Generalized interpretations of WIMP direct detection data

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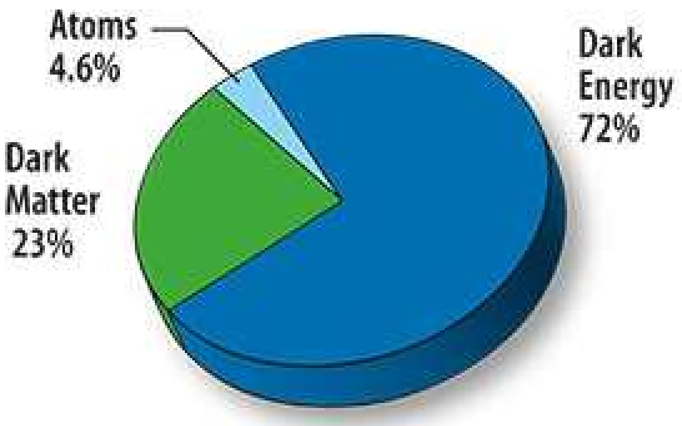
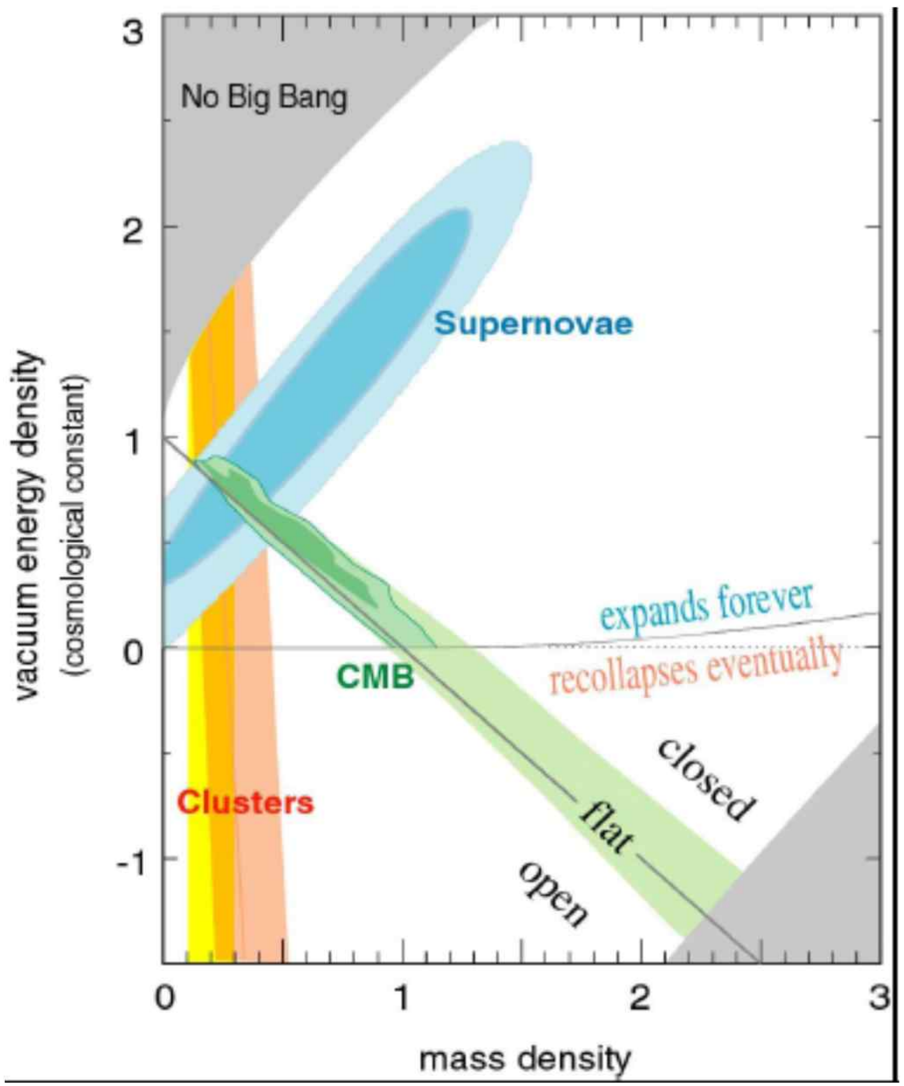
Lumley Castle

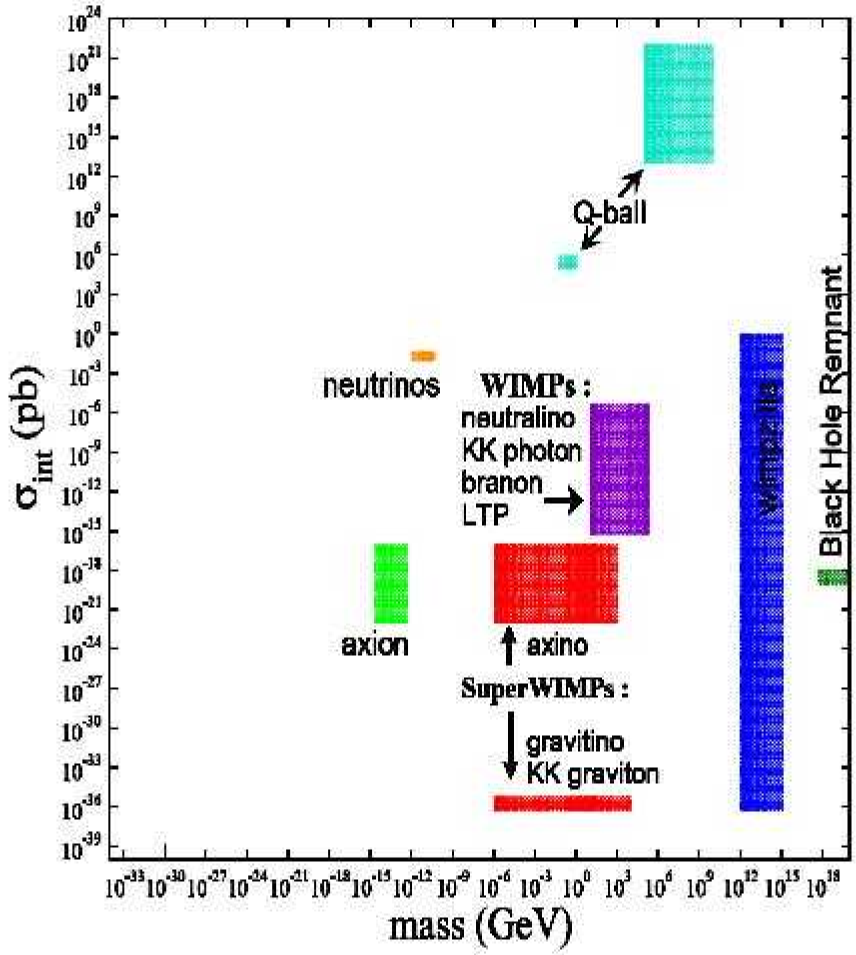
The concordance model



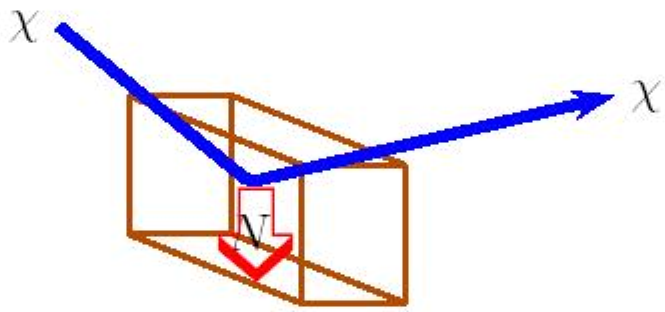


(Incomplete) List of DM candidates

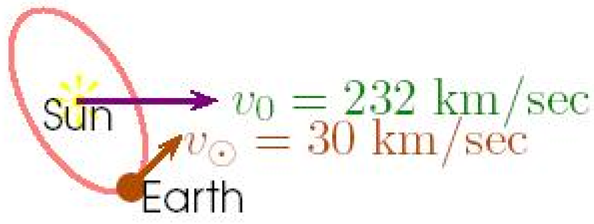
- Neutrinos
- Axions
- WIMPS (including Lightest Supersymmetric particle LSP such a neutralino or sneutrino)
- SuperWIMPS (gravitino)
- Lighest Kaluza-Klein Particle (LKP)
- Heavy photon in Little Higgs Models
- Solitons (Q-balls, B-balls)
- Black Hole remnants
- …



WIMP direct detection



- Elastic recoil of non relativistic halo WIMPs off the nuclei of an underground detector
- Recoil energy of the nucleus in the keV range
- Yearly modulation effect due to the rotation of the Earth around the Sun (the relative velocity between the halo, usually assumed at rest in the Galactic system, and the detector changes during the year)



WIMP differential detection rate

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{vmin}^{v_{max}} d\vec{v} f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v}, E_R)}{dE_R}$$

E_R=nuclear energy
N_T=# of nuclear targets
v=WIMP velocity in the Earth's rest frame

Astrophysics

- ρ_χ=WIMP local density
- f(v)= WIMP velocity distribution function

Particle and nuclear physics

- $\frac{d\sigma(\vec{v}, E_R)}{dE_R}$ =WIMP-nucleus elastic cross section

$$\frac{d\sigma(\vec{v}, E_R)}{dE_R} = \left(\frac{d\sigma(\vec{v}, E_R)}{dE_R}\right)_{\text{coherent}} + \left(\frac{d\sigma(\vec{v}, E_R)}{dE_R}\right)_{\text{spin-dependent}}$$

usually dominates, α (atomic number)^2

N.B.: dependence on galactic model contained in function:

$$\mathcal{I}(v_{min}) \equiv \int_{v_{min}} \frac{f(v)}{v} d^3\vec{v}$$

f(v) usually assumed to be at Maxwellian at rest in the Galactic system (possibility of *corotation* can be also considered):

$$f_G(\vec{v}_G) = \left(\frac{3}{2\pi v_{rms}^2}\right)^{\frac{3}{2}} e^{-\frac{3v_G^2}{2v_{rms}^2}} d^3\vec{v}_G$$

$$\vec{v}_G = \vec{w} + \vec{v}$$

WIMP velocity in Galactic reference frame

Earth velocity in Galactic reference frame

WIMP velocity in Earth reference frame

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

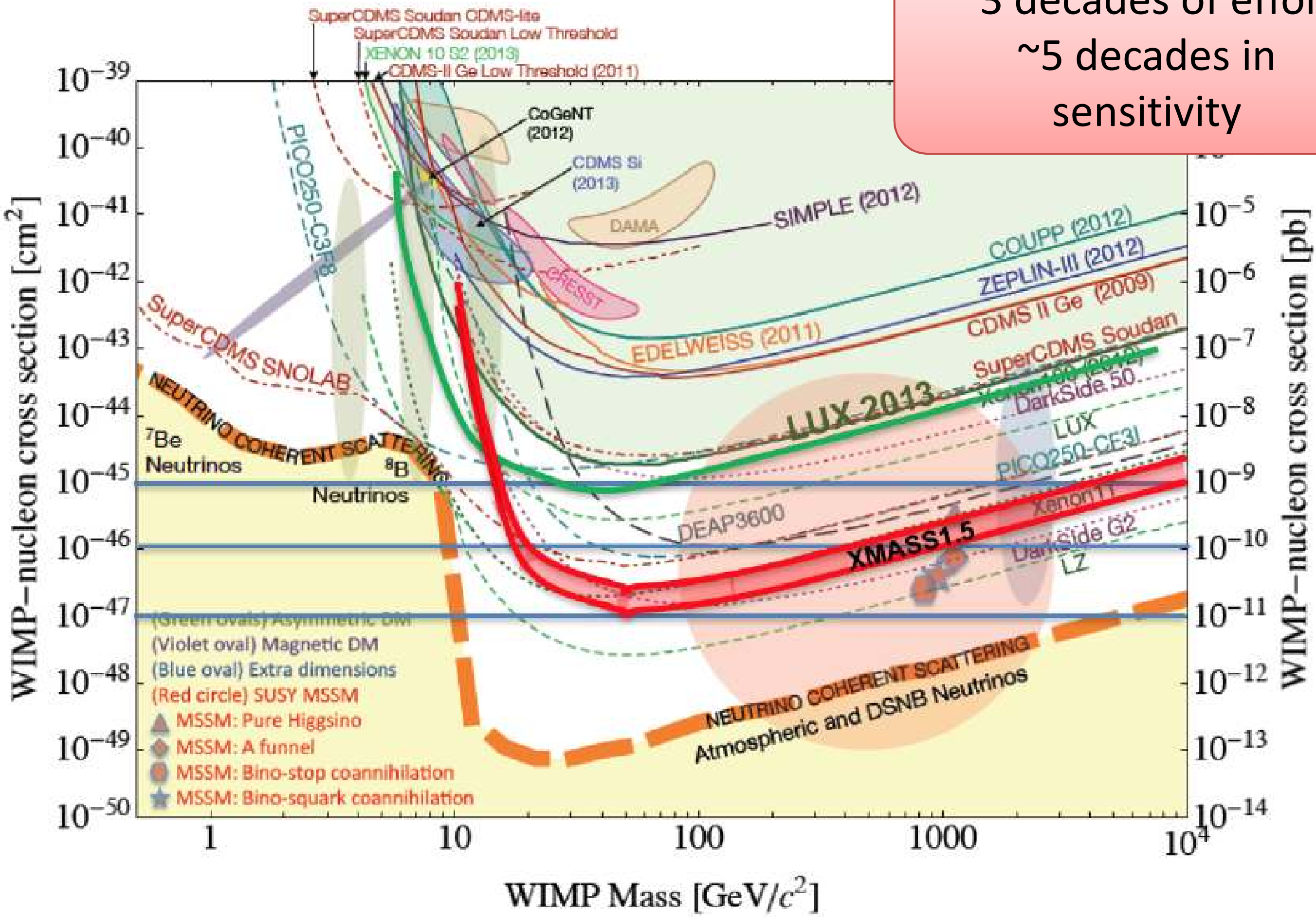
   Traditionally spin-independent cross section (proportional to (atomic mass number)^2) or spin-dependent cross section (proportional to the product $\boldsymbol{S}_{WIMP} \cdot \boldsymbol{S}_{nucleus}$ *) is assumed*

2) a model for the velocity distribution of WIMPs

   Traditionally a Maxwellian distribution is assumed

WIMP direct searches: spin-independent interaction+Maxwellian distribution

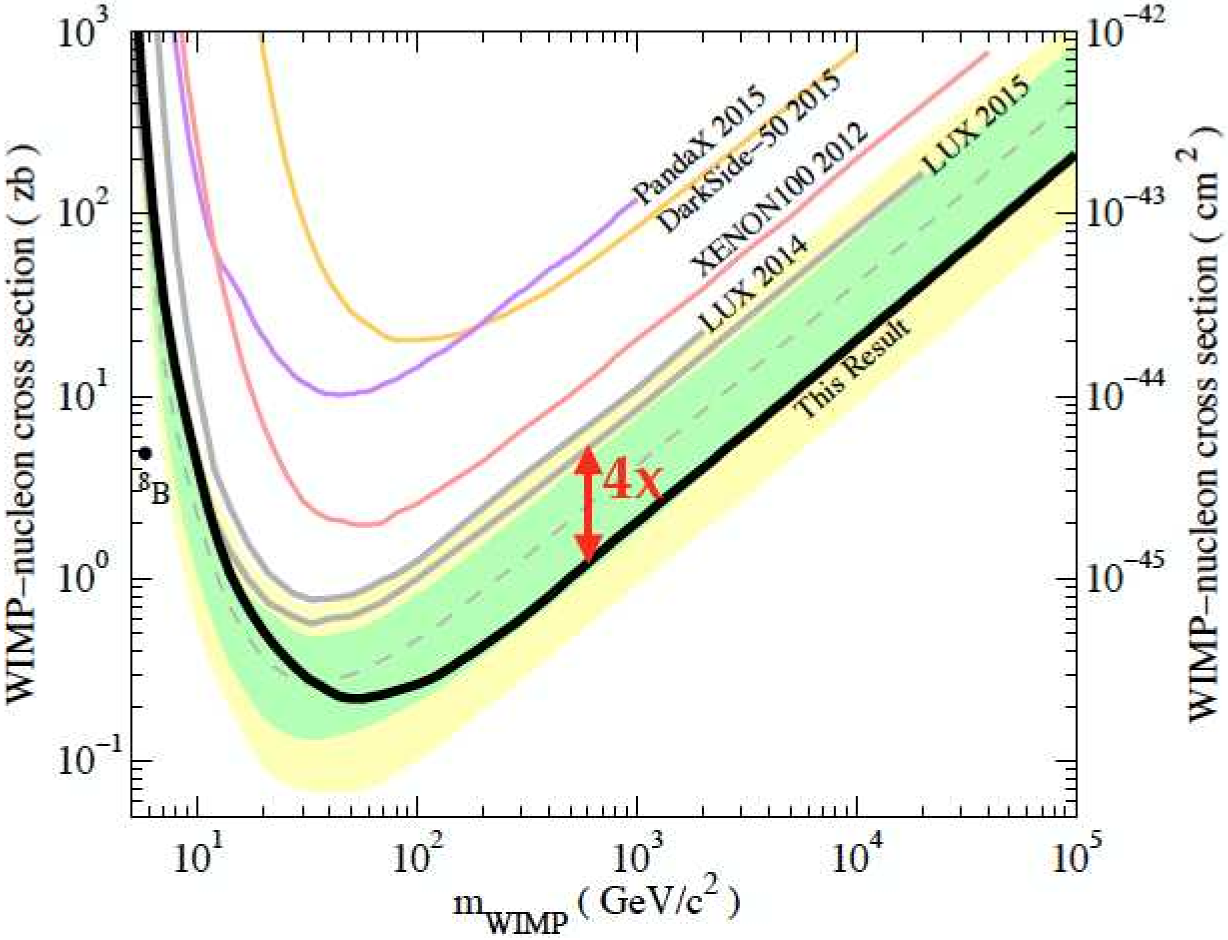
~3 decades of effort
~5 decades in sensitivity



Will the race discover DM before eventually reaching the irreducible background of solar and atmospheric neutrinos???

(from Y. Suzuki talk @IDM 2016, July 2016)

LUX 2016 (332 live days)



(A. Manalaysay, IDM 2016)

Indeed, spin-independent and spin-dependent cross sections are predicted for the neutralino in supersymmetry and numerical simulations of galaxy formation support the choice of a Maxwellian for the velocity distributions.

However a bottom-up approach would also be desireable,especially if no hints come from high-energy physics about the fundamental properties of the WIMP particle. Indeed two questions arise:

- what is the most general class of scaling laws for a WIMP-nucleus cross section?
- the detailed merger history of the Milky Way is not known, allowing for the possibility of the presence of sizeable non–thermal components for which the density, direction and speed of WIMPs are hard to predict, *especially in the high velocity tail of the distribution*: do we need to assume a Maxwellian velocity distribution?

Recently both aspects have been addressed

Compatibility among different experiments (ex. DAMA/Libra vs. CoGeNT) can be verified without assuming any model for the halo

Write expected WIMP rate as:

$$\frac{dR}{dE_R} = \frac{\rho_\chi \sigma_n}{2m_\chi \mu_{n\chi}^2} \frac{C_T}{f_n^2} F^2(E_R)\epsilon(E_R)g(v_{\min}, t)$$

$F^2(E_R)$ is the form factor, and the function:

$$g(v_{\min}, t) = \int_{v_{\min}}^{\infty} \frac{f_{\text{local}}(\vec{v}, t)}{v} d^3 v$$

contains all the dependence on the halo model with:

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu^2}}$$

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

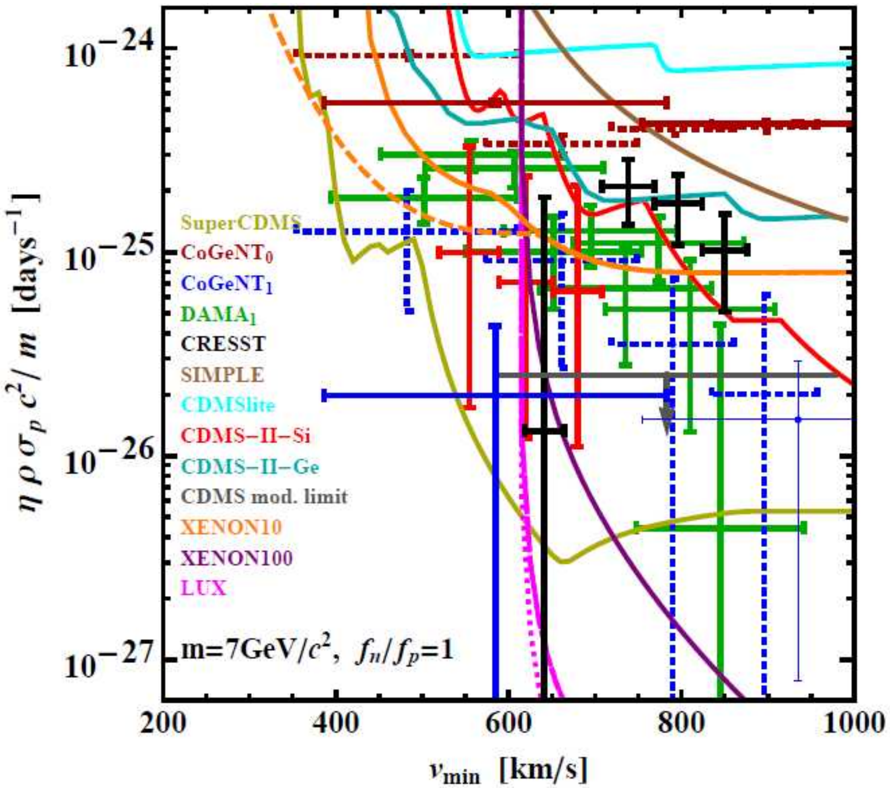
→ map the event rate expected in different experiments into the same intervals in v_{min} (P.J. Fox, J. Liu, N. Weiner, PRD83,103514 (2011))

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

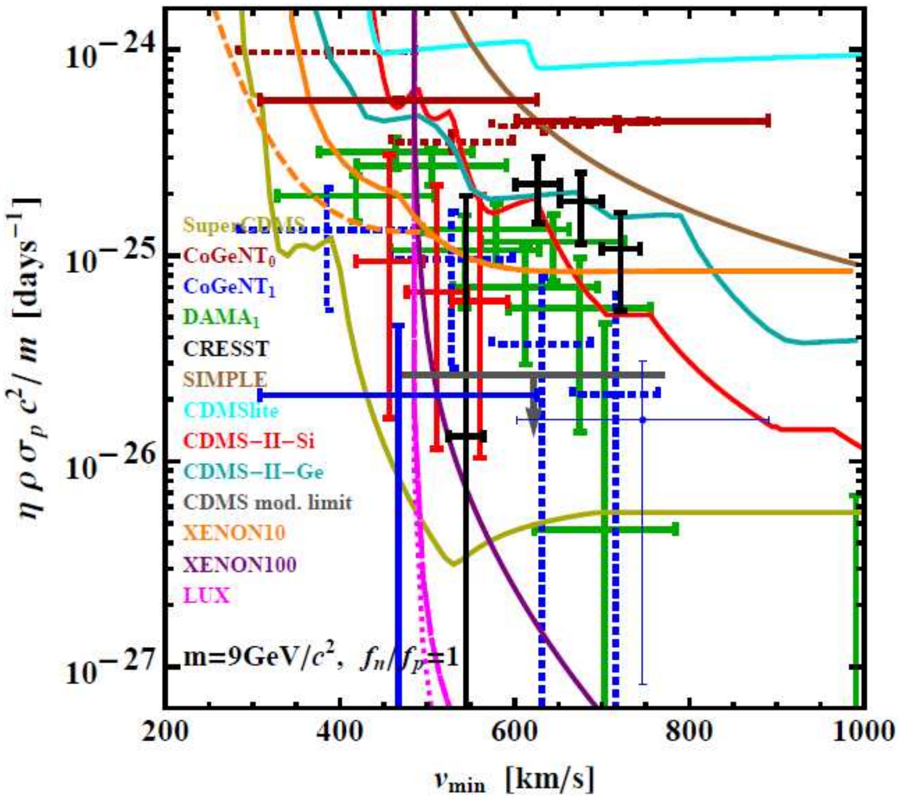
halo-independent analysis for elastic scattering

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

m_{WIMP}=7 GeV



m_{WIMP}=9 GeV



$$R^{\rm SI}_{[E_1',E_2']}(t) = \int_0^\infty {\rm d}v_{\rm min}\, \tilde\eta(v_{\rm min},t)\, \mathcal{R}^{\rm SI}_{[E_1',E_2']}(v_{\rm min})$$

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

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

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

$$\tilde{\eta}(v_{min}, t) \equiv \frac{\rho}{m_{WIMP}} \sigma_0 \eta(v_{min}, t)$$

- Annual modulation

Experimental data fits (DAMA, CoGeNT, KIMS) assume a sinusoidal behaviour:

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

The usual "halo-independent" approach to analyze yearly modulation data: factorize a modulated halo function $\tilde{\eta}_1$ with the only constraint $\tilde{\eta}_1 < \tilde{\eta}_0$.

(In the case of a Maxwellian typically $\tilde{\eta}_1 / \tilde{\eta}_0 \leq 0.07$)

Summarizing, the minimal requirements for halo functions $\eta_{0,1}$ are:

$$\tilde{\eta}_0(v_{\min,2}) \leq \tilde{\eta}_0(v_{\min,1}) \quad \text{if } v_{\min,2} > v_{\min,1} \qquad \text{(decreasing function)}$$

$$\tilde{\eta}_1 \leq \tilde{\eta}_0 \quad \text{at the same } v_{\min} \qquad \text{(modulated part<100\%)}$$

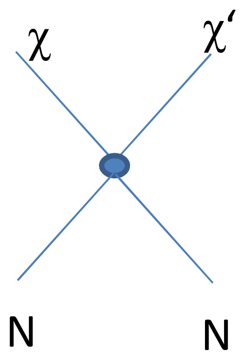
$$\tilde{\eta}_0(v_{\min} \geq v_{\rm esc}) = 0. \qquad \text{(no bound WIMPs<escape velocity)}$$

Inelastic Dark Matter

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

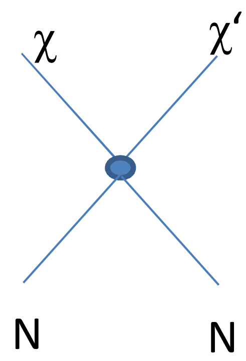
Two mass eigenstates χ and χ' very close in mass: $m_\chi - m_{\chi'} \equiv \delta$ with $\chi + N \rightarrow \chi + N$ forbidden

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



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

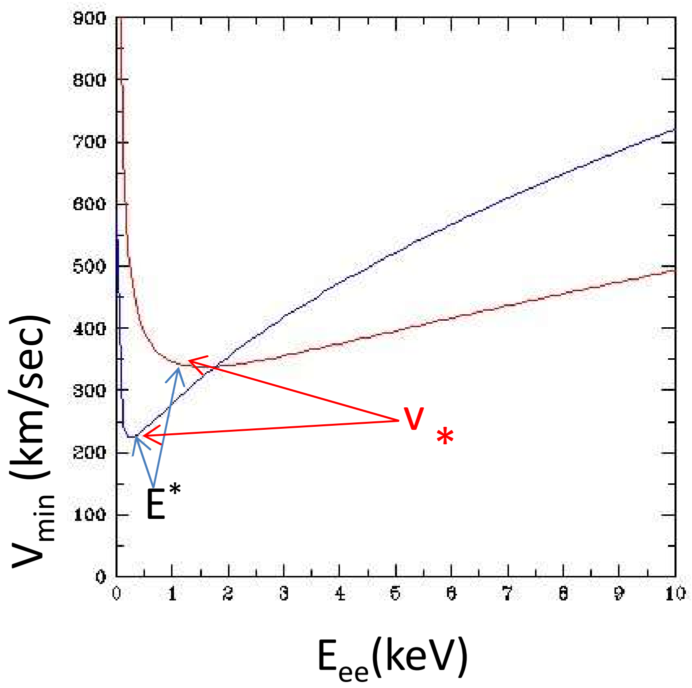
"Exothermic" scattering ($\delta<0$)



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

Inelastic DM and the halo-independent approach: recoil energy E_{ee} is no longer monotonically growing with v_{min} (energy E^* corresponds to minimal v_{min})

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



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

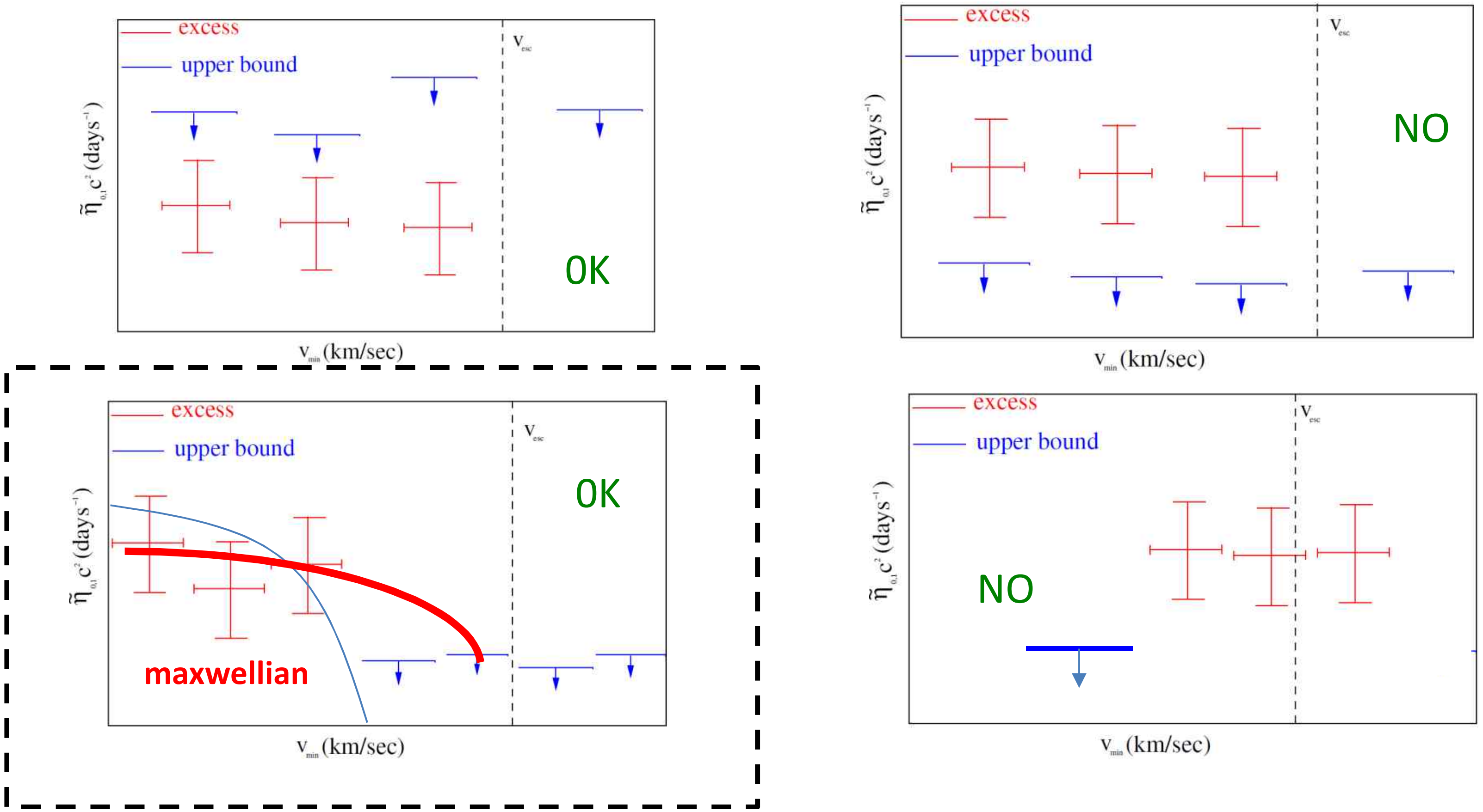
Need to rebin the data in such a way that the relation between v_{min} and E_R is invertible in each bin (easy: just ensure that for all target nuclei E^* corresponds to one of the bin boundaries)

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

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

Four cases:



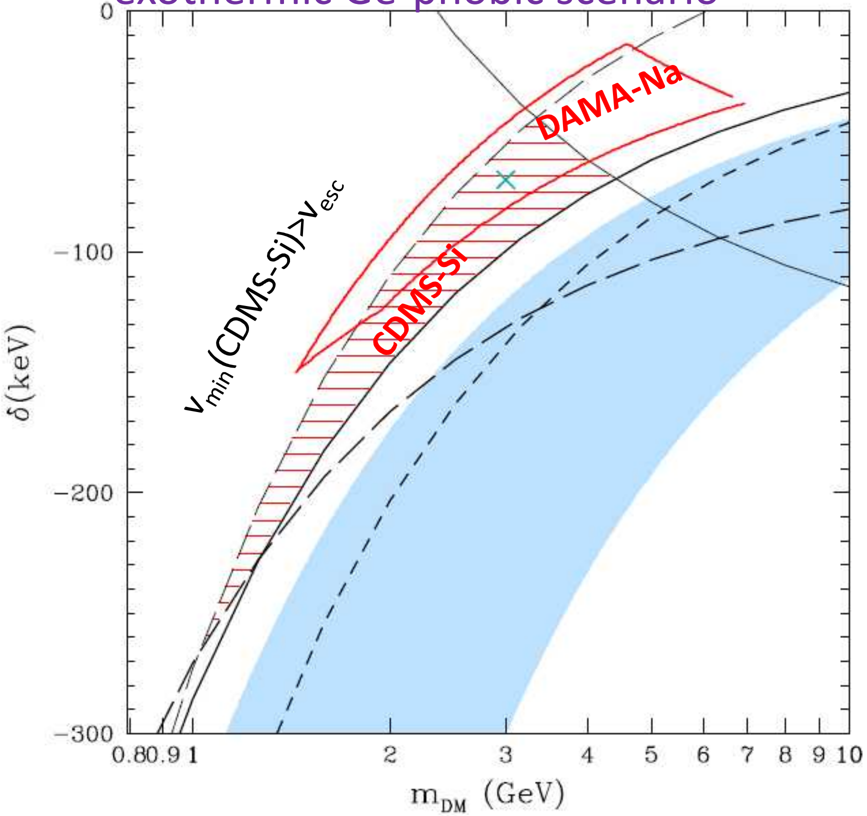
N.B: the effect of inelastic scattering (δ≠0) only implies a “horizontal shift” of η estimations (up to negligible effects) → pick appropriate m_{DM}, δ combination to shift-away the bounds without shifting away the signal!

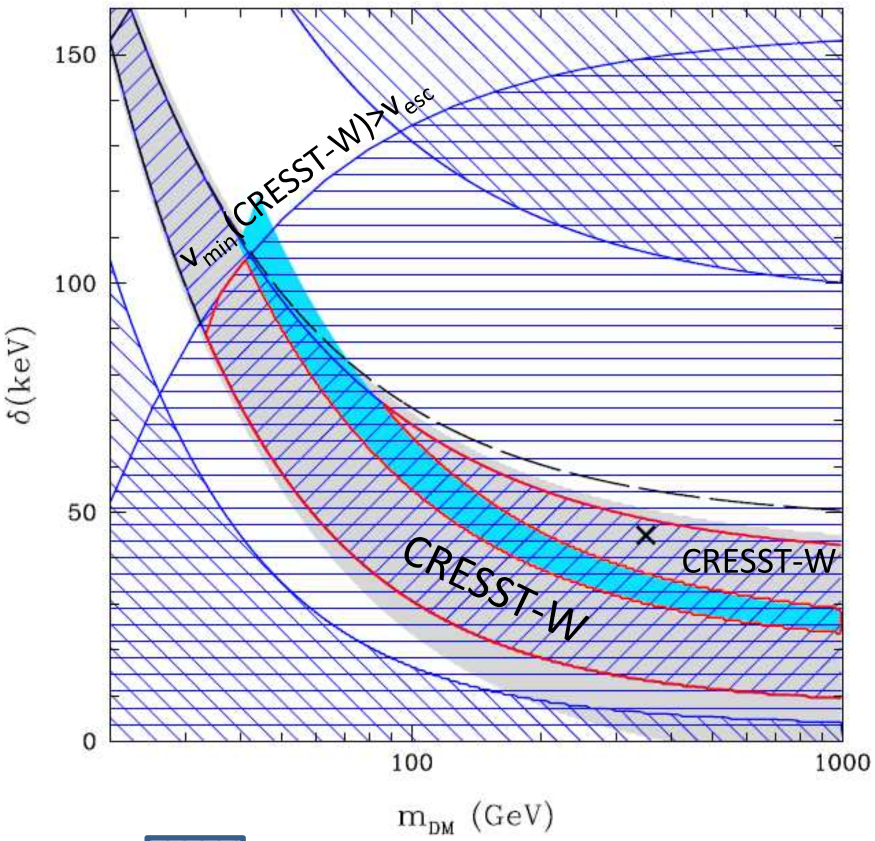
S. Scopel and K.H. Yoon, JCAP1408, 060 (2014)

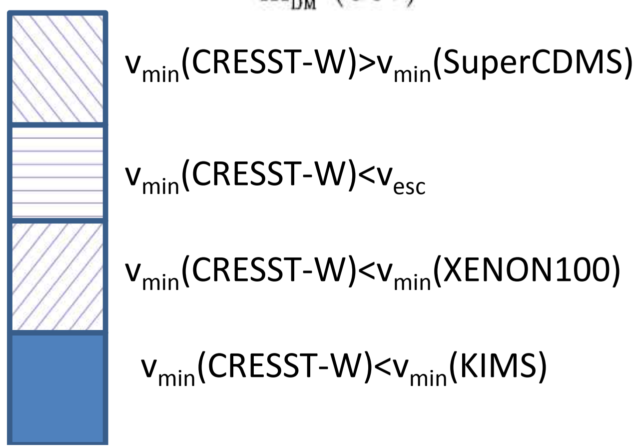
Halo-independent analysis of inelastic Dark Matter

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 upper bound of ROI is constraining

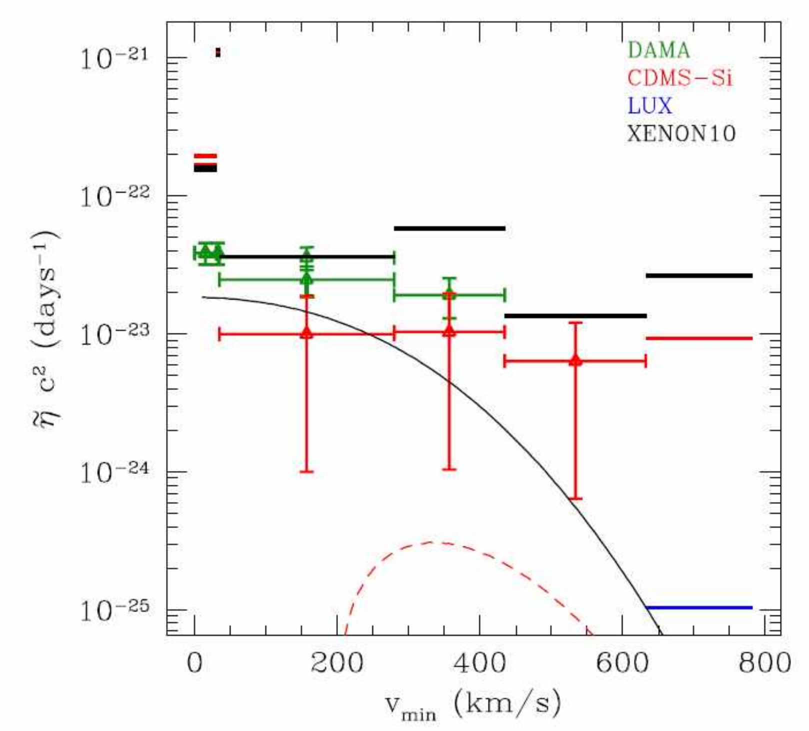
In LUX, XENON100→XENON100 more constraining than LUX due to lower light yield

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

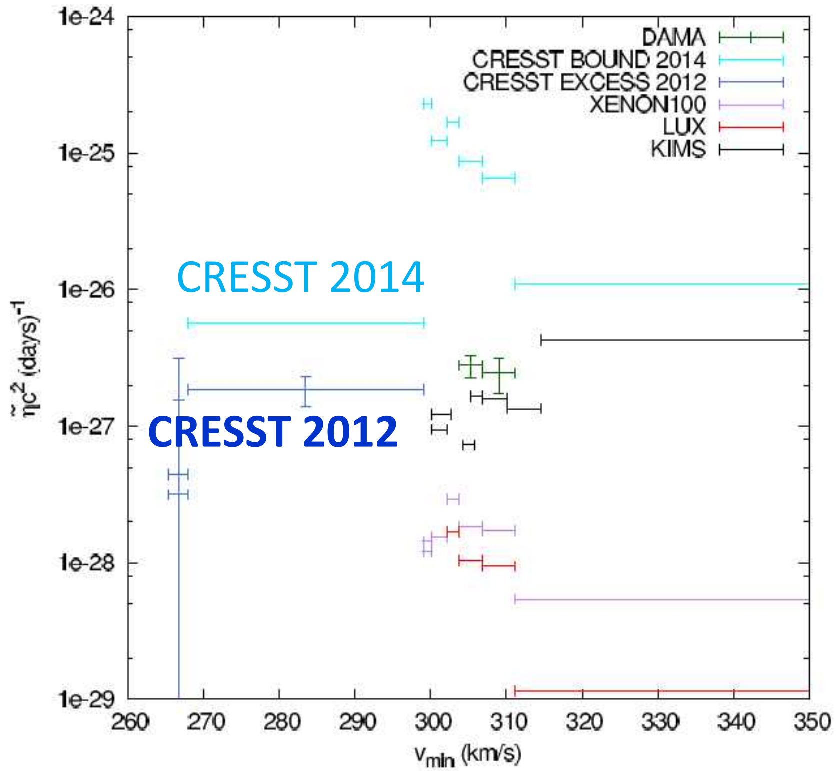
Halo-independent analysis of inelastic Dark Matter

"Agnostic" approach about velocity integral: a constraint does not affect values of v_{min} below its covered range, i.e. if $v_{min}(\text{bound}) > v_{min}(\text{signal})$

m_{DM} =3 GeV, δ=-70 keV, f_n/f_p =-0.79



m_{DM} =350 GeV, δ=45 keV, f_n/f_p =1



- DAMA and CDMS-Si can be separately OK with bounds, but are always in tension between themselves
- Assuming standard Maxwellian more tension arises
- high-mass CRESST solution not affected by recent reanalysis due to low statistics

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

isospin violation (more properly: isovector interaction)

$$R = \sigma_p \sum_i \eta_i \frac{\mu_{A_i}^2}{\mu_p^2} I_{A_i} \left[Z + (A_i - Z) f_n / f_p \right]^2$$

(spin-independent cross section, same for other interactions)

sum over isotopes

Cancellation between f_p (WIMP-proton coupling) and f_n (WIMP-nucleon coupling) when $f_n/f_p \sim -Z/(A-Z)$ → can suppress the scattering cross section ona specific target (i.e. $f_n/f_p \sim -0.79$ for Germanium)

Minimal "degrading factors", i.e. maximal factors by which the reciprocal scaling law between two elements can be reduced (limited by multiple isotopes, one choice of f_n/f_p ratio cannot fit all)

Element	Xe	Ge	Si	Ca	W	Ne	C
Xe (54, *)	1.00	8.79	149.55	138.21	10.91	34.31	387.66
Ge (32, *)	22.43	1.00	68.35	63.14	130.45	15.53	176.47
Si (14, *)	172.27	30.77	1.00	1.06	757.44	1.06	2.67
Ca (20, *)	173.60	31.53	1.17	1.00	782.49	1.10	2.81
W (74, *)	2.98	13.88	177.46	166.15	1.00	41.64	466.75
Ne (10, *)	163.65	28.91	4.39	4.09	726.09	1.00	11.52
C (6, *)	176.35	32.13	1.07	1.02	789.59	1.12	1.00
I (53, 127)	1.94	5.51	127.04	118.35	20.68	28.92	326.95
Cs (55, 133)	1.16	7.15	139.65	127.61	12.32	31.88	355.27
O (8, 16)	178.49	32.13	1.08	1.03	789.90	1.13	1.01
Na (11, 23)	101.68	13.77	8.45	8.33	481.03	2.27	22.68
Ar (18, 36)	178.49	32.13	1.08	1.03	789.90	1.13	1.01
F (9, 19)	89.39	10.88	12.44	11.90	425.93	3.05	33.47

(J.L.Feng, J.Kumar, D.Marfatia and D.Sanford, Phys.Lett.B703, 124 (2011), 1102.4331)

On the most general WIMP-nucleus cross section
(i.e. beyond “spin-dependent” and “spin”independent”)

Most general approach: consider ALL possible NR couplings, including those depending on velocity and momentum

$$\mathcal{H} = \sum_i \left(c_i^0 + c_i^1 \tau_3\right) \mathcal{O}_i$$

τ_3=nuclear isospin operator, i.e.

$$c_i^{\rm p} = (c_i^0 + c_i^1)/2 \qquad \text{(proton)}$$
$$c_i^{\rm n} = (c_i^0 - c_i^1)/2 \qquad \text{(neutron)}$$

(if $c_i^p = c_i^n \rightarrow c_i^1=0$)

N.R. operators O_i guaranteed to be Hermitian if built out of the following four 3-vectors:

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

with:

$$\vec{v}^\perp = \vec{v} + \frac{\vec{q}}{2\mu_N}$$
$$\vec{v} \equiv \vec{v}_{\chi,\rm in} - \vec{v}_{N,\rm in}$$

$\Rightarrow$ $\vec{v}^\perp \cdot \vec{q} = 0$

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

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.

Additional operators that do not arise for traditional spin-0 or spin-1 mediators:

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

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

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

$$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left[(\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{16} = -\left[(\vec{S}_\chi \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right]\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

In the expected rate WIMP physics (encoded in the R functions that depend on the c_i couplings) and the nuclear physics (contained in 8 (6+2) response functions W factorize in a simple way:

$$\frac{\mathrm{d}\mathcal{R}}{\mathrm{d}E_R}=\sum_T \frac{\mathrm{d}\mathcal{R}_T}{\mathrm{d}E_R}\equiv\sum_T \xi_T \frac{\rho_\chi}{2\pi m_\chi}\int_{v>v_{\min}(q)} \frac{f(\vec{v}+\vec{v}_e(t))}{v} P_{\rm tot}(v^2,q^2)\, d^3v$$

$$\begin{aligned} P_{\rm tot}(v^2,q^2) &= \frac{4\pi}{2j_N+1}\sum_{\tau=0,1}\sum_{\tau'=0,1}\Bigg\{\Bigg[R_M^{\tau\tau'}(v_{\chi T}^{\perp 2},\frac{q^2}{m_N^2})\,W_M^{\tau\tau'}(y) \\ &+ R_{\Sigma''}^{\tau\tau'}(v_{\chi T}^{\perp 2},\frac{q^2}{m_N^2})\,W_{\Sigma''}^{\tau\tau'}(y)+R_{\Sigma'}^{\tau\tau'}(v_{\chi T}^{\perp 2},\frac{q^2}{m_N^2})\,W_{\Sigma'}^{\tau\tau'}(y)\Bigg] \\ &+ \frac{q^2}{m_N^2}\Bigg[R_{\Phi''}^{\tau\tau'}(v_{\chi T}^{\perp 2},\frac{q^2}{m_N^2})\,W_{\Phi''}^{\tau\tau'}(y)+R_{\Phi''M}^{\tau\tau'}(v_{\chi T}^{\perp 2},\frac{q^2}{m_N^2})\,W_{\Phi''M}^{\tau\tau'}(y) \\ &+ R_{\tilde{\Phi}'}^{\tau\tau'}(v_{\chi T}^{\perp 2},\frac{q^2}{m_N^2})\,W_{\tilde{\Phi}'}^{\tau\tau'}(y)+R_{\Delta}^{\tau\tau'}(v_{\chi T}^{\perp 2},\frac{q^2}{m_N^2})\,W_{\Delta}^{\tau\tau'}(y) \\ &+ R_{\Delta\Sigma'}^{\tau\tau'}(v_{\chi T}^{\perp 2},\frac{q^2}{m_N^2})\,W_{\Delta\Sigma'}^{\tau\tau'}(y)\Bigg]\Bigg\}, \end{aligned}$$

N.B.: besides usual spin-independent and spin-dependent terms new contributions arise, with explicit dependences on the transferred momentum q and the WIMP incoming velocity

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.

WIMPs response funtions

$$R_M^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{q^2}{m_N^2} v_T^{\perp 2} c_5^\tau c_5^{\tau'} + v_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{q^2}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right]$$

$$R_{\Phi''}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \left[\frac{q^2}{4m_N^2} c_3^\tau c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau - \frac{q^2}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{q^2}{m_N^2} c_{15}^{\tau'}\right)\right]\frac{q^2}{m_N^2}$$

$$R_{\Phi'' M}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \left[c_3^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(c_{12}^\tau - \frac{q^2}{m_N^2} c_{15}^\tau\right) c_{11}^{\tau'}\right]\frac{q^2}{m_N^2}$$

$$R_{\tilde{\Phi}'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \left[\frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau c_{12}^{\tau'} + \frac{q^2}{m_N^2} c_{13}^\tau c_{13}^{\tau'}\right)\right]\frac{q^2}{m_N^2}$$

$$R_{\Sigma''}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{q^2}{4m_N^2} c_{10}^\tau c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{q^2}{m_N^2}(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}) + \frac{q^4}{m_N^4} c_6^\tau c_6^{\tau'} + v_T^{\perp 2} c_{12}^\tau c_{12}^{\tau'} + \frac{q^2}{m_N^2} v_T^{\perp 2} c_{13}^\tau c_{13}^{\tau'}\right]$$

$$R_{\Sigma'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{1}{8}\left[\frac{q^2}{m_N^2} v_T^{\perp 2} c_3^\tau c_3^{\tau'} + v_T^{\perp 2} c_7^\tau c_7^{\tau'}\right] + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{q^2}{m_N^2} c_9^\tau c_9^{\tau'} + \frac{v_T^{\perp 2}}{2}\left(c_{12}^\tau - \frac{q^2}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{q^2}{m_N^2} c_{15}^{\tau'}\right) + \frac{q^2}{2m_N^2} v_T^{\perp 2} c_{14}^\tau c_{14}^{\tau'}\right]$$

$$R_{\Delta}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{j_\chi(j_\chi+1)}{3}\left(\frac{q^2}{m_N^2} c_5^\tau c_5^{\tau'} + c_8^\tau c_8^{\tau'}\right)\frac{q^2}{m_N^2}$$

$$R_{\Delta\Sigma'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{j_\chi(j_\chi+1)}{3}\left(c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right)\frac{q^2}{m_N^2}.$$

general form:

$$R_k^{\tau\tau'} = R_{0k}^{\tau\tau'} + R_{1k}^{\tau\tau'}\frac{(v_T^\perp)^2}{c^2} = R_{0k}^{\tau\tau'} + R_{1k}^{\tau\tau'}\frac{v_T^2 - v_{min}^2}{c^2}$$

Nuclear response functions

Assuming one-body dark matter-nucleon interactions, the Hamiltonian density for dark matter-nucleus interactions is:

$$
\begin{aligned}
\mathcal{H}_{ET}(\vec{x}) &= \sum_{i=1}^{A} l_0(i)\ \delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} l_0^A(i)\ \frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\cdot\frac{1}{i}\overrightarrow{\nabla}_i\right] \\
&+ \sum_{i=1}^{A} \vec{l}_5(i)\cdot\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \sum_{i=1}^{A} \vec{l}_M(i)\cdot\frac{1}{2M}\left[-\frac{1}{i}\overleftarrow{\nabla}_i\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\frac{1}{i}\overrightarrow{\nabla}_i\right] \\
&+ \sum_{i=1}^{A} \vec{l}_E(i)\cdot\frac{1}{2M}\left[\overleftarrow{\nabla}_i\times\vec{\sigma}(i)\delta(\vec{x}-\vec{x}_i) + \delta(\vec{x}-\vec{x}_i)\vec{\sigma}(i)\times\overrightarrow{\nabla}_i\right]
\end{aligned}
$$

So the WIMP-nucleus Hamiltonian has the general form:

$$
\int d\vec{x}\ e^{-i\vec{q}\cdot\vec{x}}\ \left[l_0\langle J_i M_i|\hat{\rho}(\vec{x})|J_i M_i\rangle - \vec{l}\cdot\langle J_i M_i|\hat{\vec{j}}(\vec{x})|J_i M_i\rangle\right]
$$

With:

$$
e^{i\vec{q}\cdot\vec{x}_i} = \sum_{J=0}^{\infty}\sqrt{4\pi}\ [J]\ i^J j_J(qx_i) Y_{J0}(\Omega_{x_i})
$$

$$
\hat{e}_\lambda e^{i\vec{q}\cdot\vec{x}_i} = \begin{cases} \displaystyle\sum_{J=0}^{\infty}\sqrt{4\pi}\ [J]\ i^{J-1}\frac{\vec{\nabla}_i}{q} j_J(qx_i) Y_{J0}(\Omega_{x_i}), & \lambda = 0 \\ \displaystyle\sum_{J\geq 1}^{\infty}\sqrt{2\pi}\ [J]\ i^{J-2}\left[\lambda j_J(qx_i)\vec{Y}_{JJ1}^{\lambda}(\Omega_{x_i}) + \frac{\vec{\nabla}_i}{q}\times j_J(qx_i)\vec{Y}_{JJ1}^{\lambda}(\Omega_{x_i})\right], & \lambda = \pm 1 \end{cases}
$$

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.

which depends on the expectations of six distinct nuclear response functions, defined as:

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

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

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

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

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

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

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

•**Φ̃'**= 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.

Squaring the ampitude get the following nuclear response functions:

$$W_O^{\tau\tau'}(y) \equiv \sum_{J=0,2,\ldots}^{\infty} \langle j_N || O_{J;\tau}(q) || j_N \rangle \langle j_N || O_{J;\tau'}(q) || j_N \rangle \text{ for } O = M, \Phi'',$$

$$W_O^{\tau\tau'}(y) \equiv \sum_{J=1,3,\ldots}^{\infty} \langle j_N || O_{J;\tau}(q) || j_N \rangle \langle j_N || O_{J;\tau'}(q) || j_N \rangle \text{ for } O = \Sigma'', \Sigma', \Delta,$$

$$W_{\tilde{\Phi}'}^{\tau\tau'}(y) = \sum_{J=2,4,\ldots}^{\infty} \langle j_N || \tilde{\Phi}'_{J;\tau}(q) || j_N \rangle \langle j_N || \tilde{\Phi}'_{J;\tau'}(q) || j_N \rangle,$$

$$W_{\Phi'' M}^{\tau\tau'}(y) = \sum_{J=0,2,\ldots}^{\infty} \langle j_N || \Phi''_{J;\tau}(q) || j_N \rangle \langle j_N || M_{J;\tau'}(q) || j_N \rangle,$$

(interference terms)

$$W_{\Delta\Sigma'}^{\tau\tau'}(y) = \sum_{J=1,3,\ldots}^{\infty} \langle j_N || \Delta_{J;\tau}(q) || j_N \rangle \langle j_N || \Sigma'_{J;\tau'}(q) || j_N \rangle.$$

These 8 (6+2 interferences) W nuclear response functions have been calculated for most nuclei using a numerical (truncated) harmonic potential shell model (Fitzpatrick et al., JCAP 1302 1302(2013), Catena and Schwabe, JCAP 1504 no. 04, 042 (2015)) with oscillator parameter:

$$b[\text{fm}] = \sqrt{41.467/(45A^{-1/3} - 25A^{-2/3})}$$

$$y = (qb/2)^2$$

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%

→several authors have considered 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 $c_n << c_p$ 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

Correspondence between WIMP and non-relativistic EFT nuclear response function

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	$\Phi''(q^6)$	$\Sigma'(q^4)$
	velocity-independent	velocity-dependent		velocity-independent	velocity-dependent

(in parenthesis the explicit dependence on q)

$$\mathcal{H} = \sum_i \left(c_i^0 + c_i^1 \tau_3\right) \mathcal{O}_i$$

$$R_k^{\tau\tau'} = R_{0k}^{\tau\tau'} + R_{1k}^{\tau\tau'} \frac{(v_T^{\perp})^2}{c^2} = R_{0k}^{\tau\tau'} + R_{1k}^{\tau\tau'} \frac{v_T^2 - v_{min}^2}{c^2}$$

Relativistic couplings leading in their non-relativistic limits **to the most general spin-dependent** terms:

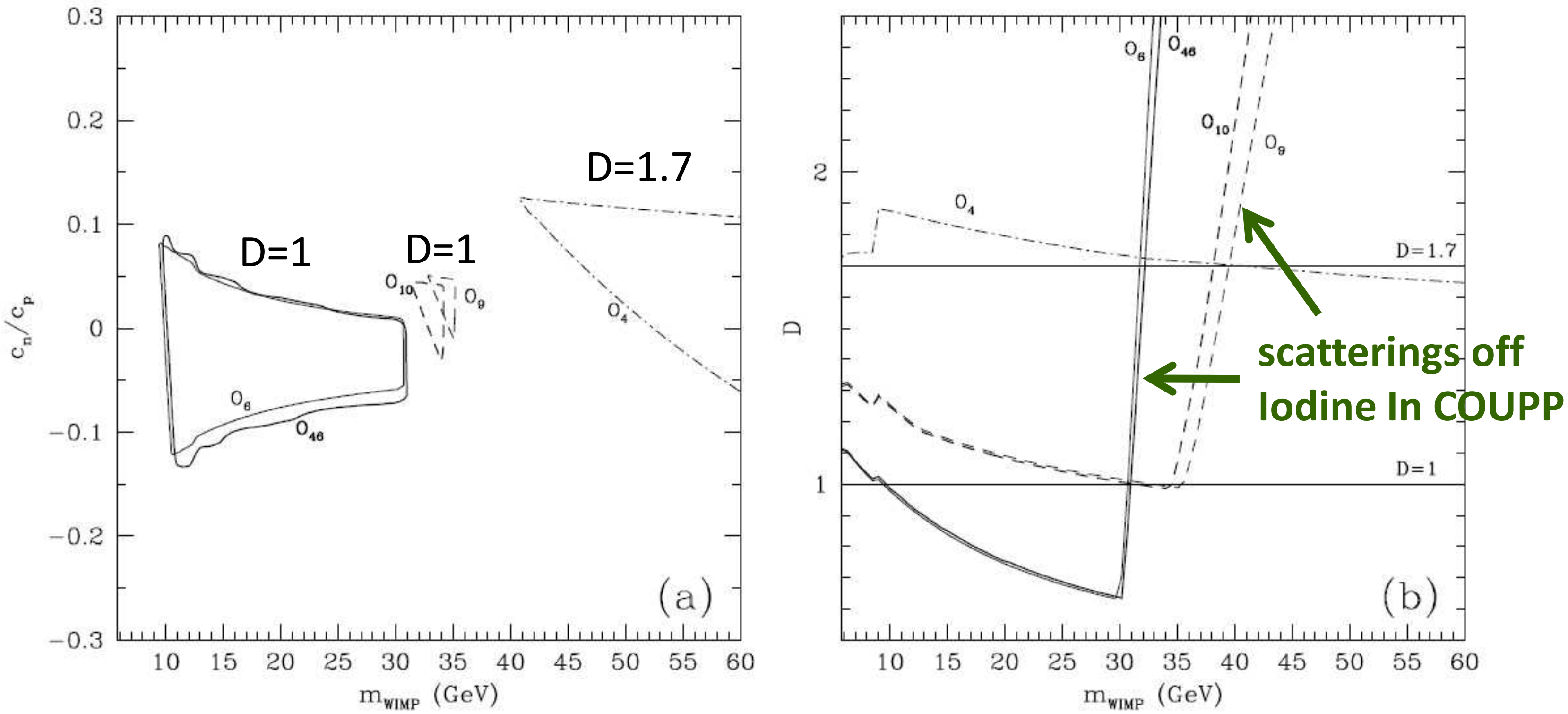
	Relativistic EFT	Nonrelativistic limit	$\sum_i \mathcal{O}_i$	cross section scaling
1	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$	$-4\vec{S}_\chi\cdot\vec{S}_N$	$-4\mathcal{O}_4$	$W^{\tau\tau'}_{\Sigma''}(q^2)+W^{\tau\tau'}_{\Sigma'}(q^2)$
2	$2\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu\gamma^5 N+$ $+\bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}i\sigma_{\mu\nu}\frac{q^\nu}{m_{WIMP}}N$	$-4\vec{S}_N\cdot\vec{v}_T^\perp$	$-4\mathcal{O}_7$	$(v_T^\perp)^2 W^{\tau\tau'}_{\Sigma'}(q^2)$
3	$2\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu\gamma^5 N+$ $-\bar{\chi}i\sigma_{\mu\nu}\frac{q^\nu}{m_{WIMP}}\chi\bar{N}\gamma^\mu\gamma_5 N$	$-4\vec{S}_N\cdot\vec{v}_T^\perp$	$-4\mathcal{O}_7$	$(v_T^\perp)^2 W^{\tau\tau'}_{\Sigma'}(q^2)$
4	$\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu\gamma^5 N$	$-2\vec{S}_N\cdot\vec{v}_T^\perp+$ $+\frac{2}{m_{WIMP}}i\vec{S}_\chi\cdot\left(\vec{S}_N\times\vec{q}\right)$	$-2\mathcal{O}_7+2\frac{m_N}{m_{WIMP}}\mathcal{O}_9$ $\simeq 2\frac{m_N}{m_{WIMP}}\mathcal{O}_9$	$\simeq q^2 W^{\tau\tau'}_{\Sigma'}(q^2)$
5	$\bar{\chi}i\sigma_{\mu\nu}\frac{q^\nu}{m_M}\chi\bar{N}\gamma^\mu\gamma_5 N$	$4i(\frac{\vec{q}}{m_M}\times\vec{S}_\chi)\cdot\vec{S}_N$	$4\frac{m_N}{m_M}\mathcal{O}_9$	$q^2 W^{\tau\tau'}_{\Sigma'}(q^2)$
6	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}i\sigma_{\mu\nu}\frac{q^\nu}{m_M}N$	$4i\vec{S}_\chi\cdot(\frac{\vec{q}}{m_M}\times\vec{S}_N)$	$-4\frac{m_N}{m_M}\mathcal{O}_9$	$q^2 W^{\tau\tau'}_{\Sigma'}(q^2)$
7	$i\bar{\chi}\chi\bar{N}\gamma^5 N$	$i\frac{\vec{q}}{m_N}\cdot\vec{S}_N$	$\mathcal{O}_{10}$	$q^2 W^{\tau\tau'}_{\Sigma''}(q^2)$
8	$i\bar{\chi}i\sigma_{\mu\nu}\frac{q^\nu}{m_M}\gamma_5\chi\bar{N}\gamma_\mu\gamma_5 N$	$-4i(\frac{\vec{q}}{m_N}\cdot\vec{S}_\chi)(\vec{v}_T^\perp\cdot\vec{S}_N)$	$-4\frac{m_N}{m_M}\mathcal{O}_{14}$	$(v_T^\perp)^2 q^2 W^{\tau\tau'}_{\Sigma'}(q^2)$
9	$\bar{\chi}\gamma_5\chi\bar{N}\gamma^5 N$	$-\frac{\vec{q}}{m_{WIMP}}\cdot\vec{S}_\chi\frac{\vec{q}}{m_N}\cdot\vec{S}_N$	$-\frac{m_N}{m_{WIMP}}\mathcal{O}_6$	$q^4 W^{\tau\tau'}_{\Sigma''}(q^2)$
10	$\bar{\chi}i\sigma^{\mu\alpha}\frac{q_\alpha}{m_M}\gamma_5\chi\bar{N}i\sigma_{\mu\beta}\frac{q^\beta}{m_M}\gamma_5 N$	$4\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$4\frac{m_N^2}{m_M^2}\mathcal{O}_6$	$q^4 W^{\tau\tau'}_{\Sigma''}(q^2)$
11	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4\left(\frac{\vec{q}}{m_M}\times\vec{S}_\chi\right)\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)$	$4\left(\frac{q^2}{m_M^2}\mathcal{O}_4-\frac{m_N^2}{m_M^2}\mathcal{O}_6\right)$	$q^4 W^{\tau\tau'}_{\Sigma'}(q^2)$

- the resulting scaling laws include the most general velocity and momentum dependences allowed by Galilean invariance through the product $(v_T^\perp)^{2n}\,(q^2)^m$ (n=0,1; m=0,1,2)

S.Scopel, J.H.Yoon and K.Yoon, JCAP 1507(2015)041

Numerical results

S.Scopel, J.H.Yoon and K.Yoon, JCAP 1507(2015)041



- 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 $q=\mathrm{sqrt}(m_{nucleus}\ E)$ 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

An alternative way to evade Fluorine constraints for a WIMP with spin-dependent coupling to protons: inelastic scattering

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

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

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

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

→ $v^{*Sodium}_{min} < v^{*Fluorine}_{min}$

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

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

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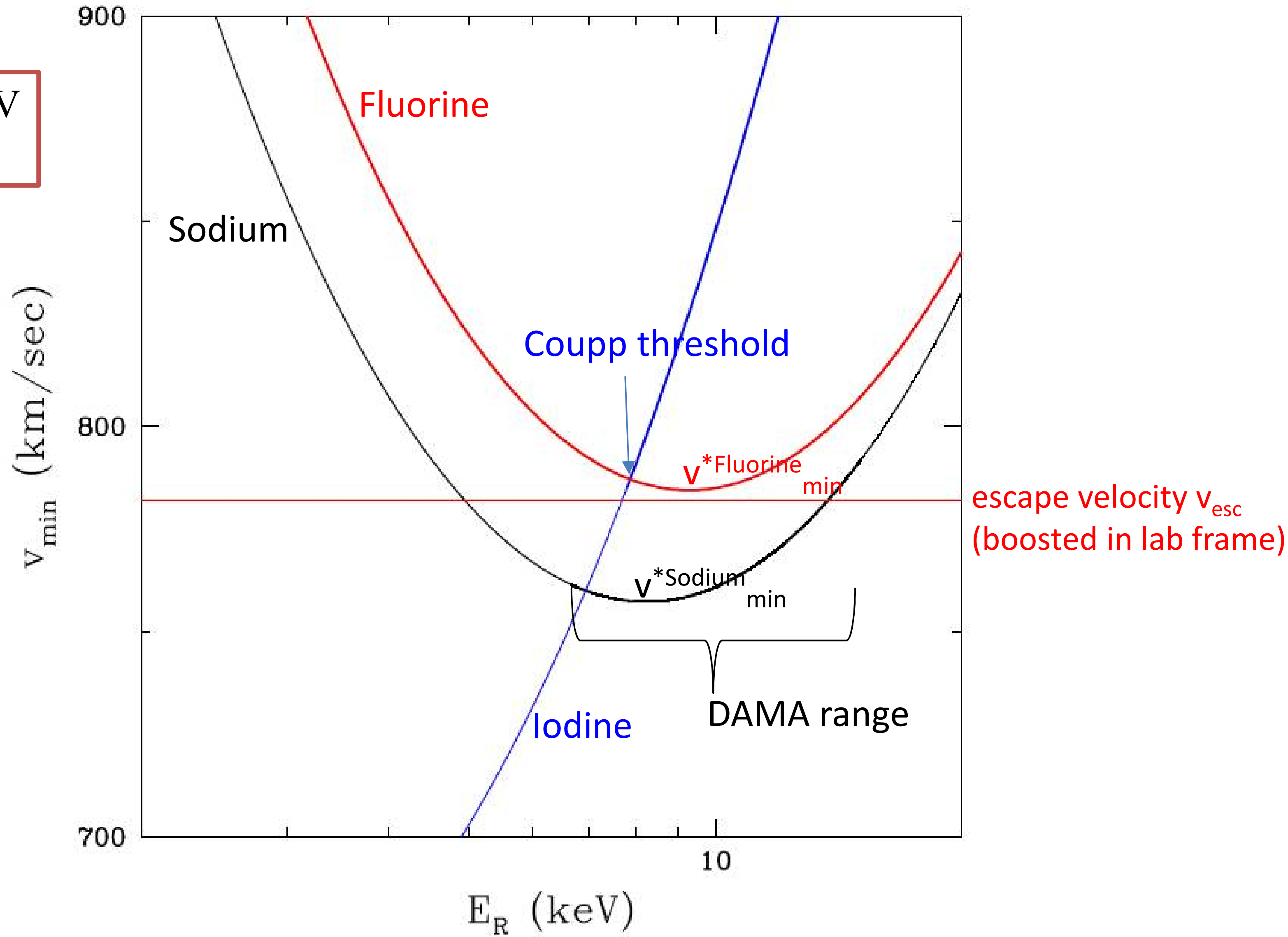
$m_\chi = 11.4$ GeV
δ=23.7 keV



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

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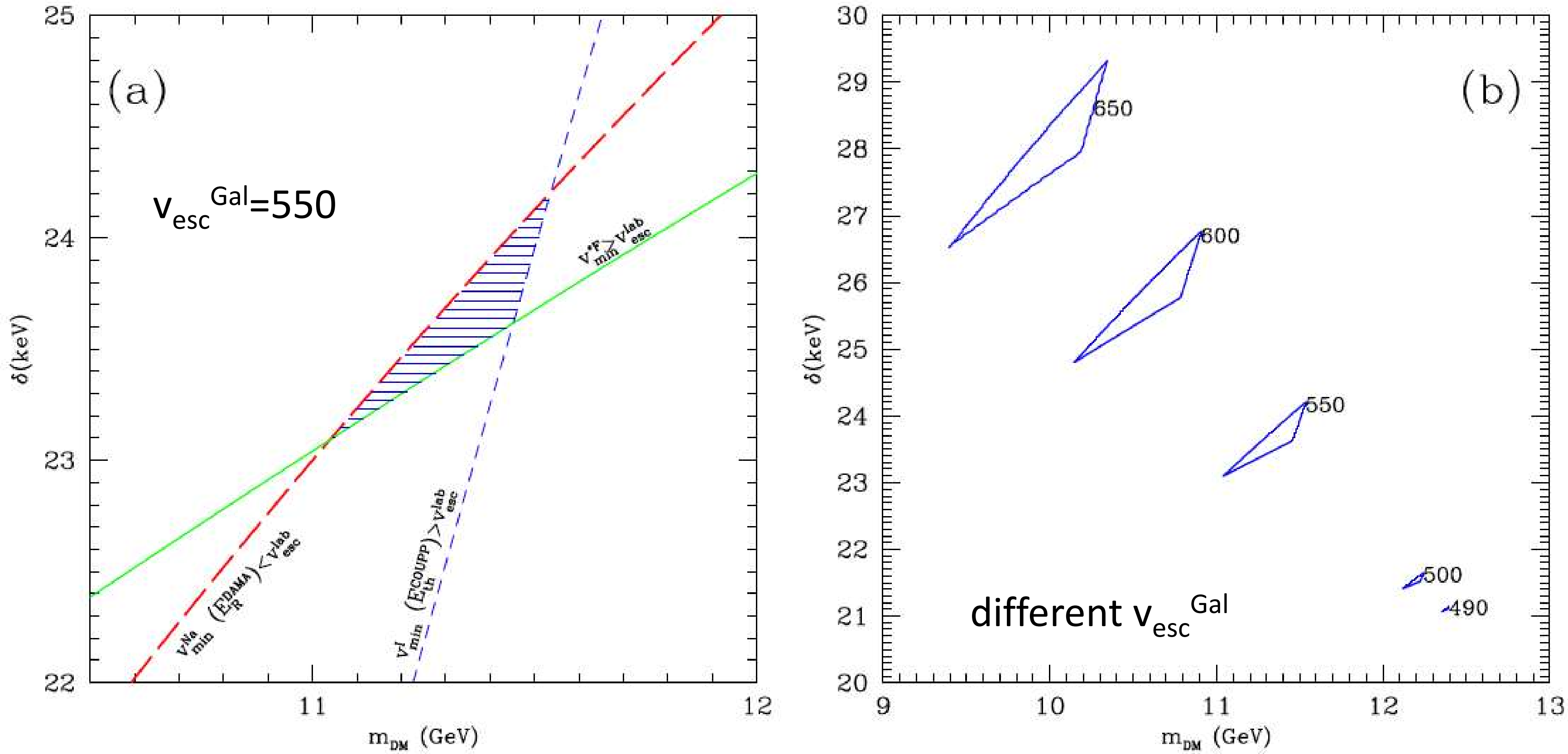

very tuned region. but this is just kinematics

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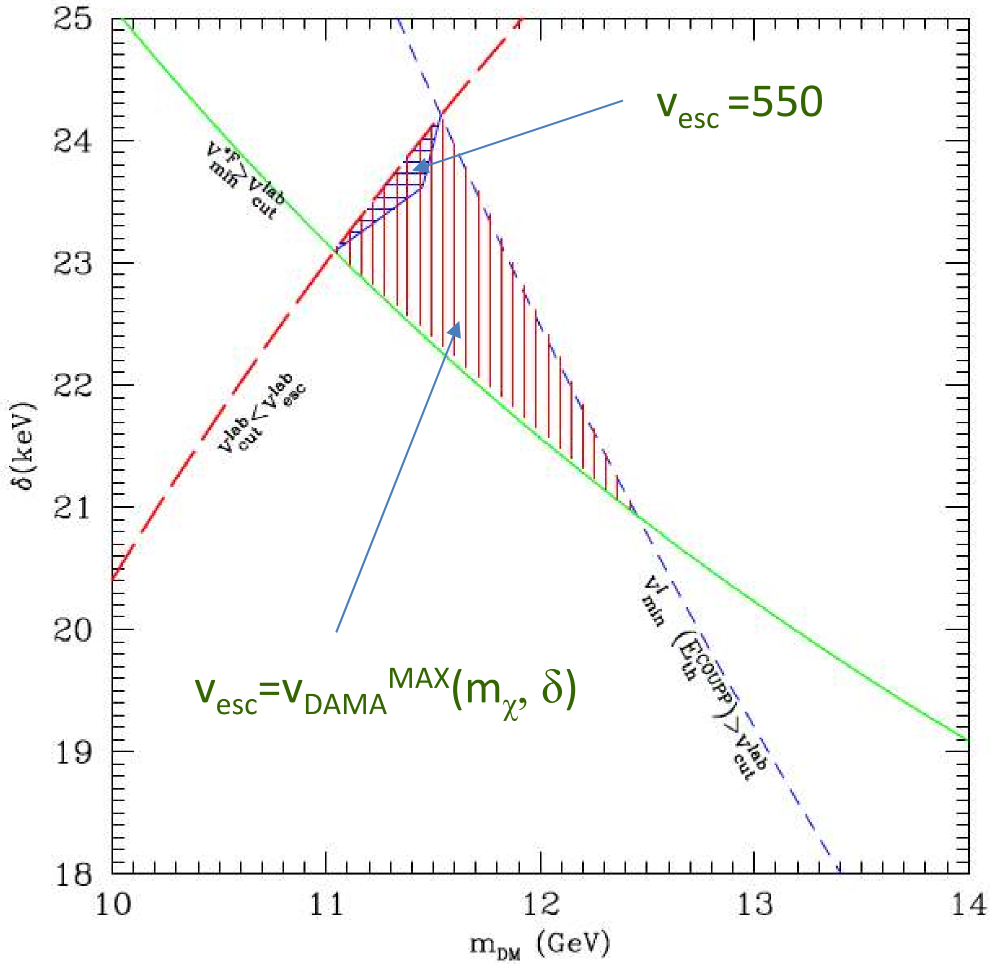
taking $v_{esc}=v_{DAMA}^{MAX}(m_\chi, \delta)$ the kinematic region enlarges considerably



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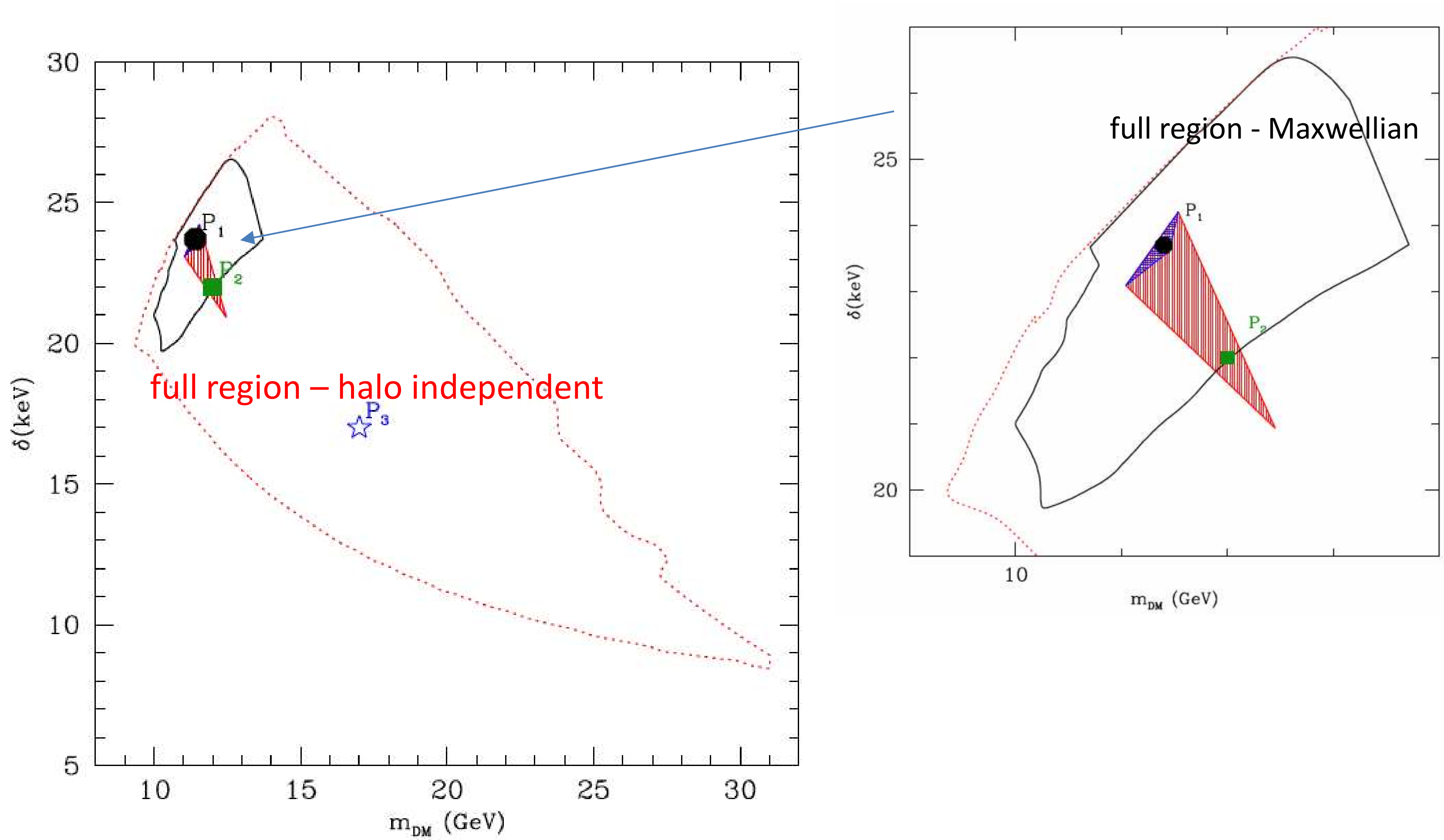
when including also the dynamics (through a full calculation of the compatibility factor) the two regions (Maxwellian and halo-independent) enlarge even more



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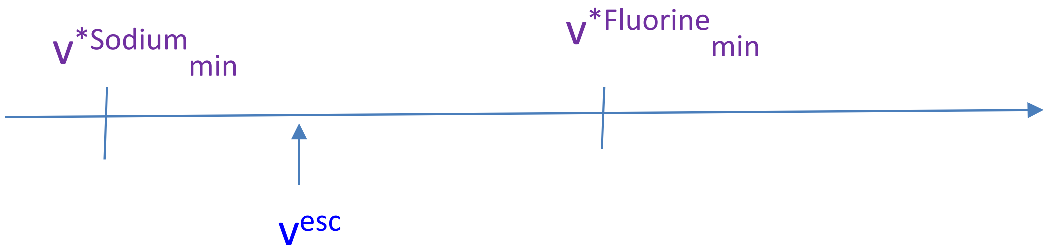
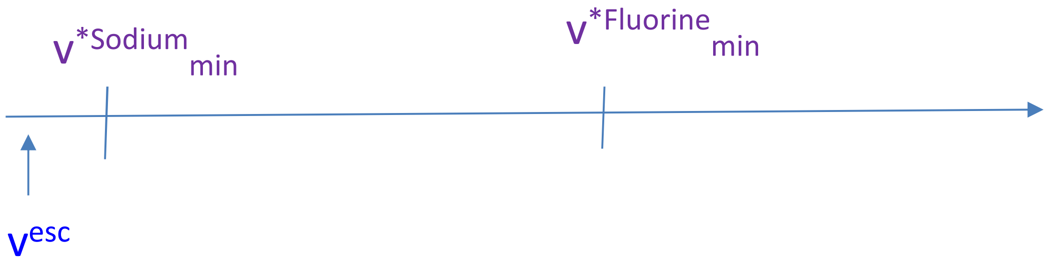
two interesting features arise naturally in this scenario:

- large modulation fraction of the signal (up to 100%)

due to the boost in the Earth rest frame v_{esc} oscillates back and forth while $v^{*Sodium}_{min}$ and $v^{*Fluorine}_{min}$ are fixed



June: signal in DAMA



December: no signal in DAMA

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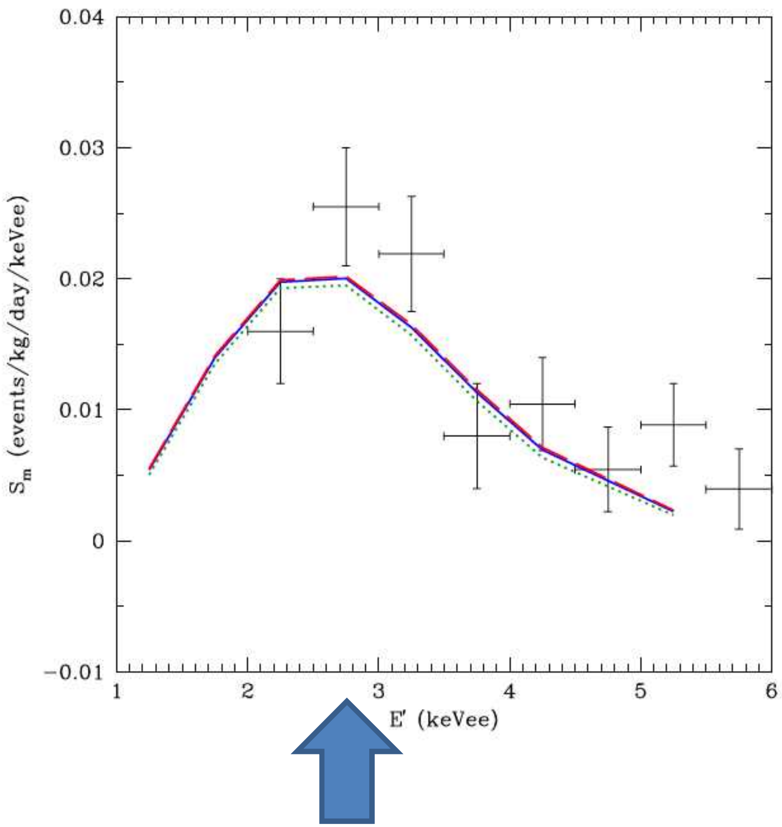
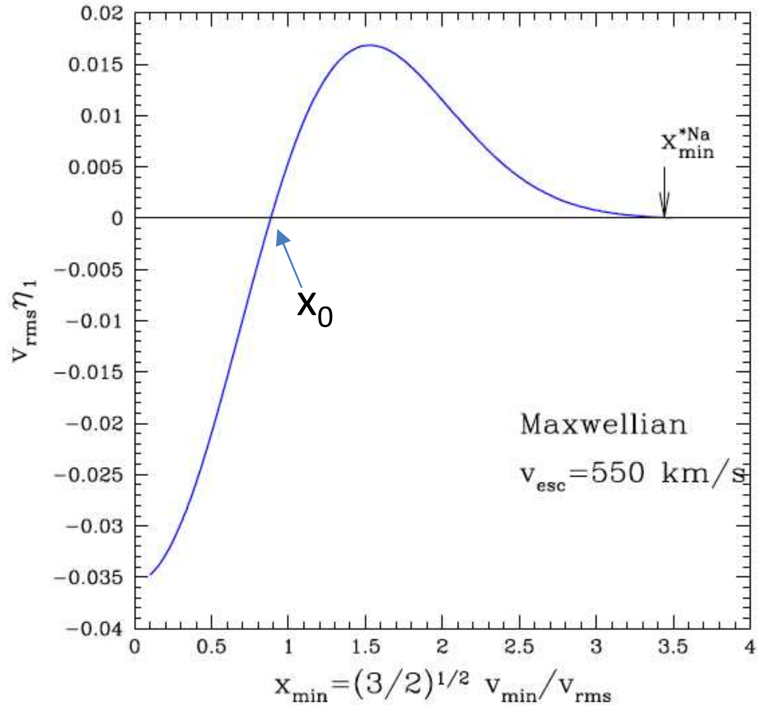
two interesting features arise naturally in this scenario:

- modulated fractions have a maximum close to the DAMA threshold

$$E_R^* = \delta \mu_{\chi N} / m_N$$ (recoil energy corresponding to $v^{*Sodium}_{min}$)



E_R^*



(close to v_{esc} η_1 is decreasing with v_{min} so has a maximum for v_{min}=v*)

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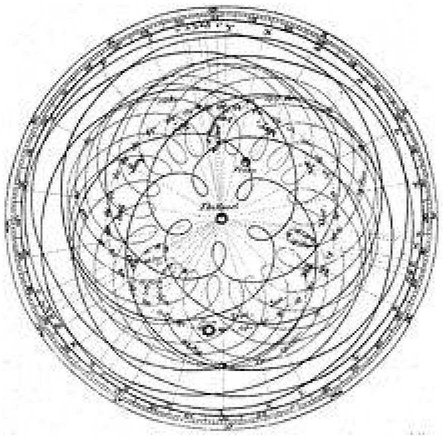
N.B. for elastic scattering the maximum in the DAMA modulation amplitudes is an indication that they change sign at low energy, i.e. that x_0 is just below the DAMA threshold. This requires *a low WIMP mass and is the reason why a Likelyhood analysis prefers the low-mass solution for elastic scattering*.

However in the inelastic case the modulation amplitude never changes sign because for any energy value $E_R<E_R^*$ there is another energy $E_R>E_R^*$ with the same η_1 (they both correspond to the same v_{min}) and at large E_R (v_{min}) η_1 is positive

if a future DAMA low-threshold analysis will not show a phase inversion at low energy this will be an indication of inelastic DM

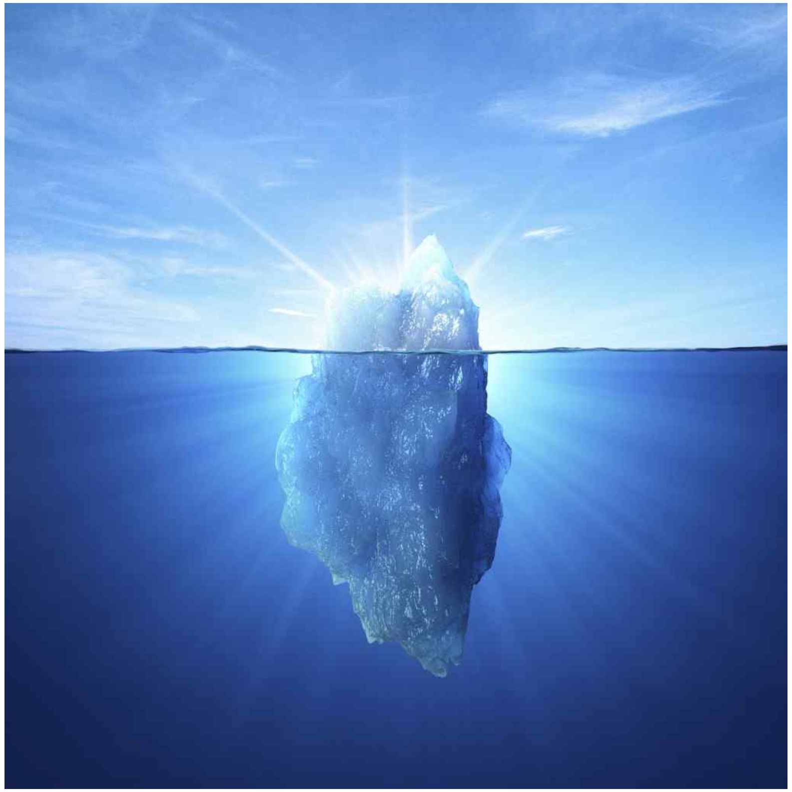


Several epicycles added to the usual scenario:

- Halo-independent
- Non-standard coupling
- Inelastic scattering
- Isospin violation
- ….

- Indeed, combining a halo-independent approach and/or a non-standard coupling (other than SI or SD) and/or inelastic scattering (different kinematics) and/or isospin violation compatibility among any of the “excesses” and constraints from null experiments can be achieved (S.S. and K.H. Yoon, JCAP 1602 (2016) no.02, 050; S.S.,K.H. Yoon and J.H. Yoon, JCAP 1507 (2015) no.07, 041; S.S. and J. H. Yoon, Phys.Rev. D91 (2015) no.1, 015019; S.S. and K.H. Yoon, JCAP 1408 (2014) 060)
- “Proofs of concept”

The bottom line:
Based on very well motivated theoretical assumptions we got used to a very simple WIMP direct detection parameter space (i.e. mass vs. SI sigma exclusion plots for isothermal sphere). However in principle it may be much larger: are we just starting now to scratch its surface?



Bottom-up approach

Conventional reference cross section and suppression scale

Given the effective Hamiltonian:

$$\mathcal{H} = \frac{1}{\Lambda^2}(c_i^0 + c_i^1 \tau_3)\mathcal{O}_i$$

τ_3=nuclear isospin operator, i.e.

$$c_i^{\mathrm{p}} = (c_i^0 + c_i^1)/2 \quad \text{(proton)}$$

$$c_i^{\mathrm{n}} = (c_i^0 - c_i^1)/2 \quad \text{(neutron)}$$

can factorize in the definition of the halo function the *conventional* reference WIMP-nucleon cross section:

$$\sigma_{ref} = \frac{(c_i^p)^2}{\Lambda^4} \frac{\mu_{\chi\mathcal{N}}^2}{\pi}$$

with:

$$\frac{1}{\mu_{\chi N}} = \frac{1}{m_\chi} + \frac{1}{m_{\mathcal{N}}}$$

$m_{\mathcal{N}}$ =nucleon mass

From direct detection data to suppression scale (simple halo-independent recipe)

Once $\tilde{\eta}$ is fixed by experiment need f(v) to get info on the cross section and the suppression scale Λ

$$\tilde{\eta}(v_{min}) \equiv \frac{\rho_\chi}{m_\chi}\sigma_0 \eta(v_{min})$$

Maximize η and *minimize* cross section taking:

$$f(\vec{v}) = \delta(v_s - v_{min})$$

(v_s = maximal value of the v_{min} range corresponding to the signal)

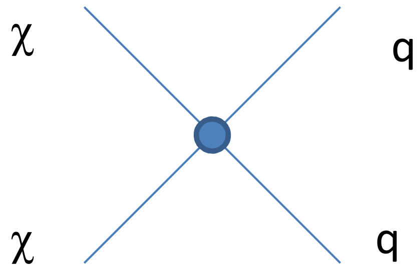
$$\Rightarrow \quad \tilde{\eta}^{max}(v_{min}) = \tilde{\eta}^{fit}\theta(v_s - v_{min})$$

N.B. corresponds to fitting the experimental etas to a constant value, works only if this is compatible to data

Then use:

$$\tilde{\eta}^{fit} = \frac{\rho}{m_\chi}\sigma\frac{1}{v_s}$$

Use Λ from the cross section determination to calculate the WIMP thermal relic abundance:



$$\Omega h^2 \simeq 0.12 \frac{< \tilde{\sigma v} >_0}{< \tilde{\sigma v} >}$$

$$< \tilde{\sigma v} >_0 = 2 \times 10^{-9} \mathrm{GeV}^{-2}$$

$$\mathcal{L} = \frac{1}{\Lambda^2} \sum_q c_q \bar{\chi} \Gamma^a \chi \bar{q} \Gamma^b q \quad \Rightarrow \quad < \tilde{\sigma v} > = \frac{1}{\Lambda^4} \sum_q |c_q|^2 < \tilde{\sigma v} >_q$$

where $< \tilde{\sigma v} >_q$ has GeV^2 dimension and grows with m_χ so that Ωh^2 decreases with m_χ

Actually, one should rescale the local DM density ρ_χ used to extract Λ:

$$\rho_\chi \to \xi \rho_\chi$$

with the rescaling factor:

$$\xi \equiv \frac{\Omega_\chi h^2}{(\Omega h^2)_{obs}} \simeq \frac{\Lambda^4}{\sum_q |c_q|^2 \frac{<\sigma\tilde{v}>_q}{<\sigma v>_0}}$$

In this case a direct detection experiment measures the combination $\varsigma\sigma_{ref,p}$ with:

$$\sigma_{ref,p} \simeq \frac{\mu^2}{\pi}\frac{c_p^2}{\Lambda^4}$$

$$\xi\sigma_{ref,p} = \frac{\mu^2}{\pi}\frac{c_p^2}{\sum_q |c_q|^2 \frac{<\sigma\tilde{v}>_q}{<\sigma v>_0}} = \frac{\mu^2}{\pi}\frac{c_p^2}{\tilde{\Lambda}^4}$$

dependence on Λ cancels out

$$\tilde{\Lambda} = \left(\frac{1}{\sum_q |c_q|^2 \frac{<\sigma\tilde{v}>_q}{<\sigma v>_0}}\right)^{\frac{1}{4}}$$

$\tilde{\Lambda}$ is just the Λ fixed by relic abundance, and would be measured also if $\Omega h^2 << (\Omega h^2)_{obs}$

Example: spin-dependent inelastic DM with coupling to protons

minimal effective coupling:

$$\mathcal{L}_{int} = \frac{c}{\Lambda^2}(\bar{\chi}_2\gamma_\mu\gamma_5\chi_1)(\bar{q}\gamma^\mu\gamma_5 q)$$

In the early Universe χ_2 and χ_1 are produced in the same amount ($\delta \ll T_{dec}$)
The decay amplitude for the process $\chi_2 \rightarrow \chi_1\,\gamma\,\gamma$ is

$$\Gamma_{\gamma\gamma} = \left(\frac{16\pi^2 f_\pi^2}{m_\pi^2}\right)^2 \frac{\alpha_{em}^2\delta^9}{512(315\pi^9)f_\pi^4}\frac{1}{\tilde{\Lambda}^4} \simeq 7.2\times 10^{-56}\left(\frac{\delta}{10\text{ keV}}\right)^9\left(\frac{10\text{ GeV}}{\tilde{\Lambda}}\right)^4 \text{GeV} \qquad \frac{c}{\Lambda^2}\equiv\frac{1}{\tilde{\Lambda}^2}$$

$$m_\pi \simeq 140\text{ MeV},\; f_\pi \simeq 93\text{ MeV}$$

So on a cosmological time scale χ_2 is stable ($\tau_0 \sim 1/(1.5 \times 10^{-42}$ GeV)) but downscatters of χ_2 to χ_1 are excluded by Fluorine detectors. Need to assume an additional coupling allowing to deplete χ_2's. For instance, assuming a direct coupling to neutrinos:

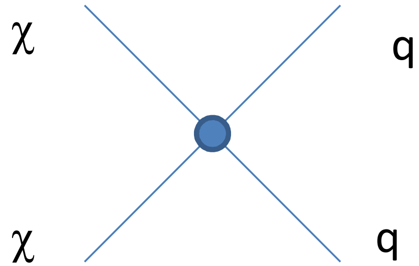
$$\mathcal{L}_{int,\nu} = \frac{c_\nu}{\tilde{\Lambda}^2}(\bar{\chi}_2\gamma_\mu\gamma_5\chi_1)(\bar{\nu}\gamma^\mu\gamma_5\nu)$$

one gets:

$$\Gamma_{\nu\nu} = \frac{11\delta^5}{768\pi^4}\frac{c_\nu^2}{\tilde{\Lambda}^4} \simeq 1.5\times c_\nu^2 10^{-33}\left(\frac{\delta}{10\text{ keV}}\right)^5\left(\frac{10\text{ GeV}}{\Lambda}\right)^4\text{GeV}$$

which allows a fast decay of the χ_2's also for $|c_\nu| \ll |c_q|$. In the latter case the correlation between the thermal relic abundance and direct detection is preserved so let's assume it in the following

1) Minimal condition for EFT validity at the scale of the relic abundance calculation:



$\Lambda > E_{TOT} = 2\, m_{\chi}$

2) Perturbativity:

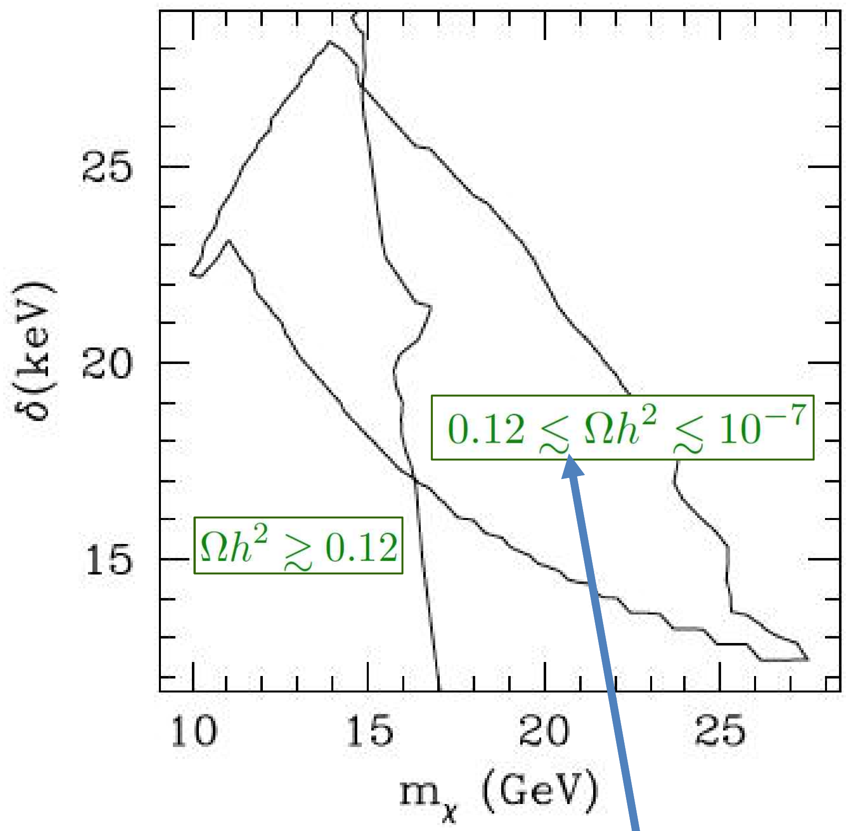
$|c_q| < 4\,\pi$

Combining the two conditions can get a minimal value for the rescaling factor ς

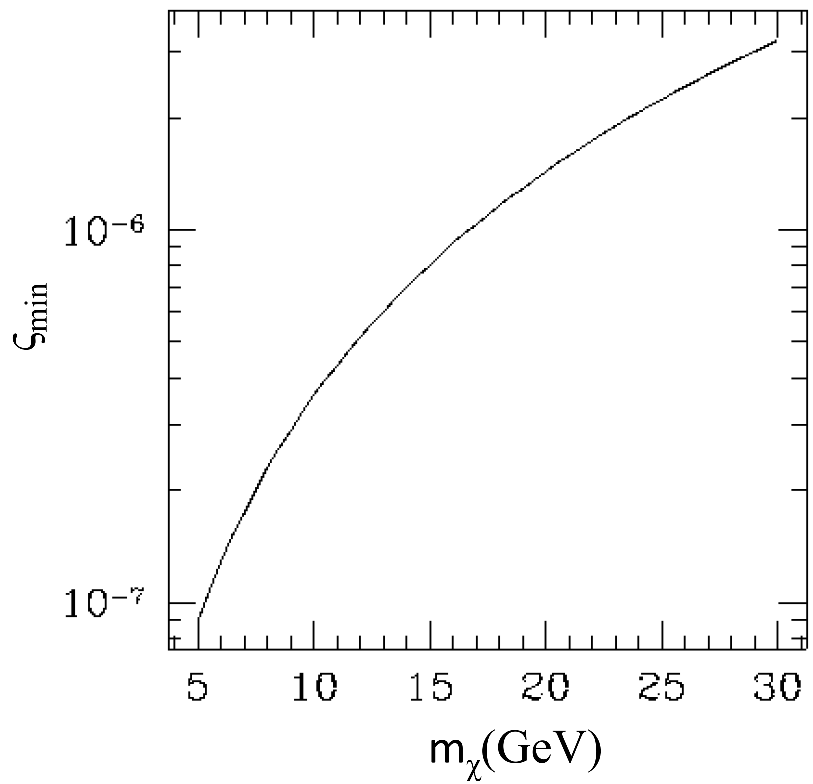
$$\xi > \frac{m_{\chi}^4 |r_q|^2 < \tilde{\sigma v} >_0}{\pi^2 \sum_q |r_q|^2 < \tilde{\sigma v} >_q}$$

with $r_q = c_q / c_u$

For spin-dependent inelastic DM with coupling to protons ($|c_v| << |c_q|$):



minimum rescaling



Λ extracted from DAMA is fine with the thermal relic density, but taking into account rescaling Ωh^2 can be anywhere between the observed value and 10^{-6} the observed value – no indirect detection for independent check since χ_2 cannot be around to annihilate with χ_1 due to direct detection contraints on downscatters

S.S., Yeonhye Yu, preliminary

Conclusions

• an explanation of the DAMA modulation result (or of other, less statistically significant "excesses") in terms of a WIMP signal is incompatible with the constraints published by other Dark Matter direct detection experiments only if direct-detection data are analyzed with ALL the following assumptions:

1) **spin-dependent** or **isoscalar spin-independent** cross section
2) **Maxwellian** velocity distribution in our Galaxy
3) WIMP **elastic** scattering

All these assumptions are reasonable if for instance the WIMP is a susy neutralino and if the DM particles in our Galaxy are fully thermalized.

•However, without any hint from the LHC about the underlying fundamental physics and without a detailed knowledge of the merger history of our Galaxy it appears safer to adopt a bottom-up layman approach. This includes:

1) using non-relativistic effective theory which introduces new response functions with explicit dependence on the transferred momentum and the WIMP incoming velocity
2) factorizing the halo-function dependence
3) allowing for inelastic scattering
4) allowing for isovector couplings

• In this way a much wider parameter space opens up.

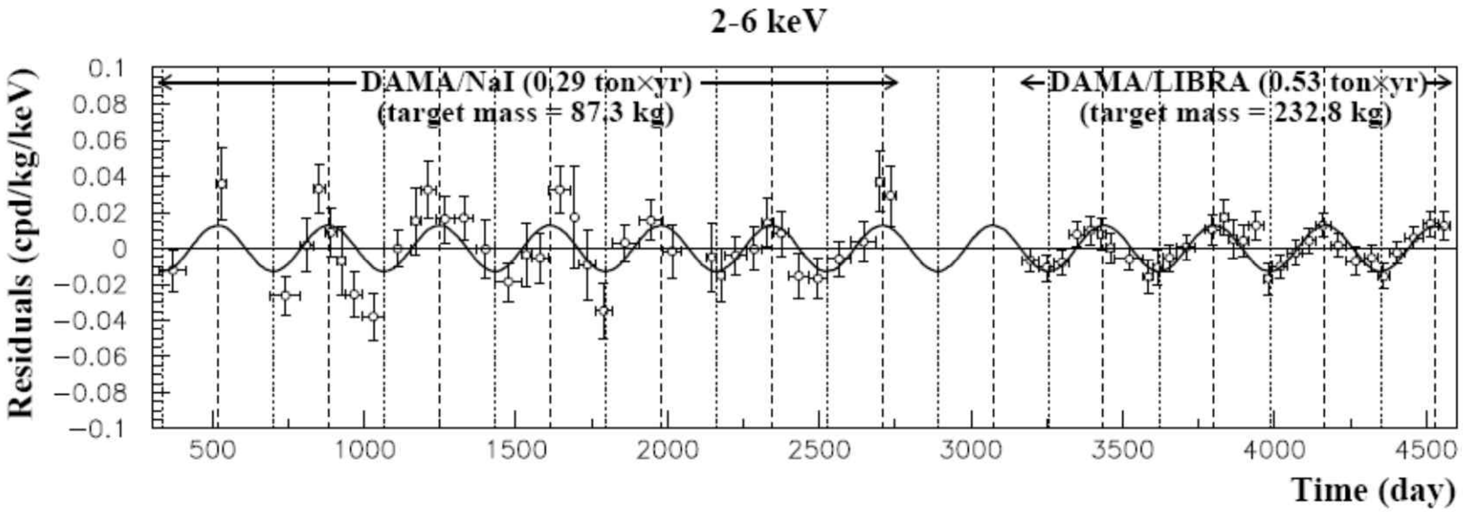
• First explorations show that indeed compatibility between excesses and constraints can be achieved → **full correlation with indirect signals and relic abundance needs still to be worked out**

• **"Proofs of concept" (but if by chance you have a nice model for spin-dependent Inelastic Dark Matter that couples only to protons it works just fine for DAMA)**

“Excesses”

DAMA/Libra result (Bernabei et al., Eur.Phys.J.C56:333-355,2008, arXiv:0804.2741)

0.53 ton x year (0.82 ton x year combining previous data)
8.2 σ C.L. effect



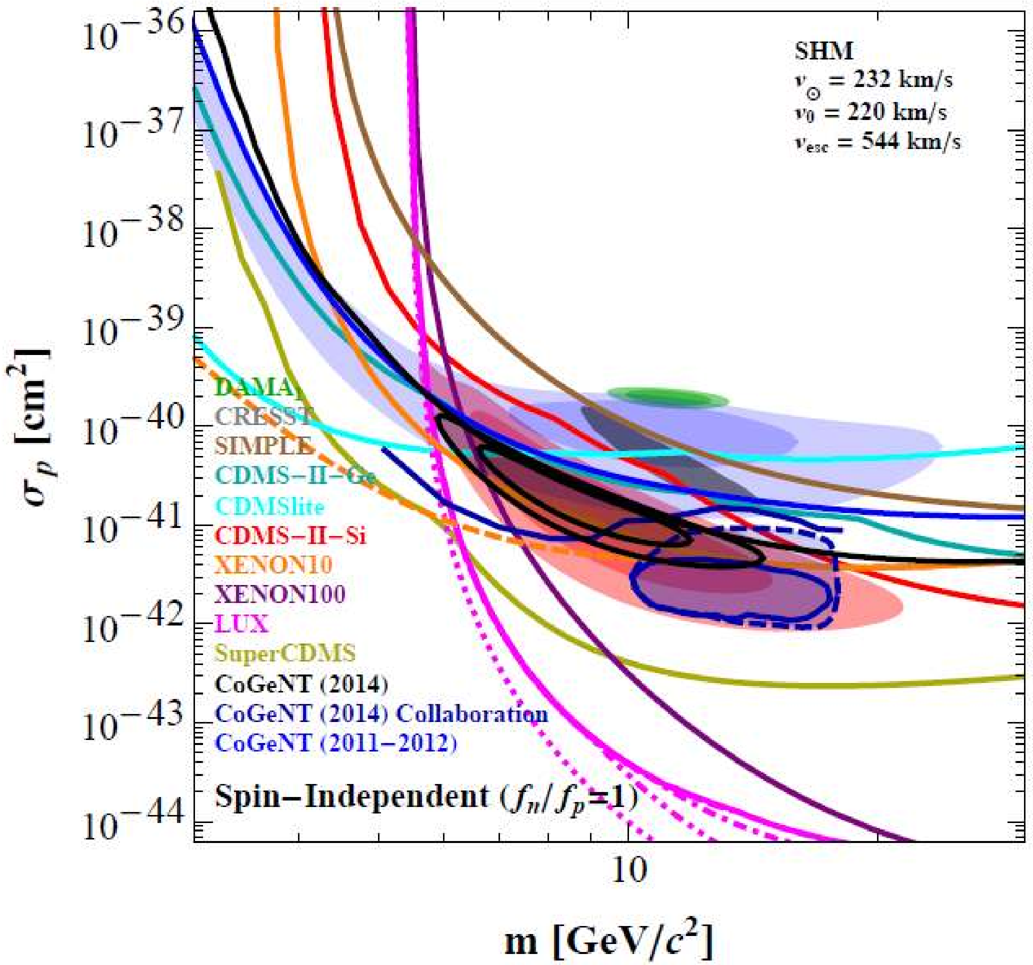
	A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (day)	C.L.
DAMA/NaI				
(2–4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2–5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2–6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA				
(2–4) keV	0.0213 ± 0.0032	0.997 ± 0.002	139 ± 10	6.7σ
(2–5) keV	0.0165 ± 0.0024	0.998 ± 0.002	143 ± 9	6.9σ
(2–6) keV	0.0107 ± 0.0019	0.998 ± 0.003	144 ± 11	5.6σ
DAMA/NaI+ DAMA/LIBRA				
(2–4) keV	0.0223 ± 0.0027	0.996 ± 0.002	138 ± 7	8.3σ
(2–5) keV	0.0178 ± 0.0020	0.998 ± 0.002	145 ± 7	8.9σ
(2–6) keV	0.0131 ± 0.0016	0.998 ± 0.003	144 ± 8	8.2σ

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

$\omega = 2\pi/T_0$

Situation @ low WIMP mass

Spin-independent interaction, isothermal sphere



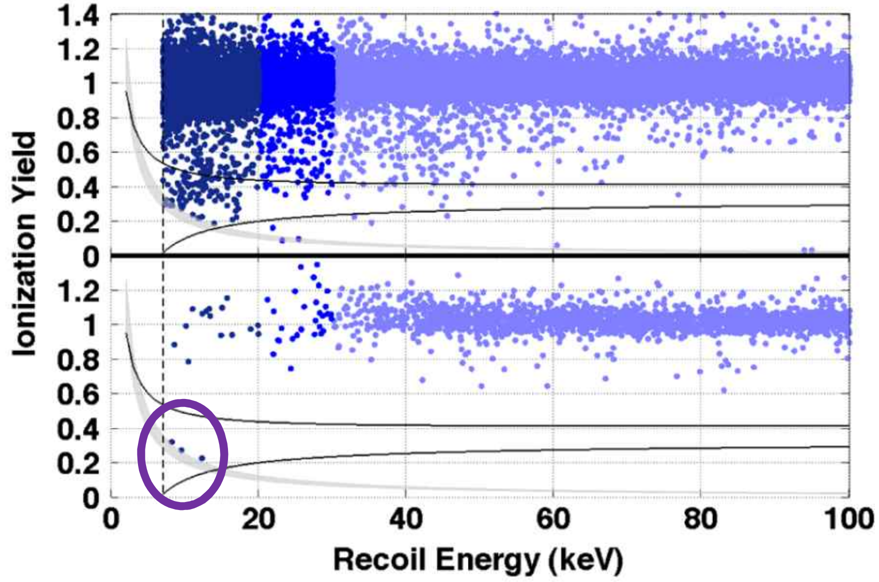
- qualitatively LUX is similar to XENON100
- stronger constraints at lowest masses from CDMSlite + Xenon10

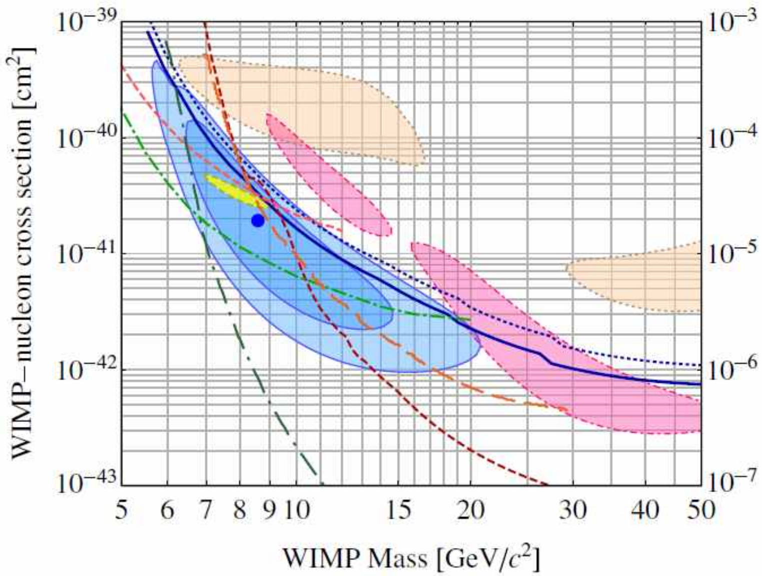
An explanation of DAMA in terms of a WIMP signal seems doomed

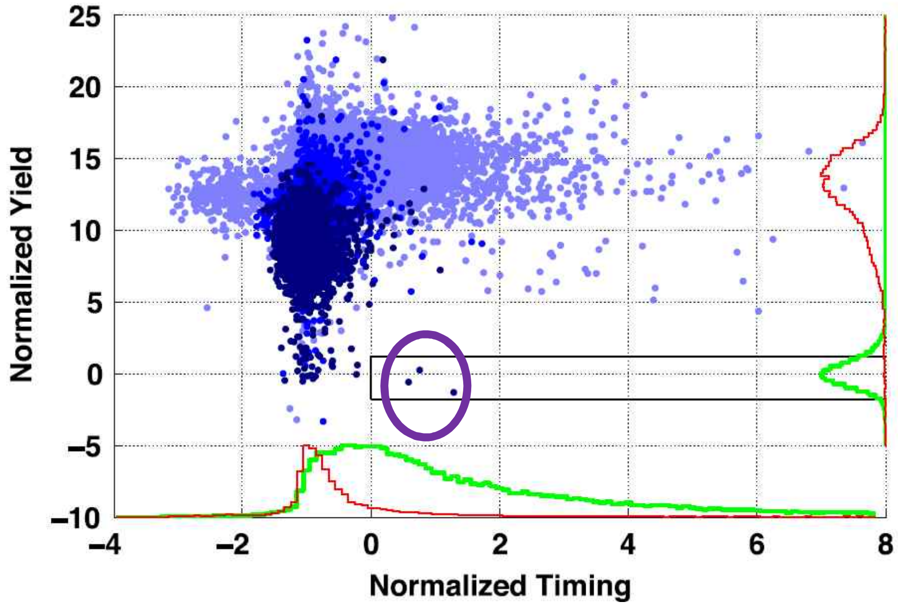
(E. Del Nobile, G. Gelmini, P. Gondolo, J.H. Huh , 1405.5582)

The CDMS II Silicon excess

- dual signal (phonons+ionization) used to discriminate background
- total exposure of 140.2 kg days with eight Silicon detectors of ~106 g each in the energy range 7-100 keV
- ~23.4 kg day equivalent exposure after selection cuts for 10 GeV WIMP
- 3 WIMP-candidate events survive with expected background <0.6 events (~5% probability of bck fluctuation)







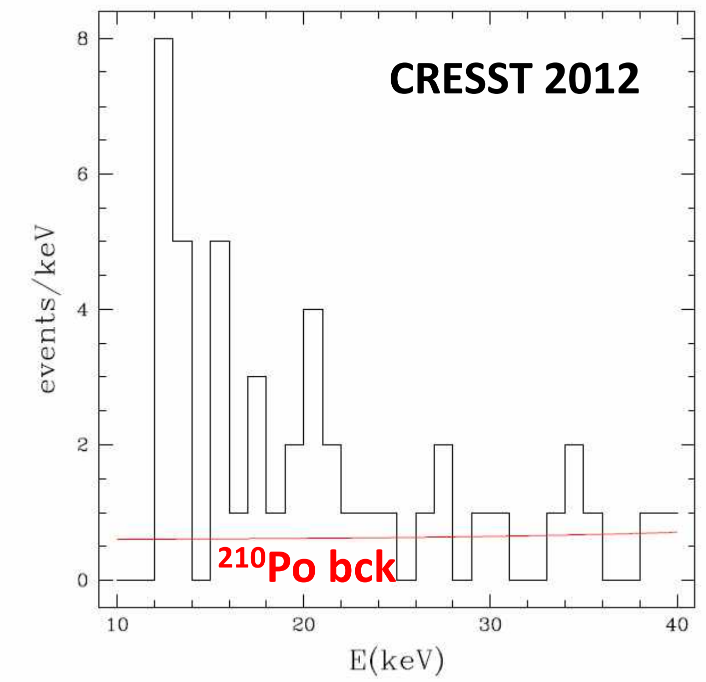
R.Agnese et al. (CDMS Collaboration), Phys.Rev.Lett.111, 251301 (2013),1304.4279

The CRESST excess (btw: is it gone)?

CRESST 2012:

G. Angloher et al (CRESST Coll.) Eur. Phys. J.C72, 1971 (2012), 1109.0702

- 730 kg day with $CaWO_4$ (light+phonons)
- "excess" (total of 34 events in Tungsten recoil band for 12 keVnr<E_R<24 keVnr vs. 7.4 expected due to lead recoil background from ^{210}Po decay)
- sizeable surface background from non-scintillating clamps holding the crystals.

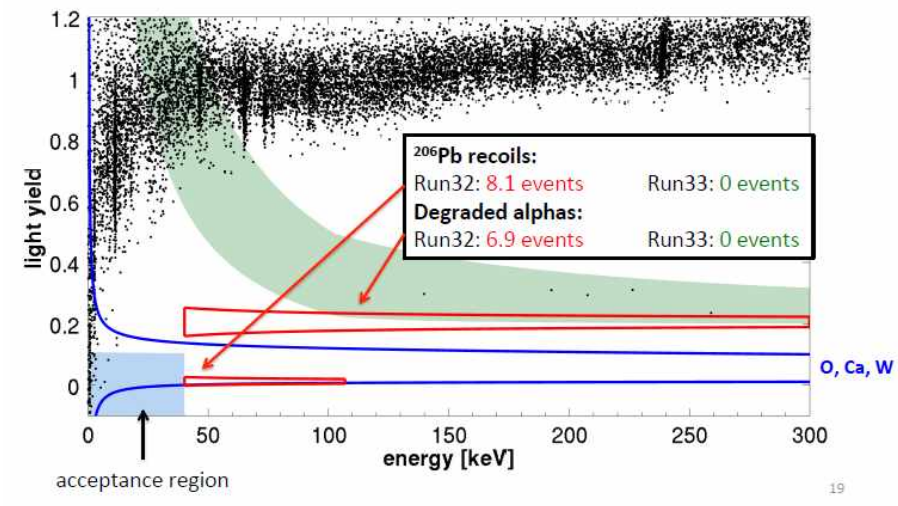


- **CRESST 2014**:

G. Angloher et al(CRESST-II Collaboration),1407.3146

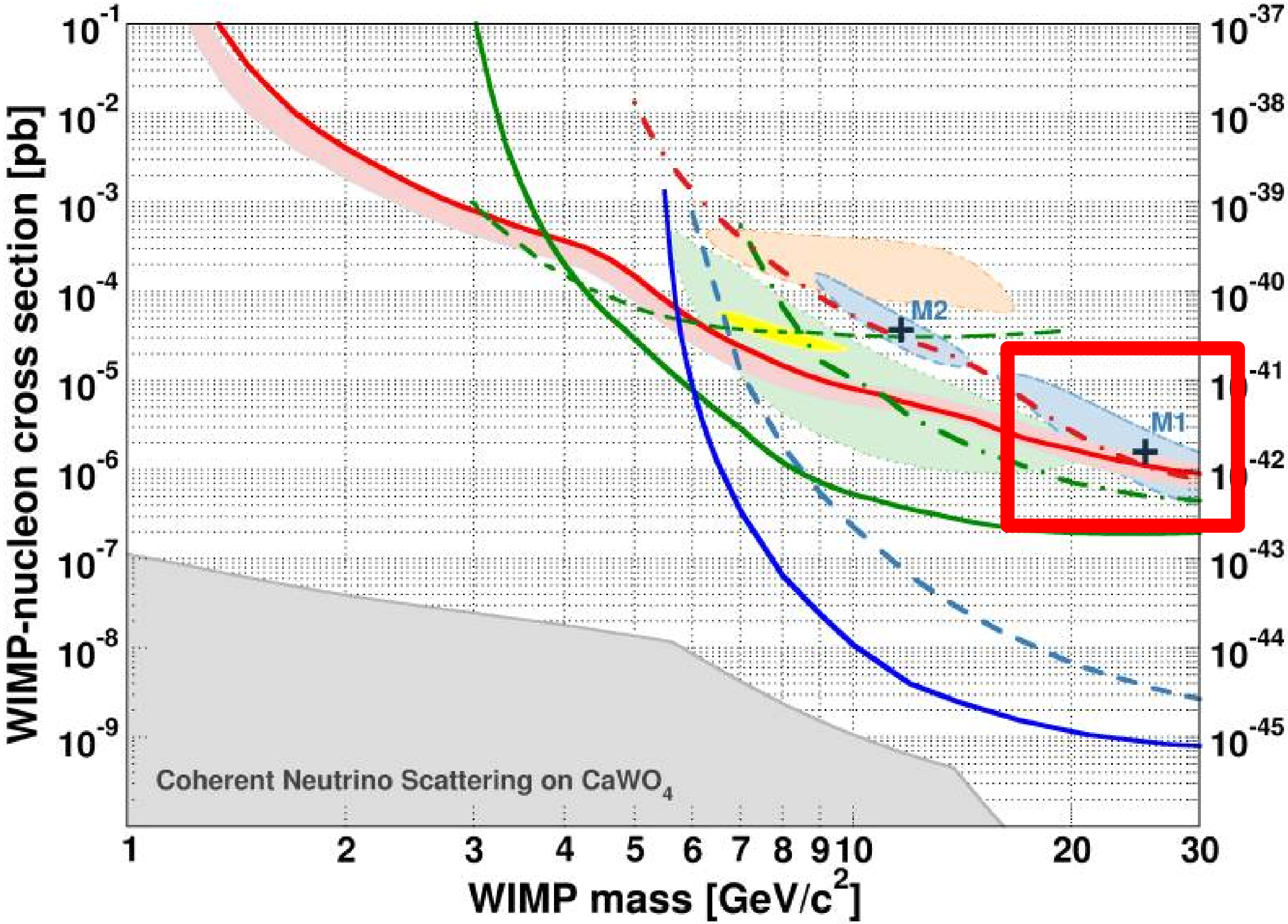
- Improved radiopurity and fully-scintillating design for one 250 g detector module (TUM-40)
- total exposure: 29 kg days
- additional light from surface events allows efficient veto of surface background
- no longer events in previous excess region and **lower threshold**: low-mass WIMP solution ruled out **while high-mass WIMP solution survives**
- back-of-the-envelope estimation: 30*29/730~1.2 events. 90% CL upper bound of 0 is 2.3, simply exposure is too low to rule out previous effect → need more stawswcs

CRESST 2014



The CRESST excess

G. Angloher et al(CRESST-II Collaboration),1407.3146



- still marginal compatibility for high-mass solution assuming isothermal sphere
- full compatibility relaxing assumptions on velocity distribution

thresholdinos?