Smoking guns of supersymmetric dark matter

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Outline

✧ Setting the stage: Higgs boson, dark matter and SUSY scale

✧ Implications of m_h~125 GeV for SUSY mass scale

✧ Impact of DM relic abundance and searches

✧ ~1 TeV higgsino DM: Smoking gun of SUSY

✧ Complementarity of LHC and DM searches (direct and CTA)

✧ Early Universe: impact of low T_R

✧ Summary

Based on:

- K. Kowalska, L. Roszkowski, E. M. Sessolo, arXiv:1302.5956, JHEP 1306 (2013) 078
- L. Roszkowski, E. M. Sessolo, A. J. Williams, arXiv:1405.4289 and arXiv:1411.5214 (JHEP)
- K. Kowalska, L. Roszkowski, E. M. Sessolo, S. Trojanowski, 1402.1328 (JHEP)
- K. Kowalska, L. Roszkowski, E. M. Sessolo, A. J. Williams, 1503.08219
- L. Roszkowski, S. Trojanowski, K. Turzyński, 1406.0012 (JHEP) and in preparation

Where is the WIMP?

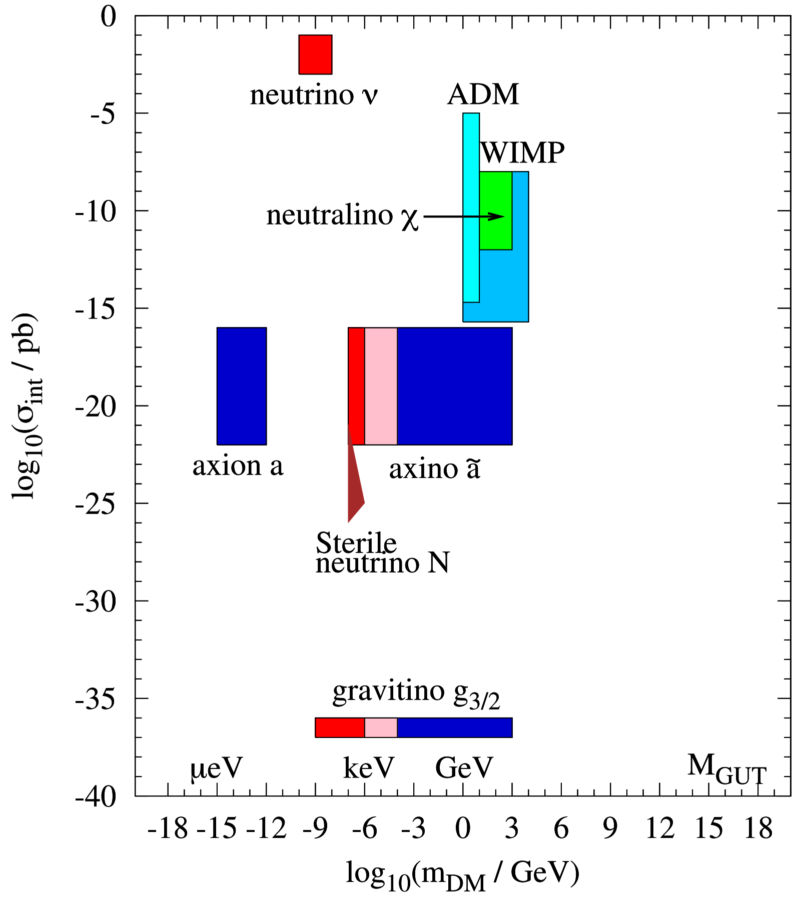
- ➢ **Mass range: at least 20 orders of magnitude**
- ➢ **Interaction range: some 32 orders of magnitude**

WIMP remains the front-runner for dark matter


WANTED
★ DEAD OR ALIVE ★
WIMP
REWARD $ 100.000
?

Well-motivated candidates for dark matter

1307.3330



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

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- 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 ``new physics”?

➢ **No convincing hint from the LHC**

but…

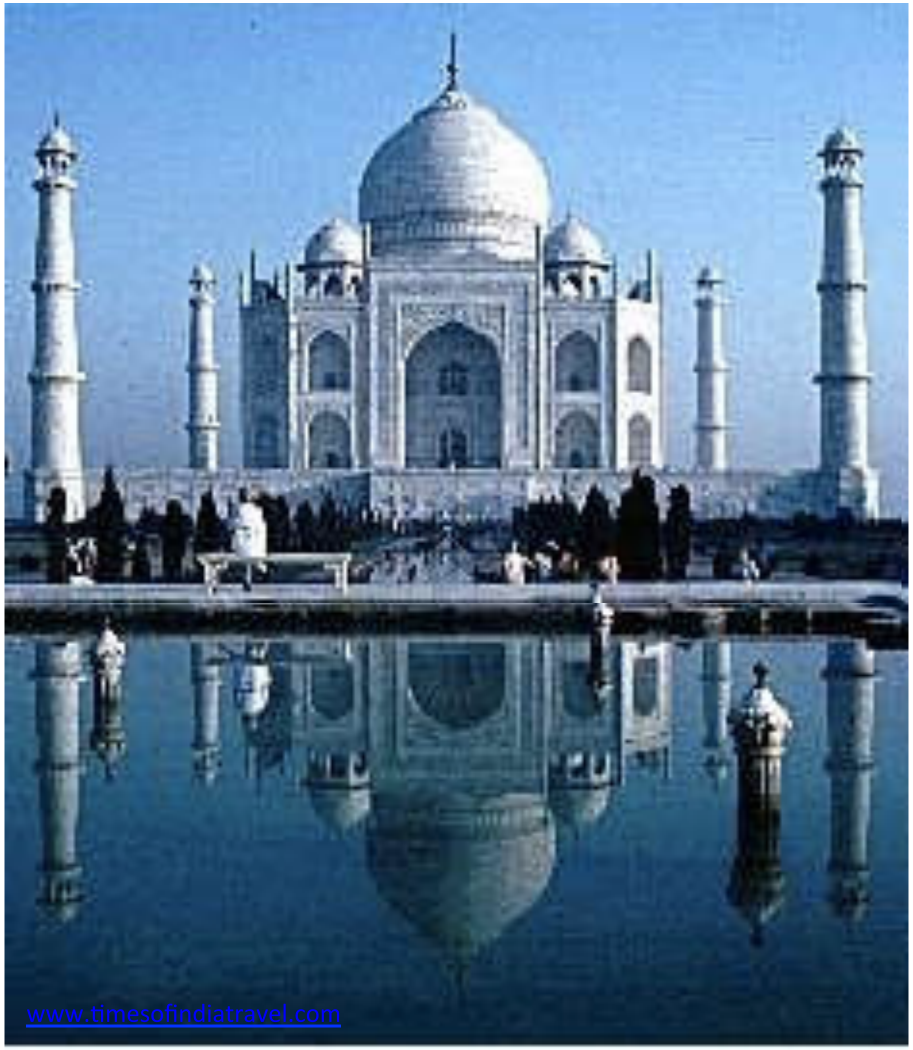
➢ **Fundamental scalar --> SUSY**

➢ **Light and SM-like --> SUSY**

Low energy SUSY remains the front-runner for ``new physics”

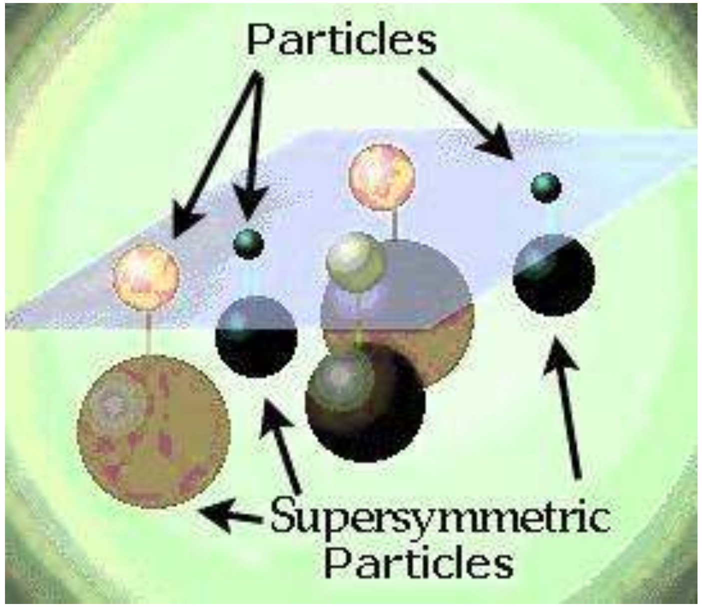

WANTED
DEAD OR ALIVE
SUSY
REWARD $ 100.000
?

Supersymmetry

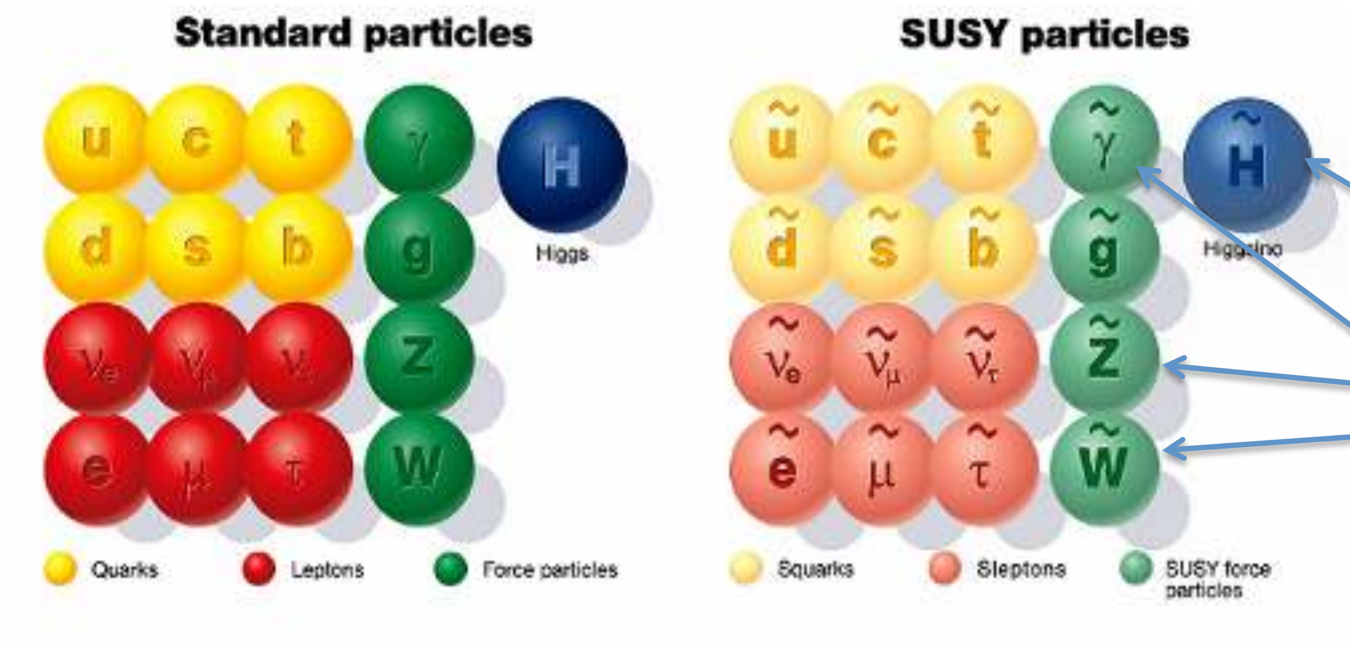


Symmetry among particles

Bosons <-> fermions



SUSY and dark matter



- bino
- wino
- higgsino

Candidates for a WIMP

- Weakly interacting
- Massive
- stable

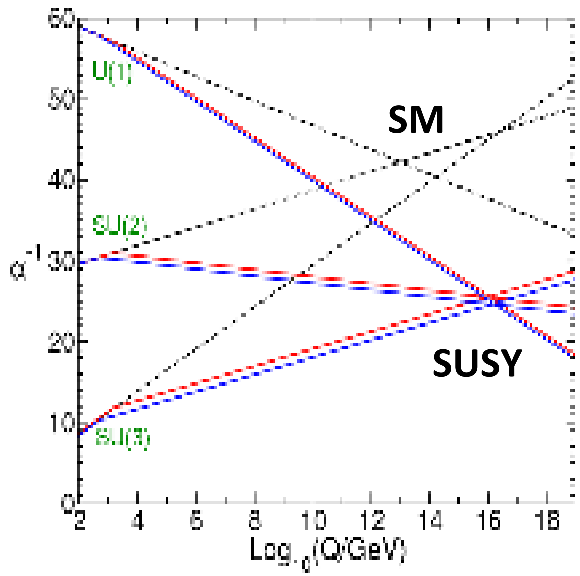
WIMP = LSP

(lightest supersymmetric particle)

Why SUSY

Provides sensible framework for:

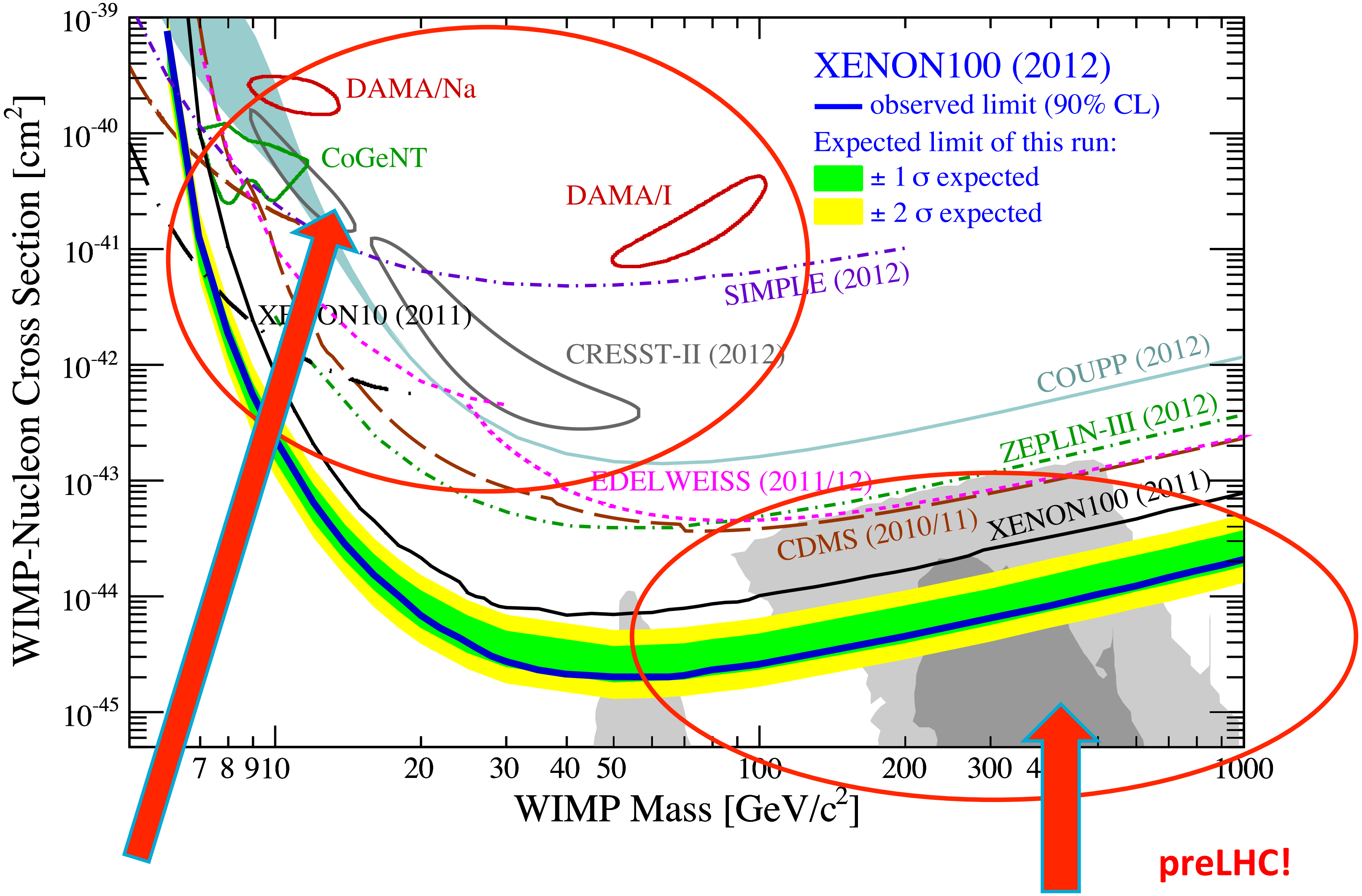
- **unification (including gravity)**
- **Early Universe cosmology (inflation, baryo/leptogenesis, …)**
- **…**



Predictions:

- **top quark mass $m_t < 200$ GeV** **Expt: 173.34 +/- 0.76 GeV**
- **(lightest) Higgs boson mass <~ 130-132 GeV (and SM-like)**
- **…plus:**
  - **Lots of new particles (superpartners)**
  - **Possible contributions to rare processes, etc**
  - **Dark matter candidate**

Direct Detection AD 2011 - Before LHC

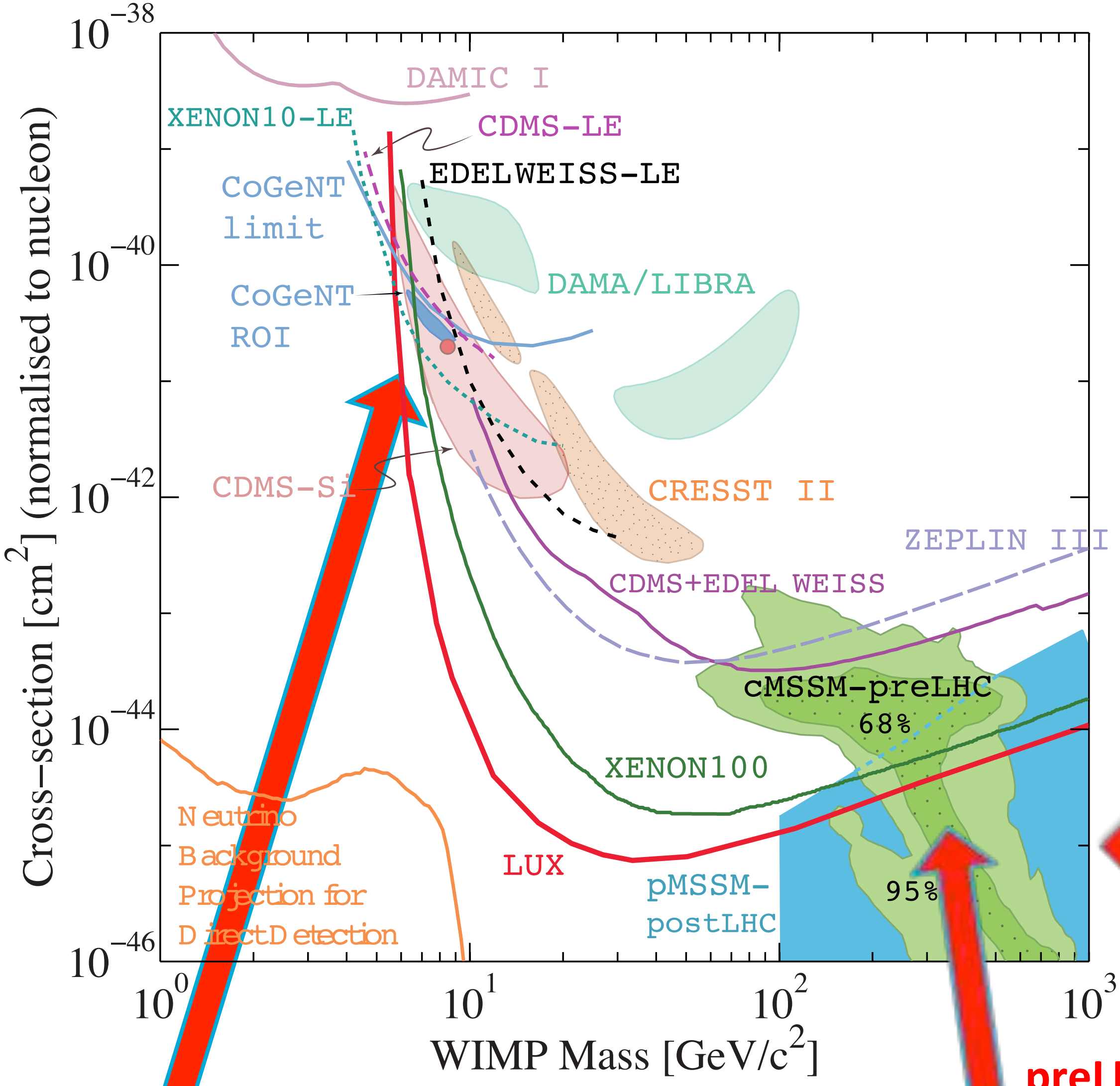


Confusion region

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 ~125 GeV**

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

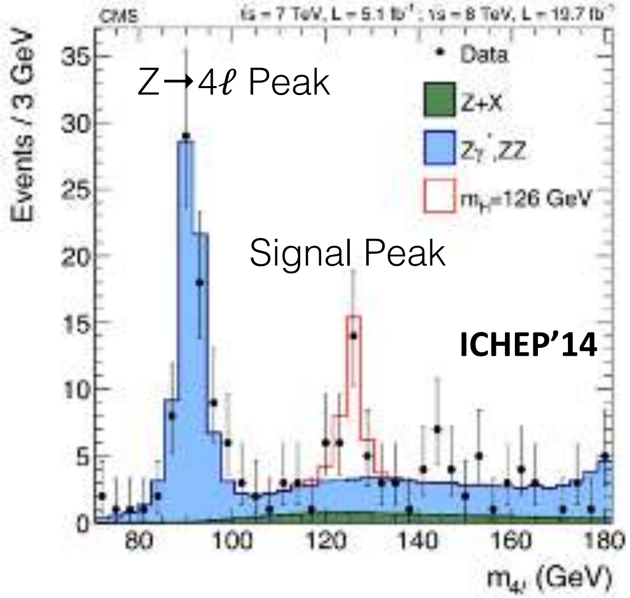
$$\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

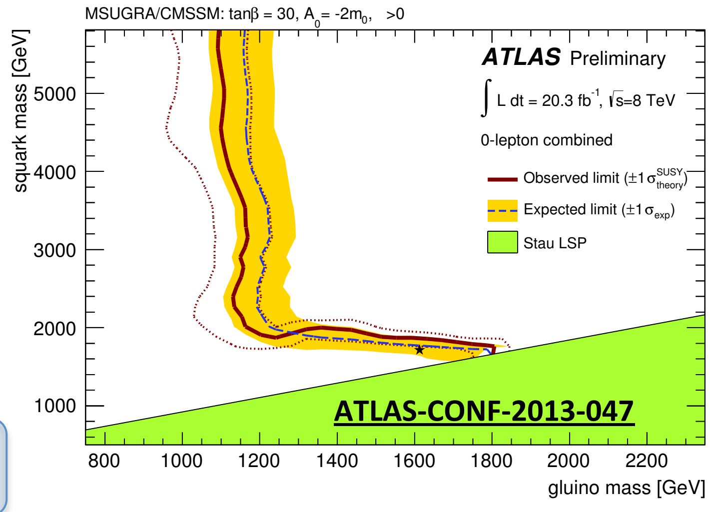
Combined LHCb+CMS

$$\mathrm{SM:}\ 3.54 \pm 0.27 \times 10^{-9}$$

superIso v.3.4

➢ **Stringent lower limits on superpartner masses**





Each independently implies:

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

<u>My conjecture:</u>

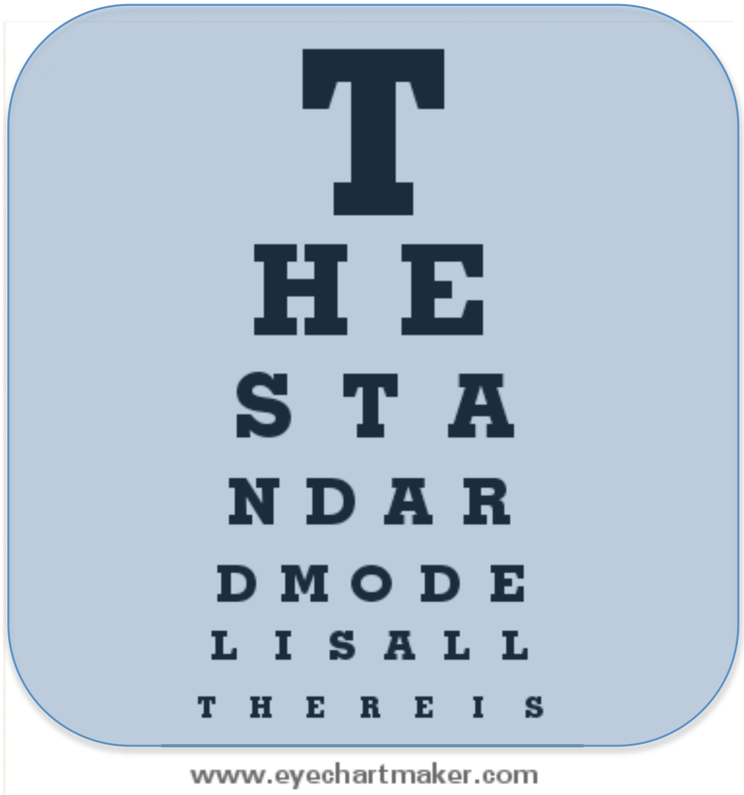
(Coined before LHC era...)

SUSY cannot be experimentally ruled out.

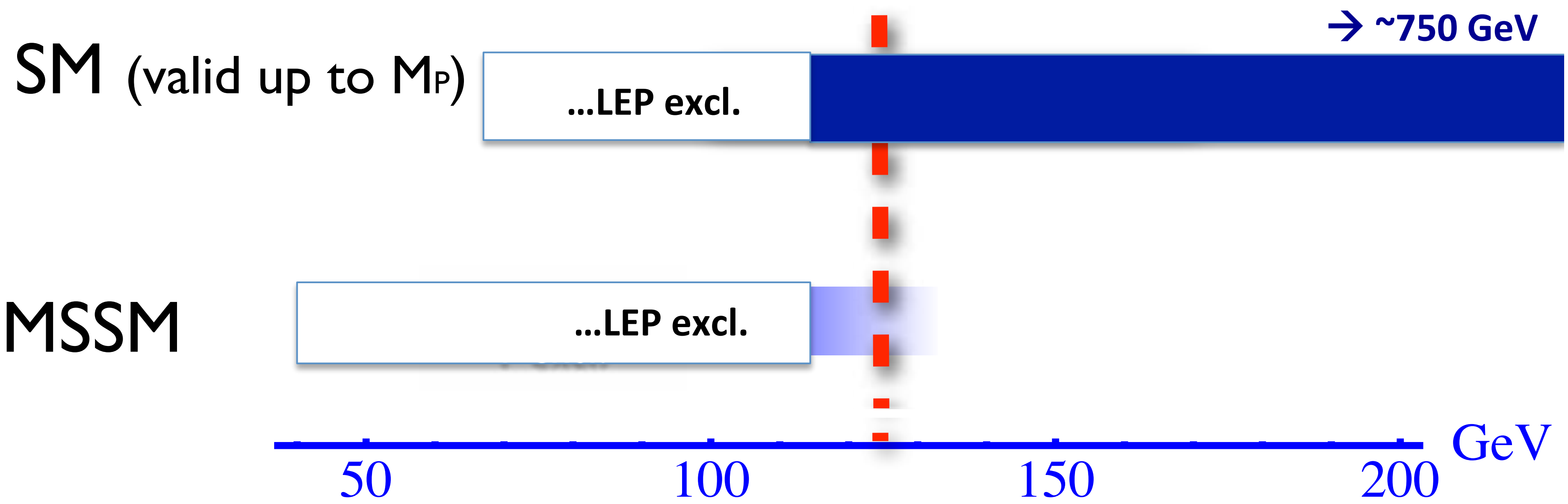
It can only be discovered.

Or else abandoned.

SM-like Higgs boson discovery



The 125 GeV Higgs boson and SUSY



Higgs boson mass of 125 GeV came out to lie in a narrow window allowed by simplest SUSY models (114.4 to ~132 GeV)

Smoking gun of SUSY?

Higgs boson:

- **fundamental scalar --> SUSY**
- **light and SM-like --> SUSY**

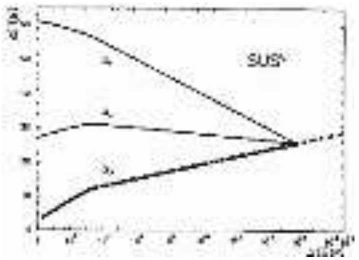
...close to the upper limit: this has strong implications...

SUSY: Constrained or Not?

SUSY is a symmetry, not a model

- **Constrained:**

Low-energy SUSY models with grand-unification relations among gauge couplings and (soft) SUSY mass parameters



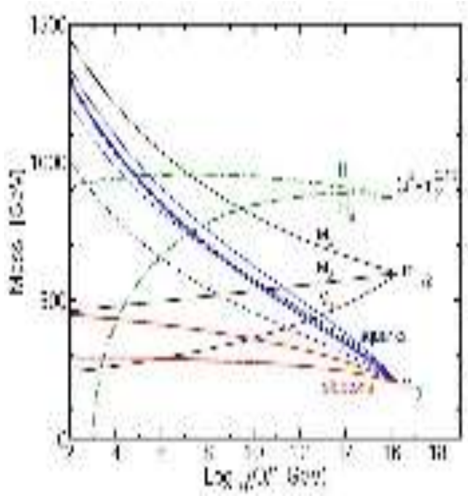


figure from hep-ph/9709356

Virtues:

- **Well-motivated**
- **Predictive (few parameters)**
- **Realistic**

Many models:

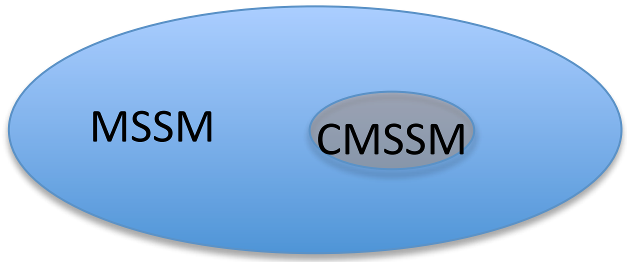
- **CMSSM (Constrained MSSM): 4+1 parameters**
- **NUHM (Non-Universal Higgs Model): 6+1**
- **CNMSSM (Constrained Next-to-MSSM) 5+1**
- **CNMSSM-NUHM: 7+1**
- **etc**

- **Phenomenological:**

Supersymmetrized SM…

Features:

- **Many free parameters**
- **Broader than constrained SUSY**



Many models:

- **general MSSM – over 120 params**
- **MSSM + simplifying assumptions**
- **pMSSM: MSSM with 19 params**
- **p9MSSM, p12MSSM, pnMSSM, …**

~125 GeV Higgs and unified SUSY

- Take only m_h~125 GeV and lower limits from direct SUSY searches

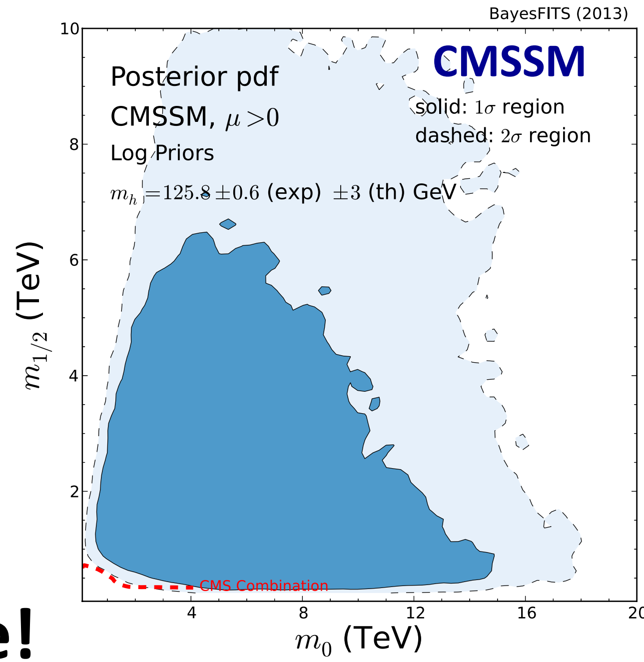
$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\ \mathrm{GeV})^2}{\sigma^2 + \tau^2}}$$

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

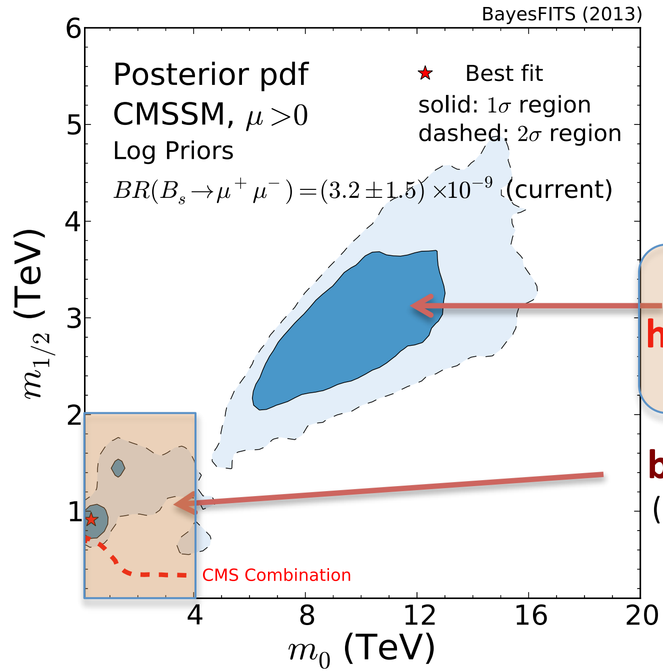
$$\Delta m_h^2 = \frac{3 m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\mathrm{SUSY}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\mathrm{SUSY}}^2}\left(1 - \frac{X_t^2}{12 M_{\mathrm{SUSY}}^2}\right)\right]$$

$$M_{\mathrm{SUSY}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \qquad X_t = A_t - \mu \cot\beta$$

- Add relic abundance $\Omega_{\mathrm{DM}} h^2 \simeq 0.12$



1302.5956



~1 TeV higgsino DM (``new")

bino DM (previously favored)

A curse!

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

Unified SUSY: NO other solutions

SUSY confronting data

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

Constraint	Mean	Exp. Error	Th. Error
Higgs sector	See text.	See text.	See text.
Direct SUSY searches	See text.	See text.	See text.
σ_p^{SI}	See text.	See text.	See text.
$\Omega_\chi h^2$	0.1199	0.0027	10%
$\sin^2 \theta_{\mathrm{eff}}$	0.23155	0.00015	0.00015
$\delta (g-2)_\mu \times 10^{10}$	28.7	8.0	1.0
$\mathrm{BR}\left(\overline{\mathrm{B}} \to \mathrm{X_s}\gamma\right) \times 10^4$	3.43	0.22	0.21
$\mathrm{BR}\left(\mathrm{B_u} \to \tau\nu\right) \times 10^4$	0.72	0.27	0.38
ΔM_{B_s}	$17.719\ \mathrm{ps}^{-1}$	$0.043\ \mathrm{ps}^{-1}$	$2.400\ \mathrm{ps}^{-1}$
M_W	80.385 GeV	0.015 GeV	0.015 GeV
$\mathrm{BR}\left(\mathrm{B_s} \to \mu^+\mu^-\right) \times 10^9$	2.9	0.7	10%

10 dof

most important (by far)

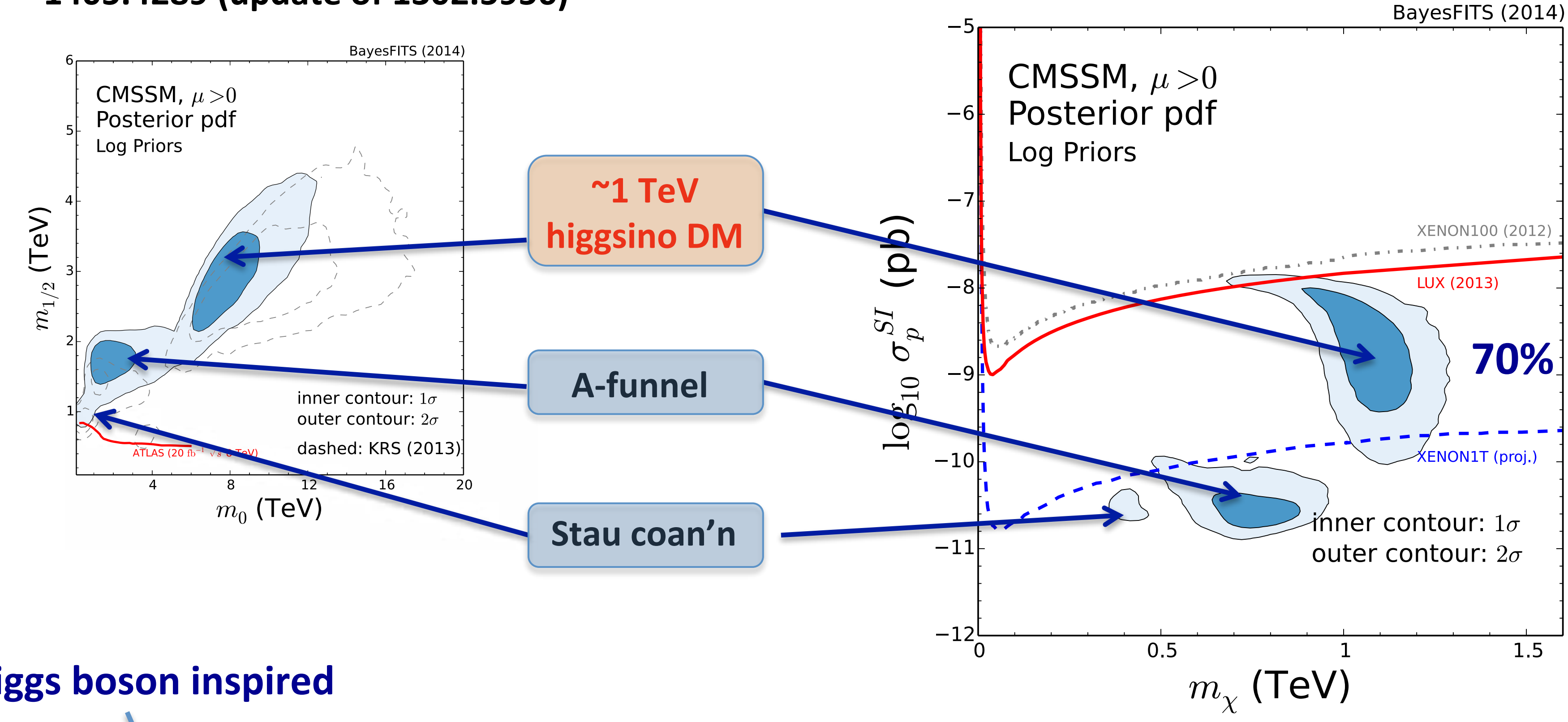
SM value: $\simeq 3.5 \times 10^{-9}$

We do simultaneous scan of at least 8 parameters (4 of CMSSM + 4 of SM)

CMSSM and direct DM searches

$\mu > 0$

1405.4289 (update of 1302.5956)



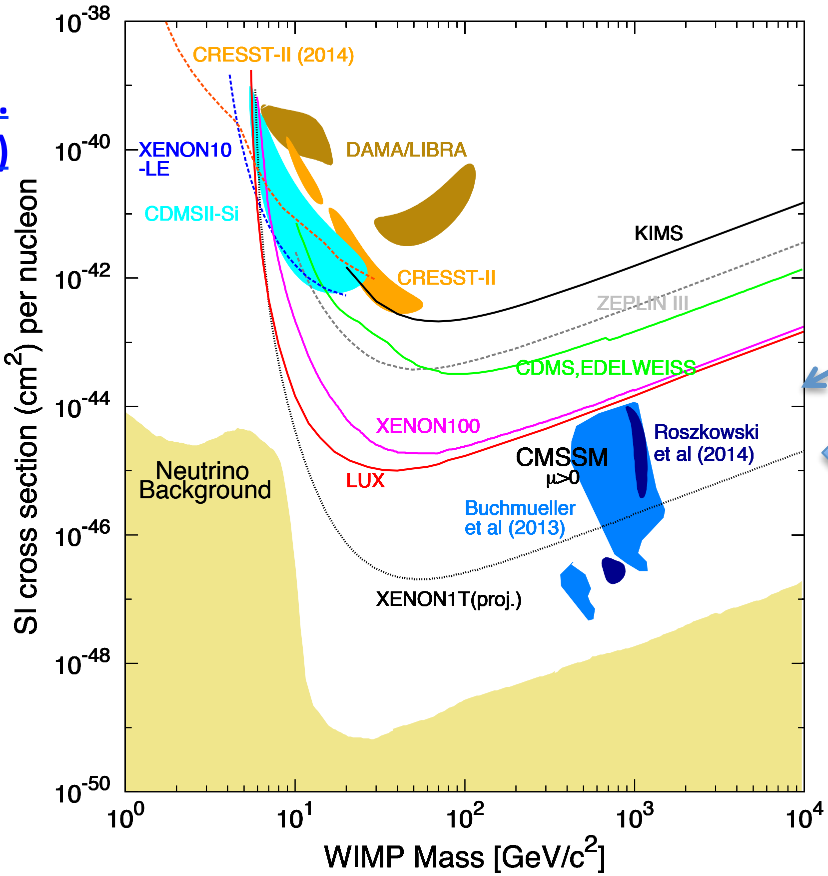
Higgs boson inspired

~1TeV higgsino DM: exciting prospects for LUX, X100 & 1t detectors

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

DM direct detection

[Recent review (H. Baer, K.-Y. Choi, JE Kim, LR, Phys. Rept.) 1407.0017]()

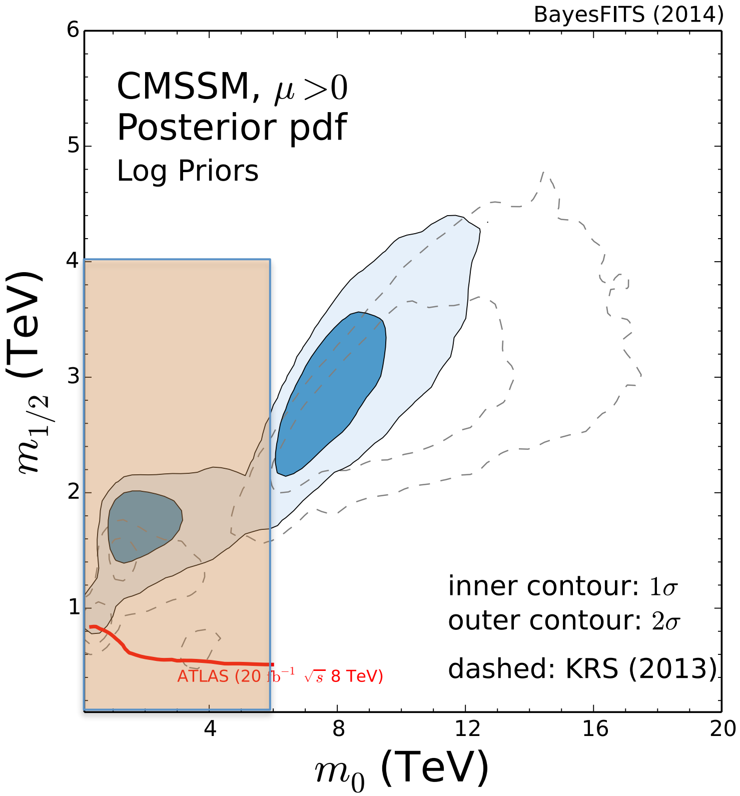


Reach of currently running experiments: LUX, Xenon100

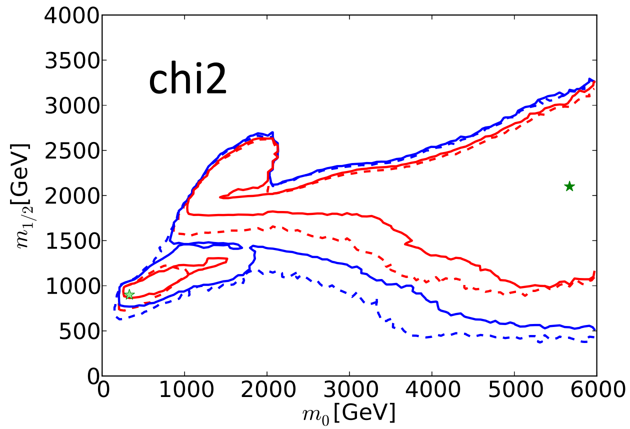
Reach by ~2017

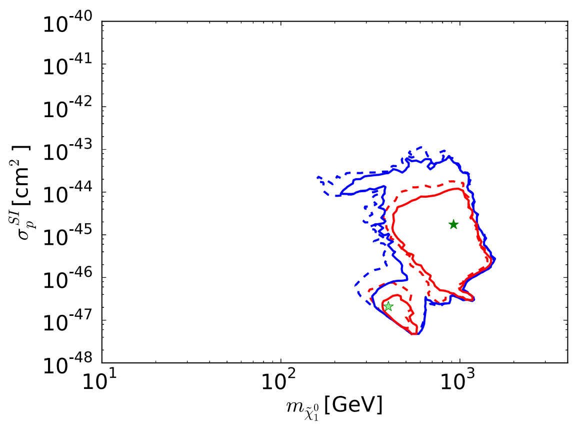
~1 TeV higgsino DM: excellent prospects!

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



Buchmueller et al 1312.5250



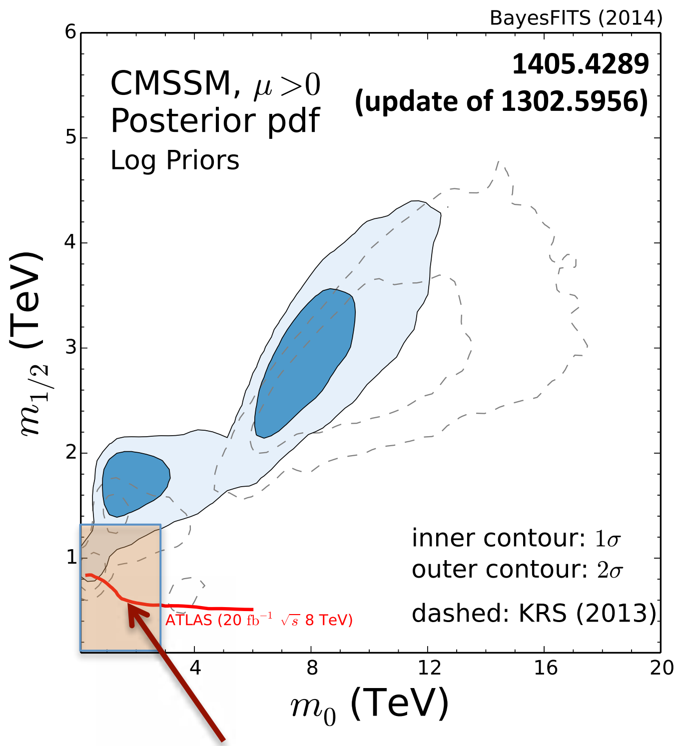


Reasonably good agreement in overlapping region

~1 TeV higgsino-like WIMP: implied by ~125 GeV Higgs -> large $m_{1/2}$ and m_0

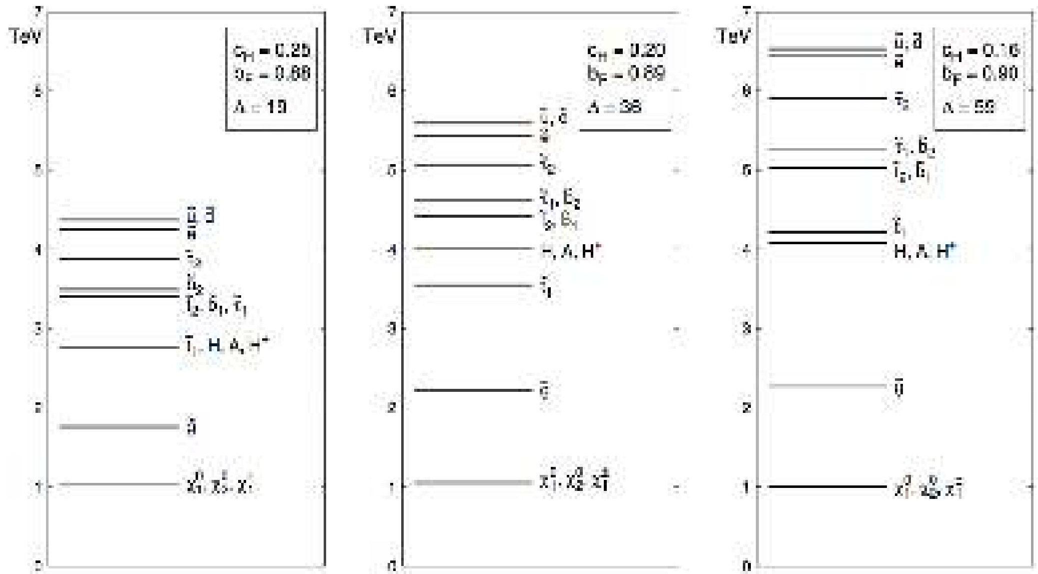
Chances of direct SUSY signal at the LHC?

The (HEP) world is not enough!



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

CMSSM: typical mass spectra: 1405.4289

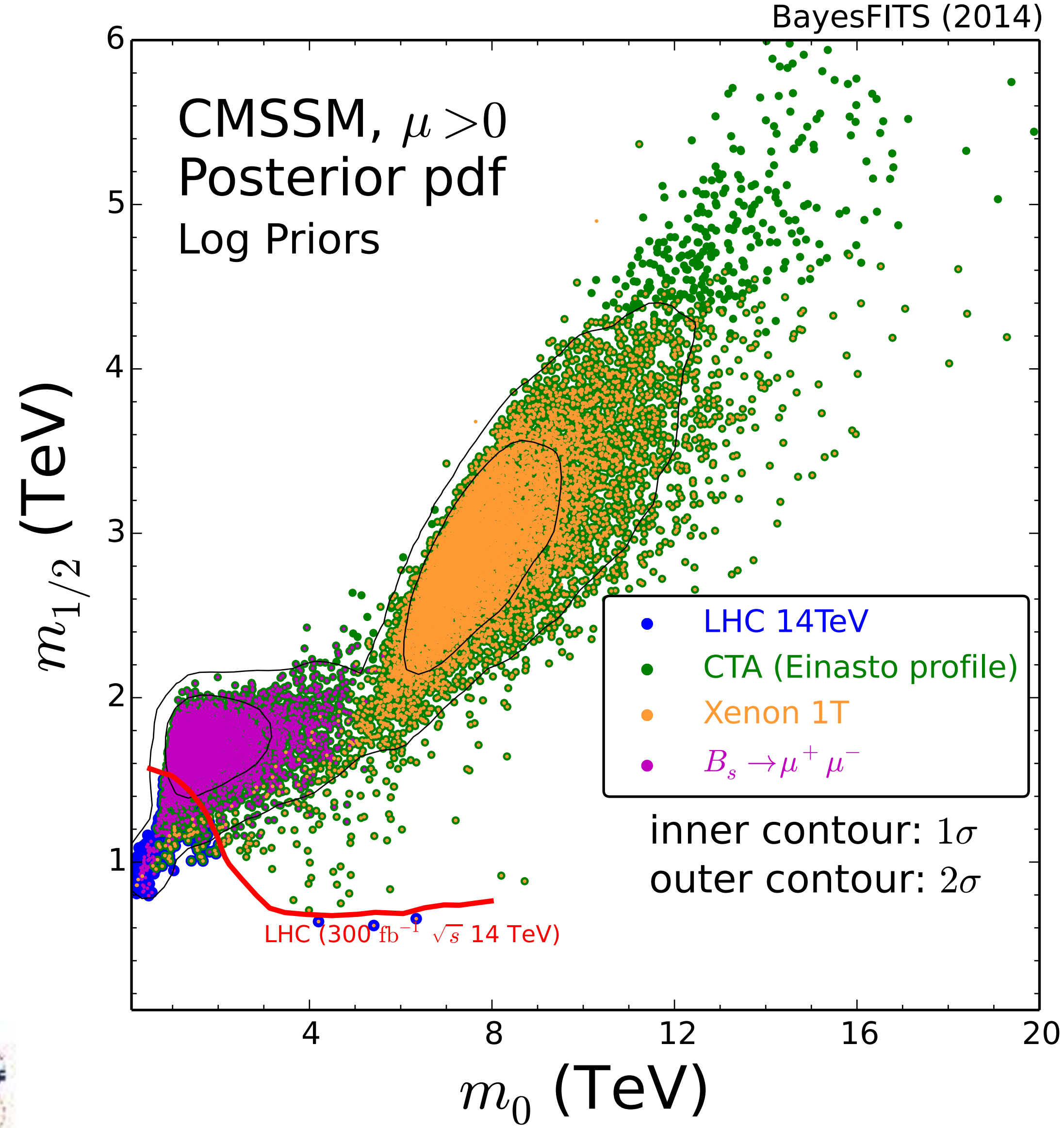


- LHC – only stau coannihilation will be +/- covered

CMSSM-like: chances look remote!

- General MSSM: much lower spartner masses allowed
- (Constrained) Non-MSSM: other light (pseudo)Higgs allowed

CMSSM: Complementarity of DD, CTA and LHC



..all parameter space covered at 2 sigma

CMSSM can be fully explored by experiment

How robust are these results?

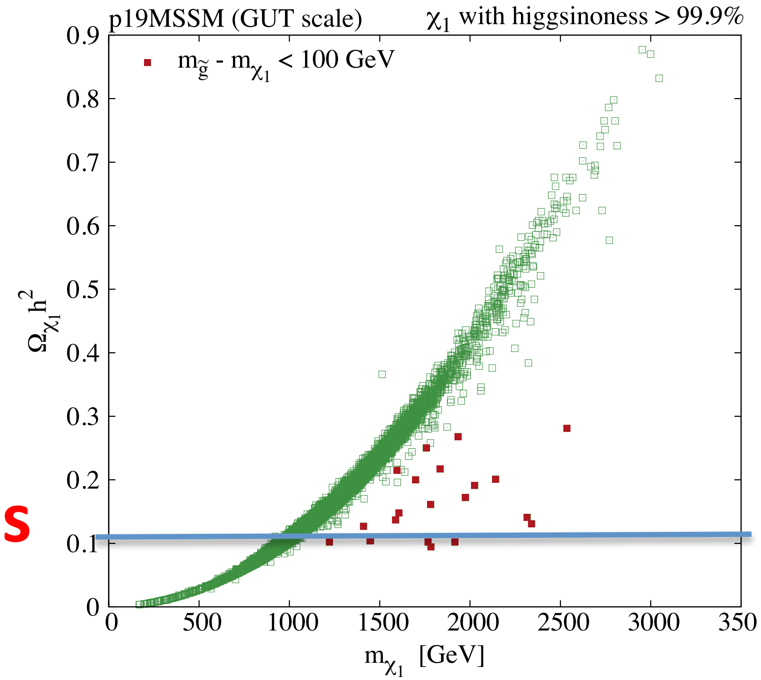
- **Particle model/assumption dependence**
- **Early Universe conditions**
  - **Standard thermal equilibrium vs low reheating T_R**
  - **Impact of inflaton decay?**
- **…**

Higgs inspired ~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
and relic density

✧ most natural among SUSY DM

✧ smoking gun of SUSY!?

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

Fall and rise of higgsino DM

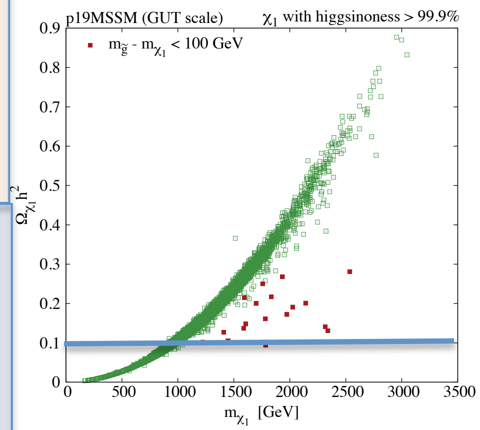
✧ **1991: put to grave**

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

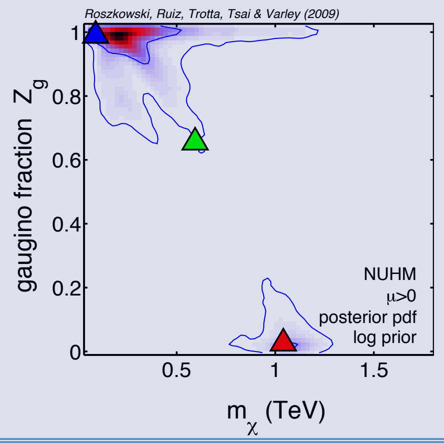
- too little DM until mass >> 1 TeV (conflict with naturalness)
- bino favored

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

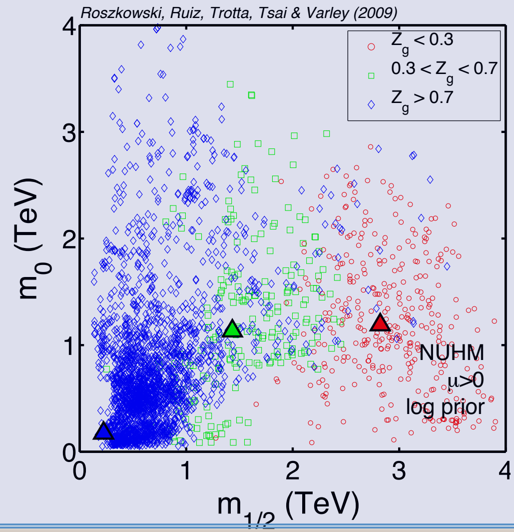
MSSM: Profumo & Yaguna, hep-ph/040703, Arkani-Hamed, Delgado, Giudice, hep-ph/0601041



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



NUHM in 0903.1279

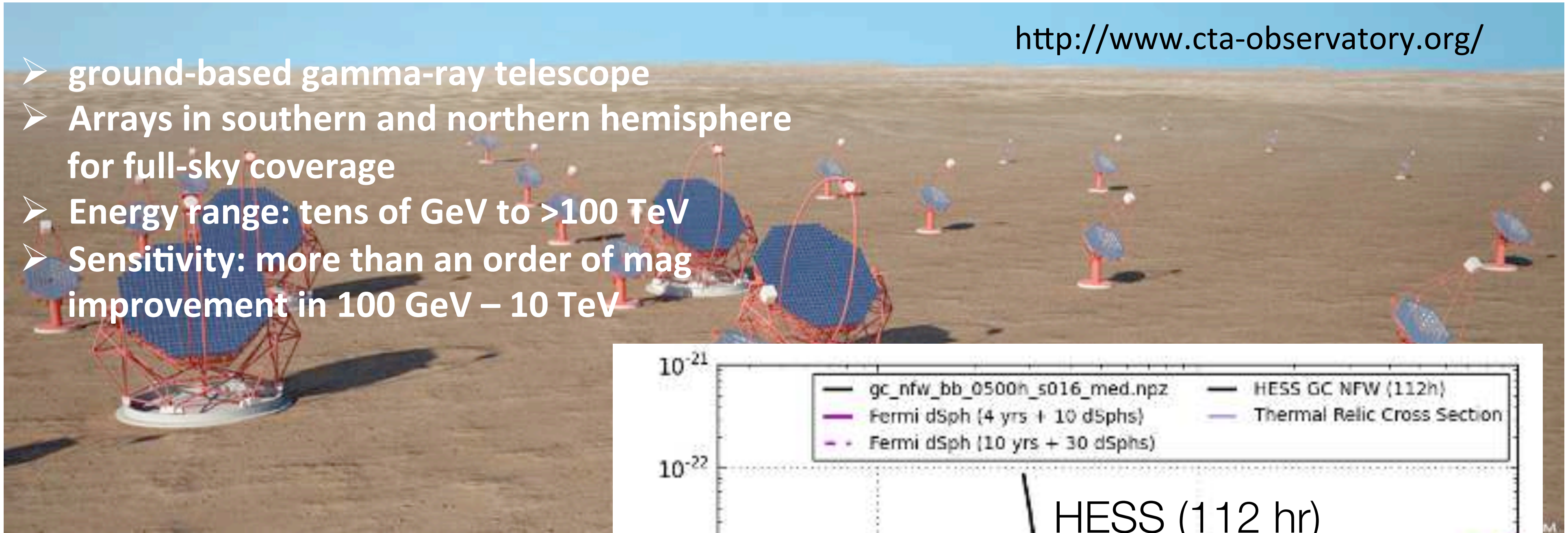


✧ **2012: favored by ~125 GeV Higgs mass**

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

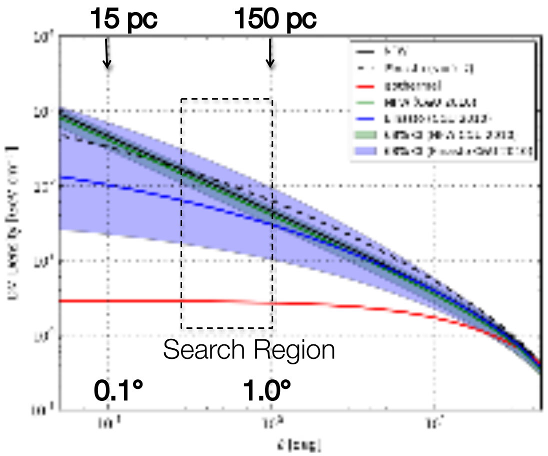
CTA – New guy in DM hunt race

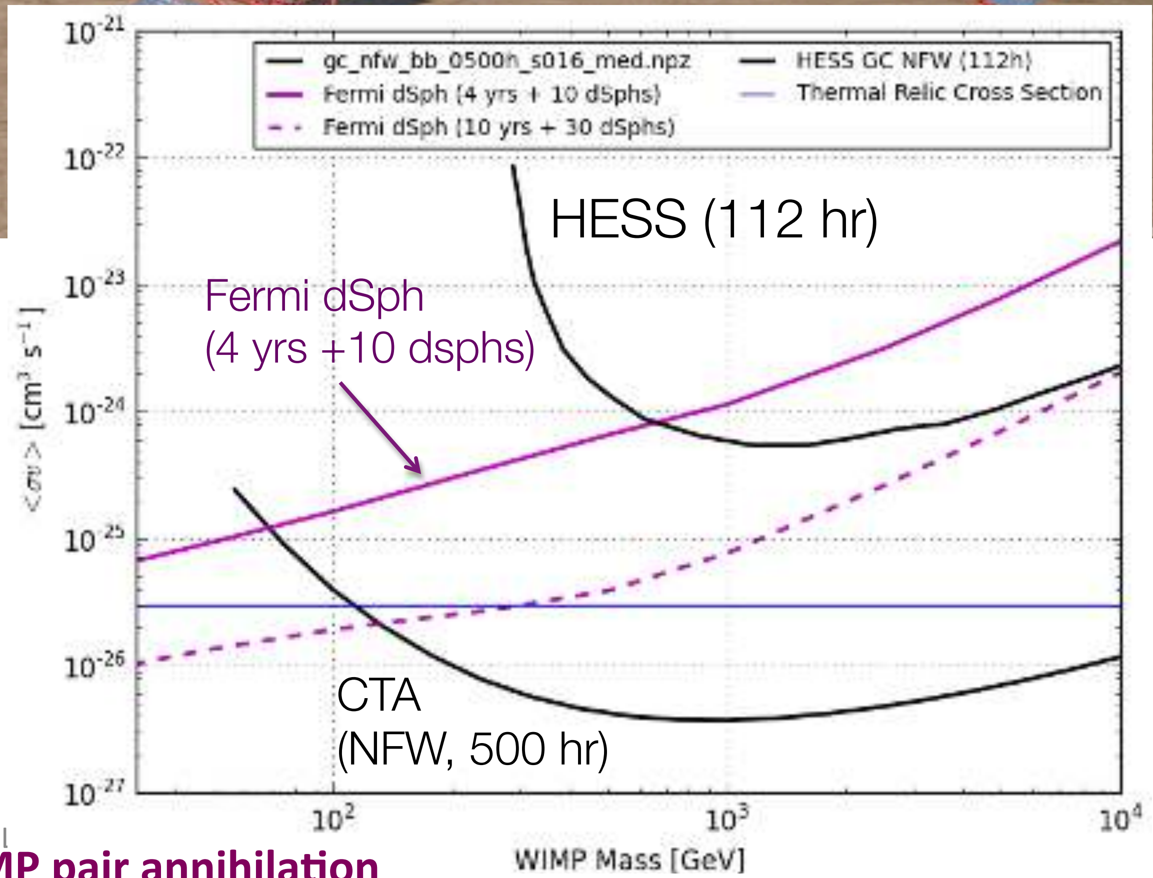


http://www.cta-observatory.org/

- 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

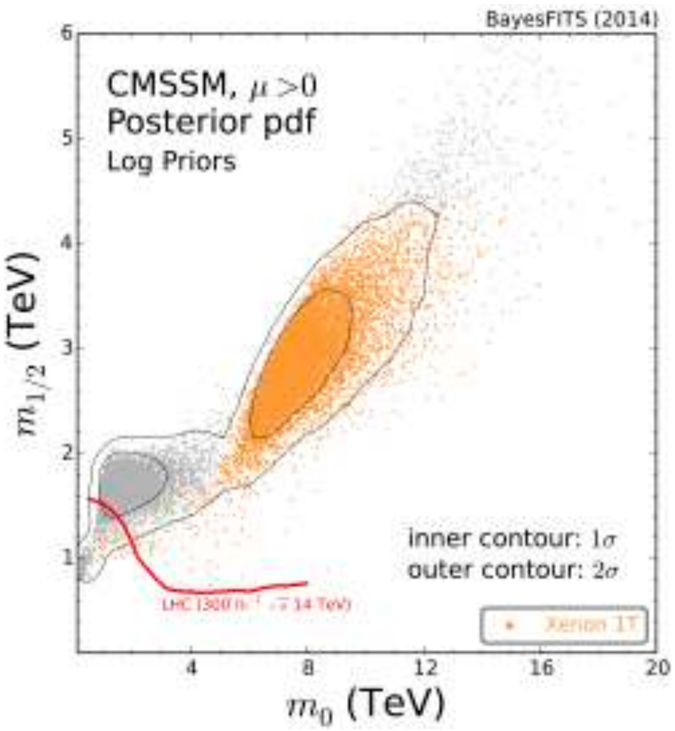




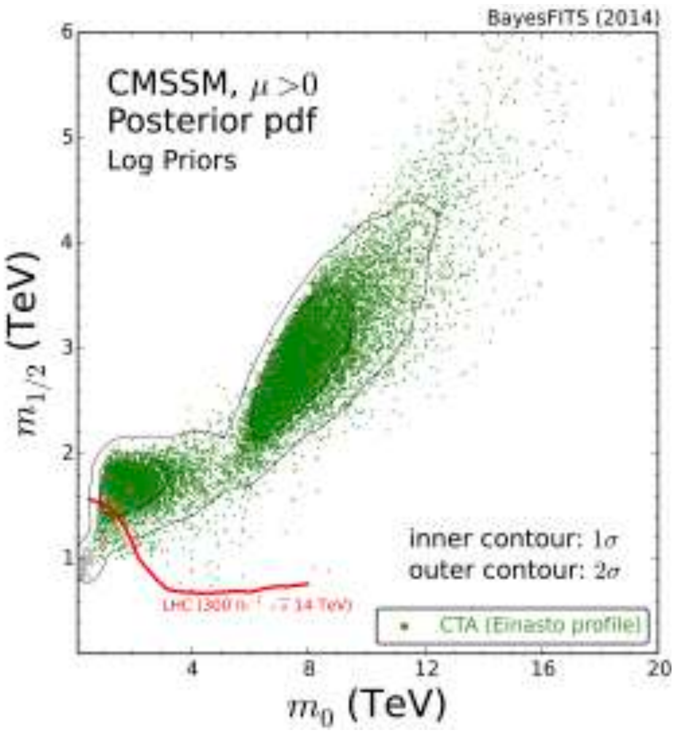
diffuse gamma radiation from WIMP pair annihilation

SUSY @ DM searches

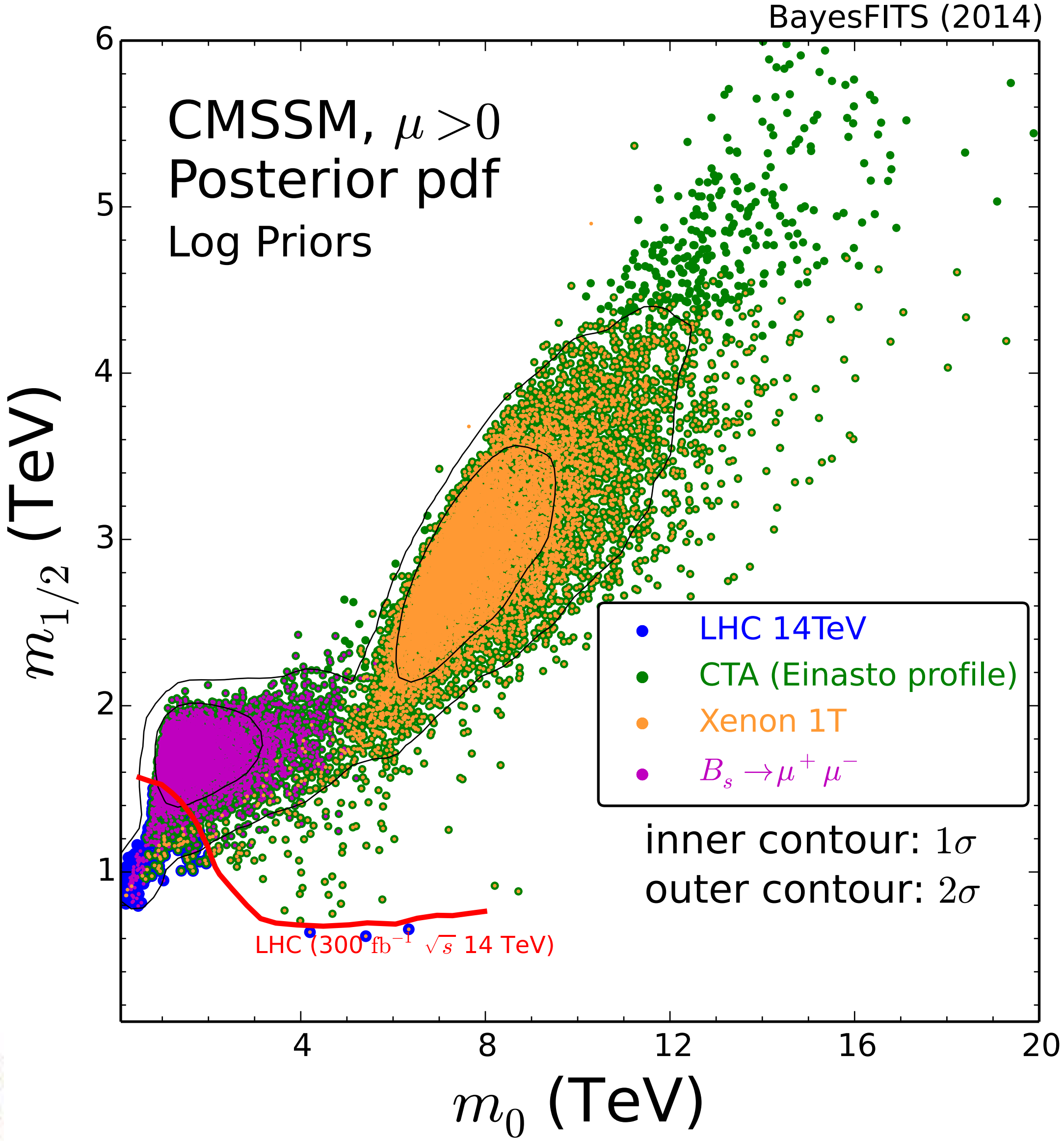
- **direct detection**



- **CTA (gamma telescope)**



CMSSM: Complementarity of DD, CTA and LHC

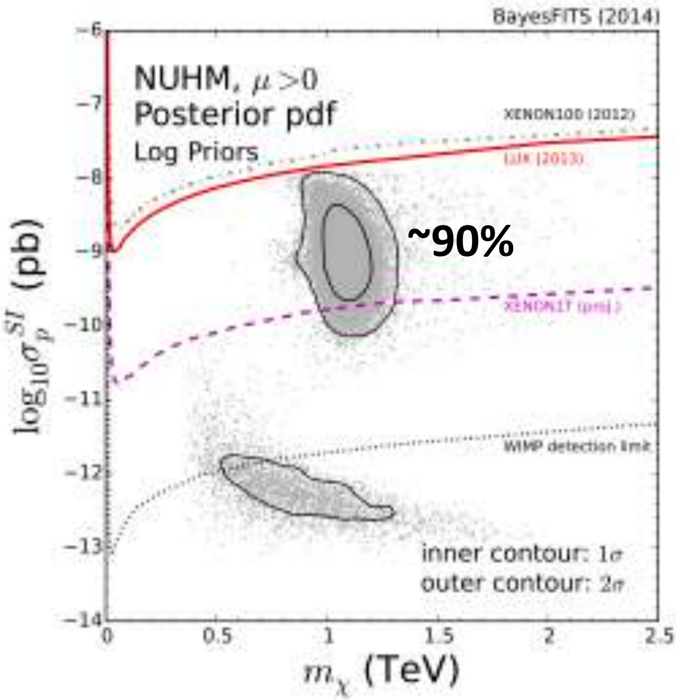


..all parameter space covered at 2 sigma

CMSSM can be fully explored by experiment

Beyond CMSSM…

- e.g., NUHM (Non-Universal Higgs Model)



- ~1 TeV higgsino DM dominant
- will be almost fully probed by 1-tonne detectors

- General MSSM: only some ``islands" will be probed by direct SUSY searches (Atlas, CMS), B_s -> mu mu (CMS, LHCb), DM 1 tonne detectors and/or CTA

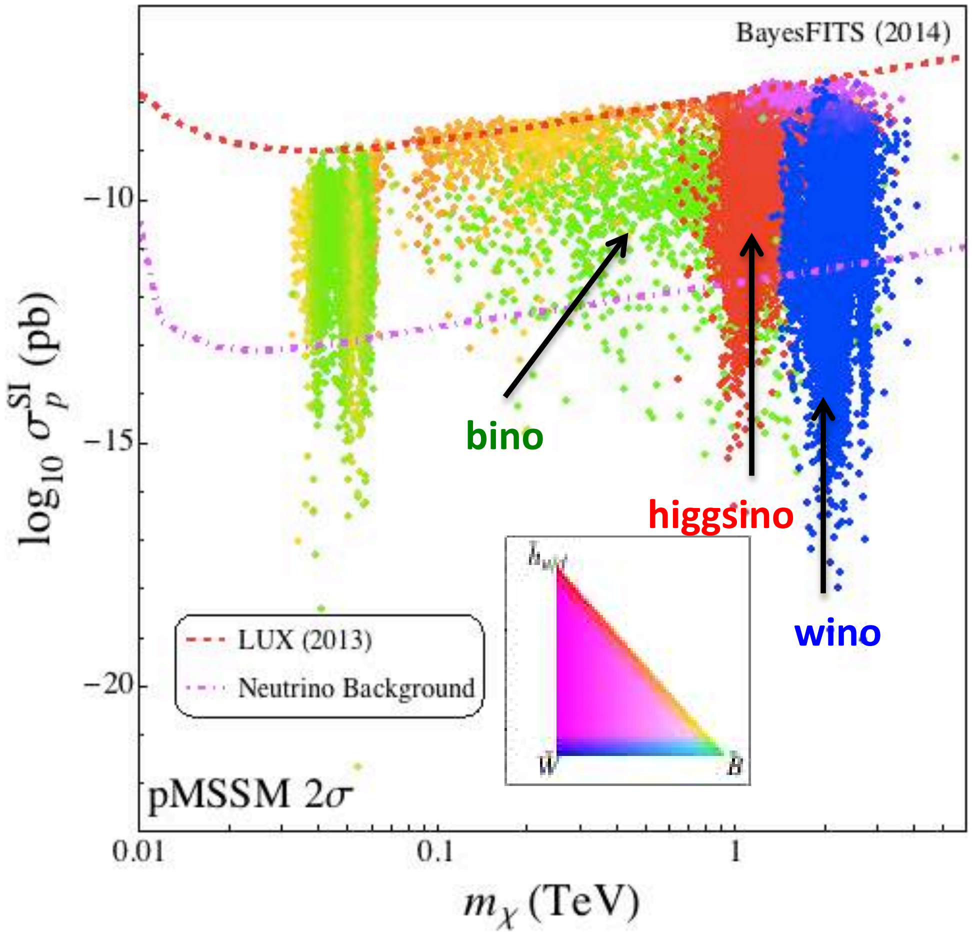
Direct Search for DM in general SUSY

Roszkowski, Sesssolo, Williams, 1411.5214

- **pMSSM** (=p19MSSM)
- **bino (M1) vs wino (M2) masses: free params**

Parameter	Range
Higgsino/Higgs mass parameter	$-10 \leq \mu \leq 10$
Bino soft mass	$-10 \leq M_1 \leq 10$
Wino soft mass	$0.1 \leq M_2 \leq 10$
Gluino soft mass	$-10 \leq M_3^* \leq 10$
Top trilinear soft coupl.	$-10 \leq A_t \leq 10$
Bottom trilinear soft coupl.	$-10 \leq A_b \leq 10$
τ trilinear soft coupl.	$-10 \leq A_\tau \leq 10$
Pseudoscalar physical mass	$0.1 \leq m_A \leq 10$
1st/2nd gen. soft L-slepton mass	$0.1 \leq m_{\tilde{L}_1} \leq 10$
1st/2nd gen. soft R-slepton mass	$0.1 \leq m_{\tilde{e}_R} \leq 10$
3rd gen. soft L-slepton mass	$0.1 \leq m_{\tilde{L}_3} \leq 10$
3rd gen. soft R-slepton mass	$0.1 \leq m_{\tilde{\tau}_R} \leq 10$
1st/2nd gen. soft L-squark mass	$0.75 \leq m_{\tilde{Q}_1} \leq 10$
1st/2nd gen. soft R-squark up mass	$0.75 \leq m_{\tilde{u}_R} \leq 10$
1st/2nd gen. soft R-squark down mass	$0.75 \leq m_{\tilde{d}_R} \leq 10$
3rd gen. soft L-squark mass	$0.1 \leq m_{\tilde{Q}_3} \leq 10$
3rd gen. soft R-squark up mass	$0.1 \leq m_{\tilde{t}_R} \leq 10$
3rd gen. soft R-squark down mass	$0.1 \leq m_{\tilde{b}_R} \leq 10$
ratio of Higgs doublet VEVs	$1 \leq \tan\beta \leq 62$

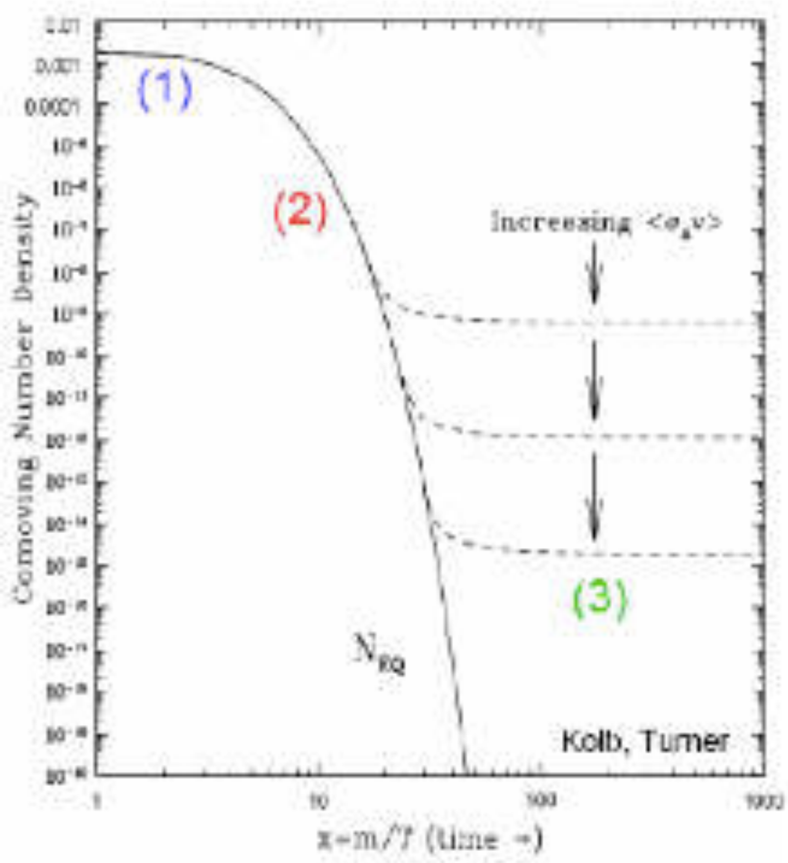
- Very wide scan
- All relevant constraints
- Sommerfeld effect included



General MSSM: No DM mass restrictions
… but different WIMP compositions

Are SUSY DM properties robust?

- **Relic density often provides one of strongest constraints**
- **Re-examine assumptions about the early Universe**
- **Standard thermal WIMP: relic density estimates assumes high reheating temperature T_R...**



Low T_R after inflation

LR, Trojanowski, Turzyński, 1406.0012

Reheating after cosmic inflation

- If assume instantaneous reheating $\Gamma_\phi = H = \sqrt{\frac{8\pi}{3M_{Pl}^2}\,\rho_\phi}$ $\rho_\phi = \rho_{rad}(T_R) \sim T_R^4$

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_*(T_R)}{45}}\,\frac{{T_R}^2}{M_{Pl}}$$

<- defines T_R

Giudice, Kolb, Riotto, hep-ph/0005123

- If assume non-instanteneous reheating

Gelmini, et al., hep-ph/0602230

coupled Boltzmann equations:

$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi\rho_\phi$$ **inflaton field**

$$\frac{d\rho_R}{dt} = -4H\rho_R + \Gamma_\phi\rho_\phi + \langle\sigma v\rangle 2\langle E_X\rangle\left[n_X^2 - (n_X^{eq})^2\right]$$ **radiation**

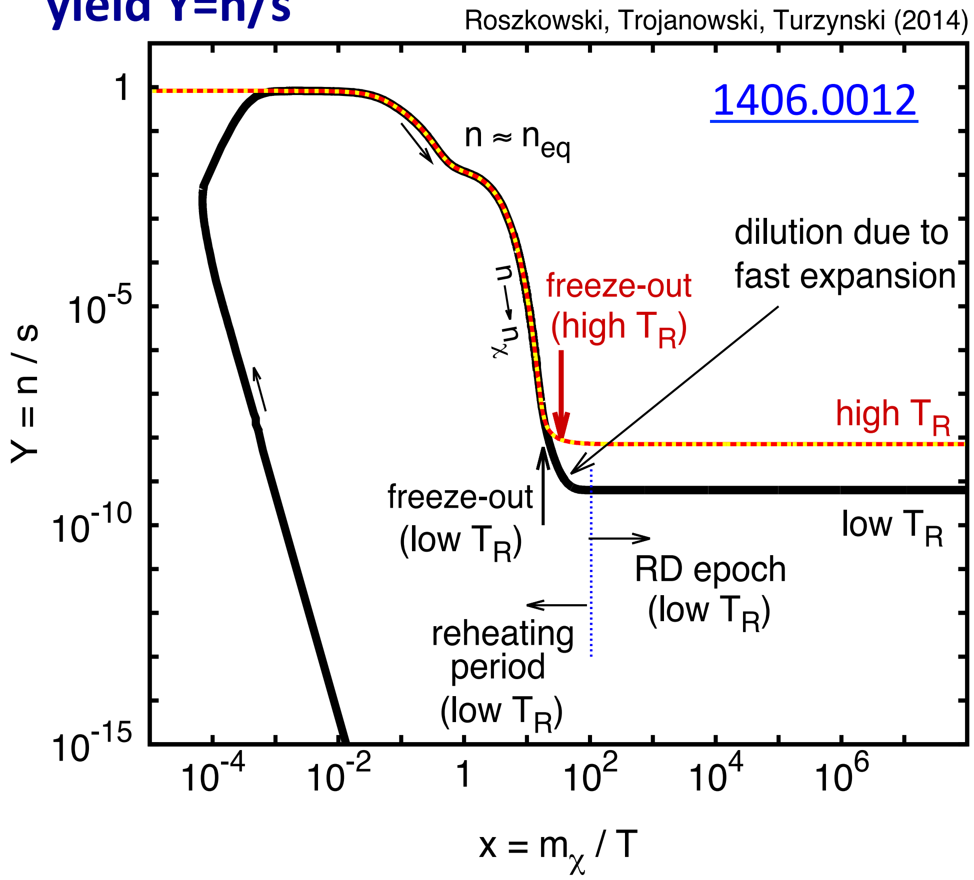
$$\frac{dn_X}{dt} = -3Hn_X - \langle\sigma v\rangle\left[n_X^2 - (n_X^{eq})^2\right] \quad \left(+\frac{b}{m_\phi}\Gamma_\phi\rho_\phi\right)$$ **dark matter**

SUSY and reheating: high vs low T_R

$$n = \sum_i n_i \xrightarrow{T\searrow} n_\chi$$

Here neglect direct inflaton decays to DM

yield Y=n/s



Reheating: faster expansion

DM production:

- **freeze-out happens at somewhat higher temperature than in the standard high T_R case**

but

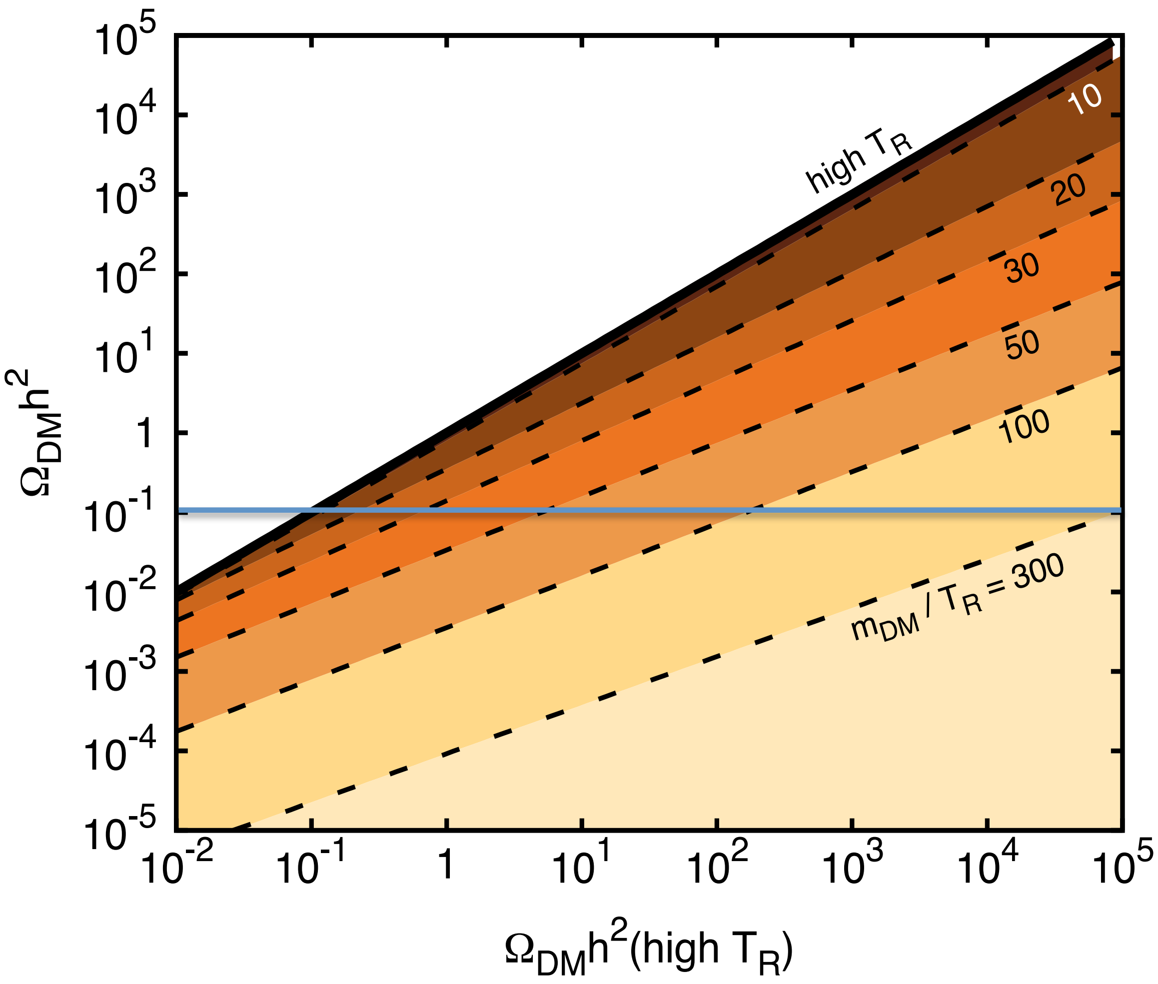
- **Subsequently, until the end of reheating, DM population is quite efficiently depleted**

$$\Omega_\chi h^2(\text{low } T_R) \sim \left(\frac{T_R}{T_{\rm fo}^{\rm new}}\right)^3 \left(\frac{T_{\rm fo}^{\rm old}}{T_{\rm fo}^{\rm new}}\right) \Omega_\chi h^2(\text{high } T_R)$$

GKR, hep-ph/0005123

End result: $\Omega_\chi h^2(\text{low } T_R) < \Omega_\chi h^2(\text{high } T_R)$

$$\Omega_\chi h^2(\mathrm{low}\ \ T_R) < \Omega_\chi h^2(\mathrm{high}\ \ T_R)$$



``standard" scenario

LR, Trojanowski, Turzyński, 1406.0012

For $m_{DM} > T_R$: usually strong constraints from relic density can get greatly relaxed

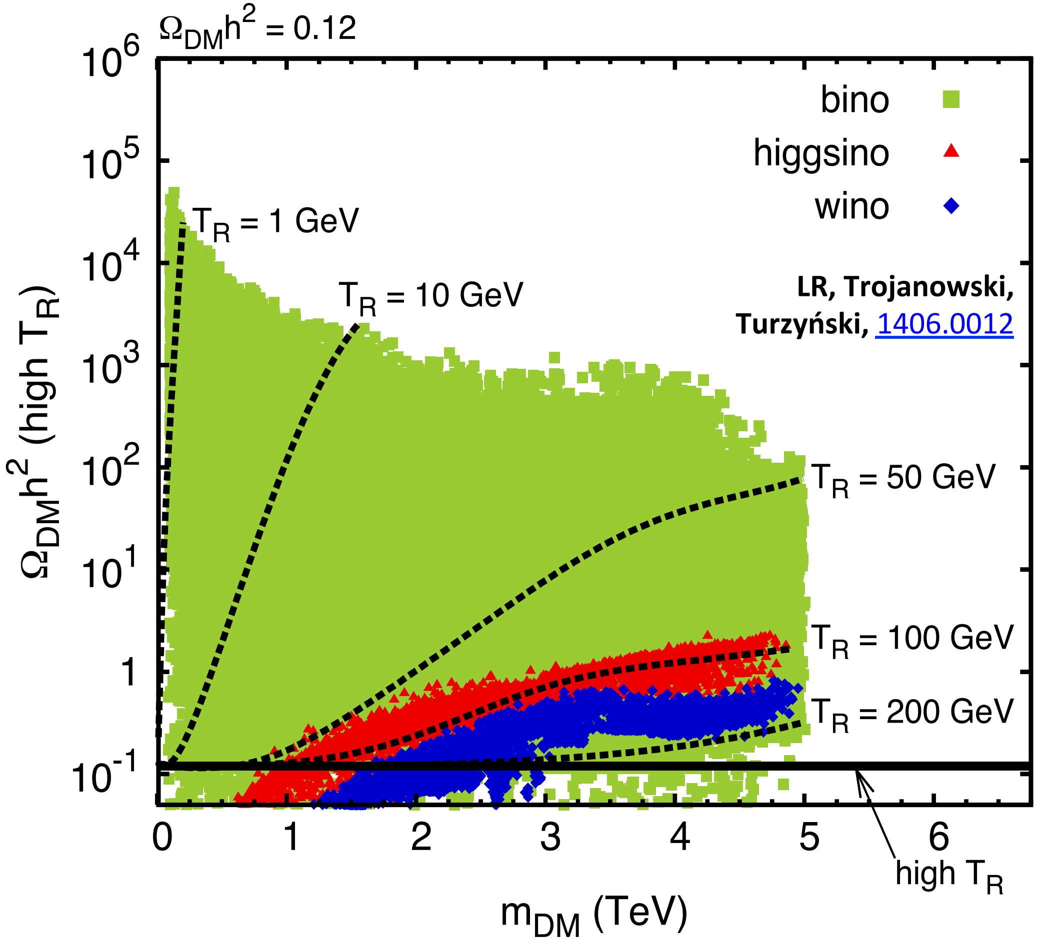
Low T_R: Effect on SUSY DM

- **relic abundance often provides the strongest constraint**

p10MSSM

Parameter	Range
bino mass	$0.1 < M_1 < 5$
wino mass	$0.1 < M_2 < 6$
gluino mass	$0.7 < M_3 < 10$
stop trilinear coupling	$-12 < A_t < 12$
stau trilinear coupling	$-12 < A_\tau < 12$
sbottom trilinear coupling	$A_b = -0.5$
pseudoscalar mass	$0.2 < m_A < 10$
μ parameter	$0.1 < \mu < 6$
3rd gen. soft squark mass	$0.1 < m_{\widetilde{Q}_3} < 15$
3rd gen. soft slepton mass	$0.1 < m_{\widetilde{L}_3} < 15$
1st/2nd gen. soft squark mass	$m_{\widetilde{Q}_{1,2}} = M_1 + 100$ GeV
1st/2nd gen. soft slepton mass	$m_{\widetilde{L}_{1,2}} = m_{\widetilde{Q}_3} + 1$ TeV
ratio of Higgs doublet VEVs	$2 < \tan\beta < 62$
Nuisance parameter	**Central value, error**
Bottom mass $m_b(m_b)^{\overline{MS}}$(GeV)	(4.18, 0.03) [25]
Top pole mass m_t(GeV)	(173.5, 1.0) [25]

p10MSSM (with gauginos not unified)



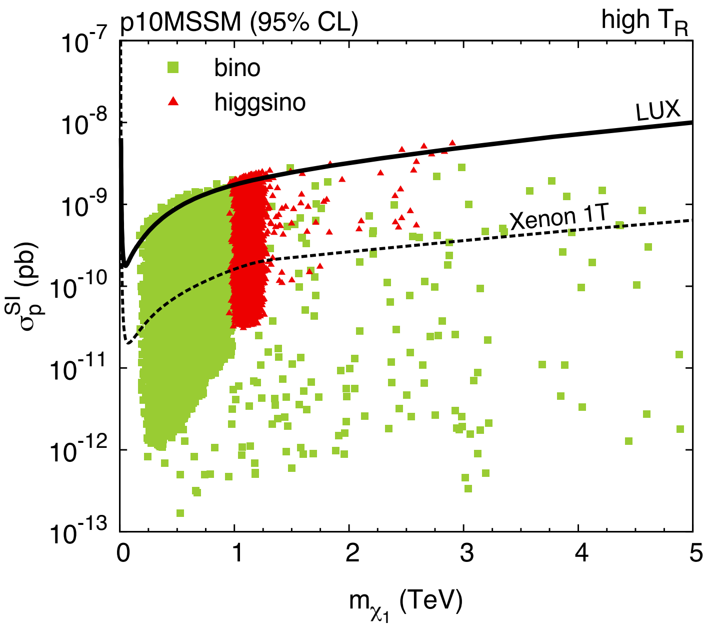
huge relaxation relative to the usual high T_R case:

- **multi-TeV higgsino DM allowed**
  → **T_R ~ 100 GeV!**

- **wino DM also again allowed over wider range**
  → **T_R ~ 100 – 200 GeV**

SUSY DM and reheating: high vs low T_R

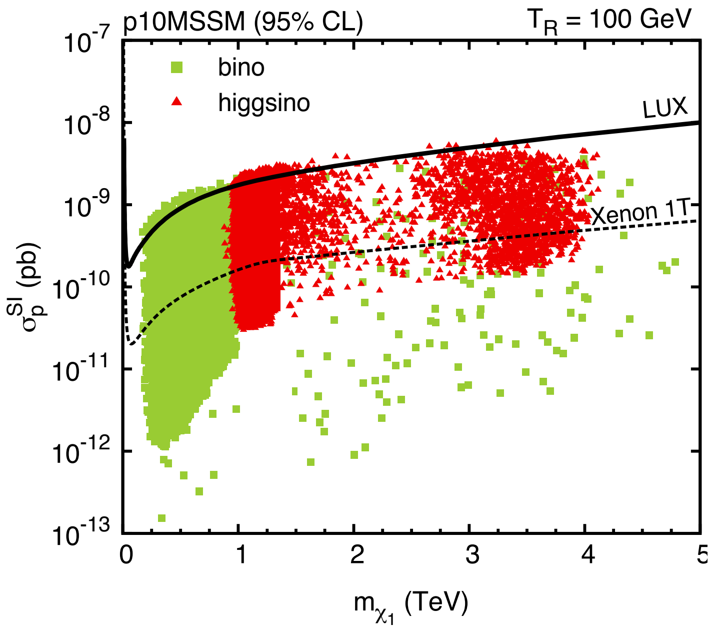
- High T_R (standard case)



- higgsino DM: m_χ ~ 1 TeV
- testable by DD and CTA

- Low T_R

LR, Trojanowski, Turzyński, 1406.0012



- Much heavier higgsino allowed
- Still testable by DD and CTA

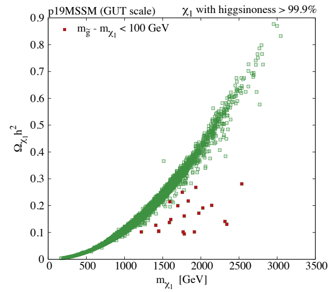
...also realized in CMSSM

If higgsino DM seen at > 1 TeV → low T_R ~100 GeV

Modulo accidental mass relations, neglect inflaton decay

What about higgsino DM < 1TeV?

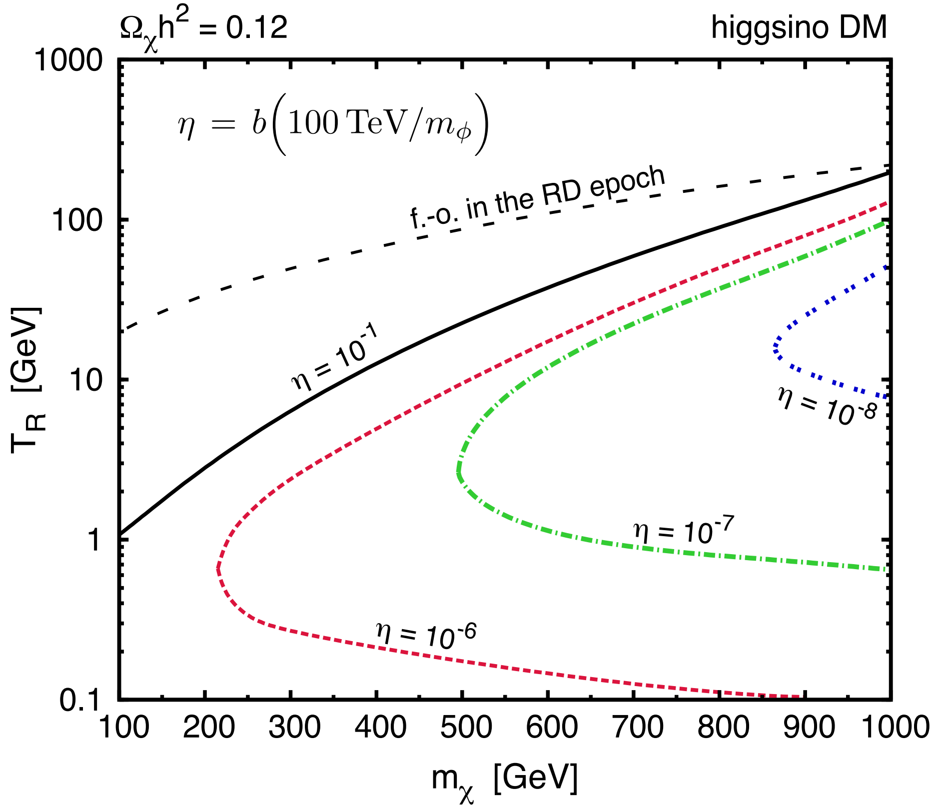
In (standard) high T_R: DM density too low



Ways out:
- **add another DM relic**
- **add non-thermal contributions to relic density**
- **…**

Allow direct/cascade inflaton decay to DM

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma v\rangle\left[n_\chi^2 - (n_\chi^{eq})^2\right] \quad \left(+\frac{b}{m_\phi}\Gamma_\phi\rho_\phi\right)$$



→ sub-TeV higgsino DM with correct relic density can easily be allowed

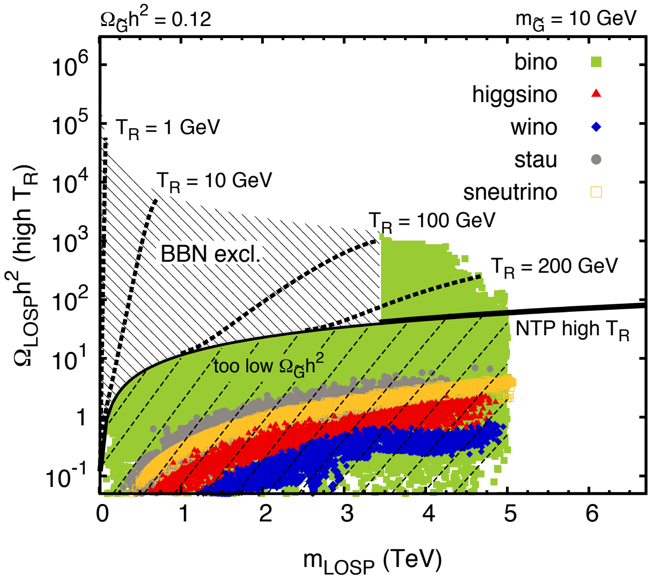
SUSY DM and low T_R

LR, Trojanowski, Turzyński, 1406.0012

We have examined also other DM relics at low T_{R}:

- **bino**
- **wino**
- **gravitino**
- **axino**

e.g., gravitino DM



- ➢ **Ranges of ``usual" solutions can get significantly relaxed.**
- ➢ **Interesting bounds arise.**

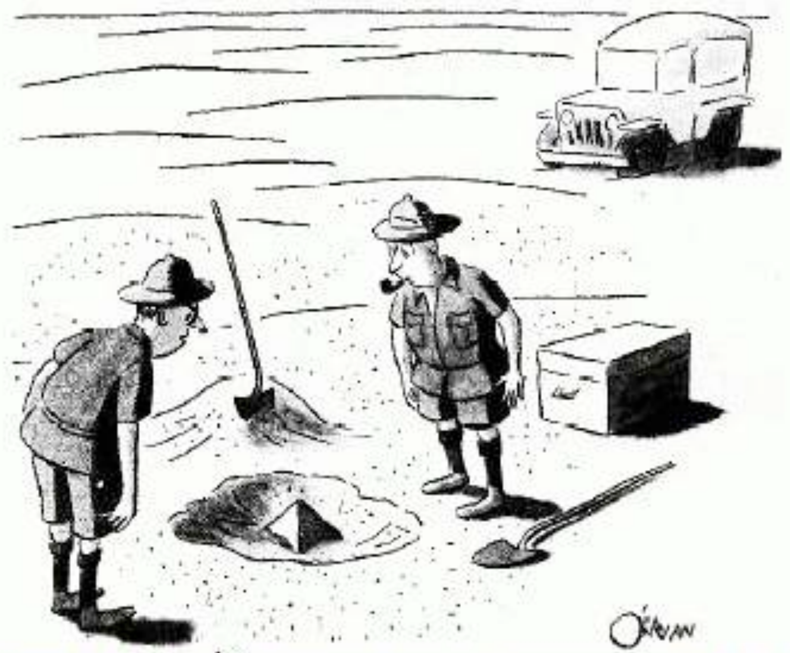
→ Effective limit of T_R> 100 GeV

To take home:

…modulo low T_R

Higgs of 125 GeV →
~1TeV (higgsino) DM – robust prediction of SUSY

Smoking gun of SUSY!?



This could be the greatest discovery of the century. Depending, of course, on how far down it goes.

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 almost fully probed by 1-tonne DM detectors**
  - **Independent probe by CTA**
  - **Other indirect detection modes (nu, e^+, …): no chance**
  - **Far beyond direct LHC reach**

  - **If higgsino mass > 1 TeV => low T_R ~ 50 – 150 GeV**
  - **If higgsino mass < 1 TeV => more than one DM? inflaton decay?**

CMSSM: Complementarity of LHC, DD and CTA

- **General SUSY (pMSSM):**
  - **CTA and direct detection show good complementarity reach (far beyond direct LHC reach)**
  - **much of higgsino region to be probed**
  - **wino DM allowed > 3.5 TeV -> T_R ~ 100 – 200 GeV**


COSMO-15
Warsaw
7-11 September
cosmo15.ncbj.gov.pl
Welcome to Poland!

BACKUP

… a question on many people's mind…

But what about fine tuning/naturalness?!

- I prefer to follow what the data implies, rather than theoretical prejudice
- Naturalness: fundamental Higgs -> SUSY
- Fine-tuning is needed at any scale above the EW scale

1 TeV is not a magic number

- m_h~125 GeV -> M_{SUSY} ~> 1 TeV -> high FT is basically ``an experimental fact''
- If SUSY is discovered, large FT issue will have to be understood/accepted
- If SUSY is not discovered, the issue will become irrelevant
- ``Naturalness'' argument gone astray:

$$\frac{m_t}{m_b} \sim \frac{m_c}{m_s} \simeq 14 \quad \Rightarrow \quad m_t \simeq 60\,\mathrm{GeV}$$

Fine tuning issue is an expression of our ignorance about the high scale!

- **FT argument:** $$\mu^2 = -\frac{1}{2}M_Z^2 + \frac{m_{H_d}^2(M_{\mathrm{SUSY}}) - \tan^2\beta\, m_{H_u}^2(M_{\mathrm{SUSY}})}{\tan^2\beta - 1}$$ $m_{H_{u,d}}^2$: tree + 1L corrs

$\boldsymbol{m_{H_u}^2, m_{H_u}^2}$ **and** $\boldsymbol{\mu^2}$ **need to be all fine-tuned to give** $\boldsymbol{M_Z^2}$

Since we don't know them, we expect them to be of order m_Z^2

- **But, imagine they are derived from some fundamental theory and come out to be of order 100 TeV, but still obey EWSB**

Would one still claim high FT in the theory? NO!

Low FT does not have to necessarily imply low M_{SUSY}.

- **FT in an effective theory may be resolved in a more complete theory**

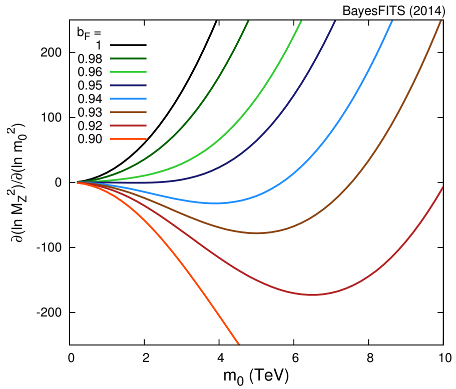
E.g. GIM mechanism: divergence in 3-quark model got resolved in 4-quark model

High scale relations to reduce FT in ~1 TeV higgsino region

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

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

optimal when $b_F = 0.92 - 0.94$

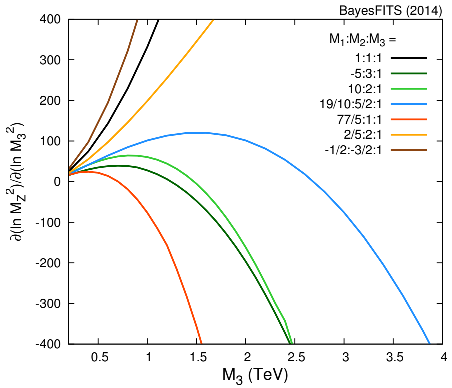


- **Gaugino non-unification** $M_1 : M_2 : M_3$

1402.1328

optimal when SU(5): $(-5:3:1)$, $(10:2:1)$

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 $\mu \simeq 1\,\mathrm{TeV}$

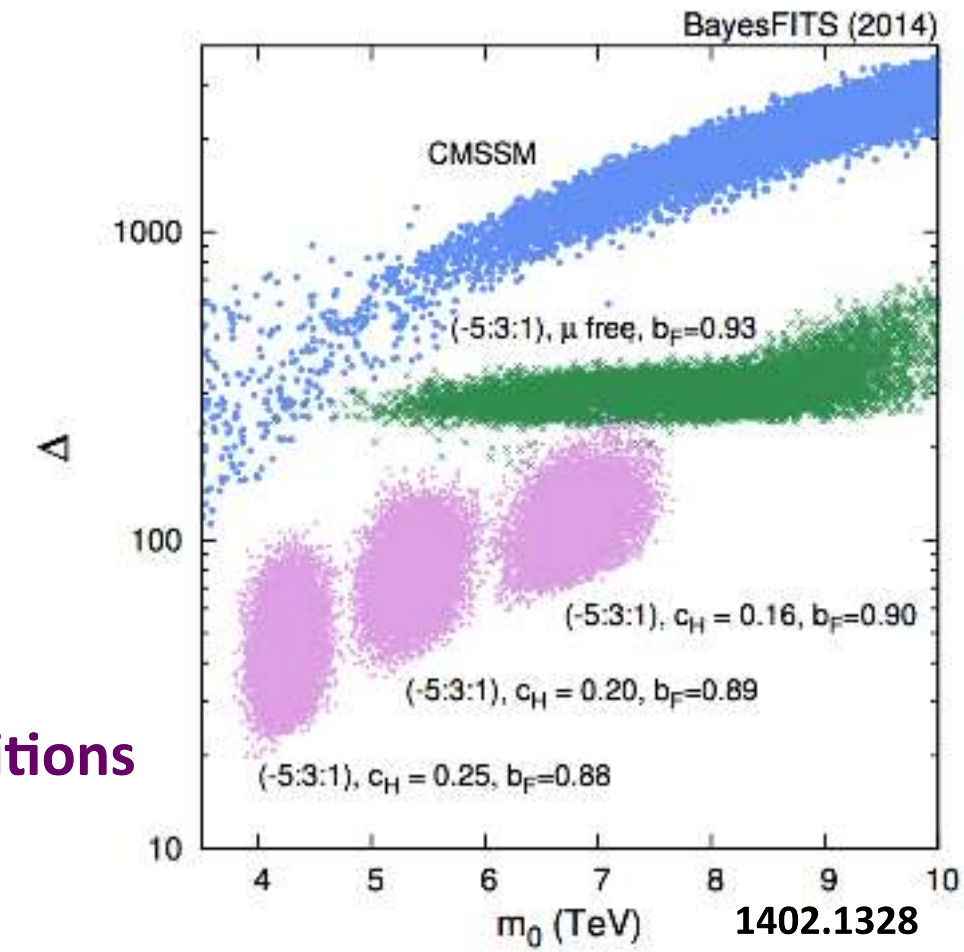
Reduce FT in ~1 TeV higgsino region

Altogether, for some BCs at unification scale

FT can be reduced as far down as ~20

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

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



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All experimental constraints satisfied

...except $(g\text{-}2)_{mu}$