Addressing theoretical uncertainties in direct dark matter searches

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In collaboration with Andreas Rappelt, arXiv:1703.09168

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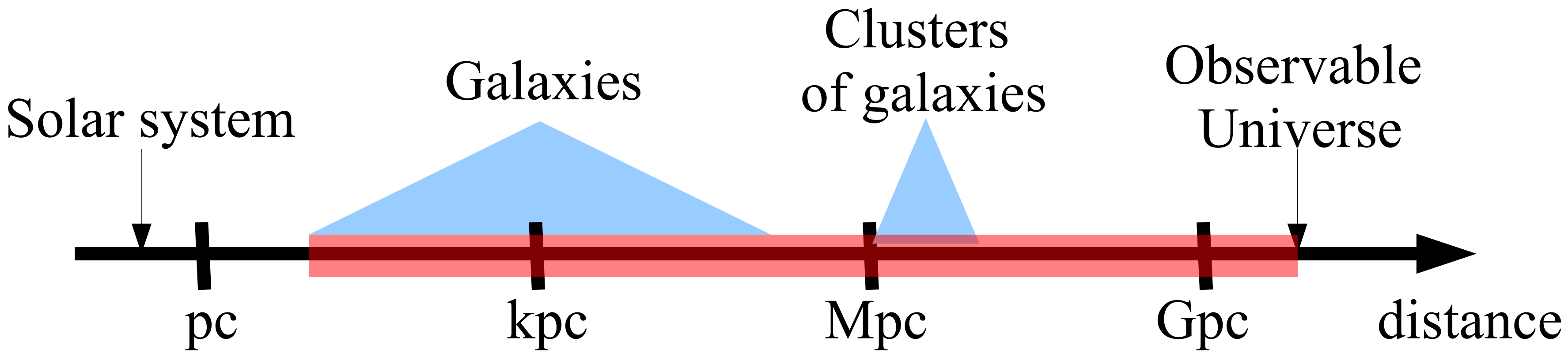
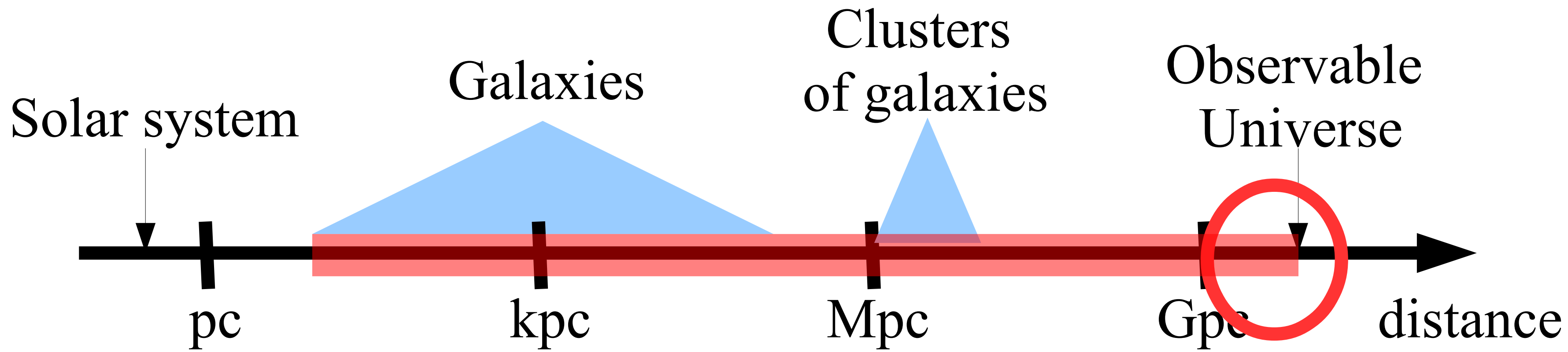
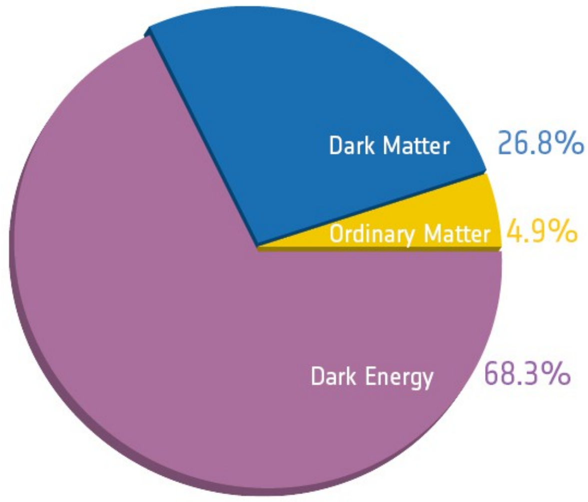
Tsukuba
Febtruary, 2018

There is evidence for dark matter in a wide range of distance scales



There is evidence for dark matter in a wide range of distance scales





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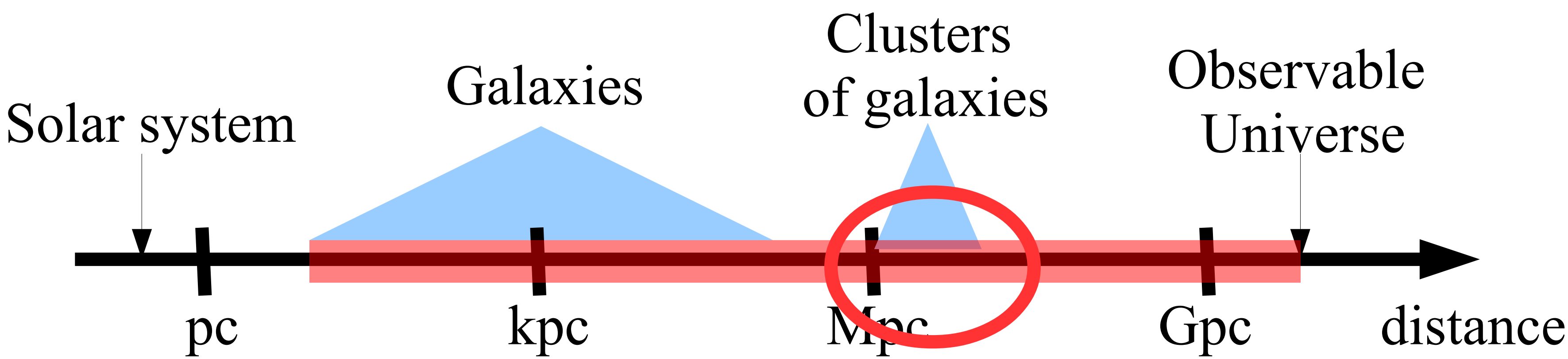

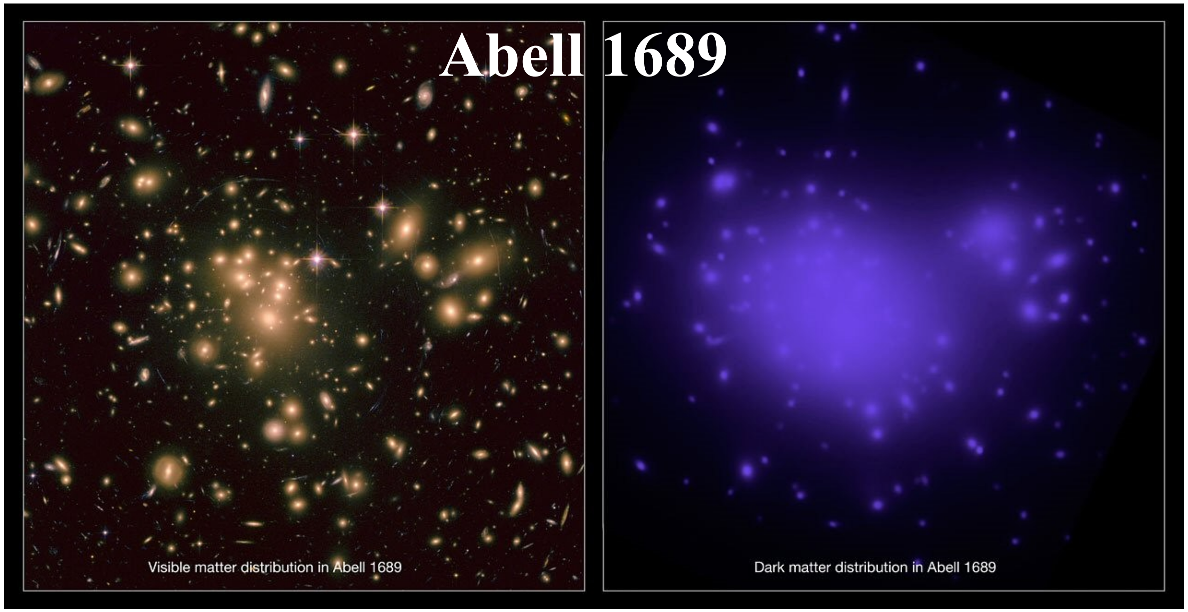

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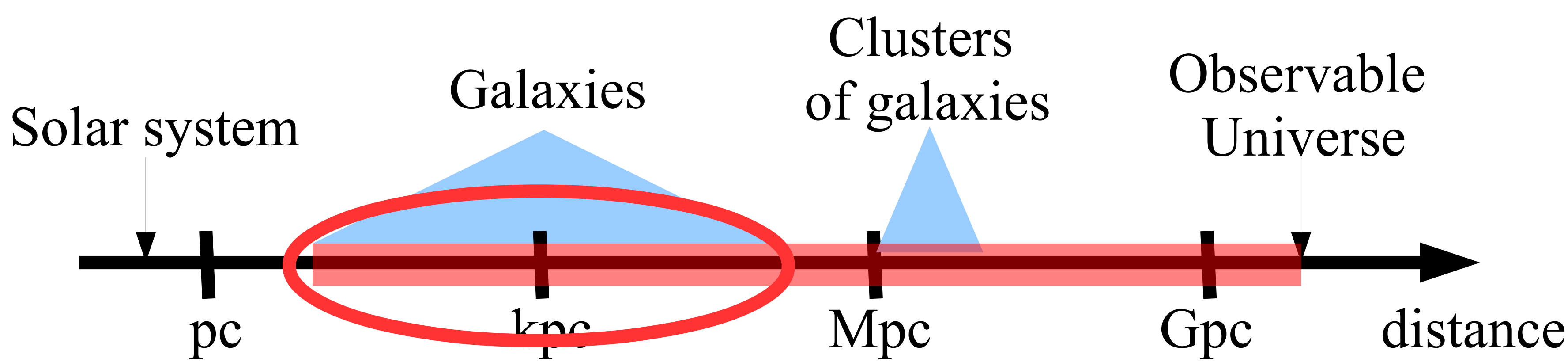

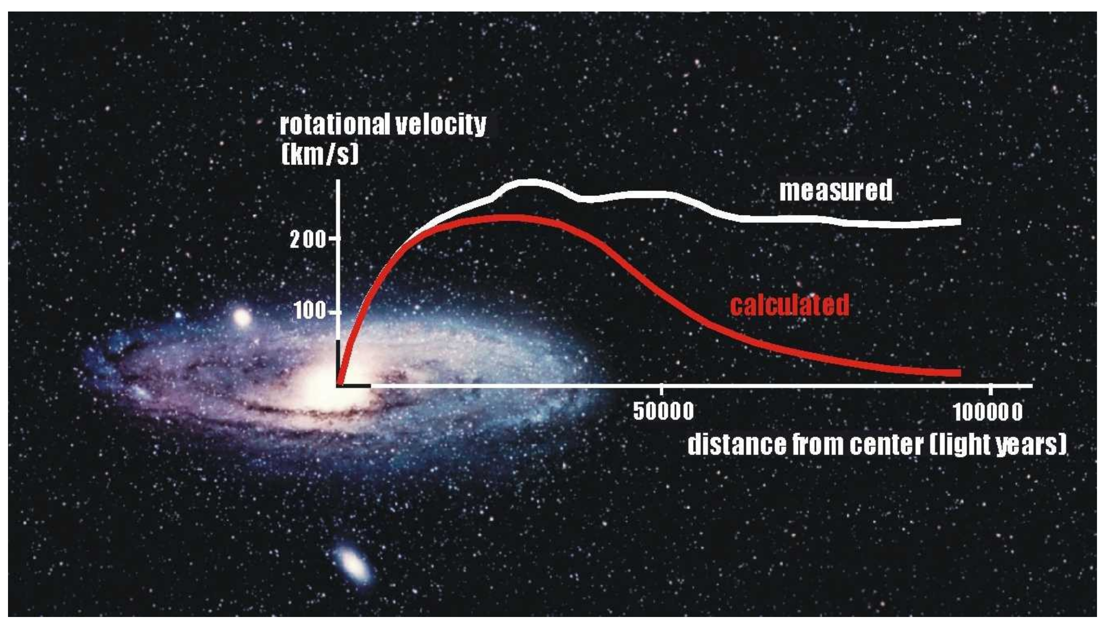

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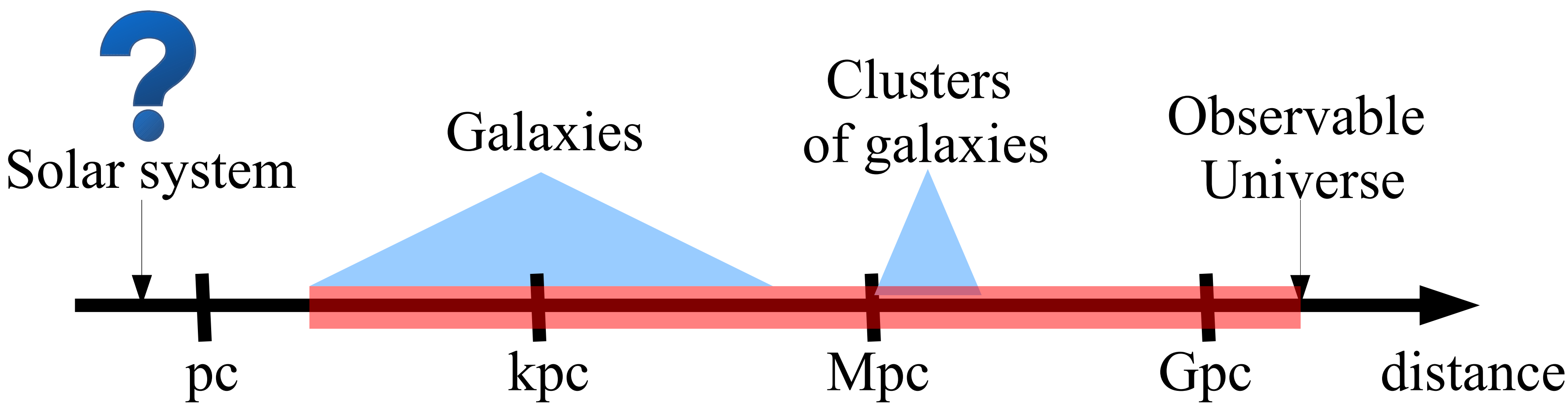

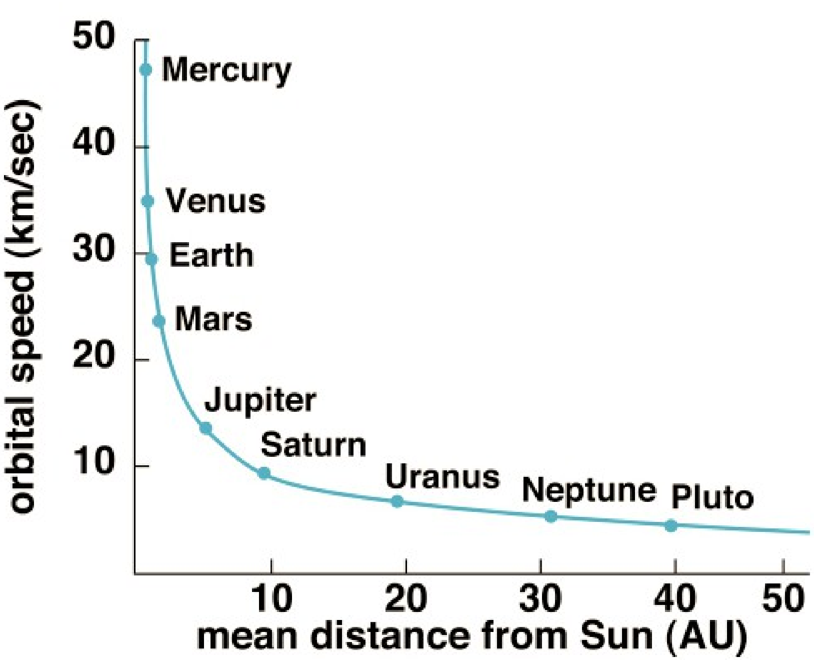

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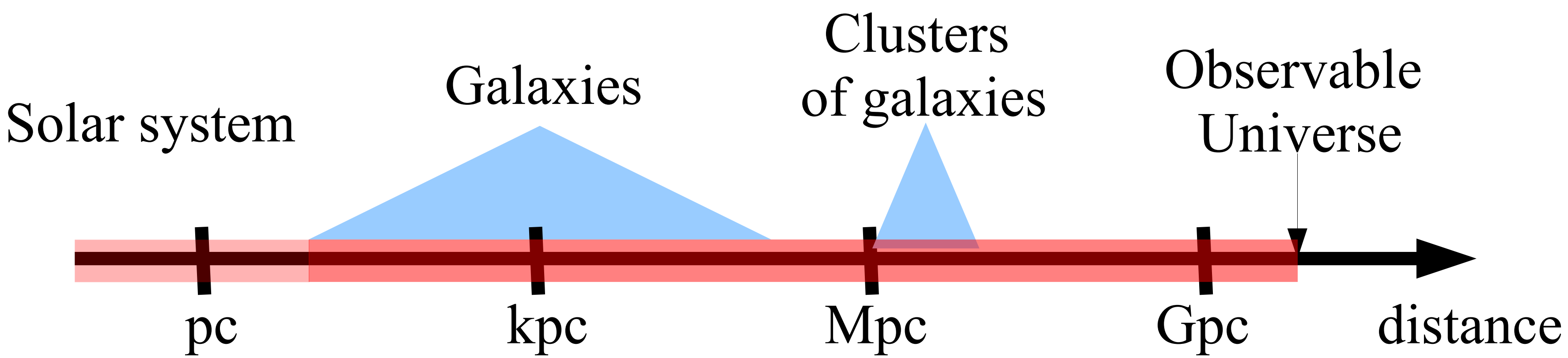


Assumption,
but well motivated

Three different methods

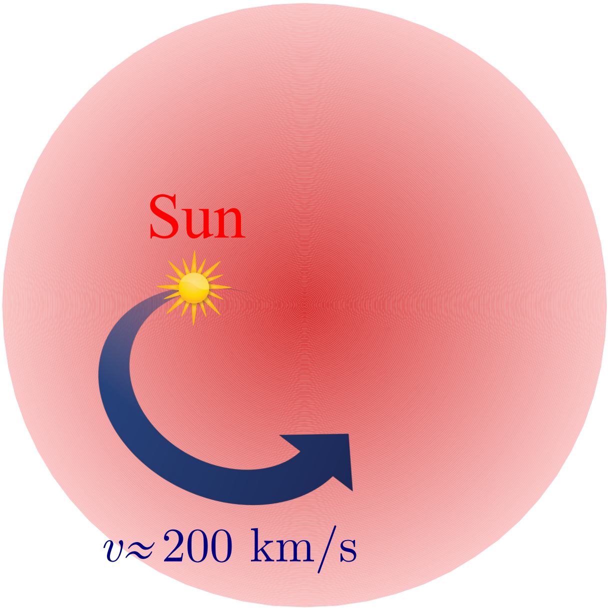
have been proposed

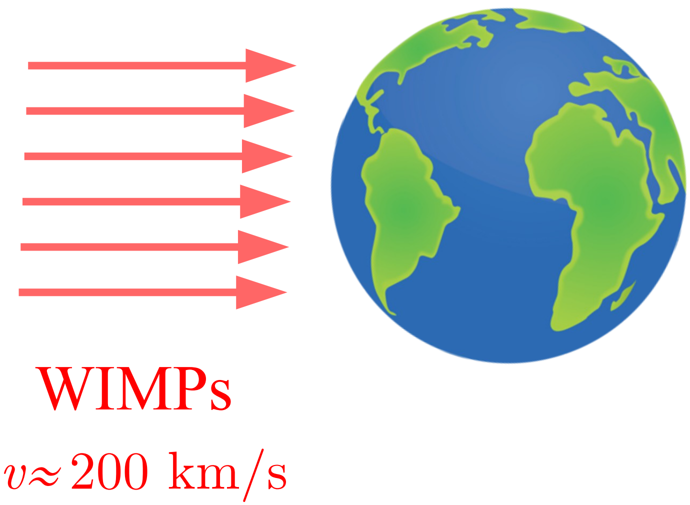
to probe WIMP dark matter

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.

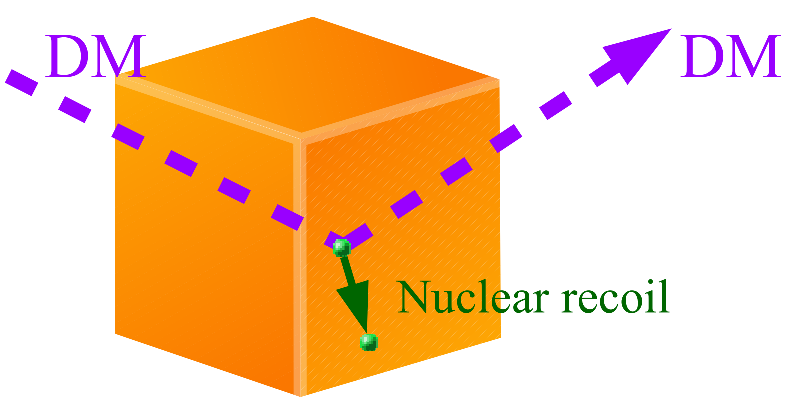




Direct dark matter searches

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.

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)

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)

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PRL 119, 181301 (2017) PHYSICAL REVIEW LETTERS week ending 3 NOVEMBER 2017

First Dark Matter Search Results from the XENON1T Experiment

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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. ski,[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] [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. [1] C. Grignon,[5] C. Hasterok,[11] E. Hogenbirk,[2] J. Howlett,[1]
R. Itay,[12] B. Kaminsky,[13,†] S. Kazama,[8] Landsman,[12] R. F. Lang,[14] D. Lellouch,[12] L. Levinson,[12]
Q. Lin,[1] S. Lindemann,[11,13] M. L Lopes,[6,‡] A. Manfredini,[12] I. Mariş,[7] T. Marrodán
Undagoitia,[11] J. Masbou,[15] F [8] M. Messina,[1] K. Micheneau,[15] A. Molinario,[3]
K. Morå,[9] M. Murra,[17] arha,[8] B. Pelssers,[9] R. Persiani,[15] F. Piastra,[8]
J. Pienaar,[14] V. Pizzell [11] S. Reichard,[8,14] C. Reuter,[14] B. Riedel,[19]
A. Rizzo,[1] S. Rose Sartorelli,[4] M. Scheibelhut,[5] S. Schindler,[5]
J. Schreiner E. Shockley,[19] M. Silva,[6] H. Simgen,[11]
M. v. Sive C. Tunnell,[19,‖] M. Vargas,[17] N. Upole,[19]
Y. Zhang,[1] and T. Zhu[1]

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 F
Changbo Fu,[1] Karl Giboni,[1] Franco Giuliani,[1] Linhui Gu,[1] Yikun Gu,[1] Xuyuan Guo,[3] Zhifan Guo,[5] Ke Han,[1]
Di Huang,[1] Shengming He,[3] Xingtao Huang,[6] Zhou Huang,[1] Xiangdong Ji,[7,1,§] Yonglin Ju,[5] Shaoli Li,[1]
Huaxuan Liu,[5] Jianglai Liu,[4,7,*] Yugang Ma,[4] Yajun Mao,[8] Kaixiang Ni,[1] Jinhua Ning,[3] Xiangxi
Andi Tan,[9,†] Cheng Wang,[5] Hongwei Wang,[4] Meng Wang,[6] Qiuhong Wang,[4,‡] Siguang
Xuming Wang,[1] Qinyu Wu,[1] Shiyong Wu,[3] Mengjiao Xiao,[9,10] Pengwei Xie,[1] Binbin Yan
Dan Zhang,[1] Hongguang Zhang,[1] Tao Zhang,[1] Tianqi Zhang,[1] Li Zhao,[1] Jifang Zhou,[3]

(PandaX-II Collaboration)

L REVIEW LETTERS week ending 23 JUNE 2017

n Results from the PICO-60 C_3F_8 Bubble Chamber

Arnquist,[3] D. M. Asner,[3] D. Baxter,[4,5,*] E. Behnke,[6] P. Bhattacharjee,[7] H. Borsodi,[6]
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]
[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]
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]
[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]
yanuk,[9] S. Priya,[16] A. E. Robinson,[5] A. Roeder,[6] R. Rucinski,[5] O. Scallon,[9] S. Seth,[7] A. Sonnenschein,[5]
[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)

no evidence for
DM-induced nuclear recoils

PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2016

rom the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment

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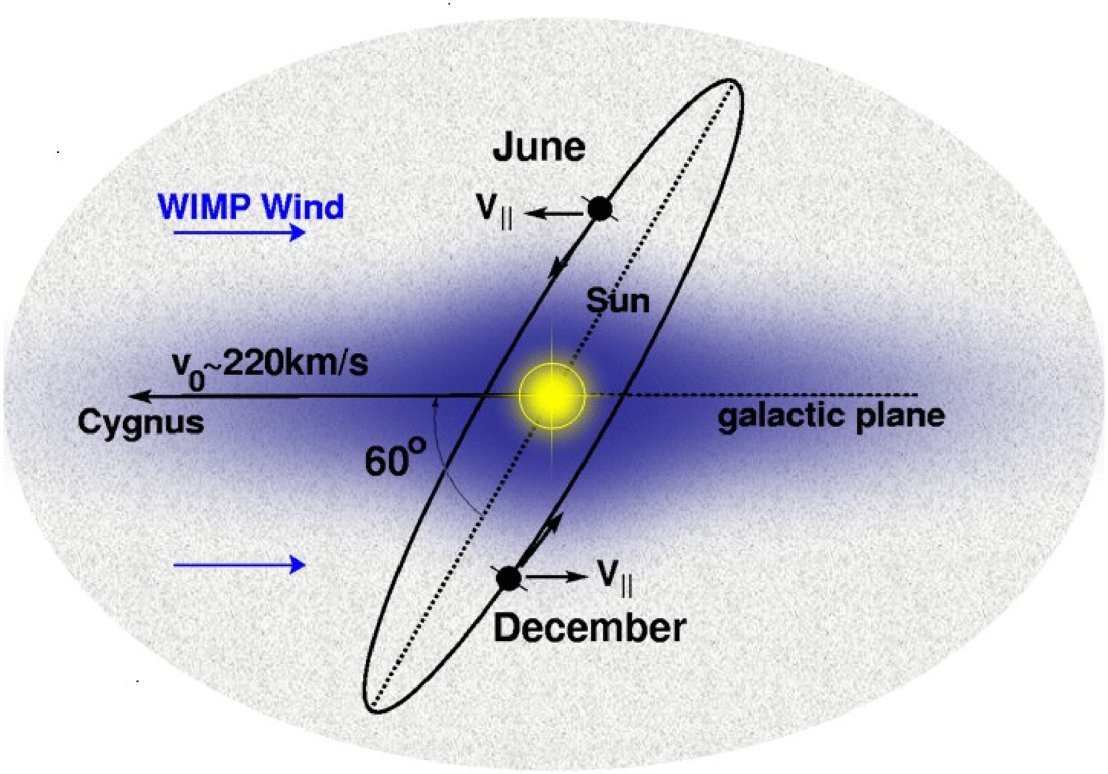
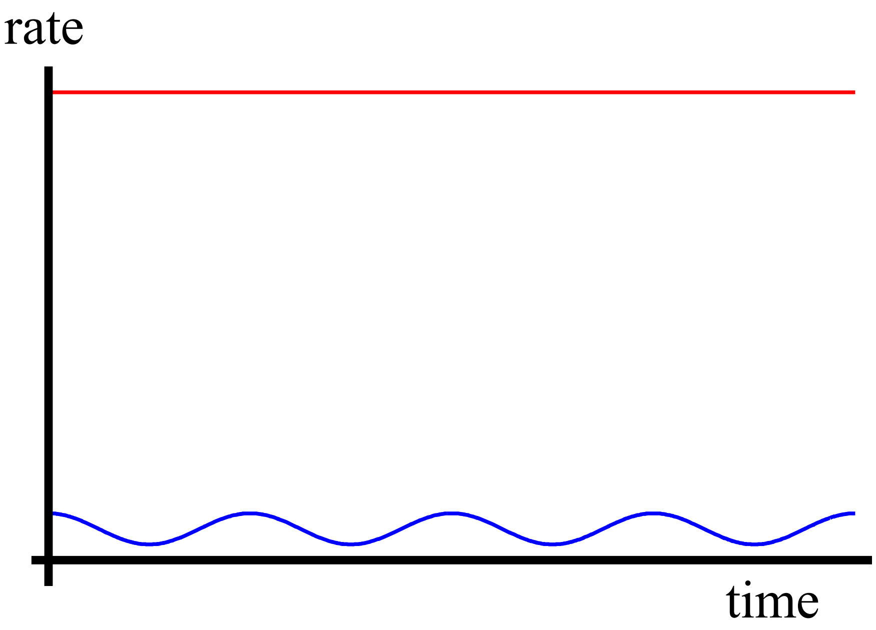
(SuperCDMS Collaboration)

Annual modulation





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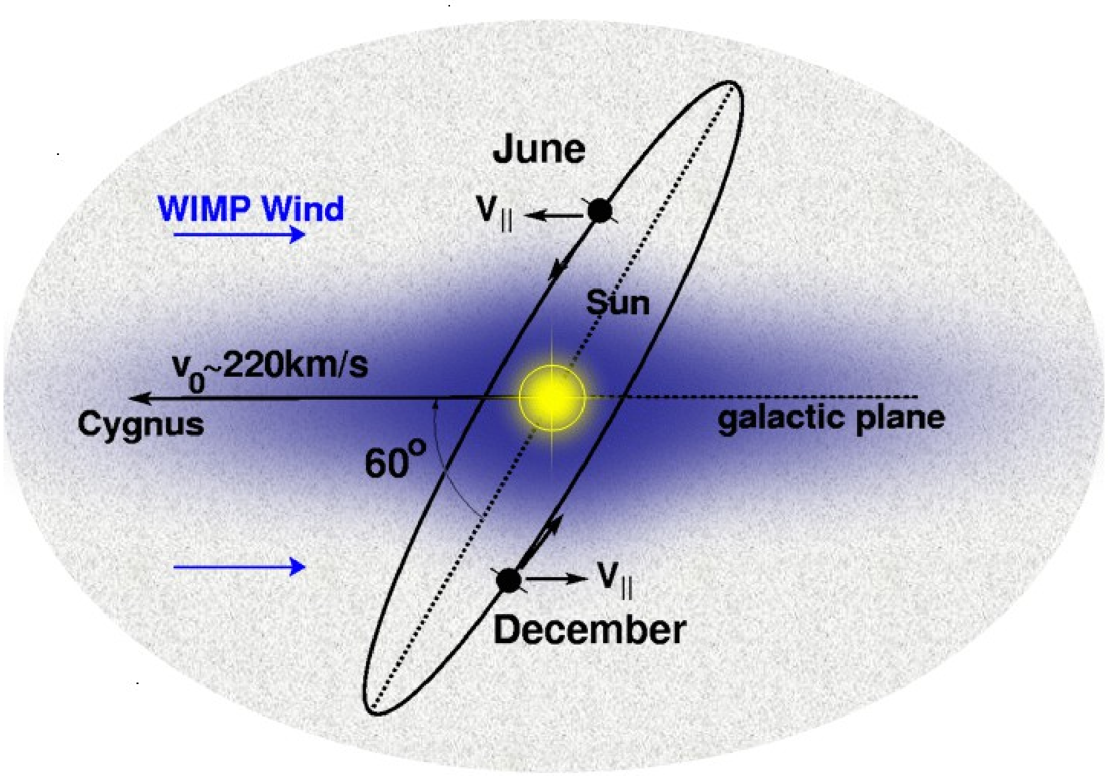

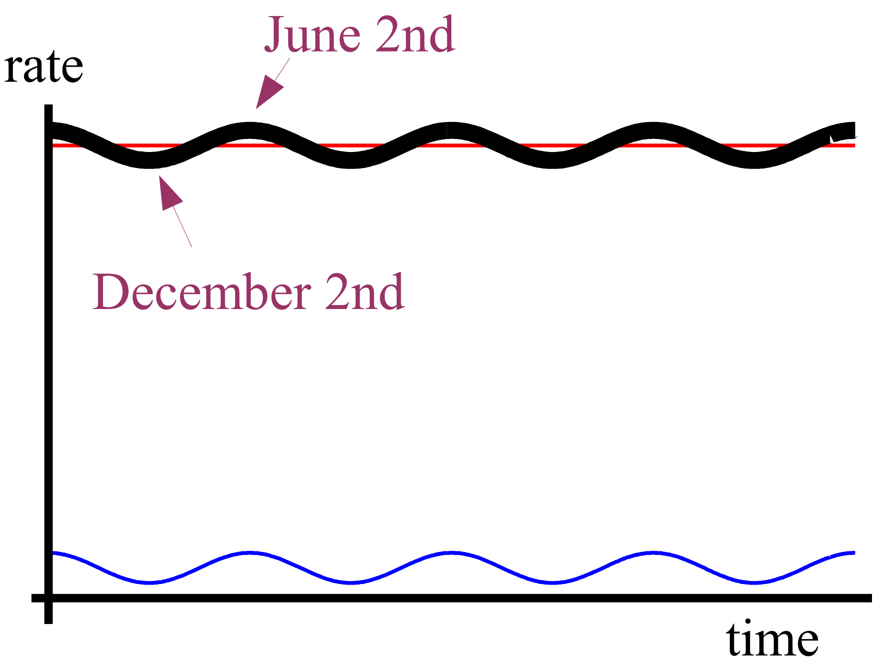

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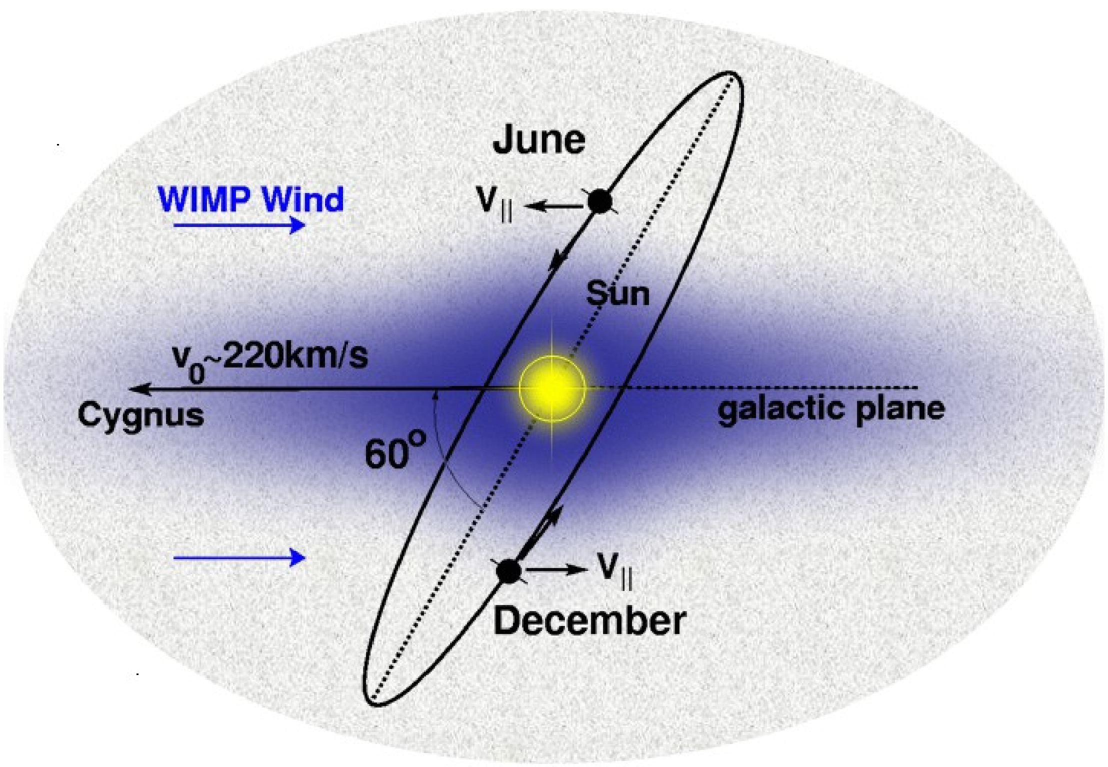
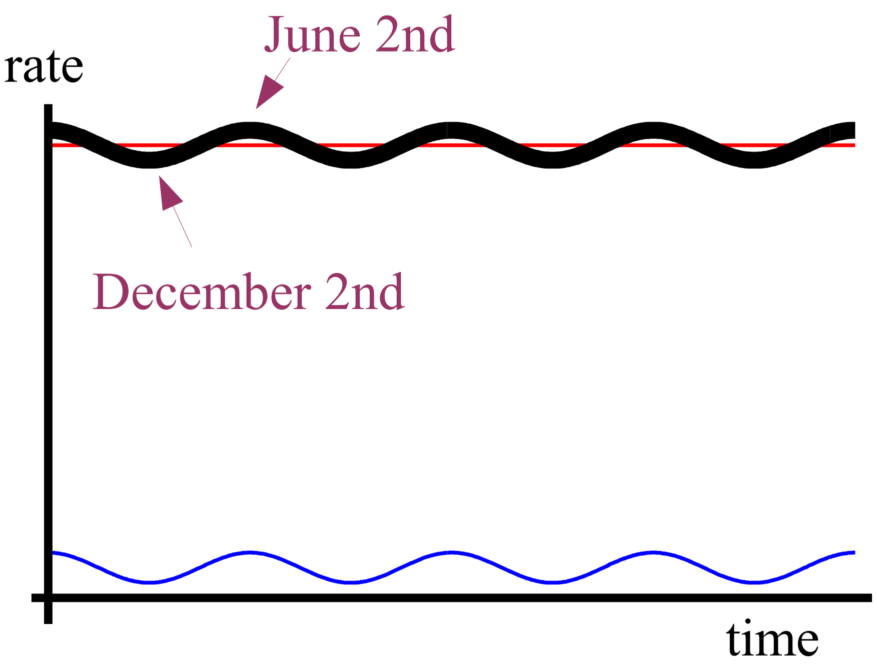
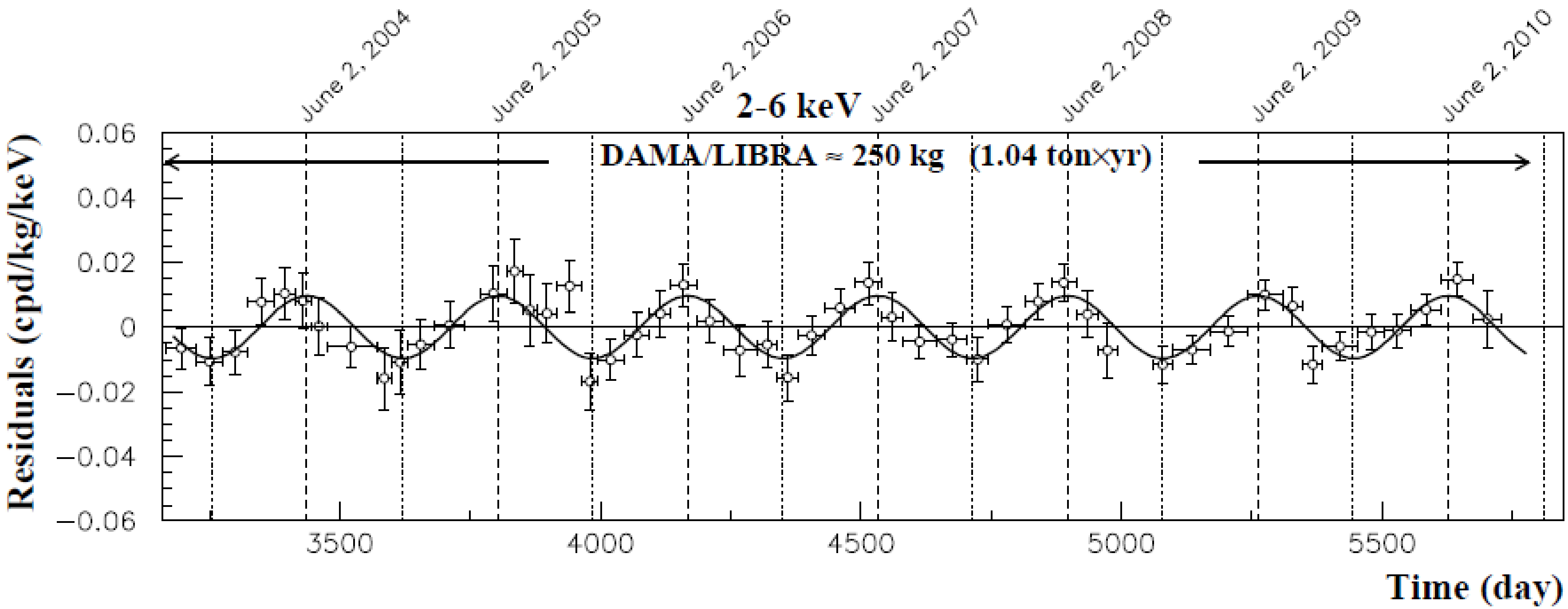




Modulation signal

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

Annual modulation: the DAMA/LIBRA experiment



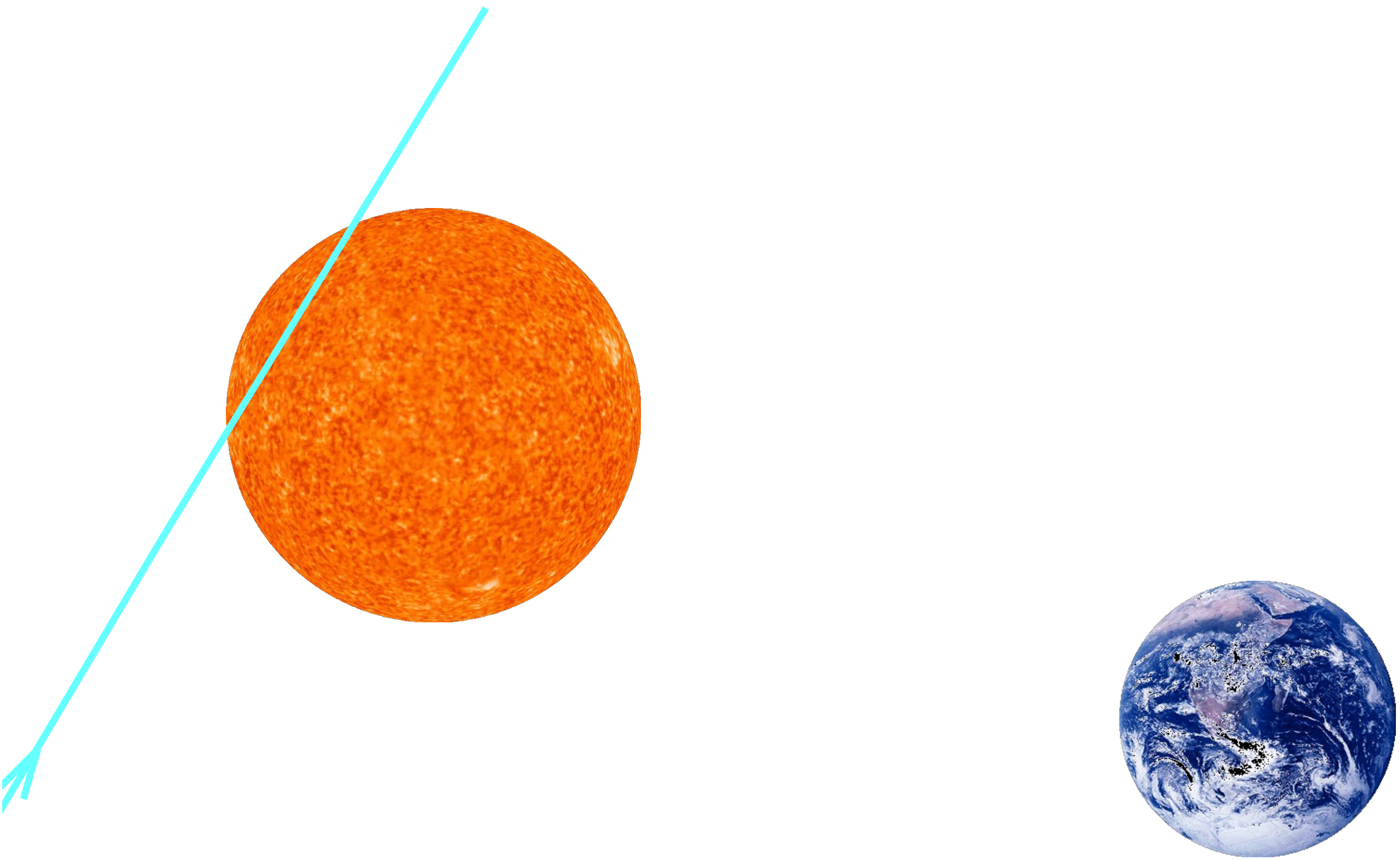
Modulation observed over 14 annual cycles, with a combined significance of 9.3σ.

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

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

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

Neutrinos from annihilations in the Sun



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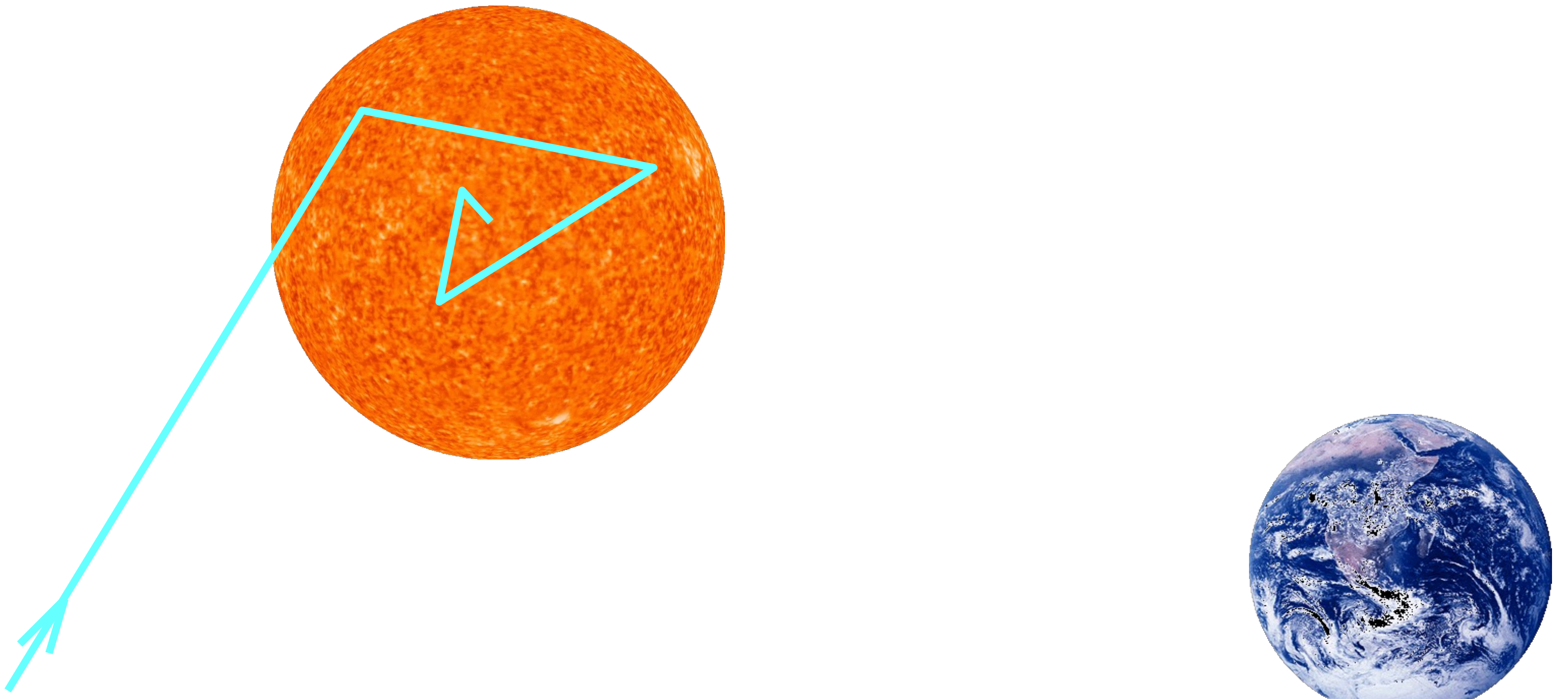

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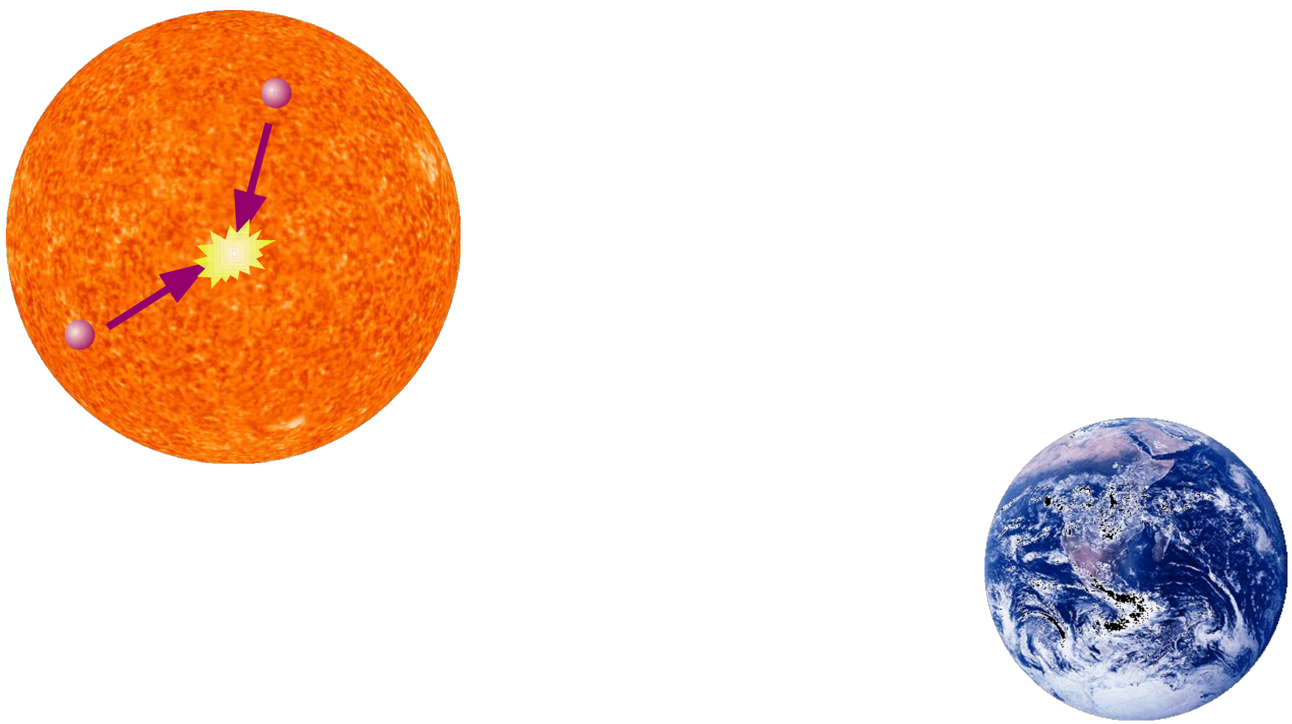

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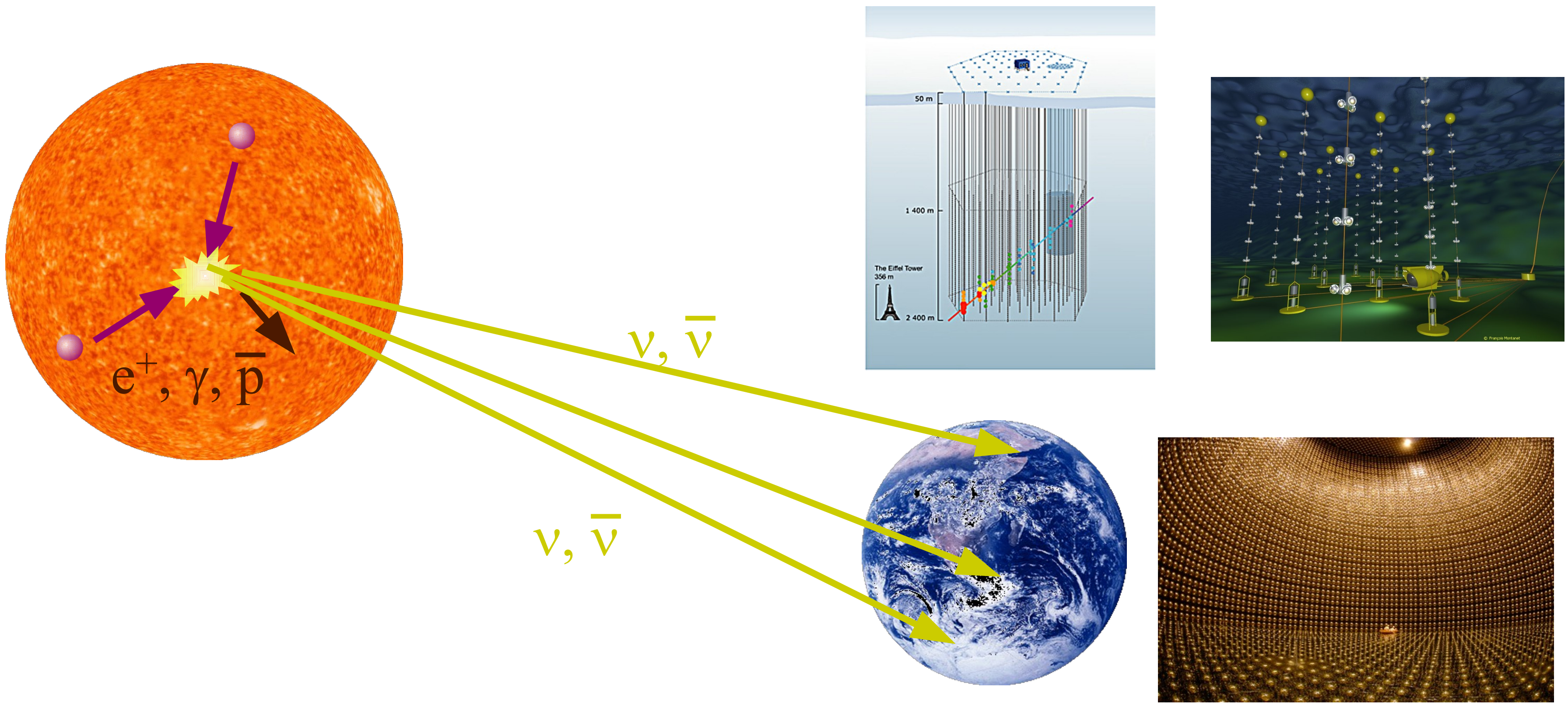
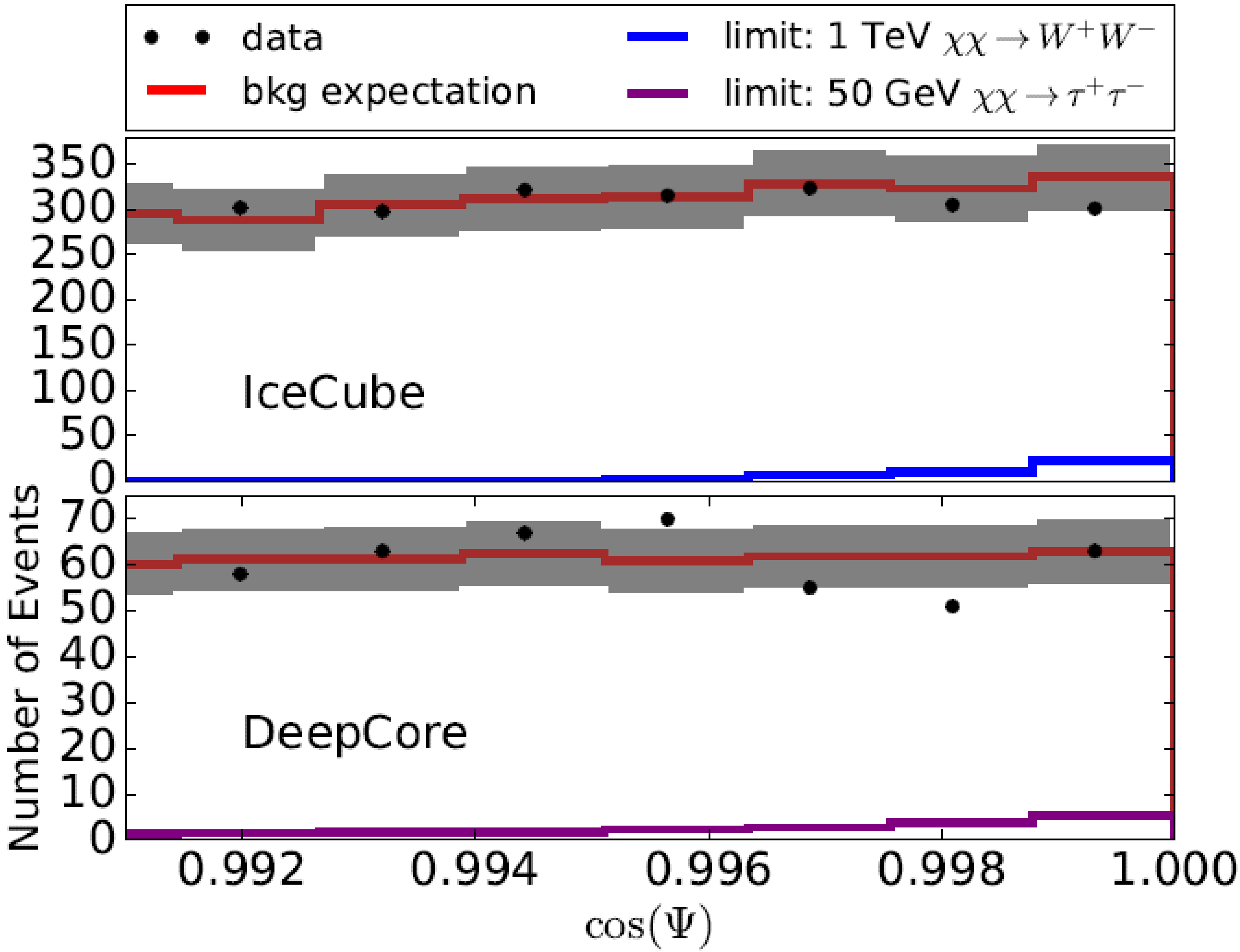


Neutrinos from annihilations in the Sun

Observations consistent with the background-only hypothesis



IceCube collaboration
ArXiv:1612.05949

Theoretical interpretation of the experimental results

Theoretical interpretation of the experimental results

- 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, $m_{\rm DM}$ = few MeV – 100 TeV

- Differential cross section?

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

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

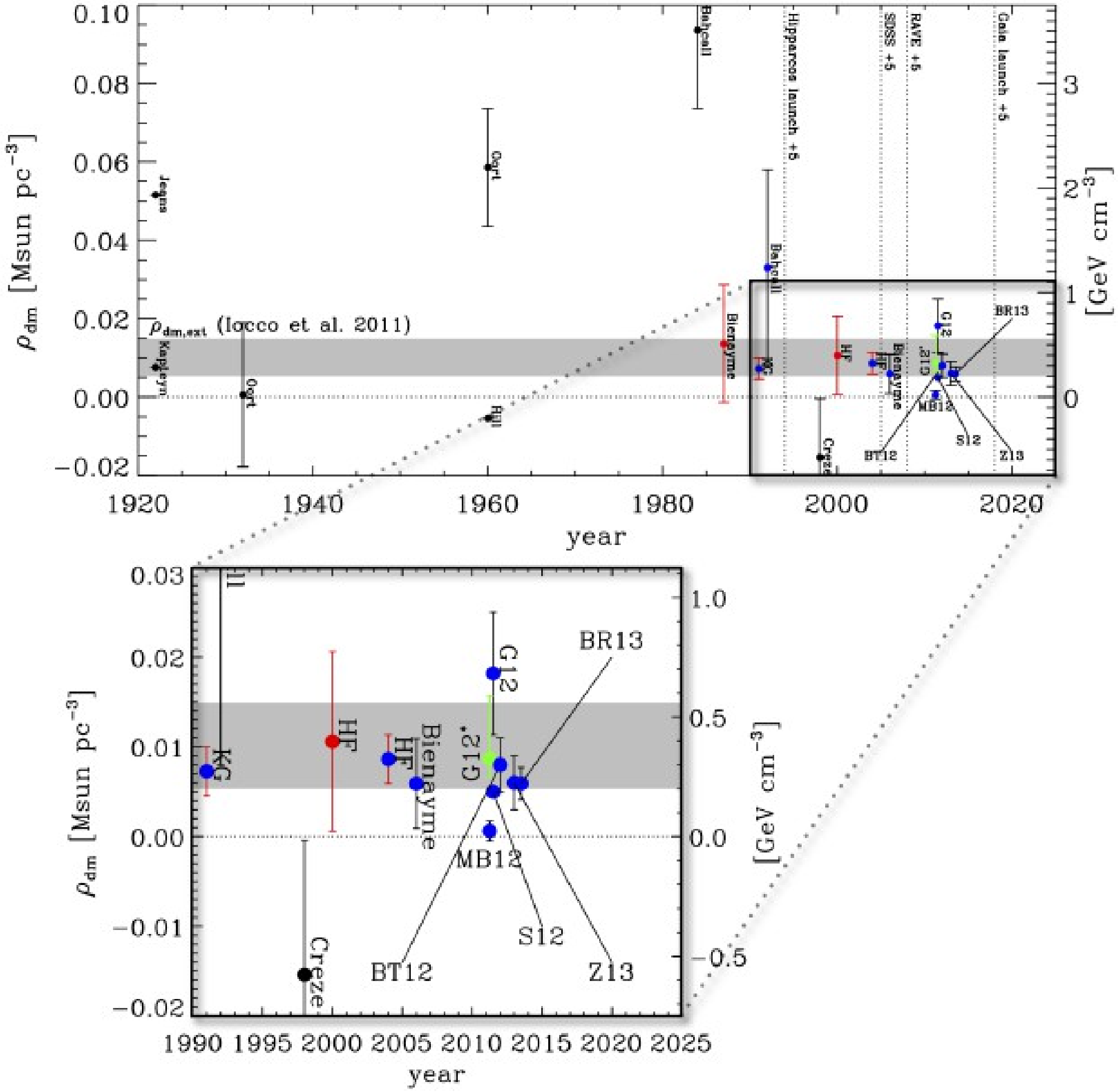
- Local dark matter density?

  - "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.

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

Theoretical interpretation of the experimental results

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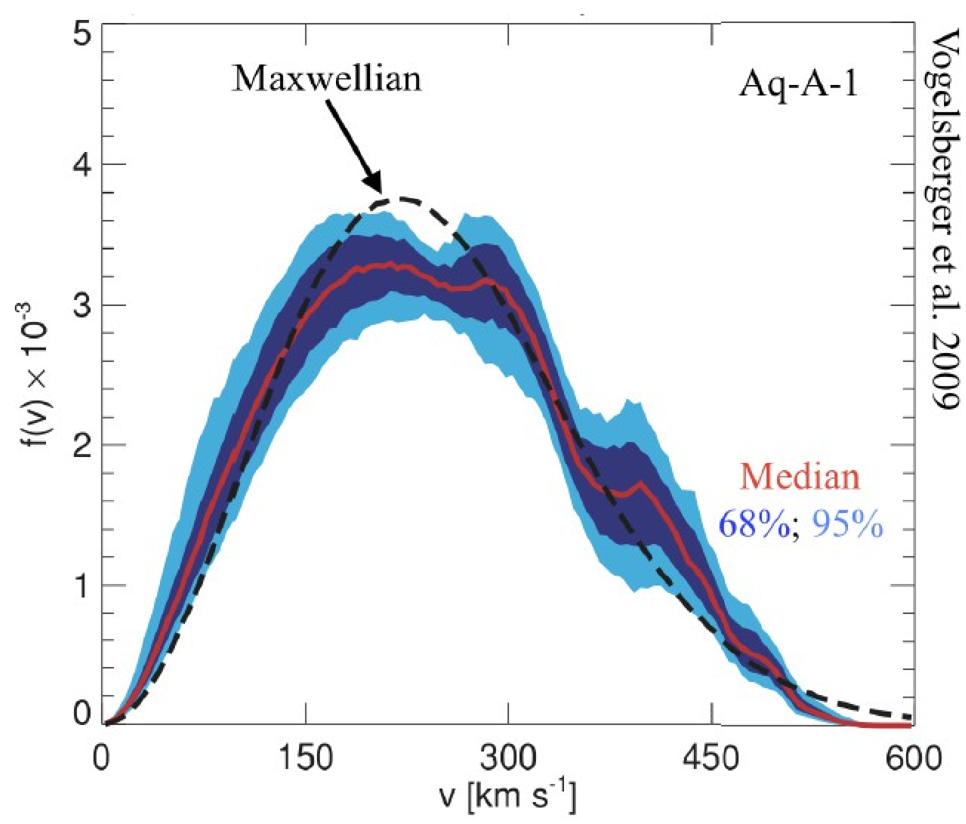

Theoretical interpretation of the experimental results

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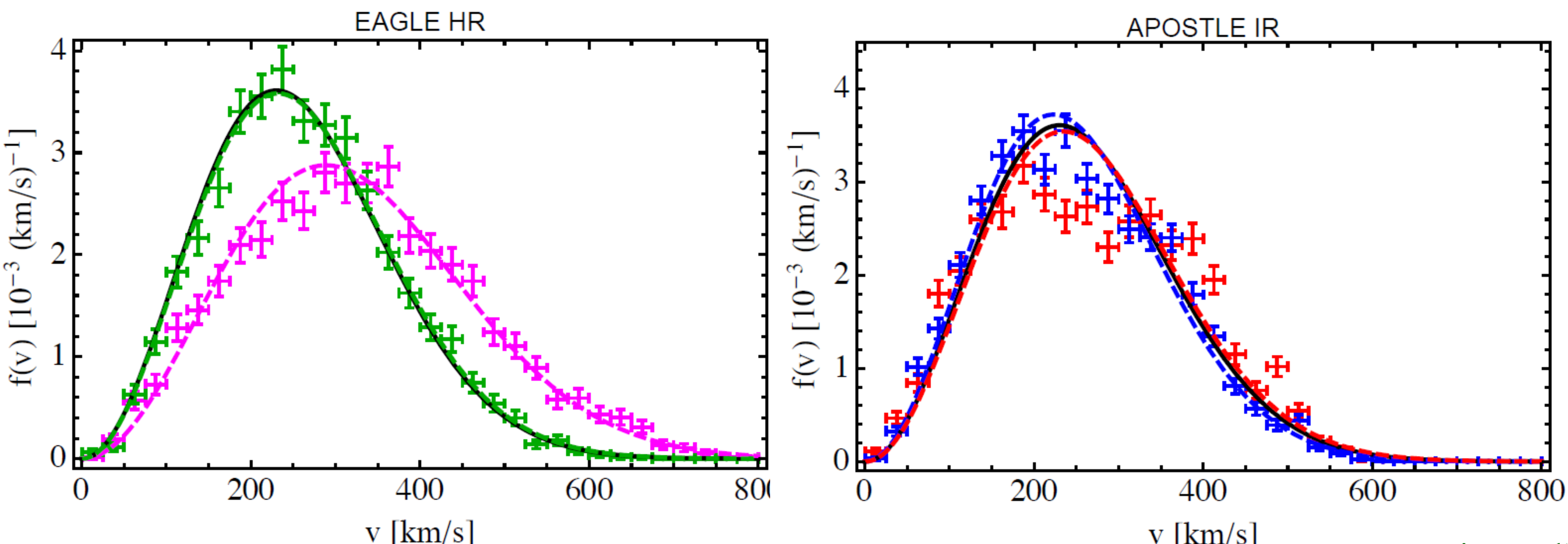
  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
  - Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.

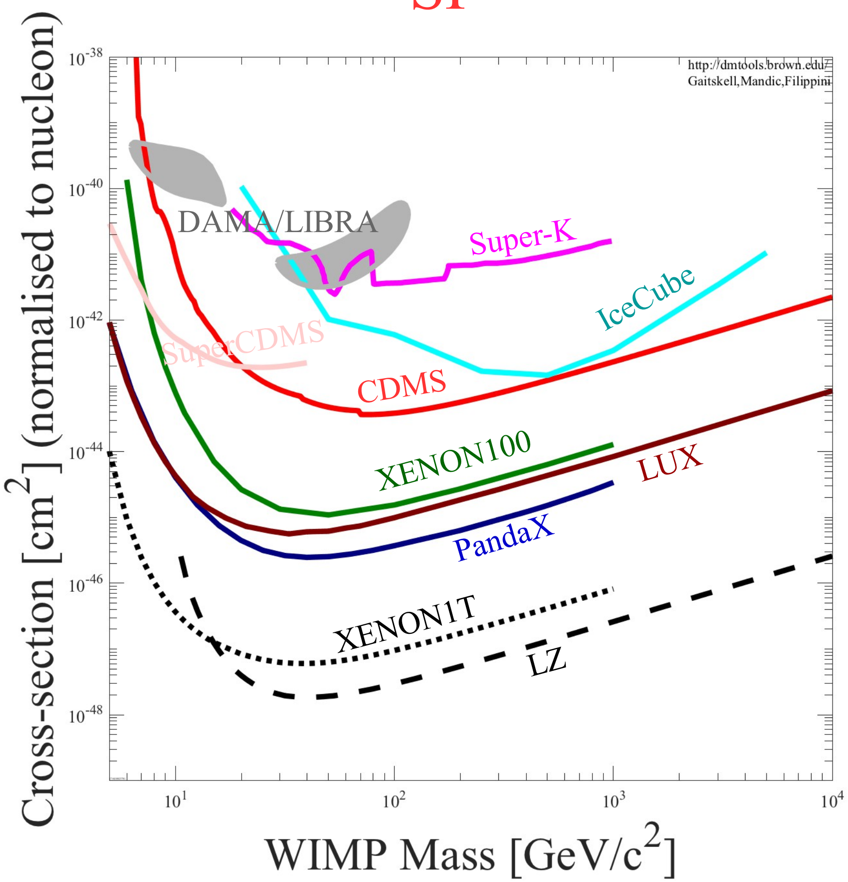


Bozorgnia et al'16

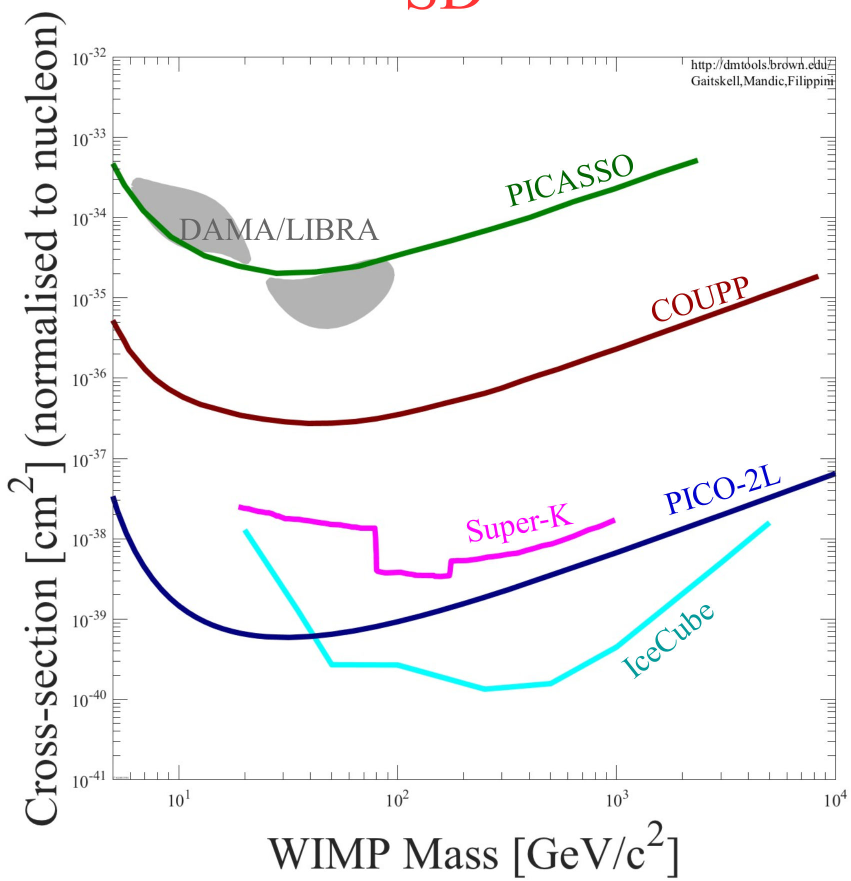
Theoretical interpretation of the experimental results

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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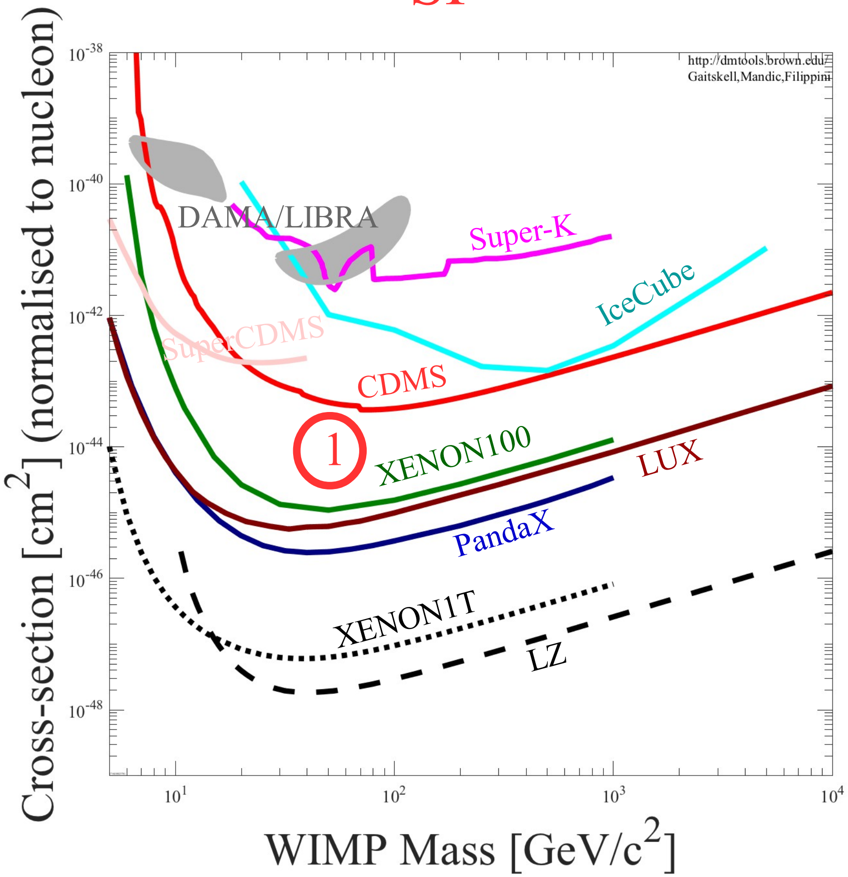

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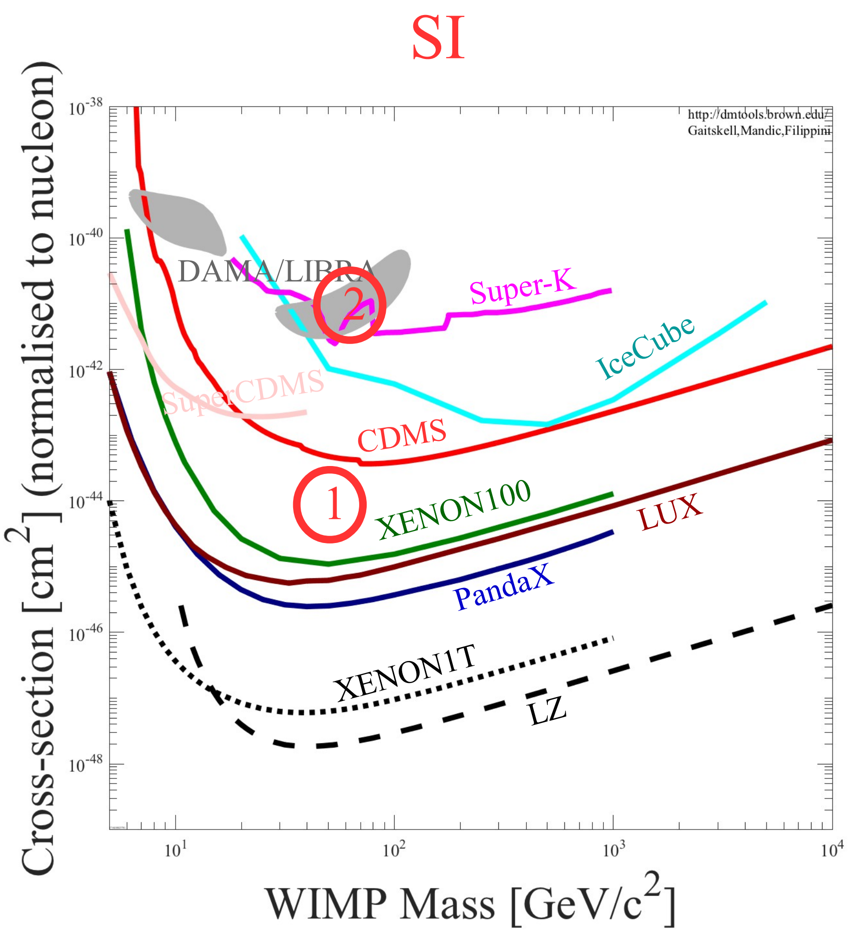

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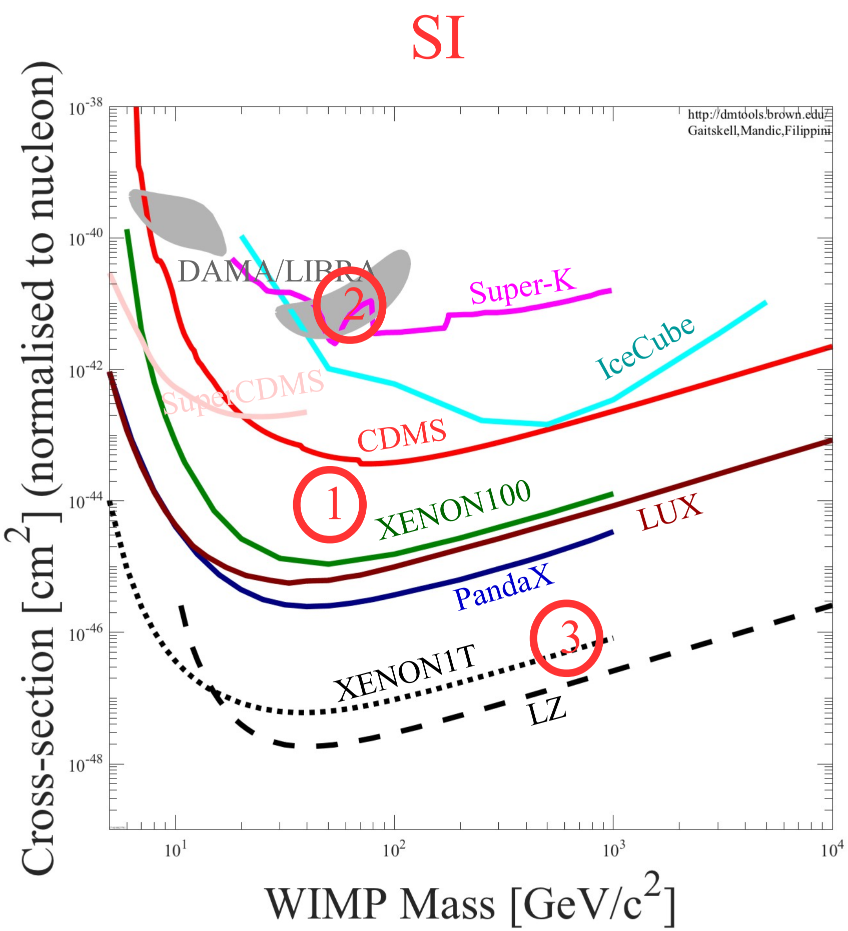

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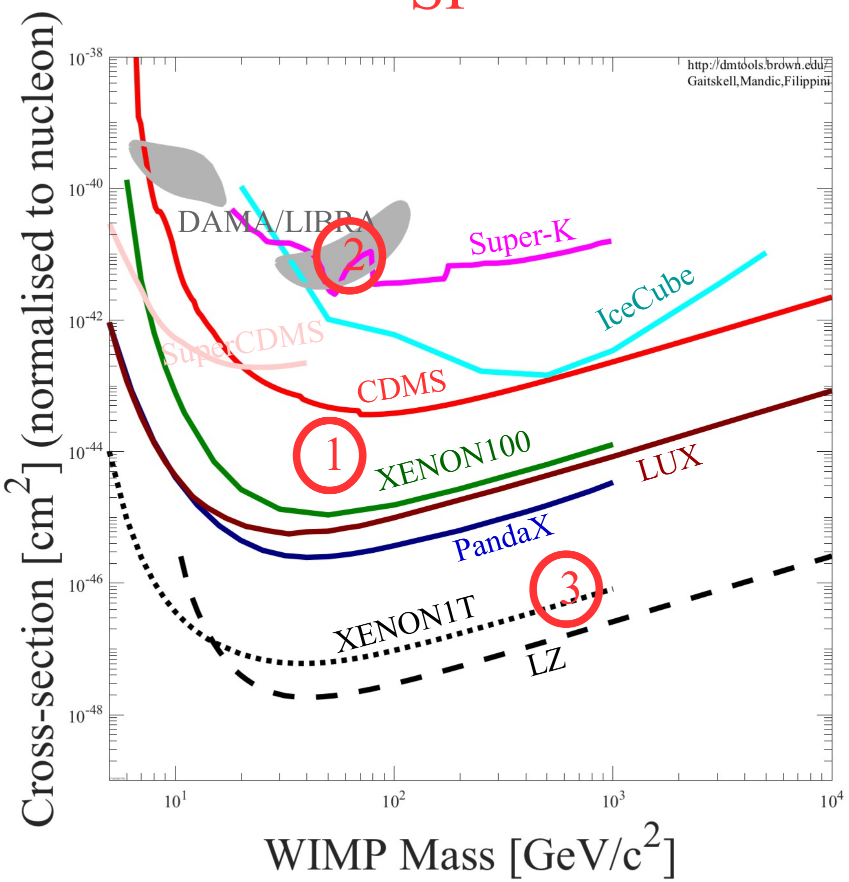

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What is the impact of the astrophysical uncertainties?

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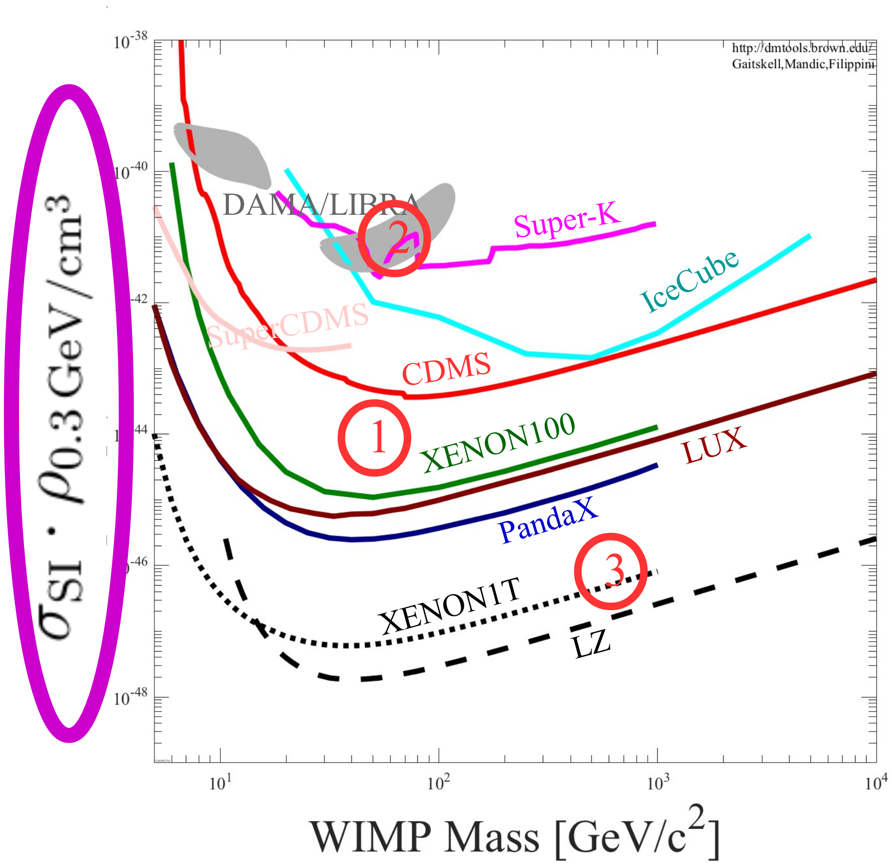

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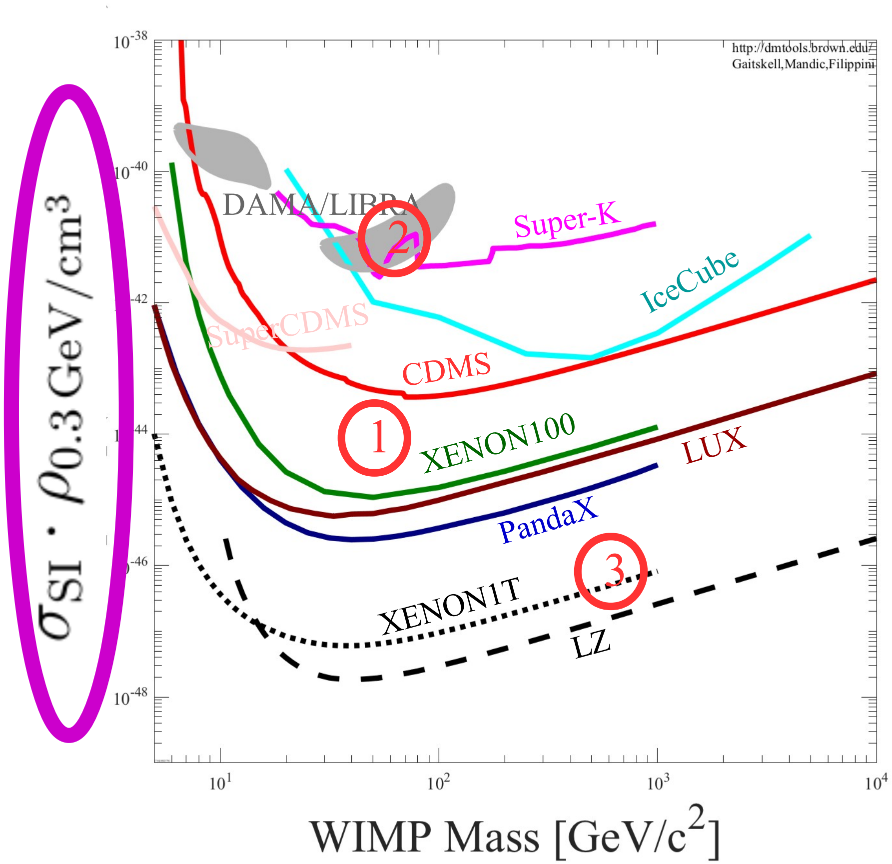

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What is the impact of the astrophysical uncertainties?

Do these conclusions hold for arbitrary velocity distributions?

Addressing astrophysical uncertainties in dark matter detection

Halo-independent approach for DM frameworks

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

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

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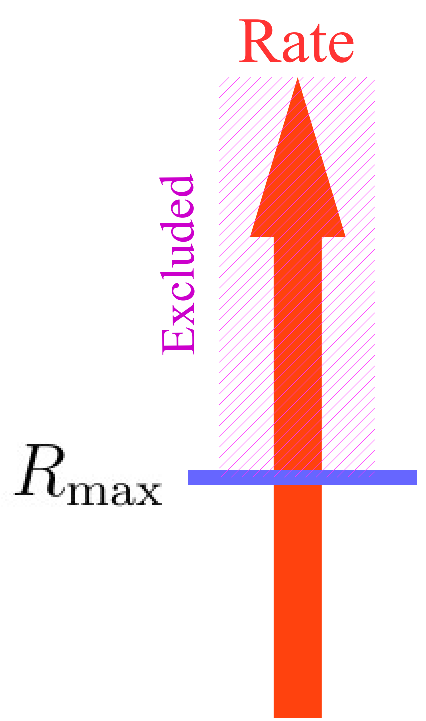

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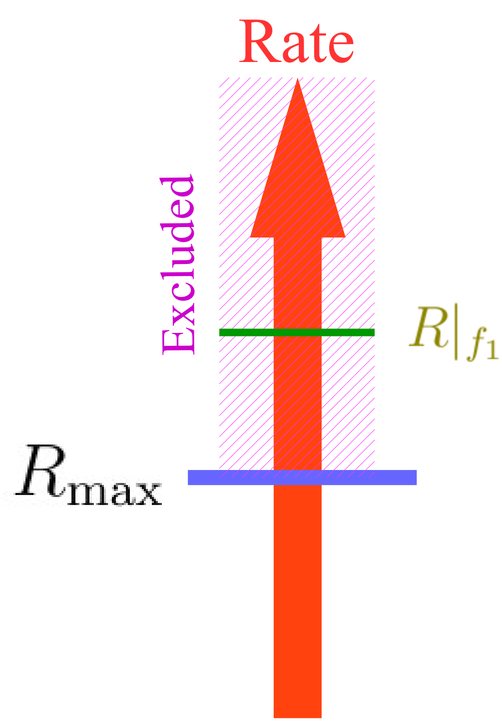

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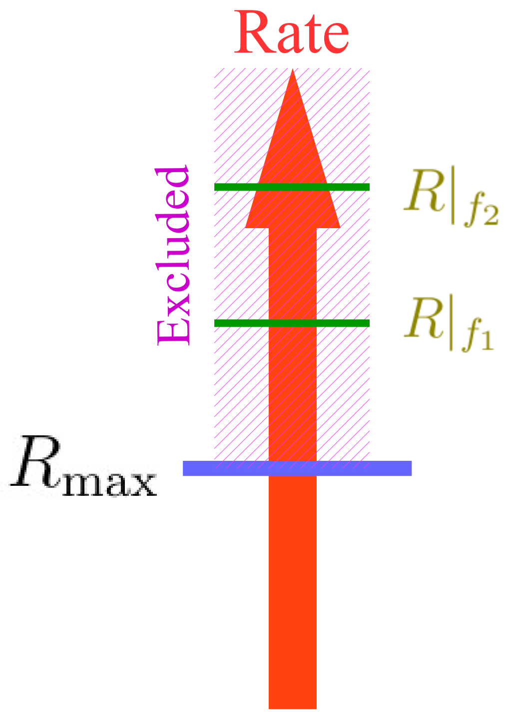

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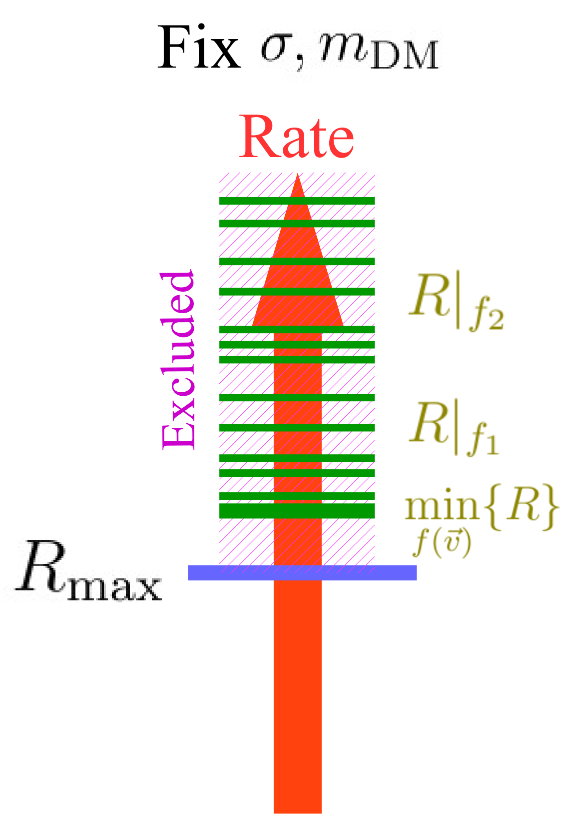

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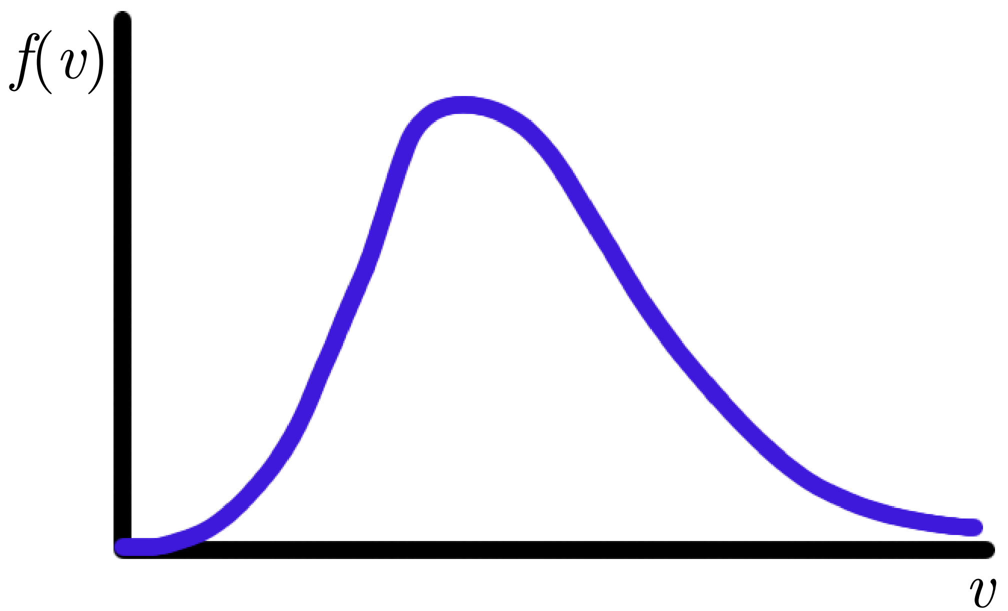

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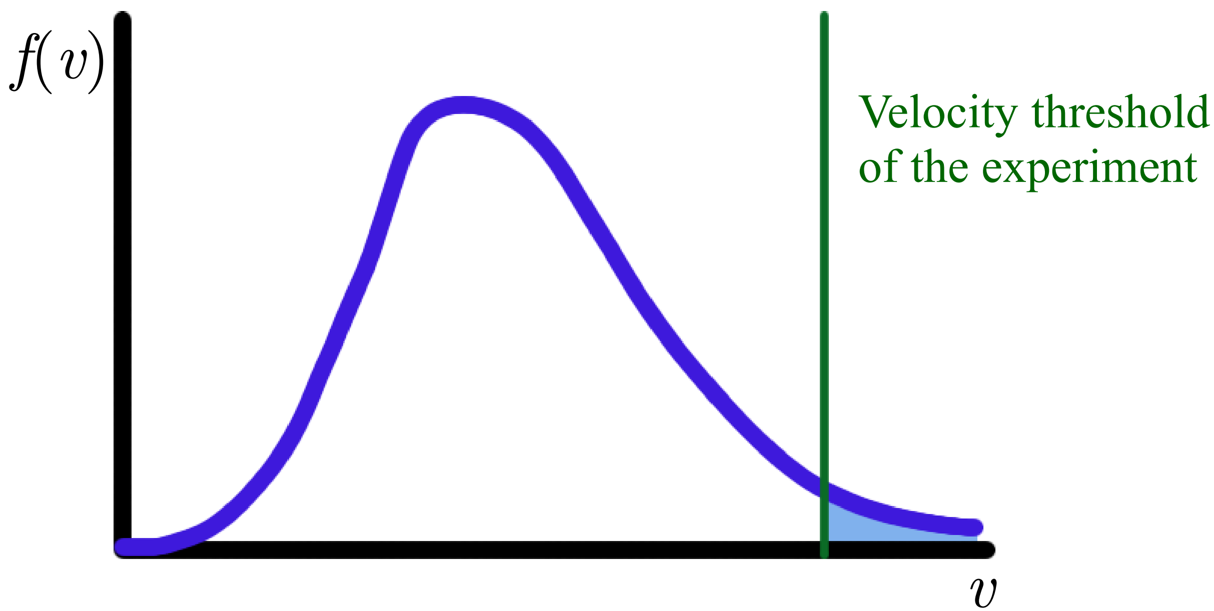

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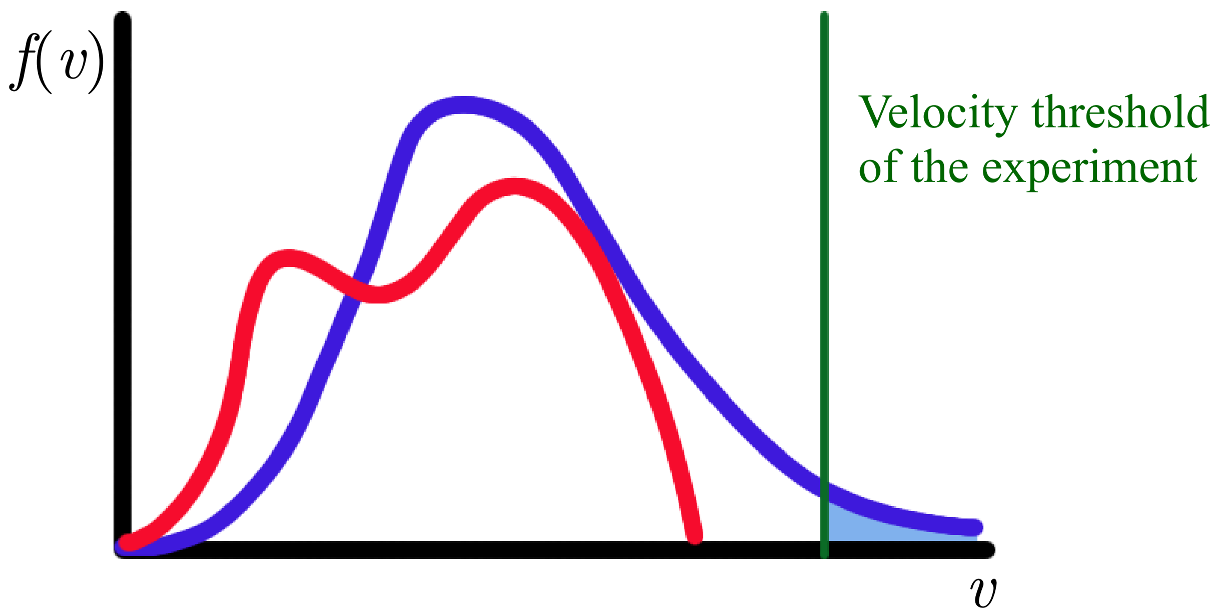

Some velocity distributions will escape detection in the experiment

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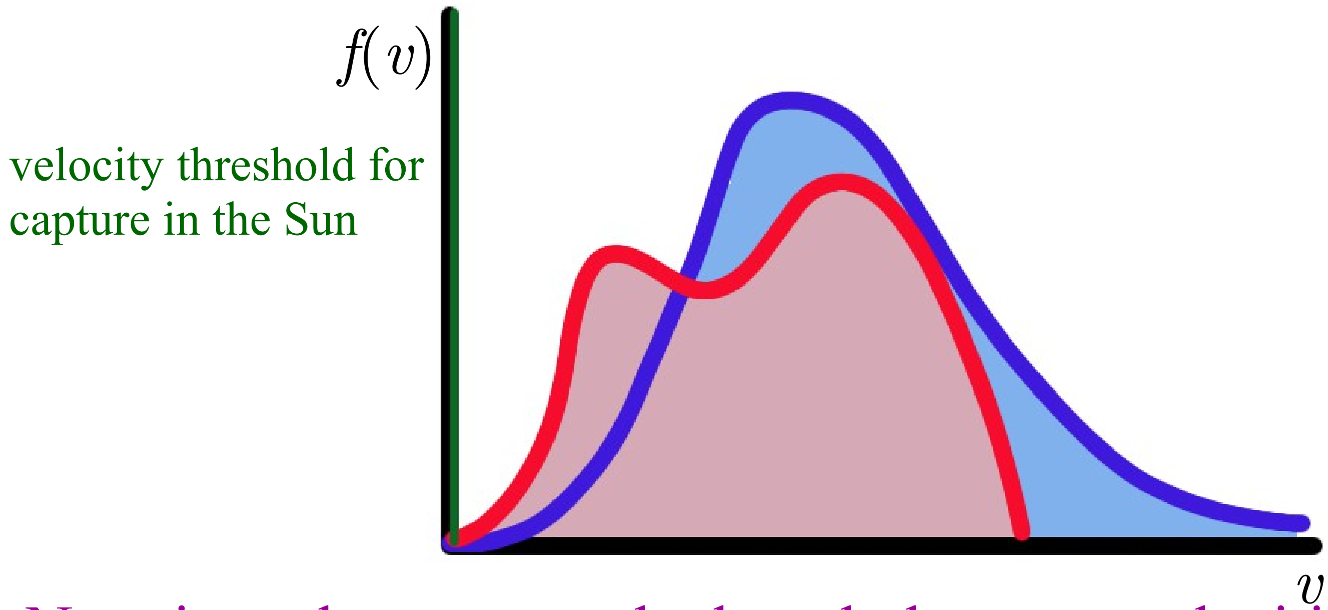

Neutrino telescopes probe low dark matter velocities. In combination with direct detection experiments, one can probe the whole velocity space

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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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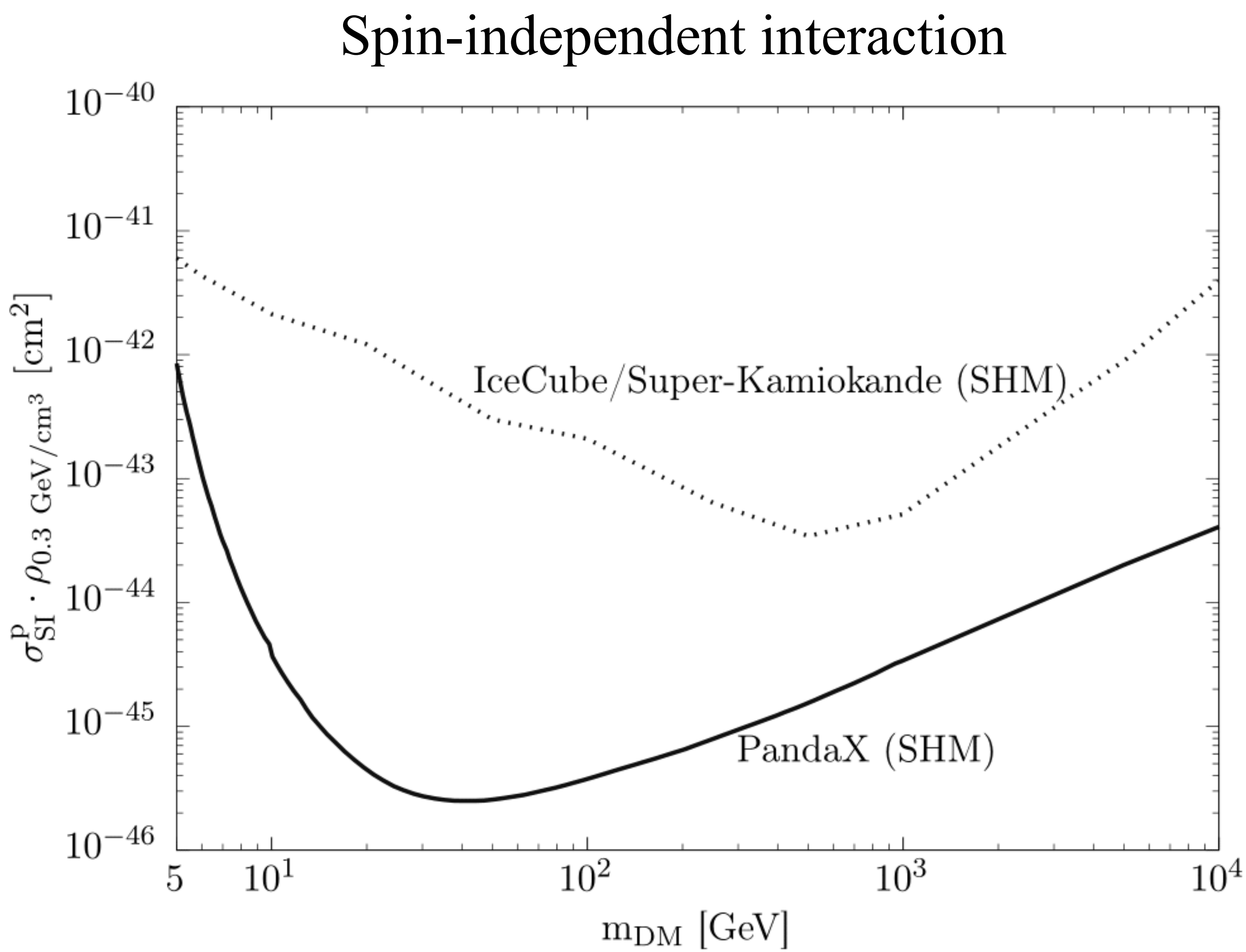
Take-home result:

The velocity distribution that minimizes the rate is composed by a number of dark matter "streams", at most as many as constraints.

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



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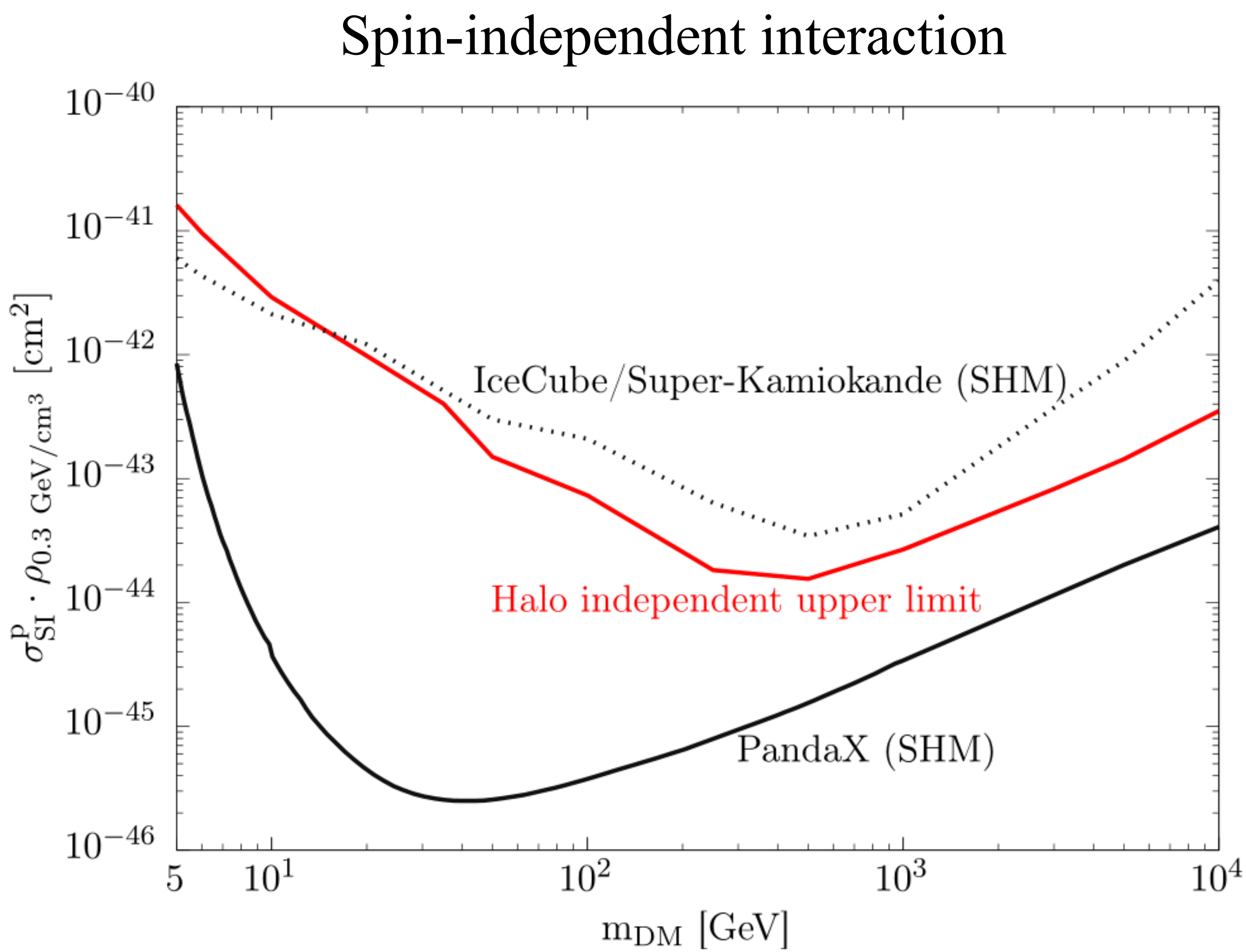

The optimal velocity distribution corresponds to a superposition of two dark matter streams.

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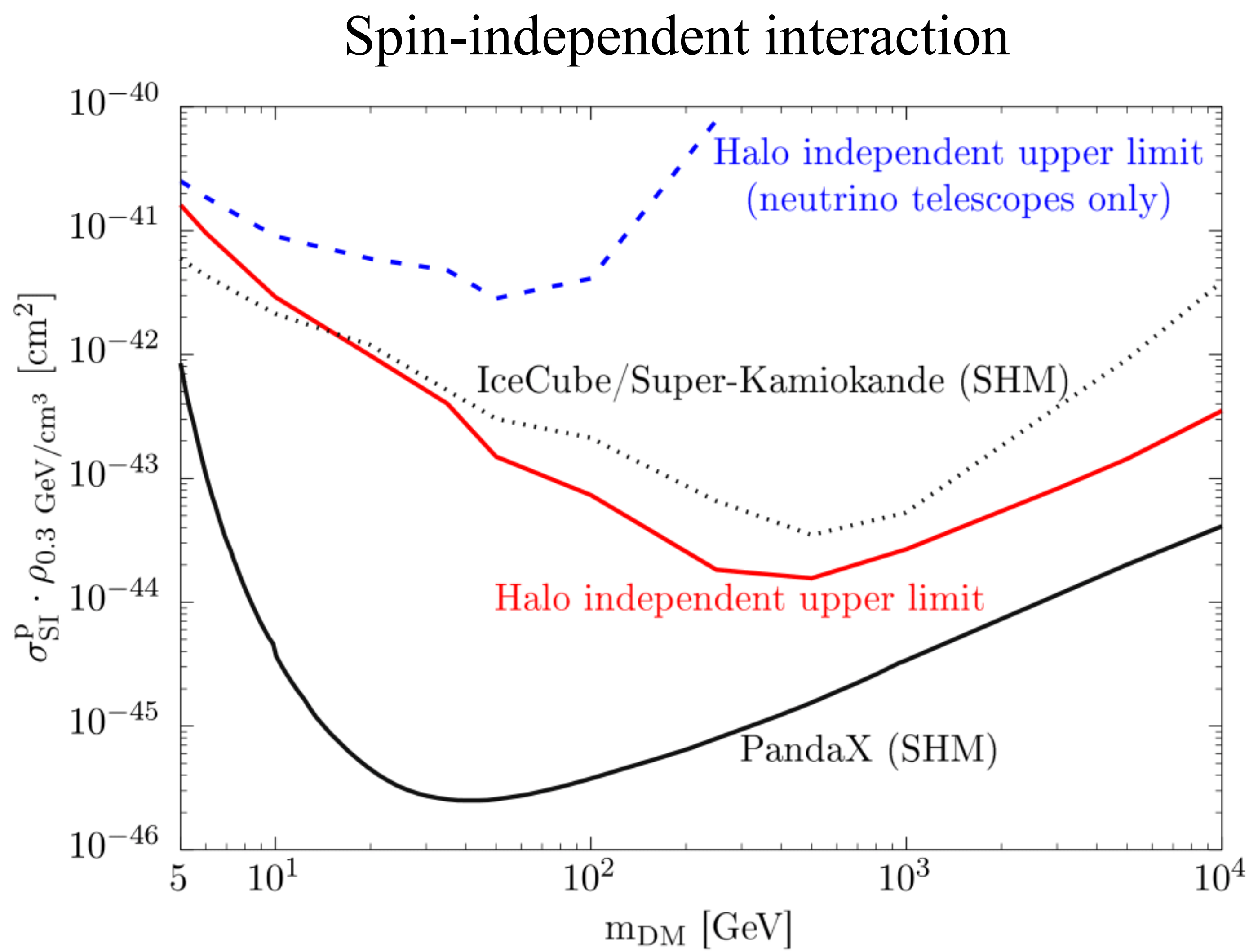
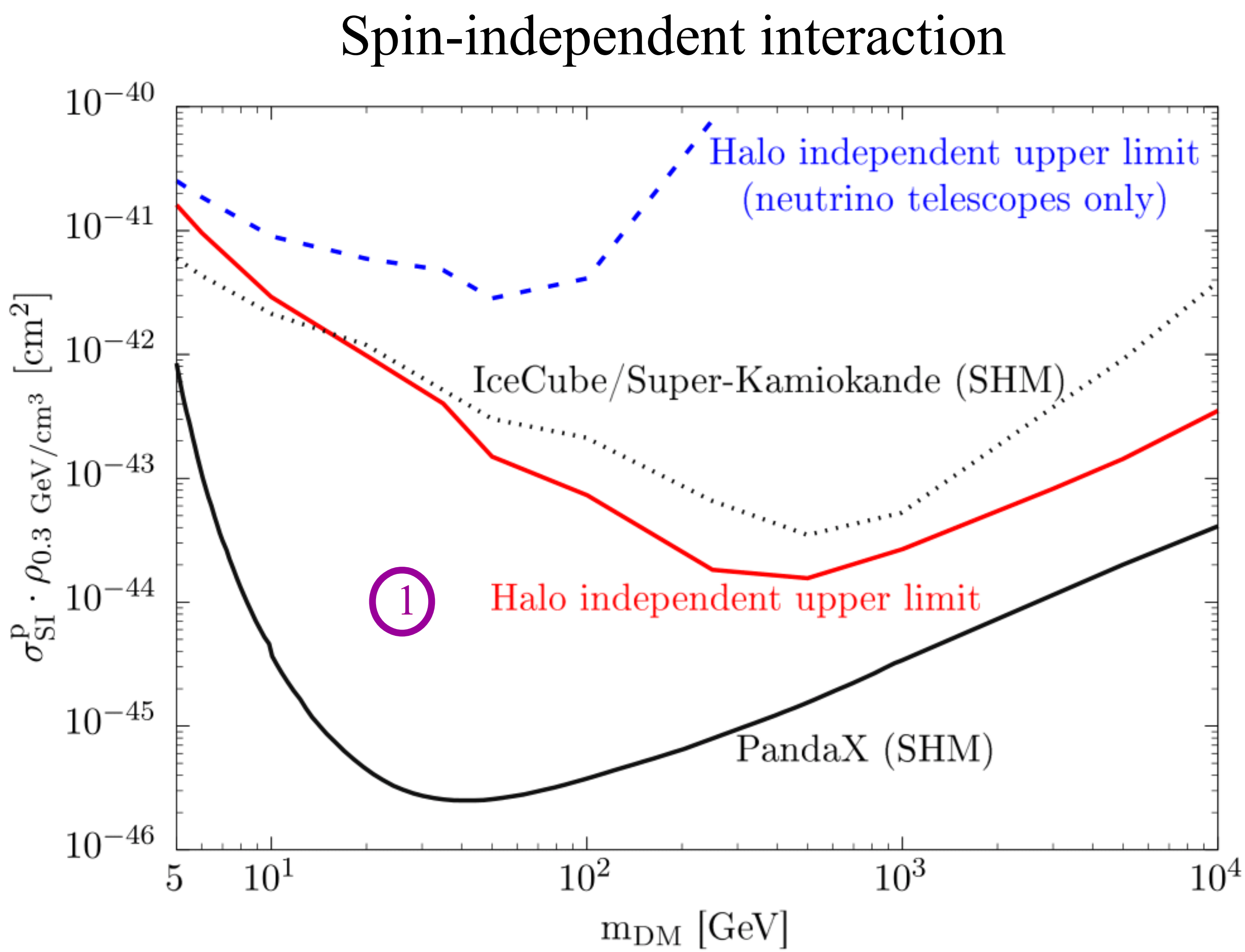
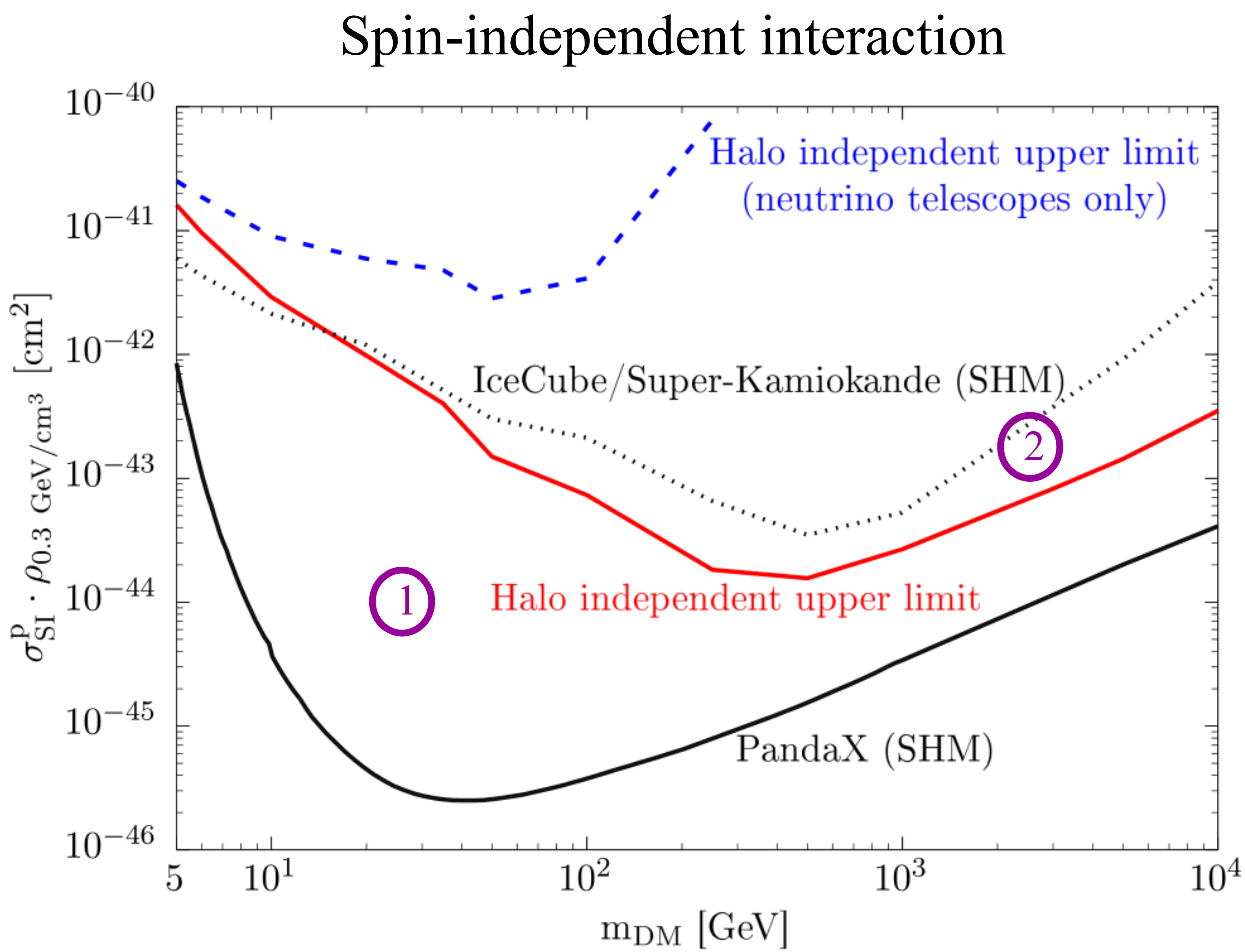


Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.



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

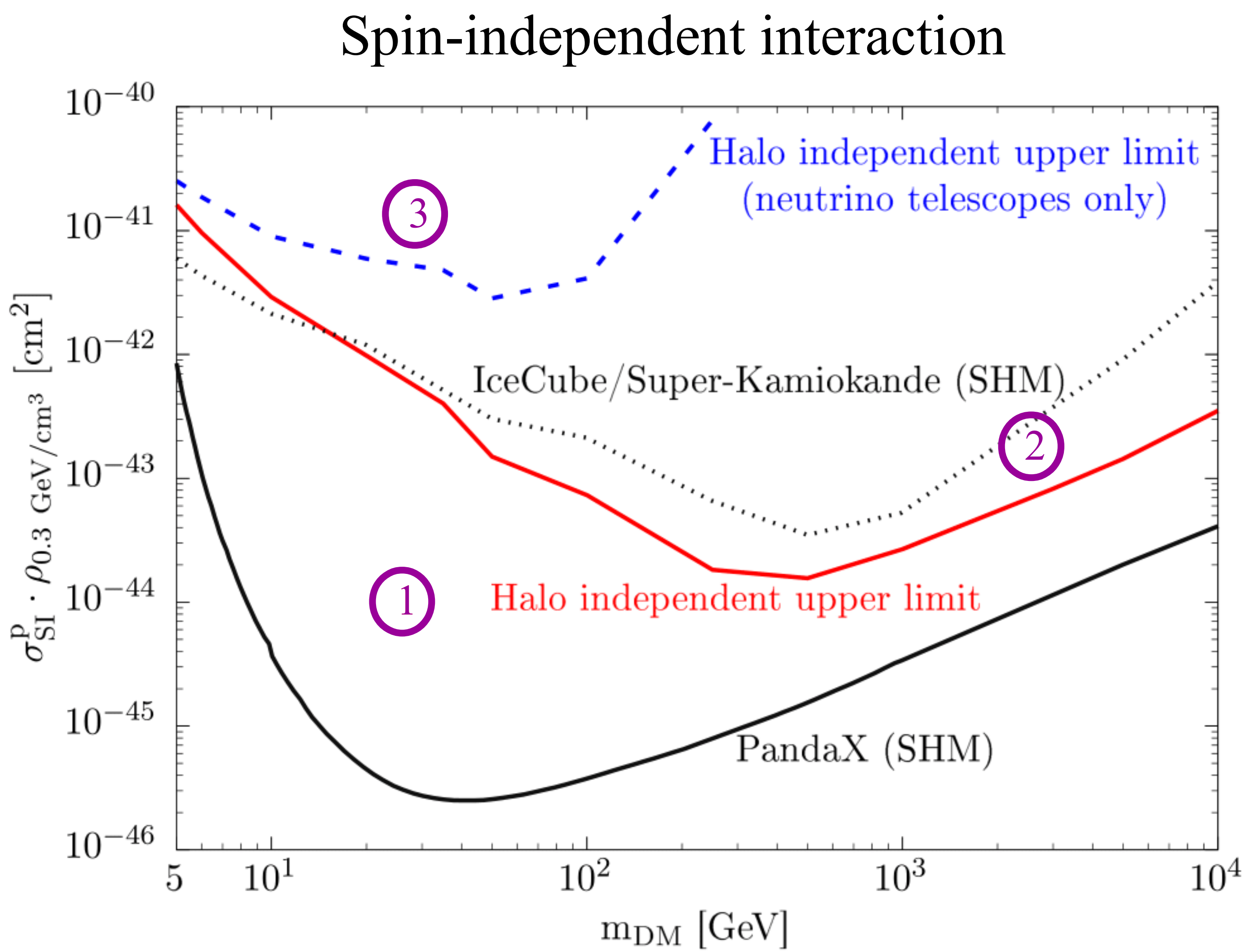
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.



(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.

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



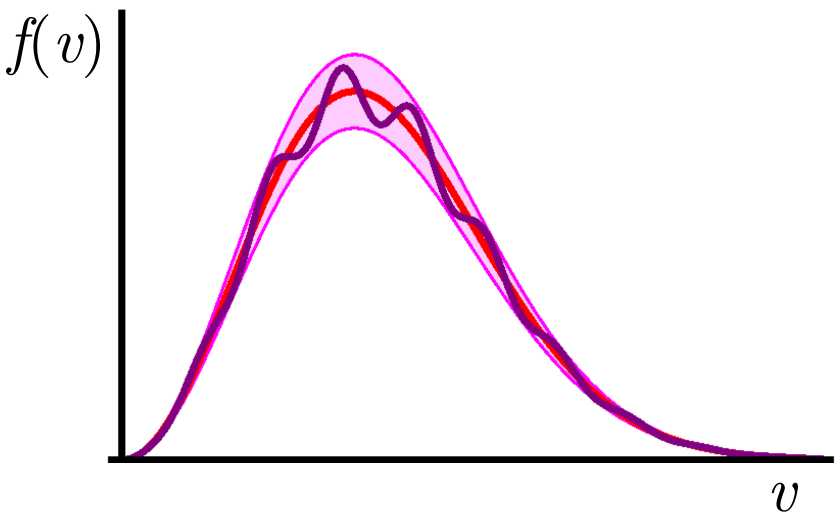
(1) is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

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

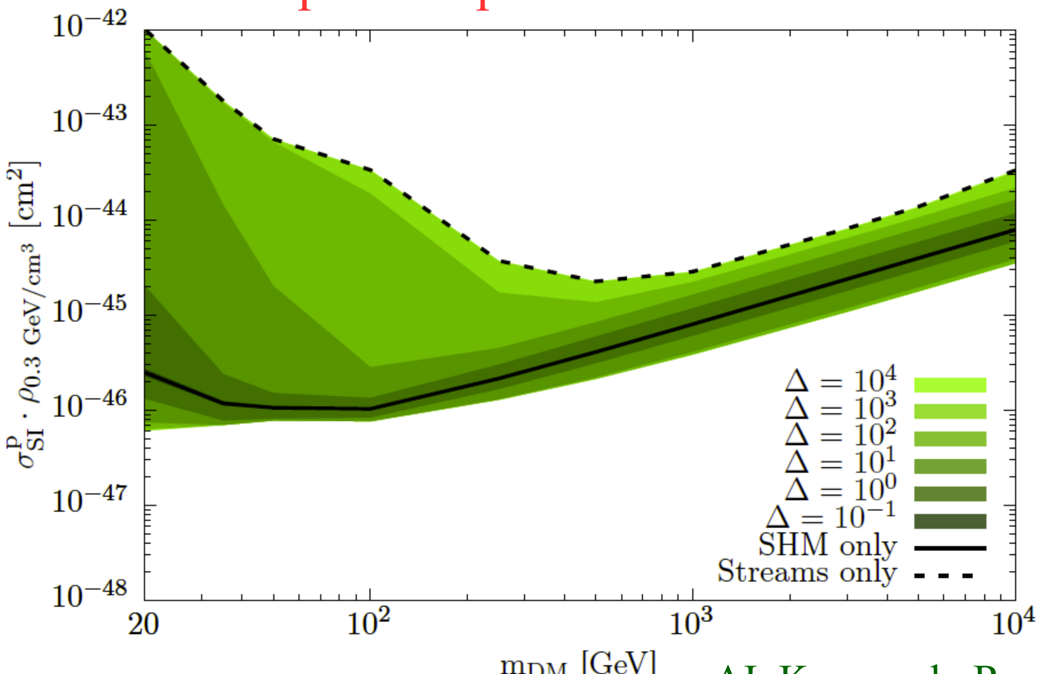
(3) is ruled out by neutrino telescopes only, for *any* velocity distribution.

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 velocity distribution consists just of two streams). Add physically plausible assumptions (e.g. MB distribution + "distortions").



Spin-independent interaction



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To appear

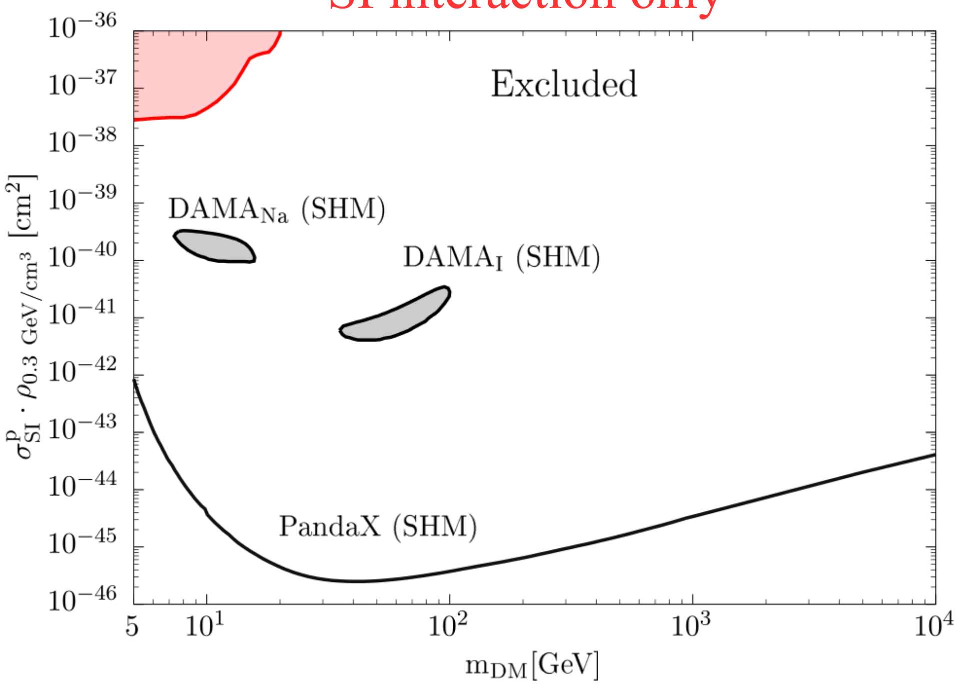
DAMA confronted to null results in a halo independent way

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 σ and m_{DM} are excluded in a halo independent manner if:

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

SI interaction only



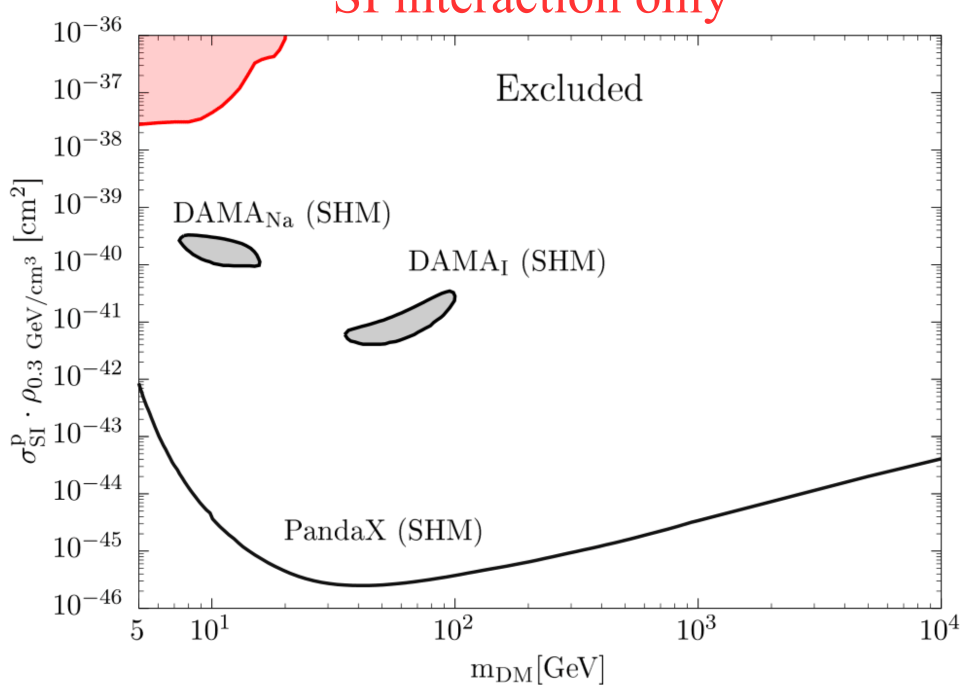
DAMA confronted to null results in a halo independent way

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.

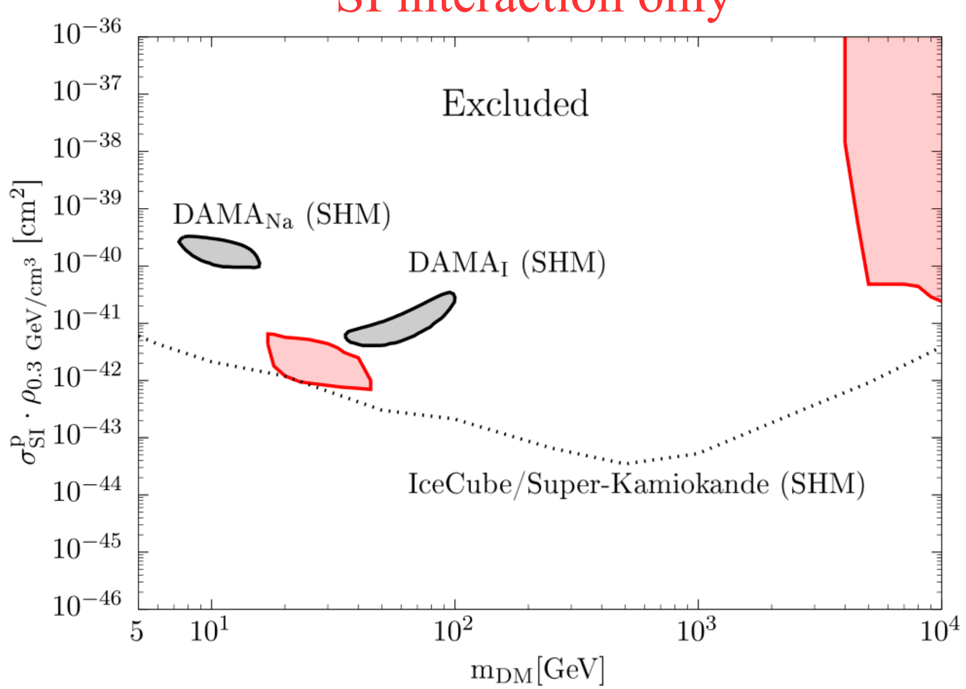
The parameters σ and m_{DM} are excluded in a halo independent manner if:

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

SI interaction only



SI interaction only



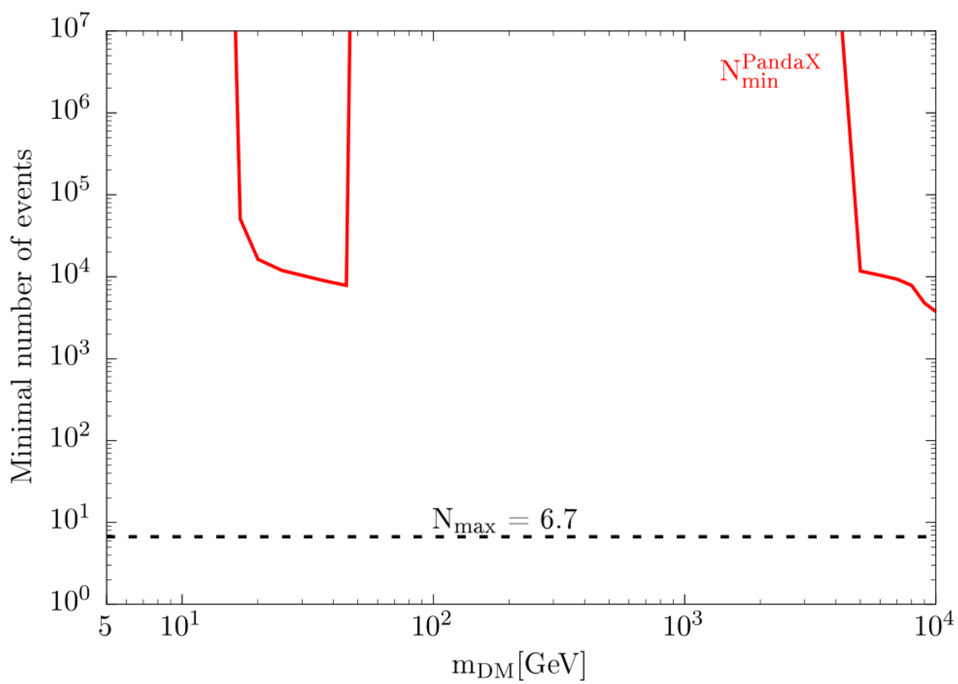
DAMA confronted to null results in a halo independent way

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 σ and m_{DM} are excluded in a halo independent manner if:

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

SI interaction only



At least 3000 events expected at Panda-X

AI, Rappelt '17

Halo independent prospects for future experiments

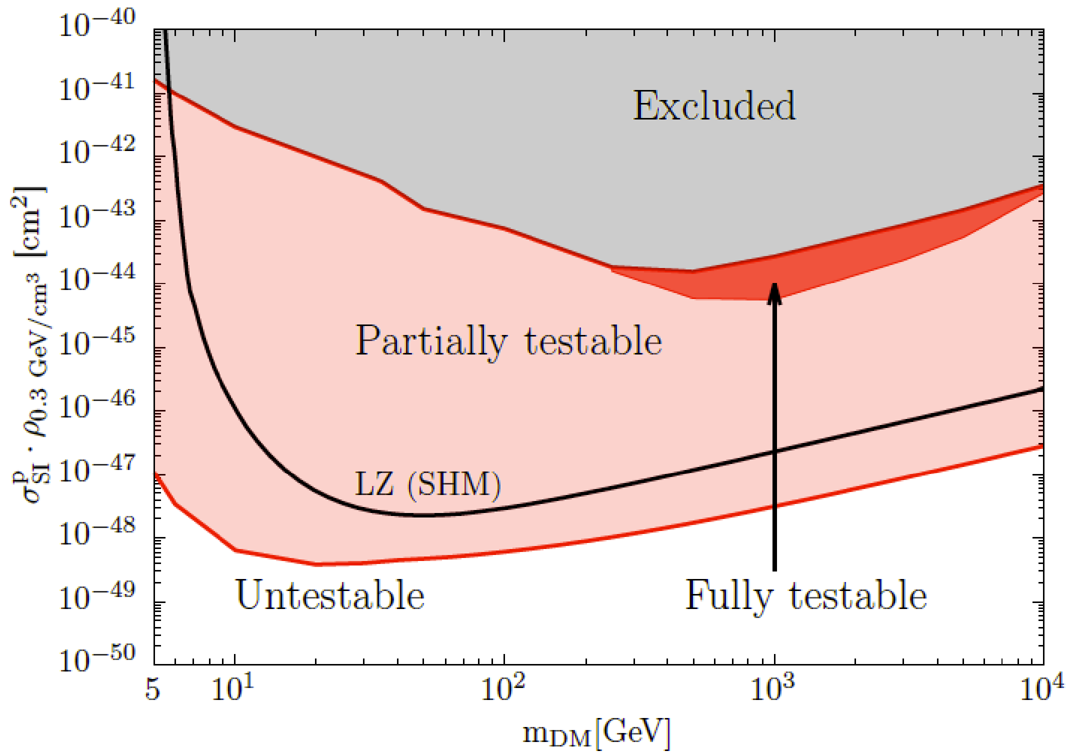
The parameters σ and m_{DM} are fully testable in a halo independent manner if :

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

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

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

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



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.

- 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.