Lecture #1: Supersymmetry and dark matter

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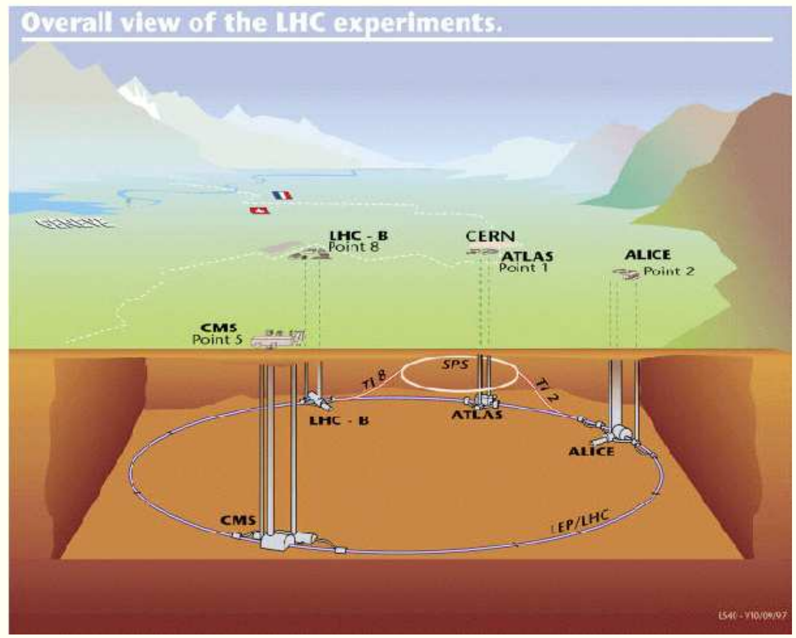
OUTLINE

- ⋆ The Standard Model
- ⋆ Inconsistencies
- ⋆ Supersymmetry
- ⋆ neutralino dark matter
  - • direct DM searches
  - • indirect DM searches
- ⋆ gravitino DM
- ⋆ mixed axion/axino DM



The Standard Model of Particle Physics

- ⋆ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow g$, $W^\pm$, Z^0, γ
- ⋆ matter content: 3 generations quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \; u_R,\; d_R; \; \begin{pmatrix} \nu \\ e \end{pmatrix}_L ,\; e_R \tag{1}$$

- ⋆ Higgs sector $\Rightarrow$ spontaneous electroweak symmetry breaking:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \tag{2}$$

- ⋆ $\Rightarrow$ massive $W^\pm$, Z^0, quarks and leptons
- ⋆ $\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{matter} + \mathcal{L}_{Yuk.} + \mathcal{L}_{Higgs}$: 19 parameters
- ⋆ good-to-excellent description of (almost) *all* accelerator data!

Shortcomings of SM

Data

- ⋆ neutrino masses and mixing
- ⋆ baryogenesis (matter anti-matter asymmetry)
- ⋆ cold dark matter
- ⋆ dark energy

Theory

- ⋆ quadratic divergences in scalar sector $\Rightarrow$ fine-tuning
- ⋆ origin of generations
- ⋆ explanation of masses/ mixing angles
- ⋆ origin of gauge symmetry/ quantum numbers
- ⋆ unification with gravity

The supersymmetry alternative

Supersymmetry: bosons⇔ fermions

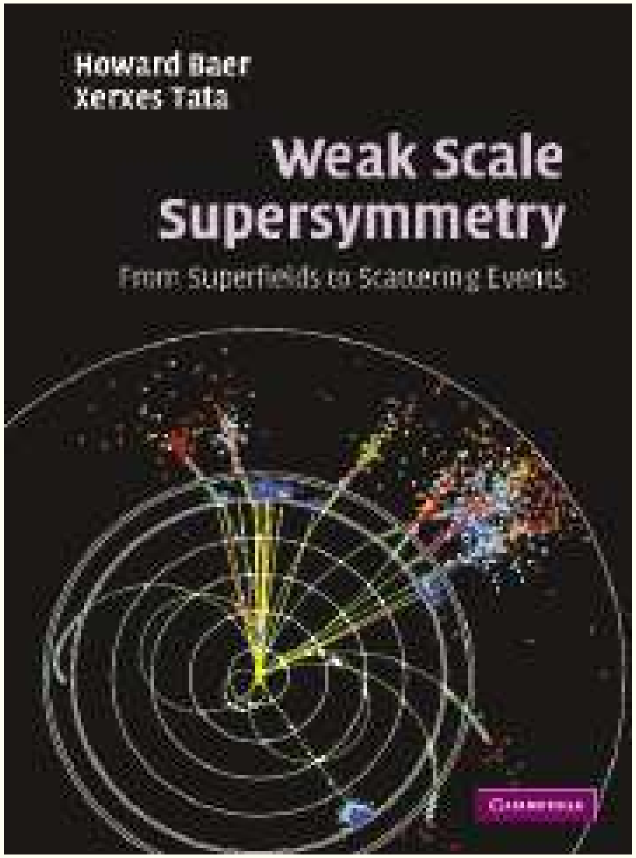
- ⋆ SUSY is a *space-time* symmetry!
- ⋆ space-time $x^\mu \Rightarrow (x^\mu, \theta_i)$ $i = 1, \cdots, 4$ superspace
- ⋆ fields $\psi \Rightarrow \hat{\phi} \ni (\phi,\ \psi)$ superfields
- ⋆ gauge fields $A^\mu \Rightarrow \hat{W} \ni (\lambda,\ A^\mu)$ gauge superfields
- ⋆ superfield formalism ⇒ general form for Lagrangian of (globally) supersymmetric gauge theory: quadratic divergences cancel!
- ⋆ SUSY can be broken by *soft* SUSY breaking terms: maintain cancellation of quadratic divergences

Weak Scale Supersymmetry

HB and X. Tata

Spring, 2006; Cambridge University Press

- Part 1: superfields/Lagrangians
  - 4-component spinor notation for exp'ts
  - master Lagrangian for SUSY gauge theories
- Part 2: models/implications
  - MSSM, SUGRA, GMSB, AMSB, $\cdots$
  - dark matter density/detection
- Part 3: SUSY at colliders
  - production/decay/event generation
  - collider signatures
  - R-parity violation



Minimal Supersymmetric Standard Model (MSSM)

- ⋆ Adopt gauge symmetry of Standard Model
  - spin $\frac{1}{2}$ gaugino for each SM gauge boson
- ⋆ SM fermions $\in$ chiral scalar superfields: $\Rightarrow$ scalar partner for each SM fermion helicity state
  - electron $\Leftrightarrow$ $\tilde{e}_L$ and $\tilde{e}_R$
- ⋆ two Higgs doublets to cancel triangle anomalies
- ⋆ add all admissible soft SUSY breaking terms
- ⋆ resultant Lagrangian has 124 parameters!
- ⋆ Lagrangian yields mass eigenstates, mixings, Feynman rules for scattering and decay processes
- ⋆ predictive model!

Physical states of MSSM:

- ⋆ usual SM gauge bosons, quarks and leptons
- ⋆ gluino: $\tilde{g}$
- ⋆ bino, wino, neutral higgsinos$\Rightarrow$ neutralinos: $\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{Z}_3, \widetilde{Z}_4$
- ⋆ charged wino, higgsino $\Rightarrow$ charginos: $\widetilde{W}_1^\pm$, $\widetilde{W}_2^\pm$
- ⋆ squarks: $\tilde{u}_L$, $\tilde{u}_R$, $\tilde{d}_L$, $\tilde{d}_R, \cdots$, $\tilde{t}_1$, $\tilde{t}_2$
- ⋆ sleptons: $\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\nu}_e, \cdots$, $\tilde{\tau}_1$, $\tilde{\tau}_2$, $\tilde{\nu}_\tau$
- ⋆ Higgs sector enlarged: h, H, A, $H^\pm$
- ⋆ a plethora of new states to be found at LHC/ILC?!

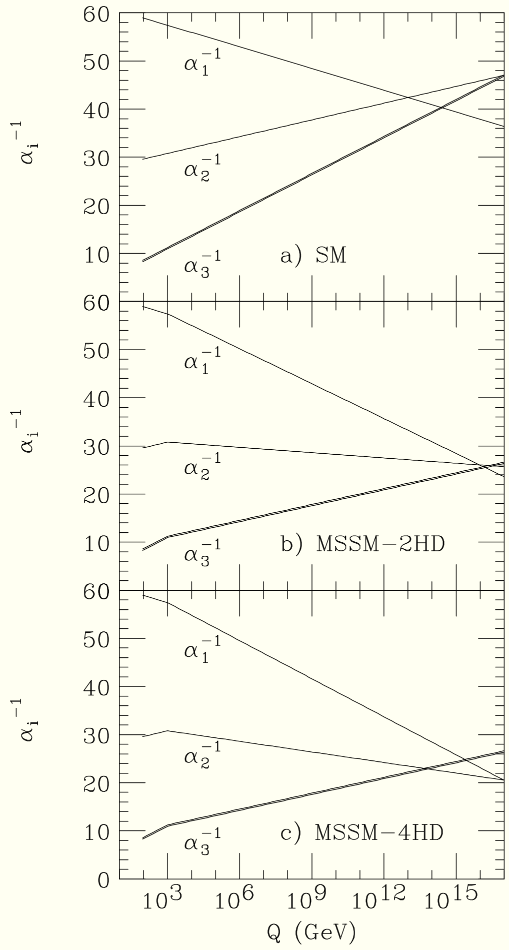
Supergravity (SUGRA)

- ⋆ $e^{i\bar{\alpha}Q}$ with $\alpha(x)$: *local* SUSY transformation
  - forces introduction of spin 2 graviton and spin $\frac{3}{2}$ gravitino
  - resultant theory $\Rightarrow$ General Relativity in classical limit!
- ⋆ rules for Lagrangian in supergravity gauge theory: Cremmer et al. (1983)
- ⋆ fertile ground: supergravity $\cup$ grand unification: LE limit of superstring?
- ⋆ minimal supergravity model (mSUGRA)
- ⋆ $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
  - $m_0 =$ mass of all scalars at $Q = M_{GUT}$
  - $m_{1/2} =$ mass of all gauginos at $Q = M_{GUT}$
  - $A_0 =$ trilinear soft breaking parameter at $Q = M_{GUT}$
  - $\tan\beta =$ ratio of Higgs vevs
  - $\mu =$ SUSY Higgs mass term; magnitude determined by REWSB!

Some successes of SUSY GUT theories

- ⋆ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- ⋆ gauge coupling unification!

Gauge coupling evolution



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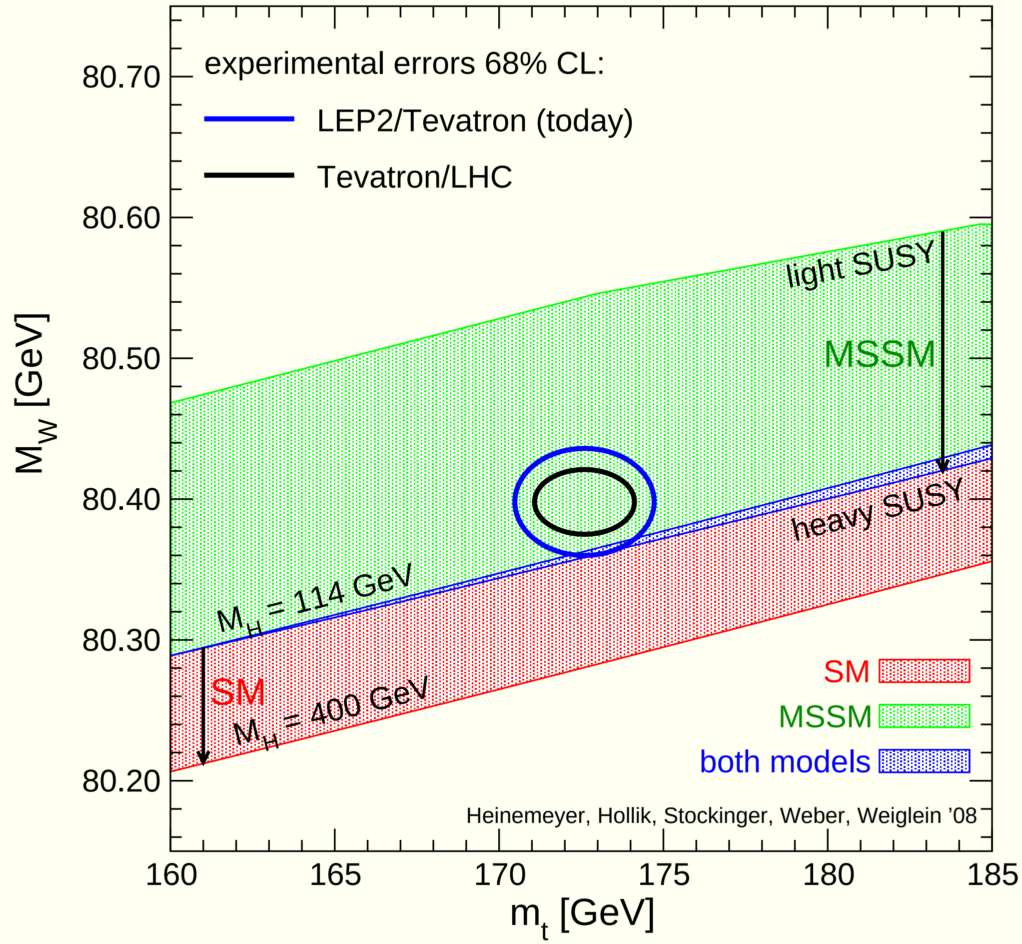
- ⋆ Lightest Higgs mass $m_h \lesssim 135$ GeV as indicated by radiative corrections!

Precision electroweak data and the Higgs mass:



S. Heinemeyer et al.

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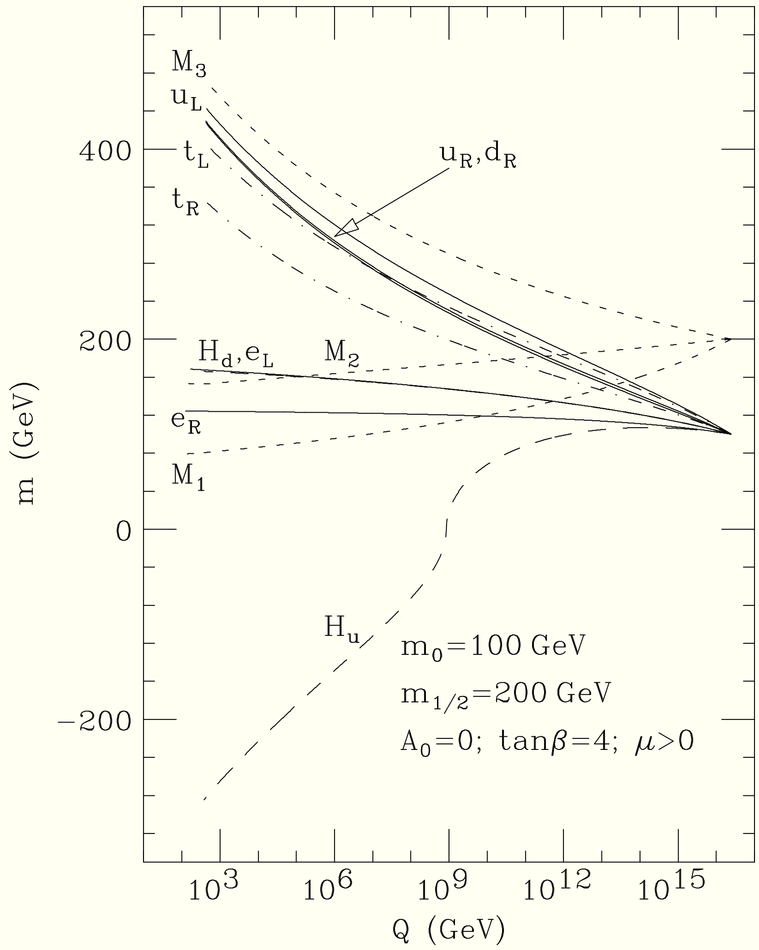
- ⋆ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!

Soft term evolution and radiative EWSB



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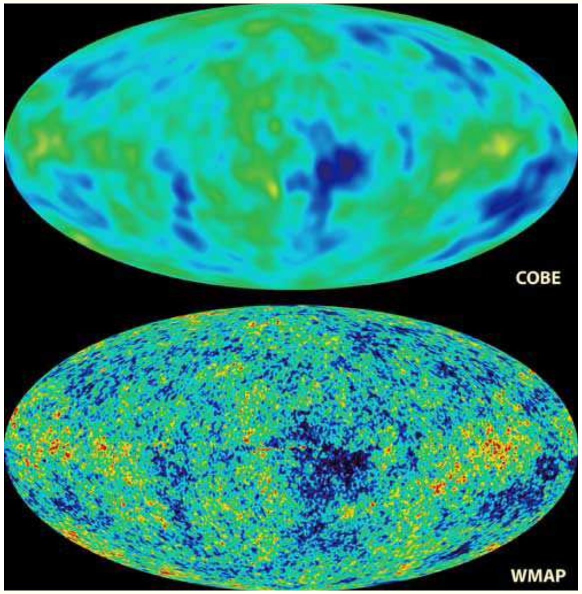
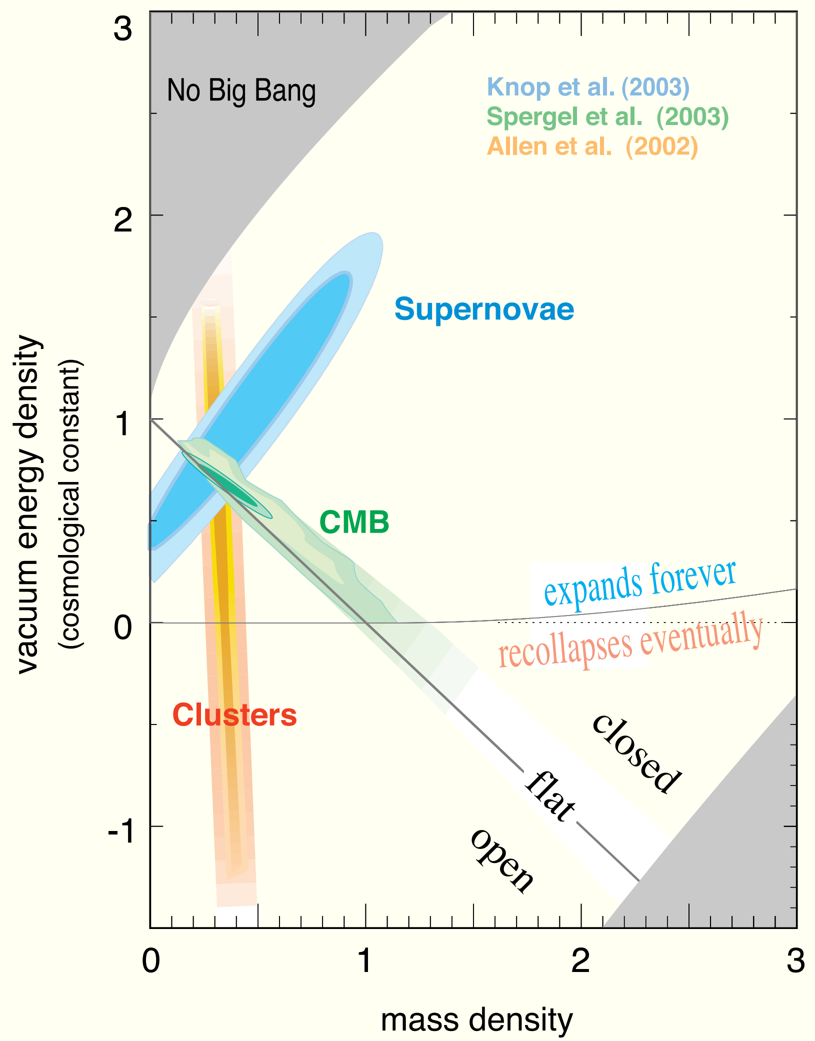
- ⋆ dark matter candidate: lightest neutralino $\tilde{Z}_1$
- ⋆ stablize neutrino see-saw scale vs. weak scale
- ⋆ $SO(10)$ SUSY GUT: baryogenesis via leptogenesis
- ⋆ can give dark energy via CC Λ (but need huge fine-tuning...)
  - SUGRA $=$ low energy limit of superstring?
  - stringy multiverse: anthropic selection of small CC?

Evidence for dark matter in the universe

- ⋆ binding of galactic clusters (Zwicky, 1930s)
- ⋆ galactic rotation curves
- ⋆ large scale structure formation
- ⋆ inflation $\Rightarrow \Omega = \rho/\rho_c = 1$
- ⋆ gravitational lensing
- ⋆ anisotropies in cosmic MB (WMAP)
- ⋆ surveys of distant galaxies via SN (DE)
- ⋆ Big Bang nucleosynthesis
  - $\Omega_\Lambda \simeq 0.7$
  - $\Omega_{CDM} \simeq 0.25$
  - $\Omega_{baryons} \simeq 0.045$ (dark baryons ~ 0.040
  - $\Omega_\nu \sim 0.005$



Dark matter versus dark energy



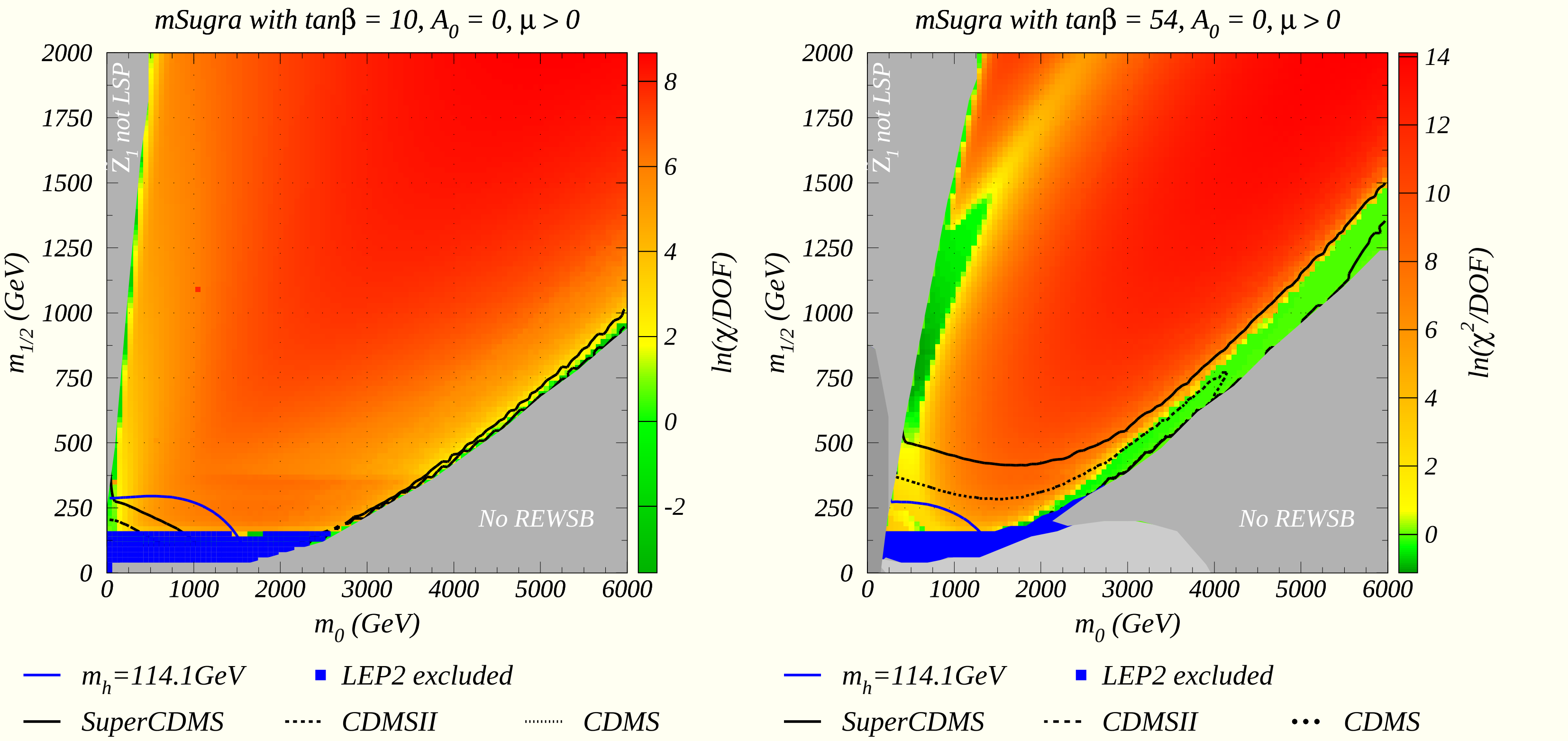
SUSY dark matter

- ⋆ R-parity conservation⇒ conserved B and L ⇒ proton stability
  - $R(particle) = 1$; $R(sparticle) = -1$
- ⋆ Naturally occurs in $SO(10)$ SUSY GUT theories
- ⋆ Some consequences:
  - Sparticles are produced in pairs
  - Sparticles decay to other sparticles
  - Lightest SUSY particle (LSP) is absolutely stable (good candidate for dark matter)
- ⋆ LSP must be charge, color neutral (bound on cosmological relics)
- ⋆ Sneutrino would have been detected in direct detection experiments
- ⋆ lightest neutralino $\tilde{Z}_1$ is LSP in wide range of models
- ⋆ $\tilde{Z}_1$ is weakly interacting, massive particle (WIMP)

Calculating the relic density of neutralinos

- ⋆ At very high T, neutralinos in thermal equilibrium with cosmic soup
- ⋆ As universe expands and cools, expansion rate exceeds interaction rate (freeze-out)
- ⋆ number density is governed by Boltzmann eq. for FRW universe
  - $dn/dt = -3Hn - \langle\sigma v_{rel}\rangle(n^2 - n_0^2)$
  - $\Omega_{\widetilde{Z}_1}h^2 = \frac{s_0}{\rho_c/h^2}\left(\frac{45}{\pi g_*}\right)^{1/2}\frac{x_f}{m_{Pl}}\frac{1}{\langle\sigma v\rangle}$
  - $\Omega_{CDM}h^2 \sim 0.1 \Rightarrow \langle\sigma v\rangle \sim 0.9$ pb!
  - $\langle\sigma v\rangle = \pi\alpha^2/8m^2 \Rightarrow m \sim 100$ GeV
  - "The WIMP miracle!": cosmic motivation for new physics at weak scale
- ⋆ SUSY: 1722 annihilation/co-annihilation reactions; 7618 Feynman diagrams
- ⋆ IsaReD program (HB, A. Belyaev , C. Balazs)

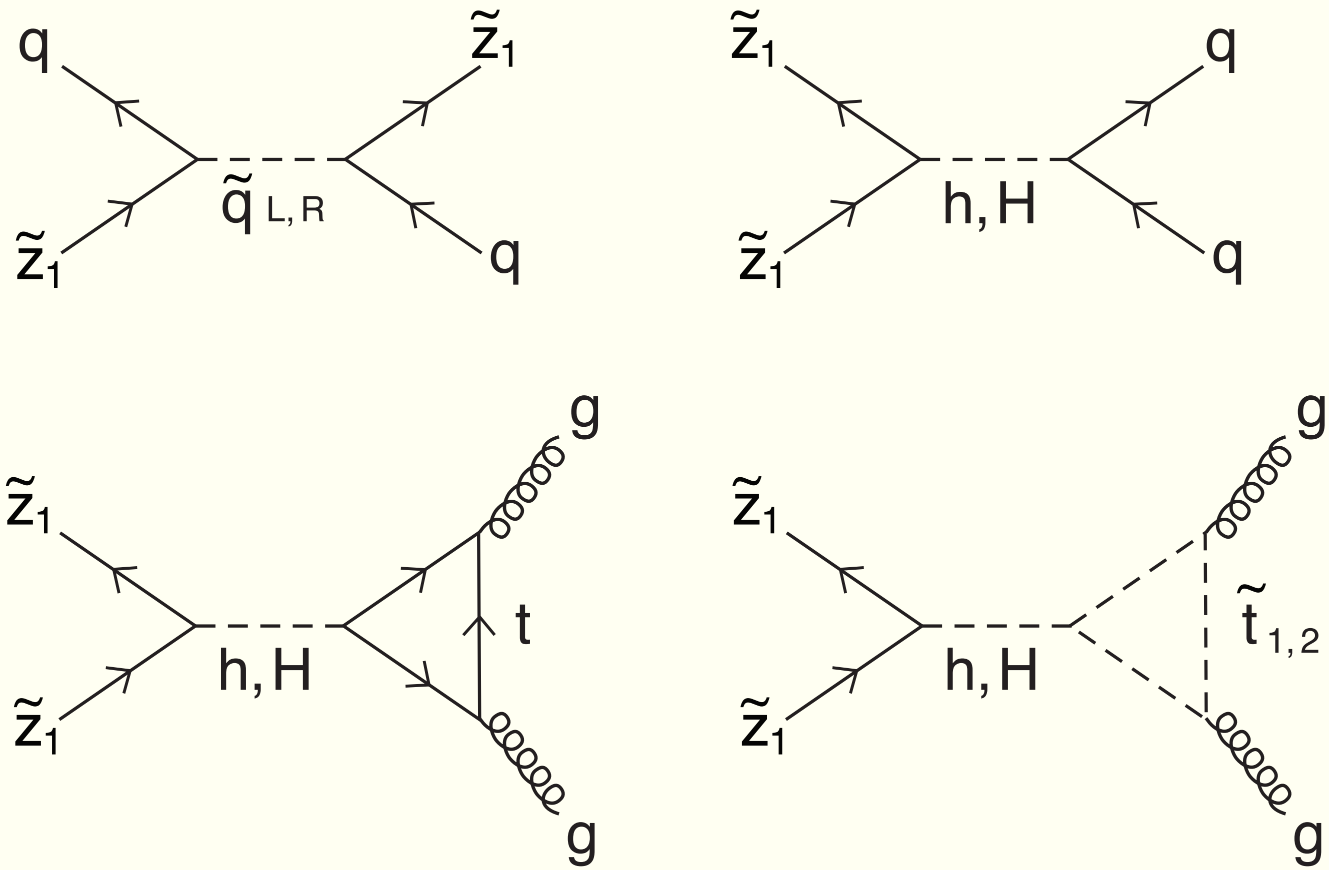
Results of χ^2 fit using τ data for a_μ:



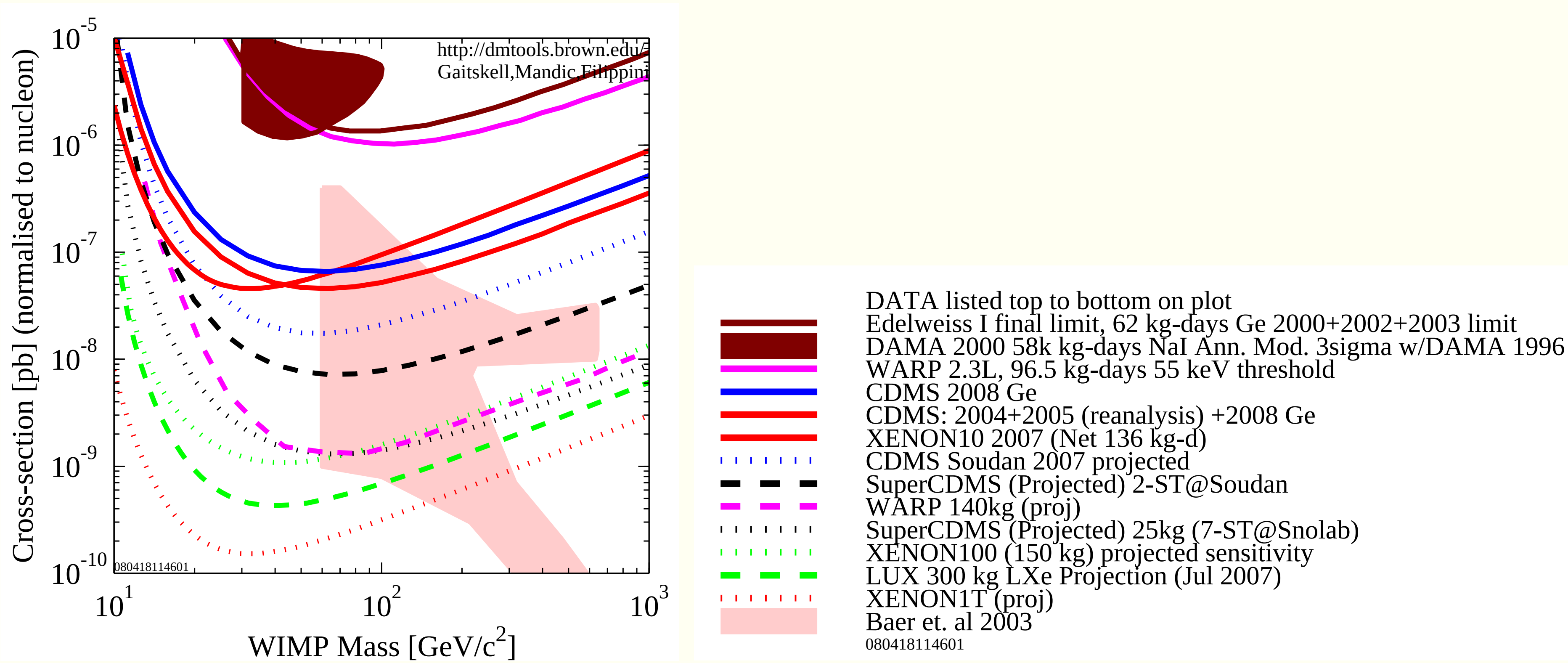
HB, C. Balazs: JCAP 0305, 006 (2003)

Direct detection of SUSY DM

⋆ Direct search via neutralino-nucleon scattering



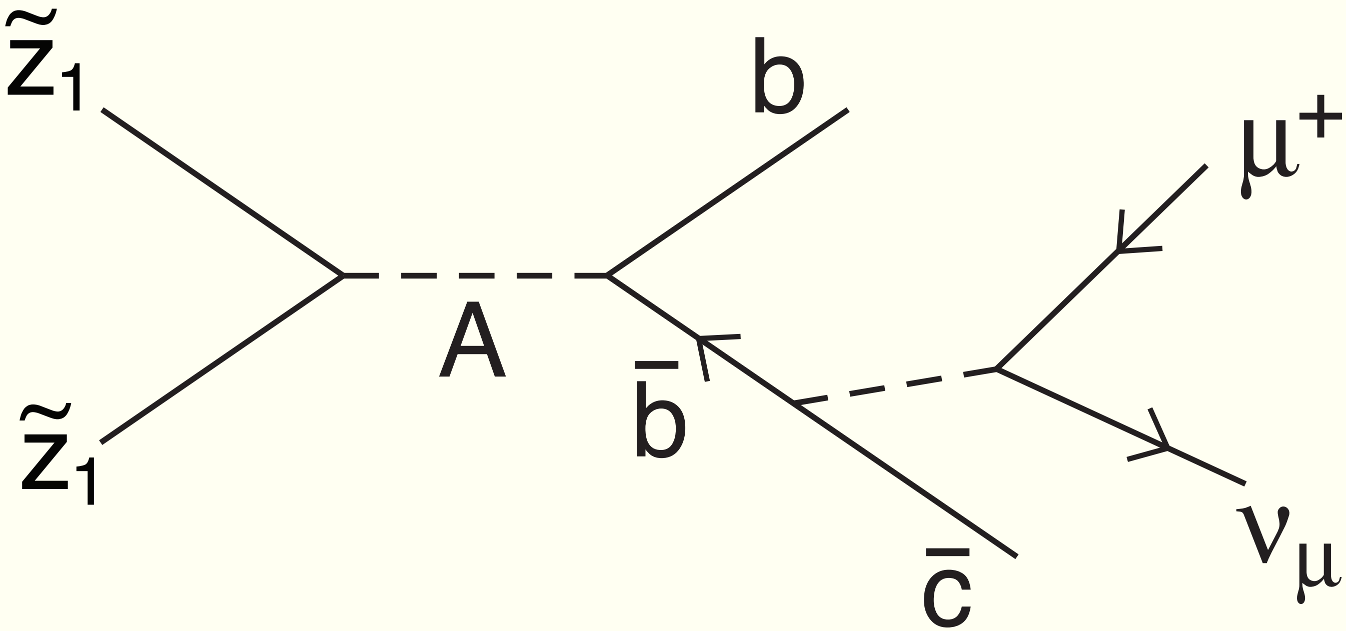
Direct detection of neutralino DM: the race is on!



Indirect detection (ID) of SUSY DM: ν-telescopes

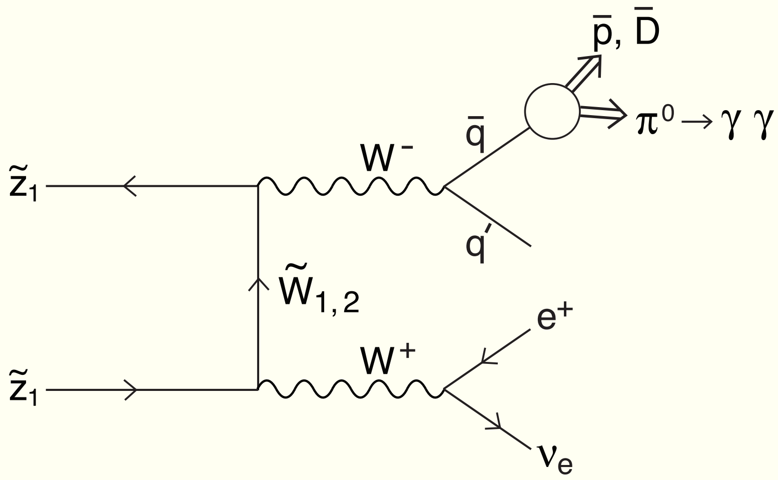
⋆ $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \to \mu$ in ν telescopes

- Amanda, Icecube, Antares

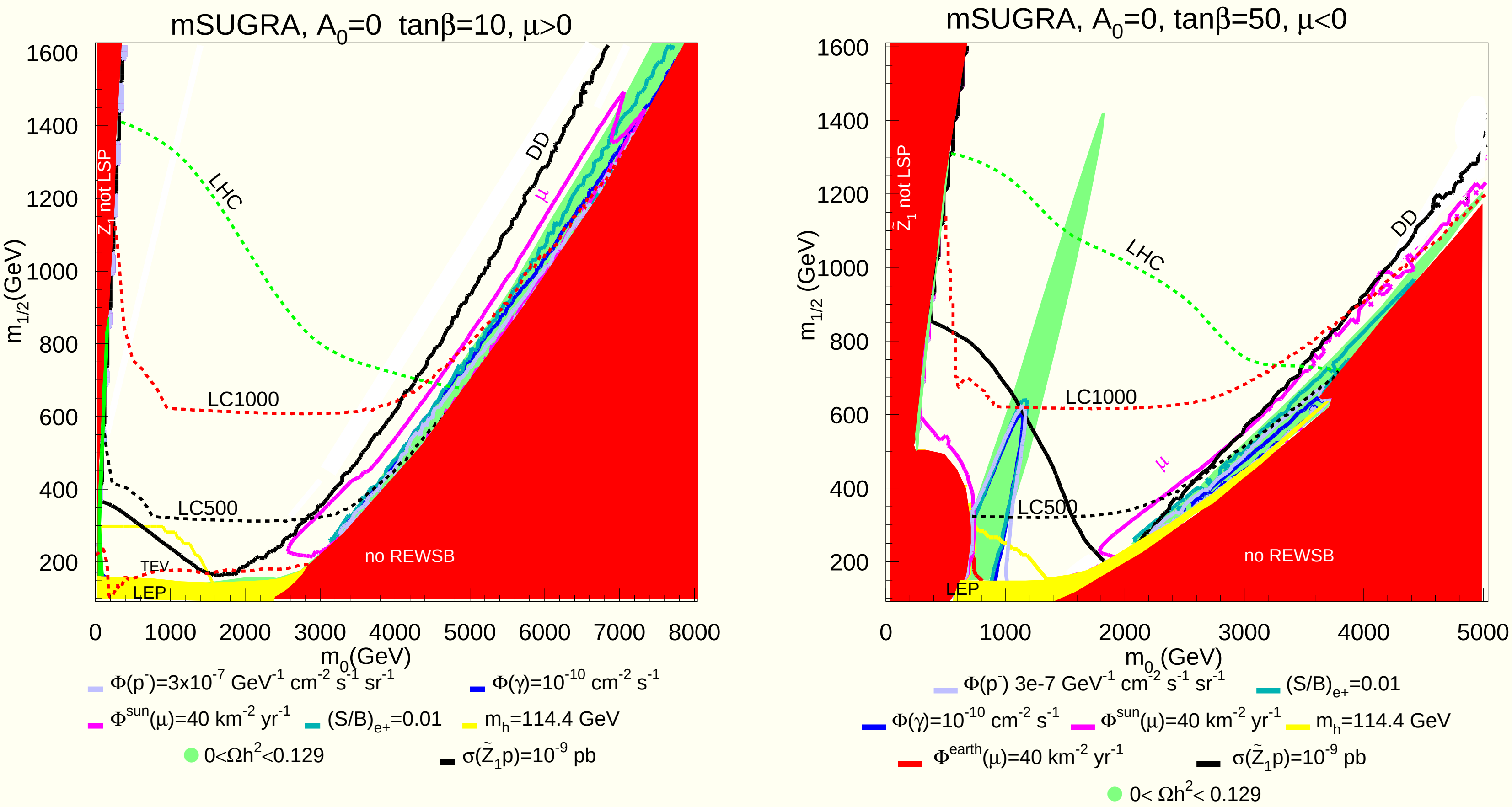


ID of SUSY DM: γ and anti-matter searches

- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \gamma$ in galactic core or halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to e^+$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{p}$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{D}$ in galactic halo



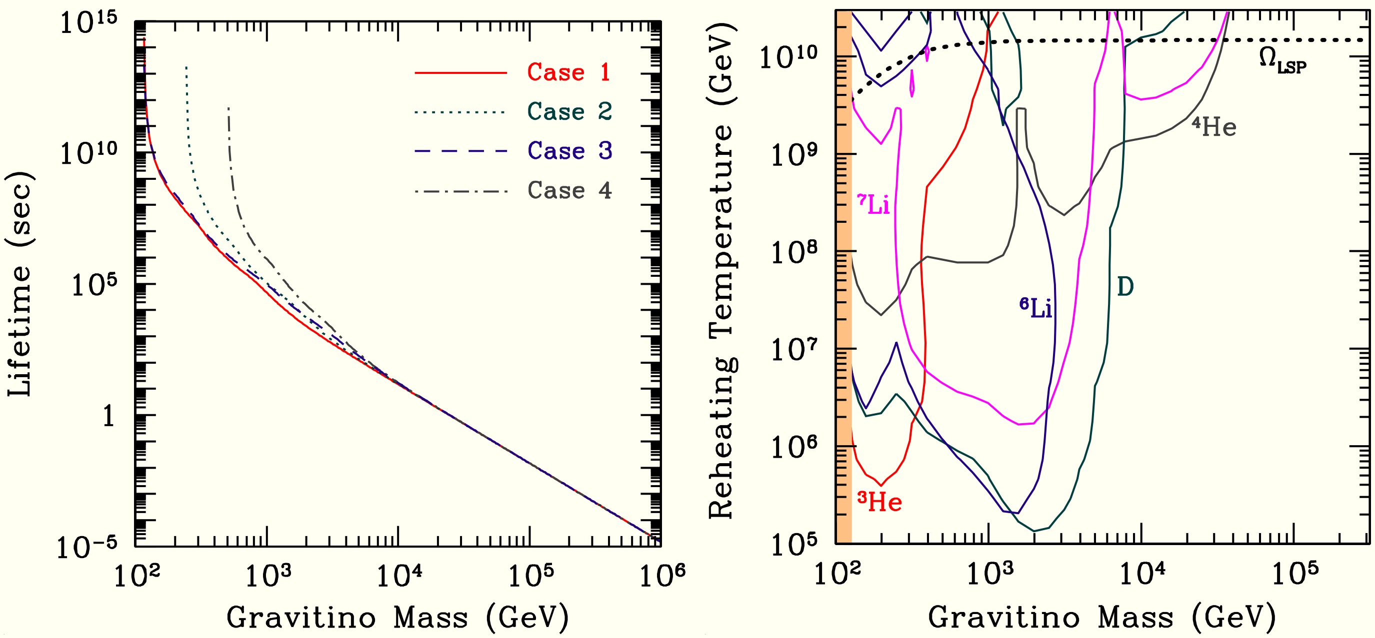
Direct and indirect detection of neutralino DM



HB, Belyaev, Krupovnickas, O'Farrill: JCAP 0408, 005 (2004)

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

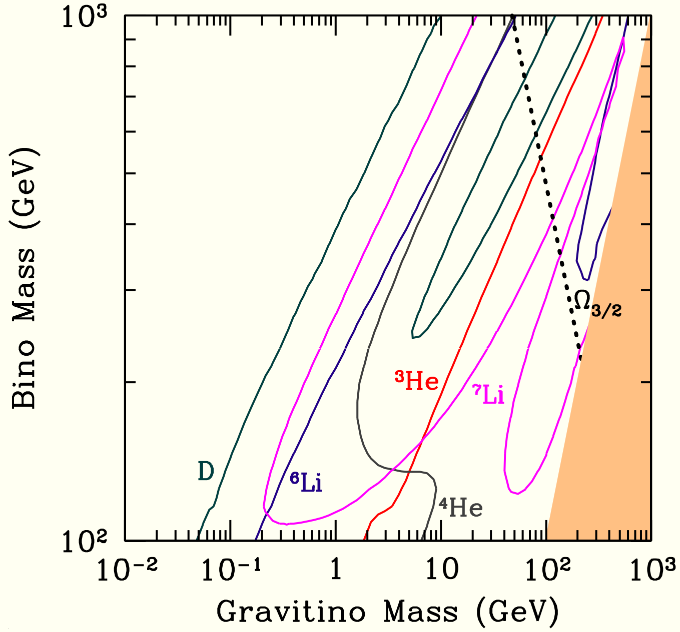
- gravitino problem in generic SUGRA models: overproduction of $\tilde{G}$ followed by late $\tilde{G}$ decay can destroy successful BBN predictons: upper bound on T_R



(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 predictons:



(see Kawasaki, Kohri, Moroi, Yotsuyanagi)

Gravitino dark matter: if one can avoid gravitino problem

⋆ $m_{\tilde G}=F/\sqrt{3}M_*\sim$ TeV in Supergravity models

- if $\tilde G$ is LSP, then calculate NLSP abundance as a thermal relic: $\Omega_{NLSP}h^2$
- $\widetilde Z_1\to h\tilde G,\ Z\tilde G,\ \gamma\tilde G$ or $\tilde\tau_1\to\tau\tilde G$ possible
  - ∗ lifetime $\tau_{NLSP}\sim 10^4-10^8$ sec
  - ∗ also produce $\tilde G$ thermally (depends on re-heat temp. T_R)
  - ∗ DM relic density is then $\Omega_{\tilde G}=\frac{m_{\tilde G}}{m_{NLSP}}\Omega_{NLSP}+\Omega_{\tilde G}^{TP}$
  - ∗ Feng et al.; Ellis et al.; Brandenberg+Steffen; Buchmuller et al.
- $\tilde G$ undetectable via direct/indirect DM searches
- unique collider signatures are possible:
  - ∗ $\tilde\tau_1$=NLSP: stable charged tracks
  - ∗ can collect NLSPs in e.g. water (slepton trapping)
  - ∗ monitor for $NLSP\to\tilde G$ decays

Various leptogenesis scenarios

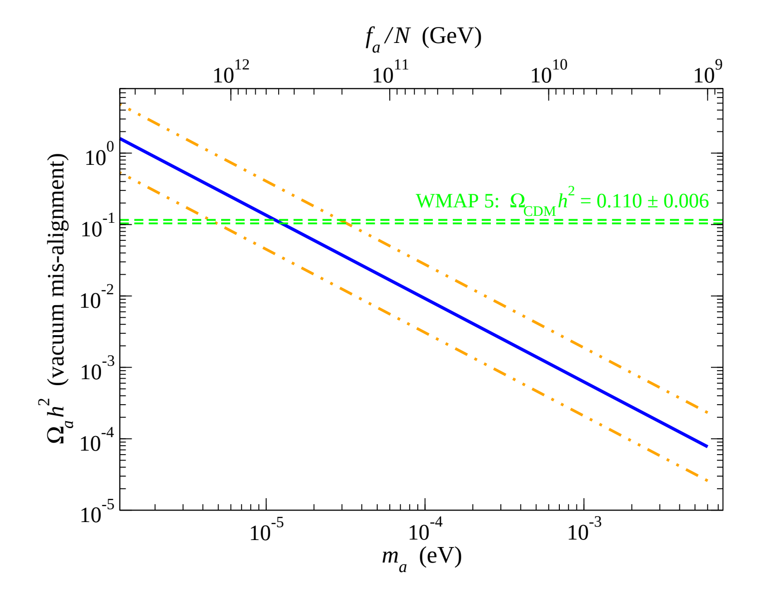
- Upper bound on T_R from BBN is below that for successful *thermal* leptogenesis: need $T_R \gtrsim 10^{10}$ GeV (Buchmuller, Plumacher)
- Alternatively, one may have non-thermal leptogenesis where inflaton $\phi \to N_i N_i$ decay (Lazarides, Shafi; Kumekawa, Moroi, Yanagida)
- additional source of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

$$\frac{n_B}{s} \simeq 8.2 \times 10^{-11} \times \left(\frac{T_R}{10^6 \text{ GeV}}\right) \left(\frac{2m_{N_1}}{m_\phi}\right) \left(\frac{m_{\nu_3}}{0.05 \text{ eV}}\right) \delta_{eff} \tag{3}$$

- Also, AD leptogenesis in $\phi = \sqrt{H\ell}$ D-flat direction: $T_R \sim 10^6 - 10^8$ GeV allowed (Dine, Randall, Thomas; Muarayama, Yanagida)
- WMAP observation: $n_b/s \sim 0.9 \times 10^{-10} \Rightarrow T_R \gtrsim 10^6$ GeV

Axions

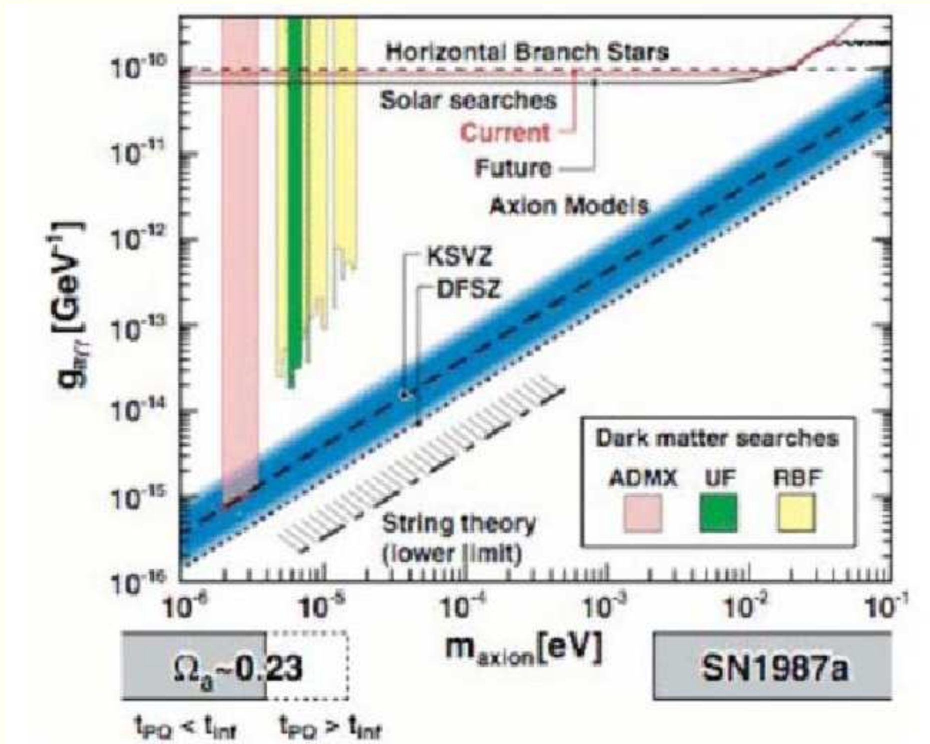
- ⋆ PQ solution to strong CP problem in QCD
- ⋆ pseudo-Goldstone boson from
  PQ breaking at scale $f_a \sim 10^9 - 10^{12}$ GeV
- ⋆ non-thermally produced
  via vacuum mis-alignment as *cold* DM
  - $m_a \sim \Lambda^2_{QCD}/f_a \sim 10^{-6} - 10^{-1} eV$
  - $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times 10^{-6} eV}{m_a}\right]^{7/6} h^2$
  - astro bound: stellar cooling $\Rightarrow m_a < 10^{-1} eV$
  - a couples to EM field: $a - \gamma - \gamma$ coupling (Sikivie)
  - axion microwave cavity searches



Axion microwave cavity searches

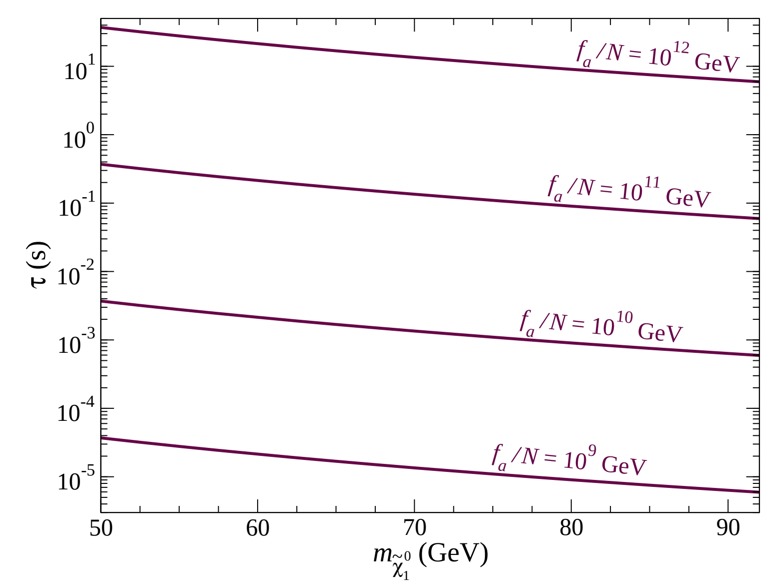
⋆ ongoing searches: ADMX experiment

- 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



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

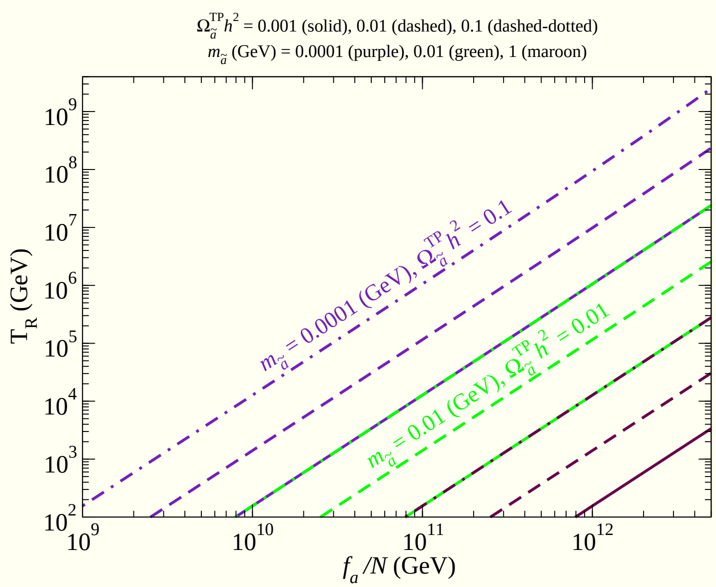
- axino is spin-$\frac{1}{2}$ element of axion supermultiplet (R-odd; can be LSP)
  - Raby, Nilles, Kim
  - Rajagopal, Wilczek, Turner
- $m_{\tilde{a}}$ model dependent: keV$\rightarrow$ GeV
- $\widetilde{Z}_1 \rightarrow \tilde{a}\gamma$
- non-thermal $\tilde{a}$ production via $\widetilde{Z}_1$ decay: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

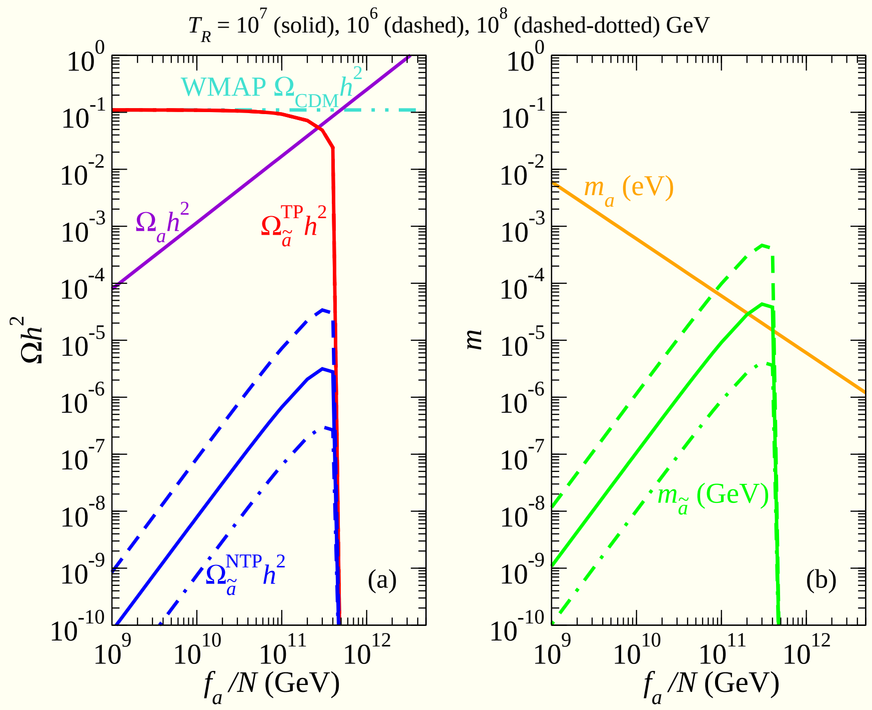
- ★ If $T_R < f_a$, then axinos never in thermal equilibrium in early universe
- ★ Can still produce $\tilde{a}$ thermally via radiation off particles in thermal equilibrium
- ★ Brandenberg-Steffen calculation:

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



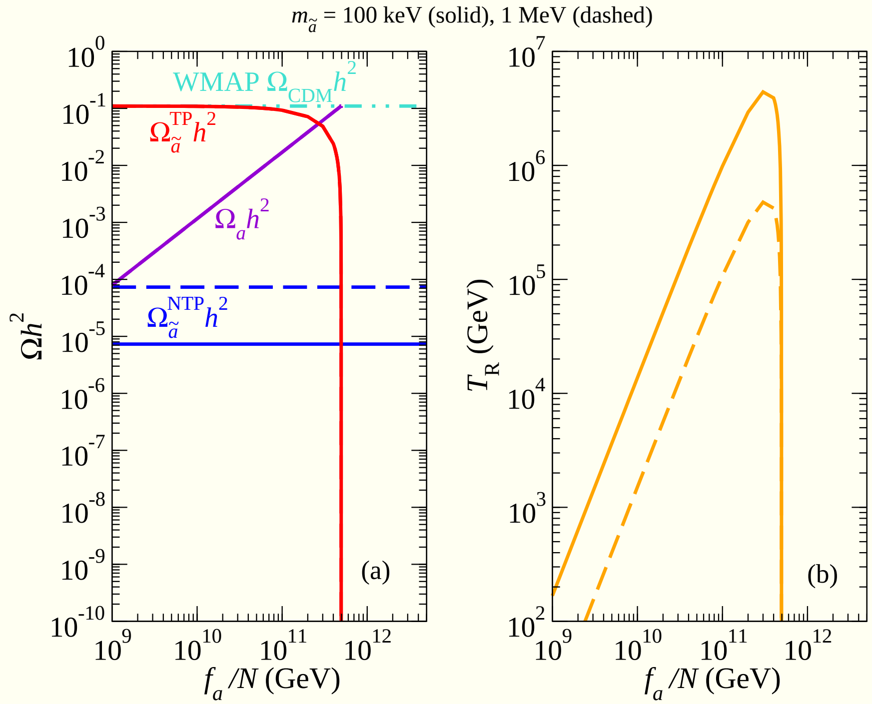
mSUGRA model with mixed axion/axino CDM: T_R fixed

- ⋆ $(m_0, m_{1/2}, A_0, \tan\beta, sgn(\mu)) = (1000\ \mathrm{GeV}, 300\ \mathrm{GeV}, 0, 10, +1)$
- ⋆ $\Omega_a h^2 + \Omega_{\tilde{a}}^{TP} h^2 + \Omega_{\tilde{a}}^{NTP} h^2 = 0.11$
- ⋆ HB, Box, Summy, JHEP**0908** (2009) 080.



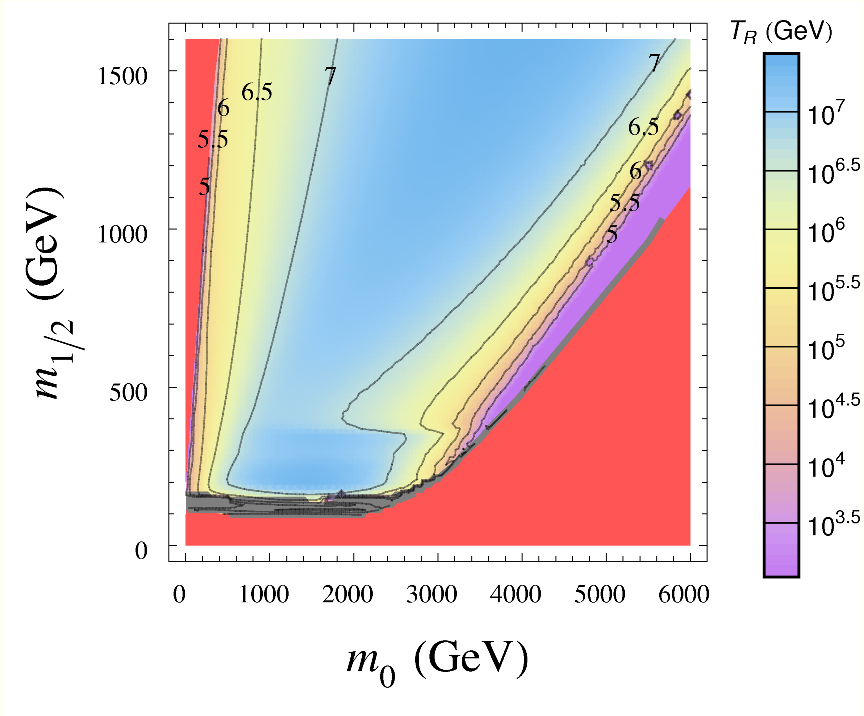
mSUGRA model with mixed axion/axino CDM: $m_{\tilde{a}}$ fixed

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



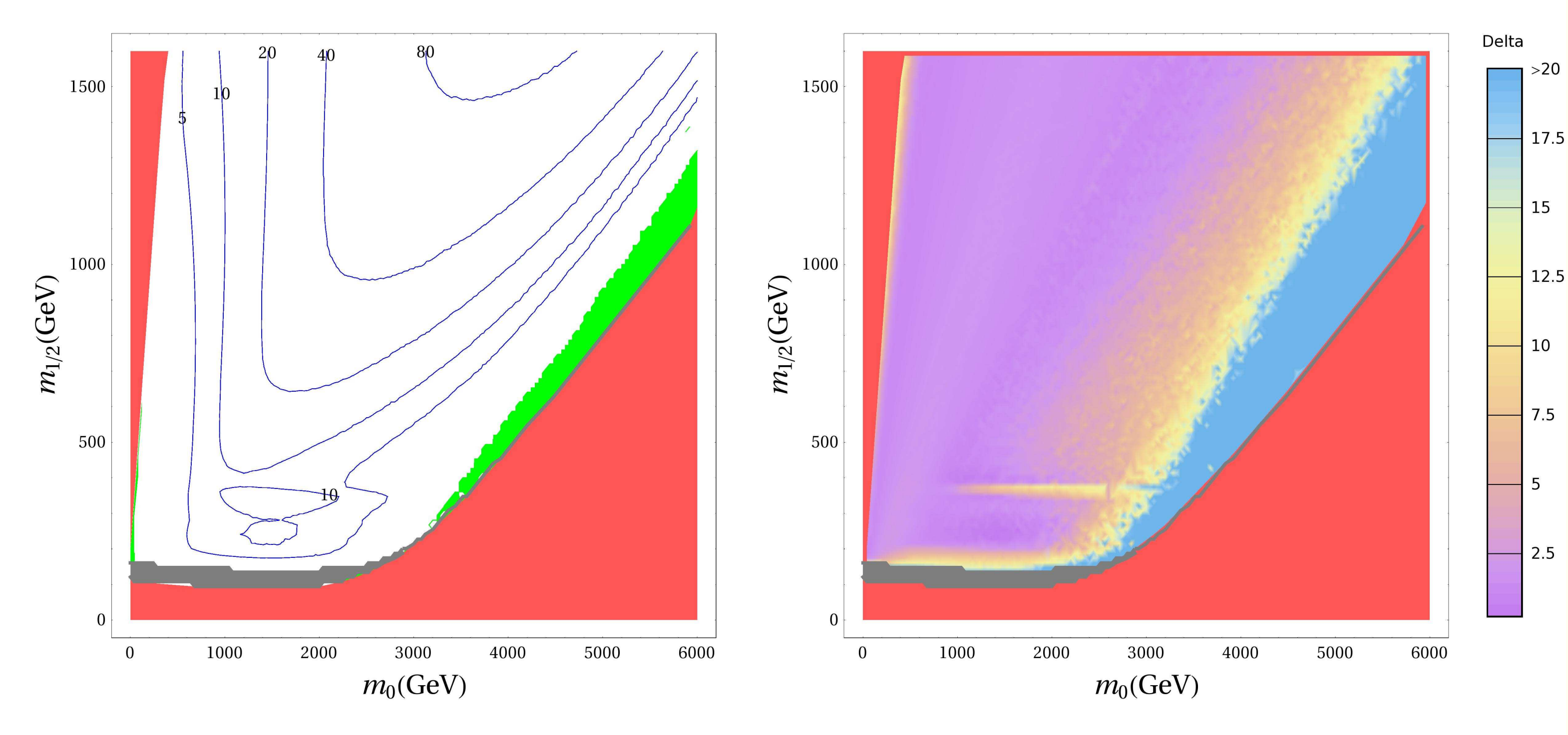
mSUGRA p-space with mainly axion cold DM

- ⋆ 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)



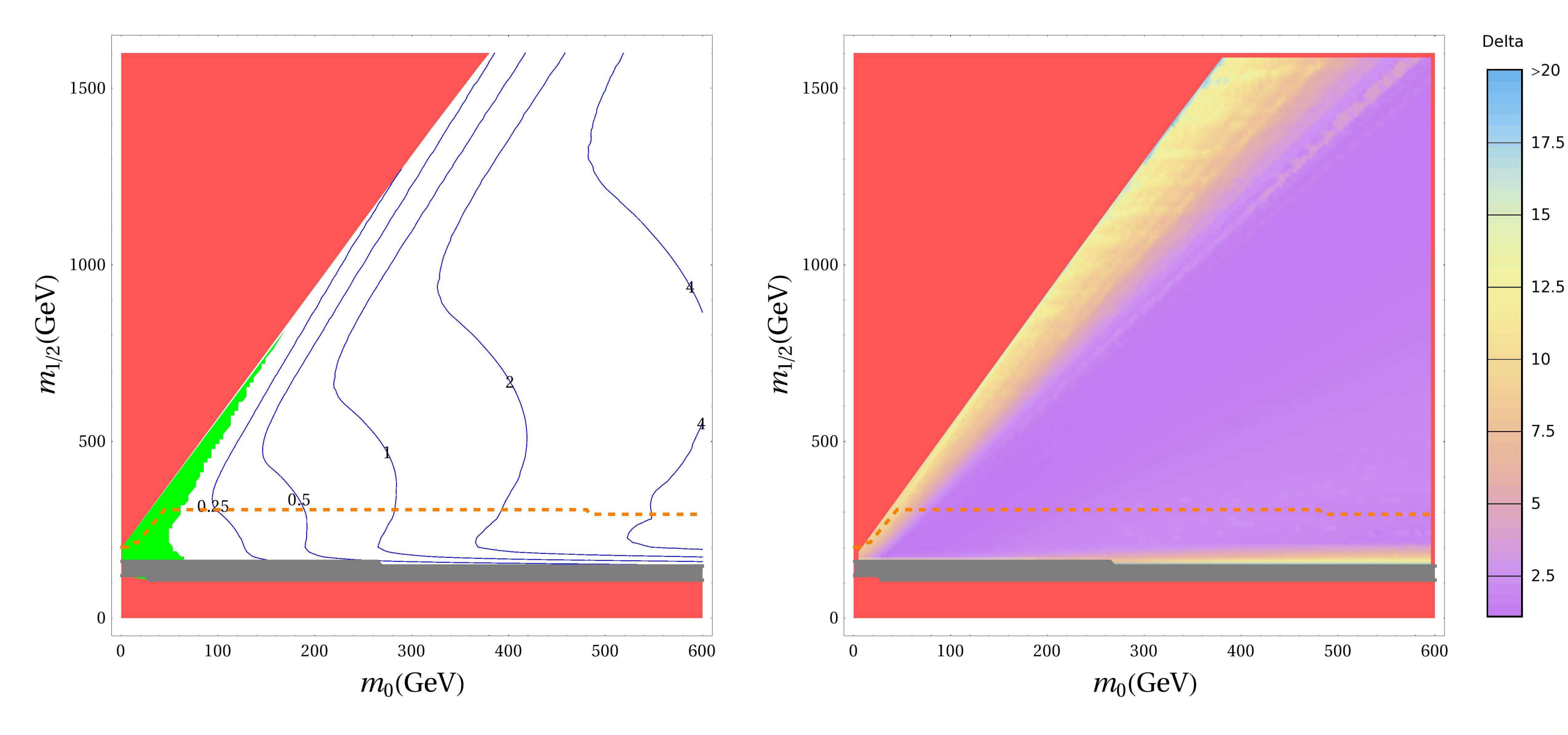
Fine-tuning in mSUGRA with neutralino CDM

- ⋆ 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)



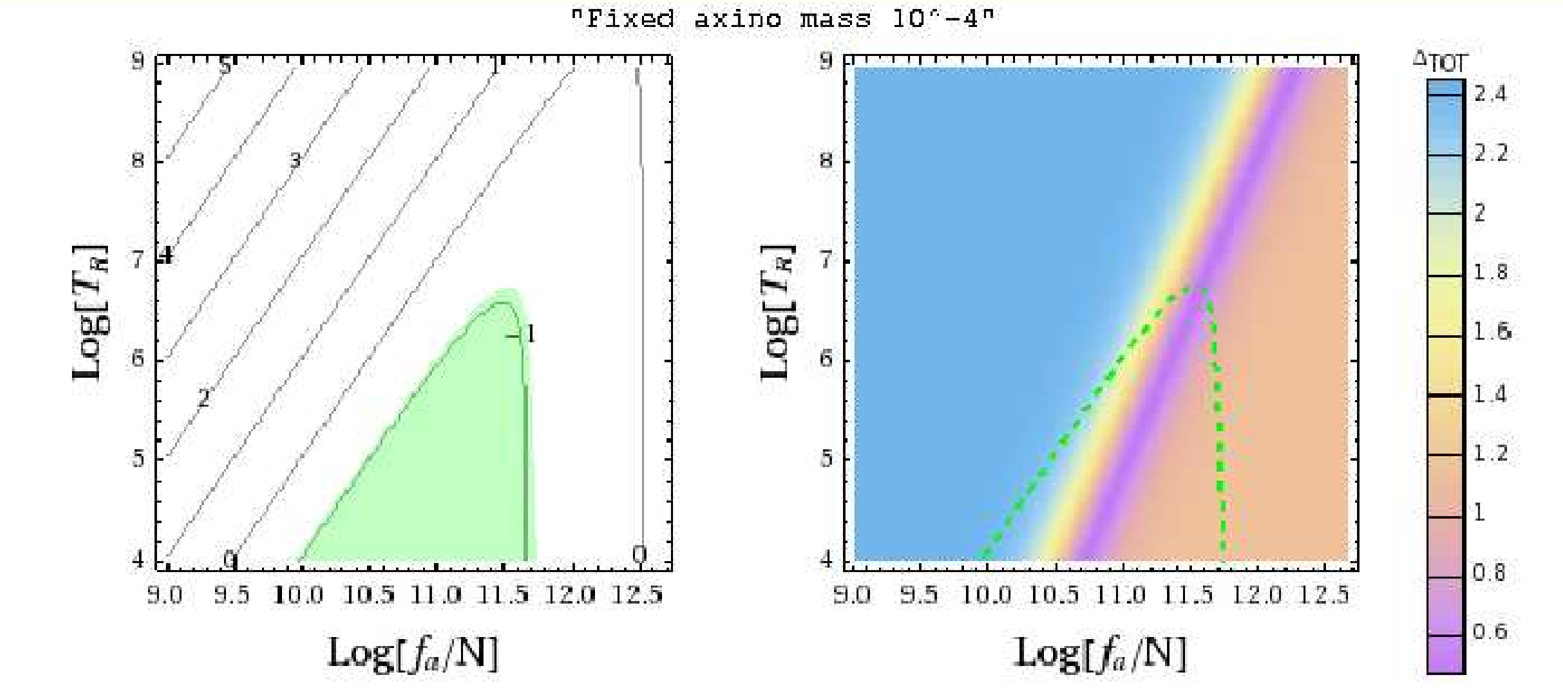
Fine-tuning zoomed in stau-co-annihilation

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



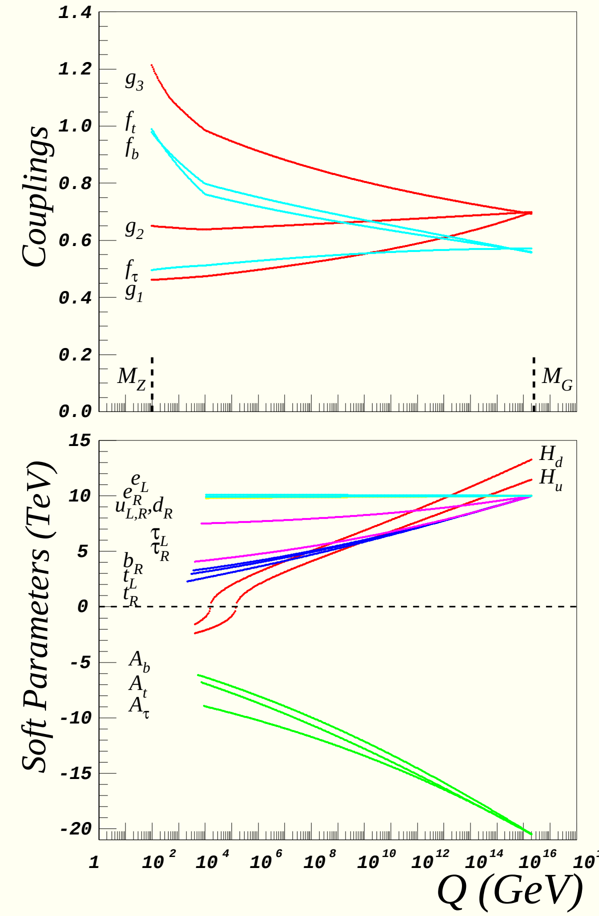
Fine-tuning for mainly axion CDM in mSUGRA

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



Prediction for LHC: SUSY with $t-b-\tau$ Yukawa unification

- $m_{16},\ m_{10},\ M_D^2,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- need $m_{16}\sim 10$ TeV and $m_{1/2}$ very small
- need $m_{10}\simeq\sqrt{2}m_{16};\ A_0\simeq -2m_{16}$
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: $m_{H_u}^2 < m_{H_d}^2$
- Auto, HB, Balazs, Belyaev, Ferrandis, Tata
- HB, Kraml, Sekmen, Summy
  - $m_{\tilde{q},\tilde{\ell}}(1,2)\sim 10$ TeV
  - $m_{\tilde{t}_1},\ m_A,\ \mu\sim 1-2$ TeV
  - $m_{\tilde{g}}\sim 300-500$ GeV
- see also Blazek, Dermisek, Raby
- Altmannshofer, Guadagnoli, Raby, Straub



Consequences of $t-b-\tau$ Yukawa unified SUSY

- for $m_{16} \sim m_{3/2} > 5$ TeV allow $T_R \sim 10^6 - 10^8$ GeV (solve gravitino problem and allow non-thermal or DRT leptogenesis)
- huge $\Omega_{\widetilde{Z}_1} h^2 \sim 10^3 \Rightarrow$ dark matter is mixed axion/axino instead of neutralino
- $m_{\tilde{g}} \sim 400$ GeV $\Rightarrow \sigma(pp \to \tilde{g}\tilde{g}X) \sim 10^5$ fb at $\sqrt{s} = 14$ TeV LHC
- $\tilde{g} \to b\bar{b}\widetilde{Z}_2$ dominant; also, $\tilde{g} \to tb\widetilde{W}_1$
- expect beautiful mass edge in $m(\ell^+\ell^-)$
- testable at LHC with $\sim 0.1 - 1$ fb^{-1}
- reconstruct $m_{\tilde{g}}$ via $m(bb\ell^+\ell^-)$
- possible axion signal at ADMX?
- WIMP direct/indirct searches yield null result

Conclusions

- ⋆ Supersymmetry is very compelling BSM theory
- ⋆ Irrefragable case for CDM has emerged
- ⋆ Direct search for WIMP/axion DM is underway
- ⋆ Indirect search for WIMP DM via Icecube ν telescope
- ⋆ Indirect search via γ, $\bar{p}$, e^+, $\bar{D}$ detection from galactic core/halo WIMP annihilations
- ⋆ Gravitino DM: possible, but suffers from "gravitino problem"
- ⋆ Mixed axion/axino as CDM: more compelling than neutralinos
- ⋆ Next: what can we learn from LHC about SUSY and DM?