Direct Detection of Exothermic Dark Matter with a Light Mediator

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JCAP 1608 (2016) no. 08, 009 [arXiv: 1605.05098]

Phys. Dark Univ. 18 (2017) 38-46 [arXiv: 1705.06546]

In Collaboration with C.-Q. Geng, C.-H. Lee and Q. Wang

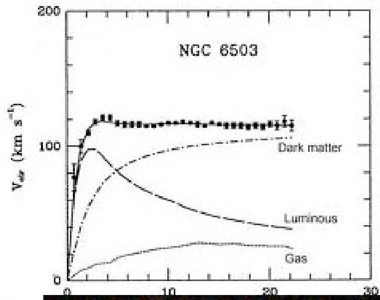
Content

- Review to Current Status of DM Direct Detection Exps.
- Possible Scenarios to Explain CDMS-Si Anomaly
- Our Setup and Calculation details
- Fitting Results
- Summary

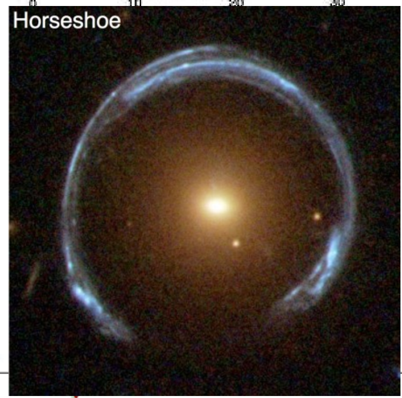
Dark Matter: Evidence

➢ There are already many established evidences for the existence of dark matter

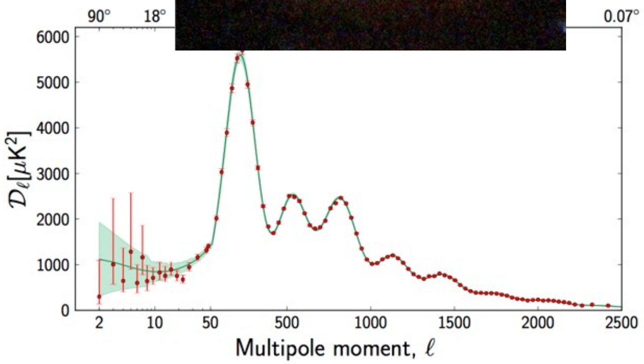
- Rotation Curves of Spiral Galaxies
  Babcock, 1939, Bosma, 1978; Rubin & Ford, 1980



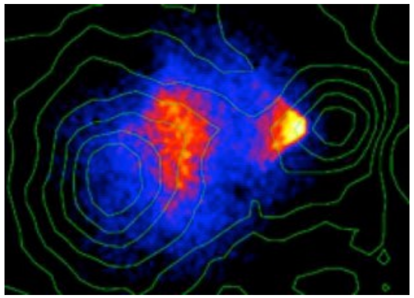
- Gravitational Lensing



- CMB

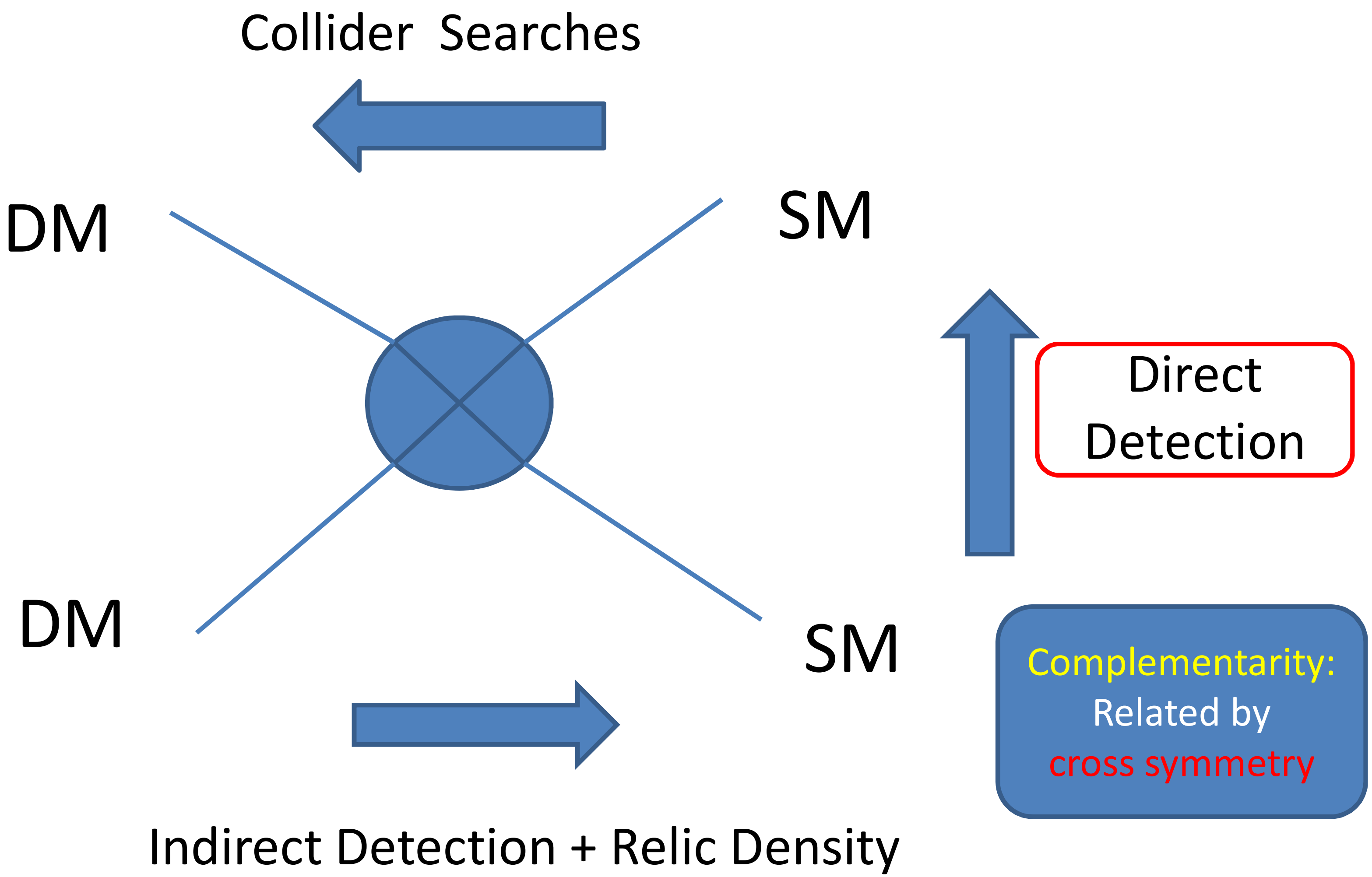


- Bullet Clusters



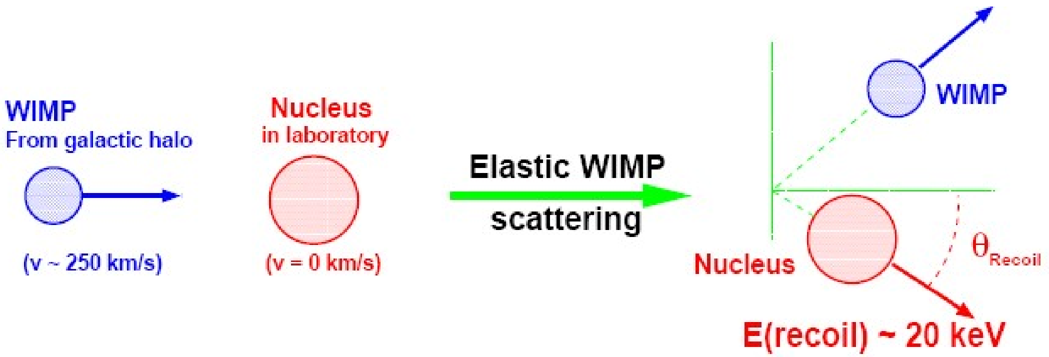
But , they are all gravitational

How to detect particle DM?



Direct Detection Principle

- Detection of the energy deposit due to (in)elastic scattering on nuclei of detector in laboratory experiment

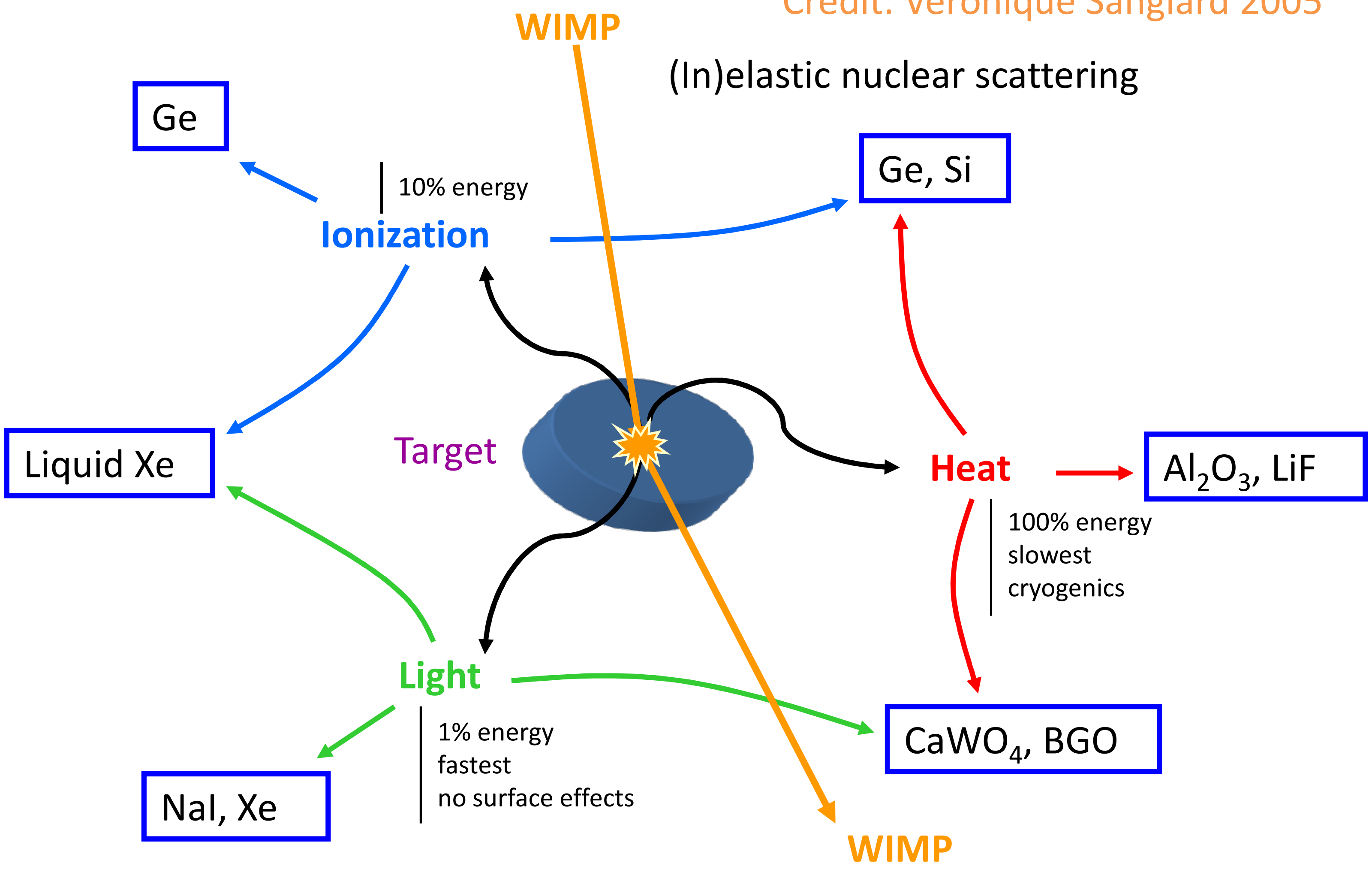


- Recoil energy : O(1~10) keV
  - ✓ Need low recoil energy threshold
- Rate < 1 evt/day/kg of detector
  - ✓ Need large detector mass (kg -> ton)
  - ✓ Need low background
    - ✓ Deep underground sites
    - ✓ Radio-purity of components
    - ✓ Active/passive shielding

G. Steigman & M.S. Turner, NPB (1985);
M. W. Goodman & E. Witten, PRD(1985);
G. Jungman, et al, Phys. Rept. (1996);
J. L. Feng, Ann. Rev. Astro. Astrophys. (2010)

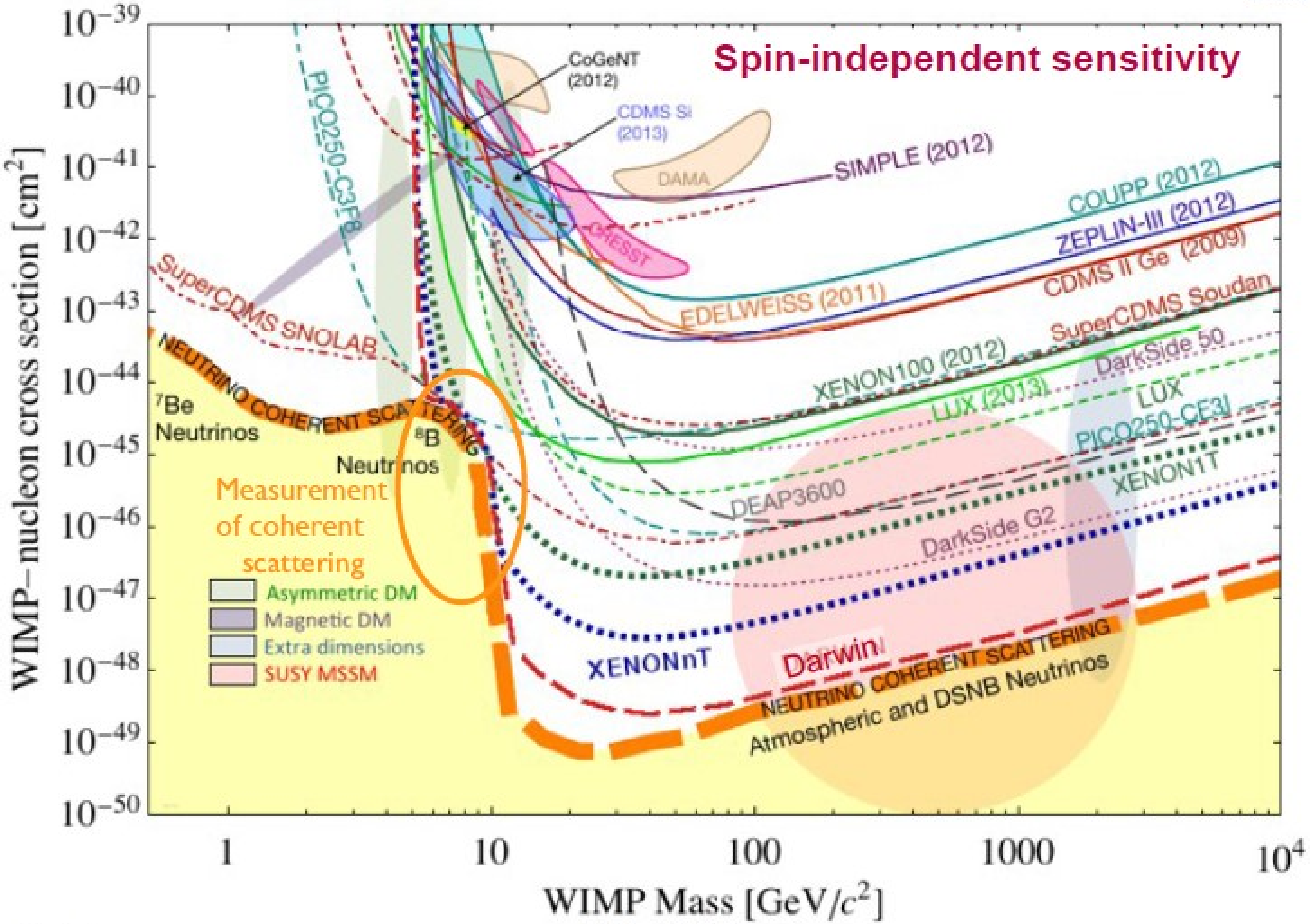
Direct Detection Techniques

Credit: Veronique Sanglard 2005



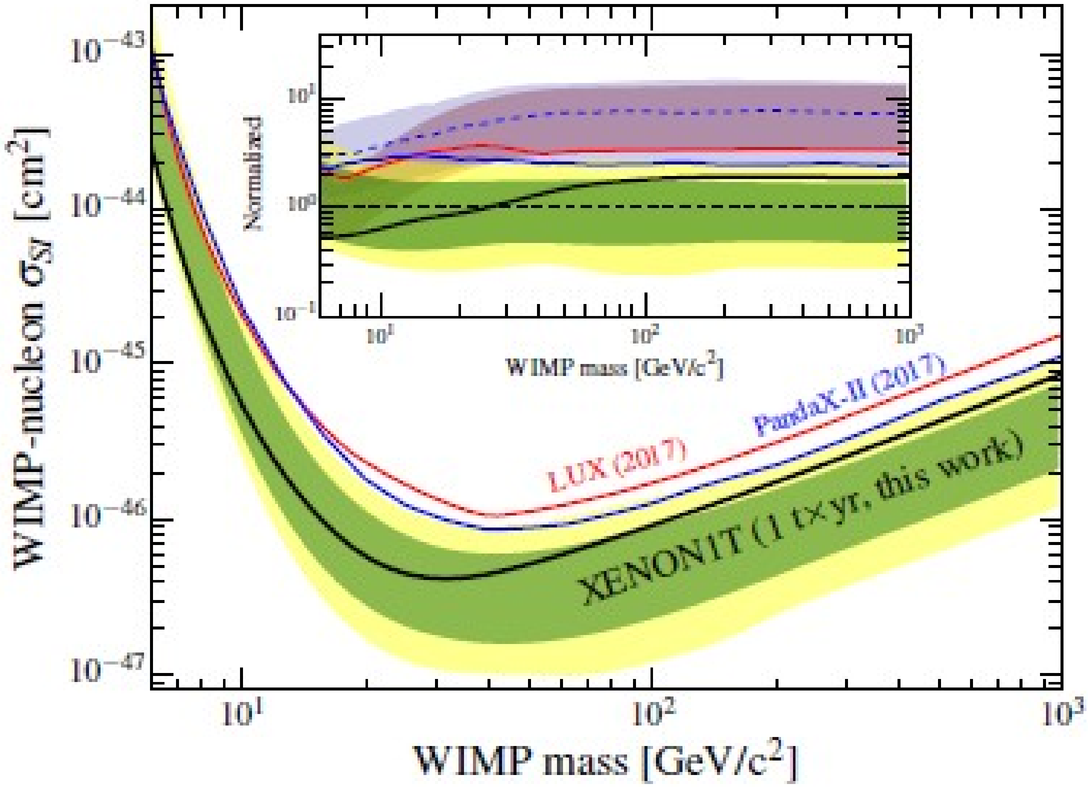
Current Status and Future Goal

Credit: Uwe Oberlack @ Darwin 2015



Recent Development

New XENON1T Result



● Strongest Constraints for WIMP masses above 6 GeV, with a minimum of 4.1* 10^{-47} cm^2 at 30 GeV

Controversies

- Confliction between positive signals and negative limits
- ✓ positive signals
    - DAMA: Annual Modulation
    - CoGent, CDMS-Si: Excess in events

Focus

- ✓ negative limits

SuperCDMS, CDMSlite, Xenon10, Xenon100, LUX, PandaX-II, Xenon1T, PICO-60

Possible Solutions

➢ 3 typical proposals to solve dilemma in DM direct searches

✓ Isospin Violation: Tuning the couplings between n and p so that the sensitivities to Ge and Xe are maximally reduced

Kurylov & Kamionkowski, PRD (2004), Giuliani, PRL (2005), Savage et al. JCAP (2009), A. Fitzpatrick et al.PRD (2010), J. Feng et al. PLB(2011) ……

✓ Exothermic DM: nuclear recoiling through the down-scattering so that it enhances the sensitivity to light nucleus

B. Batell et al, PRD (2009); P. W. Graham et al. PRD (2010); P. J. Fox et al, PRD (2014); M. T. Frandsen & Shoemaker, PRD (2014) ; ……

✓ Light Mediator: Momentum dependent interactions, so that the nuclear recoil energy spectra are changed. Hence, the light nuclei are favored

T. Li, et al, JCAP (2015); K.C. Yang, arXiv: 1604.04979

New Dilemma and Solutions

- After the LUX2013, a single mechanism above could not reconcile the CDMS-Si anomaly with other upper limits, but the combination of two of them could do the job

  - ✓ Isospin Violation + Exothermic DM: Xe-phobic ExoDM, Ge-phobic ExoDM

    N. Chen, et al., Phys. Lett. B 743, 205 (2015) [arXiv: 1404.6043]
    Gelmini, et al., JCAP 1407, 028 (2014) [arXiv: 1404.7484]

  - ✓ Isospin-Violation + A Light Mediator

    T. Li, et al., JCAP 1503, no. 03, 032 (2015) [arXiv: 1412.6220]

Our Motivation

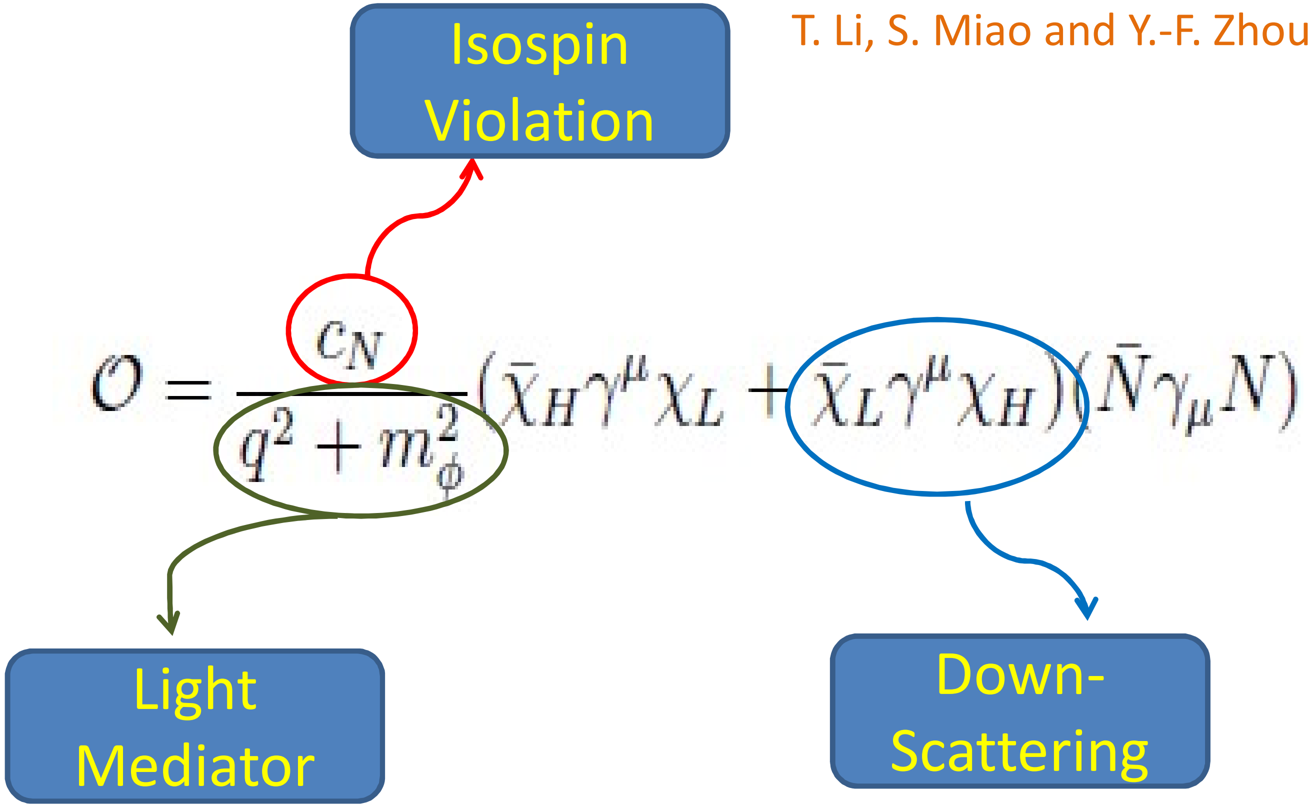
- After new datasets from CDMSlite 2015, LUX2017, PandaX-II, and XENON1T 2017, we want to investigate the status of these solutions

- New proposal: Exothermic interaction + Light Mediator (+ Isospin Violation)

Setup

- Generalized Effective Operator:

T. Li, S. Miao and Y.-F. Zhou, JCAP(2015)



$$\mathcal{O} = \frac{c_N}{q^2 + m_\phi^2}(\bar{\chi}_H \gamma^\mu \chi_L + \bar{\chi}_L \gamma^\mu \chi_H)(\bar{N}\gamma_\mu N)$$

- The above operator only gives rise to the Spin-Independent DM-nucleus Interactions

Setup

- SI DM-nucleus Differential Cross Section

$$\frac{d\sigma_T}{dq^2} = \frac{m_T}{2\mu_{\chi p}^2 v^2}\bar{\sigma}_p |Z + \xi(A - Z)|^2 G(q^2) F_T^2(q^2)\,,$$

Isospin Violation

Light Mediator

Nuclear Form Factor:
Helm Form

$$\xi \equiv c_n / c_p$$

$\bar{\sigma}_N$: Ref. Xection defined @ $v_{\rm ref} = 200\ {\rm km}\cdot{\rm s}^{-1}$

$$G(q^2, v) = \frac{(q_{\rm ref}^2 - q_{\rm min}^2)\overline{|\mathcal{M}_{\chi N}(q^2, v)|^2}}{\int_{q_{\rm min}^2}^{q_{\rm ref}^2} dq^2 \overline{|\mathcal{M}_{\chi N}(q^2, v_{\rm ref})|^2}}$$

$$= \frac{(1 + q_{\rm min}^2/m_\phi^2)(1 + q_{\rm ref}^2/m_\phi^2)}{(1 + q^2/m_\phi^2)^2}$$

Setup

➢ Differential Recoil Event Rate:

$$\frac{dR}{dE_{\rm nr}} = \frac{dN}{M_T dt dE_{\rm nr}} = \frac{\rho_\chi}{m_\chi}\int_{|\mathbf{v}|>v_{\rm min}} d^3\mathbf{v}\, v f(\mathbf{v}) \frac{d\sigma_T}{dq^2}$$

$$= \frac{\rho_\chi}{2m_\chi \mu_{\chi p}^2}\bar{\sigma}_p [Z + (A-Z)\xi]^2 G(E_{\rm nr}) F_A^2(E_{\rm nr}) \eta(E_{\rm nr}, t)\,,$$

Local DM Density
$\rho_\chi = 0.3 \ \mathrm{GeV/cm^3}$

Isospin Violation

Light Mediator

DM Velocity Distribution:
SHM

$$\eta(E_{\rm nr}, t) = \int_{|\mathbf{v}|>v_{\rm min}} d^3\mathbf{v} \frac{f(\mathbf{v})}{v}\,,$$

$$v_{\rm min} = \frac{1}{\sqrt{2E_{\rm nr} m_T}}\left|\delta + \frac{m_T E_{\rm nr}}{\mu_{\chi T}}\right|$$

$\delta = m_L - m_H < 0$

Exothermic Scattering

Observables

➢ Total Rate:

$$R(t) = \int_0^\infty dE_{\rm nr}\underline{\epsilon(s)}\,\underline{\Phi(f_s(E_{\rm nr}), s_1, s_2)}\left(\frac{dR}{dE_{\rm nr}}\right)$$

Detector Efficiency

Detector Resolution

➢ Total Recoil Events: $N_{\rm rec} = {\rm Ex}\cdot R_{\rm tot}(t)$

➢ Annual Modulation:

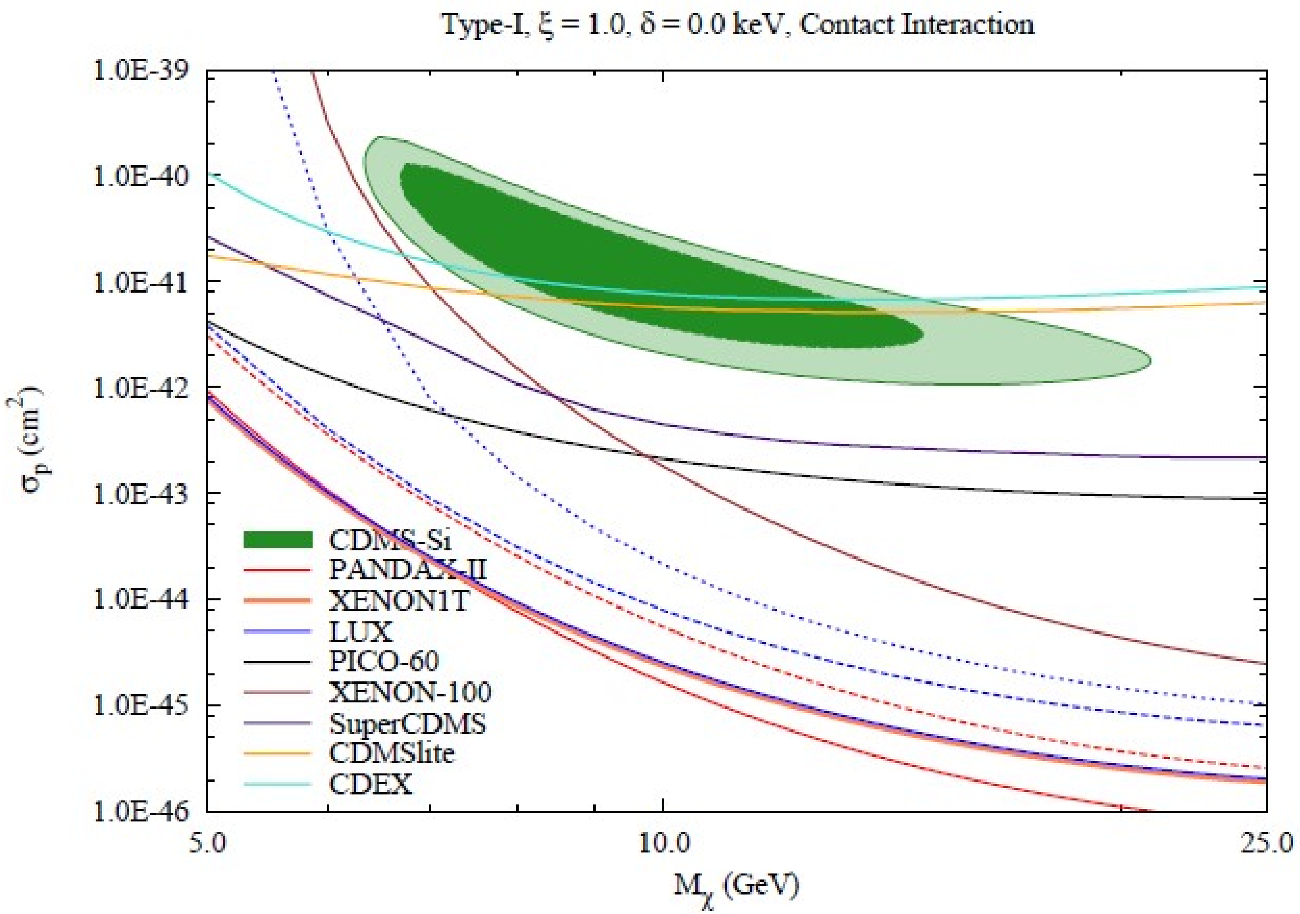
$$S_m(E_{\rm nr}) = \frac{1}{2}\left[\frac{dR}{dE_{\rm nr}}(E,\ \text{June 1}) - \frac{dR}{dE_{\rm nr}}(E_{\rm nr},\ \text{Dec. 1})\right]$$

Fitting Procedure

Exp	Fitting Method
CDMS-Si	Maximal Likelihood
SuperCDMS	p_{Max}
CDMSlite	p_{Max}
LUX2013	Maximum Gap
LUX2015	Poisson
LUX2017	Poisson
XENON10	p_{Max}
XENON100	Maximum Gap
XENON1T	Poisson
PandaX-II	Poisson
PICO-60	Poisson
CDEX-I	Binned Poinsson

Numerical Results

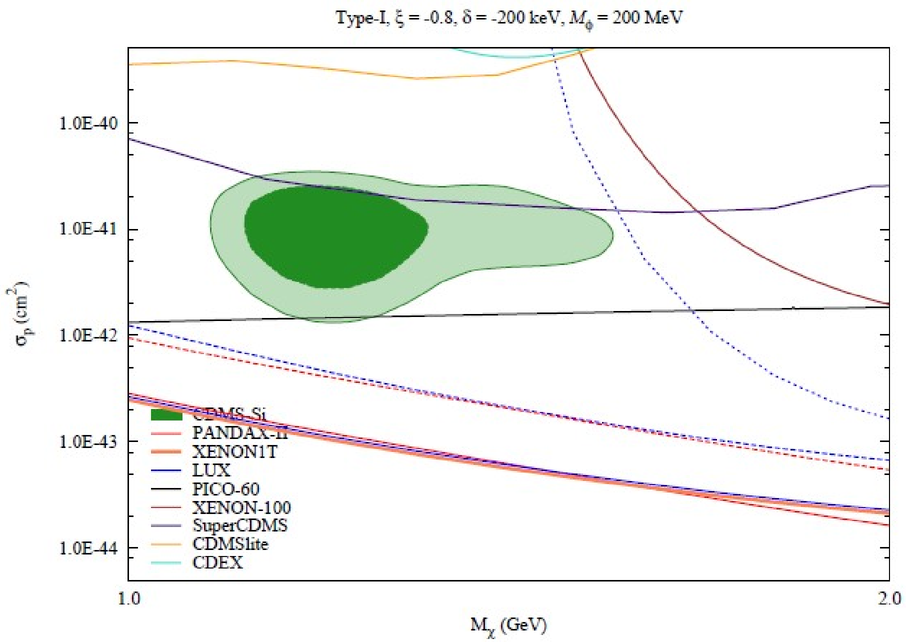
- Conventional Model – Isospin Conserving, Elastic, Contact



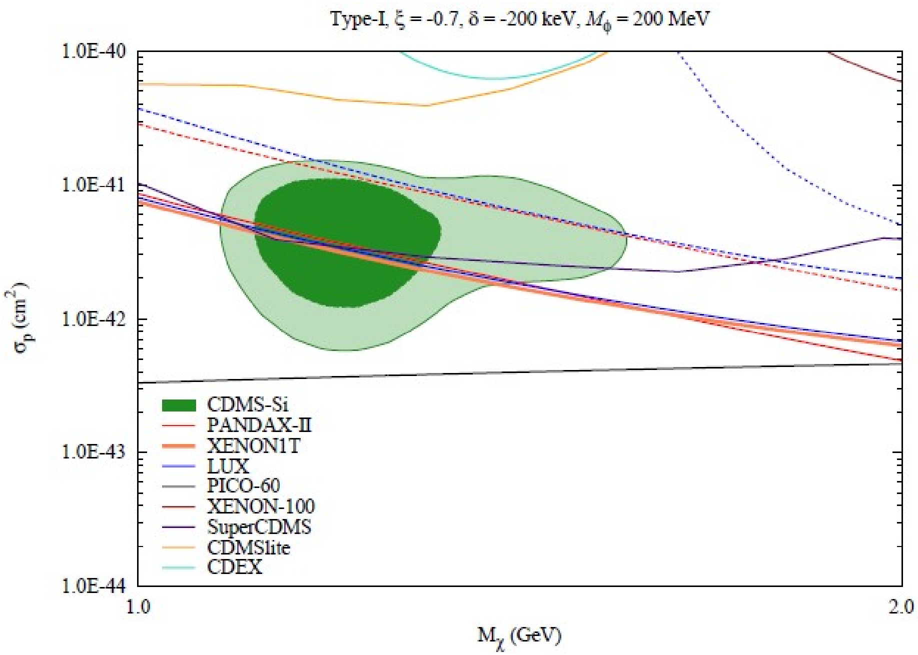
Numerical Results

➢ Isospin Violation + Exothermic Interaction

Ge-phobic



Xe-phobic

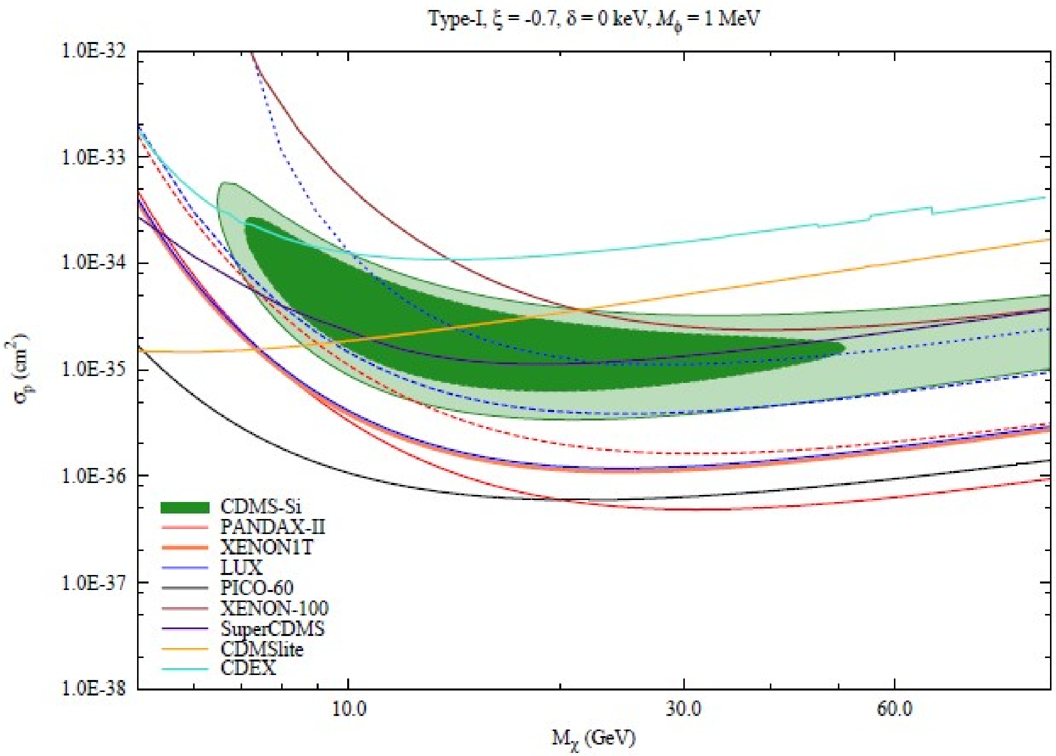


✓ The previously promising Ge- and Xe-phobic exothermic models are excluded

Numerical Results

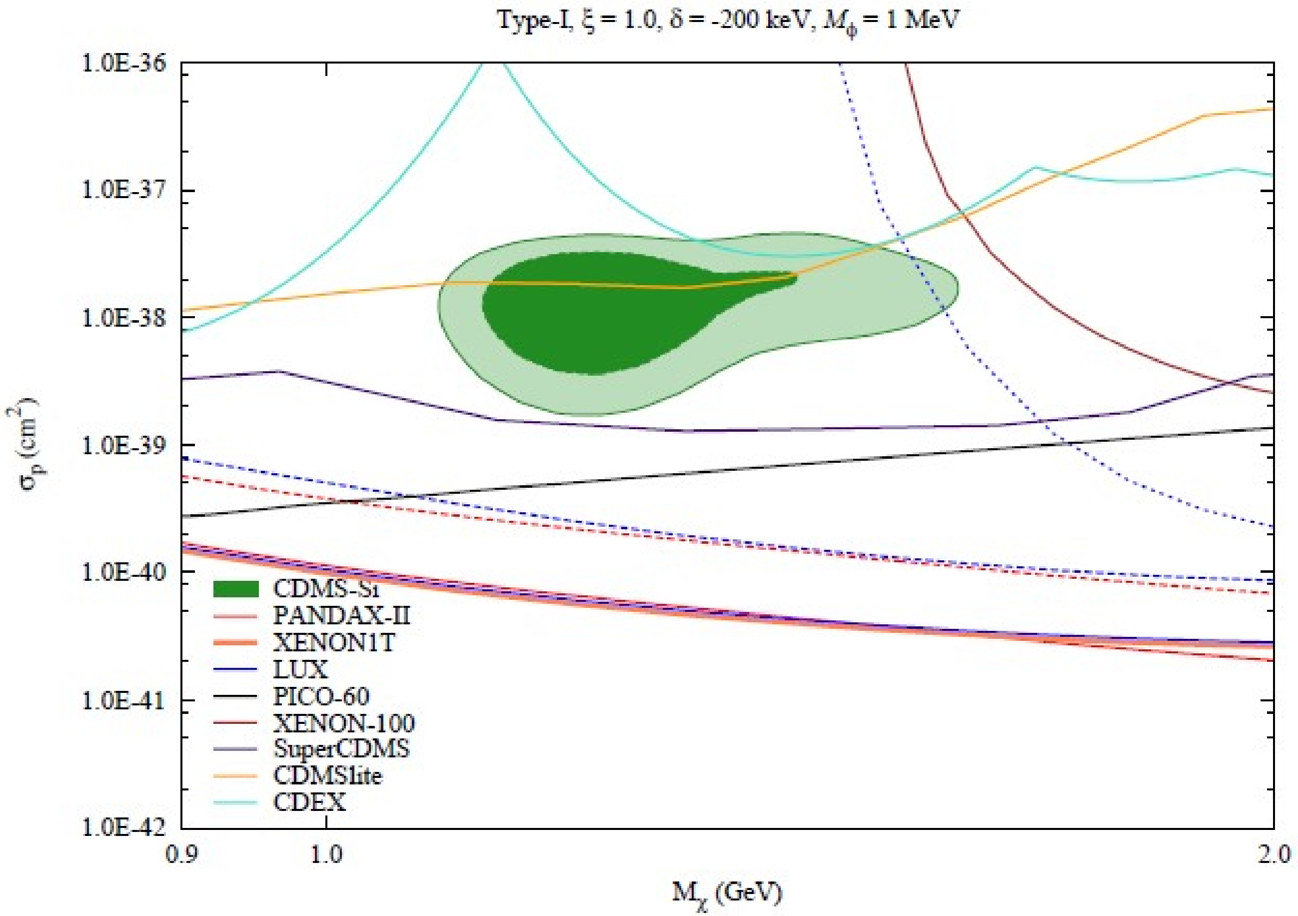
- Isospin Violation + Light Mediator

Xe-phobic



Numerical Results

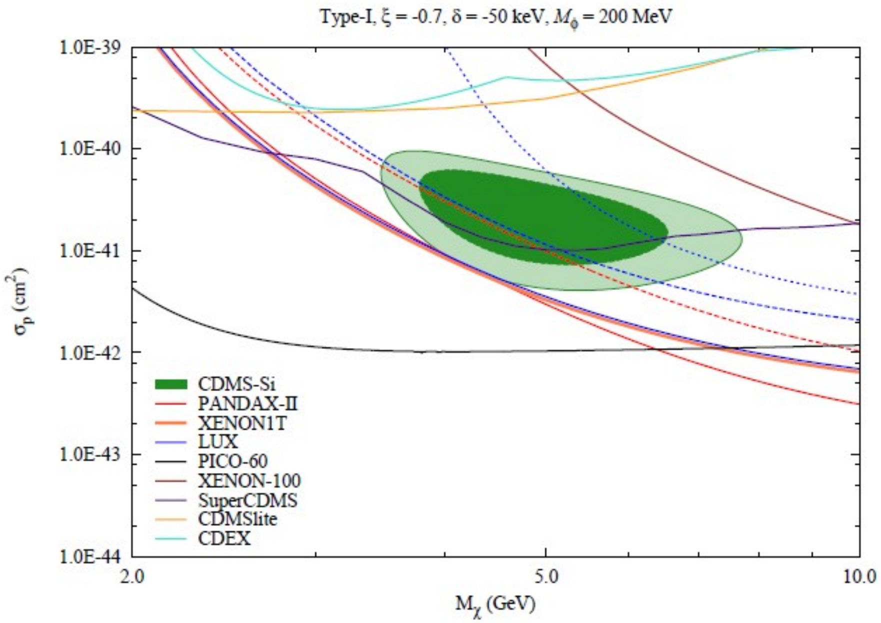
➢ Exothermic Interaction + Light Mediator: Ruled out

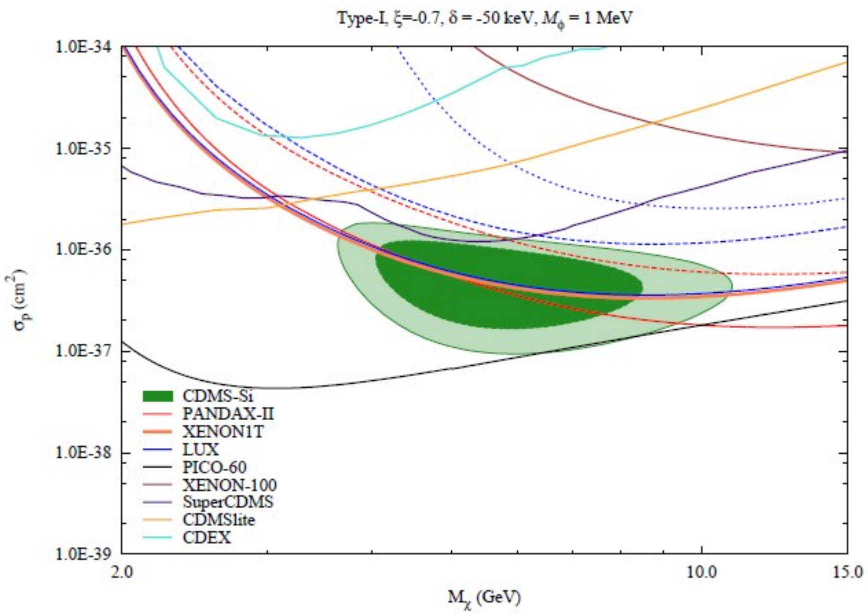


Numerical Results

- Isospin Violation +Exothermic Interaction + Light Mediator

Xe-phobic



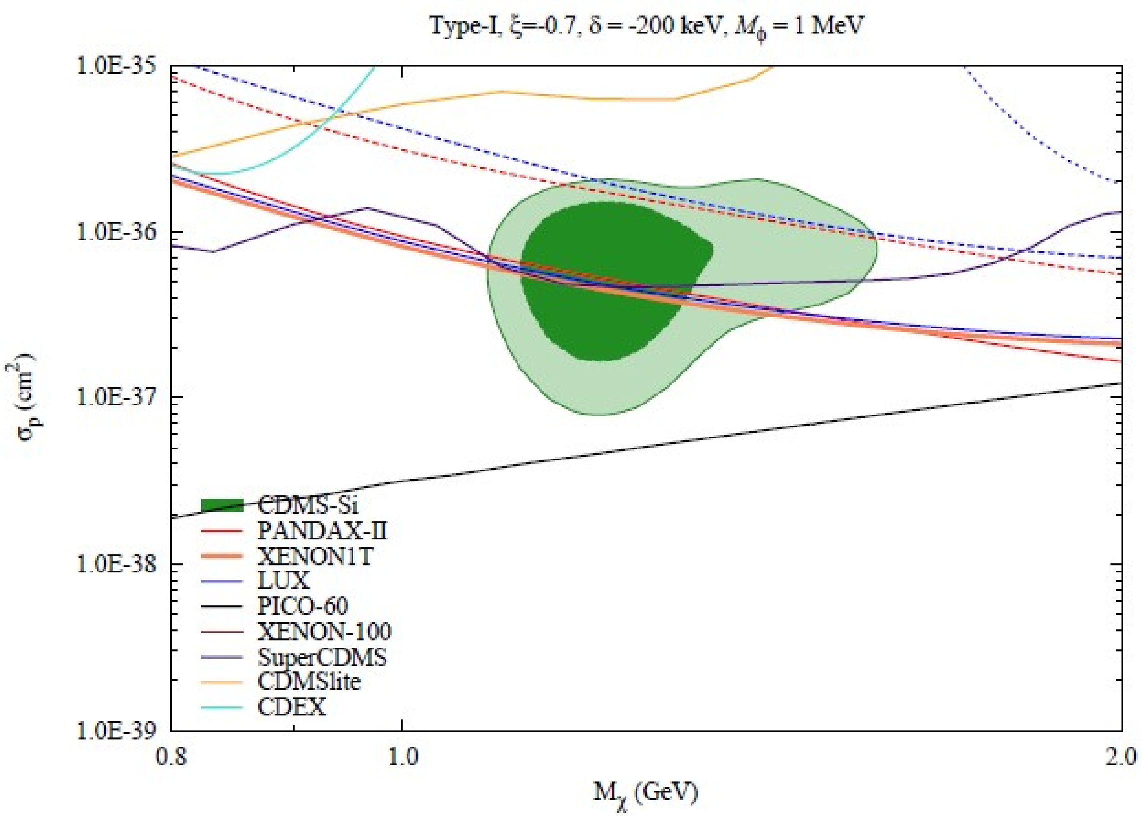


With Xe-phobic interactions and a mild DM gap, decreasing mediator mass improves the situation, but is still ruled out.

Numerical Results

➢ Isospin Violation +Exothermic Interaction + Light Mediator

Extreme case



Conclusion

- We study the direct detections of DM particles with Spin-Independent DM-nucleus interactions with the following two or three properties
  - Isospin Violation
  - Exothermic Scattering
  - A Light Meditor

- We focus on the possibility to reconcile CDMS-Si signal and other exclusion limits, especially new CDMSlite, PICO-60, LUX, PandaX, and XENON1T results
- Our fits showed that the existing proposals cannot work to reduce the tension any more, which indicates that we need some new ideas.

THANKS FOR YOUR ATTENTION!

Possible Solutions

- Isospin Violation

$$\sigma_T \propto (Zc_p + (A-Z)c_n)^2$$

Coherent Scattering

If $\xi \equiv \frac{c_n}{c_p} = \frac{Z}{Z-A}$, the sensitivity to T is maximally reduced

Xe-phobic

$$Z_{Xe} = 54, A_{Xe} = 132, \Rightarrow \xi_{Xe} \approx -0.7$$

Possible Solutions

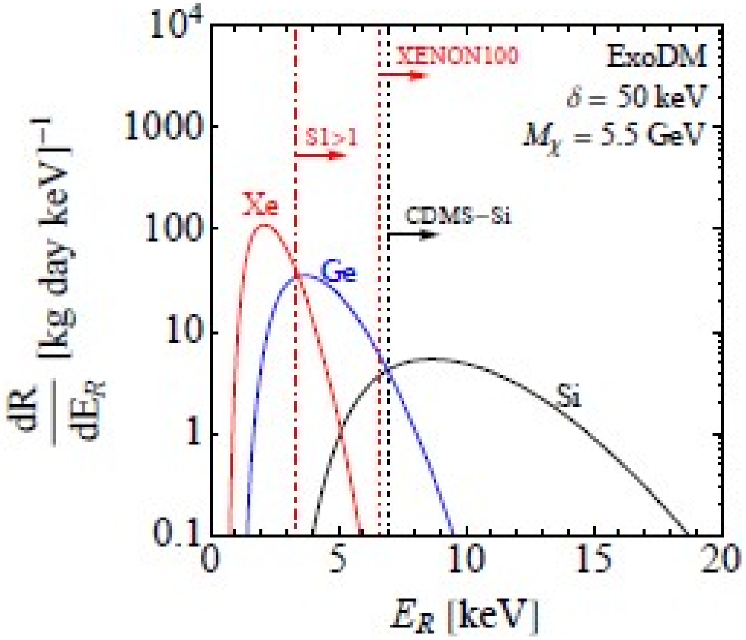
➢ Exothermic DM

✓ For two DMs, Down-Scattering Or Up-Scattering?

Up-scattering needs extra energy to overcome the gap

➡ Down-Scattering dominates

✓ Recoil Energy Spectrum for Down-Scattering:

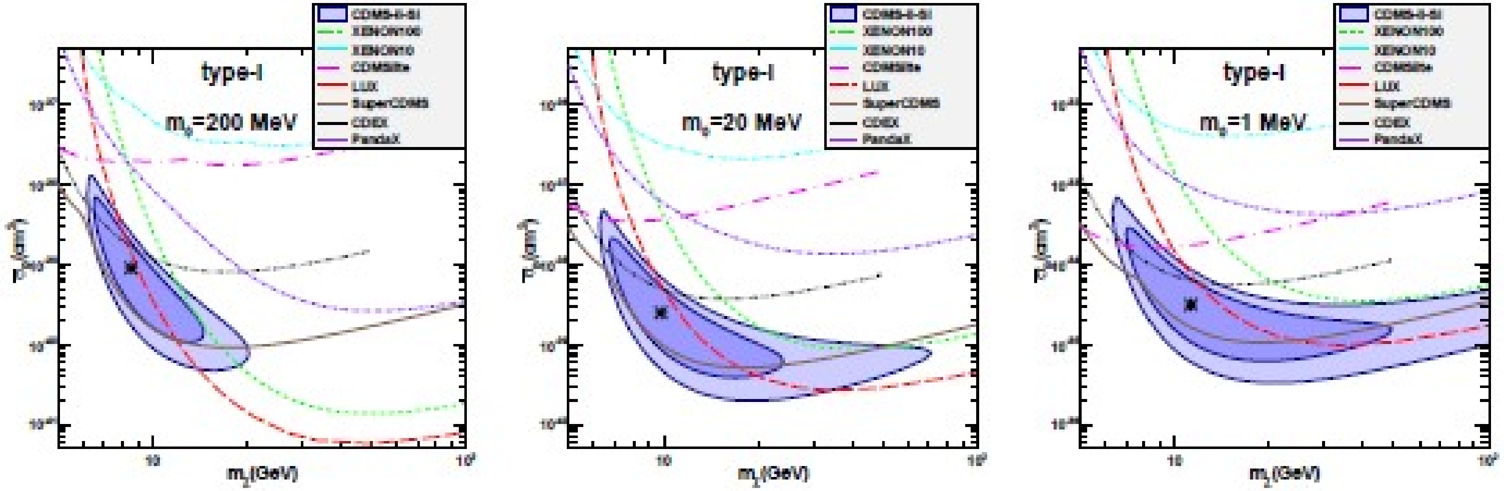


Possible Solutions

➢ A Light Meditor

$$\frac{d\sigma_T}{dq^2} \propto \frac{1}{(q^2 + m_\phi{}^2)^2}$$

If $q >> m_\phi$, σ_T is enhanced for low energy events



(a) (b) (c)

Numerical Results

➢ Isospin Violation +Exothermic Interaction + Light Mediator

Extreme case