SUSY dark matter:

lessons from and for the early Universe

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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 (JHEP)
- L. Roszkowski, S. Trojanowski, K. Turzyński, 1406.0012 (JHEP) and 1507.06164 (JHEP)

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Bayes FITS

Outline

- ✧ Setting the stage: LHC, Higgs boson, dark matter and SUSY scale
- ✧ Neutralino dark matter:
  - ✧ 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
  - ✧ CMSSM and beyond (NUHM, MSSM): complementarity of LHC and DM searches (direct and CTA)
  - ✧ Fine tuning: worry, ignore or use as guide?
  - ✧ Early Universe: impact of low T_R
- ✧ Gravitino and axino dark matter and low T_R
- ✧ Summary

Where is ``new physics”?

- No convincing hint from the LHC

but…

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

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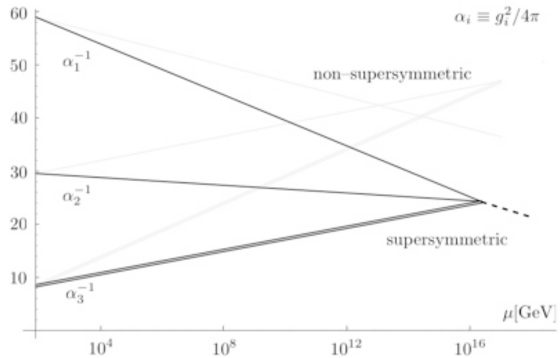
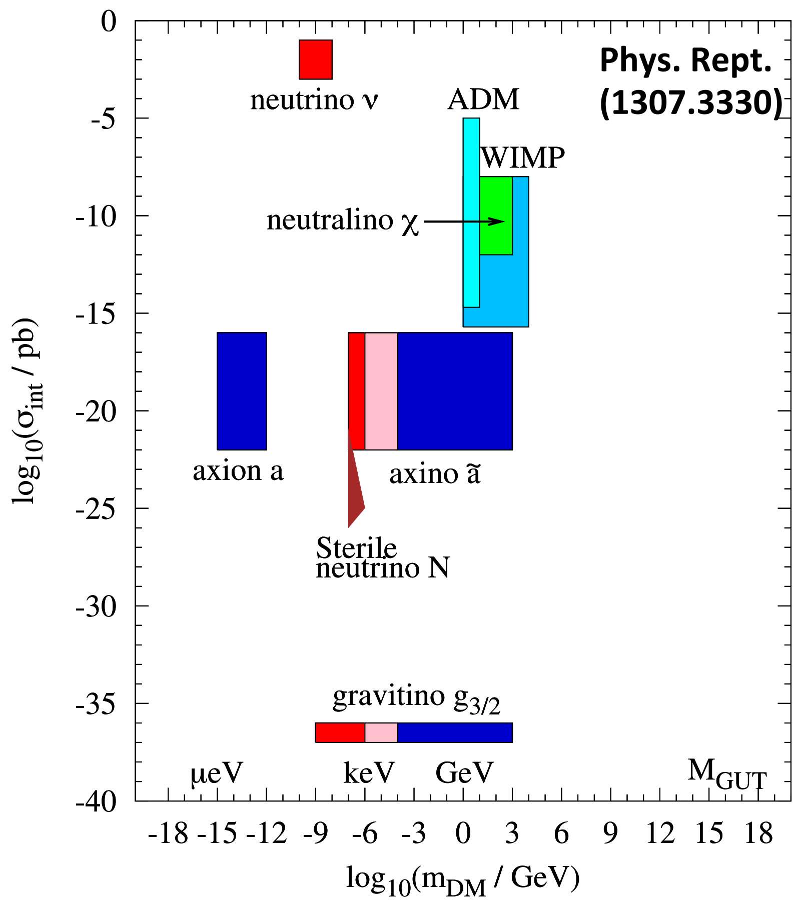
Low energy SUSY remains the front-runner for ``new physics”

Why SUSY…



- **Gauge coupling unification**
- **$M_Z - M_{GUT}$ hierarchy problem**
- **…**
- **Dark matter**
- **Higgs boson mass <~ 130 GeV** — **LHC: m_h=125 GeV**
- **Superpartners at ~ TeV scale**

Well-motivated candidates for dark matter



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

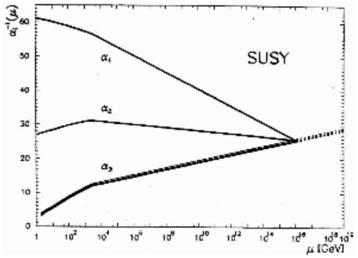
SUSY

- 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

SUSY: Constrained or Not?

- **Constrained:**

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



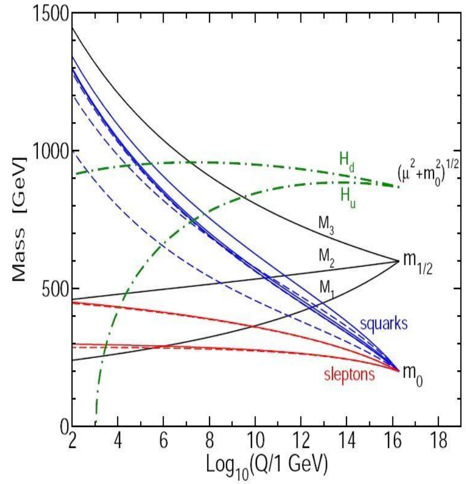


figure from hep-ph/9709356

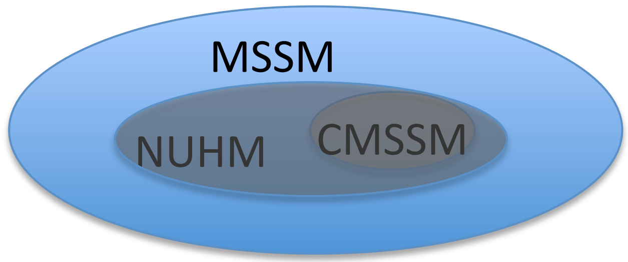
Virtues:
- **Well-motivated**
- **Predictive (few parameters)**
- **Realistic**

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, …**

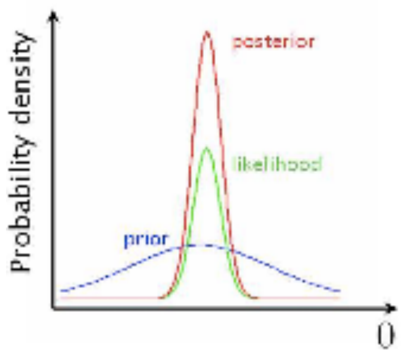
Bayesian statistics

Bayes theorem: $$\text{Posterior} = \frac{\text{Prior} \times \text{Likelihood}}{\text{Evidence}}$$

- **Prior**: what we know about hypothesis BEFORE seeing the data.
- **Likelihood**: the probability of obtaining data if hypothesis is true.
- **Posterior**: the probability about hypothesis AFTER seeing the data.
- **Evidence**: normalization constant, crucial for model comparison.

If hypothesis is a function of parameters, then posterior becomes posterior probability function (pdf).

Posterior → credible regions at chosen CL



Minimum chi2 approach: find best-fit and draw confidence regions about it

~125 GeV Higgs and unified SUSY

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

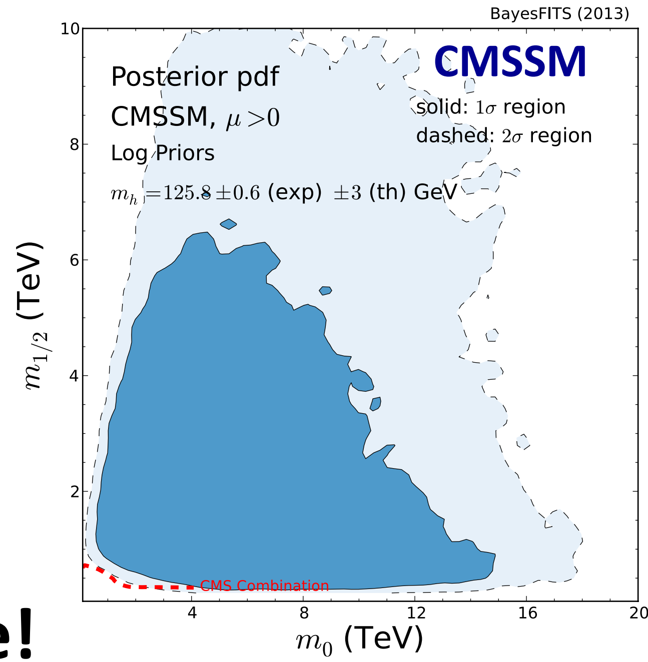
$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\ \mathrm{GeV})^2}{\sigma^2+\tau^2}}$$

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

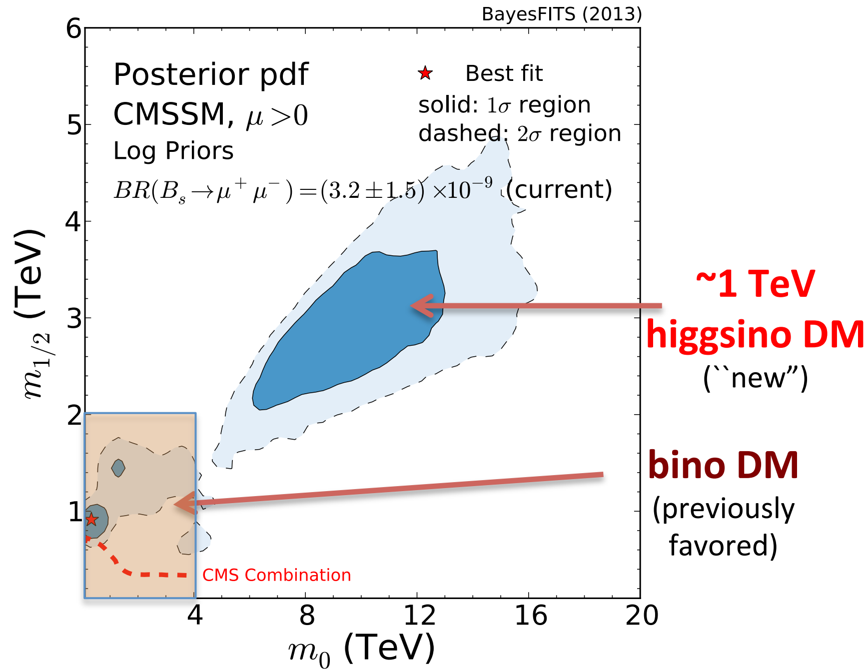
$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\mathrm{SUSY}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\mathrm{SUSY}}^2}\left(1 - \frac{X_t^2}{12M_{\mathrm{SUSY}}^2}\right)\right]$$

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

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



1302.5956



A curse!

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

Simple 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%
$\sin^2\theta_{\rm eff}$	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 ps^{-1}	0.043 ps^{-1}	2.400 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)

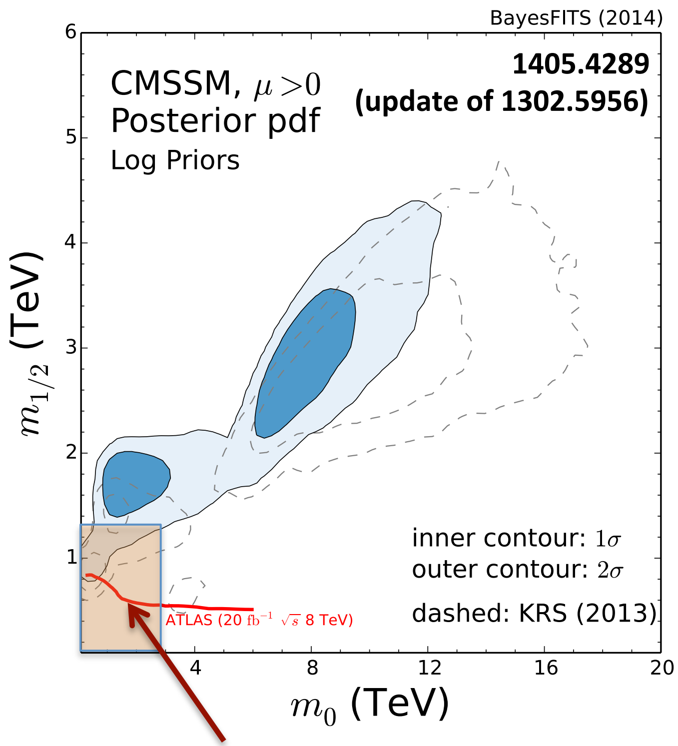
SM value: $\simeq 3.5 \times 10^{-9}$

Bayes FITS

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

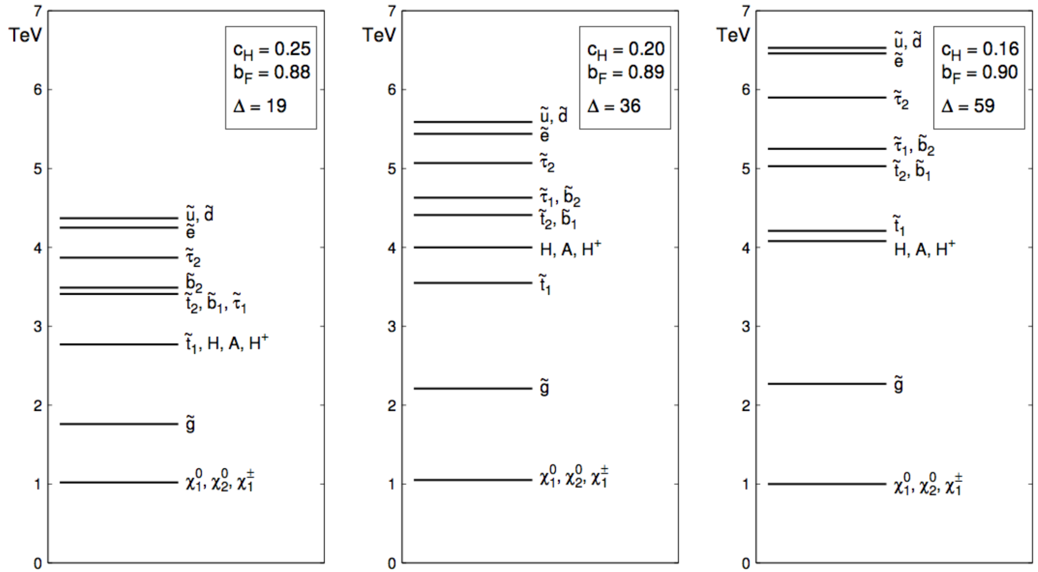
Chances of direct SUSY signal at the LHC?

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**

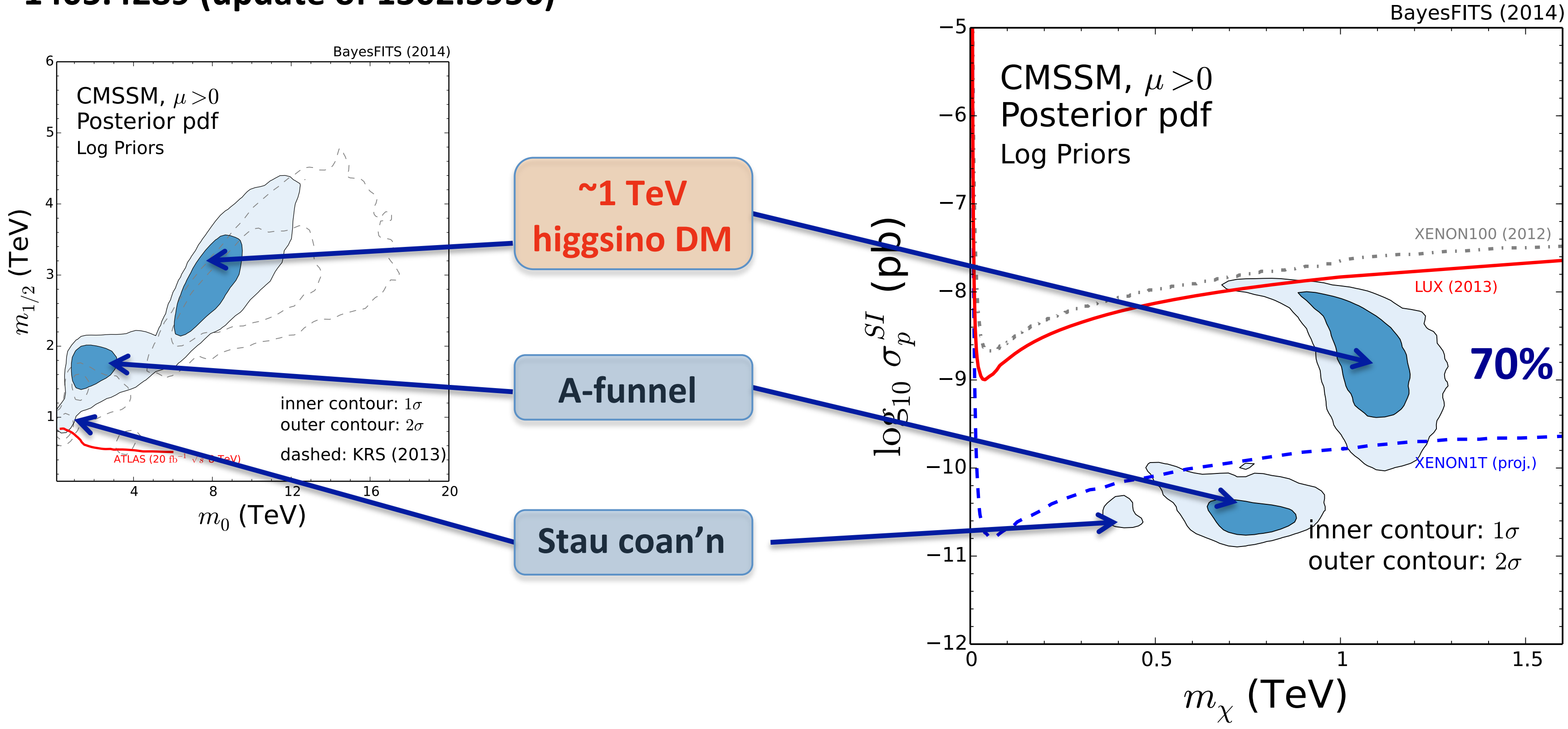
CMSSM-like: chances look remote!

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

CMSSM and direct DM searches

$\mu > 0$

1405.4289 (update of 1302.5956)

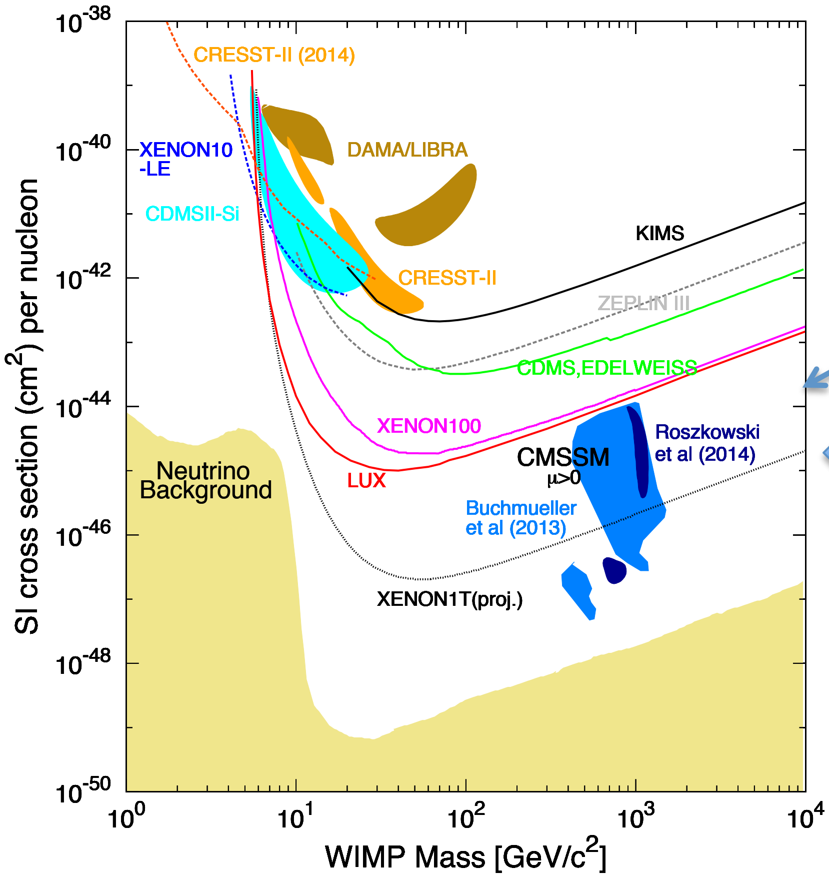


Focus point region ruled out by LUX (already tension with X100)

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

DM direct detection

Recent Phys. Rept. (1407.0017)
H. Baer, K.-Y. Choi, J.E Kim, LR



Reach of currently running experiments: LUX, Xenon100

X1T reach by ~2017

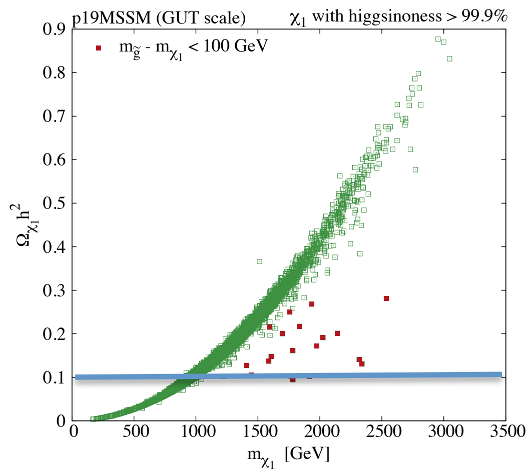
~1 TeV higgsino DM: Excellent prospects!

Why ~1 TeV higgsino DM is so interesting

✧ **robust, generically 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**

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

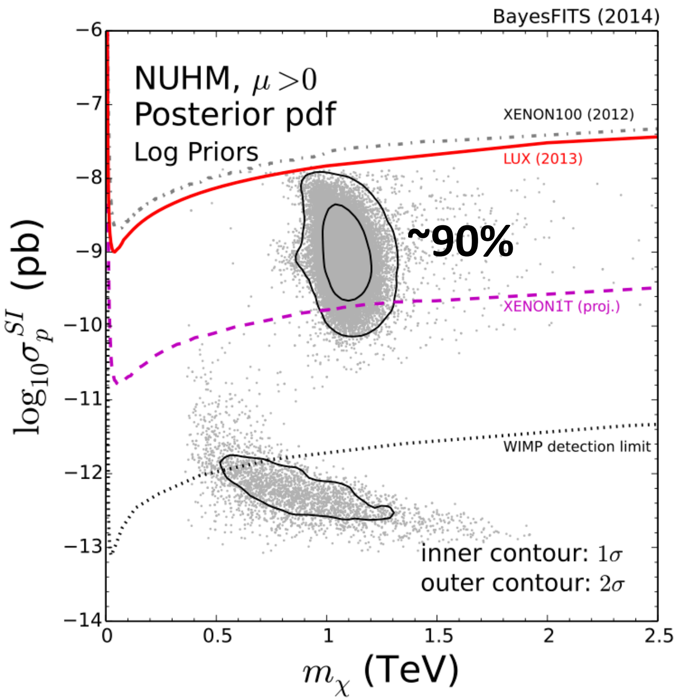
✧ **most <u>natural</u> of SUSY DM**

✧ **smoking gun of SUSY!?**

Similarly with wino but mass less determined due to Sommerfeld effect

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**

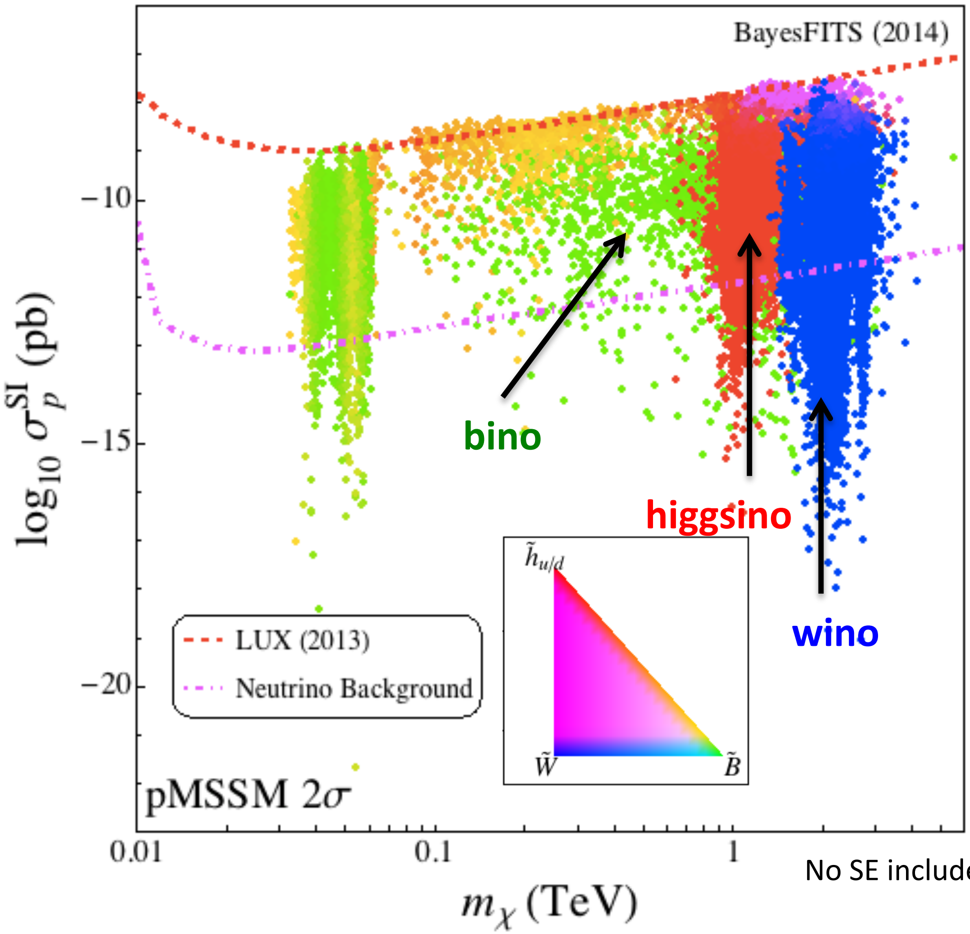
Direct Search for DM in general SUSY

Roszkowski, Sesssolo, Williams, 1411.5214

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

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

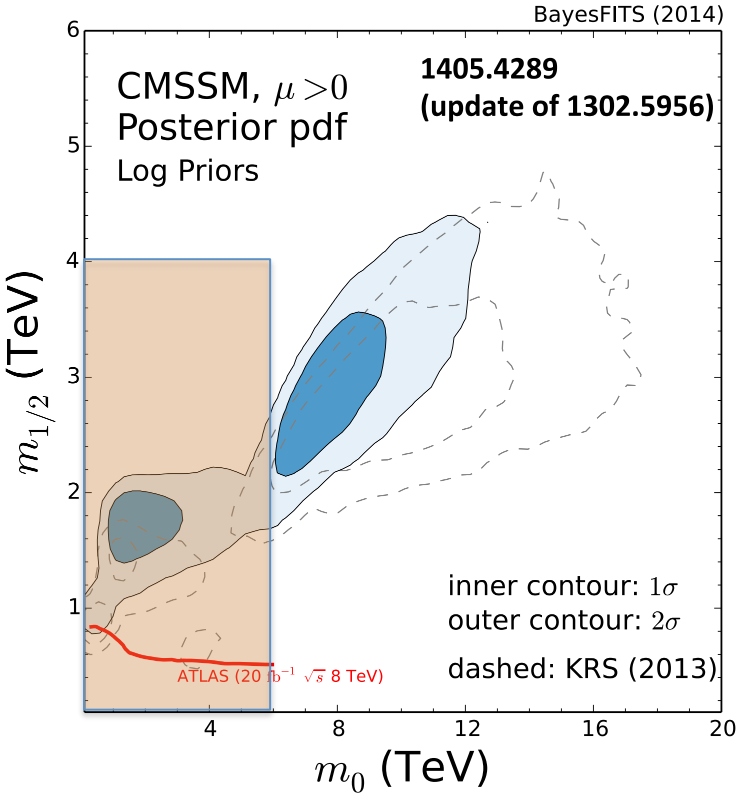
- Very wide scan
- All relevant constraints
- Sommerfeld effect included



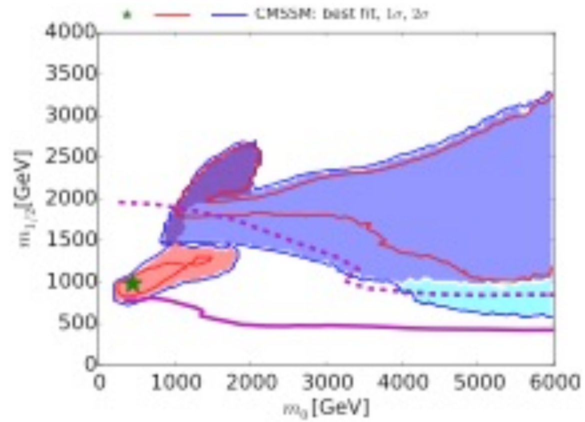
No SE included

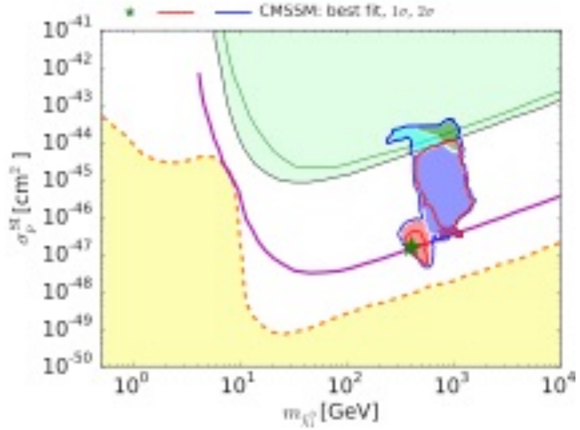
General MSSM: No DM mass restrictions
… but different WIMP compositions

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



MasterCode, [1508.01173]



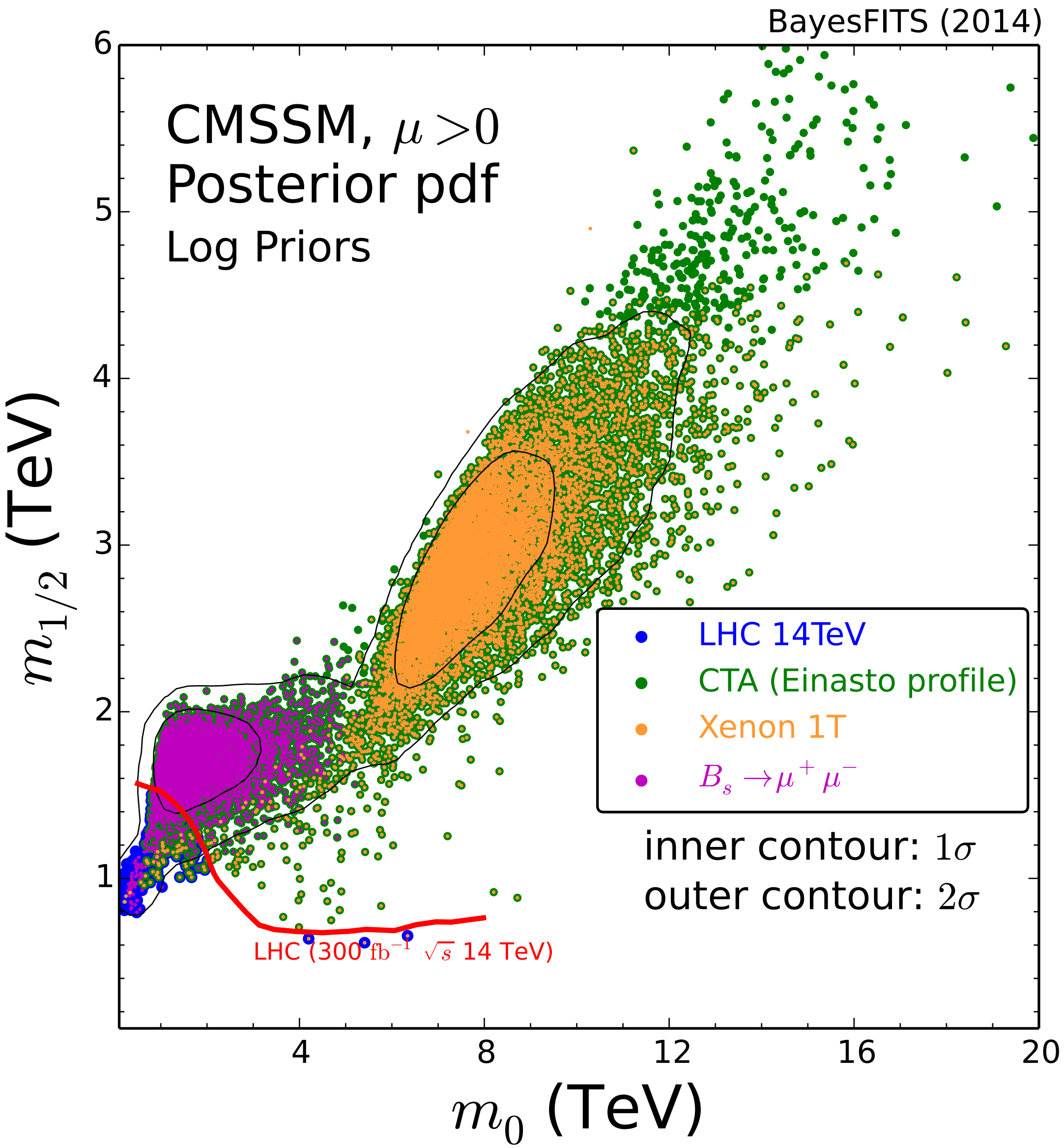


Reasonably good agreement in overlapping region

Note: Likelihood fn is rather flat

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

CMSSM: Complementarity of DD, CTA and LHC



..all parameter space covered at 2 sigma

CMSSM can be fully explored by experiment

@2sigma

Natural?

Natural is what is realized in Nature!

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

Usual definitions measure sensitivity to GUT scale values, and not FT.

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

$\boldsymbol{m_{H_u}^2}$, $\boldsymbol{m_{H_u}^2}$ **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 <u>fundamental</u> theory and come out to be very large, say of order 100 TeV, but still obey EWSB**

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

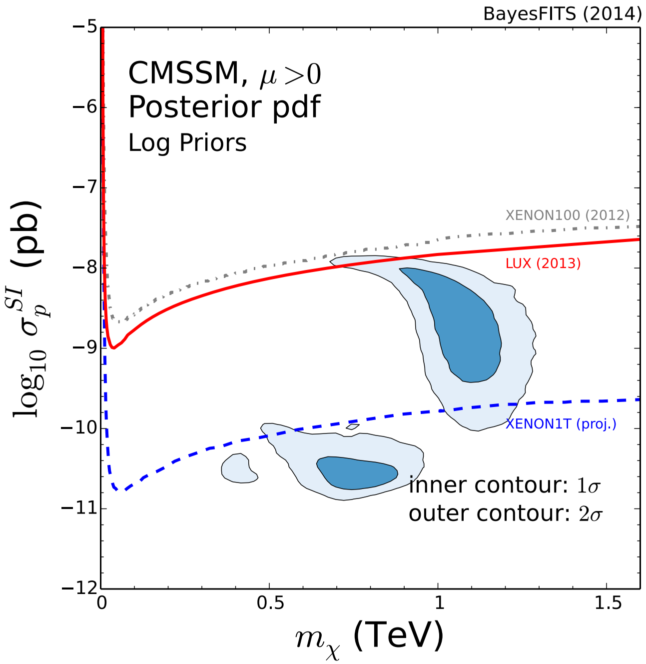
Low FT does not have to necessarily imply low $M_{SUSY.}$

- **Natural expectation gone wrong:**

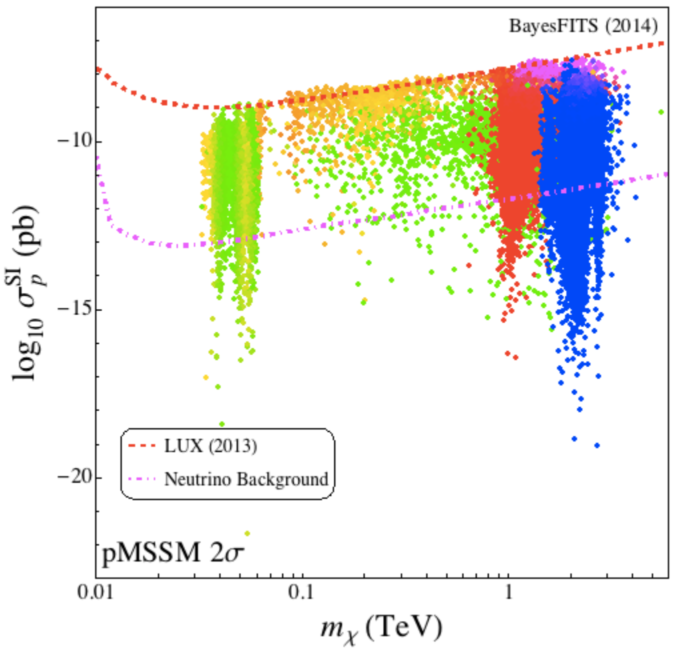
$$\frac{m_t}{m_b} \sim \frac{m_c}{m_s} \simeq 14 \;\Rightarrow\; m_t \simeq 60\,\mathrm{GeV}$$

Neutralino dark matter

- **Simple unified SUSY**



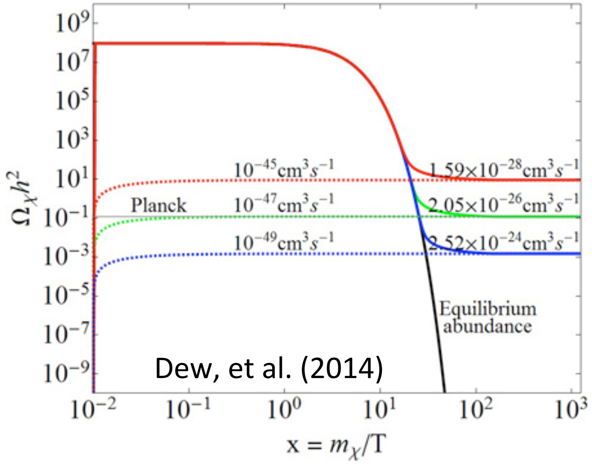
- **Phenomenological SUSY**



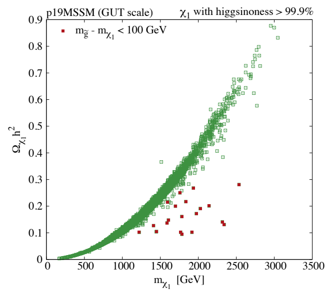
If ~1 TeV higgsino DM is confirmed by searches then:

(…or one of the other basic LSP as DM candidates)

- **Confirmation of SUSY predictions**
- **Confirmation of basic cosmological paradigm**



- **freeze-out from thermal equilibrium (assumes high T_R)**
- **No additional contributions to density**
- **No dilutions, etc.**
- **Single component DM**
- **…**



Is ~1 TeV mass of higgsino DM robust?

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, Gondolo, 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

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

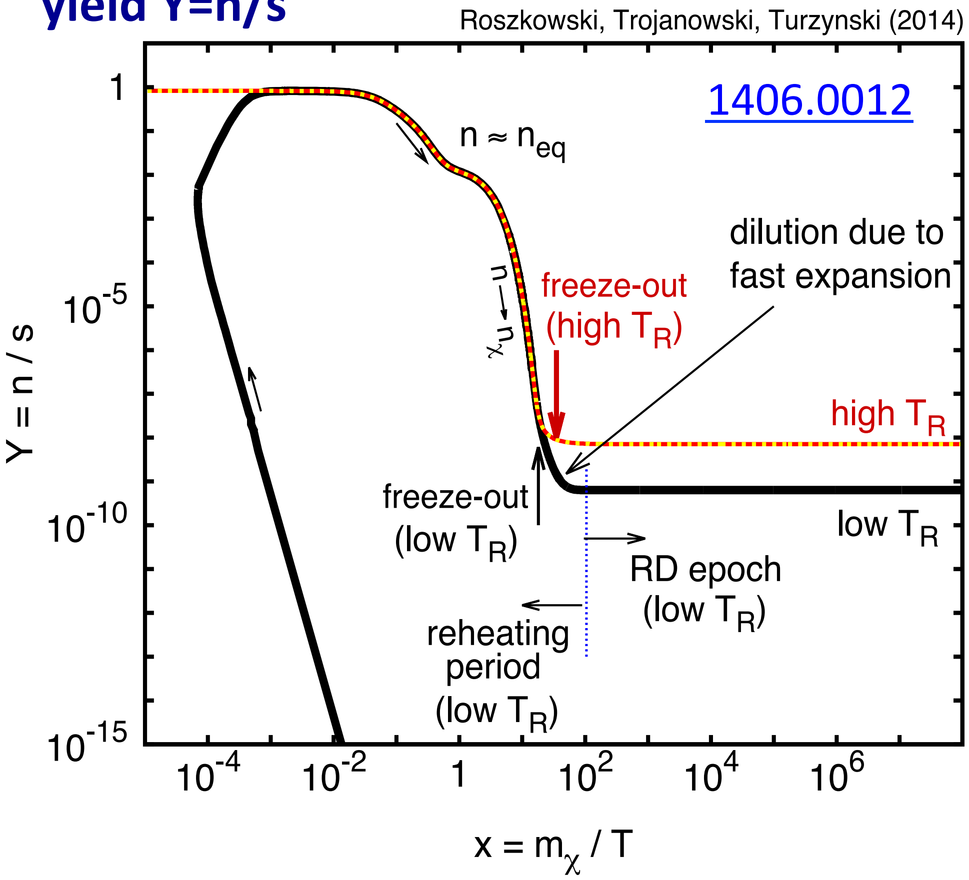
dark matter

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**

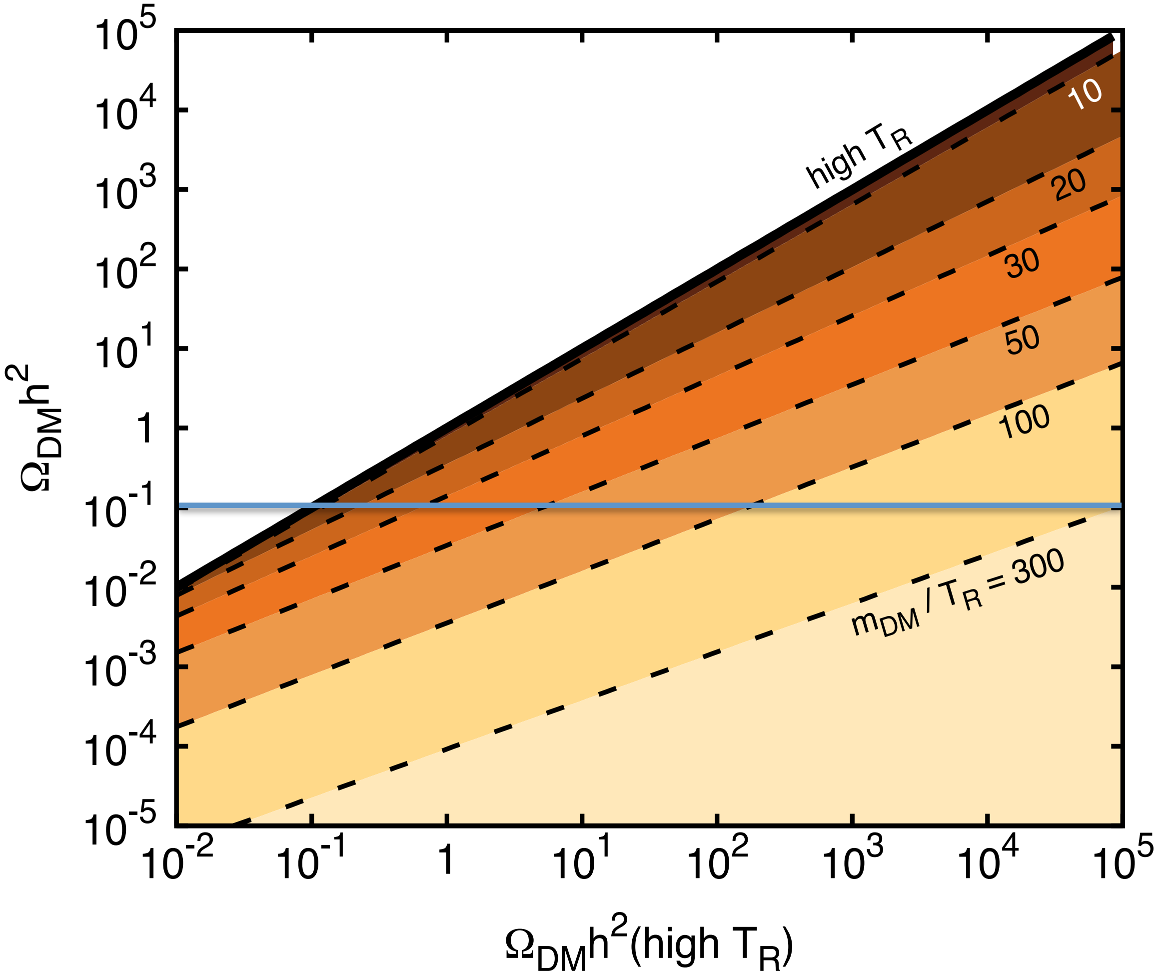
$$\Omega_\chi h^2(\mathrm{low}\ \ T_R) \sim \left(\frac{T_R}{T_{\mathrm{fo}}^{\mathrm{new}}}\right)^3 \left(\frac{T_{\mathrm{fo}}^{\mathrm{old}}}{T_{\mathrm{fo}}^{\mathrm{new}}}\right) \Omega_\chi h^2(\mathrm{high}\ \ T_R)$$

GKR, hep-ph/0005123

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

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

LR, Trojanowski, Turzyński, [1406.0012]



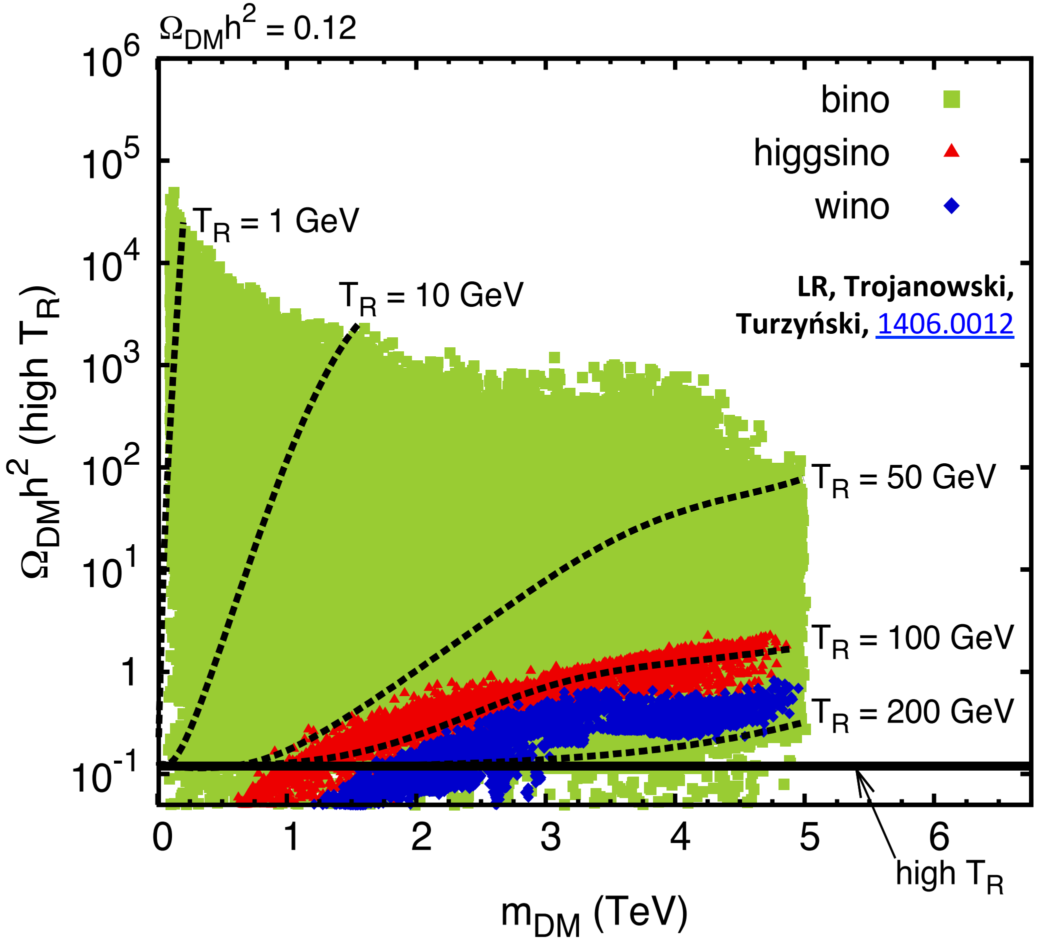
``standard" scenario

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 (with gauginos not unified)



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	$0.1 < m_{\tilde{Q}_3} < 15$
3rd gen. soft slepton mass	$0.1 < m_{\tilde{L}_3} < 15$
1st/2nd gen. soft squark mass	$m_{\tilde{Q}_{1,2}} = M_1 + 100$ GeV
1st/2nd gen. soft slepton mass	$m_{\tilde{L}_{1,2}} = m_{\tilde{Q}_3} + 1$ 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]

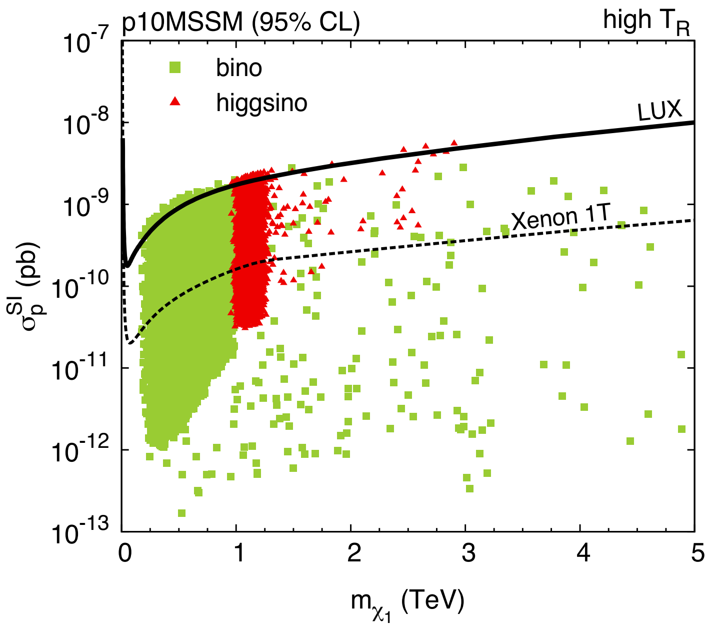
huge relaxation relative to the usual high T_R case:

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

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

Neutralino DM and reheating: high vs low T_R

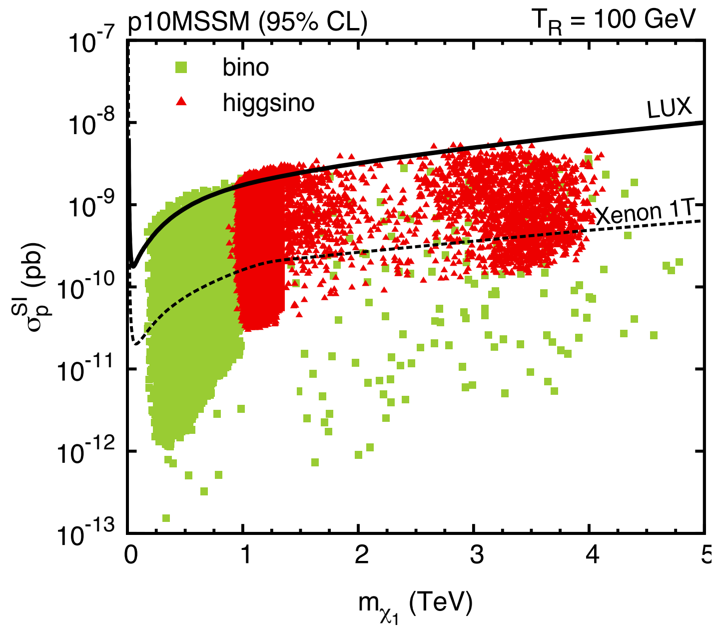
- **High T_R (standard case)**



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

- **Low T_R**

LR, Trojanowski, Turzyński, 1406.0012 (JHEP)



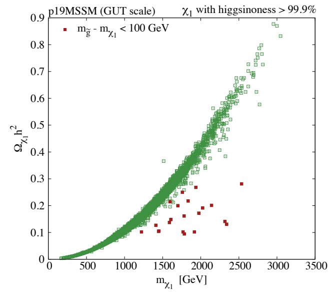
- Much heavier higgsino allowed
- Still testable by DD and CTA

...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?



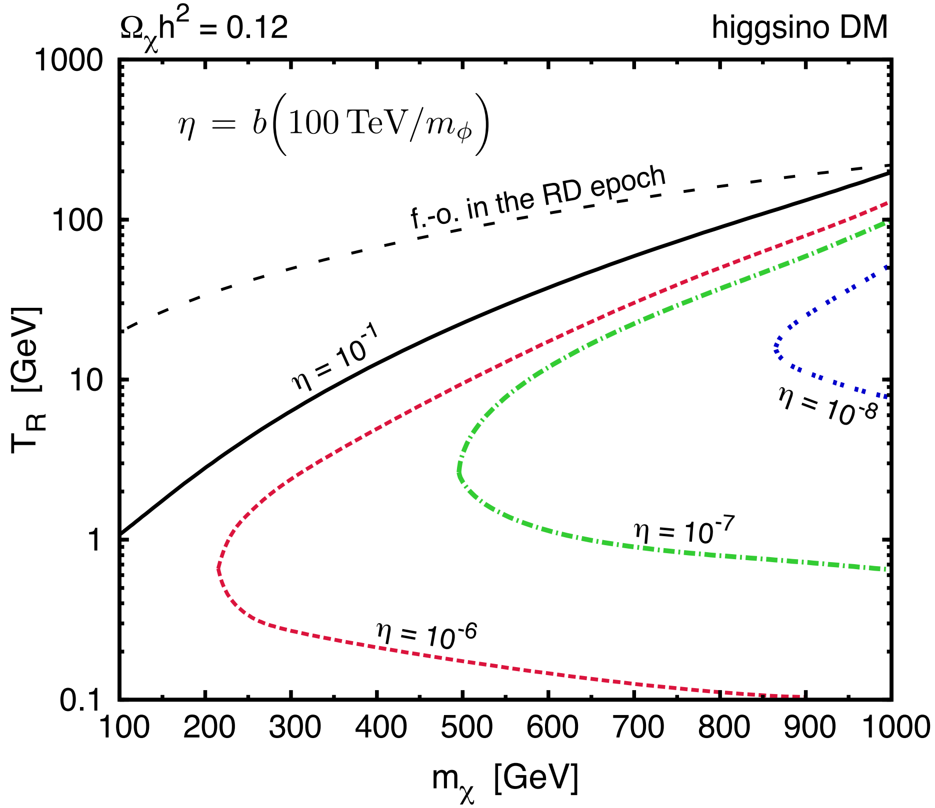
In (standard) high T_R: DM density too low

Ways out:

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

Allow direct/cascade inflaton decay to DM

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



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

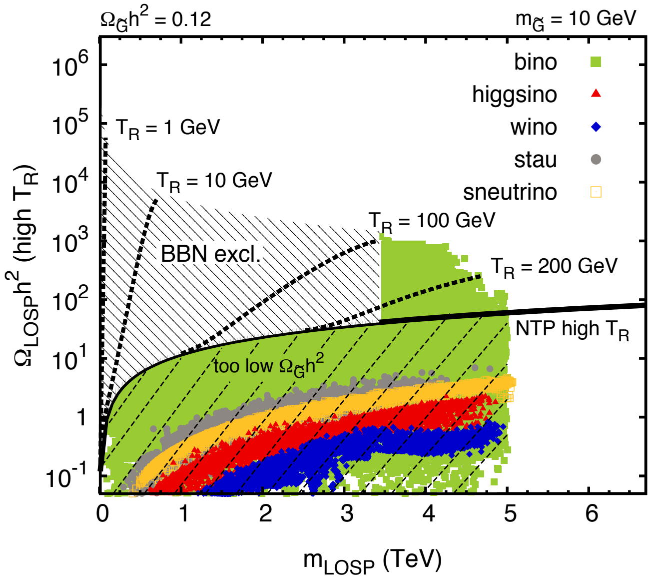
SUSY DM and low T_R

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.

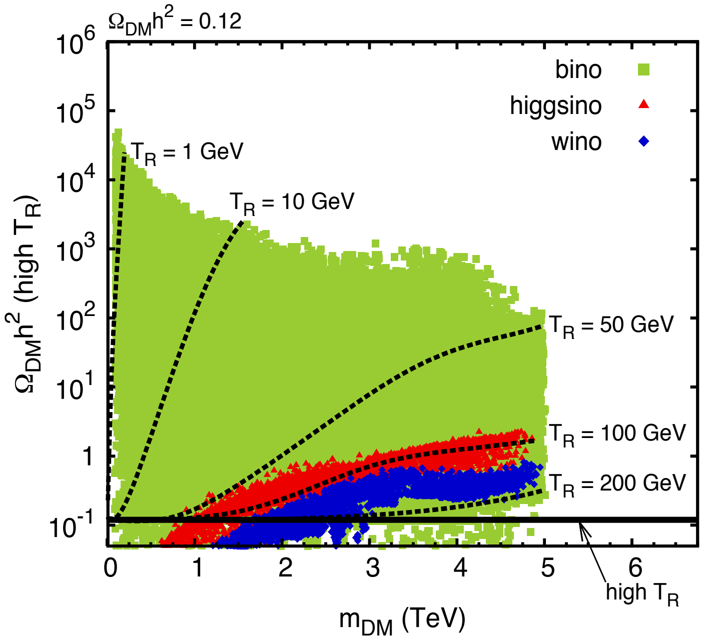
→ Effective limit of T_R> 100 GeV

Low T_R: comeback of wino DM

- **In conflict with diffuse gamma rad'n (HESS) for < 3.5 TeV**

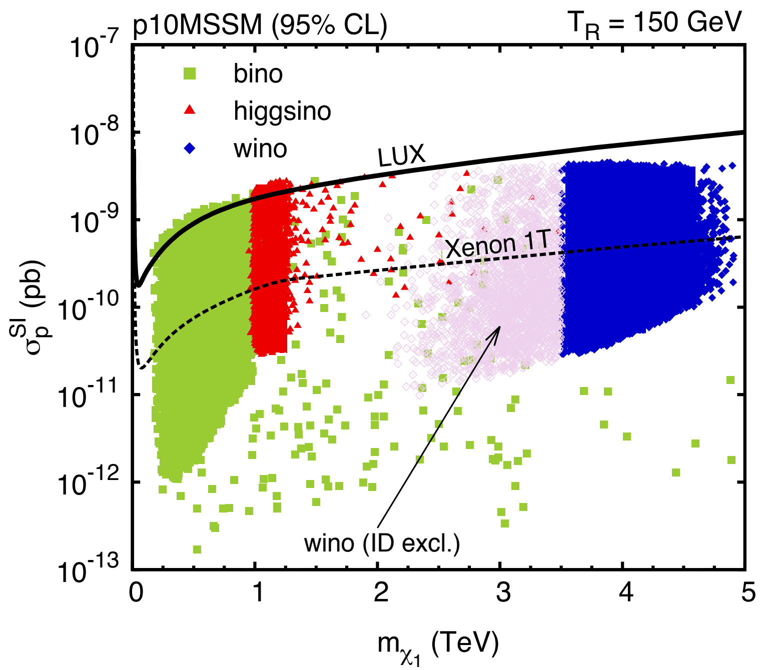
…except for nearly flat DM halo profile

Cohen, et al., 1307.4082
Fan, et al., 1307.4400
Hryczuk, et al., 1401.6212



LR, Trojanowski, Turzyński, 1406.0012

- **Low T_R**



- **Wino > 3.5 TeV again allowed**
- **partly testable**
- **T_R <~ 100 GeV: NO wino allowed**

If wino DM seen at >~3.5 TeV: T_R ~ 100 – 200 GeV

Modulo accidents

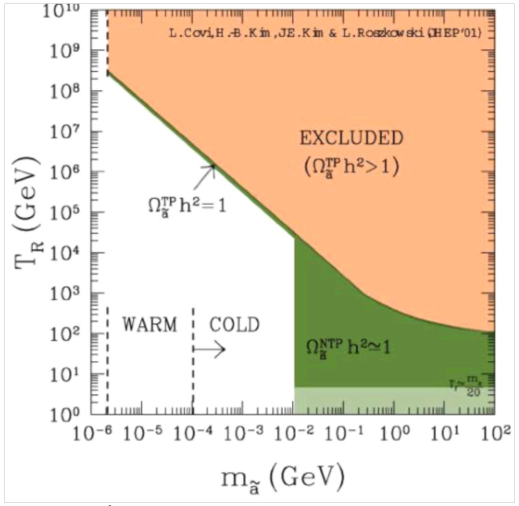
Axino DM at low T_R

LR, Trojanowski, Turzyński, 1507.06164

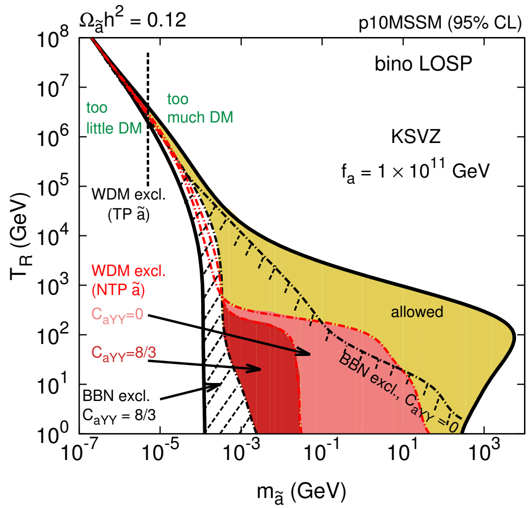
- **Two sources:**
  - **Scatterings at high T_R**
  - **NLSP decays at lower T_R**

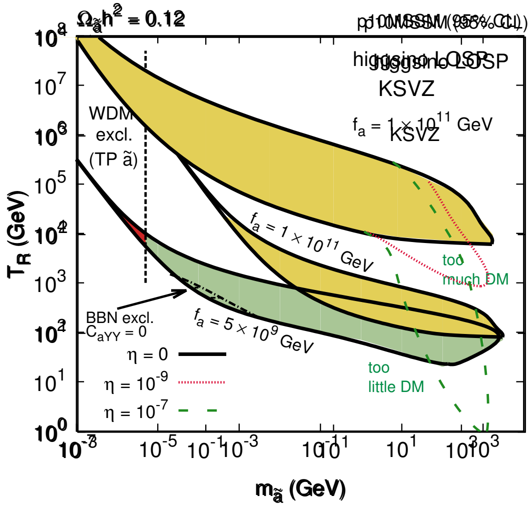
- **More proper analysis at low T_R**

non-instantaneous reheating, …



update in arXiv:1108.2282





T_R-dependent limit on axino mass

higgsino LOSP: Lower bound on T_R

Similar for wino LOSP

Axino: new effects at low T_R ~ 100 GeV

inflaton decay to axino can relax lower bound on T_R

Modulo accidents

To take home:

- Searches for SUSY are still in their early stages
- SUSY Higgs of 125 GeV:
  - M_{susy} ~ few TeV
  - DM WIMP is preferably ~1 TeV higgsino
- DM ~1 TeV higgsino case will be sensitive to only DM searches (direct + CTA)
- The most constrained SUSY model – CMSSM – is to be fully probed by combination of LHC and DM searches
- Fine-tuning argument may prove irrelevant

Complementarity of LHC, DD and CTA

- Multi-TeV higgsino DM allowed but implies T_R~ 100 GeV
- Sub-TeV higgsino single DM case can also be OK

- Gravitino DM: limit of T_R> 100 GeV
- Axino DM: limit of T_R> 100 GeV (for higgsino or wino NLSP)