Dark matter direct detection inference with minimal assumptions

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Outline

I. The challenge

II. Standard assumptions

III. Reconstructions

IV. Summary

Introduction: the inference challenge

UV WIMP model > 100 GeV

Integrate out BSM
do RGE

- see arXiv:1411.3342

Weak scale EFT ~100 GeV

EWSB, SM RGE
and QCD

- see arXiv:1409.8290 and
arXiv:1504.00915

Nucleon EFT ~1 GeV

Embed nucleons in
nuclear potential

coherence, 2-body effects
- see arXiv:1308.6288 and
arXiv:1605.08043

Nuclear matrix elements < 1 GeV

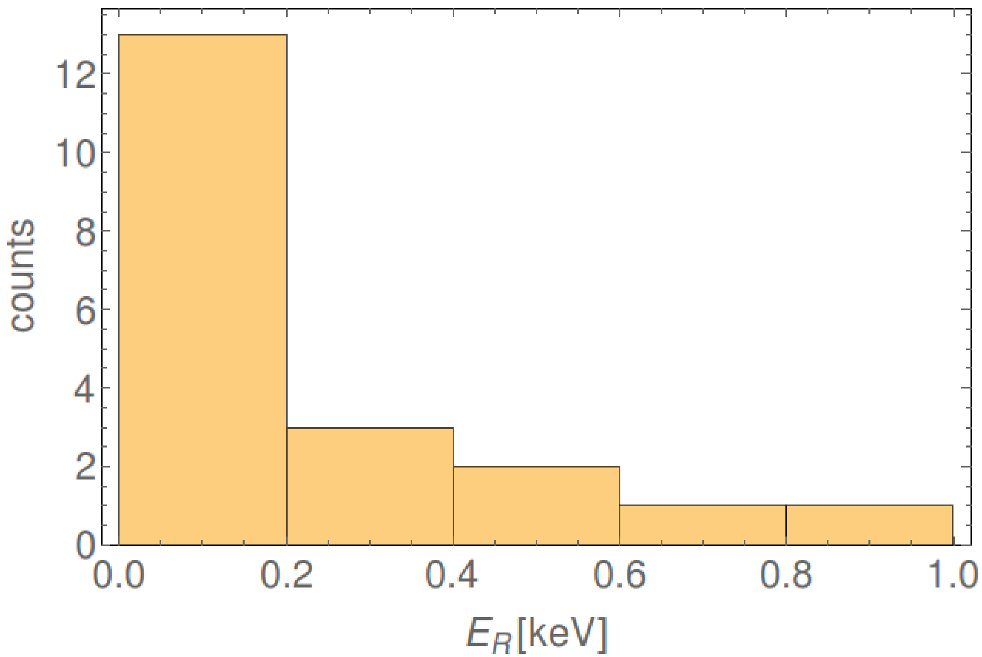
Experimental observables

Introduction: the inference challenge

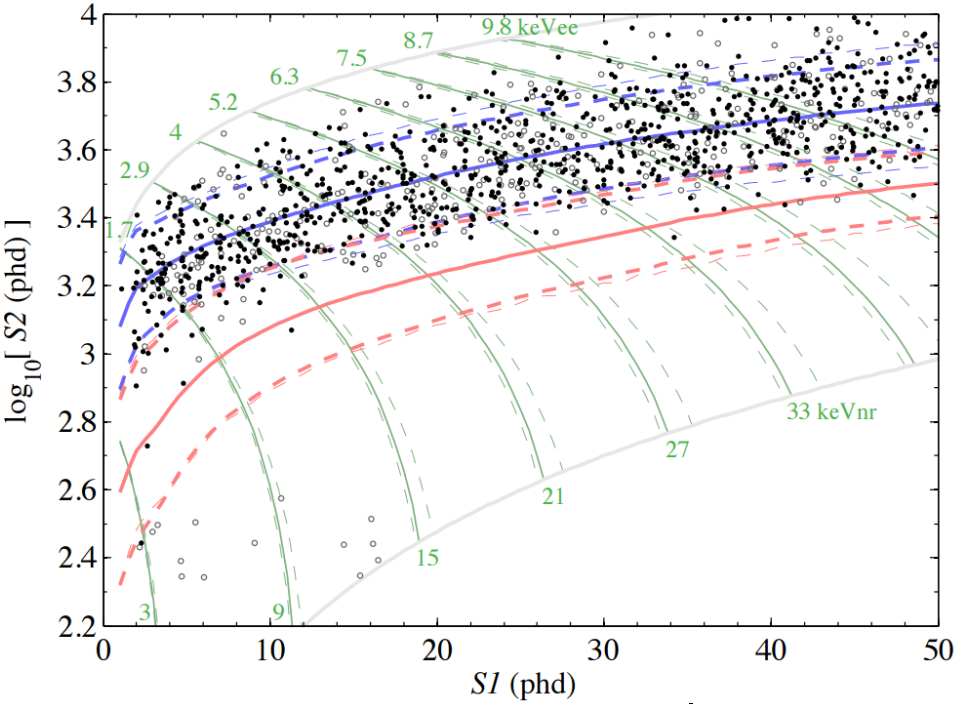
Experimental observables:

- recoil energy (normally indirectly)
- (x,y,z) position
- recoil direction (not ready for prime time)

Theorist ‘data’

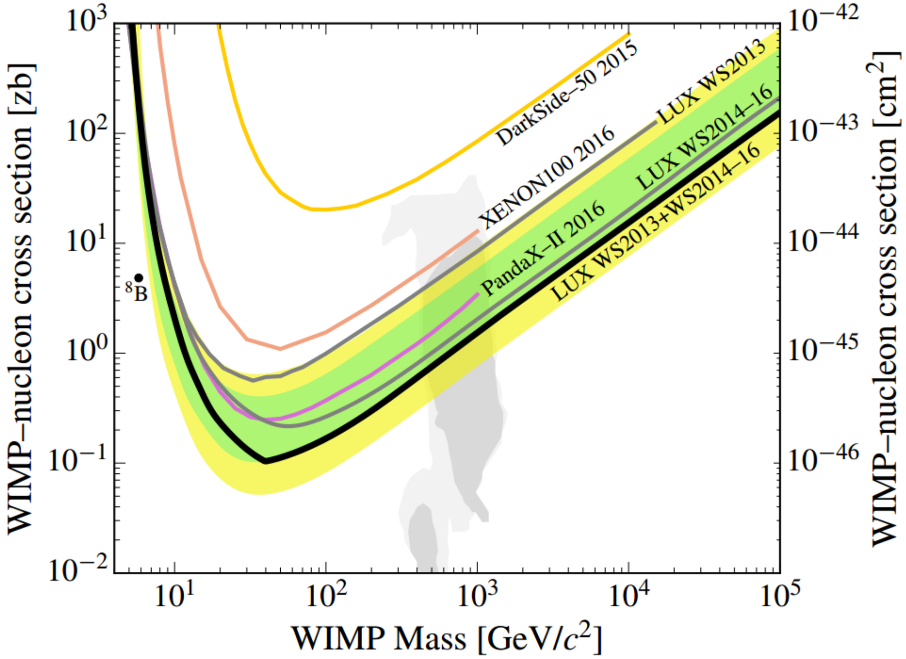


Real (LUX) data



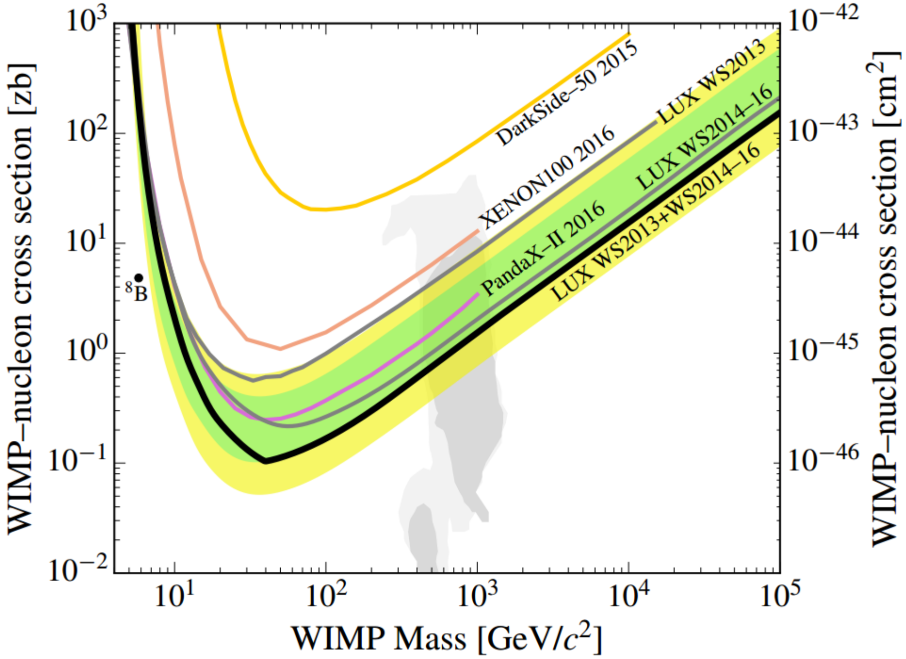
arXiv:1608.07648

Standard assumptions



- no isospin violation
- elastic scattering
- no q-dependence
- only couples to mass or spin of N
- Maxwell-Boltzman velocity distribution
- single component DM

Standard assumptions



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Let's just relax...

...some assumptions

Non-relativistic EFT for DD

WIMP spin $\vec{S}_\chi$
Nucleon spin $\vec{S}_N$
Momentum transfer $i\vec{q}$
velocity $\vec{v}^{\perp}$

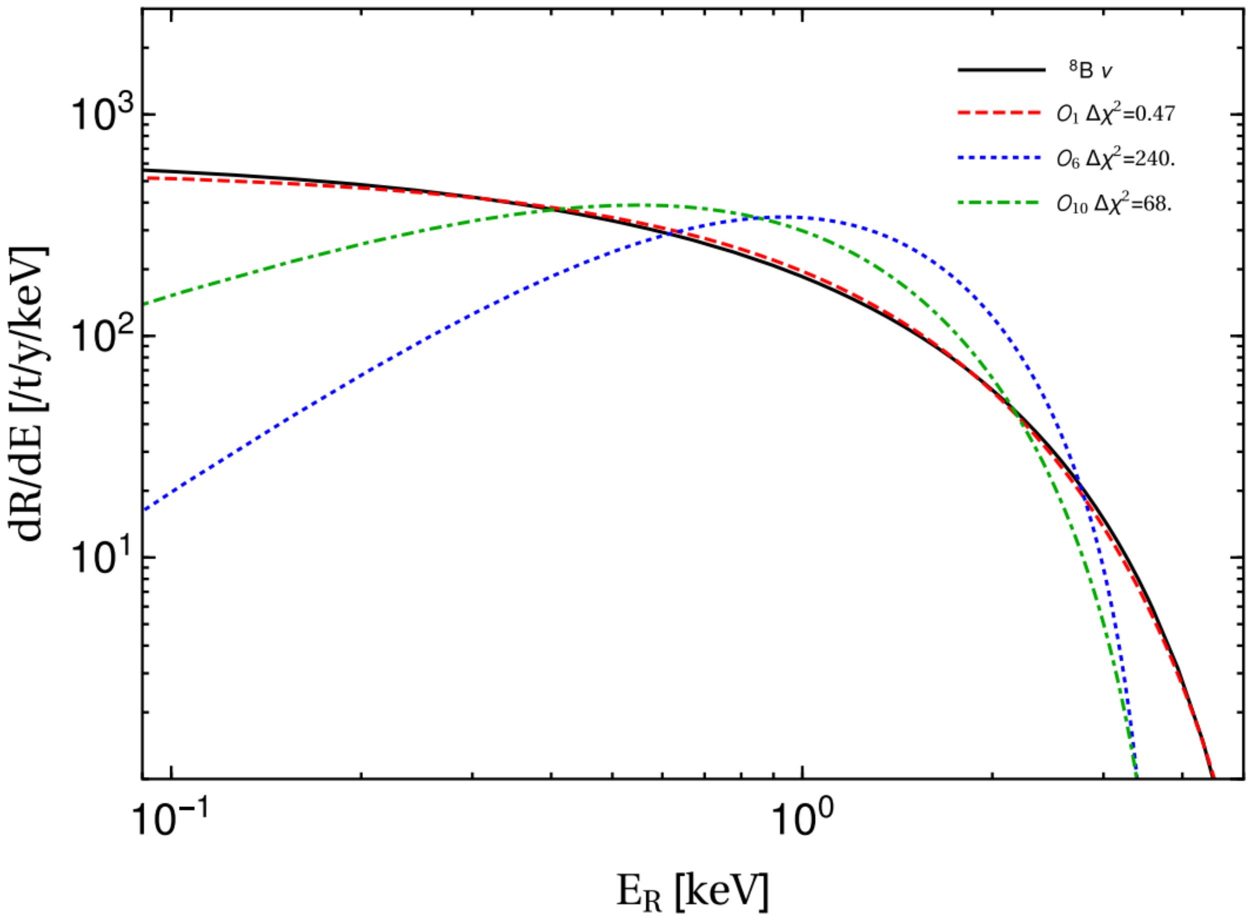
$\mathcal{O}_1$	$1_\chi 1_N$
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$

Operators by groups

- The non-relativistic operators can be grouped by their momentum dependence
- At low mass (lower recoil energies) nuclear structure is not probed and they become essentially degenerate

Operator	Mass (GeV)	Exp. (t.y)
$\mathcal{O}_1$	6	2.9
$\mathcal{O}_4$	6	3.5
$\mathcal{O}_7$*	6.2	4.3
$\mathcal{O}_8$	6.3	3.6
q^2 and $q^2 v_T^2$		
$\mathcal{O}_5$	4.8	0.43
$\mathcal{O}_9$	4.6	0.34
$\mathcal{O}_{10}$	4.6	0.36
$\mathcal{O}_{11}$	4.6	0.40
$\mathcal{O}_{12}$*	4.6	0.44
$\mathcal{O}_{14}$*	4.8	0.43
$q^2 v_T^2$, q^4 and $q^4 v_T^2$		
$\mathcal{O}_3$*	4.2	0.27
$\mathcal{O}_6$	4.2	0.29
$\mathcal{O}_{13}$*	4.2	0.27
$\mathcal{O}_{15}$*	4.1	0.21

Non-standard WIMP rates



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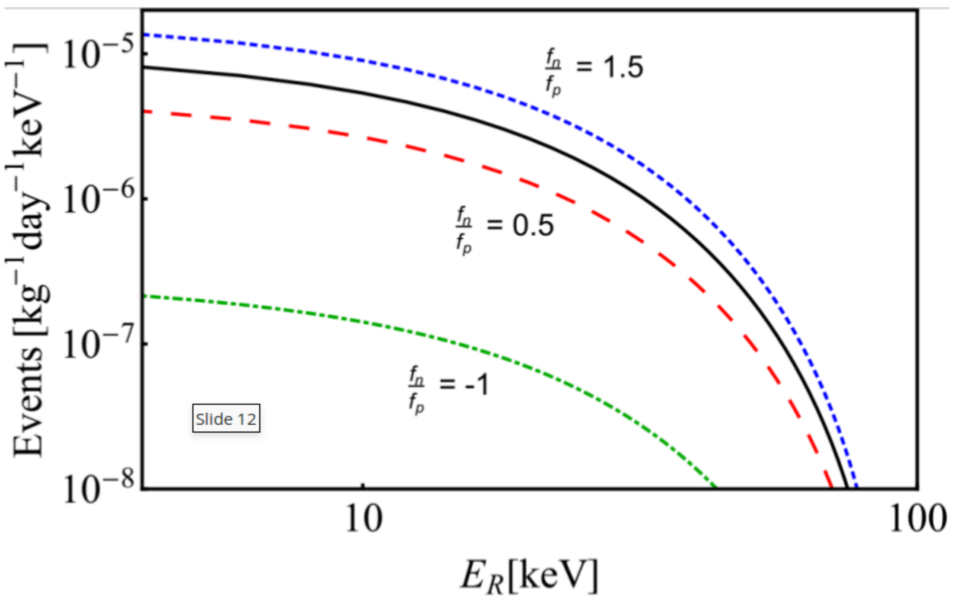
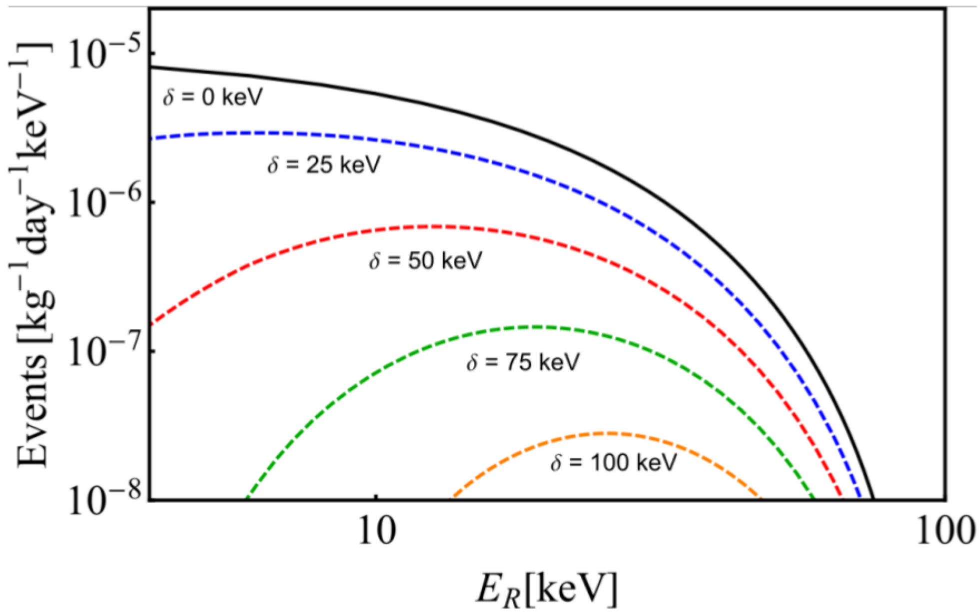
Non-standard WIMP rates

Isospin violation



- needs multiple targets to break degeneracy

Inelastic scattering



- needs lots of events to break degeneracy with q-dependent scattering

Generalized velocity distribution

We need to compute the average inverse WIMP velocity:

$$\int \frac{f(\mathbf{v})}{|\mathbf{v}|} d^3\mathbf{v} = ?$$

General forms of f(v) have been proposed in the past (e.g. Lisanti et al., Mao et al.), but they tend to bias the reconstruction. Use a more general form due to Green and Kavanagh:

$$f_1(v) = v^2 \exp\left\{ - \sum_{k=0}^{N-1} a_k P_k(v) \right\}$$

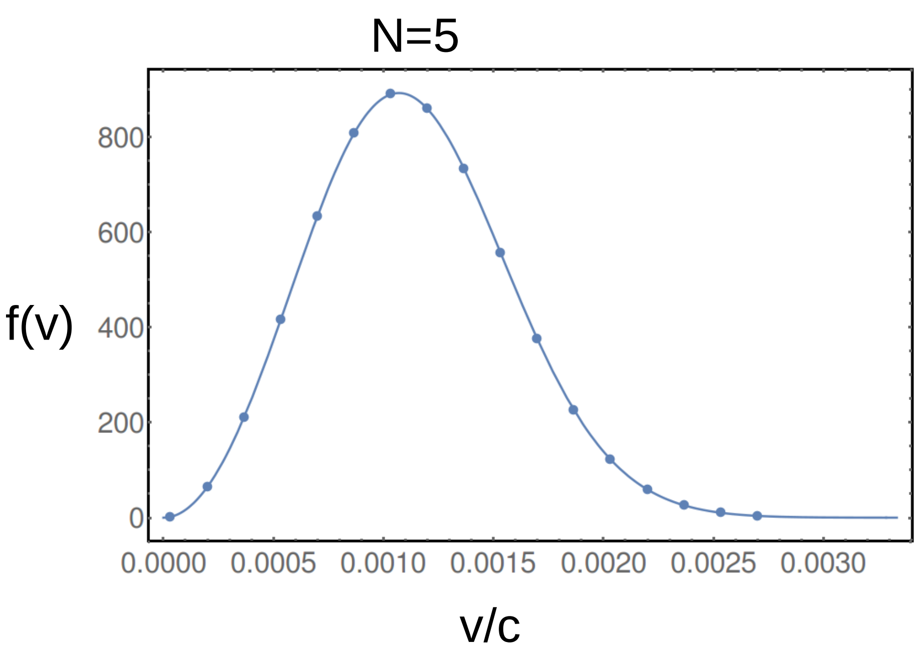
Where P(v) can be any well conditioned set of orthogonal polynomials, then fit to your data with the coefficients.

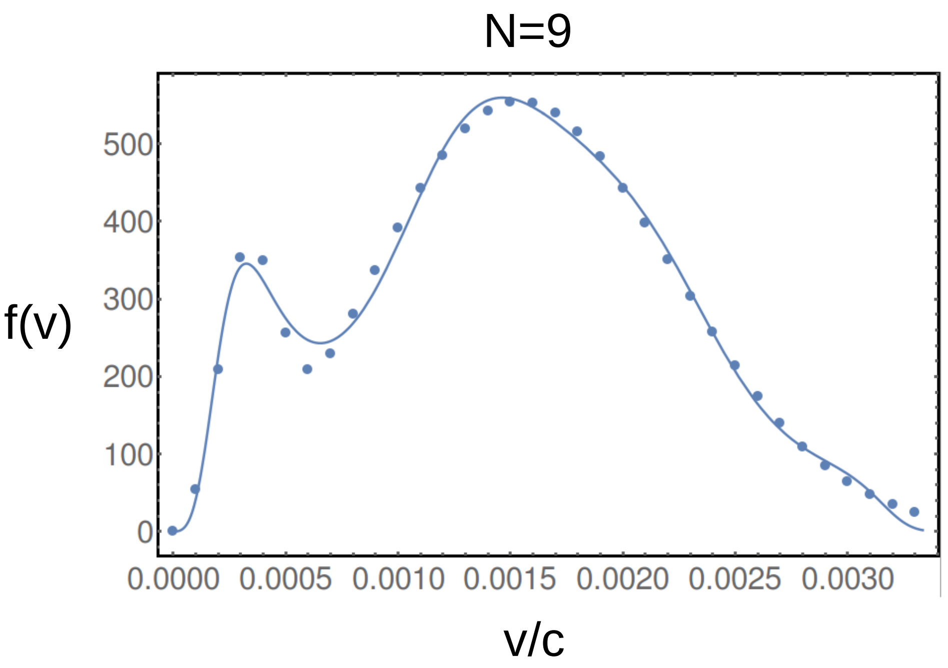
See arXiv:1312.1852 for details

Generalized velocity distribution

$$f_1(v) = v^2 \exp\left\{-\sum_{k=0}^{N-1} a_k P_k(v)\right\}$$

Taking Chebyshev polynomials as the P(v), N is dependent on the velocity distributions:





See arXiv:1312.1852 for details

Bayesian inference

- The method of choice for reconstructing WIMP properties

- Bayes' theorem:

$$\mathcal{P}(\theta, D|I) = \frac{\mathcal{L}(D|\theta, I)\pi(\theta, I)}{\epsilon(D, I)},$$

- Likelihood:

$$\mathcal{L}(\sigma, \theta) = \prod_{i=1}^{N} P(E_i(\sigma, \theta), A_i)$$

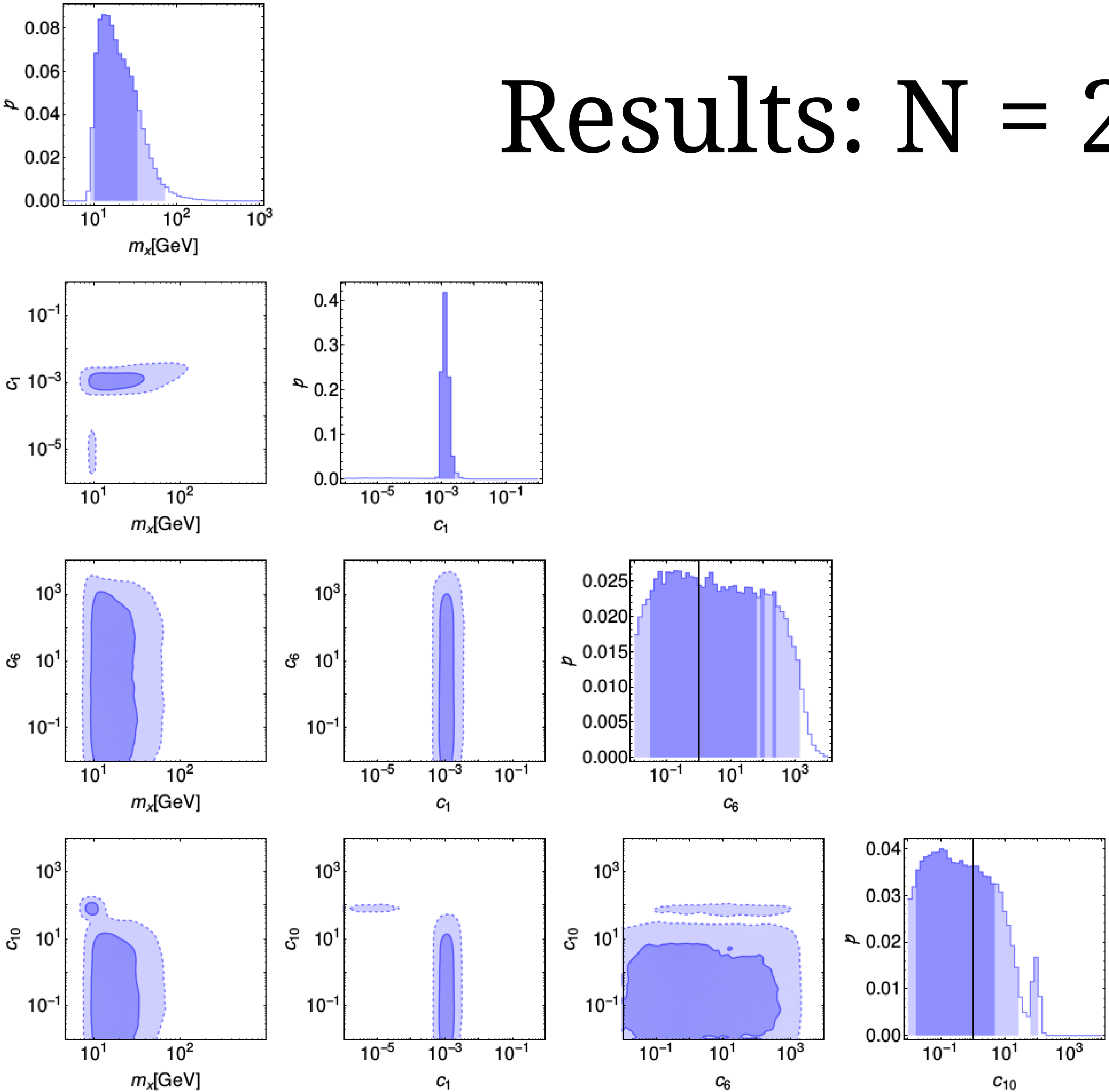
Parameter space

How many events does it take to distinguish q-dependence?
- simulate with MB, but reconstruct with Cheybshev N=5

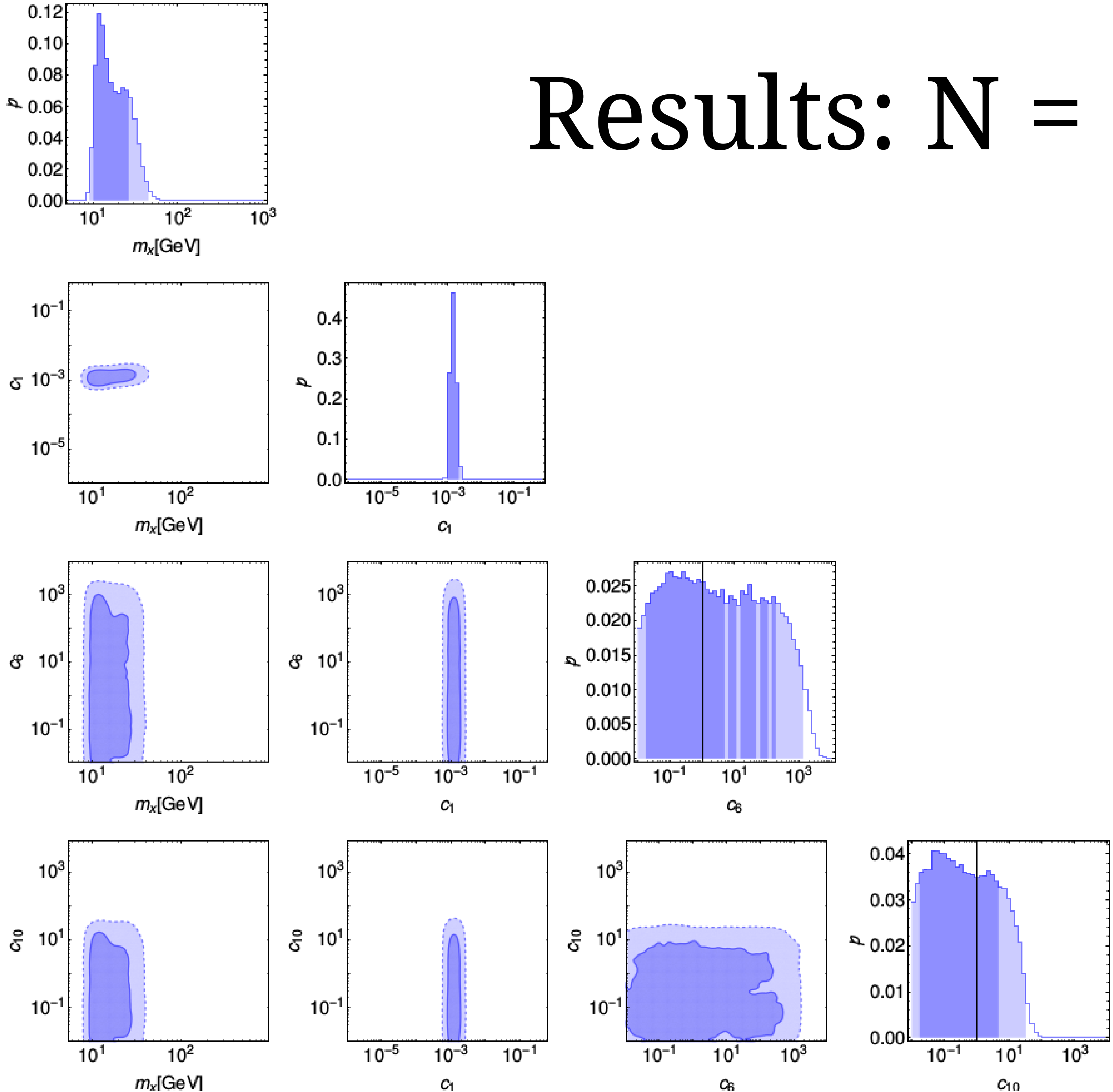
parameter	range	prior
m_χ	$1 - 10^3$	log-flat
c_1	$10^{-6} - 1$	log-flat
c_{10}	$10^{-2} - 10^4$	log-flat
c_6	$10^{-2} - 10^4$	log-flat
ρ_χ	0.3 ± 0.1	gaussian
a_i	$-20 - 100$	flat

- Sample this space with MultiNest

Results: N = 25

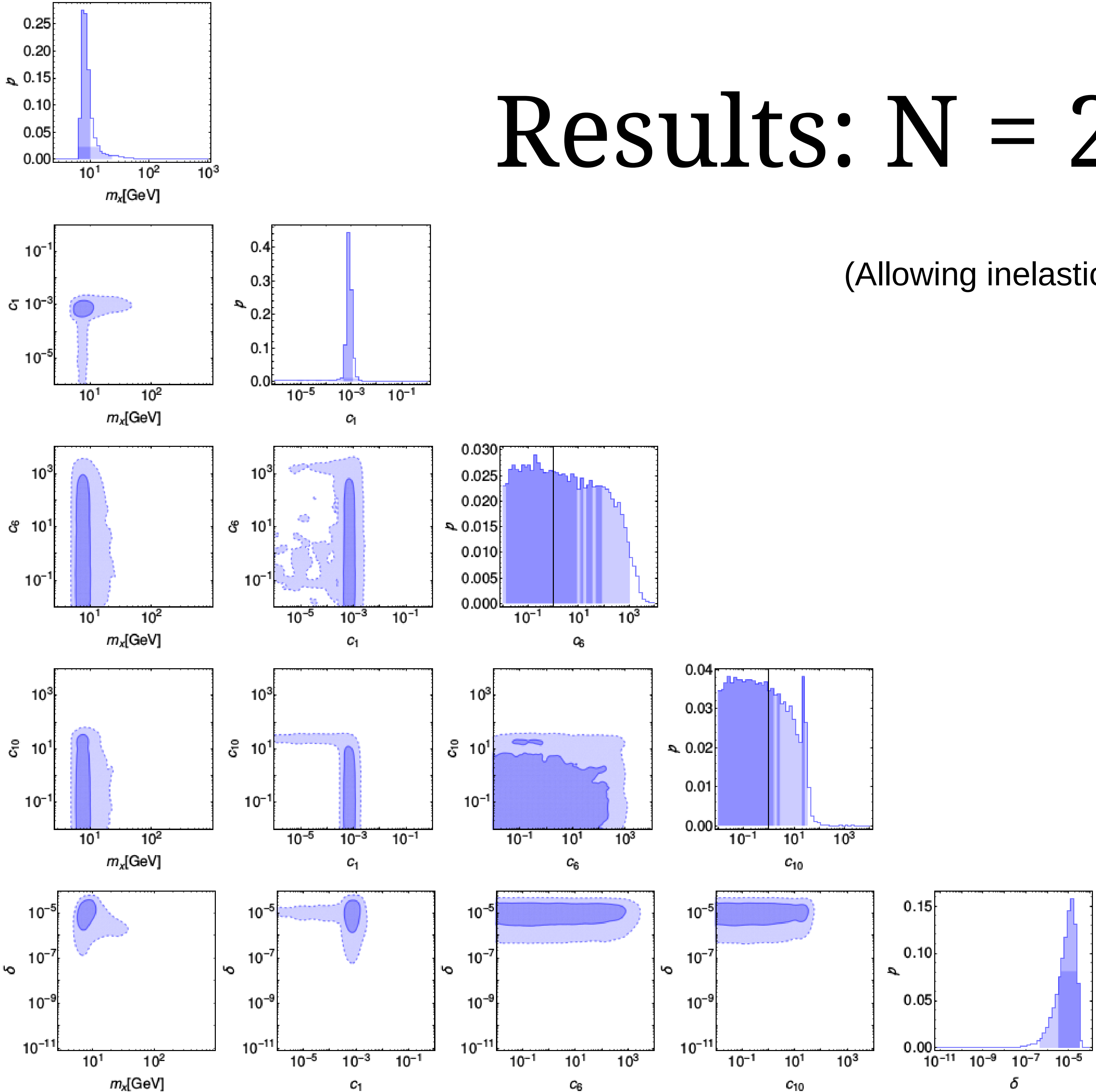


Results: N = 50



Results: N = 25

(Allowing inelastic scattering)



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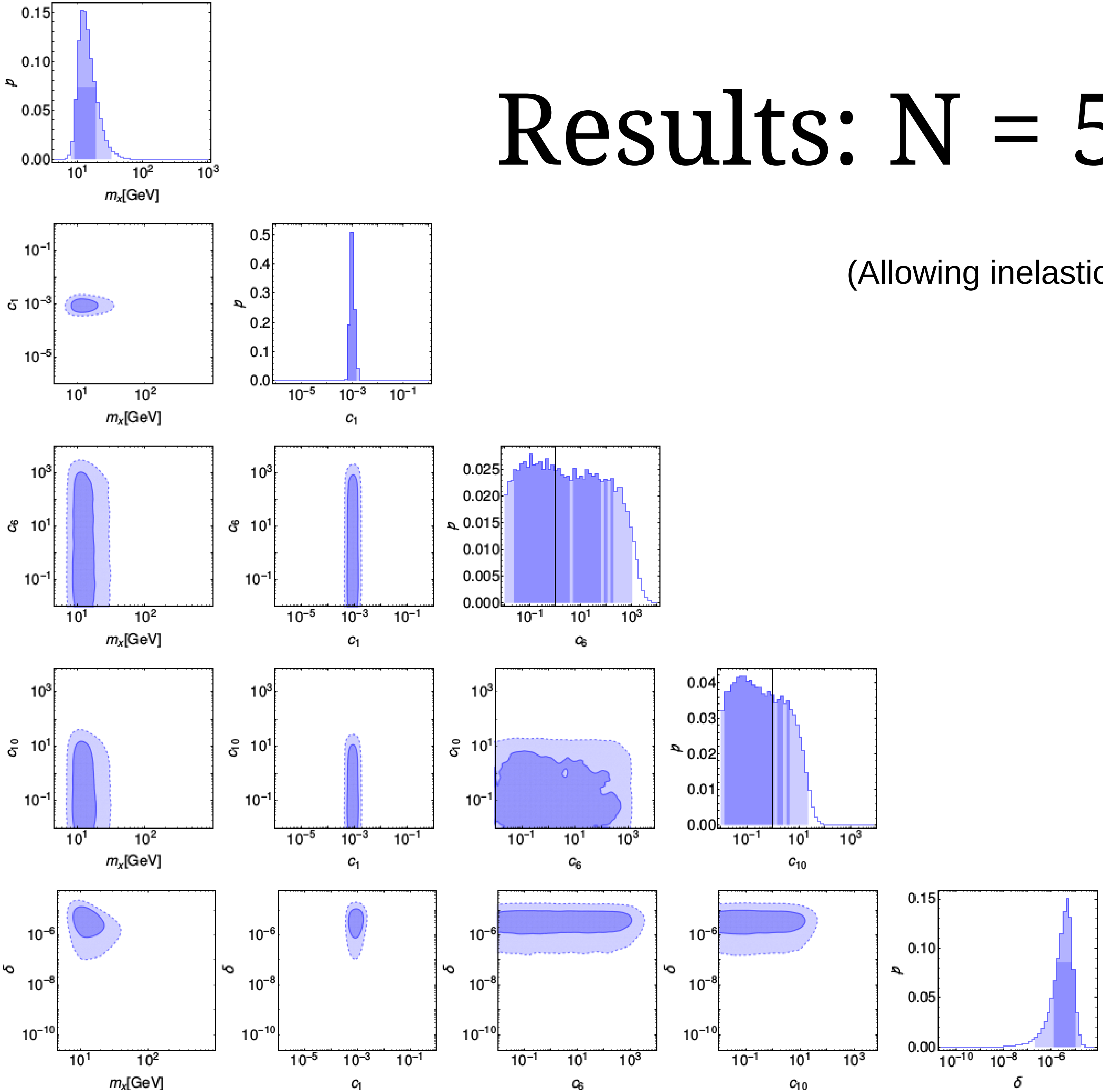
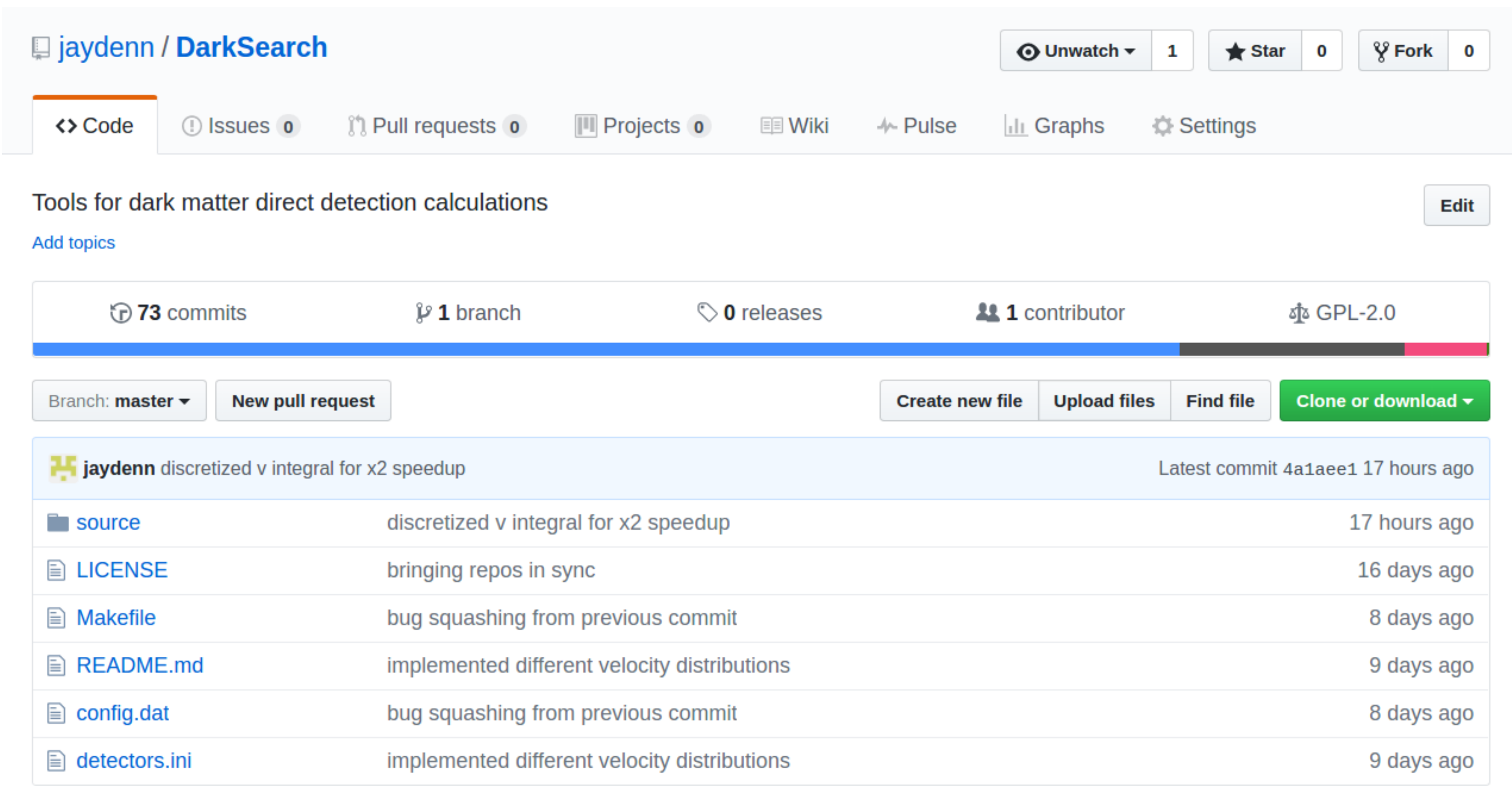


Publicly available code

https://github.com/jaydenn/DarkSearch

Simulates experiments and uses Bayesian inference (multinest) for parameter reconstructions

Visualization tools also available

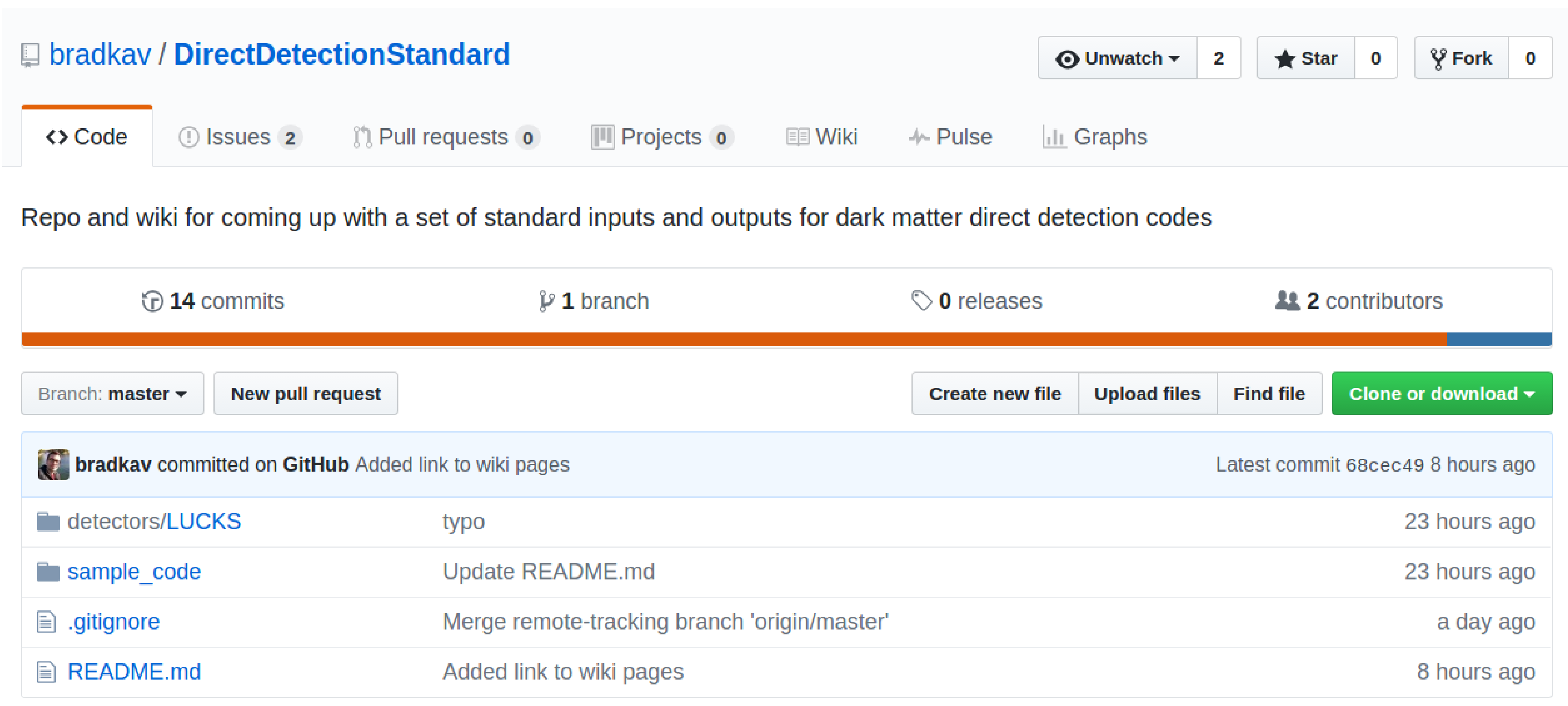


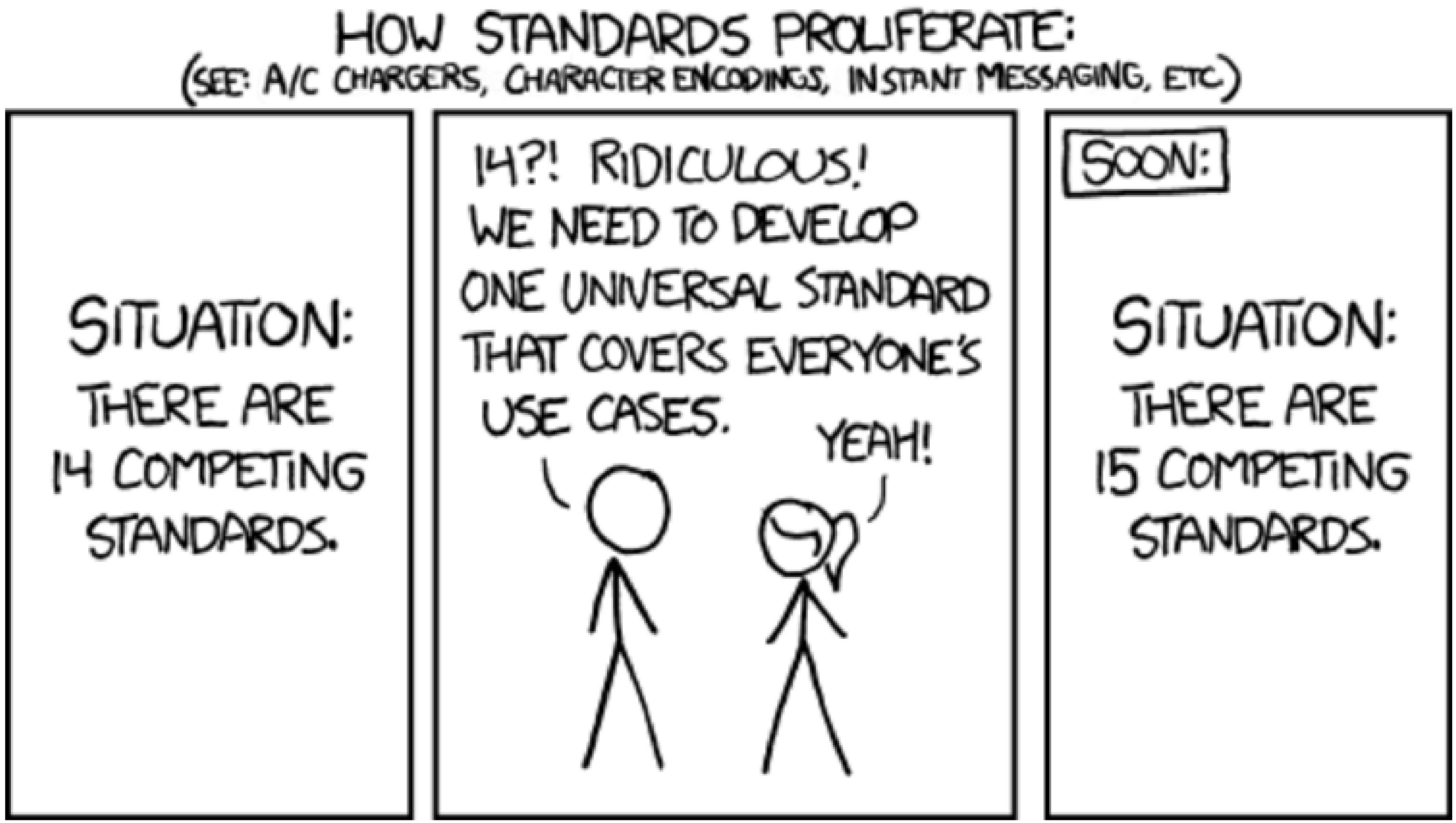
Call for input on standards

https://github.com/bradkav/DirectDetectionStandard

Goal: define data formats and keep repository of direct detection experiments

Experimentalists: please contact myself or Bradley Kavanagh, we'd love to get your advice/input




HOW STANDARDS PROLIFERATE:
(SEE: A/C CHARGERS, CHARACTER ENCODINGS, INSTANT MESSAGING, ETC.)
SITUATION: THERE ARE 14 COMPETING STANDARDS.
14?! RIDICULOUS! WE NEED TO DEVELOP ONE UNIVERSAL STANDARD THAT COVERS EVERYONE'S USE CASES.
YEAH!
SOON:
SITUATION: THERE ARE 15 COMPETING STANDARDS.

IV. Summary

- We need to consider the full direct detection parameter space

Example 1: RGE’s

arXiv.org > hep-ph > arXiv:1605.04917

Search or Article-id

High Energy Physics - Phenomenology

You can hide but you have to run: direct detection with vector mediators

Francesco D'Eramo, Bradley J. Kavanagh, Paolo Panci

(Submitted on 16 May 2016)

We study direct detection in simplified models of Dark Matter (DM) in which interactions with Standard Model (SM) fermions are mediated by a heavy vector boson. We consider fully general, gauge-invariant couplings between the SM, the mediator and both scalar and fermion DM. We account for the evolution of the couplings between the energy scale of the mediator mass and the nuclear energy scale. This running arises from virtual effects of SM particles and its inclusion is not optional. We compare bounds on the mediator mass from direct detection experiments with and without accounting for the running and find that in some cases these bounds differ by several orders of magnitude. We also highlight the importance of these effects when translating LHC limits on the mediator mass into bounds on the direct detection cross section. For an axial-vector mediator, the running can alter the derived bounds on the spin-dependent DM-nucleon cross section by a factor of two or more. Finally, we provide tools to facilitate the inclusion of these effects in future studies: general approximate expressions for the low energy couplings and a public code runDM to evolve the couplings between arbitrary energy scales.

Comments: 25 pages + appendices, 8 + 2 figures. The runDM code is available at this https URL

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy

Example 2: Loops

arXiv.org > hep-ph > arXiv:1012.5317

Search or Artic

High Energy Physics - Phenomenology

On dark matter models with uniquely spin-dependent detection possibilities

Marat Freytsis, Zoltan Ligeti

(Submitted on 23 Dec 2010 (v1), last revised 5 Dec 2011 (this version, v3))

With much higher sensitivities due to coherence effects, it is often assumed that the first evidence for direct dark matter detection will come from experiments probing spin-independent interactions. We explore models that would be invisible in such experiments, but detectable via spin-dependent interactions. The existence of much larger (or even only) spin-dependent tree-level interactions is not sufficient, due to potential spin-independent subdominant or loop-induced interactions. We find that in such a way most models with detectable spin-dependent interactions would also generate detectable spin-independent interactions. Models in which a light pseudoscalar acts as the mediator seem to uniquely evade this conclusion. We present a particular viable dark matter model generating such an interaction.

arXiv.org > hep-ph > arXiv:1302.4454

Search or Article-id

High Energy Physics - Phenomenology

On the importance of loop-induced spin-independent interactions for dark matter direct detection

Ulrich Haisch, Felix Kahlhoefer

(Submitted on 18 Feb 2013 (v1), last revised 7 Jun 2013 (this version, v2))

The latest results from LHC searches for jets in association with missing transverse energy place strong bounds on the scattering cross section of dark matter. For the case of spin-dependent or momentum suppressed interactions these limits seem to be superior to the bounds from direct detection experiments. In this article, we show that loop contributions can significantly alter this conclusion and boost direct detection bounds, whenever they induce spin-independent interactions. This effect is most striking for tensor and pseudotensor interactions, which induce magnetic and electric dipole moments at loop level. For axialvector and anapole interactions a relevant contribution to direct detection signals arises from loop-induced Yukawa-like couplings between dark matter and quarks. We furthermore compare the resulting bounds to additional constraints on these effective operators arising from indirect searches and relic density requirements.

Comments:	20 pages, 6 figures, 1 table. v2: new appendix, minor corrections, references added - matches published version
Subjects:	**High Energy Physics - Phenomenology (hep-ph)**; High Energy Astrophysical Phenomena (astro-ph.HE); High Energy Physics - Experiment (hep-ex)
Journal reference:	JCAP 1304 (2013) 050
DOI:	10.1088/1475-7516/2013/04/050
Report number:	OUTP-13-06P
Cite as:	arXiv:1302.4454 **[hep-ph]**
	(or **arXiv:1302.4454v2 [hep-ph]** for this version)

Example 3: EWSB operator mixing

arXiv.org > hep-ph > arXiv:1404.2283

Search or Article-

High Energy Physics - Phenomenology

The Fermionic Dark Matter Higgs Portal: an effective field theory approach

Michael A. Fedderke, Jing-Yuan Chen, Edward W. Kolb, Lian-Tao Wang

(Submitted on 8 Apr 2014 (v1), last revised 23 Aug 2014 (this version, v2))

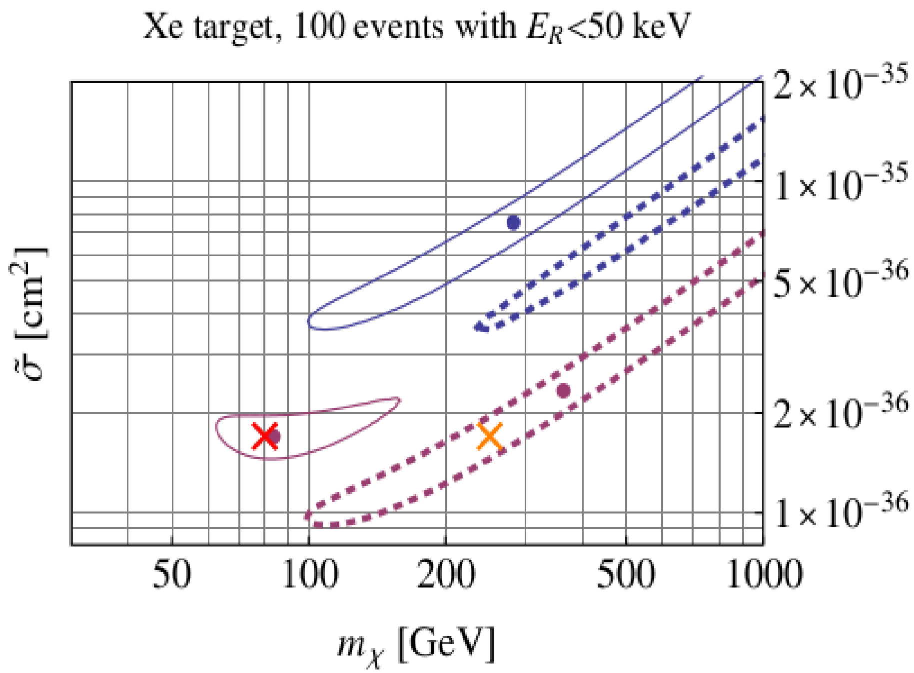
We consider fermionic (Dirac or Majorana) cold thermal relic dark-matter coupling to standard-model particles through the effective dimension-5 Higgs portal operators $\Lambda^{-1}\,\mathcal{O}_{\rm DM}\cdot H^\dagger H$, where $\mathcal{O}_{\rm DM}$ is an admixture of scalar $\bar{\chi}\chi$ and pseudoscalar $\bar{\chi}i\gamma_5\chi$ DM operators. Utilizing the relic abundance requirement to fix the couplings, we consider direct detection and invisible Higgs width constraints, and map out the remaining allowed parameter space of dark-matter mass and the admixture of scalar and pseudoscalar couplings. We emphasize a subtlety which has not previously been carefully studied in the context of the EFT approach, in which an effect arising due to electroweak symmetry breaking can cause a na\"ively pure pseudoscalar coupling to induce a scalar coupling at higher order, which has important implications for direct detection bounds. We provide some comments on indirect detection bounds and collider searches.

Comments:	22 pages, 8 figures. Published version
Subjects:	**High Energy Physics - Phenomenology (hep-ph)**
Journal reference:	JHEP08(2014)122
DOI:	10.1007/JHEP08(2014)122
Cite as:	**arXiv:1404.2283 [hep-ph]**
	(or **arXiv:1404.2283v2 [hep-ph]** for this version)

Example 4: beyond standard SI/SD

- Does not include degrees of freedom for nucleon velocities (ignores responses related to transverse spin and orbital angular momentum)

- Result: you will estimate recoil energy dependence wrongly and over/under estimate total rate



"The standard SI/SD analysis grossly misrepresents the physics of these operators, leading to errors that can exceed several orders of magnitude"
arXiv:1308.6288

Example from Gresham & Zurek
arXiv:1401.3739