Direct Detection of sub-GeV Dark Matter

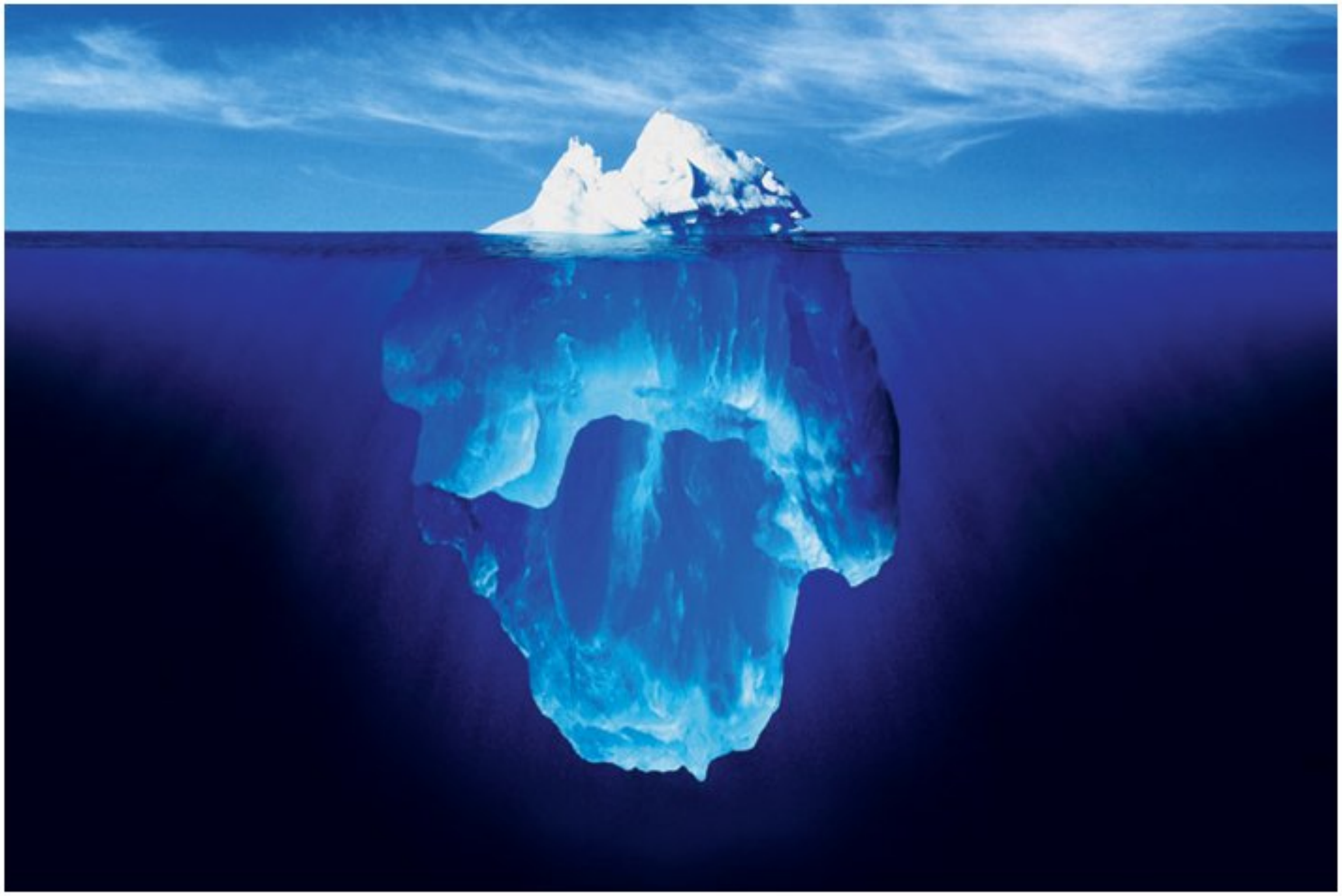
Rouven Essig

Yang Institute for Theoretical Physics

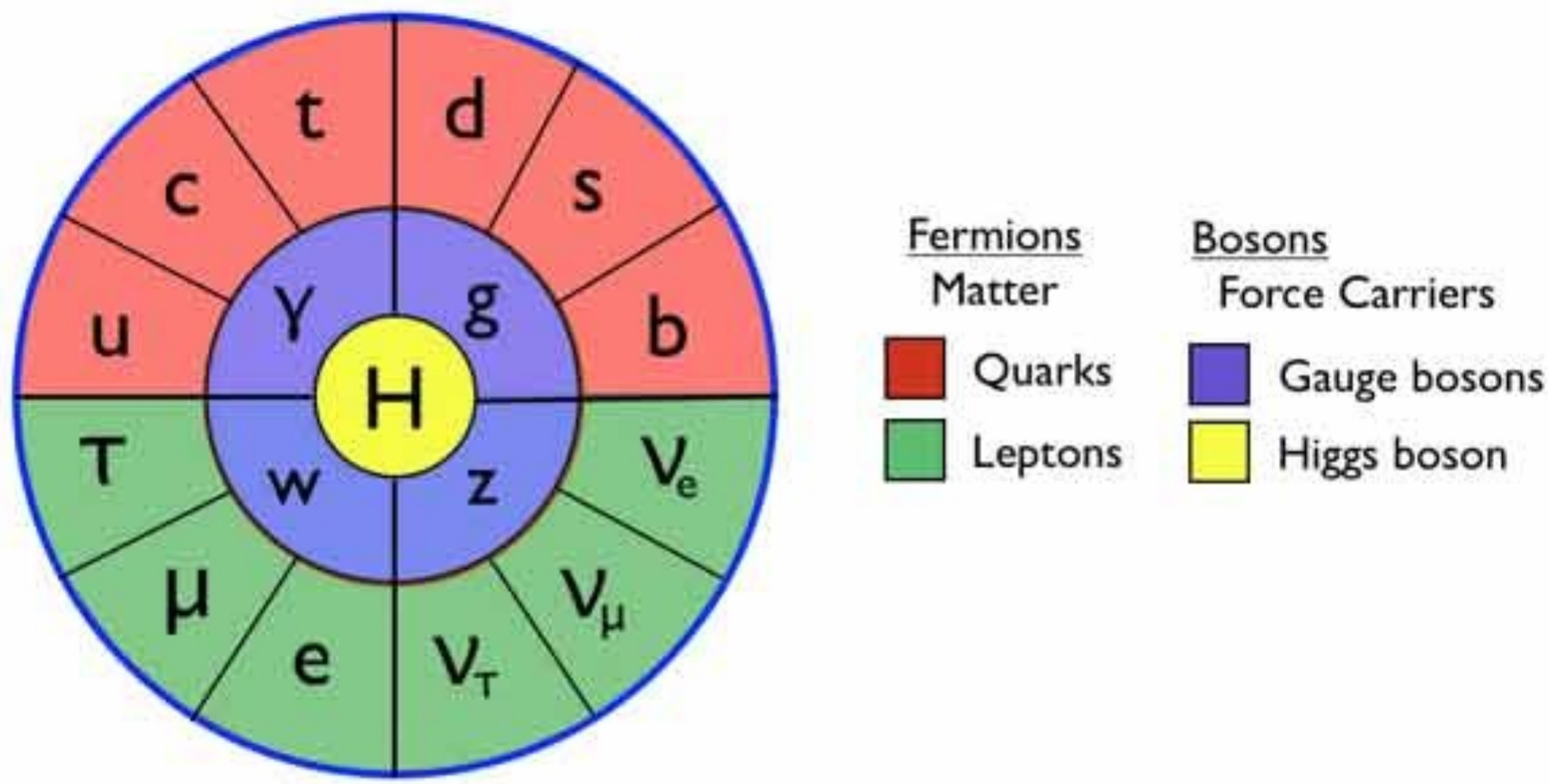
Stony Brook University

Colloquium, Brookhaven National Laboratory, May 16, 2017

We don’t understand ~85% of the Universe’s matter



The stuff we understand

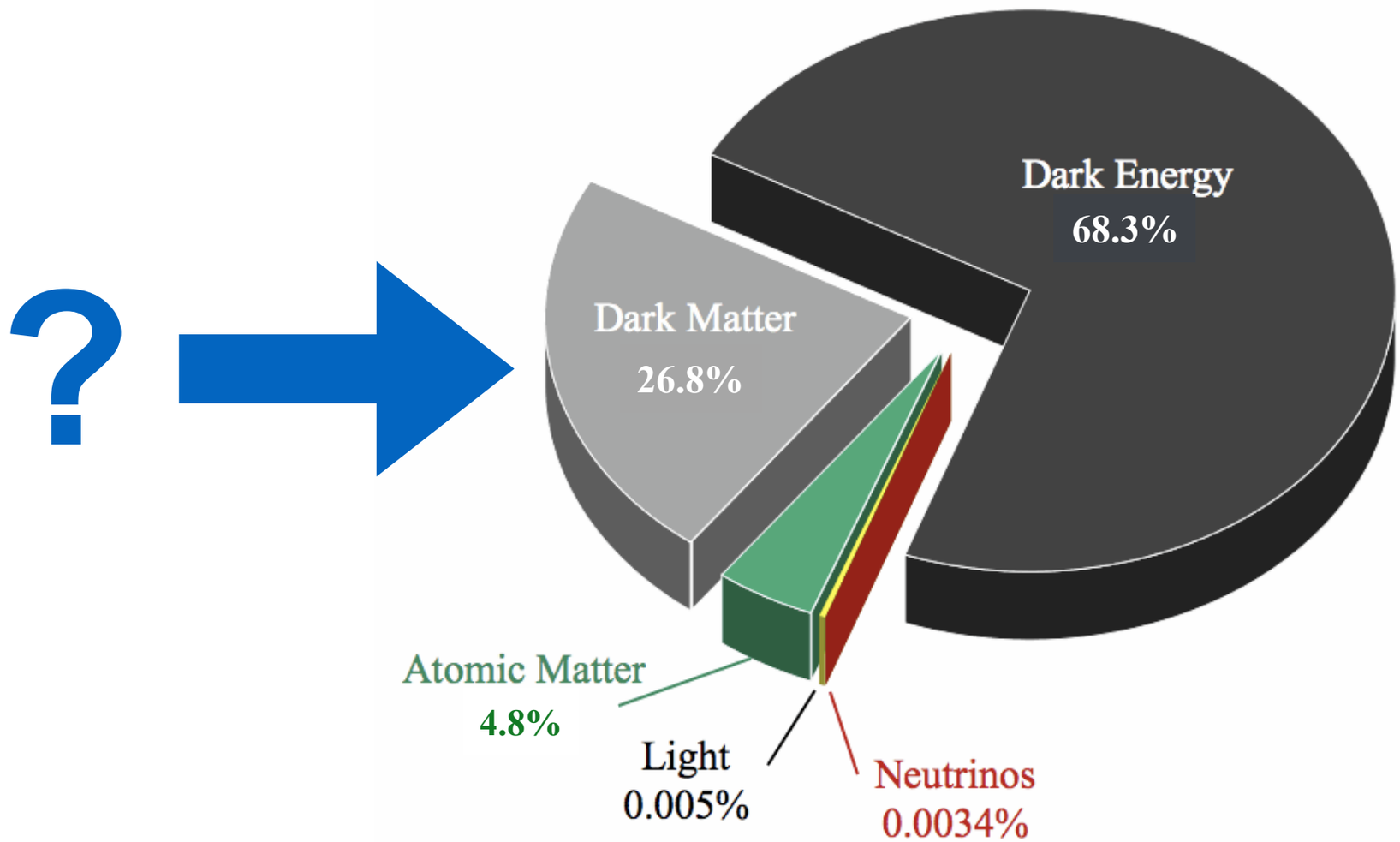


described by the amazing

Standard Model of Particle Physics

Dark Matter

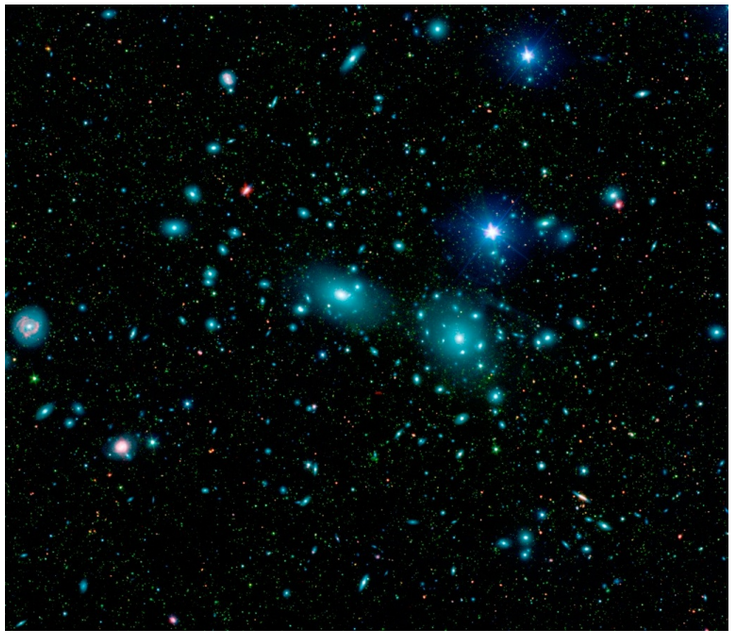
powerful evidence for New Physics

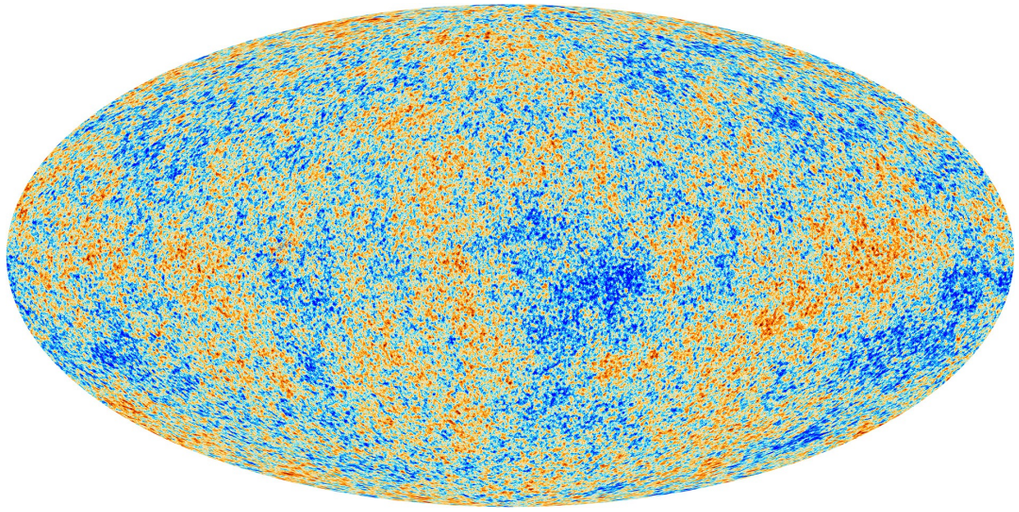


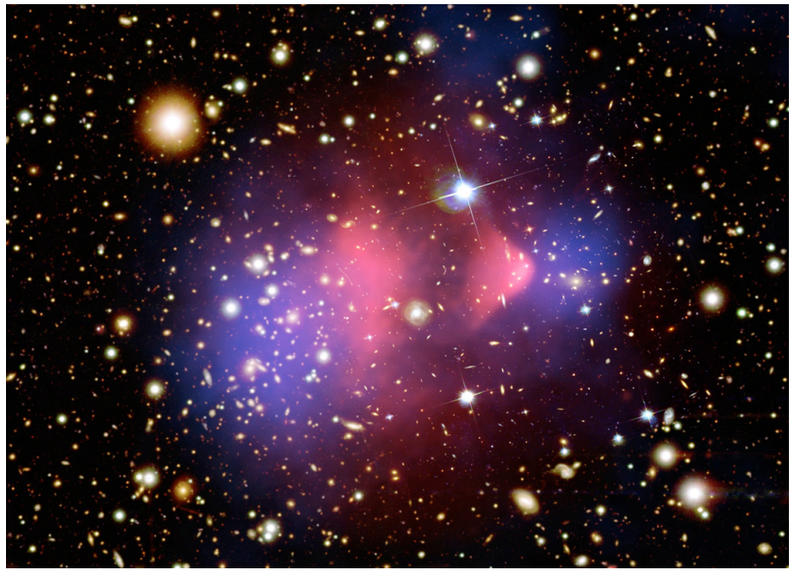
Planck

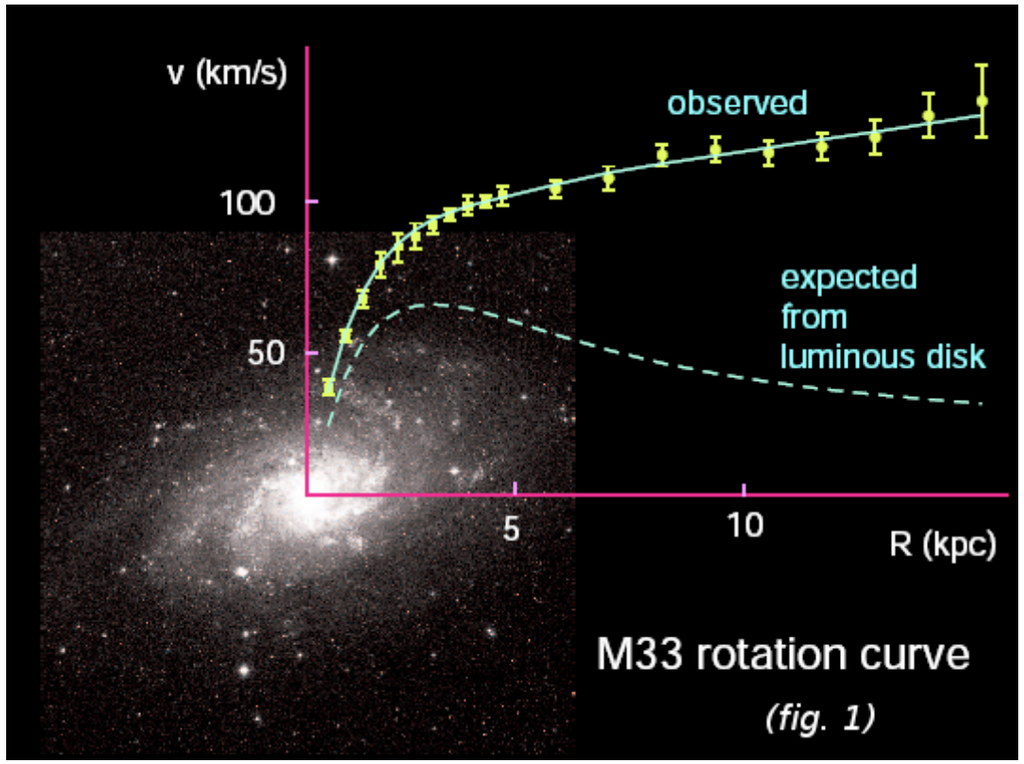
(I'll ignore this)

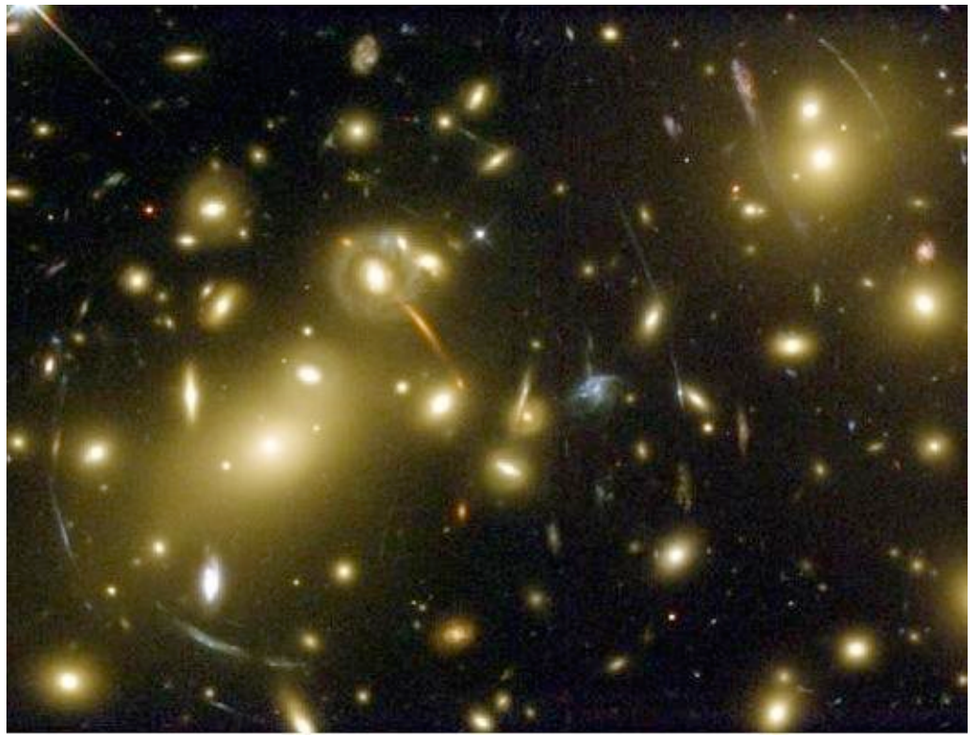
Overwhelming Evidence, for example:











What is Dark Matter?

- all evidence from gravitational interaction
- other interactions tightly constrained

Uncovering its identity is one of the most important goals in particle physics today

Is Dark Matter in a Dark Sector?

a dark sector consists of particles
that don't interact w/ known strong,
weak, or electromagnetic forces

could explain feeble interactions between
dark matter and ordinary matter

This talk

A new frontier in experimental exploration:
MeV-to-GeV masses

2016 Community summary of opportunities

arXiv:1608.08632v1 [hep-ph] 30 Aug 2016

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

- **Overview**
- Scientific Programme
- Timetable
- Contribution List
- Author index

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)

A possible opportunity to obtain funding for new small experiments

white paper to appear in O(1) month

Outline

- The dark matter landscape
- A simple dark sector
- New direct-detection techniques

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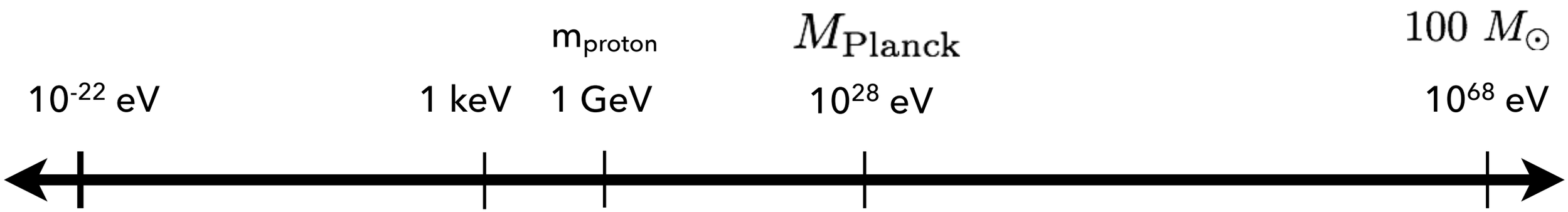
The Dark Matter Landscape



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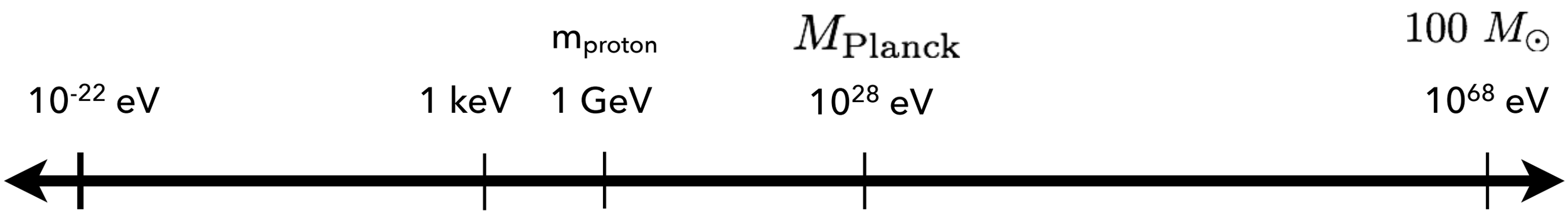
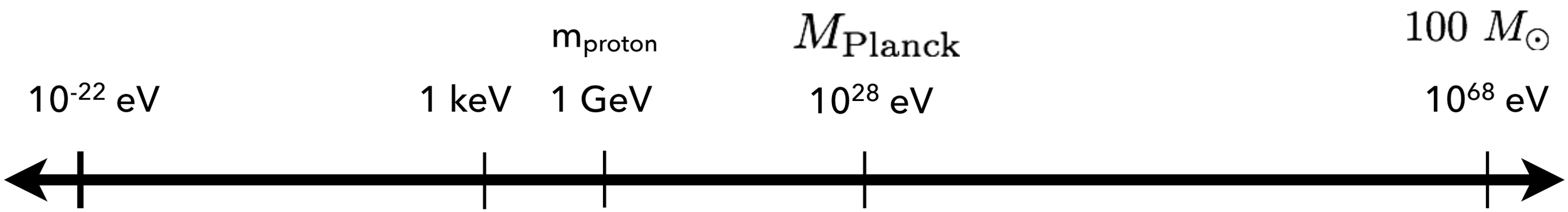


$$m_\nu \lesssim 0.2 \text{ eV}$$

$$m_{\text{electron}} \sim 0.5 \text{ MeV}$$

$$m_{\text{top}} \sim 172 \text{ GeV}$$

The Dark Matter Landscape

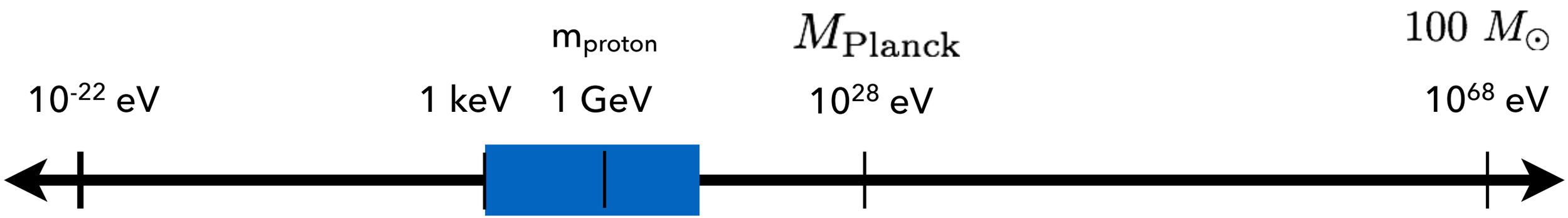


Where look for DM?

$\Longrightarrow$ target motivated areas

(and try to cover as much parameter space as possible!)

The Dark Matter Landscape



"thermal" DM

~1 keV to 100 TeV

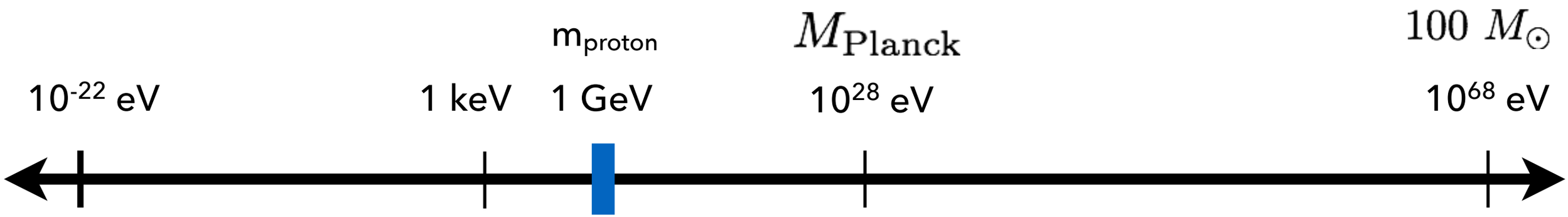
$m_{\text{DM}} \gtrsim 1\ \text{keV}$

otherwise, no structure smaller than dwarf galaxies

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

otherwise, too much dark matter

The Dark Matter Landscape



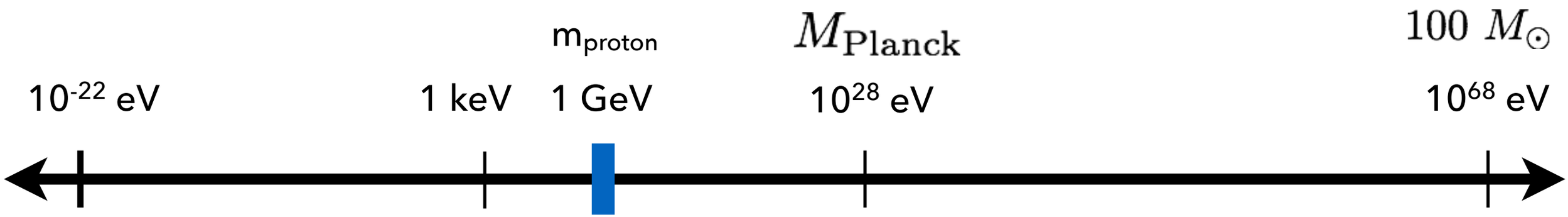
"asymmetric" DM

Kaplan, Luty, Zurek

Why is $\Omega_{\text{DM}} \sim 5\ \Omega_B$?

from a baryon asymmetry!

The Dark Matter Landscape



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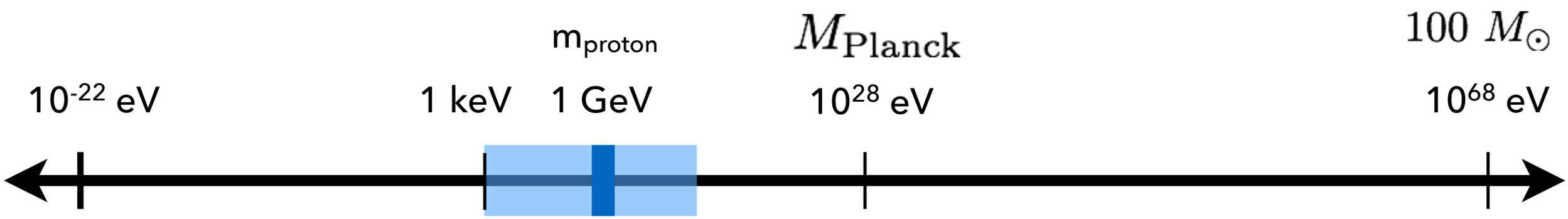
$$m_{\text{DM}} \sim 5 m_p \sim 5\ \text{GeV}$$

The Dark Matter Landscape



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$m_{\text{DM}} \sim 5 m_p \sim 5\ \text{GeV}$ (but large range possible)

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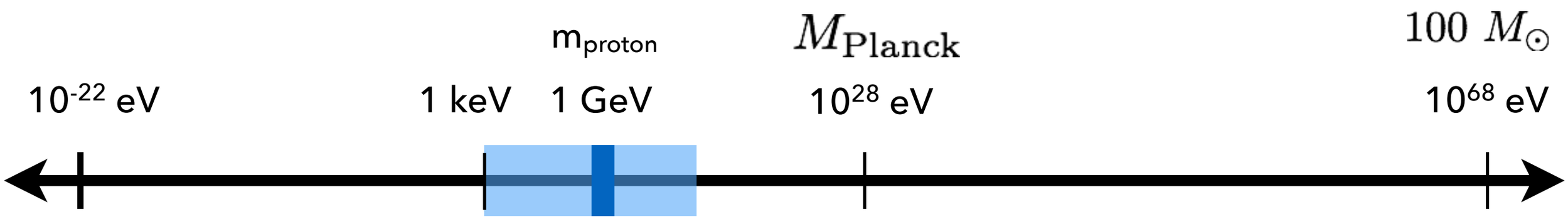

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(many other models: SIMP, ELDER, Cannibal, Forbidden, ...)

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

1 keV
1 MeV
1 GeV
1 TeV

Dark-sector
Dark Matter

More soon!

Weakly Interacting Massive Particles (WIMPs)

$m_{DM} \sim 100$ GeV (“Weak” scale)

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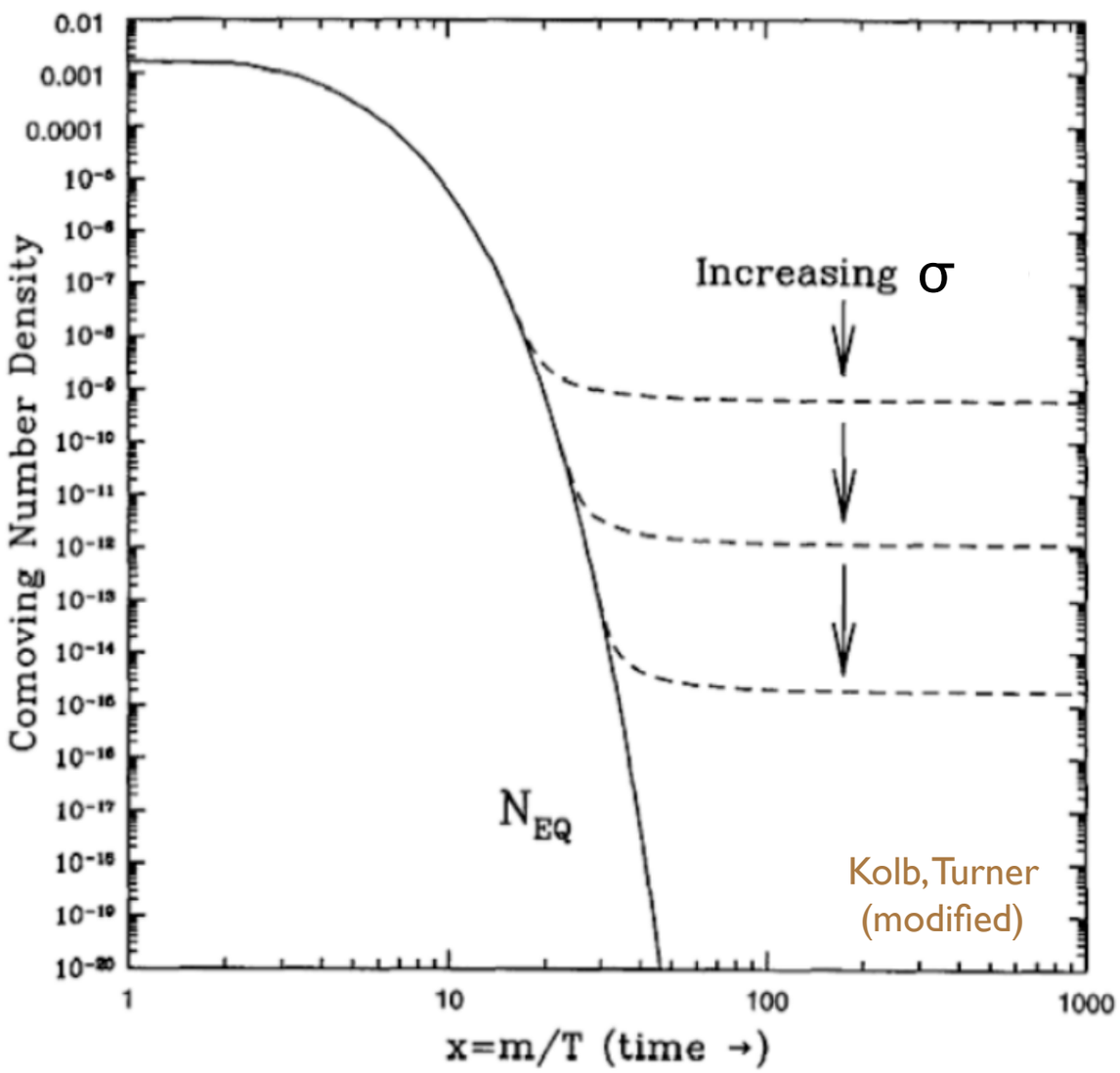
an excellent candidate for
dark matter due to

WIMP miracle

The WIMP "miracle"

Assume a new, stable particle (X) is in thermal equilibrium with ordinary matter (f) in early Universe



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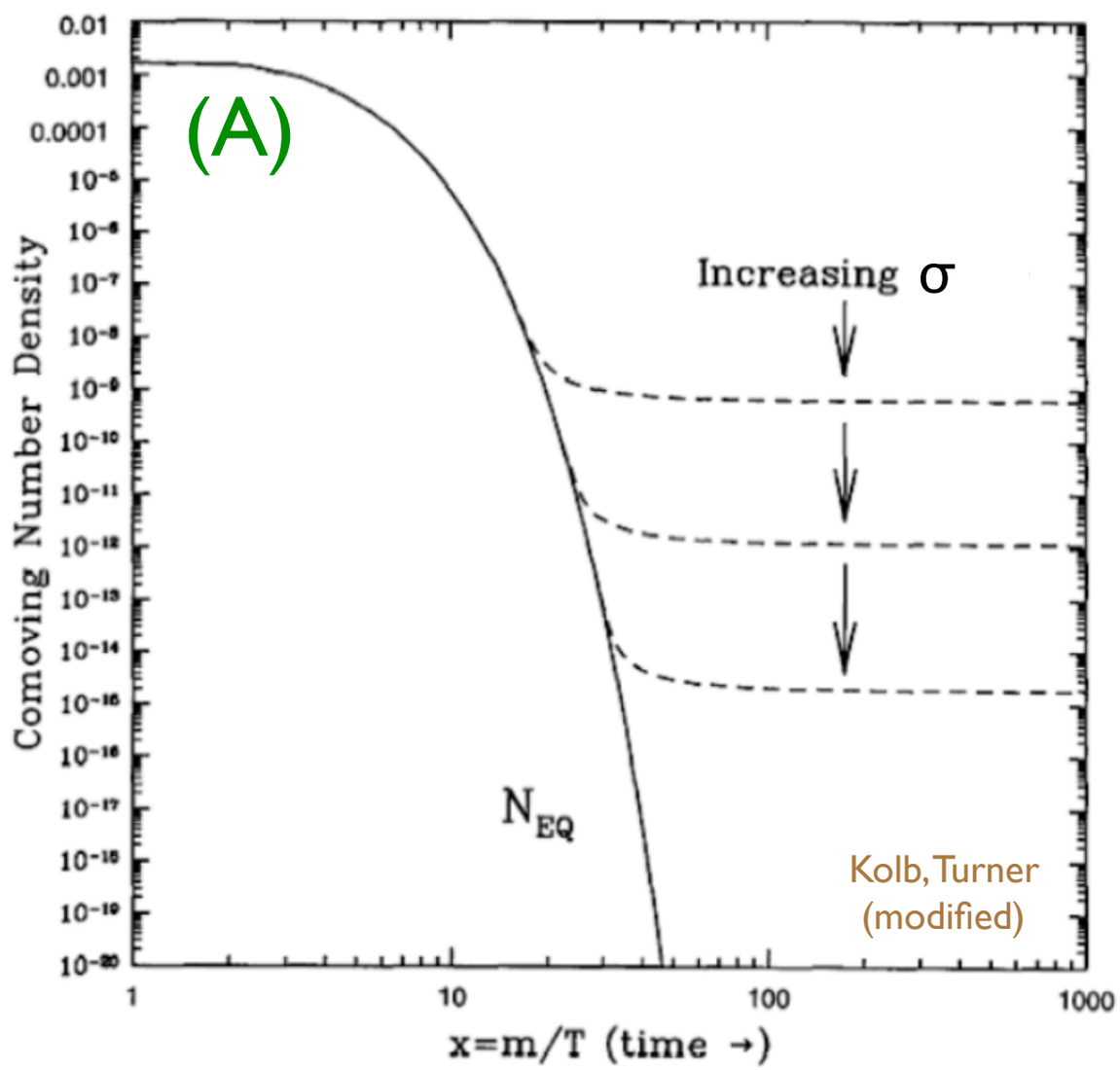

(A) thermal equilibrium

$$XX \leftrightarrow \bar{f} f$$

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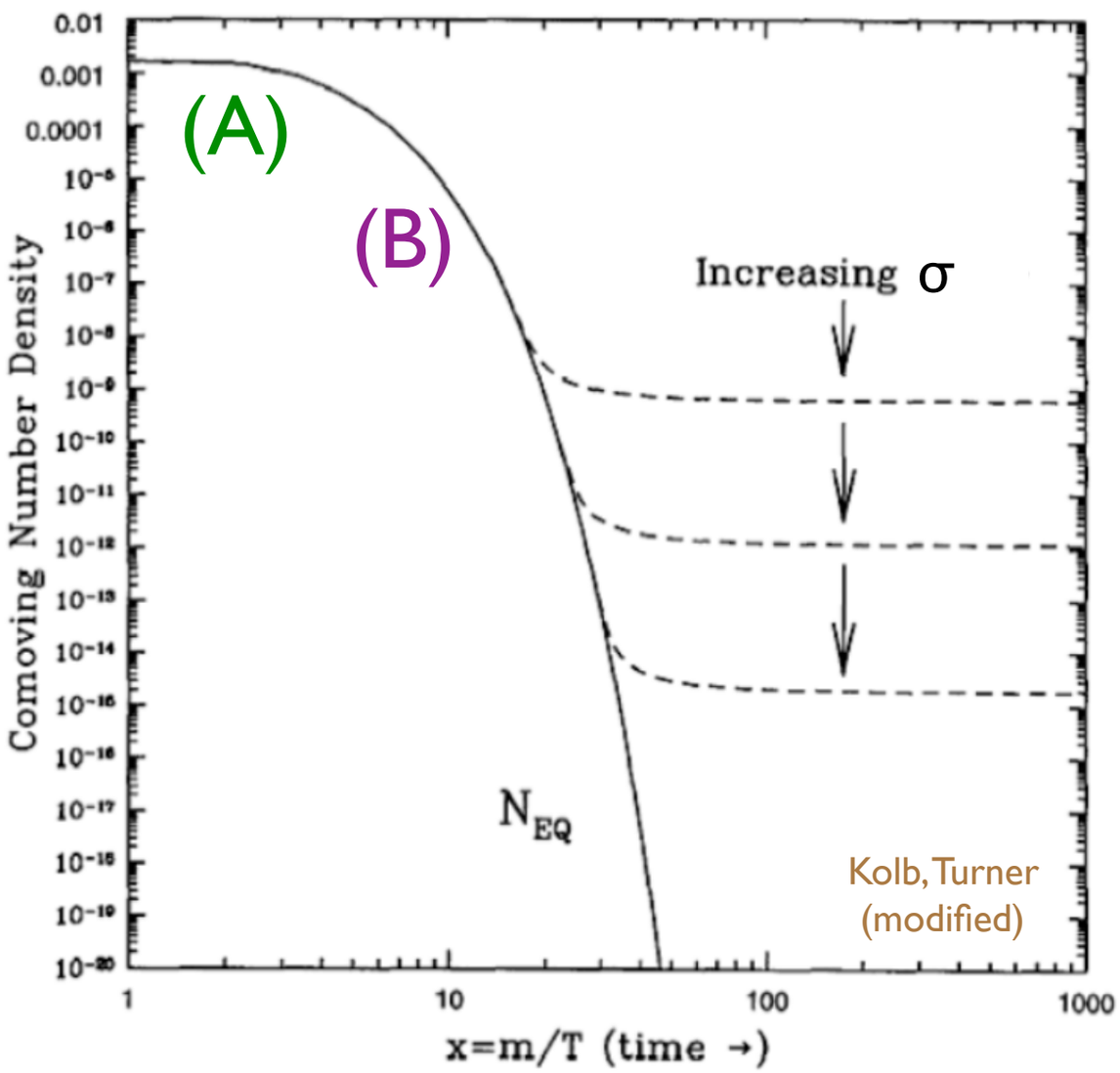

(A) thermal equilibrium

$$XX \leftrightarrow \bar{f}f$$

(B) Universe expands and cools

$$T \ll M_X \implies XX \rightarrow \bar{f}f$$

$$XX \not\leftarrow \bar{f}f$$

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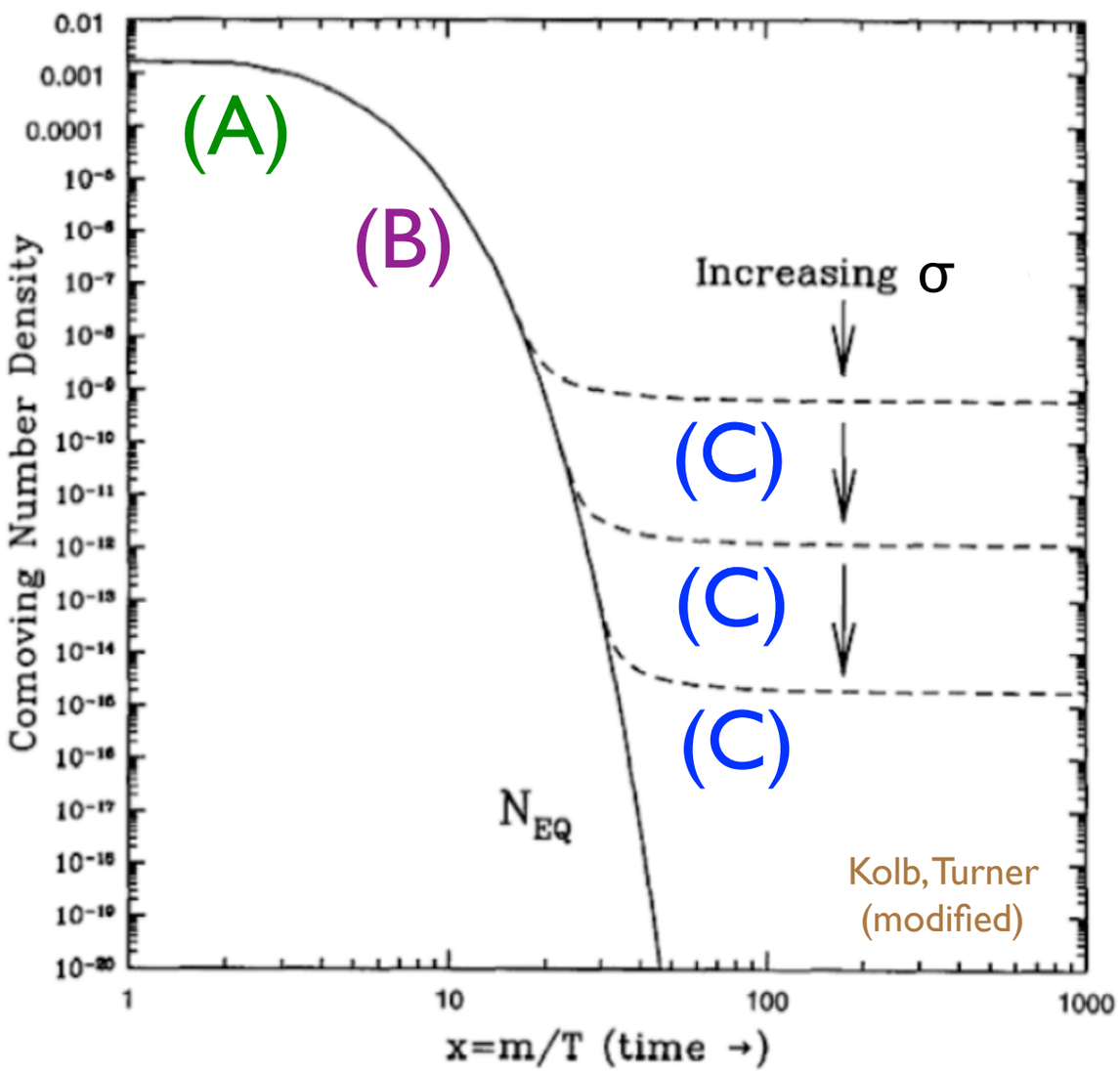

(A) thermal equilibrium

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(B) Universe expands and cools

$$T \ll M_X \implies XX \rightarrow \bar{f}f$$

$$XX \not\leftrightarrow \bar{f}f$$

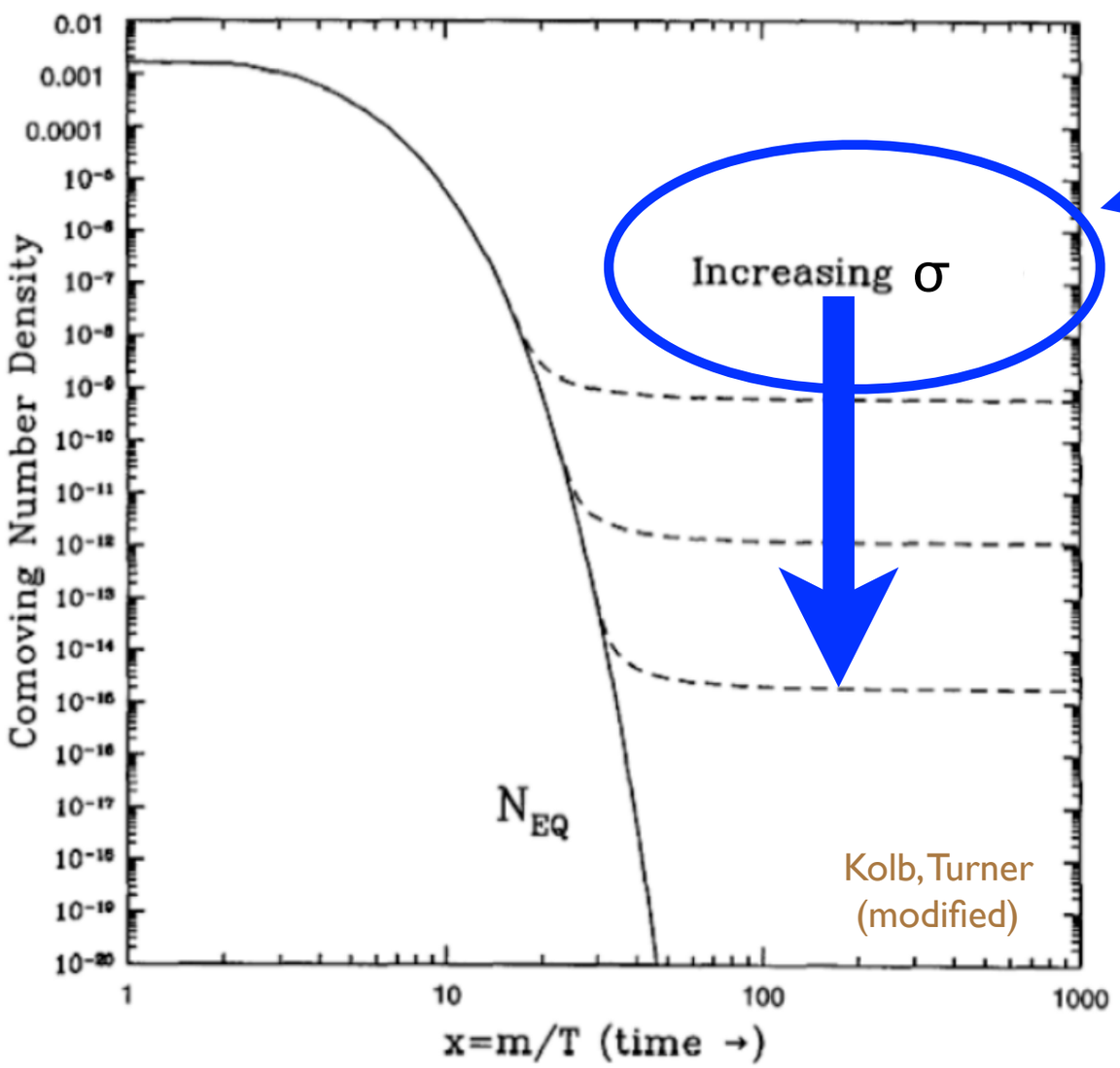
(C) further expansion

$\implies$ freeze-out

$$XX \not\leftrightarrow \bar{f}f$$

The WIMP "miracle"

$$XX \leftrightarrow \bar{f}f$$



Abundance $\propto \dfrac{1}{\sigma}$

The WIMP "miracle"

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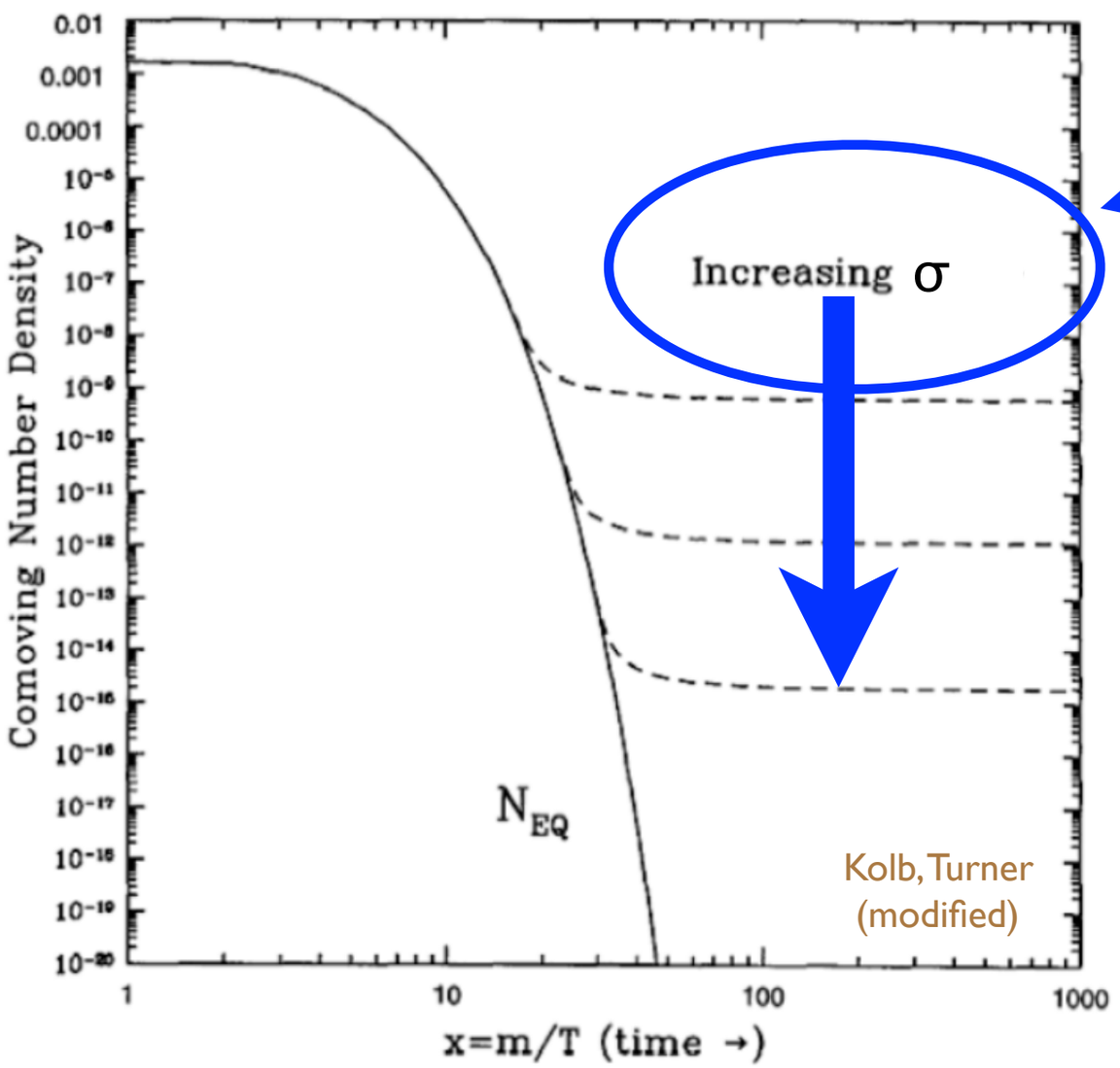

Abundance $\propto \dfrac{1}{\sigma}$

need:

$$\sigma \sim 1 \text{ pb} \sim 10^{-36} \text{ cm}^2$$

(picobarn)

The WIMP "miracle"

$$\sigma \sim \frac{\alpha_{\rm weak}^2}{(100\ {\rm GeV})^2} \sim 1\ {\rm pb}$$

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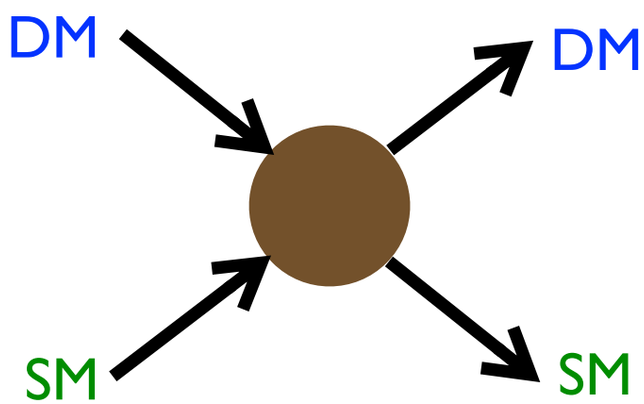
WIMPs point to ~100 GeV scale!

Higgs Hierarchy problem also predicts
new particles at ~100 GeV
(e.g. supersymmetry)

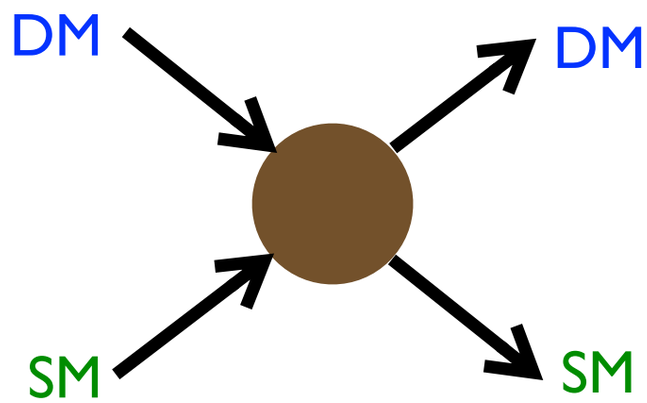
Very intriguing!

Many ongoing searches for WIMPs

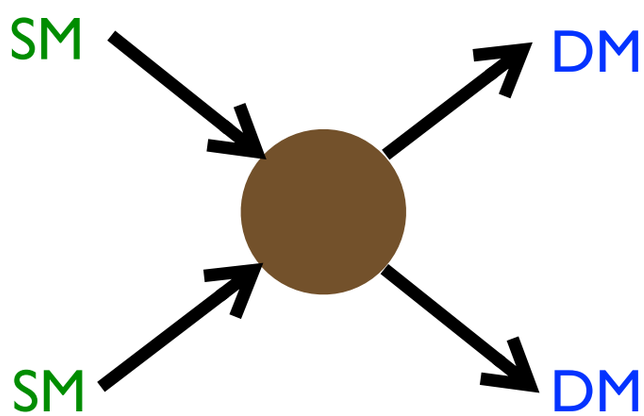


Direct
Detection

Many ongoing searches for WIMPs

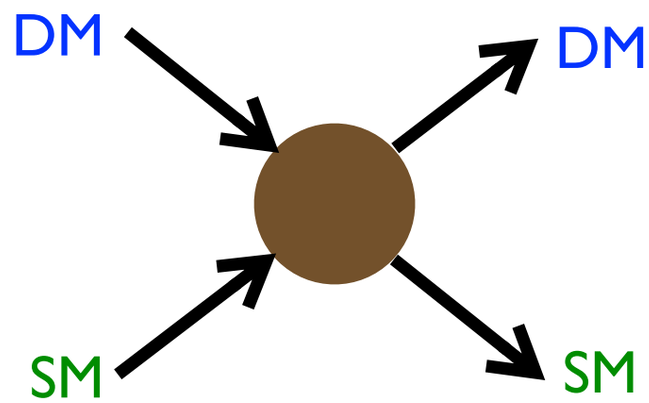


Direct Detection

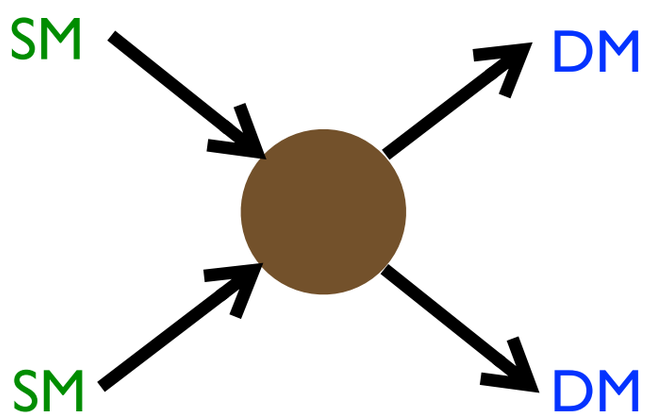


Colliders

Many ongoing searches for WIMPs



Direct Detection



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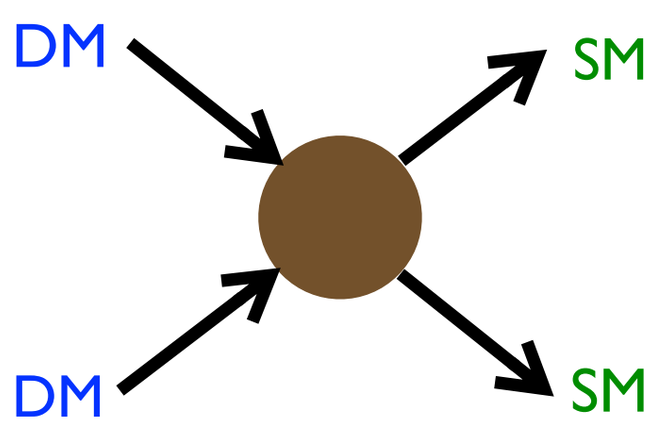

Indirect Detection

But must search also beyond WIMP paradigm!

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  freeze-out, asymmetric, freeze-in, SIMP, ELDER, Forbidden…

But must search also beyond WIMP paradigm!

- no convincing evidence for WIMPs (yet)
- no new physics at LHC (yet)
- several known production mechanisms
  freeze-out, asymmetric, freeze-in, SIMP, ELDER, Forbidden…
- "small-scale crisis" of cold DM
  (self-interactions through a new force?)

focus on
MeV-to-GeV masses

Outline

- The dark matter landscape
- A simple dark sector
- New direct-detection techniques

Dark Matter + Dark Photon

Dark Sector

DM + A'

Portal?

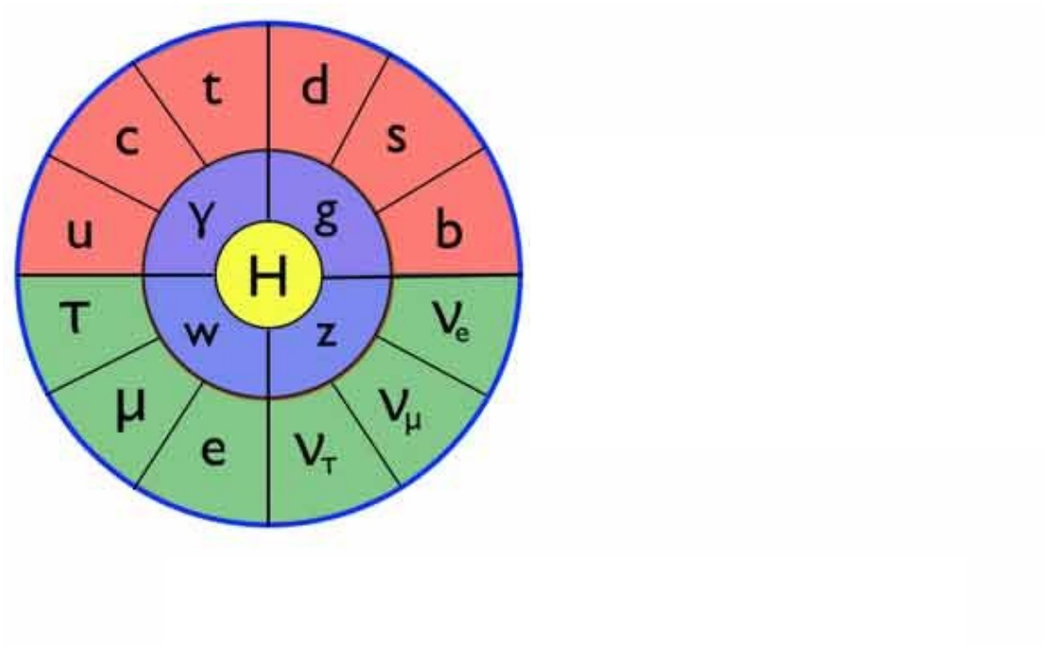
?

Standard Model

particles + forces

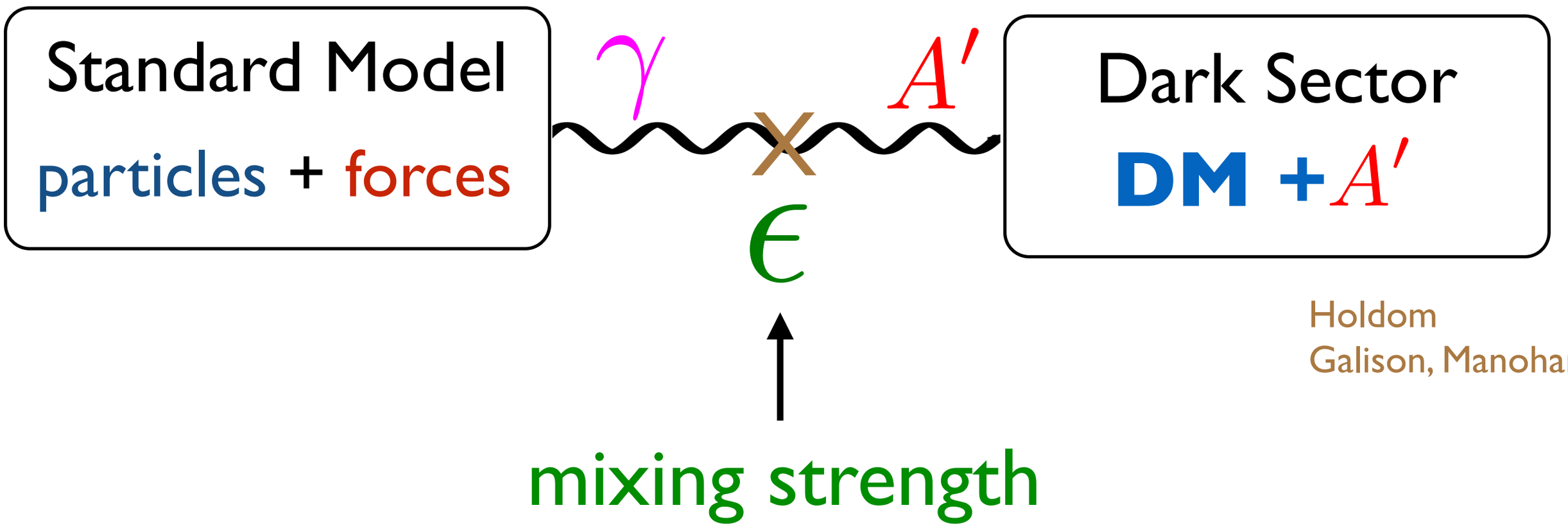
Dark Sector

DM + A'



The photon and A' can mix !

"kinetic mixing"



Holdom
Galison, Manohar

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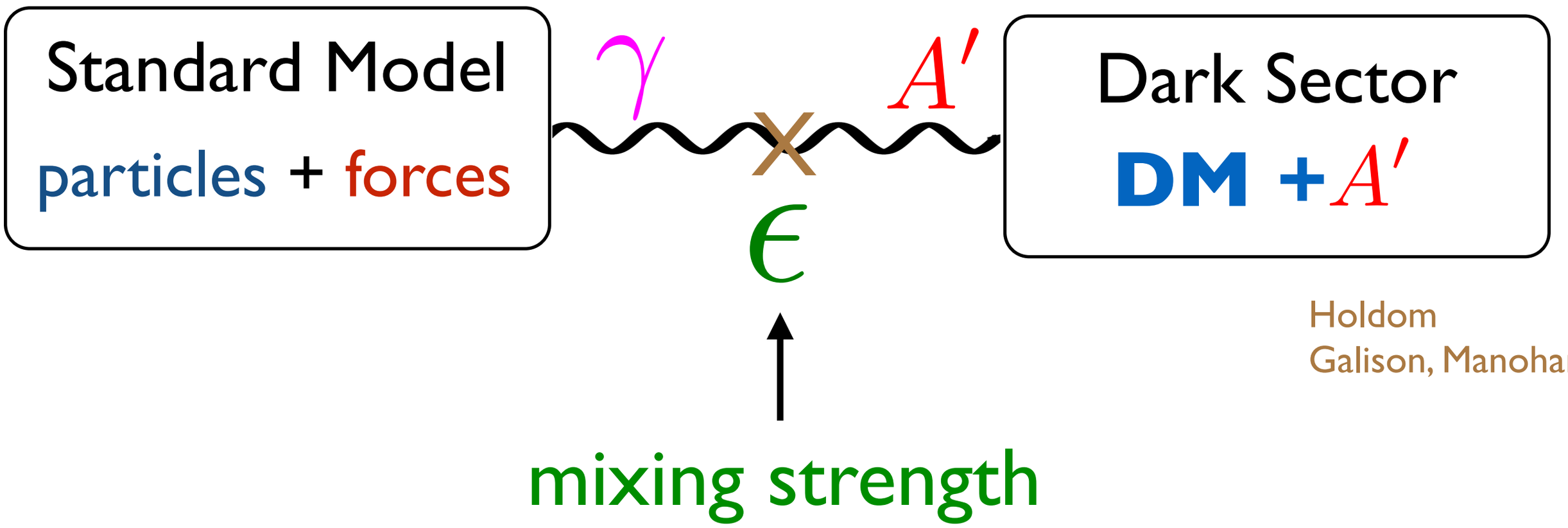
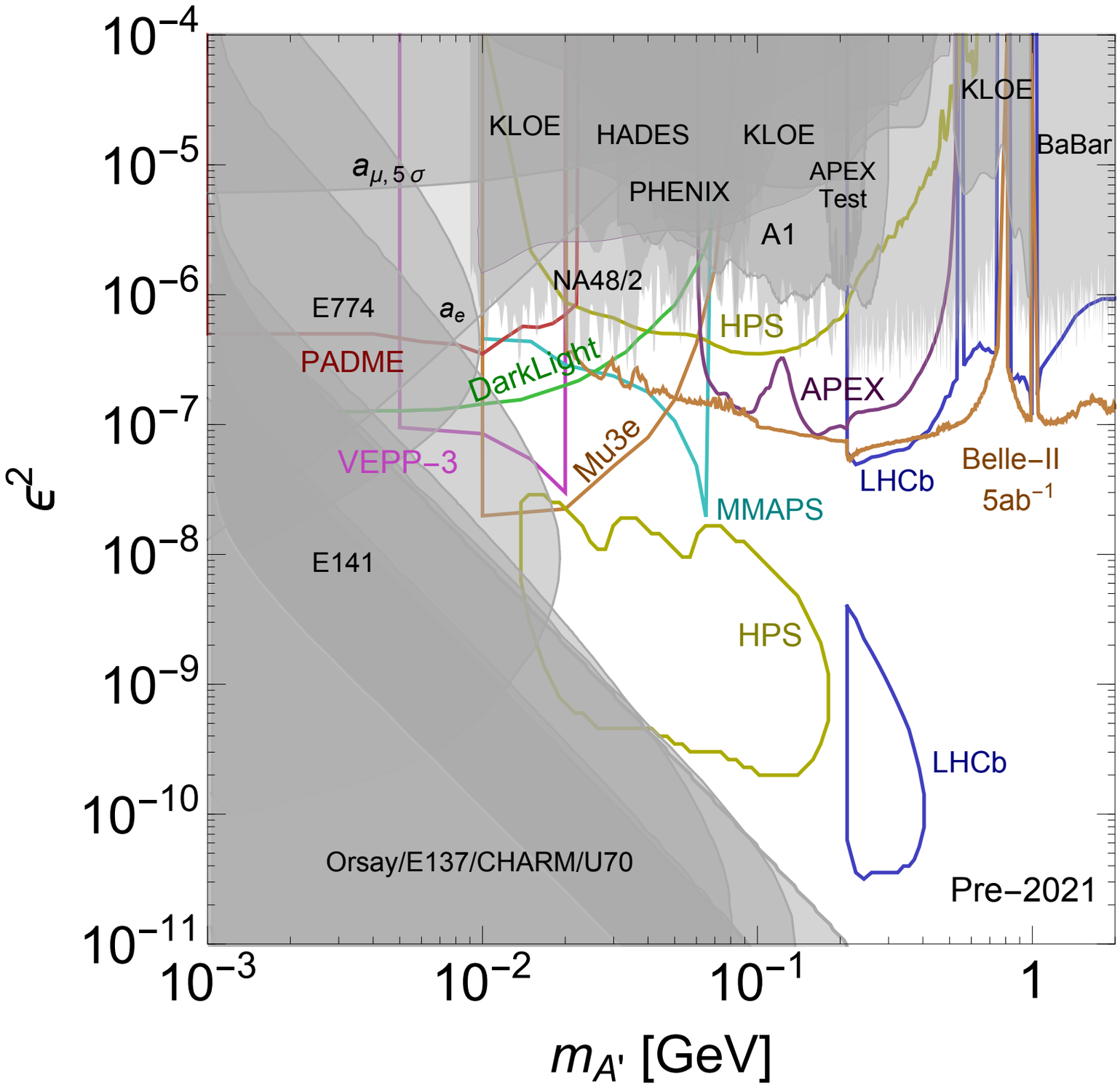


Holdom
Galison, Manohar

$\Longrightarrow$ A' couples to DM, quarks, & charged leptons

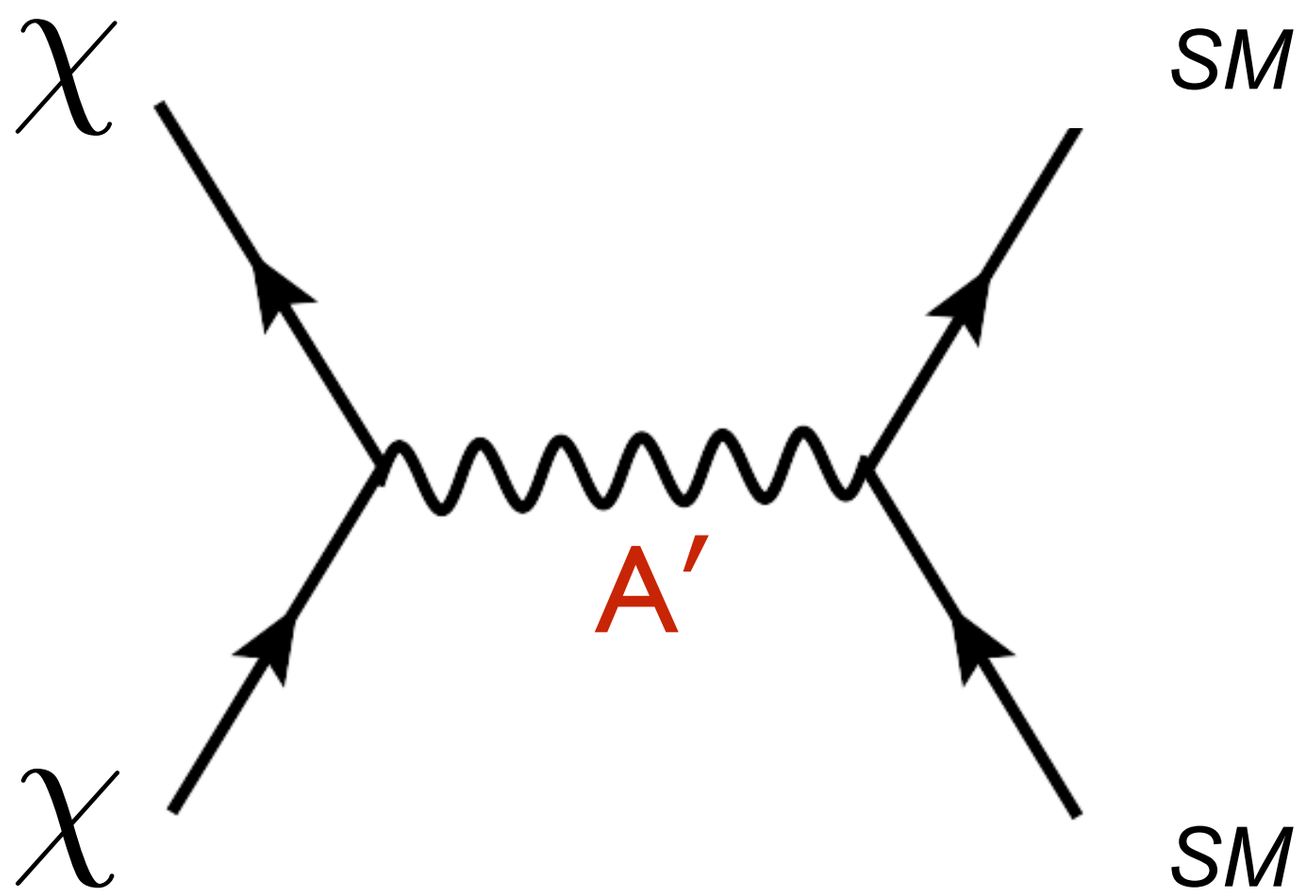
Several experiments will probe mediators directly



e.g. APEX, HPS @JLab

…

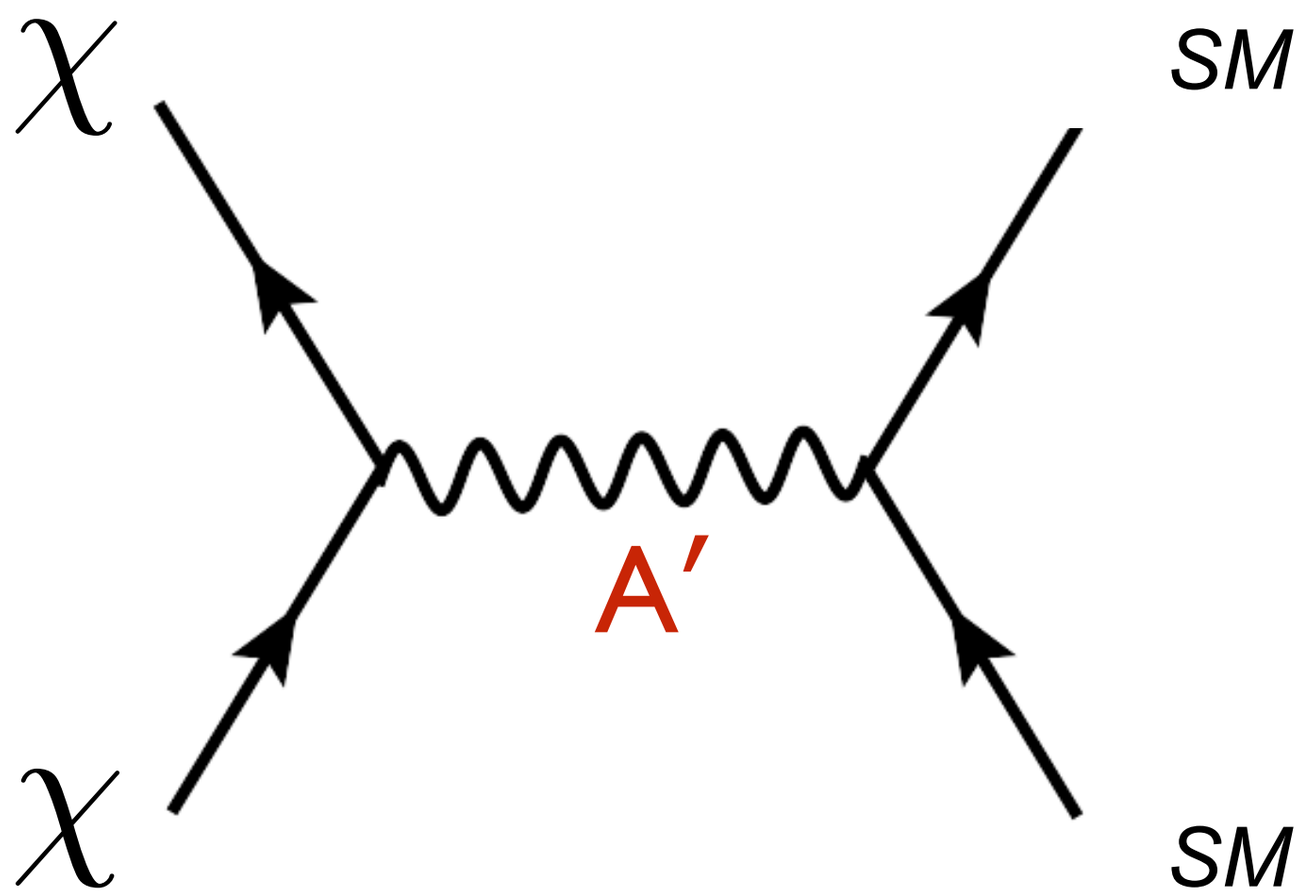
Dark Matter + Dark Photon



can obtain observed relic abundance via freeze-out

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

Dark Matter + Dark Photon

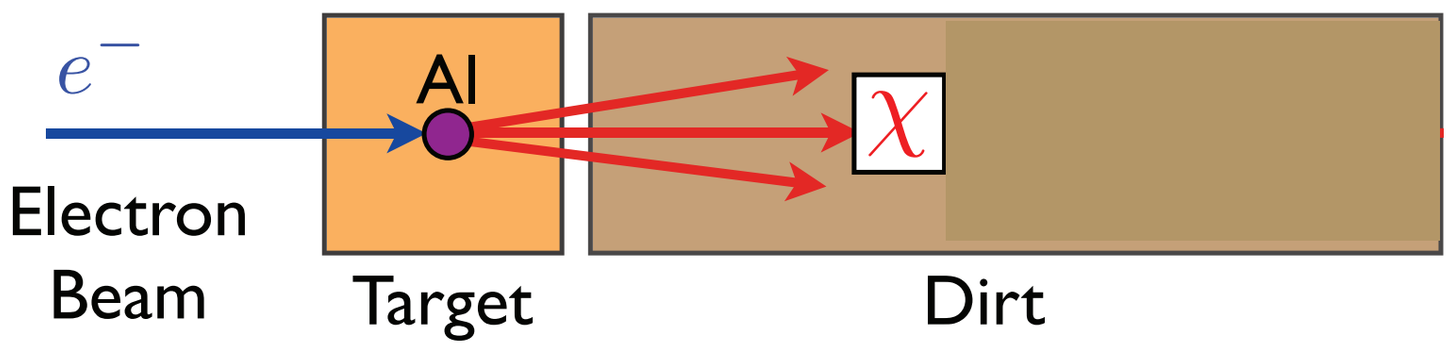


fixes cross section, σ

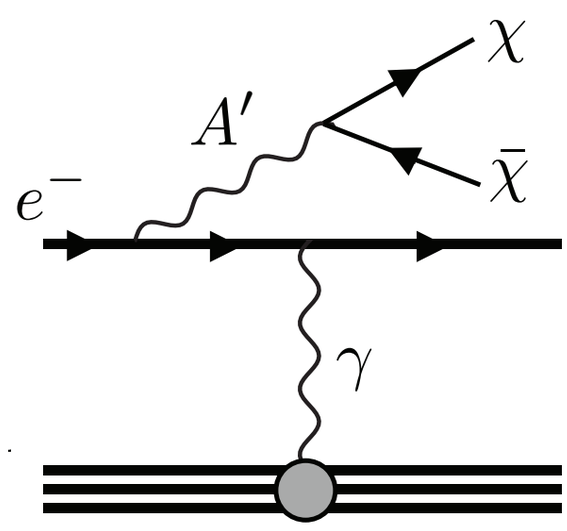
Produce Dark Matter at a beam dump

e.g.@SLAC's E137

Bjorken et.al.
Batell, RE, Surujon



Production



Produce Dark Matter at a beam dump

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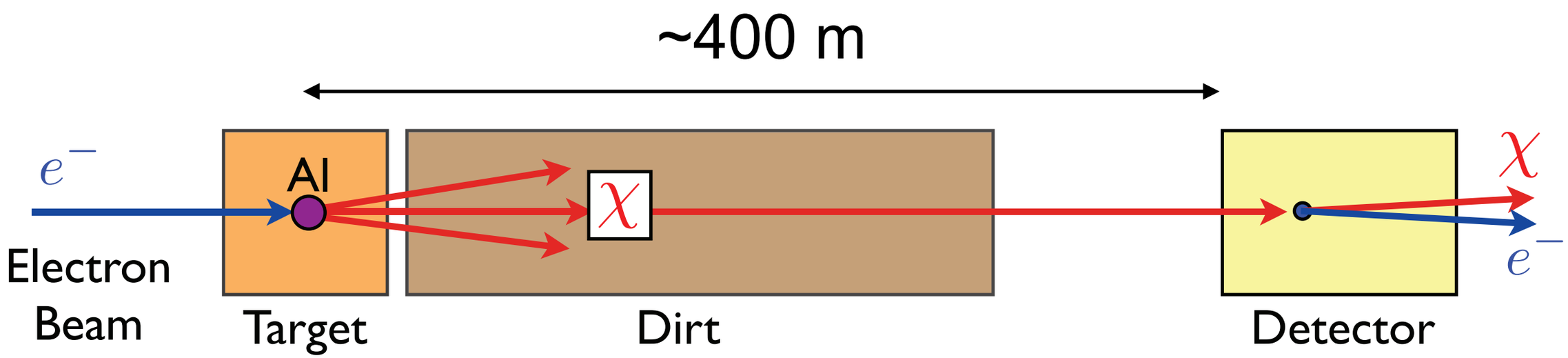
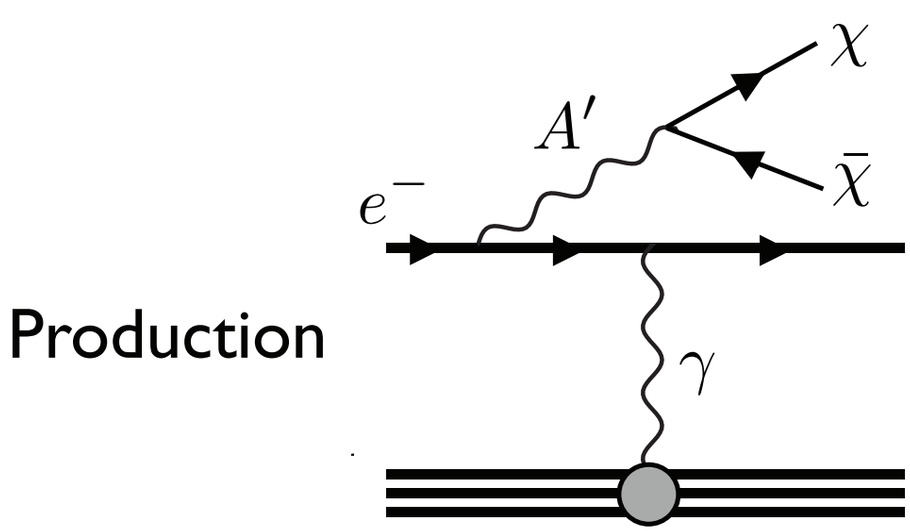
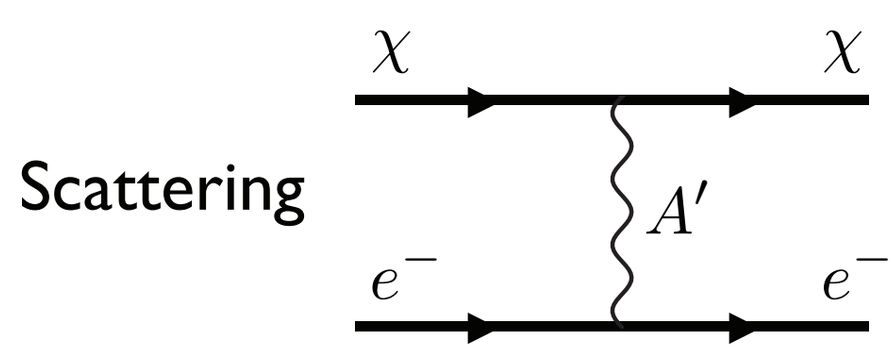
Bjorken et.al.
Batell, RE, Surujon







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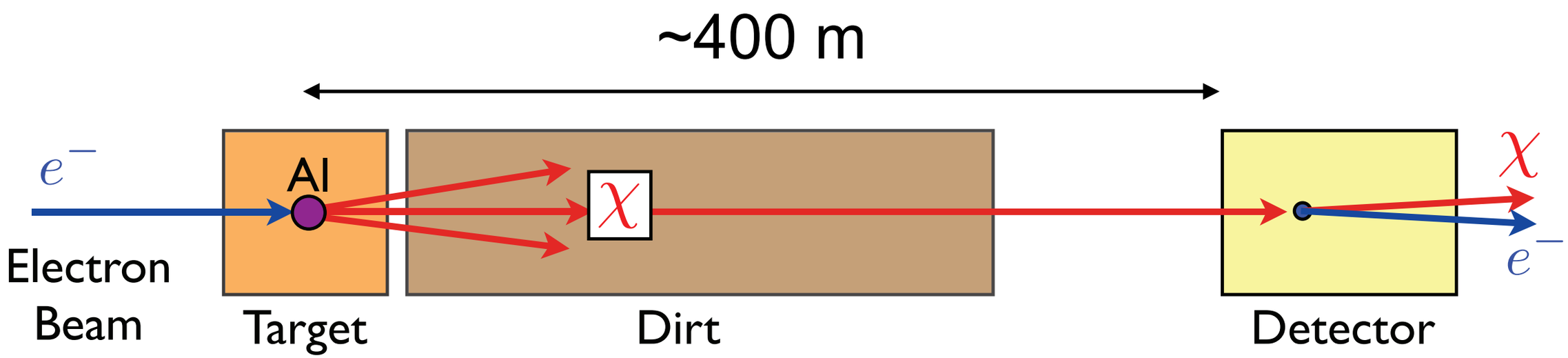
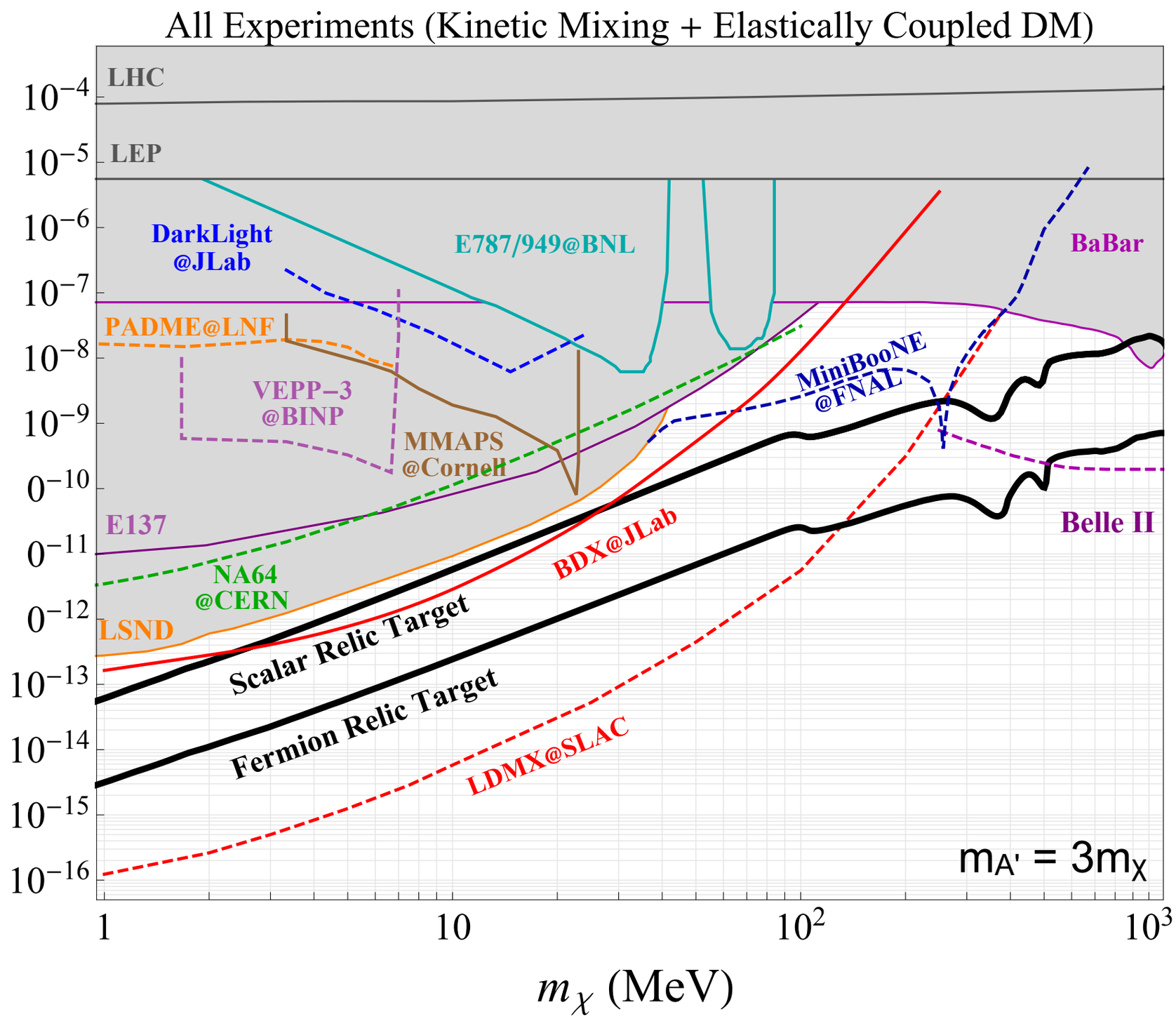


ask your local expert Eder Izaguirre about new proposed experiments (e.g. BDX, LDMX)

see also e.g. Batell, Pospelov, Ritz; Deniverville, Pospelov, Ritz; Deniverville, McKeen, Ritz; Aguilar-Arevalo et.al.; Krnjaic, Izaguirre, Schuster, Toro; Diamond, Schuster; RE, Mardon, Papucci, Volansky, Zhong; etc.

New experiments can probe several "thermal" targets!

$\propto \sigma$

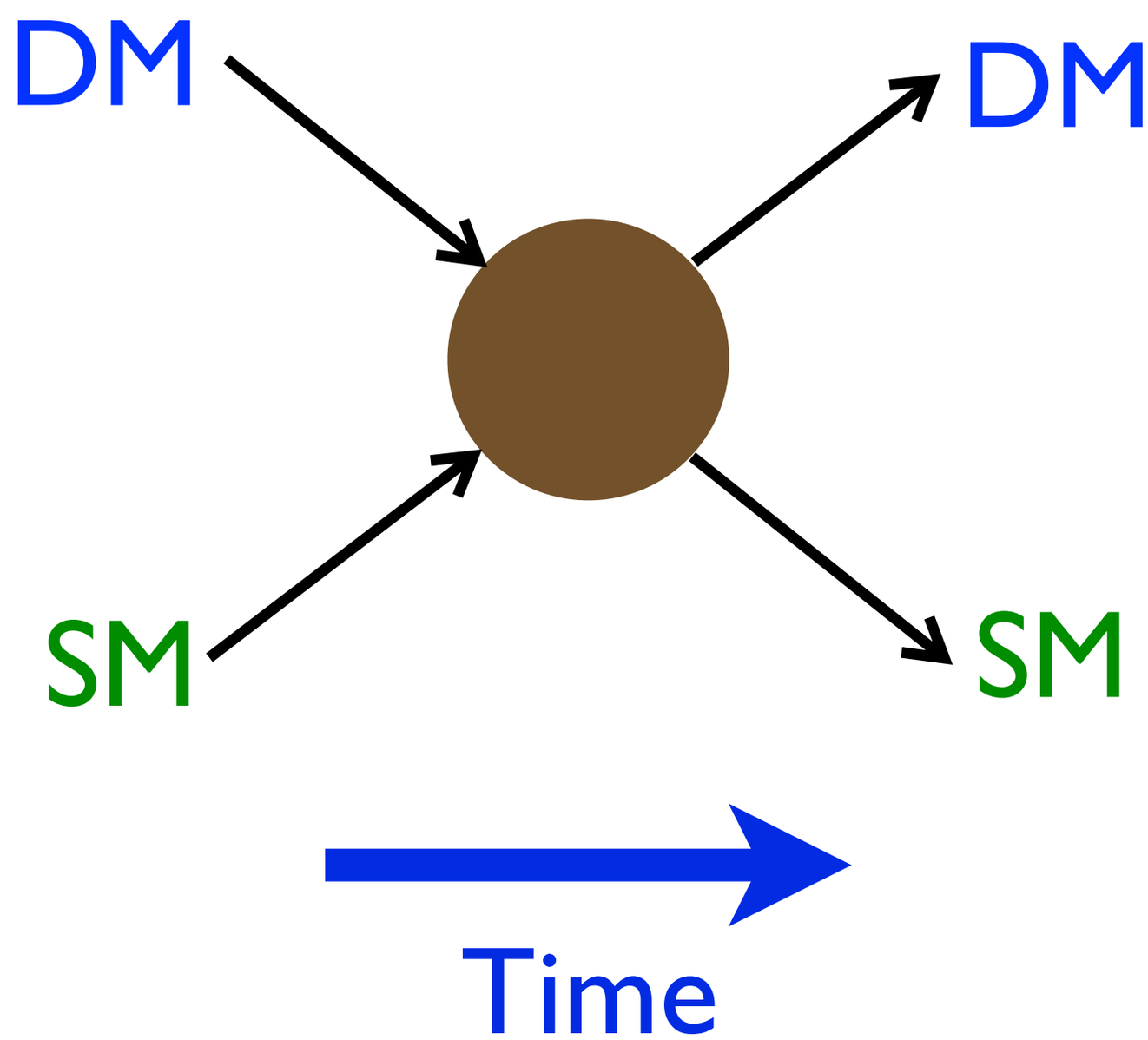


Dark Sector Report, 1608.08632

Outline

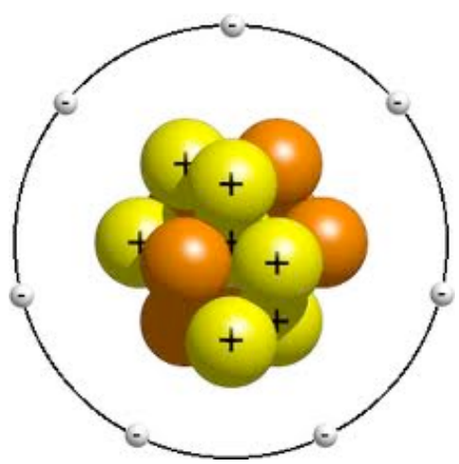
- The dark matter landscape
- A simple dark sector
- New direct-detection techniques

Direct Detection



How does this work for WIMPs?

Put a detector with lots of atoms deep underground

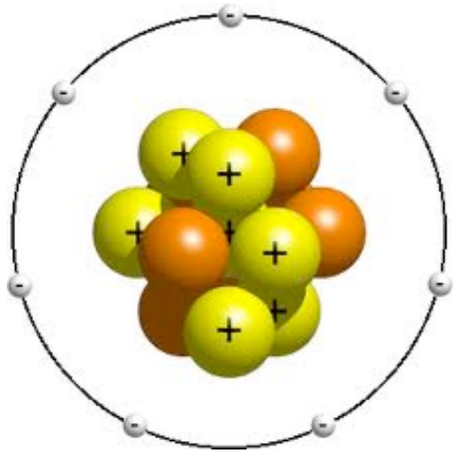


Atom

How does this work for WIMPs?

Put a detector with lots of atoms deep underground

and wait...



Atom

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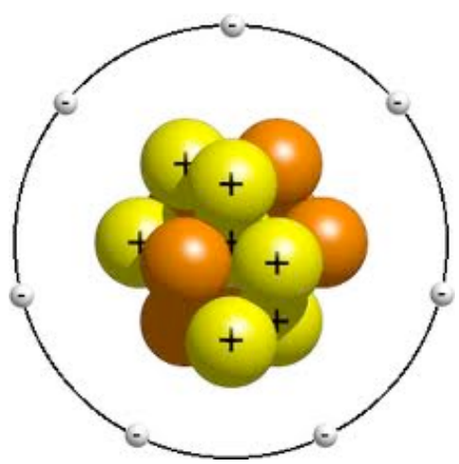

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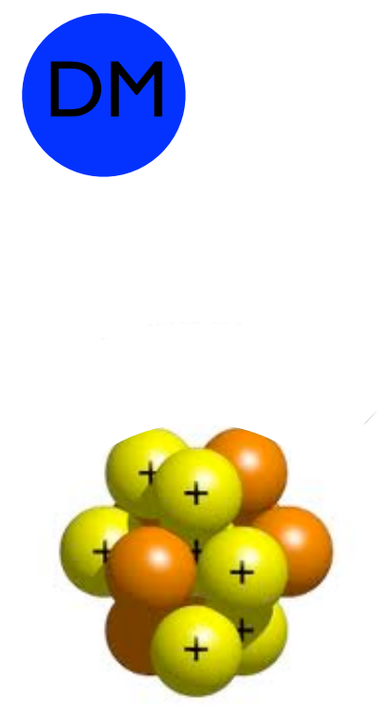

Recoiling Nucleus

How does this work for WIMPs?

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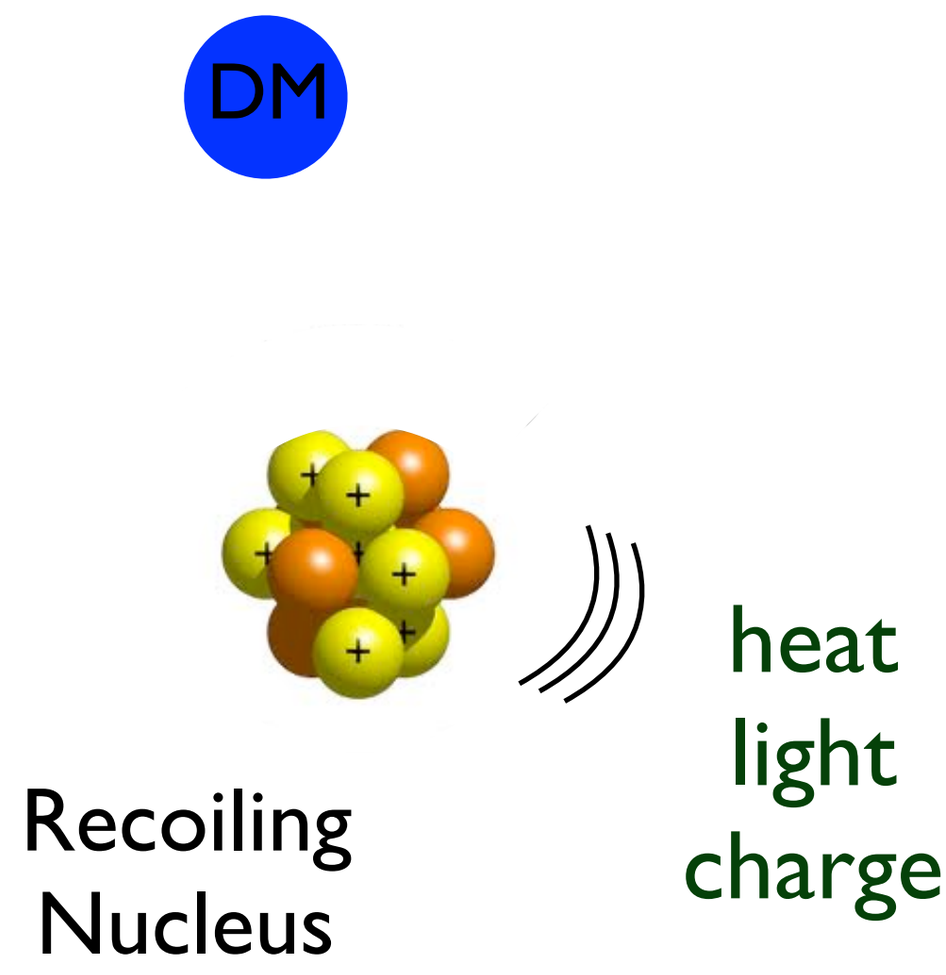
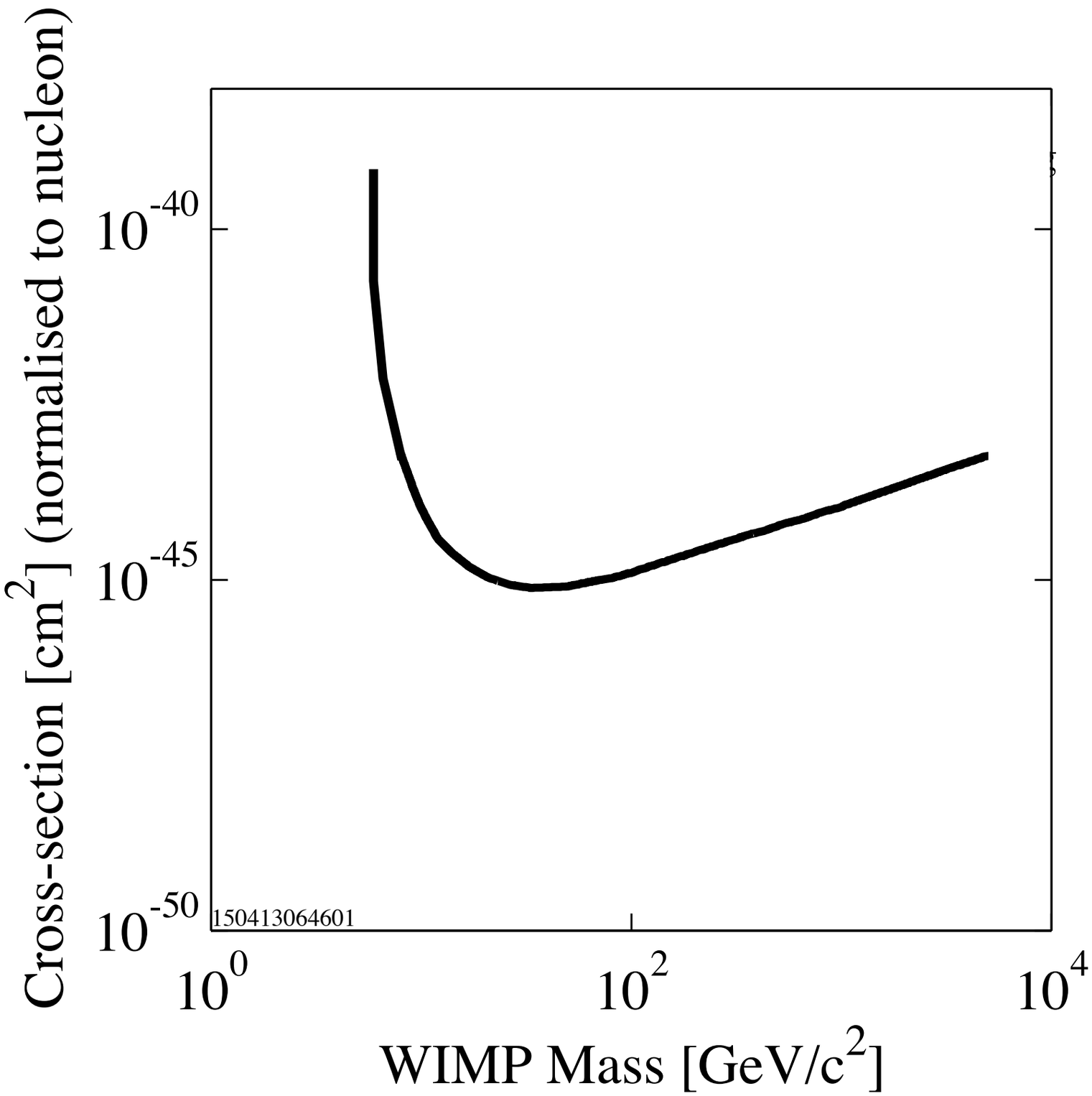
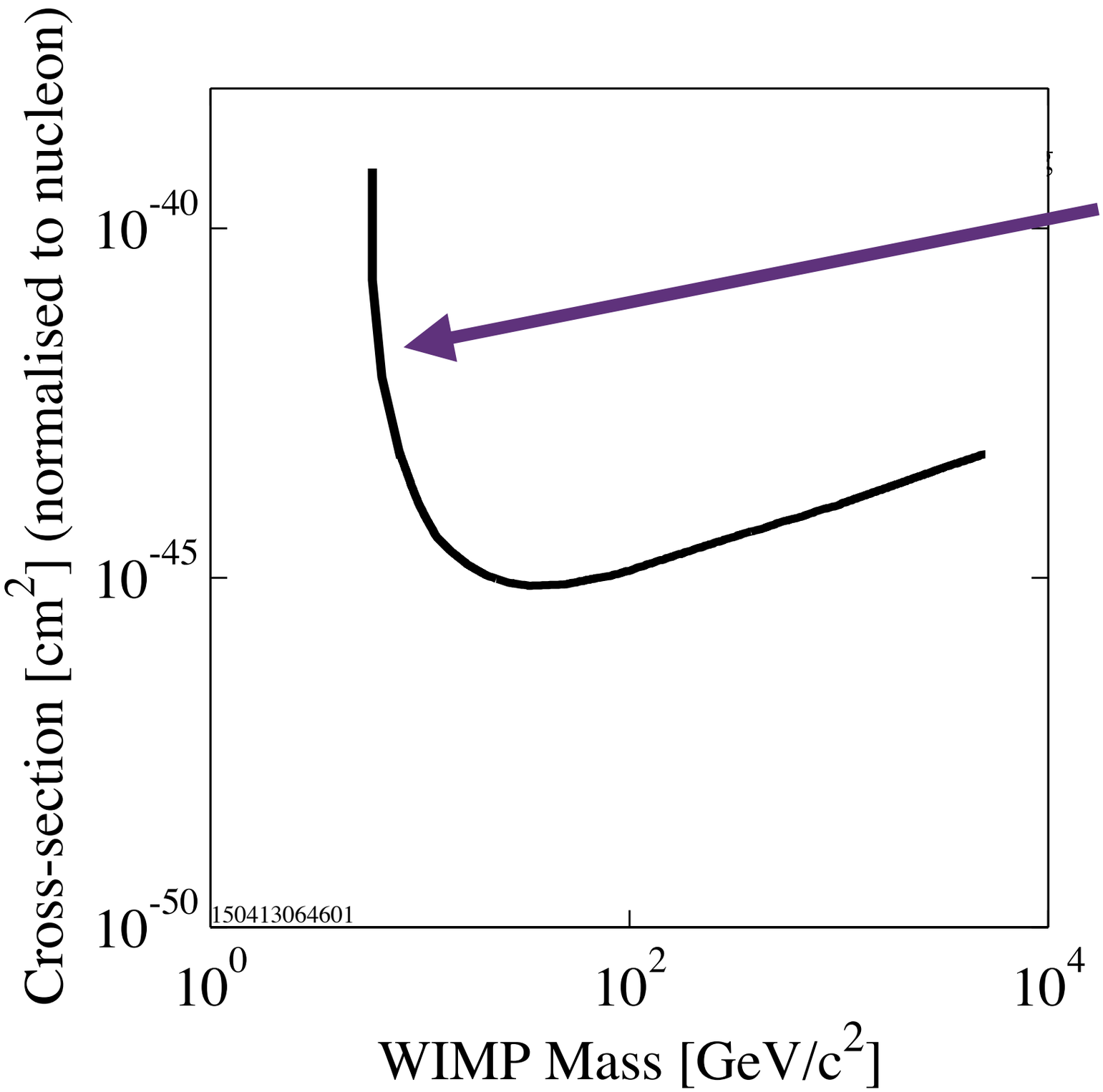


A typical direct detection curve



A typical direct detection curve



nuclear recoil energy too small

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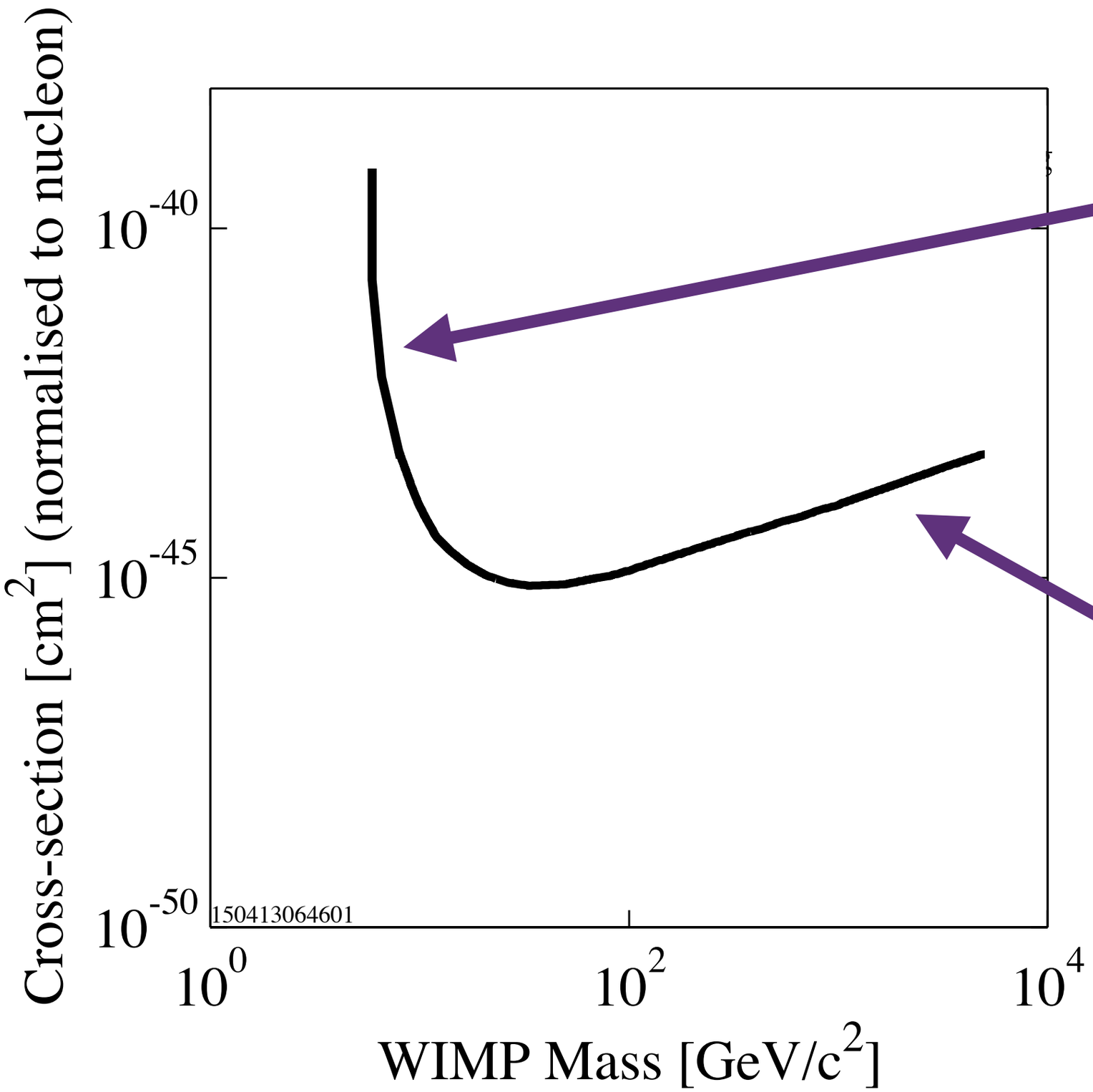


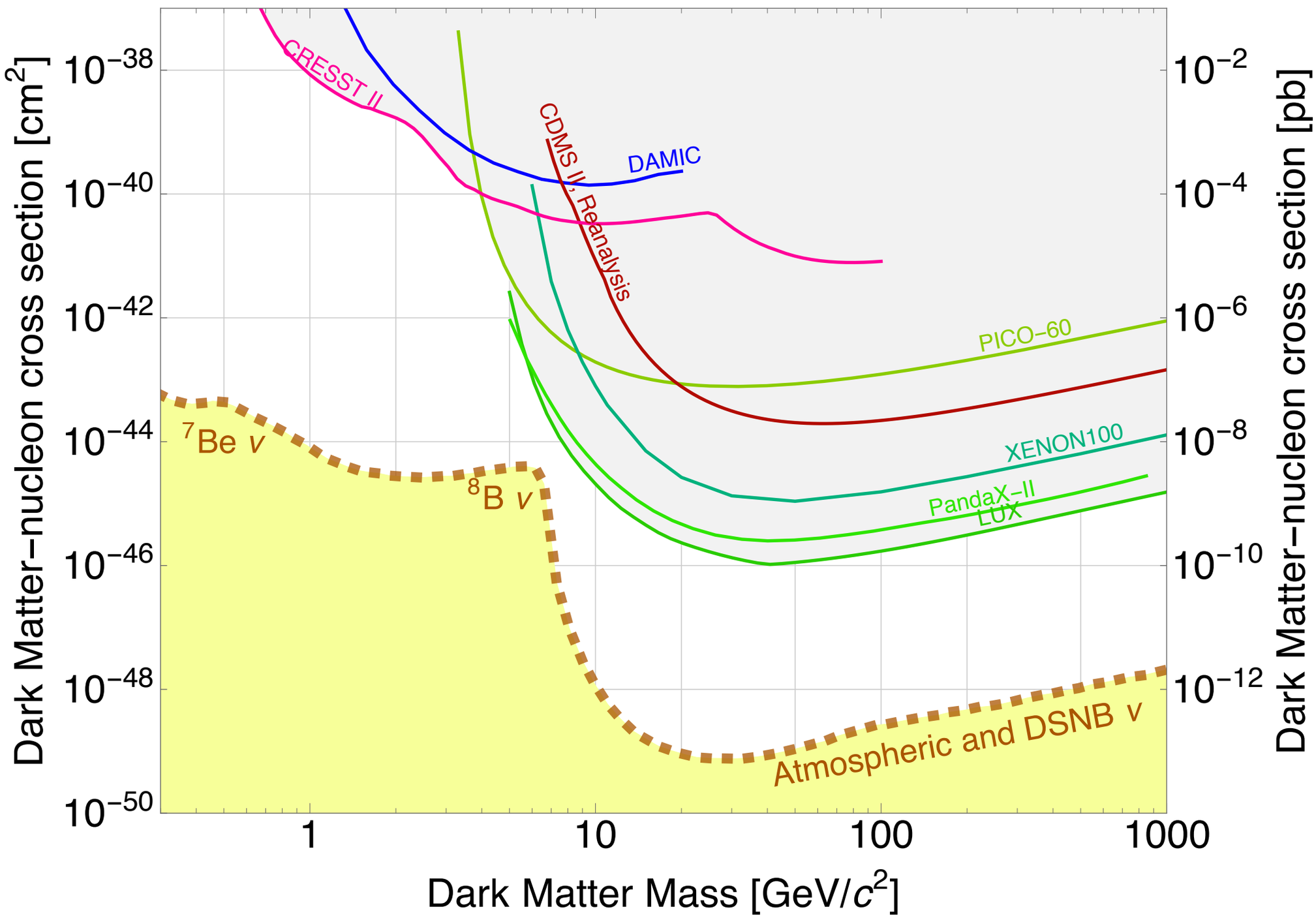
nuclear recoil energy too small

linear, since

$$\text{Rate} \propto n \propto \frac{\rho}{m}$$

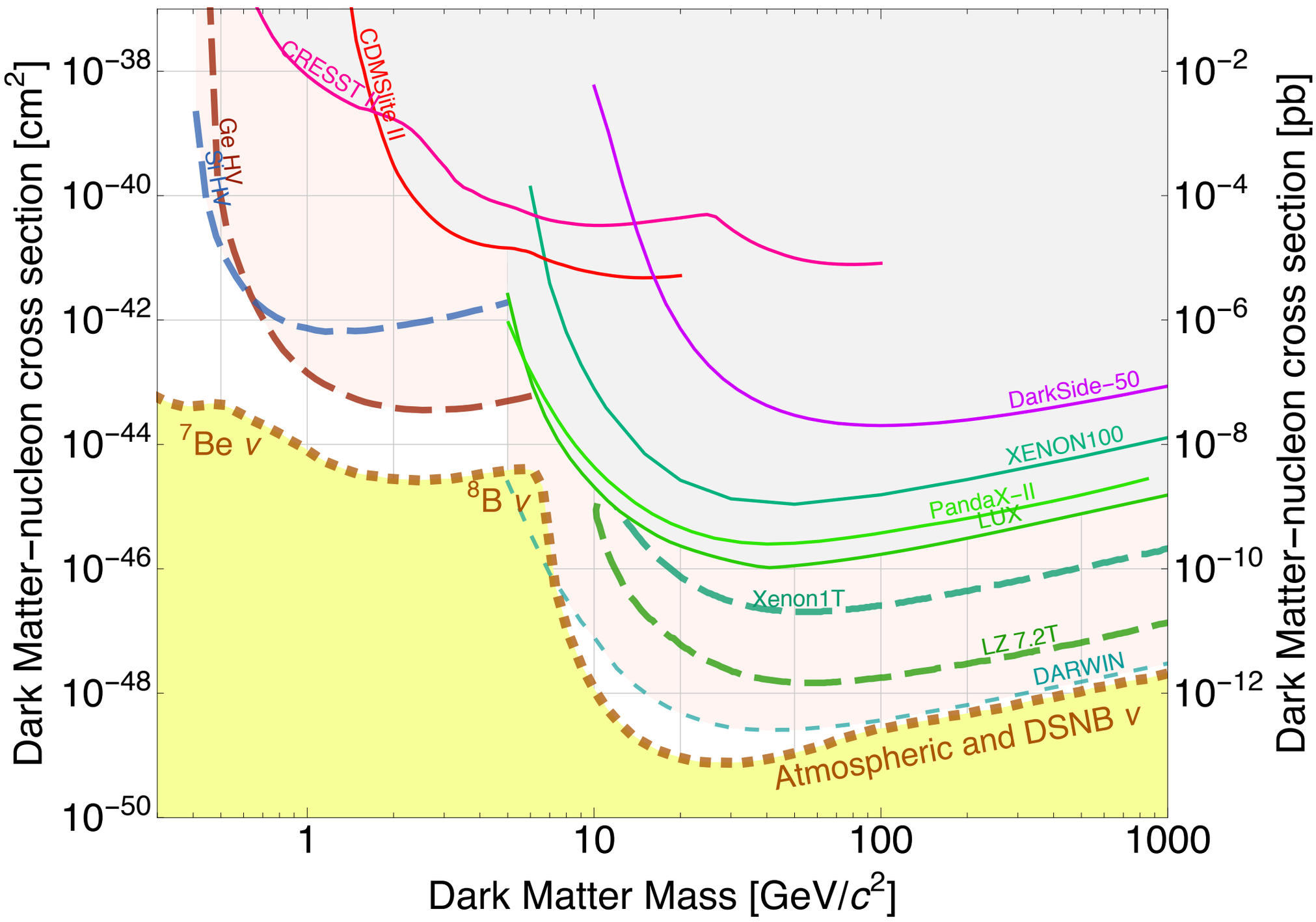
$$\propto \frac{0.4\ \text{GeV/cm}^3}{m}$$

Current Direct Detection Constraints



WIMP limit plotter: Saab & Figueroa

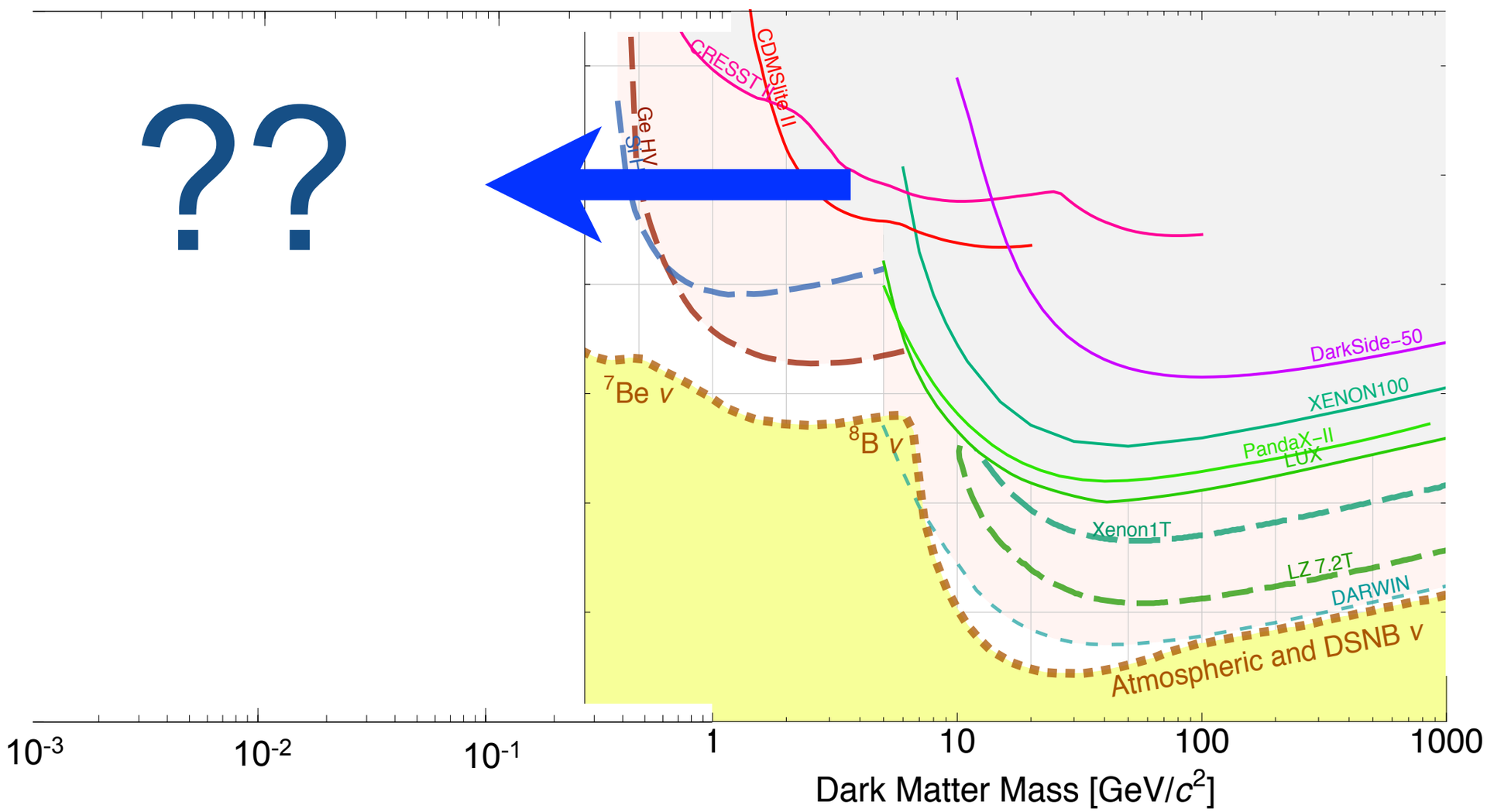
Direct detection: projections



WIMP limit plotter: Saab & Figueroa

Conventional wisdom:

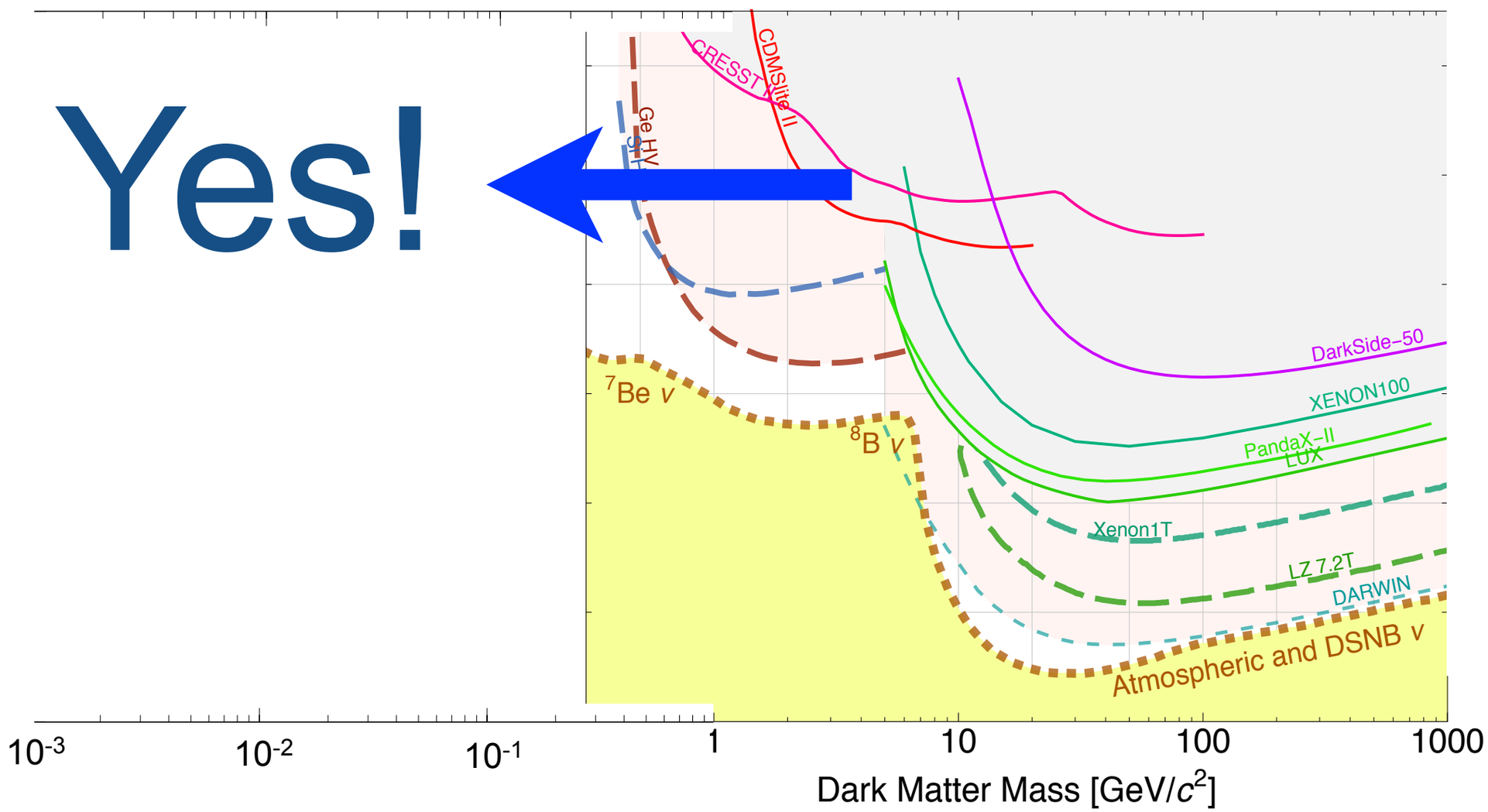
no sensitivity to DM w/ mass ≪GeV



Take-away message:

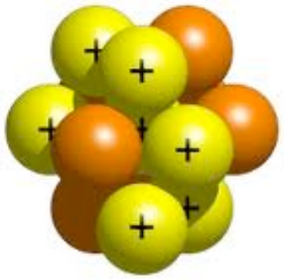
- Direct-detection constraints exist to m_{DM}~5 MeV
- significant improvements in ~2-3 years
- probe many dark matter candidates!

Yes!



Cannot use elastic nuclear recoils for detection

Light DM $\lesssim 1\ \mathrm{GeV}$



Atom

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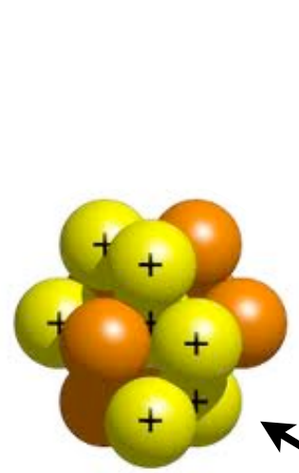
Light DM $\lesssim 1\ \mathrm{GeV}$

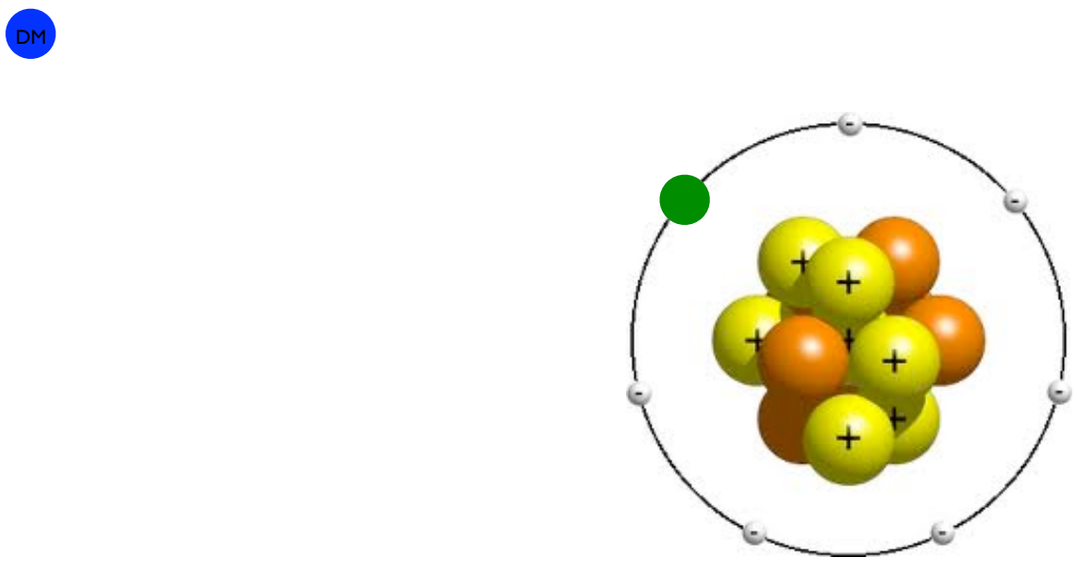


Not enough energy transfer

Can't see recoiling nucleus

But DM could also scatter off electrons!

RE, Mardon, Volansky



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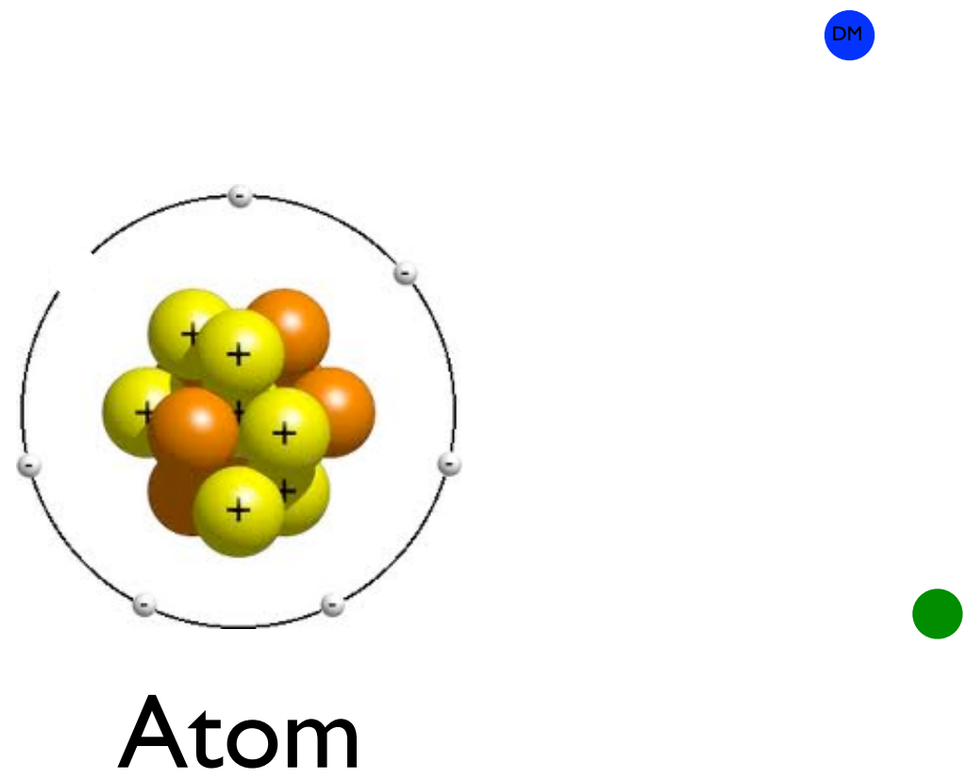

this can transfer most of DM energy

Signal: one or a few electrons or photons

DM-electron scattering can probe $\ll$GeV

to overcome binding energy ΔE

need $E_{\rm DM} \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 > \Delta E$

$$v_{\rm DM} \lesssim 800 \text{ km/s} \implies m_{\rm DM} \gtrsim 300 \text{ keV} \left(\frac{\Delta E}{1 \text{ eV}}\right)$$

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Note: <u>typical</u> recoil energy of e^- is a few eV

Target materials for electron recoils?

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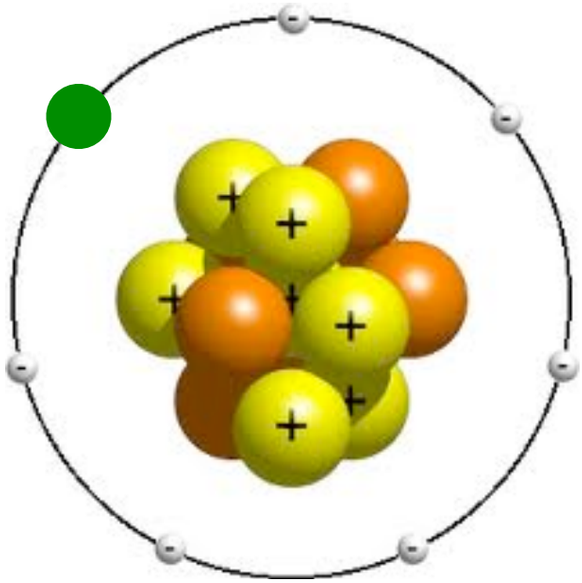
Type	Examples	mass threshold
Noble liquids	Xe, Ar, He	~5 MeV

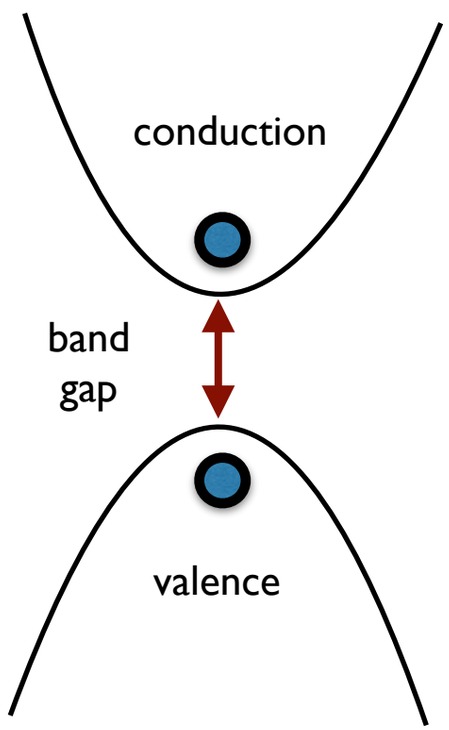


$$\Delta E \sim 10 \text{ eV}$$

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

Target materials for electron recoils?

Type	Examples	mass threshold
Noble liquids	Xe, Ar, He	~5 MeV
Semi-conductors	Ge, Si	~200 keV



$$\Delta E \sim 1 \text{ eV}$$

RE, Mardon, Volansky
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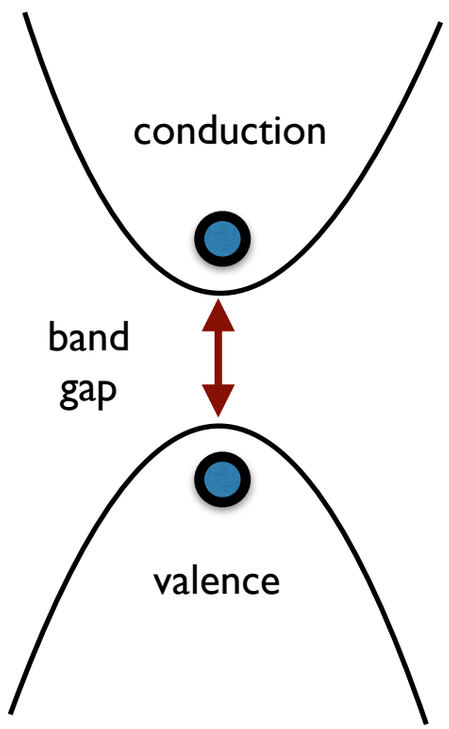

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Noble liquids	Xe, Ar, He	~5 MeV	Done w/ XENON10+100 data; improvements possible
Semi-conductors	Ge, Si	~200 keV	New experiments soon!
Scintillators	GaAs, NaI, CsI, …	~200 keV	R&D required

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many other ideas!

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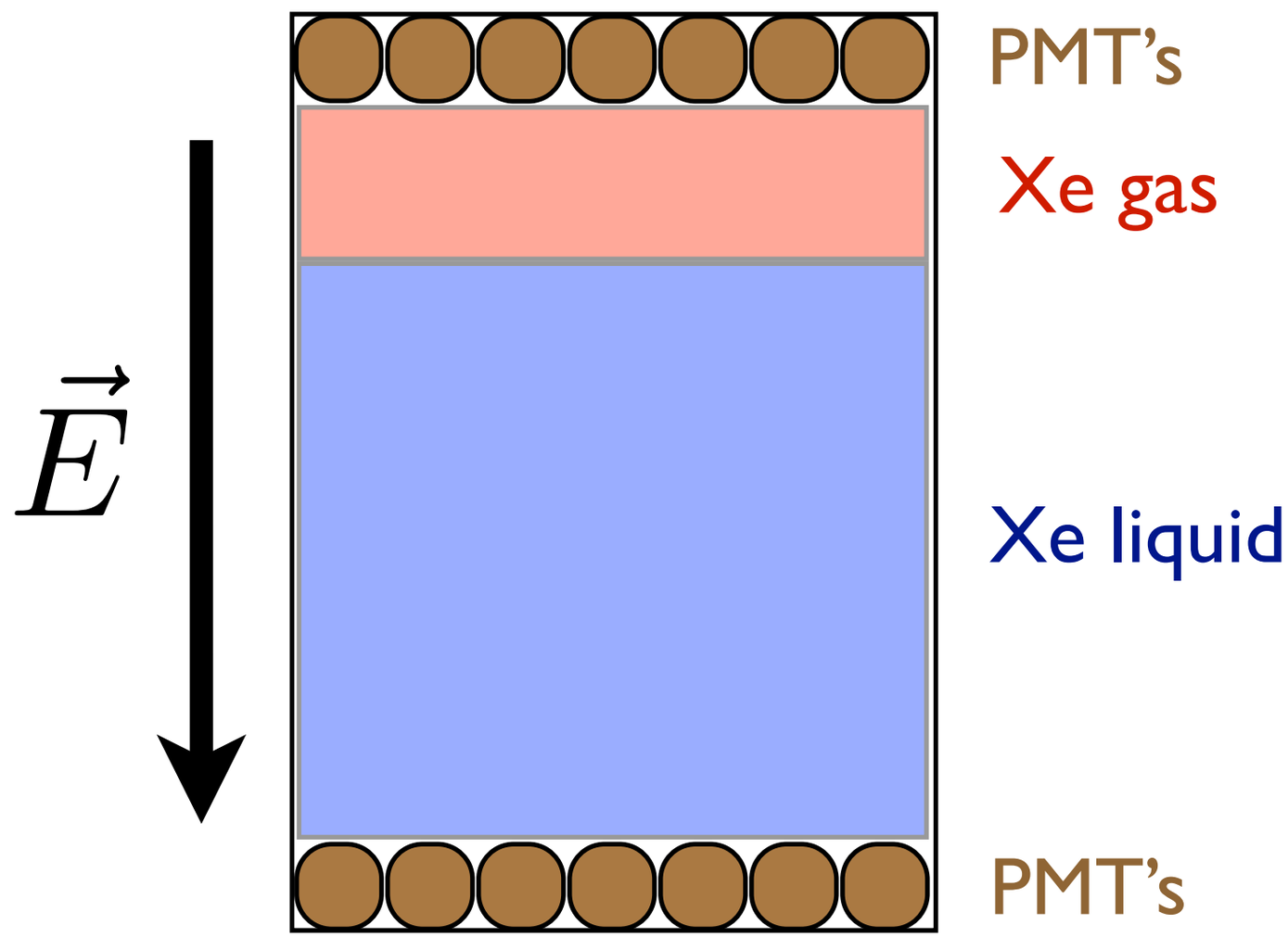
need collaborations between particle and condensed matter theorists, experimentalists, instrumentalists, …

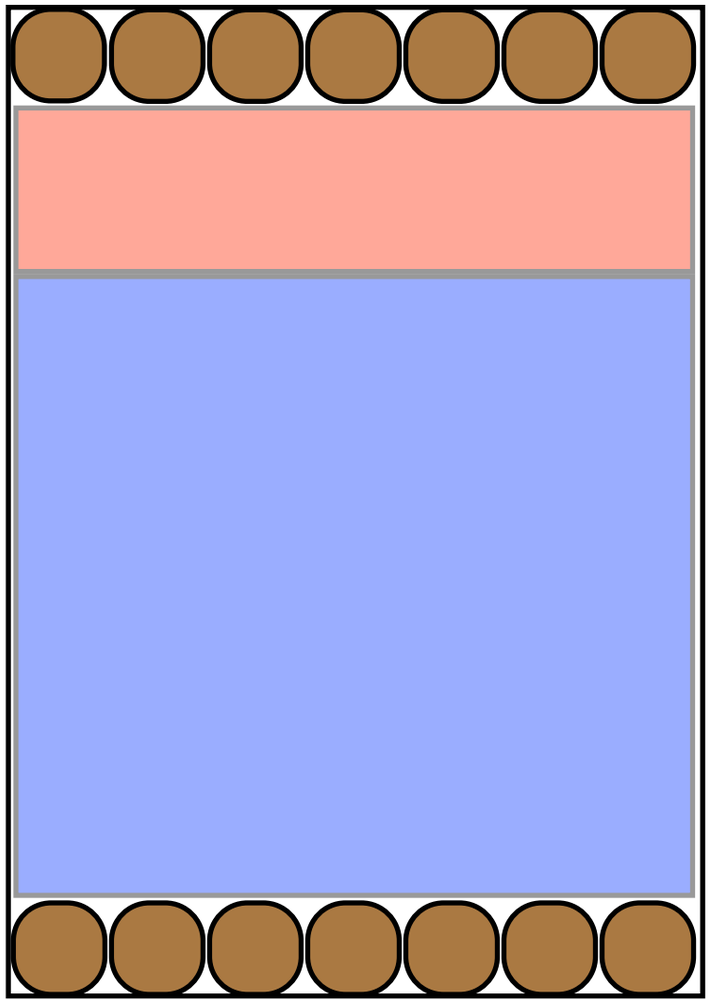
XENON10 detector schematic



ran in 2006/2007, sensitive to single electrons!

Sub-GeV DM scattering off electrons

DM



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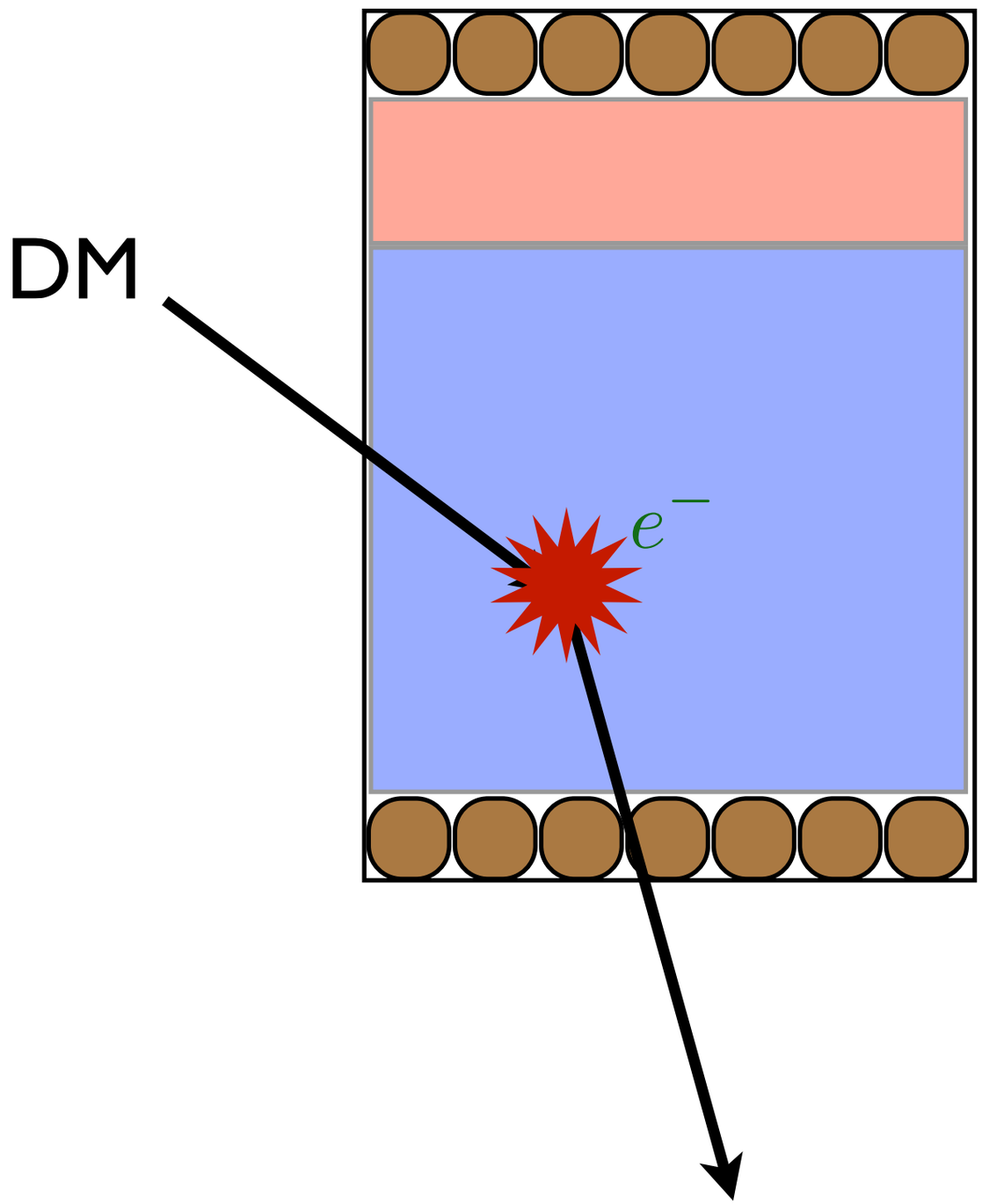

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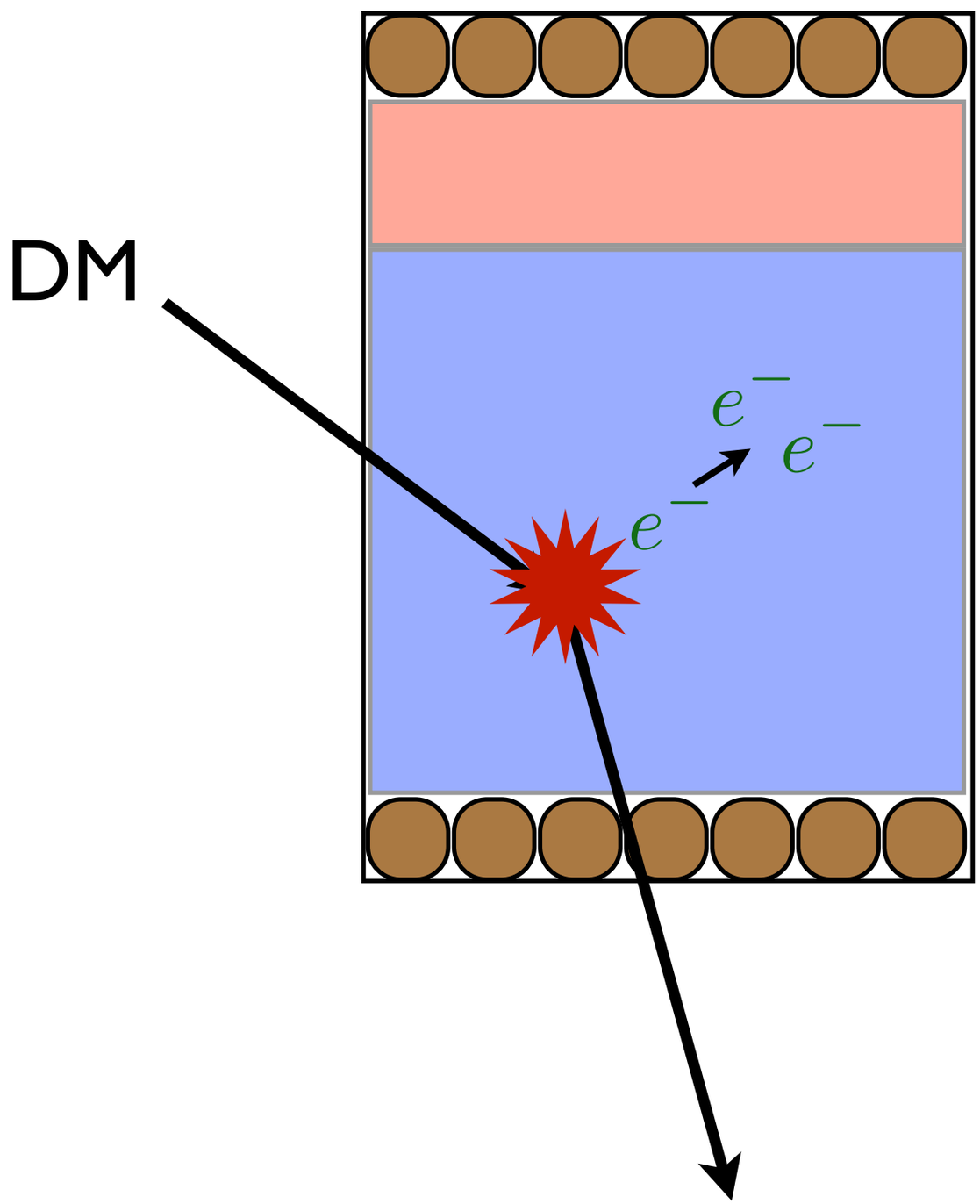

an energetic outgoing e^- can ionize other e^-'s

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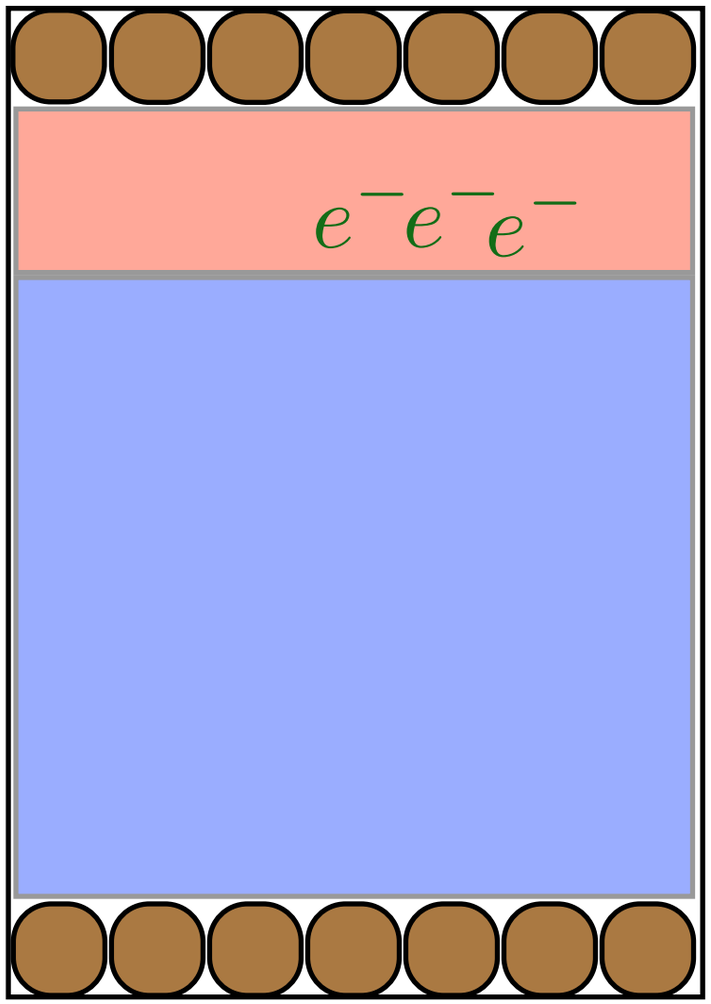

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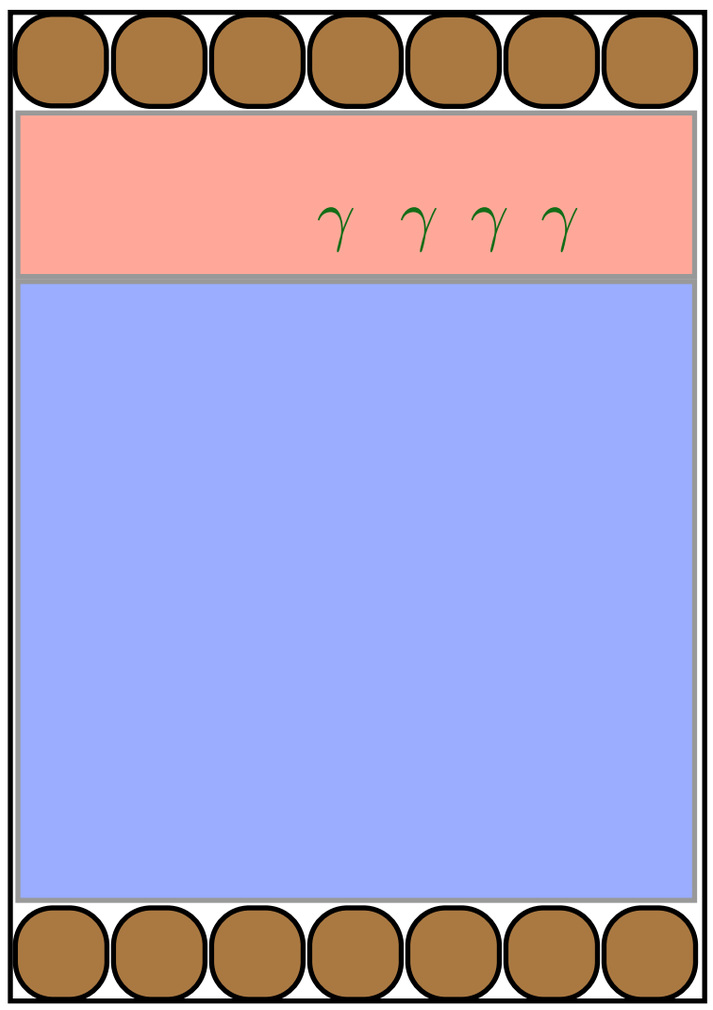

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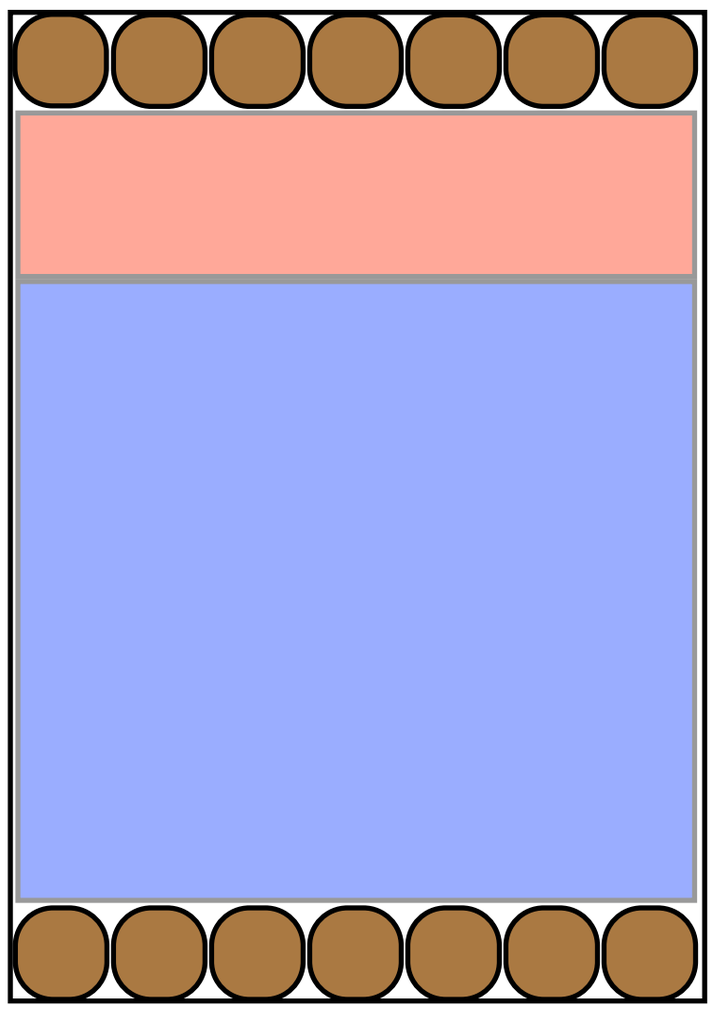
one e^- produces ~27 detected photons!

Sub-GeV DM scattering off electrons



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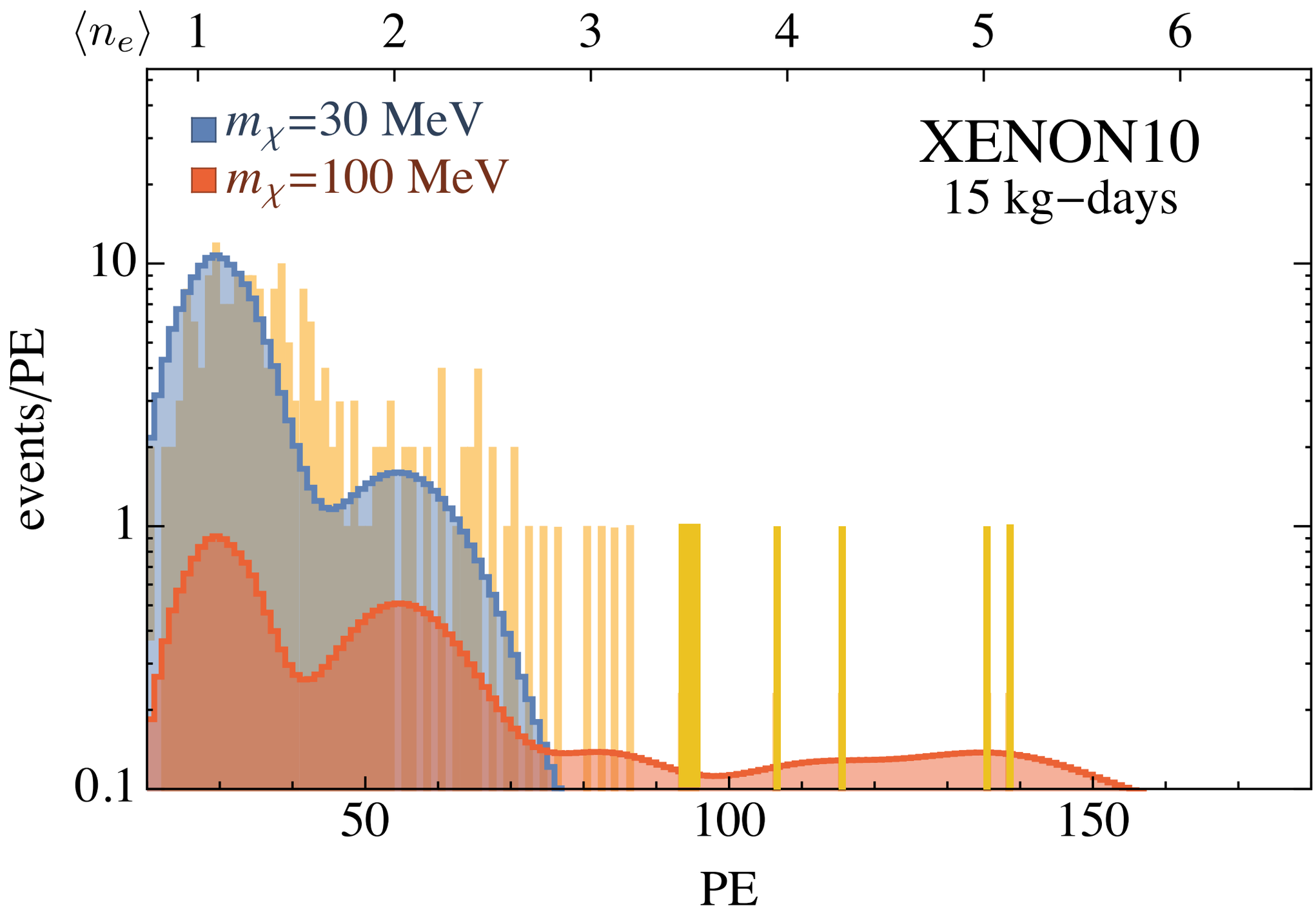
Signal and Data: XENON10

RE, Volansky, Yu

updated from

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012



XENON10: 1104.3088 (P. Sorensen et.al.)

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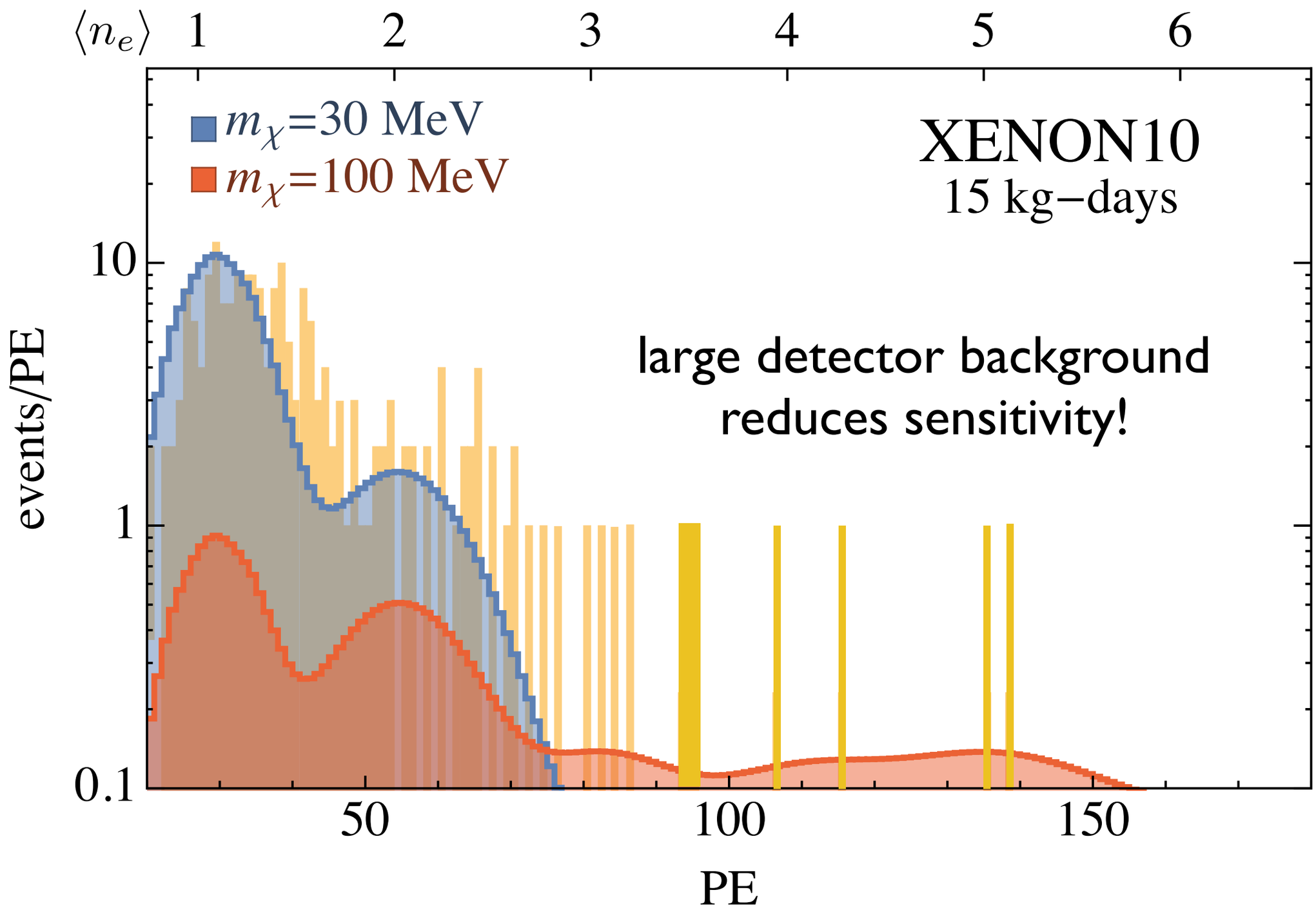


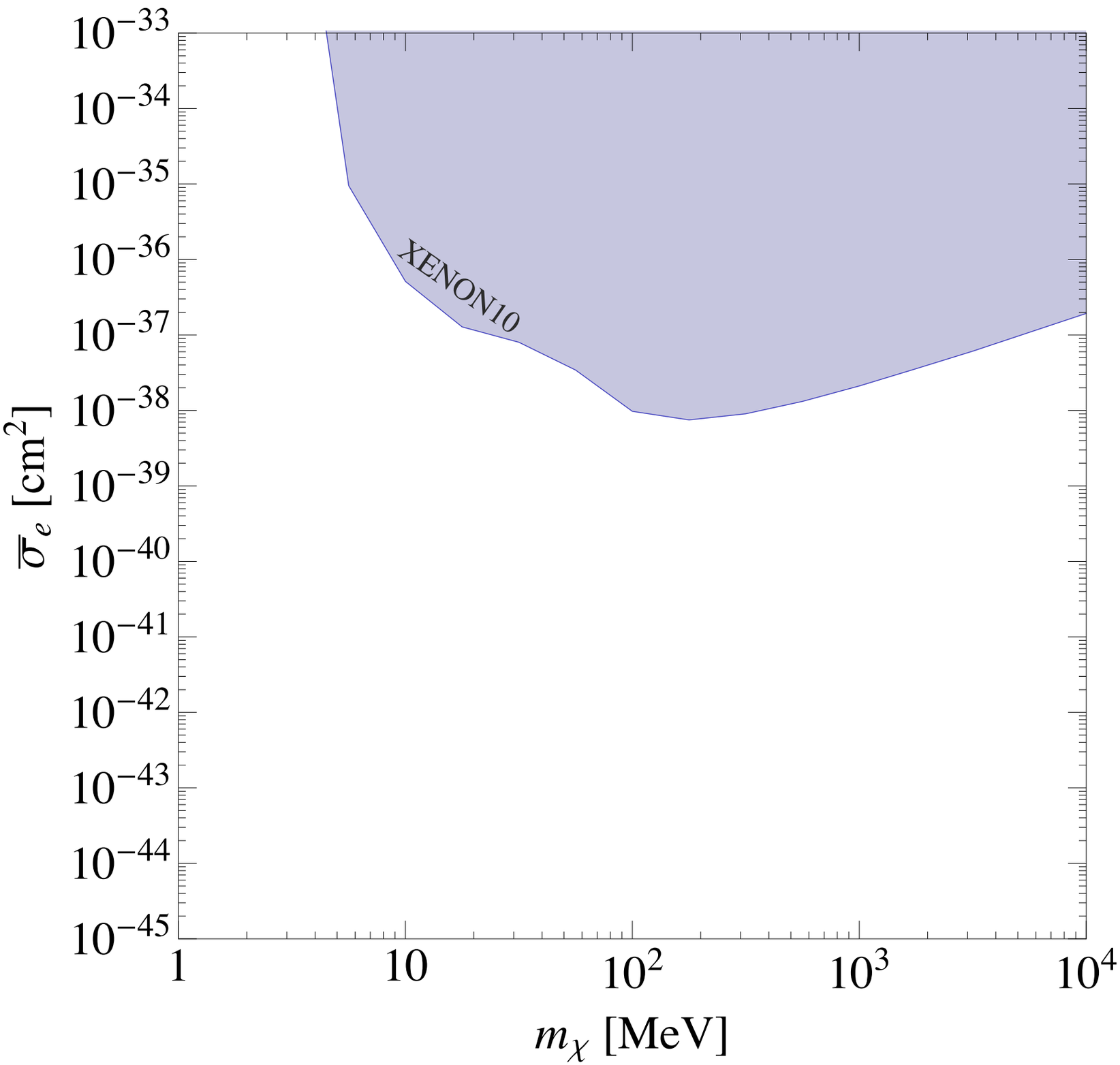
XENON10: 1104.3088 (P. Sorensen et.al.)

XENON10 constraint

RE, Volansky, Yu

updated from

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012

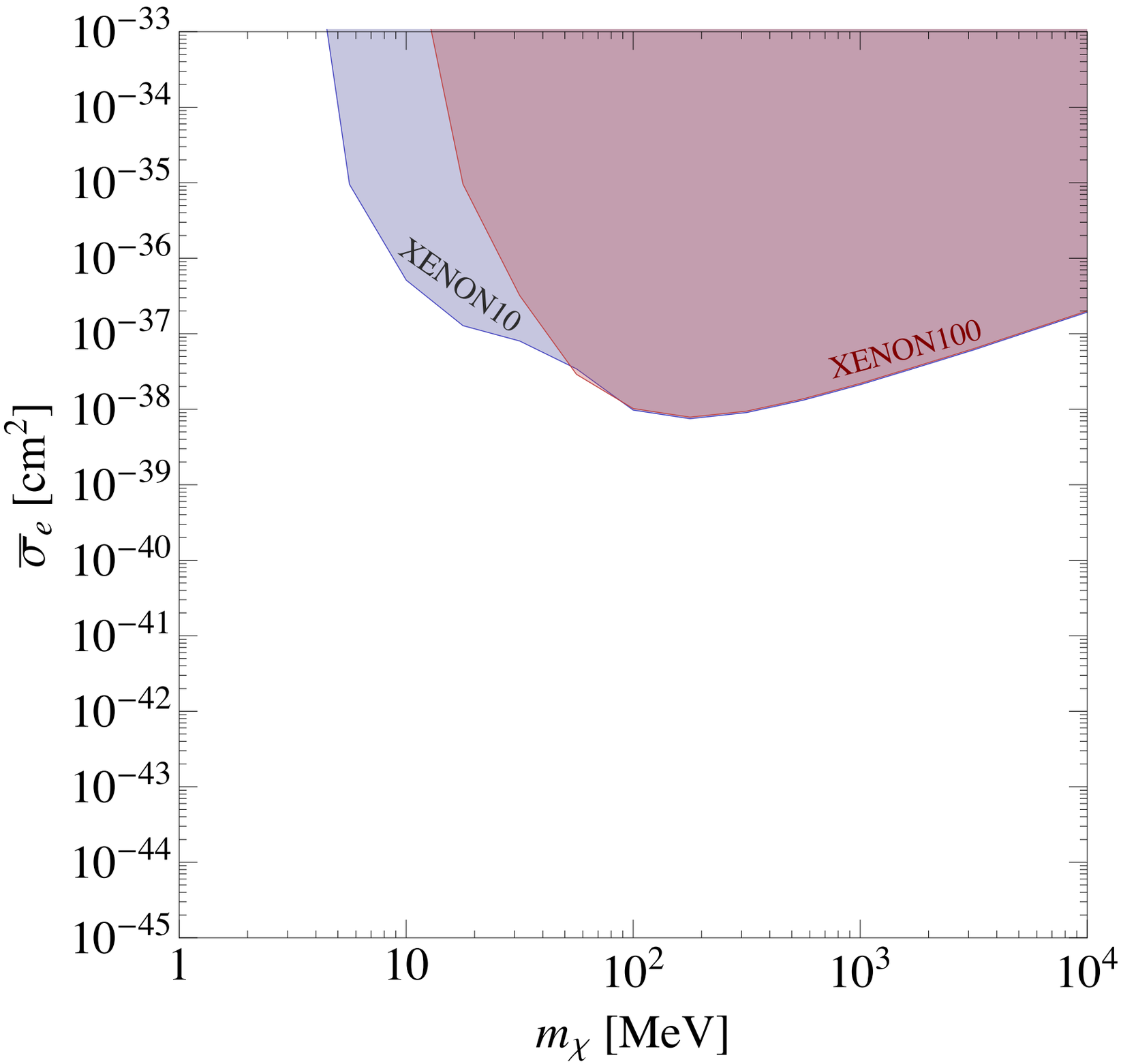


XENON10+XENON100 constraint

RE, Volansky, Yu

updated from

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012

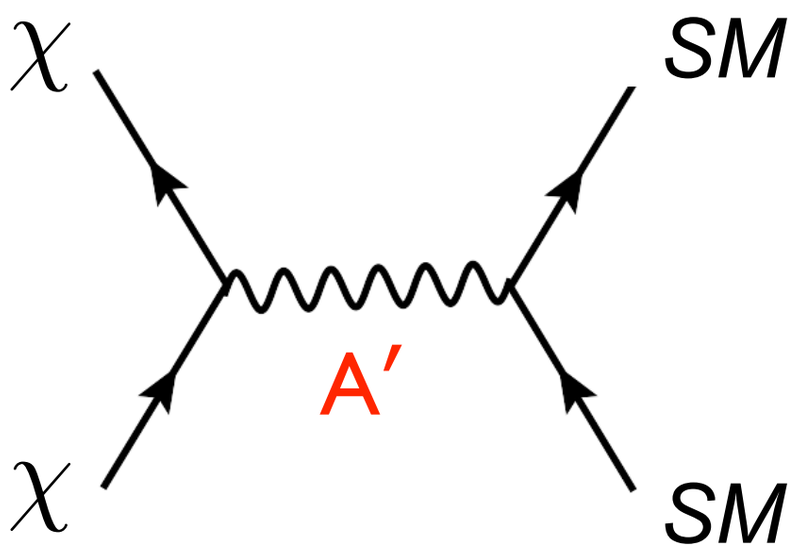


XENON100 has data for

$$n_e \gtrsim 4e^-$$

XENON100: 1605.06262

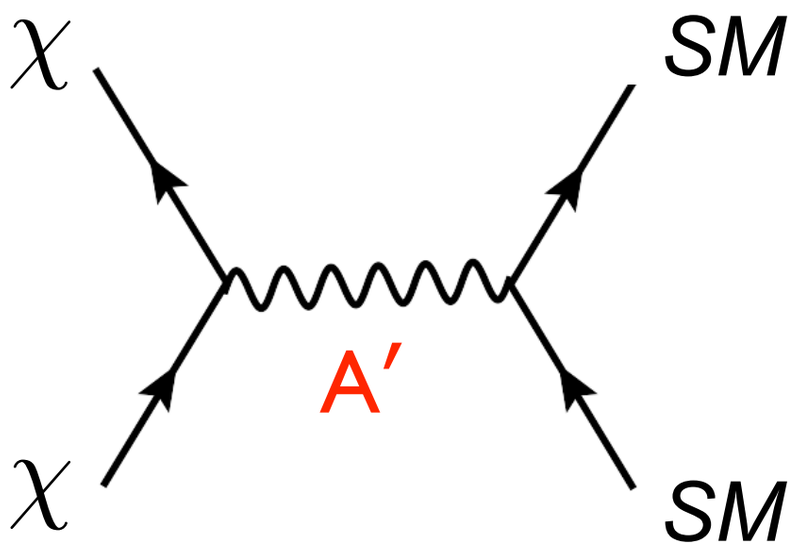
Recall: Dark matter + dark photon model

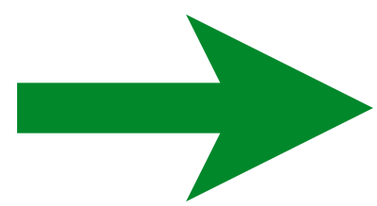


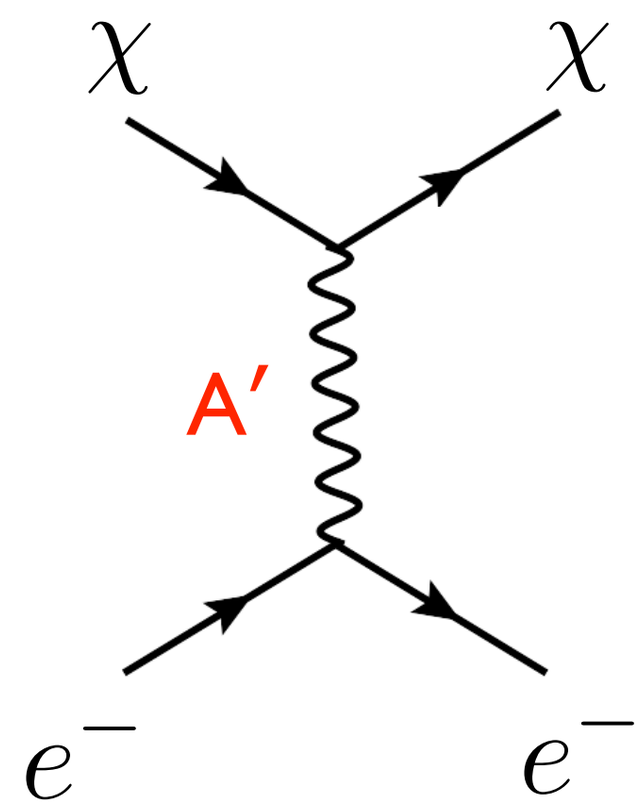
relic abundance fixes model parameters

see e.g. Boehm & Fayet (2003); Borodatchenkova, Choudhury, Drees (2005); Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)

Recall: Dark matter + dark photon model





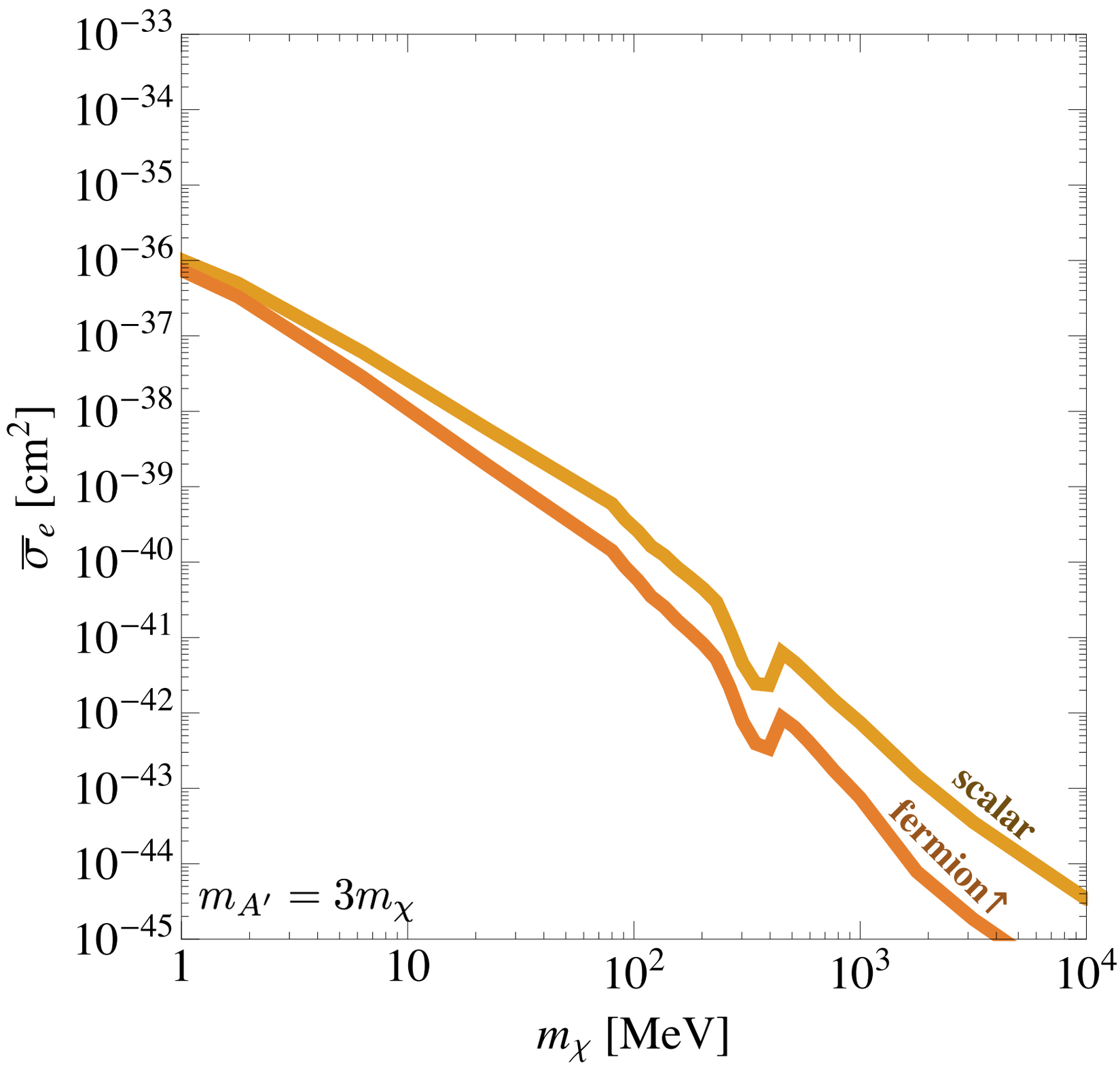


relic abundance fixes model parameters

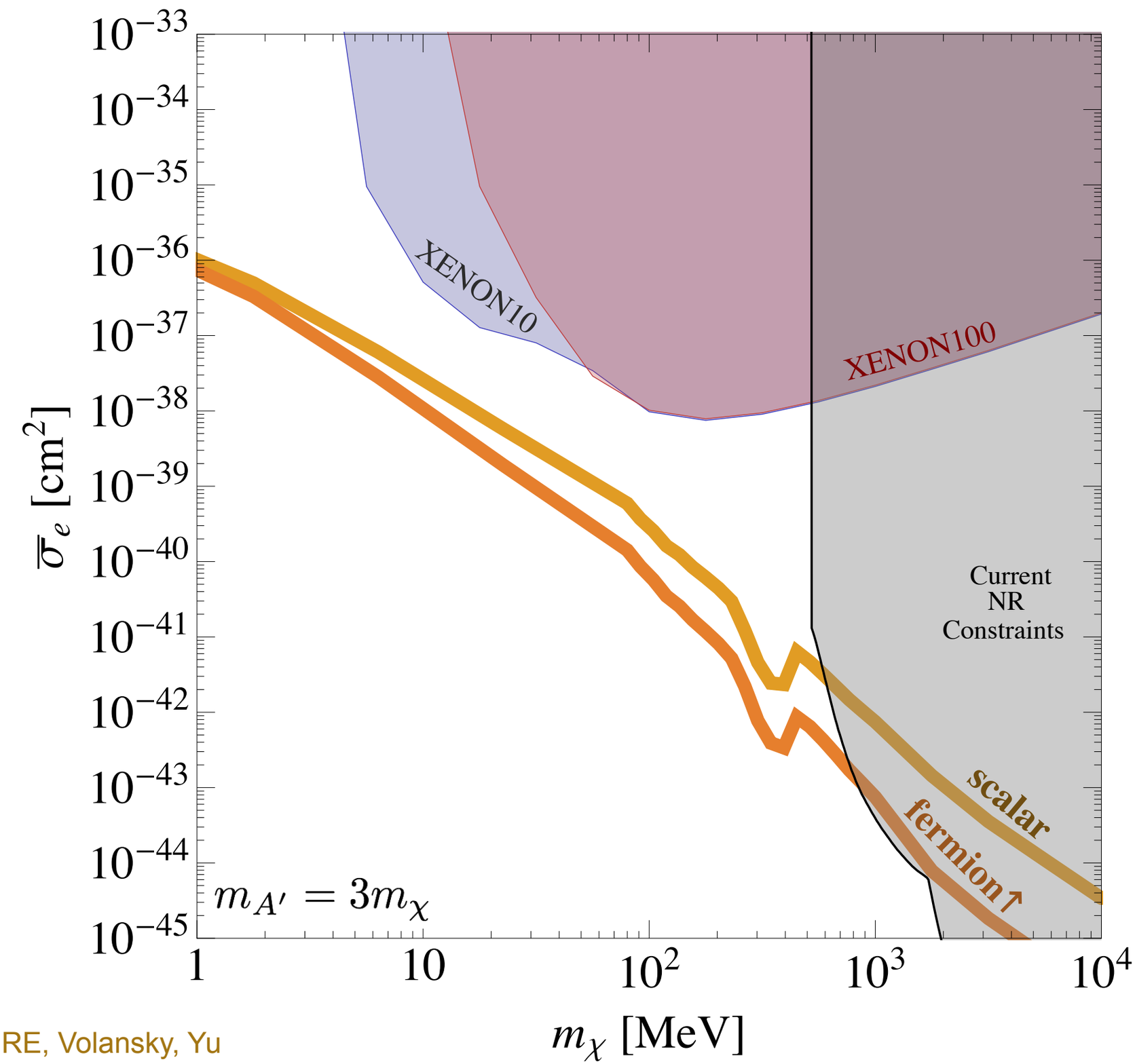
fixes direct detection rates

see e.g. Boehm & Fayet (2003); Borodatchenkova, Choudhury, Drees (2005); Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)

Two benchmark models: scalar DM & fermion DM



XENON10/100 vs Benchmarks?



RE, Volansky, Yu
RE, Manalaysay, Mardon, Sorensen, Volansky

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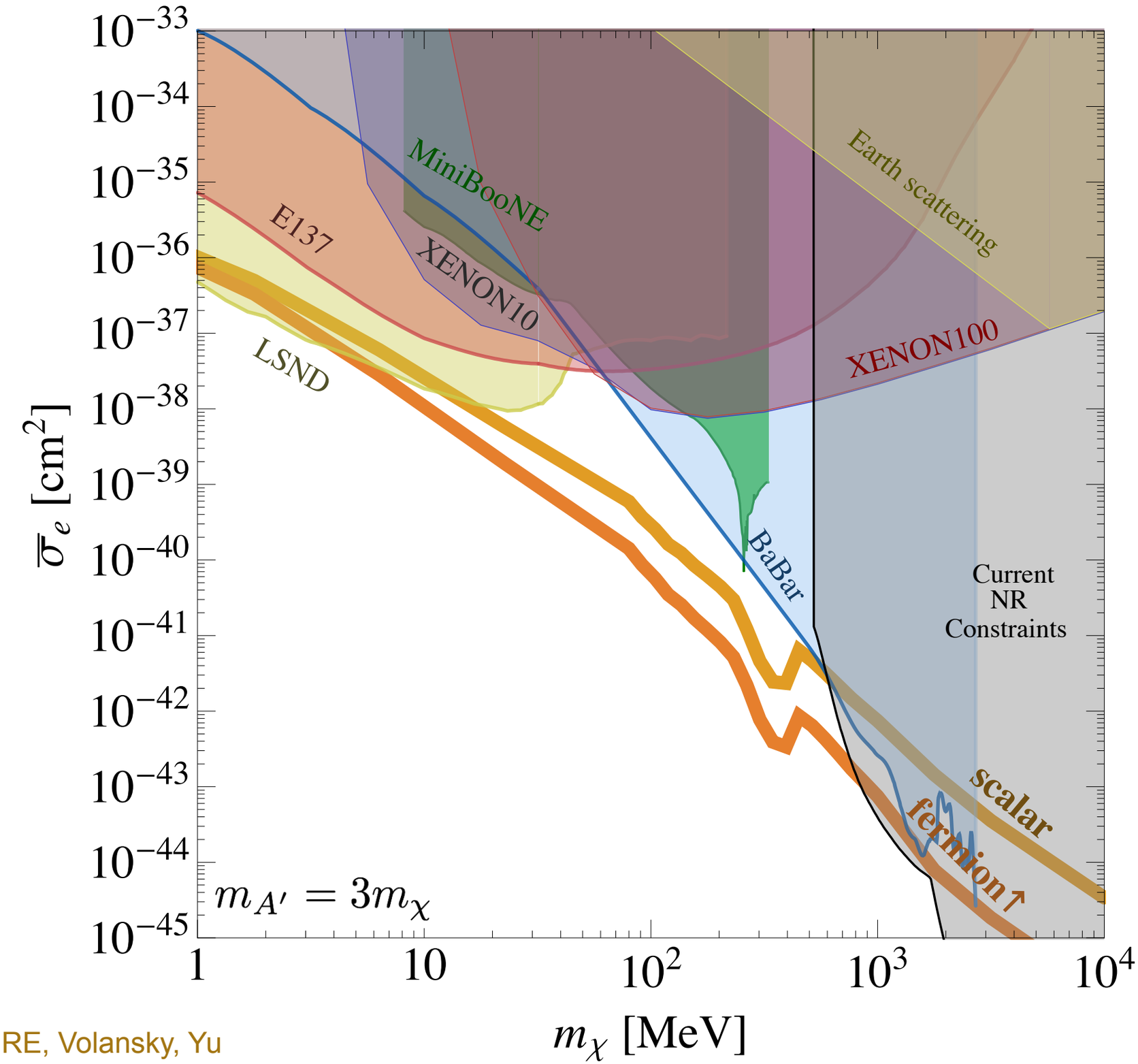

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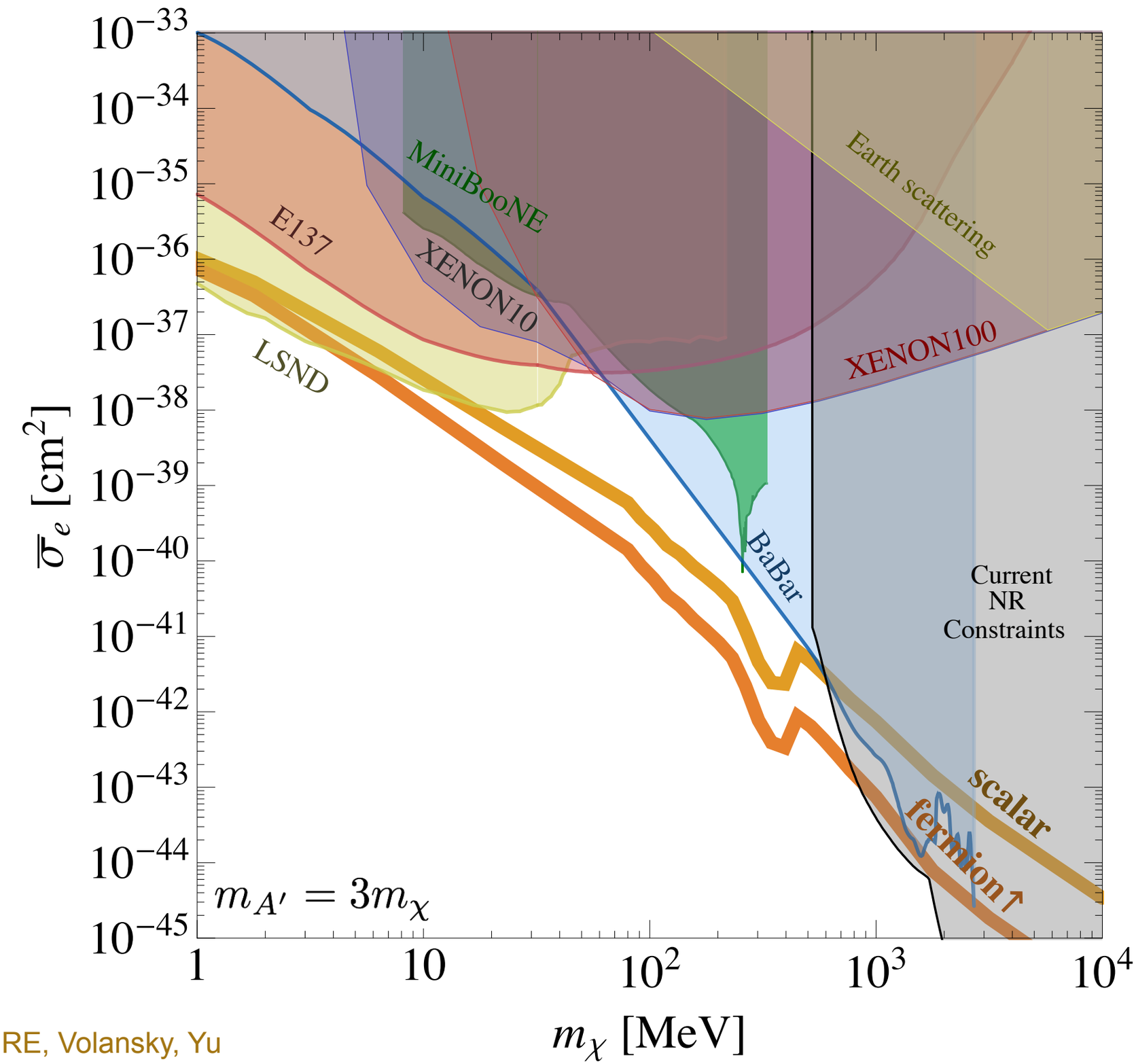

Large rates at upcoming xenon experiments… but not clear if backgrounds can be mitigated

RE, Volansky, Yu
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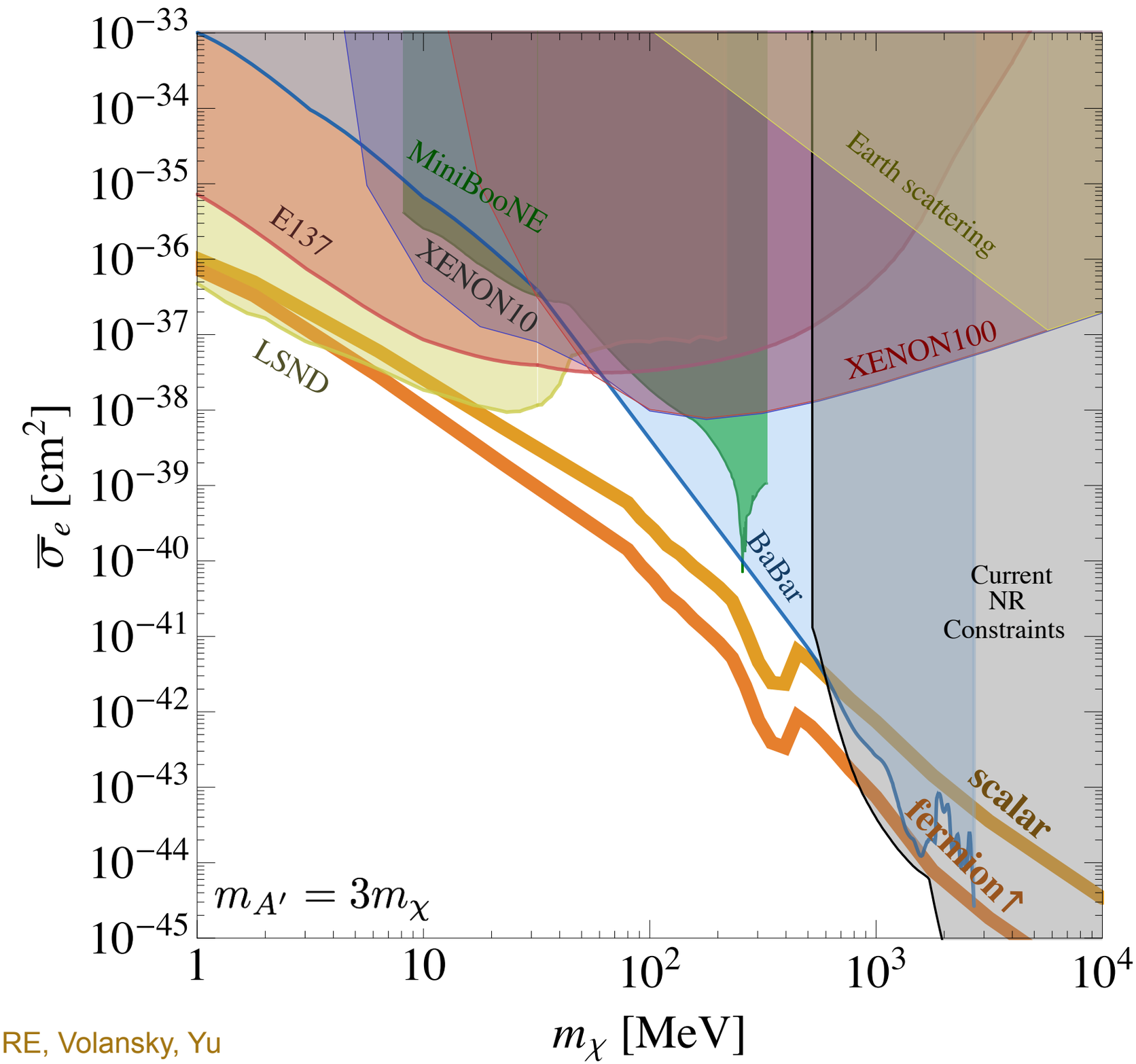
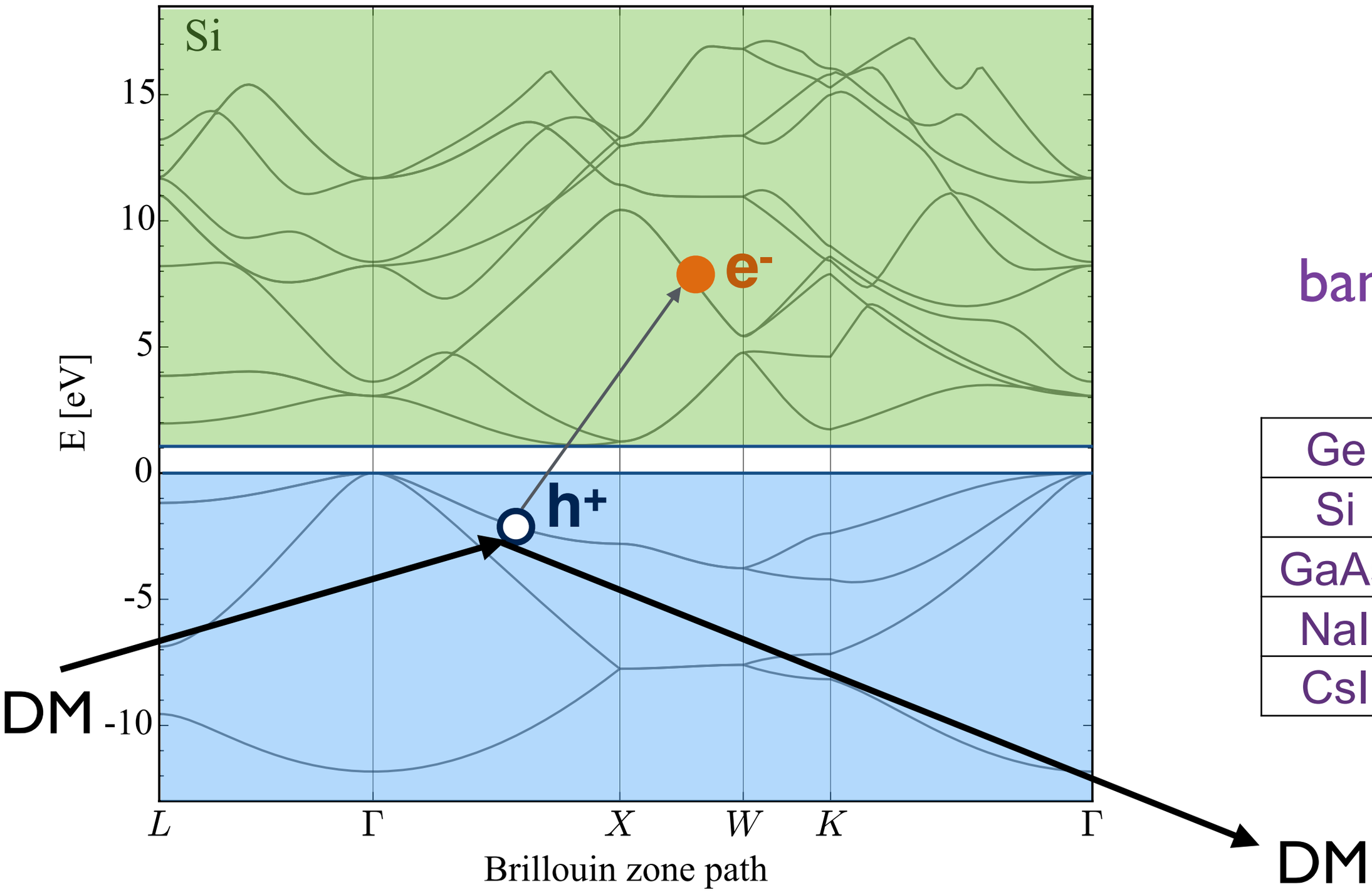


Large rates at upcoming xenon experiments… but not clear if backgrounds can be mitigated

need new experiments to improve!

RE, Volansky, Yu
RE, Manalaysay, Mardon, Sorensen, Volansky

Semiconductors & Scintillators (schematic)



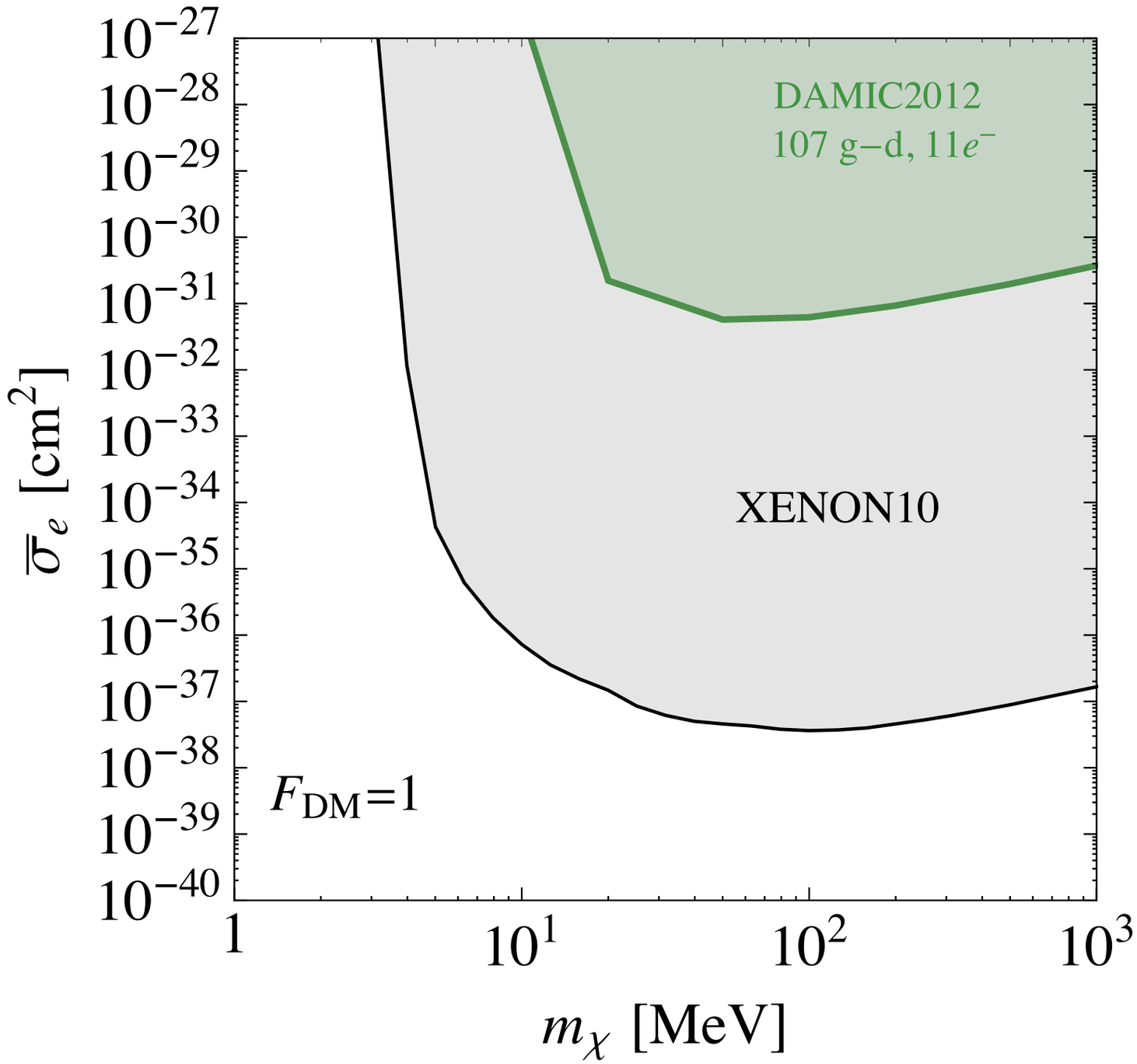
band gap

[eV]

Ge	0.67
Si	1.1
GaAs	1.5
NaI	5.9
CsI	6.4

Current best semiconductor limit (DAMIC, Si)

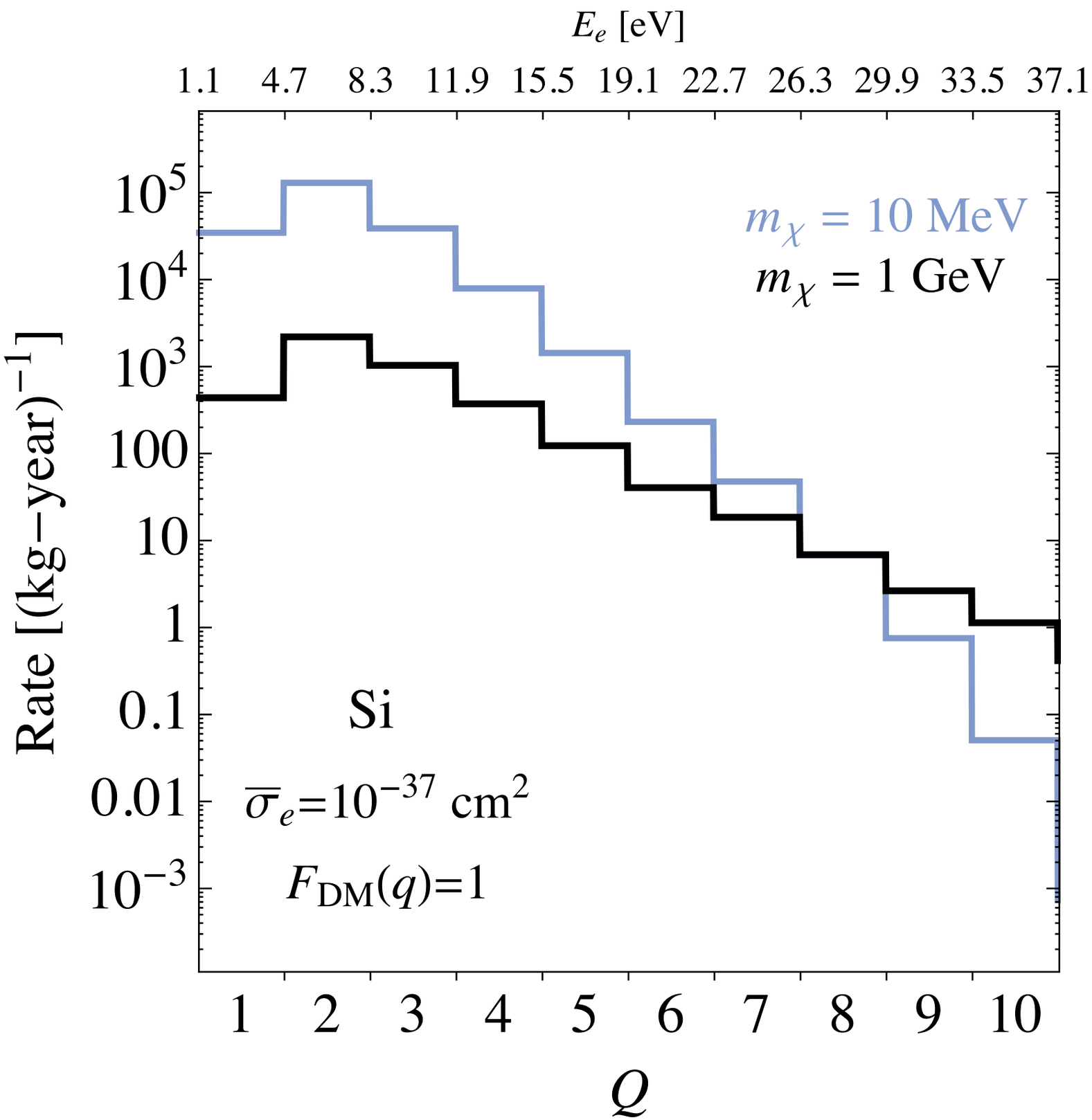
RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu



to avoid readout noise, threshold set to ~11 e^-

Rates increase dramatically for lower thresholds

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu



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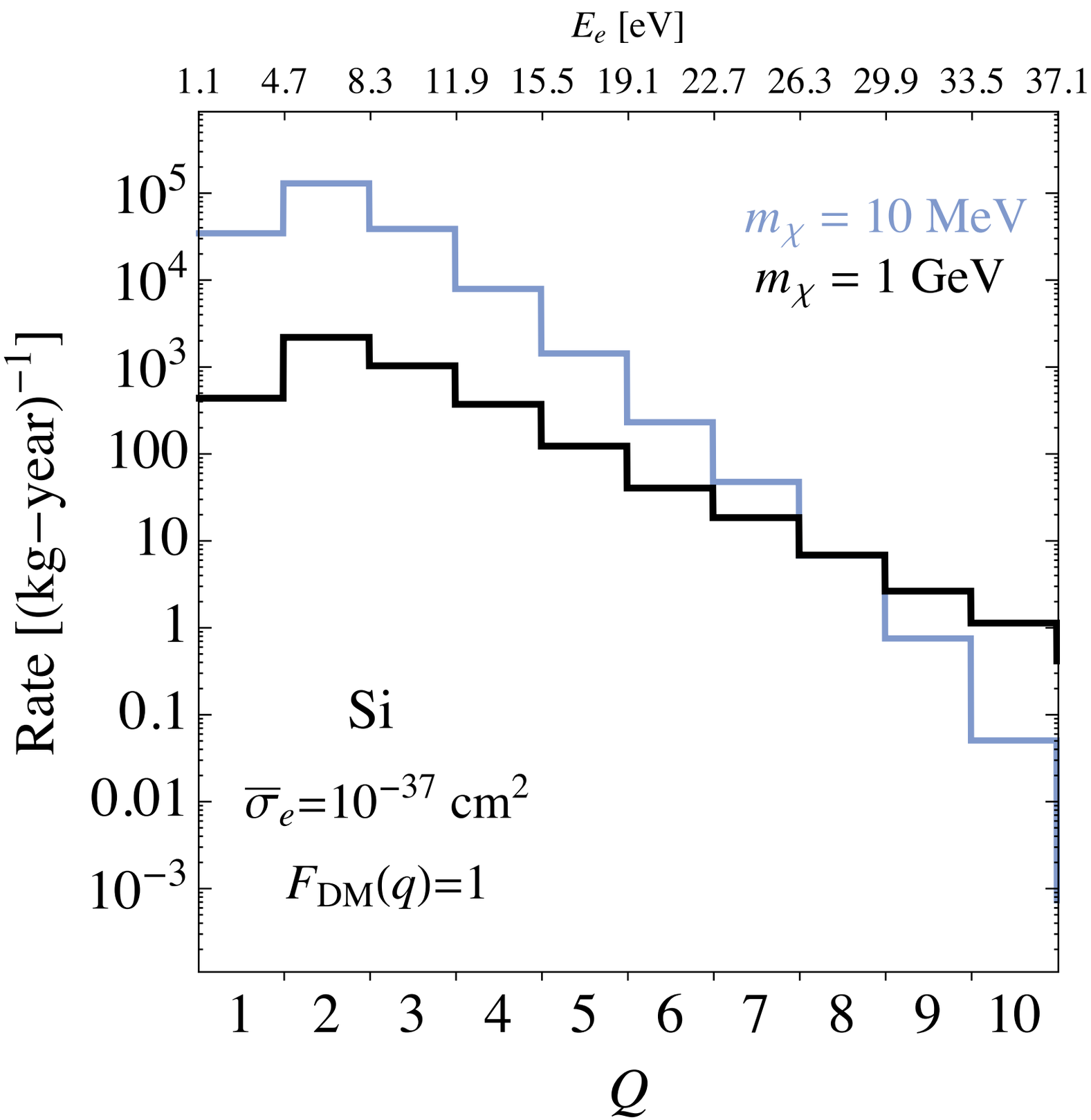

If we can reduce threshold, *enormous gain* in sensitivity

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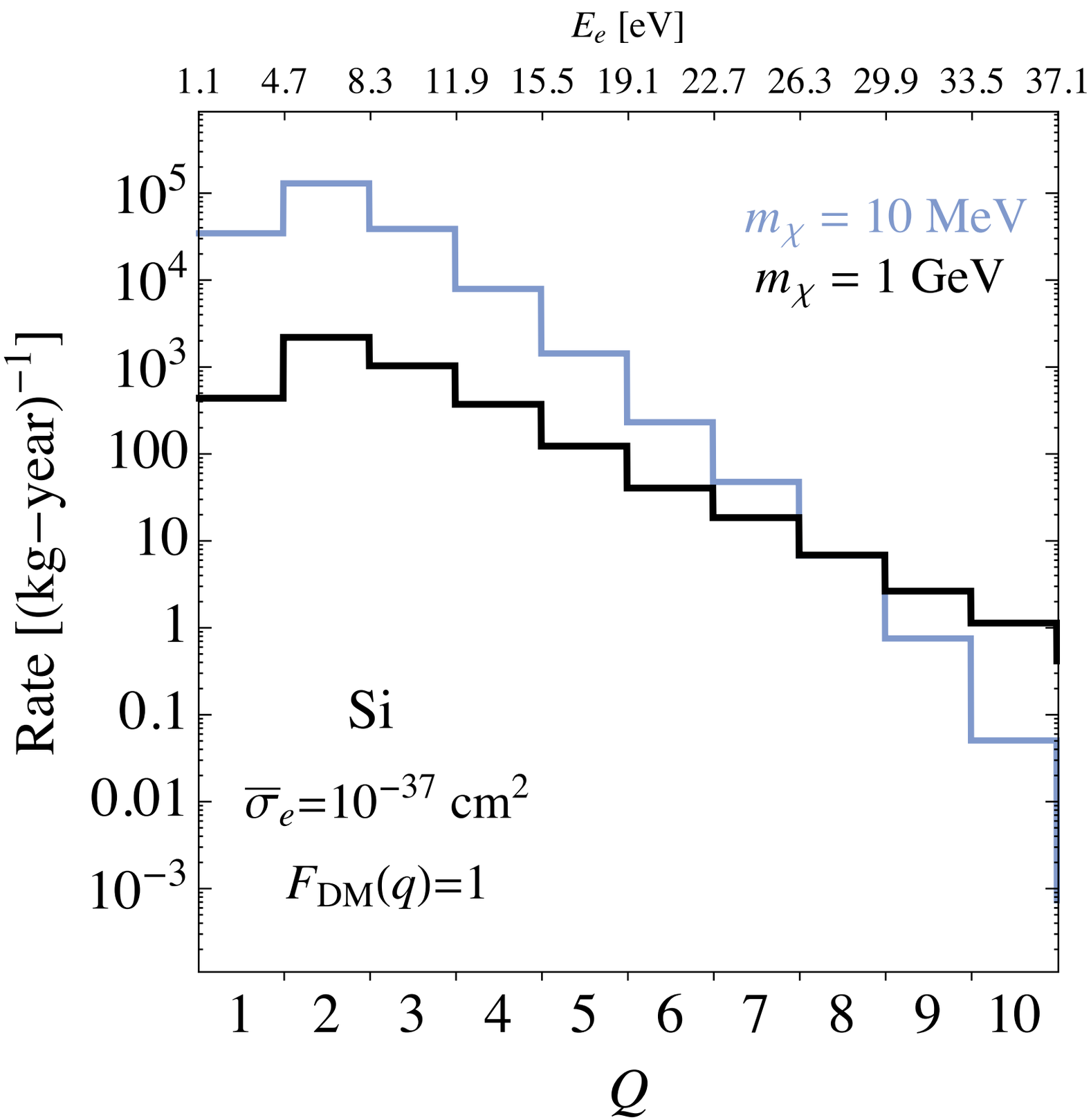


If we can reduce threshold, *enormous gain* in sensitivity

various ideas in progress, but one stands out…

An exciting new detector: SENSEI

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

silicon CCDs

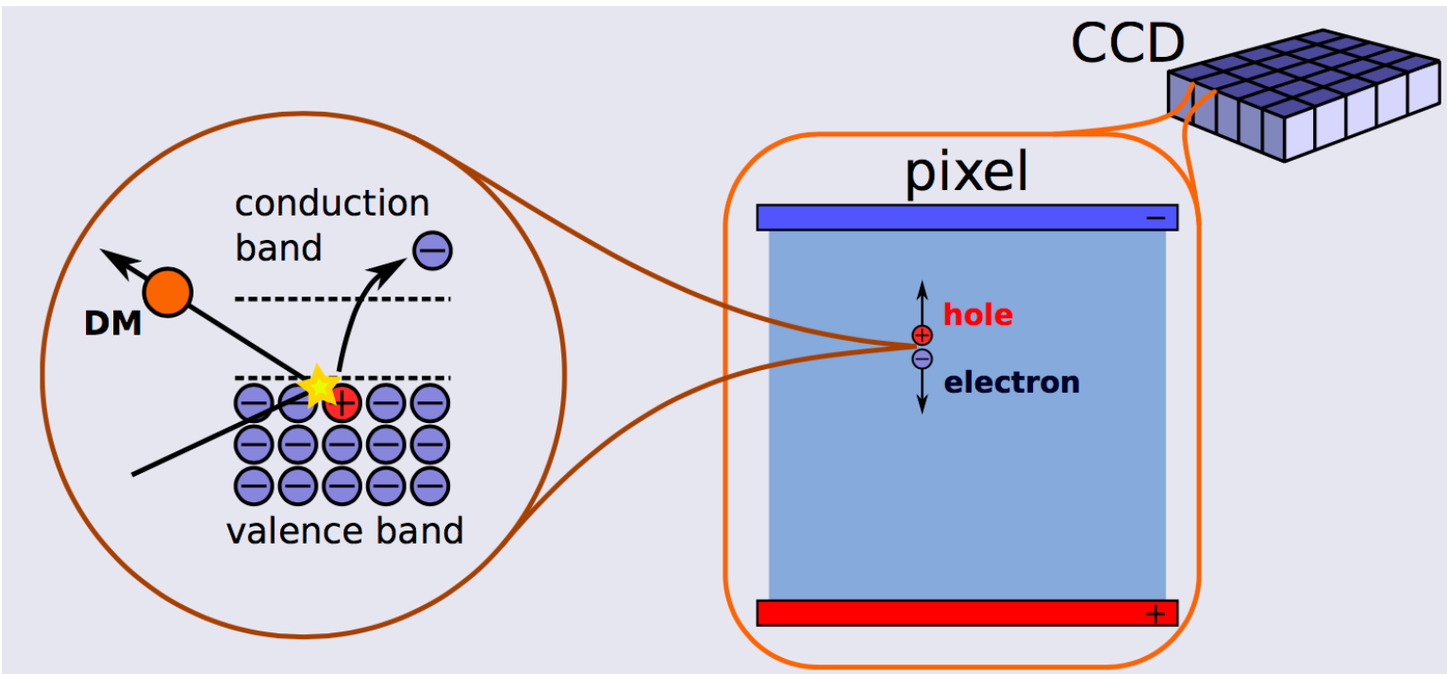
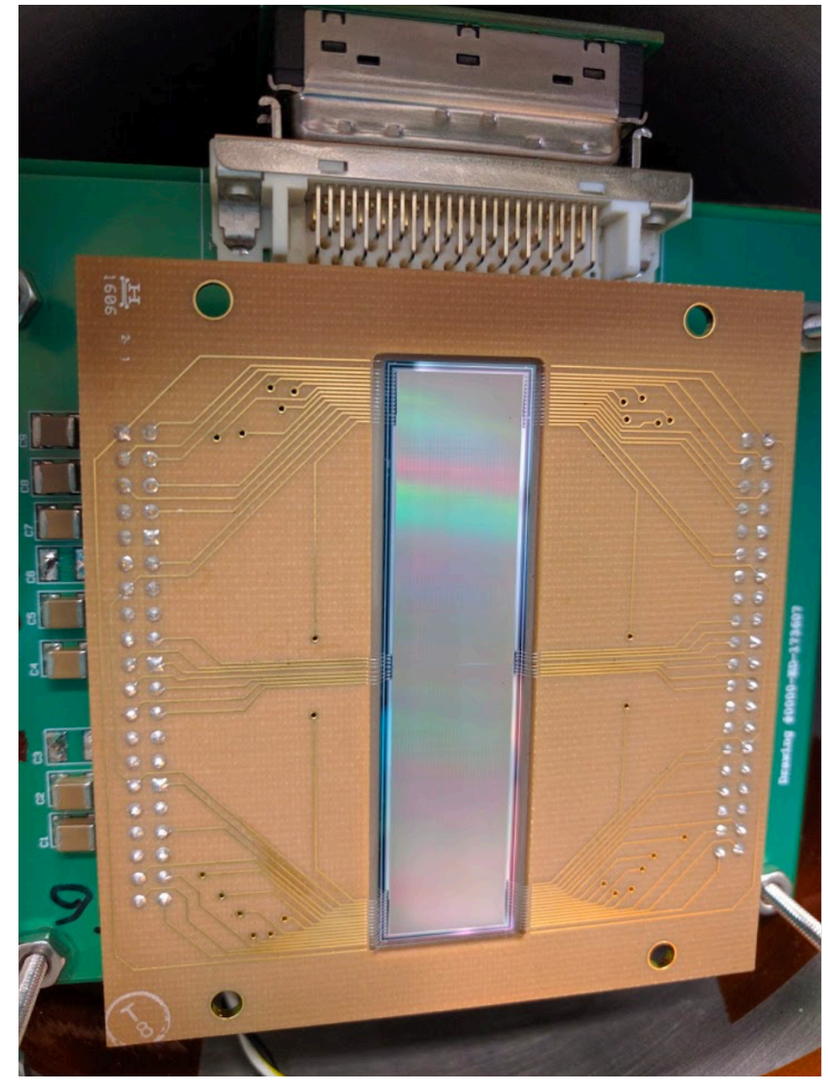


Figure credit: J. Tiffenberg



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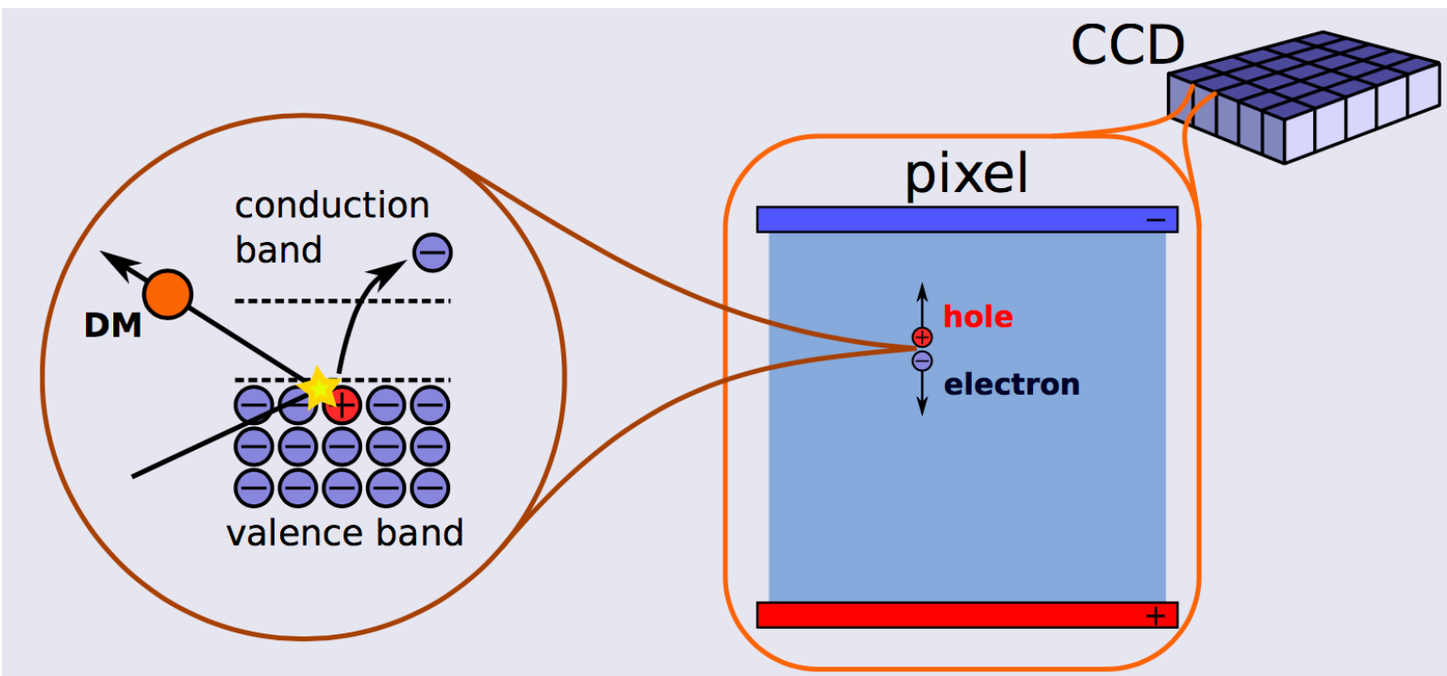

Figure credit: J. Tiffenberg

Regular CCD

"large" readout noise ($2e^-$)

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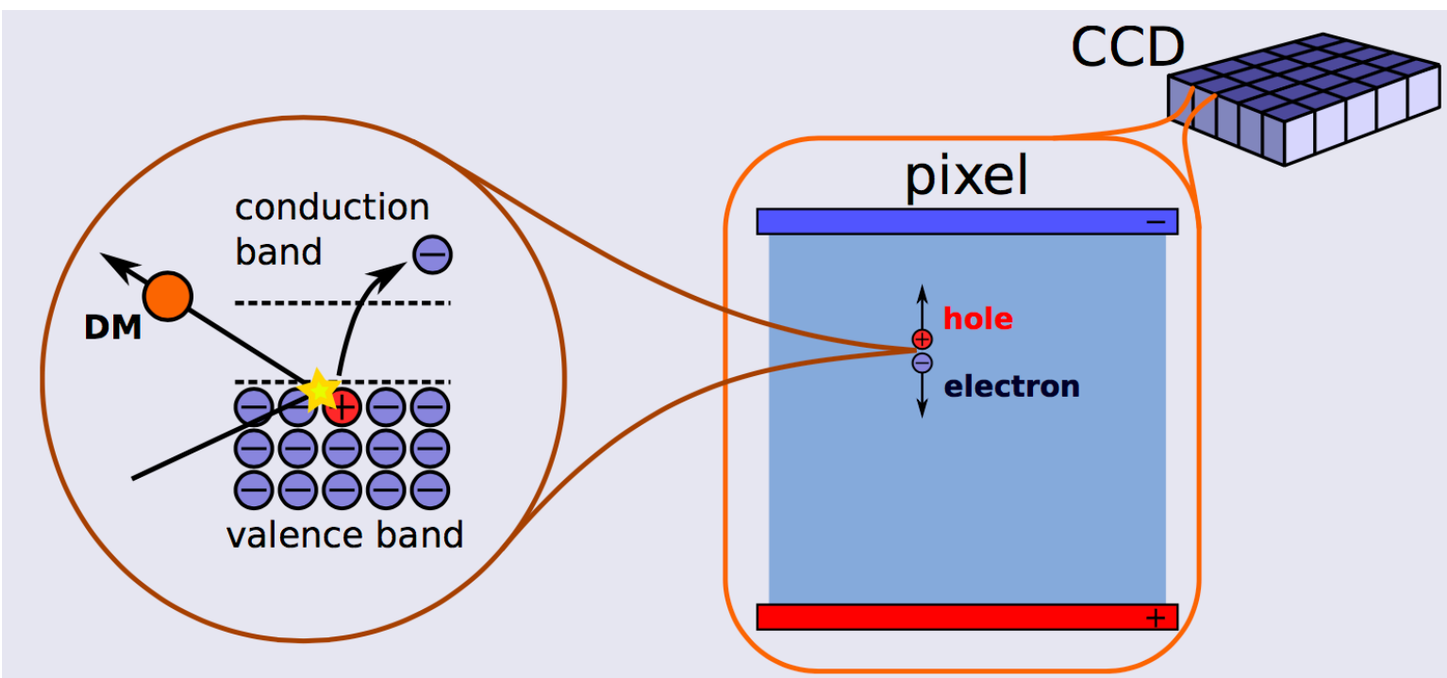

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"Skipper" CCD

recently demonstrated noise of $0.06e^-$!!!

skipper CCD developed by the LBNL MicroSystems Lab (Steve Holland, Christopher Bebek)

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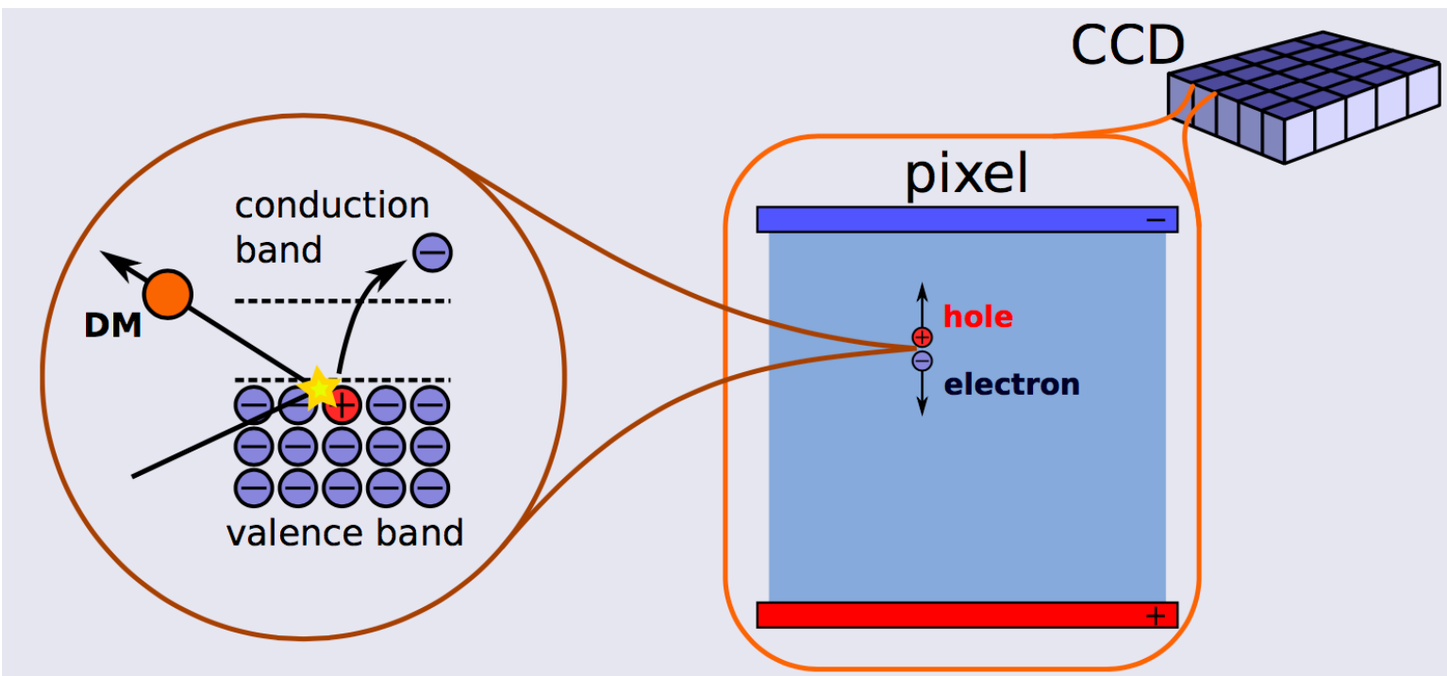

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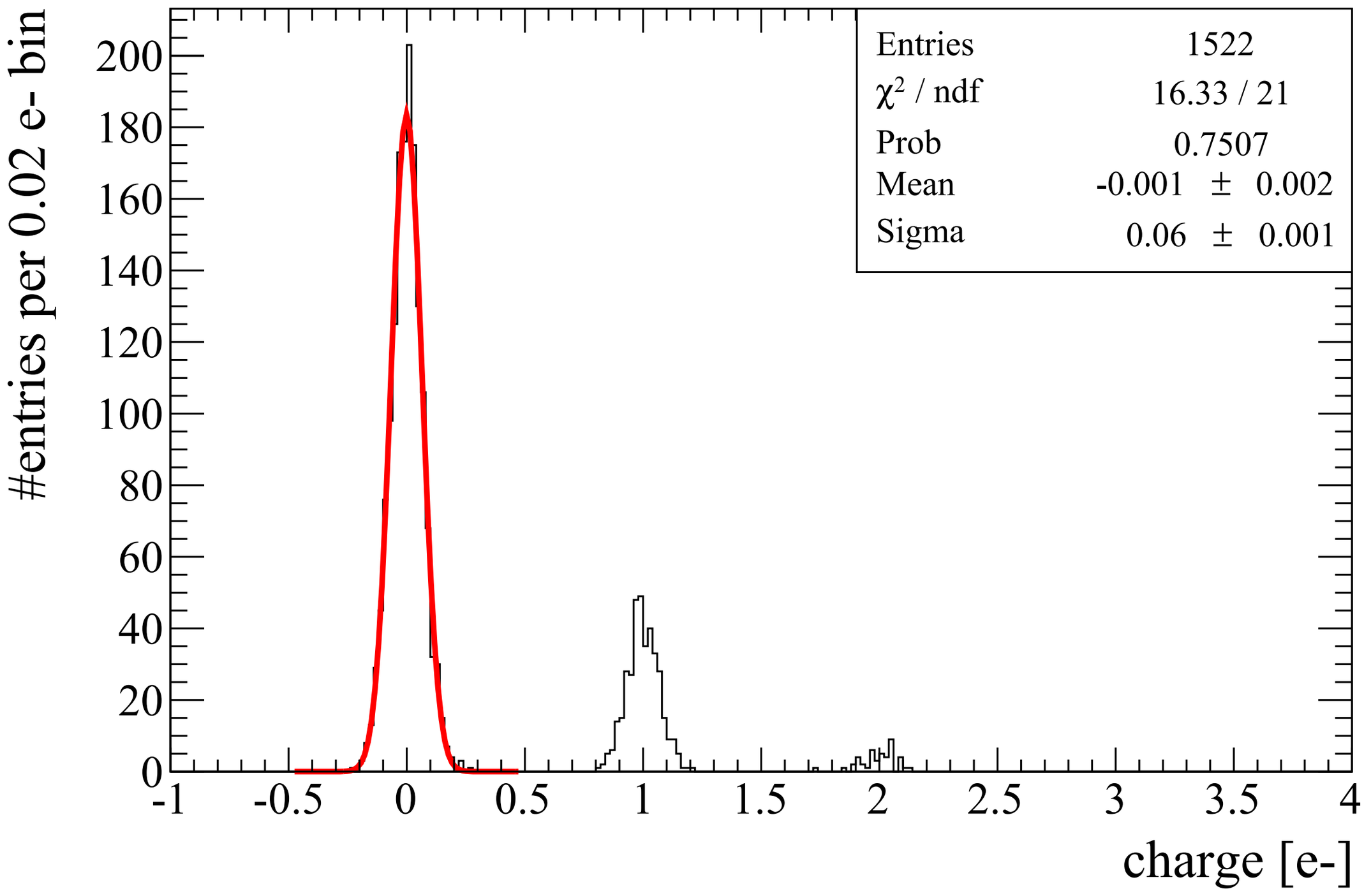
↓

Sensitivity to single electrons!

Counting Electrons



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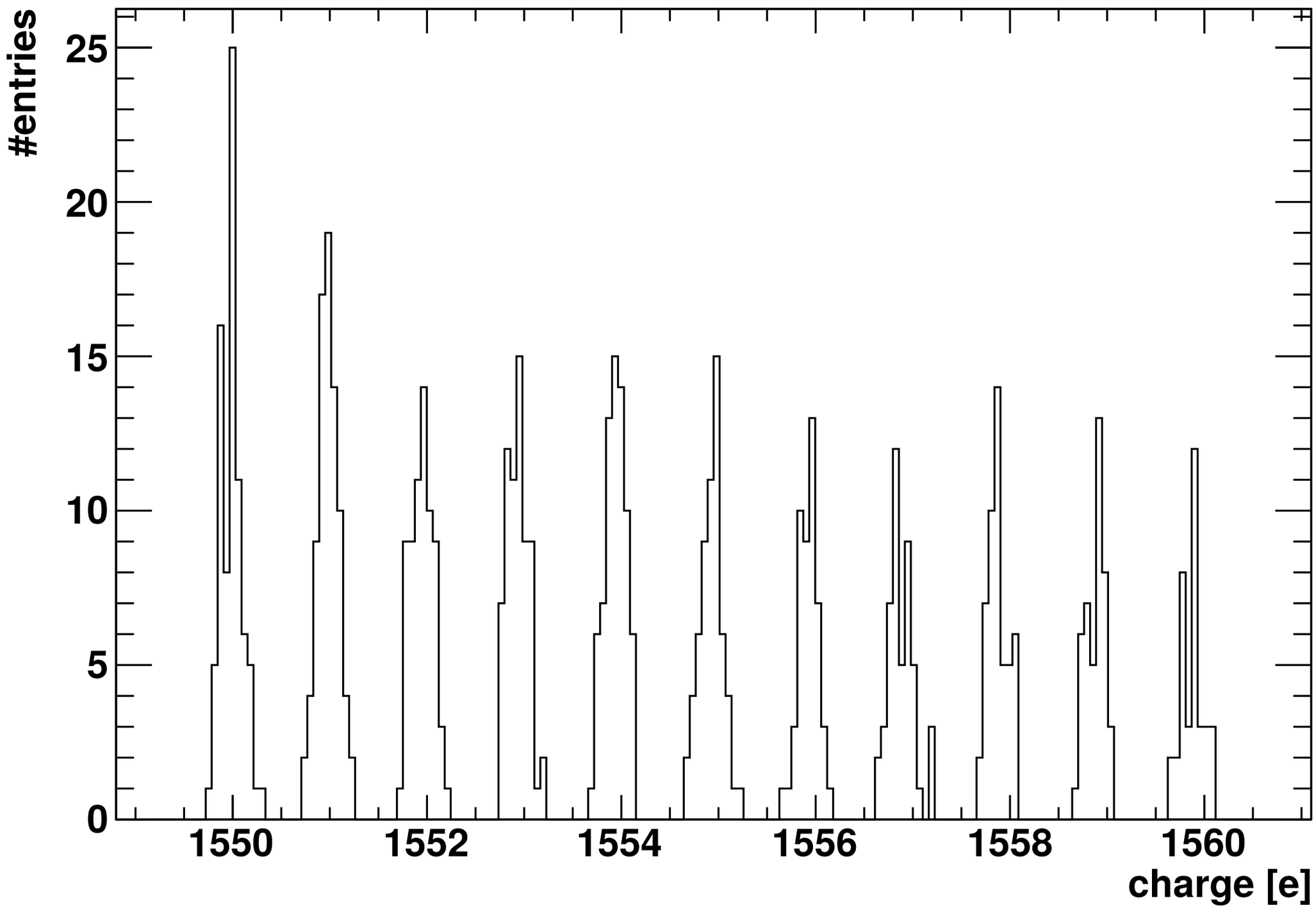

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Sub-Electron-Noise Skipper CCD Experimental Instrument

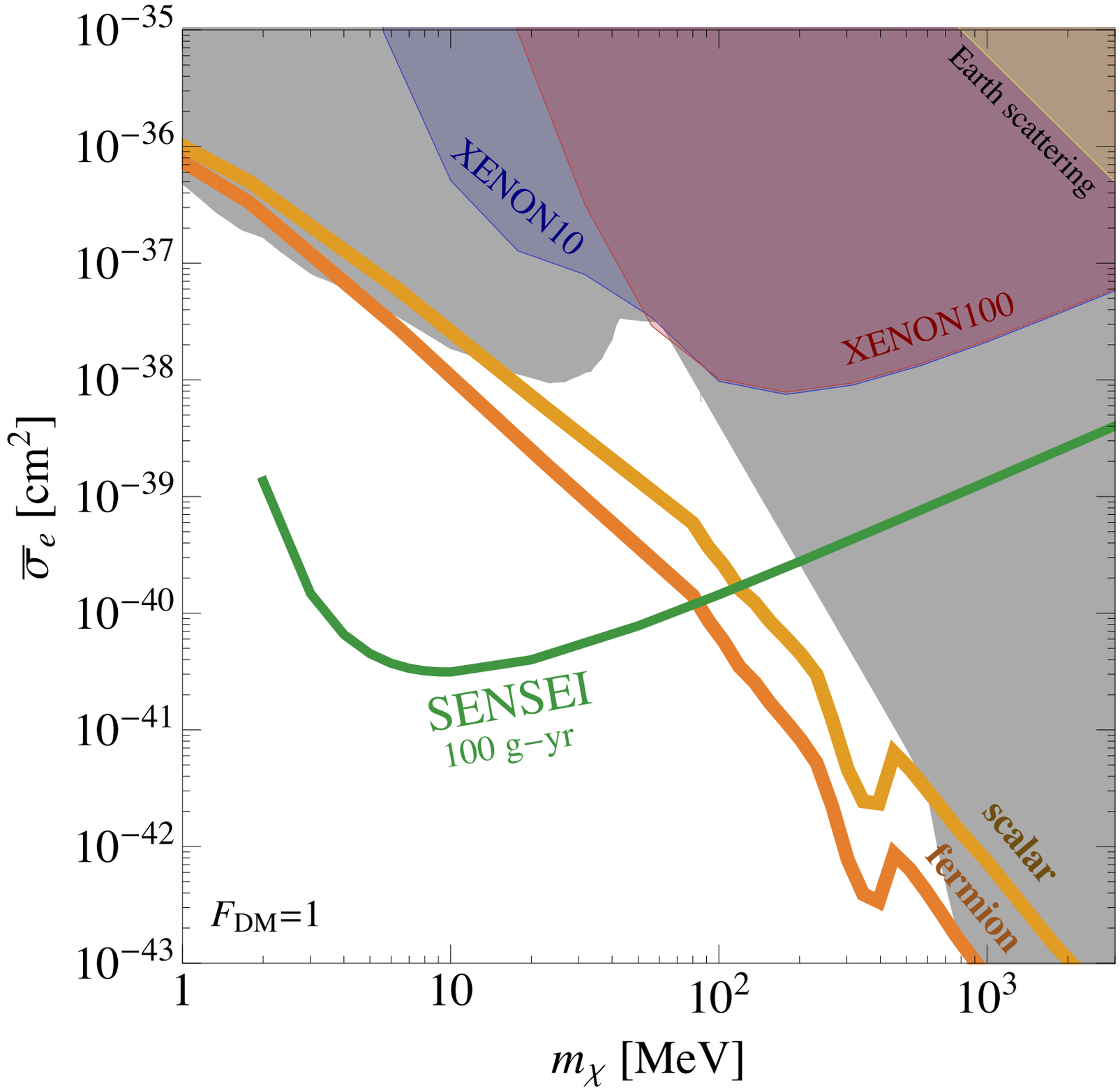
An exciting new detector: SENSEI

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

Sub-Electron-Noise Skipper CCD Experimental Instrument

- 1 gram is being installed in MINOS hall right now — expected to produce non-trivial science result!
- We're developing proposal for a ~100 gram experiment
- ~$1.2 million
- Timescale: if get money, results in <3 years

Prospects for SENSEI-like experiment



expected background is small (<1 event)

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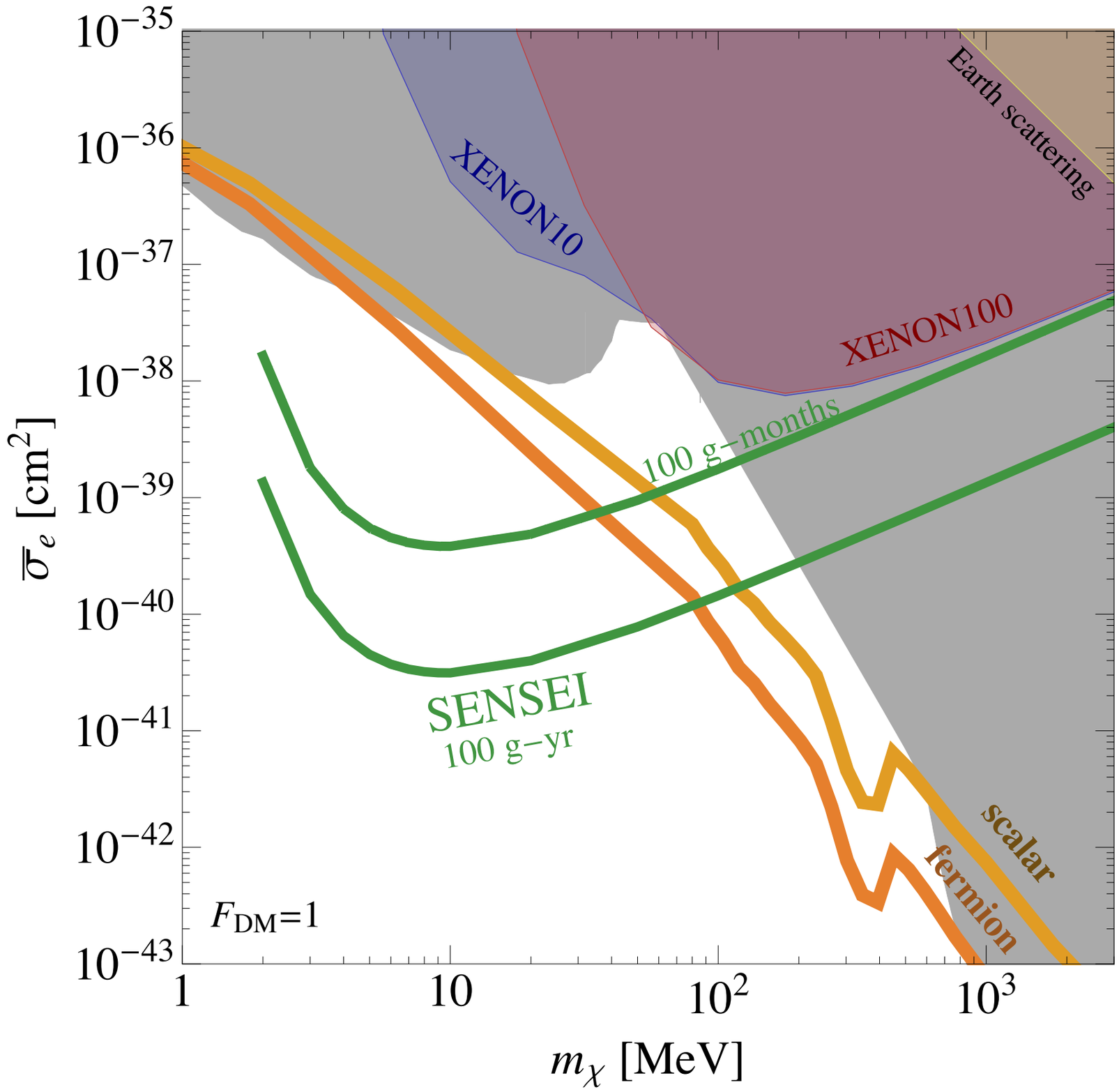

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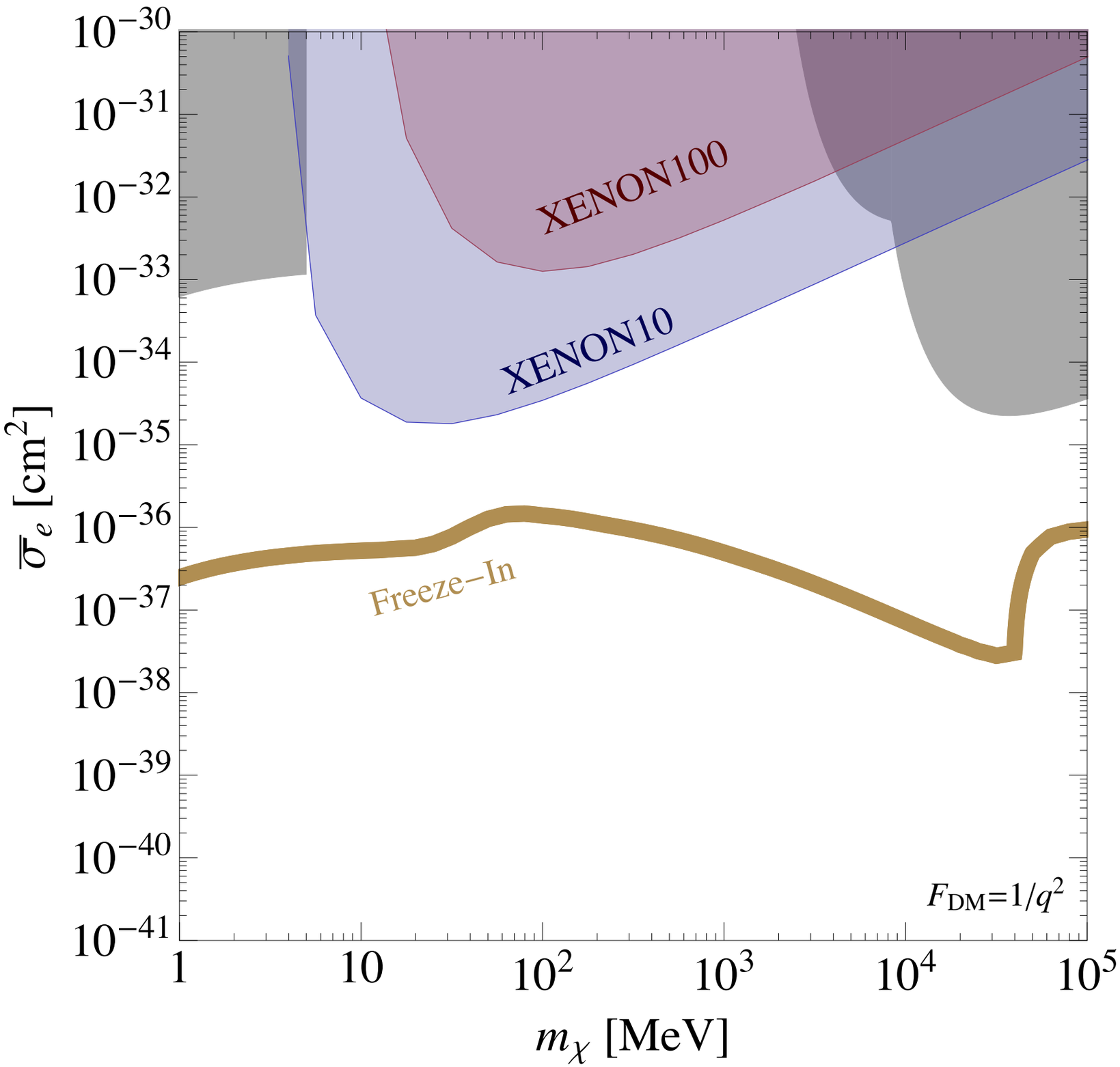
SENSEI can probe other models too!



$m_{A'} \ll 1$ keV

theory target:
"freeze-in"

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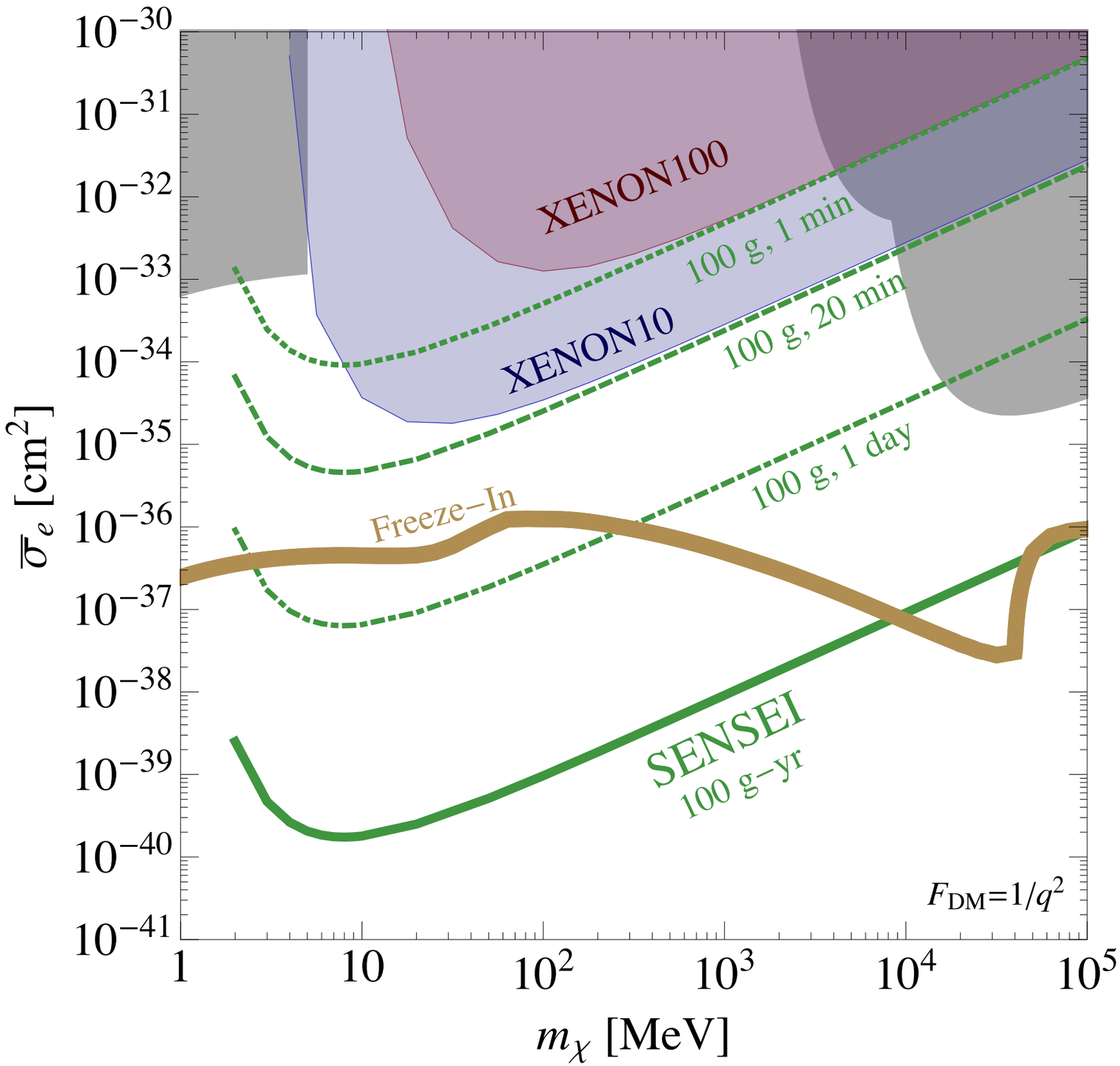

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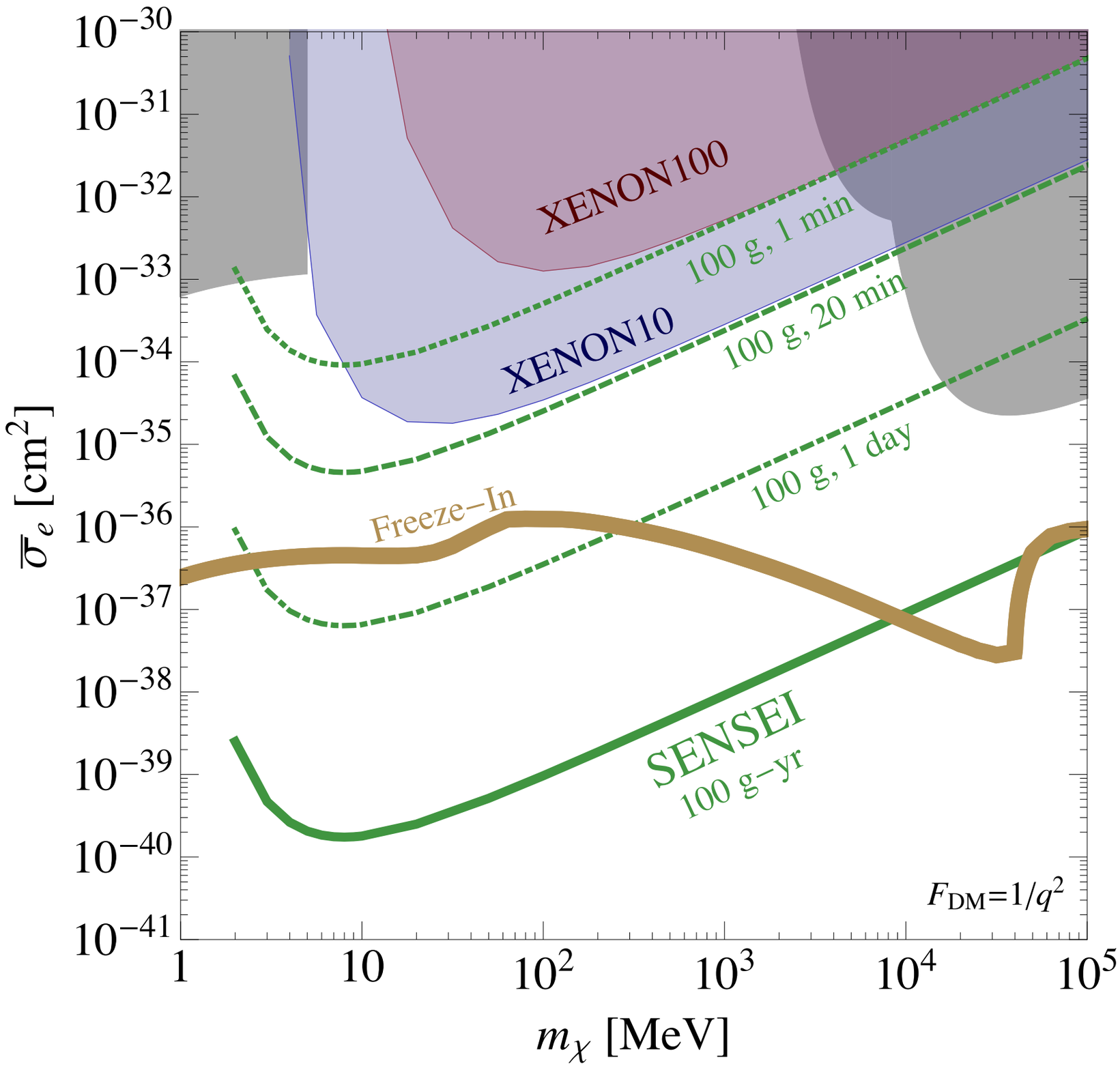

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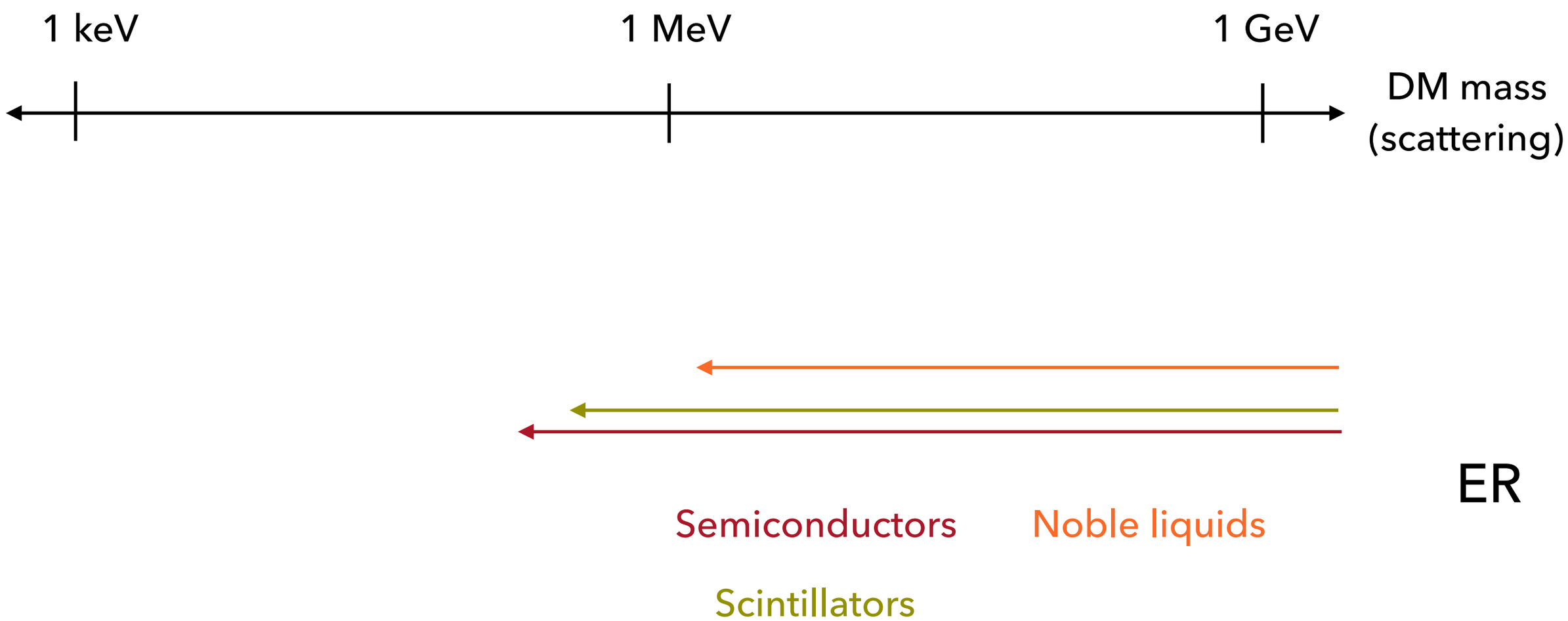
theory target: "freeze-in"

colliders cannot probe this theory target!

Explosion of new direct-detection ideas in last few years



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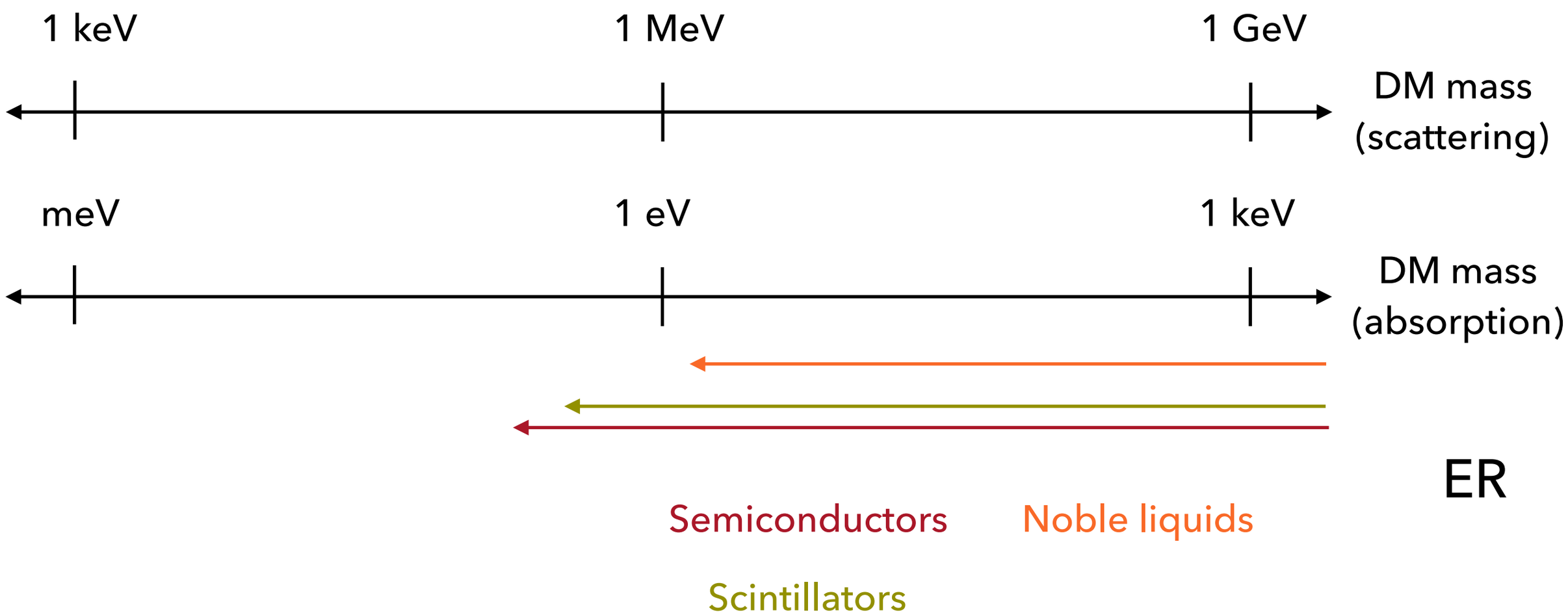

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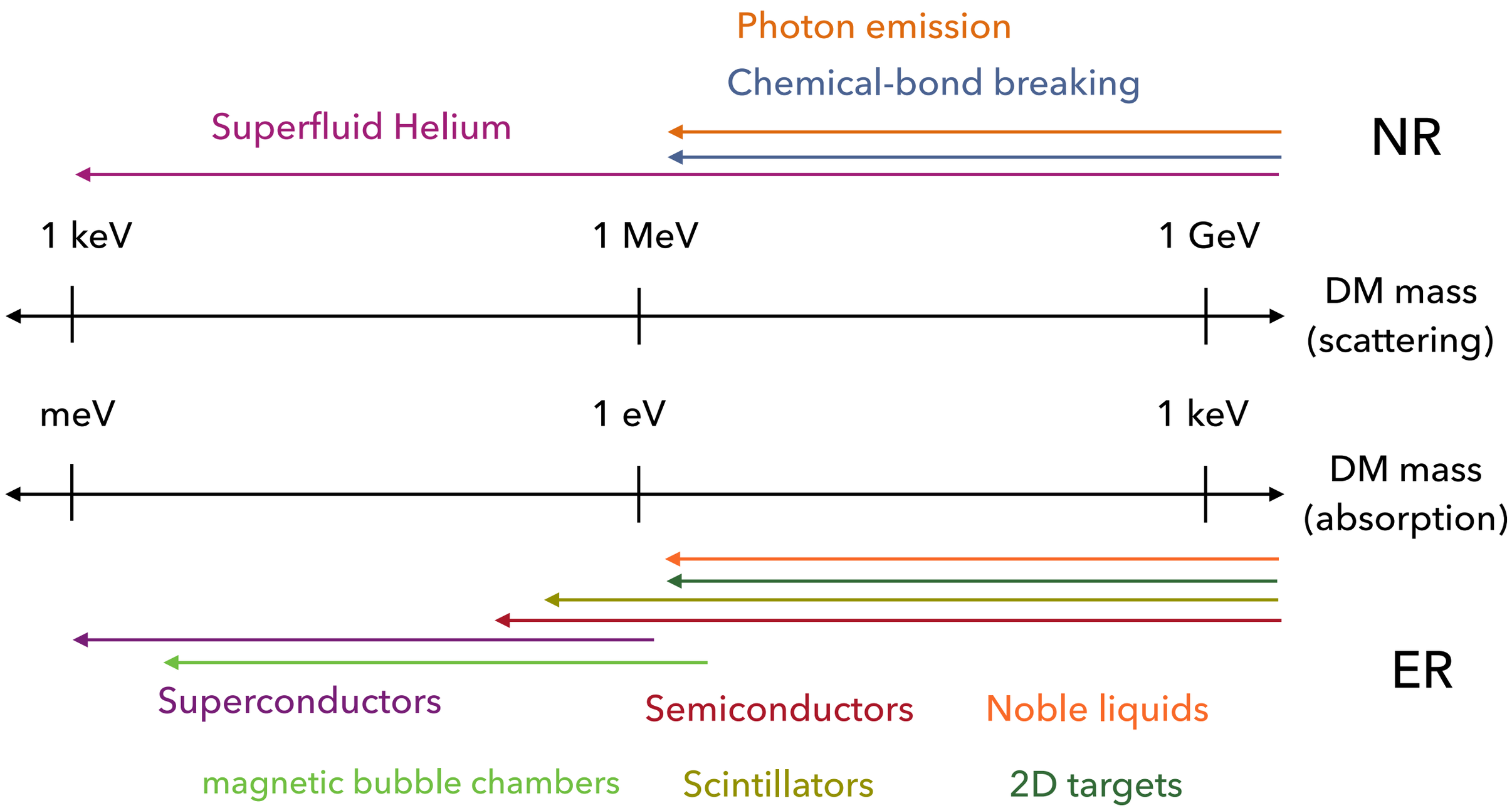

Dark Sectors Report, 1608.08632

Summary

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- Goal: uncover the identity of dark matter!
- A new frontier for experimental exploration: dark matter and new forces at the MeV-to-GeV scale
- Direct detection down to MeV masses is possible!
- Various theory targets can be extensively tested by new direct-detection, colliding-beam, & fixed-target searches in next ~3-10 years

Thank you!

SENSEI: backgrounds?

- readout noise is irrelevant
- Solar neutrinos are irrelevant RE, Sholapurkar, Yu (in progress)
- Radiogenic backgrounds <1 event in relevant energy range
  (based on projections for measured values at O(50 eV))
- threshold likely limited by dark currents to 2 or 3 e^-

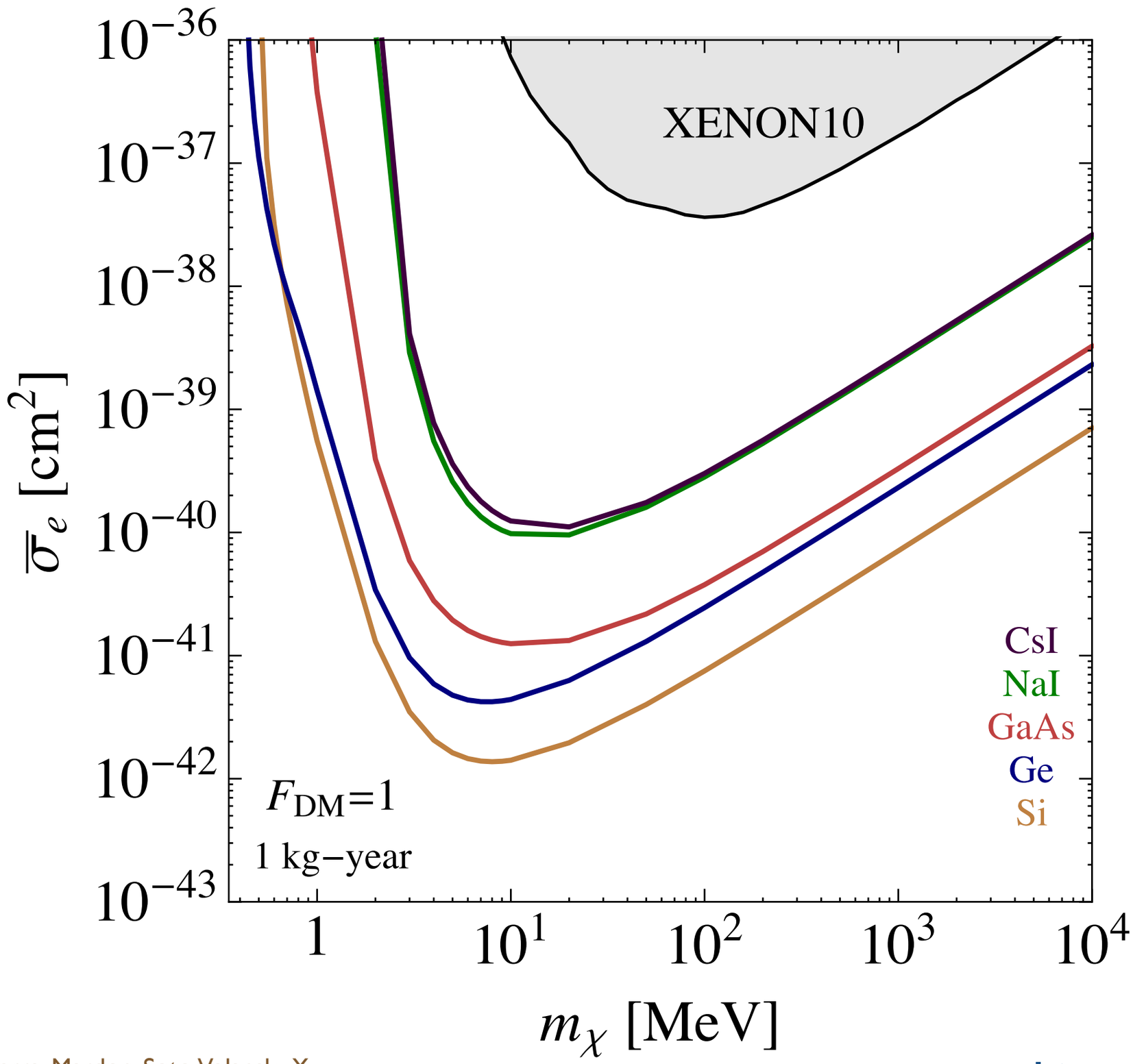
4k x 4k = 16 million pix CCD, readout time ~1 hour

	Number of DC events (100 g y)	
Q_{th}	$DC = 1 \times 10^{-3}$ e pix^{-1}day^{-1}	$DC = 10^{-7}$ e pix^{-1}day^{-1}
1	1×10^{8}	1×10^{4}
2	2×10^{4}	2×10^{-5}
3	3×10^{-2}	3×10^{-14}

J. Tiffenberg

(measured upper limit) (theoretical expectation)

Prospects?



solid:
$\geq 1\gamma$ or $1e^-$

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
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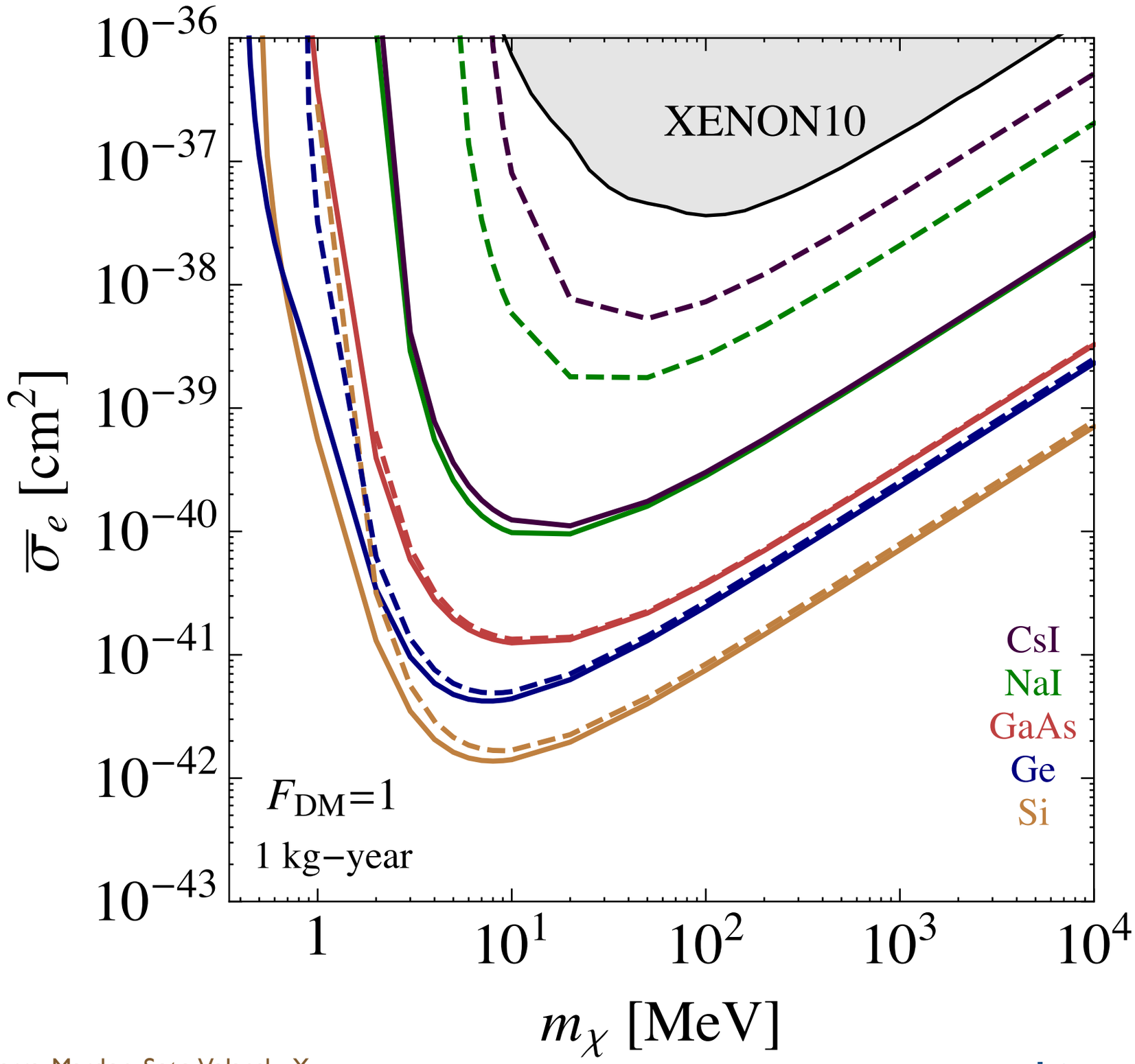
Lines assume 3 events

Prospects?



solid:
$\geq 1\gamma$ or $1e^-$

dashed:
$\geq 2\gamma$ or $2e^-$

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Derenzo, RE, Massari, Soto, Yu

Lines assume 3 events

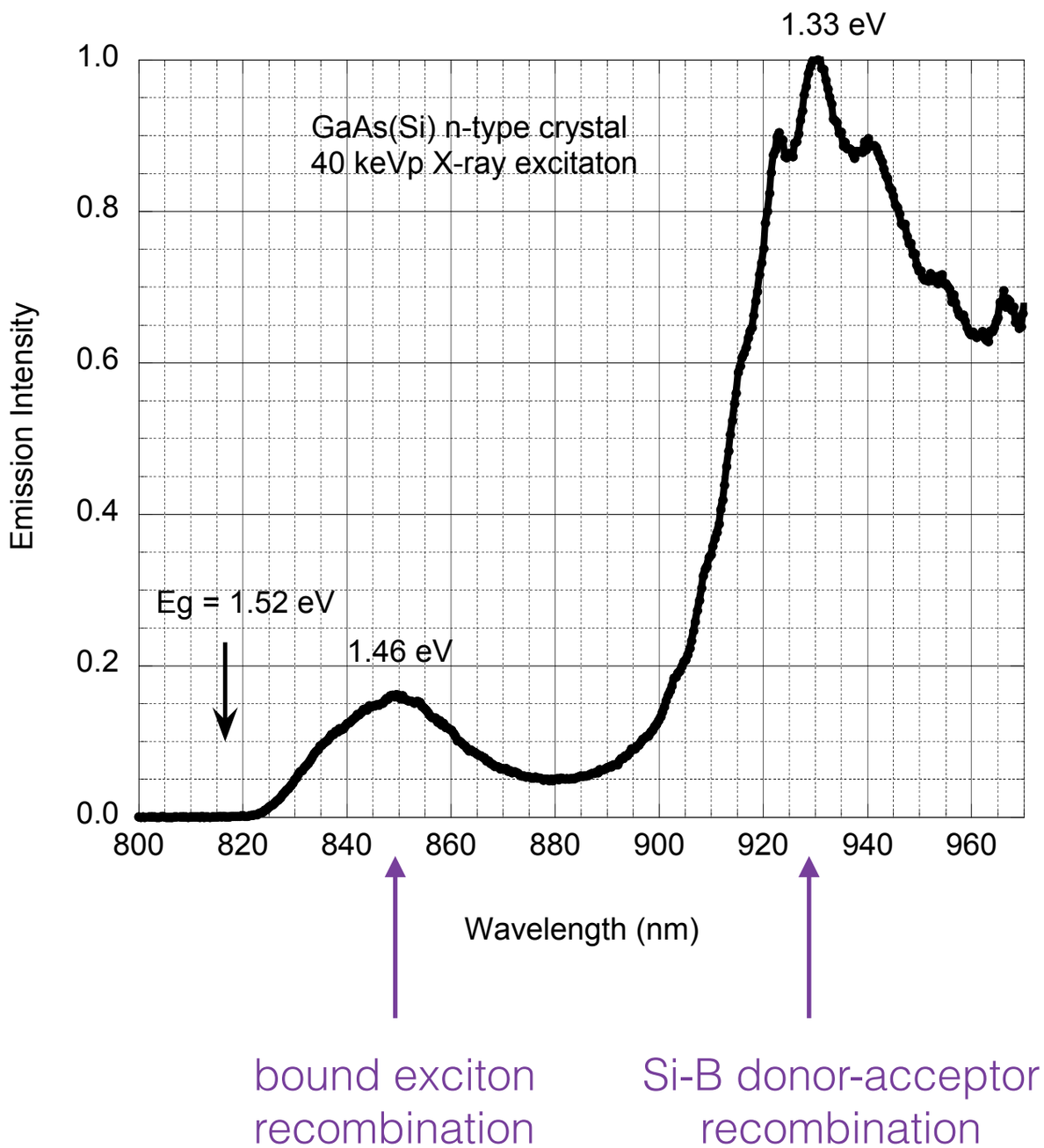
Scintillators

Derenzo, RE, Massari, Soto, Yu

- Challenges:
  - need photodetectors w/ high detection efficiency & low backgrounds
    - R&D based on SuperCDMS TES technology by M. Pyle et al. (requires cryogenic scintillator!)
  - need scintillator with low band gap, high purity, & high "radiative efficiency"
    - GaAs(Si,B) is an excellent candidate
  - Afterglow?
    - GaAs(Si,B) seems to have no afterglow!
- More R&D required, but very promising!

GaAs doped w/ Si & B as a scintillator target

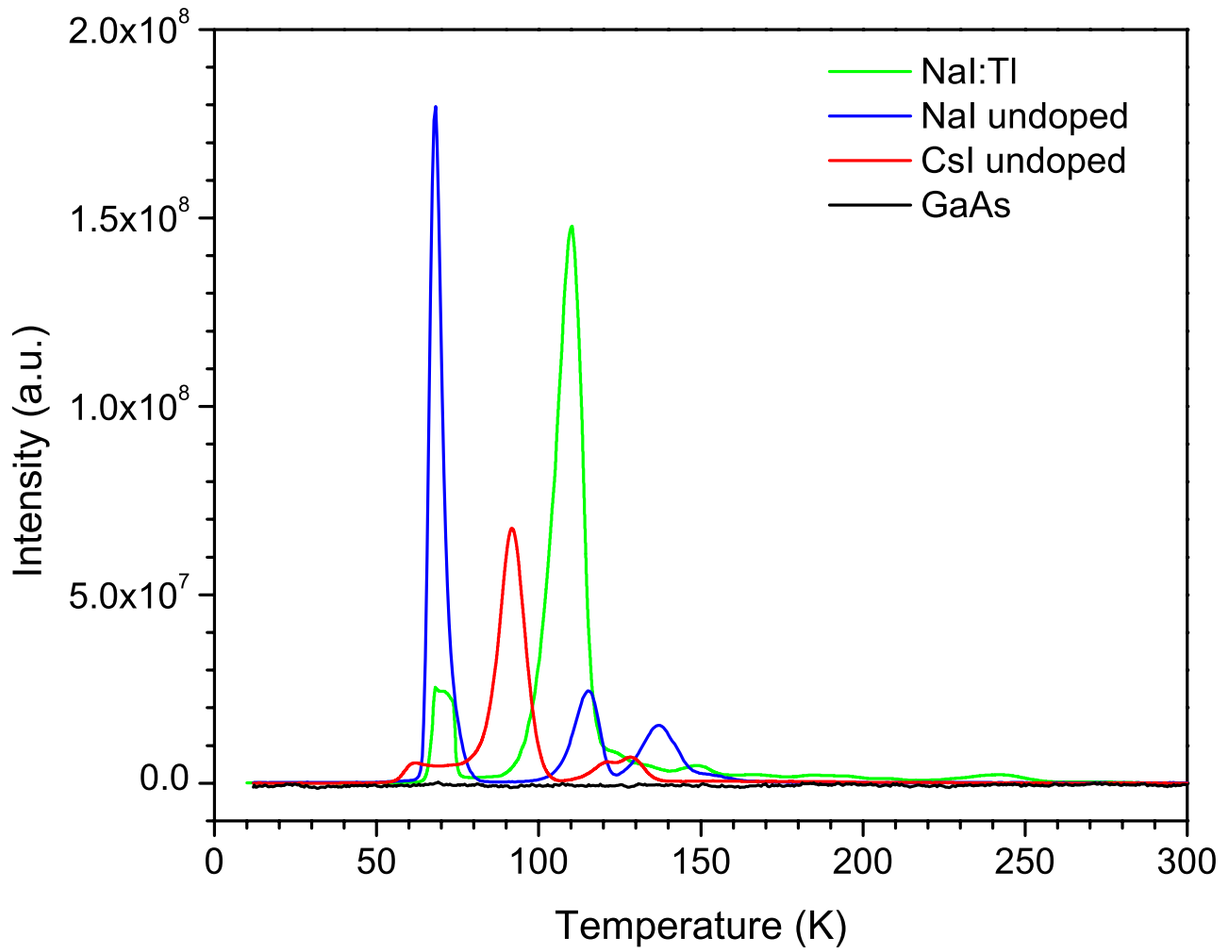
work by Stephen Derenzo & LBNL scintillator group

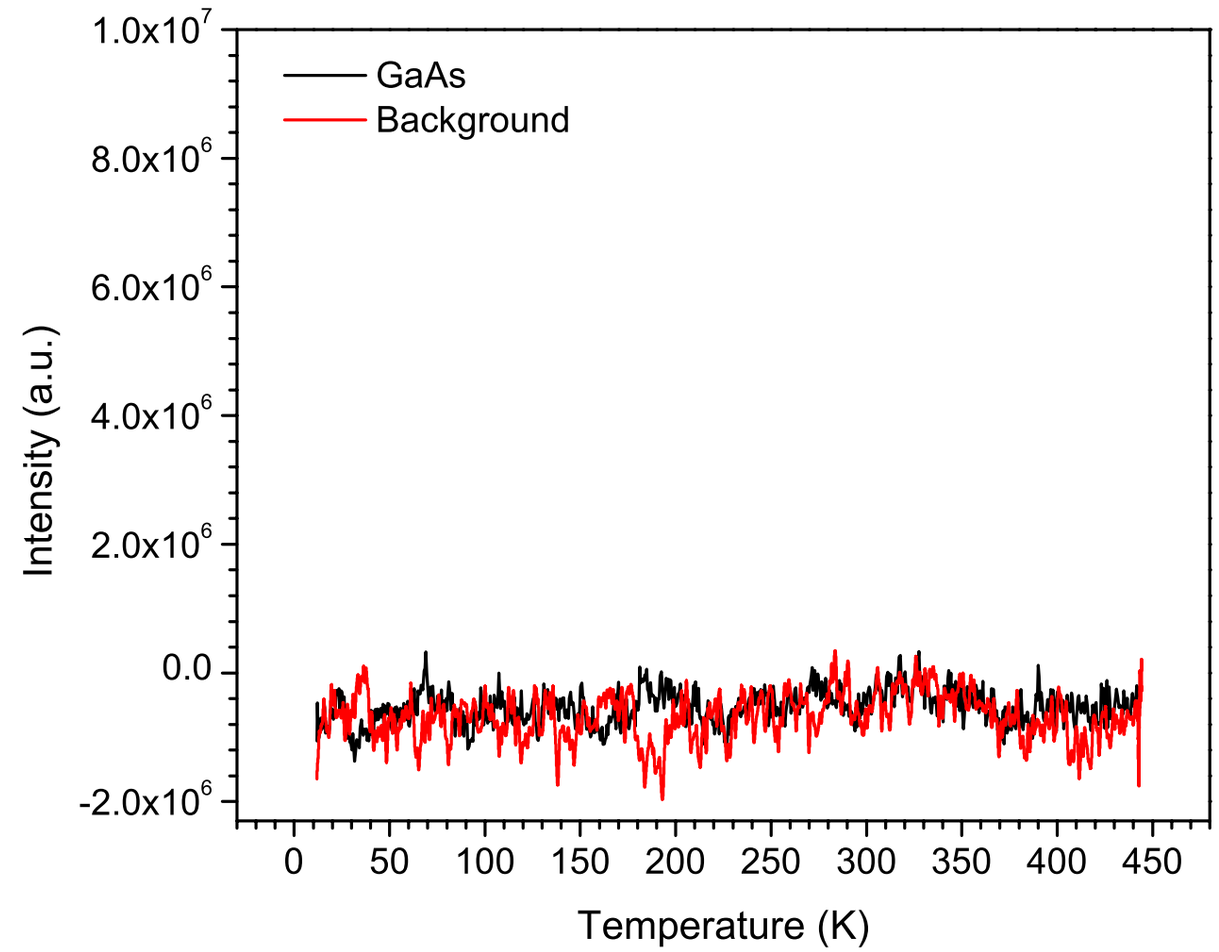


- good QE for energy transfers down to E_{gap}
- emission peaks at 1.46 & 1.33 eV
- Si, B doping is essential for cryogenic scintillation
- luminosity ~ 30 γ/keV (like LXe)

No apparent afterglow in GaAs(Si,B)!

work by Stephen Derenzo & LBNL scintillator group





- irradiate sample w/ x-rays 50 keVp at 10 K for 30 min
- turn off beam, increase temperature over 1 hr, record emission
- GaAs shows no metastable radiative traps (unlike NaI, CsI)