Mixed axion/LSP dark matter: a new paradigm

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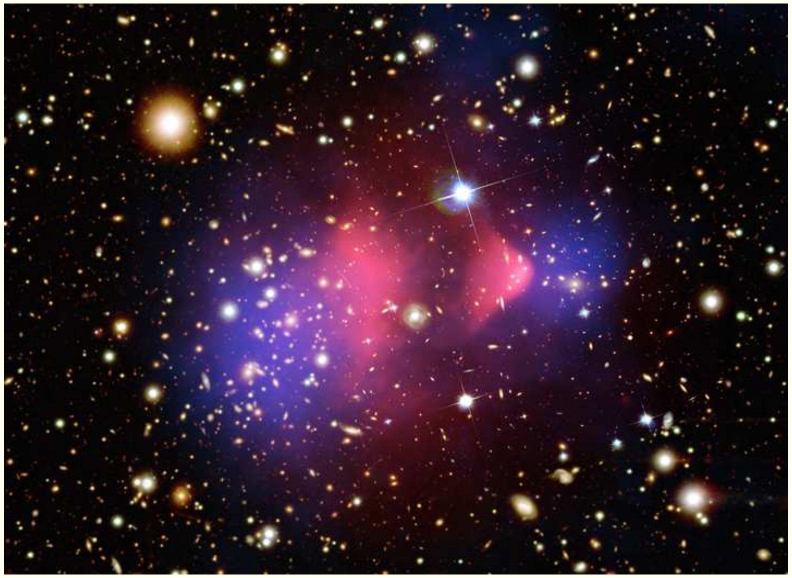
OUTLINE



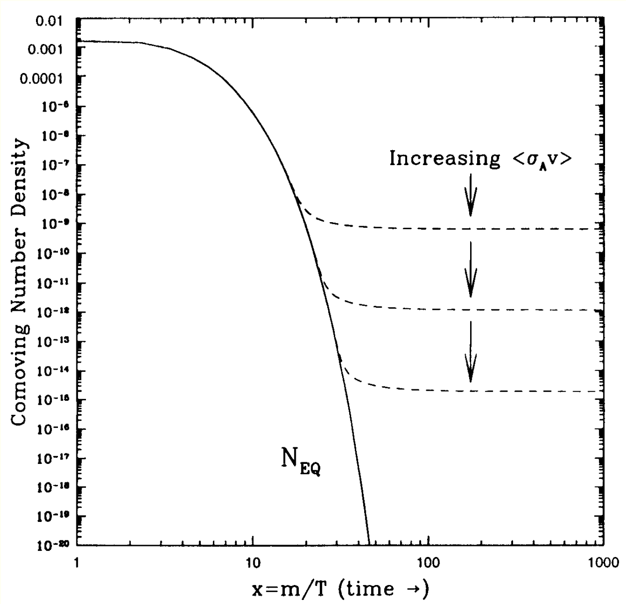
- ⋆ SUSY WIMPs: miracle or not?
- ⋆ strong CP problem and PQWW solution
- ⋆ the PQMSSM
- ⋆ mixed axion/axino CDM
- ⋆ mixed axion/neutralino CDM
- ⋆ can $f_a \sim M_{GUT}$?

WIMPs: is there a WIMP miracle for SUSY?

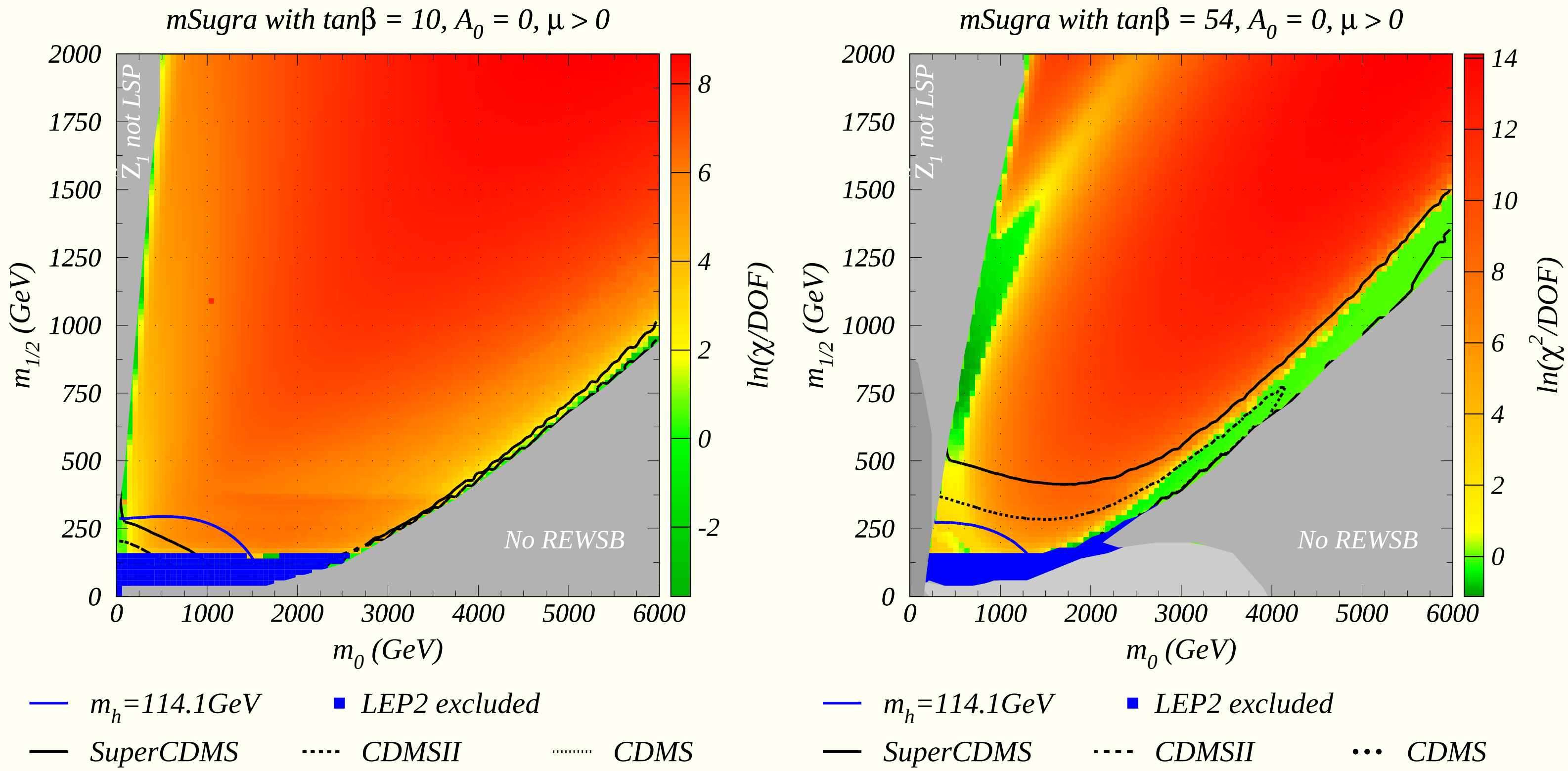
- Weakly Interacting Massive Particles
- assume in thermal equil'n in early universe
- Boltzman eq'n:

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

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



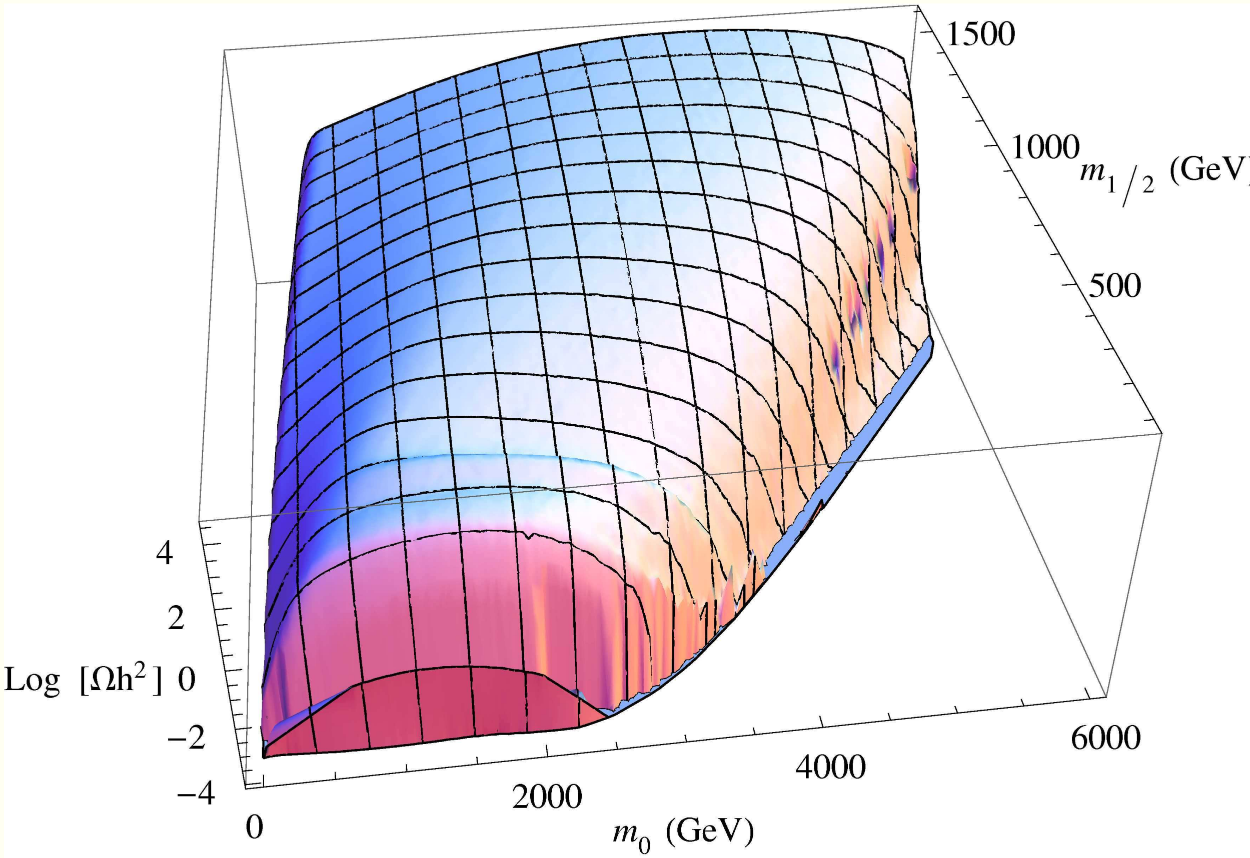
χ^2 fit of mSUGRA to $\Omega_{\widetilde{Z}_1} h^2$, $b \to s\gamma$ and $(g-2)_\mu$



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

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

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

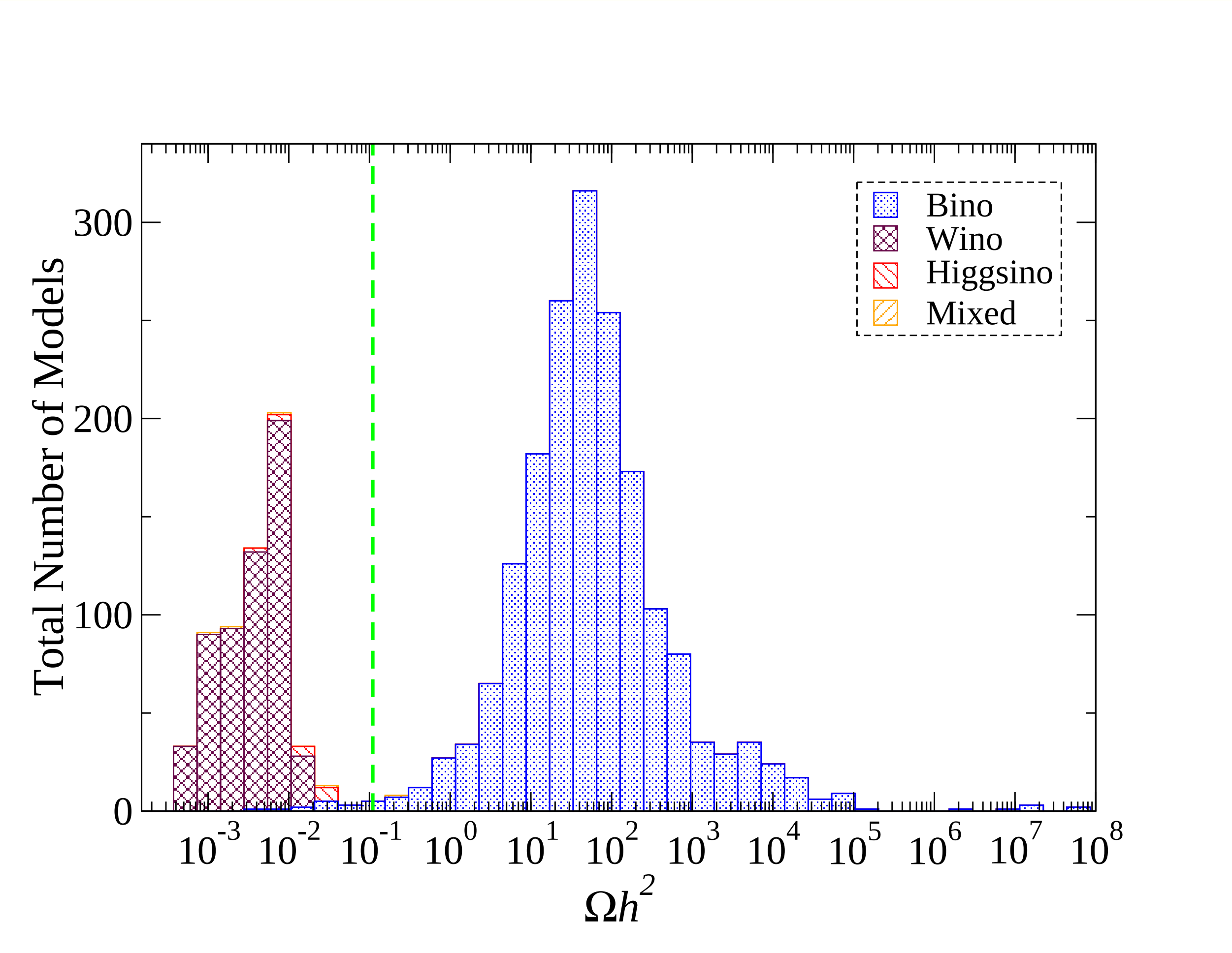


General scan over 19 param. MSSM

- ⋆ dimensionful param's defined at M_{GUT}
- $m_{Q_1}, m_{U_1}, m_{D_1}, m_{L_1}, m_{E_1}$: $0 \rightarrow 3500$ 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

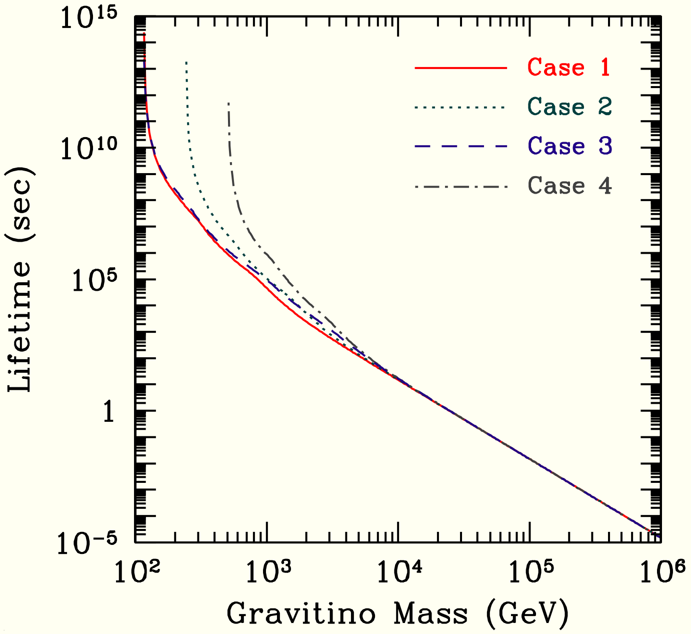
Why WIMP miracle really is a miracle for SUSY

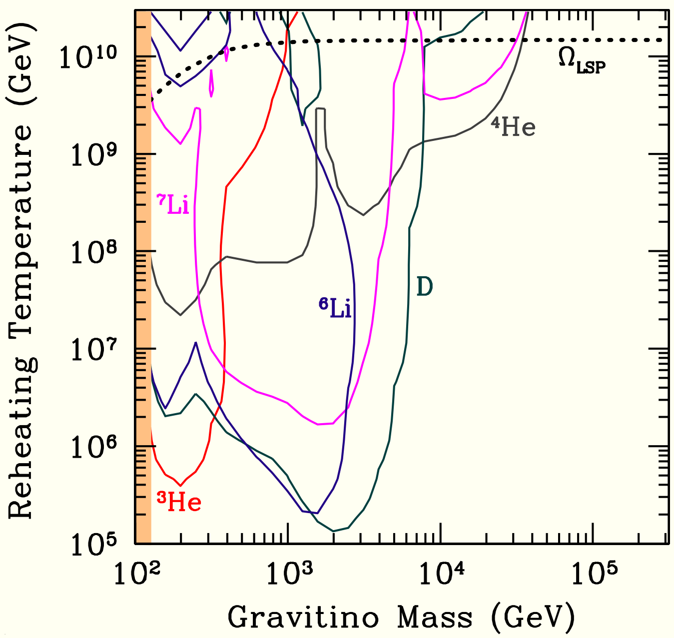
- histogram of models vs. $\Omega_{\widetilde{Z}_1} h^2$ with $m_{\widetilde{Z}_1} < 500$ GeV



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

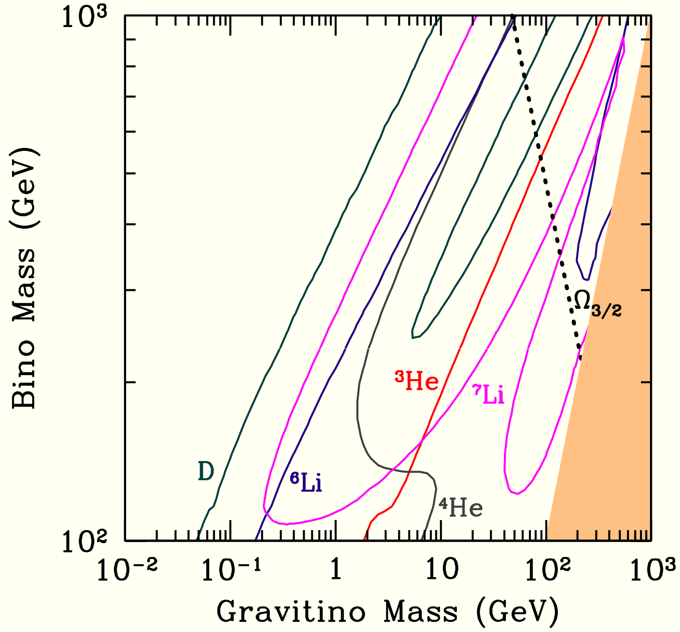




(see Kawasaki, Kohri, Moroi, Yotsuyanagi; Cybert, Ellis, Fields, Olive; Jedamzik)

Gravitinos as dark matter: again the gravitino problem

- neutralino production in generic SUGRA models: followed by late time $\widetilde{Z}_1 \to \tilde{G} + X$ 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: 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

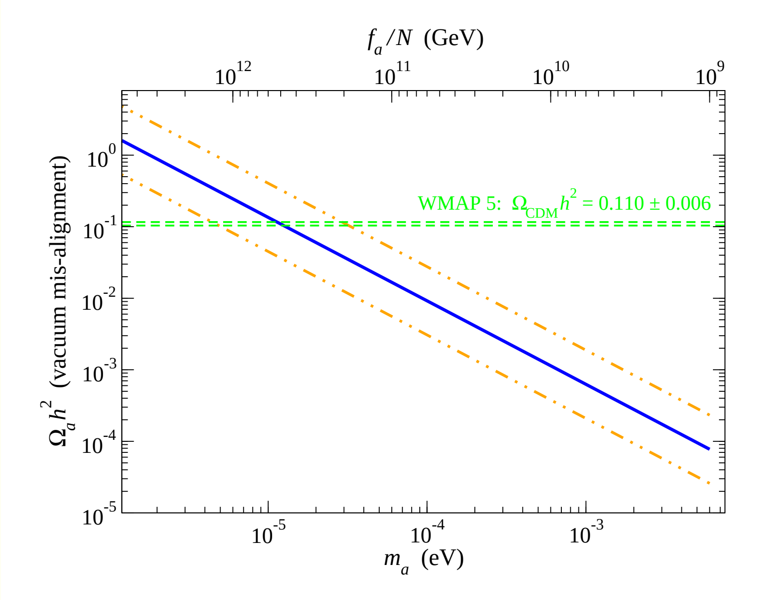
PQWW/KSVZ/DFSZ solution to the strong CP problem

⋆ 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 $\rightarrow 0$; 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

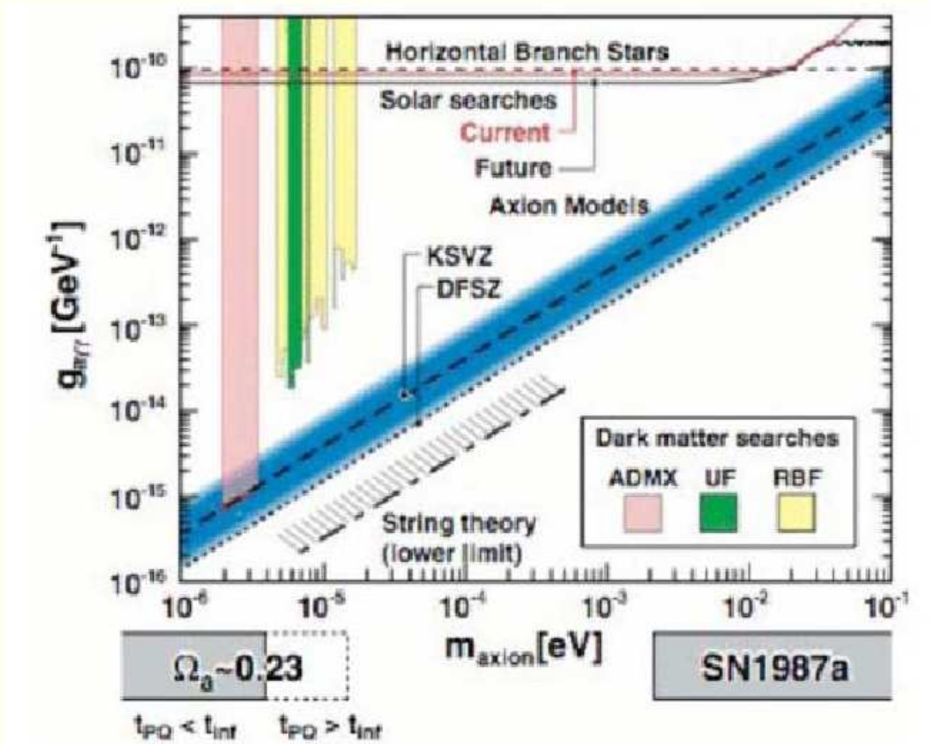
- ★ Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial\theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1-\cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$: $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
- ★ a(x) 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 $\Rightarrow f_a \gtrsim 10^9 GeV$



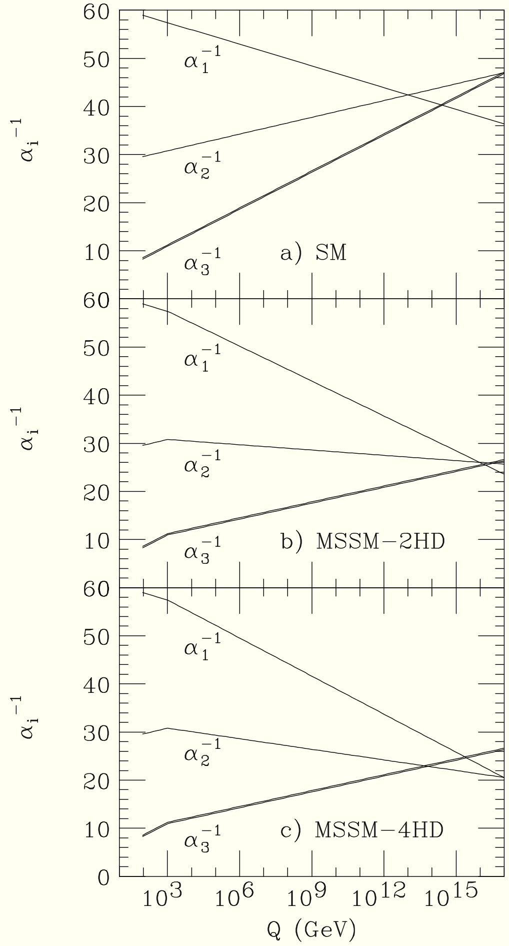
Axion microwave cavity searches

⋆ ongoing searches: ADMX experiment

- Livermore⇒ 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

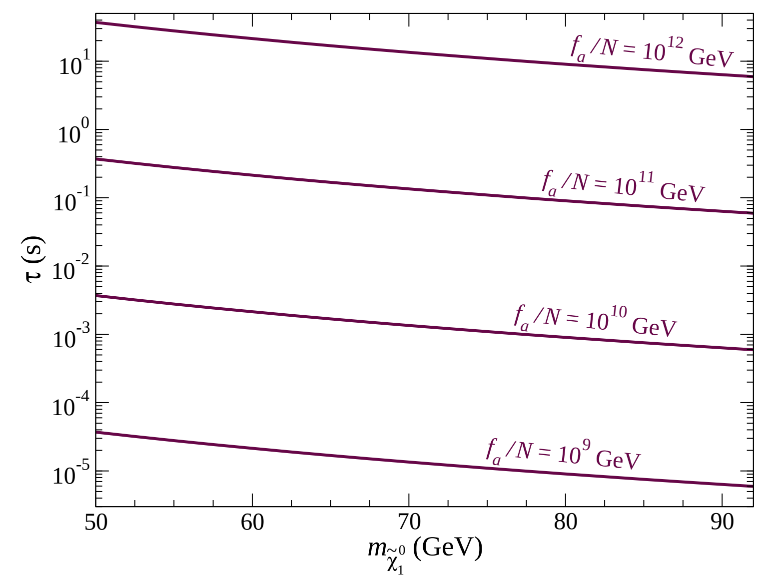


We also know MSSM (plus gauge singlets) is compelling effective theory between M_{weak} and M_{GUT}



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

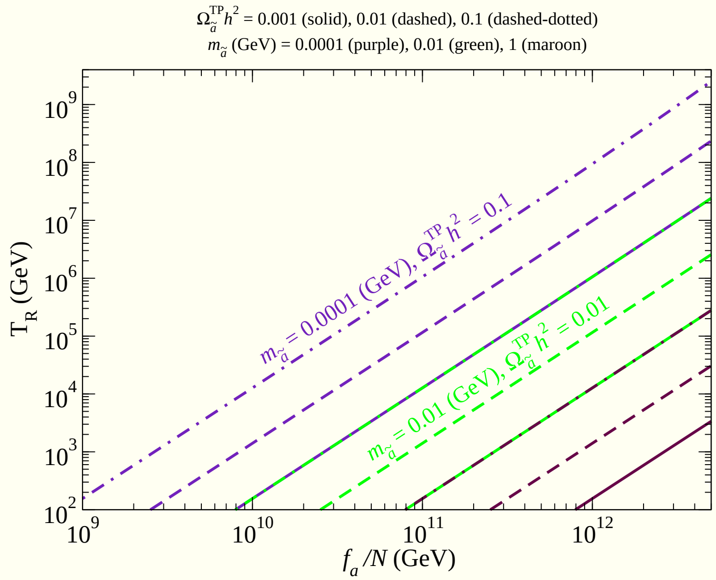
- axino is spin-$\frac{1}{2}$ element of axion supermultiplet (R-odd; can be LSP)
  - Raby, Nilles, Kim; Rajagopal, Wilczek, Turner
  - $\hat{a} = \frac{s+ia}{\sqrt{2}} + i\sqrt{2}\bar{\theta}\tilde{a}_L + i\bar{\theta}\theta_L\mathcal{F}_a$ in 4-comp. notation
- $m_{\tilde{a}}$ model dependent: keV$\rightarrow$ TeV
- $\widetilde{Z}_1 \rightarrow \tilde{a}\gamma$
- non-thermal $\tilde{a}$ production via $\widetilde{Z}_1$ decay:
- axinos inherit neutralino number density
- $\Omega_{\tilde{a}}^{NTP}h^2 = \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}}\Omega_{\widetilde{Z}_1}h^2$:
  - 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:

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



Various leptogenesis scenarios

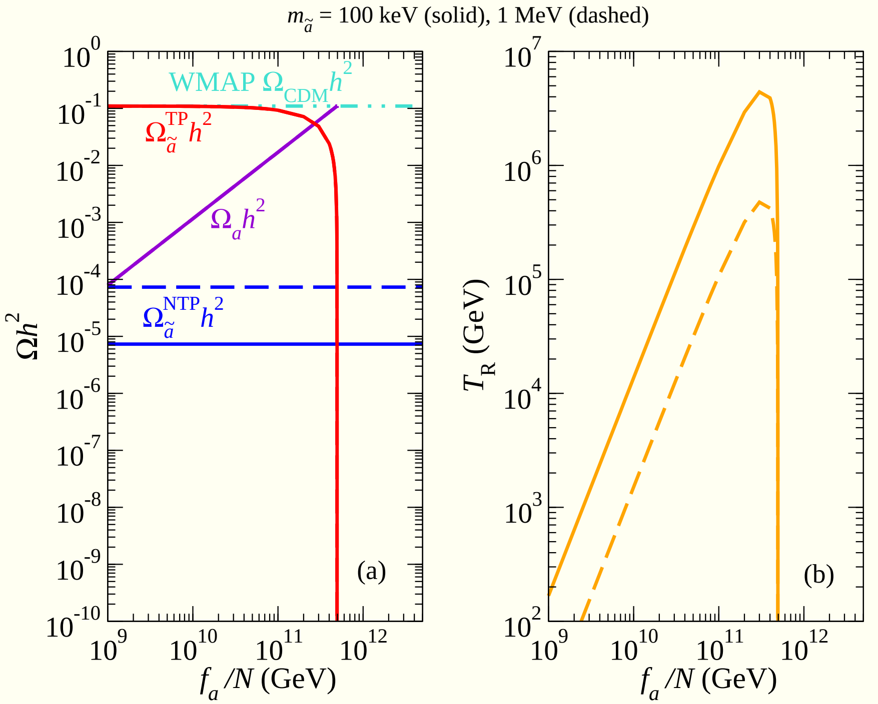
- WMAP observation: $n_b/s \sim 0.9 \times 10^{-10}$: how to generate?
- SM EW baryogenesis ruled out; SUSY EWB nearly so
- *Thermal* leptogenesis very attractive but needs $T_R \gtrsim m_{N_1} \gtrsim 2 \times 10^9$ GeV (Buchmuller, Plumacher); Naive conflict with upper bound on T_R from BBN/gravitino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

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

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

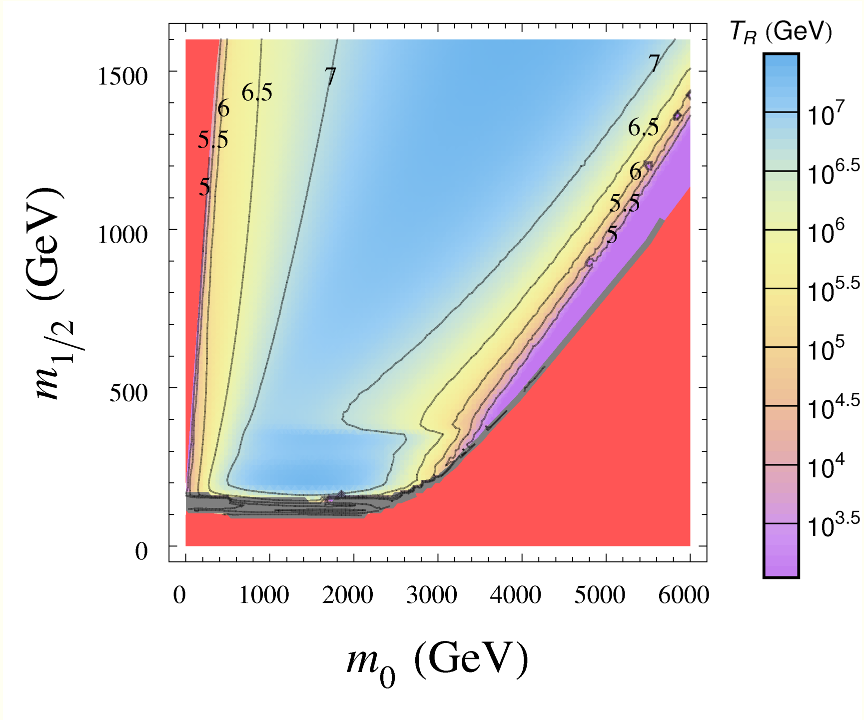
mSUGRA model with mixed axion/axino CDM: $m_{\tilde{a}}$ fixed

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

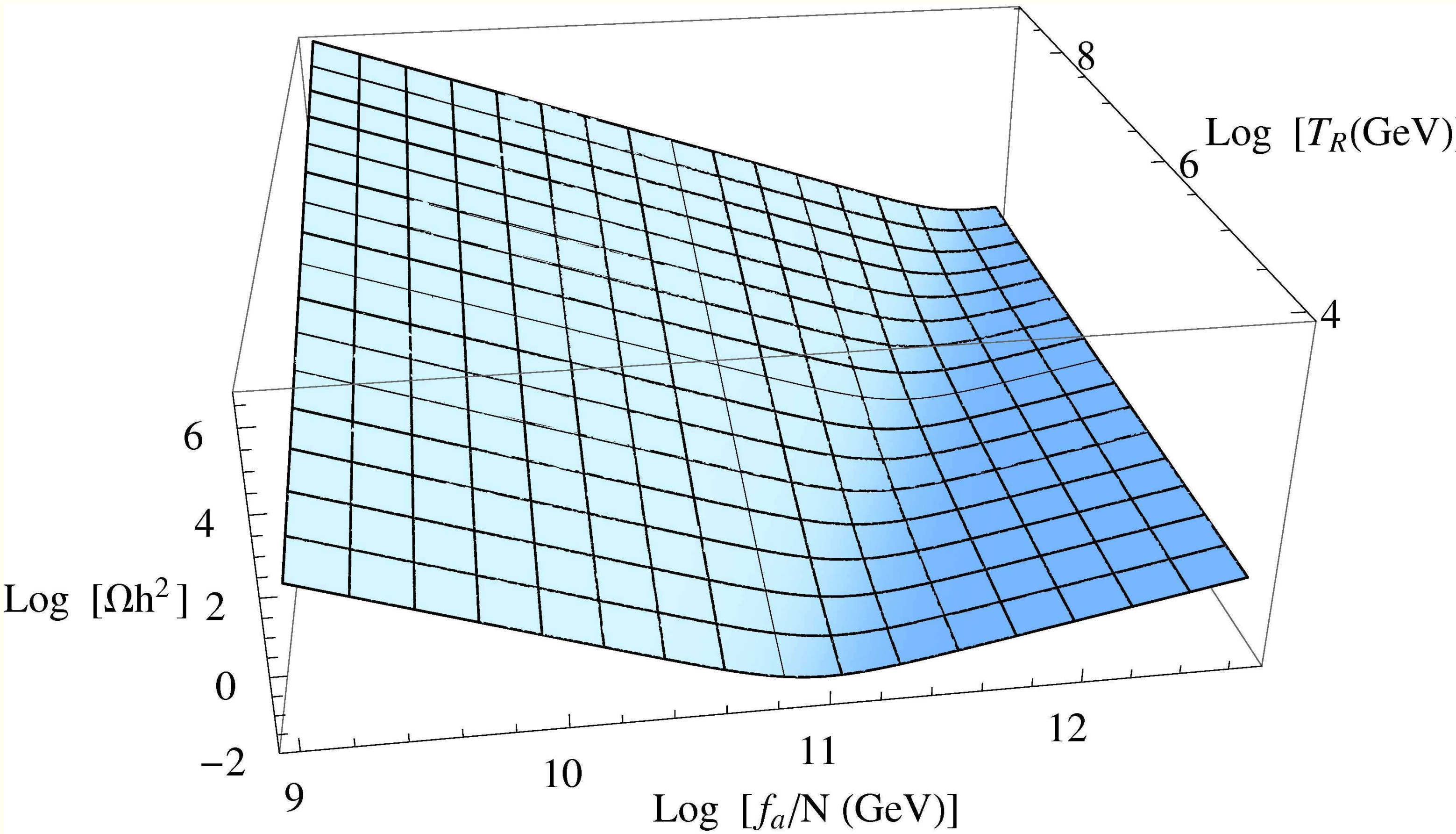


mSUGRA p-space with mainly axion cold DM

- 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!

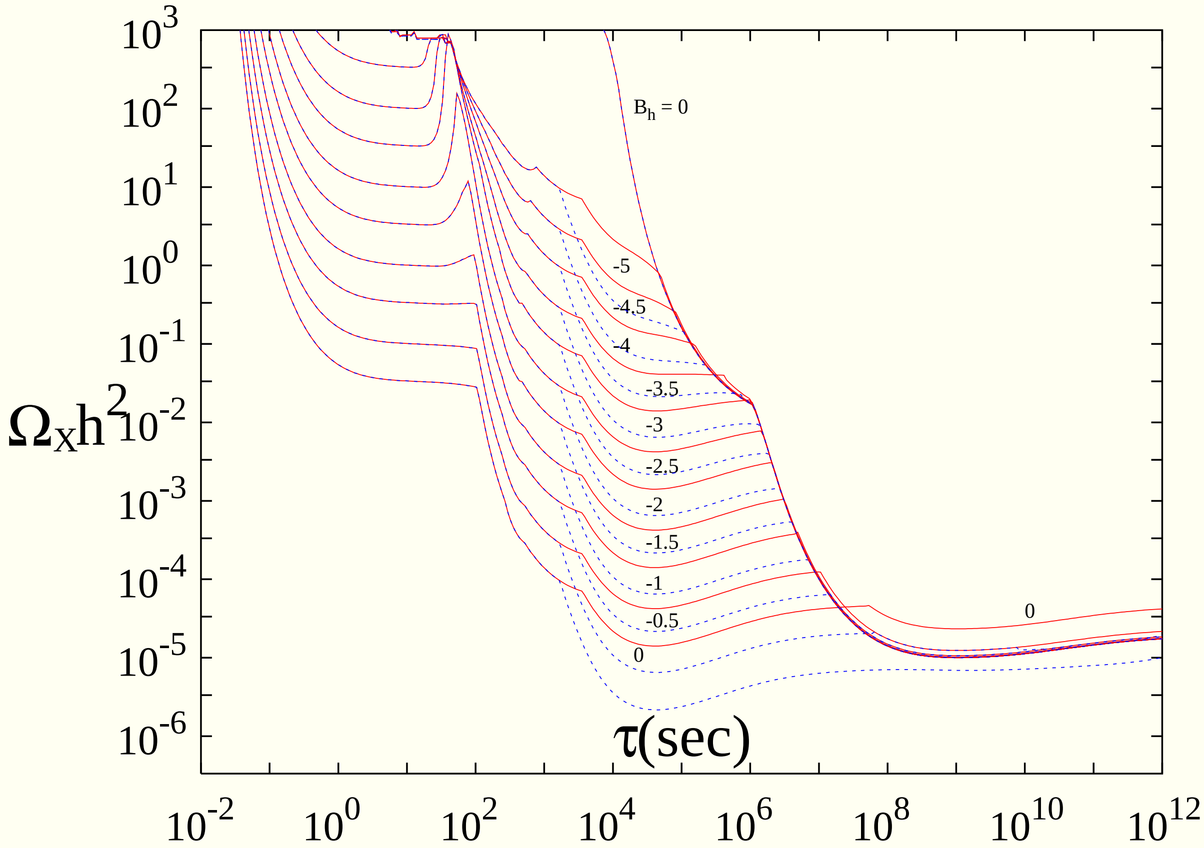


Reconcile *thermal* leptogenesis with $\tilde{G}$ problem?

- ⋆ 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 $\widetilde{Z}_1$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 $\widetilde{Z}_1 \to \tilde{a} + hadrons$
  - – low rate $\widetilde{Z}_1$ production $\Omega_{\widetilde{Z}_1} \lesssim 0.1$
  - – bino-like $\widetilde{Z}_1 \to \gamma\tilde{a}$ with $\tau(\widetilde{Z}_1) \lesssim 200$ sec.
- ⋆ Does it work?

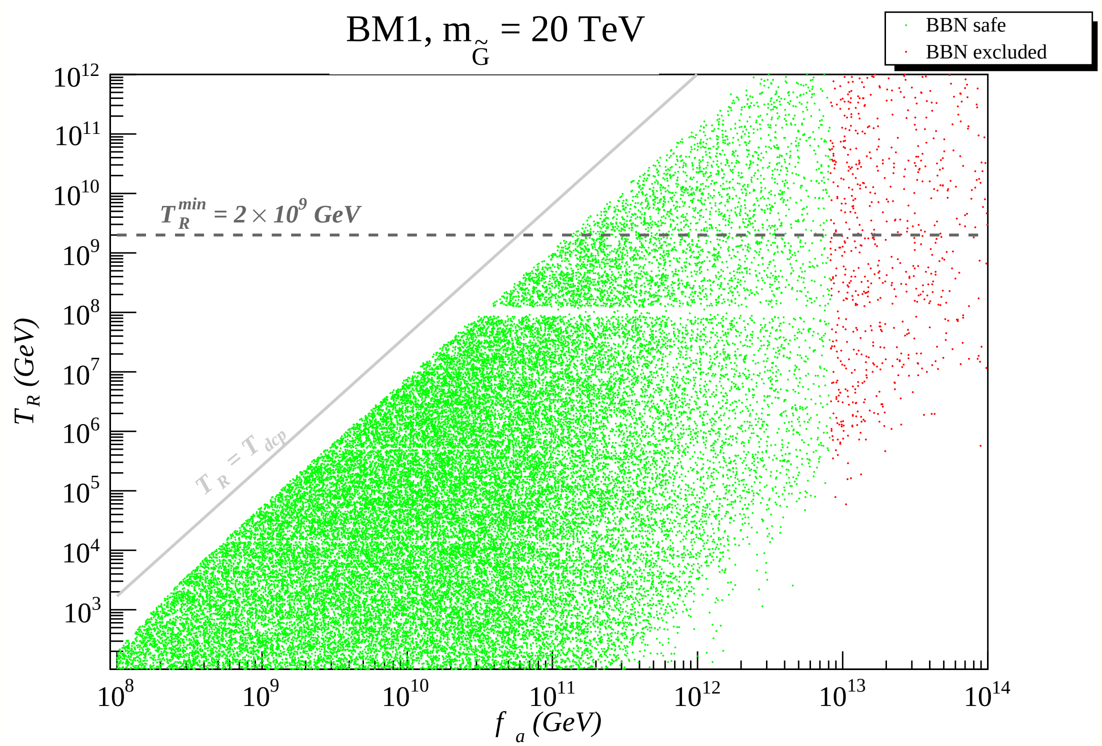
BBN constraints on late decaying neutrals (Jedamzik)

★ results for $m_X = 100$ GeV



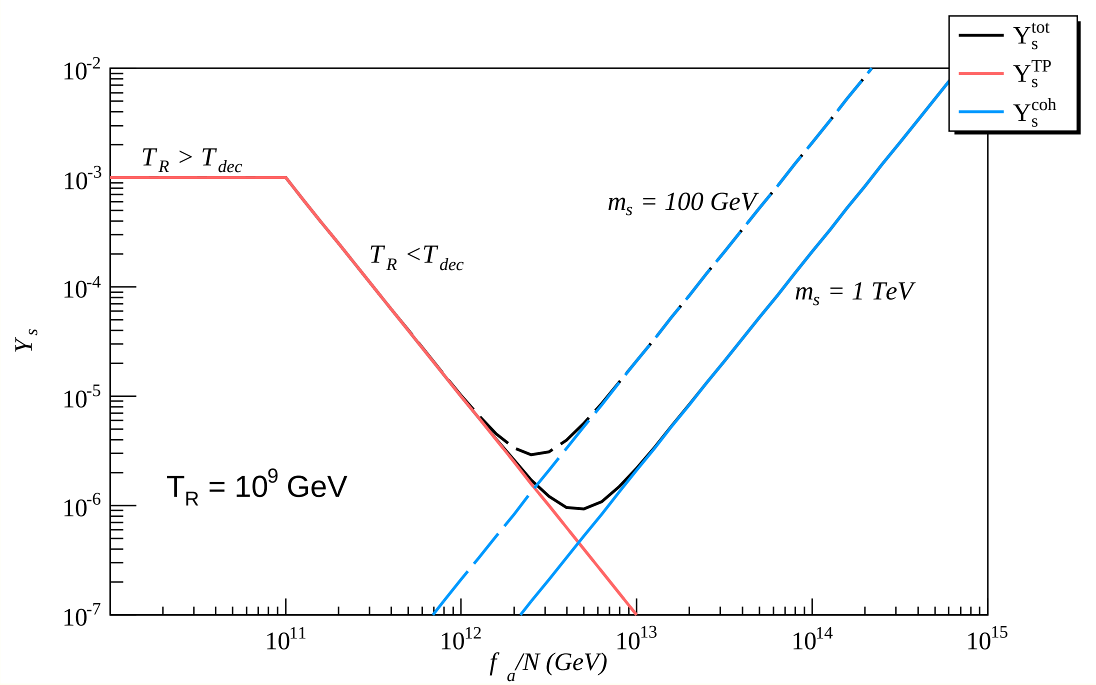
Scan over PQMSSM parameters for Eff. SUSY model

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



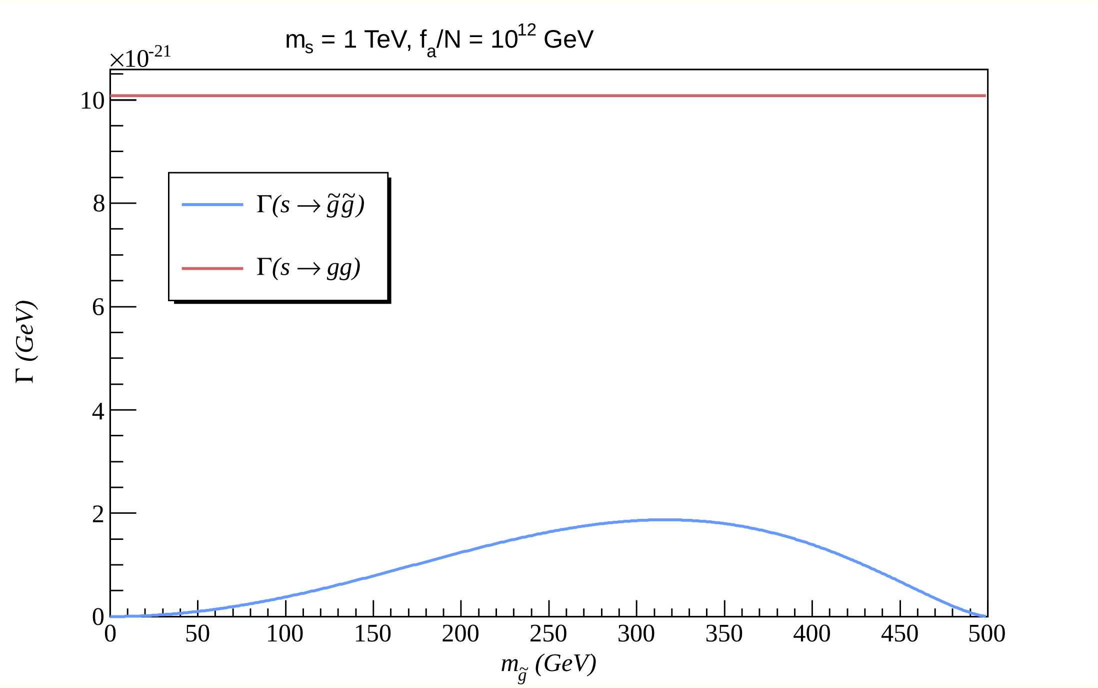
What about cosmology of saxion field $s(x)$?

- ⋆ HB, Kraml, Lessa, Sekmen [JCAP1104 (2011)039]
- ⋆ saxion production in early universe
  - Thermal production:
  - coherent oscillations:



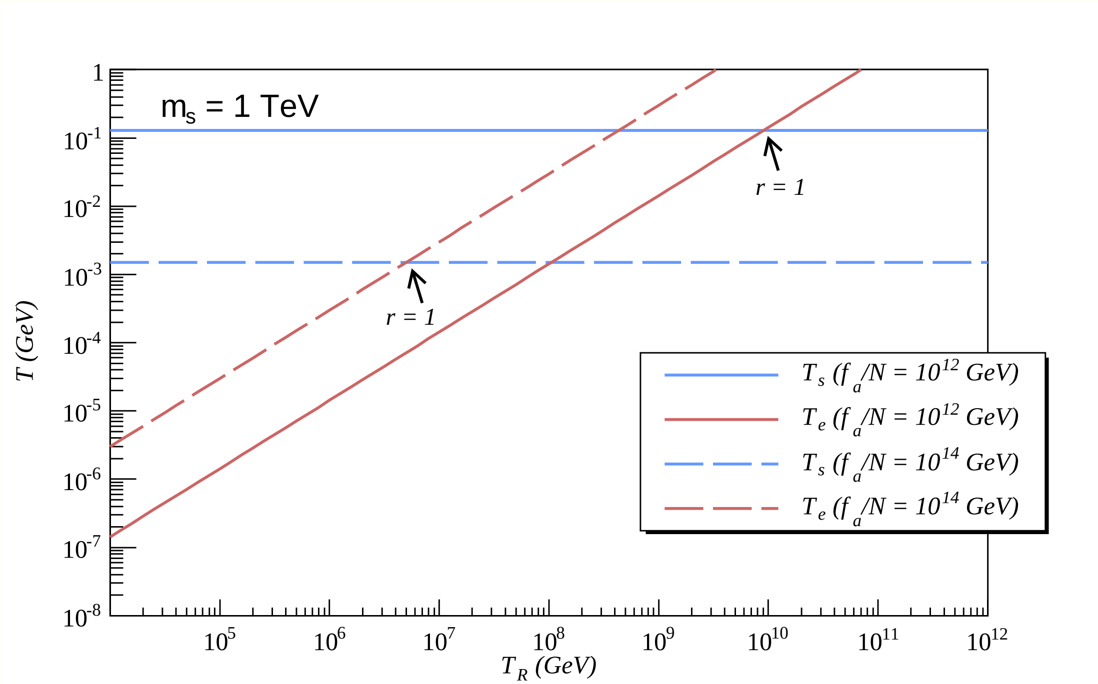
Saxion decay

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



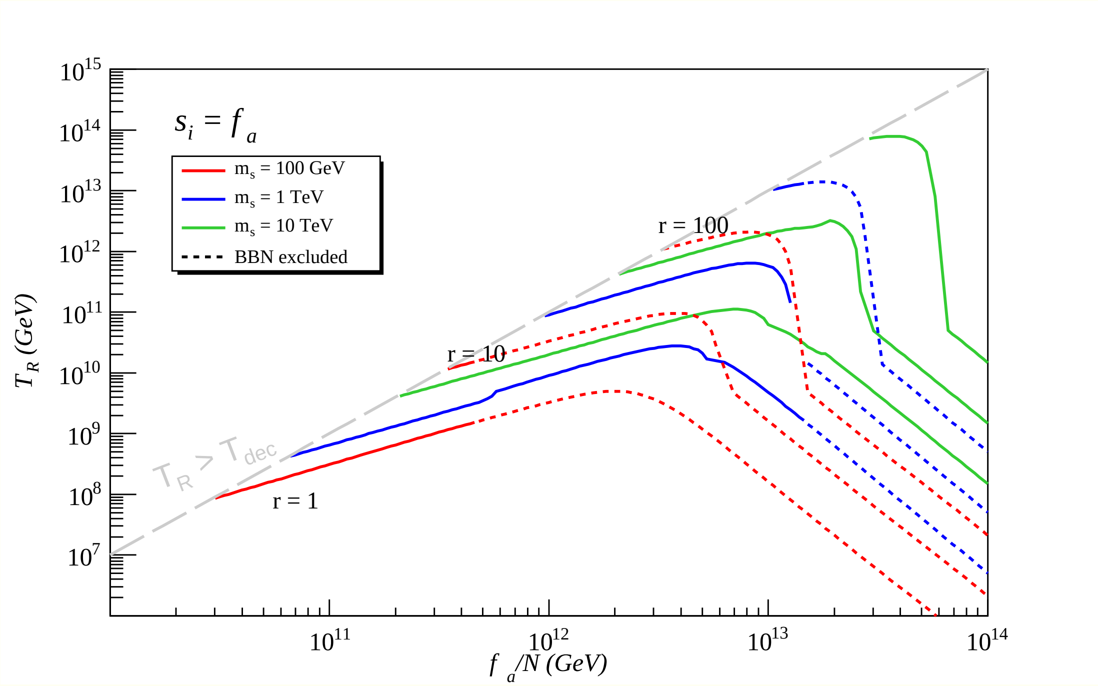
Saxion domination and entropy

- $T_e =$ 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)



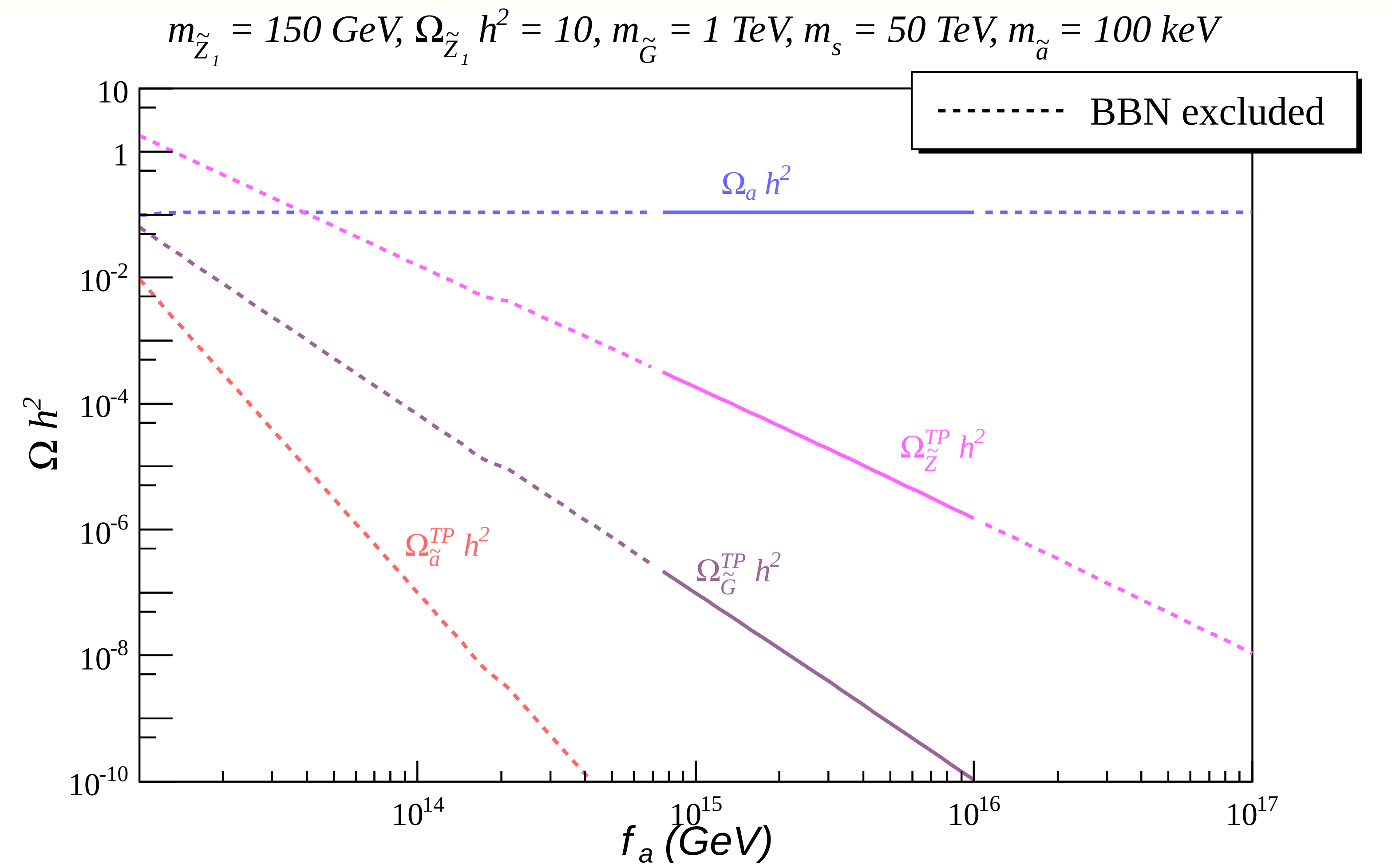
Dilution of relics due to saxion decay

- 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, JHEP**1106** (2011) 027)

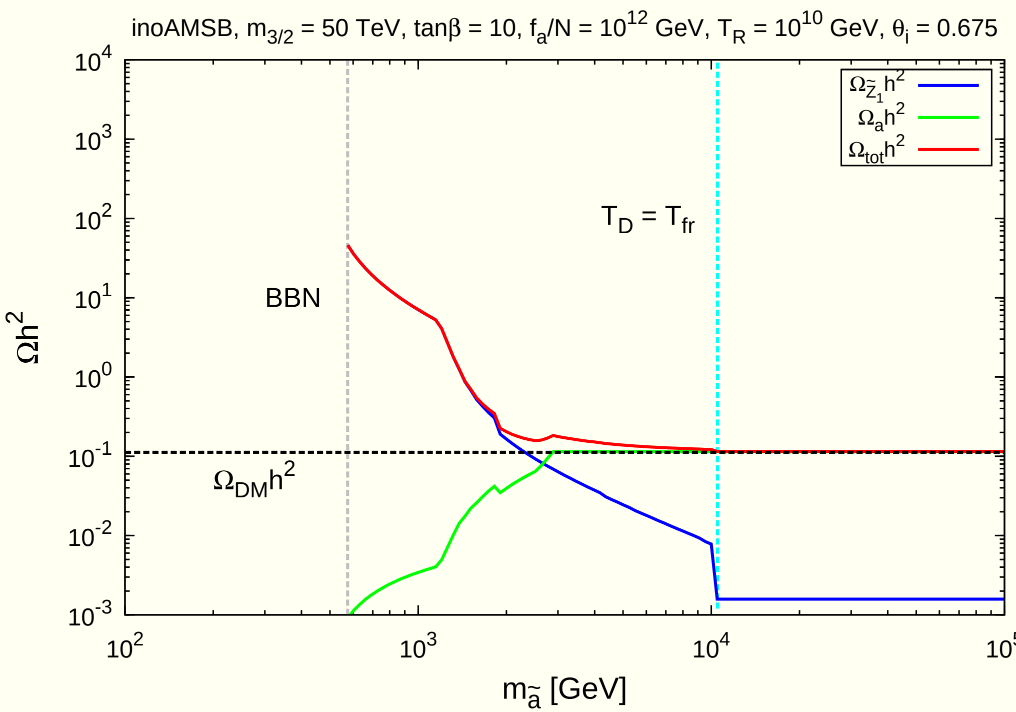


What if $m_{\tilde{a}} > m_{\widetilde{Z}_1}$ so $\widetilde{Z}_1 = LSP$?

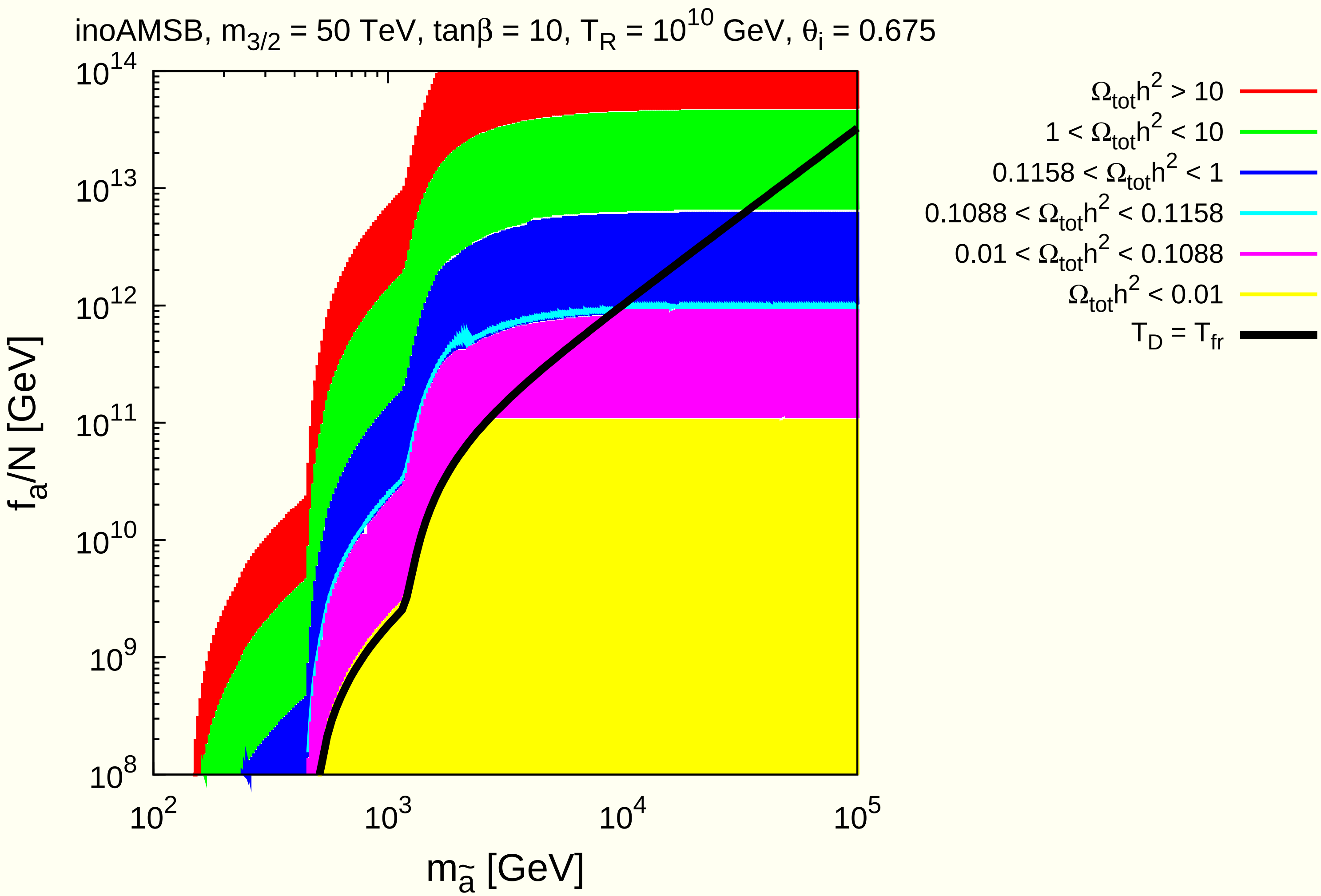
- Expect mixed axion/neutralino CDM: which will dominate?
- Neutralinos produced thermally as usual (RD, MD or DD universe)
- Axino production and decay (e.g. $\tilde{a} \to \widetilde{Z}_1\gamma$) will augment neutralino production.
- Decay produced $\widetilde{Z}_1$s at temp $T_D = \sqrt{\Gamma_{\tilde{a}} M_P}/(\pi^2 g_*(T_D)/90)^{1/4}$ 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

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

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

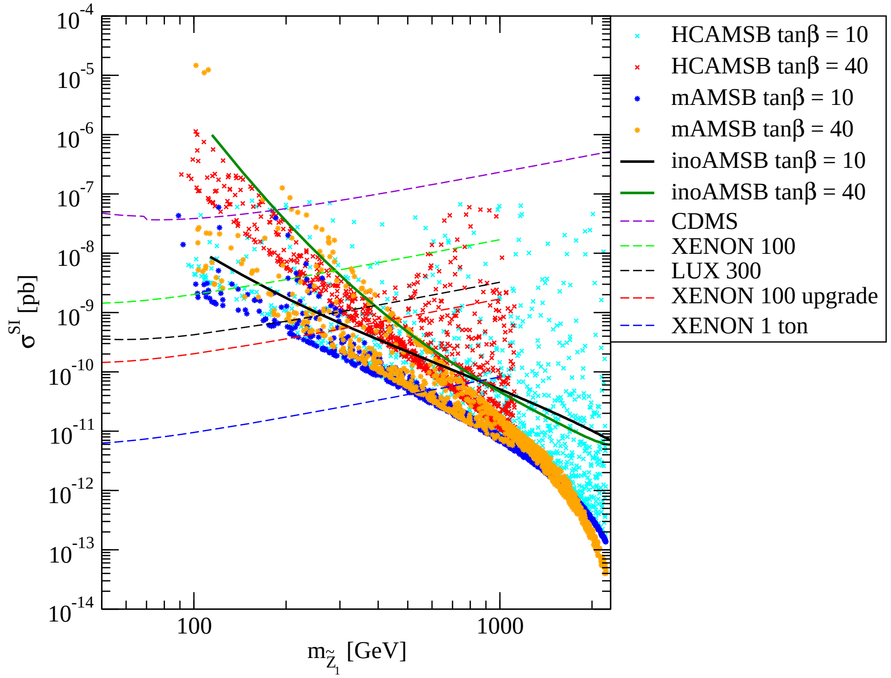


$\widetilde{Z}_1 =$ wino from gaugino AMSB model



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

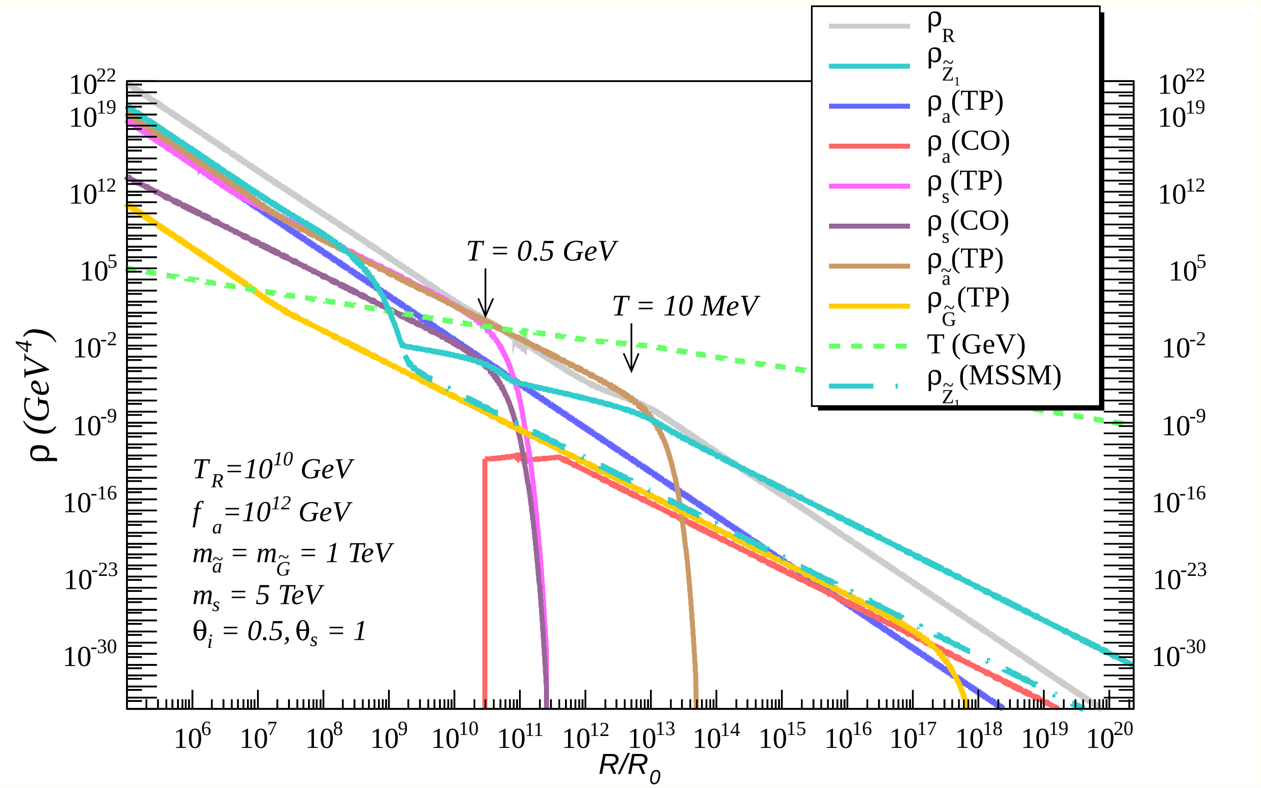
- Assume CDM is wino dominated
- Distinct lower limit to $\sigma_{SI}(\widetilde{Z}_1 p)$ unlike SUGRA
- HB, Demisek, Rajagopalan, Summy, JCAP1007 (2010) 014



HCAMSB tanβ = 10
HCAMSB tanβ = 40
mAMSB tanβ = 10
mAMSB tanβ = 40
inoAMSB tanβ = 10
inoAMSB tanβ = 40
CDMS
XENON 100
LUX 300
XENON 100 upgrade
XENON 1 ton
σ^SI [pb]
m_Z̃1 [GeV]

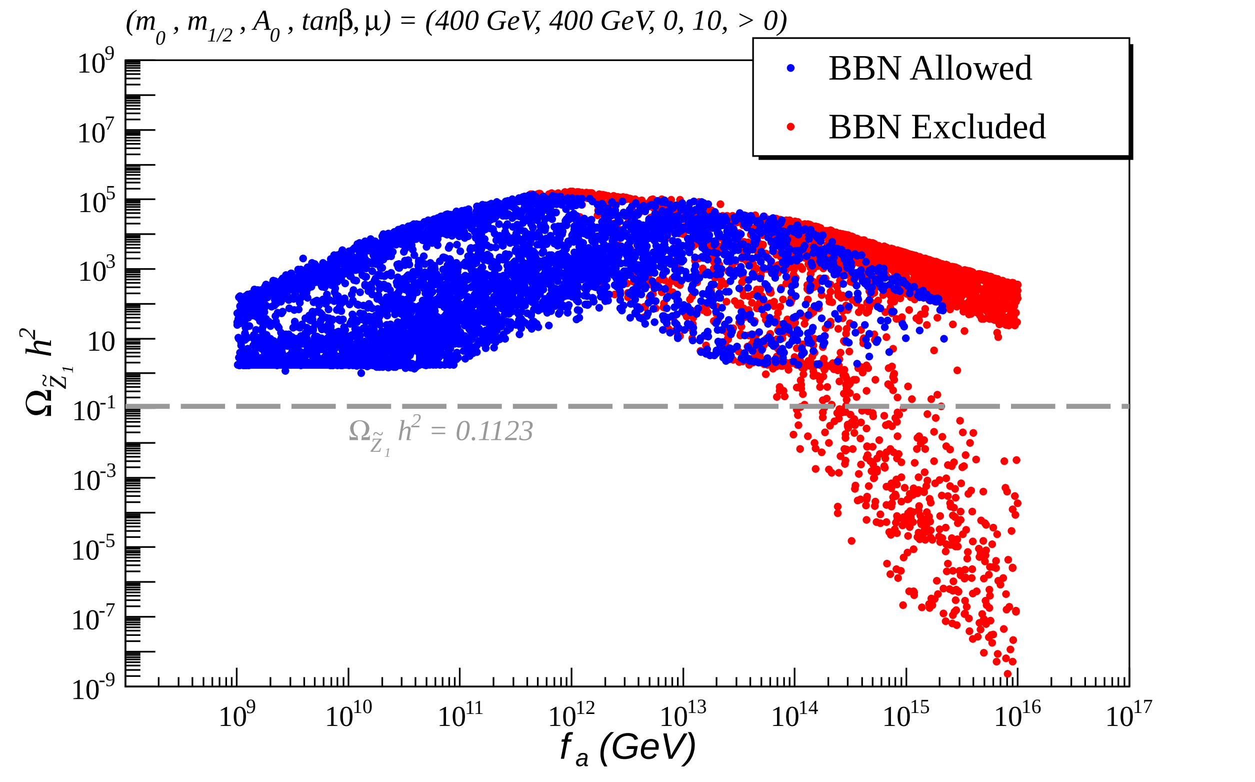
Coupled Boltzmann calculation of mixed $a/bino$ CDM

- Include $\langle \sigma v \rangle (T)$
- Include neutralino production/entropy injection from both axino/saxion decay
- HB, A. Lessa, W. Sreethawong, arXiv:1110.2491 (2011)



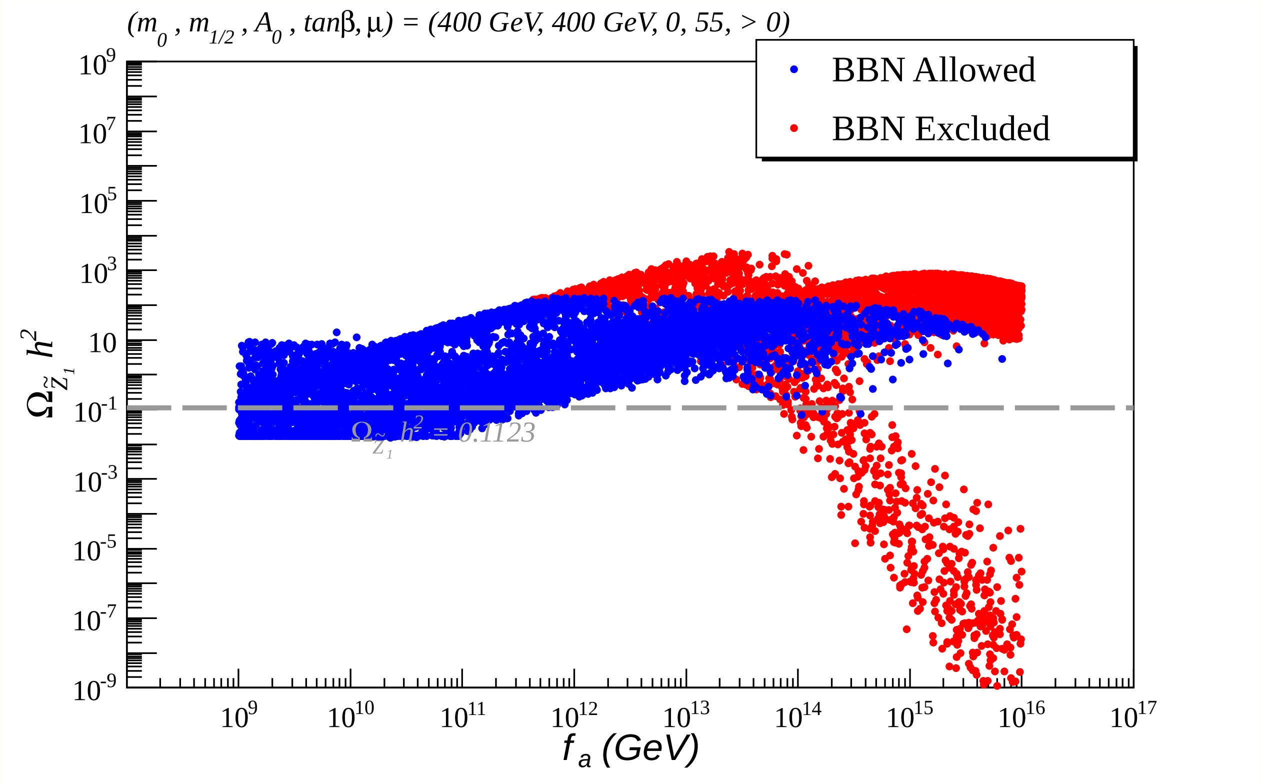
Mixed $a/bino$ CDM: coupled Boltzmann calculation

- saxion entropy versus gluino injection
- only BBN challenged points have low enough relic density



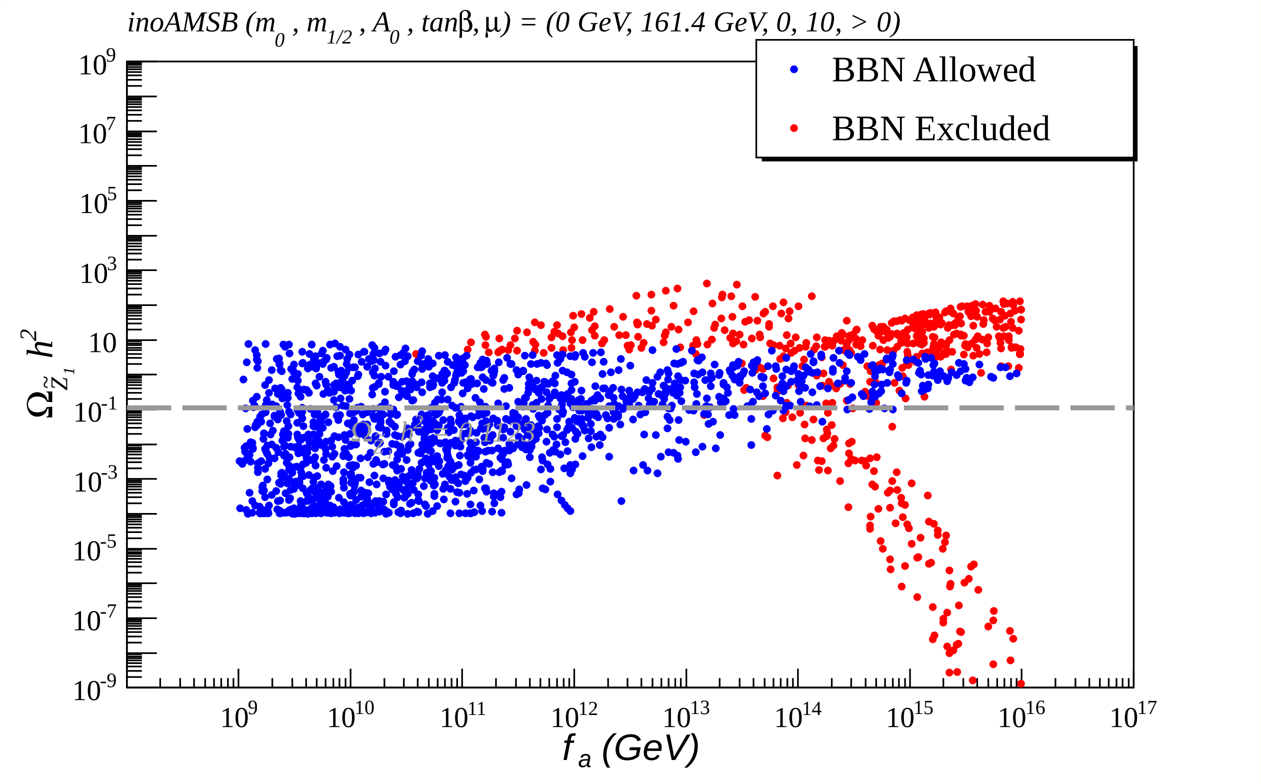
Mixed $a/bino$ CDM: A-funnel

- can allow $f_a \sim 10^{14} - 10^{15}$ GeV!
- DM tends to be neutralino rather than axion dominated at large f_a



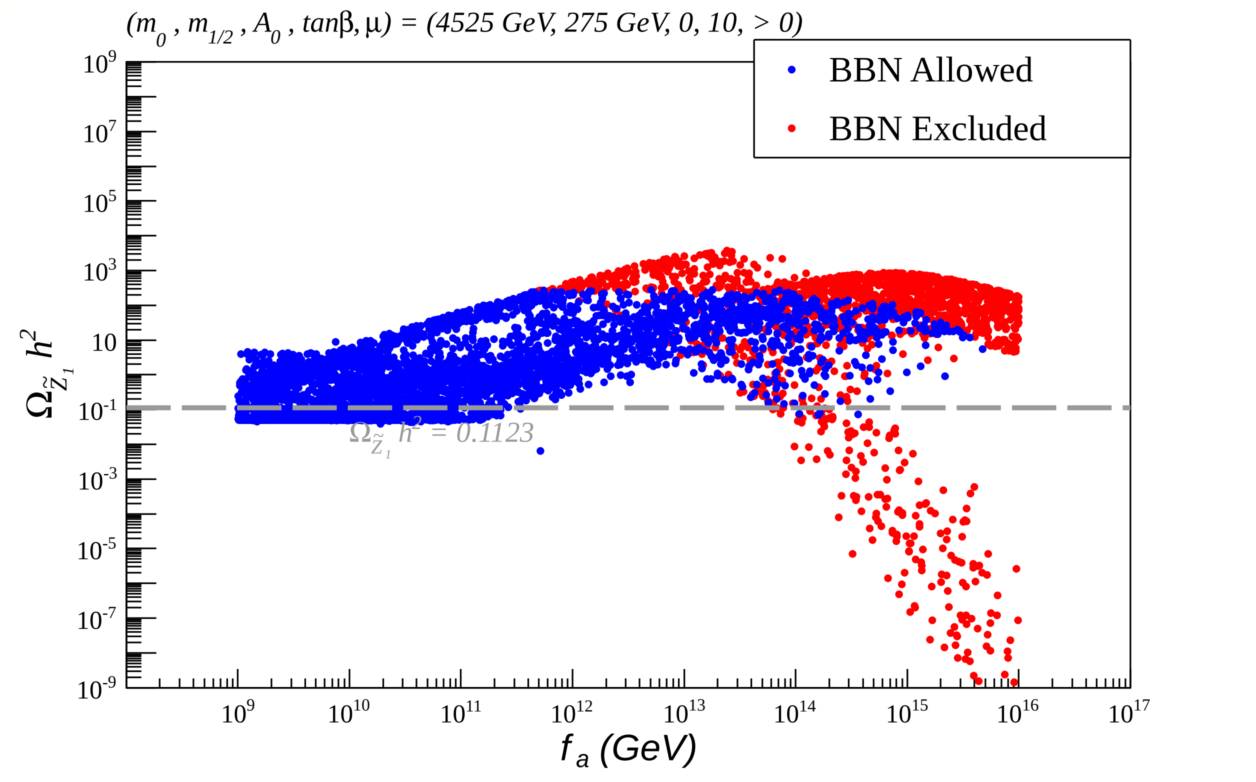
Mixed $a/wino$ CDM: AMSB

- can allow $f_a \sim 10^{14} - 10^{15}$ GeV!
- either neutralino or axion domination possible



Mixed $a/\tilde{b} - \tilde{h}$ CDM: focus point

- can allow $f_a \sim 10^{14} - 10^{15}$ GeV!
- DM tends to be neutralino rather than axion dominated at large f_a



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: need 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
- ⋆ The case $f_a \sim M_{GUT}$ *allowed* for mixed $a\tilde{a}$ DM
- ⋆ Mixed $a\widetilde{Z}_1$ CDM: wino or higgsino DM enhanced by $\tilde{a},\ s$ decay
- ⋆ Mixed $a\widetilde{Z}_1$ CDM: overabundant binos mainly enhanced by axino/saxion decays (unless BBN-challenged)