WIMPs interpretations with NaI detectors: DAMA/Libra and beyond

Stefano Scopel

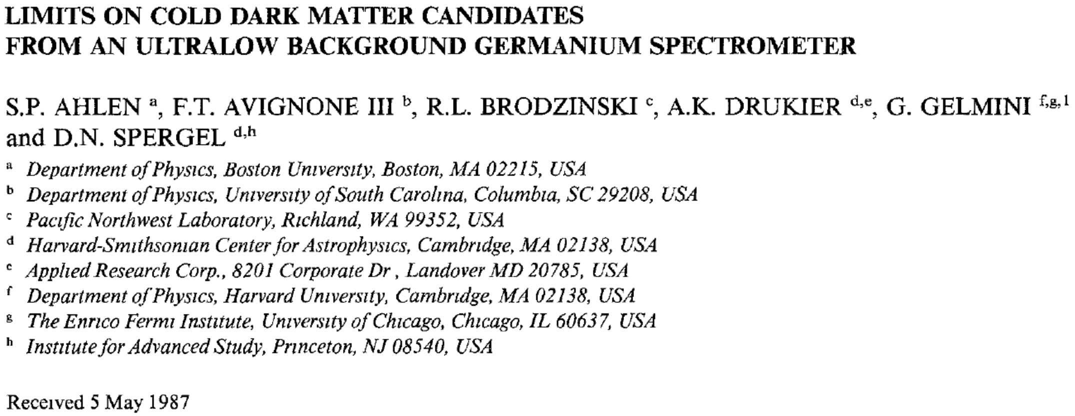
서강대학교
SOGANG UNIVERSITY

CQUeST
Center for Quantum SpaceTime

KPS 한국물리학회
The Korean Physical Society

2022 KPS Spring Meeting
Pioneer Symposium
Dark matter and neutrino searches with scintillating detectors
April 22, 2022

The direct search of Weakly Interacting Massive Particles (WIMPS) turned long ago from a cheap spin-off of neutrinoless double beta decay experiments into a serious business – in 30 years almost 8 orders of magnitude improvement in bounds on Spin-Independent WIMP-nucleon cross section

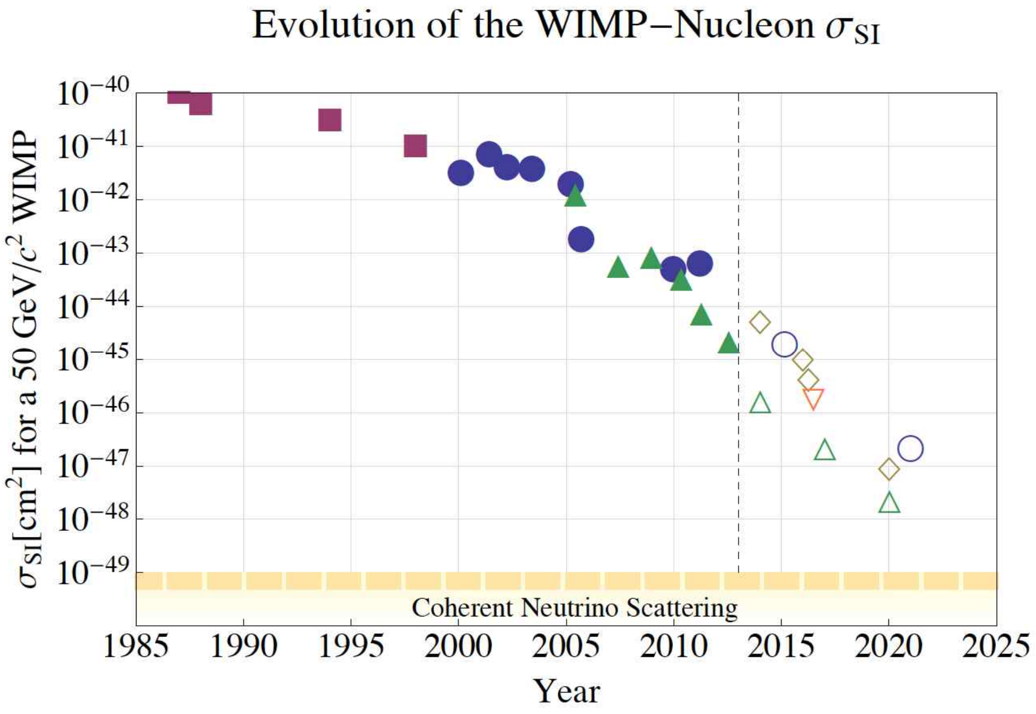


LIMITS ON COLD DARK MATTER CANDIDATES
FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

[a] *Department of Physics, Boston University, Boston, MA 02215, USA*
[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
[c] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[e] *Applied Research Corp., 8201 Corporate Dr, Landover MD 20785, USA*
[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[g] *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[h] *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987



Next generation experiments: point-contact Ge detectors, cryogenic Ge detectors, two-phase xenon detectors, bubble chambers, CCD-based searches, ...

Dramatic improvement on the experimental side. What about phenomenology?

N.B.: theoretical predictions for the WIMP direct detection rate depend on two main ingredients:

1) a scaling law for the cross section, in order to compare experiments using different targets

   Traditionally spin-independent cross section (proportional to (atomic mass number)^2) or spin-dependent cross section (proportional to the product $\mathbf{S}_{WIMP} \cdot \mathbf{S}_{nucleus}$) is assumed

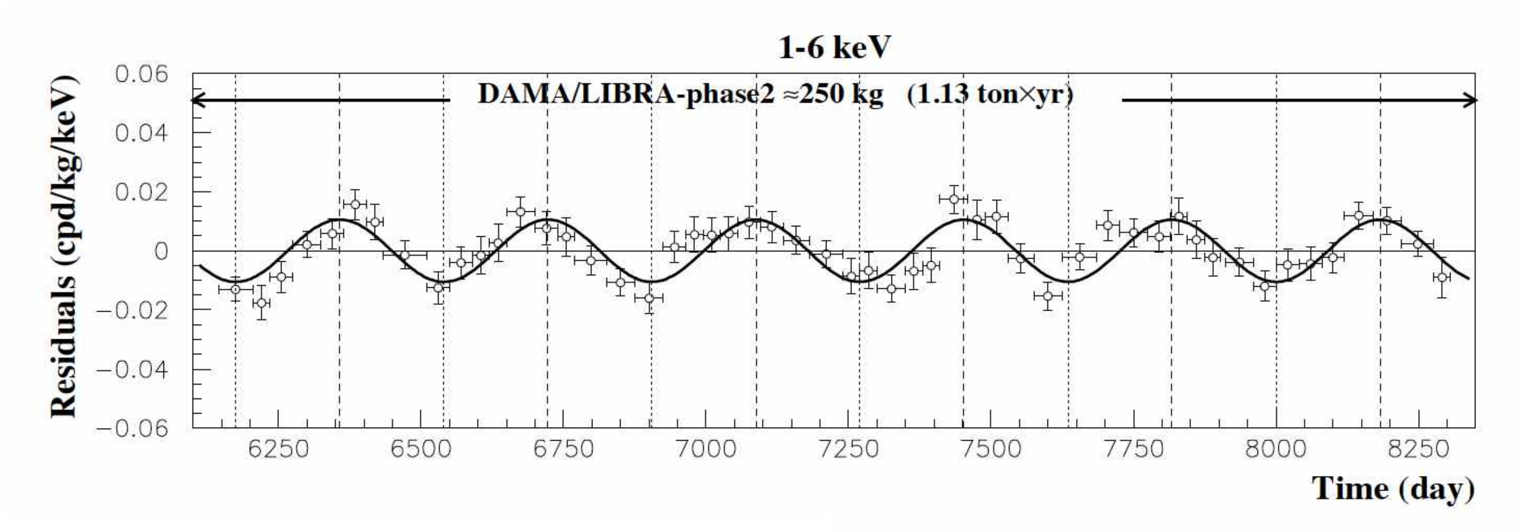
2) a model for the velocity distribution of WIMPs

   Traditionally a Maxwellian distribution is assumed

DAMA, i.e. the elephant in the DM room

DAMA/Libra phase 2 result (Bernabei et al., Nucl. Phys. At. Energy 19 (2018) 307-325, e-Print: 1805.10486)

total combined exposure phase1+phase2: 2.46 ton yr, collected over 14 annual cycles, ~ 13 sigma effect…



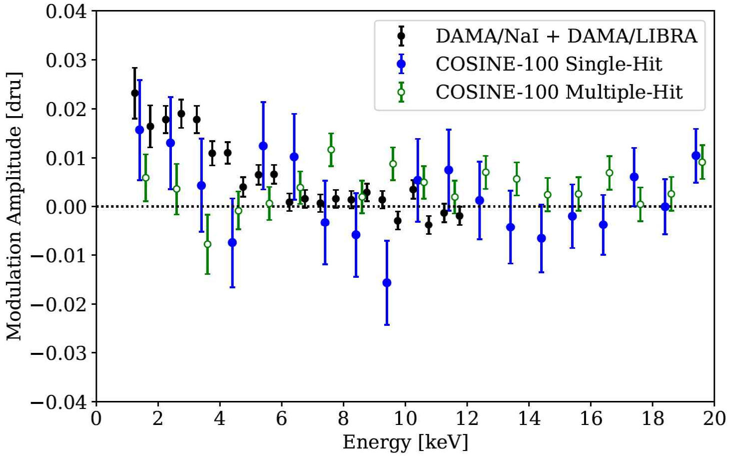
		A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (days)	C.L.
DAMA/LIBRA–phase2:					
	1-3 keV	(0.0184±0.0023)	1.0	152.5	8.0 σ
	1-6 keV	(0.0105±0.0011)	1.0	152.5	9.5 σ
	2-6 keV	(0.0095±0.0011)	1.0	152.5	8.6 σ
	1-3 keV	(0.0184±0.0023)	(1.0000±0.0010)	153±7	8.0 σ
	1-6 keV	(0.0106±0.0011)	(0.9993±0.0008)	148±6	9.6 σ
	2-6 keV	(0.0096±0.0011)	(0.9989±0.0010)	145±7	8.7 σ
DAMA/LIBRA–phase1 + phase2:					
	2-6 keV	(0.0095±0.0008)	1.0	152.5	11.9 σ
	2-6 keV	(0.0096±0.0008)	(0.9987±0.0008)	145±5	12.0 σ
DAMA/NaI + DAMA/LIBRA–phase1 + phase2:					
	2-6 keV	(0.0102±0.0008)	1.0	152.5	12.8 σ
	2-6 keV	(0.0103±0.0008)	(0.9987±0.0008)	145±5	12.9 σ

$A \cos[\omega\ (t-t_0)]$

$\omega=2\pi/T_0$

COSINE-100 and ANAIS probing DAMA using sodium iodide. Entering post-DAMA era at last

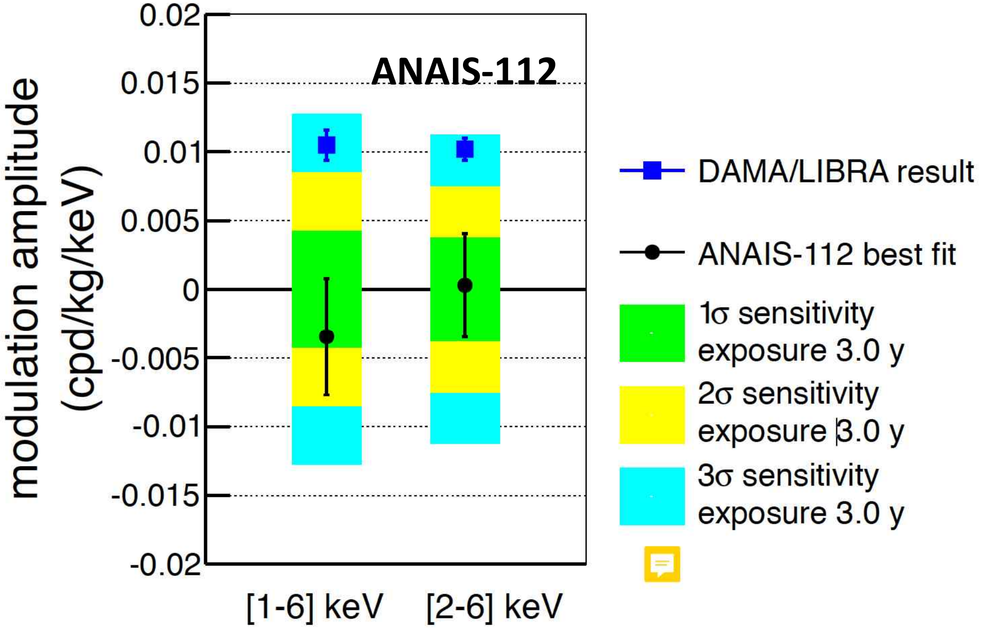
61.3 kg of NaI, 2.82 kg yr livetime



G. Adhikari et al. [COSINE-100 Collaboration], ``Three-year annual modulation search with COSINE-100”, arXiv:2111.08863

“consistent with both a null hypothesis and DAMA/LIBRA's 2-6 keV best t value”

112.5 kg of NaI, 313.95 kd day



J.~Amaré et al., ``Annual modulation results from three-year exposure of ANAIS-112'', PRD 103 (2021) 102005 (arXiv:1903.03973)

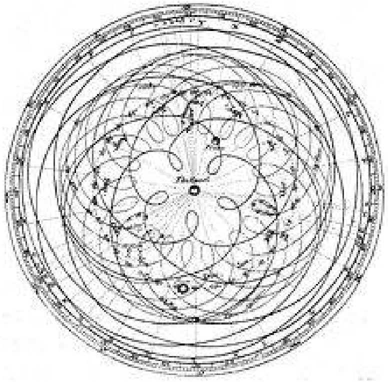
“best fit modulation amplitude […] incompatible with the DAMA/LIBRA result at 3.3 (2.6) σ, with a sensitivity of 2.5 (2.7) σ.”

Need more statistics. ANAIS has the same threshold of DAMA-Libra-phase2 (1 keV) , COSINE-100 plans to lower threshold to 1 keV soon. **More results to come: Anais+(6 year analysis), Cosine200, SABRE, PICOLON, COSINUS…**

Of course phenomenological models cannot reconcile DAMA with the null results of its replicas (however: different quenching factors? different systematics?)

Irrespective on whether DAMA is true or not it was a useful benchmark to develop model-independent approaches that will be useful for the new excess

A brief account of attempts to find compatibility between DAMA and constraints from detectors using different nuclear targets



Several **epicycles** added to the usual scenario:

- Non-standard coupling
- Inelastic scattering
- Isospin violation ($c_p \neq c_n$)
- Generalized velocity distribution
- …

Chase between viable scenarios and upcoming experimental data: DAMA phase2, XENON1T, PICO60 (~2018):

DAMA phase1 (2 keVee threshold, peak in modulation amplitude energy spectrum)
Bounds: xenon100, coupp, PICASSO, CDMS)

- 2014: Spin-Independent + inelastic + halo independent + Ge-phobic (S. S, KookHyun Yoon, JCAP 08 (2014), 060
- 2015: elastic + proton-philic generalized spin interaction + halo-independent, S.S., Kook-Hyun Yoon, Jong-Hyun Yoon, JCAP 07 (2015), 041
- 2016: inelastic + proton-philic spin interaction (pSIDM), S.S., Kook-Hyun Yoon, JCAP 02 (2016), 050

DAMA phase2 (larger exposure, 1 keVee threshold, monotonically decreasing of modulation amplitude energy spectrum)

- 2019: inelastic + proton-philic spin interaction (pSIDM update), S. S., Kook-Hyun Yoon, Jong-Hyun Yoon, JCAP 07 (2015), 041
- 2019: inelastic + full non-relativistic effective theory (NREFT), Sunghyun Kang, S. S., Gaurav Tomar, Phys.Rev.D 99 (2019) 10, 103019

Halo-independent approach

Compatibility among experiments using different targets can be verified without assuming any model for the halo (only scaling law of the cross section is required)

Write expected WIMP rate as:

$$R_{[E'_1,E'_2]}(t) = \frac{\rho_\chi}{m_\chi} \int_{v_{T*}}^{\infty} \sum_T dv \mathcal{R}_{T,[E'_1,E'_2]}(v) \eta(v,t)$$

$\mathcal{R}_{T,[E'_1,E'_2]}(v)$ =response function for target T in visible energy interval $E'_1<E'<E'_2$

$\eta(v,t) = \int_v^{\infty} \frac{f(\vec{v}',t)}{|\vec{v}'|} d^3v'$ =halo function depending on WIMP velocity distribution f(v)

with: $v_{\min} = \sqrt{\frac{m_N E_R}{2\mu^2}}$ (m_N=nuclear mass, μ =WIMP-nucleus reduced mass)

So there is a one-to-one correspondence between the recoil energy E_R and v_{min}

→ map the event rate expected in different experiments into the same intervals in v_{min}
(P.J. Fox, J. Liu, N. Weiner, PRD83,103514 (2011))

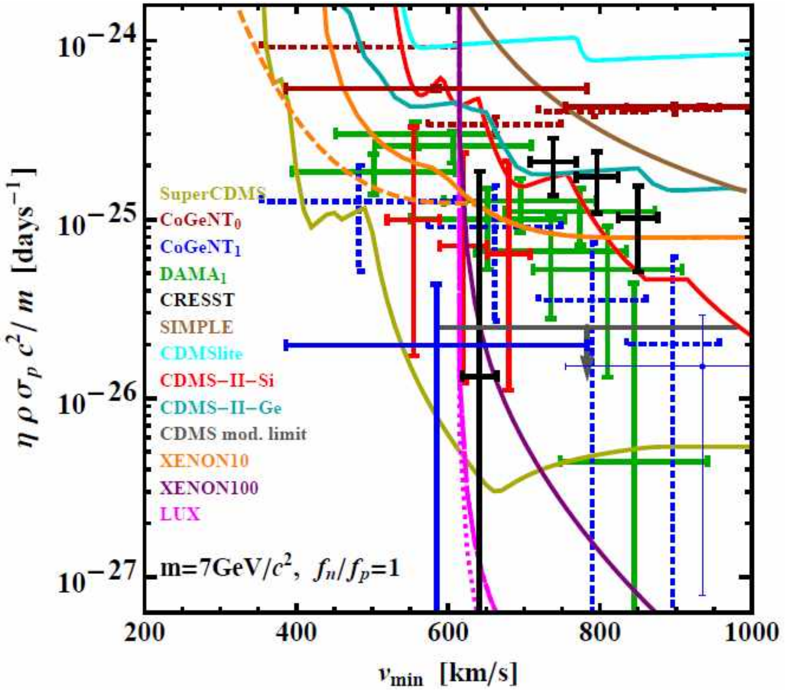
In this way the dependence on the galactic model cancels out in the ratio of the expected count rates of the two experiments because they depend on the same integrals of $f_{local}(v)$

halo-independent analysis **for elastic scattering**

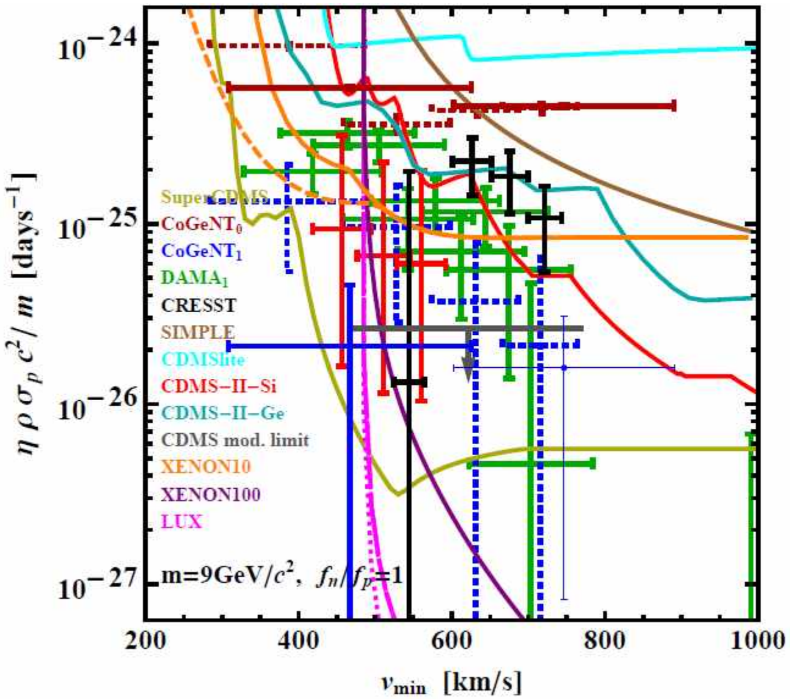
Del Nobile, Gelmini, Gondolo, Huh, arXiv:1405.5582

Standard SI interaction

m_{WIMP}=7 GeV



m_{WIMP}=9 GeV



$$R^{\rm SI}_{[E'_1,E'_2]}(t) = \int_0^\infty {\rm d}v_{\rm min}\,\tilde{\eta}(v_{\rm min},t)\,\mathcal{R}^{\rm SI}_{[E'_1,E'_2]}(v_{\rm min})$$

$$\boxed{\tilde{\eta}(v_{\rm min},t) \equiv \frac{\rho\sigma_p}{m}\int_{v\geqslant v_{\rm min}} {\rm d}^3v\,\frac{f(\mathbf{v},t)}{v}}$$

"generalized" halo function

$$\tilde{\eta}(v_{\rm min},t) \simeq \tilde{\eta}^0(v_{\rm min}) + \tilde{\eta}^1(v_{\rm min})\cos[\omega(t-t_0)]$$

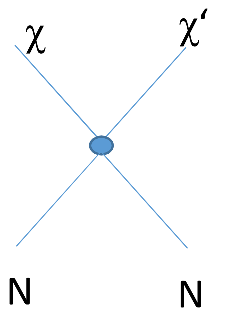
N.B. : only halo dependence factorized. Results depend on assumptions on other quantities such as quenching factors, L_{eff}, Q_y etc.

Inelastic Dark Matter

D. Tucker-Smith and N.Weiner, Phys.Rev.D 64, 043502 (2001), hep-ph/0101138

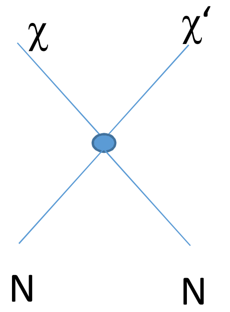
Two mass eigenstates χ and χ' very close in mass: $m_{\chi}-m_{\chi'} \equiv \delta$ with χ +N→ χ +N forbidden

"Endothermic "scattering ($\delta>0$)



Kinetic energy needed to "overcome" step → rate no longer exponentially decaying with energy, maximum at finite energy E_*

"Exothermic" scattering ($\delta<0$)

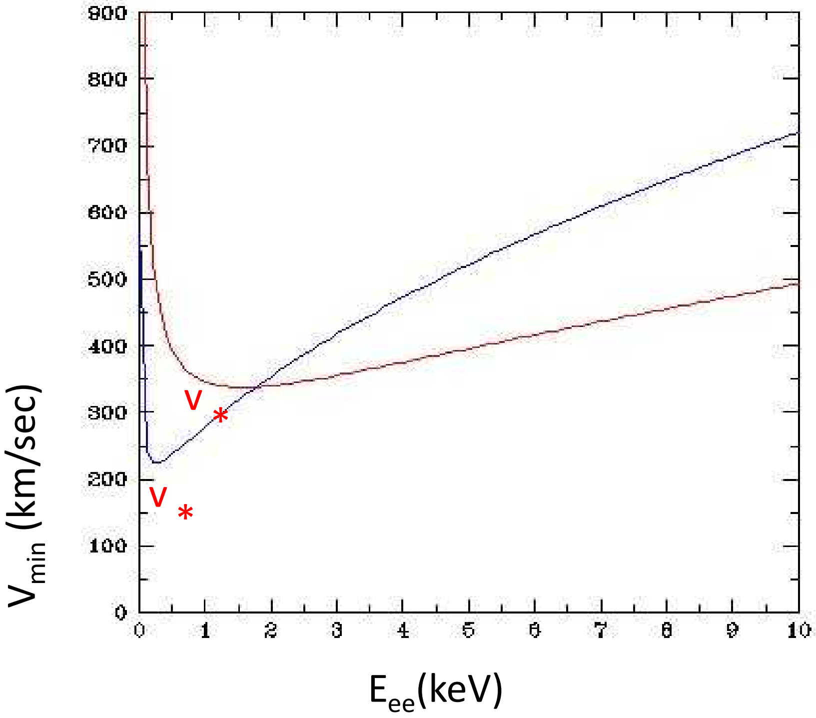


χ is metastable, δ energy deposited independently on initial kinetic energy (even for WIMPs at rest)

Can easily generalize the analysis **to inelastic scattering** (the response functions do not change, only the mapping between recoil energy and WIMP speed)

For inelastic DM the recoil energy E_R is no longer monotonically growing with v_{min} , WIMPs need at least the speed $\min(v_{min})=v_*$ to produce upscattering to heavy state

$$v_{min} = \frac{1}{\sqrt{2m_N E_R}}\left(\frac{m_N E_R}{\mu}+\delta\right) = a\sqrt{E_r} + \frac{b}{\sqrt{E_R}}$$

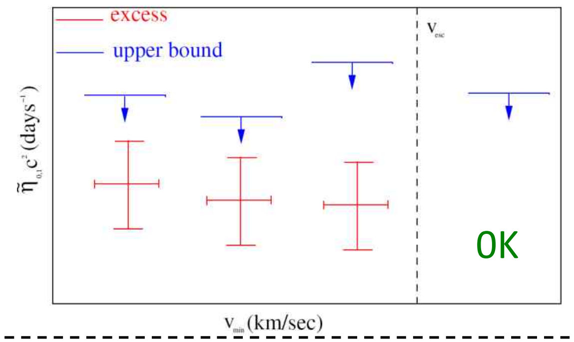


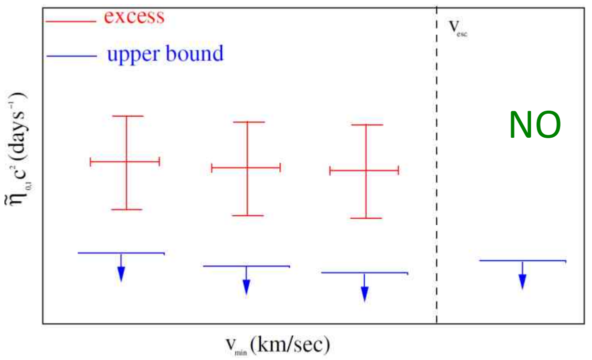
N.B. for $\delta>0$ WIMPs need a minimal absolute incoming speed v_* to upscatter to the heavier state → vanishing rate if $v_* > v_{esc}$ (escape velocity)

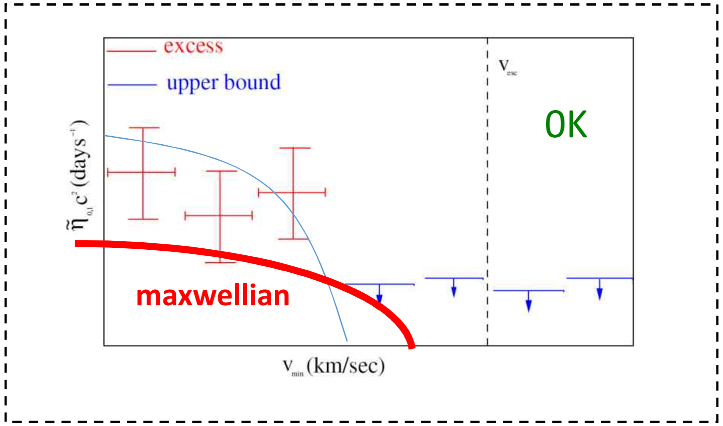
comparison among different experiments for Inelastic DM

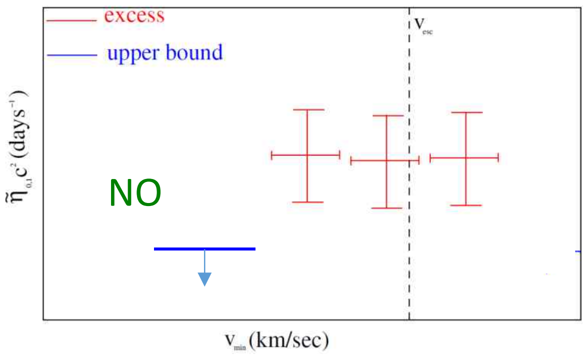
if conflicting experimental results can be mapped into non-overlapping ranges of v_{min} and if the v_{min} range of the constraint is at higher values compared to the excess (while that of the signal remains below v_{esc}) the tension between the two results can be eliminated by an appropriate choice of the $\eta_{0,1}$ functions (**only requirements**: η_0 must be a decreasing function of v_{min} and $\eta_1 \leq \eta_0$)

Four cases:









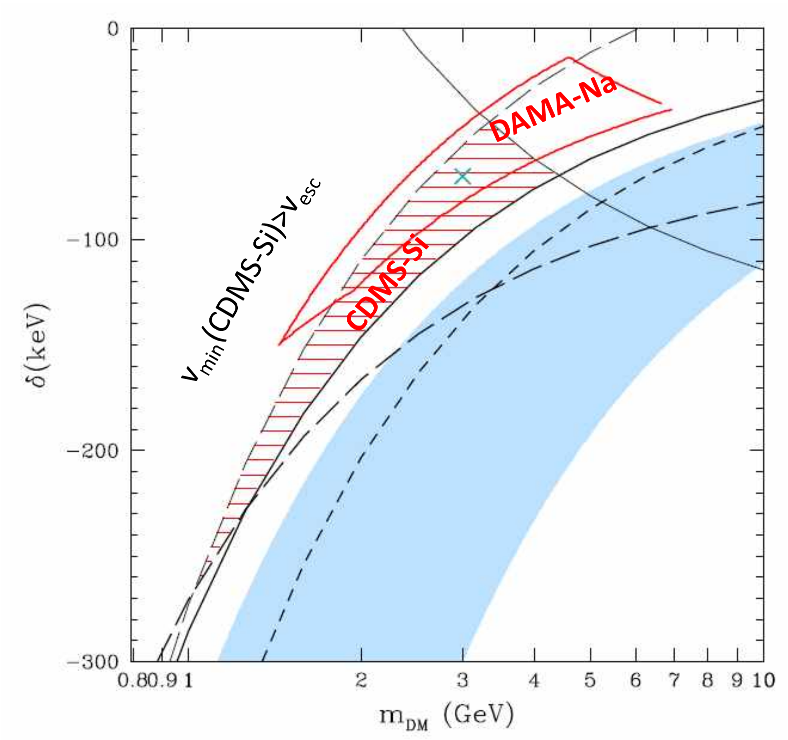
N.B: the effect of inelastic scattering ($\delta \neq 0$) only implies a “horizontal shift” of η estimations (up to negligible effects) → pick appropriate m_{DM} , δ combination to shift-away the bounds without shifting away the signal!

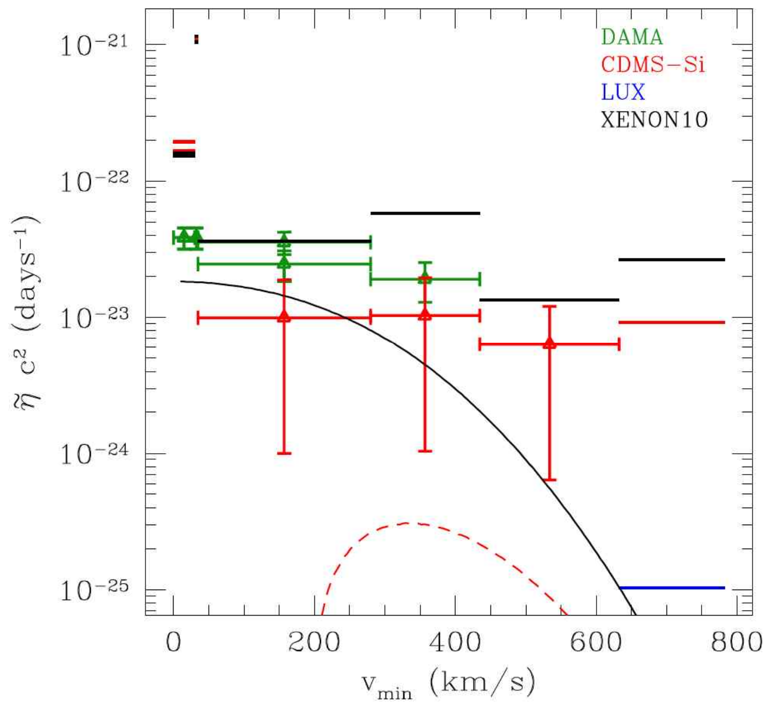
S. Scopel and K.H. Yoon, JCAP1408, 060 (2014)

Halo-independent analysis of inelastic Dark Matter

Kinematic conditions for v_{min}(bounds)>v_{min}(signals) and v_{min}(signals)<v_{esc}

"exothermic Ge-phobic scenario"





N.B. only kinematics involved (valid for different scaling laws)
At higher masses <u>upper bound</u> of ROI is constraining
In LUX, XENON100→XENON100 more constraining than LUX due to <u>lower</u> light yield

S. Scopel and K.H. Yoon, JCAP1408, 060 (2014)

One of the most popular scenarios for WIMP-nucleus scattering is a spin-dependent interaction where the WIMP particle is a χ fermion (either Dirac or Majorana) that recoils through its coupling to the spin of nucleons N=p,n:

$$\mathcal{L}_{int} \propto \vec{S}_\chi \cdot \vec{S}_N = c^p \vec{S}_\chi \cdot \vec{S}_p + c^n \vec{S}_\chi \cdot \vec{S}_n$$

(for instance, predicted by supersymmetry when the WIMP is a neutralino that couples to quarks via Z-boson or squark exchange)

A few facts of life:

Nuclear spin is mostly carried by odd-numbered nucleons. Even-even isotopes carry no spin.

- the DAMA effect is measured with Sodium Iodide. Both Na and I have spin **carried by an unpaired proton**

Isotope	Spin	Z (# of protons)	A-Z (# of neutrons)	Abundance
^{23}Na	3/2	11	12	100 %
^{127}I	5/2	53	74	100 %

Germanium experiments carry only a very small amount of ^{73}Ge, the only isotope with spin, **carried by an unpaired neutron**

Isotope	Spin	Z (# of protons)	A-Z (# of neutrons)	Abundance
^{73}Ge	9/2	32	41	7.7 %

Xenon experiment contain two isotopes with spin, **both carried mostly by an unpaired neutron**

Isotope	Spin	Z (# of protons)	A-Z (# of neutrons)	Abundance
^{129}Xe	½	54	75	26%
^{131}Xe	3/2	54	77	21%

→consider the possibility that $c_n << c_p$: in this case the WIMP particle is seen by DAMA but does not scatter on xenon and germanium detectors

However another class of Dark Matter experiments (superheated droplet detector and bubble chambers) **all use nuclear targets with an unpaired proton**:

Experiment	Target	Type	Energy thresholds (keV)	Exposition (kg day)
SIMPLE	$C_2Cl\ F_5$	superheated droplets	7.8	6.71
COUPP	$C\ F_3\ I$	bubble chamber	7.8, 11, 15.5	55.8, 70, 311.7
PICASSO	$C_3\ F_8$	bubble chamber	1.7, 2.9, 4.1, 5.8, 6.9, 16.3, 39, 55	114
PICO-2L	$C_3\ F_8$	bubble chamber	3.2, 4.4, 6.1, 8.1	74.8, 16.8, 82.2, 37.8

Isotope	Spin	Z (# of protons)	A-Z (# of neutrons)	Abundance
^{19}F	1/2	9	10	100
^{35}Cl	3/2	17	18	75.77 %
^{37}Cl	3/2	17	20	24.23 %
^{127}I	5/2	53	74	100

These experiments are sensitive to c_p , so for $c_n \ll c_p$ spin-dependent scatterings on Fluorine have been shown to lead to tension with the DAMA (C. Amole et al., (PICO Coll.) PLB711, 153(2012), E. Del Nobile, G.B. Gelmini, A. Georgescu and J.H. Huh, 1502.07682)

N.B. All only sensitive to the energy threshold, which for bubble and droplets nucleation is controlled by the pressure of the liquid

Effective theory for WIMP-nucleus scattering

Effective Hamiltonian for WIMP-nucleon (proton,neutron) interaction

$$\mathcal{H} = \sum_{\tau=0,1} \sum_{j=1}^{N} c_j^\tau \mathcal{O}_j t^\tau$$

Isospin projection (WIMP-proton and WIMP neutron coupling in principle different)

Symmetry of the problem: Galilean boost. All the operators out of the 4 vectors of the problem

$i\frac{\vec{q}}{m_N}, \quad \vec{v}^\perp, \quad \vec{S}_\chi, \quad \vec{S}_N$ (momentum transfer+WIMP velocity+ nucleon and WIMP spins)

Spin 0: 4 operators ; **Spin ½:** 14 operators A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers and Y. Xu, JCAP 1302 (2013) 004, [1203.3542]; N. Anand, A. L. Fitzpatrick and W. C. Haxton, Phys. Rev. C89 (2014) 065501, [1308.6288].

Some operators for spin 1: 8 operators J. B. Dent, L. M. Krauss, J. L. Newstead and S. Sabharwal, Phys. Rev. D92 (2015) 063515, [1505.03117]; R. Catena, K. Fridell and M. B. Krauss, JHEP 08 (2019) 030, [1907.02910].

$\mathcal{O}_1$	1
$\mathcal{O}_2$	$(\vec{v}^+_{\chi N})^2$
$\mathcal{O}_3$	$-i\vec{S}_N \cdot (\vec{\tilde{q}} \times \vec{v}^+_{\chi N})$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$
$\mathcal{O}_5$	$-i\vec{S}_\chi \cdot (\vec{\tilde{q}} \times \vec{v}^+_{\chi N})$
$\mathcal{O}_6$	$(\vec{S}_\chi \cdot \vec{\tilde{q}})(\vec{S}_N \cdot \vec{\tilde{q}})$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^+_{\chi N}$
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^+_{\chi N}$
$\mathcal{O}_9$	$-i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{\tilde{q}})$
$\mathcal{O}_{10}$	$-i\vec{S}_N \cdot \vec{\tilde{q}}$
$\mathcal{O}_{11}$	$-i\vec{S}_\chi \cdot \vec{\tilde{q}}$
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^+_{\chi N})$
$\mathcal{O}_{13}$	$\mathcal{O}_{10}\mathcal{O}_8$
$\mathcal{O}_{14}$	$\mathcal{O}_{11}\mathcal{O}_7$
$\mathcal{O}_{15}$	$-\mathcal{O}_{11}\mathcal{O}_3$
$\mathcal{O}_{16}$	$-\mathcal{O}_{10}\mathcal{O}_5$
$\mathcal{O}_{17}$	$-i\vec{\tilde{q}} \cdot \mathcal{S} \cdot \vec{v}^+_{\chi N}$
$\mathcal{O}_{18}$	$-i\vec{\tilde{q}} \cdot \mathcal{S} \cdot \vec{S}_N$
$\mathcal{O}_{19}$	$\vec{\tilde{q}} \cdot \mathcal{S} \cdot \vec{\tilde{q}}$
$\mathcal{O}_{20}$	$\left(\vec{S}_N \times \vec{\tilde{q}}\right) \cdot \mathcal{S} \cdot \vec{\tilde{q}}$
$\mathcal{O}_{21}$	$\vec{v}^+_{\chi N} \cdot \mathcal{S} \cdot \vec{S}_N$
$\mathcal{O}_{22}$	$\left(-i\vec{\tilde{q}} \times \vec{v}^+_{\chi N}\right) \cdot \mathcal{S} \cdot \vec{S}_N$
$\mathcal{O}_{23}$	$-i\vec{\tilde{q}} \cdot \mathcal{S} \cdot \left(\vec{S}_N \times \vec{v}^+_{\chi N}\right)$
$\mathcal{O}_{24}$	$-\vec{v}^+_{\chi N} \cdot \mathcal{S} \cdot \left(\vec{S}_N \times i\vec{\tilde{q}}\right)$

The rate depends on six distinct nuclear response functions, defined as:

Standard notation:
A=transverse magnetic
A’=transverse electric
A’’=longitudinal

$$M_{JM}(q\vec{x})$$

$$\Delta_{JM}(q\vec{x}) \equiv \vec{M}^M_{JJ}(q\vec{x})\cdot\frac{1}{q}\vec{\nabla}$$

$$\Sigma'_{JM}(q\vec{x}) \equiv -i\left\{\frac{1}{q}\vec{\nabla}\times\vec{M}^M_{JJ}(q\vec{x})\right\}\cdot\vec{\sigma} = [J]^{-1}\left\{-\sqrt{J}\;\vec{M}^M_{JJ+1}(q\vec{x})+\sqrt{J+1}\;\vec{M}^M_{JJ-1}(q\vec{x})\right\}\cdot\vec{\sigma}$$

$$\Sigma''_{JM}(q\vec{x}) \equiv \left\{\frac{1}{q}\vec{\nabla}M_{JM}(q\vec{x})\right\}\cdot\vec{\sigma} = [J]^{-1}\left\{\sqrt{J+1}\;\vec{M}^M_{JJ+1}(q\vec{x})+\sqrt{J}\;\vec{M}^M_{JJ-1}(q\vec{x})\right\}\cdot\vec{\sigma}$$

$$\tilde{\Phi}'_{JM}(q\vec{x}) \equiv \left(\frac{1}{q}\vec{\nabla}\times\vec{M}^M_{JJ}(q\vec{x})\right)\cdot\left(\vec{\sigma}\times\frac{1}{q}\vec{\nabla}\right)+\frac{1}{2}\vec{M}^M_{JJ}(q\vec{x})\cdot\vec{\sigma}$$

$$\Phi''_{JM}(q\vec{x}) \equiv i\left(\frac{1}{q}\vec{\nabla}M_{JM}(q\vec{x})\right)\cdot\left(\vec{\sigma}\times\frac{1}{q}\vec{\nabla}\right)$$

with $M_{JM} = j_J Y_{JM}$ Bessel spherical harmonics and $\vec{M}^M_{JL} = j_J \vec{Y}_{JM}$ vector spherical harmonics.

- **M**= vector-charge (scalar, **usual spin-independent part**, non-vanishing for all nuclei)
- **Φ’’**=vector-longitudinal, related to spin-orpit coupling σ·l (also spin-independent, non-vanishing for all nuclei)
- **Σ’** and **Σ”** = associated to longitudinal and transverse components of nuclear spin, **their sum is the usual spin-dependent interaction**, require nuclear spin j>0
- **Δ**=associated to the orbital angular momentum operator l, also requires j>0
- **$\tilde{\Phi}$’**= related to a vector-longitudinal operator that transforms as a tensor under rotations, requires j>1/2

A.L.Fitzpatrick, W.Haxton, E.Katz, N.Lubbers and Y.Xu, JCAP1302, 004 (2013),1203.3542;
N.Anand, A.L.Fitzpatrick and W.C.Haxton, Phys.Rev.C89, 065501 (2014),1308.6288.

Correspondence between each coupling and nuclear response functions

coupling	$R_{0k}^{\tau\tau'}$	$R_{1k}^{\tau\tau'}$	coupling	$R_{0k}^{\tau\tau'}$	$R_{1k}^{\tau\tau'}$
1	$M(q^0)$	-	3	$\Phi''(q^4)$	$\Sigma'(q^2)$
4	$\Sigma''(q^0)$,$\Sigma'(q^0)$	-	5	$\Delta(q^4)$	$M(q^2)$
6	$\Sigma''(q^4)$	-	7	-	$\Sigma'(q^0)$
8	$\Delta(q^2)$	$M(q^0)$	9	$\Sigma'(q^2)$	-
10	$\Sigma''(q^2)$	-	11	$M(q^2)$	-
12	$\Phi''(q^2)$,$\tilde{\Phi}'(q^2)$	$\Sigma''(q^0)$,$\Sigma'(q^0)$	13	$\tilde{\Phi}'(q^4)$	$\Sigma''(q^2)$
14	-	$\Sigma'(q^2)$	15	$\Phi''(q^6)$	$\Sigma'(q^4)$

$$R_k^{\tau\tau'} = R_{0k}^{\tau\tau'} + R_{1k}^{\tau\tau'} \frac{(v_T^{\perp})^2}{c^2} = \underset{\substack{\big\uparrow \\ \text{velocity-independent part}}}{R_{0k}^{\tau\tau'}} + \underset{\substack{\big\uparrow \\ \text{velocity-dependent part}}}{R_{1k}^{\tau\tau'}} \frac{v_T^2 - v_{min}^2}{c^2}$$

N.B.: 9 out of 14 operators give vanishing contributions on nuclei with no spin

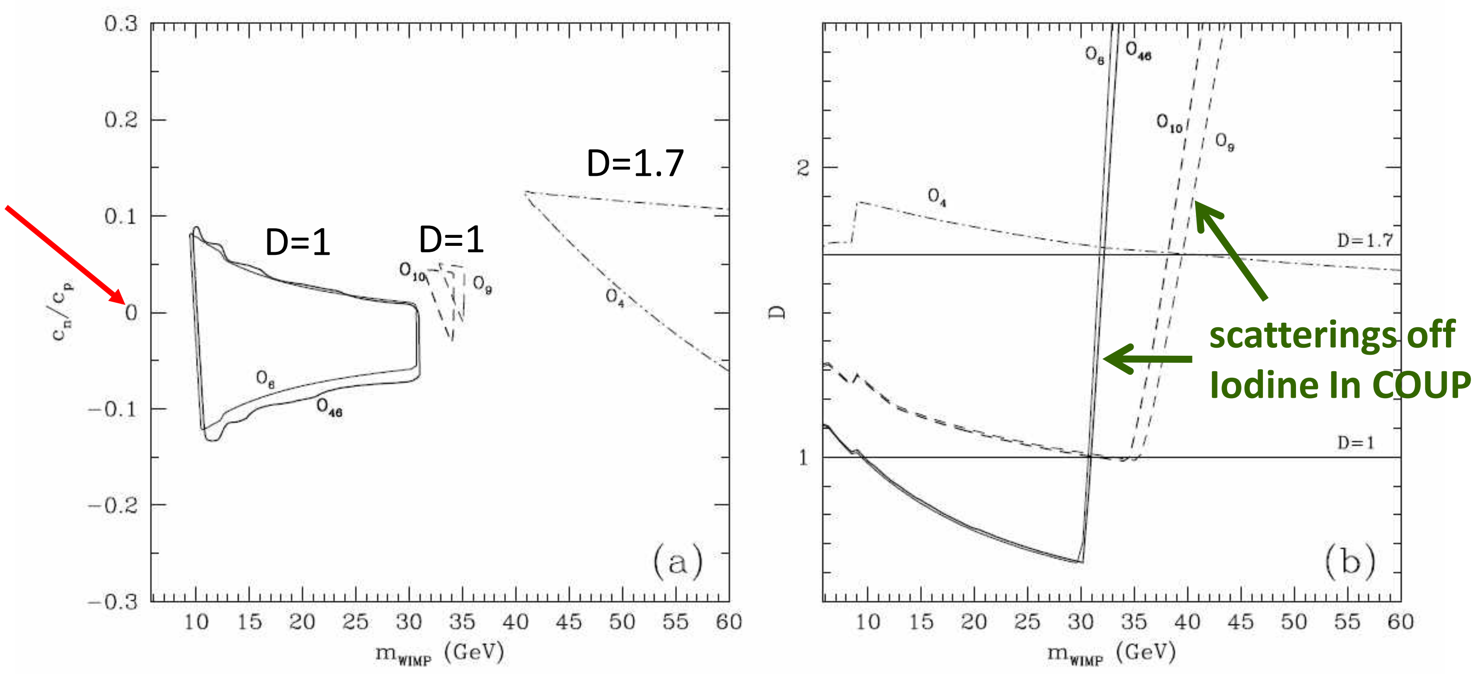
N.B2: $\tilde{\Phi}$’ response function requires a nuclear spin ≥1 (only ^{27}Al (100%), ^{73}Ge(7%), ^{131}Xe(20%), **^{127}I (100%)**)

Using non-relativistic EFT it is possible generalize the concept of spin-dependent interaction → single out the most general interaction terms leading to a scattering amplitude dominated by either $W_{\Sigma'}$ or $W_{\Sigma''}$

→ spin-dependent + momentum suppresson

Numerical results

S.Scopel, J.H.Yoon and K.Yoon, arXiv:1505.01926



“proton-philic”

scatterings off Iodine In COUPP

- If D<1 all constraints are verified
- Possible for O_6,O_{46} (q^4 momentum dependence) and to a lesser extent for O_9,O_{10} (q^2 momentum dependence), no compatibility for O_4 (usual spin-dependent interaction, no q dependence)
- as long as scatterings off Fluorine (and/or Chlorine) dominate in bubble chambers and droplets detectors momentum transfers q=sqrt($m_{nucleus}$ E) have a smaller values compared to Sodium , due to the lighter target mass and to the lower energy threshold of the former→ reduced sensitivity to DAMA for $(q^2)^n$, n=1,2
- for m_{WIMP}>30 GeV scatterings off Iodine in COUPP are kinematically accessible with much larger values of momentum transfer q →steep rise in compatibility factor when n=1,2

S.Scopel and K.Yoon, JCAP 1602(2016)050

Evading Fluorine constraints for a WIMP with spin-dependent coupling to protons: inelastic scattering (proton-philic Spin-dependent IDM, pSIDM)

$$v_{\rm min} = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu_{\chi N}} + \delta \right|$$

$v_{\rm min} > v^*_{\rm min}$

$$v^*_{\rm min} = \sqrt{\frac{2\delta}{\mu_{\chi N}}}$$

$A_{\rm sodium}=23$ $A_{\rm Fluorine}=19$

$m_{\rm Sodium} > m_{\rm Fluorine} \rightarrow \mu_{\chi N}^{\rm Sodium} > \mu_{\chi N}^{\rm Sodium}$

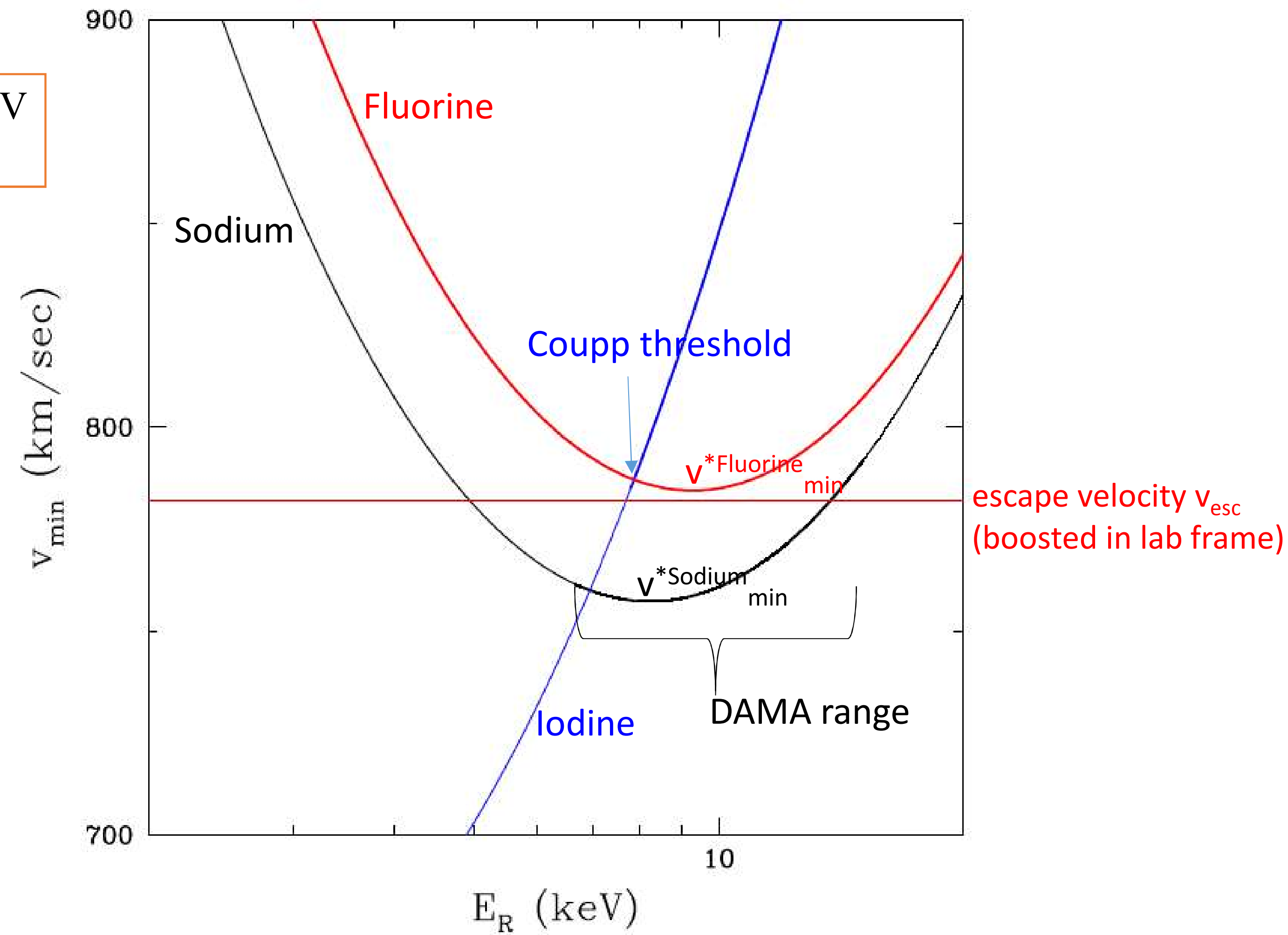
$\rightarrow v^{*\rm Sodium}_{\rm min} < v^{*\rm Fluorine}_{\rm min}$

what if $v^{*\rm Sodium}_{\rm min} < v_{\rm esc} < v^{*\rm Fluorine}_{\rm min}$?

(N.B. $v_{\rm esc}$ in lab frame)

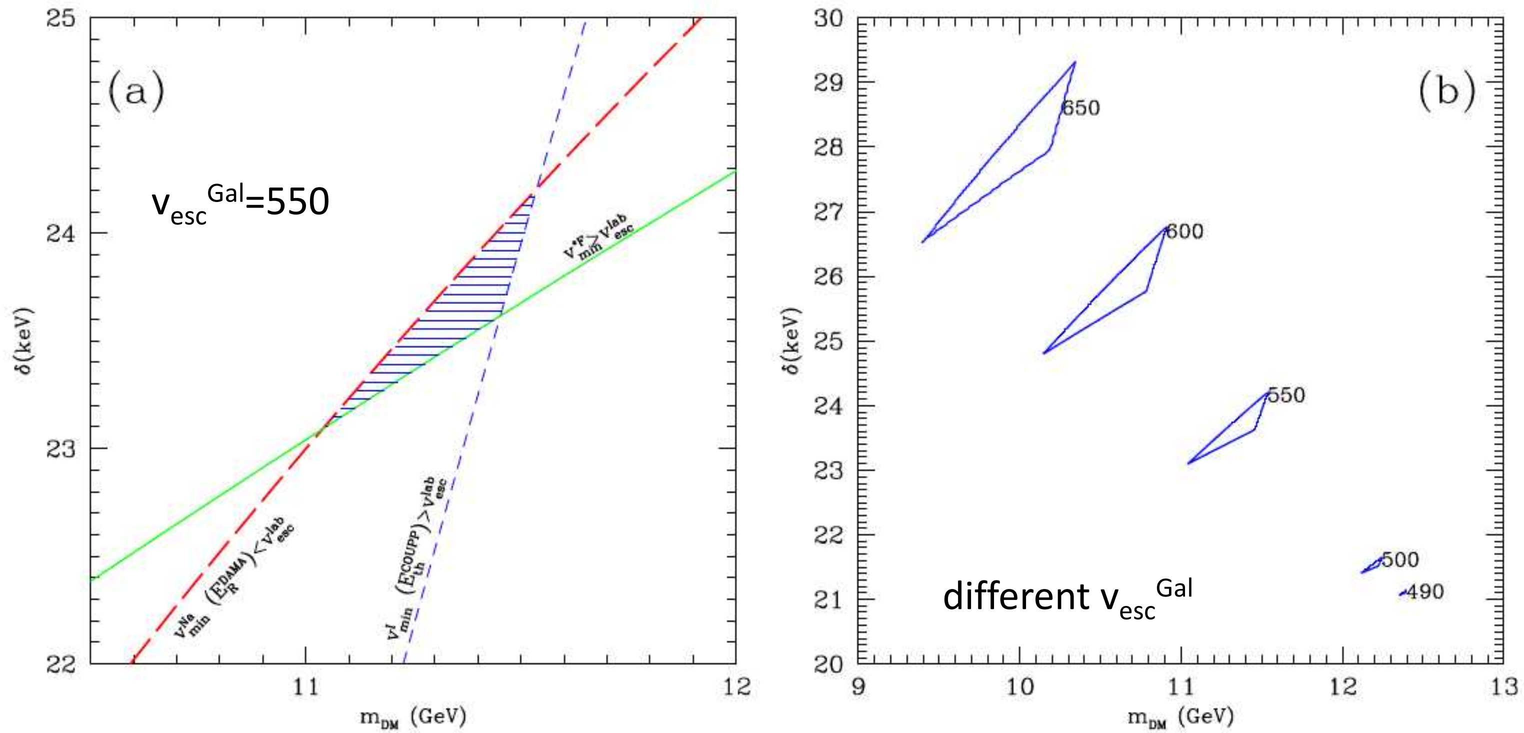
S.Scopel and K.Yoon, JCAP 1602(2016)050

$m_\chi = 11.4$ GeV
δ=23.7 keV



depending on m_χ and δ, can drive Fluorine (and Iodine in COUPP) beyond v_{esc} while Sodium remains below → no constraint on DAMA from droplet detectors and bubble chambers

S.Scopel and K.Yoon, JCAP 1602(2016)050

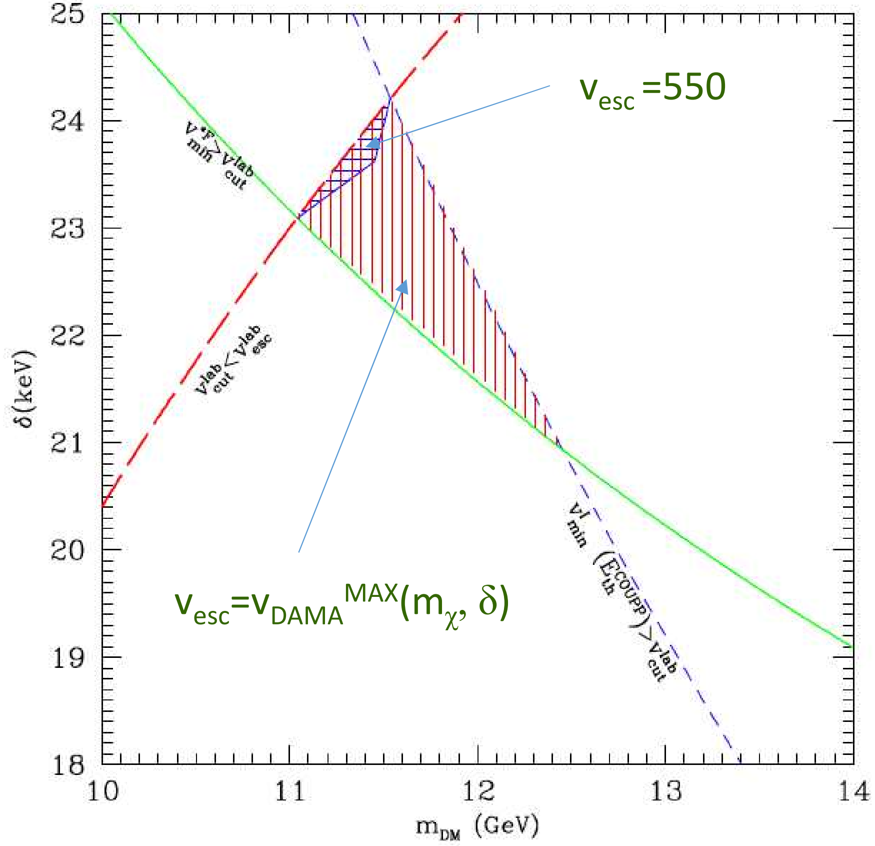


v_{esc}^{Gal}=550

different v_{esc}^{Gal}

S.Scopel and K.Yoon, JCAP 1602(2016)050

taking $v_{esc}=v_{DAMA}^{MAX}(m_{\chi}, \delta)$ the kinematic region enlarges considerably

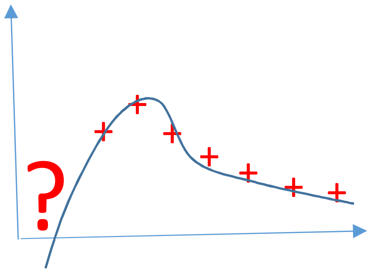


$v_{esc}=550$

$v_{esc}=v_{DAMA}^{MAX}(m_{\chi}, \delta)$

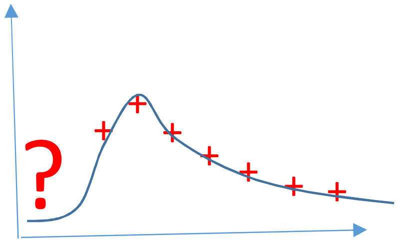
(from abstract of JCAP 02 (2016) 050)

case of a 100 % modulated fraction. Moreover the same scenario provides an explanation of the maximum in the energy spectrum of the modulation amplitude detected by DAMA in terms of WIMPs whose minimal incoming speed matches the kinematic threshold for inelastic upscatters. For the elastic case the detection of such maximum suggests an inversion of the modulation phase below the present DAMA energy threshold, while this is not expected for inelastic scattering. This may allow to discriminate between the two scenarios in a future low-threshold analysis of the DAMA data.



+ DAMA-phase1
– elastic scattering

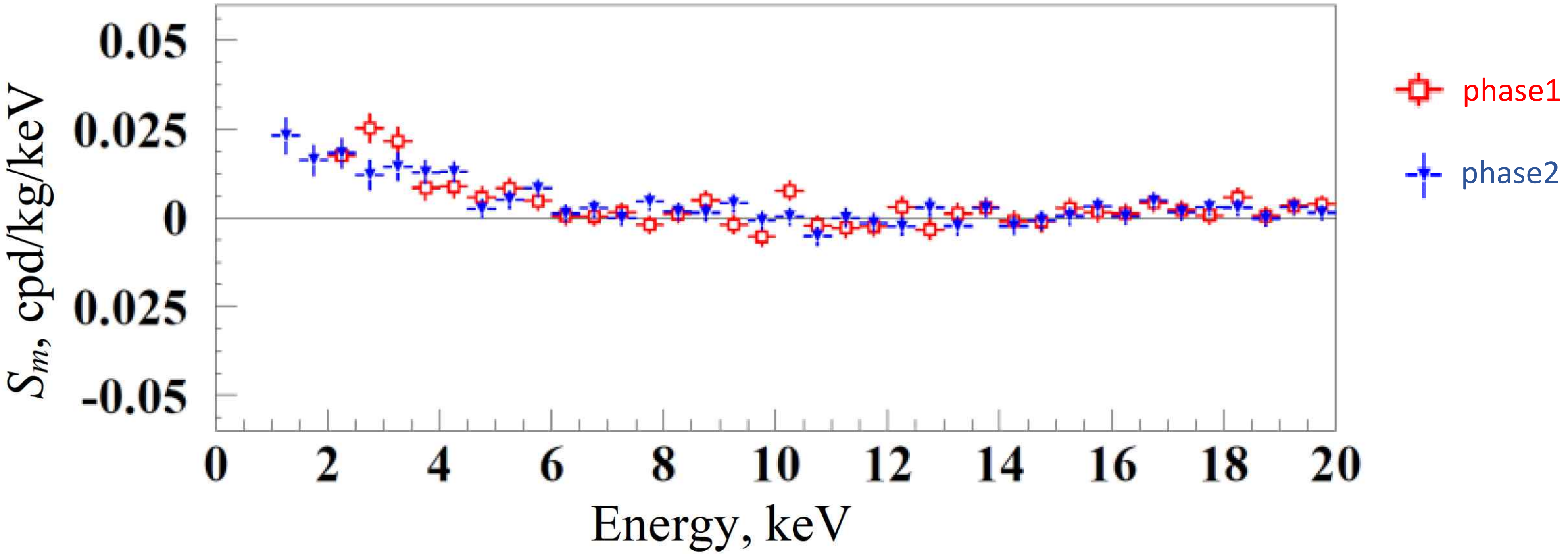
(phase inversion)



+ DAMA-phase1
– inelastic scattering

(no phase inversion)

DAMA-NaI+DAMA/Libra-phase1 vs. DAMA/Libra-phase2



Compared to DAMA/Libra-phase1:

- The peak at ~3 keV disappeared
- For energy < 2 keV the rate depends also on scattering events off Iodine

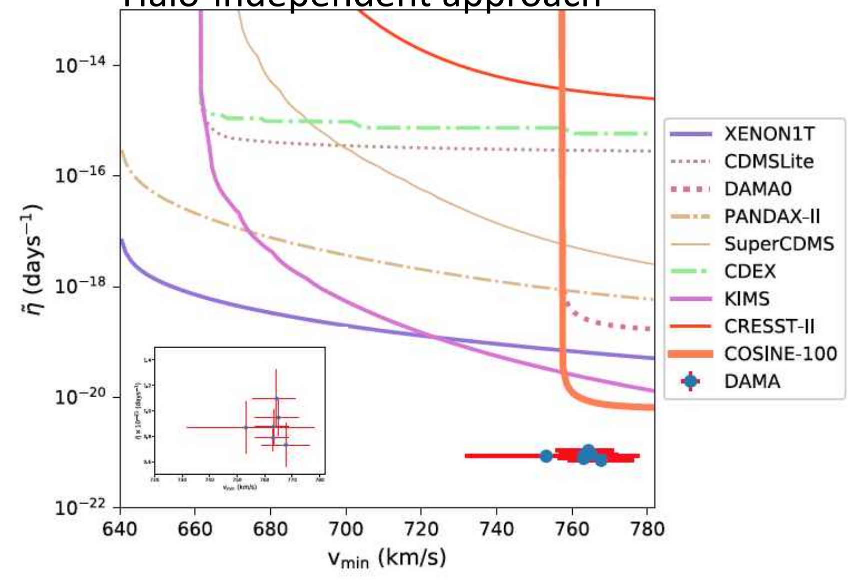
→ harder fit to pSIDM

Proton-philic Spin-dependent Inelastic Dark Matter (PSIDM) and DAMA-Libra phase2:

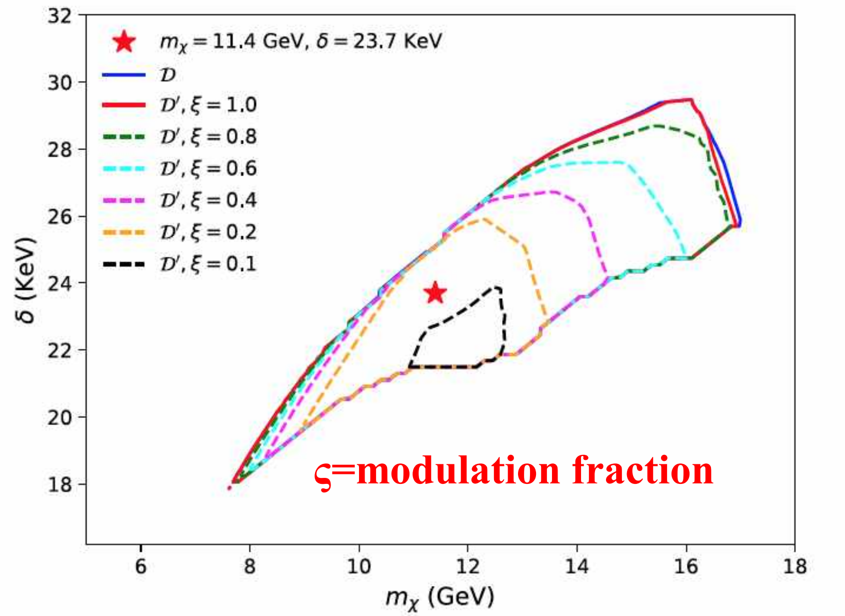
Spin-dependent coupling to protons+ inelasticity non-standard velocity distribution

Halo function

Halo-independent approach



Mass splitting



ς=modulation fraction

- **Still viable before COSINE, ANAIS** for 18 keV < δ < 29 keV, 8 GeV< m_χ< 17 GeV if velocity distribution departed from a Maxwellian
- Xenon and Germanium bounds evaded because of the small coupling to neutrons
- Escape velocity and δ tuned to forbid upscattering events off fluorine in PICO, COUPP and allow those off sodium in DAMA
- However already at the time lower threshold in DAMA-Libra phase2 made compatibility harder to achieve (**Standard Halo Model solution was no longer possible → velocity distribution needed to departs from a Maxwellian**)

S. Kang, S. Scopel, G. Tomar and J.H. Yoon, Phys. Rev. D99 (2019) 023017

Extension of NREFT operator base to WIMP arbitrary spin **P. Gondolo, Sunghyun Kang, S. S. and G. Tomar, Phys.Rev. D104, 063017(2021)**

- suitable to match *any* high-energy model of particle dark matter, including elementary particles or composite states of any spin in 1-particle approximation
- If the WIMP scattering rate is dominated by a higher rank operator non–standard phenomenological consequences → pattern of peaks at high nuclear recoil energies

For Jχ=0 4 operators. For Jχ >0 add 10 new operators each time the spin of the WIMP is increased by ½
The operators are expressed in terms the 5 fundamental nuclear currents that arise up to linear terms in v:

$$\widehat{O}_M = 1, \quad \widehat{\vec{O}}_\Sigma = \vec{\sigma}_N, \quad \widehat{\vec{O}}_\Delta = \widehat{\vec{v}}^{\,+}_N, \quad \widehat{\vec{O}}_\Phi = \widehat{\vec{v}}^{\,+}_N \times \vec{\sigma}_N, \quad \widehat{O}_\Omega = \widehat{\vec{v}}^{\,+}_N \cdot \vec{\sigma}_N$$

➡ $O_{X,s,l}$

- X=M, Ω, Σ, Δ, Φ
- s≤2Jχ : # of powers of WIMP spin (s=0,1,2,..., 2Jχ)
- l=number of powers of q

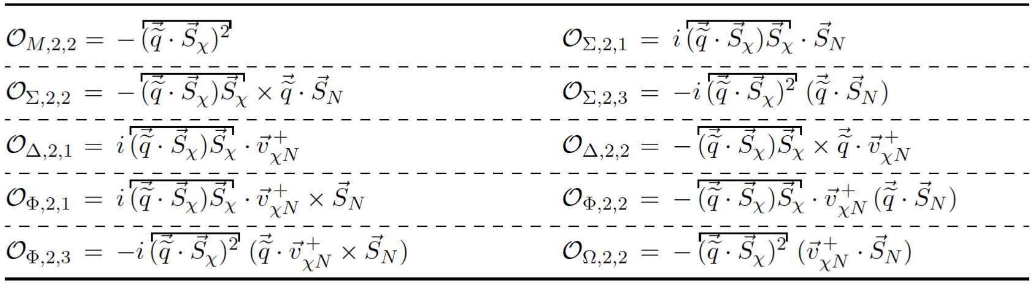
Explicitly: $O_{M,s,s}$ $O_{\Omega,s,s}$ $O_{\Sigma,s,s-1}$ $O_{\Sigma,s,s}$ $O_{\Sigma,s,s+1}$ $O_{\Delta,s,s-1}$ $O_{\Delta,s,s}$ $O_{\Phi,s,s-1}$ $O_{\Phi,s,s}$ $O_{\Phi,s,s+1}$

- Spin 0: 4 operators
- Spin ½: 4+10 = 14 operators
- Spin 1: 4+10+10=24 operators
- etc

$4+20j_\chi$ operators for a WIMP with spin j_χ

Operators for spin $j_\chi \leq 2$ explicitly written in vectorial form:

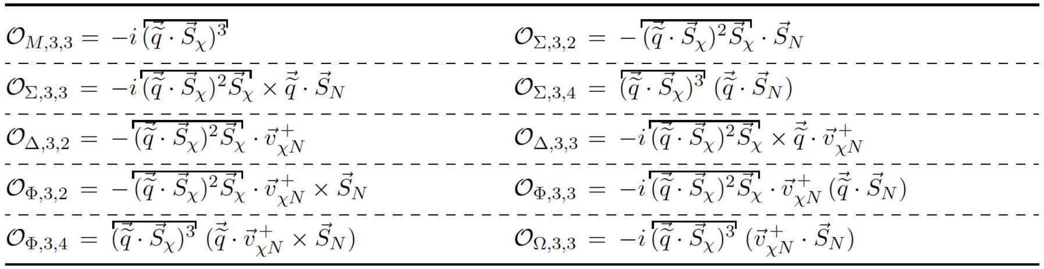
spin≥ 1



$\mathcal{O}_{M,2,2} = -\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2}$	$\mathcal{O}_{\Sigma,2,1} = i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)\vec{S}_\chi} \cdot \vec{S}_N$
$\mathcal{O}_{\Sigma,2,2} = -\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)\vec{S}_\chi} \times \vec{\tilde{q}} \cdot \vec{S}_N$	$\mathcal{O}_{\Sigma,2,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2}\,(\vec{\tilde{q}} \cdot \vec{S}_N)$
$\mathcal{O}_{\Delta,2,1} = i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)\vec{S}_\chi} \cdot \vec{v}^{+}_{\chi N}$	$\mathcal{O}_{\Delta,2,2} = -\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)\vec{S}_\chi} \times \vec{\tilde{q}} \cdot \vec{v}^{+}_{\chi N}$
$\mathcal{O}_{\Phi,2,1} = i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)\vec{S}_\chi} \cdot \vec{v}^{+}_{\chi N} \times \vec{S}_N$	$\mathcal{O}_{\Phi,2,2} = -\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)\vec{S}_\chi} \cdot \vec{v}^{+}_{\chi N}\,(\vec{\tilde{q}} \cdot \vec{S}_N)$
$\mathcal{O}_{\Phi,2,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2}\,(\vec{\tilde{q}} \cdot \vec{v}^{+}_{\chi N} \times \vec{S}_N)$	$\mathcal{O}_{\Omega,2,2} = -\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2}\,(\vec{v}^{+}_{\chi N} \cdot \vec{S}_N)$

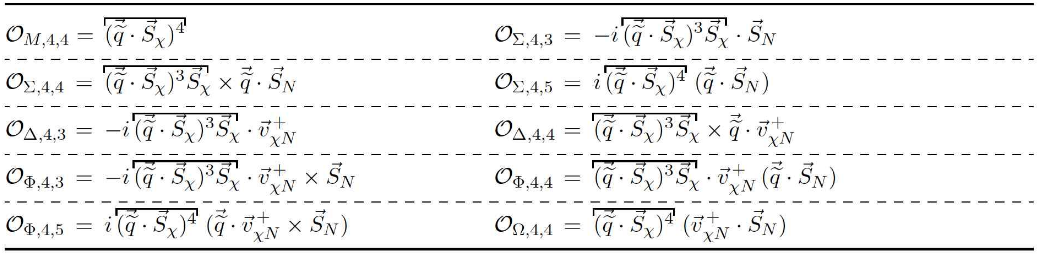
($\overline{S_{i_1} \cdots S_{i_s}}$ =irreducible tensors under rotation)

spin≥ 3/2



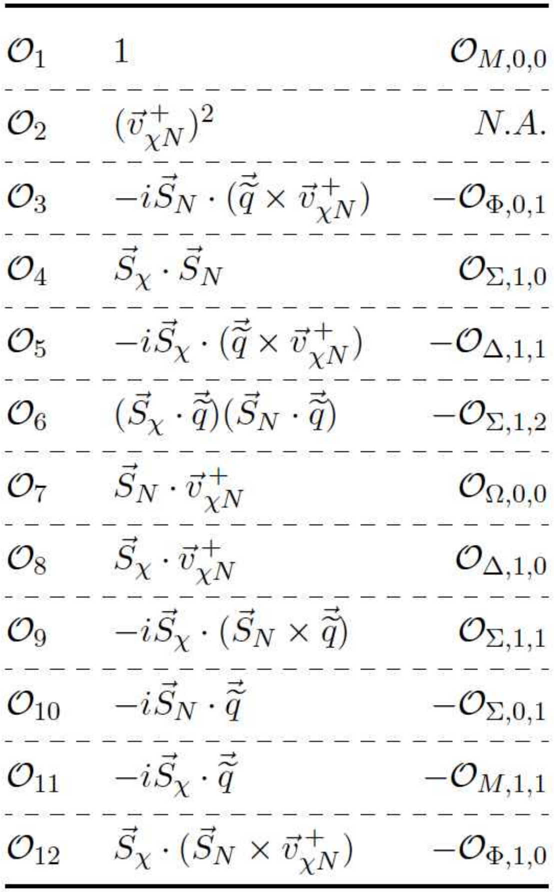
$\mathcal{O}_{M,3,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3}$	$\mathcal{O}_{\Sigma,3,2} = -\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2\vec{S}_\chi} \cdot \vec{S}_N$
$\mathcal{O}_{\Sigma,3,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2\vec{S}_\chi} \times \vec{\tilde{q}} \cdot \vec{S}_N$	$\mathcal{O}_{\Sigma,3,4} = \overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3}\,(\vec{\tilde{q}} \cdot \vec{S}_N)$
$\mathcal{O}_{\Delta,3,2} = -\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2\vec{S}_\chi} \cdot \vec{v}^{+}_{\chi N}$	$\mathcal{O}_{\Delta,3,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2\vec{S}_\chi} \times \vec{\tilde{q}} \cdot \vec{v}^{+}_{\chi N}$
$\mathcal{O}_{\Phi,3,2} = -\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2\vec{S}_\chi} \cdot \vec{v}^{+}_{\chi N} \times \vec{S}_N$	$\mathcal{O}_{\Phi,3,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^2\vec{S}_\chi} \cdot \vec{v}^{+}_{\chi N}\,(\vec{\tilde{q}} \cdot \vec{S}_N)$
$\mathcal{O}_{\Phi,3,4} = \overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3}\,(\vec{\tilde{q}} \cdot \vec{v}^{+}_{\chi N} \times \vec{S}_N)$	$\mathcal{O}_{\Omega,3,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3}\,(\vec{v}^{+}_{\chi N} \cdot \vec{S}_N)$

spin≥ 2

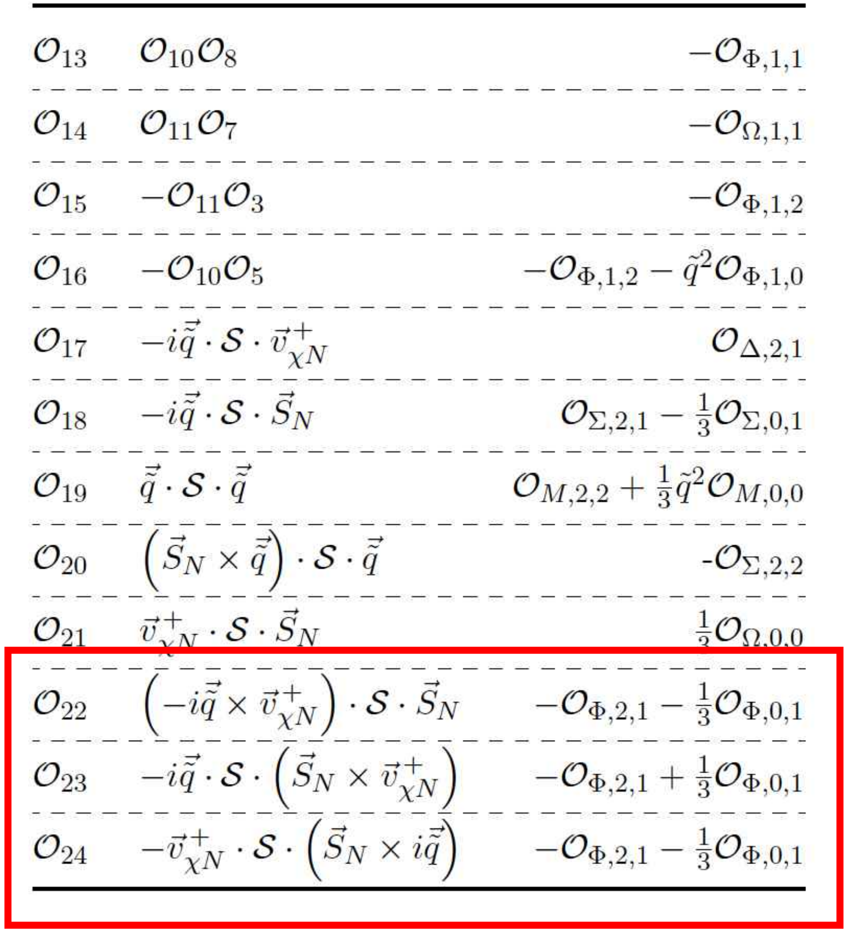


$\mathcal{O}_{M,4,4} = \overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^4}$	$\mathcal{O}_{\Sigma,4,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3\vec{S}_\chi} \cdot \vec{S}_N$
$\mathcal{O}_{\Sigma,4,4} = \overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3\vec{S}_\chi} \times \vec{\tilde{q}} \cdot \vec{S}_N$	$\mathcal{O}_{\Sigma,4,5} = i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^4}\,(\vec{\tilde{q}} \cdot \vec{S}_N)$
$\mathcal{O}_{\Delta,4,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3\vec{S}_\chi} \cdot \vec{v}^{+}_{\chi N}$	$\mathcal{O}_{\Delta,4,4} = \overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3\vec{S}_\chi} \times \vec{\tilde{q}} \cdot \vec{v}^{+}_{\chi N}$
$\mathcal{O}_{\Phi,4,3} = -i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3\vec{S}_\chi} \cdot \vec{v}^{+}_{\chi N} \times \vec{S}_N$	$\mathcal{O}_{\Phi,4,4} = \overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^3\vec{S}_\chi} \cdot \vec{v}^{+}_{\chi N}\,(\vec{\tilde{q}} \cdot \vec{S}_N)$
$\mathcal{O}_{\Phi,4,5} = i\,\overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^4}\,(\vec{\tilde{q}} \cdot \vec{v}^{+}_{\chi N} \times \vec{S}_N)$	$\mathcal{O}_{\Omega,4,4} = \overline{(\vec{\tilde{q}} \cdot \vec{S}_\chi)^4}\,(\vec{v}^{+}_{\chi N} \cdot \vec{S}_N)$

Dictionary between our operators and those already discussed in the literature:



$\mathcal{O}_1$	1	$\mathcal{O}_{M,0,0}$
$\mathcal{O}_2$	$(\vec{v}^{+}_{\chi N})^2$	$N.A.$
$\mathcal{O}_3$	$-i\vec{S}_N \cdot (\vec{\tilde{q}} \times \vec{v}^{+}_{\chi N})$	$-\mathcal{O}_{\Phi,0,1}$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_{\Sigma,1,0}$
$\mathcal{O}_5$	$-i\vec{S}_\chi \cdot (\vec{\tilde{q}} \times \vec{v}^{+}_{\chi N})$	$-\mathcal{O}_{\Delta,1,1}$
$\mathcal{O}_6$	$(\vec{S}_\chi \cdot \vec{\tilde{q}})(\vec{S}_N \cdot \vec{\tilde{q}})$	$-\mathcal{O}_{\Sigma,1,2}$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^{+}_{\chi N}$	$\mathcal{O}_{\Omega,0,0}$
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^{+}_{\chi N}$	$\mathcal{O}_{\Delta,1,0}$
$\mathcal{O}_9$	$-i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{\tilde{q}})$	$\mathcal{O}_{\Sigma,1,1}$
$\mathcal{O}_{10}$	$-i\vec{S}_N \cdot \vec{\tilde{q}}$	$-\mathcal{O}_{\Sigma,0,1}$
$\mathcal{O}_{11}$	$-i\vec{S}_\chi \cdot \vec{\tilde{q}}$	$-\mathcal{O}_{M,1,1}$
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^{+}_{\chi N})$	$-\mathcal{O}_{\Phi,1,0}$



$\mathcal{O}_{13}$	$\mathcal{O}_{10}\mathcal{O}_8$	$-\mathcal{O}_{\Phi,1,1}$
$\mathcal{O}_{14}$	$\mathcal{O}_{11}\mathcal{O}_7$	$-\mathcal{O}_{\Omega,1,1}$
$\mathcal{O}_{15}$	$-\mathcal{O}_{11}\mathcal{O}_3$	$-\mathcal{O}_{\Phi,1,2}$
$\mathcal{O}_{16}$	$-\mathcal{O}_{10}\mathcal{O}_5$	$-\mathcal{O}_{\Phi,1,2} - \tilde{q}^2\mathcal{O}_{\Phi,1,0}$
$\mathcal{O}_{17}$	$-i\vec{\tilde{q}} \cdot \mathcal{S} \cdot \vec{v}^{+}_{\chi N}$	$\mathcal{O}_{\Delta,2,1}$
$\mathcal{O}_{18}$	$-i\vec{\tilde{q}} \cdot \mathcal{S} \cdot \vec{S}_N$	$\mathcal{O}_{\Sigma,2,1} - \frac{1}{3}\mathcal{O}_{\Sigma,0,1}$
$\mathcal{O}_{19}$	$\vec{\tilde{q}} \cdot \mathcal{S} \cdot \vec{\tilde{q}}$	$\mathcal{O}_{M,2,2} + \frac{1}{3}\tilde{q}^2\mathcal{O}_{M,0,0}$
$\mathcal{O}_{20}$	$\left(\vec{S}_N \times \vec{\tilde{q}}\right) \cdot \mathcal{S} \cdot \vec{\tilde{q}}$	$-\mathcal{O}_{\Sigma,2,2}$
$\mathcal{O}_{21}$	$\vec{v}^{+}_{\chi N} \cdot \mathcal{S} \cdot \vec{S}_N$	$\frac{1}{2}\mathcal{O}_{\Omega,0,0}$
$\mathcal{O}_{22}$	$\left(-i\vec{\tilde{q}} \times \vec{v}^{+}_{\chi N}\right) \cdot \mathcal{S} \cdot \vec{S}_N$	$-\mathcal{O}_{\Phi,2,1} - \frac{1}{3}\mathcal{O}_{\Phi,0,1}$
$\mathcal{O}_{23}$	$-i\vec{\tilde{q}} \cdot \mathcal{S} \cdot \left(\vec{S}_N \times \vec{v}^{+}_{\chi N}\right)$	$-\mathcal{O}_{\Phi,2,1} + \frac{1}{3}\mathcal{O}_{\Phi,0,1}$
$\mathcal{O}_{24}$	$-\vec{v}^{+}_{\chi N} \cdot \mathcal{S} \cdot \left(\vec{S}_N \times i\vec{\tilde{q}}\right)$	$-\mathcal{O}_{\Phi,2,1} - \frac{1}{3}\mathcal{O}_{\Phi,0,1}$

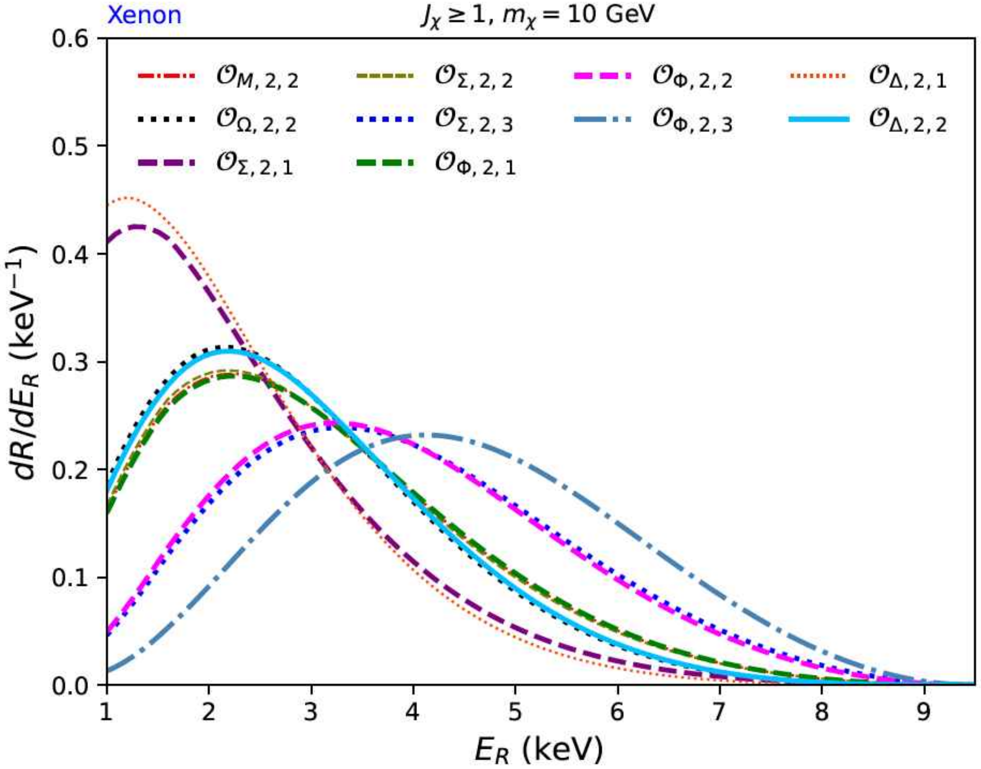
N.B. our approach shows that some of the operators appearing in the literature (see e.g. 1907.02910) are actually equivalent to the same operator, or they are linear combinations of other operators. Also 5 operators for spin 1 where missing:

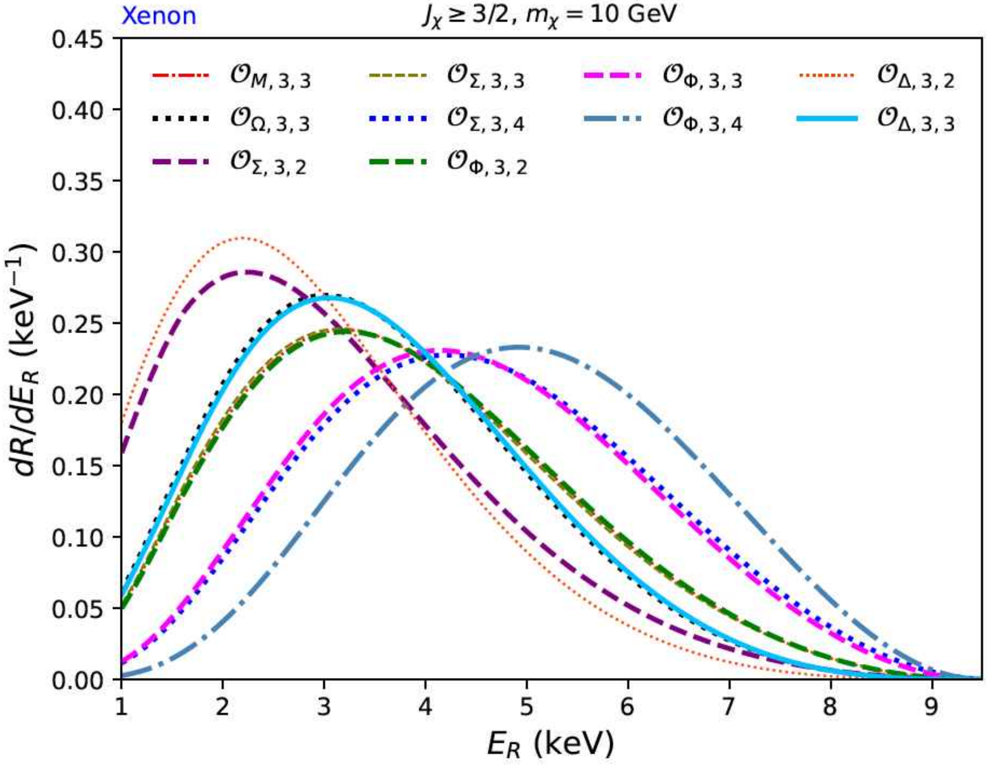
$$\mathcal{O}_{\Omega,2,2}, \quad \mathcal{O}_{\Sigma,2,3}, \quad \mathcal{O}_{\Delta,2,2}, \quad \mathcal{O}_{\Phi,2,2}, \quad \mathcal{O}_{\Phi,2,3}$$

P. Gondolo, Sunghyun Kang, S. S. and G. Tomar, Phys.Rev. D104, 063017(2021)

(standard halo model)

Main phenomenological consequence:





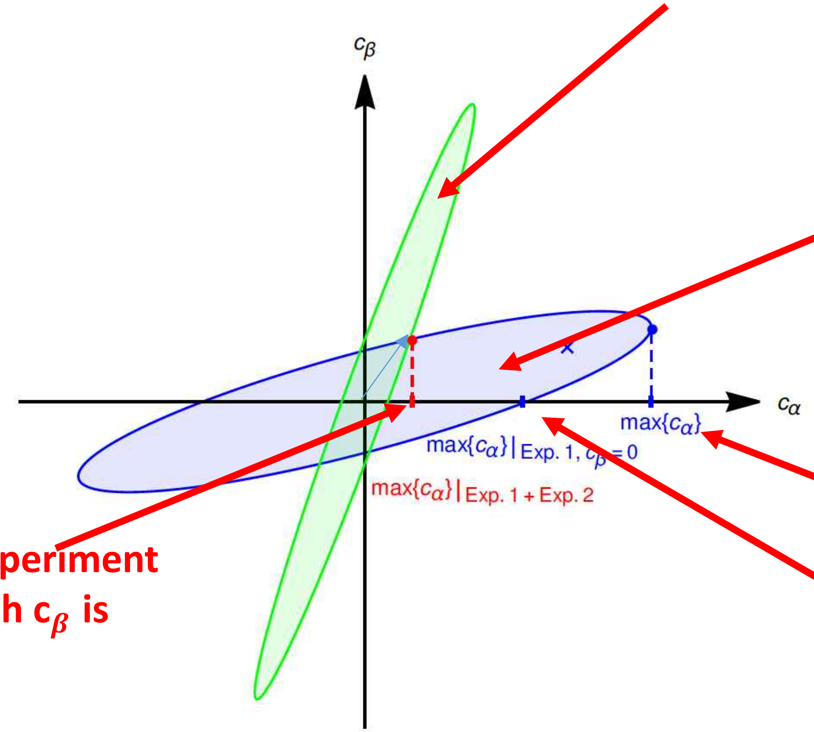
Predicted spectra for high-multipole operators **shift to higher energies due to powers of momentum transfer q**

P. Gondolo, Sunghyun Kang, S. S. and G. Tomar, Phys.Rev. D104, 063017(2021)

Generalized exclusion plots

- Since we are not driven by a specific high-energy scenario it becomes crucial to express experimental constraints in a way *as model-independent as possible*.
- However the parameter space of non –relativistic effective theory is large, how to present the experimental constraints???
- Considering one effective operator at a time does not appear satisfactory, in most situations the effective Hamiltonian is driven by several operators that can interfere.
- A possible strategy: bracket the full variation of the exclusion plot on each operator determined by interferences
- Of course, this can be useful only if the variation is not too large…

- In non-relativistic effective theory at fixed m_χ and δ all signals are quadratic forms in the couplings, $c^T M c$
- For instance, for a particle of spin ½ with contact interaction 28-dim parameter space
- Fixed positive signal → ellipsoid



Alllowed parameter space from experiment 2

Alllowed parameter space from experiment 1

Full scope of c_α if the interference with c_β is considered

Bound on c_α from experiment 1 assuming c_α is the only non-vanishing coupling ("one operator at a time limit")

Combined limit on c_α from experiment 1 and 2 if the interference with c_β is considered

- Almost flat directions in parameter space! the ellipticity can be very large for the bound on a single target → bound from single experiment strongly weakened when interferences are included
- SOLUTION: combine different targets!

A. Brenner, A. Ibarra and A. Rappelt, JCAP07(2021)012
A. Brenner, G. Herrera, A. Ibarra, S. Kang, S. Scopel and G. Tomar. in preparation

Flat directions

- In one-nucleon approximation and at the Born level the NREFT scattering amplitude <u>at fixed exchanged momentum q</u> is given by a linear combination of couplings:

$$A=a_1c_1+a_2c_2+a_3c_3+\ldots=\Sigma_i a_i c_i$$

- As a consequence the quadratic form for the squared amplitude is:

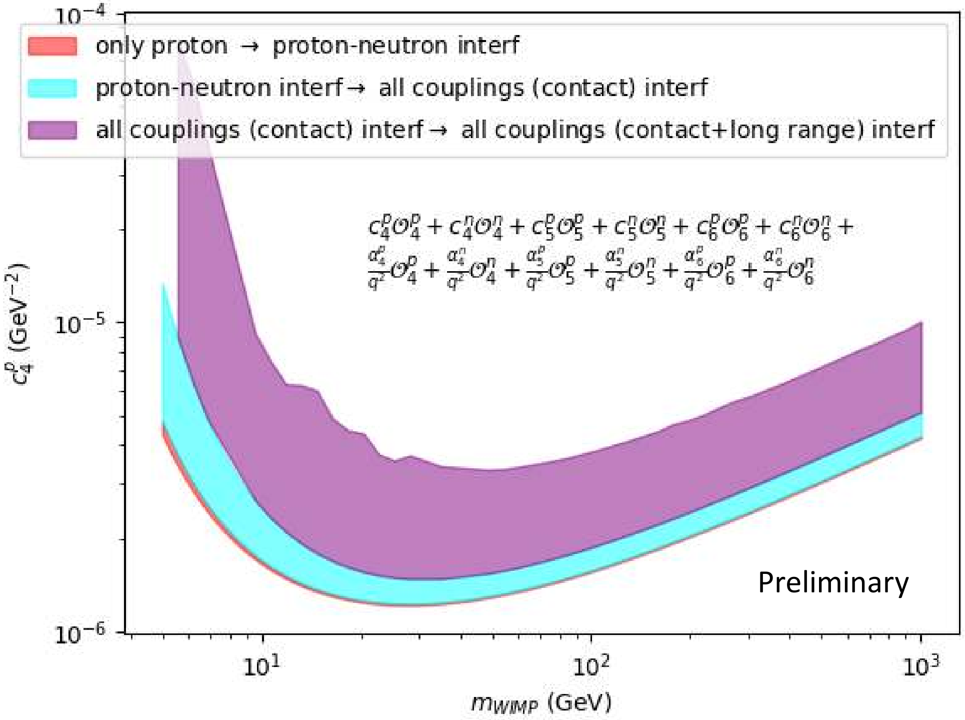
$$A^2=\Sigma_i\Sigma_j\, c_i\,(a_i a_j)\, c_j = \Sigma_i\Sigma_j\, c_i\, M_{ij}\, c_j$$

$\Rightarrow$ $M_{ij} = a_i a_j$ $\Rightarrow$ $\mathrm{Det}(M)=0$ $\Rightarrow$ **All vanishing eigenvalues in space orthogonal to $c_i=k\,a_i$**

- Along flat directions the rate vanishes even if $c_i \to \infty$ so no conservative bound is possible
- The problem is alleviated in multi-target detectors (using different targets, such as NaI, or targets with different isotopes (as Xe or Ge)
- The cancelation is spoiled by energy integration

- The constrained maximization on c_α is a well-defined convex problem that can be solved using matricial techniques (Linear Matrix Inequalities, LMI)
- NB: the matrices M break down into non-interfering blocks, to study interferences can explore subspaces of lower dimensions
- Anyway numerically tricky: so far convergence of the algorithm achieved only for some operators
- Can check the quality of convergence and the role of each bound plotting appropriate 2-dim projections of the multi-dimensional ellipsoids

Spin-dependent coupling $\vec{S}_\chi \cdot \vec{S}_N$



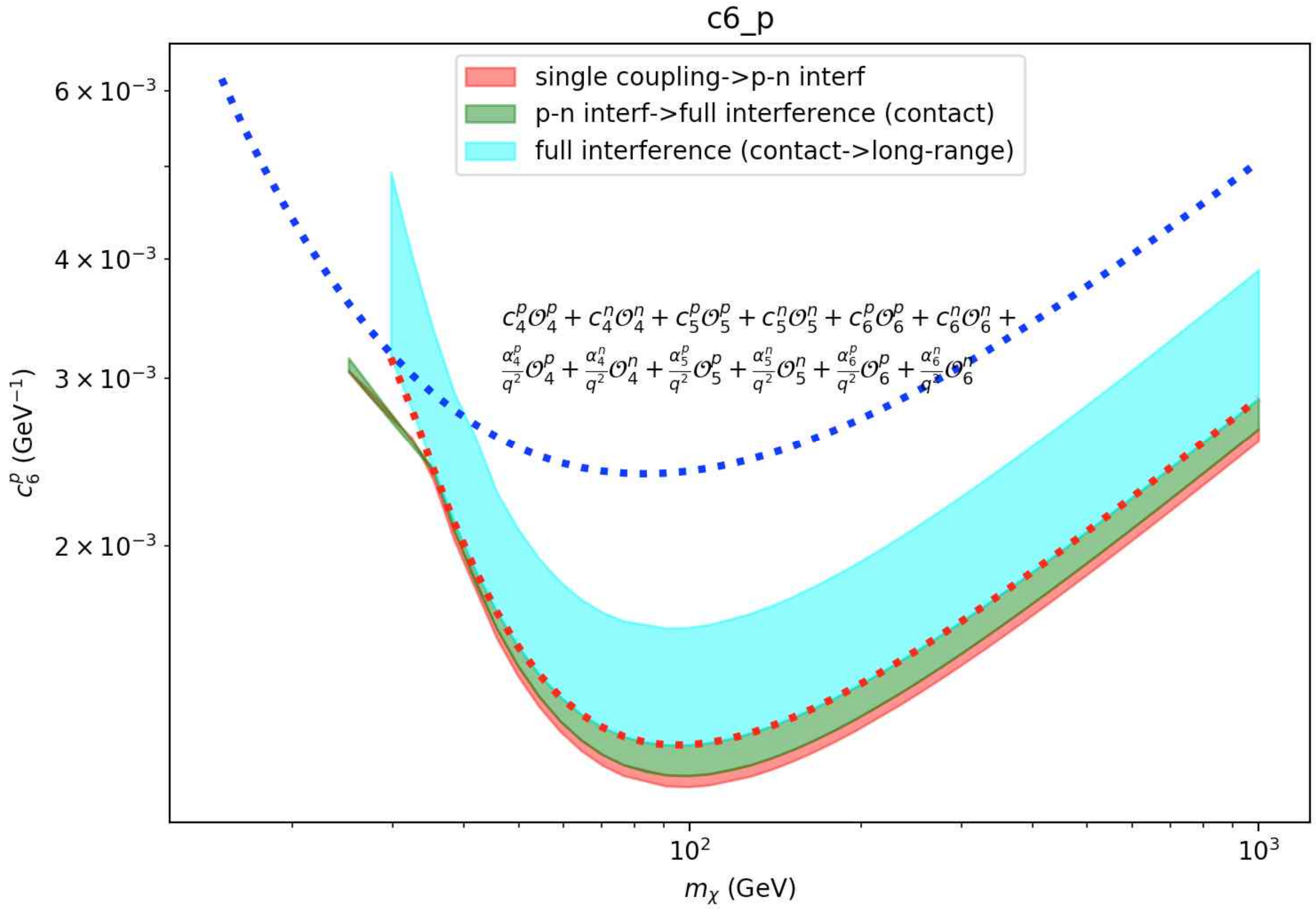
- Combination of 12 experiments: XENON1T, PICO60 (C_3F_8), PICO60 (CF_3I), CDMSLite, DAMA, COSINE, COUPP,, PICASSO, PANDAX, SuperCDMS, CRESST, DS50
- Short+long range interactions: (almost) all conceivable interferences included

At m_χ=100 GeV: a relaxation of ~20% for a contact interaction and a factor of ~2.4 including long range

I. Jeong, S. Kang, S. Scopel, in preparation

$$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{\tilde{q}})(\vec{S}_N \cdot \vec{\tilde{q}}) = -\mathcal{O}_{\Sigma,1,2}$$

$O_{\Sigma,s,s+1}$ has large power q^6 in scattering amplitude



without PICO60(CF_3I)

including PICO60(CF_3I)

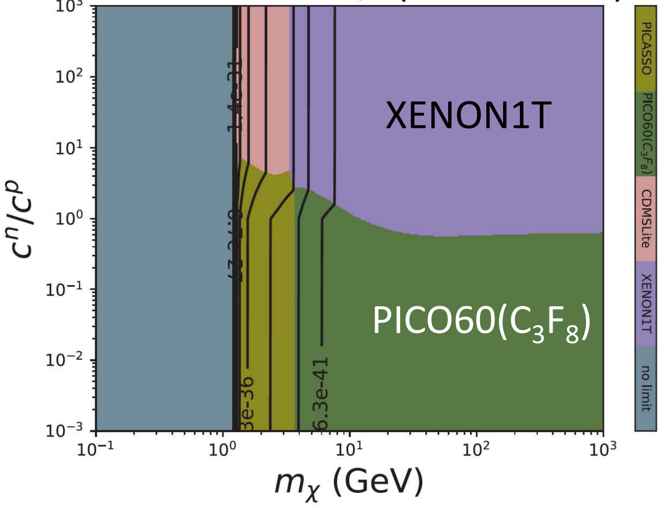
the bound is driven by Iodine in PICO60

One coupling at a time

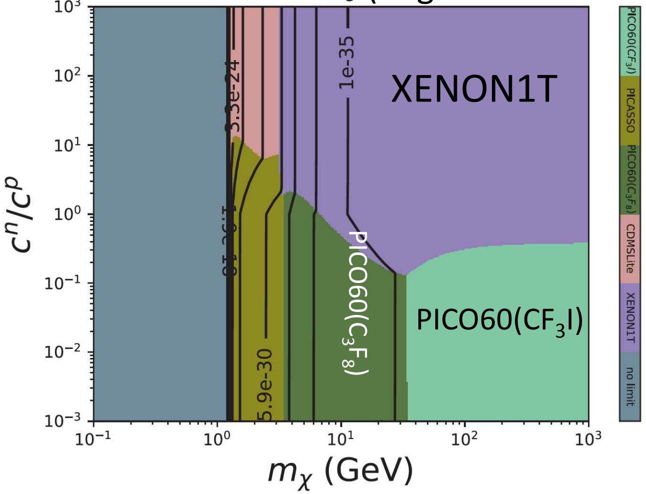
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

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

c_4 (standard SD)



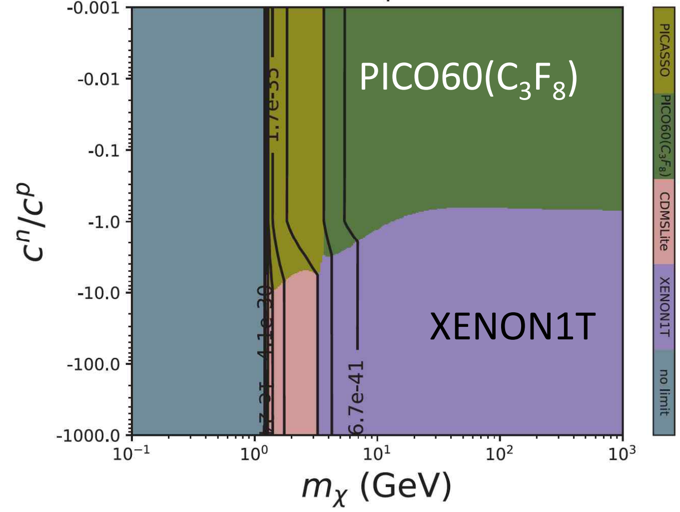
c_6 (large momentum power)



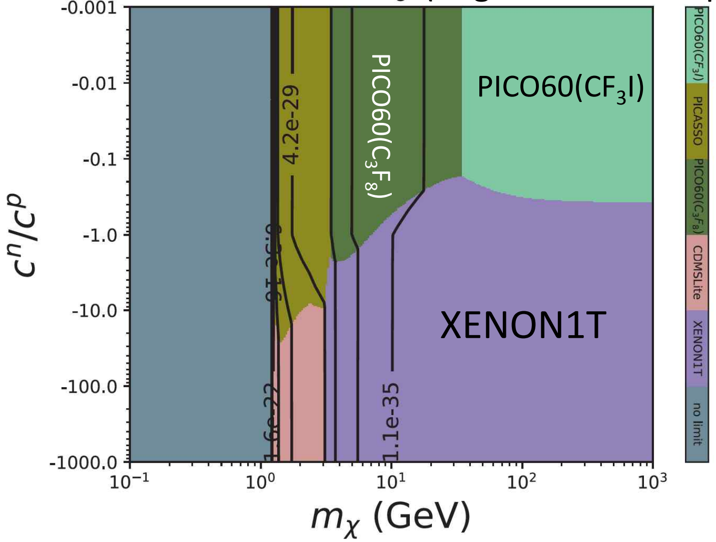
The PICO run using Iodine (CF_3I) becomes the <u>most competitive bound</u> at large WIMP mass for c_6 (large momentum power q^6 in the rate) <u>because the ROI extends to large energies</u> (PICO is a threshold detector)

<u>N.B.: other NaI detectors included in the analysis, not competitive because ROI limited to low energy</u>

c_4 (standard SD)



c_6 (large momentum power)



Sunghyun Kang, S.S., G. Tomar, J.H. Yoon, Astropart. Phys. 109, 50 (2019)

Conclusions

DAMA

- NaI detectors such as COSINE and ANAIS are crucial to settle the DAMA issue in a model-independent way
- Many “epicycles” introduced that at a given time could reconcile DAMA with the null results of experiments using **different nuclear targets**
  - inelastic scattering
  - departure from a Maxwellian velocity distribution (including Halo-independent methods)
  - Tuning of proton/neutron coupling ratio to cancel rate for specific targets (Nuclear “phobias”, Ge-phobic, Xe-phobic)
  - non-standard interactions (non-relativistic effective theory, NREFT)

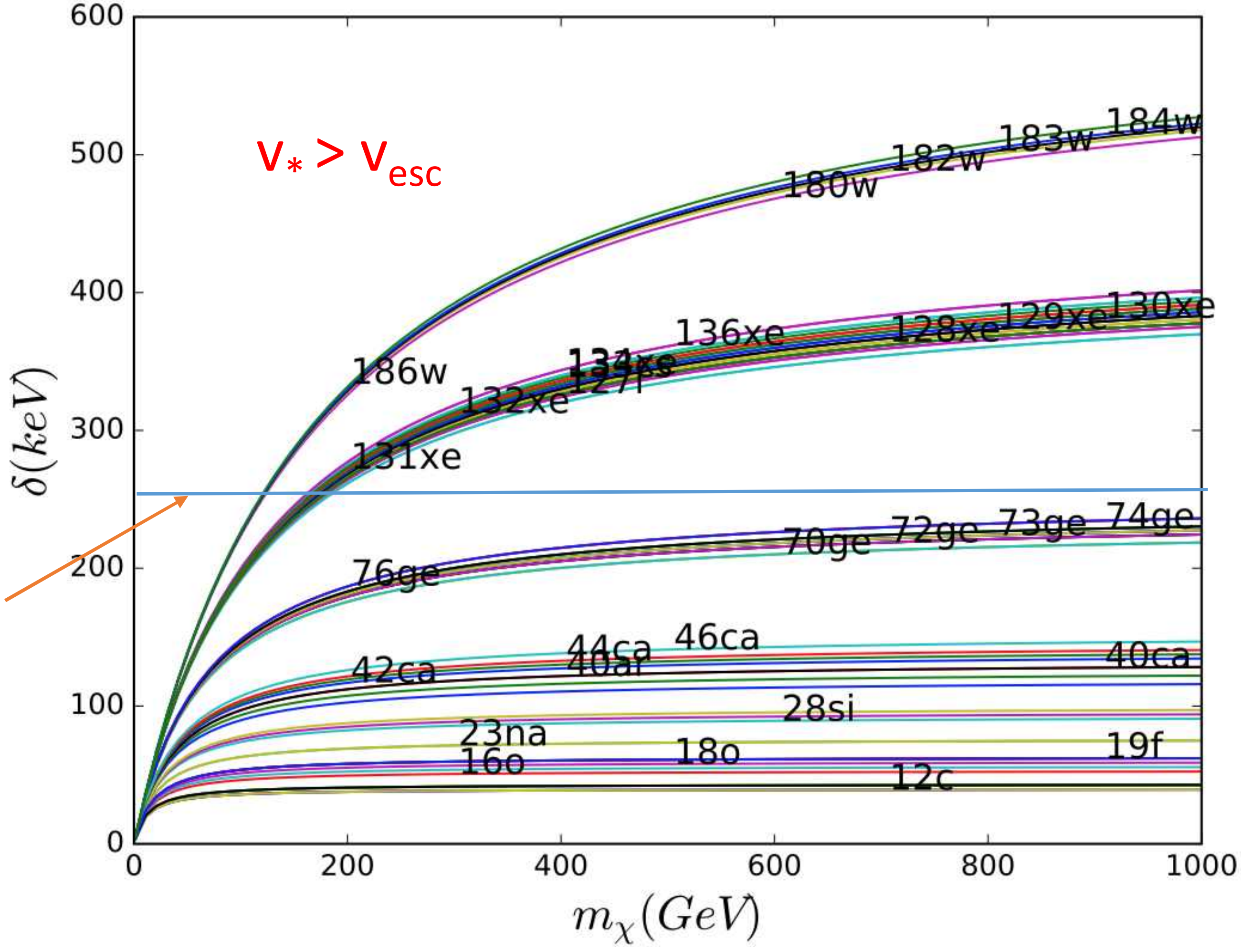
  Up to this day pSIDM (**p**roton-philic **S**pin-dependent **I**nelastic DM) reconciles DAMA with Ge, Xe and F detectors if f(v) departs from a Maxwellian
- Irrespective on whether DAMA is confirmed or not it was a useful benchmark to develop model-independent approaches that will be useful for any future excess

BEYOND DAMA

- Challenges/requirements in the exploration of the full parameter space of WIMP-nucleus scattering :
  - “Flat direcVons” in NREFT → crucial to exploit complementarity among different targets **(multi-target detectors may attenuate the problem)**
  - Most new operators require **non vanishing nuclear spin** (for instance, 9 out of 14 operators for J_χ =1/2)
  - **Heavy targets** (I, Xe,W) are sensitive to large mass splittings in inelastic scattering
  - Peculiar pattern of peaks for scattering energies E≤ 1 MeV for **large WIMP spin and large target masses**

SODIUM IODIDE detectors are among the best suited for this exploration especially if **the ROI is extended at large energies (≤ 1 MeV)**

N.B.: Inelastic scattering favors heavy elements, for each isotope inelastic upscatters become kinematically forbidden beyond maximal mass splitting δ corresponsing to escape velocity in the Galaxy



$V_* > V_{esc}$

For instance, for δ>250 keV only Xenon, Iodine and Tungsten can detect IDM

SODIUM IODIDE detectors are among the best suited to explore the full parameter space of WIMP-nucleus scattering especially if **the ROI is extended to large energies (≤ 1 MeV)**

All the results of this talk obtained with:

WimPyDD: an object–oriented and customizable Python code to calculate accurate predictions expected rates for WIMP-nucleus scattering in WIMP direct–detection experiments within the framework of Galilean–invariant non–relativistic effective theory.

I. Jeong, S. Kang, S.S. , G. Tomar, Comput.Phys.Commun. 276 (2022) 108342 (2106.06207)

Available at: https://wimpydd.hepforge.org/