Dark Matter from Higgs Boson

A come back of the Higgsino Kid

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INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

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Outline

✧ Brief Introduction

✧ Implications of mh~125 GeV and direct limits on SUSY:

DM: ~1 TeV higgsino

✧ Prospects for detection

✧ (Issue of fine tuning)

✧ Summary

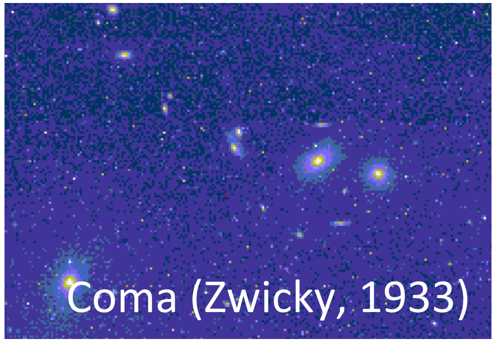
Based on BayesFITS Group papers:

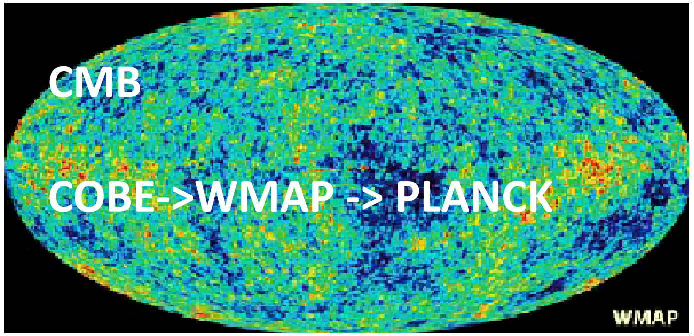
- **arXiv:1302.5956, Two ultimate tests of constrained supersymmetry,**
  K. Kowalska, L. Roszkowski, E. M. Sessolo JHEP 1306 (2013) 078
- **arXiv:1402.1328, Low fine tuning in the MSSM with higgsino dark matter and unification constraints, K. Kowalska, L. Roszkowski, E. M. Sessolo, S. Trojanowski JHEP 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**
- **… plus some earlier papers**


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

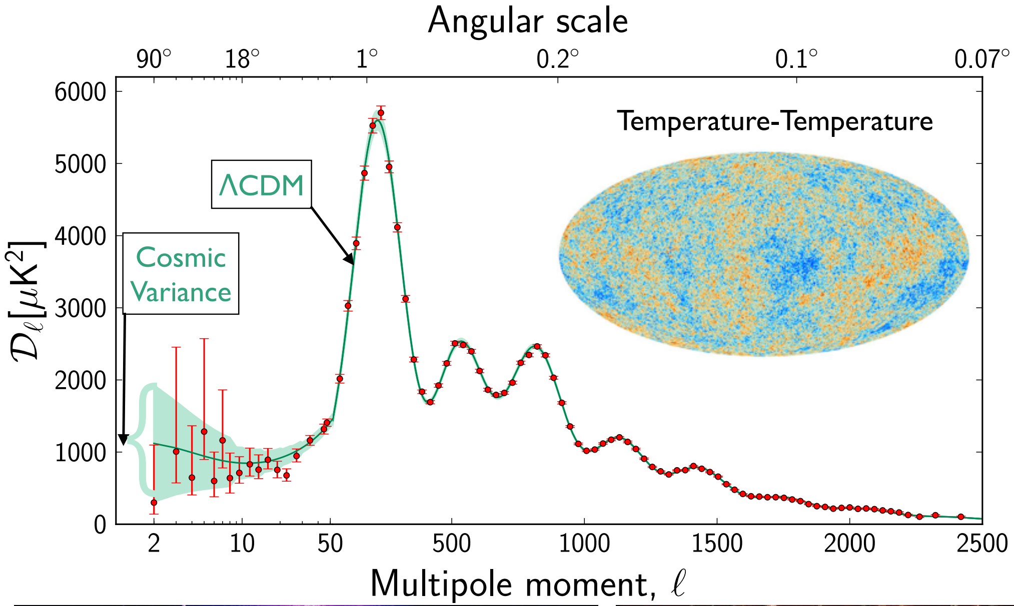

The WIMP Reigns
...but remains elusive

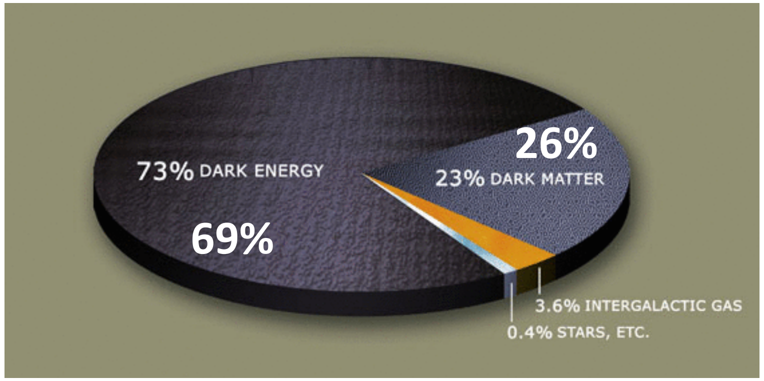
Footprints of Dark Matter

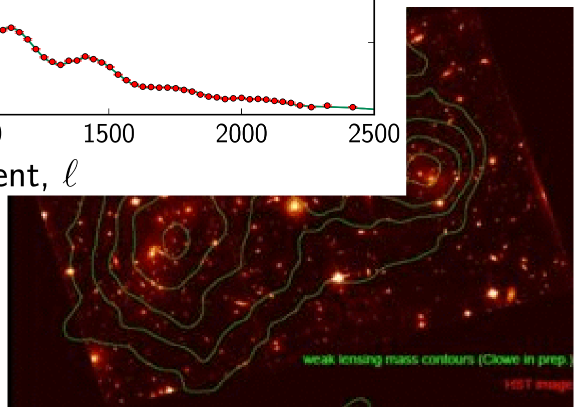


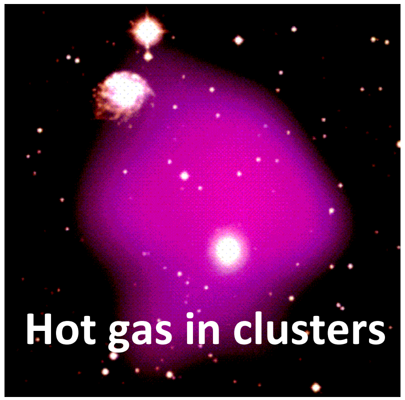


...felt but not seen

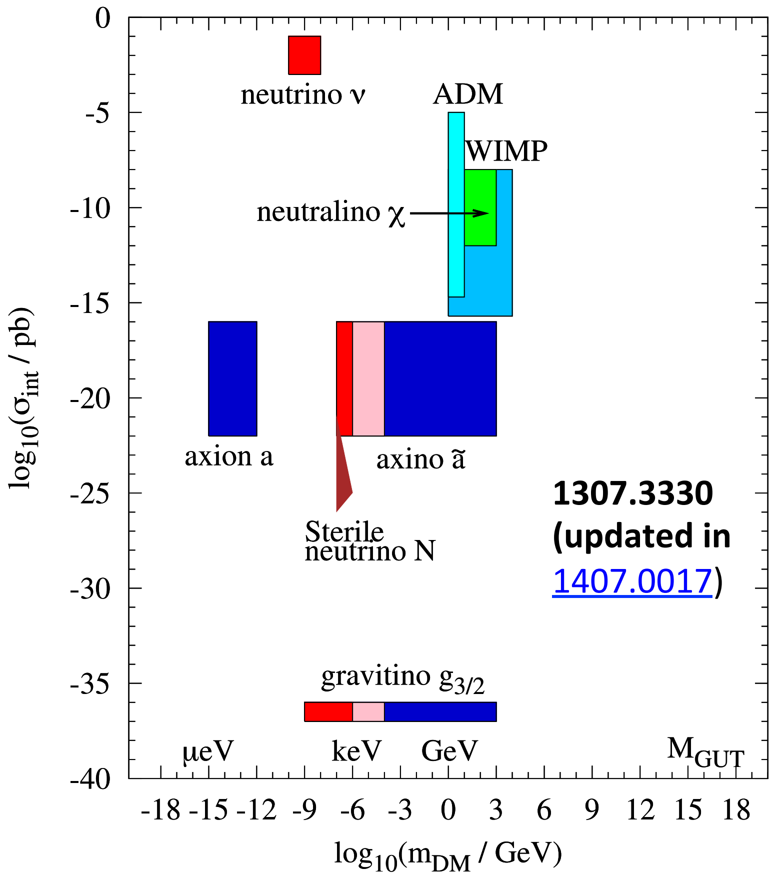








Well-motivated particle candidates for dark matter



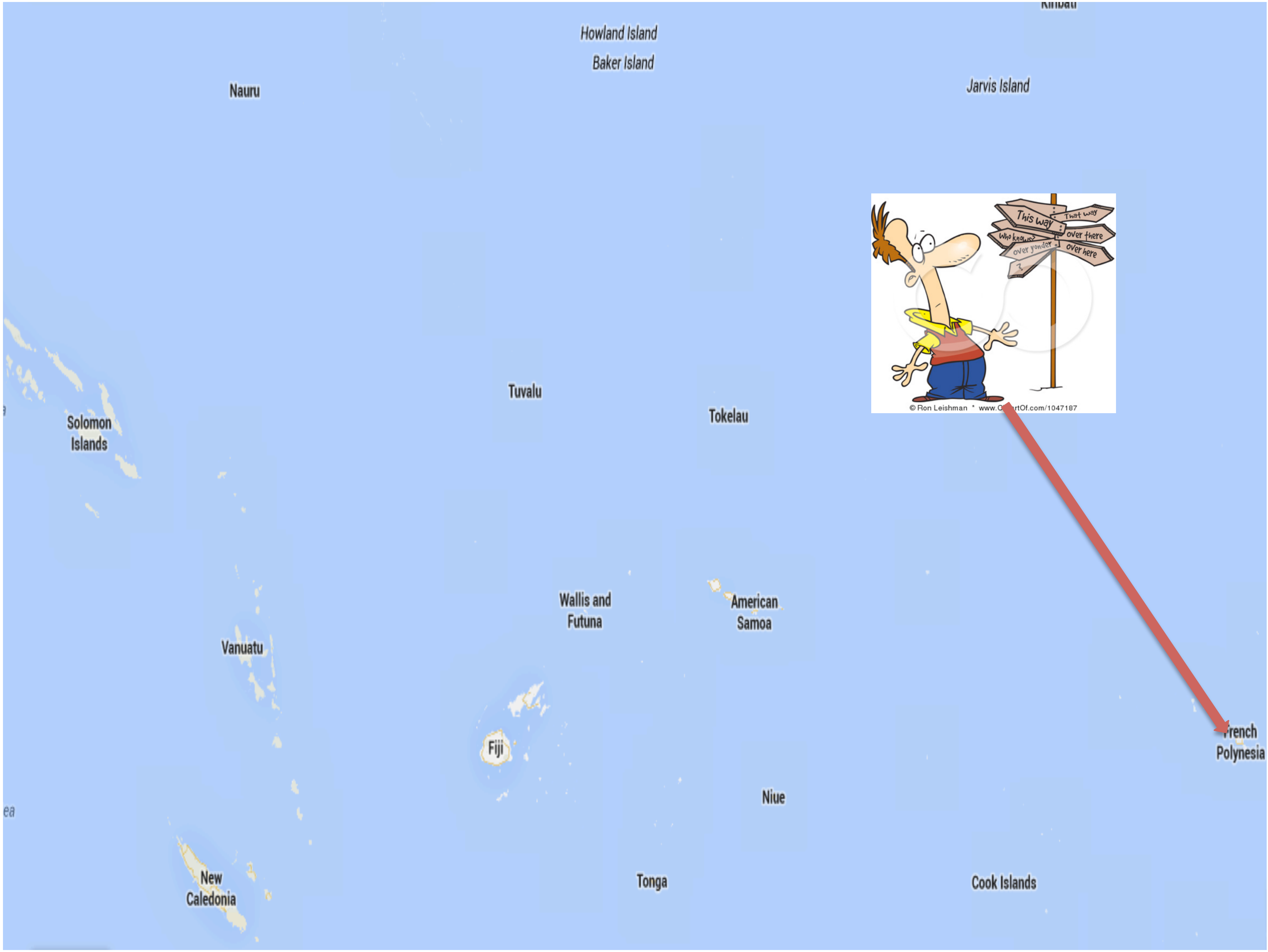
- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\widetilde{G}$

S U S Y

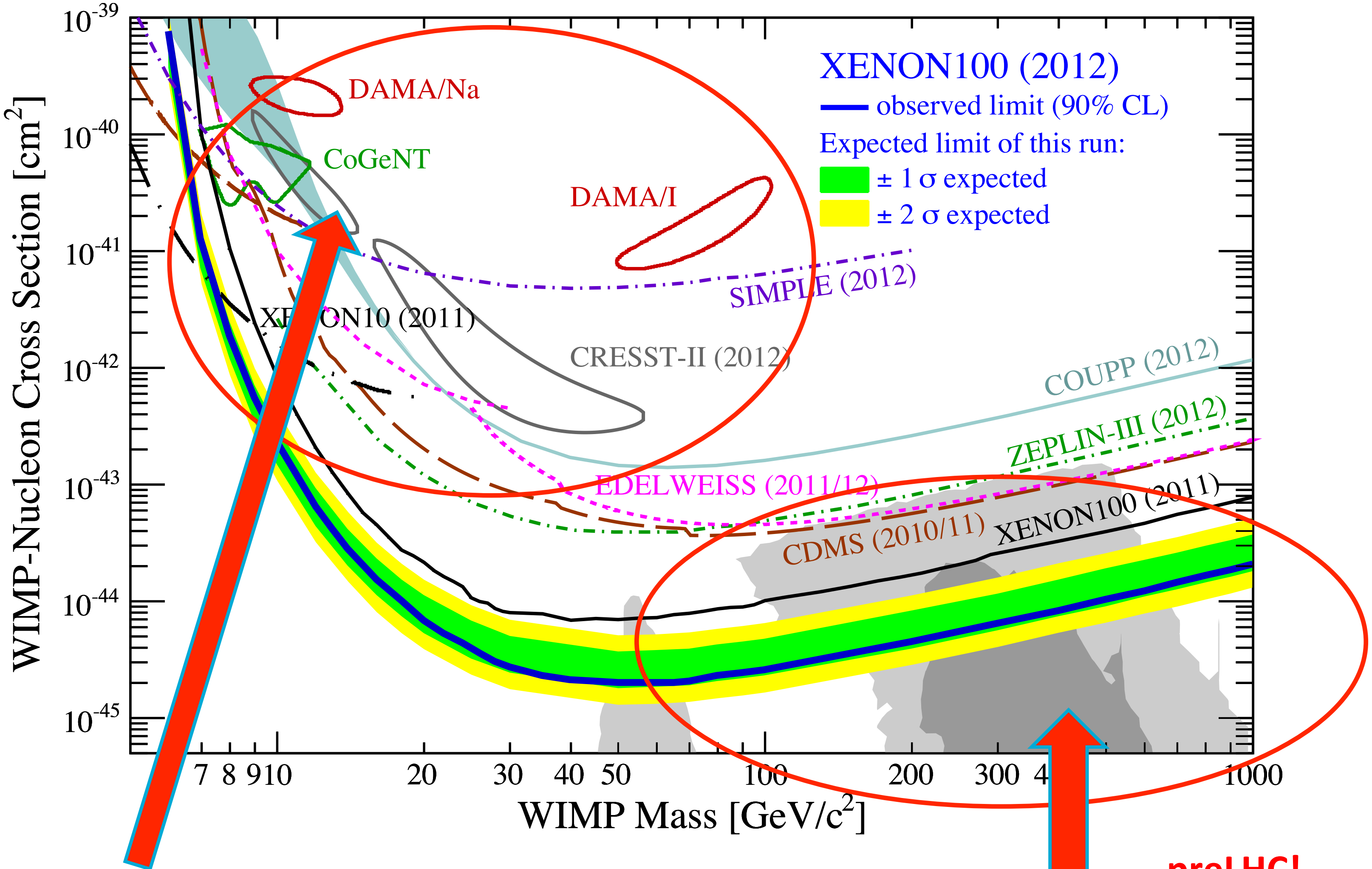
- vast ranges of interactions and masses
- different production mechanisms in the early Universe (thermal, non-thermal)
- need to go beyond the Standard Model
- WIMP candidates testable at present/near future
- axino, gravitino EWIMPs/superWIMPs not directly testable, but some hints from LHC

Where is the WIMP?

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


Howland Island
Baker Island
Nauru
Jarvis Island
This way
That way
Who knows?
over there
over yonder
over here
© Ron Leishman
Tuvalu
Tokelau
Solomon Islands
Wallis and Futuna
American Samoa
Vanuatu
Fiji
rench Polynesia
Niue
New Caledonia
Tonga
Cook Islands

Direct Detection AD 2011 - Before LHC



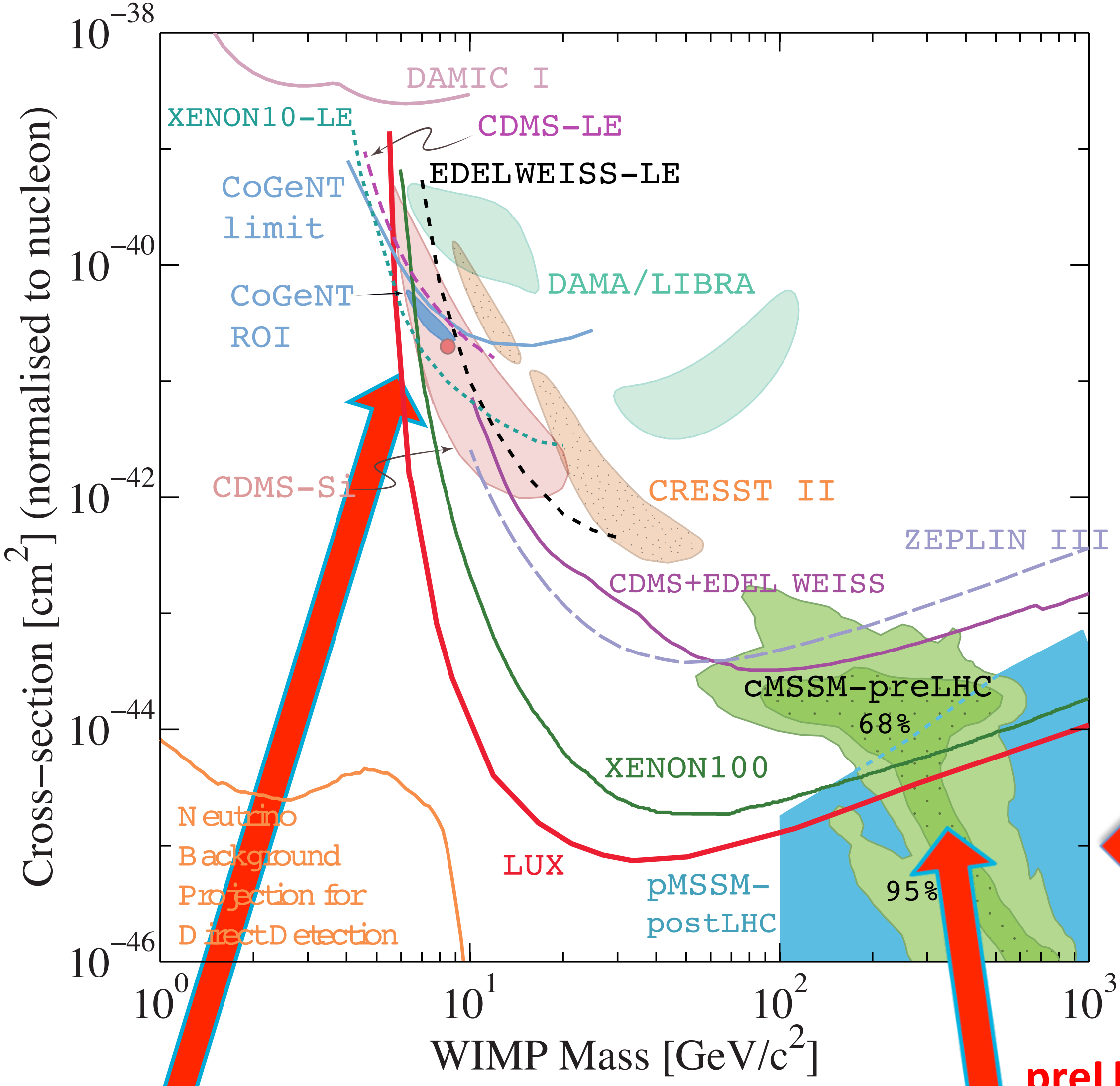
preLHC!

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!

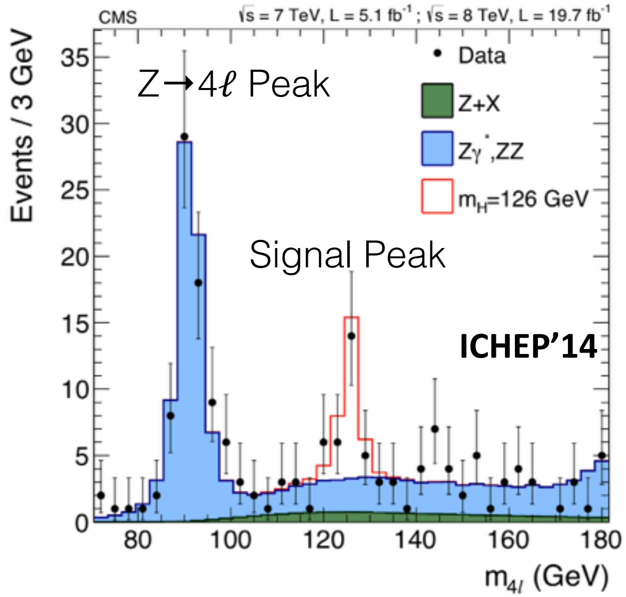
motivated by theory (SUSY)

Confusion region gone

MasterCode, BayesFITS

Main news from the LHC so far…

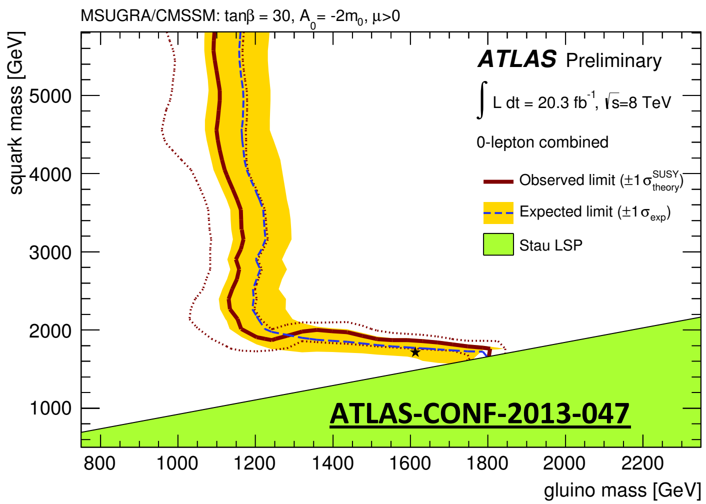
- **SM-like Higgs particle at ~125 GeV**



- **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

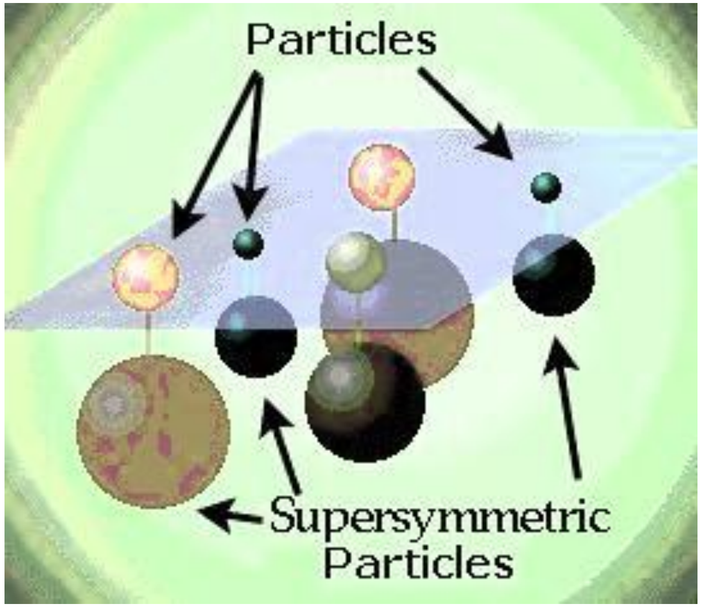
SCIENTIFIC AMERICAN™

April 2012

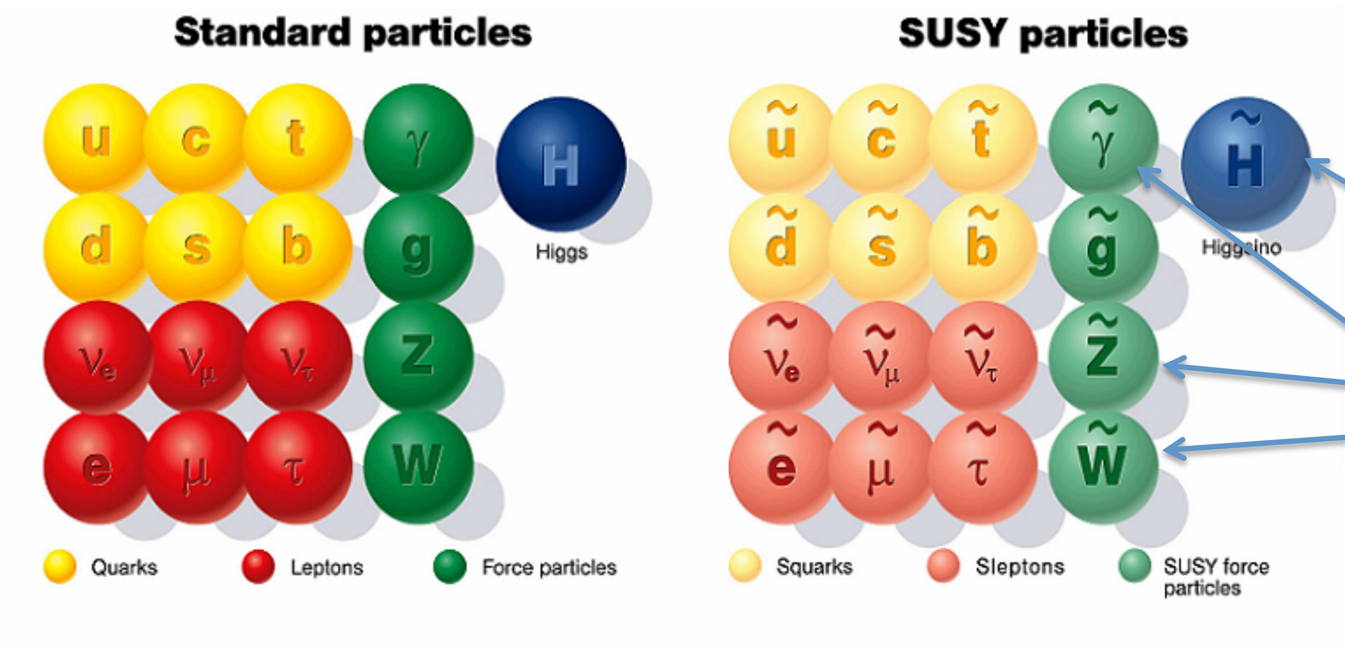
Supersymmetry

Symmetry among particles

bosons <-> fermions



SUSY and dark matter



Candidates for a WIMP

- Weakly interacting
- Massive
- stable

WIMP = lightest supersymmetric particle

The 125 GeV SM-Like Higgs Boson

A blessing or a curse for SUSY?

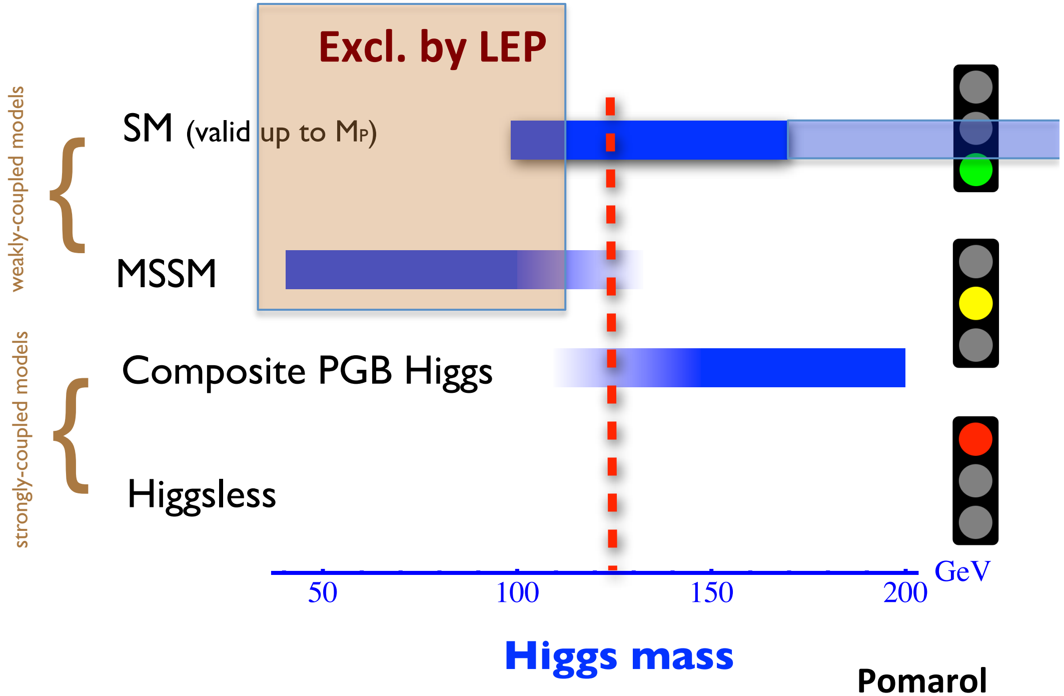
The 125 GeV Higgs Boson and SUSY

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

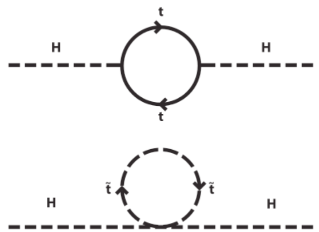
The 125 GeV Higgs Boson and SUSY

A curse...

In SUSY Higgs mass is a calculated quantity

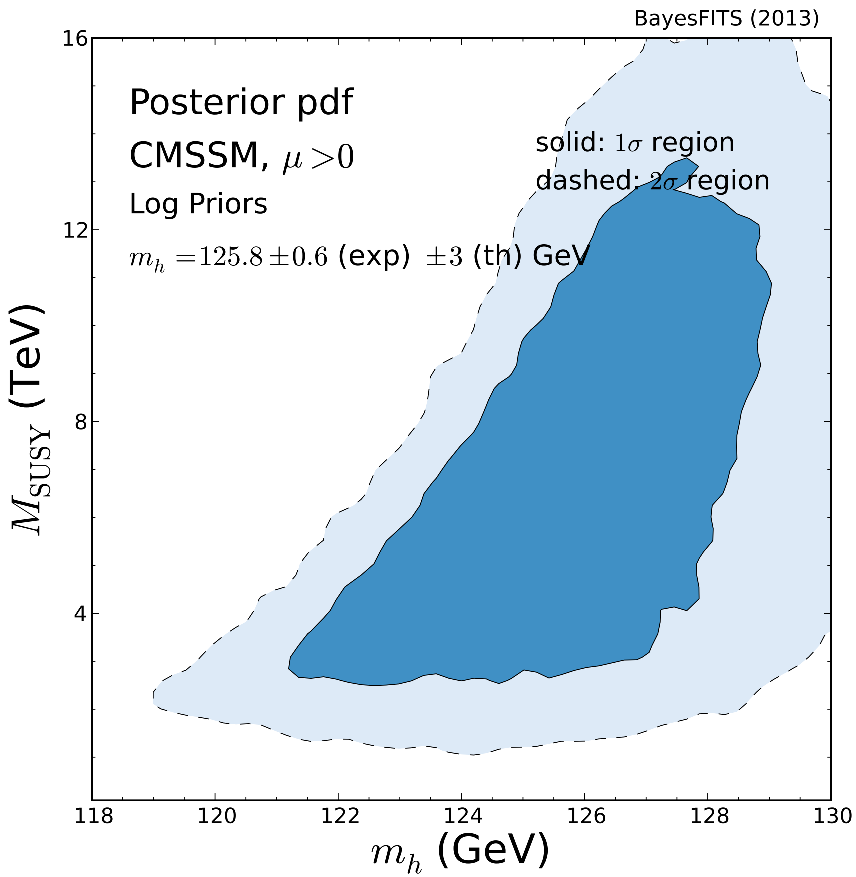
- **1 loop correction**

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



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

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



Only m_h~125 GeV and CMS lower bounds on SUSY applied here.

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

$\sigma = 0.6$ GeV, $\tau = 2$ GeV

125 GeV Higgs -> multi-TeV SUSY

Constrained Minimal Supersymmetric Standard Model (CMSSM)

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

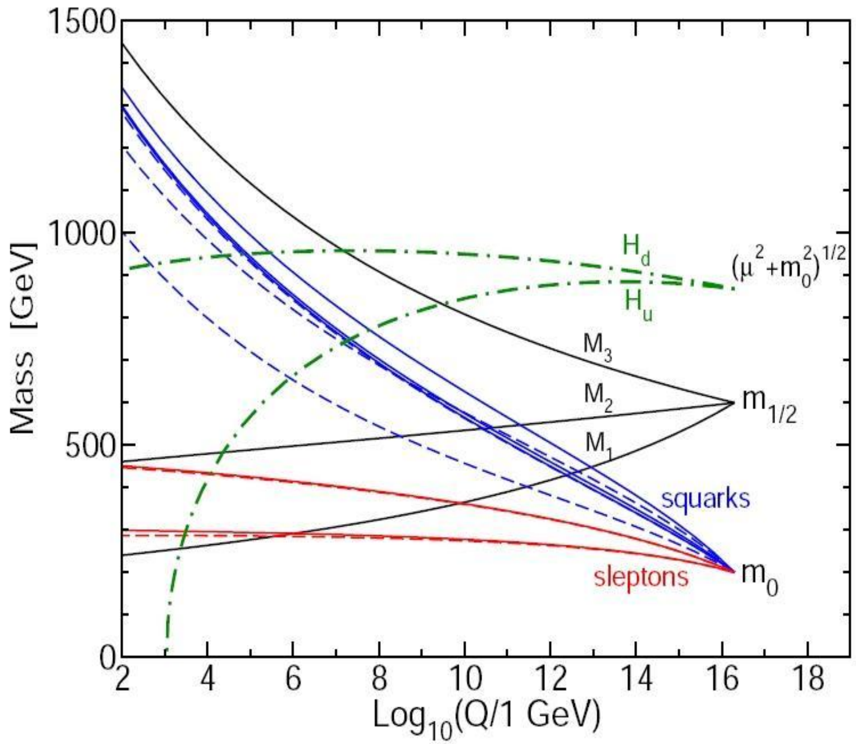


figure from hep-ph/9709356

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

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

Bayes FITS

In general supersymmetric SM too many free parameters

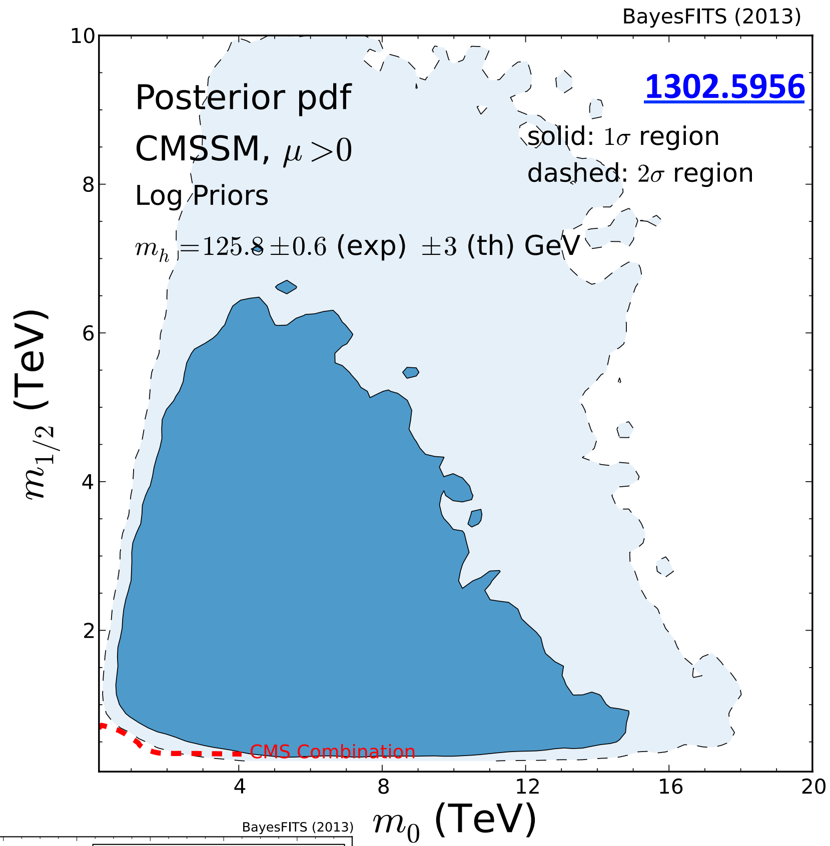
~125 GeV Higgs in the CMSSM

- Include <u>only</u> m_h~125 GeV
  and lower limits from direct
  SUSY searches

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

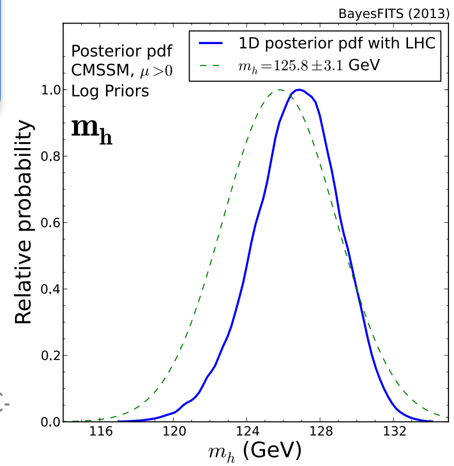
$\sigma = 0.6\ \mathrm{GeV}, \tau = 2\ \mathrm{GeV}$

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



A curse...

~125 GeV Higgs mass implies multi-TeV scale for SUSY



A weak upper bound on M_SUSY

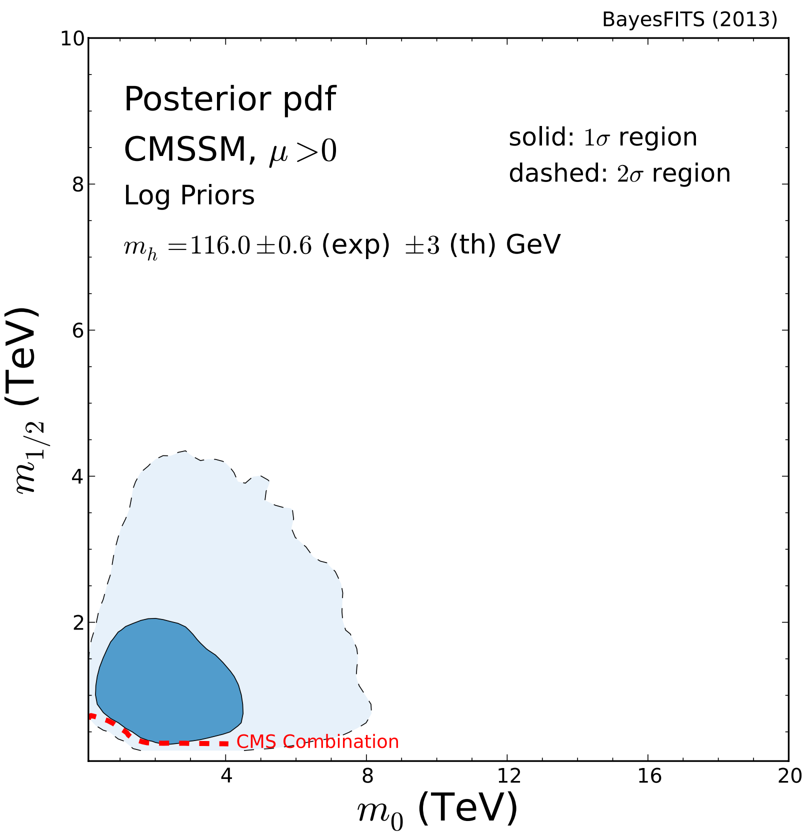
...except at very small tanb->1 where it goes away

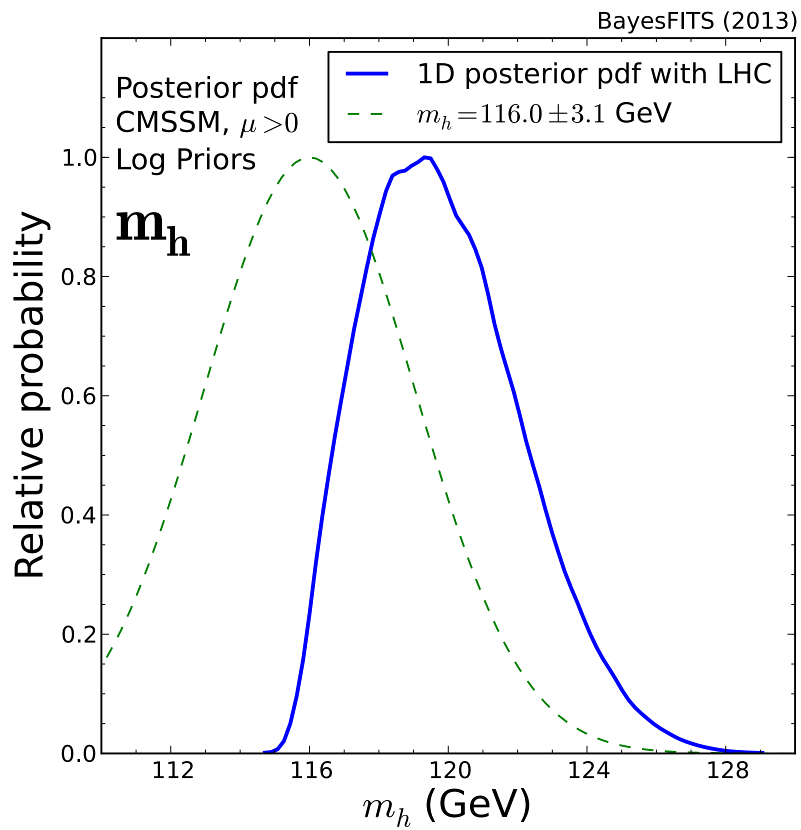
Consistent with:

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

125 GeV - worst possible value (G. Giudice)

If m_h were, say, 116 GeV...





...would have created significant tension with LHC bounds on SUSY

The 125 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 <u>simultaneously</u>**

- Very wide ranges: 1302.5956

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

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

Nuisance	Description	Central value $\pm$ std. dev.	Prior Distribution
M_t	Top quark pole mass	$173.5 \pm 1.0\,\mathrm{GeV}$	Gaussian
$m_b(m_b)_{\mathrm{SM}}^{\overline{MS}}$	Bottom quark mass	$4.18 \pm 0.03\,\mathrm{GeV}$	Gaussian
$\alpha_s(M_Z)^{\overline{MS}}$	Strong coupling	0.1184 ± 0.0007	Gaussian
$1/\alpha_{\mathrm{em}}(M_Z)^{\overline{MS}}$	Inverse of em coupling	127.916 ± 0.015	Gaussian

Use Bayesian approach (posterior)

Hide and seek with SUSY

The experimental measurements that we apply to constrain the CMSSM's parameters. Masses are in GeV.

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
$\text{BR}\left(\overline{B} \to X_s\gamma\right) \times 10^4$	3.43	0.22, 0.21	Gaussian
$\text{BR}\left(B_u \to \tau\nu\right) \times 10^4$	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
$\text{BR}\left(B_s \to \mu^+\mu^-\right)_{\text{current}} \times 10^9$	3.2	$+1.5 - 1.2$, 10% (0.32)	Gaussian
$\text{BR}\left(B_s \to \mu^+\mu^-\right)_{\text{proj}} \times 10^9$	3.5 (3.2*)	0.18 (0.16*), 5% [0.18 (0.16*)]	Gaussian

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

most important (by far)

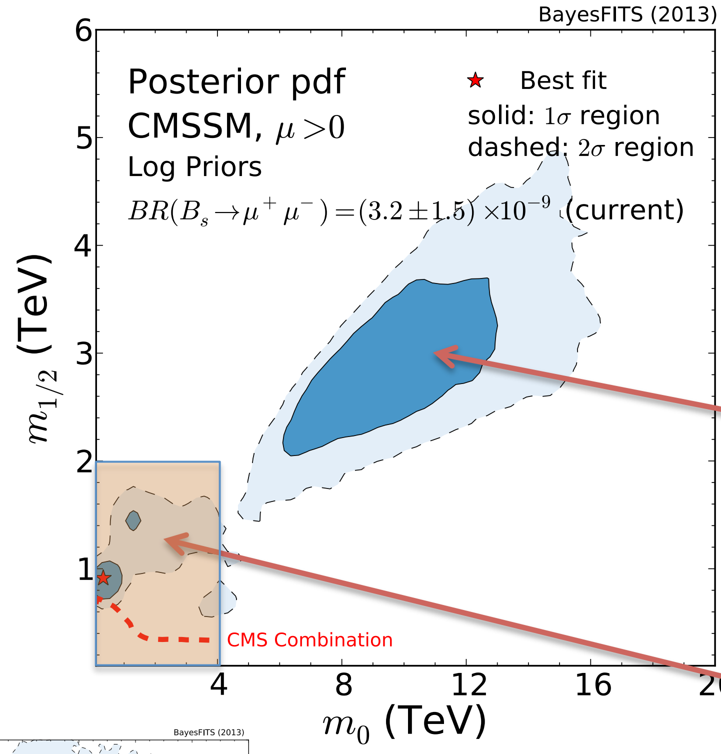
?

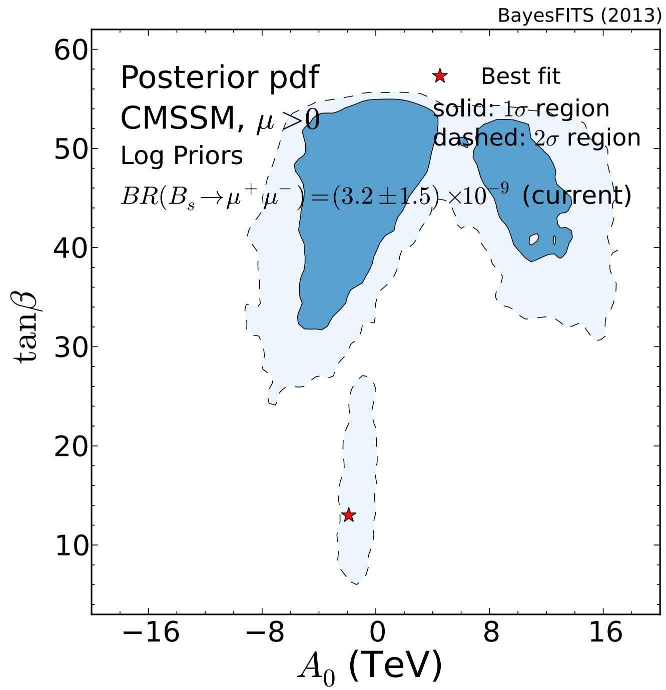
10 dof

The CMSSM with DM relic density

Global scan, Bayesian
total posterior probability regions

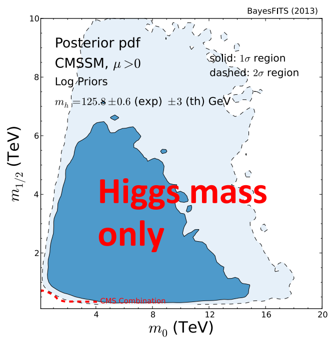
Kowalska, LR, Sessolo,
arXiv:1302.5956





~1 TeV higgsino DM

bino DM
(previously favored)



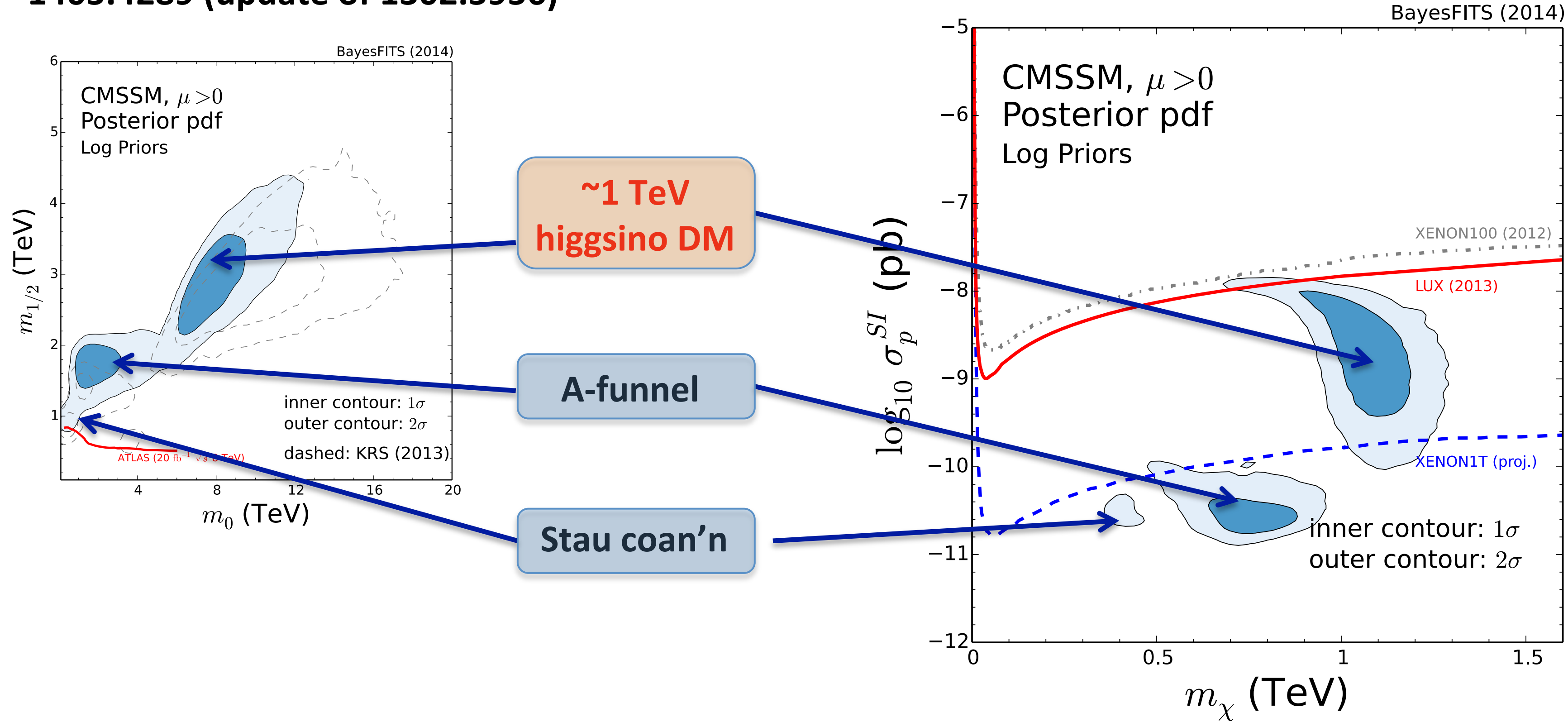
CMSSM: these are the <u>only</u> DM-favored regions

~1 TeV higgsino-like WIMP: implied by ~125 GeV Higgs

CMSSM and DD DM searches

$\mu > 0$

1405.4289 (update of 1302.5956)



Focus point region ruled out by LUX (already 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

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

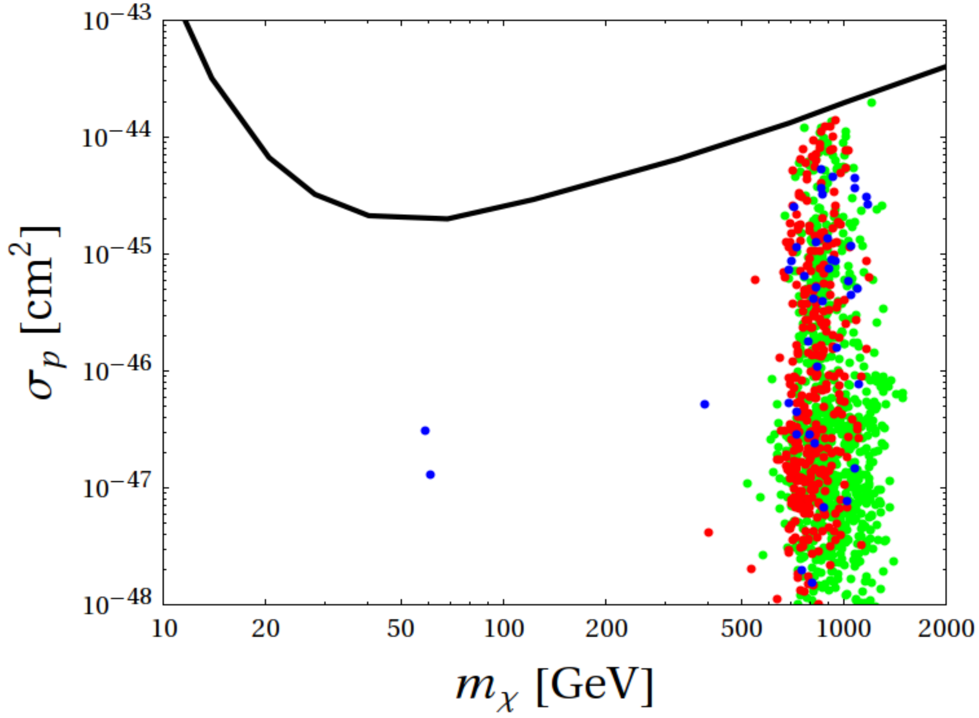
- ✧ **Implied by ~125 GeV Higgs mass <u>and</u> relic density**
- ✧ **Most natural**
- ✧ **Smoking gun of SUSY!?**

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



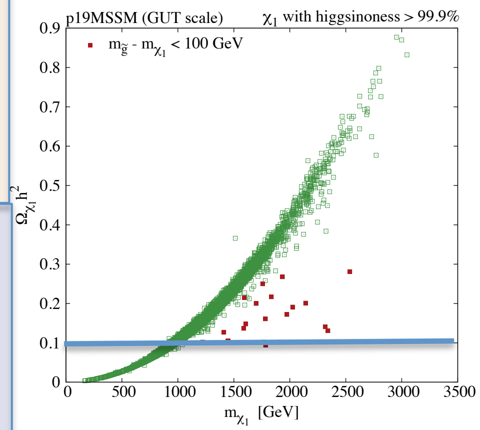
Fall and rise of higgsino DM

✧ **1991: put to grave**

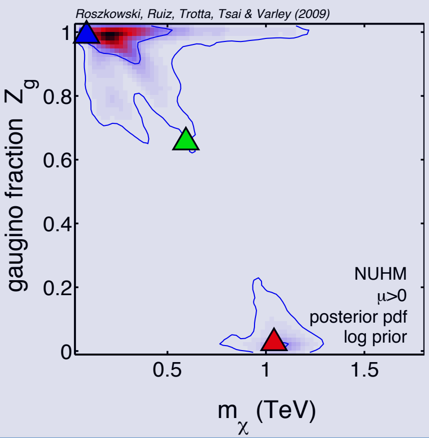
LR, PLB 262 (1991) 59: in MSSM:
- too little DM until mass >> 1 TeV (conflict with naturalness)
- bino favored

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

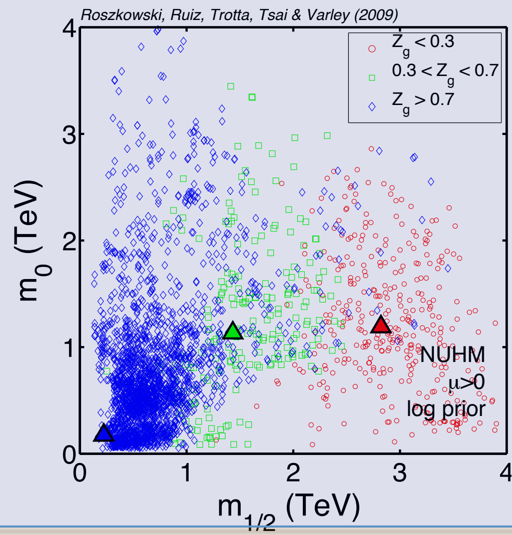
MSSM: Profumo & Yaguna, hep-ph/040703, Arkani-Hamed, Delgado, Giudice, hep-ph/0601041



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



NUHM in [0903.1279]

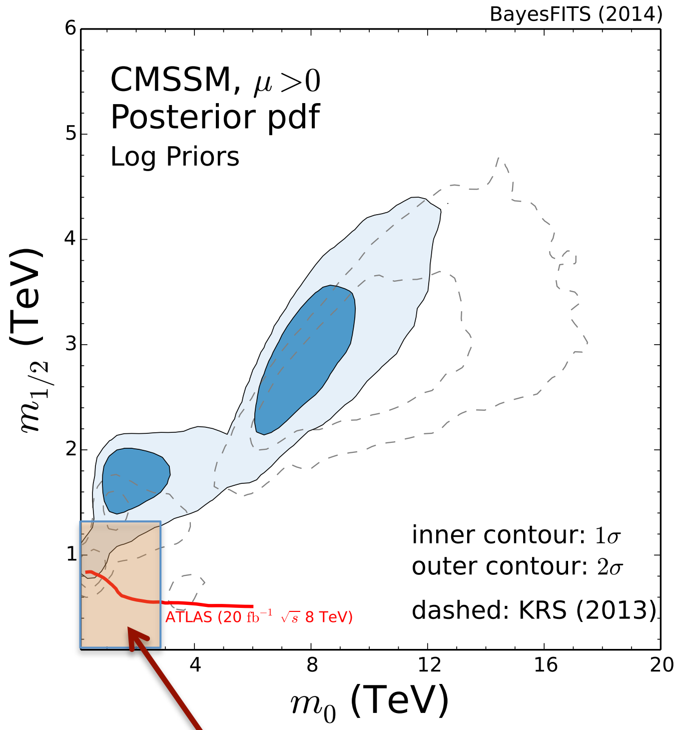


✧ **2012: favored by ~125 GeV Higgs mass**

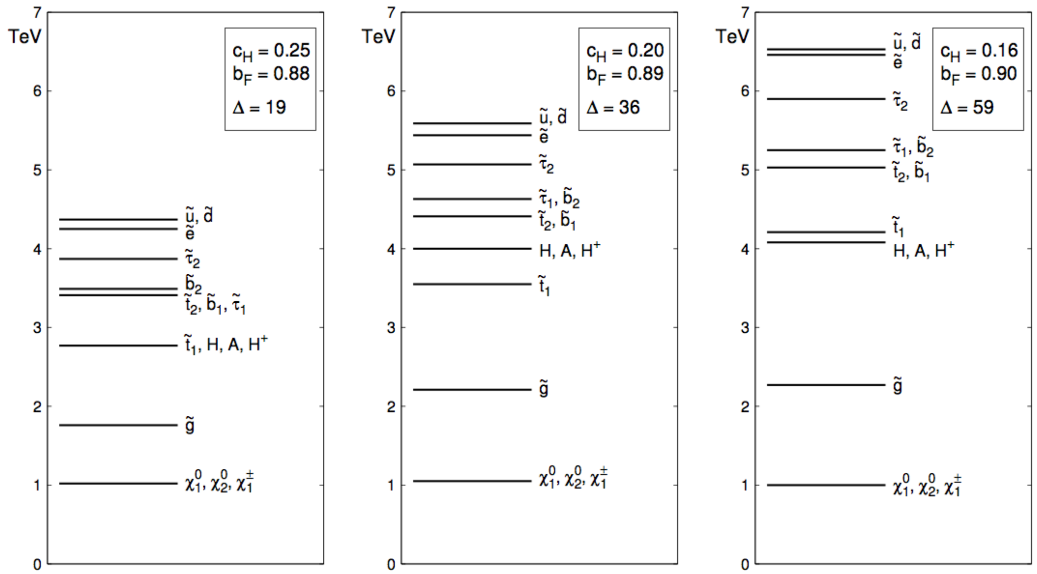
CMSSM: Cabrera et al., 1212.4821
NUHM: Strege et al., 1212.2636
CMSSM & NUHM: Kowalska, et al., 1302.5956

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

Chances of susy signal at the LHC?



CMSSM: typical mass spectra: **1405.4289**



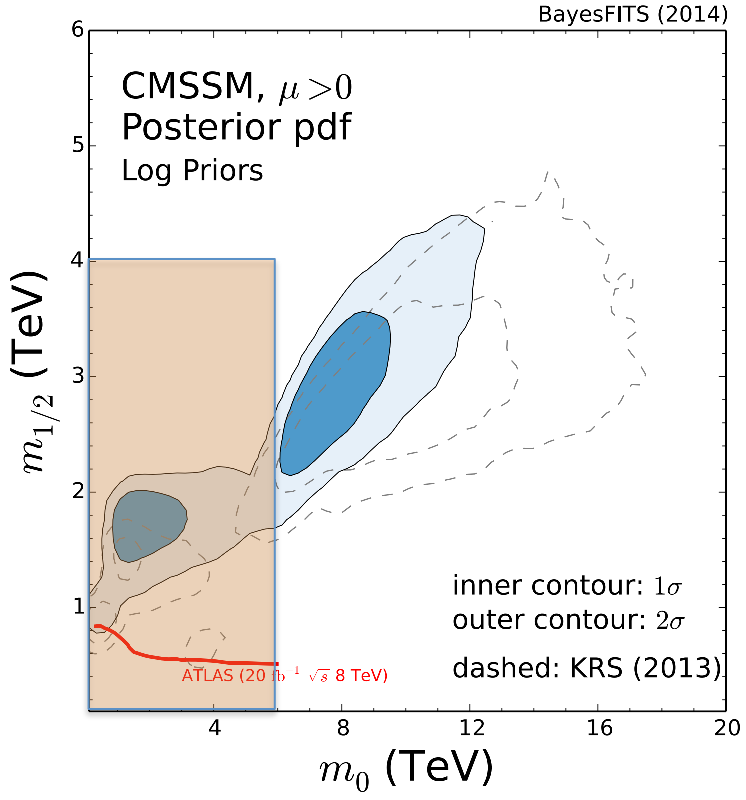
LHC14 reach:
Gluino: ~2.7 GeV
Squarks: ~3 TeV

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

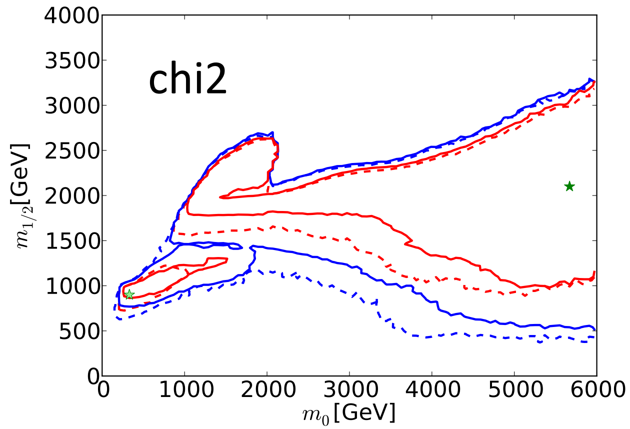
CMSSM-like: chances look remote!

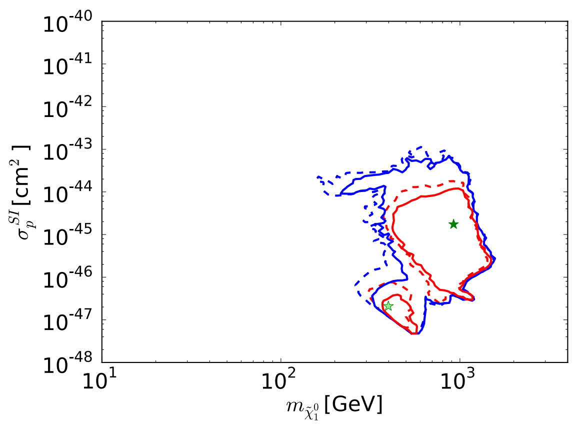
General MSSM: much lower masses allowed

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



Buchmueller et al [1312.5250]



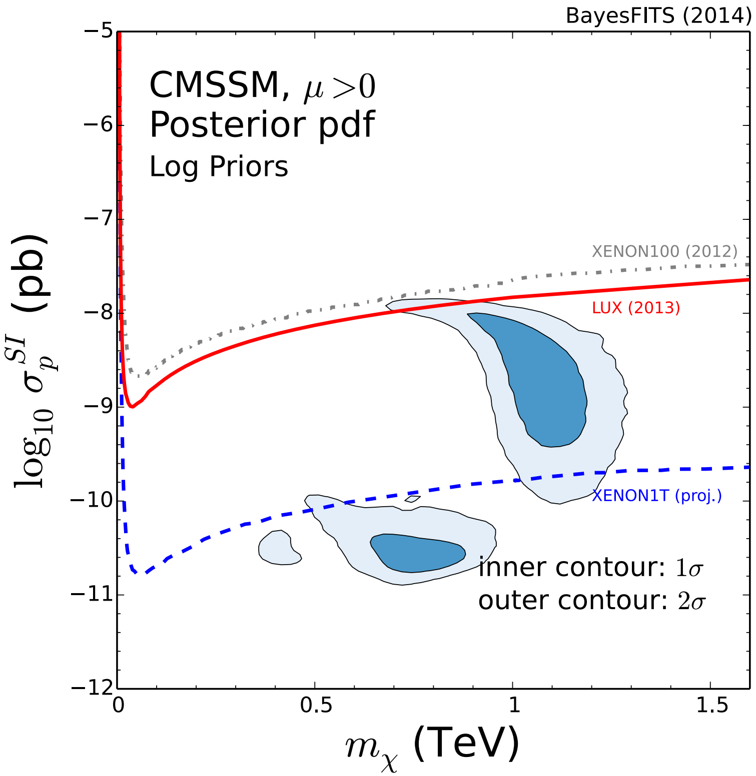


Reasonably good agreement in overlapping region

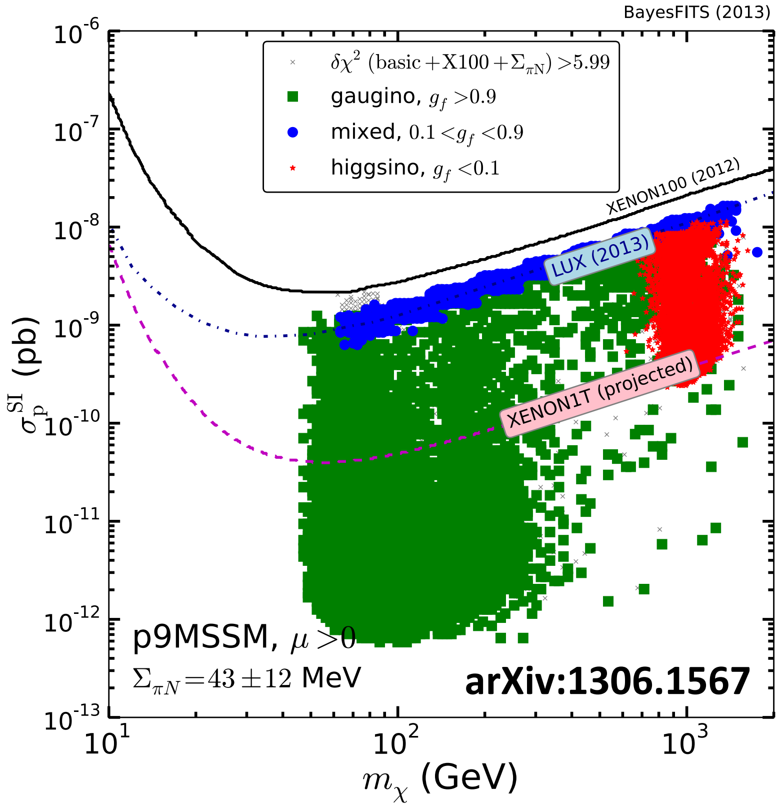
~1 TeV higgsino-like WIMP: implied by ~125 GeV Higgs -> large m1/2 and m0

Unified vs pheno SUSY

Unified SUSY (Constrained MSSM)



General SUSY (p9MSSM)

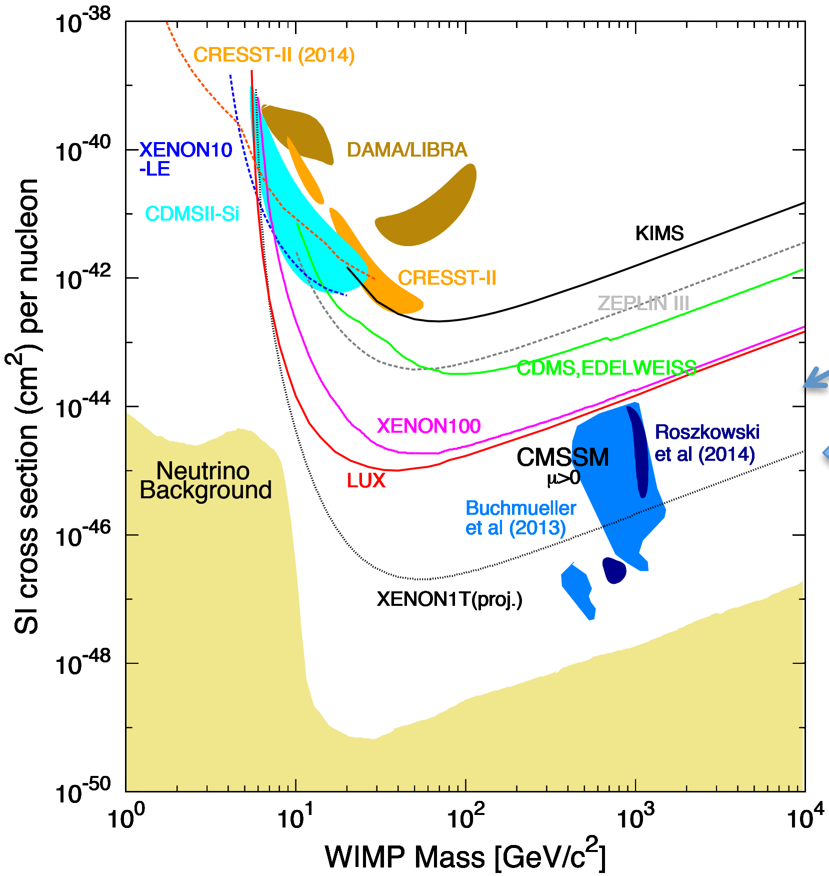


MSSM:

- **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**

DM direct detection

1407.0017



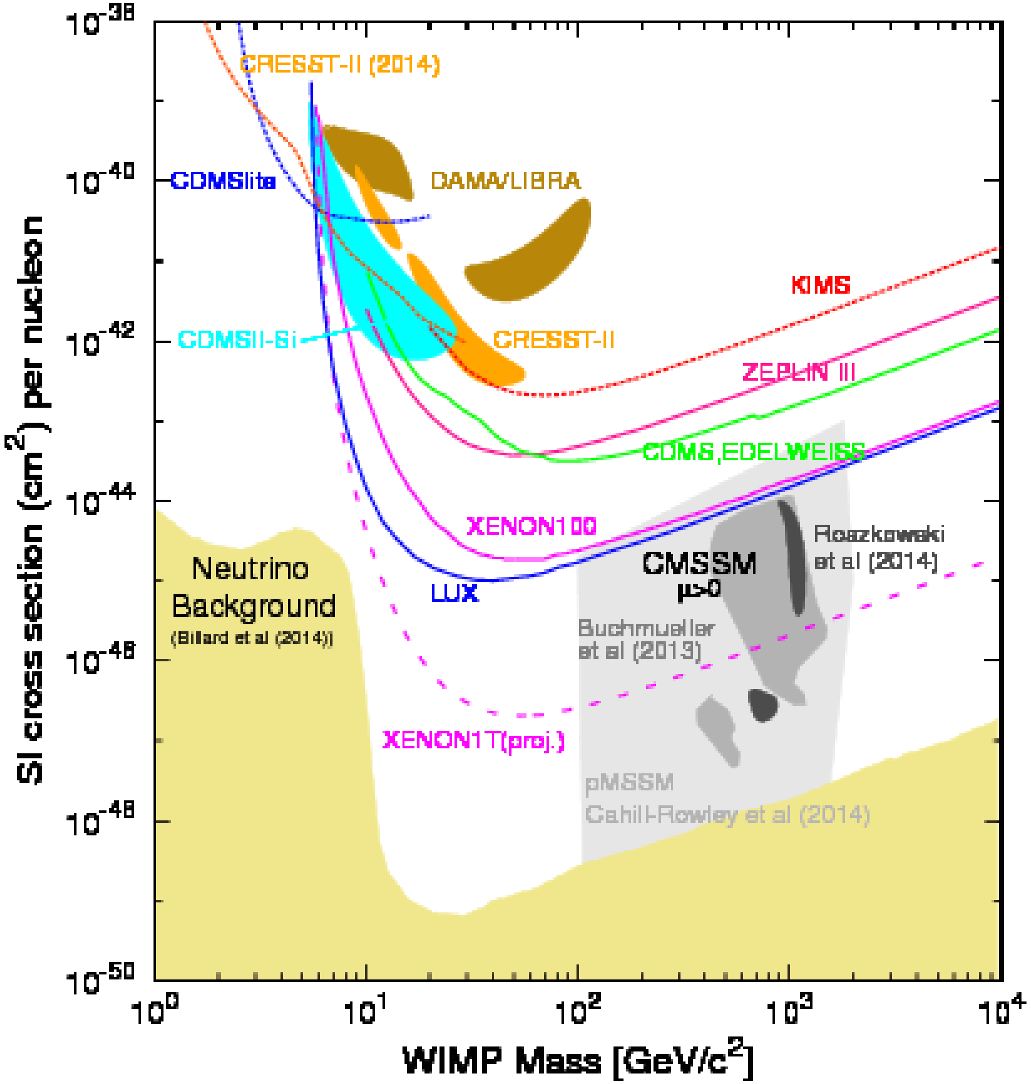
Reach of currently running experiments: LUX, Xenon100

~2017

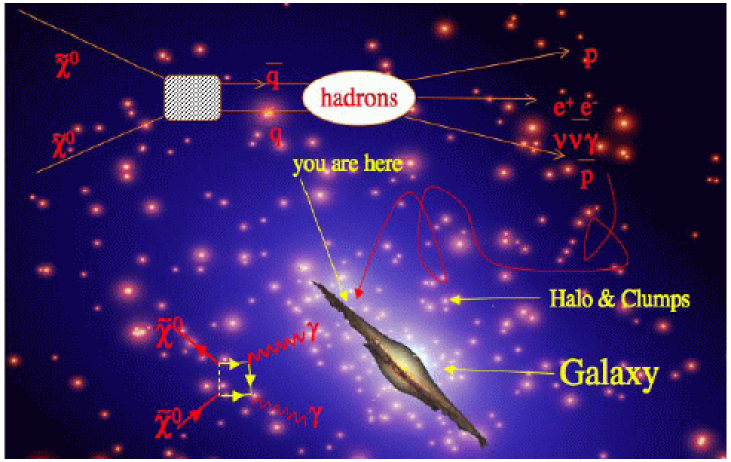
Excellent prospects!

DM Direct detection AD2014

1407.0017



Indirect detection

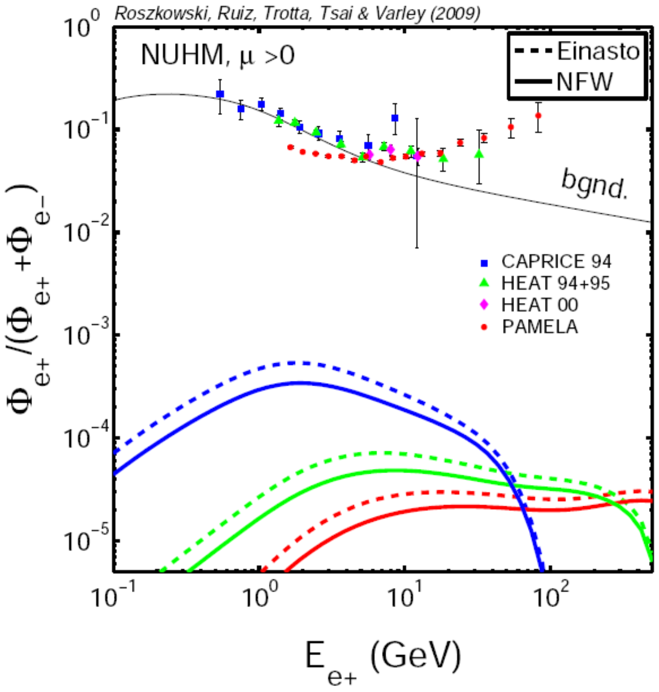


- look for traces of WIMP annihilation in the MW halo (γ's, e^+'s, $\bar{p}$, ...)
- detection prospects often strongly depend on astrophysical uncertainties (halo models, astro bgnd, ...)

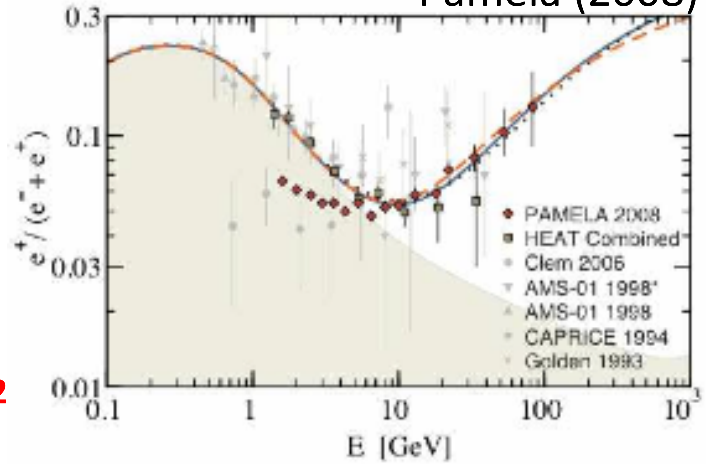
Much activity:

- PAMELA
- Fermi
- neutrino telescopes, ATCs, ...

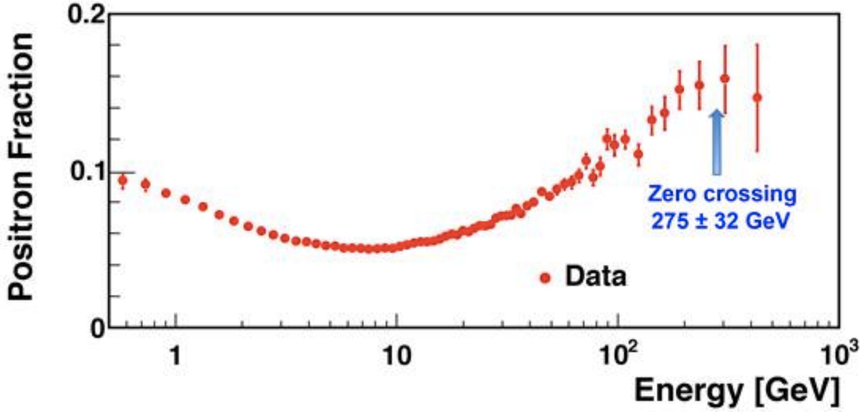
SUSY DM and positron flux



Pamela (2008)



NEW AMS-02
18/09/2014



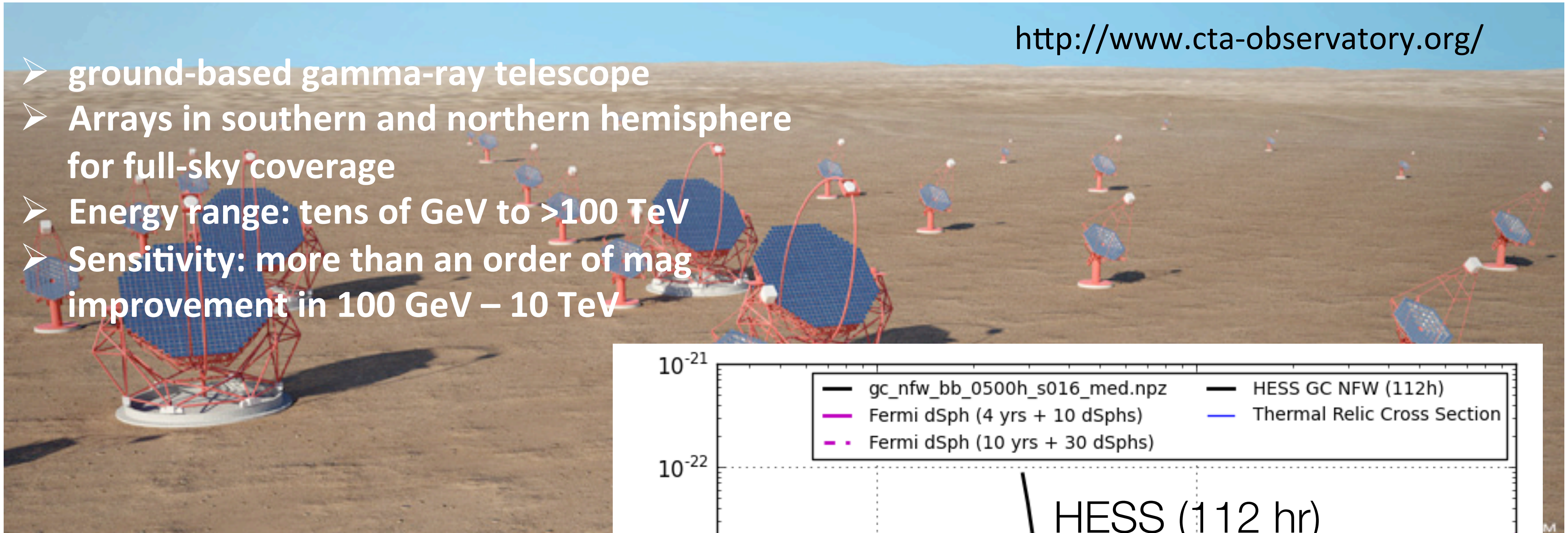
SUSY does not explain positron excess!

Also true for wino LSP (Hryczuk et al)

AMS may help settle the issue:

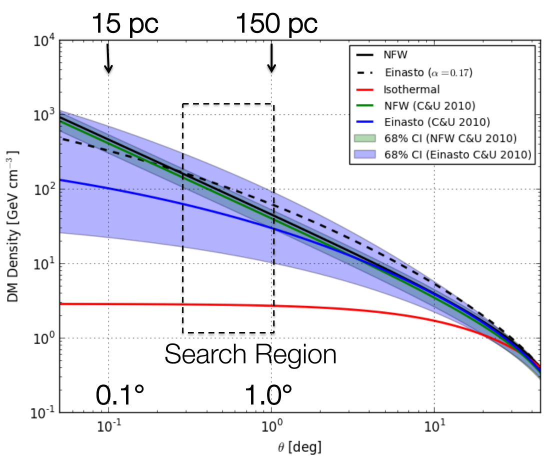
- **if isotropic: DM(?)**
- **If directional: pulsar**

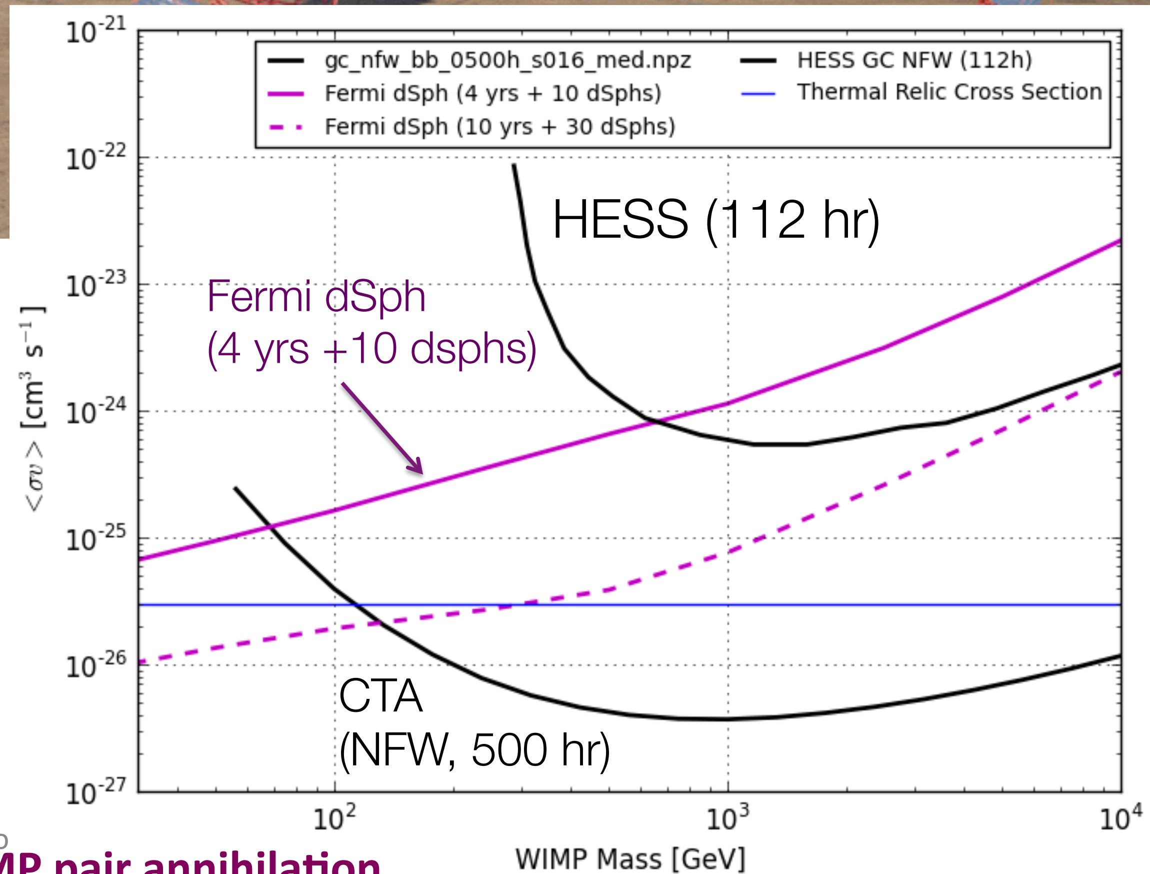
CTA – New guy in DM hunt race



- 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

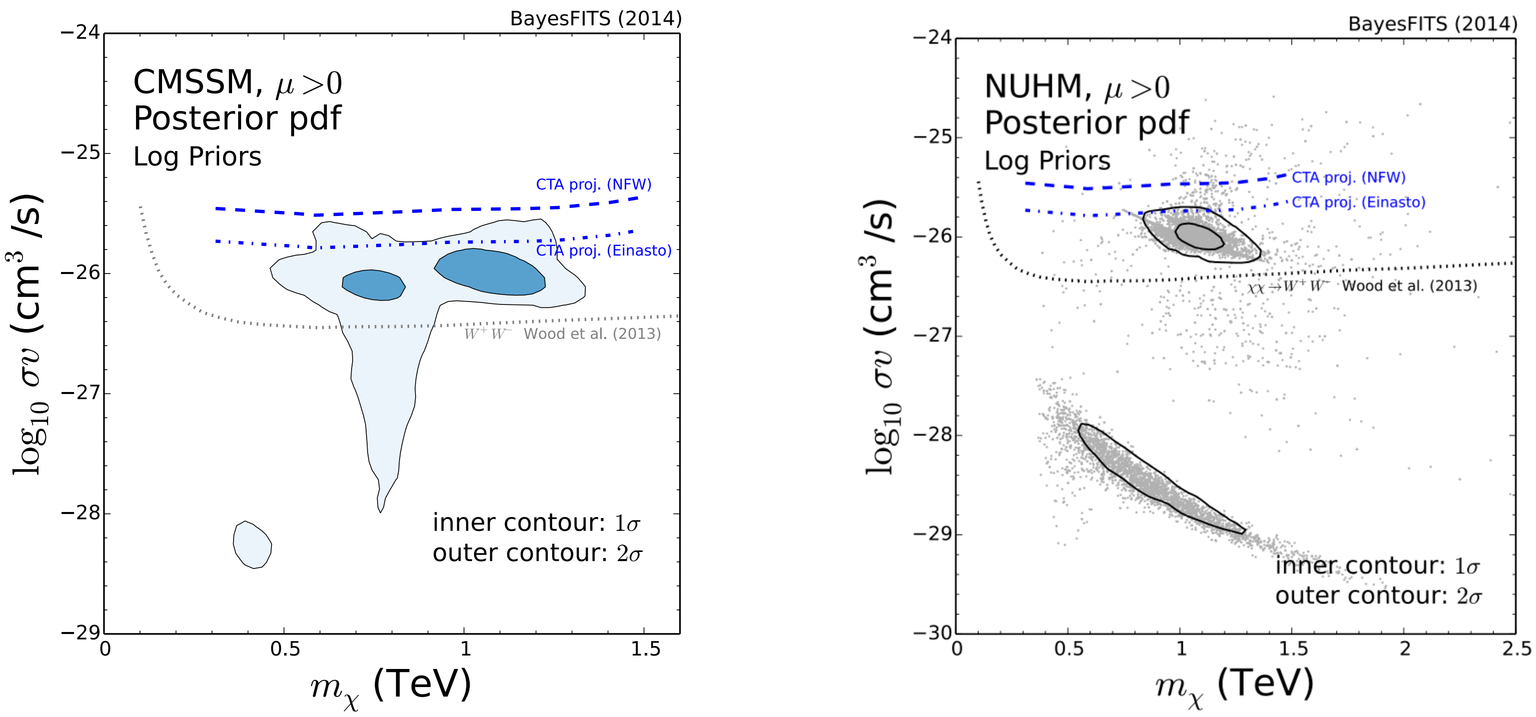




L. Ro

diffuse gamma radiation from WIMP pair annihilation

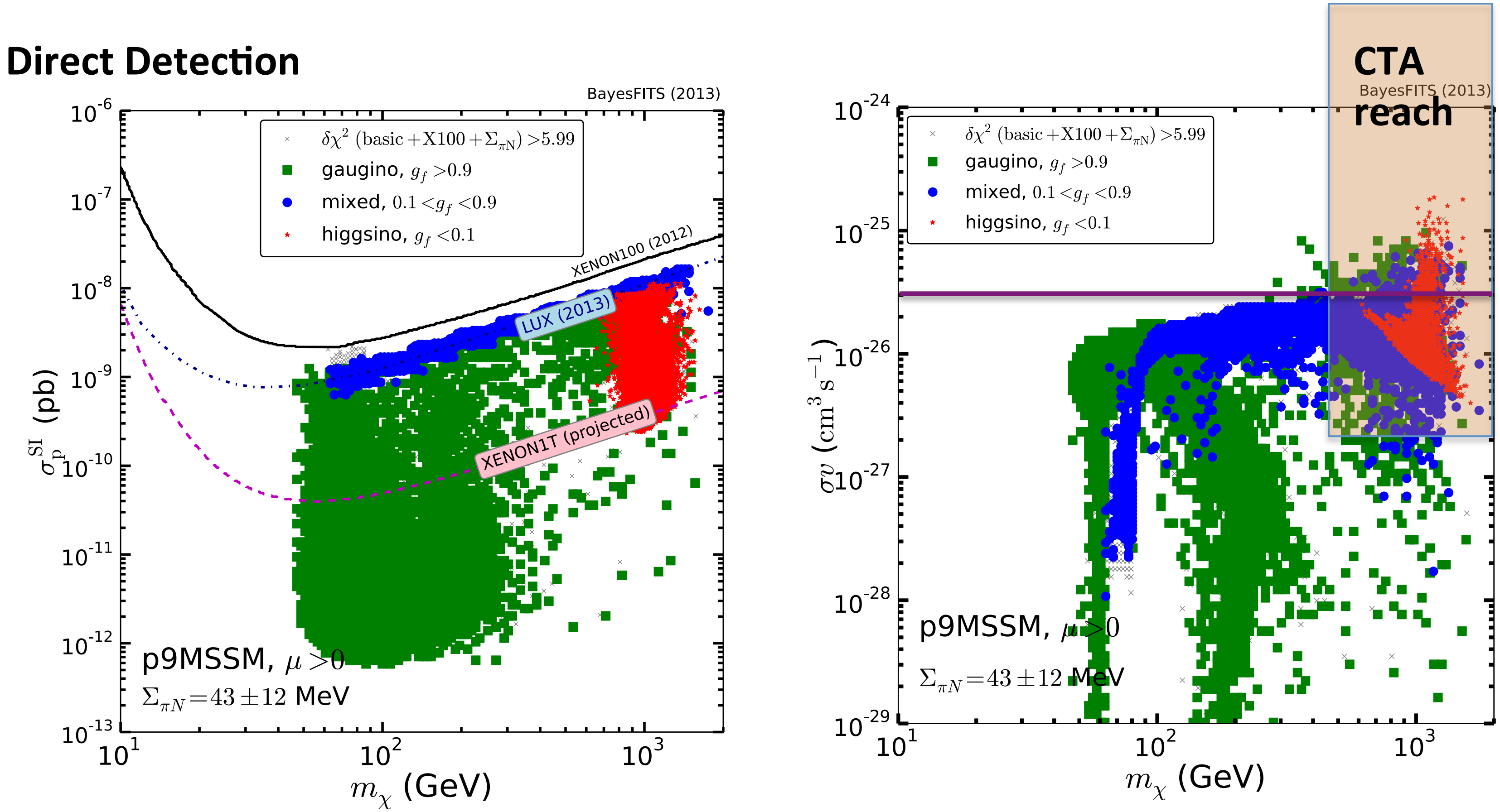
CTA and Unified SUSY DM



1405.4289

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

CTA and general SUSY DM



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

Fine-tuning in ~1 TeV higgsino region

CMSSM: FT is enormous

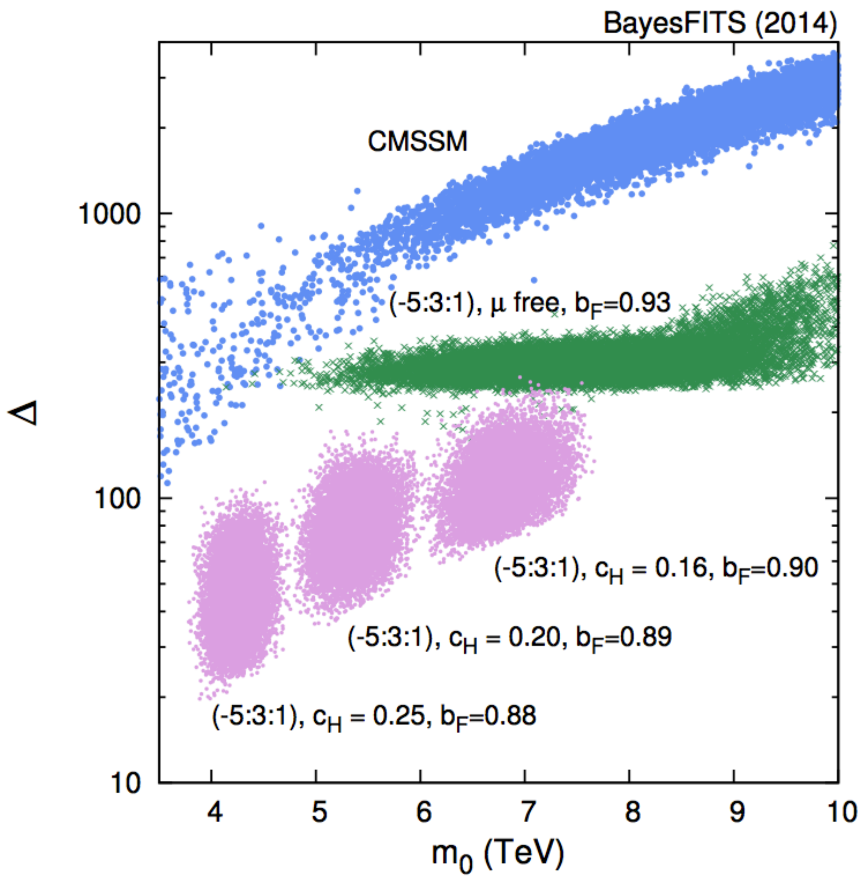
But…

FT can be reduced as far down as ~20

(all constraints satisfied)

Need to relax <u>strict</u>:

- **gauge coupling and**
- **mass unification conditions**
- **link mu to soft masses**



1402.1328

~1 TeV higgsino DM

To take home:

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

- Higgs of 125 GeV → ~1TeV (higgsino) DM – robust prediction of unified (and pheno) SUSY:

Smoking gun of SUSY!?

  - To be probed by 1-tonne DM detectors
  - Big bite by LUX already in 2014
  - Independent probe by CTA
  - Other indirect detection modes (nu, e^+, …): no chance
  - Far beyond direct LHC reach
- (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