solutions

- ❖ Phenomenological (supersymmetrized SM)
- ❖ Scenarios motivated by this or that…

e.g. Split SUSY, Natural SUSY,…

Well-motivated candidates for dark matter



- neutrino ν – hot DM
- neutralino χ
- "generic" WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$

SUSY

- vast ranges of interactions and masses
- different production mechanisms in the early Universe (thermal, non-thermal)
- need to go beyond the Standard Model
- WIMP candidates testable at present/near future
- axino, gravitino EWIMPs/superWIMPs not directly testable, but some hints from LHC

Where is the WIMP?

- **Mass range: at least 20 orders of magnitude**
- **Interaction range: some 32 orders of magnitude**

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

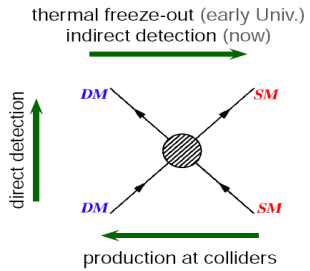
- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape
  - antimatter (e^+, $\bar{p}$, $\bar{D}$) from WIMP pair-annihilation in the MW halo

    from within a few kpc
  - gamma rays from WIMP pair-annihilation in the Galactic center

    depending on DM distribution in the GC
  - other ideas: traces of WIMP annihilation in dwarf galaxies, in rich clusters, etc

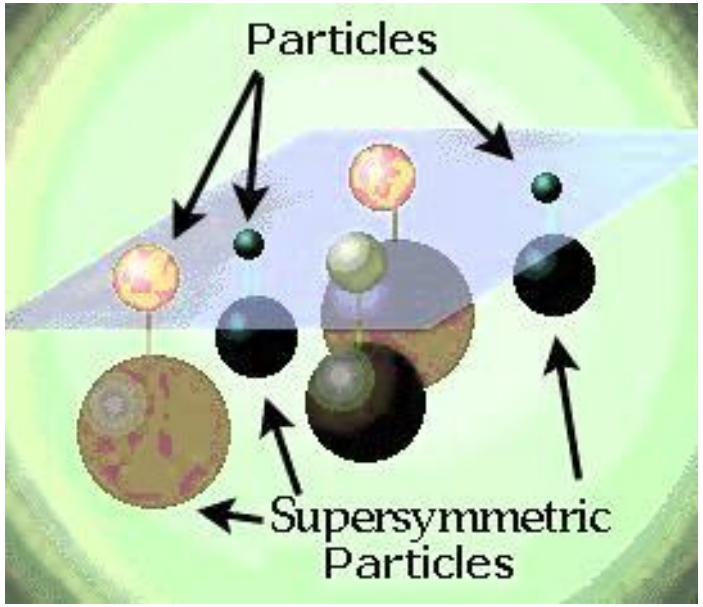
    more speculative
- the LHC



Supersymmetry

Symmetry among particles

bosons <-> fermions



Supersymmetric dark matter?

LSP – Lightest SUSY particle:

- **Weakly interacting**
  Neutral (electric+color)
- **Massive**
- **Stable (R-parity)**

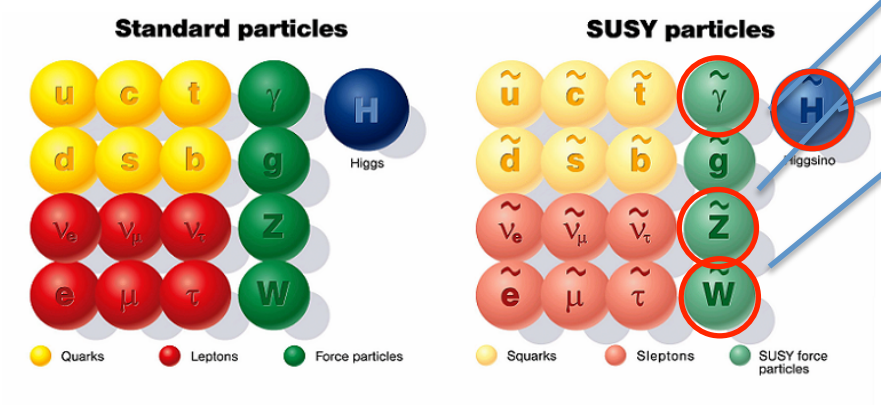
Possible candidates for LSP:

- **Part of ordinary SUSY spectrum:**

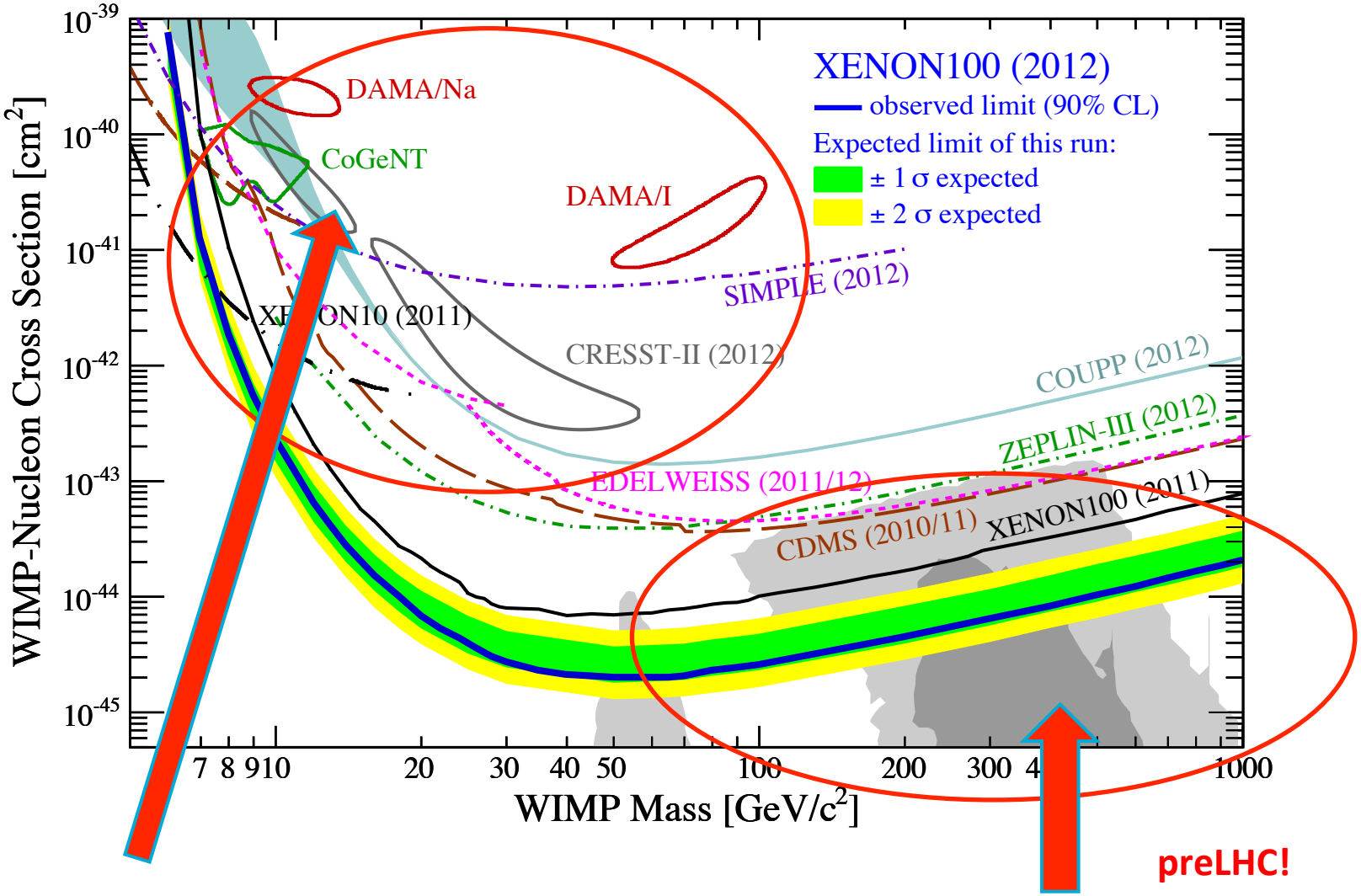
Neutralino: mass state of bino, wino, higgsinos

Sneutrino – not good (LEP, DM searches)

- Add gravity: **gravitino** LSP
- Add axion: **axino** LSP



Direct Detection AD 2011 - Before LHC



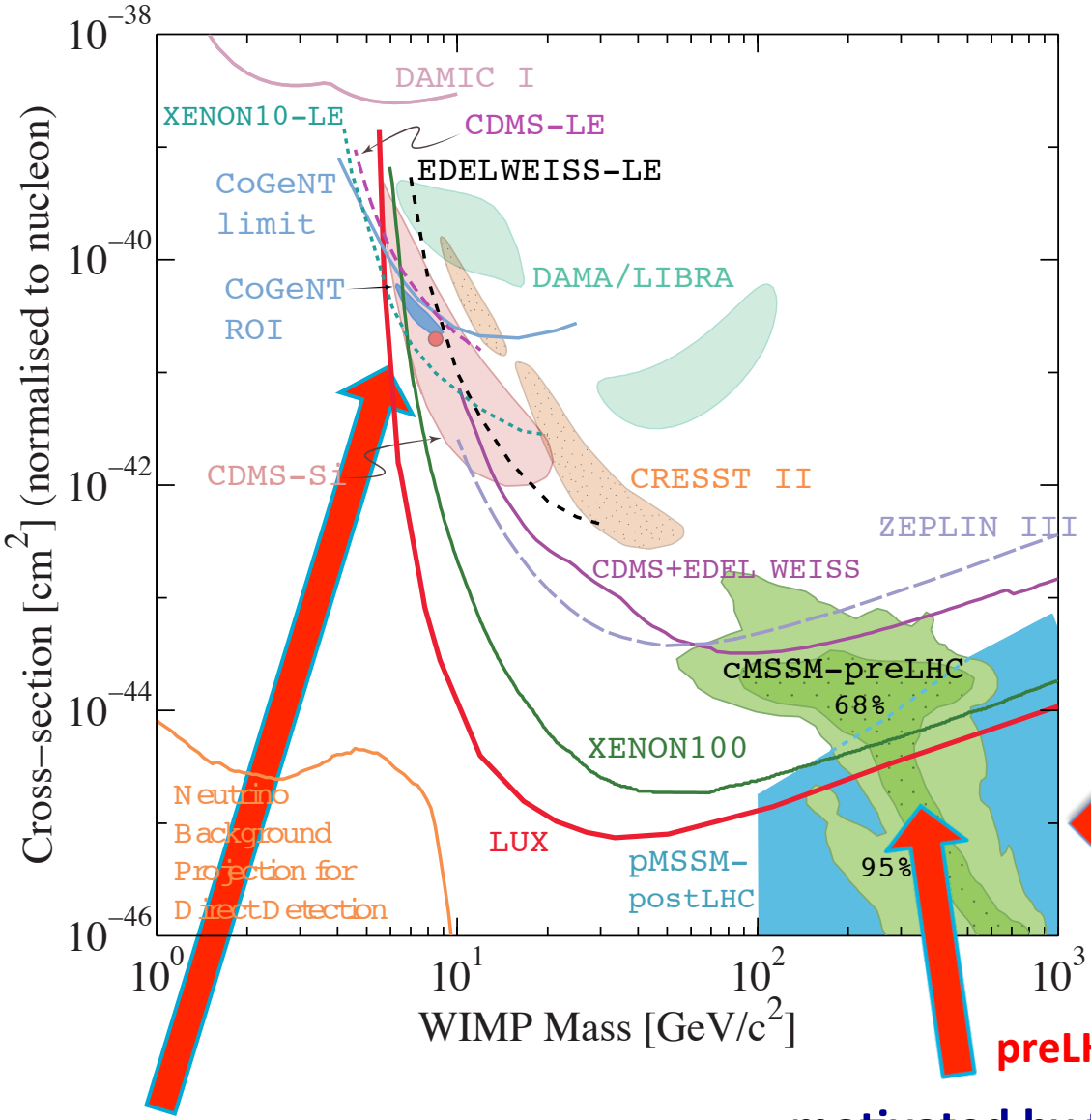
preLHC!

Confusion region

motivated by theory (SUSY)

MasterCode, BayesFITS

Direct Detection Nov. 2013



PDG update 2013 (1204.2373)

LHC: theory region has moved down and right

in a very specific way

Smoking gun of SUSY?

preLHC!

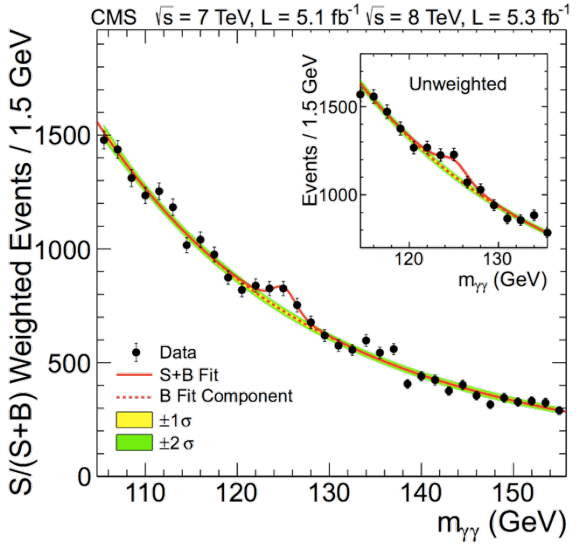
motivated by theory (SUSY)

MasterCode, BayesFITS

Confusion region gone

Main news from the LHC so far…

- **SM-like Higgs particle at ~126 GeV**



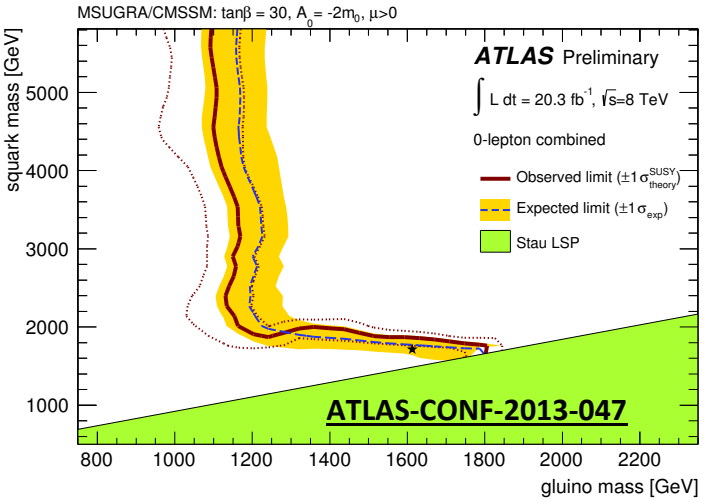
- **No (convincing) deviations from the SM**

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{LHCb}} = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{CMS}} = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

- **Stringent lower limits on superpartner masses**



SUSY masses pushed to 1 TeV+ scale…

…and from the media…

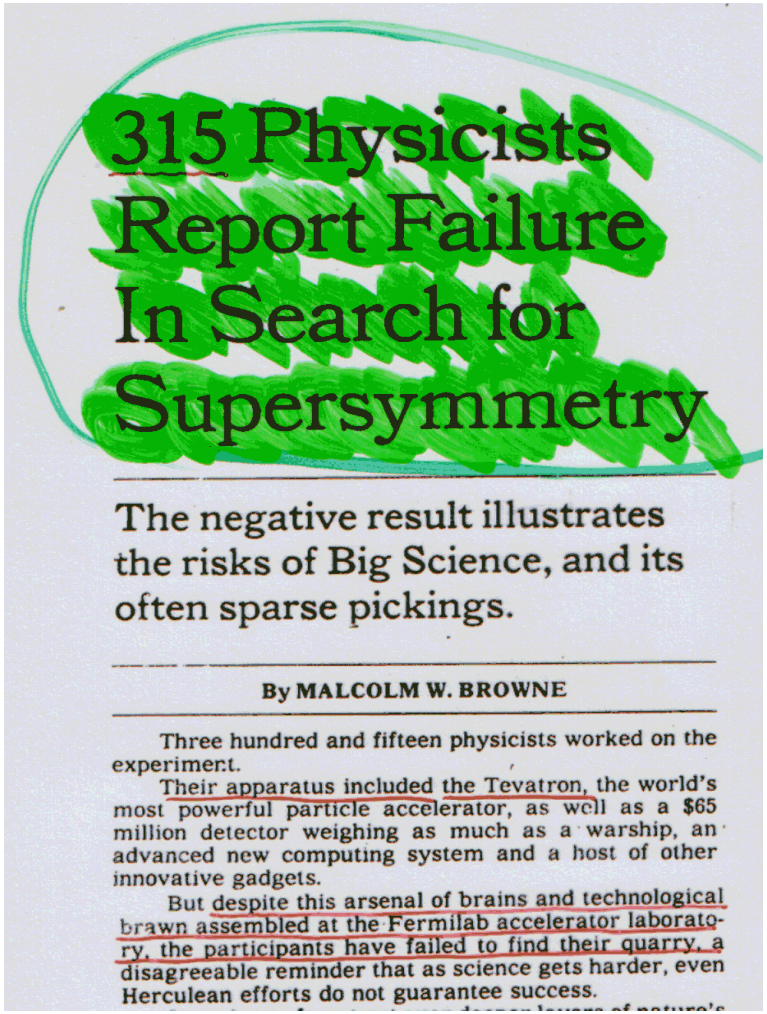
Is Supersymmetry Dead?

The grand scheme, a stepping-stone to string theory, is still high on physicists' wish lists. But if no solid evidence surfaces soon, it could begin to have a serious PR problem

SCIENTIFIC AMERICAN™

April 2012

Nothing new…



315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates the risks of Big Science, and its often sparse pickings.

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

CDF, ~2003

The 126 GeV SM-Like Higgs Boson

A blessing or a curse for SUSY?

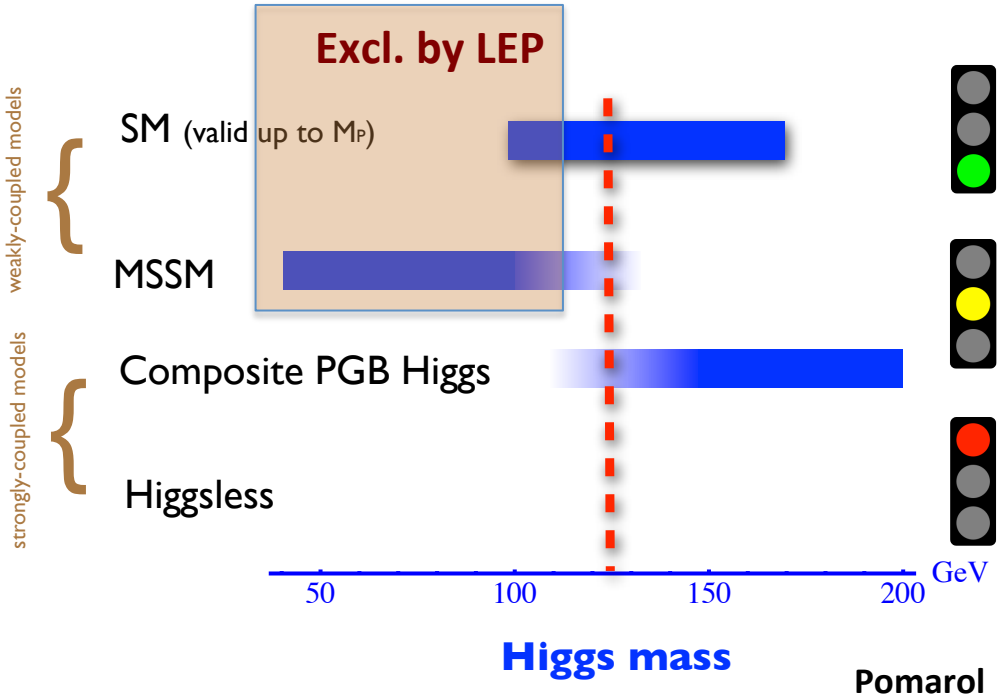
The 126 GeV Higgs Boson and SUSY

A blessing…

- Fundamental scalar --> SUSY
- Light and SM-like --> SUSY

Low energy SUSY prediction:
Higgs mass up to ~135 GeV

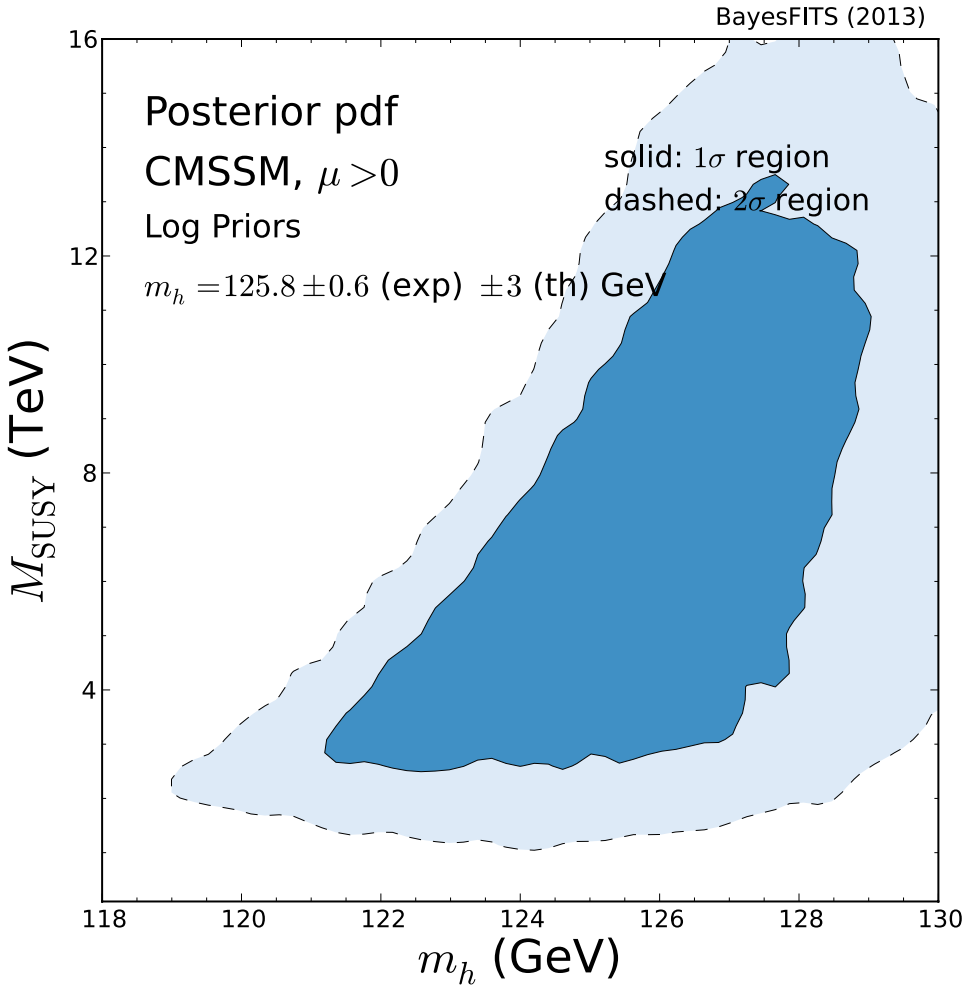
Constrained SUSY prediction:
SM-like Higgs with mass
up to ~130 GeV



The 126 GeV Higgs Boson and SUSY

A curse…

Only m_h~126 GeV and CMS lower bounds on SUSY applied.



126 GeV Higgs-> Multi-TeV SUSY

$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

Constrained Minimal Supersymmetric Standard Model (CMSSM)

G. L. Kane, C. F. Kolda, L. Roszkowski and J. D. Wells, Phys. Rev. D 49 (1994) 6173

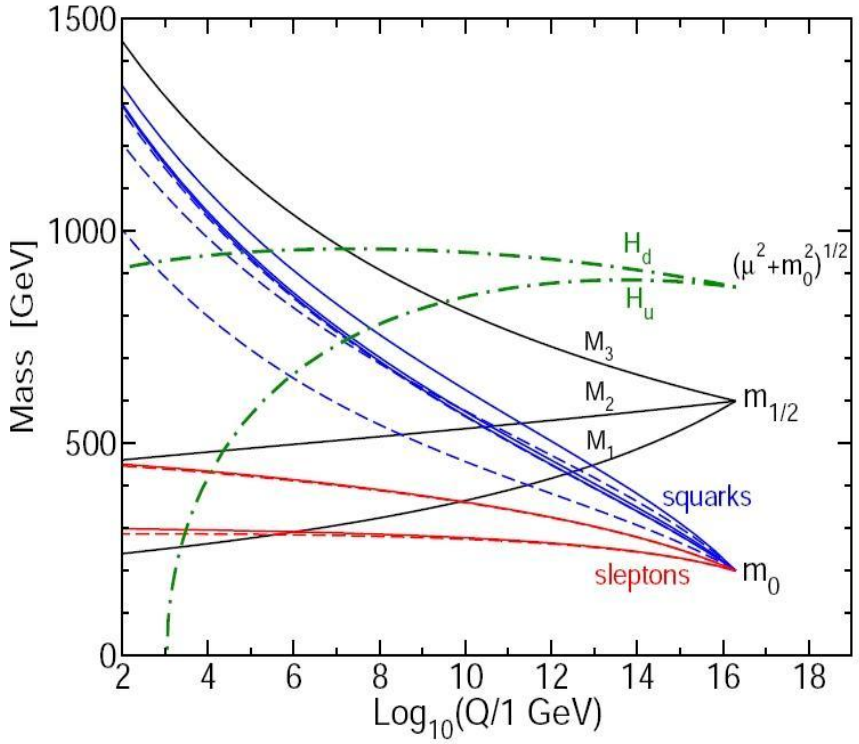


figure from hep-ph/9709356

At $M_{\rm GUT} \simeq 2 \times 10^{16}$ GeV:

- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- scalars $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m^2_0$
- 3–linear soft terms $A_b = A_t = A_0$
- radiative EWSB $\mu^2 = \frac{m^2_{H_b} - m^2_{H_t} \tan^2\beta}{\tan^2\beta - 1} - \frac{m^2_Z}{2}$
- five independent parameters: $m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)$
- well developed machinery to compute masses and couplings

In general supersymmetric SM too many free parameters

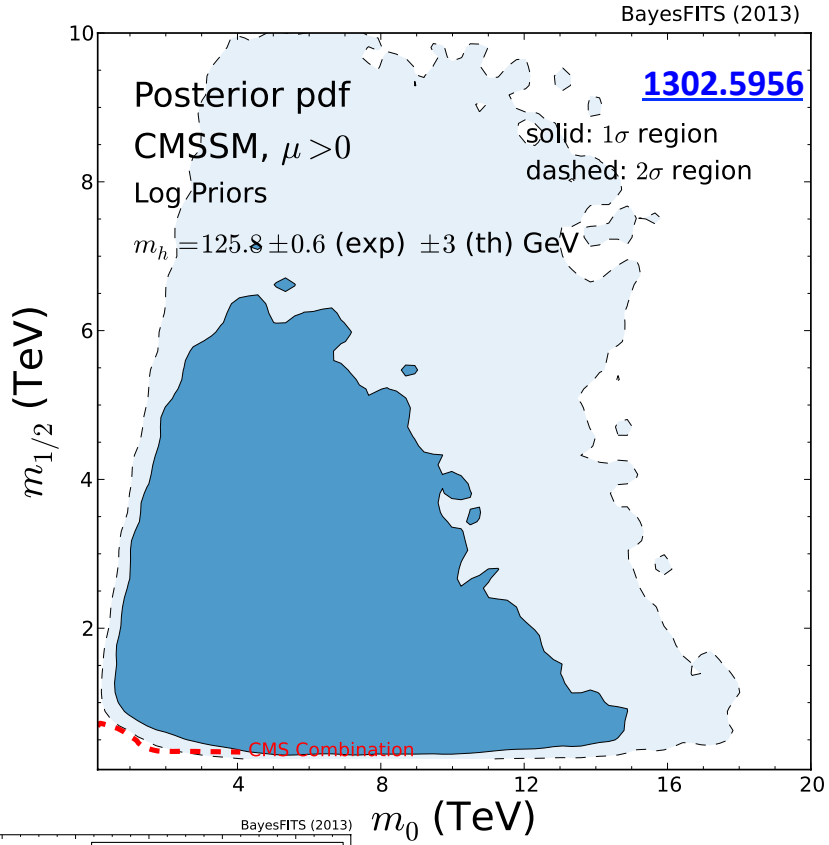
~126 GeV Higgs in the CMSSM

- **Include only m_h~126 GeV and lower limits from direct SUSY searches**

$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\,\mathrm{GeV})^2}{\sigma^2+\tau^2}}$$

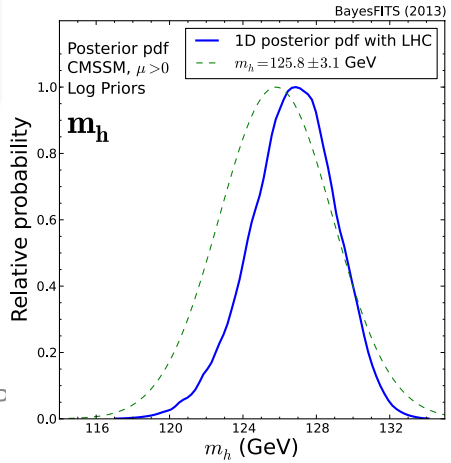
$$\sigma = 0.6\ \mathrm{GeV}, \tau = 2\ \mathrm{GeV}$$

We use DR-bar approach (SoftSusy). It gives larger m_h.



A curse…

~126 GeV Higgs mass implies multi-TeV scale for SUSY



A weak upper bound on M_SUSY

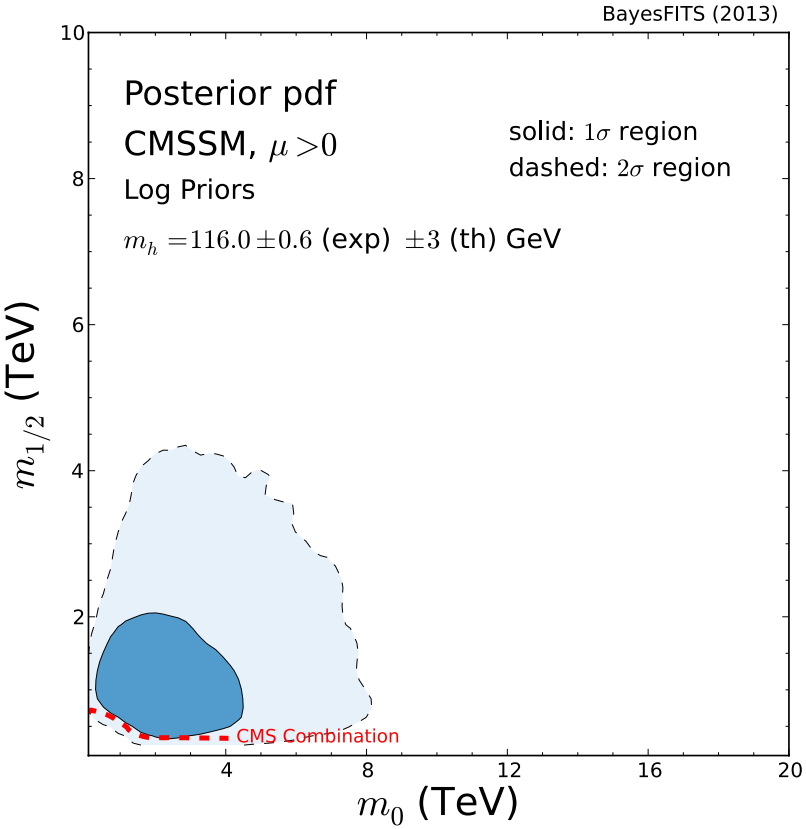
…except at very small tanb->1 where it goes away

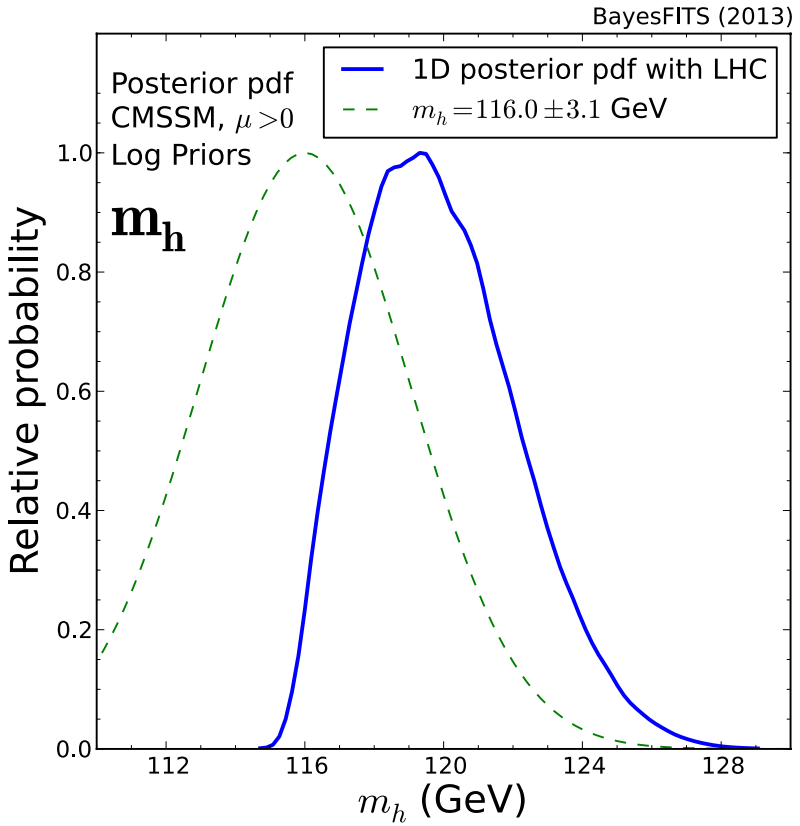
Consistent with:

- **SUSY direct search lower limits at LHC**
- **constraints from flavor**

126 GeV - worst possible value (G. Giudice)

If m_h were, say, 116 GeV…



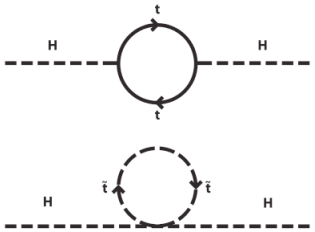


…significant tension with LHC bounds

Higgs boson mass and SUSY

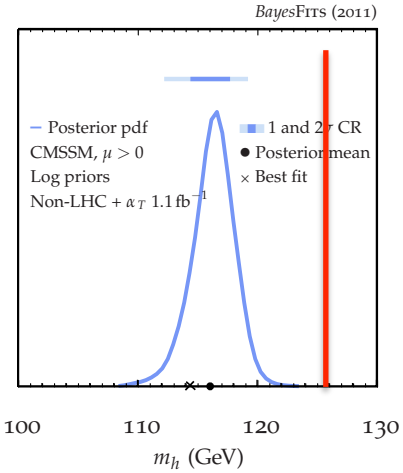
➢ **1 loop correction**

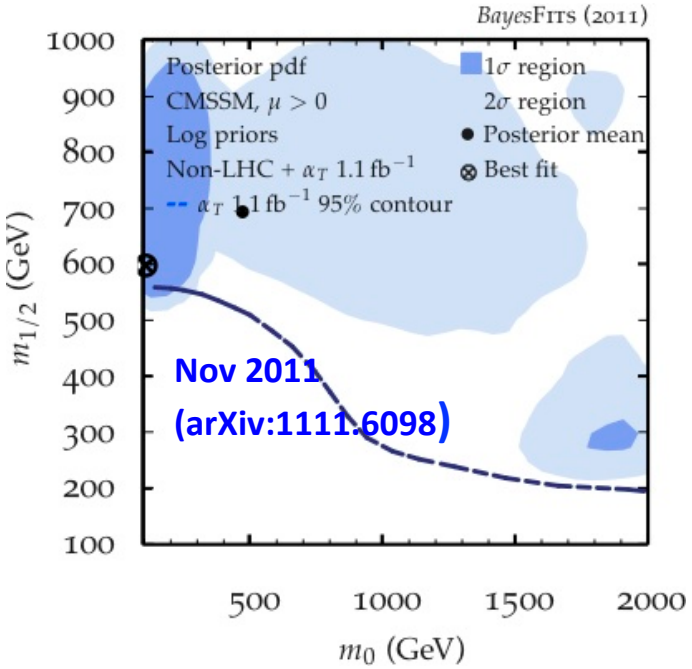
$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right)\right]$$

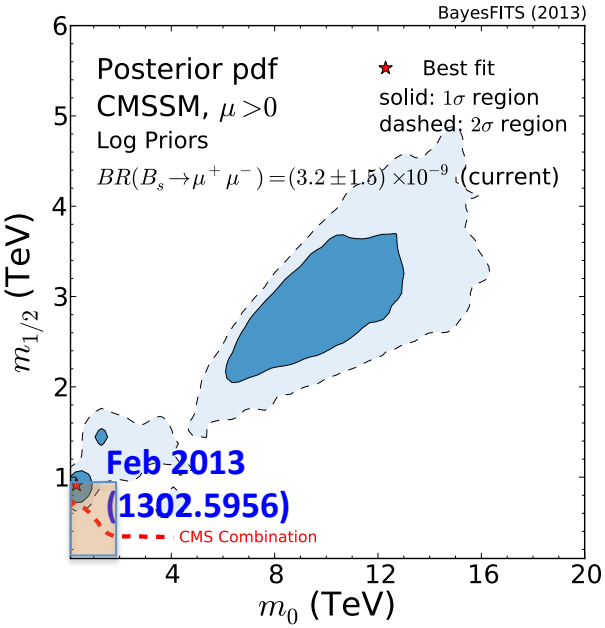


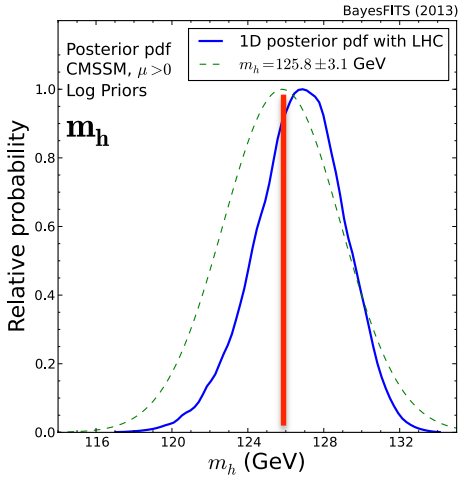
$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$$X_t = A_t - \mu \cot\beta$$



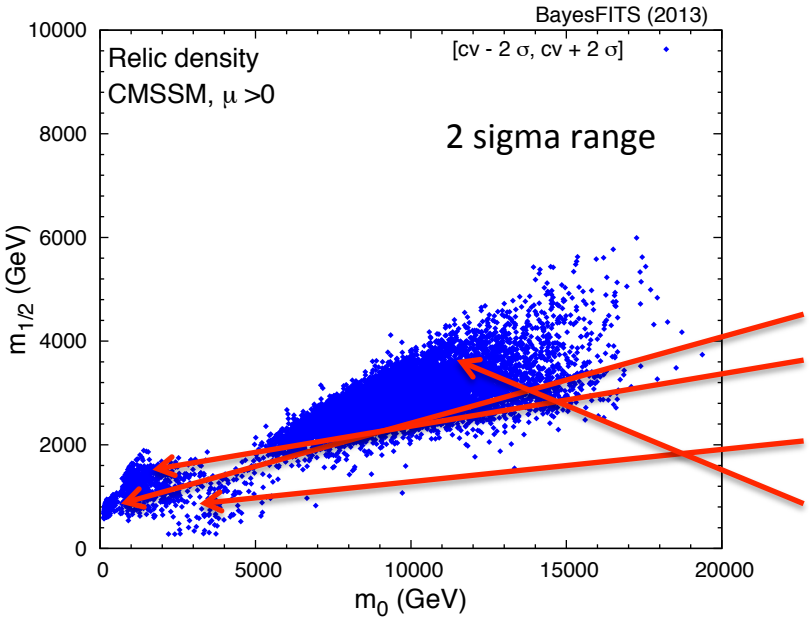




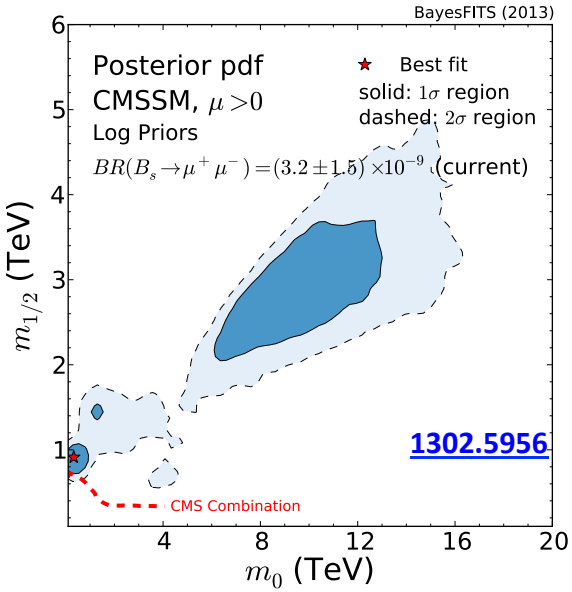


Higgs mass plus dark matter density

- **Unified SUSY: relic density is typically 1-2 orders of magnitude too large**
- **Effect of LHC direct SUSY limits much weaker**



All constraints included -->



Remaining mechanisms of reducing it to correct range:

- ✧ **neutralino-stau coannhilation**
- ✧ **pseudoscalar Higgs A resonance**
- ✧ **focus point/hyperbolic branch region**
- ✧ **~1 TeV higgsino LSP at large MSUSY**
- ✧ **and (very rare) LSP-stop coannihilation**

Akula+Nath, 1207.1839

$$\Omega h^2 \propto m_A^4 / \tan^2 \beta$$

Scan with all other relevant constraints imposed

CMSSM: these are the only DM-favored regions

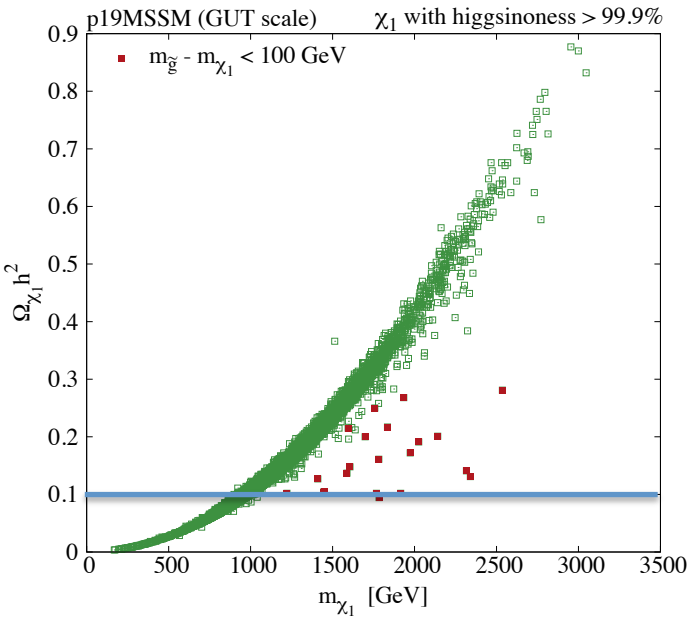
~1 TeV higgsino DM

✧ Generic, present in many SUSY models
(both GUT-based and not)

Condition: gauginos heavy enough

Unified SUSY:
First pointed out
in NUHM in 0903.1279

$$\text{When } m_{\tilde{B}} \gtrsim 1\,\text{TeV}:$$
$$\text{easiest to achieve } \Omega_\chi h^2 \simeq 0.1$$
$$\text{when } m_{\tilde{H}} \simeq 1\,\text{TeV}$$

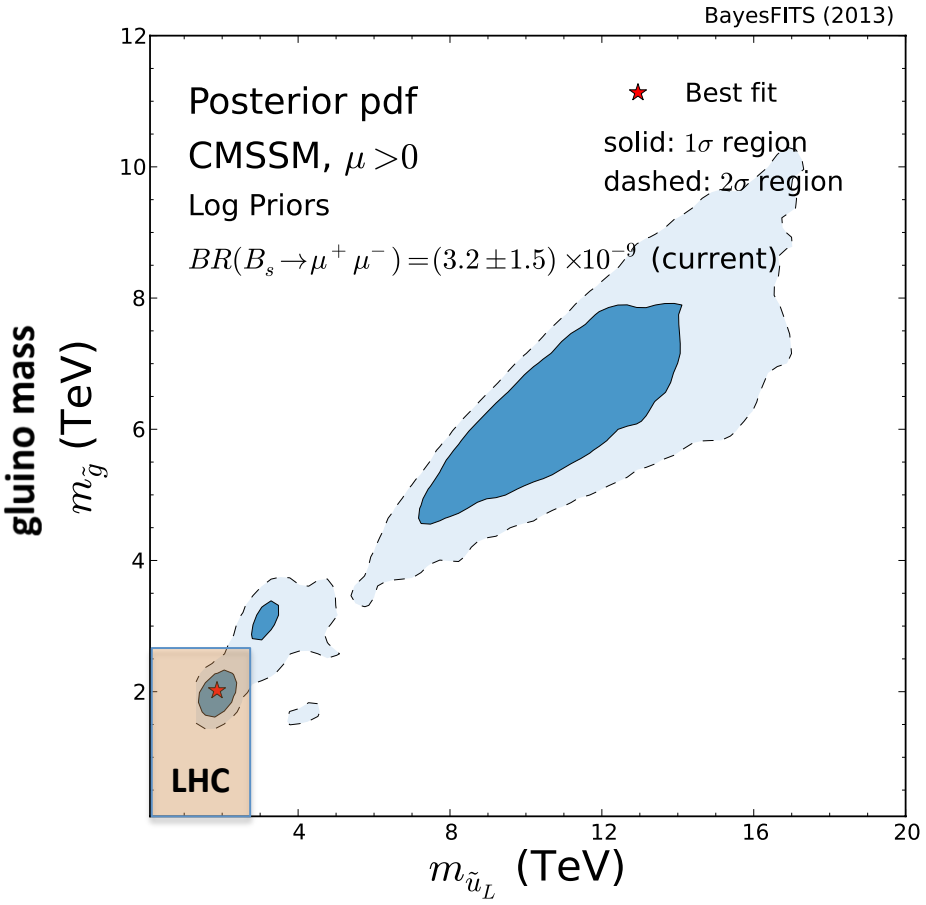


✧ Implied by ~126 GeV Higgs mass
and relic density

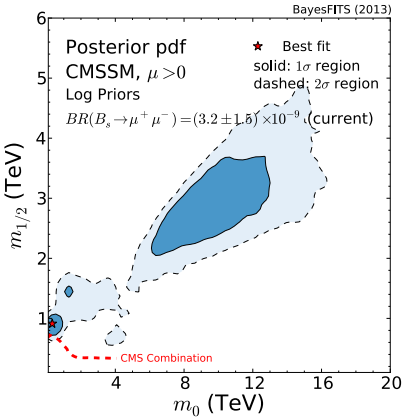
✧ Smoking gun of SUSY!?

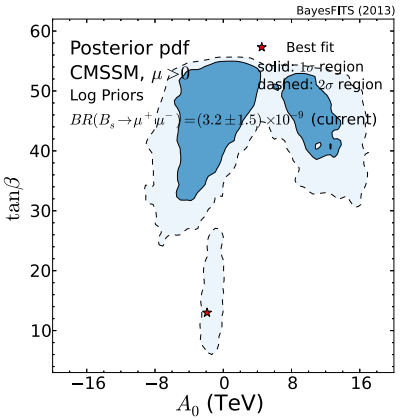
Can such multi-TeV ranges of SUSY parameters be experimentally tested?

Are we done with the LHC?



Squark mass (1st or 2nd gen)



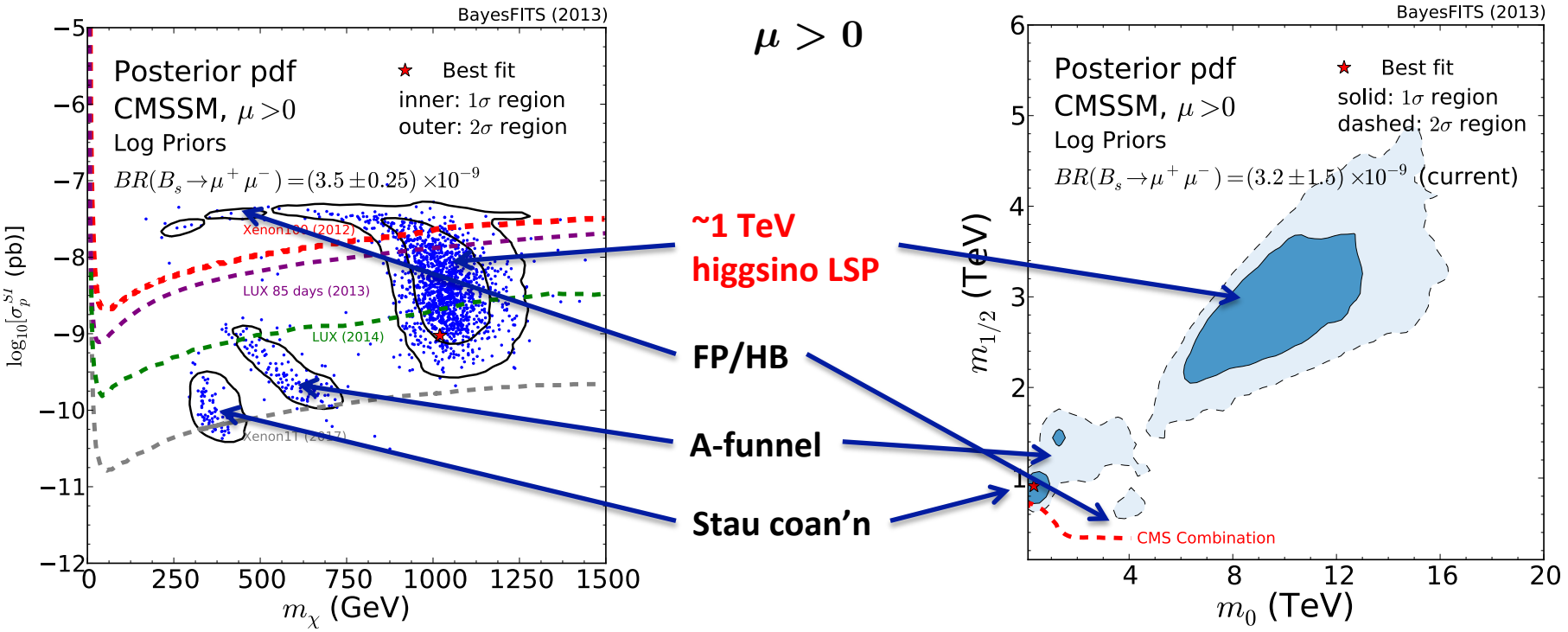


LHC14 reach:
Gluino: ~2.7 GeV
Squarks: ~3 TeV

LHC – only stau coannihilation will be +/- covered

…signal ``not guaranteed''

CMSSM and 1-tonne DM detectors

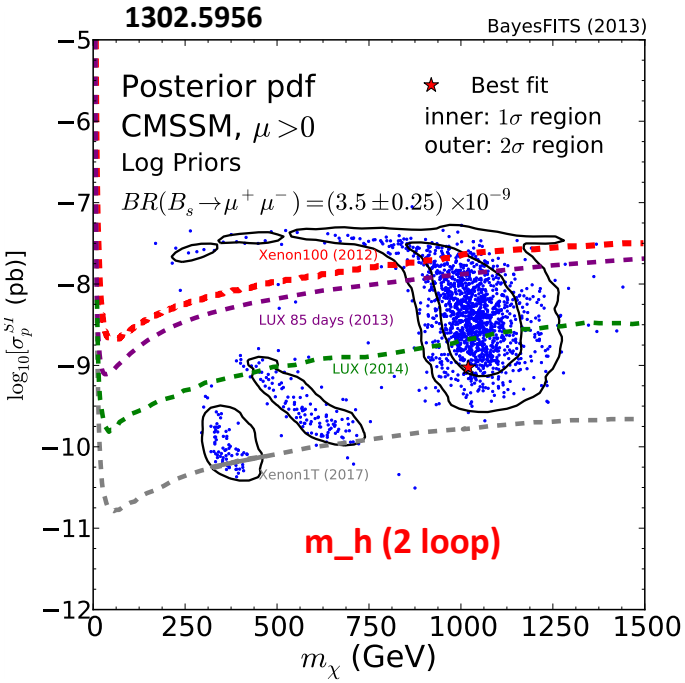


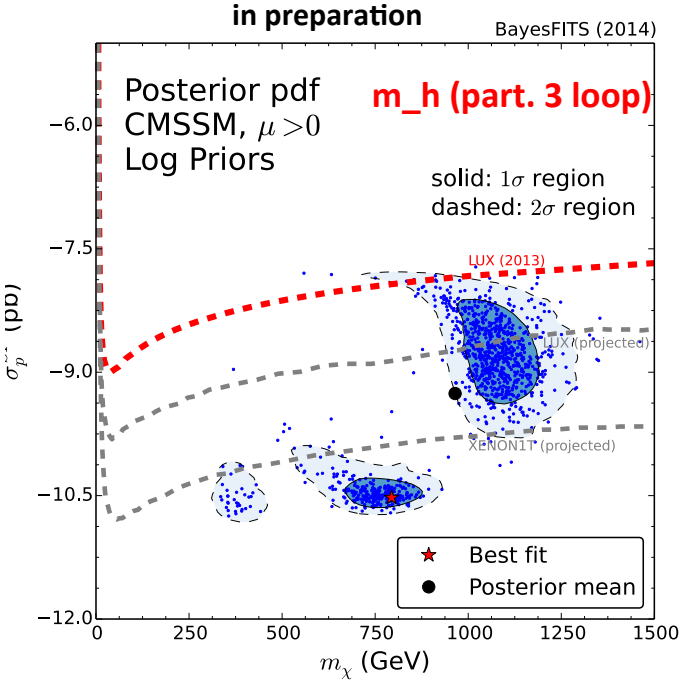
Focus point region ruled out by LUX (tension with X100)

~1TeV higgsino DM: exiting prospects for LUX, X100 and 1t detectors

Update 2014

$\mu > 0$

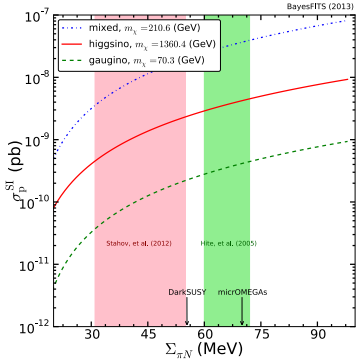




- **LUX limit: FP region practically excluded**
- **Theory sigma_p down by ~1 order of mag**

Recent (micrOmegas3.1):

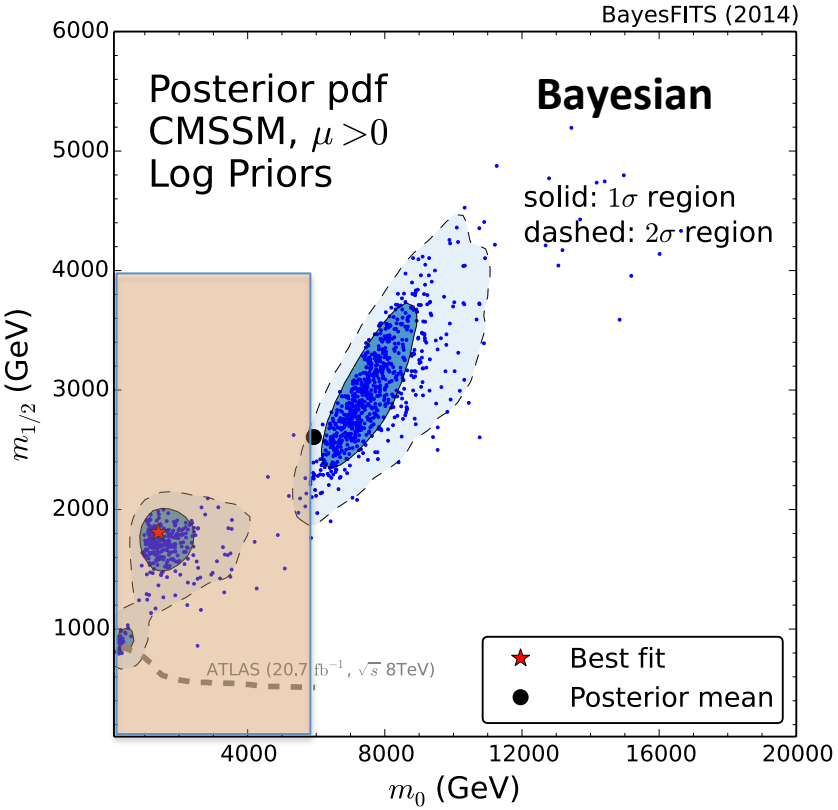
$$\sigma_{\pi N} = 34 \pm 2\,\mathrm{MeV}$$
$$\sigma_s = 42 \pm 5\,\mathrm{MeV}$$



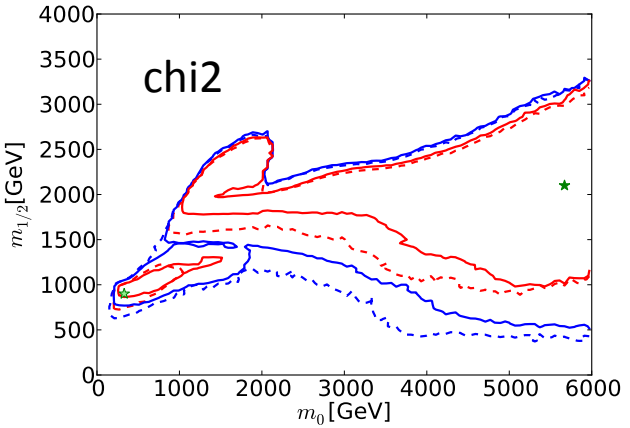
- **Effect of 3 loop corr's to m_h: not very significant**

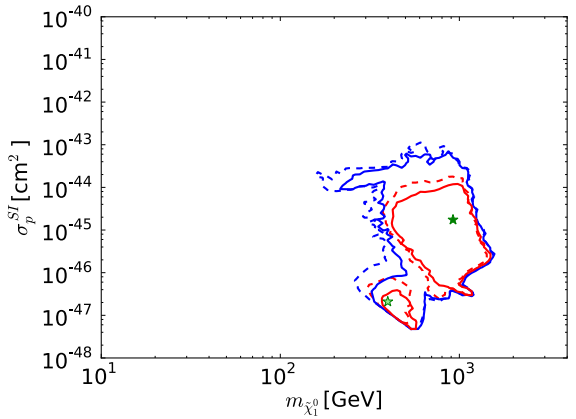
Bayesian vs chi-square analysis
(updated to include 3loop Higgs mass corrs)

In preparation



Buchmueller et al [1312.5250](1312.5250)



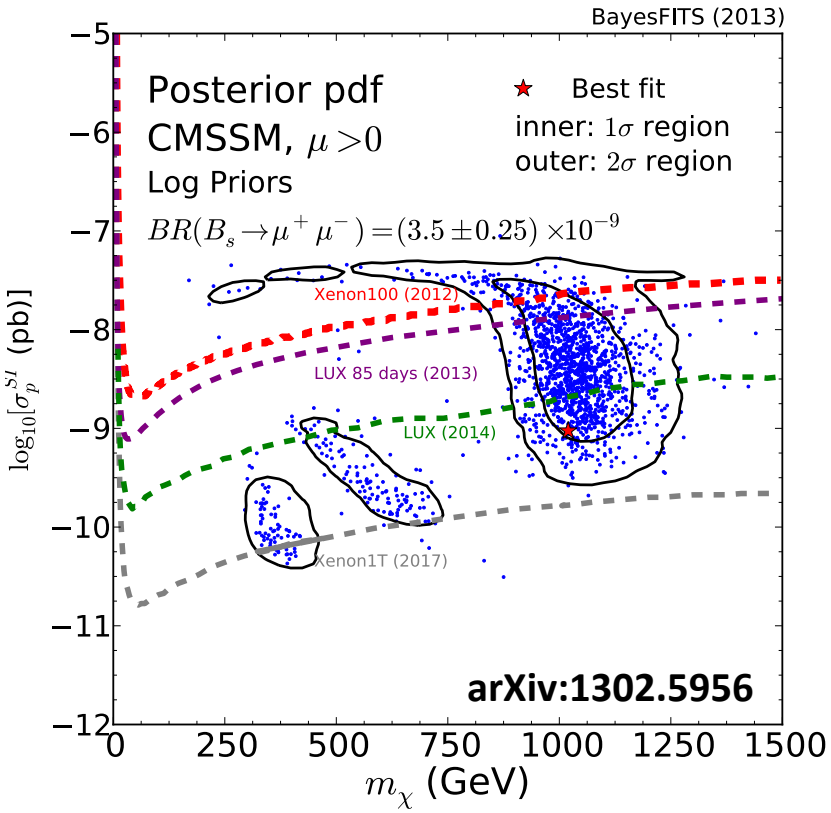


Reasonably good agreement in overlapping region

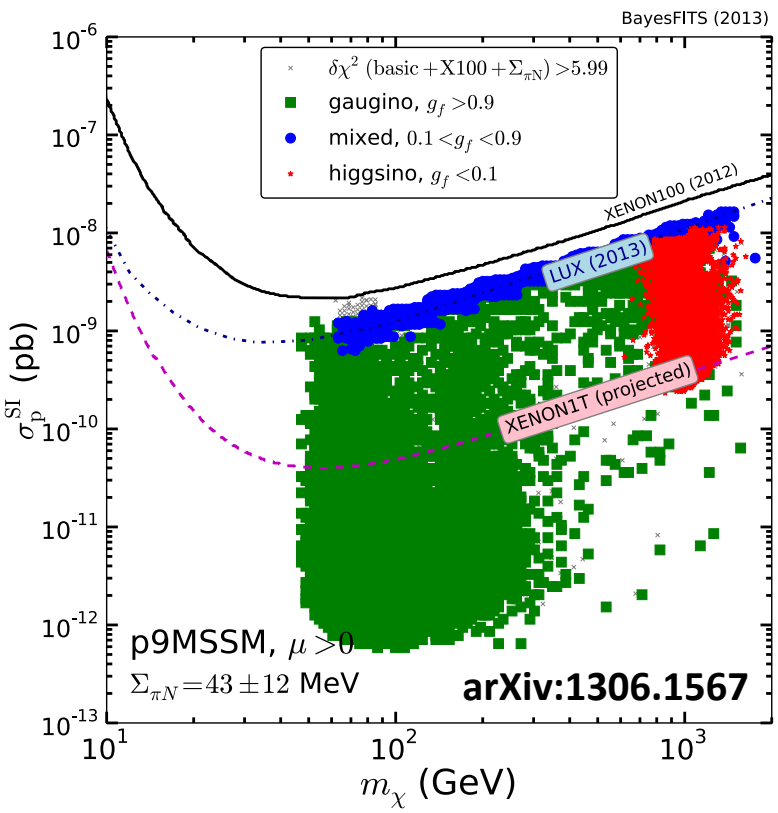
~1 TeV higgsino-like WIMP: implied by ~126 GeV Higgs -> large m1/2 and m0

Unified vs pheno SUSY

Unified SUSY (Constrained MSSM)



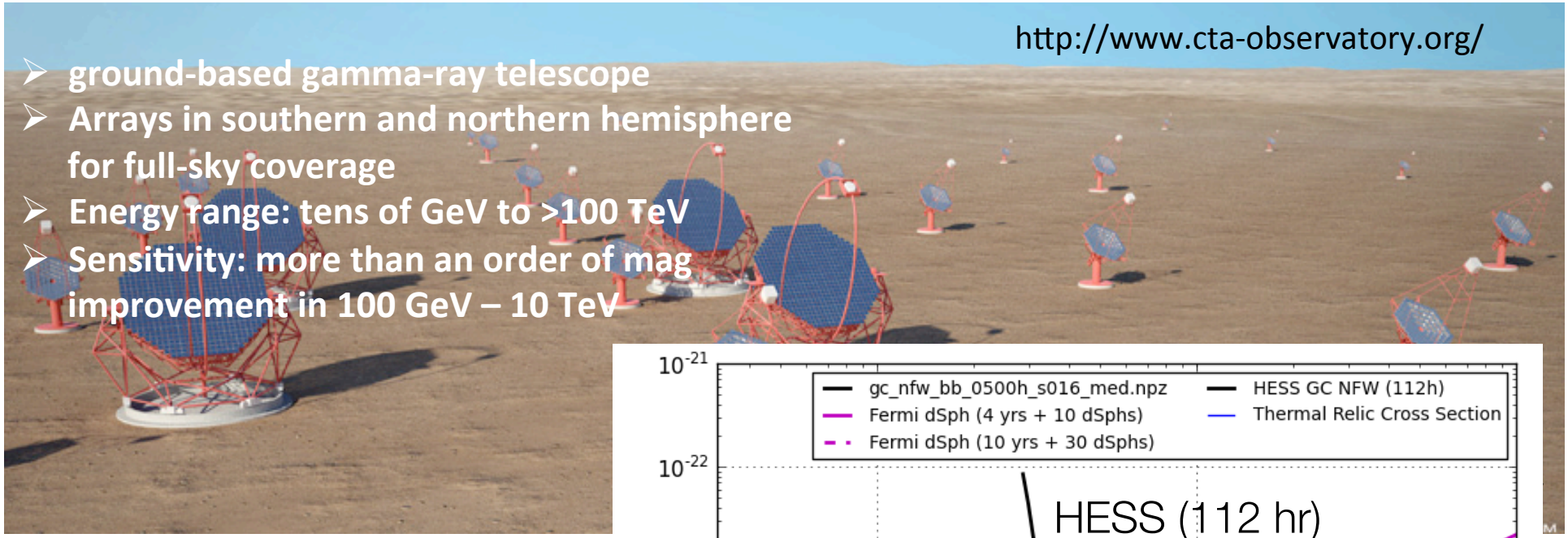
General SUSY (p9MSSM)



MSSM:

- **much bigger ranges allowed**
- **~1 TeV higgsino DM: prospects for detection similar to unified SUSY**
- **New LUX limit -> starts to exclude mixed (bino-higgsino) neutralino**

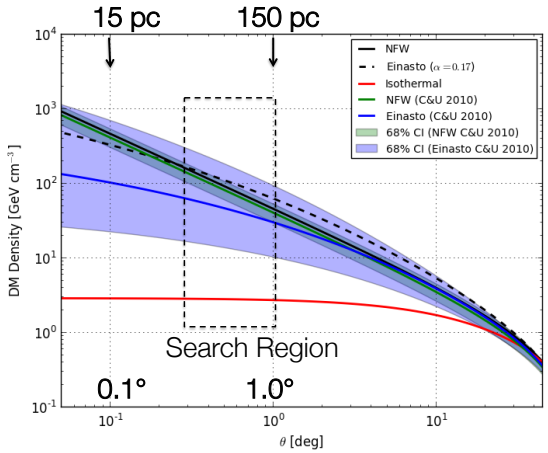
CTA – New guy in DM hunt race

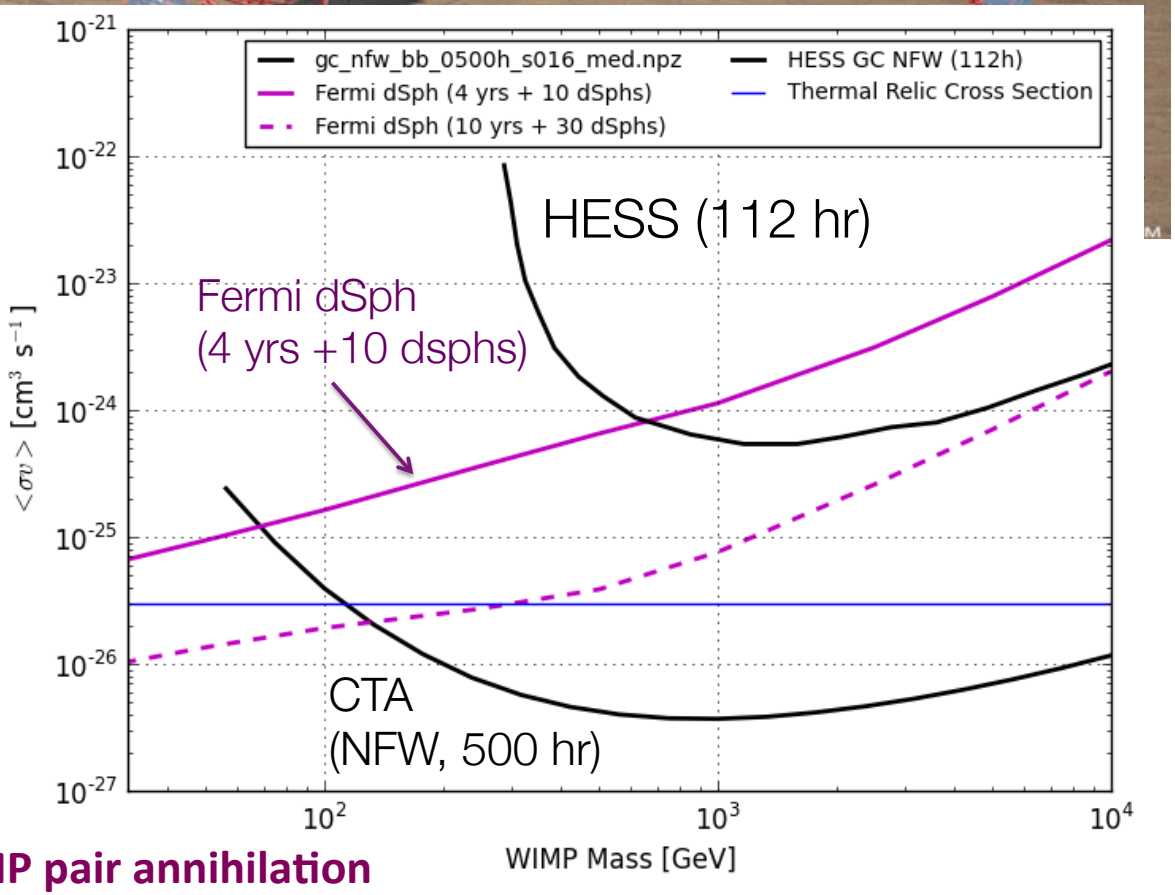


http://www.cta-observatory.org/

- ground-based gamma-ray telescope
- Arrays in southern and northern hemisphere for full-sky coverage
- Energy range: tens of GeV to >100 TeV
- Sensitivity: more than an order of mag improvement in 100 GeV – 10 TeV

Galactic Center DM Halo

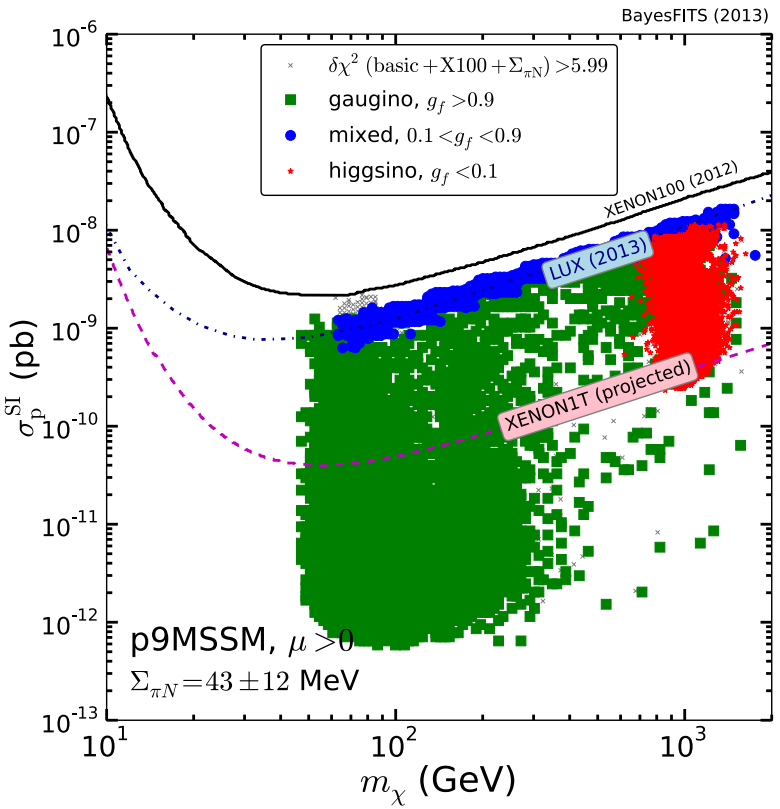


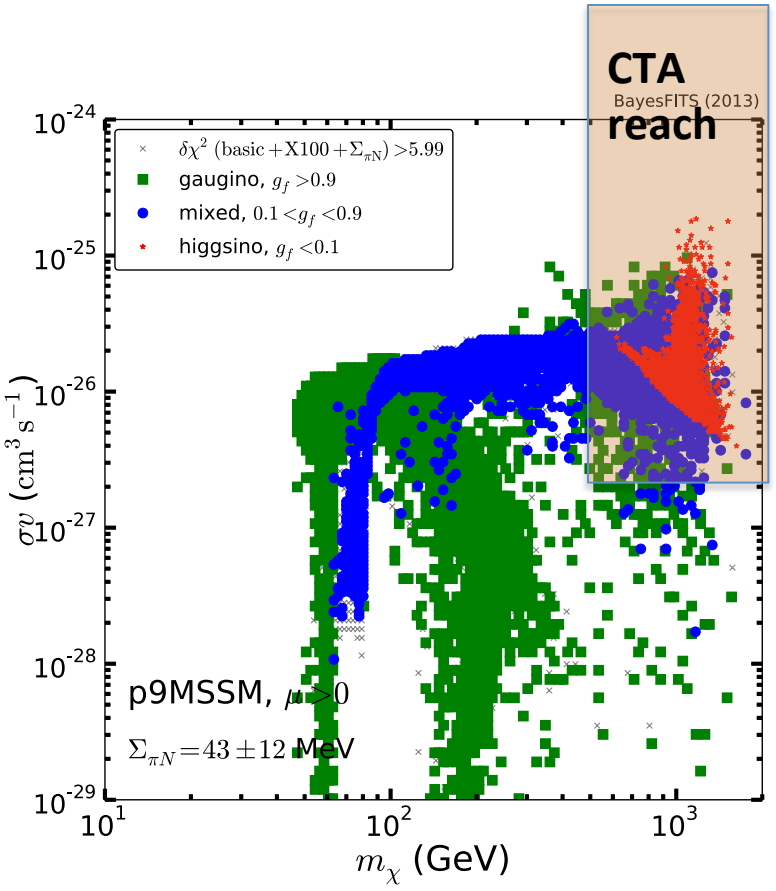


diffuse gamma radiation from WIMP pair annihilation

CTA and SUSY DM

Direct Detection





General SUSY (p9MSSM) **arXiv:1306.1567**

MSSM:

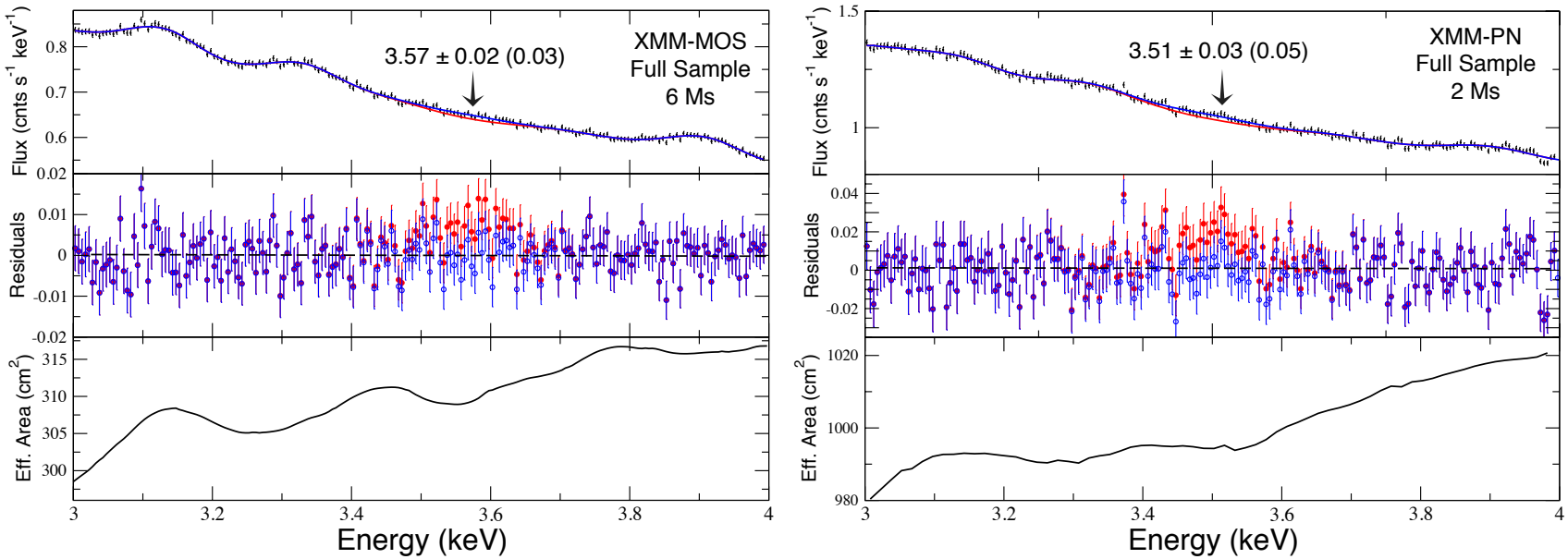
- **CTA to probe large WIMP masses**
- **~1 TeV higgsino DM: to be completely covered by DD and CTA**

X-Ray Signal of DM?

➢ **3.5 keV line is claimed to be seen in clusters of galaxies and in M31**

Bulbul, et al., 1402.2301
Boyarsky, et al., 1402.4119

(XMM data)



Combined data significance 4.4sigma

Lots of theoretical speculations:

- **Sterile neutrino decaying into an active one + photon**
- **Sterile nu -> axino**
- **Sterile nu -> axion-like particle**
- **…**

Gazing into a crystal ball...


CREDIT
CRUNCH
AHEAD


We need a genuine
WIMP signal…
… from more than one
DM search experiment

To take home:

- DM: jury is still out, discovery claims come and go…
- SUSY neutralino remains most popular choice
- Higgs of 126 GeV → ~1TeV (higgsino) DM – generic prediction of simple, generic SUSY:
  - To be probed by 1-tonne DM detectors
  - Big bite by LUX already in 2014
  - Independent probe by CTA
  - Far beyond direct LHC reach

Smoking gun of SUSY!?

SUSY may be too heavy for the LHC

DM searches may hopefully come to the rescue

- 3.5 keV X-ray line as DM signal? Too early too tell…