WIMP scenarios for DAMA/LIBRA-phase2

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In this talk I will answer the following two questions:

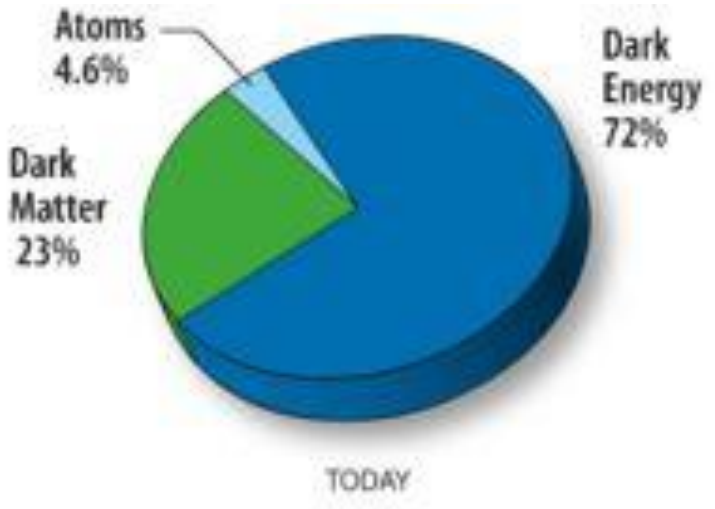
- Is it still possible to explain DAMA/LIBRA-phase2 with a WIMP?

- Does the NaI COSINE-100 bound kill the game with a model-independent exclusion?

Introduction

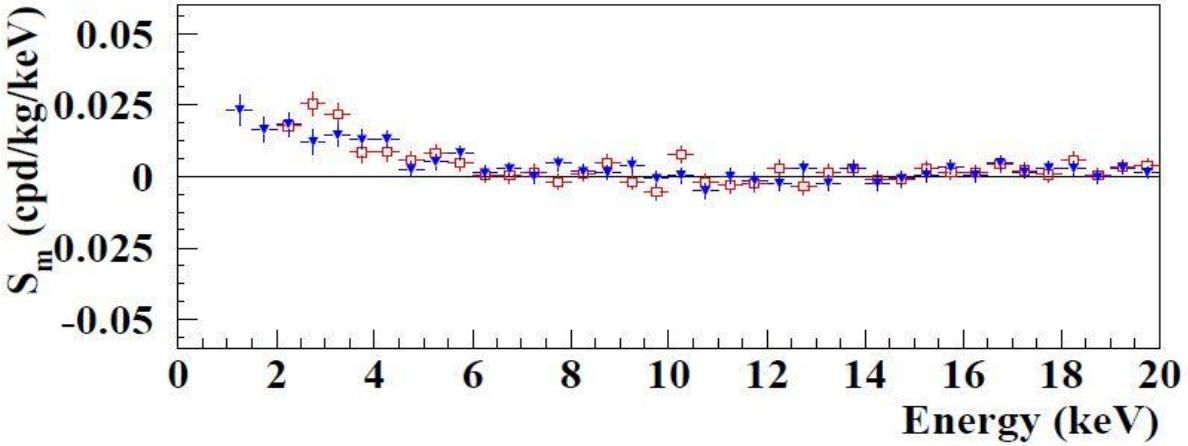
- Many evidences of Dark Matter
- CDM(Cold Dark Matter)
- Neutrino
- WIMP

  (Weakly Interacting Massive Particle)

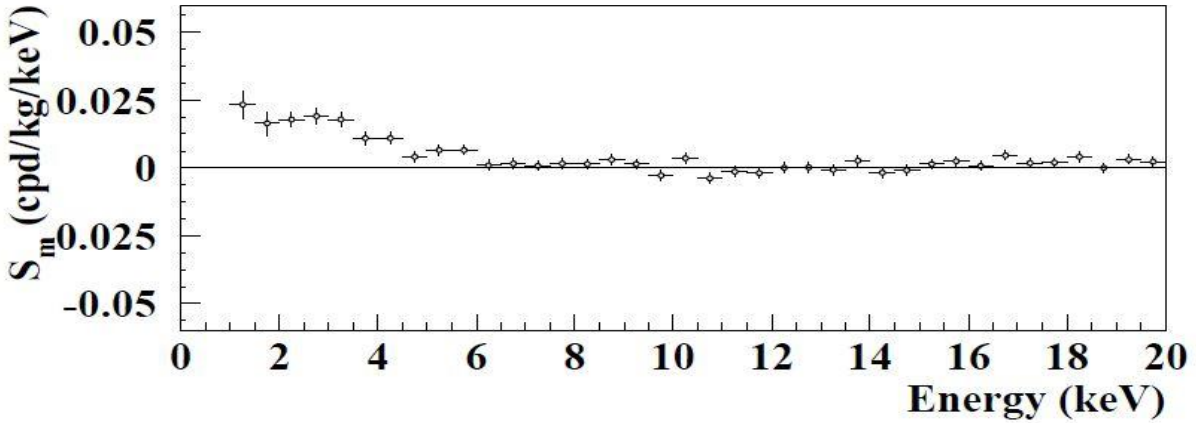


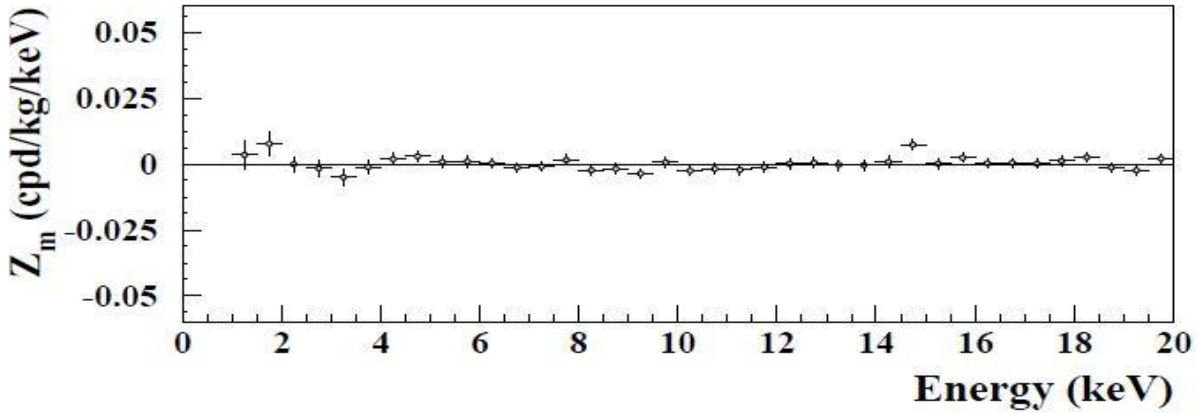
"Content of the Universe - Pie Chart“
Wilkinson Microwave Anisotropy Probe.
National Aeronautics and Space Administration.
Retrieved 9 January 2018.

DAMA/LIBRA-phase2 analyses



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)





Bernabei et al. (DAMA Collaboration), First model independent results from DAMA/LIBRA-phase2, 10.3390/universe4110116

DAMA/LIBRA-phase2 analyses

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

τ : isospin

j : interaction type

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

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

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

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

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

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

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

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

W. Haxtonet al., The Effective Field Theory of Dark Matter Direct Detection, JCAP 1302 (2013) 004

DAMA/LIBRA-phase2 analyses

$$\frac{dR}{dE'} \propto \sum_{\tau\tau'} \sum_{l} R_l^{\tau\tau'} W_l^{\tau\tau'},$$

$R_l{}^{\tau\tau'}$: WIMP response function

$W_l{}^{\tau\tau'}$: nucleus response function: M, Σ', Σ'', Δ, ϕ'', ϕ' (M=SI, , Σ', Σ''=SD)

(from Nikhil Anand, A. Liam Fitzpatrick, W. C. Haxton,Model-independent WIMP Scattering Responses and Event Rates : A Mathematica Package for Experimental Analysis)

$$R_{[E'_1,E'_2]}(t) = MT_{exp} \int_{E'_1}^{E'_2} \frac{dR}{dE'}(t)\, dE'$$

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

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

$$S_{m,[E'_1,E'_2]} \equiv \frac{2}{T_0} \int_0^{T_0} \cos\left[\frac{2\pi}{T_0}(t - t_0)\right] R_{[E'_1,E'_2]}(t) dt,$$

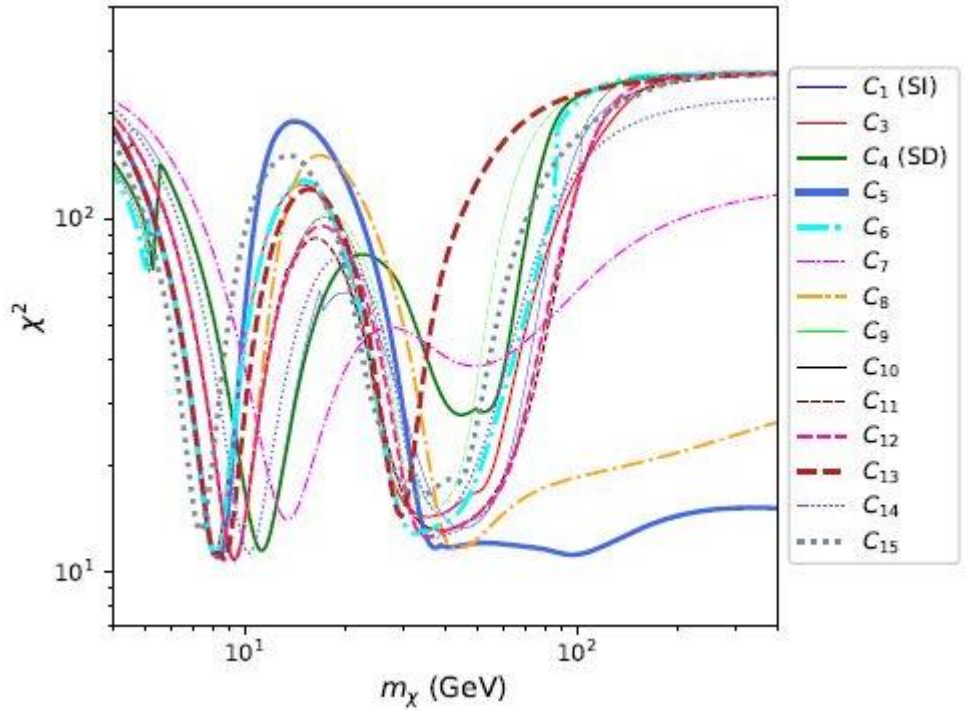
$$\mathcal{G}(E', E_{ee}) = Gauss(E'|E_{ee}, \sigma_{rms}(E_{ee}))$$

$$= \frac{1}{\sigma_{rms}(E_{ee})\sqrt{2\pi}} e^{-\frac{(E'-E_{ee})^2}{2\sigma^2_{rms}(E_{ee})}},$$

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

Sunghyun Kang, S.S., G. Tomar, J.H. Yoon DAMA/LIBRA-phase2 in WIMP effective models, JCAP07(2018)016

DAMA/LIBRA-phase2



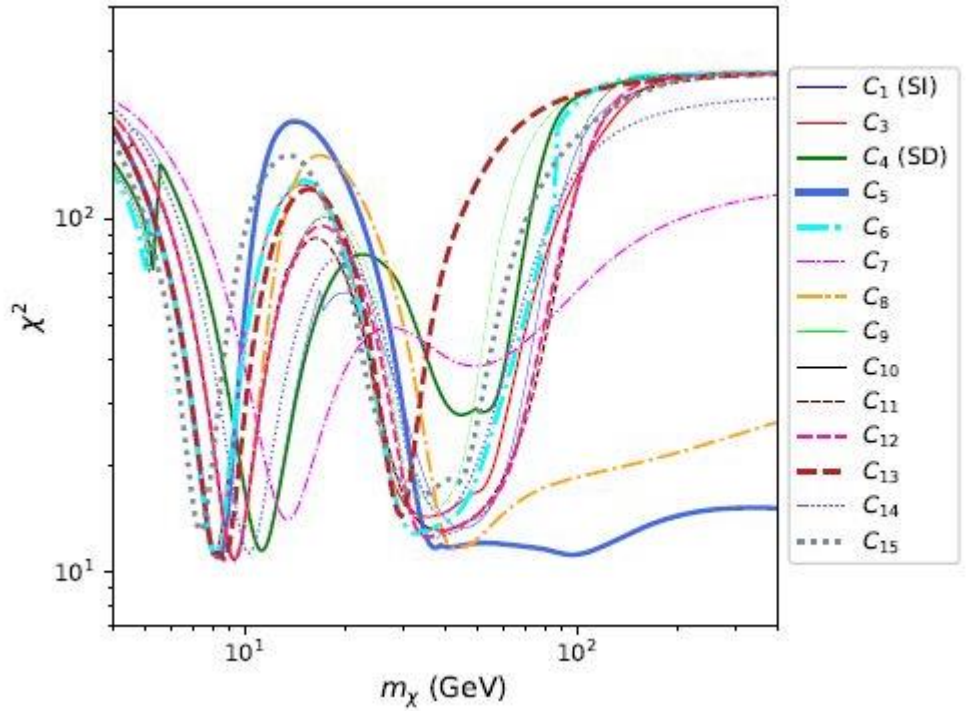
$$\chi^2(m_\chi, \sigma_p, r) = \sum_{k=1}^{14} \frac{\left[S_{m,k} - S_{m,k}^{exp}(m_\chi, \sigma_p, r)\right]^2}{\sigma_k^2}$$

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

Considering one EFT coupling at a time

Sunghyun Kang, S.S., G. Tomar, J.H. Yoon DAMA/LIBRA-phase2 in WIMP effective models, JCAP07(2018)016

DAMA/LIBRA-phase2 analyses



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

$$S_{m,[E'_1,E'_2]} \equiv \frac{2}{T_0}\int_0^{T_0} \cos\left[\frac{2\pi}{T_0}(t-t_0)\right] R_{[E'_1,E'_2]}(t)dt,$$

$$R_{[E'_1,E'_2]}(t) = MT_{exp}\int_{E'_1}^{E'_2} \frac{dR}{dE'}(t)\,dE'$$

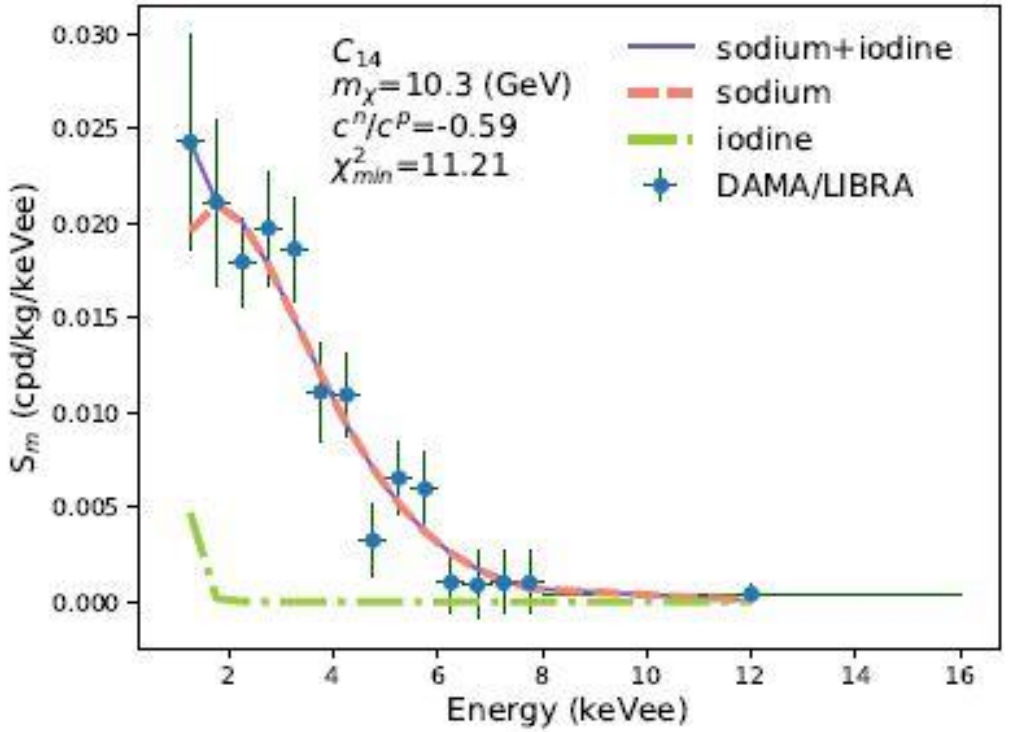
$$\frac{dR}{dE'}(t) = \sum_T \int_0^\infty \frac{dR_{\chi T}(t)}{dE_{ee}} \mathcal{G}_T(E', E_{ee})\epsilon(E')\,dE_{ee}$$

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

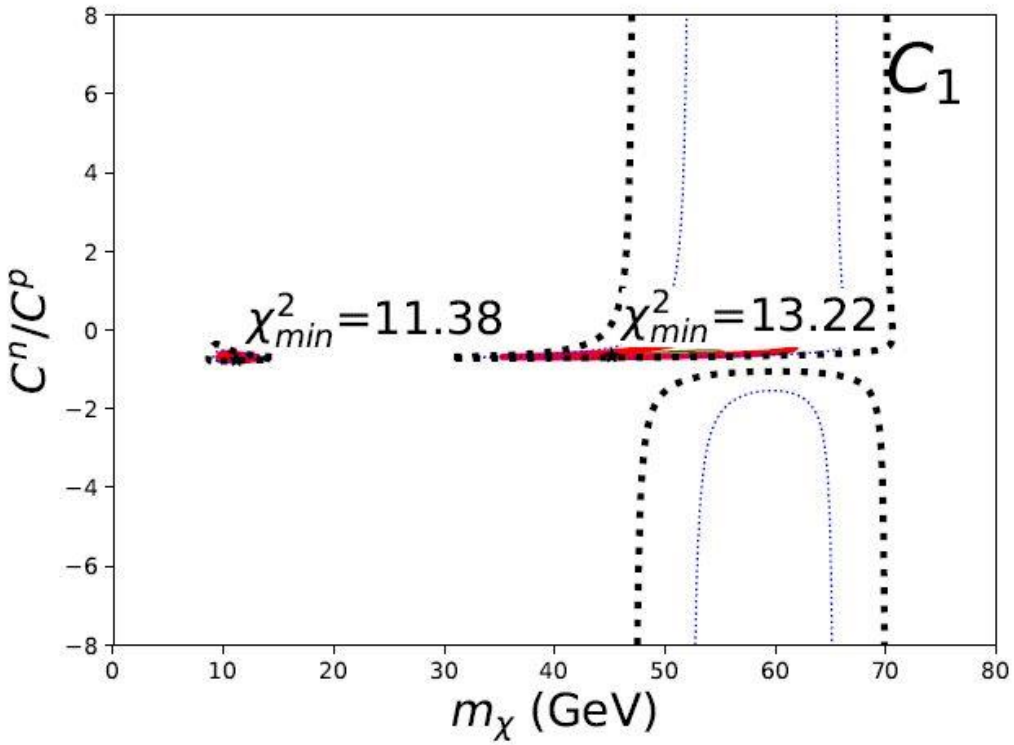
$$\frac{dR_{\chi T}}{dE_R}(t) = \sum_T N_T \frac{\rho_{\rm WIMP}}{m_{\rm WIMP}} \int_{v_{min}} d^3v_T f(\vec{v}_T, t) v_T \frac{d\sigma_T}{dE_R},$$

Sunghyun Kang, S.S., G. Tomar, J.H. Yoon DAMA/LIBRA-phase2 in WIMP effective models, JCAP07(2018)016

DAMA/LIBRA-phase2 analyses



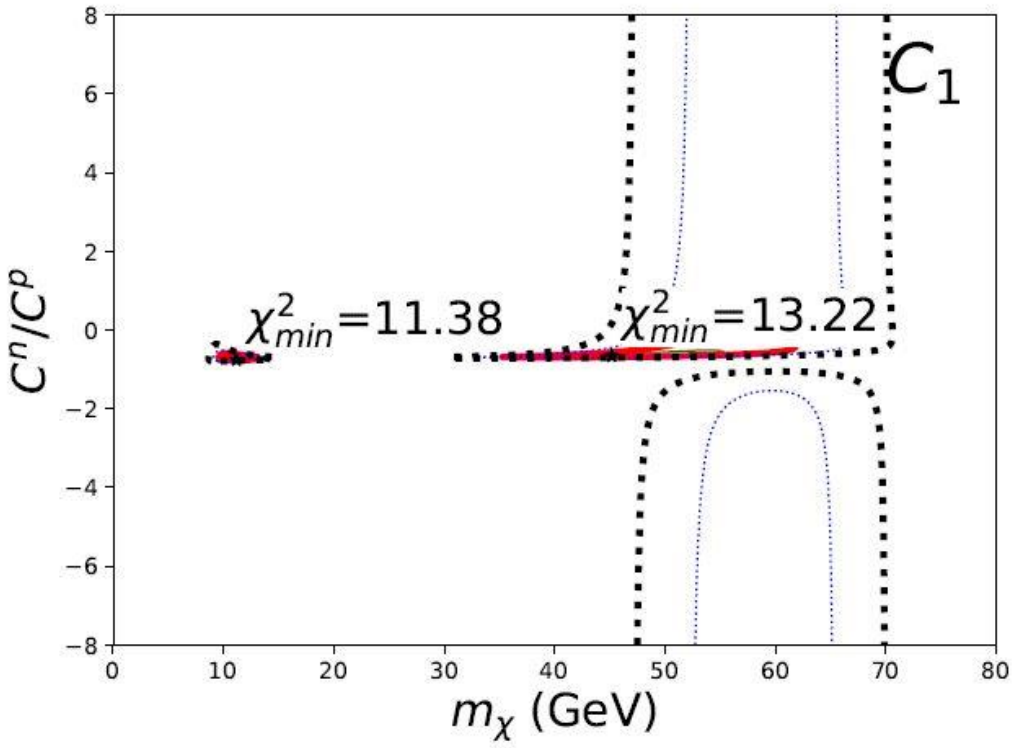
$$\sigma_{\chi N} \propto [c^p Z + (A - Z)c^n]^2 ,$$



Sunghyun Kang, S.S., G. Tomar, J.H. Yoon DAMA/LIBRA-phase2 in WIMP effective models, JCAP07(2018)016

DAMA/LIBRA-phase2 analyses

coupling	$R^{\tau\tau'}_{0k}$	$R^{\tau\tau'}_{1k}$	coupling	$R^{\tau\tau'}_{0k}$	$R^{\tau\tau'}_{1k}$
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	$\Phi''(q^6)$	$\Sigma'(q^4)$

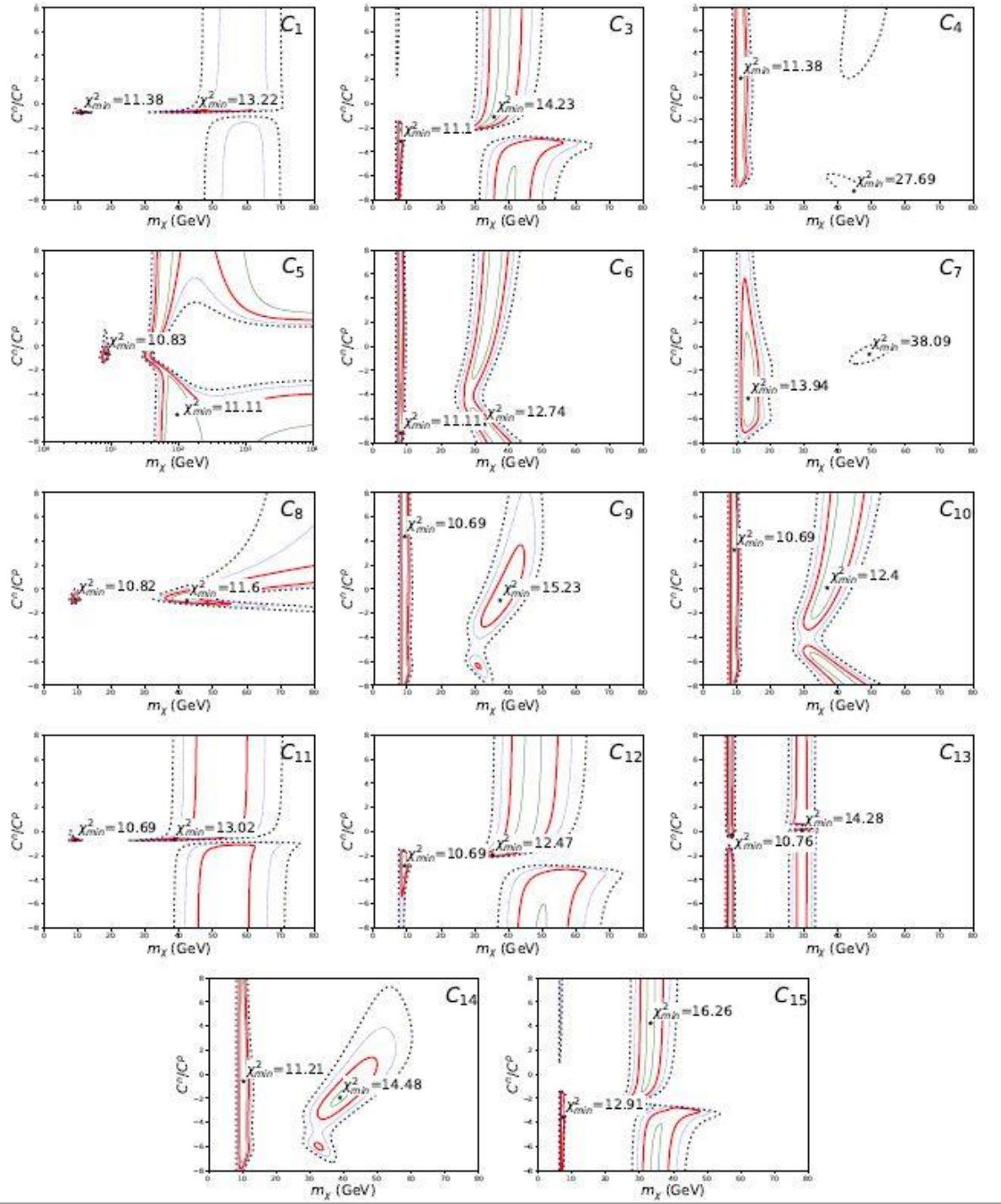


$$\sigma_{\chi N} \propto [c^p Z + (A - Z)c^n]^2 ,$$

Sunghyun Kang, S.S., G. Tomar, J.H. Yoon DAMA/LIBRA-phase2 in WIMP effective models, JCAP07(2018)016

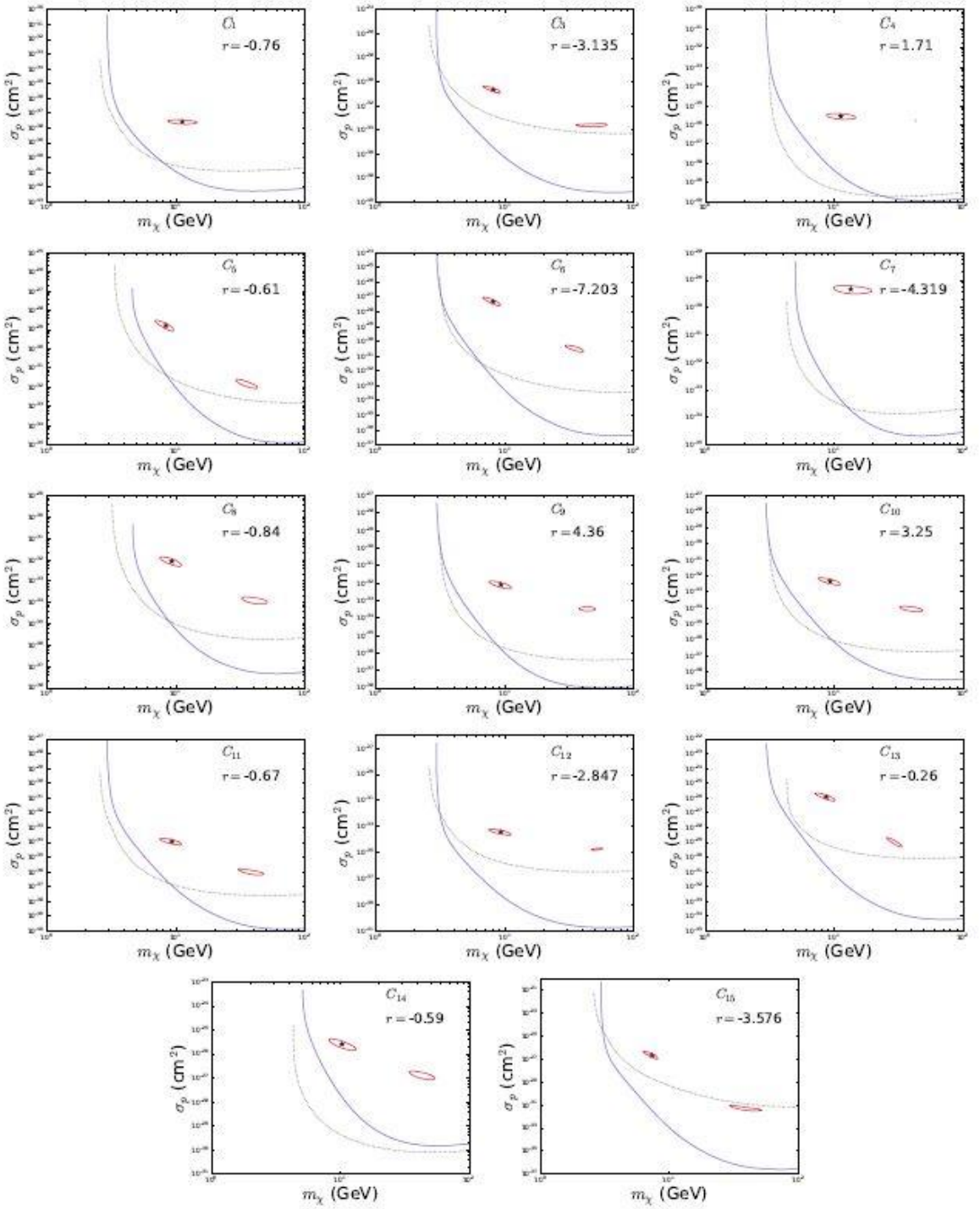
DAMA/LIBRA-phase2

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



DAMA/LIBRA-phase2

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



pSIDM (proton-Philic Spin Dependent Inelastic Dark Matter): a WIMP model for DAMA that complies with *all* constraints

- How pSIDM evades constraints

  - Xe, Ge
    : spin-dependent WIMP-proton cross section(no interaction with neutron)

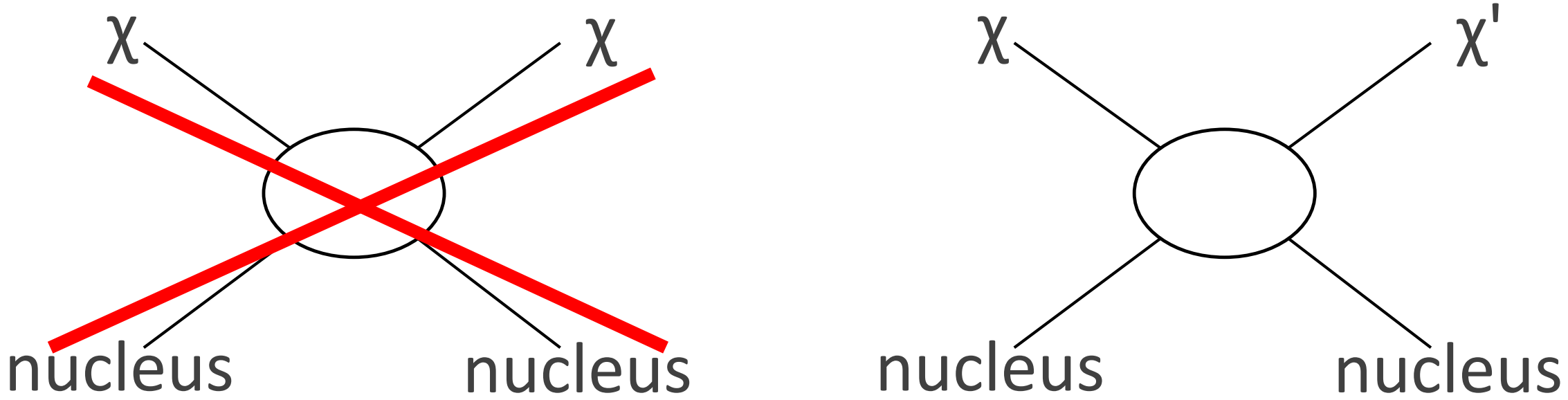
  - F : $v_{min}^{*F} > v_{esc}$

  - DAMA signal is okay since $v_{min}^{*Na}, v_{min}^{*I} < v_{esc}$

Sunghyun Kang et al., Proton-philic spin-dependent inelastic Dark Matter (pSIDM) as a viable explanation of DAMA/LIBRA-phase2, 10.1103/PhysRevD.99.023017

Inelastic Dark Matter

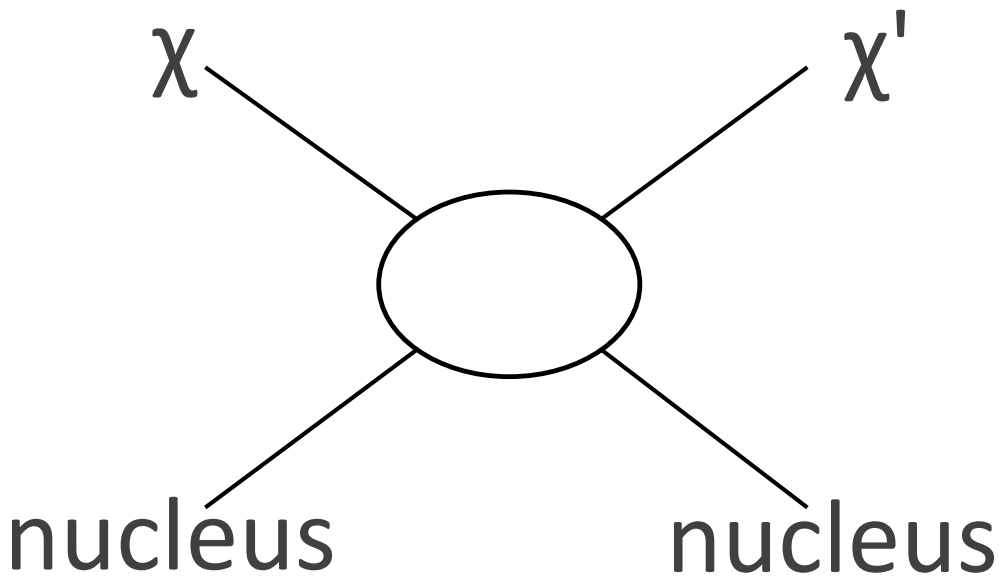
- Two states χ and χ’ with $m_\chi < m_{\chi'}$
- All χ’ states have decayed to χ by now



- Only upscatters of χ to χ’ are allowed

D. Tucker-Smith and N.Weiner, Inelastic dark matter, Phys. Rev. D64, 043502

Inelastic Dark Matter



$$m_{\chi'} - m_{\chi} = \delta$$

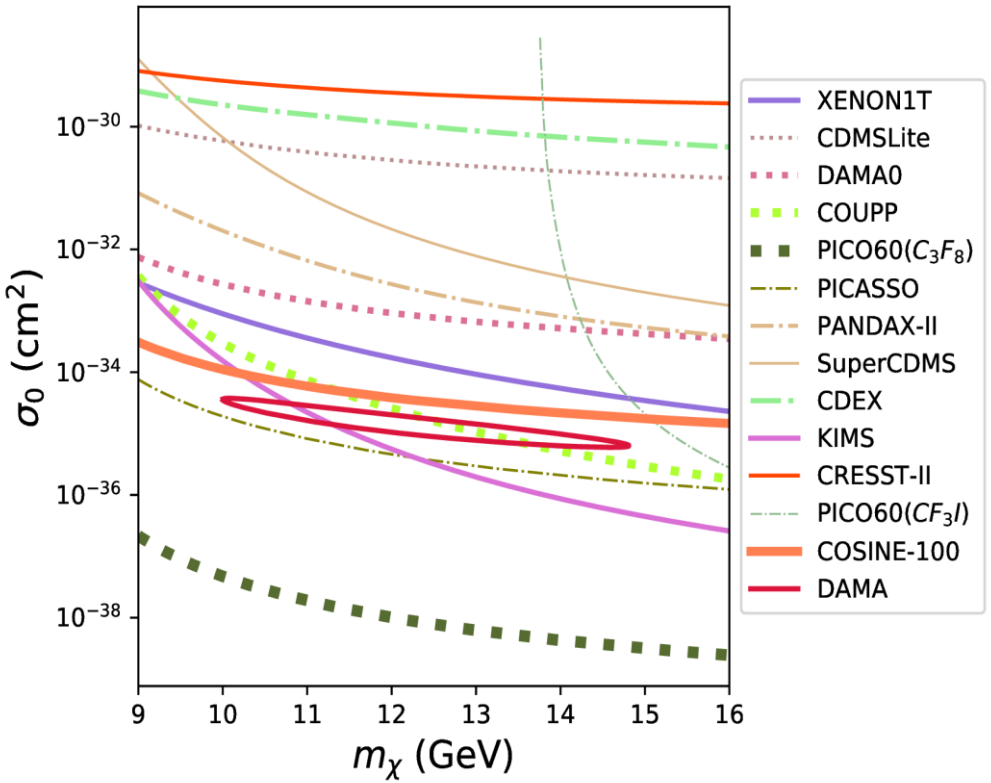
Inelastic case : $\delta \neq 0$

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

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

Sunghyun Kang et al., Proton-philic spin-dependent inelastic Dark Matter (pSIDM) as a viable explanation of DAMA/LIBRA-phase2, 10.1103/PhysRevD.99.023017

pSIDM



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

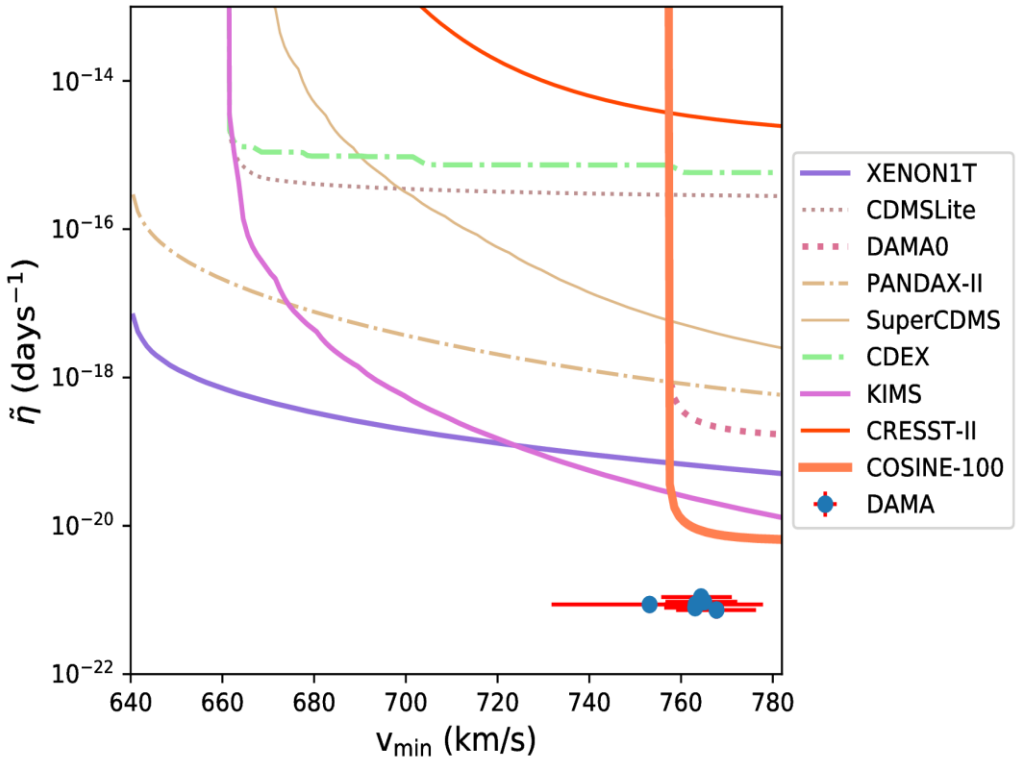
$$v^*_{min} = \sqrt{\frac{2\delta}{\mu_{\chi N}}},$$

$$v^{*Na}_{min} < v_{esc} < v^{*F}_{min}$$

Maxwellian velocity distribution

Sunghyun Kang et al., Proton-philic spin-dependent inelastic Dark Matter (pSIDM) as a viable explanation of DAMA/LIBRA-phase2, 10.1103/PhysRevD.99.023017

pSIDM



Halo independent case

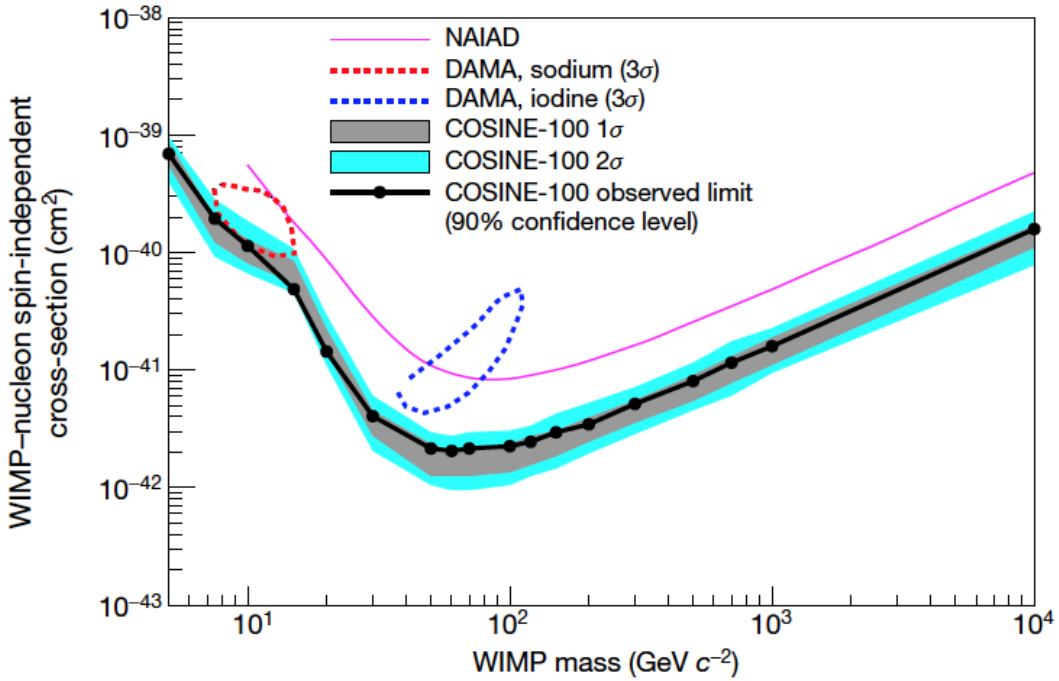
$$\tilde{\eta}(v_{min}, t) = \tilde{\eta}^0(v_{min}) + \tilde{\eta}^1(v_{min})\ \cos[\omega(t - t_0)]$$

$$\overline{\tilde{\eta}^i}_{[v_{\mathrm{min},1}, v_{\mathrm{min},2}]} = \frac{\int_0^\infty dv_{min}\, \tilde{\eta}^i(v_{min})\, \mathcal{R}_{[E'_1,E'_2]}(v_{min})}{\int_0^\infty dv_{min}\, \mathcal{R}_{[E'_1,E'_2]}(v_{min})} = \frac{R^i_{[E'_1,E'_2]}}{\int_0^\infty dv_{min}\, \mathcal{R}_{[E'_1,E'_2]}(v_{min})}, \qquad (18)$$

Sunghyun Kang et al., Proton-philic spin-dependent inelastic Dark Matter (pSIDM) as a viable explanation of DAMA/LIBRA-phase2, 10.1103/PhysRevD.99.023017

pSIDM and COSINE-100

- First exclusion of DAMA at low mass using NaI



- Spin-Independent Interaction
- Maxwellian

COSINE-100 Collaboration, G. Adhikari et al., An experiment to search for dark-matter interactions using sodium iodide detectors, Nature 564 (2018), no. 7734 83{86.

pSIDM and COSINE-100

- **A crucial point**: DAMA measures modulation S_m^{DAMA}, COSINE-100 constrains time average S_0^{COSINE} and S_m^{DAMA}/S_0^{COSINE} is *model dependent*
- $S_m^{DAMA} \cong 0.02$ events/kg/day/keVee
- $S_0^{COSINE} \leq 0.13$ events/kg/day/keVee
- $\frac{S_m^{DAMA}}{S_0^{DAMA}} = \frac{S_m^{DAMA}}{S_0^{COSINE}} \times \frac{S_0^{COSINE}}{S_0^{DAMA}} \geq 0.12$
- SI case : $\frac{S_m^{DAMA}}{S_0^{DAMA}} < 0.12$, pSIDM scenario : $\frac{S_m^{DAMA}}{S_0^{DAMA}} > 0.12$

Sunghyun Kang et al., Proton-philic spin-dependent inelastic Dark Matter (pSIDM) as a viable explanation of DAMA/LIBRA-phase2, 10.1103/PhysRevD.99.023017

Answers to the two questions:

- Is it still possible to explain DAMA/LIBRA-phase2 with a WIMP?

pSIDM can do the job

- Does the NaI COSINE-100 kill the game with a model-independent exclusion?

COSINE constraints time average, DAMA measures modulation, and the ratio between the two is still model dependent

Conclusions

- non-relativistic effective models can fit the DAMA/LIBRA-phase2 data with less fine tuning compared to a standard SI interaction
  - all model excluded by fluorine&xenon detectors
- pSIDM could explain DAMA/LIBRA-phase1 in compliance with constraints from other experiments. Still OK after DAMA/LIBRA-phase2 if WIMP velocity distribution departs from a Maxwellian.
- COSINE-100 bound is naturally evaded in the pSIDM scenario due to its large expected modulation fractions.