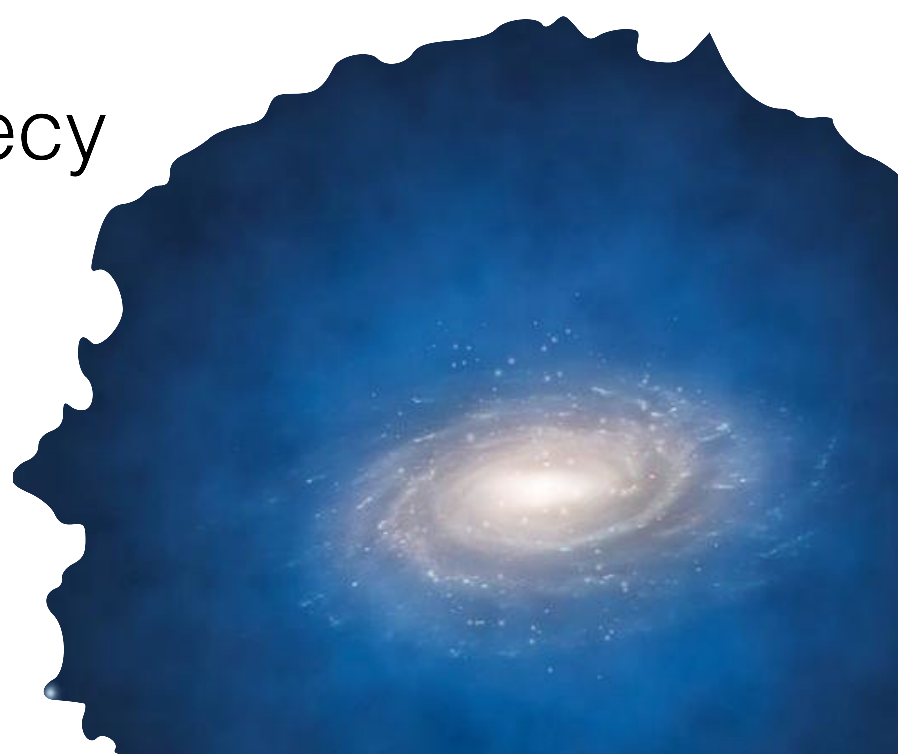
Signal Diversity and EFT in Dark Matter Direct Detection

Bradley J Kavanagh
GRAPPA, University of Amsterdam

25th June 2018, DSU, Annecy

GRAPPA
GRavitation AstroParticle Physics Amsterdam

b.j.kavanagh@uva.nl
@BradleyKavanagh



Last time I was in Annecy was January 2016…

Rencontre de Physique des Particules (RPP) 2016

25-27 January 2016
LAPTh, Annecy-le-Vieux
Europe/Paris timezone

- Overview
- Timetable
- Registration
- Travel and Directions

The ***Rencontre de Physique des Particules (RPP)*** is an annual m
working in France in the field of elementary particles and high en

The 2016 edition will be held at **Laboratoire d'Annecy-le-Vieux de**
25 to 27 January 2016.

9. **What is the $\gamma\gamma$ resonance at 750 GeV?**
Roberto Franceschini, Gian F. Giudice (CERN), Jernej F. Kamenik (CERN & Ljubljana U. & Stefan Ins
(ITPP, Lausanne), Michele Redi (INFN, Florence), Francesco Riva (CERN), Alessandro Strumia (CER
Published in **JHEP 1603 (2016) 144**
CERN-PH-TH-2015-302
DOI: 10.1007/JHEP03(2016)144
e-Print: **arXiv:1512.04933 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to Article from SCOAP3
Detailed record - Cited by 371 records 250+

10. **First interpretation of the 750 GeV diphoton resonance at the LHC**
Stefano Di Chiara (NICPB, Tallinn), Luca Marzola, Martti Raidal (NICPB, Tallinn & Tartu, Inst. Phys.).
Published in **Phys.Rev. D93 (2016) no.9, 095018**
DOI: 10.1103/PhysRevD.93.095018
e-Print: **arXiv:1512.04939 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 216 records 100+

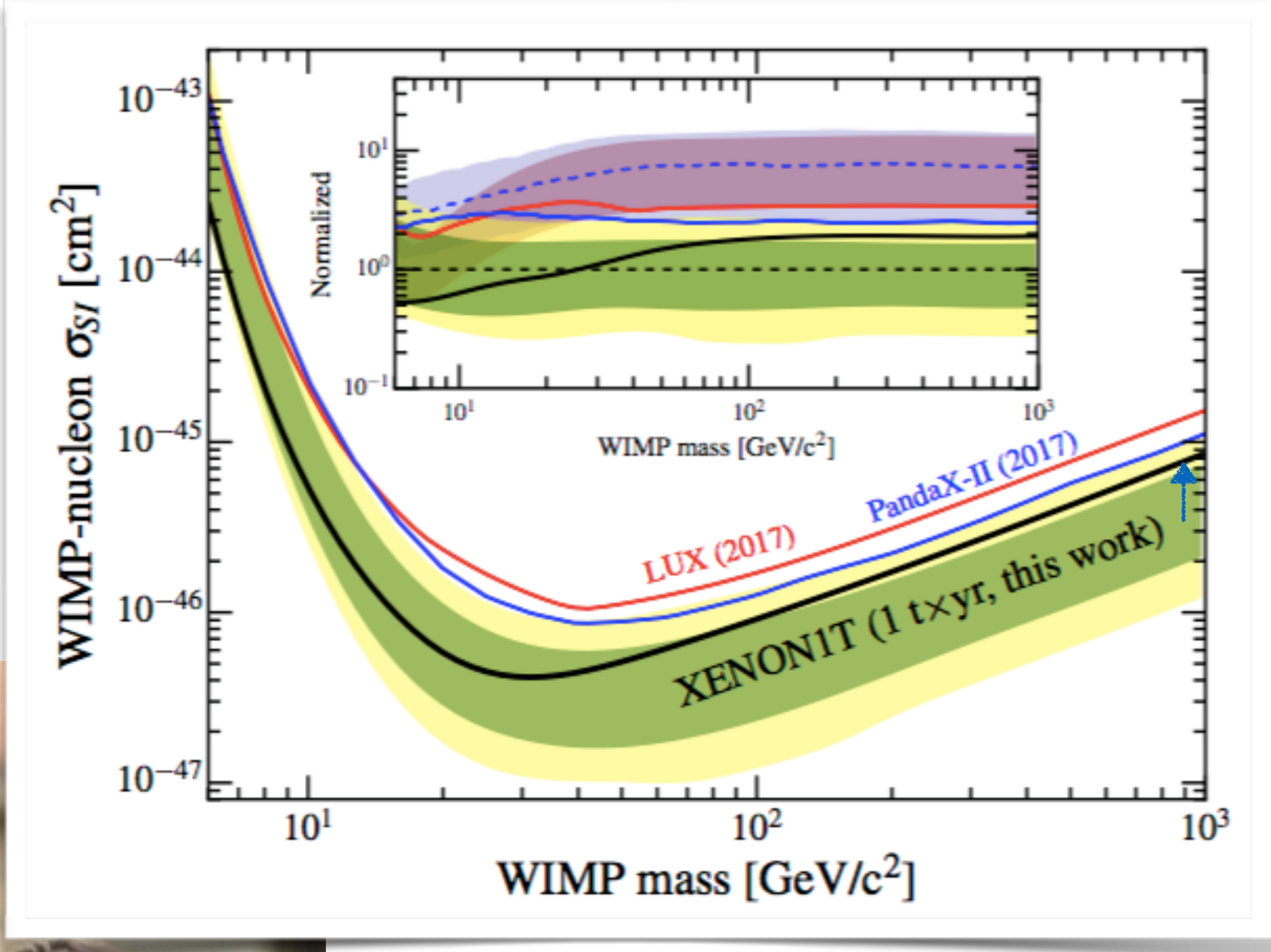
11. **On the Interpretation of a Possible ~ 750 GeV Particle Decaying into $\gamma\gamma$**
John Ellis (CERN & King's Coll. London), Sebastian A. R. Ellis (Michigan U. & Michigan U., MCTP), J
2015. 36 pp.
Published in **JHEP 1603 (2016) 176**
KCL-PH-TH-2015-56, LCTS-2015-46, CERN-PH-TH-2015-303, MCTP-15-33, CAVENDISH-HEP-15-
DOI: 10.1007/JHEP03(2016)176
e-Print: **arXiv:1512.05327 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI.gov Server; Link to Article from SCOAP
Detailed record - Cited by 248 records 100+

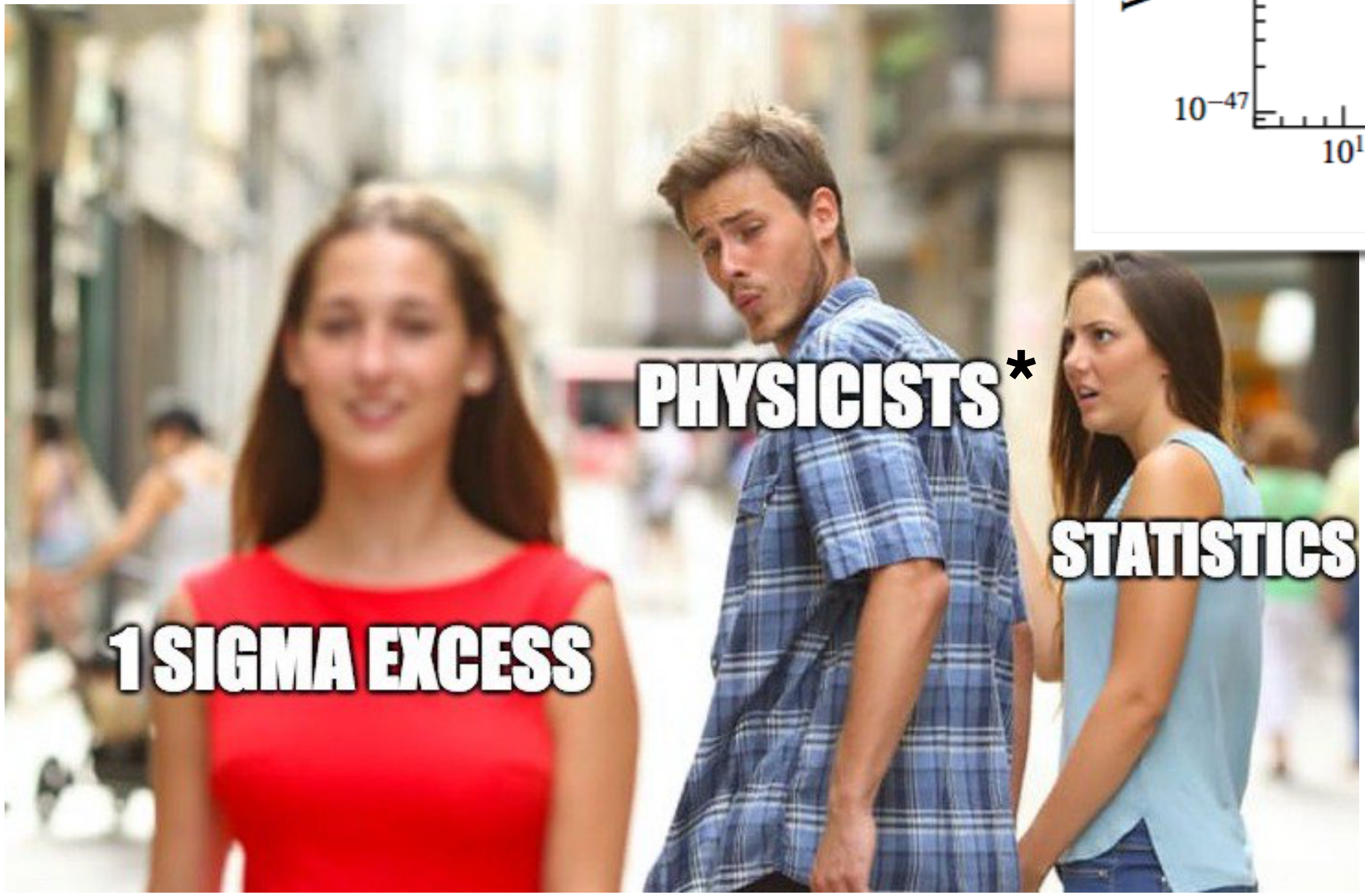
12. **Interpreting a 750 GeV Diphoton Resonance**
Rick S. Gupta (Weizmann Inst.), Sebastian Jäger (Weizmann Inst. & Sussex U.), Yevgeny Kats, Gilad
Published in **JHEP 1607 (2016) 145**
DOI: 10.1007/JHEP07(2016)145
e-Print: **arXiv:1512.05332 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to Article from SCOAP3
Detailed record - Cited by 221 records 100+

13. **750 GeV Diphoton Excess from the Goldstino Superpartner**
Christoffer Petersson (Brussels U., PTM & Chalmers U. Tech. & Intl. Solvay Inst., Brussels), Riccardo
Published in Phys.Rev.Lett. 116 (2016) no.15, 151804

… and everyone in the audience looked a little sleep deprived…

Anyway, now we have the XENON1T 1-sigma excess…





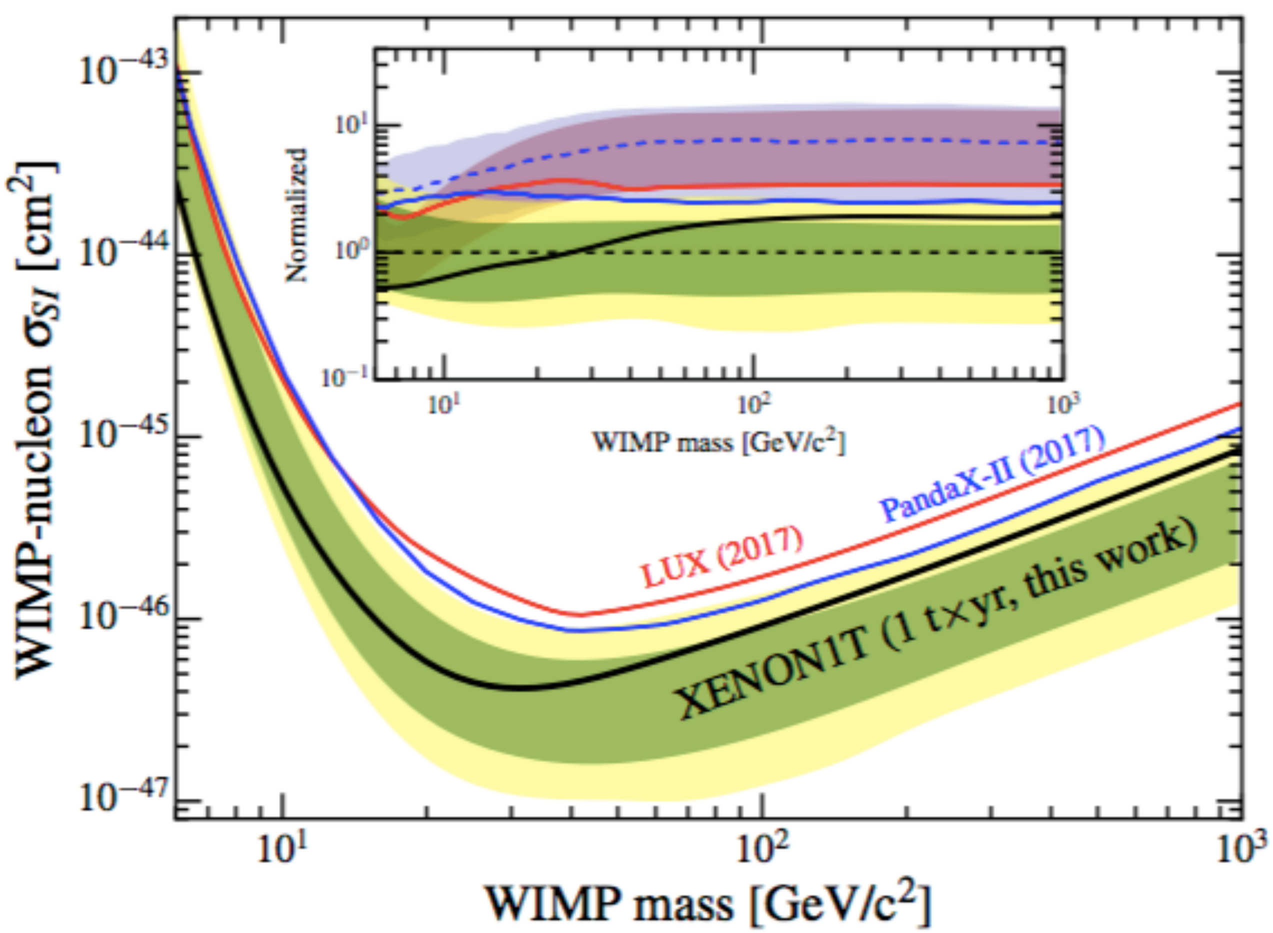
*or rather, theorists…

@pjtunney

‘Standard’ direct detection

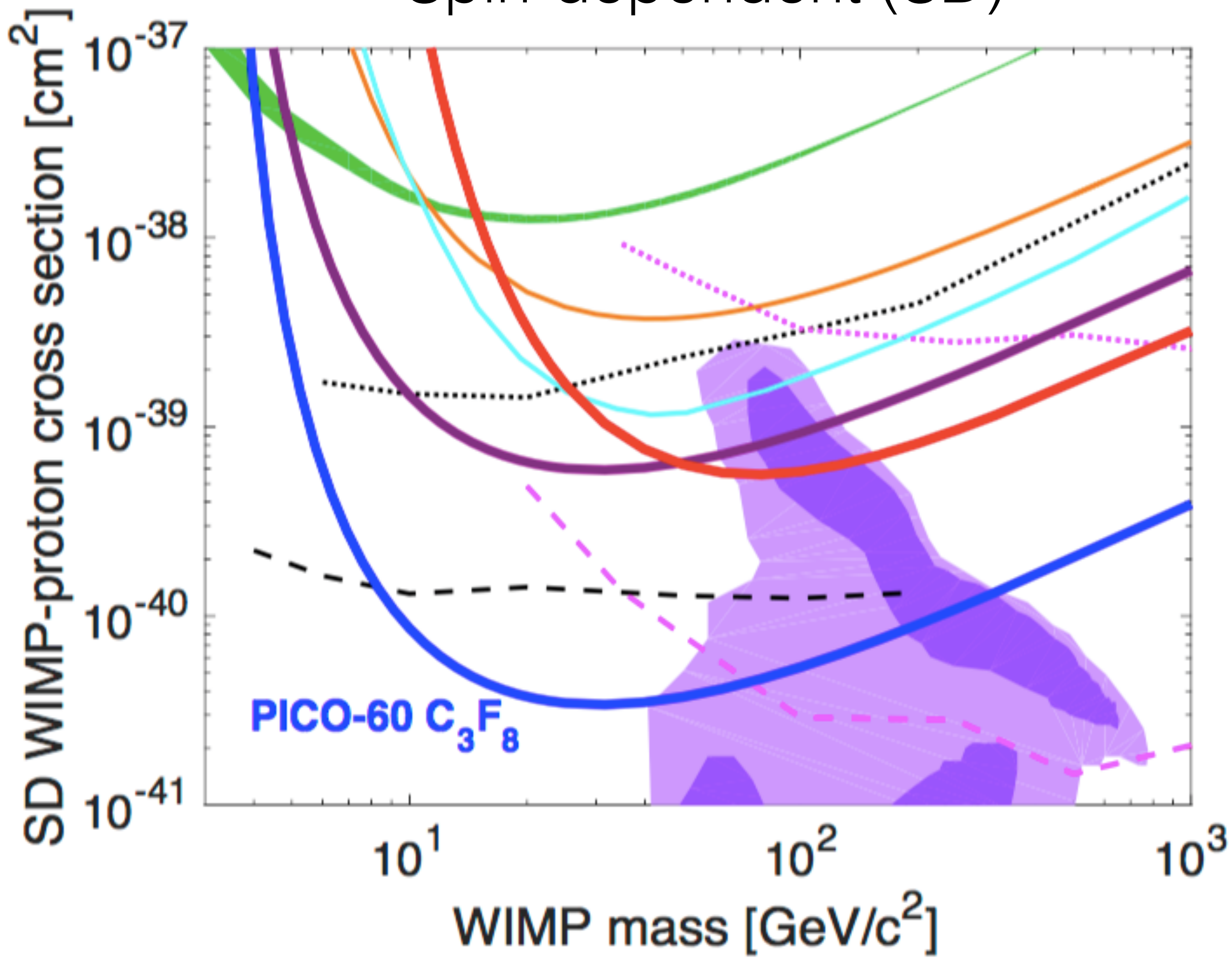
$$\sigma^p_{\mathrm{SI/SD}} \sim v^0 q^0$$

Spin-independent (SI)



[1805.12562]

Spin-dependent (SD)



[1702.07666]

But these interactions are not always there…

Non-standard interactions? Why?

- **Out of curiosity**

  Don't you just want to *know…?* What could DM look like? What could we be missing?

- **Input for experimental analysis**

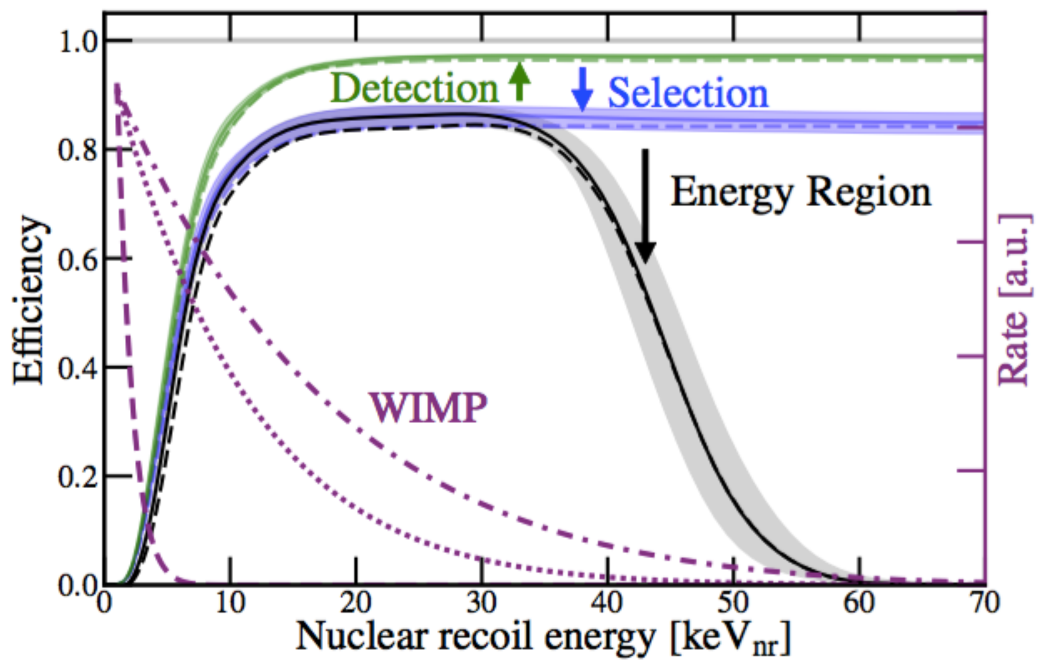
  Experimental searches are not simple cut-and-counts - need to know what the signal looks like to get the best sensitivity

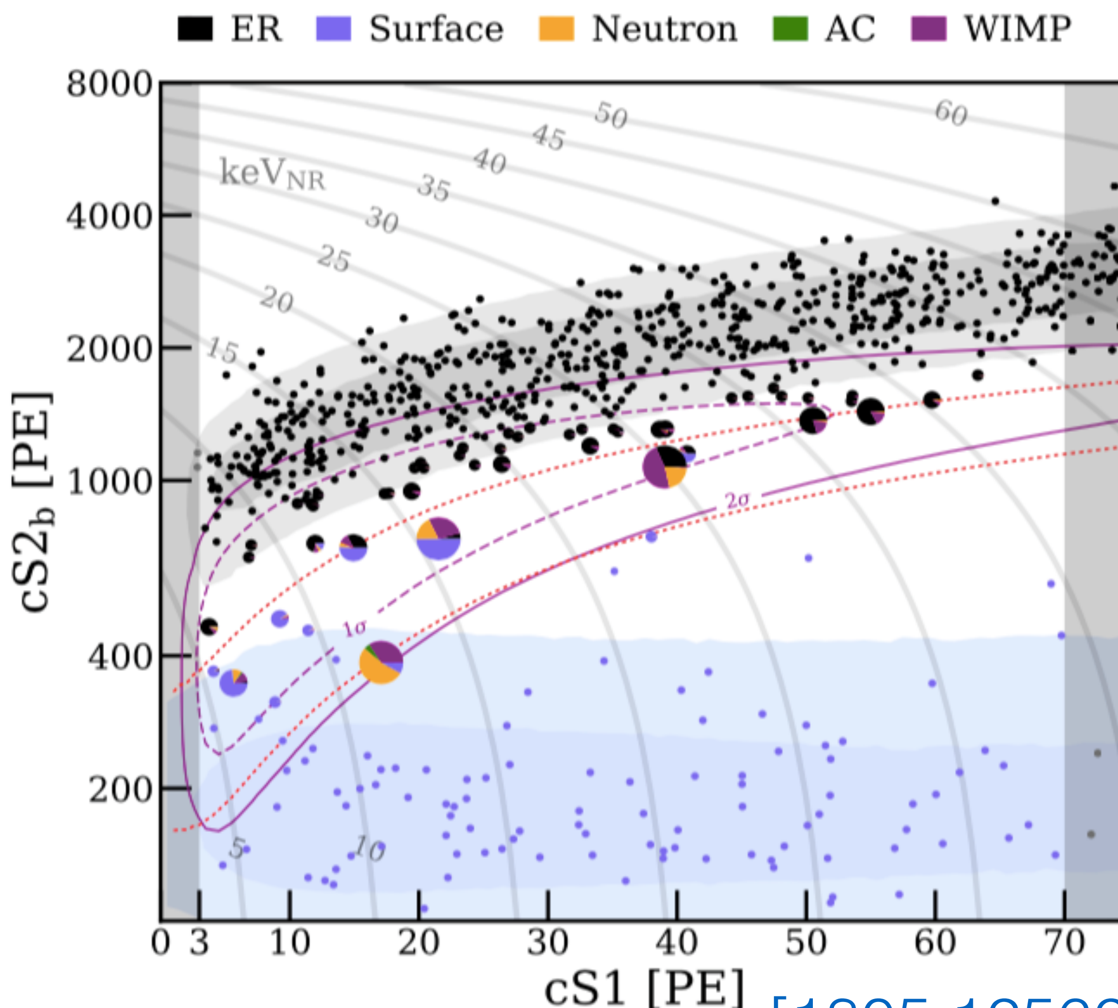
- **Optimisation of future experiments**

  Which experiments should we use to get the best sensitivity, or the most information out of a future detection? (more on this later)

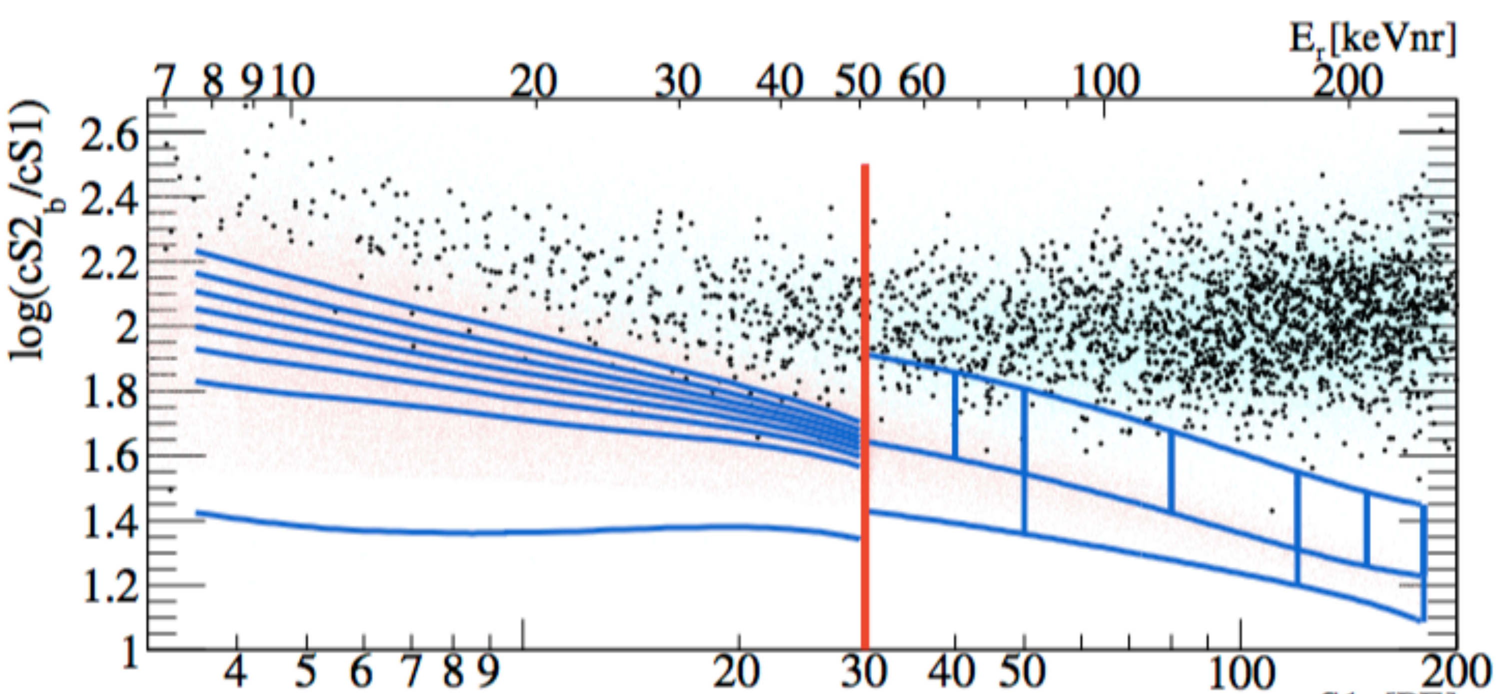
Experimental analysis

Limits depend on a signal hypothesis and we need to know where to look!





[1805.12562]



[1705.02614]

So where should we look?

More general interactions

Can write non-relativistic (NR) DM-*nucleon* Lagrangian as an expansion in:
[Fan et al - 1008.1591, Fitzpatrick et al. - 1203.3542]

Recoil momentum - $\vec{q} \ll m_N$

DM velocity - $\vec{v} \ll c$

$$\mathcal{L} \supset \boxed{\mathcal{L}_0} + \boxed{\mathcal{L}_1(\vec{v}) + \mathcal{L}_2(\vec{q}) + \mathcal{L}_3(\vec{v}, \vec{q}) + \dots}$$

'Standard' interactions
(zeroth order)

'Non-standard' interactions
(higher order)

More general interactions

Can write non-relativistic (NR) DM-*nucleon* Lagrangian as an expansion in:

[Fan et al - 1008.1591, Fitzpatrick et al. - 1203.3542]

Recoil momentum - $\vec{q} \ll m_N$

Transverse DM velocity - $\vec{v}_\perp \ll c$

$$\mathcal{L} \supset \boxed{\mathcal{L}_0} + \boxed{\mathcal{L}_1(\vec{v}_\perp) + \mathcal{L}_2(\vec{q}) + \mathcal{L}_3(\vec{v}_\perp, \vec{q}) + ...}$$

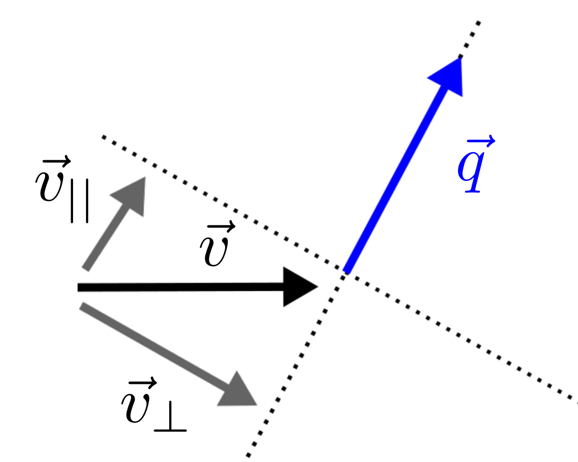
'Standard' interactions
(zeroth order)

'Non-standard' interactions
(higher order)

The DM velocity operator is not Hermitian, so it can appear only through the Hermitian *transverse velocity*:

Invariant under exchange of
incoming and outgoing particles

$$\vec{v}_\perp = \vec{v} + \frac{\vec{q}}{2\mu_{\chi N}} \qquad \Rightarrow \vec{v}_\perp \cdot \vec{q} = 0$$



Non-relativistic effective field theory (NREFT)

Write down all operators which are Hermitian, Galilean invariant and time-translation invariant from building blocks: $\vec{v}^\perp$, $\vec{q}$, $\vec{S}_\chi$, $\vec{S}_N$.

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

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

[1008.1591,1203.3542,1308.6288,1505.03117]

Non-relativistic effective field theory (NREFT)

Write down all operators which are Hermitian, Galilean invariant and time-translation invariant from building blocks: $\vec{v}^{\perp}$, $\vec{q}$, $\vec{S}_\chi$, $\vec{S}_N$.

SI

SD

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

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

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

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

$$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})/m_N^2$$

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

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

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

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

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

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

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

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

$$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \vec{q})((\vec{S}_N \times \vec{v}^{\perp}) \cdot \vec{q}/m_N^2$$

$$\vdots$$

Whole list of new operators, higher order in $\mathrm{v}_\perp$ and $E_R \sim q^2$

[1008.1591,1203.3542,1308.6288,1505.03117]

Nuclear Responses

[1203.3542,1501.03729,1612.09165]

The differential cross section can then be written as a sum over couplings (inside R_k) multiplied by nuclear response functions:

$$\frac{\mathrm{d}\sigma_{\chi A}}{\mathrm{d}E_R} \propto \frac{1}{v^2} \sum_{N,N'=p,n} \sum_k R_k^{NN'} \left(v_T^{\perp 2}, \frac{q^2}{m_N^2} \right) W_k^{NN'} \left(q^2 \right)$$

$$k = M, \Sigma', \Sigma'', \Phi', \Phi'' M, \tilde{\Phi}', \Delta, \Delta\Sigma'$$

M - Nucleon density inside the nucleus (SI)
Σ', Σ'' - Nucleon spin inside the nucleus (SD)
Δ - Nucleon orbital angular momentum
Φ'' - Nucleon spin-orbit coupling …and more

Once you've mapped onto the NREFT couplings, the direct detection rate can be calculated immediately, accounting for nuclear structure

Beyond NREFT

The formalism can incorporate more complicated interactions too.

Light mediators and long range interactions can be incorporated with an appropriate propagator:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q^2} \rightarrow \frac{m_\phi^4}{(q^2 + m_\phi^2)^2} \frac{\mathrm{d}\sigma}{\mathrm{d}q^2}$$

For example, DM with a magnetic dipole

$$\mathcal{M}_{\mathrm{MD}}^{D} = 2e\frac{c_{\mathrm{MD}}}{\Lambda}\left[Q_N m_N \mathcal{O}_1^{\mathrm{NR}} + 4Q_N \frac{m_\chi m_N}{q^2}\mathcal{O}_5^{\mathrm{NR}} + 2g_N m_\chi \left(\mathcal{O}_4^{\mathrm{NR}} - \frac{1}{q^2}\mathcal{O}_6^{\mathrm{NR}}\right)\right]$$

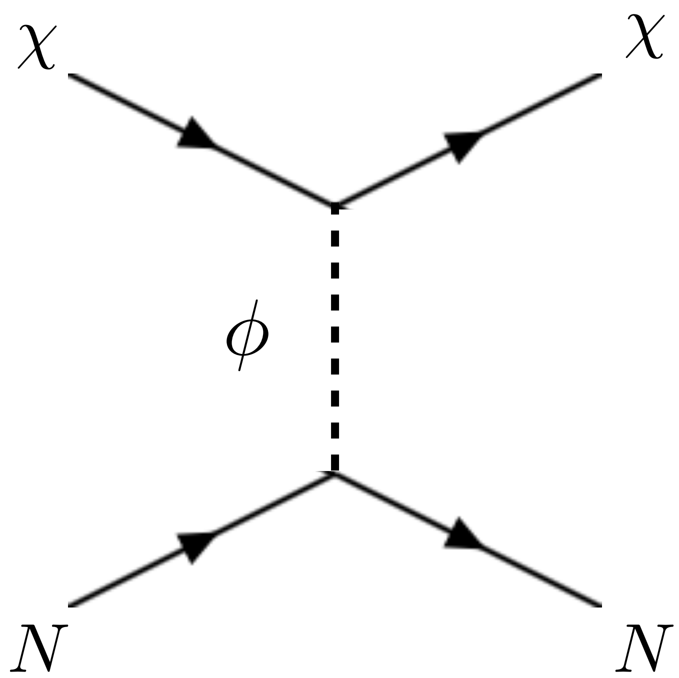
We don't need to do the full calculation - we just need to look up the appropriate structure functions!

[1108.4661,1007.5515,1203.6652,1707.08571 and many others]

Examples

[1211.0503,1401.4508,1506.04454]

Pseudo-scalar coupling

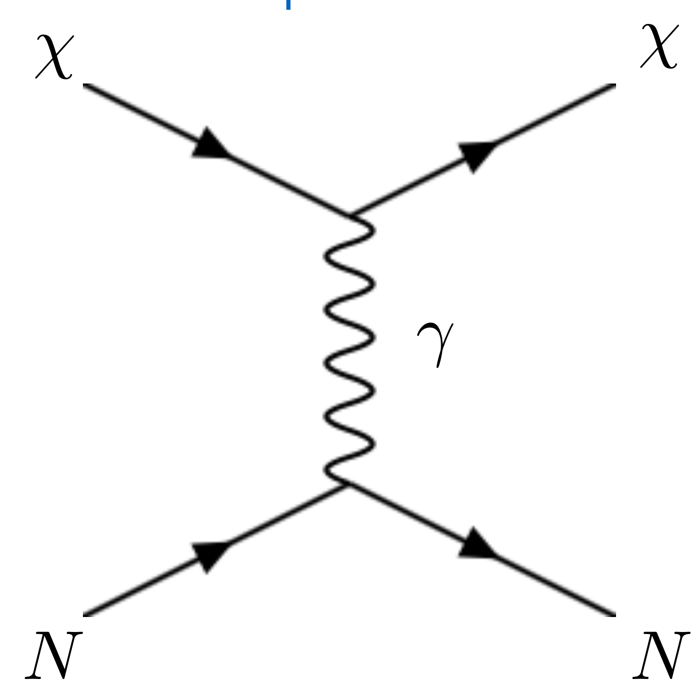


$$\mathcal{O}_{\rm PS} = \overline{\chi}\gamma^5\chi\overline{N}N$$

$$\mathcal{O}_{\rm PS}^{\rm NR} = -4m_N i\vec{S}_\chi \cdot \vec{q}$$

$$= -4m_N^2 \mathcal{O}_{11}^{\rm NR}$$

Anapole DM



$$\mathcal{O}_A = \bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$

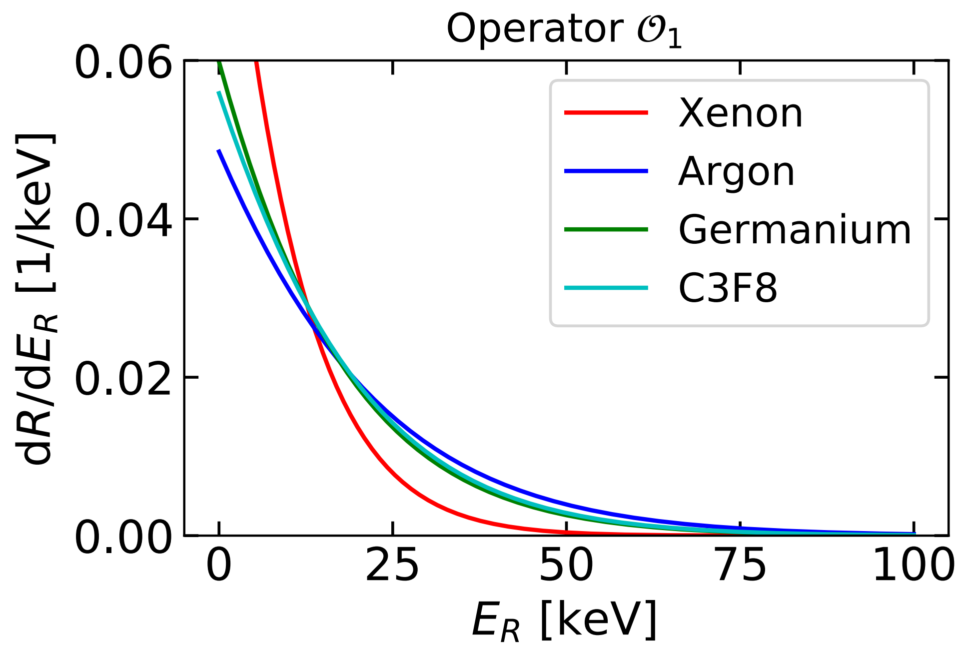
$$\mathcal{O}_A^{(N)} = eQ_N\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{N}\gamma_\mu N$$

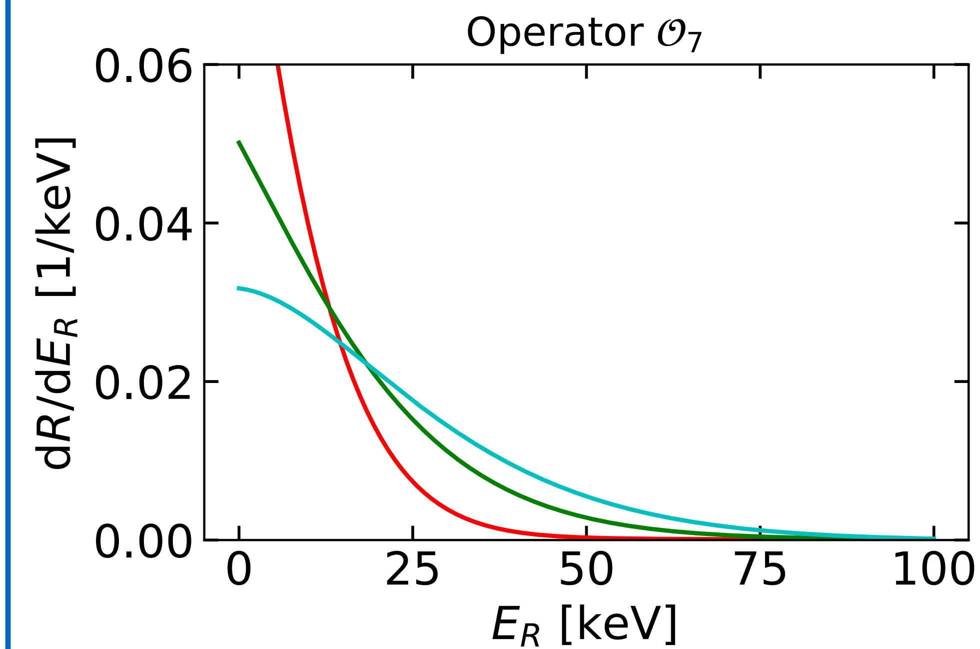
$$\mathcal{O}_A^{\rm NR} = 8eQ_N m_\chi m_N(\mathcal{O}_8^{\rm NR} + \mathcal{O}_9^{\rm NR})$$

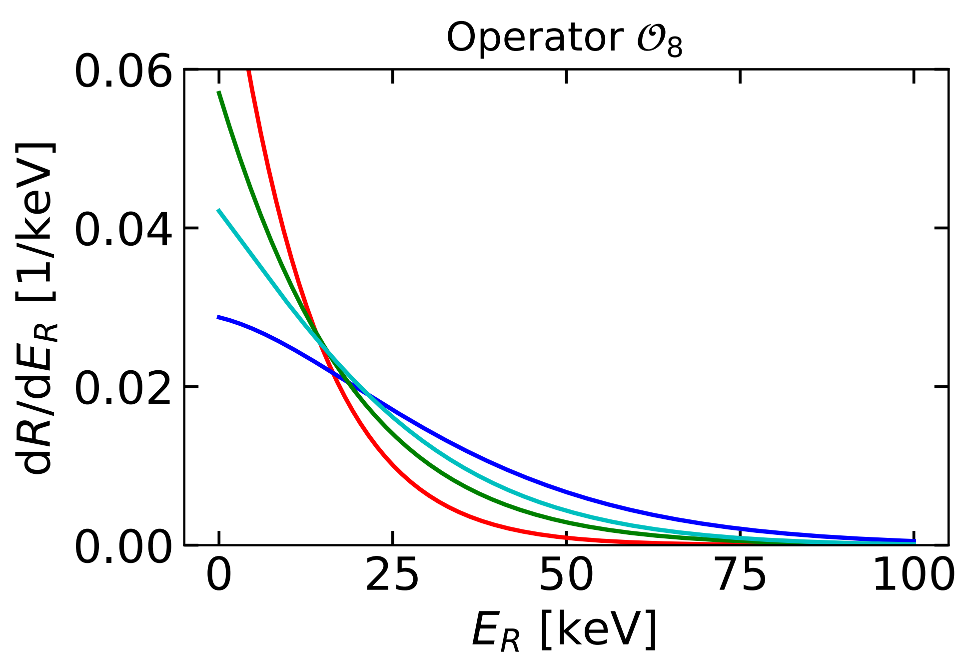
Spectral Signatures

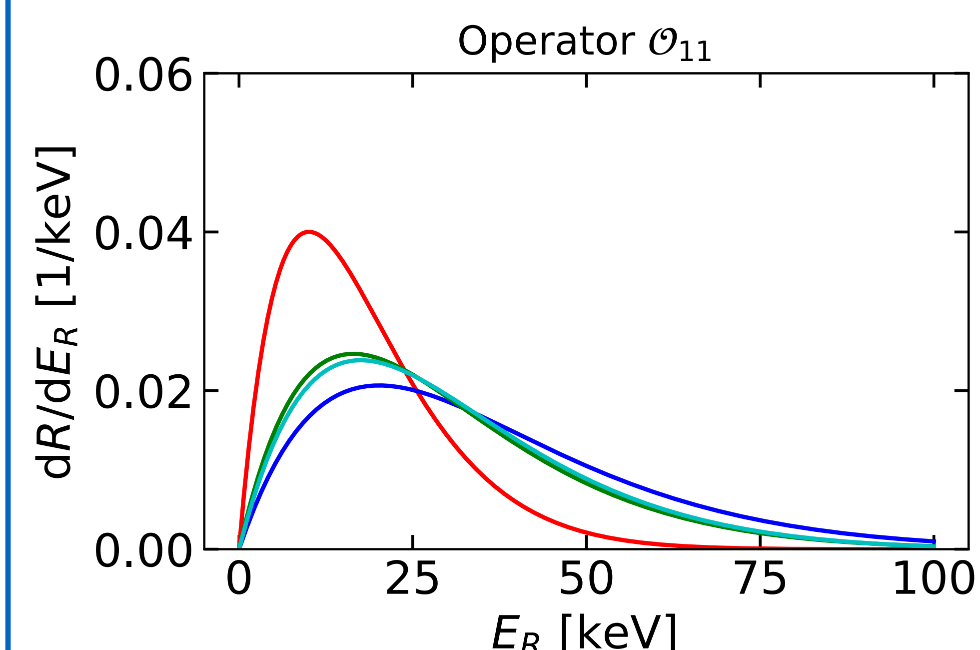
Spin-independent

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









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

(Pseudo-scalar) $\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}/m_N$

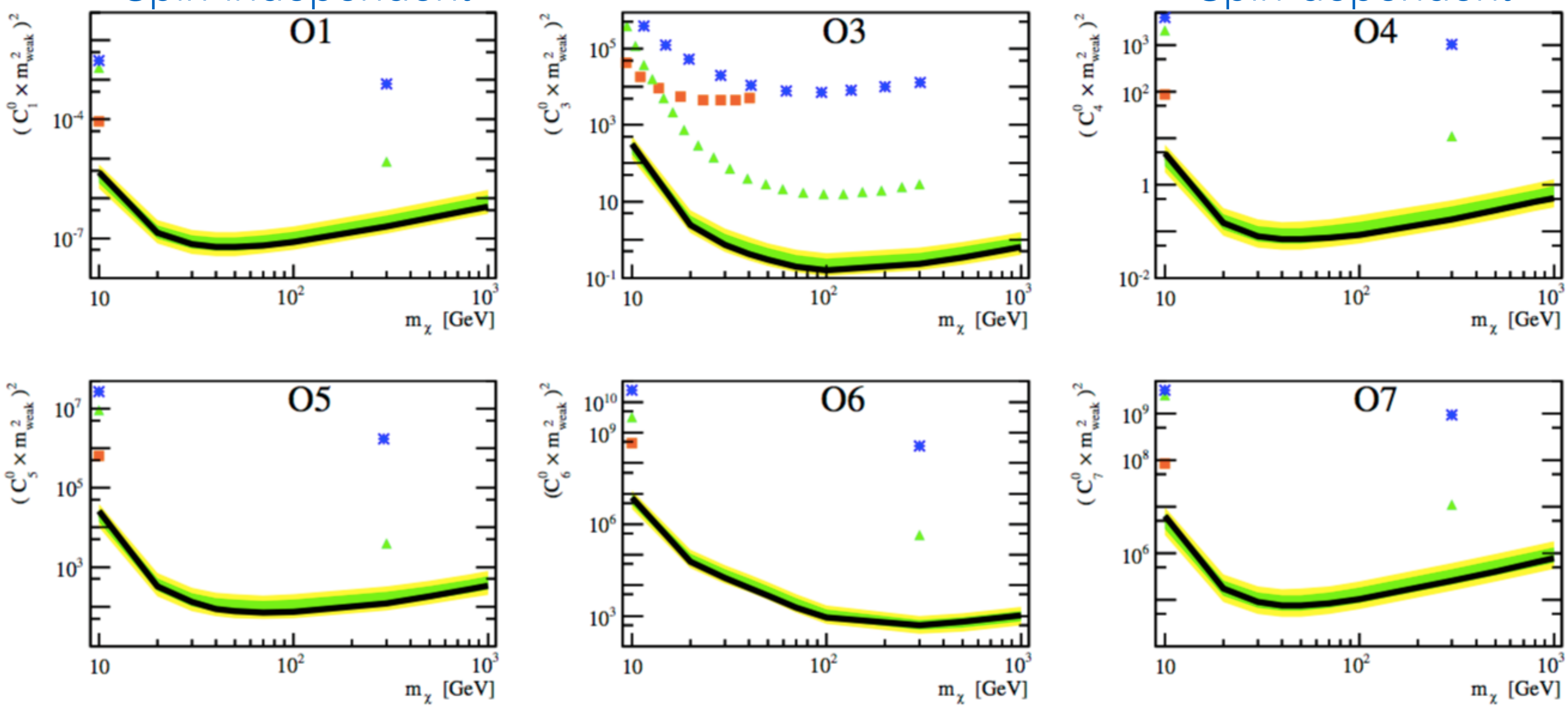
Limits

[1705.02614]

XENON100 high recoil energy analysis:

Spin-independent

Spin-dependent



Limits on $c^2 m_{\rm weak}^4 (\propto \sigma)$

[See also CDMS 1503.03379 and CRESST-II 1601.04447]

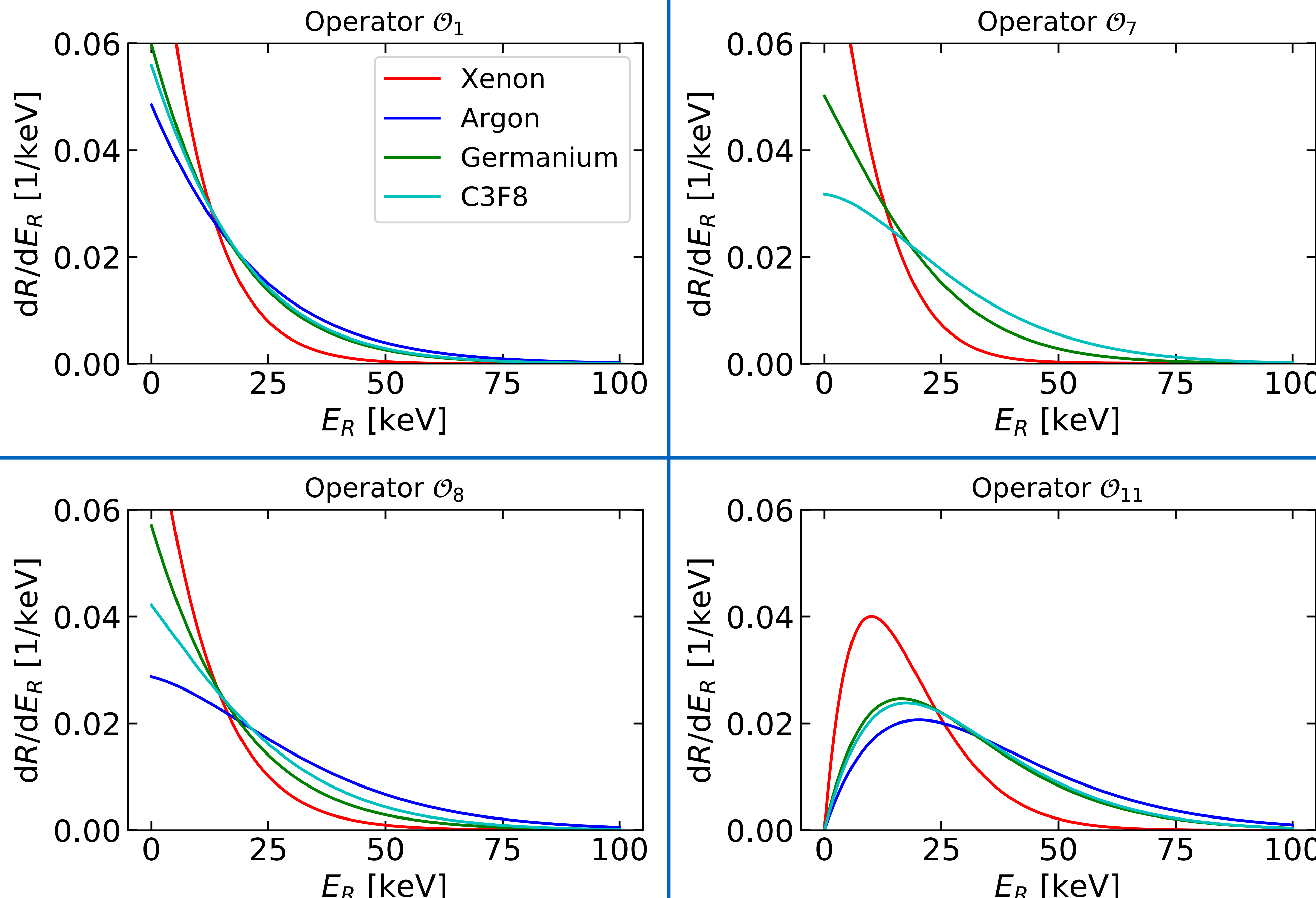
Signatures

or “Fantastic interactions and how to distinguish them”

Spectral Signatures

Spin-independent

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



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

(Anapole)

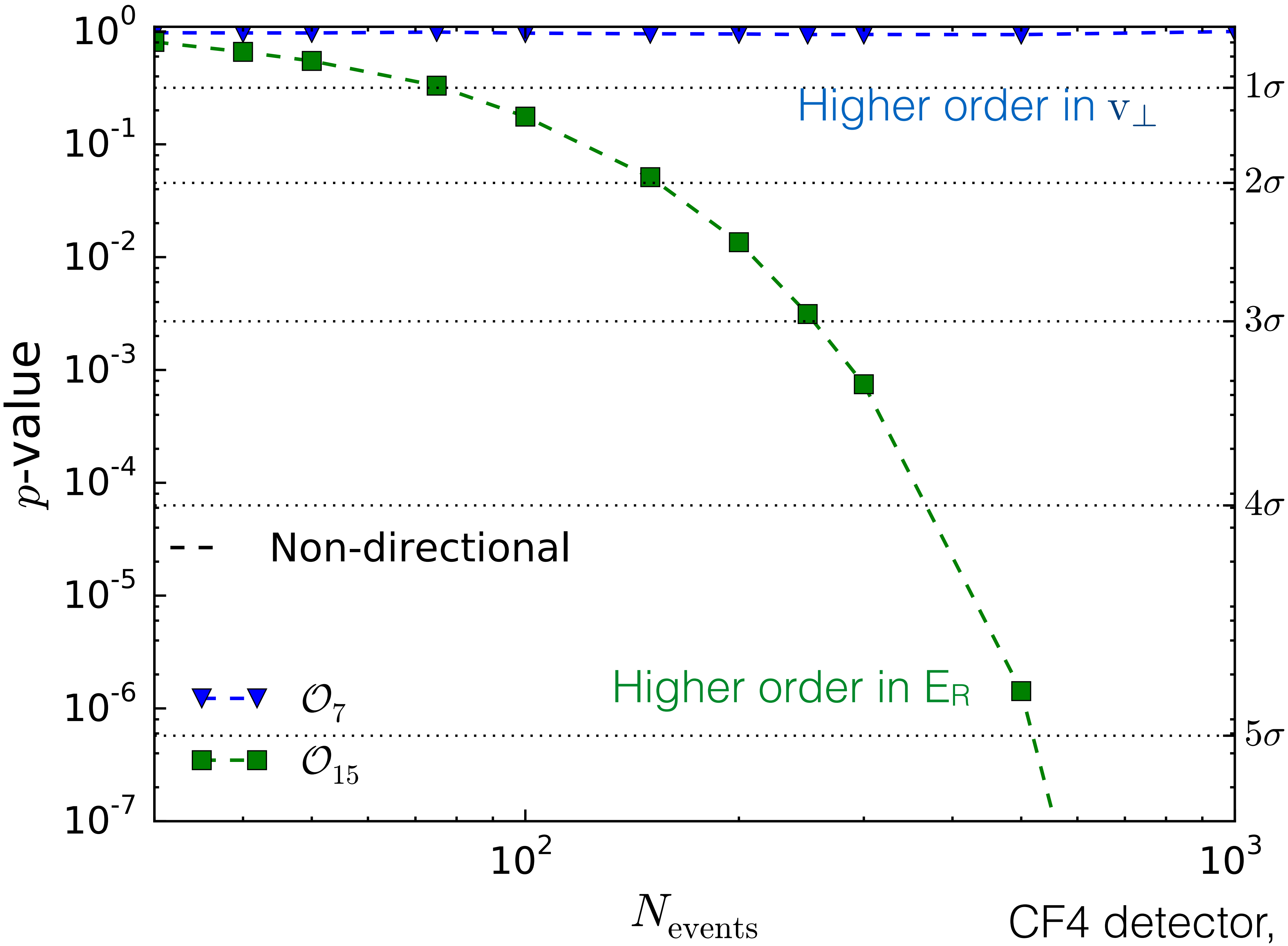
(Pseudo-scalar)

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

Distinguishing operators

[**BJK**, 1505.07406]

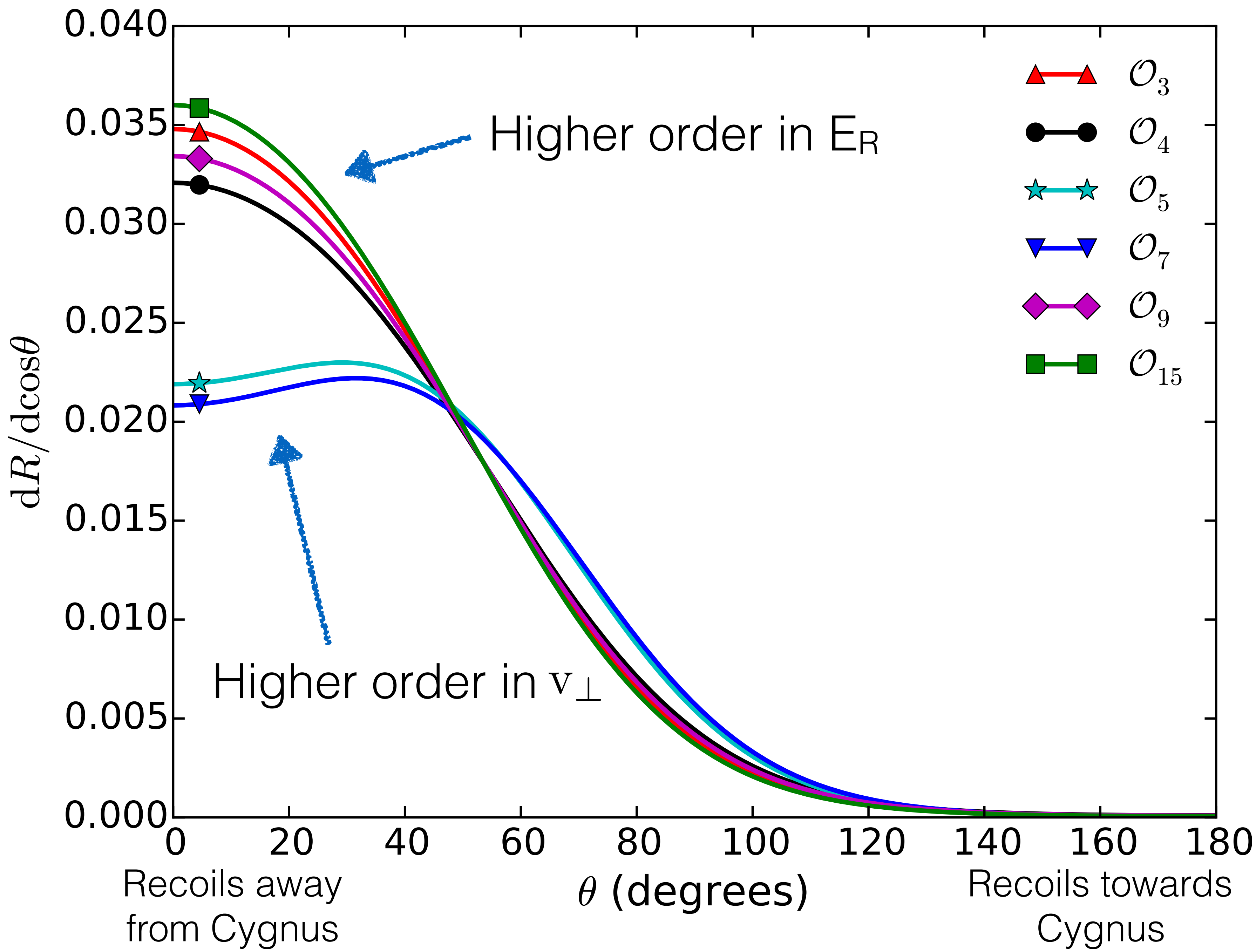
How many events are required to detect the effect of a 'non-standard' interaction?

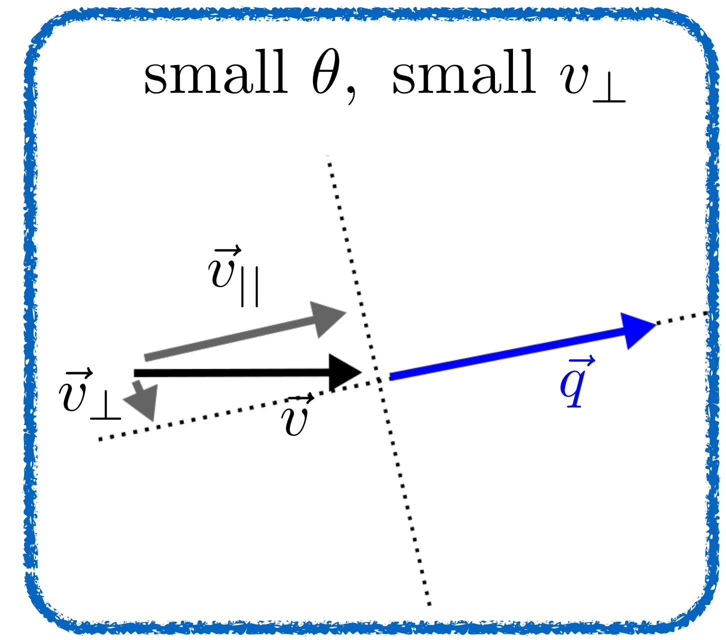


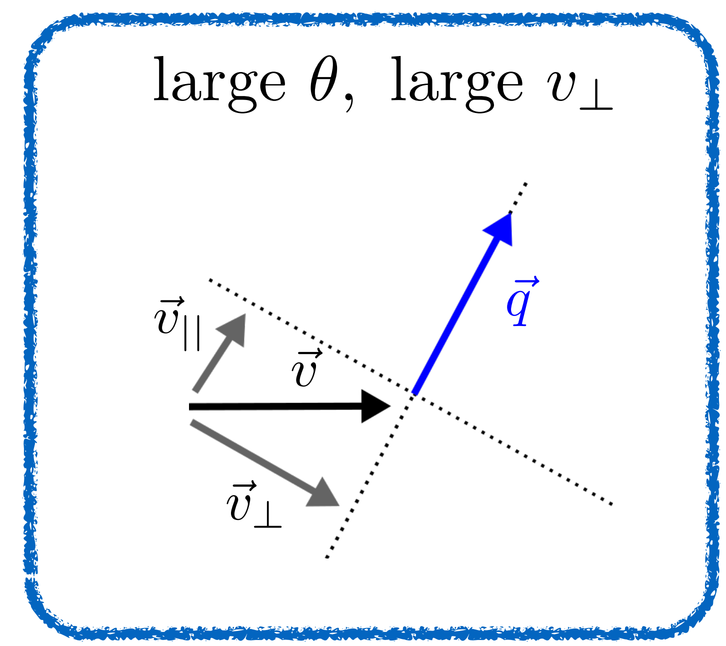
CF4 detector, 100 GeV

Directional Signatures

[**BJK**, 1505.07406]







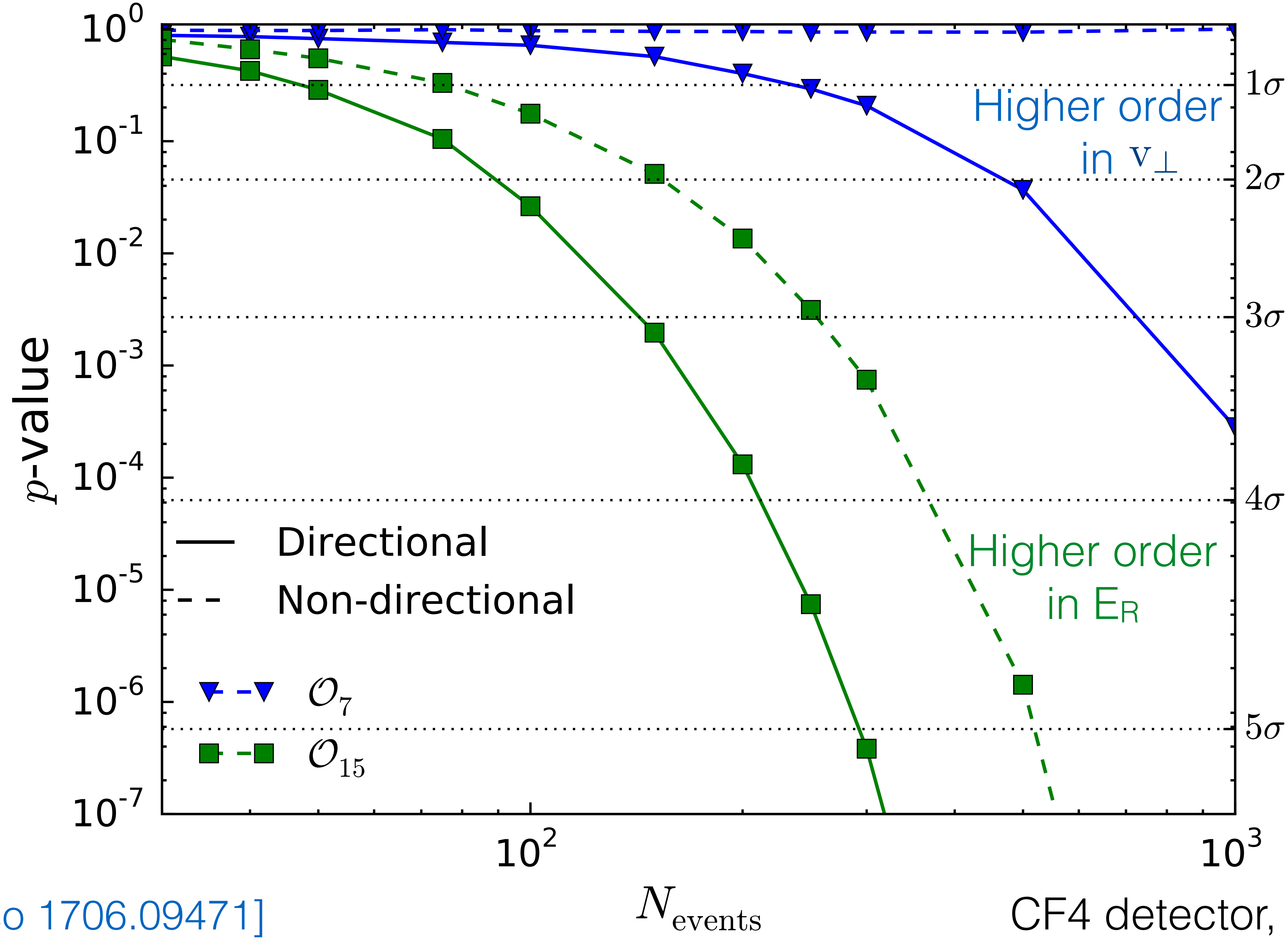
Also note: $q = 2\mu_{\chi N}\vec{v}\cdot\hat{q}$
$= 2\mu_{\chi N} v \cos\theta$

[See also 1505.06441]

Distinguishing operators

[**BJK**, 1505.07406]

How many events are required to detect the effect of a 'non-standard' interaction?

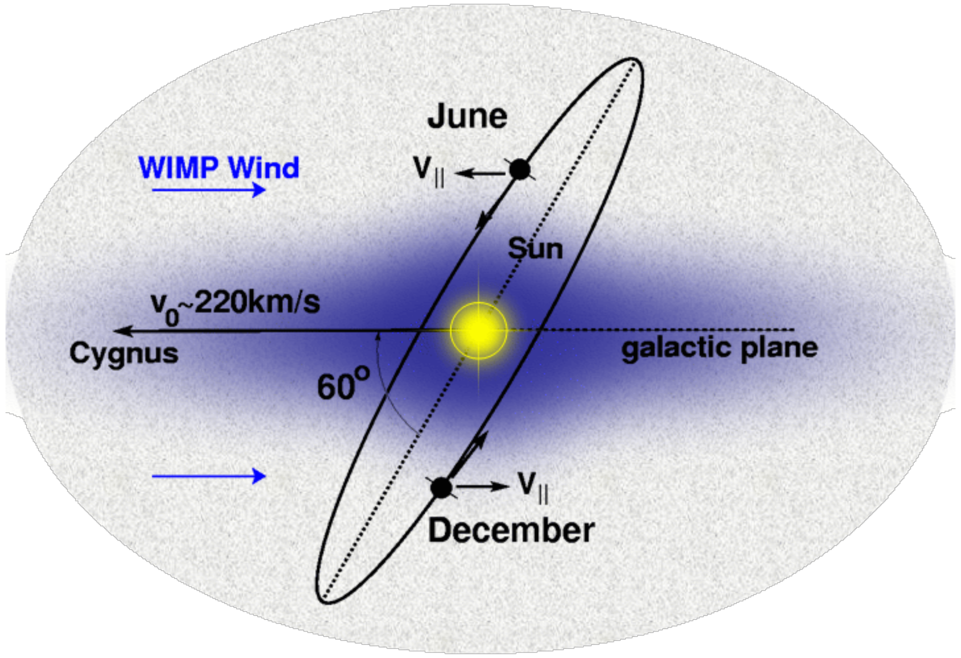


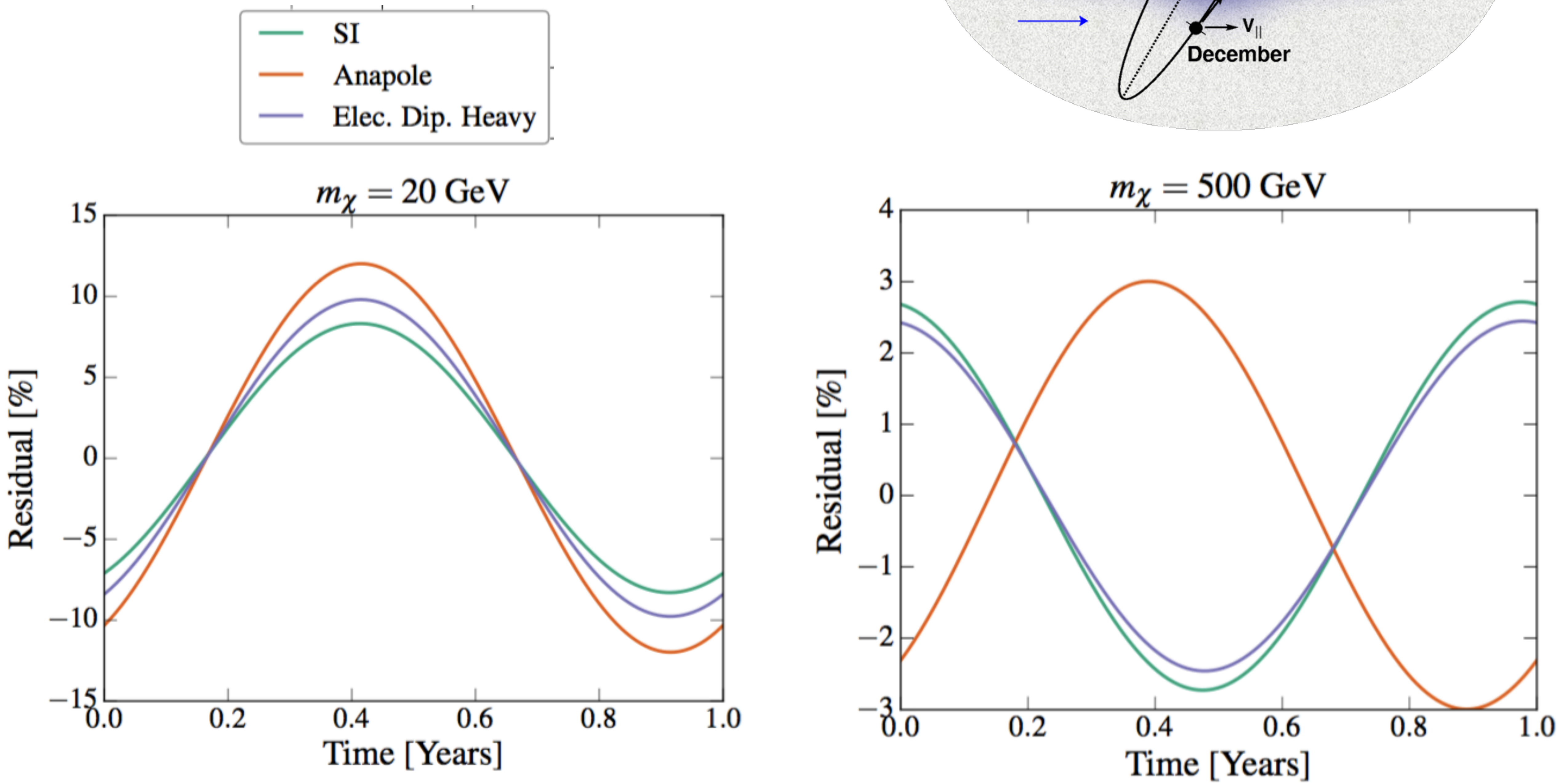
[See also 1706.09471]

CF4 detector, 100 GeV

Modulation Signatures

[1504.06772,1512.03961,1612.07808]



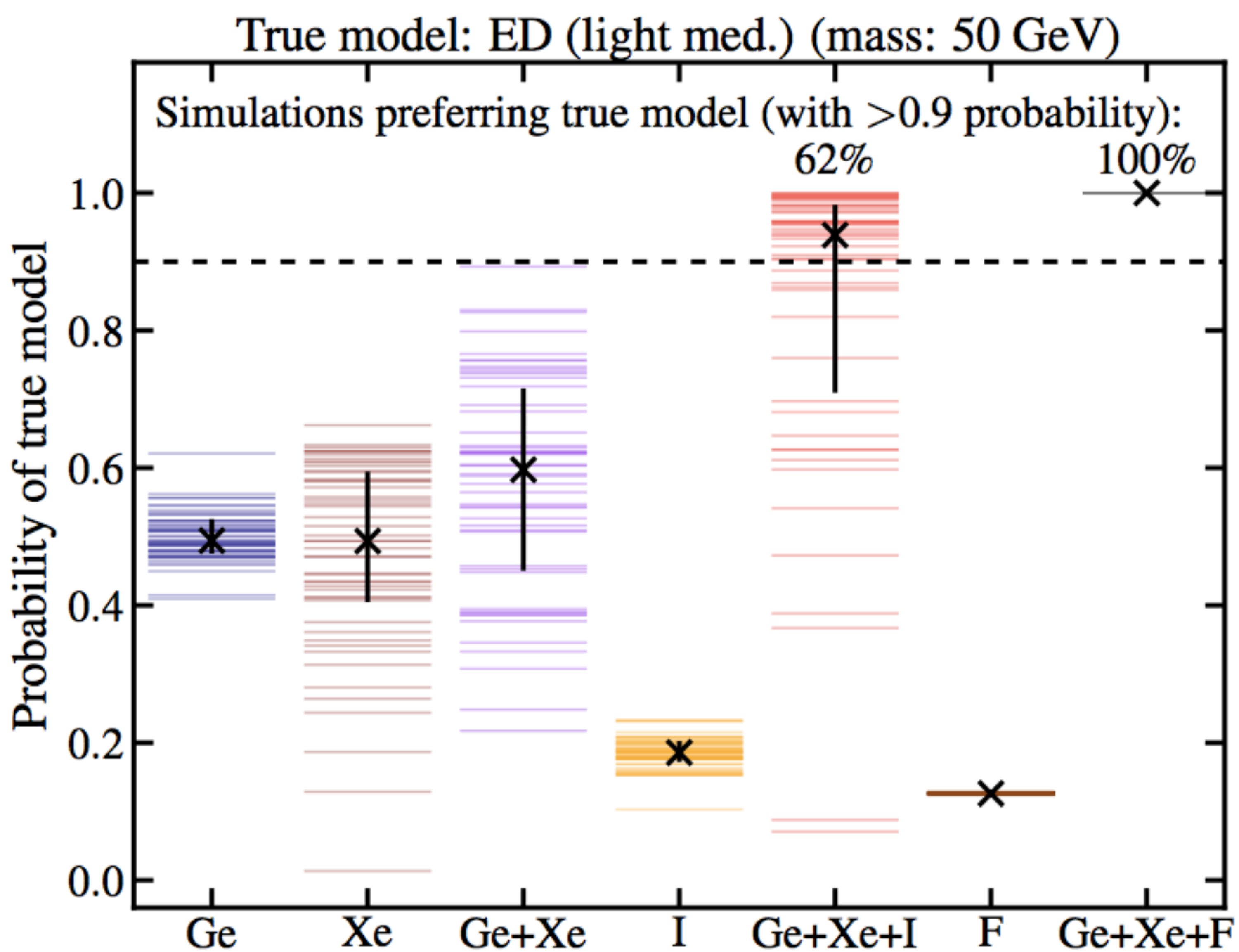


But you would need O(1000) events to detect and distinguish the modulation phase…

Materials Signatures

Different operators couple to different nuclear charges
Compare normalisation across different detectors…

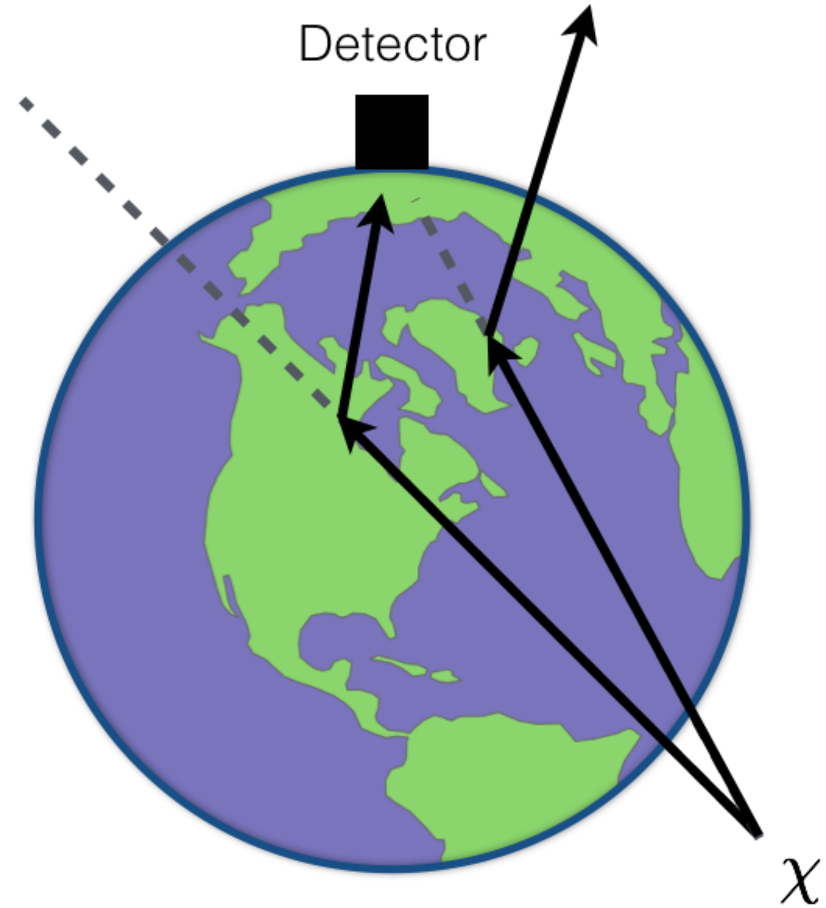
Electric Dipole Dark Matter



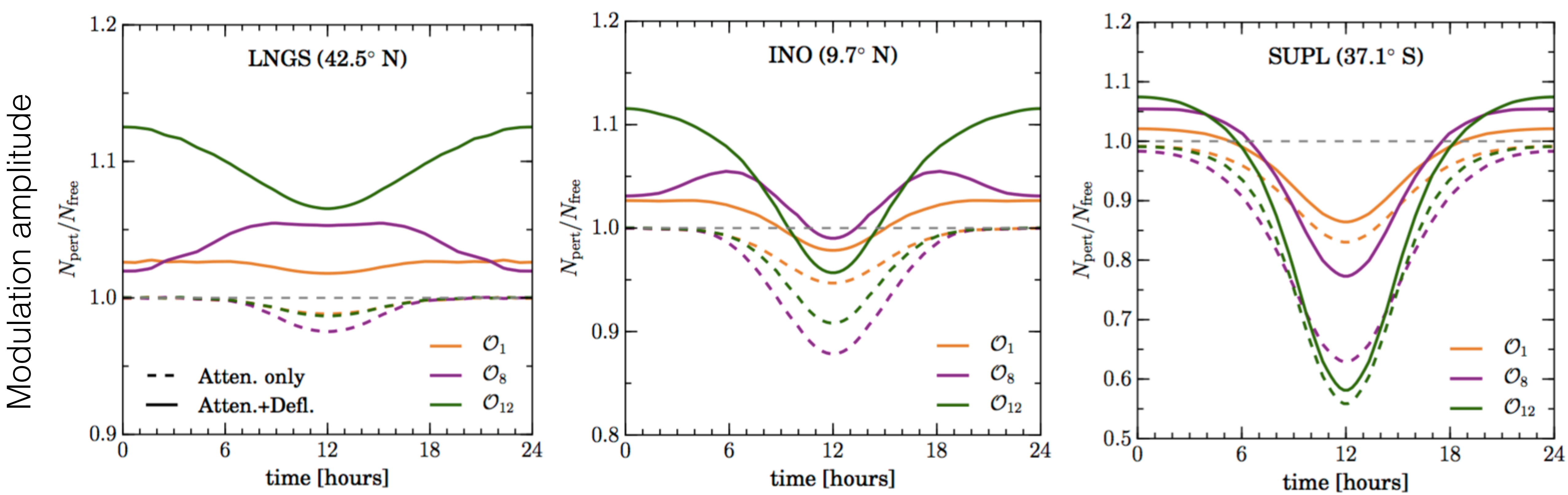
[1506.04454]

Earth Scattering Signatures

[**BJK**, Catena, Kouvaris, 1611.05453]

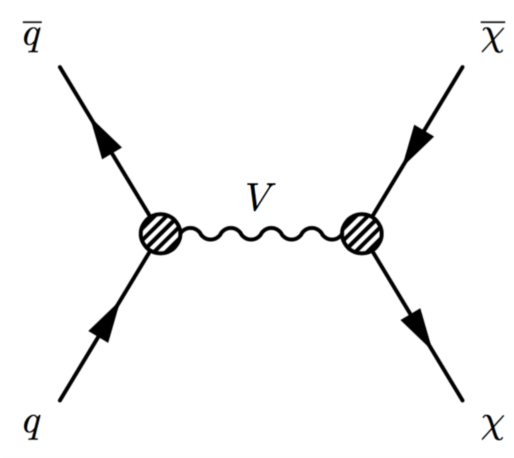


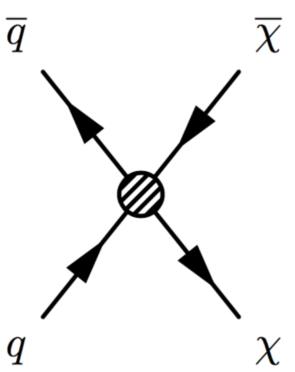
If DM-nucleon interactions are strong enough, could observe a daily modulation in the rate…



Simplified Models and EFT

or "Lorentz symmetry is better than Galilean symmetry"





EFT and Simplified Models

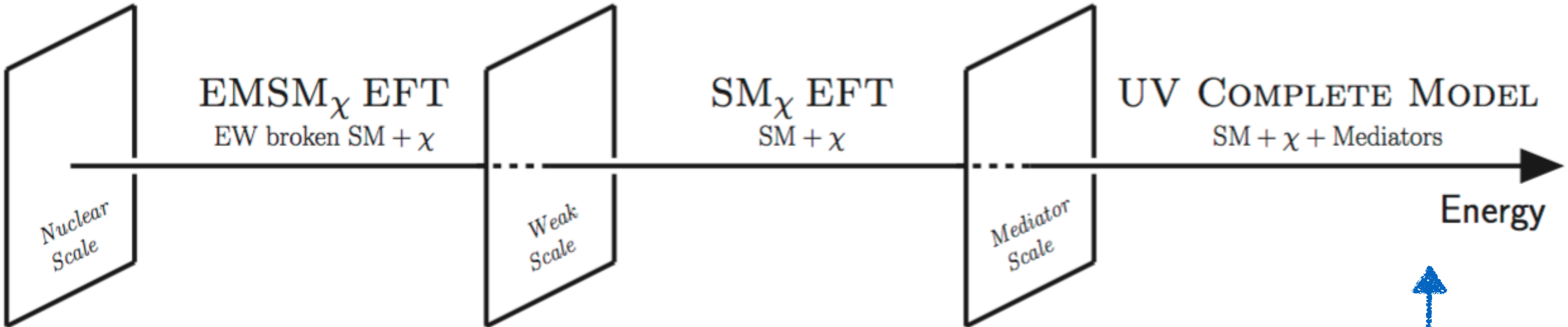
Leading NREFT operators

Couplings to different mediators

		$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
Spin-0 WIMP	(h_1, g_1)	✓																	
	(h_2, g_1)											✓							
	(h_4, g_4)											✓							
	(y_1)	✓										✓							
	(y_2)	✓										✓							
	(y_1, y_2)											✓							
Spin-$\frac{1}{2}$ WIMP	(h_1, λ_1)	✓																	
	(h_2, λ_1)											✓							
	(h_1, λ_2)												✓						
	(h_2, λ_2)							✓											
	(h_3, λ_3)	✓																	
	(h_4, λ_3)								✓		✓								
	(h_3, λ_4)									✓	✓								
	(h_4, λ_4)				✓														
	(l_1)	✓			✓			✓											
	(l_2)	✓			✓			✓											
	(d_1)	✓			✓			✓											

[1505.03117, see also 1806.01291]

Connecting High Scales and Low Scales

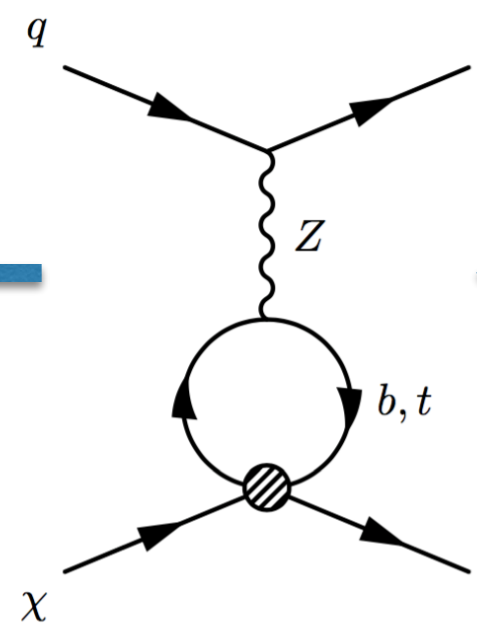


Direct Detection

New Physics

Velocity *un-suppressed*:

$$\overline{\chi}\gamma^\mu\chi\,\overline{q}\gamma_\mu q$$



Velocity suppressed:

$$\overline{\chi}\gamma^\mu\chi\,\overline{q}\gamma_\mu\gamma^5 q$$

Important for connecting to other probes…

[1402.1173,1411.3342,1707.06998,1710.10218]

[D'Eramo, **BJK**, Panci - 1605.04917,1702.00016]

EFT and Simplified Models

Leading NREFT operators

Couplings to different mediators

		$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
Spin-0 WIMP	(h_1, g_1)	✓																	
	(h_2, g_1)											✓							
	(h_4, g_4)											✓							
	(y_1)	✓										✓							
	(y_2)	✓										✓							
	(y_1, y_2)											✓							
Spin-$\frac{1}{2}$ WIMP	(h_1, λ_1)	✓																	
	(h_2, λ_1)											✓							
	(h_1, λ_2)												✓						
	(h_2, λ_2)							✓											
	(h_3, λ_3)	✓																	
	(h_4, λ_3)								✓		✓								
	(h_3, λ_4)									✓	✓								
	(h_4, λ_4)				✓														
	(l_1)	✓			✓			✓											
	(l_2)	✓			✓			✓											
	(d_1)	✓			✓			✓											

[1505.03117, see also 1806.01291]

Optimal search strategy

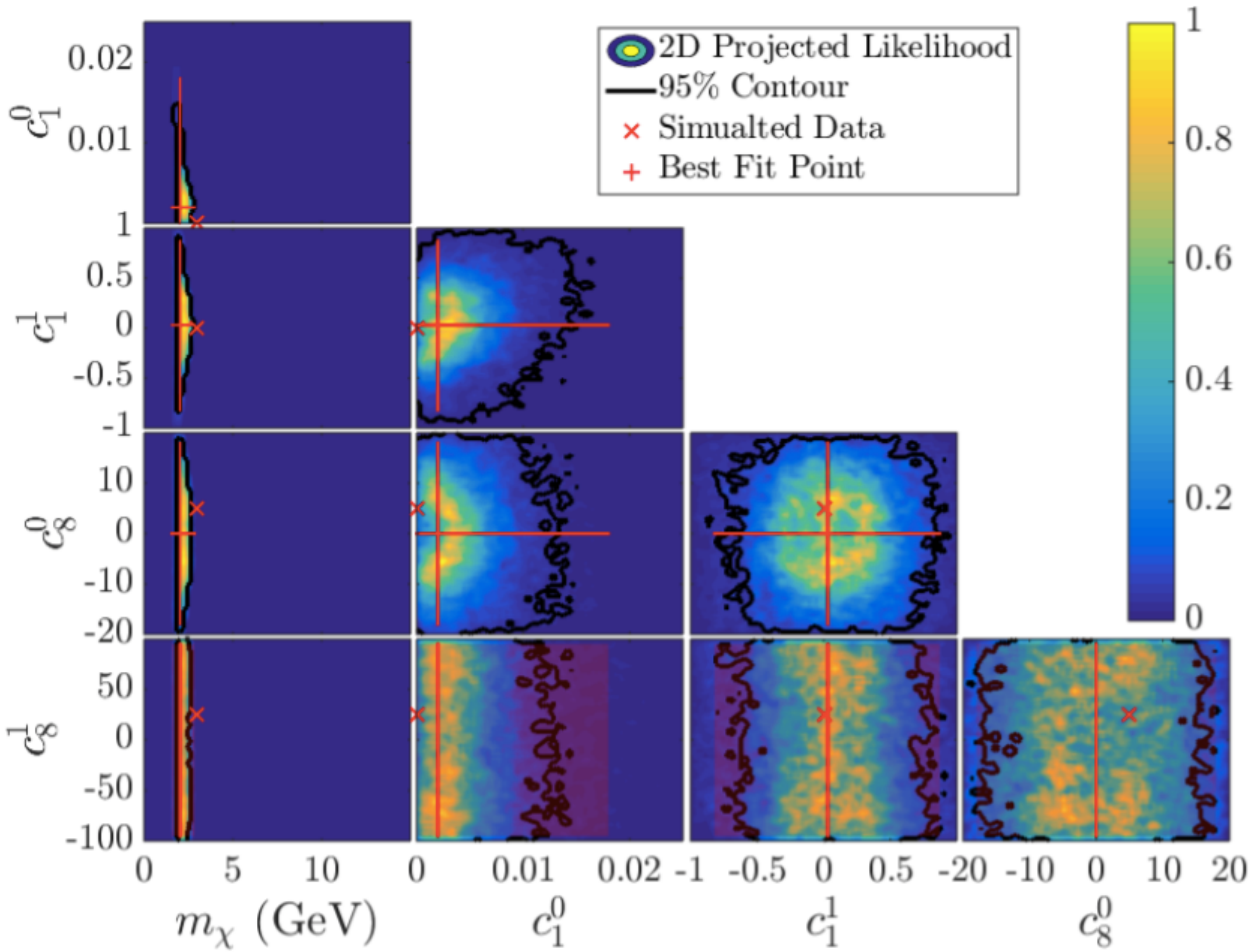
or “If you build it, they will come”

A huge parameter space

Projected signal reconstruction with Xe+Ge+Si

$\mathcal{O}_1 = 1$

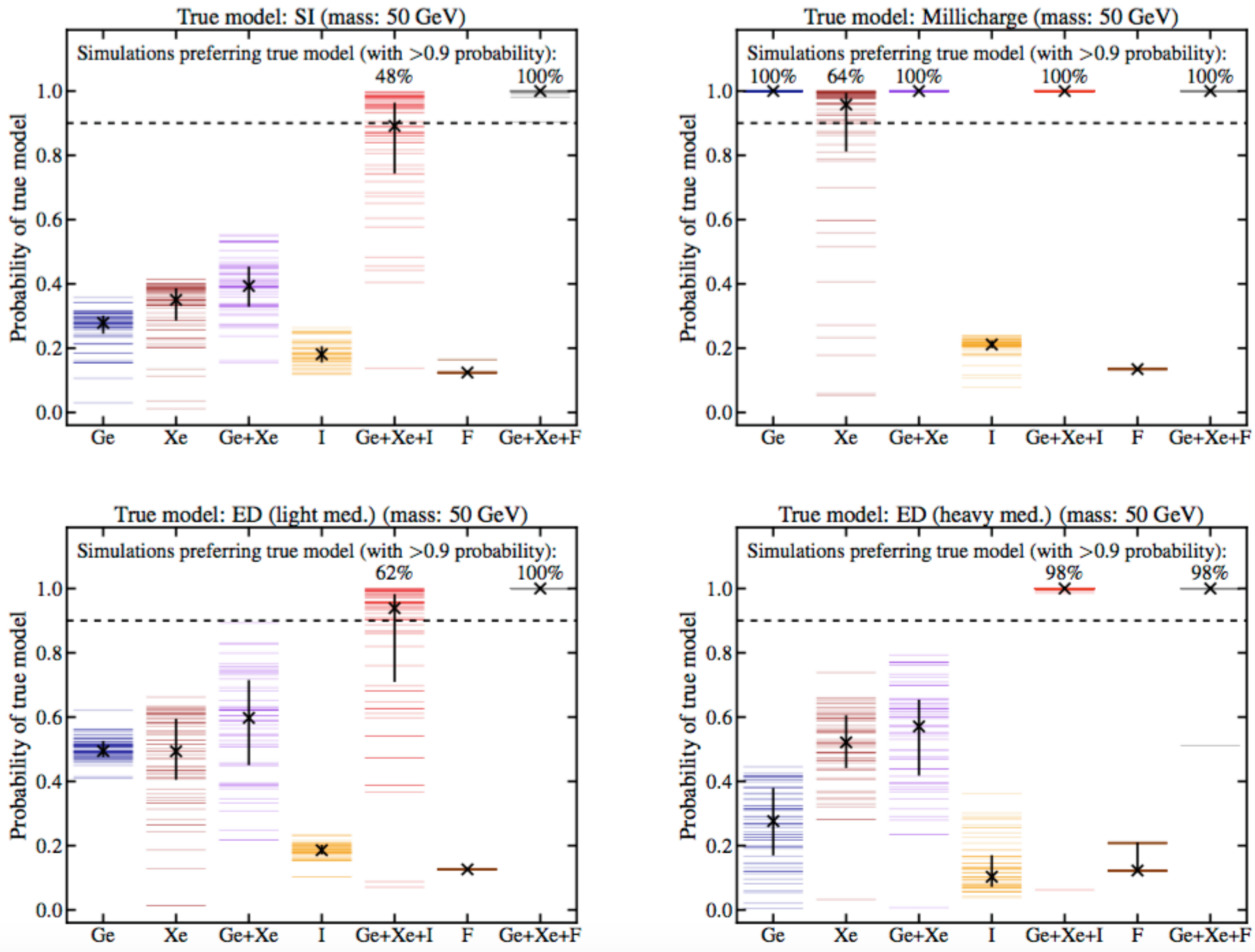
$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$



$c^{0,1} = c^p \pm c^n$

[1407.0127,1405.2637,1504.06554,**1612.09038,** 1805.06113]

Prospects for the future



[1406.0524,**1506.04454**,1607.04418,1706.09471,1709.06051]

Some preliminary thoughts

- Operators with an additional q^2 dependence are typically easily discriminated from standard interactions (except DM is light)

- If we could build a directional detector or observe a modulation signature, we could discriminate operators with an additional v^2 dependence from standard interactions

- Otherwise, we probably need multiple detectors (‘materials’ signature) to make a discrimination

- Xenon + Argon is generally good (to discriminate SI vs SD-type interactions). But what is the ‘optimal’ combination of detectors?

- Is there a comprehensive basis of operators which capture all the relevant signatures?

Tools - Exploring signal diversity

RunDM
[1605.04917]

Connecting high-scale physics with low-scale observables in direct detection

[See also DirectDM,1708.02678]

WIMpy
[tinyurl.com/WIMpy-NREFT]

Direct detection spectrum generator, including a range of interactions

[See also DDCalc v2.0.0]

RAPIDD
[1802.03174]

Surrogate model for direct detection - accelerates rate calculations & parameter scans

[See Andrew Cheek's talk on Thursday]

SwordFish
[1712.05401,1805.04117]

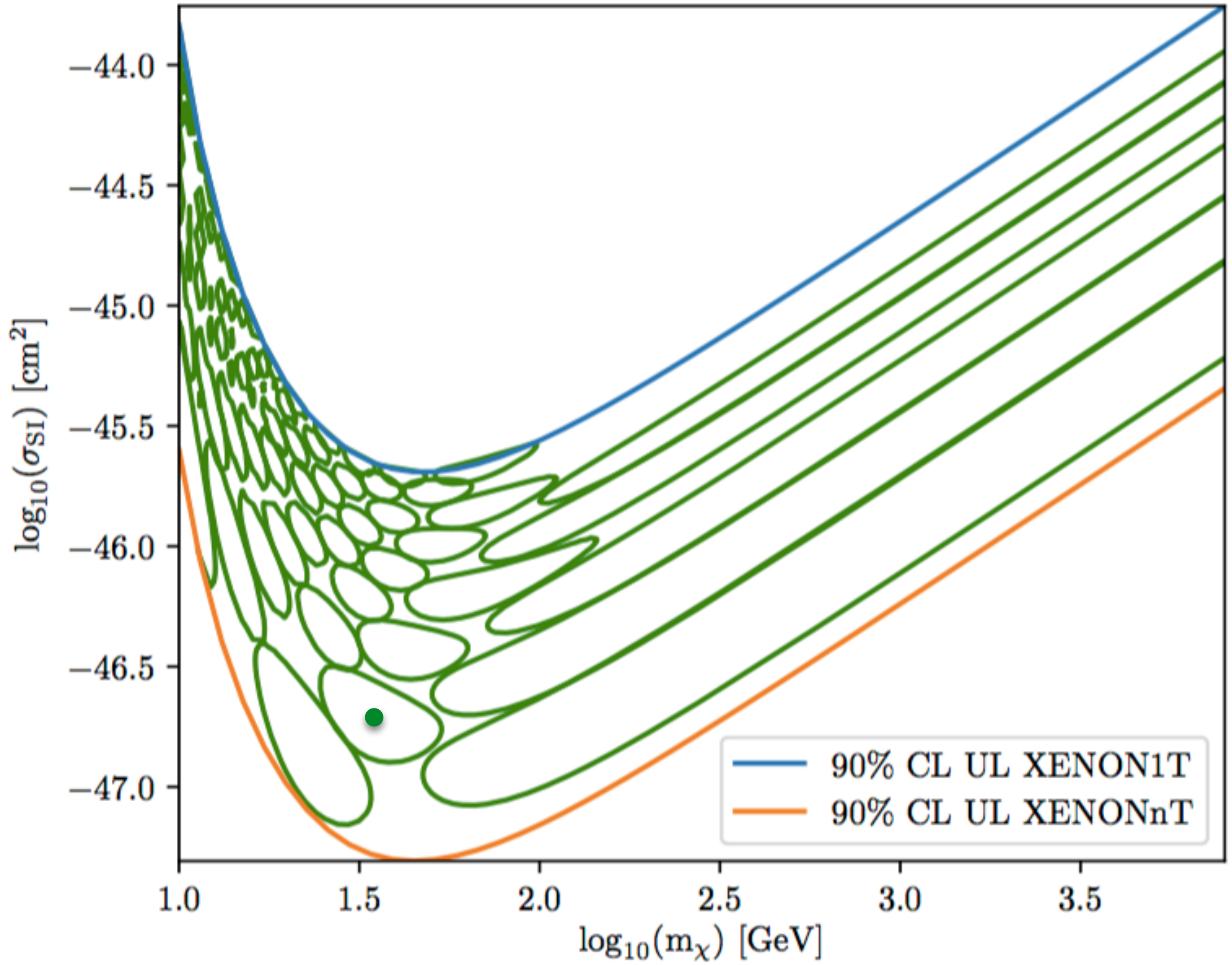
A tool for benchmark-free forecasting - allows efficient exploration of parameter spaces

[See Tom Edwards' talk this afternoon]

Benchmark Free Forecasting

[Edwards, **BJK**, Weniger, 1805.04117]

Fast forecasting without doing lots of pairwise comparisons of points.



Useful for complicated, high-dimensional parameter spaces… allowing use to understand which future experiments we need to get the most information out of a discovery

[See Tom Edwards' talk this afternoon]

Non-standard interactions? Why?

- **Out of curiosity**

  Don't you just want to *know…?* What could DM look like? What could we be missing?

- **Input for experimental analysis**

  Experimental searches are not simple cut-and-counts - need to know what the signal looks like to get the best sensitivity

- **Optimisation of future experiments**

  Which experiments should we use to get the best sensitivity, or the most information out of a future detection?

Non-standard interactions? Why?

- **Out of curiosity**

  Don't you just want to *know…?* What could DM look like? What could we be missing?

- **Input for experimental analysis**

  Experimental searches are not simple cut-and-counts - need to know what the signal looks like to get the best sensitivity

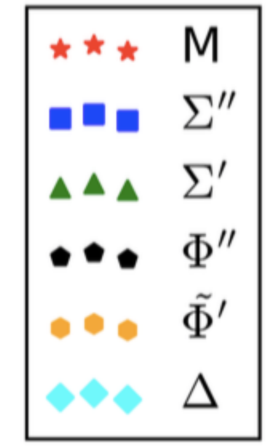
- **Optimisation of future experiments**

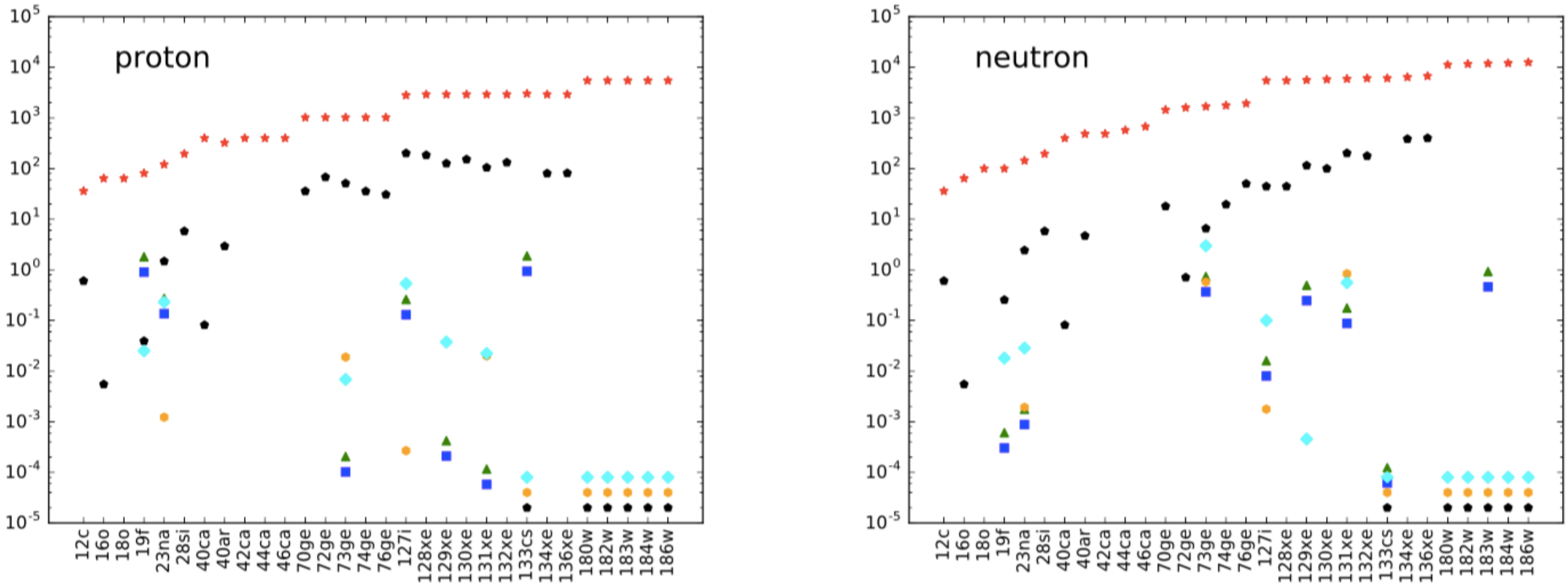
  Which experiments should we use to get the best sensitivity, or the most information out of a future detection?

Thank you!

Backup Slides

Nuclear responses





[1805.06113]

Simplified Models: Spin-0 DM

		$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
Spin-0 WIMP	(h_1, g_1)	✓																	
	(h_2, g_1)											✓							
	(h_4, g_4)											✓							
	(y_1)	✓										✓							
	(y_2)	✓										✓							
	(y_1, y_2)											✓							

[1505.03117]

Simplified Models: Spin-1/2 DM

Spin-$\frac{1}{2}$ WIMP	(h_1, λ_1)	✓																	
	(h_2, λ_1)											✓							
	(h_1, λ_2)												✓						
	(h_2, λ_2)							✓											
	(h_3, λ_3)	✓																	
	(h_4, λ_3)								✓		✓								
	(h_3, λ_4)									✓	✓								
	(h_4, λ_4)				✓														
	(l_1)	✓			✓			✓											
	(l_2)	✓			✓			✓											
	(d_1)	✓			✓			✓											
	(d_2)	✓			✓			✓											

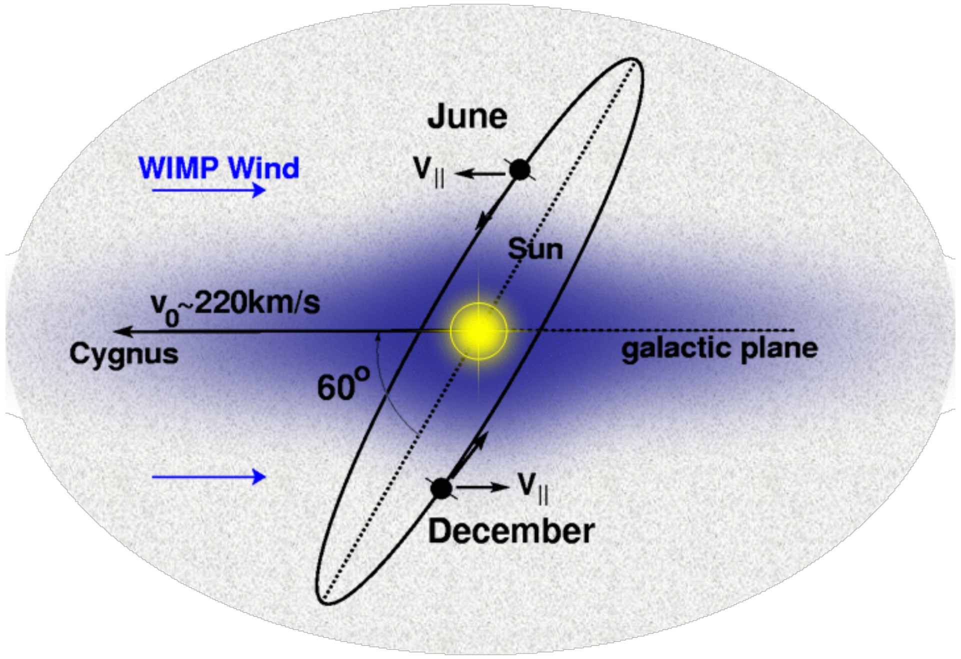
[1505.03117]

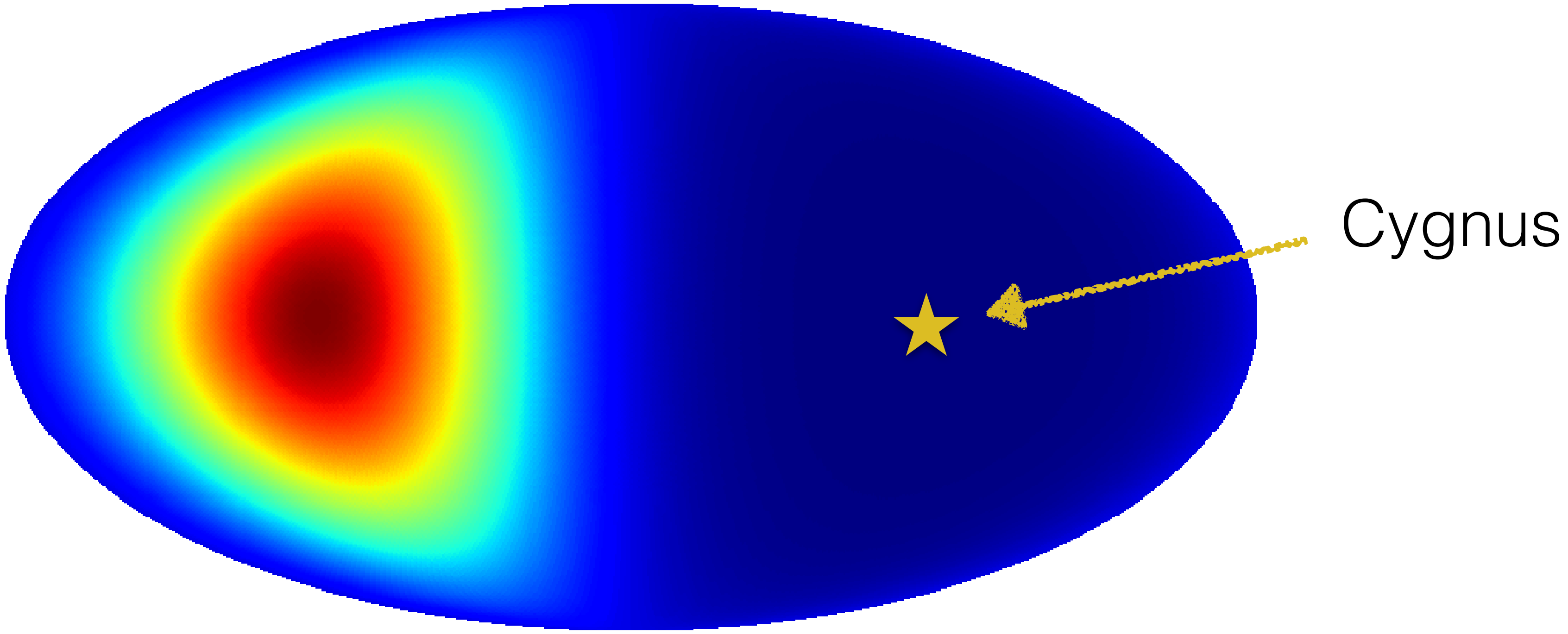
Simplified Models: Spin-1 DM

Spin-1 WIMP	(h_1, b_1)	✓																	
	(h_2, b_1)										✓								
	(h_4, b_5)										✓								
	(h_3, b_6)					✓	✓	✓										✓*	
	(h_4, b_6)										✓								✓*
	(h_3, b_7)									✓*	✓*		✓						
	(h_4, b_7)				✓*	✓		✓								✓			
	(y_3)	✓			✓							✓	✓	✓					✓
	(y_4)	✓			✓							✓	✓	✓					✓
	(y_3, y_4)											✓	✓	✓					✓

[1505.03117]

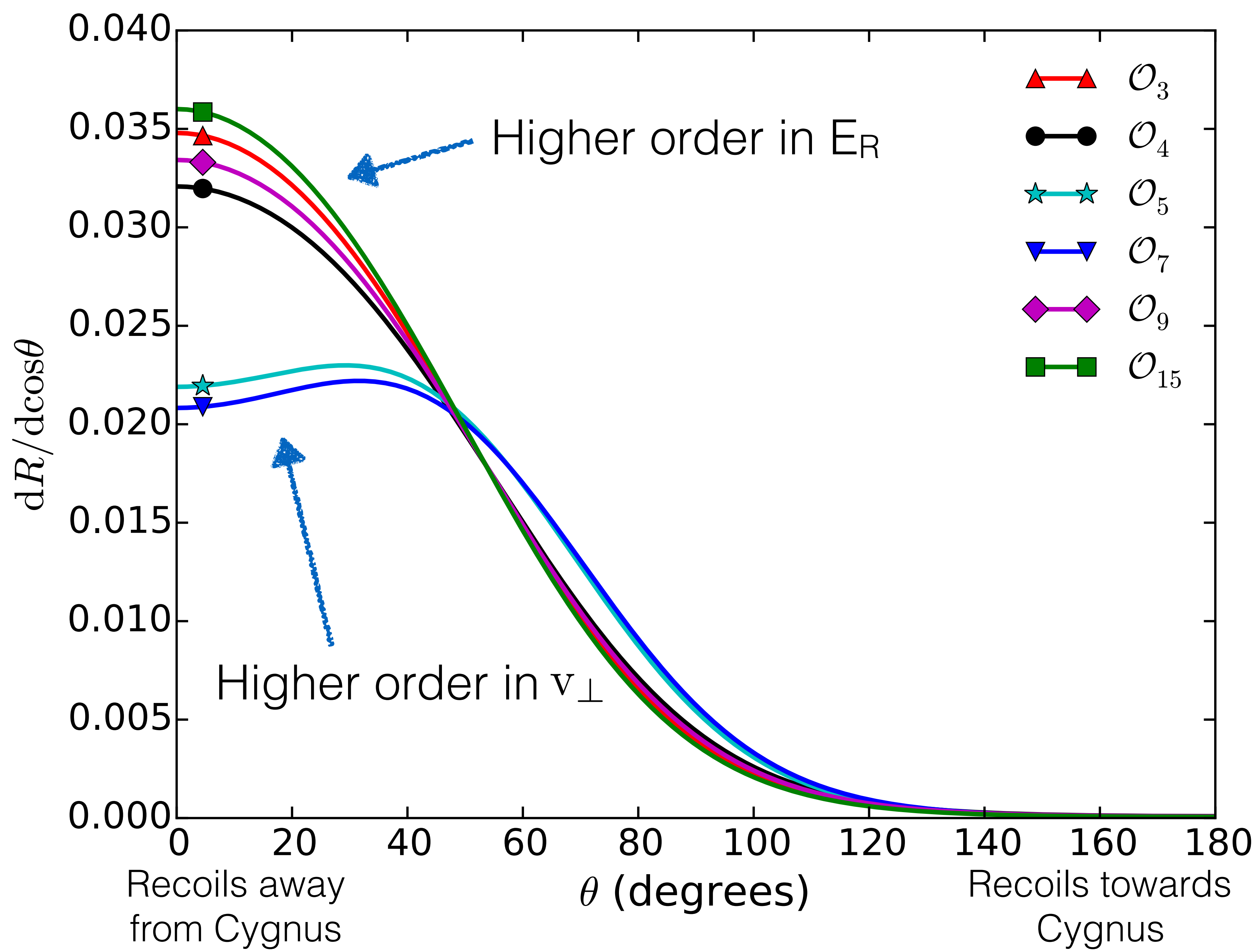
Directional Detection

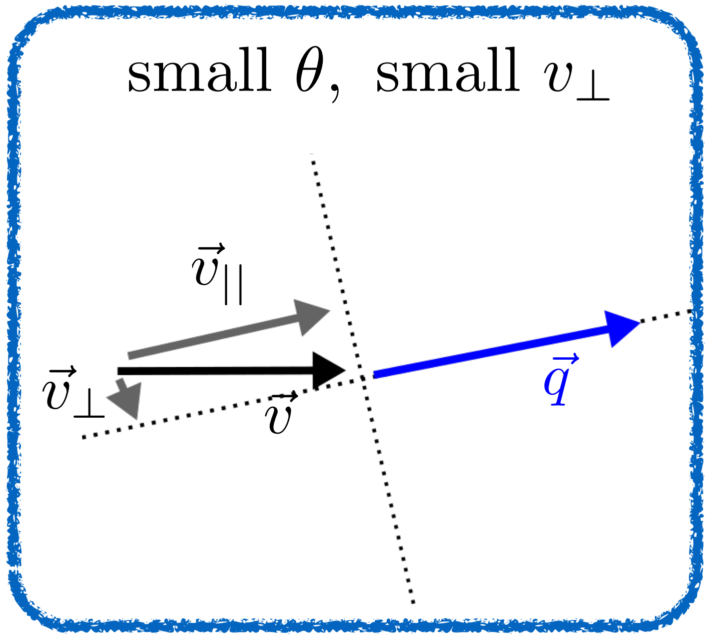


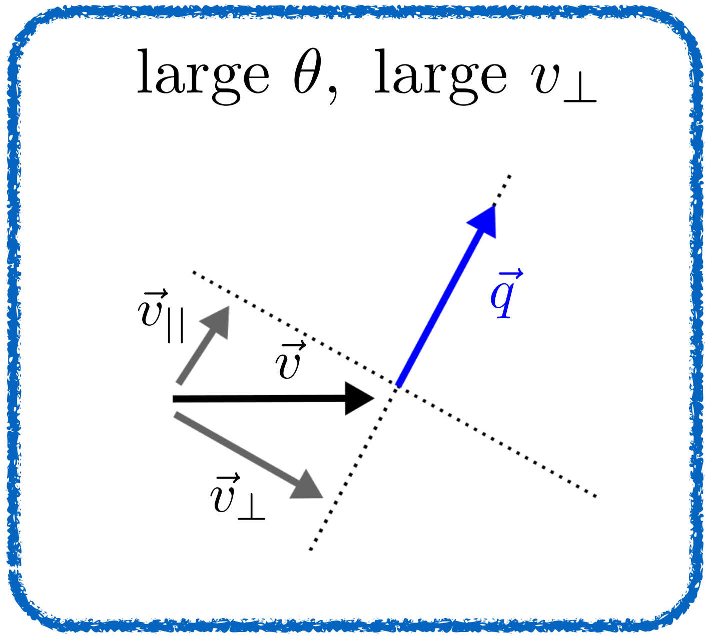


Directional Signatures

[**BJK** 1505.07406]



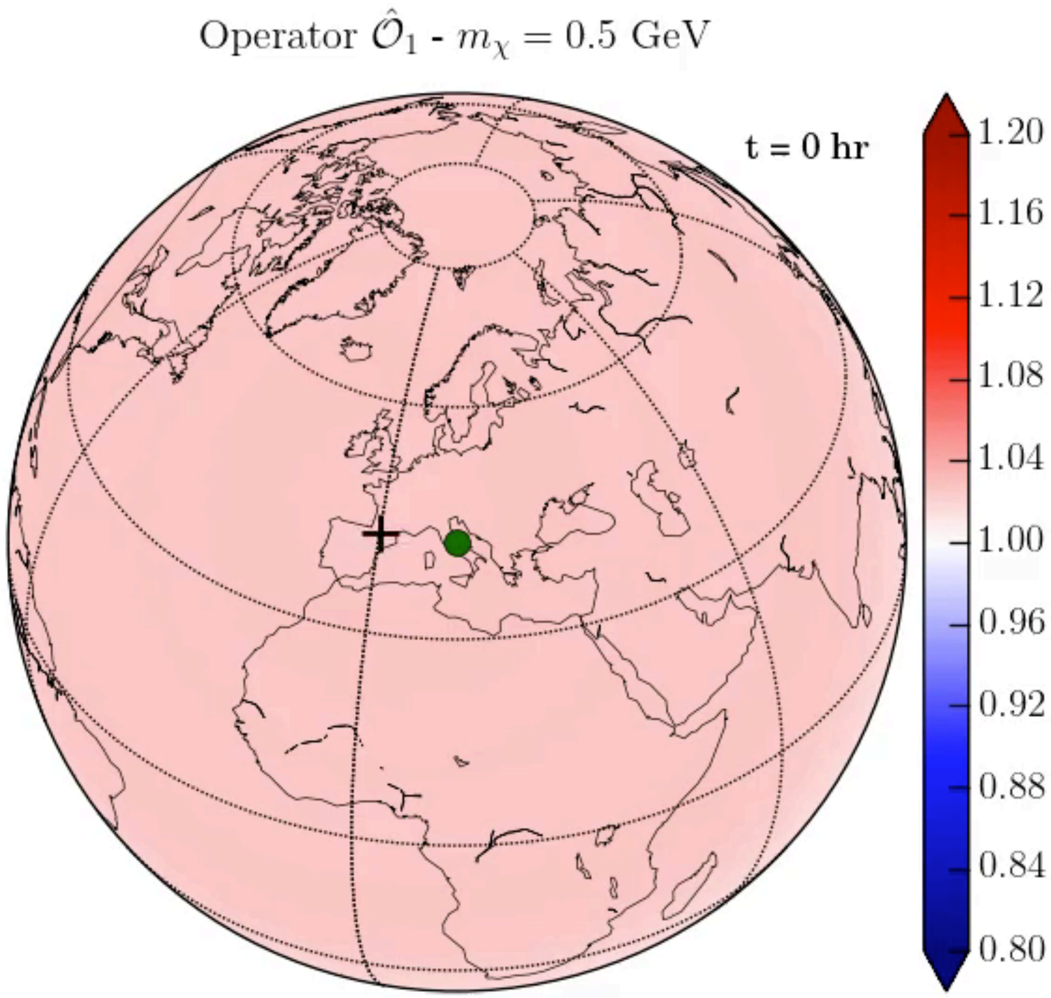




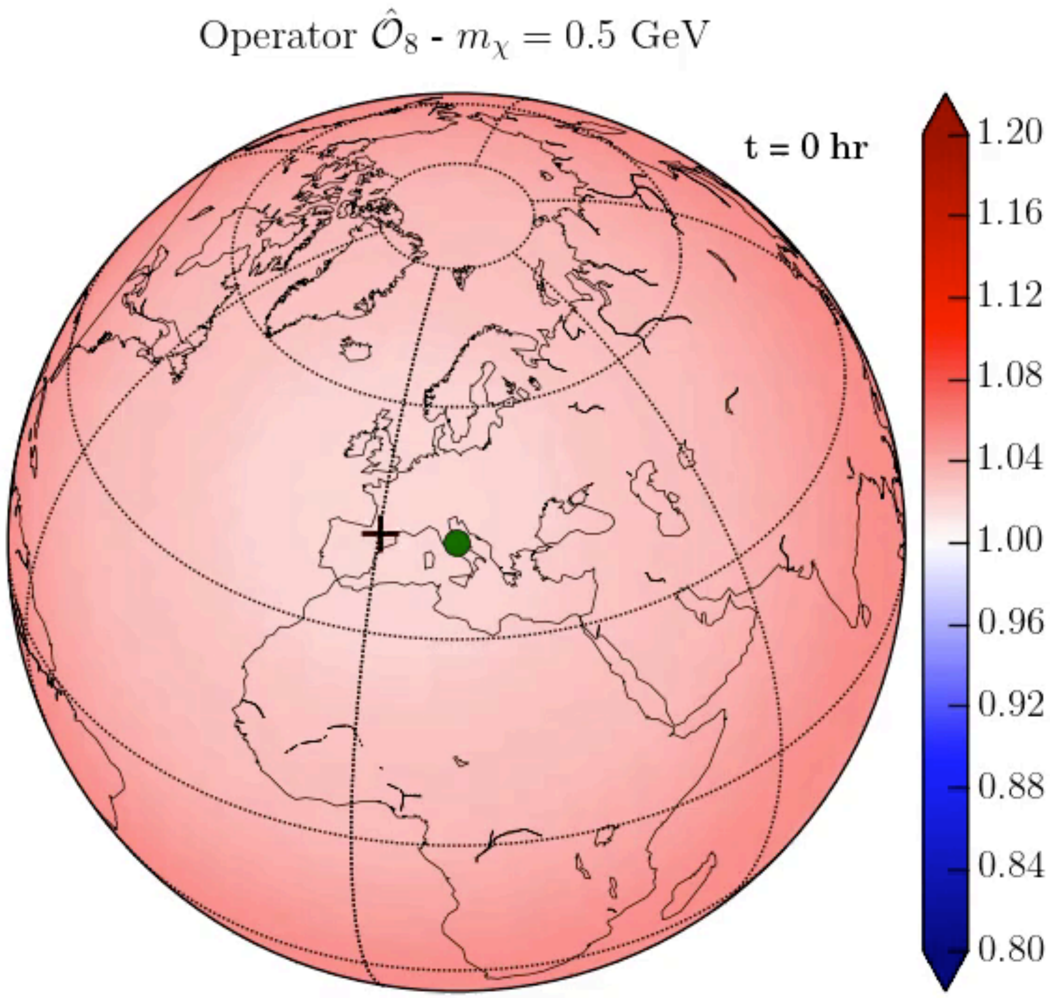
Also note: $q = 2\mu_{\chi N}\vec{v}\cdot\hat{q}$
$= 2\mu_{\chi N} v\cos\theta$

[See also 1505.06441]

Earth Scattering

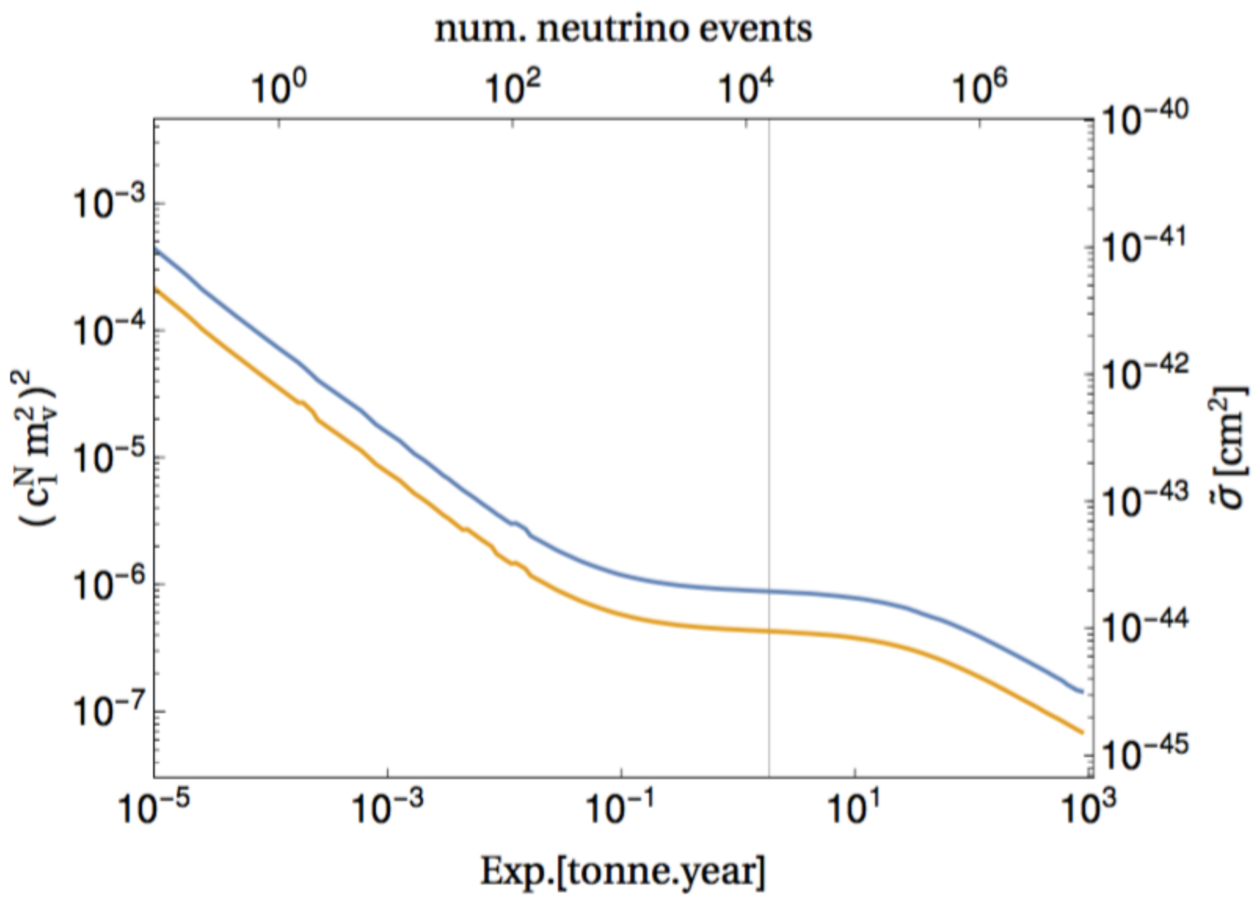


Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*



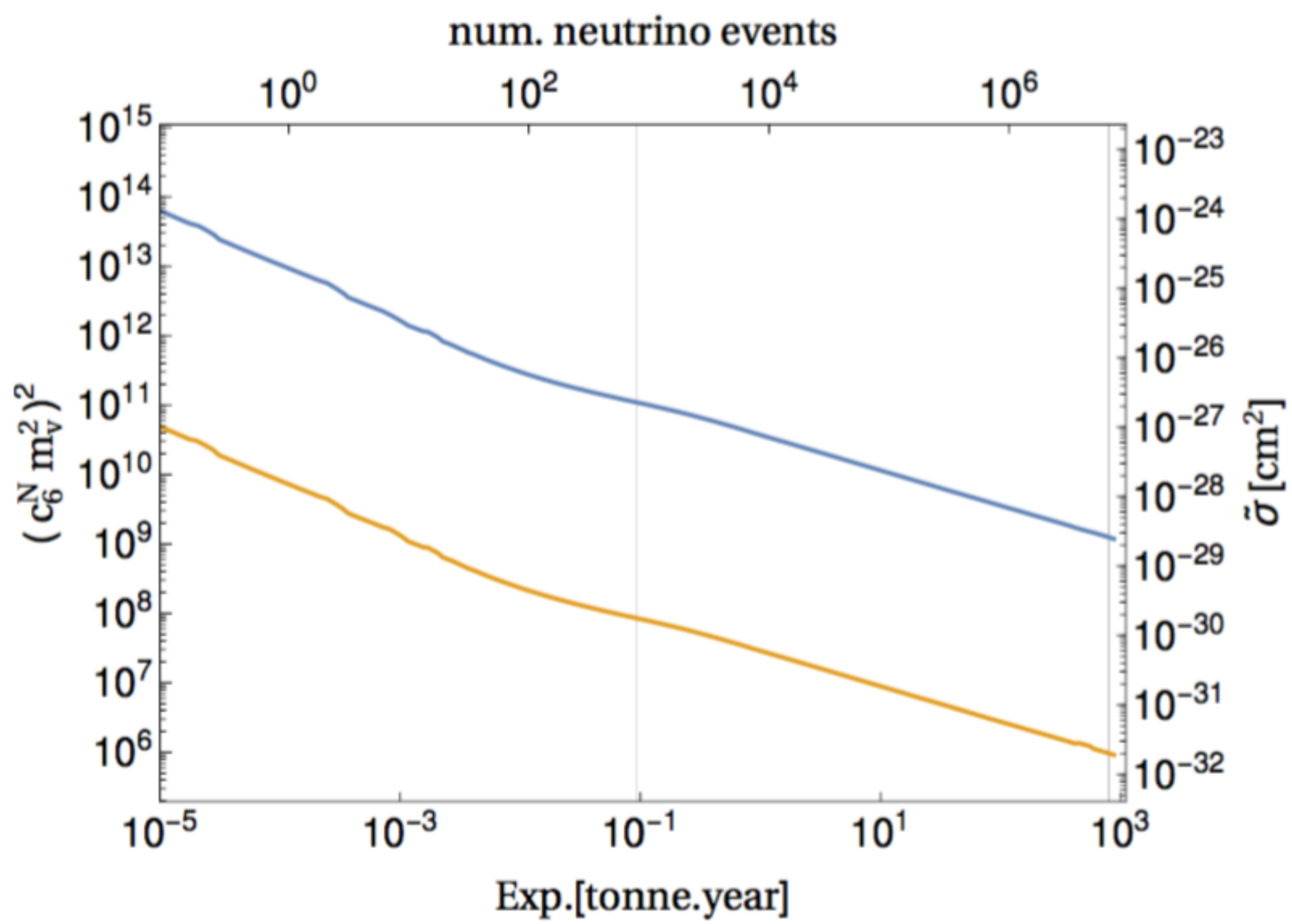
Relative rate enhancement due to Earth-scattering *(attenuation + deflection)*

Neutrino Floor in EFT



Spin-independent interaction

q²-dependent interaction

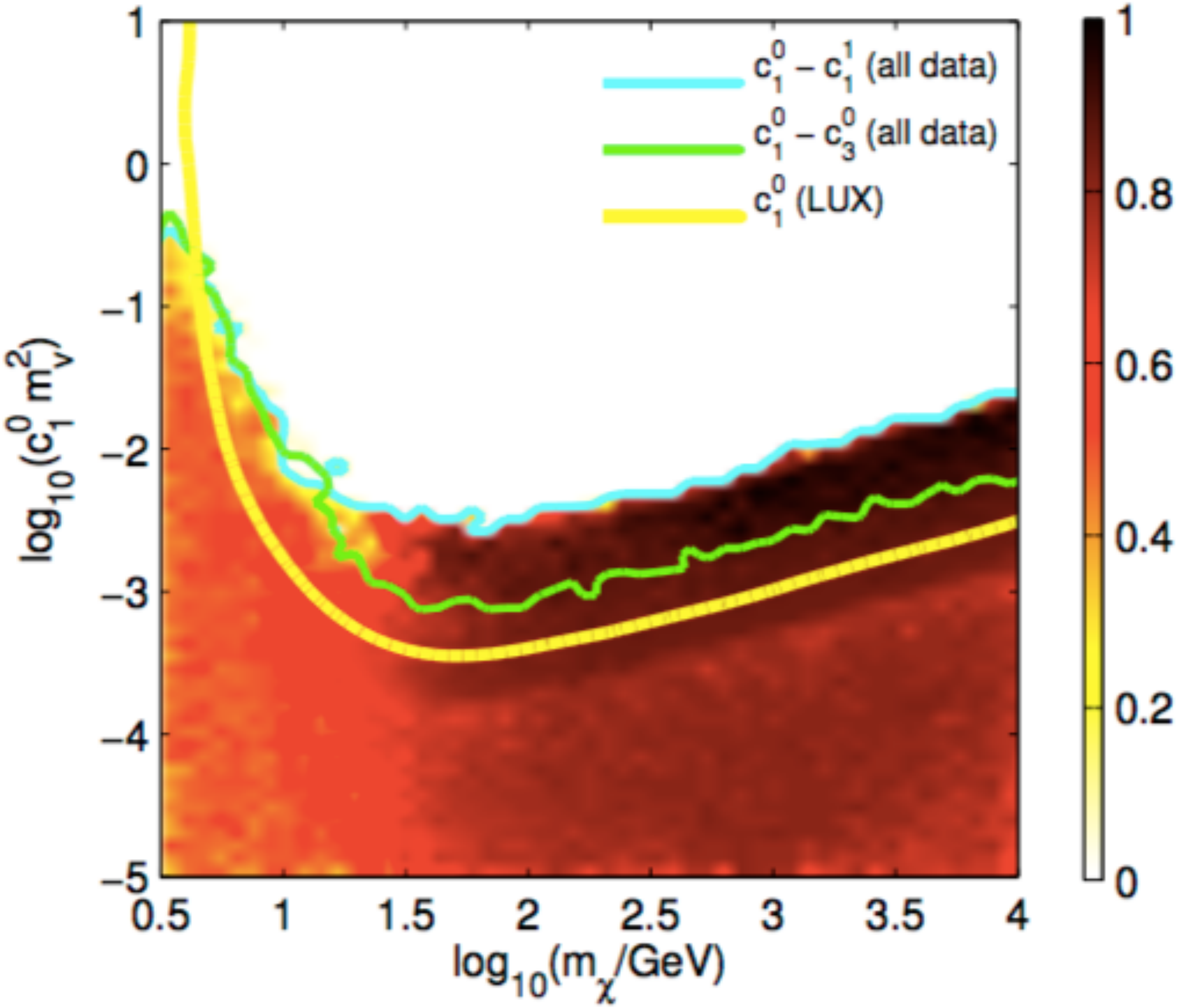


[1602.05300]

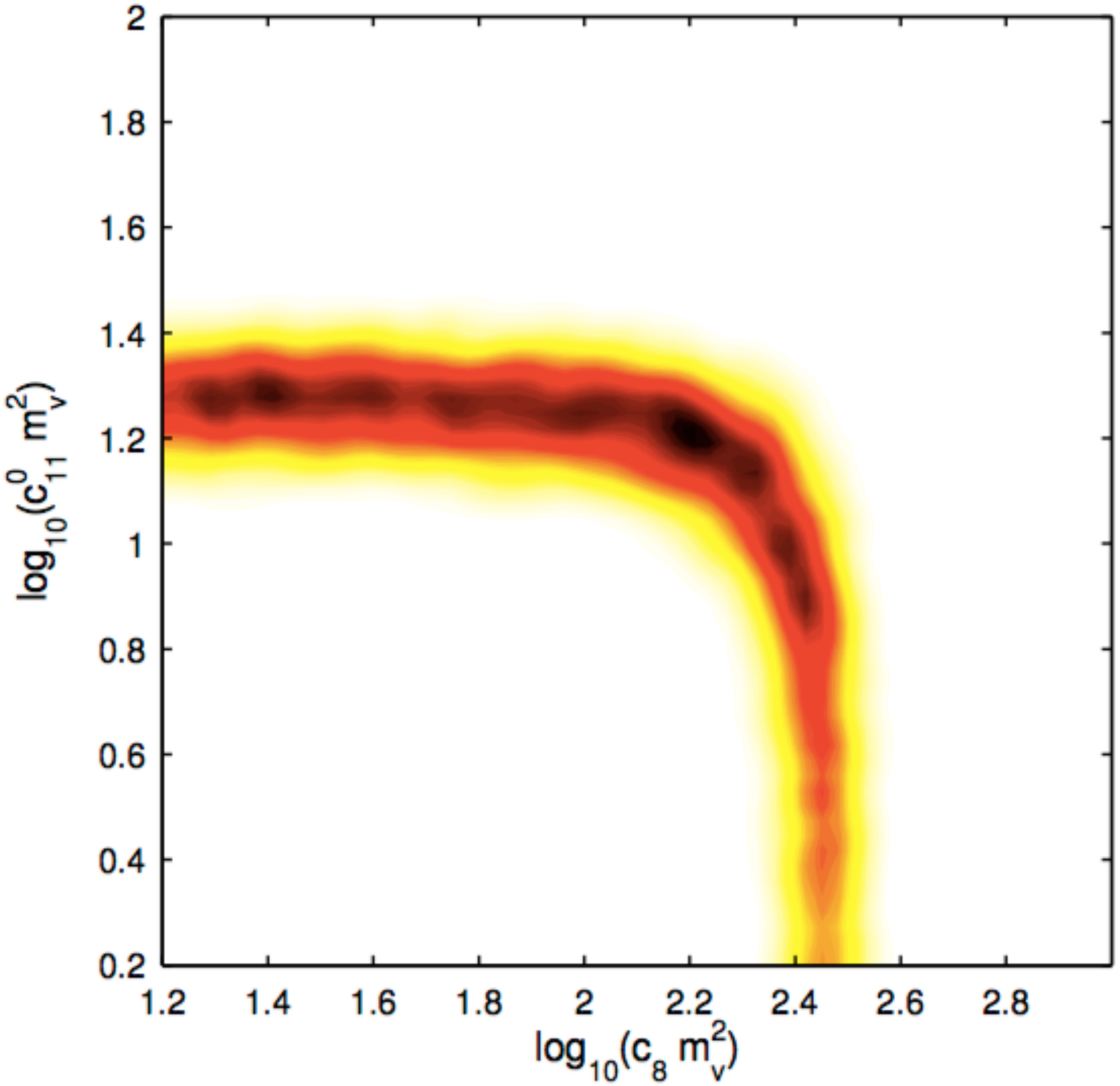
Interference and degeneracy

[1407.0127,1405.2637, 1504.06554,**1612.09038,** 1805.06113]

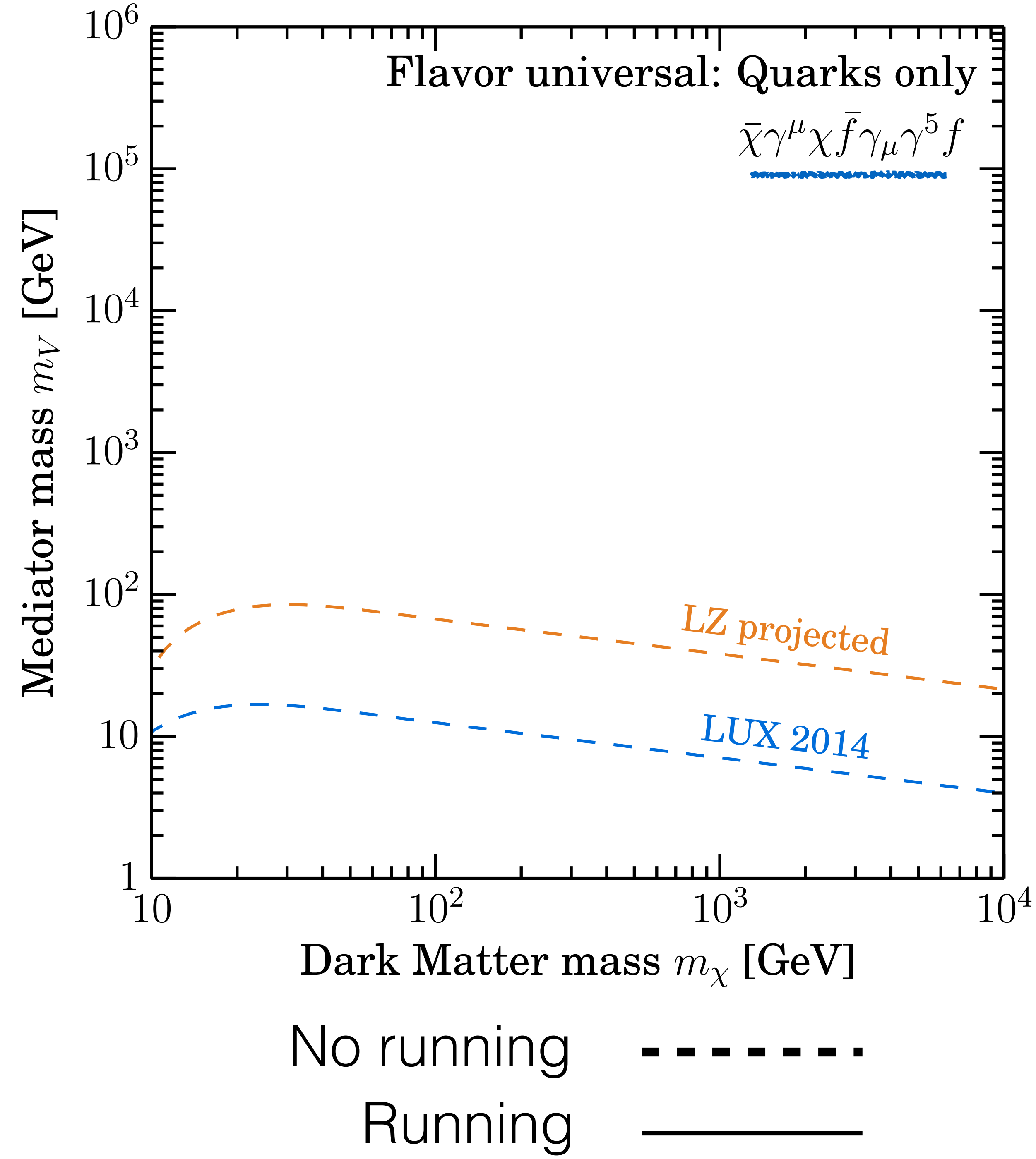
Upper Limits



Putative Signal

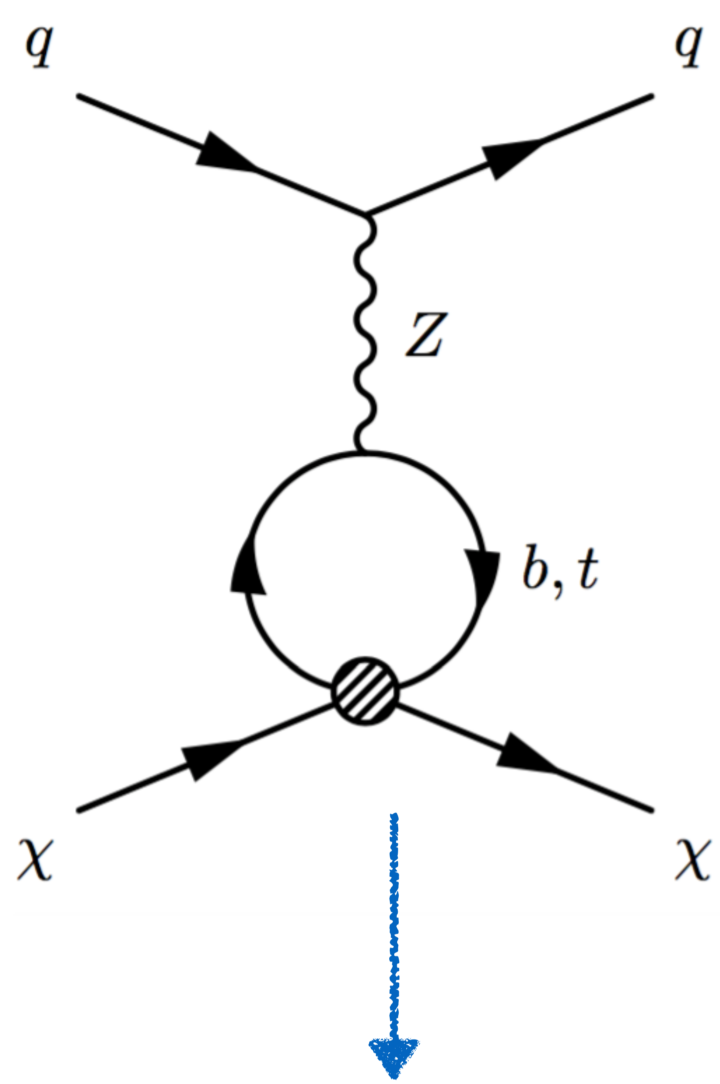


Connecting High Scales and Low Scales

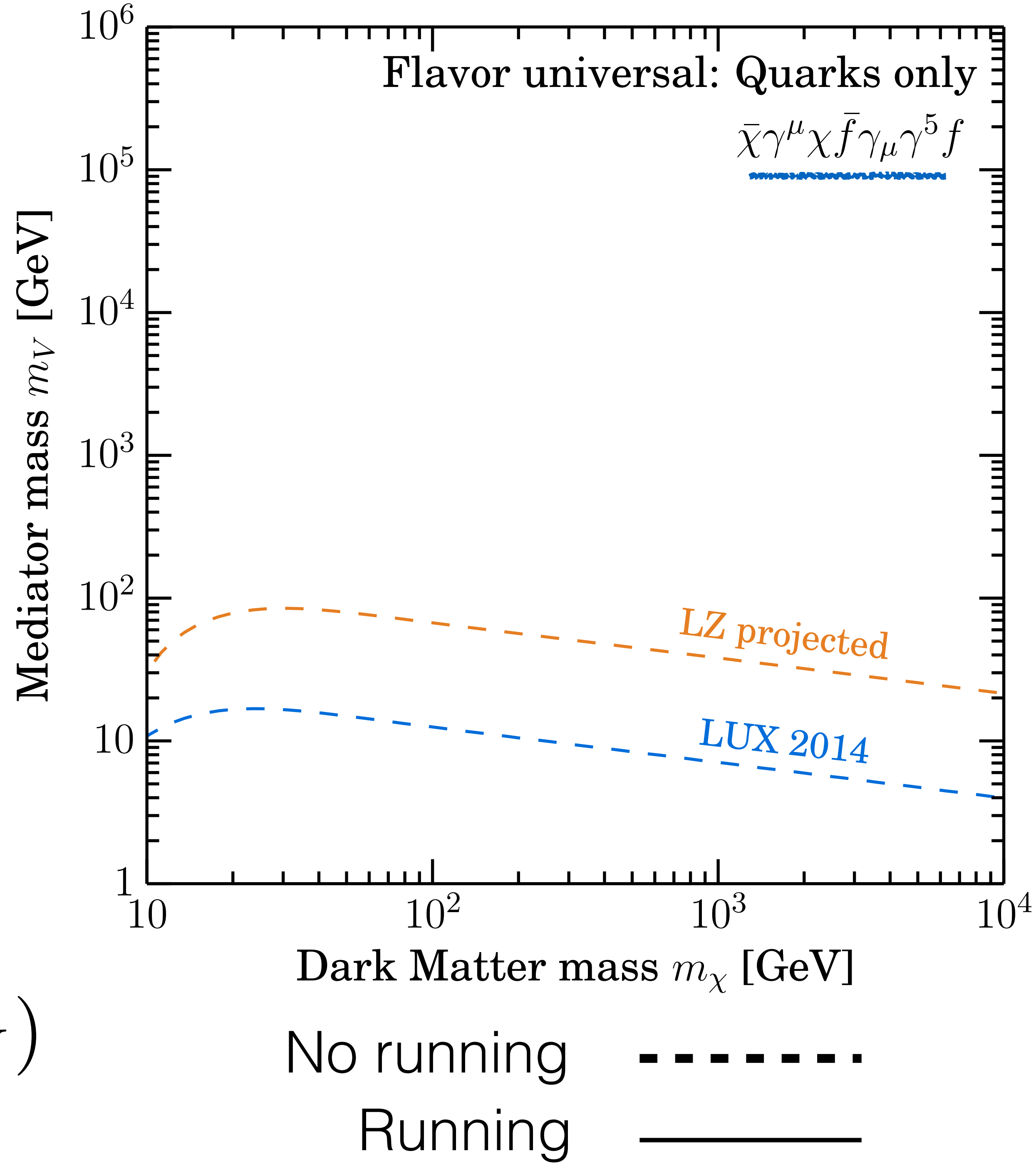


[D'Eramo, **BJK**, Panci - 1605.04917,1702.00016]

Connecting High Scales and Low Scales

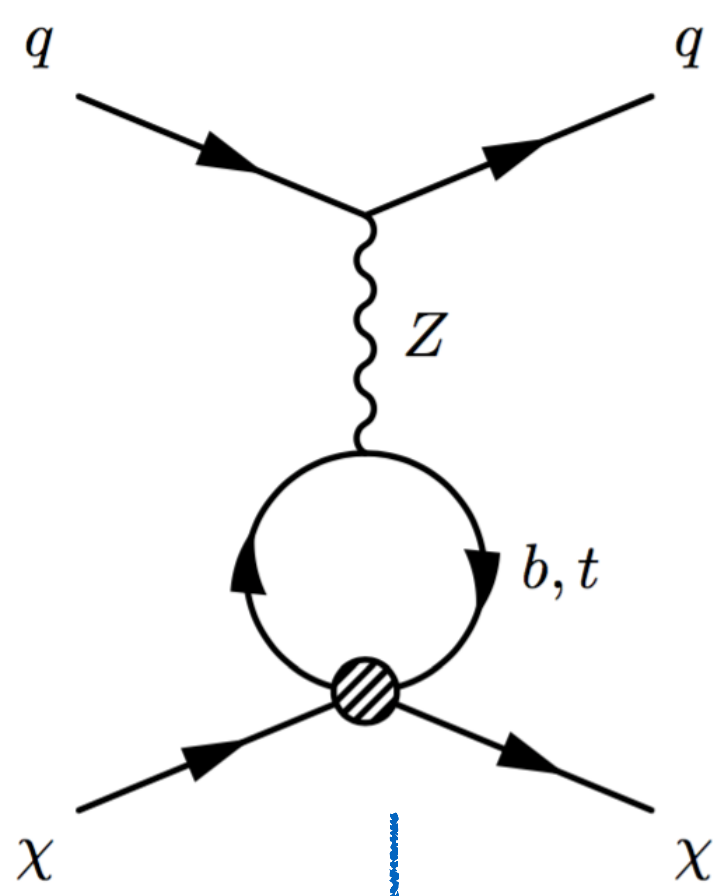


$$c_V^{(q)} \sim 0 + \# \frac{\lambda_{b,t}^2}{16\pi^2} \ln(m_V/m_N)$$

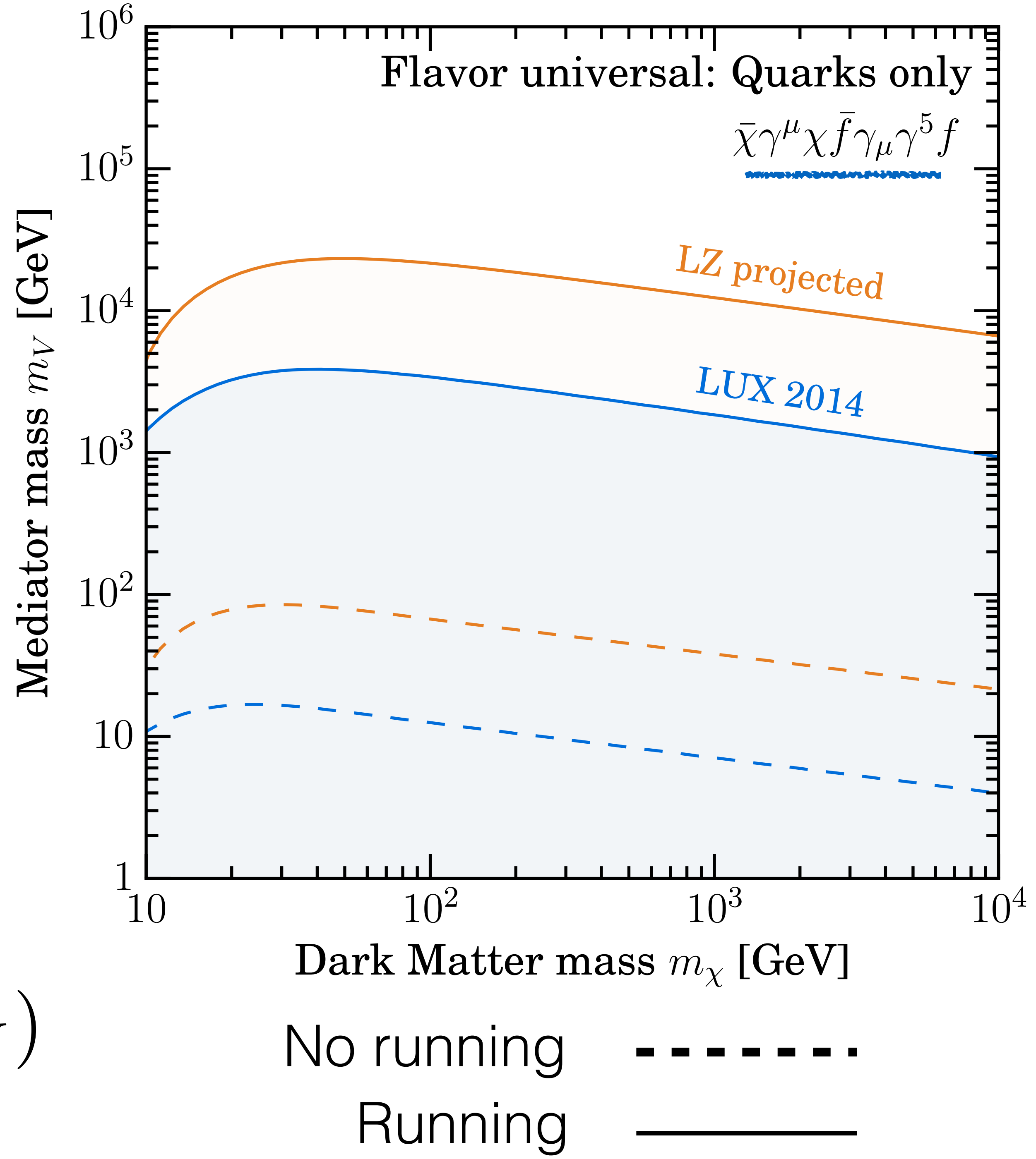


[D'Eramo, **BJK**, Panci - 1605.04917,1702.00016]

Connecting High Scales and Low Scales



$$c_V^{(q)} \sim 0 + \# \frac{\lambda_{b,t}^2}{16\pi^2} \ln(m_V/m_N)$$



[D'Eramo, **BJK**, Panci - 1605.04917,1702.00016]