Dark Matter implied by Higgs Boson

A come back of the higgsino Kid

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INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY
FNP Foundation for Polish Science
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Grants for innovation. Project operated within the Foundation for Polish Science "WELCOME" co-financed by the European Regional Development Fund

Outline

- ✧ Brief Introduction
- ✧ Implications of mh~126 GeV and direct limits on SUSY:

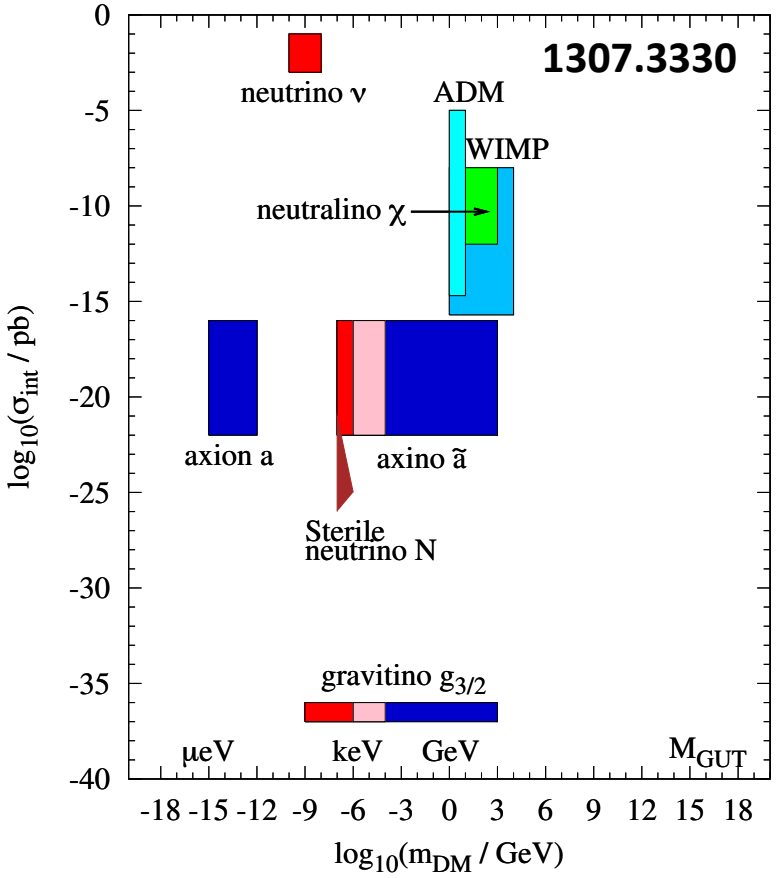
DM: ~1 TeV higgsino

- ✧ Prospects for detection
- ✧ Issue of fine tuning
- ✧ Summary

Based on:

- arXiv:1302.5956, Two ultimate tests of constrained supersymmetry, K. Kowalska, L. Roszkowski, E. M. Sessolo JHEP 1306 (2013) 078
- arXiv:1402.1328, Low fine tuning in the MSSM with higgsino dark matter and unification constraints, K. Kowalska, L. Roszkowski, E. M. Sessolo, S. Trojanowski JHEP 1404 (2014) 166
- arXiv:1405.4289, What next for the CMSSM and the NUHM: Improved prospects for superpartner and dark matter detection, L. Roszkowski, E. M. Sessolo, A. J. Williams
- and some earlier papers

Well-motivated candidates for dark matter



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

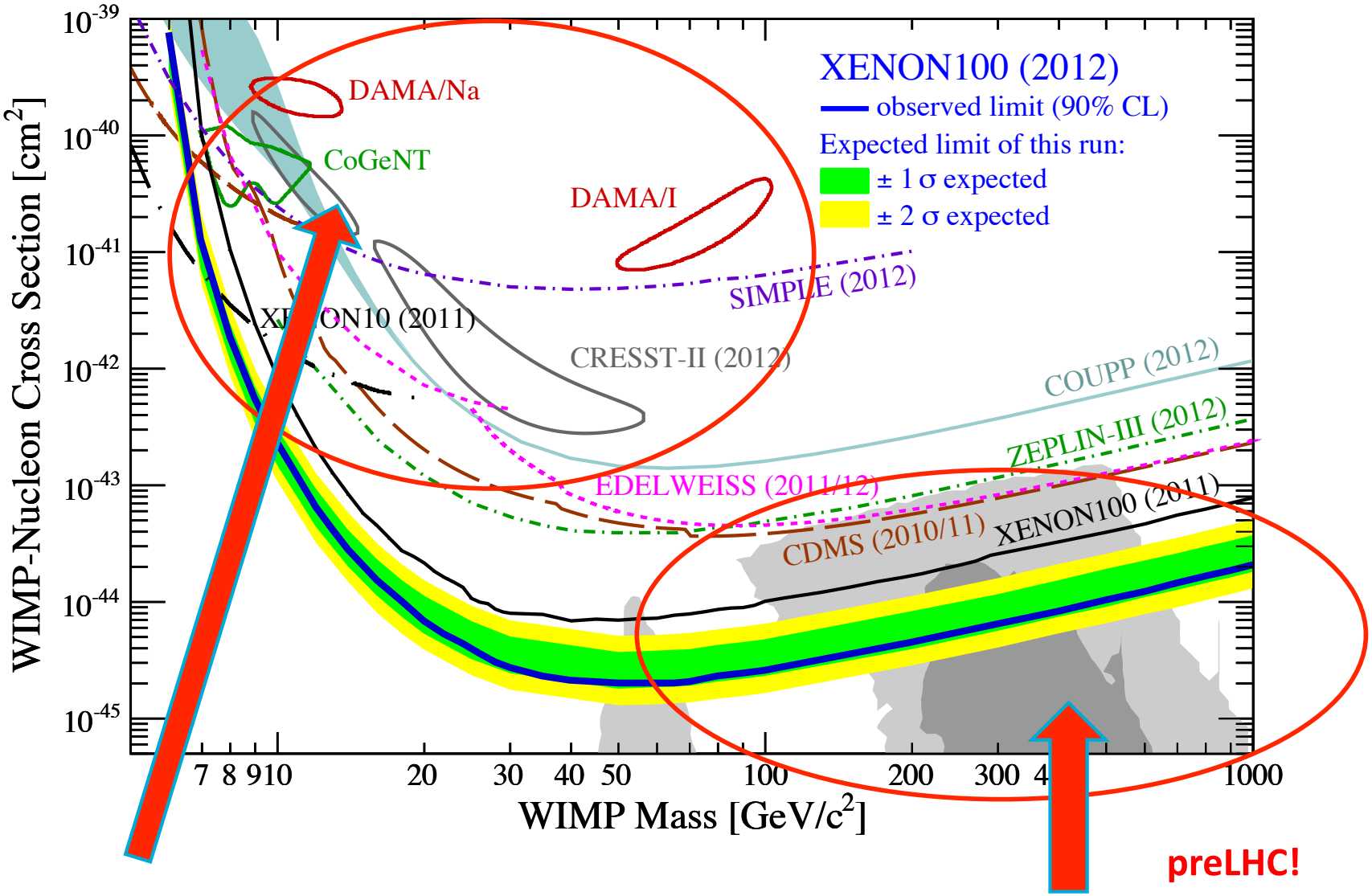
SUSY

- 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**

Direct Detection AD 2011 - Before LHC

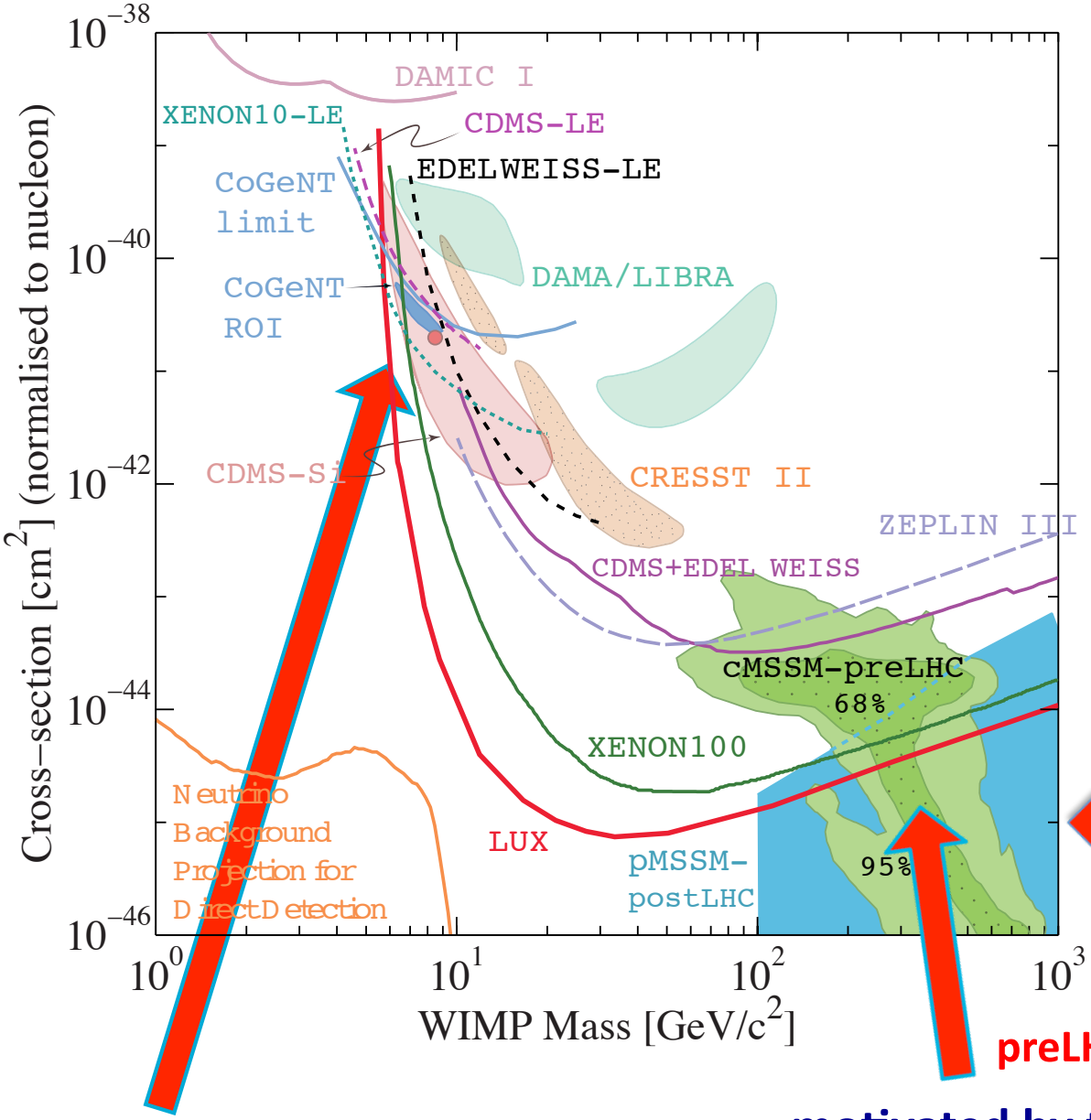


Confusion region

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!

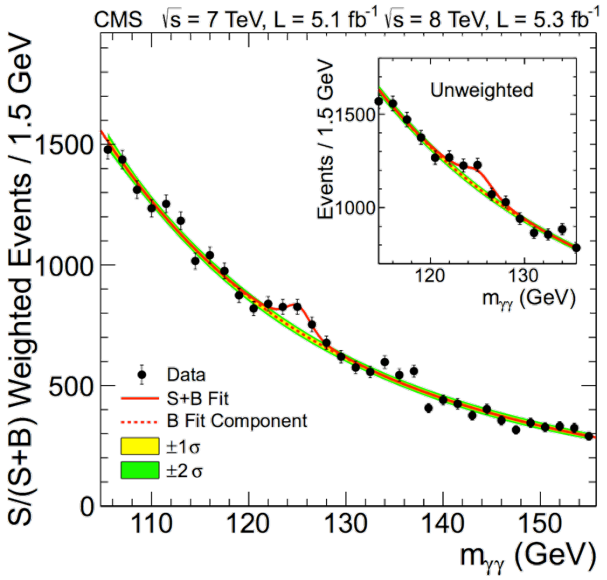
motivated by theory (SUSY)

MasterCode, BayesFITS

Confusion region gone

Main news from the LHC so far…

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

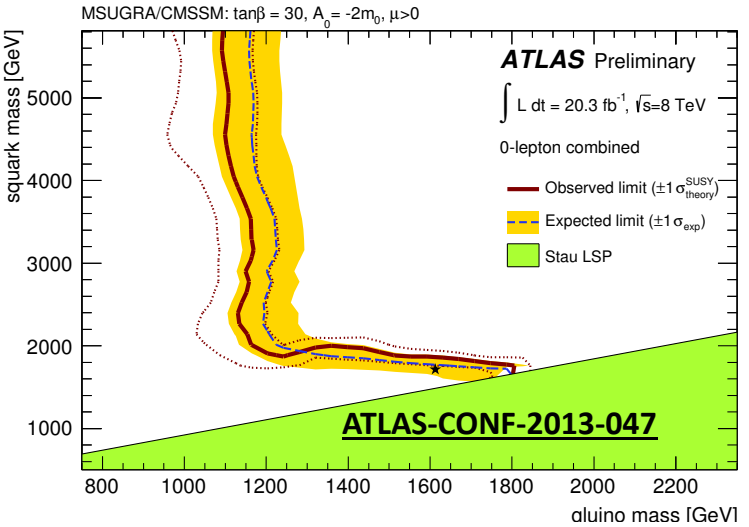


- **No (convincing) deviations from the SM**

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{LHCb}} = (2.9^{+1.1}_{\ \ \ldots}) \times 10^{-9}$$
$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{CMS}} = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

with the SM TA expectations [56] (see also

- **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

The 126 GeV SM-Like Higgs Boson

A blessing or a curse for SUSY?

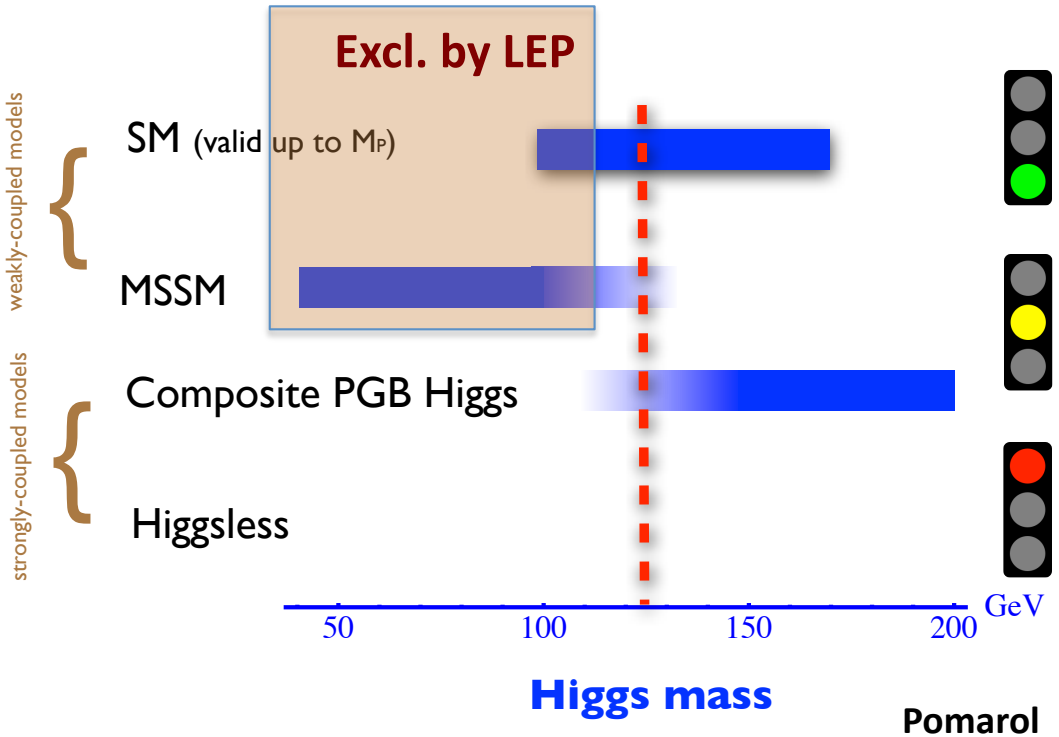
The 126 GeV Higgs Boson and SUSY

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



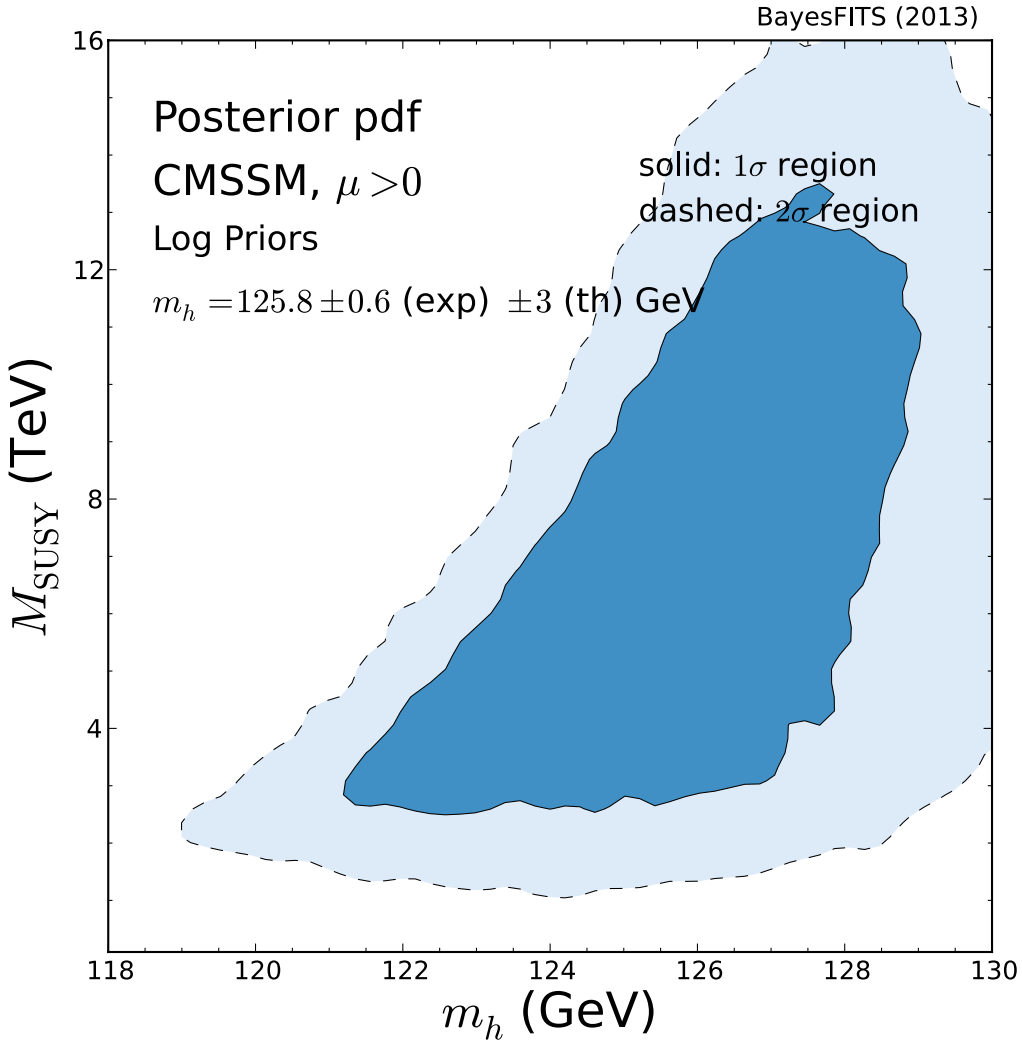
Pomarol

The 126 GeV Higgs Boson and SUSY

A curse…

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

126 GeV Higgs-> Multi-TeV SUSY



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

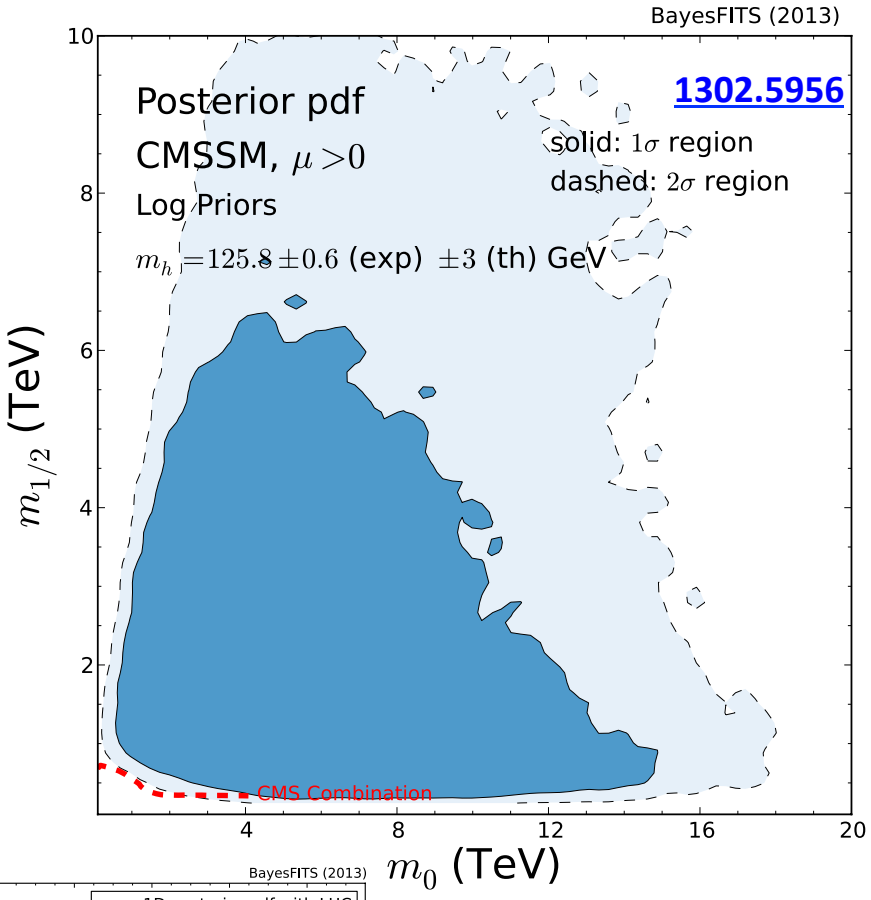
~126 GeV Higgs in the CMSSM

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

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

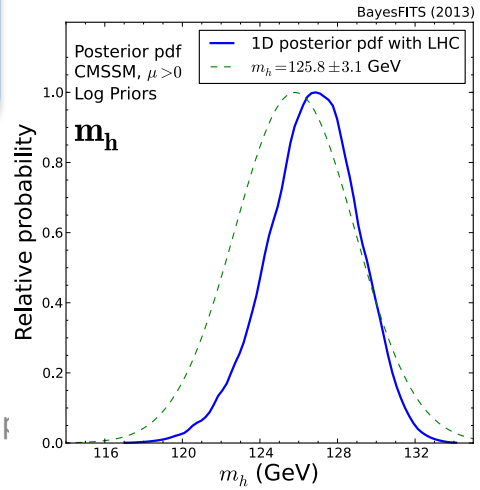
$$\sigma = 0.6\ \mathrm{GeV}, \tau = 2\ \mathrm{GeV}$$

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



A curse…

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



Consistent with:

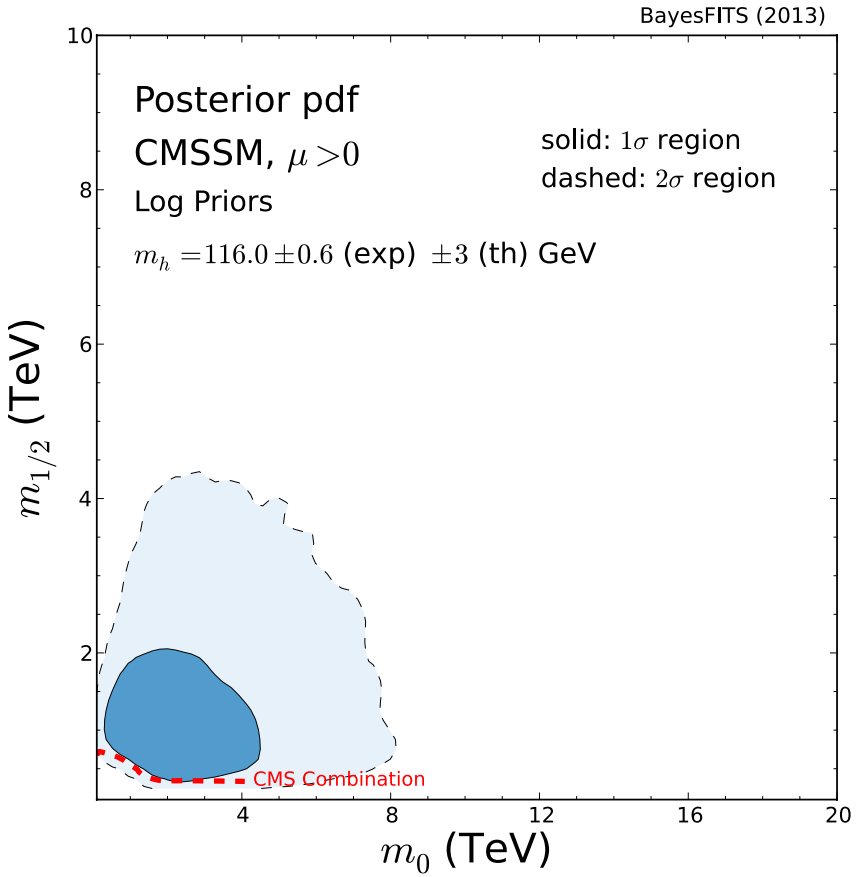
- **SUSY direct search lower limits at LHC**
- **constraints from flavor**

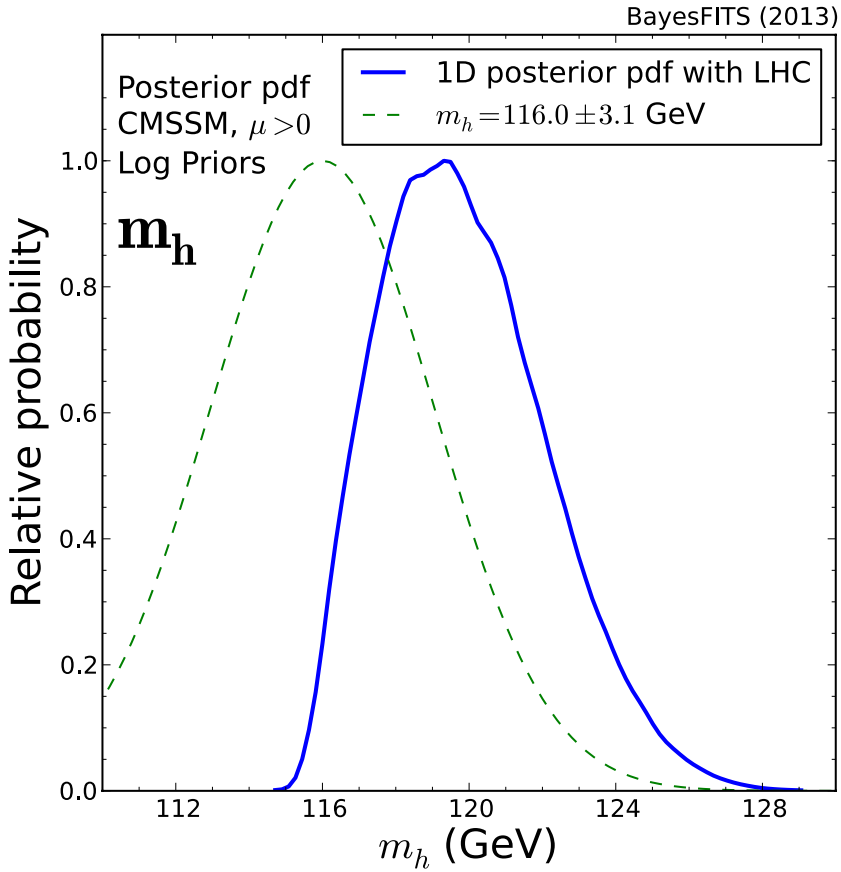
A weak upper bound on M_SUSY

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

126 GeV - worst possible value (G. Giudice)

If m_h were, say, 116 GeV...





...significant tension with LHC bounds

The 126 GeV SM-Like Higgs Boson

A blessing or a curse for DM?

CMSSM: numerical scans

- **Perform random scan over 4 CMSSM +4 SM (nuisance) parameters simultaneously**

- Very wide ranges:

1302.5956

$$100\,\text{GeV} \leq m_0 \leq 20\,\text{TeV}$$
$$100\,\text{GeV} \leq m_{1/2} \leq 10\,\text{TeV}$$
$$-20\,\text{TeV} \leq A_0 \leq 20\,\text{TeV}$$
$$3 \leq \tan\beta \leq 62$$

- Use Nested Sampling algorithm to evaluate posterior
- Use 4 000 live points

$\text{sgn}\,\mu$	Sign of Higgs parameter	$+1$ or -1	Fixed[a]
Nuisance	Description	Central value $\pm$ std. dev.	Prior Distribution
M_t	Top quark pole mass	$173.5 \pm 1.0\,\text{GeV}$	Gaussian
$m_b(m_b)^{\overline{MS}}_{\text{SM}}$	Bottom quark mass	$4.18 \pm 0.03\,\text{GeV}$	Gaussian
$\alpha_s(M_Z)^{\overline{MS}}$	Strong coupling	0.1184 ± 0.0007	Gaussian
$1/\alpha_{em}(M_Z)^{\overline{MS}}$	Inverse of [illegible] coupling	127.916 ± 0.015	[illegible]

Use Bayesian approach (posterior)

Hide and seek with SUSY

ΔM_{B_s}	17.77	0.12	2.40	Gaussian	[47]
BR ($B_s \to \mu^+\mu^-$)	$< 4.5 \times 10^{-9}$	0	14%	Upper limit	Error Fn [23]

Measurement	Mean or Range	Error: (Exp., Th.)	Distribution
Combination of:			
CMS razor 4.4/fb , $\sqrt{s} = 7\,\text{TeV}$	See text	See text	Poisson
CMS α_T 11.7/fb , $\sqrt{s} = 8\,\text{TeV}$	See text	See text	Poisson
m_h by CMS	$125.8\,\text{GeV}$	$0.6\,\text{GeV}, 3\,\text{GeV}$	Gaussian
$\Omega_\chi h^2$	0.1120	0.0056, 10%	Gaussian
$\delta\,(g-2)_\mu^{\text{SUSY}} \times 10^{10}$	28.7	8.0, 1.0	Gaussian
BR $(\overline{B} \to X_s\gamma) \times 10^4$	3.43	0.22, 0.21	Gaussian
BR $(B_u \to \tau\nu) \times 10^4$	1.66	0.33, 0.38	Gaussian
ΔM_{B_s}	$17.719\,\text{ps}^{-1}$	$0.043\,\text{ps}^{-1},\ 2.400\,\text{ps}^{-1}$	Gaussian
$\sin^2\theta_{\text{eff}}$	0.23116	0.00012, 0.00015	Gaussian
M_W	80.385	0.015, 0.015	Gaussian
BR $(B_s \to \mu^+\mu^-)_{\text{current}} \times 10^9$	3.2	$+1.5 - 1.2$, 10% (0.32)	Gaussian
BR $(B_s \to \mu^+\mu^-)_{\text{proj}} \times 10^9$	3.5 (3.2*)	0.18 (0.16*), 5% [0.18 (0.16*)]	Gaussian

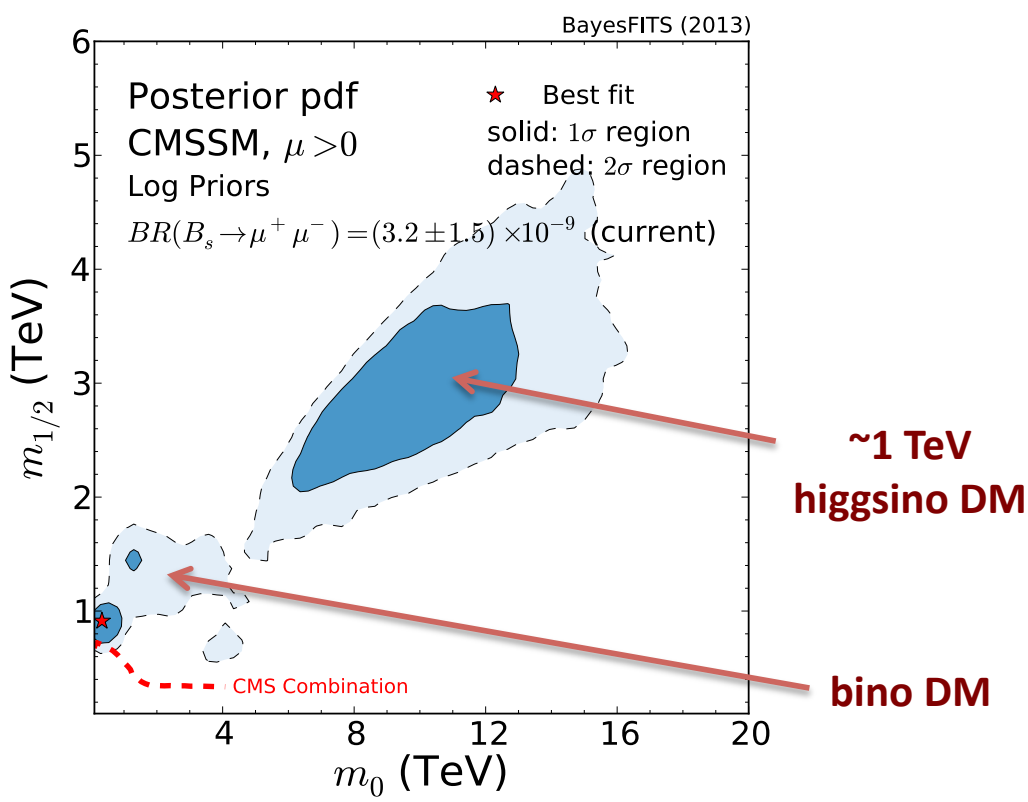
SM value: $\simeq 3.5 \times 10^{-9}$

10 dof

CMSSM

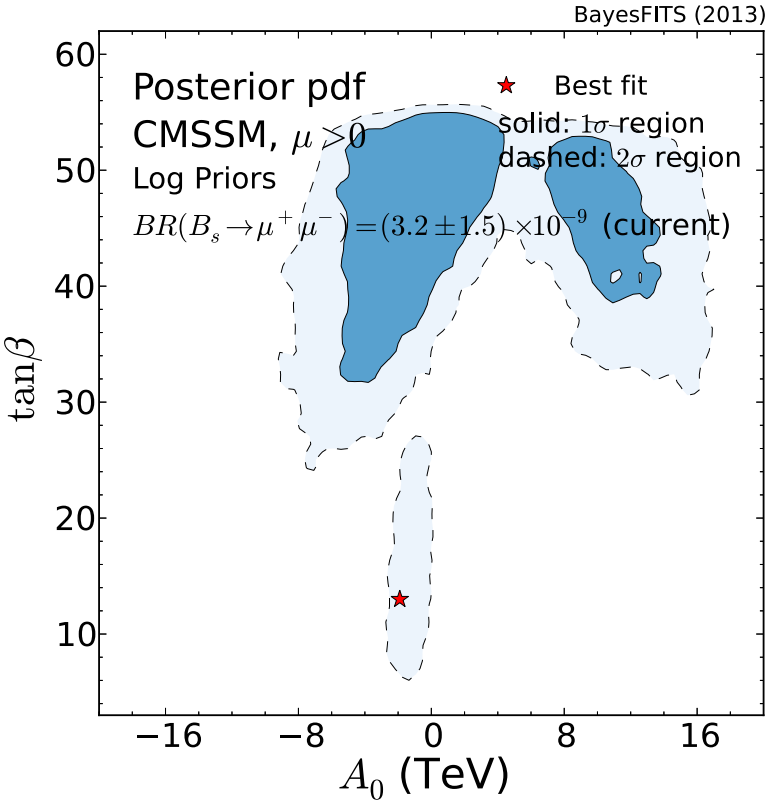
Global scan, Bayesian
total posterior probability regions

Kowalska, LR, Sessolo,
arXiv:1302.5956



~1 TeV higgsino DM

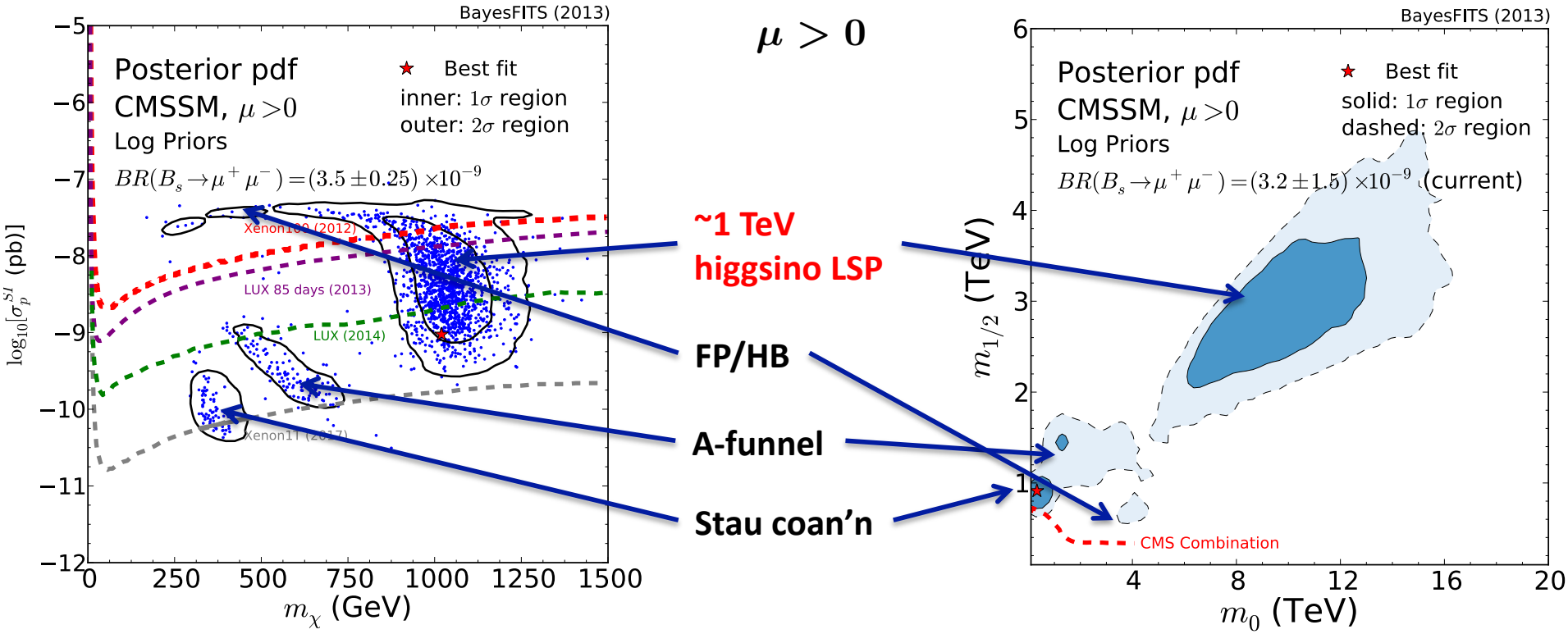
bino DM



CMSSM: these are the <u>only</u> DM-favored regions

~1 TeV higgsino-like WIMP: implied by ~126 GeV Higgs

CMSSM and DM searches



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

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

~1 TeV higgsino DM

✧ **Robust, present in many SUSY models**

(both GUT-based and not)

Condition: heavy enough gauginos

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

✧ **Implied by ~126 GeV Higgs mass**

and relic density

✧ **Most natural**

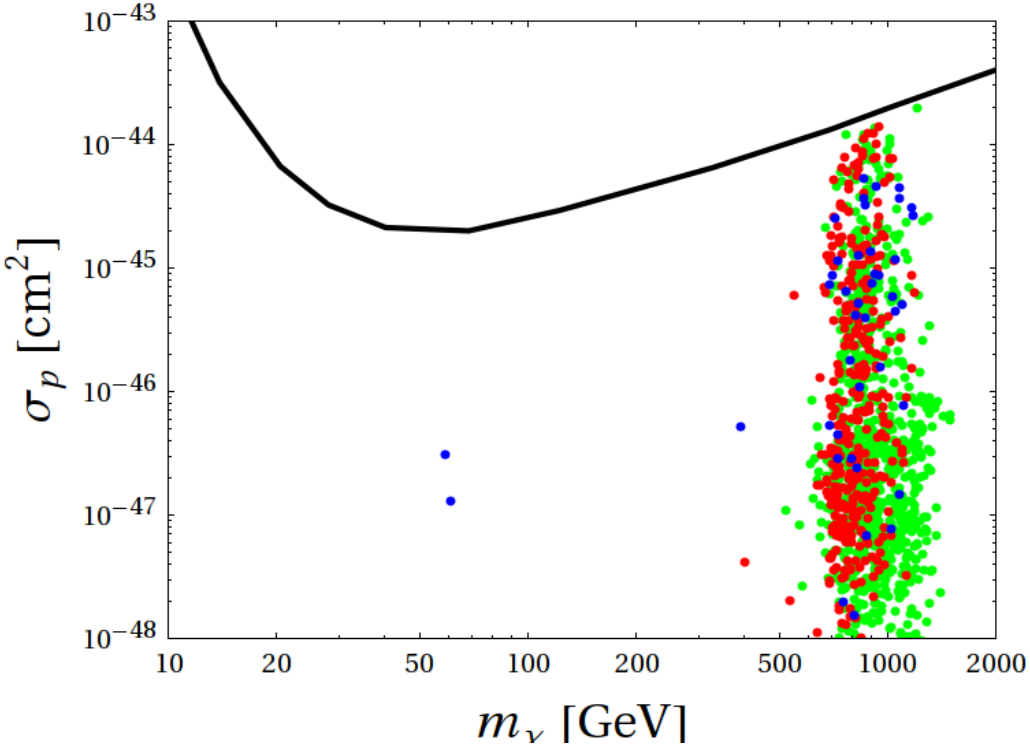
✧ **Smoking gun of SUSY!?**

No need to employ special mechanisms (A-funnel or coannihilation) to obtain correct relic density

… generic

e.g., Next-to-MSSM (extra singlet Higgs)

Kaminska, Ross, Schmidt-Hoberg, 1308.4168



Fall and rise of higgsino DM

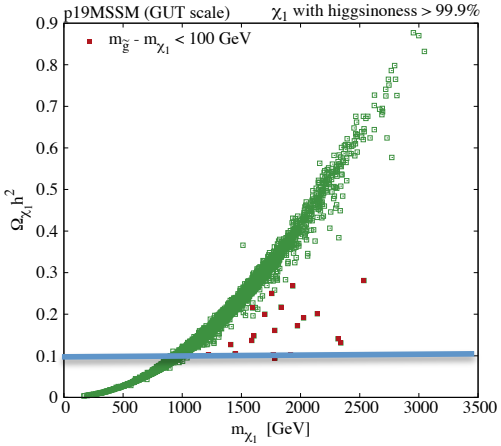
✧ 1991: put to grave

LR, PLB 262 (1991) 59: in MSSM:

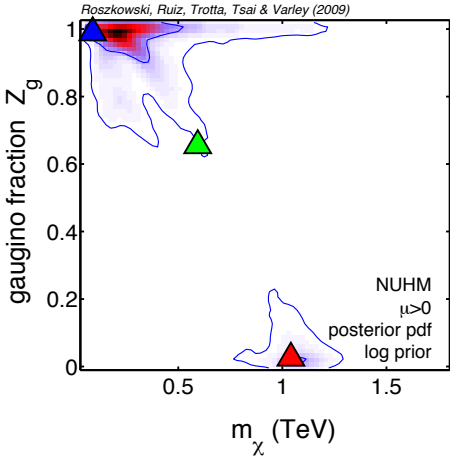
- too little DM until mass >> 1 TeV
  (in conflict with naturalness)
- bino favored

✧ 2004: first signs of being still (again?) alive

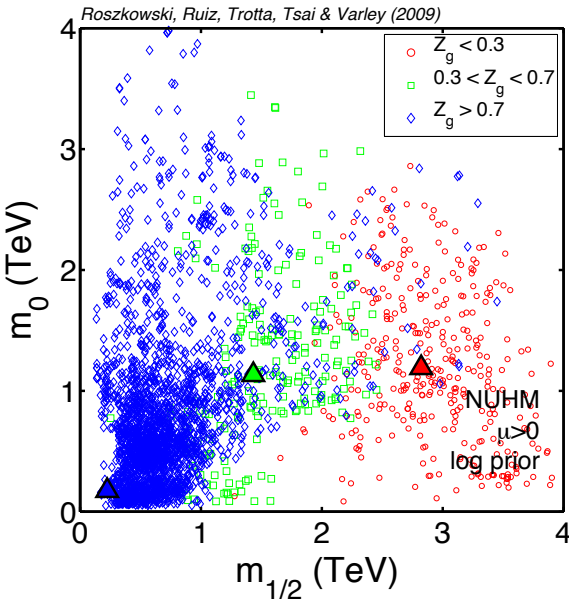
MSSM (Profumo & Yaguna, hep-ph/040703)



✧ 2009: favored in unified SUSY at m_1/2>~2 TeV



NUHM in 0903.1279



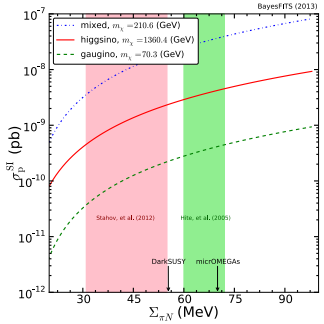
✧ 2012: favored by ~126 GeV Higgs mass

Strege et al., 1212.2636
Kowalska, et al., 1302.5956

~1 TeV higgsino DM:
NUHM: even at low m_0, CMSSM: m_0 of few TeV

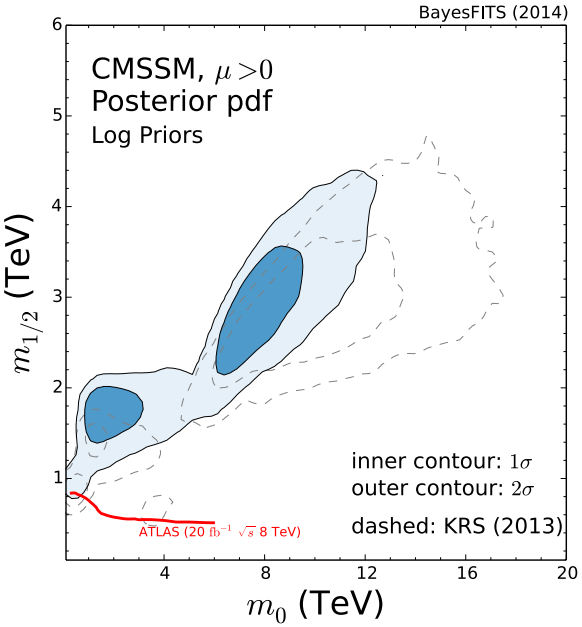
Update 2014

- **Effect of 3 loop corr's to m_h: increase by ~2 GeV**
- **LUX limit: FP region practically excluded**
- **Theory sigma_p down by ~1 order of mag**

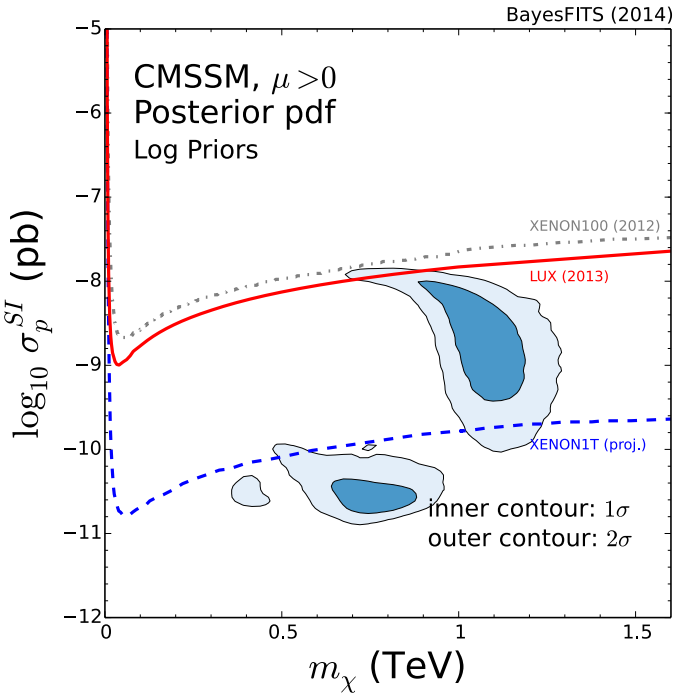


Recent (micrOmegas3.1):

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



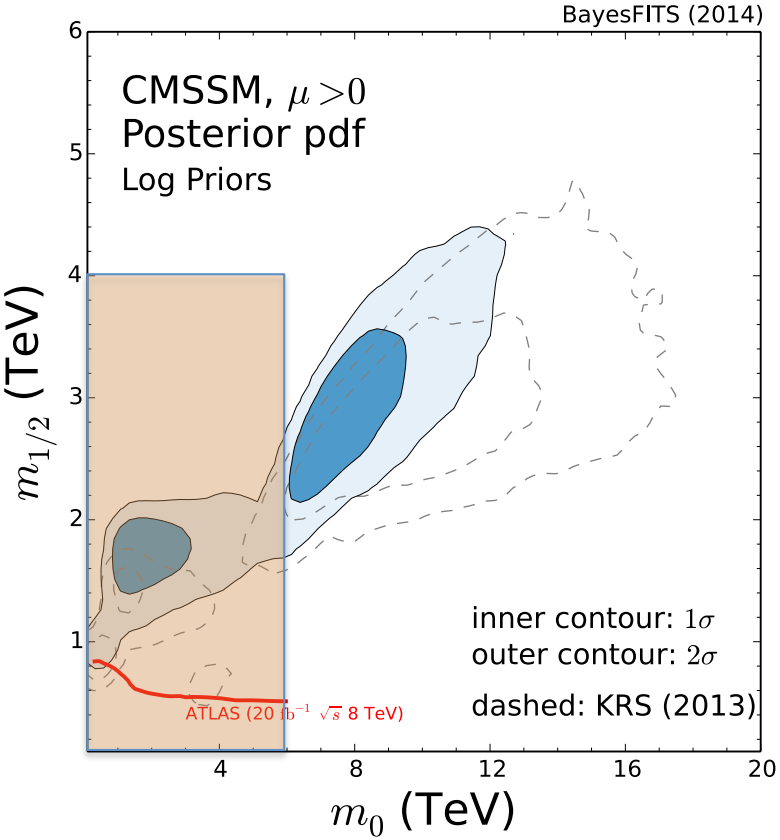
1405.4289



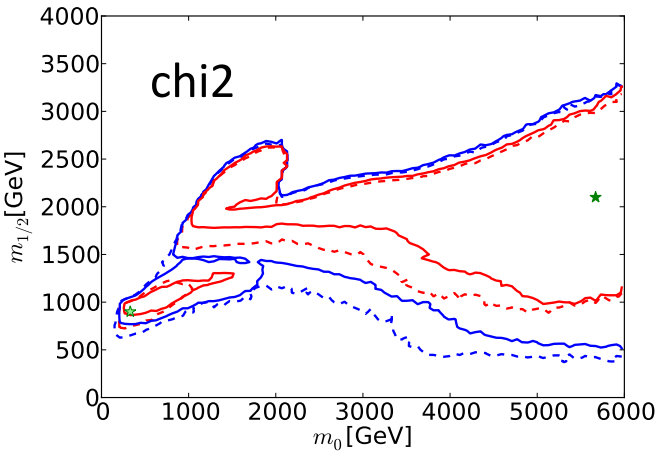
Main effects:

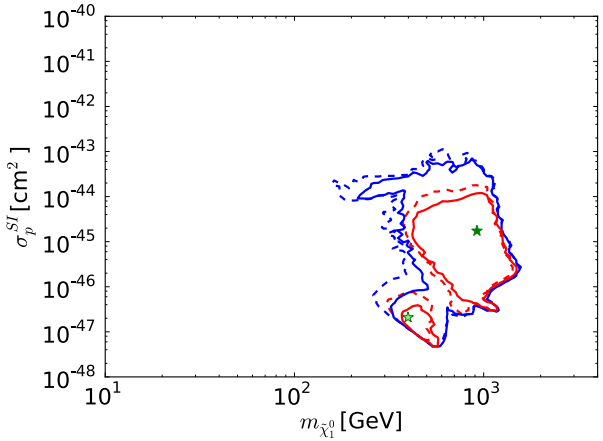
- **m_0: slight shift down**
- **~1 TeV higgsino still dominant**
- **some increase of A-funnel region**
- **FP region excluded**

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



Buchmueller et al [1312.5250](1312.5250)



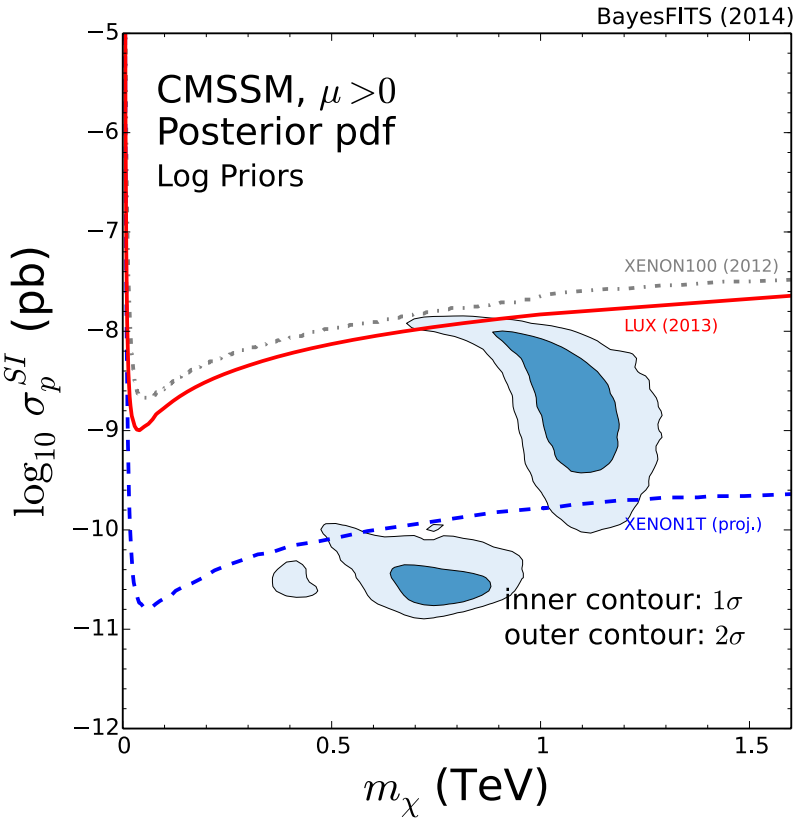


Reasonably good agreement in overlapping region

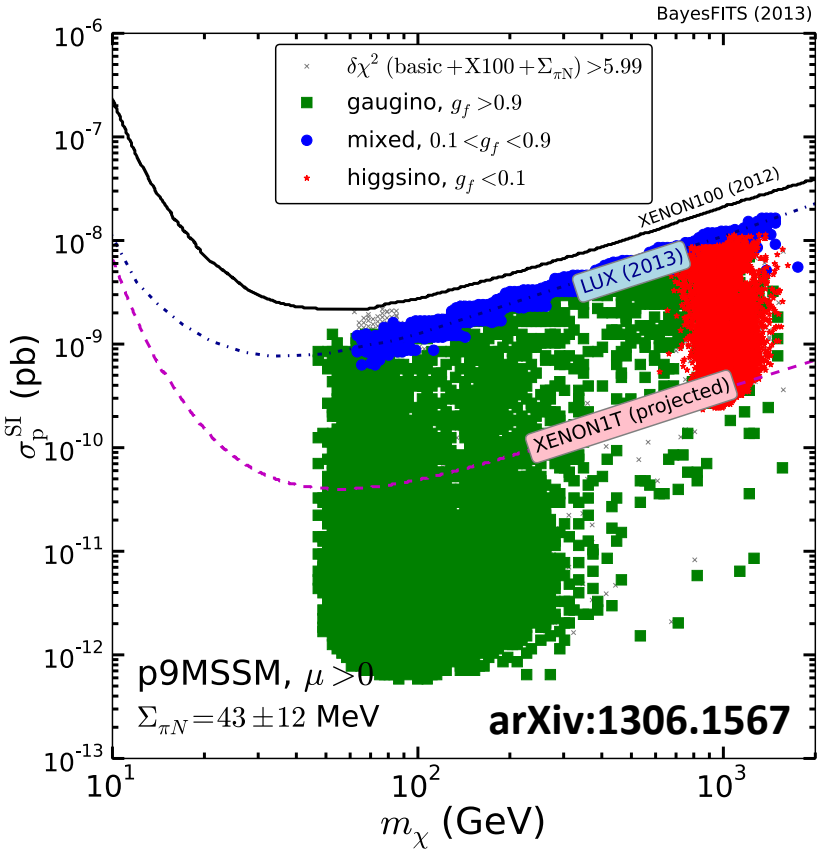
~1 TeV higgsino-like WIMP: implied by ~126 GeV Higgs -> large m1/2 and m0

Unified vs pheno SUSY

Unified SUSY (Constrained MSSM)



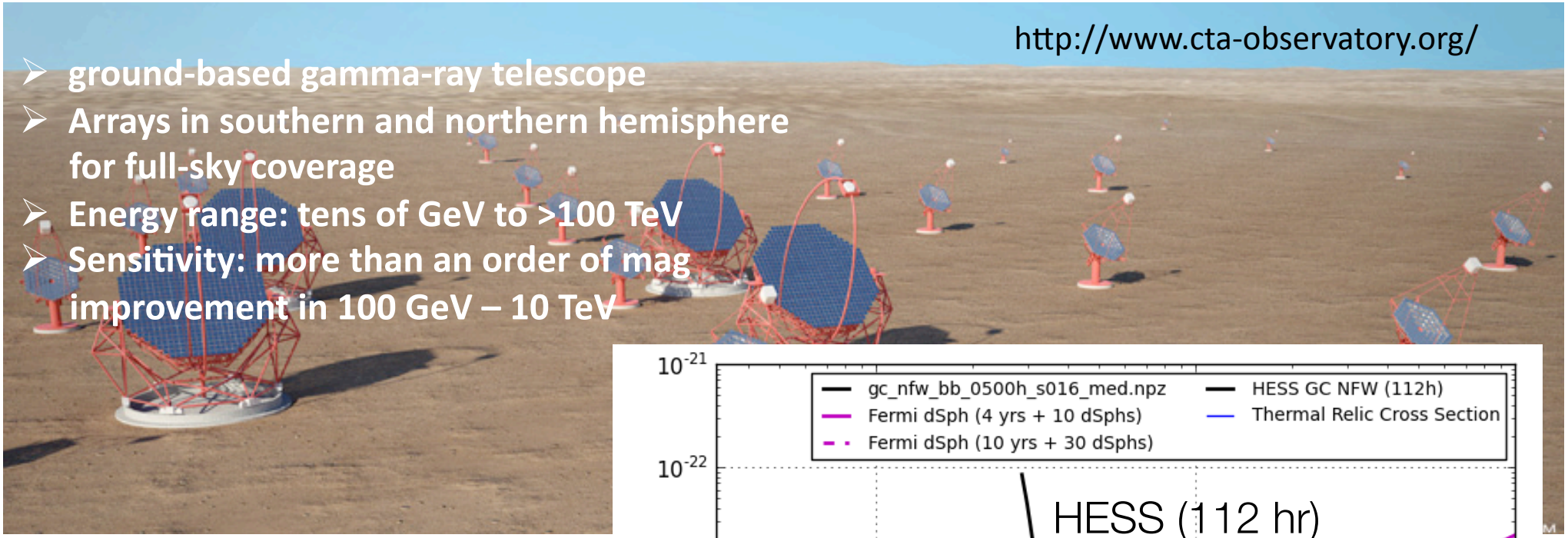
General SUSY (p9MSSM)



MSSM:

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

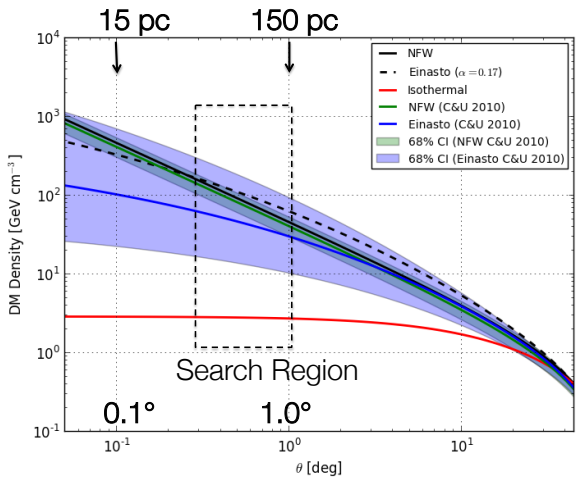
CTA – New guy in DM hunt race

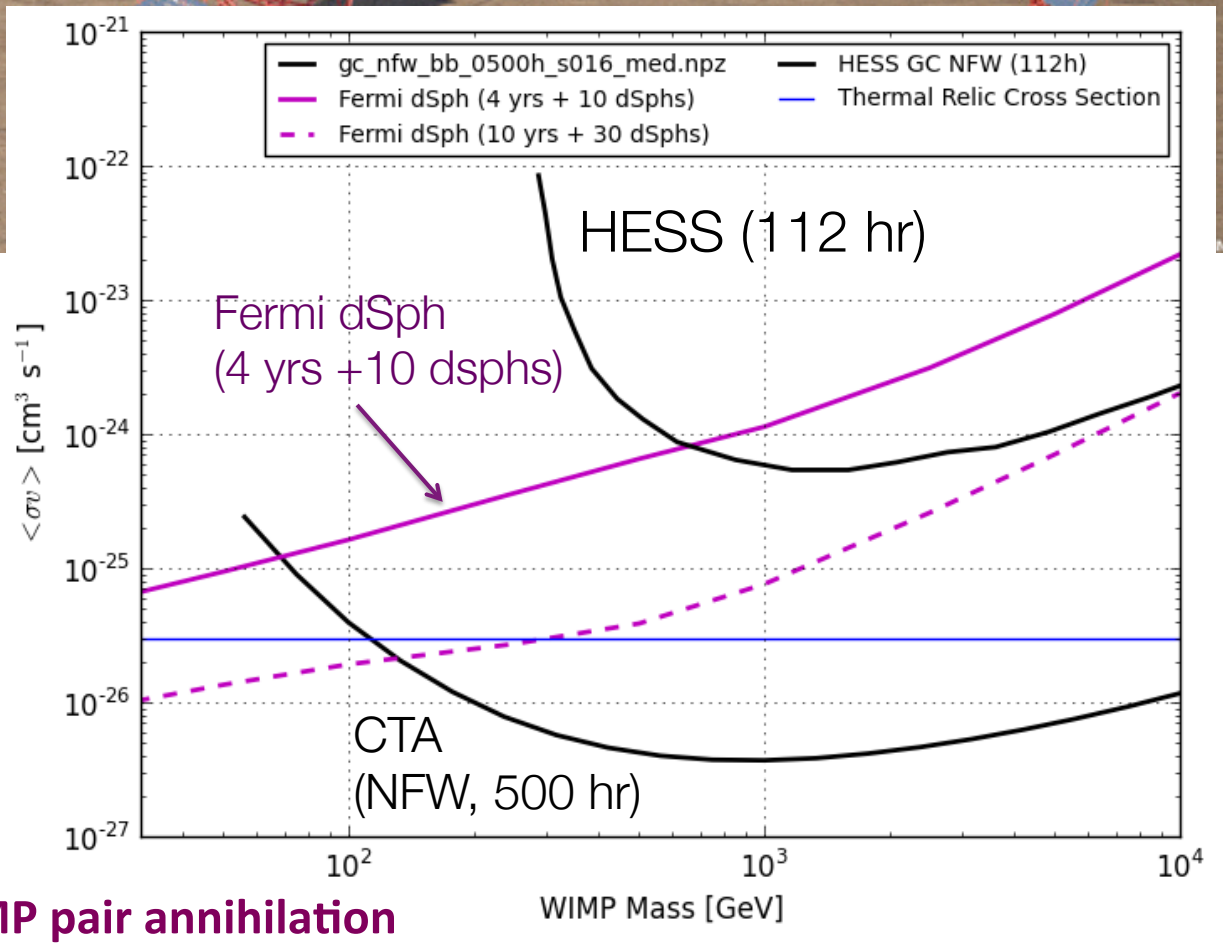


http://www.cta-observatory.org/

- 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

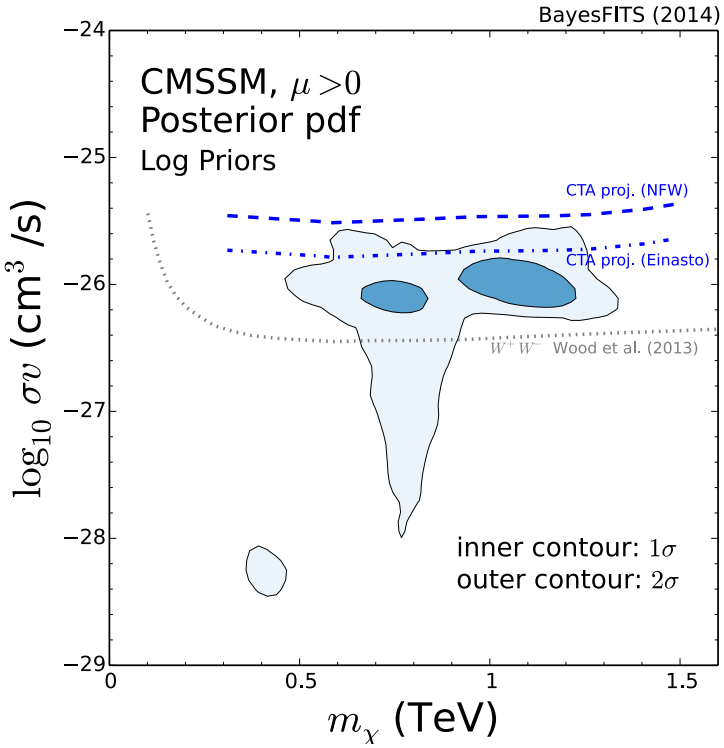
Galactic Center DM Halo

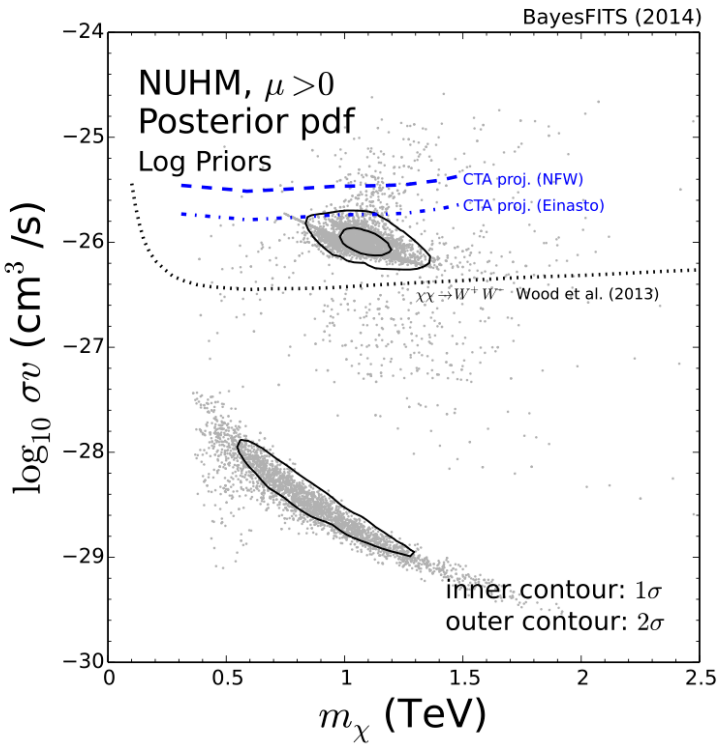




diffuse gamma radiation from WIMP pair annihilation

CTA and Unified SUSY DM





1405.4289

- **CTA to probe large WIMP masses**
- **~1 TeV higgsino DM: to be almost fully covered CTA**

Unified SUSY: ~1 TeV higgsino DM favored:

- **~126 GeV Higgs mass**
- **Lower bounds on MSUSY**
- **Most natural solution**

No need to employ special mechanisms (A-funnel or coannihilation) to obtain correct relic density

But what about fine-tuning!?

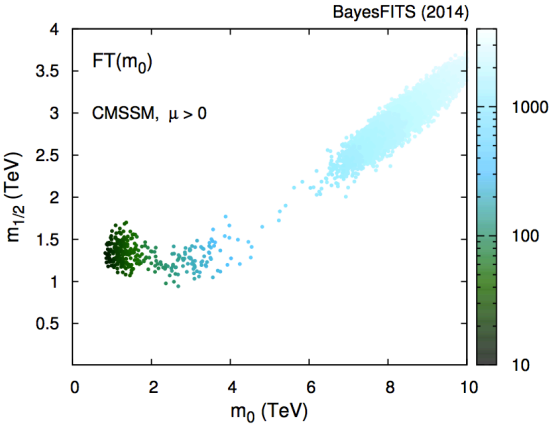
Fine tuning in the CMSSM

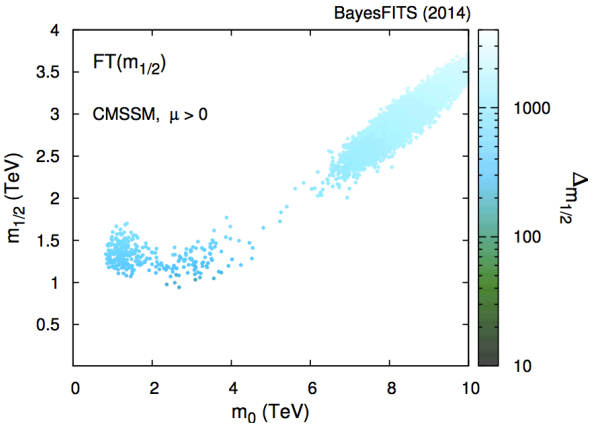
Δ_{p_i}), where

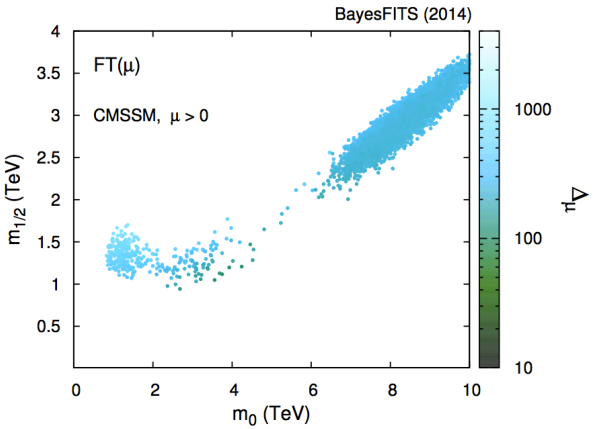
Barbieri-Giudice $$\Delta_{p_i} = \left| \frac{\partial \ln M_Z^2}{\partial \ln p_i^2} \right| = \frac{1}{2} \left| \frac{\partial \ln M_Z^2}{\partial \ln p_i} \right|$$

K. Kowalska et al., arXiv:1402.1328, JHEP 1404 (2014) 166

In ~1 TeV higgsino region:







$\mathbf{m_0}$: $\mathbf{FT > 1000}$ $\mathbf{m_{1/2}}$: $\mathbf{FT > 1000}$ μ : $\mathbf{FT \simeq 250}$

Simplest boudary conditions at GUT: enormous FT

RGE focussing

EWSB at large $\tan\beta$

$$\frac{M_Z^2}{2} \approx -\mu^2 - m_{H_u}^2 - \Sigma_u^u + \mathcal{O}(m_{H_d}^2/\tan^2\beta)$$

Focus Point mechanism:

Chan, Chattopadhay, Nath '98
Feng, Matchev, Moroi '99

$m_{H_u}^2$ at $M_{\rm SUSY}$ stable wrt variations of GUT initial conditions

Dependence on inputs at GUT scale:

Integrate 2-loop RGEs:

$$\begin{aligned}
m_{H_u}^2(M_{\rm SUSY}) = {} & 0.645 m_{H_u}^2 + 0.028 m_{H_d}^2 - 0.024 m_{\tilde{Q}_1}^2 - 0.024 m_{\tilde{Q}_2}^2 - 0.328 m_{\tilde{Q}_3}^2 \\
& + 0.049 m_{\tilde{u}_1}^2 + 0.049 m_{\tilde{u}_2}^2 - 0.251 m_{\tilde{u}_3}^2 - 0.024 m_{\tilde{d}_1}^2 - 0.024 m_{\tilde{d}_2}^2 - 0.019 m_{\tilde{d}_3}^2 \\
& + 0.024 m_{\tilde{L}_1}^2 + 0.024 m_{\tilde{L}_2}^2 + 0.024 m_{\tilde{L}_3}^2 - 0.025 m_{\tilde{e}_1}^2 - 0.025 m_{\tilde{e}_2}^2 - 0.025 m_{\tilde{e}_3}^2 \\
& + 0.014 M_1^2 + 0.210 M_2^2 - 1.097 M_3^2 + 0.001 M_1 M_2 - 0.047 M_1 M_3 - 0.089 M_2 M_3 \\
& - 0.113 A_t^2 + 0.010 A_b^2 + 0.006 A_\tau^2 + 0.008 A_t A_b + 0.005 A_t A_\tau + 0.004 A_b A_\tau \\
& + M_1(0.007 A_t - 0.005 A_b - 0.004 A_\tau) + M_2(0.062 A_t - 0.009 A_b + 0.005 A_\tau) \\
& + M_3(0.295 A_t + 0.024 A_b + 0.030 A_\tau)
\end{aligned}$$

$m_{H_U}^2, m_{\tilde{Q}_3}^2, m_{\tilde{u}_3}^2$ almost cancel if all $= m_0^2$

$$m_{H_u}^2(M_{\rm SUSY}) = 0.074 m_0^2 - 1.008 m_{1/2}^2 - 0.080 A_0^2 + 0.406 m_{1/2} A_0$$

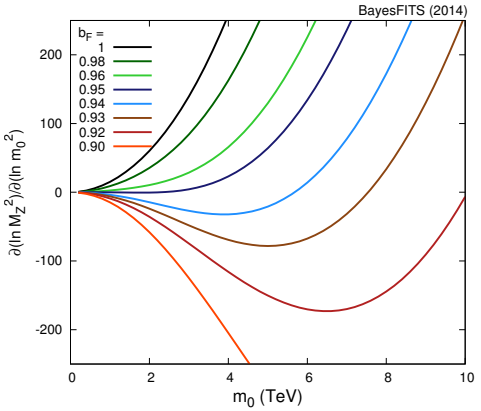
Some contributions can correlate.

Reduce FT in higgsino region

$$m_H^2\ (M_{\rm SUSY}) = 0.074 m_0^2 - 1.008 m_{1/2}^2 - 0.080 A_0^2 + 0.406 m_{1/2} A_0$$

- **Higgs non-unification** $m_{H_u}^2 = b_F^2 m_0^2$

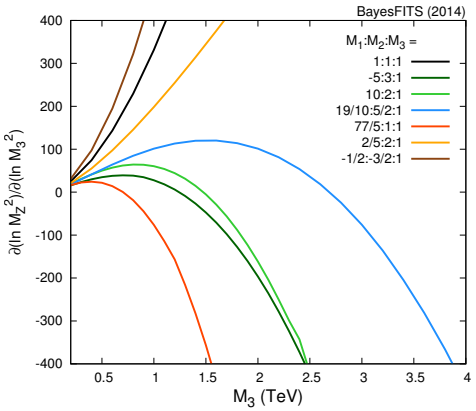
  optimal when $b_F = 0.92 - 0.94$



- **Gaugino non-unification** $M_1 : M_2 : M_3$

  1402.1328

  optimal when
  $\mathrm{SU}(5)$: $(-5:3:1),\ (10:2:1)$
  $\mathrm{SO}(10)$: $(19/10:5/2:1)$



- **Relate mu to scalars** $\mu = c_H m_0$

  e.g, Giudice-Masiero

otherwise $\Delta_\mu \simeq 250$ since $\mu \simeq 1\,\mathrm{TeV}$

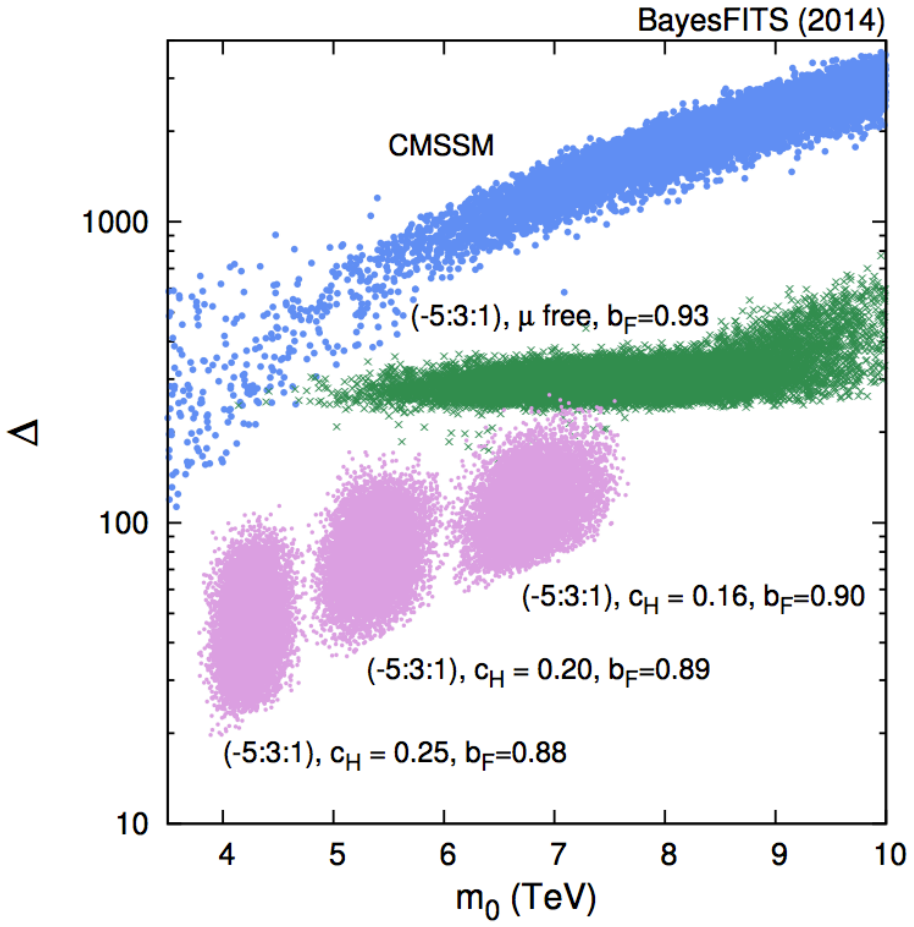
Reduce FT in higgsino region

altogether:

FT can be reduced as far down as ~20

all constraints satisfied

~1 TeV higgsino DM

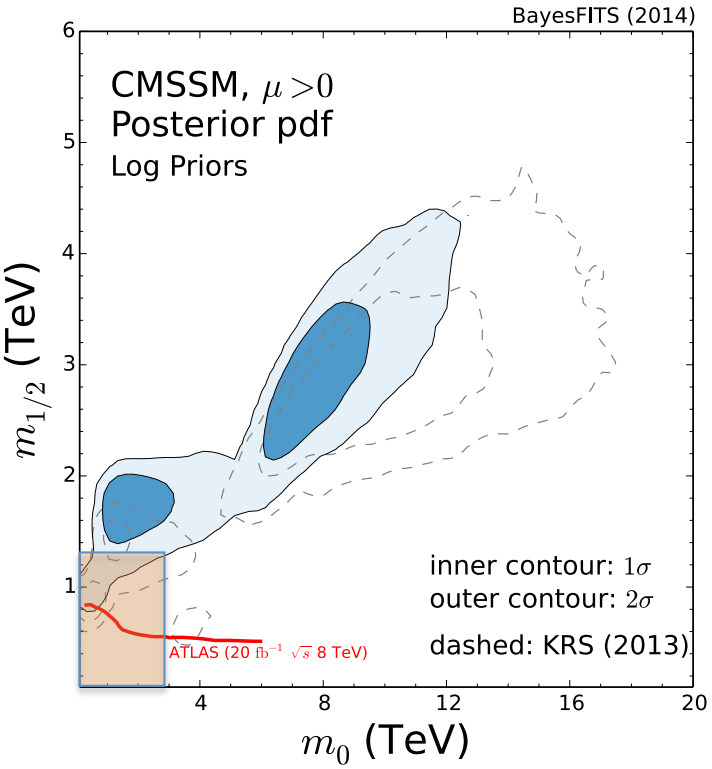


1402.1328

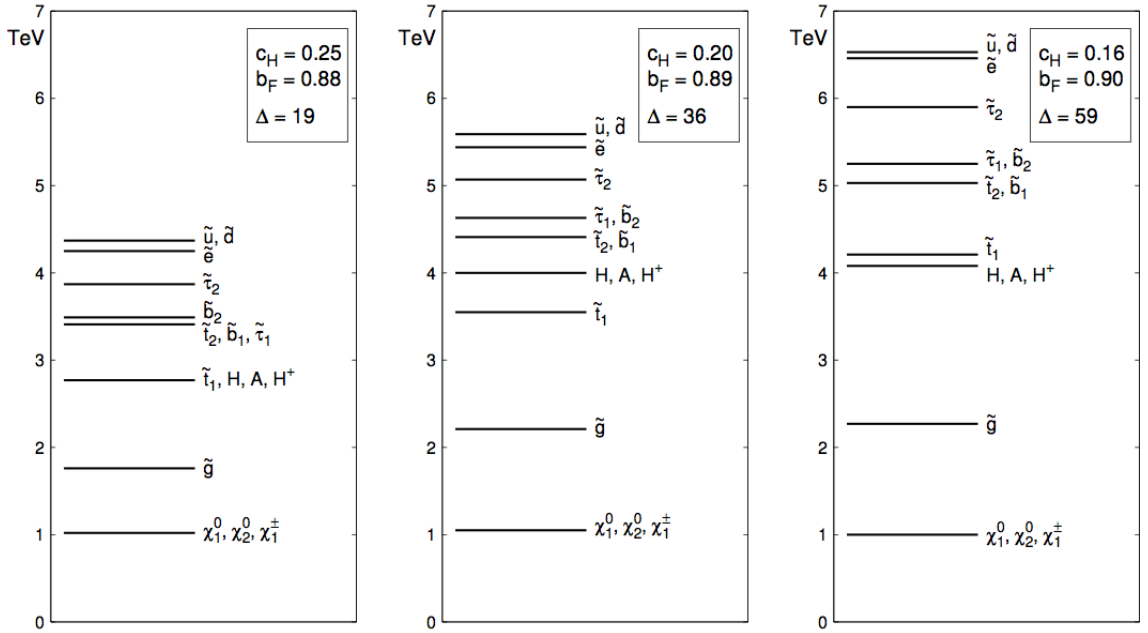
Great thanks go
to
Giulia and all the organizers!!!

…don’t forget to do it again!

Are we done with the LHC?



Typical mass spectra: **1405.4289**



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

- **LHC – only stau coannihilation will be +/- covered**
- **Need a lot of luck!**

To take home:

- **DM: jury is still out, discovery claims come and go, …but**

- **Higgs of 126 GeV → ~1TeV (higgsino) DM – robust prediction of unified (and pheno) 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!?

- **Fine-tuning can be reduced down to 1 in 20**

SUSY may be too heavy for the LHC

DM searches may hopefully come to the rescue