Dark Matter Overview

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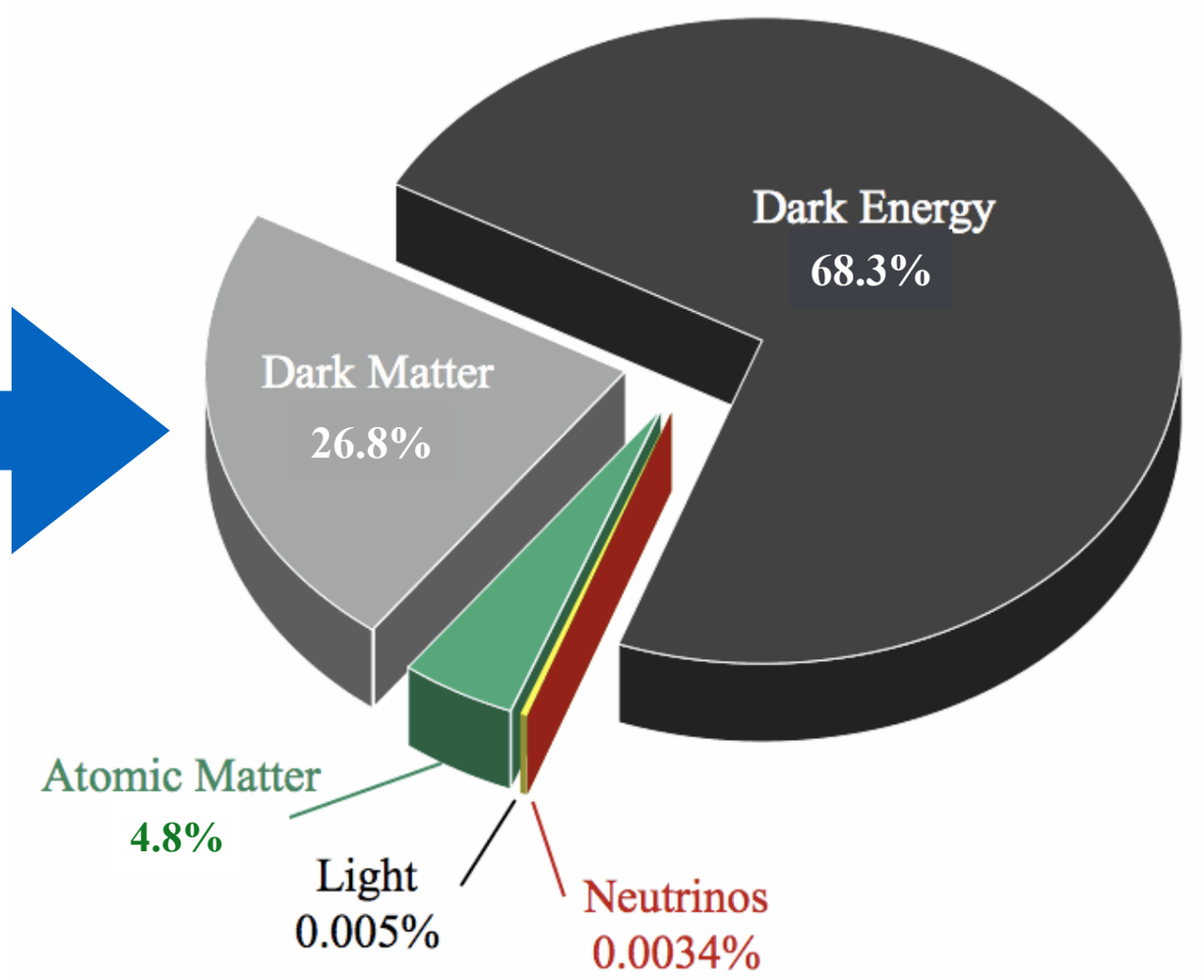
Stony Brook University

MC4BSM, SLAC, 5/12/2017

Dark Matter

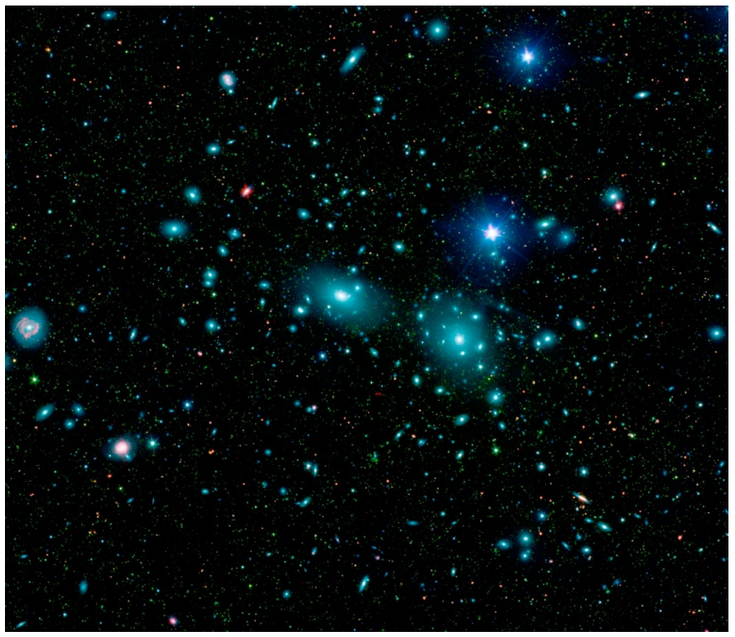
overwhelming evidence for New Physics

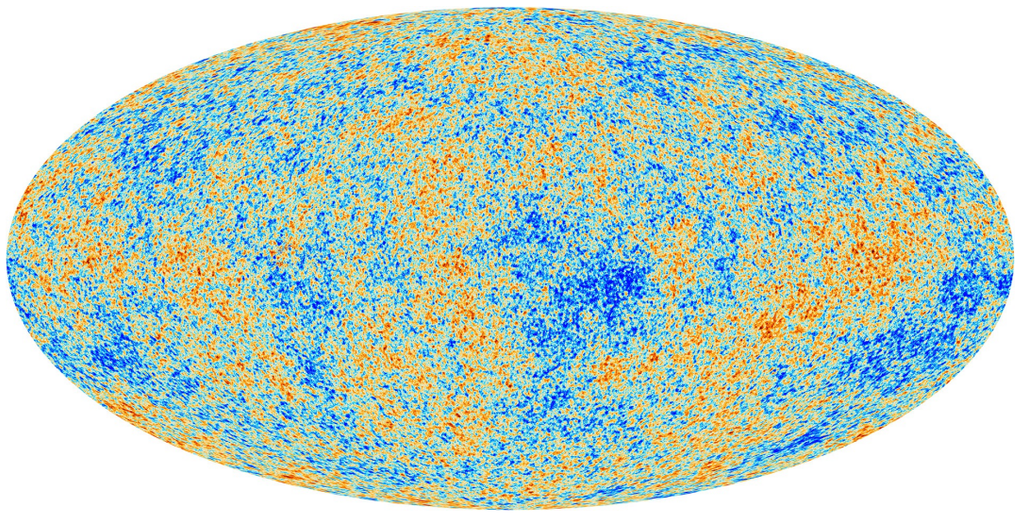
?

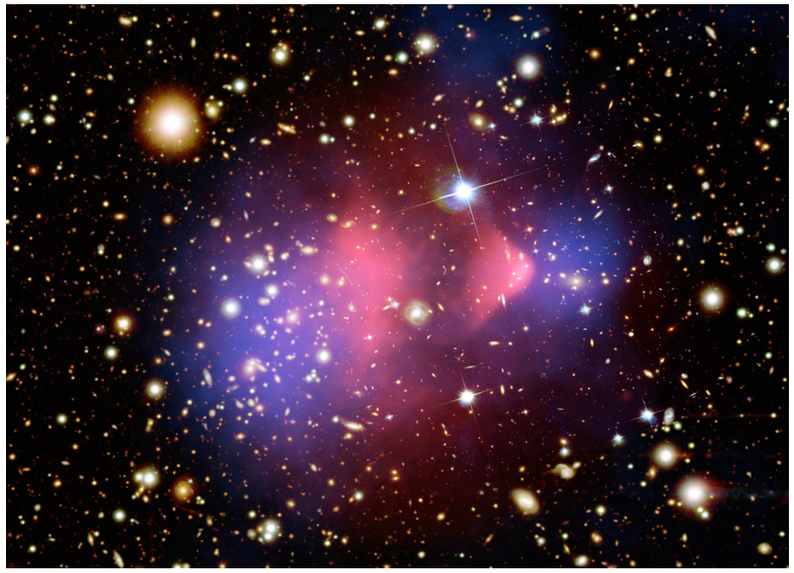


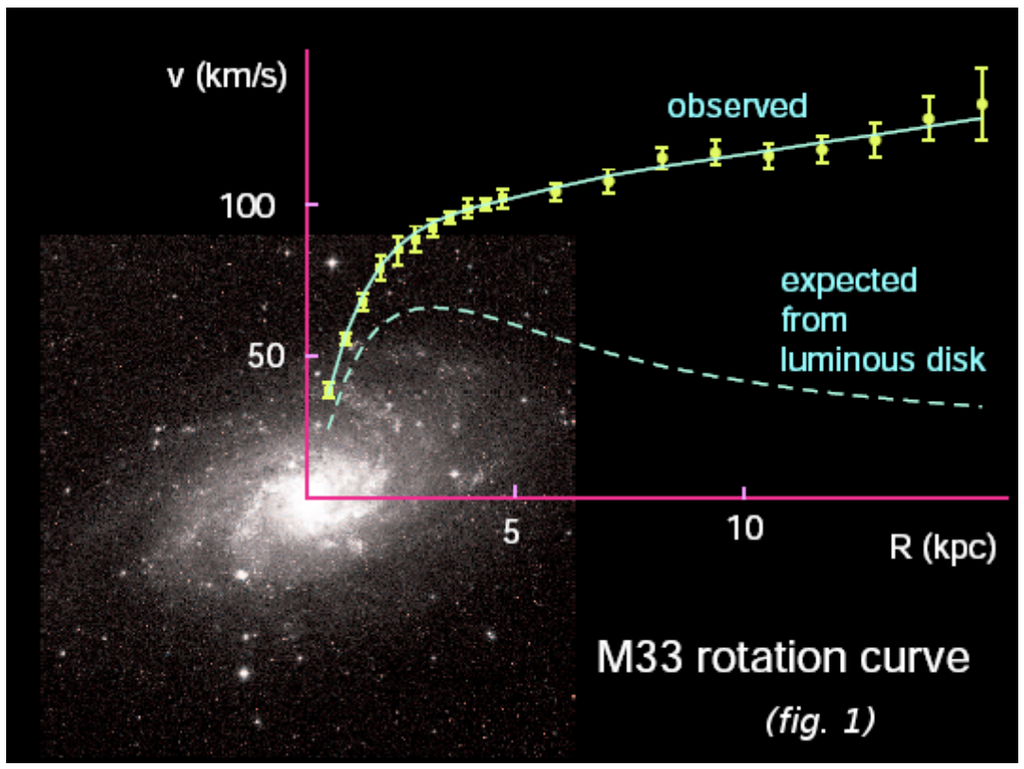
Planck

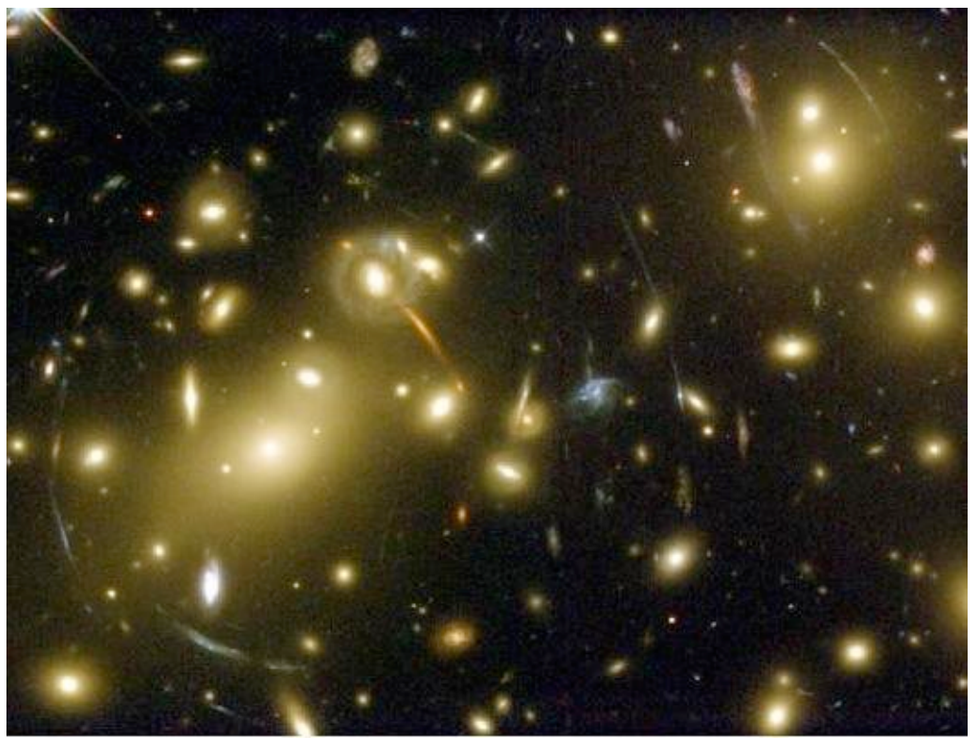
Overwhelming Evidence, for example:



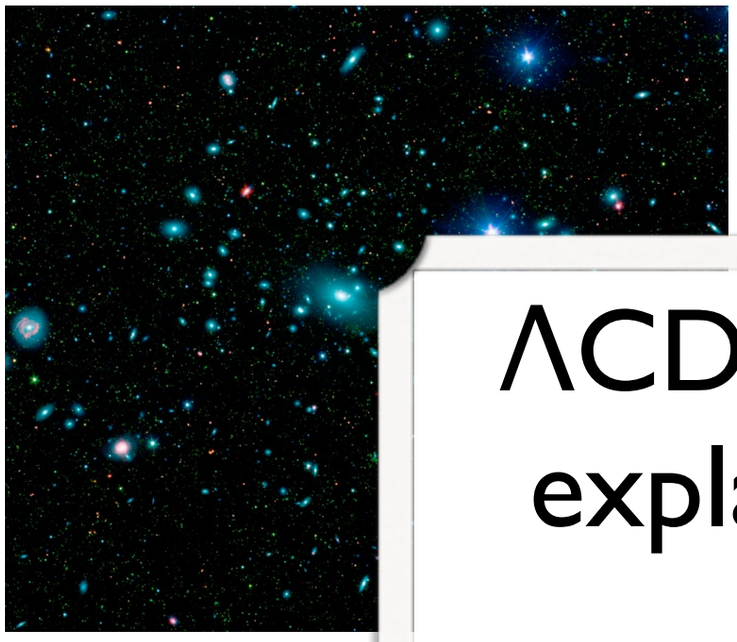


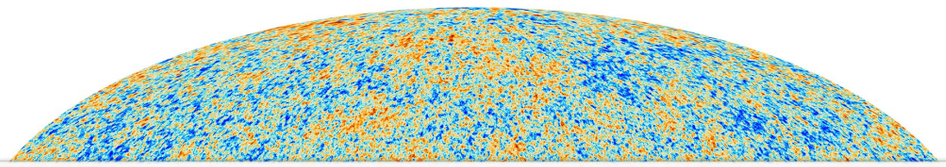






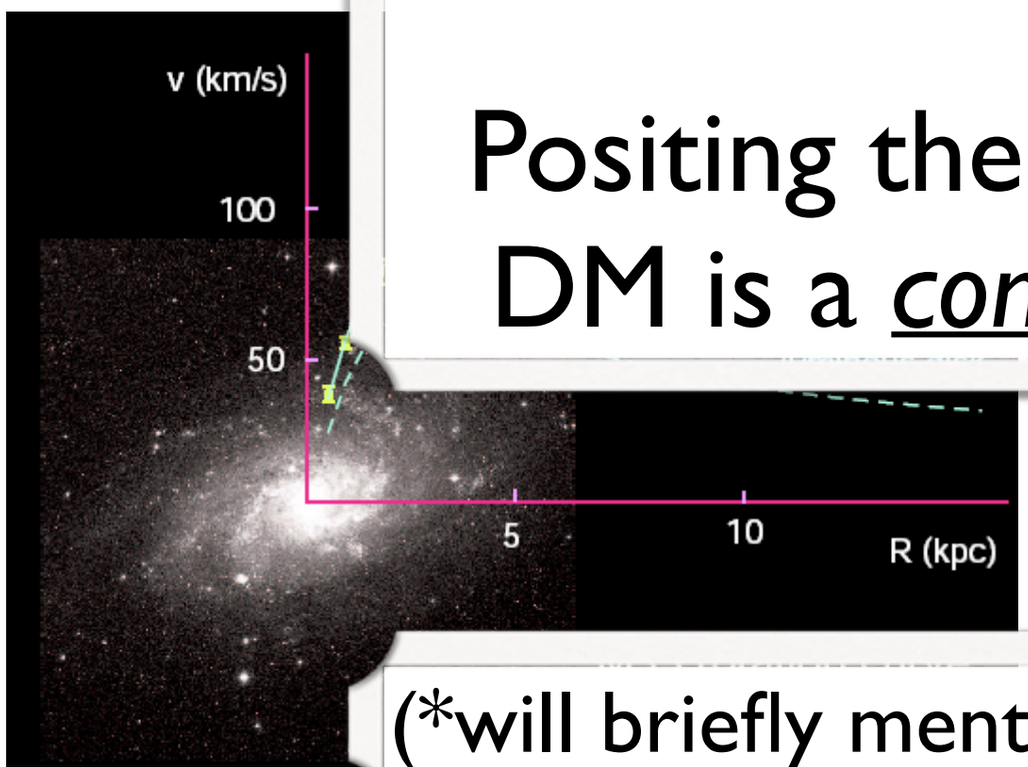
Overwhelming Evidence, for example:

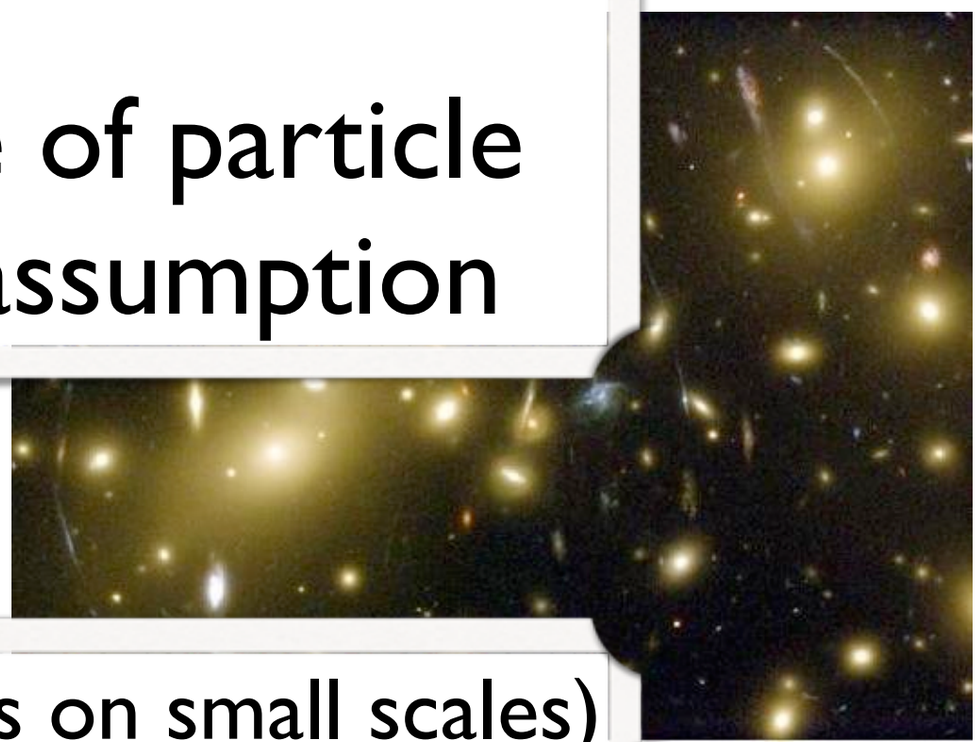




ΛCDM w/ cold, collisionless DM explains observations on scales ~10 kpc* and larger

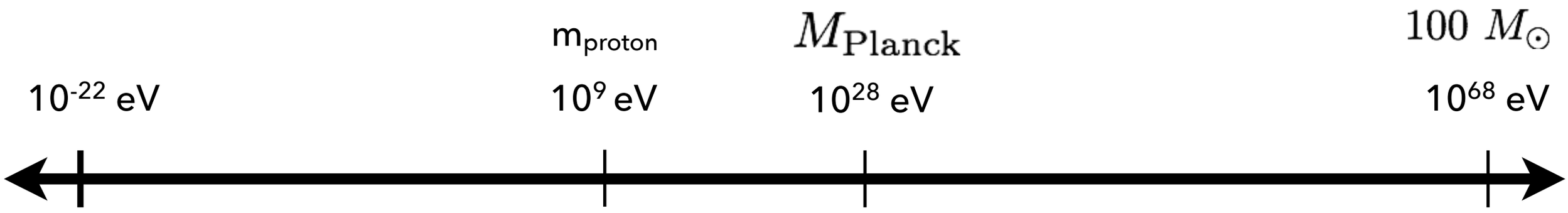
Positing the existence of particle DM is a *conservative* assumption





(*will briefly mention challenges on small scales)

The Dark Matter Landscape



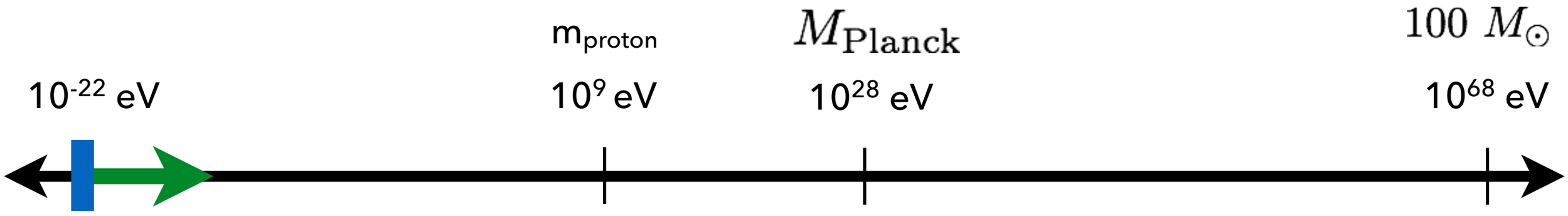
The Dark Matter Landscape

Lower bound on dark matter

de Broglie wavelength: $\lambda \sim \frac{h}{p} \sim \frac{h}{mv} \sim 1\ \text{kpc}$

dwarf galaxies cannot form for lower dark matter masses

The Dark Matter Landscape

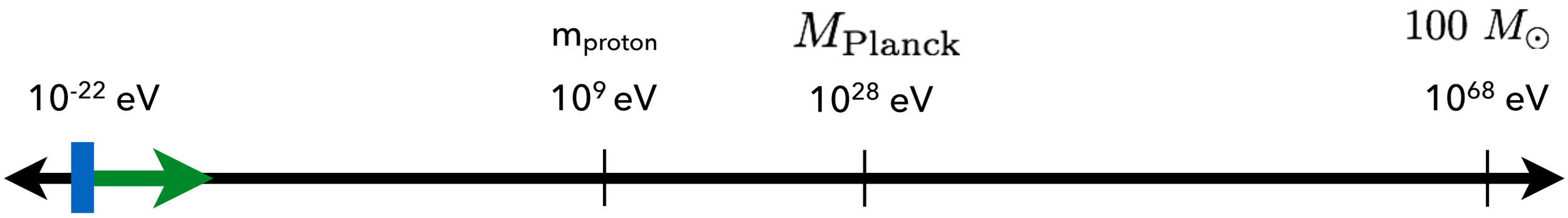


"Fuzzy" Dark Matter

Hu, Barkana, Gruzinov 2000

Hui, Ostriker, Tremaine, Witten 1610.08297

The Dark Matter Landscape



"Fuzzy" Dark Matter

Hu, Barkana, Gruzinov 2000

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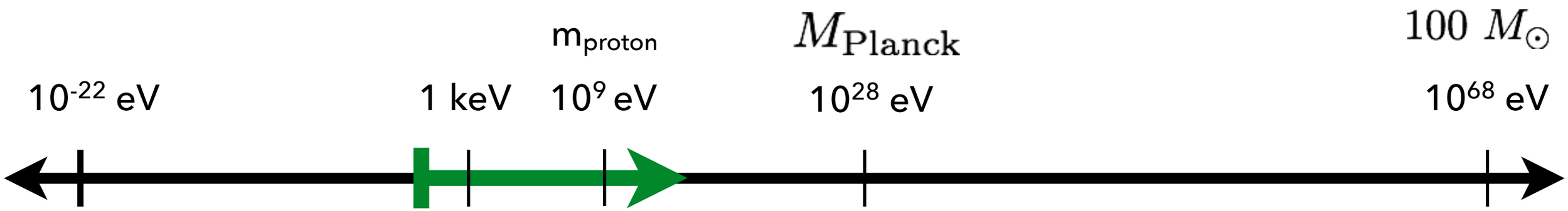
recent bound, using Lyman-α forest: $m_a \gtrsim 29 \times 10^{-22}$

Armengaud, Baur, Marsh, Palanque-Delabrouille, Yeche

The Dark Matter Landscape



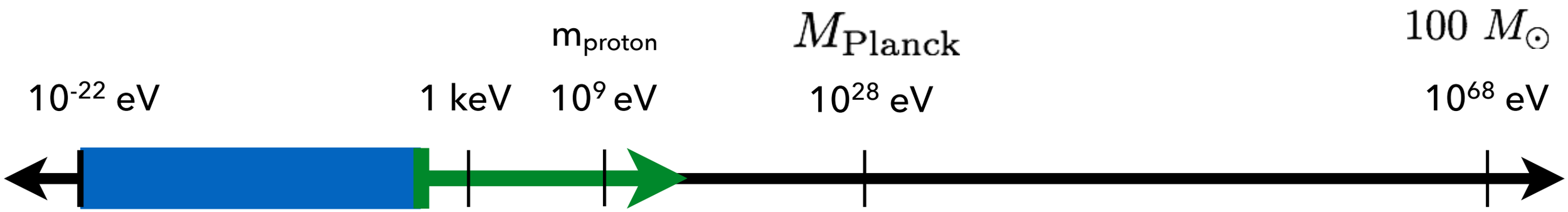
Lower bound on fermionic DM

Fermi repulsion would create too-large cores in dwarf galaxies for $m_\chi \lesssim 70\ \text{eV}$

Tremaine, Gunn 1979

Randall, Scholtz, Unwin 2016

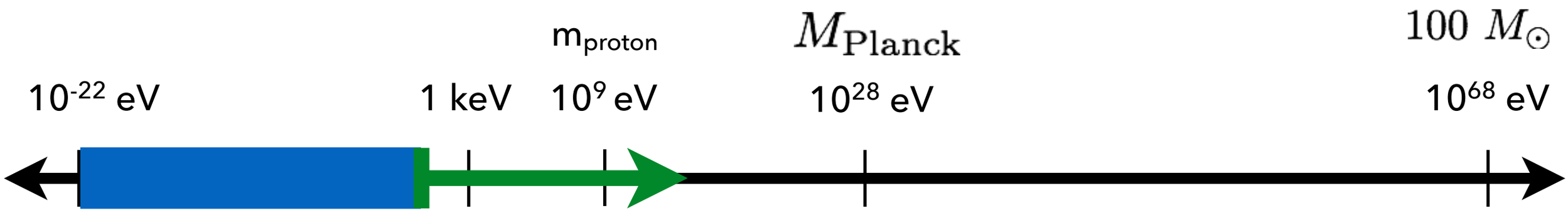
The Dark Matter Landscape



bosonic DM

Lower bound on fermionic DM

The Dark Matter Landscape

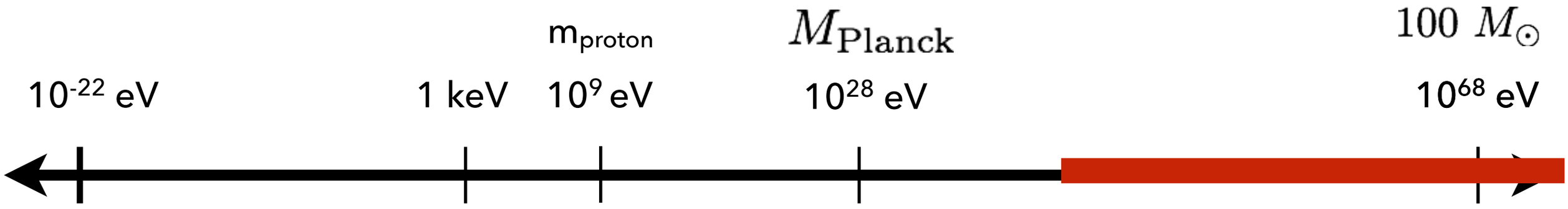


bosonic DM

e.g. QCD axion, other pseudoscalars, scalars, vectors

- high phase-space density
- detect coherent effect of entire field (cf. gravitational wave detectors)
- e.g. ADMX, CASPEr, …

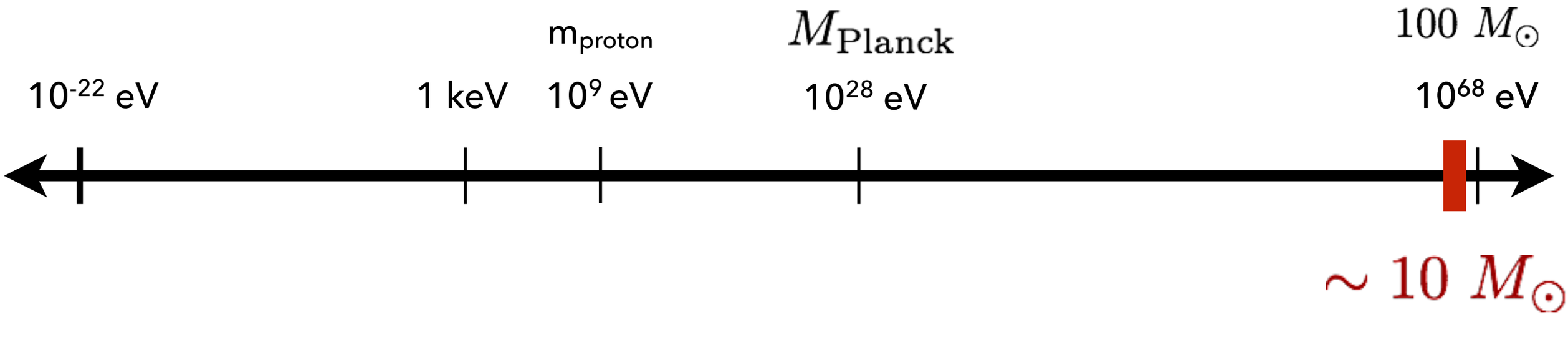
The Dark Matter Landscape



Primordial Black Holes?

Carr, Hawking 1974
Carr 1975

The Dark Matter Landscape



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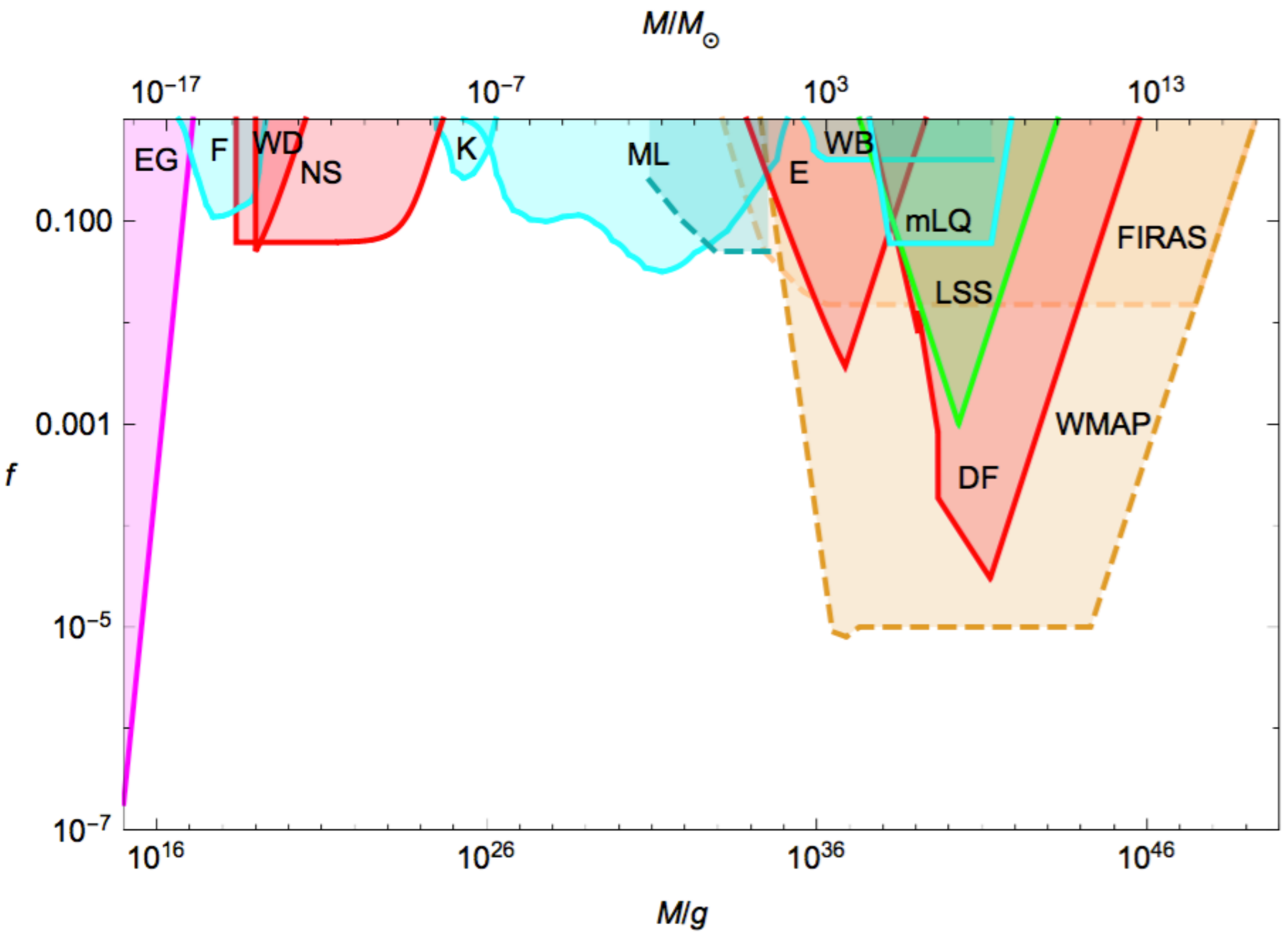
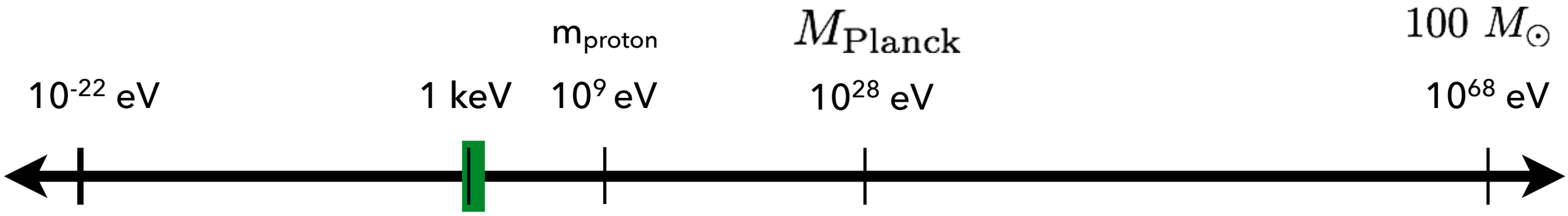
Carr 1975

Did LIGO detect Dark Matter?

Bird et.al. 1603.00464

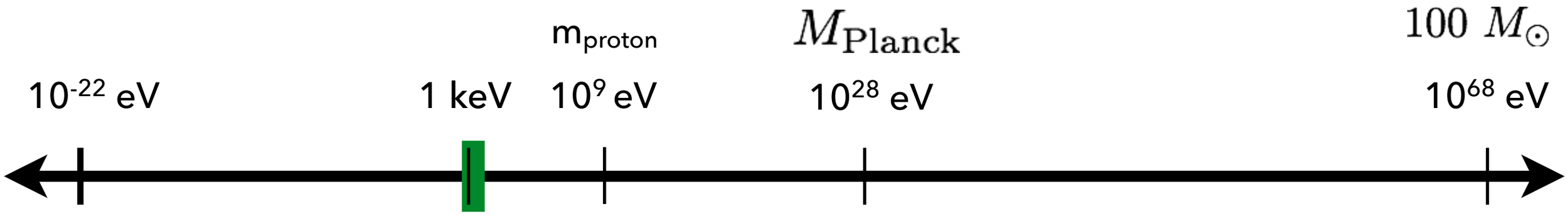

$M/M_\odot$
10^{-17}
10^{-7}
10^{3}
10^{13}
EG
F
WD
NS
K
ML
E
WB
mLQ
FIRAS
LSS
WMAP
DF
0.100
0.001
10^{-5}
10^{-7}
f
10^{16}
10^{26}
10^{36}
10^{46}
M/g

The Dark Matter Landscape



sterile neutrinos at ~few keV

The Dark Matter Landscape

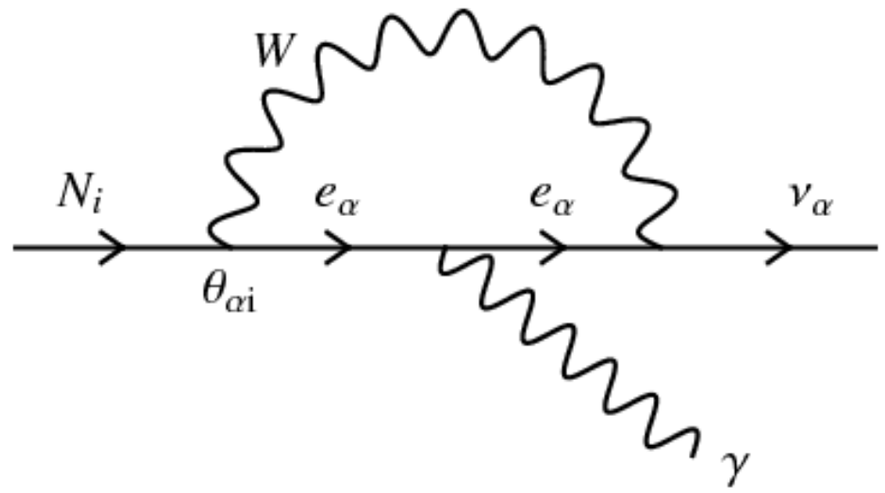


sterile neutrinos at ~few keV

search for X-rays from:

$$\nu_s \to \nu_a + \gamma$$

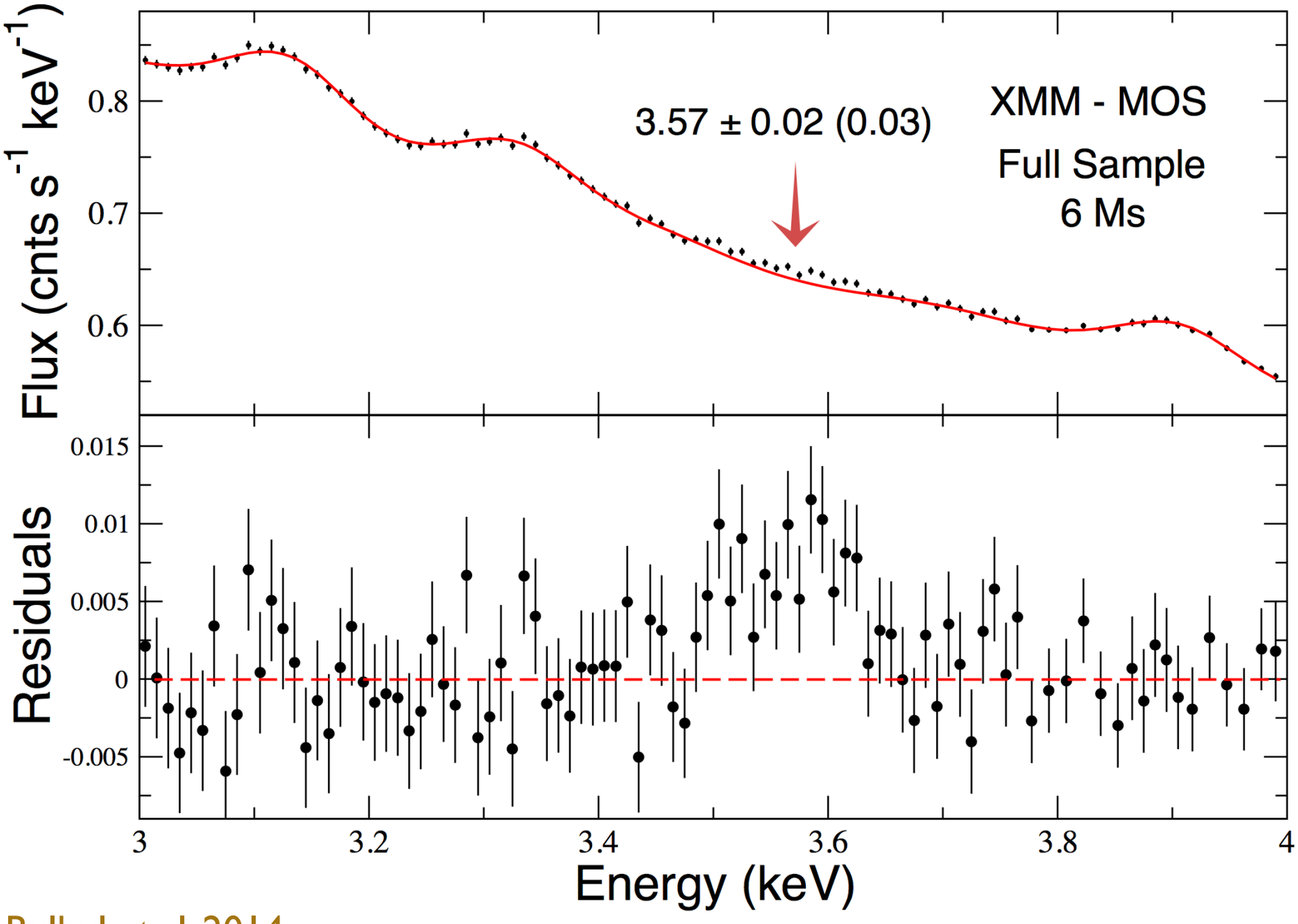
$$E_\gamma = \frac{m_s}{2}$$



Shrock 1974; Pal & Wolfenstein 1981

Abazajian, Fuller & Tucker 2001

X-ray data: evidence for ~7 keV ν_s?

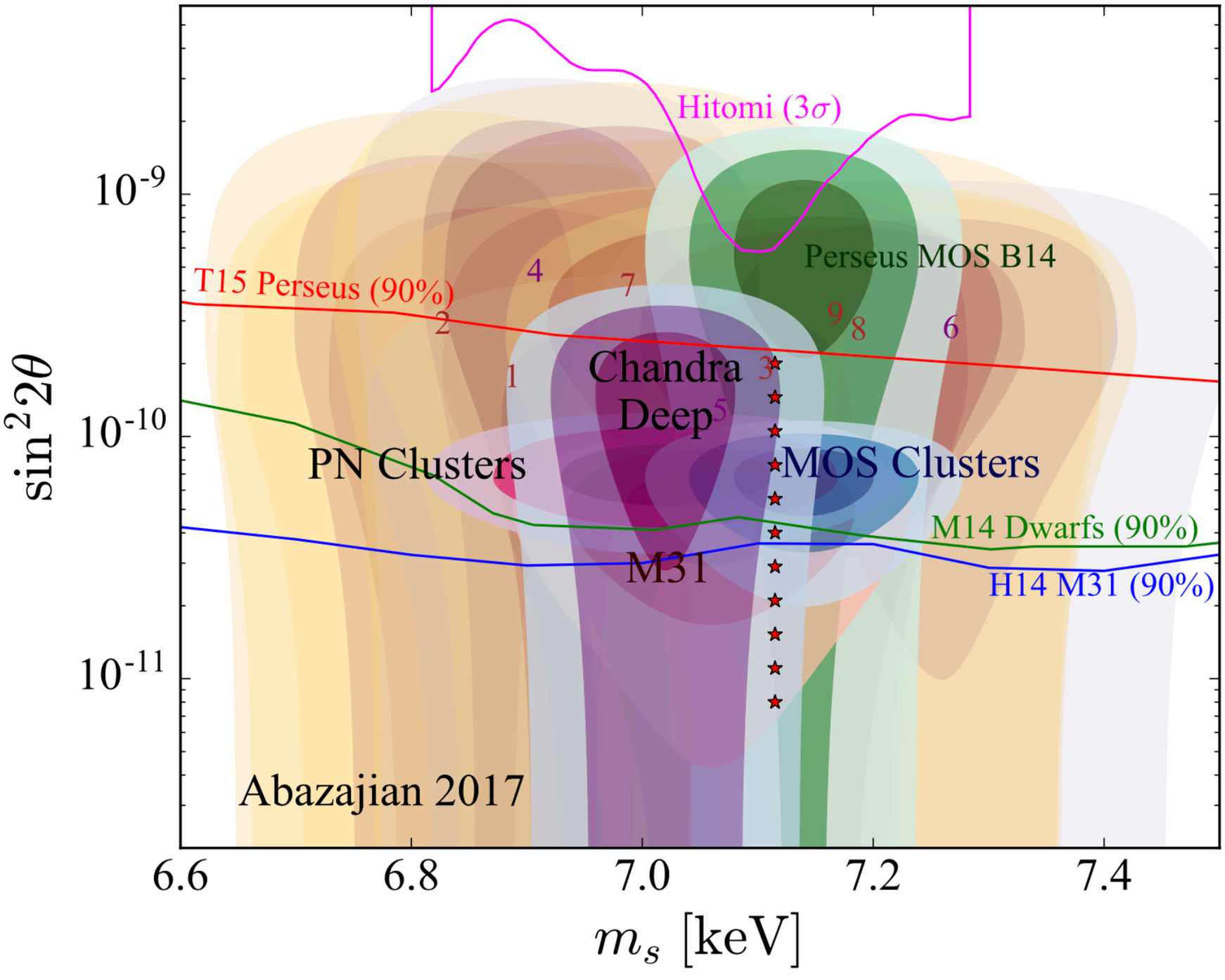


- 73 clusters
- 4-5σ
- XMM-Newton

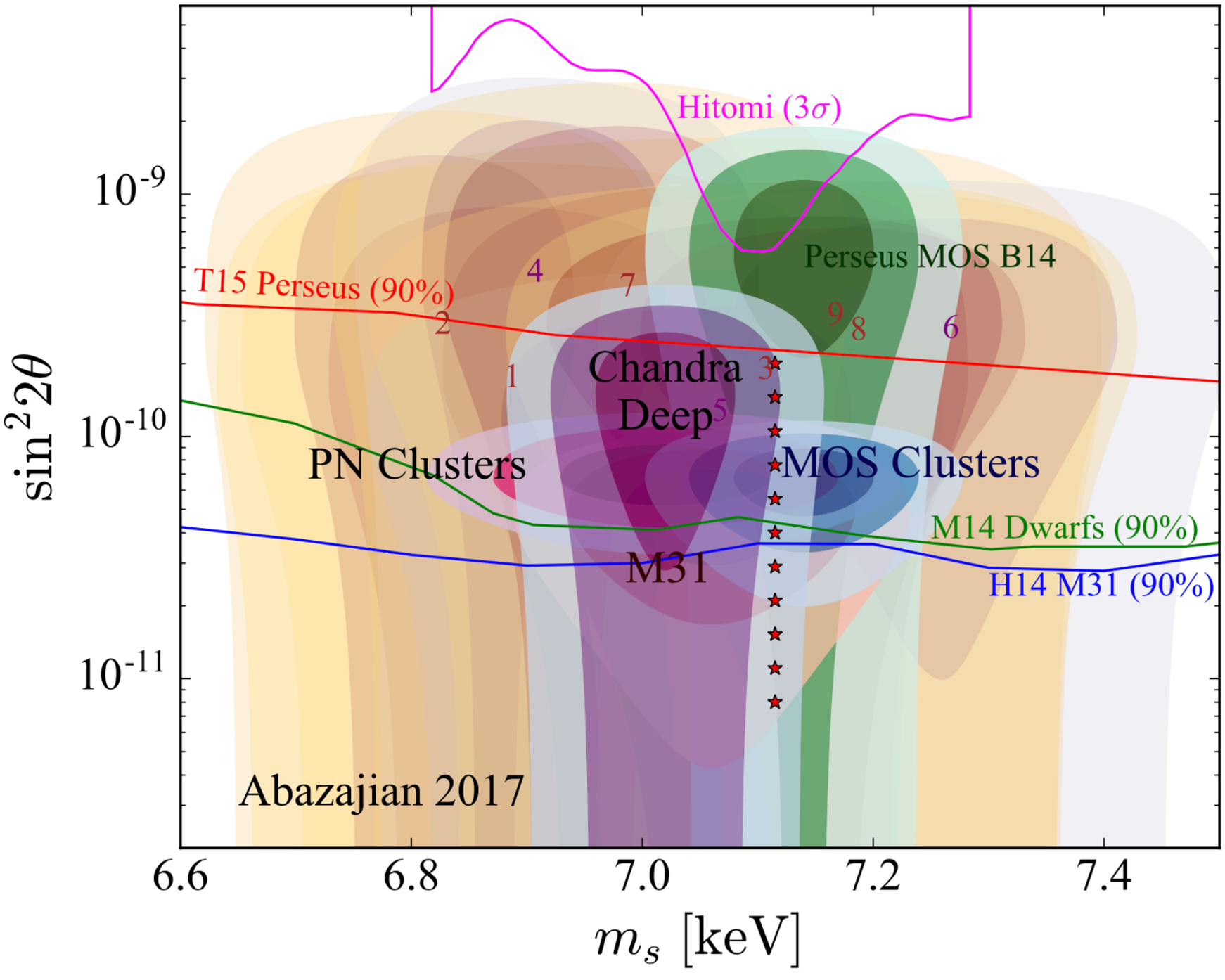
Bulbul et.al. 2014

this was followed by several other claims of detection…

Anomalies and constraints near 7 keV



Anomalies and constraints near 7 keV



seen w/ XMM-Newton (clusters, M31, Perseus, MW-GC), Chandra (Perseus, deep field), SUZAKU X-ray space telescope (Perseus, etc)

So what does it mean?

- v_s ?

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  But should have seen large partner lines…

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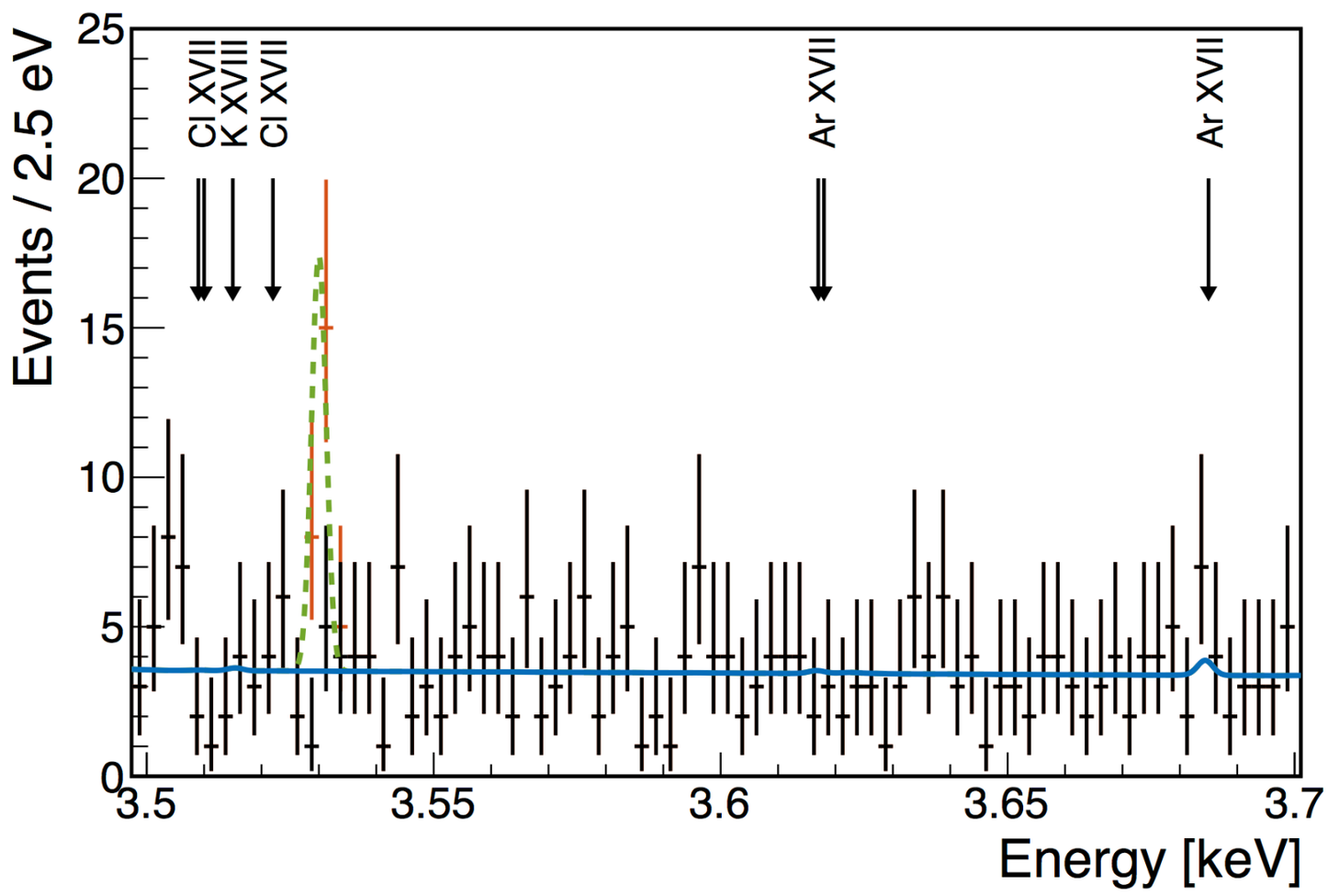
  - Micro-X, XQC (sounding rocket, ~2017/8)

Figueroa-Feliciano et.al.



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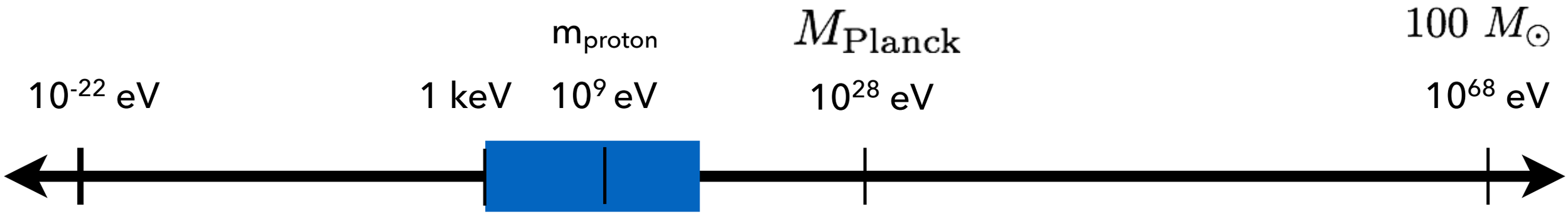
- Stay tuned!

The Dark Matter Landscape



thermal DM

~1 keV to 100 TeV

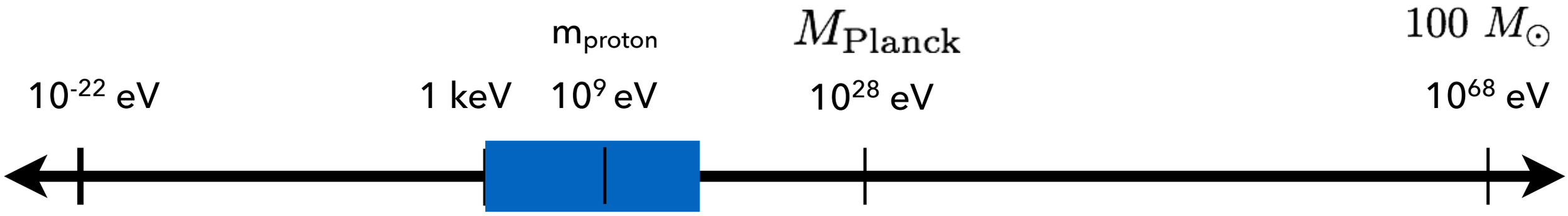
$m_{\rm DM} \gtrsim 1\ {\rm keV}$

otherwise, no structure smaller than dwarf galaxies

$m_{\rm DM} \lesssim 100\ {\rm TeV}$

otherwise, too much dark matter

The Dark Matter Landscape



But many other possible models, including asymmetric, freeze-in, SIMP, ELDER, Cannibal, Forbidden, …

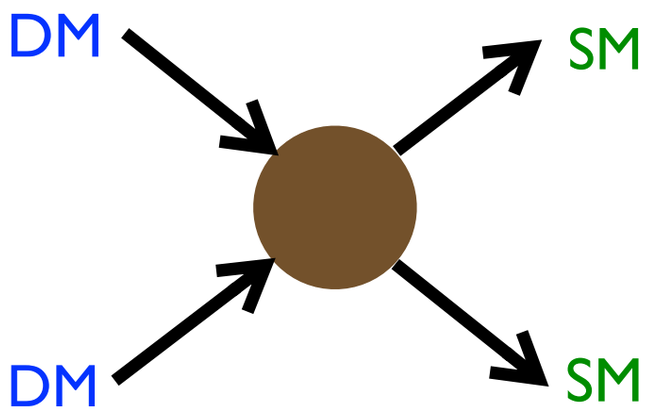
Kaplan, Luty, Zurek; Hall, Jedamzik, March-Russell, West; Falkowski, Ruderman, Volansky; Hochberg, Kuflik, Volansky, Wacker; +Murayama; Kuflik, Lorier, Perelstein, Tsai; Farina, Pappadopulo, Ruderman, Trevisan; D'Agnolo, Ruderman

Dark sectors

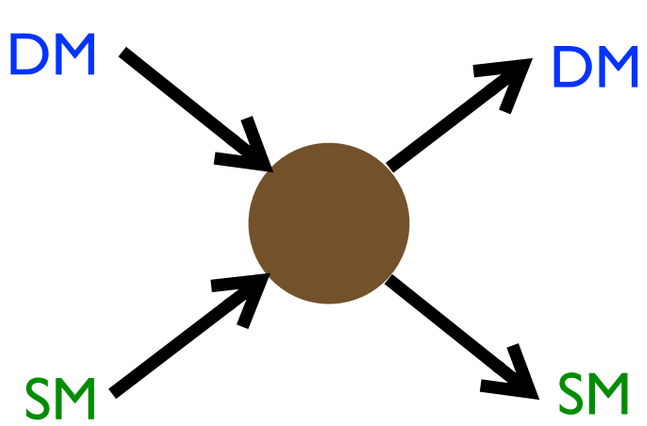
(DM + new mediators)

WIMPs

Searching for WIMPs



Indirect Detection



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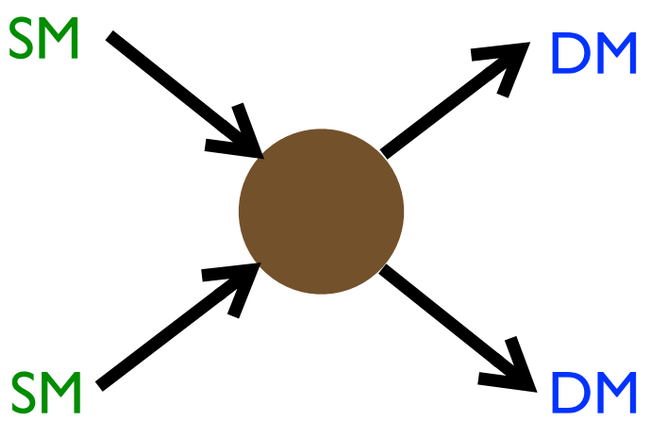
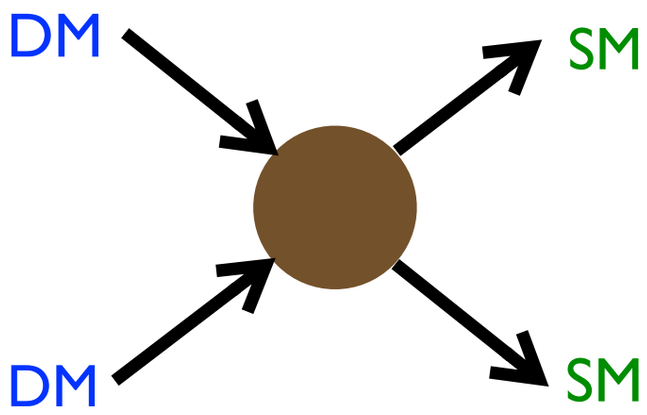
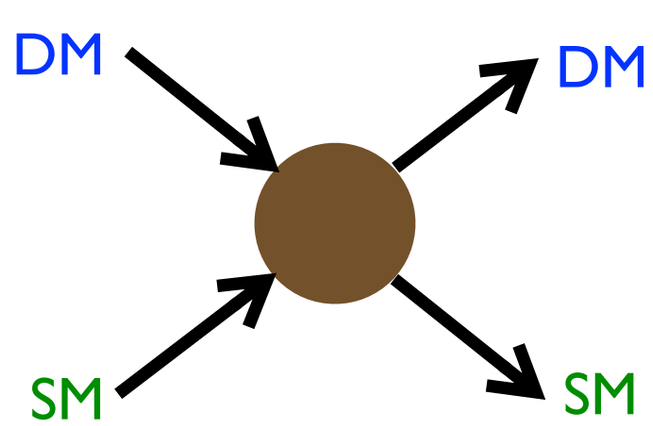


Colliders

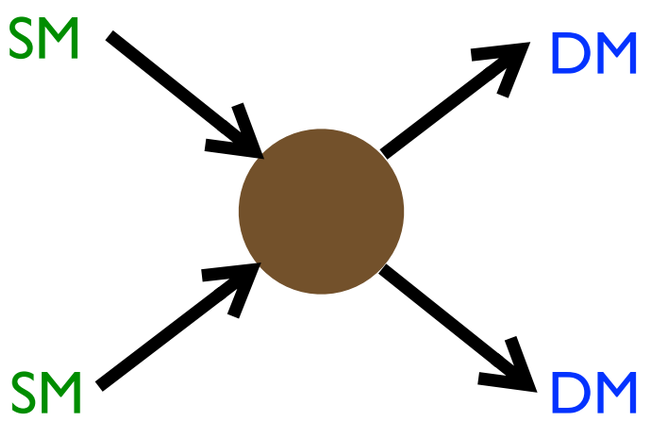
Searching for WIMPs



Indirect Detection



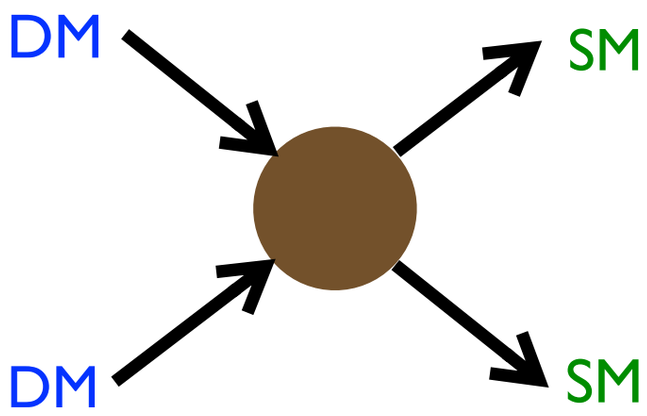
Direct Detection



Colliders

Status summary

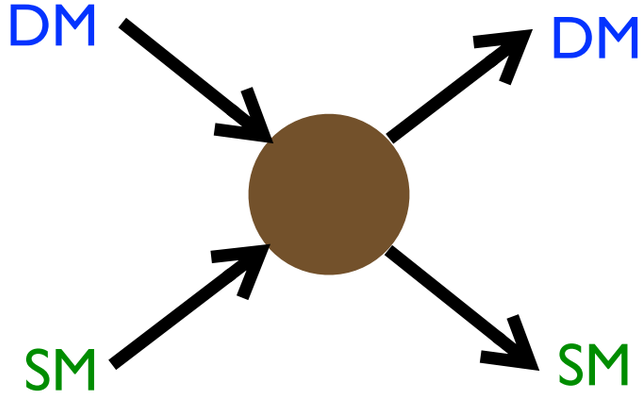
Searching for WIMPs



Indirect Detection

Status summary

Constraints!



Direct Detection

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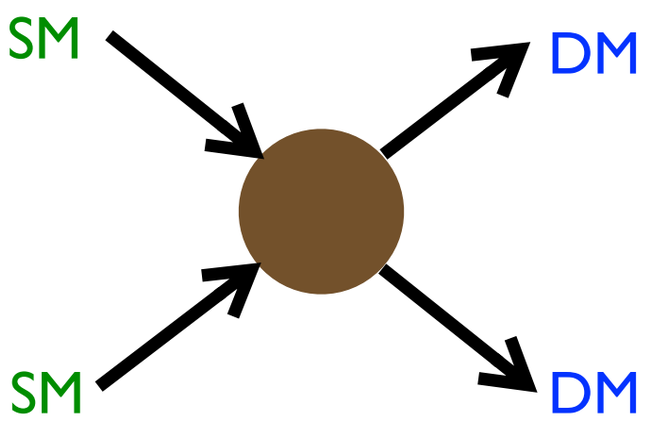

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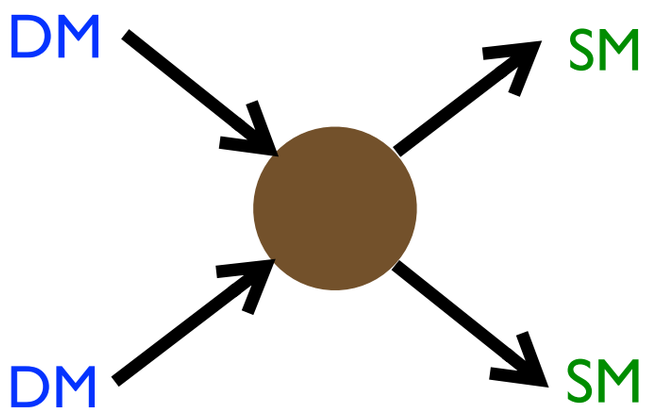
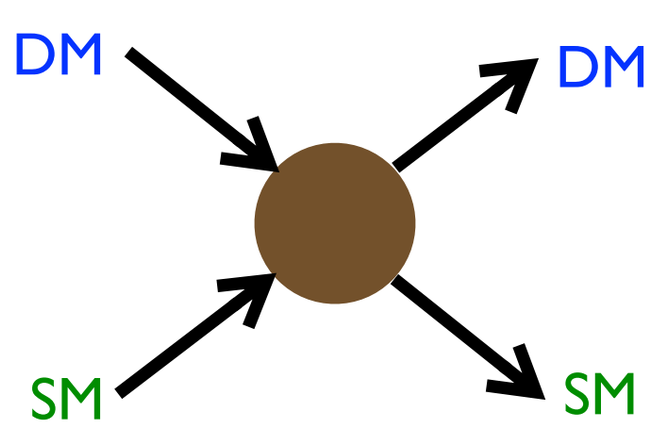


Indirect Detection

Status summary

Constraints!

GC excess is interesting (won't review)



Direct Detection

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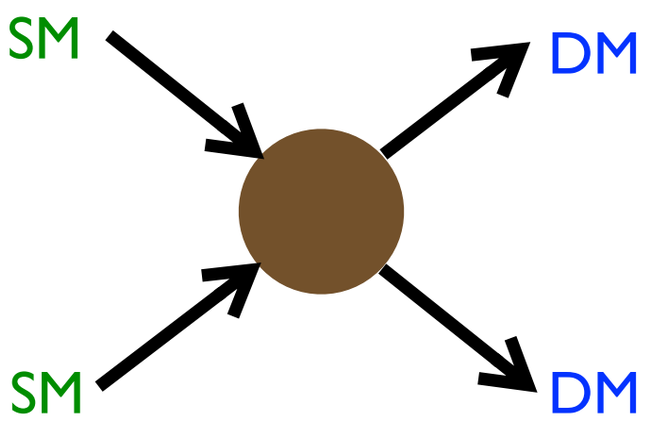
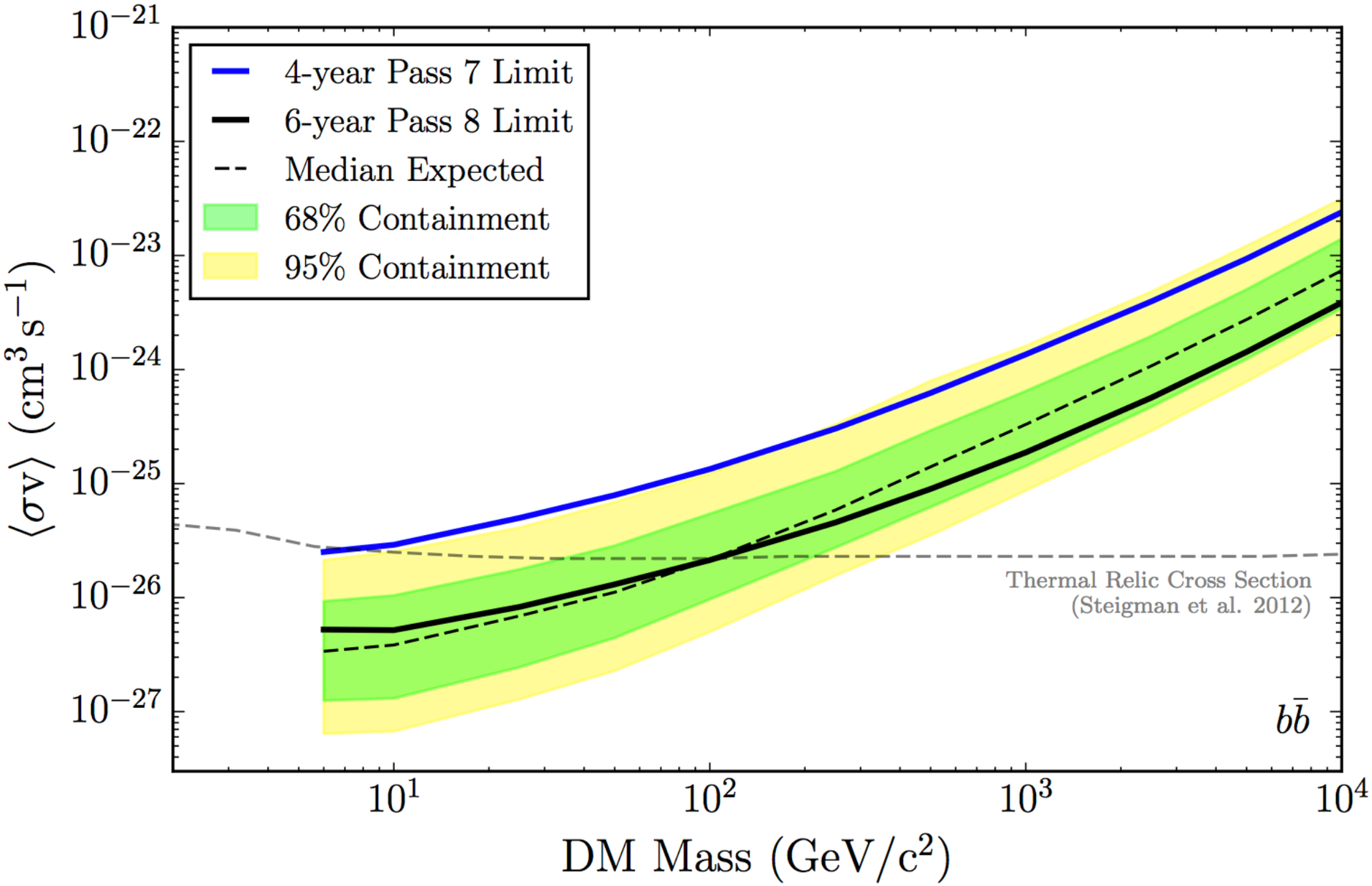


Colliders

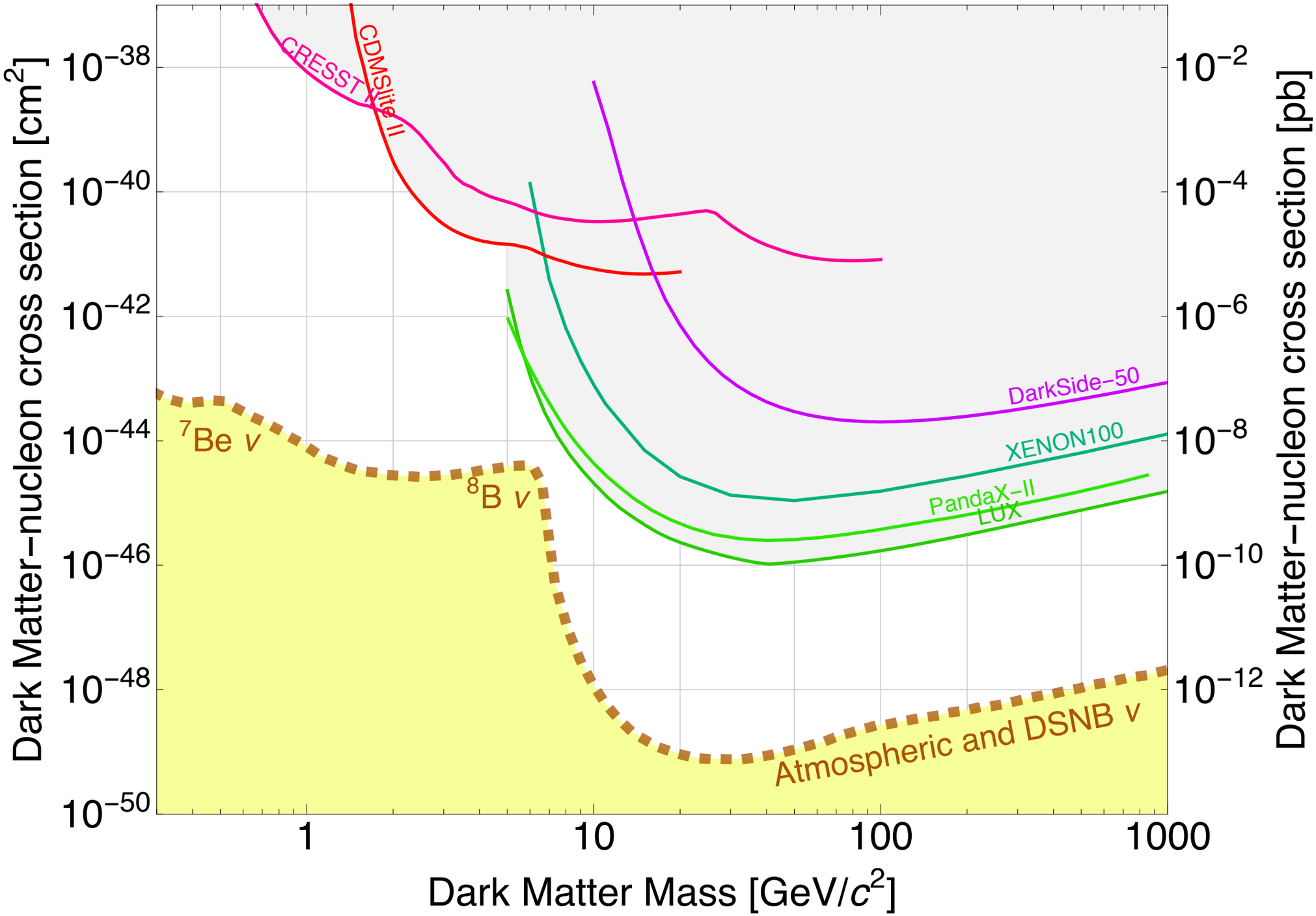
Constraints!

Indirect detection constraints from dwarf galaxies probe WIMPs



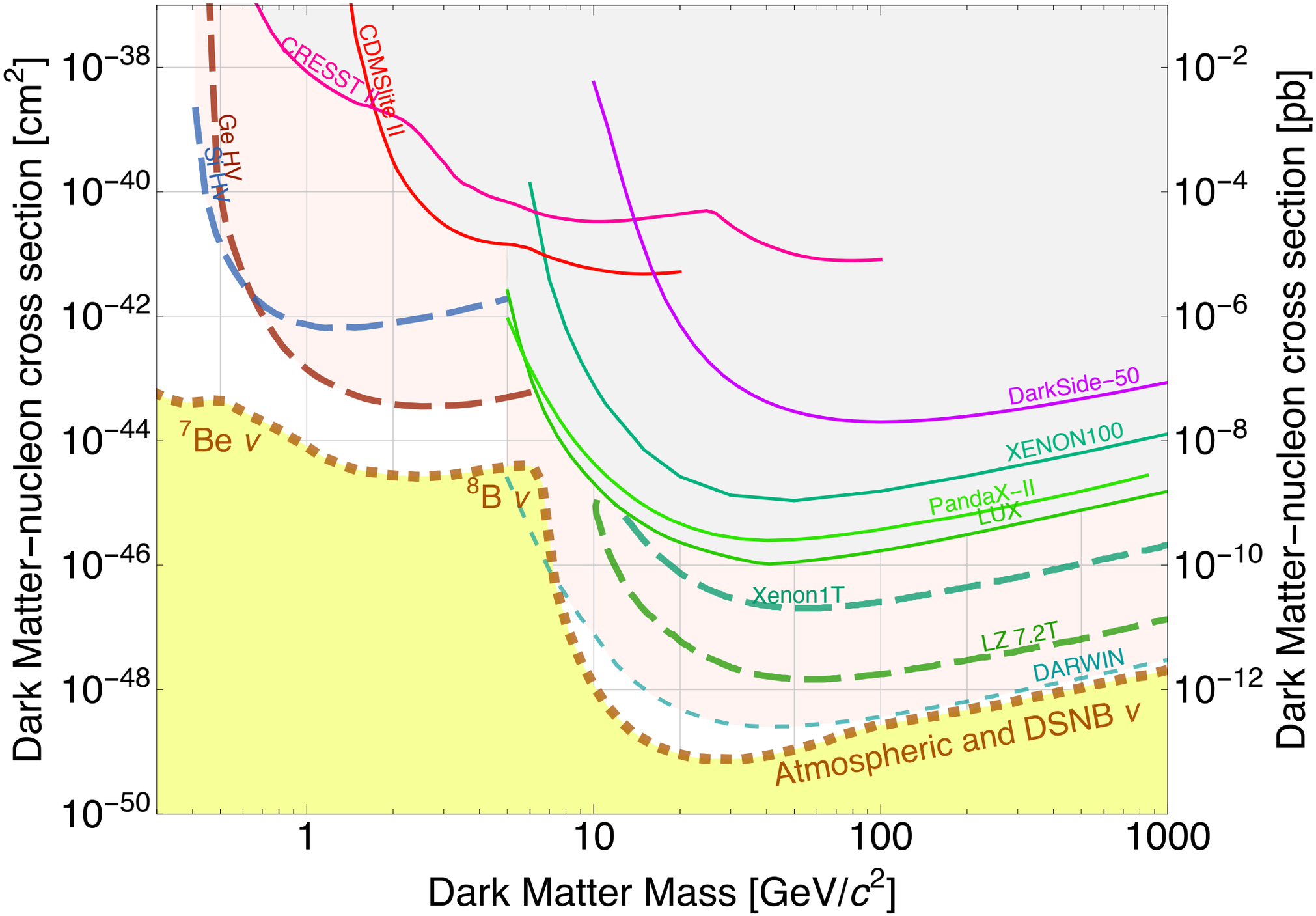
Fermi LAT collaboration

Direct detection: limits



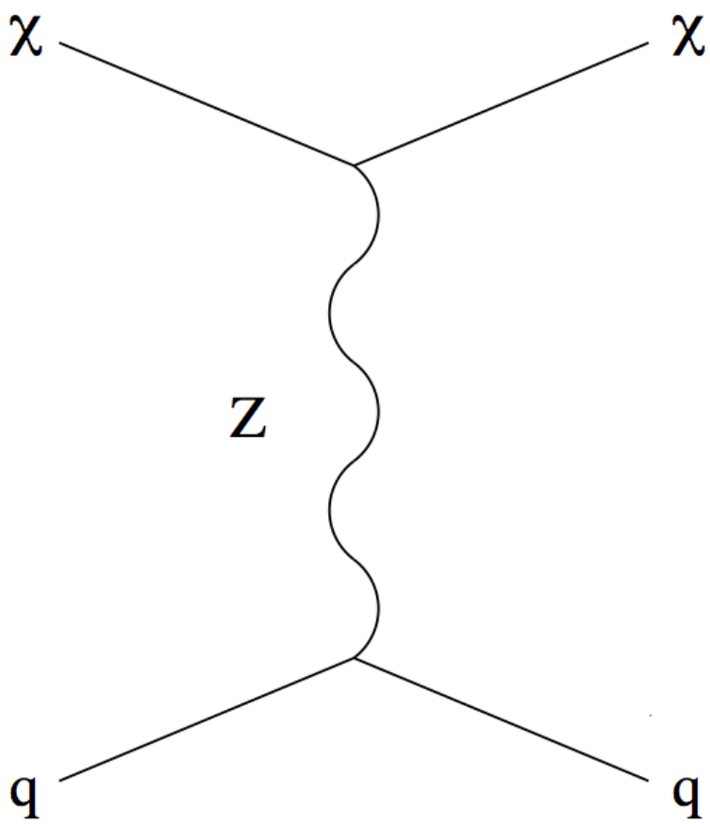
WIMP limit plotter: Saab & Figueroa

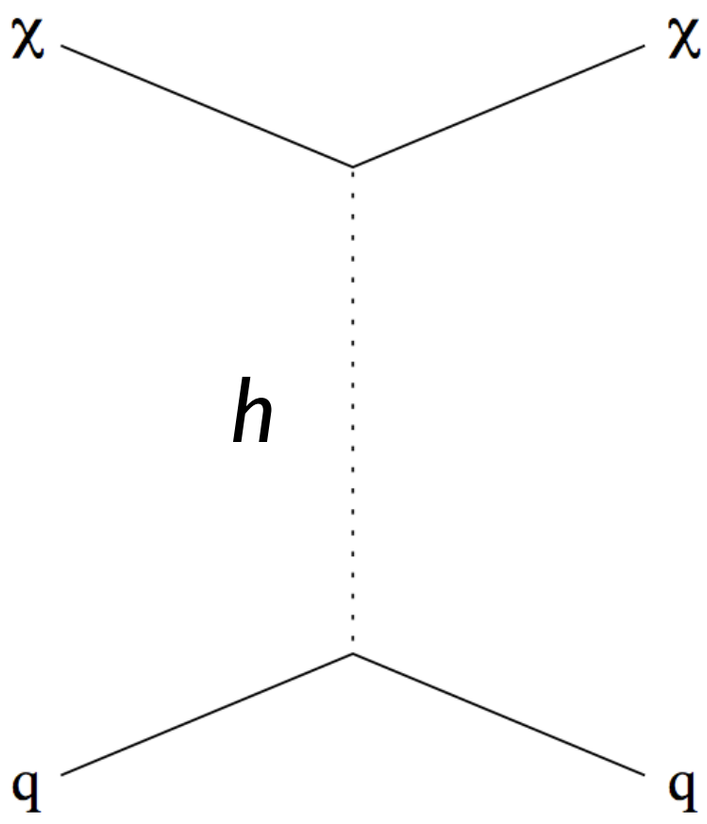
Direct detection: projections

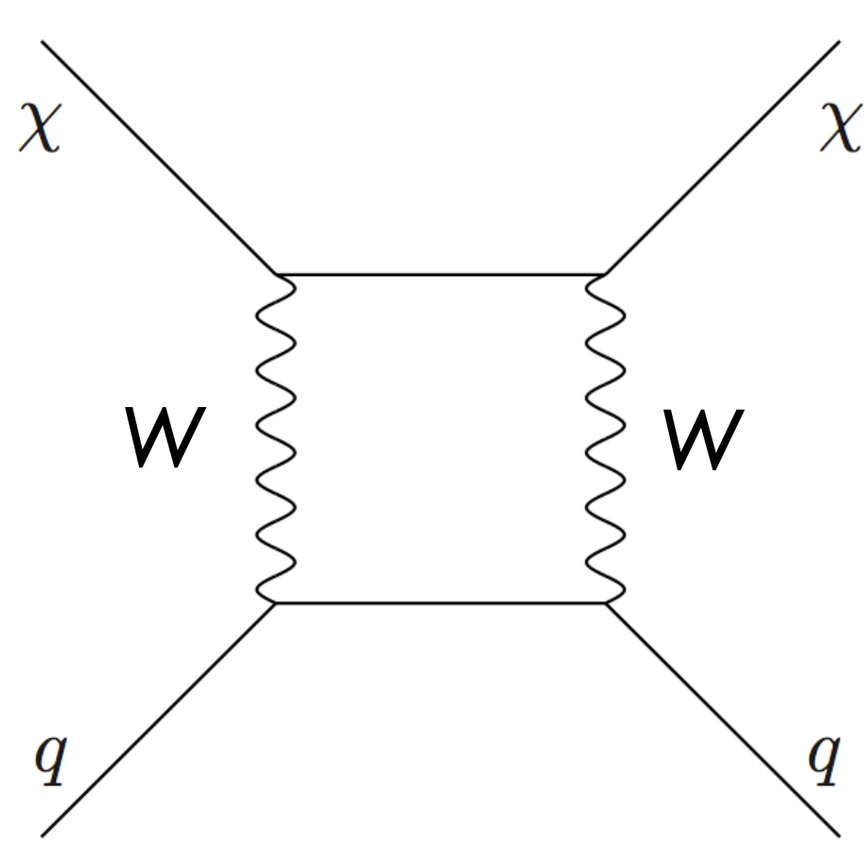


WIMP limit plotter: Saab & Figueroa

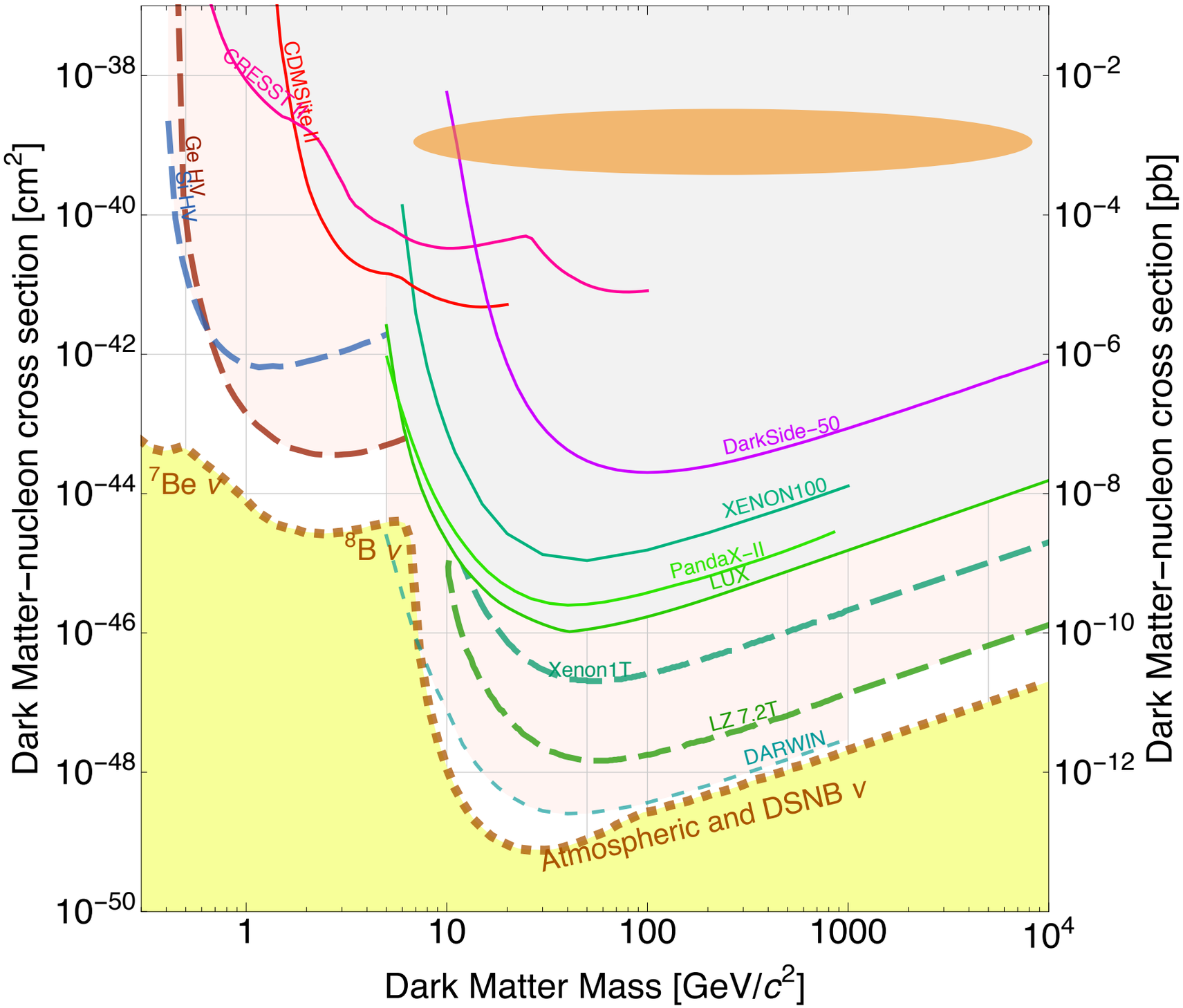
What cross sections do we expect for a WIMP?

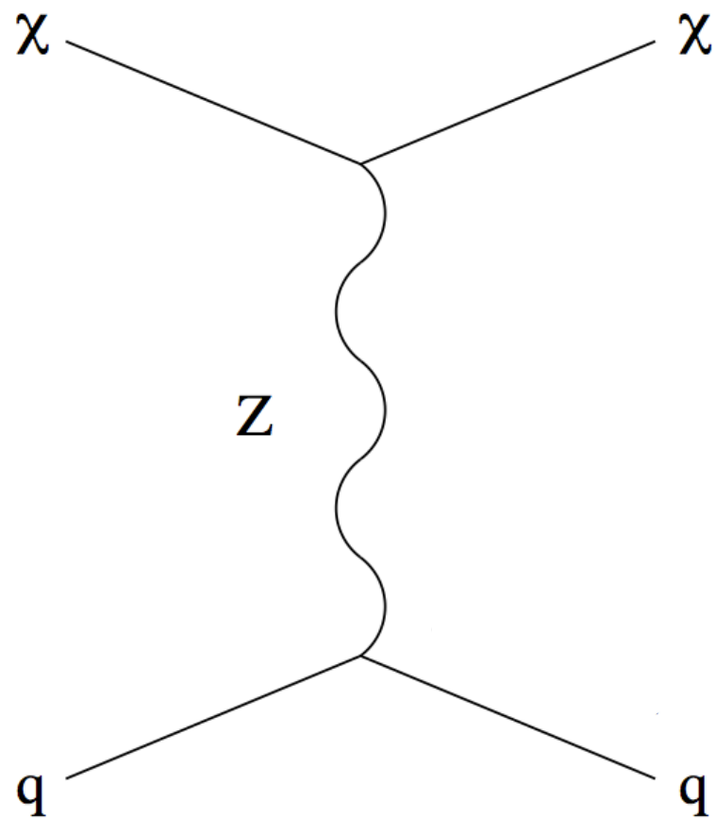






Probing WIMPs

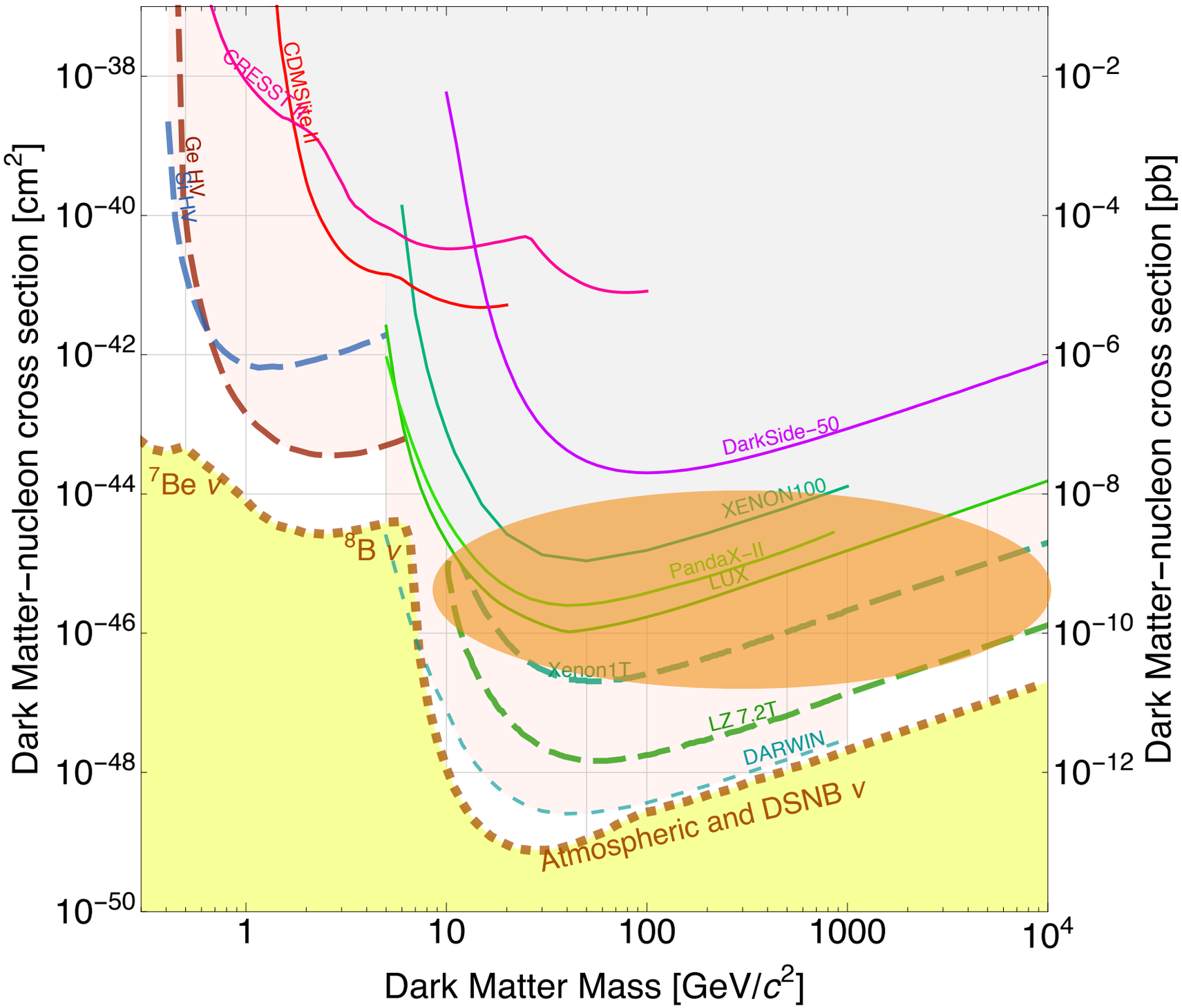


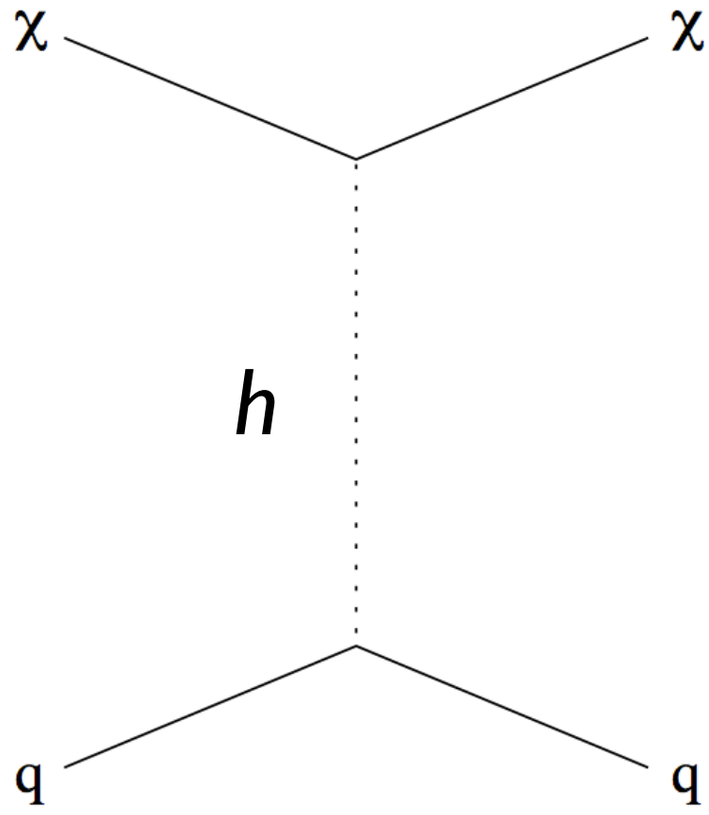


ruled out long ago…

WIMP limit plotter: Saab & Figueroa

Probing WIMPs



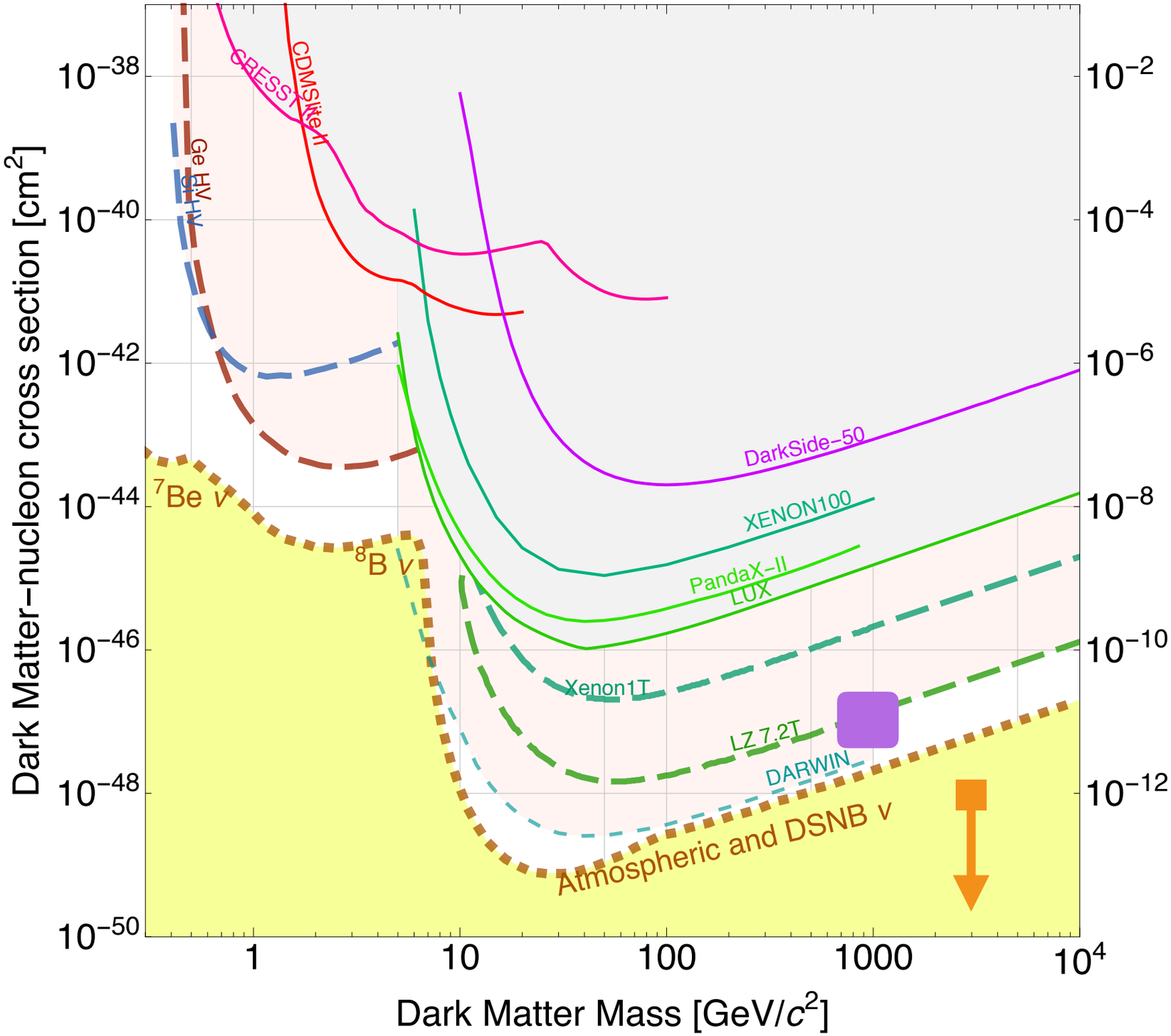


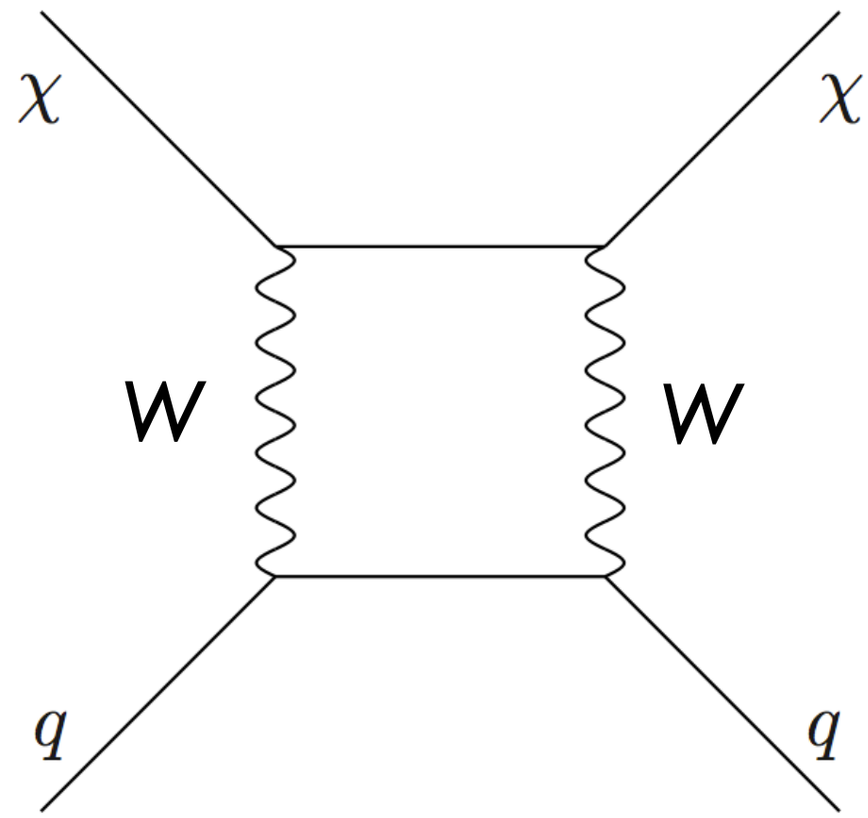
We're probing this range now!

(also expect SUSY models here)

WIMP limit plotter: Saab & Figueroa

Probing WIMPs





SU(2) triplet, Y=0: probably

SU(2) doublet, Y=1/2: unlikely

WIMP limit plotter: Saab & Figueroa

Cirelli, Strumia, Tamburini; Hill, Solon

WIMPs remain motivated… but…

- no convincing evidence for WIMPs (yet)

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- "small-scale crisis" of cold DM

Theory community has recently largely focused on beyond WIMPs

ΛCDM crisis on galactic scales (<10-100 kpc):

- Core vs cusp — e.g. Navarro et al. 1997
- Diversity of rotation curves — Oman et.al., 2015
- Too big too fail — e.g. Boylan-Kolchin et.al. 2011
- Missing satellites — e.g. Klypin et al. 1999; Moore et.al. 1999

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Resolution?

- Baryons?
- Warm Dark Matter?
- Self-interacting Dark Matter? — Spergel, Steinhardt 1999

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CDM, WDM, & SIDM all need to be simulated w/ baryons — work in progress by several groups

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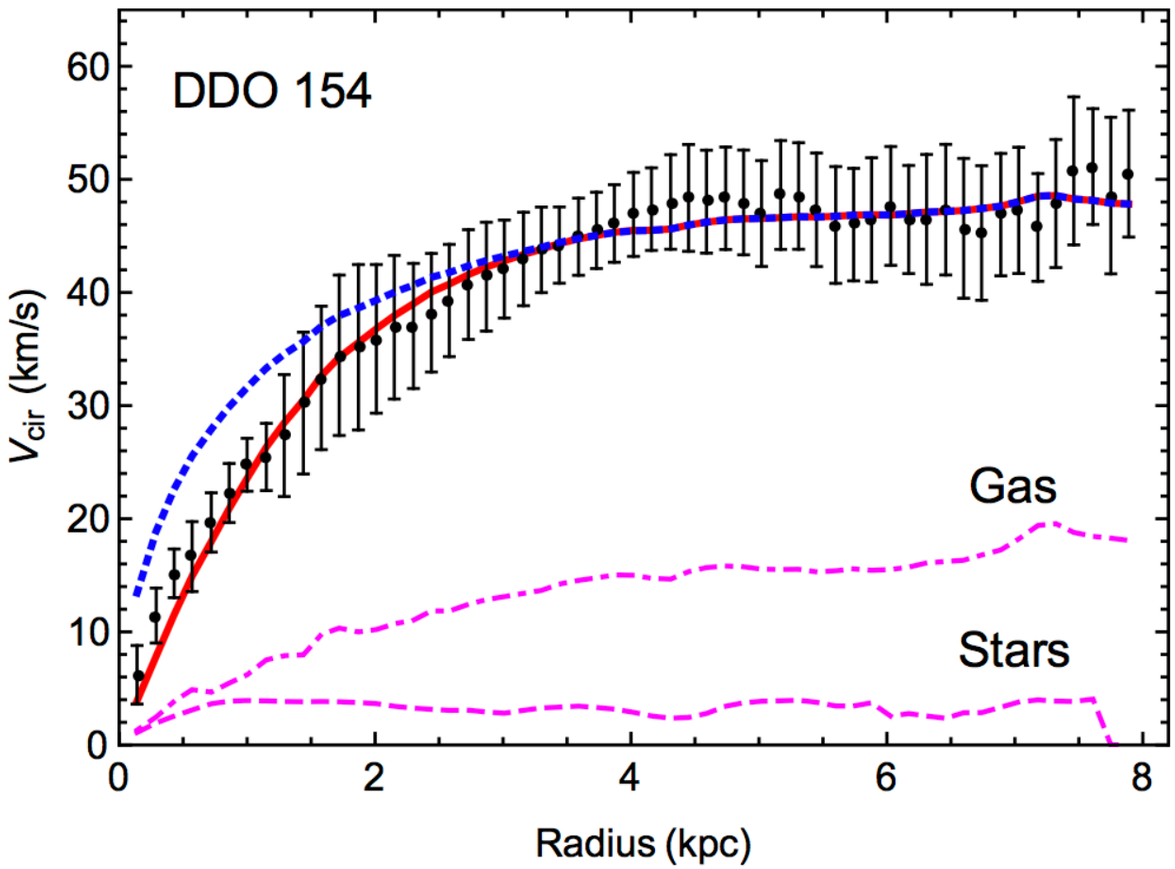
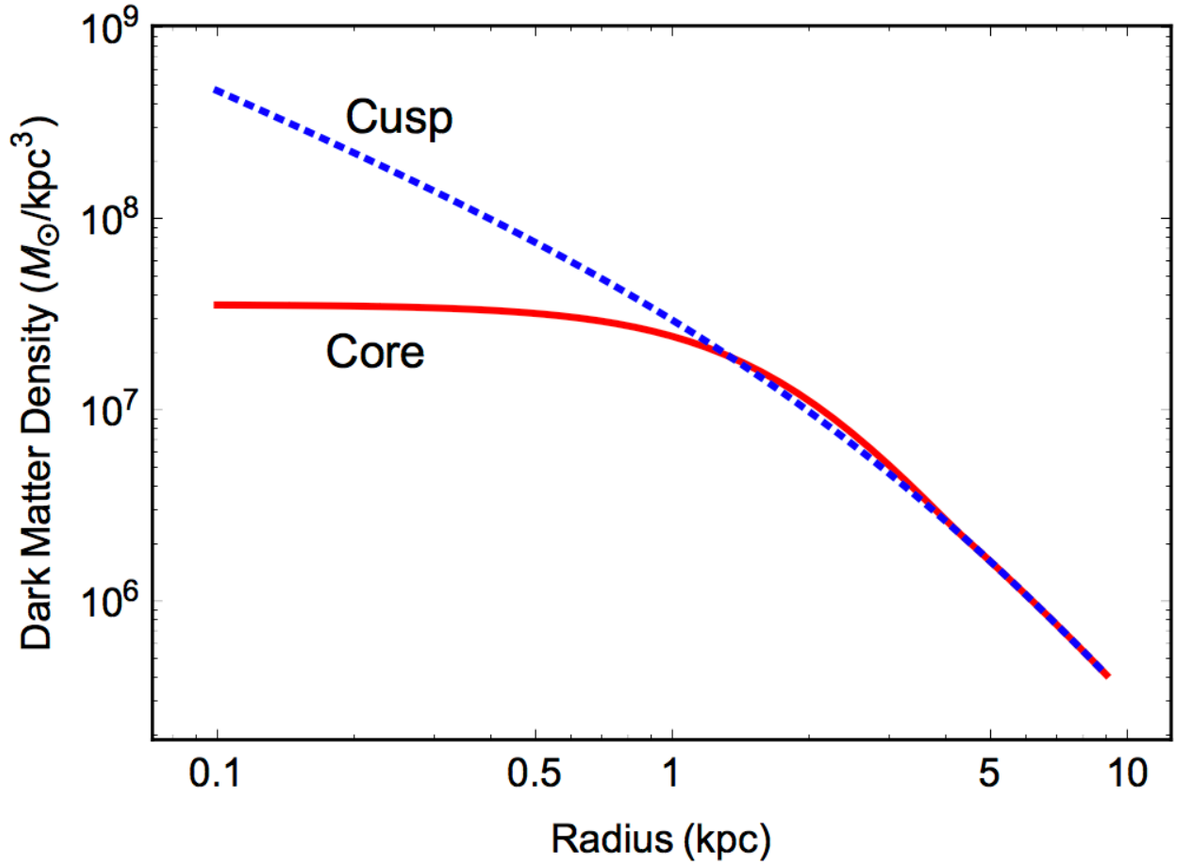
Core - Cusp Problem

an old problem,
e.g. Navarro et al. 1997





- DM-only simulations predict $\rho(r) \propto 1/r$
- Dwarf and LSB galaxies prefer $\rho(r) \propto r^0$

Tulin, Yu
Kamada, Kaplinghat, Pace, Yu

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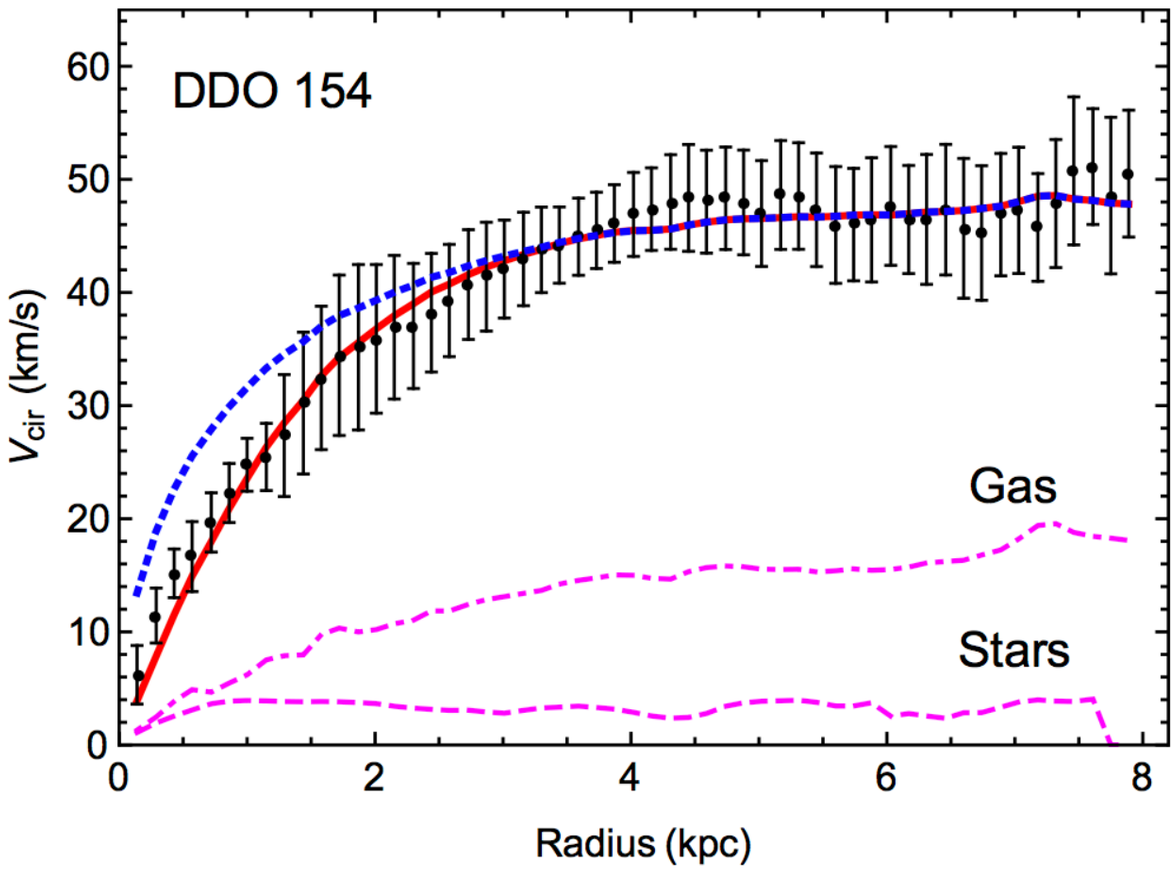

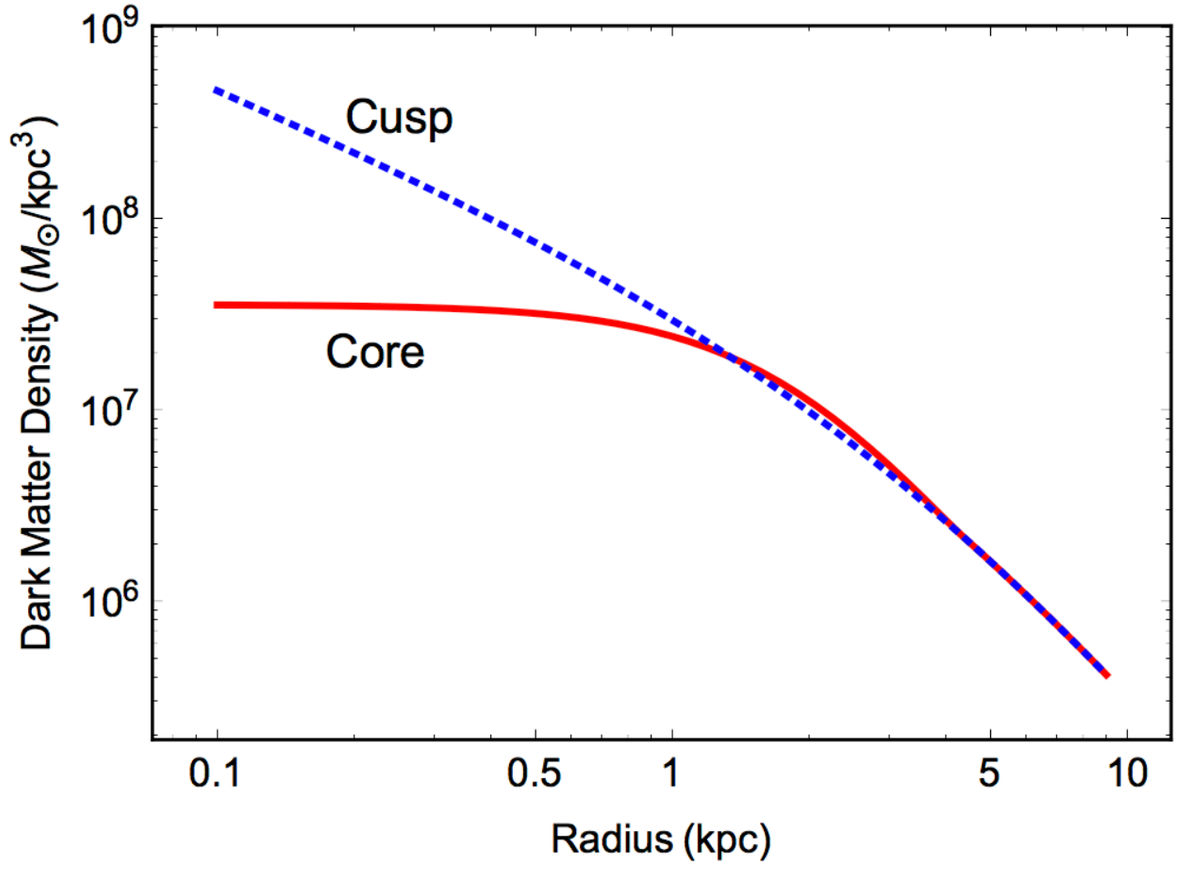

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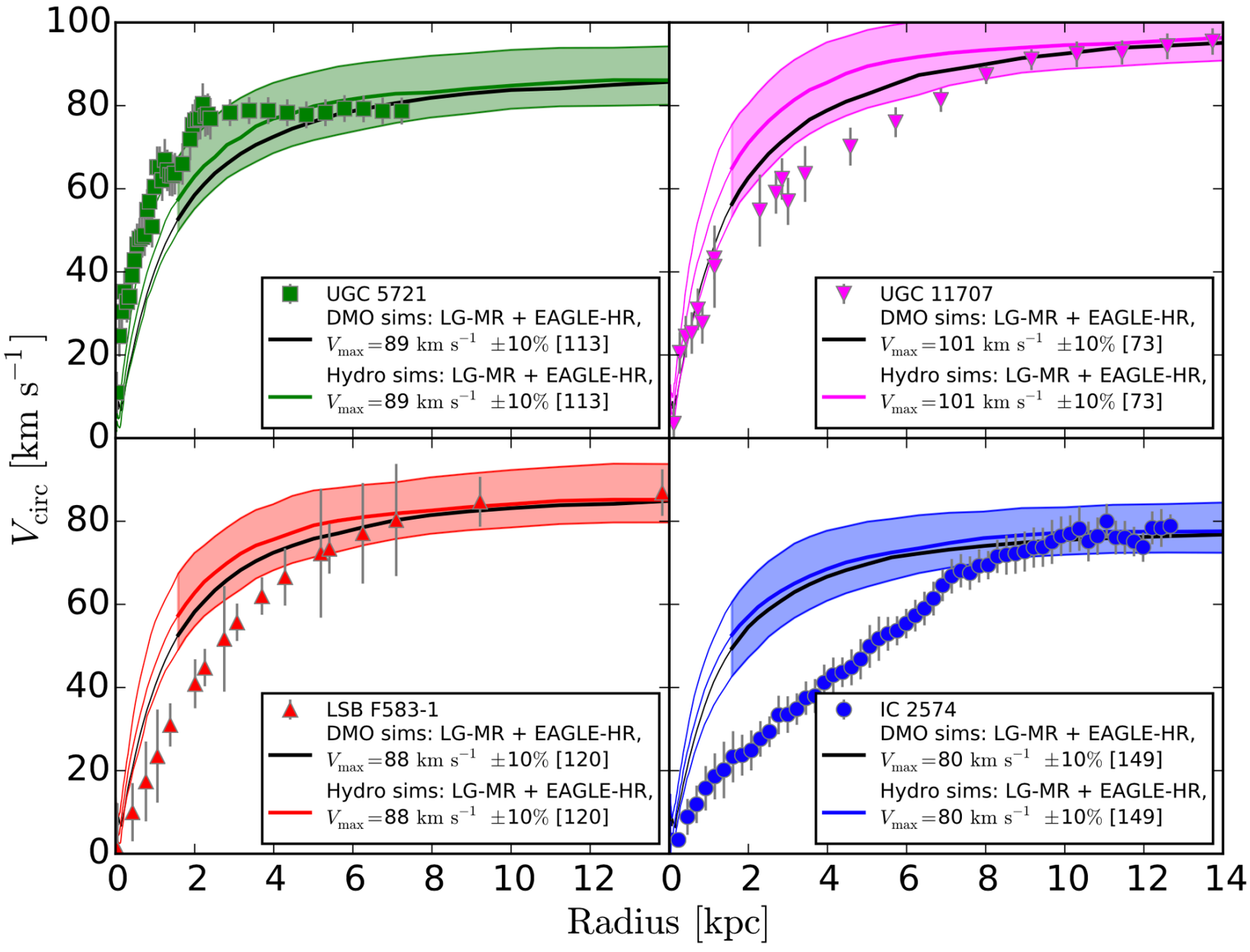
Tulin, Yu
Kamada, Kaplinghat, Pace, Yu

- ΛCDM + baryons may explain this
- SIDM works too! Allows heat transfer from outer to inner halo

Diversity problem

Oman et.al., 2015

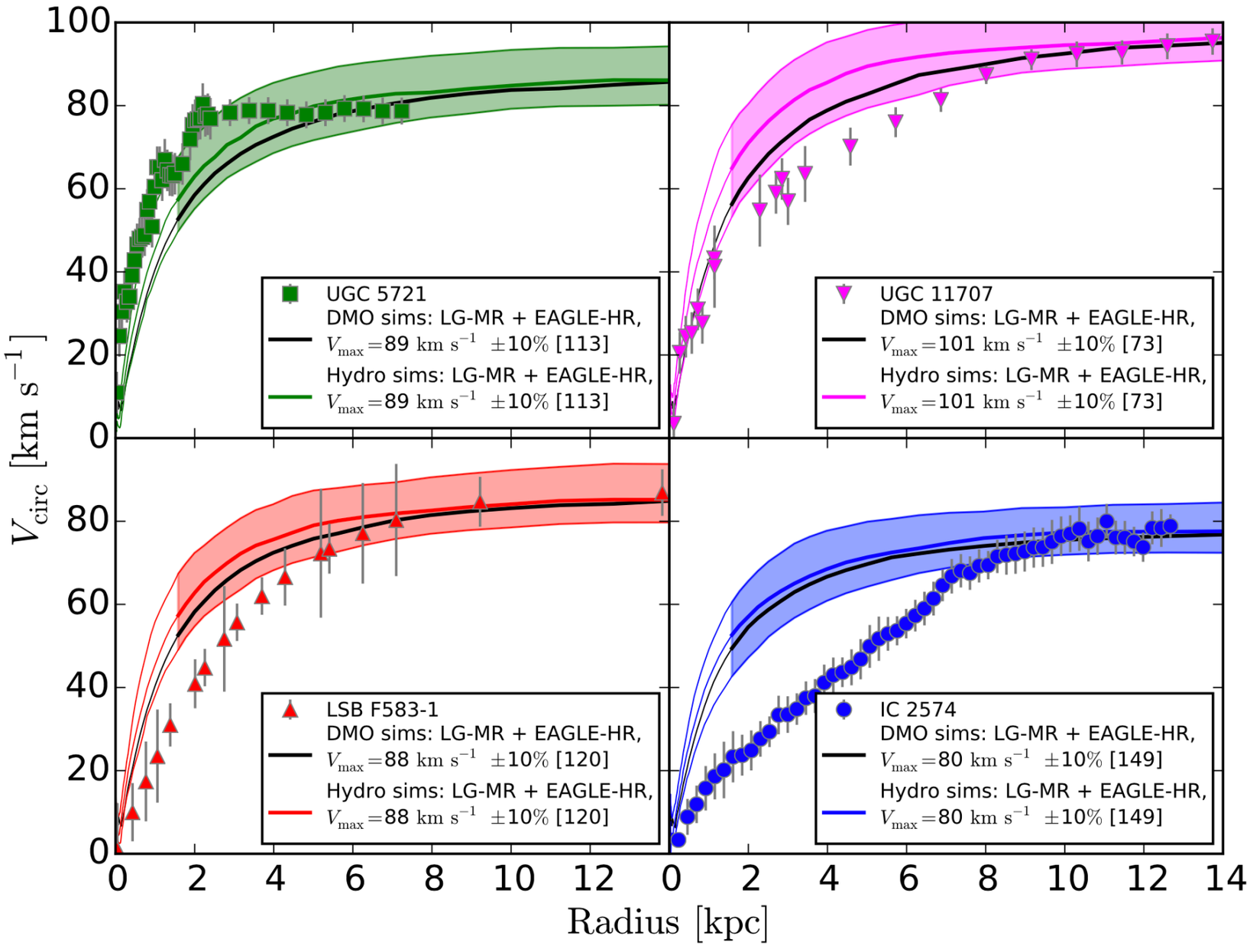


Example: four dwarf irregular galaxies w/ similar v_{max} (i.e. similar total halo mass), but diverse rotation curves in inner halo

hydrodynamical simulations of ΛCDM shown with colored bands

Diversity problem

Oman et.al., 2015



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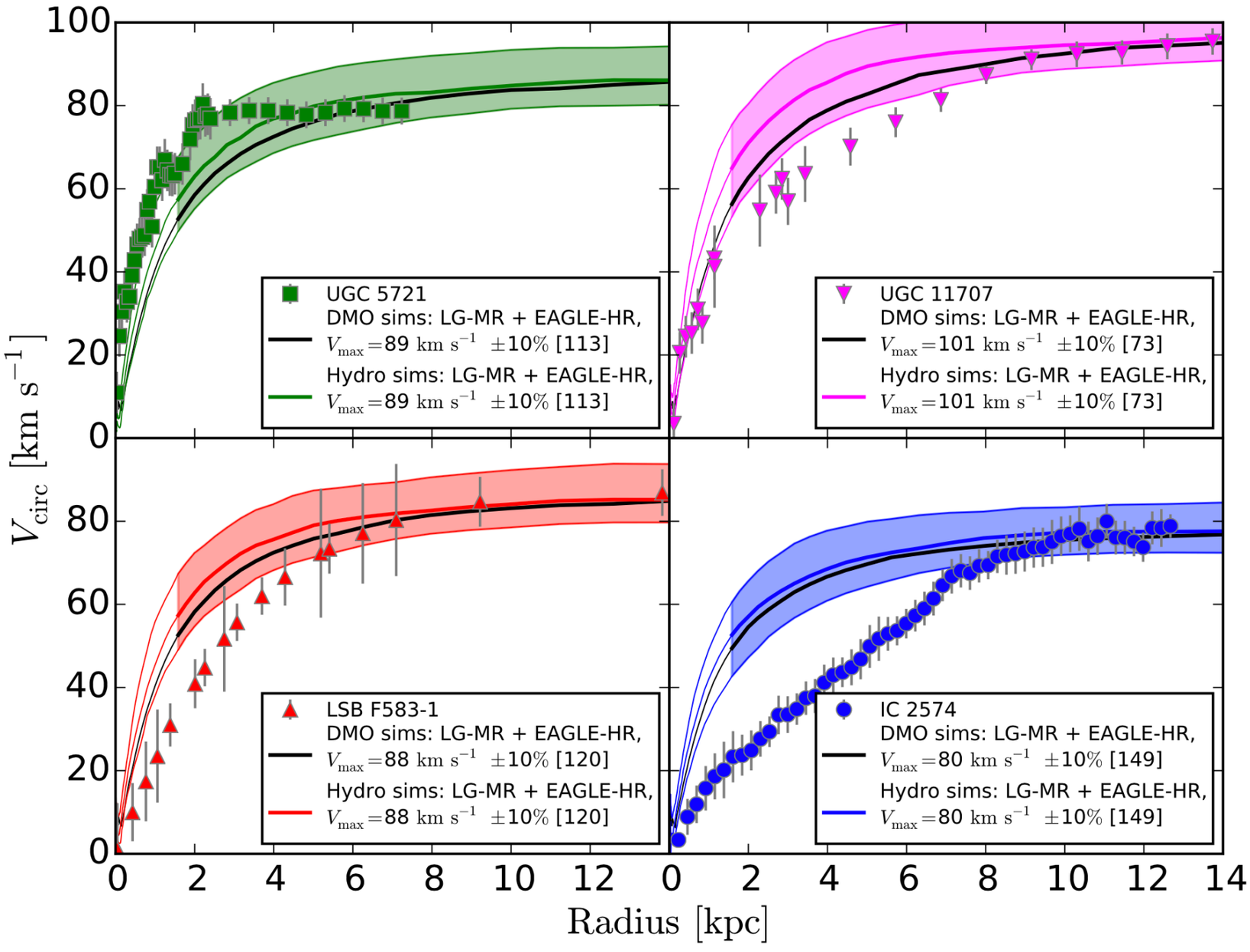

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hydrodynamical simulations of ΛCDM shown with colored bands

Baryonic effects? But SIDM also seems to resolve problem!

Kamada, Kaplinghat, Pace, Yu

much activity in last few years!

2016 Community summary of opportunities

Dark Sectors 2016 Workshop: Community Report

Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] Eder Izaguirre (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan Krnjaic (DMA Convener),[7] Jeremy Mardon (DD Convener),[8] David Morrissey (RDS Convener),[9] Tim Nelson (Organizer),[5,§] Maxim Perelstein (VDP Convener),[1] Matt Pyle (DD Convener),[10] Adam Ritz (DMA Convener),[11] Philip Schuster (Organizer),[5,6,¶] Brian Shuve (RDS Convener),[5] Natalia Toro (Organizer),[5,6,**] Richard G Van De Water (DMA Convener),[12] Daniel Akerib,[5,13] Haipeng An,[3] Konrad Aniol,[14] Isaac J. Arnquist,[15] David M. Asner,[15] Henning O. Back,[15] Keith Baker,[16] Nathan Baltzell,[17] Dipanwita Banerjee,[18] Brian Batell,[19] Daniel Bauer,[7] James Beacham,[20] Jay Benesch,[17] James Bjorken,[5] Nikita Blinov,[5] Celine Boehm,[21] Mariangela Bondí,[22] Walter Bonivento,[23] Fabio Bossi,[24] Stanley J. Brodsky,[5] Ran Budnik,[25] Stephen Bueltmann,[26] Masroor H. Bukhari,[27] Raymond Bunker,[15] Massimo Carpinelli,[28,29] Concetta Cartaro,[5] David Cassel,[1,5] Gianluca Cavoto,[30] Andrea Celentano,[2] Animesh Chaterjee,[31] Saptarshi Chaudhuri,[8] Gabriele Chiodini,[24] Hsiao-Mei Sherry Cho,[5] Eric D. Church,[15] D. A. Cooke,[18] Jodi Cooley,[32] Robert Cooper,[33] Ross Corliss,[34] Paolo Crivelli,[18] Francesca Curciarello,[35] Annalisa D'Angelo,[36,37] Hooman Davoudiasl,[38] Marzio De Napoli,[22] Raffaella De Vita,[2] Achim Denig,[39] Patrick deNiverville,[11] Abhay Deshpande,[40] Ranjan Dharmapalan,[41] Bogdan Dobrescu,[7] Sergey Donskov,[42] Raphael Dupre,[43] Juan Estrada,[7] Stuart Fegan,[39] Torben Ferber,[44] Clive Field,[5] Enectali Figueroa-Feliciano,[45] Alessandra Filippi,[46] Bartosz Fornal,[47] Arne Freyberger,[17] Alexander Friedland,[5] Iftach Galon,[47] Susan Gardner,[48,47] Francois-Xavier Girod,[17] Sergei Gninenko,[49] Andrey Golutvin,[50] Stefania Gori,[51] Christoph Grab,[18] Enrico Graziani,[52] Keith Griffioen,[53] Andrew Haas,[54] Keisuke Harigaya,[10,55] Christopher Hearty,[44] Scott Hertel,[10,55] JoAnne Hewett,[5] Andrew Hime,[15] David Hitlin,[3] Yonit Hochberg,[10,55,1] Roy J. Holt,[41] Maurik Holtrop,[56] Eric W. Hoppe,[15] Todd W. Hossbach,[15] Lauren Hsu,[7] Phil Ilten,[34] Joe Incandela,[57] Gianluca Inguglia,[58] Kent Irwin,[5] Igal Jaegle,[59] Robert P. Johnson,[60] Yonatan Kahn,[61] Grzegorz Kalicy,[62] Zhong-Bo Kang,[12] Vardan Khachatryan,[4] Venelin Kozhuharov,[63] N. V. Krasnikov,[49] Valery Kubarovsky,[17] Eric Kuflik,[1] Noah Kurinsky,[5,8] Ranjan Laha,[13,8] Gaia Lanfranchi,[35] Dale Li,[5] Tongyan Lin,[10,55] Mariangela Lisanti,[61] Kun Liu,[12] Ming Liu,[12] Ben Loer,[15] Dinesh Loomba,[64] Valery E. Lyubovitskij,[65,66,67] Aaron Manalaysay,[68] Giuseppe Mandaglio,[69] Jeremiah Mans,[70] W. J. Marciano,[38] Thomas Markiewicz,[5] Luca Marsicano,[2] Takashi Maruyama,[5] Victor A. Matveev,[49] David McKeen,[71] Bryan McKinnon,[72] Dan McKinsey,[10] Harald Merkel,[39] Jeremy Mock,[68] Maria Elena Monzani,[5] Omar Moreno,[5] Corina Nantais,[73] Sebouh Paul,[53] Michael Peskin,[5] Vladimir Poliakov,[74] Antonio D Polosa,[75,76] Maxim Pospelov,[6,11] Igor Rachek,[77] Balint Radics,[18] Mauro Raggi,[30] Nunzio Randazzo,[22] Blair Ratcliff,[5] Alessandro Rizzo,[36,37] Thomas Rizzo,[5] Alan Robinson,[7] Andre Rubbia,[18] David Rubin,[1] Dylan Rueter,[8] Tarek Saab,[78] Elena Santopinto,[2] Richard Schnee,[79] Jessie Shelton,[80] Gabriele Simi,[81,82] Ani Simonyan,[43] Valeria Sipala,[28,29] Oren Slone,[83] Elton Smith,[17] Daniel Snowden-Ifft,[84] Matthew Solt,[5] Peter Sorensen,[10,55] Yotam Soreq,[34] Stefania Spagnolo,[24,85] James Spencer,[5] Stepan Stepanyan,[17] Jan Strube,[15] Michael Sullivan,[5] Arun S. Tadepalli,[86] Tim Tait,[47] Mauro Taiuti,[2,87] Philip Tanedo,[88] Rex

many ideas for new, complementary experiments & searches:

- direct detection
- fixed target
- low-energy colliders

arXiv:1608.08632

https://indico.fnal.gov/conferenceDisplay.py?confId=13702

U.S. Cosmic Visions: New Ideas in Dark Matter

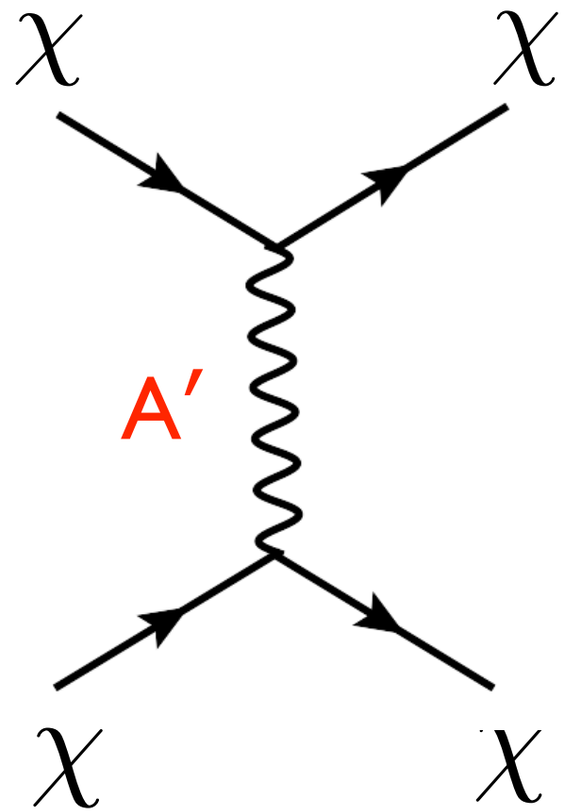
23-25 March 2017 *Stamp Student Union*
US/Eastern timezone

Search

DOE Office of High Energy Physics (HEP) is interested in identifying new, small projects for dark matter searches in areas of parameter space [...] not currently [...] explored. (cost < $10 million)

white paper to appear in O(1) month

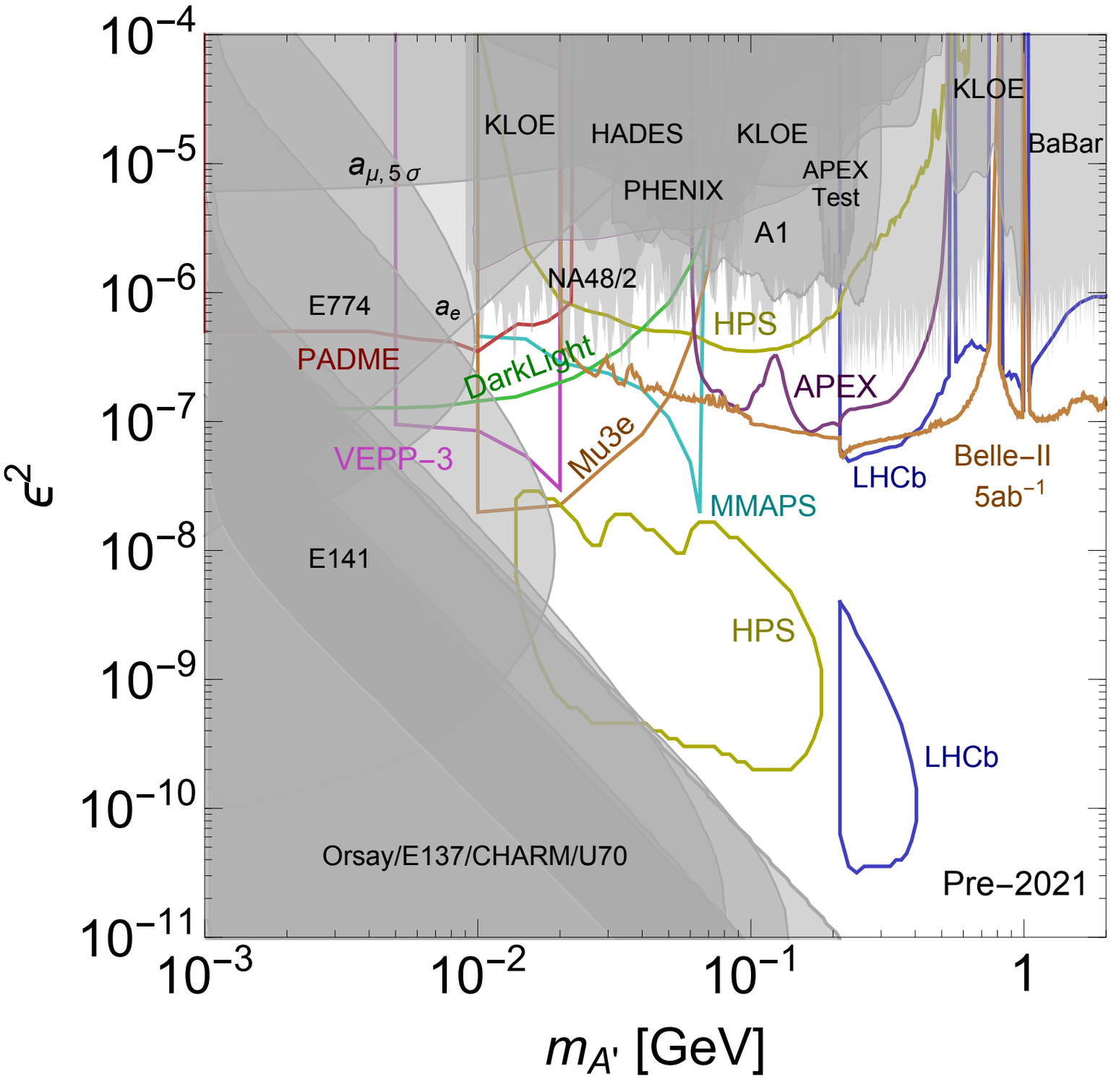
Dark Matter w/ new mediators



e.g. dark photon mediator

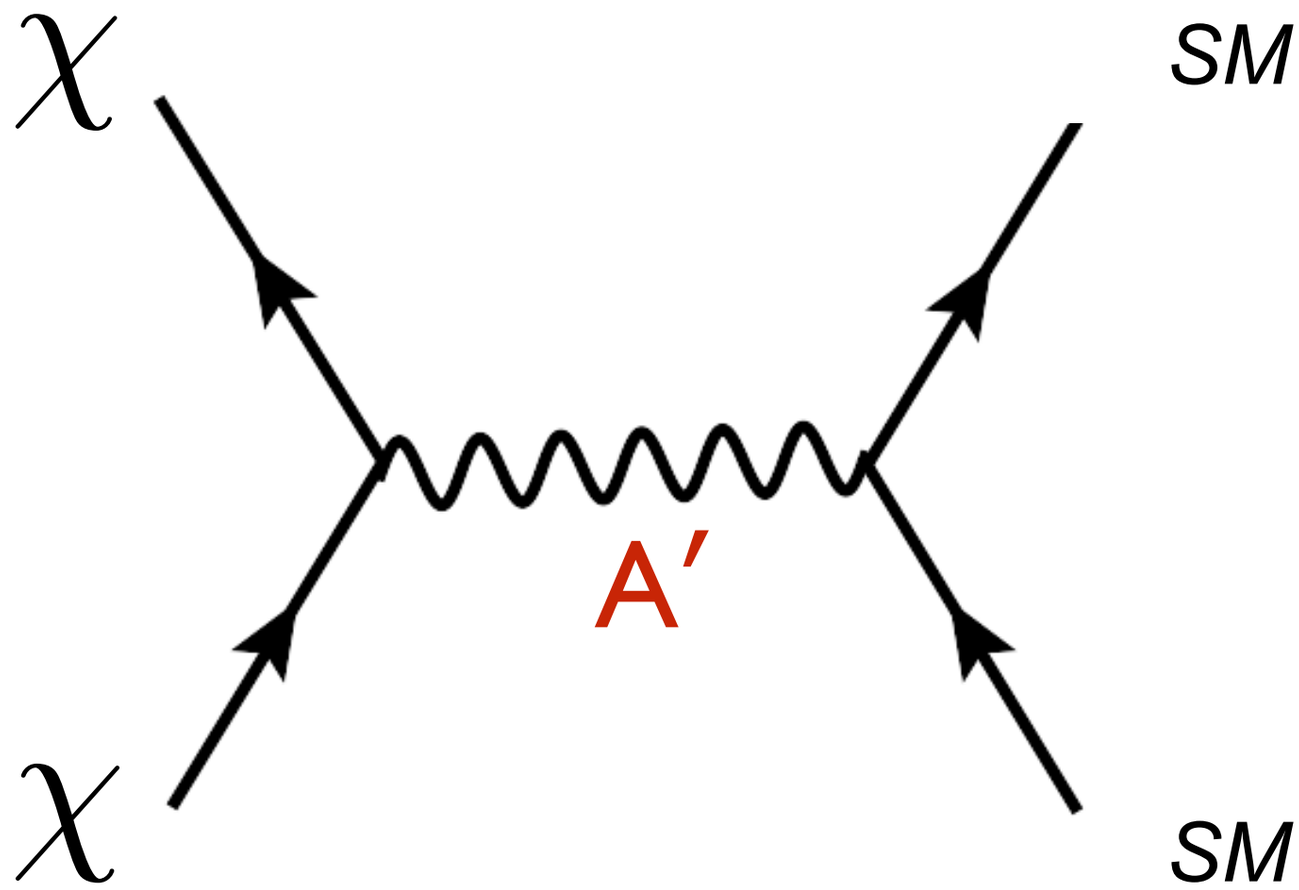
self-interactions could help resolve "small-scale crisis"

Can search for mediators directly



First results from HPS engineering run presented last week!

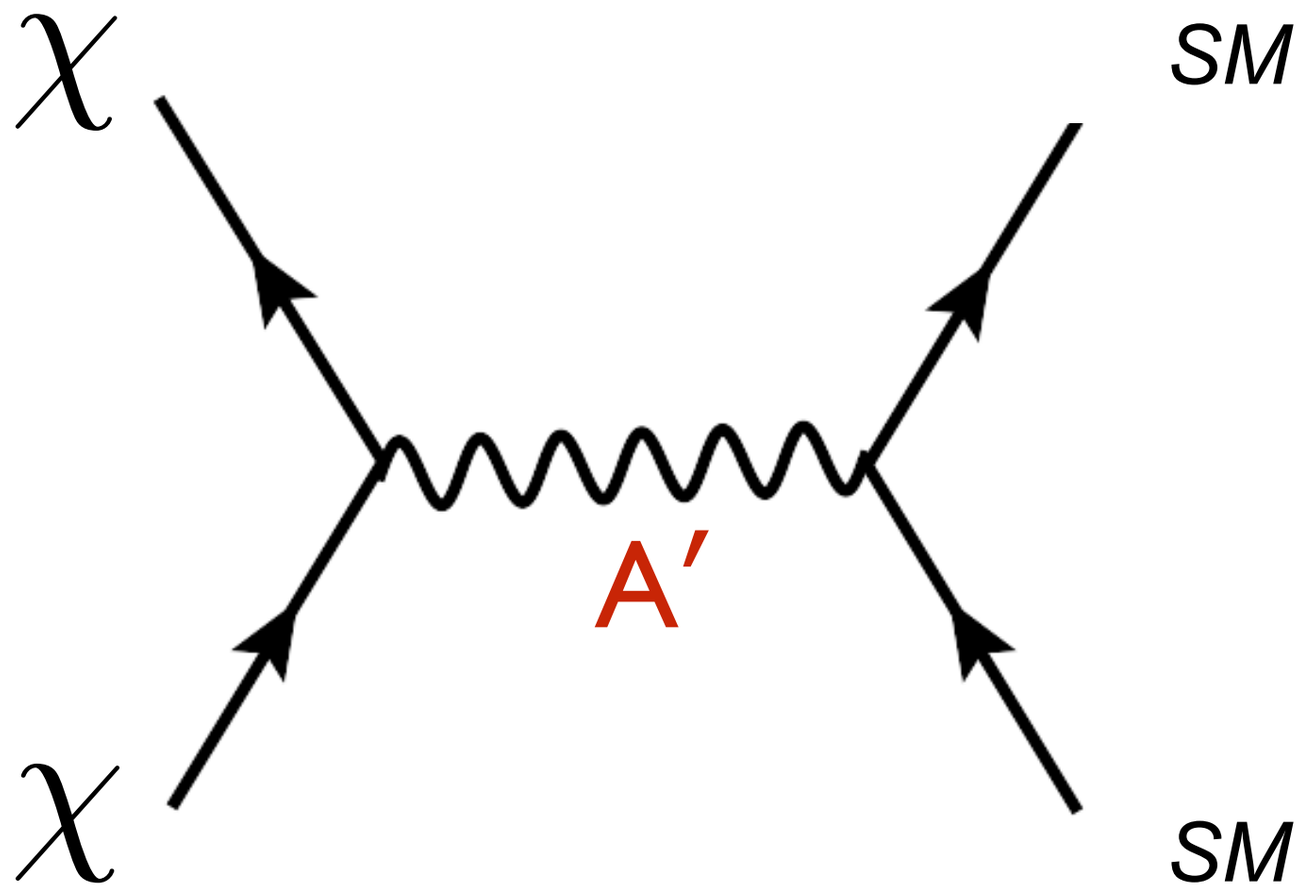
Dark Matter + Dark Photon



can obtain observed relic abundance via freeze-out

(also via freeze-in, asymmetric, SIMP…)

Dark Matter + Dark Photon



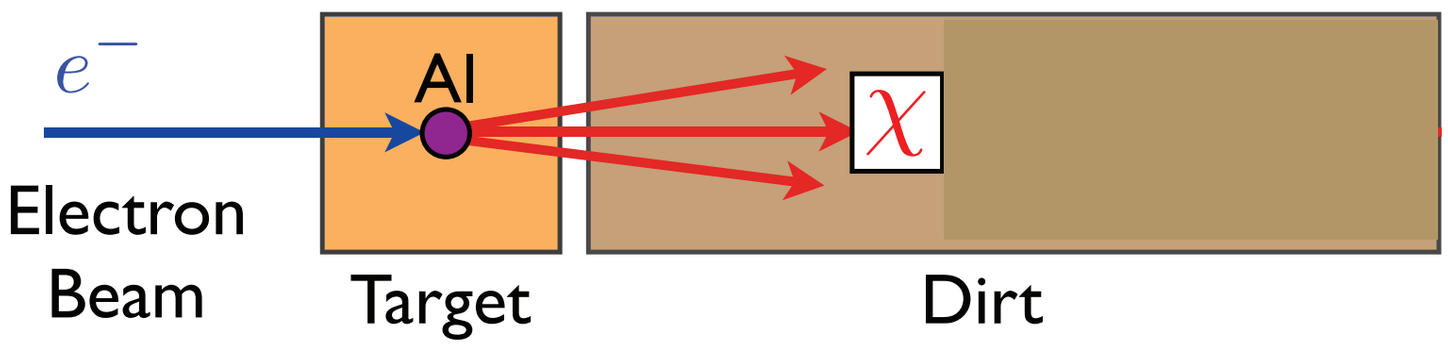
fixes cross section, σ

Produce Dark Matter at a beam dump

e.g.@SLAC's E137

Bjorken et.al.

Batell, RE, Surujon



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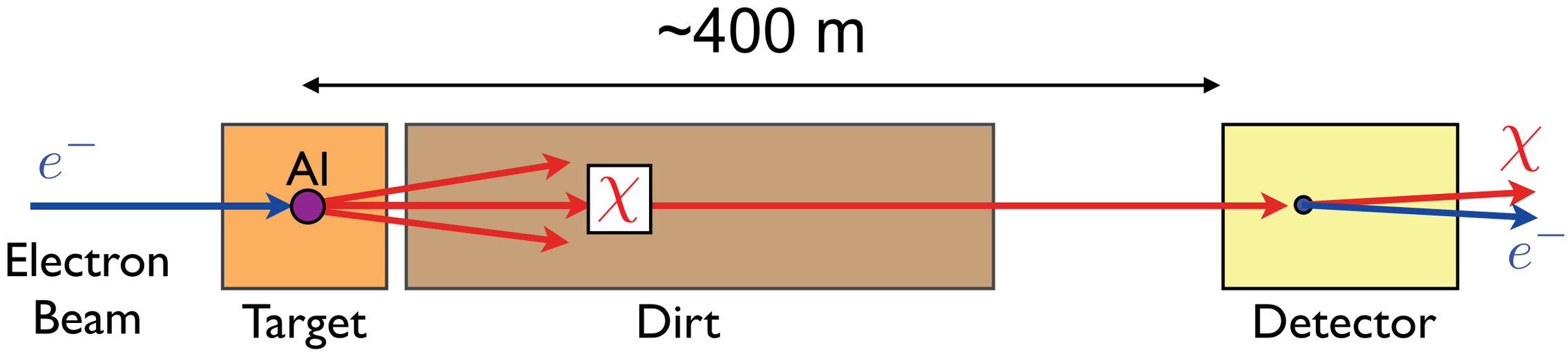
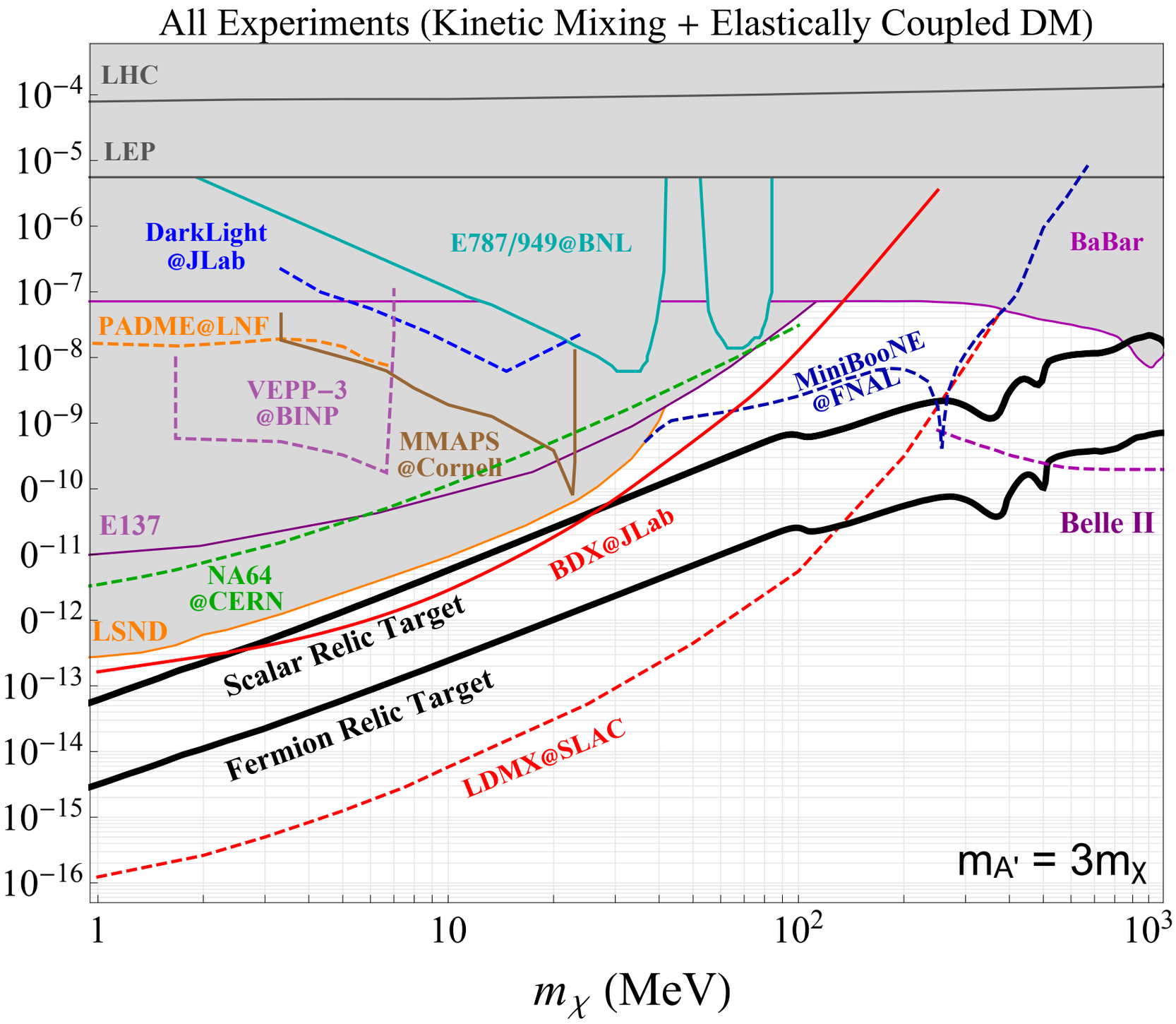


see also e.g. Batell, Pospelov, Ritz; Deniverville, Pospelov, Ritz; Deniverville, McKeen, Ritz; Aguilar-Arevalo et.al.; Krnjaic, Izaguirre, Schuster, Toro (several); Diamond, Schuster; etc.

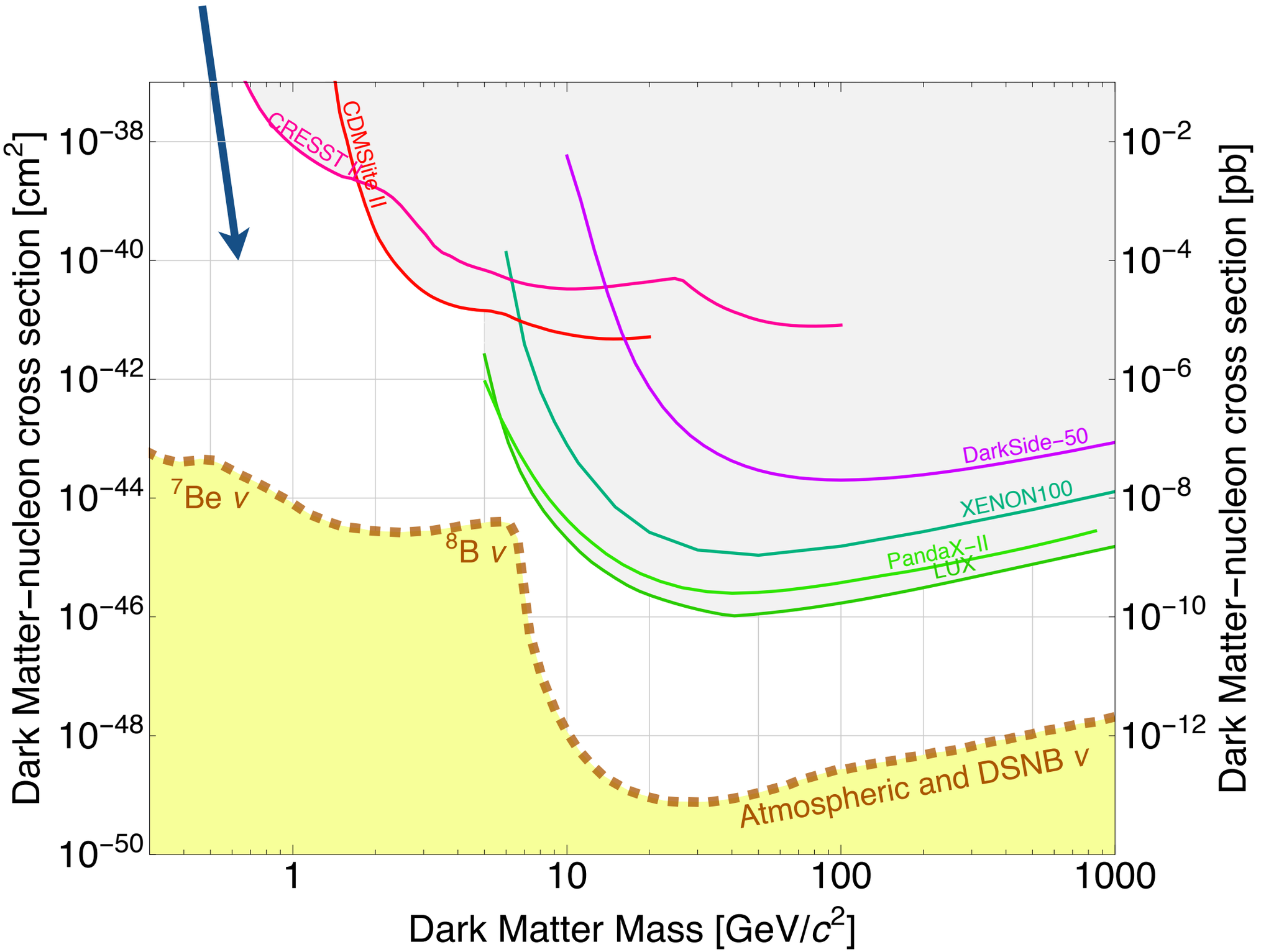
New experiments can probe several "thermal" targets!

$\propto \sigma$



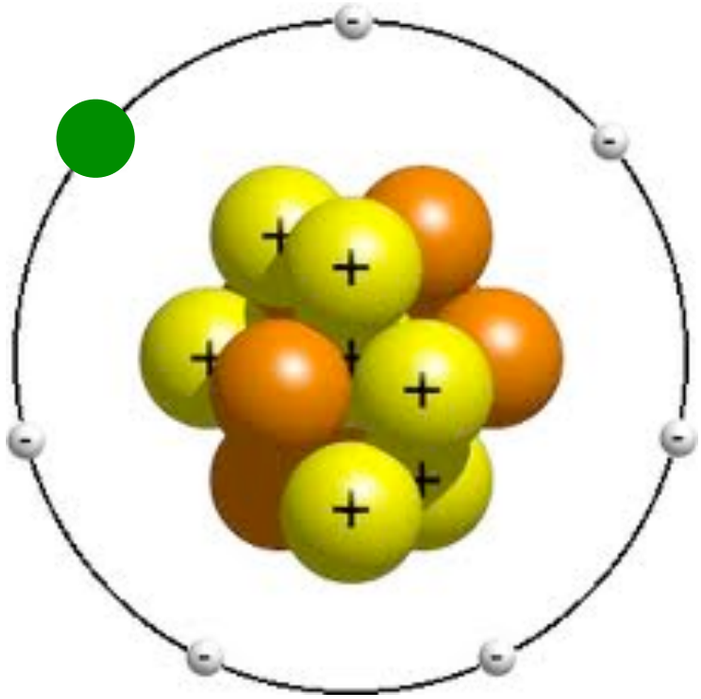
Dark Sector Report, 1608.08632

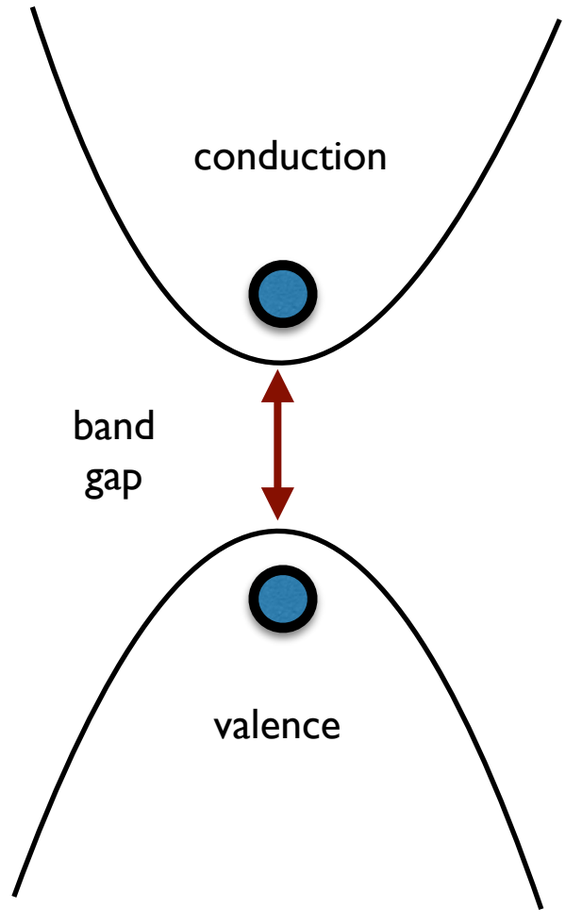
Conventional wisdom: no sensitivity below ~GeV



WIMP limit plotter: Saab & Figueroa

But DM-electron scattering can probe $\ll$ GeV





noble liquids

semiconductors

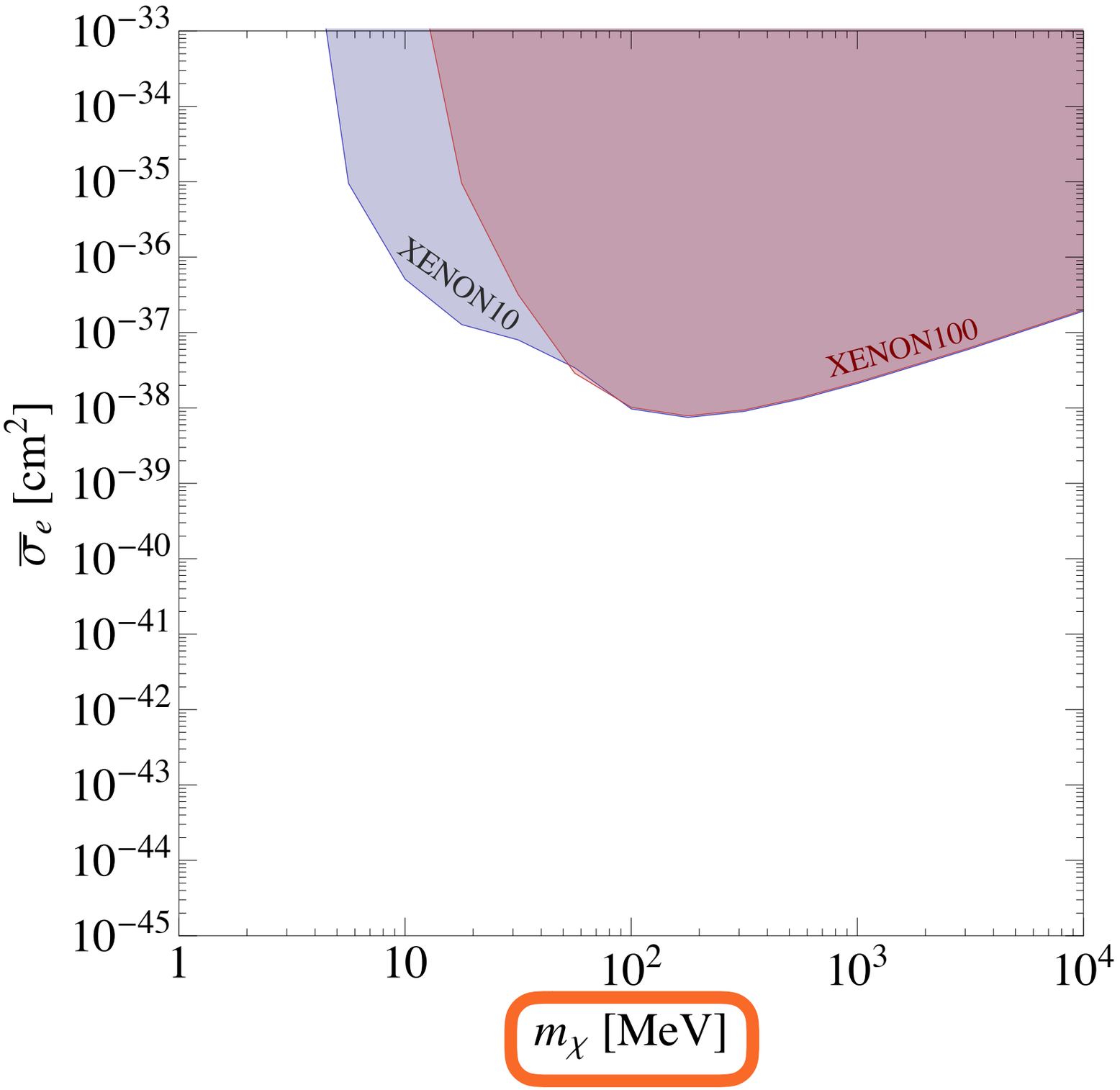
RE, Mardon, Volansky
RE, Manalaysay, Mardon, Sorensen, Volansky
RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Derenzo, RE, Massari, Soto, Yu
RE, Volansky, Yu
Graham, Kaplan, Rajendran, Walters
Lee, Lisanti, Mishra-Sharma, Safdi
Sorensen

New constraints on DM-electron scattering using XENON10/100 data

RE, Volansky, Yu 2017

updated from

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012



An exciting new detector: SENSEI

Fermilab LDRD: Tiffenberg (PI), Bebek, Guardincerri, Haro, Holland, RE, Mardon, Volansky, Yu

silicon CCDs

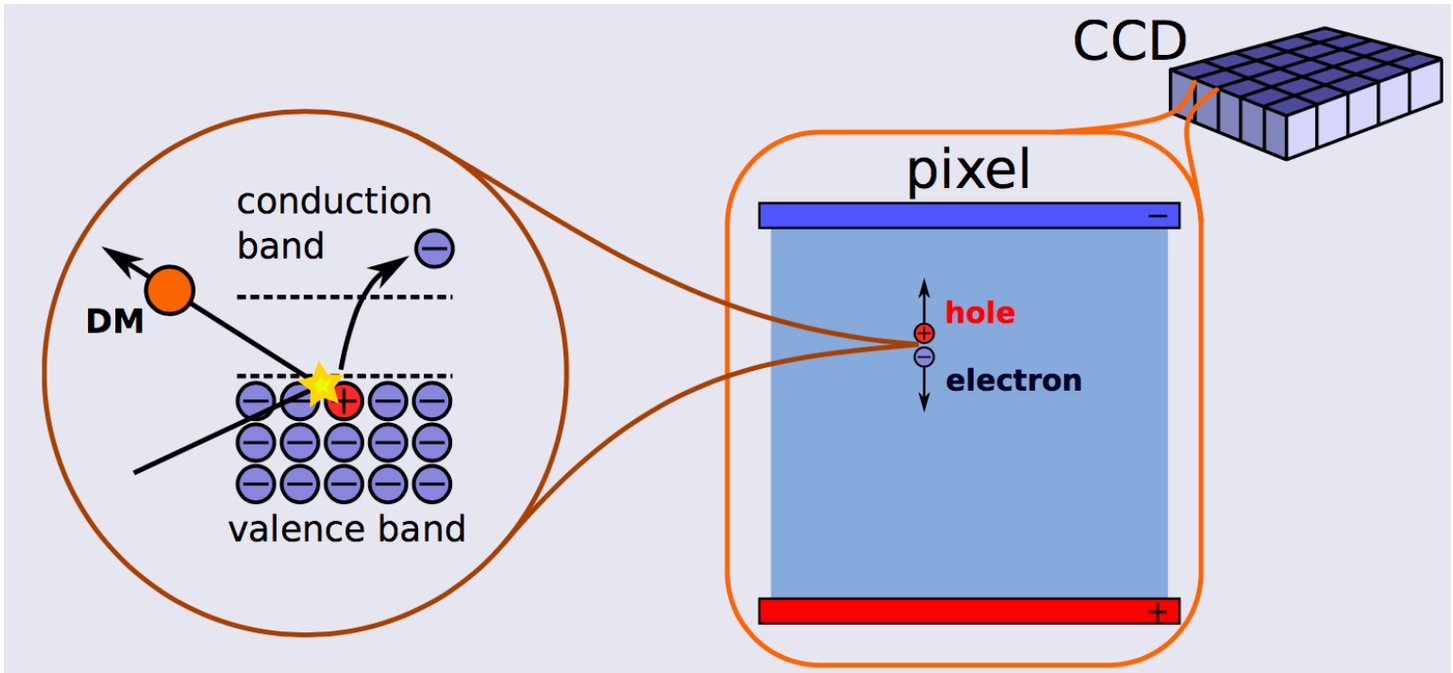
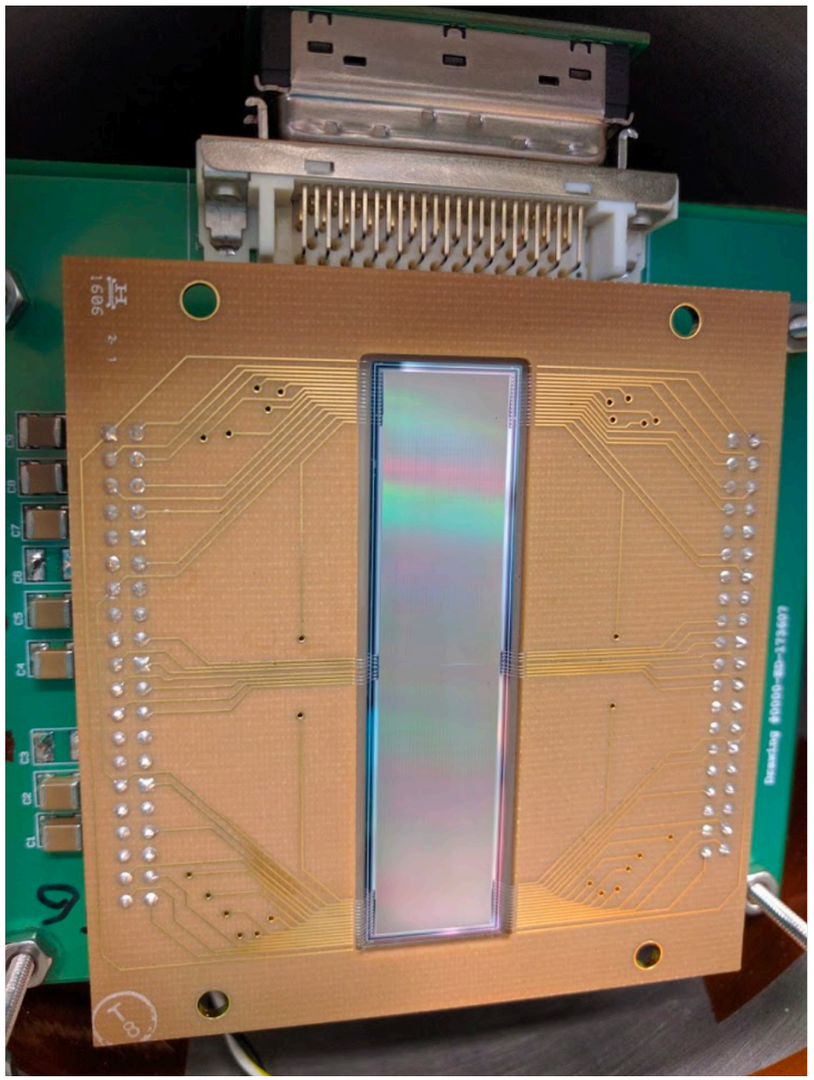


Figure credit: J. Tiffenberg



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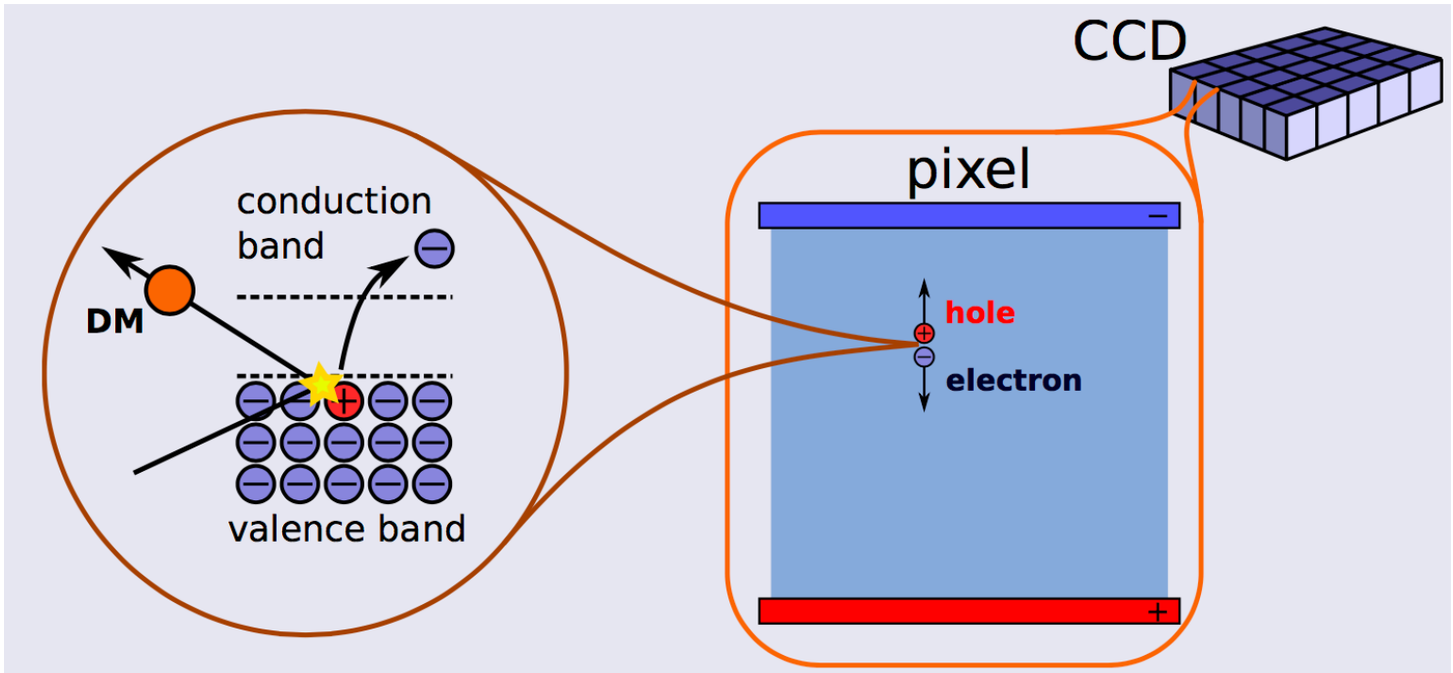

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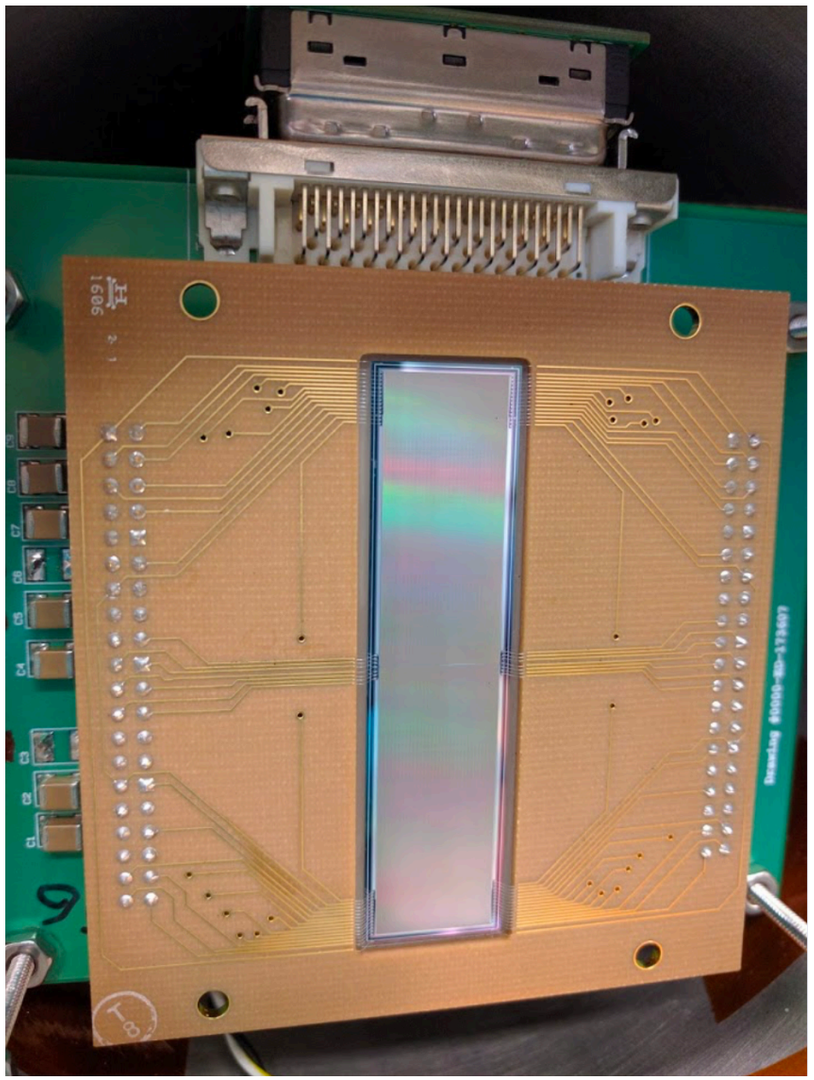
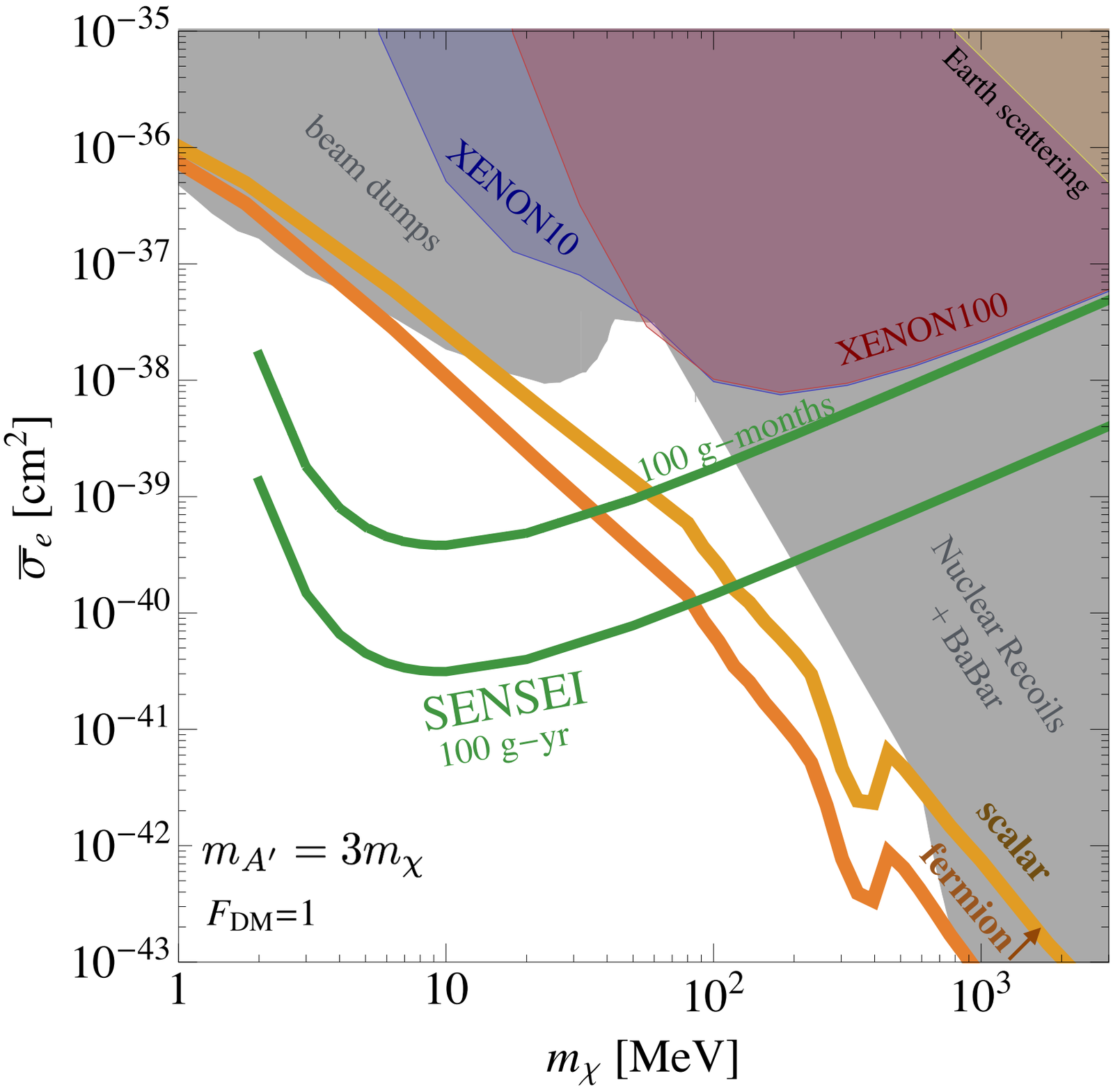


Recently demonstrated sensitivity to single electrons!

SENSEI can probe "thermal" targets



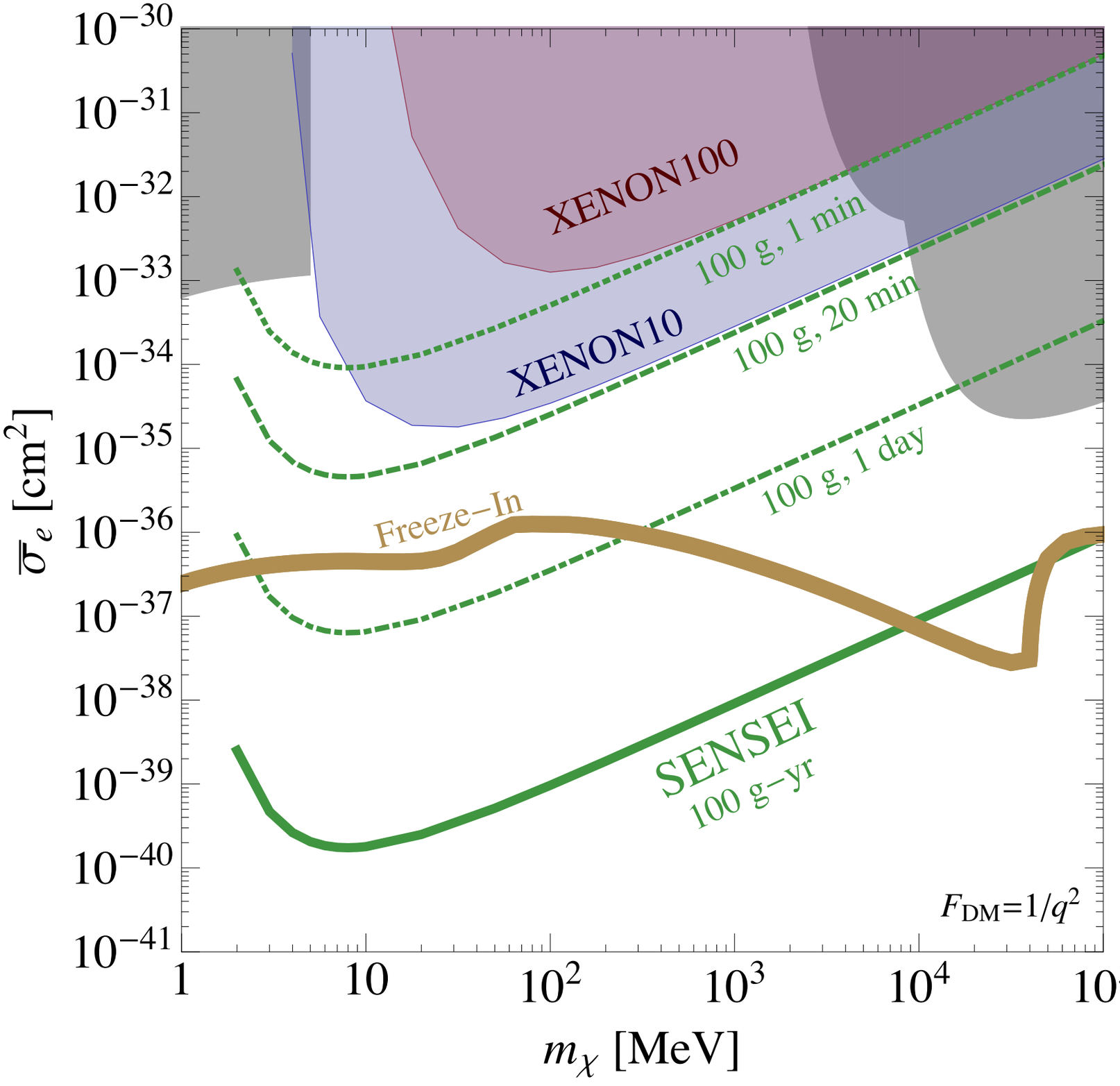
1 gram
operating soon

we're developing
proposal for
~100 gram

expected background
<1 event

*fermion must be asymmetric DM

SENSEI can probe "freeze-in" target

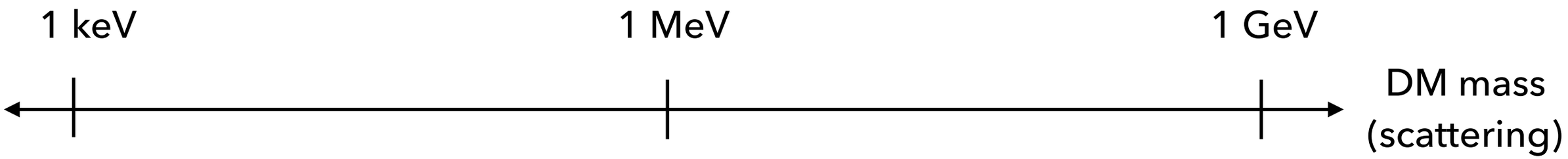


$$m_{A'} \ll 1 \text{ keV}$$

(σ_e enhanced at low q)

uniquely probed by DD!

Many new direct-detection ideas in last few years!



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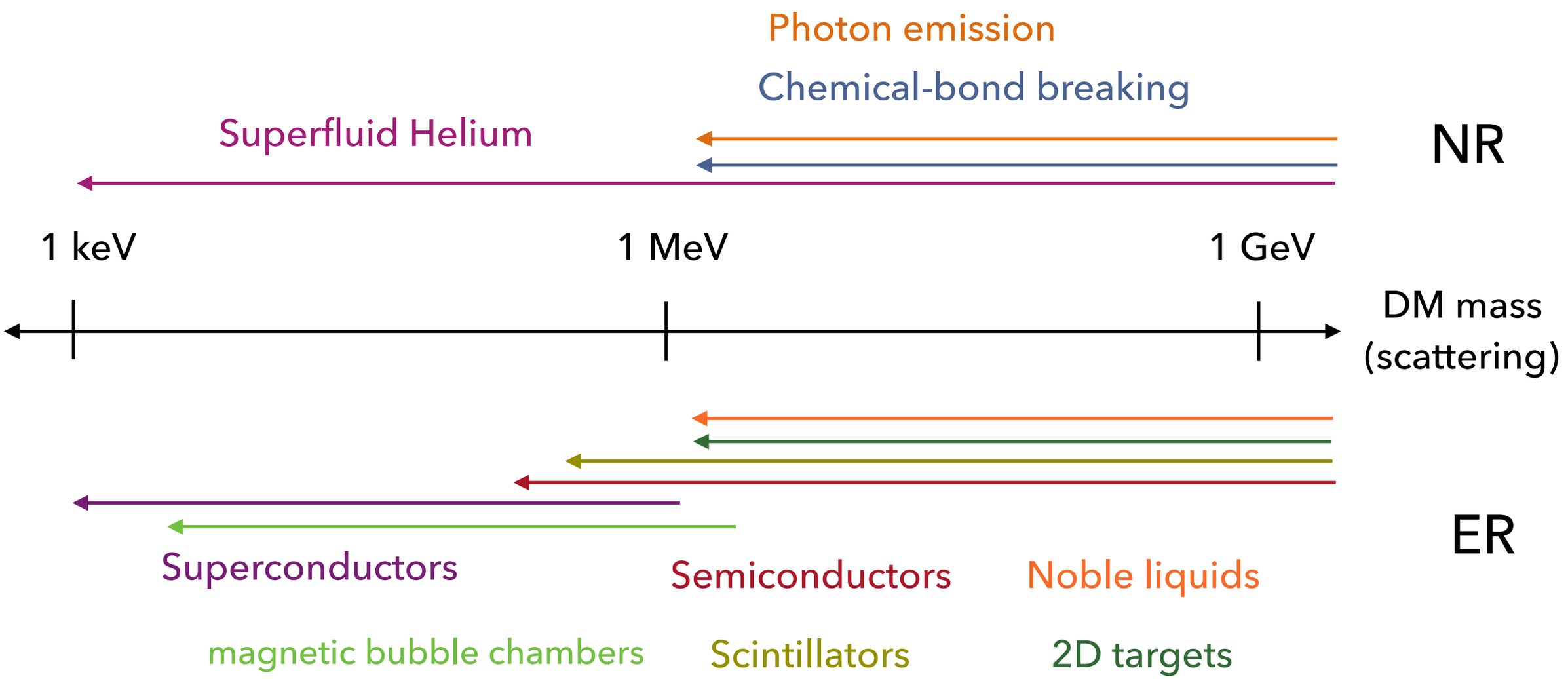

RE, Mardon, Volansky; RE, Manalaysay, Mardon, Sorensen, Volansky; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; Derenzo, RE, Massari, Soto, Yu; RE, Volansky, Yu; Graham, Kaplan, Rajendran, Walters; Lee, Lisanti, Mishra-Sharma, Safdi; Sorensen; Hochberg, Kahn, Lisanti, Tully, Zurek; Hochberg, Zhao, Zurek; Hochberg, Pyle, Zhao, Zurek; Hochberg, Lin, Zurek; Schutz, Zurek; Knapen, Lin, Zurek; RE, Mardon, Slone, Volansky; Bunting, Gratta, Melia, Rajendran;

Dark Sectors Report, 1608.08632

Summary

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Summary

- Goal: uncover the identity of dark matter!
- Many possibilities for DM… must search broadly
- Small-scale crisis: suggestive of self-interactions + non-trivial dark sector (more work needed!)
- WIMPs remain important, but attention is shifting more and more to beyond-WIMP candidates
- A new frontier has emerged: 10^{-22} eV — 1 GeV; close collaboration between theory & experiment promise enormous progress in targeting well-motivated candidates in next few years