DARK PARTICLES

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APS April Meeting
Garden Grove, California
3 May 2011

OUTLINE

- The WIMP Paradigm
- Direct Detection
  - Big Picture
  - Low Cross Section Frontier

    "Heart of Darkness: The Significance of the Zeptobarn Scale for Neutralino Dark Matter," Feng, Sanford (2010)
  - Low Mass Frontier

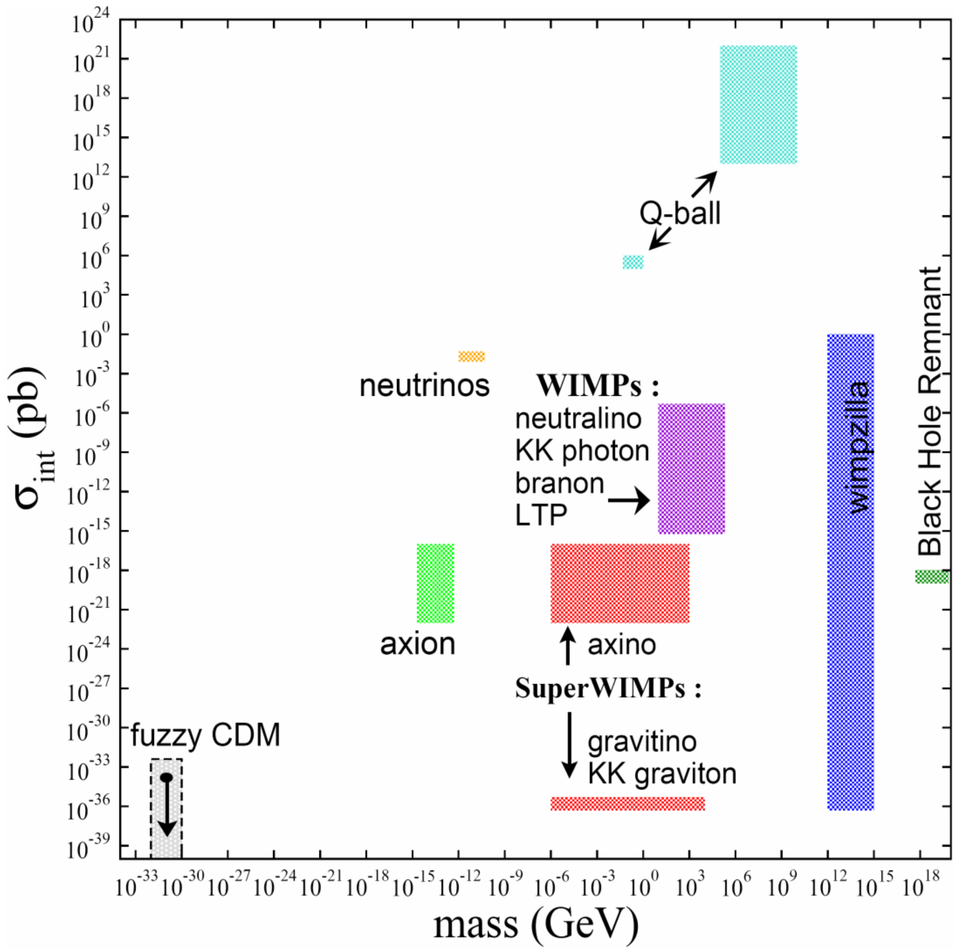
    "Isospin-Violating Dark Matter," Feng, Kumar, Marfatia, Sanford (2011)
- Conclusions

THE WIMP PARADIGM

- All non-controversial evidence for DM comes from its gravitational interactions

- There are therefore many viable particle candidates

- Their masses and interaction strengths span many, many orders of magnitude, but masses near the weak scale m_{weak} ~ 100 GeV are especially motivated



HEPAP/AAAC DMSAG Subpanel (2007)

FREEZE OUT

(1) Assume a new heavy particle X is initially in thermal equilibrium:

$$XX \leftrightarrow \bar{q}q$$

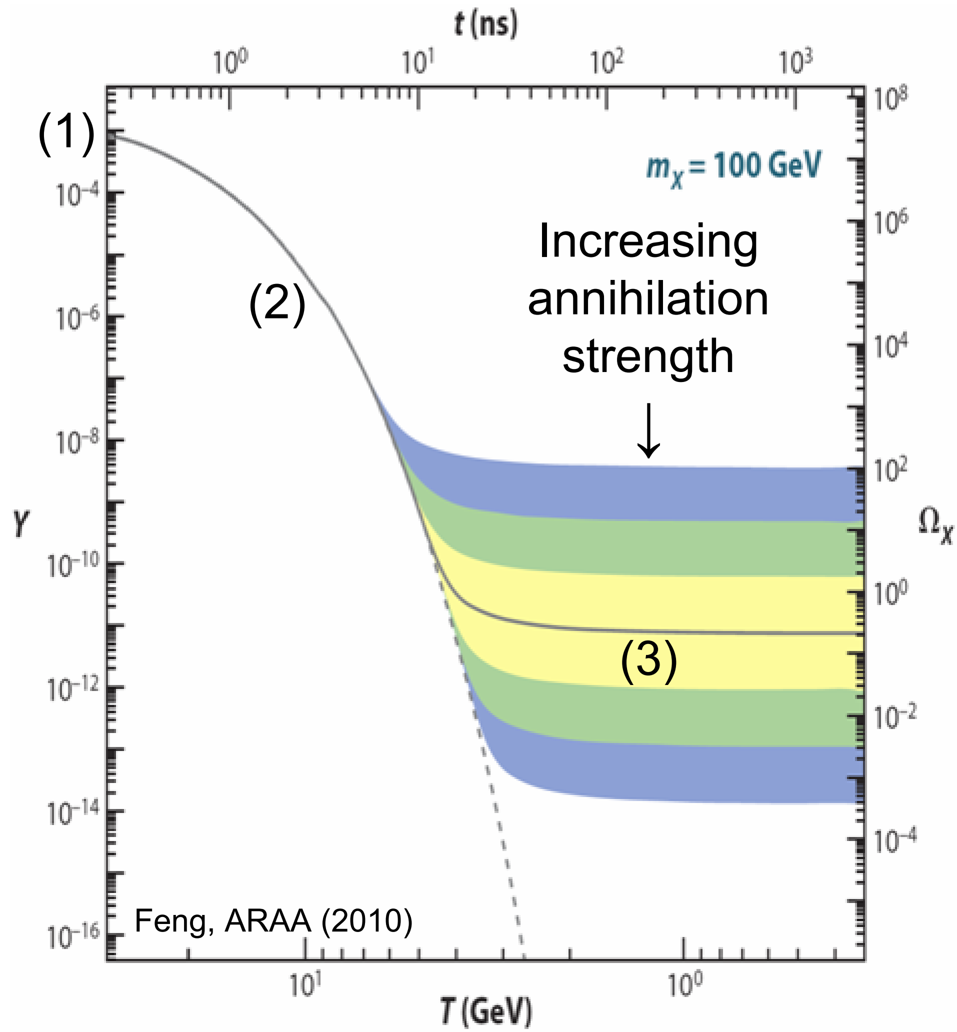
(2) Universe cools:

$$XX \;\substack{\rightarrow \\ \not\leftarrow}\; \bar{q}q$$

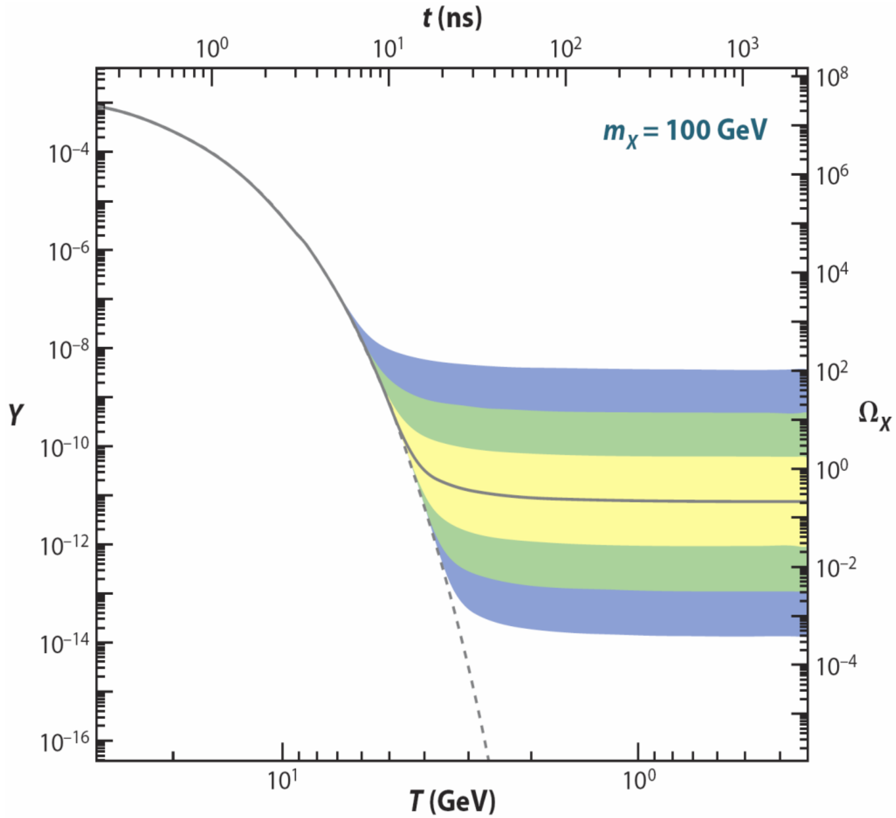
(3) Universe expands:

$$XX \;\substack{\not\rightarrow \\ \not\leftarrow}\; \bar{q}q$$

Zeldovich et al. (1960s)

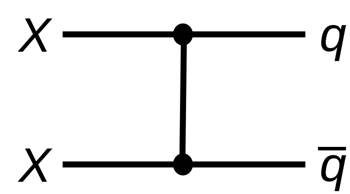


THE WIMP MIRACLE



- The relation between Ω_X and annihilation strength is wonderfully simple:

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

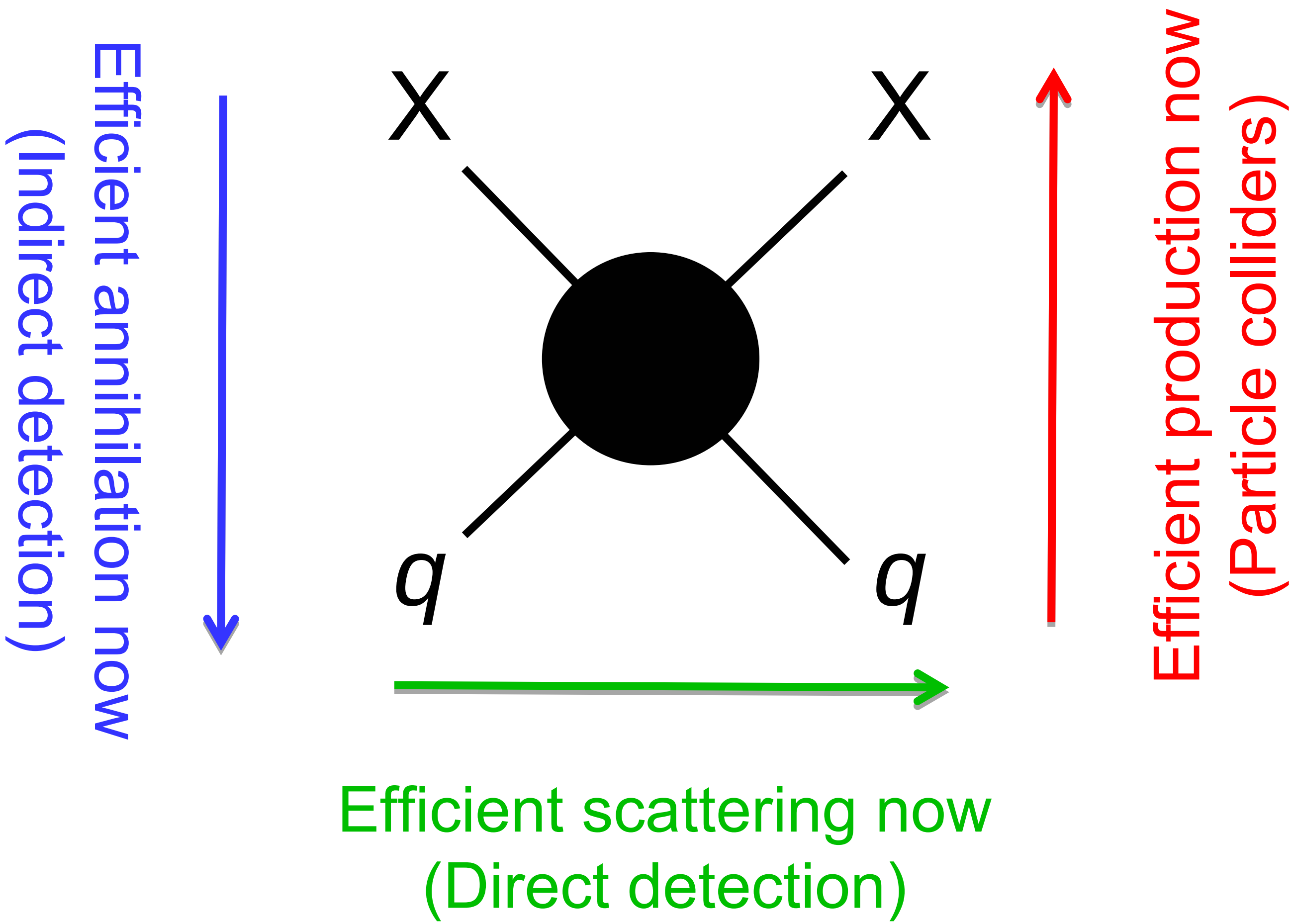


- m_X ~ 100 GeV, g_X ~ 0.6 → Ω_X ~ 0.1

- Remarkable coincidence: weak-scale mass particles generically have the right relic density to be dark matter

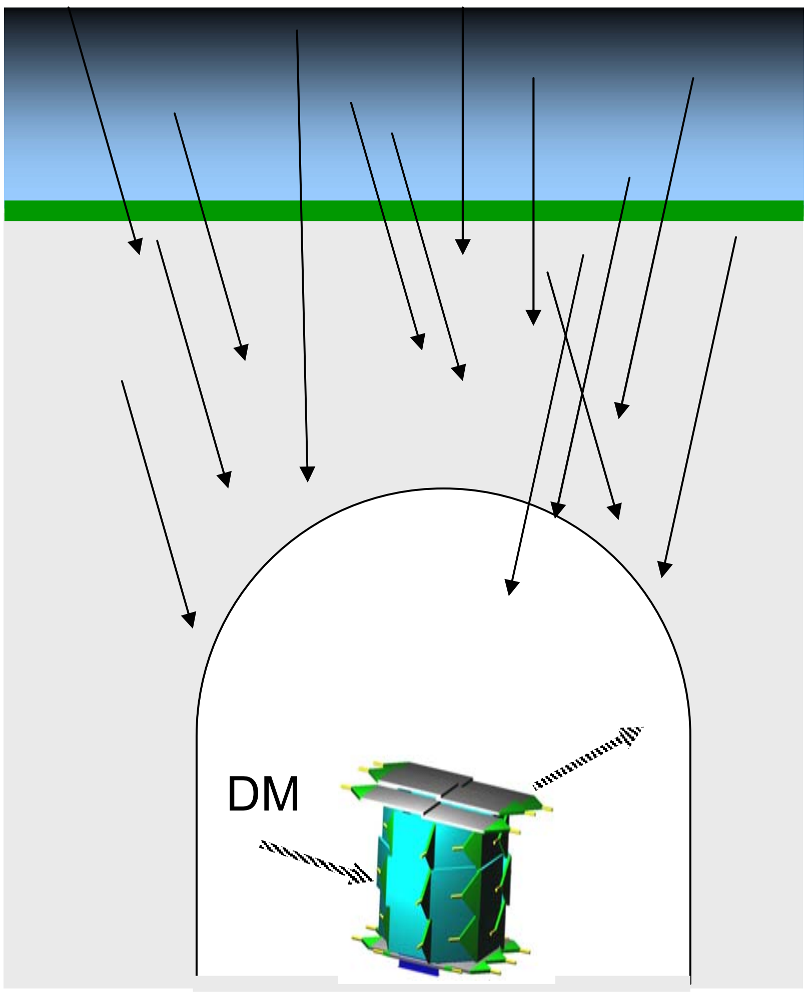
EXPERIMENTAL PROBES

Correct relic density → Efficient annihilation then



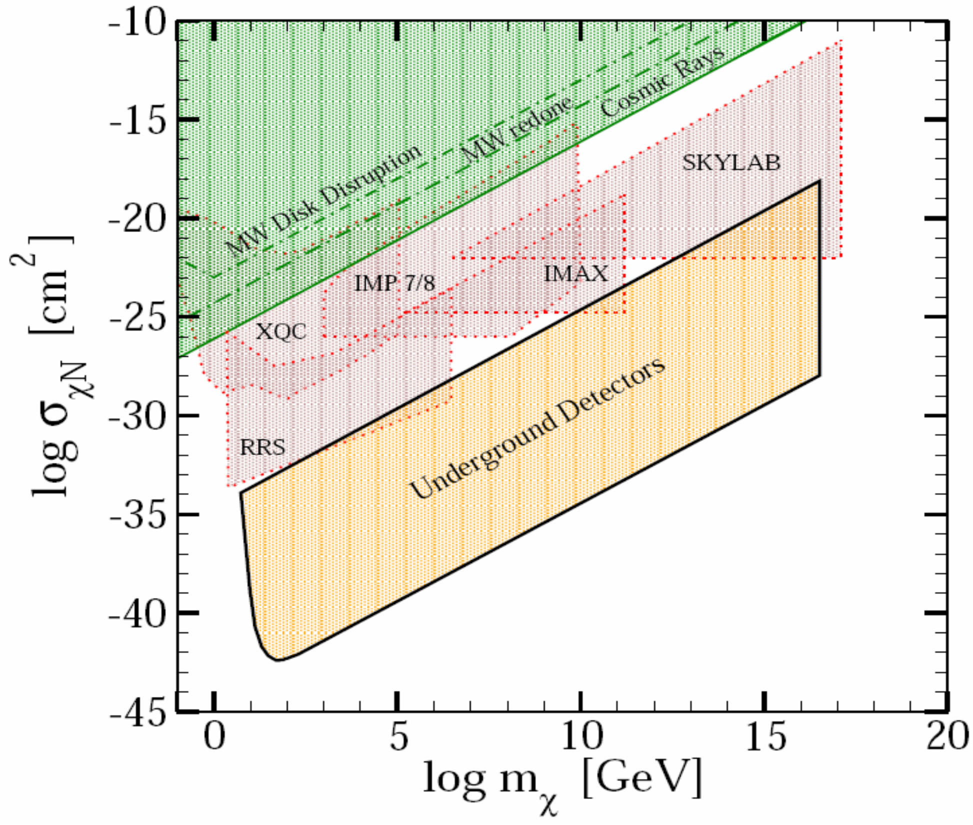
DIRECT DETECTION

- Look for normal matter recoiling from DM collisions
- WIMP properties
  - m ~ 100 GeV
  - velocity ~ 10^{-3} c
  - Recoil energy ~ 1-100 keV
- Typically focus on ultra-sensitive detectors placed deep underground
- But first, what range of interaction strengths are possible?



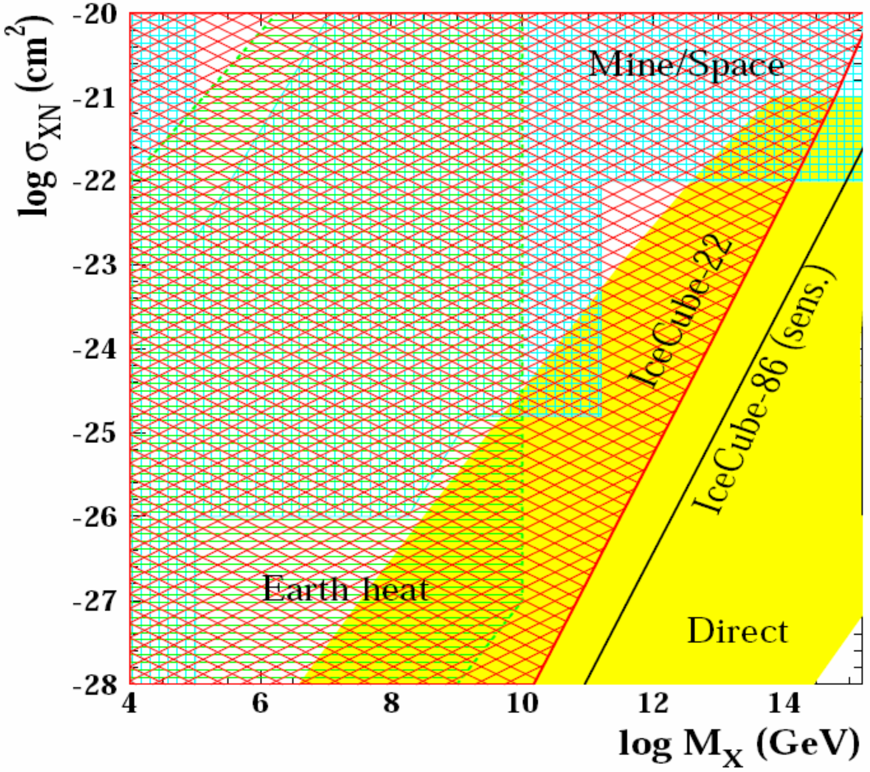
THE BIG PICTURE

- What is the upper bound?



Mack, Beacom, Bertone (2007)

- Strongly-interacting window is now closed

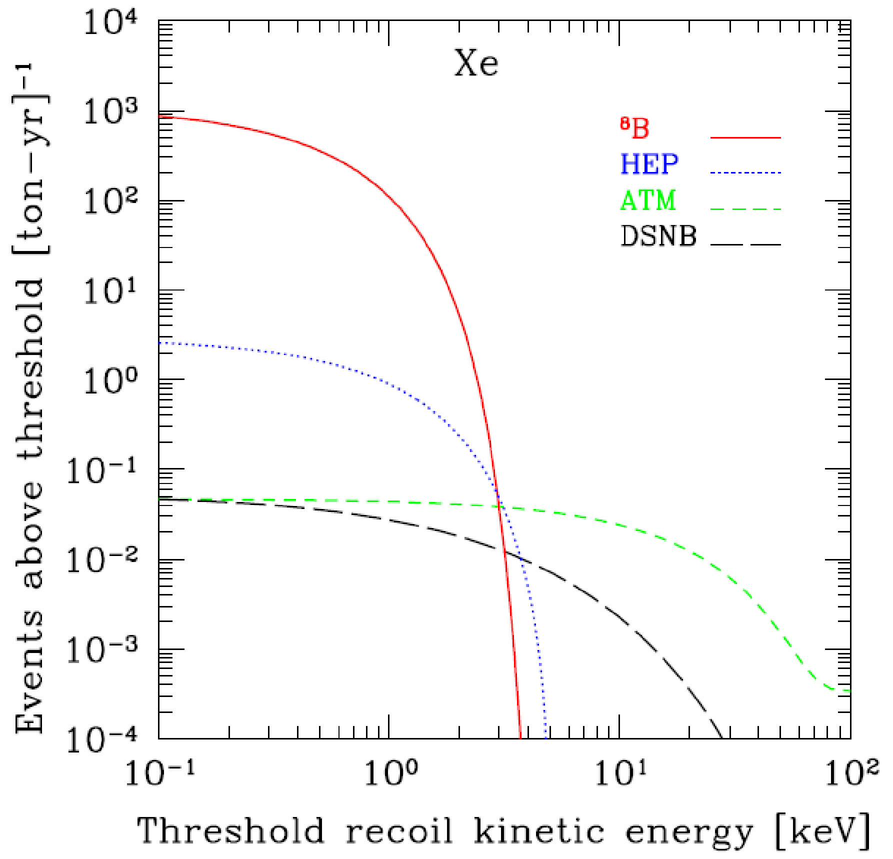


Albuquerque, de los Heros (2010)

THE BIG PICTURE

- Is there (effectively) a lower bound?
- Solar, atmospheric, and diffuse supernova background neutrinos provide an "irreducible background"
- The limits of background-free, non-directional direct detection searches (and also the metric prefix system!) will be reached by ~10 ton experiments probing

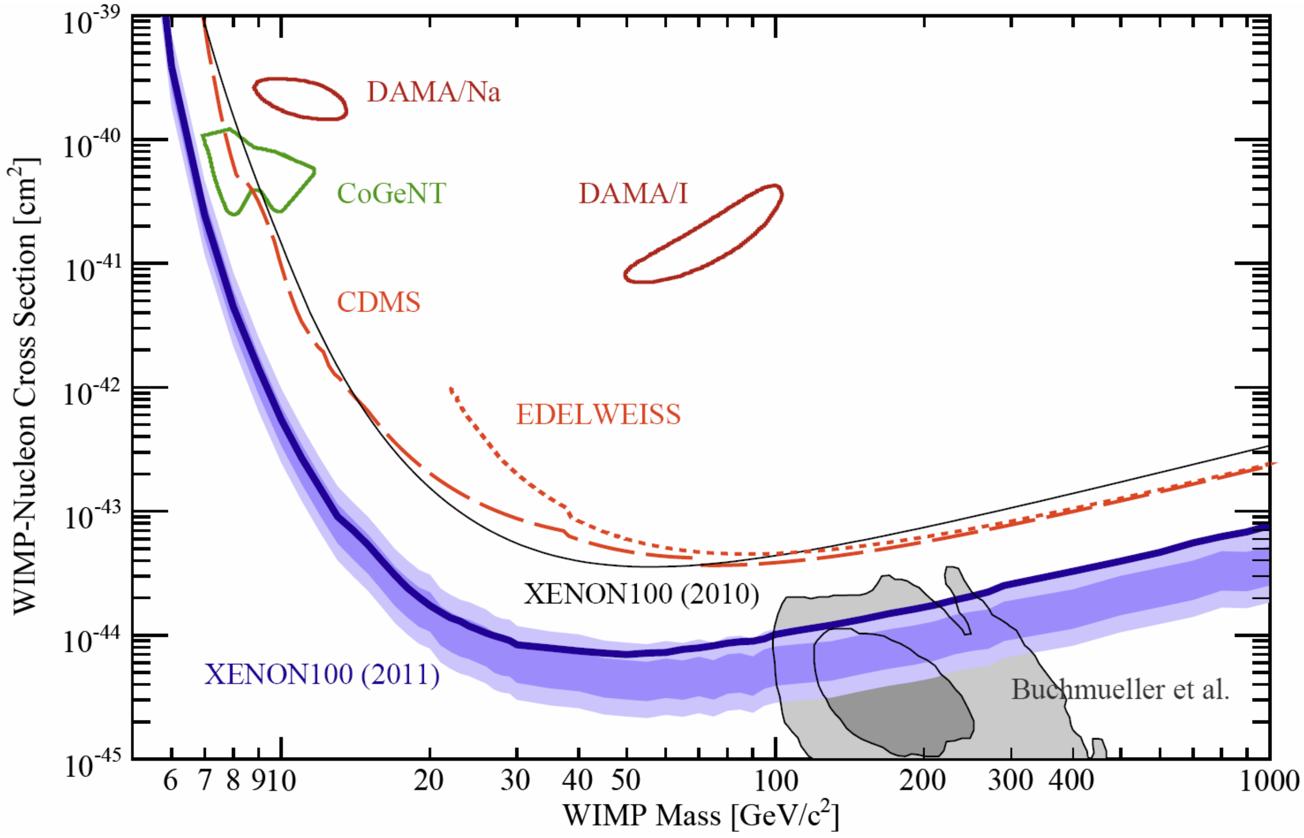
σ ~ 1 yb (10^{-3} zb, 10^{-12} pb, 10^{-48} cm^2)



Strigari (2009); Gutlein et al. (2010)

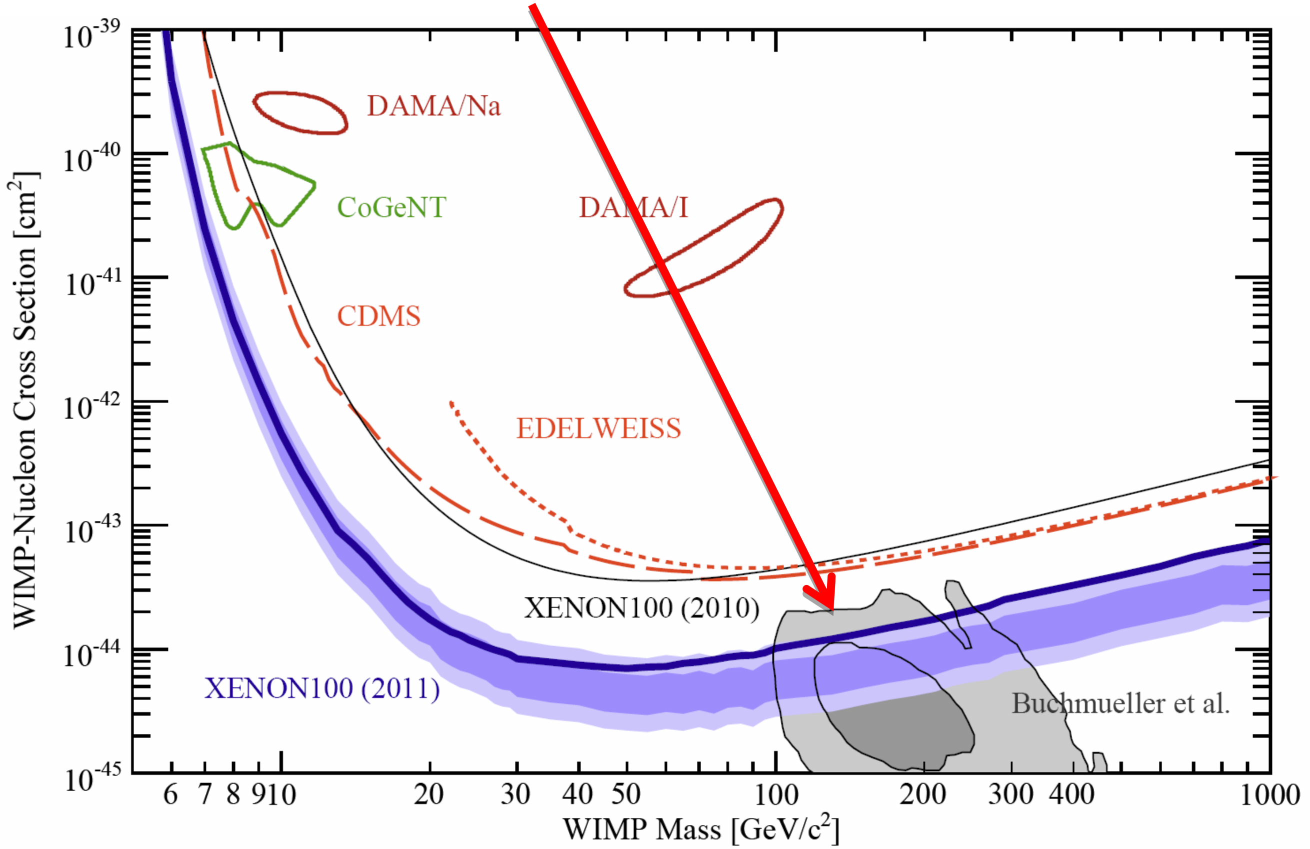
CURRENT STATUS

- Focus on spin-independent results, which are typically normalized to X-proton cross sections. Much exciting progress; see talks of Baudis, Collar, and many others here
- Two frontiers: low cross section and low mass



LOW CROSS SECTION FRONTIER

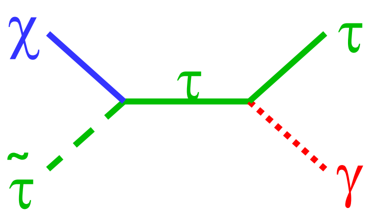
- The excitement stems from the confrontation of experiment (Baudis talk) with theory
- What are the shaded regions?



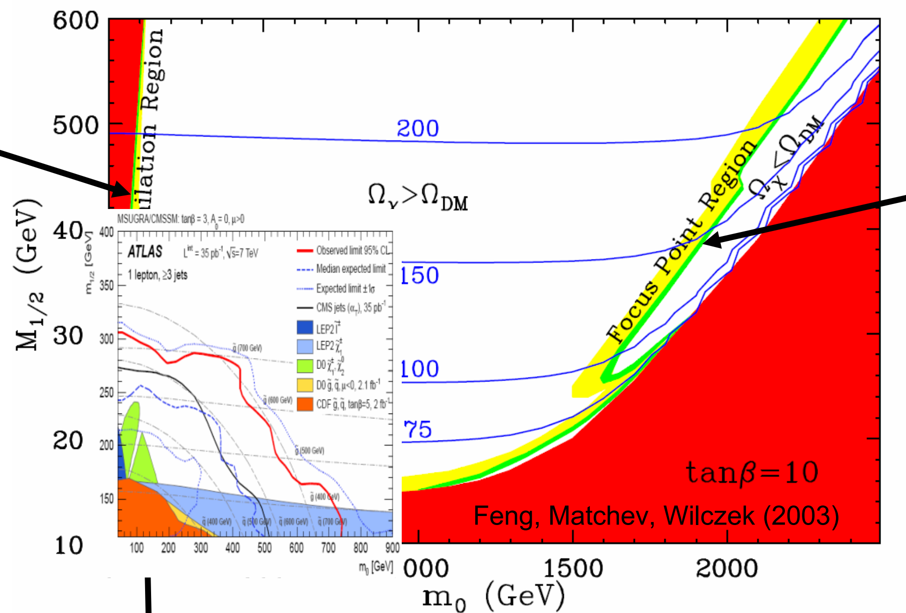
SUPERSYMMETRY

- Ad hoc theoretical assumptions → 4+1 parameters
- Assume Ω_x = 0.23 → require efficient annihilation channel
- Now constrained by LHC searches

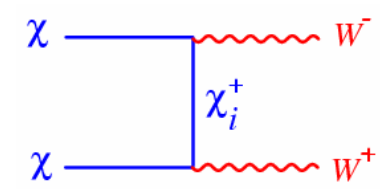
Co-annihilation region



Degenerate χ and stau

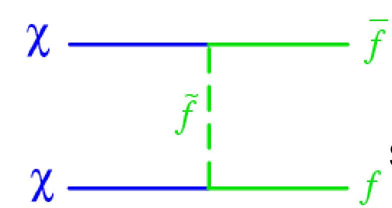


Focus point region



Mixed Higgsino-Bino Neutralinos

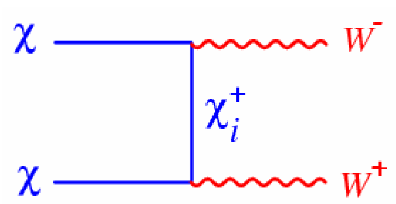
Bulk region

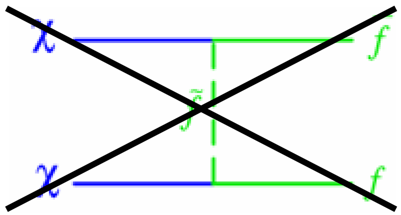


Light sfermions

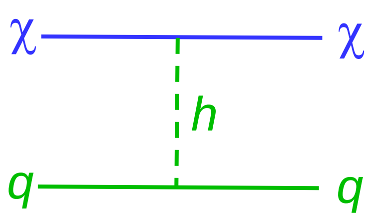
DIRECT DETECTION IMPLICATIONS

- The LHC is eliminating one option. If $M_2 > M_1$, no co-annihilation, resonances, this fixes the DM's coupling to Ws

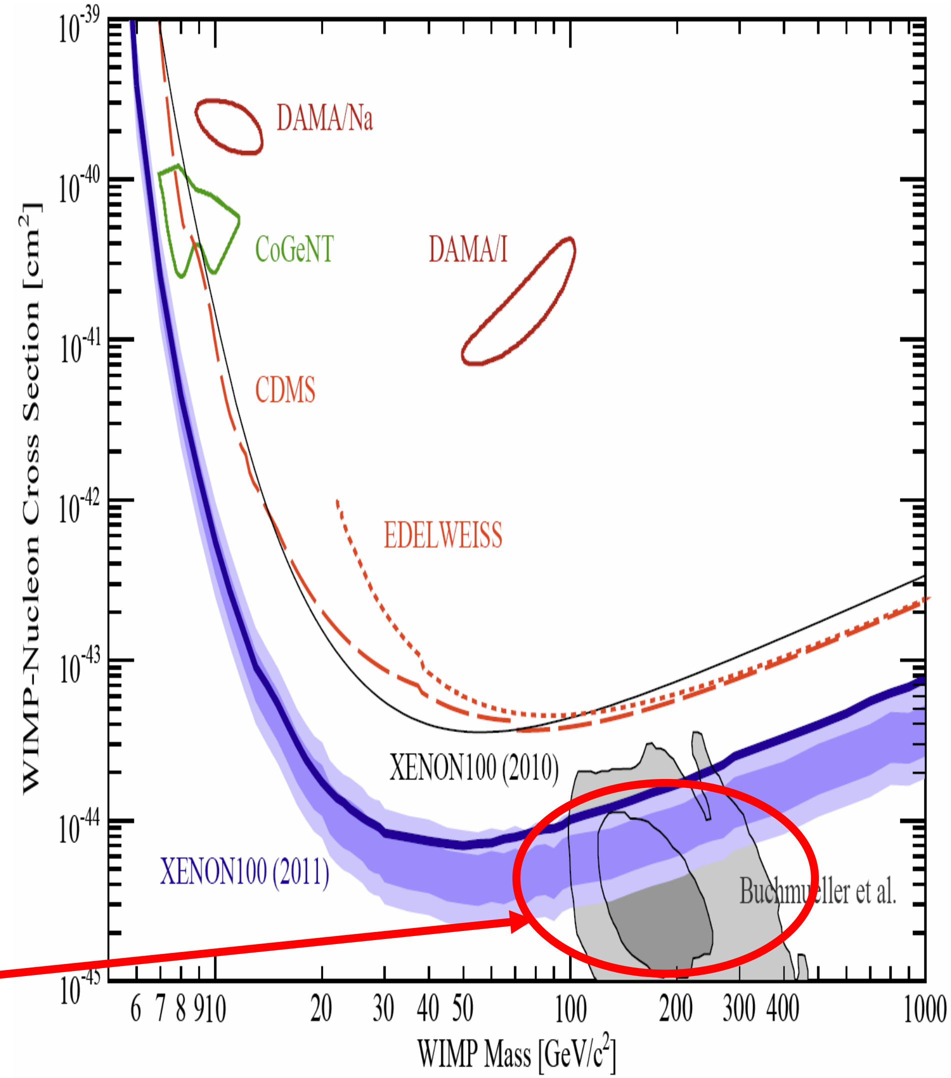




- But this also fixes the DM's coupling to the Higgs boson

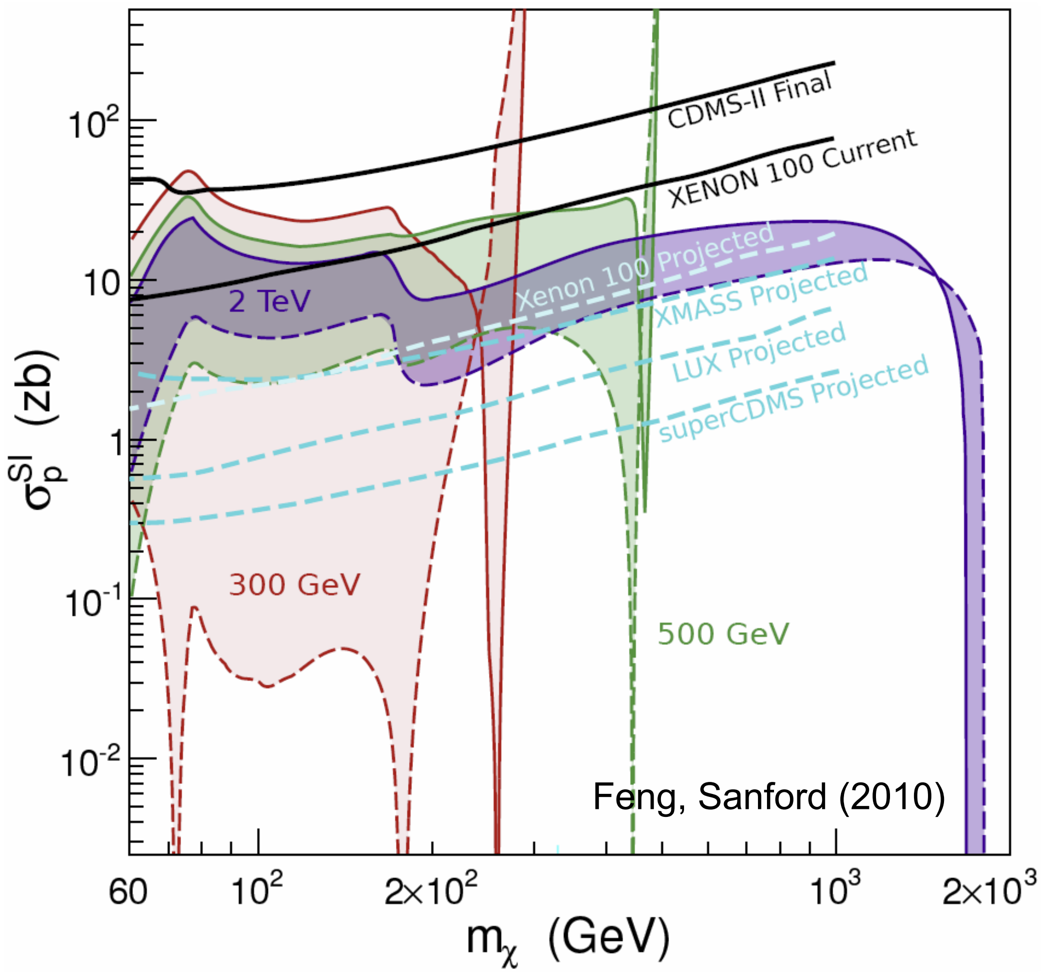


- Since the Higgs mass is almost fixed, predictions collapse to a small region with $\sigma \sim$ zb



MODEL INDEPENDENCE

- Relax unification assumptions
- There are exceptions from accidental mass degeneracies, leading to co-annihilation and resonances, but the generic conclusions are surprisingly robust
- The bottom line: the LHC is starting to eliminate models with poor direct detection prospects, but those with bright prospects remain



STATUS OF NEUTRALINO DM

~10 zeptobarn

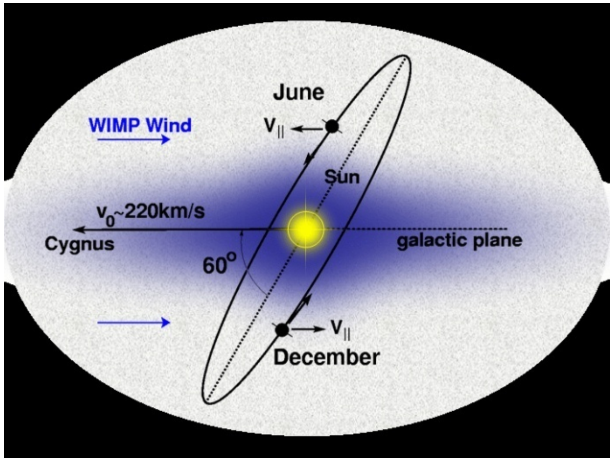
~zeptobarn

No signal

Signal

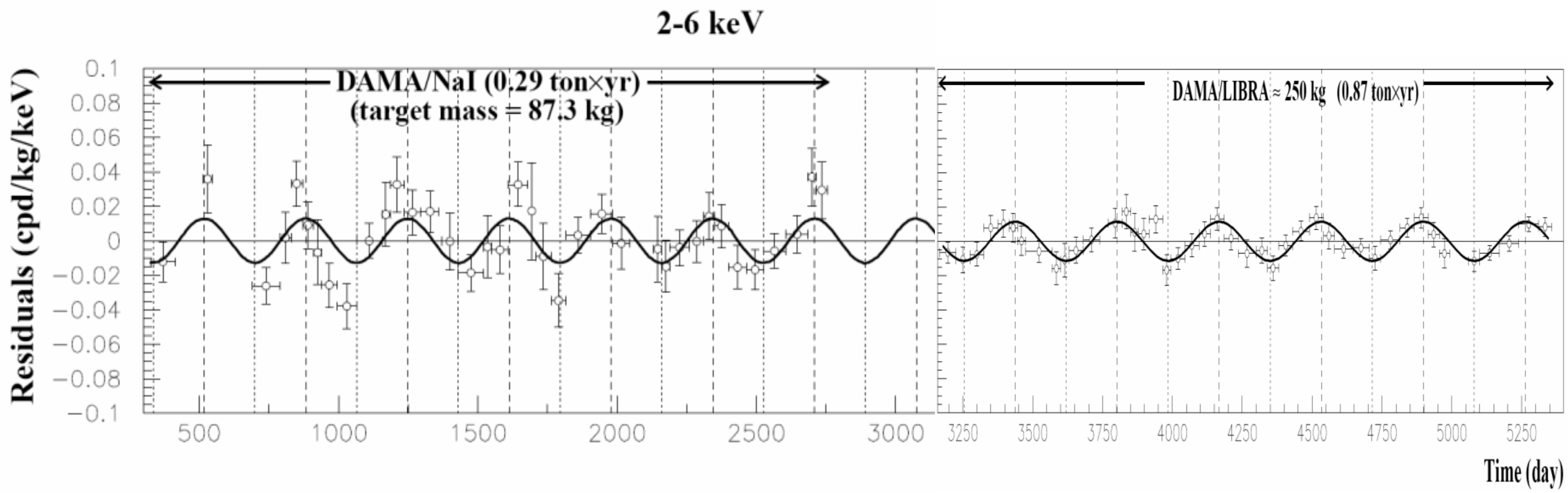
LOW MASS FRONTIER

Collision rate should change as Earth's velocity adds constructively/destructively with the Sun's → annual modulation



Drukier, Freese, Spergel (1986)

DAMA/LIBRA: 8.9σ signal with T ≈ 1 year, maximum ≈ June 2

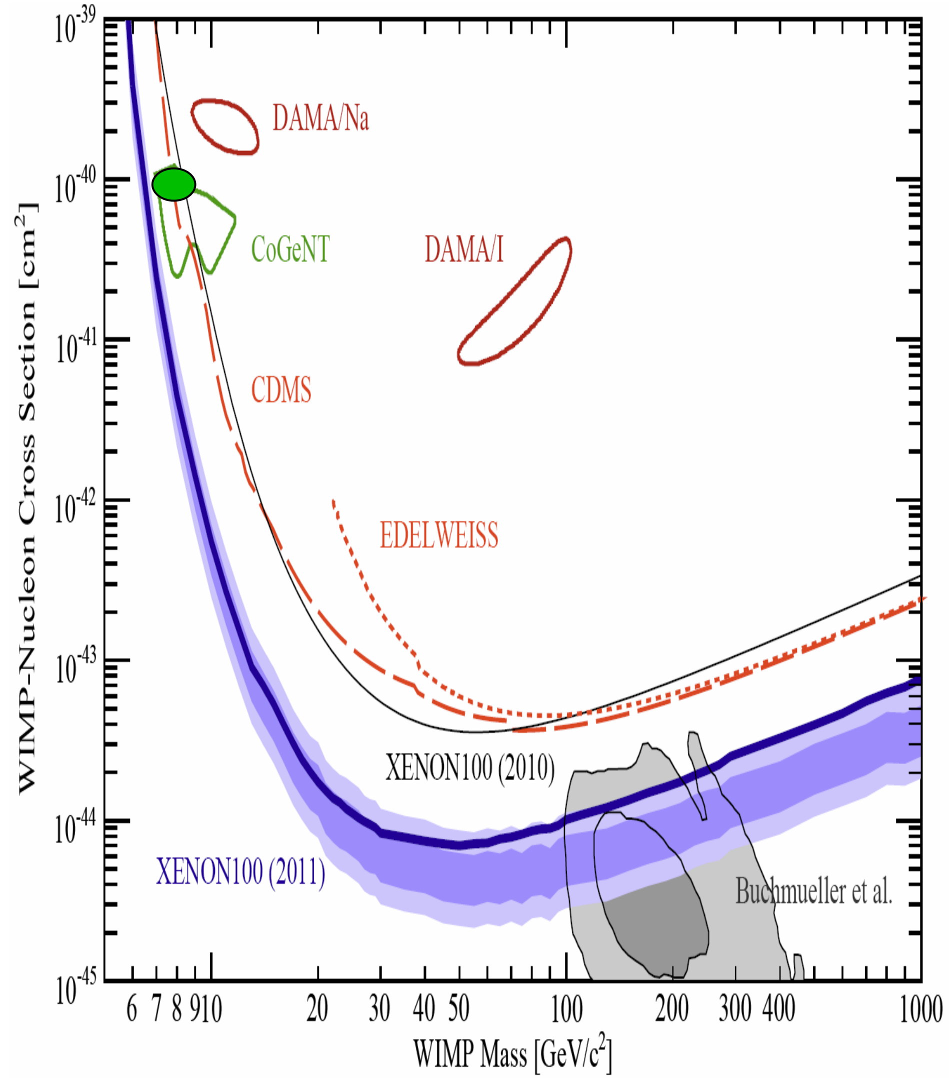


DAMA/LIBRA (2010)

CURRENT STATUS

- DAMA is now supplemented by CoGeNT
- At this meeting: favored region further constrained, preliminary 2.8σ annual modulation signal presented (see Collar's talk)
- Theoretical puzzles
  - Low mass and high σ
  - DAMA ≠ CoGeNT
  - Excluded by XENON, CDMS
- Many proposed explanations

Hooper, Collar, Hall, McKinsey (2010)
Fitzgerald, Zurek (2010)
Fox, Liu, Weiner (2010)
…



ISOSPIN-VIOLATING DARK MATTER

- Recall that DM scattering off nuclei is coherent
  - $\sigma_A \sim [\, f_p Z + f_n (A-Z)\,]^2$
- If flavor isospin is conserved
  - $f_n = f_p$
  - $\sigma_A \sim A^2$
  - Can present all results for various target nuclei in the (m, σ_p) plane
- But this is an unwarranted theoretical assumption; even in mSUGRA, isospin violation in spin-independent cross sections is present (and in rare cases, significant)

Ellis, Feng, Ferstl, Matchev, Olive (2001)

- To investigate IVDM, introduce 1 extra parameter: f_n / f_p

Giuliani (2005)
Chang, Liu, Pierce, Weiner, Yavin (2010)
Feng, Kumar, Marfatia, Sanford (2011)

- Crucially important to account for isotope distributions

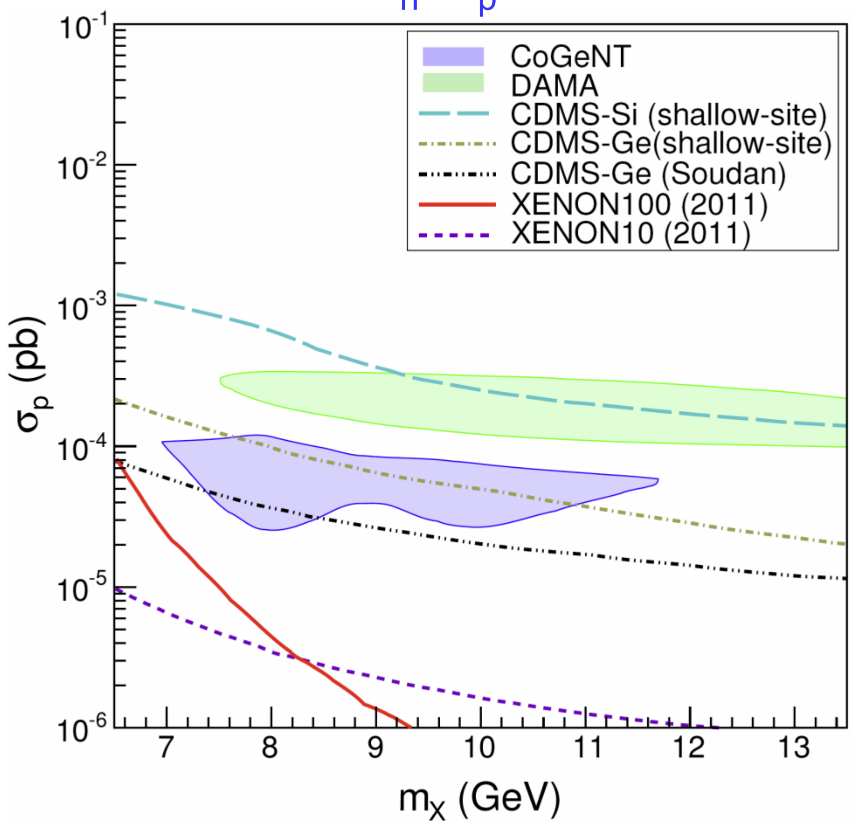
TABLE II. A_i for isotopes and their fractional number abundances η_i in percent for all isotopes with $\eta_i > 1\%$.

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)					

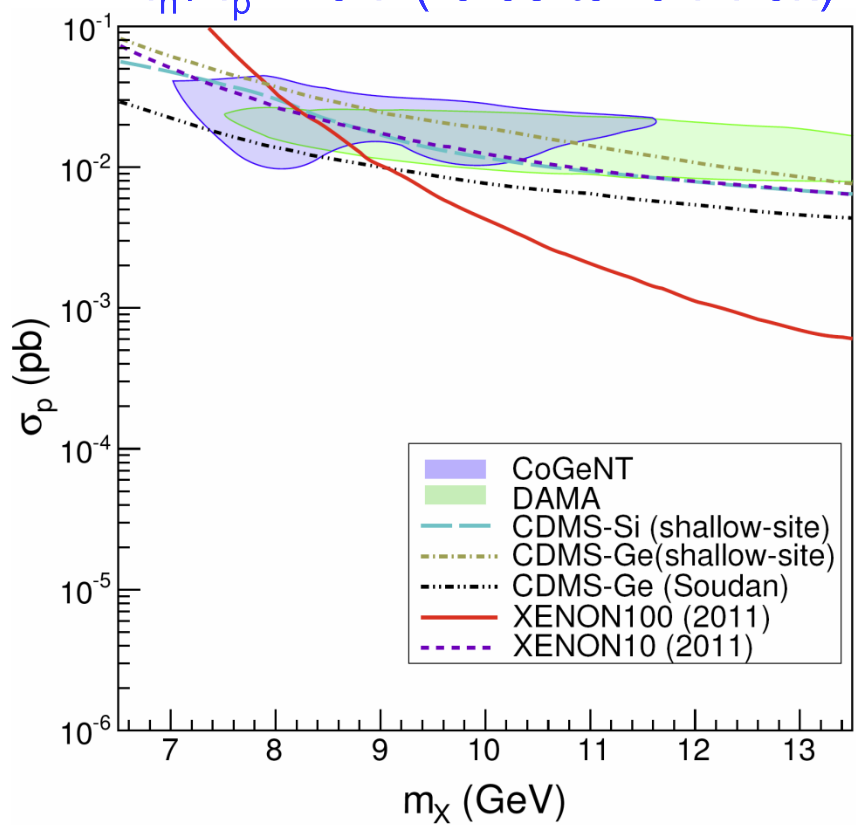
Feng, Kumar, Marfatia, Sanford (2011)

RECONCILING XENON/DAMA/COGENT

$f_n / f_p = 1$



$f_n / f_p = -0.7$ (-0.63 to -0.74 ok)



Feng, Kumar, Marfatia, Sanford (2011)

IMPLICATIONS OF THE IVDM RESOLUTION

- IVDM cannot resolve disagreements between identical targets; if correct, IVDM implies CDMS and CoGeNT are marginally consistent

- Predictions for all other elements are fixed. For example, as conventionally plotted (assuming $f_p = f_n$),

$$\sigma_p(\text{carbon}) \approx 8.4\ \sigma_p(\text{germanium})$$
$$\sigma_p(\text{oxygen}) \approx 8.5\ \sigma_p(\text{germanium})$$
$$\sigma_p(\text{flourine}) \approx 4.2\ \sigma_p(\text{germanium})$$

- XENON will see a signal soon; CRESST may have already

- Reverses $\sigma \sim A^2$ conventional wisdom. Need more than one target material and more than one experiment per material

QUARK-LEVEL REALIZATION

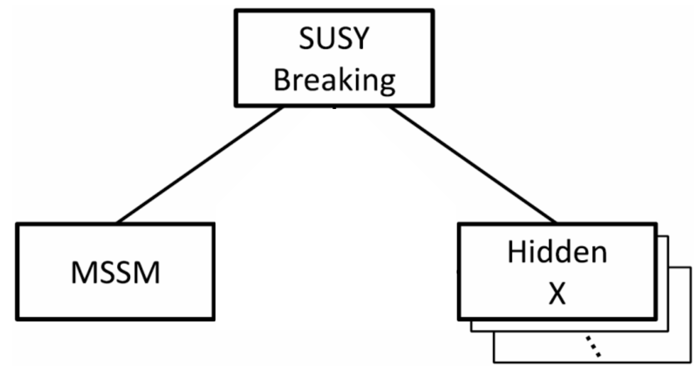
- This is at the nucleon level. Can this actually be realized in a particle physics theory?
- The dark matter is light – doesn't this ruin the WIMP miracle?
- Destructive interference plays a key role, requires larger couplings than usual. Does this violate other constraints?
- All this requires a quark-level realization of IVDM

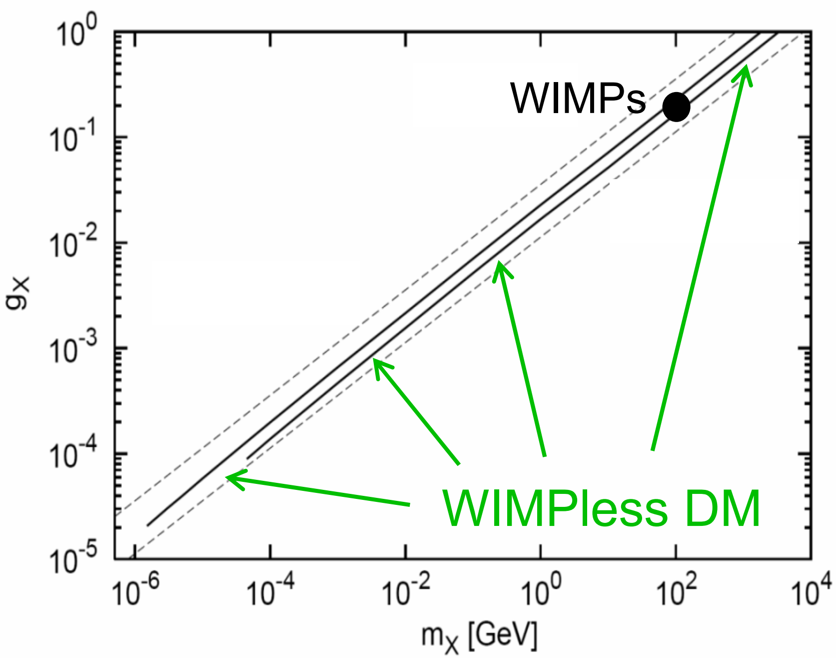
WIMPLESS DARK MATTER

- Consider SUSY with a hidden sector. If GMSB or AMSB, the masses satisfy $m_X \sim g_X^2$
- This leaves the relic density invariant

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

- "WIMPless Miracle": hidden sectors of these theories automatically have DM with the right Ω, even if light (~ GeV)



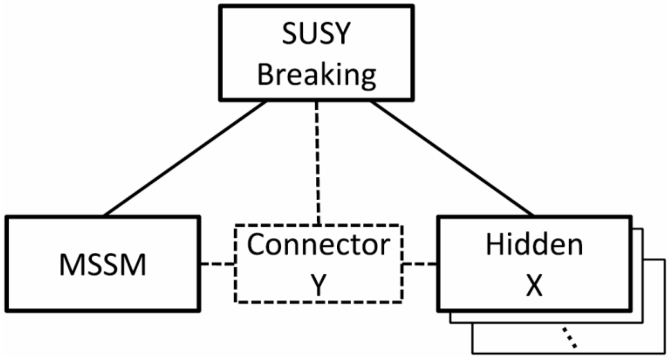


Feng, Kumar (2008); Feng, Tu, Yu (2009)
Feng, Shadmi (2011)

WIMPLESS IVDM

- Couple the WIMPless DM to quarks:

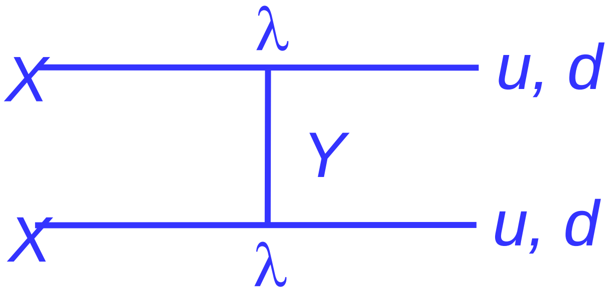
$$W = \sum_i (\lambda_q^i X Y_{q_L} q_L^i + \lambda_u^i X Y_{u_R} u_R^i + \lambda_d^i X Y_{d_R} d_R^i)$$



- The parameters

$$m_Y = 400 \text{ GeV}$$
$$\lambda_u^1 \simeq -1.08\, \lambda_d^1$$
$$0.013 \lesssim \lambda_q^1 \lambda_d^1 \lesssim 0.024$$

give the required IVDM cross sections



- Y is similar to a 4th generation quark, with collider signal YY → jjXX

Alwall, Feng, Kumar, Su (2010)

CONCLUSIONS

- Particle Dark Matter
  - Both cosmology and particle physics → weak scale ~ 100 GeV
- Direct Detection: Supersymmetry
  - Low cross section frontier: will test generic SUSY theories soon
- Direct Detection: Isospin-violating DM
  - Low mass frontier: existing constraints and signals may be reconciled with isospin-violating DM, an extremely simple and highly predictive framework that preserves WIMP motivations