Why SUSY GUTs imply that the bulk of dark matter is made of axions

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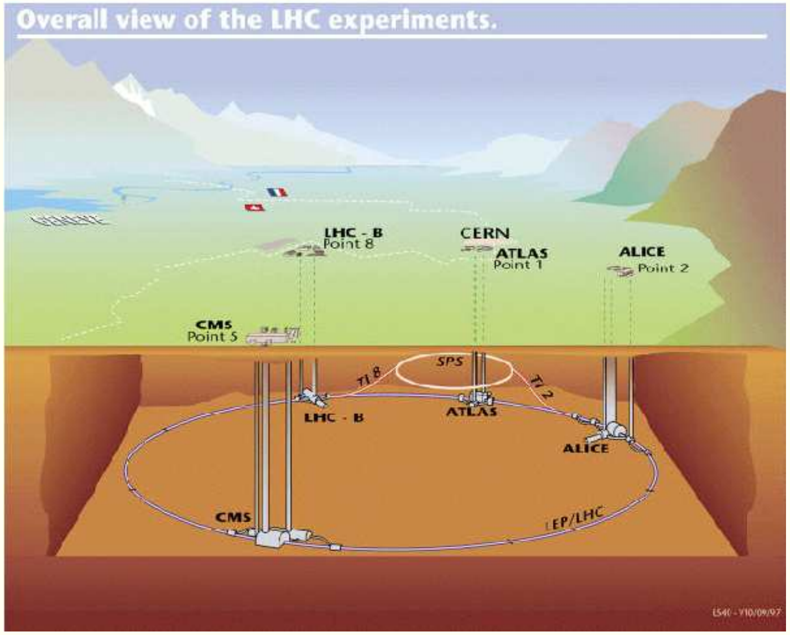
- ⋆ $SO(10)$ motivation
- ⋆ Yukawa unification
- ⋆ Sparticle mass calculation
- ⋆ Dark matter problem
  - • mixed axion/axino DM
- ⋆ cosmology of SUSY $SO(10)$
- ⋆ $SO(10)$ at LHC
  - – can see with just 0.1 fb^{-1}!



$SO(10)$: synopsis

⋆ $SO(10)$ is a rank-5 Lie group which contains the SM gauge symmetry.

- matter unification in *spinorial* $\mathbf{16}$
- The $\mathbf{16}$ contains *all* the matter in a single generation of the SM, plus a RHN state $\hat{N}^c$: see-saw ν-masses
- $SO(n)$ (except $n = 6$) are naturally anomaly-free, thus explaining the seemingly fortuitous anomaly cancellation in the SM and in $SU(5)$.
- Explains R-parity conservation
- Explains why 2 Higgs doublets in MSSM
- Expect $t - b - \tau$ Yukawa unification in simplest models

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: $m_{\tilde{G}} \sim 1$ TeV and soft SUSY breaking terms ~ 1 TeV
- $SO(10)$ breaks to MSSM or MSSM plus gauge singlets at $Q = M_{GUT}$ 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 assume that $t - b - \tau$ Yukawa couplings unify at $Q = M_{GUT}$

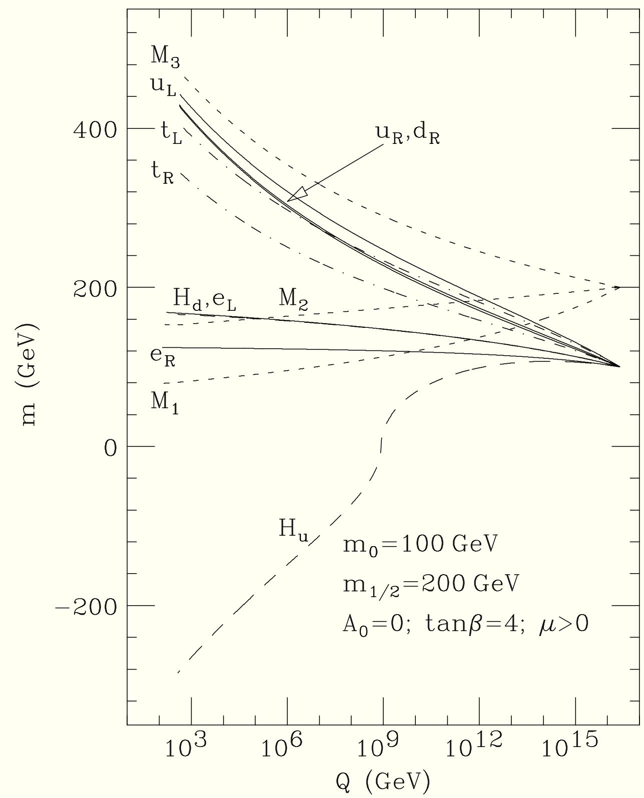
lots of previous work!

- 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

- H. Baer, M. Diaz, J. Ferrandis and X. Tata, PRD61 (2000)111701
- H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana and X. Tata, PRD63 (2001)015007;
- H. Baer and J. Ferrandis, PRL87 (2001)211803;
- T. Blazek, R. Dermisek and S. Raby, PRL88 (2002)111804 and PRD65 (2002)115004;
- D. Auto, H. Baer, C. Balazs, A. Belyaev, J. Ferrandis and X. Tata, JHEP0306 (2003)023
- D. Auto, H. Baer, A. Belyaev and T. Krupovnickas, JHEP0410 (2004)066;
- R. Dermisek, S. Raby, L. Roszkowski and R. Ruiz de Austri, JHEP0304 (2003)037 and JHEP0509 (2005)029
- H. Baer, S. Kraml, S.Sekmen and H. Summy, arXiv:0801.1831 (2008).

Sparticle mass spectra



★ Mass spectra codes

★ RGE running: $M_{GUT} \to M_{weak}$

- Isajet 7.78 (HB, Paige, Protopopescu, Tata)
  - $\ast$ $\geq$7.72: Isatools
- SuSpect (Djouadi, Kneur, Moultaka)
- SoftSUSY (Allanach)
- Spheno (Porod)

★ Comparison (Belanger, Kraml, Pukhov)

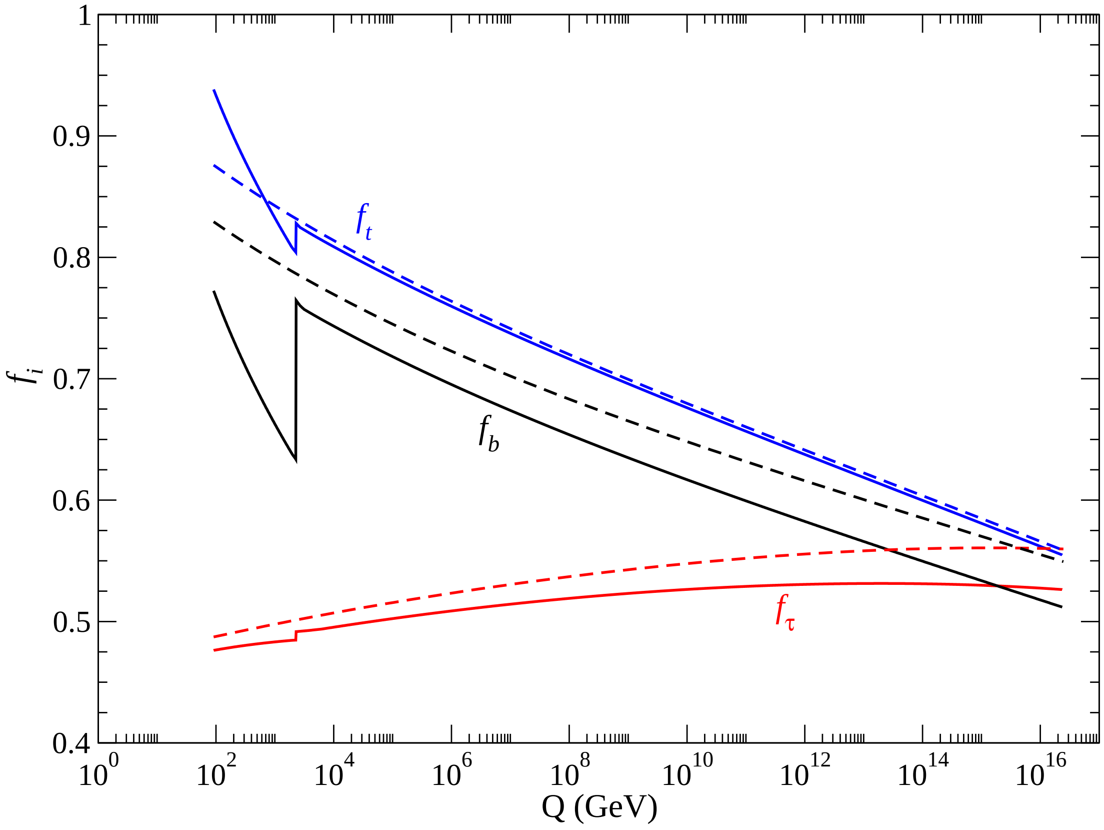
★ Website: `http://kraml.home.cern.ch/kraml/comparison/`

Yukawa unification requires precision calculation of SUSY spectrum:

Hall, Rattazzi, Sarid; Pierce *et al.* (PBMZ)

- need full 2-loop RGE running
- full threshold corrections calculated at optimized scale
  - applies especially to b-quark self-energy
  - $\tilde{g}\tilde{b}_i$, $\widetilde{W}_i\tilde{t}_j$, $\cdots$ loops included
- off-sets Yukawa coupling RG trajectory
- use Isajet/Isasugra spectrum generator

Yukawa unification in MSSM: Isajet and SoftSUSY



$SO(10)$-inspired parameter space:

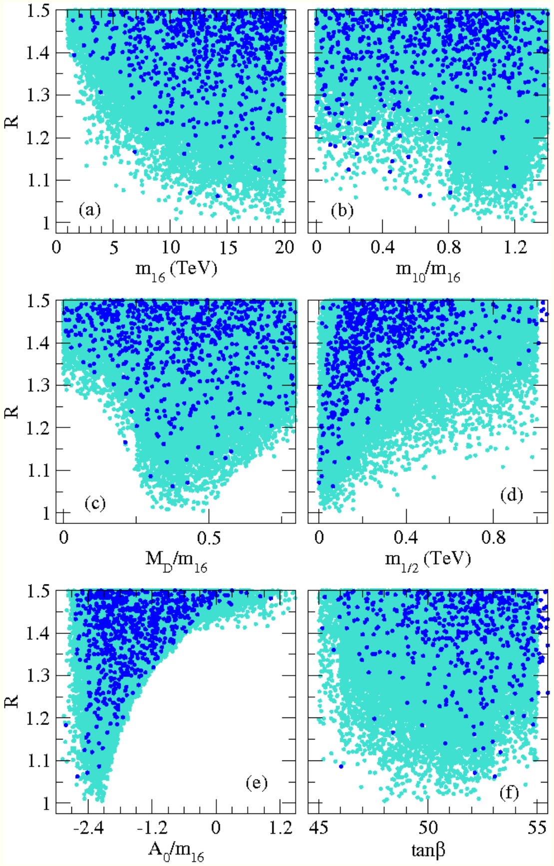
- $m_{16},\ m_{10},\ M_D^2,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- Here, M_D^2 parametrizes splitting of Higgs soft terms at M_{GUT}:

$$m_{H_{u,d}}^2 = m_{10}^2 \mp 2M_D^2$$

⋆ The Higgs splitting only (HS) method gives better Yukawa unification than full D-term splitting (DT) model for $\mu > 0$ and $m_{16} \gtrsim 2$ TeV

- HS can arise at 10-15% level at GUT scale due to threshold corrections (BDR)

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



Auto, HB, Balazs, Belyaev, Ferrandis, Tata

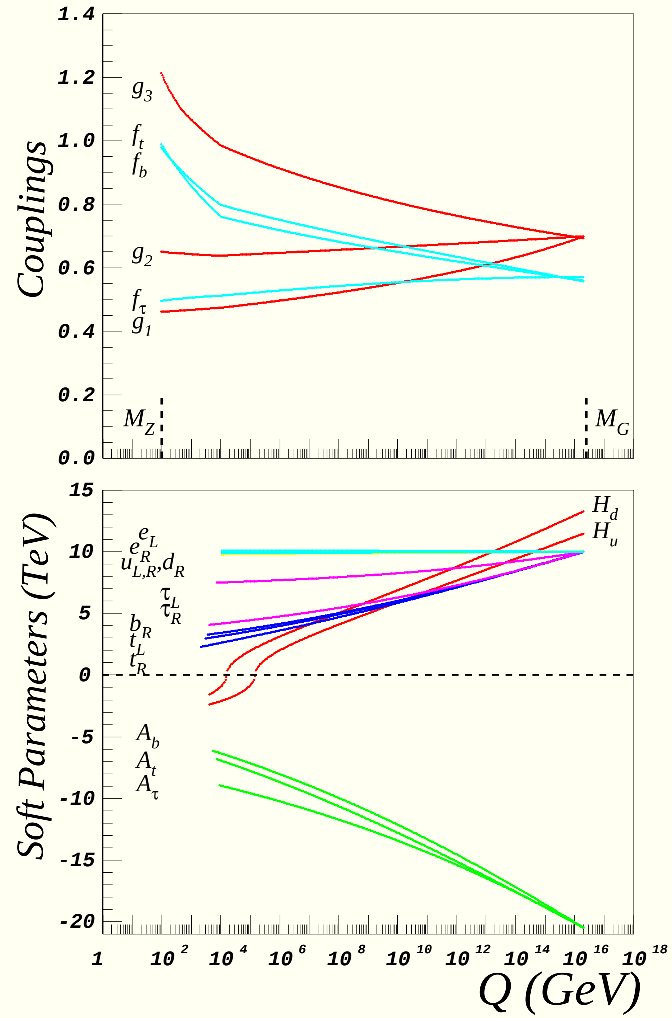
New analysis: HB, Kraml, Sekmen, Summy

Correlation of SSB terms for YU models

- ⋆ Note correlation amongst parameters:
  - $A_0 \sim -2m_{16}$
  - $m_{10} \sim 1.2m_{16}$
  - $\tan\beta \sim 50$
- ⋆ 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: in context of "radiatively induced inverted scalar mass hierarchy model"
  - – Meant to reconcile naturalness with FCNC suppression by having $m(third\ gen.\ scalars) \ll m(1st/2nd\ ge.\ scalars)$
  - – Original model needed to be reconciled with EWSB; get hierarchy, but much less than anticipated: HB, Balazs, Mercadante, Tata, Wang (2001)

$t - b - \tau$ Yukawa unification in HS model!

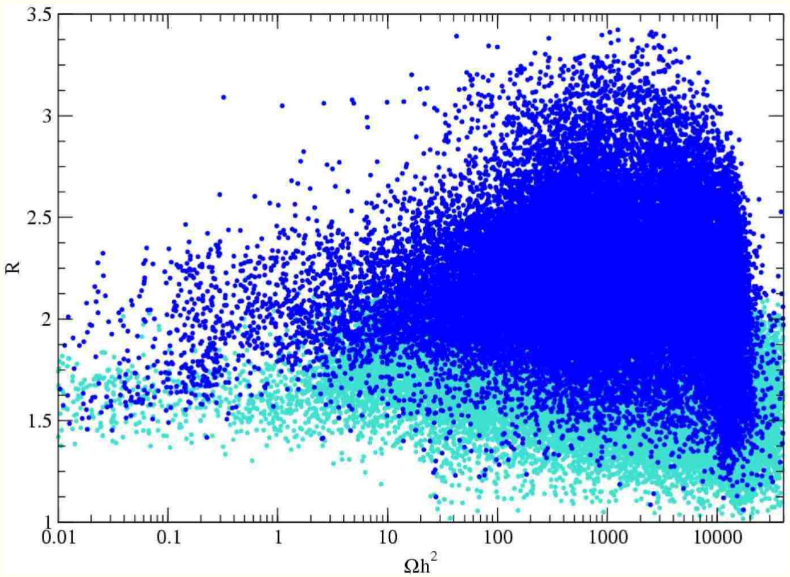
- need $m_{10} \simeq \sqrt{2} m_{16}$
- $A_0 \simeq -2m_{16}$
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: $m_{H_u}^2 < m_{H_d}^2$
- Auto, HB, Balazs, Belyaev, Ferrandis, Tata
  - $m_{\tilde{q},\tilde{\ell}}(1,2) \sim 10$ TeV
  - $m_{\tilde{t}_1},\ m_A,\ \mu \sim 1-2$ TeV
  - $m_{\tilde{g}} \sim 300-500$ GeV
- Blazek, Dermisek, Raby
  - small $\mu,\ m_A \sim 100-200$ GeV



Neutralino dark matter

- ⋆ Why R-parity? natural in $SO(10)$ SUSYGUTS if properly broken, or broken via compactification (Mohapatra, Martin, Kawamura, $\cdots$)
- ⋆ In thermal equilibrium in early universe
- ⋆ As universe expands and cools, freeze out
- ⋆ Number density obtained from Boltzmann eq'n
  - $dn/dt = -3Hn - \langle\sigma v_{rel}\rangle(n^2 - n_0^2)$
  - depends critically on thermally averaged annihilation cross section times velocity
- ⋆ many thousands of annihilation/co-annihilation diagrams
- ⋆ several computer codes available
  - DarkSUSY, Micromegas, IsaReD (part of Isajet)

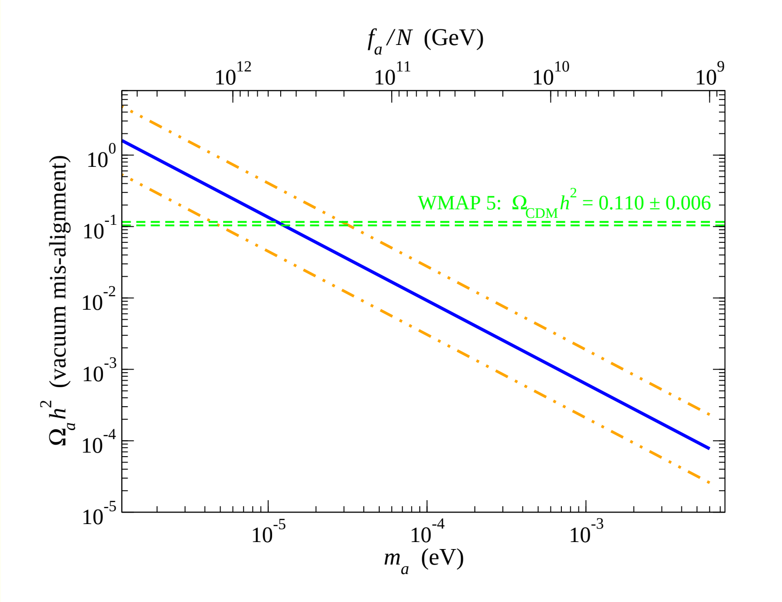
Problem: reconcile DM with Yukawa unification



- ⋆ best solution: axion/axino DM instead of neutralino
- each $\widetilde{Z}_1 \to \tilde{a}\gamma$ so $\Omega_{\tilde{a}} h^2 \sim \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}} \Omega_{\widetilde{Z}_1} h^2$: $\Rightarrow$ warm DM
- also thermal component depending on T_R: $\Rightarrow$ CDM
- also axion DM via vacuum mis-alignment

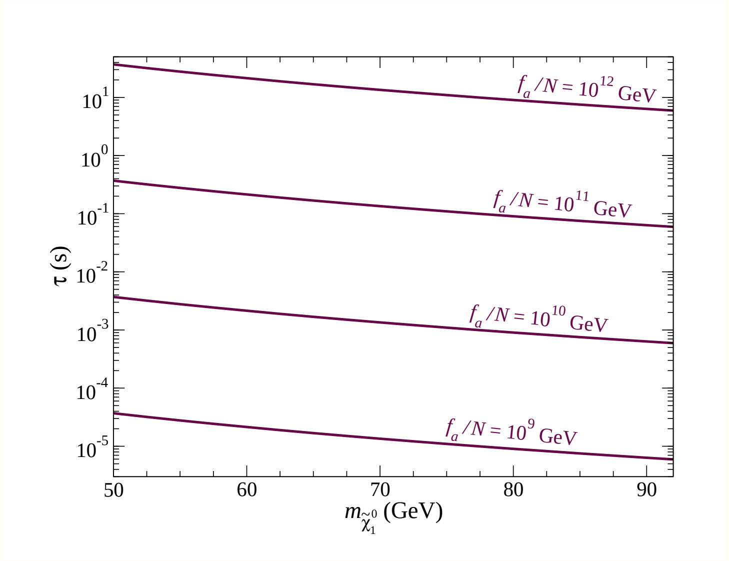
Axions

- ⋆ 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
  - $m_a \sim \Lambda_{QCD}^2/f_a \sim 10^{-6} - 10^{-1} eV$
  - $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times 10^{-6} eV}{m_a}\right]^{7/6} h^2$
  - astro bound: stellar cooling $\Rightarrow m_a < 10^{-1} eV$
  - a couples to EM field: $a - \gamma - \gamma$ coupling (Sikivie)
  - axion microwave cavity searches



Axino $\tilde{a}$ dark matter

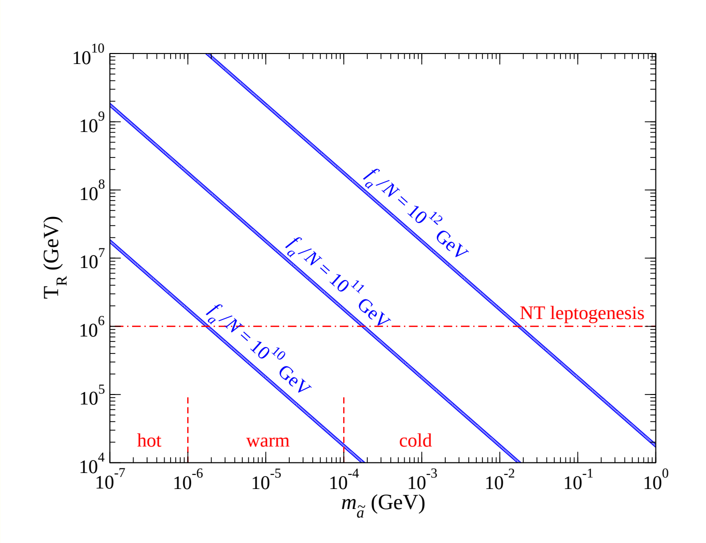
- axino is spin-$\frac{1}{2}$ element of axion supermultiplet (R-odd; can be LSP)
- $m_{\tilde{a}}$ model dependent: keV$\rightarrow$ GeV
- $\widetilde{Z}_1 \rightarrow \tilde{a}\gamma$
- non-thermal $\tilde{a}$ production via $\widetilde{Z}_1$ decay:
- axinos inherit neutralino number density
- $\Omega_{\tilde{a}}^{NTP}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



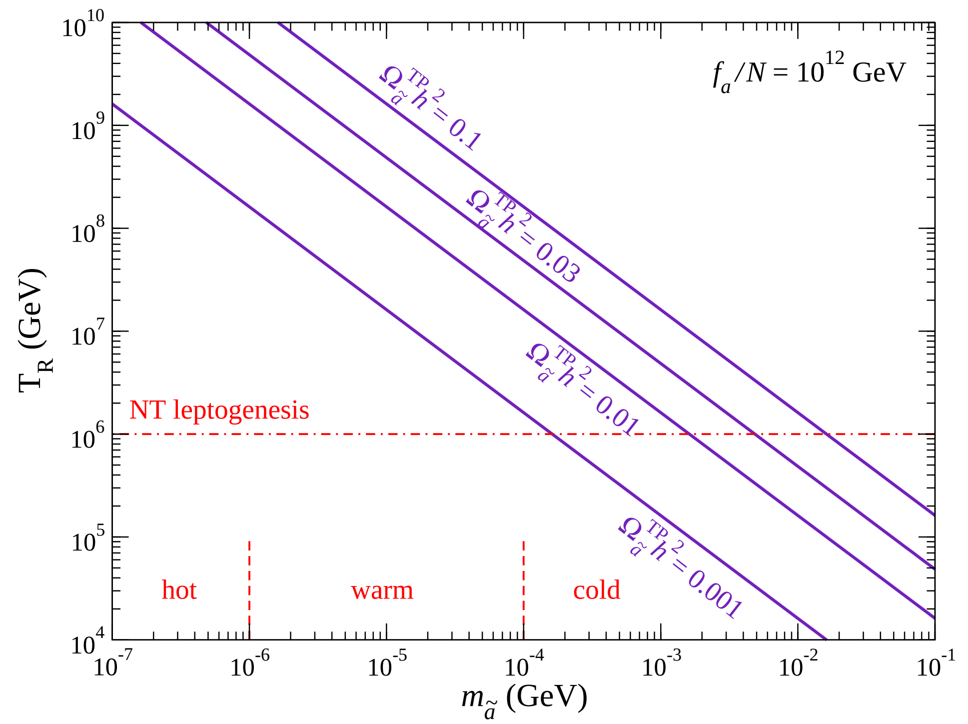
Thermally produced axinos

- ⋆ 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:

$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 5.5 g_s^6 \ln\left(\frac{1.108}{g_s}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2\left(\frac{m_{\tilde{a}}}{0.1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right) \quad (1)$$

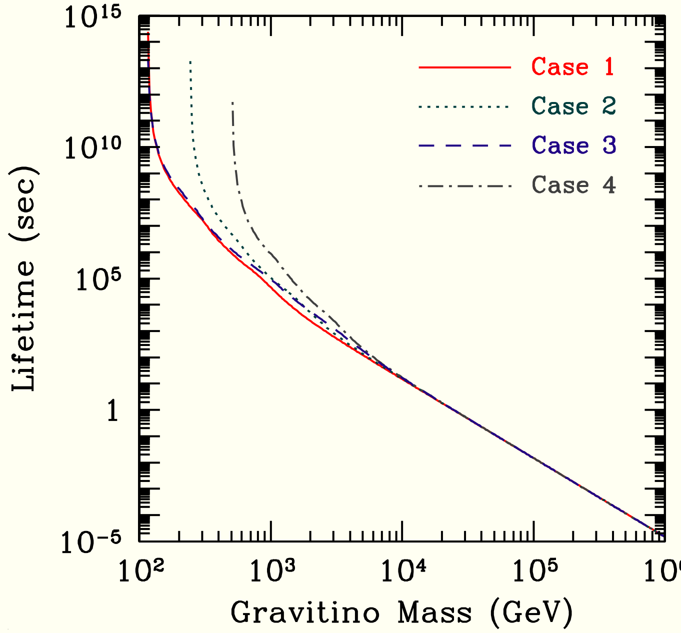


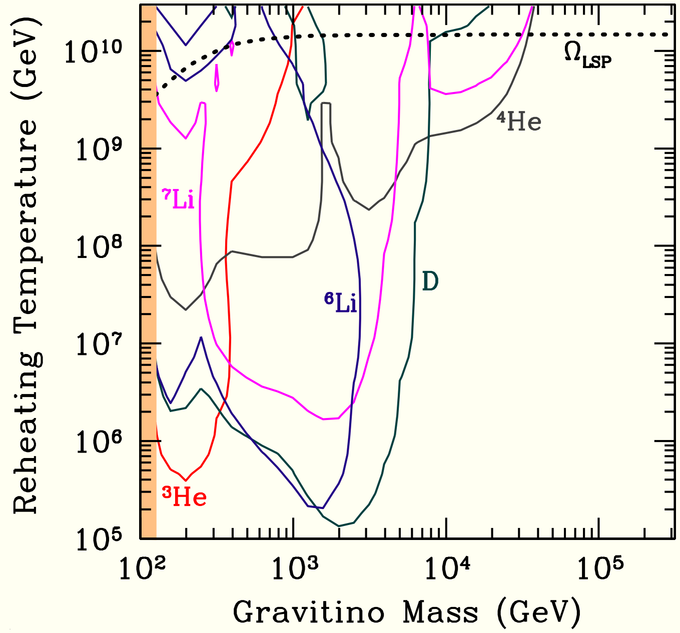
Thermally produced axinos for $f_a/N = 10^{12}$ GeV



Consistent cosmology for SUSY $SO(10)$: gravitino problem

- 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)

Alternative 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
- 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, Affleck-Dine leptogenesis in $\phi = \sqrt{H\ell}$ D-flat direction: $T_R \sim 10^6 - 10^8$ GeV allowed
- WMAP observation: $n_b/s \sim 0.9 \times 10^{-10} \Rightarrow T_R \gtrsim 10^6$ GeV

Cold axion and cold/warm axino DM in the universe

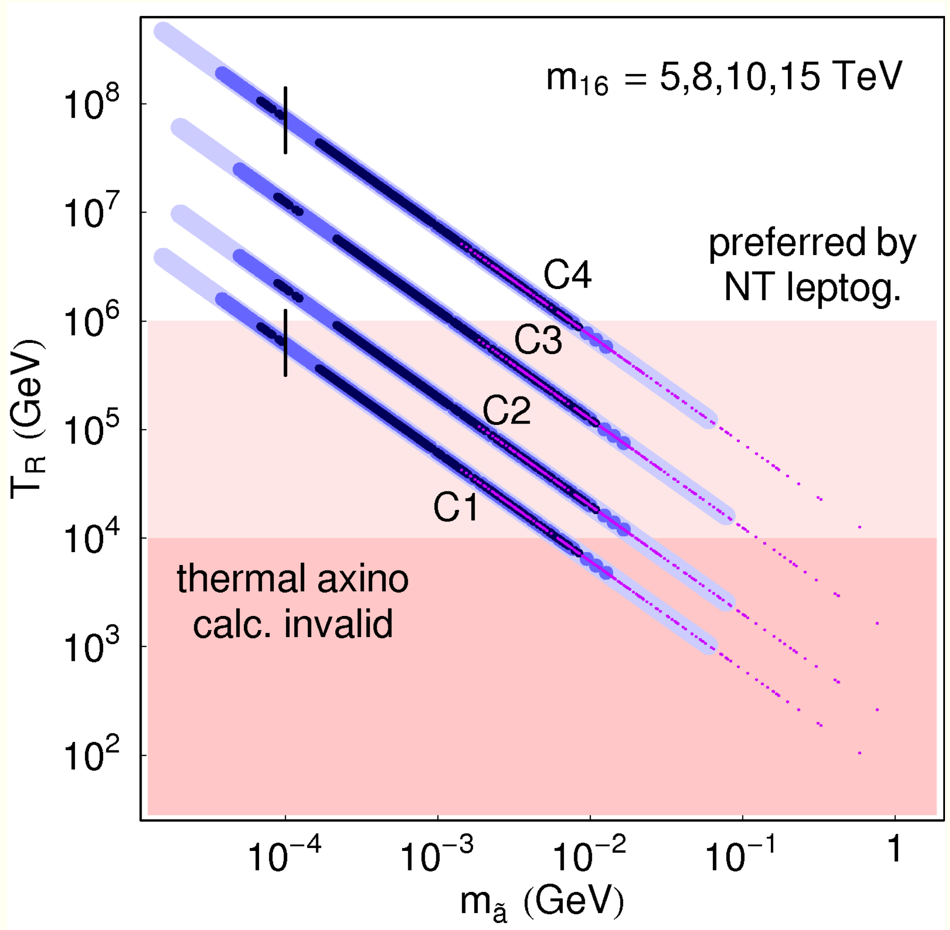
⋆ Four cases:

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 $\Omega_{\tilde{a}}^{NTP} = 0.01$

- 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

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

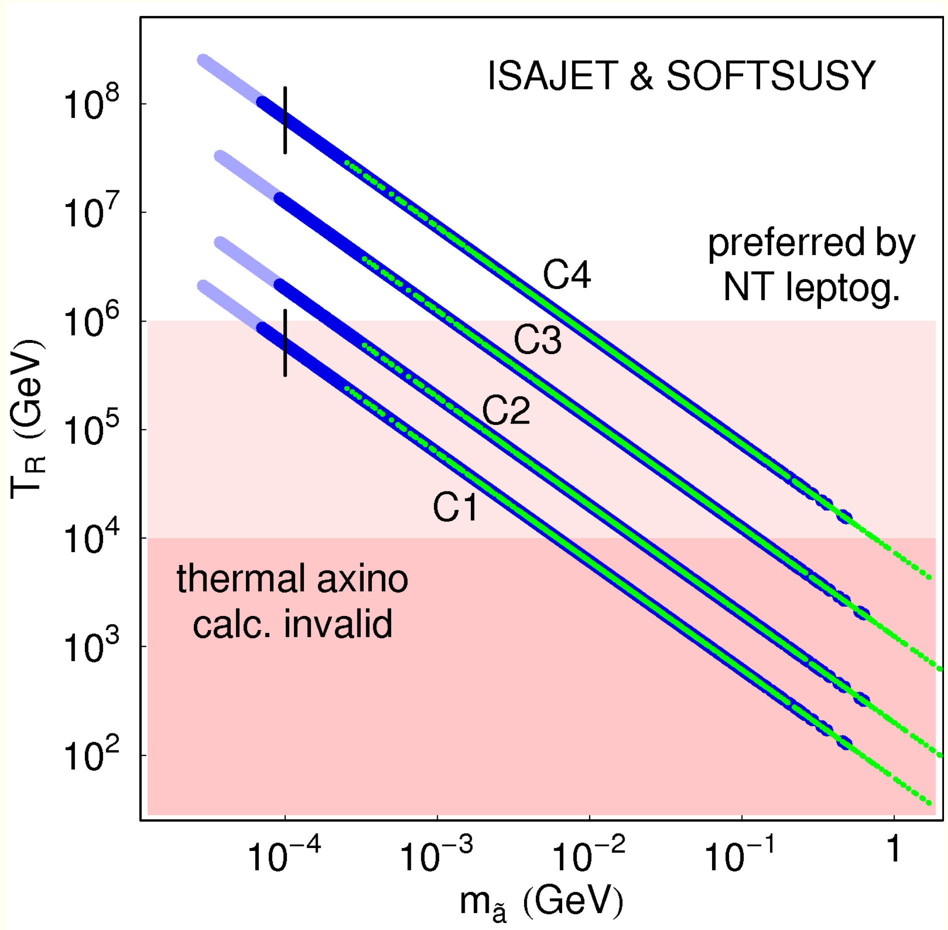
- Happily, T_R falls into the right range to give *cold* axion/axino DM with a small admixture of warm axino DM, preserve BBN predictions and have non-thermal leptogenesis!
- See HB and H. Summy, PLB666, 5 (2008)
- HB, Kraml, Haider, Sekmen and Summy, arXiv:0812.2693



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

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

- Want $T_R \gtrsim 10^6$ GeV for NT leptogenesis but $< 10^{10}$ GeV to solve BBN/gravitino problem
- Below: Isajet/SoftSUSY comparison
- viable solutions need $f_a/N \gtrsim 4 \times 10^{11}$ GeV
- also prefer $m_{16} \gtrsim 10$ TeV


ISAJET & SOFTSUSY
preferred by
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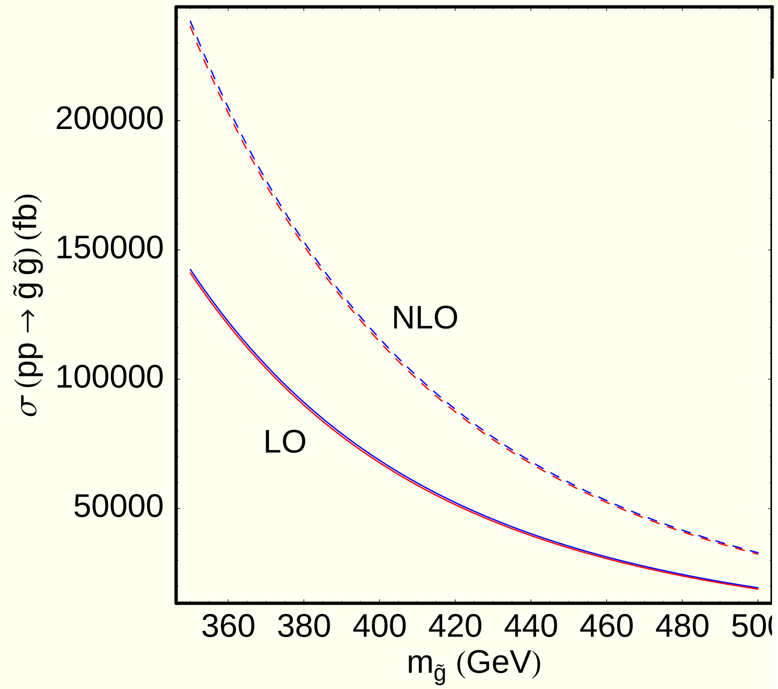
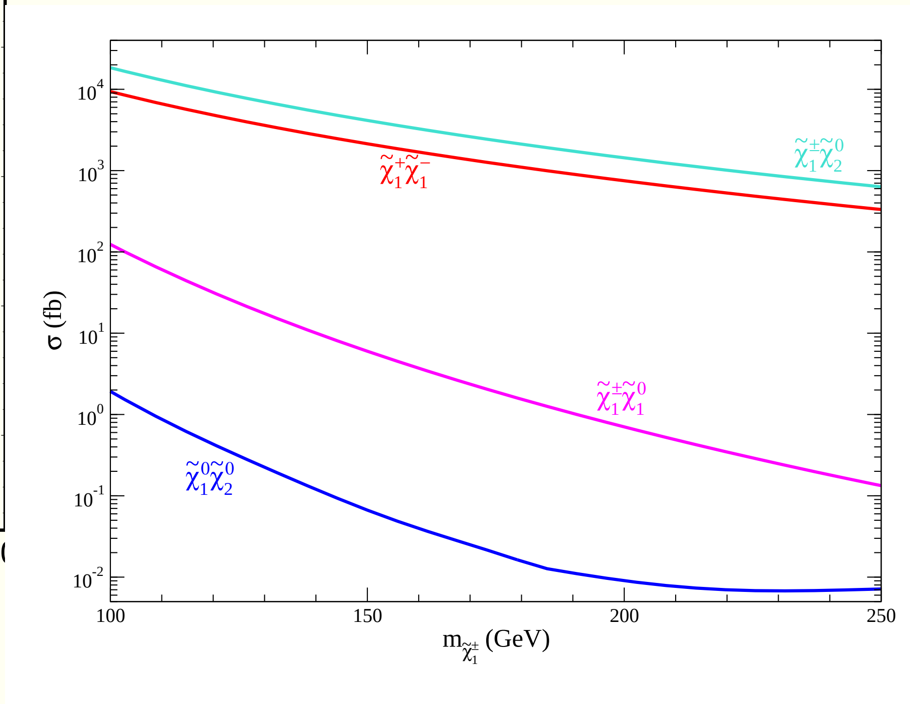
C4
C3
C2
C1
thermal axino
calc. invalid
10^8
10^7
10^6
10^5
10^4
10^3
10^2
T_R (GeV)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$m_{\tilde{a}}$ (GeV)

Prediction of new physics at LHC from $SO(10)$ SUSYGUTs:

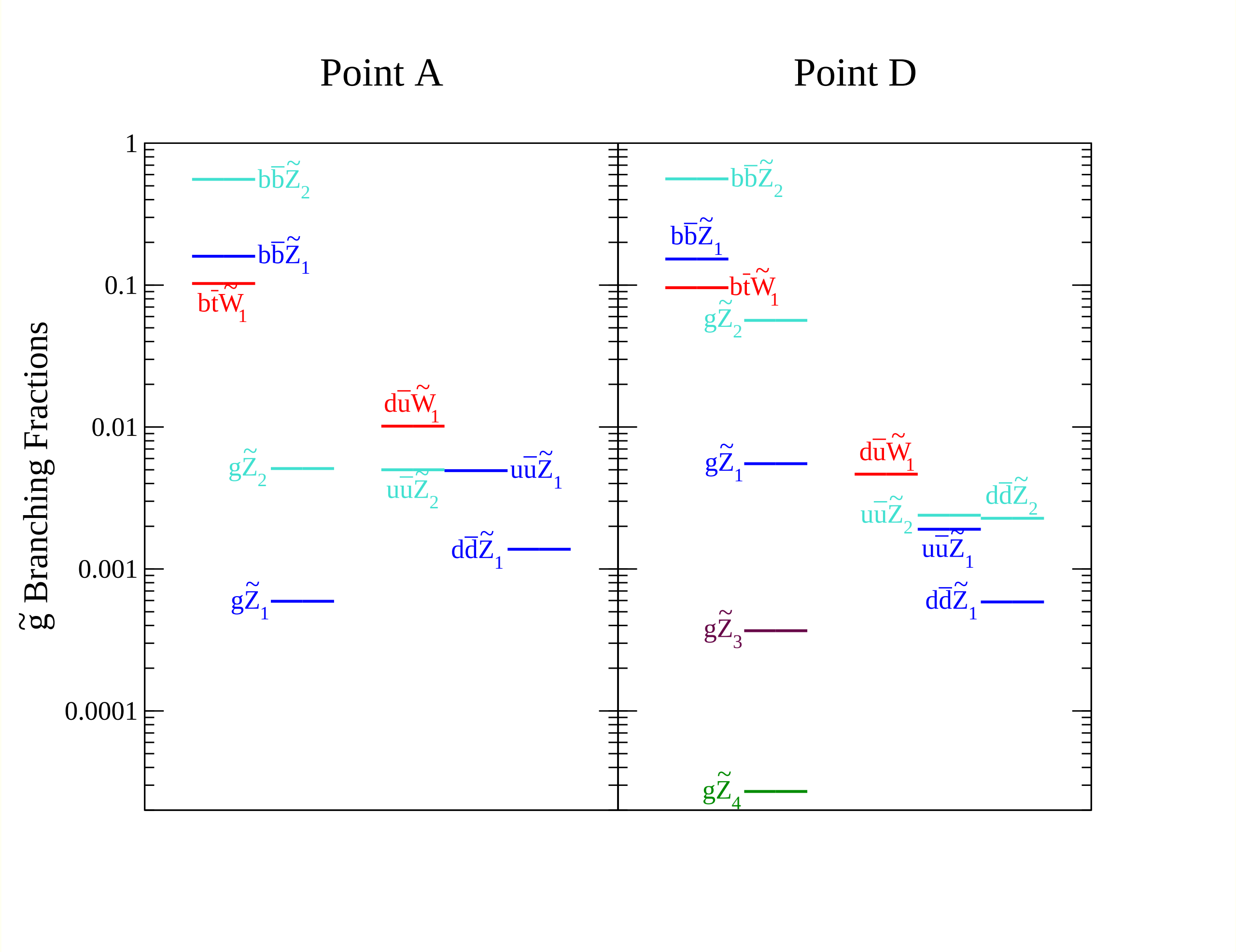
- gluino pair production with $m_{\tilde{g}} \sim 350 - 450$ GeV
- $\sigma(pp \to \tilde{g}\tilde{g}X) \sim 10^5$ fb
- major decays: $\tilde{g} \to b\bar{b}\widetilde{Z}_2$, $\tilde{g} \to t\bar{b}\widetilde{W}_1 + c.c.$
- high b-jet multiplicity
- $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \sim 50 - 75$ GeV dilepton mass edge

Production of sparticles at LHC





Gluino branching fractions in Yukawa unified SUSY



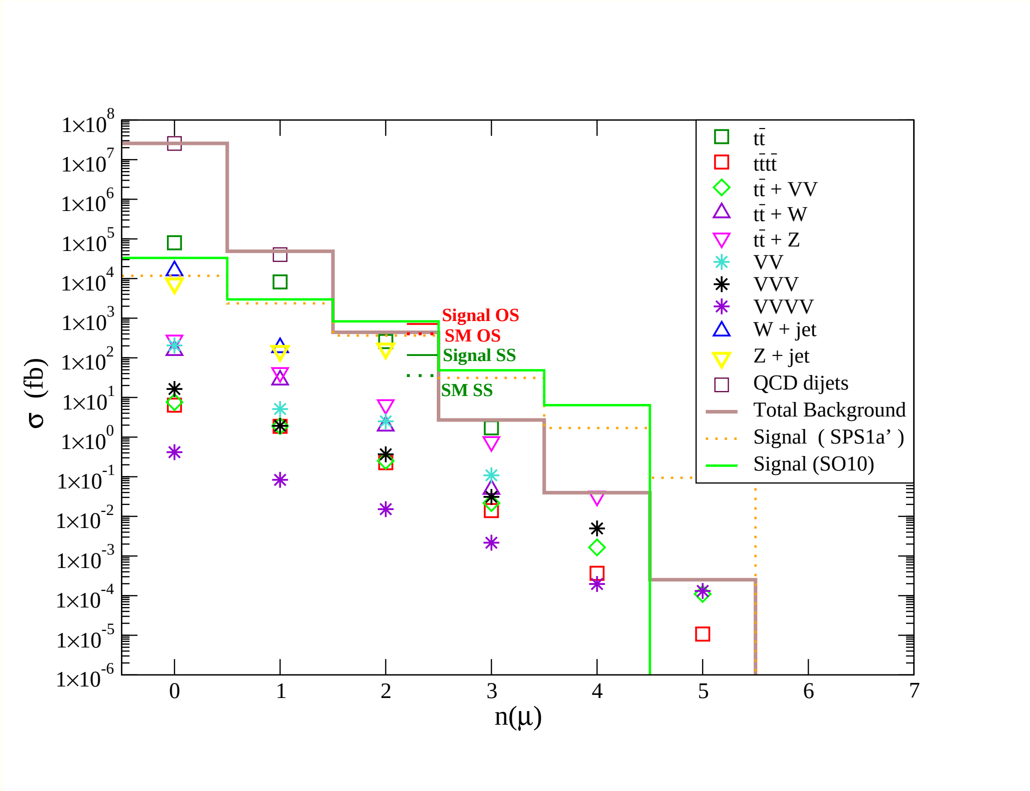
What $SO(10)$ SUSY GUTs look like at LHC

- with $m_{\tilde{g}} \sim 400$ GeV, expect $\sigma(pp \to \tilde{g}\tilde{g}X) \sim 10^5$ fb!
- LHC detectors would have LOTS of SUSY events!
- But, it will take time to measure many SM processes to reliably calibrate the entire detector for $jets + \not{E}_T$ search
- Could be a year or two if experience is similar to that of Tevatron D0 detector....

As theorists, we are an impatient bunch...

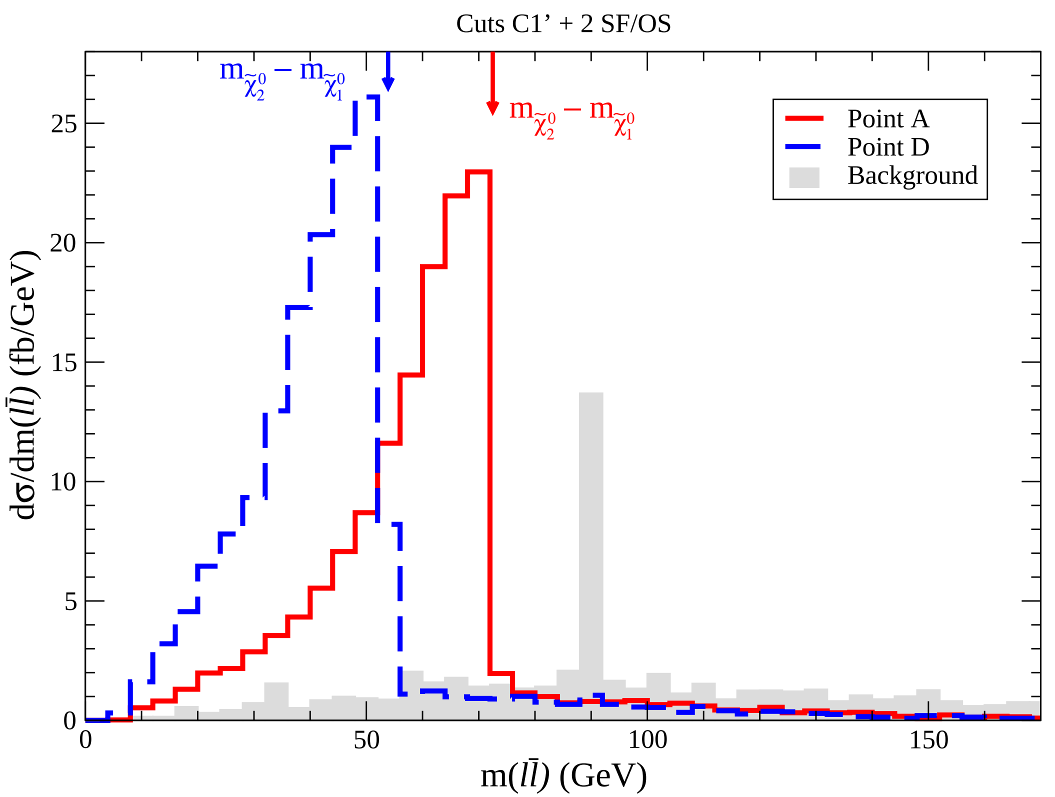
- Can we make early discovery of SUSY at LHC *without* $\not\!\!E_T$?
- Expect $\tilde{g}\tilde{g}$ events to be rich in jets, b-jets, isolated ℓs, τ-jets,....
- These are *detectable*, rather than inferred objects
- Inferred objects like $\not\!\!E_T$ require knowledge of complete detector performance
  - dead regions
  - "hot" cells
  - cosmic rays
  - calorimeter mis-measurement
- Answer: YES! See HB, Prosper, Summy, PRD77, 055017 (2008)
- electron ID problem? go with multi-muons: HB, Lessa, Summy, arXiv:0809.4719

If early e ID problematic: focus on SS and multi-muons

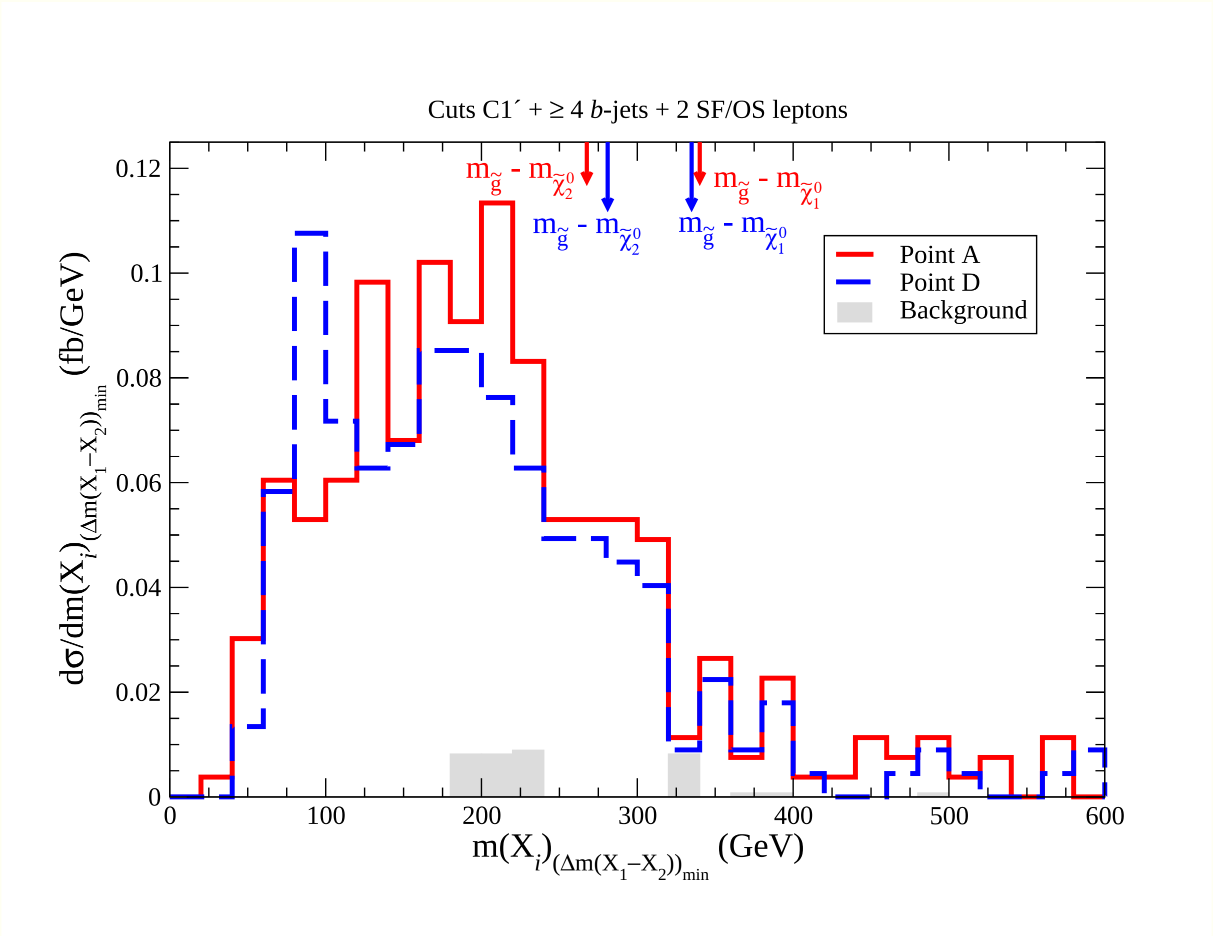


- HB, A. Lessa and H. Summy, PLB674 (2009) 49.

Cuts C1′ plus $\geq 2\ OS/SF\ \ell$

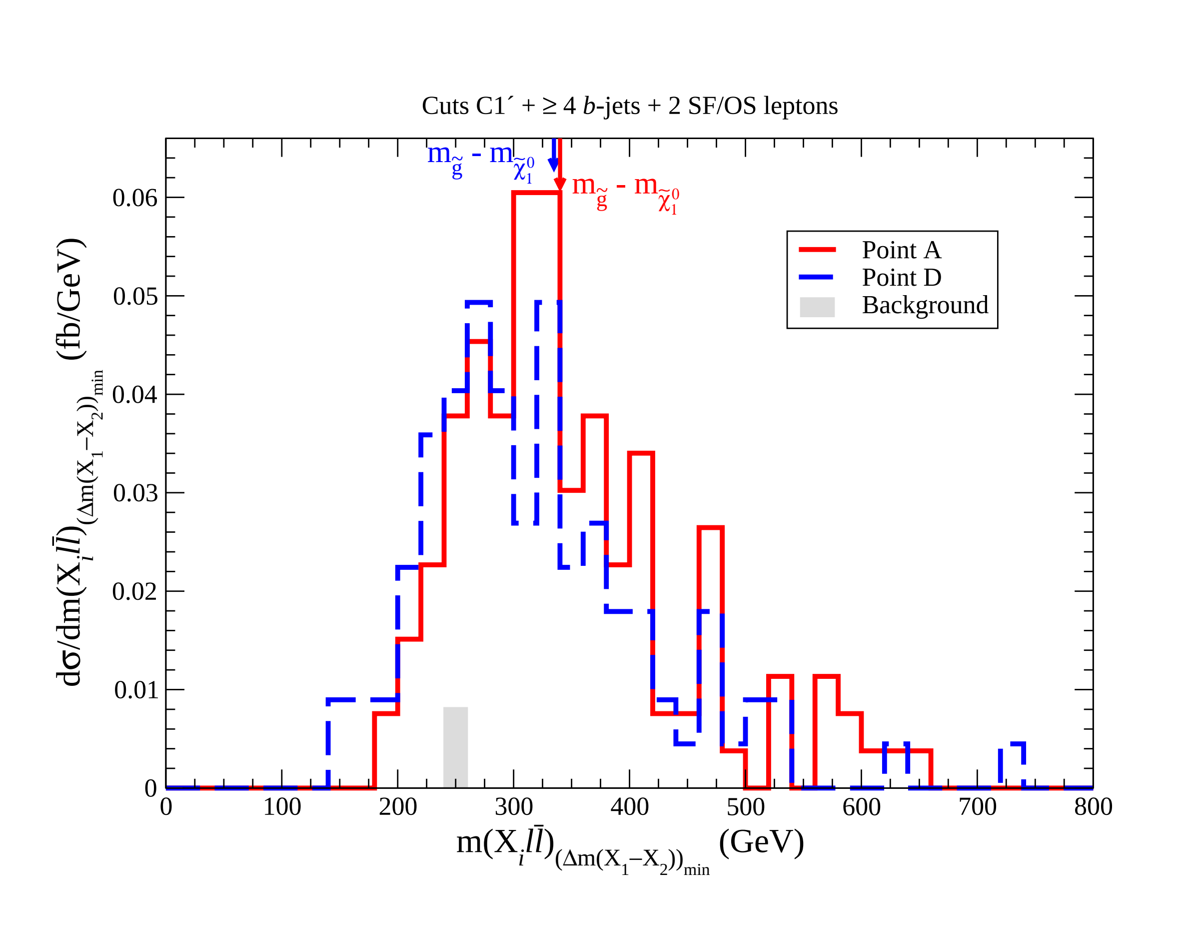


Cuts C1′ plus ≥ 4 b-jets+ $\ell^+\ell^-$



- Get $m(b\bar{b})$ from $\tilde{g} \to b\bar{b}\widetilde{Z}_2$ decay

Cuts C1′ plus ≥ 4 b-jets+ $\ell^+\ell^-$

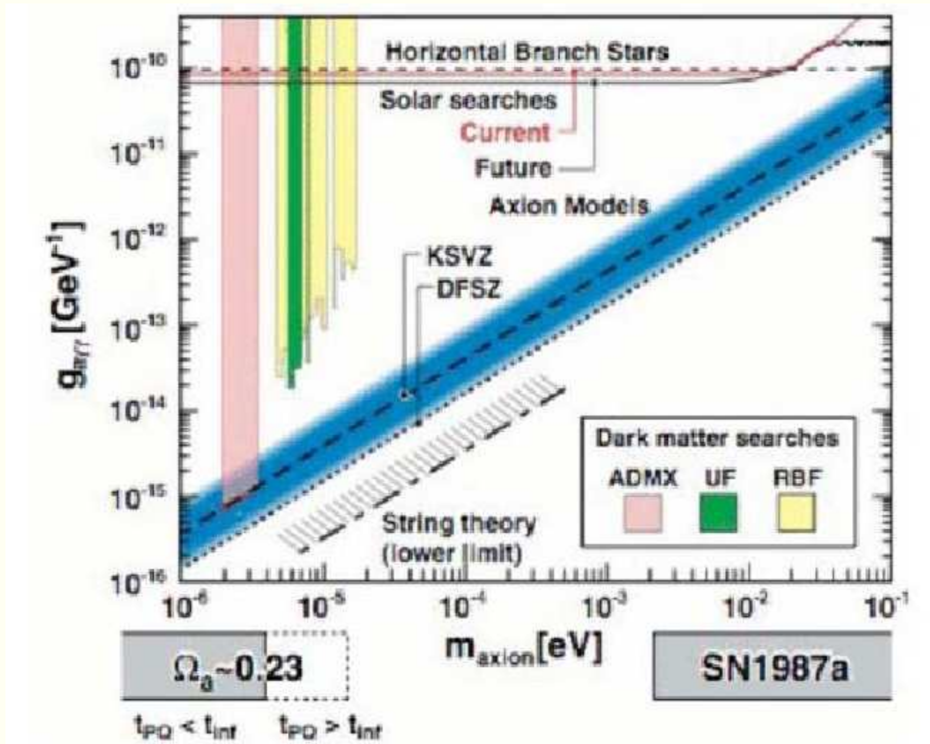


- Get $m(b\bar{b}\ell^+\ell^-)$ from $\tilde{g} \to b\bar{b}\widetilde{Z}_2$ decay

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



Conclusions

- ⋆ $SO(10)+SUSY$: expect $t-b-\tau$ Yukawa unification
- ⋆ For $\mu>0$, get YU for HS model with $A_0^2 \sim 2m_{10}^2 = 4m_{16}^2$
- ⋆ Can reconcile with DM abundance: $\widetilde{Z}_1 \to \tilde{a}\gamma$
- ⋆ Cosmology: axion/axino DM solution gives consistent cosmology: gravitino problem and non-thermal leptogenesis
- ⋆ Predict possible a discovery but no WIMP signals
- ⋆ Predict $m_{\tilde{g}} \sim 400$ GeV, decoupled scalars: LHC awash in $\tilde{g}\tilde{g}$ events
- ⋆ Can see signal with only 0.1 fb^{-1} of integrated luminosity in jets $+OS/SF$ di-muon or $\geq 3\mu$ channel
- ⋆ $m(\ell^+\ell^-)$ mass edge $\sim 50-75$ GeV; reconstruct $m_{\tilde{g}}$, $m_{\widetilde{Z}_2}$, $m_{\widetilde{Z}_1}$?
- ⋆ We will soon know if Yukawa unified SUSY is correct theory of weak scale physics! LHC data in 2009!