ICHEP2018 SEOUL

A frequentist analysis of proton-philic spin-dependent inelastic Dark Matter (pSIDM) as an explanation of the DAMA effect

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In collaboration with
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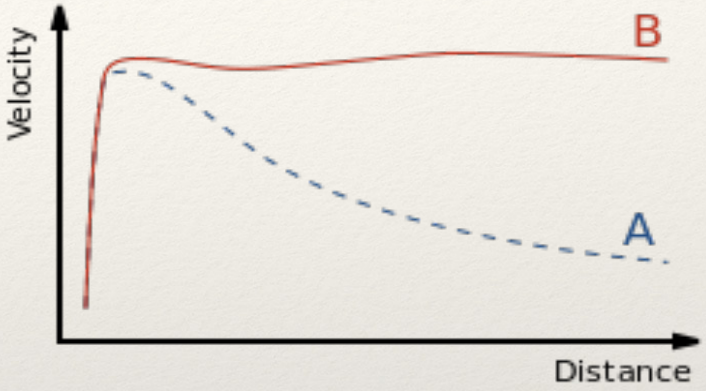
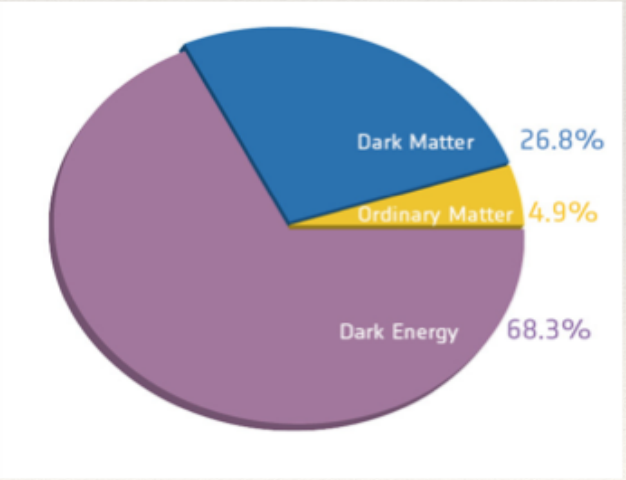
Introduction

- Dark Matter and the Standard Model
- Numerous evidences
- A variety of candidates
- WIMP (Weakly Interacting Massive Particle)
- Worldwide efforts to search for DM

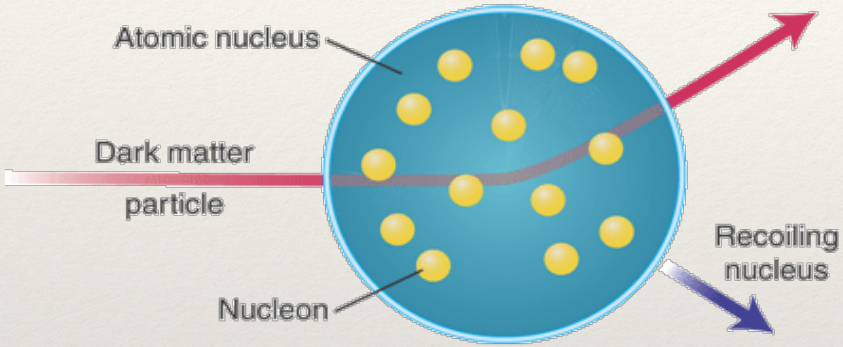




(Credit: ESA and the Planck Collaboration.)

Introduction

- Dark Matter Direct Detection



(CREDIT: PRESTON HUEY/SCIENCE)

(COSINE-100 Dark Matter Experiment)

- WIMP rates

$$R_{[E'_1,E'_2]} = MT \int_{E'_1}^{E'_2} \frac{dR}{dE'}\, dE'$$

$$\frac{dR}{dE'} = \sum_T \int_0^\infty \frac{dR_{\chi T}}{dE_{ee}} \mathcal{G}_T(E', E_{ee}) \epsilon(E')\, dE_{ee}$$

$$E_{ee} = q(E_R) E_R,$$

proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

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%

If the WIMP particle couples only to protons ($c^n/c^p \ll 1$) in a spin-dependent way the rate for Germanium and Xenon detectors is strongly suppressed and their bounds can be evaded

proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

- Low v_min can explain the DAMA excess and the null signal from other experiments

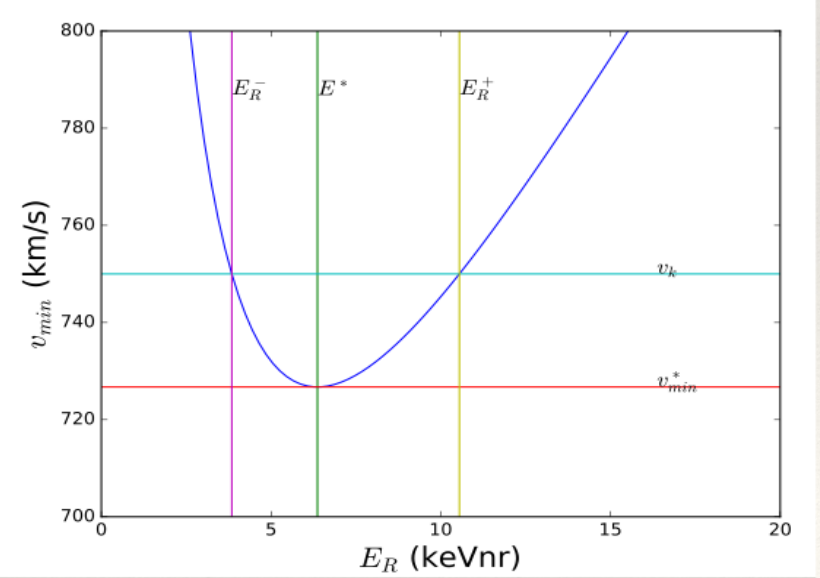
$$\frac{dR_{\chi T}}{dE_R} = N_T \int_{v_{min}}^{v_{esc}} \frac{\rho_\chi}{m_\chi} v \frac{d\sigma_{\chi T}}{dE_R} f(v) dv,$$

$$\int_0^\infty dE_R \int_{v_{min}}^\infty dv \rightarrow \int_{v^*_{min}}^\infty dv \int_{E_R^-(v)}^{E_R^+(v)} dE_R, \quad E_R^\pm(v_{min}, m_\chi, \delta) = \frac{\mu_{\chi N}^2}{m_N}\left[v_{min}^2 - \frac{(v^*_{min})^2}{2} \pm \sqrt{v_{min}^2 - (v^*_{min})^2}\right],$$

$$v^*_{min} = \sqrt{\frac{2\delta}{\mu_{\chi N}}}, \quad v_{min} = \frac{1}{\sqrt{2 m_N E_R}}\left|\frac{m_N E_R}{\mu_{\chi N}} + \delta\right|,$$

$$v^{*Na}_{min} < v^{lab}_{cut} < v^{*F}_{min},$$

For appropriate choice of parameters WIMP-fluorine scatterings can be kinematically forbidden while WIMP-sodium scatterings can explain the DAMA effect



proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

- Non-relativistic effective models

$$\mathcal{H} = \sum_{\tau=0,1}\sum_{k=1}^{15} c_k^\tau \mathcal{O}_k\, t^\tau, \quad t^0 = 1,\ t^1 = \tau_3$$

$$\frac{d\sigma_{\chi T}}{dE_R} = \frac{1}{10^6}\frac{2m_T}{4\pi}\frac{c^2}{v^2}\left[\frac{1}{2j_\chi+1}\frac{1}{2j_T+1}\sum_{spin}|\mathcal{M}_T|^2\right]$$

$$\frac{1}{2j_\chi+1}\frac{1}{2j_T+1}\sum_{spin}|\mathcal{M}_T|^2 = \frac{4\pi}{2j_T+1}\sum_{\tau\tau'}\sum_{l} R_l^{\tau\tau'} W_{T,l}^{\tau\tau'}, \quad l{=}M,\Sigma'',\Sigma',\Phi'',\Phi''M,\tilde{\Phi}',\Delta,\Delta\Sigma'$$

$$R_l^{\tau\tau'} = R_{0,l}^{\tau\tau'} + R_{1,l}^{\tau\tau'}(v^2 - v_{min}^2).$$

$$\mathcal{L}_{int} \ni c^p \vec{S}_\chi \cdot \vec{S}_p + c^n \vec{S}_\chi \cdot \vec{S}_n,$$

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.

proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

- Reassemble the integration

$$R_{[E_1',E_2']} = \frac{\rho_\chi}{m_\chi}\sigma_p \int_{v_{min}^*}^{\infty} dv \hat{\mathcal{H}}(v) f(v), \quad \sigma_p = (c_4^p)^2 \frac{\mu_{\chi N}^2}{\pi},$$

$$\hat{\mathcal{H}}(v) = \sum_T N_T M T \frac{c^2}{v} \frac{m_T}{\mu_{\chi T}^2} \frac{2\pi}{10^6} \int_{E_R^-(v)}^{E_R^+(v)} dE_R \int_{E_1'}^{E_2'} dE' \epsilon(E') \mathcal{G}_T[E', q(E_R)E_R] \times$$
$$\frac{1}{2j_T+1} \sum_{\tau\tau'} \sum_l \left[\hat{R}_{0,l}^{\tau\tau'} + \hat{R}_{1,l}^{\tau\tau'}(v^2 - v_{min}^2)\right] W_l^{\tau\tau'} =$$
$$\frac{c^2}{v} \int_{E_R^-(v)}^{E_R^+(v)} dE_R \left\{\hat{\mathcal{R}}_0(E_R) + \hat{\mathcal{R}}_1(E_R)(v^2 - v_{min}(E_R)^2)\right\},$$

$$\hat{\mathcal{R}}_{\{0,1\}} = \sum_T N_T M T \frac{m_T}{\mu_{\chi T}^2} \frac{2\pi}{10^6} \int_{E_1'}^{E_2'} dE' \epsilon(E') \mathcal{G}_T[E', q(E_R)E_R] \frac{1}{2j_T+1} \sum_{\tau\tau'} \sum_l \hat{R}_{\{0,1\},l}^{\tau\tau'} W_l^{\tau\tau'}$$

$$= \sum_T \left[\hat{\mathcal{R}}_{\{0,1\}}\right]_T, \qquad \hat{R}_{0,l}^{\tau\tau'} \equiv R_{0,l}^{\tau\tau'}/(c_4^p)^2$$

proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

- Halo-independent analysis

$$f(v) \equiv -v\frac{d}{dv}\eta(v), \quad R_{[E'_1,E'_2]} = \frac{\rho_\chi}{m_\chi}\sigma_p \int_0^\infty dv\hat{\mathcal{R}}(v)\eta(v) = \int_0^\infty dv\mathcal{R}(v)\tilde{\eta}(v),$$

$$\tilde{\eta}(v,t) = \frac{\rho_\chi}{m_\chi}\sigma\eta(v,t), \quad \eta(v,t) = \int_v^\infty \frac{f(v,t)}{v}\,dv, \qquad \hat{\mathcal{R}}(v) = \frac{d}{dv}\left[v\hat{\mathcal{H}}(v)\right]$$

$$\tilde{\eta}_{0,1}(v) = \sum_{k=1}^{N} \tilde{\eta}^k_{0,1}\theta(v - v_{k-1})\theta(v_k - v), \quad \tilde{\eta}^k_{0,1}(v_{min}) = \sum_{i=k}^{N} \delta\tilde{\eta}^i_{0,1},$$

$$R_{[E'_1,E'_2]} = N_T MT\frac{\rho_\chi}{m_\chi}\sigma \int_{v^*_{min}}^\infty dv\frac{d}{dv}\left\{v\frac{c^2}{v}\int_{E_R^-(v)}^{E_R^+(v)} dE_R\left\{\hat{\mathcal{R}}_0(E_R) + \hat{\mathcal{R}}_1(E_R)[v^2 - v_{min}(E_R)^2]\right\}\right\}$$

$$\times \sum_{k=1}^{N}\delta\tilde{\eta}^k\theta(v_k - v) = N_T MT\frac{\rho_\chi}{m_\chi}\sigma c^2\sum_{k=1}^{N}\delta\tilde{\eta}^k \times$$

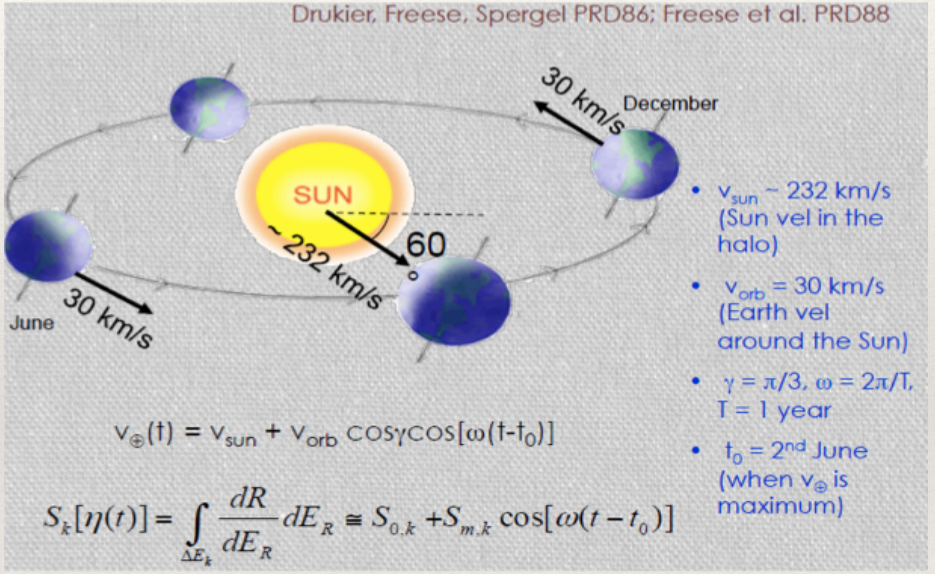
$$\int_{E_R^-(v)}^{E_R^{max}(v_k)} dE_R\left\{\hat{\mathcal{R}}_0(E_R) + \hat{\mathcal{R}}_1(E_R)[v_k^2 - v_{min}(E_R)^2]\right\}.$$

proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

- DAMA experiment and Annual modulation

Average rate

$$S_0 \equiv \frac{1}{T}\int_0^T S(t)dt = \int_0^\infty \mathcal{R}(v)\tilde{\eta}_0(v)\,dv,$$
$$\tilde{\eta}_0(v) \equiv \frac{1}{T}\int_0^T \tilde{\eta}(v,t)dt,$$



Annual modulation

$$S_1 \equiv \frac{2}{T}\int_0^T \cos\left[\frac{2\pi}{T}(t-t_0)\right] S(t)dt = \int_0^\infty \mathcal{R}(v)\tilde{\eta}_1(v)\,dv,$$
$$\tilde{\eta}_1(v) \equiv \frac{2}{T}\int_0^T \cos\left[\frac{2\pi}{T}(t-t_0)\right] \tilde{\eta}(v,t)dt,$$

proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

- Likelihood analysis

$$-2\ln\mathcal{L}(\mathbf{d}|\Theta) = \sum_{n=1}^{N_{DAMA}} \left(\frac{S_{1,n}(\Theta) - S_{1,n}^{exp}}{2\sigma_n^{exp}}\right)^2 - 2\sum_{i=1}^{N_{exp}}\sum_{j=1}^{N_{bin}^i} \mathcal{L}_j^i(\Theta) \qquad \theta \equiv (m_\chi, \delta, r)$$

$$\Theta = (\theta, \eta) \quad -2\mathcal{L}_j^i(\Theta) = 2\left[S_{0,j}^i(\Theta) + B_j^i - N_j^i - N_j^i \ln\frac{S(\Theta)_{0,j}^i + B_j^i}{N_j^i}\right]$$

$S_{1,n}$ is the prediction of the DAMA modulation amplitude in the n–th bin

$S_{1,n}^{exp}$ the corresponding measurement with error σ_n^{exp}

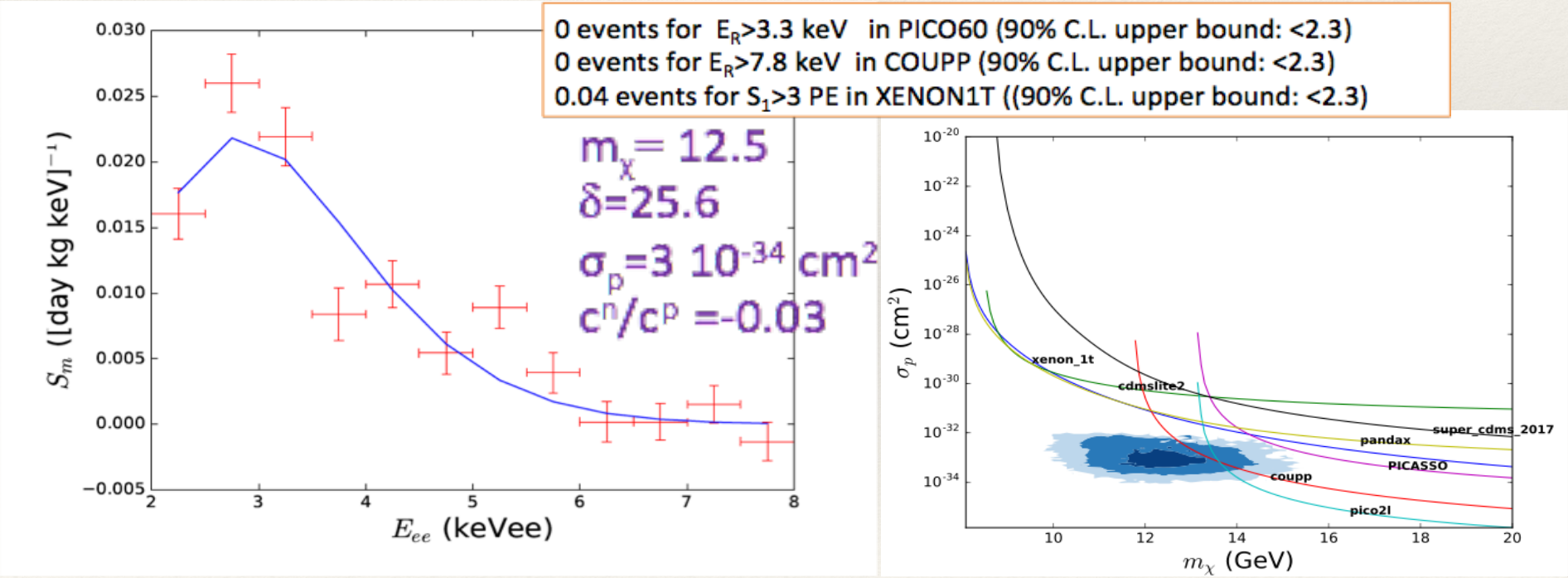
$S_{0,j}^i$ the expected rate in the i–the energy bin of the j–th experiment

N_j^i the corresponding measured count rate

B_j^i the expected background

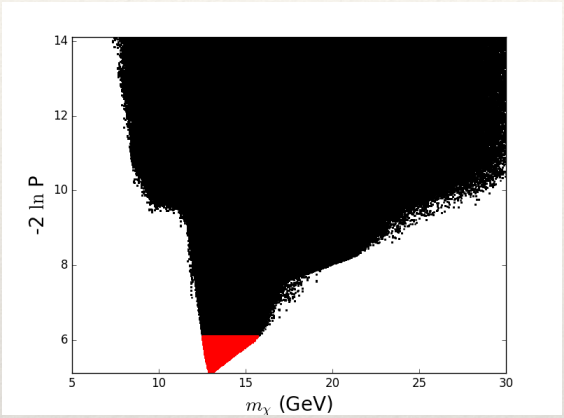
proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

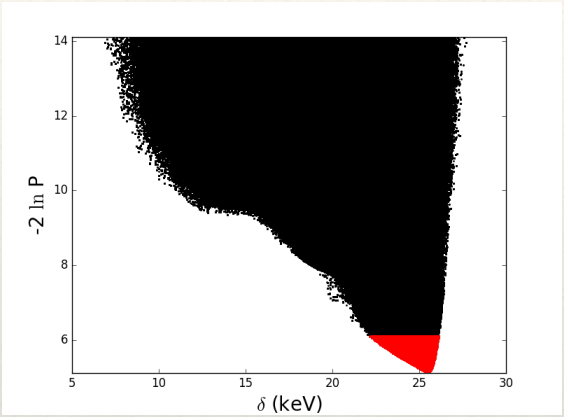
- DAMA run 1
- Best fit: $\chi 2 = 8.5$ with 12-4 d.o.f. (p-value: 0.38)

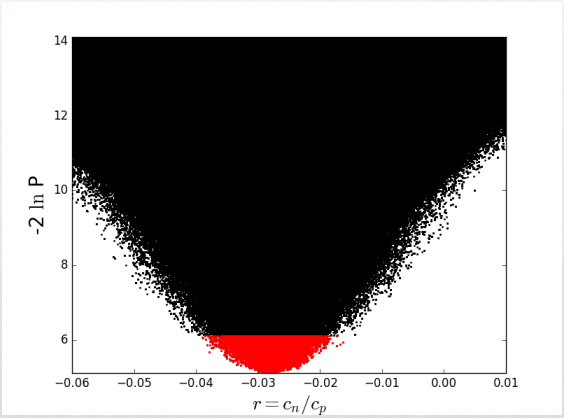


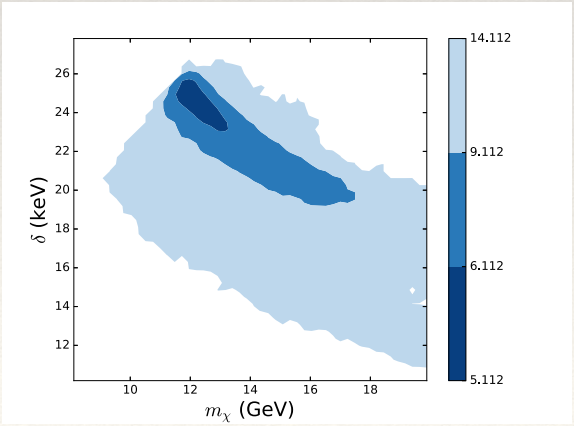
proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

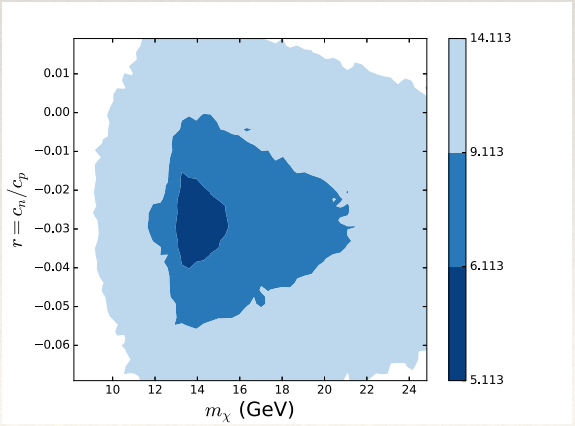
DAMA/LIBRA phase-1 (frequentist interval for three parameters: WIMP mass, mass splitting and c^n/c^p)

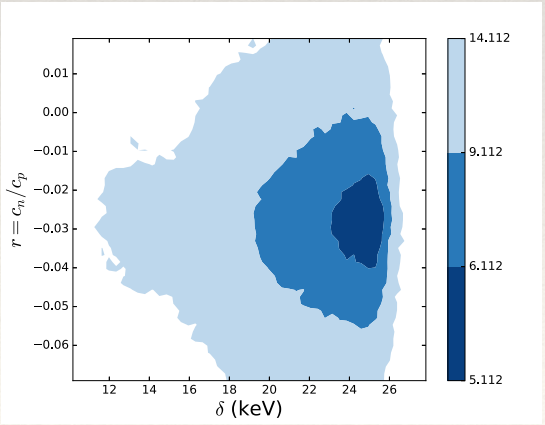












proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

DAMA/LIBRA phase-1 (frequentist interval for three parameters: WIMP mass, mass splitting and c^n/c^p)

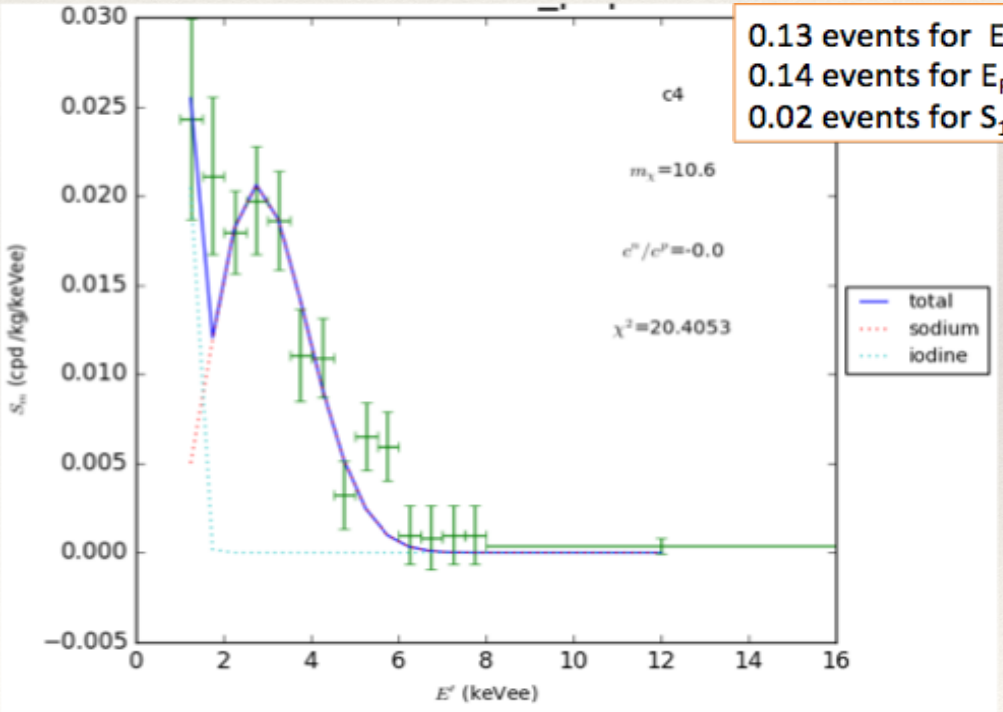
$$12.5\ \text{GeV} \leq m_\chi \leq 15.7\ \text{GeV}$$
$$22.1\ \text{keV} \leq \delta \leq 26.1\ \text{keV}$$
$$-0.039 \leq r \leq -0.016.$$

For this choice of parameters, pSIDM explains DAMA/LIBRA phase-1 in compliance with ALL other constraints!

DAMA/LIBRA phase-2 changed it all : lower threshold brings in WIMP-iodine scatterings

proton–philic Spin–dependent Inelastic Dark Matter (pSIDM)

- pSIDM update with DAMA run2
- Harder to fit iodine in the first two bin
- Best fit: $\chi 2 = 20.4$ with 11 d.o.f. (p-value: 0.04)



0.13 events for E_R>3.3 keV in PICO60 (90% C.L. upper bound: <2.3)
0.14 events for E_R>7.8 keV in COUPP (90% C.L. upper bound: <2.3)
0.02 events for S_1>3 PE in XENON1T ((90% C.L. upper bound: <2.3)

$m_\chi = 10.6$
$\delta = 22.5$
$\sigma_p = 1.5\ 10^{-33}\ cm^2$
$c^n/c^p = 0$

Work in progress

- We are working on it
- In the meantime today I will discuss DAMA phase2 in non-relativistic effective models

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DAMA/LIBRA-phase2 in WIMP effective models

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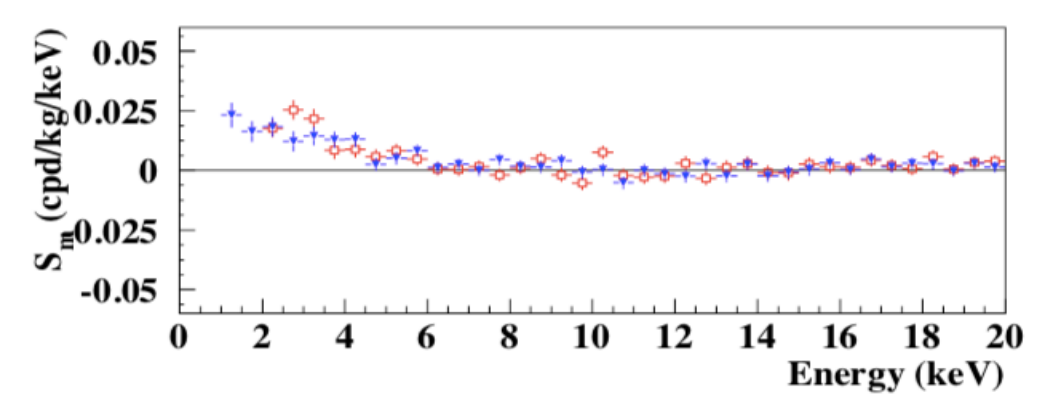
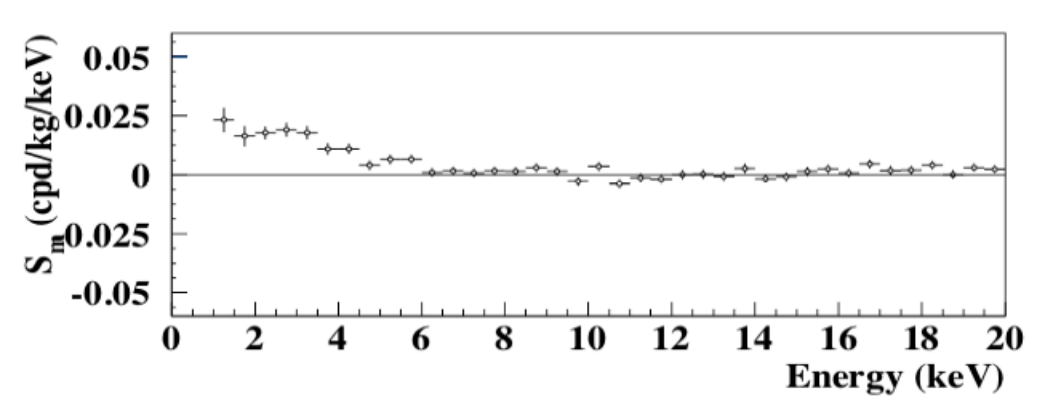
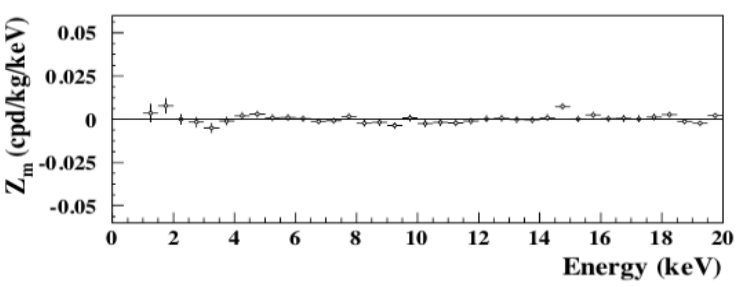
DAMA/LIBRA-phase2 in WIMP effective models

- DAMA released the first model independent results





Energy	S_m (cpd/kg/keV)	Energy	S_m (cpd/kg/keV)
(1.0–1.5) keV	(0.0232±0.0052)	(6.5–7.0) keV	(0.0016±0.0018)
(1.5–2.0) keV	(0.0164±0.0043)	(7.0–7.5) keV	(0.0007±0.0018)
(2.0–2.5) keV	(0.0178±0.0028)	(7.5–8.0) keV	(0.0016±0.0018)
(2.5–3.0) keV	(0.0190±0.0029)	(8.0–8.5) keV	(0.0014±0.0018)
(3.0–3.5) keV	(0.0178±0.0028)	(8.5–9.0) keV	(0.0029±0.0018)
(3.5–4.0) keV	(0.0109±0.0025)	(9.0–9.5) keV	(0.0014±0.0018)
(4.0–4.5) keV	(0.0110±0.0022)	(9.5–10.0) keV	-(0.0029±0.0019)
(4.5–5.0) keV	(0.0040±0.0020)	(10.0–10.5) keV	(0.0035±0.0019)
(5.0–5.5) keV	(0.0065±0.0020)	(10.5–11.0) keV	-(0.0038±0.0019)
(5.5–6.0) keV	(0.0066±0.0019)	(11.0–11.5) keV	-(0.0013±0.0019)
(6.0–6.5) keV	(0.0009±0.0018)	(11.5–12.0) keV	-(0.0019±0.0019)



$$S_i(E) = S_0(E) + S_m(E)\cos\omega(t_i - t_0) + Z_m(E)\sin\omega(t_i - t_0)$$
$$= S_0(E) + Y_m(E)\cos\omega(t_i - t^*).$$

Bernabei et al. (DAMA Collaboration), 1805.10486

DAMA/LIBRA-phase2 in WIMP effective models

- Elastic effective models with the standard Maxwellian

$$\mathcal{H}(\mathbf{r}) = \sum_{\tau=0,1}\sum_{j=1}^{15} c_j^\tau \mathcal{O}_j(\mathbf{r})\, t^\tau,$$

$$t^0 = 1,\ t^1 = \tau_3$$

$$\mathcal{O}_1 = 1_\chi 1_N; \quad \mathcal{O}_2 = (v^\perp)^2; \quad \mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N; \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp); \quad \mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp; \quad \mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp; \quad \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}; \quad \mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}; \quad \mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$$

$$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N}); \quad \mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$$

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

$$\chi^2(m_\chi, \sigma_p, r) = \sum_{k=1}^{14} \frac{\left[S_{m,k} - S_{m,k}^{exp}(m_\chi, \sigma_p, r)\right]^2}{\sigma_k^2}$$

$$(v_T^\perp)^2 = v_T^2 - v_{min}^2.$$

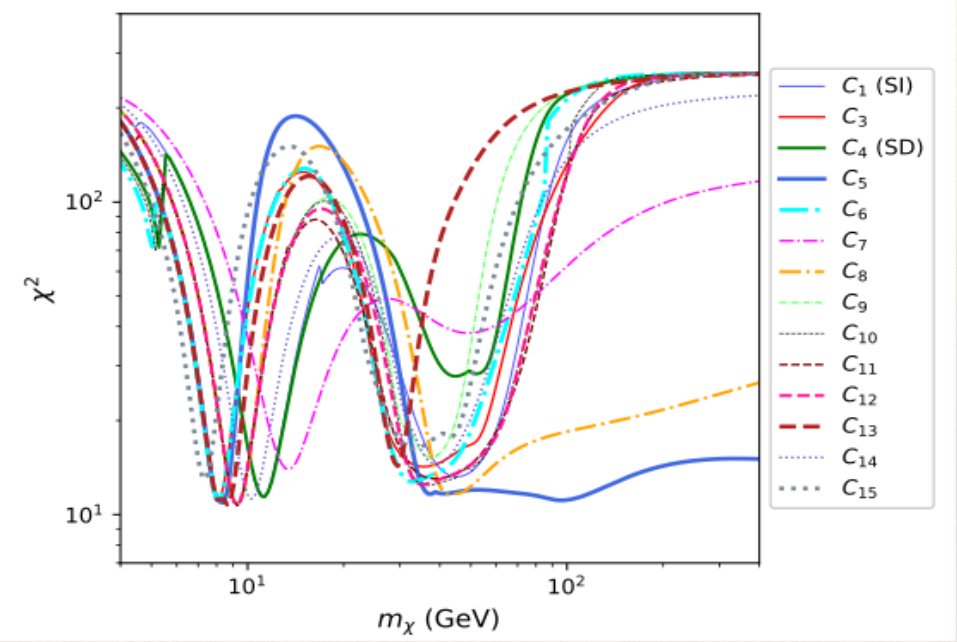
$$v_{min}^2 = \frac{q^2}{4\mu_T^2} = \frac{m_T E_R}{2\mu_T^2},$$

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.

DAMA/LIBRA-phase2 in WIMP effective models

- Likelihood analysis



$$\chi^2(m_\chi, \sigma_p, r) = \sum_{k=1}^{14} \frac{\left[S_{m,k} - S_{m,k}^{exp}(m_\chi, \sigma_p, r)\right]^2}{\sigma_k^2}$$

c_j	$m_{\chi,min}$ (GeV)	$r_{\chi,min}$	σ (cm^2)	χ^2_{min}
c_1	11.17	-0.76	2.67e-38	11.38
	45.19	-0.66	1.60e-39	13.22
c_3	8.10	-3.14	2.27e-31	11.1
	35.68	-1.10	9.27e-35	14.23
c_4	11.22	1.71	2.95e-36	11.38
	44.71	-8.34	5.96e-36	27.7
c_5	8.34	-0.61	1.62e-29	10.83
	96.13	-5.74	3.63e-34	11.11
c_6	8.09	-7.20	5.05e-28	11.11
	32.9	-6.48	5.18e-31	12.74
c_7	13.41	-4.32	4.75e-30	13.94
	49.24	-0.65	1.35e-30	38.09
c_8	9.27	-0.84	8.67e-33	10.82
	42.33	-0.96	1.30e-34	11.6
c_9	9.3	4.36	8.29e-33	10.69
	37.51	-0.94	1.07e-33	15.23
c_{10}	9.29	3.25	4.74e-33	10.69
	36.81	0.09	2.25e-34	12.40
c_{11}	9.27	-0.67	1.15e-34	10.69
	38.51	-0.66	9.17e-37	13.02
c_{12}	9.26	-2.85	3.92e-34	10.69
	35.22	-1.93	2.40e-35	12.47
c_{13}	8.65	-0.26	1.21e-26	10.76
	29.42	0.10	5.88e-29	14.28
c_{14}	10.28	-0.59	2.61e-26	11.21
	38.88	-1.93	2.19e-27	14.48
c_{15}	7.32	-3.58	2.04e-27	12.91
	33.28	4.25	2.05e-33	16.26

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DAMA/LIBRA-phase2 in WIMP effective models

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

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

- **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

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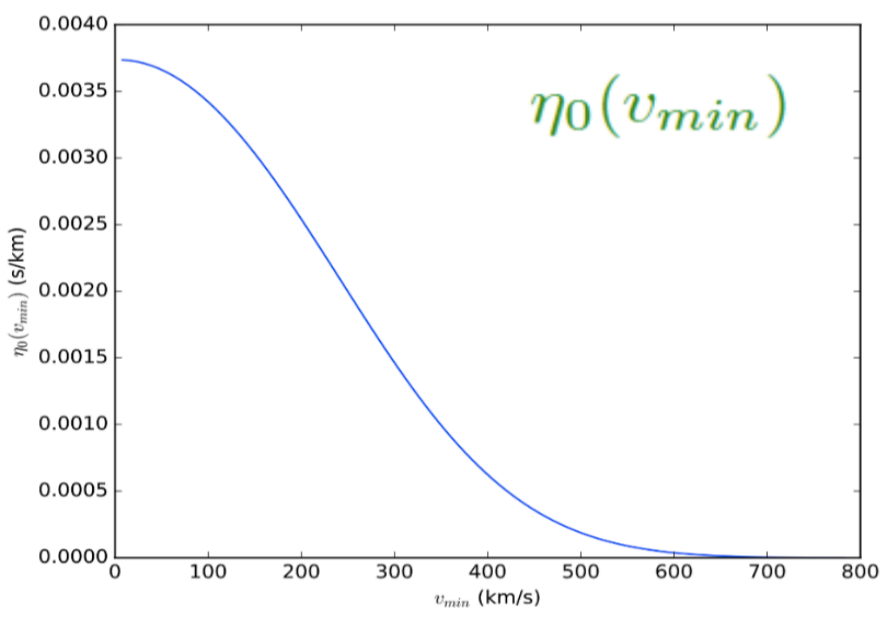
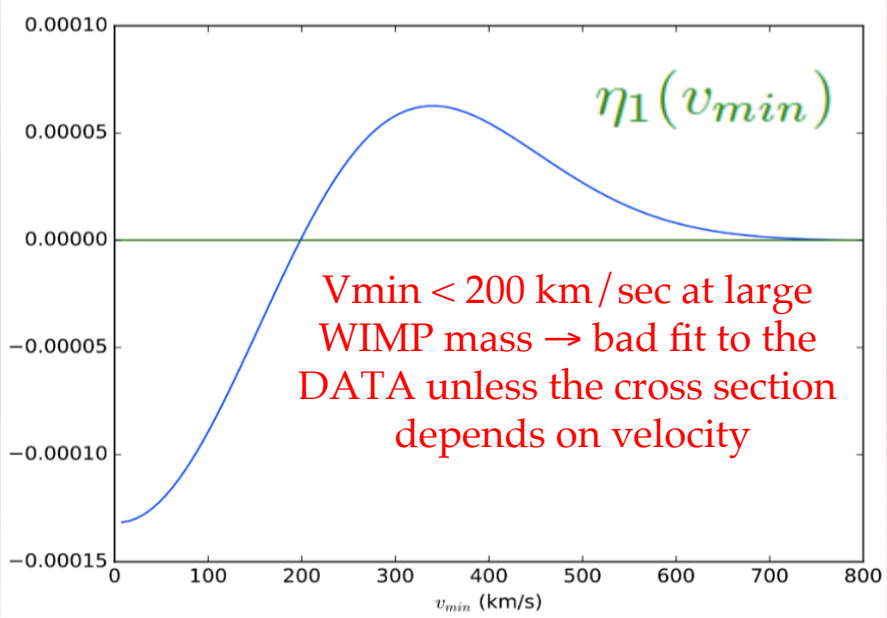
DAMA/LIBRA-phase2 in WIMP effective models

- WIMP velocity distribution

$$\eta(v_{min}, t) = \int_{v_{min}}^{\infty} \frac{f(v)}{v} dv = \eta_0(v_{min}) + \eta_1(v_{min}) \cos\omega(t - t_0)$$





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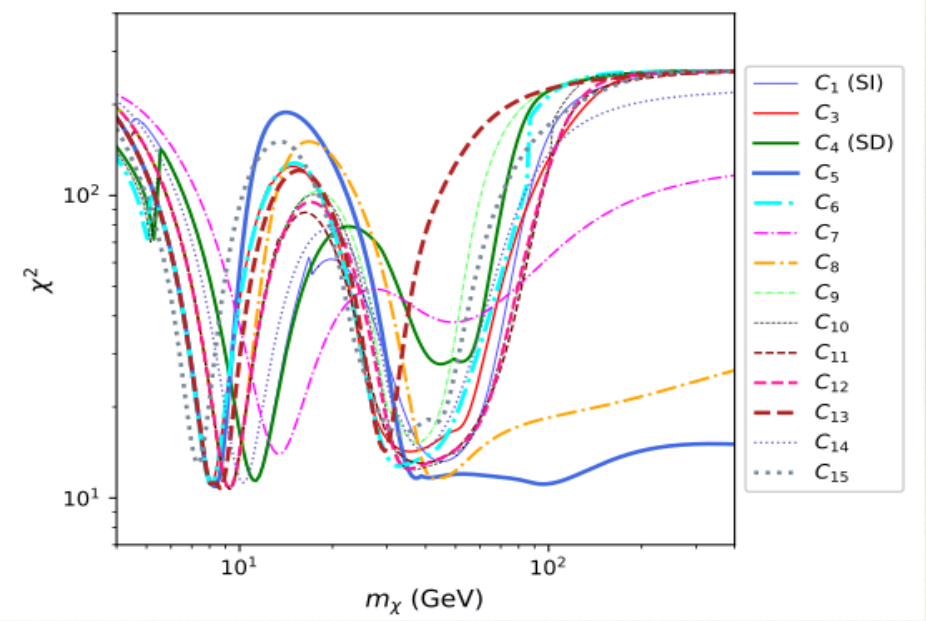

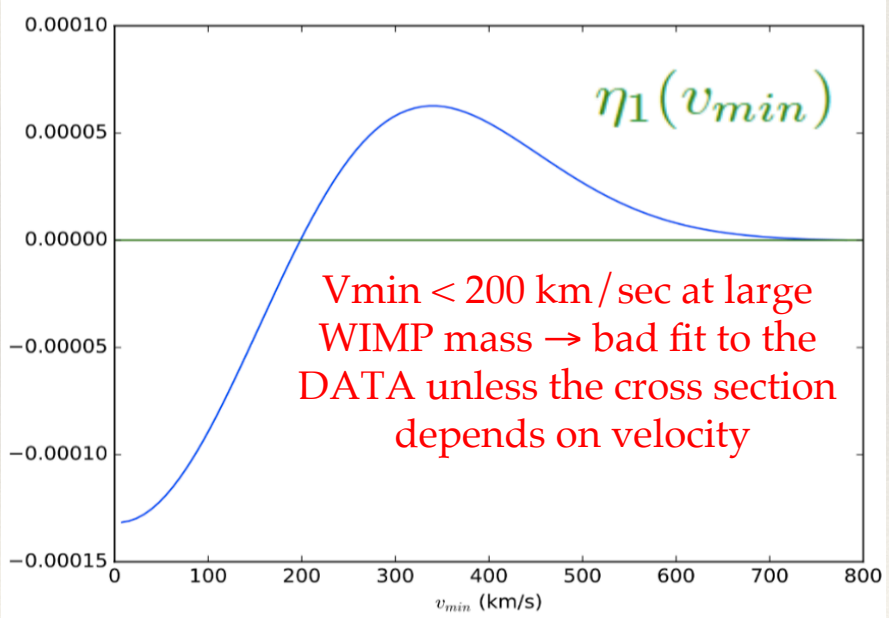

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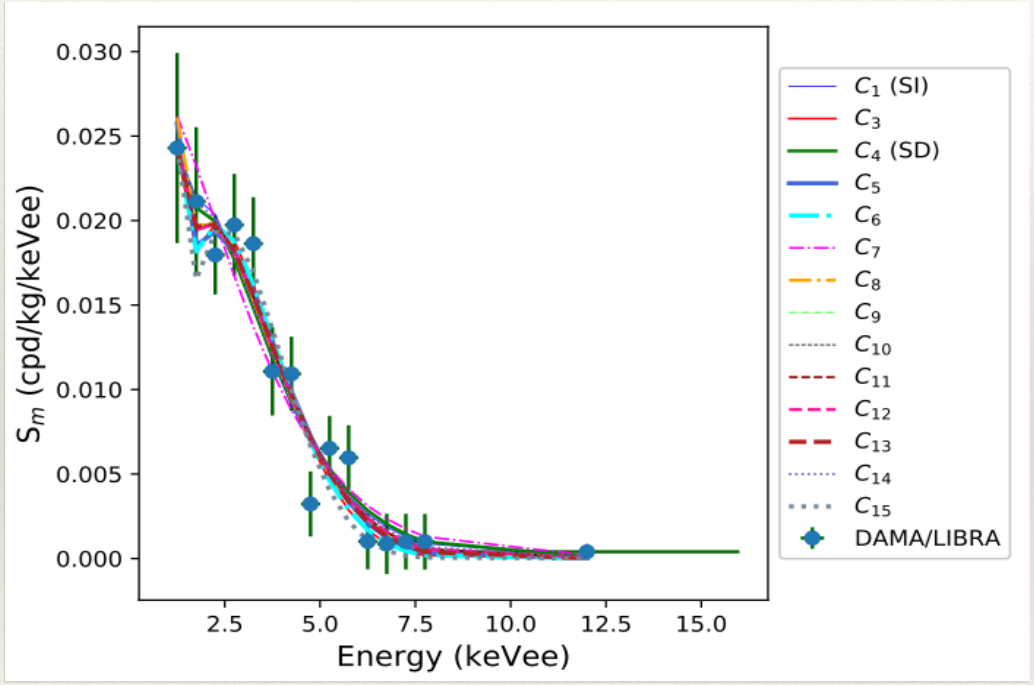
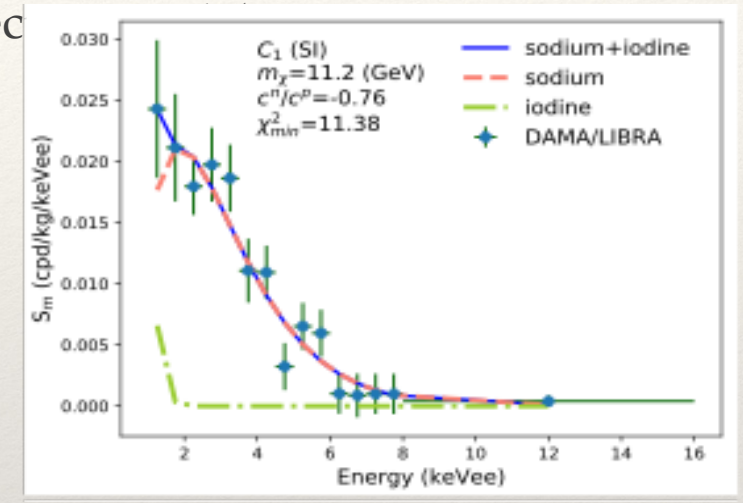
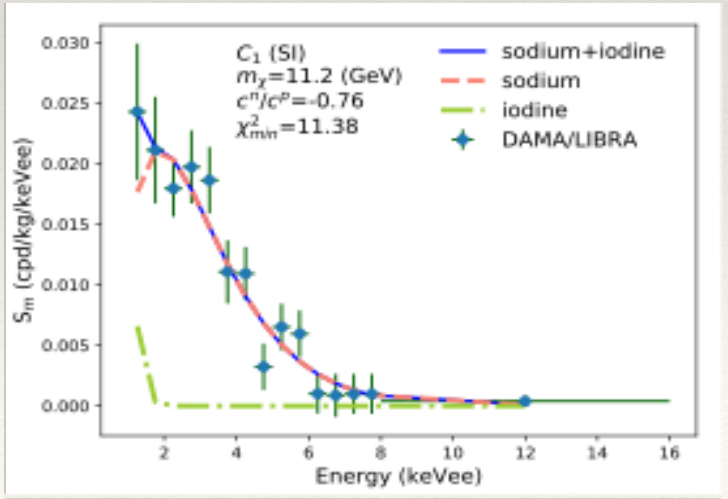
DAMA/LIBRA-phase2 in WIMP effective models

- DAMA modulation amplitudes as a function of the measured ionization energy Eee for the absolute minima of each effec







$$\sigma_{\chi N} \propto [c^p Z + (A - Z)c^n]^2$$

$r_{Iodine} \simeq -53/(127-53) \simeq$ -0.7 ($\simeq$ -0.9) for sodium

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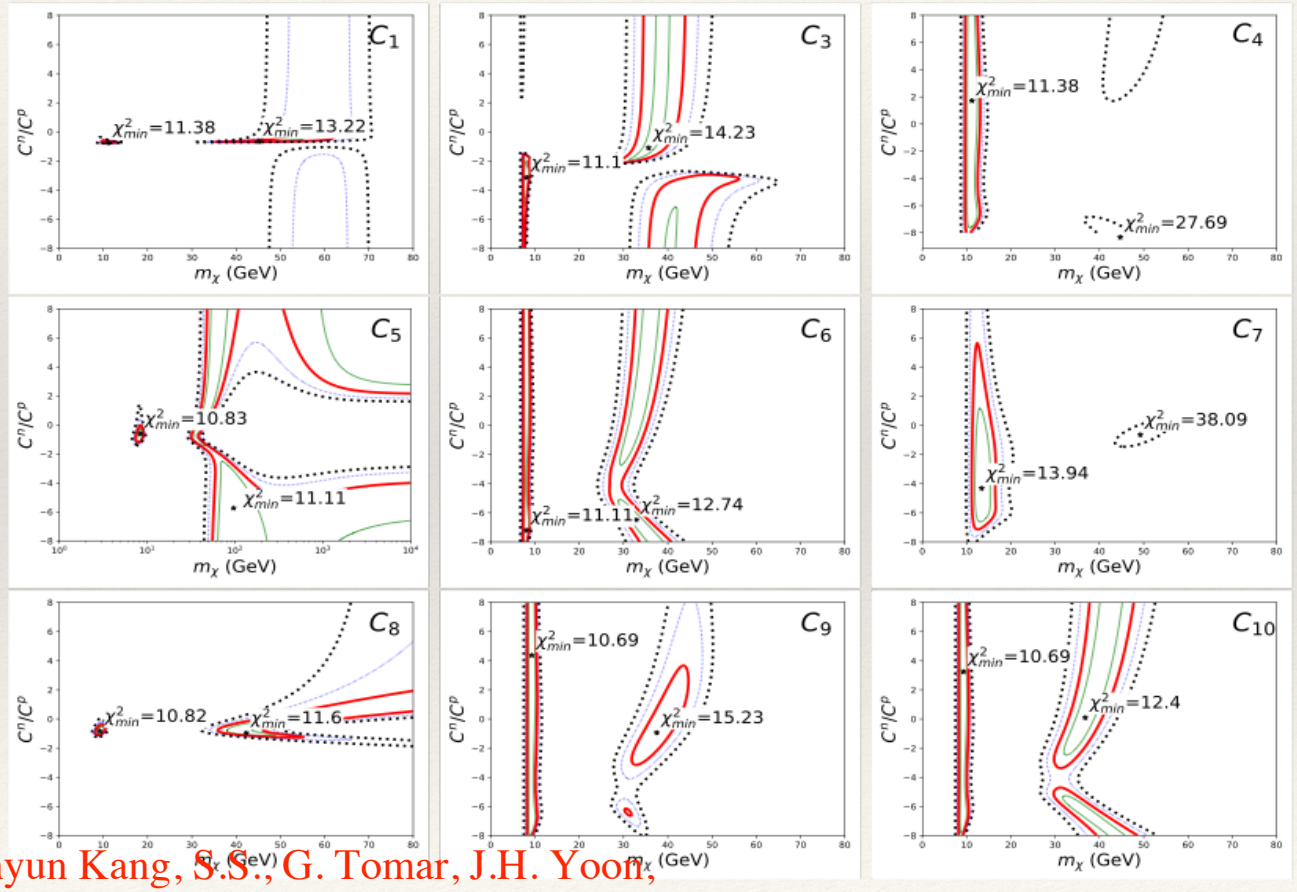
DAMA/LIBRA-phase2 in WIMP effective models

- Contour plots of $\chi 2$ on the WIMP mass v.s. r plane



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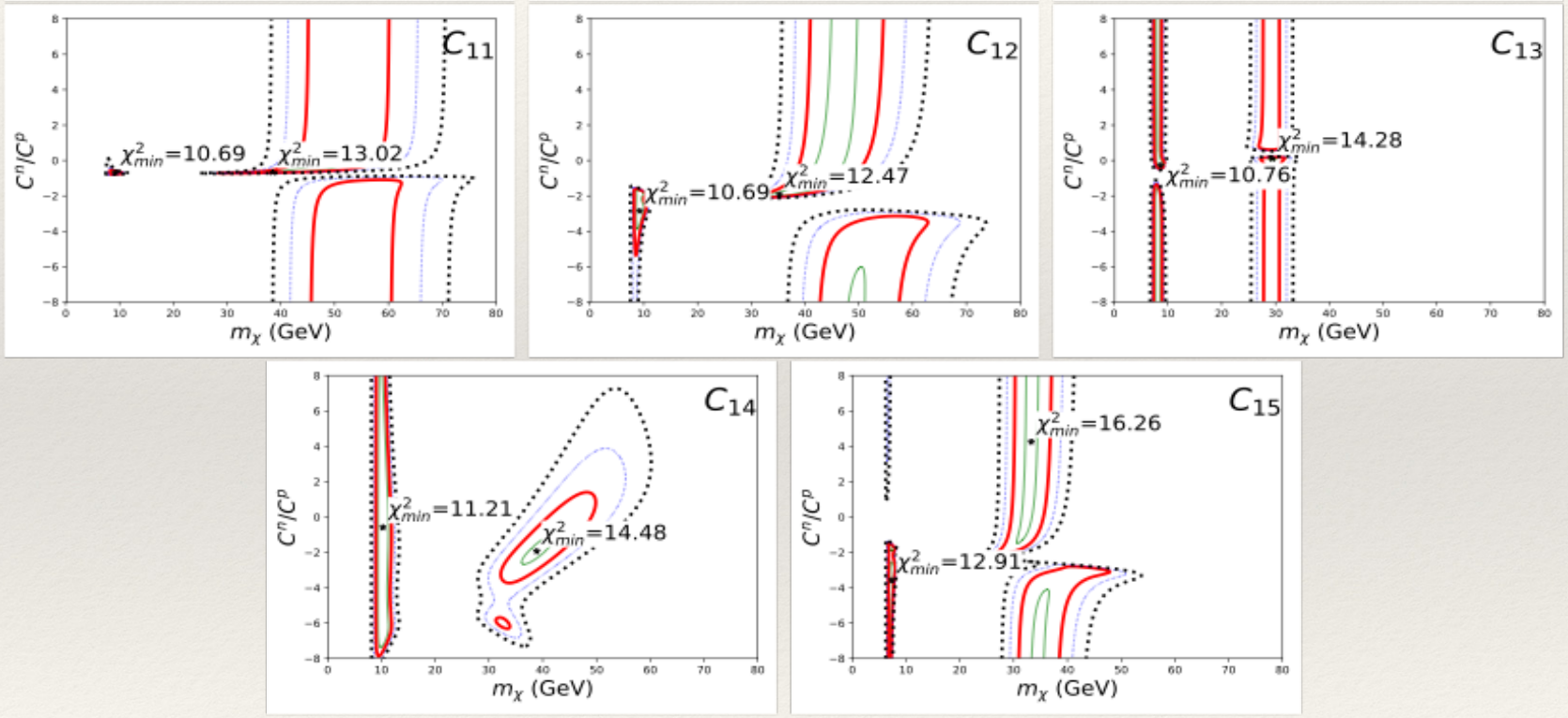

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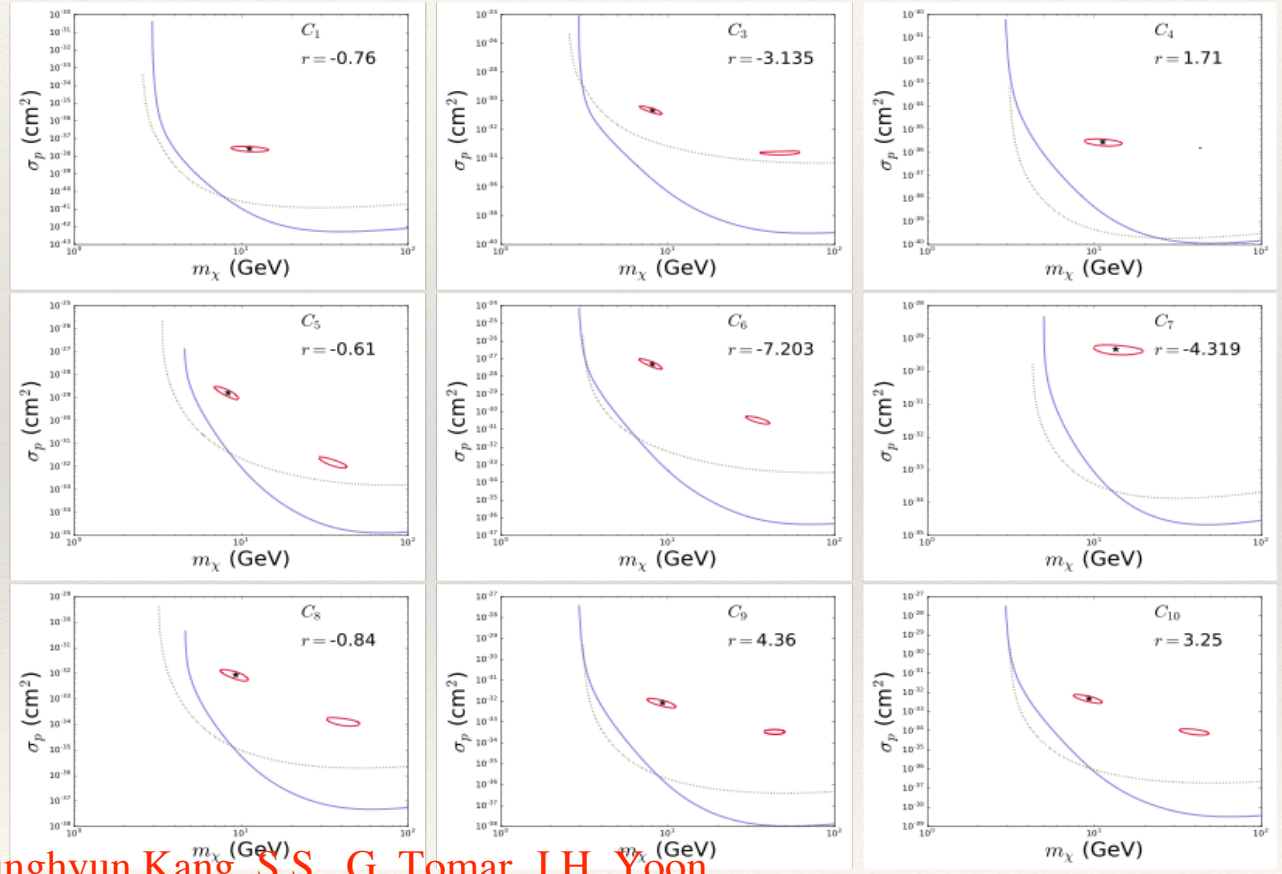
DAMA/LIBRA-phase2 in WIMP effective models

- 5-sigma best fit DAMA regions with XENON1T(solid purple line) and PICO60(green dots)



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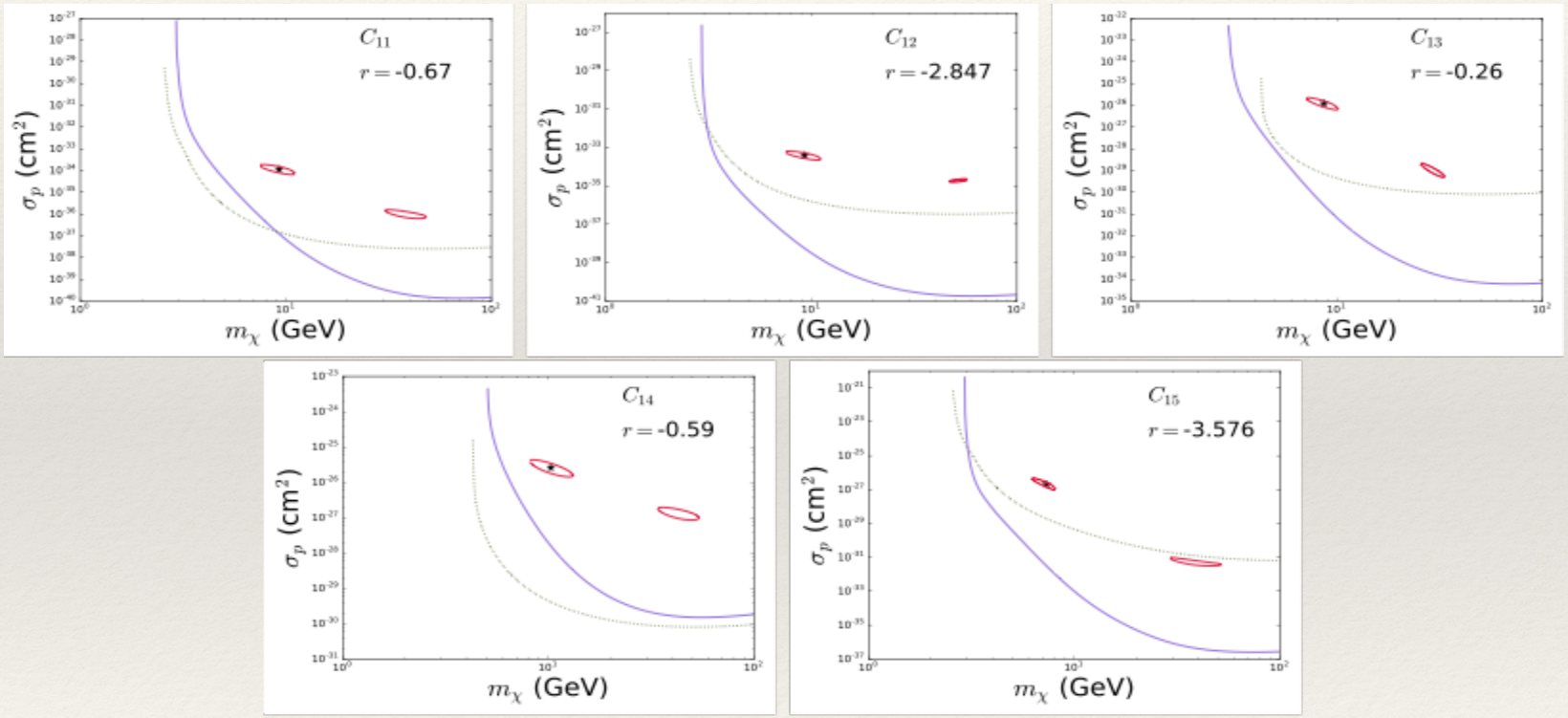

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Conclusions

- No fit of the DAMA result is available in the literature in terms of non–relativistic EFT models
- In addition to increasing the exposure, the phase2 result also includes a lower energy threshold, and the new spectrum of modulation amplitudes no longer shows a maximum, but is rather monotonically decreasing with energy
- We extended an assessment of the goodness of fit of the new DAMA result to NREFT scenarios
- All models yield an acceptable $\chi 2$
- All best-fit minima are inconsistent with the bounds from XENON1T and PICO60

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