LUX Sensitivity to Effective Field Theory Interactions

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Direct Detection Basics

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_A} \underbrace{\int_{v>v_{min}} v f(\vec{v}) \frac{d\sigma}{dE_R} d^3v}_{\text{Average over WIMP velocity distribution}}$$

Differential event rate with respect to recoil energy (events/keV/kg/day)

Differential cross-section

Average over WIMP velocity distribution

- WIMP-nucleon recoil spectrum is approximately a decaying exponential
- f(v) depends on halo model:
  - “Spherical cow” model: Maxwellian distribution truncated at galactic v_{escape} = 544 km/s
  - Accounts for Earth’s motion through galaxy (220 km/s + annual modulation)
- Local dark matter density also depends on halo model ($\rho_0 \sim 0.3$ GeV/cm^3)
- Differential cross section:

$$\frac{d\sigma}{dE_R} = \frac{m_A}{2\pi v^2} |\mathcal{M}|^2$$

FERMI’S GOLDEN RULE

Scattering amplitude $|M|^2$ contains all the particle physics

An EFT Framework for Direct Detection

Standard SI+SD-only WIMP scattering analyses assume a point-nucleus limit with non-relativistic momenta but…

- Tension between experiments and the lack of a definitive positive detection suggest it is prudent to look for new interactions!
  - Parton momenta inside the nucleus are not necessarily small (q ~ 1/r)
  - New operators could add corrections to SI or SD interactions that are momentum- or velocity-dependent…
  - … or produce entirely new nuclear responses that interfere with SI, SD interactions
- Would like to address possible WIMP-nucleon interactions in a complete and model-independent way

Fitzpatrick et al. arXiv:1203.3542
Fitzpatrick et al. arxiv:1211.2818

Anand et al. arXiv: 1308.6288
Anand et al. arXiv: 1405.6690

A Complete Set of EFT Interactions

$$\mathcal{L}_{\rm int} = c\,\Psi^*_\chi\,\mathcal{O}_\chi\Psi_\chi\,\Psi^*_N\,\mathcal{O}_N\Psi_N = \sum_{i=1}^{\mathcal{N}}\left(c_i^{(n)}\mathcal{O}_i^{(n)} + c_i^{(p)}\mathcal{O}_i^{(p)}\right)$$

- O_i restricted to be Galilean-invariant and Hermitian
- Allowed building blocks are WIMP spin S_χ, nucleon spin S_N, incident velocity v^2, momentum transfer q^2.

SI Interaction

$$\mathcal{O}_1 = 1$$

Cannot obtain at lowest order

$$\mathcal{O}_2 = (v^\perp)^2$$

$$\mathcal{O}_3 = i\vec{S}_N\cdot(\vec{q}\times\vec{v}^\perp)$$

SD Interaction

$$\mathcal{O}_4 = \vec{S}_\chi\cdot\vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi\cdot(\vec{q}\times\vec{v}^\perp)$$

$$\mathcal{O}_6 = (\vec{S}_\chi\cdot\vec{q})(\vec{S}_N\cdot\vec{q})$$

$$\mathcal{O}_7 = \vec{S}_N\cdot\vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi\cdot\vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi\cdot(\vec{S}_N\times\vec{q})$$

$$\mathcal{O}_{10} = i\vec{S}_N\cdot\vec{q}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi\cdot\vec{q}$$

Exotic; do not arise from exchange of a spin-0 or spin-1 mediator

$$\mathcal{O}_{12} = \vec{S}_\chi\cdot(\vec{S}_N\times\vec{v}^\perp)$$

$$\mathcal{O}_{13} = i(\vec{S}_\chi\cdot\vec{v}^\perp)(\vec{S}_N\cdot\vec{q})$$

$$\mathcal{O}_{14} = i(\vec{S}_\chi\cdot\vec{q})(\vec{S}_N\cdot\vec{v}^\perp)$$

$$\mathcal{O}_{15} = -(\vec{S}_\chi\cdot\vec{q})((\vec{S}_N\times\vec{v}^\perp)\cdot\vec{q})$$

$$\mathcal{O}_{16} = -((\vec{S}_\chi\times\vec{v}^\perp)\cdot\vec{q})(\vec{S}_N\cdot\vec{q})$$

Linear combo. of O_{12} and O_{15}

Nuclear Responses

M	Σ''	Σ'	Δ	Φ''	$\tilde{\Phi}'$
SI	**SD longitudinal**	**SD transverse**	**LD (ang.-mom.-dependent)**	**LSD (spin-orbit)**	**Tensor LSD**

- **All interactions are linear combos. of 6 independent nuclear responses**
- **These are the leading-order multipoles that show up in terms of the nuclear scattering matrix – depend only on the nuclear physics of the target**

SI Interaction $\mathcal{O}_1 = 1$

~~$\mathcal{O}_2 = (v^\perp)^2$~~

Spin-orbit $\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp)$

SD (both components) $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

Ang.-mom.-dep. $\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp)$

SD (longitudinal only) $\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$

$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$

$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$ **SD (transverse only)**

$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}$

$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}$ **SI**

$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$

$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \vec{q})$ **Tensor spin-orbit**

$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{v}^\perp)$

$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \vec{q})((\vec{S}_N \times \vec{v}^\perp) \cdot \vec{q})$

~~$\mathcal{O}_{16} = -((\vec{S}_\chi \times \vec{v}^\perp) \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$~~

Direct Detection of Interactions

The scattering amplitude can then be written as

$$|\mathcal{M}|^2 \equiv \frac{m_A^2}{m_N^2} \sum_{i,j} \sum_{N,N'=n,p} c_i^N c_j^{N'} F_{i,j}^{(N,N')}$$

where:

- c_i, c_j are the WIMP-nucleon coupling constants for operators O_i and O_j
- $F_{i,j}$ is a form factor that contains all the particle and nuclear physics
- Each $F_{i,j}$ is a linear combination of nuclear responses $F_{k\,=}$ M, Σ”, Σ’, Δ, Φ”, Φ’:

$$F_{i,j}^{(N,N')} = \sum_{k=\mathrm{M},\Sigma'',\Sigma',\Delta,\Phi'',\tilde{\Phi}'} a_{ijk} F_k^{(N,N')}$$

- Calculate the F_k numerically using your favorite method, e.g. nuclear shell model

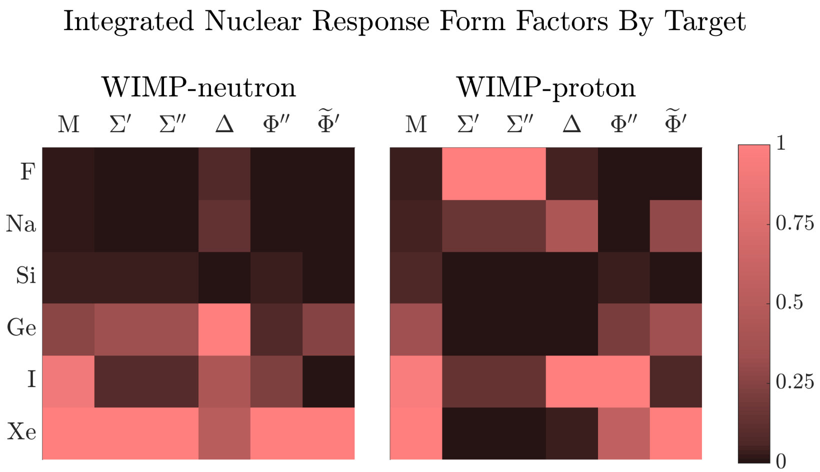
WIMP-Nucleon Sensitivity by Target

M (SI): Response goes as A^2; favors heavy targets (e.g. Xe, I).

Σ”, Σ’ (SD): The two components can appear independently; each favors targets with unpaired neutrons (e.g. ^{73}Ge, ^{129}Xe, ^{131}Xe) or protons (^{19}F, ^{127}I).

Δ (LD): Arises from operators dependent on nucleon velocities. Favors targets with high A.

Φ”, Φ’ (LSD, tLSD): Favor elements with unfilled orbitals above the *s*-shell; only targets with spin > 1 are sensitive (e.g. ^{131}Xe).



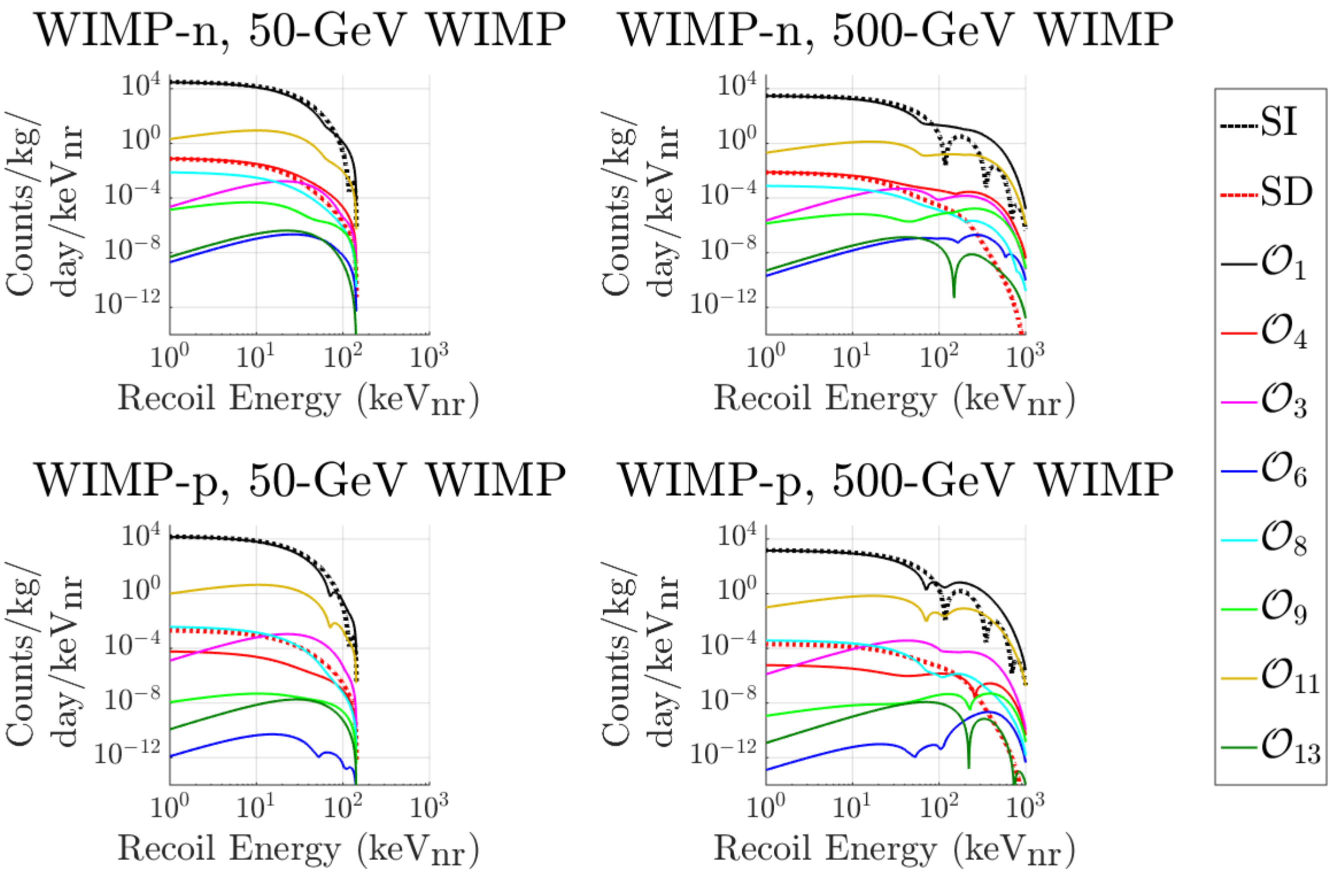
Plot adapted from Fitzpatrick et al. arXiv:1203.3542

Xenon is sensitive to all but WIMP-proton Σ”, Σ’

This can be overcome by:

- **The large size and scalability of xenon-based detectors**
- **Complementarity of targets**

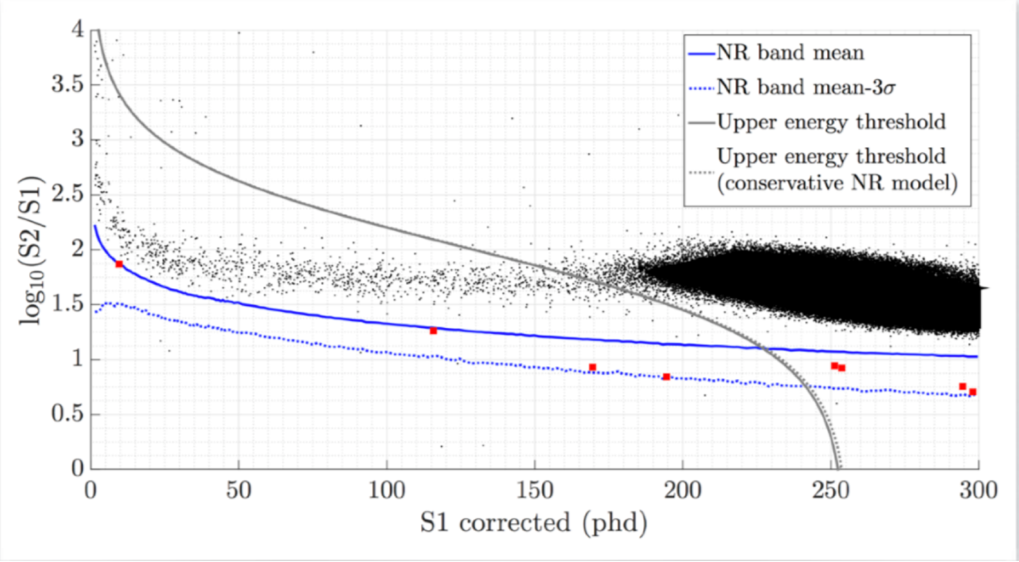
Selected WIMP-Nucleon Recoil Spectra in Xenon



- SI and SD spectra are approximately decaying exponentials.
- For other operators, the momentum dependence affects the spectral shape.
- Spectra for large m_χ stay flat or rise out to O(100-1000) keV!

An EFT Analysis of the First LUX Science Run

- LUX is a dual-phase 370-kg xenon-based TPC whose 2013, 2014-2016 runs set world-leading** constraints on SI WIMP-nucleon scatters (see M. Szydagis talk)
- 2013 LUX WIMP search run: 118 kg fiducial volume * 94.98 livedays



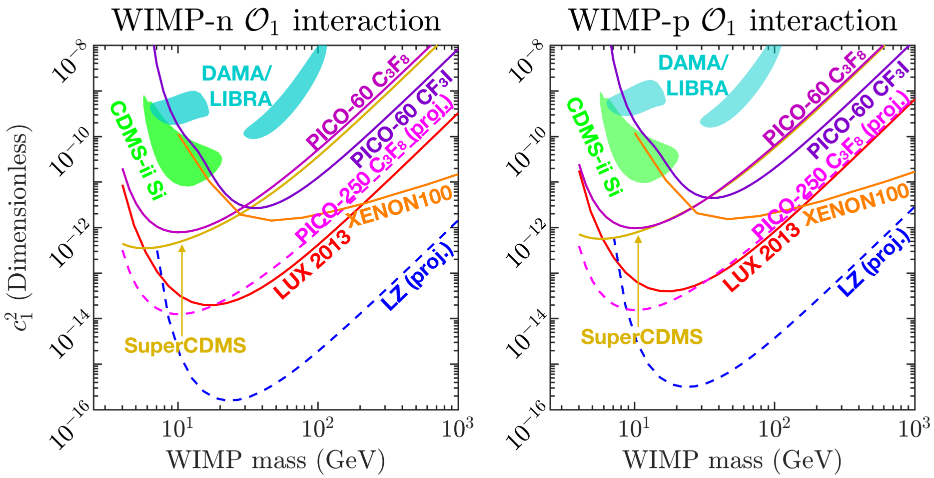
- For EFT interactions:
  - Large upper energy threshold desirable but limited by available calibration data and ^{83m}Kr events in the WIMP search dataset
  - Choose E_{upper} = 30 keV_{ee} (Kr mean - 5σ) = 168.7 keV_{nr}. Limits are robust to +/- 1σ variations in the NR model
  - Remove events >3σ below the NR band mean
  - 4 events observed; 4.78 background events expected
  - Computationally expensive => Feldman-Cousins cut-and-count approach

** XENON1T now in the lead

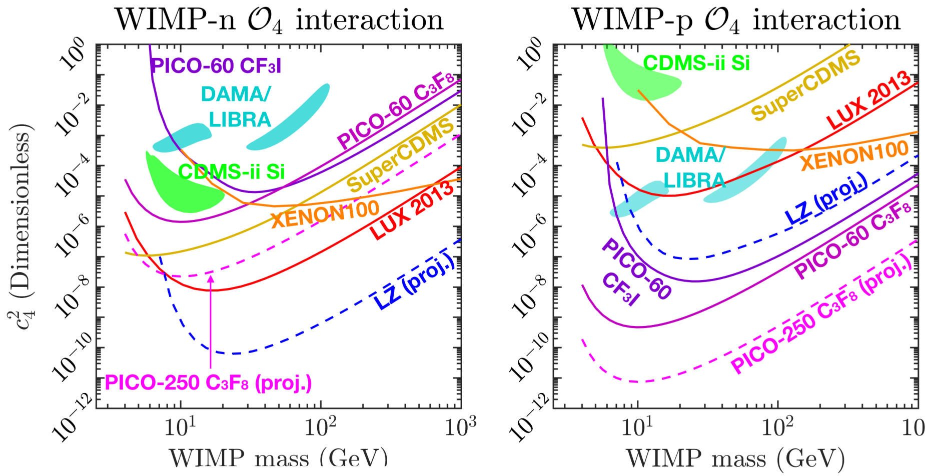
Comparing LUX to Other Experiments

	Experiment	Target	Exposure	Reference
Consistent with Background	LUX	Xe	118 kg * 94.98d	PRL 116, 161301 (2016)
	SuperCDMS	Ge	577 kg*d	PRD 91, 092004 (2015) and PRL 112, 241302 (2014)
	PICO-2L	C_3F_8	129 kg*d	PRD 93, 061101 (2016) and PRL 114, 231302 (2015)
	PICO-60 (CF_3I)	CF_3I	1335 kg*d	PRD 93, 052014 (2016)
	PICO-60 (C_3F_8)	C_3F_8	1167 kg*day	PRL 118, 251301 (2017)
	XENON100	Xe	34 kg * 224.6 d	PRD 96, 042004 (2017)
Excess of Events	DAMA/LIBRA	NaI	0.82 ton * year	EPJ C56 333-355 (2008) and JCAP04 ID010 (2009)
	CDMS-ii Si	Si	23.4 kg*d	Arxiv:1304.4279v3
Projections	LZ	Xe	5600 kg * 1000d	Arxiv:1509.02910
	PICO-250	C_3F_8	250 kg * 1000d	EPJ Web Conf. 95 (2015) 04020

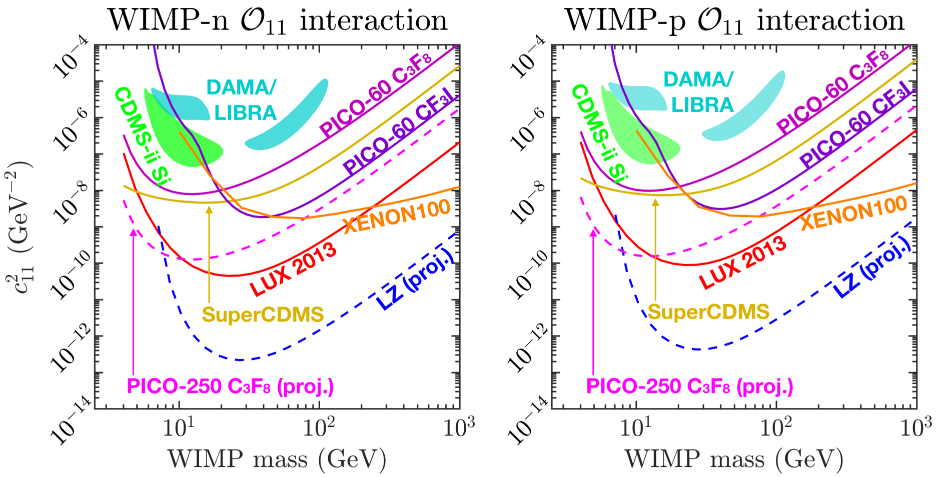
Limits on Selected Operators



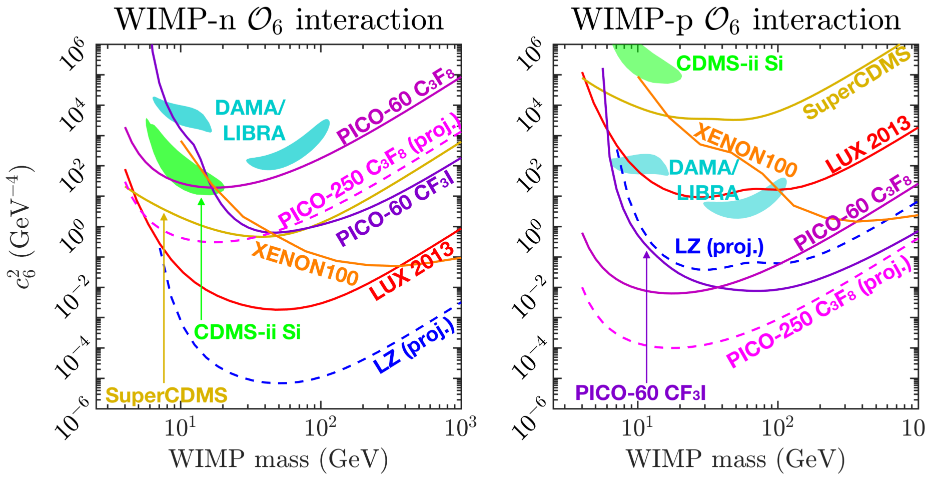
M **(Standard SI)**



$\Sigma'' + \Sigma'$ **(Standard SD)**

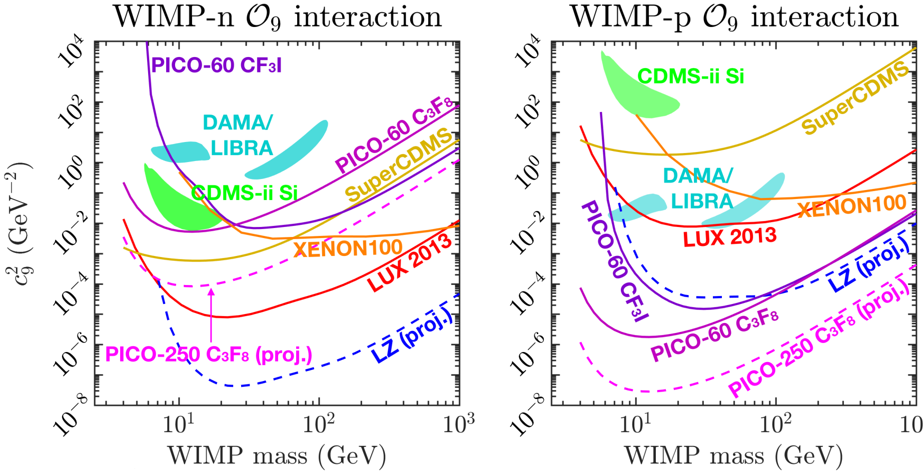


M, **q^2-dependence**

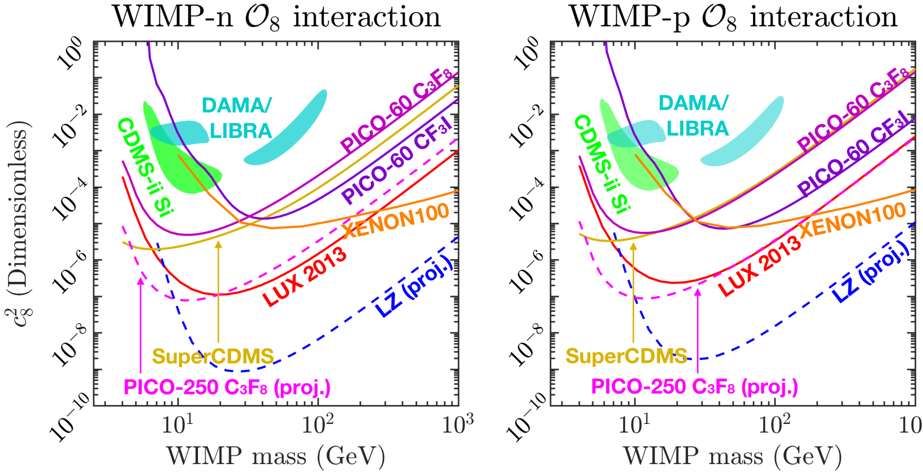


Σ'' **(SD longitudinal), q^4-dependence**

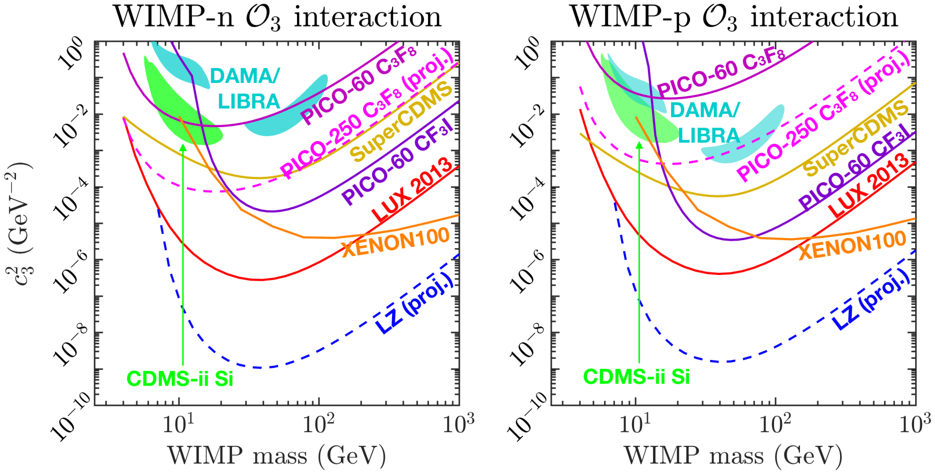
Limits on Selected Operators



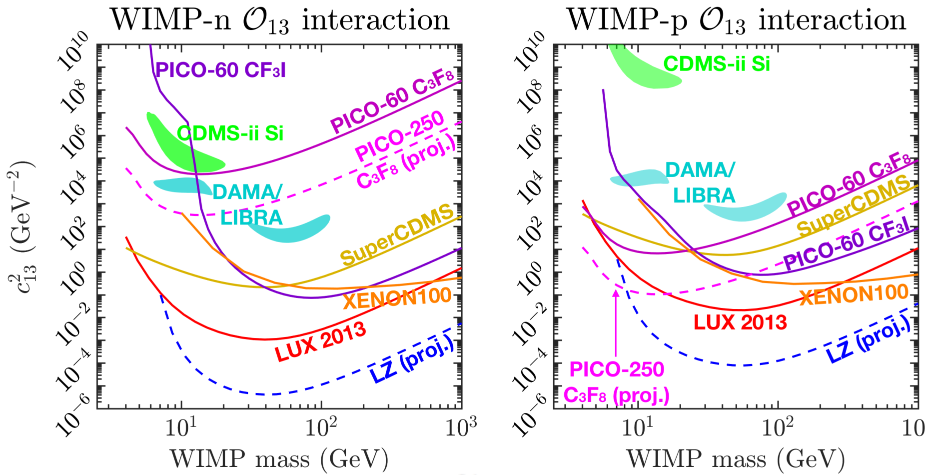
Σ' (SD transverse), q2-dependence



M, Δ (LD)



Σ', Φ'' (LSD)



Σ'', $\tilde{\Phi}'$ (tLSD)

Isospin-Independent Limits

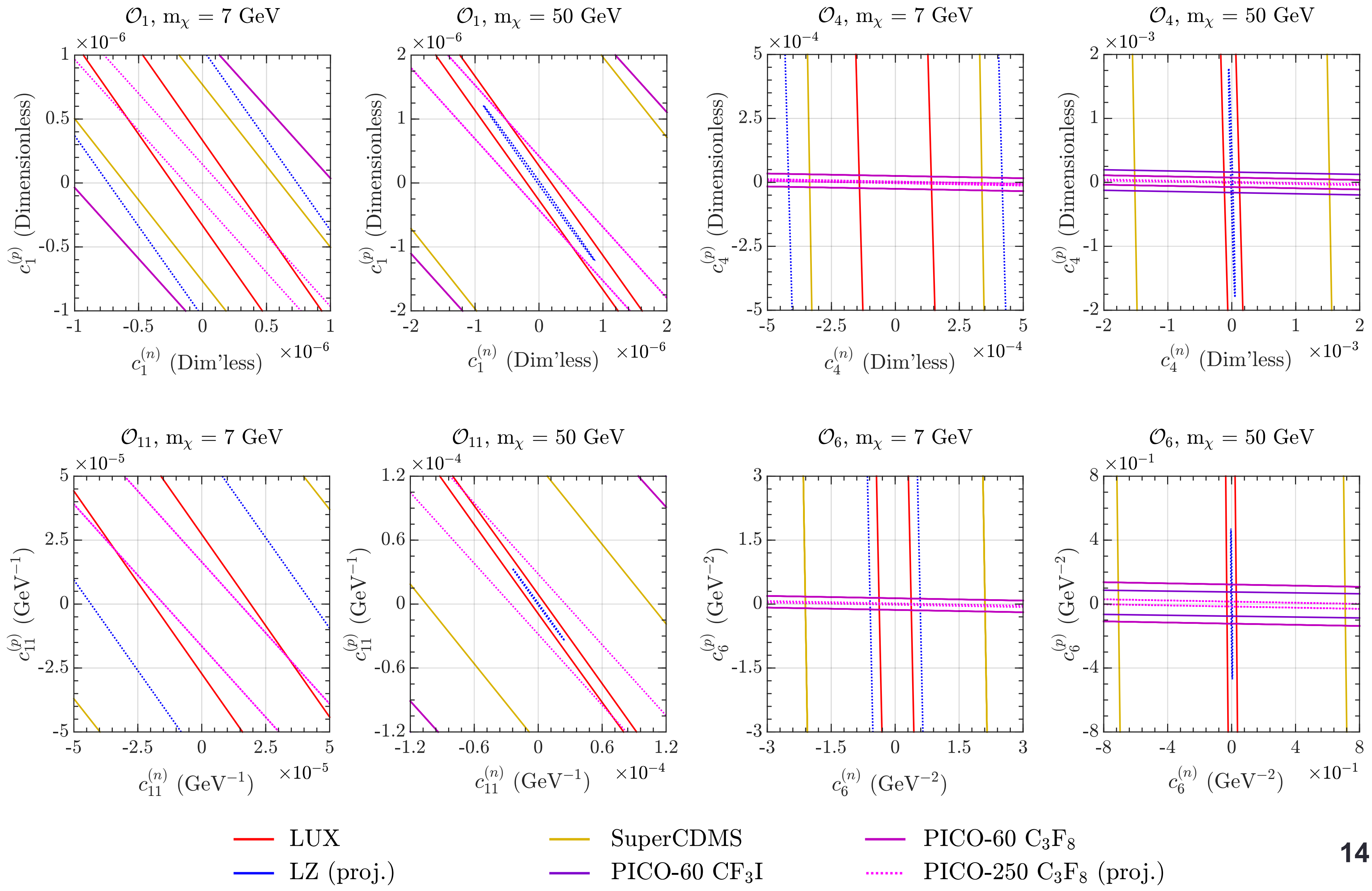
- **Limits on previous slides not model-independent (restrict either WIMP-neutron or WIMP-proton coupling strength to be zero)**
- **For a fixed WIMP mass, can set limits on WIMP-p and WIMP-n interactions in arbitrary combinations, i.e. define an allowed region in c_p vs. c_n space**
- **For a multi-isotope target with isotopes A_i:**

$$\sum_{A_i}\left(\frac{c_p}{c_p^{lim(A_i)}} \pm \frac{c_n}{c_n^{lim(A_i)}}\right) < 1$$

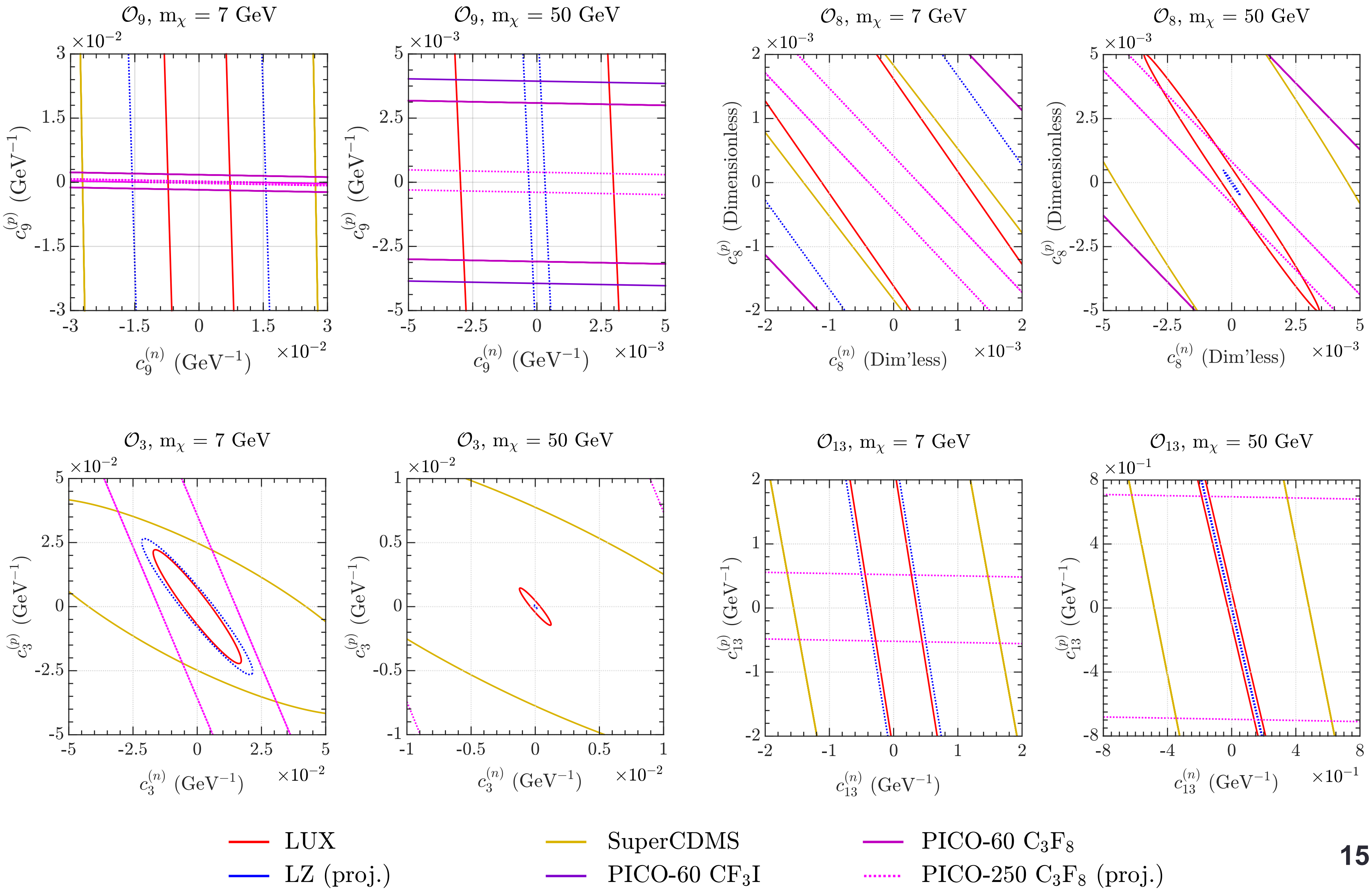
(Reduces to $\left(\frac{c_p}{c_p^{lim}} \pm \frac{c_n}{c_n^{lim}}\right) < 1$ for a single-isotope target)

- **(c_p^{lim} is the limit on c_p assuming $c_n = 0$ and vice versa; $c_p^{lim(Ai)}$, $c_n^{lim(Ai)}$ additionally assume only isotope A_i contributes to event rate)**
- **Standard SD limits often presented in this way.**

Limits on Selected Operators



Limits on Selected Operators

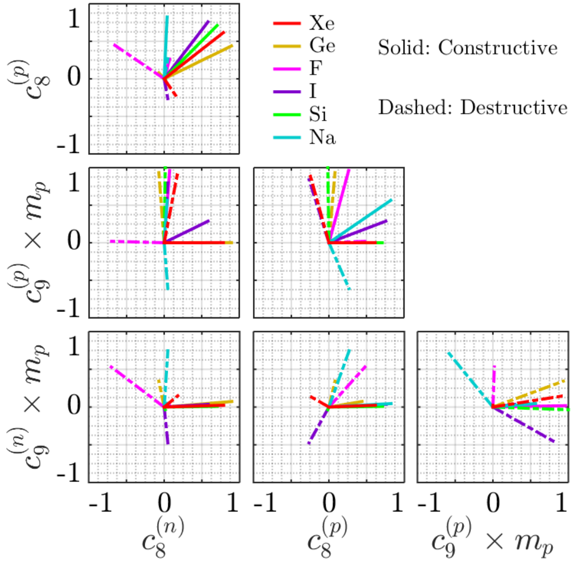


Operator Interference

- **Operators interfere pairwise**
  - **Neutron-proton interference for a single O_i (e.g. “xenophobic” dark matter)**
  - **Two operators O_i and O_j can interfere**
- **Such scenarios may relieve tension between experiments**
- **Or drive the selection of targets to probe previously inaccessible regions in WIMP parameter space**
- **In general, maximal interference found by solving a 4x4 eigenvector problem:**

$$\underbrace{\begin{bmatrix} d_i^{(n)} & d_i^{(p)} & d_j^{(n)} & d_j^{(p)} \end{bmatrix}}_{\text{Dimensionless (normalized) coupling constants}} \underbrace{\begin{bmatrix} G_{iinn} & G_{iinp} & G_{ijnn} & G_{ijnp} \\ G_{iipn} & G_{iipp} & G_{ijpn} & G_{ijpp} \\ G_{jinn} & G_{jinp} & G_{jjnn} & G_{jjnp} \\ G_{jipn} & G_{jijp} & G_{jjpn} & G_{jjpp} \end{bmatrix}}_{\text{Form factors, evaluated at fixed } m_\chi\text{, v, and } E_r \text{ and averaged over isotope}} \begin{bmatrix} d_i^{(n)} \\ d_i^{(p)} \\ d_j^{(n)} \\ d_j^{(p)} \end{bmatrix}$$

Projections of 4D $\mathcal{O}_8/\mathcal{O}_9$ Interference Eigenvectors



(Evaluated using benchmark WIMP mass m_χ = 50 GeV, incident velocity v = 220 km/s, and recoil energy E_r = 30 keV_{nr})

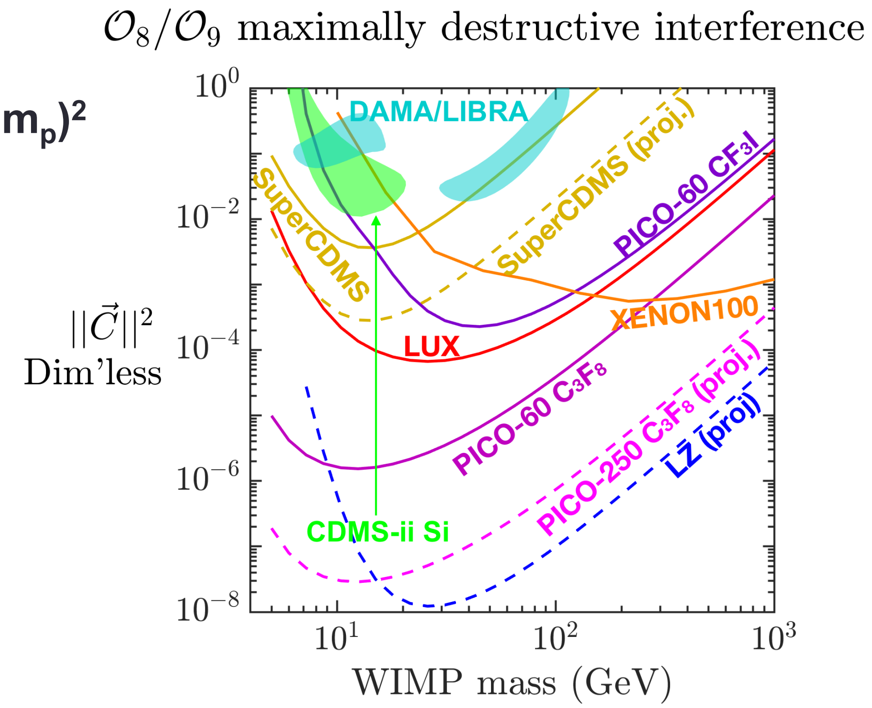
Interference Between Selected Operators

- Limits on

  $||C||^2 = C_8^{(n)2} + C_8^{(p)2} + (C_9^{(n)} \times m_p)^2 + (C_9^{(p)} \times m_p)^2$

  are evaluated at the maximally destructive eigenvector for a xenon target for a benchmark WIMP mass of 50 GeV and recoil energy E_r = 30 keV_{nr}:

  $C_8^{(n)} : C_8^{(p)} : (C_9^{(n)} \times m_p) : (C_9^{(p)} \times m_p)$
  = 0.1803 : -2.603 : 0.1491 : 0.9367



$\mathcal{O}_8/\mathcal{O}_9$ maximally destructive interference

- Xenon-based experiments are competitive at all masses
- PICO-type experiments (unpaired proton) are complementary
- A dark matter explanation for event excesses from DAMA/LIBRA and CDMS-ii Si is ruled out – if XENON/LUX doesn't see it, then PICO will!
- Other interference sectors yield similar results (not shown)

Summary and Conclusion

- LUX has previously set world-leading limits on SI WIMP-nucleon interactions.
- We set limits on each momentum- and velocity-dependent operator in the effective field theory framework developed by Anand + Fitzpatrick + Haxton, et al. using data from the initial 95-day first LUX dark matter search.
  - Individually for each nucleon…
  - … in an isospin-independent way….
  - … and for destructive interference scenarios

Summary and Conclusion

- **LUX has previously set world-leading limits on SI WIMP-nucleon interactions.**
- **We set limits on each momentum- and velocity-dependent operator in the effective field theory framework developed by Anand + Fitzpatrick + Haxton, et al. using data from the initial 95-day first LUX dark matter search.**

For all operators (except WIMP-proton Σ” and Σ’) and WIMP masses above ~12 GeV, LUX is able to set stringent limits. Even in maximally destructive interference scenarios, LUX is competitive.

Ge targets are sensitive to EFT interactions for low-mass WIMPs. At high masses, Xe targets win in all but the most fine-tuned scenarios.

For coverage of WIMP-proton Σ” and Σ’ interactions PICO-type experiments (F targets) are complementary to LUX/LZ/XENON1T.

In all cases, an EFT dark matter explanation for DAMA is ruled out!

Summary and Conclusion

- LUX has previously set world-leading limits on SI WIMP-nucleon interactions.
- We set limits on each momentum- and velocity-dependent operator in the effective field theory framework developed by Anand + Fitzpatrick + Haxton, et al. using data from the initial 95-day first LUX dark matter search.

Look forward to results from the full LUX exposure incorporating:

- The full set of calibrations
- Improved background models
- S1 pulse shape discrimination
- And a larger energy window to probe high-mass WIMP parameter space

THANK YOU!

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