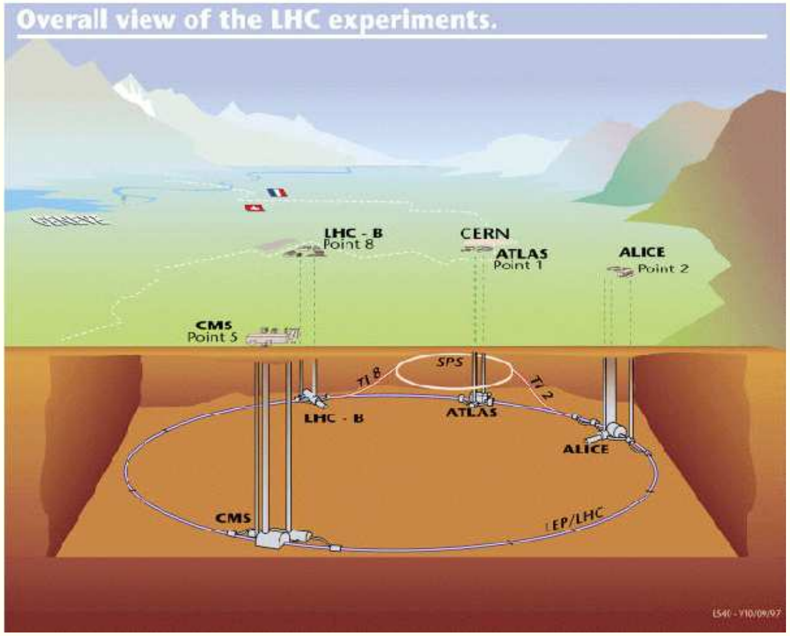
Mixed axion/axino cold dark matter in SUSY: with implications for LHC

Howard Baer

University of Oklahoma

OUTLINE

- ⋆ old ideas from 1970s
- ⋆ strong CP problem and PQWW solution
- ⋆ the PQMSSM
- ⋆ axion/axino CDM
- ⋆ mSUGRA (CMSSM)
- ⋆ Effective SUSY
- ⋆ Yukawa-unified SUSY



Old ideas from the dawn of time: (1970s)

- renormalizable gauge theories
- QCD
- the Standard Model
- supersymmetry
- GUTs
- superstrings
- see-saw neutrinos
- PQ strong CP solution

Origin of strong CP problem

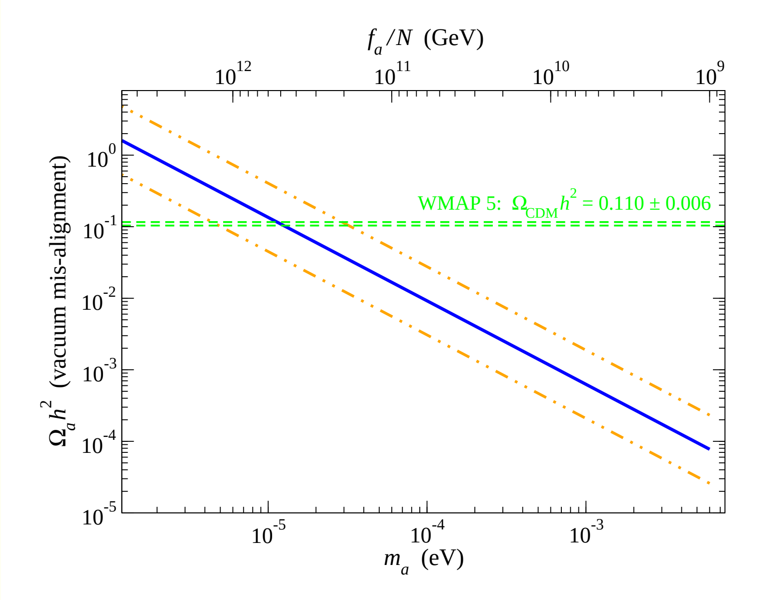
- ⋆ QCD $\ni U(2)_V \times U(2)_A$ global symmetry (2 light quarks)
- ⋆ $U(2)_V = SU(2)_I \times U(1)_B$ realized; $U(2)_A$ broken spontaneously
- ⋆ expect 4 Goldstone bosons: πs and η, but instead $m_\eta \gg m_\pi$: QCD does not respect somehow $U(1)_A$ (Weinberg)
- ⋆ t'Hooft resolution: QCD θ vacuum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

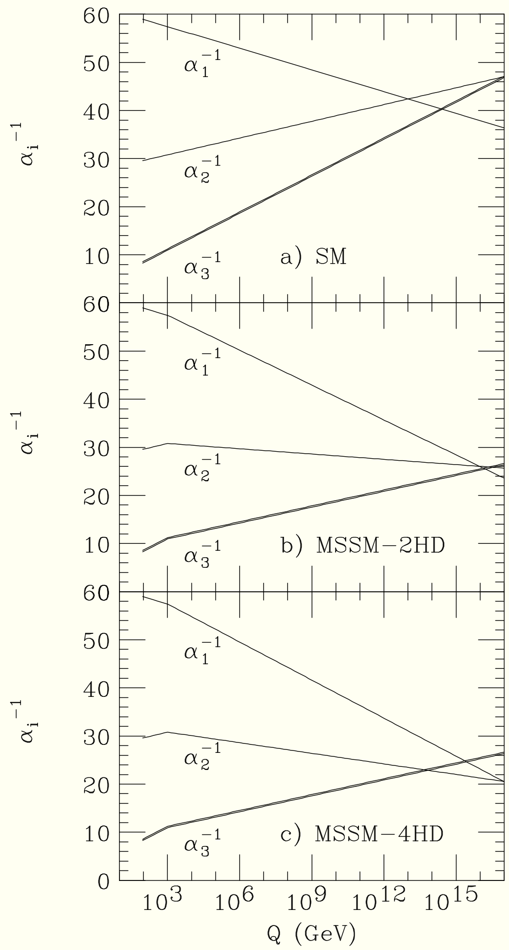
- ⋆ Anthropic: $\bar{\theta}$ luckily small
- ⋆ Spontaneously broken CP: induced $\bar{\theta}$ is small (loop level)
- ⋆ a new chiral symmetry $U_{PQ}(1)$ exists (Peccei-Quinn); $U_{PQ}(1)$ spontaneously broken at scale f_a $(\sim 10^9 - 10^{12}$ GeV)
- ⋆ Goldstone boson field $a(x)$, the axion must 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

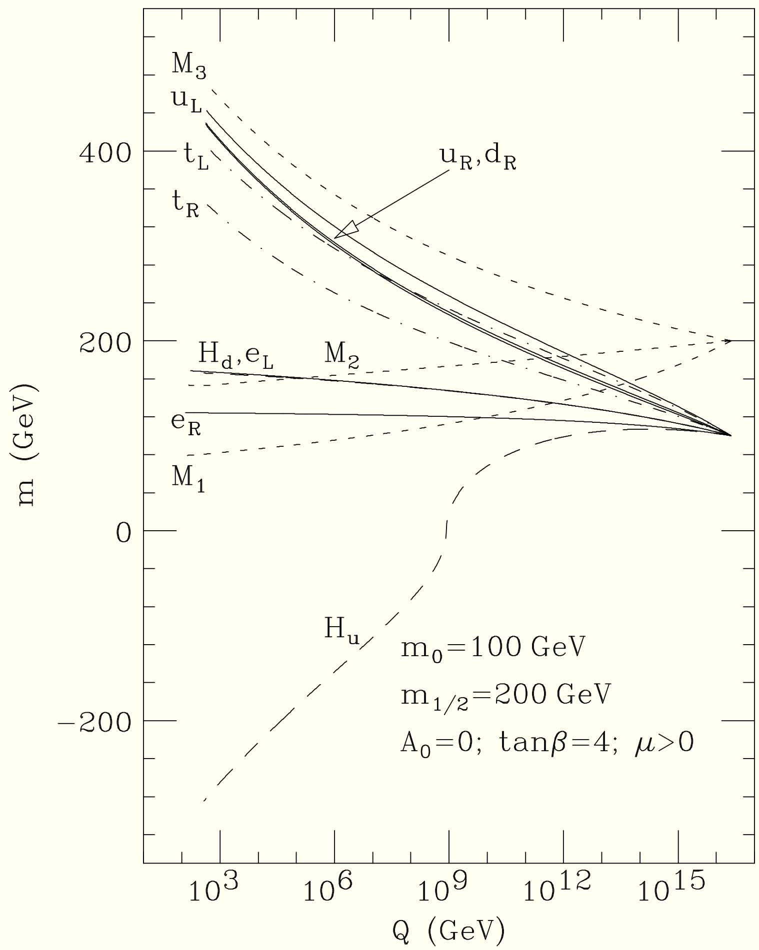
- ⋆ Axion field eq'n of motion: $\theta = a(x)/f_a$
  - $\ddot{\theta} + 3H(T)\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial \theta} = 0$
  - $V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$
  - Solution for T large, $m_a(T) \sim 0$: $\theta = const.$
  - $m_a(T)$ turn-on ~ 1 GeV
- ⋆ a(x)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



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

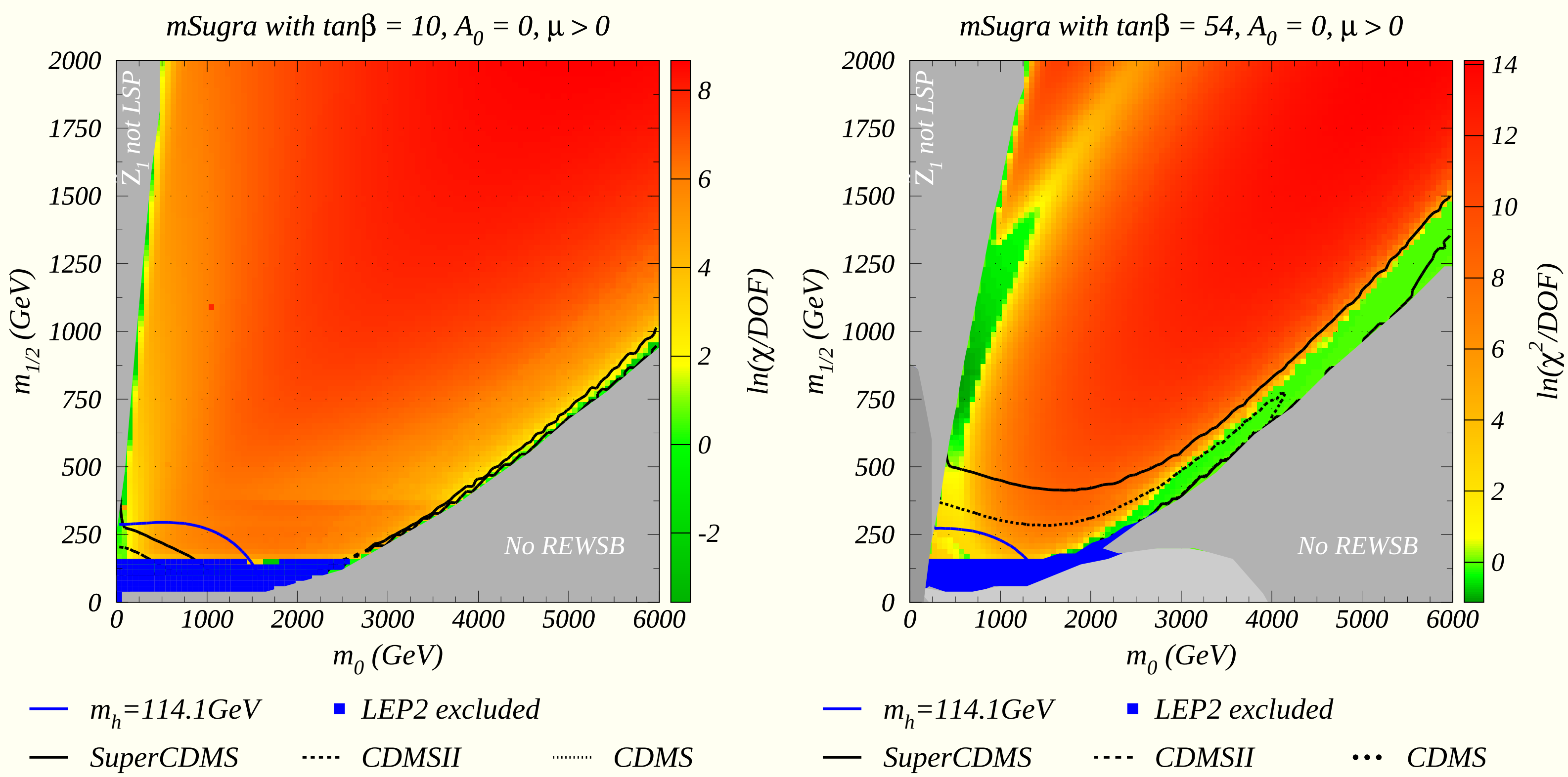


Most analyses work in mSUGRA (CMSSM) model



- $m_0,\ m_{1/2},\ A_0,\ \tan\beta, sign(\mu)$

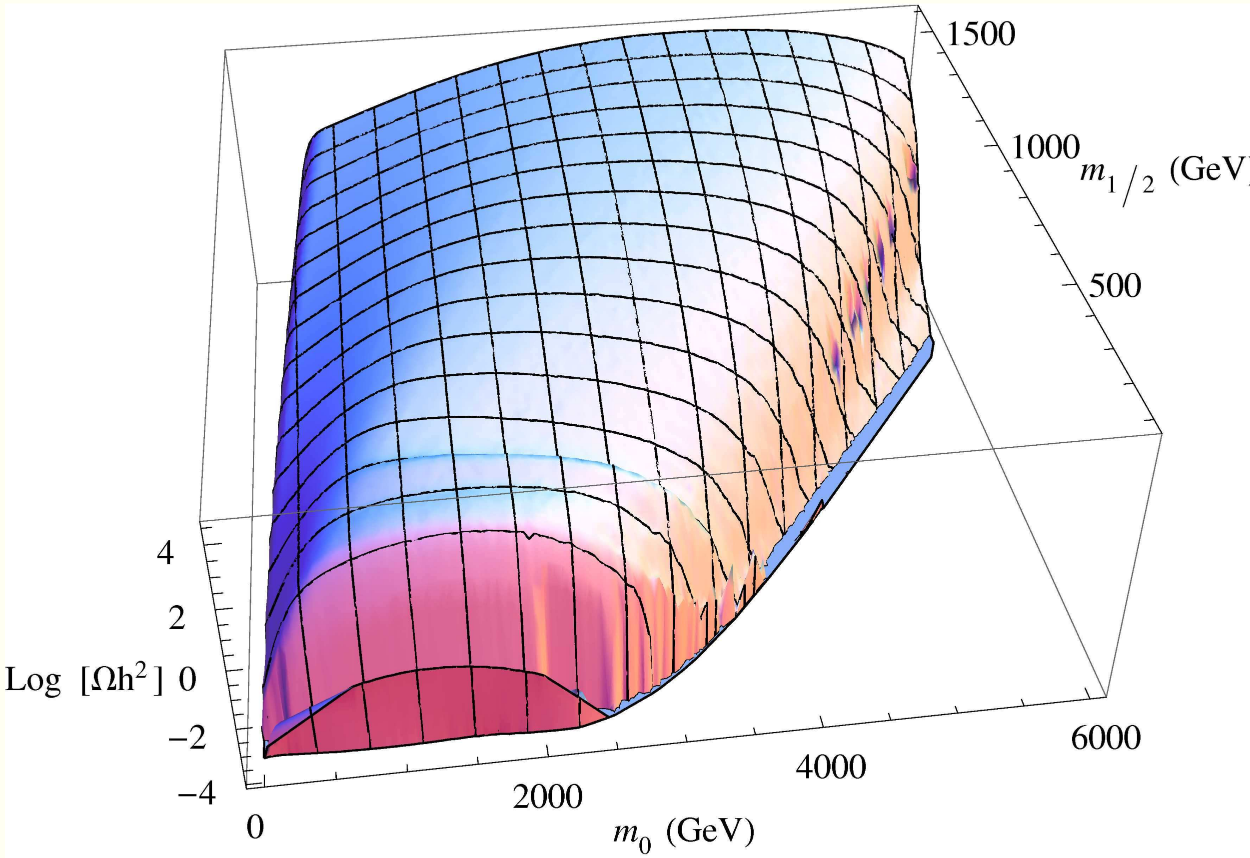
Results of χ^2 fit using τ data for a_μ:



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

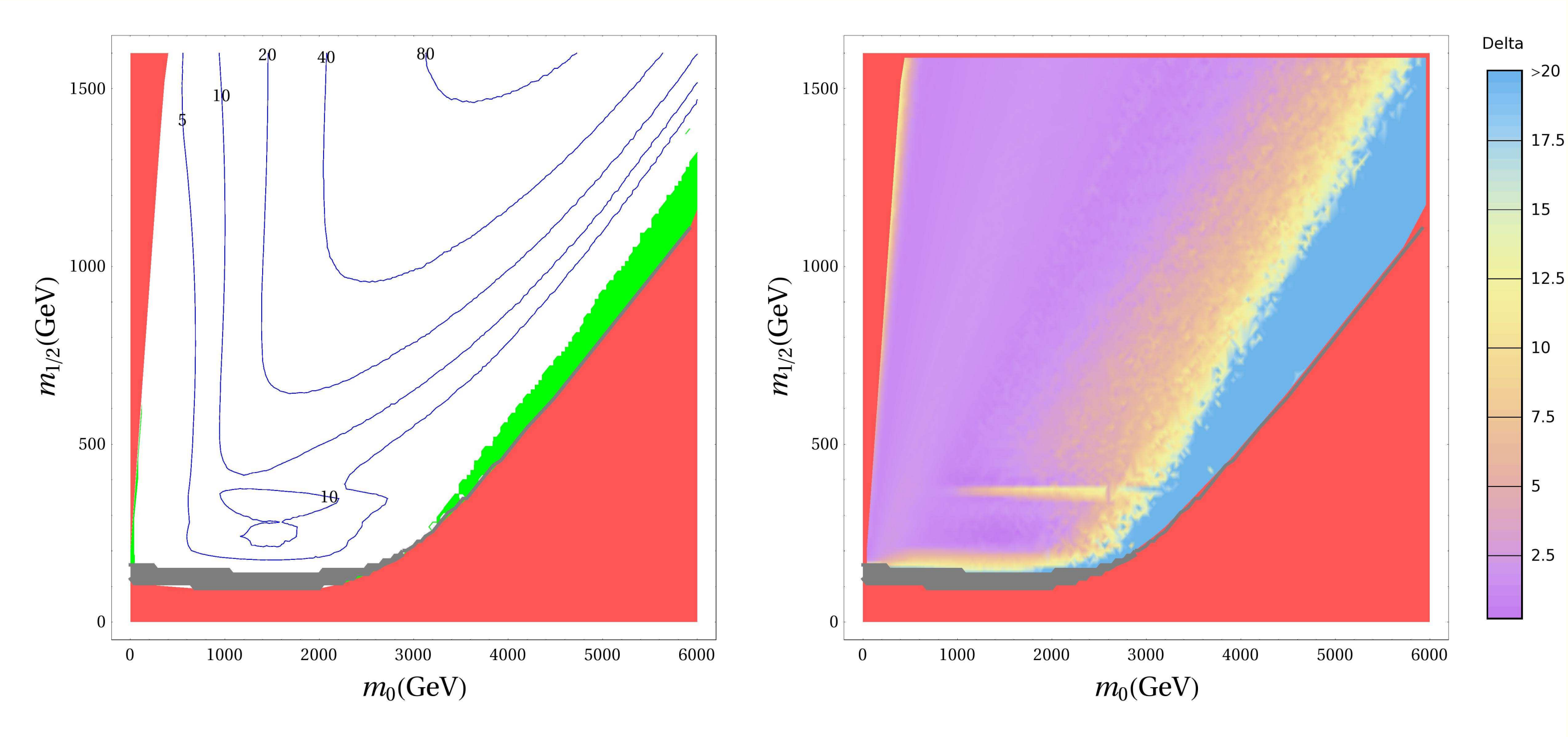
$\Omega_{\widetilde{Z}_1} h^2$ as surface in m_0 vs. $m_{1/2}$ space

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



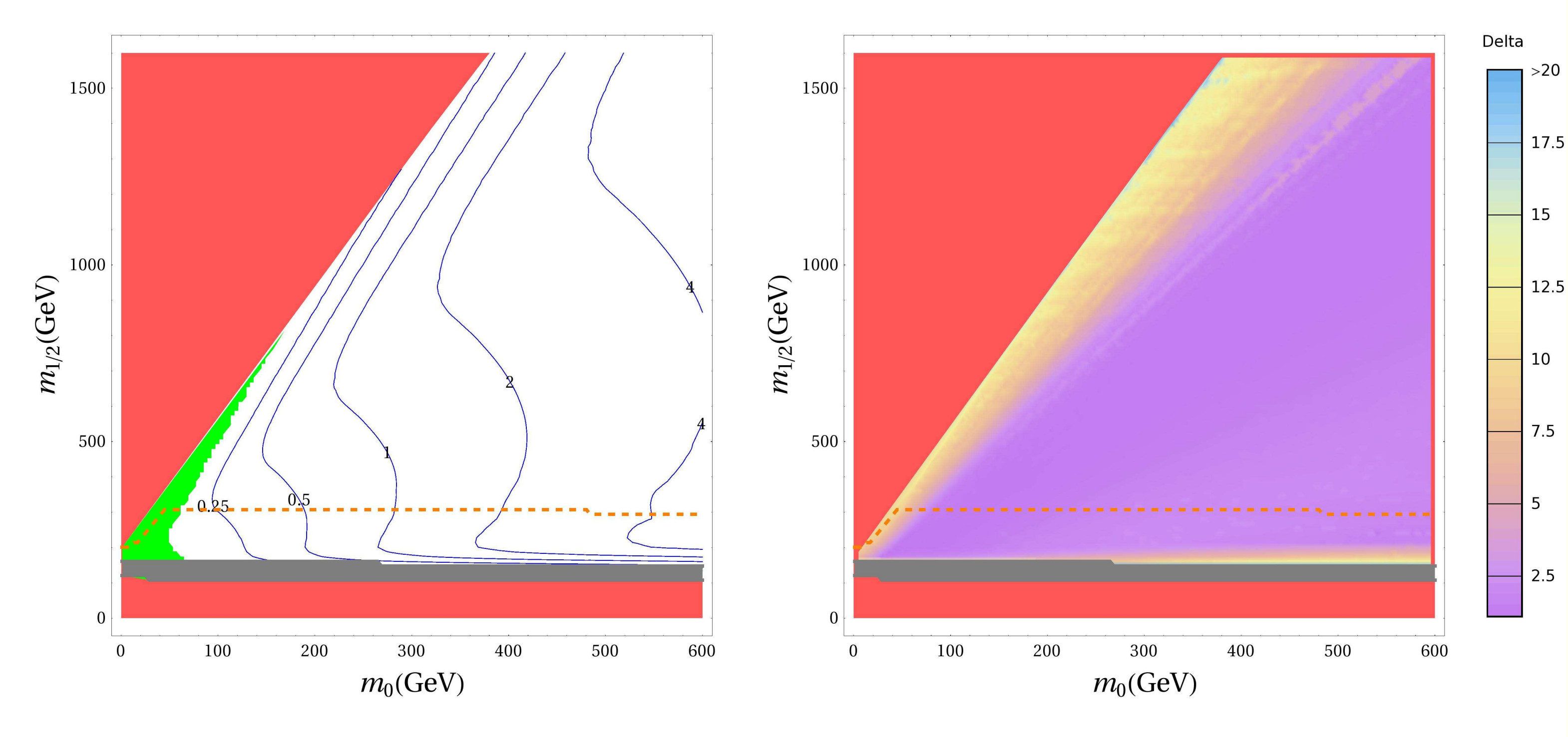
Fine-tuning in mSUGRA with neutralino CDM

- ⋆ 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: $\Delta \equiv \frac{\partial \log \Omega_{\widetilde{Z}_1} h^2}{\partial \log a_i}$



General scan over 19 param. MSSM

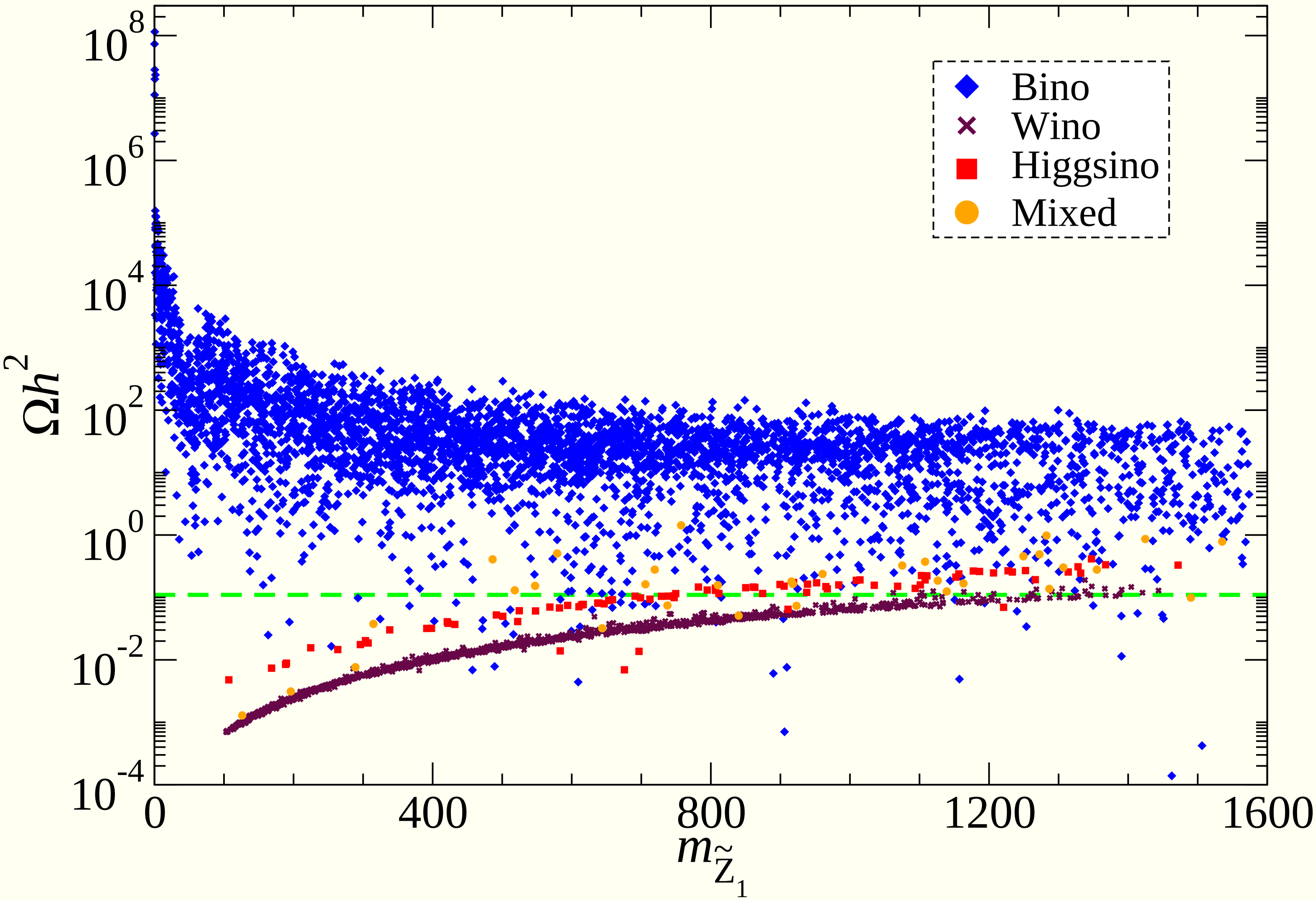
⋆ dimensionful param's defined at M_{GUT}

- $m_{Q_1}, m_{U_1}, m_{D_1}, m_{L_1}, m_{E_1} : 0 \rightarrow 3500$ 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)

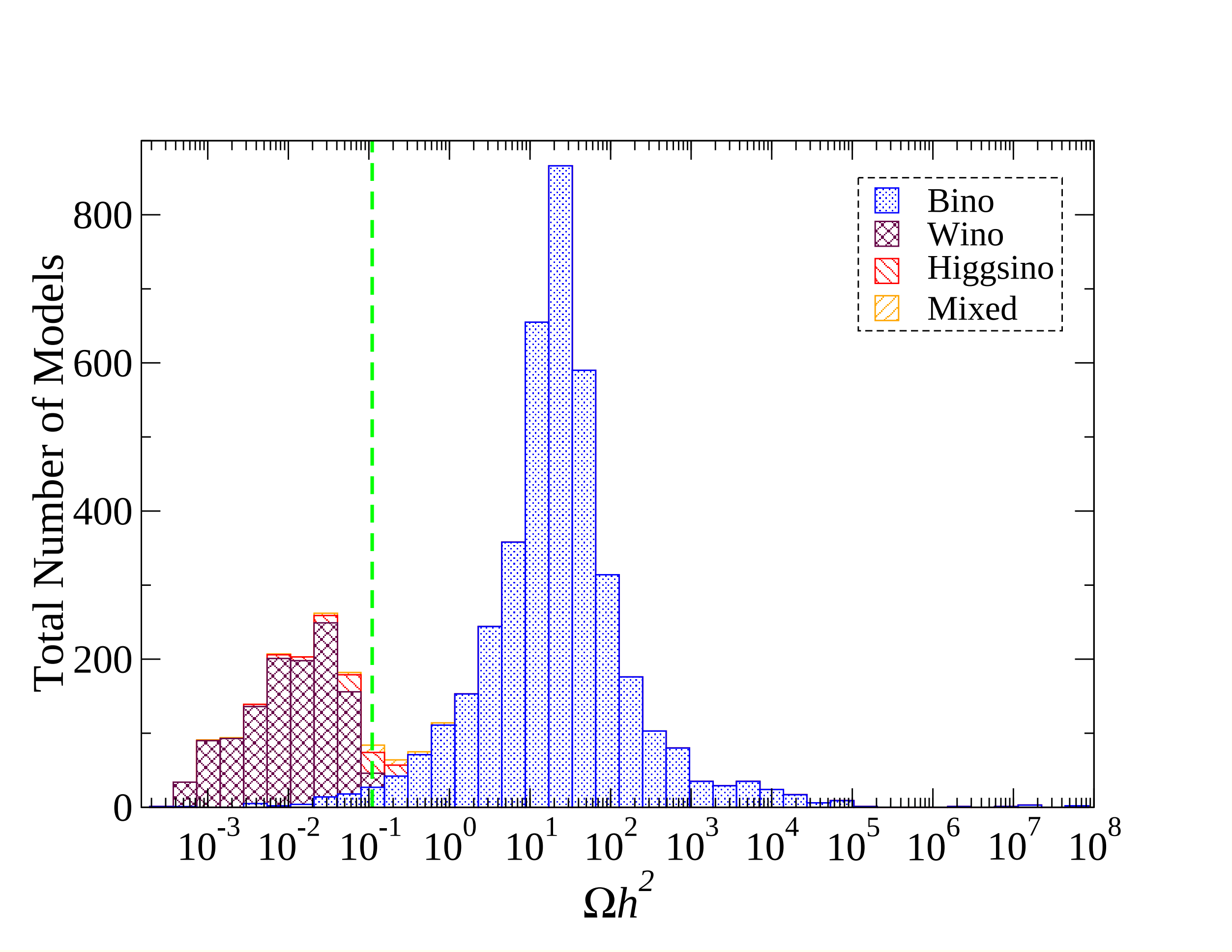
⋆ $m_h > 111$ GeV



Bino
Wino
Higgsino
Mixed
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
Ωh^2
0
400
800
1200
1600
$m_{\tilde{Z}_1}$

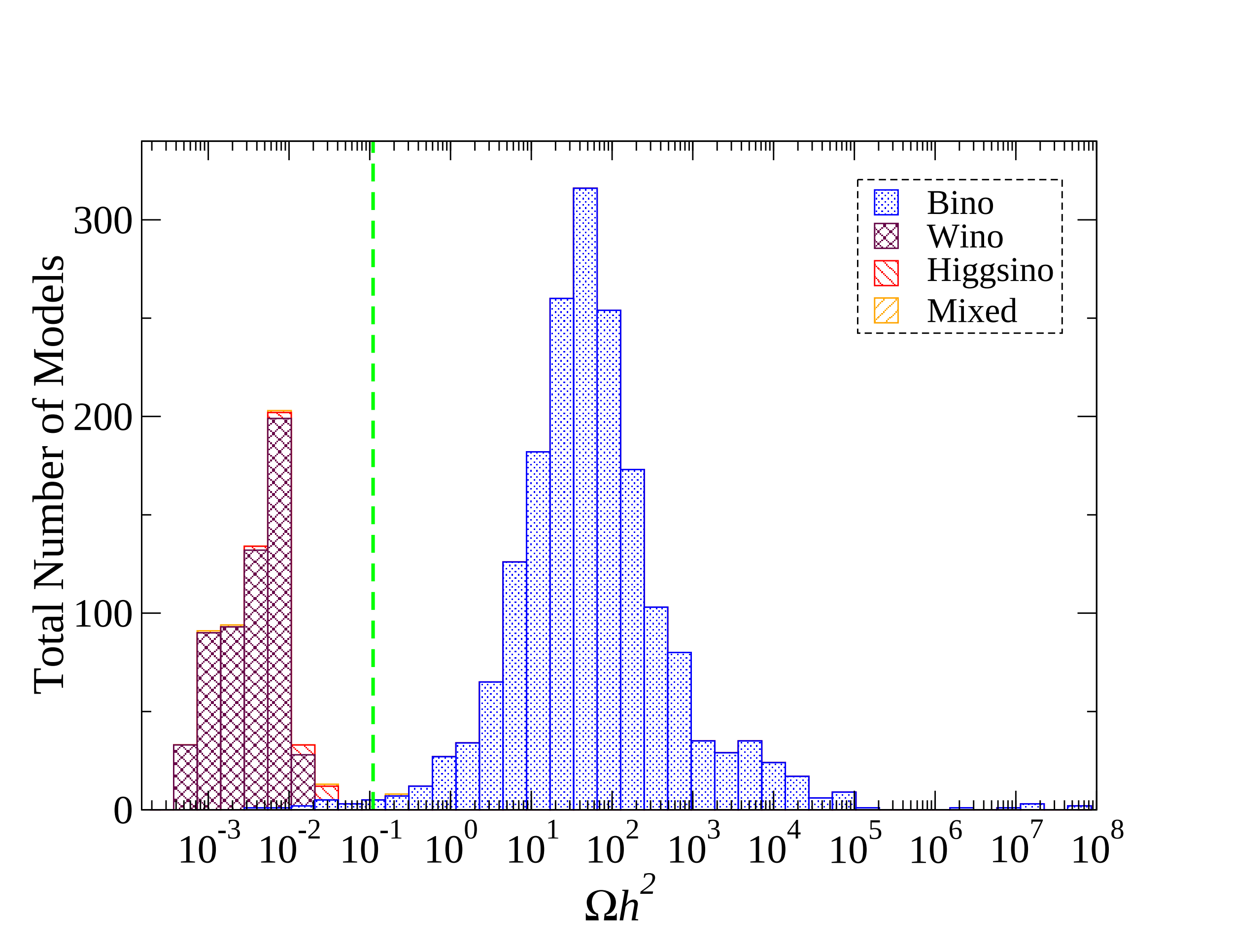
General MSSM 19 param. scan

- histogram of models vs. $\Omega_{\widetilde{Z}_1} h^2$



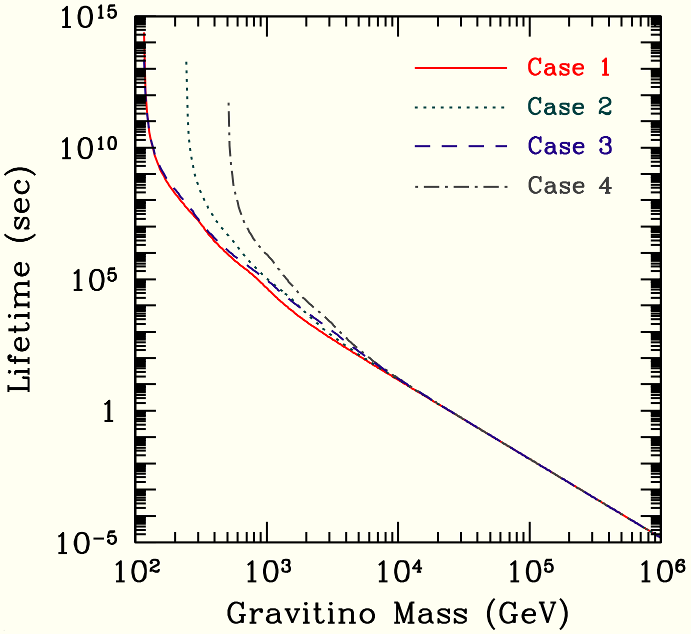
Why WIMP miracle really is a miracle for SUSY

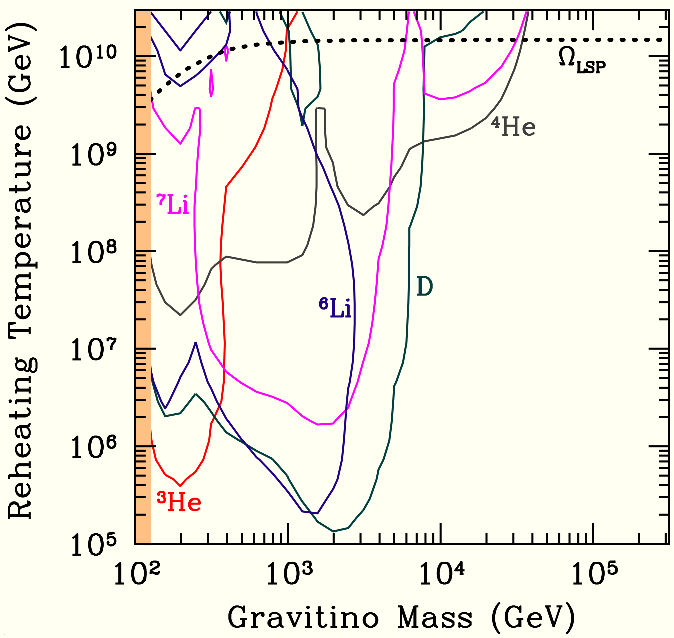
- histogram of models vs. $\Omega_{\widetilde{Z}_1} h^2$ with $m_{\widetilde{Z}_1} < 500$ GeV



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

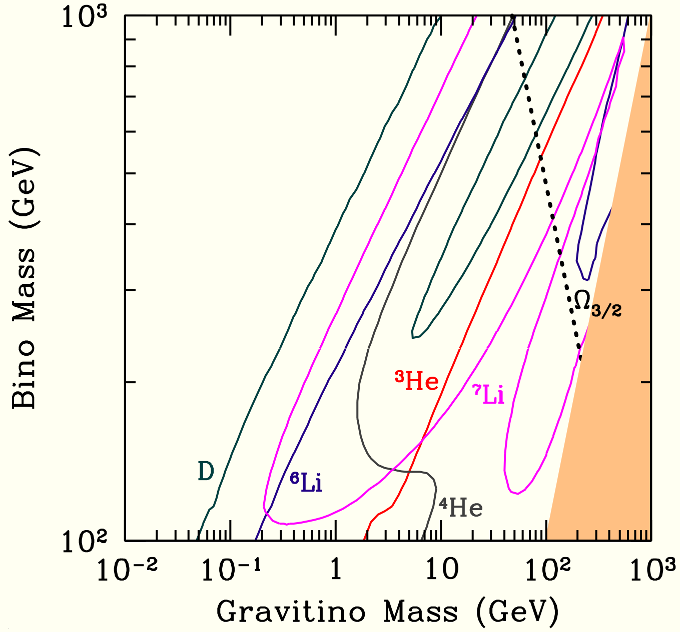




(see Kawasaki, Kohri, Moroi, Yotsuyanagi; Cybert, Ellis, Fields, Olive)

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)

Various leptogenesis scenarios

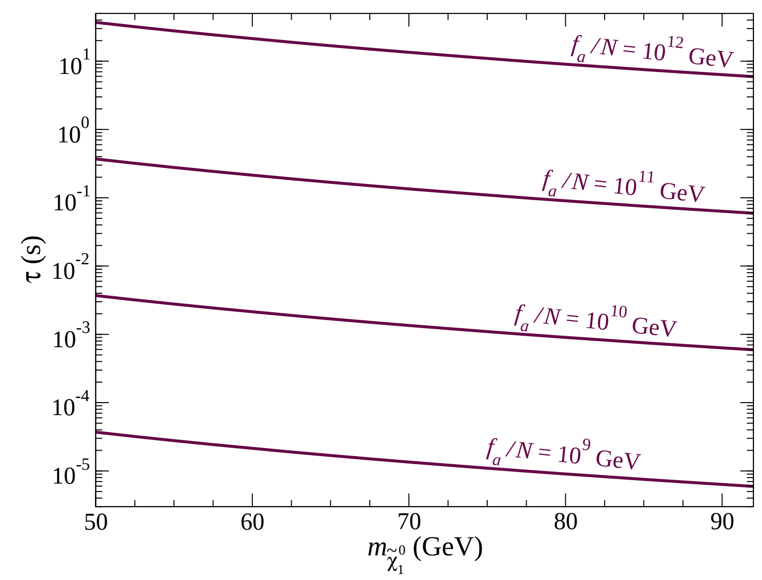
- Upper bound on T_R from BBN is below that for successful *thermal* leptogenesis: need $T_R \gtrsim 10^{10}$ GeV (Buchmuller, Plumacher)
- Alternatively, one may have non-thermal leptogenesis where inflaton $\phi \to N_i N_i$ decay (Lazarides, Shafi; Kumekawa, Moroi, Yanagida)
- additional source of N_i in early universe allows lower T_R:

$$\frac{n_B}{s} \simeq 8.2 \times 10^{-11} \times \left(\frac{T_R}{10^6\ \mathrm{GeV}}\right)\left(\frac{2m_{N_1}}{m_\phi}\right)\left(\frac{m_{\nu_3}}{0.05\ \mathrm{eV}}\right)\delta_{eff} \qquad (1)$$

- 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

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

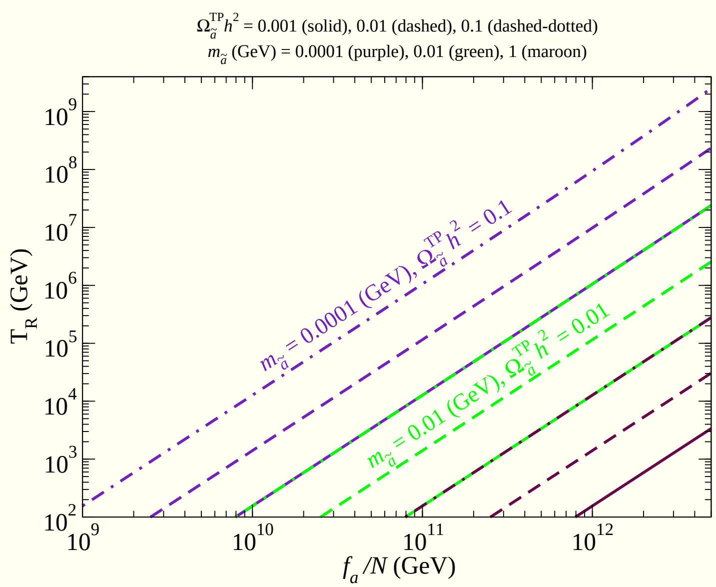
- axino is spin-$\frac{1}{2}$ element of axion supermultiplet (R-odd; can be LSP)
  - Raby, Nilles, Kim
  - Rajagopal, Wilczek, Turner
- $m_{\tilde{a}}$ model dependent: keV$\rightarrow$ GeV
- $\widetilde{Z}_1 \rightarrow \tilde{a}\gamma$
- non-thermal $\tilde{a}$ production via $\widetilde{Z}_1$ decay: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

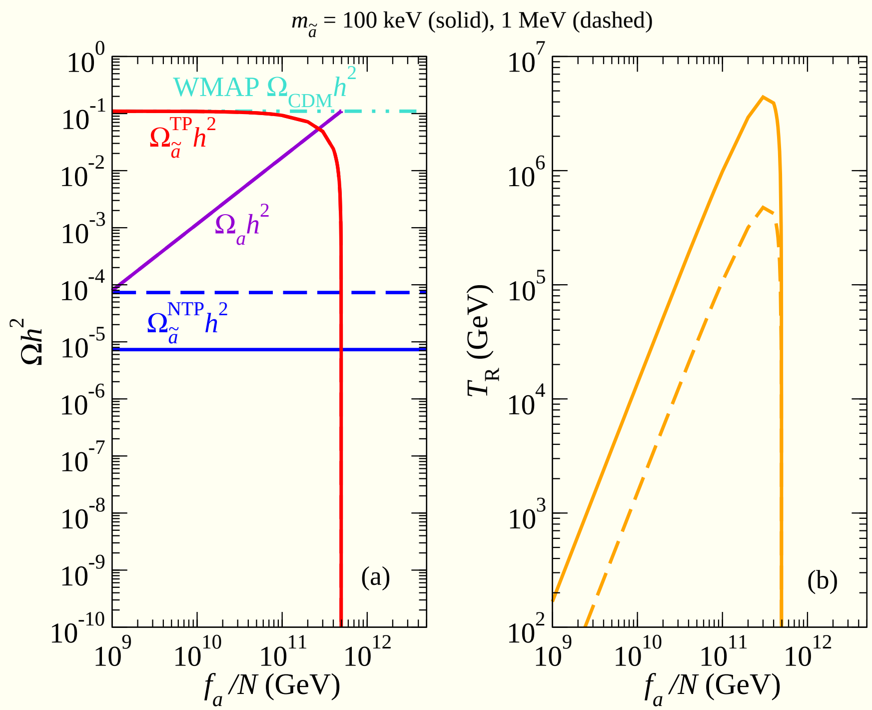
- ⋆ If $T_R < f_a$, then axinos never in thermal equilibrium in early universe
- ⋆ Can still produce $\tilde{a}$ thermally via radiation off particles in thermal equilibrium
- ⋆ Brandenberg-Steffen calculation:

$$\Omega_{\tilde{a}}^{TP}h^2 \simeq 5.5 g_s^6 \ln\left(\frac{1.108}{g_s}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2\left(\frac{m_{\tilde{a}}}{0.1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right) \qquad (2)$$



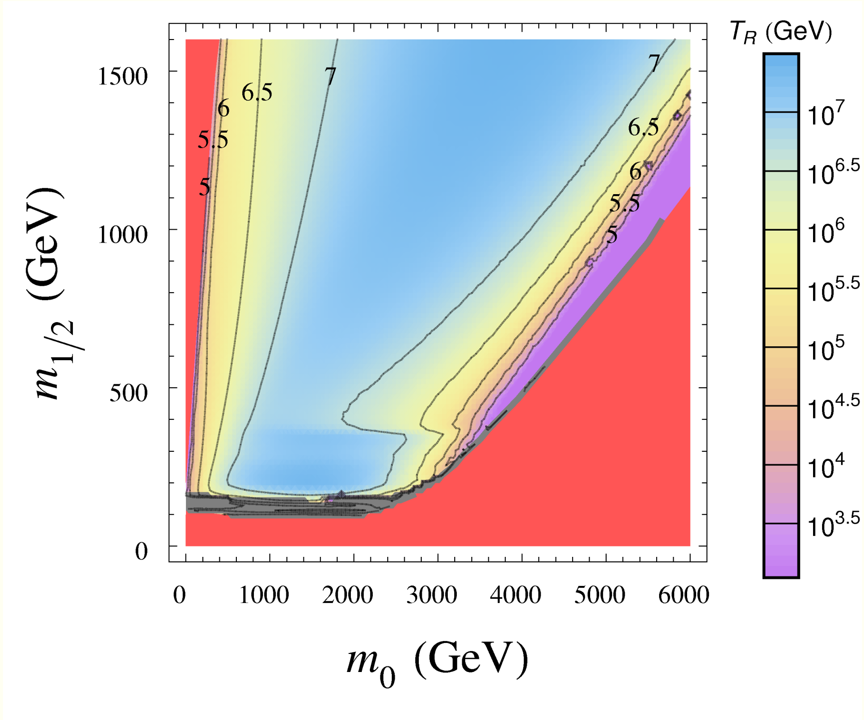
mSUGRA model with mixed axion/axino CDM: $m_{\tilde{a}}$ fixed

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

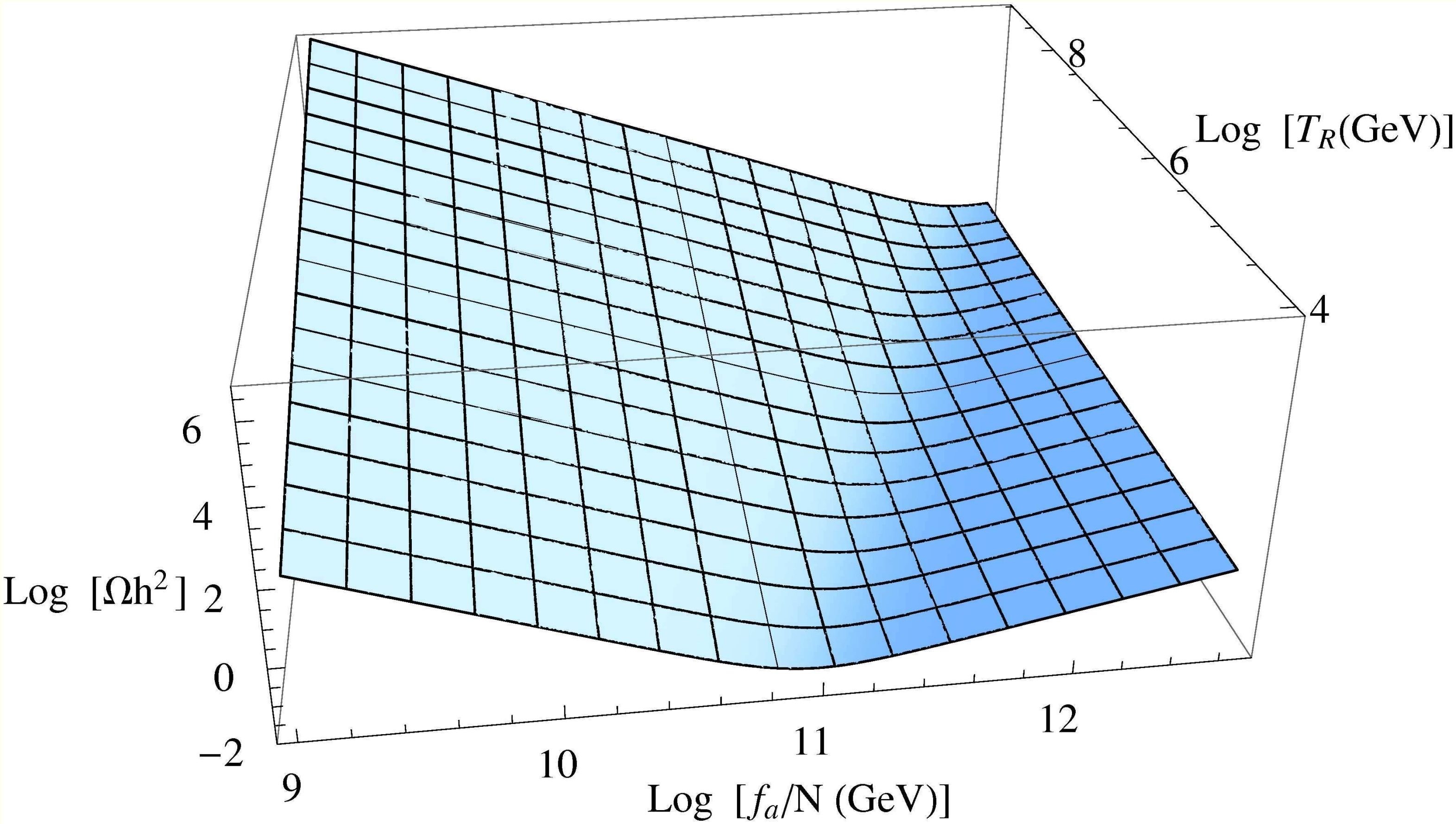


mSUGRA p-space with mainly axion cold DM

- ⋆ 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)

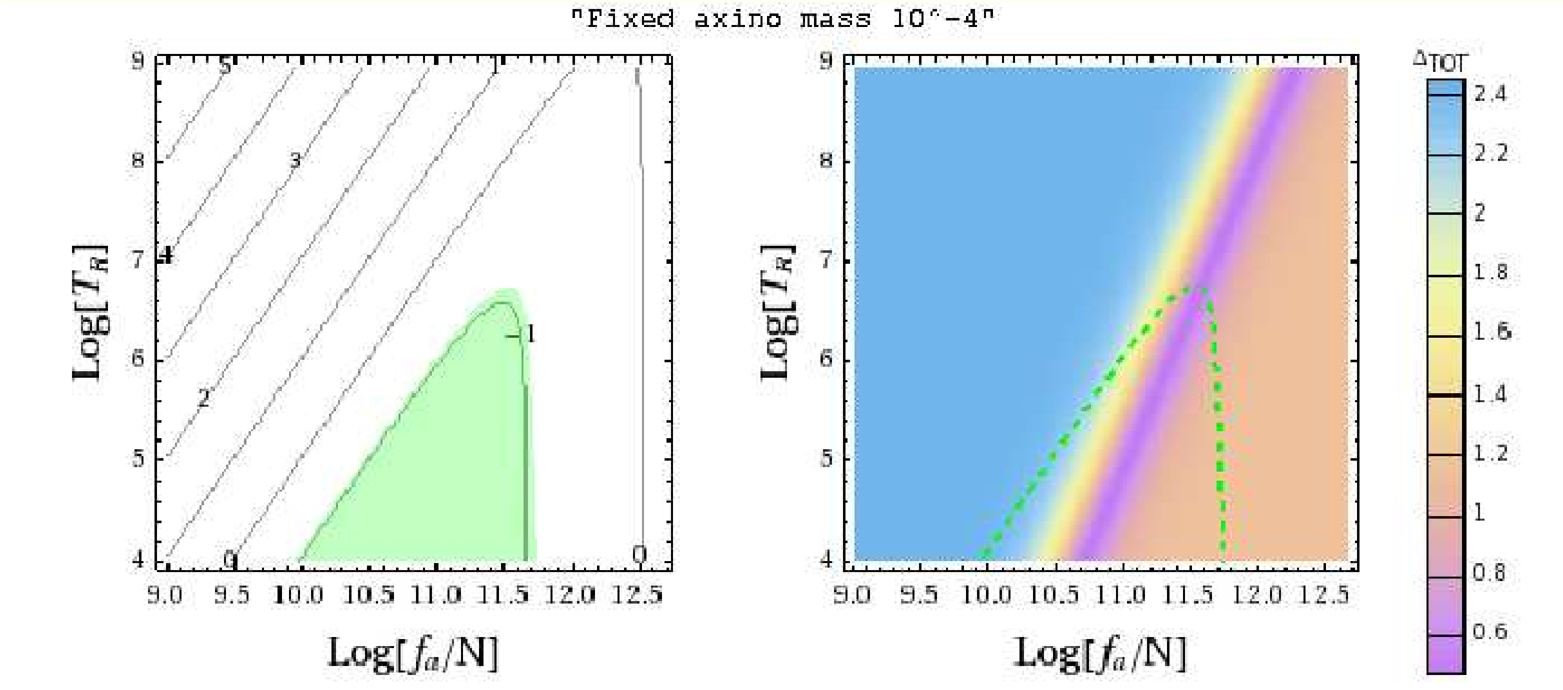


Axion/axino relic density in mSUGRA



Fine-tuning for mainly axion CDM in mSUGRA

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



supersymetric $SO(10)$: synopsis

- ⋆ $SO(10)$ is a rank-5 Lie group which contains the SM gauge symmetry.
  - $SO(n)$ (except $n = 6$) are naturally anomaly-free, thus explaining the seemingly fortuitous anomaly cancellation in the SM and in $SU(5)$.
  - matter unification in *spinorial* **16**: The **16** contains *all* the matter in a single generation of the SM, plus a RHN state $\hat{N}^c$: see-saw ν-masses
  - Higgs unification: explains why 2 Higgs doublets in MSSM
  - Explains R-parity conservation: only matter-matter-Higgs couplings
  - Expect $t - b - \tau$ Yukawa unification in simplest models
- ⋆ These features have convinced many theorists that the main features of SUSY $SO(10)$ are surely right!

Yukawa unification in SUSY: assumptions

- some form of 4-d or x-d $SO(10)$ SUGRA-GUT valid at $Q > M_{GUT}$
- SUGRA breaking via superHiggs mechanism: will find $m_{\tilde{G}} \sim 10$ TeV so soft SUSY breaking terms ~ 10 TeV
- $SO(10)$ breaks to MSSM or MSSM plus gauge singlets at $Q \simeq M_{GUT}$ either via Higgs mechanism (4-d) or x-d compactification
- MSSM (or MSSM plus $\hat{N}^c$) is correct effective theory between M_{SUSY} and M_{GUT}
- EWSB broken radiatively due to large m_t
- we will require that $t - b - \tau$ Yukawa couplings unify at $Q = M_{GUT}$

lots of previous work!

- B. Ananthanarayan, G. Lazarides and Q. Shafi, PRD44 (1991)1613 and PLB300 (1993)245;
- V. Barger, M. Berger and P. Ohmann, PRD49 (1994)4908;
- M. Carena, M. Olechowski, S. Pokorski and C. Wagner, NPB426 (1994)269;
- B. Ananthanarayan, Q. Shafi and X. Wang, PRD50 (1994)5980;
- L. Hall, R. Rattazzi and U. Sarid, PRD50 (1994)7048;
- R. Rattazzi and U. Sarid, PRD53 (1996)1553;
- T. Blazek, M. Carena, S. Raby and C. Wagner, PRD56 (1997)6919; T. Blazek and S. Raby, PLB392 (1997)371 and PRD59 (1999)095002; T. Blazek, S. Raby and K. Tobe, PRD60 (1999)113001 and PRD62 (2000)055001;

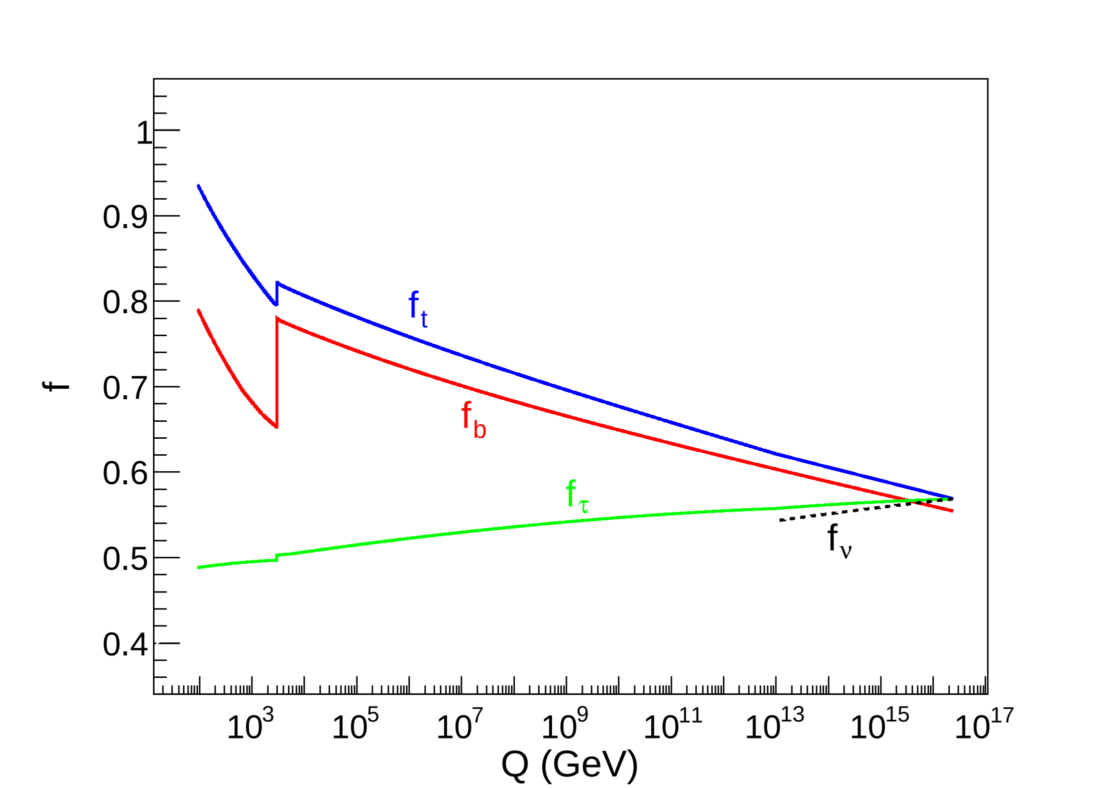
more recent work

- HB, Diaz, Ferrandis, Tata, PRD61 (2000) 111701
- HB, Brhlik, Diaz, Ferrandis, Mercadante, Quintana, Tata, PRD63 (2001)015007;
- HB, Ferrandis, PRL87 (2001) 211803;
- Blazek, Dermisek and Raby, PRL88 (2002) 111804 and PRD65 (2002) 115004; Tobe and Wells, NPB663 (2003) 123
- Auto, HB, Balazs, Belyaev, Ferrandis, Tata, JHEP0306 (2003) 023
- Dermisek, Raby, Roszkowski, Ruiz de Austri, JHEP0304 (2003) 037 and JHEP0509 (2005) 029
- HB, Kraml, Sekmen, Summy, JHEP0803 (2008) 056
- HB, Kraml, Sekmen, JHEP0909 (2009) 005

Yukawa unification requires precision calculation of SUSY spectrum:

- need full 2-loop RGE running
- full threshold corrections calculated at optimized scale
  - applies especially to b-quark self-energy: include $\tilde{g}\tilde{b}_i$, $\widetilde{W}_i\tilde{t}_j$, $\cdots$ loops
  - Hall, Rattazzi, Sarid; Pierce, Bagger, Matchev, Zhang
- off-sets Yukawa coupling RG trajectory
- minimize scalar potential away from unstable $Q = M_Z$; use $Q = M_{SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ instead
- we elect to use Isajet/Isasugra spectrum generator

Yukawa unification in MSSM+RHN model via Isajet



SUSY $SO(10)$ parameter space:

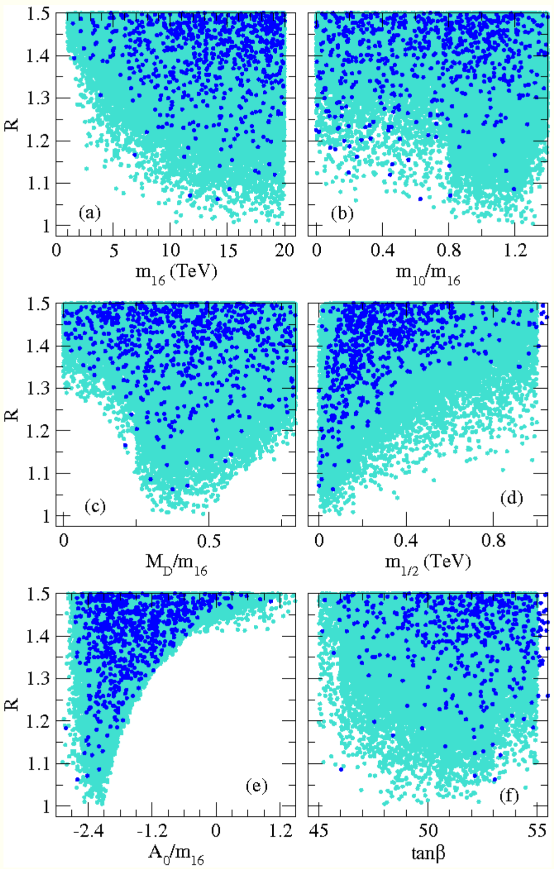
- $m_{16},\ m_{10},\ M_D^2,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- Here, M_D^2 parametrizes D-term splitting of scalar soft terms at M_{GUT}:

$$\begin{aligned} m_Q^2 = m_E^2 = m_U^2 &= m_{16}^2 + M_D^2 \\ m_D^2 = m_L^2 &= m_{16}^2 - 3M_D^2 \\ m_{\tilde{\nu}_R}^2 &= m_{16}^2 + 5M_D^2 \\ m_{H_{u,d}}^2 &= m_{10}^2 \mp 2M_D^2, \end{aligned}$$

⋆ Two cases:

- "Just-so Higgs splitting" (HS model)
- Full D-term splitting plus RHN plus 3rd gen. splitting (DR3 model)

Top-down scan of HS model with $\mu > 0$



- Auto, HB, Balazs, Belyaev, Ferrandis, Tata; HB, Kraml, Sekmen, Summy
- $R = max(f_t, f_b, f_\tau)/min(f_t, f_b, f_\tau)$ at $Q = M_{GUT}$

Correlation of SSB terms for YU models

- $A_0 \sim -2m_{16}$
- $m_{10} \sim 1.2m_{16}$
- $\tan\beta \sim 50$
- $m_{16} \sim 10$ TeV
- $m_{1/2}$ small

★ Earlier work: Bagger, Feng, Polonsky, Zhang derived $A_0^2 = 2m_{10}^2 = 4m_{16}^2$ with $m_{1/2}$ tiny and Yukawa unified couplings: (RIMH model)

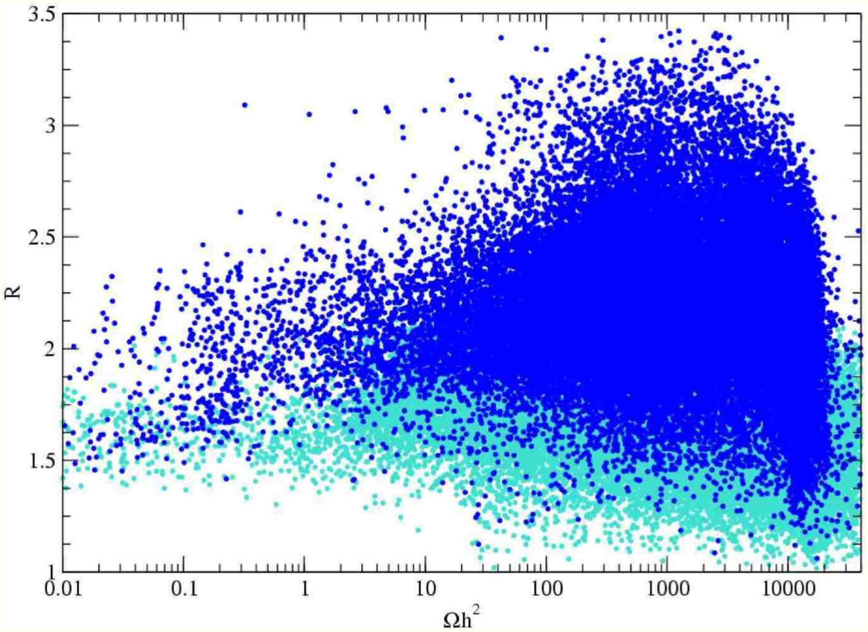
- Reconcile naturalness with decoupling via $m_{\tilde{f}_3} \ll m_{\tilde{f}_{1,2}}$

★ Characteristic spectrum for Yukawa unified SUSY:

- $m_{\tilde{q},\tilde{\ell}}(1,2) \sim 10$ TeV
- $m_{\tilde{t}_1},\ m_A,\ \mu \sim 1-2$ TeV
- $m_{\tilde{g}} \sim 300-500$ GeV

$SO(10)$ sparticle spectra $\Rightarrow$ trouble for neutralino DM!

- ⋆ use IsaReD (part of Isajet) to compute relic density
- ⋆ large $m_{\tilde{f}_{1,2}}$ suppresses neutralino annihilation
- ⋆ $\Omega_{\widetilde{Z}_1} h^2$ too large by $10^3 - 10^5$!



Cold axion and cold/warm axino DM in the universe

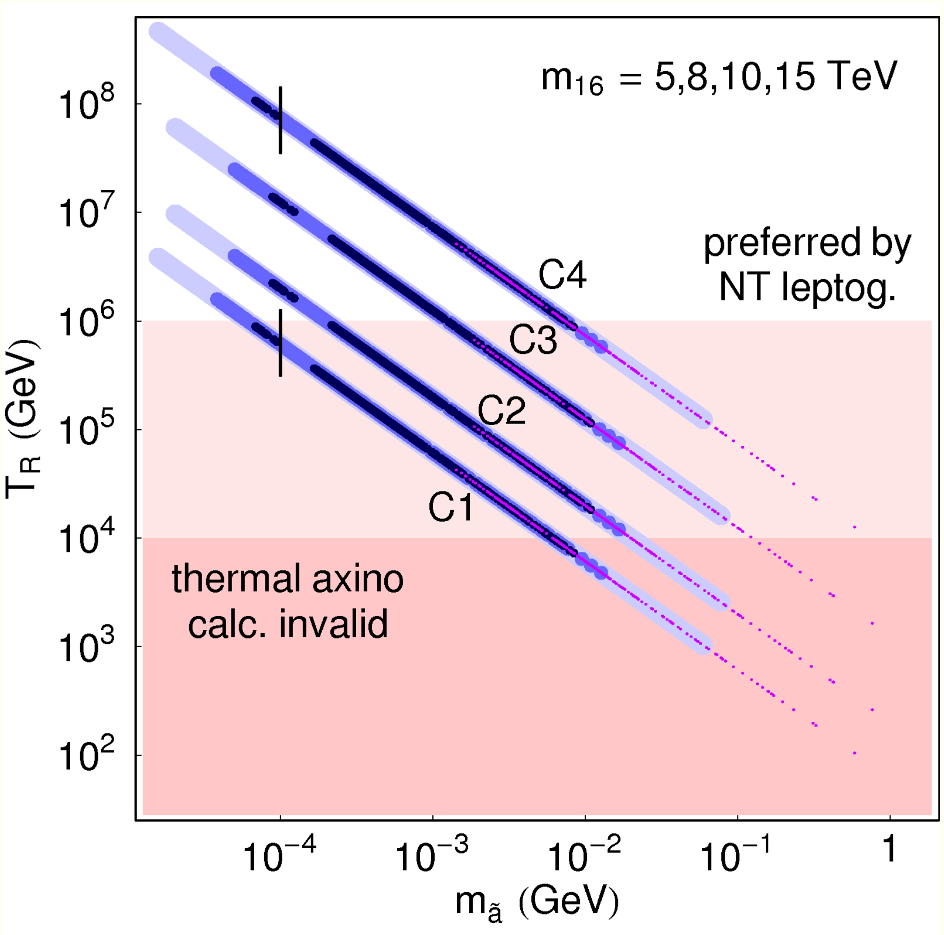
- Given $\Omega_{\widetilde{Z}_1} h^2$ and $m_{\widetilde{Z}_1}$ and $\Omega_{\tilde{a}}^{NTP} h^2$ can calculate $m_{\tilde{a}}$.
- Given $\Omega_{\tilde{a}}^{TP} h^2$, $m_{\tilde{a}}$ and f_a/N, can calculate re-heat temperature of universe

⋆ Four cases:

1. Take $f_a/N = 10^{11}$ GeV so $\Omega_a h^2 = 0.017$. Bulk of DM must be thermally produced $\tilde{a}$. Take $\Omega_{\tilde{a}}^{TP} = 0.083$ and $\Omega_{\tilde{a}}^{NTP} = 0.01$
2. Take $f_a/N = 4 \times 10^{11}$ GeV so $\Omega_a h^2 = 0.084$. (Bulk of DM is cold axions.) Take $\Omega_{\tilde{a}}^{TP} = \Omega_{\tilde{a}}^{NTP} = 0.013$
3. Take $f_a/N = 10^{12}$ GeV and lower mis-align error bar so $\Omega_a h^2 = 0.084$. (Bulk of DM is cold axions.) Take $\Omega_{\tilde{a}}^{TP} = \Omega_{\tilde{a}}^{NTP} = 0.013$
4. Take $f_a/N = 10^{12}$ GeV but allow accidental near vacuum alignment so $\Omega_a h^2 \sim 0$. Bulk of DM must be thermally produced axinos. Take $\Omega_{\tilde{a}}^{TP} = 0.1$ and $\Omega_{\tilde{a}}^{NTP} = 0.01$

Consistent cosmology for $SO(10)$ SUSY GUTs with mixed $a/\tilde{a}$ DM

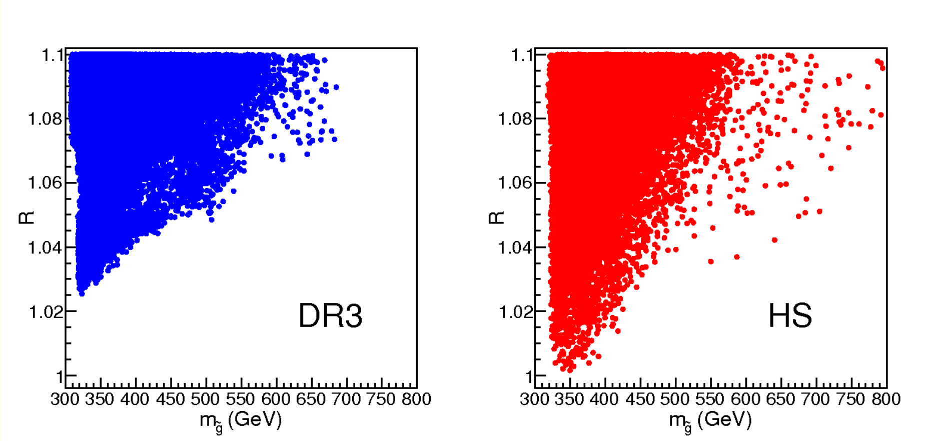
- Happily, T_R falls into the right range to give *cold* axion/axino DM with a small admixture of warm axino DM, preserve BBN predictions and have non-thermal leptogenesis!
- See HB and H. Summy, PLB666, 5 (2008)
- HB, Kraml, Haider, Sekmen and Summy, JCAP0902 (2009) 002



m16 = 5,8,10,15 TeV
preferred by
NT leptog.
C4
C3
C2
C1
thermal axino
calc. invalid
T_R (GeV)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^−4
10^−3
10^−2
10^−1
1
m_ã (GeV)

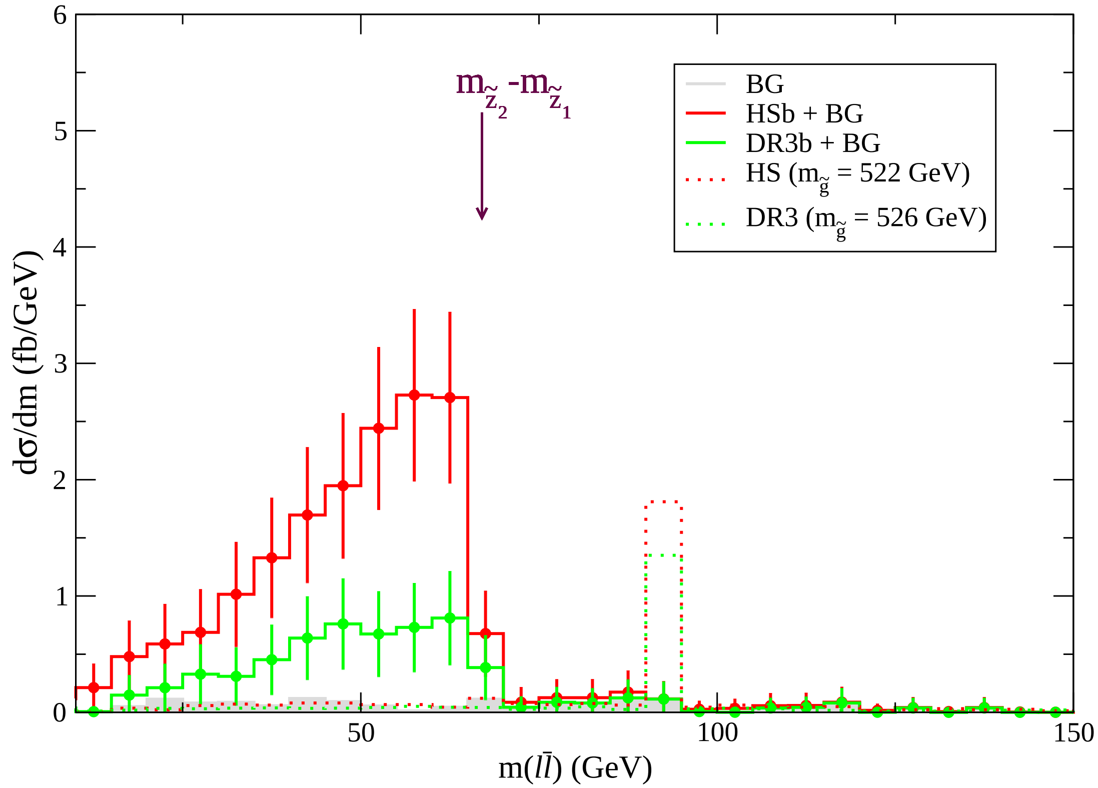
Best Yukawa unification favors light gluino!

- Possible to see at Tevatron $p\bar{p}$ collider? $m_{\tilde{g}} \sim 440$ GeV! HB, Kraml, Lessa, Sekmen and Summy, arXiv:0910.2988
- Possible to see in year 1 of LHC? $m_{\tilde{g}} \sim 640$ GeV! HB, Kraml, Sekmen and Summy, JHEP0810 (2008) 079; HB, Kraml, Lessa, Sekmen, arXiv:0911.4739



LHC during year 1 with $\sqrt{s} = 7$ TeV

- using multi-$b$jet final state, can see $m_{\tilde{g}} \sim 400$ GeV with just 0.2 fb^{-1}, even without using $\not{E}_T$!
- with ~ 1 fb^{-1} and $\not{E}_T$, can see $m_{\tilde{g}} \sim 630$ GeV
- In HS and DR3 model, distinct $m(\mu^+\mu^-)$ mass edge

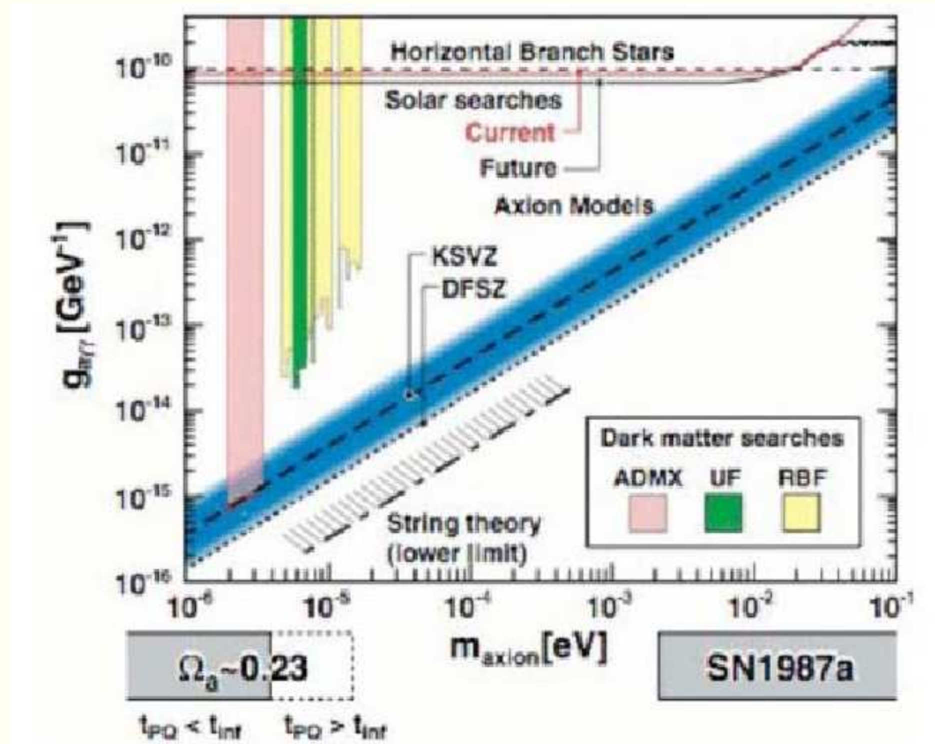


BG
HSb + BG
DR3b + BG
HS (m$_{\tilde{g}}$ = 522 GeV)
DR3 (m$_{\tilde{g}}$ = 526 GeV)
$m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$
dσ/dm (fb/GeV)
m($l\bar{l}$) (GeV)
0
1
2
3
4
5
6
50
100
150

Axion microwave cavity searches

⋆ ongoing searches: ADMX experiment

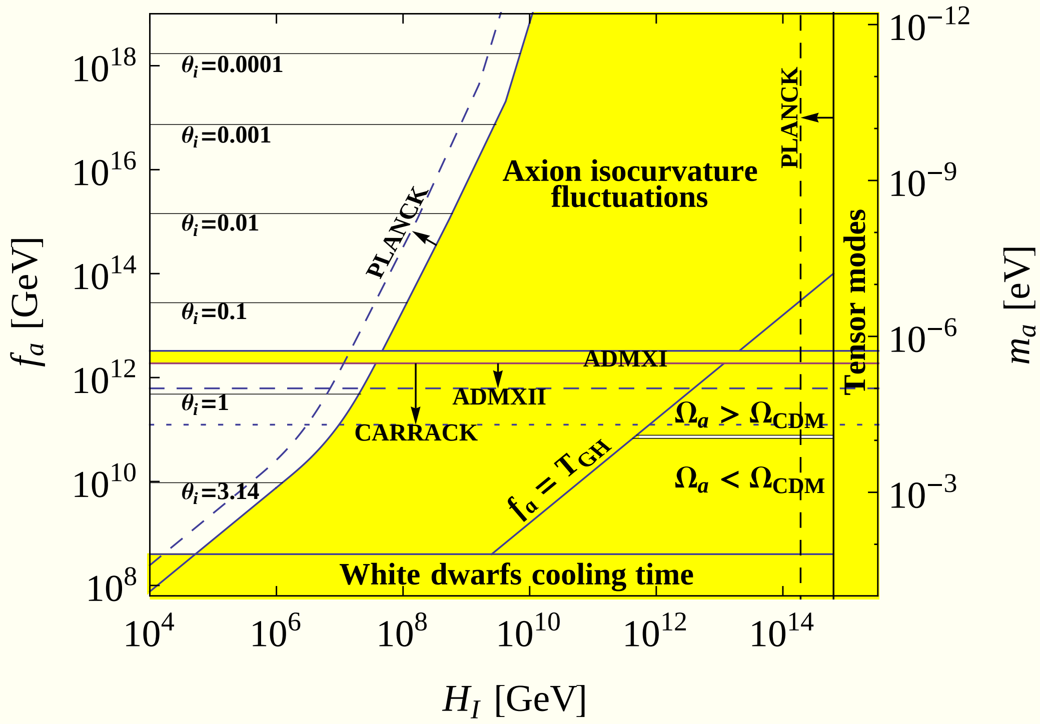
- Livermore⇒ U Wash.
- Phase I: probe KSVZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- Phase II: probe DFSZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- beyond Phase II:
  probe higher values m_a



Need for broader, deeper axion searches

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

- we have only begun $\cdots$



Conclusions

- ⋆ neutralino CDM: usually too much or too little
- ⋆ neutralino CDM with $\Omega_{\tilde{Z}_1}h^2 \sim 0.1$ 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 dis-favored models now allowed
  - Effective SUSY
  - Yukawa-unified SUSY