# Addressing theoretical uncertainties in direct detection experiments

Alejandro Ibarra
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Based on:
AI, Rappelt, arXiv:1703.09168, JCAP 1708 (2017) no.08, 039
AI, Kavanagh, Rappelt, arXiv:1806.xxxxx
Catena, AI, Wild, arXiv:1602.04074, JCAP 1605 (2016) no.05, 039
Catena, AI, Rappelt, Wild, arXiv:1801.08466

Chalmers University
of Technology
13 June, 2018

Three different methods

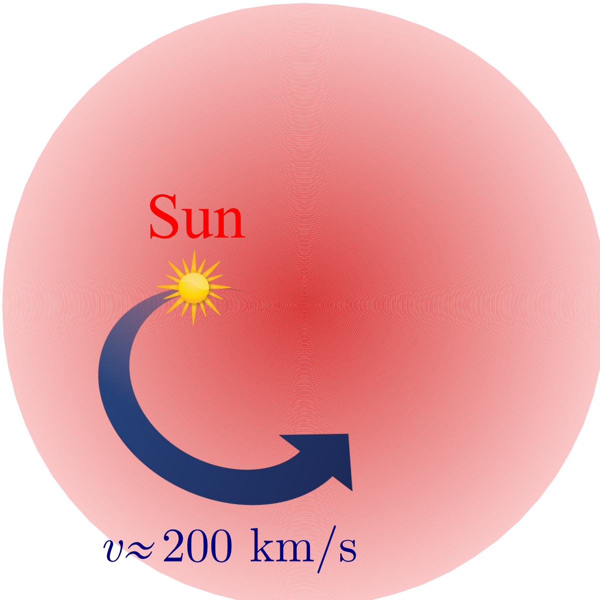
have been proposed

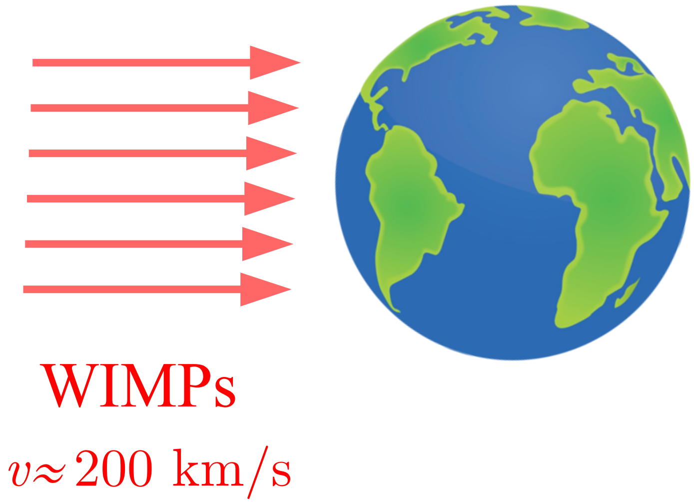
to probe the DM distribution

inside the Solar System

# Direct dark matter searches

The Sun (and the Earth) is moving through a “gas” of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.



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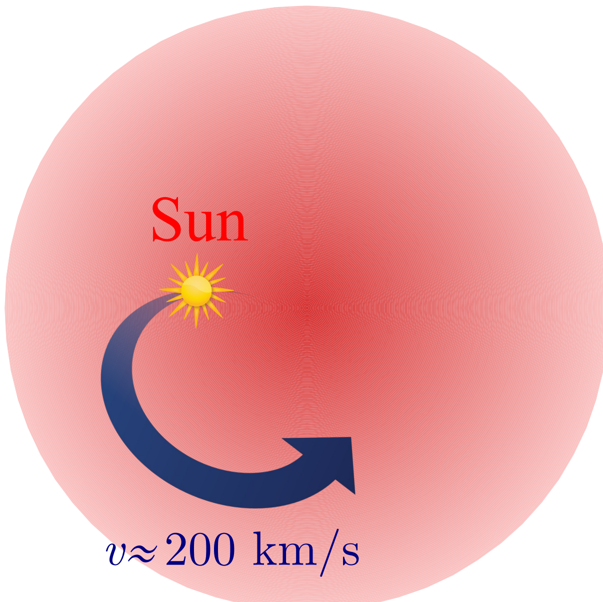
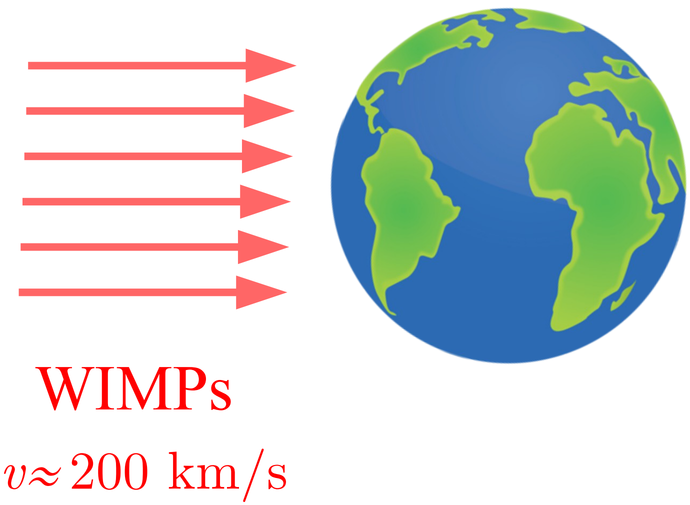
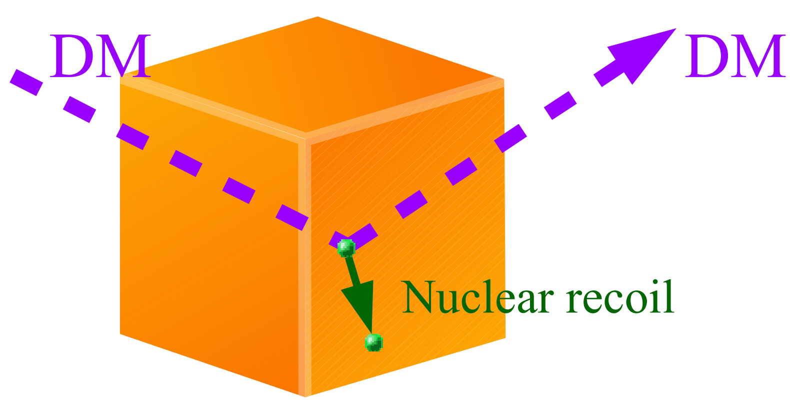



Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.



# Direct dark matter searches

Selected for a Viewpoint in *Physics*
PRL **118,** 021303 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

### Results from a Search for Dark Matter in the Complete LUX Exposure

D. S. Akerib,[1,2,3] S. Alsum,[4] H. M. Araújo,[5] X. Bai,[6] A. J. Bailey,[5] J. Balajthy,[7] P. Beltrame,[8] E. P. Bernard,[9,10] A. Bernstein,[11] T. P. Biesiadzinski,[1,2,3] E. M. Boulton,[9,10] R. Bramante,[1,2,3] P. Brás,[12] D. Byram,[13,14] S. B. Cahn,[10] M. C. Carmona-Benitez,[15] C. Chan,[16] A. A. Chiller,[13] C. Chiller,[13] A. Currie,[5] J. E. Cutter,[17] T. J. R. Davison,[8] A. Dobi,[18] J. E. Y. Dobson,[19] E. Druszkiewicz,[20] B. N. Edwards,[10] C. H. Faham,[18] S. Fiorucci,[16,18] R. J. Gaitskell,[16] V. M. Gehman,[18] C. Ghag,[19] K. R. Gibson,[1] M. G. D. Gilchriese,[18] C. R. Hall,[7] M. Hanhardt,[6,14] S. J. Haselschwardt,[15] S. A. Hertel,[9,10,*] D. P. Hogan,[9] M. Horn,[14,9,10] D. Q. Huang,[16] C. M. Ignarra,[2,3] M. Ihm,[9] R. G. Jacobsen,[9] W. Ji,[1,2,3] K. Kamdin,[9] K. Kazkaz,[11] D. Khaitan,[20] R. Knoche,[7] N. A. Larsen,[10] C. Lee,[1,2,3] B. G. Lenardo,[17,11] K. T. Lesko,[18] A. Lindote,[12] M. I. Lopes,[12] A. Manalaysay,[17,†] R. L. Mannino,[21] M. F. Marzioni,[8] D. N. McKinsey,[9,18,10] D.-M. Mei,[13] J. Mock,[22] M. Moongweluwan,[20] J. A. Morad,[17] A. St. J. Murphy,[8] C. Nehrkorn,[15] H. N. Nelson,[15] F. Neves,[12] K. O'Sullivan,[9,18,10] K. C. Oliver-Mallory,[9] K. J. Palladino,[4,2,3] E. K. Pease,[9,18,10] P. Phelps,[1] L. Reichhart,[19] C. Rhyne,[16] S. Shaw,[19] T. A. Shutt,[1,2,3] C. Silva,[12] M. Solmaz,[15] V. N. Solovov,[12] P. Sorensen,[18] S. Stephenson,[17] T. J. Sumner,[5] M. Szydagis,[22] D. J. Taylor,[14] W. C. Taylor,[16] B. P. Tennyson,[10] P. A. Terman,[21] D. R. Tiedt,[6] W. H. To,[1,2,3] M. Tripathi,[17] L. Tvrznikova,[9,10] S. Uvarov,[17] J. R. Verbus,[16] R. C. Webb,[21] J. T. White,[21] T. J. Whitis,[1,2,3] M. S. Witherell,[18] F. L. H. Wolfs,[20] J. Xu,[11] K. Yazdani,[5] S. K. Young,[22] and C. Zhang[13]

(LUX Collaboration)

Selected for a Viewpoint in *Physics*
PRL **119,** 181301 (2017) PHYSICAL REVIEW LETTERS week ending 3 NOVEMBER 2017

### First Dark Matter Search Results from the XENON1T Experiment

E. Aprile,[1] J. Aalbers,[2,*] F. Agostini,[3,4] M. Alfonsi,[5] F. D. Amaro,[6] M. Anthony,[1] F. Arneodo,[7] P. Barrow,[8] L. Baudis,[8] B. Bauermeister,[9] M. L. Benabderrahmane,[7] T. Berger,[10] P. A. Breur,[2] A. Brown,[2] A. Brown,[8] E. Brown,[10] S. Bruenner,[11] G. Bruno,[3] R. Budnik,[12] L. Bütikofer,[13,†] J. Calvén,[9] J. M. R. Cardoso,[6] M. Cervantes,[14] D. Cichon,[11] D. Coderre,[13] A. P. Colijn,[2] J. Conrad,[9] J. P. Cussonneau,[15] M. P. Decowski,[2] P. de Perio,[1] P. Di Gangi,[4] A. Di Giovanni,[7] S. Diglio,[15] G. Eurin,[11] J. Fei,[16] A. D. Ferella,[9] A. Fieguth,[17] W. Fulgione,[3,18] A. Gallo Rosso,[3] M. Galloway,[8] F. Gao,[1] M. Garbini,[4] R. Gardner,[19] C. Geis,[5] L. W. Goetzke,[1] L. Grandi,[19] Z. Greene,[1] C. Grignon,[5] C. Hasterok,[11] E. Hogenbirk,[2] J. Howlett,[1] R. Itay,[12] B. Kaminsky,[13,†] S. Kazama,[8] G. Kessler,[8] A. Kish,[8] H. Landsman,[12] R. F. Lang,[14] D. Lellouch,[12] L. Levinson,[12] Q. Lin,[1] S. Lindemann,[11,13] M. Lindner,[11] F. Lombardi,[16] J. A. M. Lopes,[6,‡] A. Manfredini,[12] I. Mariş,[7] T. Marrodán Undagoitia,[11] J. Masbou,[15] F. V. Massoli,[4] D. Masson,[14] D. Mayani,[8] M. Messina,[1] K. Micheneau,[15] A. Molinario,[3] K. Morå,[9] M. Murra,[17] J. Naganoma,[20] K. Ni,[16] U. Oberlack,[5] P. Pakarha,[8] B. Pelssers,[9] R. Persiani,[15] F. Piastra,[8] J. Pienaar,[14] V. Pizzella,[11] M.-C. Piro,[10] G. Plante,[1,§] N. Priel,[12] L. Rauch,[11] S. Reichard,[8,14] C. Reuter,[14] B. Riedel,[19] A. Rizzo,[1] S. Rosendahl,[17] N. Rupp,[11] R. Saldanha,[19] J. M. F. dos Santos,[6] G. Sartorelli,[4] M. Scheibelhut,[5] S. Schindler,[5] J. Schreiner,[11] M. Schumann,[13] L. Scotto Lavina,[21] M. Selvi,[4] P. Shagin,[20] E. Shockley,[19] M. Silva,[6] H. Simgen,[11] M. v. Sivers,[13,†] A. Stein,[22] S. Thapa,[19] D. Thers,[15] A. Tiseni,[2] G. Trinchero,[18] C. Tunnell,[19,‖] M. Vargas,[17] N. Upole,[19] H. Wang,[22] Z. Wang,[3] Y. Wei,[8] C. Weinheimer,[17] J. Wulf,[8] J. Ye,[16] Y. Zhang,[1] and T. Zhu[1]

(XENON Collaboration)[¶]

Selected for a Viewpoint in *Physics*
PRL **119,** 181302 (2017) PHYSICAL REVIEW LETTERS week ending 3 NOVEMBER 2017

### Dark Matter Results from 54-Ton-Day Exposure of PandaX-II Experiment

Xiangyi Cui,[1] Abdusalam Abdukerim,[2] Wei Chen,[1] Xun Chen,[1] Yunhua Chen,[3] Binbin Dong,[1] Deqing Fang,[4] Changbo Fu,[1] Karl Giboni,[1] Franco Giuliani,[1] Linhui Gu,[1] Yikun Gu,[1] Xuyuan Guo,[3] Zhifan Guo,[5] Ke Han,[1] Changda He,[1] Di Huang,[1] Shengming He,[3] Xingtao Huang,[6] Zhou Huang,[1] Xiangdong Ji,[7,1,§] Yonglin Ju,[5] Shaoli Li,[1] Yao Li,[1] Heng Lin,[1] Huaxuan Liu,[5] Jianglai Liu,[4,7,*] Yugang Ma,[4] Yajun Mao,[8] Kaixiang Ni,[1] Jinhua Ning,[3] Xiangxiang Ren,[1] Fang Shi,[1] Andi Tan,[9,†] Cheng Wang,[5] Hongwei Wang,[4] Meng Wang,[6] Qiuhong Wang,[4,‡] Siguang Wang,[8] Xiuli Wang,[5] Xuming Wang,[1] Qinyu Wu,[1] Shiyong Wu,[3] Mengjiao Xiao,[9,10] Pengwei Xie,[1] Binbin Yan,[6] Yong Yang,[1] Jianfeng Yue,[3] Dan Zhang,[1] Hongguang Zhang,[1] Tao Zhang,[1] Tianqi Zhang,[1] Li Zhao,[1] Jifang Zhou,[3] Ning Zhou,[1] and Xiaopeng Zhou[8]

(PandaX-II Collaboration)

PRL **118,** 251301 (2017) PHYSICAL REVIEW LETTERS week ending 23 JUNE 2017

### Dark Matter Search Results from the PICO-60 $C_3F_8$ Bubble Chamber

C. Amole,[1] M. Ardid,[2] I. J. Arnquist,[3] D. M. Asner,[3] D. Baxter,[4,5,*] E. Behnke,[6] P. Bhattacharjee,[7] H. Borsodi,[6] M. Bou-Cabo,[2] P. Campion,[8] G. Cao,[1] C. J. Chen,[4] U. Chowdhury,[1] K. Clark,[9,10] J. I. Collar,[11] P. S. Cooper,[5] M. Crisler,[5,3] G. Crowder,[1] C. E. Dahl,[4,5] M. Das,[7] S. Fallows,[12] J. Farine,[9] I. Felis,[2] R. Filgas,[13] F. Girard,[9,14] G. Giroux,[1,†] J. Hall,[3] O. Harris,[6,15] E. W. Hoppe,[3] M. Jin,[4] C. B. Krauss,[12] M. Laurin,[14] I. Lawson,[9,10] A. Leblanc,[9] I. Levine,[6] W. H. Lippincott,[5] F. Mamedov,[13] D. Maurya,[16] P. Mitra,[12] T. Nania,[6] R. Neilson,[8] A. J. Noble,[1] S. Olson,[1] A. Ortega,[11] A. Plante,[14] R. Podviyanuk,[9] S. Priya,[16] A. E. Robinson,[5] A. Roeder,[6] R. Rucinski,[5] O. Scallon,[9] S. Seth,[7] A. Sonnenschein,[5] N. Starinski,[14] I. Štekl,[13] F. Tardif,[14] E. Vázquez-Jáuregui,[17,9] J. Wells,[6] U. Wichoski,[9] Y. Yan,[16] V. Zacek,[14] and J. Zhang[4]

(PICO Collaboration)

PRL **116,** 071301 (2016) PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2016

### New Results from the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment

R. Agnese,[22] A. J. Anderson,[3] T. Aramaki,[10] M. Asai,[10] W. Baker,[15] D. Balakishiyeva,[22] D. Barker,[24] R. Basu Thakur,[3,23] D. A. Bauer,[3] J. Billard,[5] A. Borgland,[10] M. A. Bowles,[14] P. L. Brink,[10] R. Bunker,[11] B. Cabrera,[13] D. O. Caldwell,[19] R. Calkins,[12] D. G. Cerdeno,[2] H. Chagani,[24] Y. Chen,[14] J. Cooley,[12] B. Cornell,[1] P. Cushman,[24] M. Daal,[18] P. C. F. Di Stefano,[8] T. Doughty,[18] L. Esteban,[16] S. Fallows,[24] E. Figueroa-Feliciano,[6] M. Ghaith,[8] G. L. Godfrey,[10] S. R. Golwala,[1] J. Hall,[7] H. R. Harris,[15] T. Hofer,[24] D. Holmgren,[3] L. Hsu,[3] M. E. Huber,[20] D. Jardin,[12] A. Jastram,[15] O. Kamaev,[8] B. Kara,[12] M. H. Kelsey,[10] A. Kennedy,[24] A. Leder,[5] B. Loer,[3] E. Lopez Asamar,[16] P. Lukens,[3] R. Mahapatra,[15] V. Mandic,[24] N. Mast,[24] N. Mirabolfathi,[18] R. A. Moffatt,[13] J. D. Morales Mendoza,[15] S. M. Oser,[17] K. Page,[8] W. A. Page,[17] R. Partridge,[10] M. Pepin,[24,*] A. Phipps,[18] K. Prasad,[15] M. Pyle,[18] H. Qiu,[12] W. Rau,[8] P. Redl,[13] A. Reisetter,[21] Y. Ricci,[8] A. Roberts,[25] H. E. Rogers,[24] T. Saab,[22] B. Sadoulet,[18,4] J. Sander,[25] K. Schneck,[10] R. W. Schnee,[11] S. Scorza,[12] B. Serfass,[18] B. Shank,[13] D. Speller,[18] D. Toback,[15] R. Underwood,[8] S. Upadhyayula,[15] A. N. Villano,[24] B. Welliver,[22] J. S. Wilson,[15] D. H. Wright,[10] S. Yellin,[13] J. J. Yen,[13] B. A. Young,[9] and J. Zhang[24]

(SuperCDMS Collaboration)

Selected for a Viewpoint in *Physics*
PRL **111,** 251301 (2013) PHYSICAL REVIEW LETTERS week ending 20 DECEMBER 2013

### Silicon Detector Dark Matter Results from the Final Exposure of CDMS II

R. Agnese,[18] Z. Ahmed,[1] A. J. Anderson,[4] S. Arrenberg,[20] D. Balakishiyeva,[18] R. Basu Thakur,[2] D. A. Bauer,[2] J. Billard,[4] A. Borgland,[8] D. Brandt,[8] P. L. Brink,[8] T. Bruch,[20] R. Bunker,[11] B. Cabrera,[10] D. O. Caldwell,[15] D. G. Cerdeno,[13] H. Chagani,[19] J. Cooley,[9] B. Cornell,[1] C. H. Crewdson,[6] P. Cushman,[19] M. Daal,[14] F. Dejongh,[2] E. do Couto e Silva,[8] T. Doughty,[14] L. Esteban,[13] S. Fallows,[19] E. Figueroa-Feliciano,[4,*] J. Filippini,[1] J. Fox,[6] M. Fritts,[19] G. L. Godfrey,[8] S. R. Golwala,[1] J. Hall,[5] R. H. Harris,[12] S. A. Hertel,[4] T. Hofer,[19] D. Holmgren,[2] L. Hsu,[2] M. E. Huber,[16] A. Jastram,[12] O. Kamaev,[6] B. Kara,[9] M. H. Kelsey,[8] A. Kennedy,[19] P. Kim,[8] M. Kiveni,[11] K. Koch,[19] M. Kos,[11] S. W. Leman,[4] B. Loer,[2] E. Lopez Asamar,[13] R. Mahapatra,[12] V. Mandic,[19] C. Martinez,[6] K. A. McCarthy,[4] N. Mirabolfathi,[14] R. A. Moffatt,[10] D. C. Moore,[1] P. Nadeau,[6] R. H. Nelson,[1] K. Page,[6] R. Partridge,[8] M. Pepin,[19] A. Phipps,[14] K. Prasad,[12] M. Pyle,[14] H. Qiu,[9] W. Rau,[6] P. Redl,[10] A. Reisetter,[17] Y. Ricci,[6] T. Saab,[18] B. Sadoulet,[14,3] J. Sander,[12] K. Schneck,[8] R. W. Schnee,[11] S. Scorza,[9] B. Serfass,[14] B. Shank,[10] D. Speller,[14] K. M. Sundqvist,[14] A. N. Villano,[19] B. Welliver,[18] D. H. Wright,[8] S. Yellin,[10] J. J. Yen,[10] J. Yoo,[2] B. A. Young,[7] and J. Zhang[19]

(CDMS Collaboration)

# Direct dark matter searches

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PRL 118, 021303 (2017) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 13 JANUARY 2017

**Results from a Search for Dark Matter in the Complete LUX Exposure**

PRL 119, 181301 (2017) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 3 NOVEMBER 2017

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(PandaX-II Collaboration)

(PICO Collaboration)

PRL 116, 071301 (2016) — PHYSICAL REVIEW LETTERS — week ending 19 FEBRUARY 2016

**New Results from the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment**

(SuperCDMS Collaboration)


We report results of a search for weakly interacting massive particles (WIMPS) with the silicon detectors of the CDMS II experiment. This blind analysis of 140.2 kg day of data taken between July 2007 and September 2008 revealed three WIMP-candidate events with a surface-event background estimate of $0.41^{+0.20}_{-0.08}$(stat)$^{+0.28}_{-0.24}$(syst). Other known backgrounds from neutrons and $^{206}$Pb are limited to <0.13 and <0.08 events at the 90% confidence level, respectively. The exposure of this analysis is equivalent to 23.4 kg day for a recoil energy range of 7–100 keV for a WIMP of mass 10 GeV/$c^2$. The probability that the known backgrounds would produce three or more events in the signal region is 5.4%. A profile likelihood ratio test of the three events that includes the measured recoil energies gives a 0.19% probability for the known-background-only hypothesis when tested against the alternative WIMP + background hypothesis. The highest likelihood occurs for a WIMP mass of 8.6 GeV/$c^2$ and WIMP-nucleon cross section of $1.9 \times 10^{-41}$ cm$^2$.



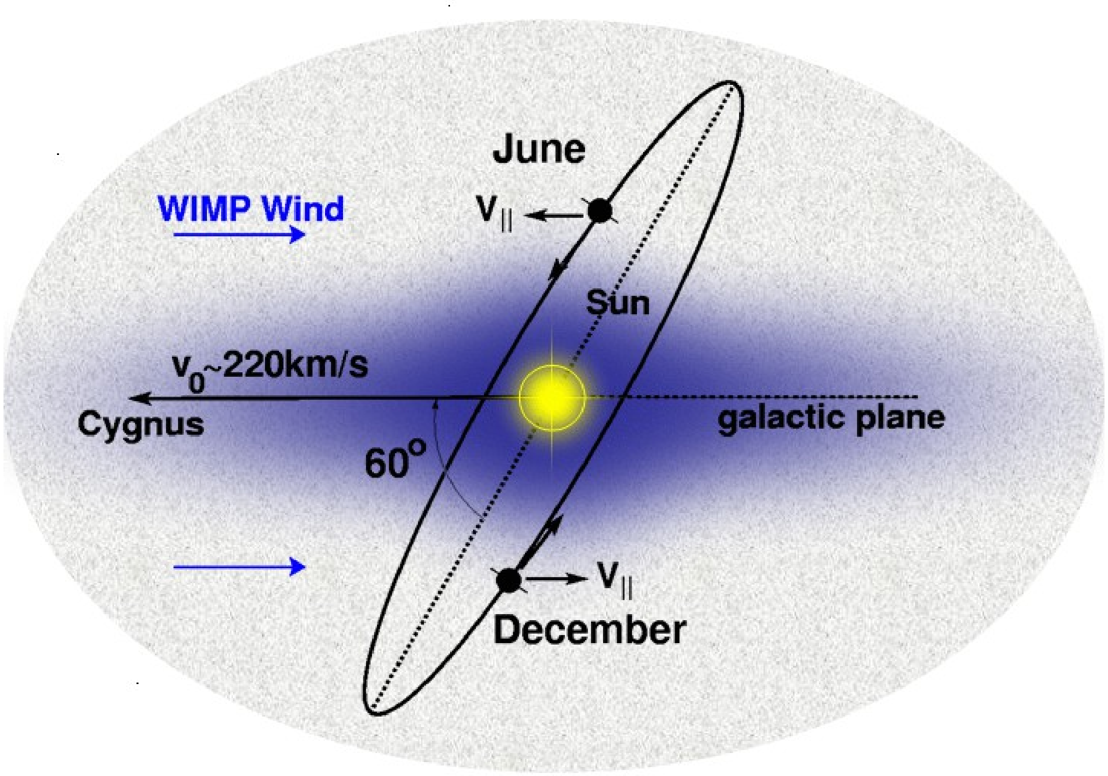
PRL 111, 251301 (2013) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 20 DECEMBER 2013

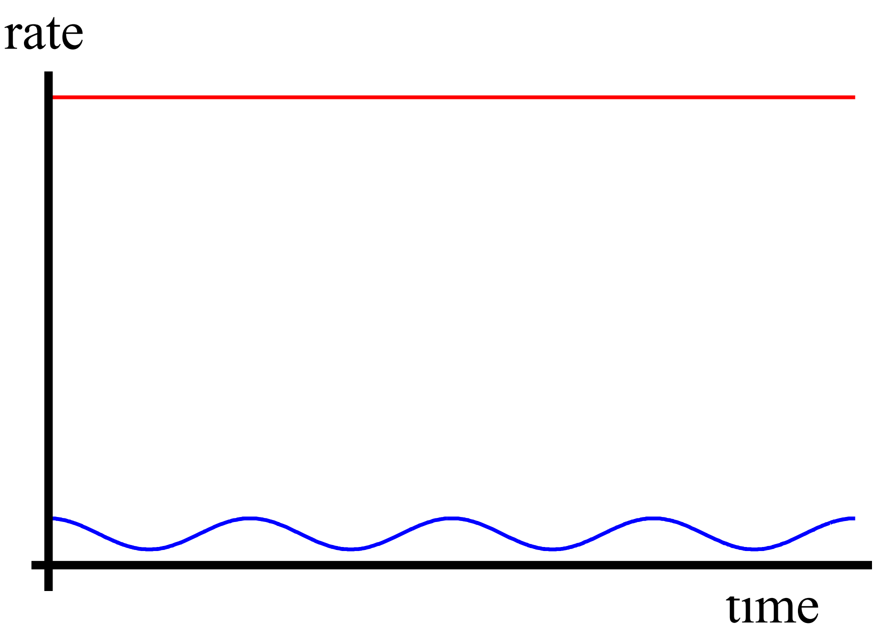

**Silicon Detector Dark Matter Results from the Final Exposure of CDMS II**


R. Agnese,[18] Z. Ahmed,[1] A. J. Anderson,[4] S. Arrenberg,[20] D. Balakishiyeva,[18] R. Basu Thakur,[2] D. A. Bauer,[2] J. Billard,[4] A. Borgland,[8] D. Brandt,[8] P. L. Brink,[8] T. Bruch,[20] R. Bunker,[11] B. Cabrera,[10] D. O. Caldwell,[15] D. G. Cerdeno,[13] H. Chagani,[19] J. Cooley,[9] B. Cornell,[1] C. H. Crewdson,[6] P. Cushman,[19] M. Daal,[14] F. Dejongh,[2] E. do Couto e Silva,[8] T. Doughty,[14] L. Esteban,[13] S. Fallows,[19] E. Figueroa-Feliciano,[4,*] J. Filippini,[1] J. Fox,[6] M. Fritts,[19] G. L. Godfrey,[8] S. R. Golwala,[1] J. Hall,[5] R. H. Harris,[12] S. A. Hertel,[4] T. Hofer,[19] D. Holmgren,[2] L. Hsu,[2] M. E. Huber,[16] A. Jastram,[12] O. Kamaev,[6] B. Kara,[9] M. H. Kelsey,[8] A. Kennedy,[19] P. Kim,[8] M. Kiveni,[11] K. Koch,[19] M. Kos,[11] S. W. Leman,[4] B. Loer,[2] E. Lopez Asamar,[13] R. Mahapatra,[12] V. Mandic,[19] C. Martinez,[6] K. A. McCarthy,[4] N. Mirabolfathi,[14] R. A. Moffatt,[10] D. C. Moore,[1] P. Nadeau,[6] R. H. Nelson,[1] K. Page,[6] R. Partridge,[8] M. Pepin,[19] A. Phipps,[14] K. Prasad,[12] M. Pyle,[14] H. Qiu,[9] W. Rau,[6] P. Redl,[10] A. Reisetter,[17] Y. Ricci,[6] T. Saab,[18] B. Sadoulet,[14,3] J. Sander,[12] K. Schneck,[8] R. W. Schnee,[11] S. Scorza,[9] B. Serfass,[14] B. Shank,[10] D. Speller,[14] K. M. Sundqvist,[14] A. N. Villano,[19] B. Welliver,[18] D. H. Wright,[8] S. Yellin,[10] J. J. Yen,[10] J. Yoo,[2] B. A. Young,[7] and J. Zhang[19]

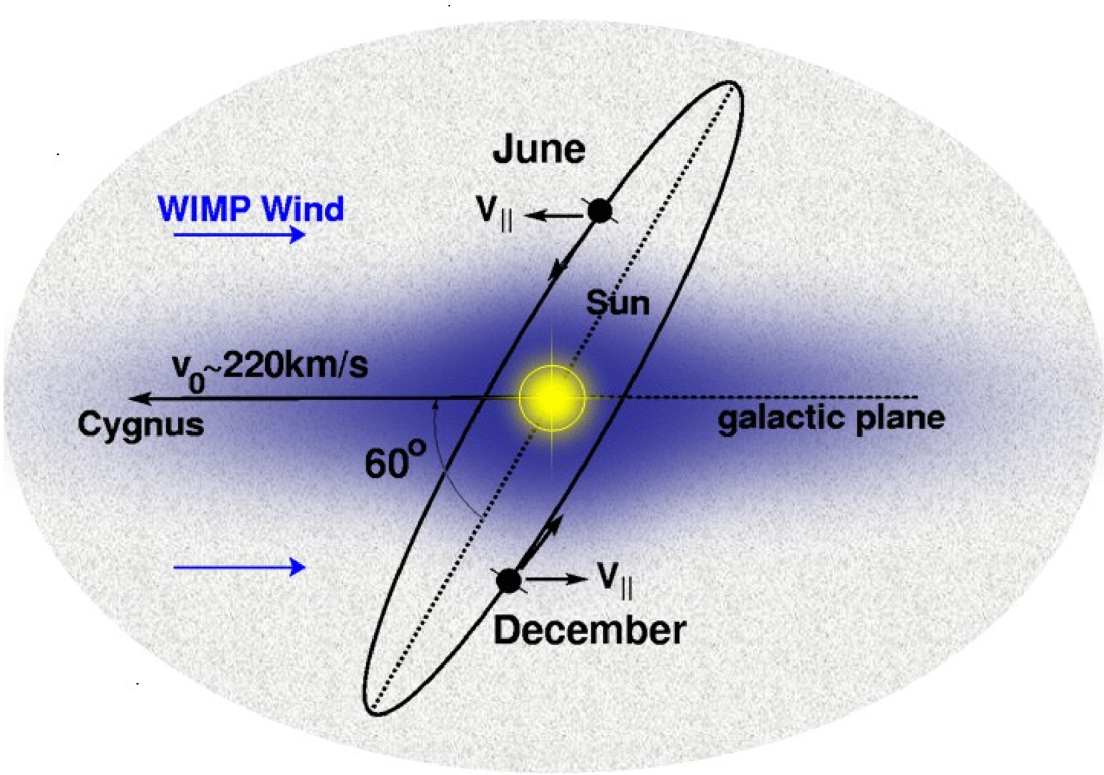
(CDMS Collaboration)

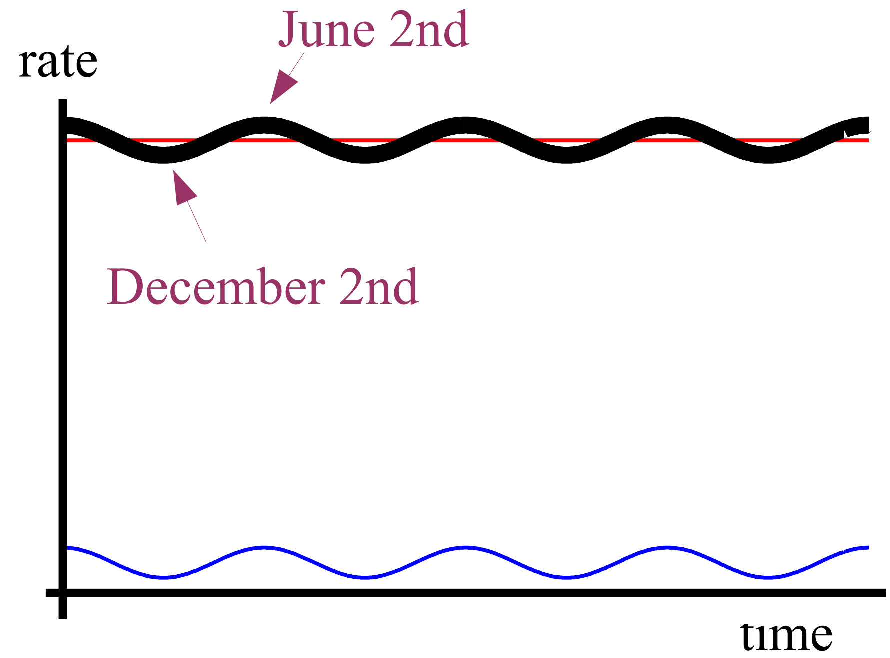
# Annual modulation



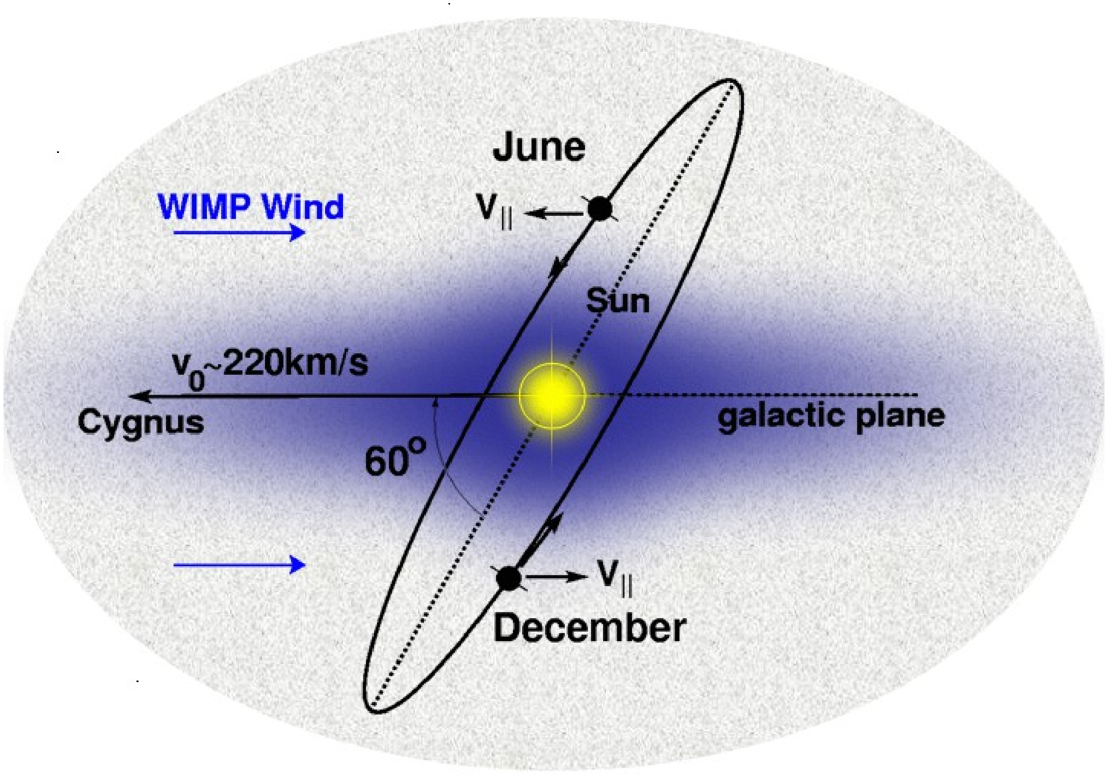



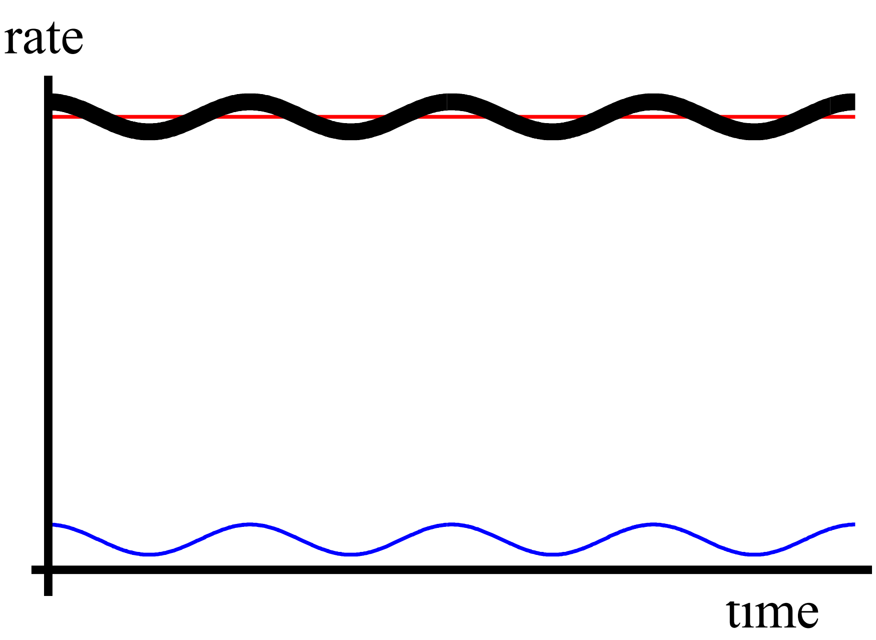
# Annual modulation



# Annual modulation

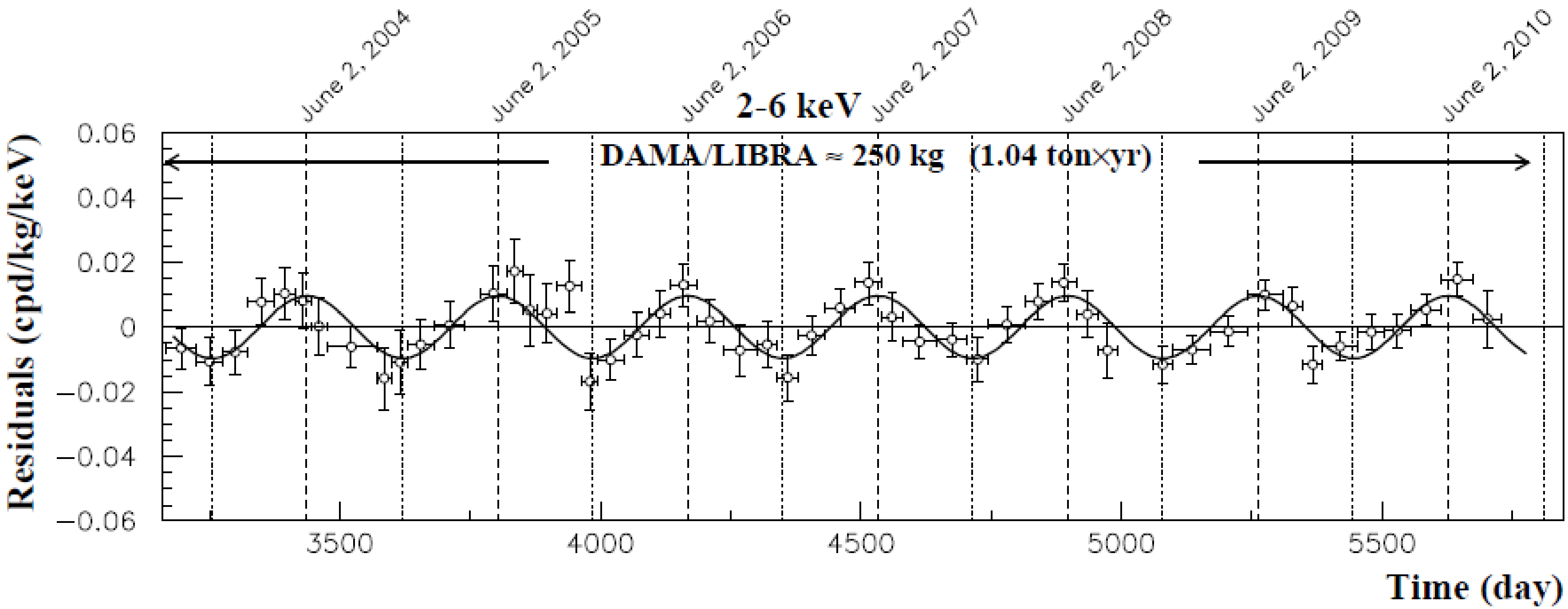



Modulation signal

$$S_{[E_-,E_+]} = \frac{1}{2}\frac{1}{E_+ - E_-}\left( R_{[E_-,E_+]}\Big|_{\text{June 1st}} - R_{[E_-,E_+]}\Big|_{\text{Dec 1st}} \right)$$

# Annual modulation: the DAMA/LIBRA experiment



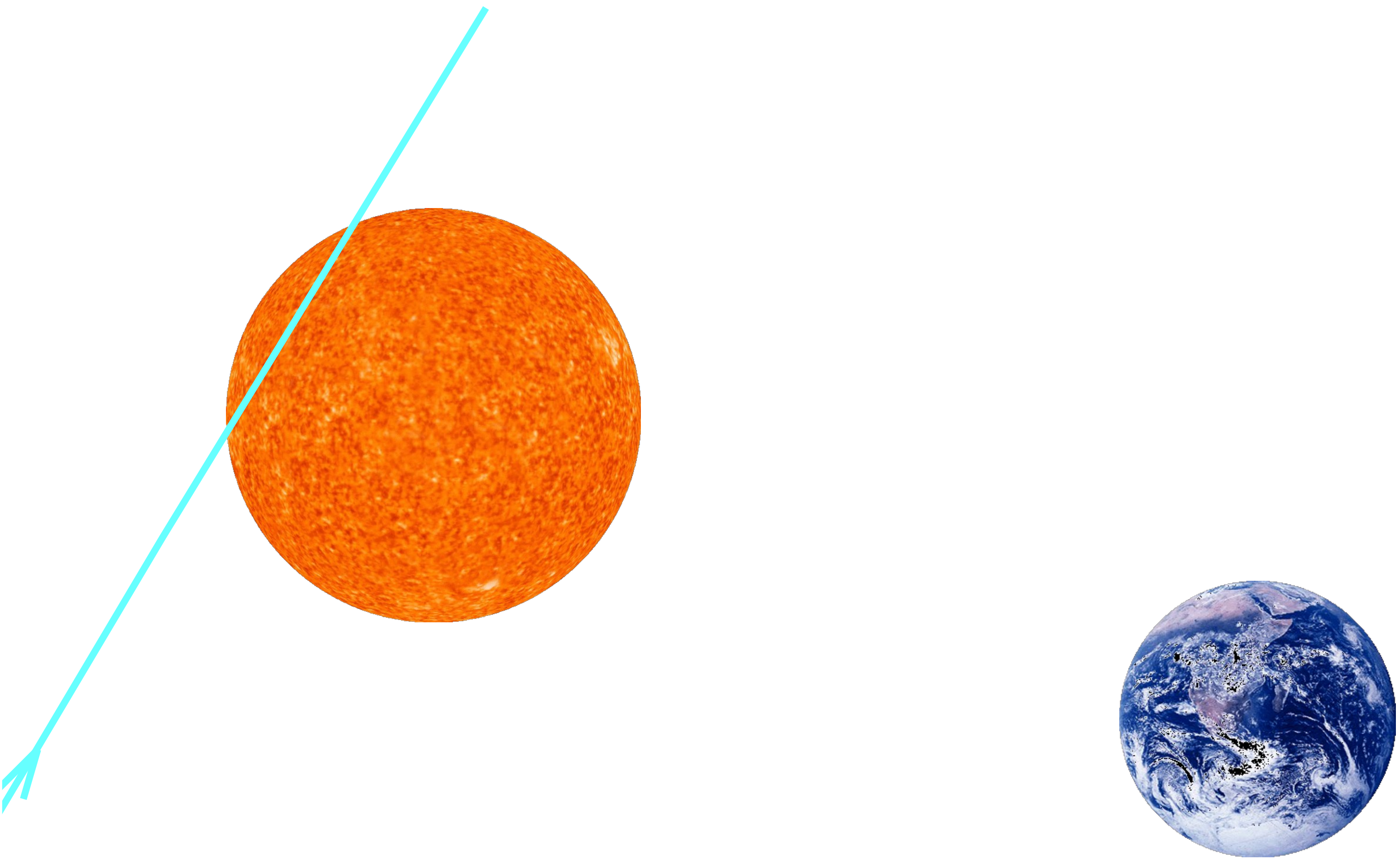

Modulation observed over 14 annual cycles, with a combined significance of $9.3\sigma$.

$$S^{(\mathrm{DAMA})}_{[2.0,2.5]} = (1.75 \pm 0.37) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

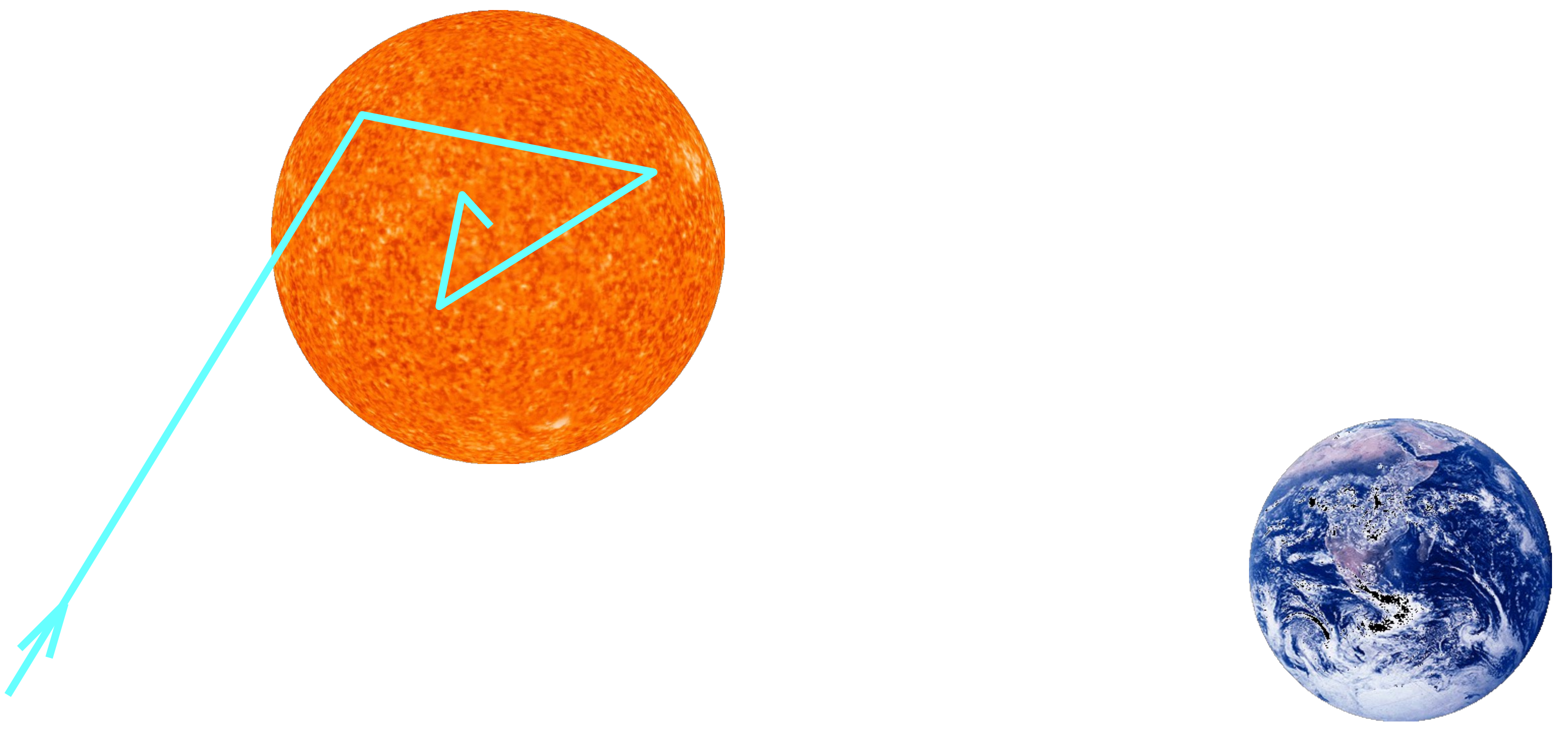
$$S^{(\mathrm{DAMA})}_{[2.5,3.0]} = (2.51 \pm 0.40) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

$$S^{(\mathrm{DAMA})}_{[3.0,3.5]} = (2.16 \pm 0.40) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

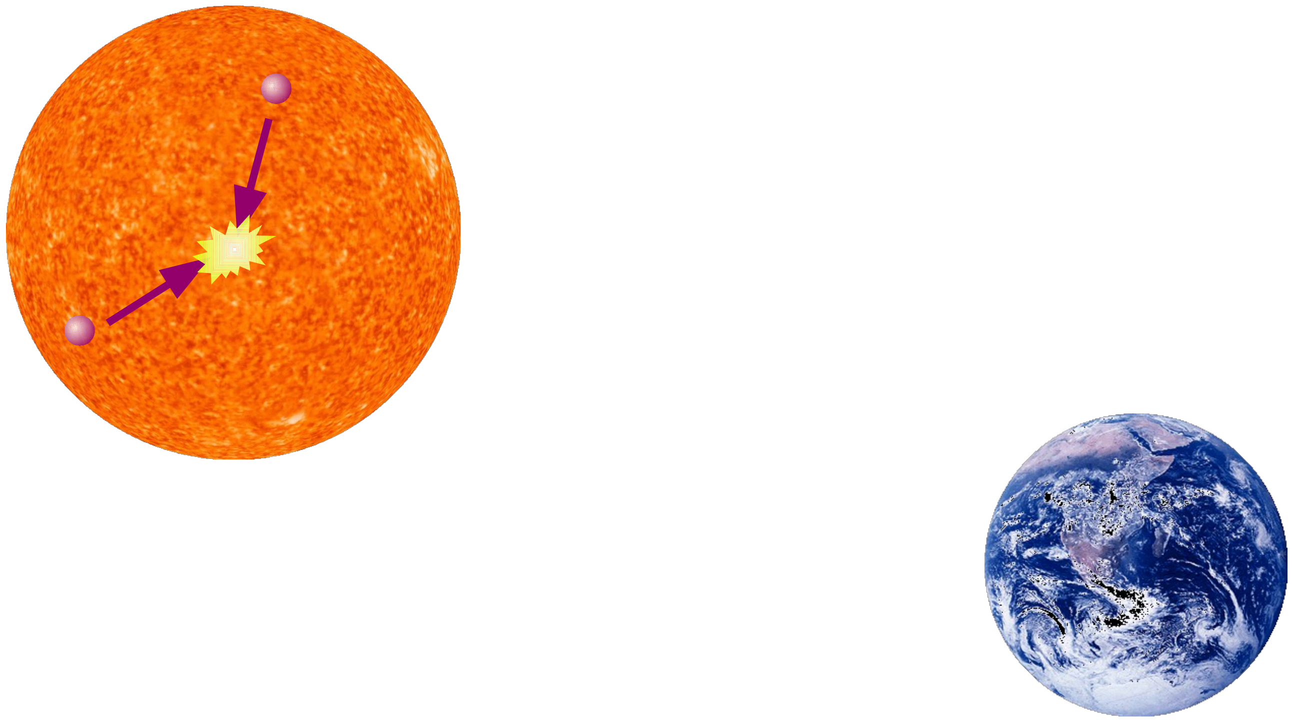
# Neutrinos from annihilations in the Sun



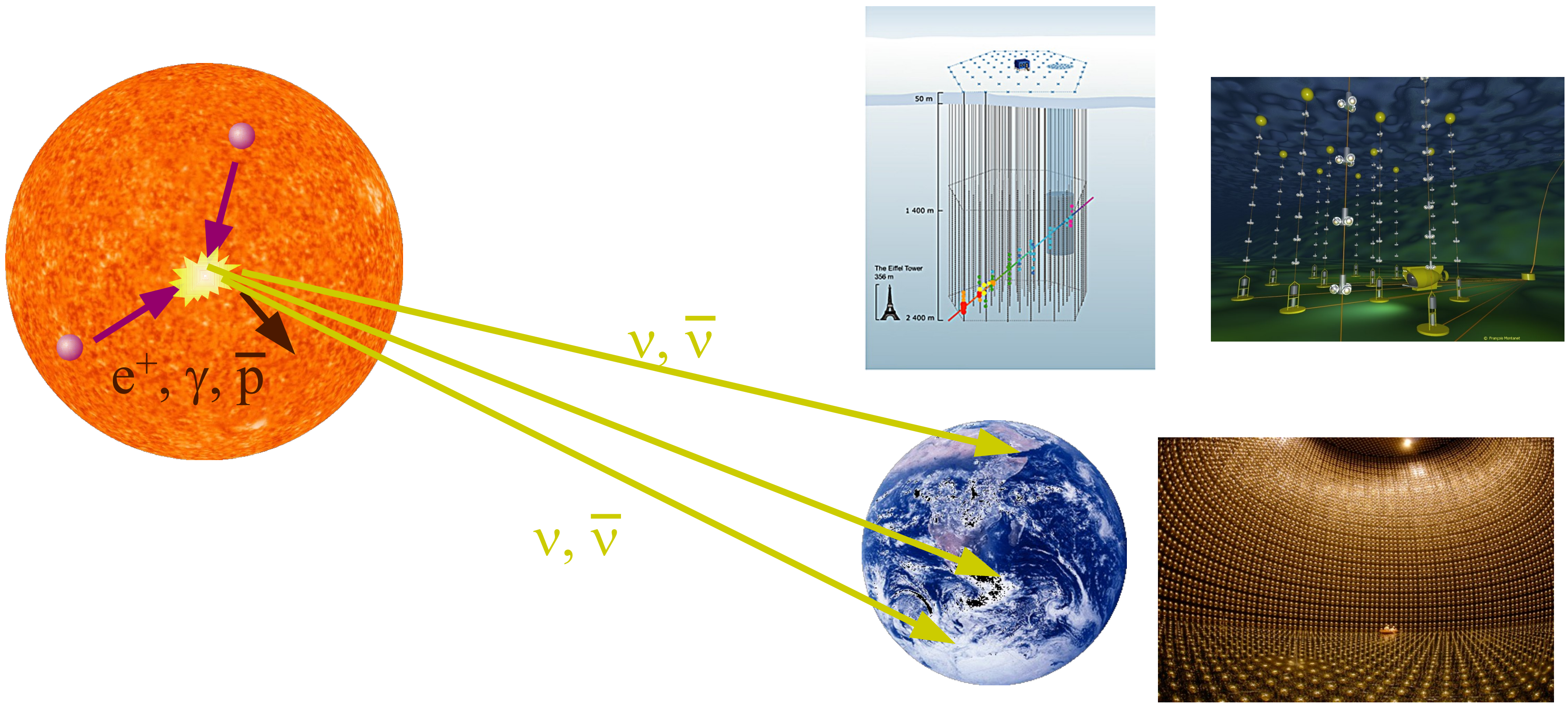
# Neutrinos from annihilations in the Sun



# Neutrinos from annihilations in the Sun

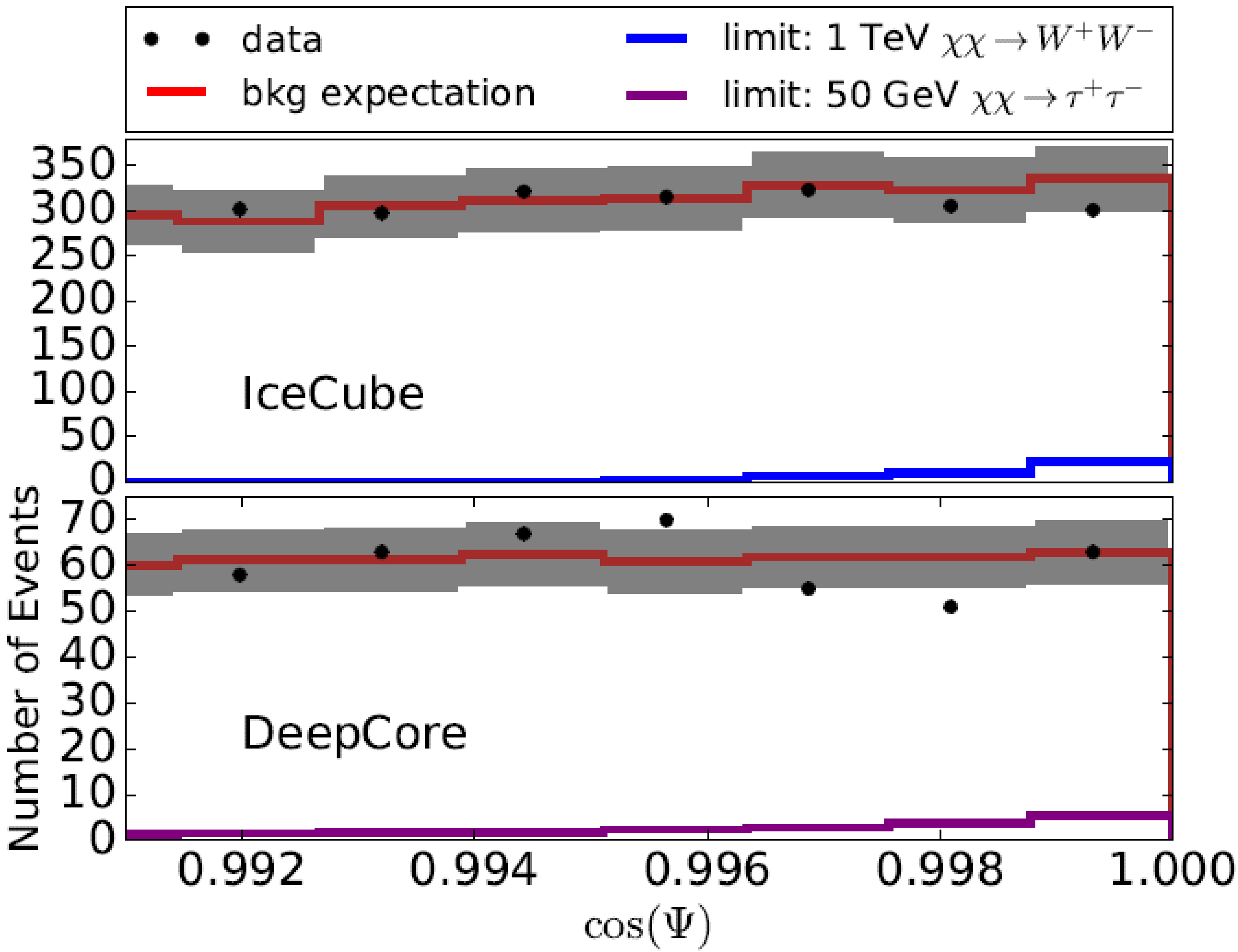


# Neutrinos from annihilations in the Sun



# Neutrinos from annihilations in the Sun

Observations consistent with the background-only hypothesis




IceCube collaboration
ArXiv:1612.05949

# Theoretical interpretation of the experimental results

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- Differential rate of DM-induced scatterings

$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3 v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \frac{{\rm d}\sigma}{{\rm d}E_R}$$

- The neutrino flux from annihilations inside the Sun is, under plausible assumptions, determined by the capture rate inside the Sun:

$$C = \int_0^{R_\odot} 4\pi r^2 {\rm d}r \, \frac{\rho_{\rm loc}}{m_{\rm DM}} \int_{v \leq v_{\rm max}^{\rm (Sun)}(r)} {\rm d}^3 v \, \frac{f(\vec{v})}{v} \left(v^2 + [v_{\rm esc}(r)]^2\right) \times \int_{m_{\rm DM} v^2/2}^{2\mu_A^2 \left(v^2 + [v_{\rm esc}(r)]^2\right)/m_A} {\rm d}E_R \, \frac{{\rm d}\sigma}{{\rm d}E_R}$$

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Uncertainties from particle/nuclear physics and from astrophysics

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# Theoretical interpretation of the experimental results

Uncertainties from particle/nuclear physics.

- Dark matter mass?

For thermally produced dark matter, $m_{\mathrm{DM}} = \text{few MeV} - 100\ \text{TeV}$

- Differential cross section?

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \frac{m_A}{2\mu_A^2 v^2}\left(\sigma_{\mathrm{SI}} F_{\mathrm{SI}}^2(E_R) + \sigma_{\mathrm{SD}} F_{\mathrm{SD}}^2(E_R)\right)$$

Spin-independent and spin-dependent cross sections at zero momentum transfer

Nuclear form factors

(In some DM frameworks, other operators may also arise )

# Theoretical interpretation of the experimental results

Uncertainties from astrophysics

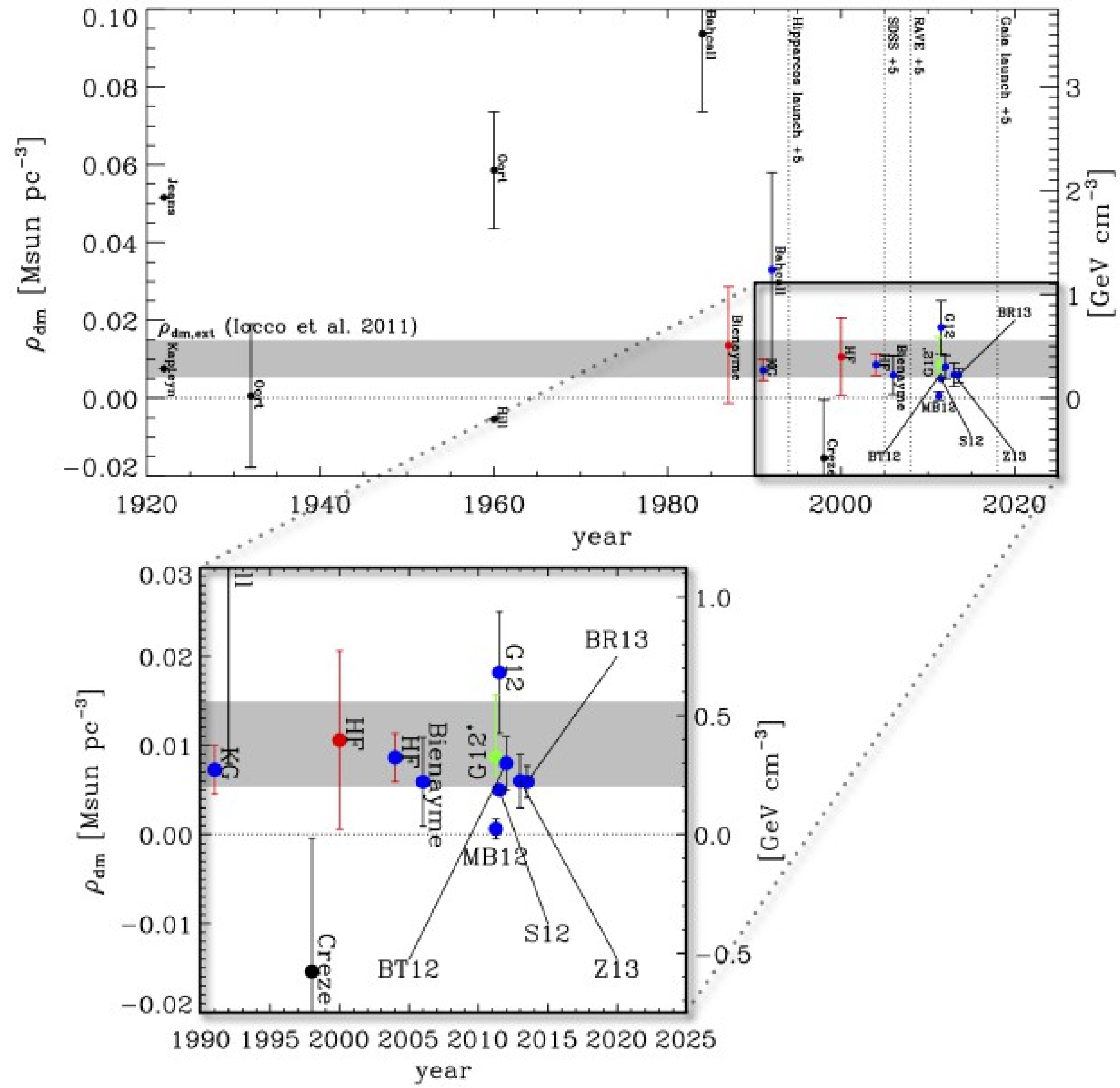
- Local dark matter density?

  - "local measurements":

    From vertical kinematics of stars near (~1 kpc) the Sun

  - "global measurements":

    From extrapolations of $\rho(r)$ determined from rotation curves at large $r$, to the position of the Solar System.




Read '14

# Theoretical interpretation of the experimental results

Uncertainties from astrophysics

- Local dark matter velocity distribution?

  Completely unknown. Rely on theoretical considerations

  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.

$$\rho(r) \sim \frac{1}{r^2} \longrightarrow f(v) \sim \exp(-v^2/v_0^2)$$

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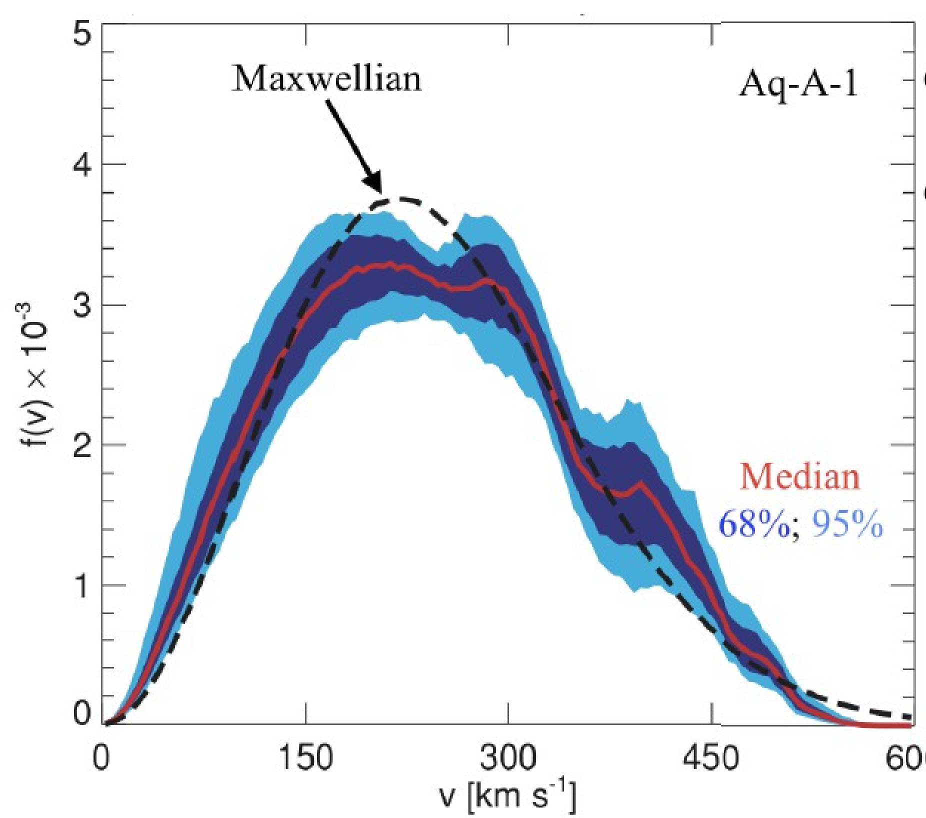
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann




Vogelsberger et al. 2009

# Theoretical interpretation of the experimental results

Uncertainties from astrophysics

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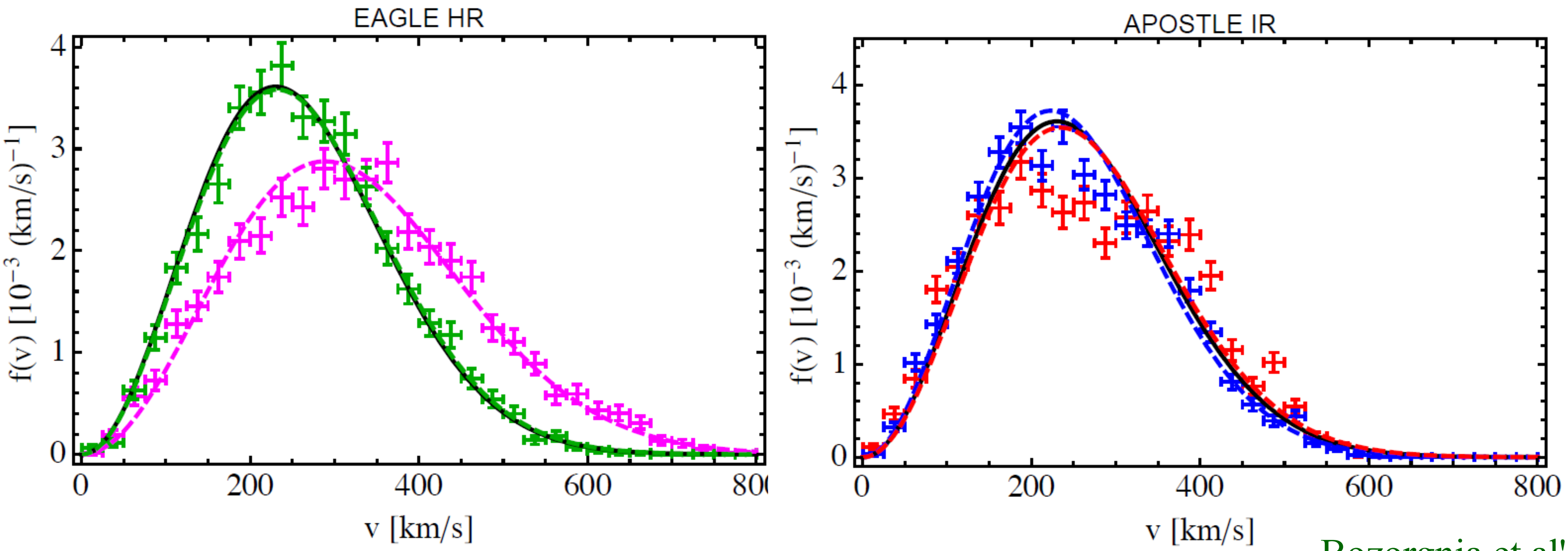
  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
  - Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.

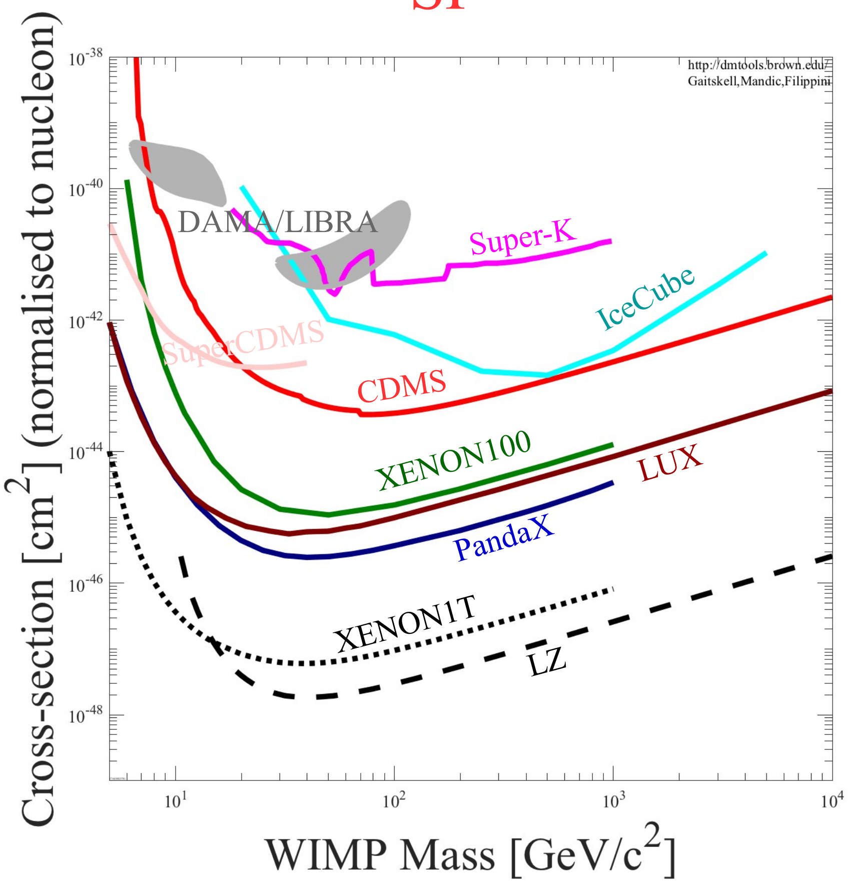



Bozorgnia et al'16

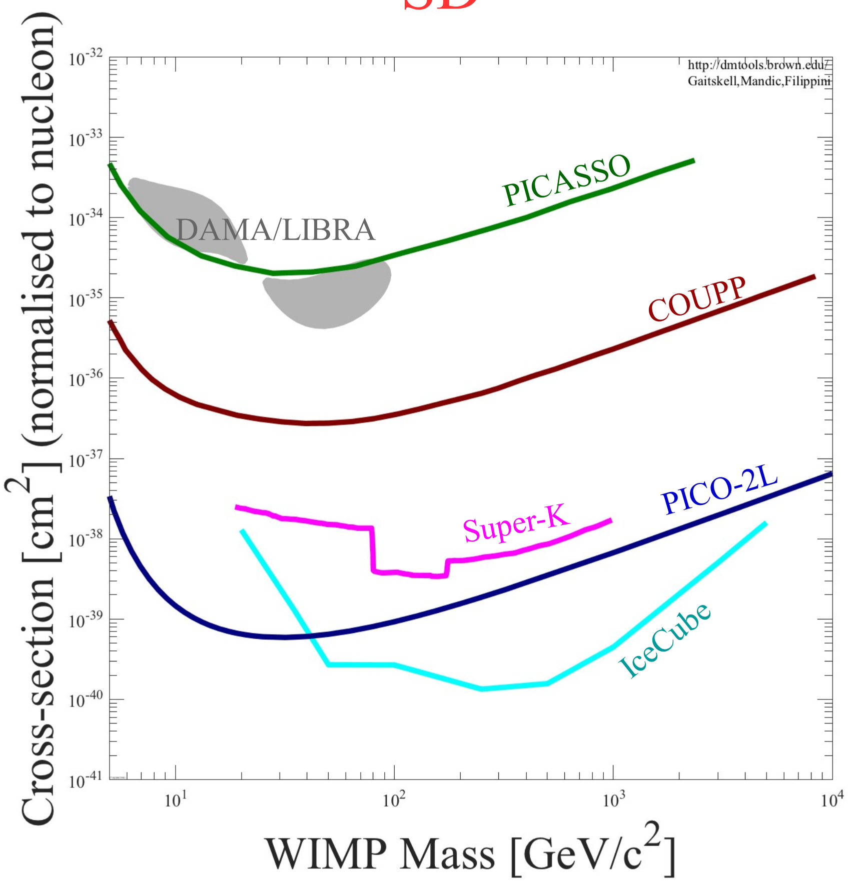
# Theoretical interpretation of the experimental results

Common approach: assume SI or SD interaction only, assume $\rho_{loc} = 0.3$ GeV/cm$^3$ and assume a Maxwell-Boltzmann velocity distribution

SI




SD



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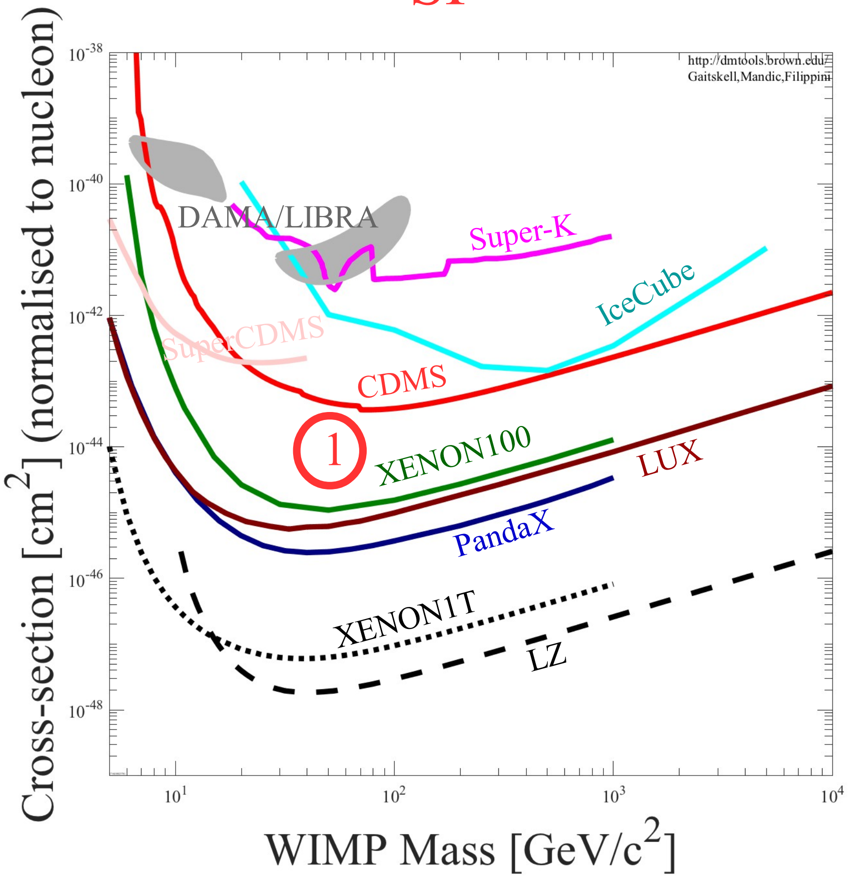


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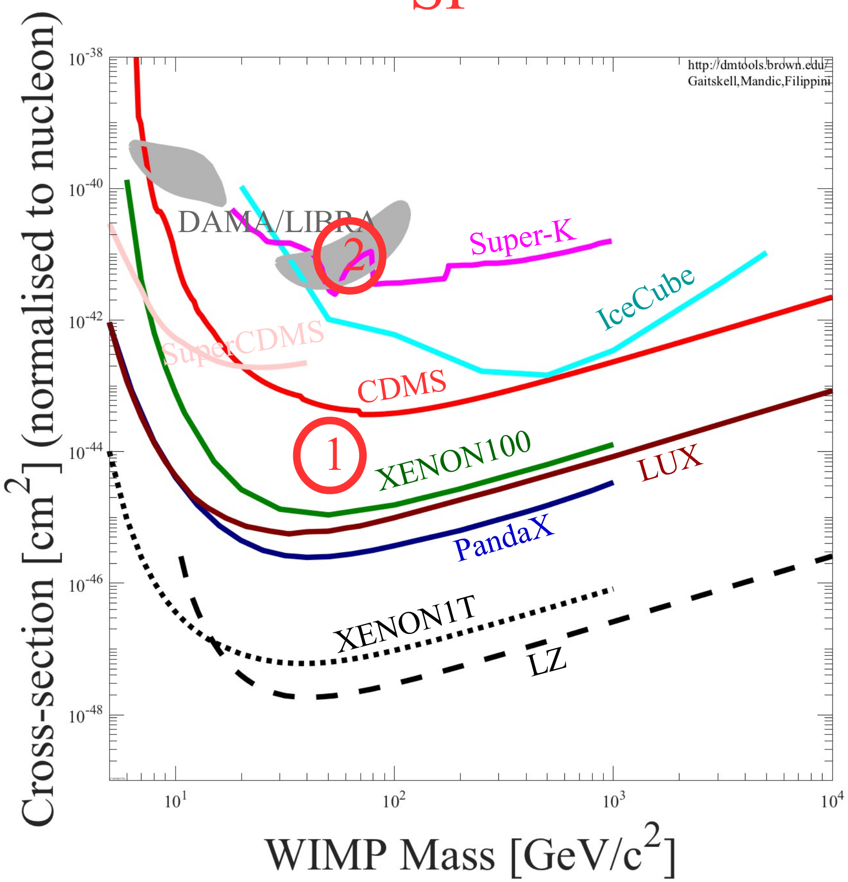


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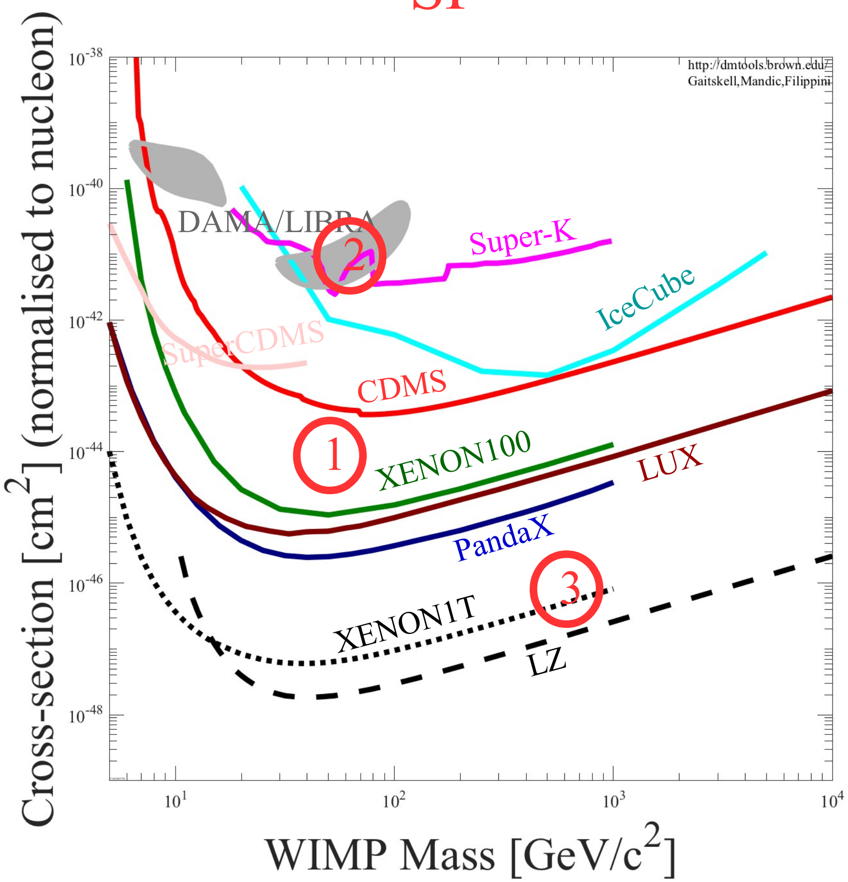


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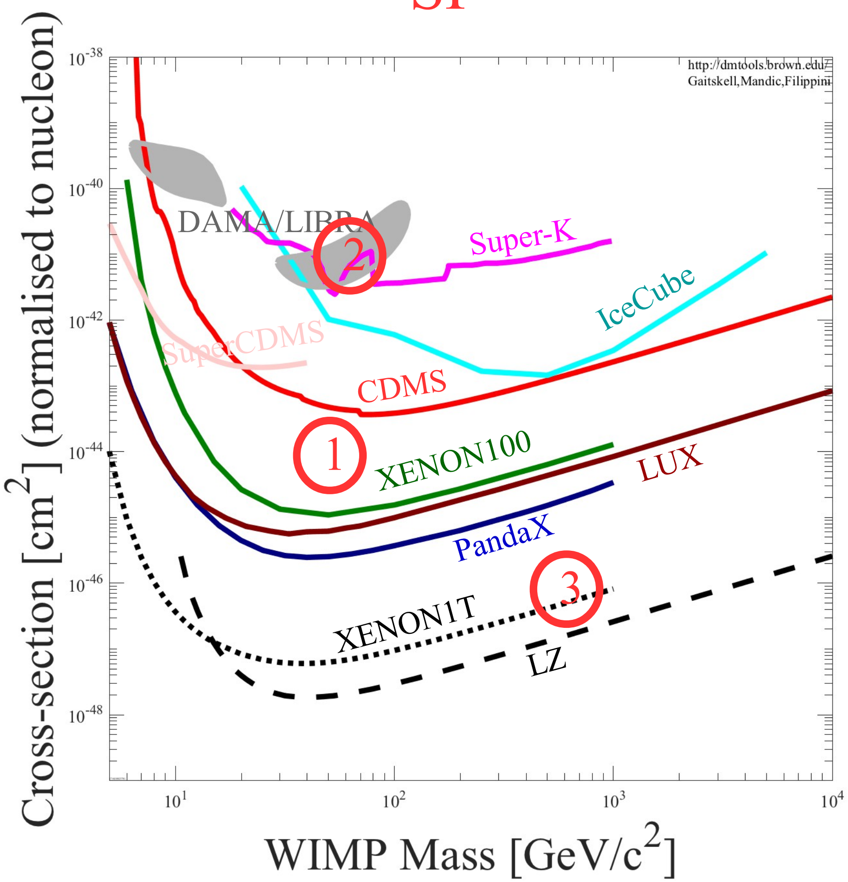


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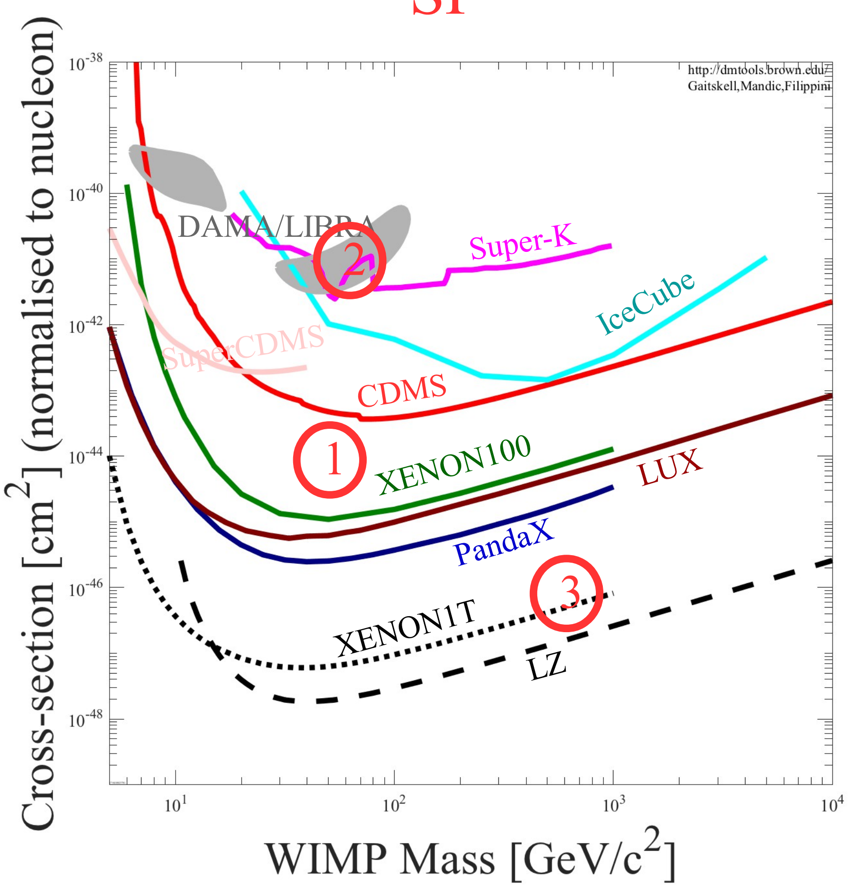


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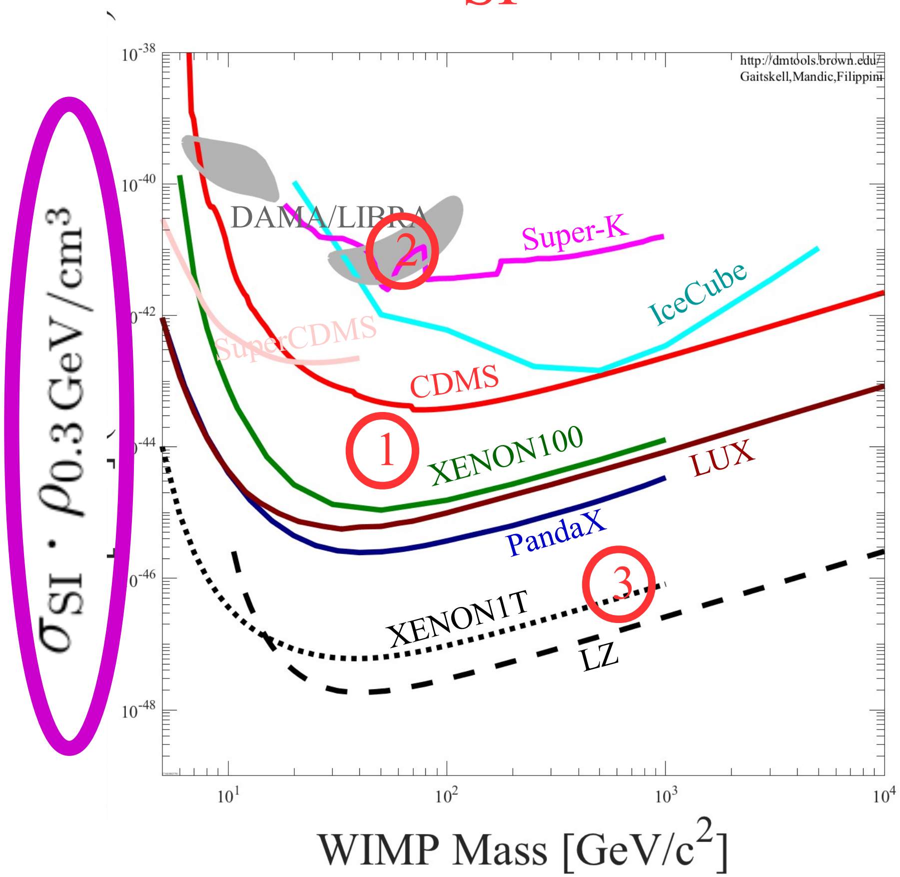


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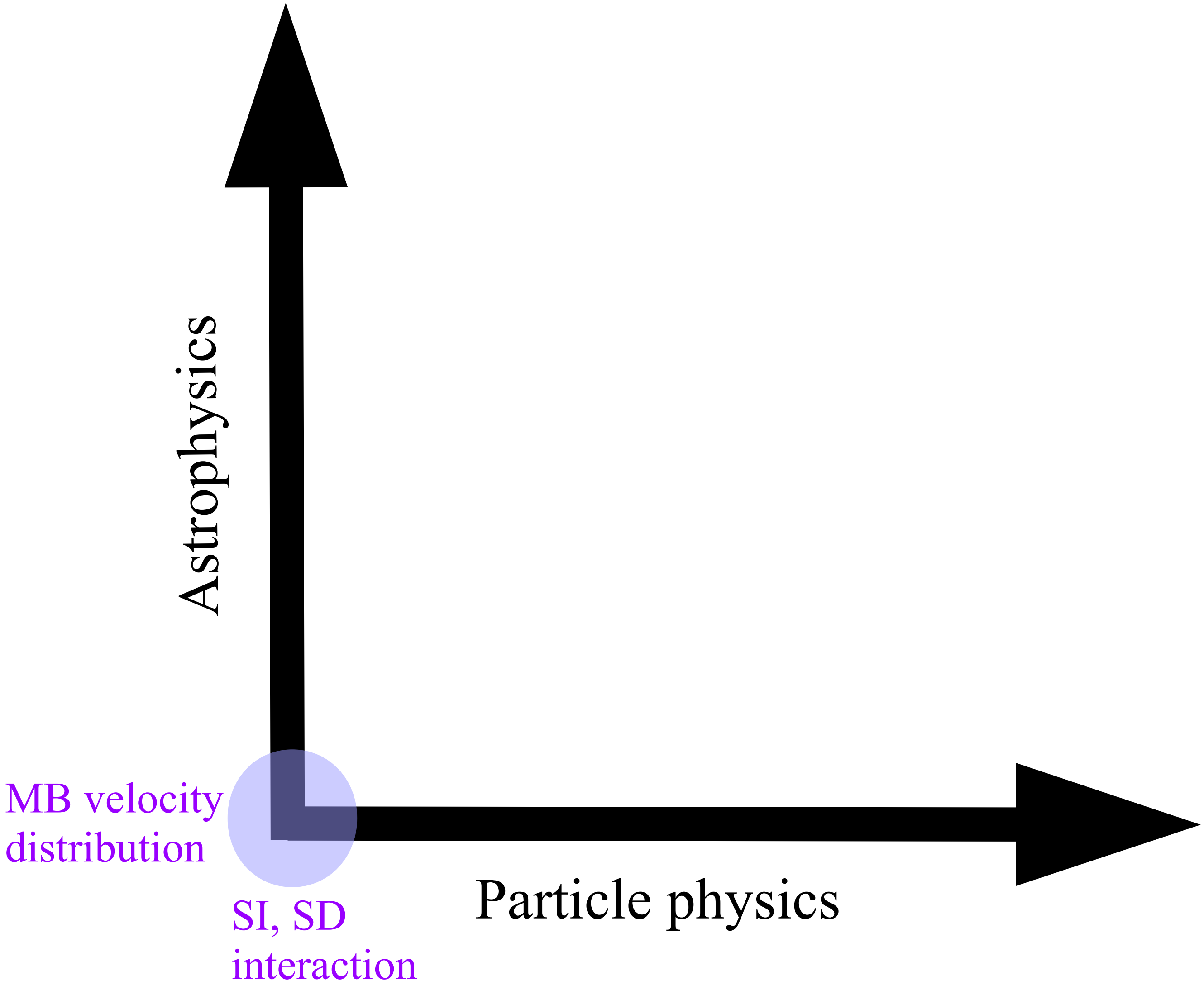
Are all particle physics models covered?

What is the impact of the astrophysical uncertainties on these conclusions?

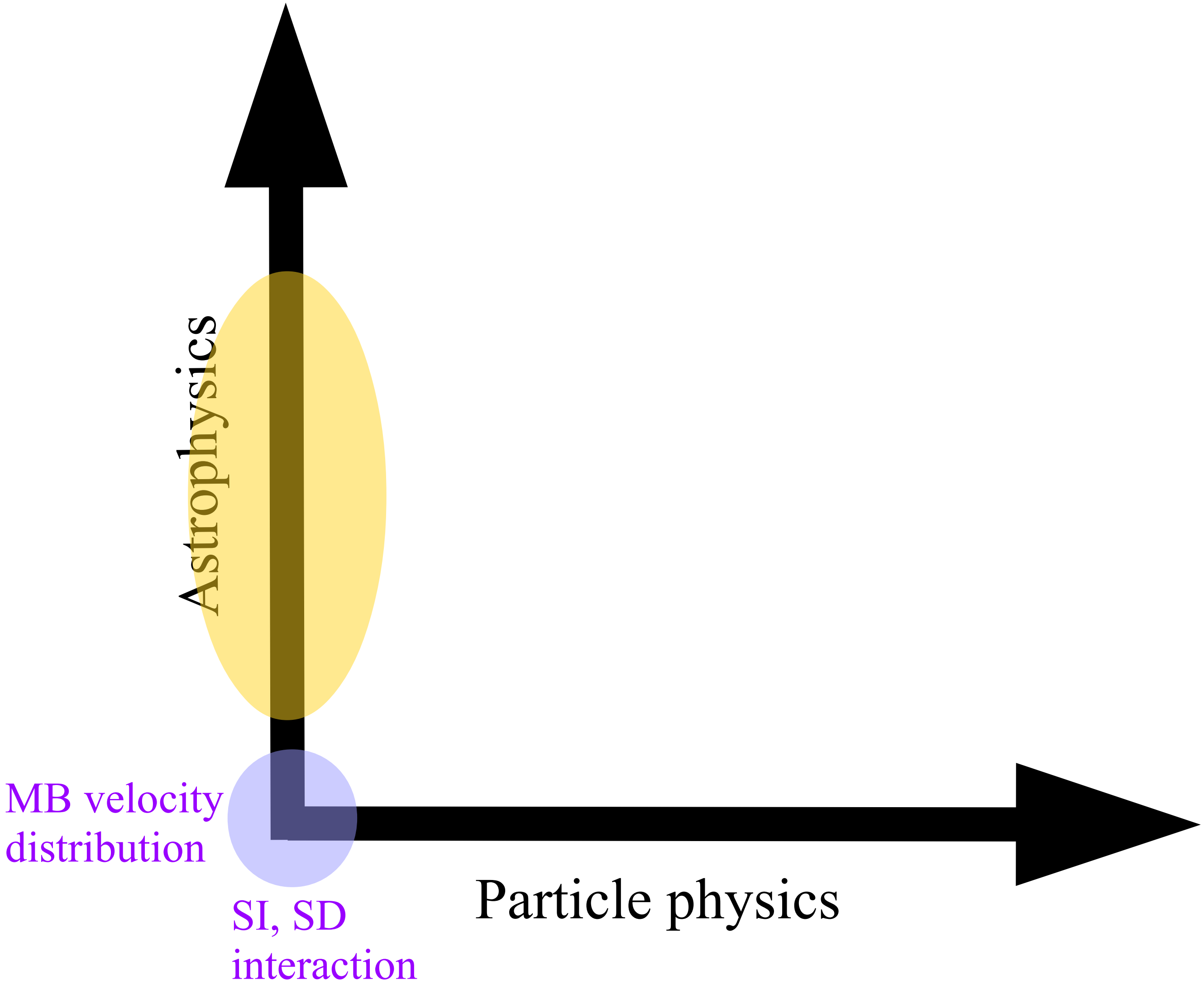
Do these conclusions hold for arbitrary velocity distributions?

# Addressing theoretical uncertainties in dark matter detection

# DM theory parameter space



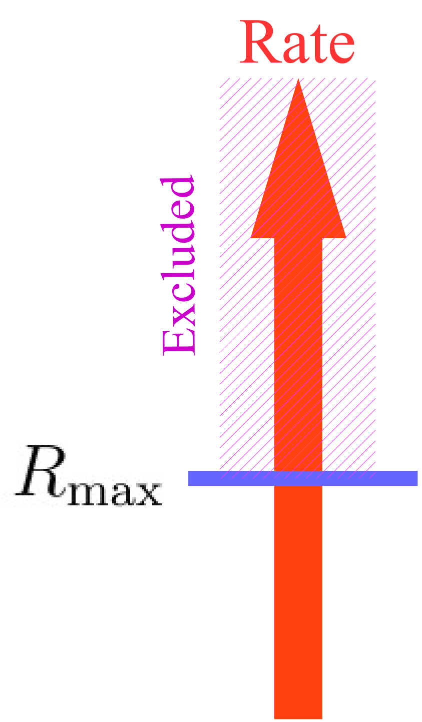
## DM theory parameter space



# Halo-independent approach for DM frameworks

- $(\sigma, m_{\rm DM})$ is ruled out regardless of the velocity distribution if

$$\min_{f(\vec{v})} \Big\{ R(\sigma, m_{\rm DM}) \Big\} > R_{\rm max}$$



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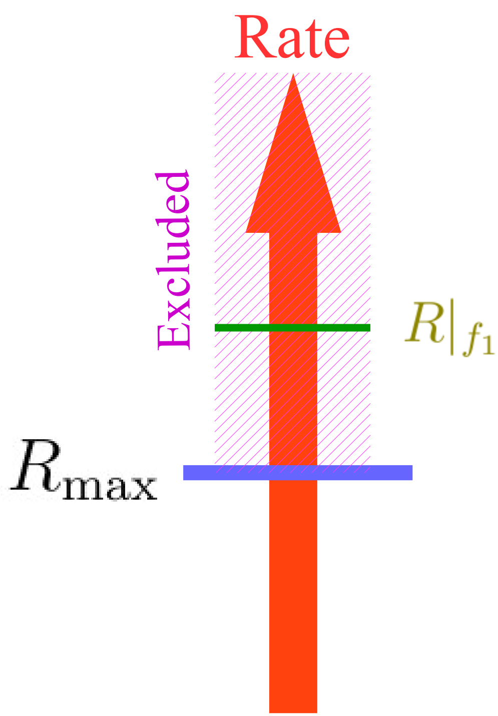

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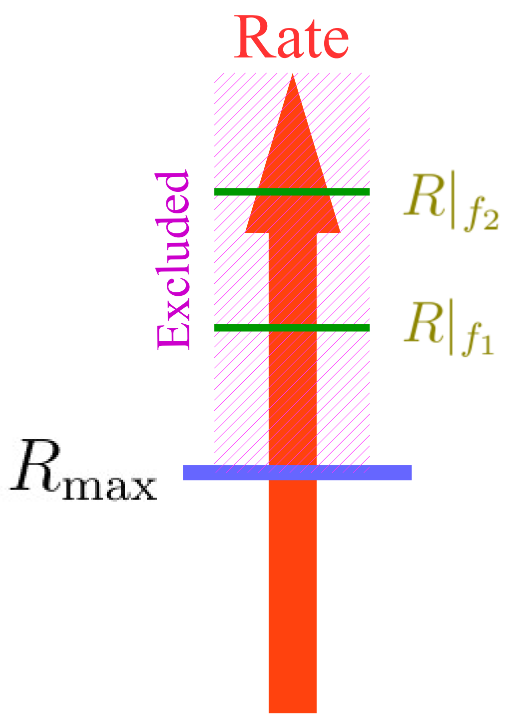

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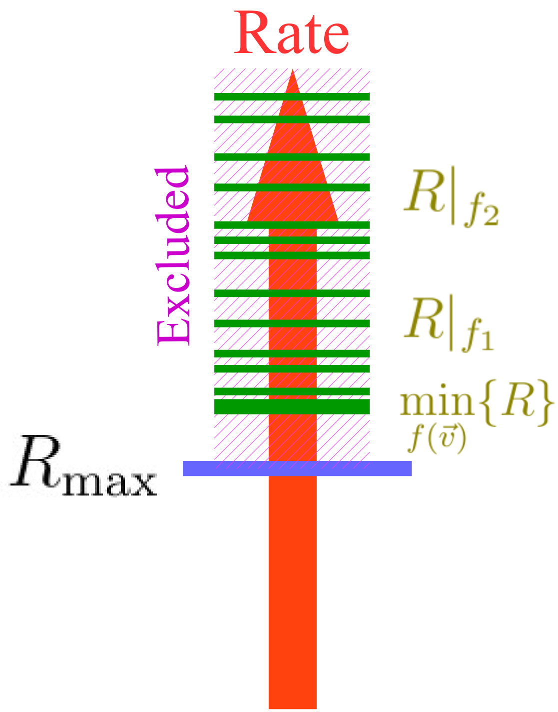

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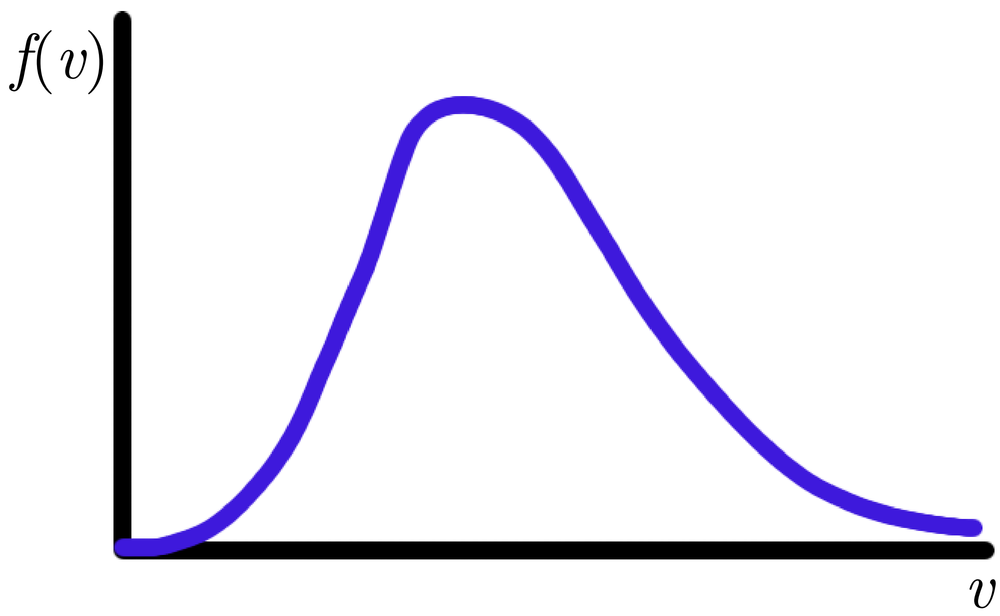

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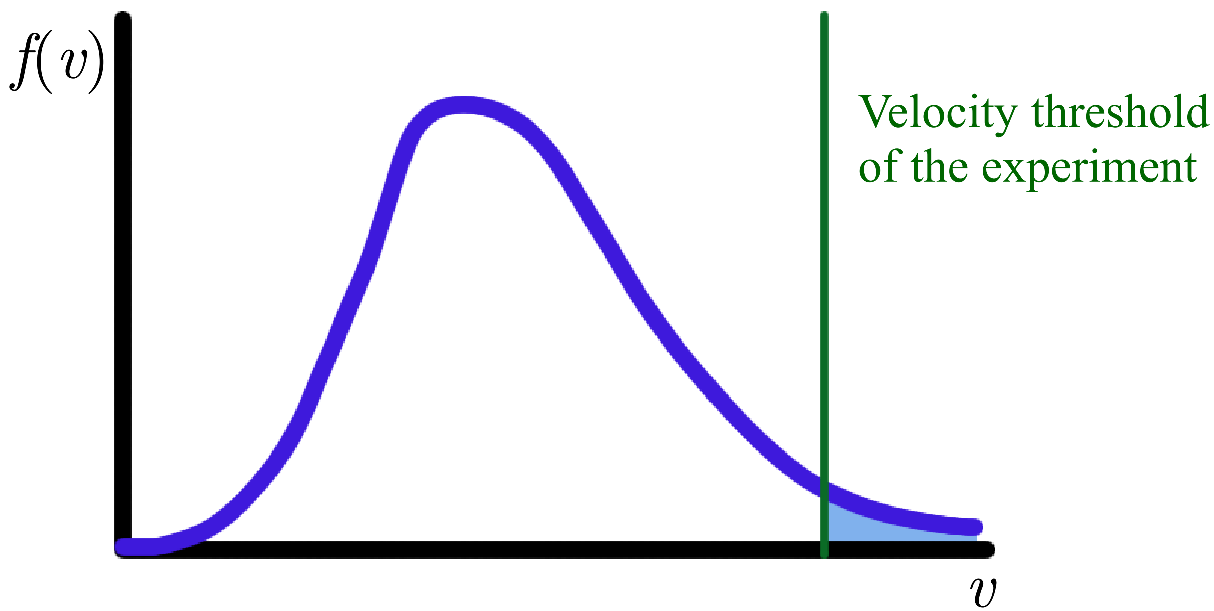

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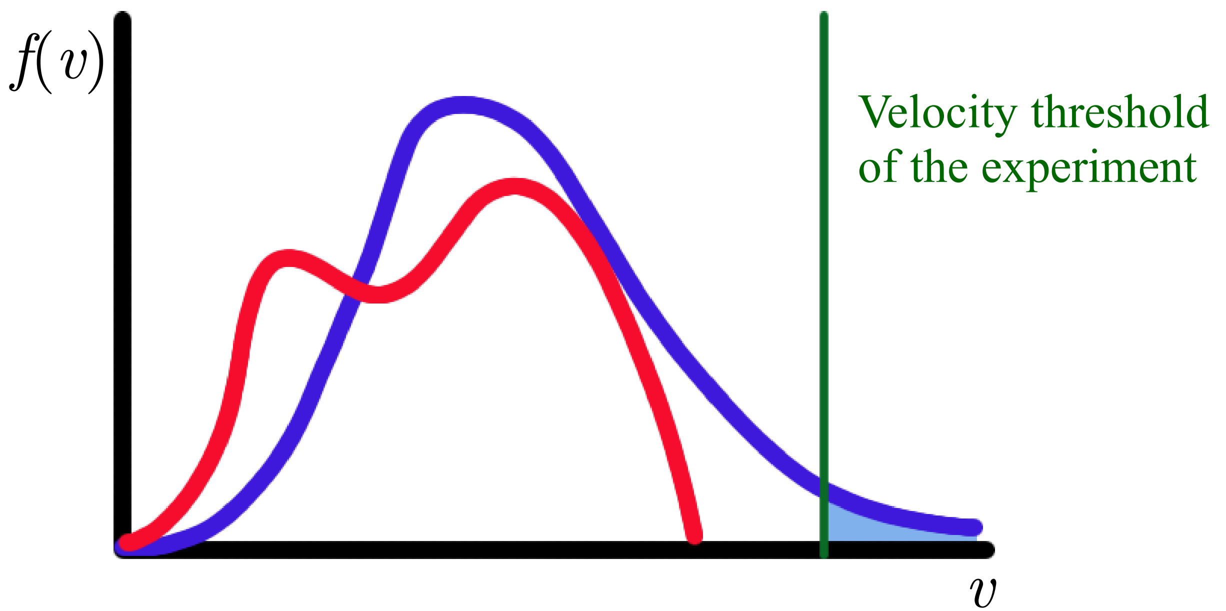


Some velocity distributions will escape detection in the experiment

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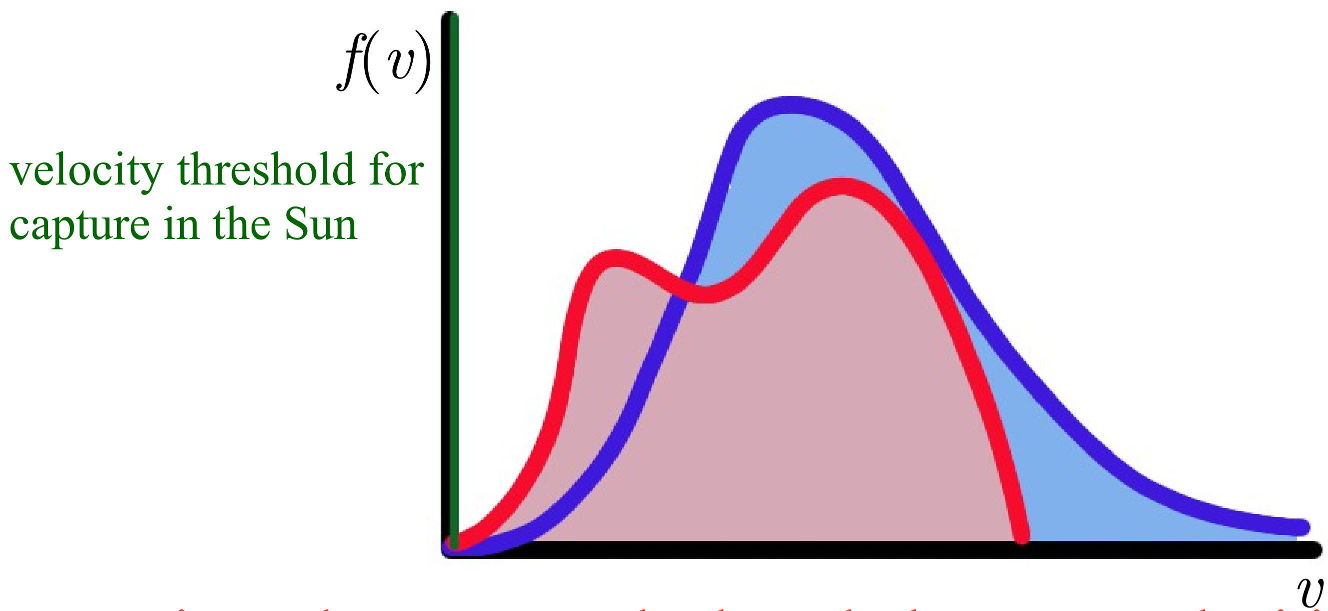


Neutrino telescopes probe low dark matter velocities. In combination with direct detection experiments, one can probe the whole velocity space

# Halo-independent approach for DM frameworks

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$$\min_{f(\vec{v})} \left\{ R(\sigma, m_{\rm DM}) \right\} \Big|_{\substack{C(\sigma,m) \leq C_{\rm max} \\ \int f = 1}} > R_{\rm max}$$

**Optimization problem with constraints**

# Halo-independent approach for DM frameworks

Technically complicated...

$$R(\sigma, m_{\rm DM}) = \int_{E_{\rm th}}^{\infty} dE_R \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3v \, v \, f(\vec{v} + \vec{v}_{\rm obs}(t)) \, \frac{{\rm d}\sigma}{{\rm d}E_R}$$

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# Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Express the velocity distribution as a superposition of many many streams:

$$f(\vec{v}) = \sum_{i=1}^{n} c_{\vec{v}_i}\ \delta(\vec{v} - \vec{v}_i)$$

Minimization problem. For given DM mass and cross-section:

$$\text{minimize} \quad R^{(\text{PandaX})}(c_{\vec{v}_1} \ldots, c_{\vec{v}_n}) = \sum_{i=1}^{n} c_{\vec{v}_i} R^{(\text{PandaX})}_{\vec{v}_i} \,,$$

$$\text{subject to} \quad \sum_{i=1}^{n} c_{\vec{v}_i} C^{(\text{NT})}_{\vec{v}_i} \leq C^{(\text{NT})}_{\text{max}} \,,$$

$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1 \,,$$

$$\text{and} \quad c_{\vec{v}_i} \geq 0, \quad i = 1 \ldots, n \,,$$

The parameters $\sigma$ and $m_{DM}$ are excluded in a halo independent manner if :

$$\min\left\{R^{(\text{PandaX})}(c_{\vec{v}_1} \ldots, c_{\vec{v}_n})\right\}\Big|_{\text{constraints}} > R^{(\text{PandaX})}_{\text{max}}$$

## Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

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$$\text{subject to} \quad \sum_{i=1}^{n} c_{\vec{v}_i} C_{\vec{v}_i}^{(\text{NT})} \leq C_{\max}^{(\text{NT})},$$

$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1\,,$$

$$\text{and} \quad c_{\vec{v}_i} \geq 0, \quad i = 1\ldots, n\,,$$

The objective function and the constraints are linear in the weights of the DM streams

↪ Optimize using linear programming techniques.

# A tour in linear programming

An automobile company produces cars and trucks. For each car obtains 400€ profit, and for each truck, 700€. What should be the strategy of the company to optimize the weekly profit?

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In real life, the production is subject to constraints

- It takes 4 hours to assemble the engine of a car, and 3 hours for a truck
- It takes 2 hours to paint a car, and 4 hours to paint a truck
- The assembly line operates 14 hours a day, and the paint workshop operates 10 hours a day, 5 days a week.

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Linear programming problem:

$$\begin{aligned} \text{Maximize} \quad & P = 400N_c + 700N_t \\ \text{subject to} \quad & 4N_c + 3N_t \leq 14 \times 5 \\ \text{and} \quad & 2N_c + 4N_t \leq 10 \times 5 \\ \text{and} \quad & N_c \geq 0, N_t \geq 0 \end{aligned}$$

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Linear programming problem:

"Objective function" Maximize $P = 400N_c + 700N_t$

"Constraints"

$$\begin{aligned} &\text{subject to} \quad 4N_c + 3N_t \leq 14 \times 5 \\ &\text{and} \quad 2N_c + 4N_t \leq 10 \times 5 \\ &\text{and} \quad N_c \geq 0,\ N_t \geq 0 \end{aligned}$$

"Decision variables"

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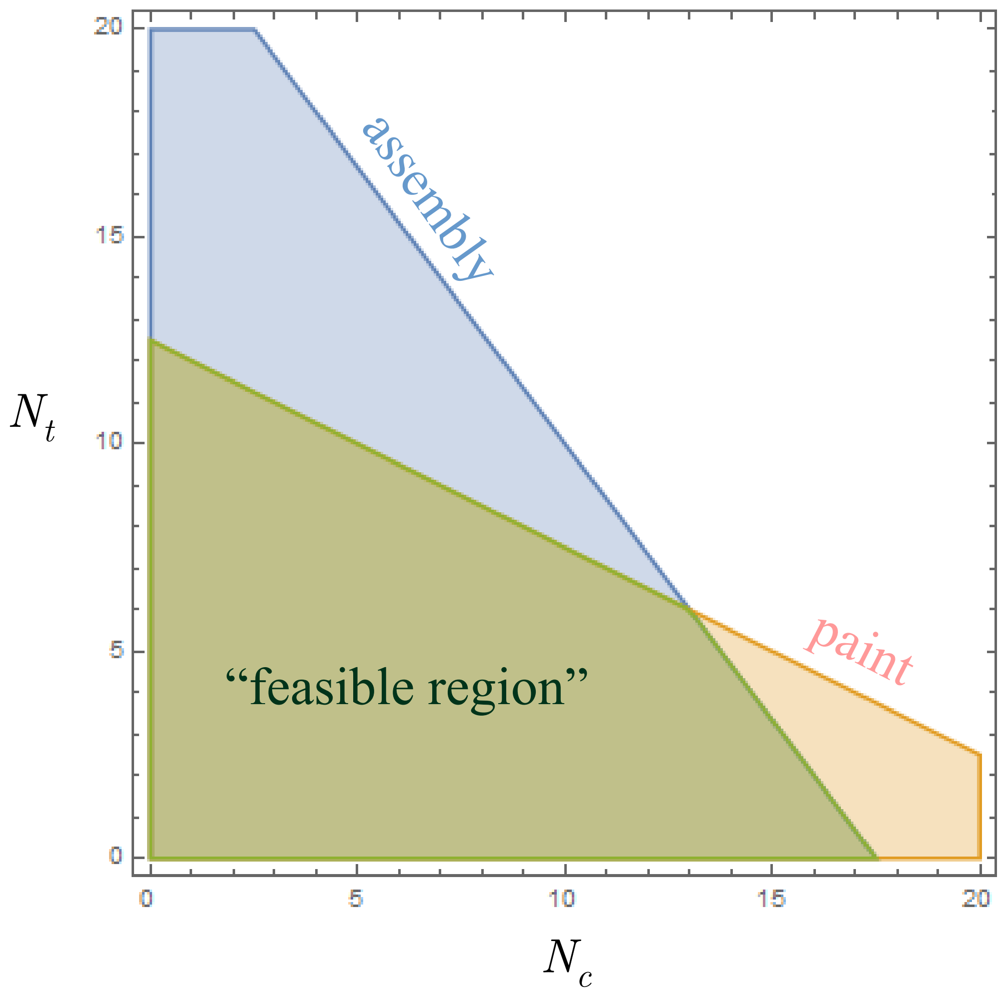

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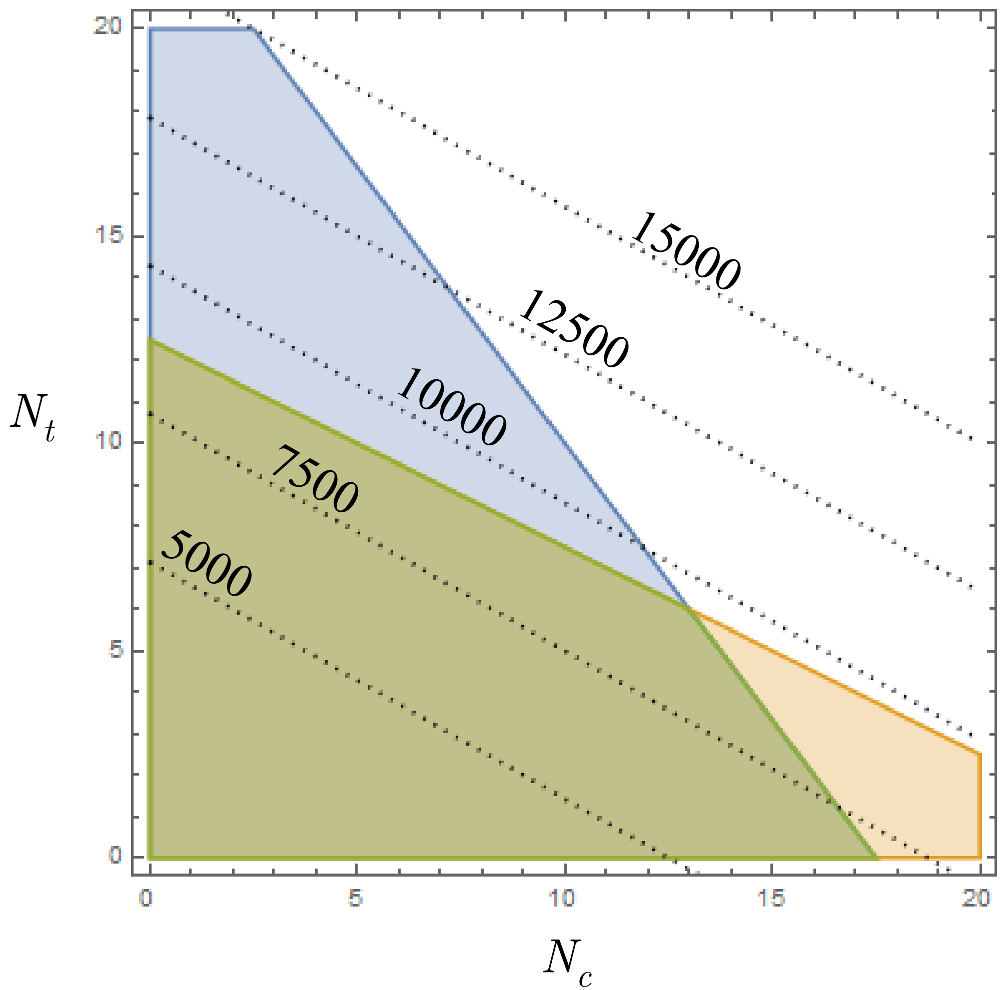

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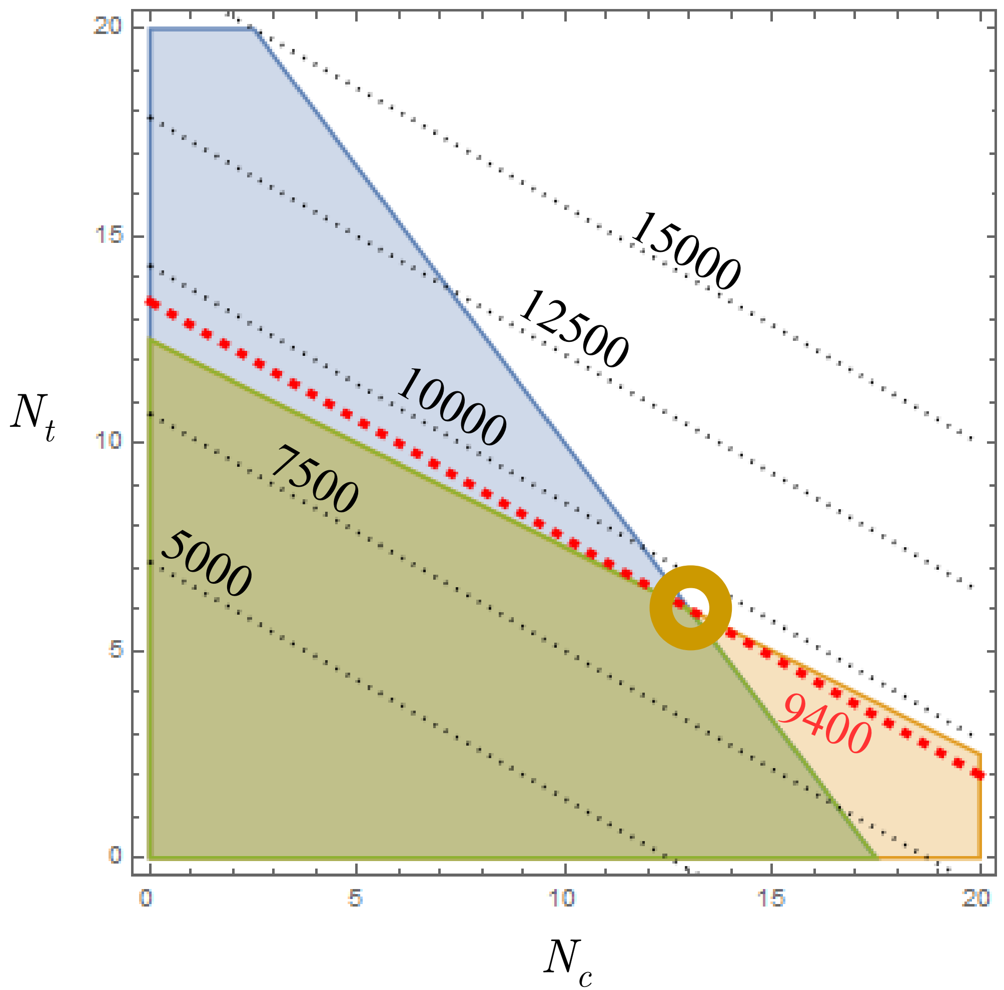
$N_c = 13$

$N_t = 6$

Profit = 9400 €/week



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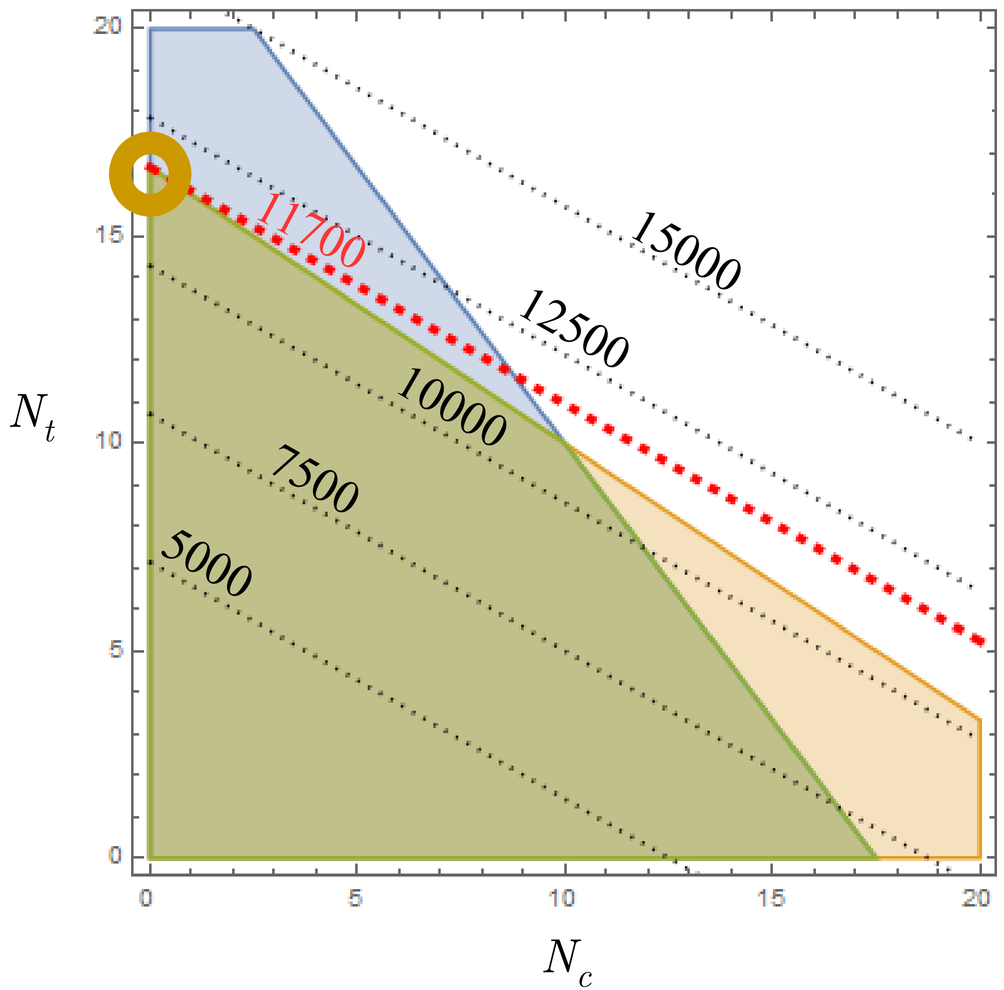
$N_c = 0$
$N_t = 16.7$
Profit = 11700 €/week



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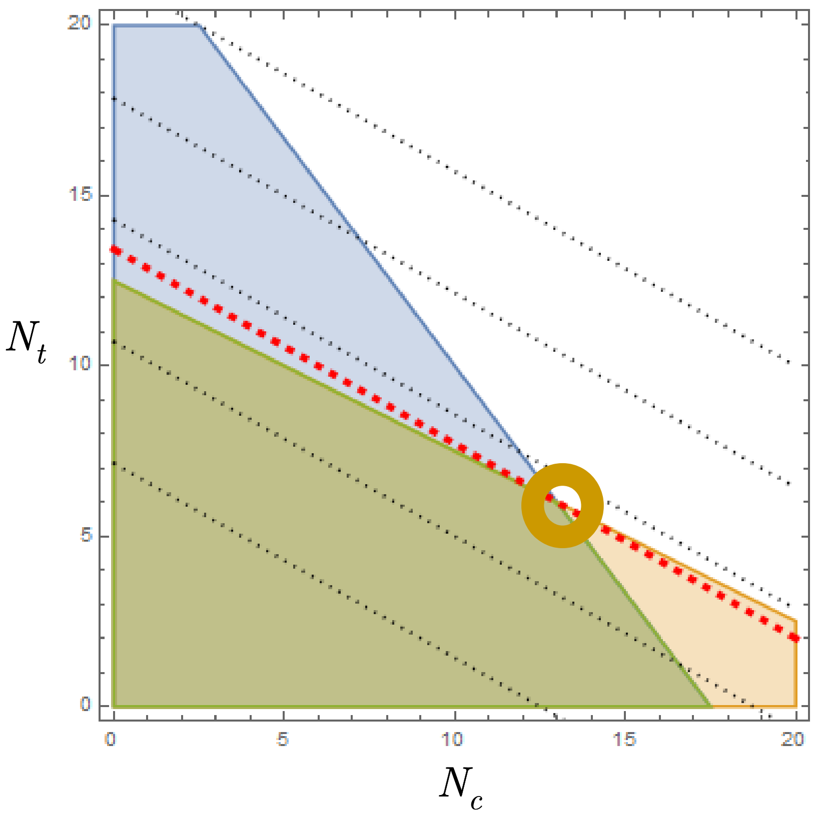
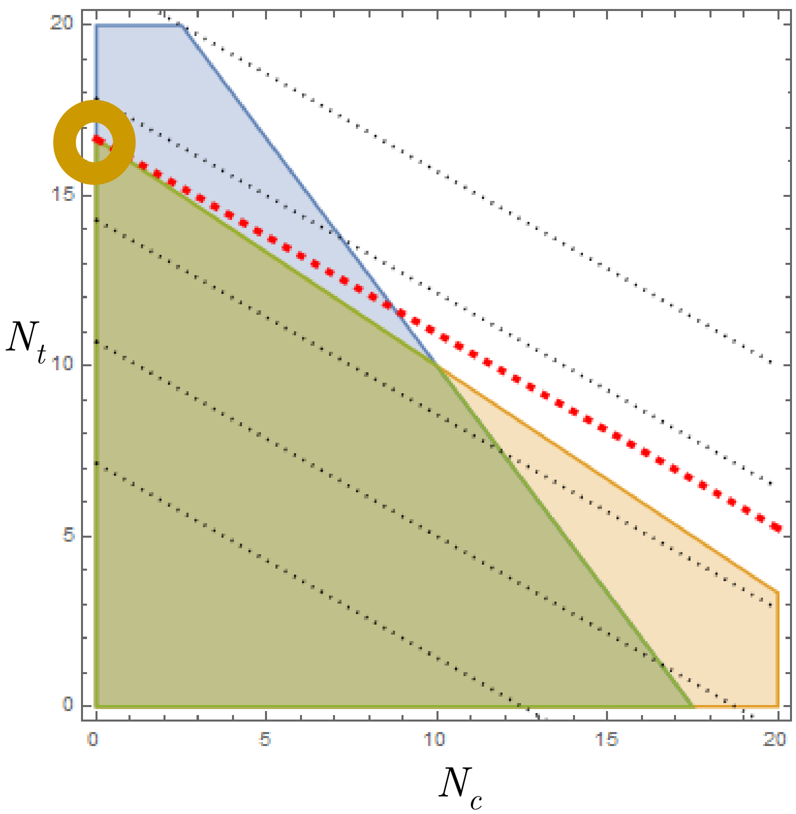



Lessons:

1) The solution lies at one of the vertices of the feasible region (polygon)

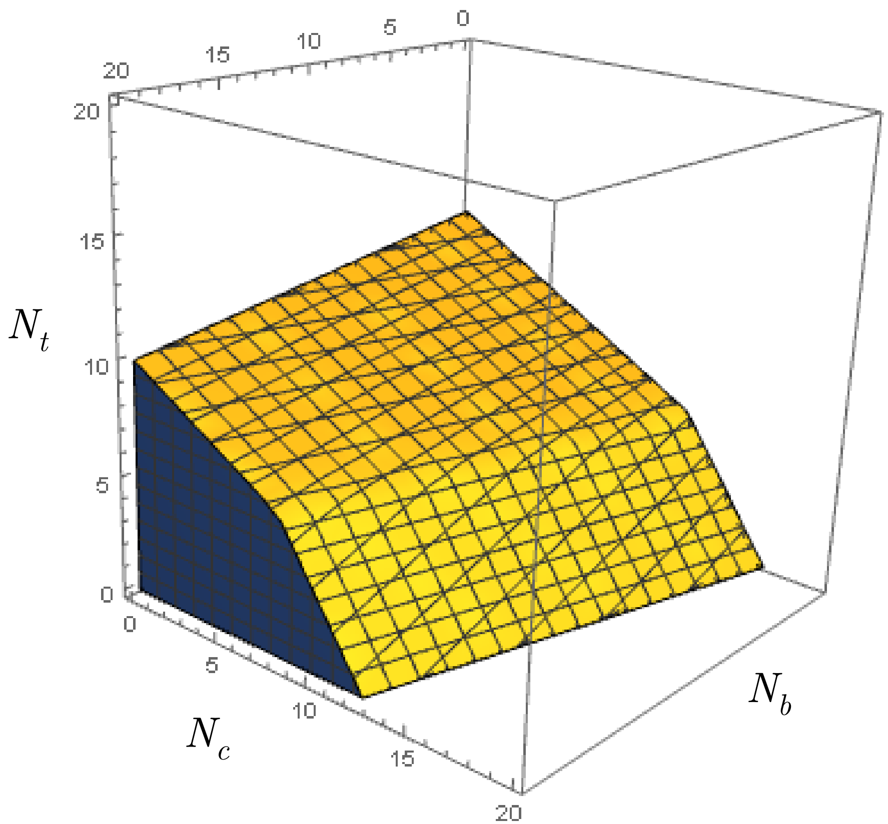
2) For two constraints there are:

- two non-vanishing decision variables, when the two constraints are saturated
- one non-vanishing decision variable, when one of the constraints is not saturated

# A tour in linear programming

Suppose that the company also produces motorbikes. The profit is 100€ per motorbike, it takes 1 hour to assemble the engine of the motorbike, and it takes 30 minutes to paint the motorbike.

$$\begin{aligned} \text{Maximize} \quad & P = 400N_c + 700N_t + 100N_b \\ \text{subject to} \quad & 4N_c + N_t + N_b \leq 14 \times 5 \\ \text{and} \quad & 2N_c + 4N_t + 0.5N_b \leq 10 \times 5 \\ \text{and} \quad & N_c \geq 0, N_t \geq 0, N_b \geq 0 \end{aligned}$$



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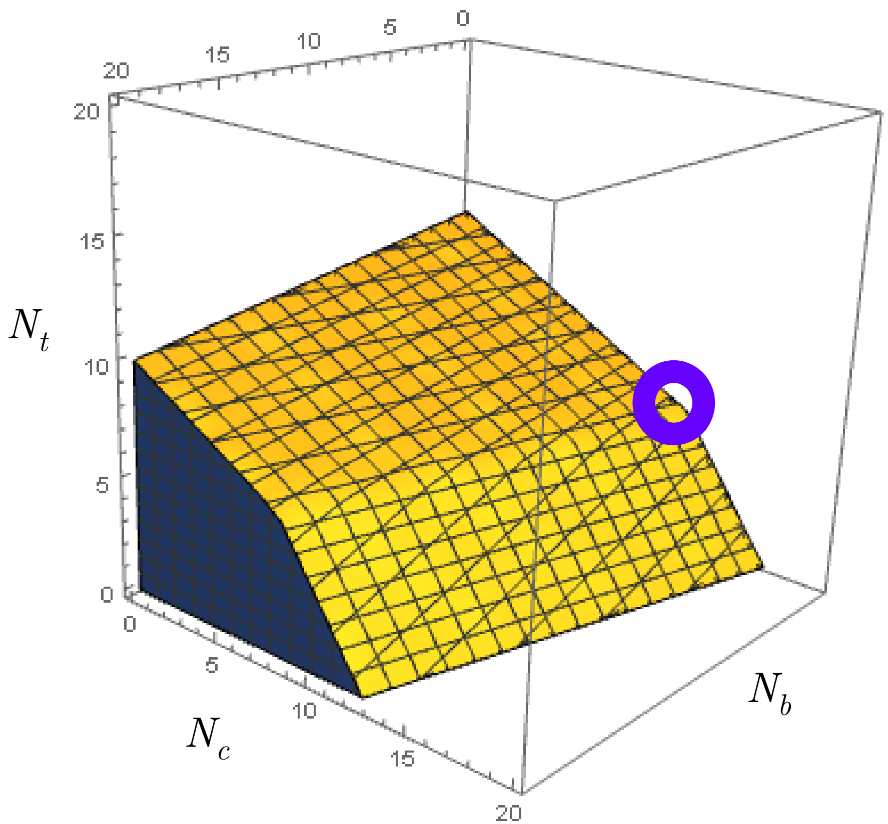


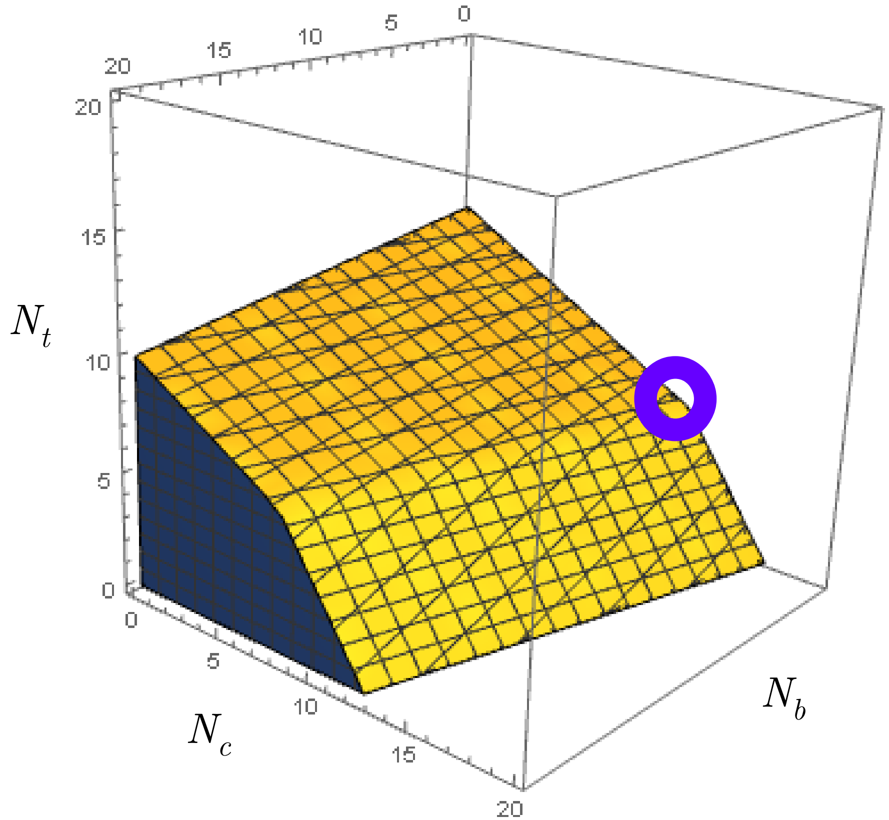

$N_b = 0$

$N_c = 13$

$N_t = 6$

Profit = 9400 €/week

# A tour in linear programming




For three decision variables and two constraints, the optimized solution *necessarily* has at least one vanishing decision variable (or, alternatively, at most two non-vanishing decision variables).

(Three non-vanishing decision variables would correspond to a point singled-out by the intersection of three planes, but we only have two constraints!)

## Take-home lessons from linear programming:

1) The solution lies at one of the vertices of the “feasible region”

2) For $N$ constraints, there are between 1 and $N$ non-vanishing decision variables.

(when $r$ of the constraints are not saturated, then the optimal solution consists of $N - r$ decision variables)

## Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Express the velocity distribution as a superposition of many many streams:

$$f(\vec{v}) = \sum_{i=1}^{n} c_{\vec{v}_i}\ \delta(\vec{v} - \vec{v}_i)$$

Minimization problem. For given DM mass and cross-section:

$$\text{minimize} \quad R^{(\text{PandaX})}(c_{\vec{v}_1}\ldots, c_{\vec{v}_n}) = \sum_{i=1}^{n} c_{\vec{v}_i} R_{\vec{v}_i}^{(\text{PandaX})}$$

$$\text{subject to} \quad \sum_{i=1}^{n} c_{\vec{v}_i} C_{\vec{v}_i}^{(\text{NT})} \leq C_{\max}^{(\text{NT})},$$

$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1\,,$$

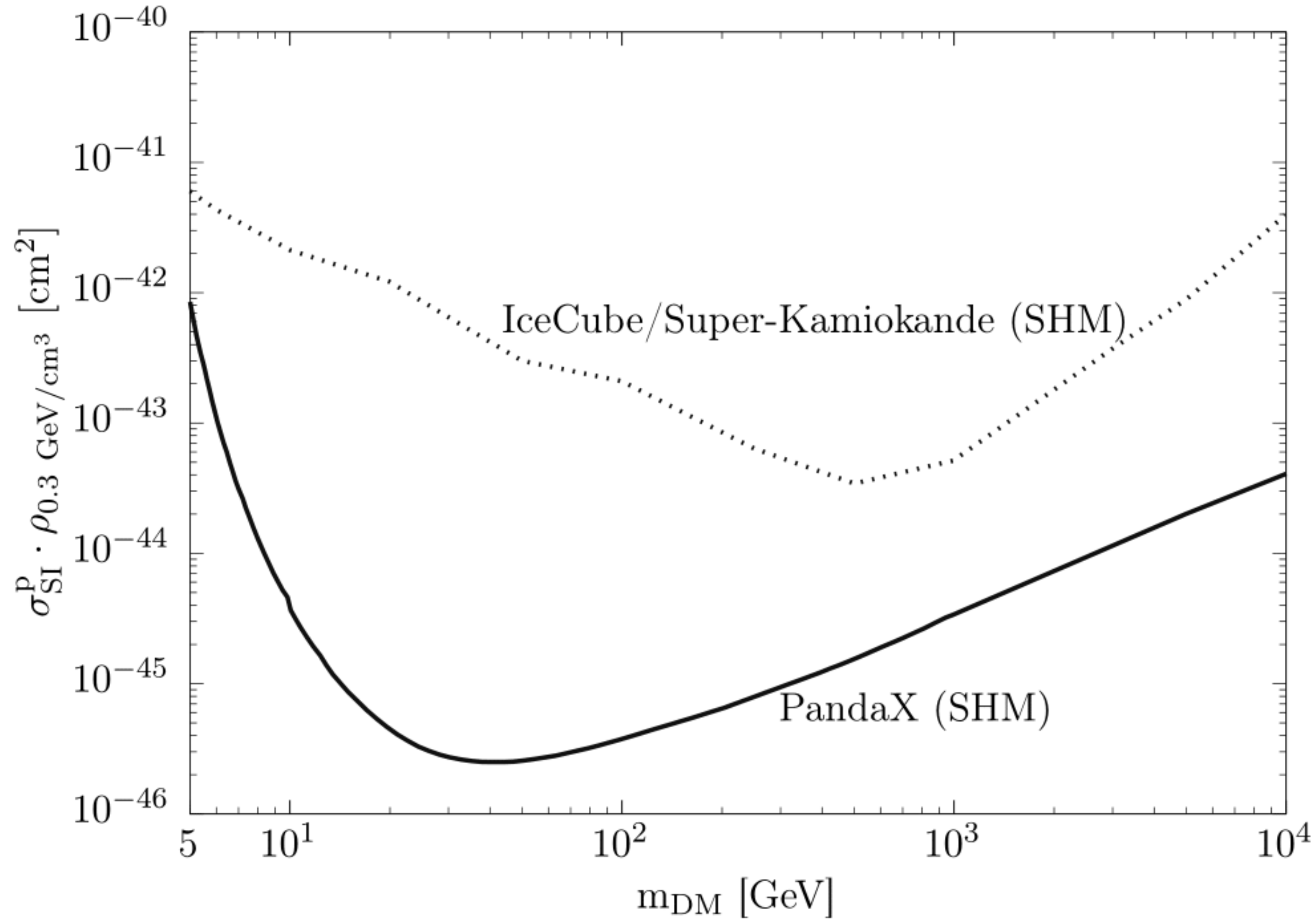
$$\text{and} \quad c_{\vec{v}_i} \geq 0, \quad i = 1\ldots, n\,,$$

1) The solution lies at one of the vertices of the "feasible region"

2) The optimized velocity distribution contains either one or two streams (depending on the number of constraints that are not saturated).

# Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction



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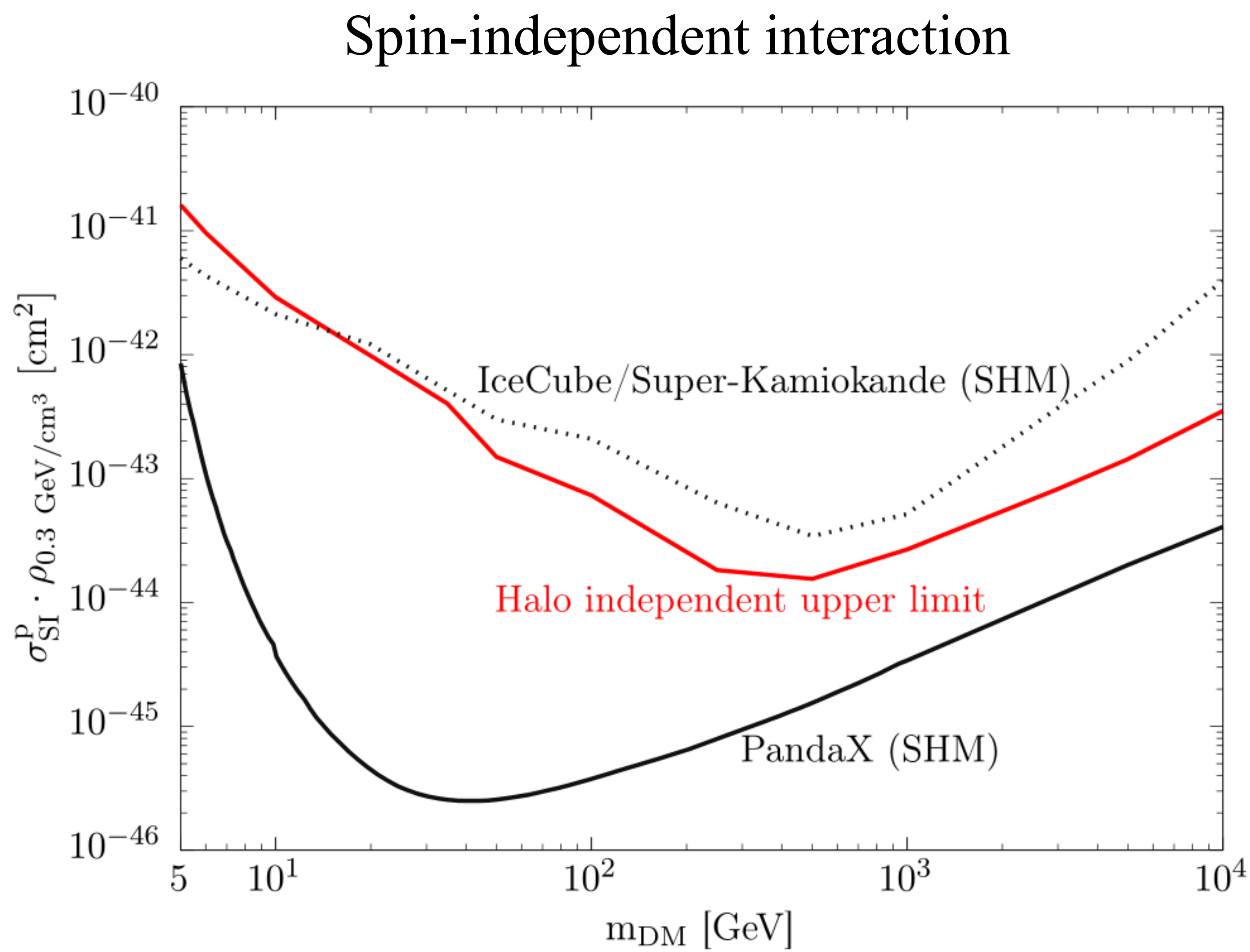

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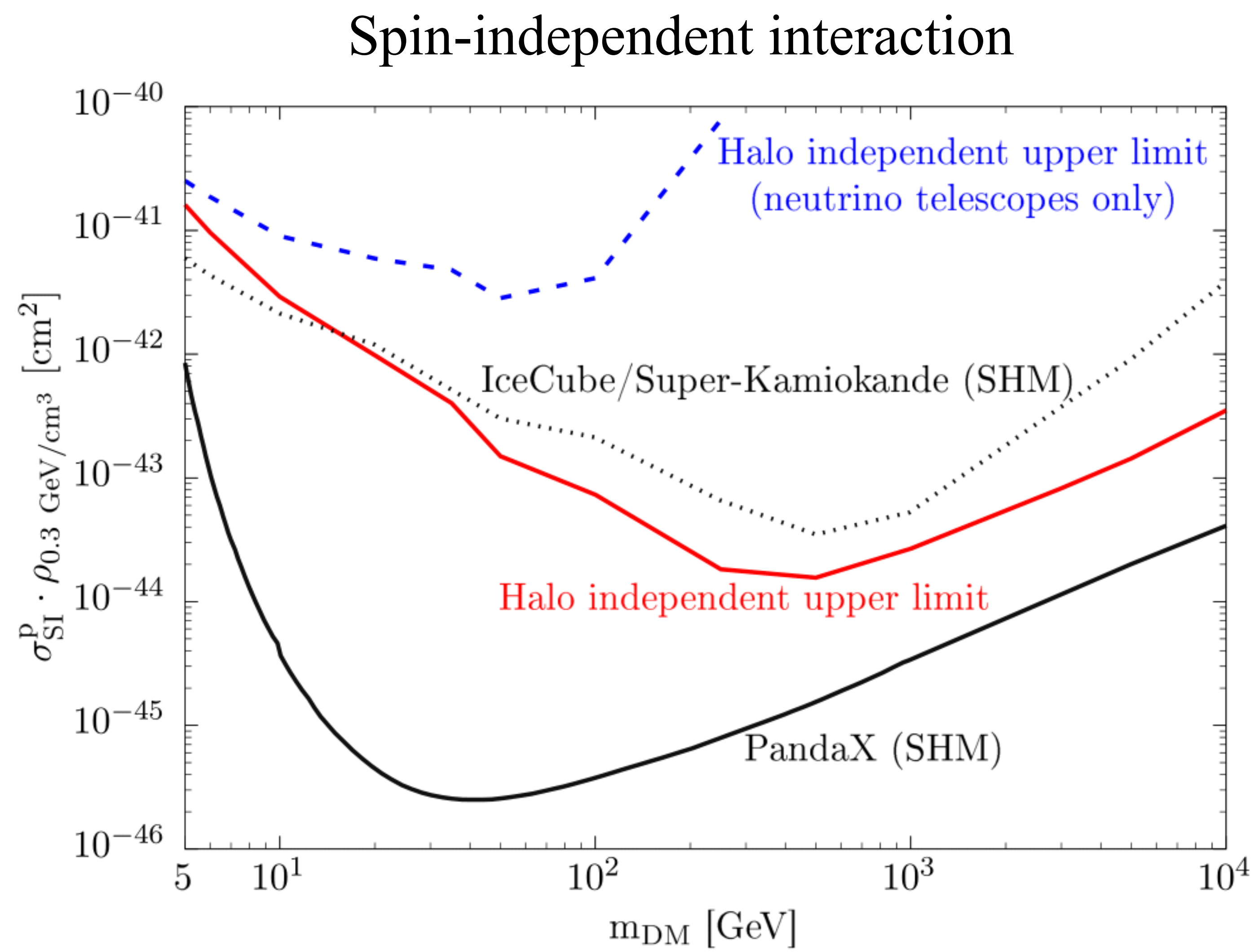

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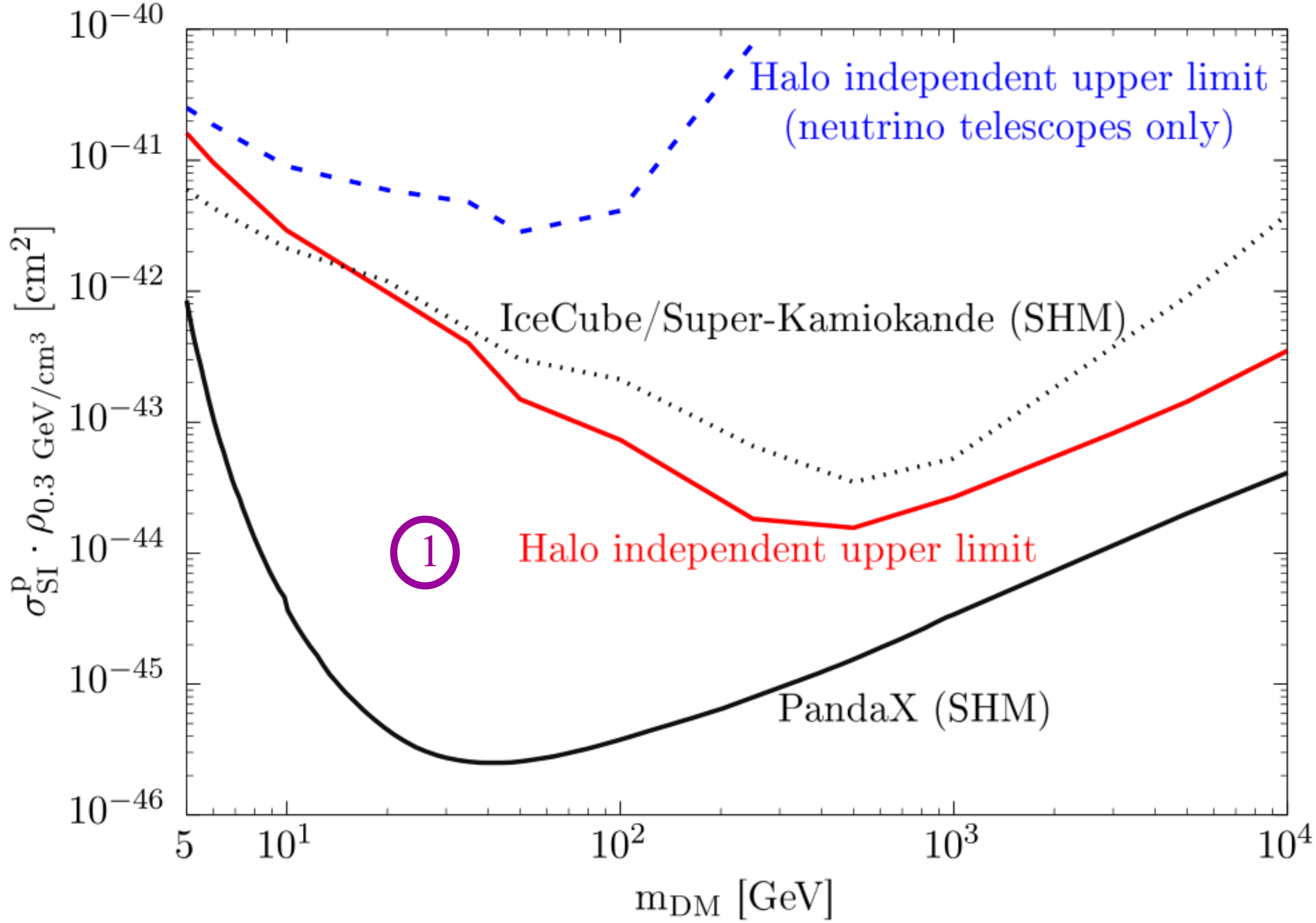
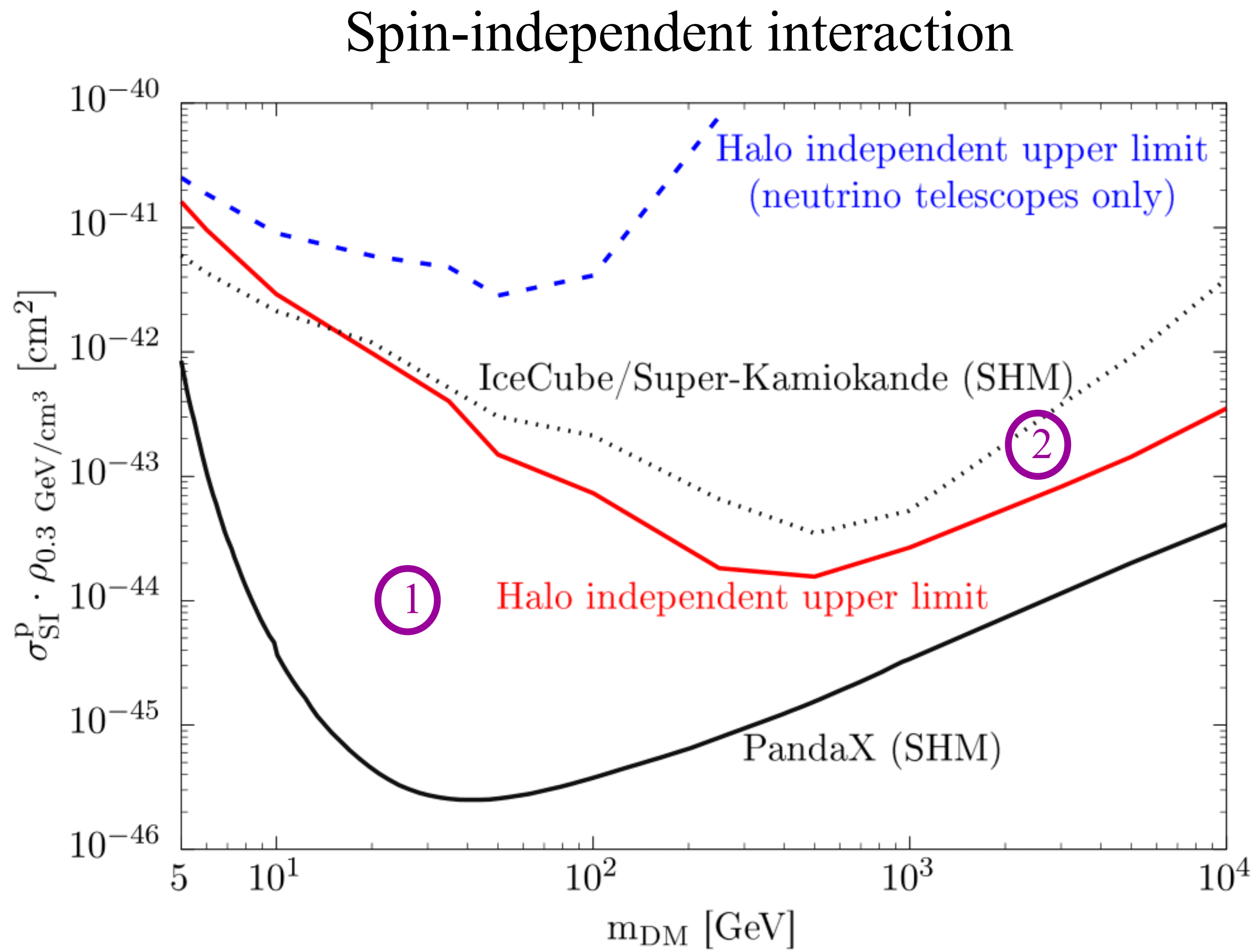



① is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

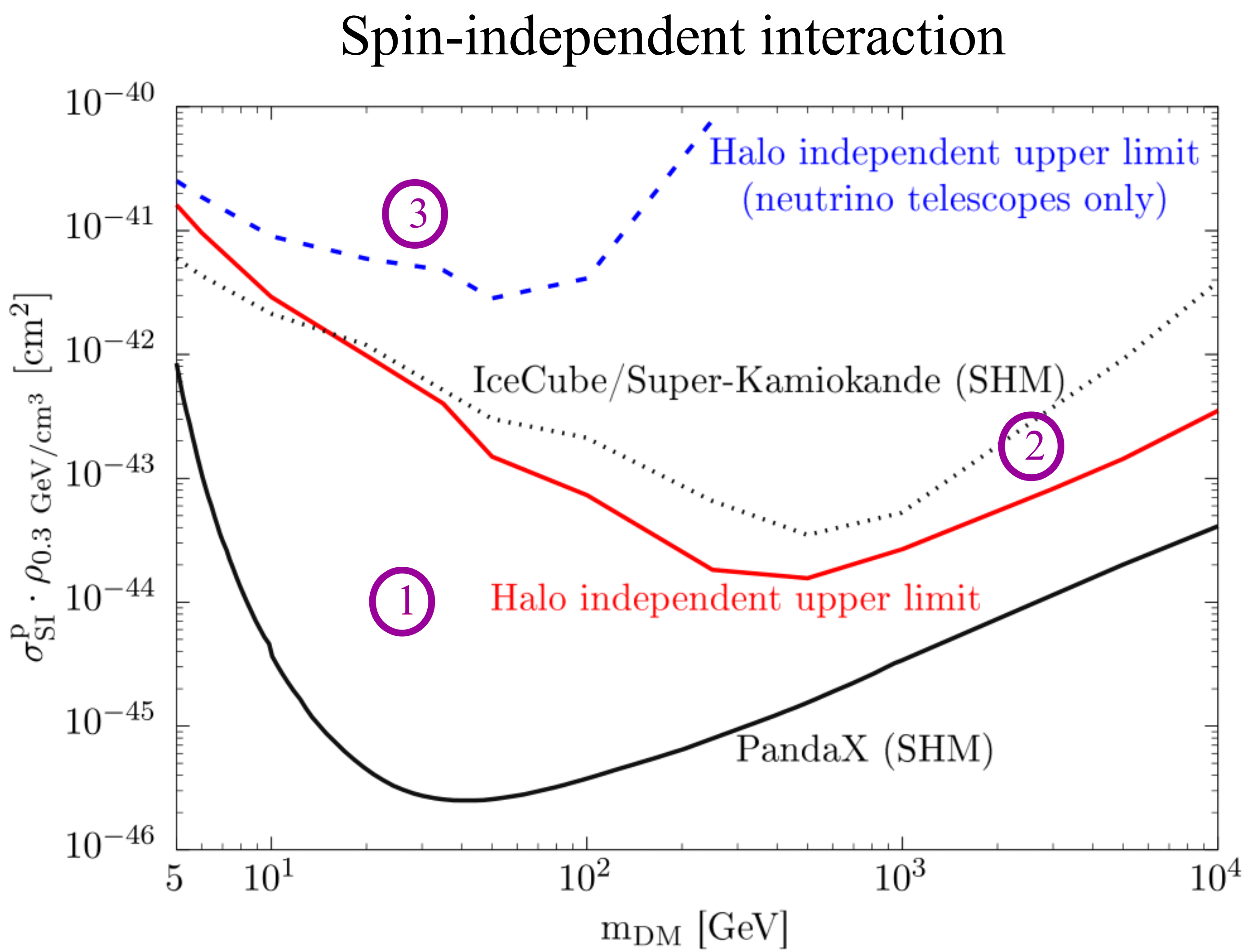
# Upper limit on the scattering cross section from combining PandaX and IceCube/SK.




(1) is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

(2) is ruled out from combining PandaX and neutrino telescopes, for *any* velocity distribution.

# Upper limit on the scattering cross section from combining PandaX and IceCube/SK.



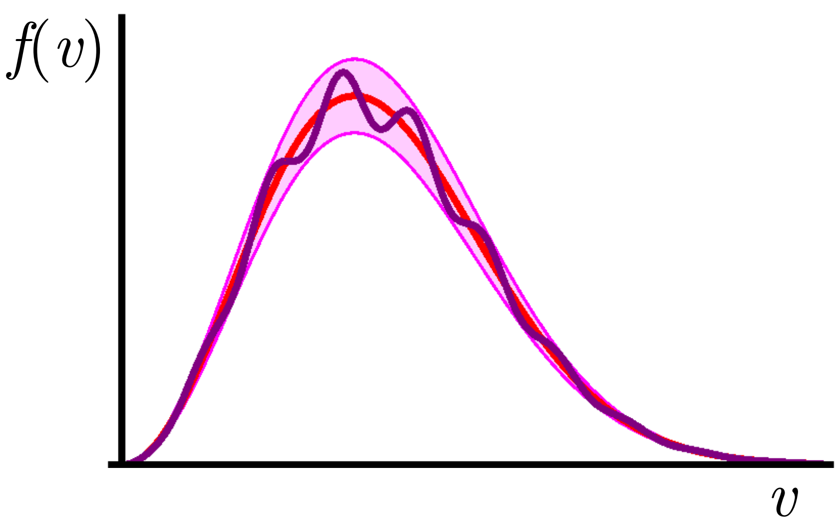

(1) is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

(2) is ruled out from combining PandaX and neutrino telescopes, for *any* velocity distribution.

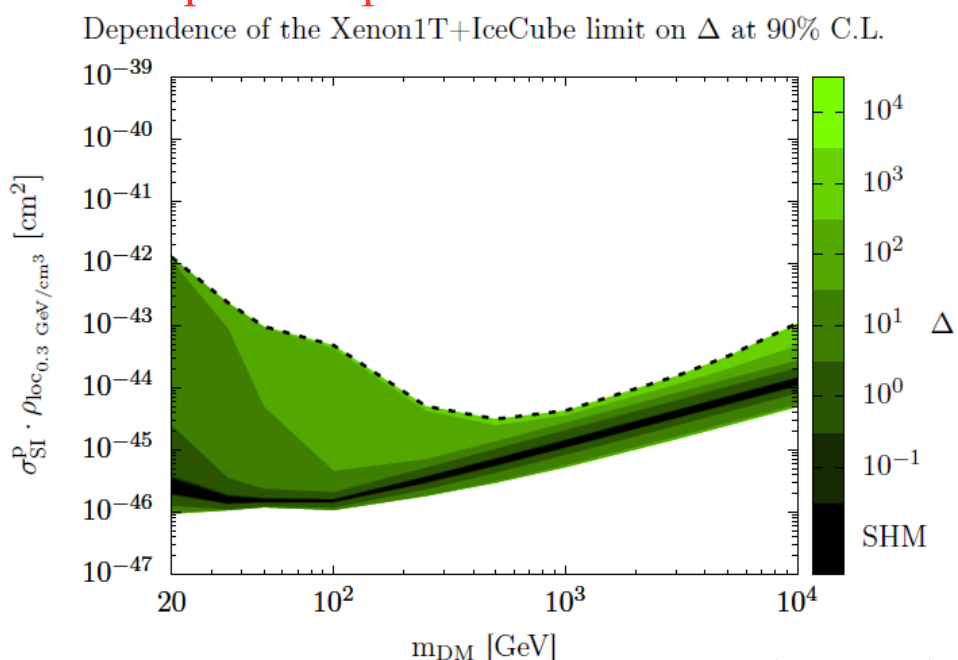
(3) is ruled out by neutrino telescopes only, for *any* velocity distribution.

# Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

It is unlikely that the halo independent upper limit saturates (it is unlikely that the true velocity distribution consists just of two streams).
Add physically plausible assumptions (e.g. MB distribution +"distortions").




Spin-independent interaction

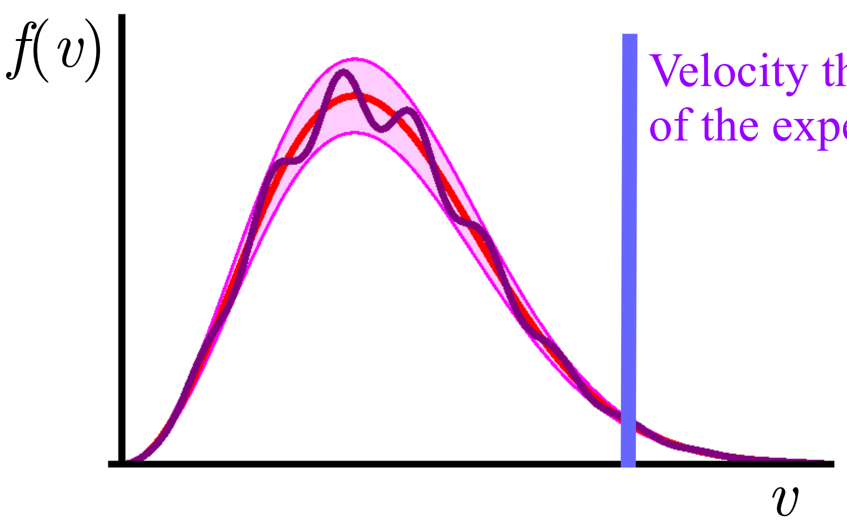



AI, Kavanagh, Rappelt
To appear

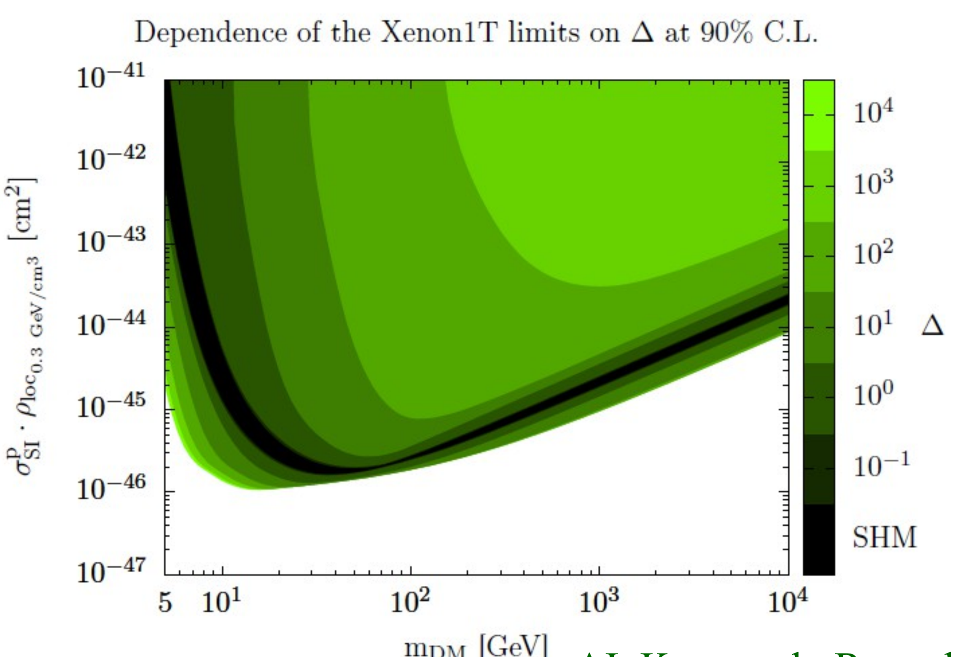
$$\left| \frac{f(\vec{v}) - f_{\rm MB}(\vec{v})}{f_{\rm MB}(\vec{v})} \right| \leq \Delta$$

# Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

The same method can be applied to bracket the astrophysical uncertainties in any experiment.




Spin-independent interaction




AI, Kavanagh, Rappelt
To appear

$$\left|\frac{f(\vec{v}) - f_{\rm MB}(\vec{v})}{f_{\rm MB}(\vec{v})}\right| \leq \Delta$$

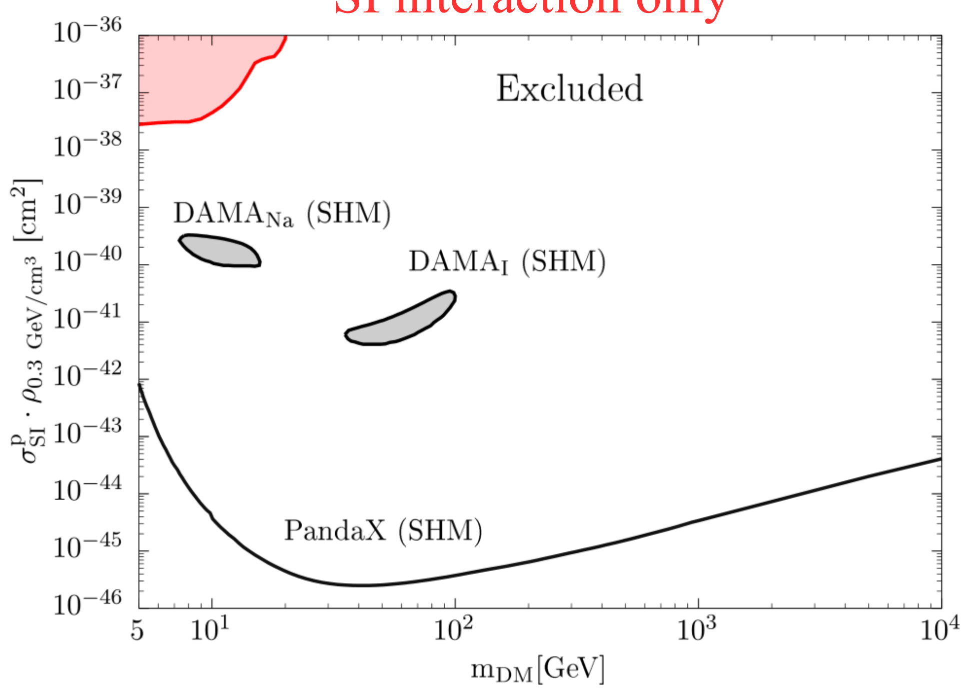
# DAMA confronted to null results in a halo independent way

Strategy: minimize the rate at a given experiment, with the constraints that the modulation signal at DAMA in the bins [2.0,2.5], [2.5,3.0] and [3.0,3.5] keV are as reported by the experiment.

The parameters $\sigma$ and $m_{DM}$ are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ R^{(\mathrm{PandaX})}(\sigma, m_{\mathrm{DM}}) \right\} \Big|_{\mathrm{constraints}} \geq R_{\max}^{(\mathrm{PandaX})}$$

SI interaction only



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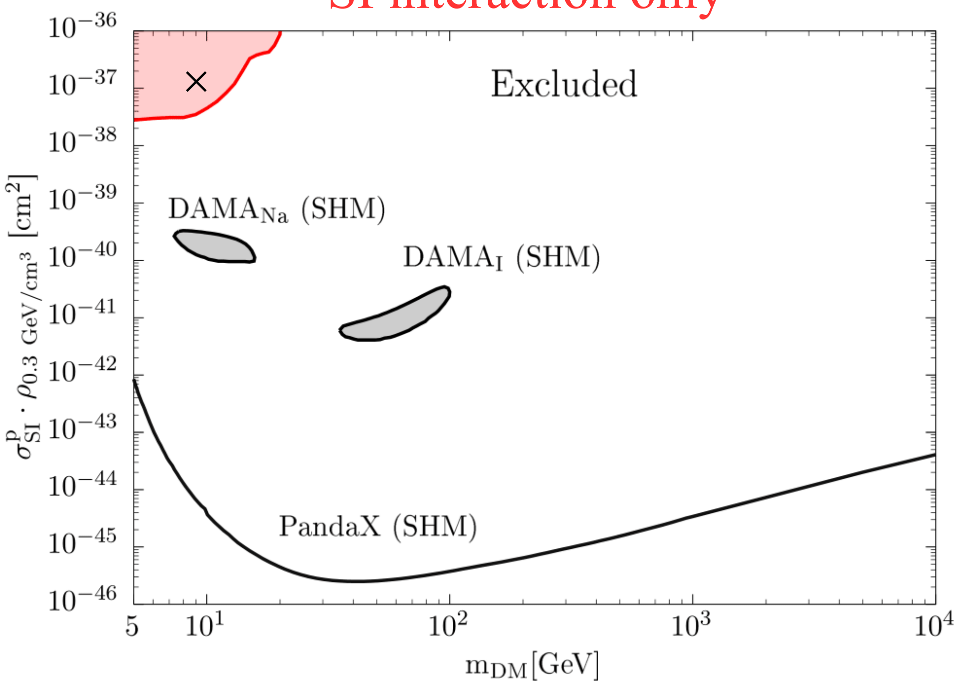


| | stream #1 | stream #2 | stream #3 |
|---|---|---|---|
| $c_{\vec{v}_i}$ | 0.54 | 0.28 | 0.18 |
| $\vec{v}_i$ [km/s] | $(-10, -123, 191)$ | $(100, -167, -161)$ | $(56, 119, -183)$ |
| $\lvert\vec{v}^{\,(\mathrm{PandaX})}_{i,\mathrm{max}}\rvert$ [km/s] | 257.1 | 264.3 | 255.1 |
| $\lvert\vec{v}^{\,(\mathrm{DAMA})}_{i,\mathrm{June}}\rvert$ [km/s] | 256.1 | 245.0 | 195.7 |
| $\lvert\vec{v}^{\,(\mathrm{DAMA})}_{i,\mathrm{Dec}}\rvert$ [km/s] | 198.8 | 263.2 | 255.1 |

Velocity thresholds

$$v^{(\mathrm{PandaX})}_{\mathrm{min}} = 259.6\,\mathrm{km/s}$$

$$v^{(\mathrm{DAMA}[3.0,3.5])}_{\mathrm{min}} = 143.9\,\mathrm{km/s}$$

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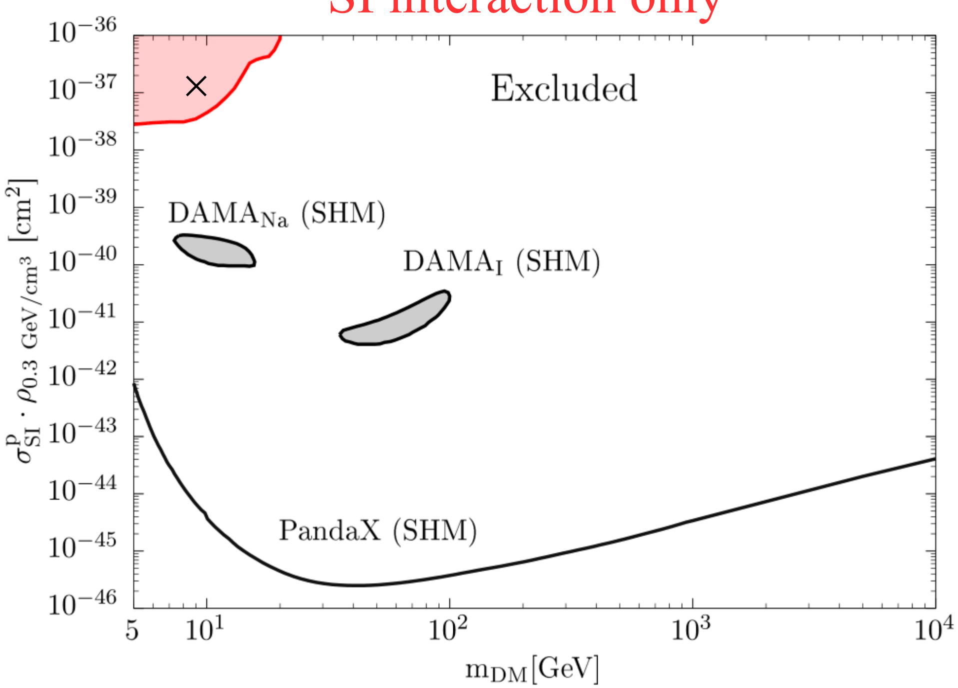
SI interaction only

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0.0036 events

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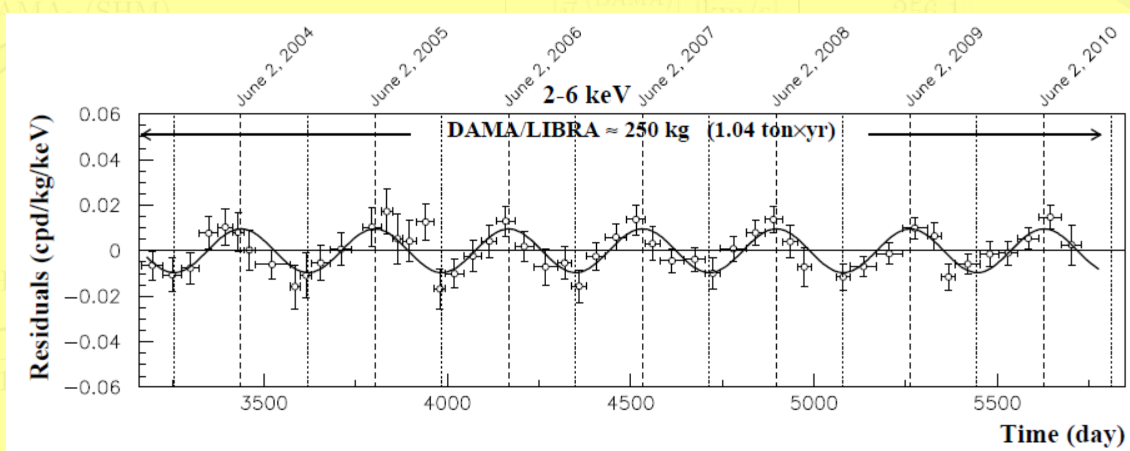
The parameters $\sigma$ and $m_{DM}$ are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ R^{(\mathrm{PandaX})}(\sigma, m_{\mathrm{DM}}) \right\}\Big|_{\mathrm{constraints}} \geq R^{(\mathrm{PandaX})}_{\mathrm{max}}$$

Allowed in this analysis, but probably ruled out:

- Unlikely that the velocity distribution consists of 3 streams.
- A small smearing of the streams (~1%) already spoils the solution
- Only the modulation signals were used, but not the time dependence of the signal



# DAMA confronted to null results in a halo independent way

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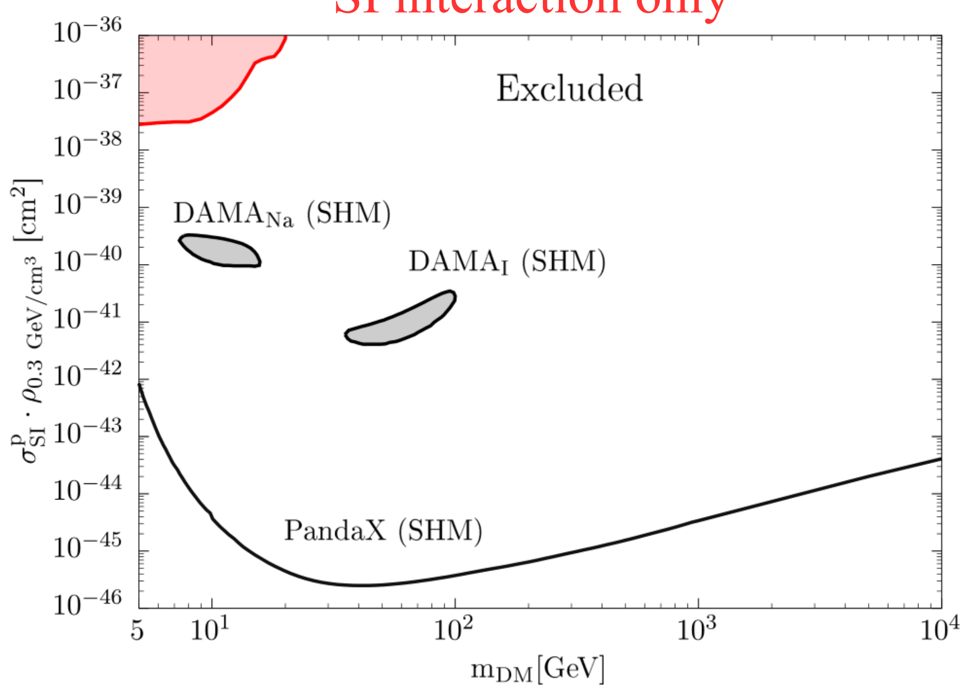
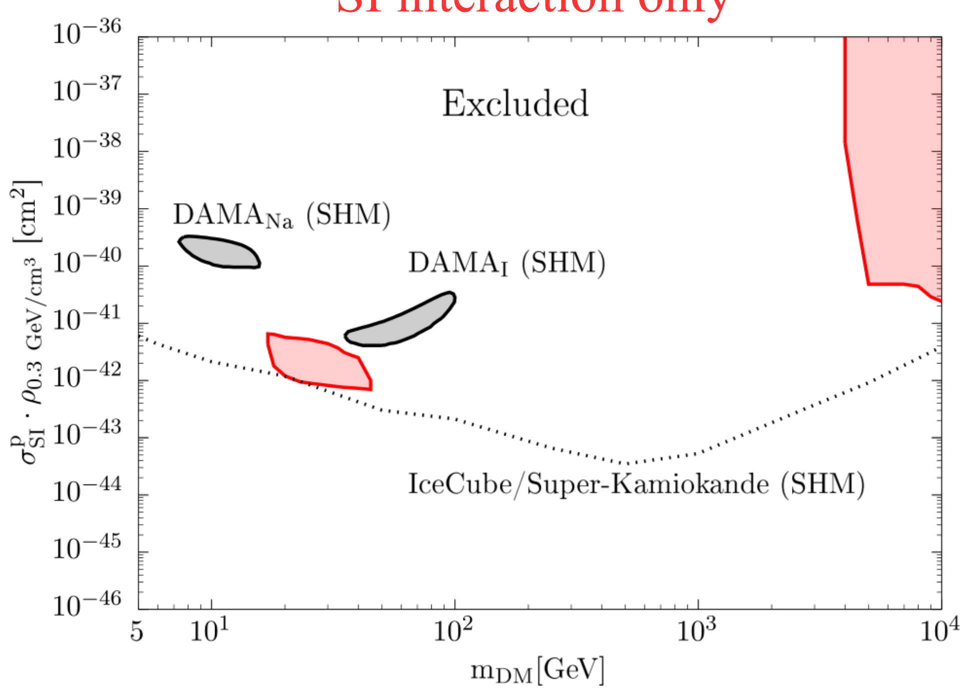
The parameters $\sigma$ and $m_{DM}$ are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ C^{(NT)}(\sigma, m_{DM}) \right\} \Big|_{\text{constraints}} \geq C^{(NT)}_{\max}$$

SI interaction only




SI interaction only



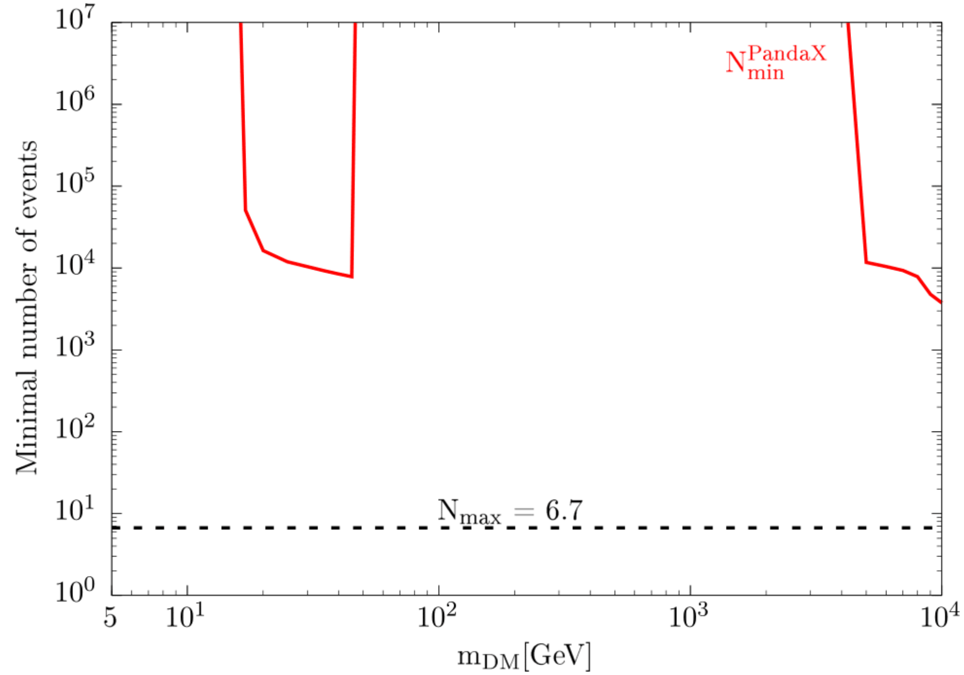
# DAMA confronted to null results in a halo independent way

Strategy 2: minimize the rate at a given direct detection experiment, with the constraints that the modulation signal at DAMA in the bins [2.0,2.5], [2.5,3.0] and [3.0,3.5] keV are as reported by the experiment, and the capture rate at IceCube is below the current upper limit.

The parameters $\sigma$ and $m_{DM}$ are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ R^{(\text{PandaX})}(\sigma, m_{\text{DM}}) \right\} \Big|_{\text{constraints}} \geq R^{(\text{PandaX})}_{\max}$$

SI interaction only




AI, Rappelt '17

# Halo independent prospects for future experiments

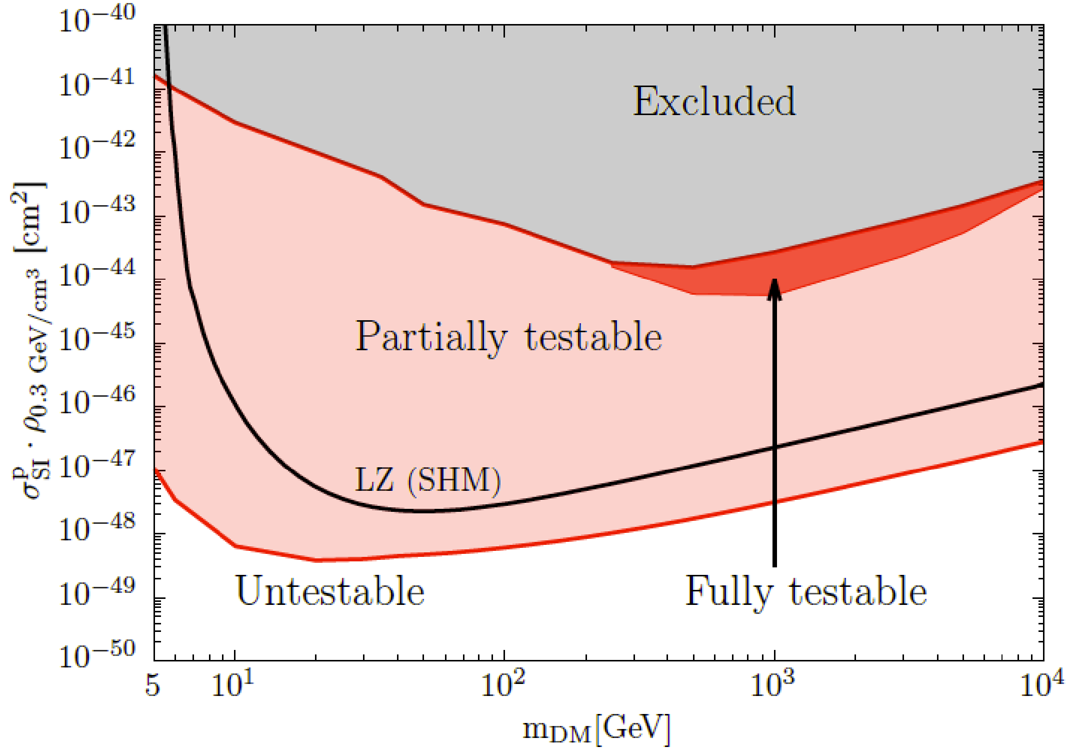
The parameters $\sigma$ and $m_{DM}$ are fully testable in a halo independent manner if :

$$\min_{f(\vec{v})} \left\{ R^{(LZ)}(\sigma, m_{DM}) \right\} \Big|_{\text{constraints}} > 1$$

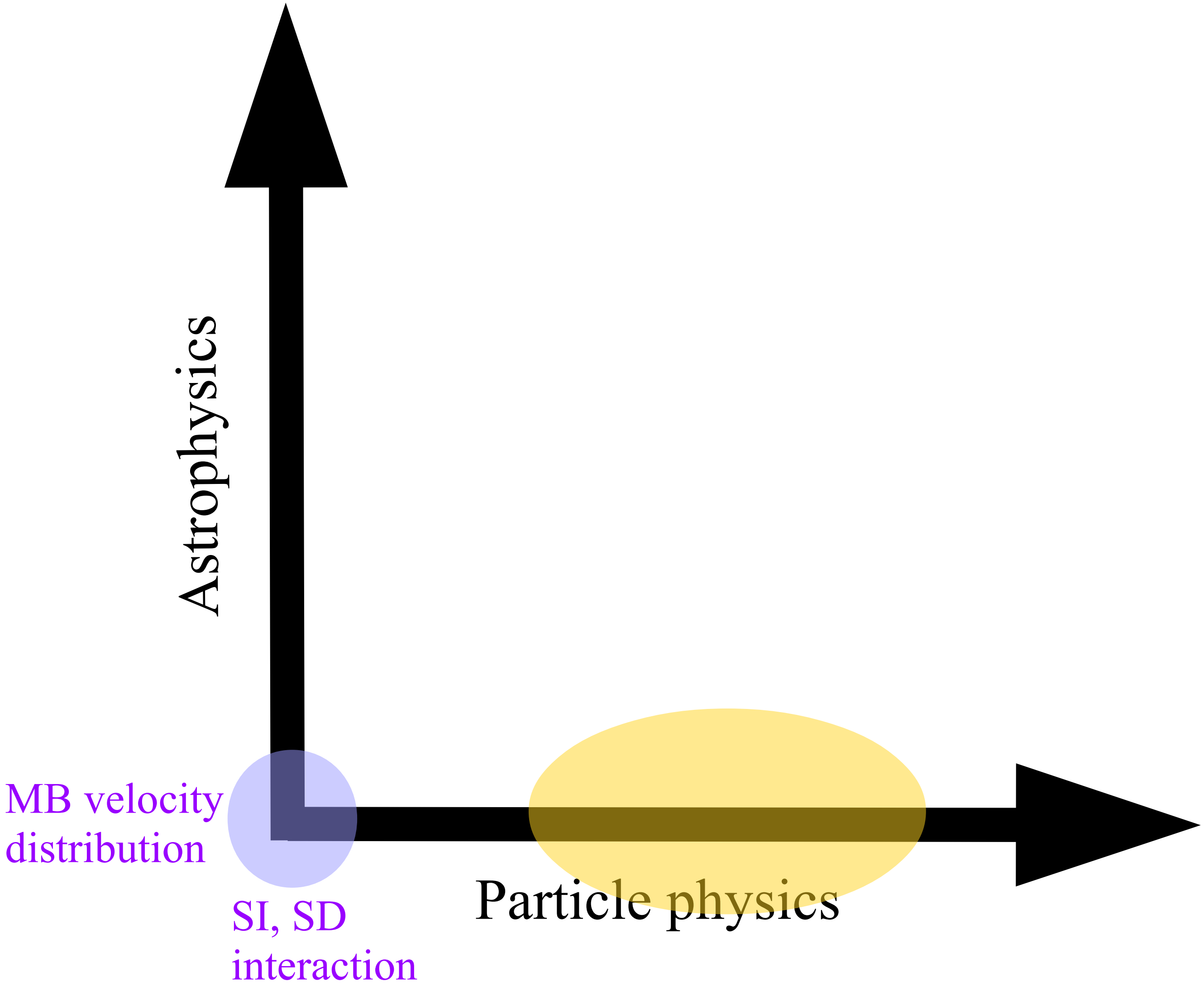
The parameters $\sigma$ and $m_{DM}$ are untestable in a halo independent manner if :

$$\max_{f(\vec{v})} \left\{ R^{(LZ)}(\sigma, m_{DM}) \right\} \Big|_{\text{constraints}} < 1$$

LZ reach to the SI cross-section from null results at neutrino telescopes



# DM theory parameter space



# The effective theory of dark matter-nucleon interactions

In the non-relativistic limit, the scattering amplitude is restricted by:

- momentum conservation
- Galilean invariance

Most general form of the invariant amplitude:

$$\mathcal{M} = \mathcal{M}(\vec{q}, \vec{v}, \vec{S}_\chi, \vec{S}_N)$$

Momentum transfer

Relative incoming velocity

Dark matter spin

Nuclear spin

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$$\mathcal{M} = \mathcal{M}(\vec{q}, \vec{v}^{\perp}, \vec{S}_{\chi}, \vec{S}_N)$$

Momentum transfer

"Transverse velocity"

Dark matter spin

Nuclear spin

$$\vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\mu_N}$$

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

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$$\mathcal{M} = \mathcal{M}(\vec{q}, \vec{v}^{\perp}, \vec{S}_\chi, \vec{S}_N)$$

Momentum transfer

"Transverse velocity"

Dark matter spin

Nuclear spin

The Hamiltonian of the system must be a combination of operators that depend only on $i\vec{q},\ \vec{v}^{\perp},\ \vec{S}_\chi,\ \vec{S}_N,\ \mathbb{1}$

# The effective theory of dark matter-nucleon interactions

14 possible operators, up to first order in the velocity and momentum transfer:

Fitzpatrick et al'12

$$\mathcal{O}_1 = \mathbb{1}_{\chi N}$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$

$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

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

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

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

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Hamiltonian: $\mathcal{H}_{\rm N}(r) = \sum_k c_k\, \mathcal{O}_k(\mathbf{r})$

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Hamiltonian: $\mathcal{H}_{\rm N}(r) = \sum_{\tau=0,1} \sum_k c_k^\tau \, \mathcal{O}_k(\mathbf{r}) \, t^\tau$

$$c_k^p = (c_k^0 + c_k^1)/2$$

$$c_k^n = (c_k^0 - c_k^1)/2$$

$$t^0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$t^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

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$\mathcal{O}_1 = 1_{\chi N}$ SI interaction

$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$

$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$ SD interaction

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$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$

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

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

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

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

Hamiltonian: $\mathcal{H}_{\mathrm{N}}(r) = \sum_{\tau=0,1} \sum_k c_k^\tau \, \mathcal{O}_k(\mathbf{r}) \, t^\tau$

$c_k^p = (c_k^0 + c_k^1)/2$

$c_k^n = (c_k^0 - c_k^1)/2$

$t^0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

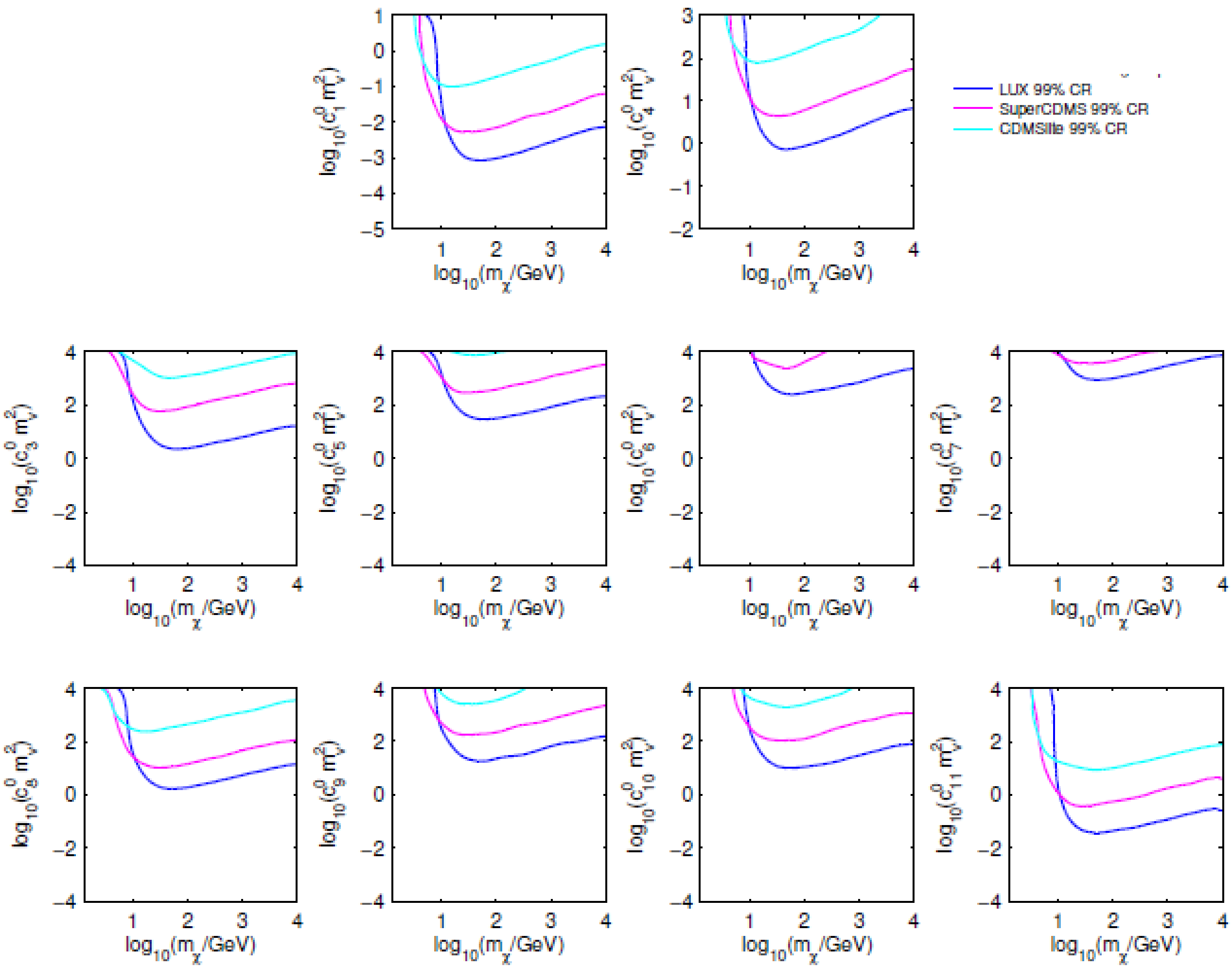
$t^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

# The effective theory of dark matter-nucleon interactions

Some applications:

1) Model independent analysis of null search experiments (in the same spirit as for the “traditional” SI and SD interactions

Fitzpatrick et al'12
Catena, Gondolo'15
..



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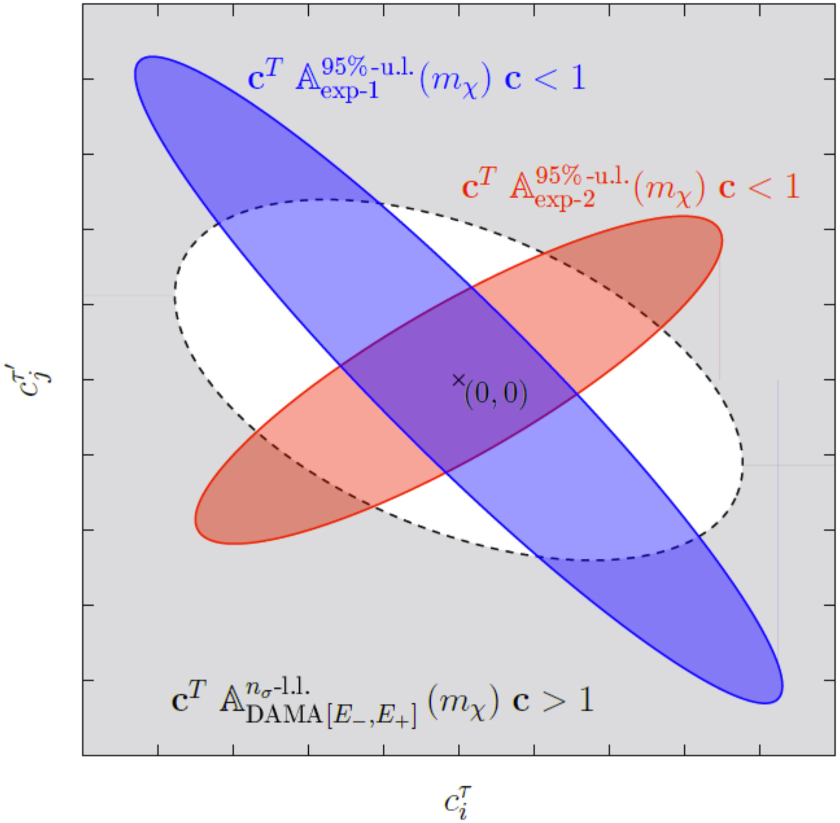
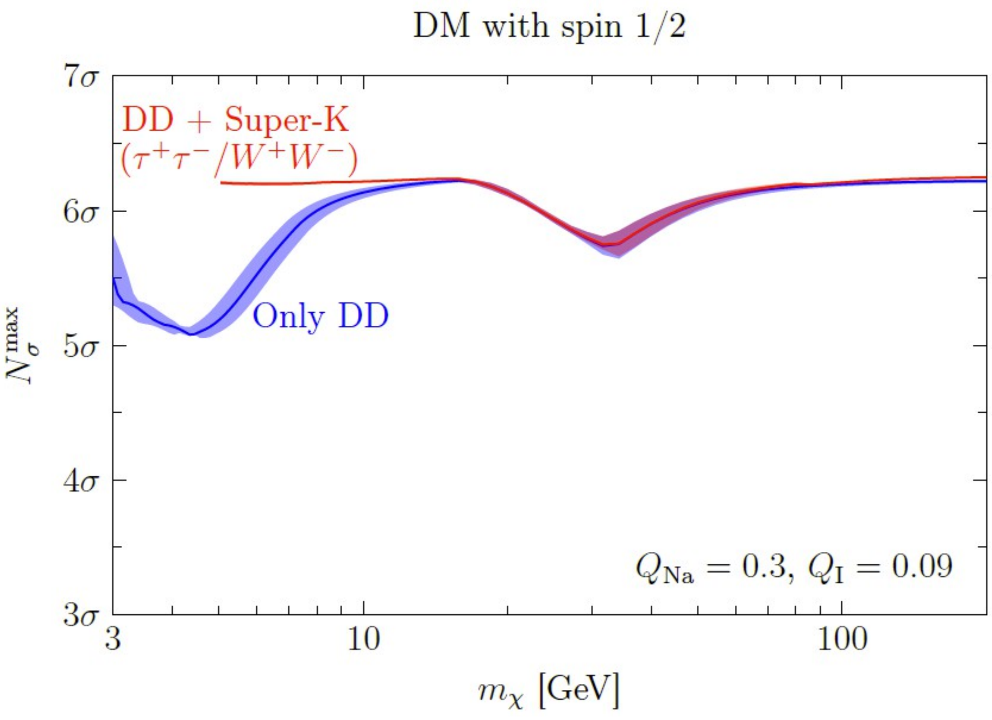



event rate $\propto\ \mathbf{c}^T\mathbf{X}(m_\chi)\ \mathbf{c}$




Catena, AI, Wild '16

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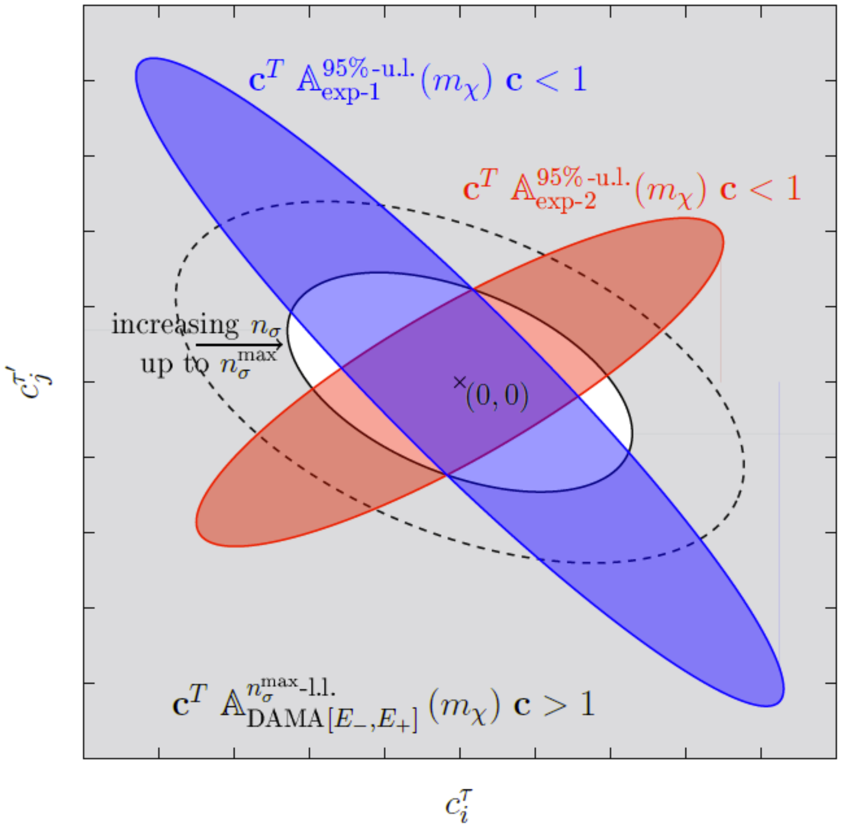


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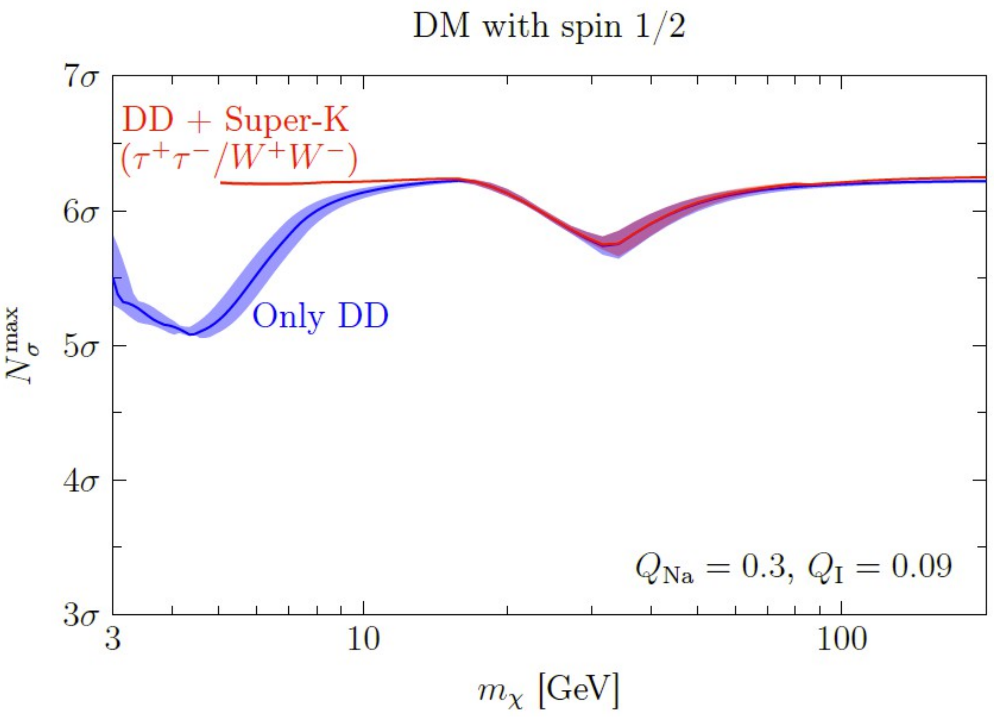
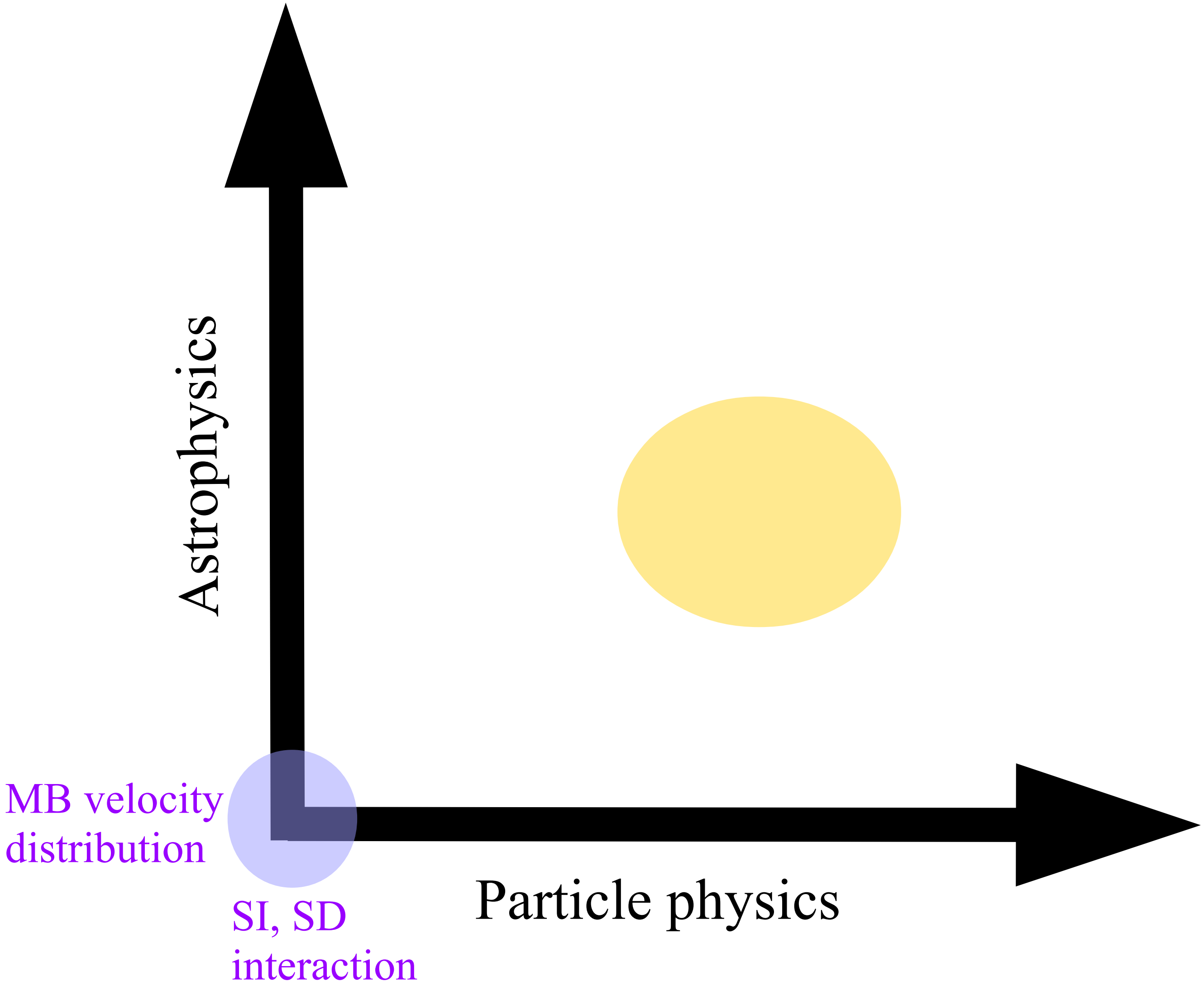



Catena, AI, Wild '16

# DM theory parameter space



# CDMS-Si confronted to null results in a halo independent way

The silicon detectors of the CDMS II experiments observed three DM candidate events, with relatively little exposure (23.4 kg day).

Is the DM interpretation ruled out, for all models and all velocity distributions?

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$$\text{subject to} \quad N_{f(\mathbf{v})}^{(\rm XENON1T)}(\mathbf{c}) \leq N_{\rm u.l.}^{(\rm XENON1T)} ,$$

$$\text{and} \quad N_{f(\mathbf{v})}^{(\rm PICO)}(\mathbf{c}) \leq N_{\rm u.l.}^{(\rm PICO)} ,$$

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Step 2: Sample over velocity distributions and determine the maximal number of events

Analytically, $f_{\alpha,v_1,v_2}(v) = \alpha\,\delta(v - v_1) + (1-\alpha)\delta(v - v_2)$

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Step 1: Calculate the maximum number of events for a fixed-velocity distribution.

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Step 3: If the maximal number of events is < 3, then the DM interpretation is ruled-out in a halo- and particle physics independent way.

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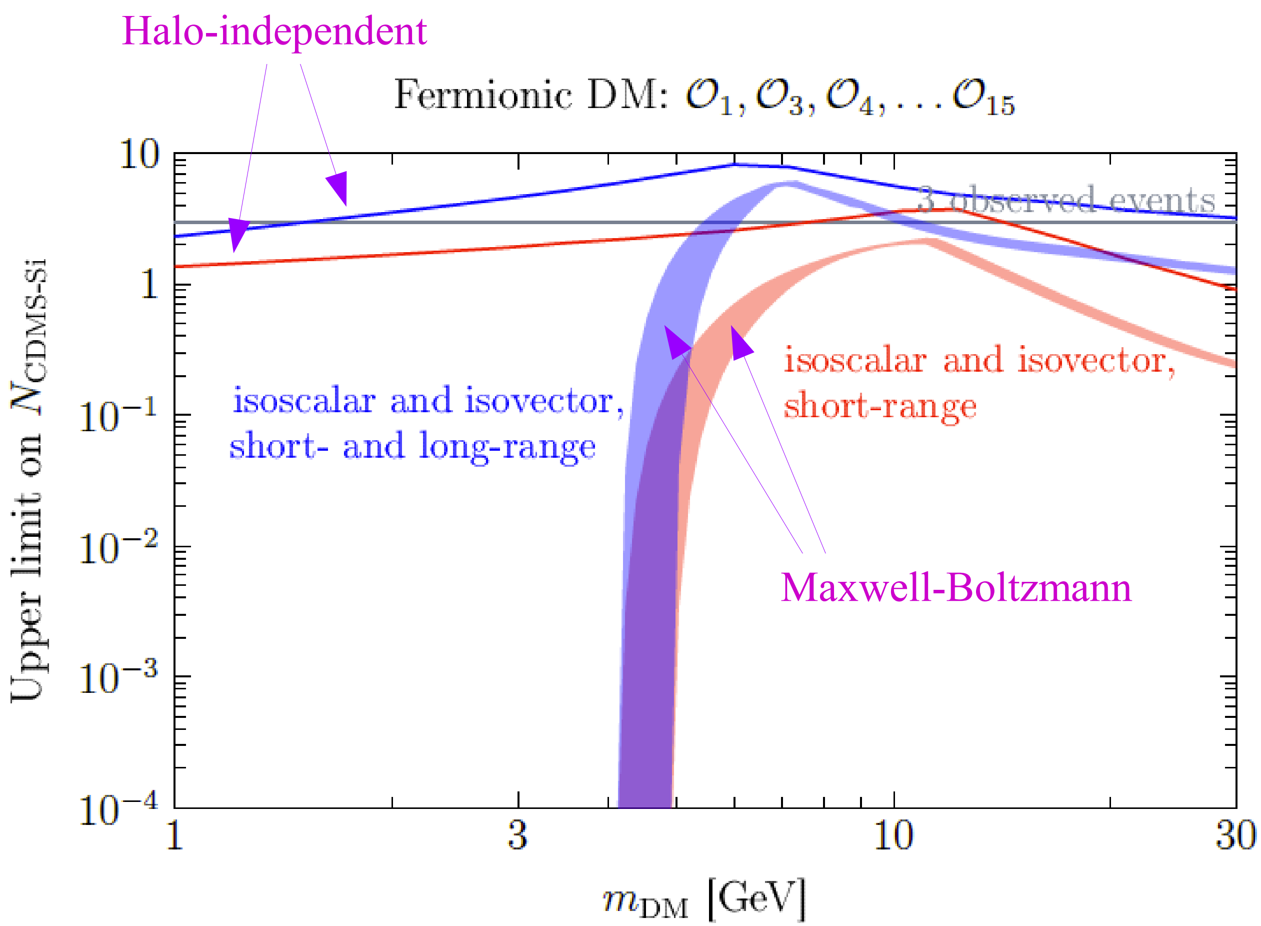


Catena, AI, Rappelt, Wild
arXiv:1801.08466

# Conclusions

- The interpretation of any experiment probing the dark matter distribution inside the Solar System is subject to our ignorance of the local dark matter density and velocity distribution, as well as of the underlying particle physics model.

- We have developed a method to calculate the minimum/maximum number of signal events in an experiment probing the dark matter distribution inside the Solar System, in view of a number of constraints from direct detection experiments and/or neutrino telescopes.

- Some applications are:

  i) to derive a halo-independent upper limit on the cross section from a set of null results.
  ii) to confront in a halo-independent way a detection claim to a set of null results.
  iii) to assess, in a halo-independent manner, the prospects for detection in a future experiment given a set of current null results.

- The method could be extended to include other dark matter interactions, or to account for more realistic velocity configurations.