Mixed axion/axino cold dark matter in SUSY models

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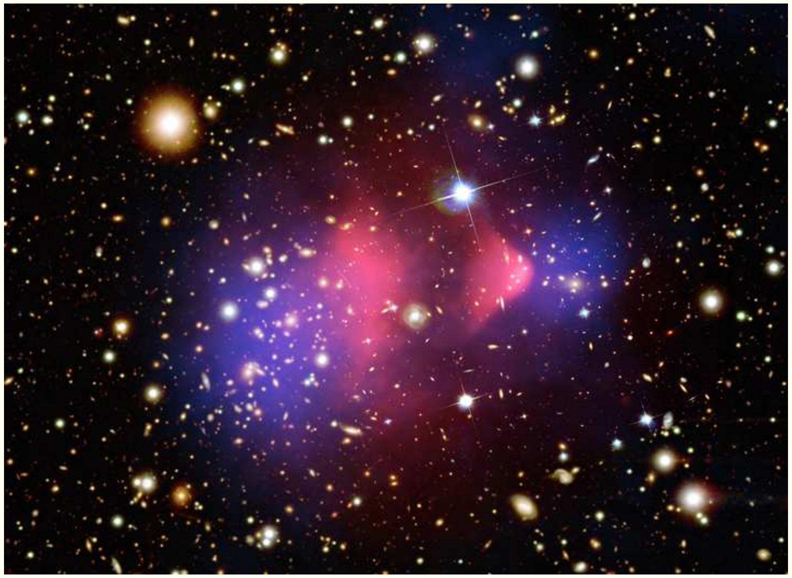
OUTLINE

- ⋆ SUSY WIMPs: miracle or not?
- ⋆ strong CP problem and PQWW solution
- ⋆ the PQMSSM
- ⋆ axion/axino CDM
- ⋆ mSUGRA (CMSSM)
- ⋆ leptogenesis, gravitinos and $a\tilde{a}$ DM
- ⋆ my compliments to our chairperson for her pioneering work!

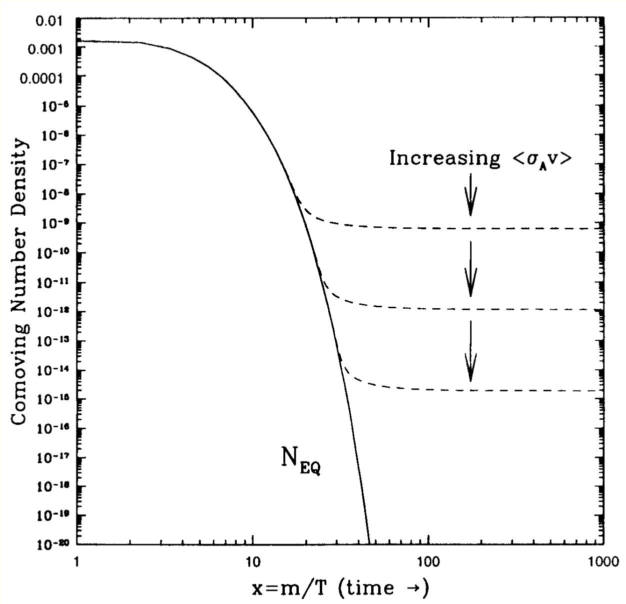


WIMPs: is there a WIMP miracle for SUSY?

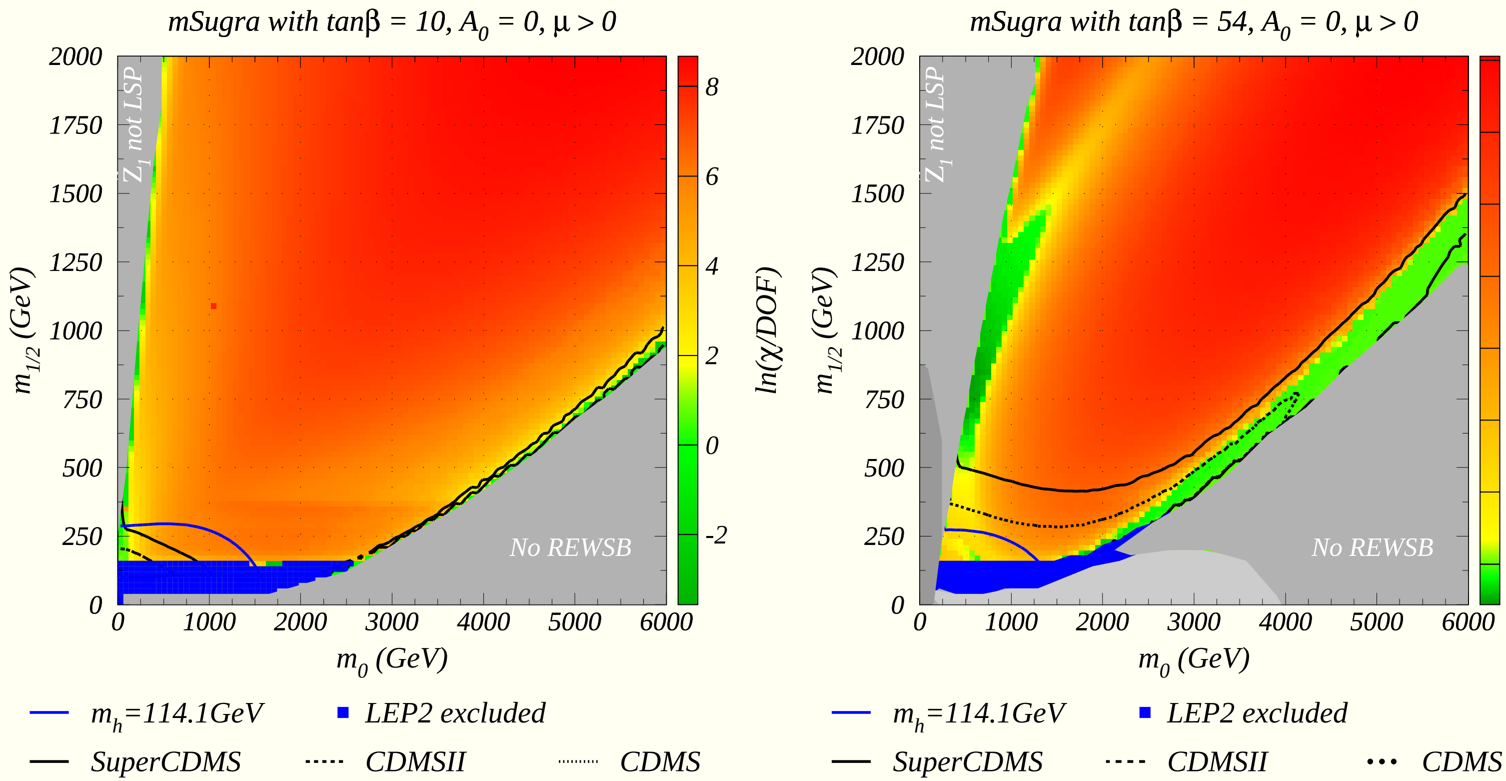
- Weakly Interacting Massive Particles
- assume in thermal equil'n in early universe
- Boltzman eq'n:

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

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



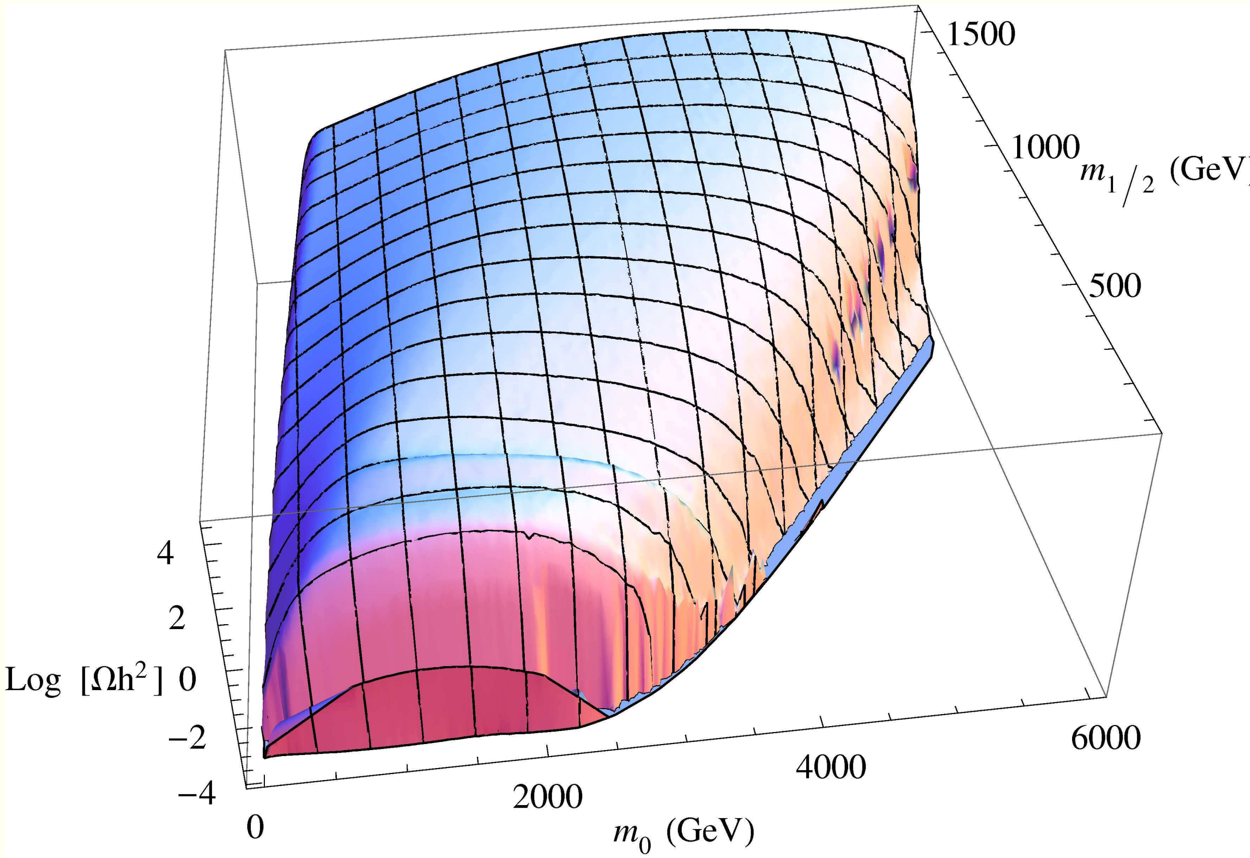
Results of χ^2 fit using τ data for a_μ:



- HB, C. Balazs: JCAP 0305, 006 (2003)
- numerous 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

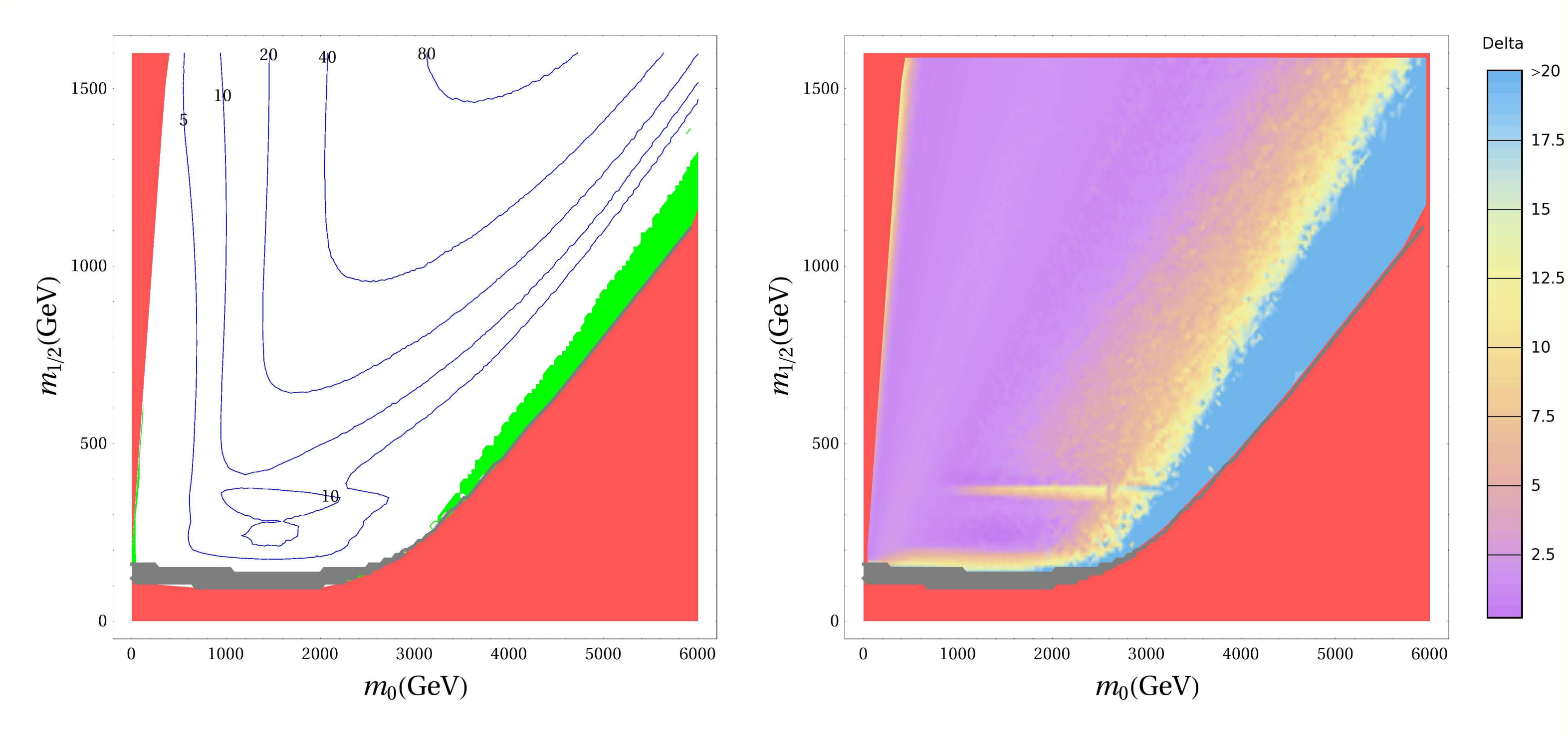
- $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$ (HB, A. Box)



Fine-tuning in mSUGRA with neutralino CDM

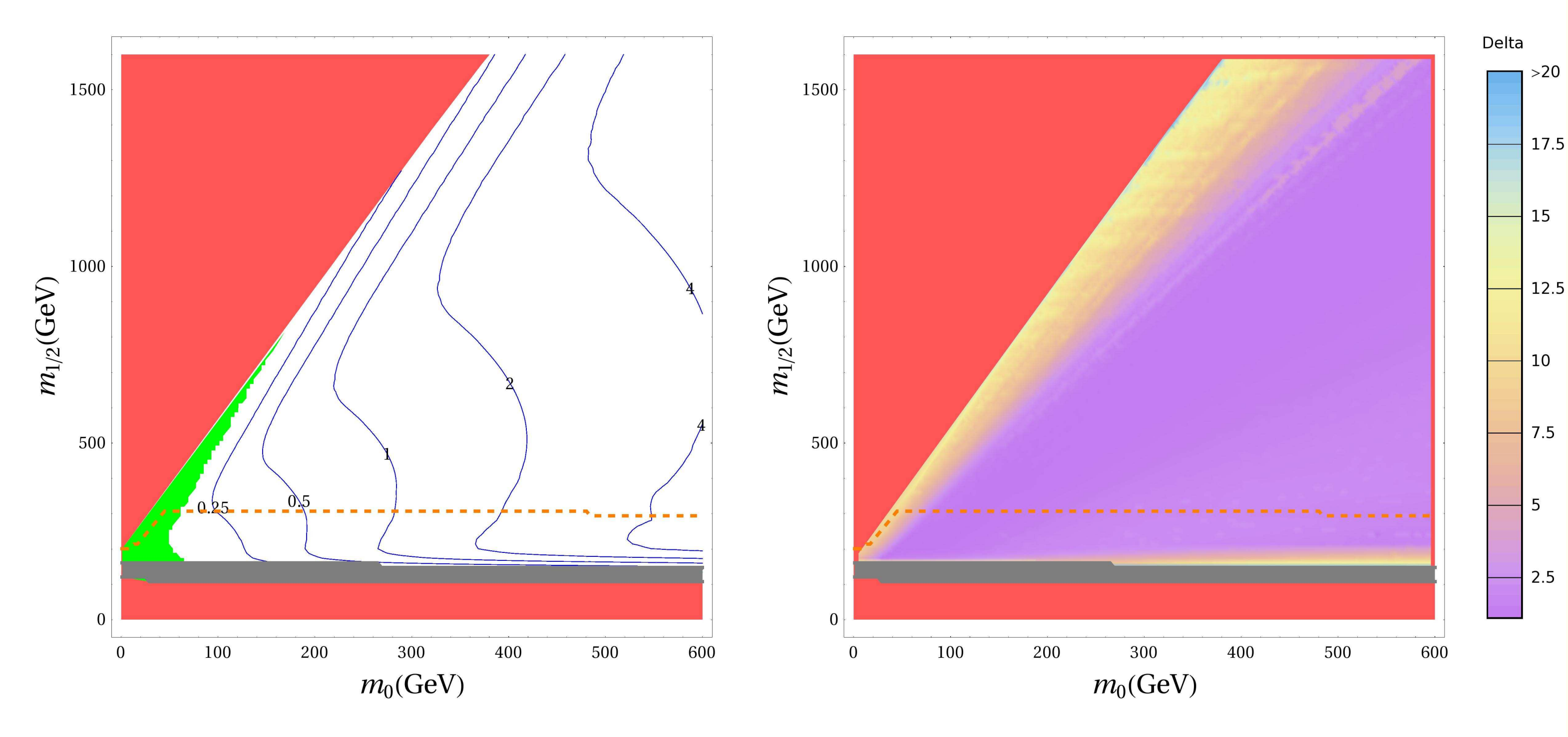
★ contours of $\Omega_{\widetilde{Z}_1} h^2$

★ regions of fine-tune: $\Delta \equiv \frac{\partial \log \Omega_{\widetilde{Z}_1} h^2}{\partial \log a_i}$: (HB, A. Box)



Fine-tuning zoomed in stau-co-annihilation

- ⋆ contours of $\Omega_{\widetilde{Z}_1} h^2$
- ⋆ regions of fine-tune: $\Delta \equiv \dfrac{\partial \log \Omega_{\widetilde{Z}_1} h^2}{\partial \log a_i}$



- ⋆ maybe less fine-tuning with more parameters?

General scan over 19 param. MSSM

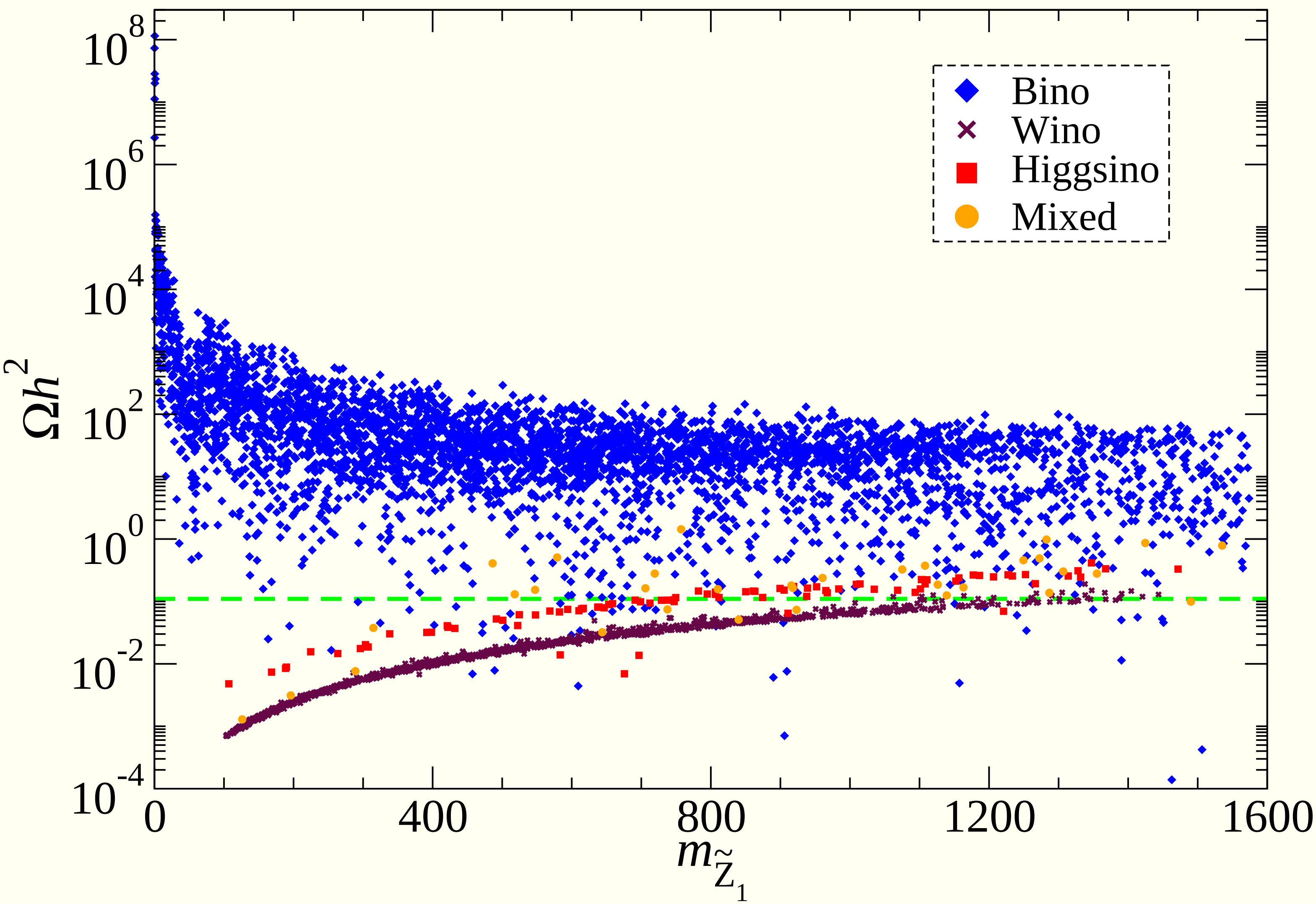
⋆ dimensionful param's defined at M_{GUT}

- $m_{Q_1}, m_{U_1}, m_{D_1}, m_{L_1}, m_{E_1} : 0 \to 3500$ GeV
- $m_{Q_3}, m_{U_3}, m_{D_3}, m_{L_3}, m_{E_3} : 0 \to 3500$ GeV
- $M_1, M_2, M_3 : 0 \to 3500$ GeV
- $A_t,\ A_b,\ A_\tau : -3500 \to 3500$ GeV
- $m_{H_u},\ m_{H_d} : 0 \to 3500$ GeV
- $\tan\beta : 2 \to 60$

⋆ $m_{\widetilde{W}_1} > 103.5$ GeV

⋆ $m_{\widetilde{W}_1} > 91.9$ GeV (wino-like)

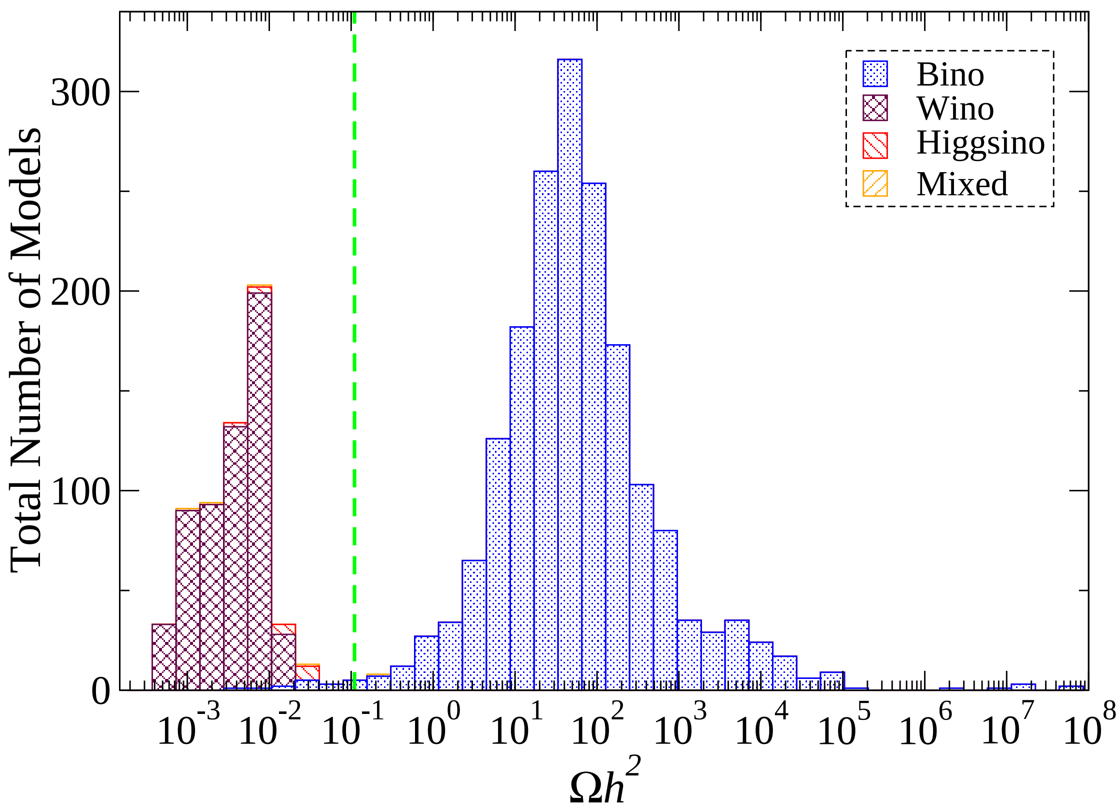
⋆ $m_h > 111$ GeV



★ HB, Box, Summy, arXiv:1005.2215 (2010)

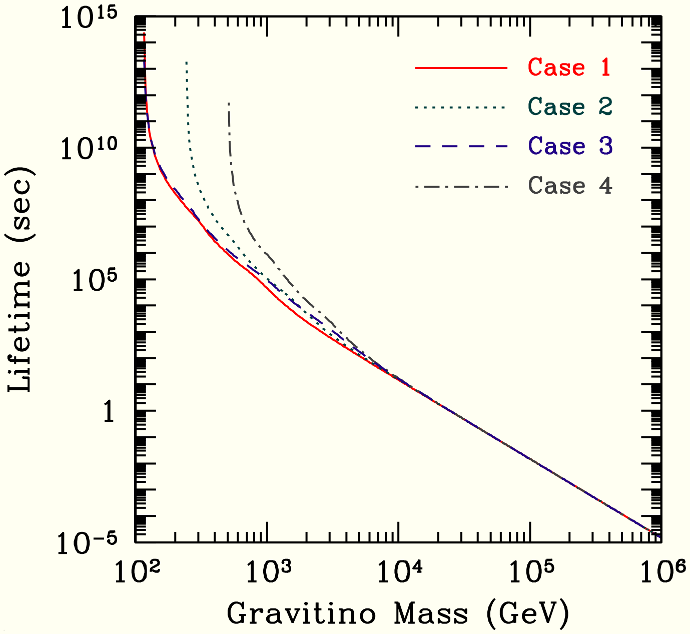
Why WIMP miracle really is a miracle for SUSY

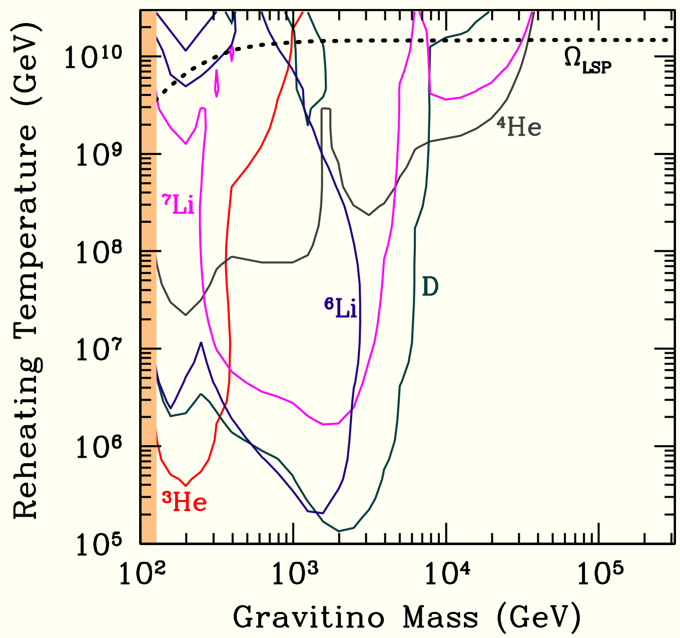
- histogram of models vs. $\Omega_{\widetilde{Z}_1} h^2$ with $m_{\widetilde{Z}_1} < 500$ GeV



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: upper bound on T_R

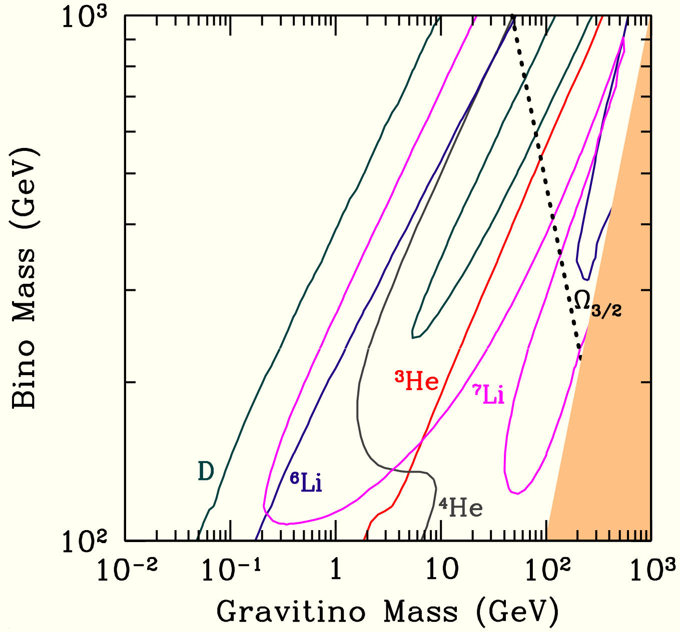




(see Kawasaki, Kohri, Moroi, Yotsuyanagi; Cybert, Ellis, Fields, Olive)

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

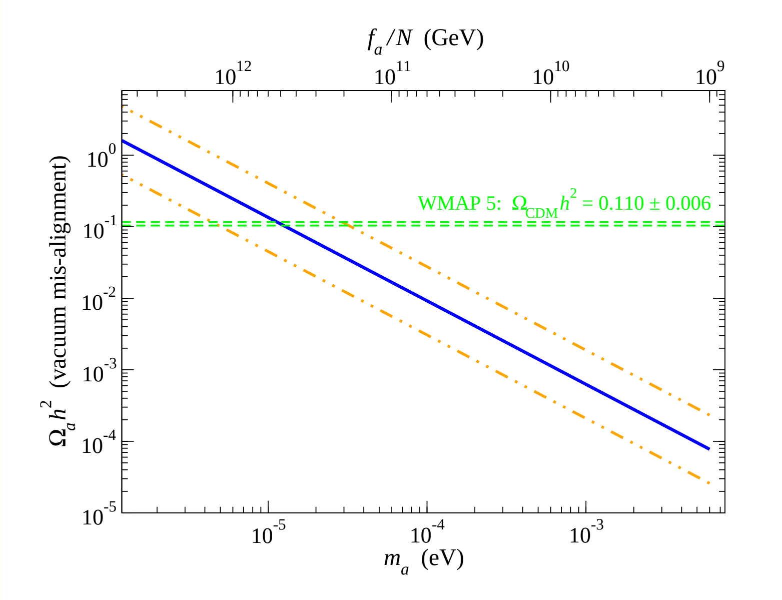
- ⋆ QCD $\ni U(2)_V \times U(2)_A$ global symmetry (2 light quarks)
- ⋆ $U(2)_V = SU(2)_I \times U(1)_B$ realized; $U(2)_A$ broken spontaneously
- ⋆ expect 4 Goldstone bosons: πs and η, but instead $m_\eta \gg m_\pi$: QCD does not respect somehow $U(1)_A$ (Weinberg)
- ⋆ t'Hooft resolution: QCD θ vacuum $\Rightarrow$ 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

Solutions to the strong CP problem

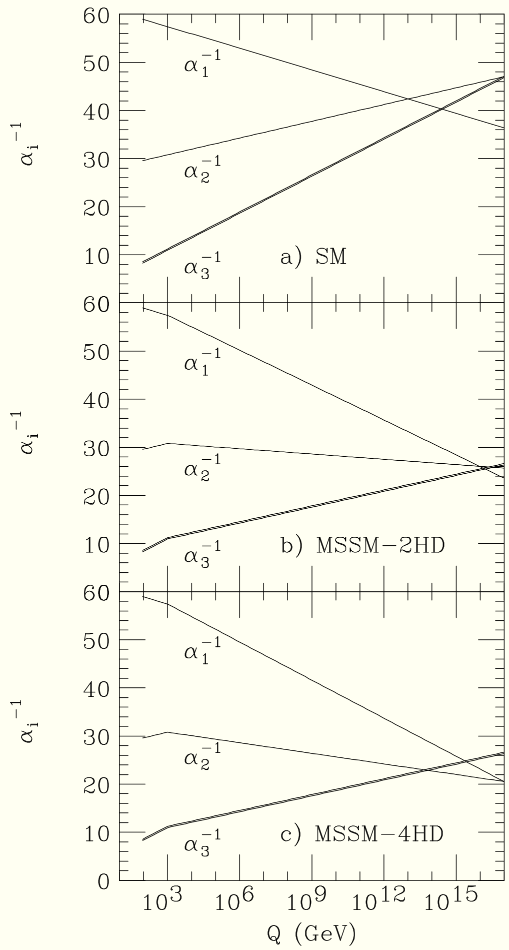
- ⋆ Anthropic: $\bar{\theta}$ luckily small
- ⋆ Spontaneously broken CP: induced $\bar{\theta}$ is small (loop level)
- ⋆ a new chiral symmetry $U_{PQ}(1)$ exists (Peccei-Quinn); $U_{PQ}(1)$ spontaneously broken at scale f_a $(\sim 10^9 - 10^{12}$ GeV)
- ⋆ Goldstone boson field $a(x)$, the axion must exist (Weinberg, Wilczek)
- ⋆ $\mathcal{L} \ni -\frac{1}{2}\partial^\mu a \partial_\mu a + \xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} F_A^{\mu\nu} \tilde{F}_{A\mu\nu} + \mathcal{L}_{int}$
- ⋆ $V_{eff} \sim -(1 - \cos(\bar{\theta} + \xi \frac{a}{f_a}))$
- ⋆ axion field settles to minimum of potential: $\langle a \rangle = -\frac{f_a}{\xi}\bar{\theta}$
- ⋆ strong CP problem solved!
- ⋆ $m_a^2 = \langle \frac{\partial^2 V_{eff}}{\partial a^2} \rangle$

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 $\Rightarrow f_a \gtrsim 10^9 GeV$

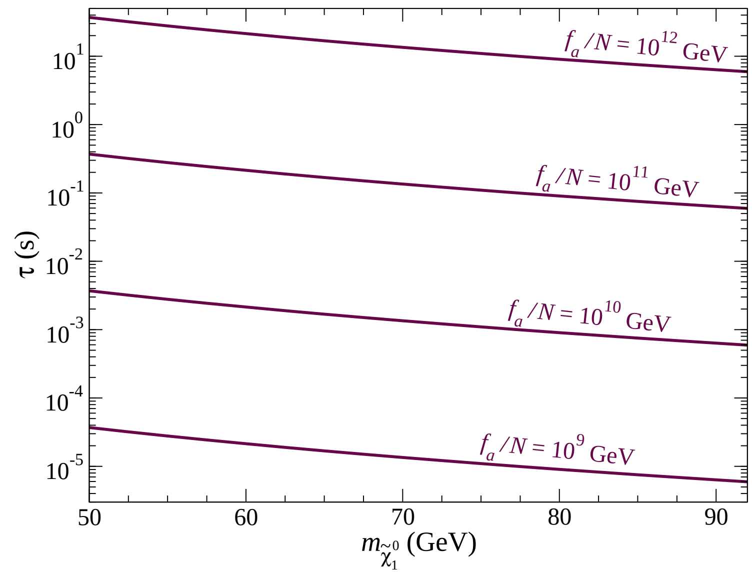


We also know MSSM (plus gauge singlets) is compelling effective theory between M_{weak} and M_{GUT}



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

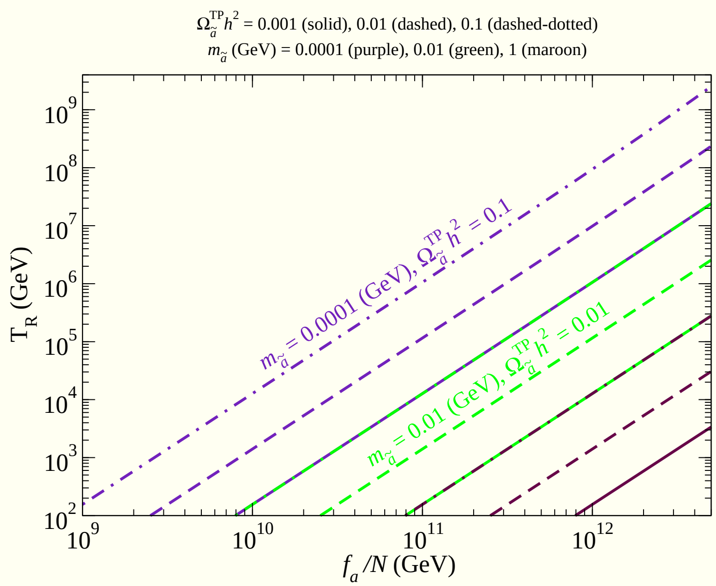
- axino is spin-$\frac{1}{2}$ element of axion supermultiplet (R-odd; can be LSP)
  - Raby, Nilles, Kim
  - Rajagopal, Wilczek, Turner
- $m_{\tilde{a}}$ model dependent: keV$\to$ GeV
- $\widetilde{Z}_1 \to \tilde{a}\gamma$
- non-thermal $\tilde{a}$ production via $\widetilde{Z}_1$ decay:
- axinos inherit 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:

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



Various leptogenesis scenarios

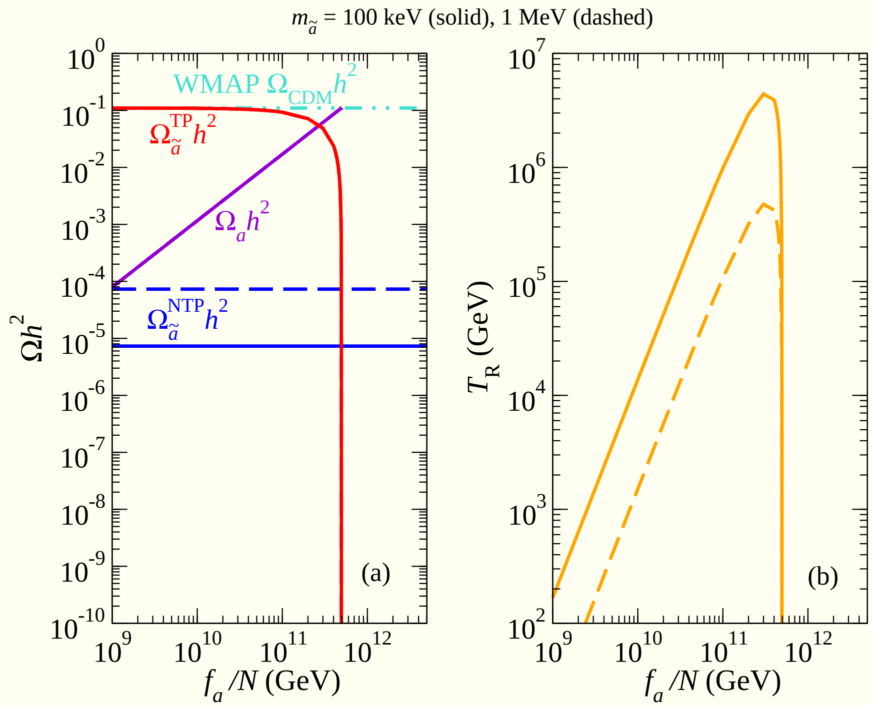
- Upper bound on T_R from BBN is below that for successful *thermal* leptogenesis: need $T_R \gtrsim 10^{10}$ GeV (Buchmuller, Plumacher)
- Alternatively, one may have non-thermal leptogenesis where inflaton $\phi \to N_i N_i$ decay (Lazarides, Shafi; Kumekawa, Moroi, Yanagida)
- additional source of 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: $T_R \sim 10^6 - 10^8$ GeV allowed (Dine, Randall, Thomas; Murayama, Yanagida)
- WMAP observation: $n_b/s \sim 0.9 \times 10^{-10} \Rightarrow T_R \gtrsim 10^6$ GeV

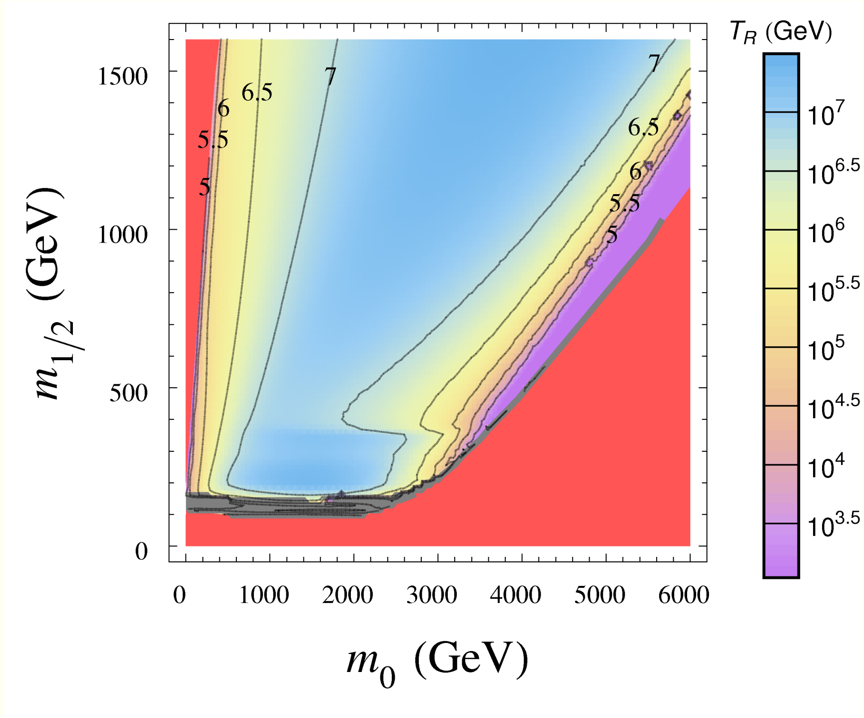
mSUGRA model with mixed axion/axino CDM: $m_{\tilde{a}}$ fixed

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

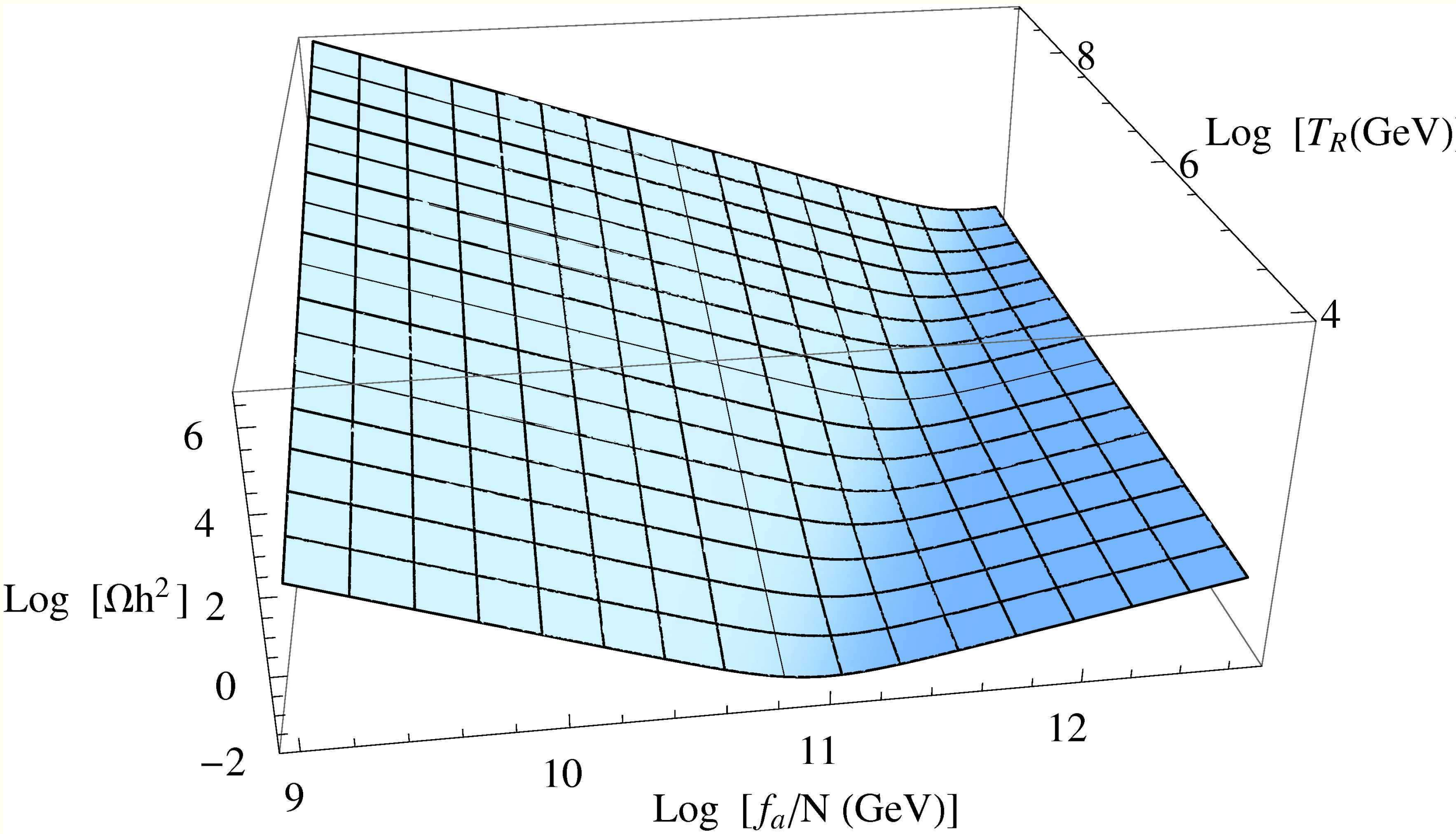


mSUGRA p-space with mainly axion cold DM

- ⋆ 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)



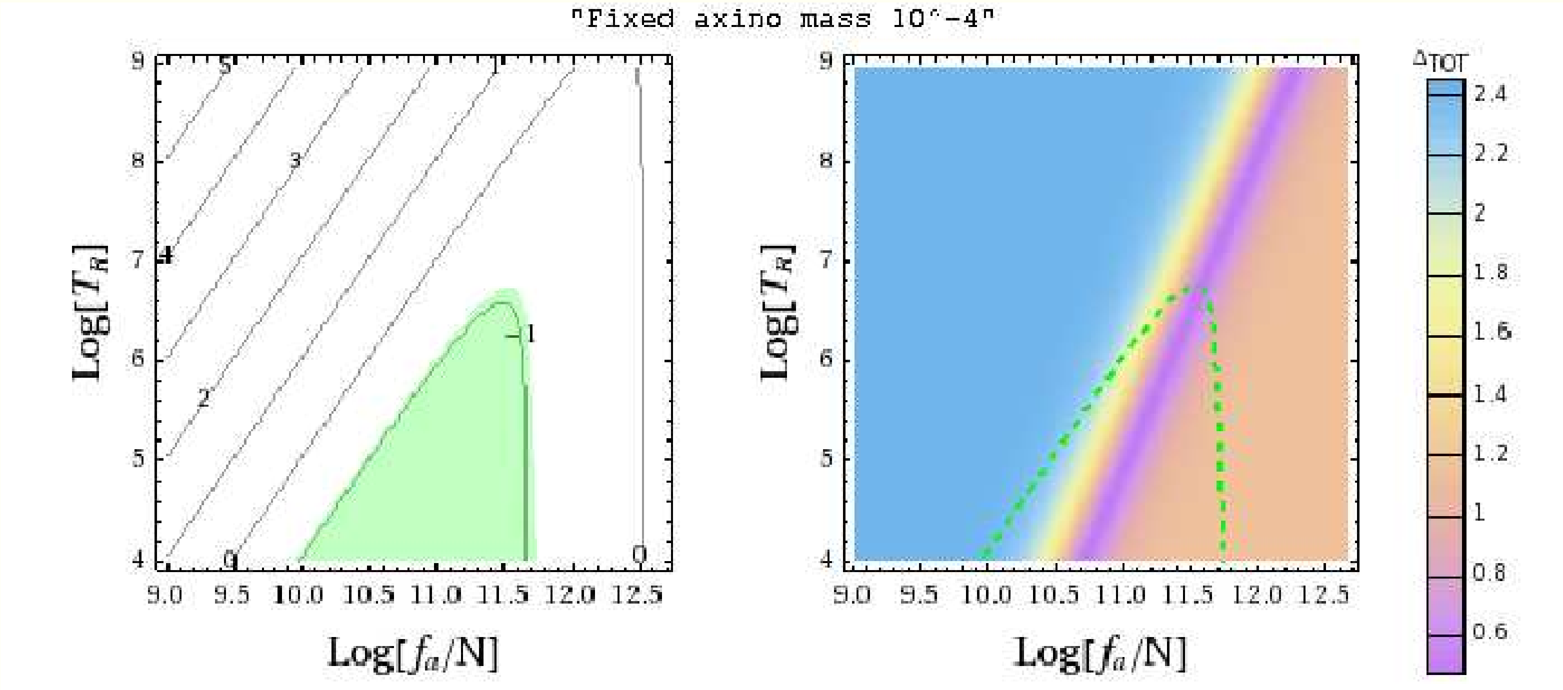
Axion/axino relic density in mSUGRA



Fine-tuning for mainly axion CDM in mSUGRA

★ a). contours of $\Omega_{\widetilde{Z}_1} h^2$

★ regions of fine-tune: $\Delta \equiv \frac{\partial \log \Omega_{\widetilde{Z}_1} h^2}{\partial \log a_i}$

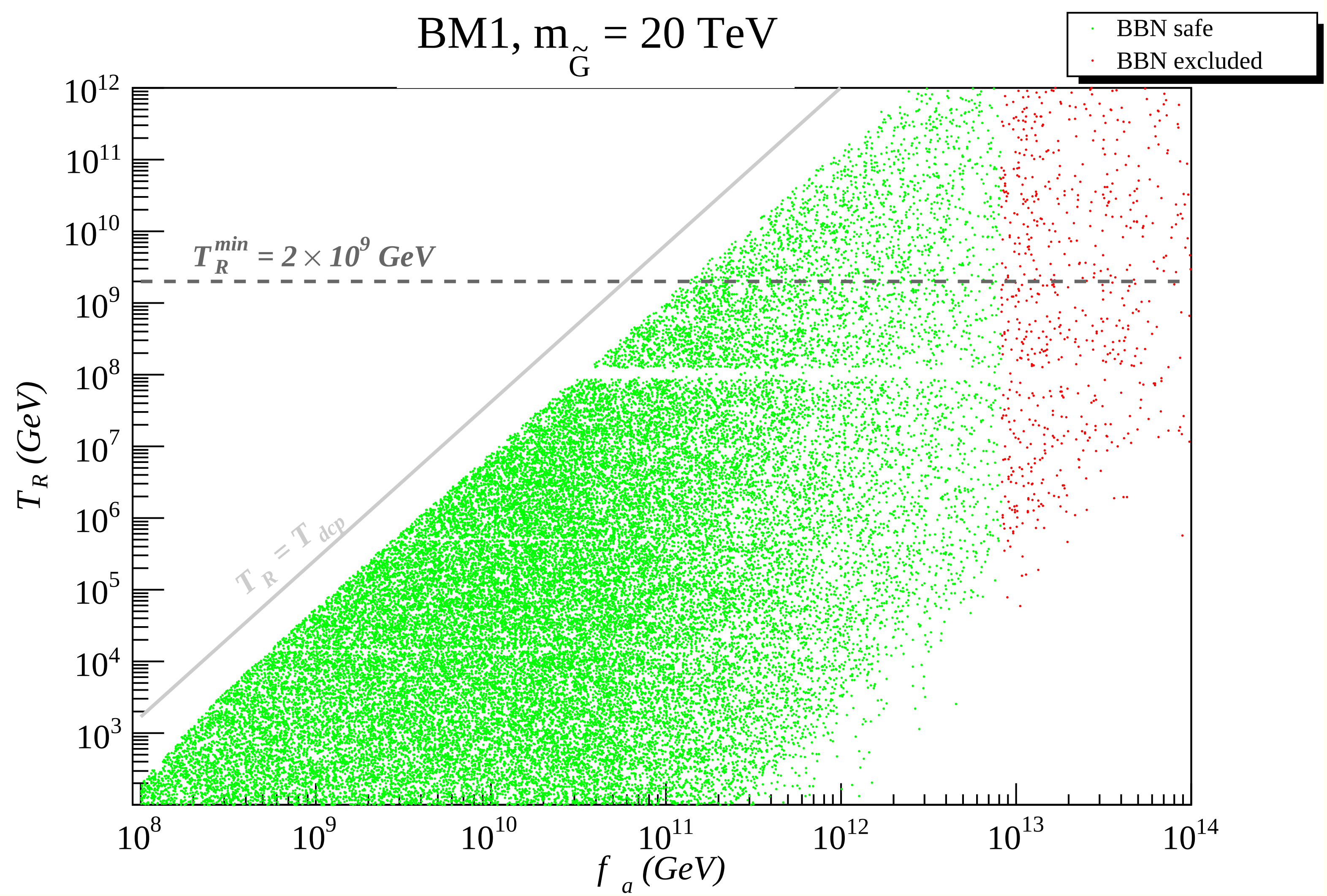


Reconcile *thermal* leptogenesis with $\tilde{G}$ problem?

- ⋆ need $m_{\tilde{G}} \gtrsim 20-30$ TeV to avoid BBN constraints
  - • Yukwaw 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?

Scan over PQMSSM parameters for ESUSY model

★ HB, Kraml, Lessa, Sekmen



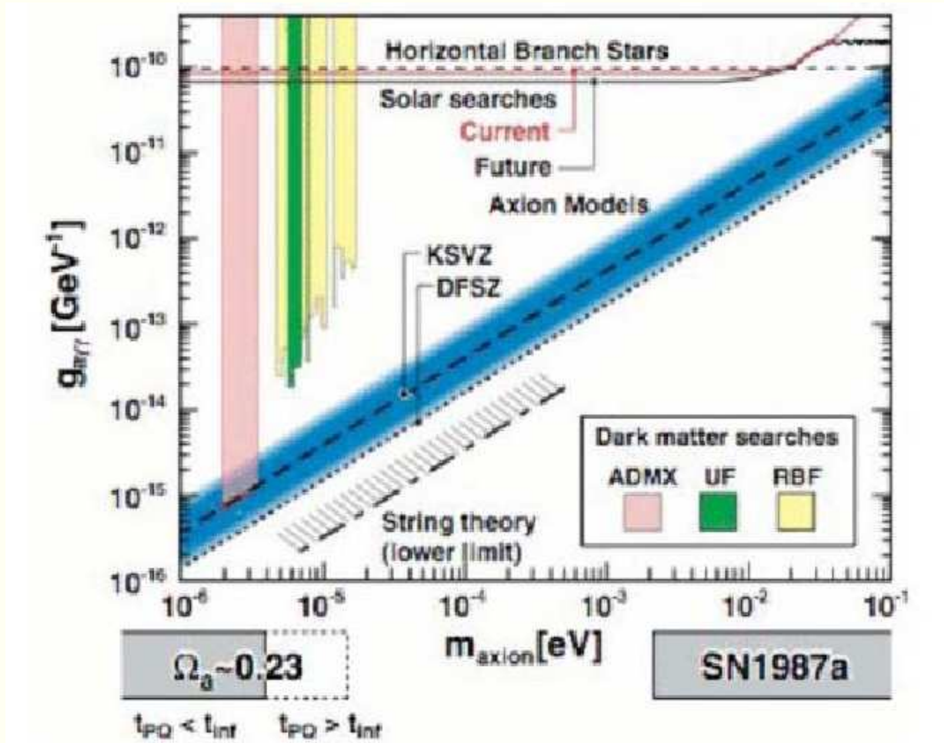
Conclusions

- ⋆ neutralino CDM: usually too much or too little
- ⋆ neutralino CDM with $\Omega_{\widetilde{Z}_1} h^2 \sim 0.1$ fine-tuned
- ⋆ PQ strong CP solution $+$ SUSY: why not both?
- ⋆ expect mixed axion/axino CDM if $\tilde{a}$ is LSP
- ⋆ then low fine-tuning of $\Omega_{a\tilde{a}} h^2$
- ⋆ $T_R \sim 10^6 - 10^8$ possible:
  - solve gravitino problem if $m_{\tilde{G}} \gtrsim 5$ TeV
  - allow for non-thermal leptogenesis
- ⋆ Neutralino CDM forbidden benchmarks now favored!
- ⋆ Also reconcile *thermal* leptogenesis with gravitino problem in certain SUSY models with $m_{\tilde{G}} \gtrsim 30$ TeV

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



Need for broader, deeper axion searches

⋆ axion param. space: Gondolo & Visinelli, 2009 study

- we have only begun $\cdots$