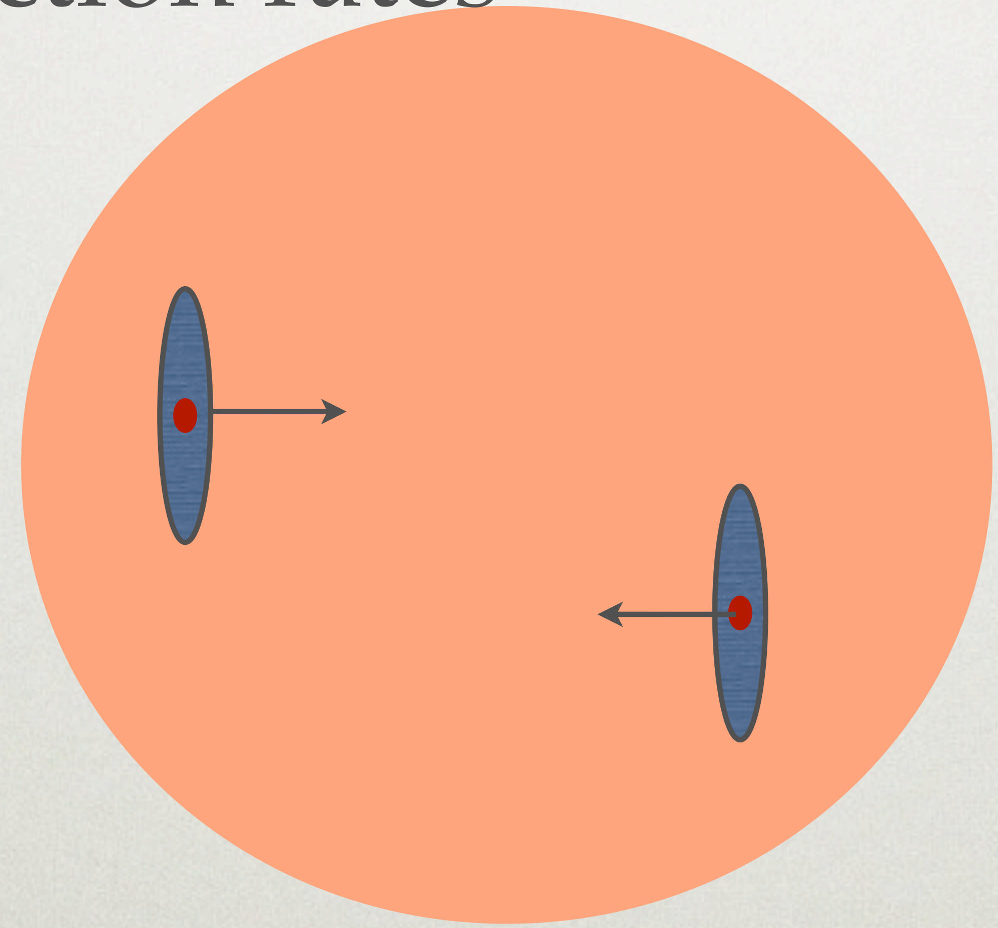
Hunt For Dark Matter: Direct Detection Update

Kathryn M. Zurek
University of Michigan

Why the (sub-)Weak Scale is Compelling

- Abundance of new stable states set by interaction rates



Freeze-out

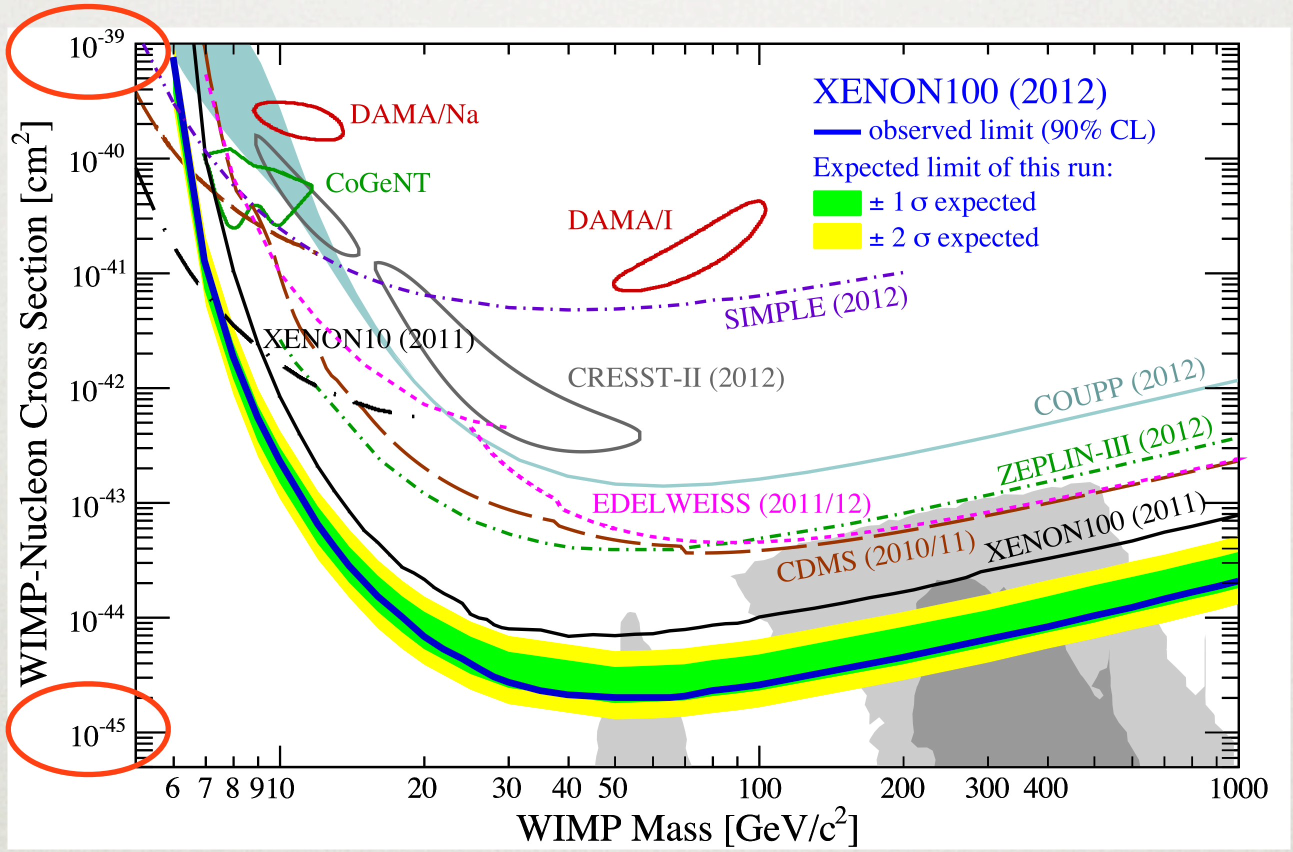
Measured by WMAP + LSS

$$\Gamma = n\sigma v = H \qquad \rightarrow \sigma \sim \frac{1}{\text{few TeV}^2}$$

Sub-Weakly Interacting Massive Particles

Scattering through the Z boson: ruled out

$$\sigma_n \sim 10^{-39}\ \text{cm}^2$$

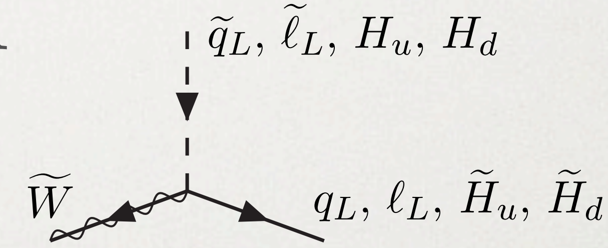


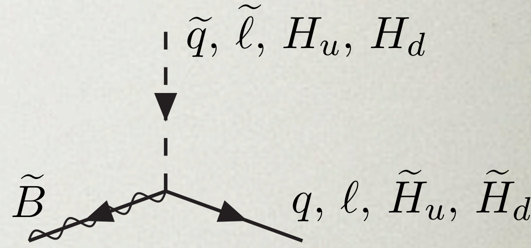
Next important benchmark:
Scattering through the Higgs

$$\sigma_n \sim 10^{-45-46}\ \text{cm}^2$$

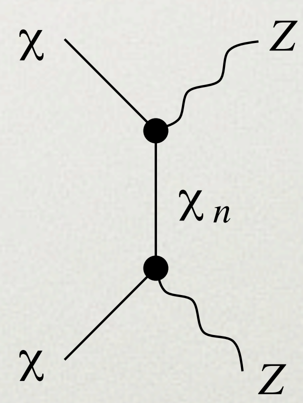
Are there ways around for the Neutralino?

- Make the Neutralino a pure state -- coupling to Higgs vanishes





- However, Wino and Higgsino pure states can be probed by indirect detection

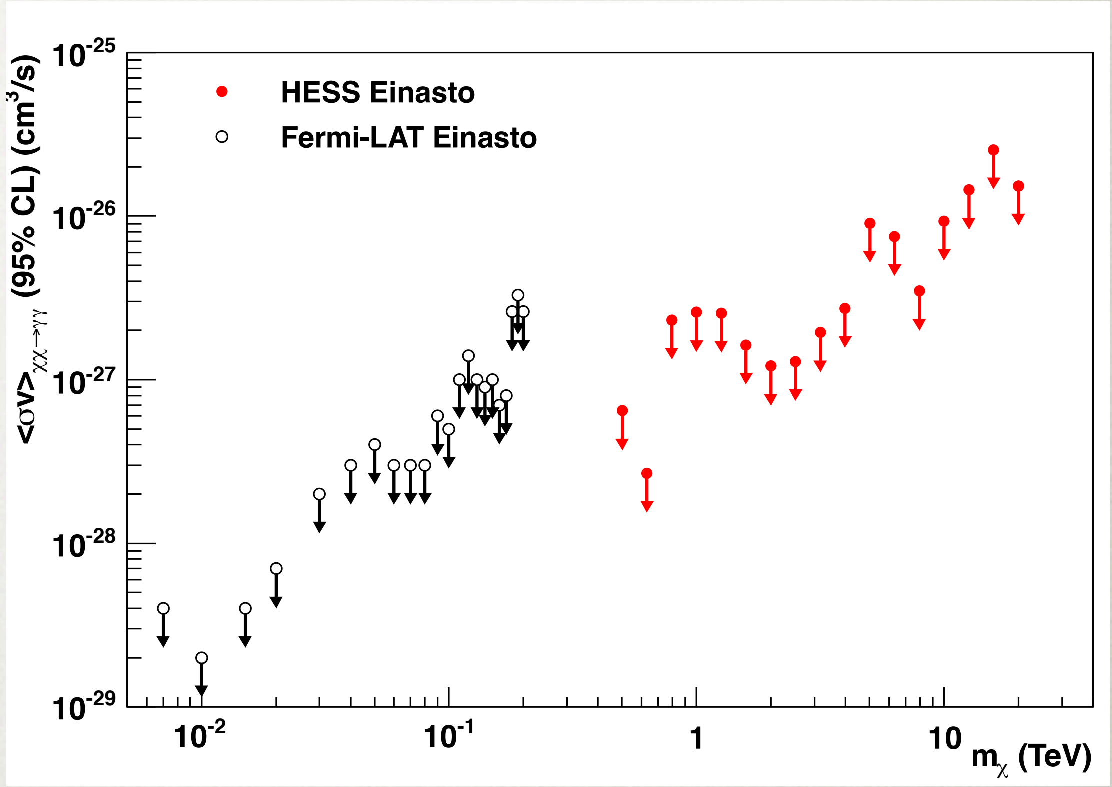


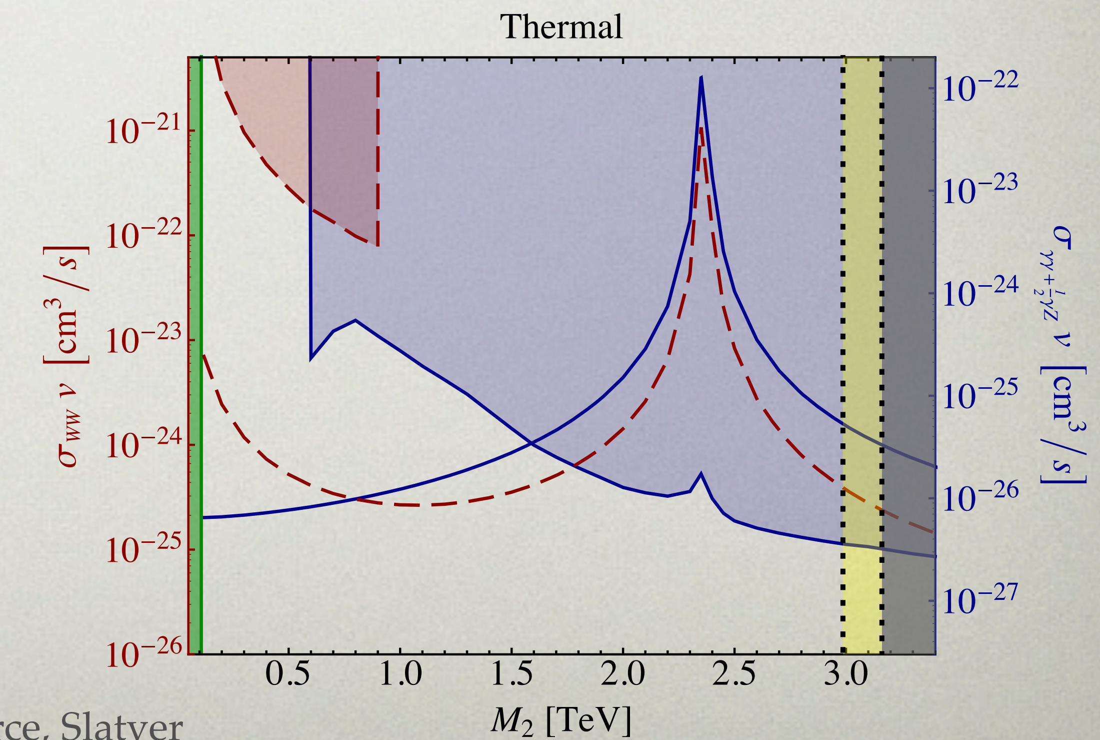
Large!

$$\langle \sigma v \rangle \sim \left(\frac{2 \text{ TeV}}{m_\chi} \right)^2 10^{-26} \text{cm}^3/\text{s}$$

Are there ways around for the Neutralino?

- Make the Neutralino a pure state -- coupling to Higgs vanishes
- However, Wino and Higgsino pure states can be probed by indirect detection





Cohen, Lisanti, Pierce, Slatyer

Are there ways around for the Neutralino?

- Bino escapes
- Pay a fine-tuning price

$$\mu \gg M_1 \sim m_{wk}$$

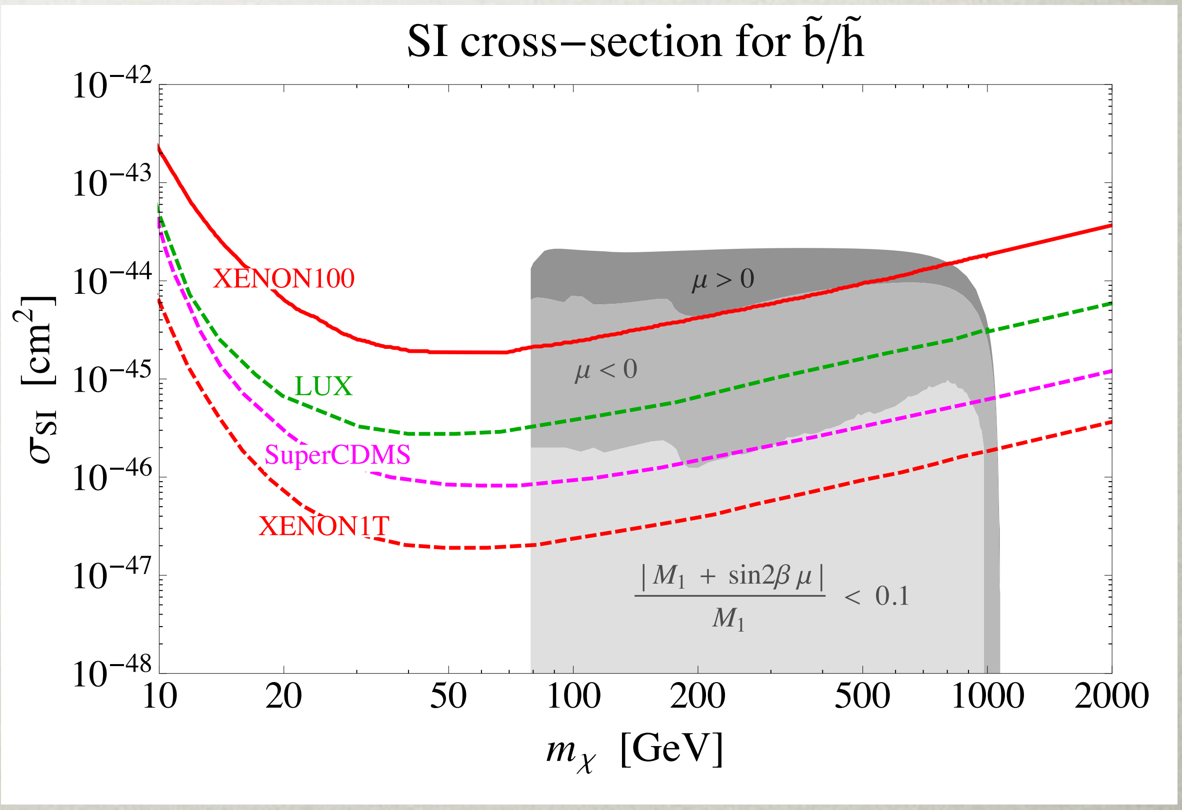
$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

Are there ways around for the Neutralino?

- Tune away the coupling to the Higgs
- Smaller cross-sections correspond to more tuning in the neutralino components

m_χ	condition
M_1	$M_1 + \mu \sin 2\beta = 0$
M_2	$M_2 + \mu \sin 2\beta = 0$
$-\mu$	$\tan\beta = 1$
M_2	$M_1 = M_2$

Cheung, Hall, Pinner, Ruderman

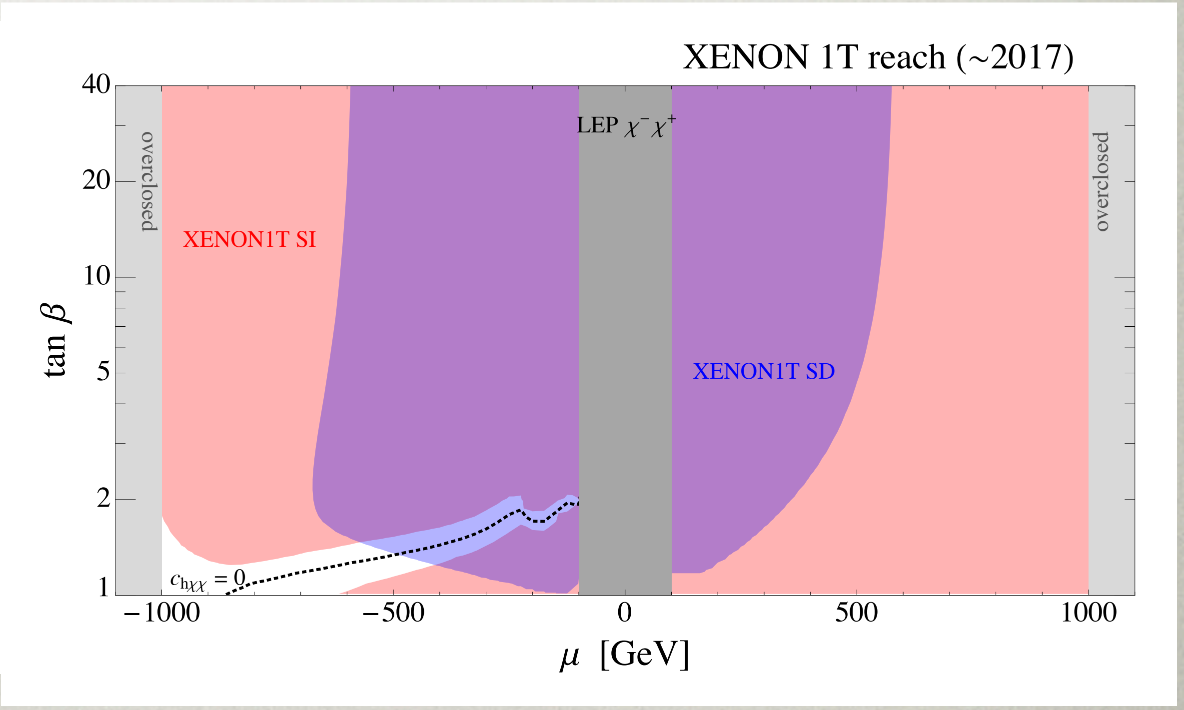


Are there ways around for the Neutralino?

m_χ	condition
M_1	$M_1 + \mu \sin 2\beta = 0$
M_2	$M_2 + \mu \sin 2\beta = 0$
$-\mu$	$\tan \beta = 1$
M_2	$M_1 = M_2$

- Tune away the coupling to the Higgs
- Smaller cross-sections correspond to more tuning in the neutralino components

Cheung, Hall, Pinner, Ruderman

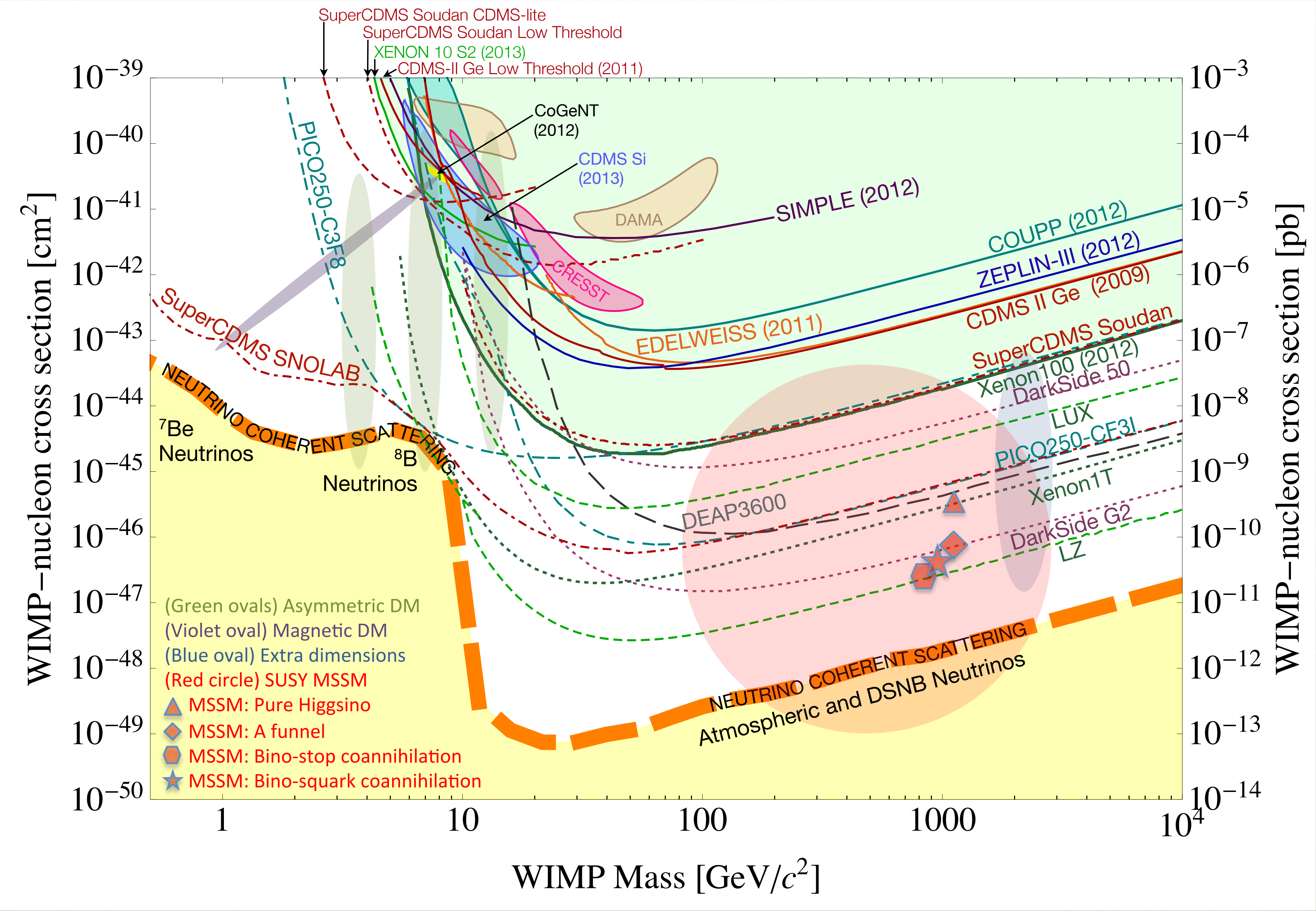


When Should We Start Looking Elsewhere?

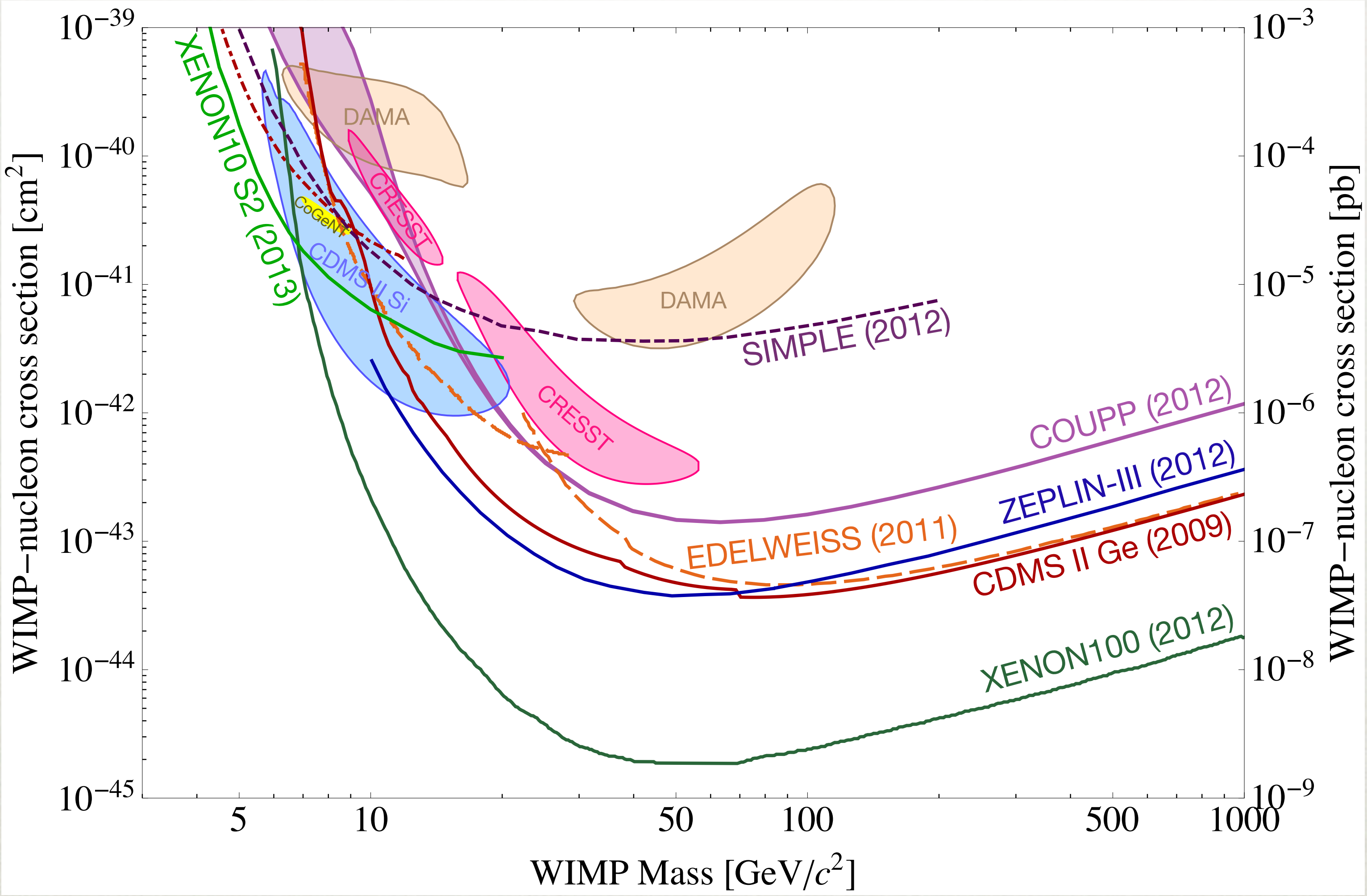
- Cannot kill neutralino DM via direct detection, but paradigm does become increasingly tuned
- Somewhat below Higgs pole -- Neutrino background?
- Well-motivated candidates that are much less costly to probe
- Light WIMPs

Terra Incognita

CF1 Snowmass report, 1310.8327

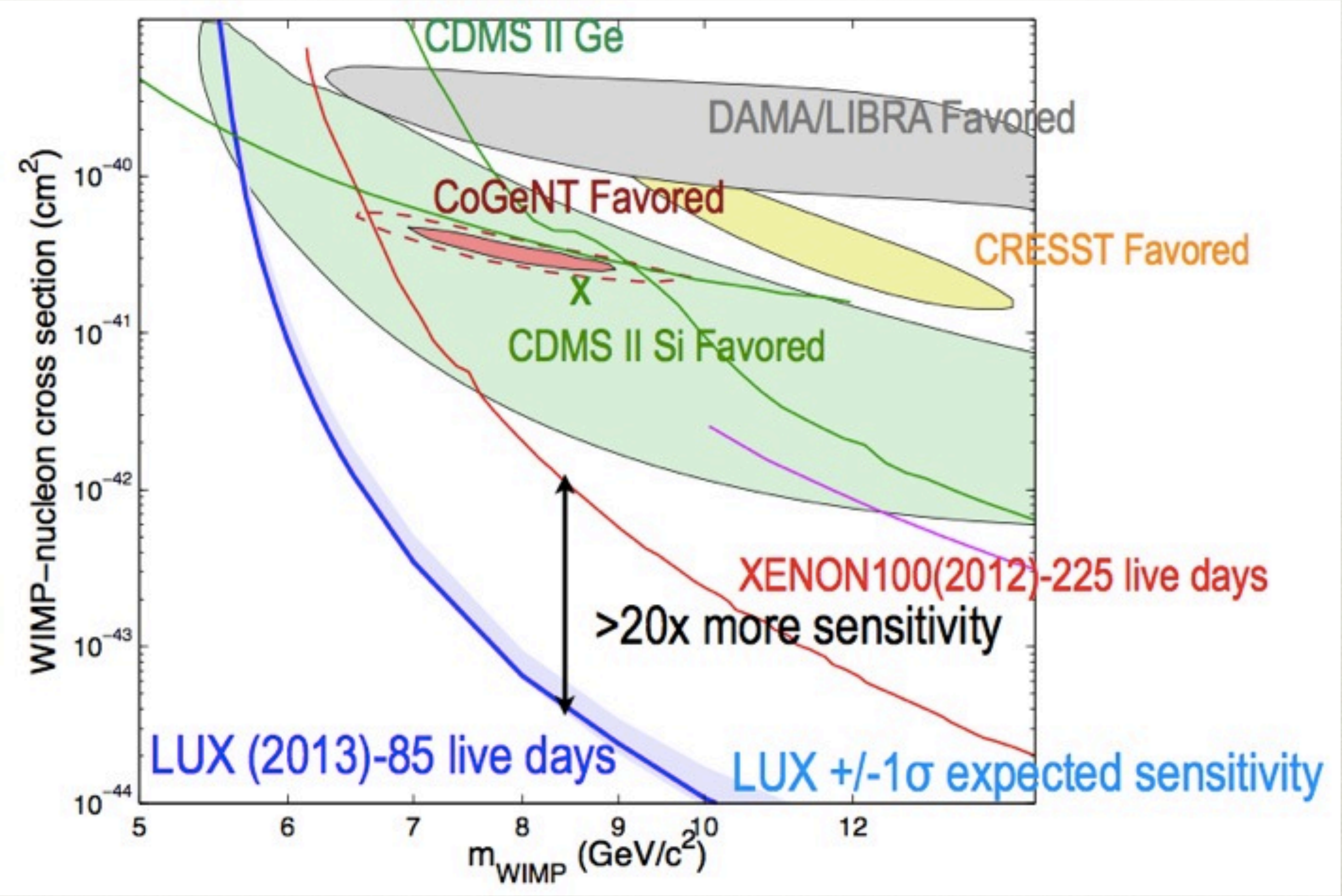


Current Sensitivity Limited



CF1 Snowmass report, 1310.8327

Anomalies and LUX

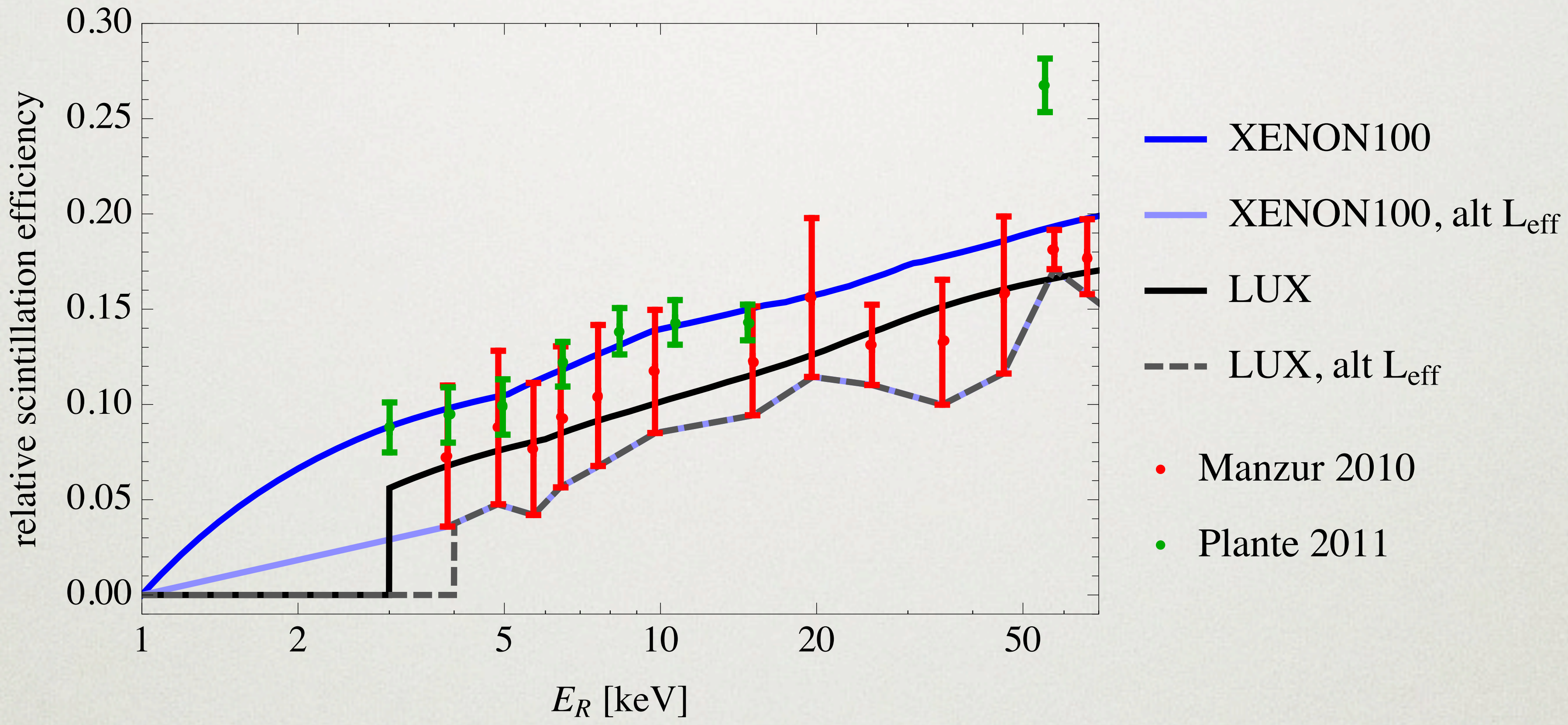


Uncertainties

- Experiment: Result assumes a particular choice of the energy calibration
- Theory: Also assumes spin-independent, momentum-independent scattering
- How do the results fare under more general assumptions?

Energy Calibration Uncertainties

Gresham, KZ 1311.2082

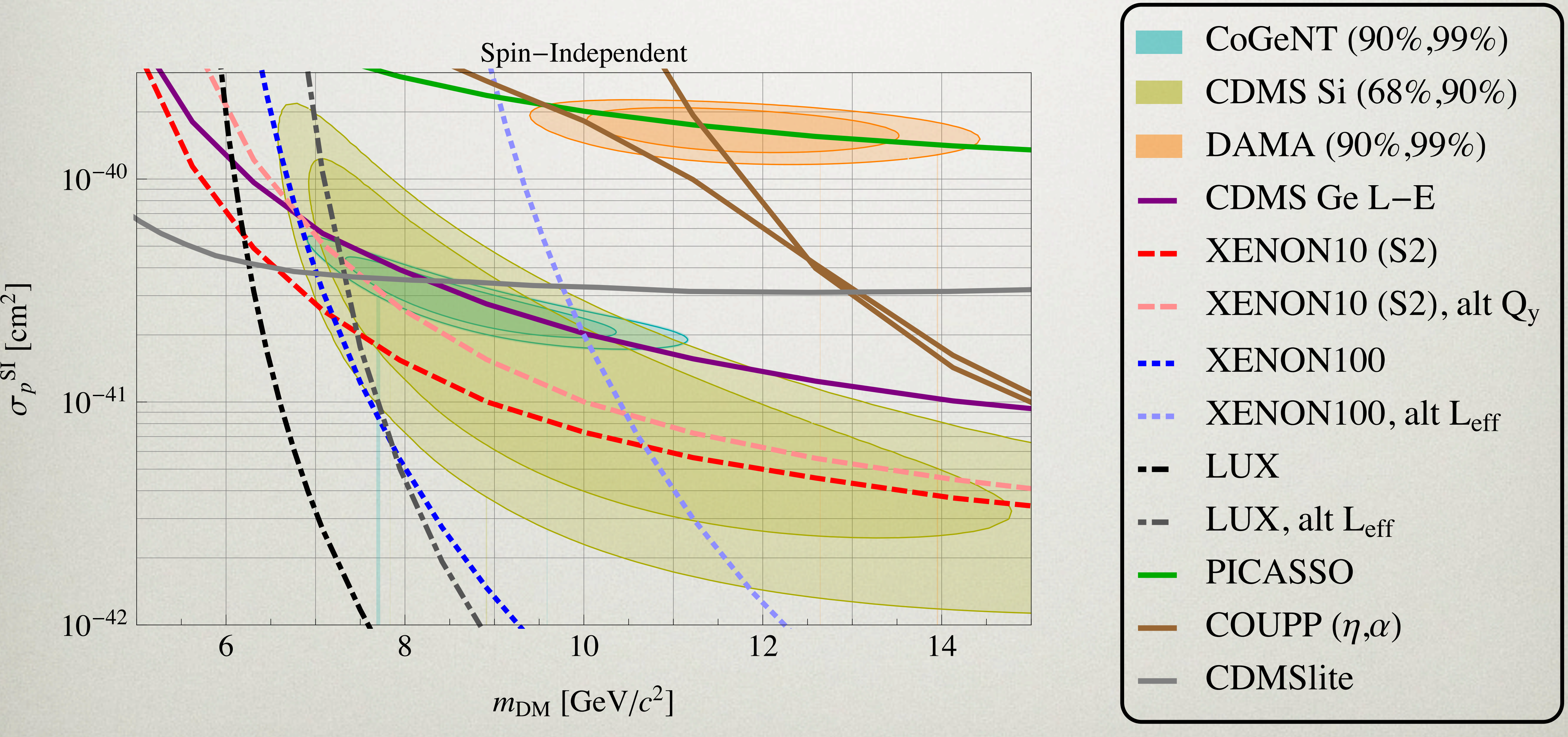


$$\nu(E_R) = \frac{S_{\rm nr}}{S_{\rm ee}} L_y E_R \mathcal{L}_{\rm eff}(E_R)$$

Amount of signal

Energy Calibration Uncertainties

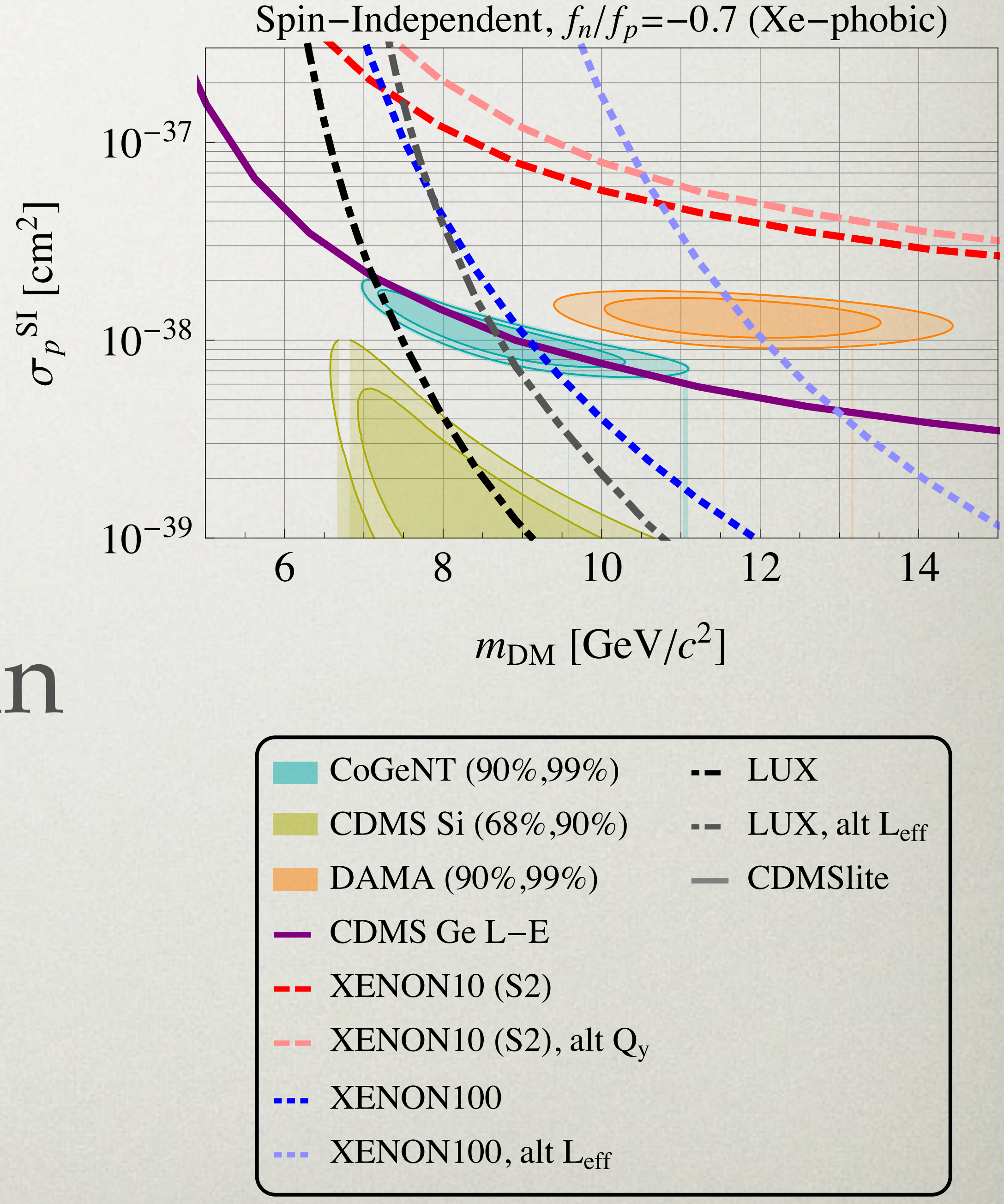
Gresham, KZ 1311.2082



Operator Uncertainties

Gresham, KZ 1311.2082

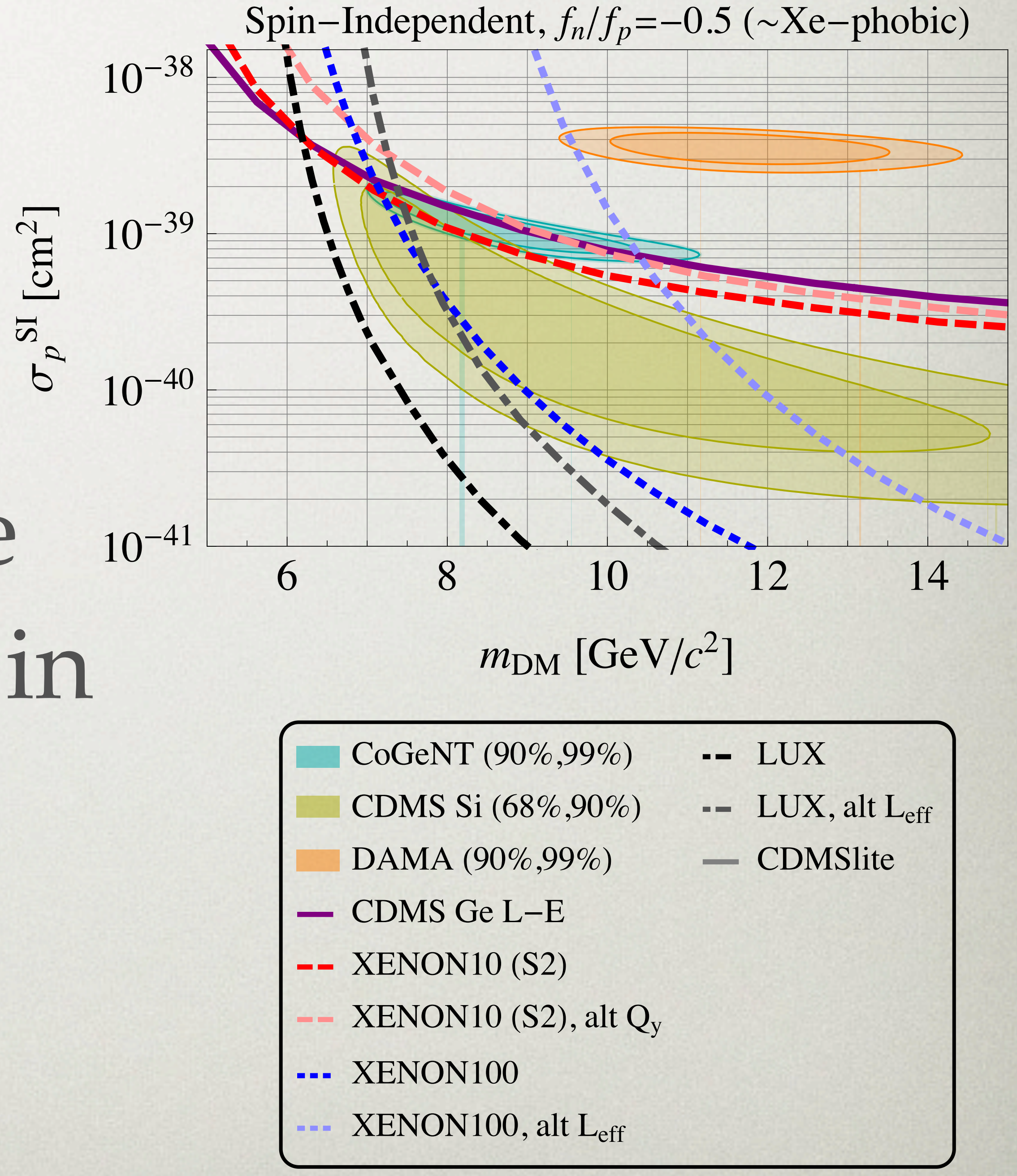
- Xenophobic -- tune away coupling to xenon
- However, none of the signal regions match in that case
- LUX constraints still strong



Operator Uncertainties

Gresham, KZ 1311.2082

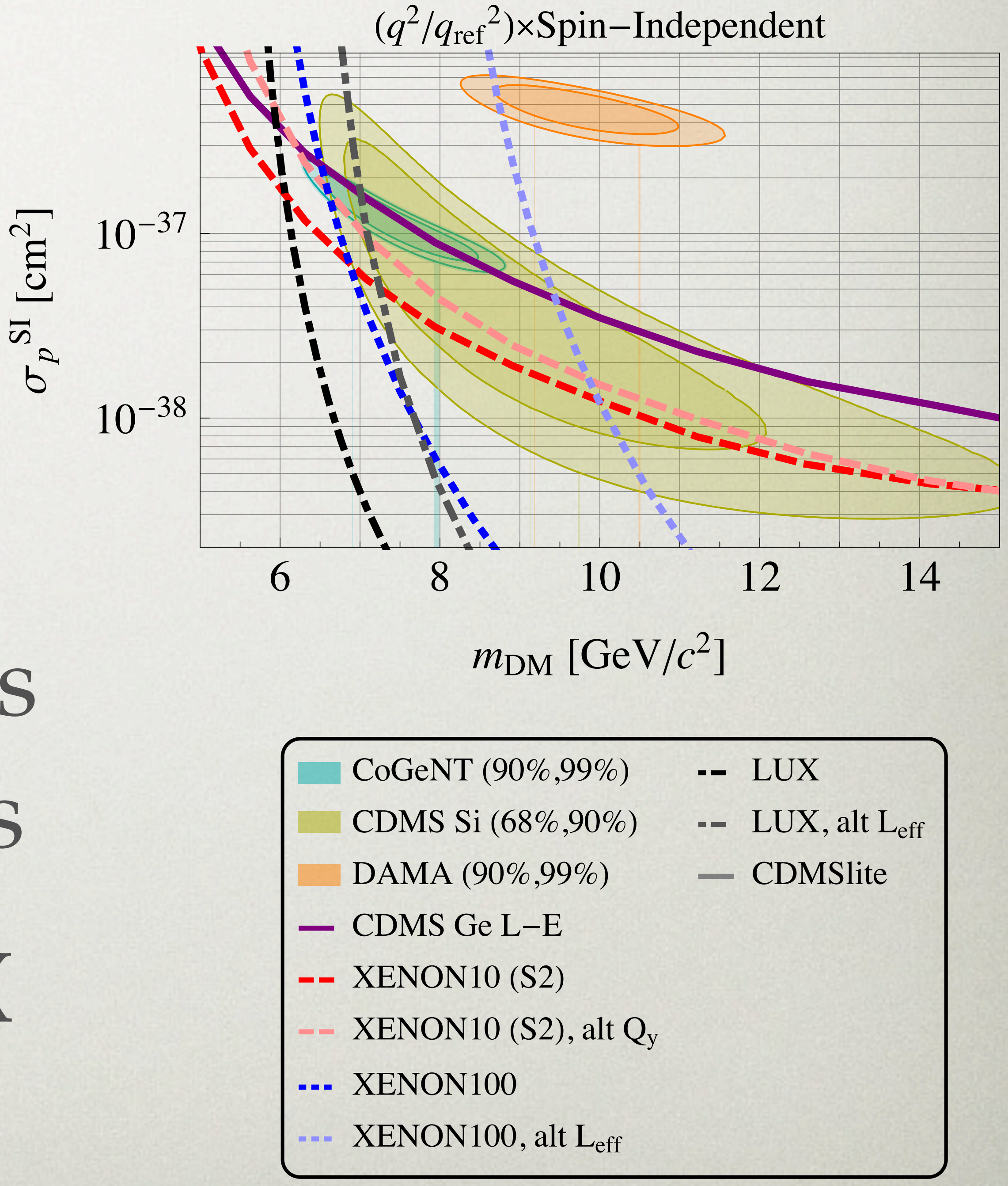
- Xenophobic -- tune away coupling to xenon
- However, none of the signal regions match in that case
- LUX constraints still strong



Operator Uncertainties

- Momentum dependent
- Shift allowed signal regions to lower mass relative to constraints
- Does not escape LUX

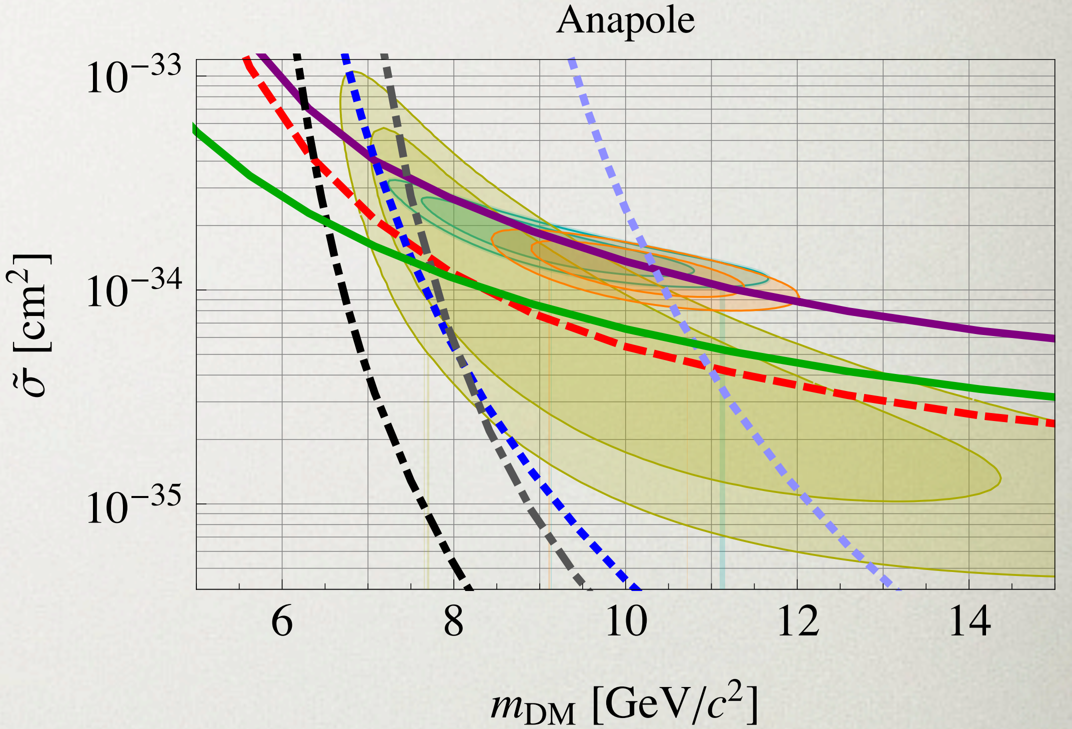
Gresham, KZ 1311.2082



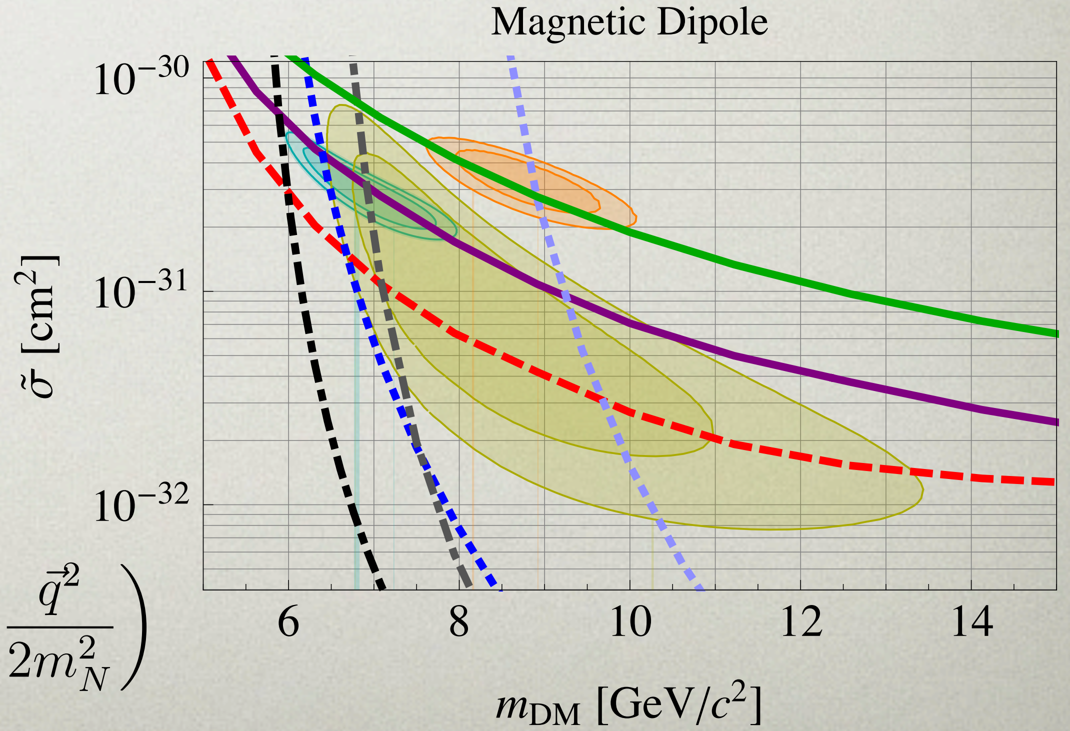
Operator Uncertainties

Gresham, KZ 1311.2082

- Anapole and Dipole operators do best job, but neither escapes constraints



$$\mathcal{O}_a = \bar{\chi}\gamma^\mu\gamma_5\chi A_\mu$$
$$\mathcal{O}_d = \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}/\Lambda$$



$$\sigma_N^a = f_a^2\frac{\mu_N^2}{\pi M^4}\left(Z^2F^2(A;\vec{q}^2)\left(\vec{v}^2-\frac{\vec{q}^2}{4\mu_N^2}\right)+\frac{J+1}{3J}g_N^2A^2\frac{\vec{q}^2}{2m_N^2}\right)$$
$$\sigma_N^d = f_d^2\frac{\mu_N^2}{\pi M^4}\frac{\vec{q}^2}{\Lambda^2}\left(Z^2F^2(A;\vec{q}^2)\left(\vec{v}^2-\frac{\vec{q}^2}{4\mu_N^2}+\frac{\vec{q}^2}{4m_{\rm DM}^2}\right)+\frac{J+1}{3J}g_N^2A^2\frac{\vec{q}^2}{2m_N^2}\right)$$

Contact with Nuclear Physics

- Signals have cause DM theorists to look beyond the simplest types of DM-nucleus interactions
- From spin-dependent and spin-independent to
  - anapole DM
  - electric and magnetic dipole DM
  - momentum dependent DM

Contact with Nuclear Physics

- These interactions are theoretically well-motivated

$$\mathcal{L}_{\rm int}^{\rm anapole} = \frac{f_a}{M^2}\bar{\chi}\gamma^\mu\gamma^5\chi\mathcal{J}_\mu^{\rm EM}$$

$$\mathcal{L}_{\rm int}^{\rm magnetic\ dipole} = \frac{f_{\rm md}}{M^2}\bar{\chi}\frac{i\sigma^{\mu\nu}q_\nu}{\Lambda}\chi\mathcal{J}_\mu^{\rm EM}$$

$$\mathcal{L}_{\rm int}^{\rm electric\ dipole} = \frac{f_{\rm ed}}{M^2}\bar{\chi}\frac{\sigma^{\mu\nu}q_\nu\gamma^5}{\Lambda}\chi\mathcal{J}_\mu^{\rm EM}$$

$$\mathcal{L}_{\rm int}^{\rm pseudoscalar} = \frac{1}{M^2}\sum_{N=n,p}\left(f_1^N i\bar{\chi}\gamma^5\chi\bar{N}N + f_2^N i\bar{\chi}\chi\bar{N}\gamma^5 N + f_3^N\bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N\right)$$

- But the proper modeling of the nuclear response has not been taken into account until recently

X		$\frac{4\pi}{2J+1}W_X^{(p,p)}(0)$
M	spin-independent	Z^2
Σ''	spin-dependent (longitudinal)	$4\frac{J+1}{3J}\langle S_p\rangle^2$
Σ'	spin-dependent (transverse)	$8\frac{J+1}{3J}\langle S_p\rangle^2$
Δ	angular-momentum-dependent	$\frac{1}{2}\frac{J+1}{3J}\langle L_p\rangle^2$
Φ''	angular-momentum-and-spin-dependent	$\sim\langle\vec{S}_p\cdot\vec{L}_p\rangle^{2\rm a}$

Fitzpatrick, Haxton, Katz et al
1203.3542, 1211.2818, 1308.6288

Does it matter?

- Put into the context of sensible UV completions

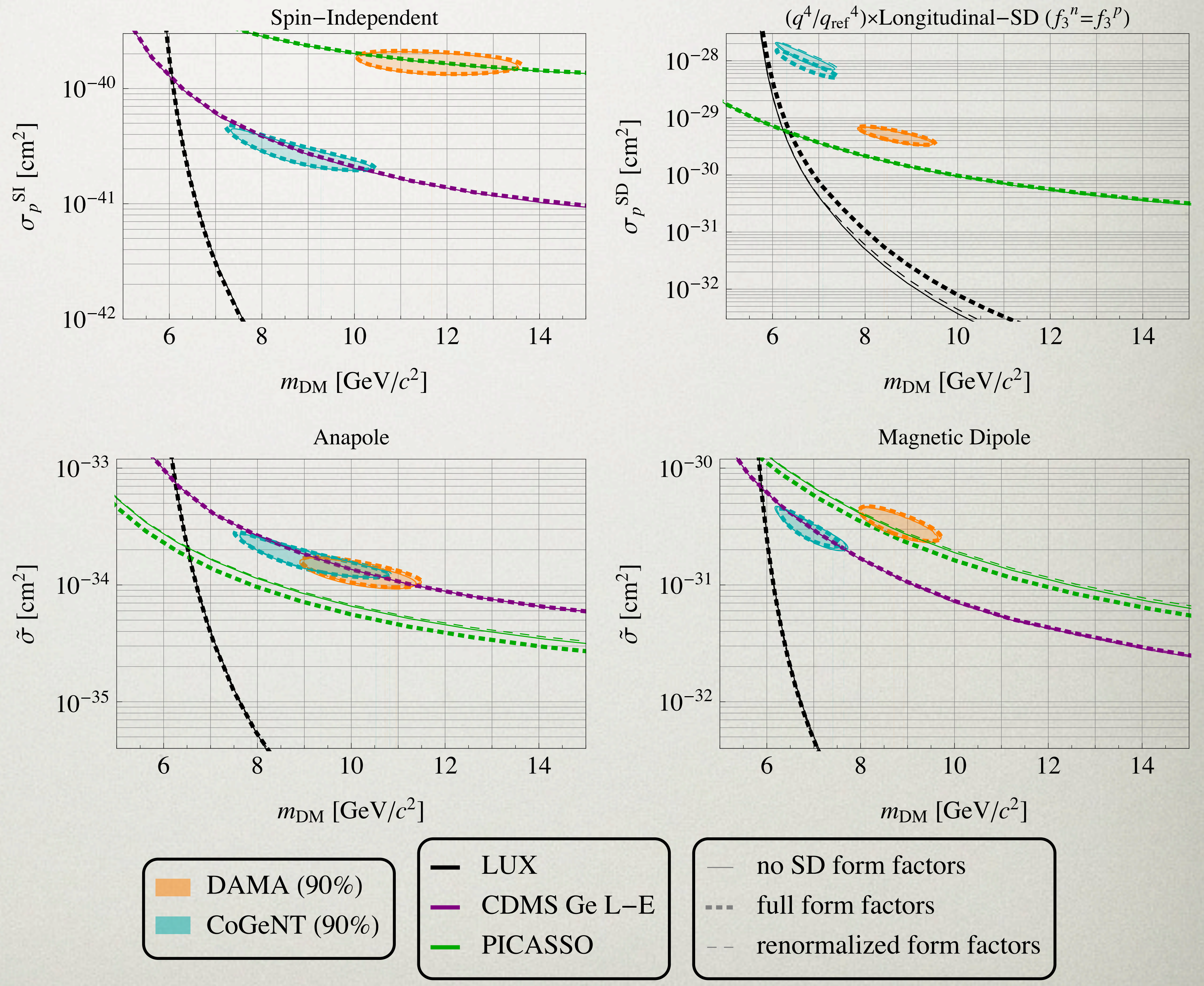
Model	Relativistic Ops.	Nonrel. Ops.	Resp.
pseudo-mediated	$\mathcal{O}_2^{\rm rel}=i\bar{\chi}\chi\bar{N}\gamma^5 N$	$\mathcal{O}_{10}=i\vec{S}_N\cdot\frac{\vec{q}}{m_N}$	Σ''
	$\mathcal{O}_3^{\rm rel}=i\bar{\chi}\gamma^5\chi\bar{N}N$	$\mathcal{O}_{11}=i\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}$	M
	$\mathcal{O}_4^{\rm rel}=\bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N$	$\mathcal{O}_6=(\vec{S}_\chi\cdot\frac{\vec{q}}{m_N})(\vec{S}_N\cdot\frac{\vec{q}}{m_N})$	Σ''
magnetic dipole	$\mathcal{O}_9^{\rm rel}=\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\frac{K_\mu}{m_M}\bar{N}N$	$\mathcal{O}_1=\mathbf{1}_\chi\mathbf{1}_N, \mathcal{O}_5=i\vec{S}_\chi\cdot(\frac{\vec{q}}{m_N}\times\vec{v}^\perp)$	M,Δ
	$\mathcal{O}_{10}^{\rm rel}=\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\mathcal{O}_4=\vec{S}_\chi\cdot\vec{S}_N, \mathcal{O}_6$	Σ'',Σ'
anapole	$\mathcal{O}_{13}^{\rm rel}=\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$	$\mathcal{O}_8=\vec{S}_\chi\cdot\vec{v}^\perp$	M,Δ
	$\mathcal{O}_{14}^{\rm rel}=\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\frac{i\sigma_{\mu\nu}q^\nu}{m_M}N$	$\mathcal{O}_9=i\vec{S}_\chi\cdot(\vec{S}_N\times\frac{\vec{q}}{m_N})$	Σ'
electric dipole	$\mathcal{O}_{17}^{\rm rel}=i\frac{P^\mu}{m_M}\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$	$\mathcal{O}_{11}=i\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}$	M
	$\mathcal{O}_{18}^{\rm rel}=i\frac{P^\mu}{m_M}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\frac{i\sigma_{\mu\nu}q^\nu}{m_M}N$	$\mathcal{O}_{11},\mathcal{O}_{15}=-\left(\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}\right)\left((\vec{S}_N\times\vec{v}^\perp)\cdot\frac{\vec{q}}{m_N}\right)$	M,Φ'',Σ'
$\vec{L}\cdot\vec{S}$-generating	$\mathcal{O}_5^{\rm rel}=\frac{P^\mu}{m_M}\bar{\chi}\chi\frac{K_\mu}{m_M}\bar{N}N$	$\mathcal{O}_1$	M
	$\mathcal{O}_6^{\rm rel}=\frac{P^\mu}{m_M}\bar{\chi}\chi\bar{N}\frac{i\sigma_{\mu\nu}q^\nu}{m_M}N$	$\mathcal{O}_1,\mathcal{O}_3=i\vec{S}_N\cdot\left(\frac{\vec{q}}{m_N}\times\vec{v}^\perp\right)$	M,Φ'',Σ'
	and $\mathcal{O}_{10}^{\rm rel}$ (see above)		

- Under what circumstances should one be concerned?

Gresham, KZ 1401.3739

Light Dark Matter

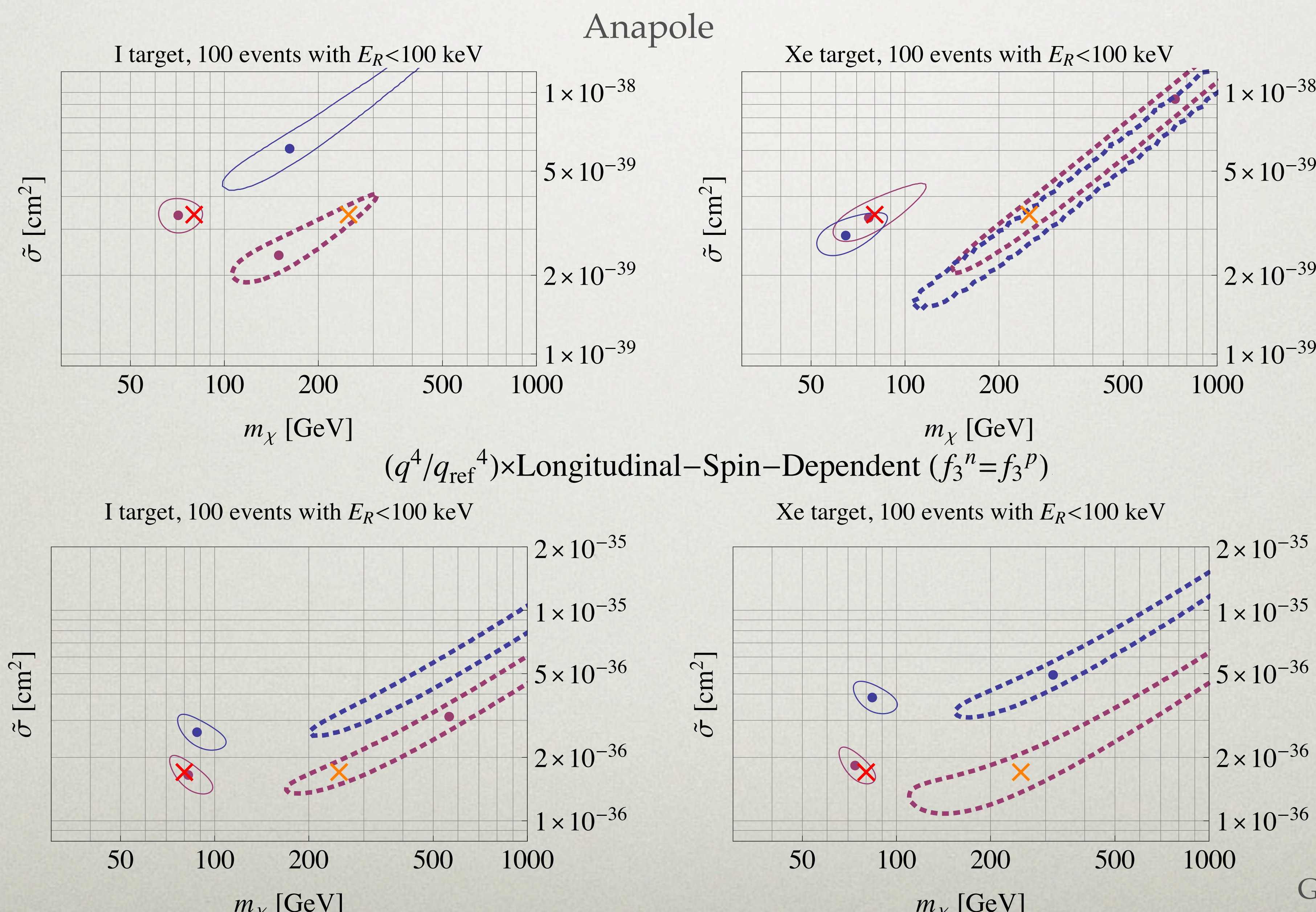
- Low momentum transfer; essentially irrelevant once properly normalized



Gresham, KZ 1401.3739

Heavy Dark Matter

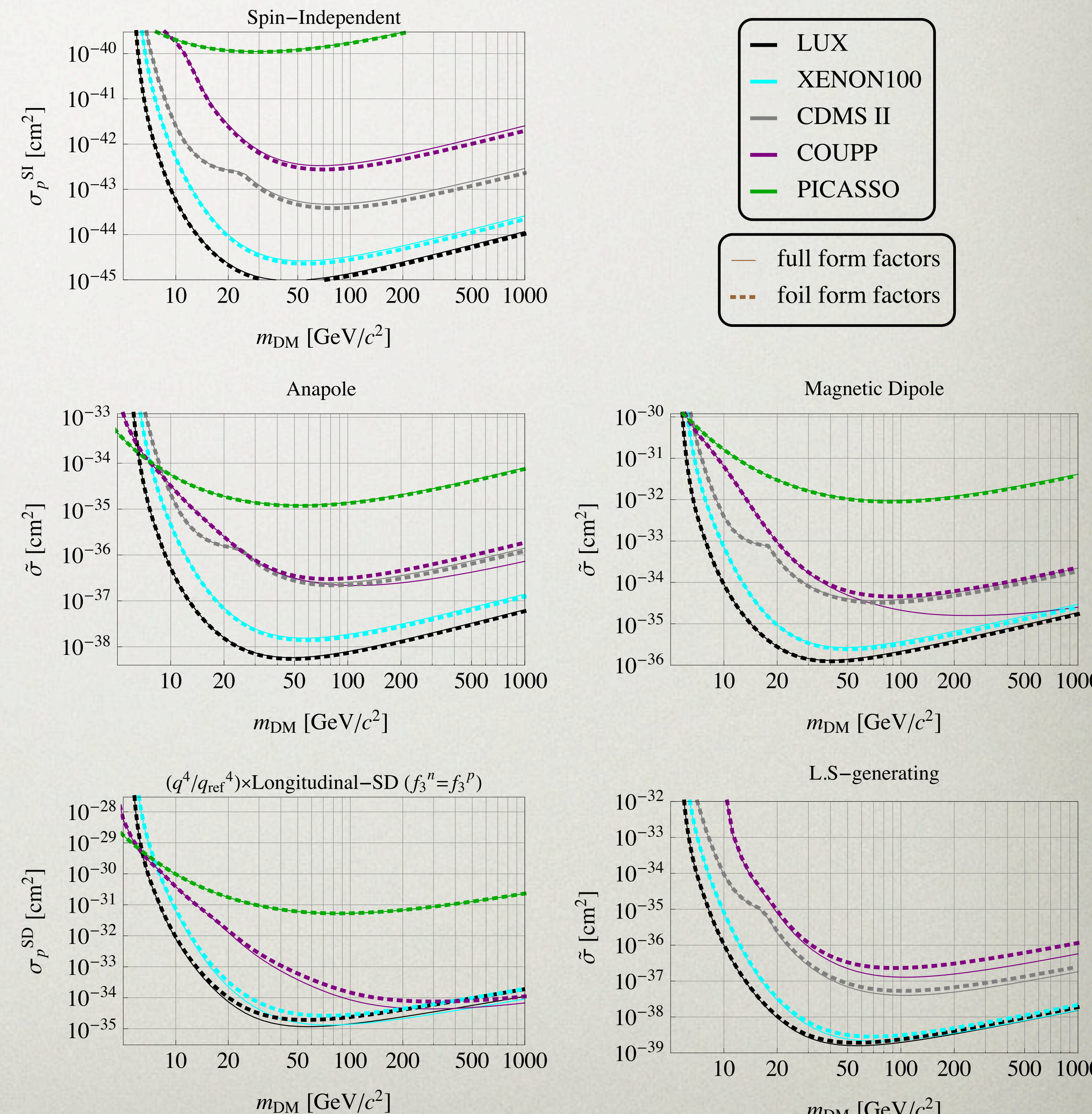
- Potentially important for certain elements; simulated signal



Gresham, KZ 1401.3739

Heavy Dark Matter

- Mostly not relevant for current constraints, except COUPP
- Would be relevant for Xenon, except for low recoil



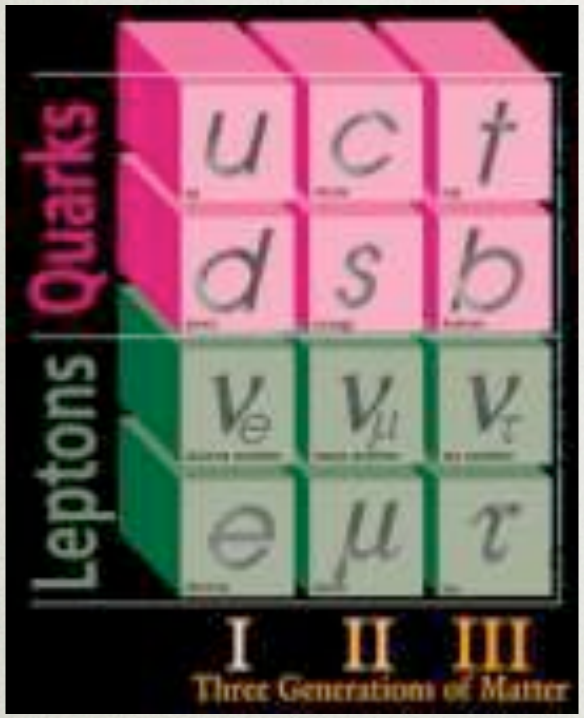
Gresham, KZ 1401.3739

Summary

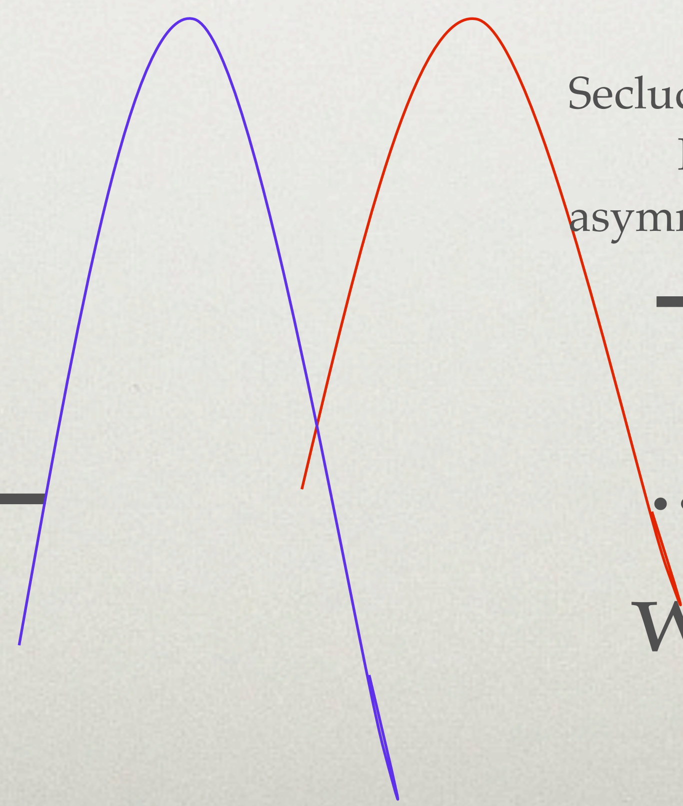
- The window for the standard WIMP is closing, though it will be difficult to close completely
- Well-motivated lower mass candidates, though purported signals seem in substantial tension with constraints
- Signals have pushed us to look at non-standard types of interactions, but must be careful to appropriately attach nuclear physics

Hidden Dark Worlds

Our thinking has shifted



From a single, stable weakly interacting particle ..... (WIMP, axion)



Models: Supersymmetric light DM sectors, Secluded WIMPs, WIMPless DM, Asymmetric DM .....
Production: freeze-in, freeze-out and decay, asymmetric abundance, non-thermal mechanicsms .....

$M_p \sim 1$ GeV

Standard Model

...to a hidden world with multiple states, new interactions