Axions in SUSY, and what we have/will we learn from accelerators

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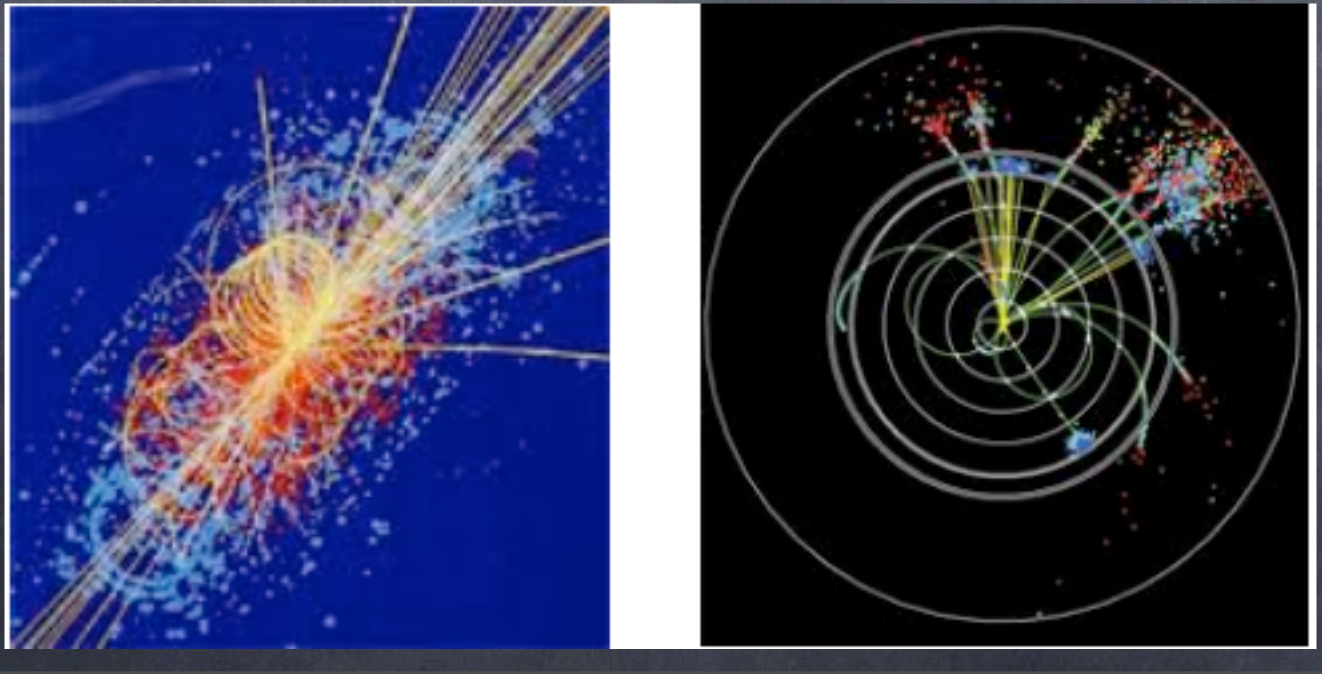
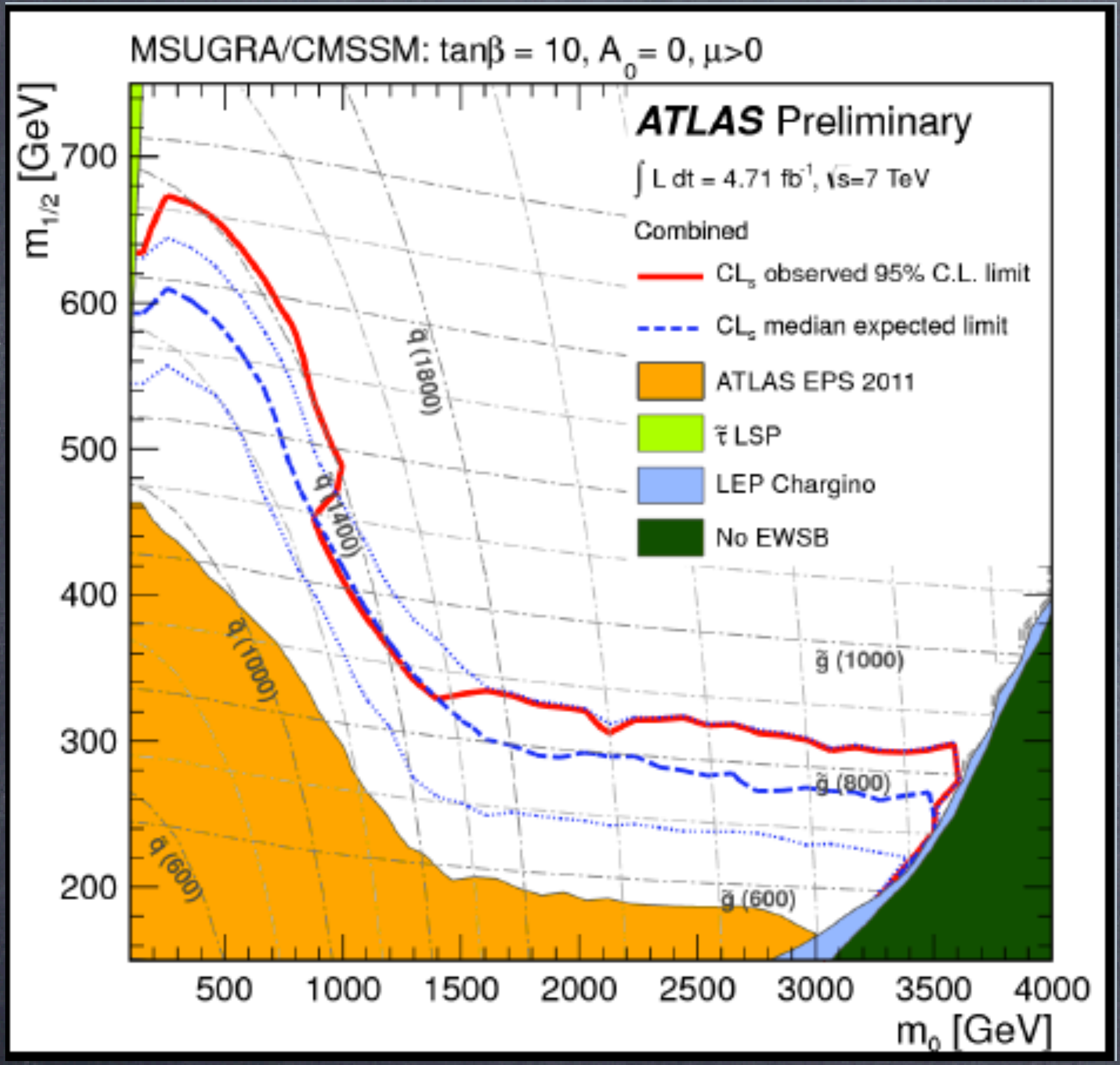
A view from the theory/experiment interface

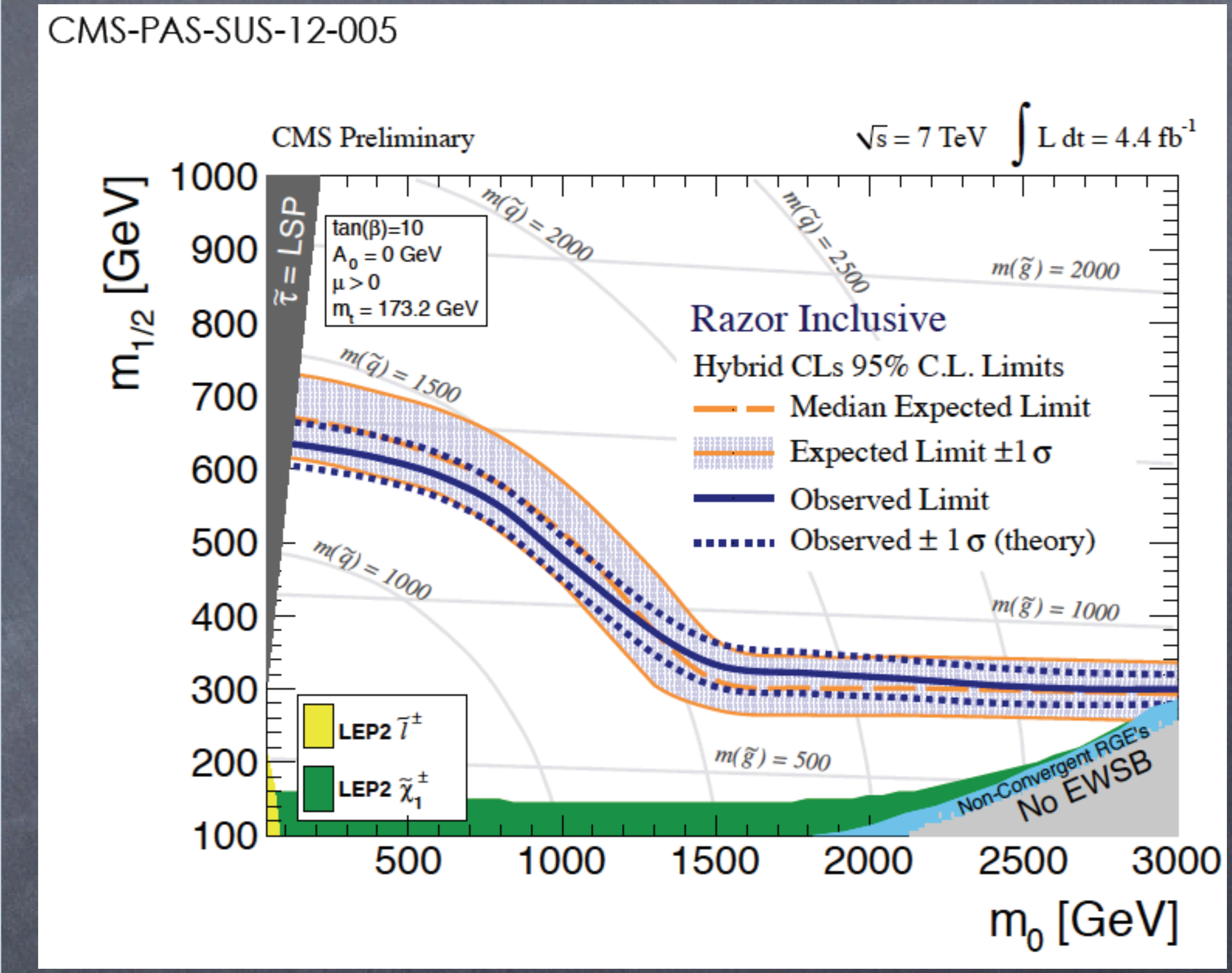


Some ideas are so profound it is hard to believe they don't play a role in nature

- see-saw neutrinos
- weak scale SUSY
- Peccei-Quinn-Weinberg-Wilczek-Kim (nearly) invisible axion
- inflationary cosmology
- string theory
- $SO(10) \supset SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$

First, in honor of LHC turn-on, an update on SUSY searches at LHC

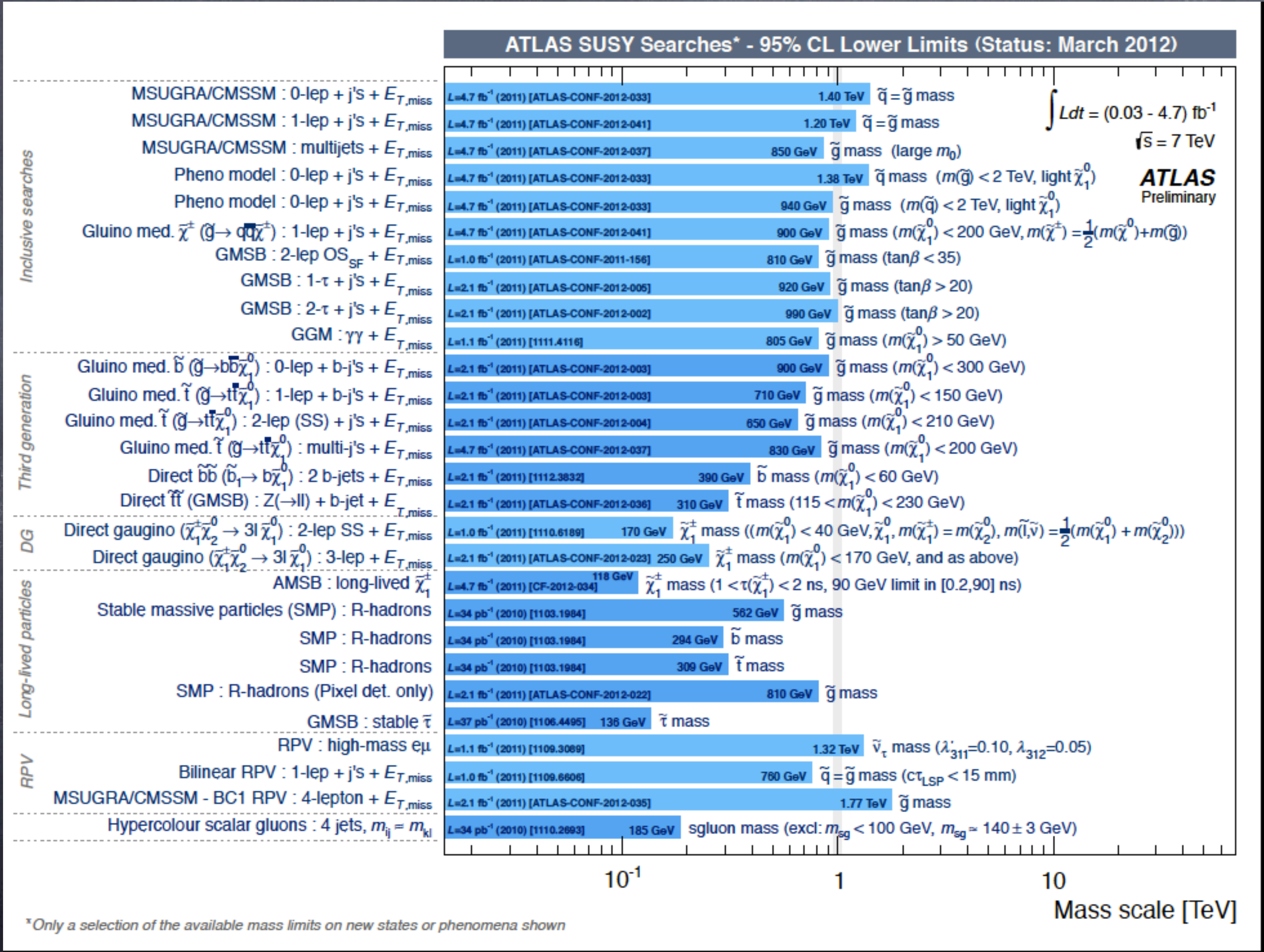




Atlas/CMS: no sign of mSUGRA at LHC7:

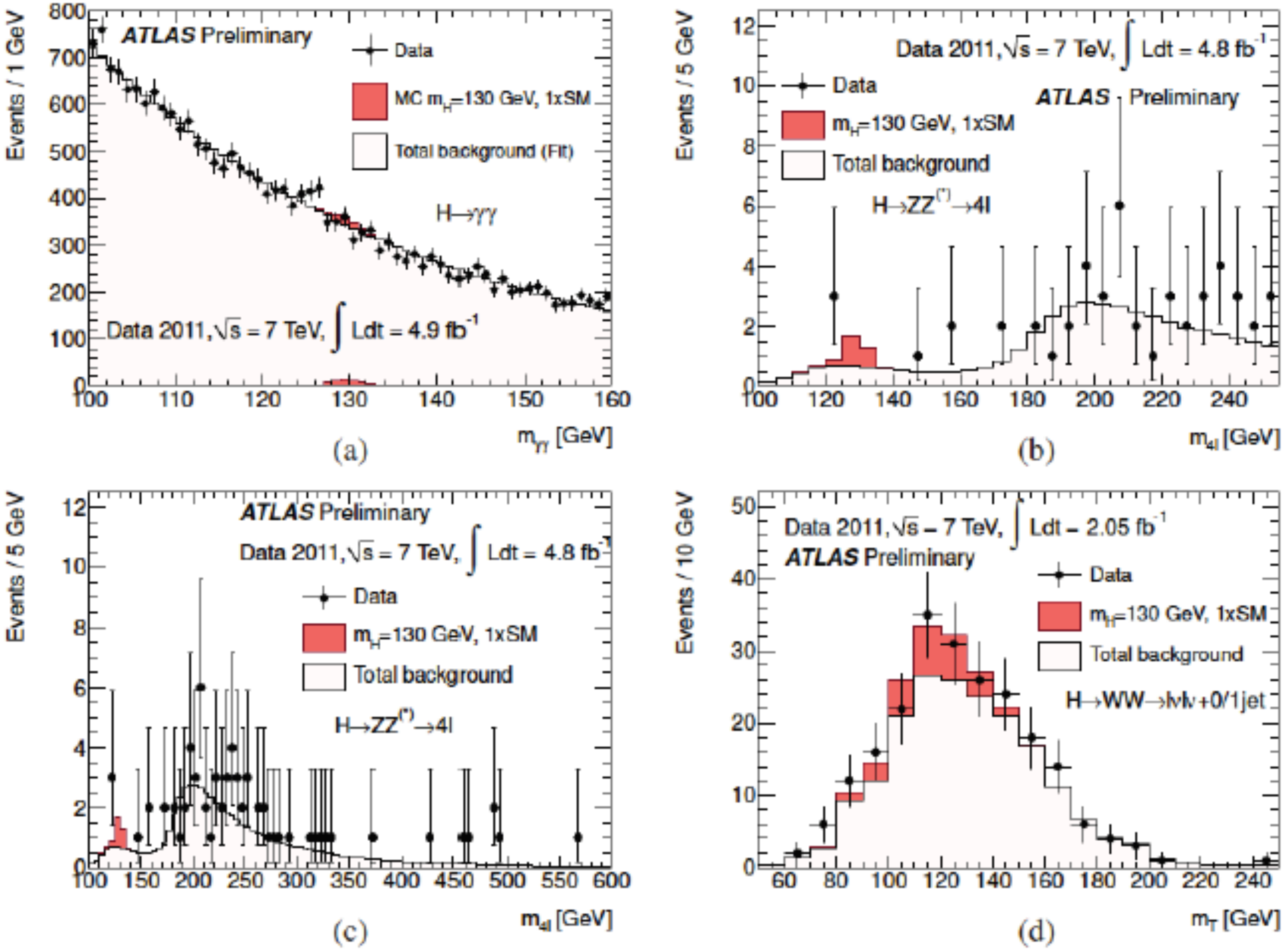
$$m_{\tilde g} > 1400 \text{ GeV for } m_{\tilde q} \simeq m_{\tilde g};\ m_{\tilde g} > 800 \text{ GeV for } m_{\tilde q} \gg m_{\tilde g}$$

Lots and lots of other searches



*Only a selection of the available mass limits on new states or phenomena shown

Possible Higgs signal at 125 GeV?



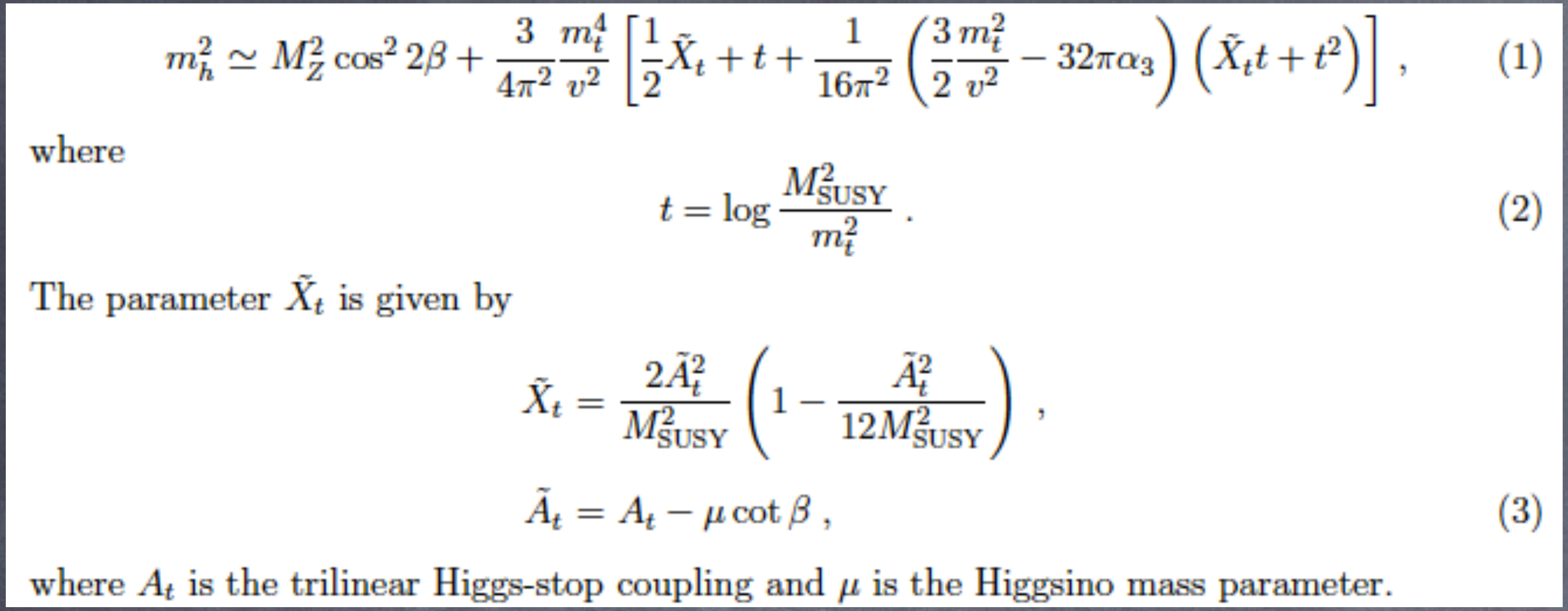
(a)

(b)

(c)

(d)

Higgs mass in SUSY



$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right], \qquad (1)$$

where

$$t = \log\frac{M_{\rm SUSY}^2}{m_t^2}. \qquad (2)$$

The parameter $\tilde{X}_t$ is given by

$$\tilde{X}_t = \frac{2\tilde{A}_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{\tilde{A}_t^2}{12M_{\rm SUSY}^2}\right),$$

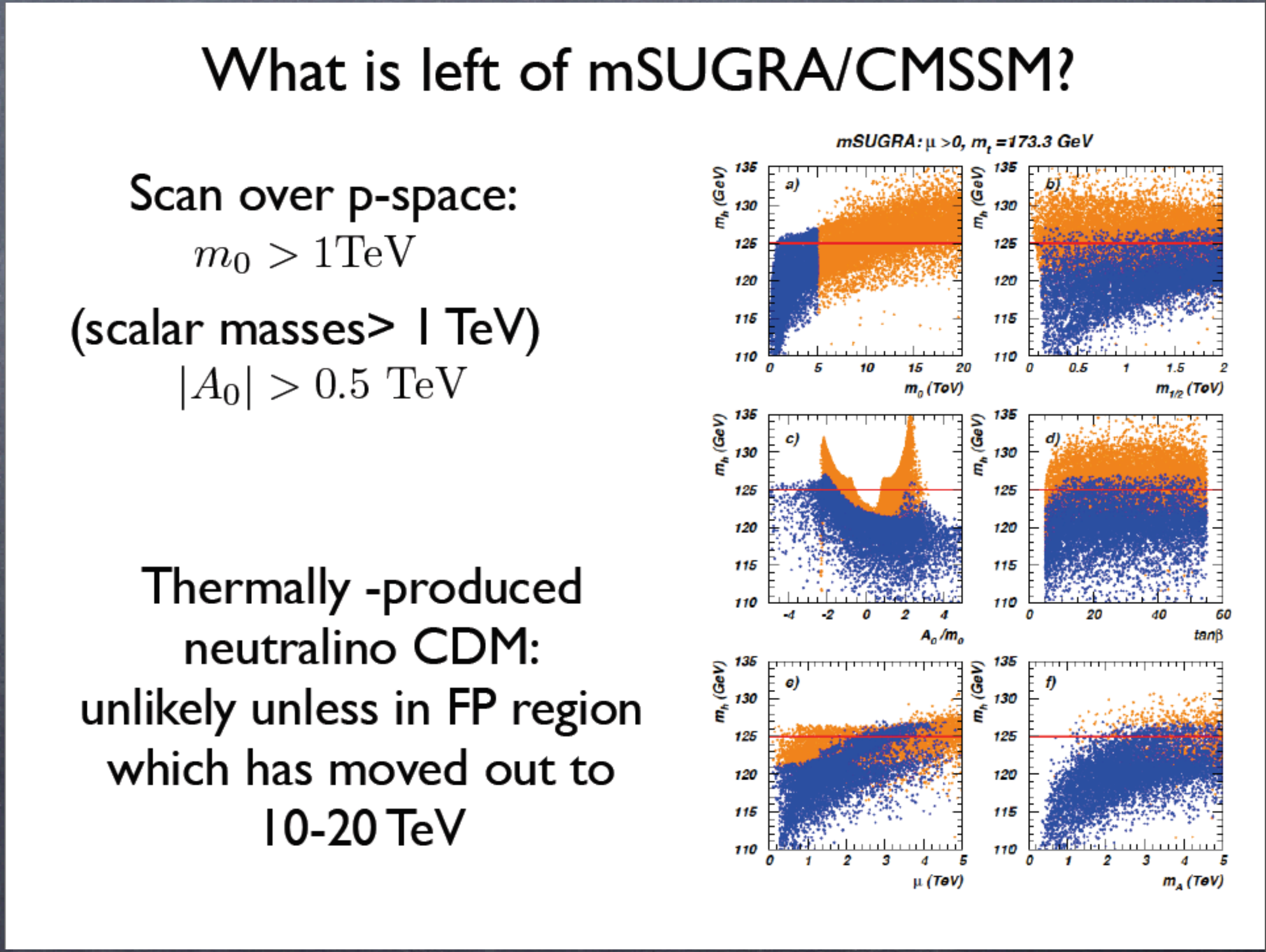
$$\tilde{A}_t = A_t - \mu\cot\beta, \qquad (3)$$

where A_t is the trilinear Higgs-stop coupling and μ is the Higgsino mass parameter.

Carena, Gori, Shah, Wagner

Prefer mt1>1 TeV and large mixing

HB, Barger, Mustafayev

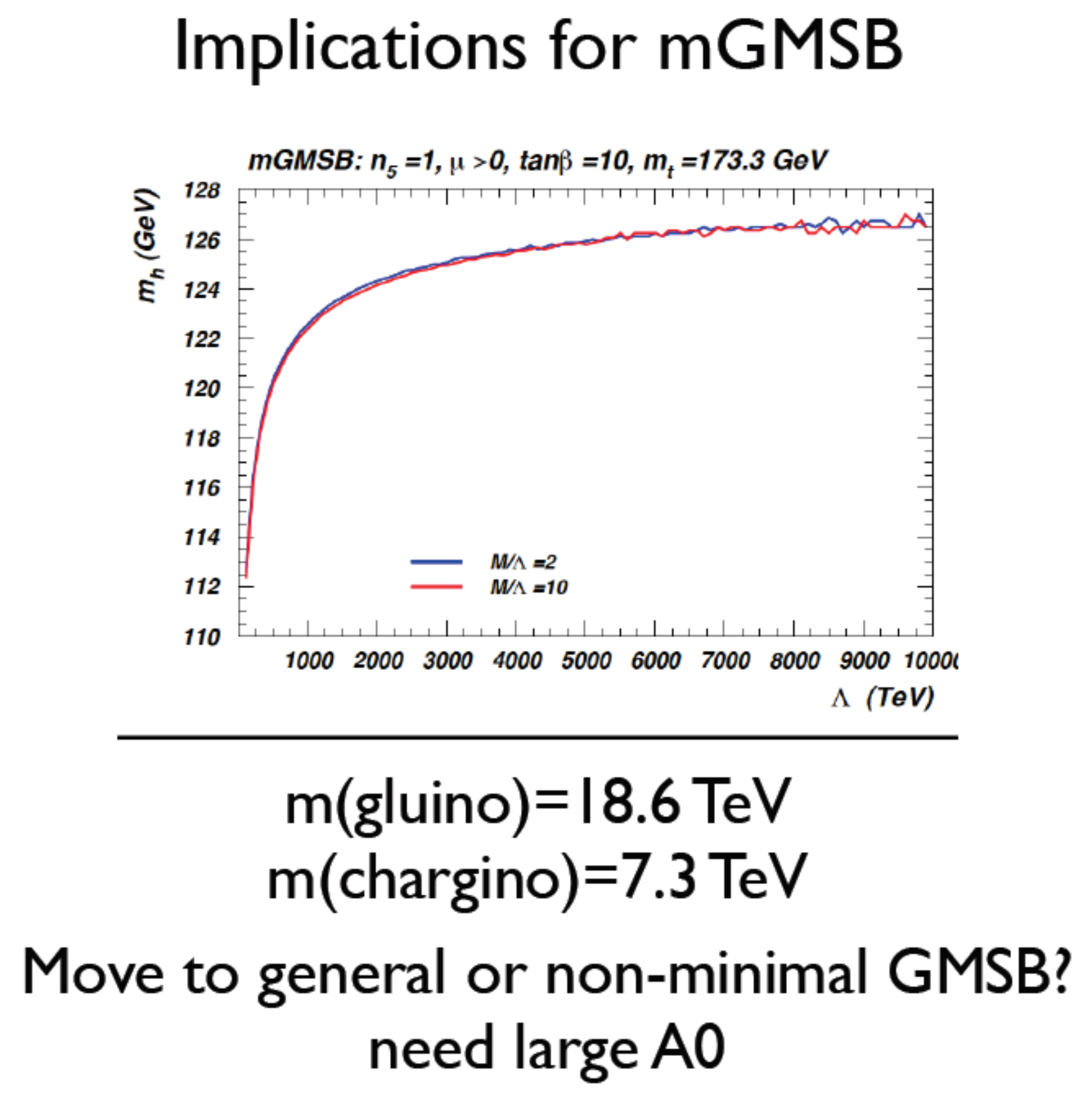


What is left of mSUGRA/CMSSM?

Scan over p-space:
$m_0 > 1\mathrm{TeV}$
(scalar masses> 1 TeV)
$|A_0| > 0.5$ TeV

Thermally -produced neutralino CDM: unlikely unless in FP region which has moved out to 10-20 TeV

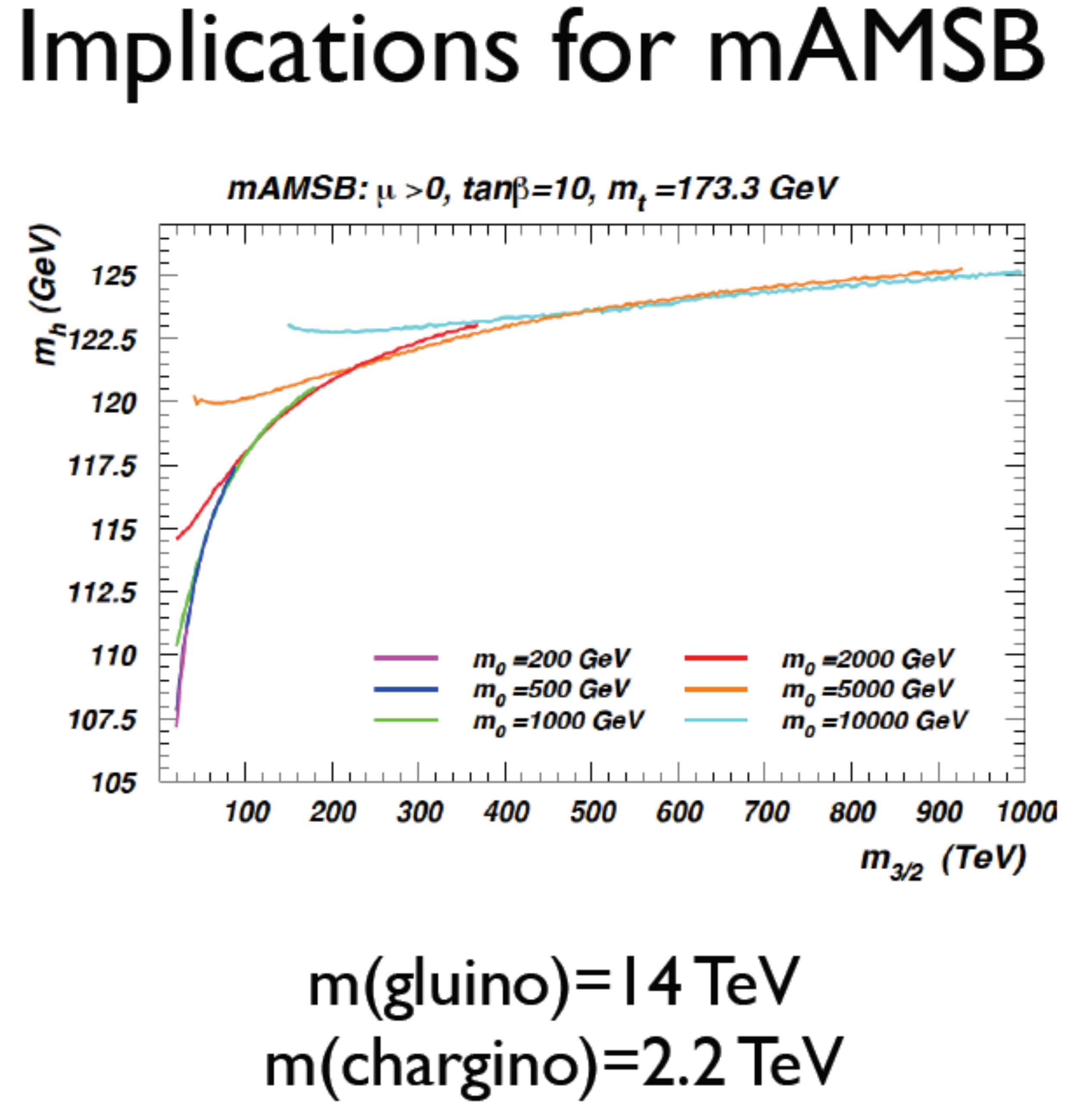
Some implications if $m_h \simeq 125\ \mathrm{GeV}$



Implications for mGMSB

m(gluino)=18.6 TeV
m(chargino)=7.3 TeV

Move to general or non-minimal GMSB?
need large A0



Implications for mAMSB

m(gluino)=14 TeV
m(chargino)=2.2 TeV

minimal GMSB, AMSB highly stressed:
go to more general models

No sign of SUSY at LHC so far: should we be alarmed?

- To large extent, these results have been anticipated by many theorists
- Well-known result: gravity mediation suffers from SUSY flavor/CP problems- in fact, these were motivation to create GMSB/AMSB alternatives
- In gravity mediation, $m(sparticle) \simeq m_{3/2}$; if $m_{3/2} < 5\ \mathrm{TeV}\ and\ T_R > 10^4\ \mathrm{GeV}$ then gravitinos overproduced; BBN constraints
- one solution solves all: decoupling

Dine, Kagan, Samuel;
Cohen, Kaplan, Nelson

1st/2nd generation scalars~10-50 TeV

But what of fine-tuning:
SUSY and EW scale link?

Minimization of SUSY scalar potential:

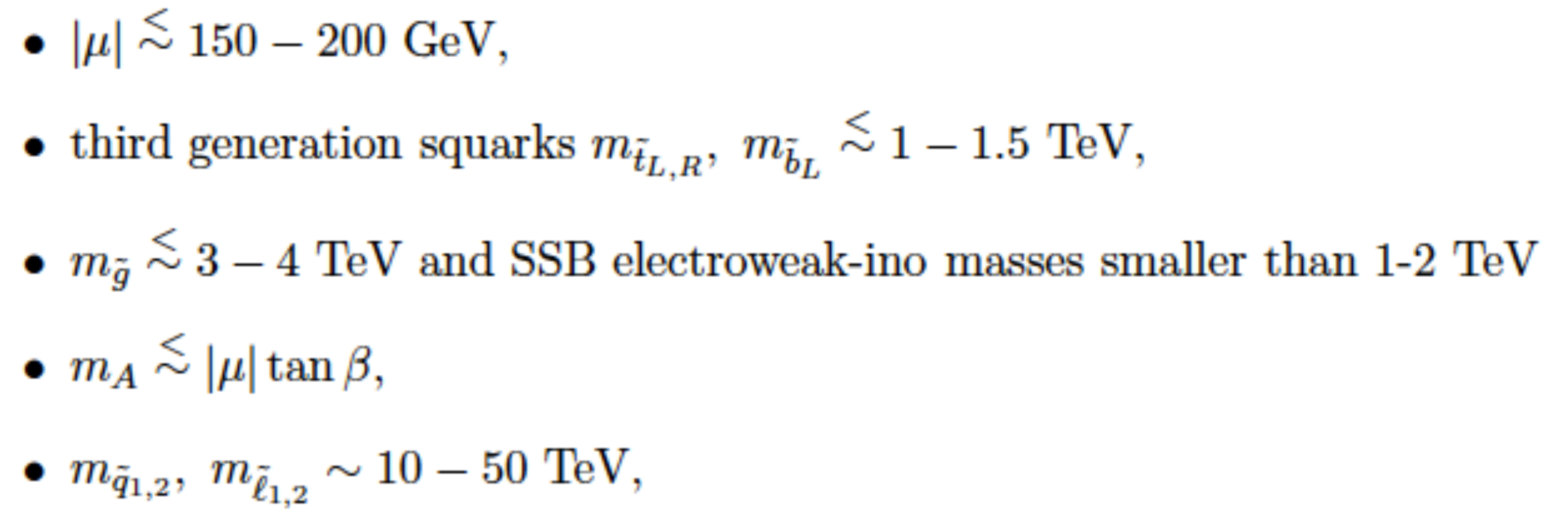
$$\frac{1}{2}M_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2$$

All terms on RHS $\sim M_Z^2$

$$\Sigma_u \sim \frac{3f_t^2}{16\pi^2} \times m_{\tilde{t}_i}^2 \left(\ln(m_{\tilde{t}_i^2}/Q^2) - 1\right)$$

$$\delta m_{\tilde{q}}^2 \sim \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \times log$$

Then:
Natural
SUSY!



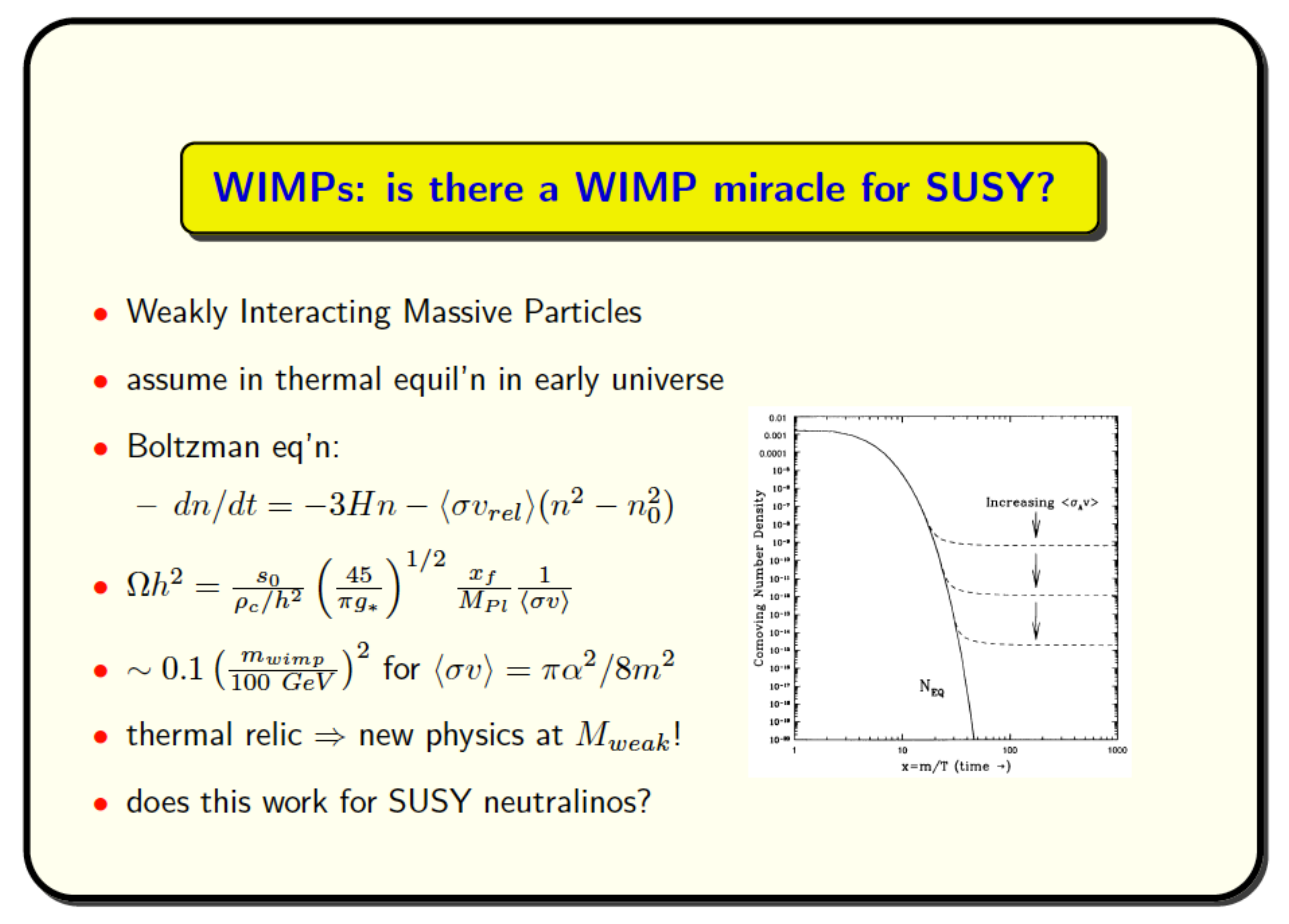
- $|\mu| \lesssim 150 - 200$ GeV,
- third generation squarks $m_{\tilde{t}_{L,R}}$, $m_{\tilde{b}_L} \lesssim 1 - 1.5$ TeV,
- $m_{\tilde{g}} \lesssim 3 - 4$ TeV and SSB electroweak-ino masses smaller than 1-2 TeV
- $m_A \lesssim |\mu| \tan\beta$,
- $m_{\tilde{q}_{1,2}}$, $m_{\tilde{\ell}_{1,2}} \sim 10 - 50$ TeV,

Natural SUSY at colliders

- 1st/2nd gen. squarks: far beyond LHC reach
- likely gluino also beyond LHC reach
- 3rd generation squarks: maybe within LHC reach
- lightest EWinos higgsino-like: $\mu \sim 100 - 300\ \mathrm{GeV}$ small mass gap-> soft decay products
- ILC would likely be higgsino factory!
- $\Omega_\chi^{std} h^2 \sim 0.007$; low by factor of ~16

see e.g. HB, Barger, Huang, Tata, arXiv:1203.5539

What about SUSY dark matter?



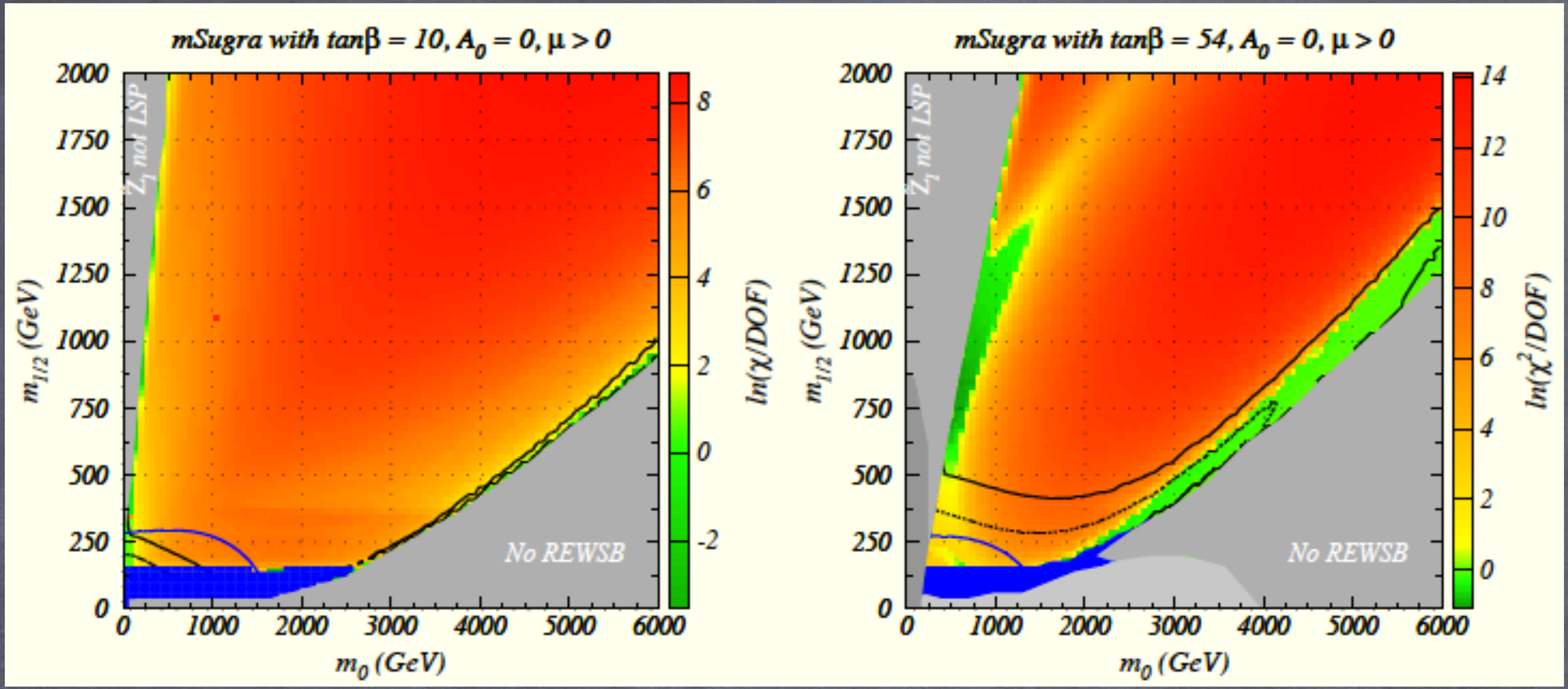
WIMPs: is there a WIMP miracle for SUSY?

- Weakly Interacting Massive Particles
- assume in thermal equil'n in early universe
- Boltzman eq'n:

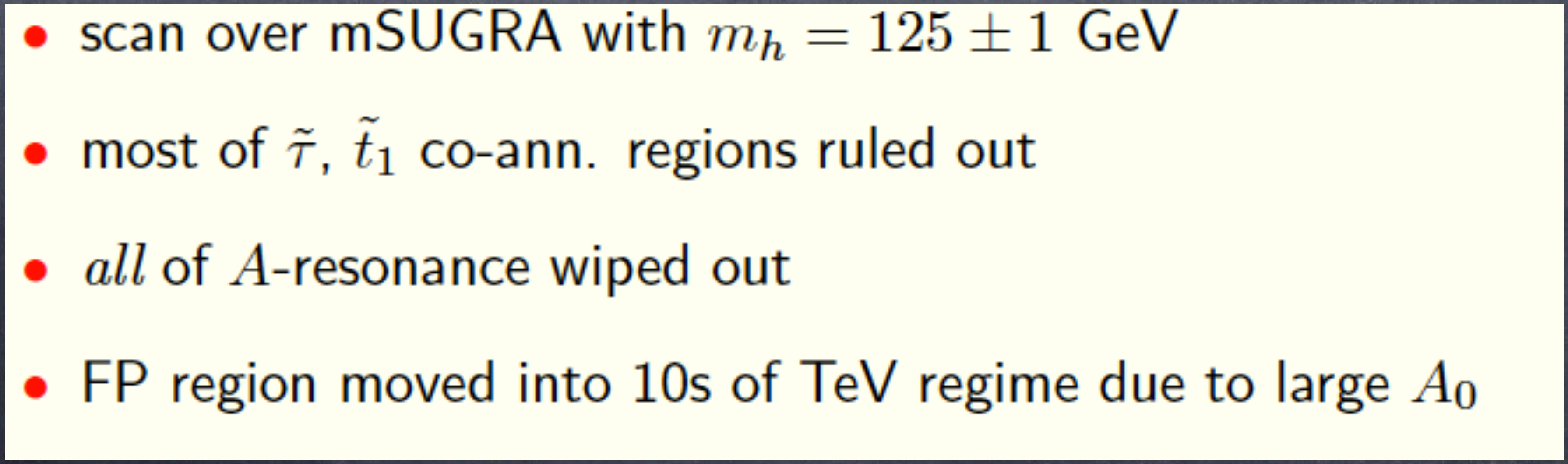
$$-\ dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$$

- $\Omega h^2 = \frac{s_0}{\rho_c/h^2} \left(\frac{45}{\pi g_*} \right)^{1/2} \frac{x_f}{M_{Pl}} \frac{1}{\langle \sigma v \rangle}$
- $\sim 0.1 \left(\frac{m_{wimp}}{100\ GeV} \right)^2$ for $\langle \sigma v \rangle = \pi \alpha^2 / 8m^2$
- thermal relic $\Rightarrow$ new physics at M_{weak}!
- does this work for SUSY neutralinos?

Neutralino DM in mSUGRA

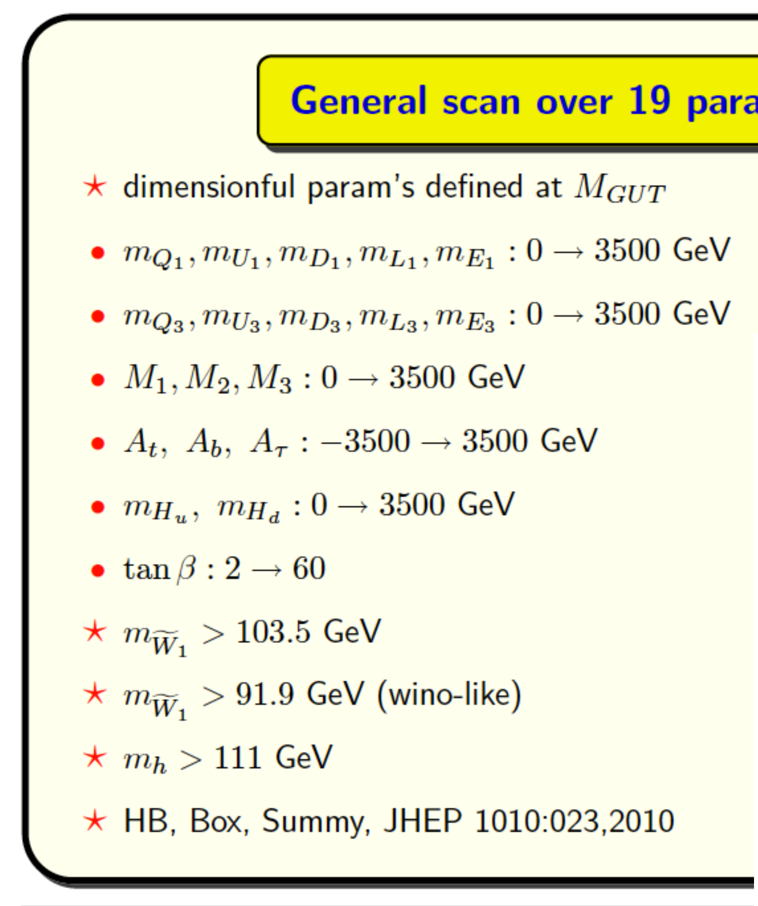


Green regions with $\Omega_\chi^{std} h^2 < 0.12$ highly fine-tuned



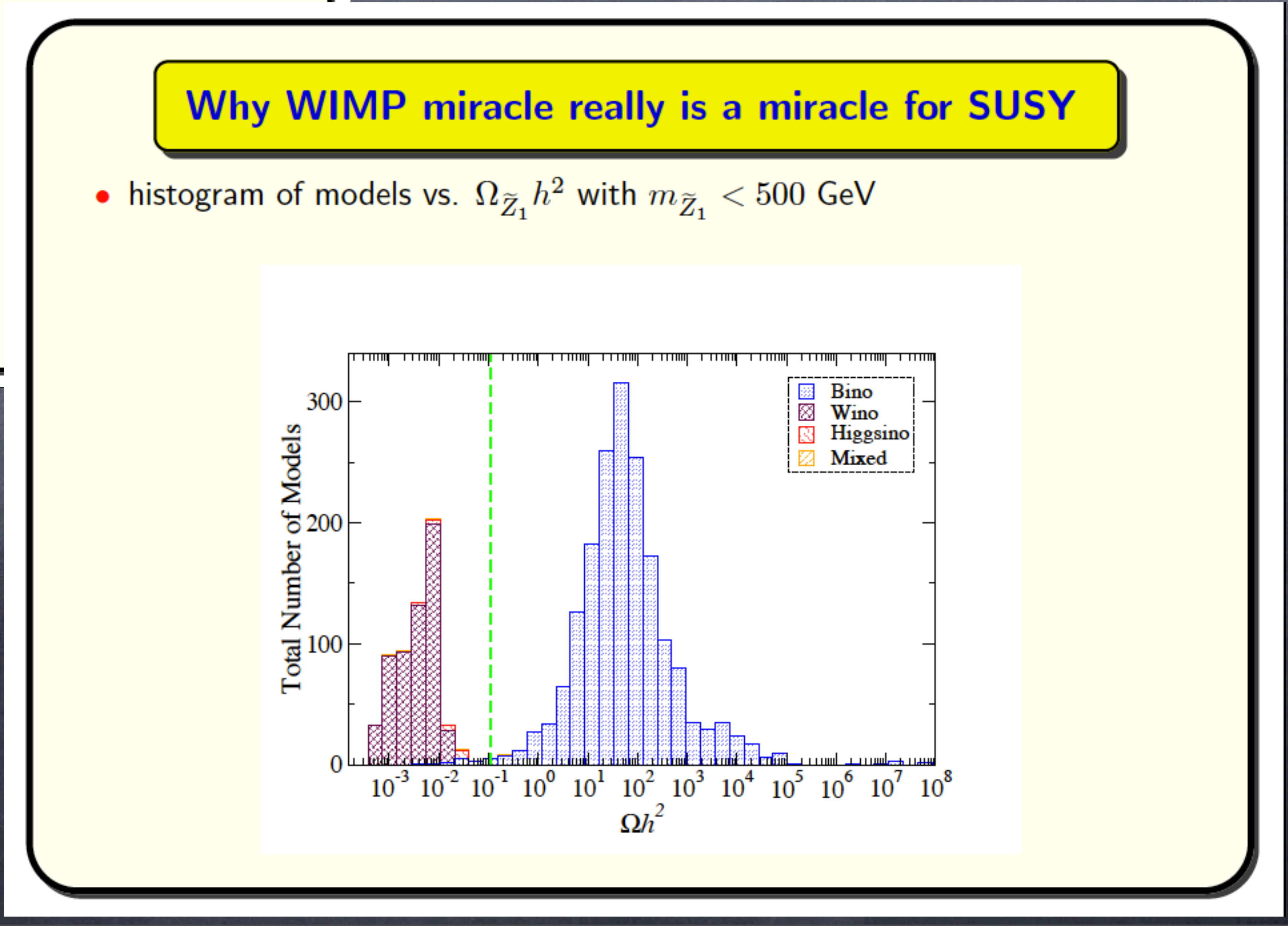
- scan over mSUGRA with $m_h = 125 \pm 1$ GeV
- most of $\tilde{\tau}$, $\tilde{t}_1$ co-ann. regions ruled out
- *all* of A-resonance wiped out
- FP region moved into 10s of TeV regime due to large A_0

More general SUSY scan



General scan over 19 param. MSSM

- ★ dimensionful param's defined at M_{GUT}
- • $m_{Q_1}, m_{U_1}, m_{D_1}, m_{L_1}, m_{E_1} : 0 \rightarrow 3500$ GeV
- • $m_{Q_3}, m_{U_3}, m_{D_3}, m_{L_3}, m_{E_3} : 0 \rightarrow 3500$ GeV
- • $M_1, M_2, M_3 : 0 \rightarrow 3500$ GeV
- • $A_t,\ A_b,\ A_\tau : -3500 \rightarrow 3500$ GeV
- • $m_{H_u},\ m_{H_d} : 0 \rightarrow 3500$ GeV
- • $\tan\beta : 2 \rightarrow 60$
- ★ $m_{\widetilde{W}_1} > 103.5$ GeV
- ★ $m_{\widetilde{W}_1} > 91.9$ GeV (wino-like)
- ★ $m_h > 111$ GeV
- ★ HB, Box, Summy, JHEP 1010:023,2010



Why WIMP miracle really is a miracle for SUSY

- histogram of models vs. $\Omega_{\widetilde{Z}_1} h^2$ with $m_{\widetilde{Z}_1} < 500$ GeV

Measured DM density lies at most unlikely value of SUSY predictions!

Why thermally-produced neutralino-only DM is not the answer (in spite of the hype):

- Generates too much or too little DM; only rarely is $\Omega_\chi^{std} h^2 \sim 0.11$: fine-tuned!
- gravitino problem and BBN constraints
- neglects the strong CP problem and its solution

Strong CP problem

- QCD $\ni U(2)_V \times U(2)_A$ global symmetry (2 light quarks)
- $U(2)_V = SU(2)_I \times U(1)_B$ realized; $U(2)_A$ broken spontaneously
- expect 4 Goldstone bosons: πs and η, but instead $m_\eta \gg m_\pi$: QCD does not respect somehow $U(1)_A$ (Weinberg)
- t'Hooft resolution: QCD θ vacuum and instantons $\Rightarrow$ theory not $U(1)_A$ symmetric, and $m_\eta \gg m_\pi$ explained
- Generate additional term to QCD Lagrangian: $\mathcal{L} \ni \theta \frac{g_s^2}{32\pi} F_A^{\mu\nu} \tilde{F}_{A\mu\nu}$
  - violates P and T; conserves C
- In addition, weak interactions $\Rightarrow \mathcal{L} \ni Arg\ detM \frac{g_s^2}{32\pi} F_A^{\mu\nu} \tilde{F}_{A\mu\nu}$
  - $\bar{\theta} = \theta + Arg\ detM$
- experiment: neutron EDM $\Rightarrow \bar{\theta} \lesssim 10^{-10}$
- How can this be? The strong CP problem

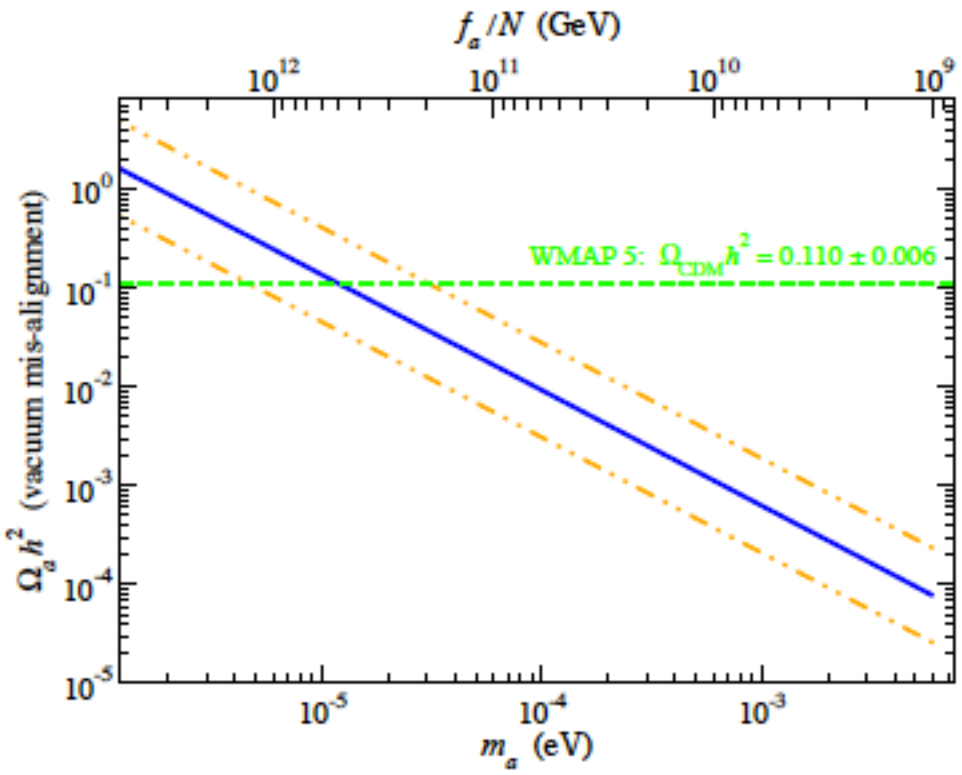
PQWW/KSVZ/DFSZ solution to the strong CP problem

⋆ propose new chiral (Peccei-Quinn) symmetry $U_{PQ}(1)$; $U_{PQ}(1)$ spontaneously broken at scale f_a $(\sim 10^9 - 10^{12}$ GeV)

- requires Goldstone boson field $a(x)$, the **axion**
- $\mathcal{L} \ni \frac{1}{2}\partial^\mu a \partial_\mu a + \left(\frac{a}{f_a} + \bar\theta\right) \frac{\alpha_s}{8\pi} F_A^{\mu\nu} \tilde{F}_{A\mu\nu}$
- $V_{eff} \sim (1 - \cos(\bar\theta + \frac{a}{f_a}))$
- axion field settles to minimum of potential: $\langle a \rangle = -f_a \bar\theta$
- offending $F\tilde{F}$ term → 0; strong CP problem solved!
- $m_a^2 = \langle \frac{\partial^2 V_{eff}}{\partial a^2} \rangle$ with $m_a \sim 6\ \mu\mathrm{eV} \frac{10^{12}\ \mathrm{GeV}}{f_a}$

Axion cosmology

- Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial \theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$:
    $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
- a(x) oscillates,
  creates axions with $\vec{p} \sim 0$:
  production via vacuum mis-alignment
- $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times10^{-6} eV}{m_a}\right]^{7/6} \theta_i^2 h^2$
- astro bound: stellar cooling $\Rightarrow f_a \gtrsim 10^9 G$



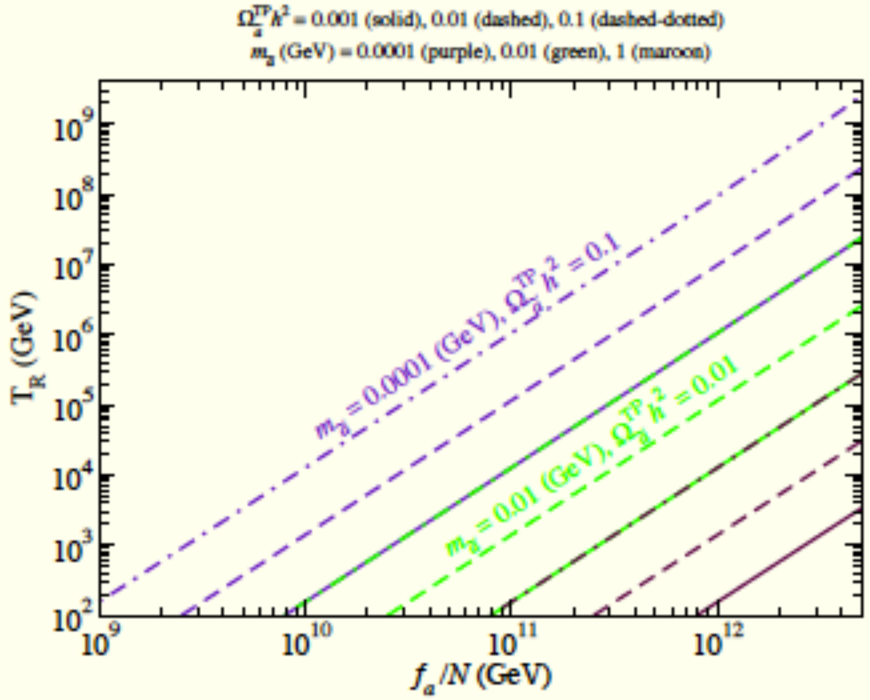
PQMSSM: Axions $+$ SUSY $\Rightarrow$ mixed $a - LSP$ dark matter

- $\hat{a} = \frac{s+ia}{\sqrt{2}} + i\sqrt{2}\bar{\theta}\tilde{a}_L + i\bar{\theta}\theta_L\mathcal{F}_a$ in 4-comp. notation
- Raby, Nilles, Kim; Rajagopal, Wilczek, Turner
- axino is spin-$\frac{1}{2}$ element of axion supermultiplet (R-odd; possible LSP candidate)
- $m_{\tilde{a}}$ model dependent: keV→ TeV, but $\sim M_{SUSY}$ in gravity mediation
- saxion is spin-0 element: R-even but gets SUSY breaking mass ~ 1 TeV
- axion is usual QCD axion: gets produced via vacuum mis-alignment/ coherent oscillations as usual
- additional PQ parameters: $(f_a,\ m_{\tilde{a}},\ m_s,\ \theta_i,\ \theta_s,\ )$ and T_R

Thermally produced axinos

- ★ If $T_R < f_a$, then axinos never in thermal equilibrium in early universe
- ★ Can still produce $\tilde{a}$ thermally via radiation off particles in thermal equilibrium
- ★ Covi et al.; Brandenberg Steffen; Strumia; Choi et al. calculations:

$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 24.8 g_s^6 \ln\left(\frac{3}{g_s}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2\left(\frac{m_{\tilde{a}}}{1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right) \qquad (1)$$

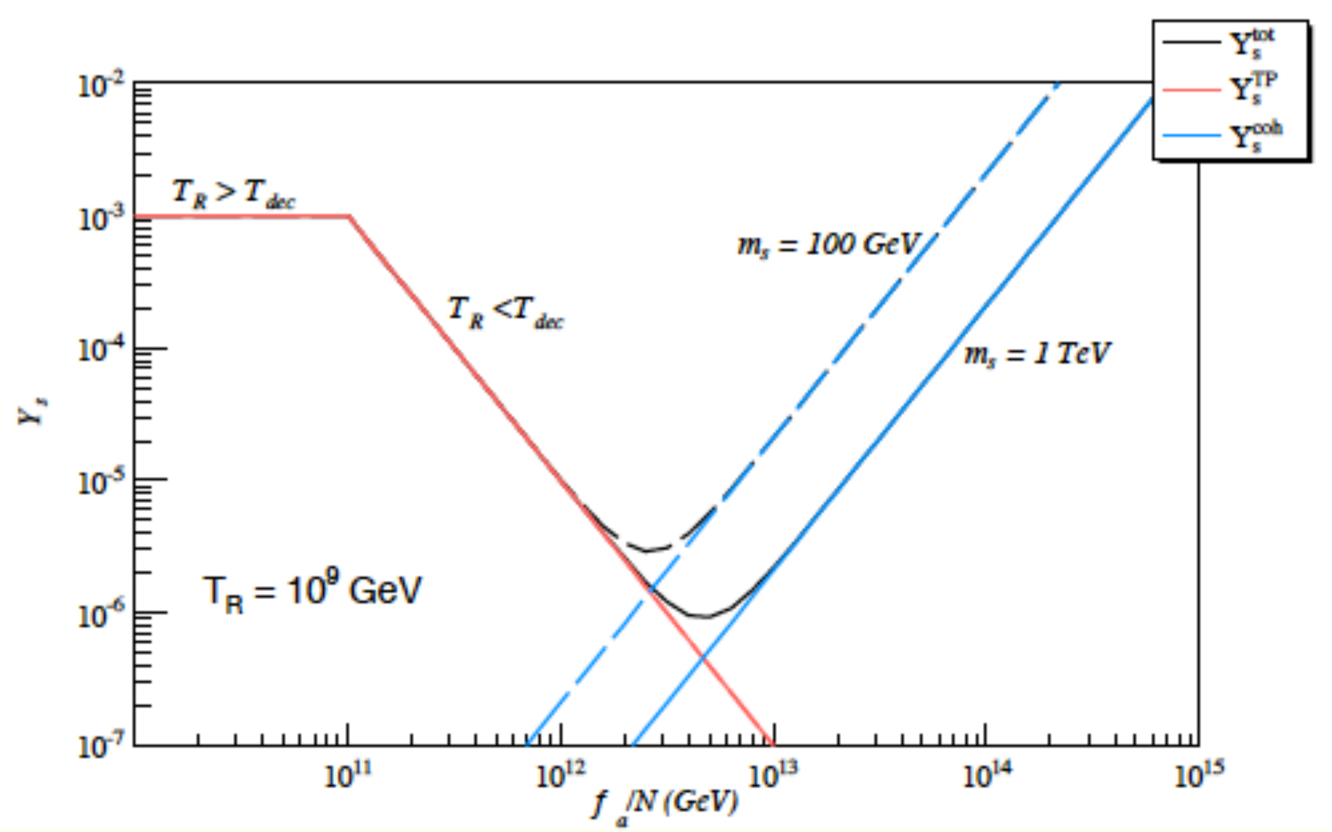


What if $m_{\tilde{a}} > m_{\widetilde{Z}_1}$ so $\widetilde{Z}_1 = LSP$?

- (see also Choi, Kim Lee, Seto)
- Expect mixed axion/neutralino CDM: which will dominate?
- Neutralinos produced thermally as usual (RD, MD or DD universe)
- Axino production and decay (e.g. $\tilde{a} \rightarrow \widetilde{Z}_1\gamma$) will augment neutralino production.
- Decay produced $\widetilde{Z}_1$s at temp $T_D = \sqrt{\Gamma_{\tilde{a}} M_P}/(\pi^2 g_*(T_D)/90)^{1/4}$ can re-annihilate if $\langle\sigma v\rangle n_{\widetilde{Z}_1}(T_D) > H(T_D)$
- Axions produced as usual via vacuum misalignment (but evaluate in RD, MD or DD universe); can be diluted by entropy from axino decay
- Neglecting saxions, expect to work best for models with too low of usual thermal abundance (wino-like or higgsino-like neutralinos)
- HB, Lessa, Rajagopalan, Sreethawong, JCAP**1106** (2011) 031

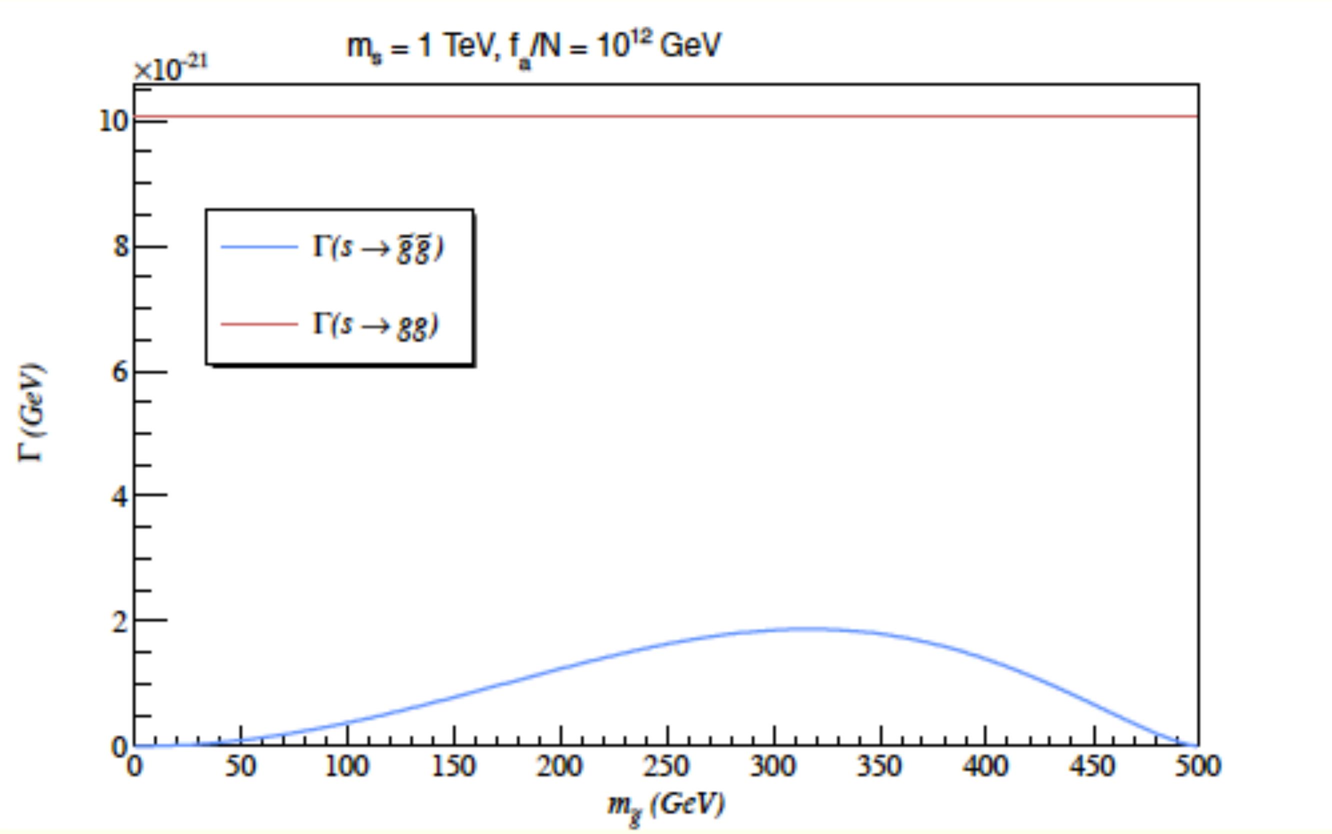
What about cosmology of saxion field $s(x)$?

- ★ HB, Kraml, Lessa, Sekmen [JCAP1104 (2011)039]
- ★ saxion production in early universe
  - Thermal production dominates at low f_a
  - production via coherent oscillations dominates at large f_a



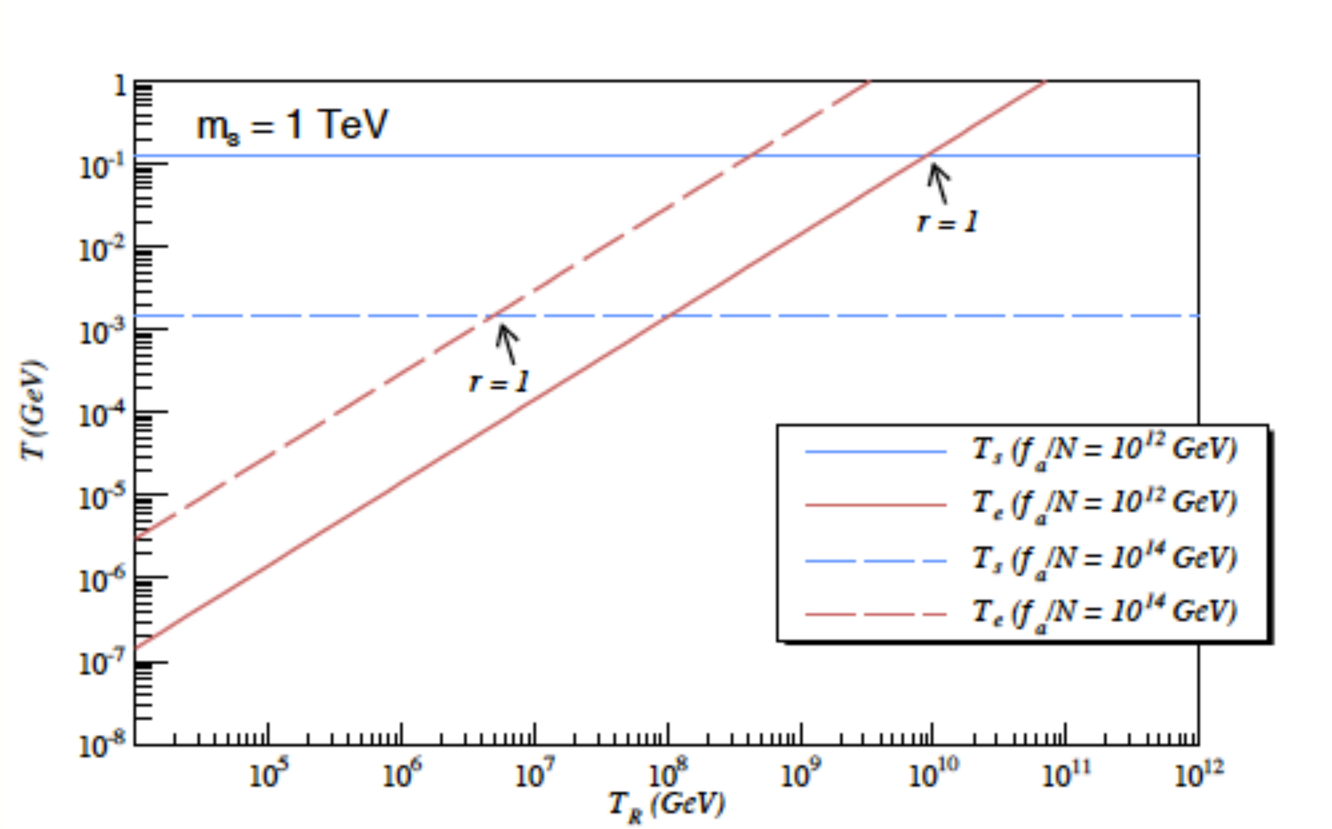
Saxion decay:

- $s \to gg, \tilde{g}\tilde{g}$; $s \to aa$ more model dependent, but may dominate
- $T_s =$ temp at which saxion entropy injection nearly complete
- $T_s \simeq 0.78 g_*^{-1/4} \sqrt{\Gamma_s M_{Pl}}$



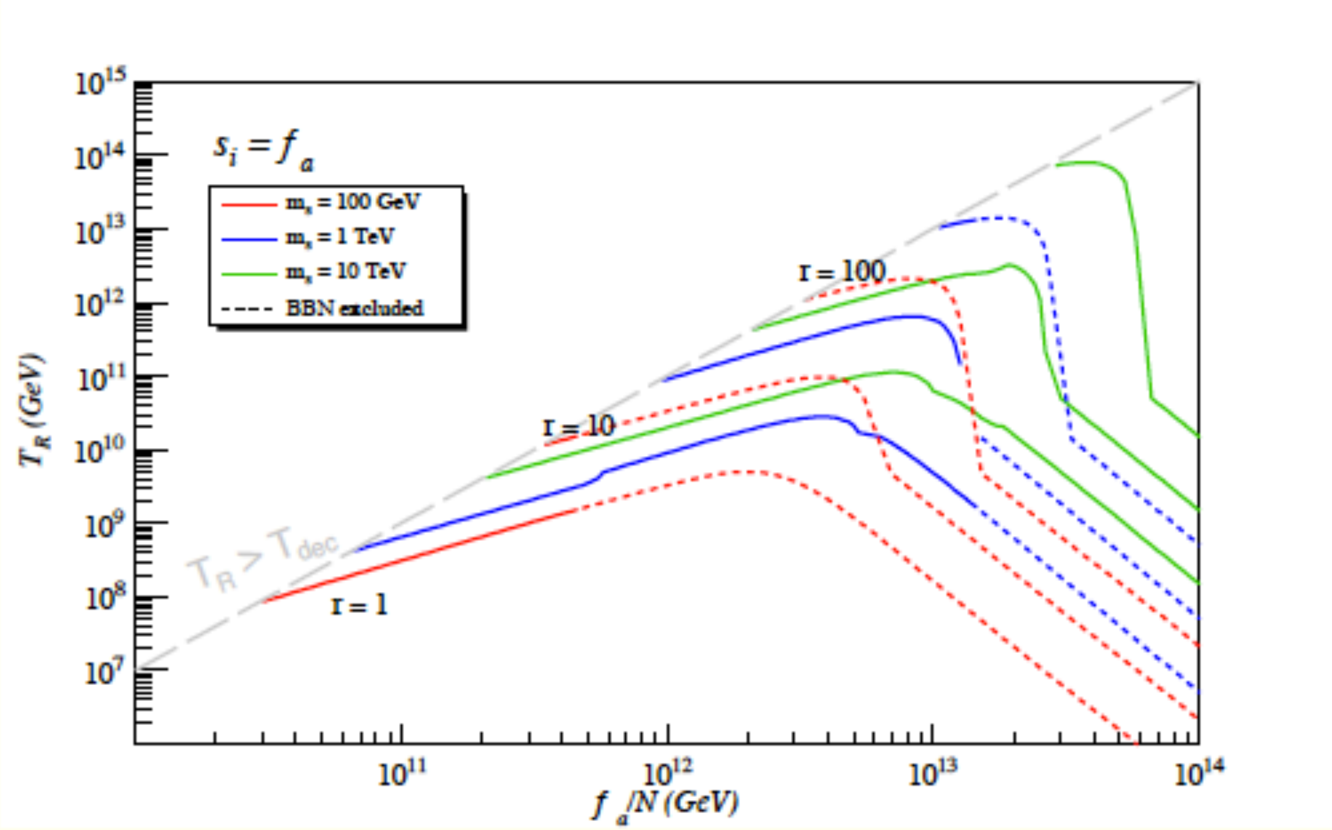
Saxion domination and entropy injection

- $T_e =$ temp at which saxion density equals radiation
- If $T_s < T_e$, then saxions may dominate universe
- Entropy from saxion decay: $r = S_f/S_i \simeq T_e/T_s$ (Scherrer, Turner)



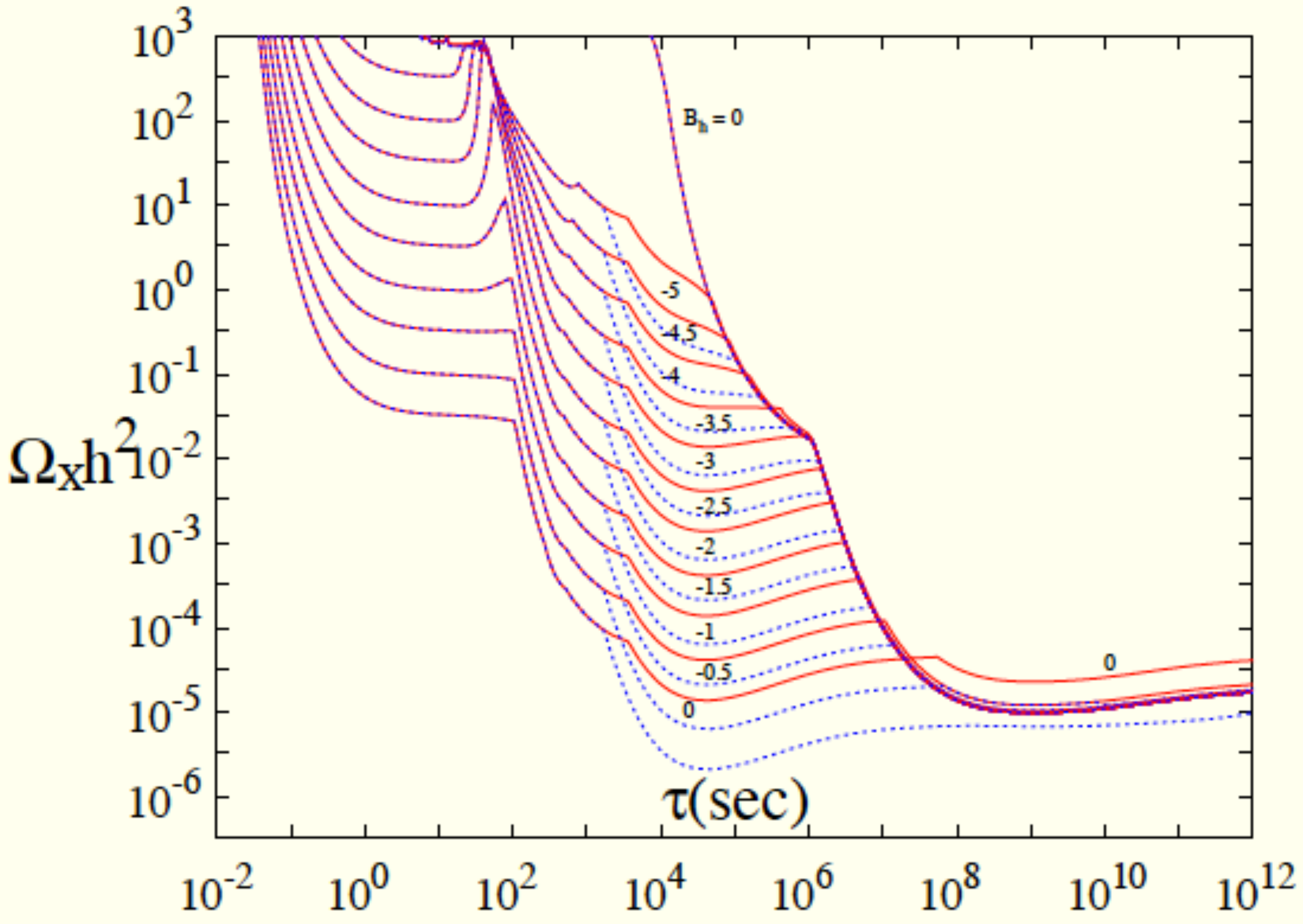
Dilution of relics due to saxion decay

- If $r > 1$, saxions can dominate universe
- Entropy injection may dilute relics (including baryon asymmetry!)
- Beware BBN constraints on late decaying particles (Jedamzik)
- Must calculate relic abundances in RD, MD or DPD universe



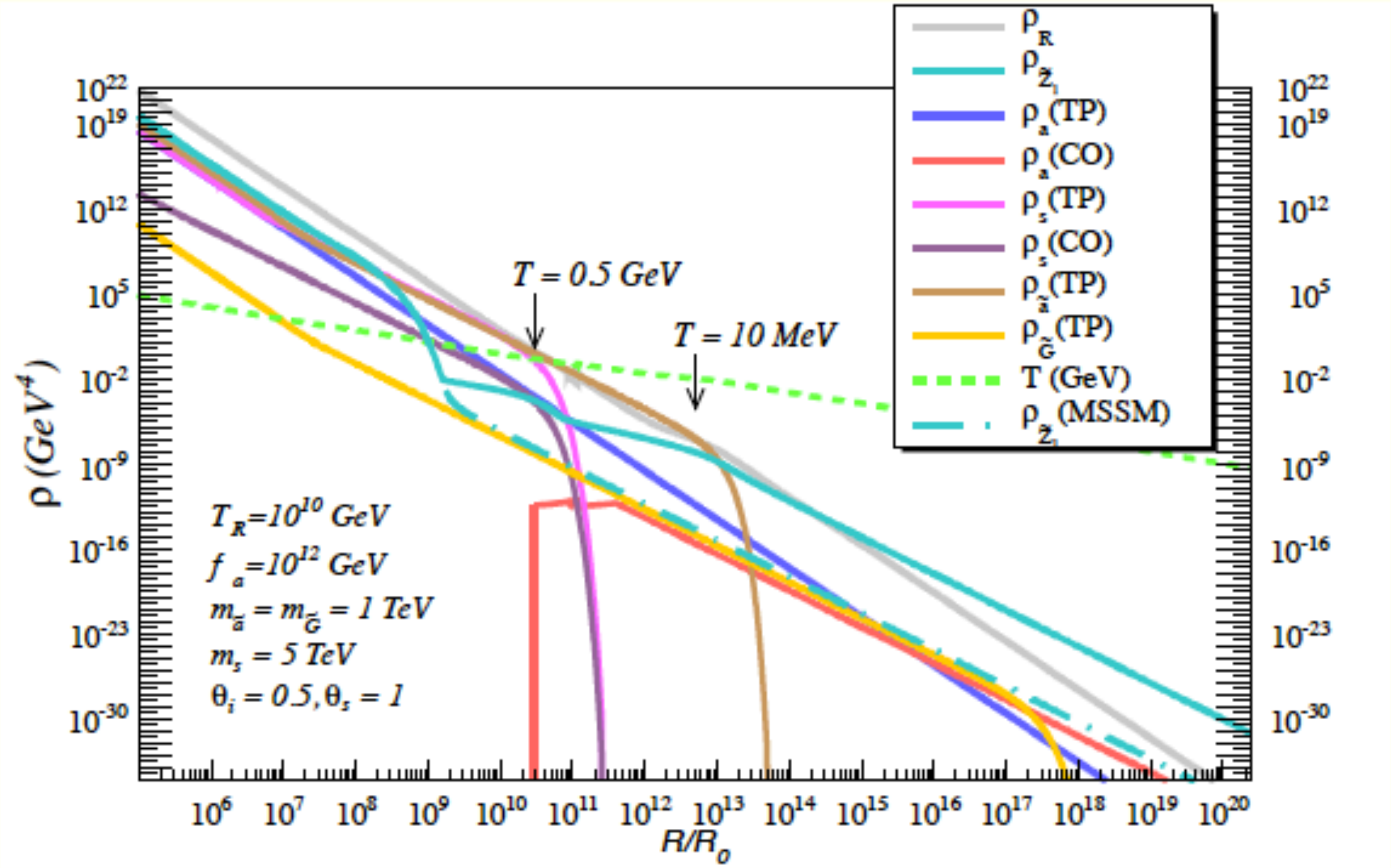
BBN constraints on late decaying neutrals (Jedamzik)

- ★ results for $m_X = 100$ GeV



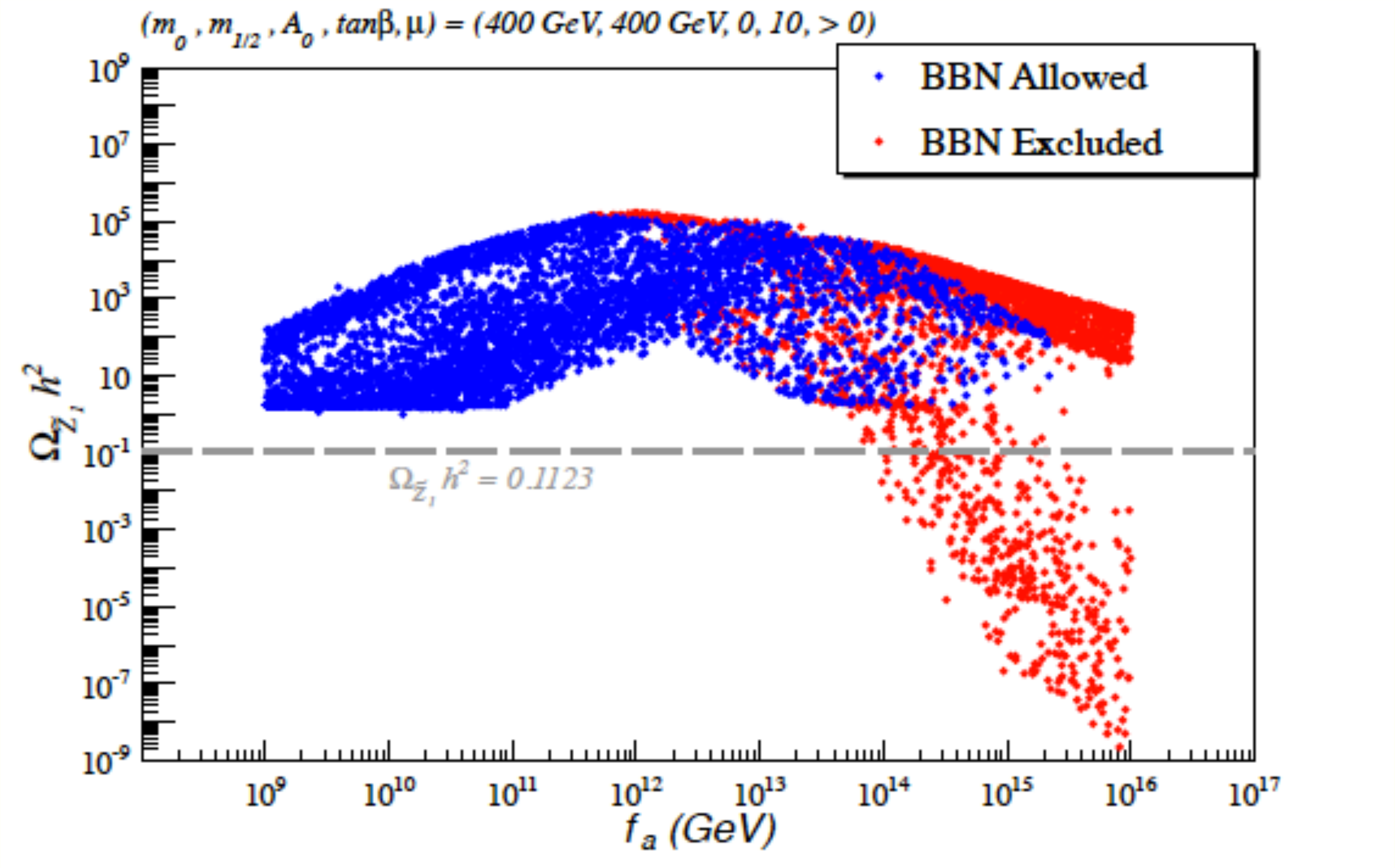
Coupled Boltzmann calculation of mixed $a/bino$ CDM

- Include $\langle\sigma v\rangle(T)$, neutralino production/entropy injection from both axino/saxion decay
- HB, A. Lessa, W. Sreethawong, JCAP**1201**(2012)036
- A. Lessa: Sakurai award 2012 for outstanding theory thesis



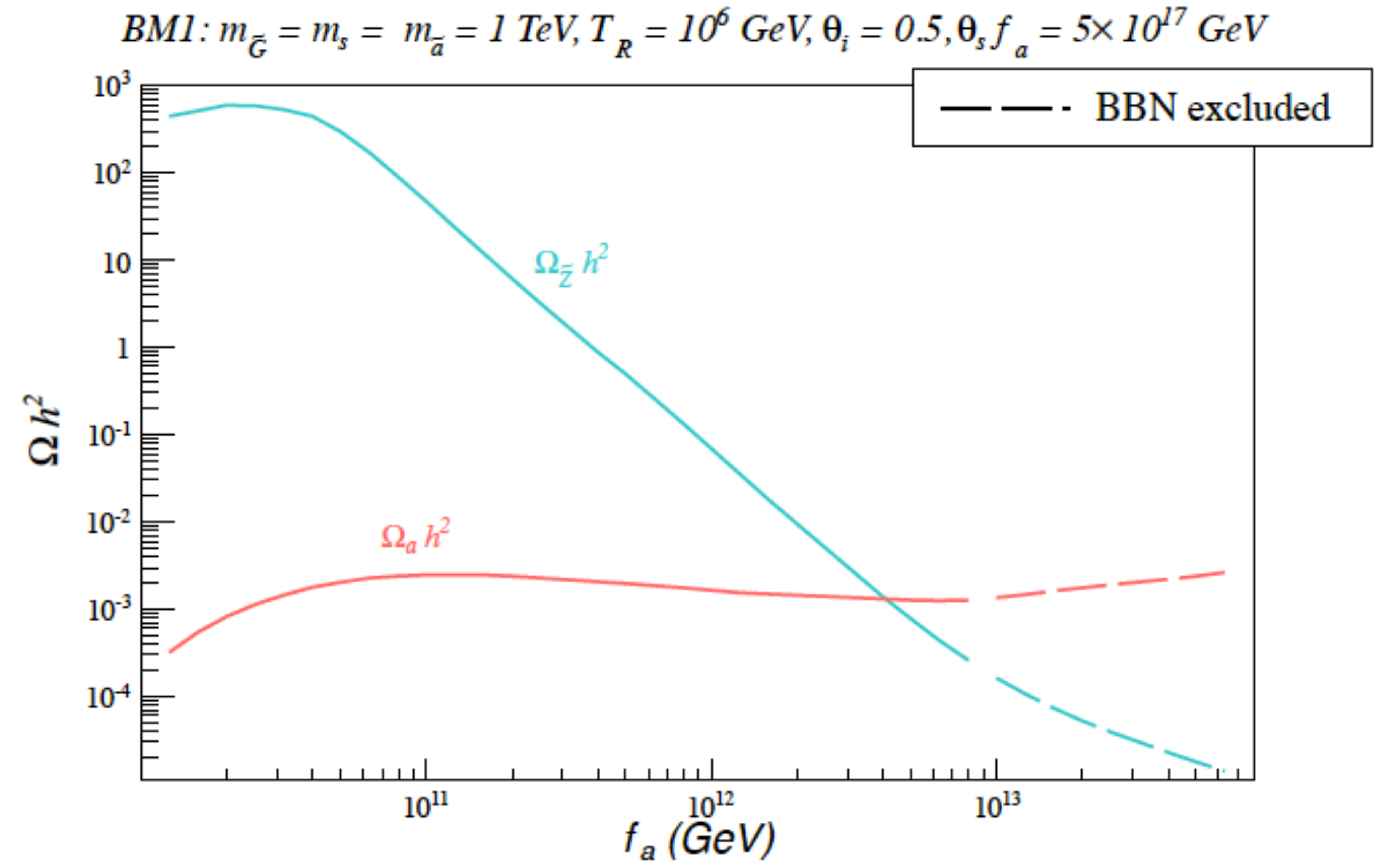
Mixed $a/bino$ CDM: coupled Boltzmann calculation

- saxion entropy versus gluino injection: $0.1 < s(x)/f_a < 10$ case
- only BBN challenged points have low enough relic density



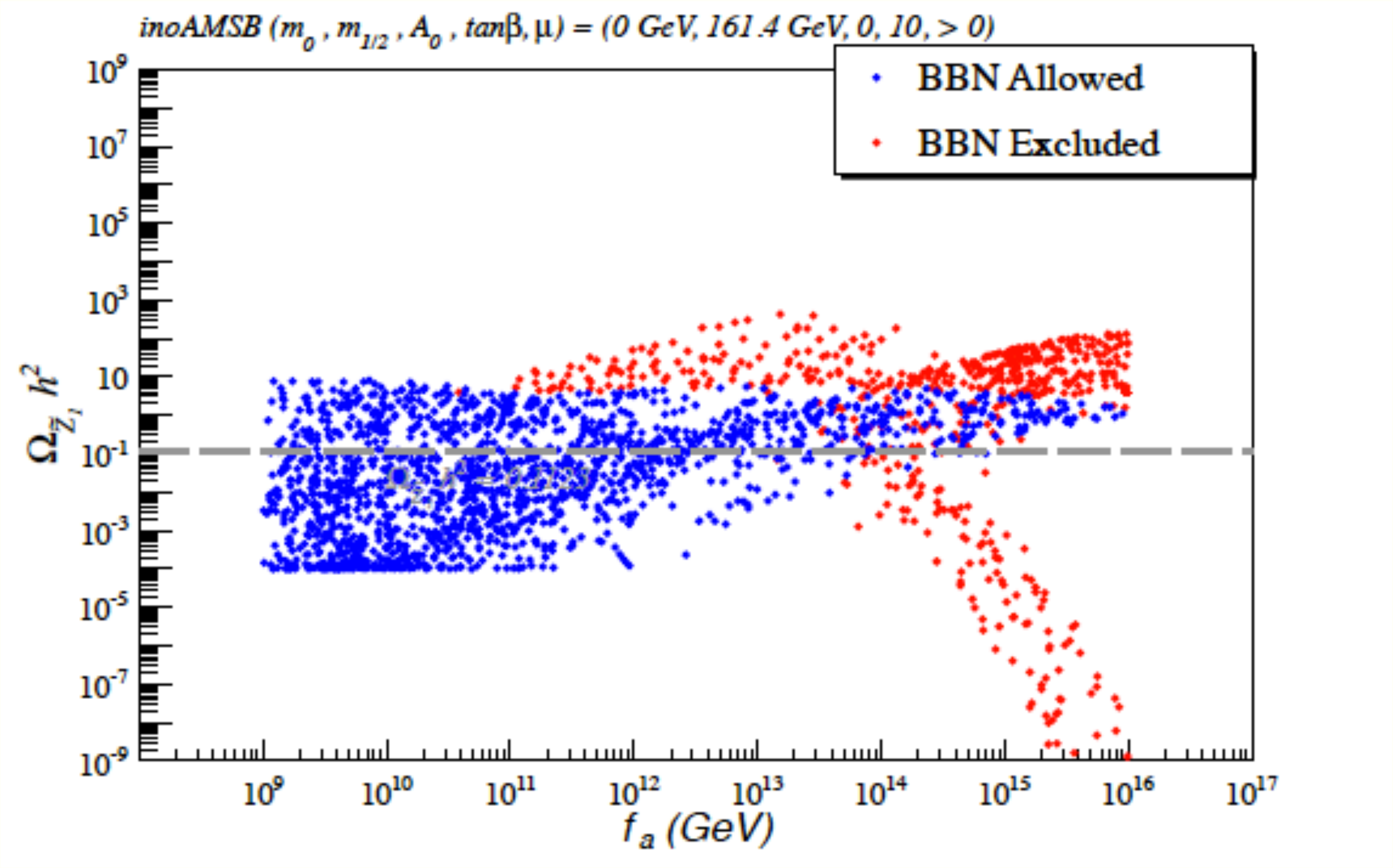
Large entropy dilution of all relics by saxion if $\cdots$

- $m_s < 2m_{\tilde{g}}$ so no $\widetilde{Z}_1$ production
- saxion field strength far higher than f_a

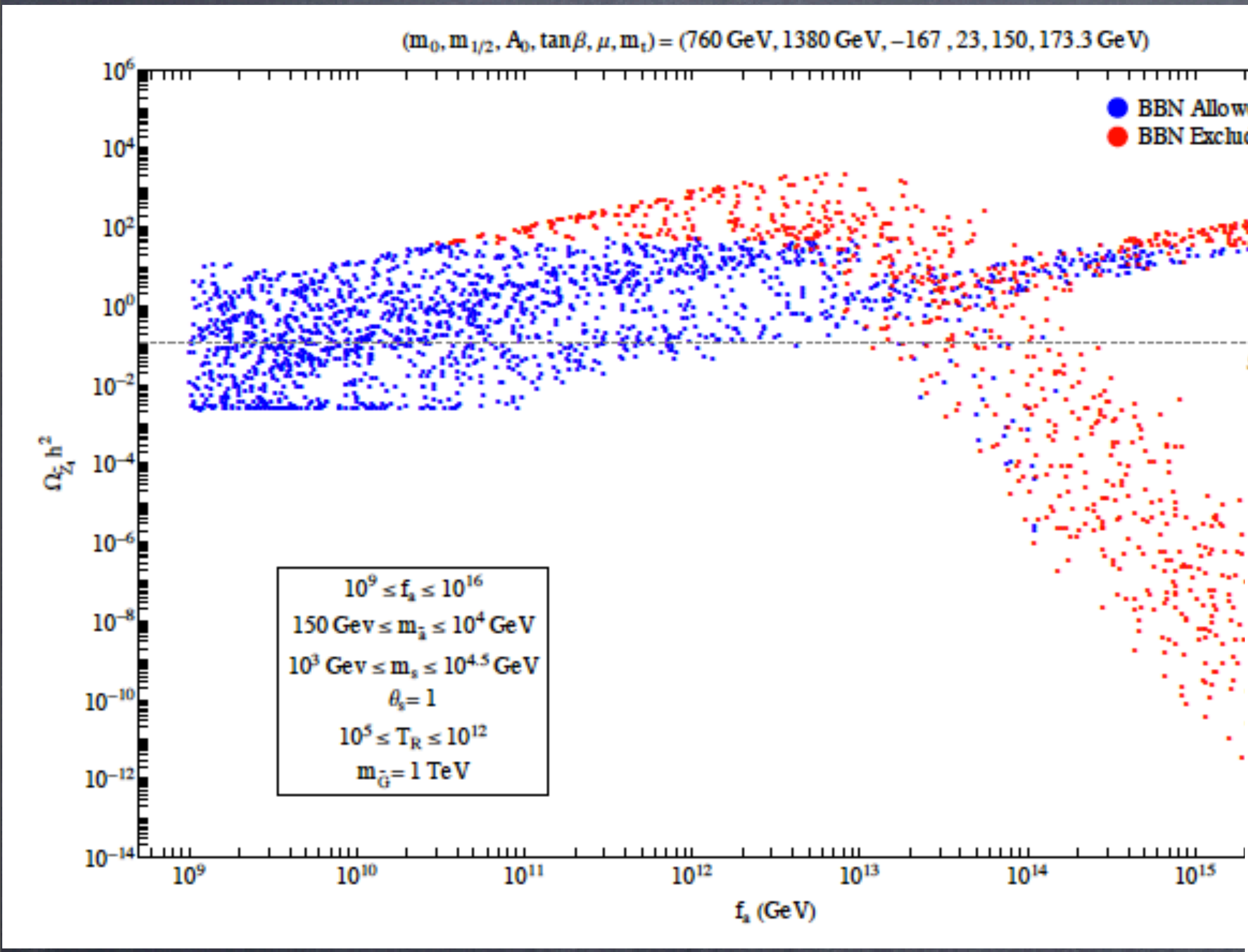


Mixed $a/wino$ CDM: AMSB

- can allow $f_a \sim 10^{14} - 10^{15}$ GeV!
- either neutralino or axion domination possible
- alternative to Moroi/Randall, Gelmini/Gondolo moduli decay scheme



Mixed higgsino-axion CDM in natural SUSY

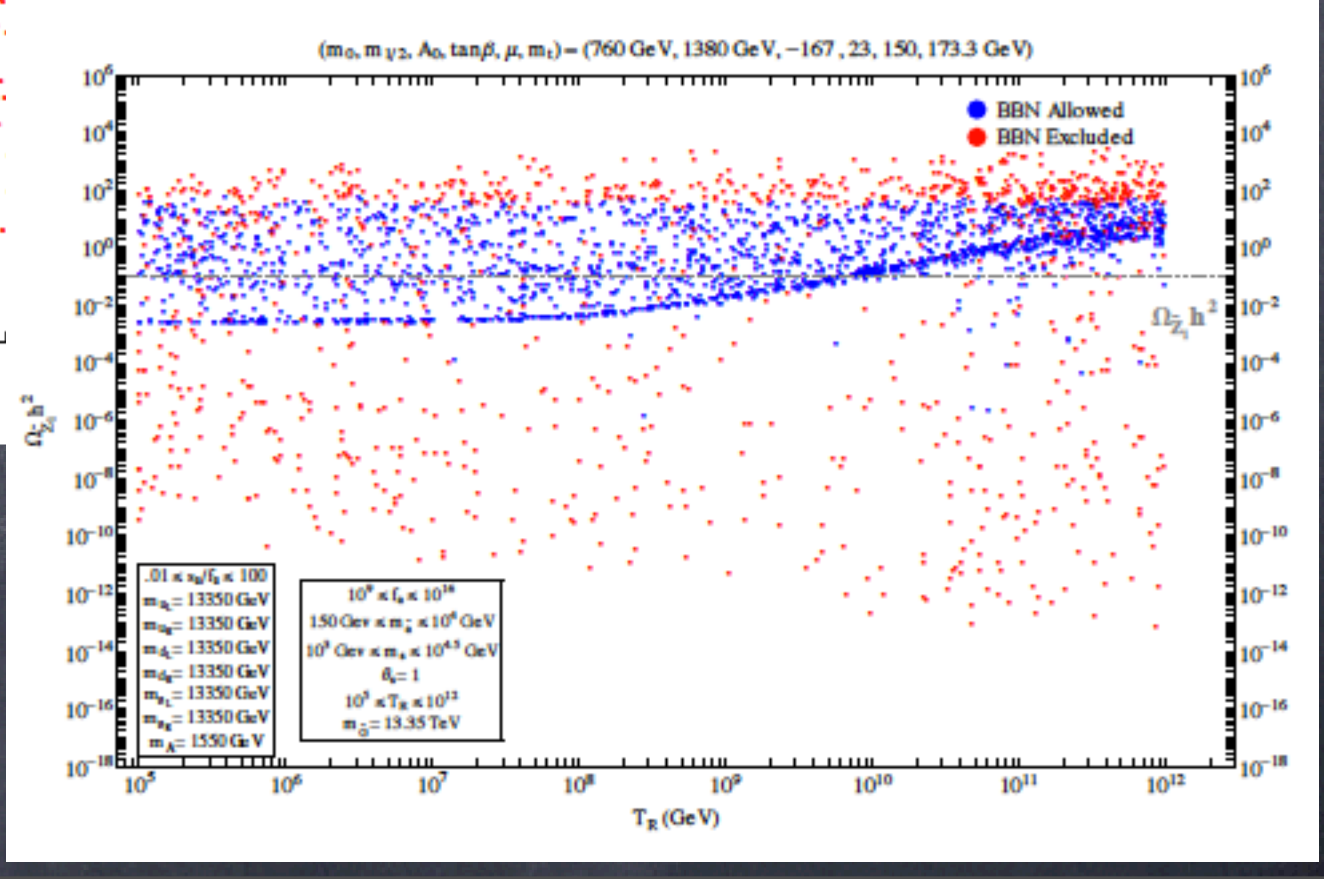


$f_a \sim 10^{14}$ GeV *allowed*!

HB, Lessa, Weis

$T_R \sim 10^5 - 10^{12}$ GeV *allowed*!

allows leptogenesis



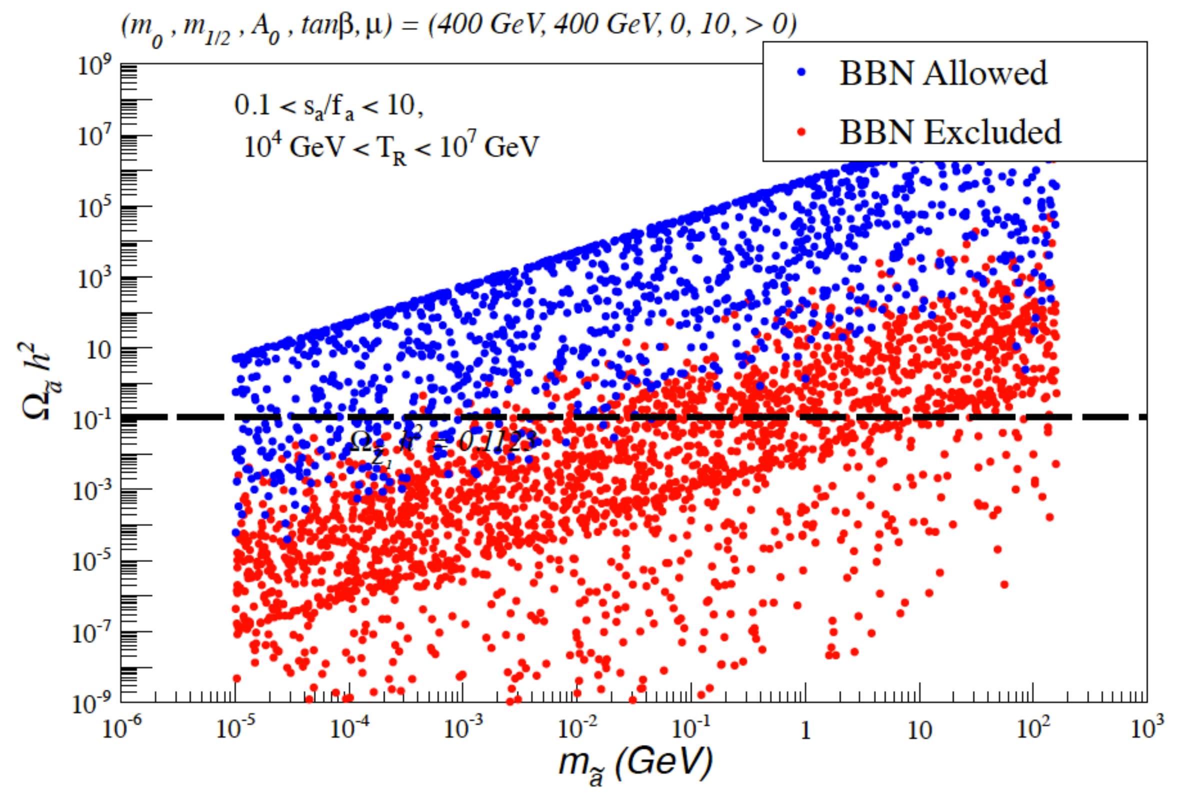
What if axino=LSP?

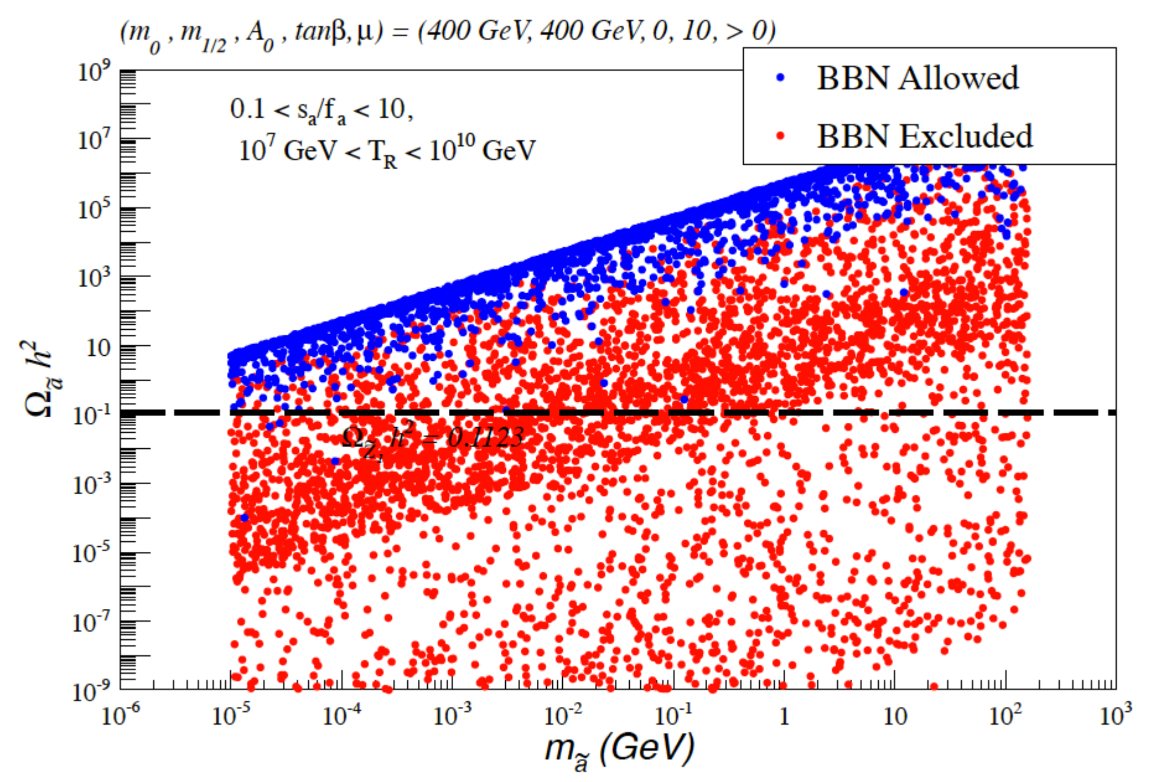
$$\Omega_{a\tilde{a}}h^2 = \Omega_a h^2 + \Omega_{\tilde{a}}^{\rm TP}h^2 + \Omega_{\tilde{a}}^{\widetilde{Z}}h^2 + \Omega_{\tilde{a}}^{\widetilde{G}}h^2$$

$$\Omega_{\tilde{a}}^{\widetilde{Z}}h^2 = \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}}\Omega_{\widetilde{Z}_1}^{TP}h^2$$

$$\Omega_{\tilde{a}}^{\widetilde{G}}h^2 = \frac{m_{\tilde{a}}}{m_{\widetilde{G}}}\Omega_{\widetilde{G}}^{TP}h^2$$

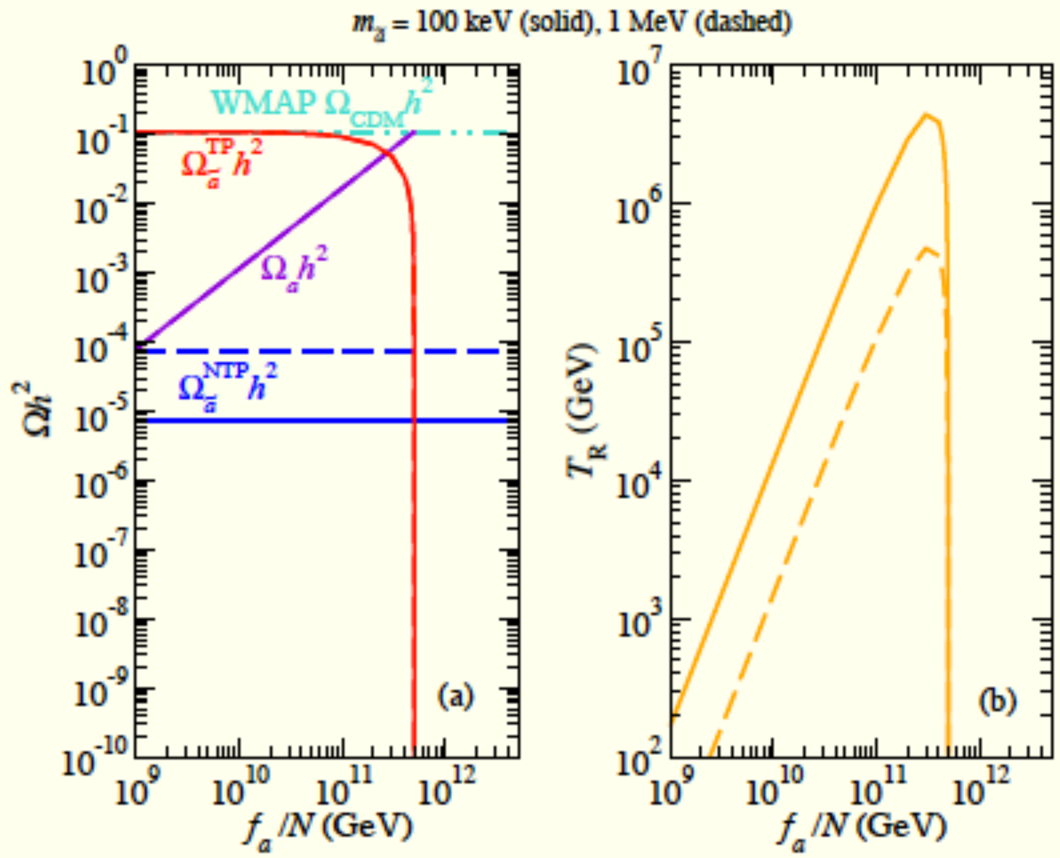
- Opportunity to greatly lower DM abundance in models with gross overabundance of thermally produced neutralinos
- But m(axino) required usually very small; conflict with expectations from SUGRA





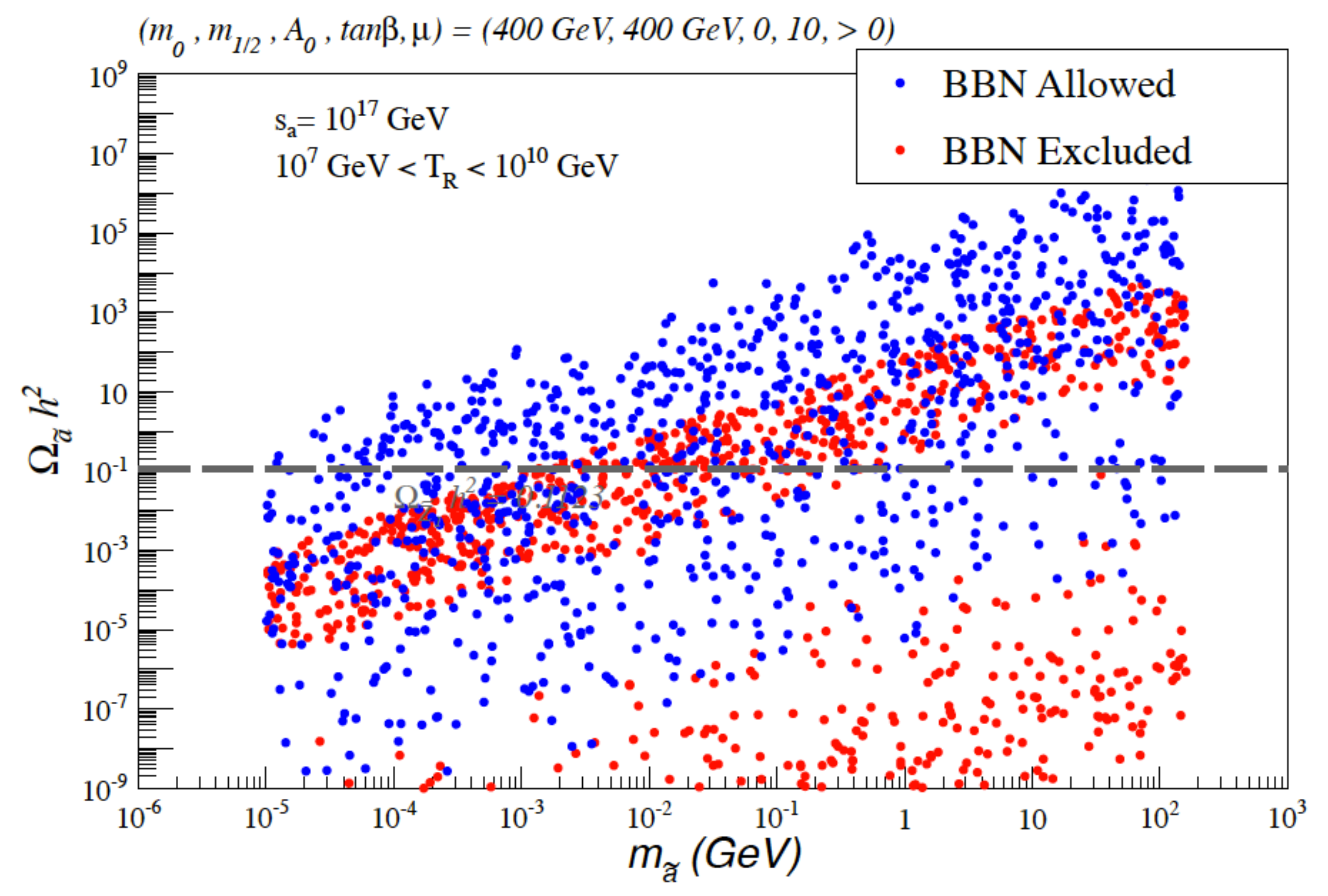
mSUGRA model with mixed axion/axino CDM: $m_{\tilde{a}}$ fixed

- ⋆ $(m_0, m_{1/2}, A_0, \tan\beta, sgn(\mu)) = (1000\ \mathrm{GeV}, 300\ \mathrm{GeV}, 0, 10, +1)$
- ⋆ $\Omega_a h^2 + \Omega_{\tilde{a}}^{TP} h^2 + \Omega_{\tilde{a}}^{NTP} h^2 = 0.11$
- ⋆ model with *mainly* axion CDM favored for large T_R!

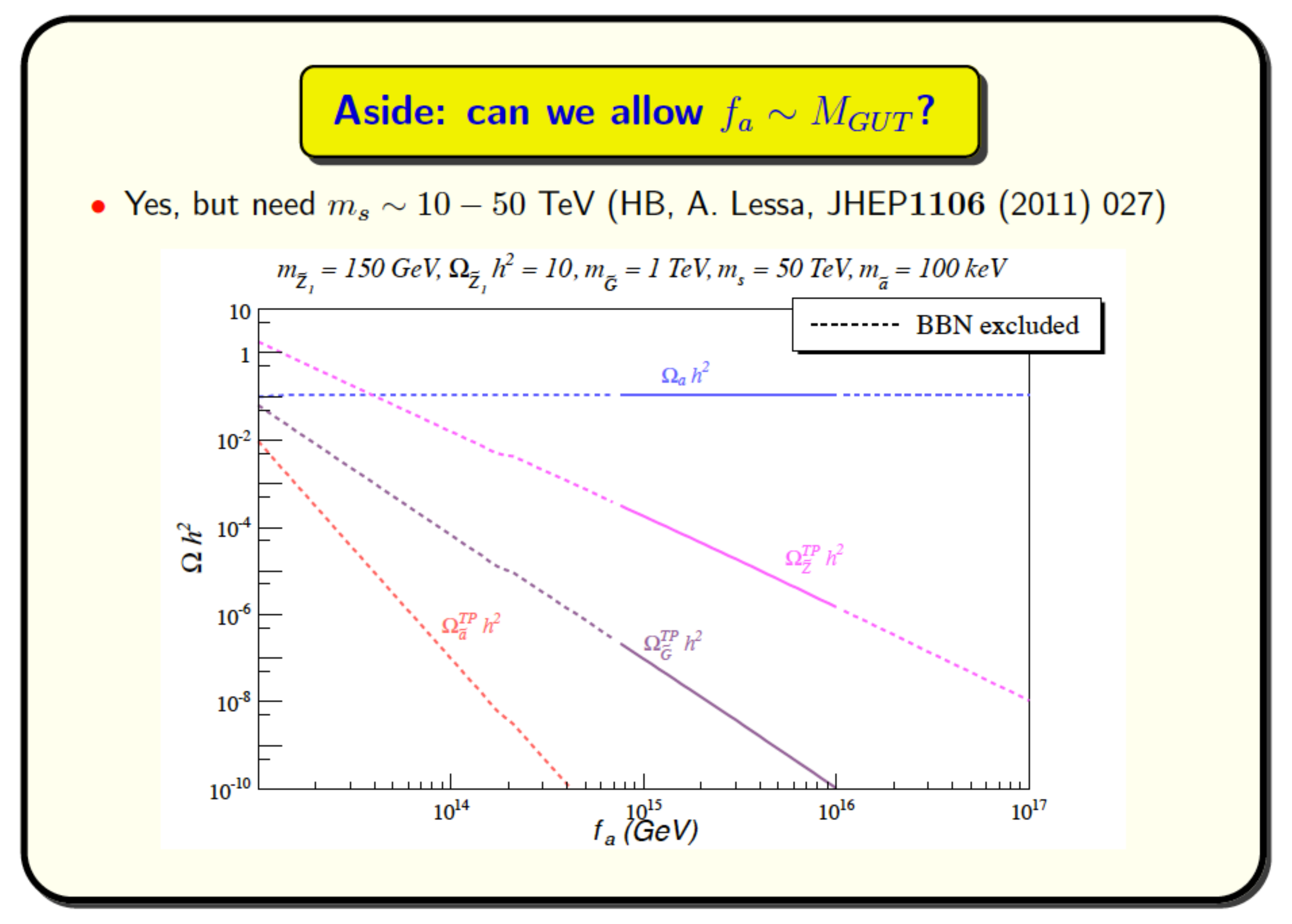


$m_{\tilde{a}}$ = 100 keV (solid), 1 MeV (dashed)

If we allow extreme entropy injection from very large saxion field strength, then most or all axino masses allowed:



Can even push PQ scale up to m (GUT) while avoiding BBN bounds:



Aside: can we allow $f_a \sim M_{GUT}$?

- Yes, but need $m_s \sim 10-50$ TeV (HB, A. Lessa, JHEP**1106** (2011) 027)

What will we learn from accelerators?

- LHC8 with ~15fb-1: Does the Higgs exist? Is its mass really ~125 GeV? This value lies in midst of narrow range predicted by MSSM. m(higgs)~125 in MSSM prefers m_t1>1 TeV and large mixing (A_t); there are additional contributions to mh in models such as NMSSM
- No Higgs signal at LHC effectively excludes SUSY unless baroque hiding mechanism...

- Is there any sign of SUSY? Some of the recent models (Natural SUSY, Kallosh-Linde, G2MSSM,...) can easily evade detection at LHC

- These same models tend to be accessible to a linear e+e- collider, due to spectrum of light higgsinos or possibly light winos:
Is the LHC the right machine for SUSY discovery or would ILC/CLIC do better?

- If SUSY is there, what type of SUSY? Is R-parity conserved? If not, then maybe axion=100% of CDM. If so, then get mixed axion-LSP CDM. Which is LSP?
- Neutralino, axino, gravitino, others...
- Axino=LSP, stau=NLSP: see F. Steffen talk
- Axino=LSP, neutralino=bino as NLSP then can diminish DM density but usually need m(axino)~MeV and low TR<10^5 GeV else overproduce DM; highest allowed TR values favor axion domination of CDM; such light axinos seem disfavored by SUGRA calculations

- Neutralino=LSP: get mixed axion-neutralino CDM; usually neutralino abundance is enhanced by thermal axino production and decay, so this tends to favor SUSY models which give rise to a standard thermal neutralino underabundance (e.g. neutralino=higgsino or wino)

- Can also diminish by entropy dilution from saxion production and decay, but must avoid BBN constraints: prefer high m(saxion), high s_i (saxion field strength) compared to f_a

- If SUSY is there, and so is axion, then much larger values of f_a are natural, and consequently the axion may exist in the 10^-6-10^-9 eV range, well below that which is currently being explored. The axion only makes up a portion of DM abundance, which may be axion or LSP dominated (unless RPV)

Wish list to experimentalists from theorists:

1. axion detectors that can probe much larger f_a all the way up to M_GUT; then if mixed axion-LSP DM, axions may only constitute a portion

2. OWL-type space-based satellite which could detect gamma ray depositions in atmosphere of tens of GeV energy coming from $\tilde{Z}_1 \to \gamma\tilde{a}$ originating from sparticle cascade decays when LHC is on; when LHC is turned off, signal vanishes.