Supersymmetry and Dark Matter

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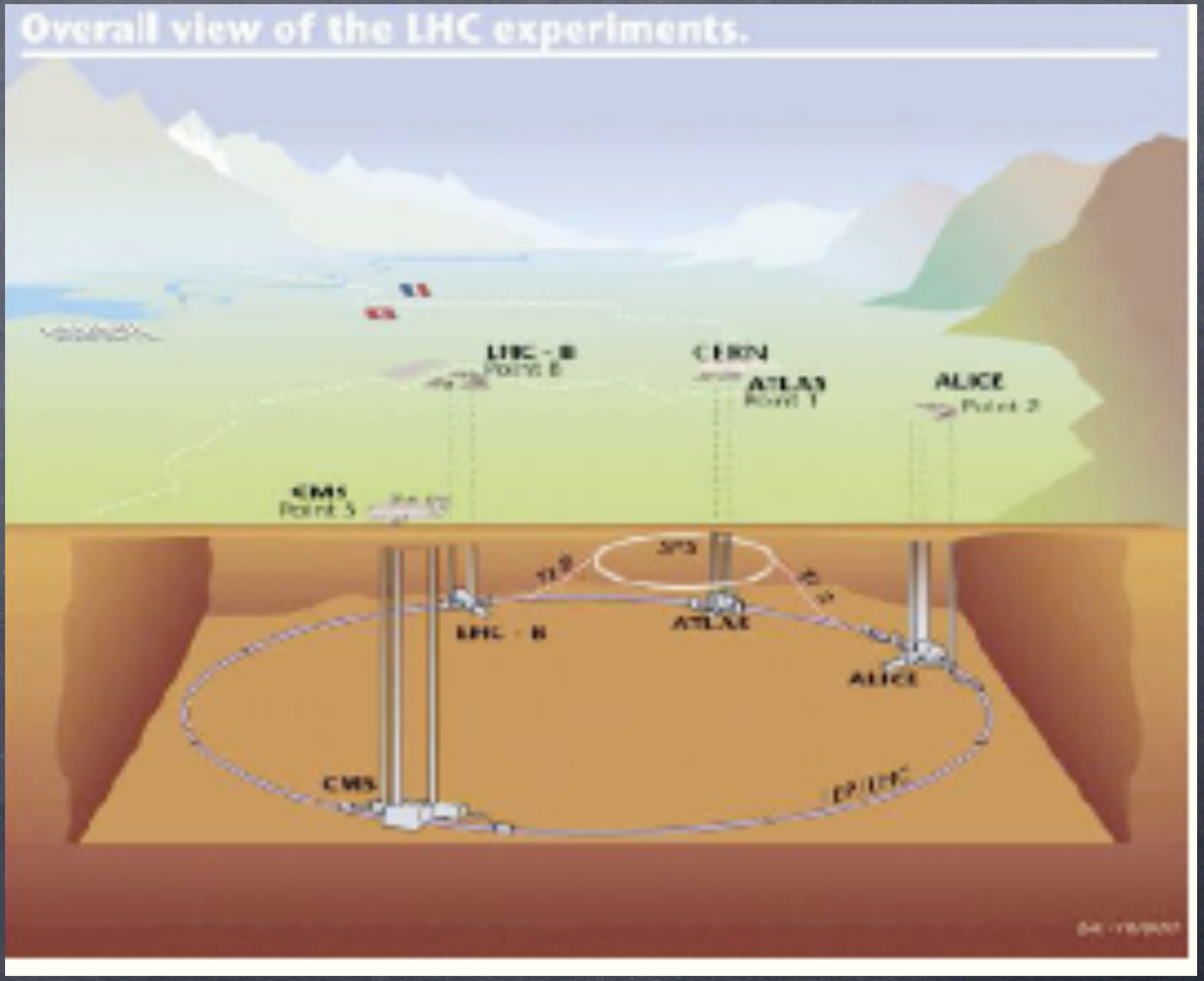
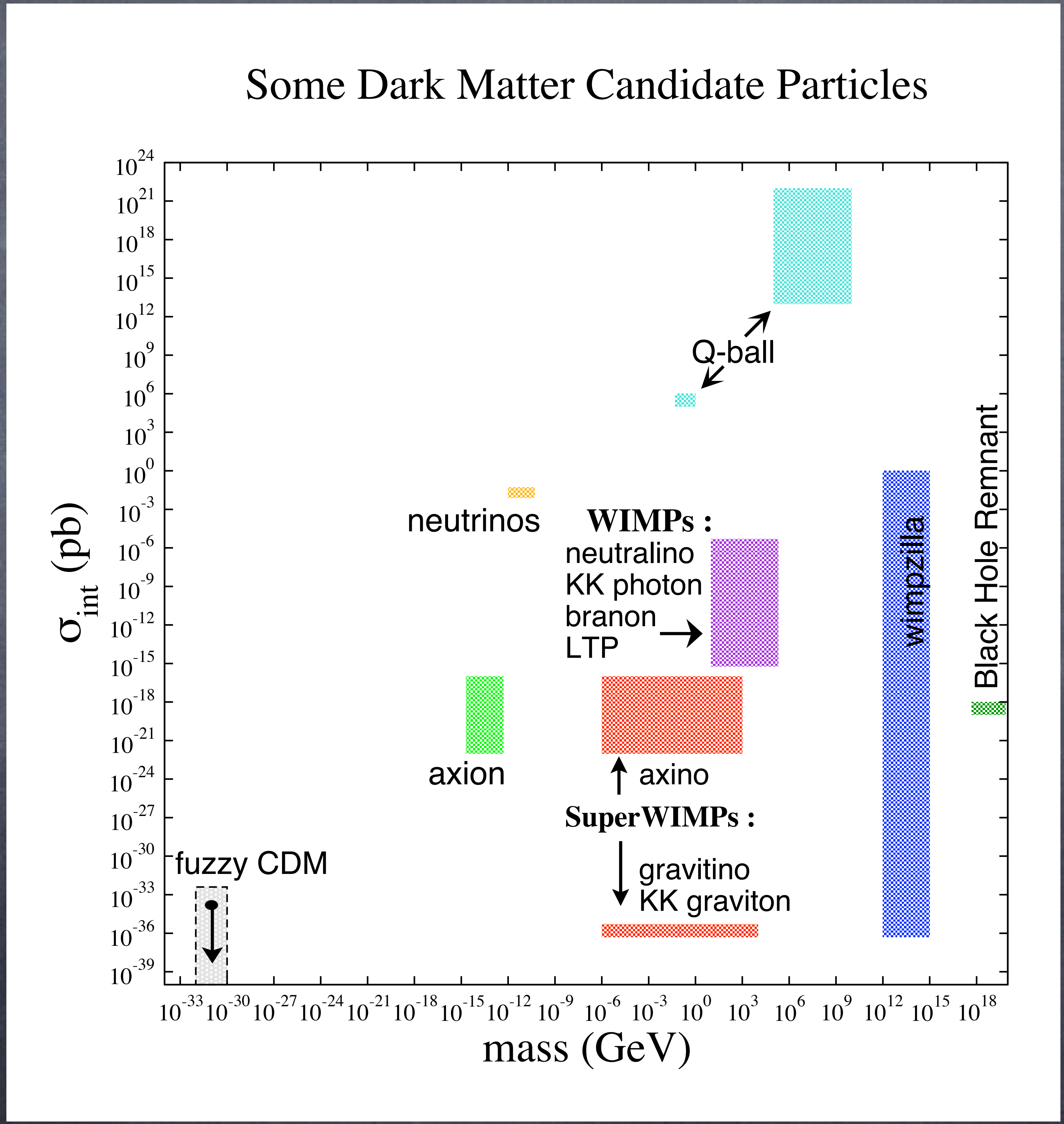


- Evidence for dark matter: overwhelming, and from numerous disparate sources!
- Properties: massive, neutral, cold (warm...)
- Of particles in the Standard Model (SM), only neutrinos have the right properties: but they constitute hot dark matter, and abundance is known
- Dark matter must be some particle state not contained in the SM: NEW PHYSICS NEEDED!

Some dark matter candidates: mass vs. interaction strength plane



- While some candidates are made up specifically to solve the DM problem, others emerge as part of solutions to long standing problems in particle physics:
- Peccei-Quinn solution to strong CP problem: axions
- Supersymmetry: at least 3 viable DM candidates: neutralino, gravitino, axino/(axion)

SUSY motivations:

- naturalness in quantum field theory (no quadratic divergences)
- means to unification with gravity (supergravity)
- gauge coupling unification provided superpartners at TeV scale
- precision EM corrections and Higgs mass
- radiative EWSB and the top mass
- accommodate baryogenesis: at least 3 ways

Supersymmetric models:

how SUSY breaking is communicated from hidden sector to visible sector

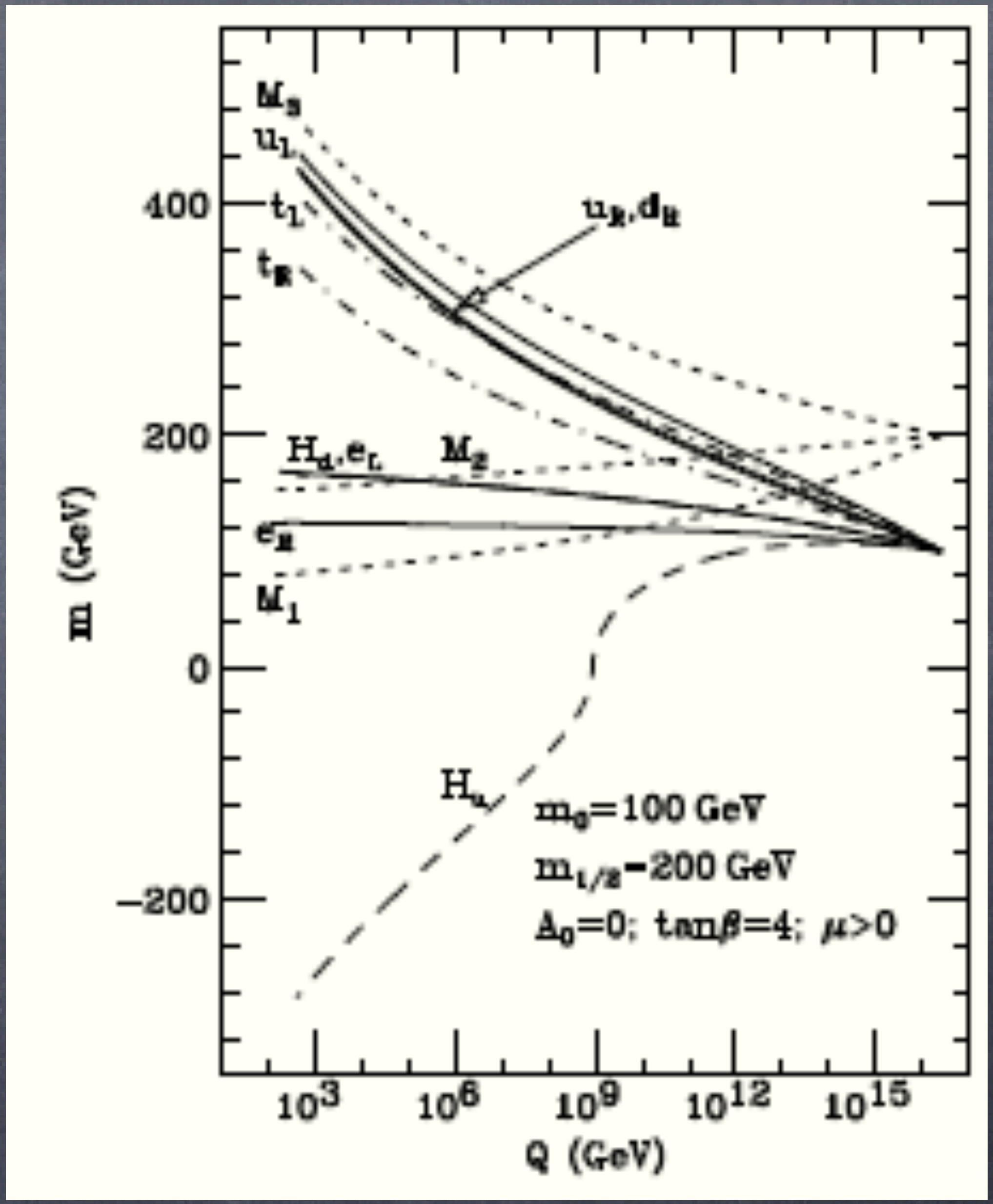
- GMSB:solves SUSY flavor problem, very light gravitino: does not naturally yield CDM
- AMSB: solves flavor problem, tachyonic sleptons; does not usually yield measured abundance of CDM
- AMSB $\rightarrow$ Mixed-moduli AMSB $\longrightarrow$ CDM
- SUGRA: 3 candidate DM particles:

$$\tilde{G},\ \tilde{Z}_1\ or\ \chi,\ \tilde{a}/a$$

Simplest: mSUGRA or CMSSM

- embed MSSM into SUGRA gauge theory
- SUSY breaking in simple hidden sector
- parameter space:

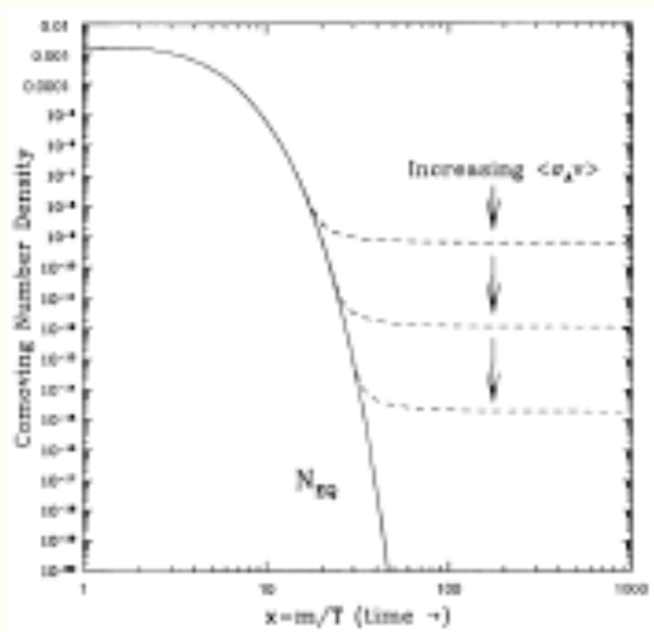
$m_0,\ m_{1/2},\ A_0\ \tan\beta,\ sign(\mu)$



The WIMP miracle

WIMPs: the WIMP miracle!

- 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}!



Neutralino is an excellent WIMP candidate!

Calculation of relic density

★ 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

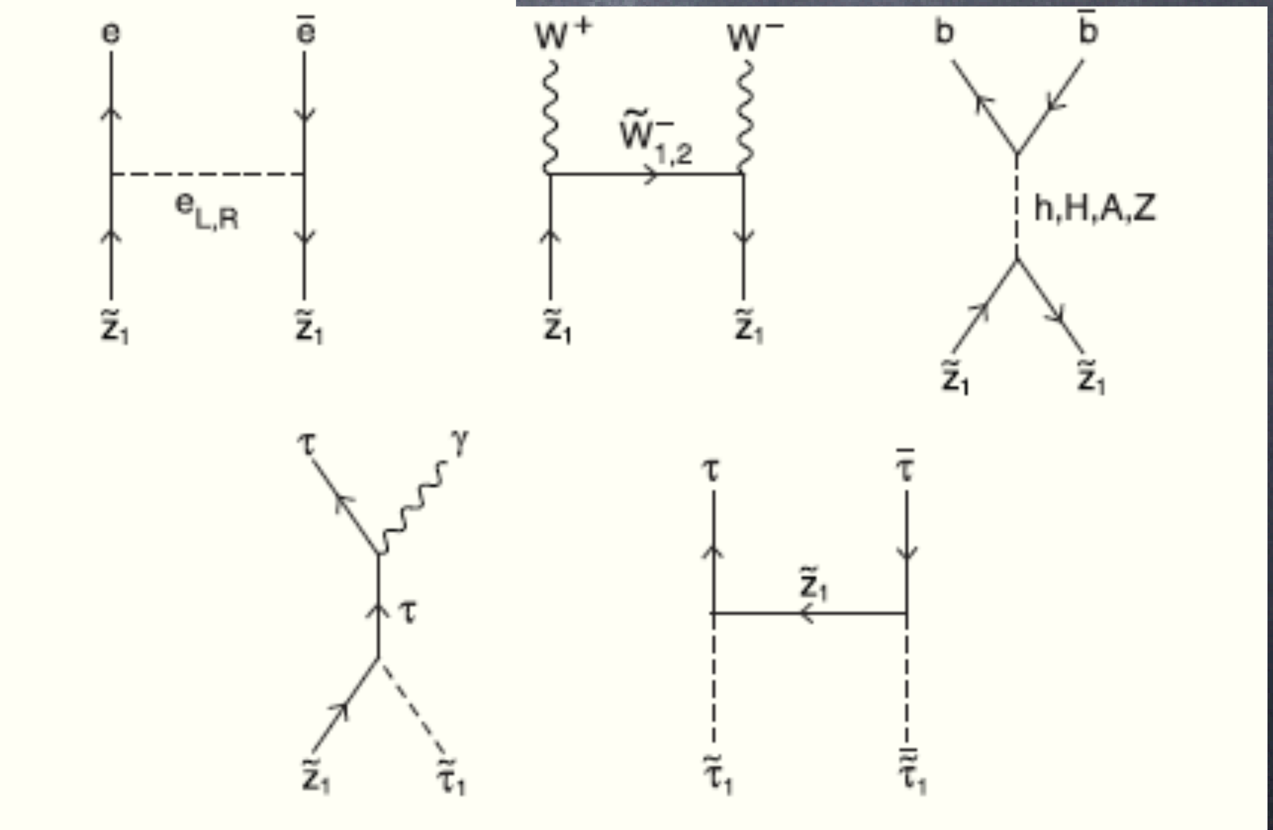
★ Number density obtained from Boltzmann eq'n

- $dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$
- depends critically on thermally averaged annihilation cross section times velocity

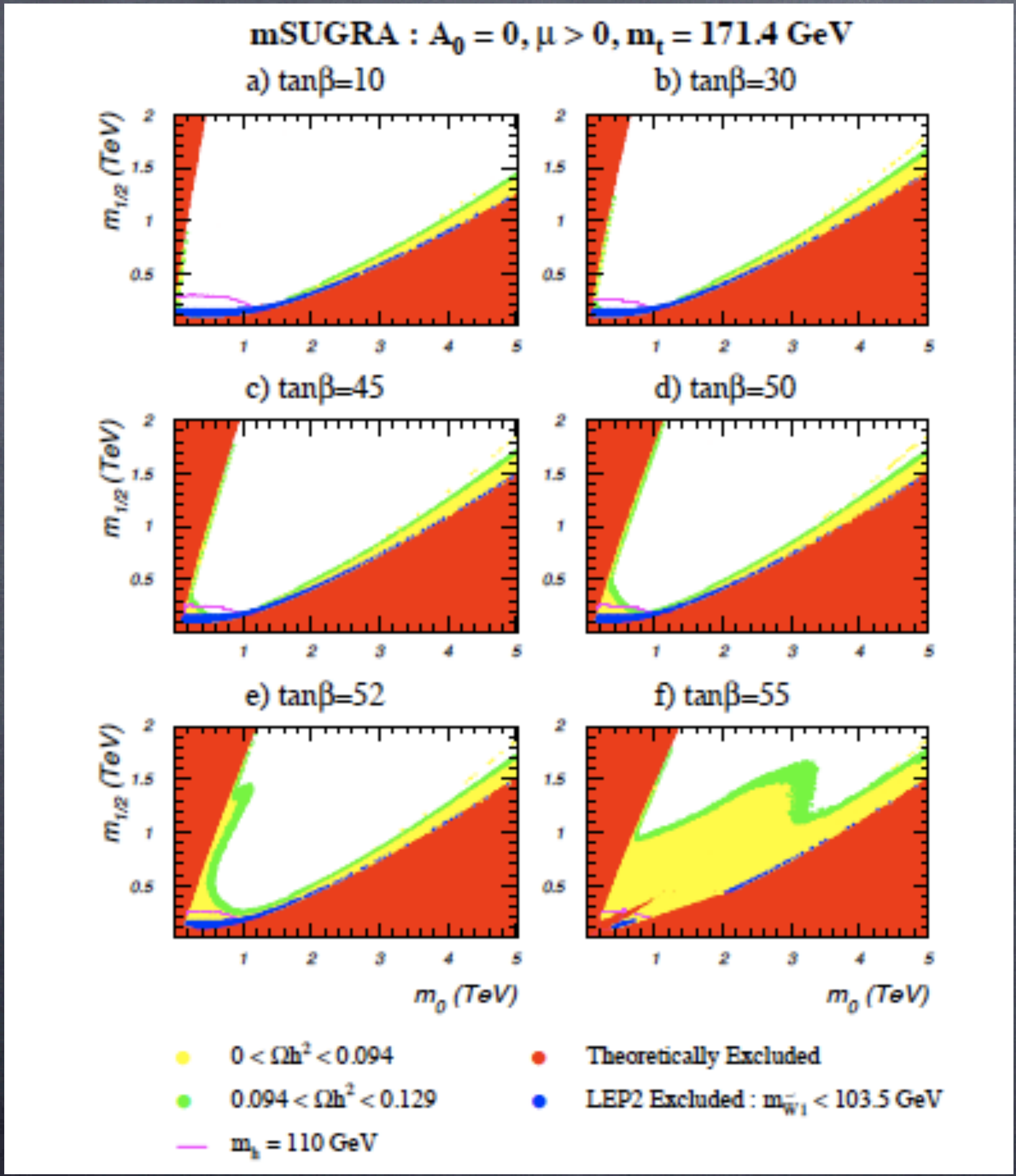
★ many thousands of annihilation/co-annihilation diagrams

★ several computer codes available

- DarkSUSY, Micromegas, IsaReD (part of Isajet)



mSUGRA parameter space



HB, Mustafayev, Park, Tata

Beware non-standard cosmology!

Gelmini-Gondolo

Search for mSUGRA at LHC

- ⋆ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- ⋆ lengthy cascade decays of $\tilde{g}$ $\tilde{q}$ are likely
- ⋆ events characterized by multiple hard jets, isolated and non-isolated leptons es and μs, and $\not{E}_T$ from $\widetilde{Z}_1$ or $\tilde{G}$ or νs escaping
- ⋆ many jets are b (displaced vertices due to long B lifetime) and τ (1 or 3 charged prongs) jets
- ⋆ one way to classify signatures is according to number of isolated leptons

- $\not{E}_T +$ jets
- $1\ell + \not{E}_T +$ jets
- $opposite - sign\ (OS)\ 2\ell + \not{E}_T +$ jets
- $same - sign\ (SS) 2\ell + \not{E}_T +$ jets
- $3\ell + \not{E}_T +$ jets
- $4\ell + \not{E}_T +$ jets
- $5\ell + \not{E}_T +$ jets

SM backgrounds to SUSY

★ numerous SM processes give same signature as SUSY!

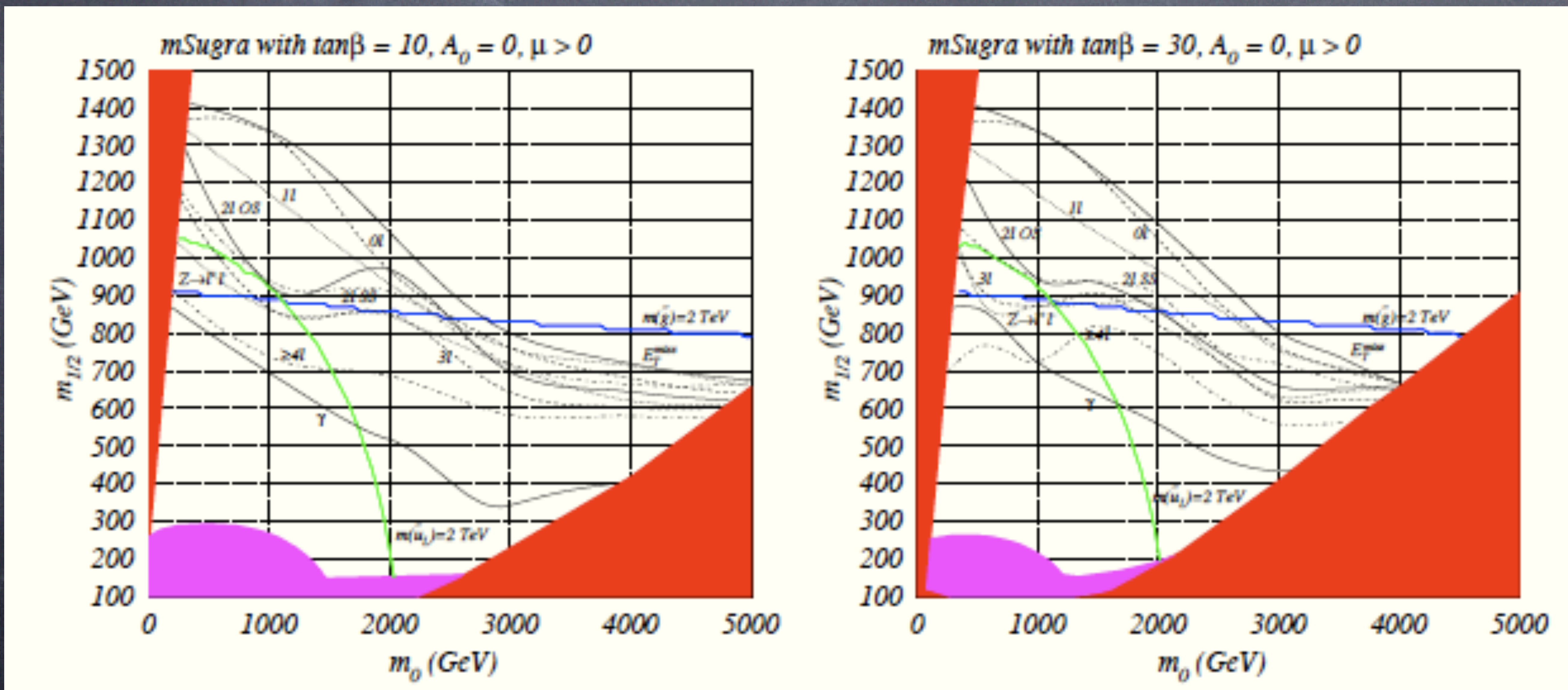
★ SM BGs include:

- QCD: multi-jet qq, $q\bar{q}$, qg, gg production where $\not{E}_T$ comes from mis-measurement, cracks, etc.
  - $t\bar{t}$, $b\bar{b}$, $c\bar{c}$
  - W or $Z+$ multi-jet production
  - WW, WZ, ZZ production, where $Z \to \nu\bar{\nu}$ or $\tau\bar{\tau}$
    - ∗ all of above embedded in Isajet, Pythia, Herwig
  - four particle processes: $e.g.$ $t\bar{t}t\bar{t}$, $ttbb$, etc.
  - WWW, etc.
    - ∗ the $2 \to n$ for $n > 2$ processes usually need CalcHEP/Madgraph
  - overlapping events; fake b-jets; fake leptons, etc

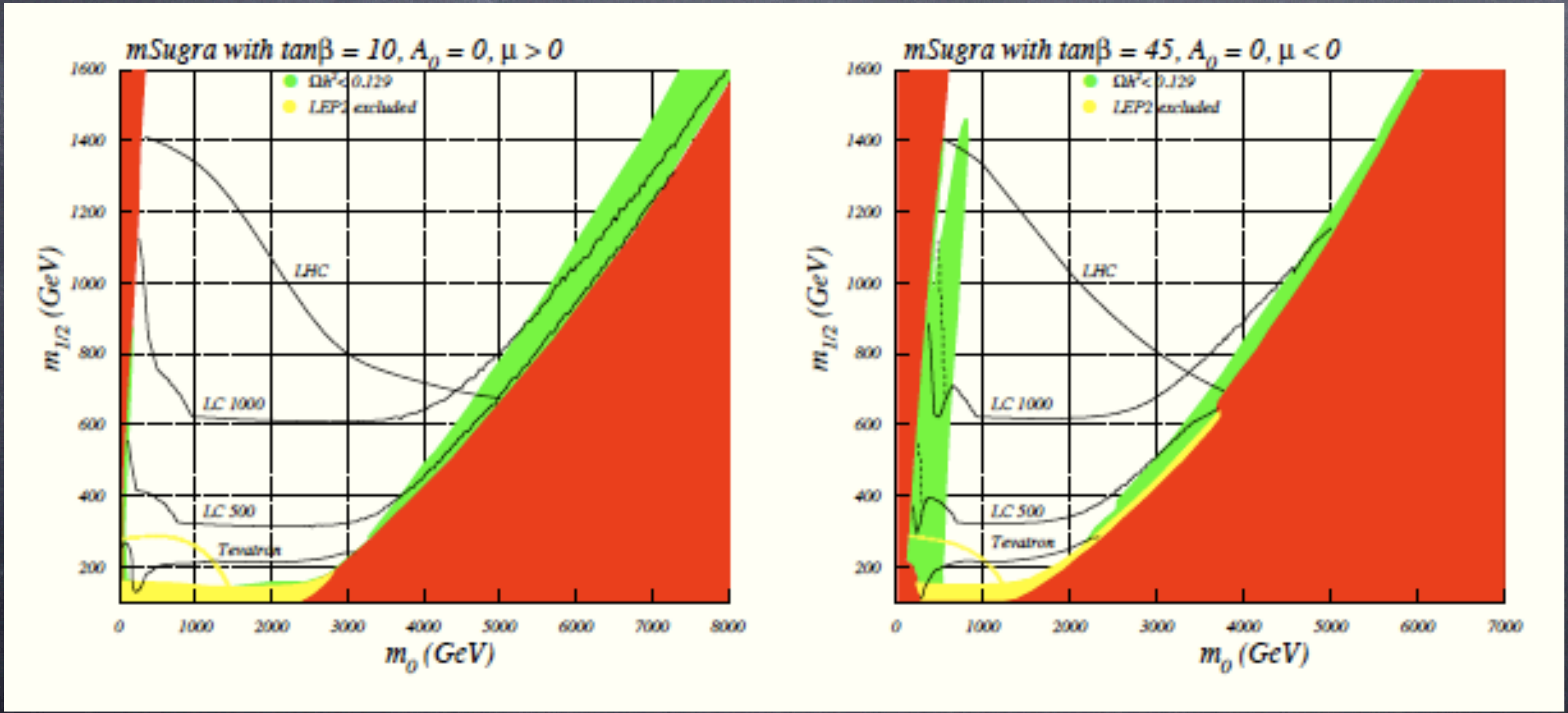
Optimize cuts over parameter space

- ⋆ Cuts and pre-cuts:
- ⋆ $\not{E}_T > 200$ GeV
- ⋆ $N_j \geq 2$ (where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$
- ⋆ Grid of cuts for optimized S/B:
  - $N_j \geq 2 - 10$
  - $\not{E}_T > 200 - 1400$ GeV
  - $E_T(j1) > 40 - 1000$ GeV
  - $E_T(j2) > 40 - 500$ GeV
  - $S_T > 0 - 0.2$
  - muon isolation
- ⋆ $S > 10$ events for 100 fb^{-1}
- ⋆ $S > 5\sqrt{B}$ for optimal set of cuts

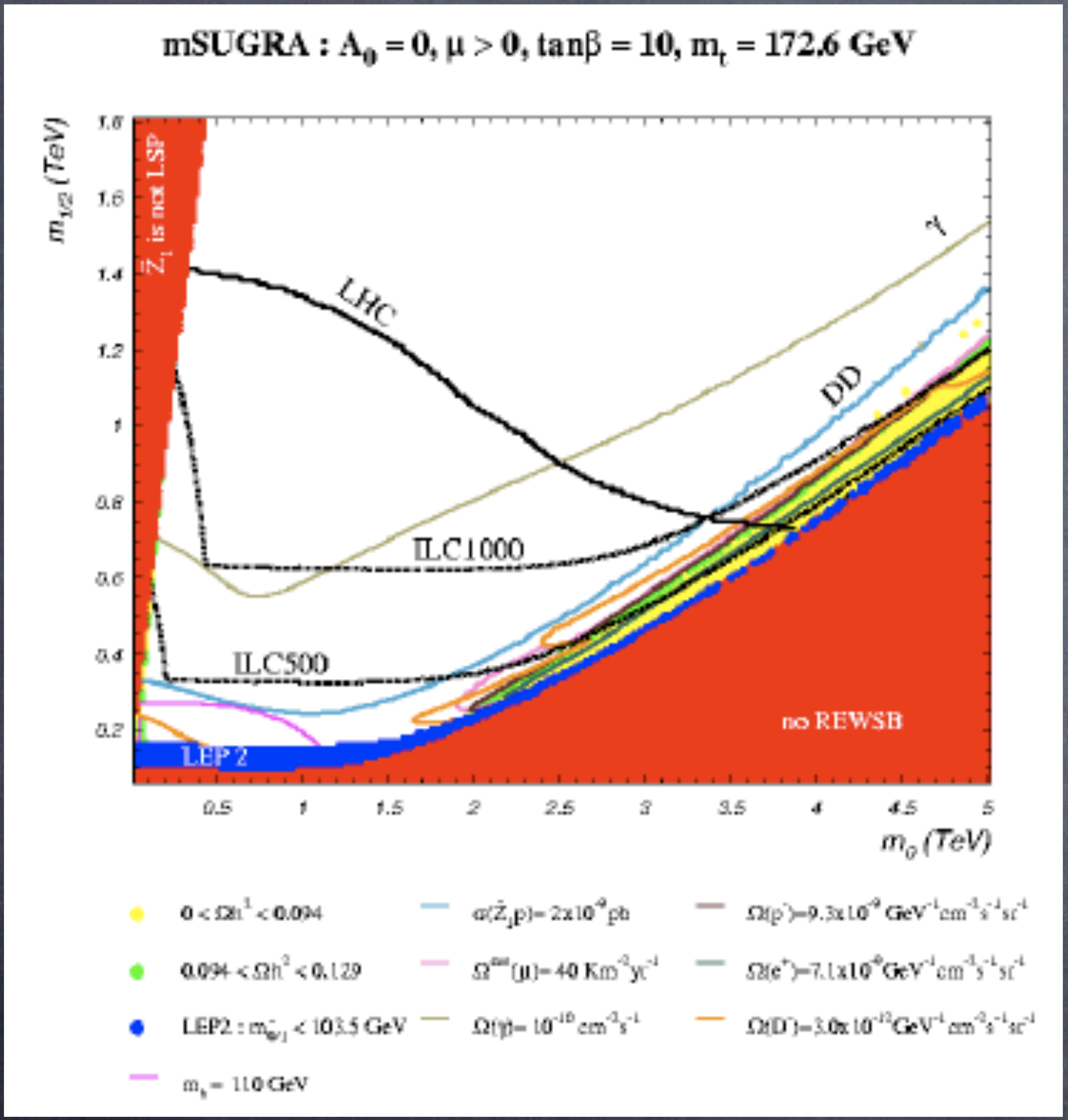
Reach of LHC for various signals and 100 fb^-1

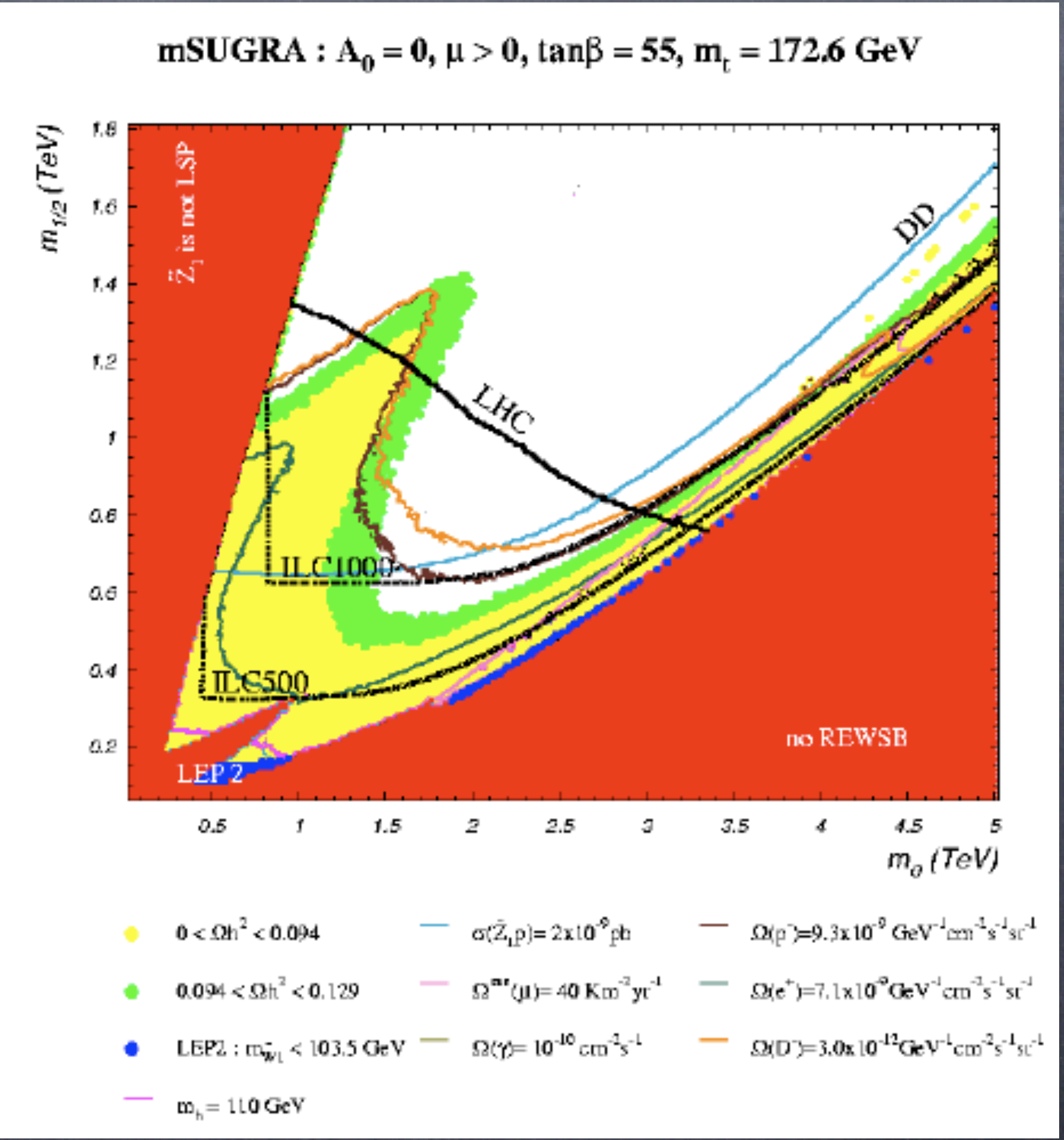


Reach of LHC compared to Tevatron and ILC



Reach of LHC, ILC compared to DD/ID WIMP search

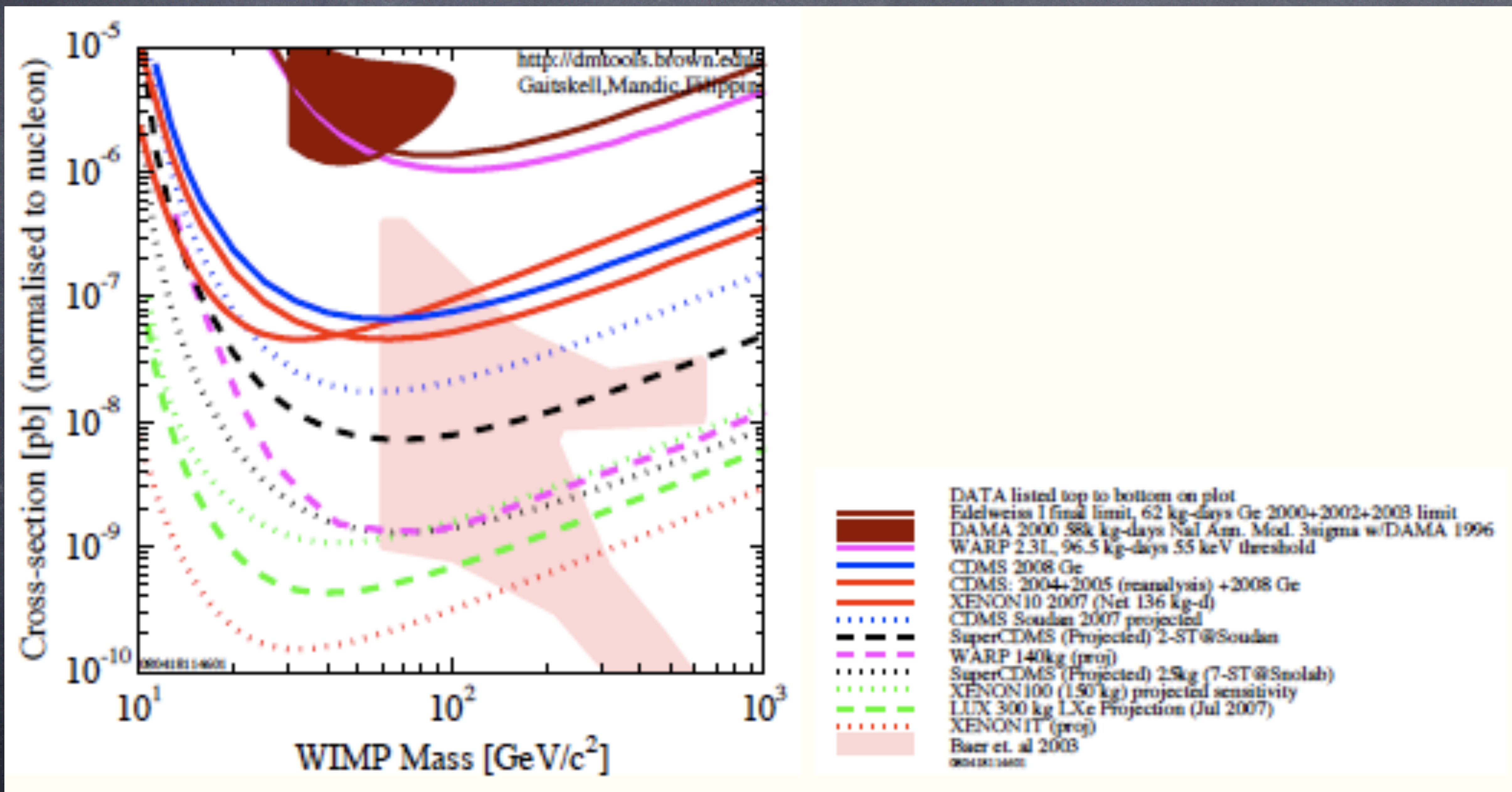




HB, Park, Tata

DD vs. LHC in mSUGRA:

Xenon-100 should cover FP region!

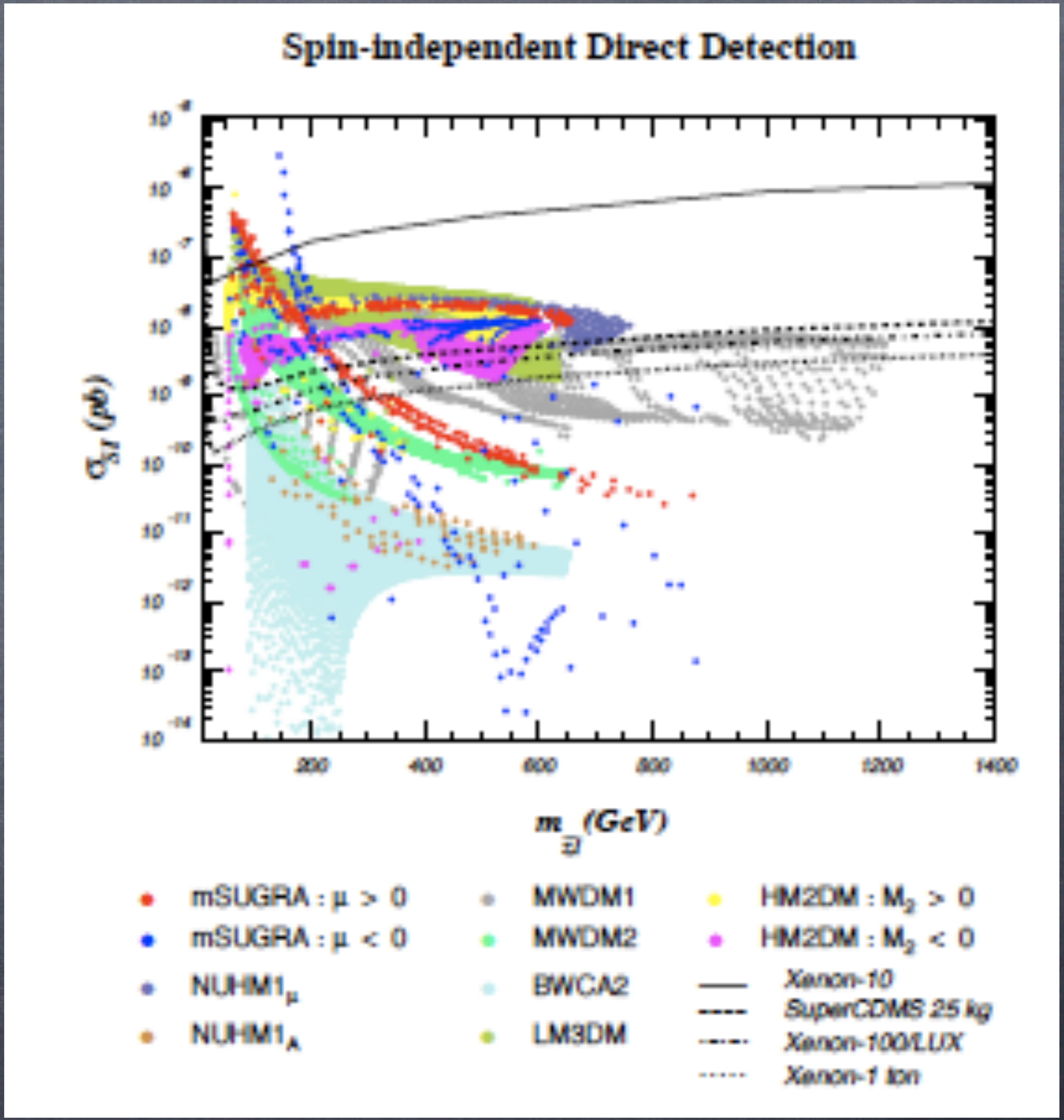


Well-tempered neutralinos

Arkani-Hamed, Delgado, Giudice

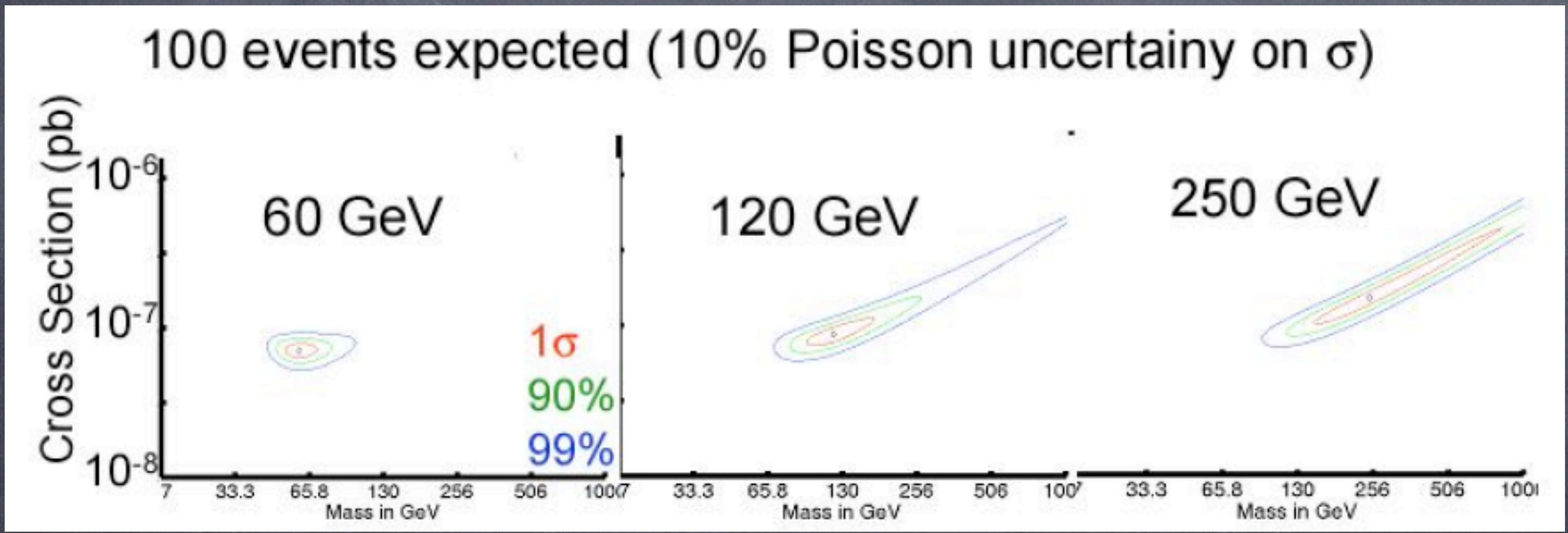
Scan over 10 models with and without universality; keep only models with correct relic abundance

Bulk of models asymptote at 10^-8 pb! Accessible to next Xenon-100 run!



HB, Mustafayev, Park, Tata

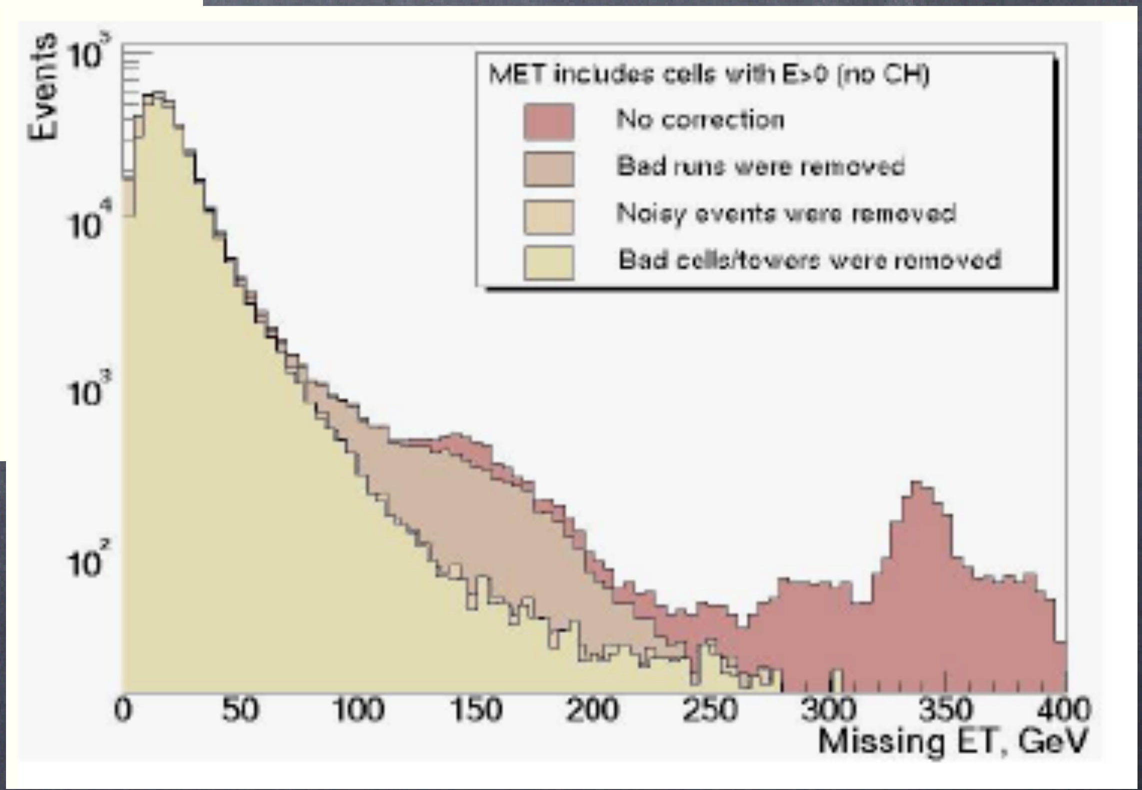
If WIMP seen in DD, then mass measurement



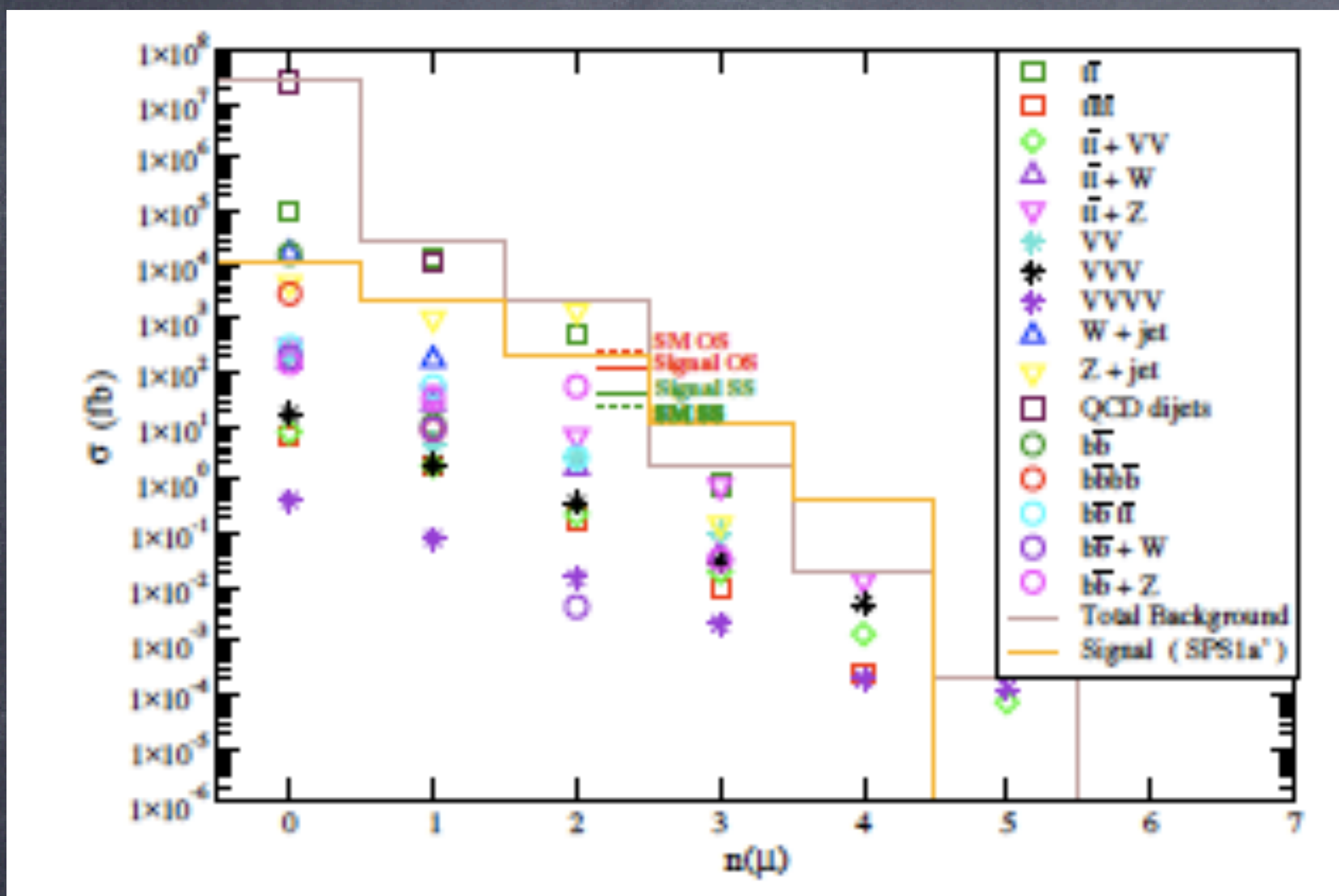
Study by Schnee; Green; Drees&Shan shows m(WMP) may be extracted from energy spectrum in DD experiments, for lower range of WIMP masses: crucial input for LHC?

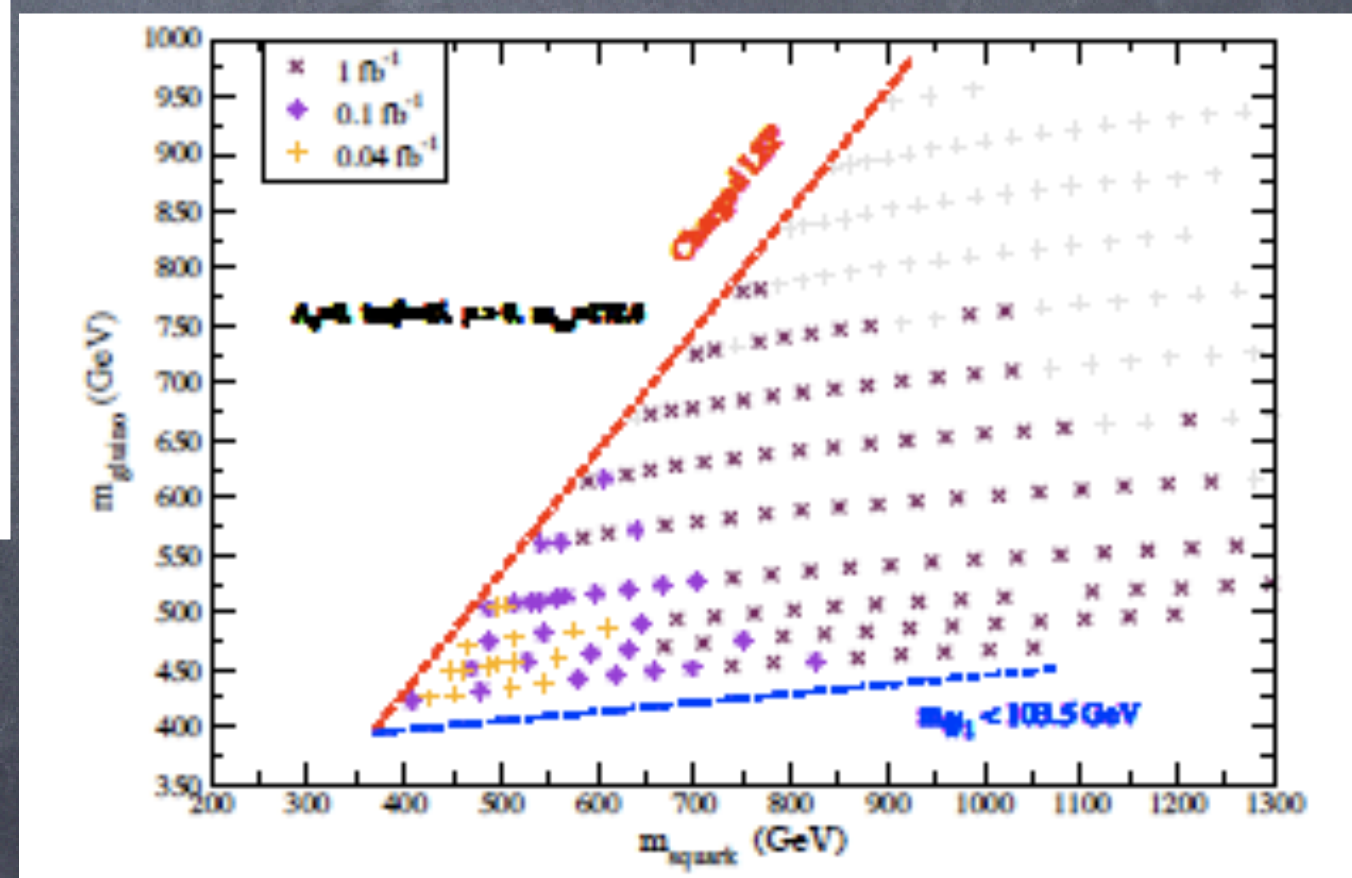
Early search for SUSY at LHC: 0.1-0.5 fb^-1

- 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



Reach of LHC for SUSY via SS dimuons and *no* ETMISS





HB, A. Lessa, H. Summy
arXiv:0809.4719 (PLB)

Precision sparticle measurements at LHC

- $M_{eff} = \not{E}_T + E_T(j1) + \cdots + E_T(j4)$ sets overall $m_{\tilde{g}},\ m_{\tilde{q}}$ scale
- $m(\ell\bar{\ell}) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ mass edge
- $m(\ell\bar{\ell})$ distribution shape
- combine $m(\ell\bar{\ell})$ with jets to gain $m(\ell\bar{\ell}j)$ mass edge: info on $m_{\tilde{q}}$
- further mass edges possible *e.g.* $m(\ell\bar{\ell}jj)$
- Higgs mass bump $h \to b\bar{b}$ likely visible in $\not{E}_T + jets$ events
- in favorable cases, may overconstrain system for a given model

★ methodology very p-space dependent

★ some regions are very difficult *e.g.* HB/FP

Paige, Hinchliffe et al. studies

- examined many model case studies in mSUGRA, GMSB, high $\tan\beta$...
- classic study: pt.5 of PRD**55**, 5520 (1997) and PRD**62**, 015009 (2000)
- $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu) = (100, 300, 0, 2, 1)$ in GeV
- dominant $\tilde{g}\tilde{g}$ production with $\tilde{g} \to q\tilde{q}_L \to qq\widetilde{Z}_2 \to q_1q_2\ell_1\tilde{\ell} \to q_1q_2\ell_1\ell_2\widetilde{Z}_1$ (string of 2-body decays)
- can reconstruct 4 mass edges; allows one to fit four masses: $m_{\tilde{q}_L},\ m_{\widetilde{Z}_2},\ m_{\tilde{\ell}},\ m_{\widetilde{Z}_1}$ to $3-12\%$
- can also find Higgs h in the SUSY cascade decay events
- if enough sparticle masses measured, can fit to MSSM/SUGRA parameters

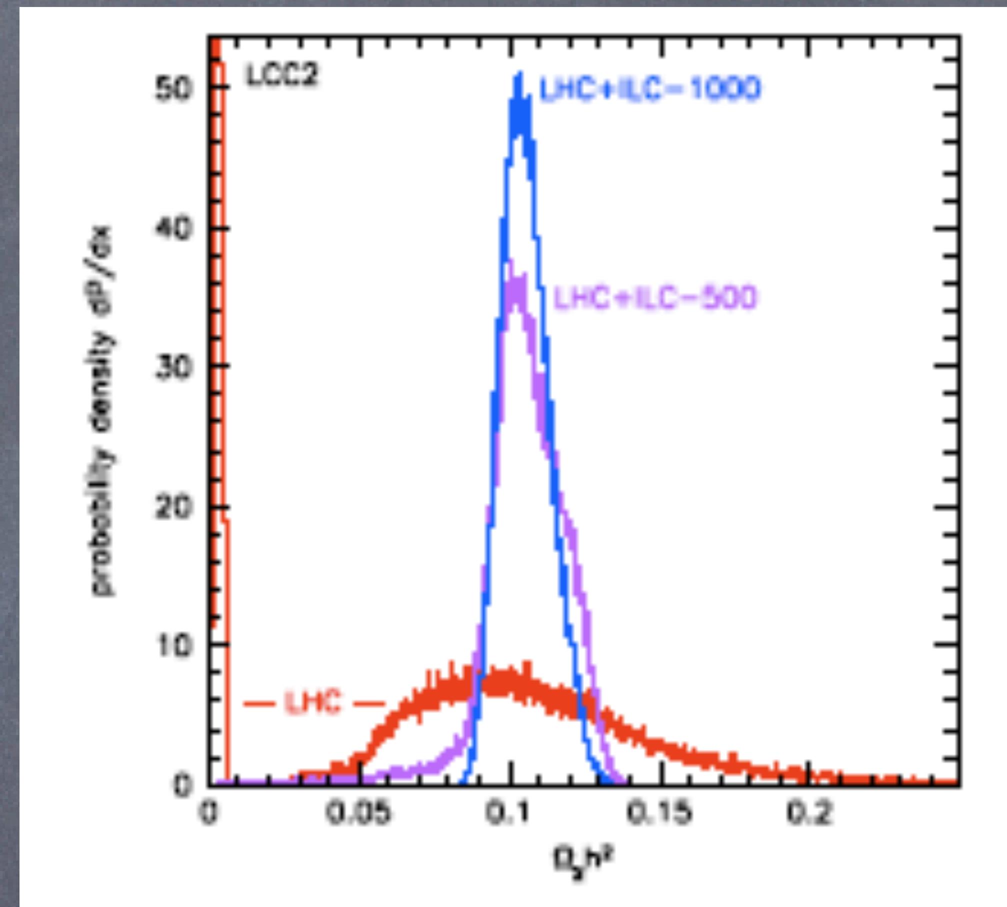
Precision SUSY measurements and cosmology

- Find which parameter space choices lead to precision measurements

- Map parameters onto e.g. relic density, DD cross section, ID <sigma.v>

- -> Collider measurement of

$$\Omega_\chi h^2,\ \sigma(\chi p),\ \langle \sigma \cdot v \rangle, \cdots$$

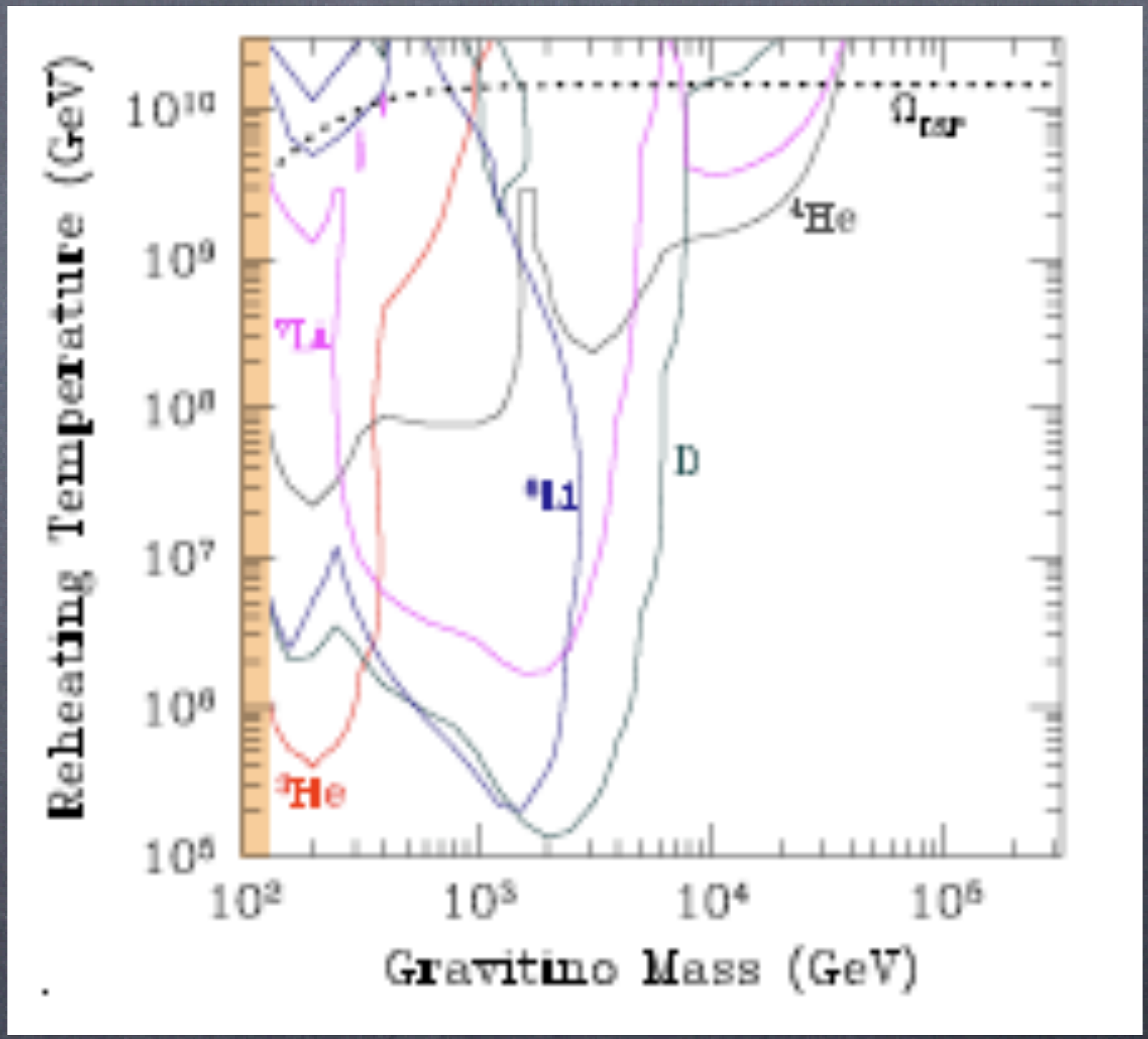


Allanach, Belanger, Boudjema, Pukhov
Nojiri, Polesello, Tovey
Baltz, Battaglia, Peskin, Wisansky
Arnowitt, Dutta, Kamon, ..

Beware: points chosen are SPS1a or accessible to ILC500

The gravitino problem in SUGRA models

- Gravitinos can be produced thermally in early universe
- Gravitino lifetime suppressed by M_Pl^-2
- Late decays disrupt successful BBN predictions
- Need either m_grav > 5 TeV or T_R<10^5 GeV (but then problems with baryogenesis)



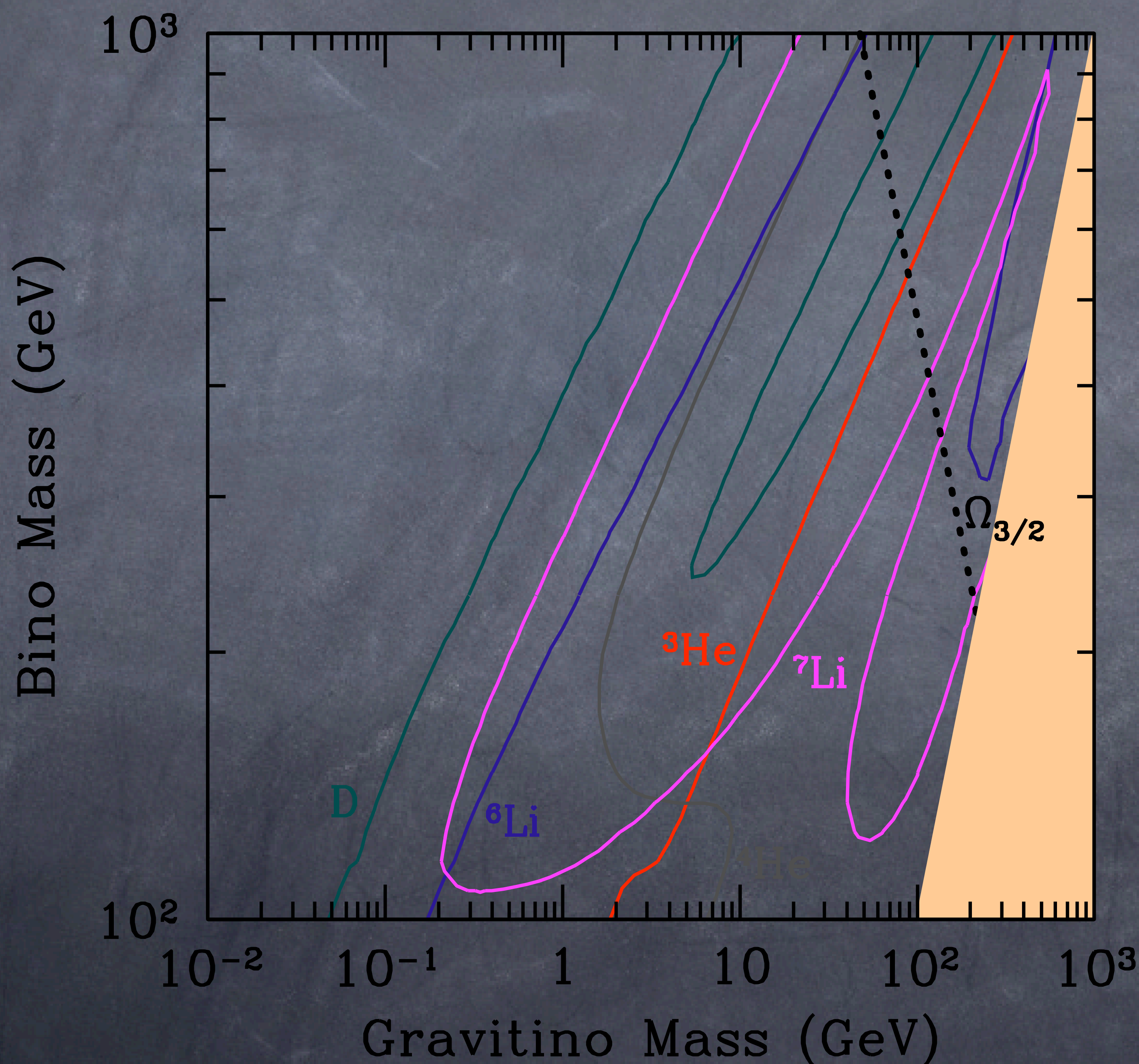
Kawasaki et al; Ellis et al.

Gravitino DM

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

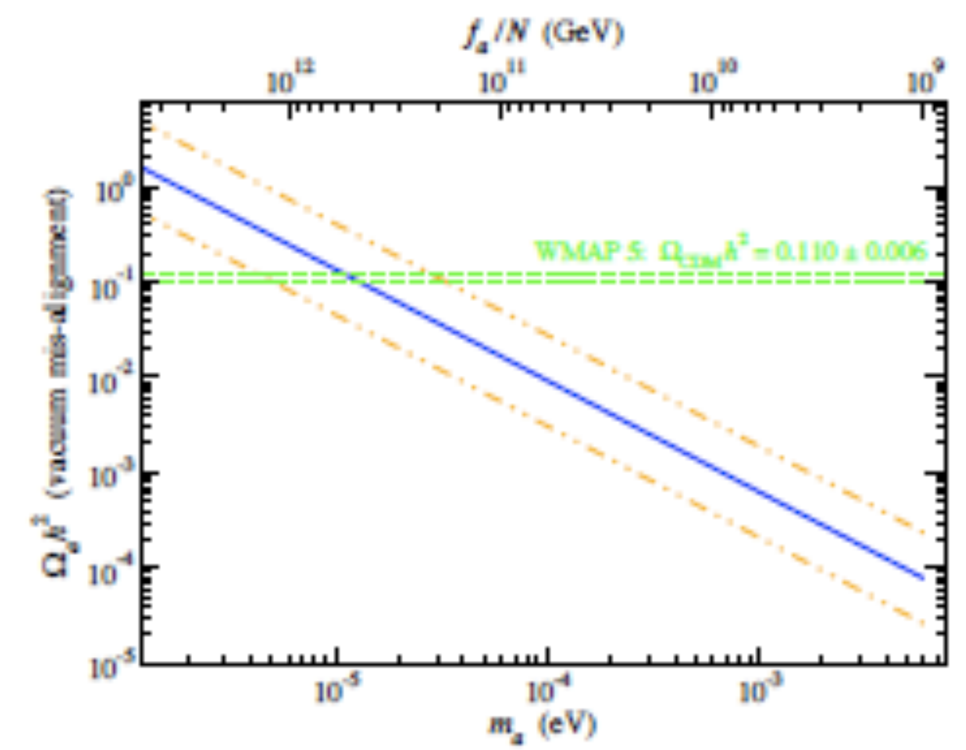
- usually $\tilde{G}$ decouples (but see Moroi et al. for BBN constraints)
- if $\tilde{G}$ is LSP, then calculate NLSP abundance as a thermal relic: $\Omega_{NLSP}h^2$
- $\widetilde{Z}_1 \to h\tilde{G},\ Z\tilde{G},\ \gamma\tilde{G}$ or $\tilde{\tau}_1 \to \tau\tilde{G}$ possible
  - ∗ lifetime $\tau_{NLSP} \sim 10^4 - 10^8$ sec
  - ∗ constraints from BBN, CMB not too severe
  - ∗ DM relic density is then $\Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{NLSP}}\Omega_{NLSP} + \Omega_{\tilde{G}}^{TP}(T_R)$
  - ∗ Feng, Rajaraman, Su, Takayama; Ellis et al; Buchmuller et al.
- $\tilde{G}$ undetectable via direct/indirect DM searches
- unique collider signatures:
  - ∗ $\tilde{\tau}_1$=NLSP: stable charged tracks
  - ∗ can collect NLSPs in e.g. water (slepton trapping)
  - ∗ monitor for $NLSP \to \tilde{G}$ decays

BBN constraints on gravitino LSP: Kohri et al.



Axion dark matter

- ★ 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



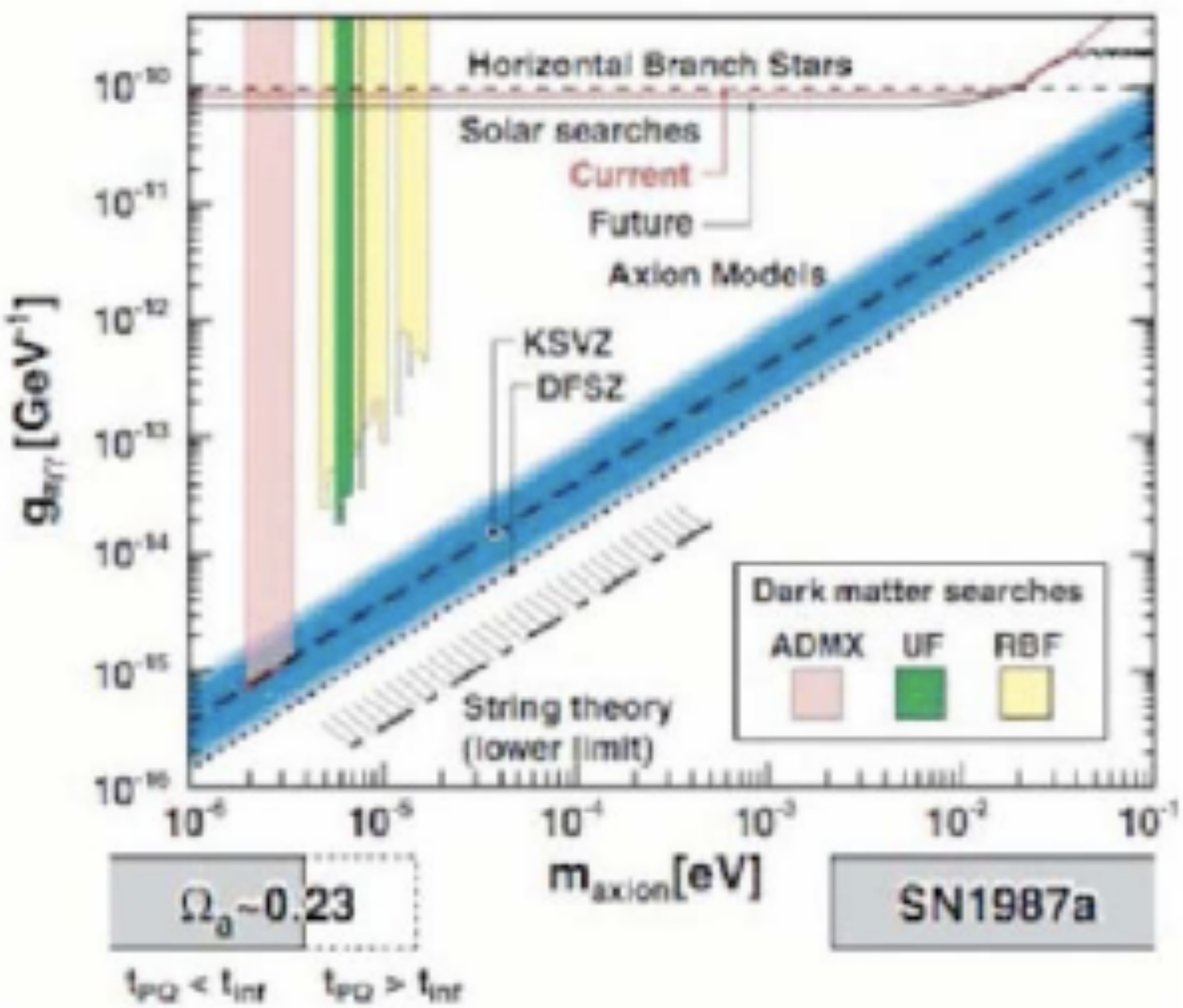
Axion DM: forms BEC, suppresses small scale structure, gives mechanism for galactic rotation

Sikivie, Wang arXiv:0901.1106

Axion microwave cavity seach

★ 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=> axinos

- axino is spin-1/2, R-odd spartner of axion
- axino mass is model dependent: keV-> GeV
- axino is an EWIMP; coupling suppressed by Peccei-Quinn scale $f_a : 10^9 - 10^{12}$ GeV
- good candidate for cold DM
- for review, see Covi, Kim, Kim, Roszkowski JHEP 0105 (2001) 033

Non-thermal axino production via NLSP decay

- If $\tilde{a}$ is LSP, then it can be produced via decay of NLSP
- e.g. $\tilde{Z}_1 \rightarrow \tilde{a}\gamma \; or \; \tilde{\tau}_a \rightarrow \tilde{a}\tau$
- NLSP lifetime: $10^{-3} - 10^{1}$ sec: (BBN safe)
- axinos inherit NLSP number density
- $$\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1} h^2$$
- NTP axino is warm DM for $m_{\tilde{a}} < 1 - 10$ GeV

Thermal production of axinos

- Axinos likely never in thermal equilibrium
- Can be produced thermally via bremsstrahlung off particles in thermal equilibrium
- TP axinos are cold DM for $m_{\tilde{a}} > 100$ keV

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

- CKKR; Brandenberg, Steffen

SO(10) SUSY GUTs

- gauge coupling unification
- matter unification into 16-dim. spinor rep.
- 16th element contains RHN: see-saw
- explain anomaly cancellation in MSSM and SU(5)
- explain R-parity conservation
- allow for t-b-tau Yukawa unification

SO(10) model 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}:

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

★ 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

HB, Kraml, Sekmen, Summy

- Scan over p-space using Isasugra to check for Yukawa unified solutions:
- $R = max(f_t, f_b, f_\tau)/min(f_t, f_b, f_\tau)$

Related work: Blazek, Dermisek, Raby;
Wells, Tobe; Dermisek, Raby, Roszkowski, Ruiz; Altmannshofer, Guadagnoli, Raby,Straub

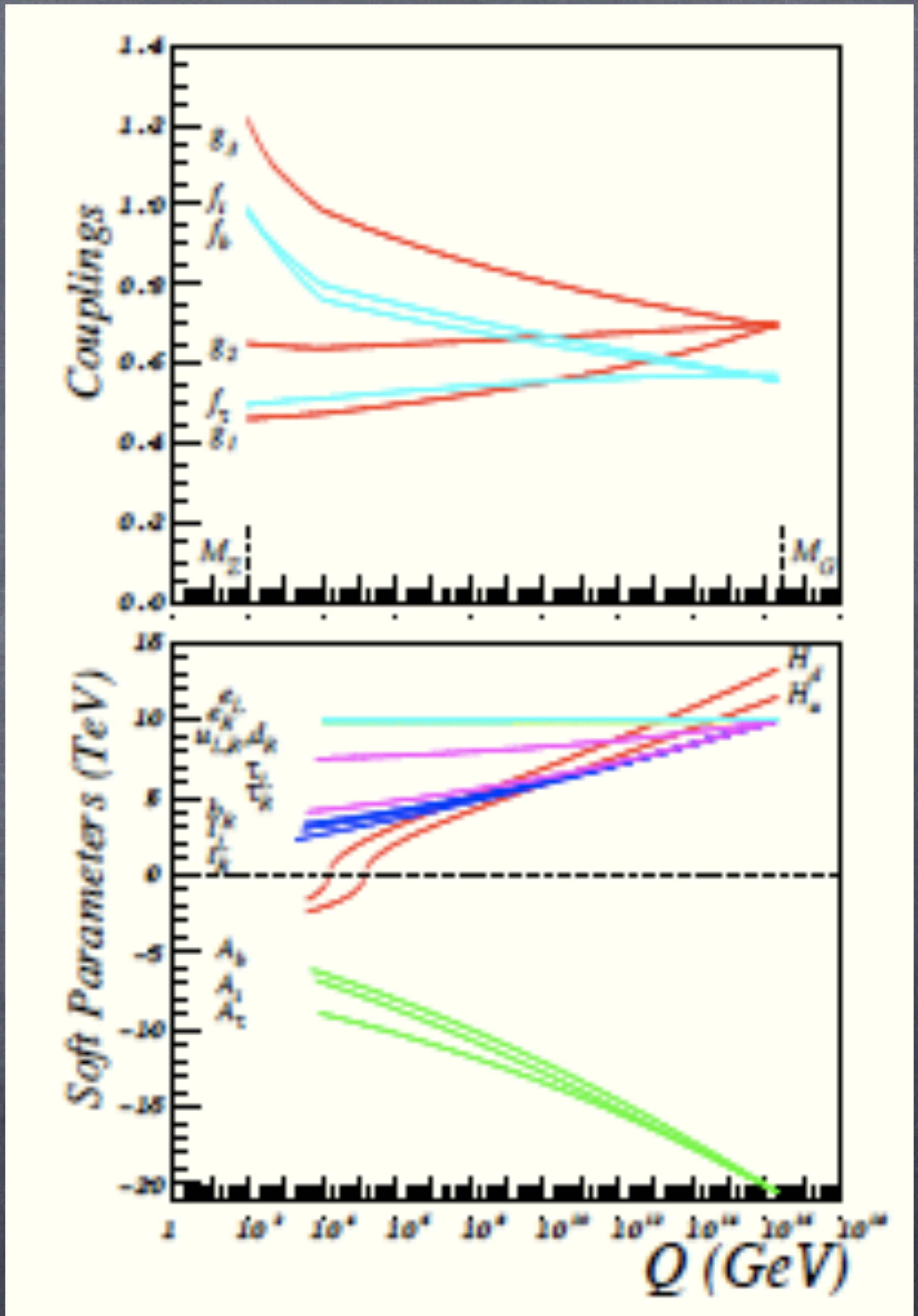
t-b-tau unified solutions

$m_{16} \sim 10\ TeV$

$m_{1/2}\ small$

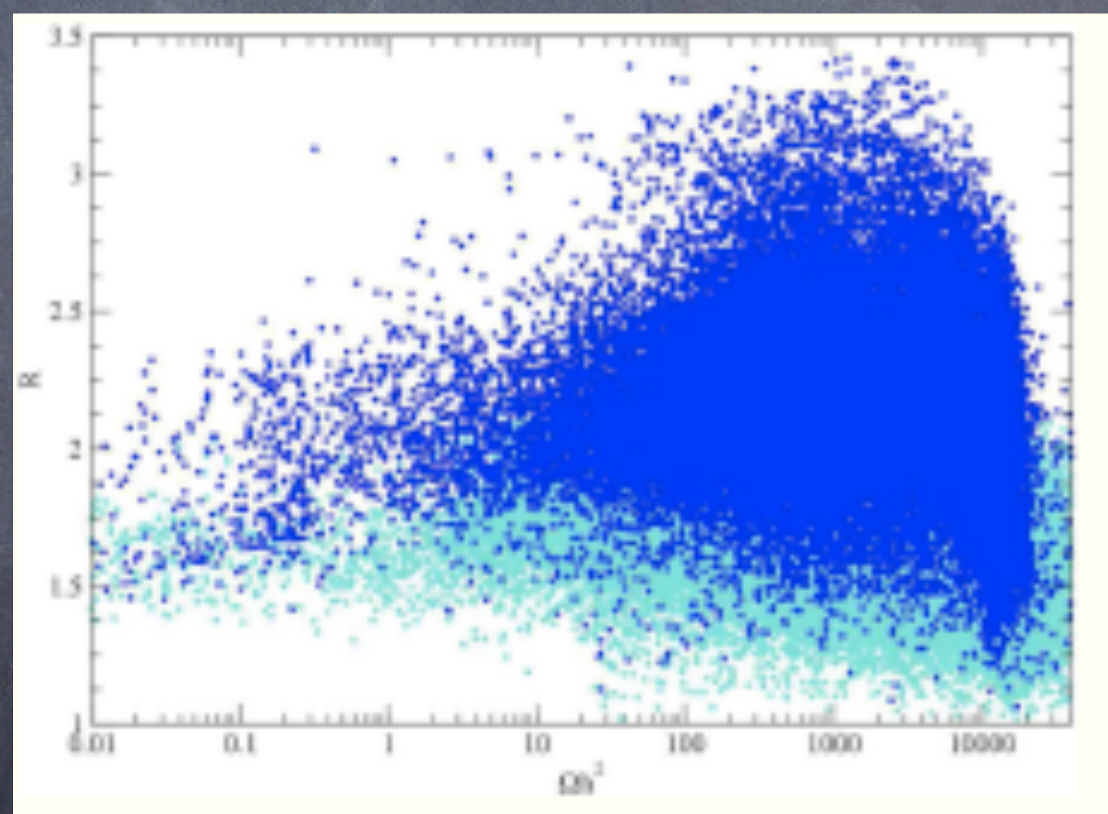
- need $m_{10} \simeq \sqrt{2} m_{16}$
- $A_0 \simeq -2 m_{16}$
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: $m_{H_u}^2 < m_{H_d}^2$

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



Dark matter problem in Yukawa-unified models

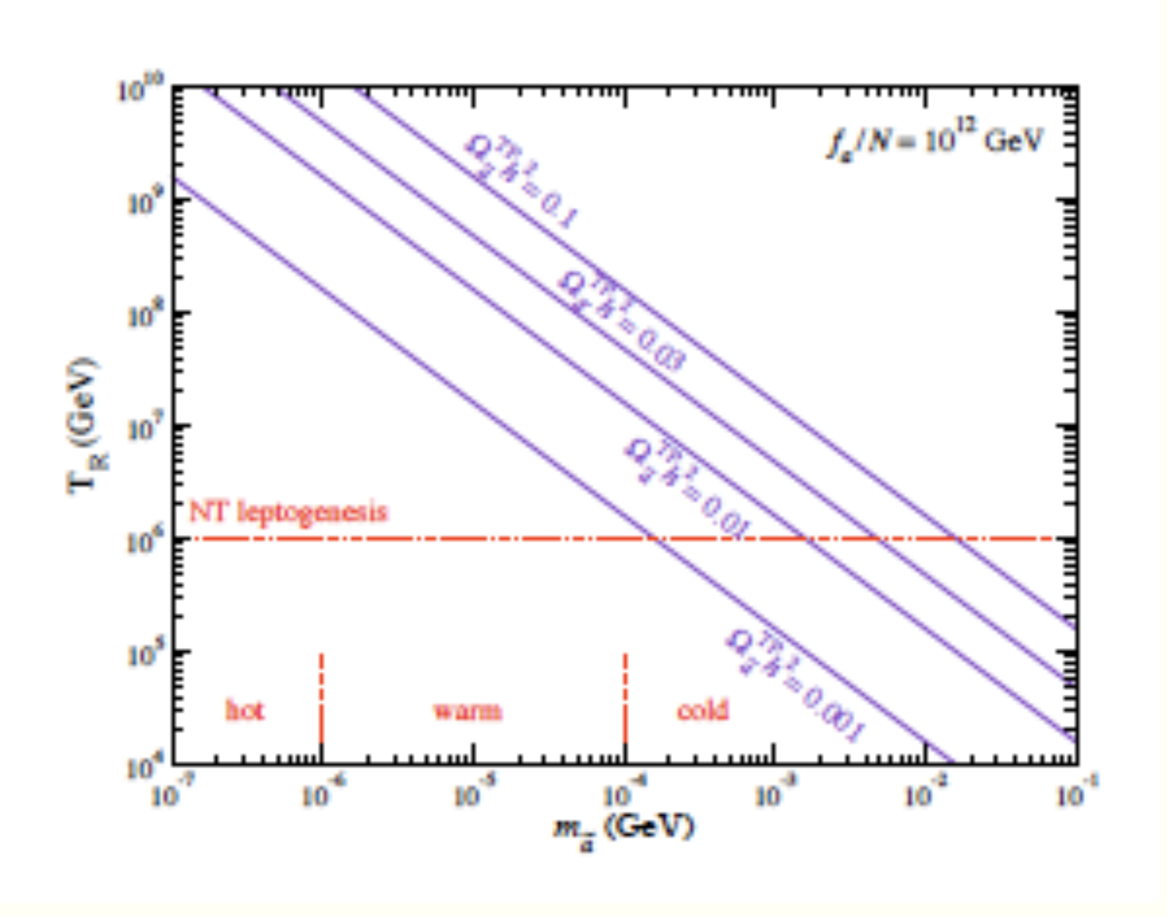
- m(16)~10 TeV with m_1/2 small
- neutralino is pure bino-like



relic density too high by factor 10^3-10^5!

DM solution: three components: warm axinos, cold axinos, cold axions!

- ★ 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



HB, Kraml, Sekmen, Summy
JHEP 0803 (2008) 056

HB,Summy
PLB666 (2008) 5

HB, Haider, Kraml, Sekmen, Summy
arXiv:0812.2693

Can we find Yukawa-unified models with dominant CDM?

- Given $\Omega_{\tilde{Z}_1} h^2$ and $m_{\tilde{Z}_1}$ 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

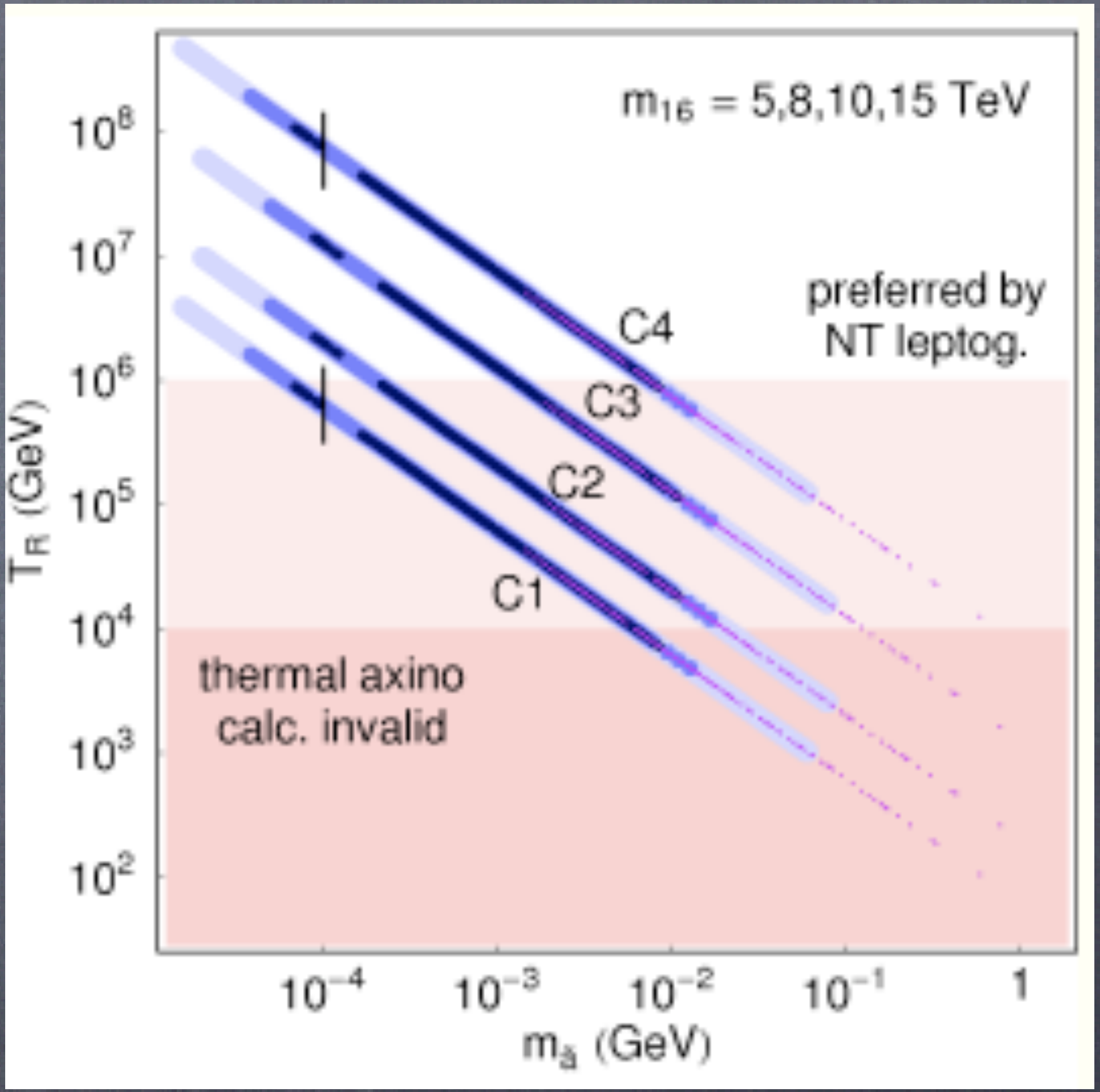
★ Four cases:

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

Mixed axion/axino cold and warm DM in Yukawa-unified models

Need:

1. large f_a~10^12 GeV
2. solutions C2, C3 with dominant axion CDM
3. solution C4 has accidental vacuum alignment and dominant TP axino CDM

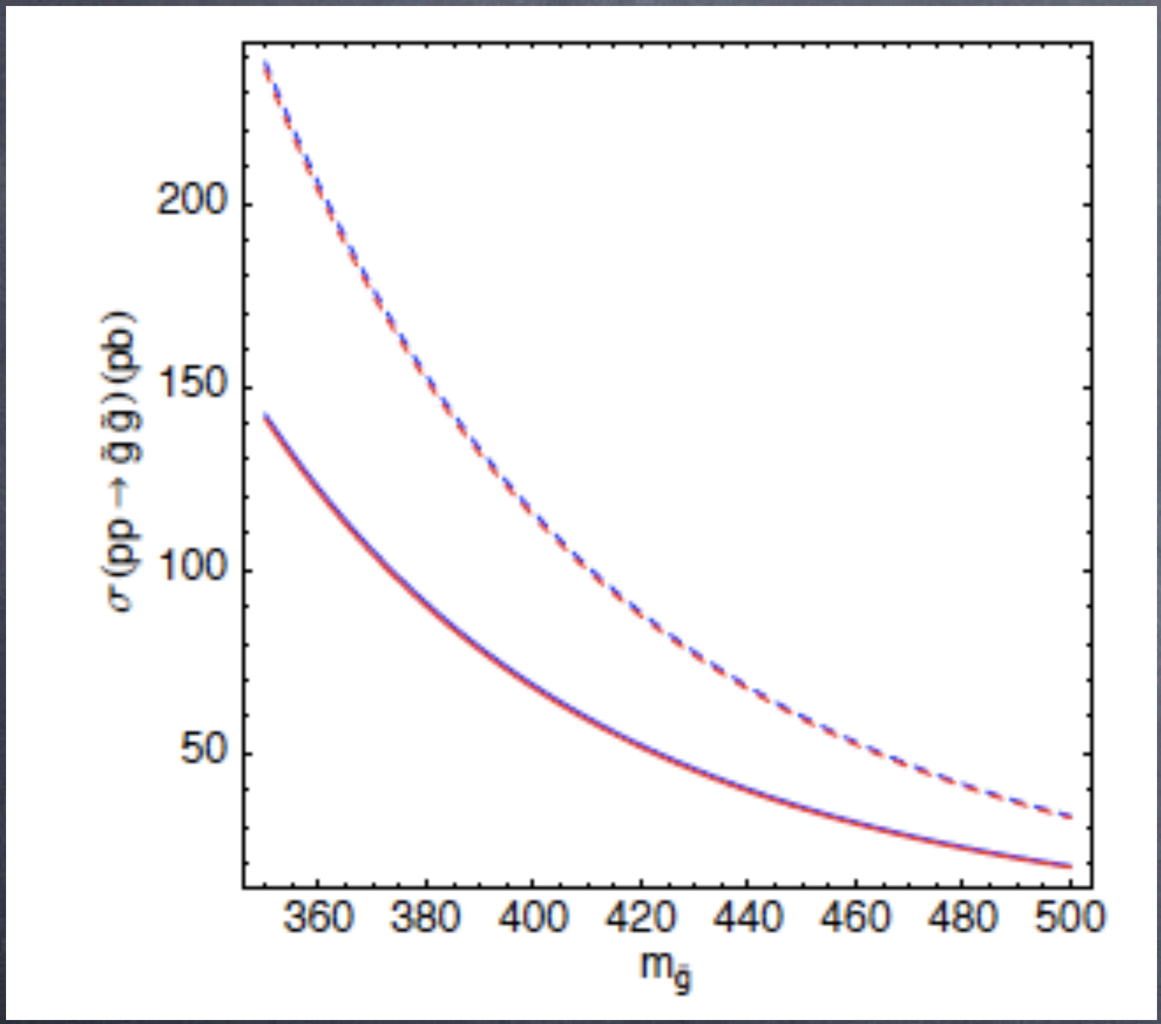


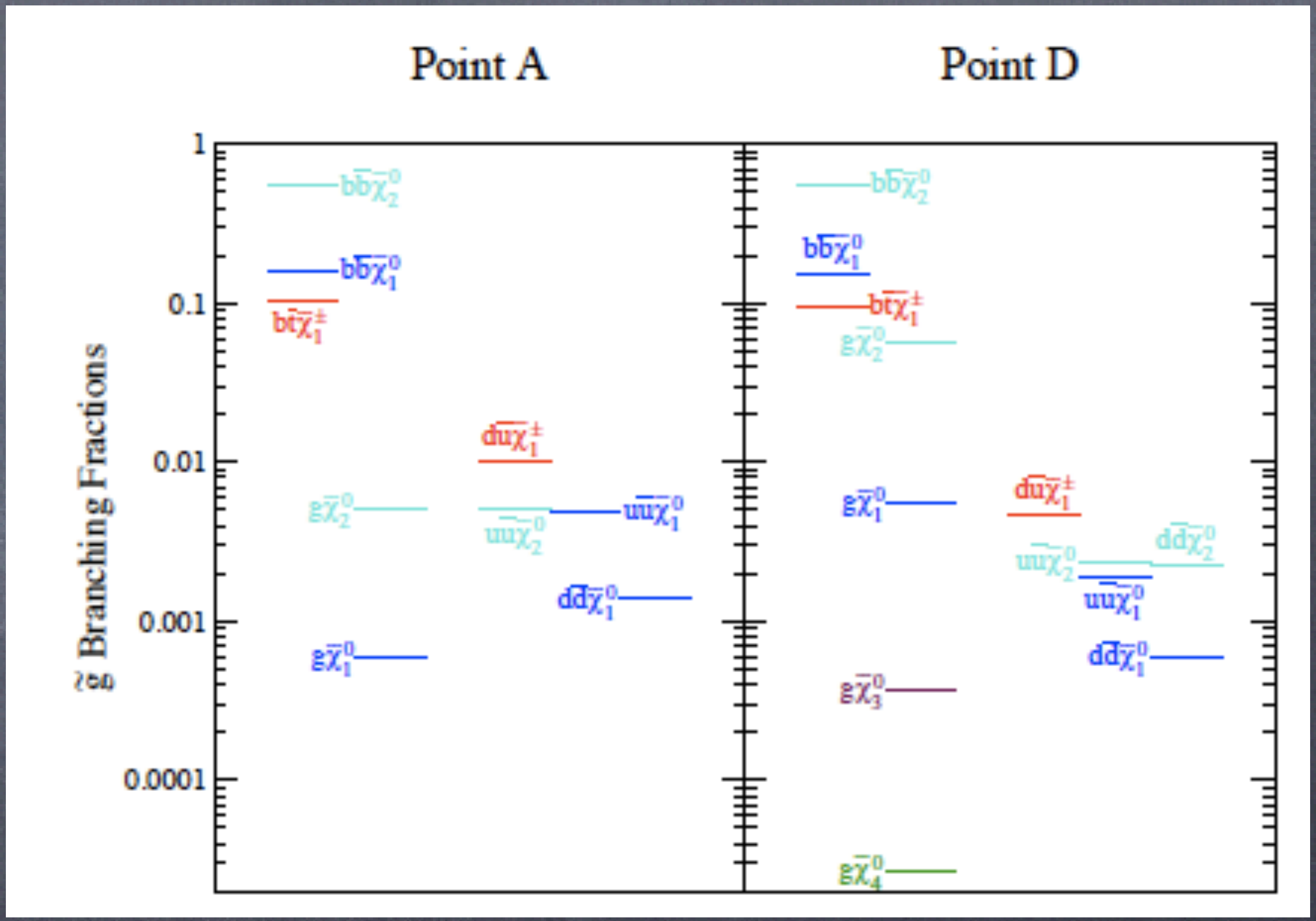
4. Solutions with m16>8 TeV have TR>10^6 GeV

Many pieces of puzzle fit:

- PQ solution to strong CP problem
- Solve gravitino problem: m(Grav'ino)~10 TeV
- CDM: dominated by axions, but also cold/ warm axinos
- Allow high enough re-heat 10^6-10^9 GeV for e.g. non-thermal leptogenesis
- Large m16~10 TeV suppresses FCNC, CPV, p-decay
- All within framework of simple SO(10) SUSY GUT

Cross sections/BFs, LHC signatures





HB, Kraml, Sekmen, Summy: JHEP 0810 (2008) 079

Testable consequences:

- m(gluino)~350-500 GeV: abundant LHC signatures: early discovery via isolated multi-leptons plus jets (ETMISS not needed)
- LHC dilepton mass edge: 50-90 GeV; no second edge implies bino-like neutralino
- high b-jet multiplicity
- reconstruct m(gluino) via m(lljj)
- possible axion signal at ADMX
- no direct/indirect WIMP signals

Conclusions:

- Role of LHC: produce matter states associated with dark matter; decay to stable DM candidate (LHT, UED, SUSY, etc) usually gives ETMISS signature (charged stable NLSP counter-example)
- In case of WIMP dark matter, additional signals from DD/ID of DM will provide complementary information (e.g. WIMP mass?)
- Xenon-100/LUX will soon test FP region of mSUGRA and well-tempered neutralino models
- precision measurements may allow collider measurement of relic density, associated quantities
- SuperWIMP, EWIMP DM possible (gravitino, axino/axion)
- SO(10) Yukawa-unified SUSY with axion/axino DM very compelling!