

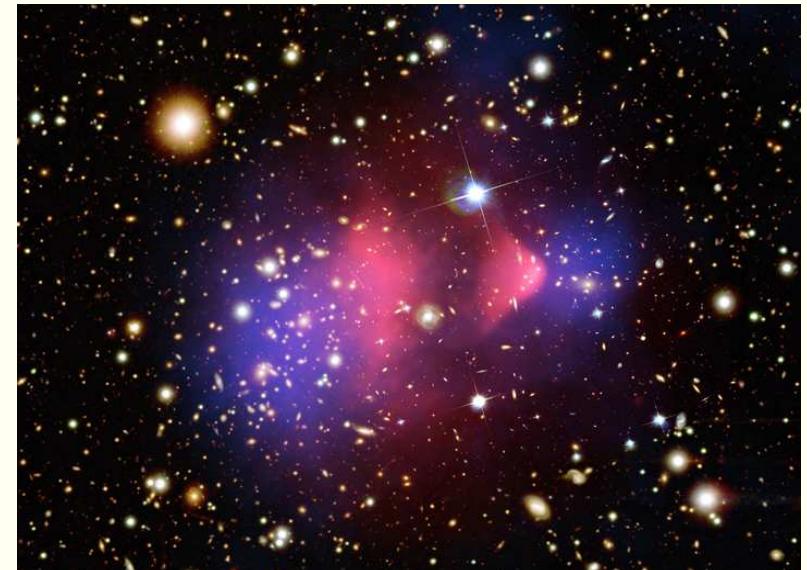
Axions, saxions and axinos: a new dark matter paradigm

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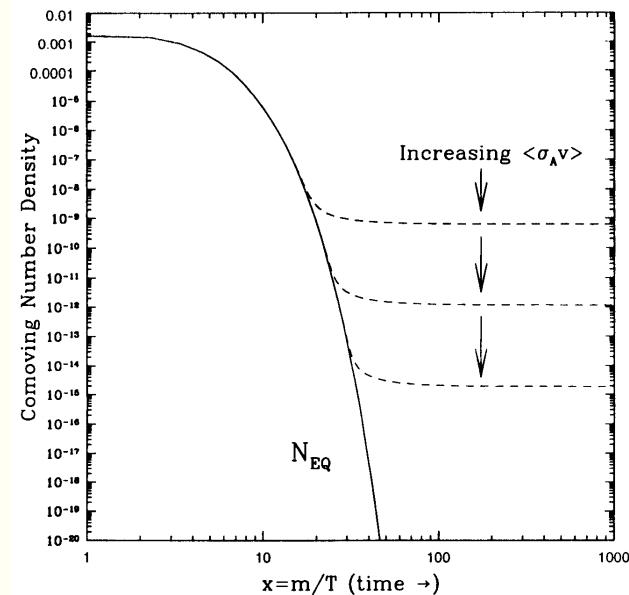
OUTLINE

- ★ SUSY WIMPs: miracle or not?
- ★ strong CP problem and PQWW solution
- ★ the PQMSSM
- ★ mixed axion/axino CDM
- ★ mixed axion/neutralino CDM
- ★ can $f_a \sim M_{GUT}$? YES! provided that...

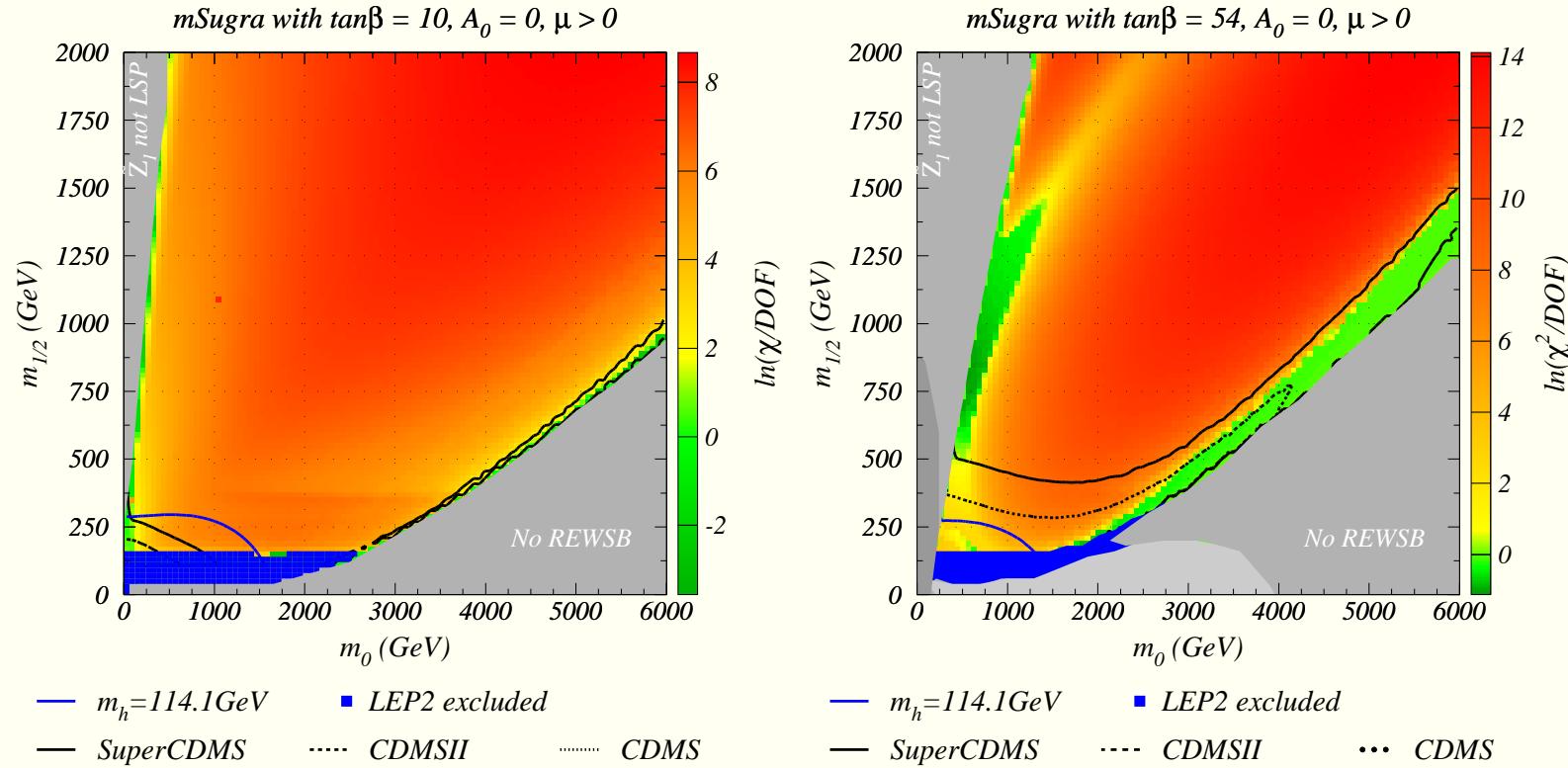


WIMPs: is there a WIMP miracle for SUSY?

- Weakly Interacting Massive Particles
- assume in thermal equil'n in early universe
- Boltzman eq'n:
 - $dn/dt = -3Hn - \langle\sigma v_{rel}\rangle(n^2 - n_0^2)$
- $\Omega h^2 = \frac{s_0}{\rho_c/h^2} \left(\frac{45}{\pi g_*} \right)^{1/2} \frac{x_f}{M_{Pl}} \frac{1}{\langle\sigma v\rangle}$
- $\sim \frac{0.1 \text{ pb}}{\langle\sigma v\rangle} \sim 0.1 \left(\frac{m_{wimp}}{100 \text{ GeV}} \right)^2$
- thermal relic \Rightarrow new physics at M_{weak} !
- does this work for SUSY neutralinos?



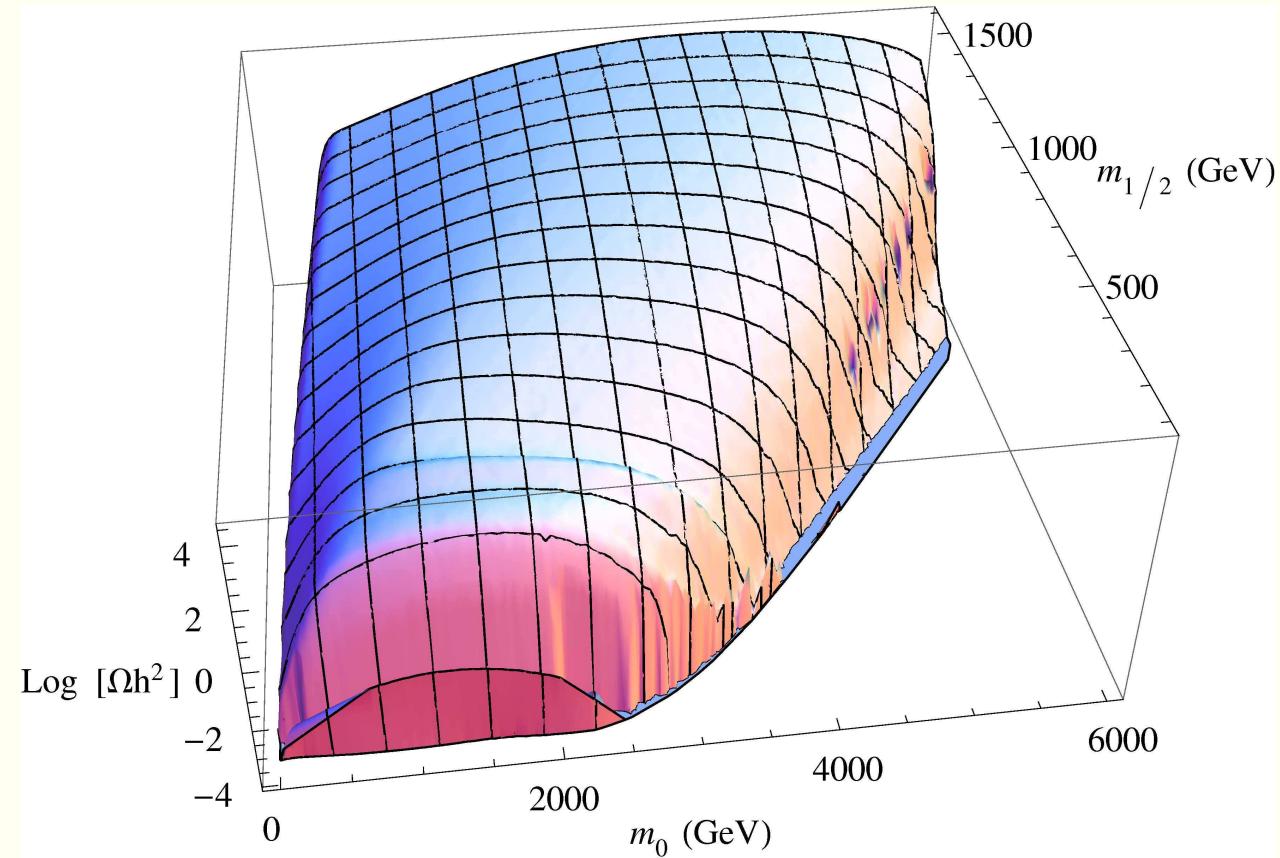
χ^2 fit of mSUGRA to $\Omega_{\tilde{Z}_1} h^2$, $b \rightarrow s\gamma$ and $(g - 2)_\mu$



- HB, C. Balazs: JCAP 0305, 006 (2003)
- (numerous other recent χ^2 , MCMC fits to find preferred regions)

$\Omega_{\tilde{Z}_1} h^2$ as surface in m_0 vs. $m_{1/2}$ space

- $\tan \beta = 10, A_0 = 0, \mu > 0$ (HB, A. Box)

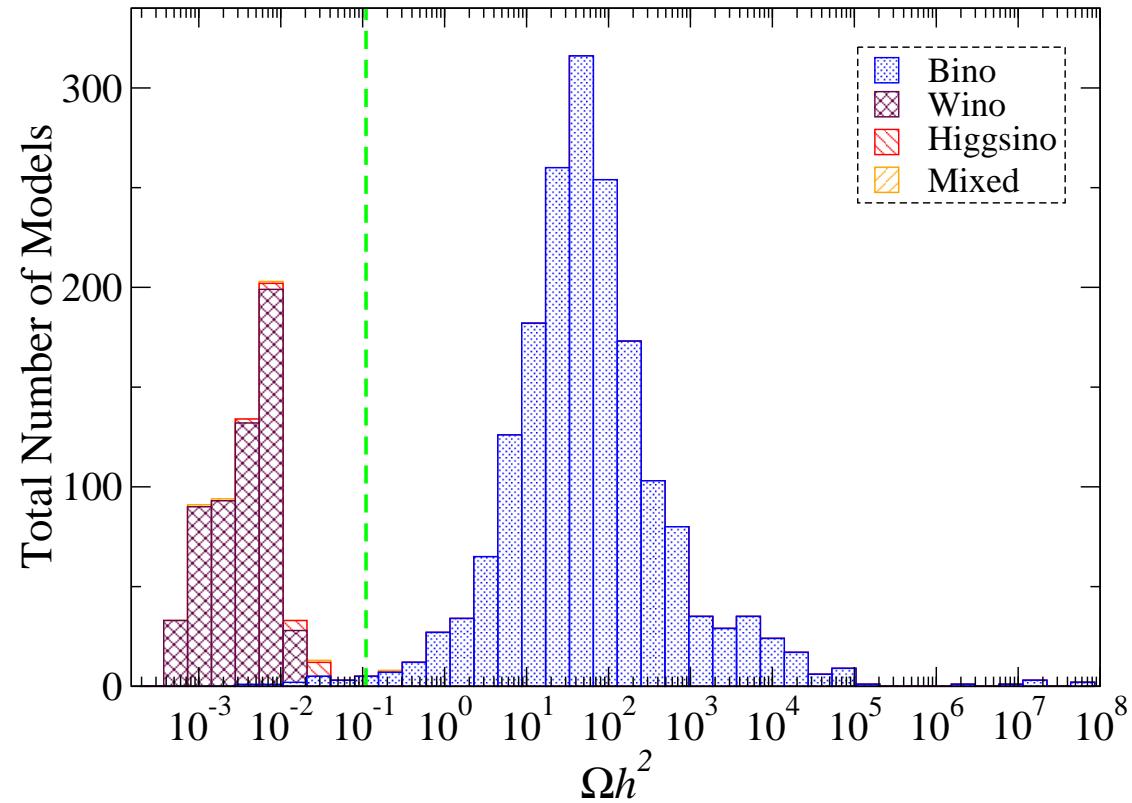


General scan over 19 param. MSSM

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

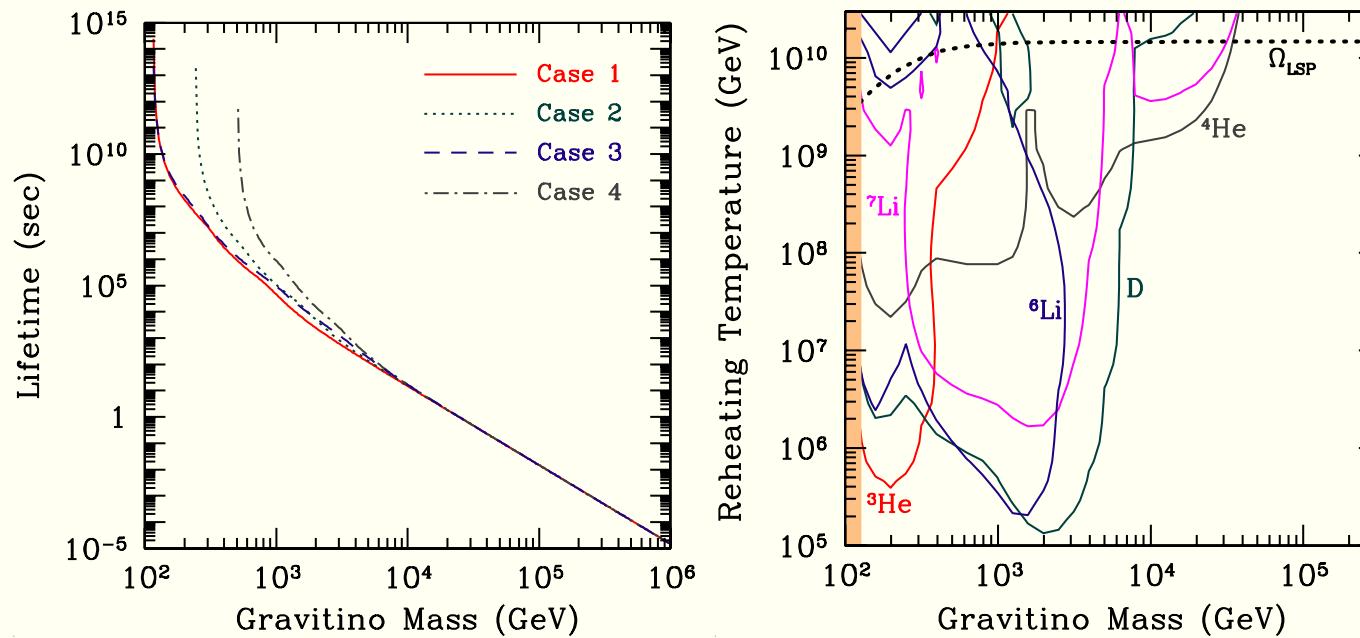
Why WIMP miracle really is a miracle for SUSY

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



Gravitinos: spin- $\frac{3}{2}$ partner of graviton

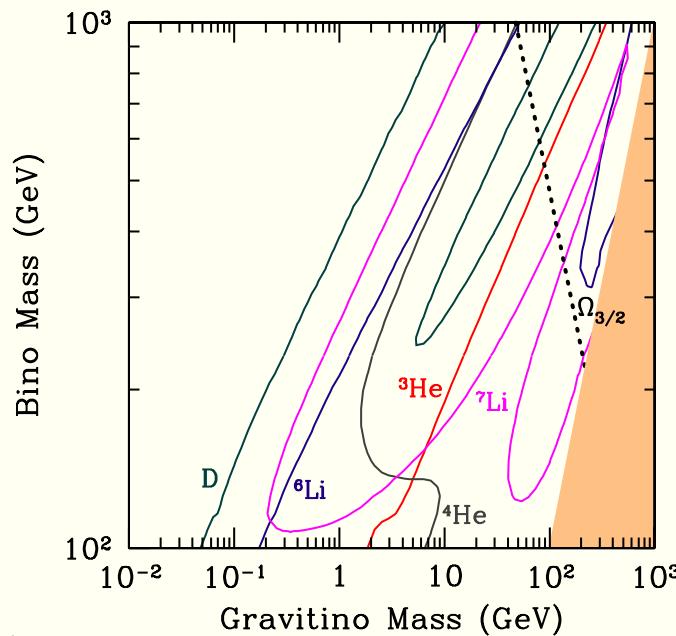
- gravitino problem in generic SUGRA models: overproduction of \tilde{G} followed by late \tilde{G} decay can destroy successful BBN predictions unless $T_R \lesssim 10^5$ GeV



(see Kawasaki, Kohri, Moroi, Yotsuyanagi; Cybert, Ellis, Fields, Olive; Jedamzik)

Gravitinos as dark matter: again the gravitino problem

- neutralino production in generic SUGRA models: followed by late time $\tilde{Z}_1 \rightarrow \tilde{G} + X$ decays can destroy successful BBN predictions:



(see Kawasaki, Kohri, Moroi, Yotsuyanagi)

Origin of 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: π_s 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 $\Rightarrow \mathcal{L} \ni \text{Arg det} M \frac{g_s^2}{32\pi} F_A^{\mu\nu} \tilde{F}_{A\mu\nu}$
 - $\bar{\theta} = \theta + \text{Arg det} M$
- ★ 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 $\rightarrow 0$; strong CP problem solved!
 - $m_a^2 = \langle \frac{\partial^2 V_{eff}}{\partial a^2} \rangle$ with $m_a \sim 6 \text{ } \mu\text{eV} \frac{10^{12} \text{ GeV}}{f_a}$

Axion cosmology

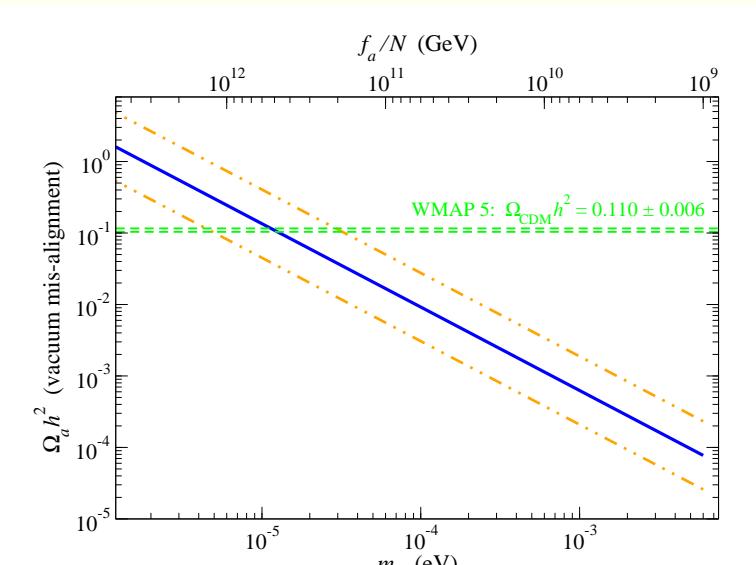
- ★ Axion field eq'n of motion: $\theta = a(x)/f_a$

- $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2} \frac{\partial V(\theta)}{\partial \theta} = 0$
- $V(\theta) = m_a^2(T)f_a^2(1 - \cos \theta)$
- 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

$$★ \Omega_a h^2 \sim \frac{1}{2} \left[\frac{6 \times 10^{-6} eV}{m_a} \right]^{7/6} \theta_i^2 h^2$$

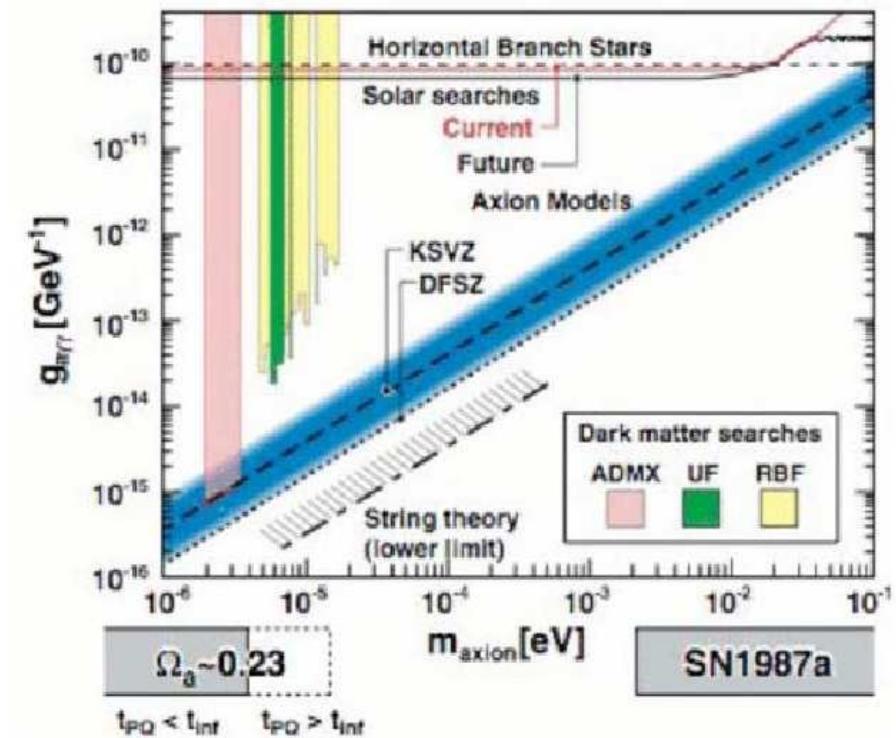
- ★ astro bound: stellar cooling $\Rightarrow f_a \gtrsim 10^9 GeV$



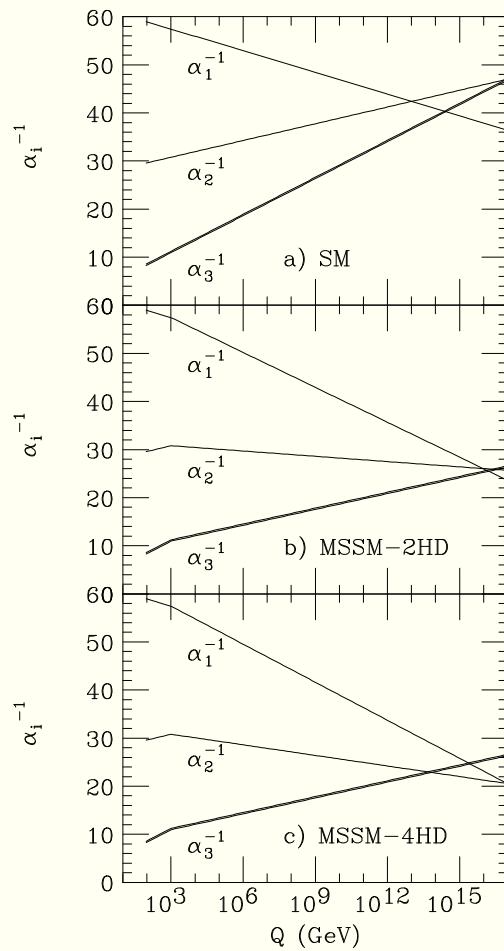
Axion microwave cavity searches

★ ongoing searches: ADMX experiment

- Livermore \Rightarrow U Wash.
- Phase I: probe KSVZ
for $m_a \sim 10^{-6} - 10^{-5}$ eV
- Phase II: probe DFSZ
for $m_a \sim 10^{-6} - 10^{-5}$ eV
- beyond Phase II:
probe higher values m_a

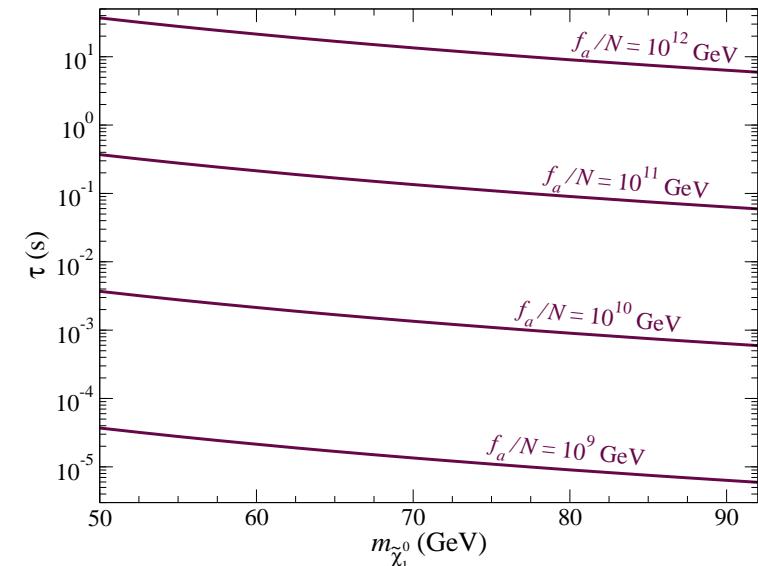


We also know MSSM (plus gauge singlets) is compelling
effective theory between M_{weak} and M_{GUT}



PQMSSM: Axions + SUSY \Rightarrow mixed $a\tilde{a}$ dark matter?

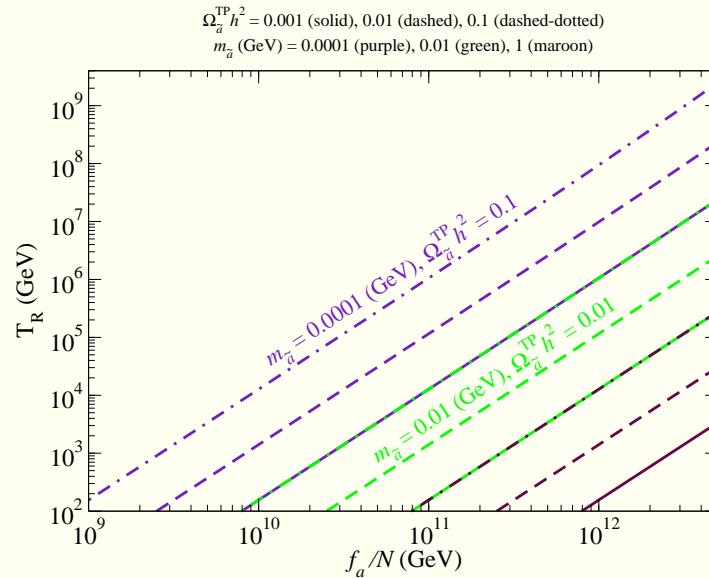
- axino is spin- $\frac{1}{2}$ element of axion supermultiplet (R -odd; can be LSP)
 - Raby, Nilles, Kim
 - Rajagopal, Wilczek, Turner
- $m_{\tilde{a}}$ model dependent: keV \rightarrow TeV
- $\tilde{Z}_1 \rightarrow \tilde{a}\gamma$
- non-thermal \tilde{a} production via \tilde{Z}_1 decay:
- axinos inherit neutralino number density
- $\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1} h^2$:
 - Covi, Kim, Kim, Roszkowski



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
- ★ CKKR, BS, Strumia calculation:

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



Various leptogenesis scenarios

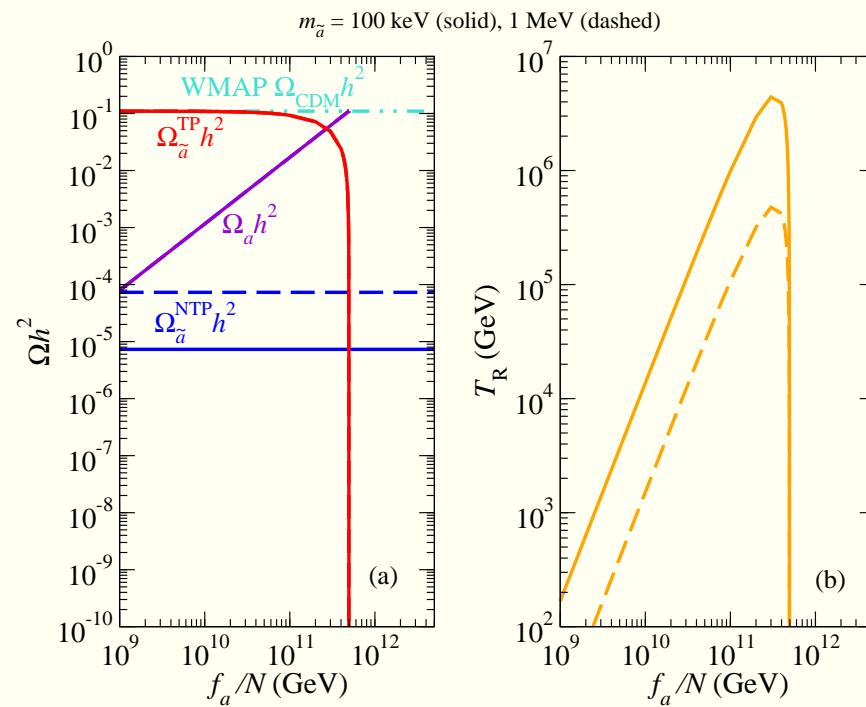
- WMAP observation: $n_b/s \sim 0.9 \times 10^{-10}$: how to generate?
- SM EW baryogenesis ruled out; SUSY EWB nearly so
- *Thermal* leptogenesis very attractive but needs $T_R \gtrsim m_{N_1} \gtrsim 2 \times 10^9$ GeV (Buchmuller, Plumacher); Naive conflict with upper bound on T_R from BBN/gravitino problem
- Alternatively, one may have non-thermal leptogenesis where inflaton $\phi \rightarrow N_i N_i$ decay (Lazarides, Shafi; Kumekawa, Moroi, Yanagida)
- additional source of N_i in early universe allows lower T_R :

$$\frac{n_B}{s} \simeq 8.2 \times 10^{-11} \times \left(\frac{T_R}{10^6 \text{ GeV}} \right) \left(\frac{2m_{N_1}}{m_\phi} \right) \left(\frac{m_{\nu_3}}{0.05 \text{ eV}} \right) \delta_{eff} \quad (2)$$

- Also, AD leptogenesis in $\phi = \sqrt{H\ell}$ D -flat direction: wide range of T_R allowed (Dine, Randall, Thomas; Murayama, Yanagida)

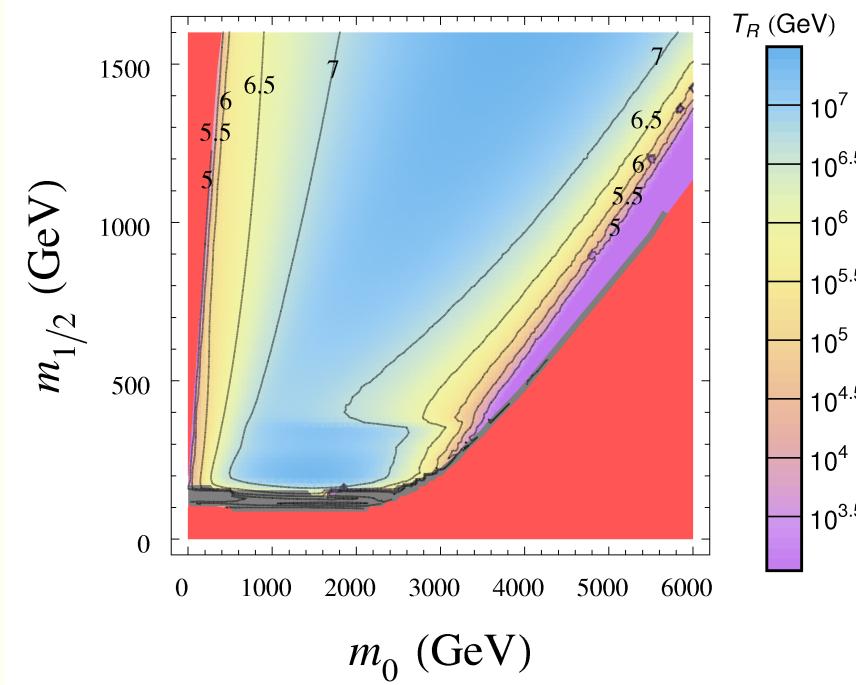
mSUGRA model with mixed axion/axino CDM: $m_{\tilde{a}}$ fixed

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

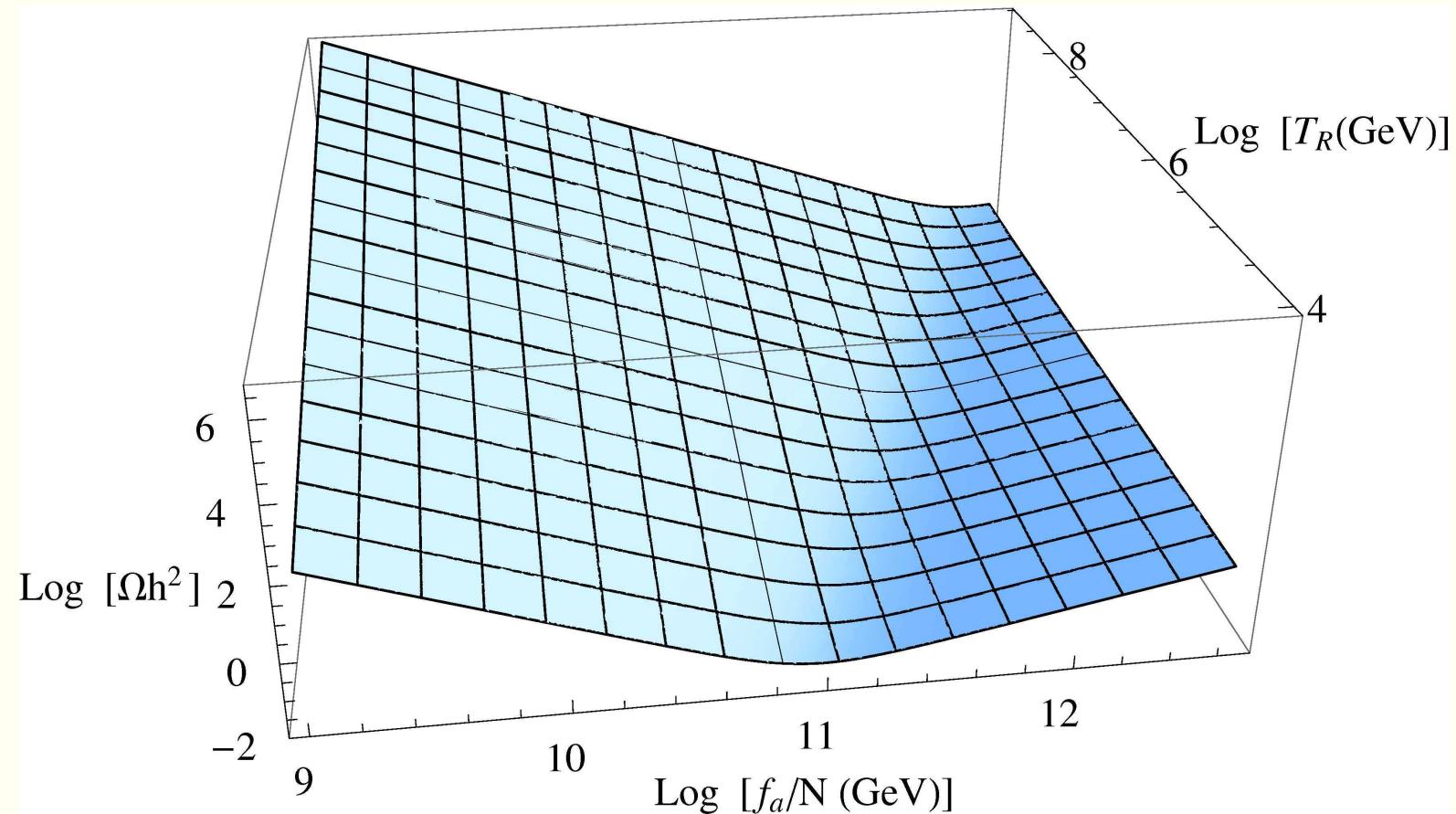


mSUGRA p-space with mainly axion cold DM

- ★ contours of $\log_{10} T_R$: mSUGRA w/ $\tan \beta = 10$, $A_0 = 0$
- ★ $T_R \gtrsim 10^6$ consistent with non-thermal leptogenesis
- ★ most dis-favored mSUGRA regions with neutralino DM are most favored by mSUGRA with mainly axion DM! (HB, Box, Summy)



Axion/axino relic density in mSUGRA: low fine-tune!

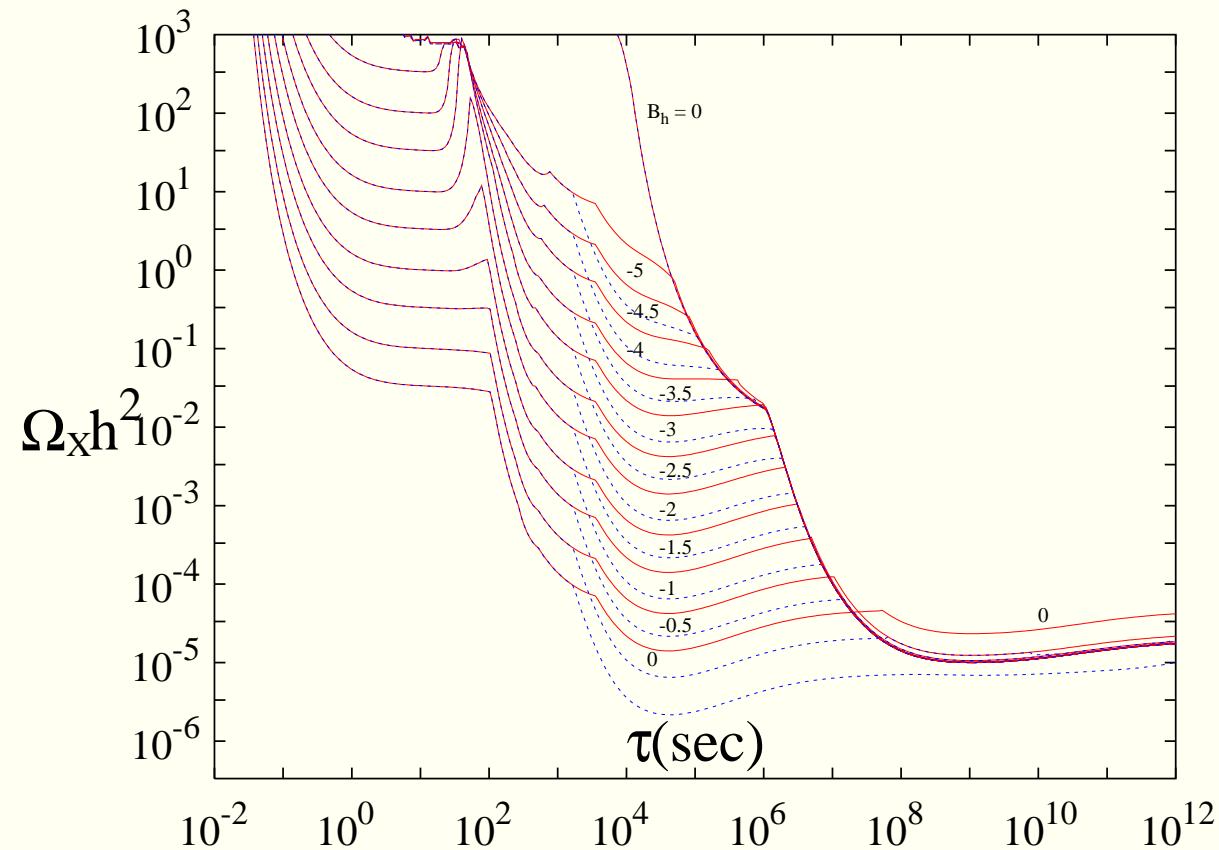


Reconcile *thermal leptogenesis* with \tilde{G} problem?

- ★ need $m_{\tilde{G}} \gtrsim 20 - 30$ TeV to avoid BBN constraints
 - Yukawa-unified SUSY, Effective SUSY, AMSB, mirage unification
- ★ invoke $a\tilde{a}$ DM with $\tilde{a} = LSP$ to avoid overproduction of \tilde{Z}_1 s
- ★ suppress thermal axino overproduction with large $f_a/N \gtrsim 10^{12}$ GeV
- ★ suppress axion overproduction via misalignment angle $\theta_i \lesssim 1$
- ★ avoid BBN constraints on late decaying $\tilde{Z}_1 \rightarrow \tilde{a} + \text{hadrons}$
 - low rate \tilde{Z}_1 production $\Omega_{\tilde{Z}_1} \lesssim 0.1$
 - bino-like $\tilde{Z}_1 \rightarrow \gamma\tilde{a}$ with $\tau(\tilde{Z}_1) \lesssim 200$ sec.
- ★ Does it work?

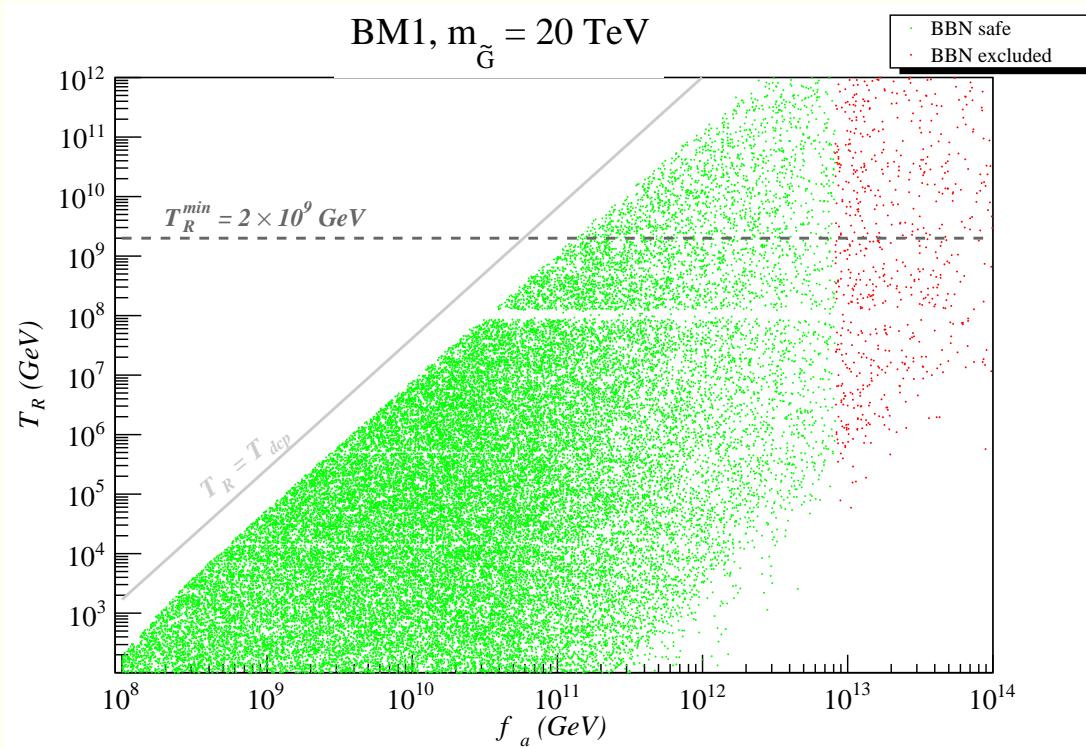
BBN constraints on late decaying neutrals (Jedamzik)

- ★ results for $m_X = 100$ GeV



Scan over PQMSSM parameters for Eff. SUSY model

- ★ HB, Kraml, Lessa, Sekmen JCAP1011 (2010) 040
- ★ (also works well for Mirage Mediation)

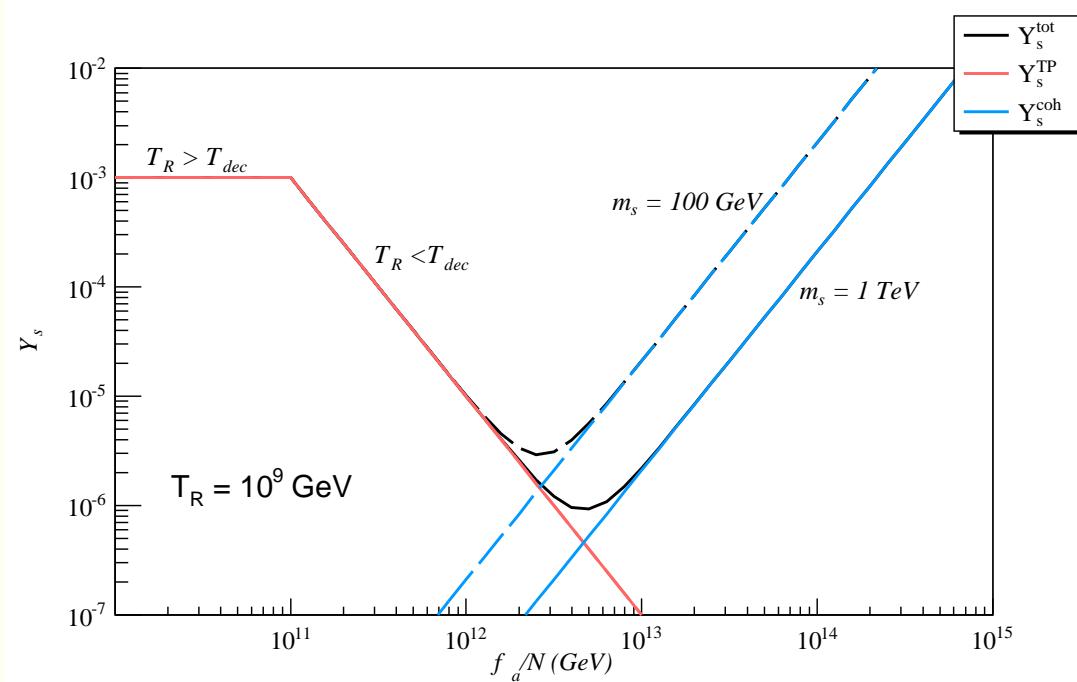


What about cosmology of saxion field $s(x)$?

★ HB, Kraml, Lessa, Sekmen [JCAP1104 (2011)039]

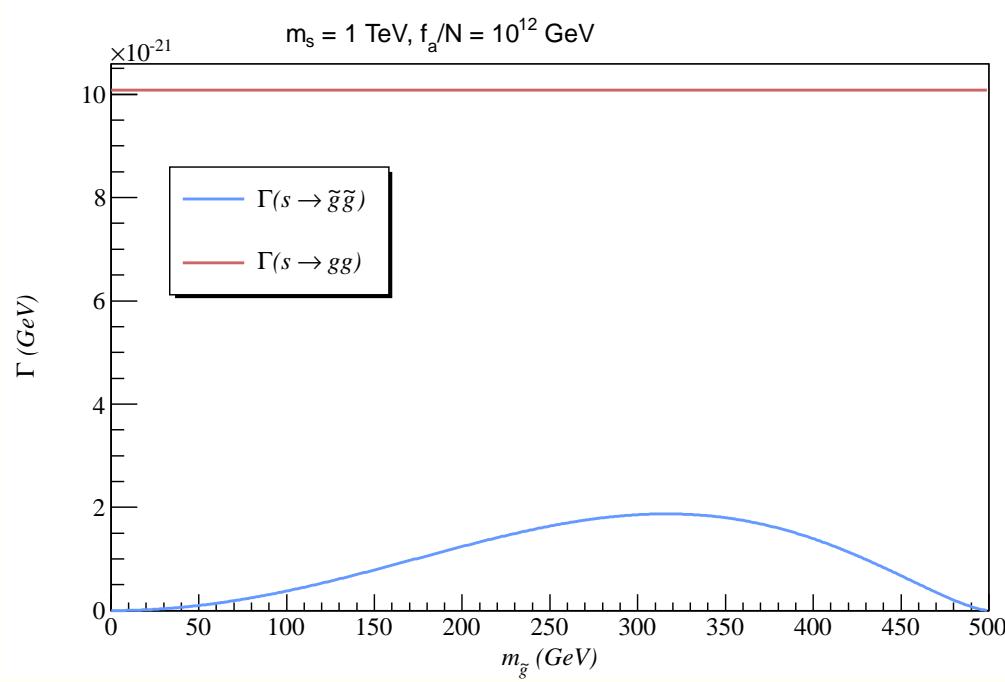
★ saxion production in early universe

- Thermal production:
- coherent oscillations:



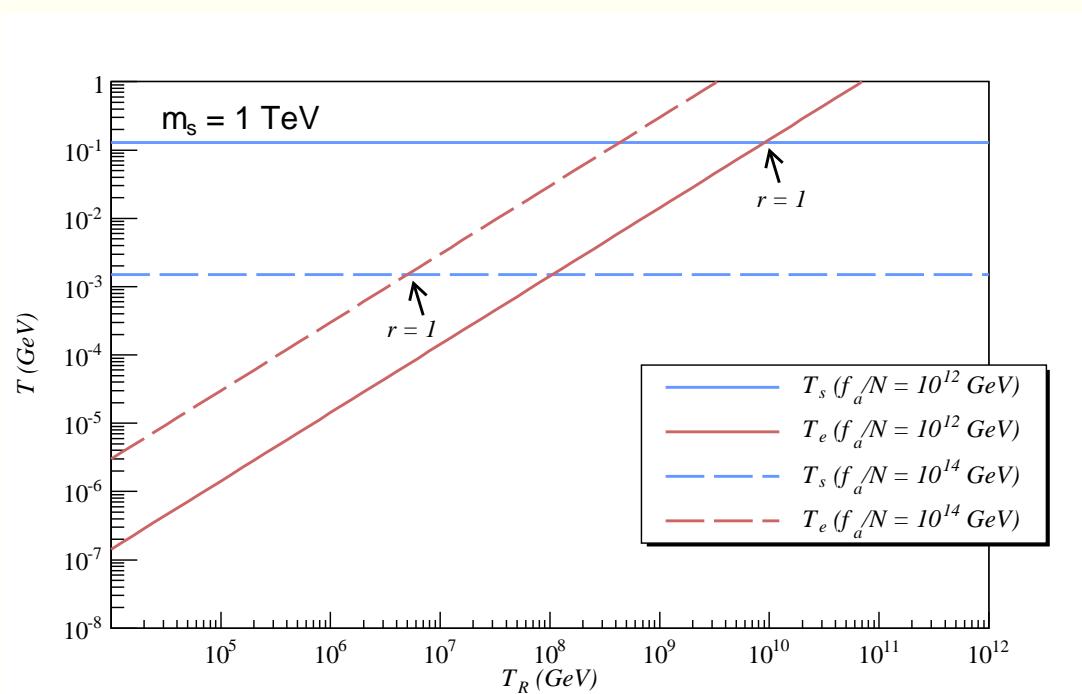
Saxion decay

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



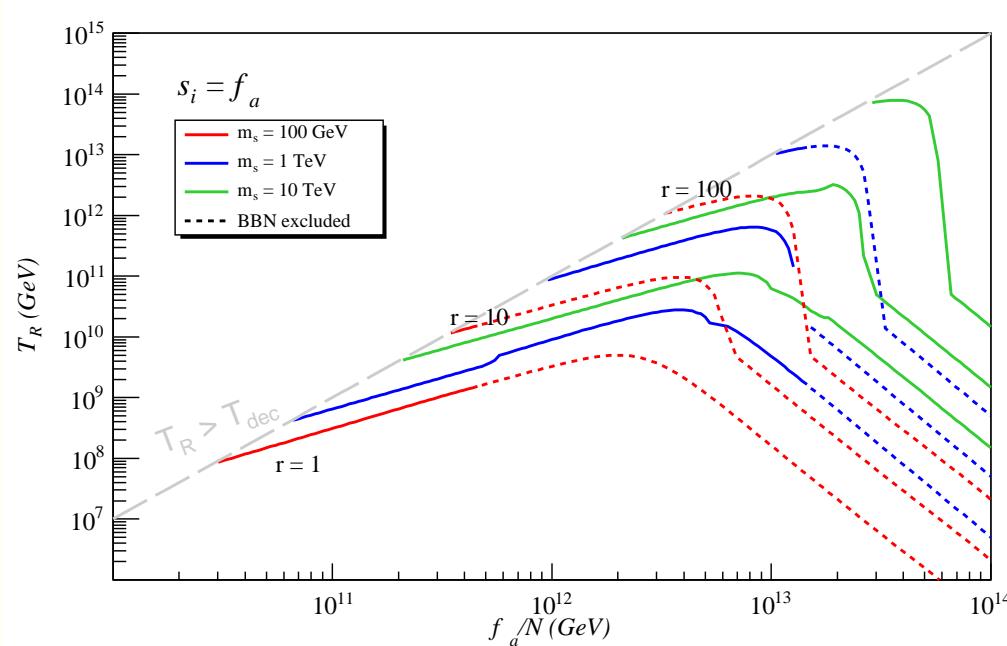
Saxion domination and entropy

- 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)



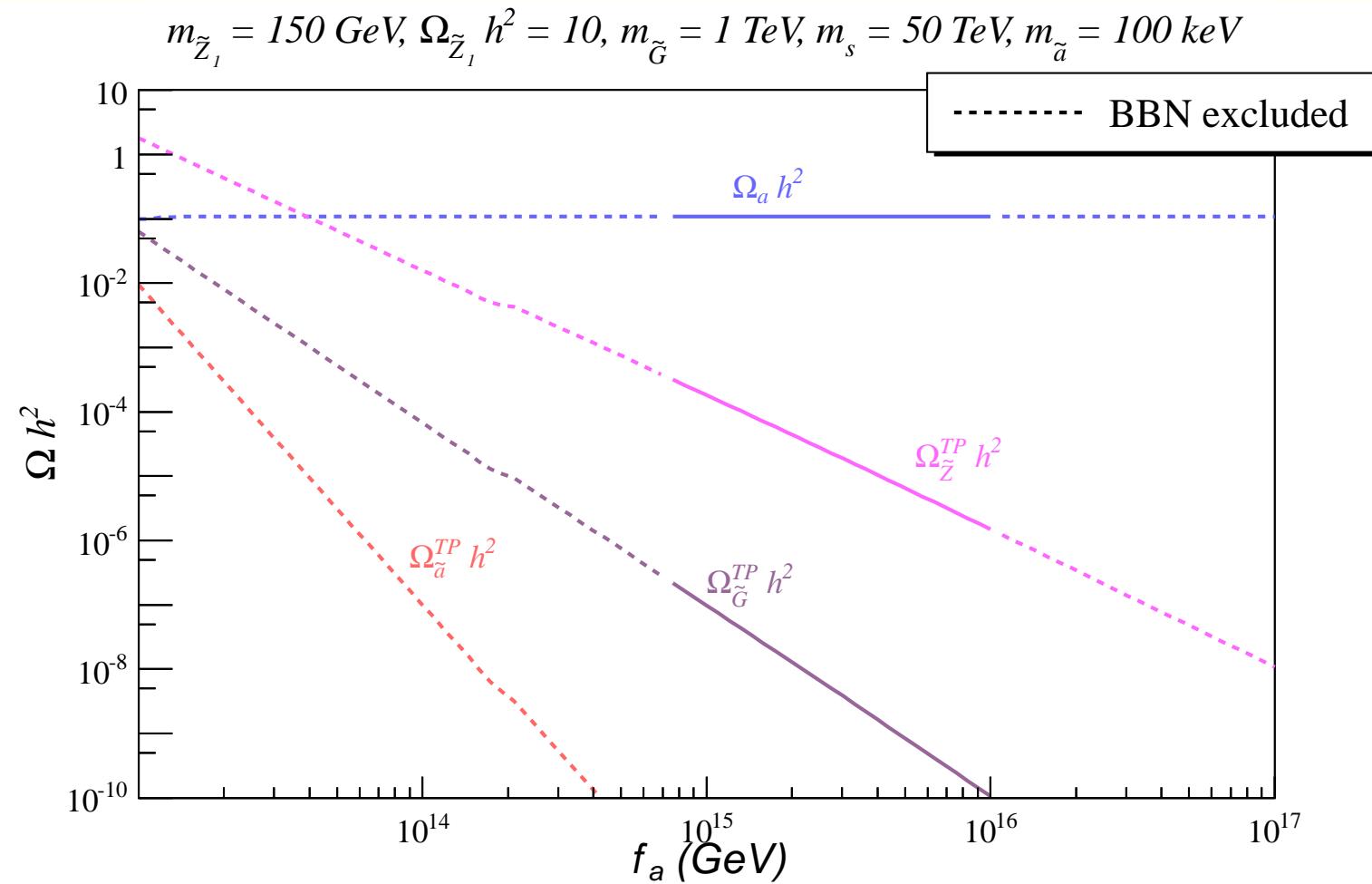
Dilution of relics due to saxion decay

- 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



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

- Yes, but need $m_s \sim 10 - 50$ TeV (HB, A. Lessa, JHEP1106 (2011) 027)

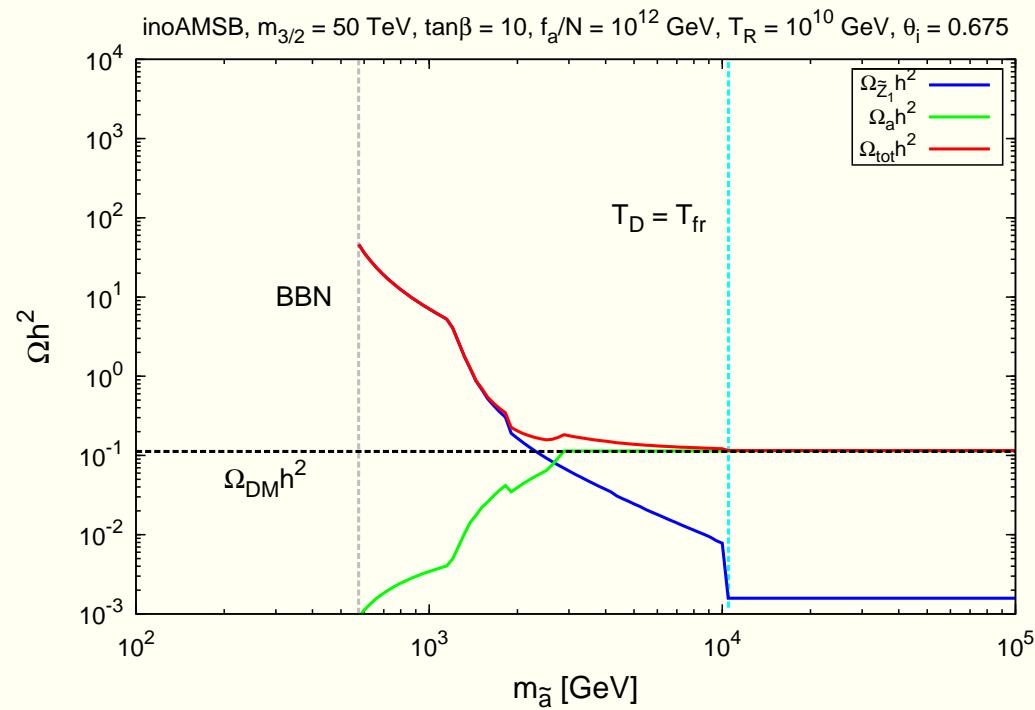


What if $m_{\tilde{a}} > m_{\tilde{Z}_1}$ so $\tilde{Z}_1 = LSP$?

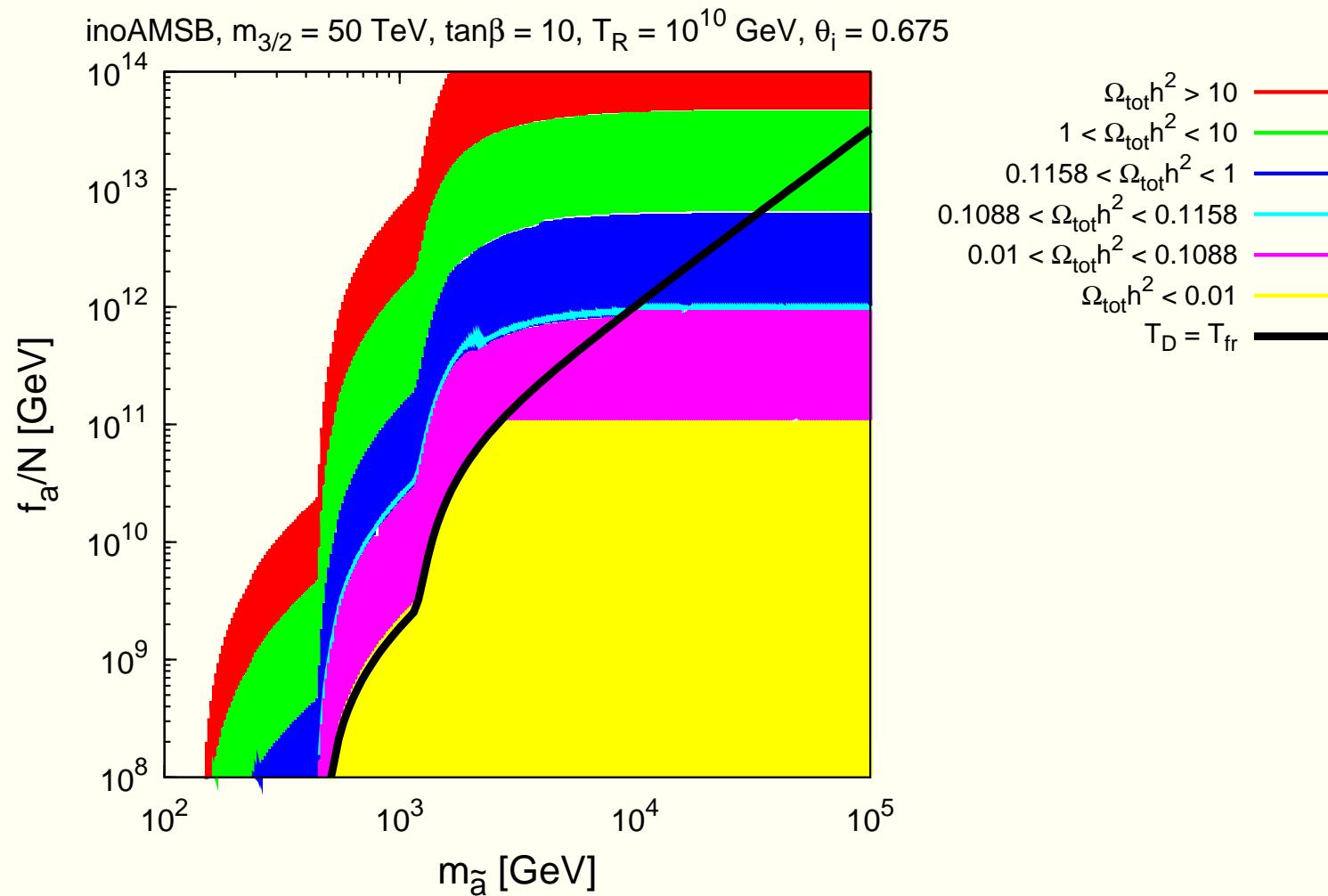
- Expect mixed axion/neutralino CDM: which will dominate?
- Neutralinos produced thermally as usual (RD, MD or DD universe)
- Axino production and decay (e.g. $\tilde{a} \rightarrow \tilde{Z}_1 \gamma$) will augment neutralino production.
- Decay produced \tilde{Z}_1 s at temp $T_D = \sqrt{\Gamma_{\tilde{a}} M_P}/(\pi^2 g_*(T_D)/90)^{1/4}$ can re-annihilate if $\langle \sigma v \rangle n_{\tilde{Z}_1}(T_D) > H(T_D)$
- 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, JCAP1106 (2011) 031

\tilde{Z}_1 = wino from gaugino AMSB model

- Expect mixed axion/neutralino CDM: which will dominate?

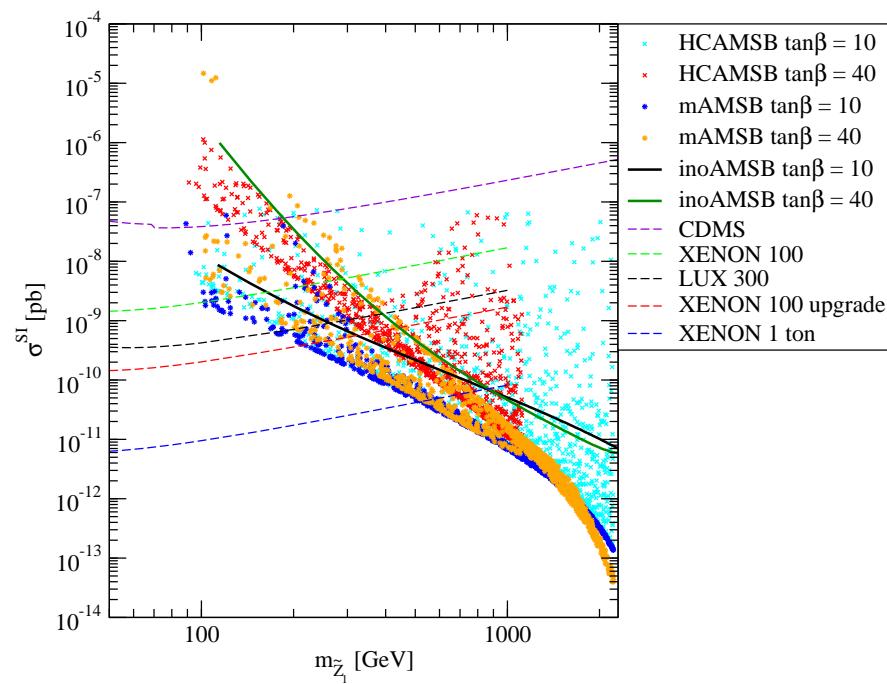


$\tilde{Z}_1 = \text{wino from gaugino AMSB model}$



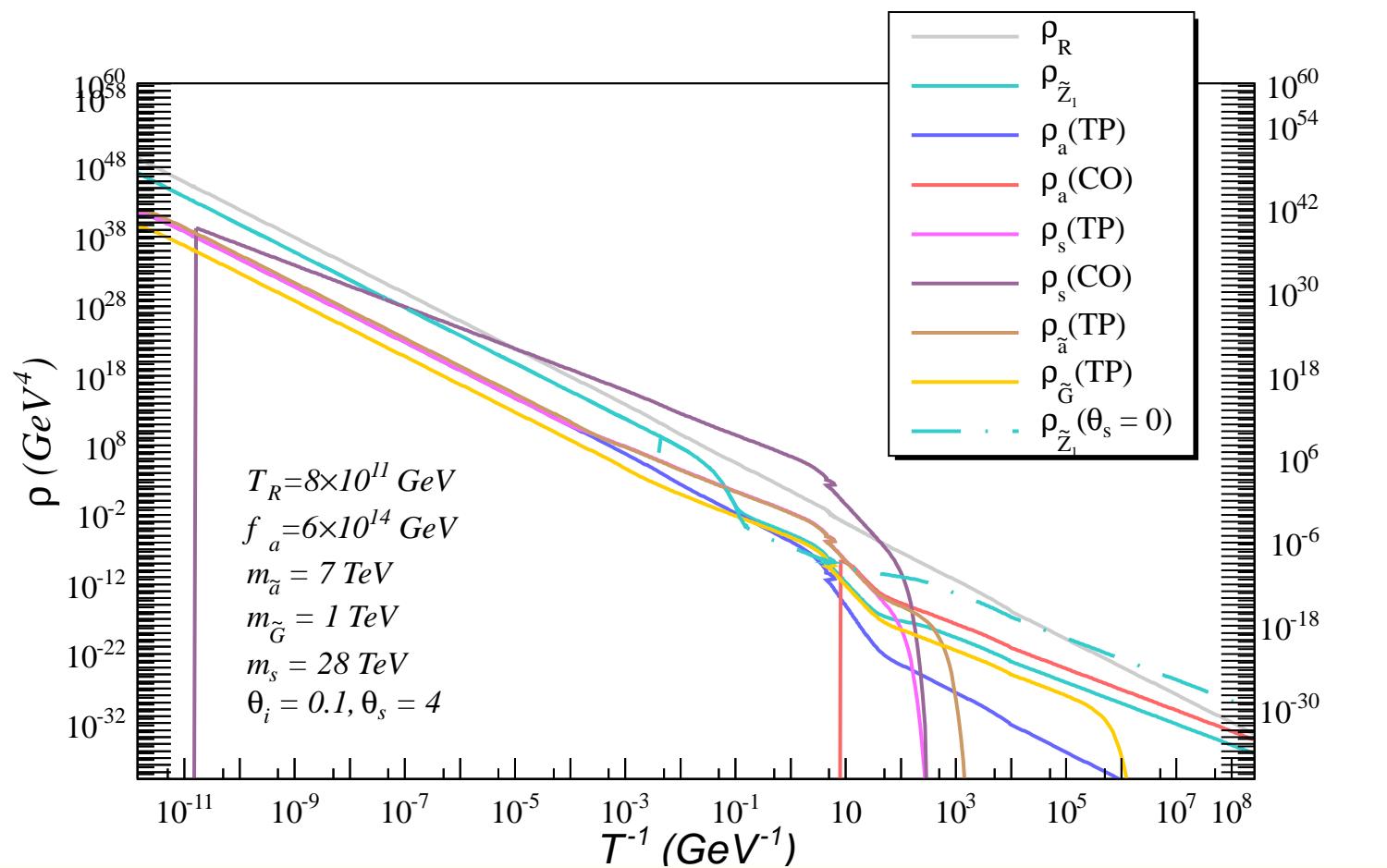
In case $\tilde{Z}_1 = \text{wino}$ from AMSB, see at Xe-100, 1-ton

- Assume CDM is wino dominated
- Distinct lower limit to $\sigma_{SI}(\tilde{Z}_1 p)$ unlike SUGRA



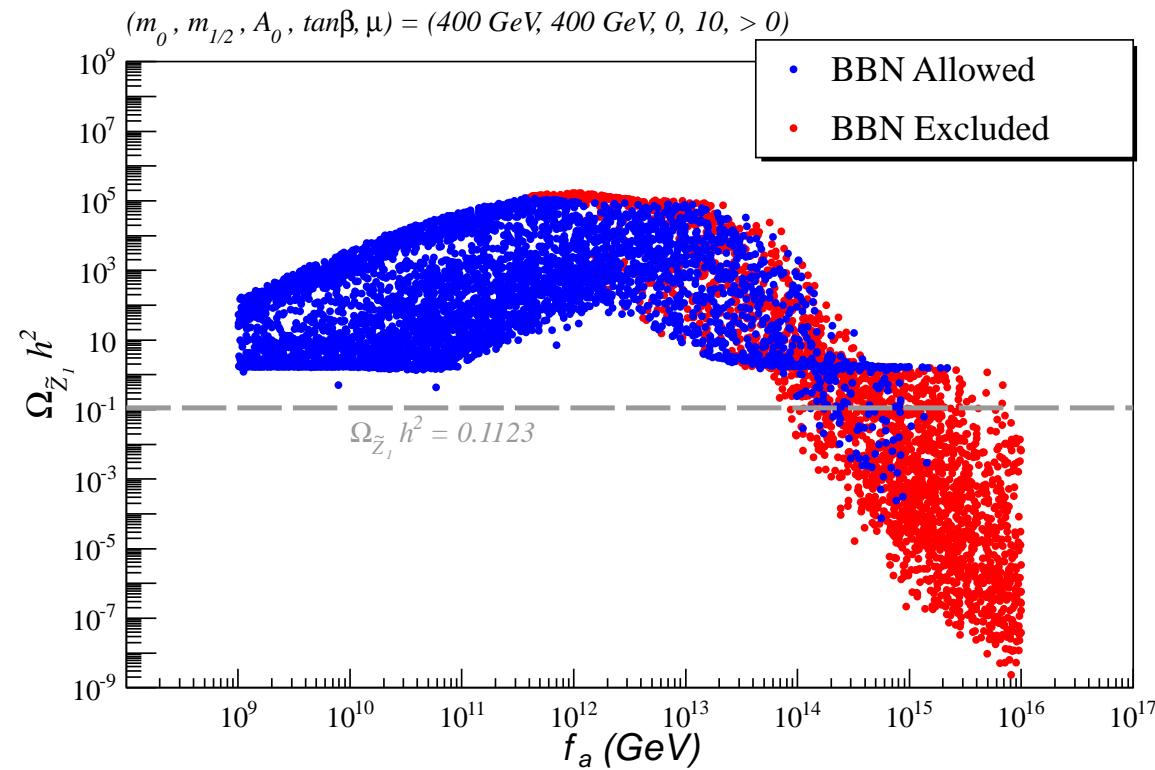
Mixed *a/bino* CDM: coupled Boltzmann calculation needed

- Include $\langle \sigma v \rangle(T)$; effect of saxions
- (HB, A. Lessa, W. Sreethawong, to appear)



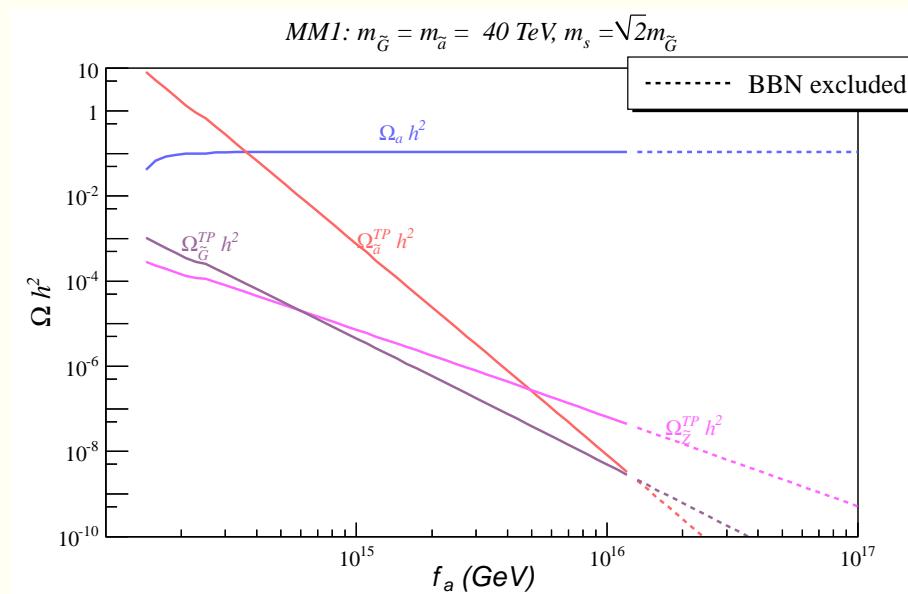
Mixed $a/bino$ CDM: coupled Boltzmann calculation needed

- lower limit: $f_a \gtrsim 10^{14}$ GeV
- $m_s \gtrsim 5 - 10$ TeV; $m_{\tilde{a}} \gtrsim 1$ TeV



Can we allow $f_a \sim M_{GUT}$ with mixed $a\tilde{Z}_1$ DM?

- Yes, example in mirage unification with $m_s = \sqrt{2}m_{\tilde{a}} = m_{3/2}$
- Need large entropy injection from saxion decay and $\theta_i \lesssim 0.05$
- HB, A. Lessa, JHEP1106 (2011) 027



Conclusions

- ★ SUSY WIMP-only CDM suffers 3 problems:
 - too much or too little CDM; \tilde{G} problem; strong CP problem
- ★ PQ strong CP solution + SUSY: why not both?
- ★ mixed axion/axino CDM if \tilde{a} is LSP
- ★ then low fine-tuning of $\Omega_{a\tilde{a}} h^2$
- ★ $T_R \sim 10^6 - 10^{11}$ possible:
 - solve gravitino problem if $m_{\tilde{G}} \gtrsim 5$ TeV
 - allow for non-thermal (possibly thermal) leptogenesis
- ★ Mixed $a\tilde{Z}_1$ CDM: wino or higgsino DM enhanced by \tilde{a} decay
- ★ Mixed $a\tilde{Z}_1$ CDM: bino suppressed by saxion decay if $f_a \gtrsim 10^{14}$ GeV
- ★ The case $f_a \sim M_{GUT}$ allowed under certain conditions