A combined analysis of PandaX, LUX, and XENON1T experiments within the framework of dark matter effective theory

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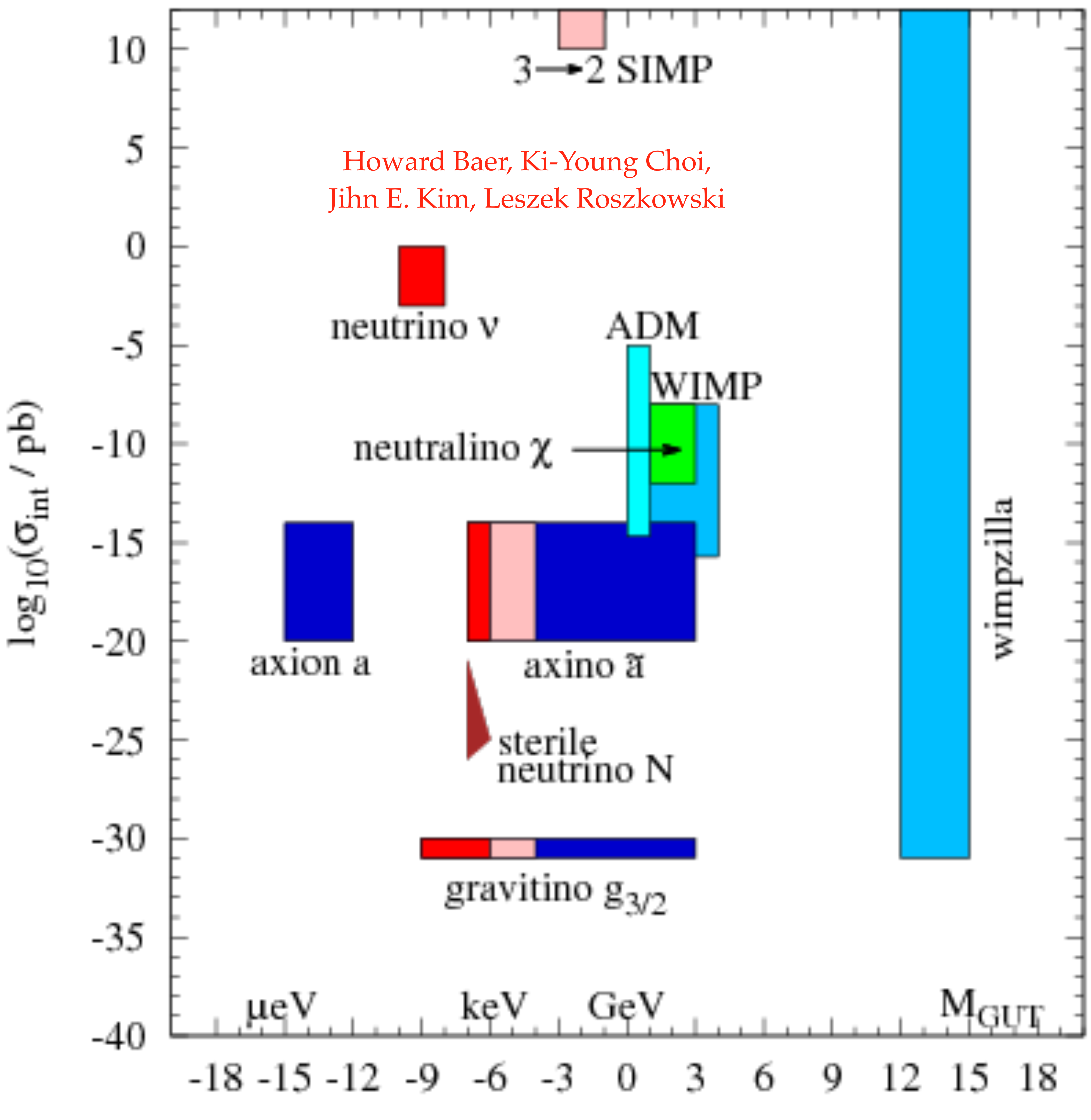
(NCTS, HsinChu)

Energy Frontier in Particle Physics: LHC and Future Colliders

This work is in collaboration with
Yushan Su, Binrong Yu
Zuowei Liu, and Qiang Yuan
(based on 1708.04630)



Howard Baer, Ki-Young Choi,
Jihn E. Kim, Leszek Roszkowski

There are so many DM models located at different mass scales.

A few particle dark matter theories:

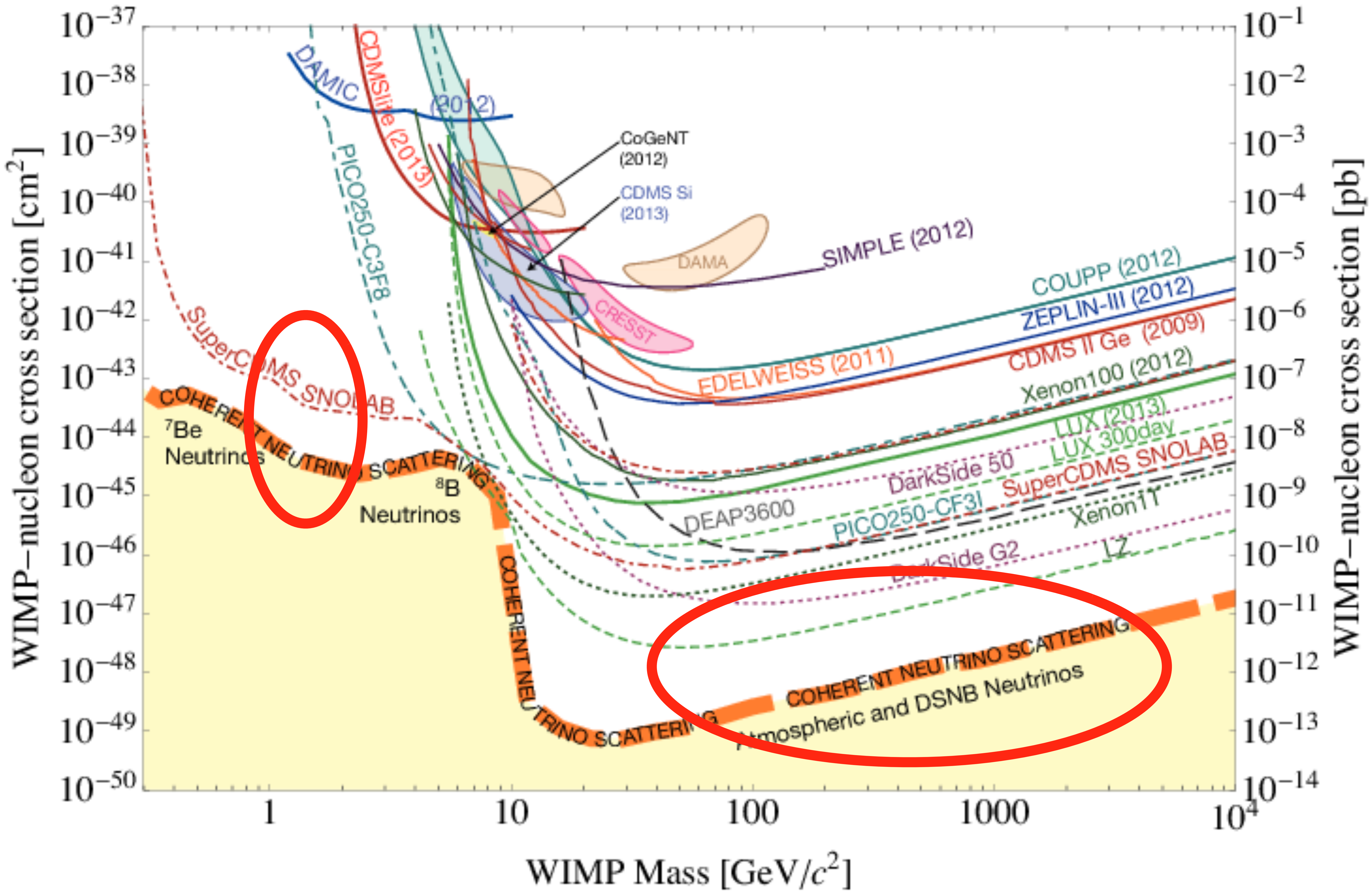
- axion
- sterile neutrino
- SUSY DM
  - neutralino in MSSM
  - Bino/Wino/Higgsino/Photino
  - sneutrino
  - gravitino
  - decaying gravitino
  - gravitino with large messenger mass
  - split SUSY DM
  - bound states for Sommerfeld enhancement
  - bino in E_6SSMwith massless inert singlets
  - neutralino from axion decay
  - NMSSM DM
  - mixed axion/neutralino
  - invisible photino
  - etc., etc. etc.
- Kaluza-Klein DM
- leptophilic DM
- leptophilic from non-abelian discrete symmetry
- asymmetric DM
- scalar singlet DM
- superGUT unified
- mirror DM

- non-thermal from decay of moduli
- resonance with momentum dependence
- helicity modification due to QED corrections
- dipole moment interacting DM
- dark instanton
- bosonic gas DM
- anti-baryonic
- ultra-light bosonic DM
- invisible photino
- T13 flavor symmetry decaying DM
- hydrodynamic vacuum DM
- dilatation anomaly DM
- bulk viscous unified DM
- ELKO field DM
- two singlet DM
- cosmic braneworld ultra-light DM
- superheavy quark clusters
- luxino
- non-canonical kinetic term DM
- branes filled with scalar fields
- real gauge singlet
- Higgs portal
- number theory DM
- asymmetric sneutrino
- modified Ricci model DM
- vacuum solitons
- complex singlet scalar
- D4 x Z2 flavor group DM
- non-minimal KK DM
- axion portal cascade
- light (MeV mass) DM

- two singlet DM
- self-interacting DM
- isospin violating DM
- inert Higgs
- skyrmion in littlest Higgs model
- techni-dilaton DM
- type-II seesaw mSUGRA DM
- vector DM
- goldsini
- WIMPless DM
- inert triplet DM
- vacuum solitons
- BEC from U(1) symmetry breaking
- eXciting DM (XDM)
- inelastic DM (iDM)
- flavor SU(3)Q triplet/singlet
- isospin violating
- axion-like repulsive DM
- D6 flavor symmetry
- warped Radion
- G2-MSSM
- gauged right-handed neutrino
- integration constant Horava DM
- tensor-four-scalar
- scalarons in R2 gravity
- secluded DM
- etc., etc., etc., etc., etc

Taken from Griest (2014).

Future prospect for WIMP direct detection

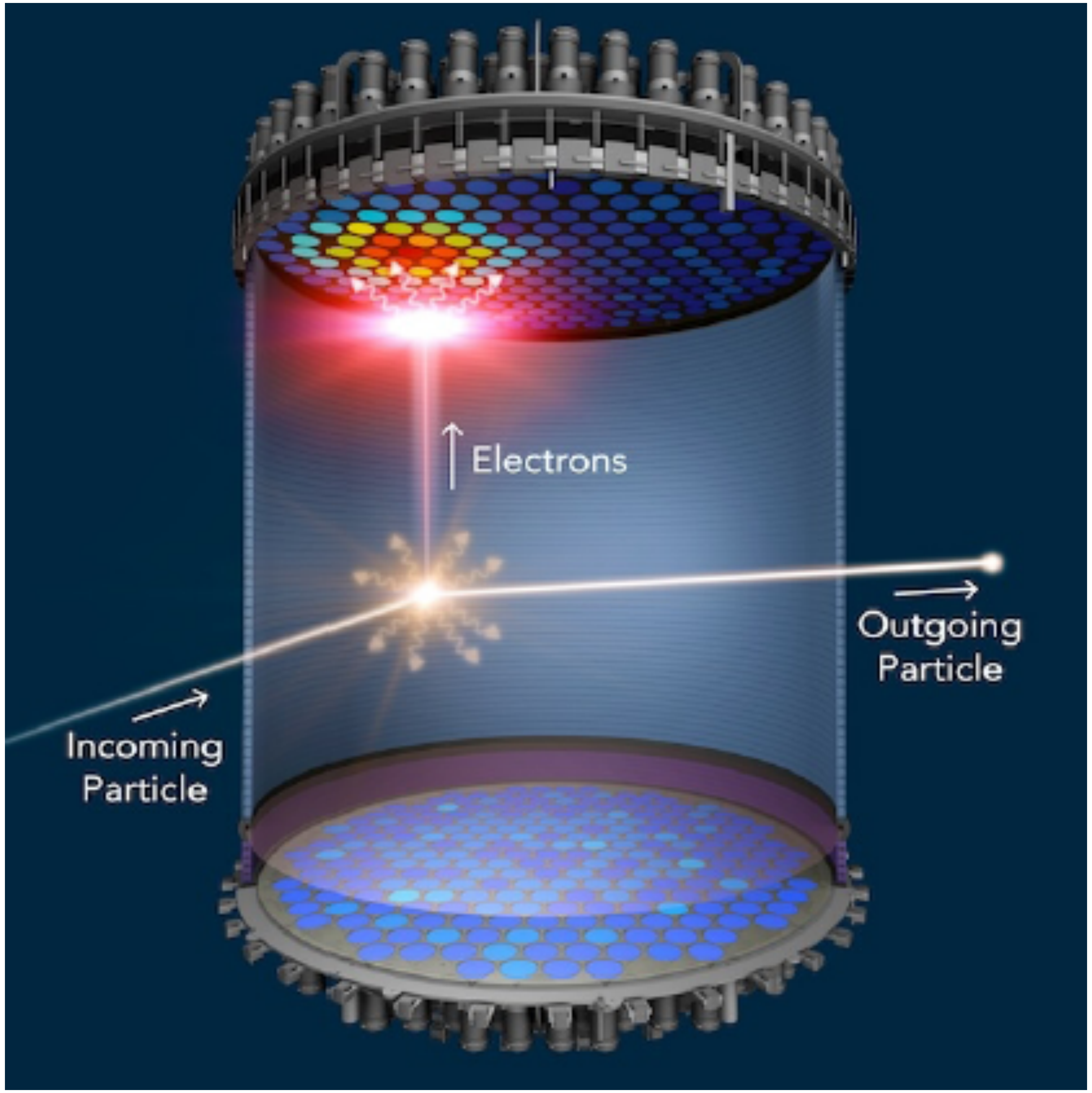


- Direct detection will close WIMP windows very soon.
- The published result is based on traditional spin-independent cross section.
- Some other non-traditional interaction might not be pessimistic.

Outline

- Motivations ✓
- Experiments review
- Dark Matter effective theory
  - DM and nucleus response function
  - Isospin conserved and violating
  - Astrophysical uncertainties
- Fitting and result
- Summary

Configuration of PandaX, LUX, and X1T



- PandaX and LUX are both a dual-phase xenon time-projection chamber.
- 250 Kg (LUX) , 500 Kg (PandaX), and 1042 Kg (X1T). We use exposure 3.35e4 day-kg for LUX, 3.3e4 day-kg for PandaX, and 3.5e4 day-kg for X1T.
- The X1T is a ton-size detector.
- S1: primary scintillation signal.
- S2: the drift ionization charge produce photon.

Background discrimination:
S1 vs S2

① S1 ✓

② S2 ✓

③ Radius r of the event location.

④ Depth z of the event signal.

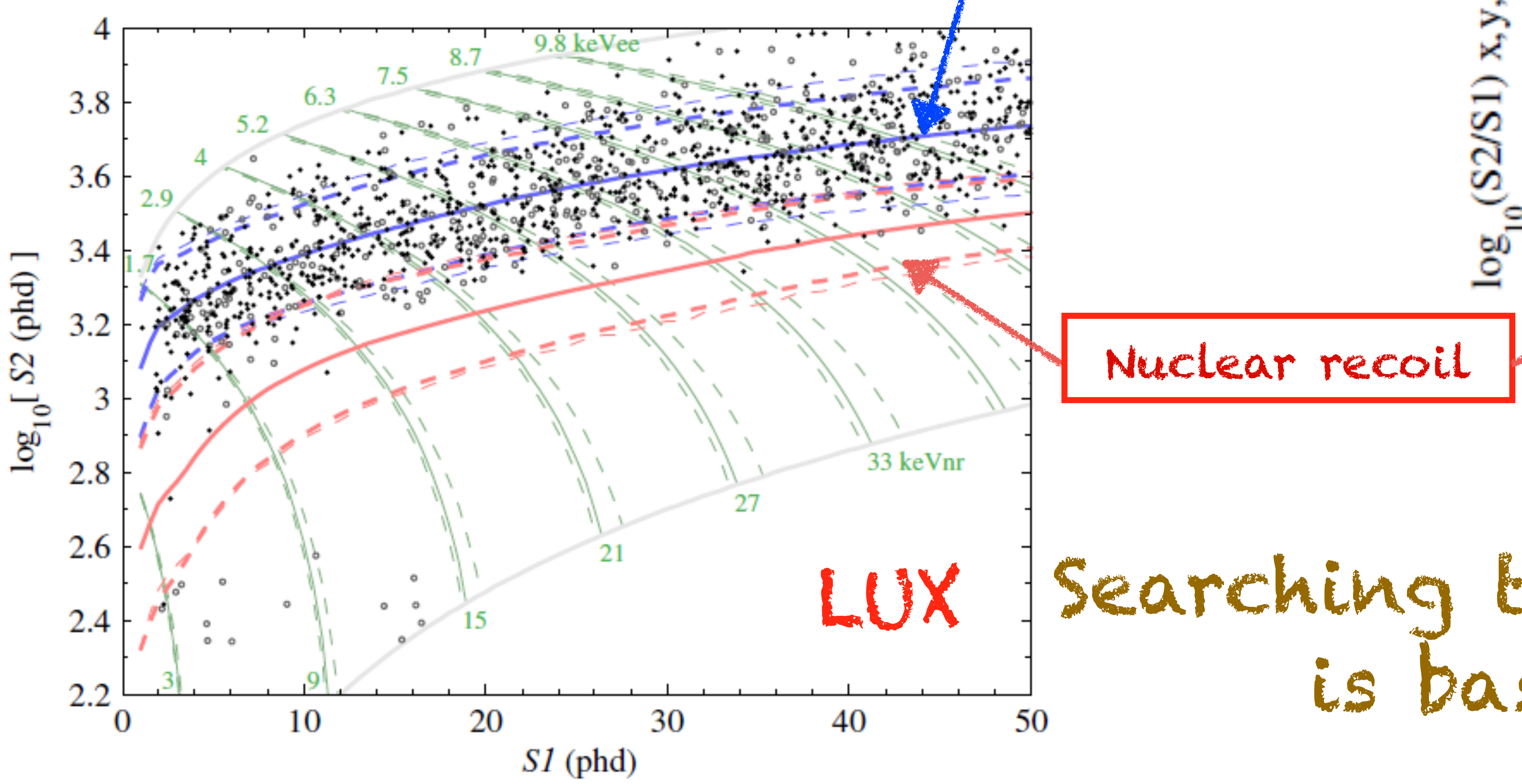
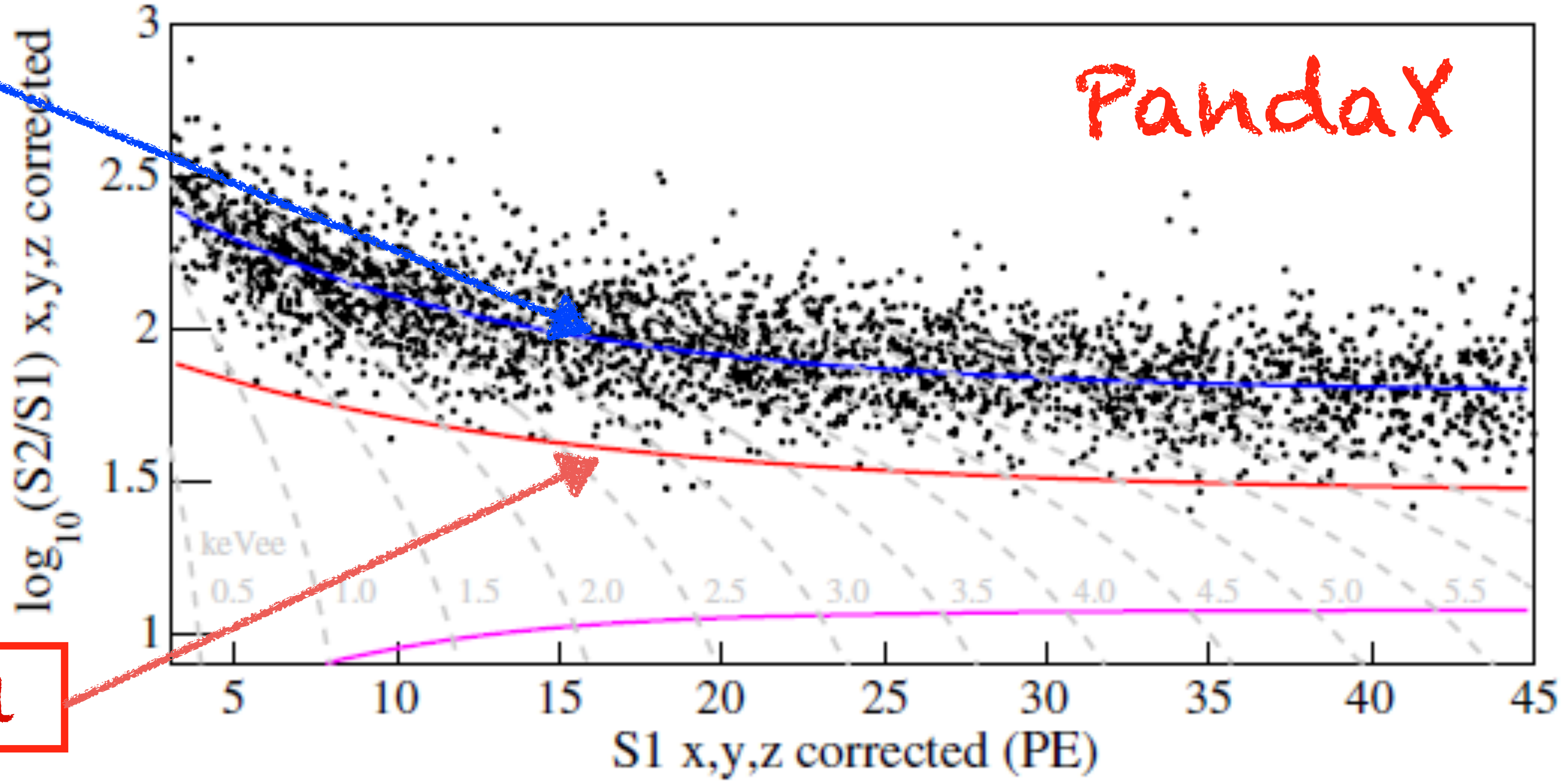


FIG. 1. WS2014–16 data passing all selection criteria. Fiducial



Searching the dark matter nuclear recoil is basically background free!

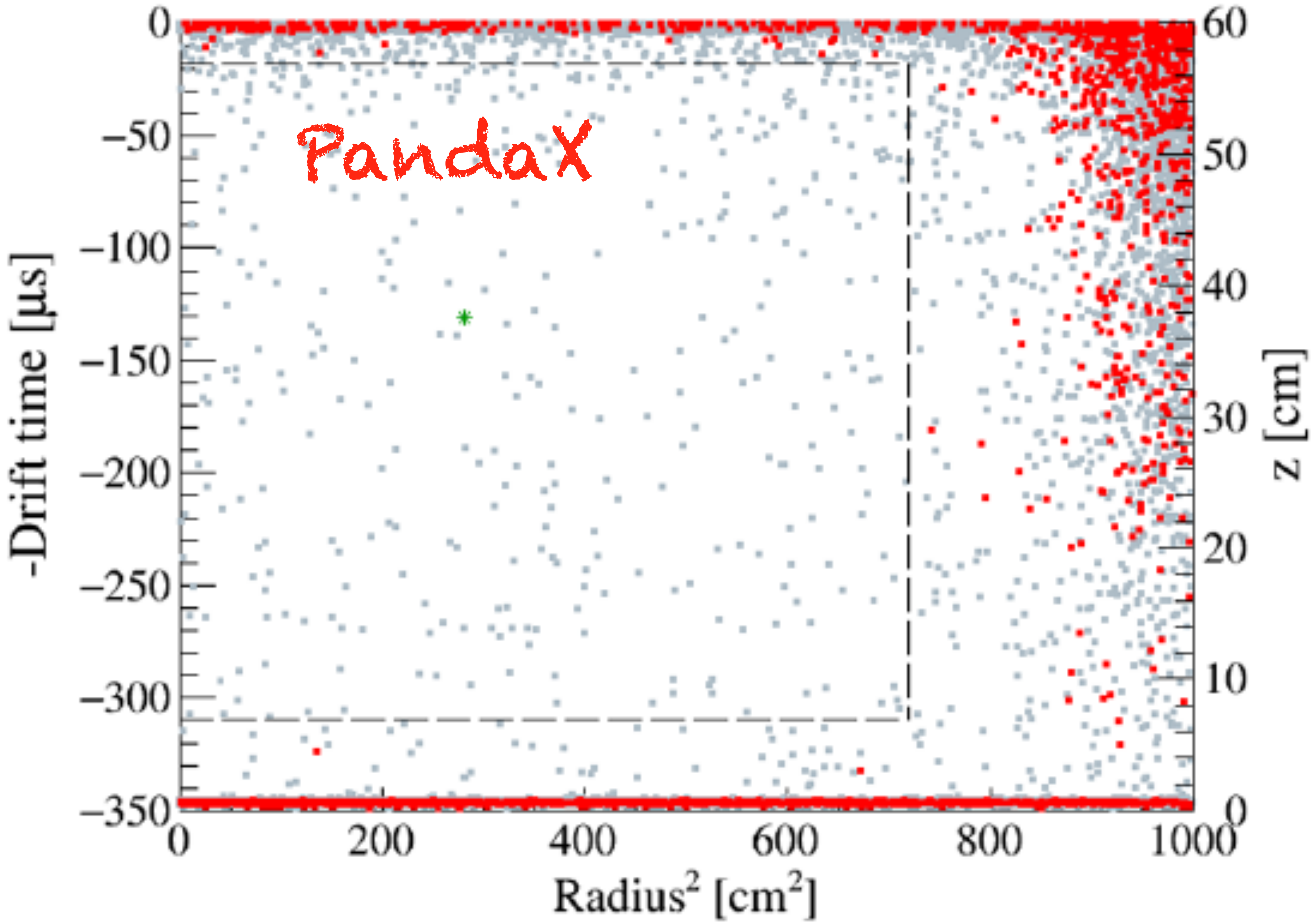
① S1

② S2

✓③ Radius r of the event location.

✓④ Depth z of the event signal.

Background discrimination: Radius and depth

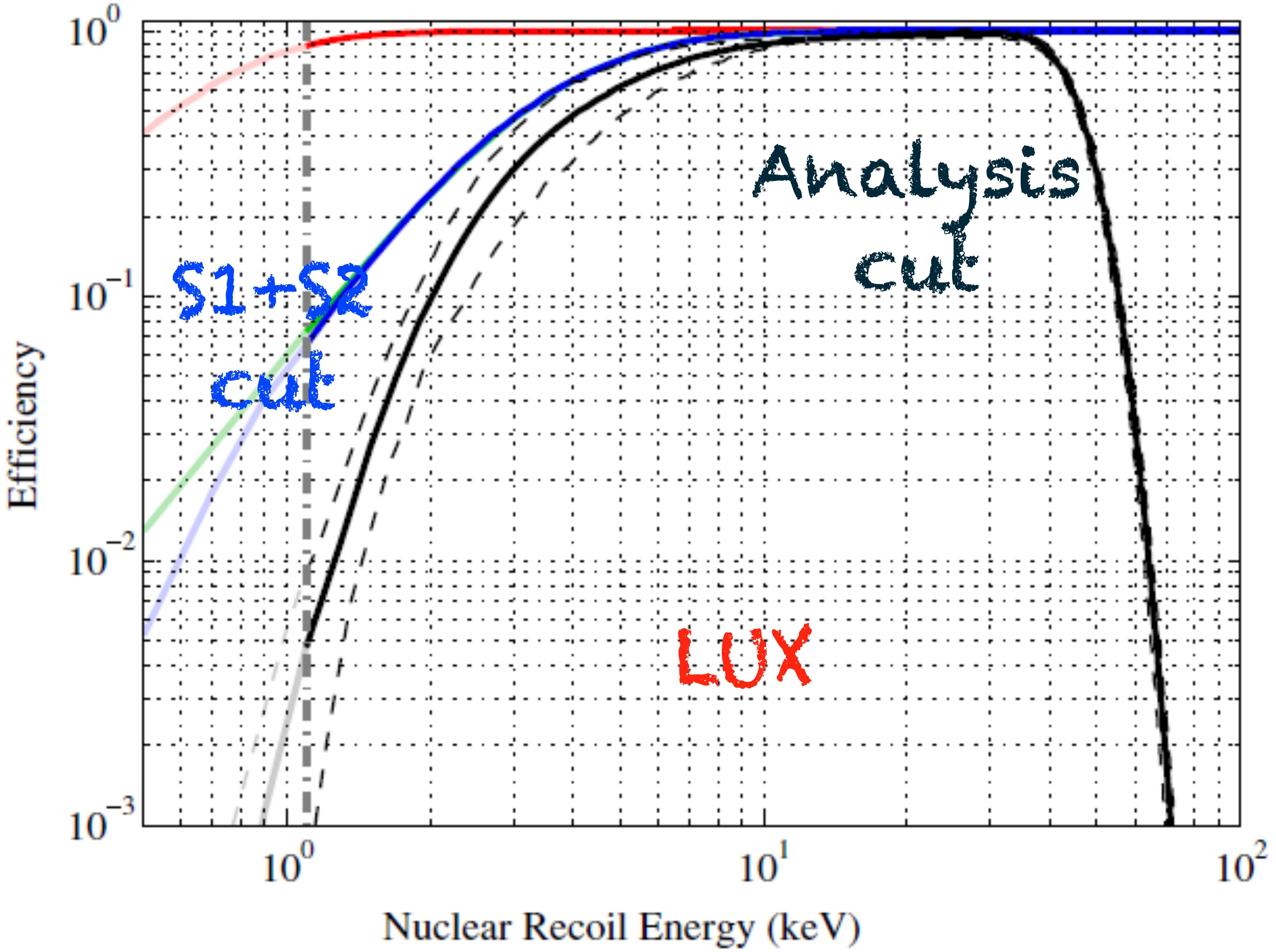


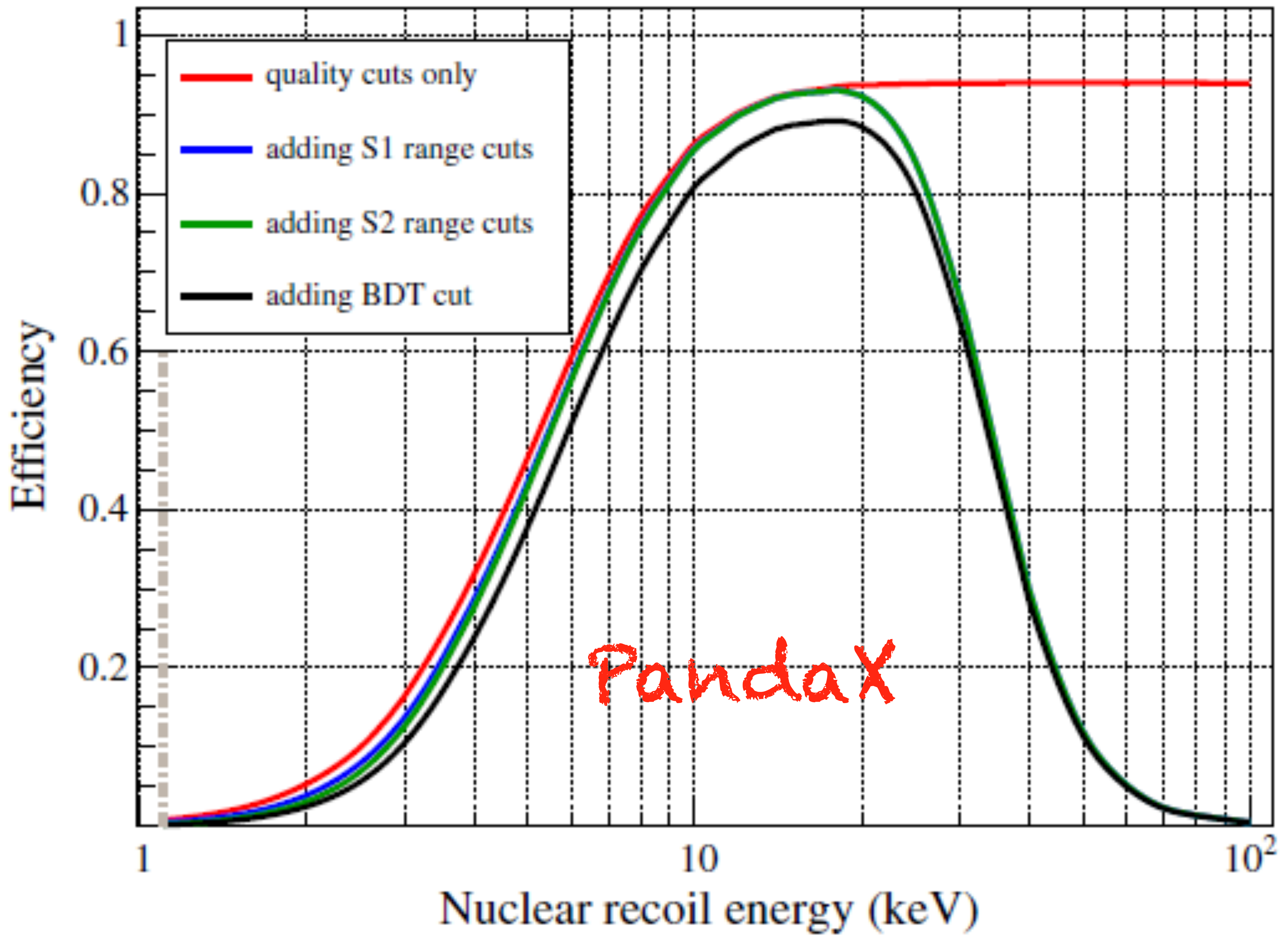
- Most background located at the edge of container.
- One can identify the signal very easily.

$v_{\min}(Q) = \sqrt{\frac{Q m_T}{2M_r^2}},$

Cut efficiency

$q^2 = 2m_T Q.$





The overall efficiency of LUX is blue line times black and PandaX is black one only. (~few keV to 30 KeV)

Events after Cuts

	PandaX run-8	PandaX run-9	LUX WS2013	LUX WS2014-2016	XENON1T
Bkg.	2.4 ± 0.8	2.4 ± 0.7	NOT reported	NOT reported	0.36 +0.11-0.7
Data	2	1	NOT reported	NOT reported	1

$$\ln \mathcal{L}_{\text{LUX}} = \sum_{i=\text{WS2013,WS2014-16}} \ln \mathcal{L}_i(m_\chi, \mathcal{R}),$$

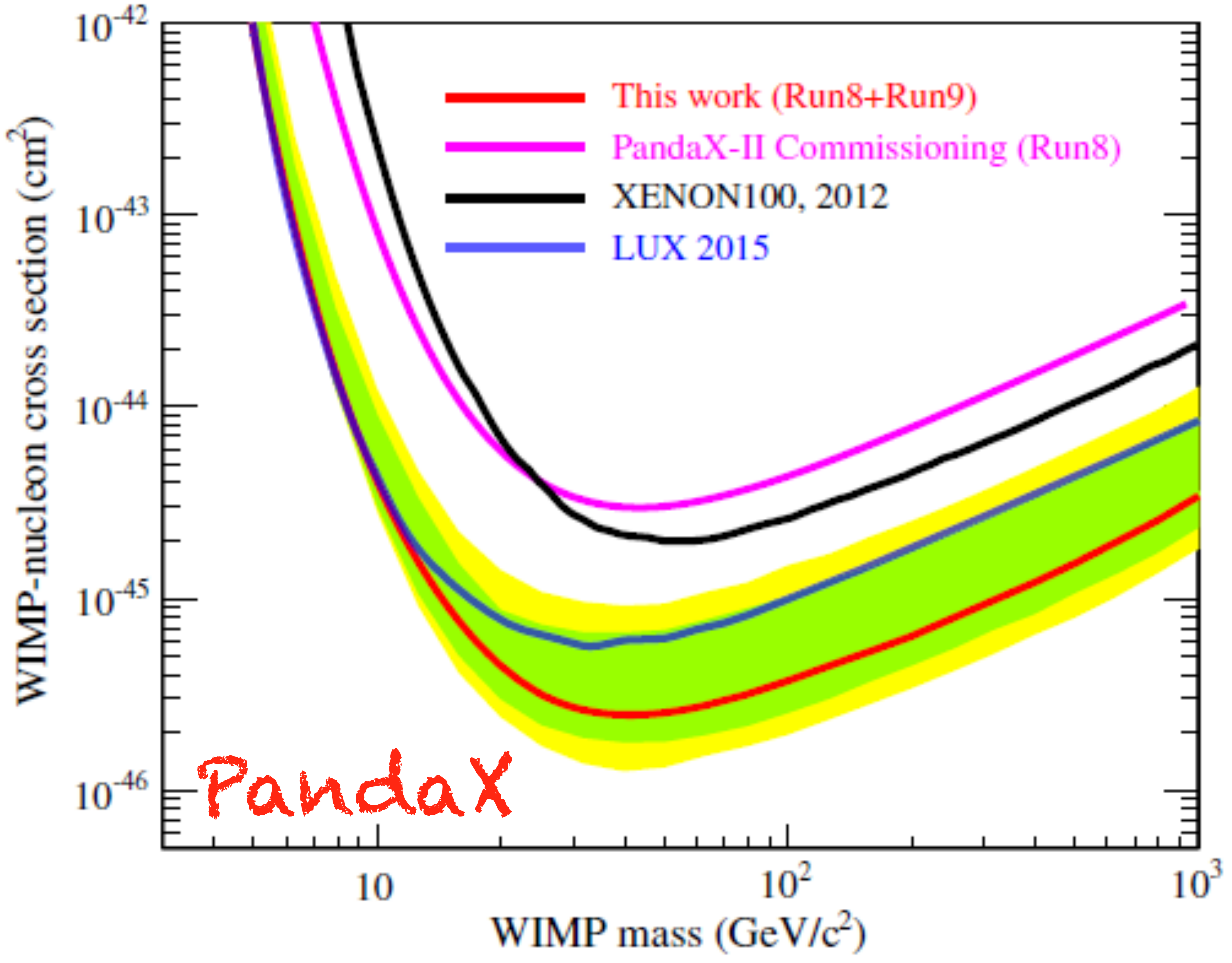
$$-2\ln \mathcal{L}_i(m_\chi, \mathcal{R}) = \left[\frac{s_i(\mathcal{R})}{s_{i,95}(m_\chi)/1.64}\right]^2,$$

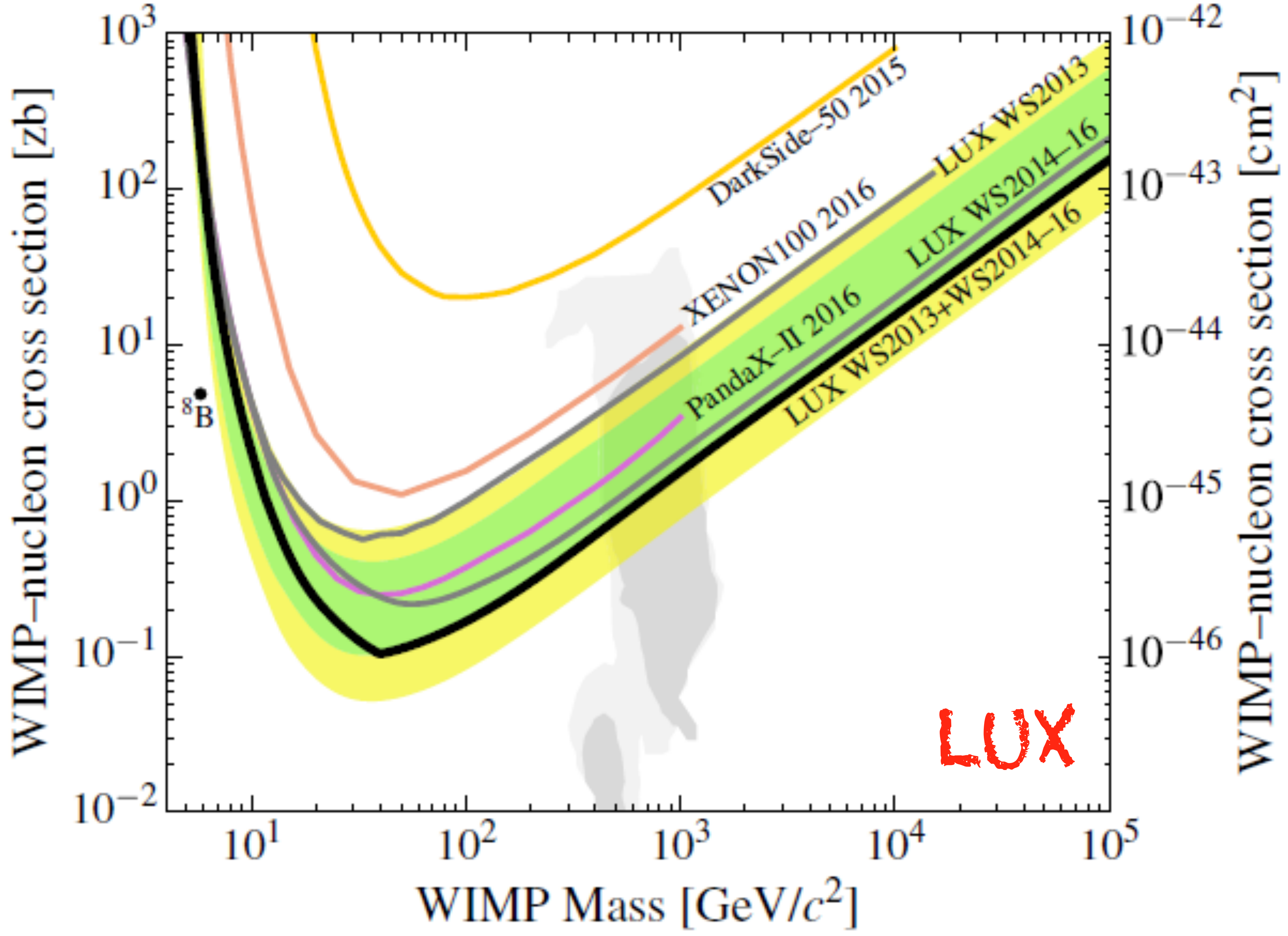
We need the tails of Likeliood functions.

$$\mathcal{L}_{\text{PandaX}} \propto \prod_{i=\text{run8,run9}} \max_{b'_i} \frac{\exp[-(s_i+b'_i)](s_i+b'_i)^{o_i}}{o_i!} \exp[-\frac{(b'_i-b_i)^2}{2\delta b_i^2}]$$

$$f(m_\chi) = \frac{s_{95}^{th.}(m_\chi)}{s_{95}^{stat.}}$$

Reconstructed and Combined Likelihood



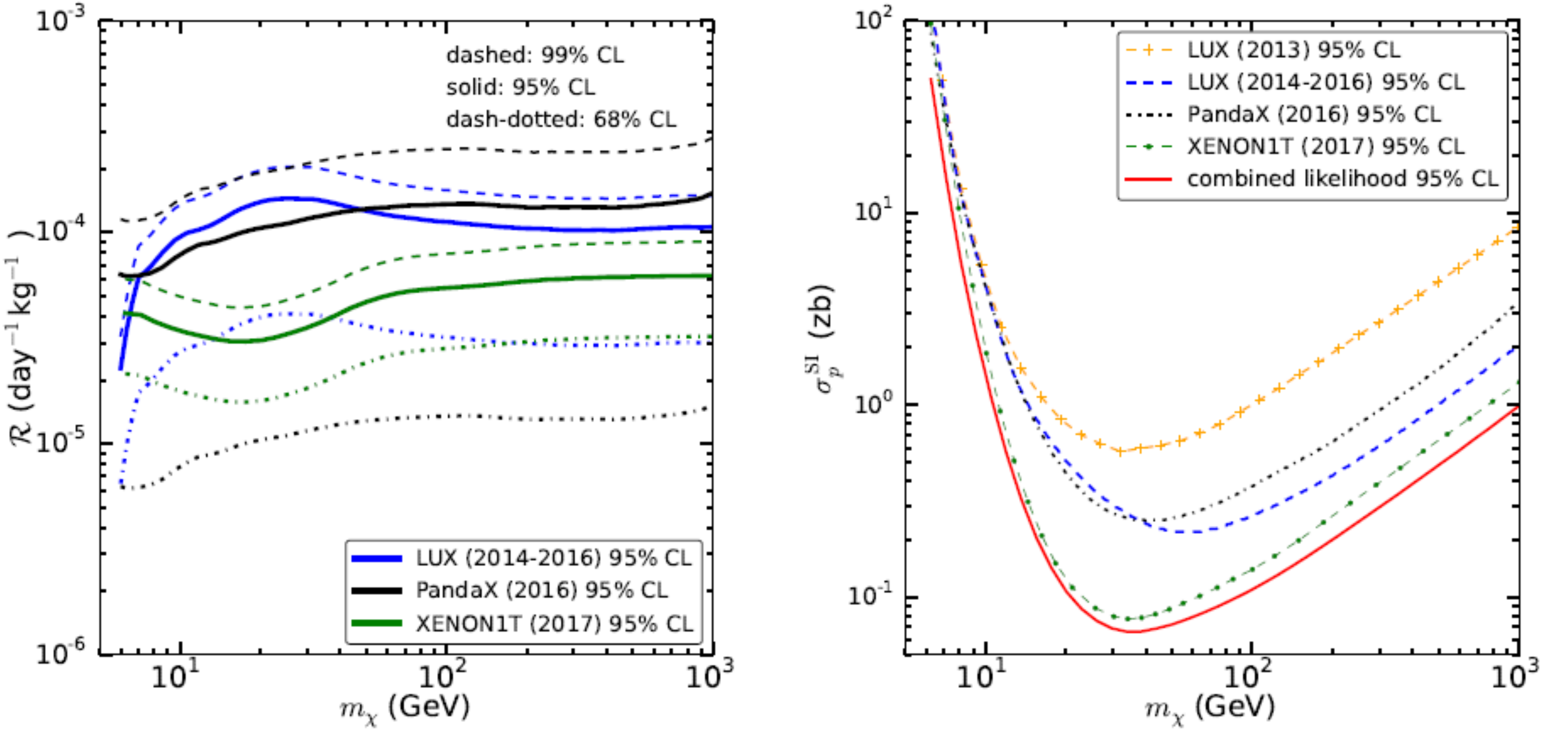


$$f(m_\chi) = \frac{s_{95}^{th.}(m_\chi)}{s_{95}^{stat.}}$$

$$-2 \ln \mathcal{L}_i(m_\chi, \mathcal{R}) = \left[\frac{s_i(\mathcal{R})}{s_{i,95}(m_\chi)/1.64}\right]^2$$

Reconstructed and Combined Likelihood

The error bar of PandaX is larger than LUX. This can explain why LUX can constrain the parameter space further than PandaX even with the almost same exposure.



$$f(m_\chi) = \frac{s_{95}^{th.}(m_\chi)}{s_{95}^{stat.}}$$

With an equal weight for PandaX, LUX, and X1T, we are able to combine their likelihood.

WIMP-nucleon EFT

- Standard paradigm: spin-independent and spin-dependent dark matter-nucleon interactions

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_R} = \frac{m_T}{2\pi v^2} \frac{1}{(2j_\chi + 1)(2J+1)} \sum_{\text{spins}} \left| \langle F | \sum_{i=1}^{A} e^{-i\mathbf{q}\cdot\mathbf{r}_i} (\mathcal{H}_{\text{SI}} + \mathcal{H}_{\text{SD}}) | I \rangle \right|^2$$

one-body DM-nucleon interaction

nucleus $\otimes$ DM state

- Underlying **non-relativistic Hamiltonian**

$$\mathcal{H}_{\text{SI}} = \sum_{\tau=0,1} b_\tau \mathbb{1}_\chi \mathbb{1}_N t^\tau \equiv \sum_{\tau=0,1} c_1^\tau \mathbb{1}_{\chi N} t^\tau$$

- Underlying **non-relativistic Hamiltonian**

$$\mathcal{H}_{\text{SD}} = \sum_{\tau=0,1} a_\tau \boldsymbol{\sigma}_\chi \cdot \boldsymbol{\sigma}_N t^\tau \equiv \sum_{\tau=0,1} c_4^\tau \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N t^\tau$$

Taken from Catena (2016)

Relevant Scales

m_χ E

heavy — Λ – heavy mediators

Simplified models, or "SM-EFT" + DM

e/w — v_{EW} – electroweak symmetry breaking

five-flavor QCD + DM

(ultra-)light — m_b – b-quark threshold

four-flavor QCD + DM

m_c – c-quark threshold

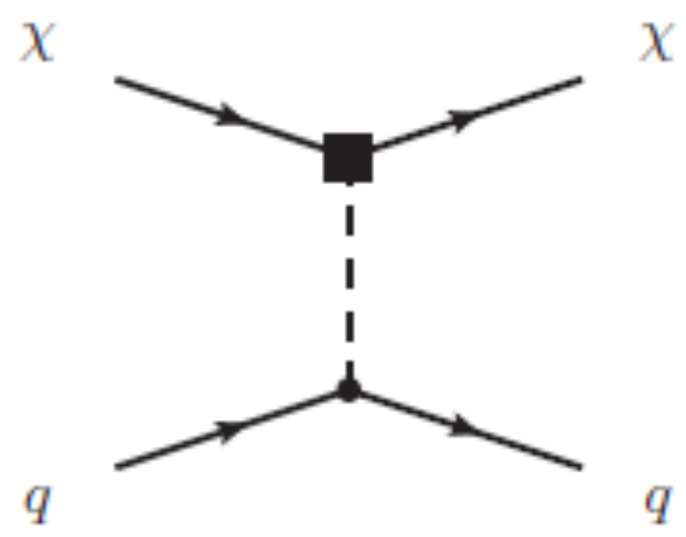
three-flavor QCD + DM

Λ_{QCD} – chiral symmetry breaking

(Heavy Baryon) Chiral Effective Theory

$v, \vec{q}$ – DM-nucleus scattering kinematics

NR theory of nuclear response



WIMP-nucleon EFT

$$\mathcal{L}_{\rm int}(\vec{x}) = c\ \Psi^*_\chi(\vec{x})\mathcal{O}_\chi\Psi_\chi(\vec{x})\ \Psi^*_N(\vec{x})\mathcal{O}_N\Psi_N(\vec{x})$$

$$U(p) = \sqrt{\frac{E+m}{2m}}\begin{pmatrix}\xi \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+m_\chi}\xi\end{pmatrix} \sim \begin{pmatrix}\xi \\ \frac{\vec{\sigma}\cdot\vec{p}}{2m}\xi\end{pmatrix}$$

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

$$\hat{v}^\perp = \frac{1}{2}(\hat{v}_{\chi,in} + \hat{v}_{\chi,out} - \hat{v}_{N,in} - \hat{v}_{N,out})$$

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

Spin-0 or Spin-1 mediator

O1: traditional spin independent.
O4: traditional spin dependent.

Matching: High energy theory to low energy operator

$$\mathcal{L}_\chi = \sum_{a,d} \hat{\mathcal{C}}_a^{(d)} \mathcal{Q}_a^{(d)}, \quad \text{where} \quad \hat{\mathcal{C}}_a^{(d)} = \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}}.$$

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)F_{\mu\nu}, \qquad \mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}i\gamma_5\chi)F_{\mu\nu},$$

$$\mathcal{Q}_{1,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu q), \qquad \mathcal{Q}_{2,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu q),$$

$$\mathcal{Q}_{3,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu\gamma_5 q), \qquad \mathcal{Q}_{4,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu\gamma_5 q),$$

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi\chi)G^{a\mu\nu}G^a_{\mu\nu}, \qquad \mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu},$$

$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}, \qquad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu},$$

$$\mathcal{Q}_{5,q}^{(7)} = m_q(\bar\chi\chi)(\bar q q), \qquad \mathcal{Q}_{6,q}^{(7)} = m_q(\bar\chi i\gamma_5\chi)(\bar q q),$$

$$\mathcal{Q}_{7,q}^{(7)} = m_q(\bar\chi\chi)(\bar q i\gamma_5 q), \qquad \mathcal{Q}_{8,q}^{(7)} = m_q(\bar\chi\gamma_5\chi)(\bar q\gamma_5 q),$$

$$\mathcal{Q}_{9,q}^{(7)} = m_q(\bar\chi\sigma^{\mu\nu}\chi)(\bar q\sigma_{\mu\nu}q), \qquad \mathcal{Q}_{10,q}^{(7)} = m_q(\bar\chi i\sigma^{\mu\nu}\gamma_5\chi)(\bar q\sigma_{\mu\nu}q).$$

$$\mathcal{O}_1^N = \mathbb{1}_\chi\mathbb{1}_N, \qquad \mathcal{O}_2^N = (v_\perp)^2\mathbb{1}_\chi\mathbb{1}_N,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi\vec S_N\cdot\left(\vec v_\perp\times\frac{i\vec q}{m_N}\right), \qquad \mathcal{O}_4^N = \vec S_\chi\cdot\vec S_N,$$

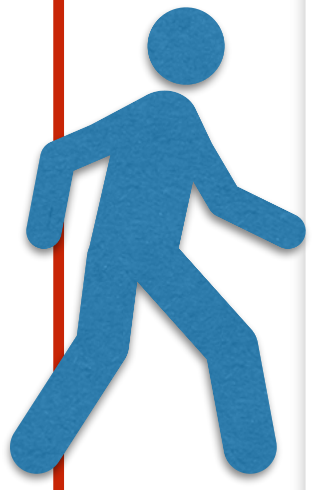
$$\mathcal{O}_5^N = \vec S_\chi\cdot\left(\vec v_\perp\times\frac{i\vec q}{m_N}\right)\mathbb{1}_N, \qquad \mathcal{O}_6^N = \left(\vec S_\chi\cdot\frac{\vec q}{m_N}\right)\left(\vec S_N\cdot\frac{\vec q}{m_N}\right),$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi\left(\vec S_N\cdot\vec v_\perp\right), \qquad \mathcal{O}_8^N = \left(\vec S_\chi\cdot\vec v_\perp\right)\mathbb{1}_N,$$

$$\mathcal{O}_9^N = \vec S_\chi\cdot\left(\frac{i\vec q}{m_N}\times\vec S_N\right), \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi\left(\vec S_N\cdot\frac{i\vec q}{m_N}\right),$$

$$\mathcal{O}_{11}^N = -\left(\vec S_\chi\cdot\frac{i\vec q}{m_N}\right)\mathbb{1}_N, \qquad \mathcal{O}_{12}^N = \vec S_\chi\cdot\left(\vec S_N\times\vec v_\perp\right),$$

$$\mathcal{O}_{13}^N = -\left(\vec S_\chi\cdot\vec v_\perp\right)\left(\vec S_N\cdot\frac{i\vec q}{m_N}\right), \qquad \mathcal{O}_{14}^N = -\left(\vec S_\chi\cdot\frac{i\vec q}{m_N}\right)\left(\vec S_N\cdot\vec v_\perp\right),$$



Magnetic dipole interaction, $Q^{(5)}{}_1$, $c_1=1$:

$$C_1 = -\frac{0.00116171}{\Lambda\, m_\chi}$$

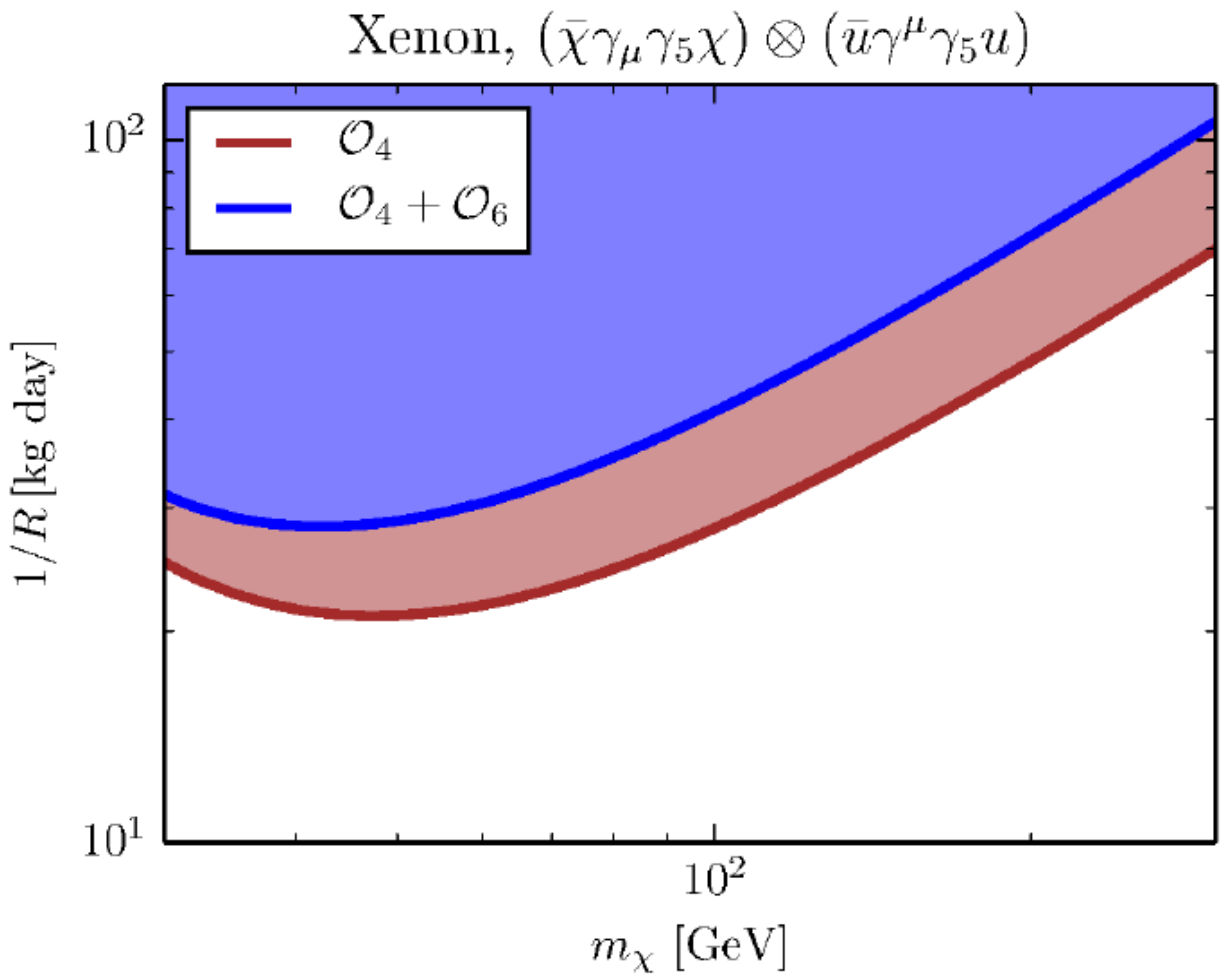
$$C_4 = -\frac{0.0138082}{\Lambda}$$

$$C_5 = \frac{0.00436302}{q^2\,\Lambda}$$

$$C_6 = \frac{0.0121728}{q^2\,\Lambda}$$

The Matching

Effect of NLO operators – meson exchange



$$\mathcal{L}_\chi = \sum_{a,d} \hat{\mathcal{C}}_a^{(d)} \mathcal{Q}_a^{(d)}, \quad \text{where} \quad \hat{\mathcal{C}}_a^{(d)} = \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} .$$

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)F_{\mu\nu} , \qquad \mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}i\gamma_5\chi)F_{\mu\nu} ,$$

$$\mathcal{Q}_{1,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu q), \qquad \mathcal{Q}_{2,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu q),$$

$$\mathcal{Q}_{3,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu\gamma_5 q) , \qquad \mathcal{Q}_{4,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu\gamma_5 q) ,$$

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi\chi)G^{a\mu\nu}G^a_{\mu\nu} , \qquad \mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu} ,$$

$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu} , \qquad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu} ,$$

$$\mathcal{Q}_{5,q}^{(7)} = m_q(\bar\chi\chi)(\bar q q) , \qquad \mathcal{Q}_{6,q}^{(7)} = m_q(\bar\chi i\gamma_5\chi)(\bar q q) ,$$

$$\mathcal{Q}_{7,q}^{(7)} = m_q(\bar\chi\chi)(\bar q i\gamma_5 q) , \qquad \mathcal{Q}_{8,q}^{(7)} = m_q(\bar\chi\gamma_5\chi)(\bar q\gamma_5 q) ,$$

$$\mathcal{Q}_{9,q}^{(7)} = m_q(\bar\chi\sigma^{\mu\nu}\chi)(\bar q\sigma_{\mu\nu} q) , \qquad \mathcal{Q}_{10,q}^{(7)} = m_q(\bar\chi i\sigma^{\mu\nu}\gamma_5\chi)(\bar q\sigma_{\mu\nu} q) .$$

Response function

We follow the conventions of Ref. [4] and the differential event rate of scattering between DM and target *per time per detector mass* as function of the recoil energy Q is given by

$$\frac{d\mathcal{R}}{dQ} = \sum_T \xi_T \frac{\rho_0}{m_\chi m_T} \int_{v>v_{\min}(Q)} v f(\vec{v}+\vec{v}_e) \frac{d\sigma}{dQ} d^3v, \quad (3)$$

where differential cross section is

$$\frac{d\sigma}{dQ} = \frac{m_T}{2\pi v^2} \langle |\mathcal{M}_{NR}|^2 \rangle_{\text{spins}}$$

and the averaged amplitudes can be written as

$$\langle |\mathcal{M}_{NR}|^2 \rangle_{\text{spins}} = \frac{4\pi}{2J+1} \sum_{\tau,\tau'} \Bigg[\sum_{k=M,\Sigma',\Sigma''} R_k^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_k^{\tau\tau'}(y) + \frac{q^2}{m_N^2} \sum_{k=\Phi'',\Phi''M,\tilde{\Phi}',\Delta,\Delta\Sigma'} R_k^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_k^{\tau\tau'}(y) \Bigg].$$

- Spin-independent ("M"): e.g. $\mathcal{O}_1^p = 1_\chi 1_N$
- Spin-dependent ("Σ', Σ''"): e.g. $\mathcal{O}_4^p = \vec{S}_\chi \cdot \vec{S}_N$
- Nuclear angular momentum ("Δ"): e.g. $\mathcal{O}_9^p = \vec{S}_\chi \cdot (\vec{S}_p \times \frac{i\vec{q}}{m_N})$

Rk: DM response function
Wk: Nuclear response function

$W_{\Phi''} > W_M$ quasicoherent

- $W_M \sim \mathcal{O}(A^2)$
- $W_{\Sigma'}, W_{\Sigma''}, W_\Delta, W_{\Delta\Sigma'} \sim \mathcal{O}(1)$

we also label the response type by using the notations M, Δ, Σ', Σ'', $\tilde{\Phi}'$, and Φ'', which refer to the DM current by vector charge, vector transverse magnetic, axial transverse electric, axial longitudinal, vector transverse electric, and vector longitudinal operators, respectively

Isospin conserved and violating

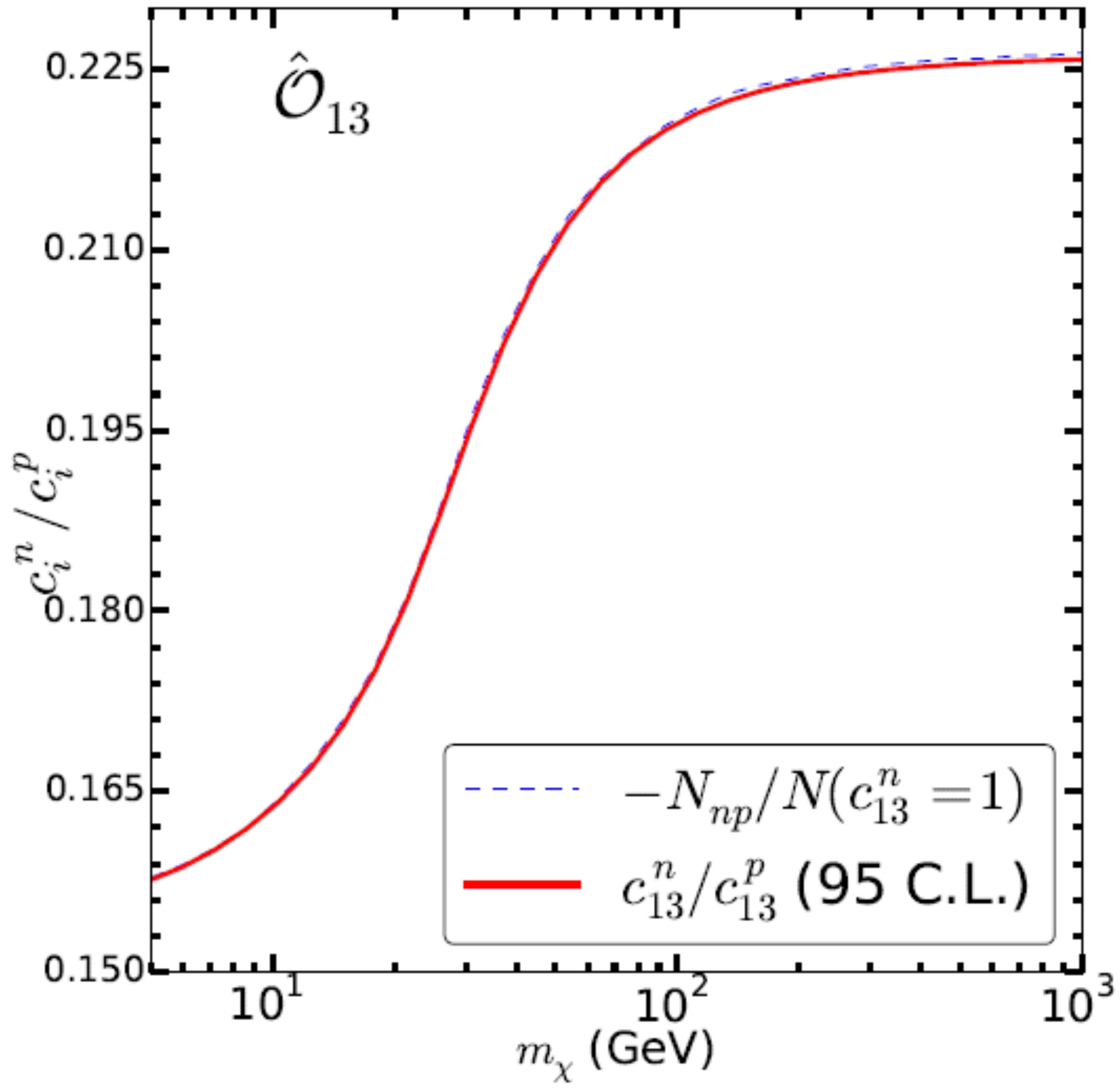
$$\psi_N = C_p |p\rangle + C_n |n\rangle$$

$$\frac{c_i^n}{c_i^p} = -\frac{N_{np}}{N_{nn}}.$$

$$\psi_N \, O_i \, \psi_N = \left[\langle p| , \langle n| \right] O_i \begin{bmatrix} C_p^2 , & C_p C_n \\ C_p C_n , & C_n^2 \end{bmatrix} \begin{bmatrix} |p\rangle \\ |n\rangle \end{bmatrix}$$

C_p*C_p and C_n*C_n must be larger than zero.
However, C_p*C_n can be either positive or negative.

The maximum ISV ratio

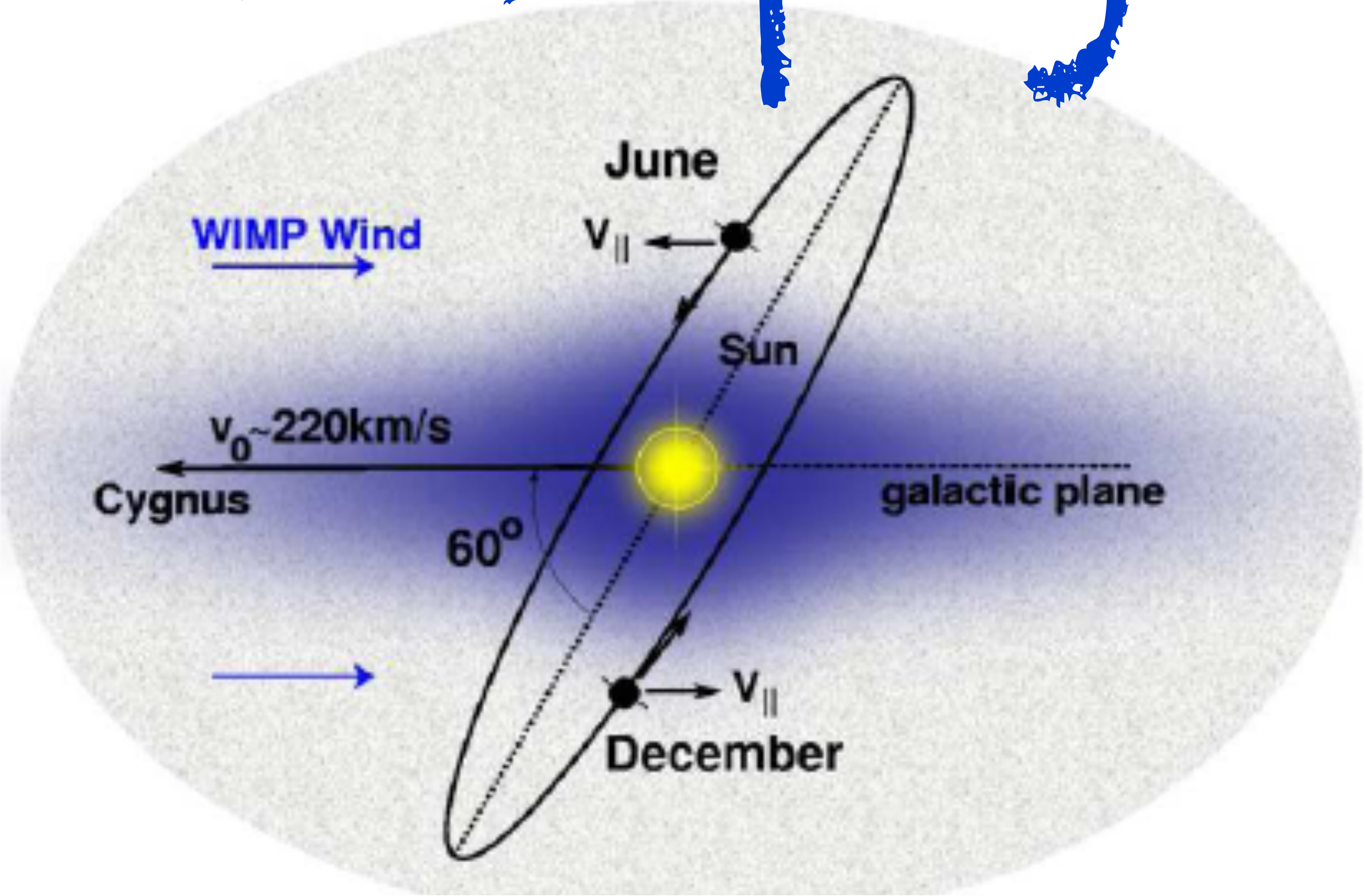


$$N(c_i^n, c_i^p) = \begin{pmatrix} c_i^n & c_i^p \end{pmatrix} \begin{bmatrix} N(c_i^n=1) & N_{np} \\ N_{np} & N(c_i^p=1) \end{bmatrix} \begin{pmatrix} c_i^n \\ c_i^p \end{pmatrix}$$

$$\frac{c_i^n}{c_i^p} = -\frac{N_{np}}{N(c_i^n=1)}.$$

This ratio is not fixed value!

Astrophysical uncertainties



$$\int_{v>v_{\min}(Q)} v^3 dv \int_0^{2\pi} d\varphi \int_0^{\pi} \frac{d\sigma}{dQ} f(\vec{v}+\vec{v}_e) \sin\theta d\theta$$

$$f(\vec{v}+\vec{v}_e) = \frac{(e^{-(\vec{v}+\vec{v}_e)^2/v_0^2} - e^{-v_{esc}^2/v_0^2})\Theta(v_{esc}^2 - (\vec{v}+\vec{v}_e)^2)}{\pi^{3/2} v_0^3 \times \text{Norm}}$$

Astrophysical nuisances		
ρ_0 (GeV/cm^{-3})	0.32 ± 0.02	[7]
v_0 (km/s)	240.0 ± 6.0	[7]
v_{esc} (km/s)	$541.28^{+16.58}_{-12.18}$	[7]

[7] Yang Huang (Peking University), et.al.

LUX

cross sections at each value of WIMP mass. Nuclear-recoil energy spectra for the WIMP signal are derived from a standard Maxwellian velocity distribution with $v_0 =$ 220 km/s, $v_{esc} = 544$ km/s, $\rho_0 = 0.3$ GeV/cm^3, average Earth velocity of 245 km/s, and a Helm form factor.

For velocity dependent operators, how could we ignore this if there is signal?

Fitting and result

Parameters and Likelihood

- mx is fixed at given value.
- Ci^p, Ci^n
  if ISC: Ci^p=Ci^n.
  if ISV: Ci^p and Ci^n are two free parameters.
- Local density varied and profiled.
- v0 varied and profiled.
- escape velocity varied and profiled.

PandaX and X1T: run8+run9+X1T (Poisson+Gaussian)
LUX: WS2013+WS2014-16 (Gaussian)

Astrophysical nuisances		
ρ_0 (GeV/cm^{-3})	0.32 ± 0.02	[7]
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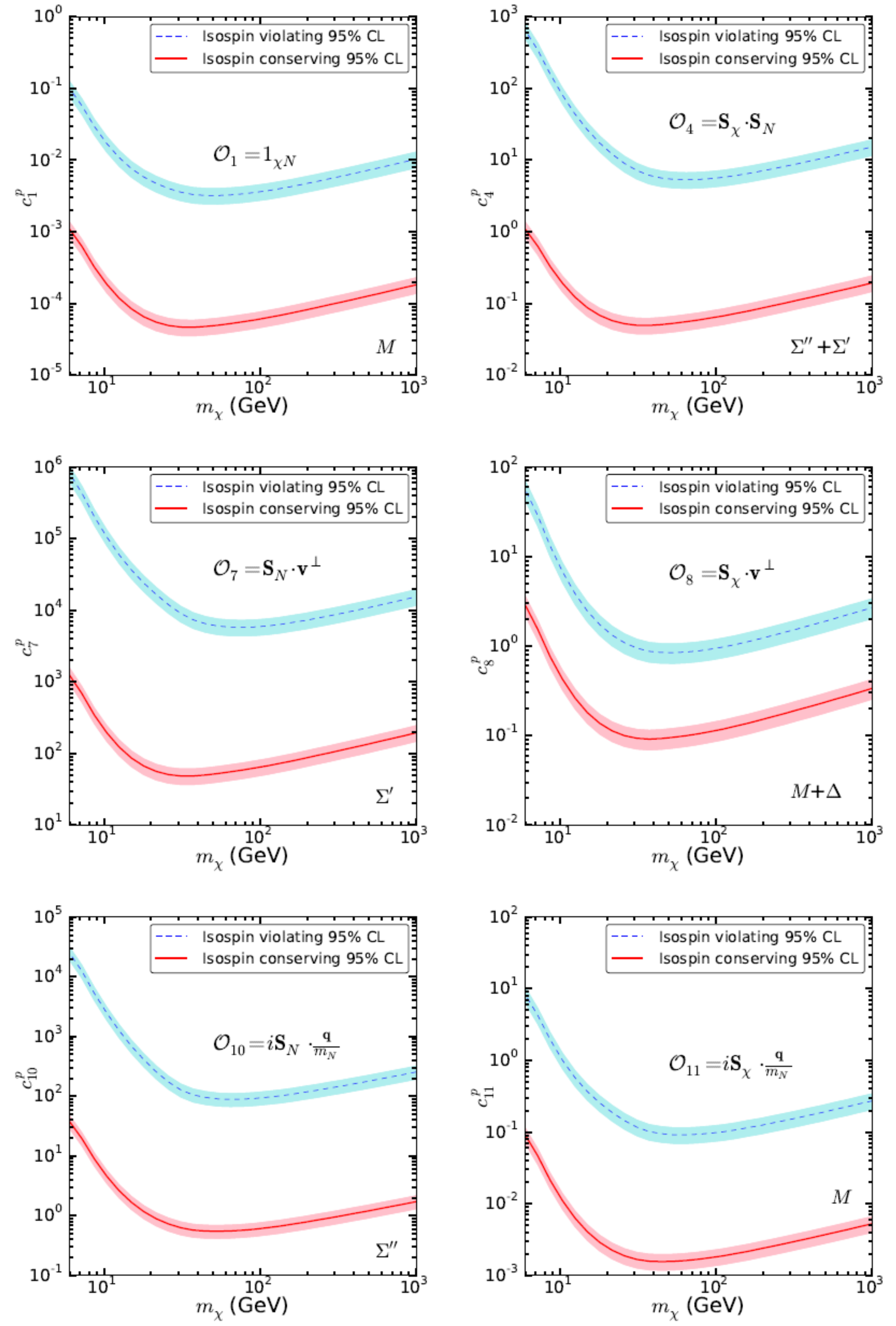
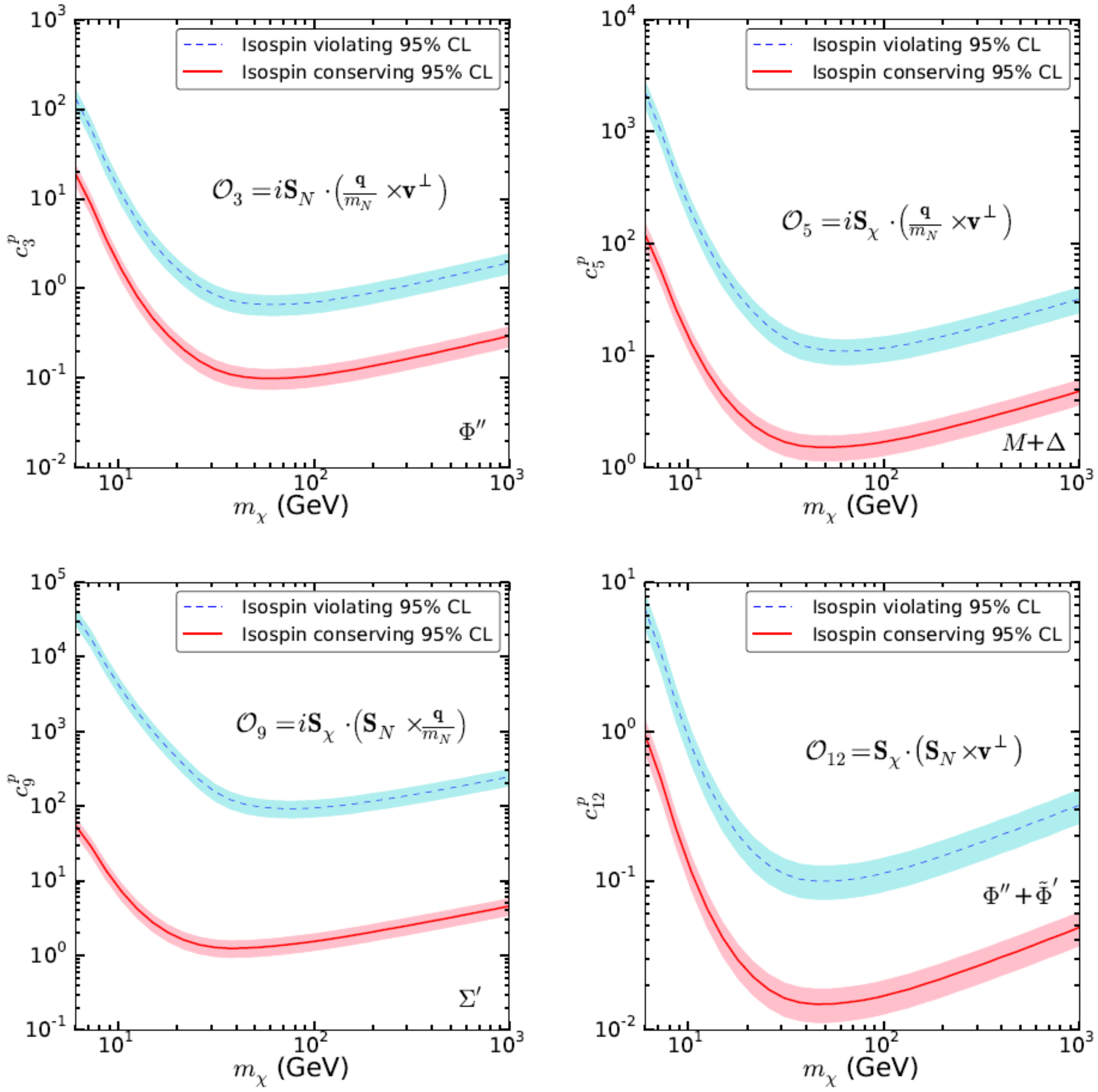


The upper combined limits of operators

- O1 and O4 are only two velocity independent operators. O1: spin independent component. O4: spin dependent component.
- As expected, the constraints from O4 is weaker than O1.
- Those limits for nuclear spin dependent operators (O7 and O10) are always weaker than DM spin dependent operators (O8 and O11).
  - $W_M \sim \mathcal{O}(A^2)$
  - $W_{\Sigma'}, W_{\Sigma''}, W_\Delta, W_{\Delta\Sigma'} \sim \mathcal{O}(1)$

$$W_{\Phi''} > W_M$$

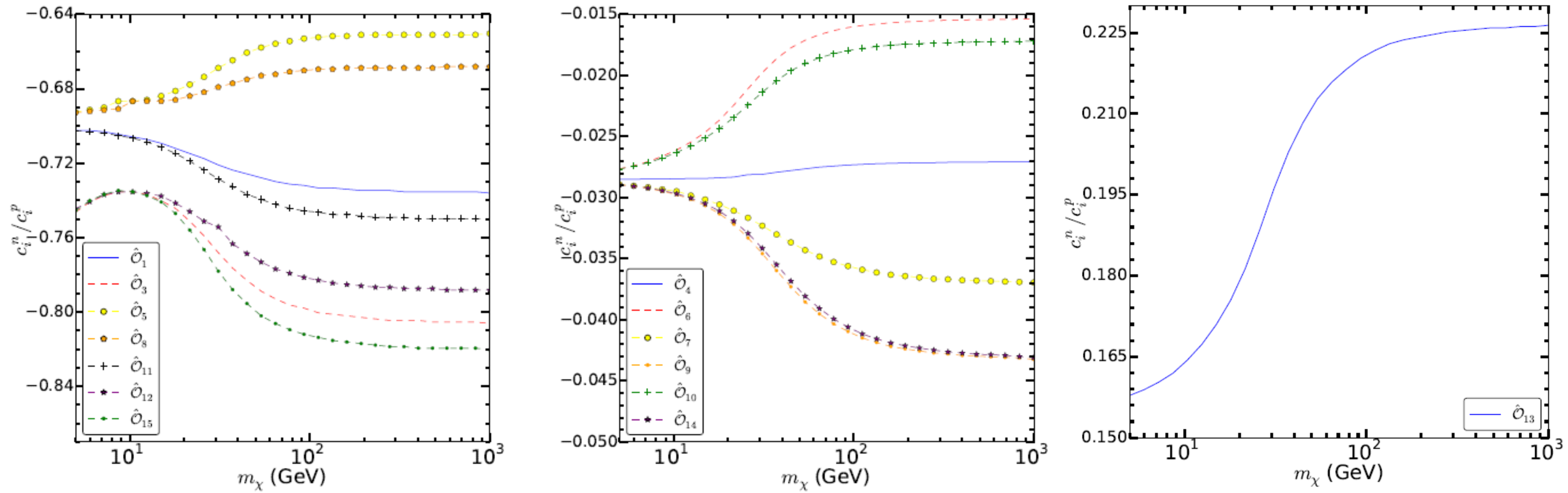


- (O3 vs O5) shows an opposite picture with (o7 vs O8) and (O10 vs O11).
- The Limit for O12 is stronger than O9 because the response function of O9 is proportional to exchange moment.

$W_{\Phi''} > W_M$ quasicoherent

- $W_M \sim \mathcal{O}(A^2)$
- $W_{\Sigma'}, W_{\Sigma''}, W_\Delta, W_{\Delta\Sigma'} \sim \mathcal{O}(1)$

The maximum ISV ratio



Only O1 and O4 change mildly at small mass region,
but all of operators are achieved to a constant at large mx.

Conclusion

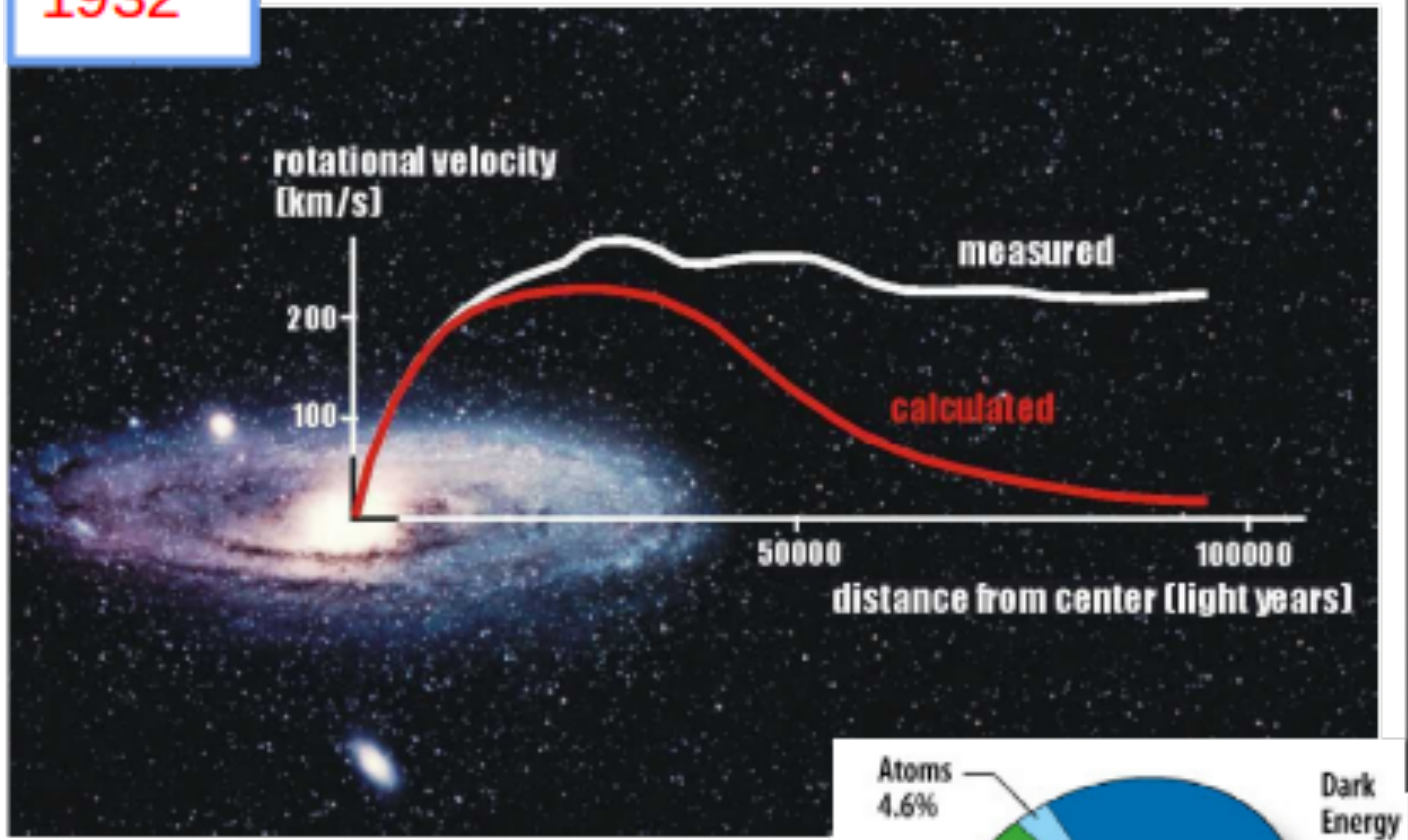
- We are able to combine THREE independent likelihood functions from latest PandaX, LUX, XENON1T data.
- A better combined limit on each effective coupling for both isospin conserved and violating cases.
- The astrophysical uncertainties and isospin violating setups are both properly taken into account.
- A statistical maximum isospin coupling violating ratio is reported.

The End

Thank you for your attention.

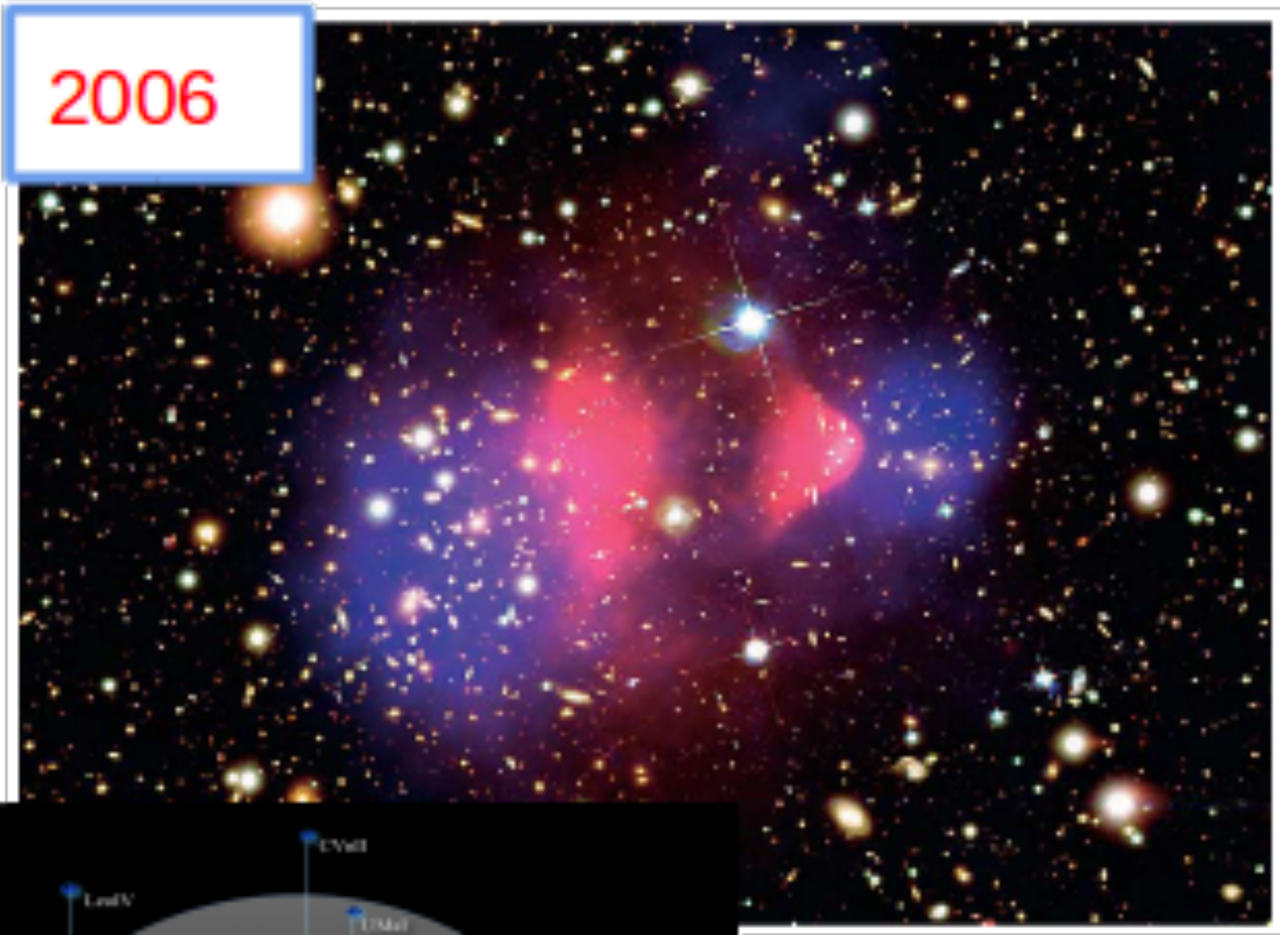
Dark Matter evidence

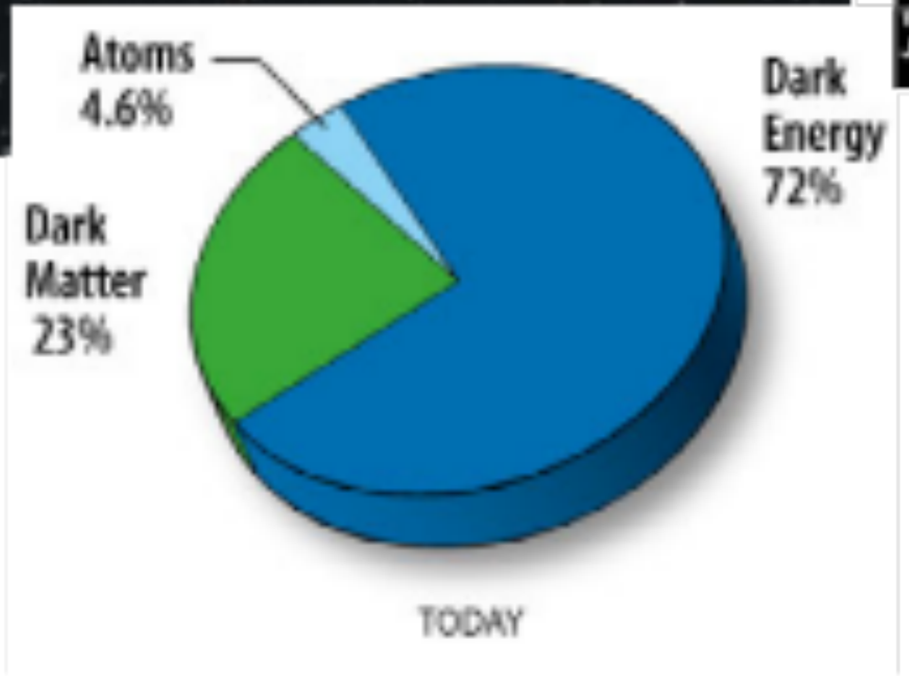
1932

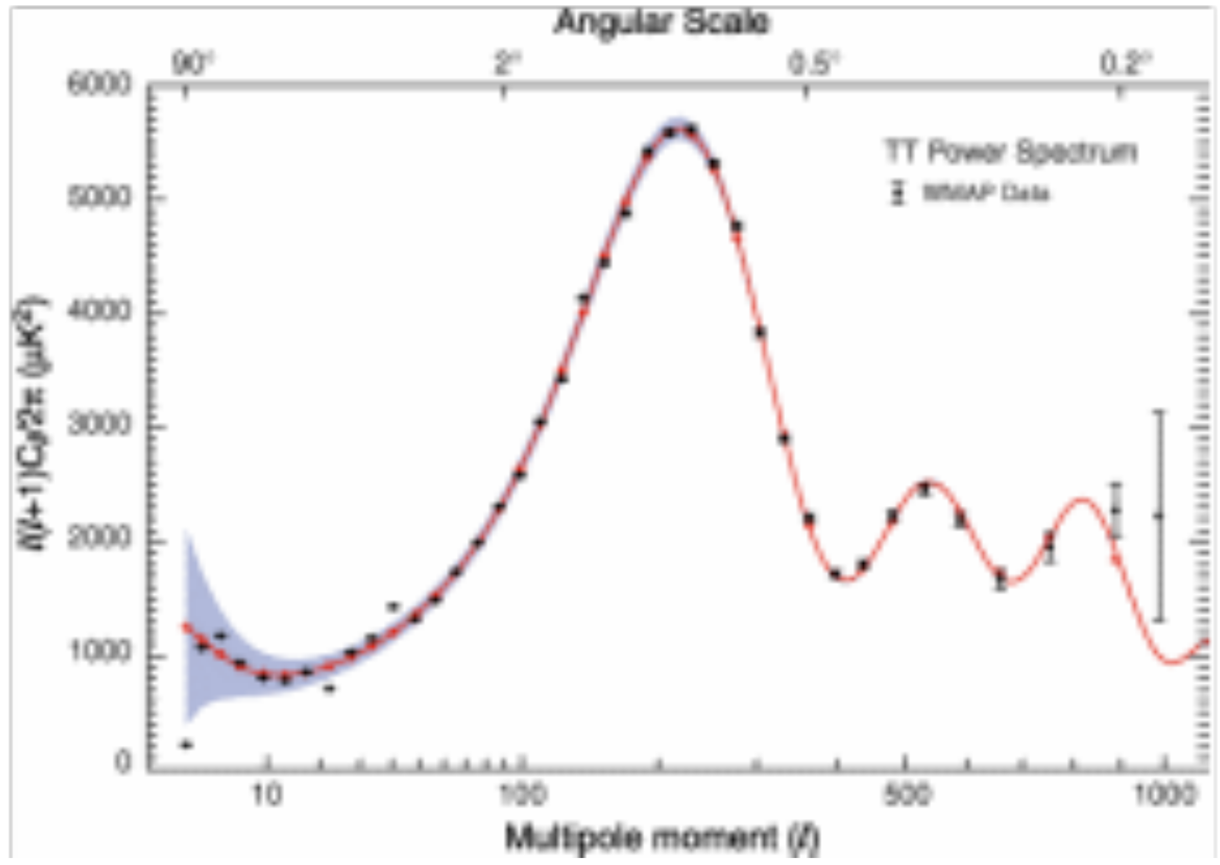


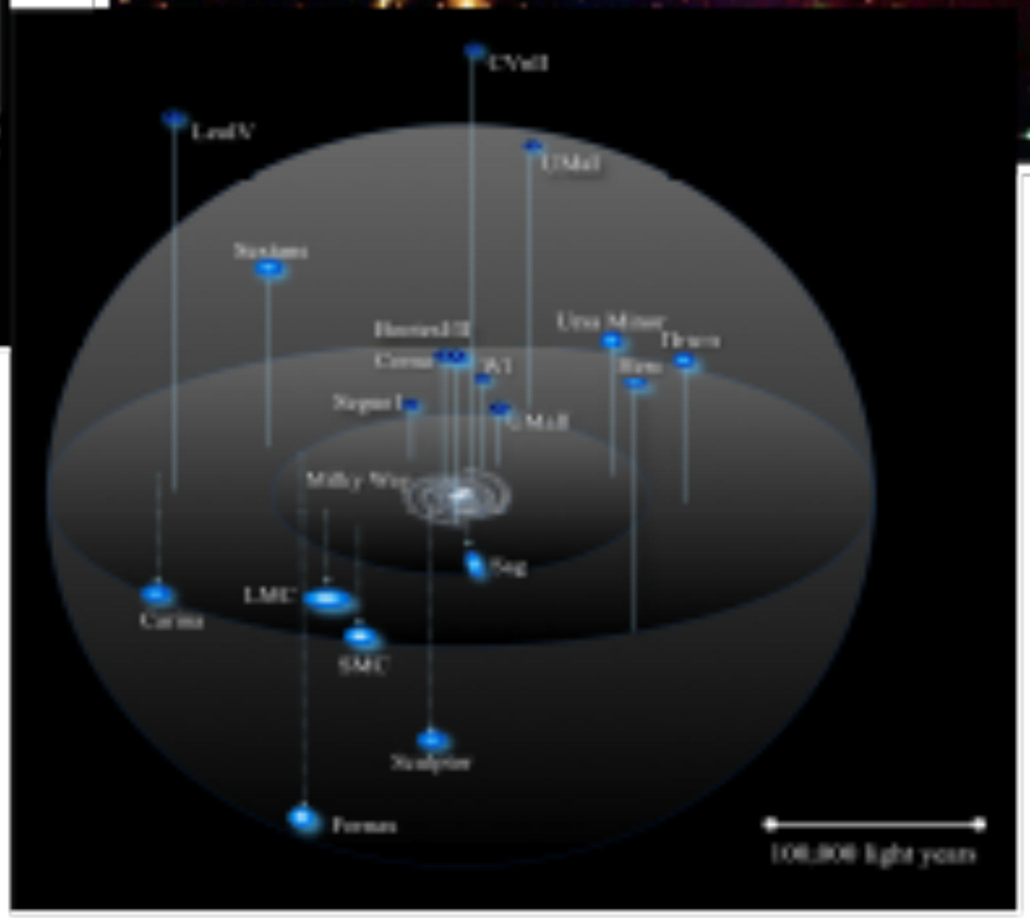
1980

2006



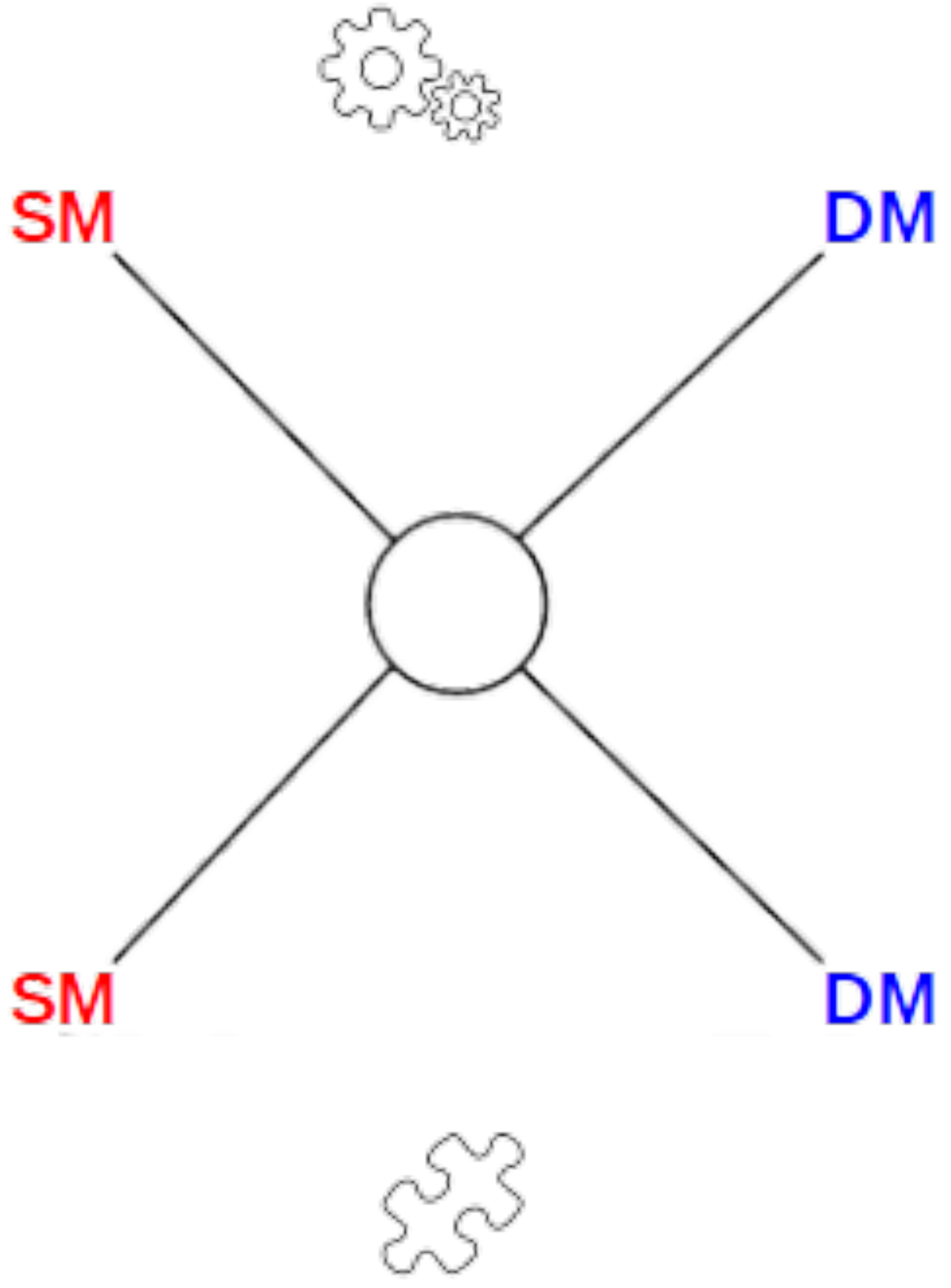




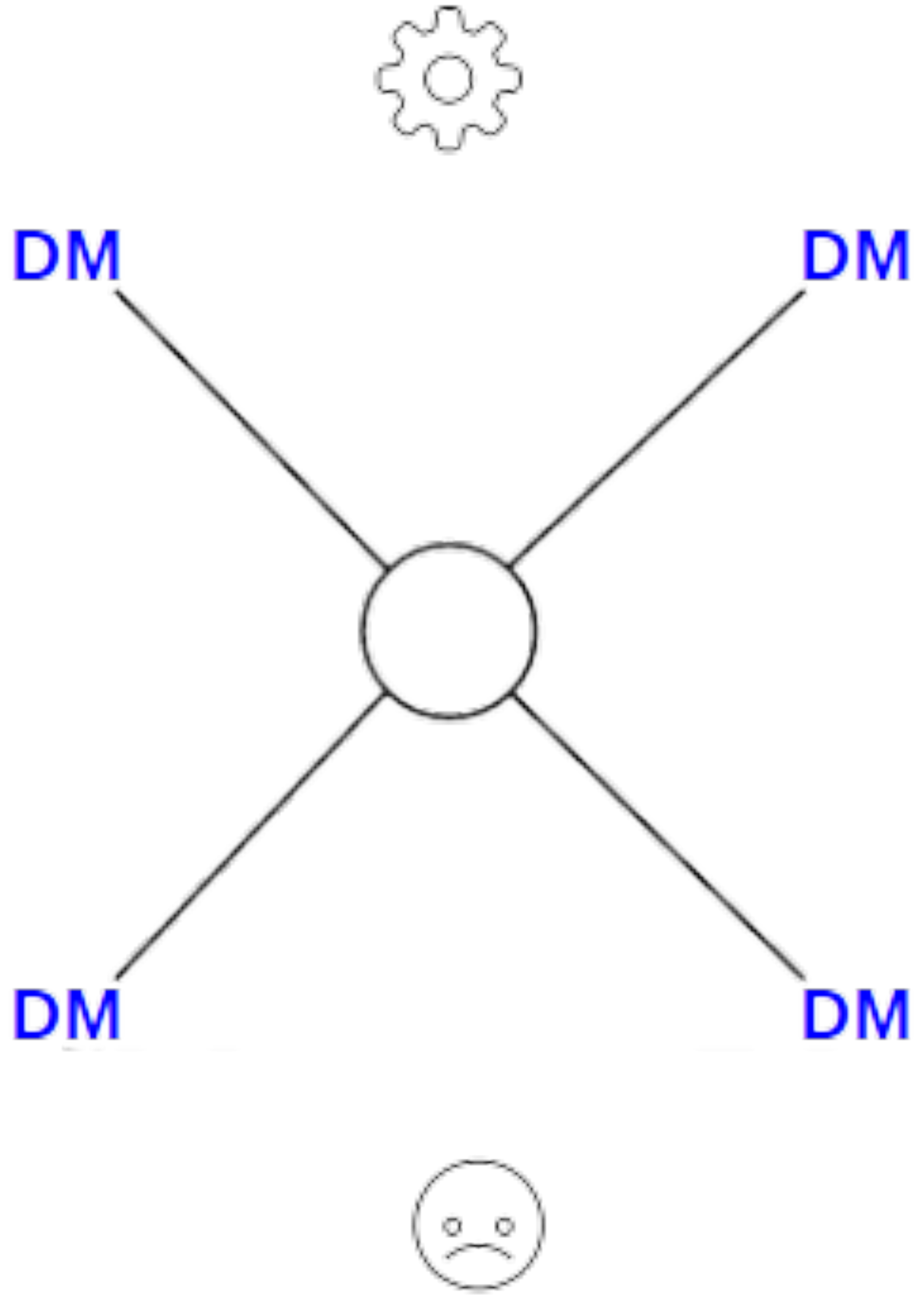


It will be difficult to explain the universe without dark matter assumption.

The strategy of DM hunting



- SM SM > DM DM. Measurement of the missing energy at the colliders
- SM DM > SM DM. Measurement of the recoil energy of SM particles.
- DM DM > SM SM Measurement of the flux of cosmic ray.
- DM DM > DM DM. Astrophysical structure



- Dark Matter is EXPECTED to have weak interaction between SM and DM but it is not necessary to be.
- However, without weak interaction between DM and SM, method 1-3 are useless.
- WIMPs search in this era is very important.

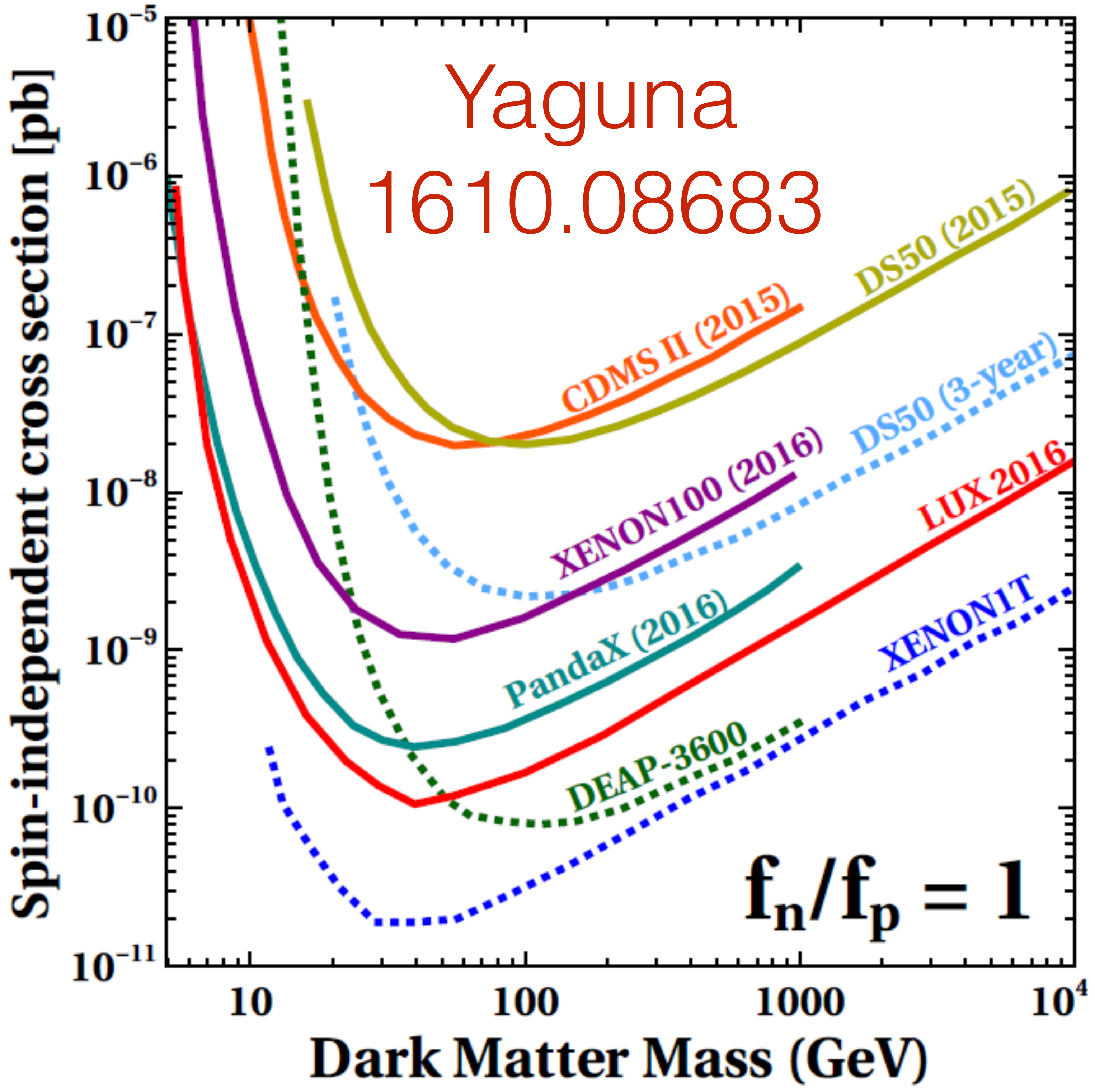
Effective Lagrangian

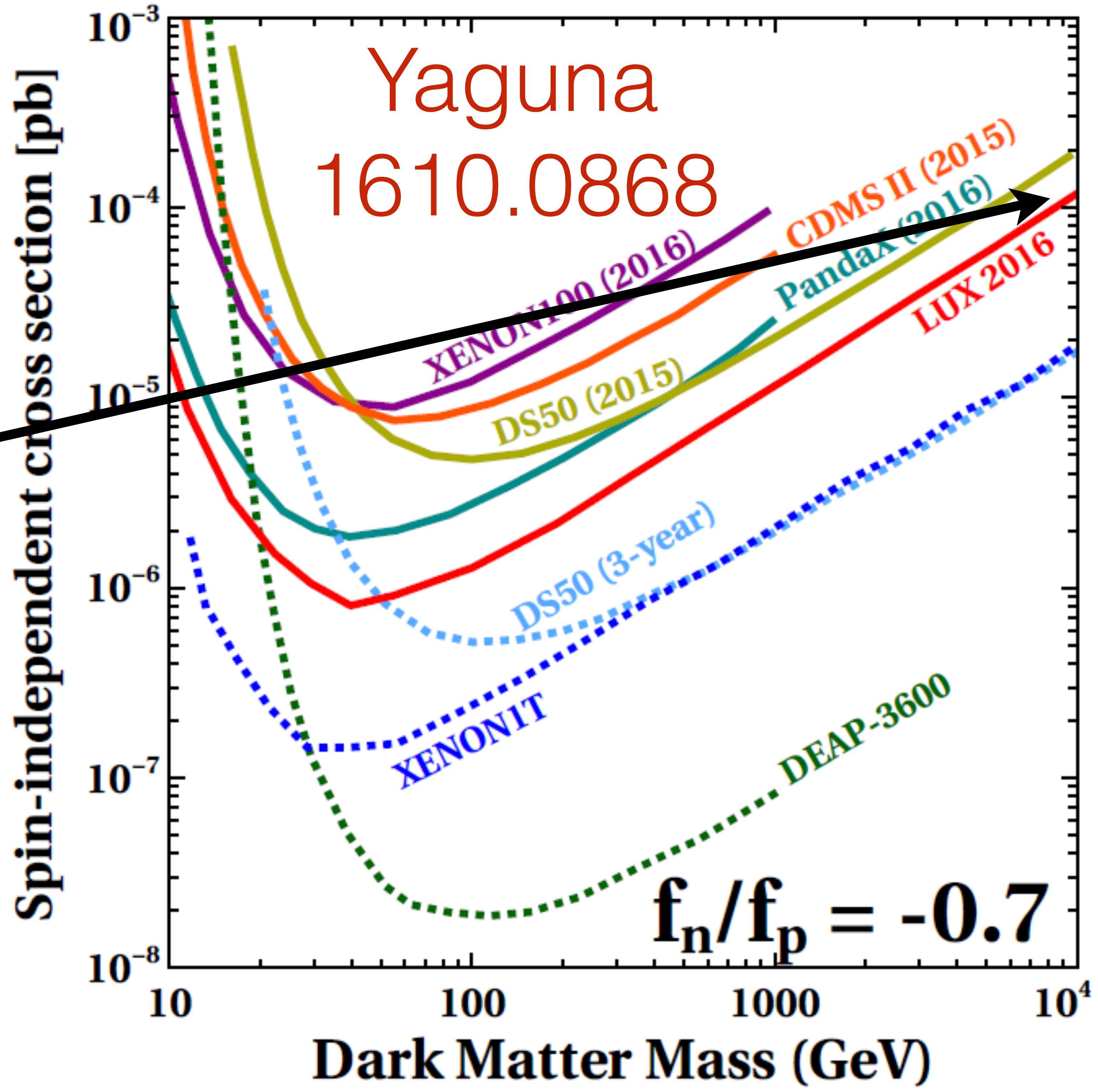
j	$\mathcal{L}^j_{\text{int}}$	Nonrelativistic reduction	$\sum_i c_i \mathcal{O}_i$
1	$\bar{\chi}\chi\bar{N}N$	$1_\chi 1_N$	$\mathcal{O}_1$
2	$i\bar{\chi}\chi\bar{N}\gamma^5 N$	$i\frac{\vec{q}}{m_N}\cdot\vec{S}_N$	$\mathcal{O}_{10}$
3	$i\bar{\chi}\gamma^5\chi\bar{N}N$	$-i\frac{\vec{q}}{m_\chi}\cdot\vec{S}_\chi$	$-\frac{m_N}{m_\chi}\mathcal{O}_{11}$
4	$\bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N$	$-\frac{\vec{q}}{m_\chi}\cdot\vec{S}_\chi\frac{\vec{q}}{m_N}\cdot\vec{S}_N$	$-\frac{m_N}{m_\chi}\mathcal{O}_6$
5	$\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu N$	$1_\chi 1_N$	$\mathcal{O}_1$
6	$\bar{\chi}\gamma^\mu\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\frac{\vec{q}^{\,2}}{2m_N m_M}1_\chi 1_N + 2(\frac{\vec{q}}{m_\chi}\times\vec{S}_\chi + i\vec{v}^\perp)\cdot(\frac{\vec{q}}{m_M}\times\vec{S}_N)$	$\frac{\vec{q}^{\,2}}{2m_N m_M}\mathcal{O}_1 - 2\frac{m_N}{m_M}\mathcal{O}_3 + 2\frac{m_N^2}{m_M m_\chi}\left(\frac{q^2}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6\right)$
7	$\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu\gamma^5 N$	$-2\vec{S}_N\cdot\vec{v}^\perp + \frac{2}{m_\chi}i\vec{S}_\chi\cdot(\vec{S}_N\times\vec{q})$	$-2\mathcal{O}_7 + 2\frac{m_N}{m_\chi}\mathcal{O}_9$
8	$i\bar{\chi}\gamma^\mu\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$2i\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$2\frac{m_N}{m_M}\mathcal{O}_{10}$
9	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}\gamma_\mu N$	$-\frac{\vec{q}^{\,2}}{2m_\chi m_M}1_\chi 1_N - 2(\frac{\vec{q}}{m_N}\times\vec{S}_N + i\vec{v}^\perp)\cdot(\frac{\vec{q}}{m_M}\times\vec{S}_\chi)$	$-\frac{\vec{q}^{\,2}}{2m_\chi m_M}\mathcal{O}_1 + \frac{2m_N}{m_M}\mathcal{O}_5 - 2\frac{m_N}{m_M}\left(\frac{\vec{q}^{\,2}}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6\right)$
10	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4(\frac{\vec{q}}{m_M}\times\vec{S}_\chi)\cdot(\frac{\vec{q}}{m_M}\times\vec{S}_N)$	$4(\frac{\vec{q}^{\,2}}{m_M^2}\mathcal{O}_4 - \frac{m_N^2}{m_M^2}\mathcal{O}_6)$
11	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}\gamma^\mu\gamma^5 N$	$4i(\frac{\vec{q}}{m_M}\times\vec{S}_\chi)\cdot\vec{S}_N$	$4\frac{m_N}{m_M}\mathcal{O}_9$
12	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$-[i\frac{\vec{q}^{\,2}}{m_\chi m_M} - 4\vec{v}^\perp\cdot(\frac{\vec{q}}{m_M}\times\vec{S}_\chi)]\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$-\frac{m_N}{m_\chi}\frac{\vec{q}^{\,2}}{m_M^2}\mathcal{O}_{10} - 4\frac{\vec{q}^{\,2}}{m_M^2}\mathcal{O}_{12} - 4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$
13	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu N$	$2\vec{v}^\perp\cdot\vec{S}_\chi + 2i\vec{S}_\chi\cdot(\vec{S}_N\times\frac{\vec{q}}{m_N})$	$2\mathcal{O}_8 + 2\mathcal{O}_9$
14	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4i\vec{S}_\chi\cdot(\frac{\vec{q}}{m_M}\times\vec{S}_N)$	$-4\frac{m_N}{m_M}\mathcal{O}_9$
15	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma^\mu\gamma^5 N$	$-4\vec{S}_\chi\cdot\vec{S}_N$	$-4\mathcal{O}_4$
16	$i\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$4i\vec{v}^\perp\cdot\vec{S}_\chi\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$4\frac{m_N}{m_M}\mathcal{O}_{13}$
17	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar{N}\gamma_\mu N$	$2i\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi$	$2\frac{m_N}{m_M}\mathcal{O}_{11}$
18	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi[i\frac{\vec{q}^{\,2}}{m_N m_M} - 4\vec{v}^\perp\cdot(\frac{\vec{q}}{m_M}\times\vec{S}_N)]$	$\frac{\vec{q}^{\,2}}{m_M^2}\mathcal{O}_{11} + 4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$
19	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$	$-4i\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi\vec{v}_\perp\cdot\vec{S}_N$	$-4\frac{m_N}{m_M}\mathcal{O}_{14}$
20	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$4\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$4\frac{m_N^2}{m_M^2}\mathcal{O}_6$

- Any effective Lagrangian can be the combination of non-relativistic operators.
- Only j=6,7,9,10,12,13,18 are summing more than one operators.
- Note Ci (non-relativistic coefficients) is not alway equal to di (relativistic coefficients).

Isospin conserved and violating

If DM-proton and DM-neutron couplings are not the same, especially for the case that the ratio of two couplings are negative, a cancellation between DM-proton and DM-neutron happens.



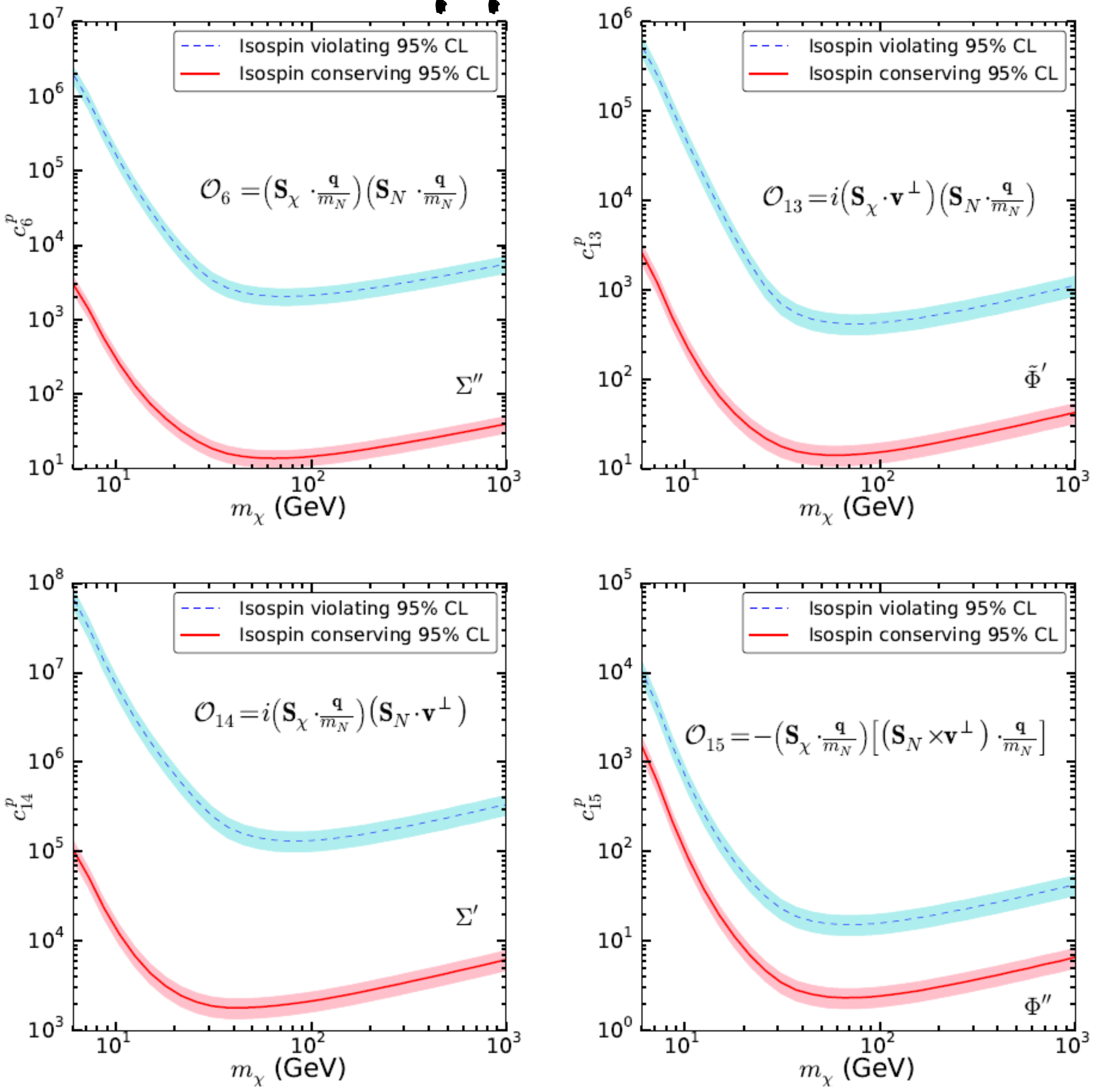


$$\left[\frac{c_i^p}{\Lambda^2}\frac{1+\tau_3}{2}+\frac{c_i^n}{\Lambda^2}\frac{1-\tau_3}{2}\right]\mathcal{O}_i.$$

ISC: cp ==cn

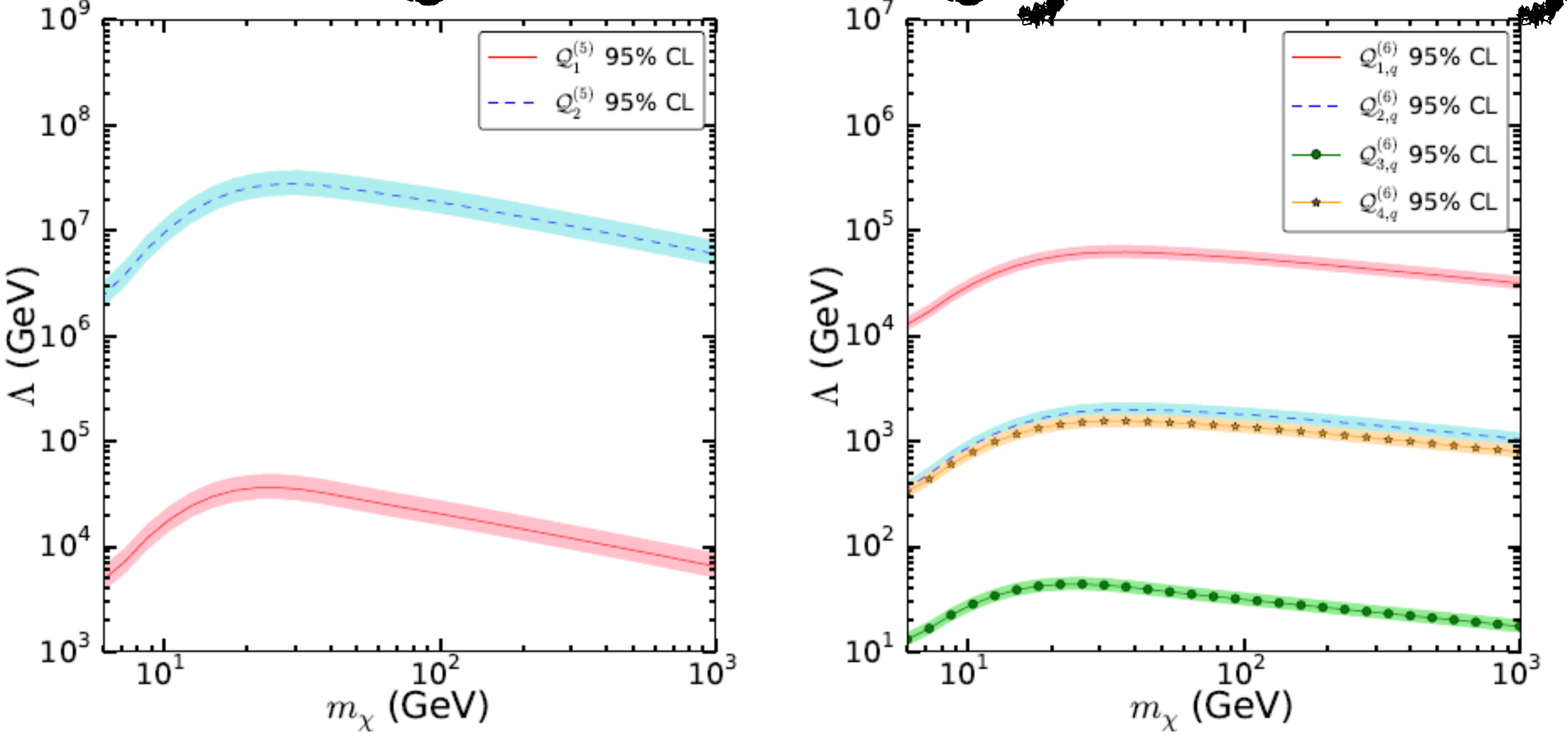
ISV: cp!=cn

The upper combined limits of operators



- Comparing O6 and O13, the ISC limits are similar but ISV limits differ around one order of magnitude.
- O14 weaker than O6 and O13.
- O15 has 5 vectors combination and the difference between ISC and ISV are smallest than other 14 operators.

The High Energy theory



$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2\Lambda}(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}\,, \qquad \mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2\Lambda}(\bar{\chi}\sigma^{\mu\nu}i\gamma_5\chi)F_{\mu\nu}$$