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

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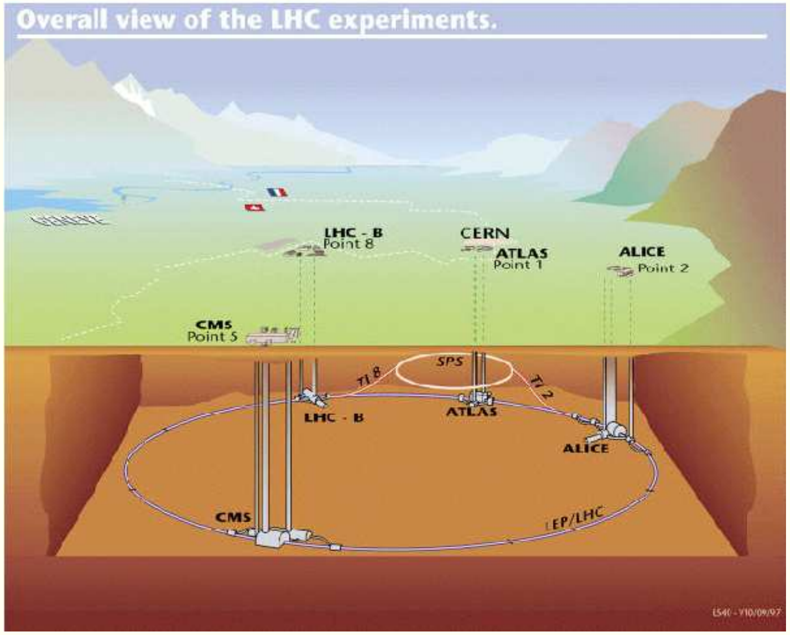
- ⋆ $SO(10)$ motivation
- ⋆ Yukawa unification
- ⋆ Sparticle mass calculation
- ⋆ Dark matter problem
  - • mixed axion/axino DM
- ⋆ cosmology of SUSY $SO(10)$
- ⋆ $SO(10)$ at LHC
  - – can see with just 0.1 fb^{-1}!



$SO(10)$: synopsis

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

- 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
- $SO(n)$ (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 $Q = M_{GUT}$

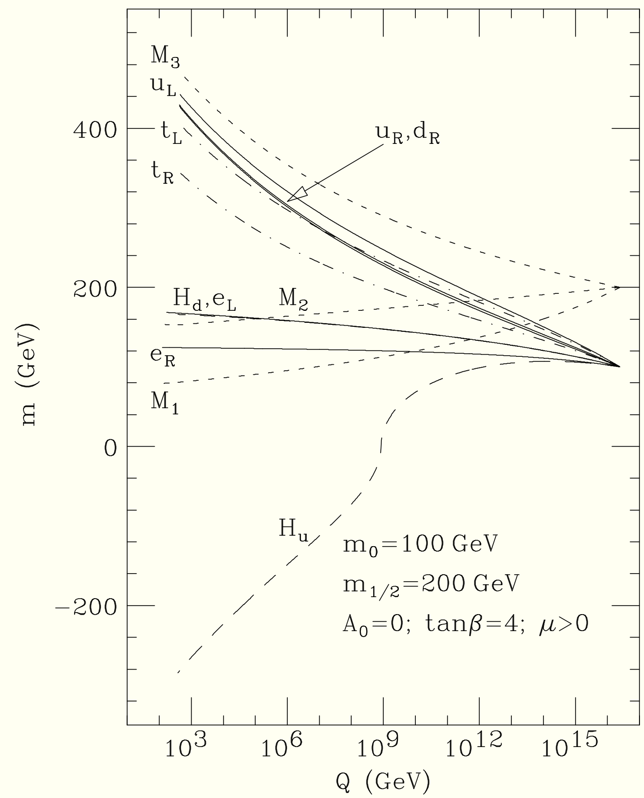
lots of previous work!

- 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)
    - $\geq$7.72: Isatools
- SuSpect (Djouadi, Kneur, Moultaka)
- SoftSUSY (Allanach)
- Spheno (Porod)

★ Comparison (Belanger, Kraml, Pukhov)

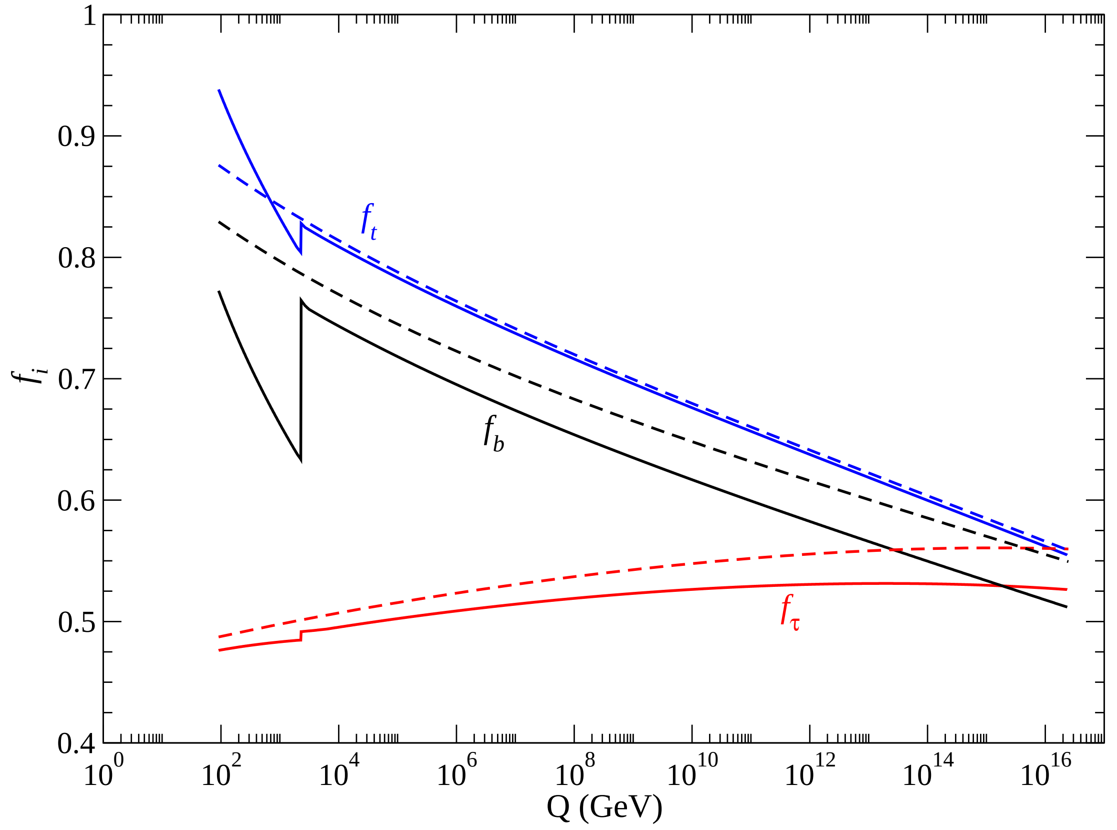
★ Website: `http://kraml.home.cern.ch/kraml/comparison/`

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



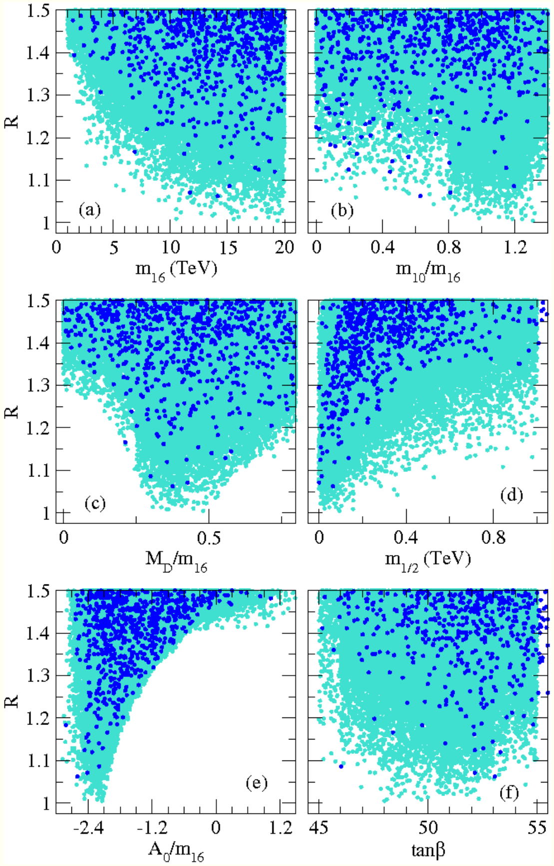
$SO(10)$-inspired parameter space:

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

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

★ 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

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:

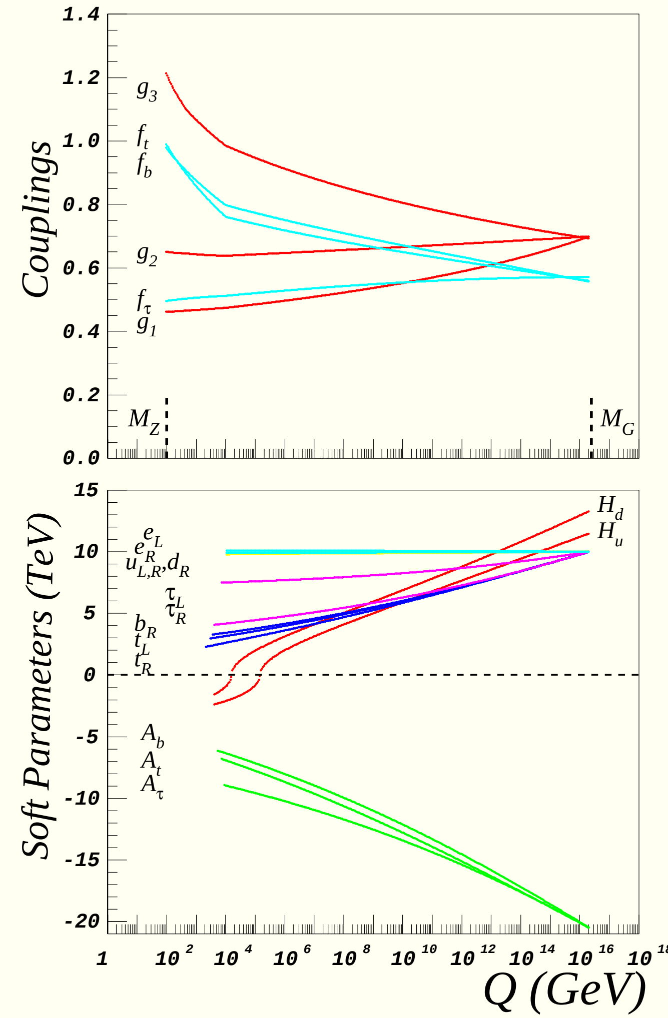
- $A_0 \sim -2m_{16}$
- $m_{10} \sim 1.2m_{16}$
- $\tan\beta \sim 50$

⋆ 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!

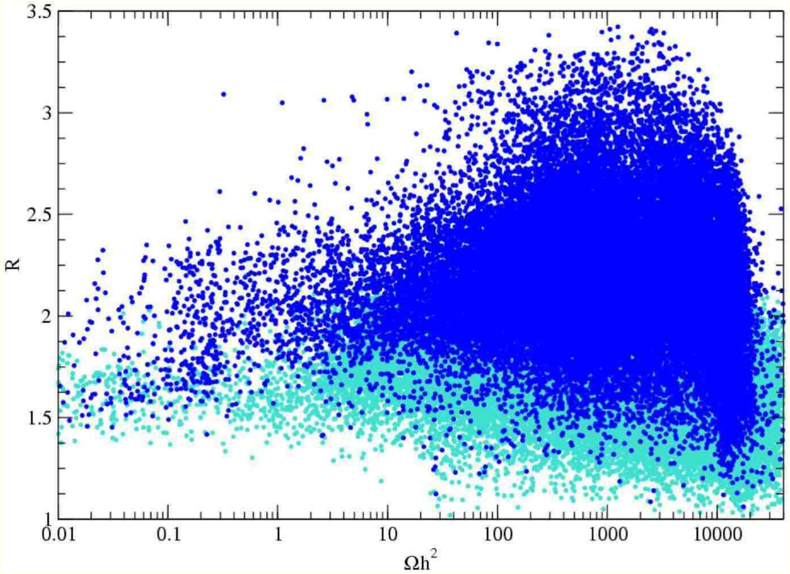
- need $m_{10} \simeq \sqrt{2} m_{16}$
- $A_0 \simeq -2m_{16}$
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: $m_{H_u}^2 < m_{H_d}^2$
- Auto, HB, Balazs, Belyaev, Ferrandis, Tata
  - $m_{\tilde{q},\tilde{\ell}}(1,2) \sim 10$ TeV
  - $m_{\tilde{t}_1},\ m_A,\ \mu \sim 1-2$ TeV
  - $m_{\tilde{g}}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

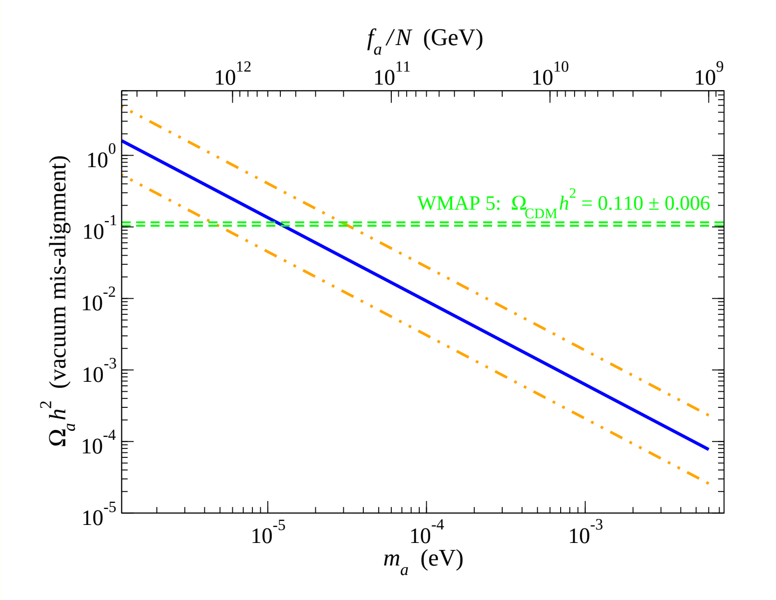
Problem: reconcile DM with Yukawa unification



- ⋆ 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

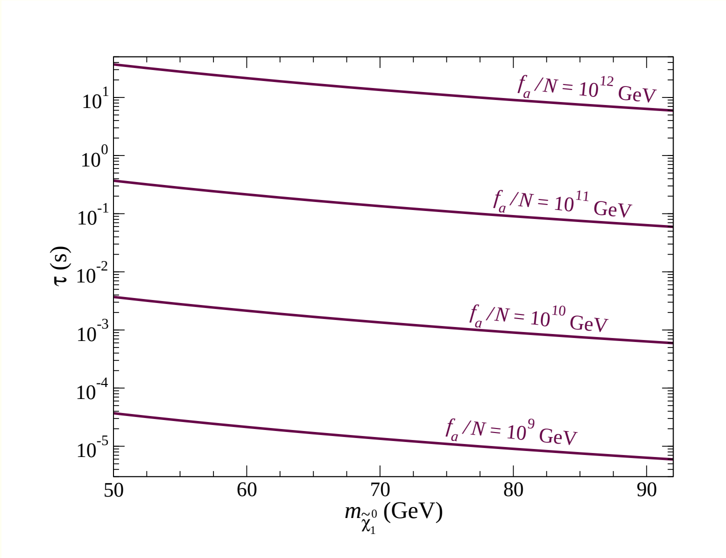
Axions

- ⋆ 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
- $\Omega_{\tilde{a}}^{NTP}h^2 = \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}}\Omega_{\widetilde{Z}_1}h^2$:



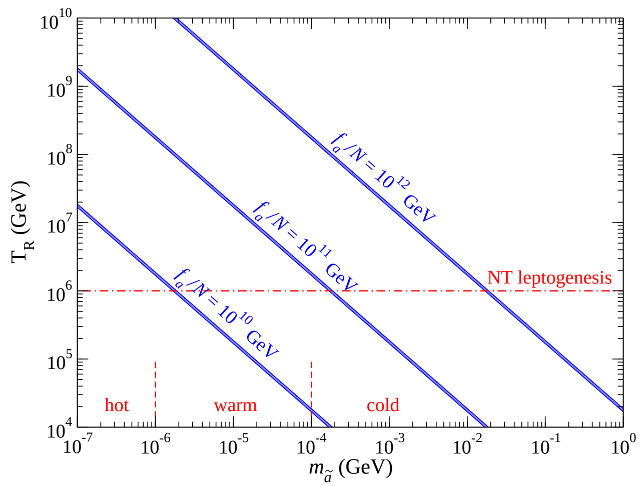
Thermally produced axinos

★ If $T_R < f_a$, then axinos never in thermal equilibrium in early universe

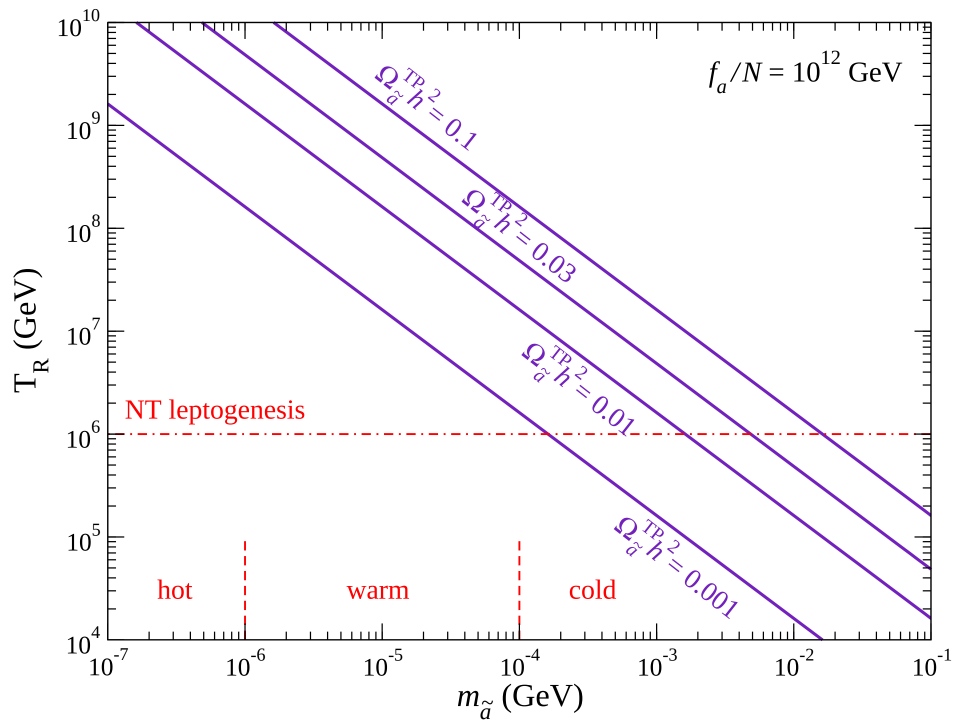
★ Can still produce $\tilde{a}$ thermally via radiation off particles in thermal equilibrium

★ Brandenberg-Steffen calculation:

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

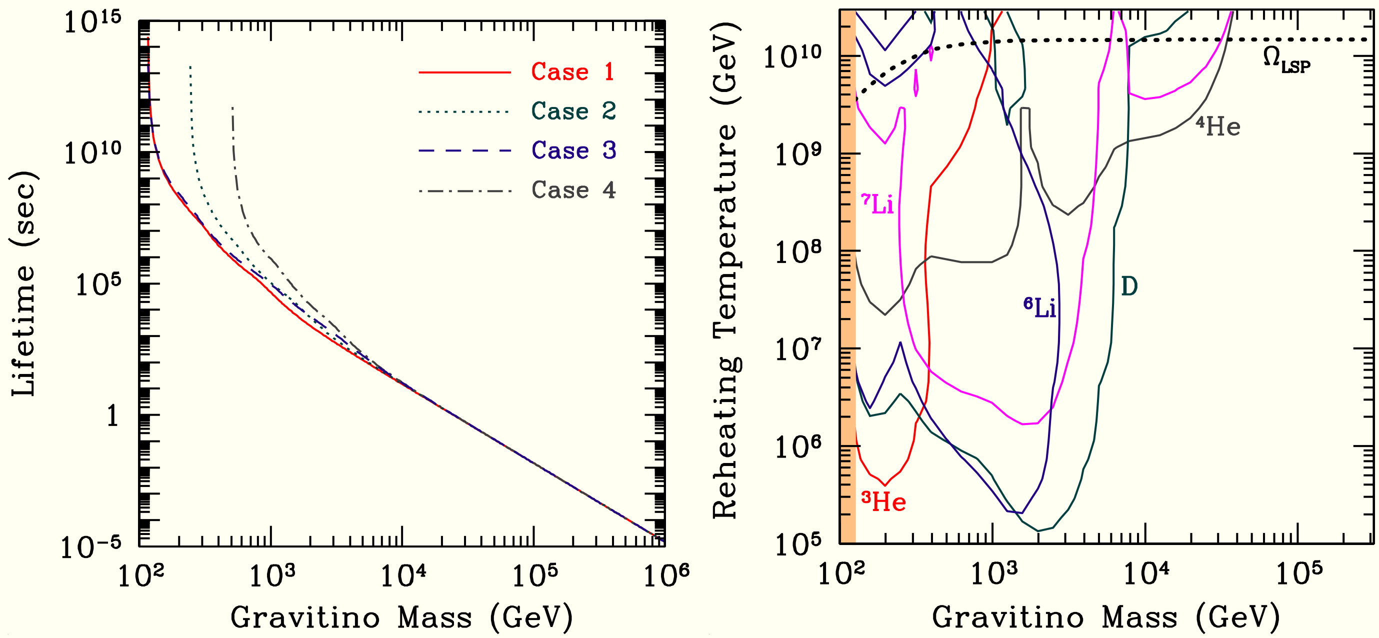


Thermally produced axinos for $f_a/N = 10^{12}$ GeV



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:

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

- 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

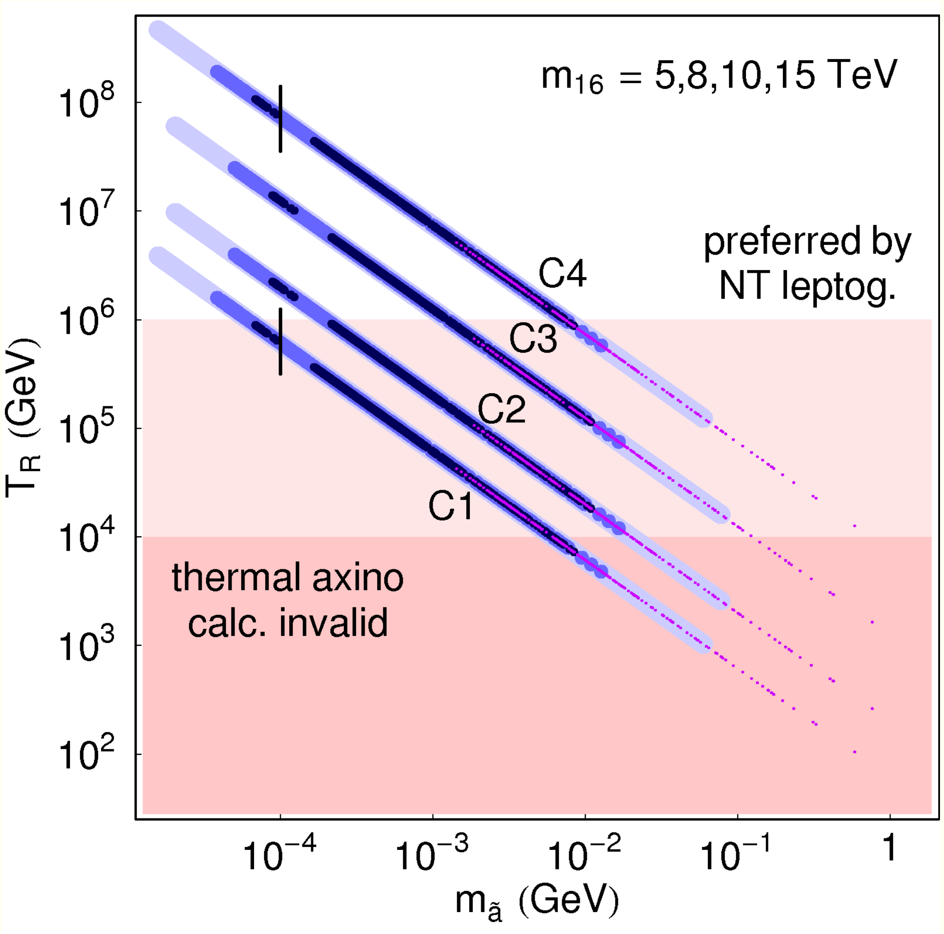
⋆ Four cases:

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

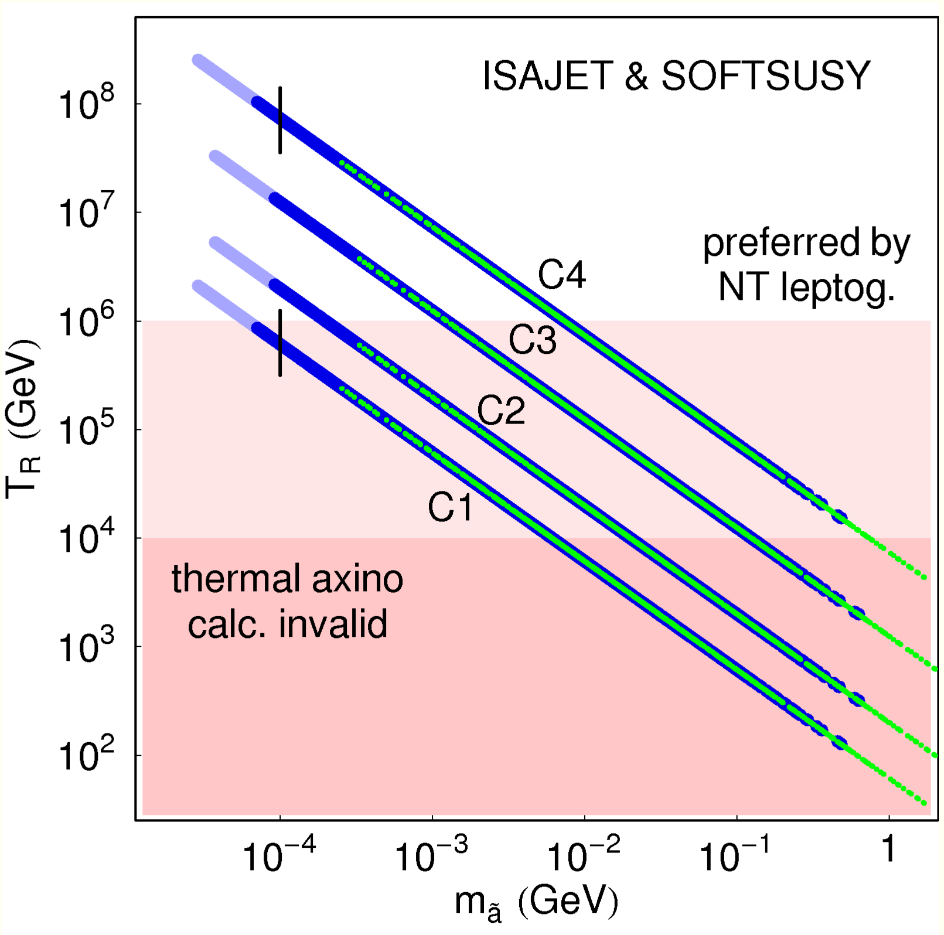
- Happily, T_R falls into the right range to give $cold$ axion/axino DM with a small admixture of warm axino DM, preserve BBN predictions and have non-thermal leptogenesis!
- See HB and H. Summy, PLB666, 5 (2008)
- HB, Kraml, Haider, Sekmen and Summy, arXiv:0812.2693



m16 = 5,8,10,15 TeV
preferred by NT leptog.
thermal axino calc. invalid
C4
C3
C2
C1
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

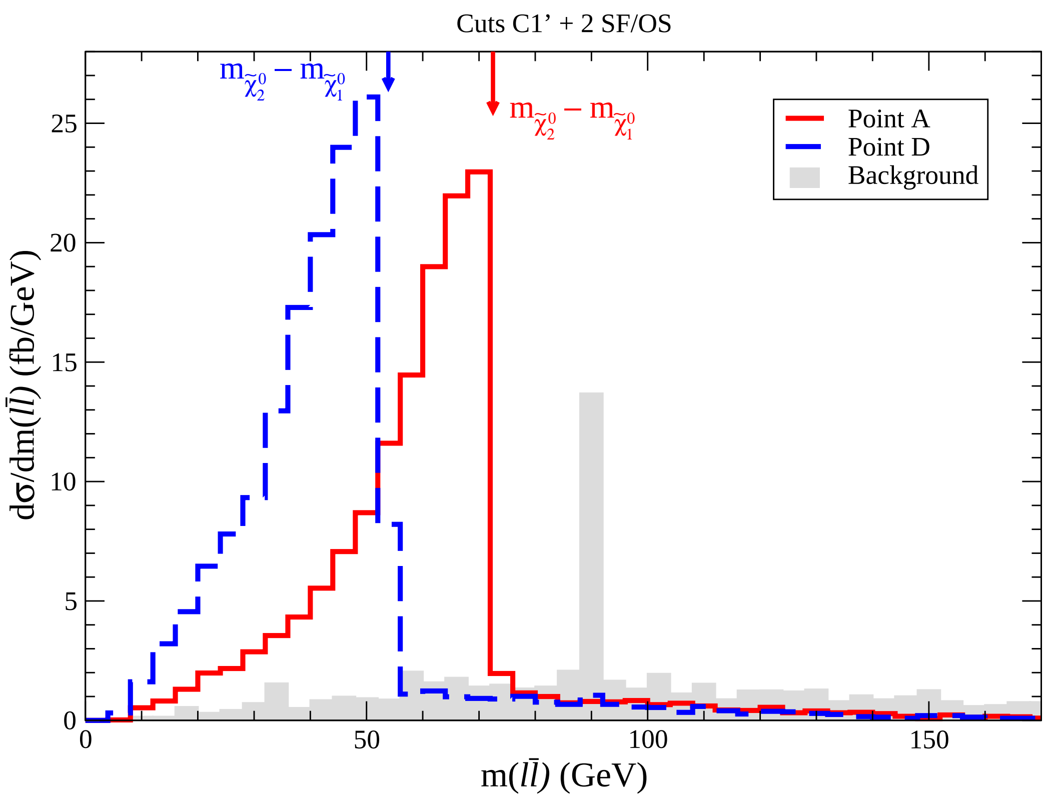
- Want $T_R \gtrsim 10^6$ GeV for NT leptogenesis but $< 10^{10}$ GeV to solve BBN/gravitino problem
- Below: Isajet/SoftSUSY comparison
- viable solutions need $f_a/N \gtrsim 4 \times 10^{11}$ GeV
- also prefer $m_{16} \gtrsim 10$ TeV


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

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

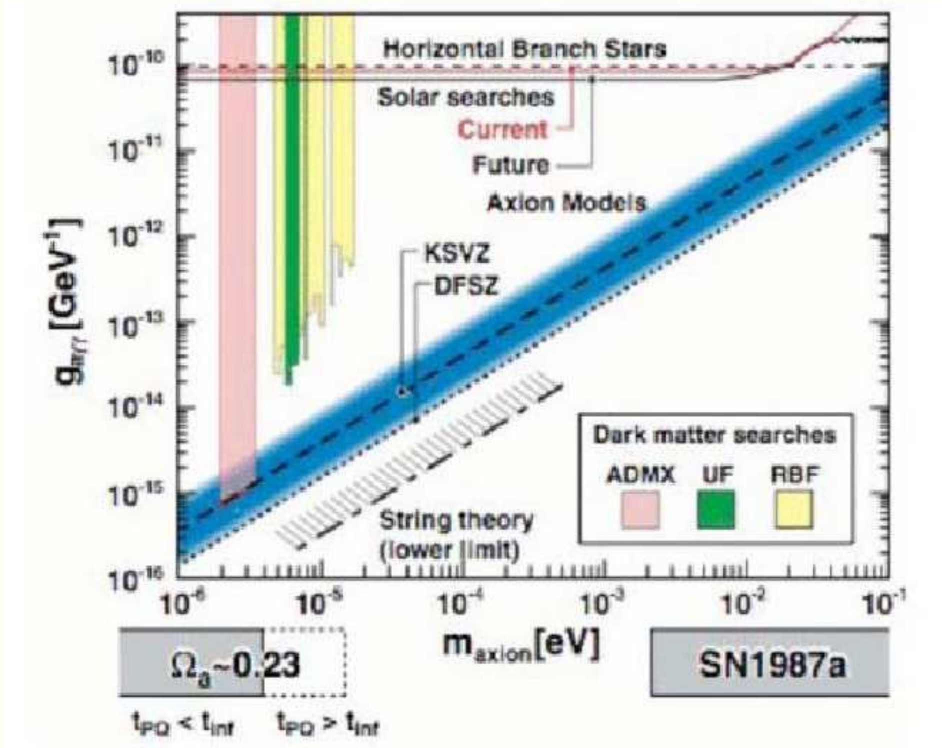
Cuts C1′ plus $\geq 2\ OS/SF\ \ell$



Axion microwave cavity searches

⋆ ongoing searches: ADMX experiment

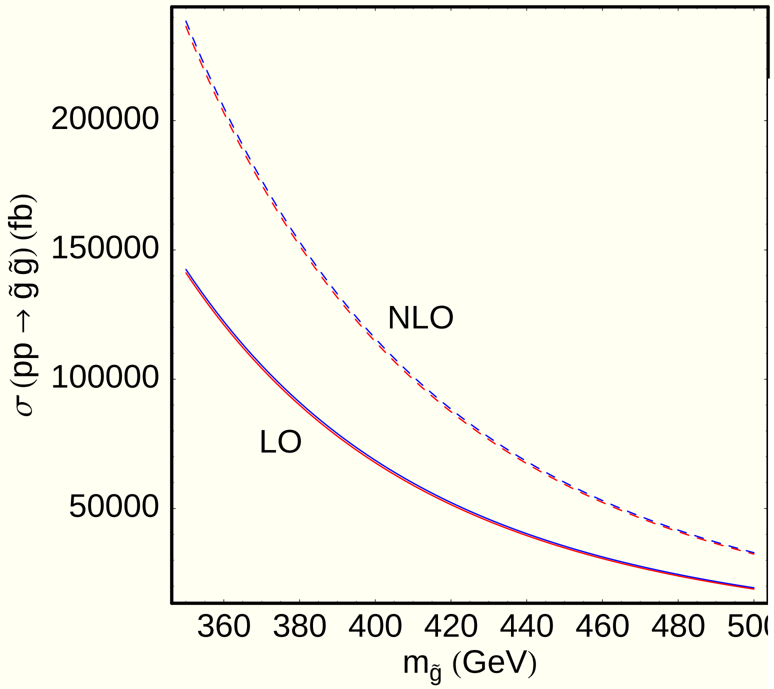
- Livermore⇒ U Wash.
- Phase I: probe KSVZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- Phase II: probe DFSZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- beyond Phase II:
  probe higher values m_a

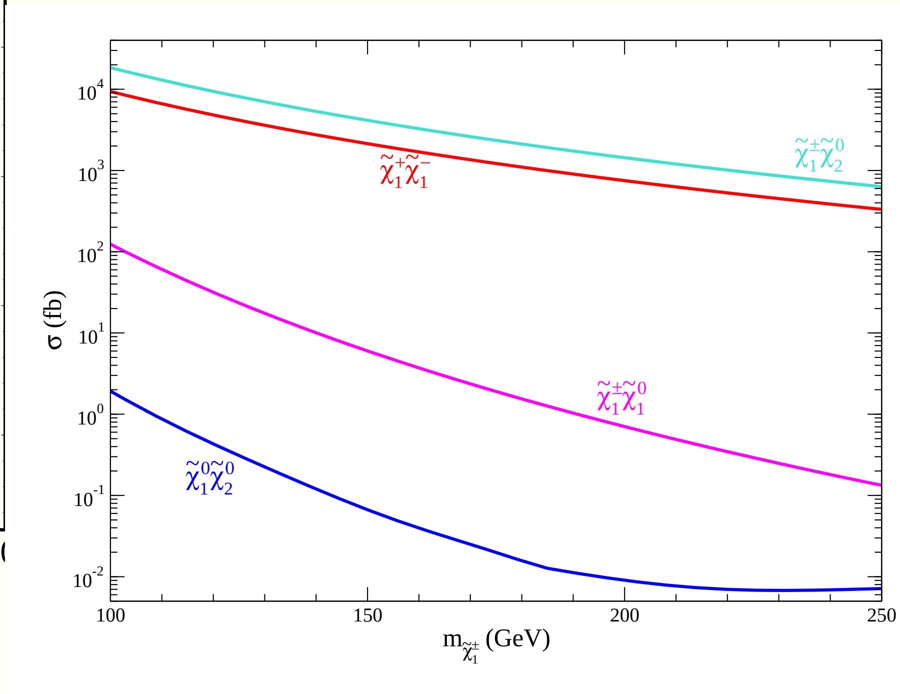


Conclusions

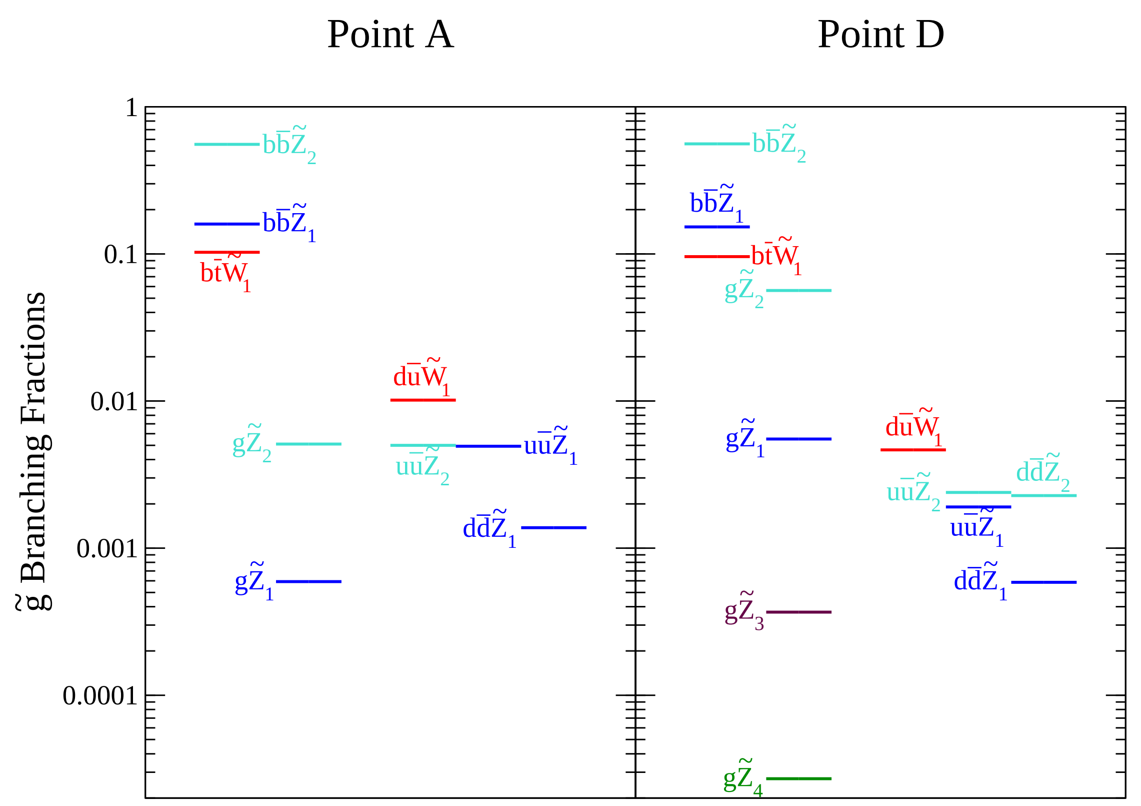
- ⋆ $SO(10)+SUSY$: expect $t-b-\tau$ Yukawa unification
- ⋆ For $\mu>0$, get YU for HS model with $A_0^2 \sim 2m_{10}^2 = 4m_{16}^2$
- ⋆ Can reconcile with DM abundance: $\widetilde{Z}_1 \rightarrow \tilde{a}\gamma$
- ⋆ Cosmology: axion/axino DM solution gives consistent cosmology: gravitino problem 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!

Production of sparticles at LHC





Gluino branching fractions in Yukawa unified SUSY



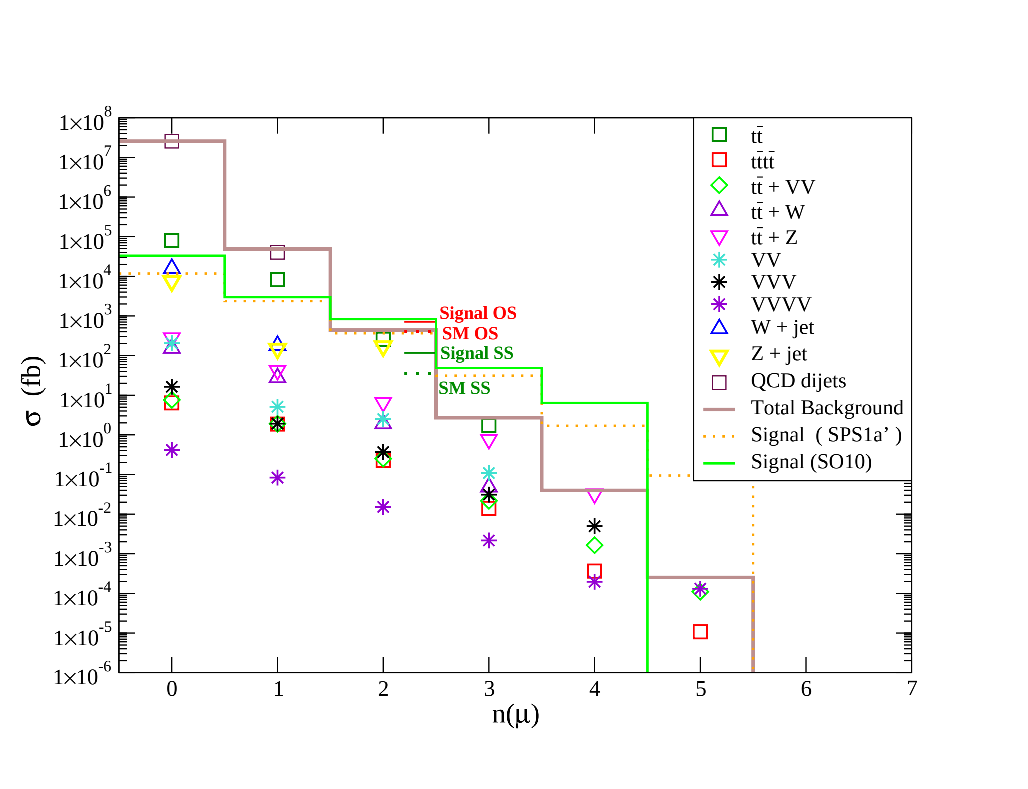
What $SO(10)$ SUSY GUTs look like at LHC

- 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...

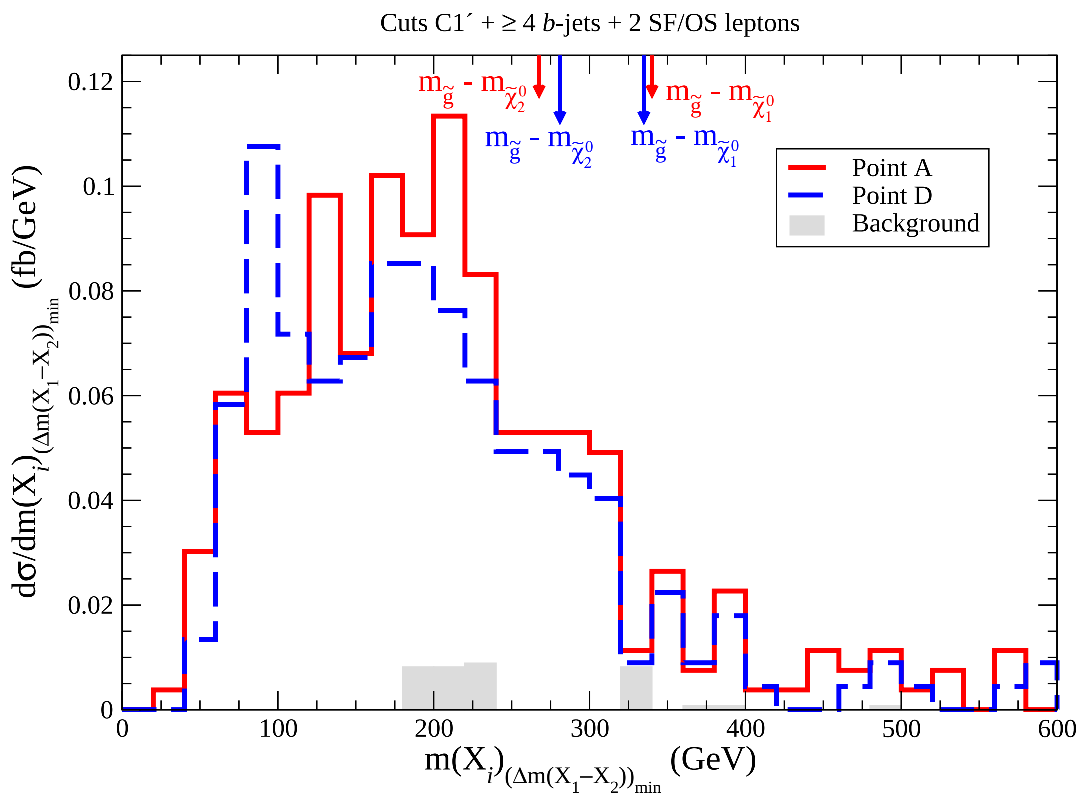
- Can we make early discovery of SUSY at LHC *without* $\not{E}_T$?
- Expect $\tilde{g}\tilde{g}$ events to be rich in jets, b-jets, isolated ℓs, τ-jets,....
- These are *detectable*, rather than inferred objects
- Inferred objects like $\not{E}_T$ require knowledge of complete detector performance
  - 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



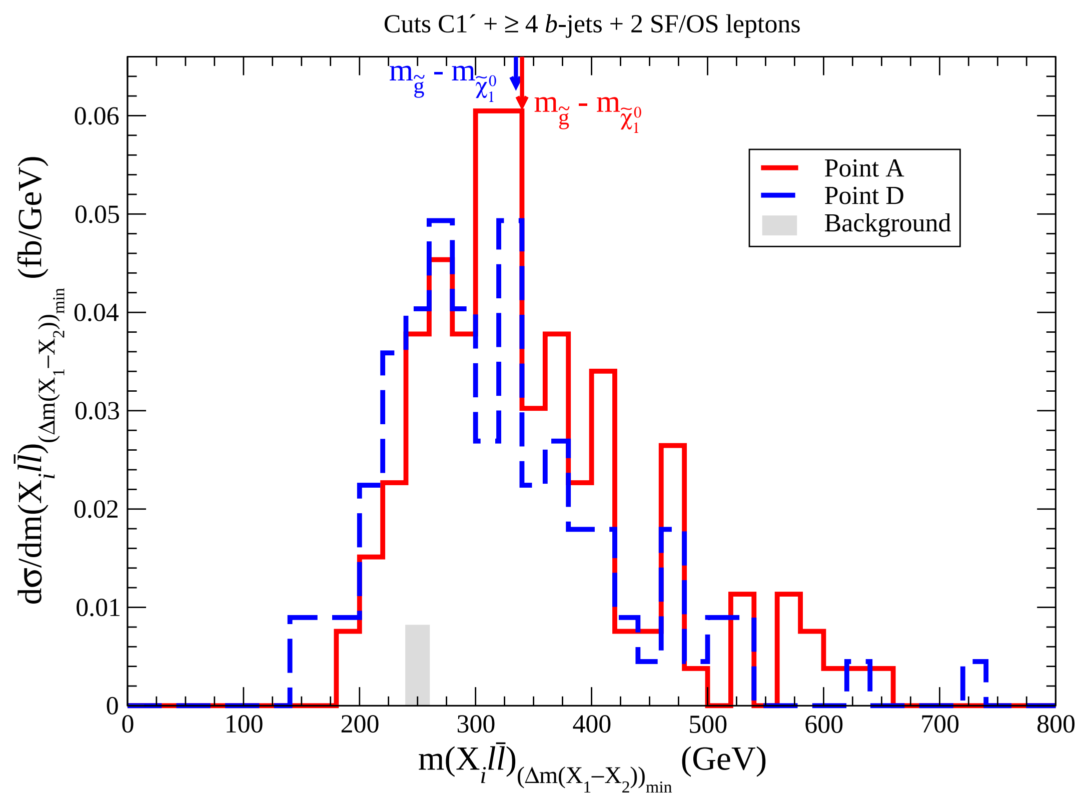
- HB, A. Lessa and H. Summy, PLB674 (2009) 49.

Cuts C1′ plus ≥ 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