The Heart of Darkness

Neutralino Dark Matter, the Zeptobarn Scale, and Implications for Supersymmetric Models

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Outline

Dark Matter Background

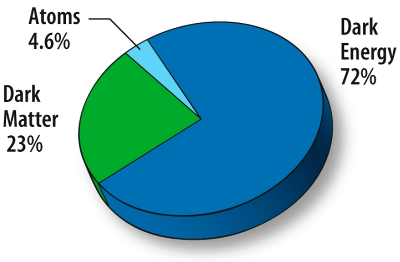
Characteristic Cross-Section for Neutralino Dark Matter

Neutralinos in the Focus Point

Isospin Violating Dark Matter

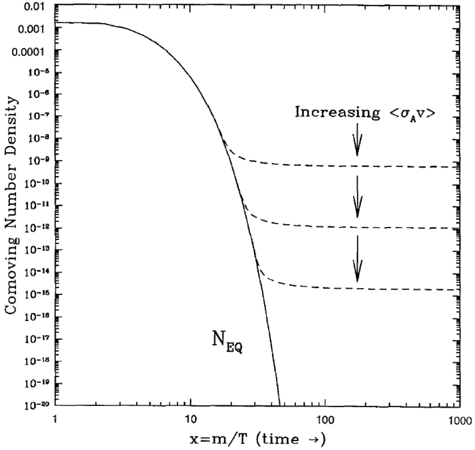
Dark Matter

- Dark matter composes $\sim$ 23% of the energy density of the universe
- Stable and at least somewhat massive
- All non-controversial evidence is gravitational
- Dark matter is dark!



NASA - WMAP Science Team

The WIMP Miracle



Kolb & Turner

- All "light" particles are in thermal equilibrium in the early universe
- Massive stable particles "freeze out" of equilibrium as the universe cools
- Characteristic "relic density" based on annihilation cross-section
- For a DM particle X,

$$\Omega_{\rm DM} \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

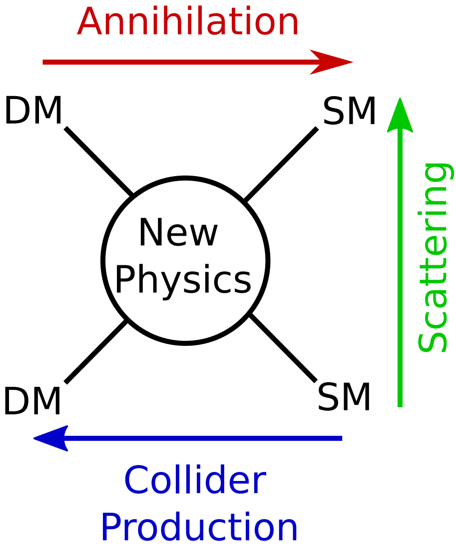
$$m_X \sim 100 \text{ GeV}, \; g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$$

Experimental Probes of WIMPs

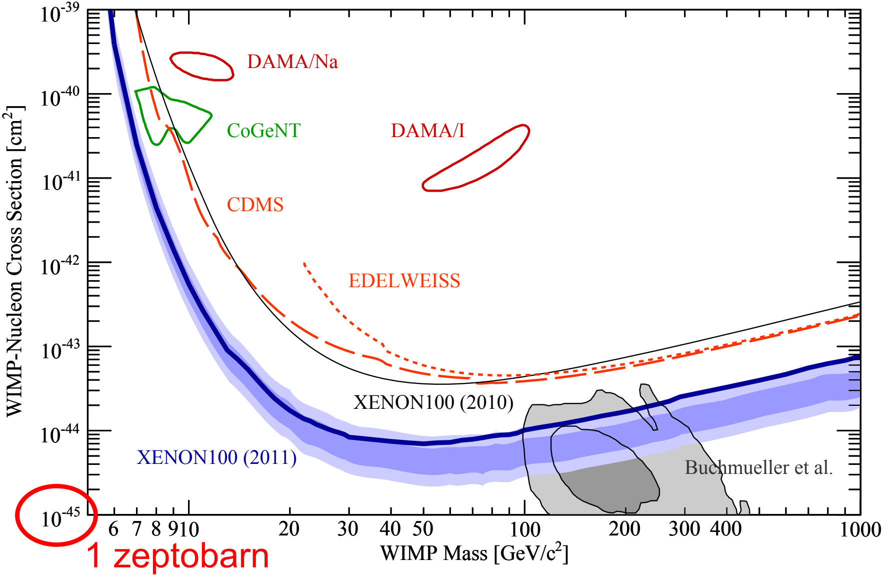
- Indirect detection of annihilation products from the halo
- Direct detection scattering off atomic nuclei
- Production at colliders

Meaningful annihilation rates in the early universe generally imply meaningful rates of annihilation, scattering, and collider production now

Spin-independent direct detection has been of particular interest recently



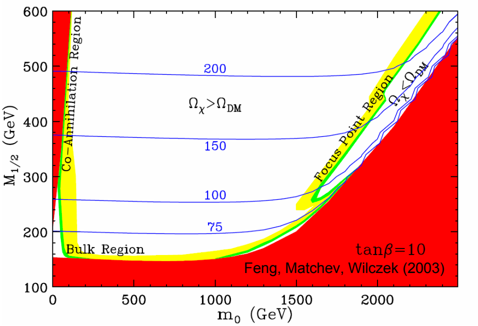
Current Status of Spin-Independent Direct Detection



XENON100 (2011)

Neutralino Dark Matter in the CMSSM

- CMSSM (mSUGRA) has 4 continuous and 1 discrete parameters (m_0, M_1, A, $\tan\beta$, sign[μ])
- Generally need to enhance annihilation for $\Omega_\chi = 0.23$
- Mass spectrum and DD predictions are non-trivial



Neutralin
Coannihi

Alvarez-Gaume, Polchinski, Wise (1983); Kane, Kolda, Roszkowski, Wells (1993); Ellis, Falk, Olive, Srednicki (2000); Feng, Matchev, Wilczek (2000); Baer, Balazs, Belyaev (2002)

Alternate Approach: Simplified Low Scale Model

We seek to find a *characteristic* neutralino cross-section in a generic low-scale model

Work with Jonathan Feng, JCAP 1105:018,2011

- Establish the existence of “generic” neutralino cross-sections
- Explain the range of neutralino cross-section without dependence on high-energy parameter space

So what does “characteristic” mean anyway?

- Is the possibility of imminent discovery well-motivated?
- At what point, if any, are the implications of no signals profound for the SUSY parameter space?

Model Framework

We work in a low-scale framework based on parameters defined at the weak scale

Mandic, Pierce, Murayama, Gondolo (2002)
Berger, Gainer, Hewett, Rizzo (2009)

$$\tilde{m}, M_1, \mu, m_A, \tan\beta$$

- Universal scalar mass
- Bino mass with gaugino mass unification at GUT scale
- Supersymmetric Higgs mass
- Pseudoscalar Higgs mass
  - Similar to non-unified Higgs models (NUHM)

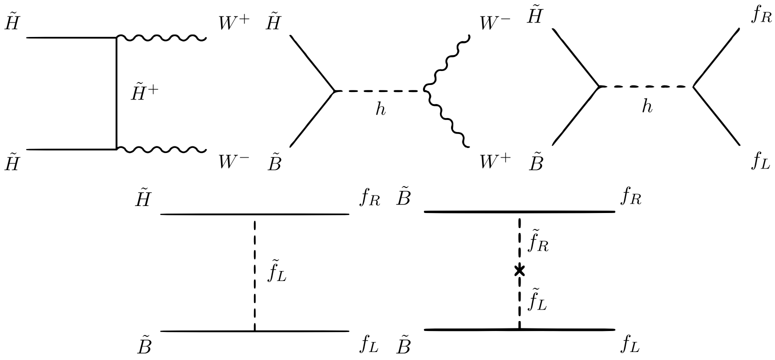
Ellis, Falk, Olive, Santoso (2002)

- Ratio of Higgs vevs, v_u/v_d

Set left-right mixing to zero
Neglect loop corrections to sfermion masses

Neutralino Annihilation

We assume the neutralino is a thermal relic with $\Omega_\chi = 0.23$



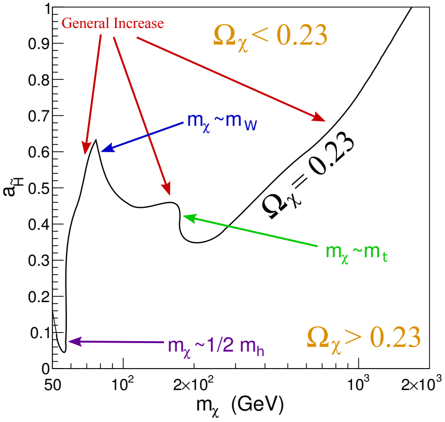
Drees and Nojiri (1992)

Most processes depend on “Higgsino-ness” of the neutralino

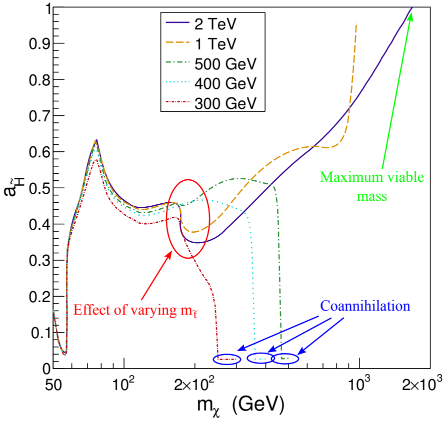
$$\chi = a_{\tilde{B}}\tilde{B} + a_{\tilde{W}}\tilde{W} + a_{\tilde{H}_u}\tilde{H}_u + a_{\tilde{H}_d}\tilde{H}_d$$

$$a_{\tilde{H}} = \sqrt{a^2_{\tilde{H}_d} + a^2_{\tilde{H}_u}}$$

Higgsino Content of the Neutralino

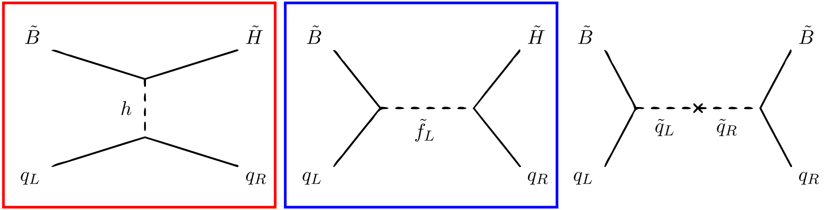


$\tilde{m} = 2$ TeV



Varying $\tilde{m}$

Neutralino Scattering



These processes produce effective quark couplings of

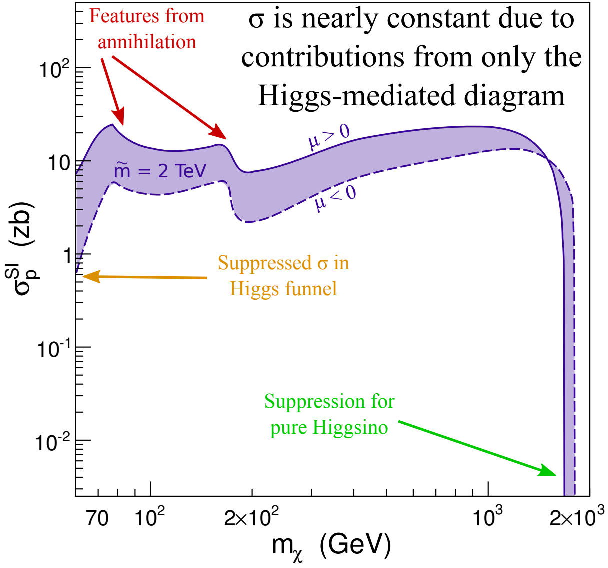
$$\lambda_u = -\frac{g^2 m_u (a_{\tilde{W}} - \tan\theta_W a_{\tilde{B}})}{4 m_W \sin\beta}\left[\frac{a_{\tilde{H}_u}}{\tilde{m}^2 - m_\chi^2} + \frac{-a_{\tilde{H}_d}\sin\beta\cos\beta + a_{\tilde{H}_u}\sin^2\beta}{m_h^2}\right]$$

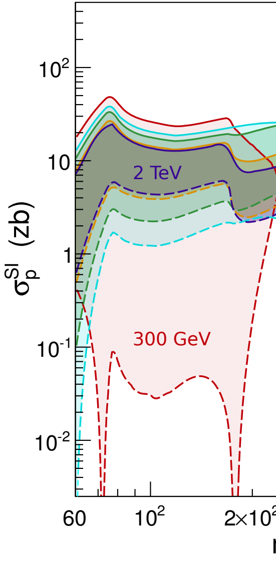
$$\lambda_d = \frac{g^2 m_d (a_{\tilde{W}} - \tan\theta_W a_{\tilde{B}})}{4 m_W \cos\beta}\left[\frac{a_{\tilde{H}_d}}{\tilde{m}^2 - m_\chi^2} + \frac{-a_{\tilde{H}_u}\sin\beta\cos\beta + a_{\tilde{H}_d}\cos^2\beta}{m_h^2}\right]$$

Ellis, Ferstl, Olive (2001)

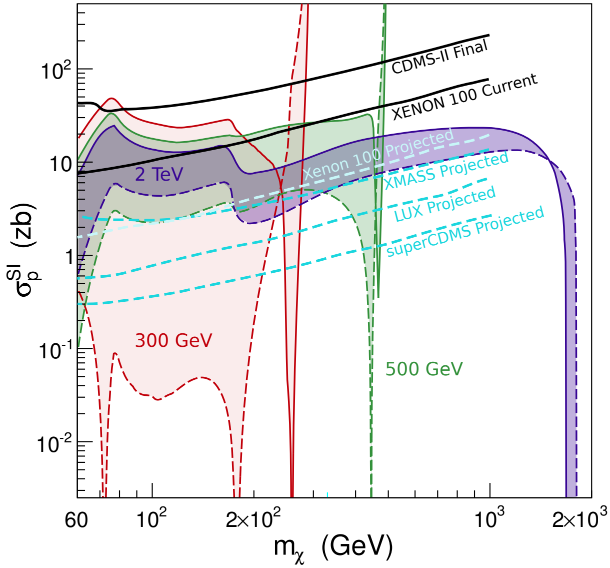
Higgs-mediated contribution has nearly fixed size

Spin-Independent Cross-Section



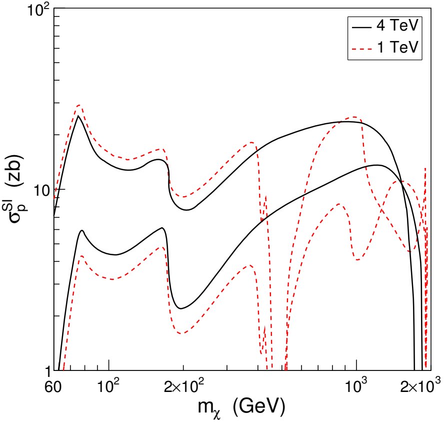


Comparison to Existing and Future Limits

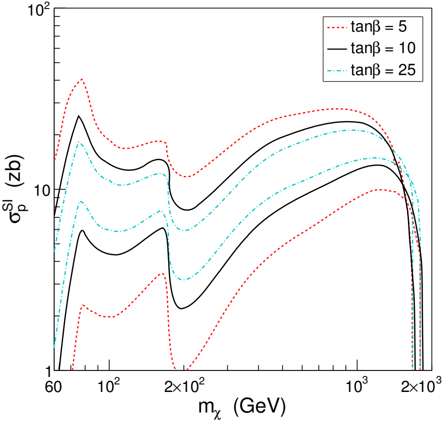


$m_A = 4$ TeV, $\tan\beta = 10$

Variations in the Higgs Potential

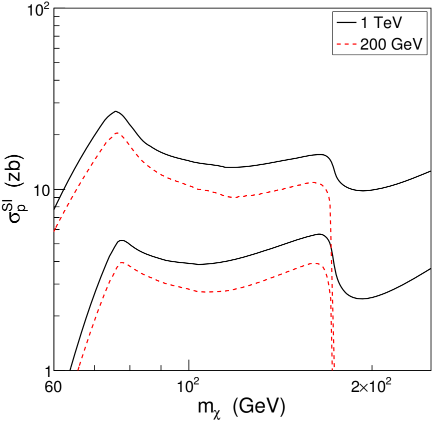


Variation of m_A

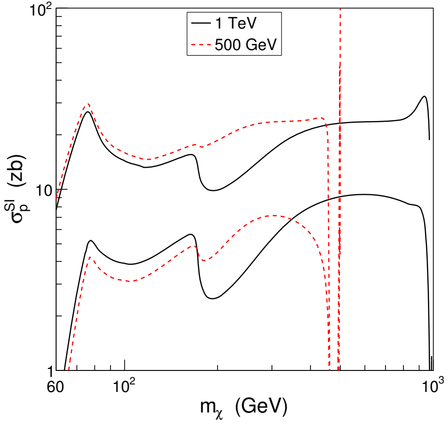


Variation of tan β

Lighter Sfermions

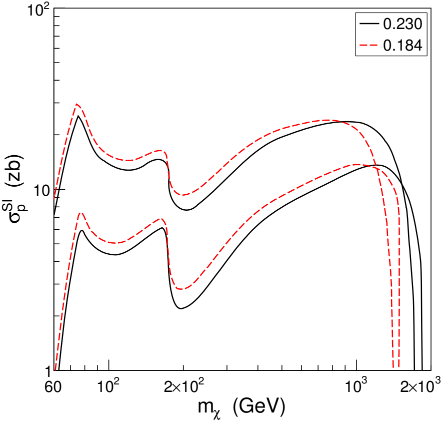


Variation in $m_{\tilde{\ell}}$

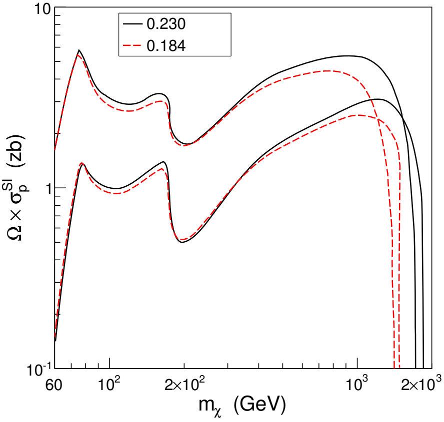


Variation in $m_{\tilde{t},\tilde{b}}$

Mixed Component Dark Matter



Cross-Section



Event Rate

Focus Point Dark Matter in the CMSSM

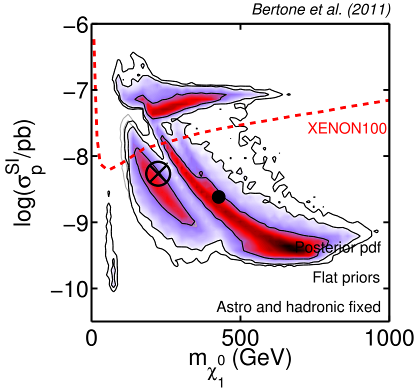
Several studies have claimed serious constraints on the MSSM from XENON100

Buchmueller et al. (hep-ph/1106.2529)

Farina, Kadastik, Raidal, Pappadopulo, Pata, Strumia (2011)

Bertone, Cerdeno, Fornasa, Ruiz de Austri, Strege, Trotta (2011)

- Select random points in CMSSM parameter space
- Perform a χ^2 analysis using known constraints
- Claim strong constraints on focus point scenarios



Viability of the Focus Point

Two major complications in this claim

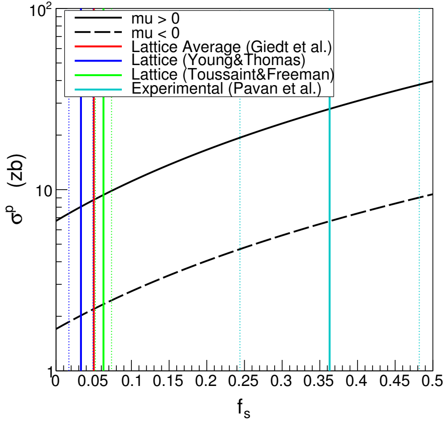
- Significant uncertainty from the strange quark form factor

Ellis, Olive, Savage (2008)
Giedt, Thomas, Young (2009)

- Highly influenced by $(g-2)_\mu$ constraint

Understanding these who issues is critical to combined limits on the focus point!

Preliminary work with Jonathan Feng, Konstantin Matchev, Won Sang Cho

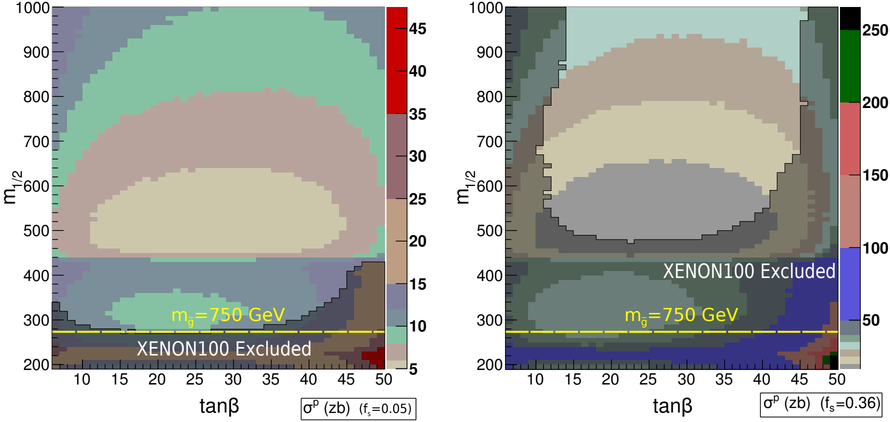


$$\frac{\lambda_N}{m_N} = \sum_{q=1}^{6} f_q^N \frac{\lambda_q}{m_q} \, ,$$

$m0 = 3$ TeV, $m_{1/2} \approx 550$ GeV, $\tan\beta = 10$; $m_{\chi_0^1} \approx 227$ GeV

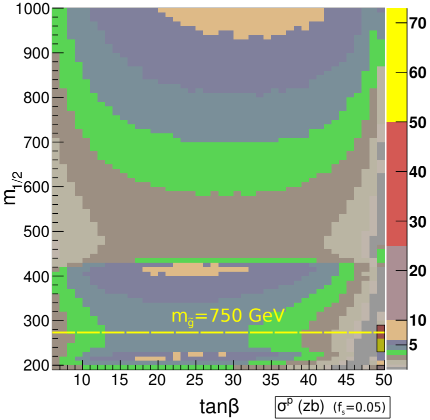
XENON100 Limits with Varying f_s

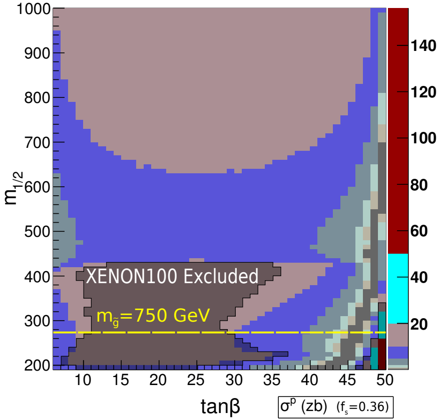
- Work in CMSSM with $(\tan\beta, m_{1/2})$ free
- Set m_0 to make $\Omega = 0.23$



$$A = 0, \mu > 0$$

XENON100 Limits with Varying f_s





$$A = 0, \mu < 0$$

Effect of $(g-2)_\mu$

The observed value of $(g-2)_\mu$ is discrepant with the Standard Model at $\sim 3\sigma$

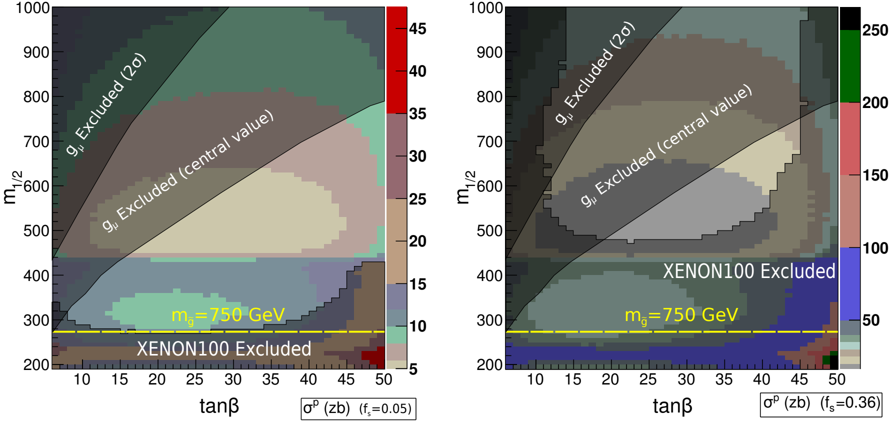
- SUSY contribution is proportional to μ and favors $\mu > 0$
- Need a light $\tilde{\mu}$ to produce a sufficiently large SUSY contribution
- In CMSSM framework, this heavily favors low m_0

Conclusions rely critically on unification of masses, both between different families and between sfermions and Higgs multiplets

As a test case, set $m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R} = m_{\tilde{\nu}_\mu} = M$ at the weak scale, and vary to produce the desired SUSY contribution to $(g-2)_\mu$

$(g-2)_\mu$ Limits with Light $m_{\tilde{\mu}}$

σ^p with non-unified $m_{\tilde{\mu}}$



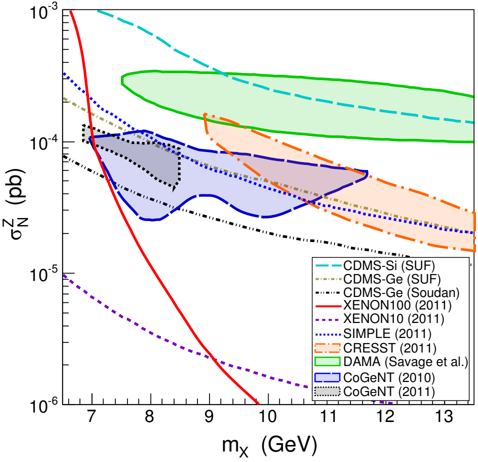
$A = 0$, $\mu < 0$

Partial Summary

- Supersymmetry favors zeptobarn spin-independent cross sections, $1\text{zb} < \sigma^{\text{SI}} < 40\text{zb}$
- Conclusions are robust even with
  - Variation of m_A and $\tan\beta$
  - Non-unified sfermion masses
  - Inclusion of left-right mixing
  - Uncertainty in the strange quark content of the nucleon
  - Neutralinos as only partial component of the relic density
  - Small-scale structure considerations
- Direct detection provides complementarity to the LHC for SUSY parameter space
- Viable even in CMSSM parameter space

Something a Bit Different: Light Dark Matter

Great recent interest in light dark matter



Major inconsistencies between experimental results

- DAMA and CoGeNT regions do not agree
- XENON10/XENON100 rule out DAMA and CoGeNT
- **CDMS-Ge (Soudan)** rules out much of CoGeNT and all of DAMA
- Annual modulation observed at both DAMA and CoGeNT

Drukier, Freese, Spergel (1986)

- Some consistency between CRESST and DAMA/CoGeNT
- SIMPLE rules out DAMA and constraints CoGeNT and CRESST

Possible Explanations of the Discrepancy

Many theories have been put forward

- Inelastic dark matter

Tucker-Smith and Weiner (2001)

- Details of L_{eff} in liquid xenon at low recoil energy

Collar and McKinsey (2010)

- Channeling in NaI at DAMA

Bernabei et al. [DAMA] (2007); Bozorgnia, Gelmini, Gondolo (2010)

We propose to rescind the assumption of isospin conservation

- Non-generic theoretical assumption
- Simple resolution of several discrepancies

Feng, Kumar, Marfatia, Sanford – Phys.Lett.B703:124-127,2011

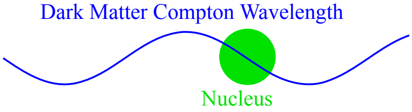
Chang, Liu, Pierce, Weiner, Yavin (2010)

Guiliani (2005)

Kurylov and Kamionkowski (2004)

Isospin Conservation and Violation

- DM-nucleus scattering is coherent
- The single atom SI scattering cross-section is



$$\sigma_A \propto [f_p Z + f_n(A-Z)]^2$$
$$\propto f_p^2 A^2 \qquad (f_p = f_n)$$

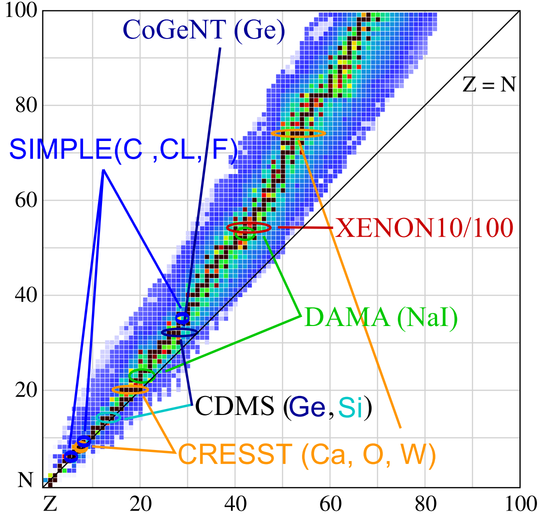
- Well-known A^2 enhancement for $(f_p = f_n)$

Z: atomic number
A: number of nucleons
f_p: coupling to protons
f_n: coupling to neutrons

- For $f_p \neq f_n$, this result must be altered
- In fact, for $f_n/f_p = -\frac{Z}{A-Z}$, σ_A vanishes from completely destructive interference
- $\frac{Z}{A-Z}$ decreases for higher Z

Dark Matter Experiments and Proton/Neutron Ratio

$\frac{Z}{A-Z}$ decreases for higher Z



National Nuclear Data Center

Effects of Multiple Isotopes

Stable isotopes of Xenon ($Z = 54$):

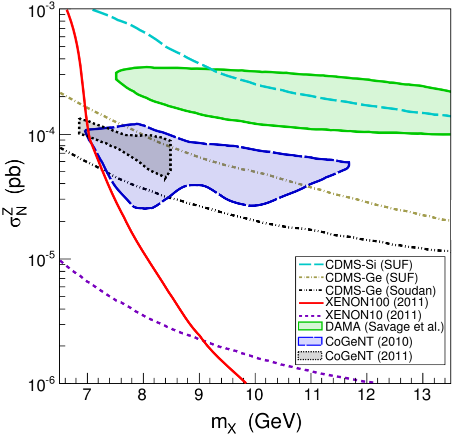
A	128	129	130	131	132	134	136
Abundance (%) [η_i]	1.9	26.4	4.1	21.2	26.9	10.4	8.9
$\sigma_A = 0$ at $f_n/f_p =$	-0.73	-0.72	-0.71	-0.70	-0.69	-0.675	-0.66

- Cannot have completely destructive interference for more than one isotope of an element
- We define the "per-nucleon cross-section" measured by experiments

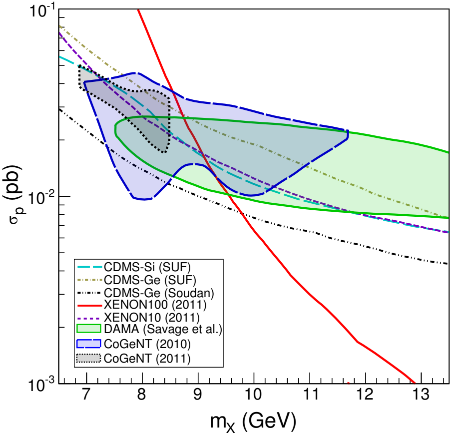
$$\sigma_N^Z = \sigma_p \frac{\sum_i \eta_i {\mu_{A_i}}^2 \left[Z + (A_i - Z) f_n/f_p\right]^2}{\sum_i \eta_i {\mu_{A_i}}^2 A_i^2}$$

σ_p: DM-proton cross-section
η_i: Relative abundance of an isotope
μ_{A_i}: Reduced nucleon-DM mass for an isotope

Light DM for $f_n/f_p = 1$ and $f_n/f_p = -0.7$

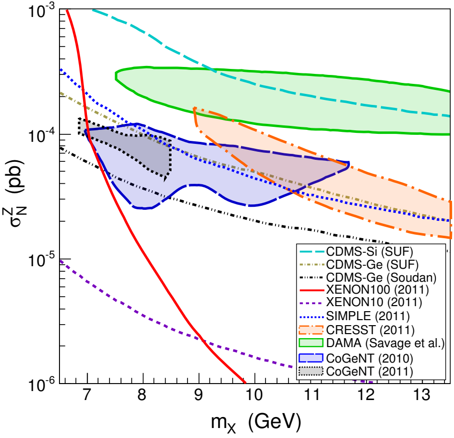


$f_n/f_p = 1$

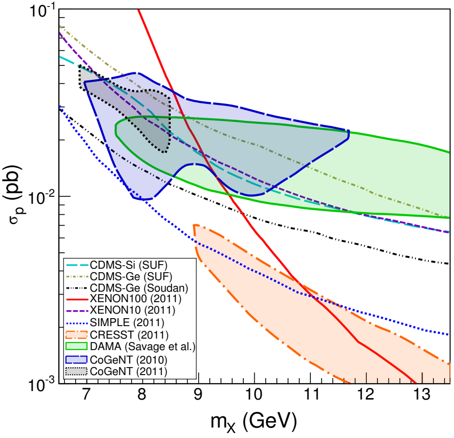


$f_n/f_p = -0.7$

Recent Results: SIMPLE and CRESST



$f_n/f_p = 1$



$f_n/f_p = -0.7$

Comparing Direct Detection Experiments

Can we rule out DAMA/CoGeNT with XENON? YES

- Due to the presence of multiple isotopes, a sufficiently tight XENON bound can rule out both CoGeNT and DAMA

How tight does the XENON constraint have to be?

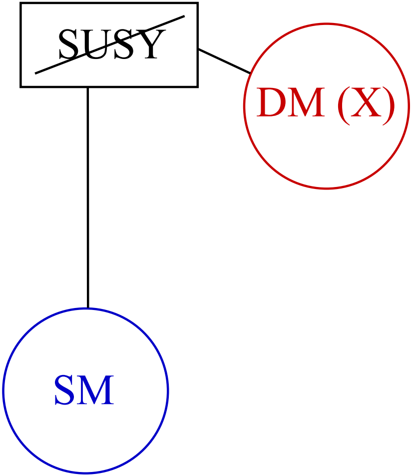
- Scan over f_n/f_p to maximize the apparent discrepancy between the values σ_N^Z for two elements
- CoGeNT (Ge) can consistently exceed XENON100 bounds by a factor of 23.5
- DAMA (Na) can consistently exceed XENON100 bounds by a factor of 103.1

Maximum Enhancement of Cross-Sections

Element (Z,A)	Xe	Ge	Si	Ca	W	Ne
Xe (54, *)	1.0	8.9	169.5	169.5	9.92	42.2
Ge (32, *)	23.5	1.0	76.9	77.5	117.6	19.2
Si (14, *)	172.4	30.2	1.0	1.1	666.7	1.05
Ca (20, *)	178.6	30.5	1.1	1.0	666.7	1.07
W (74, *)	3.5	16.1	238.1	238.1	1.0	59.2
Ne (10, *)	166.7	28.9	4.0	4.0	666.7	1.0
I (53, 127)	1.9	5.7	147.1	147.1	18.0	36.4
Cs (55, 133)	1.1	7.4	158.7	161.3	10.7	39.5
O (8, 16)	181.8	31.5	1.1	1.1	714.3	1.1
Na (11, 23)	103.1	13.2	9.7	10.3	416.7	2.8
Ar (18, 40)	35.38	1.87	45.39	42.56	190.26	10.32

- Maximum factor by which the reported σ_N^Z of elements listed in rows can exceed that of those listed in columns
- Scattering off single-isotope elements can always be arbitrarily suppressed

Quark-Level Realization: WIMPless Models



- SUSY model w/ DM (X) in a hidden sector
- GMSB provides naturally similar mass/coupling ratios, generating the "WIMPless" miracle in the hidden sector

$$\Omega_{DM} \propto \frac{m_X^2}{g_X^4}$$

Dark Matter Mass

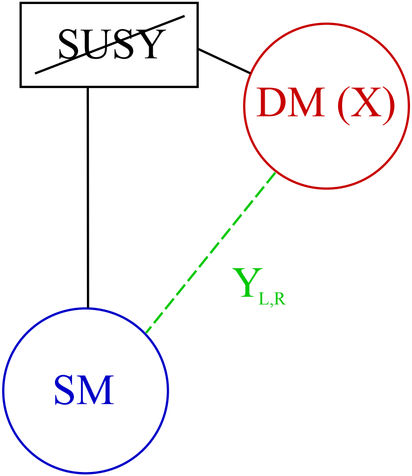
Hidden Sector Gauge Coupling

Feng and Kumar (2008)

Feng, Tu, Yu (2008)

Quark-Level Realization: WIMPless Models

$$W \supset \sum_i \left(\lambda_q^i X Y_{q_L} q_L^i + \lambda_u^i X Y_{u_R} u_R^i + \lambda_d^i X Y_{d_R} d_R^i \right)$$



- X couples to SM through yukawa couplings to Y
- All couplings to vanish except those to up and down quarks for simplicity
- With $m_X = 8$ GeV and $m_Y = 400$ GeV, the DAMA/CoGeNT/XENON coincidence can be achieved with

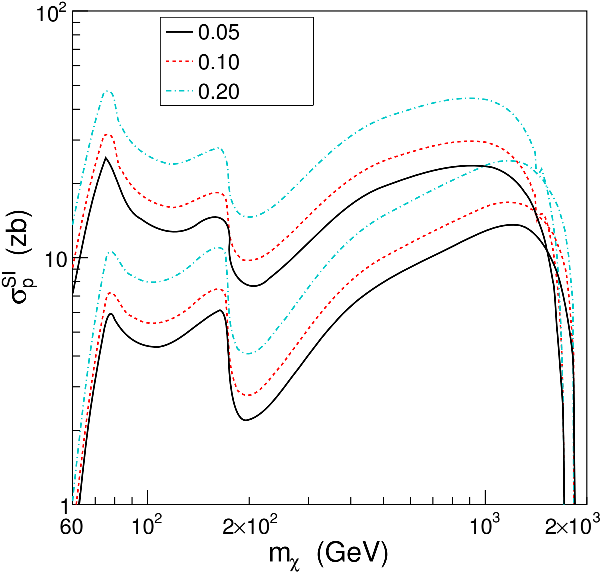
$$\lambda_{L_1} \lambda_{R_u} \sim \pm 0.02$$
$$\lambda_{L_1} \lambda_{R_d} \sim \mp 0.02$$

Summary

- Dark matter may generically couple in a way that violates isospin
- For $f_n/f_p \sim -0.7$, CoGeNT and DAMA results agree for a significant mass range and are partially unbounded by XENON
- The possibility of IVDM motivates the use of a variety of materials in experimental searches
- Explicit WIMPless Realization

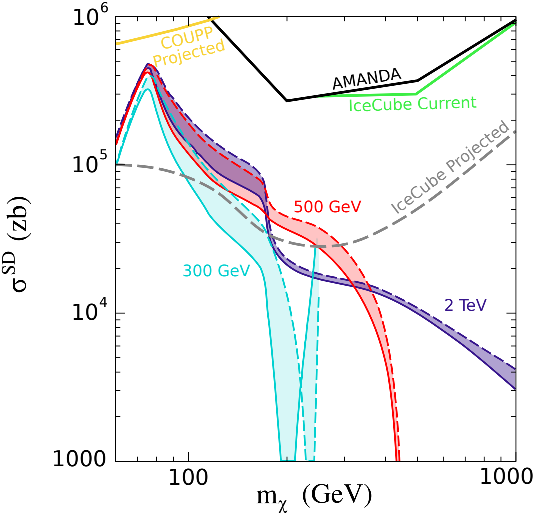
Backup Slides

Strange Quark Content of the Proton



Giedt, Thomas, Young (2009)

Spin-Dependent Detection



$$q - \chi \text{ coupling } \sim \left(\left| a_{\tilde{H}_d} \right|^2 - \left| a_{\tilde{H}_u} \right|^2 \right)$$

Quark-Level Realization

We desire a quark level realization of isospin-violation

- Provides a proof-of-concept
  - Already present in the MSSM, but not typically destructive

Cotta, Gainer, Hewett, Rizzo (2009)

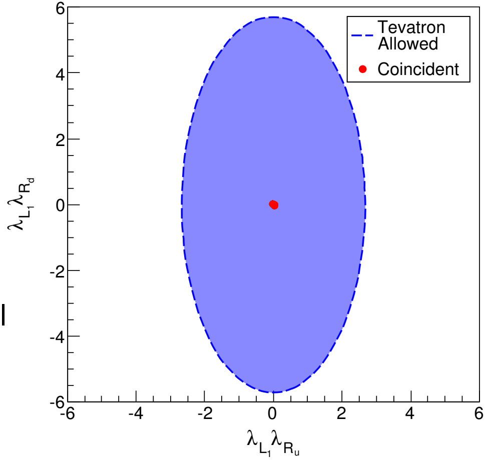
- Required for comparison to other types of detection
  - Collider bounds
  - Spin-dependent direct detection
  - Indirect detection
- Isospin violation is found only in couplings to up and down quarks

Collider Constraints

- Collider single-jet searches constrain the operator $X\bar{X}q\bar{q}$

  Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010); Bai, Fox, Harnik (2010)
- There is no destructive interference in collider searches, so bounds become much stronger
- Coincident region still well within experimental bounds

$$\lambda_{L_1}\lambda_{R_u} \sim \pm 0.02$$
$$\lambda_{L_1}\lambda_{R_d} \sim \mp 0.02$$



$M_X = 8\ \mathrm{GeV},\ M_Y = 400\ \mathrm{GeV}$

Extra Slides: Isotope Abundances

Xe	Ge	Si	Ca	W	Ne
128 (1.9)	70 (21.2)	28 (92.2)	40 (96.9)	182 (26.5)	20 (90.5)
129 (26.4)	72 (27.7)	29 (4.7)	44 (2.1)	183 (14.3)	22 (9.3)
130 (4.1)	73 (7.7)	30 (3.1)		184 (30.6)	
131 (21.2)	74 (35.9)			186 (28.4)	
132 (26.9)	76 (7.4)				
134 (10.4)					
136 (8.9)					