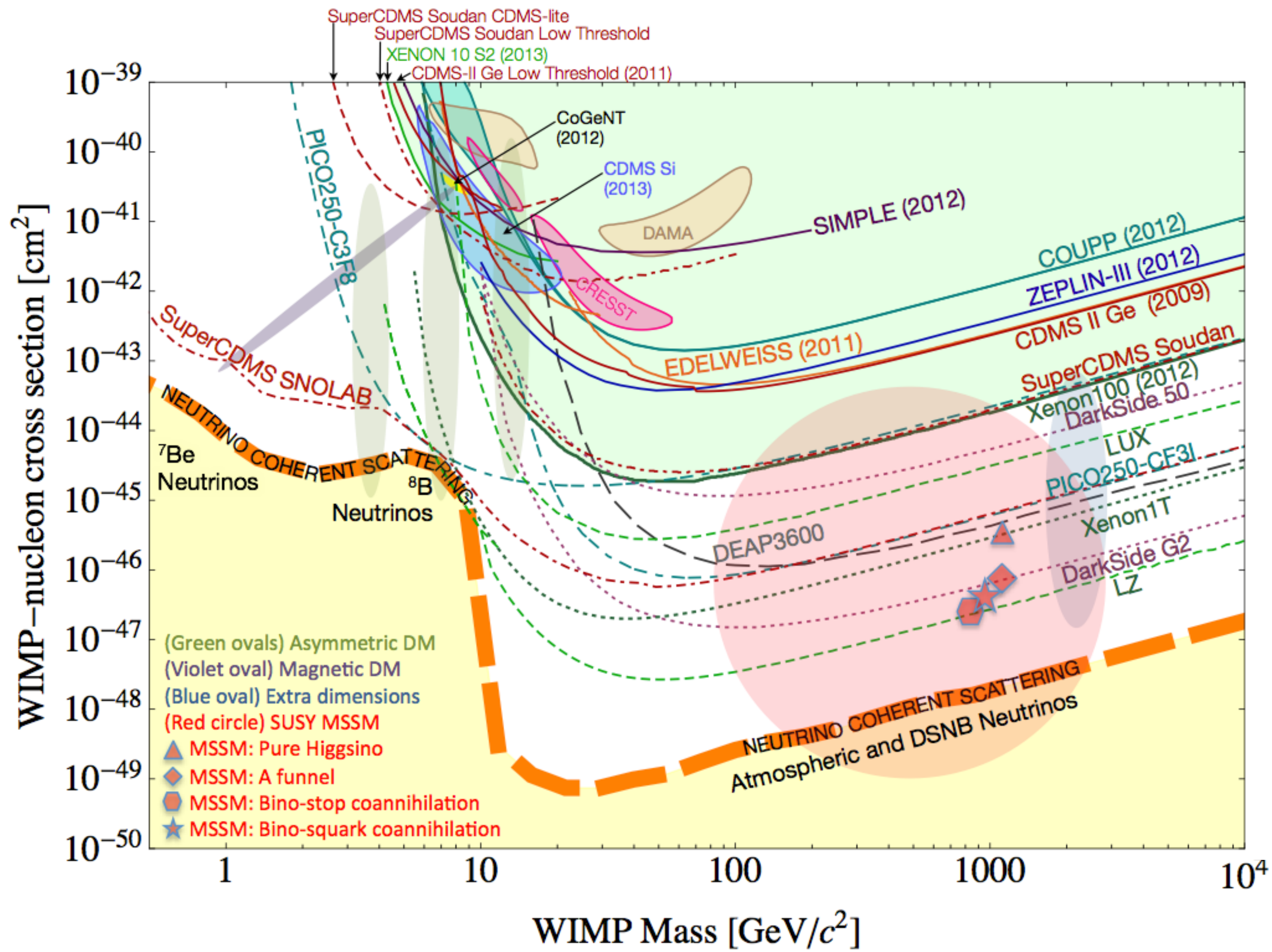
Direct Detection of sub-GeV Dark Matter

Rouven Essig

Yang Institute for Theoretical Physics

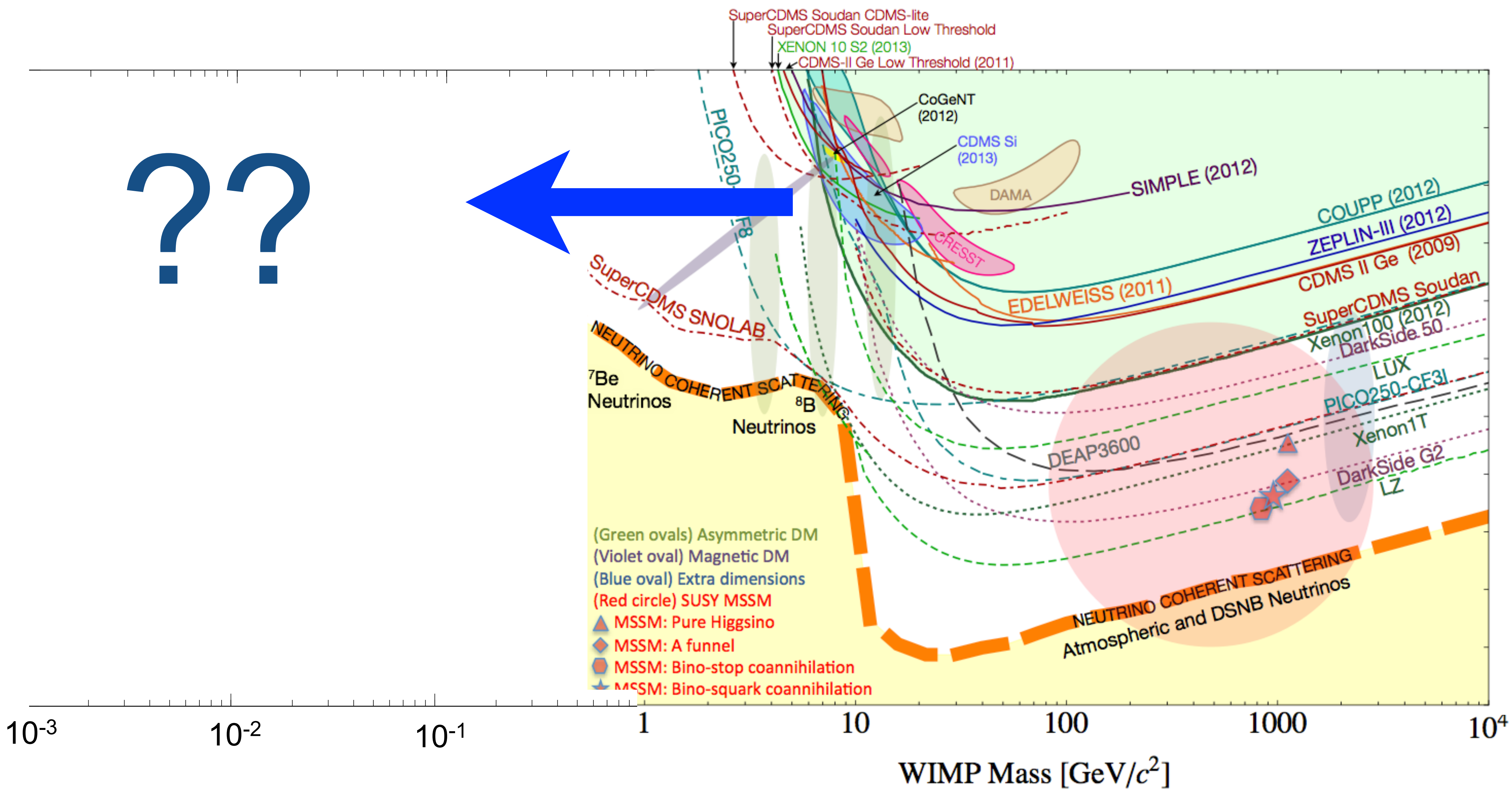
Stony Brook University

Direct Detection Landscape



1310.8327

The WIMP program is active, important, and exciting!

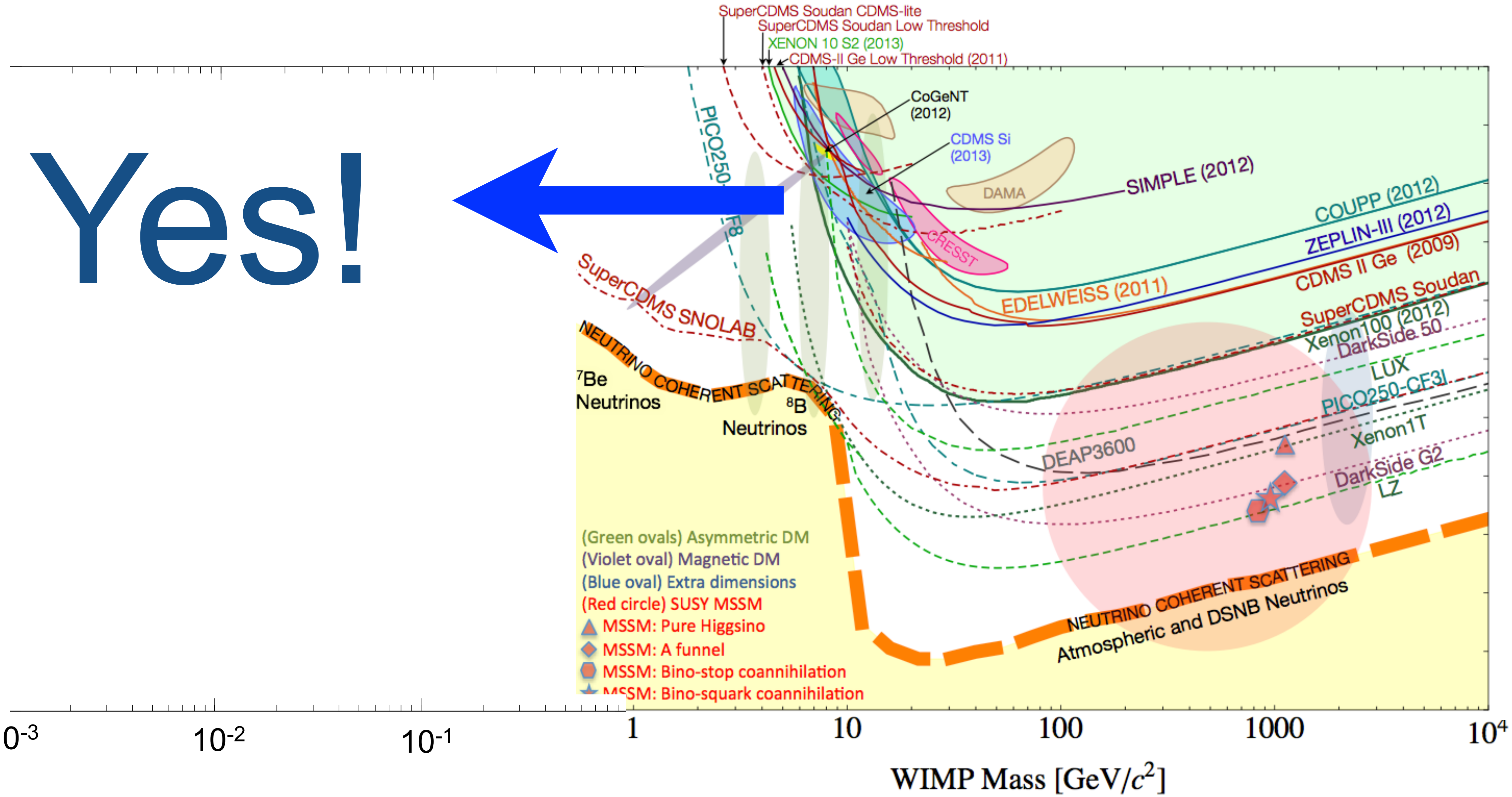


??
SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
PICO250-C3F8
SuperCDMS SNOLAB
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DEAP3600
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
10^{-3}
10^{-2}
10^{-1}
1
10
100
1000
10^4
WIMP Mass [GeV/c^2]

Take-away message:

- DD constraints exist to m_{DM}~5 MeV
- significant improvements in ~2-3 years
- probe simple & predictive benchmark models

Yes!



Collaborators

Theorists:

- Tomer Volansky (Tel-Aviv), Jeremy Mardon
- Tien-Tien Yu (CERN)
- Marivi Fernandez-Serra, Adrian Soto (SBU, condensed matter theory)
- Jeremy Chang, Andrea Massari, Mukul Sholapurkar, Xuanhua Wang, Yiming Zhong (SBU students)
- Sam McDermott (SBU postdoc)
- Oren Slone, Itay Bloch, Tobioka Kohsaku (Tel-Aviv)

Experimentalists

- Aaron Manalaysay, Peter Sorensen (xenon)
- Javier Tiffenberg, Juan Estrada, Stephen Holland, Christopher Bebek, Miguel Sofo Haro (SENSEI)
- Stephen Derenzo, Matt Pyle (scintillators)

An ongoing program

- “Direct Detection of sub-GeV Dark Matter”, 1108.5383, PRD
  RE, Mardon, Volansky
- “First Direct Detection Limits on sub-GeV Dark Matter from XENON10”, 1206.2644, PRL
  RE, Manalaysay, Mardon, Sorensen, Volansky
- “Direct Detection of sub-GeV Dark Matter with Semiconductor Targets”, 1509.01598, JHEP
  RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
- “Direct Detection of sub-GeV Dark Matter with Scintillating Targets”, 1607.01009;
  Derenzo, RE, Massari, Soto, Yu
- “Detection of sub-GeV DM and Solar ν’s via Chemical-Bond Breaking”, 1608.02940, PRD
  RE, Mardon, Slone, Volansky
- “Searching for Dark Absorption with Direct Detection Experiments”, 1608.02123;
  Bloch, RE, Tobioka, Volansky, Yu
- “New Constraints & Prospects for sub-GeV DM Scattering off Electrons in Xenon”, 1703.00910;
  RE, Volansky, Yu

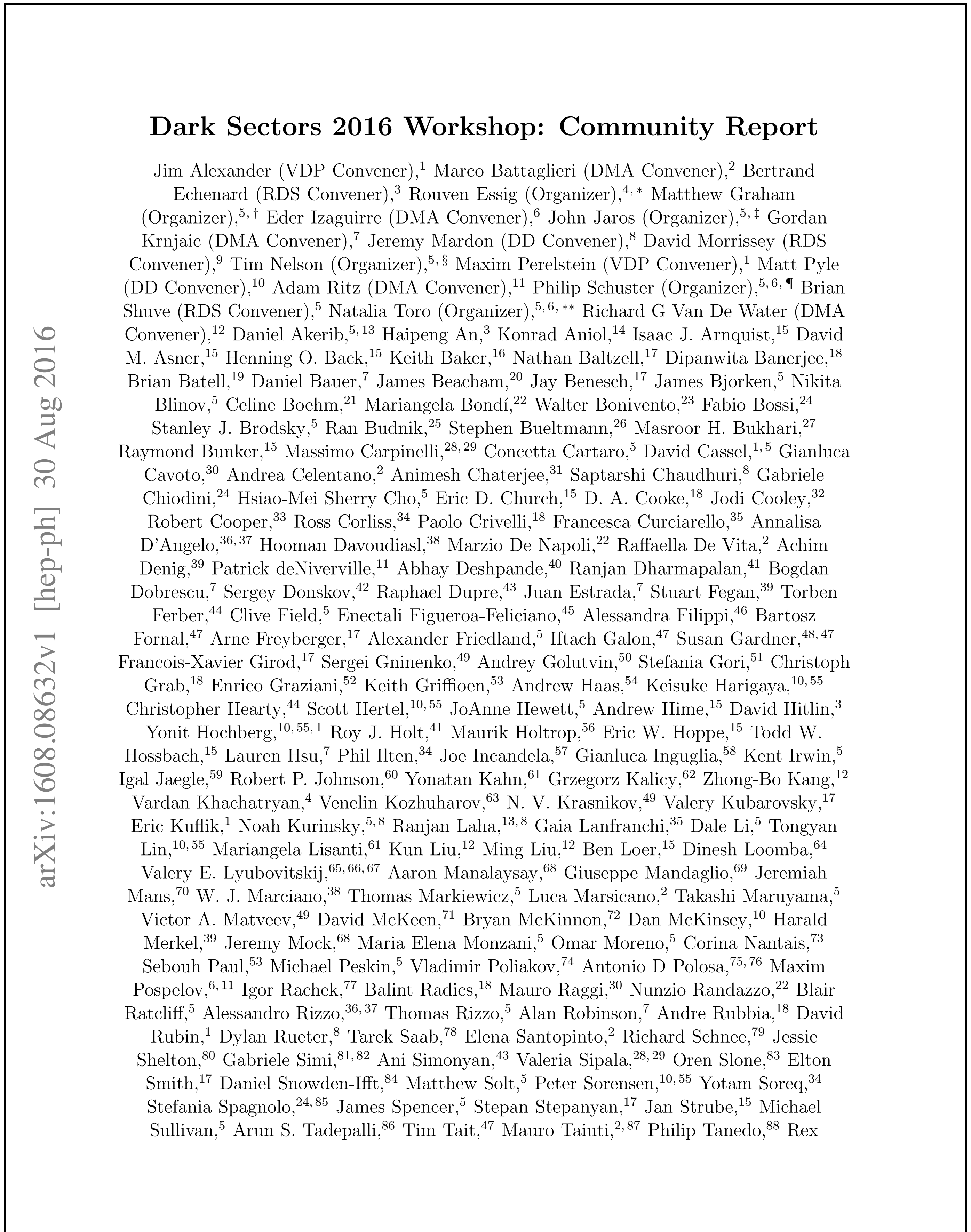
+ several works in progress

Related work

- Graham, Kaplan, Rajendran, Walters, "Semiconductor Probes of Light Dark Matter", 1203.2531
- An, Pospelov, Pradler, "Dark Matter Detectors as Dark Photon Helioscopes", 1304.3461
- An, Pospelov, Pradler, Ritz, "Direct Detection Constraints on Dark Photon Dark Matter", 1412.8378
- Hochberg, Zhao, Zurek, "Superconducting Detectors for Super Light Dark Matter", 1504.07237
- Lee, Lisanti, Mishra-Sharma, Safdi, "Modulation Effects in DM-Electron Scattering Experiments", 1508.07361
- Hochberg, Pyle, Zhao, Zurek, "Superconducting Detectors for Super Light Dark Matter", 1504.07237
- Dzuba, Flambaum, Pospelov, Roberts, Stadnik, "DM scattering on electrons: Accurate calculations…", 1604.04559
- Hochberg, Lin, Zurek, "Detecting Ultralight Bosonic Dark Matter via Absorption in Superconductors", 1604.06800
- Schutz, Zurek, "On the Detectability of Light Dark Matter with Superfluid Helium", 1604.08206
- Hochberg, Kahn, Lisanti, Tully, Zurek, "Directional Detection of Dark Matter with 2D Targets", 1606.08849
- Hochberg, Lin, Zurek, "Absorption of light dark matter in semiconductors", 1608.01994
- Knapen, Lin, Zurek, "Light DM in Superfluid Helium: Detection with Multi-excitation Production", 1611.06228
- Bunting, Gratta, Melia, Rajendran, "Magnetic Bubble Chambers and Sub-GeV Dark Matter Direct Detection", 1701.06566
- Sorensen, "Electron train backgrounds in liquid Xe DM search detectors are indeed due to thermalization & trapping", 1702.04805

for DD review/overview, see
Dark Sectors 2016 Workshop: Community Report
1608.08632
written by RE, J. Mardon, M. Pyle w/ input from others

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
- low-energy colliders
- fixed target

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

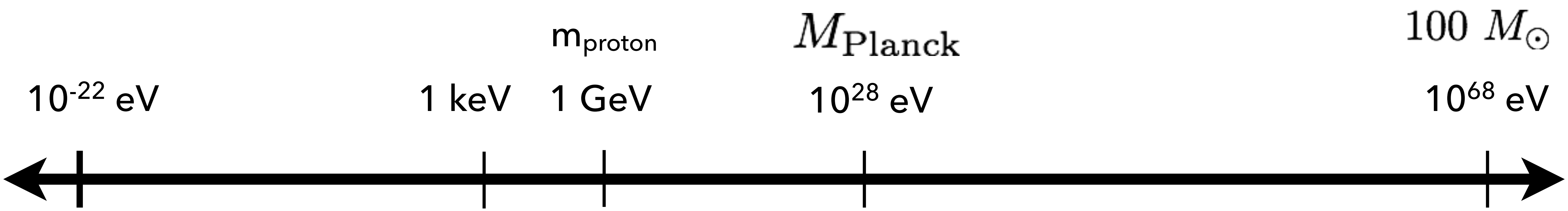
Search

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)

A possible opportunity to obtain funding for new small experiments

white paper to appear in O(1) month

The Dark Matter Landscape

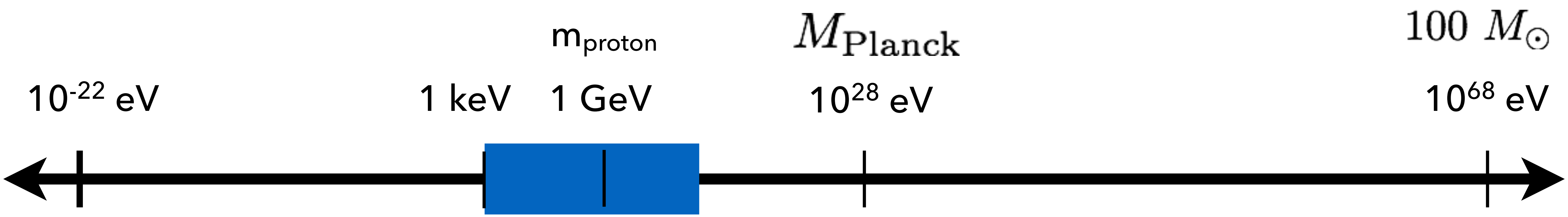


Where look for DM?

$\Longrightarrow$ target motivated areas

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

The Dark Matter Landscape



thermal DM

~1 keV to 100 TeV

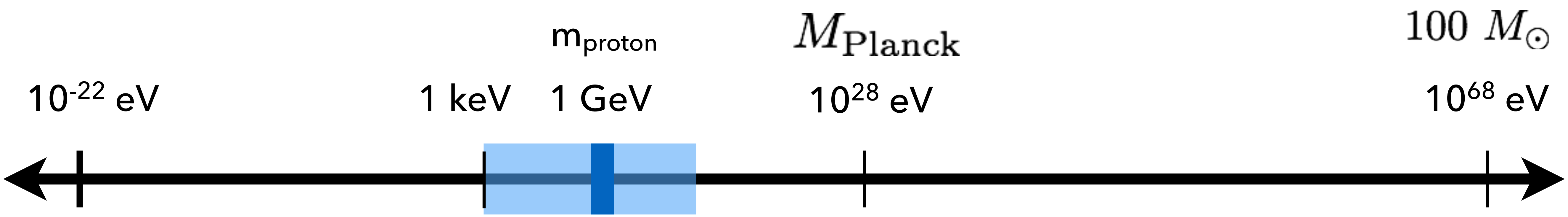
$$m_{\rm DM} \gtrsim 1\ \text{keV}$$

otherwise, no structure smaller than dwarf galaxies

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

otherwise, too much dark matter

The Dark Matter Landscape



asymmetric DM

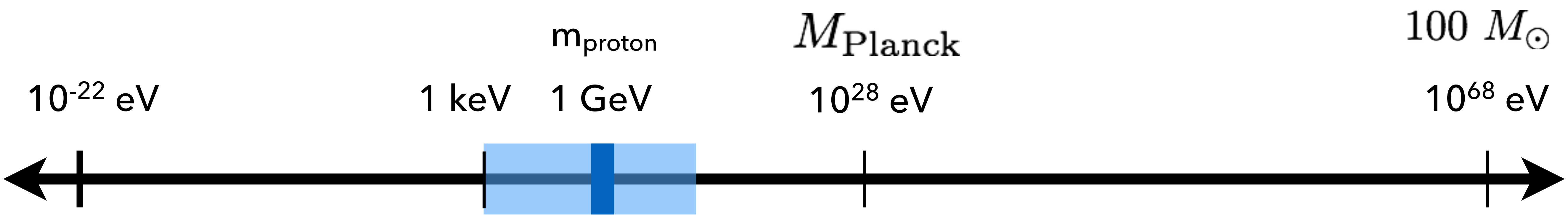
Kaplan, Luty, Zurek

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

from a baryon asymmetry!

$m_X \sim O(5$ GeV), but could be 1 keV to 10 TeV

The Dark Matter Landscape



asymmetric DM

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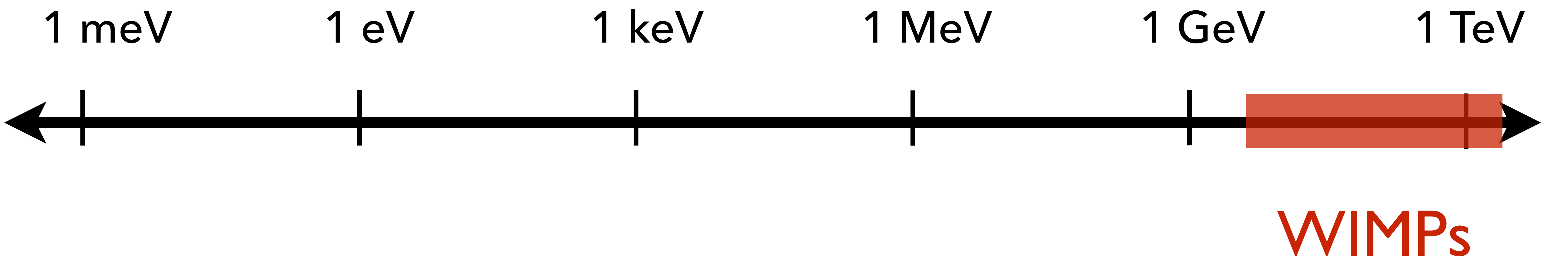
Why is $\Omega_{\rm DM} \sim 5\ \Omega_B$?

from a baryon asymmetry!

m_X~O(5 GeV), but could be 1 keV to 10 TeV

(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



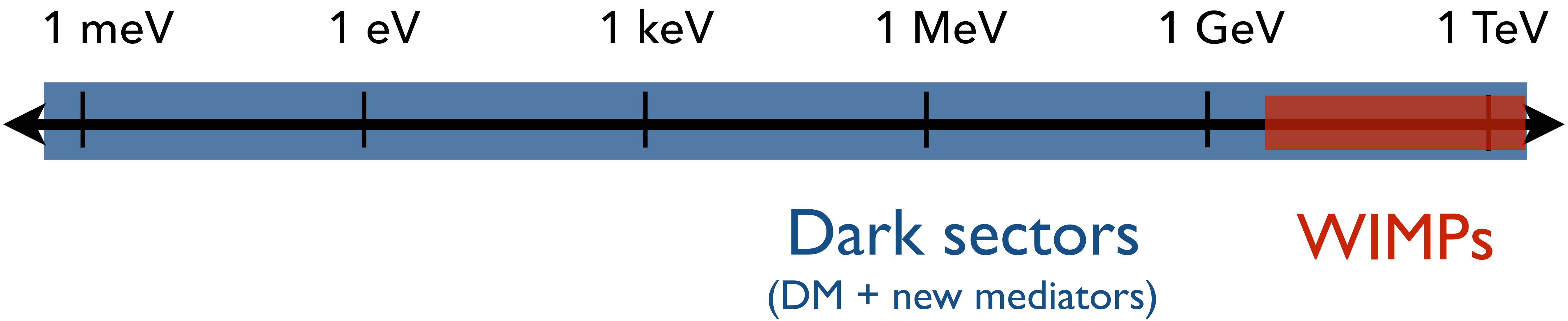
WIMPs are great candidates!

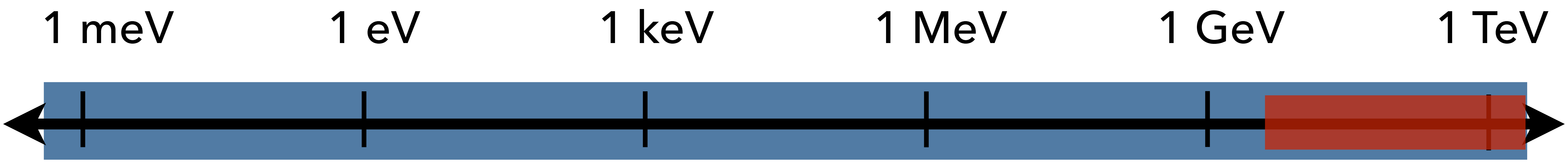
WIMPs are great candidates!

But…

- no convincing evidence for WIMPs (yet)
- no new physics at LHC (yet)
- "small-scale crisis" of cold DM
  (self-interactions through a new force?)

see Kaplinghat's RPM last week


1 meV
1 eV
1 keV
1 MeV
1 GeV
1 TeV
Dark sectors
(DM + new mediators)
WIMPs



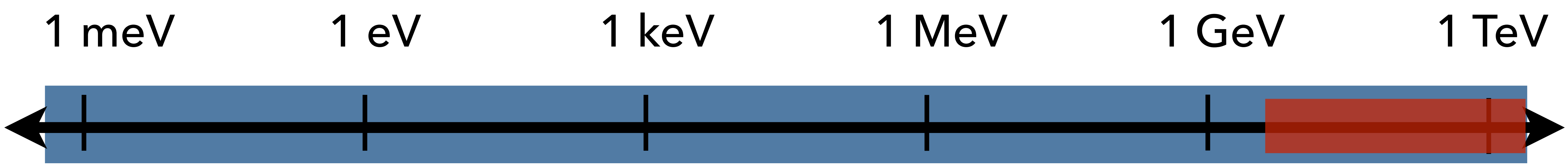
Dark sectors

(DM + new mediators)

WIMPs

several sharp “theory” targets

(freeze-out, asymmetric, freeze-in, SIMP, ELDER)



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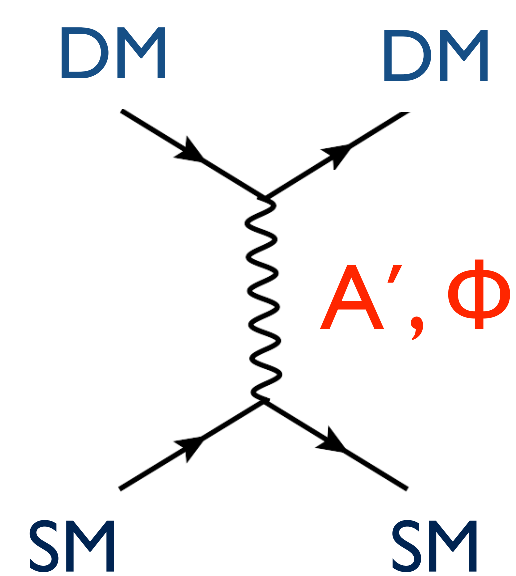
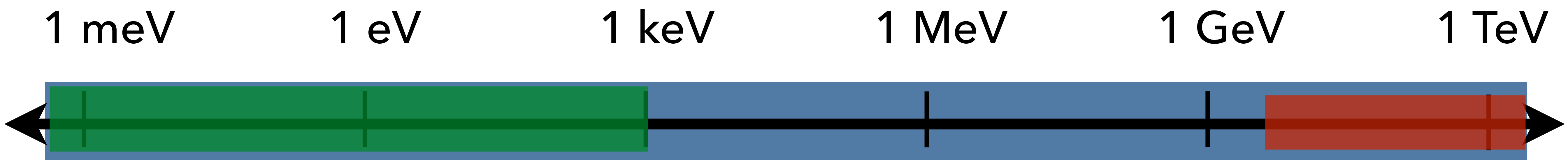


DM scattering



Bosonic DM

scalar, pseudoscalar,
vector DM

Dark sectors

(DM + new mediators)

WIMPs

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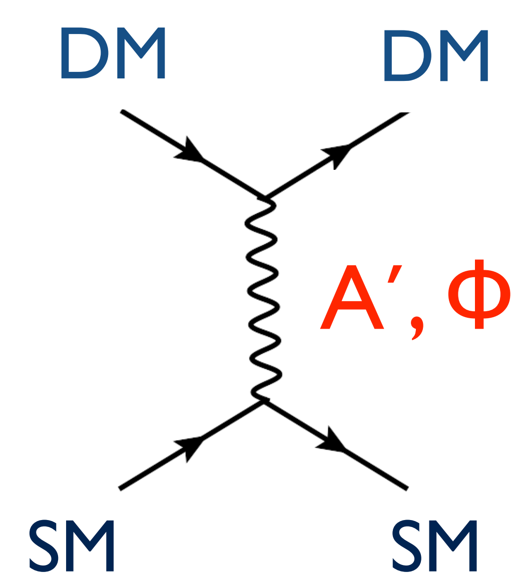
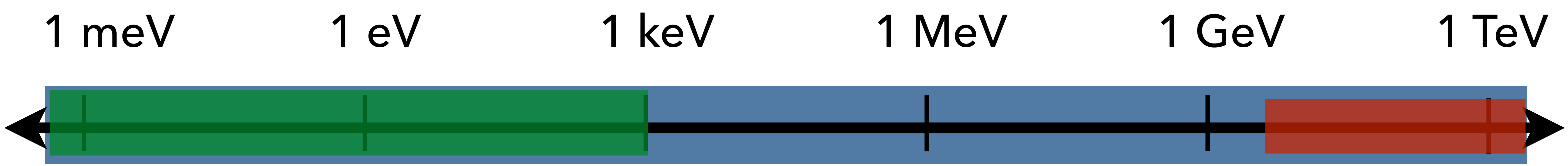
(freeze-out, asymmetric, freeze-in, SIMP, ELDER)



DM scattering



Bosonic DM

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scalar, pseudoscalar, vector DM

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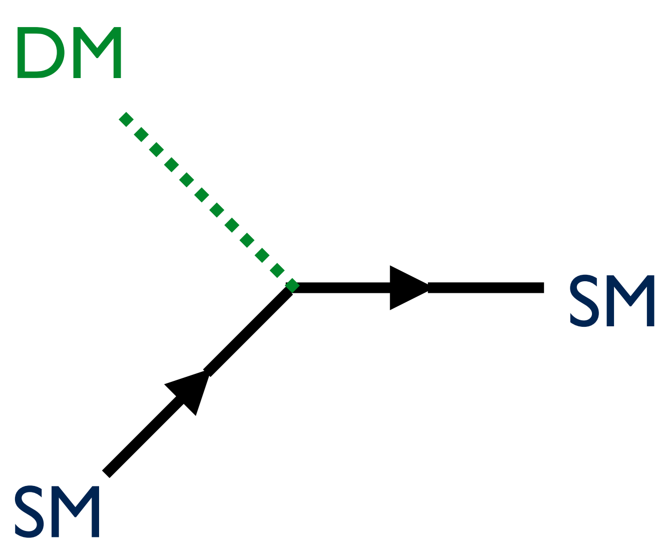
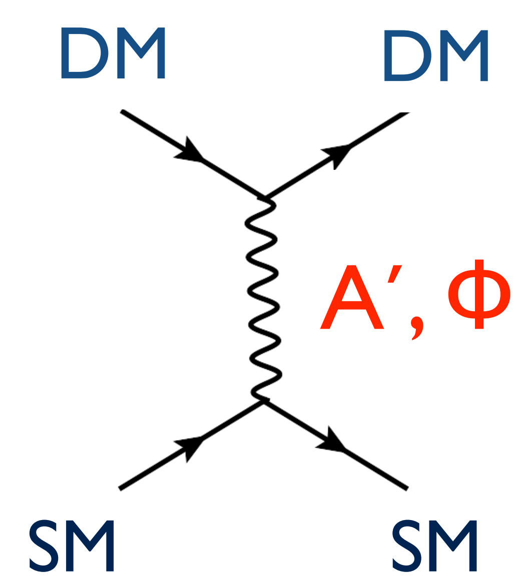
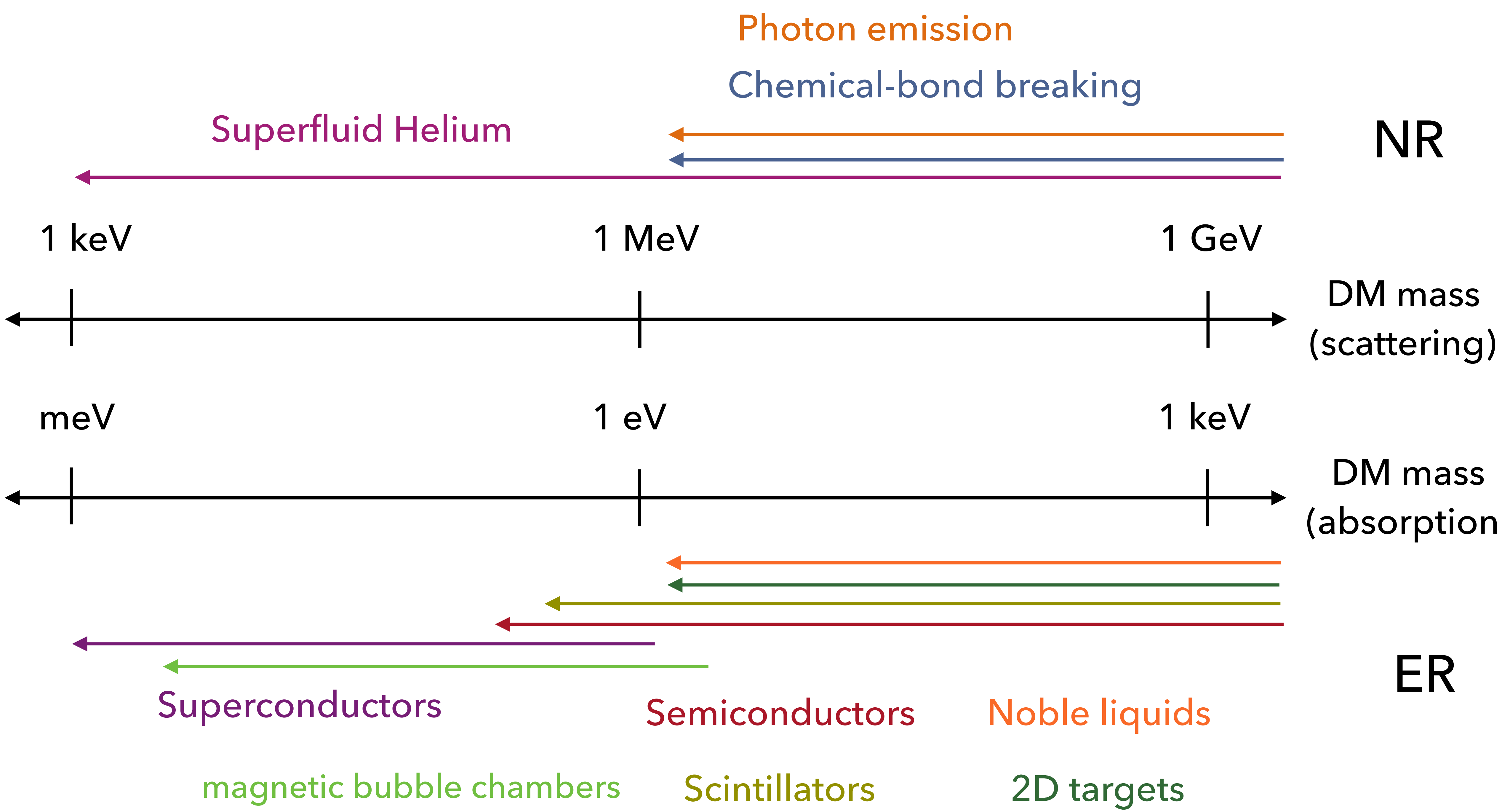


DM absorption



DM scattering

Explosion of new direct-detection ideas in last few years



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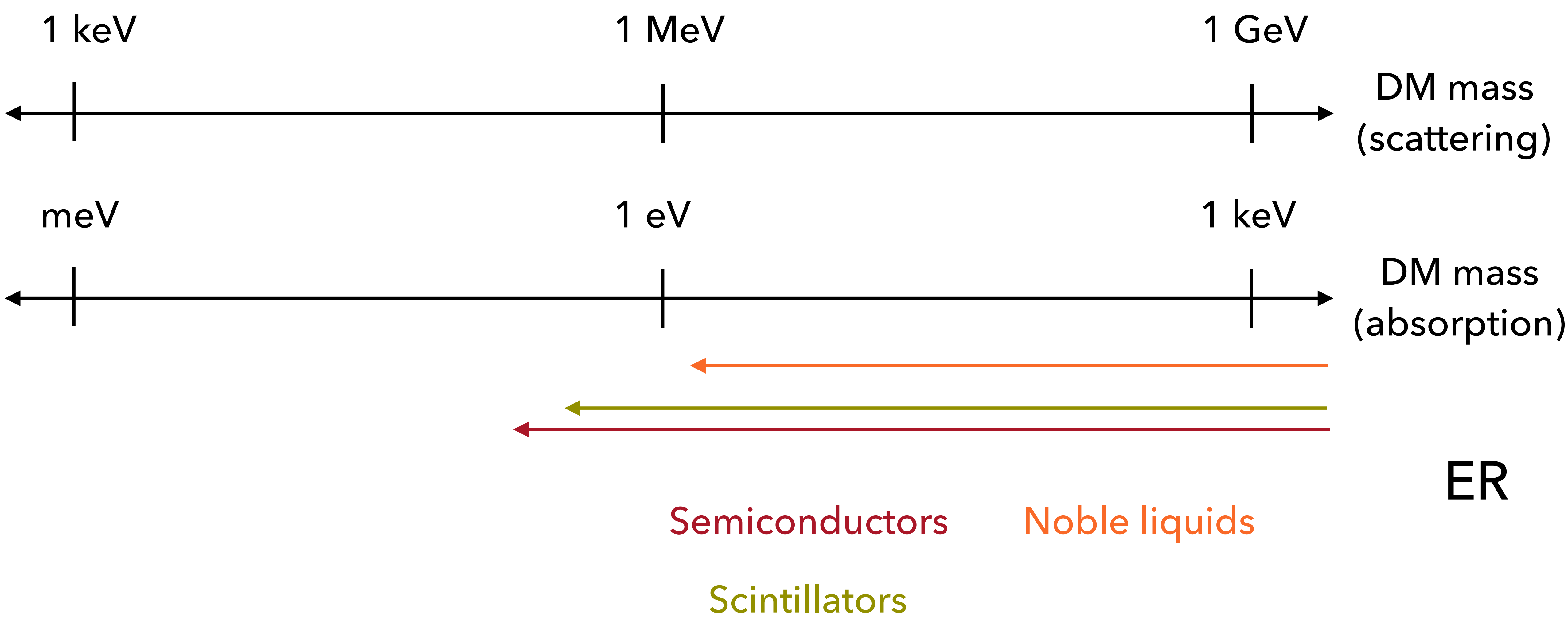

(focus on this… happy to discuss other possibilities)

Outline

- Direct detection concept
- Benchmark models for sub-GeV DM
- Xenon (new constraints & prospects)
- Semiconductors & Scintillators

Outline

- Direct detection concept
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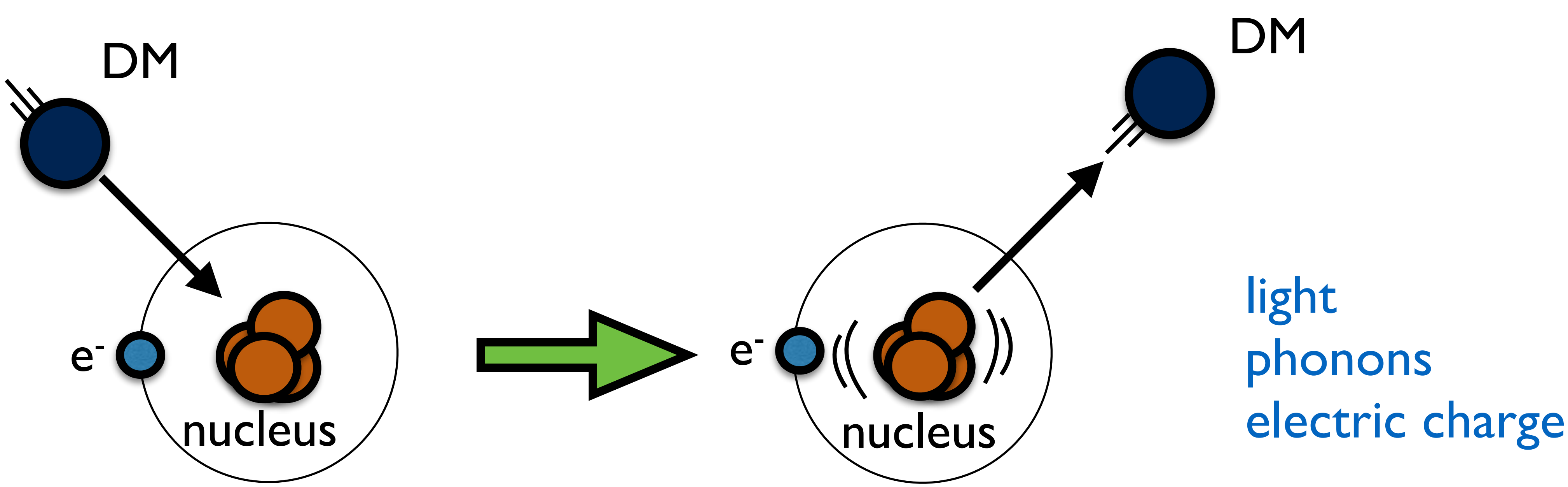
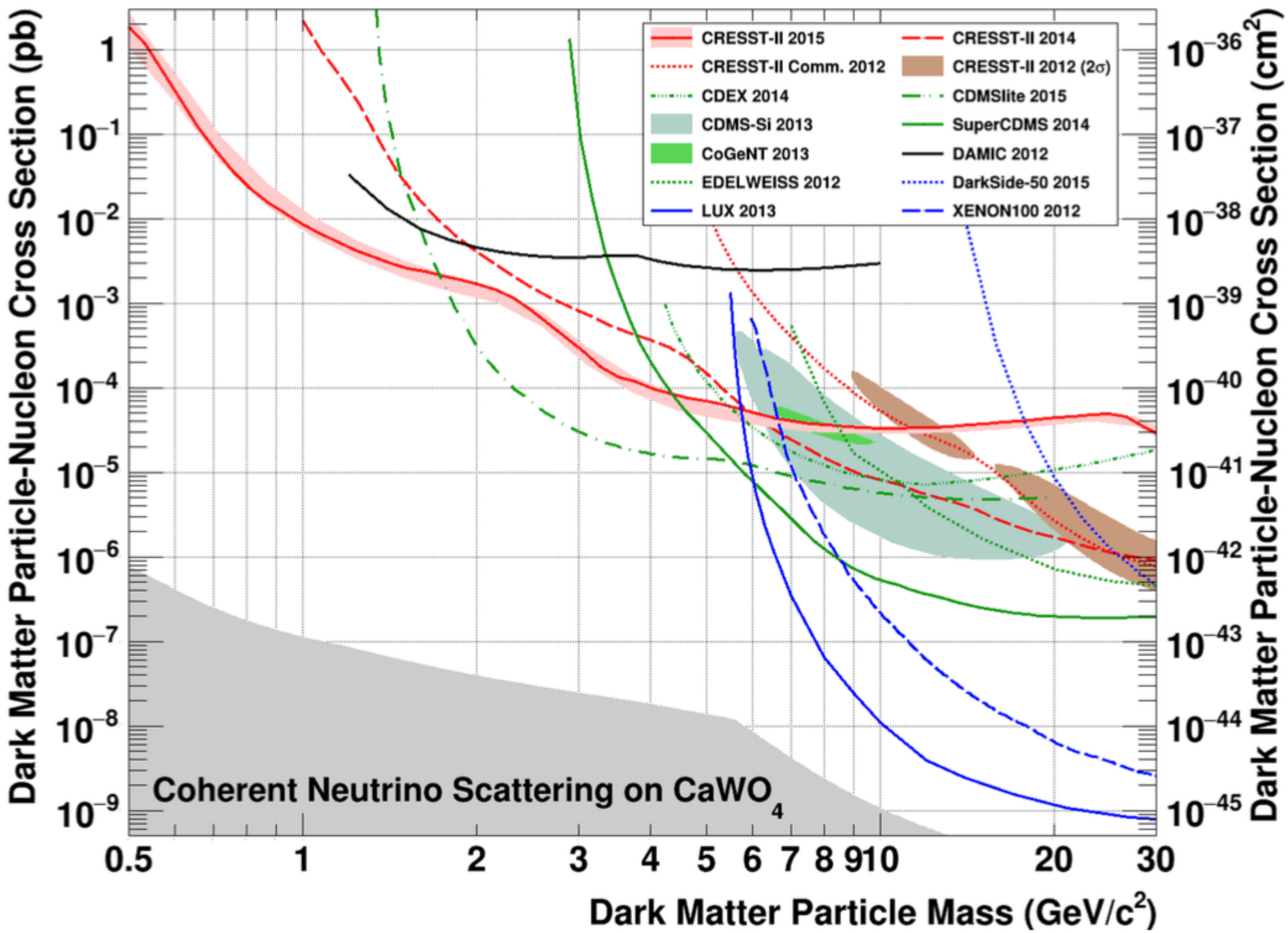
Traditional Direct Detection strategy:

look for nuclear recoils from
WIMP-nucleus scattering



Direct Detection below 1 GeV?

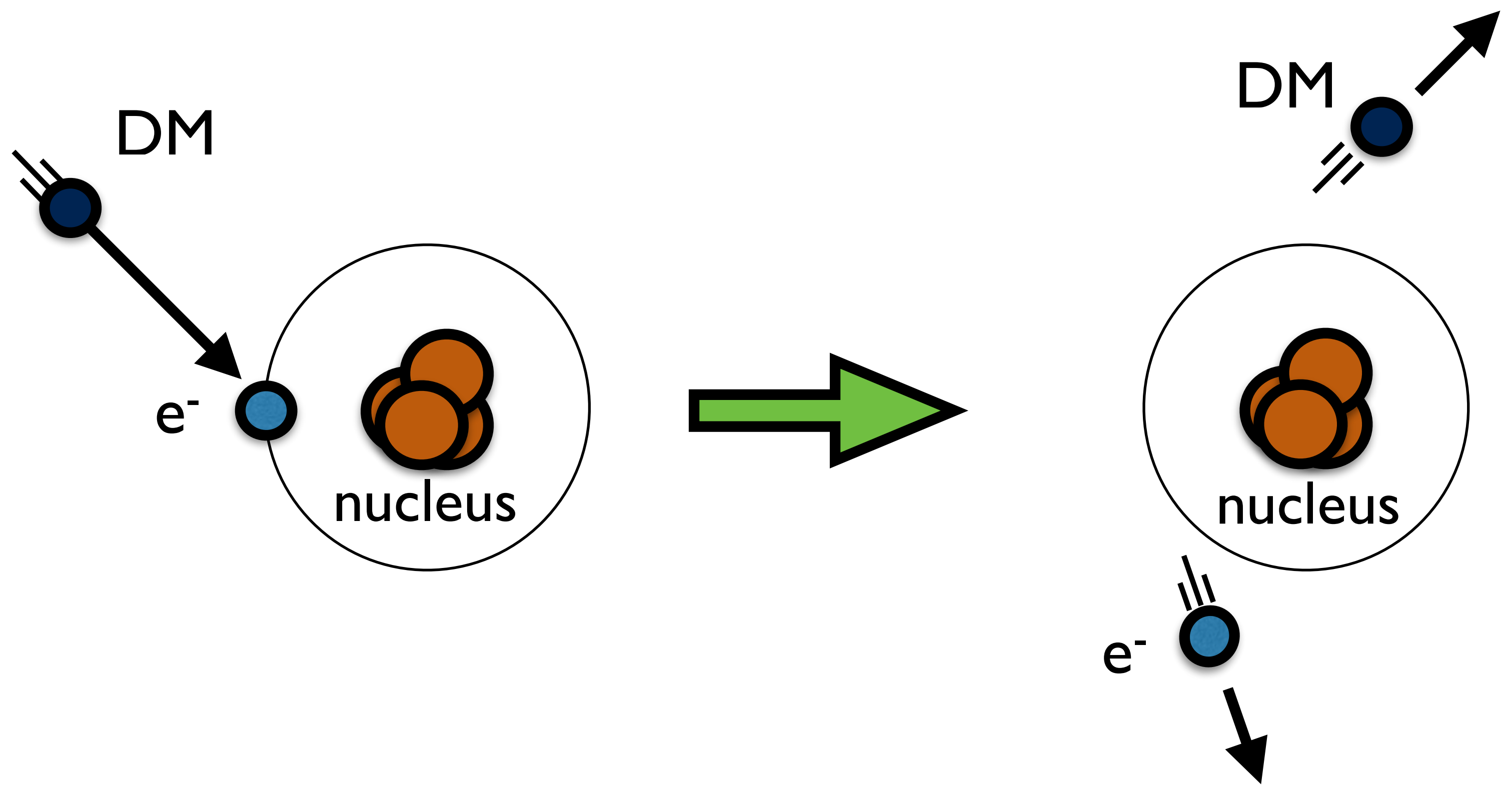
current best limit from CRESST II



1509.01515

DM-electron scattering can probe $\ll$GeV

RE, Mardon, Volansky



Signal depends on detector setup

DM-electron scattering can probe ≪GeV

to overcome binding energy ΔE

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

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

Typical momentum & energy transfer

bound e^- does not have definite momentum

Typical momentum transfer is set by e^- not DM!

$$q_{\rm typ} \sim \alpha m_e \sim 4\ {\rm keV}$$ (for outer shell electron)

transferred energy: $\Delta E_e \sim \vec{q} \cdot \vec{v}_{\rm DM}$

$$\boxed{\Delta E \sim 4\ {\rm eV}}$$

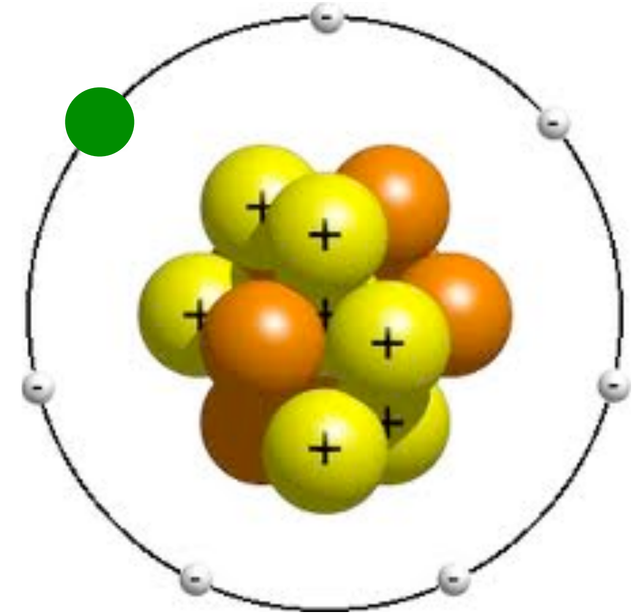
typical
recoil energy

higher ΔE requires q on tail of e^- wavefunction

Target materials for electron recoils?

Target materials for electron recoils?

Type	Examples	E_{th}	mass threshold
Noble liquids	Xe, Ar, He	~10 eV	~5 MeV



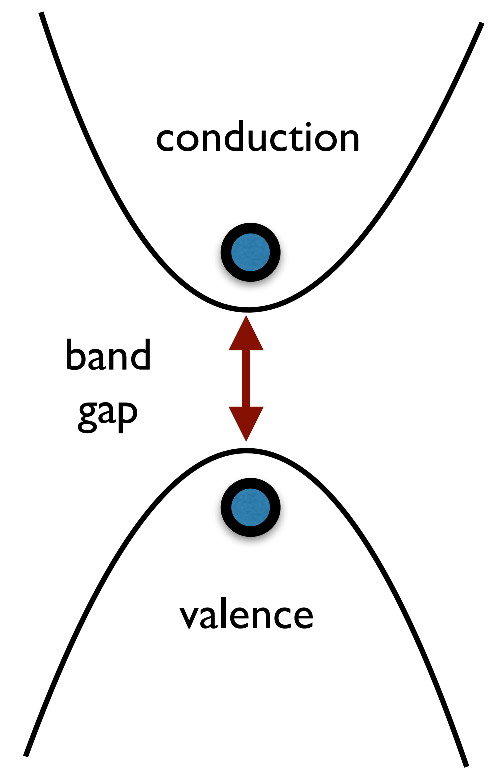
RE, Mardon, Volansky

RE, Manalaysay, Mardon, Sorensen, Volansky

RE, Volansky, Yu

Target materials for electron recoils?

Type	Examples	E_{th}	mass threshold
Noble liquids	Xe, Ar, He	~10 eV	~5 MeV
Semi-conductors	Ge, Si	~1 eV	~200 keV



RE, Mardon, Volansky

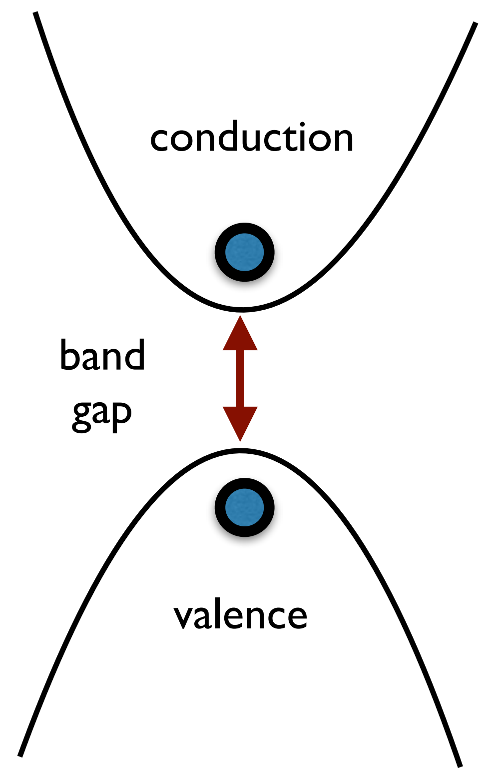
Graham, Kaplan, Rajendran, Walters

Lee, Lisanti, Mishra-Sharma, Safdi

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

Target materials for electron recoils?

Type	Examples	E_{th}	mass threshold
Noble liquids	Xe, Ar, He	~10 eV	~5 MeV
Semi-conductors	Ge, Si	~1 eV	~200 keV
Scintillators	GaAs, NaI, CsI, …	~1 eV	~200 keV



Derenzo, RE, Massari, Soto, Yu

Target materials for electron recoils?

Type	Examples	E_{th}	mass threshold	Status
Noble liquids	Xe, Ar, He	~10 eV	~5 MeV	Done w/ XENON10+100 data; improvements possible
Semi-conductors	Ge, Si	~1 eV	~200 keV	E_{th} ~ 40 eV (SuperCDMS, DAMIC*) E_{th} ~ 1 eV (SENSEI R&D) R&D ongoing
Scintillators	GaAs, NaI, CsI, …	~1 eV	~200 keV	R&D required

+ several others!

Outline

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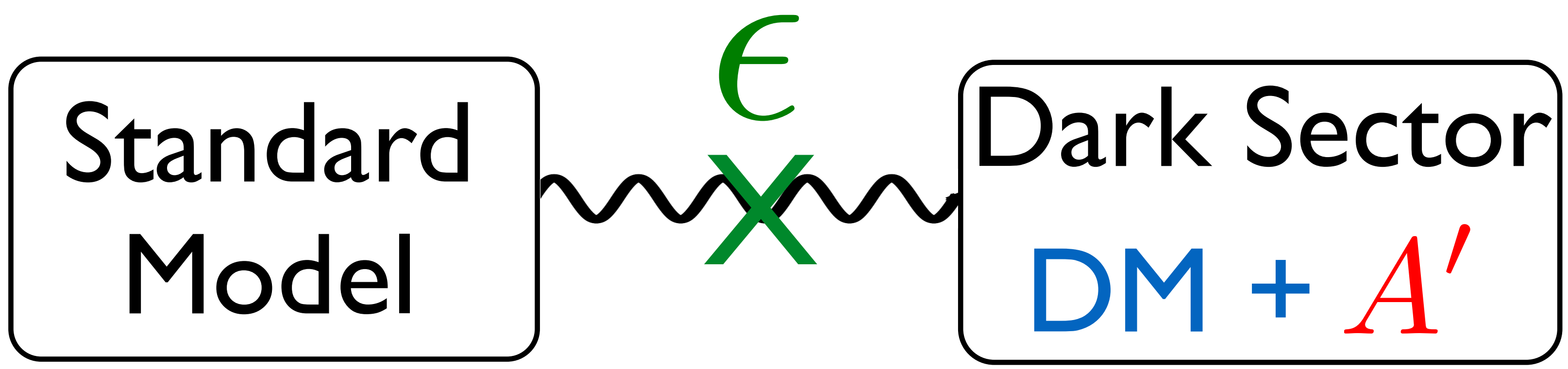
Benchmark Models

DM w/ dark photon (A′) mediator



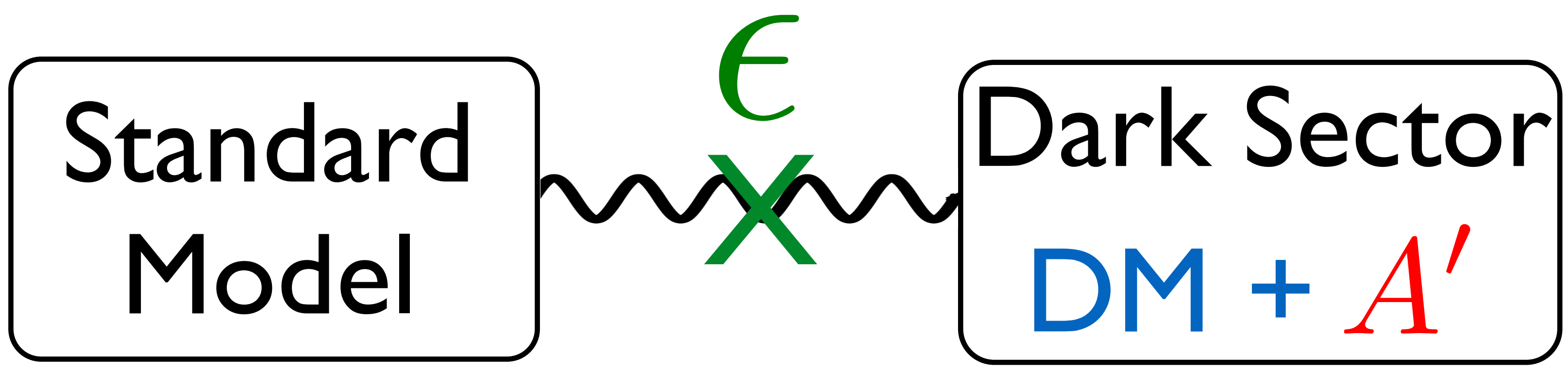
- light A′ (~m_{DM})
- ultra-light A′ ($\ll$keV)

simple & predictive

several variations possible (vector w/ pure q or e^- coupling; scalar)

Benchmark Models

DM w/ dark photon (A′) mediator



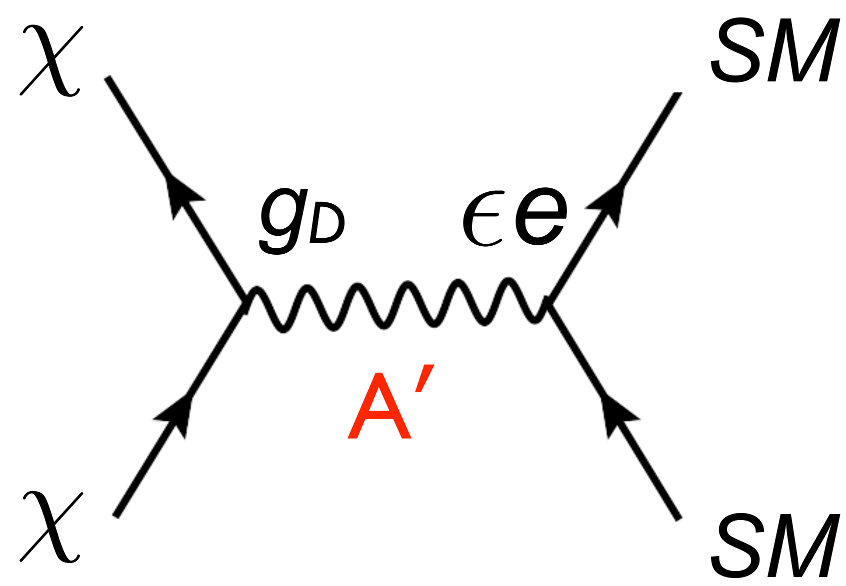
- $\boxed{\text{light A}' \ (\sim m_{DM})}$
- ultra-light A′ ($\ll$ keV)

simple & predictive

several variations possible (vector w/ pure q or e^- coupling; scalar)

see e.g. Arkani-Hamed et.al.; Weiner et.al.; Pospelov & Ritz; RE, Kaplan, Schuster, Toro; RE, Mardon, Volansky; Lin, Yu, Zurek; Chu, Hambye, Tytgat; Hall, Jedamzik, March-Russell, West; Boehm, Fayet; Borodatchenkova, Choudhury, Drees; Pospelov, Ritz, Voloshin; Batell, Pospelov, Ritz; Izaguirre, Krnjaic, Schuster, Toro; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; …

Thermal Freeze-out

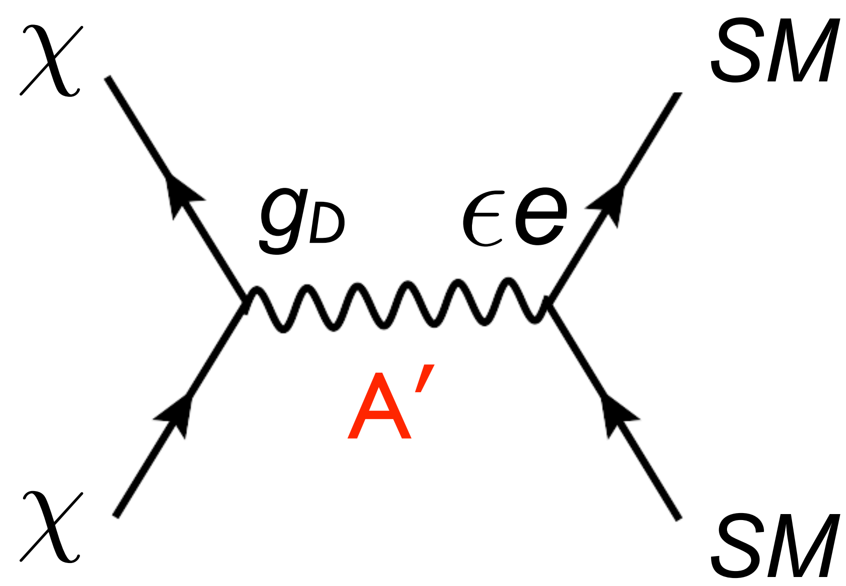


$m_{A'} > 2m_\chi$

(very predictive)

e.g. Boehm & Fayet (2003); Borodatchenkova, Choudhury, Drees (2005); Lin, Yu, Zurek (2011); Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)

Thermal Freeze-out



$m_{A'} > 2m_\chi$

(very predictive)

scalar χ: $$\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2 \, v^2$$

p-wave

unconstrained by CMB

Dirac fermion χ: $$\sigma v \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} m_\chi^2$$

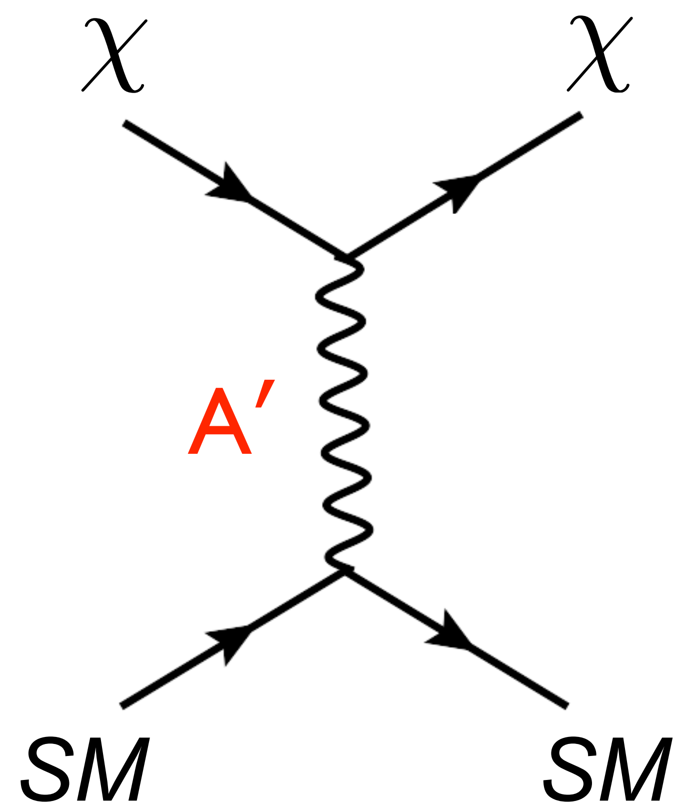
s-wave

$\Longrightarrow$ need asymmetric DM

CMB sets <u>*lower*</u> bound on σv

provides nice targets for direct detection experiments!

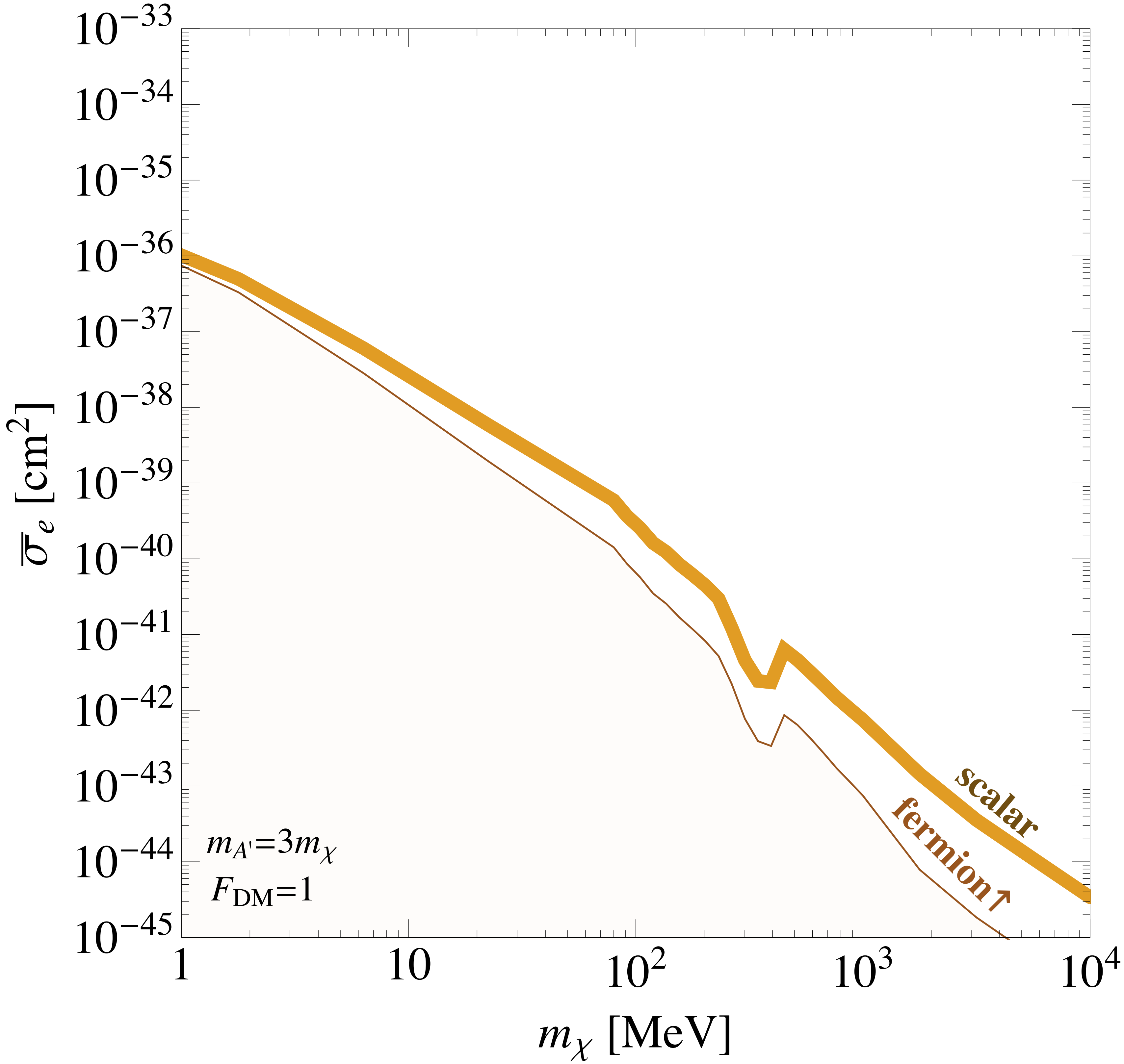
Direct Detection



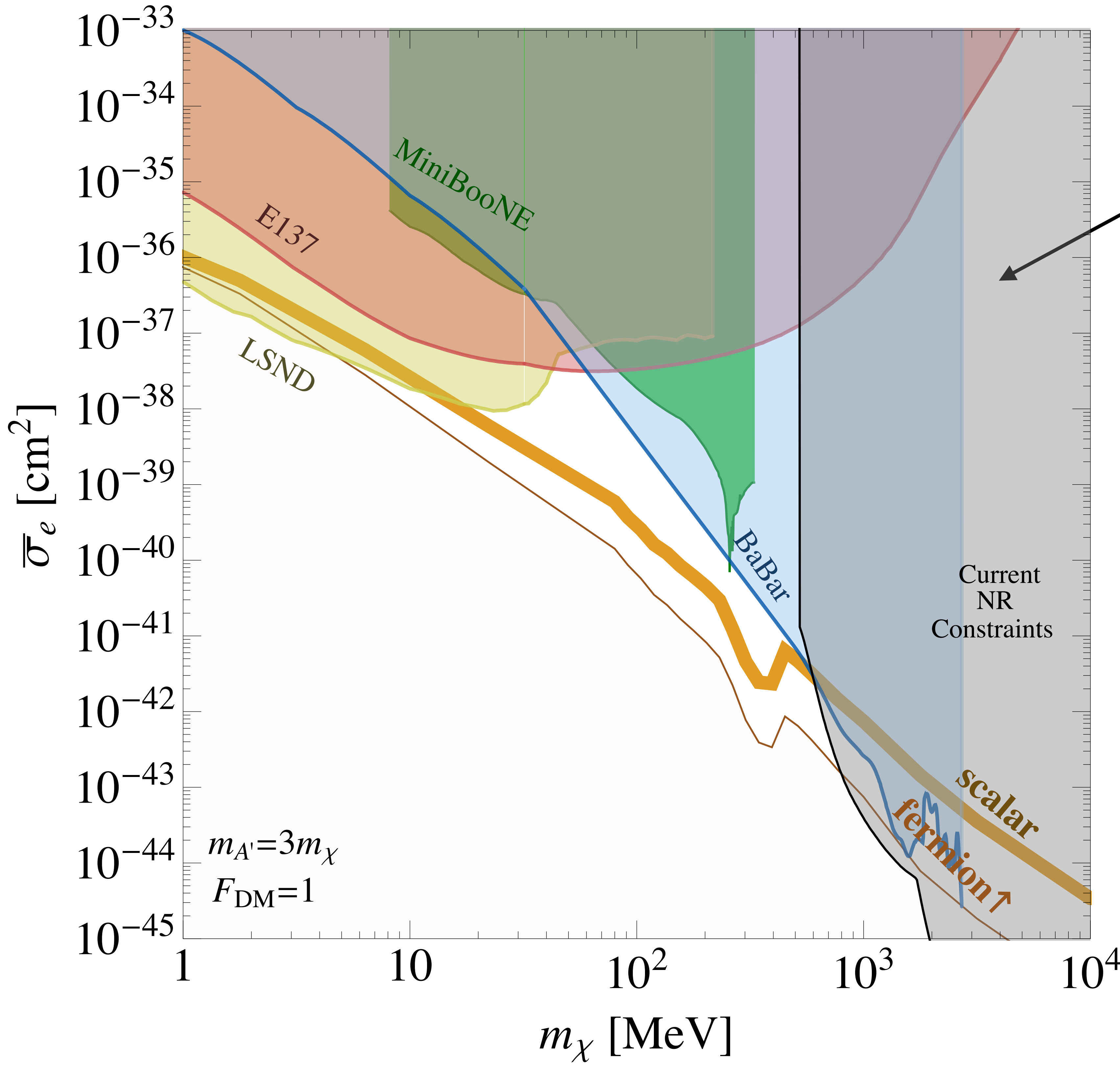
$$\bar{\sigma}_e \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4}\,\mu_{\chi e}^2 \qquad\qquad F_{\mathrm{DM}} = 1$$

similar combination as freeze-out parameters!

Freeze-out & Asymmetric DM targets



Constraints?



Traditional DD searches

MiniBooNE

1702.02688

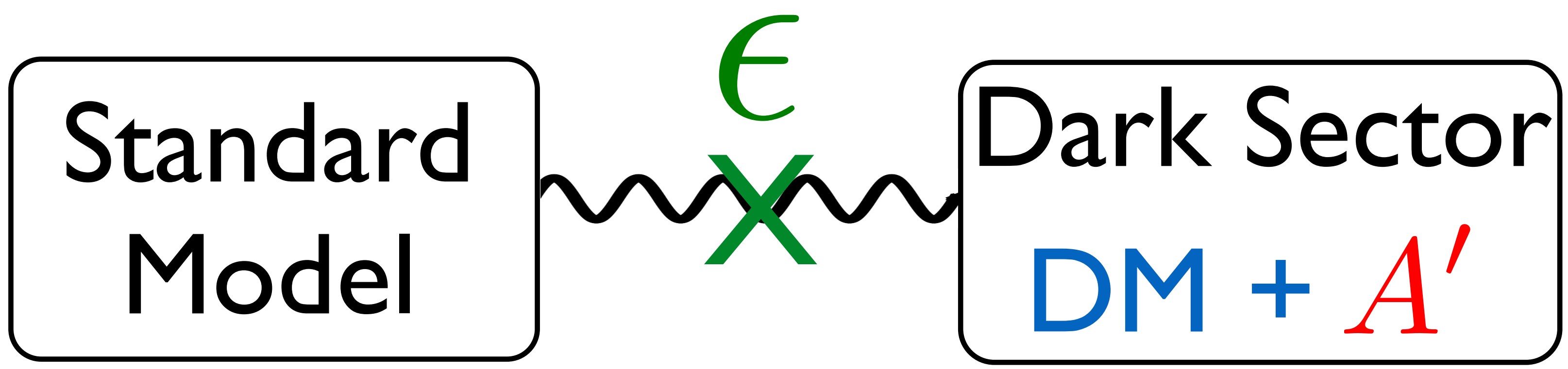
BaBar

1702.03327

new DD searches not yet shown!

Benchmark Models

DM w/ dark photon (A′) mediator



- light A′ (~m_{DM})
- ultra-light A′ ($\ll$ keV)

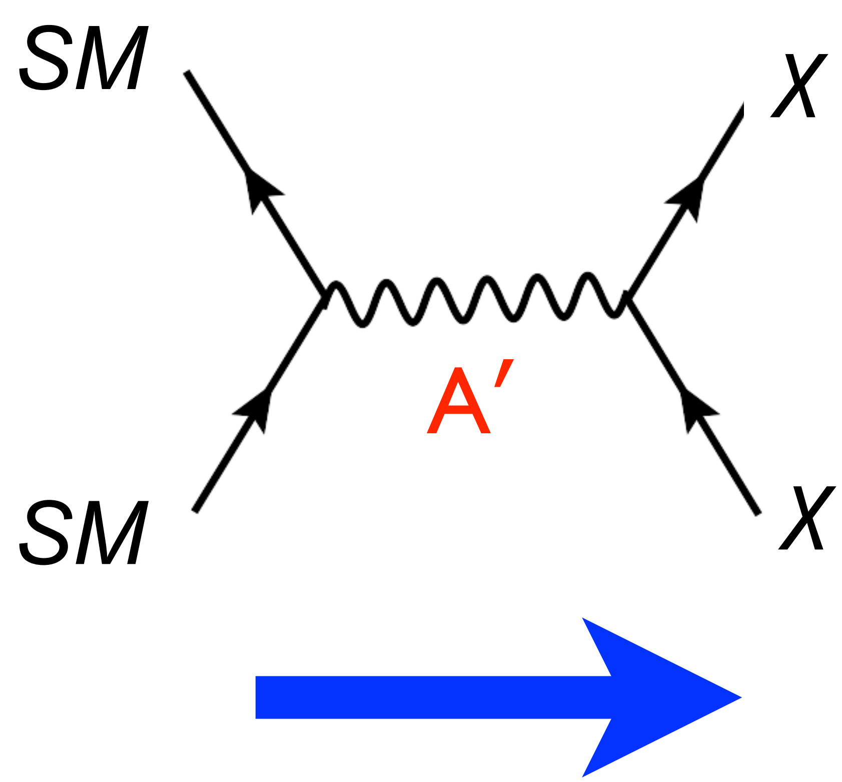
simple & predictive

see e.g. Arkani-Hamed et.al.; Weiner et.al.; Pospelov & Ritz; RE, Kaplan, Schuster, Toro; RE, Mardon, Volansky; Lin, Yu, Zurek; Chu, Hambye, Tytgat; Hall, Jedamzik, March-Russell, West; Boehm, Fayet; Borodatchenkova, Choudhury, Drees; Pospelov, Ritz, Voloshin; Batell, Pospelov, Ritz; Izaguirre, Krnjaic, Schuster, Toro; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; …

"Freeze-in"

can generate correct DM
relic density by "freeze-in"

Hall et.al. (0911.1120)



build up DM
abundance as
Universe cools

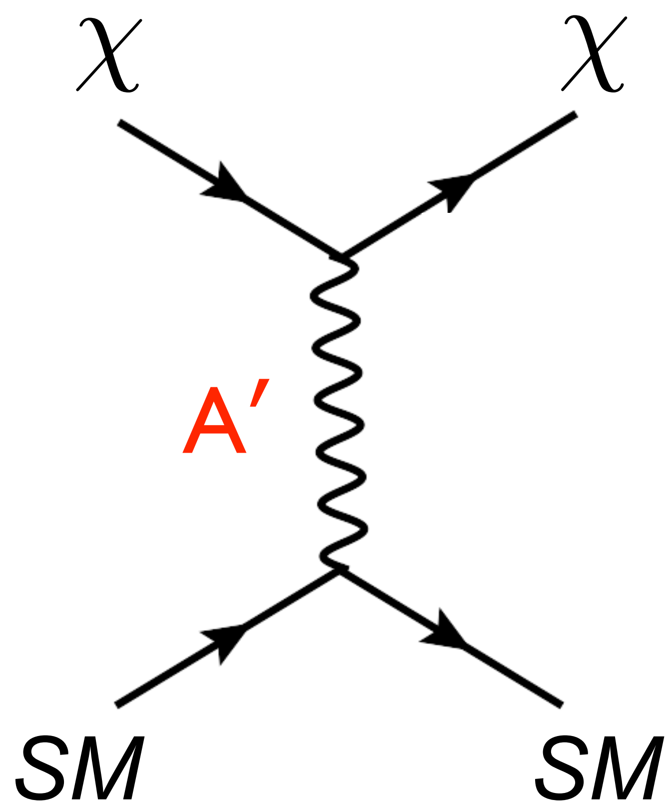
e.g. m_X = 100 MeV, correct relic abundance for $\alpha_D \epsilon^2 \sim 5 \times 10^{-24}$

(~independent of $m_{A'}$)

RE, Mardon, Volansky

Chu, Hambye, Tytgat (calculated w/ thermal effects by Jae Hyeok Chang)

Direct Detection w/ ultralight A′ (≪ keV)

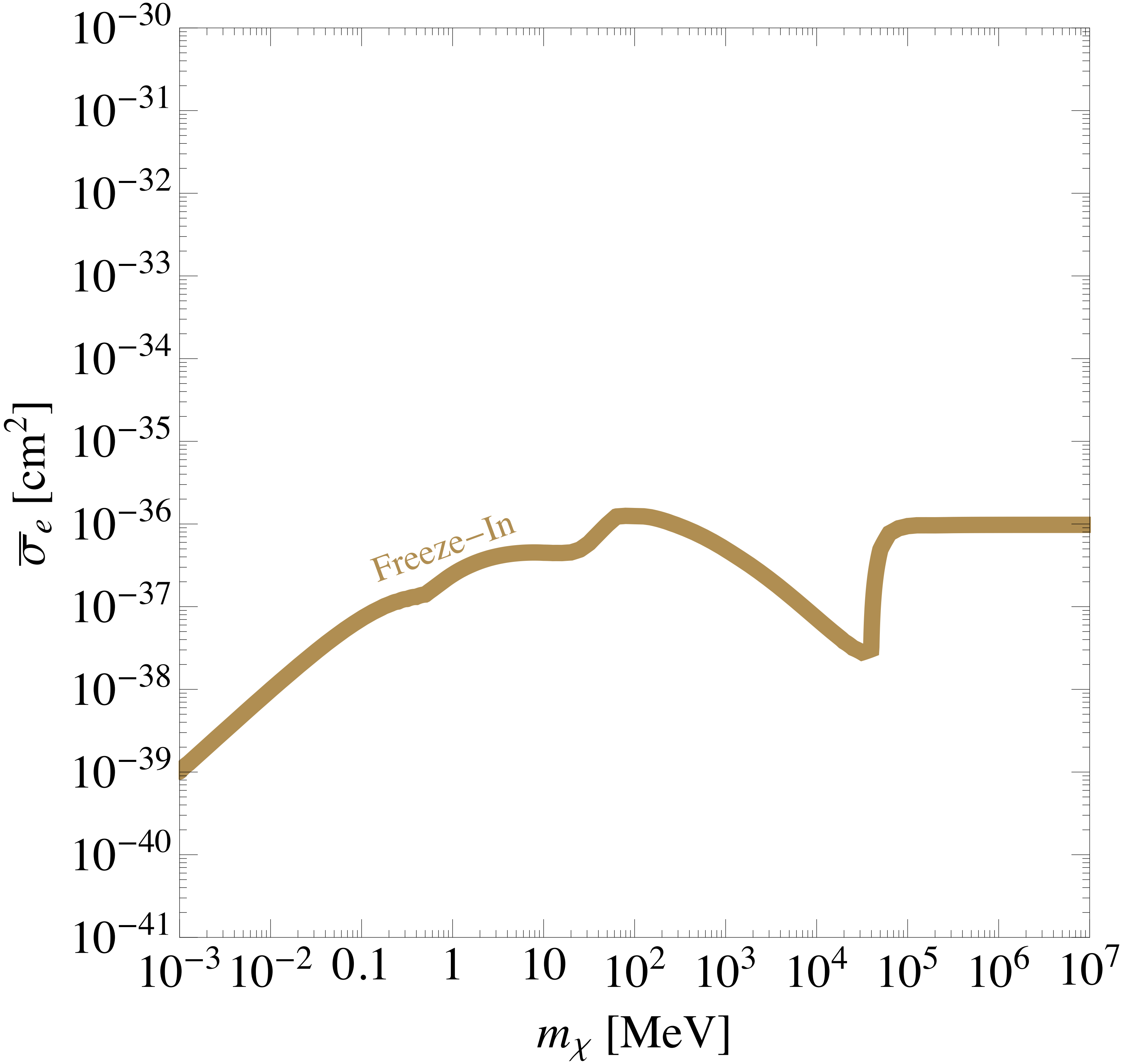


large enhancement at low q^2 !

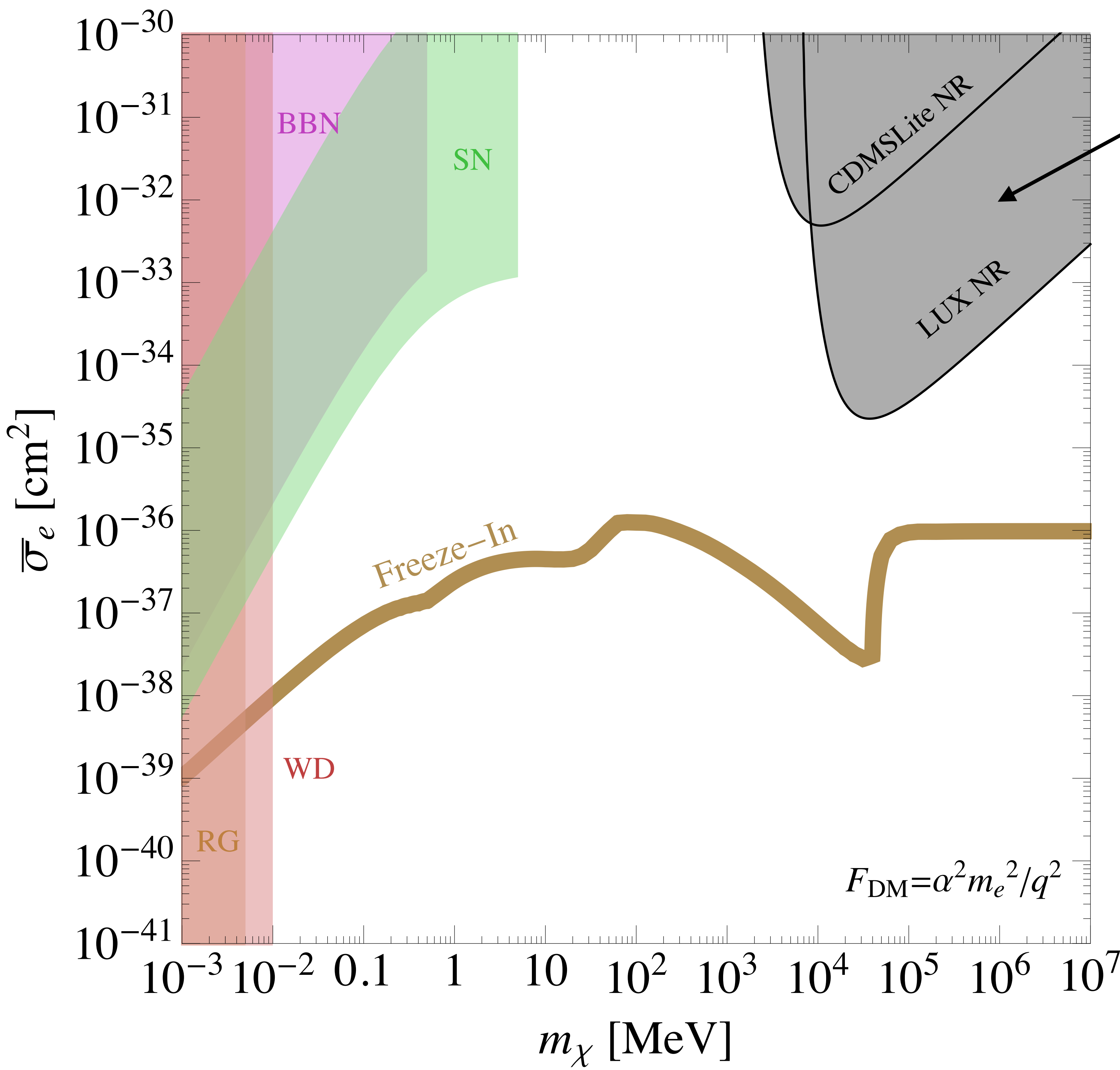
$$\sigma \propto \frac{16\pi\mu_{\chi e}^2 \alpha\alpha_D \epsilon^2}{q^4} = \underbrace{\frac{16\pi\mu_{\chi e}^2 \alpha\alpha_D \epsilon^2}{(\alpha^2 m_e^2)^2}}_{} \times \underbrace{\left(\frac{\alpha^2 m_e^2}{q^2}\right)^2}_{}$$

$$\equiv \quad \bar{\sigma}_e \quad \times \quad (F_{\mathrm{DM}}(q))^2$$

Freeze-in target



Constraints



Traditional DD searches

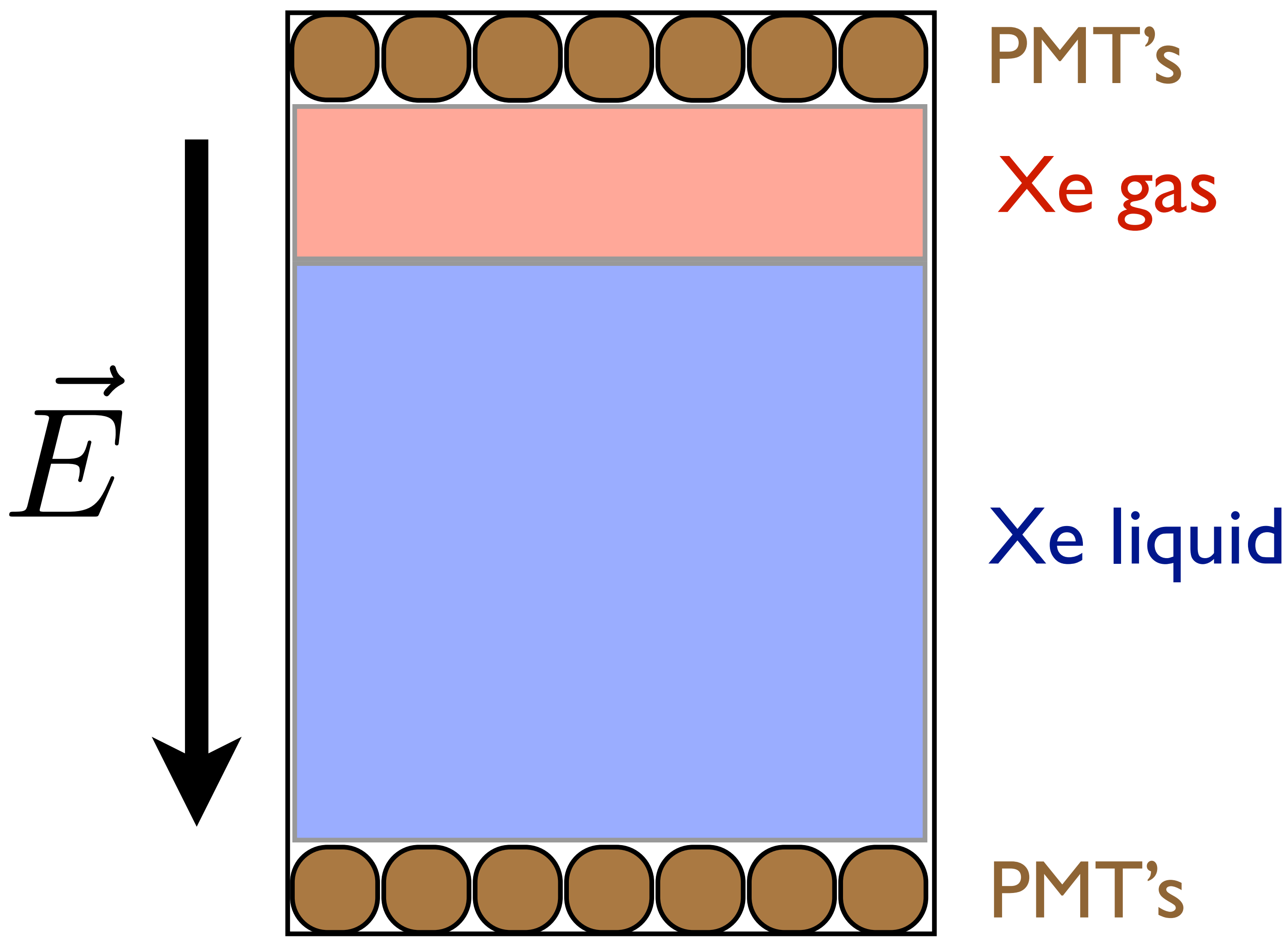
collider & beam-dump constraints irrelevant

new DD searches not yet shown!

Outline

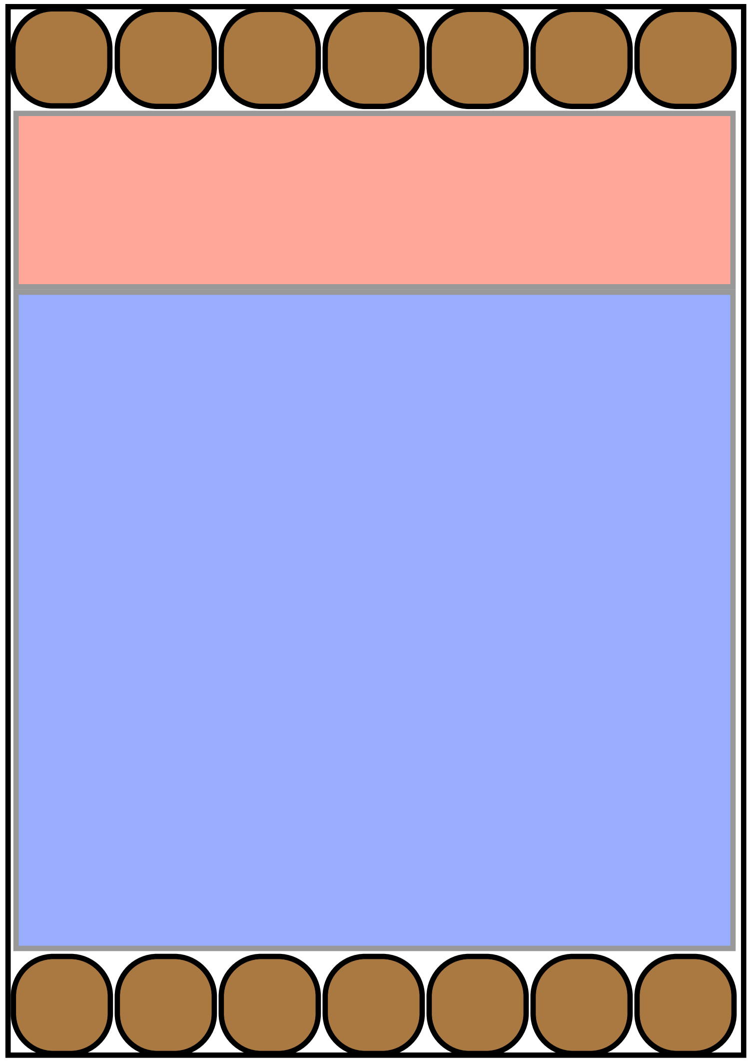
- Direct detection concept
- Benchmark models for sub-GeV DM
- Xenon (new constraints & prospects)
- Semiconductors & Scintillators

XENON10/100 detector schematic

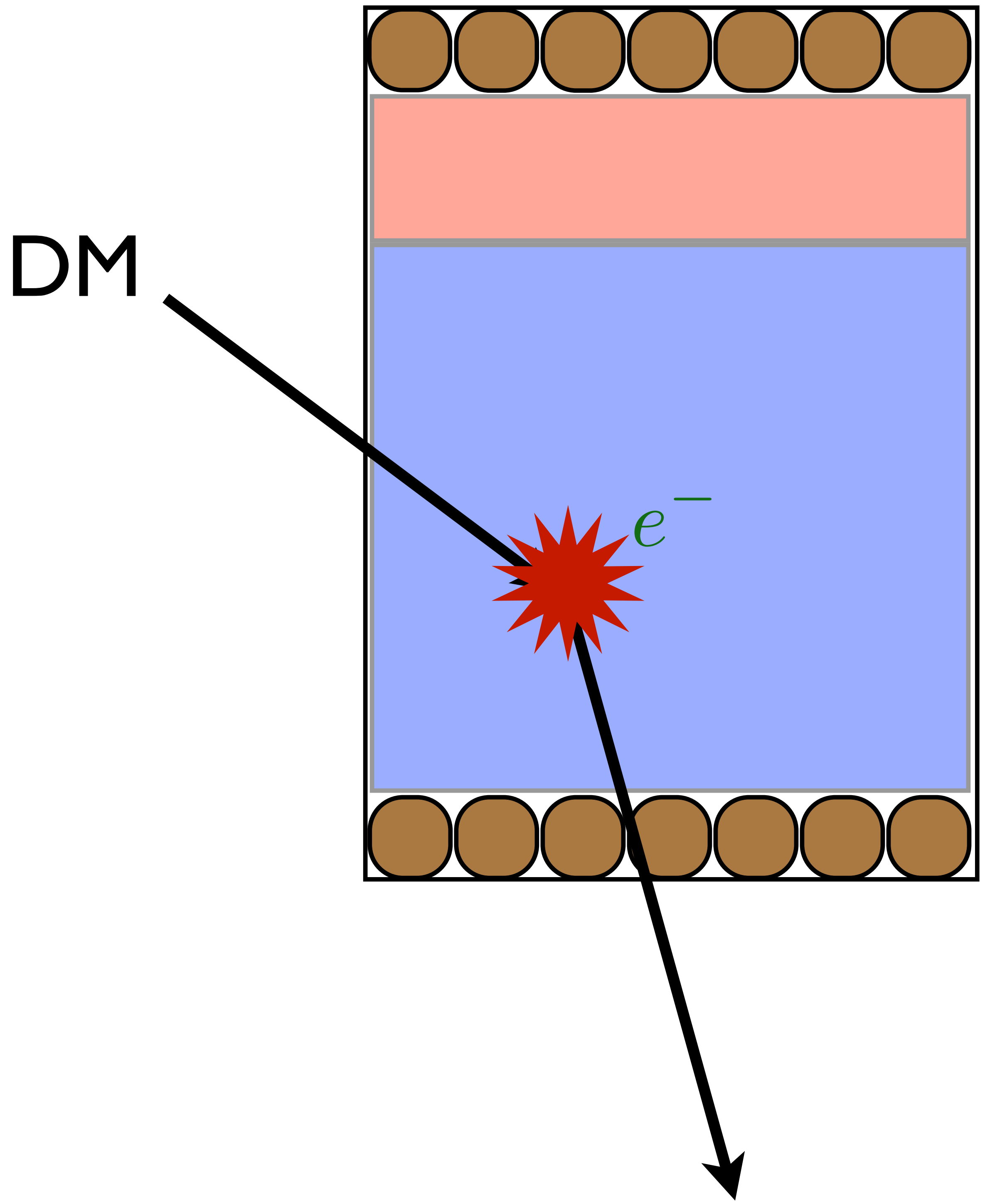


Sub-GeV DM scattering off electrons

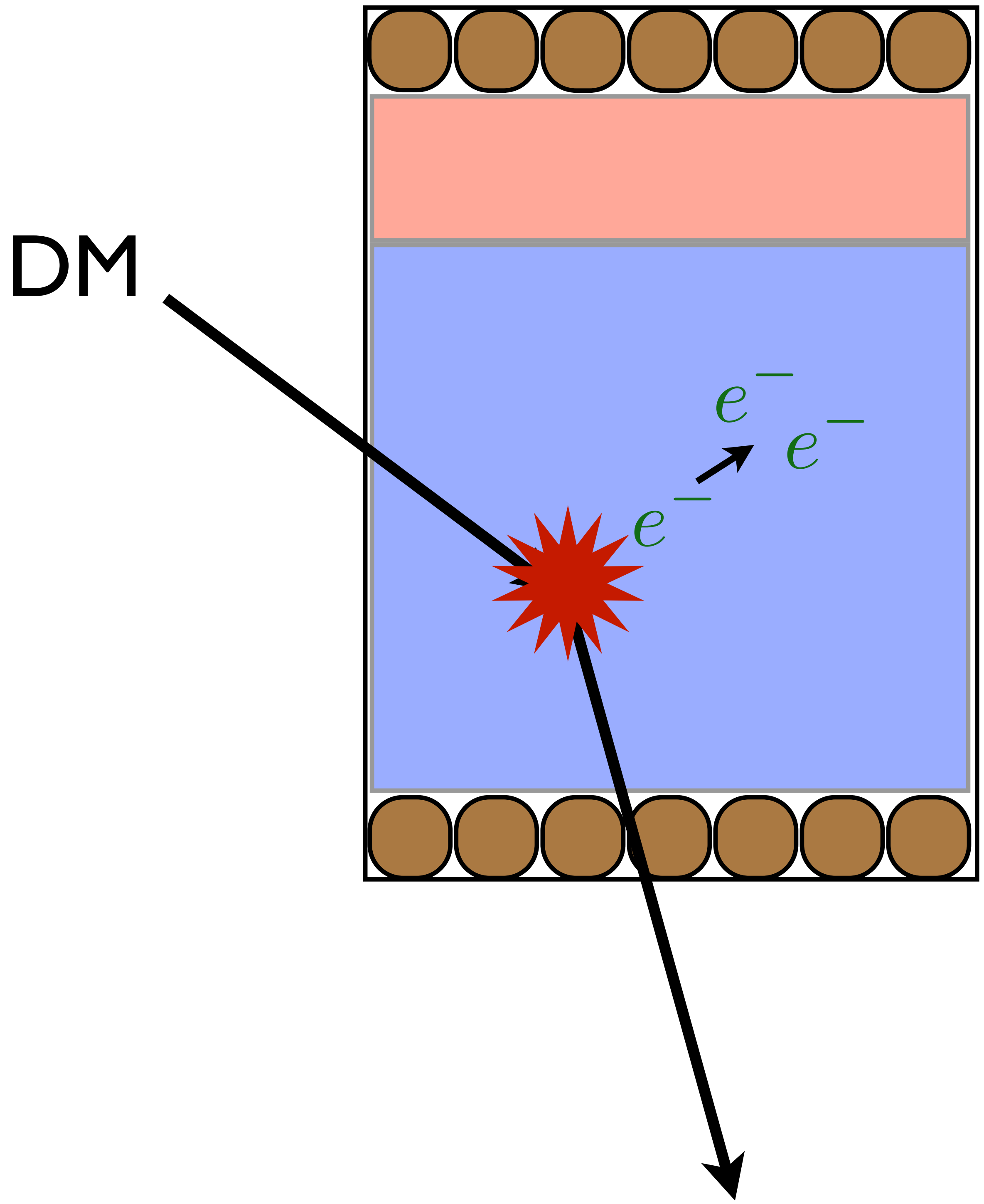
DM



Sub-GeV DM scattering off electrons

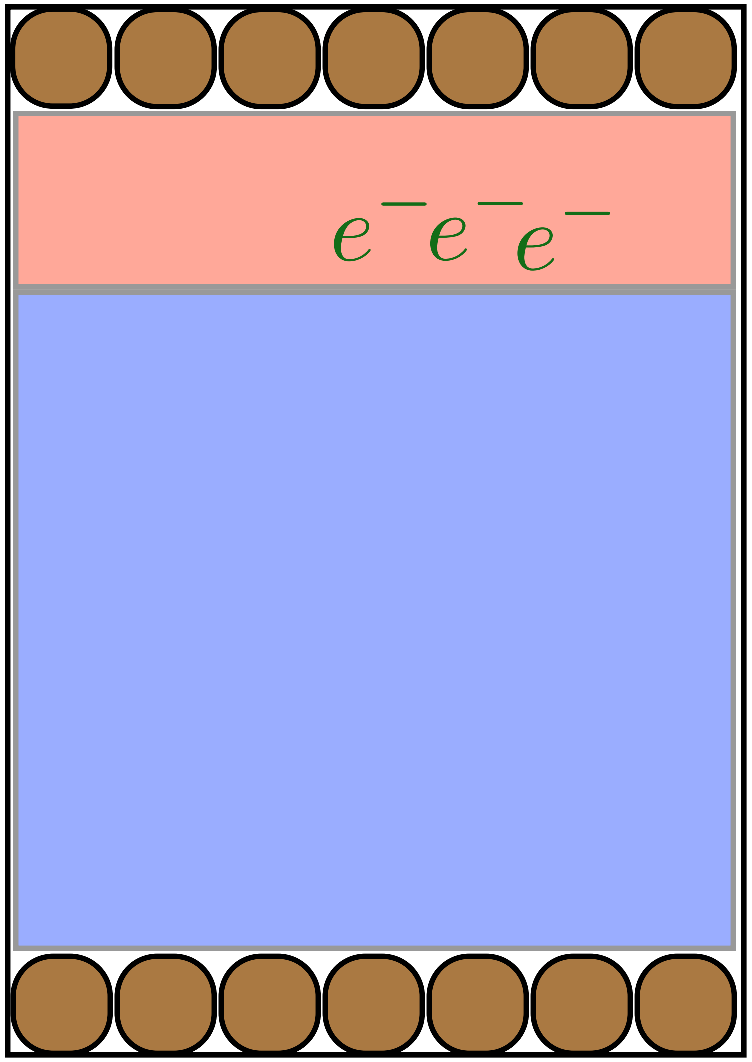


Sub-GeV DM scattering off electrons



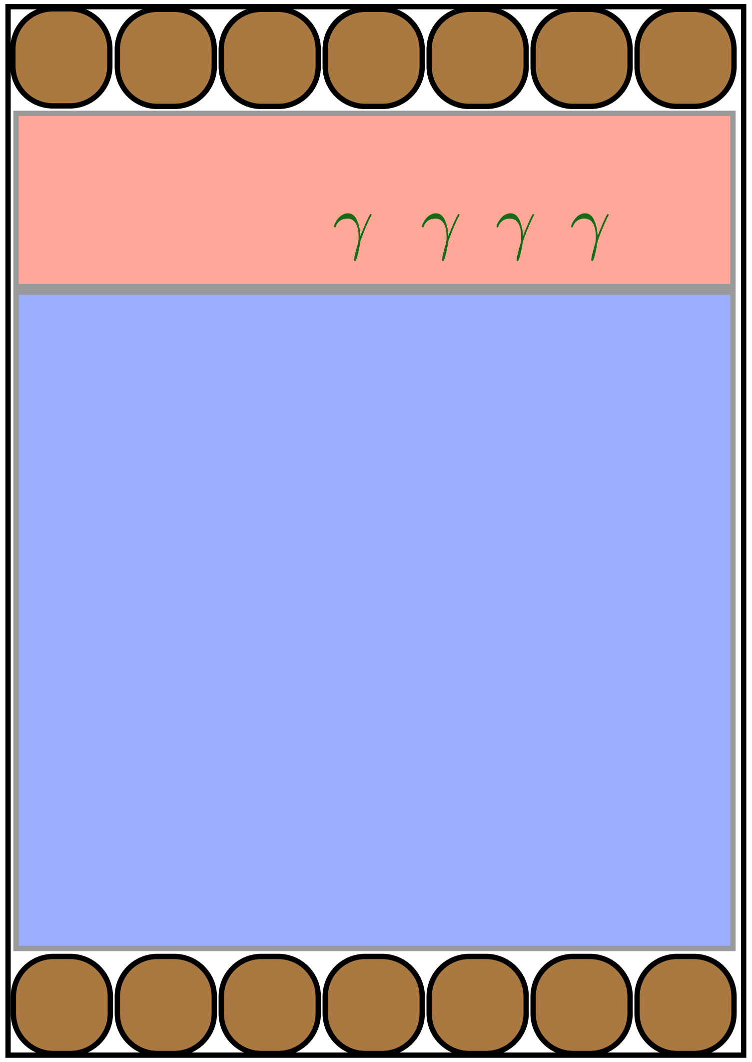
an energetic outgoing e^- can ionize other e^-'s

Sub-GeV DM scattering off electrons



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

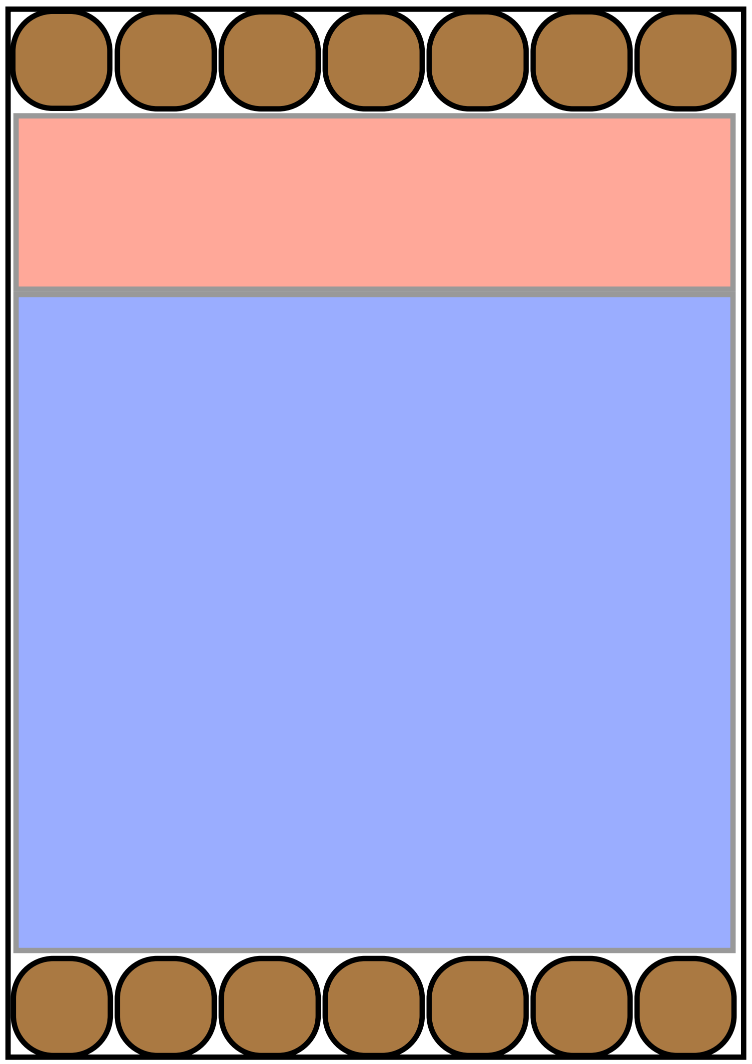
Sub-GeV DM scattering off electrons



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

one e^- produces ~27 (20) detected photons in Xe10 (Xe100)
("S2-signal")

Sub-GeV DM scattering off electrons



an energetic outgoing
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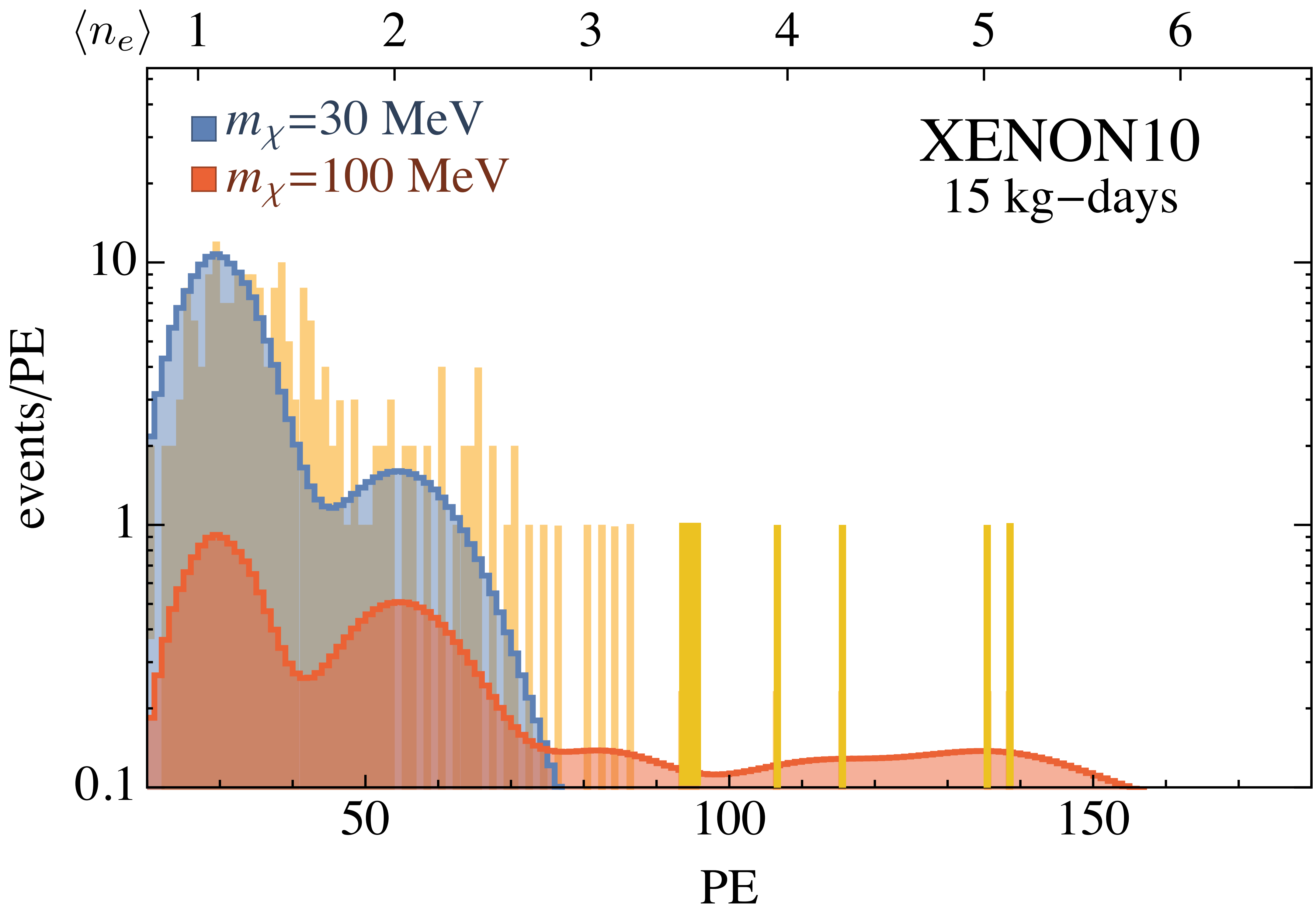
one e^- produces
~27 (20) detected photons
in Xe10 (Xe100)
("S2-signal")

Signal and Data: XENON10

RE, Volansky, Yu

updated from

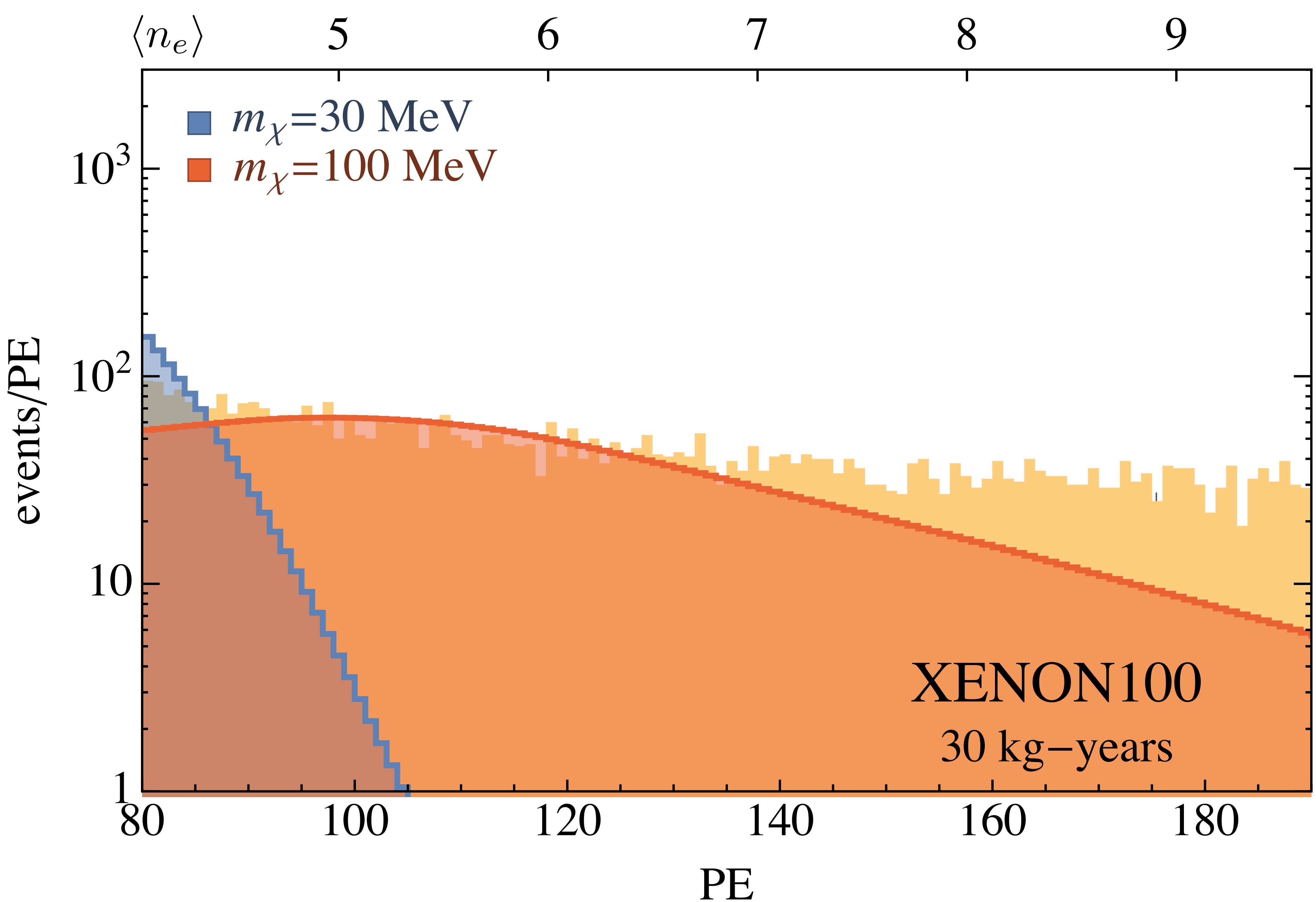
RE, Manalaysay, Mardon, Sorensen, Volansky, 2012



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

Signal and Data: XENON100

RE, Volansky, Yu



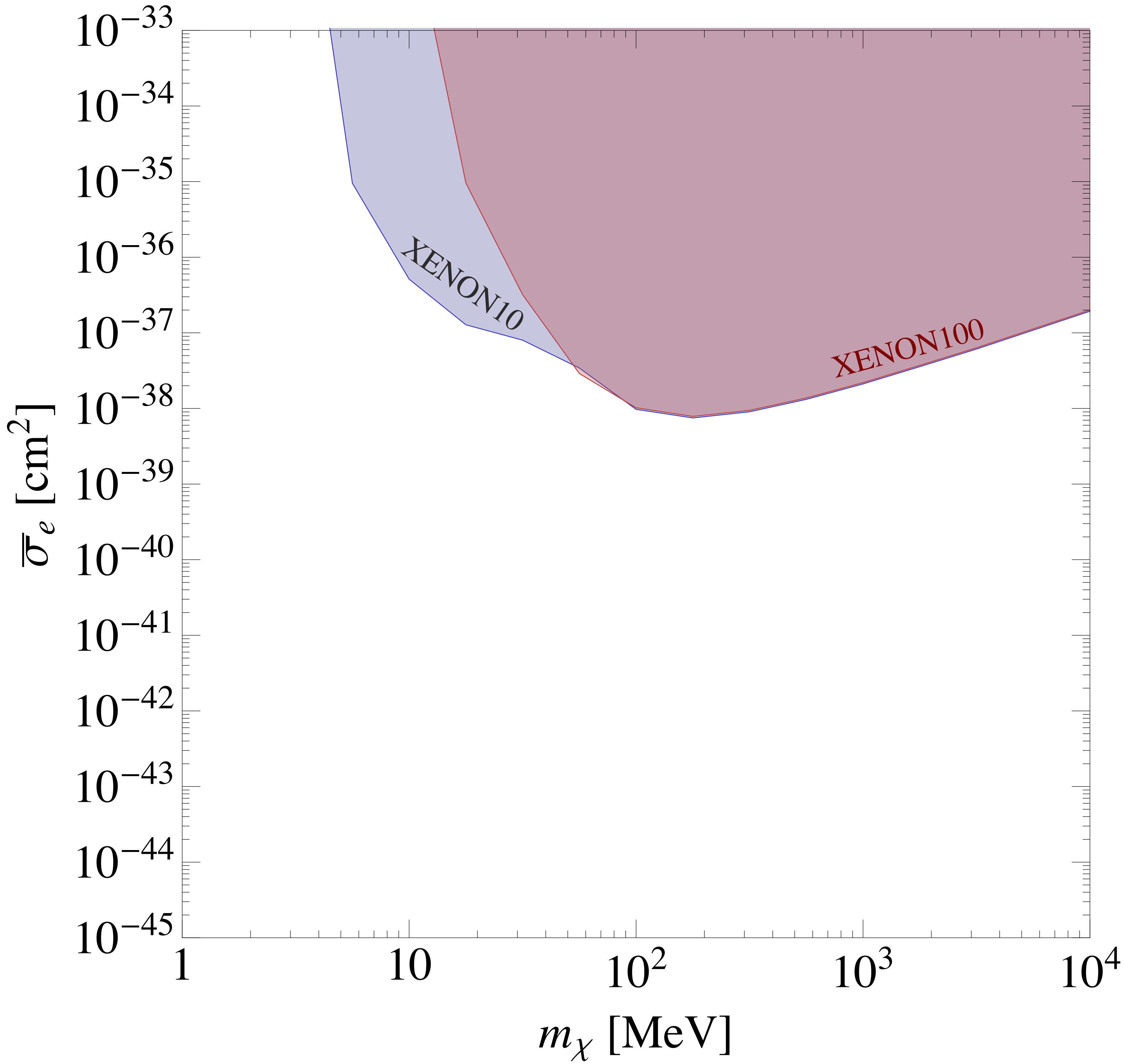
XENON100: 1605.06262

XENON10/100 constraints

RE, Volansky, Yu

updated from

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012



XENON10/100 constraints

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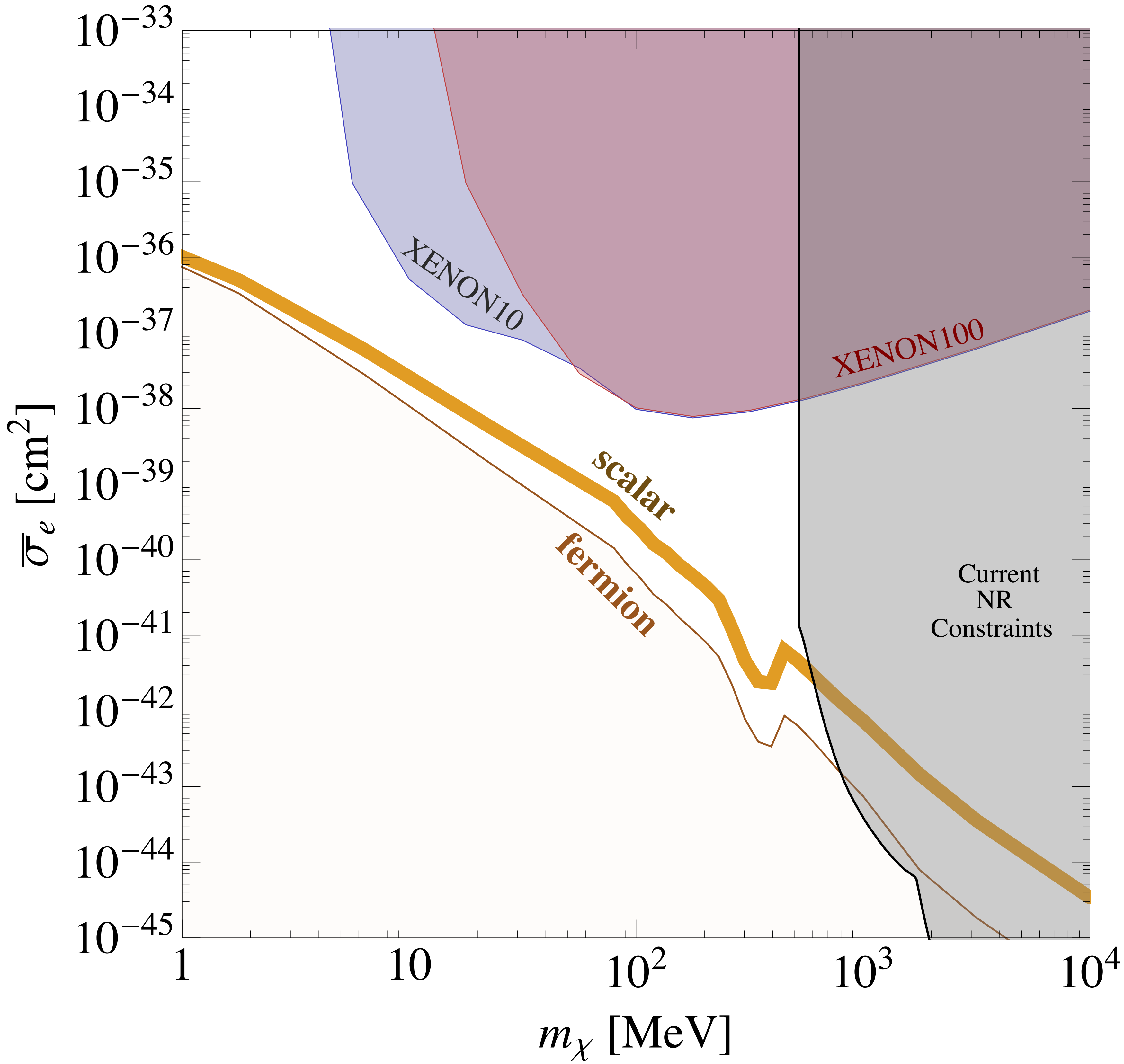


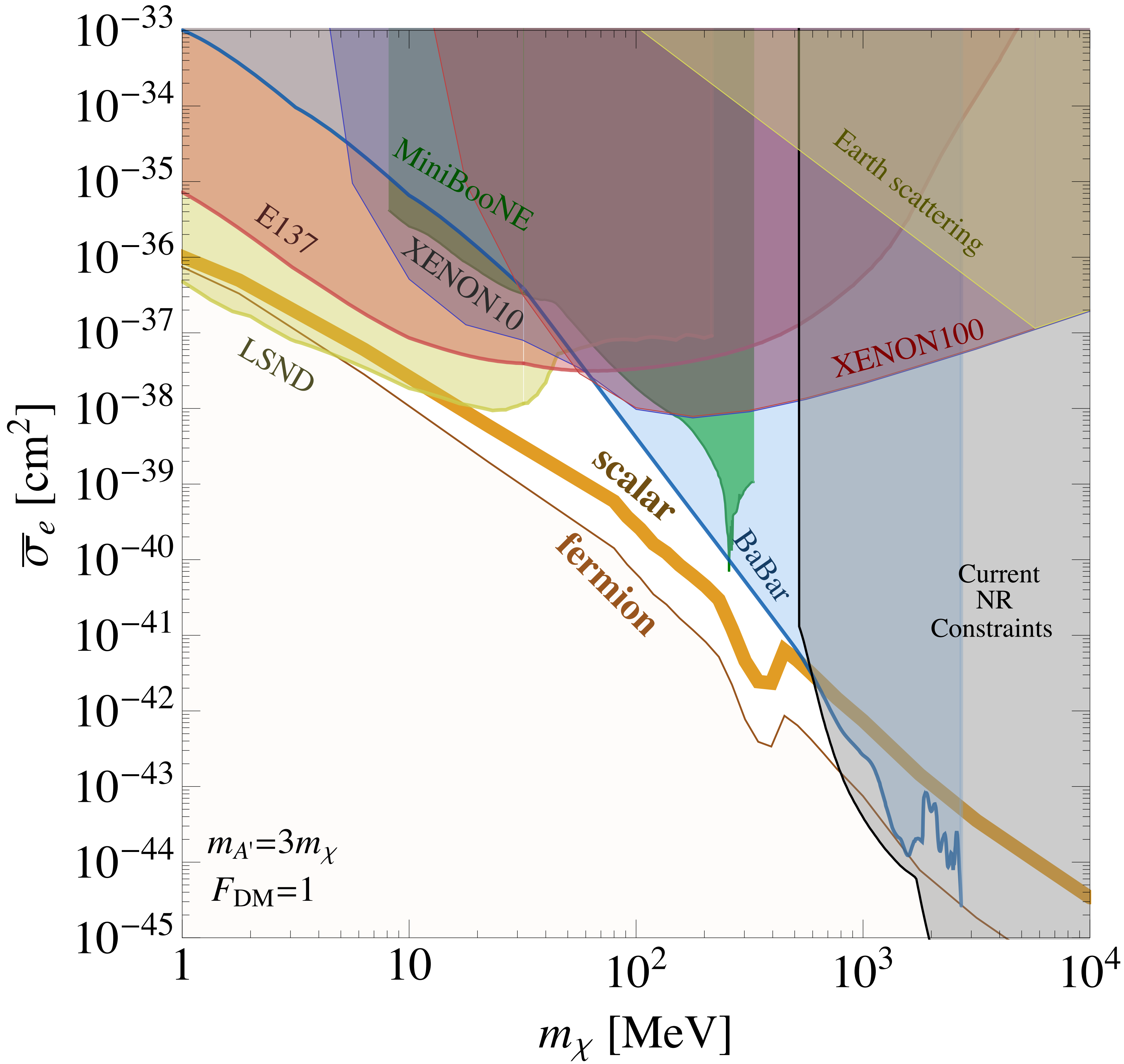
Benchmark targets
+
DD constraints

XENON10/100 constraints

RE, Volansky, Yu

updated from

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012



Benchmark targets
+
All constraints

XENON10/100 constraints

RE, Volansky, Yu

updated from

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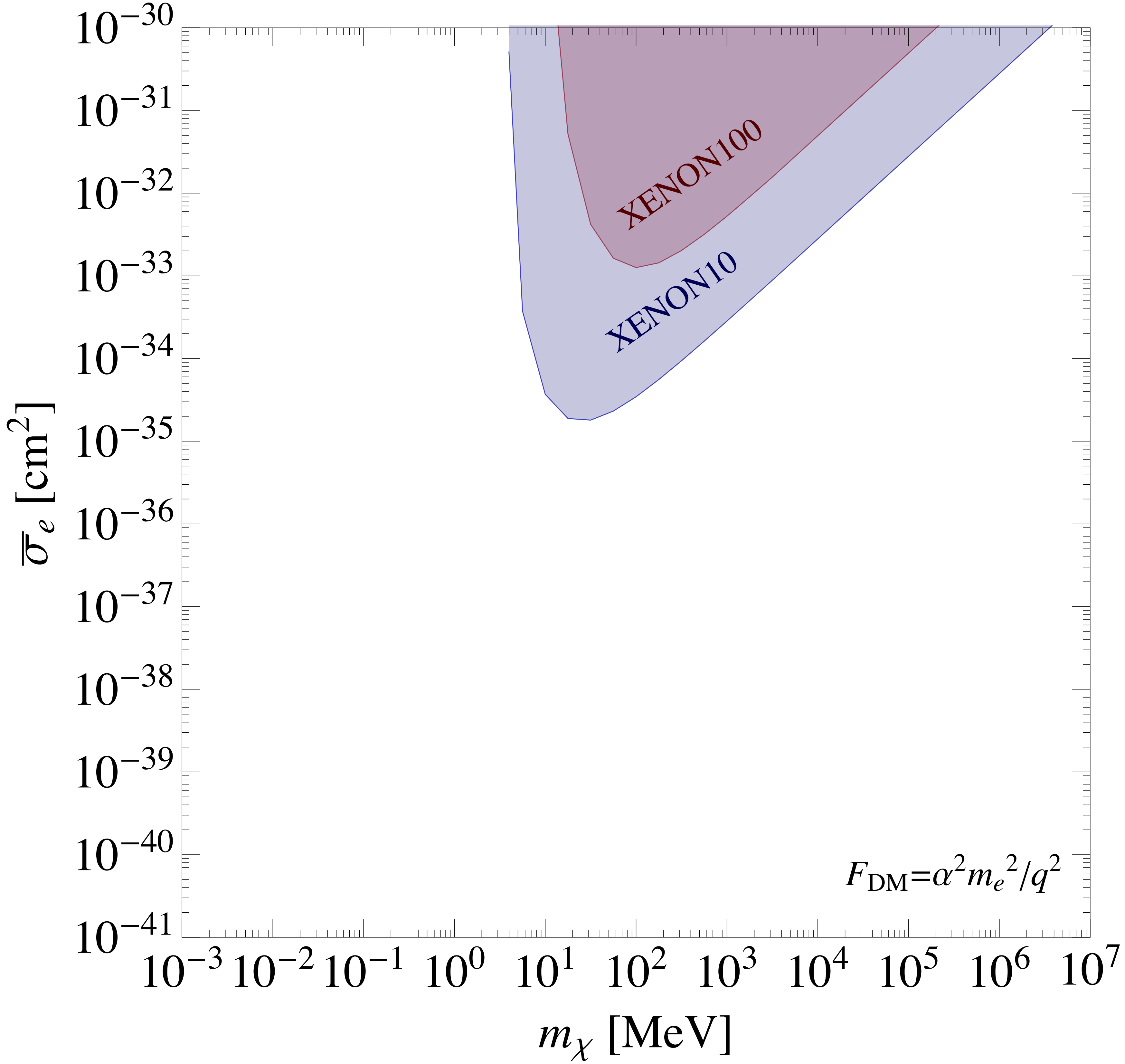
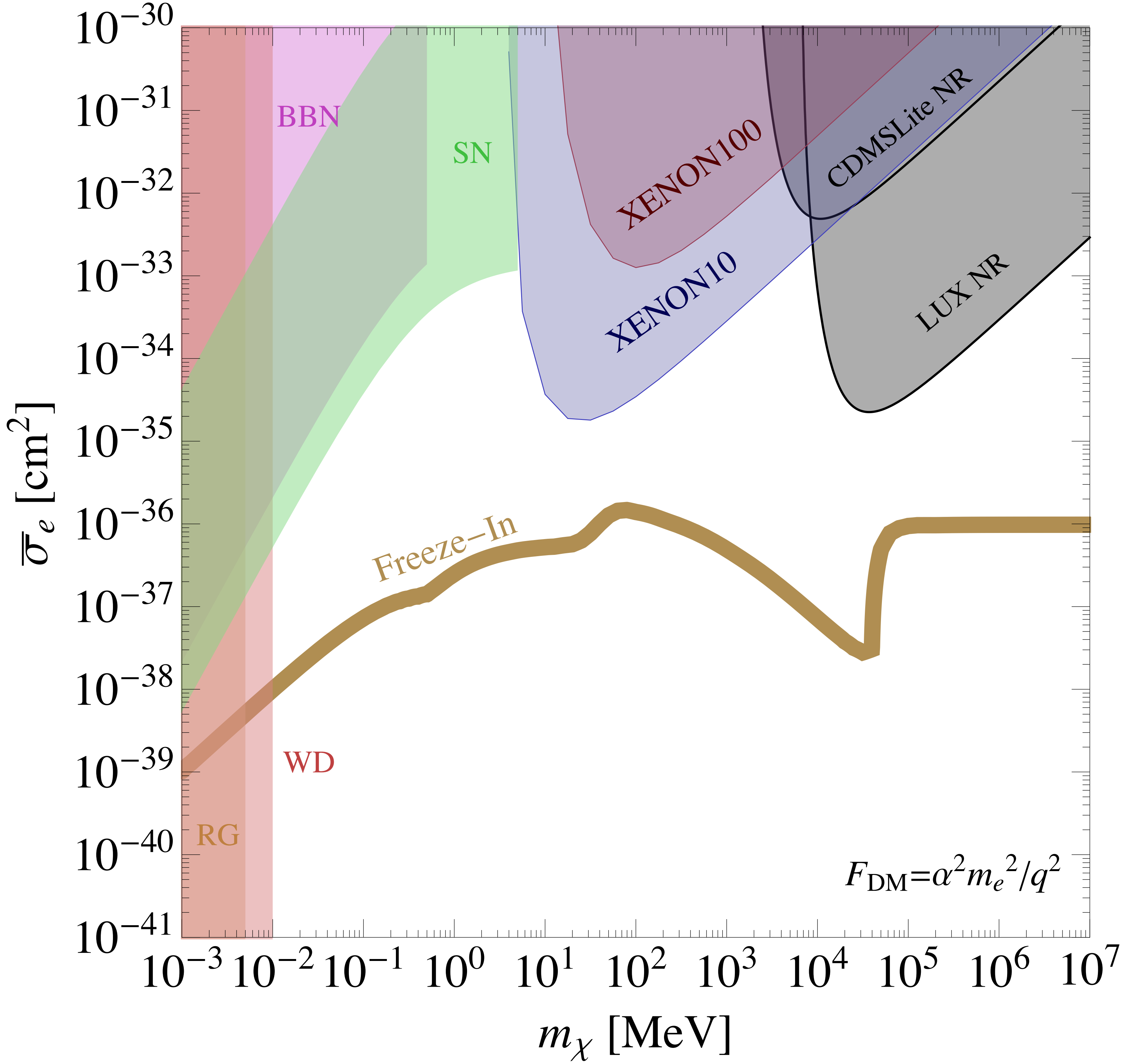


XENON10/100 constraints

RE, Volansky, Yu

updated from

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012



Benchmark targets

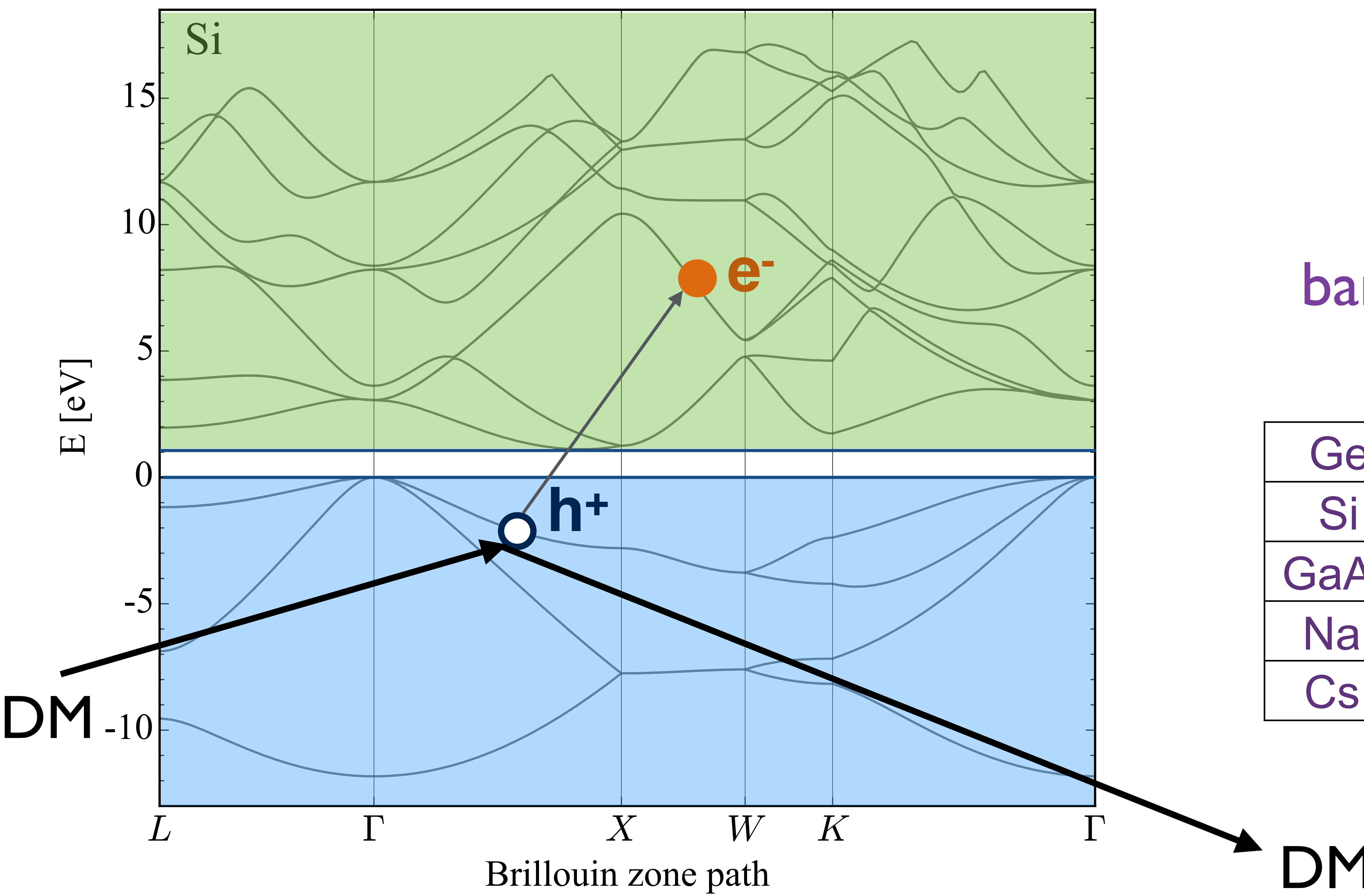
+

All constraints

Outline

- Direct detection concept
- Benchmark models for sub-GeV DM
- Xenon (new constraints & prospects)
- Semiconductors & Scintillators

Semiconductors & Scintillators (schematic)



band gap

[eV]

Ge	0.67
Si	1.1
GaAs	1.5
NaI	5.9
CsI	6.4

QEdark: rate calculations made easy

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

calculating rates is challenging since electron is part of many-body interacting system

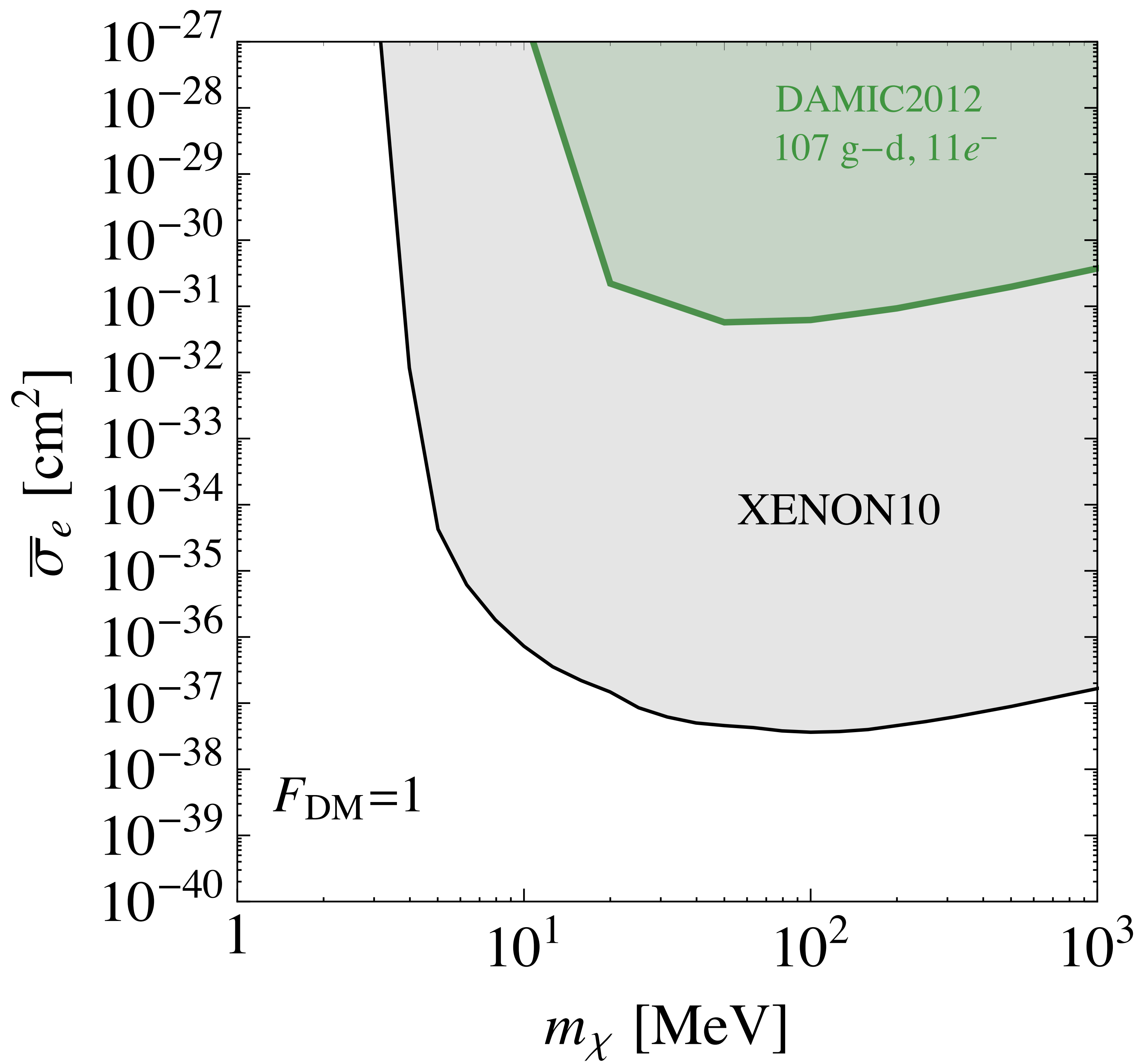
QEdark

http://ddldm.physics.sunysb.edu

input your favorite DM model and DM velocity distribution to calculate rates

Current best semiconductor limit (DAMIC, Si)

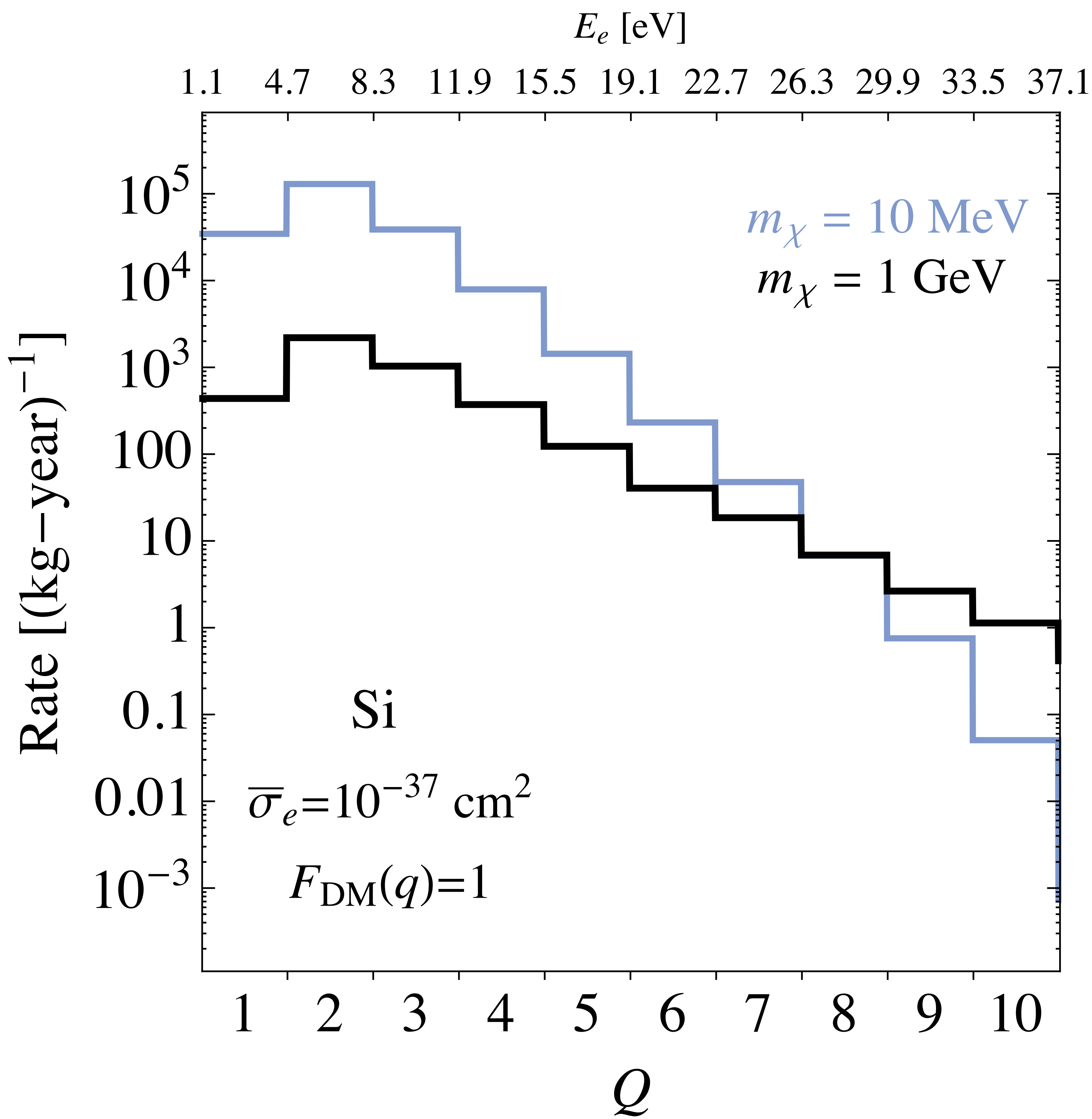
RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu



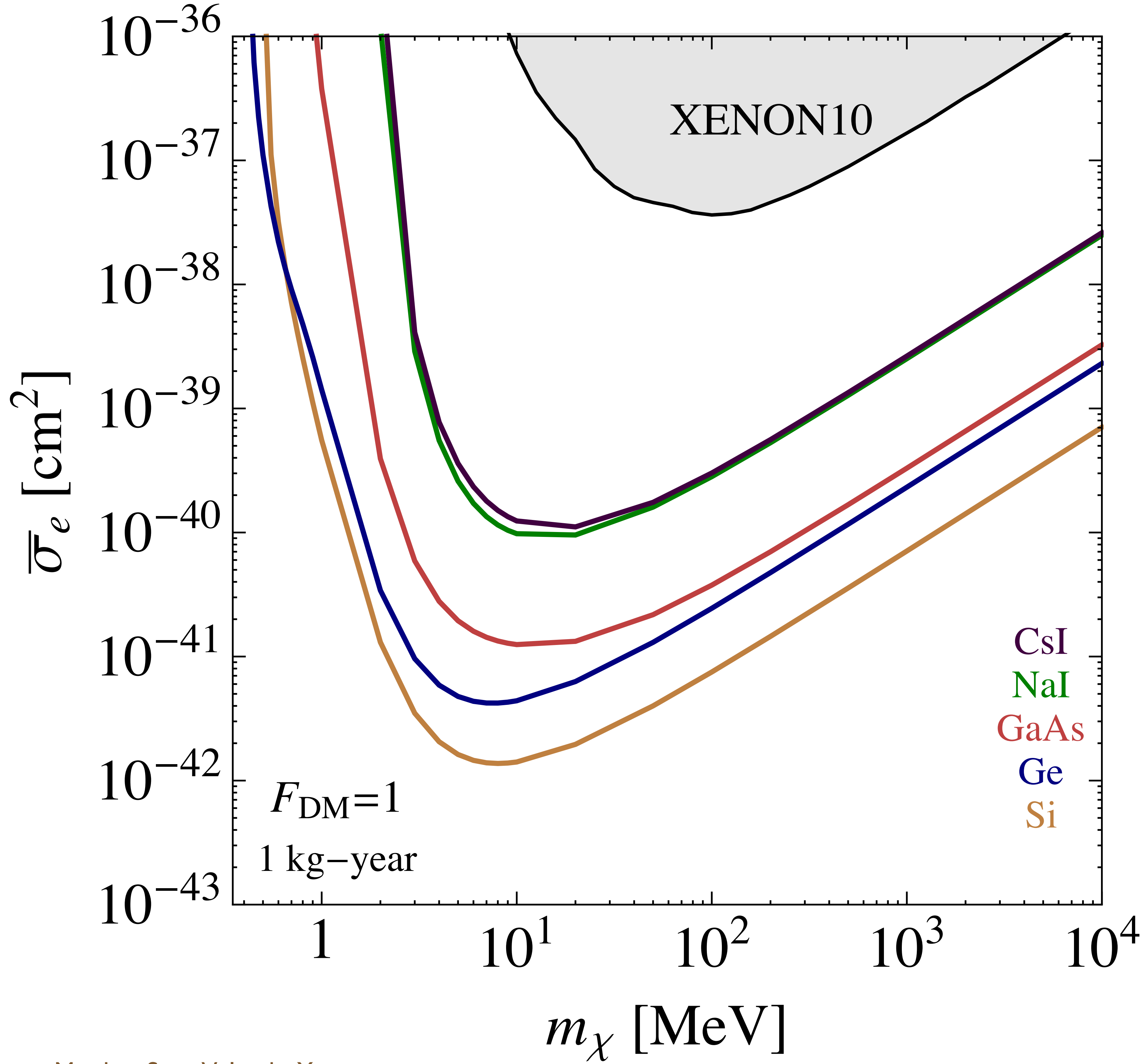
to avoid readout noise, threshold set to ~11 e^-

Rates increase dramatically for lower thresholds

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



Prospects?

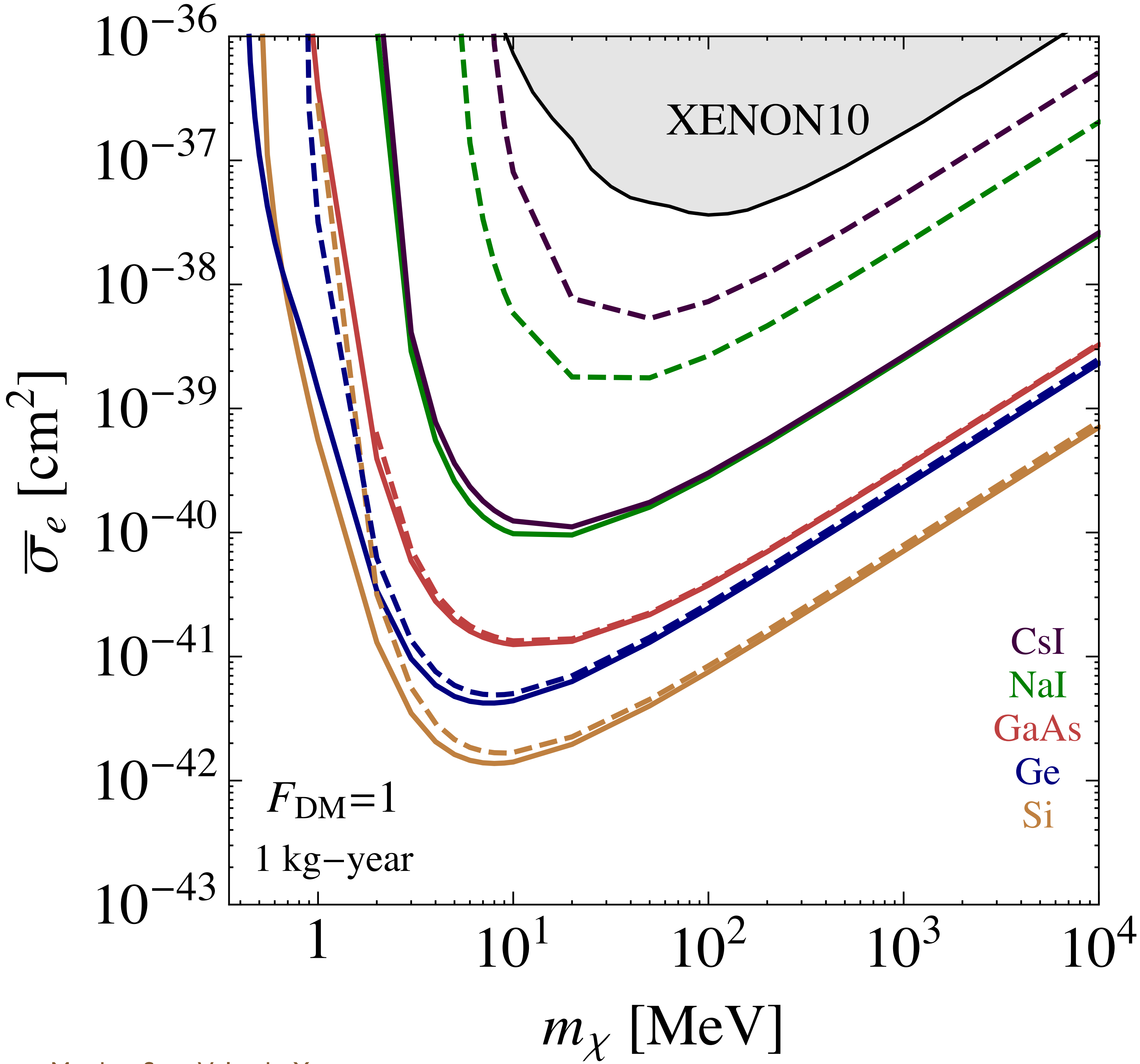


solid:
$\geq 1\gamma$ or $1e^-$

Lines assume 3 events

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

Prospects?



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

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

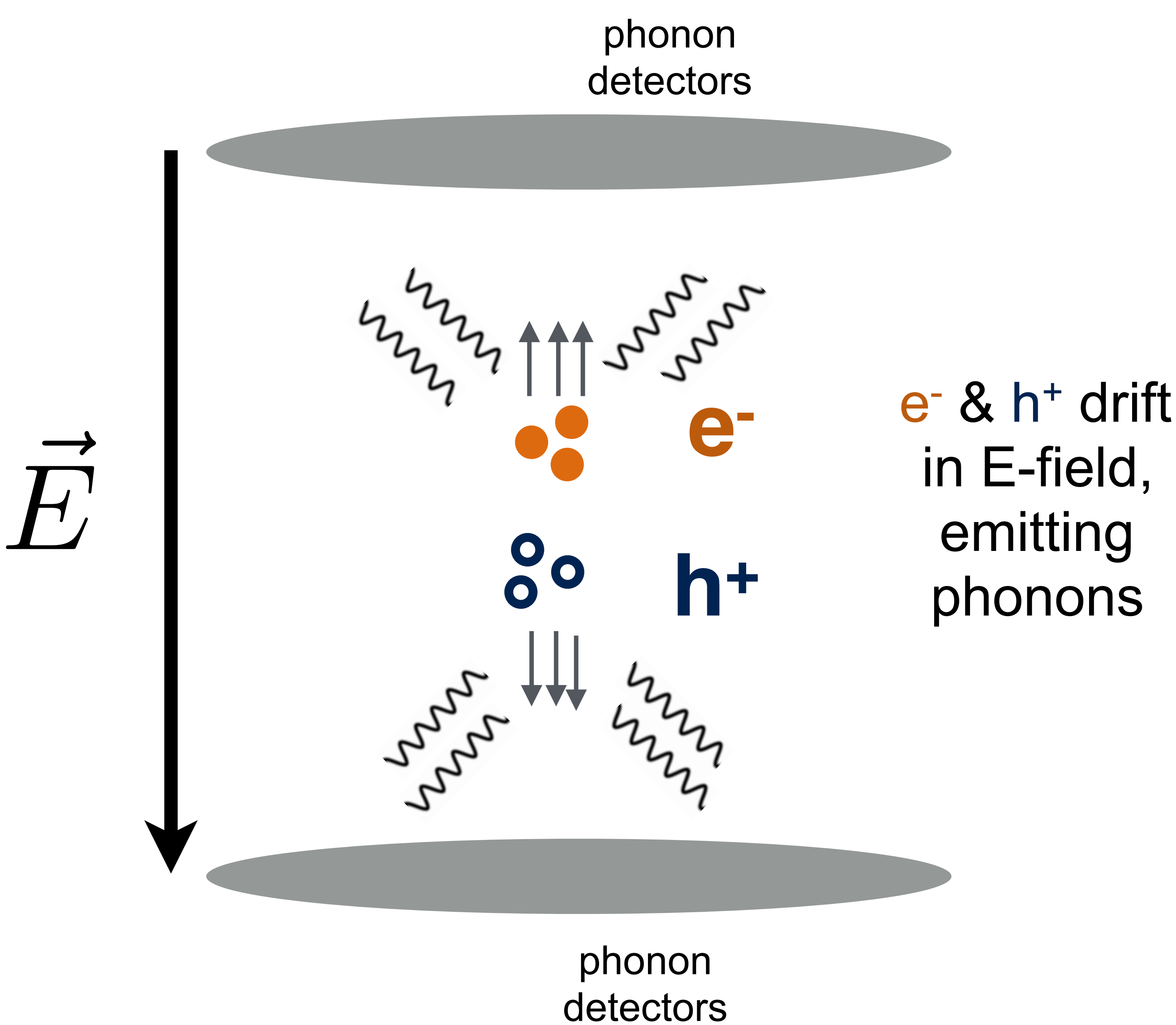
RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Derenzo, RE, Massari, Soto, Yu

Lines assume 3 events

Semiconductors: how detect electrons (I)?

drift e^- in E-field,
measure phonons w/ TES

e.g. CDMSlite,
SuperCDMS



current threshold
~40 eV

Work to lower
thresholds is in progress

Semiconductors: how detect electrons (II)?

use Si CCDs as target: drift & read out charge directly

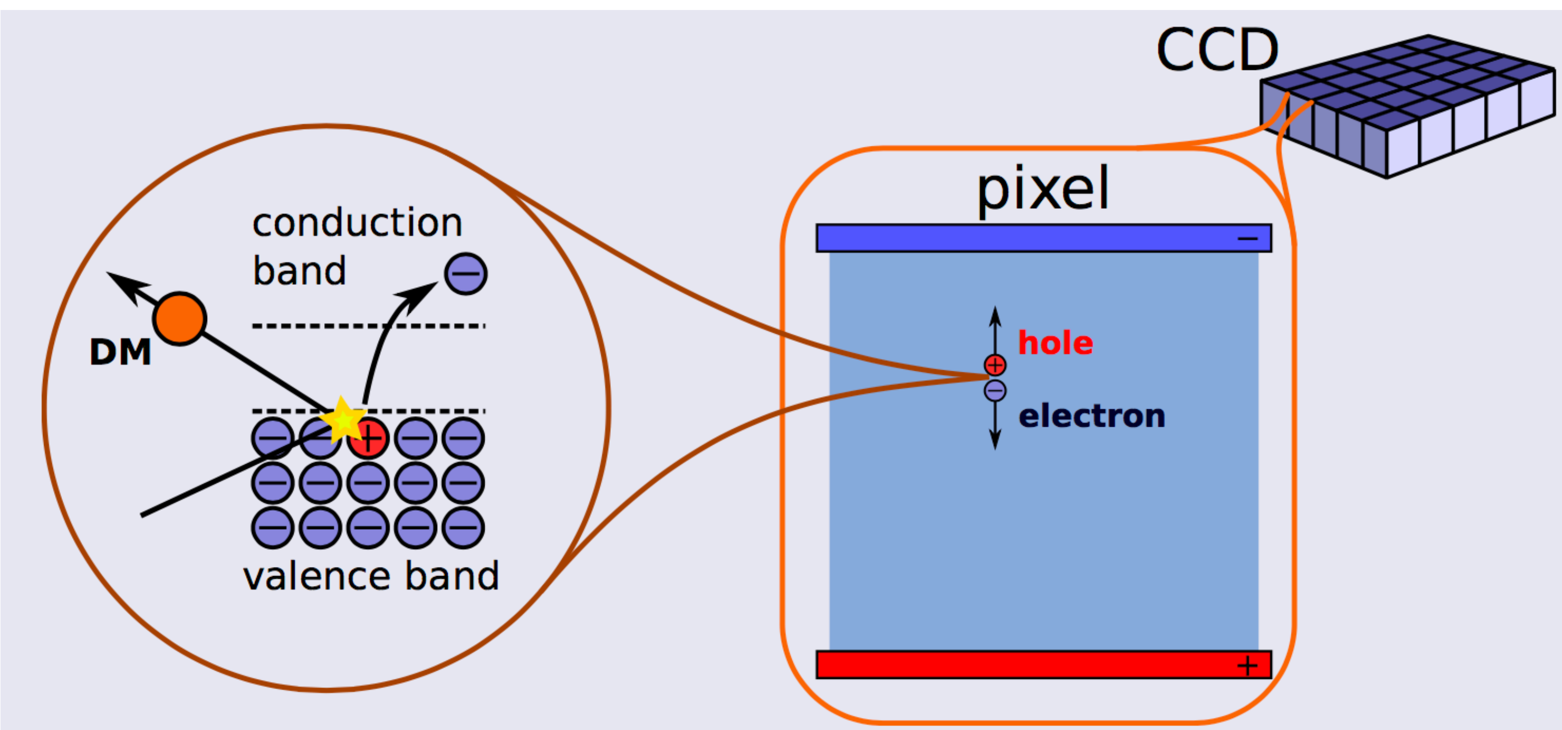
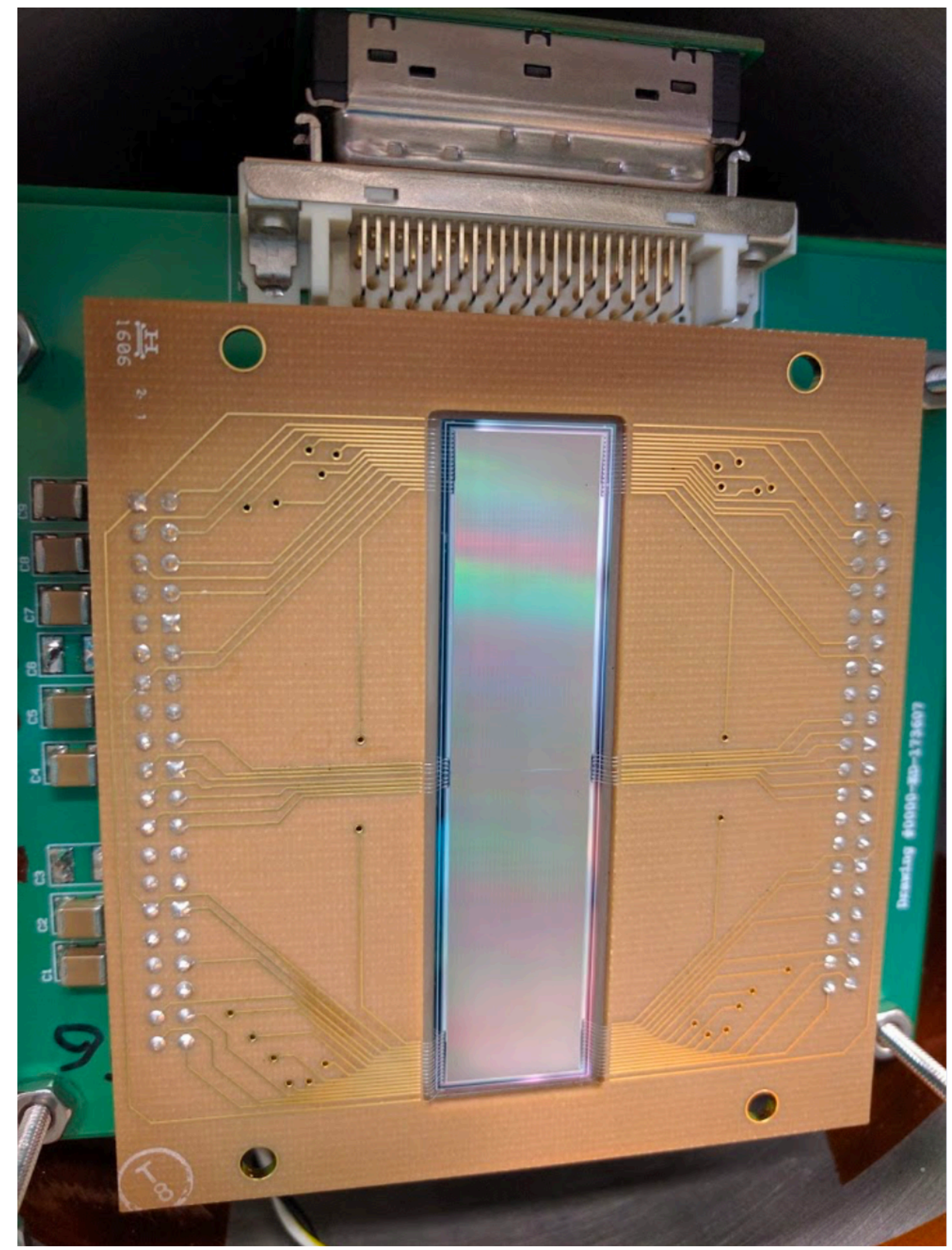


Figure credit: J. Tiffenberg



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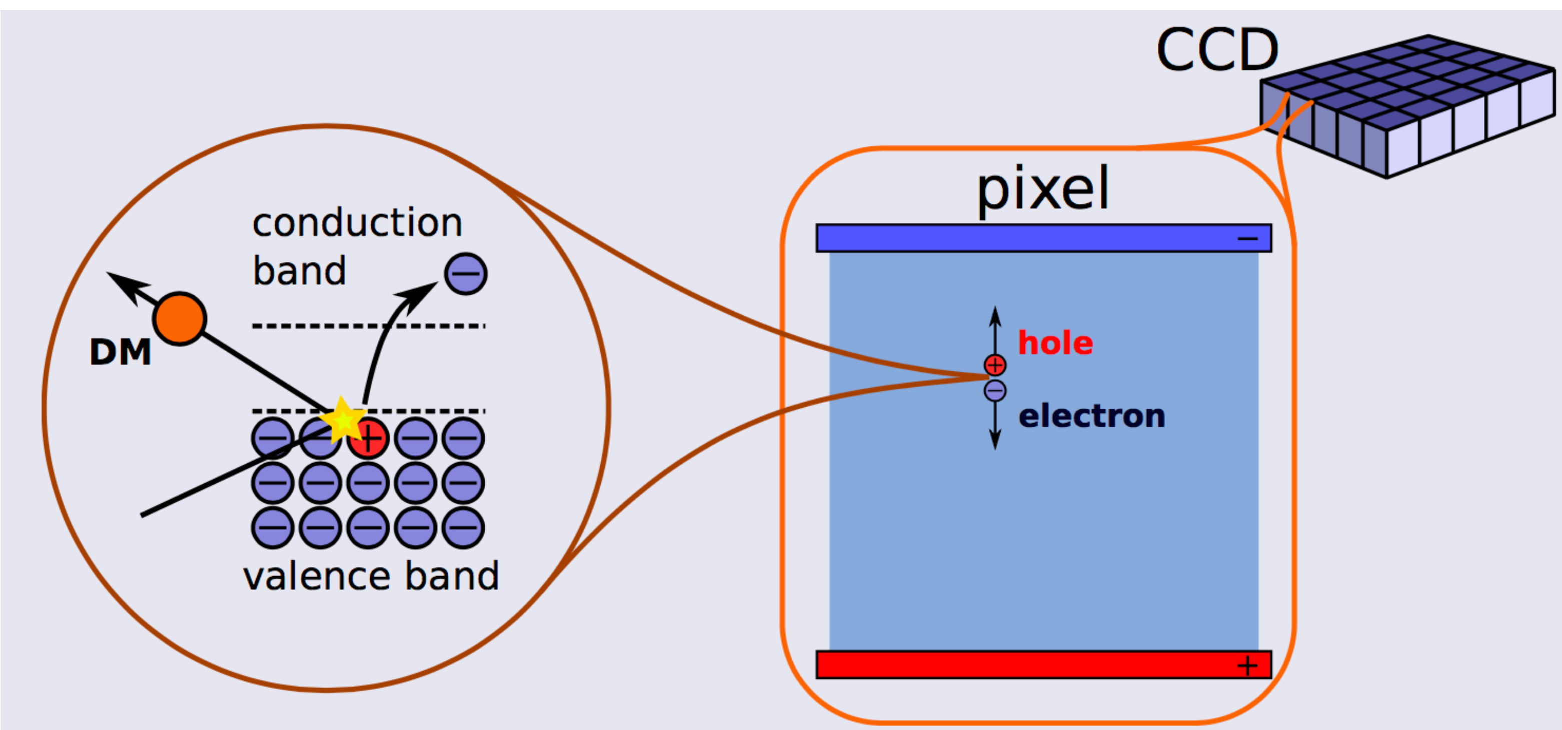


Figure credit: J. Tiffenberg

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

Regular CCD

"large" readout noise

"high" threshold ~ 40 eV

"Skipper" CCD

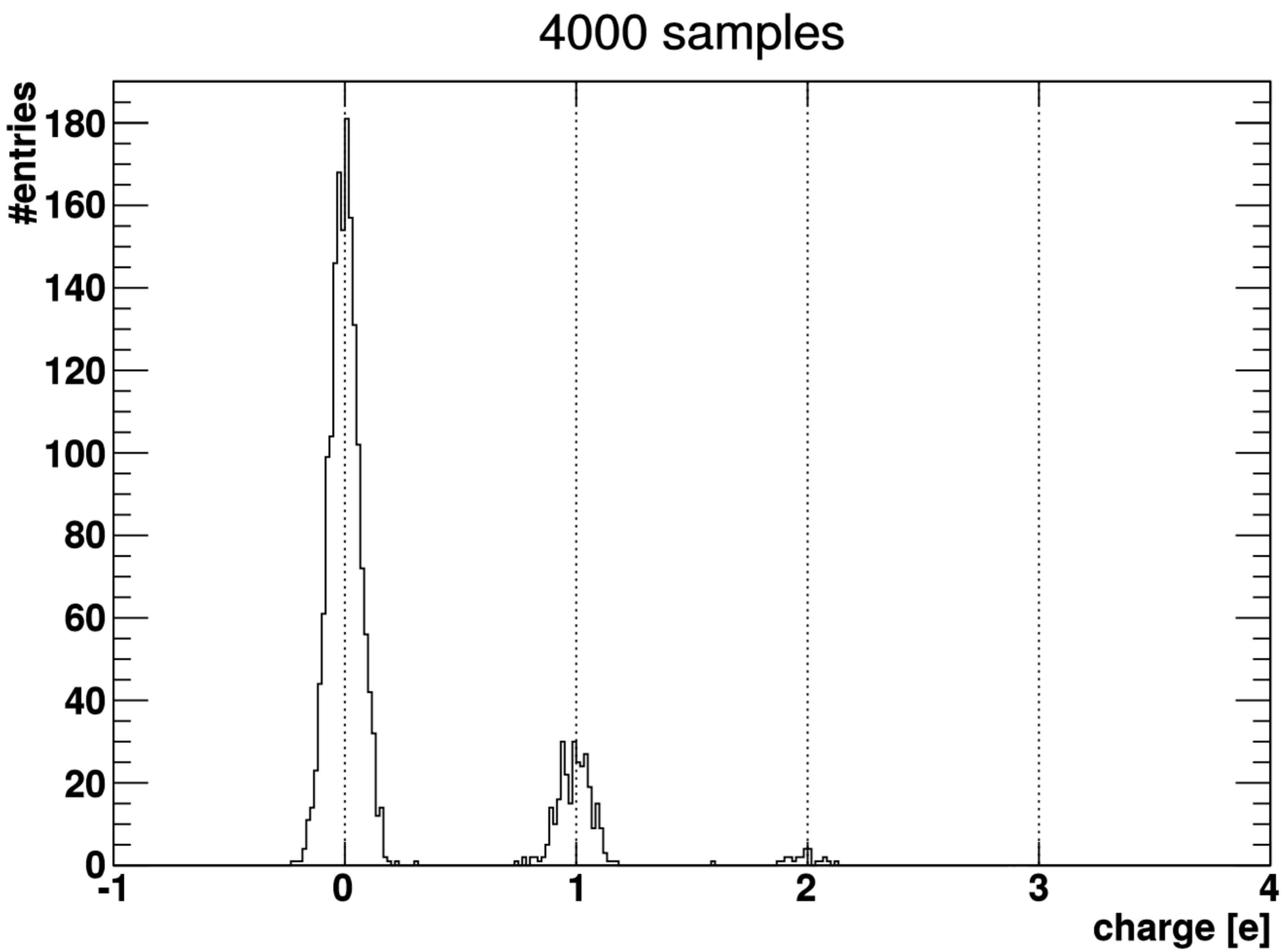
dramatic reduction
in readout noise

threshold ~ few eV !

An exciting new detector: SENSEI

Talk by Javier Tiffenberg, 12/2016

Counting electrons: 0, 1, 2..



Fermilab

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

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)	
$\mathbf{Q_{th}}$	$\mathbf{DC = 1 \times 10^{-3}\ e\ pix^{-1} day^{-1}}$	$\mathbf{DC = 10^{-7}\ e\ pix^{-1} day^{-1}}$
1	1×10^{8}	1×10^{4}
2	2×10^{4}	2×10^{-5}
3	3×10^{-2}	3×10^{-14}

J. Tiffenberg

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J. Tiffenberg

(measured <u>upper</u> limit) (theoretical expectation)

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J. Tiffenberg

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J. Tiffenberg

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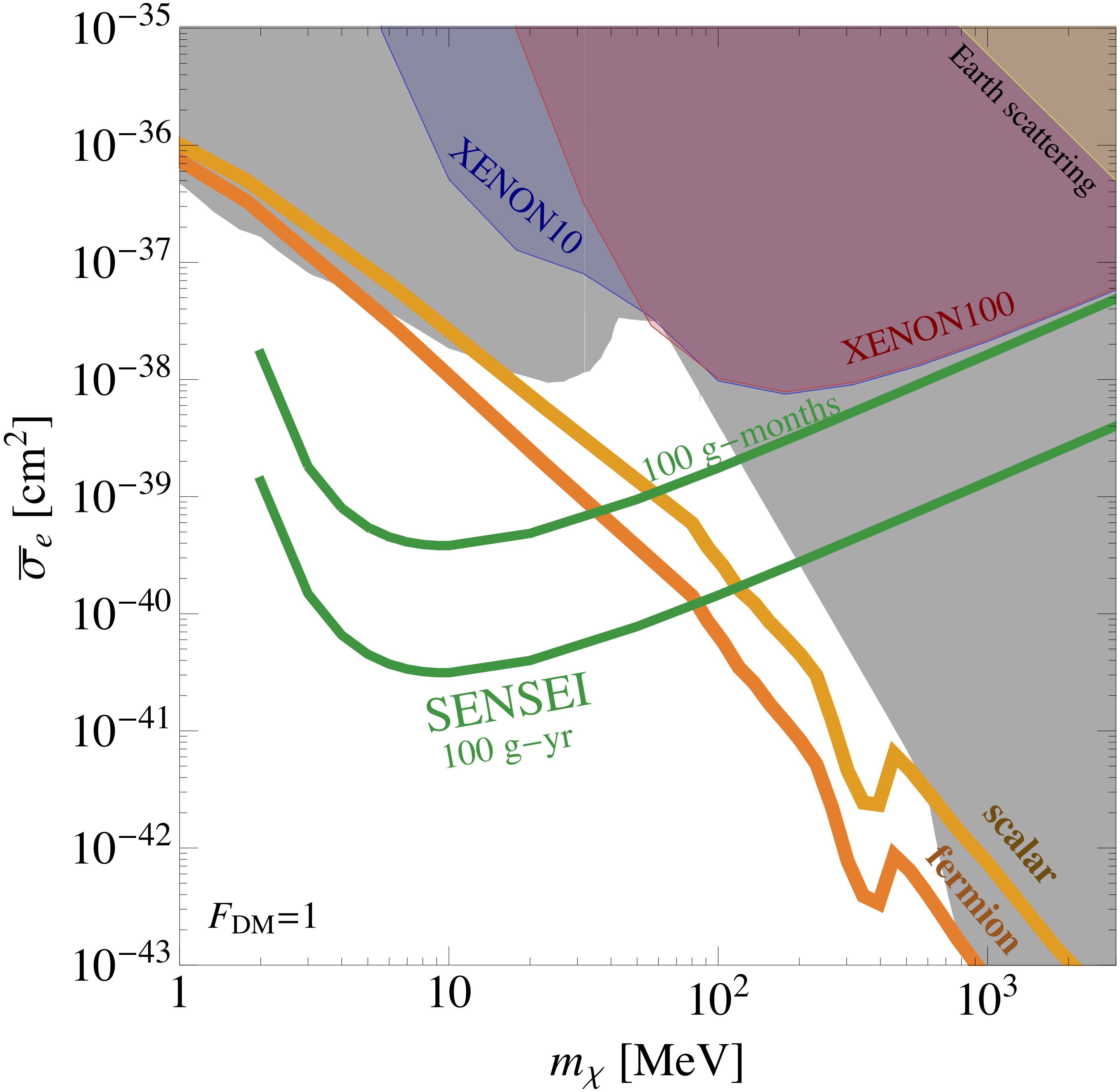
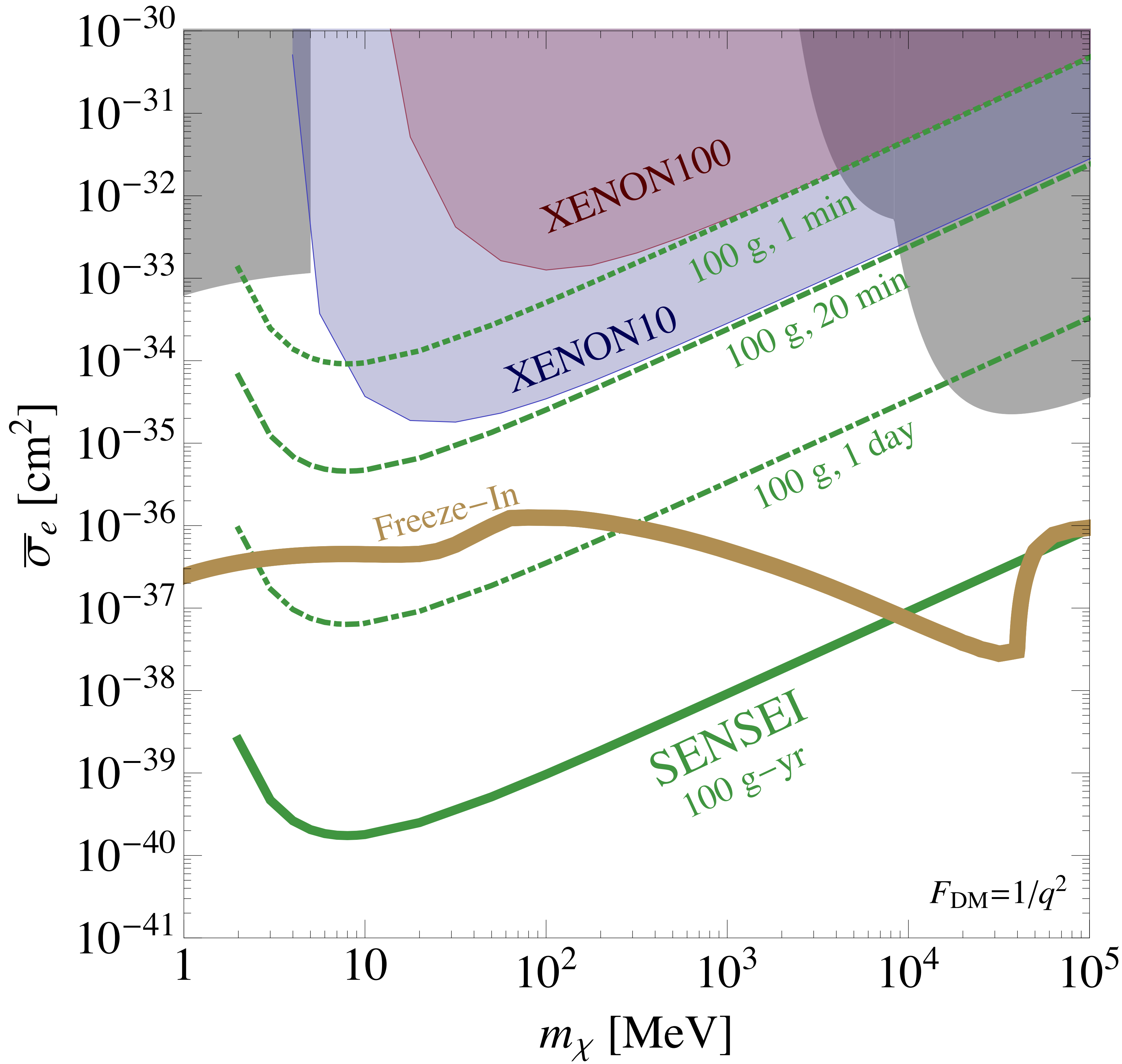
Prospects for SENSEI-like experiment



assumes expected background <1 event

Prospects for SENSEI-like experiment



100 gram detector probes new parameter space in <1 minute

1 gram detector would improve on XENON10 in ~1 day

Summary

- DD can probe DM via scattering to $\lesssim$1 MeV (and via absorption to ~eV), and possibly much lower
- Benchmark models provide sharp targets
- Xenon experiments have demonstrated sensitivity (significant improvements possible if backgrounds can be mitigated)
- semiconductors, scintillators etc have great potential
- SENSEI, SuperCDMS, $U_{A'}(1)$ could probe vast new regions of uncharted territory in next ~2–3 years