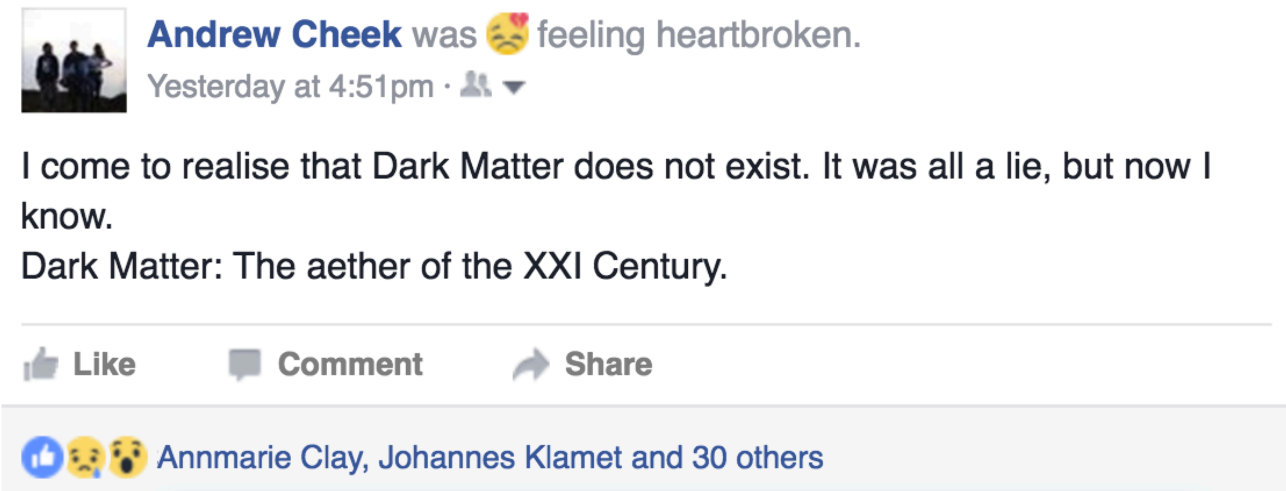
Distinguishing Dark Matter in Direct Detection

Andrew Cheek
Supervisor: David Cerdeño
In Collaboration with Miguel Peiró and Elias Gerstmayr

Dark Matter



- Despite what my Facebook status might imply. I'm still prescribing to the DM paradigm.

Dark Matter

Andrew Cheek was 😣 feeling heartbroken.
Yesterday at 4:51pm ·

I come to realise that Dark Matter does not exist. It was all a lie, but now I know.
Dark Matter: The aether of the XXI Century.

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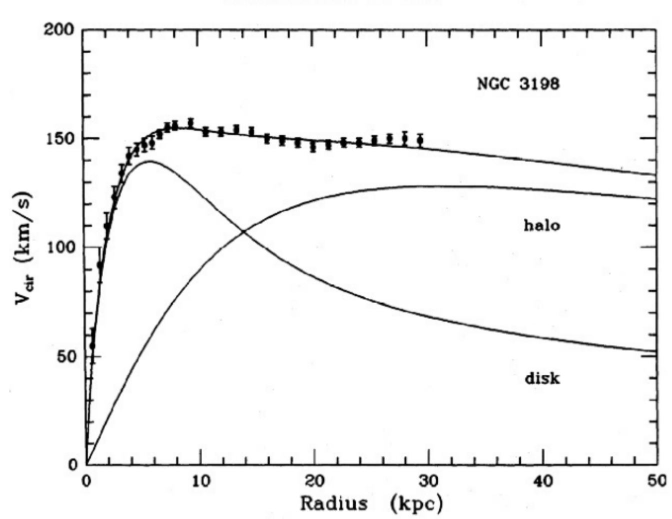
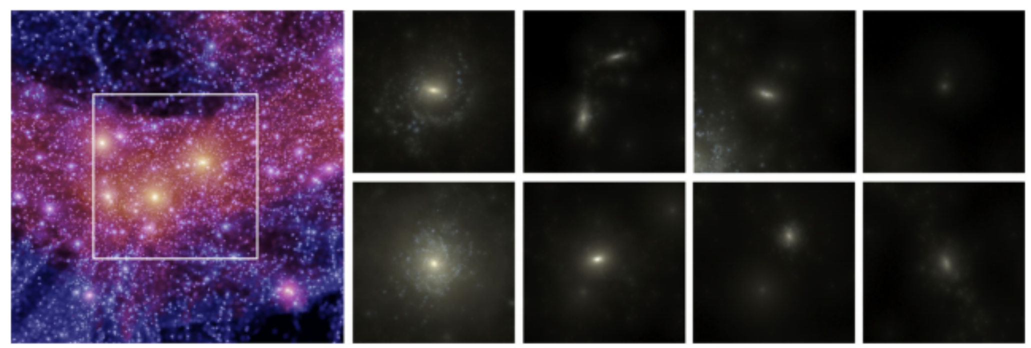
Annmarie Clay, Johannes Klamet and 30 others

- Despite what my Facebook status might imply. I'm still prescribing to the DM paradigm.

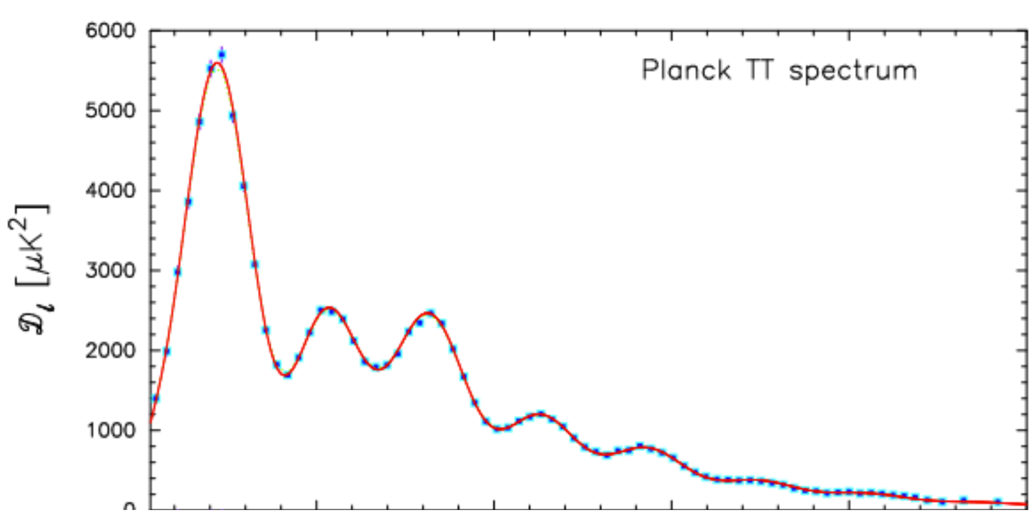
VAN ALBADA *ET AL.*





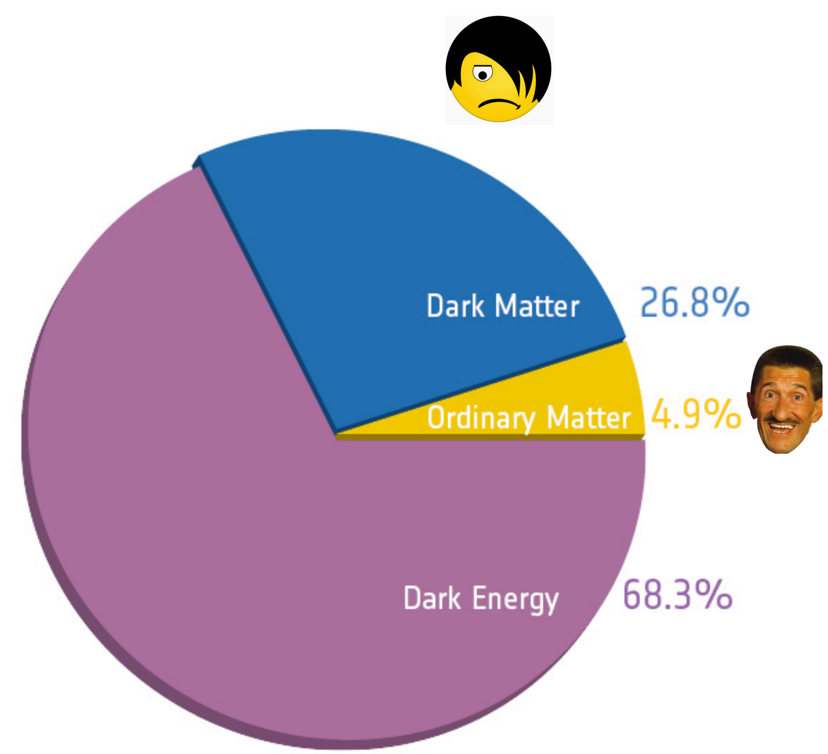
The APOSTLE simulations: solutions to the Local Group's cosmic puzzles

Till Sawala,[1,2★] Carlos S. Frenk,[1] Azadeh Fattahi,[3] Julio F. Navarro,[3†]
Richard G. Bower,[1] Robert A. Crain,[4] Claudio Dalla Vecchia,[5,6] Michelle Furlong,[1]
John. C. Helly,[1] Adrian Jenkins,[1] Kyle A. Oman,[2] Matthieu Schaller,[1] Joop Schaye,[7]
Tom Theuns,[1] James Trayford[1] and Simon D. M. White[8]

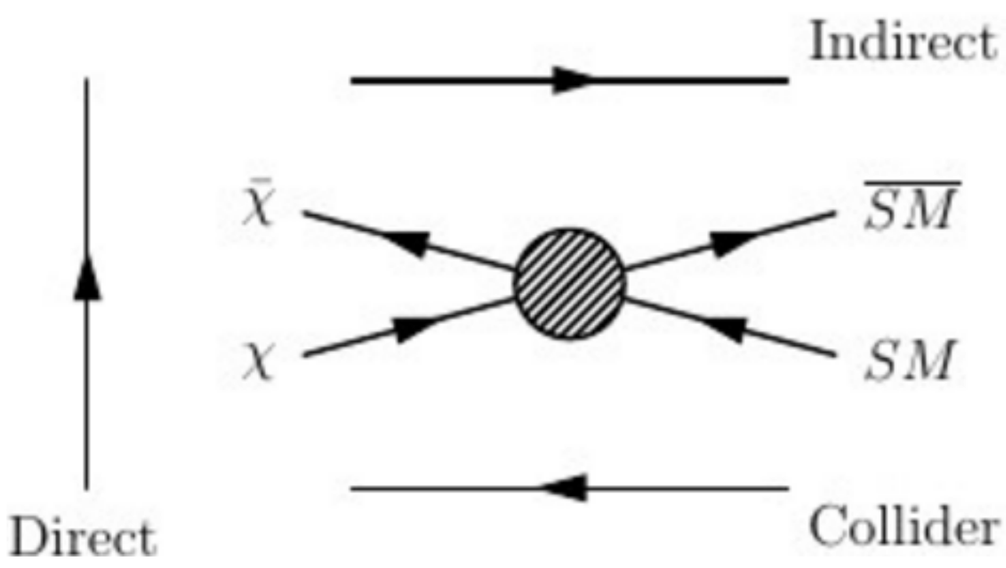


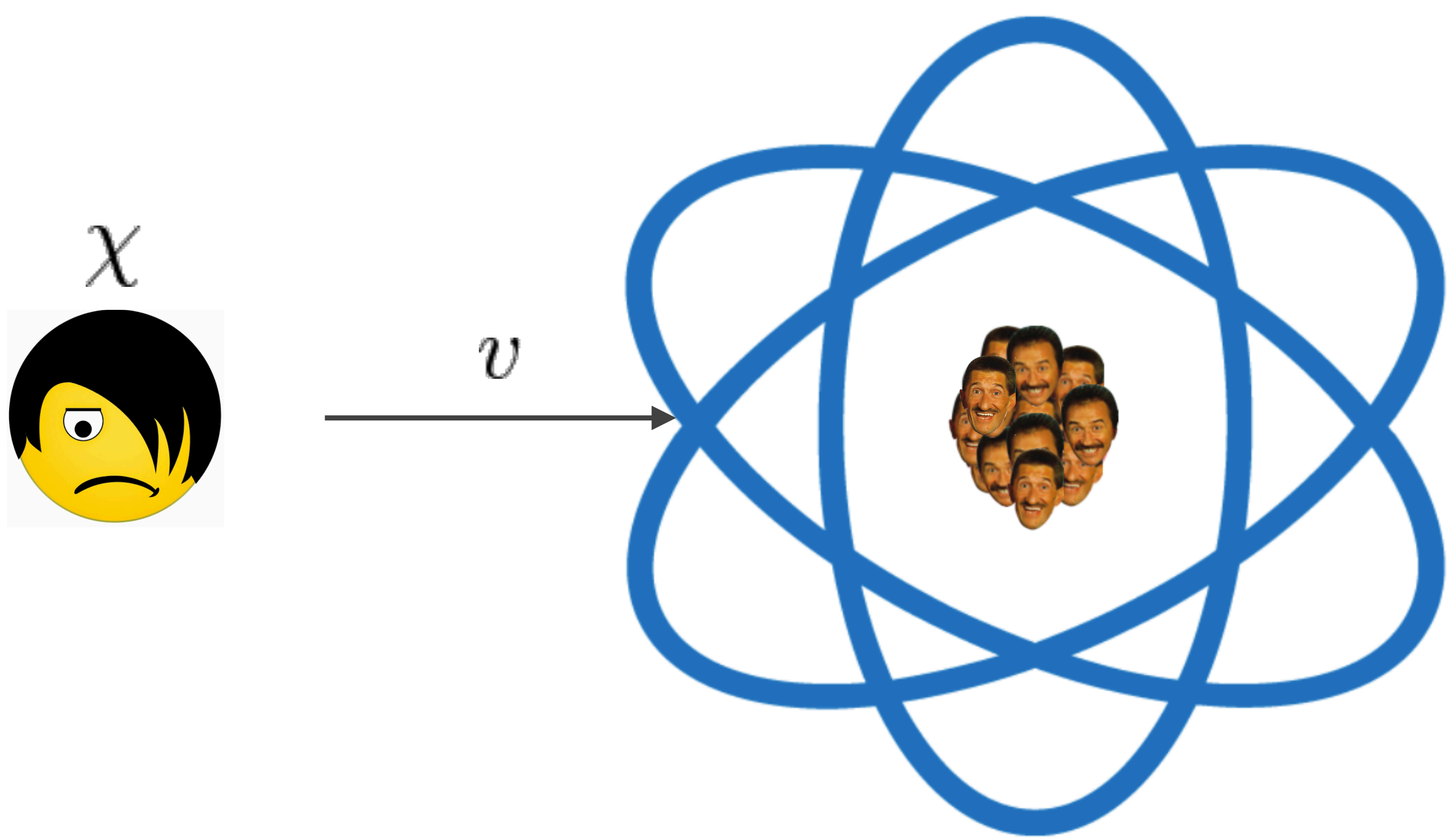
***Planck* 2013 results. XVI. Cosmological parameters**

Planck Collaboration: P. A. R. Ade[93], N. Aghanim[65], C. Armitage-Caplan[99], M. Arnaud[79], M. Ashdown[76,6], F. Atrio-Barandela[19], J. Aumont[65], C. Baccigalupi[92], A. J. Banday[102,10], R. B. Barreiro[72], J. G. Bartlett[1,74], E. Battaner[105], K. Benabed[66,101], A. Benoît[63], A. Benoit-Lévy[26,66,101], J.-P. Bernard[102,10], M. Bersanelli[38,55], P. Bielewicz[102,10,92], J. Bobin[79], J. J. Bock[74,11], A. Bonaldi[75], J. R. Bond[9], J. Borrill[14,96], F. R. Bouchet[66,101], M. Bridges[76,6,69], M. Bucher[1], C. Burigana[54,36], R. C. Butler[54], E. Calabrese[99], B. Cappellini[55], J.-F. Cardoso[80,1,66], A. Catalano[81,78],

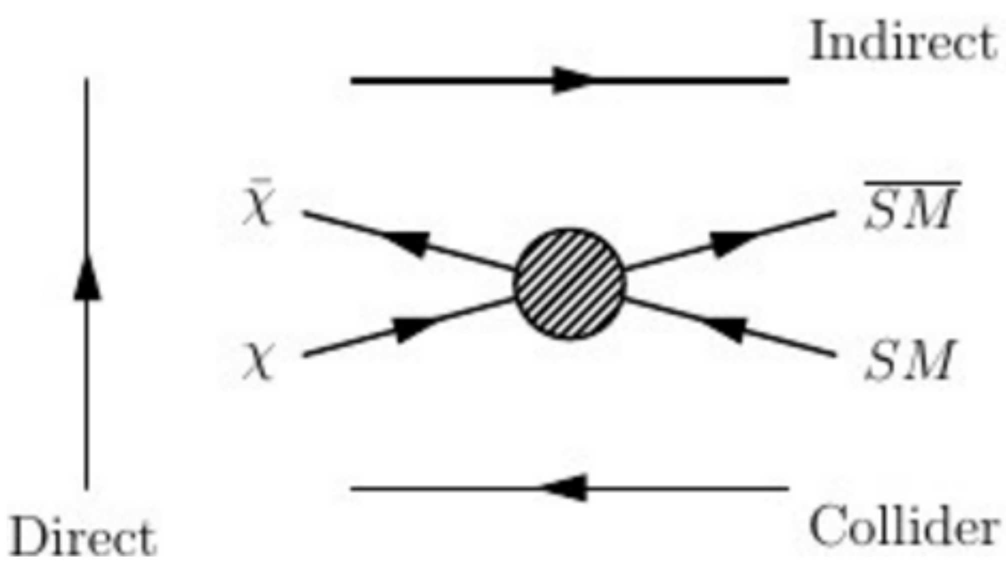


Direct Detection of Dark Matter

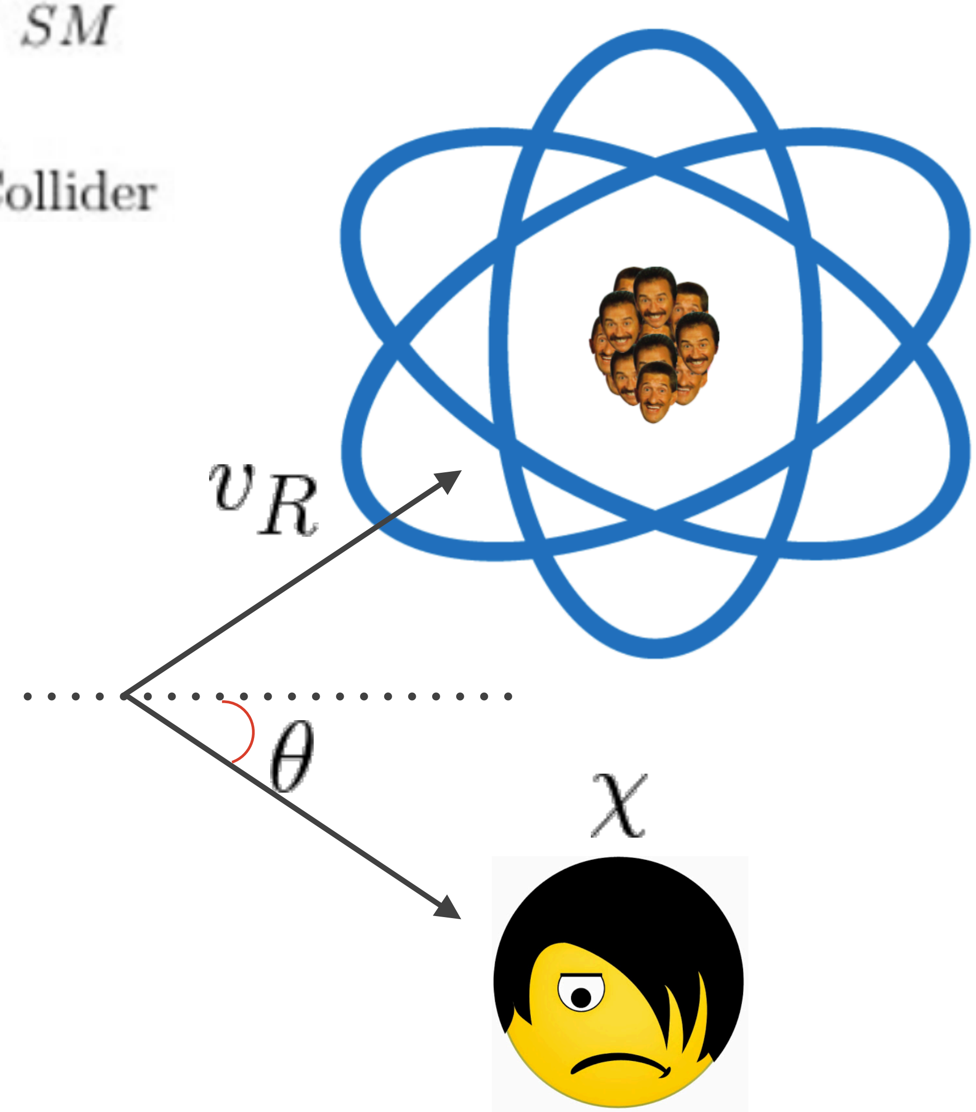




Direct Detection of Dark Matter



$$E_r = \frac{1}{2} m_\chi v^2 \frac{4 m_A m_\chi}{(m_A + m_\chi)^2} \frac{1 + cos\theta}{2}$$



How many counts does an experiment expect?

$$N = tnvN_T\sigma \qquad v \to \int v \cdot f(v)dv$$

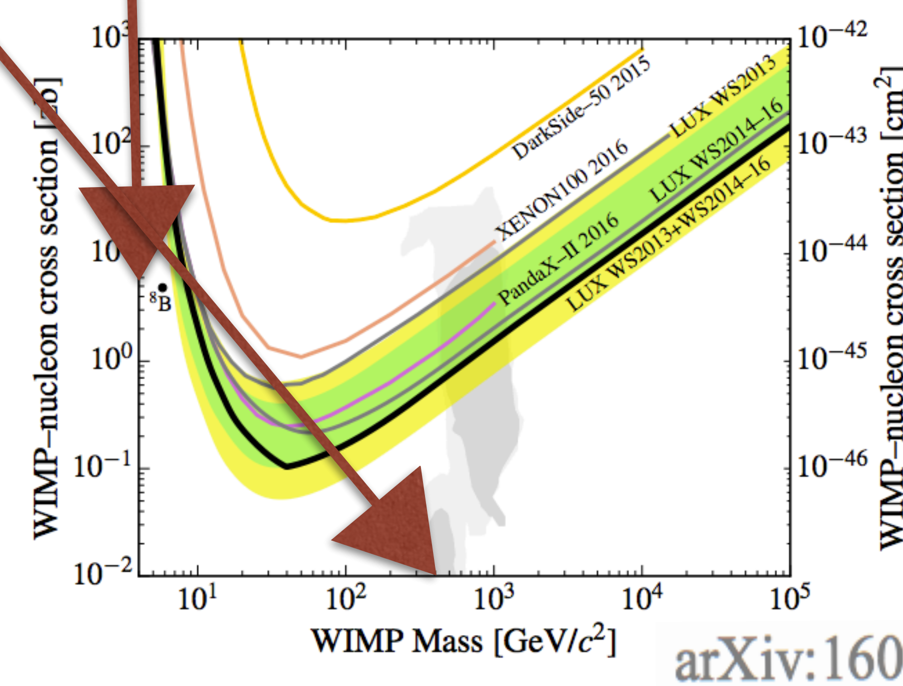
$$\frac{dN}{dE_R} = tM_T\frac{\rho}{m_\chi m_A}\int_{v_{\min}} vf(\vec{v})\frac{d\sigma}{dE_R}d\vec{v}$$

$$\frac{d\sigma}{dE_R} = \frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{dE_R} = \frac{m_A}{2\mu_{A\chi}^2}\frac{\sigma}{v^2}$$

$$\sigma \to \sigma_0 F^2(E_r)$$

$$q = \sqrt{2m_A E_R}$$

$$\frac{dN}{dE_R} = tM_T\frac{\rho}{m_\chi \mu_{A\chi}^2}\sigma_0 F^2(E_R)\int_{v_{\min}}\frac{f(\vec{v})}{v}d\vec{v}$$



arXiv:1608.07648v2

Spin Independent and Spin Dependent

$$\mathcal{L} = \bar{\chi}(\alpha+\beta\gamma^5)\chi\bar{q}(\tilde{\alpha}+\tilde{\beta}\gamma^5)q+\lambda\bar{\chi}\Gamma^{\mu}\chi\bar{q}\tilde{\Gamma}_{\mu}q+\lambda_q\bar{\chi}\Lambda^{\mu\nu}\chi\bar{q}\tilde{\Lambda}_{\mu\nu}q$$

$E_r \sim 1\mathrm{KeV}$ So Non-Relativistic $\psi \sim au + b^{\dagger}v$

$$u = \begin{pmatrix} \sqrt{p\cdot\sigma}\xi \\ \sqrt{p\cdot\sigma}\xi \end{pmatrix} \rightarrow \sqrt{m}\begin{pmatrix} \xi \\ \xi \end{pmatrix} \qquad v = \begin{pmatrix} \sqrt{p\cdot\sigma}\eta \\ -\sqrt{p\cdot\sigma}\eta \end{pmatrix} \rightarrow \sqrt{m}\begin{pmatrix} \eta \\ -\eta \end{pmatrix}$$

This limiting case simplifies the Lagrangian and gives two generic cross-sections

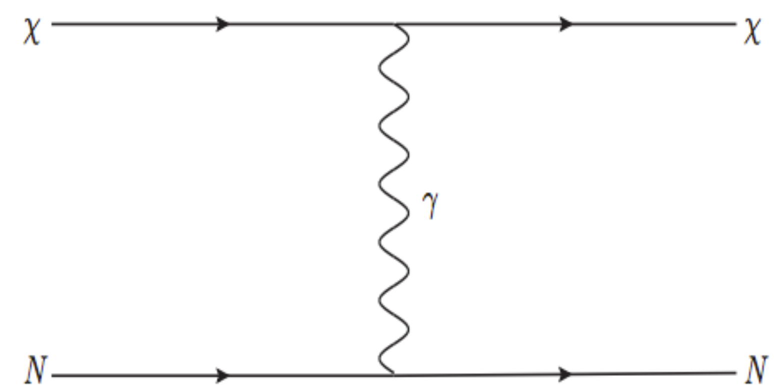
$$\sigma_0^{SI,N} = \frac{4\mu_{\chi A}}{\pi}[Zf_p + (A-Z)f_n]^2$$

$$\sigma_0^{SD,N} = \frac{32\mu_{\chi N}^2 G_F^2}{\pi}[a_pS_p + a_nS_n]^2\left(\frac{J+1}{J}\right)$$

Spin Independent and Spin Dependent is Not Completely General

Anapole DM

$$\mathcal{L}_I = \frac{g}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu}$$



Uncharged DM vector mediated.

$$\begin{aligned}\mathcal{L}_{XGq} = &-\frac{1}{2}\mathcal{X}^\dagger_{\mu\nu}\mathcal{X}^{\mu\nu} + m_X^2 X^\dagger_\mu X^\mu - \frac{\lambda_X}{2}(X^\dagger_\mu X^\mu)^2 \\ &-\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \frac{1}{2}m_G^2 G_\mu^2 - \frac{\lambda_G}{4}(G_\mu G^\mu)^2 \\ &+i\bar{q}\not{D}q - m_q\bar{q}q \\ &-\frac{b_3}{2}G_\mu^2(X^\dagger_\nu X^\nu) - \frac{b_4}{2}(G^\mu G^\nu)(X^\dagger_\mu X_\nu) - \Big[ib_5 X^\dagger_\nu \partial_\mu X^\nu G^\mu \\ &+b_6 X^\dagger_\mu \partial^\mu X_\nu G^\nu + b_7\epsilon_{\mu\nu\rho\sigma}(X^{\dagger\mu}\partial^\nu X^\rho)G^\sigma + h.c.\Big] \\ &-h_3 G_\mu\bar{q}\gamma^\mu q - h_4 G_\mu\bar{q}\gamma^\mu\gamma^5 q\end{aligned}$$

The Effective Field Theory Formalism

- The EFT formalism is similar to current work at the high scale frontier. Just in non-relativistic limit.
- In an attempt to remain model independent, Fitzpatrick et al. introduced basic building blocks that are Galilean invariant and Hermitian.

$$\frac{i\vec{q}}{m_N}, \quad \vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2m_N}, \quad \vec{S}_{\chi}, \quad \vec{S}_N$$

The Effective Field Theory of Dark Matter Direct Detection

A. Liam Fitzpatrick[1], Wick Haxton[2], Emanuel Katz[1,3,4], Nicholas Lubbers[3], Yiming Xu[3]

[1] *Stanford Institute for Theoretical Physics, Stanford University, Stanford, CA 94305*

[2] *Dept. of Physics, University of California, Berkeley, 94720, and Lawrence Berkeley*

The list of NR Operators

- Since we're only interested in elastic scattering, this formalism only considers four-field operators.

$$\mathcal{L}_{\text{int}} = \chi\mathcal{O}_\chi\chi N\mathcal{O}_N N \;=\; \sum_{N=n,p}\sum_i c_i^{(N)}\mathcal{O}_i\chi^+\chi^-N^+N^-$$

- Remembering the NR limit is being taken, we combine operators up to quadratic in momentum.

$$\boxed{\begin{array}{rclrcl}
O_1 &=& 1_\chi 1_N & O_7 &=& \vec{S}_N\cdot\vec{v}^\perp \\
O_3 &=& i\vec{S}_N\cdot\left(\frac{\vec{q}}{m_N}\times\vec{v}^\perp\right) & O_8 &=& \vec{S}_\chi\cdot\vec{v}^\perp \\
O_4 &=& \vec{S}_\chi\cdot\vec{S}_N & O_9 &=& i\vec{S}_\chi\cdot\left(\vec{S}_N\times\frac{\vec{q}}{m_N}\right) \\
O_5 &=& i\vec{S}_\chi\cdot\left(\frac{\vec{q}}{m_N}\times\vec{v}^\perp\right) & O_{10} &=& i\vec{S}_N\cdot\frac{\vec{q}}{m_N} \\
O_6 &=& \left(\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}\right)\left(\vec{S}_N\cdot\frac{\vec{q}}{m_N}\right) & O_{11} &=& i\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}
\end{array}}$$

EFT: The "New" Differential Rate

- The differential rate now takes a different form.

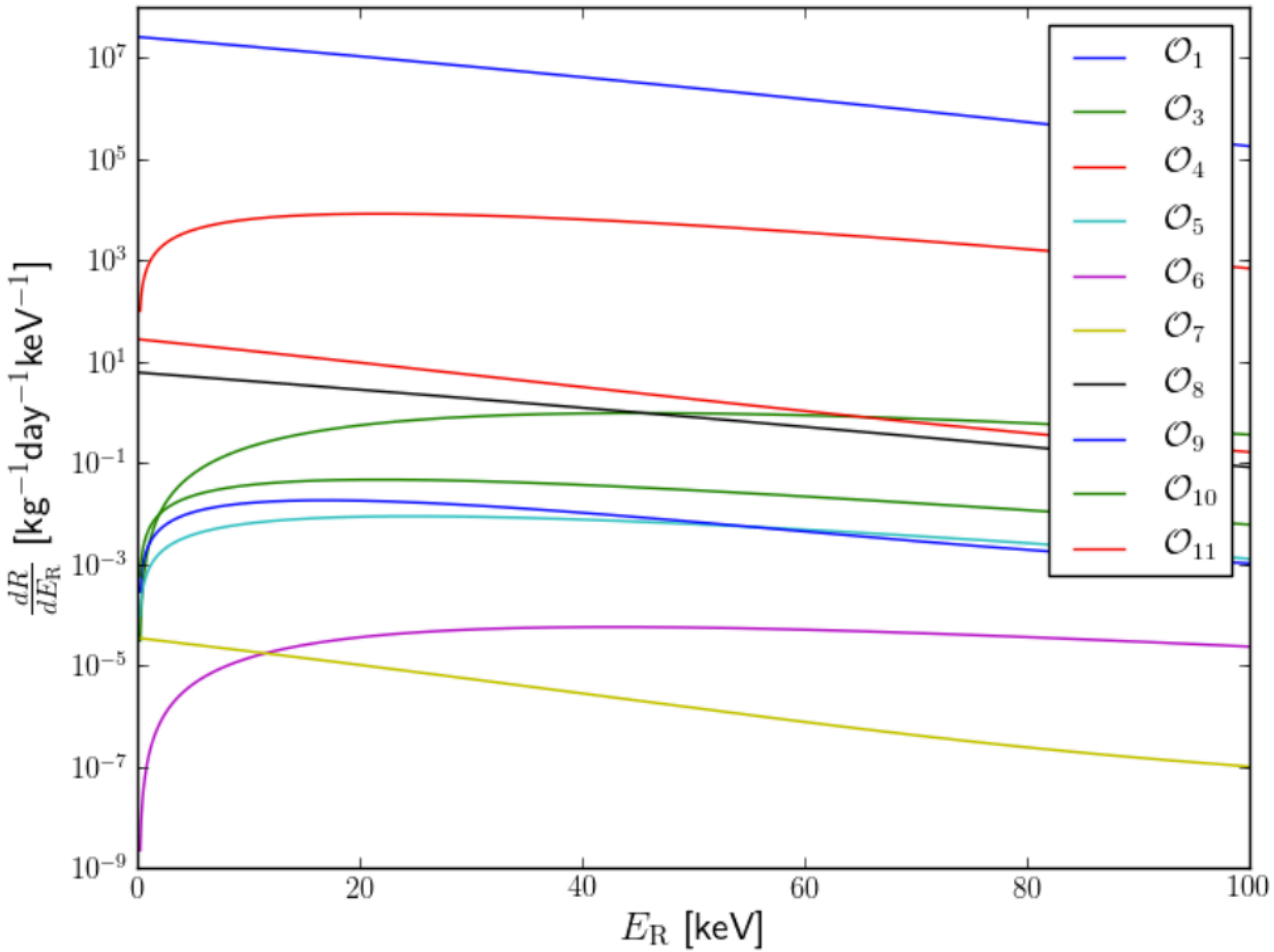
$$\frac{dN}{dE_R} = \frac{\epsilon\rho}{32\pi m_\chi^3 m_N^2} \left\langle \frac{1}{v} \sum_{i,j} \sum_{N,N'=p,n} c_i^N c_j^{N'} F_{i,j}^{N,N'}(v^2, q^2) \right\rangle$$

- The operator behaviour is embedded into the new EFT form factors.

- The Form Factors are are defined by

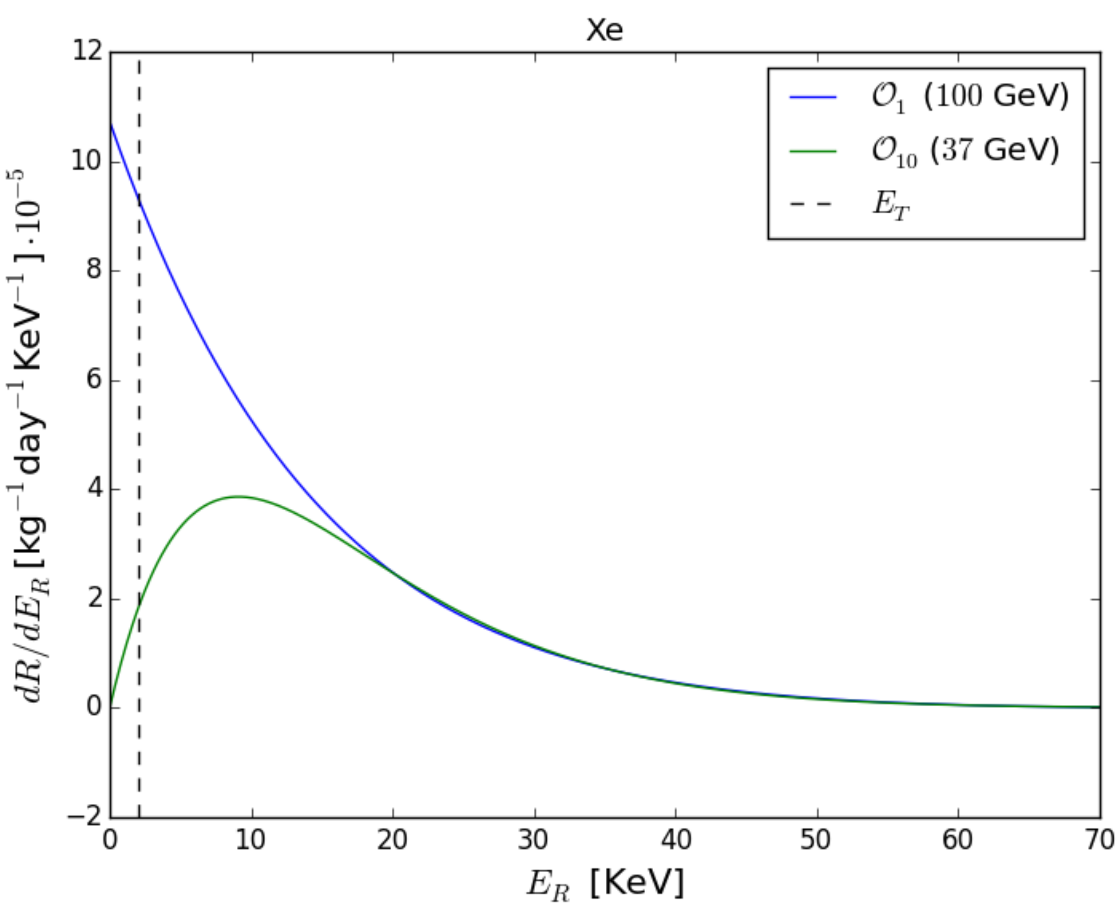
$$\frac{1}{2j_\chi+1}\frac{1}{2j+1}\sum_{\text{spins}}|\mathcal{M}|^2 \equiv \frac{m_T^2}{m_N^2}\sum_{i,j=1}^{12}\sum_{N,N'=p,n} c_i^{(N)} c_j^{(N')} F_{ij}^{(N,N')}(v^2, q^2),$$

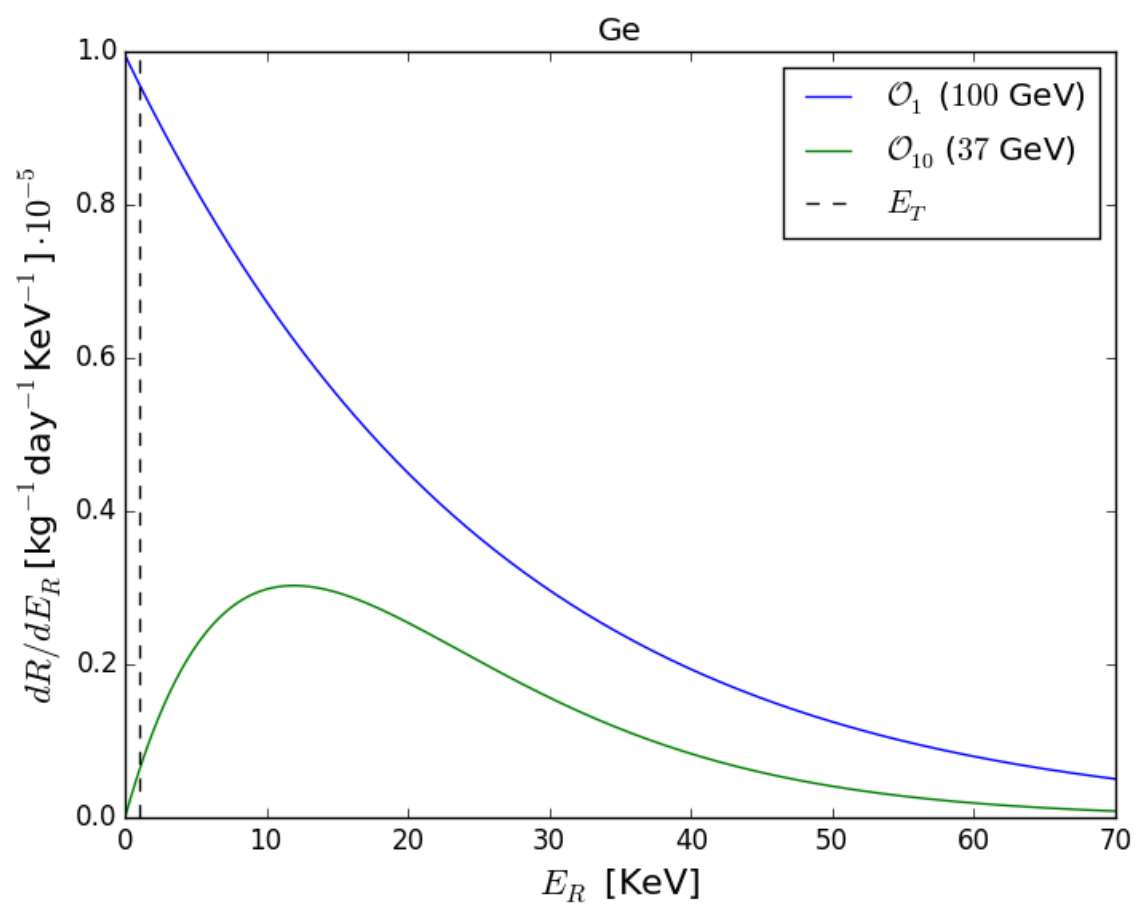
The Spectrum for Different Operators.



If we detect DM now, NREFT signals will be degenerate.

Having complementarity of different targets means we can distinguish between the real DM model and one that purely mimics it.





How Does The Degeneracy look in an reconstruction?

Need to simulate the new generation of experiment.

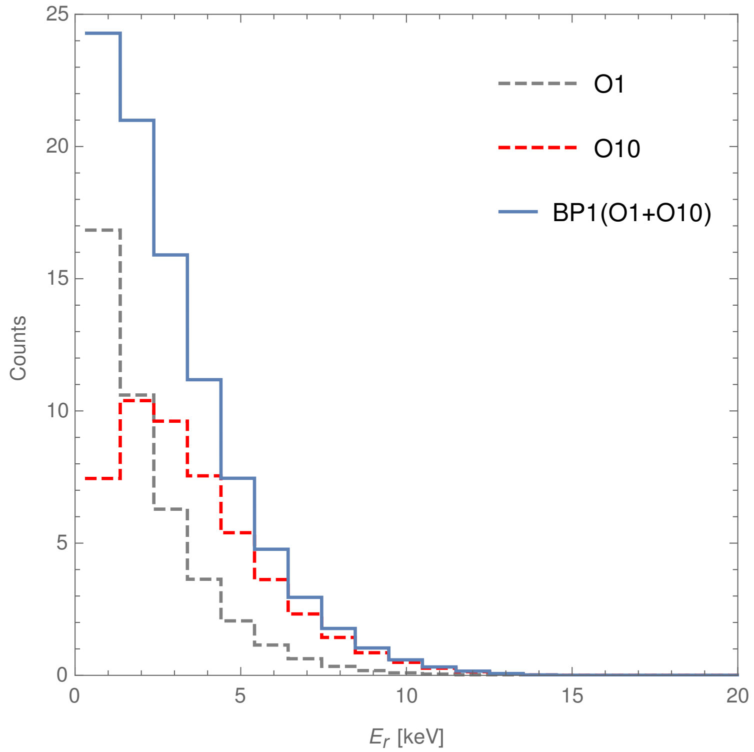
Target	Exposure kg day	Energy Range (keV)	Background
G2-Ge	91250	0.35 - 50	0
G2-Xe	9125000	3 - 50	0

Come up with some interesting candidate signals for this setup.

Point	m_χ (GeV)	$c_1^1 m_v^2, c_1^0 m_v^2$	$c_8^1 m_v^2, c_8^0 m_v^2$	$c_{10}^1 m_v^2, c_{10}^0 m_v^2$
BP1	10	$0, 3.0 \times 10^{-4}$	$0, 0$	$0, 1.50 \times 10^1$
BP2	13	$0, 0$	$0.975, 0.975$	0.0, 0.0

How does this Look in an Reconstruction?

Just XENON G2



Point	m_χ (GeV)	$c_1^1 m_v^2, c_1^0 m_v^2$	$c_8^1 m_v^2, c_8^0 m_v^2$	$c_{10}^1 m_v^2, c_{10}^0 m_v^2$
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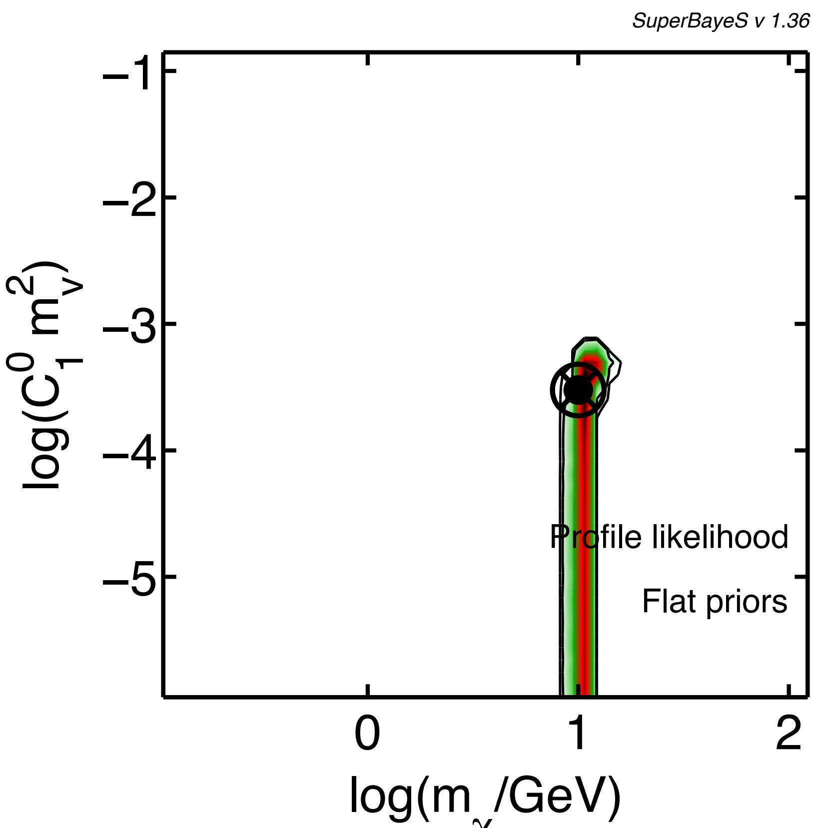
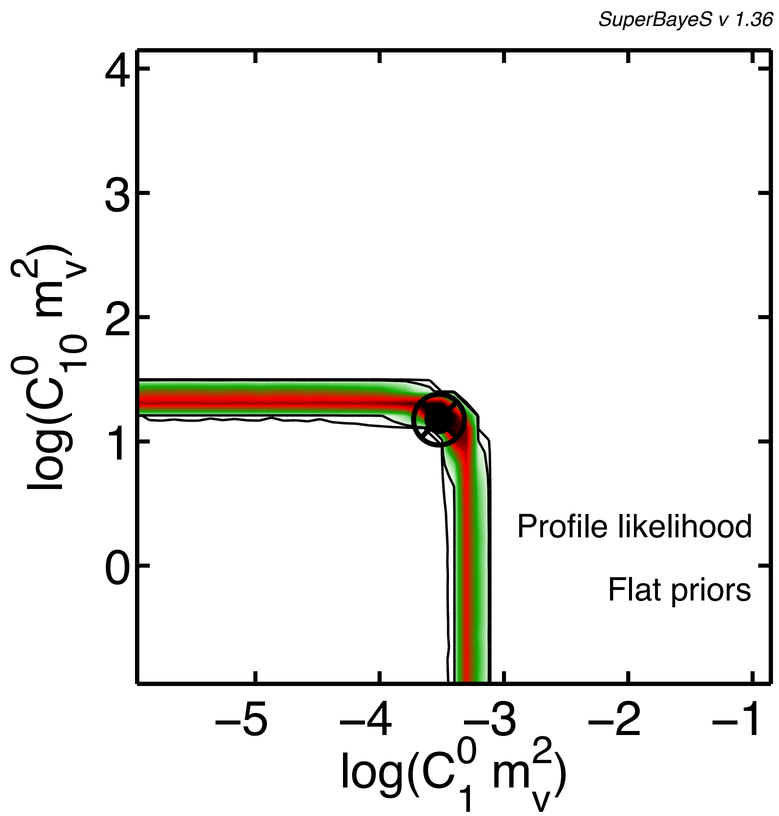
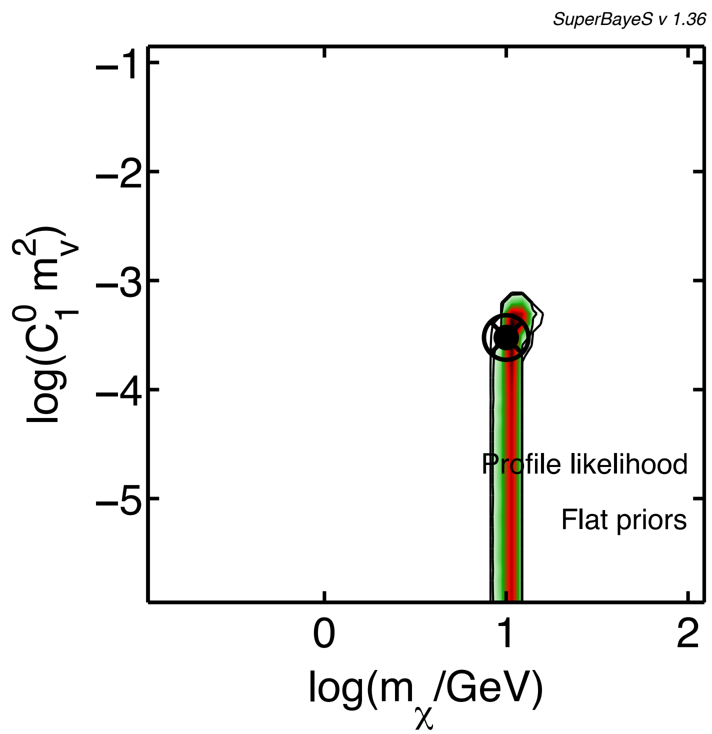
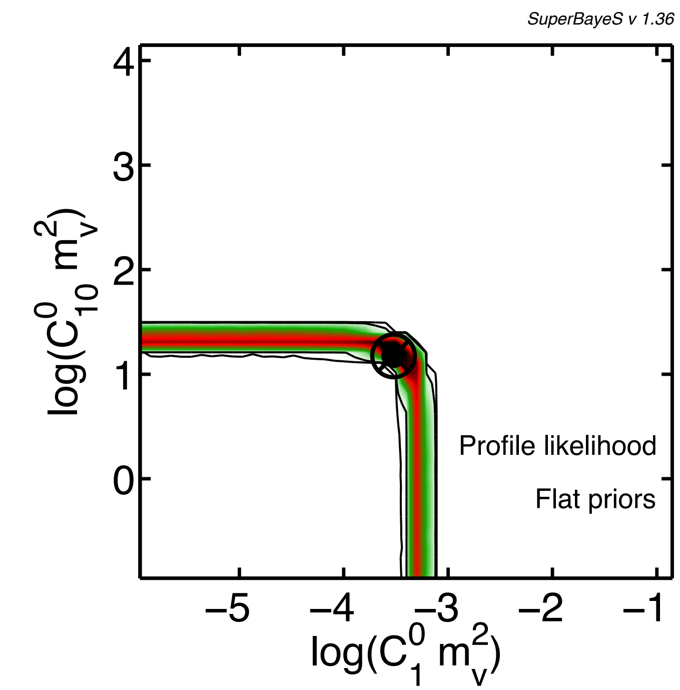
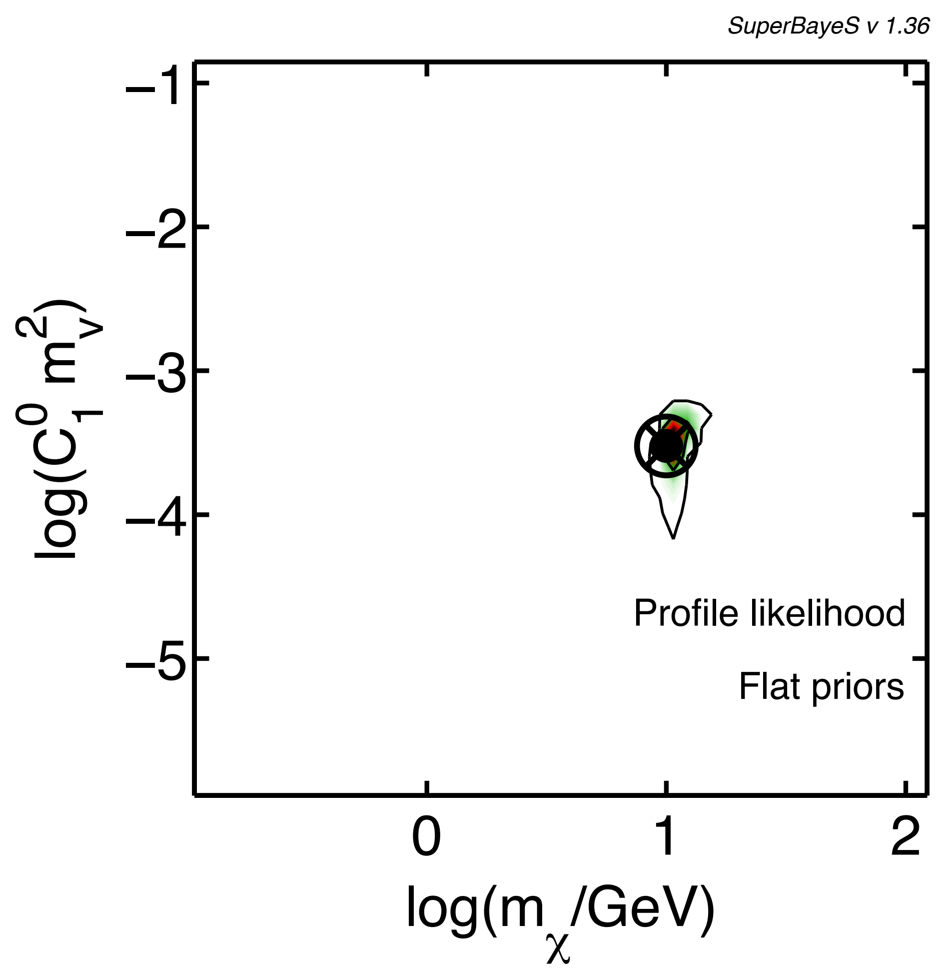


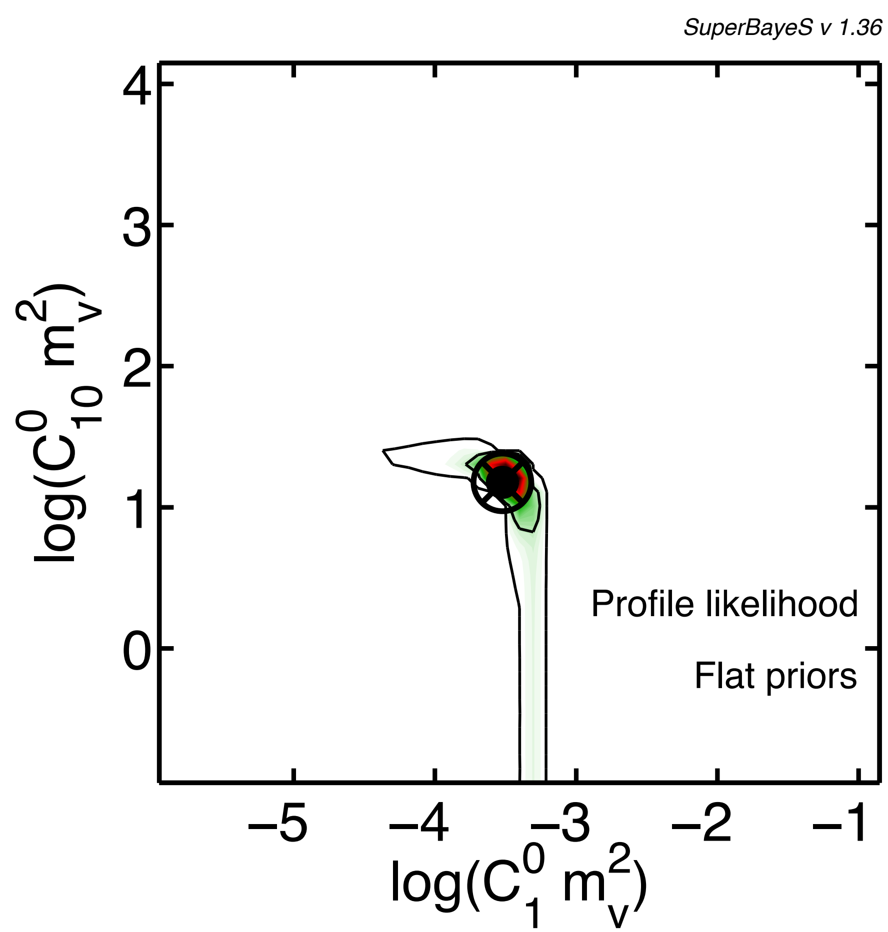


Combining Xenon and Germanium

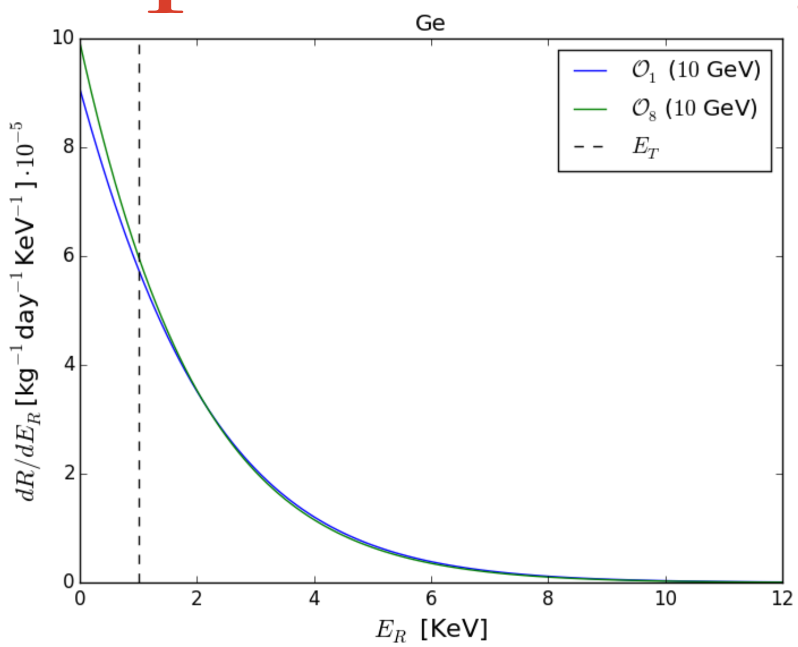


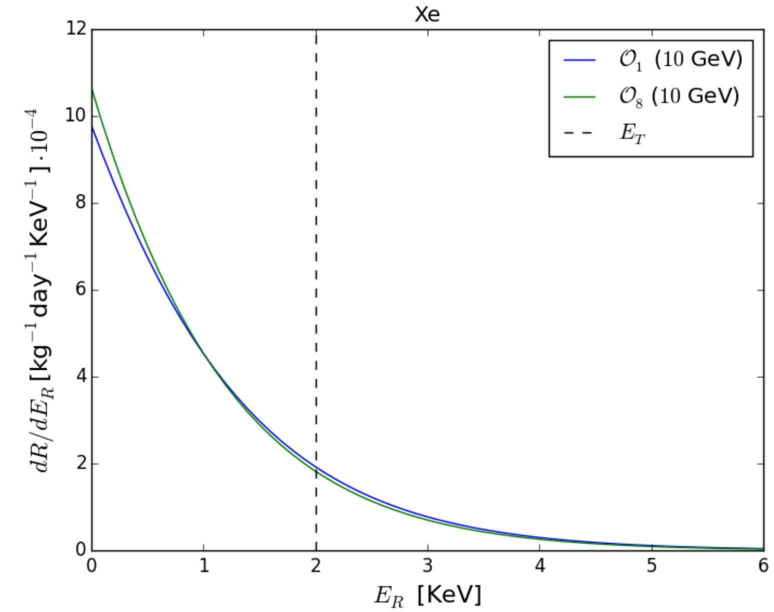






Complementarity May Not be Enough





Point	m_χ (GeV)	$c_1^1 m_v^2, c_1^0 m_v^2$	$c_8^1 m_v^2, c_8^0 m_v^2$	$c_{10}^1 m_v^2, c_{10}^0 m_v^2$
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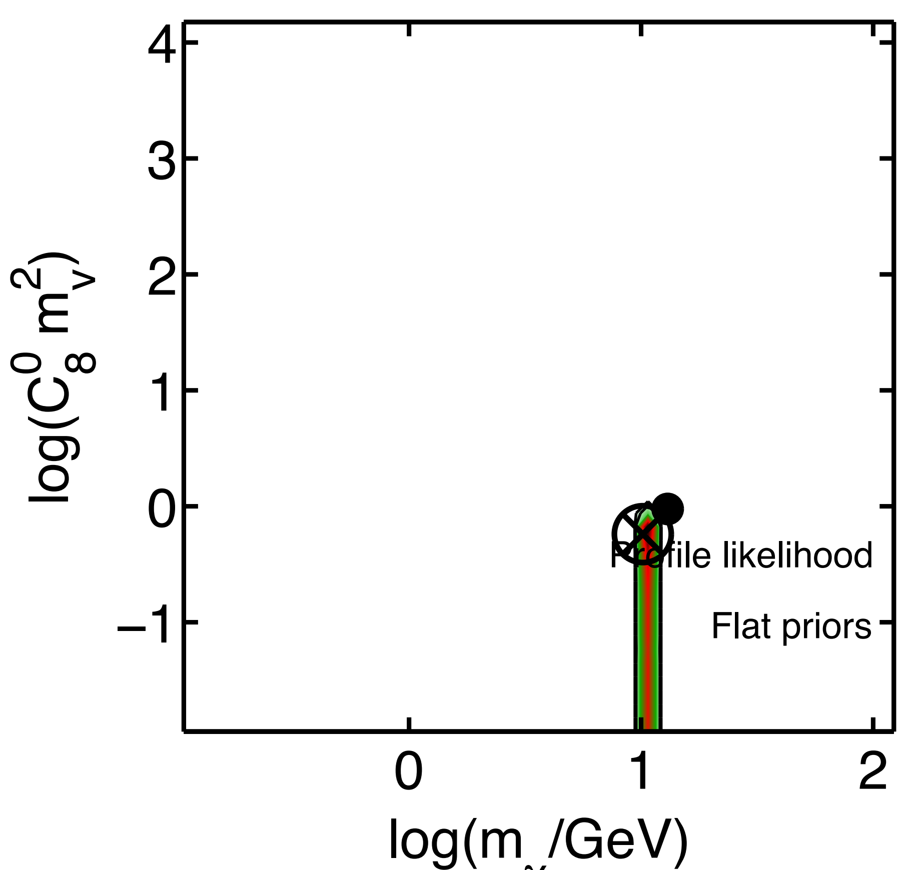
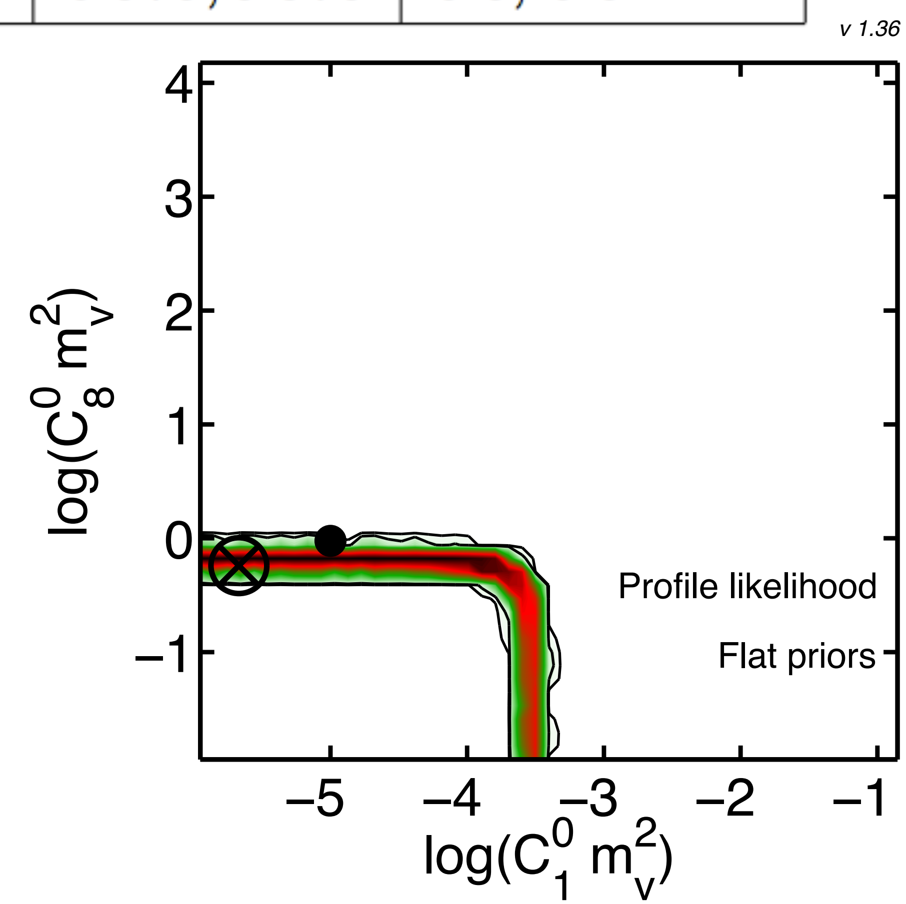
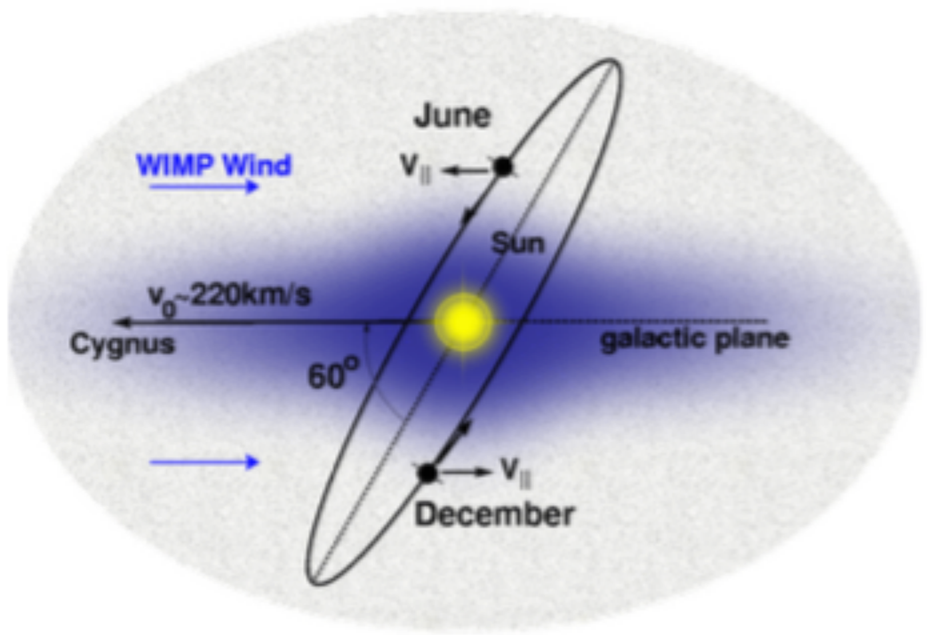




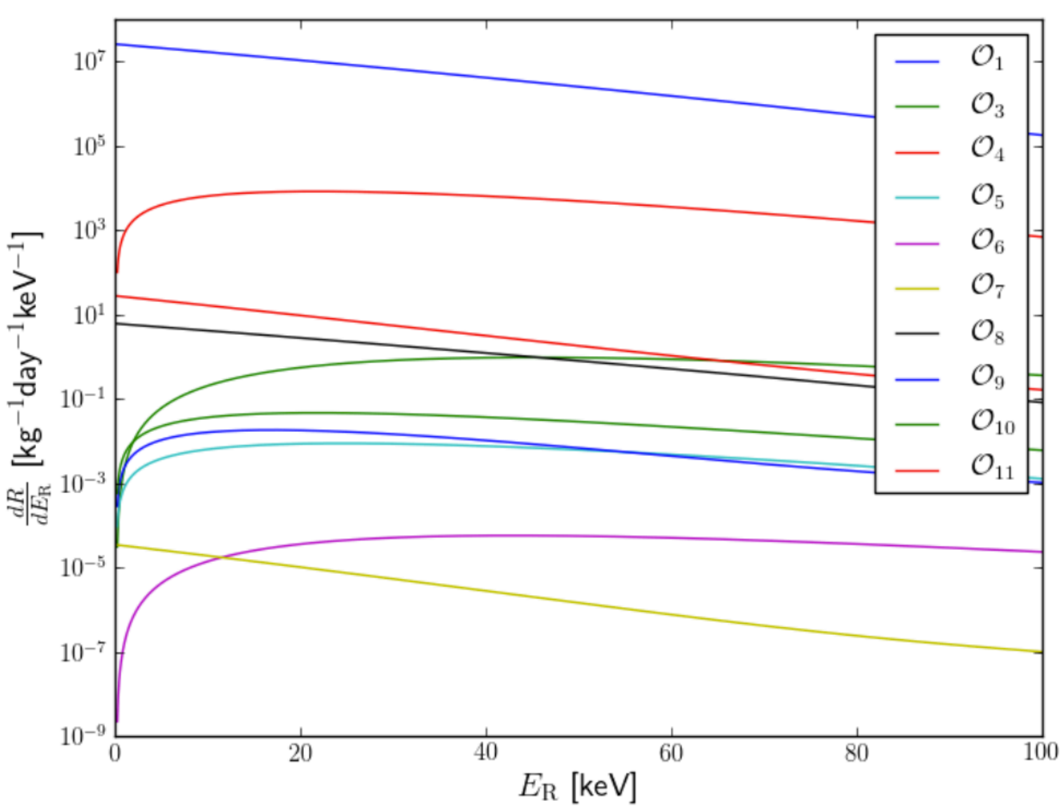
Annual modulation: a Potential Degeneracy Breaker

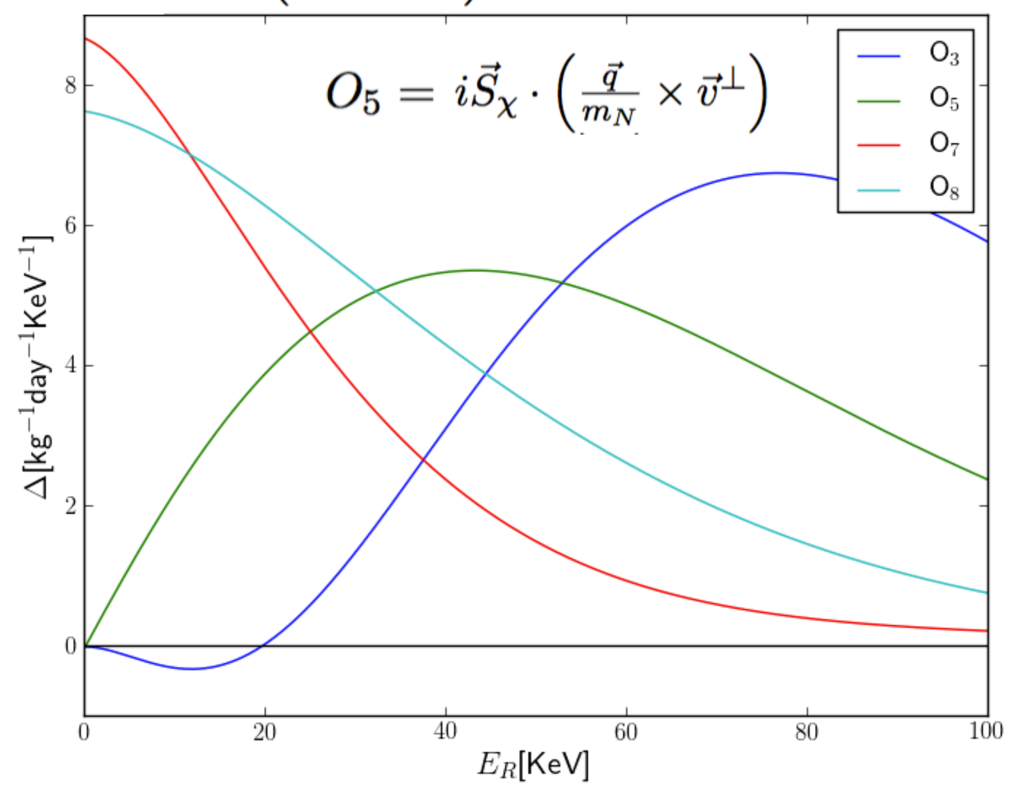


$$\Delta \approx \frac{1}{2}\left(\frac{dR}{dE_R}\Big|_{June} - \frac{dR}{dE_R}\Big|_{Dec}\right)$$

$O_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}\right)$ $\quad O_7 = \vec{S}_N \cdot \vec{v}^{\perp}$ $\quad O_8 = \vec{S}_\chi \cdot \vec{v}^{\perp}$

$O_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}\right)$





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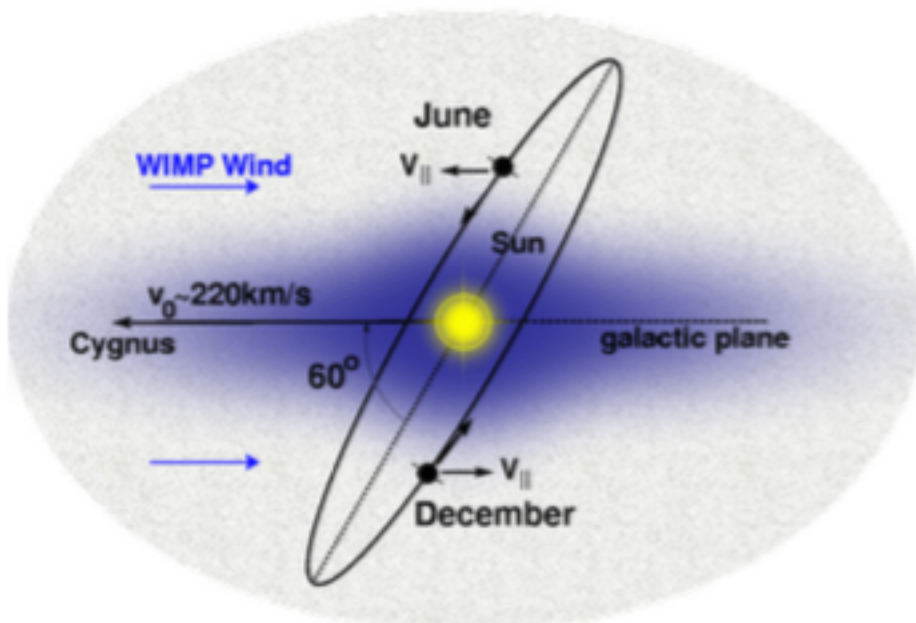
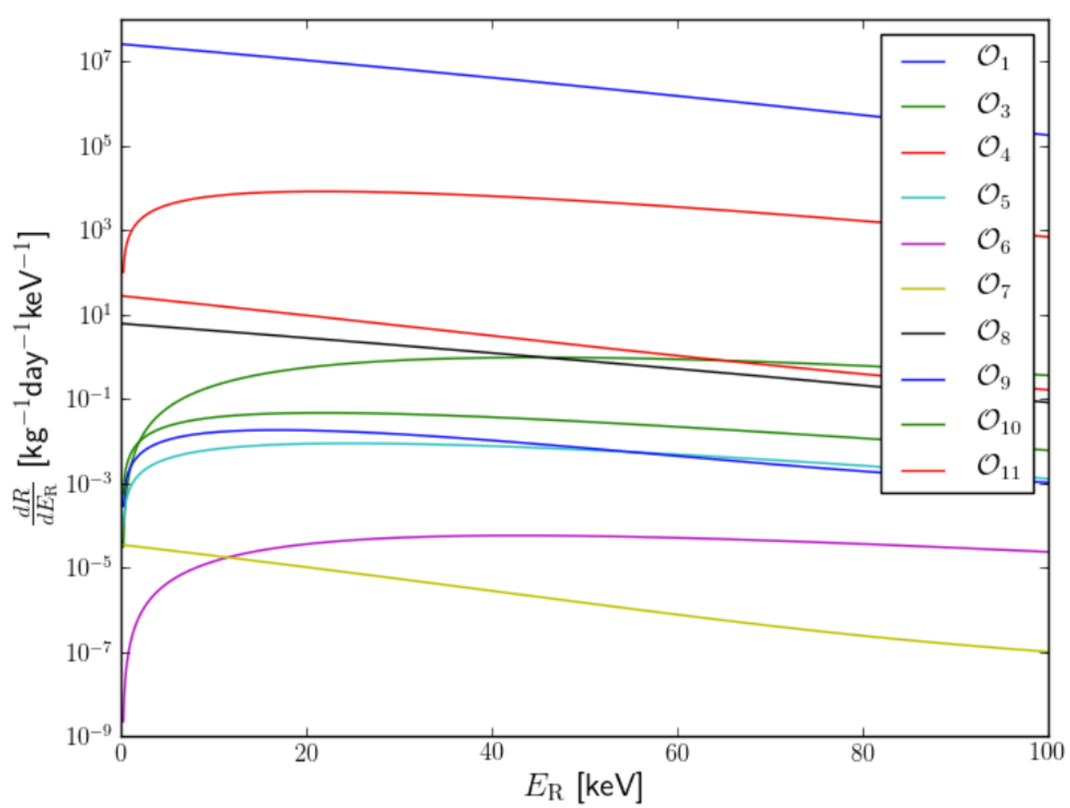
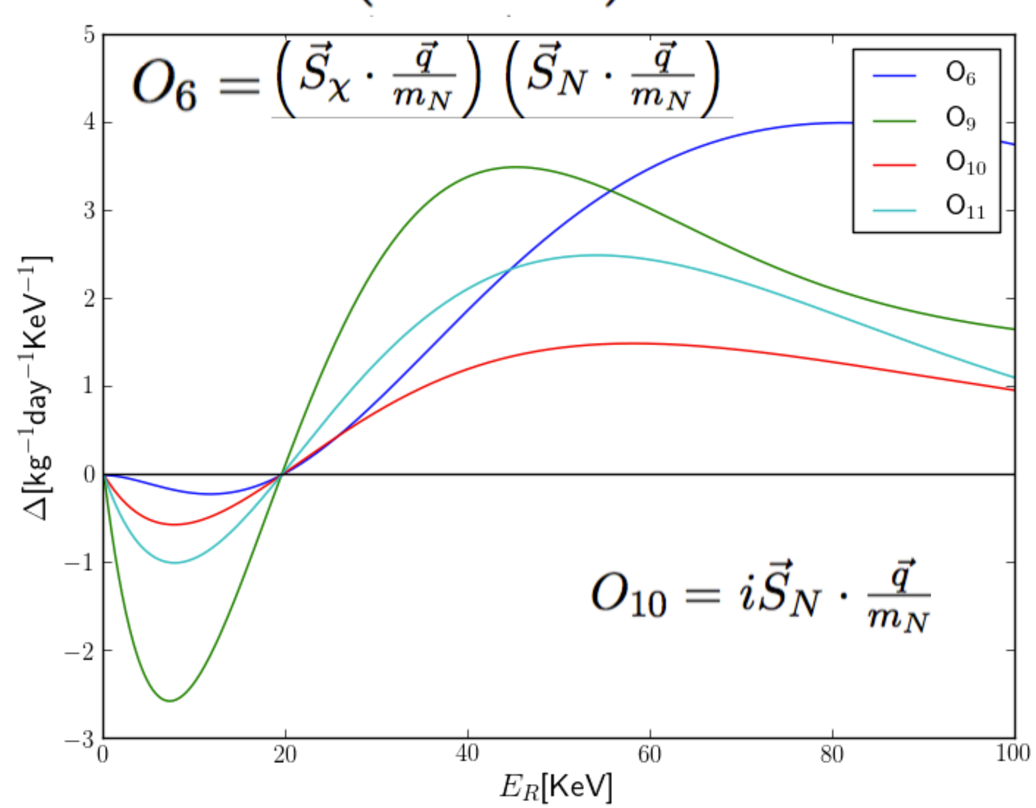


$$\Delta \approx \frac{1}{2}\left(\frac{dR}{dE_R}\Big|_{June} - \frac{dR}{dE_R}\Big|_{Dec}\right)$$

$$O_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right) \quad O_{11} = \; i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$





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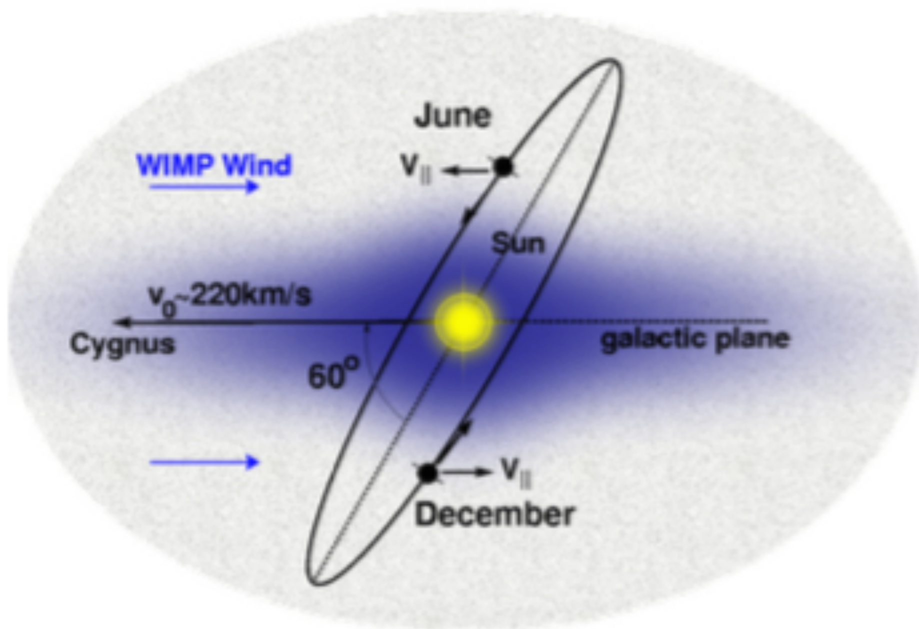

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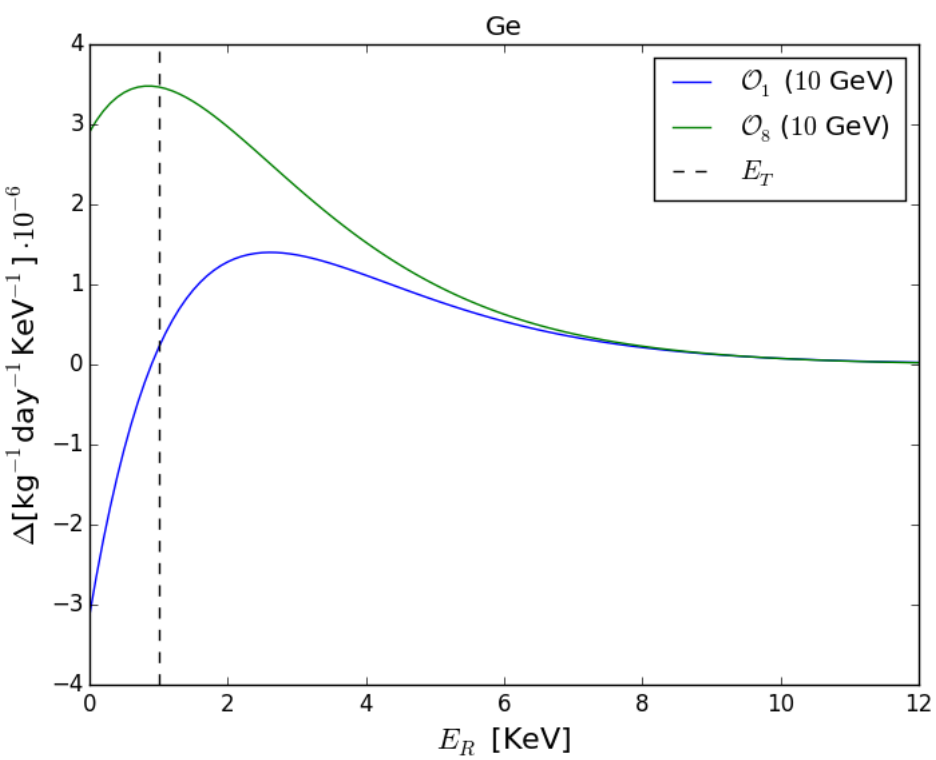

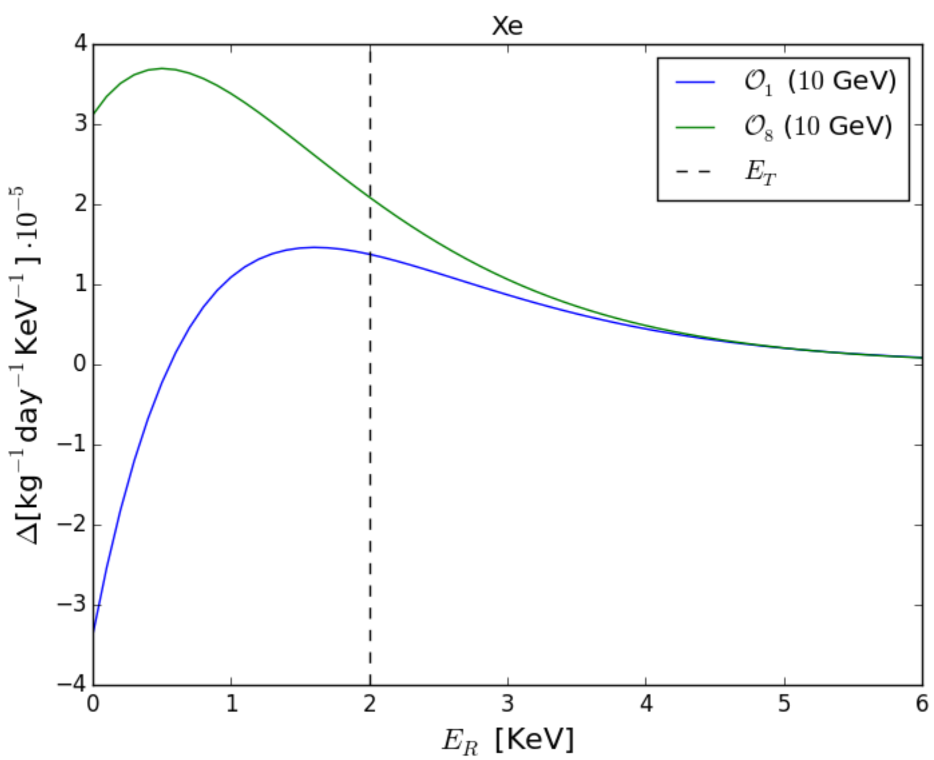

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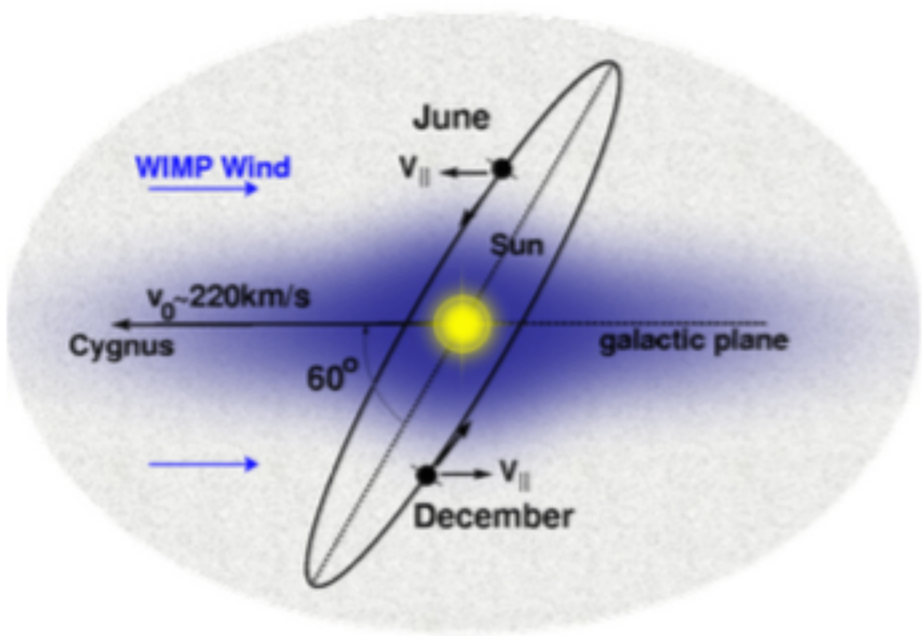

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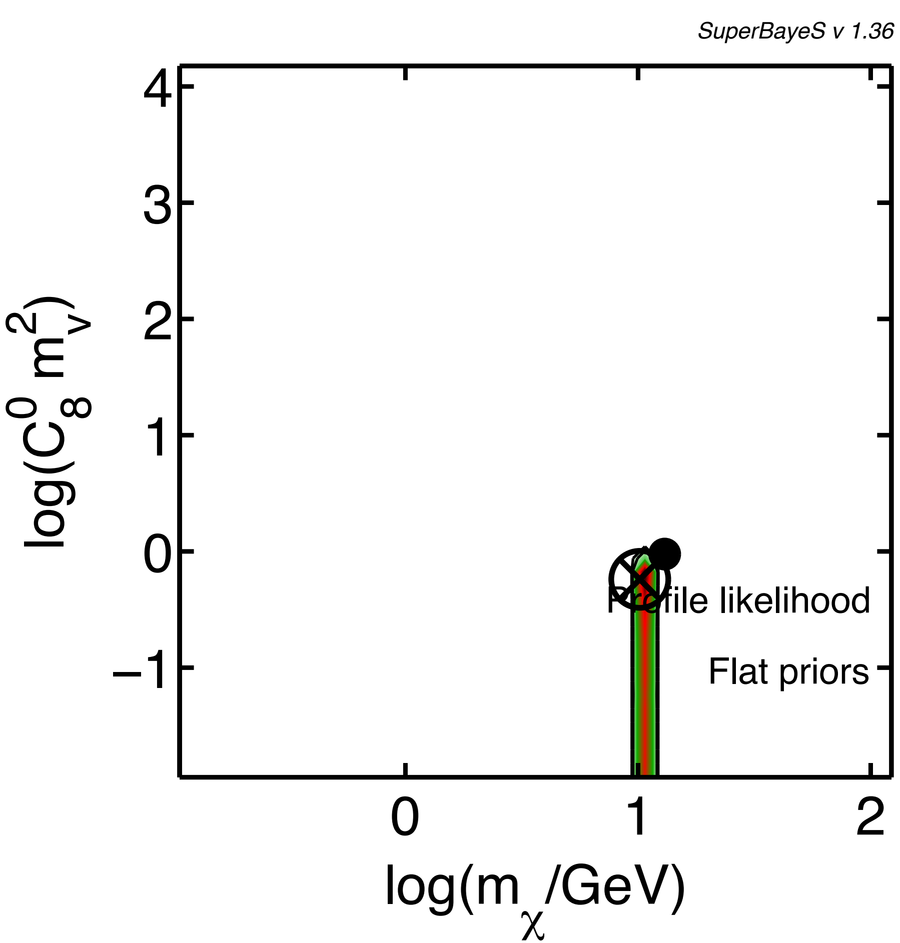

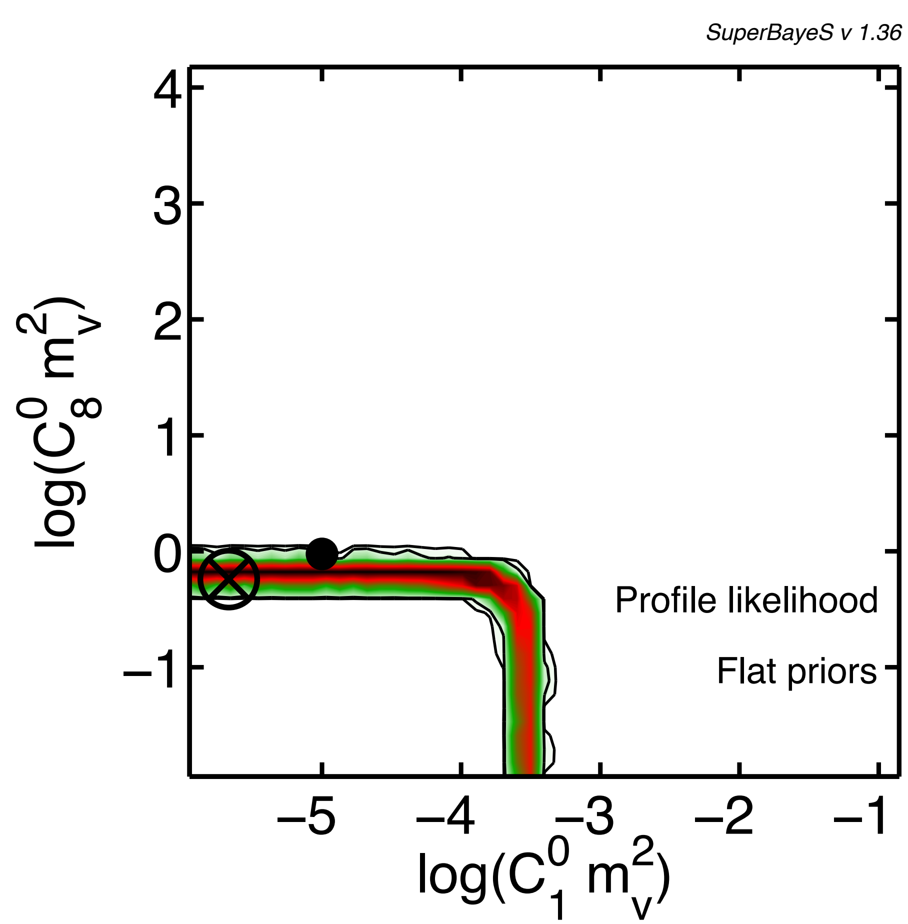

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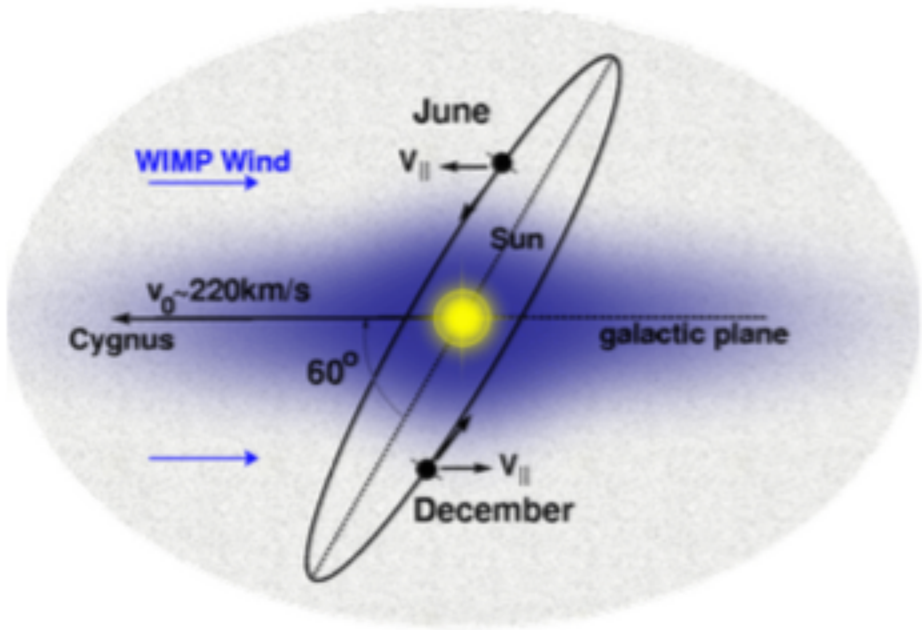

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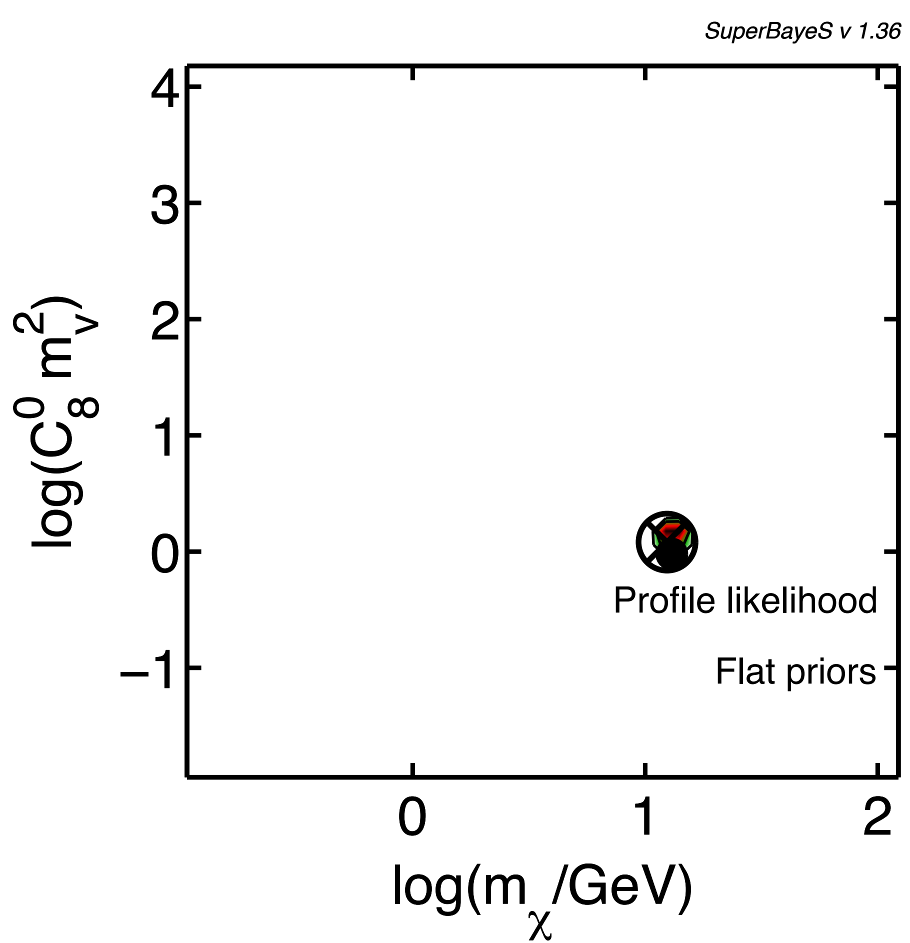

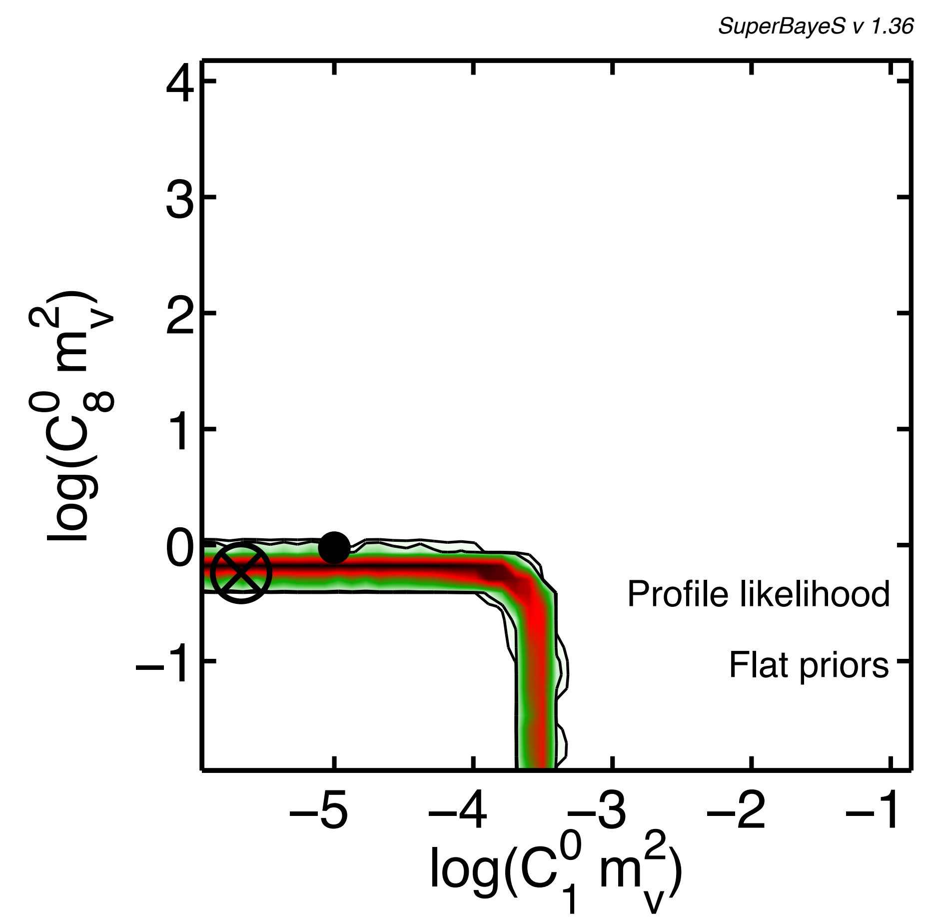

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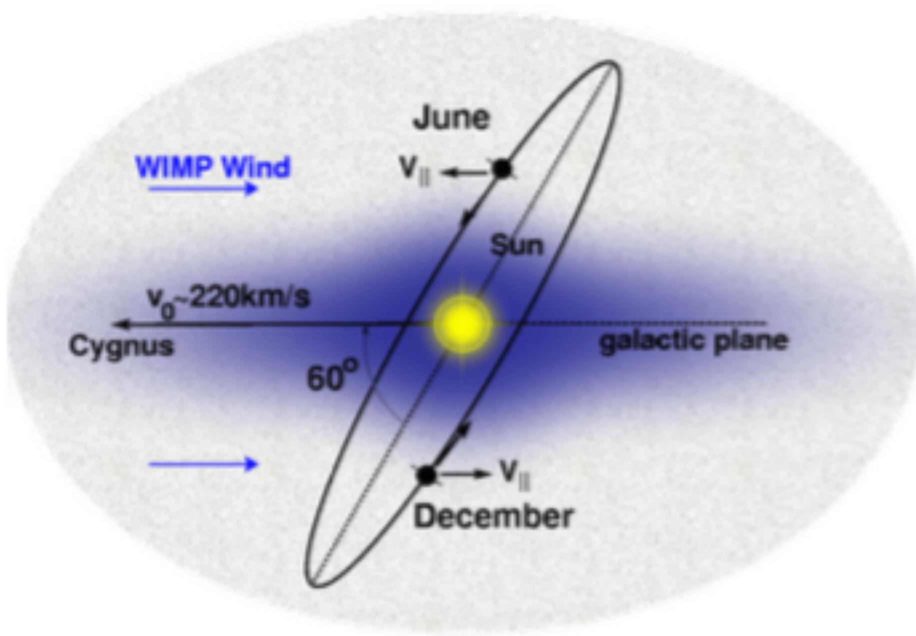
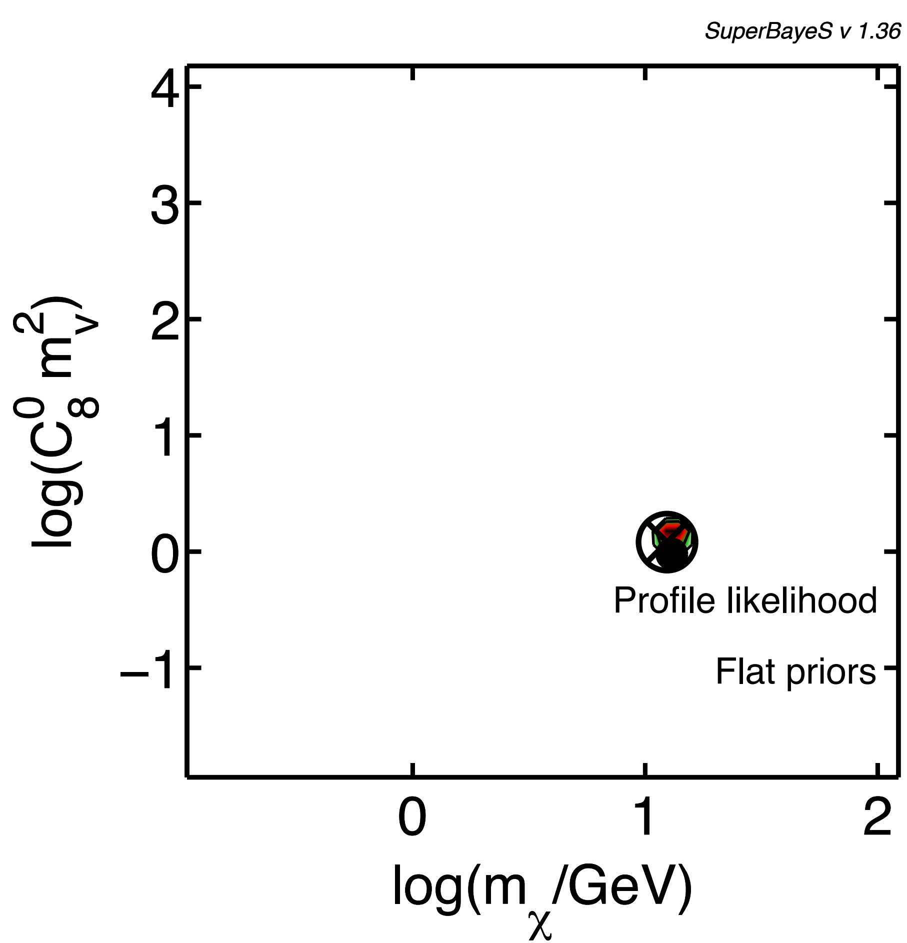
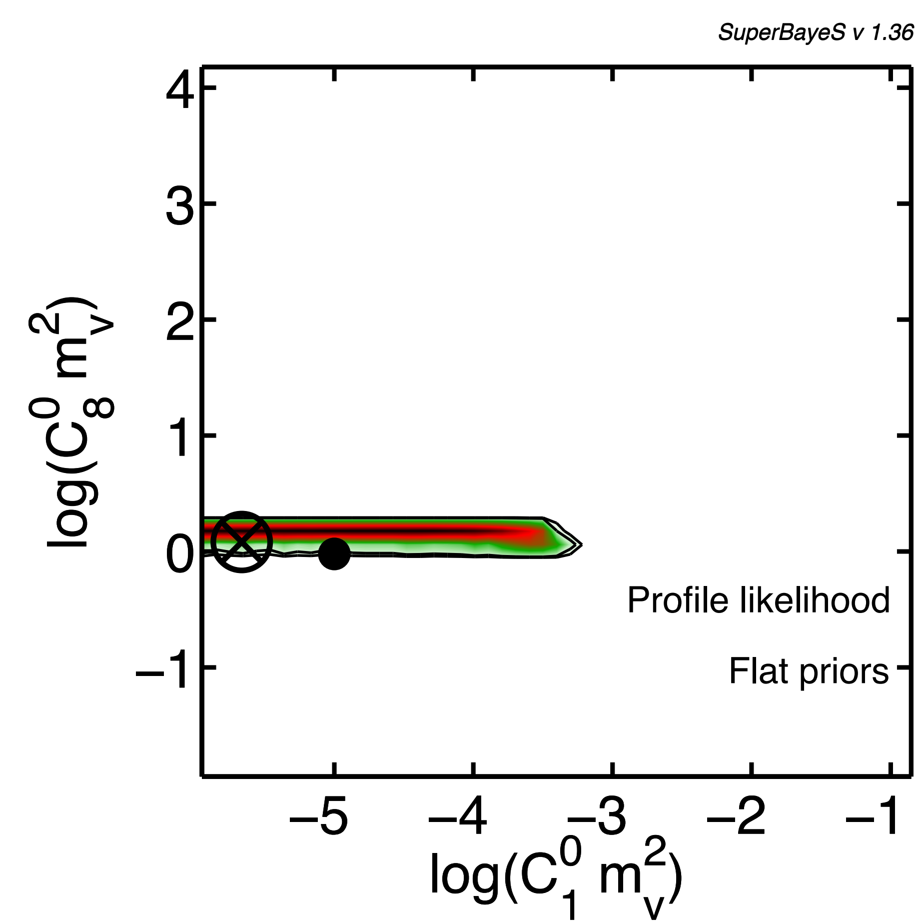


$$\Delta \approx \frac{1}{2}\left(\frac{dR}{dE_R}\Big|_{June} - \frac{dR}{dE_R}\Big|_{Dec}\right)$$





Then we were Scooped!

Miguel Peiró — 26 December 2016 at 08:17

To: CHEEK, ANDREW Cc: David G Cerdeno

Details

Hey Guys!
First of all merry christmas!
Far from being a christmas present, today I have found this paper on arXiv:https://arxiv.org/abs/1612.07808
I have not read it carefully enough but it seems it goes in the same direction we wanted to follow...

Prospects for Distinguishing Dark Matter Models Using Annual Modulation

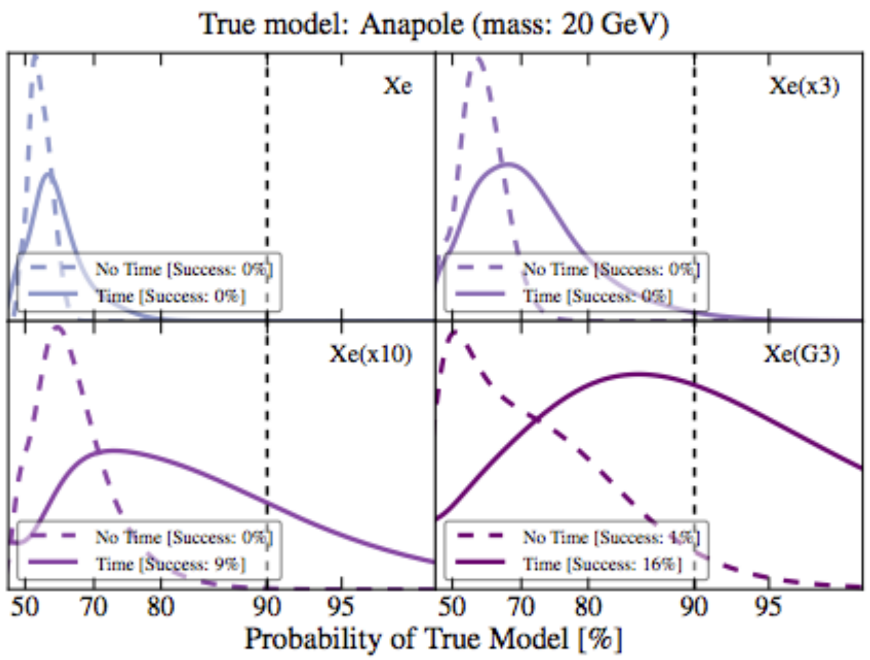
Samuel J. Witte,[a,b] **Vera Gluscevic,**[c] **and Samuel D. McDermott**[d]

[a]University of California, Los Angeles, Department of Physics and Astronomy, Los Angeles, CA 90095

Abstract. It has recently been demonstrated that, in the event of a putative signal in dark matter direct detection experiments, properly identifying the underlying dark matter–nuclei interaction promises to be a challenging task. Given the most optimistic expectations for the number counts

. . .

given experimental setup. We find that including information on the annual modulation of the rate may significantly enhance the ability of a single target to distinguish dark matter models with nearly degenerate recoil spectra, but only with exposures beyond the expectations of Generation 2 experiments.



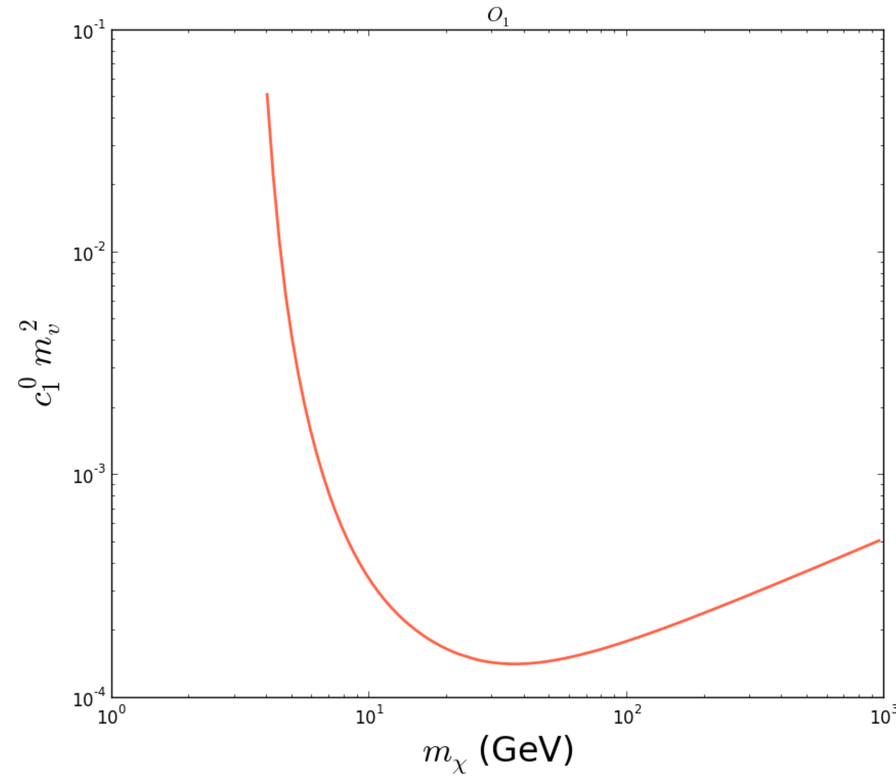
Thank You!

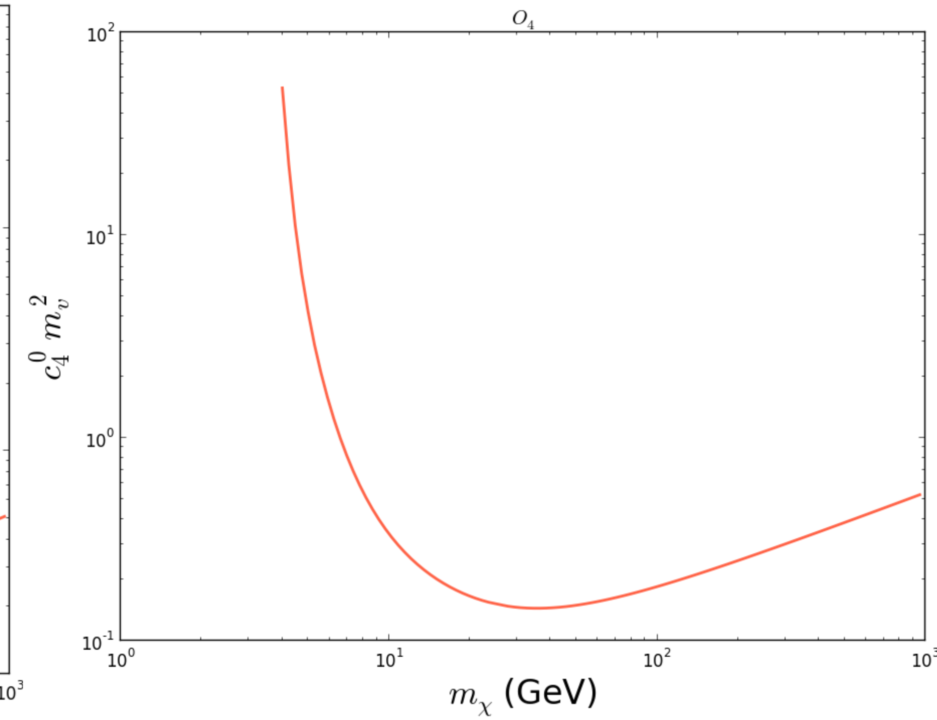
The Exclusion Plots for each Coefficient

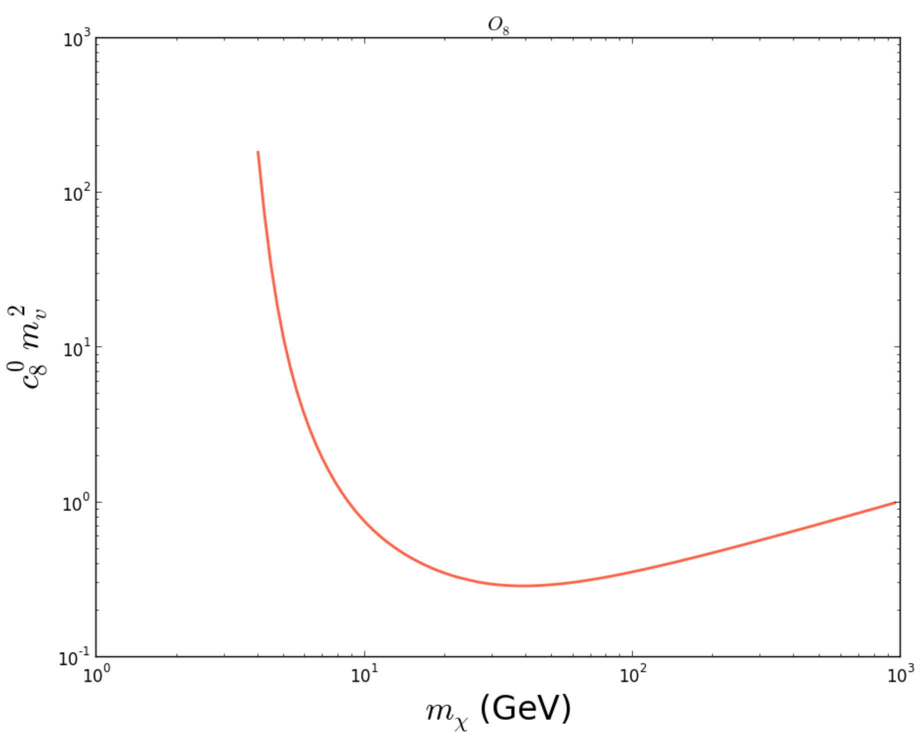
$$c_i^1 = 0$$

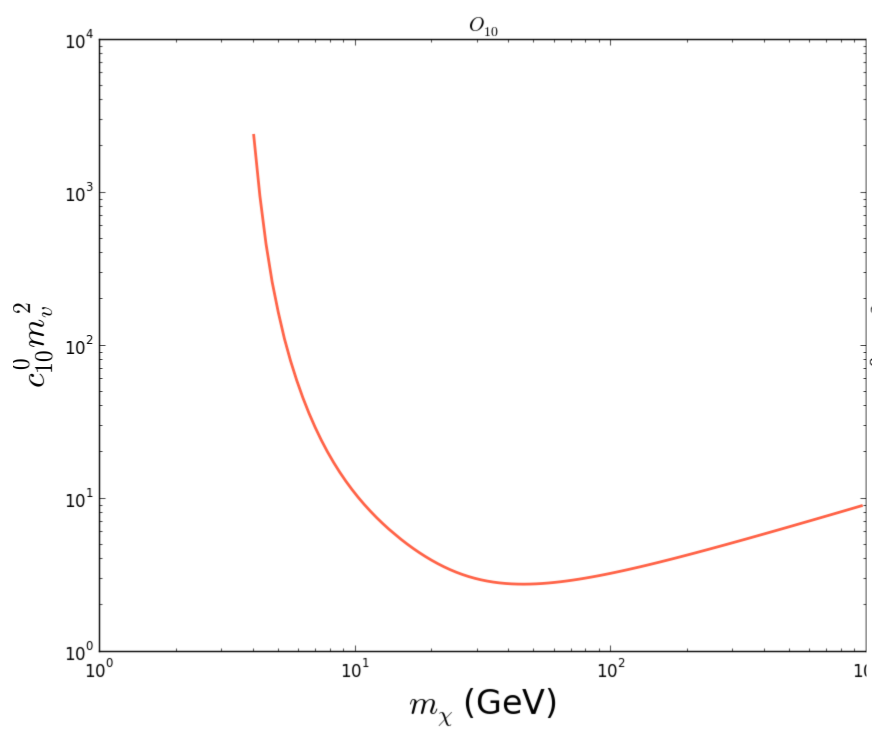
$$P(N|\mu) = \frac{\mu^N e^{-\mu}}{N!}$$

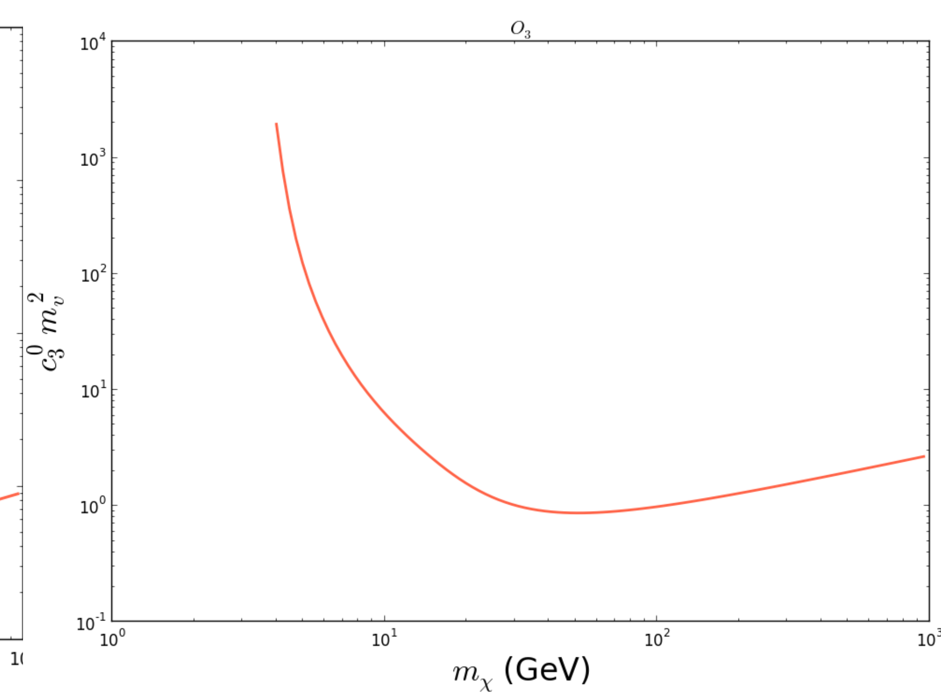
$$\sum_{m=n+1}^{\infty} P(m|\mu) = 0.9$$











Simplified Models for EFTs

- Simplified models approach is where only operators at leading order and one single type of mediator is considered.

A General Analysis of Direct Dark Matter Detection: From Microphysics to Observational Signatures

James B. Dent[a], Lawrence M. Krauss[b,c], Jayden L. Newstead[b], and Subir Sabharwal[b]

[a] *Department of Physics, University of Louisiana at Lafayette, Lafayette, LA 70504, USA,*

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

anapole $\mathcal{O}_{13}^{\rm rel}=\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$

$\mathcal{O}_{14}^{\rm rel}=\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\frac{i\sigma_{\mu\nu}q^\nu}{m_M}N$

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

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

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)	✓			✓			✓											

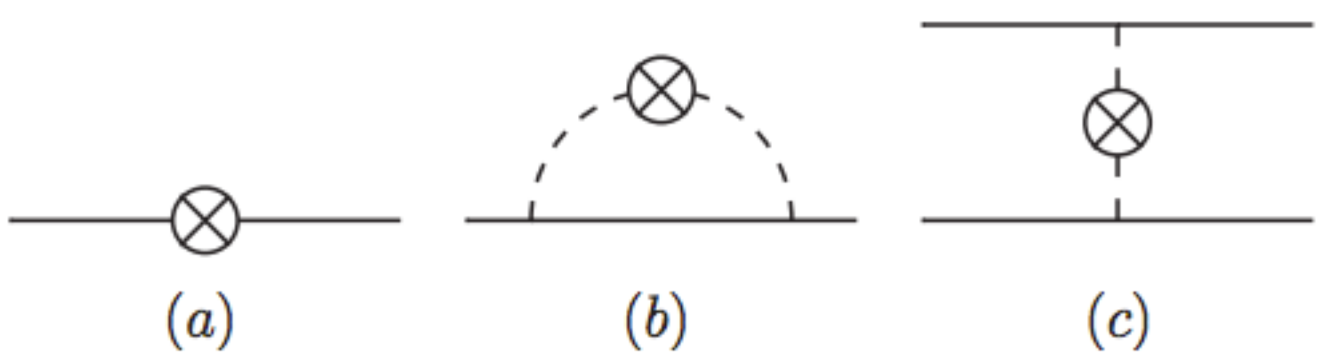
Recently it was shown that the standard SI interaction is contributed by 8 independent coefficients.

Analysis strategies for general spin-independent WIMP–nucleus scattering

Martin Hoferichter,[1,*] Philipp Klos,[2,3,†] Javier Menéndez,[4,‡] and Achim Schwenk[2,3,5,§]

[1]*Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550, USA*
[2]*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[3]*ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[4]*Department of Physics, The University of Tokyo, 113-0033 Tokyo, Japan*
[5]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

We propose a formalism for the analysis of direct-detection dark-matter searches that covers all coherent responses for scalar and vector interactions and incorporates QCD constraints imposed by chiral symmetry, including all one- and two-body WIMP–nucleon interactions up to third order in chiral effective field theory. One of the free parameters in the WIMP–nucleus cross section corresponds to standard spin-independent searches, but in general different combinations of new-physics couplings are probed. We identify the interference with the isovector counterpart of the standard spin-independent response and two-body currents as the dominant corrections to the leading spin-independent structure factor, and discuss the general consequences for the interpretation of direct-detection experiments, including minimal extensions of the standard spin-independent analysis. Fits for all structure factors required for the scattering off xenon targets are provided based on state-of-the-art nuclear shell-model calculations.



1. two (isoscalar and isovector) leading coefficients of the M response

$$c_\pm^M = \frac{\zeta}{2}\Big[f_p \pm f_n + f_1^{V,p} \pm f_1^{V,n}\Big], \tag{59}$$

2. two coefficients of the two-body responses

$$c_\pi = \zeta f_\pi, \qquad c_\pi^\theta = \zeta f_\pi^\theta, \tag{60}$$

3. two (isoscalar and isovector) radius corrections to the M response

$$\dot{c}_\pm^M = \frac{\zeta m_N^2}{2}\bigg[\dot{f}_p \pm \dot{f}_n + \dot{f}_1^{V,p} \pm \dot{f}_1^{V,n} + \frac{1}{4m_N^2}\Big(f_2^{V,p} \pm f_2^{V,n}\Big)\bigg], \tag{61}$$

4. two (isoscalar and isovector) coefficients of the Φ'' response

$$c_\pm^{\Phi''} = \frac{\zeta}{2}\Big(f_2^{V,p} \pm f_2^{V,n}\Big). \tag{62}$$