Dark Matter, Supersymmetry and the LHC

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Quick Review

Gaugino Sector Basics

- Gauginos part of vector supermultiplets: $A_a = \{\lambda_a,\ (A_\mu)_a,\ D_a\}$, $a = 1, 2, 3$

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\ \mathbf{8},\ \mathbf{1}\ ,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\quad \widetilde{W}^0$	$W^\pm\quad W^0$	$(\ \mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$

- Supersymmetry breaking independent of EWSB
  Thus in SUSY limit we have massless gauginos up to EWSB effects

- Soft SUSY-breaking gaugino masses: $\mathcal{L}_{\rm soft} \ni -\frac{1}{2} M_a \lambda_a \lambda_a + {\rm c.c.}$

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⇒ Neutralinos: Higgsinos ($\widetilde{H}_u^0$, $\widetilde{H}_d^0$), W-ino $\widetilde{W}^0$ and B-ino $\widetilde{B}$

$$\psi^0 = \left(\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0\right)$$

- Mass terms in 4×4 notation: $\mathcal{L} \ni -\frac{1}{2}\left(\psi^0\right)^T M_{\widetilde{N}} \left(\psi^0\right) \ +\text{c.c.}$

$$M_{\widetilde{N}} = \begin{pmatrix} M_1 e^{i\varphi_1} & 0 & -g' v_d/\sqrt{2} & g' v_u/\sqrt{2} \\ 0 & M_2 e^{i\varphi_2} & g v_d/\sqrt{2} & -g v_u/\sqrt{2} \\ -g' v_d/\sqrt{2} & g v_d/\sqrt{2} & 0 & -\mu e^{i\varphi_\mu} \\ g' v_u/\sqrt{2} & -g v_u/\sqrt{2} & -\mu e^{i\varphi_\mu} & 0 \end{pmatrix}$$

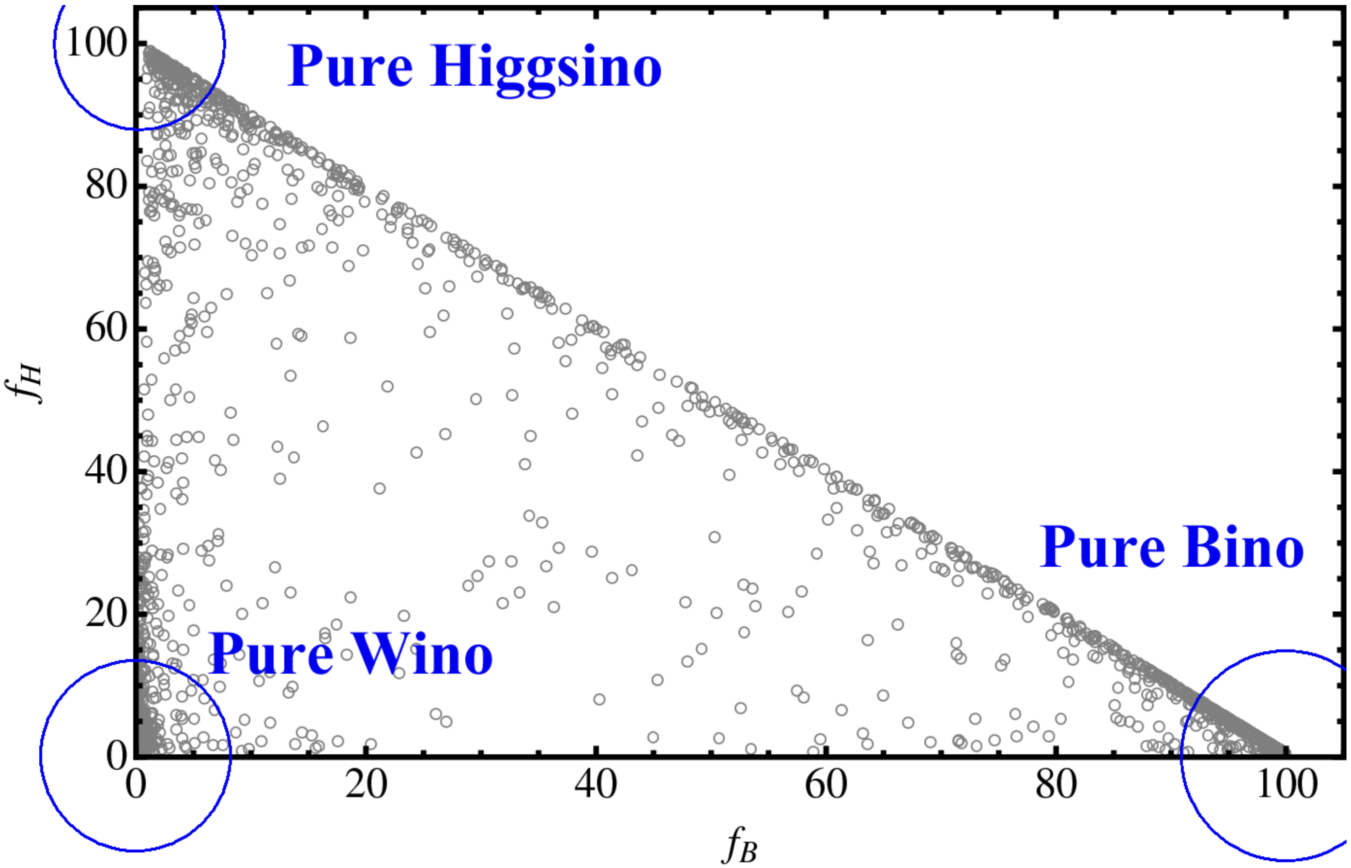
The Nature of the Lightest Supersymmetric Particle (LSP)

⇒ Can model possibilities via $M_a = m_{1/2}\,(1+\delta_a)$

- $\delta_1 = \delta_2 = \delta_3$ produces bino-like LSP: $\widetilde{N}_1 \sim \widetilde{B}; \quad \widetilde{N}_2 \sim \widetilde{W}^0$
- $\{\delta_1 = 0,\ \delta_2 < 0\}$ produces wino-like LSP
- $\{\delta_2 > 0,\ \delta_3 < 0\}$, $|\delta_3| < |\delta_2|$ produces Higgsino-like LSP via RGEs + EWSB

$$M_Z^2 = 5.9M_3^2 - 1.8\mu^2 + 0.4m_0^2 - 0.4M_2^2 + \ldots$$

Kane, Lykken, BDN, Wang, PLB **551** (2003) 146



Relic Density: *mirabile dictu!*

Standard Thermal Cosmology

⇒ WIMP “miracle” never expected to be better than two orders of magnitude!

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

with $\langle \sigma_{\mathrm{ann}} v \rangle \,|_{\mathrm{weak}} \sim \alpha^2_{\mathrm{weak}} (100\ \mathrm{GeV})^{-2} \sim 10^{-25}\,\mathrm{cm}^3/\mathrm{s}$ for $\alpha \sim 1/100$.

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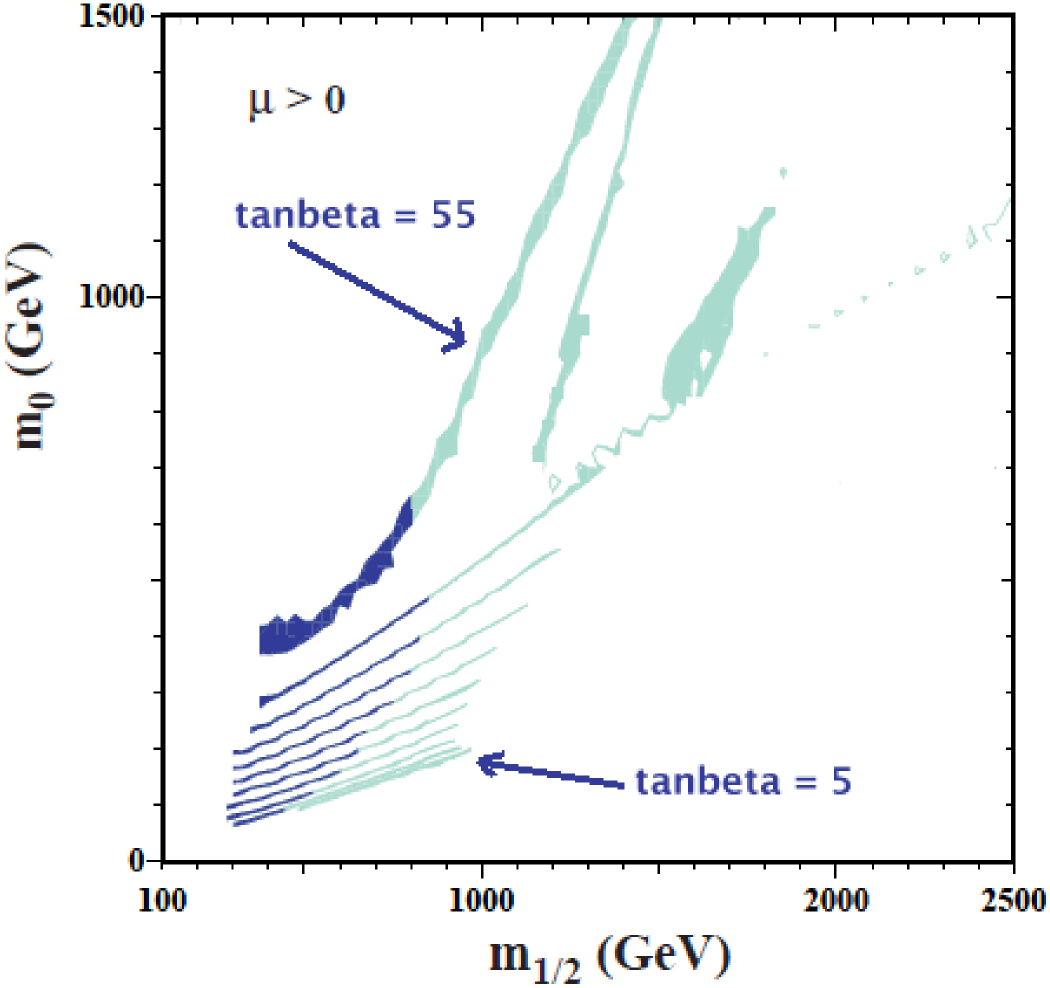
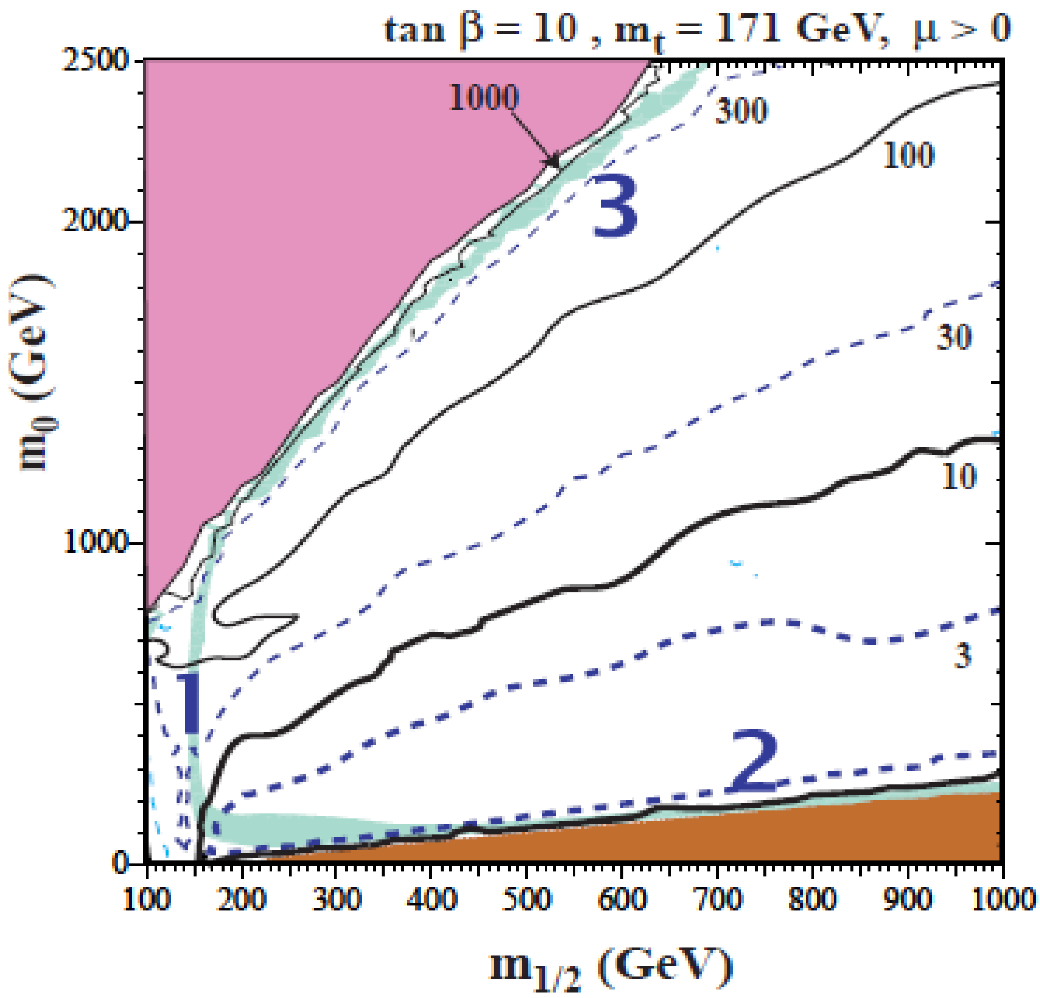
Ellis, Olive, Santoso, Spanos, PLB **565** (2003) 176



- WMAP Seven Year Data: $\Omega_\chi h^2 = 0.1109 \pm 0.0056$
- mSUGRA with Bino LSP: $\Omega_\chi h^2 \sim 10$
- Thin strip in $(m_0, m_{1/2})$ plane which varies with $\tan\beta$
- At very large $\tan\beta$ reach resonant annihilation $m_\chi \simeq 0.5 m_A,\, 0.5 m_H$

Standard Thermal Cosmology – Special Places

⇒ Three generic mSUGRA configurations consistent with WMAP data



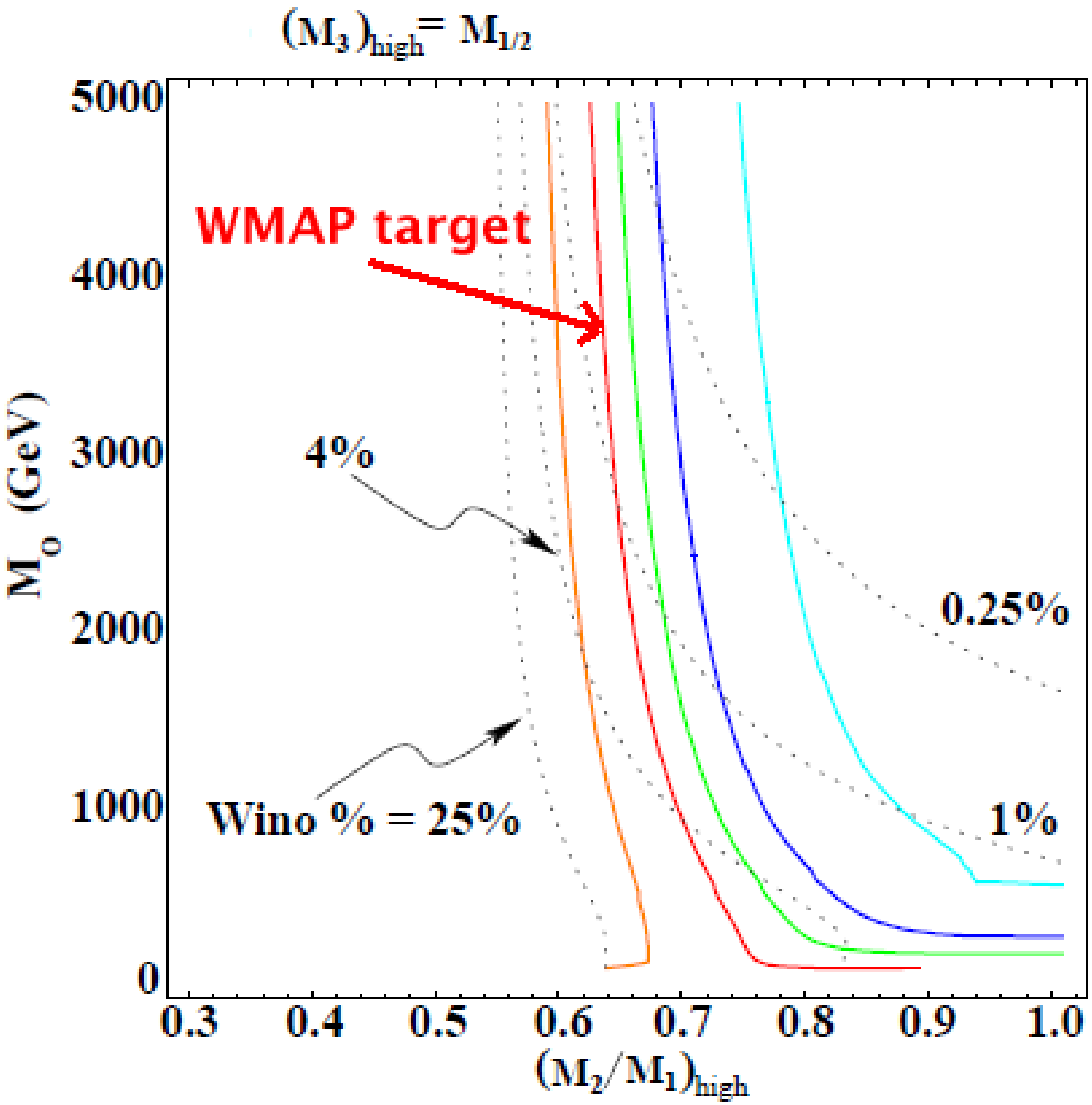
Ellis & Olive, PLB **514** (2001) 114

- **1** “Bulk region”: light sleptons facilitate annihilation in early universe; possible light CP-even Higgs resonance
- **2** “Stau Co-annihilation”: skirts region where $m_{\tilde{\tau}} < m_\chi$
- **3** “Gaugino Co-annihilation”: in focus point region where $\mu^2 \to 0$; degenerate chargino/neutralino states co-annihilate with Higgsino-like LSP

Impact of LSP Wavefunction

$\Rightarrow$ Previous conclusions heavily dependent on wavefunction of the LSP

Birkedal-Hansen & BDN, PRD **64** (2001) 015008



- Deviations from $\delta_1 = \delta_2 = \delta_3$ can have huge impacts on annihilation rates
- A small amount of wino content dramatically improves the thermal relic density result
- Anomaly-mediated extreme with 100% Wino LSP: $\Omega_\chi h^2 \sim 10^{-3}$
- Mildly dependent on value of M_3 – suggests a “sweet spot” in the space of gaugino masses (“well-tempered” neutralino)

Arkani-Hamed, Delgado, Giudice, NPB **741** (2006) 108

Non-Thermal Production

⇒ If wino/Higgsino content of the LSP is large the model (probably) requires non-thermal production mechanisms

- Moduli (scalar fields with gravitational couplings to Standard Model) generally dominate energy density in early universe
- Subsequent decays will (eventually) produce LSPs – and “reheat” the cosmos to some temperature $T_{\rm R}$
- Requiring $T_R \gtrsim 10\,{\rm MeV}$ to preserve BBN predictions implies $m_\phi \sim m_{3/2} \gtrsim 10\,{\rm TeV}$

⇒ What are the typical relic densities in this scenario?

$$\Omega_\chi h^2 \simeq 0.1 \times \left(\frac{m_\chi}{100\,{\rm GeV}}\right)\left(\frac{3\times 10^{-24}\,{\rm cm}^3/{\rm s}}{\langle\sigma_{\rm ann} v\rangle}\right)\left(\frac{100\,{\rm TeV}}{m_\phi}\right)^{3/2}$$

Acharya, Kane, Kumar & Watson, PRD **80** (2009) 083529

⇒ Note: $\langle\sigma_{\rm ann} v\rangle \simeq 2.4 \times 10^{-24}\,{\rm cm}^3/{\rm s}$ for pure-wino LSP (AMSB-limit)

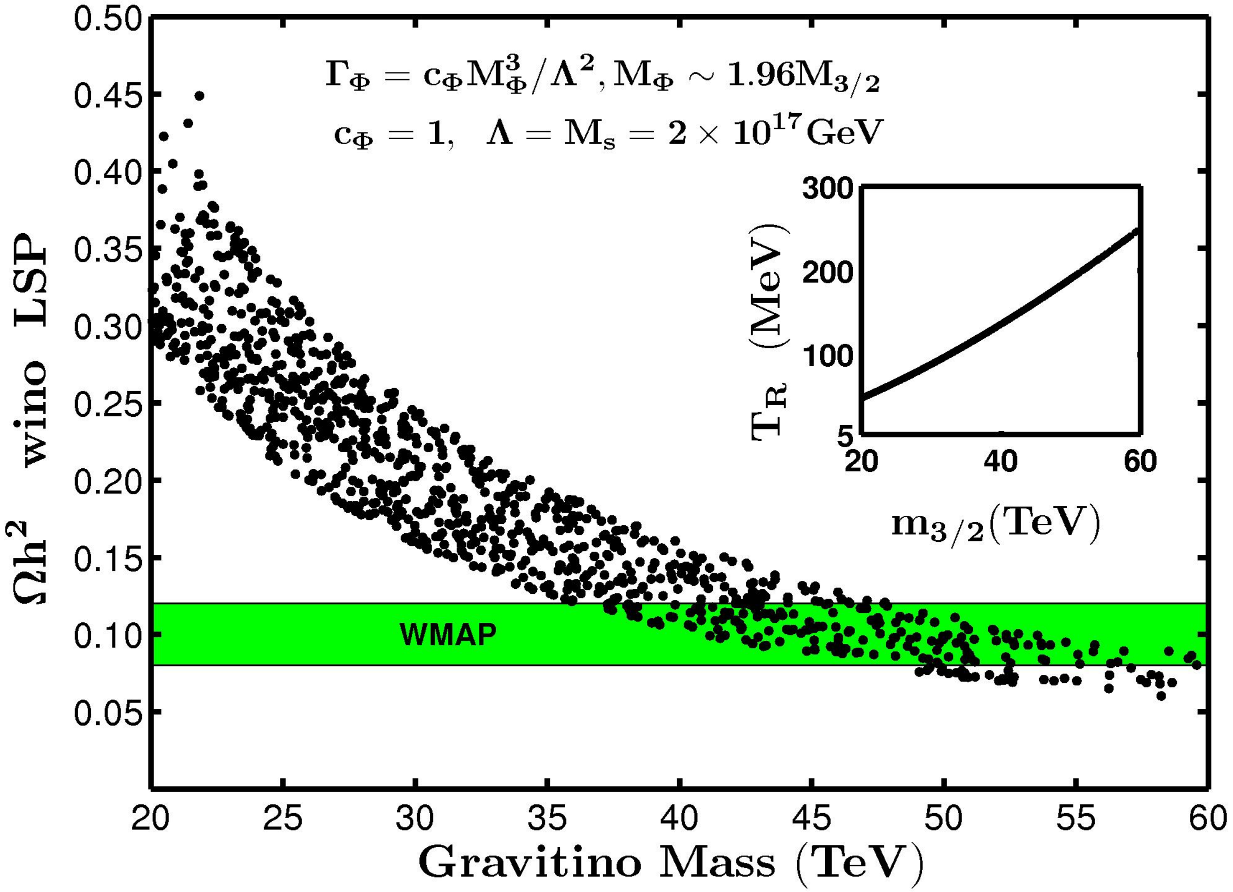
Moroi and Randall, NPB **570** (2000) 455

An Abundances of “Miracles”

- Such basic ingredients are generically present in string-motivated effective field theories

Acharya et al., JHEP **0806** (2008) 064
Acharya, Kane, Kumar & Watson, PRD **80** (2009) 083529
Acharya, Kane & Kuflik, arXiv:1006.3272

⇒ **Non-thermal WIMP miracle**



⇒ See also **WIMPless miracle** in gauge-mediated models

Feng and Kumar, PRL **101** (2008) 231301

Dark Matter Detection

Dark Matter Signals – the Earliest SUSY Signature

- Assumption: lightest neutralino is stable LSP ⇒ dark matter

Goldberg, PRL **50** (1983) 1419

- Prediction: annihilation into photons, positrons, anti-protons, neutrinos

Silk & Srednicki, PRL **53** (1984) 624

  - ⋆ Photons & neutrinos "point" back to source: high density areas such as galactic center or center of sun/earth
  - ⋆ Charged particles must be propagated from origin to earth numerically
  - ⋆ Both depend on the *halo profile* $\rho_\chi(r)$ assumed for the dark matter candidate, but to varying degrees

Goodman & Witten, PRD **31** (1985) 3059

⇒ Differential recoil rate at direct detection experiments given by

$$\frac{dR}{dE} = \sum_i c_i \frac{\rho_\chi \sigma^{\mathrm{SI}}_{\chi i} |F_i(q_i)|^2}{2 m_\chi \mu^2_{i\chi}} \int_{v_{min}}^{\infty} \frac{f(\vec{v},t)}{v} d^3v \,,$$

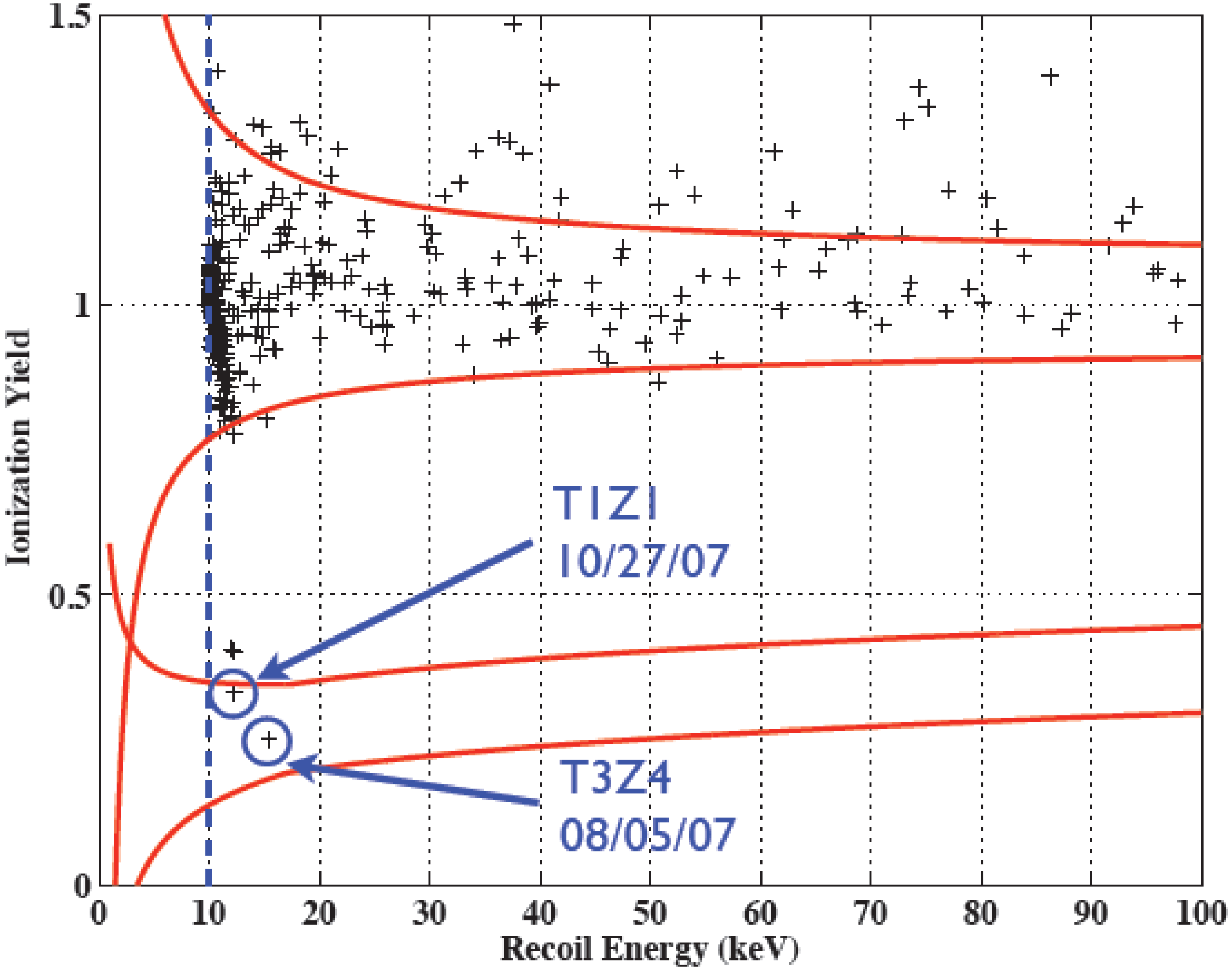
with $F_i(q_i)$ being a nuclear form factor for i-th target nucleus

- Calculation of integrated event rate depends on experimental configuration

$$R = \int_{E_{\min}}^{E_{\max}} \frac{dR}{dE}\, dE\,; \quad (\mathrm{Germanium}) : 10\,\mathrm{keV} \leq E_{\mathrm{recoil}} \leq 100\,\mathrm{keV}$$

Direct Detection Experiments: CDMS II

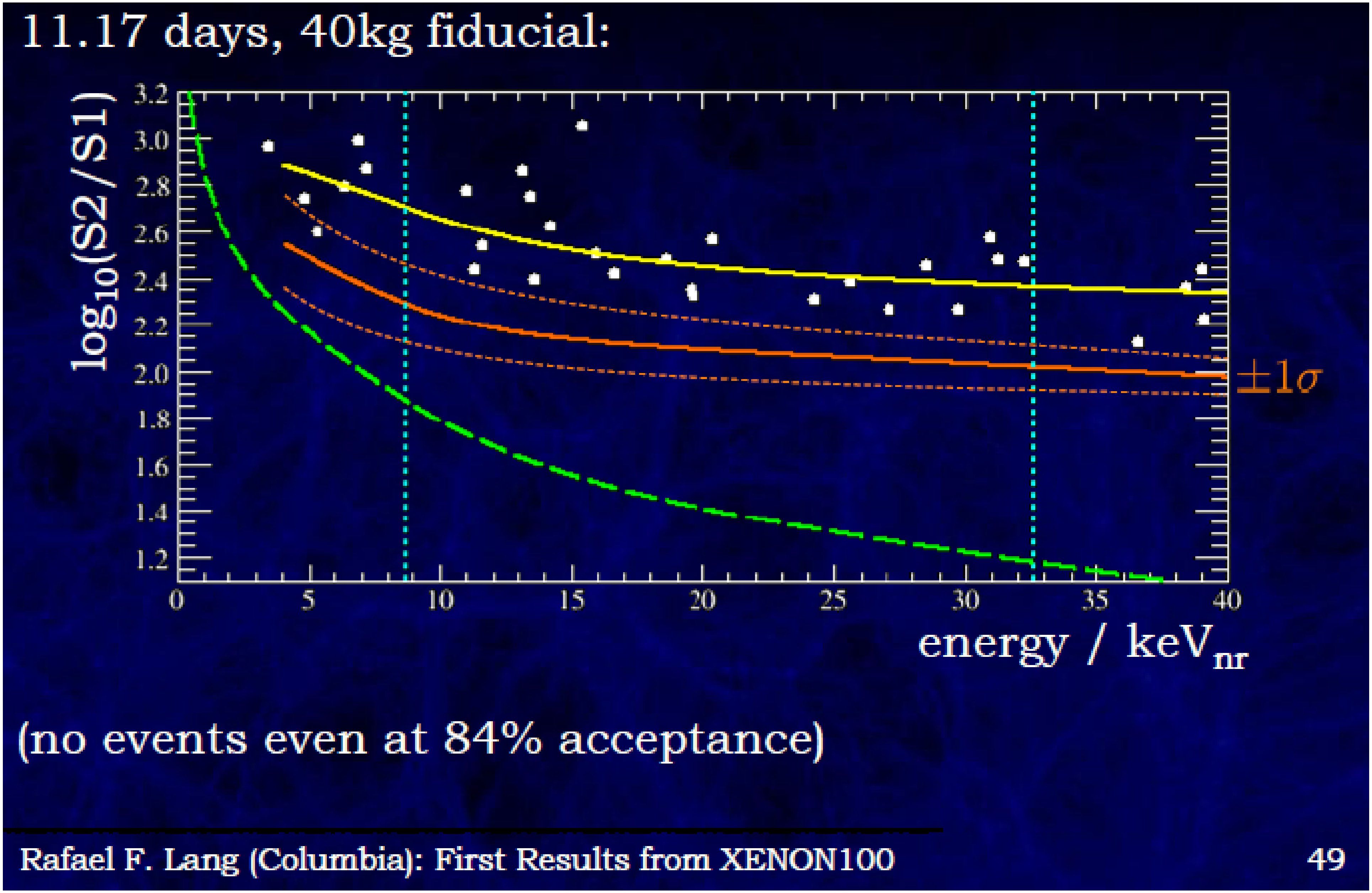
⇒ December 2009 data release for 14 Ge detectors by CDMS-II Collaboration



Jodi Cooley, data presentation, SLAC, 12/12/09

- Two events in signal region with (revised) background estimate of $0.8 \pm 0.1\,(\mathrm{stat}) \pm 0.2\,(\mathrm{sys})$ events
- Implies an interaction cross-section $\sigma_{\chi p}^{\mathrm{SI}} \sim 10^{-44}\,\mathrm{cm}^2 = 1 \times 10^{-8}\,\mathrm{pb}$

Confirmation in Xenon?



11.17 days, 40kg fiducial:

(no events even at 84% acceptance)

Rafael F. Lang (Columbia): First Results from XENON100

49

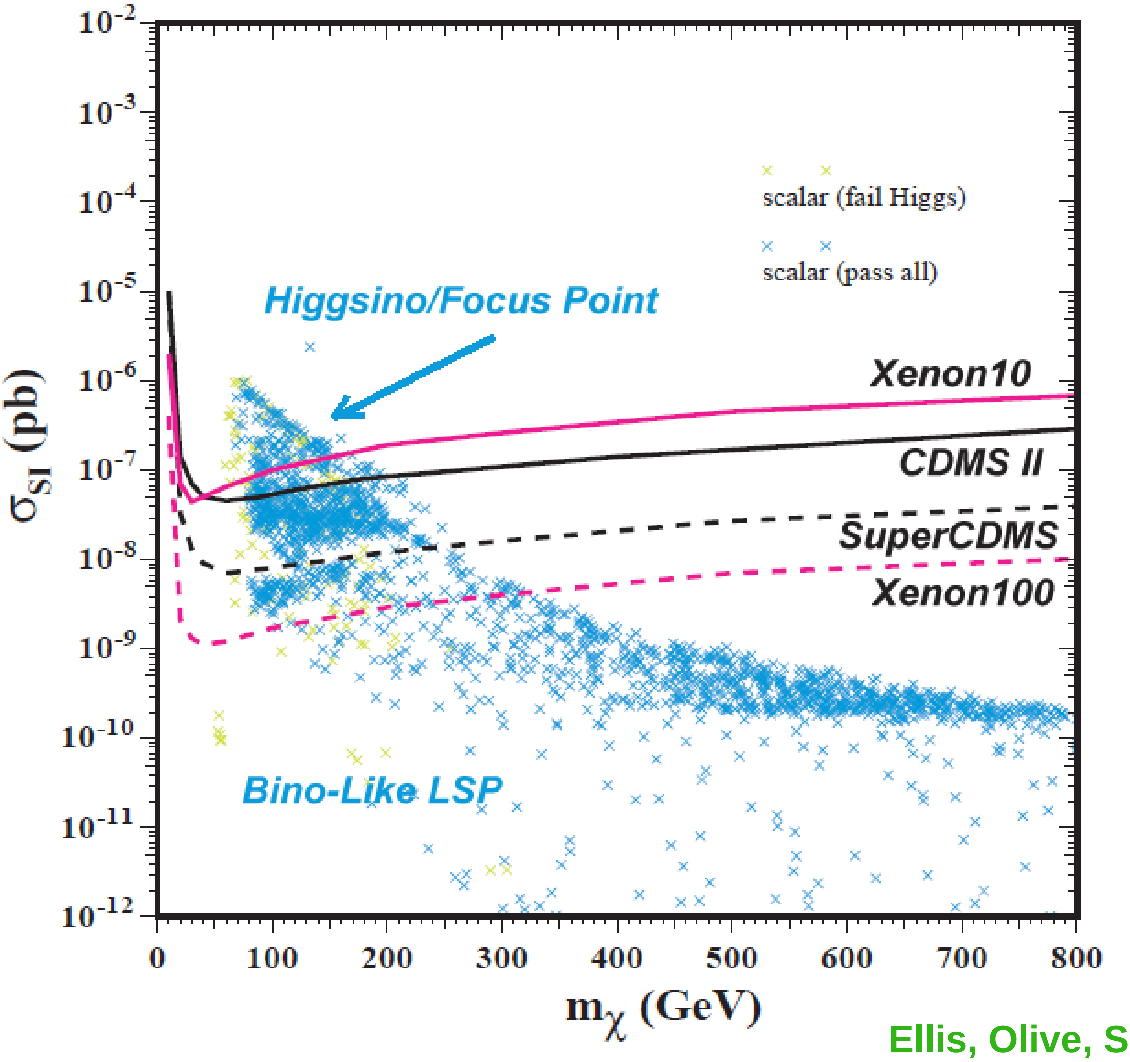
Xenon100 Collaboration, arXiv:1005.0380

Direct Detection in mSUGRA

⇒ Large direction detection rate implies Higgs exchange dominates

Hooper & Taylor, JCAP **0703** (2007) 017

$$\sigma_{\chi N} \propto |N_{11}|^2 |N_{13}|^2 \left(\frac{\tan\beta}{m_A}\right)^2$$



Ellis, Olive, Sandick, arXiv:0905.0107

Positron Excess

- Decade's worth of data suggests an excess of positrons in cosmic ray data

Cirelli et al., NPB **800** (2008) 204; **813** (2009) 1

$$\Phi_{\bar{e}}(E) \simeq \frac{\tau_E B_{\bar{e}} c}{8\pi b(E)} \frac{\rho_\chi^2(r = R_0)}{m^2_{\widetilde{N}_1}} F(E)\,, \quad b(E) = 1\,\mathrm{GeV}\left(\frac{E}{1\,\mathrm{GeV}}\right)^2$$

$$F(E) = \int_E^{M_{\widetilde{N}_1}} dE' \sum_k \langle\sigma v\rangle^k_{\mathrm{halo}} \frac{dN^k_{\bar{e}}}{dE'} \cdot \mathcal{I}(E, E')$$

  - ⋆ $B_{\bar{e}}$ = boost factor, $\tau_E = \tau \times 10^{16}\,\mathrm{sec}$ is the diffusion time scale and $\mathcal{I}(E, E')$ is the halo function
  - ⋆ For SUSY models, most important final state is usually $k = W^+W^-$

- Best fits require $\langle\sigma v\rangle_{WW} \simeq 2 \times 10^{-24}\,\mathrm{cm}^3/\mathrm{s}$ and prefer NFW "min" profile

  - ⋆ Former easy to achieve if LSP significantly wino-like

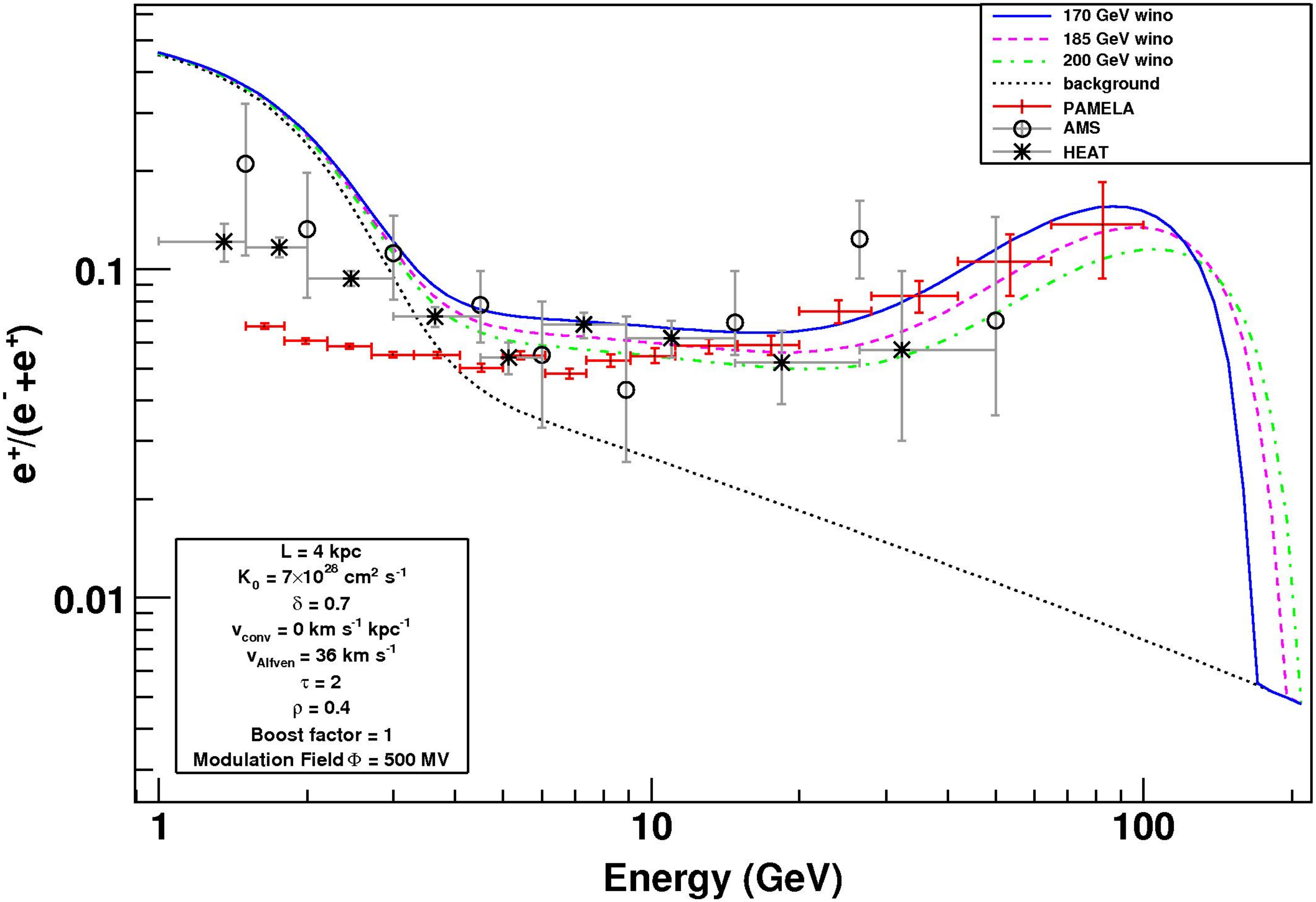
Kane, L. Wang & Wells, PRD **65** (2002) 057701
Grajek, Kane, Phalen, Pierce, Watson, PRD **79** (2009) 043506
Kane, Lu, Watson, PLB **681** (2009) 151

SUSY Fits to Positron Flux Measurements

HEAT Collaboration, Astrophys. J. **559** (2001) 296; PRL **93** (2004) 241102

AMS Collaboration, PLB **646** (2007) 145

PAMELA Collaboration, Nature **458** (2009) 607; PRL **102** (2009) 051101



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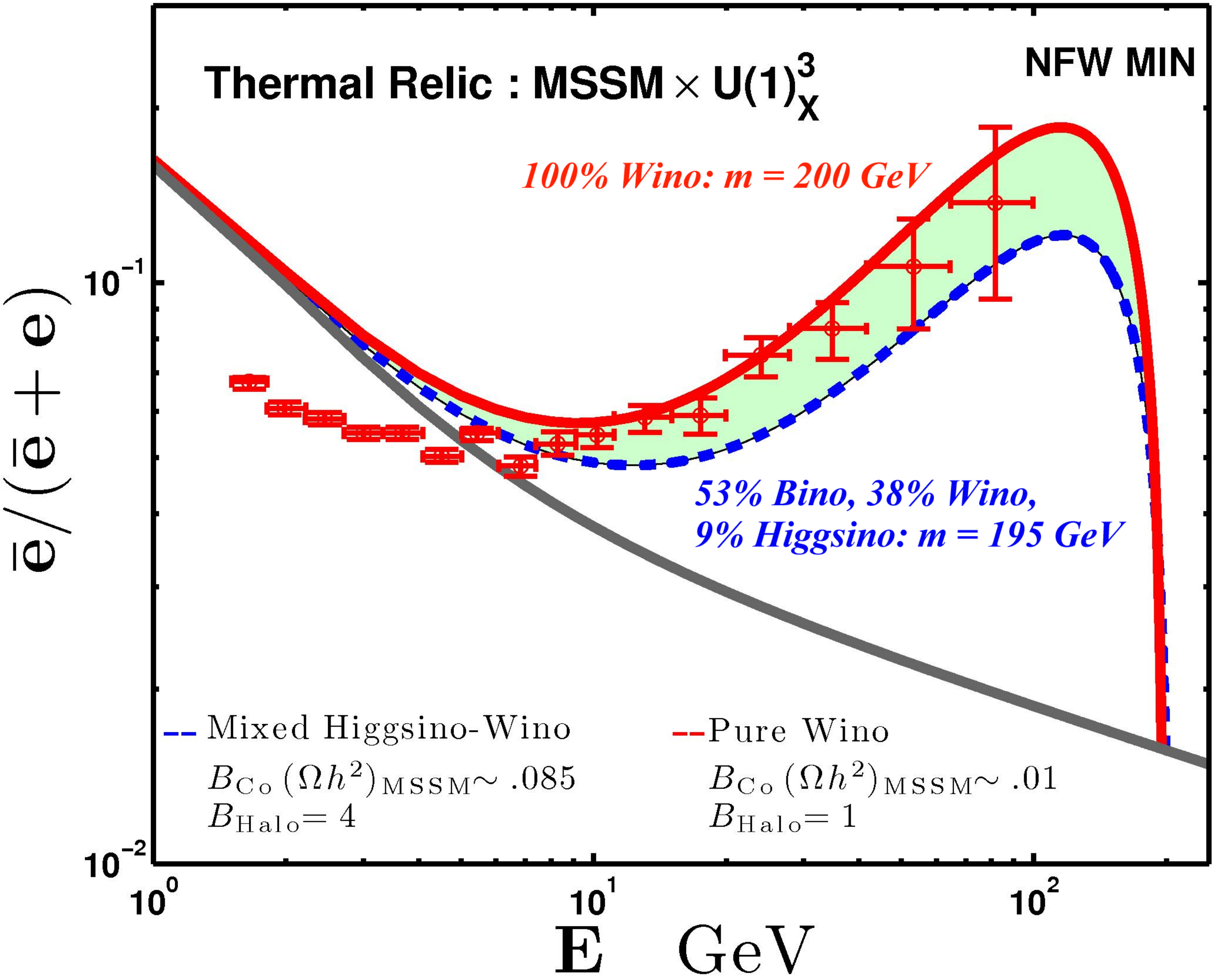
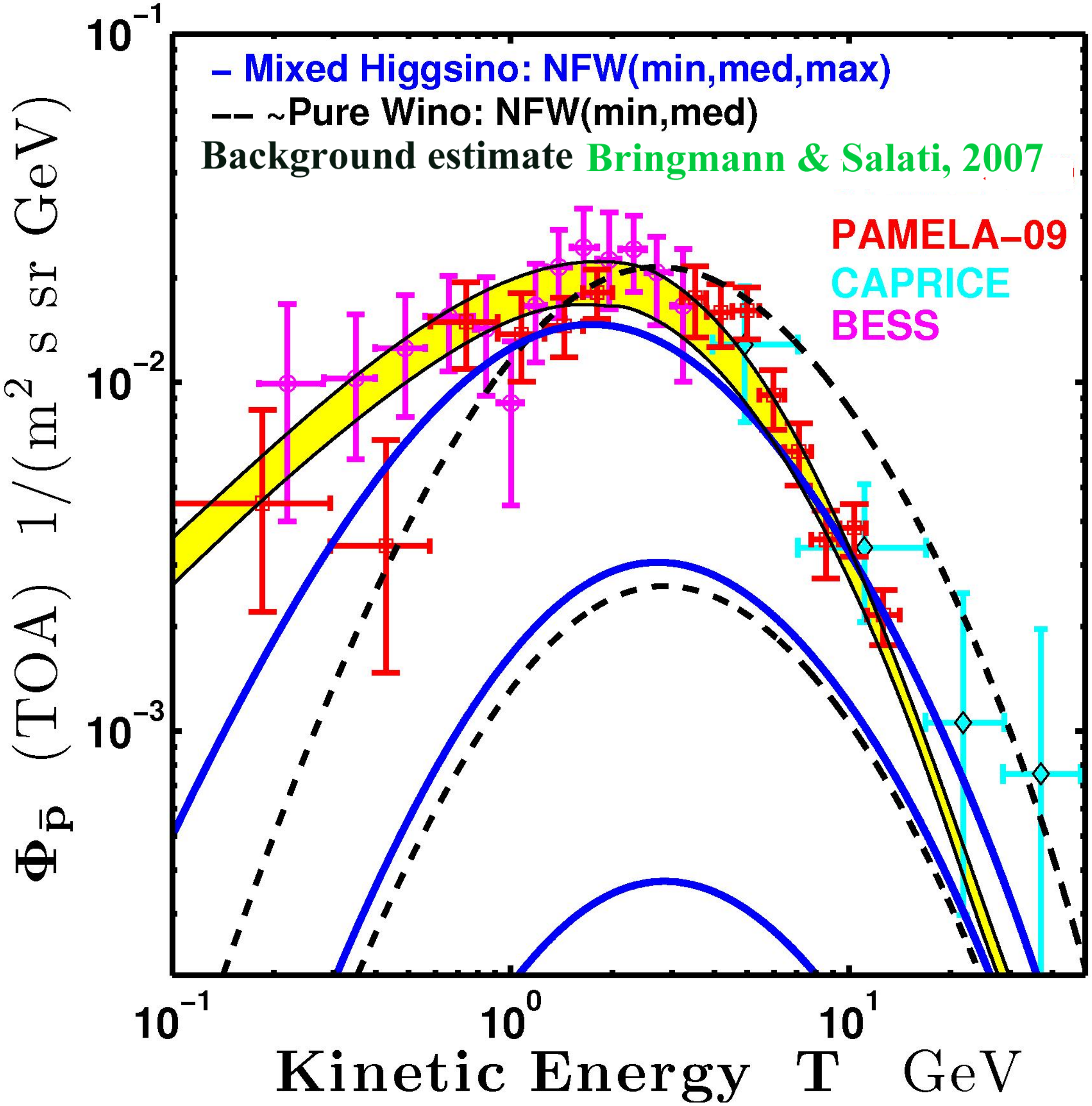


⇒ Pure wino not necessary – but must compensate with $B_{\bar{e}}$ (here $B_{\rm HALO}$)

Feldman, Liu, Nath, BDN, PRD **D80** (2009) 075001

What About Anti-protons?

BESS Collaboration, PRL **84** (2000) 1078; **CAPRICE Collaboration**, Astrophys. J. **561** (2001) 787

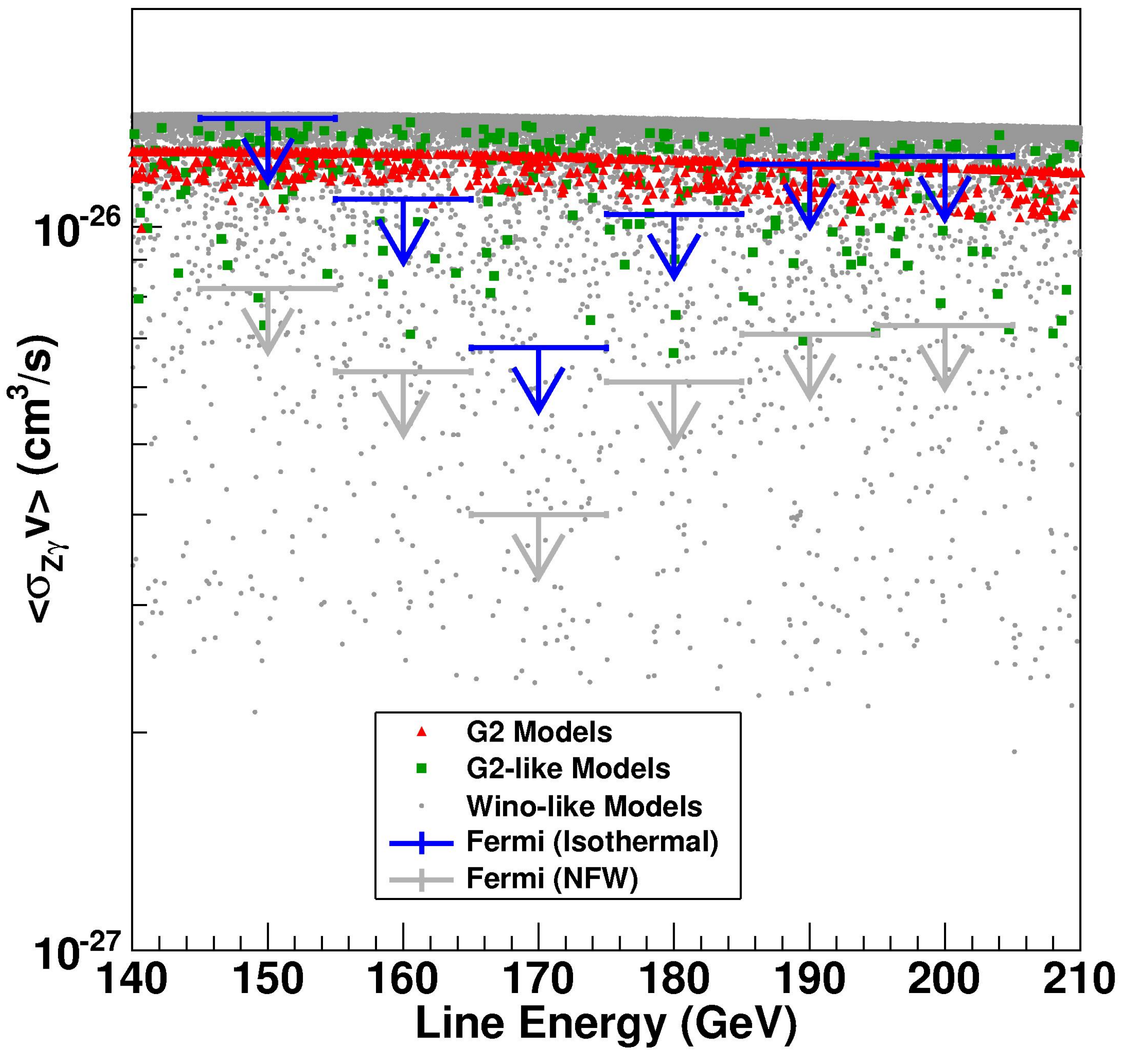


⇒ Higgsino has no problems; Wino OK for NFW “min” and “med” halo profiles

Monochromatic Signals

⇒ Monochromatic gamma ray signals a “smoking gun” for dark matter

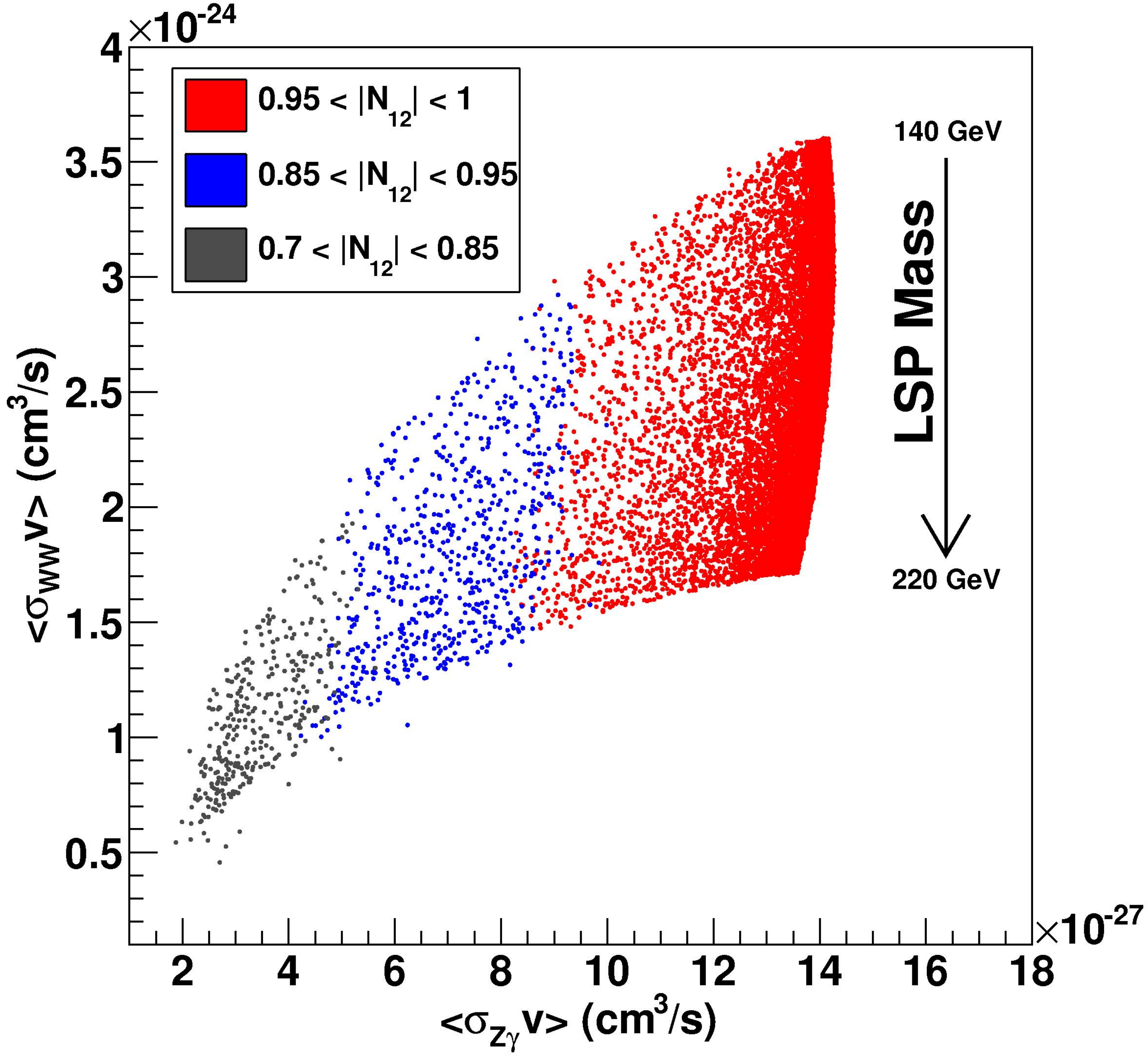
Fermi-LAT Collaboration, arXiv: 1001.4531



- Loop-induced diagrams provide annihilation into $\gamma\gamma$ and γZ final states
- Monoenergetic signals with $E_{\gamma\gamma} = m_\chi$ and $E_{\gamma Z} = m_\chi - M_Z^2/4m_\chi$
- Easy to pick out over background, but branching fractions reduce rate by factors of 10^3 - 10^4
- Pure-wino models capable of getting PAMELA correct in trouble!

Feldman, Kane, Lu, BDN, PLB **687** (2010) 363

Photons versus Positrons



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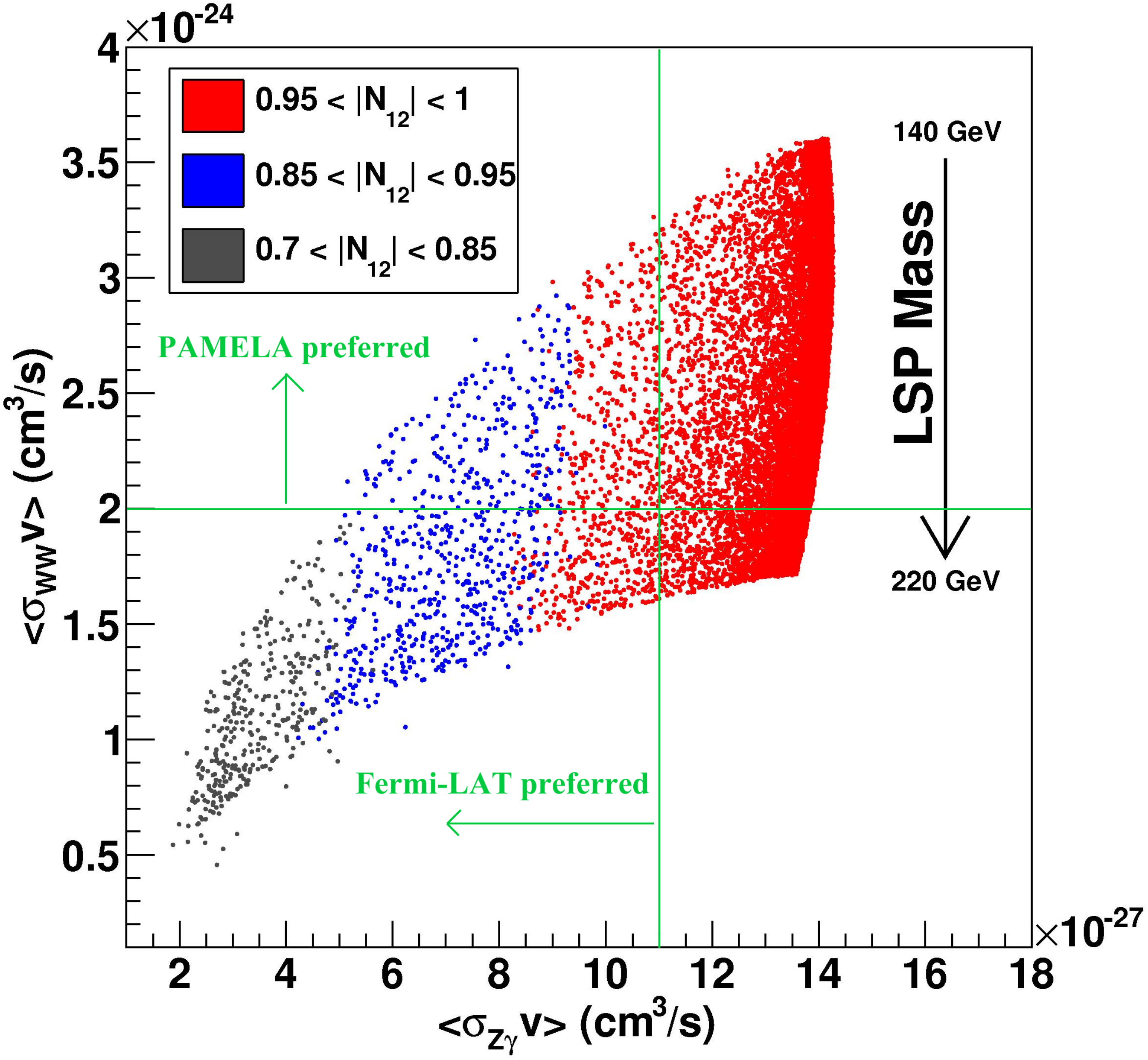


Non-Universal Gauginos and String-Motivated Models

$\Rightarrow$ PAMELA preferred models with potentially large direct detection rates prefer non-universal gaugino masses

The mirage pattern (competition between tree and anomaly-mediated contributions to soft masses) appears in a number of phenomenologically successful string constructions:

- Kähler stabilized heterotic string models

Binetruy, Gaillard, Wu, **NPB 481** (1996) 109
Gaillard and BDN, **IJMP A22** (2007) 1451

- Type-IIB flux compactifications with anti-D_3 branes

Kachru, Kallosh, Linde, Trivedi, **PRD 68** (2003) 046005
Choi, Falkowski, Nilles, Olechowski, **NPB 718** (2005) 113

- M-theory compactified on fluxless G_2 manifolds

Acharya, Kane, et al.,
PRL 97(2006) 191601
PRD 76 (2007) 126010
PRD 78 (2008) 065038

$\Rightarrow$ Common features:

- Single modulus stabilized by gaugino condensation
- Kähler potential for this modulus substantially altered from tree-level value
- Tuning of cosmological constant ($\langle V \rangle$) to zero by adjusting parameters

LHC Implications

mSUGRA Stau Coannihilation Region

⇒ Most promising mSUGRA scenario: stau co-annihilation region

Arnowitt, Dutta, Kamon, et al., PLB **639** (2006) 46; PLB **649** (2007) 73; PRL **100** (2008) 231802

- Physical hierarchies very stable in this region

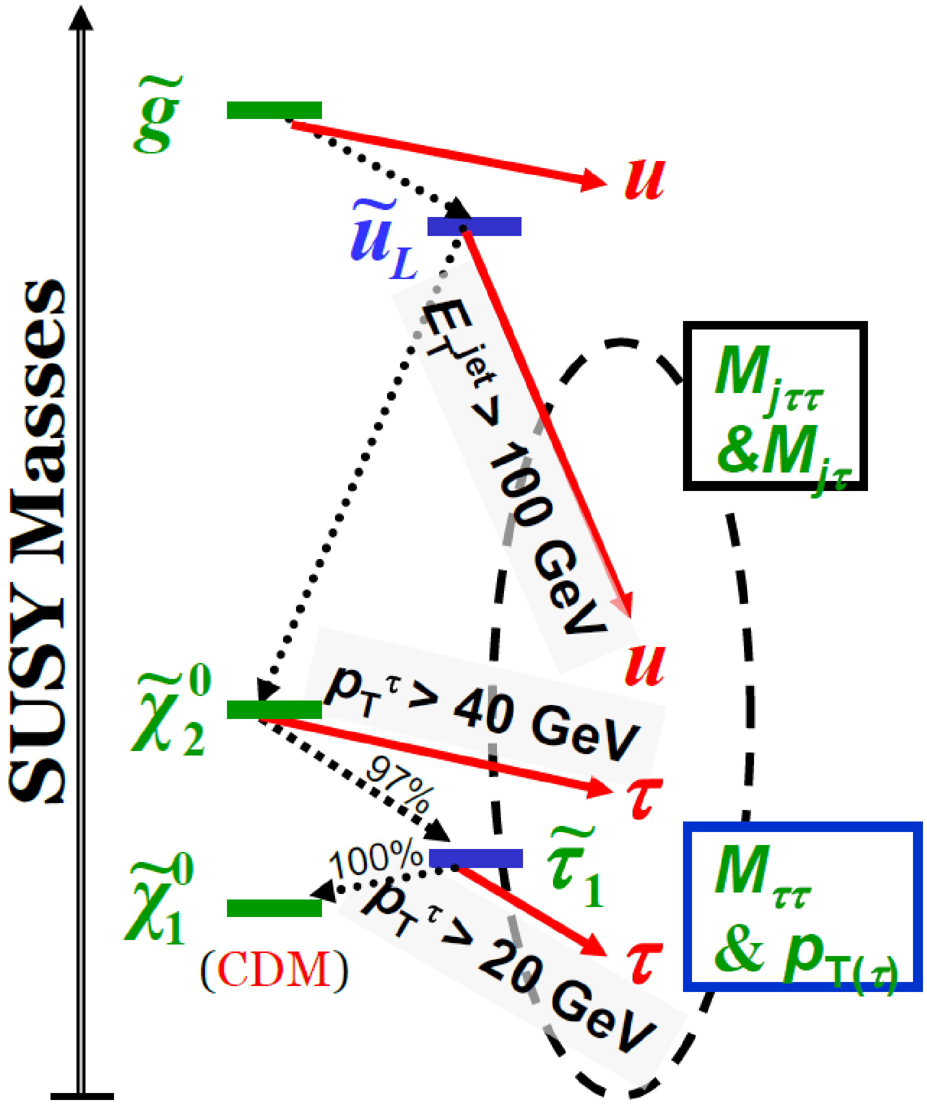
  Konar et al., PRL **105** (2010) 221801

- Characterized by $m_{N_2} > m_{\tilde{\tau}_1} > m_{N_1}$ and $\Delta M = m_{\tilde{\tau}_1} - m_{N_1} = 5 - 15\,\mathrm{GeV}$

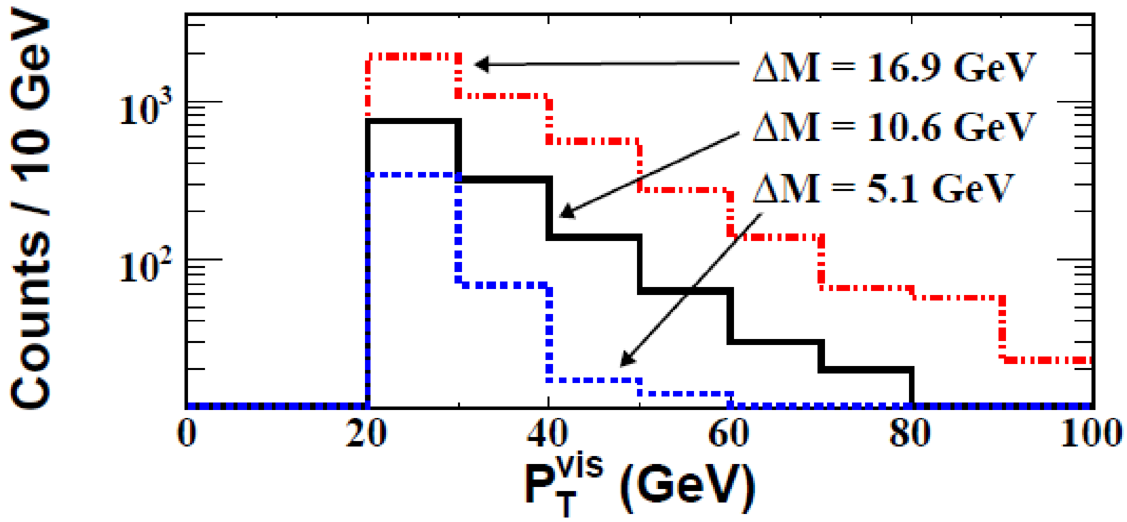
- Main production mode: $\tilde{g}\tilde{q}$ $(\sigma_{\mathrm{SUSY}} \sim 10\,\mathrm{fb})$

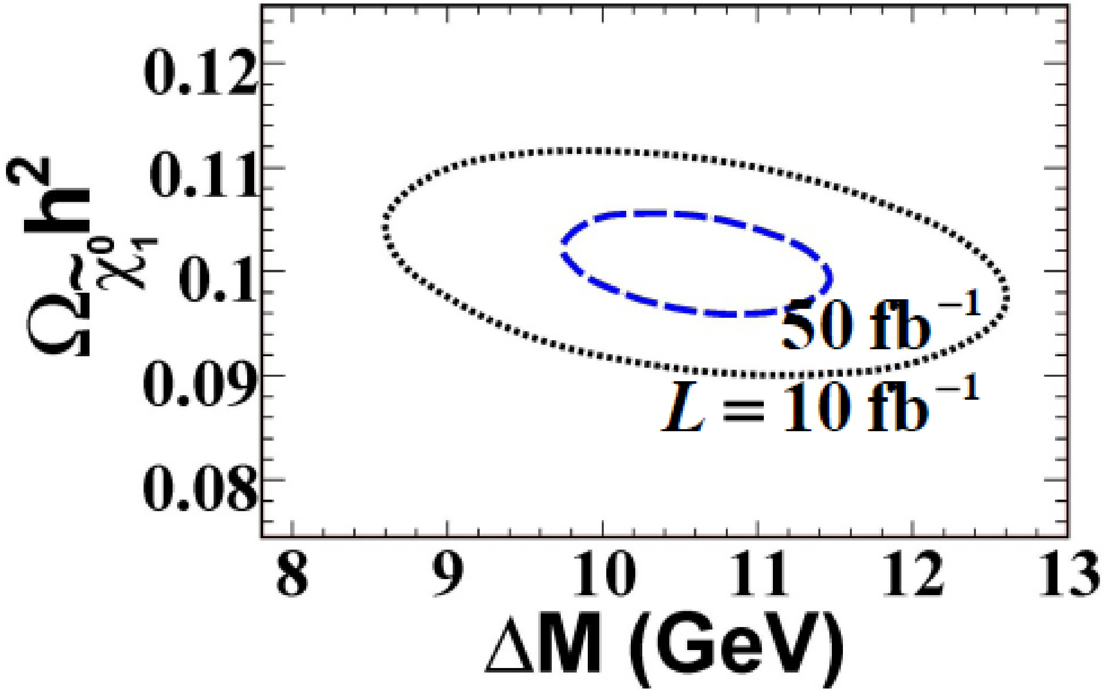
- Discovery channels:
  - 4^+ jets + $\not{E}_T$
  - 2^+ jets + $2\,\tau$ + $\not{E}_T$

- $\tilde{\chi}_2^0 \to \tau\tilde{\tau}$ 97% of time!
  - Need 50% efficiency or better for hadronically-decaying taus
  - Second tau likely to be very soft



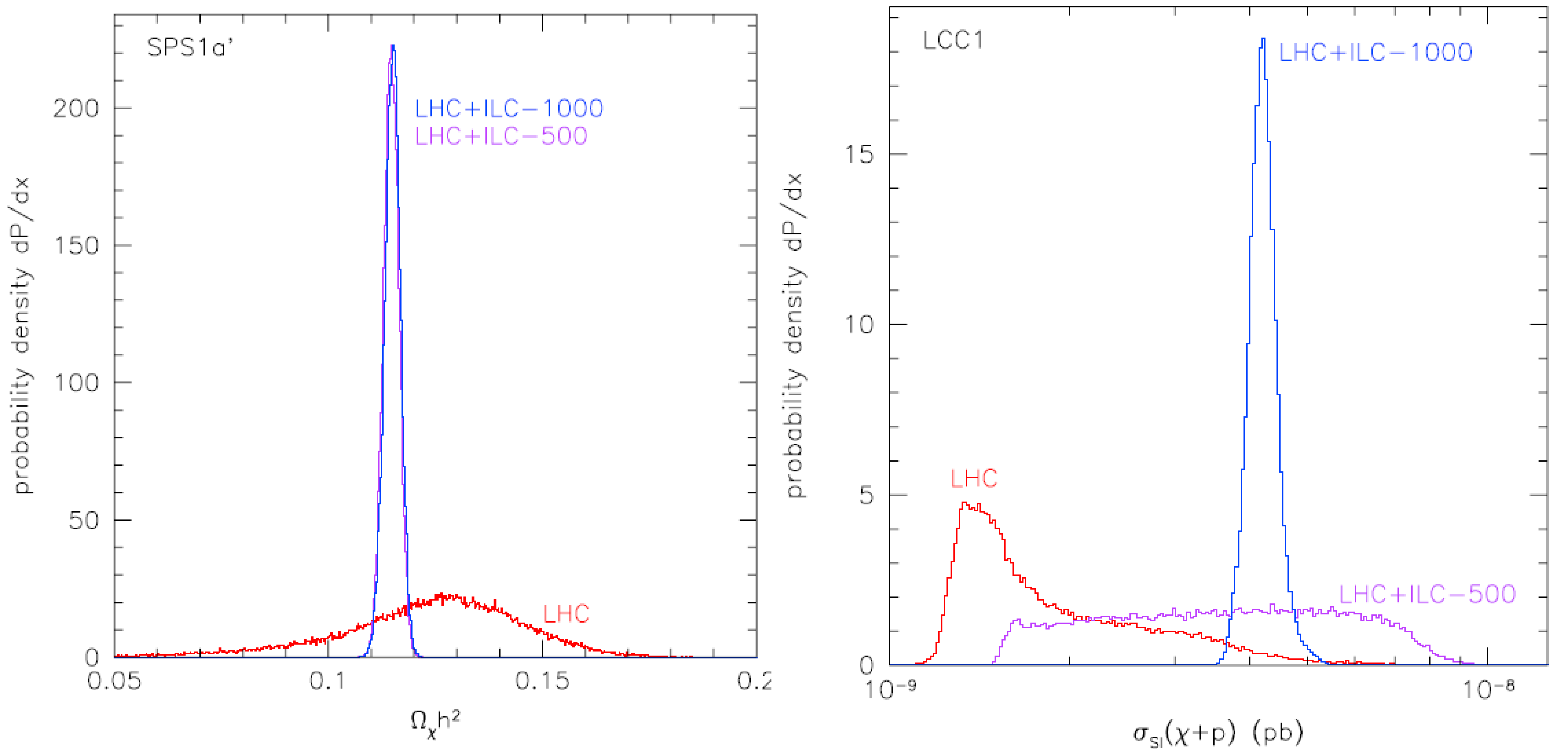
mSUGRA Stau Coannihilation Region





- Global fit to extract four mSUGRA parameters from the kinematics of dominant processes
    - Slope of p_T for softer tau
    - Di-tau invariant mass
    - Jet + ditau invariant mass
    - Jet + single tau invariant mass (two of these)
    - M_{eff} for 4^+ jet events (b-jet veto)
    - M^b_{eff} for 4^+ jet events (leading jet b-tagged)
- Invert to obtain m_0, $m_{1/2}$, A_0 and $\tan\beta$
- Use these as inputs (with uncertainties) to compute thermal relic abundance

Using LHC to Predict (Cross-Check) Dark Matter



⇒ Numerous studies of LHC/ILC influence on making dark matter predictions in mSUGRA – much fewer in generic SUSY models

Baltz, Battaglia, Peskin, Wizansky, PRD **74** (2006) 103521
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, arXiv:1008.1783
Bertone, Cerdeno, Fornasa, Ruiz de Austri, Trotta, PRD **82** (2010) 055008
Konar, Kong, Matchev, Perelstein, New J. Physics **11** (2009) 105004
Chung, Everett, Kong, Matchev, JHEP **0710** (2007) 016
Nojiri, Polesello, Tovey, JHEP **0603** (2006) 063
Allanach, Bellanger, Boudjema, Pukhov, JHEP **0412** (2004) 020
Birkedal, Matchev, Perelstein, PRD **70** (2004) 077701

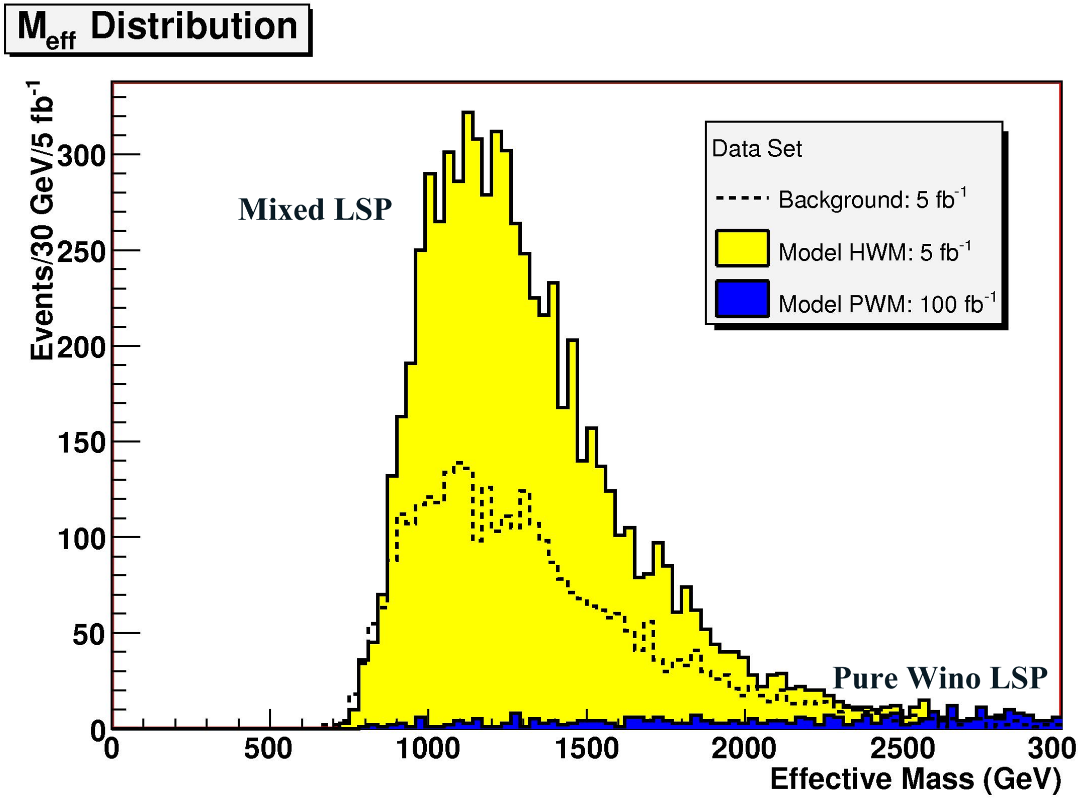
Benchmark Models I: PAMELA Examples

Feldman, Liu, Nath, BDN, PRD **80** (2009) 075001

Mass	Mixed LSP	Pure Wino LSP
$m_{\tilde{N}_1}$	198.9	195.2
$m_{\tilde{N}_2}$	217.0	357.0
$m_{\tilde{N}_3}$	429.9	1025
$m_{\tilde{N}_4}$	451.3	1029
$m_{\tilde{C}_1}$	208.8	195.5
$m_{\tilde{C}_2}$	448.6	1036
$m_{\tilde{t}_1}$	648.5	1516
$m_{\tilde{t}_2}$	866.8	1749
$m_{\tilde{b}_1}$	841.4	1729
$m_{\tilde{b}_2}$	970.2	1902
$m_{\tilde{\tau}_1}$	817.7	1011
$m_{\tilde{\tau}_2}$	822.8	1041
$m_{\tilde{g}}$	707.1	1929

	Mixed LSP		Pure Wino LSP	
Signature	Events	$S/\sqrt{B}$	Events	$S/\sqrt{B}$
Multijets	8766	183.74	50	1.05
Lepton + jets	2450	32.25	26	0.34
OS dileptons + jets	110	6.39	4	0.23
SS dileptons + jets	60	11.77	0	NA
Trileptons + jets	14	2.47	0	NA

- Big impact of gluino mass in number of multijet events
- Small mass gaps significantly reduce number of leptonic events



10 fb^{-1} **at** $\sqrt{s} = 14\,\mathrm{TeV}$

Benchmark Models II: CDMS-II Examples

Holmes and BDN, PRD **81** (2010) 055002

Point	C	D	E
δ_2	-0.6	0.82	-0.47
δ_3	-0.3	-0.35	-0.3
B%	0.3%	5.4%	40.9%
W%	95.8%	0.5%	53.0%
H%	3.9%	94.1%	6.1%
$m_{\tilde{N}_1}$	175	112	230
$m_{\tilde{N}_2}$	235	130	239
$m_{\tilde{N}_3}$	505	252	504
$m_{\tilde{N}_4}$	513	846	515
$m_{\tilde{C}_1}$	175	123	234
$m_{\tilde{C}_2}$	514	846	515
$m_{\tilde{g}}$	952	890	951
$m_{\tilde{t}_1}$	719	544	709
$m_{\tilde{t}_2}$	862	964	865
$m_{\tilde{b}_1}$	809	766	812
$m_{\tilde{b}_2}$	874	943	871
$m_{\tilde{\tau}_1}$	344	338	352
$m_{\tilde{\tau}_2}$	414	752	424
m_h	113	114	113
$\sigma_{\rm SUSY}^{7\,\rm TeV}$ (pb)	1.2	2.7	0.4
$\sigma_{\rm SUSY}^{10\,\rm TeV}$ (pb)	2.5	5.1	1.3
$\sigma_{\rm SUSY}^{14\,\rm TeV}$ (pb)	5.7	10.0	3.7

- All models can produce signals at CDMS II – C & E can fit PAMELA data as well
- Signal simulated: 1 fb^{-1} at $\sqrt{s} = 14\,\rm TeV$
- Again, healthy multijets but disappearance of leptonic events

Numbers of Events

Point	C	D	E
Multijets	402	436	298
1ℓ + jets	202	310	111
OS 2ℓ + jets	12	45	7
SS 2ℓ + jets	6	16	3
3ℓ + jets	4	6	1

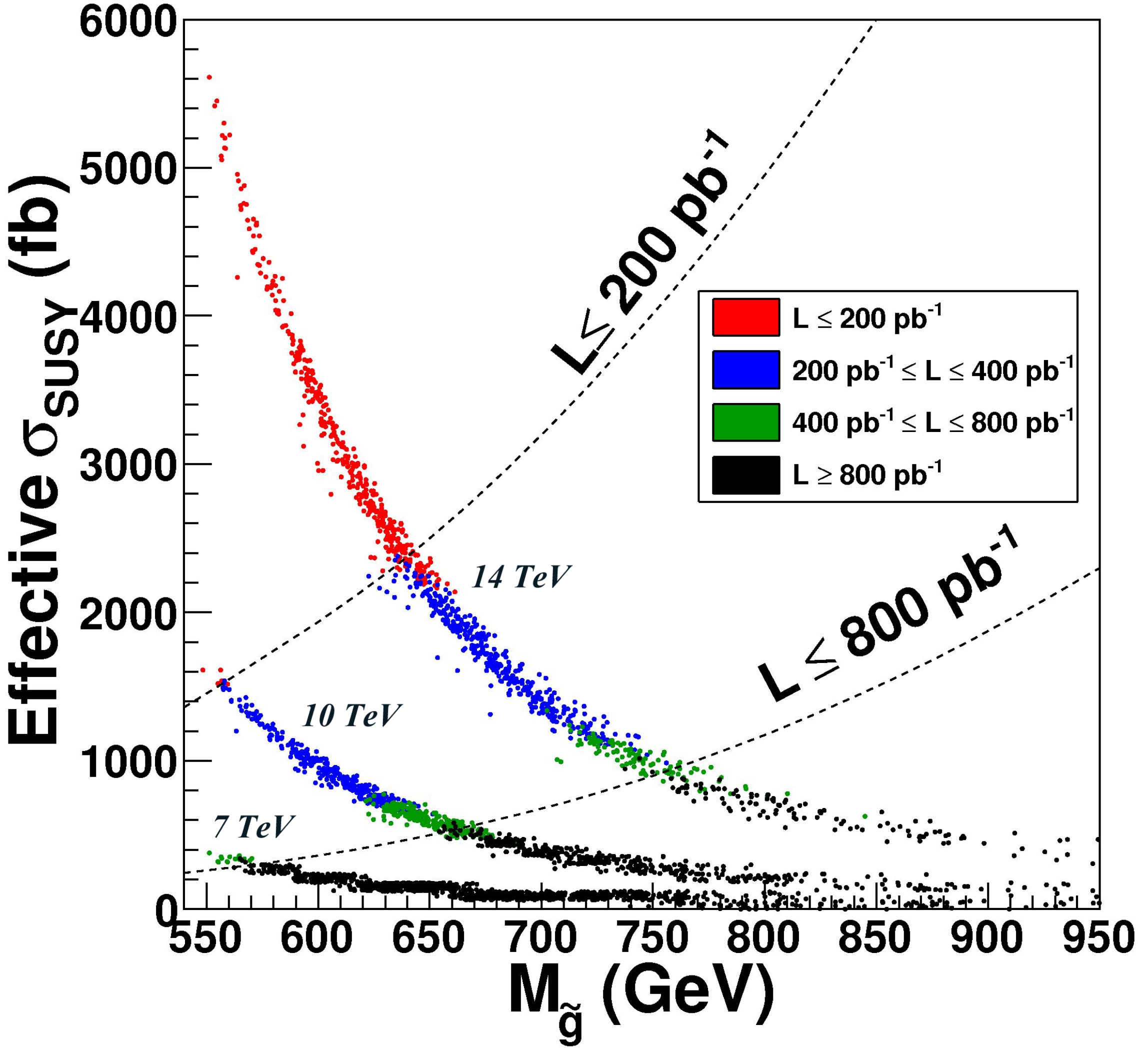
Significance $S/\sqrt{B}$

Point	C	D	E
Multijets	26.9	29.1	19.9
1ℓ + jets	8.2	12.5	4.5
OS 2ℓ + jets	2.0	7.4	1.2
SS 2ℓ + jets	2.3	6.0	1.1
3ℓ + jets	1.6	2.5	0.4

General PAMELA-consistent Models

⇒ General rule: Discovery of DM-motivated models needs a light gluino

Feldman, Kane, Lu, BDN, PLB **687** (2010) 363

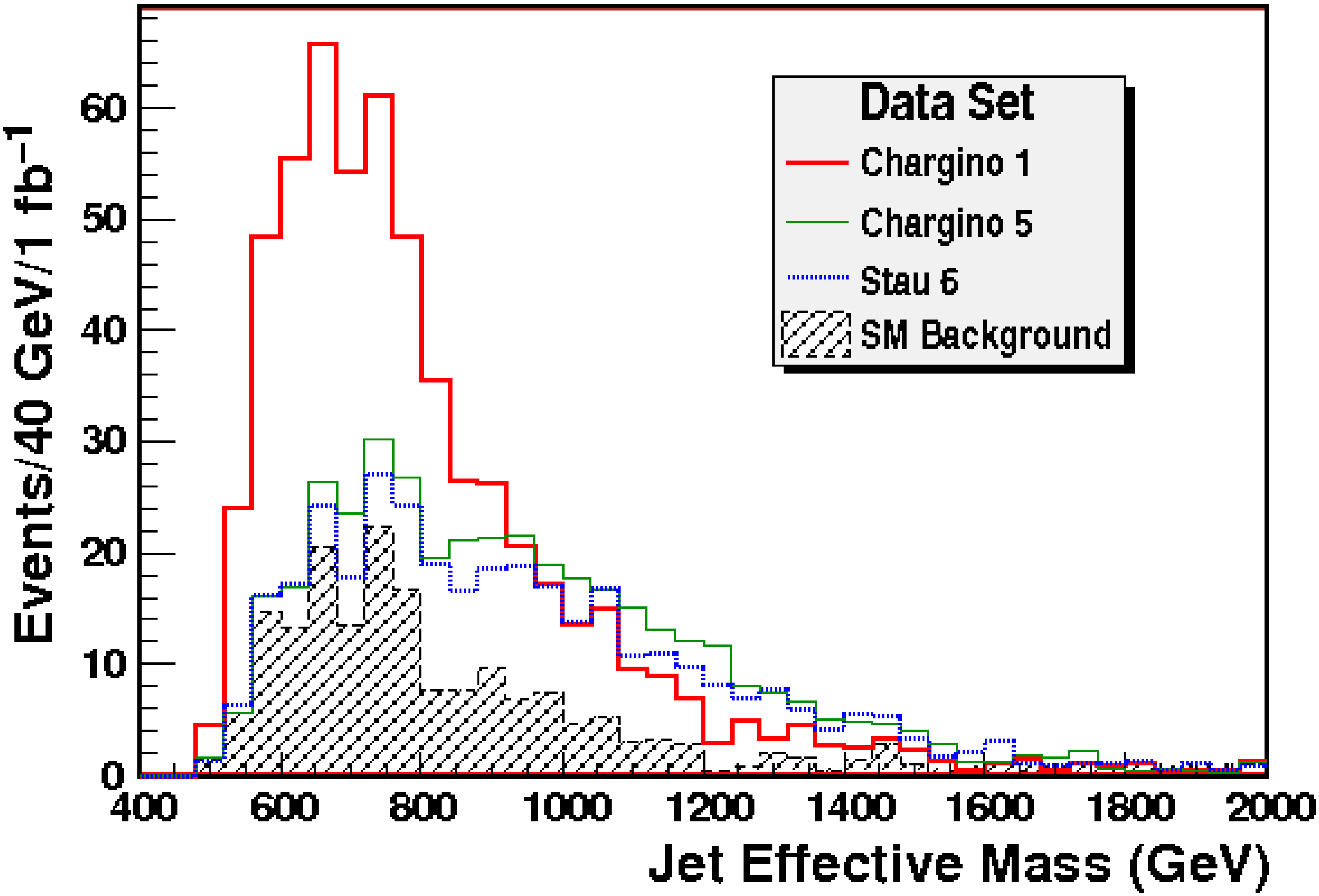


- High wino-content (for PAMELA) implies small mass gap between $\widetilde{C}_1/\widetilde{N}_2$ and LSP
- Result: major reduction in expected leptonic SUSY signatures
- Increasing Higgsino content to match CDMS (and photon data) requires a light gluino
- Result: multijet signals may be our only handle

⇒ We will need to learn how to do more with less!
Must look for new signatures targeted to non-universalities in gaugino sector

Prospects for Early LHC Discovery

Altunkaynak, Holmes, Nath, BDN & Peim, arXiv:1008.3423



⇒ All three are mirage-type models; “Stau 6” is in the PAMELA-preferred regime

Epilogue: Dark Matter and the LHC Inverse Problem

The “LHC Inverse Problem” – in One Slide

Arkani-Hamed, Kane, Thaler & Wang, “Supersymmetry and the LHC inverse problem,” JHEP **0608**, 070 (2006)

⇒ Basic premise: multiple SUSY parameter sets likely to fit the LHC data

- After many years of data-taking at LHC we have a well-defined “signature space” bounded only be experimental errors

- A global fit to a “minimal” multi-parameter MSSM model is performed

$$\left\{ \begin{array}{c} \tan\beta,\ \mu,\ M_1,\ M_2,\ M_3 \\ m_{Q_{1,2}}, m_{U_{1,2}}, m_{D_{1,2}}, m_{L_{1,2}}, m_{E_{1,2}} \\ m_{Q_3}, m_{U_3}, m_{D_3}, m_{L_3}, m_{E_3} \\ m_A,\ A_t,\ A_b,\ A_\tau \end{array} \right\}$$

- Several (isolated) points in “parameter space” will be good fits to the observed data

⇒ This conjecture was explicitly verified by brute force

- 45,000 SUSY models sampled and 10 fb^{-1} of simulated data generated

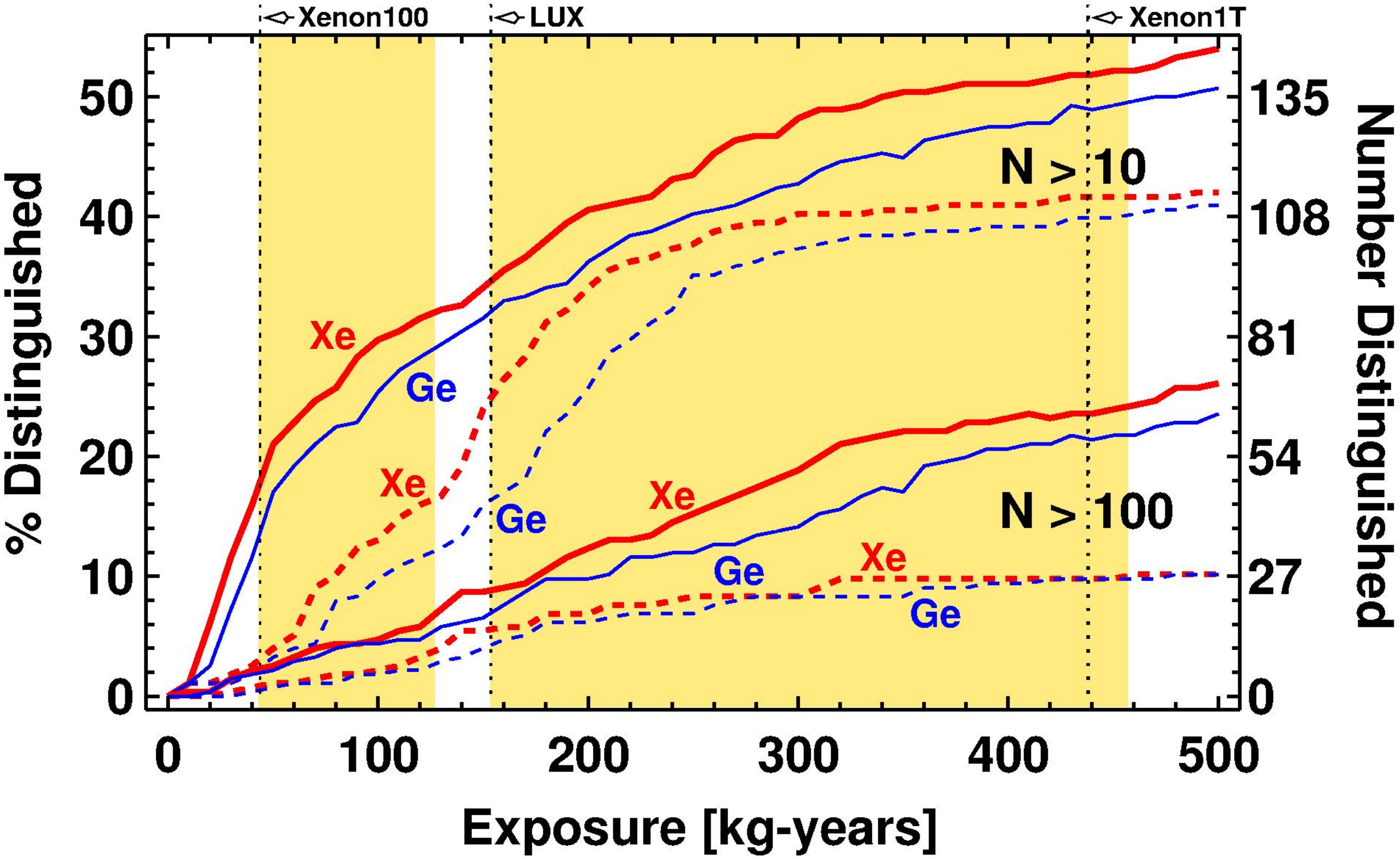
- Out of 45,000 test models they found 276 degenerate pairs

Direct Detection and SUSY Degeneracies

⇒ Requirements to consider a degenerate pair resolved:

Altunkaynak, Holmes, BDN, JHEP **0810** (2008) 013

1. Counts N_A and N_B (N_i = rate$_i$ × exposure) must *both* exceed $N_{\rm min}$ events
2. The two quantities N_A and N_B must differ by at least $5\,\sigma^{AB}$
3. For the moment assume statistical errors only: $\sigma^{AB} = \sqrt{N_A + N_B}$



Summary

- Dark matter hints may disfavor pure Bino LSP (i.e. mSUGRA)
- PAMELA needs wino predominance; CDMS/photons want strong Higgsino admixture
- Such models find a natural home in many (all?) semi-realistic string constructions
- Likely that mass gaps between $\widetilde{C}_1/\widetilde{N}_2$ and LSP small, so leptonic signatures a bust
- Will need to learn to do more with jet-based signatures and hope the gluino is lighter than in mSUGRA models

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$\Rightarrow$ *Gaugino sector is truly a window on the high-energy world:*
we may be on the verge of revolutionary discoveries!