Direct Detection of Dark Matter: Paradigm Confirmation or Shift?

Part 2: Sub-GeV Dark Matter

(Beyond Traditional WIMP Searches)

(some slides slightly updated from what was presented)

Rouven Essig

Yang Institute for Theoretical Physics

KITP Conference, May 3, 2018

Questions

1. Where else should we look?
2. Can we see a signal?
3. What are the backgrounds?
4. How will we know that we've found DM?
5. How low should we go in cross section?
6. Complementarity between DD & collider searches?
7. Put limits/projections from direct, indirect, and collider searches on same plot?

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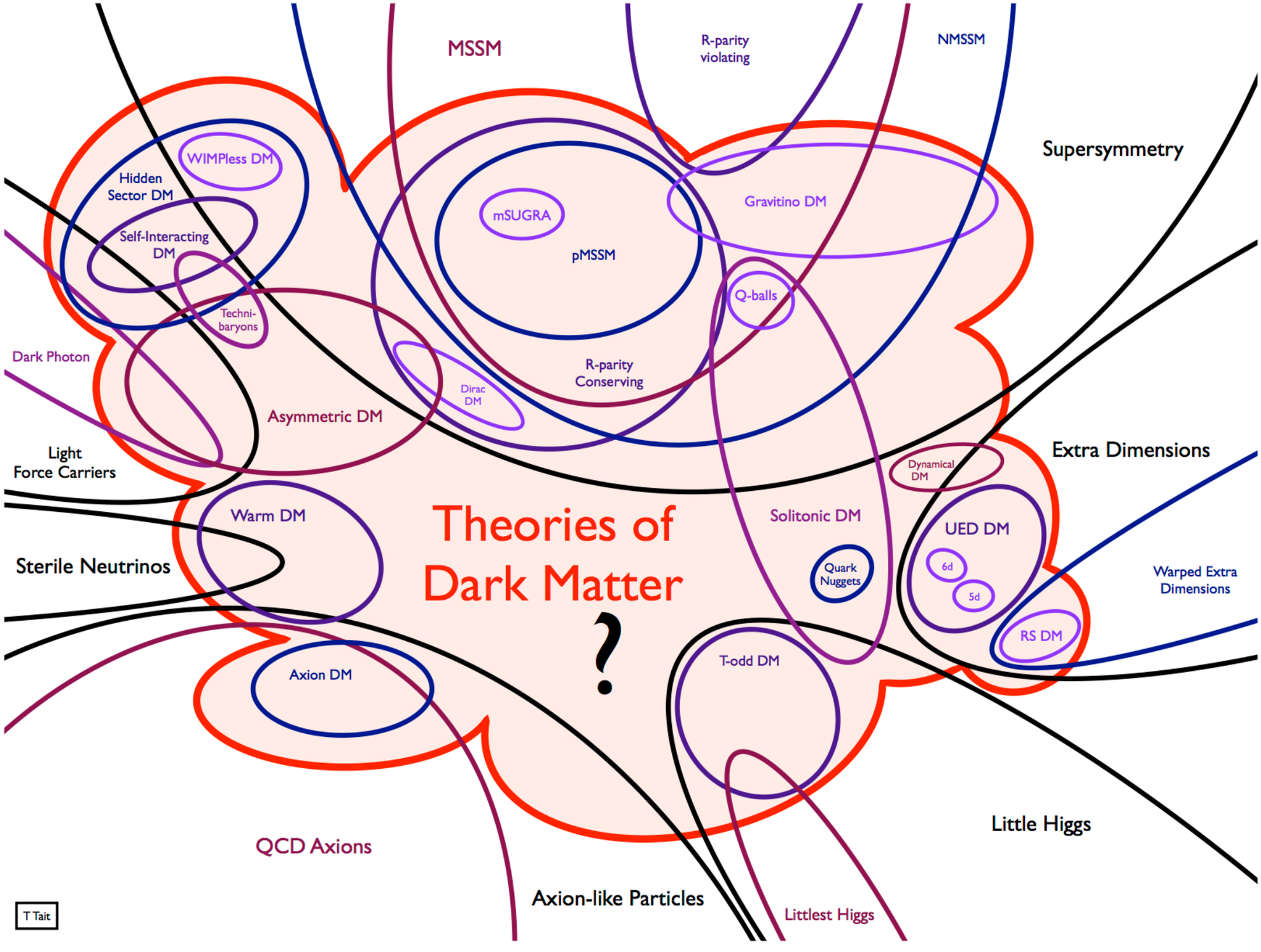
Tim's famous art — anguish about so many models?



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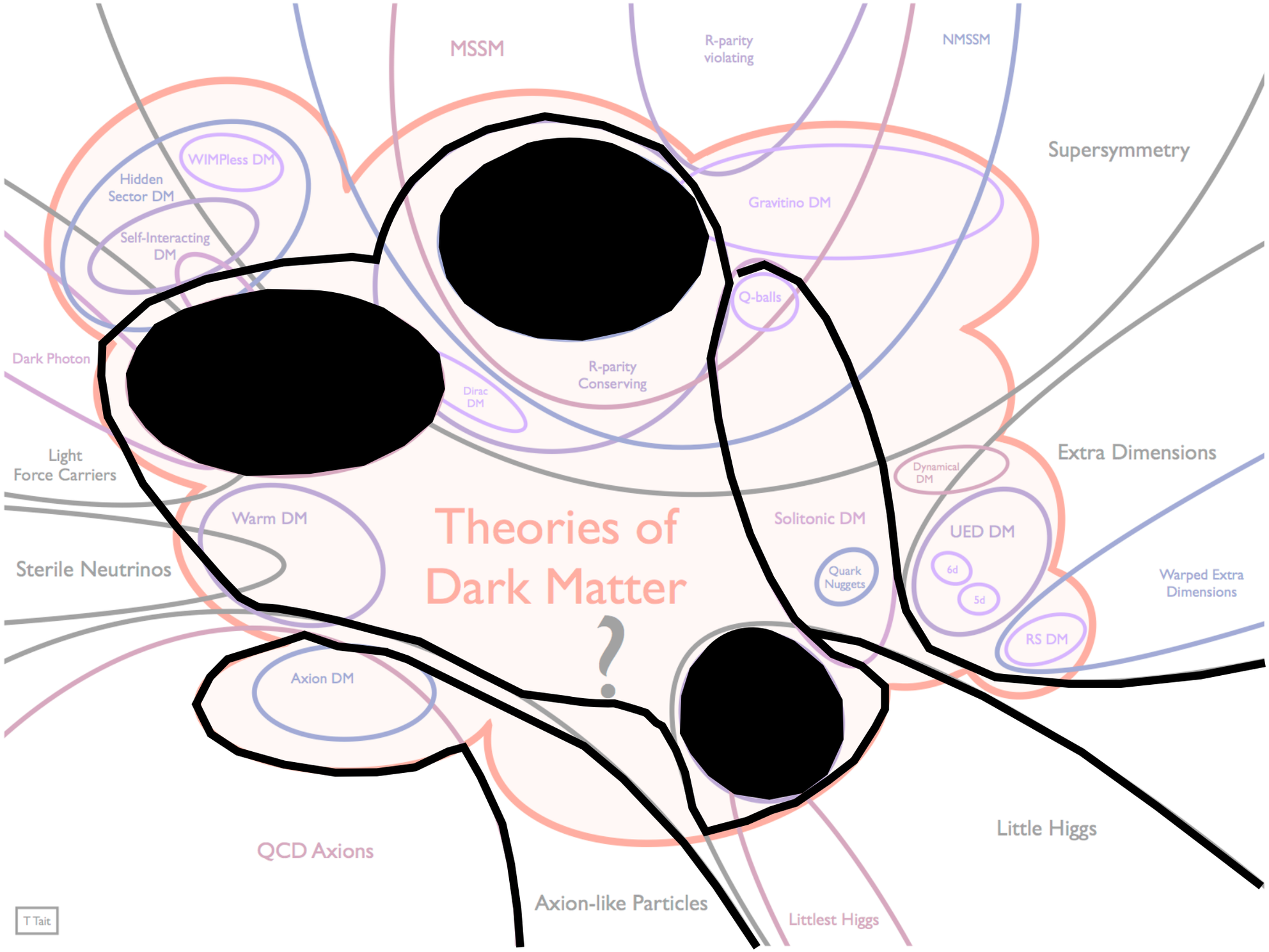
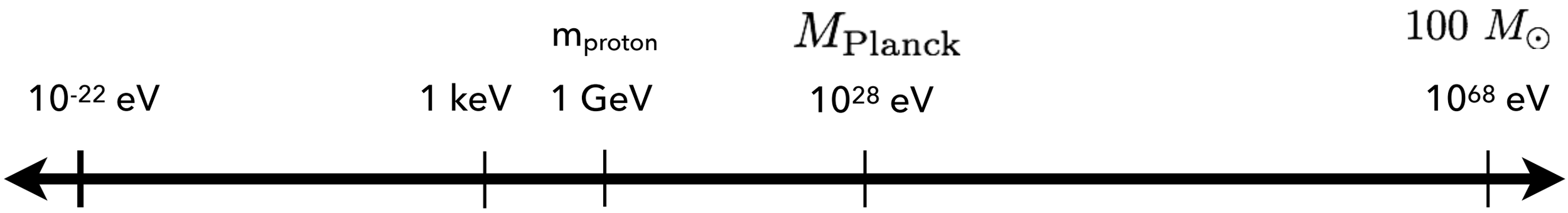


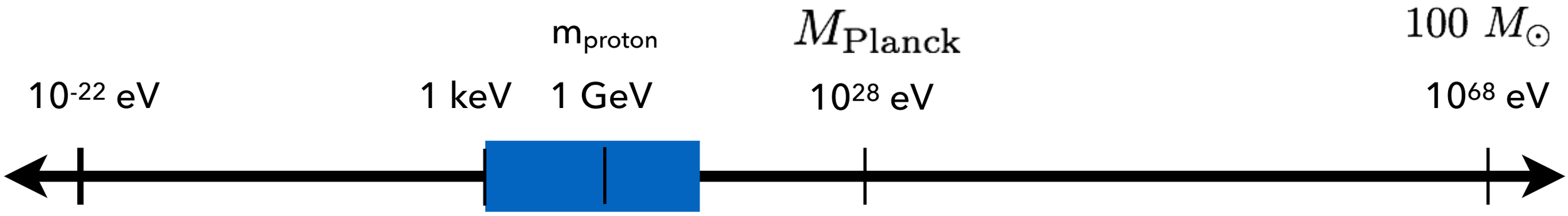
Where else should we look?



many possibilities

$\Longrightarrow$ target motivated areas

Where else should we look?



"thermal" DM

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

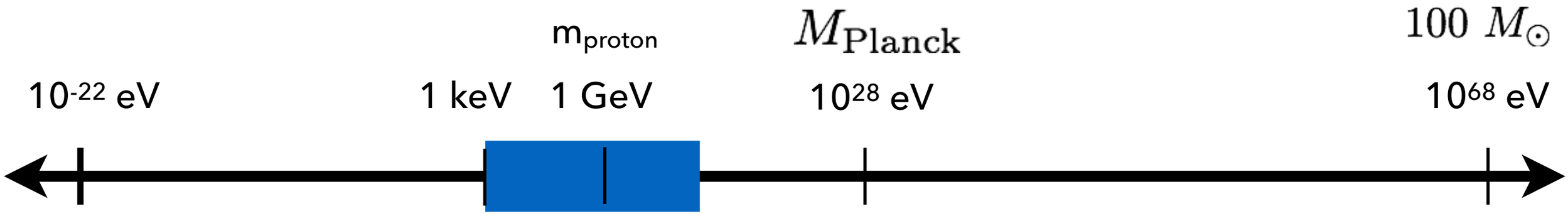
otherwise, no structure smaller than dwarf galaxies

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

otherwise, too much dark matter

(note: BBN/CMB constraints often strong < 1 MeV)

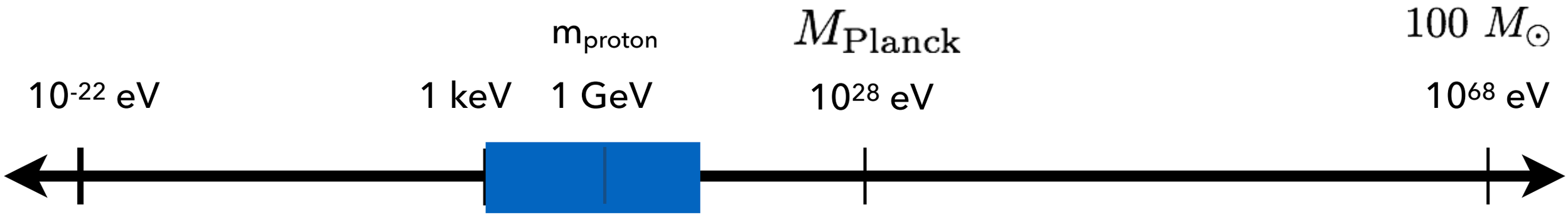
Where else should we look?



"thermal" DM

Thermal contact implies non-zero coupling between DM & SM, allowing for laboratory probes!

Where else should we look?



Many viable models:

Asymmetric, SIMP, ELDER, Freeze-in, Cannibal, Forbidden, …

Kaplan, Luty, Zurek; Falkowski, Ruderman, Volansky; Hochberg, Kuflik, Volansky, Wacker; +Murayama; Kuflik, Lorier, Perelstein, Tsai; Farina, Pappadopulo, Ruderman, Trevisan; D'Agnolo, Ruderman

require complementary techniques, including:

- direct detection (our focus)
- accelerator-based searches

(also astro/cosmo probes, see e.g. Vera's talk)

US Cosmic Visions: New Ideas in DM 2017

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng (WG4 Convener),[7] Brenna Flaugher (Coordinator),[3] Patrick J. Fox (WG4 Convener),[3] Peter Graham (WG2 Convener),[8] Carter Hall (Coordinator),[2] Roni Harnik (SAC member),[3] JoAnne Hewett (Coordinator),[9,8] Joseph Incandela (Coordinator),[10] Eder Izaguirre (WG3 Convener),[11] Daniel McKinsey (WG1 Convener),[12] Matthew Pyle (SAC member),[12] Natalie Roe (Coordinator),[13] Gray Rybka (SAC member),[14] Pierre Sikivie (SAC member),[15] Tim M.P. Tait (SAC member),[7] Natalia Toro (SAC co-chair),[9,16] Richard Van De Water (SAC member),[17] Neal Weiner (SAC member),[18] Kathryn Zurek (SAC member),[13,12] Eric Adelberger,[14] Andrei Afanasev,[19] Derbin Alexander,[20] James Alexander,[21] Vasile Cristian Antochi,[22] David Mark Asner,[23] Howard Baer,[24] Dipanwita Banerjee,[25] Elisabetta Baracchini,[26] Phillip Barbeau,[27] Joshua Barrow,[28] Noemie Bastidon,[29] James Battat,[30] Stephen Benson,[31] Asher Berlin,[9] Mark Bird,[32] Nikita Blinov,[9] Kimberly K. Boddy,[33] Mariangela Bondì,[34] Walter M. Bonivento,[35] Mark Boulay,[36] James Boyce,[37,31] Maxime Brodeur,[38] Leah Broussard,[39] Ranny Budnik,[40] Philip Bunting,[12] Marc Caffee,[41] Sabato Stefano Caiazza,[42] Sheldon Campbell,[7] Tongtong Cao,[43] Gianpaolo Carosi,[44] Massimo Carpinelli,[45,46] Gianluca Cavoto,[22] Andrea Celentano,[1] Jae Hyeok Chang,[6] Swapan Chattopadhyay,[3,47] Alvaro Chavarria,[48] Chien-Yi Chen,[49,16] Kenneth Clark,[50] John Clarke,[12] Owen Colegrove,[10] Jonathon Coleman,[51] David Cooke,[25] Robert Cooper,[52] Michael Crisler,[23,3] Paolo Crivelli,[25] Francesco D'Eramo,[53,54] Domenico D'Urso,[45,46] Eric Dahl,[29] William Dawson,[44] Marzio De Napoli,[34] Raffaella De Vita,[1] Patrick DeNiverville,[55] Stephen Derenzo,[13] Antonia Di Crescenzo,[56,57] Emanuele Di Marco,[58] Keith R. Dienes,[59,2] Milind Diwan,[11] Dongwi Handiipondola Dongwi,[43] Alex Drlica-Wagner,[3] Sebastian Ellis,[60] Anthony Chigbo Ezeribe,[61,62] Glennys Farrar,[18] Francesc Ferrer,[63] Enectali Figueroa-Feliciano,[64] Alessandra Filippi,[65] Giuliana Fiorillo,[66] Bartosz Fornal,[67] Arne Freyberger,[31] Claudia Frugiuele,[40] Cristian Galbiati,[68] Iftah Galon,[7] Susan Gardner,[69] Andrew Geraci,[70] Gilles Gerbier,[71] Mathew Graham,[9] Edda Gschwendtner,[72] Christopher Hearty,[73,74] Jaret Heise,[75] Reyco Henning,[76] Richard J. Hill,[16,3] David Hitlin,[5] Yonit Hochberg,[21,77] Jason Hogan,[8] Maurik Holtrop,[78] Ziqing Hong,[29] Todd Hossbach,[23] T. B. Humensky,[79] Philip Ilten,[80] Kent Irwin,[8,9] John Jaros,[9] Robert Johnson,[53] Matthew Jones,[41] Yonatan Kahn,[68] Narbe Kalantarians,[81] Manoj Kaplinghat,[7] Rakshya Khatiwada,[14] Simon Knapen,[13,12] Michael Kohl,[43,31] Chris Kouvaris,[82] Jonathan Kozaczuk,[83] Gordan Krnjaic,[3] Valery Kubarovsky,[31] Eric Kuflik,[21,77] Alexander Kusenko,[84,85] Rafael Lang,[41] Kyle Leach,[86] Tongyan Lin,[12,13] Mariangela Lisanti,[68] Jing Liu,[87] Kun Liu,[17] Ming Liu,[17] Dinesh Loomba,[88] Joseph Lykken,[3] Katherine Mack,[89] Jeremiah Mans,[4] Humphrey Maris,[90] Thomas Markiewicz,[9] Luca Marsicano,[1] C. J. Martoff,[91] Giovanni Mazzitelli,[26] Christopher McCabe,[92] Samuel D. McDermott,[6] Art McDonald,[71] Bryan McKinnon,[93] Dongming Mei,[87] Tom Melia,[13,85] Gerald A. Miller,[14] Kentaro Miuchi,[94] Sahara Mohammed Prem Nazeer,[43] Omar Moreno,[9] Vasiliy Morozov,[31] Frederic Mouton,[61] Holger Mueller,[12] Alexander Murphy,[95] Russell Neilson,[96] Tim

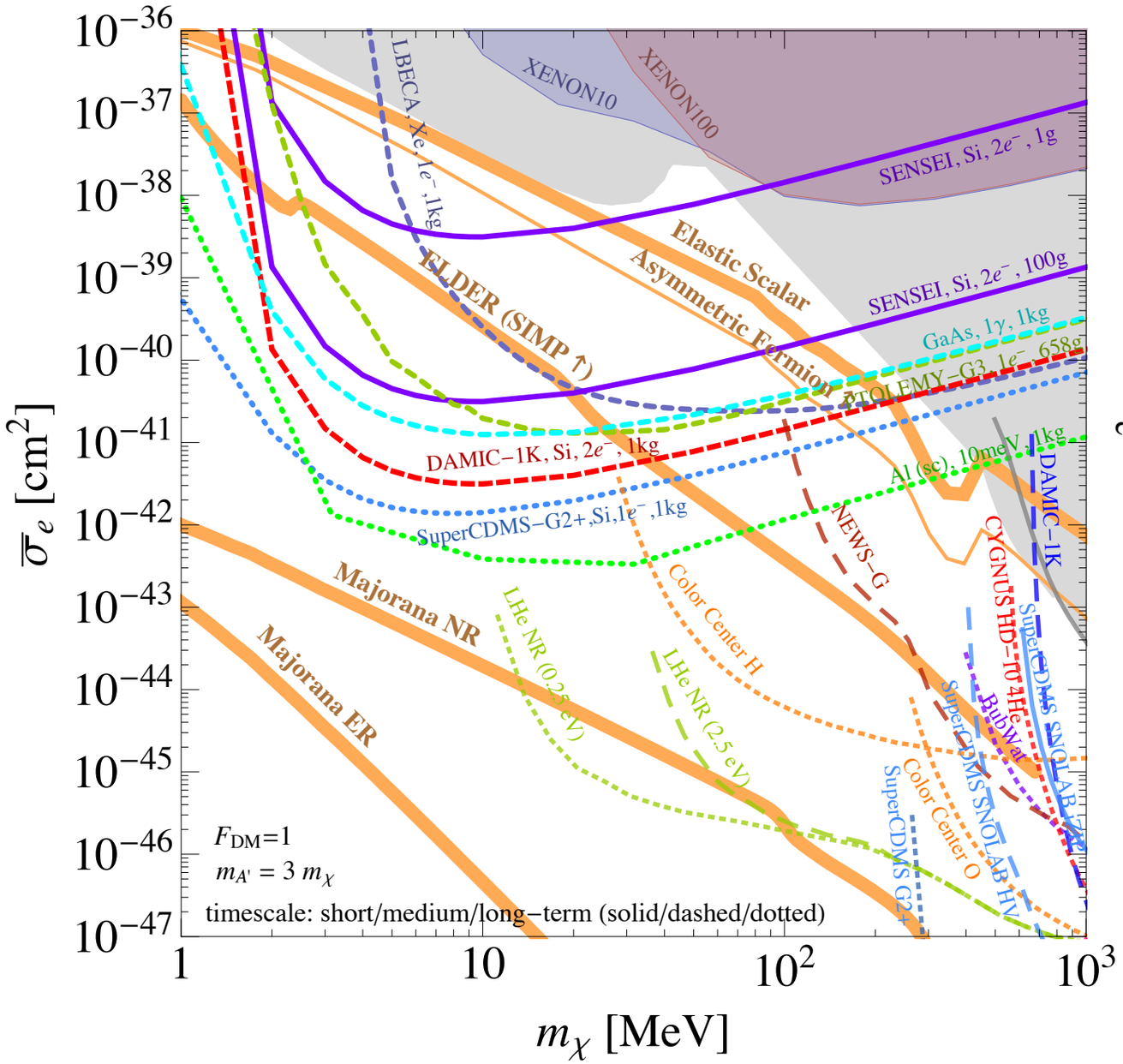
DD Working Group Conveners:
RE, J. Estrada, D. McKinsey

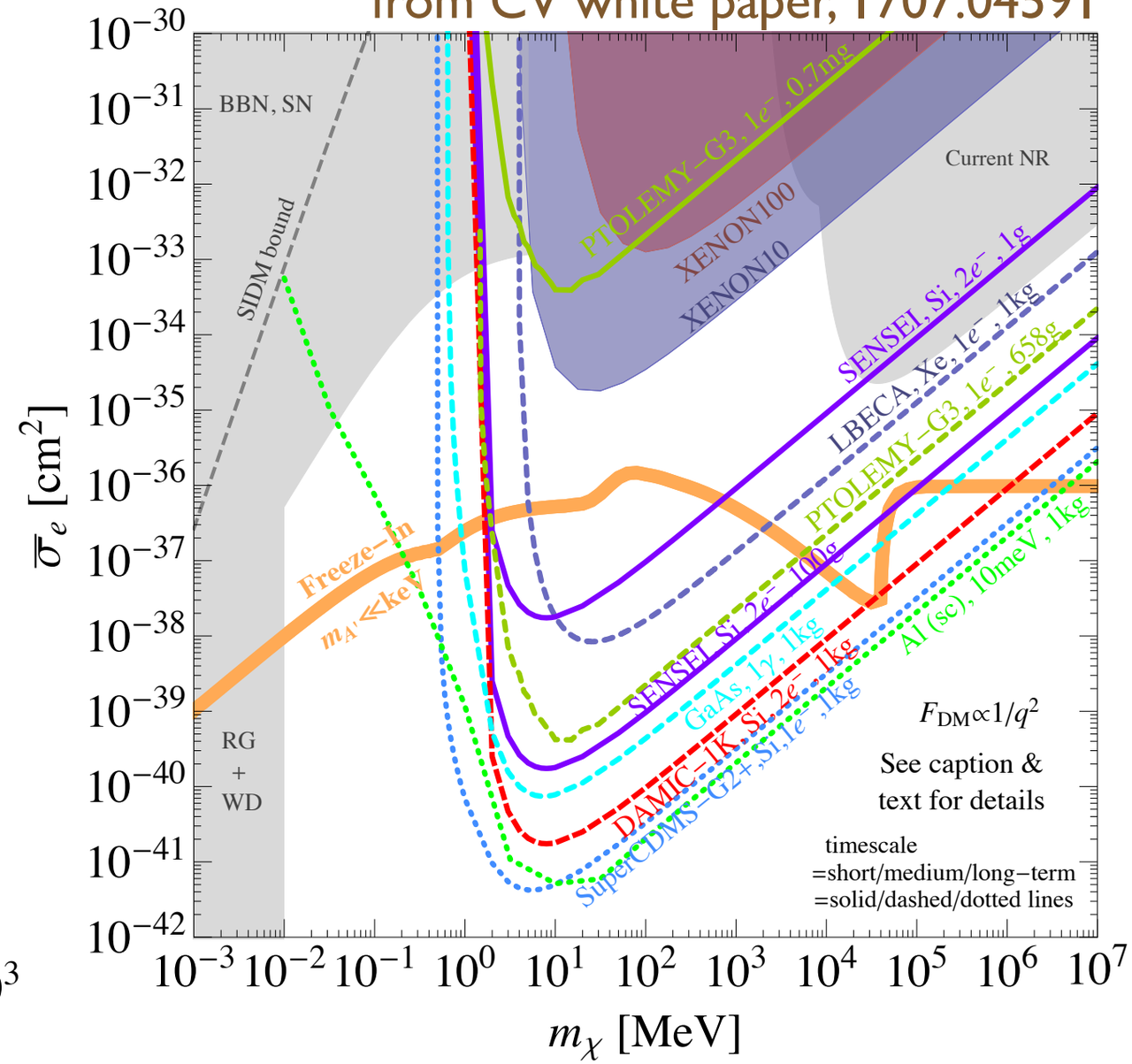
gives overview of new ideas
(already slightly outdated)

arXiv:1707.04591

Many Direct Detection Proposals

from CV white paper, 1707.04591





shaded region = current constraints

orange lines = benchmark models

colored lines = proposed new DD ideas w/ approximate timescale

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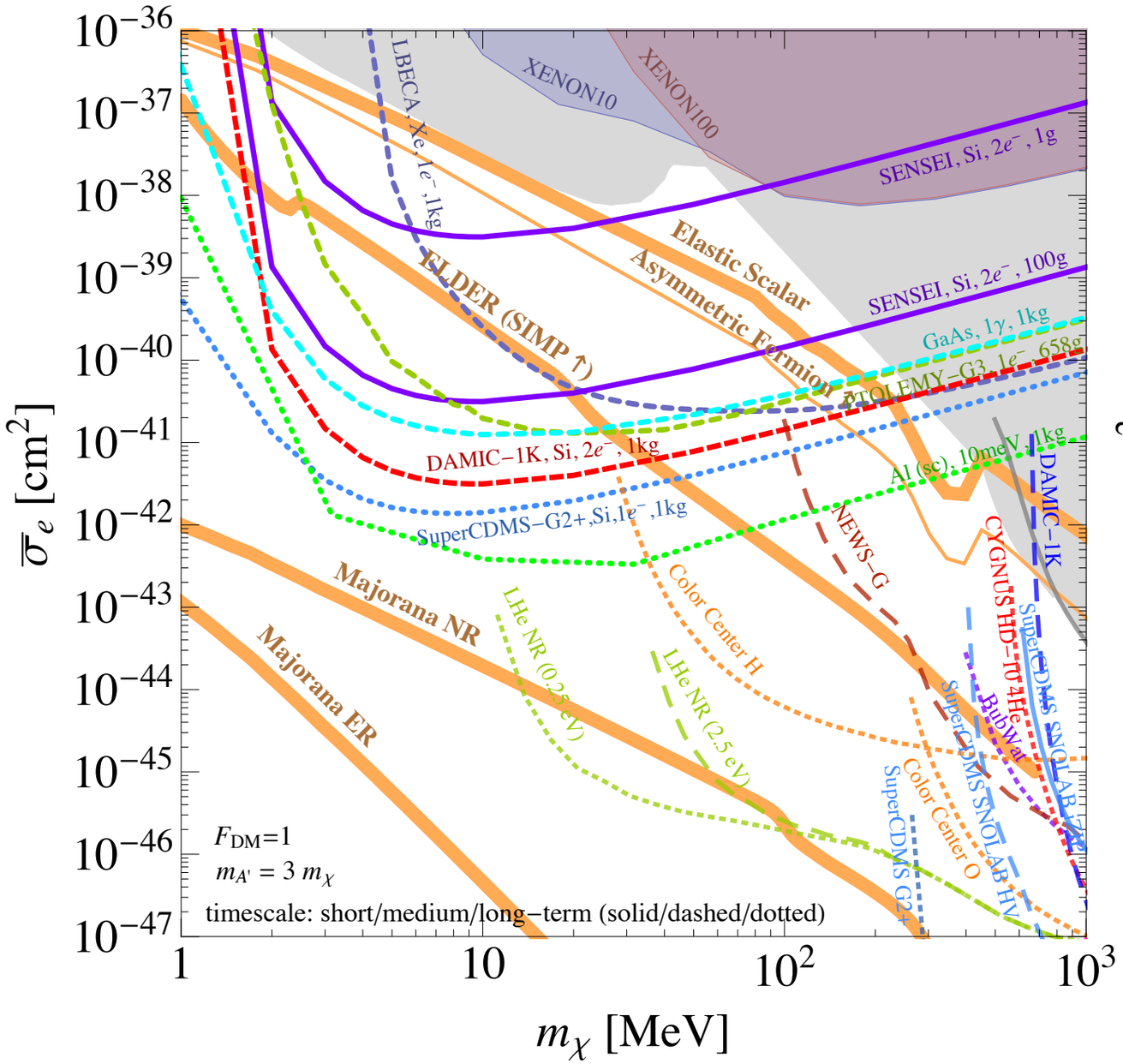

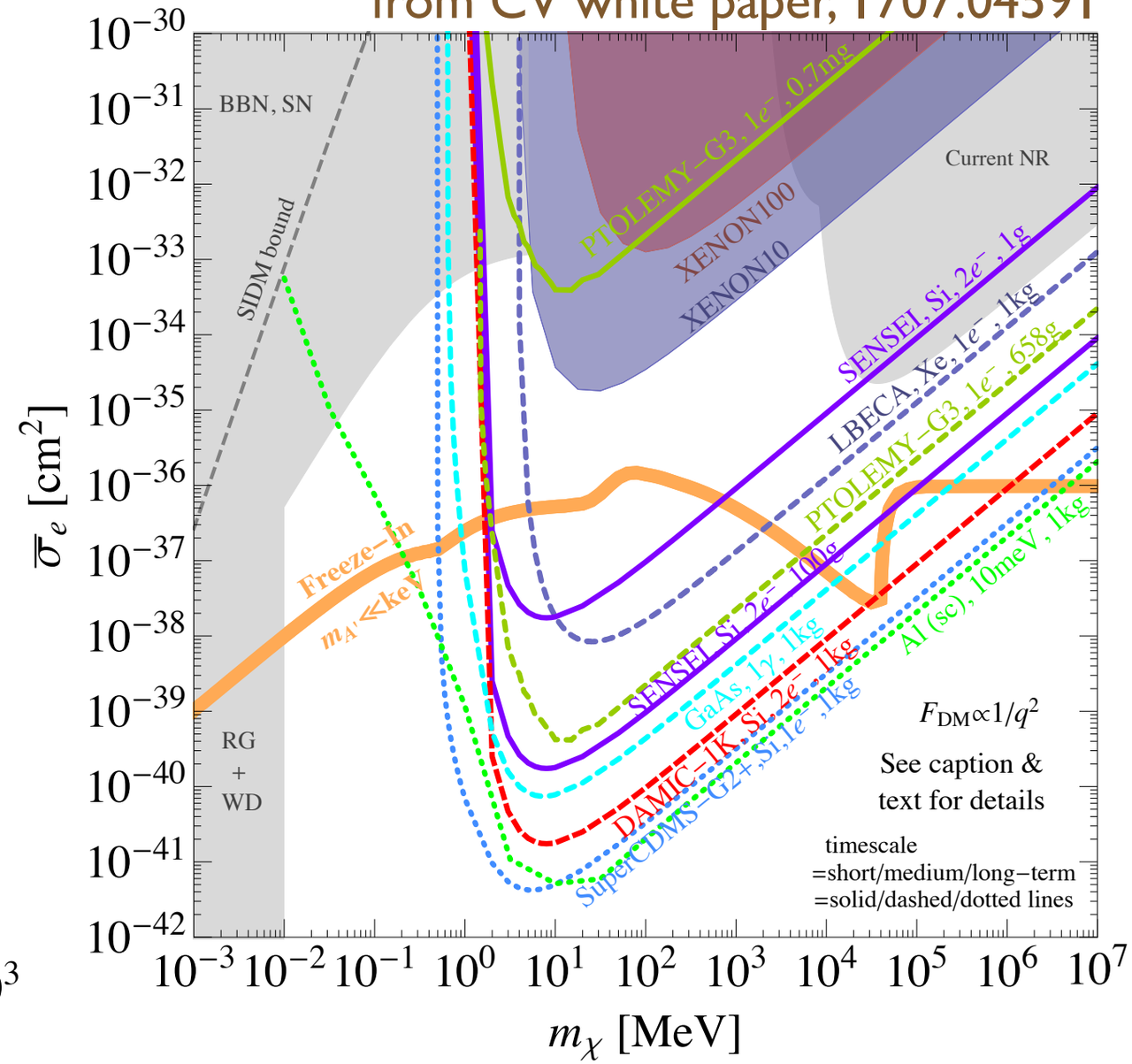

(all proposals were treated equally but some proposals are more equal than others…)

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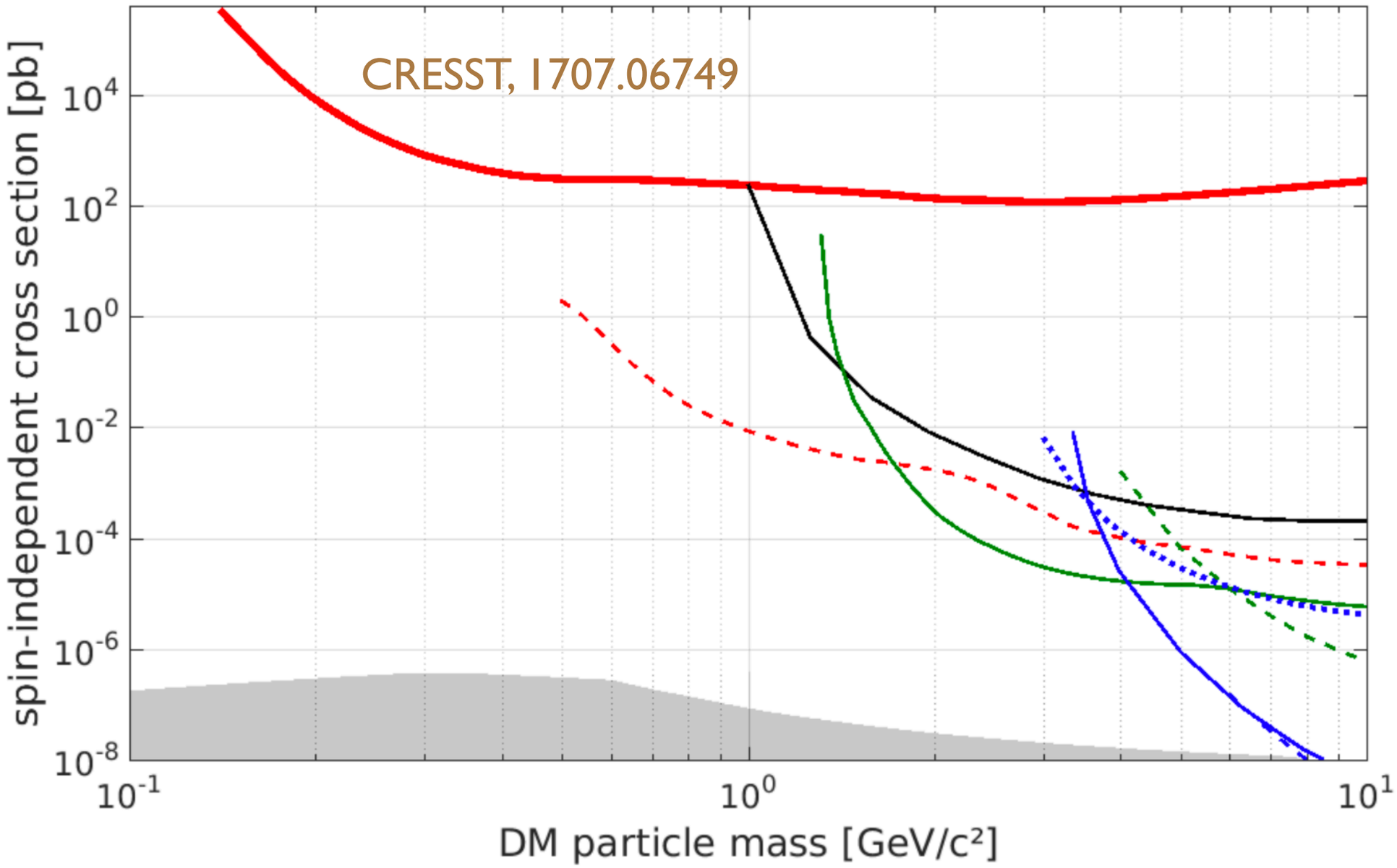
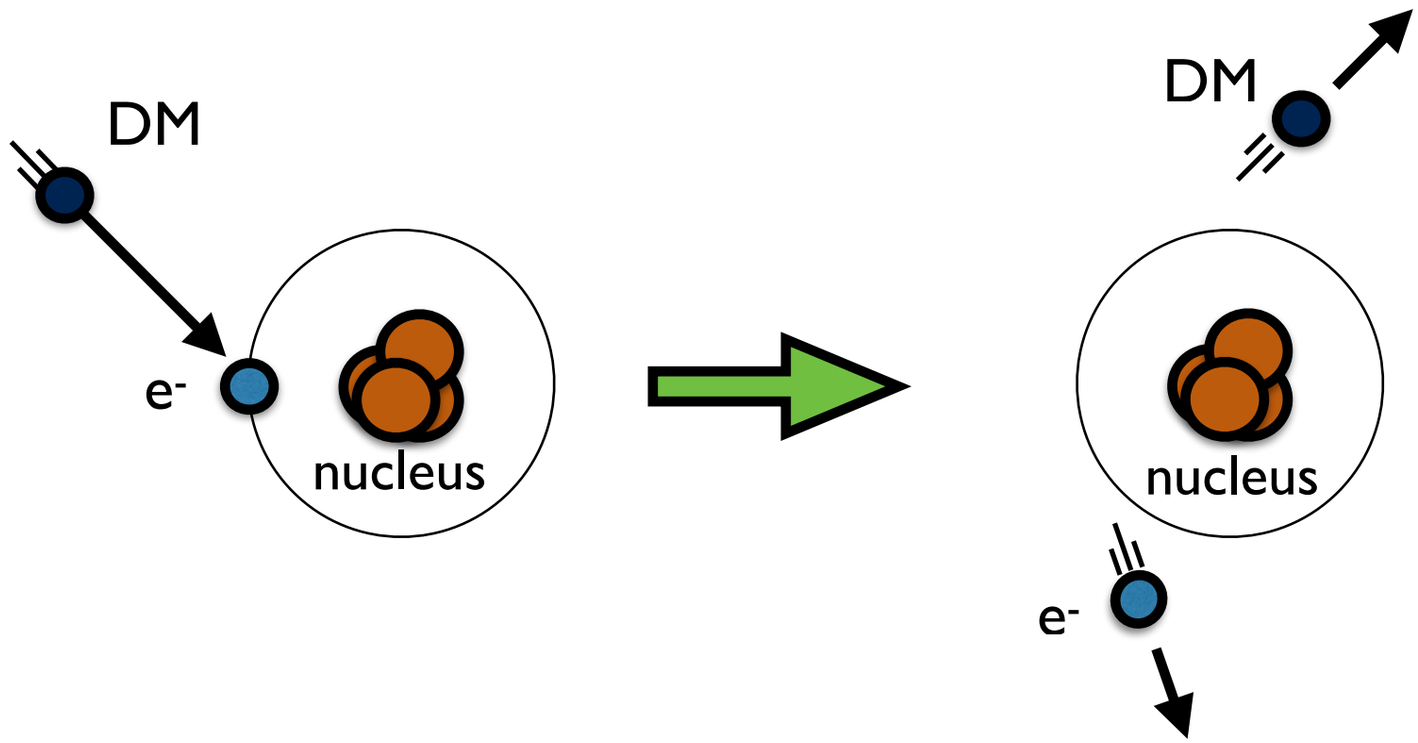
Direct Detection w/ nuclear recoils: challenging to have sensitivity ≪1 GeV



(however, see talks by Tongyan & Dan M. for some proposals)

DM-electron scattering can probe $\ll$GeV

RE, Mardon, Volansky, 2011



Typically produces a signal
of one or a few electrons

demonstrated sensitivity w/ noble liquid detectors & silicon detectors

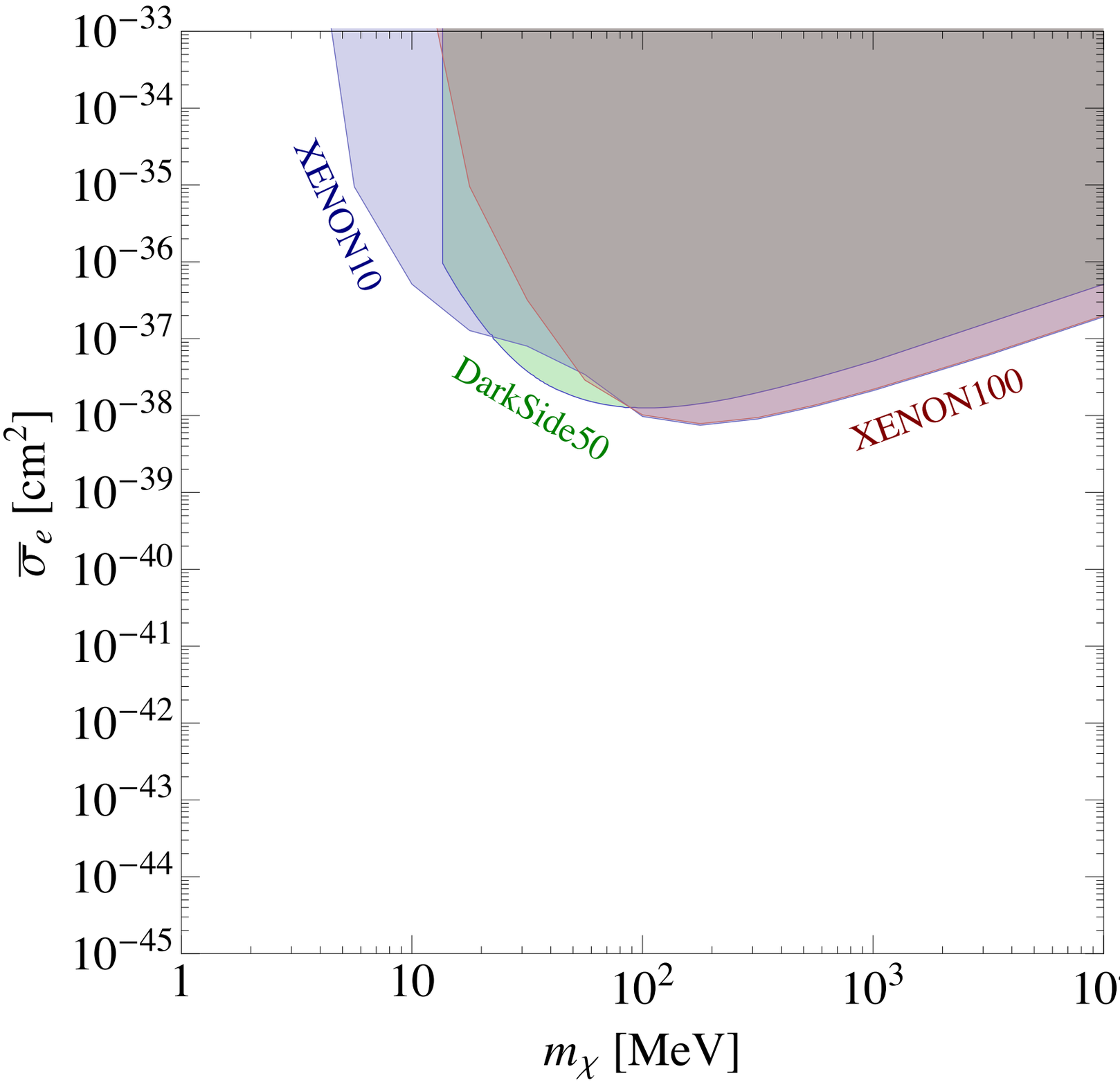
XENON10 + XENON100 + DarkSide-50

RE, Mardon, Volansky, 2011

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012

RE, Volansky, Yu 2017

DarkSide-50, 2018



(see Elena's talk later today for how xenon TPCs can see this)

XENON10: 1104.3088

XENON100: 1605.06262

DarkSide-50: 1802.06998

XENON10 + XENON100 + DarkSide-50

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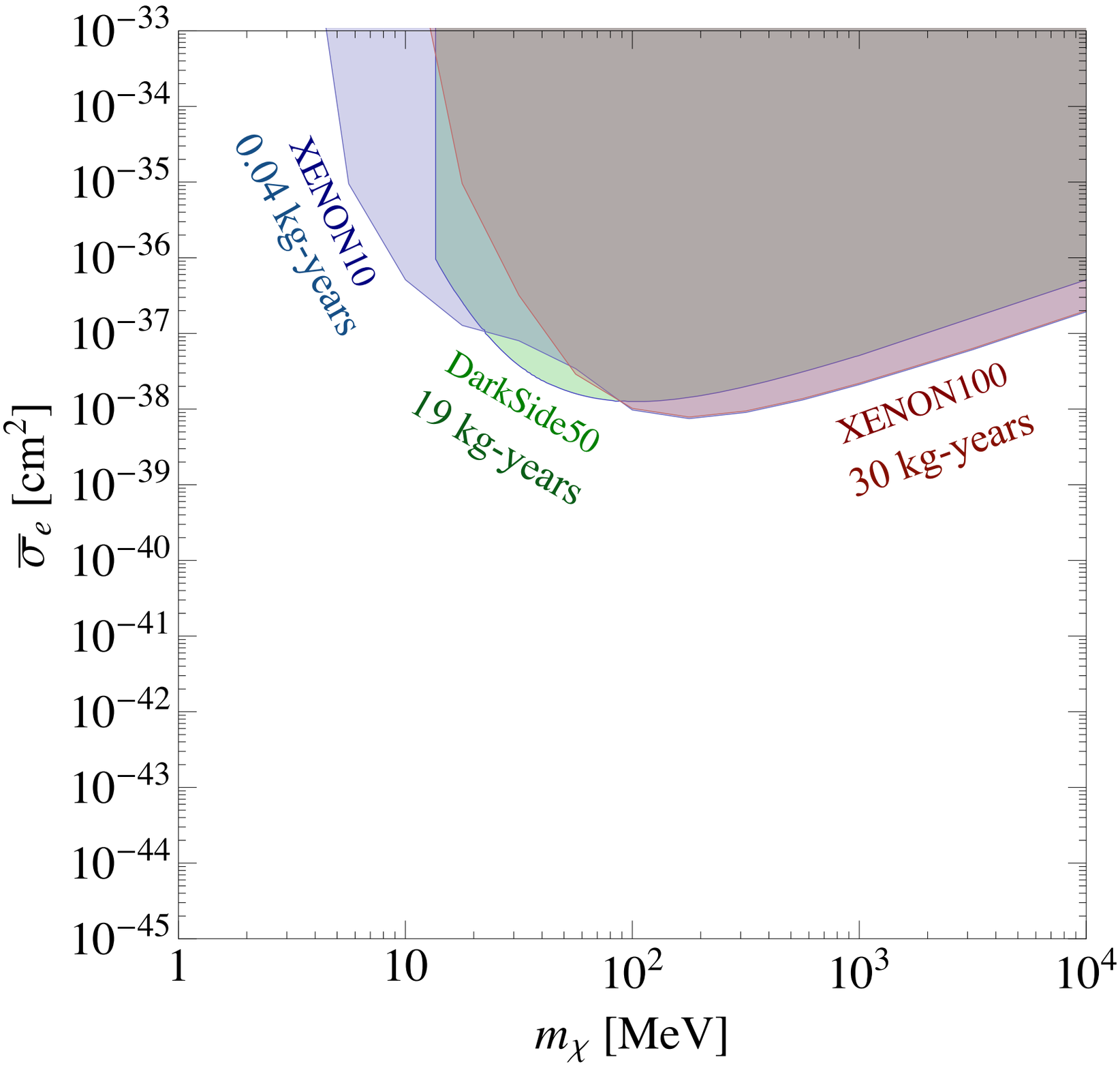

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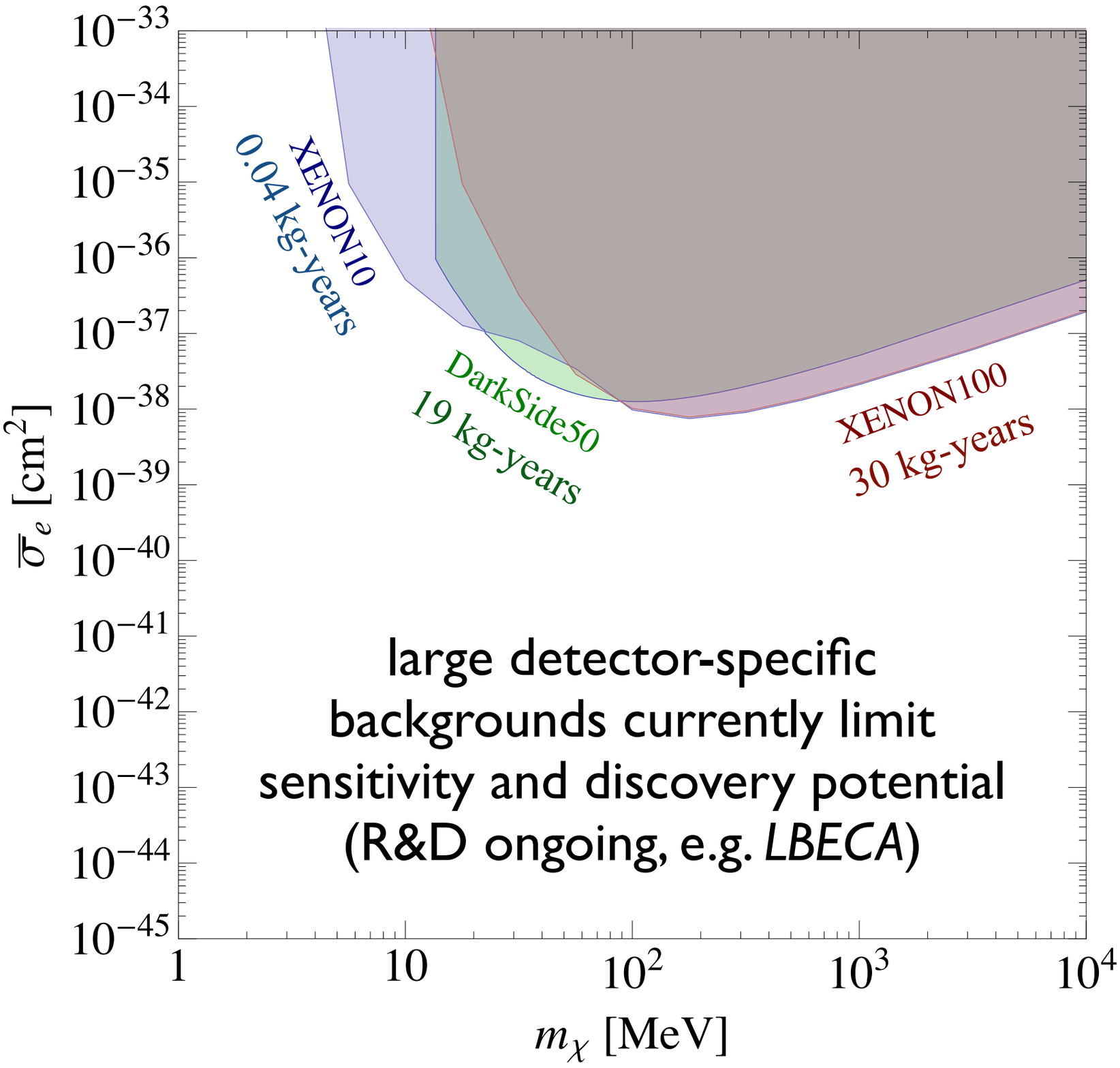

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LBECA = Low Background Electron Counting Apparatus

Bernstein, RE, Fernandez-Serra, Lang, Ni, Sorensen, Xu

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SENSEI

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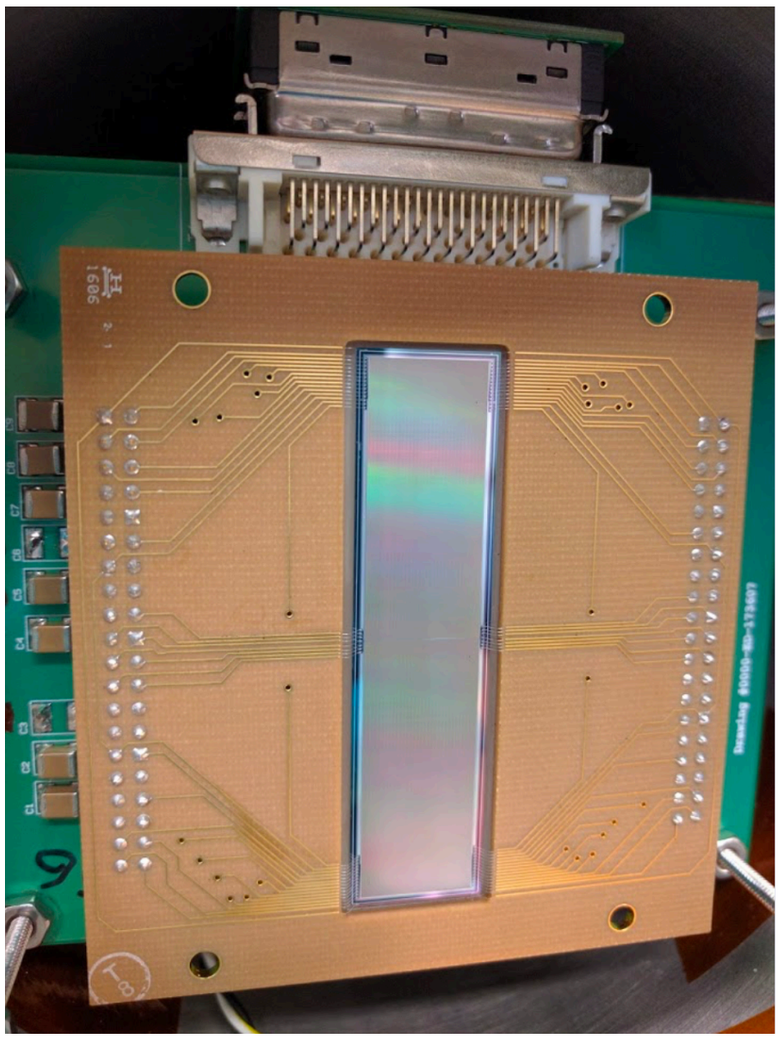
The SENSEI Collaboration: L. Barack, M. Crisler, A. Drlica-Wagner, RE, E. Ezion, J. Estrada, G. Fernandez, J. Tiffenberg, M. Sofo Haro, T. Volansky, T-T. Yu



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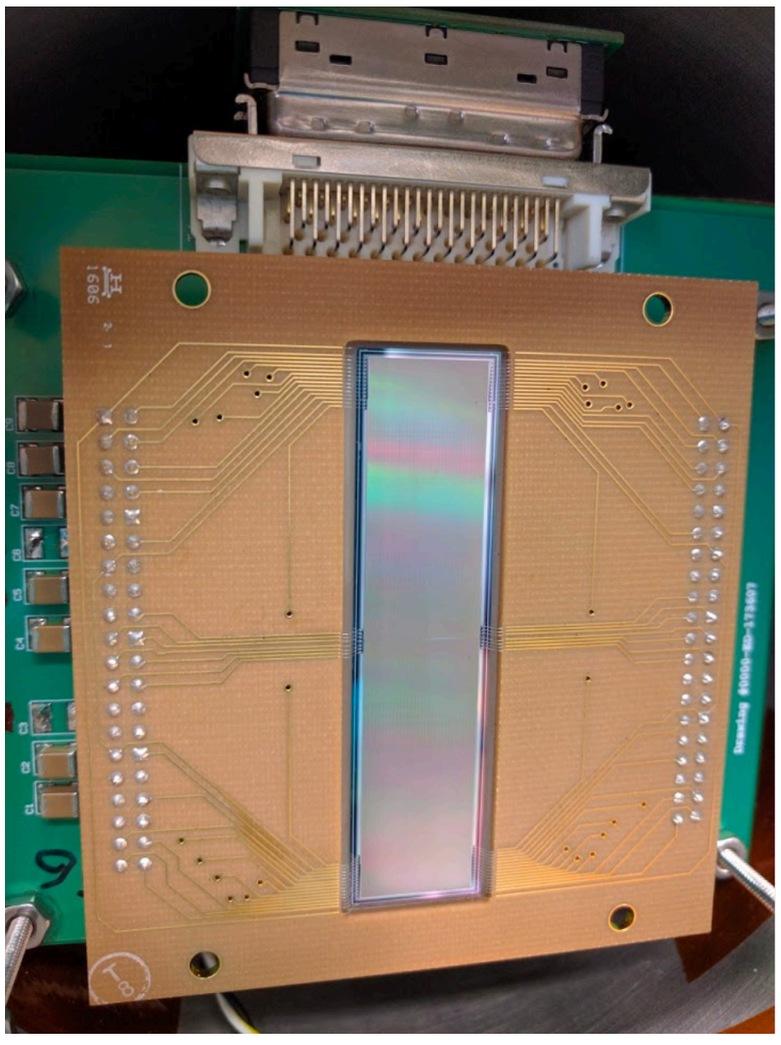

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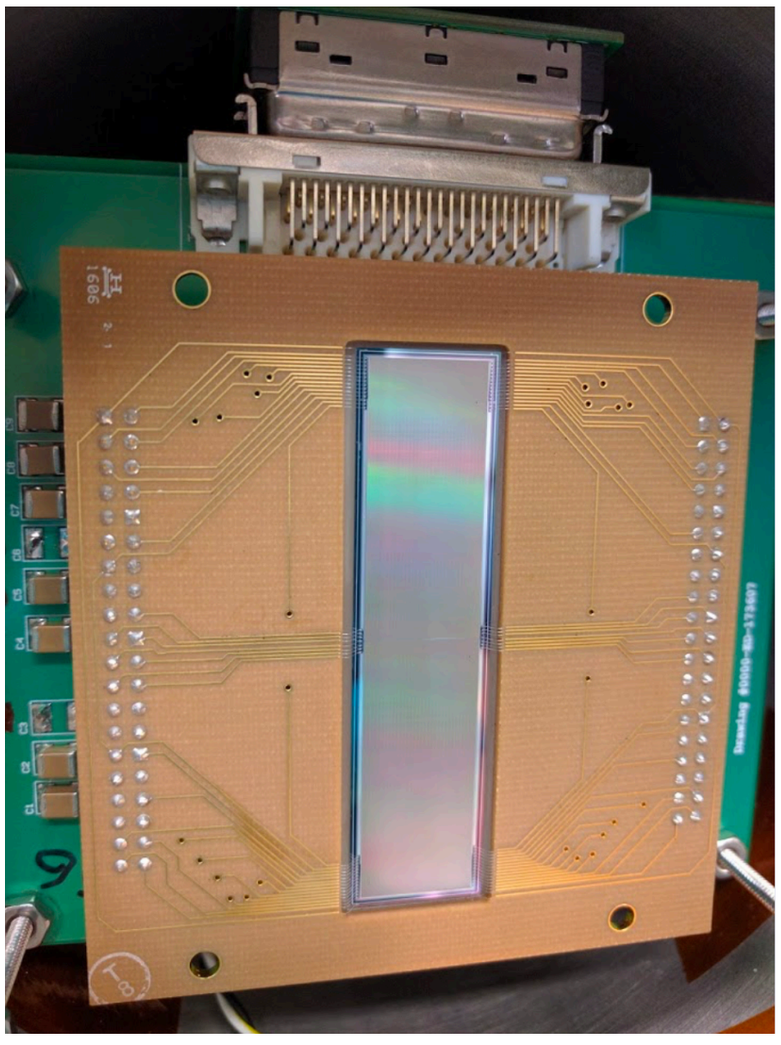

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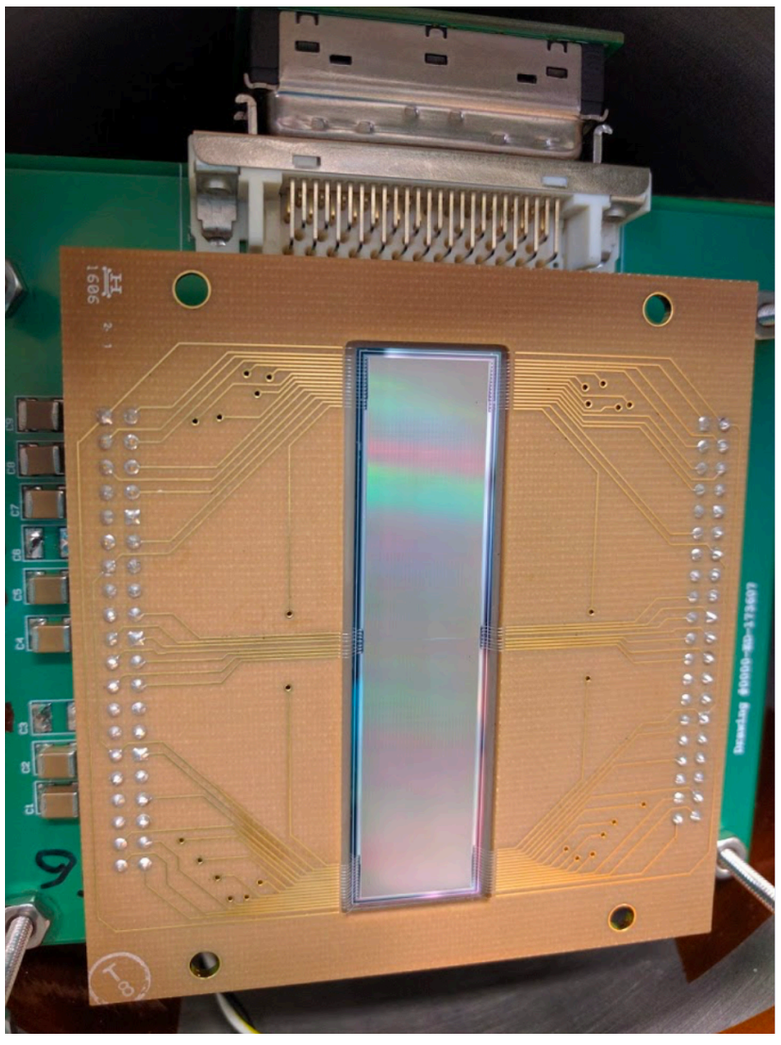

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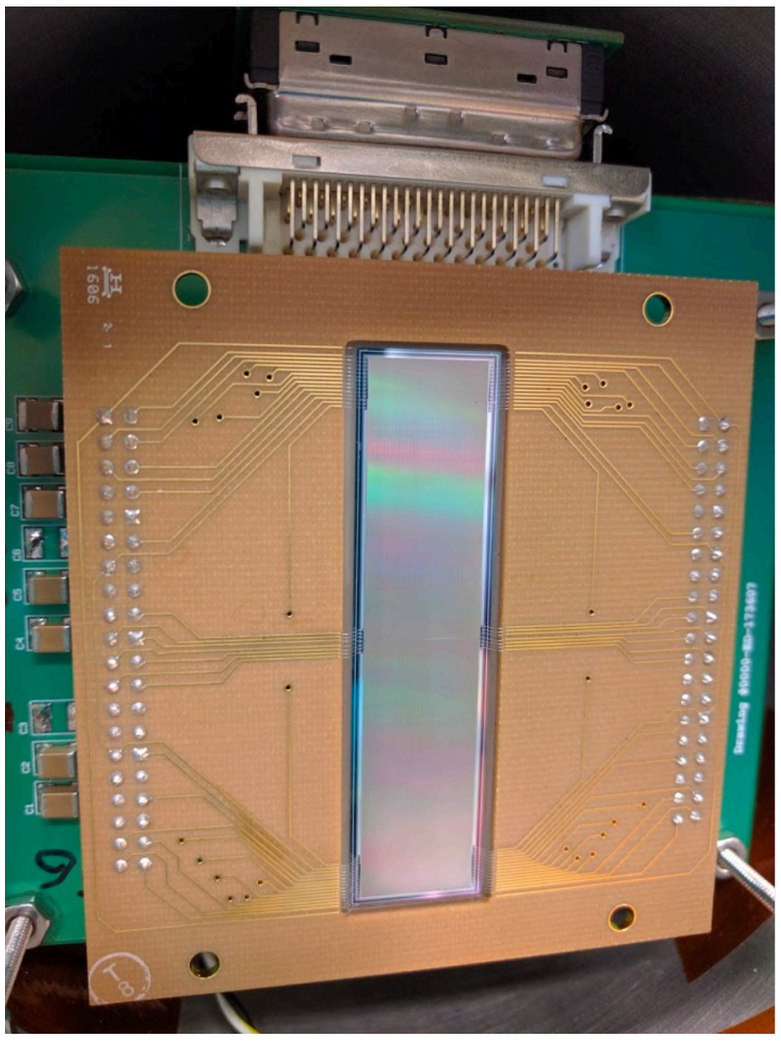

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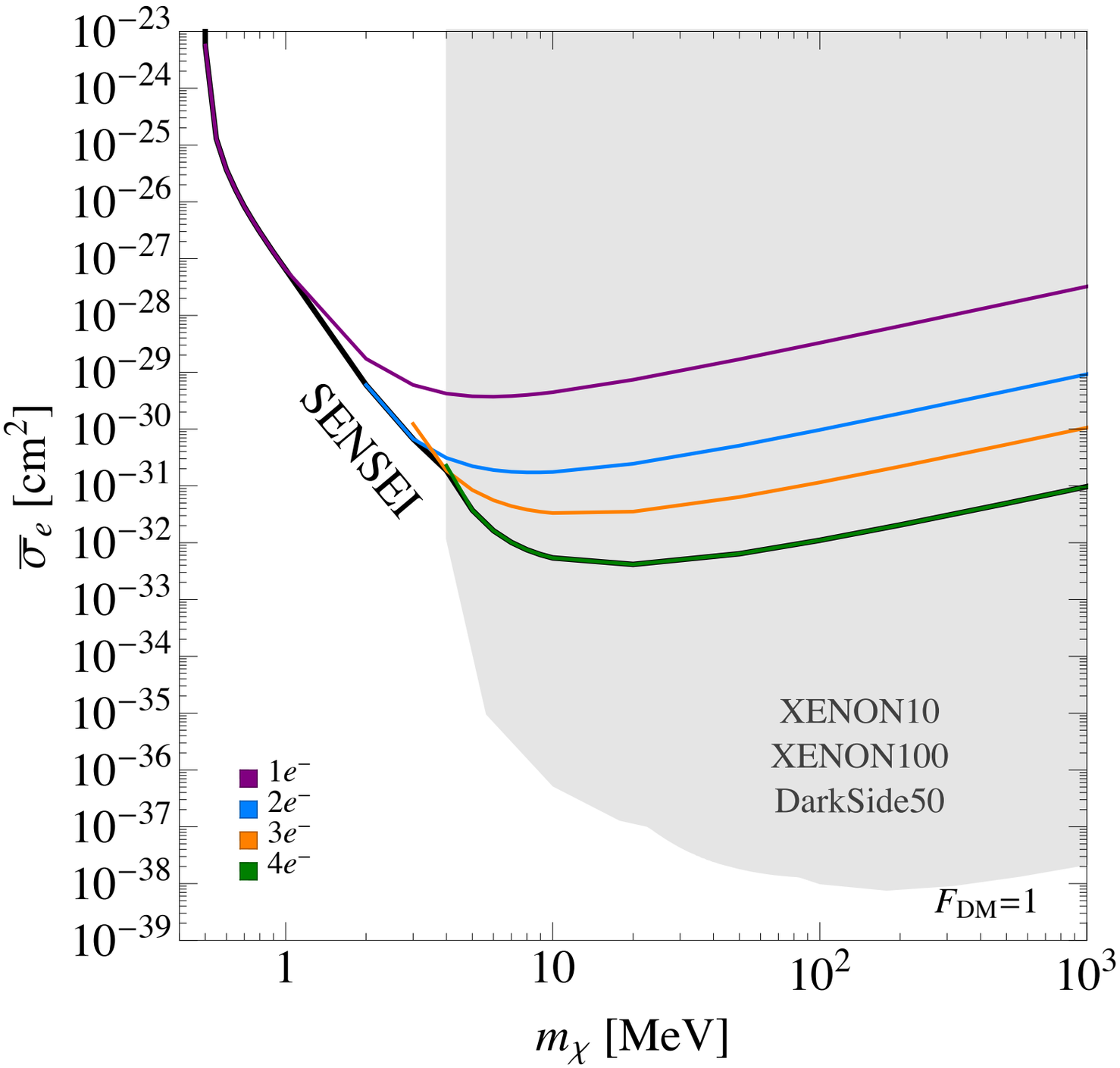
- first dedicated experiment searching for electron recoils from sub-GeV DM
- fully funded by Heising-Simons Foundation and Fermilab
- Goal: use 100-grams of Skipper CCDs

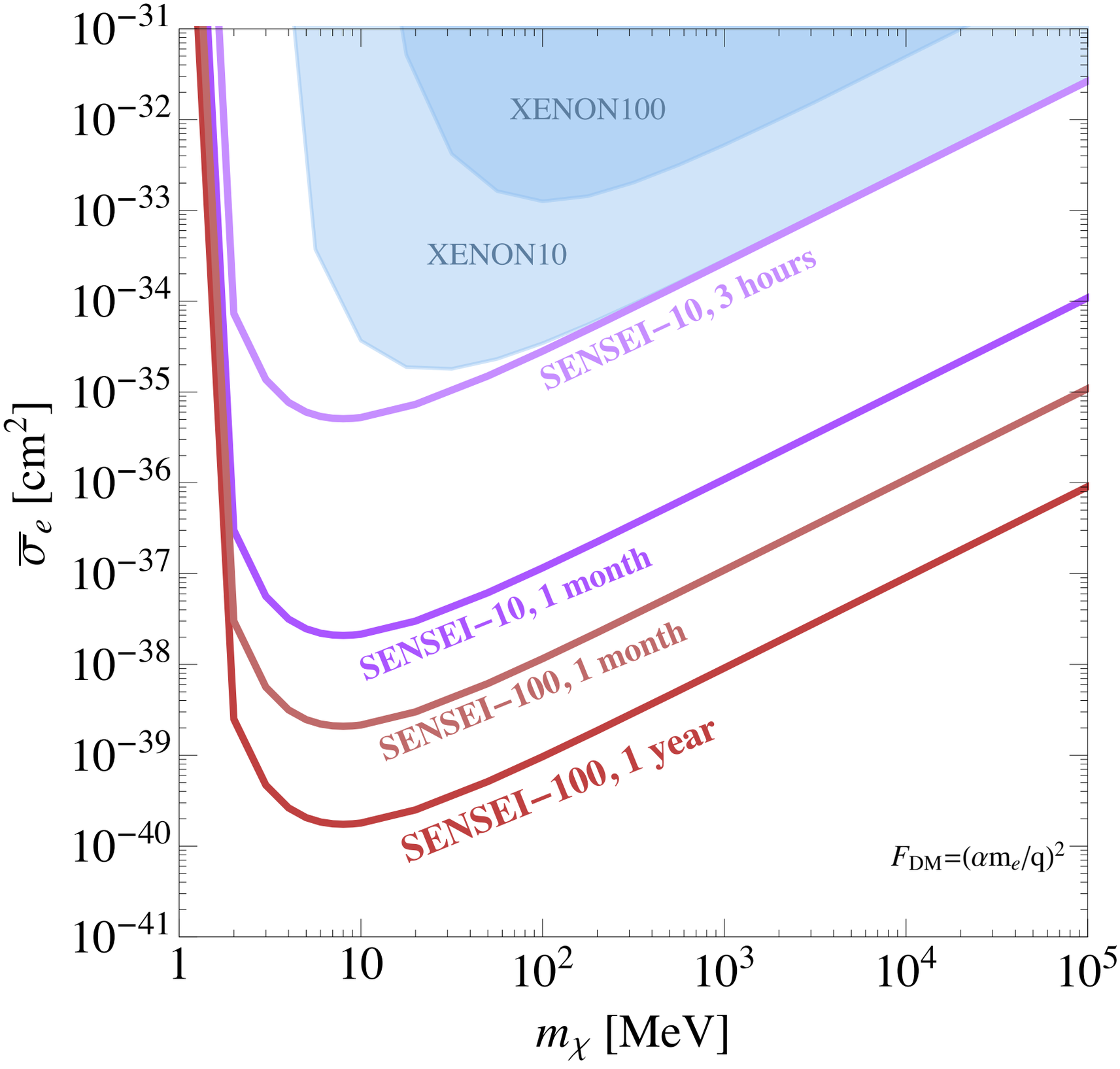
First SENSEI results (from surface commissioning run)



- prototype Skipper-CCD
- only 0.019 gram-days
- first constraints between ~500 keV to 4 MeV

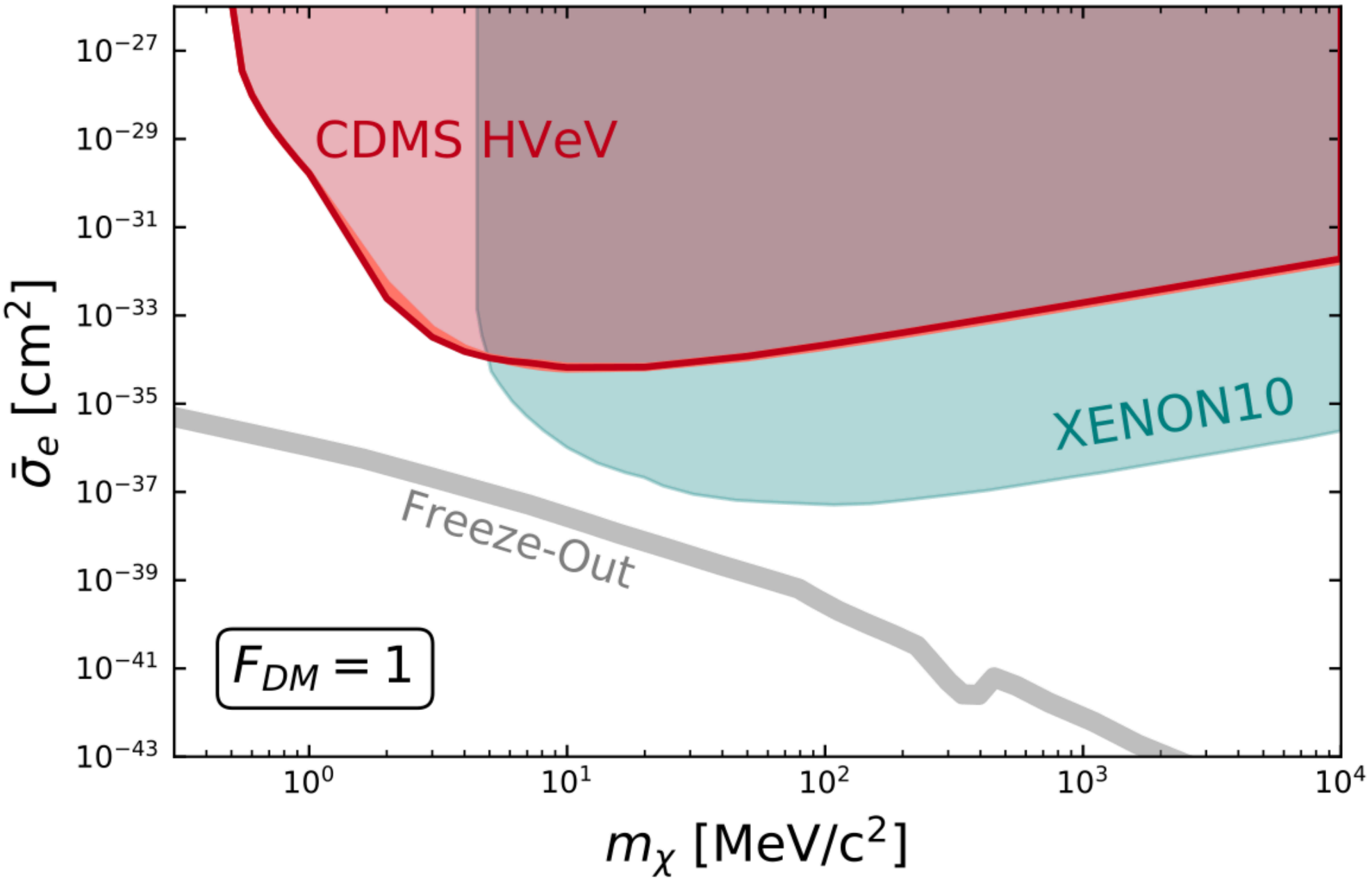
1804.00088, submitted to PRL

SENSEI projection



SuperCDMS: first limits from a high-voltage detector

earlier this week: 1804.10697



(see Jodi's talk)

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What are the backgrounds?

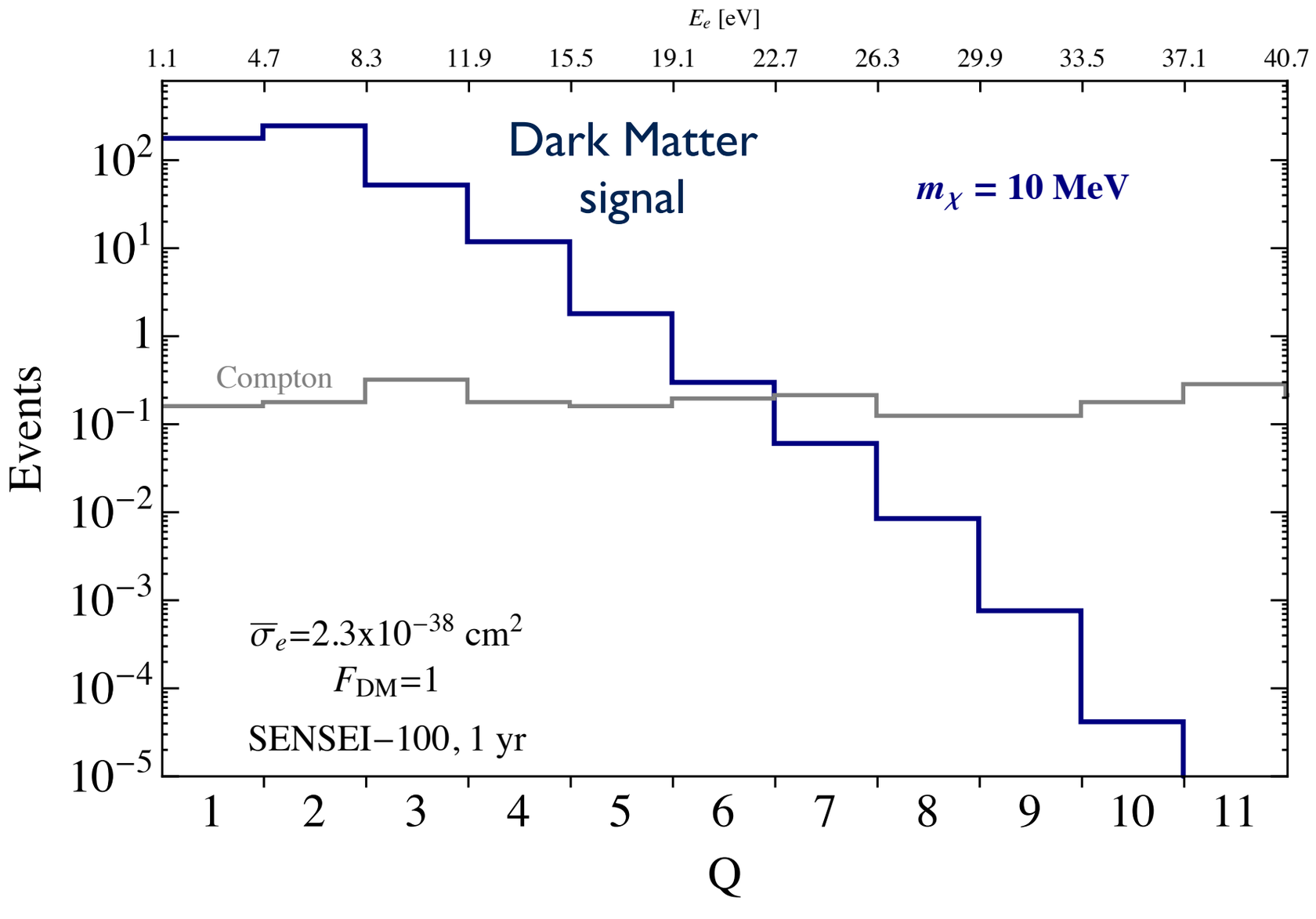
- Radioactivity
- Solar neutrinos
- Dark counts

(depending on type of DM search and experimental setup, other critical backgrounds can include vibrations, electronic noise, coherent photon scattering)

Radioactivity

Expect <1 event/kg/year/eV

based on <u>known</u> ways to shield, purify, and handle materials



SENSEI backgrounds

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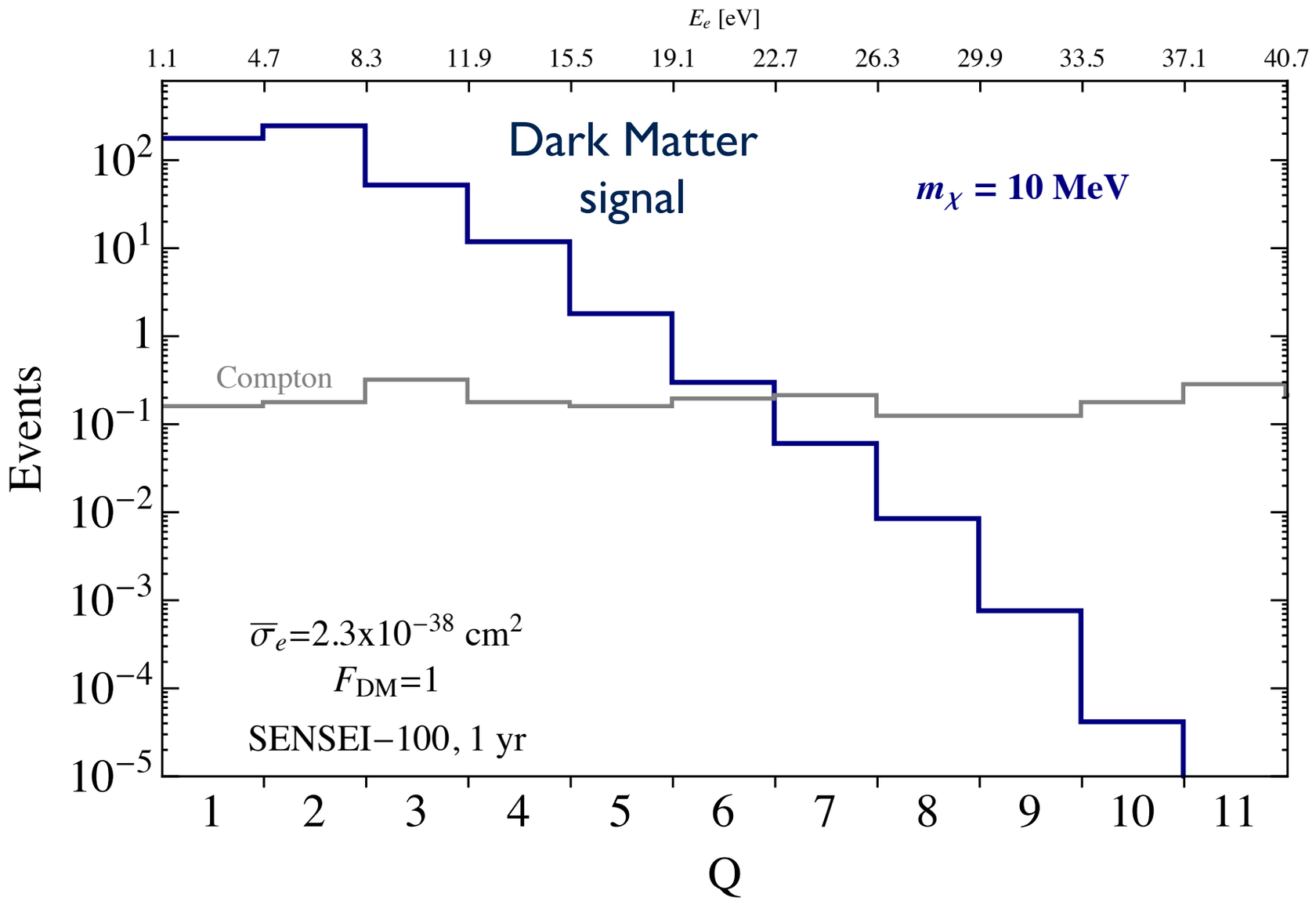


SENSEI backgrounds

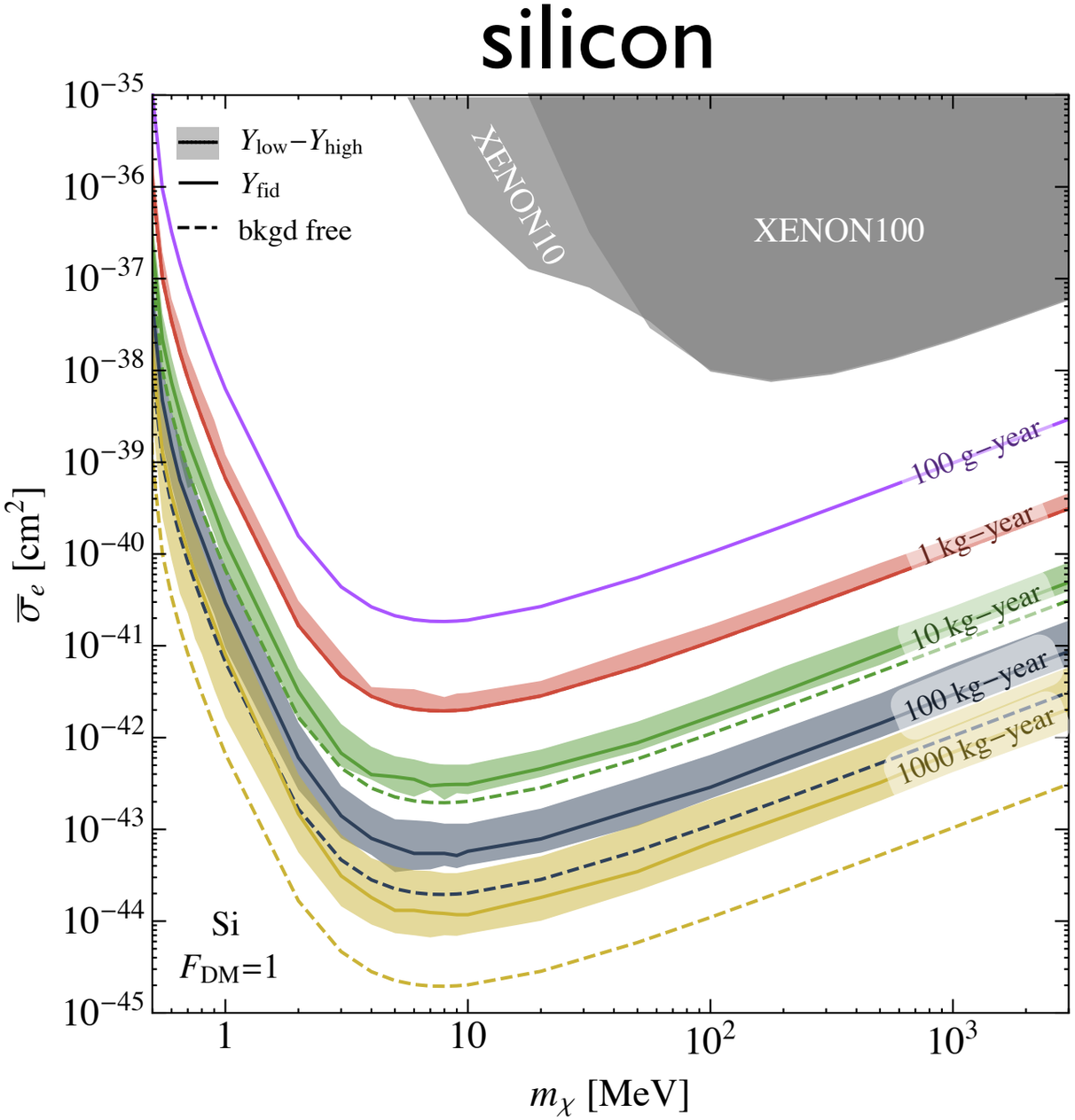
(based on DAMIC measurement at energies >50 eV)

For larger exposures need better shielding etc. or use signal shape

Solar neutrinos

Solar neutrinos

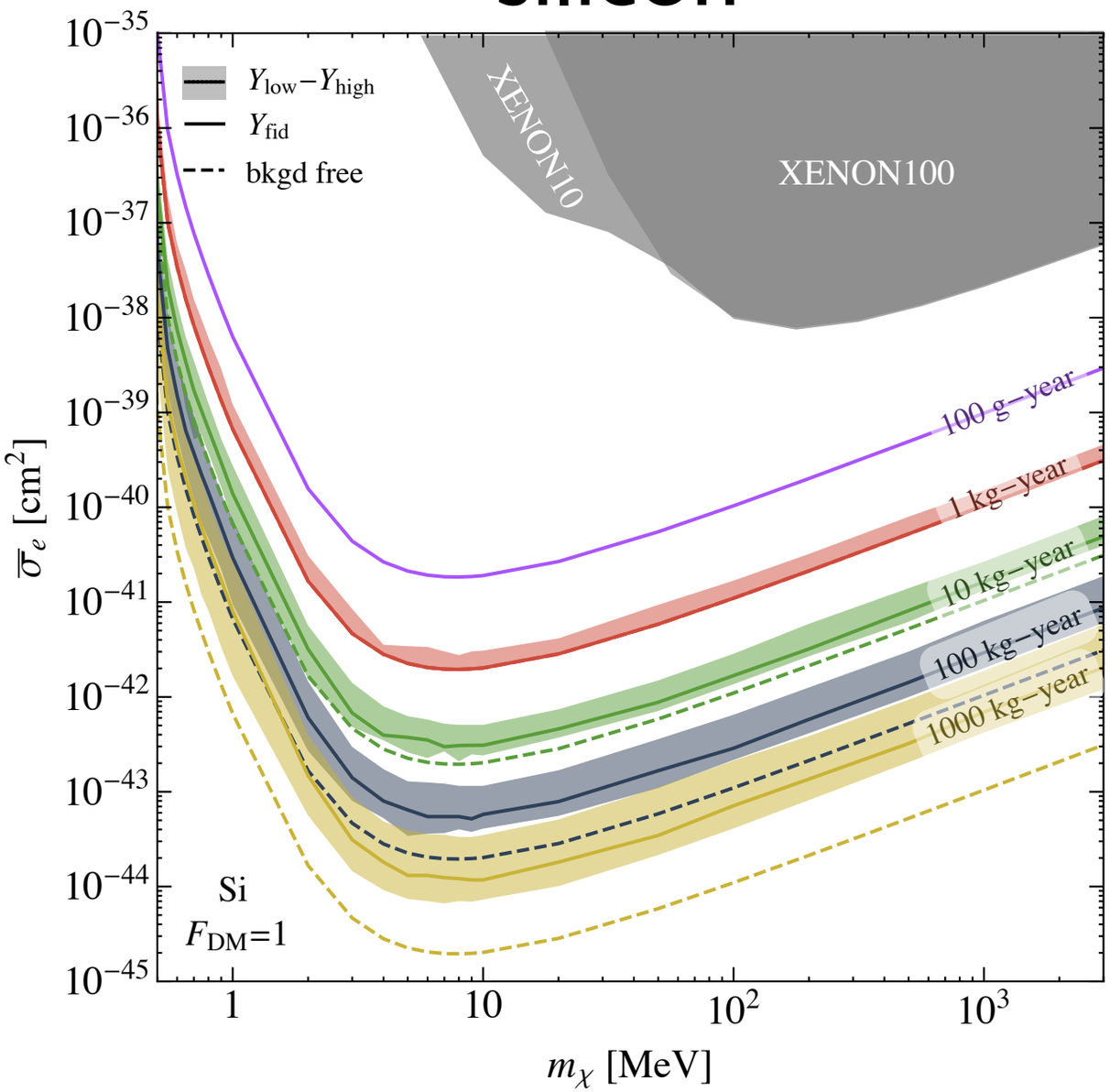
RE, Mukul Sholapurkar, Yu



Solar neutrinos

RE, Mukul Sholapurkar, Yu

silicon



ν's begin limiting sensitivity for

$$\gtrsim \text{few kg} - \text{year}$$

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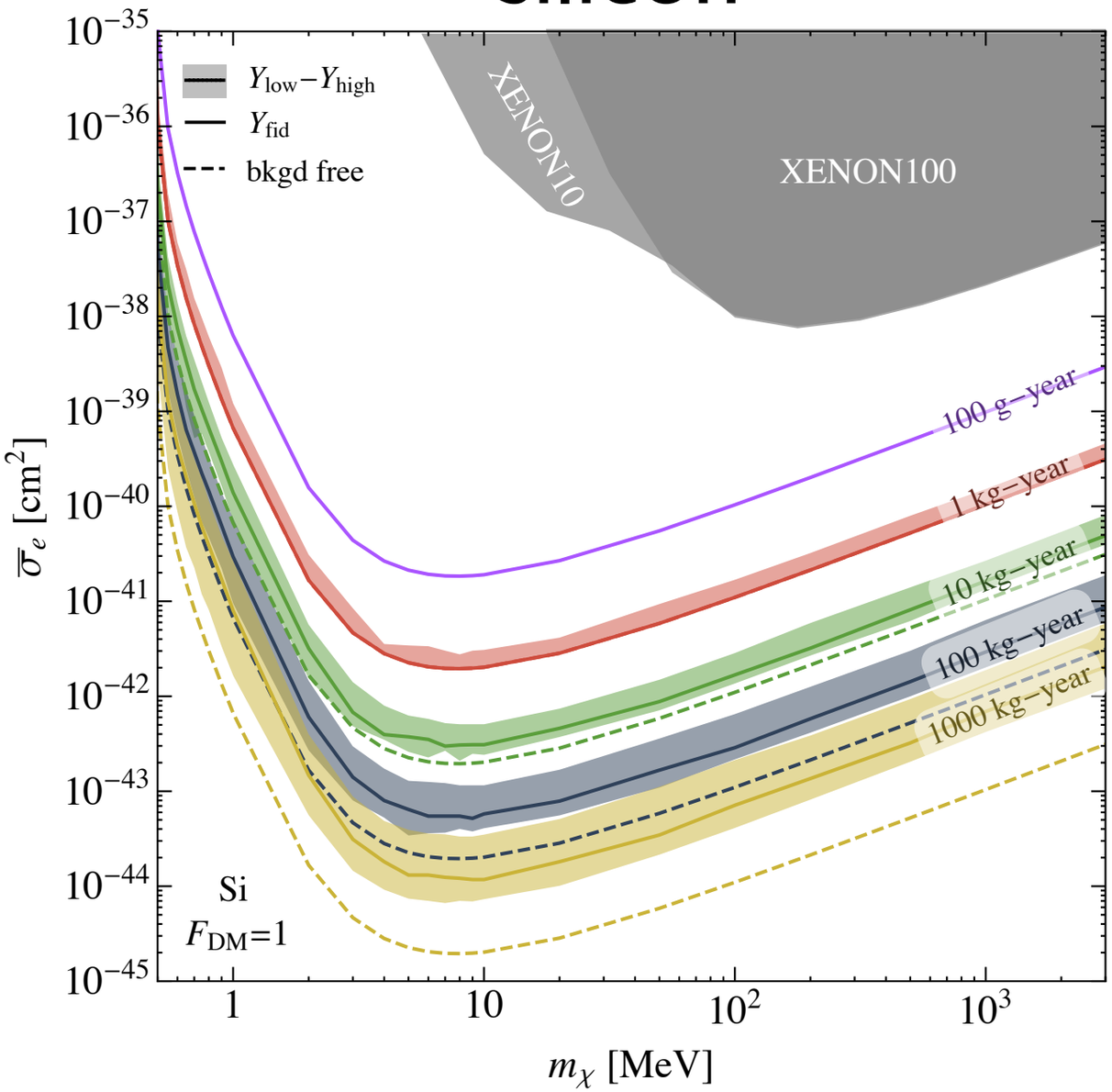
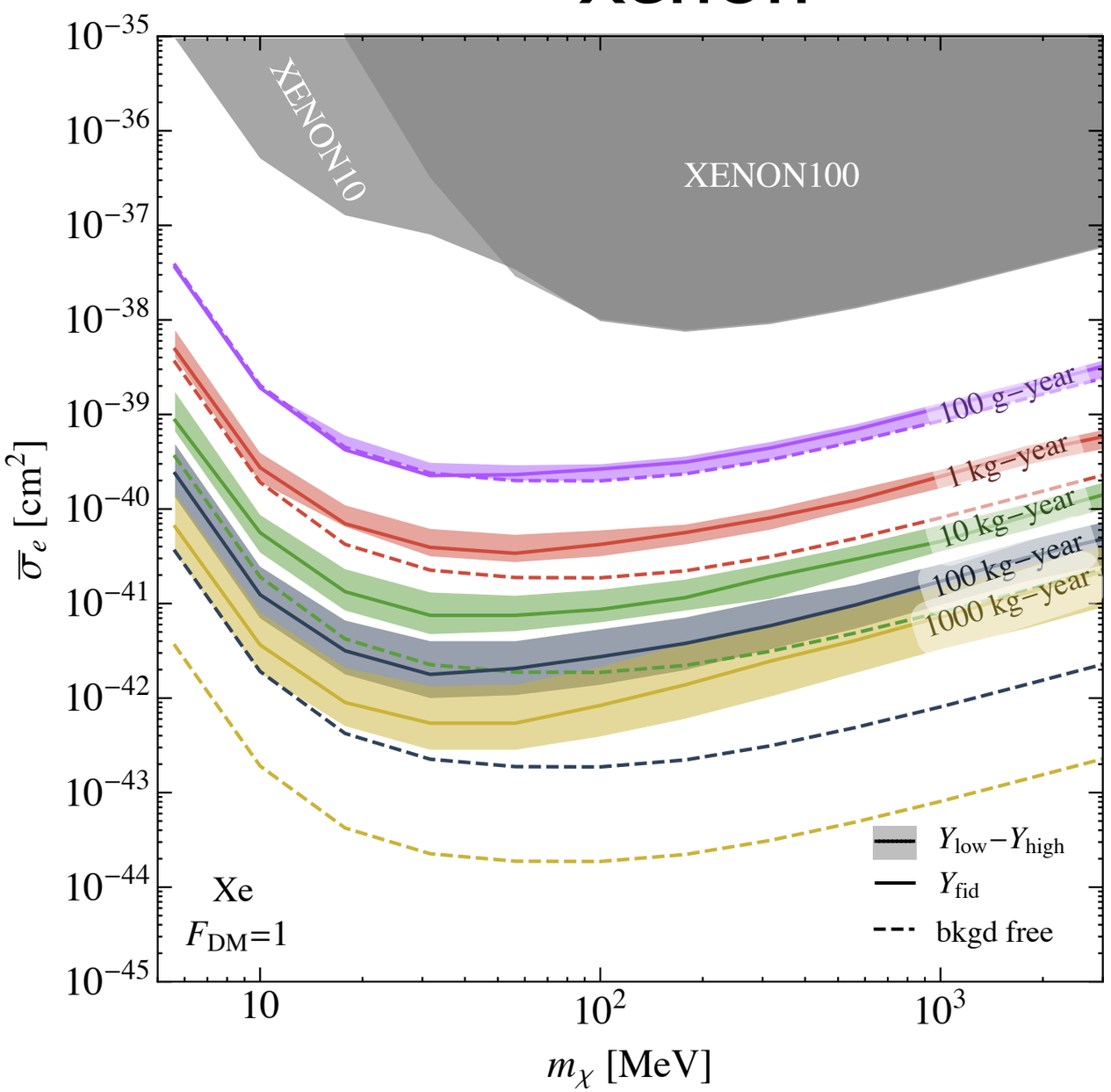


xenon



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Dark Counts

- Detector-specific backgrounds that mimic DM signal

  (impurities, leakage currents, thermal fluctuations, …)

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- SuperCDMS: charge leakage currently limits threshold
- *unknown dark counts…?*

Questions

1. Where else should we look?
2. Can we see a signal?
3. What are the backgrounds?
4. How will we know that we've found DM?
5. How low should we go in cross section?
6. Complementarity between DD & collider searches?
7. Put limits/projections from direct, indirect, and collider searches on same plot?

How will we know that we've found sub-GeV DM?

- Several handles exist to understand an excess
  (annual mod, signal shape, temperature dependence…)
- But… a single experiment will unlikely be convincing…
  ideally check with another detector technology
- Search for both electron and nuclear couplings
- Probe with accelerators
  (visibility depends on specific DM candidate)

I'm optimistic, but it'll likely be a long road….

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How low should we go in cross section?

- Keep going, at least until solar neutrinos begin to limit severely your sensitivity, and making progress becomes too expensive

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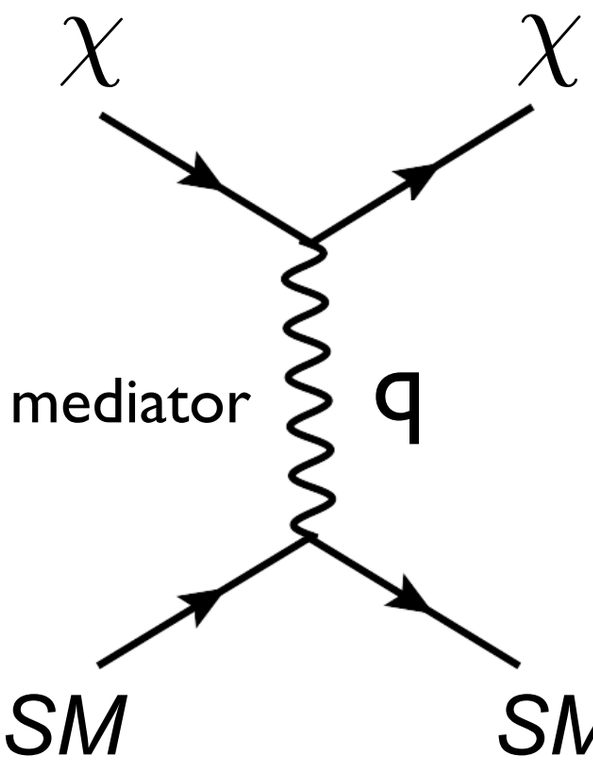
(I'm not discussing interesting complementarity w/ cosmological probes, but see e.g. Vera's talk)

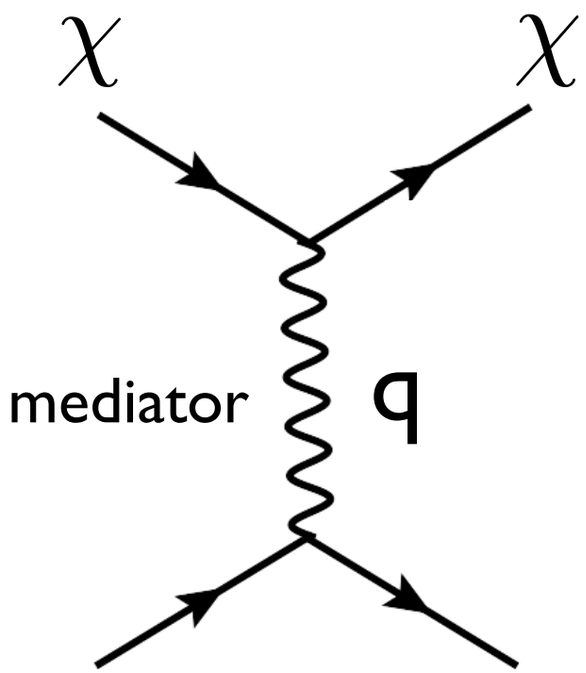
Complementarity: need both DD & Accelerators



$m_{mediator} > q$

DD & Accelerators
are great

Complementarity: need both DD & Accelerators



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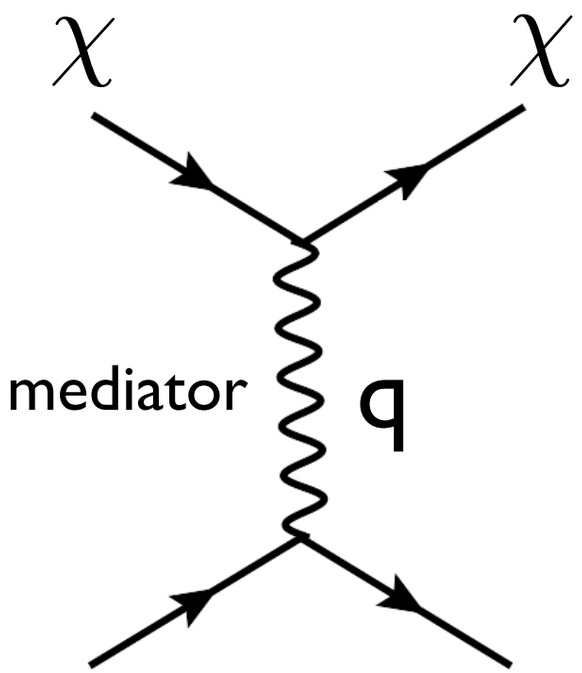
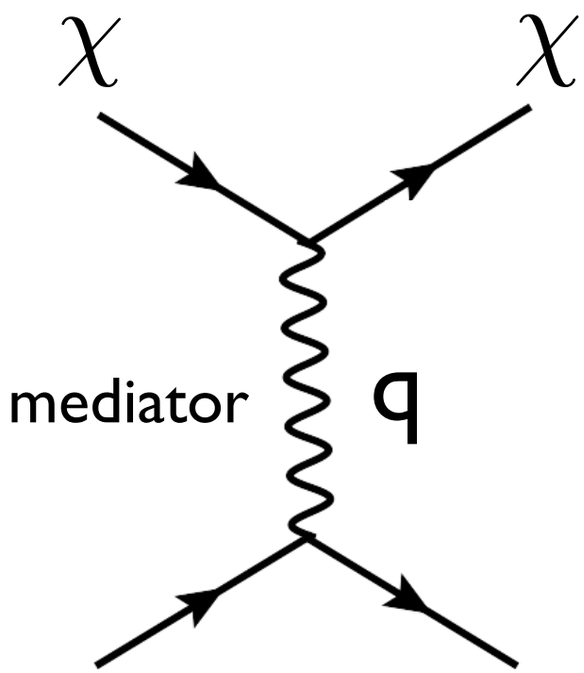


$m_{mediator} \ll q$

$$\bar{\sigma}_e \propto \frac{1}{q^4}$$

DD is much better

Complementarity: need both DD & Accelerators



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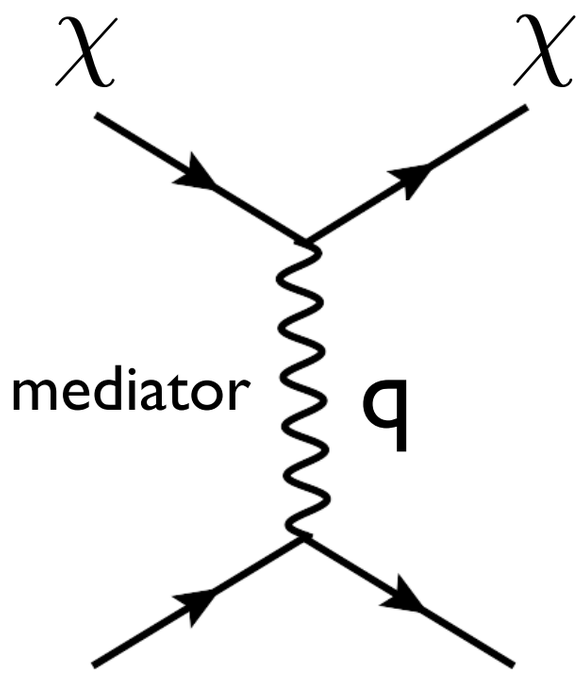
DD & Accelerators are great



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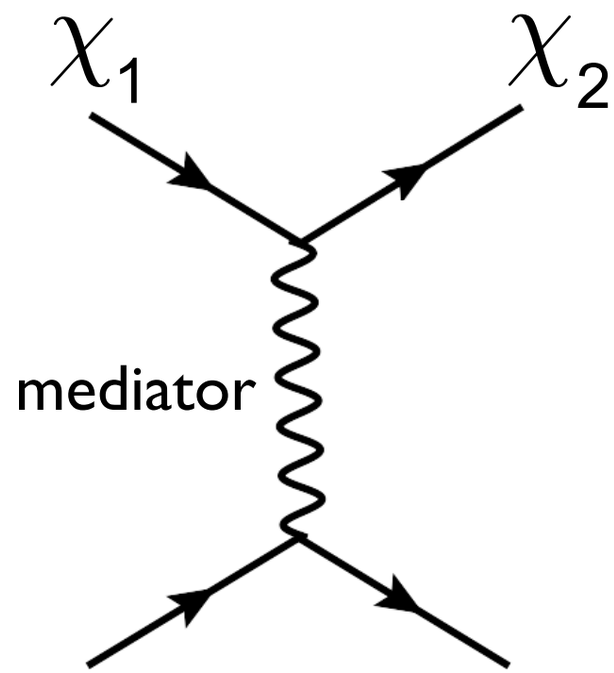

inelastic DM

$$E_{\chi 1} < m_{\chi 2} - m_{\chi 1}$$

Accelerator is much better

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Put limits/projections from direct, indirect, and collider searches on same plot?

- It is useful to consider sometimes specific, concrete models and make plots that contain all known limits (and possibly projections)
- However, note that often small changes in the model assumption can completely change the sensitivity of particular probes. Great care must therefore be taken when comparing the sensitivity of one type of probe with another
- When presenting a plot that contains constraints/ projections from different types of probes, the model should be specified precisely

Summary

1. Where else should we look?

   Sub-GeV DM is well-motivated and ripe for experimental exploration; modest R&D funding for developing new ideas is essential!

2. Can we see a signal?

   Yes

3. What are the backgrounds?

   For 1st generation searches (~100 grams) radioactivity is under control, neutrinos not important, but various handles on dark counts is crucial

4. How will we know that we've found DM?

   I'm optimistic, but it'll be a lengthy road

5. How low should we go in cross section?

   Just keep going! Will be limited by ν's eventually

6. Complementarity between DD & collider searches?

   Both are essential

7. Put limits/projections from direct, indirect, & colliders on same plot?

   It is useful, but please specify your model precisely