Some Recent Progress & Challenges for Direct-Detection of Sub-GeV Dark Matter

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Dark Pollica, June 6, 2022

Outline

- Some Recent Progress
- Sources of Low-Energy Backgrounds
- Diurnal Modulation
- New Detection Concepts
- Calibrating the Migdal Effect w/ Neutrons

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- Sources of Low-Energy Backgrounds
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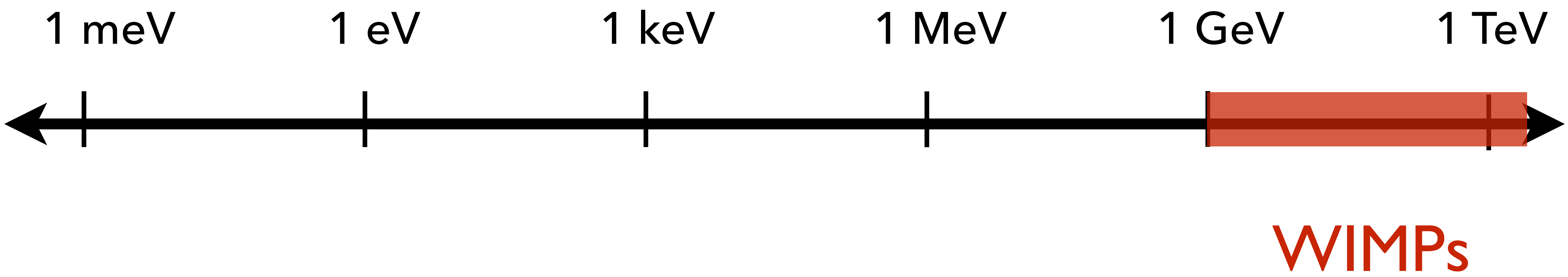
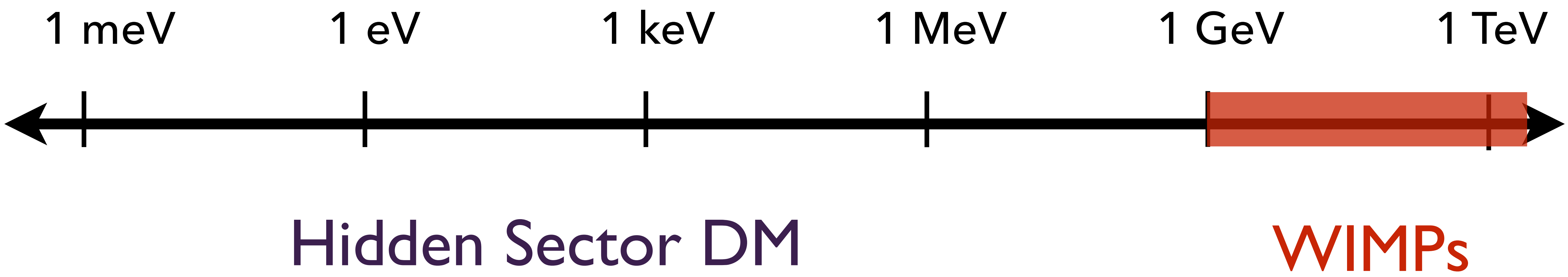
- New Detection Concepts
- Calibrating the Migdal Effect w/ Neutrons


1 meV
1 eV
1 keV
1 MeV
1 GeV
1 TeV
WIMPs


1 meV
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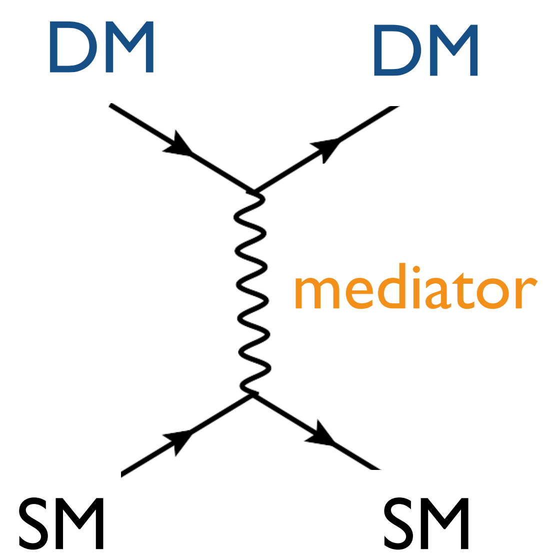
Hidden Sector DM
WIMPs

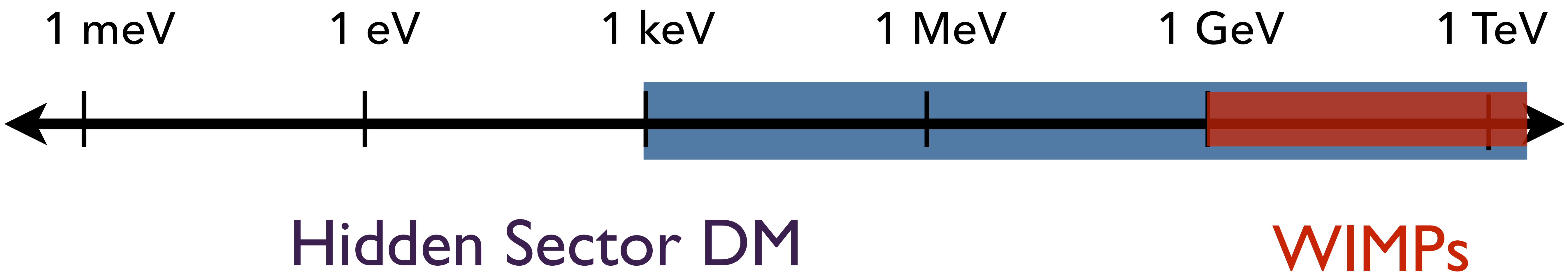
Hidden Sector DM

WIMPs

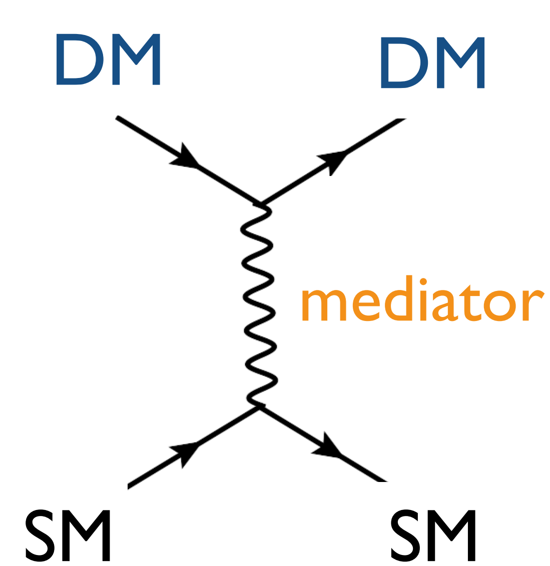
DM Scattering



need to probe nuclear <u>and</u> electron interactions



DM Scattering

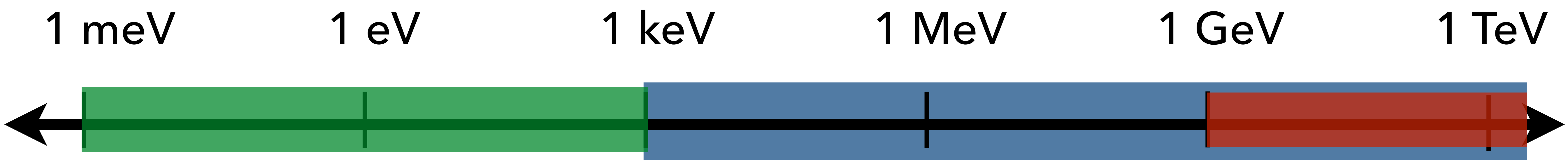


need to probe nuclear <u>and</u> electron interactions

see e.g. Boehm & Fayet; Borodatchenkova, Choudhury, Drees; Kaplan, Luty, Zurek; Falkowski, Ruderman, Volansky; RE, Mardon, Volansky; Chu, Hambye, Tytgat; Hochberg, Kuflik, Volansky, Wacker; +Murayama; Izaguirre, Krnjaic, Schuster, Toro; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; Kuflik, Lorier, Perelstein, Tsai; Farina, Pappadopulo, Ruderman, Trevisan; D'Agnolo, Ruderman…

several DM production scenarios

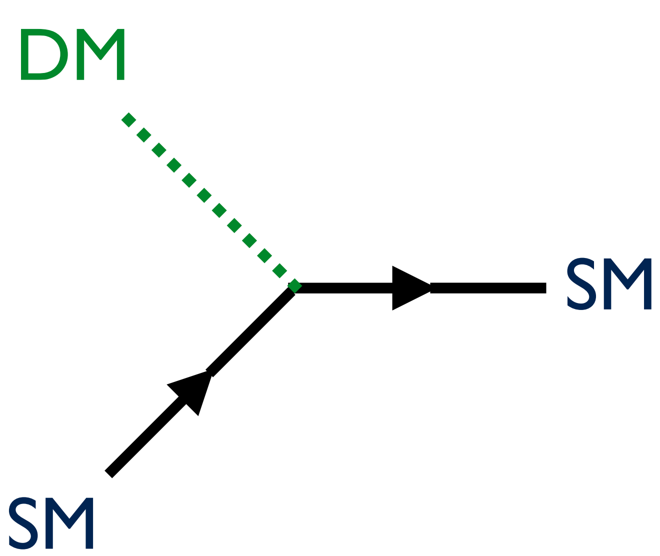
(e.g. freeze-out, asymmetric, freeze-in, SIMP, ELDER)



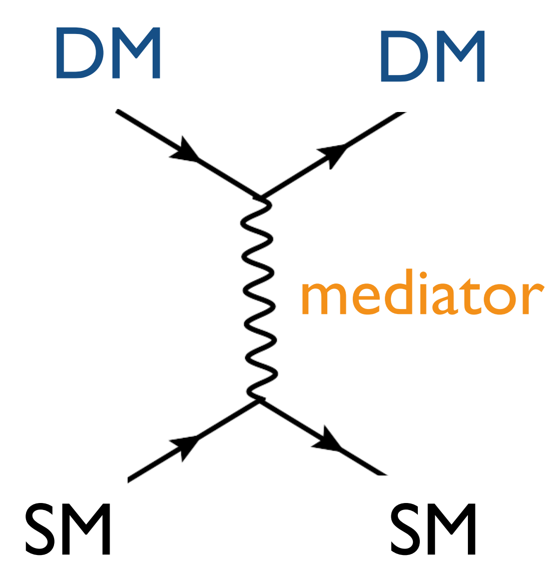
Hidden Sector DM

WIMPs

DM Absorption (bosons)



DM Scattering



need to probe nuclear and electron interactions

several DM production scenarios

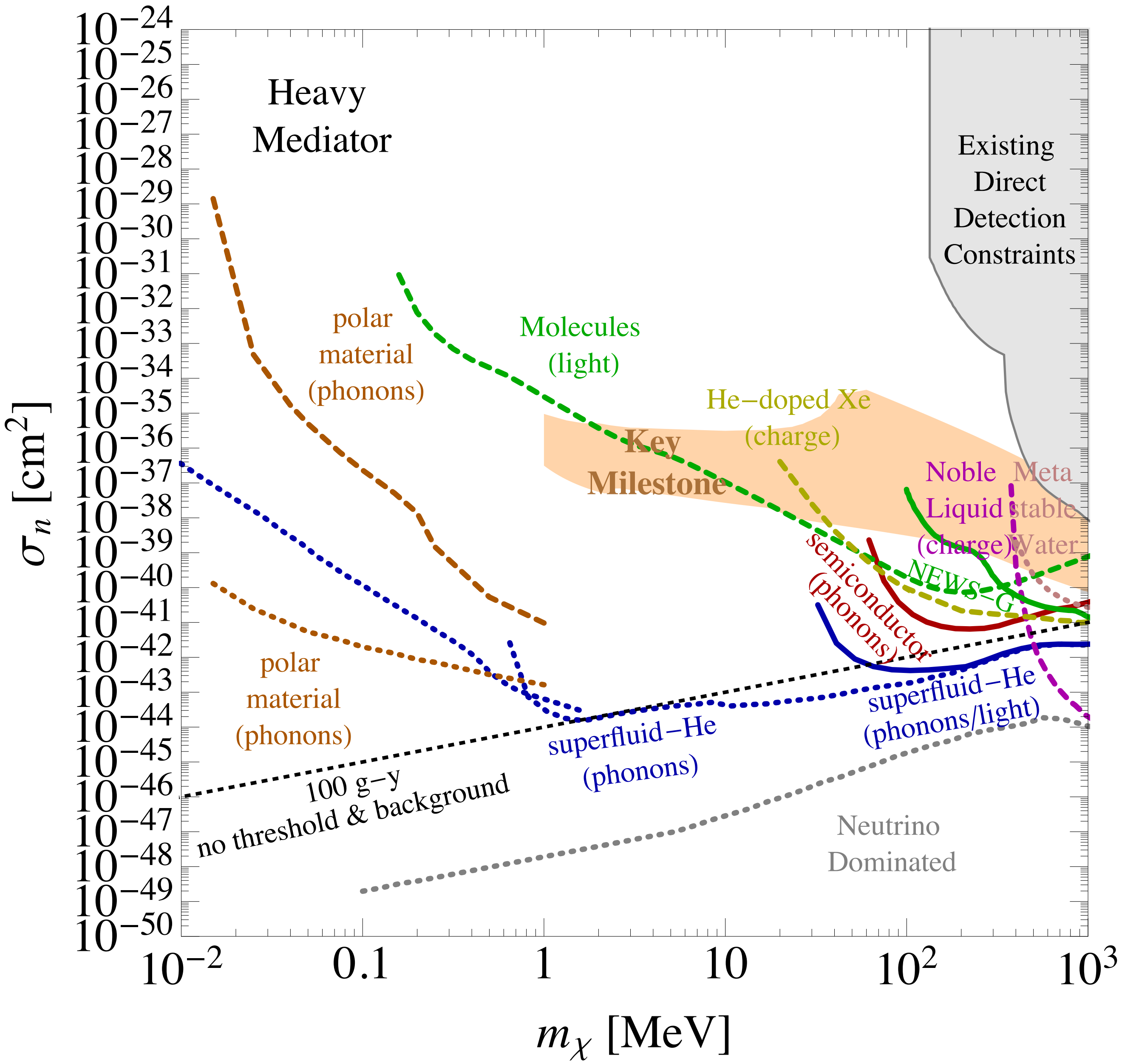
(e.g. freeze-out, asymmetric, freeze-in, SIMP, ELDER)

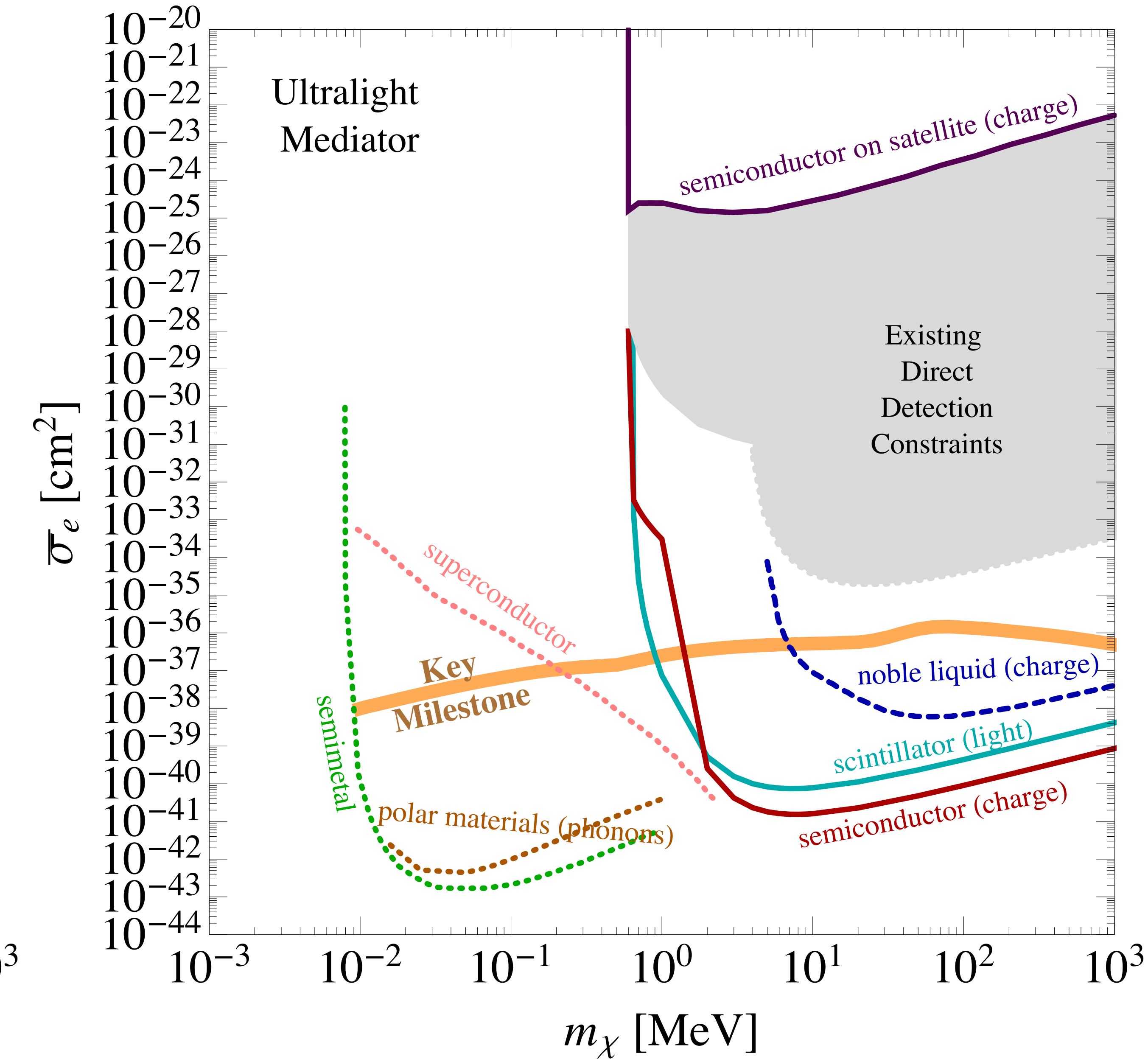
Significant progress in probing sub-GeV dark matter

- Theory:
  - several detection concepts, using variety of target materials
  - improved calculations of DM scattering in crystals
  - improved understanding of low-energy backgrounds

Many Detection Concepts

- DM scattering: $m_\chi \gtrsim \mathrm{keV}$

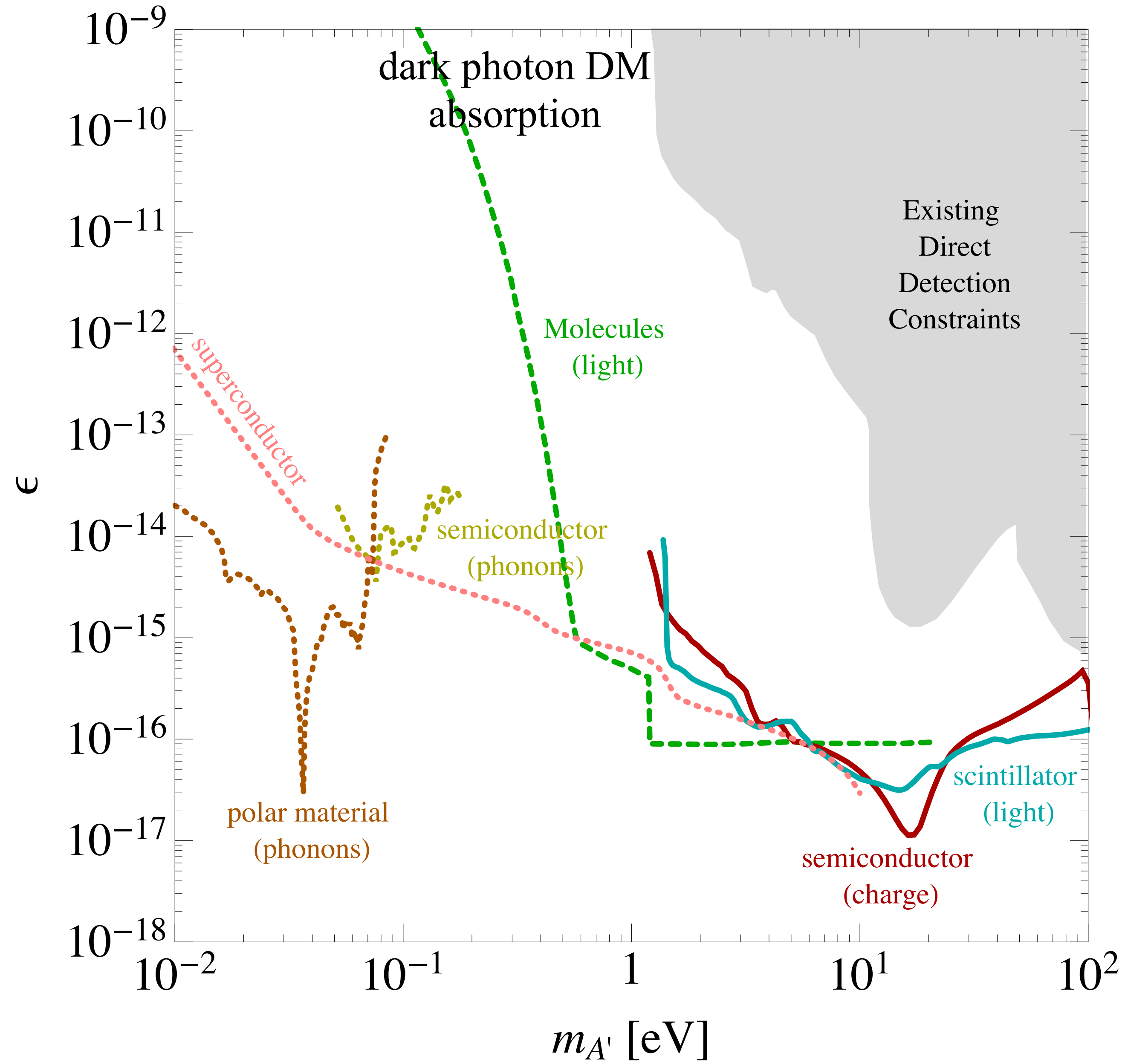




Figs from US DOE Basic Research Needs report 2018 (slightly outdated)

Many Detection Concepts

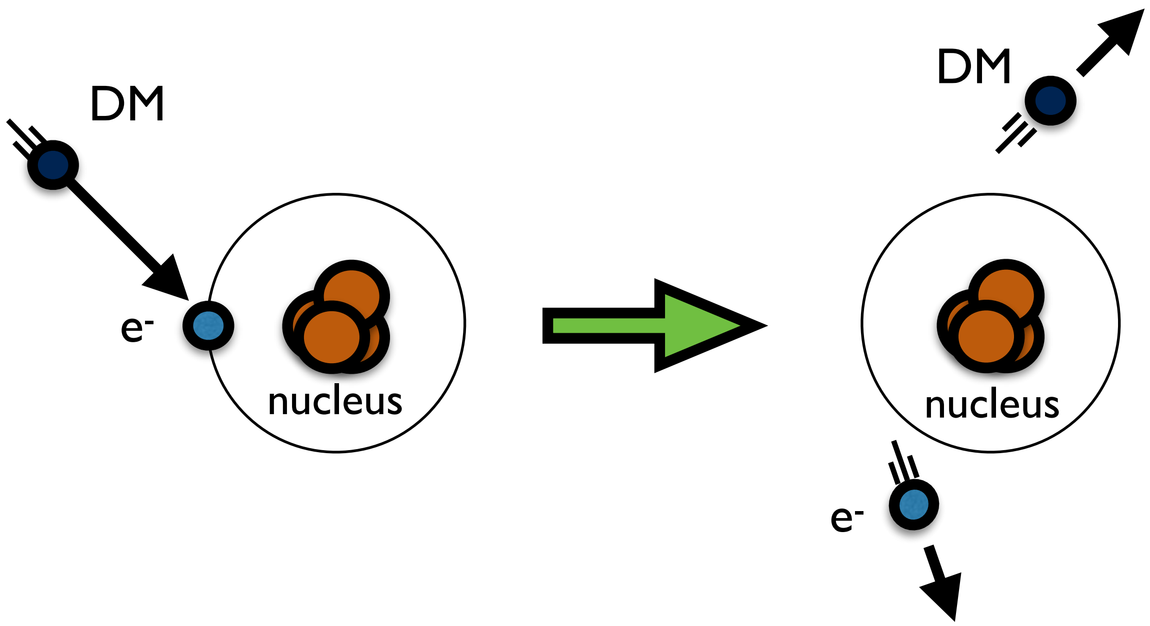
- DM scattering: $m_\chi \gtrsim \text{keV}$
- (bosonic) DM absorption: $m_\chi \gtrsim \text{meV}$



Figs from US DOE Basic Research Needs report 2018 (slightly outdated)

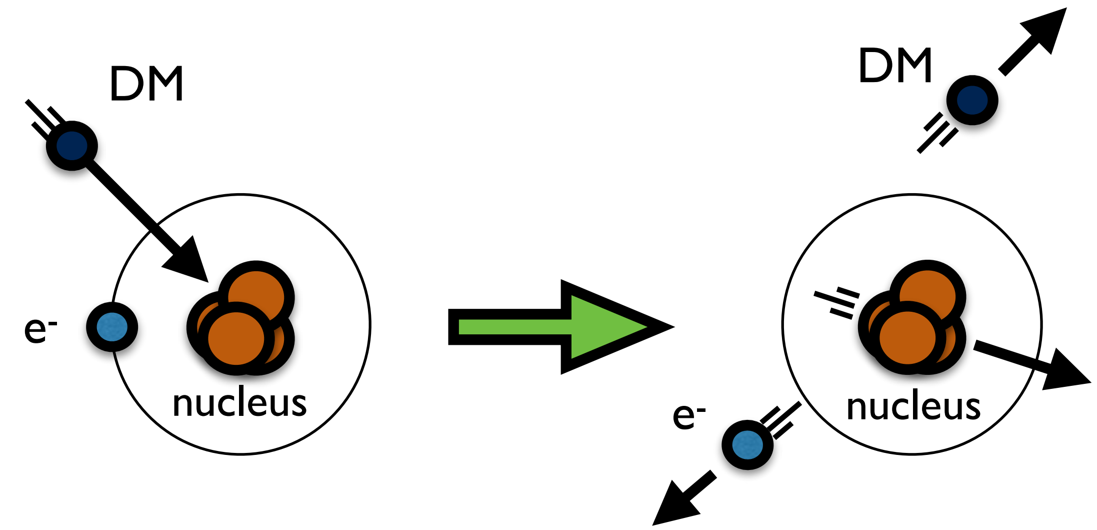
Main concepts currently used to probe DM ≪ GeV

- DM-e scattering:



RE, Mardon, Volansky

- DM-N scattering, Migdal effect:



Migdal; Vergados & Ejiri; Bernabei; Ibe, Nakano, Shoji, Suzuki

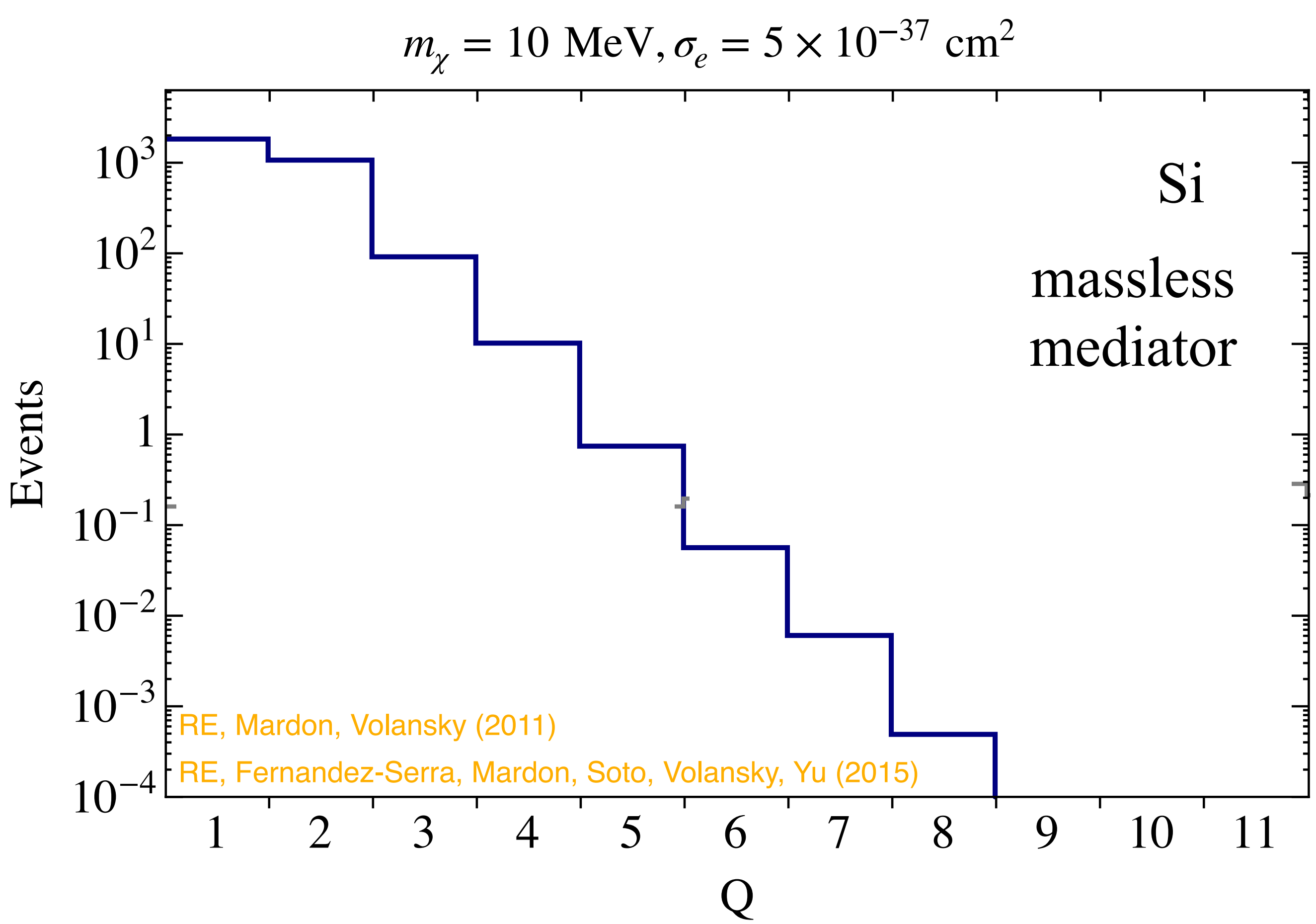
Allows transfer of O(1) amount of DM kinetic energy

$$E_{\rm kin} = \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 1 \text{ eV} \left(\frac{m_{\rm DM}}{500 \text{ keV}} \right) \qquad (v_{\rm DM}^{\rm max} \sim 2 \times 10^{-3})$$

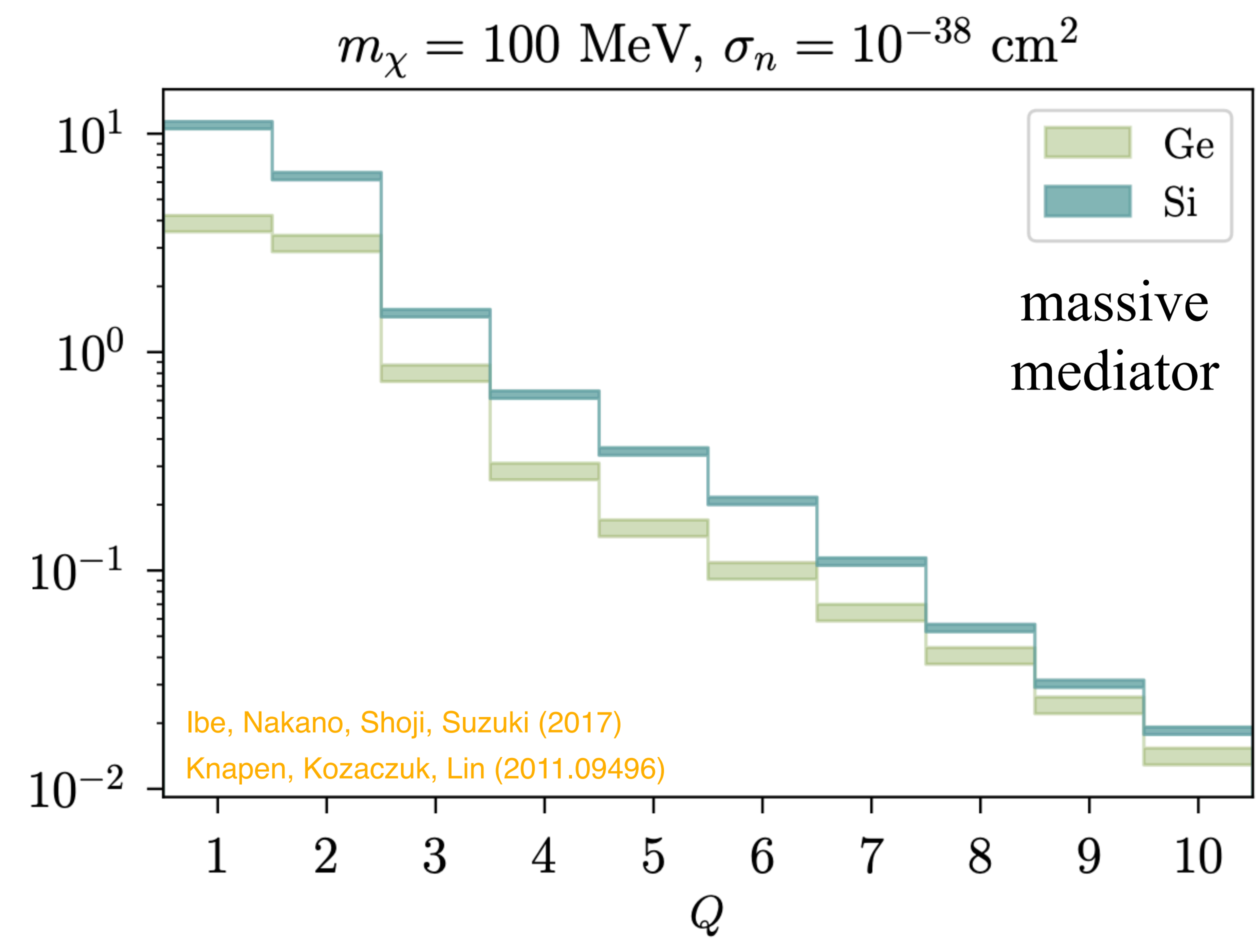
Typically produces a signal of only <u>one</u> to a <u>few</u> <u>electrons</u>

Spectrum of electrons produced by DM scattering

DM-electron scattering



DM-nucleus scattering (Migdal)

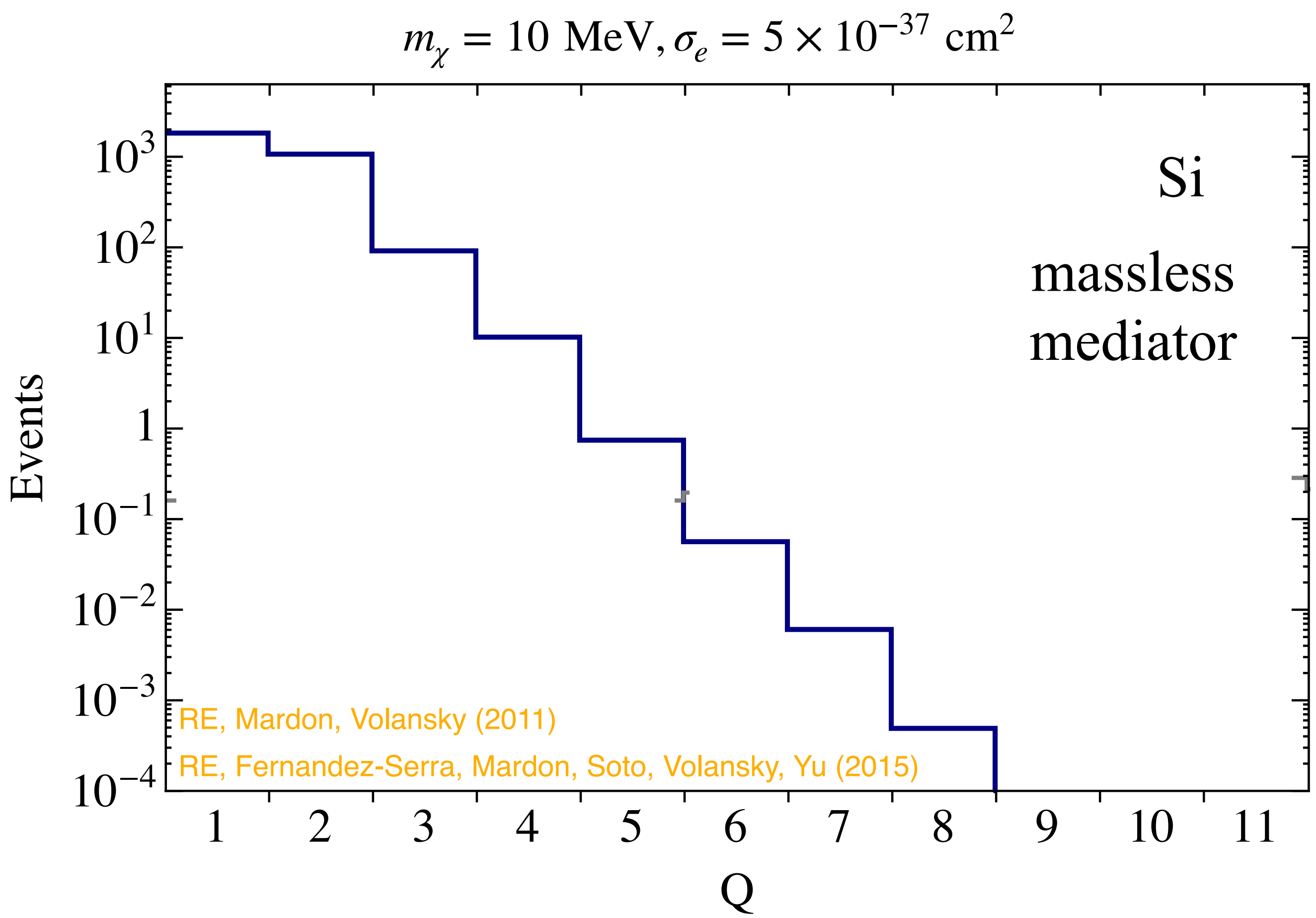


in both cases, have a sharply rising spectrum towards lower energies:

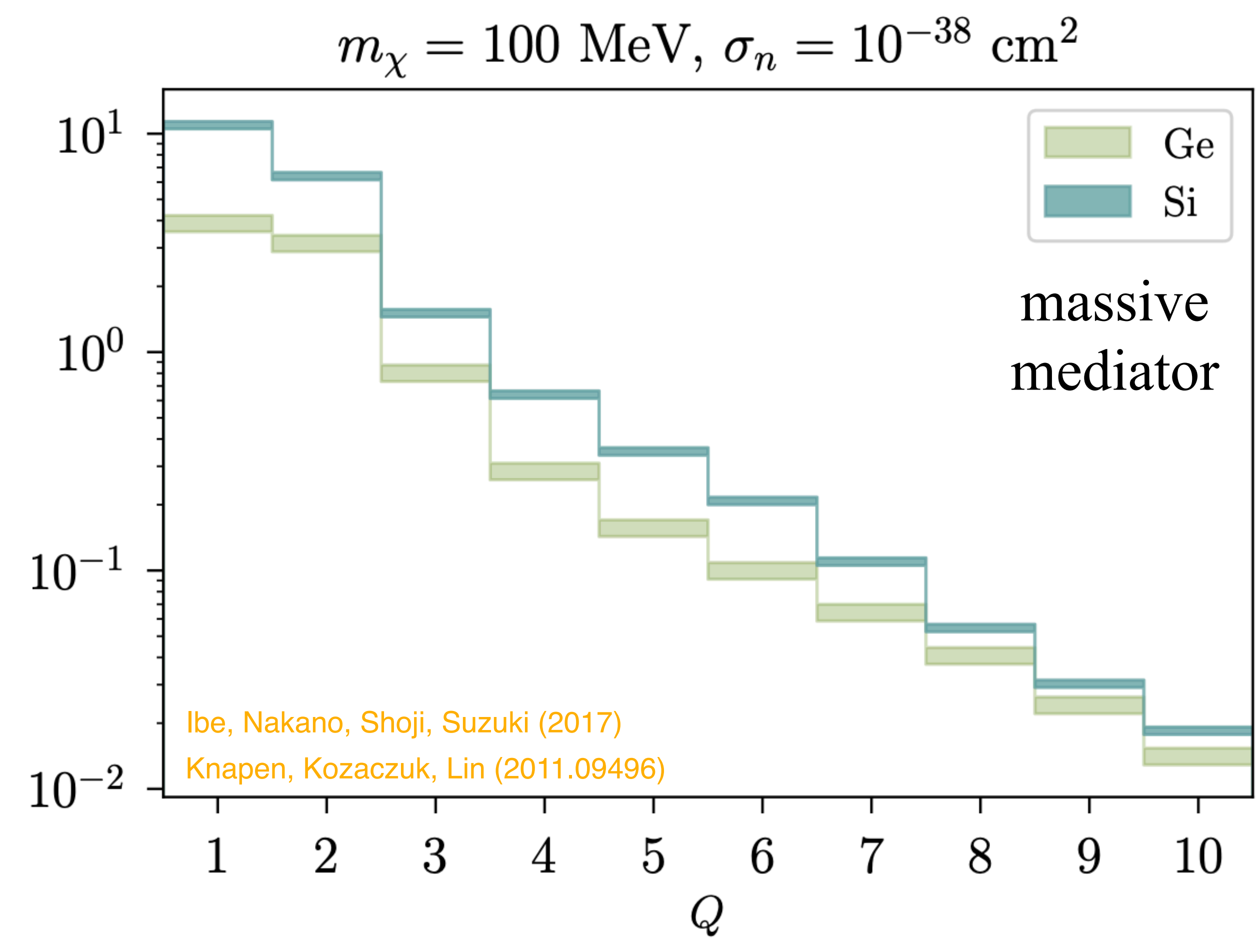
single/few-electron sensitivity is crucial for capturing more potential DM events

Spectrum of electrons produced by DM scattering

DM-electron scattering



DM-nucleus scattering (Migdal)



various theory improvements for calculating scattering rates in crystals, e.g.

relate rates to electron loss function of crystal; crystal form factors for general DM-electron interactions; include all electrons (not only valence)

Knapen, Kozaczuk, Lin (2101.08275, 2104.12786); Hochberg, Kahn, Kurinsky, Lehmann, Yu (2101.08263)

Catena, Emken, Matas, Spaldin, Urdshals (2105.02233)

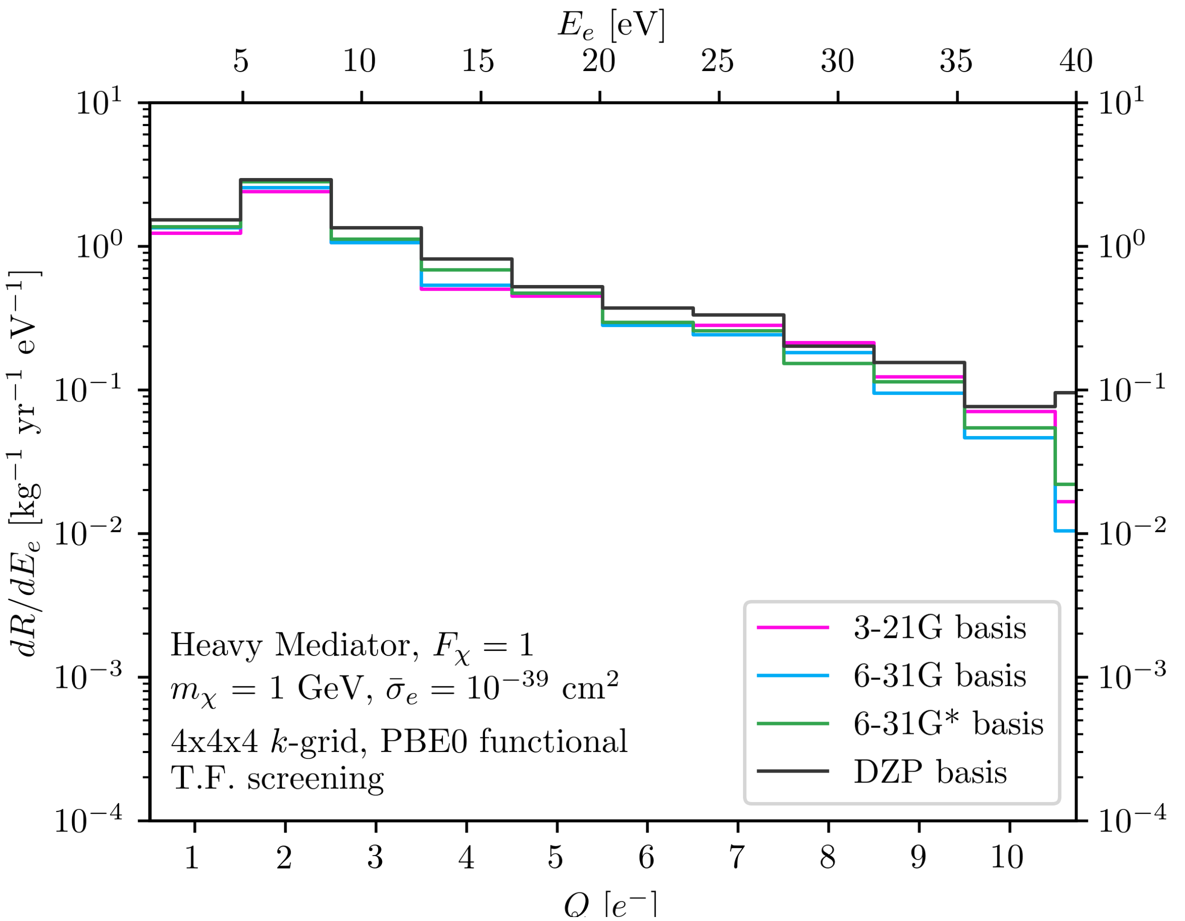
Griffin, Inzani, Trickle, Zhang, Zurek (2105.05253)

Dreyer, RE, Fernandez-Serra, Singal, Zhen (to appear)

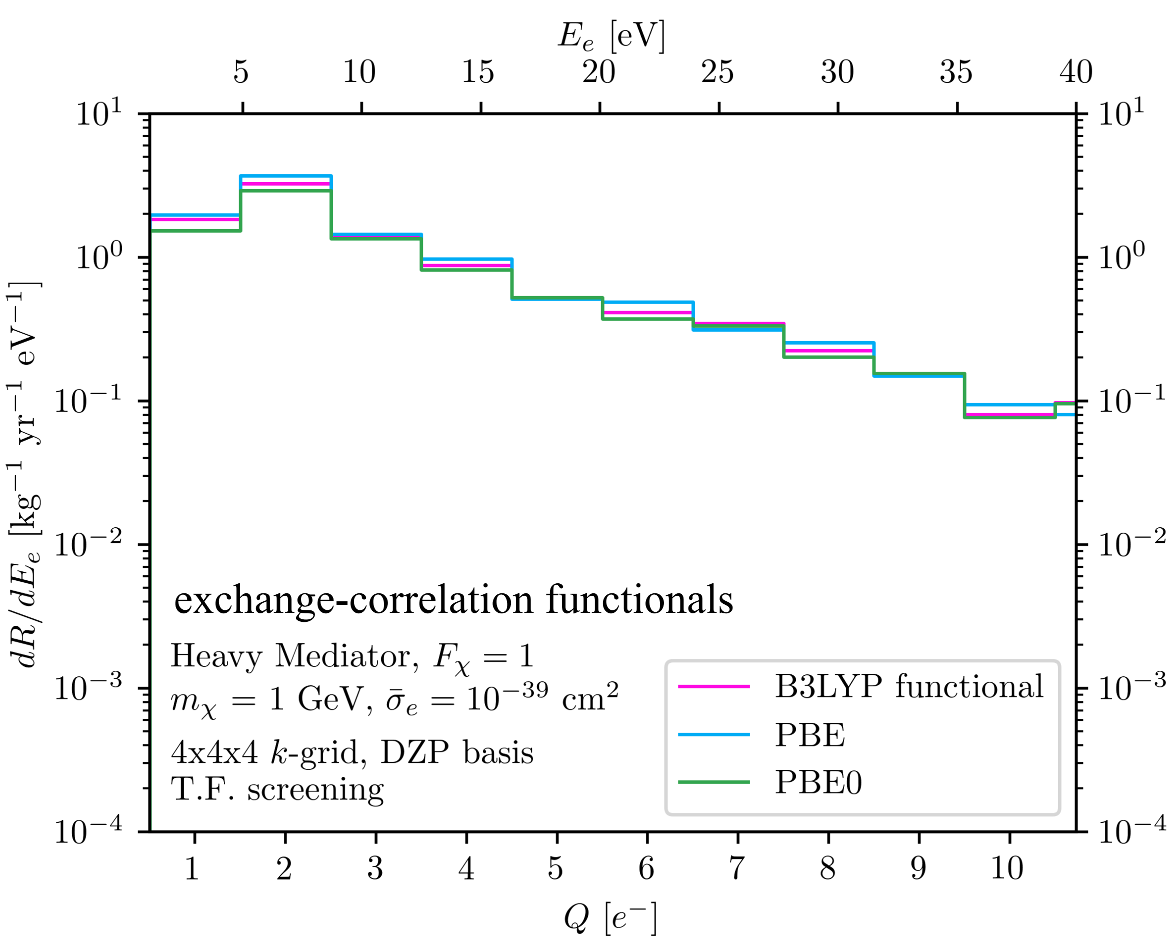
Theory uncertainties are being evaluated

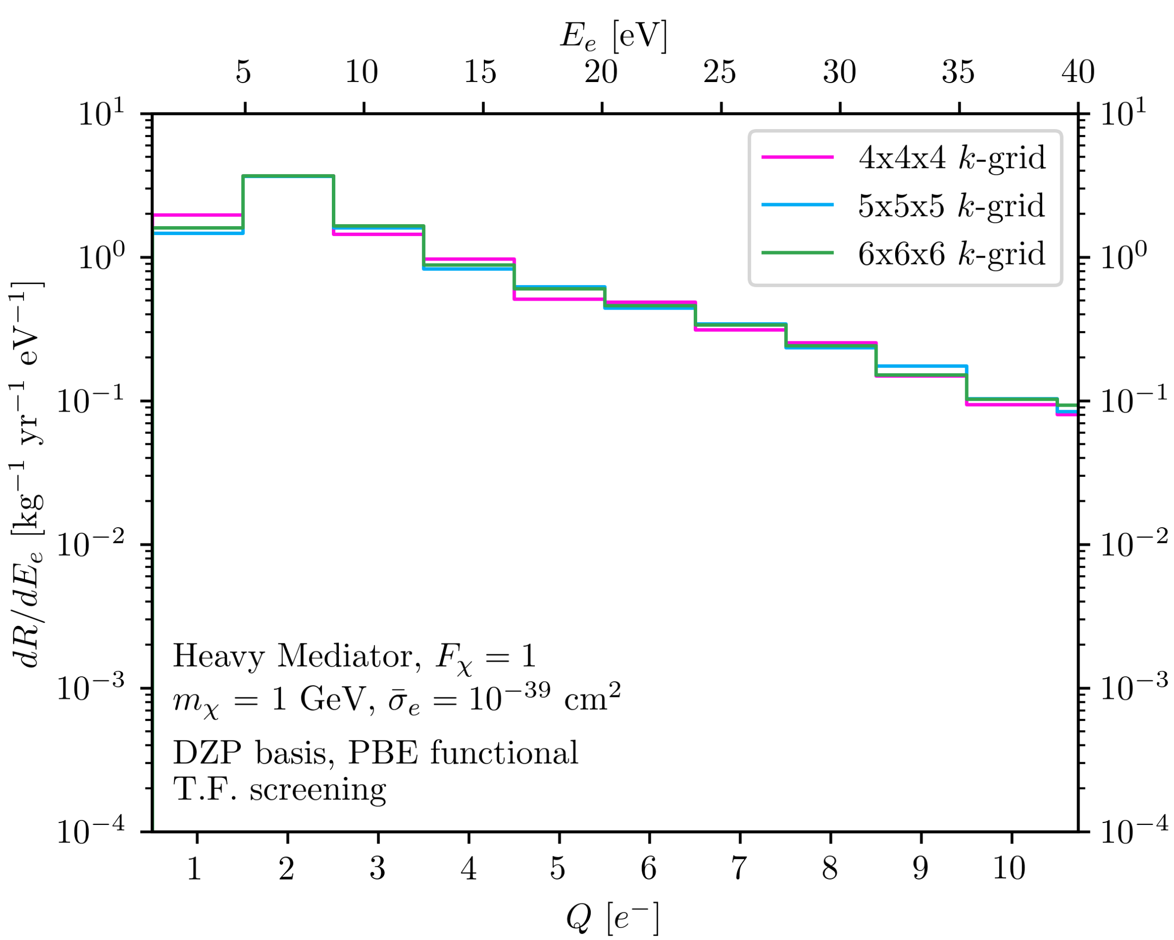
DM-electron scattering

Dreyer, RE, Fernandez-Serra, **Aman Singal**, Cheng Zhen (in progress)



theory uncertainties are not zero, but are under control

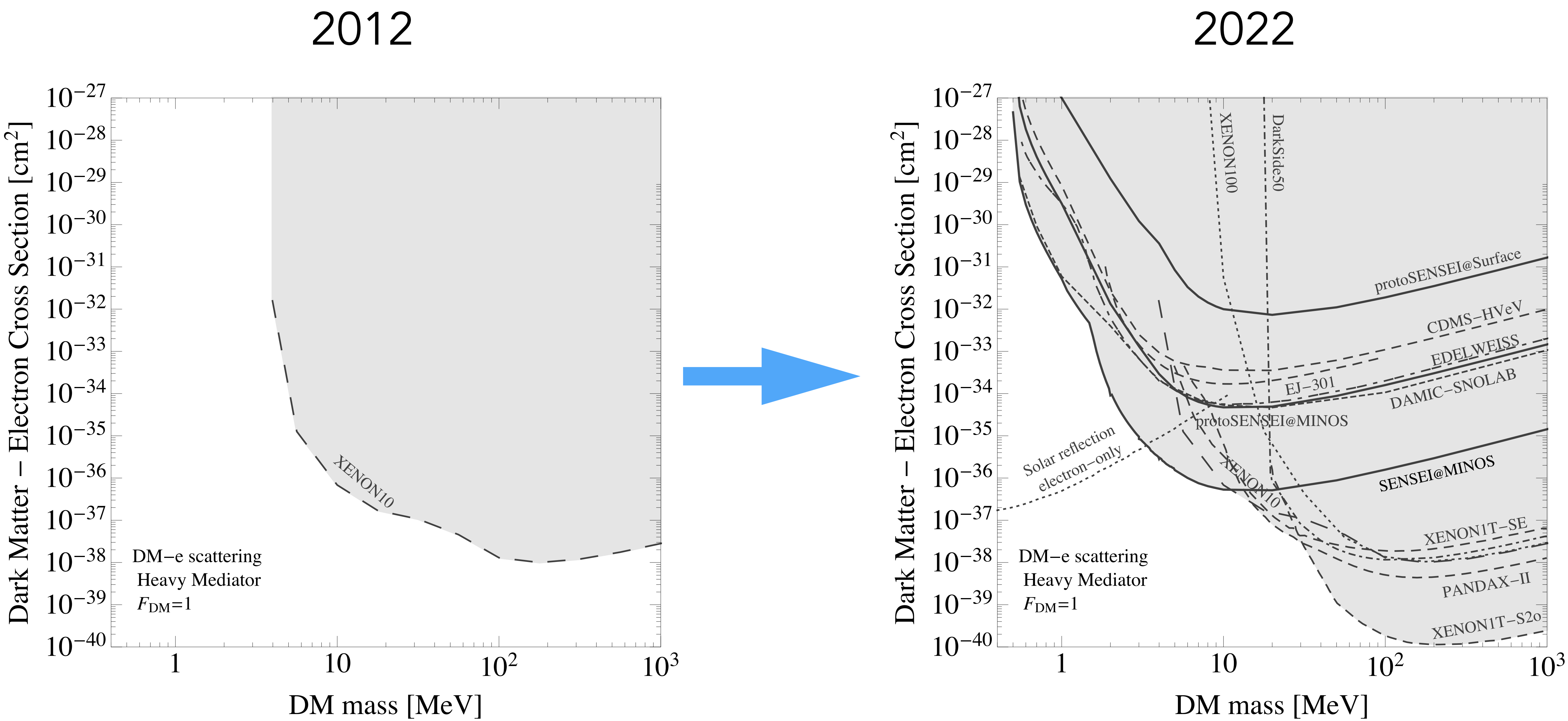




Significant progress in probing sub-GeV dark matter

- Theory:
  - several detection concepts, using variety of target materials
  - improved calculations of DM scattering in crystals
  - improved understanding of low-energy backgrounds
- Experiments: multiple technologies can measure small signals, e.g.
  - Xe/Ar 2-phase TPC (XENON10/100/1T/nT, LZ, DarkSide, …)
  - Phonon/heat sensors (SuperCDMS, EDELWEISS, CRESST, TESSERACT)
  - Skipper-CCDs (SENSEI, DAMIC-M, Oscura)

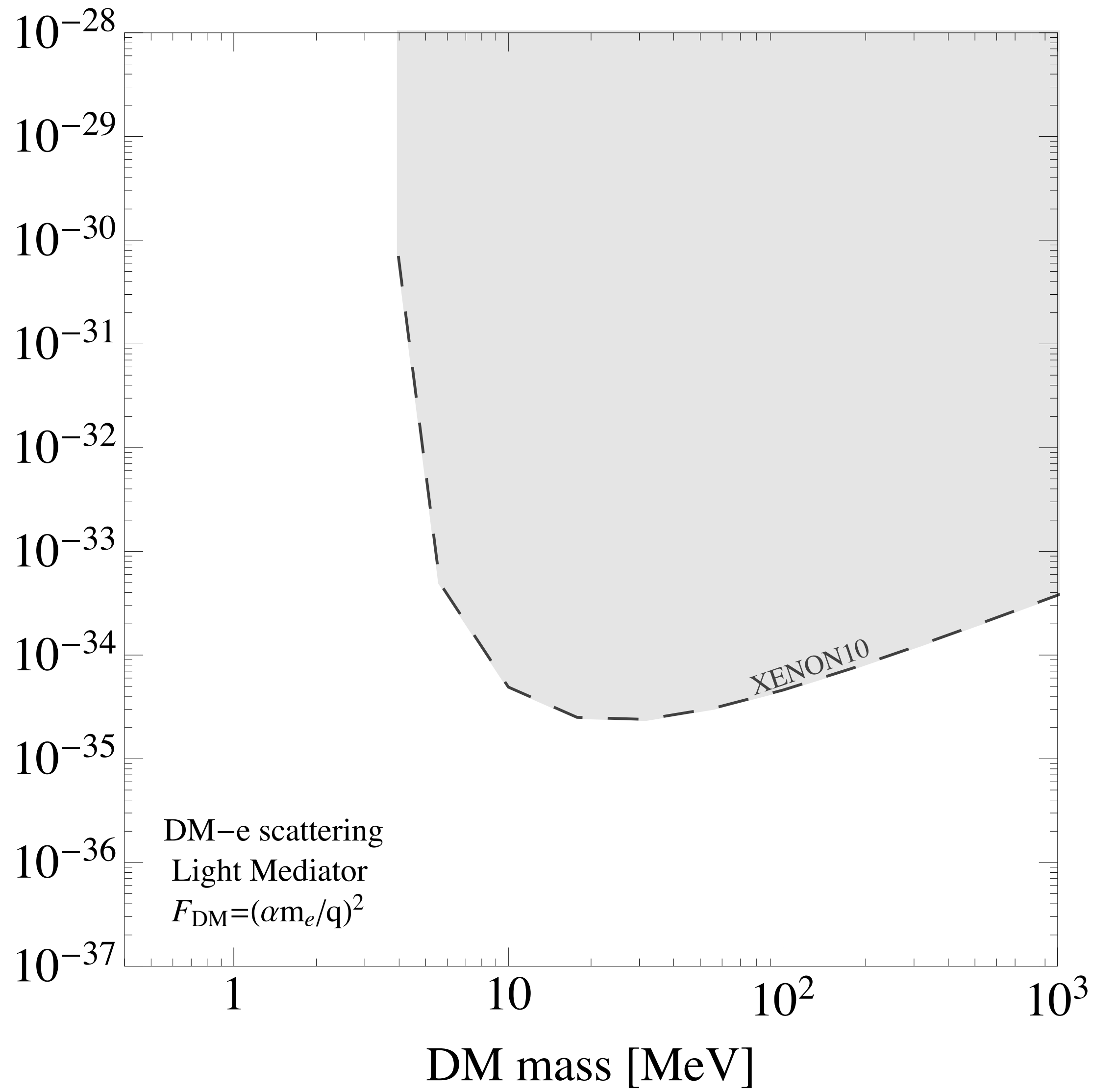
Exciting experimental progress: DM-electron scattering



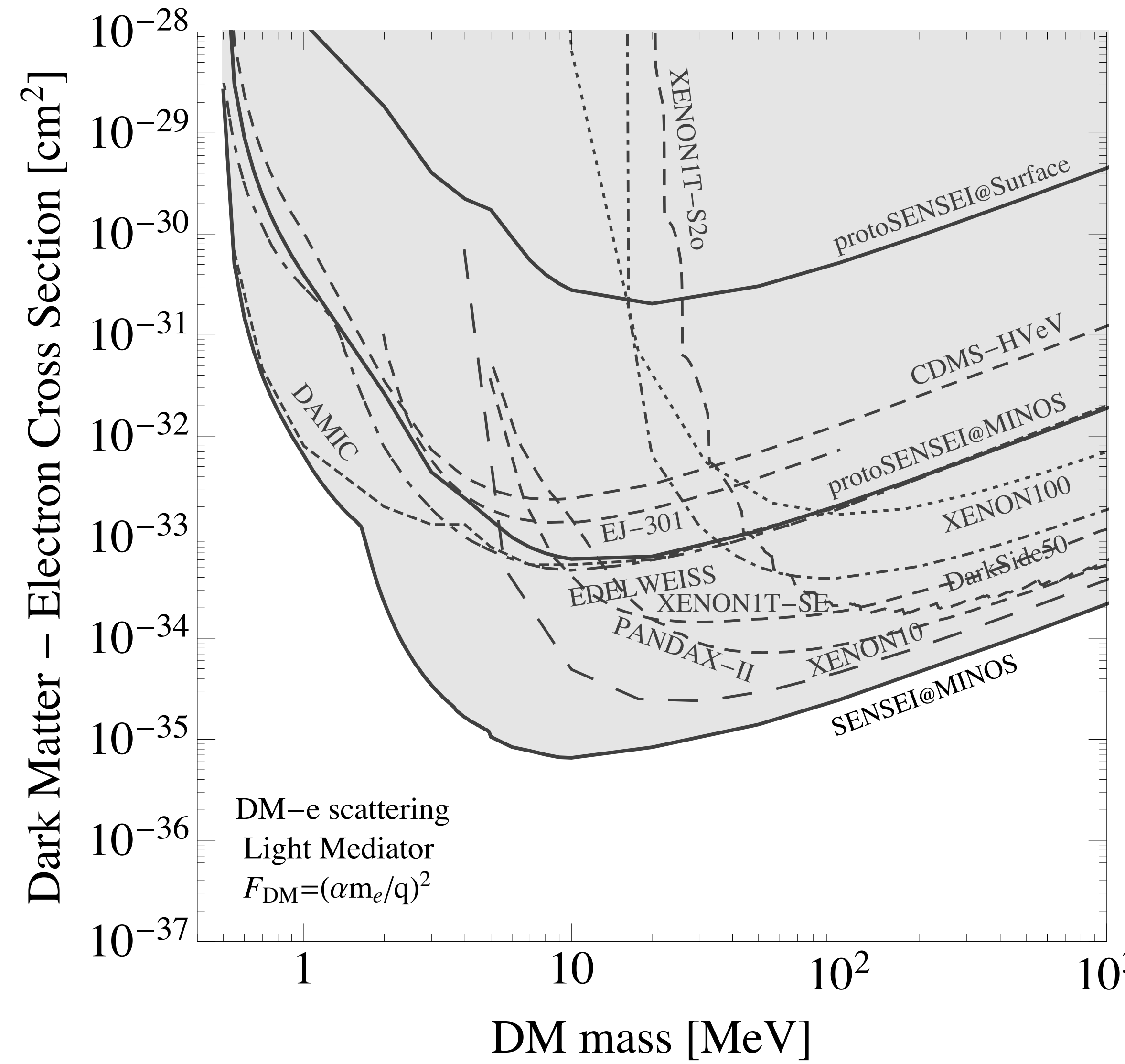
heavy mediator

Exciting experimental progress: DM-electron scattering

2012



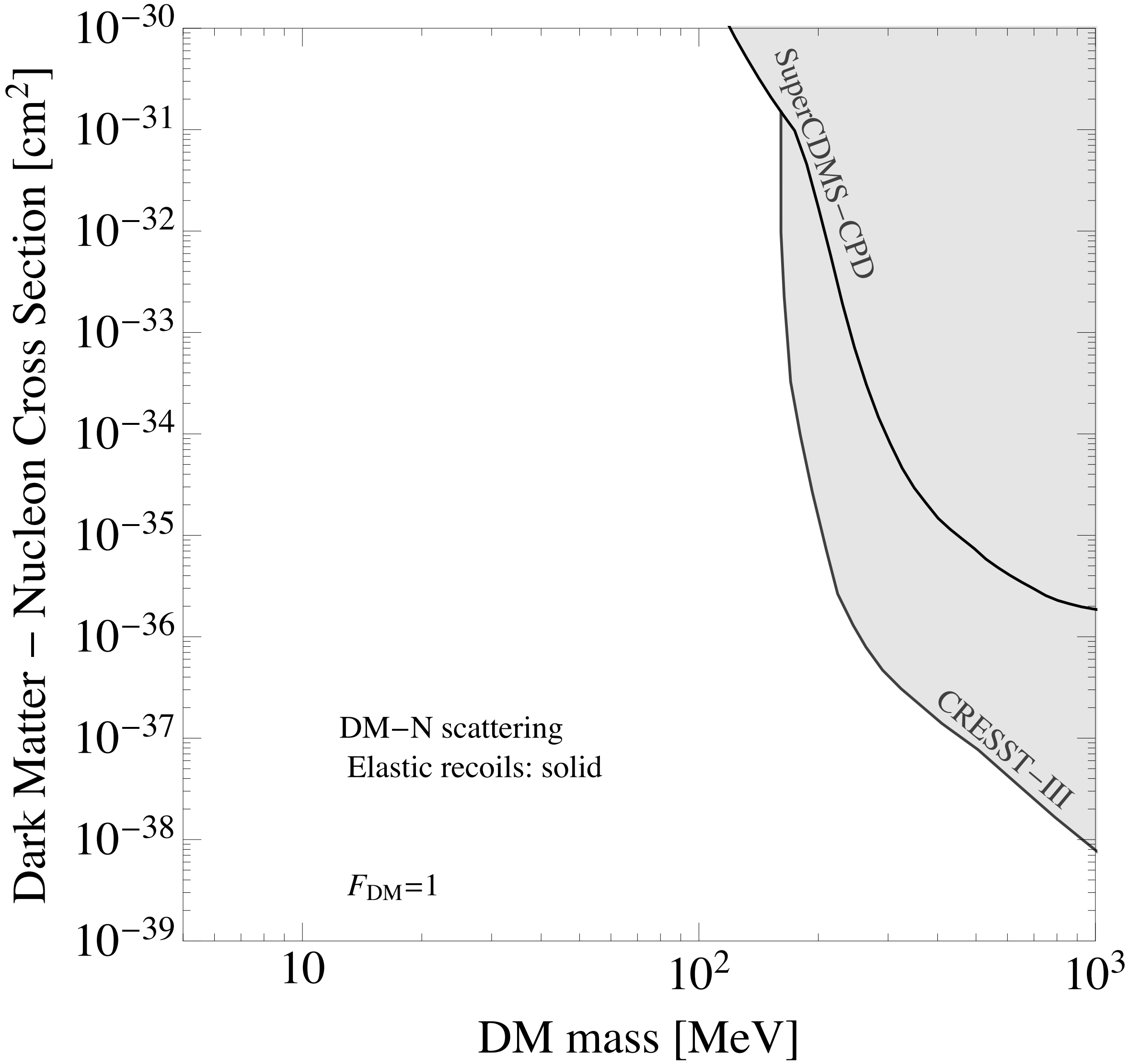
2022



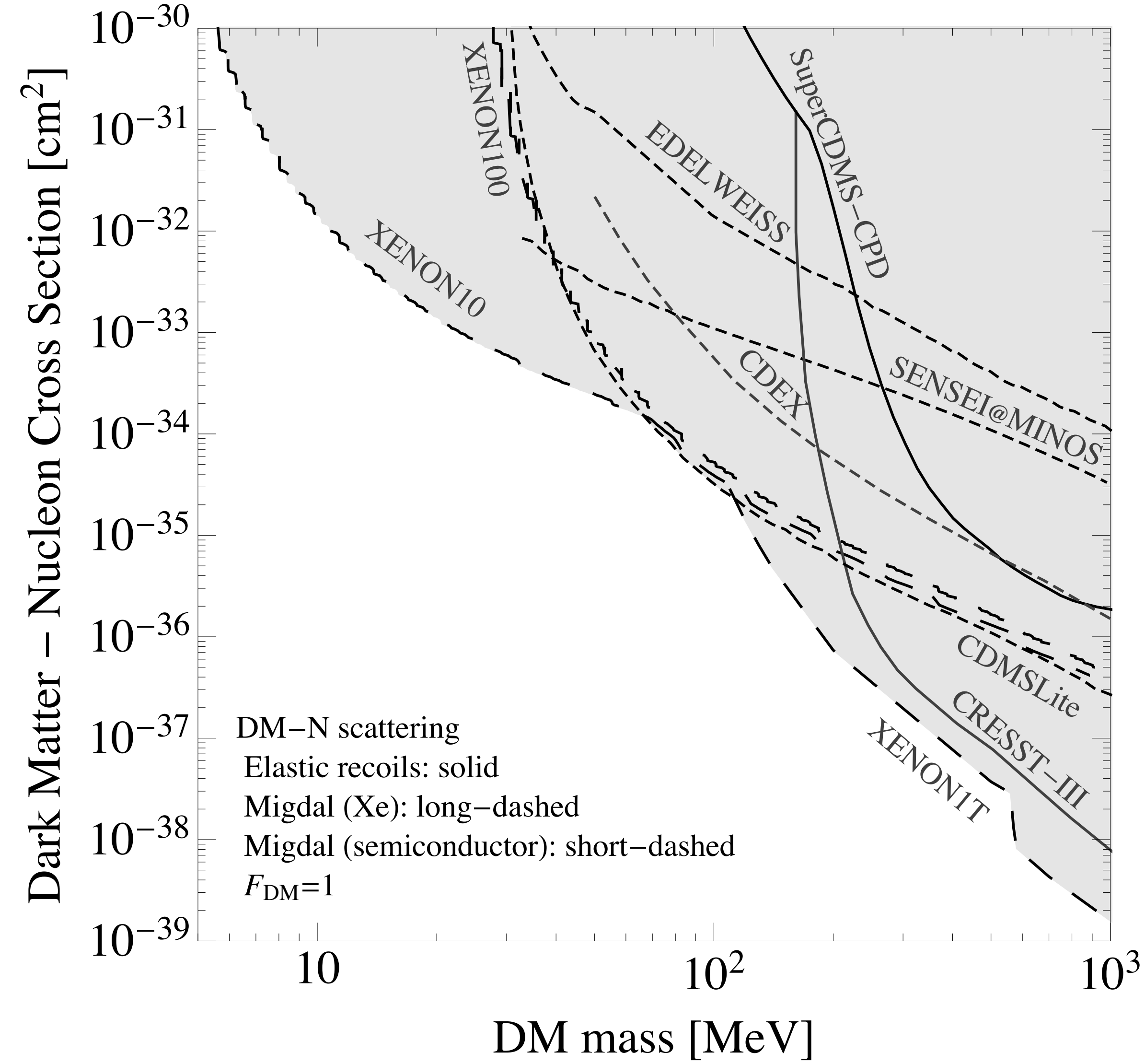
ultralight mediator, $\sigma \propto \frac{1}{q^4}$

Exciting experimental progress: DM-nucleus scattering

elastic DM-nucleus scattering

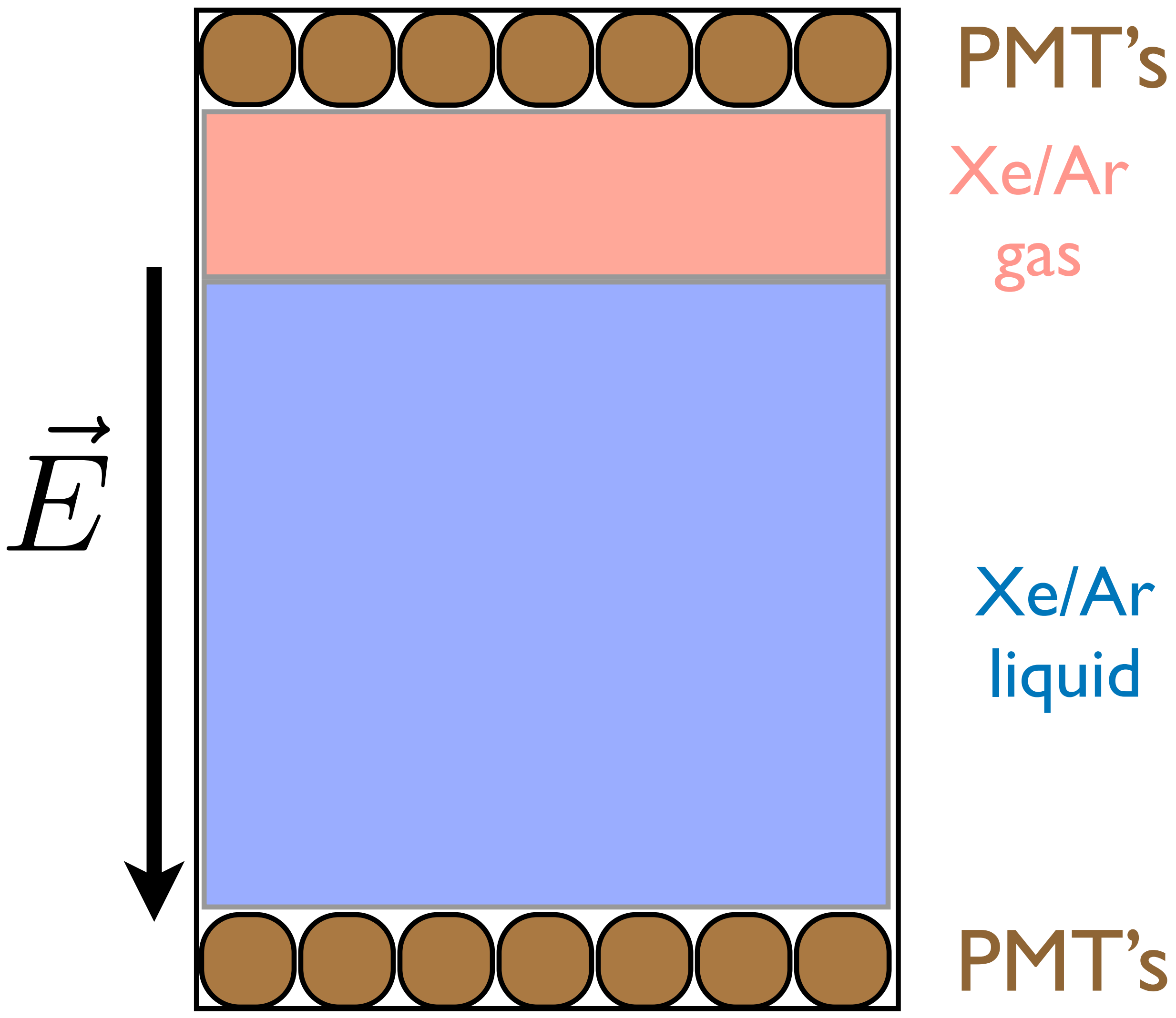


DM-nucleus scattering **w/ Migdal**



heavy mediator

Two-phase TPCs (Xe, Ar)



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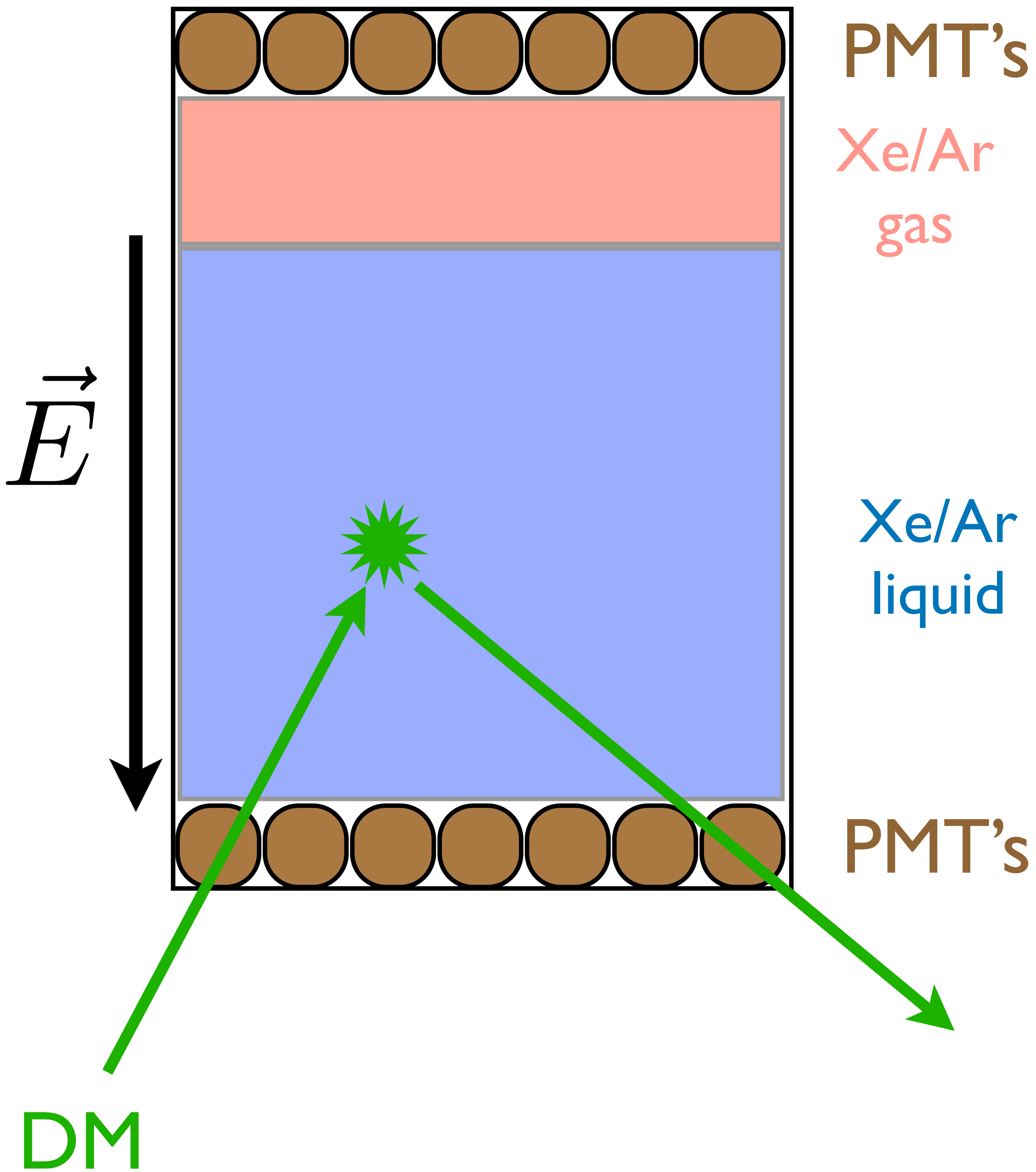

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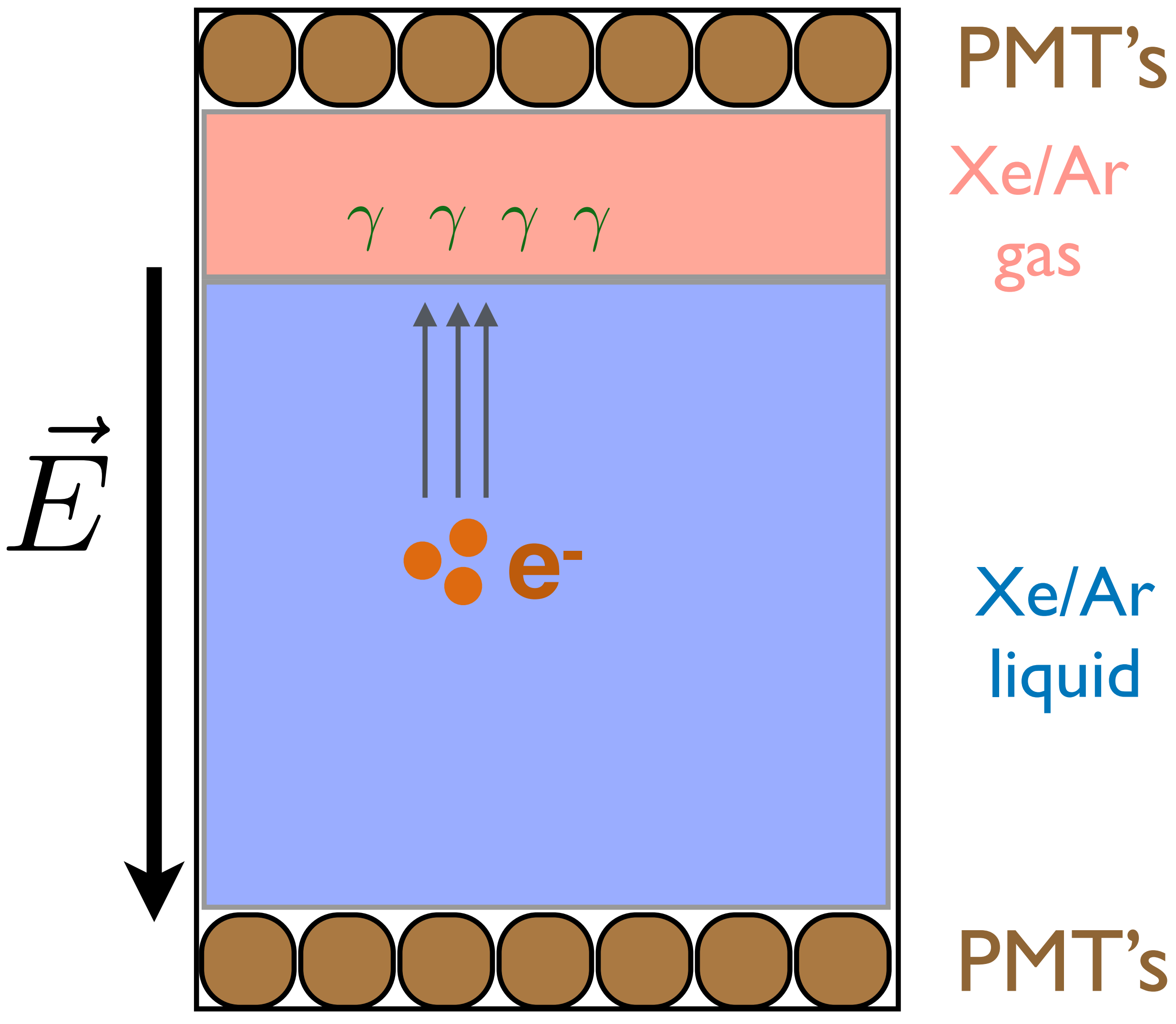
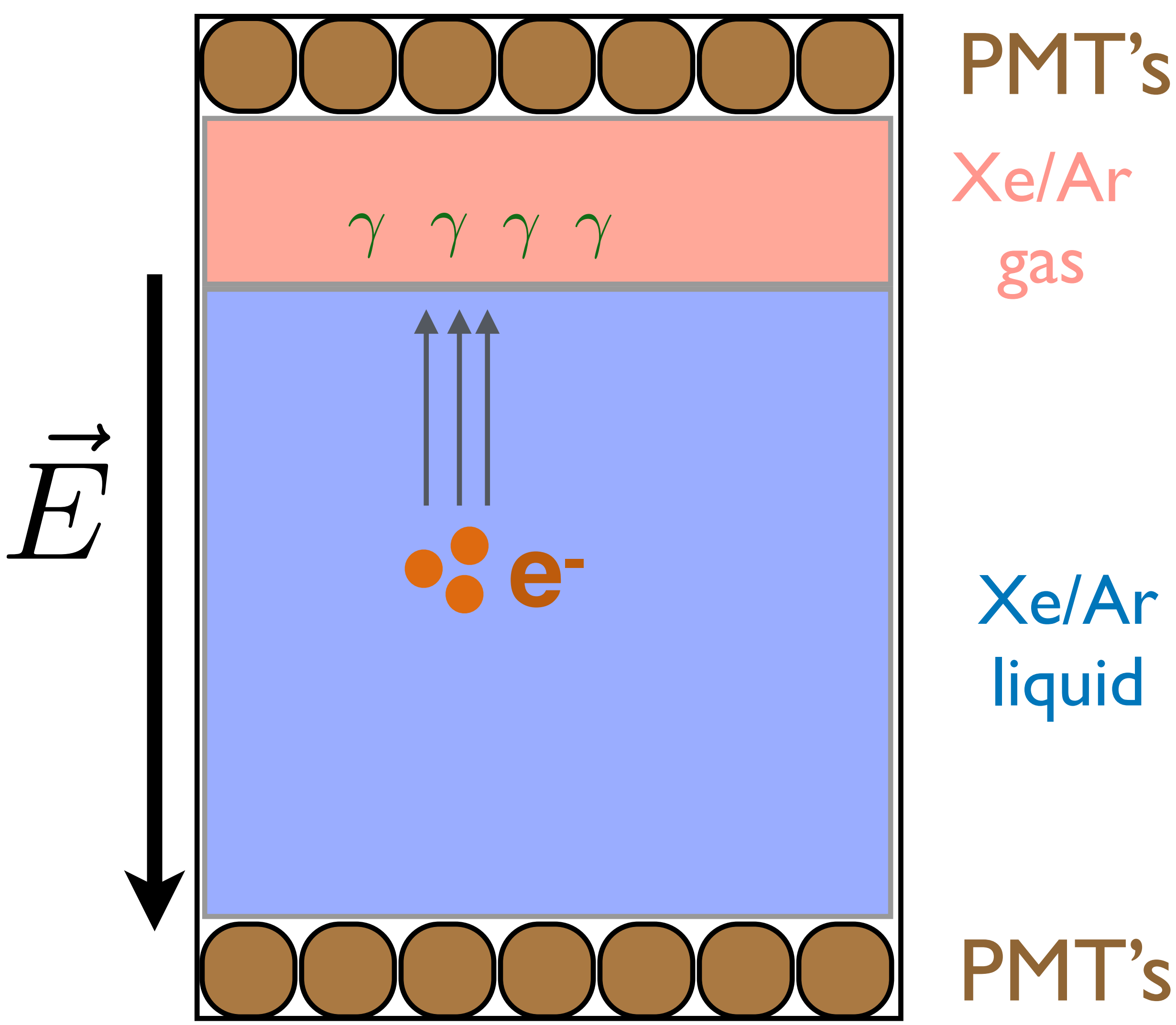


e⁻ produce
scintillation light

XENON10/100/1T, DarkSide

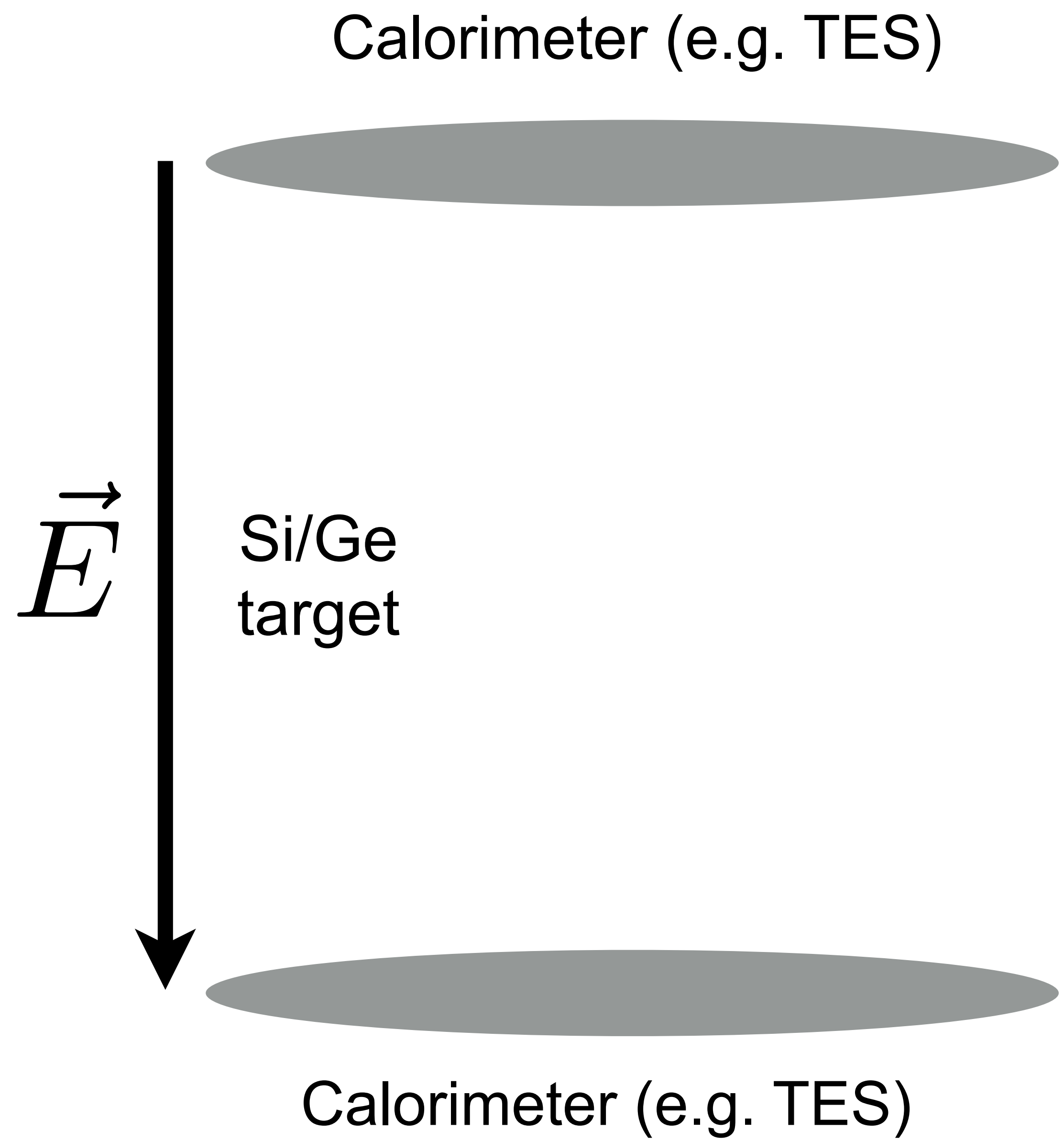
Two-phase TPCs (Xe, Ar)



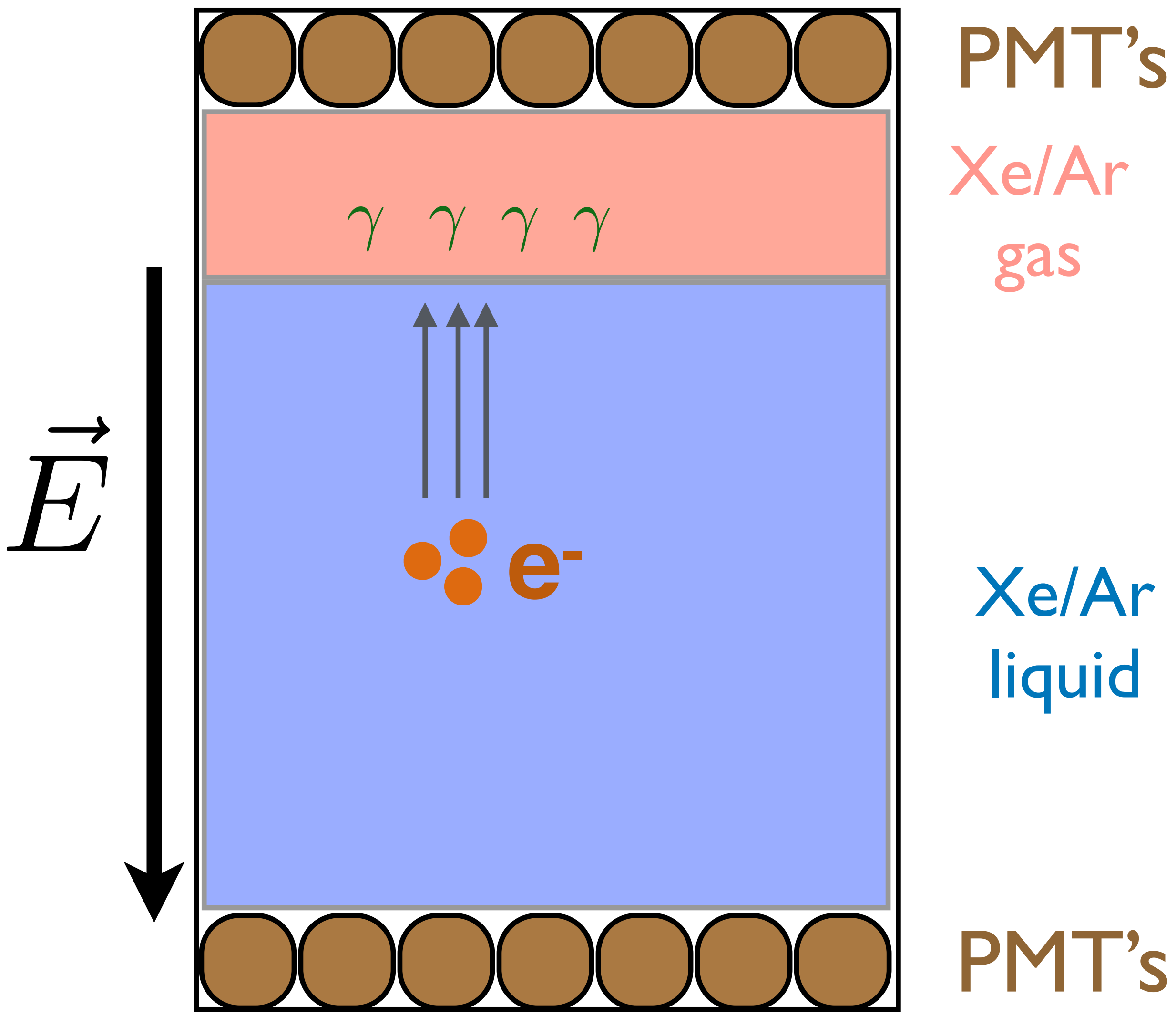
e^- produce
scintillation light

XENON10/100/1T, DarkSide

Phonon Sensors



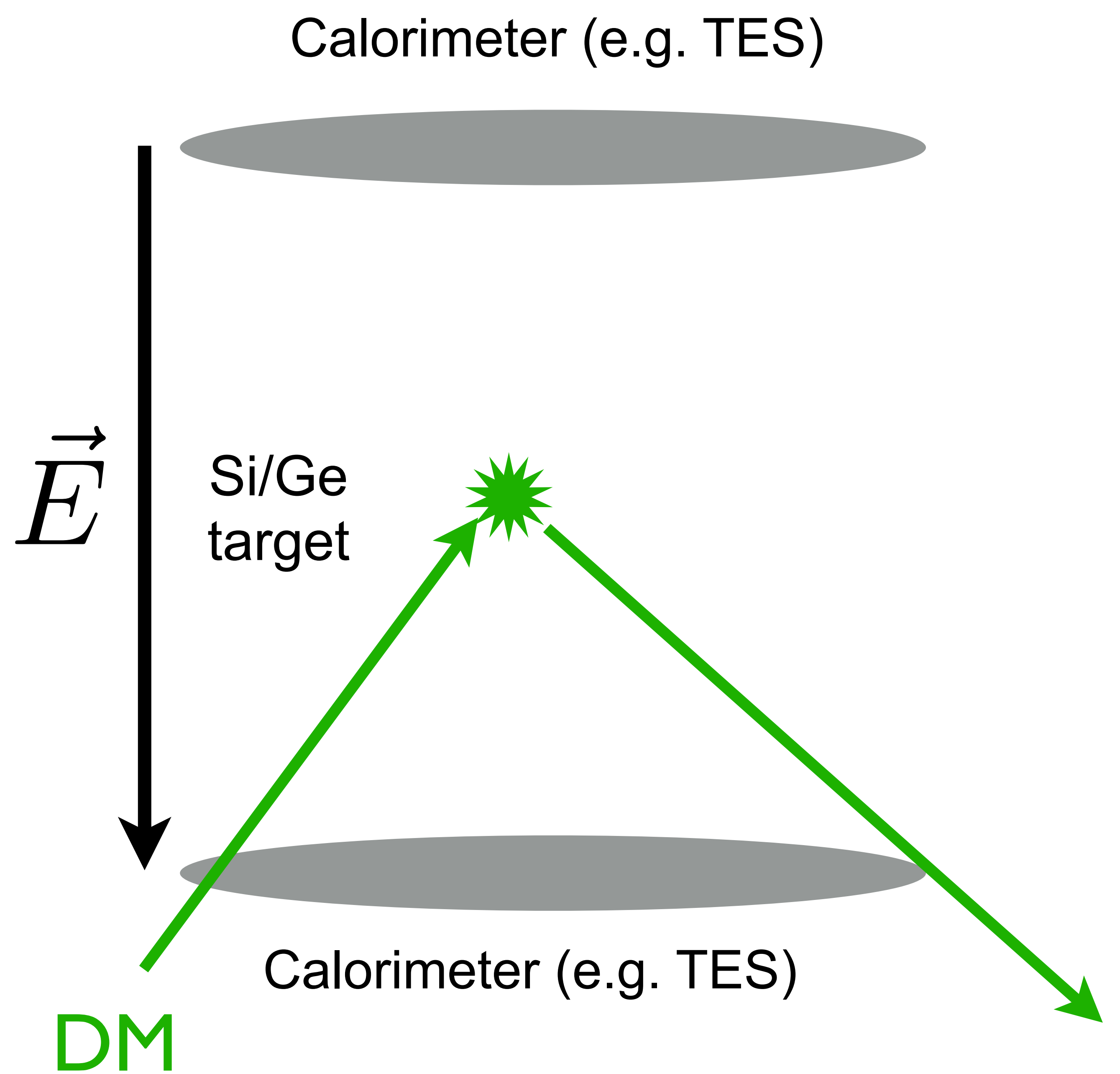
Two-phase TPCs (Xe, Ar)



e- produce
scintillation light

XENON10/100/1T, DarkSide

Phonon Sensors



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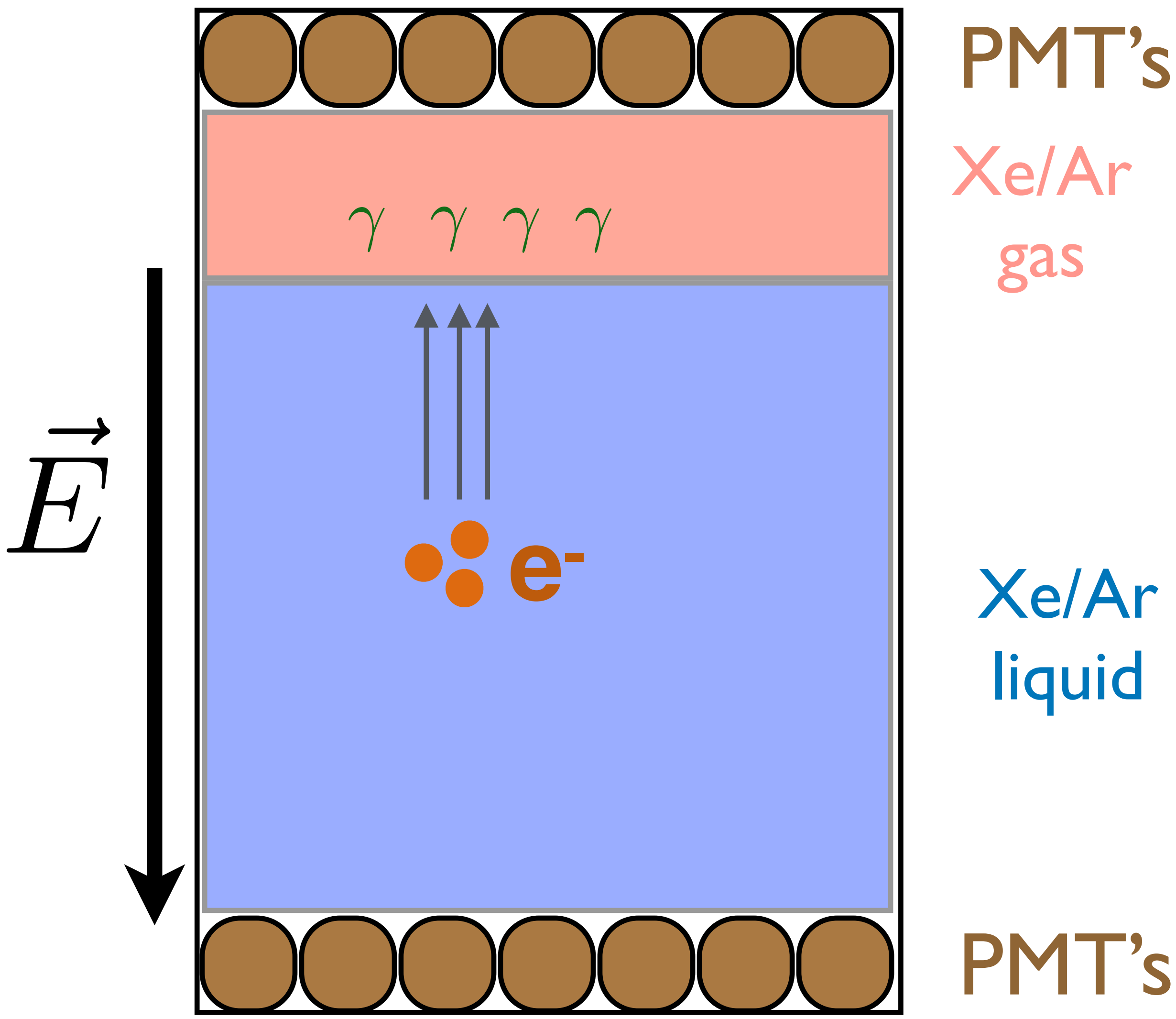

e^- produce
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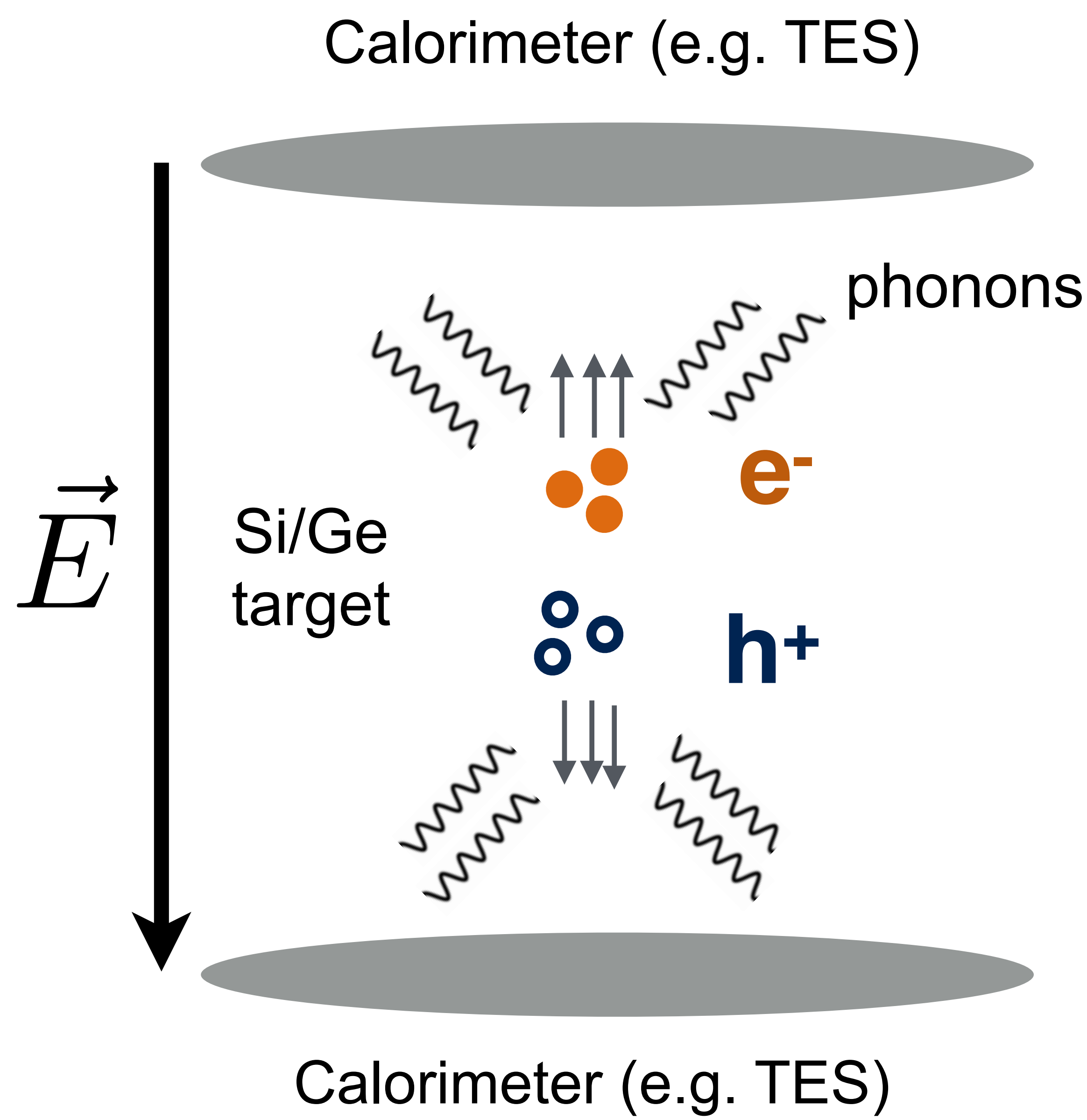
XENON10/100/1T, DarkSide

Phonon Sensors



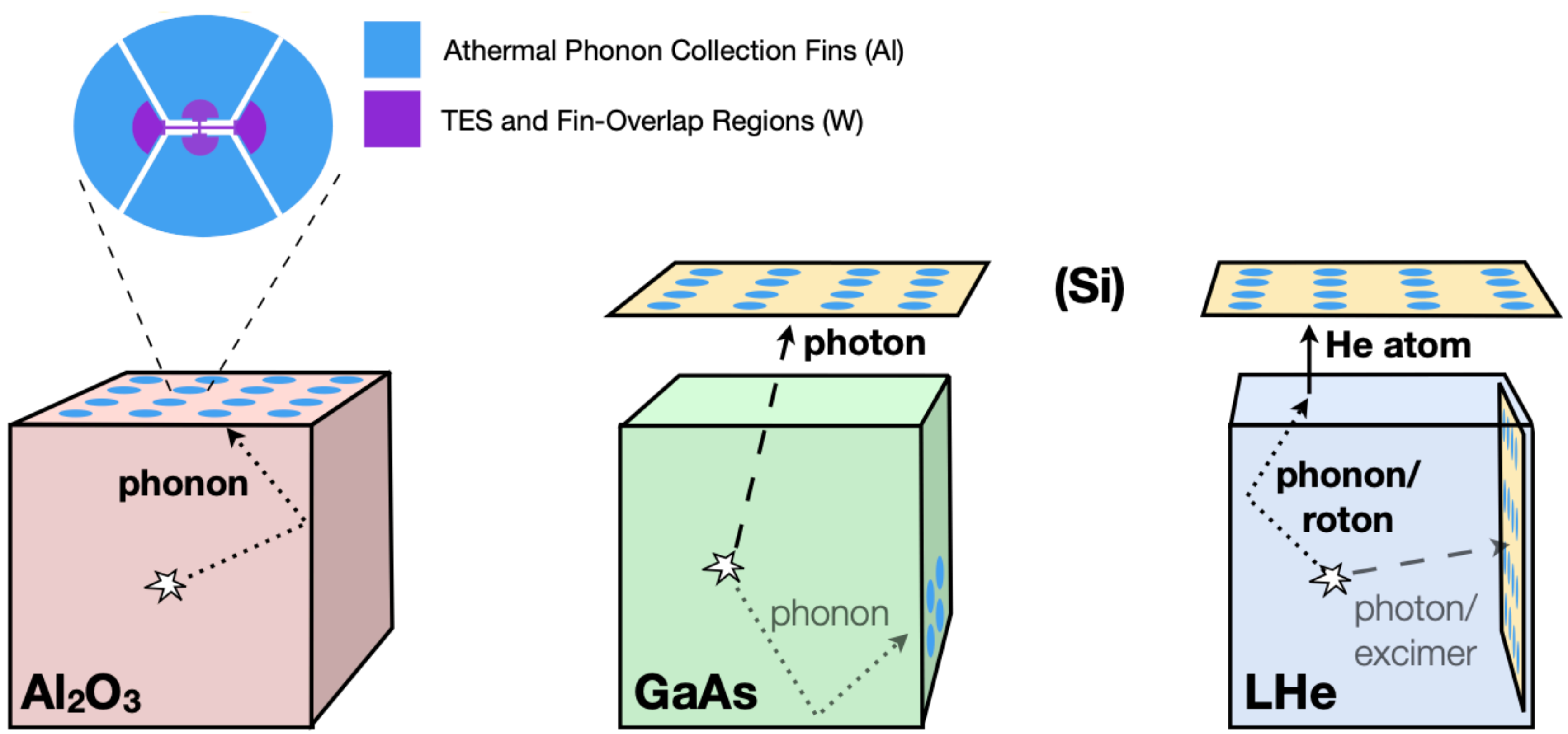
e^- & h^+ drift in E-field,
emitting phonons

SuperCDMS, EDELWEISS

TESSERACT (proposed project)

Transition Edge Sensors with Sub-EV Resolution And Cryogenic Targets

Goal: use multiple target materials + advances in TES sensor technology

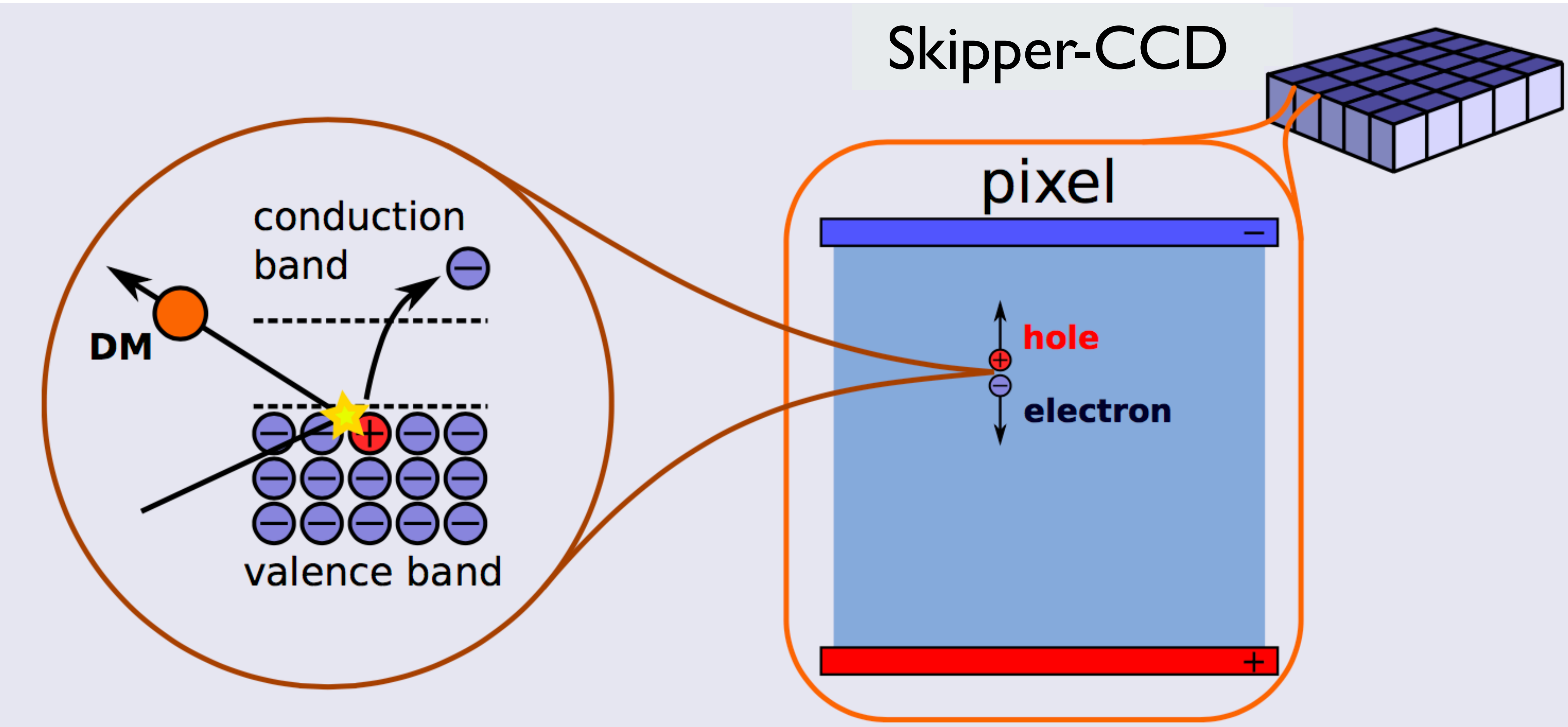


Liquid helium experiment (HeRALD)
GaAs and Sapphire-based experiments (SPICE)

R&D funded by US DoE

Info & Figure from: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-IF1_IF8-120.pdf

SENSEI: Detection concept



DM would create <u>one</u> or a <u>few</u> electrons in a pixel

Skipper-CCD operation (SENSEI)

~ 2 cm $\times$ 10 cm, 5.4 Mpix

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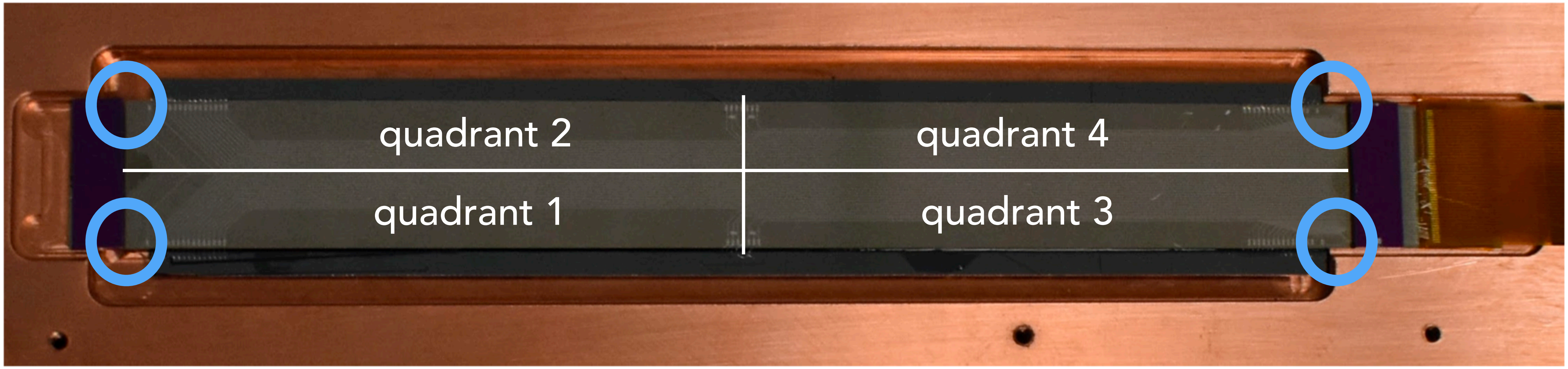

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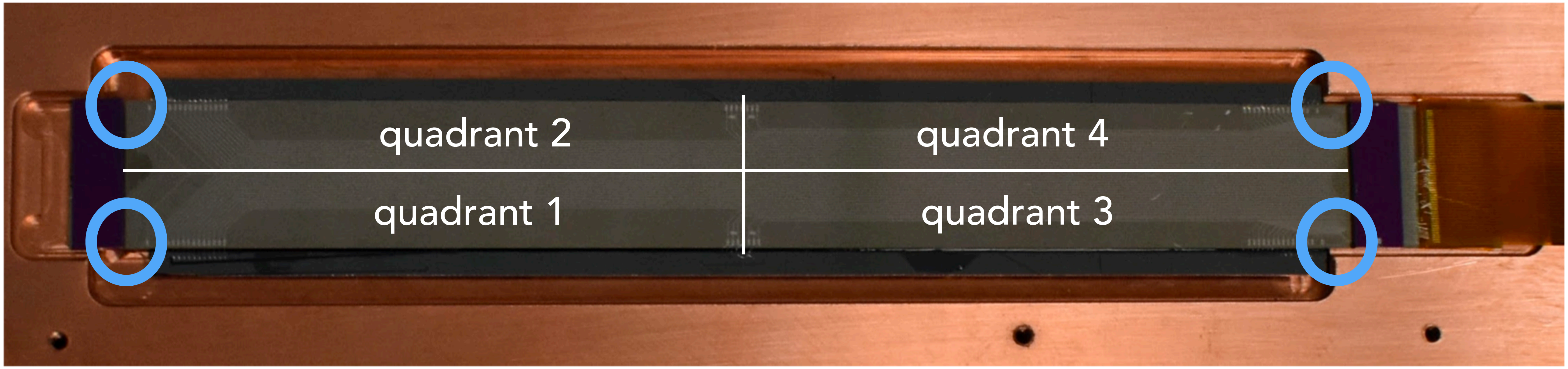

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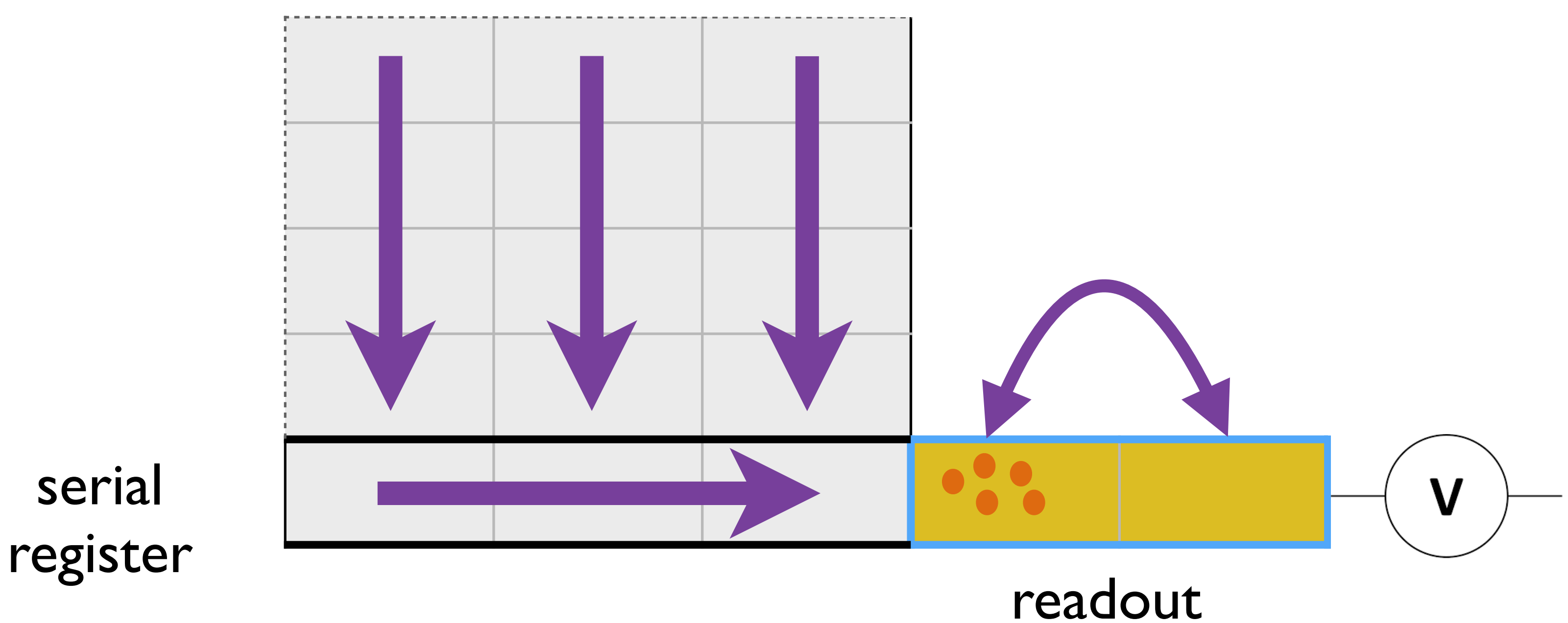
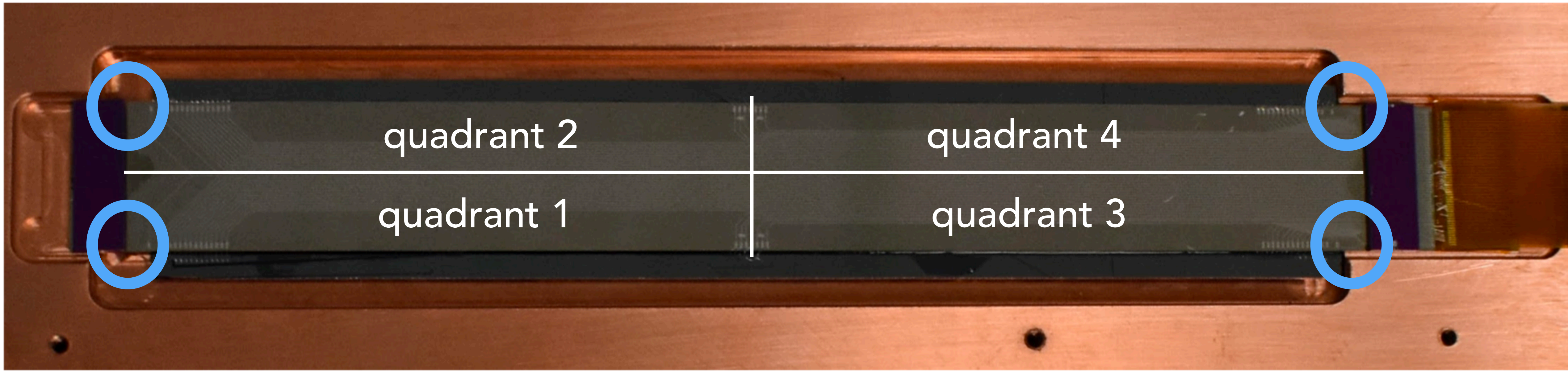
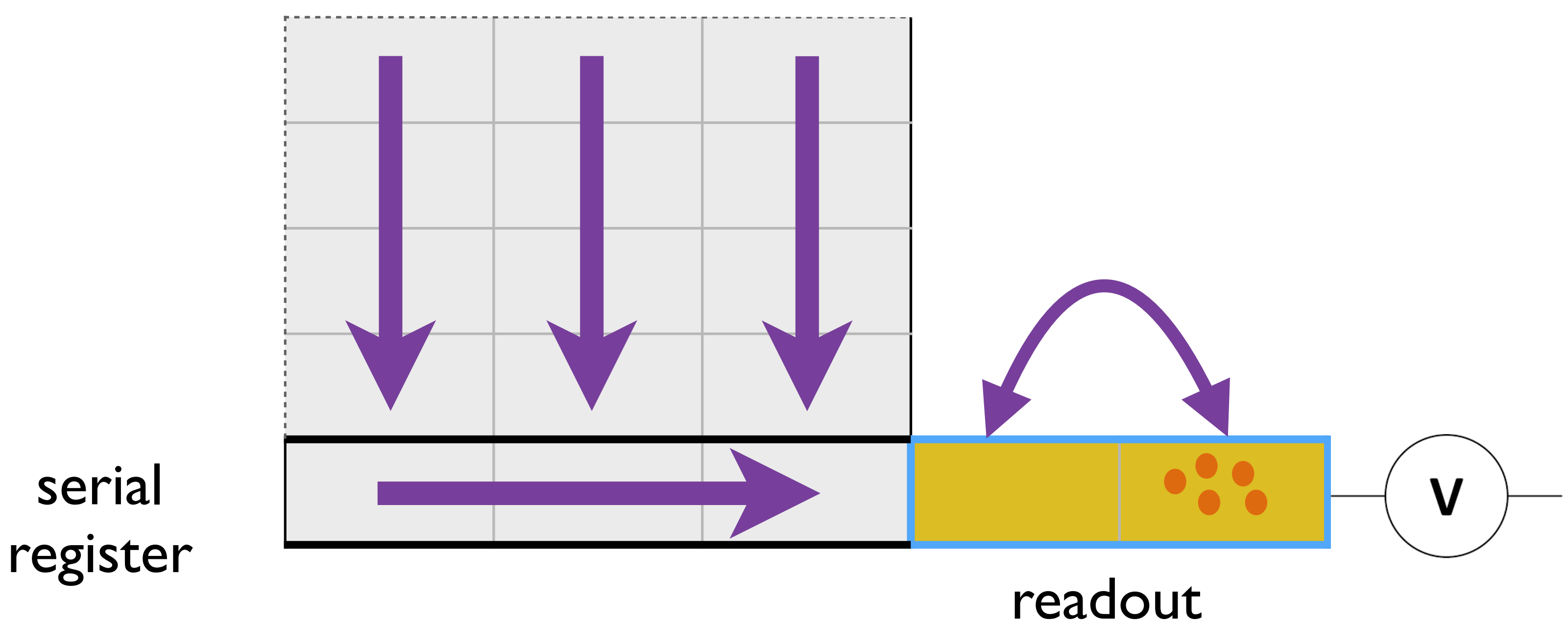


Skipper-CCD operation (SENSEI)



$\sim 2\ \text{cm} \times 10\ \text{cm},\ 5.4\ \text{Mpix}$



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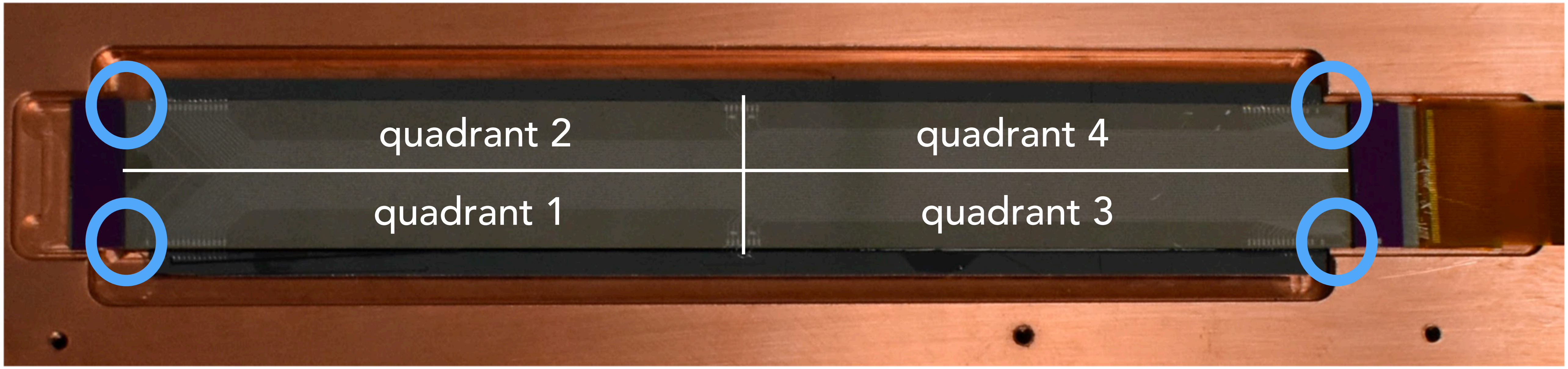

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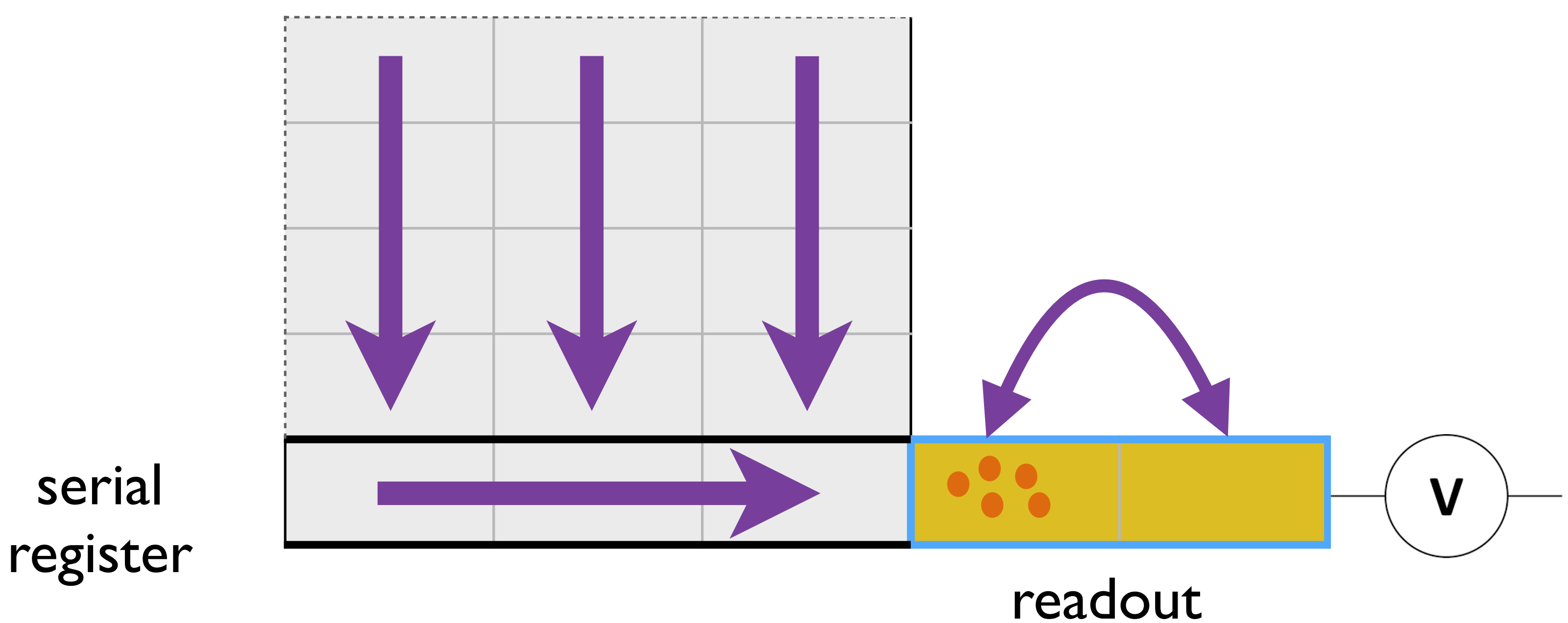

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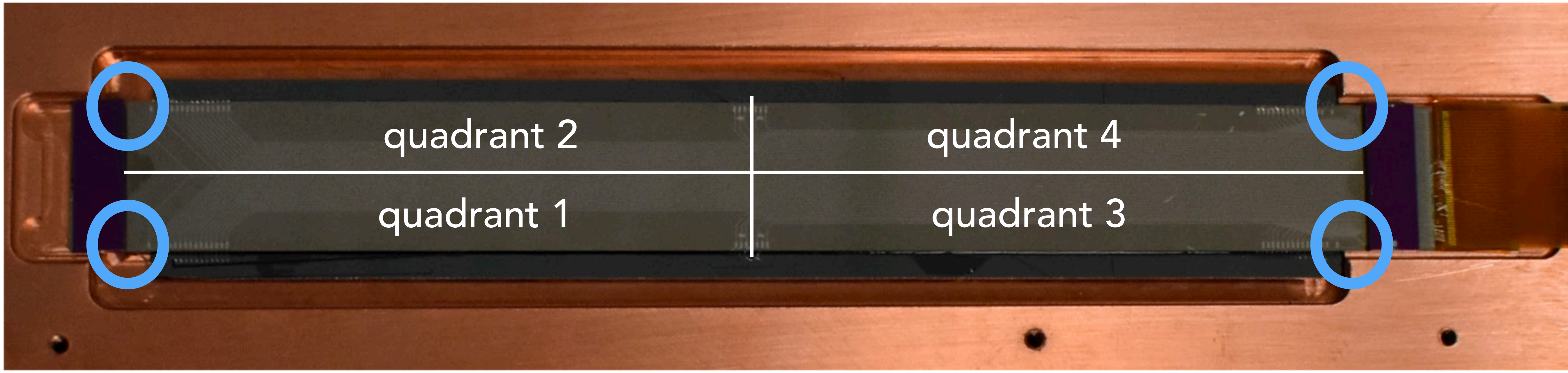

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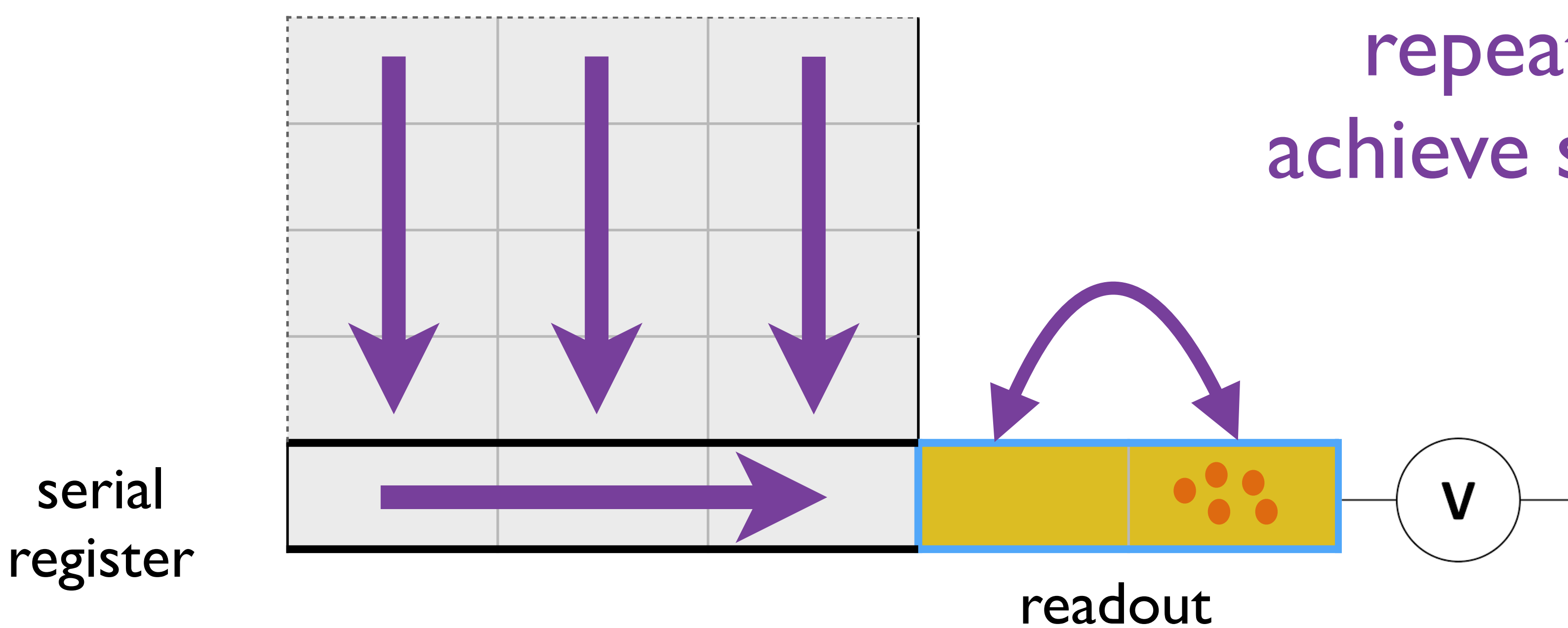


repeatedly measure charge to achieve sub-electron readout noise

Tiffenberg et.al. 2017

designed at LBNL and fabricated at Teledyne DALSA Semiconductor

The SENSEI Collaboration

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Liron Barak
Yonathan Ben Gal
Itay Bloch
Erez Etzion
Yaron Korn
Aviv Orly
Tomer Volansky

Fermilab

Ana Botti
Gustavo Cancelo
Fernando Chierchie
Michael Crisler
Alex Drilca-Wagner
Juan Estrada
Guillermo Fernandez
Miguel Sofo-Haro
Leandro Stefanazzi
Javier Tiffenberg
Sho Uemura

Stony Brook University

Prakruth Adari
Luke Chaplinsky
Dawa
Ansh Desai
Daniel Gift
Rouven Essig
Sravan Munagavalasa
Aman Singal

UNIVERSITY OF OREGON

Tien-Tien Yu

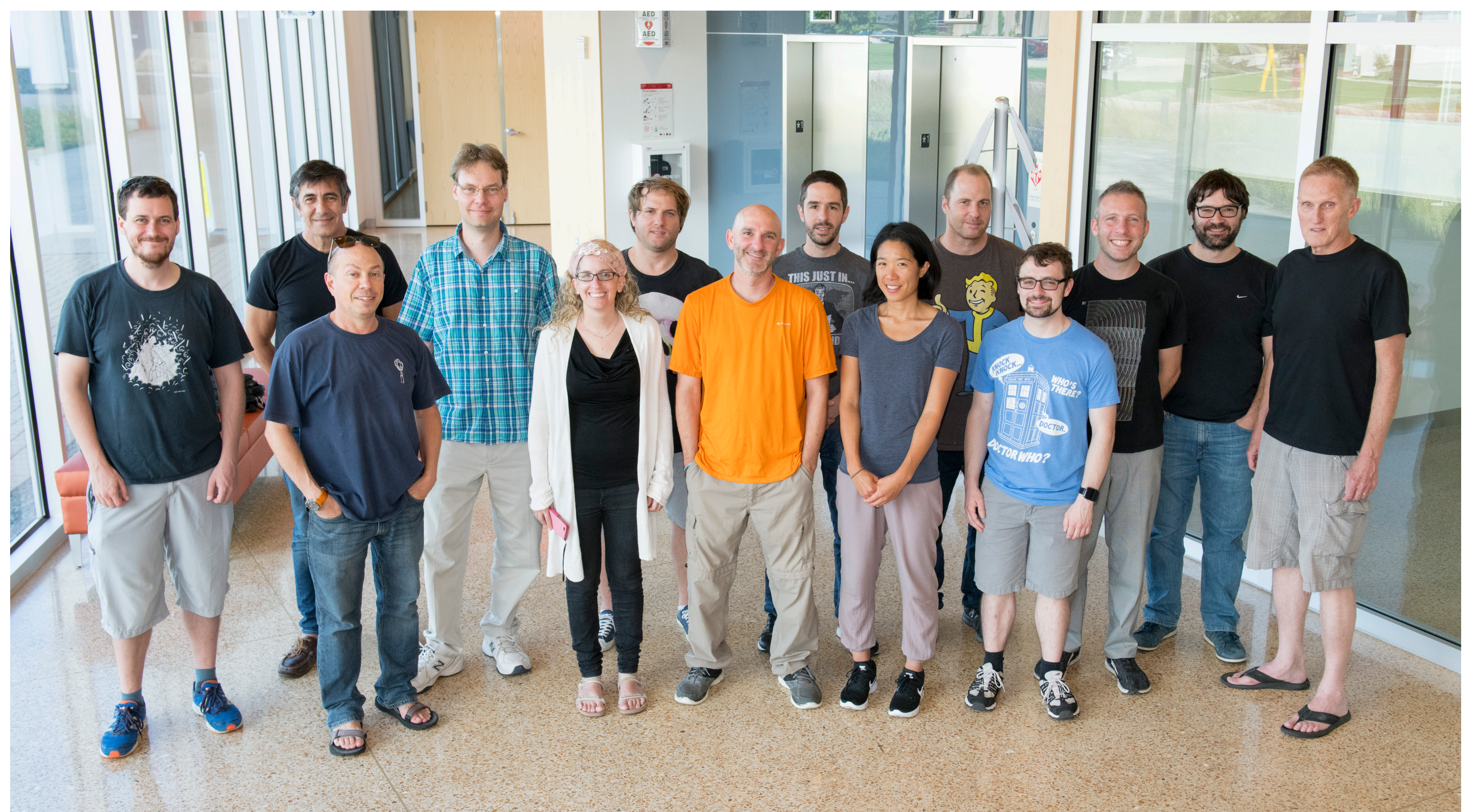
universidad de buenos aires - exactas departamento de Física Juan José Giambiagi

Mariano Cababie
Dario Rodrigues

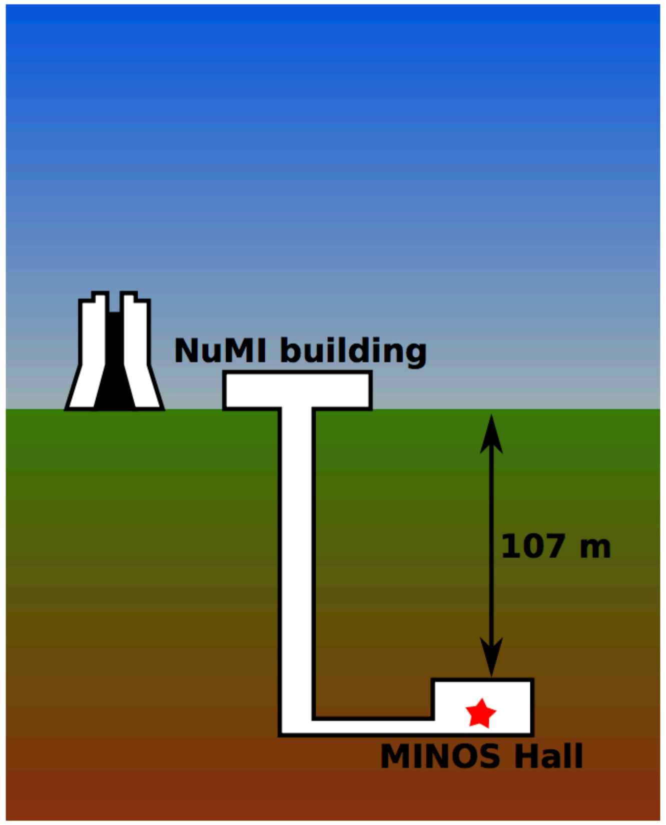
SNOLAB

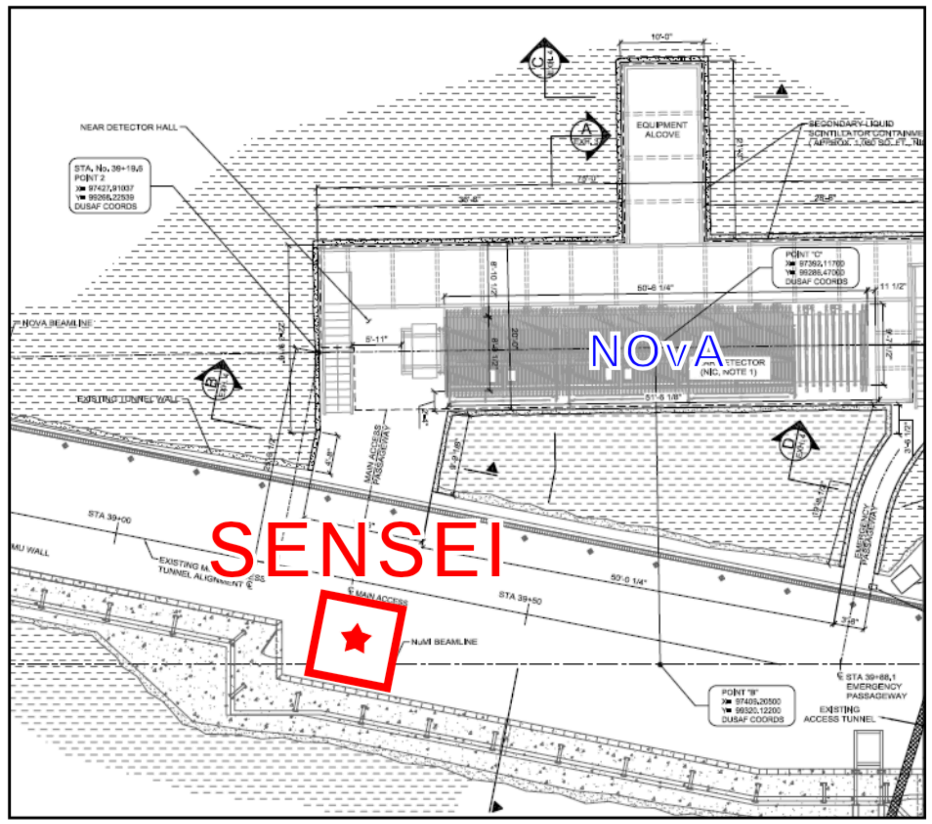
Ian Lawson
Silvia Scorza
Steffon Luoma

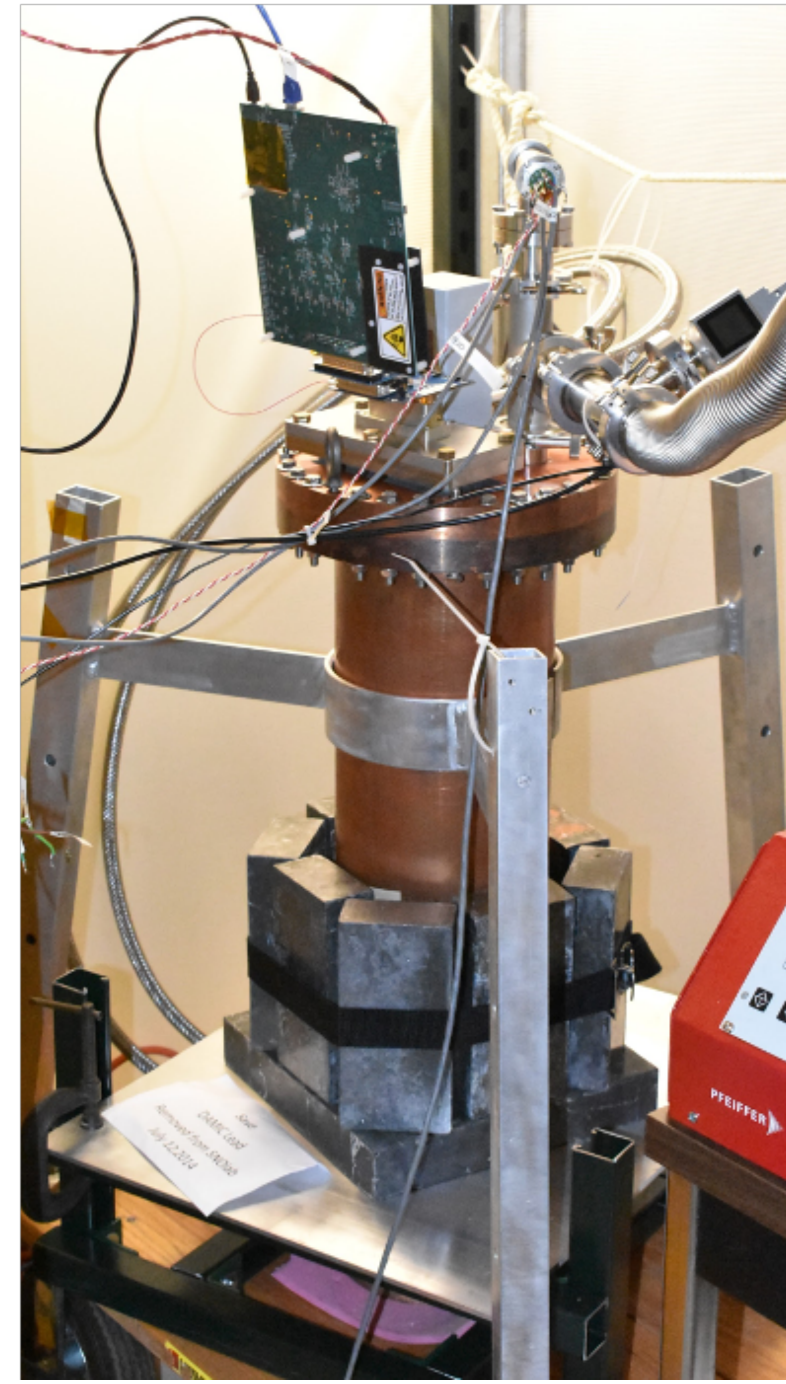
HEISING-SIMONS FOUNDATION



SENSEI Detector Setup @ Fermilab

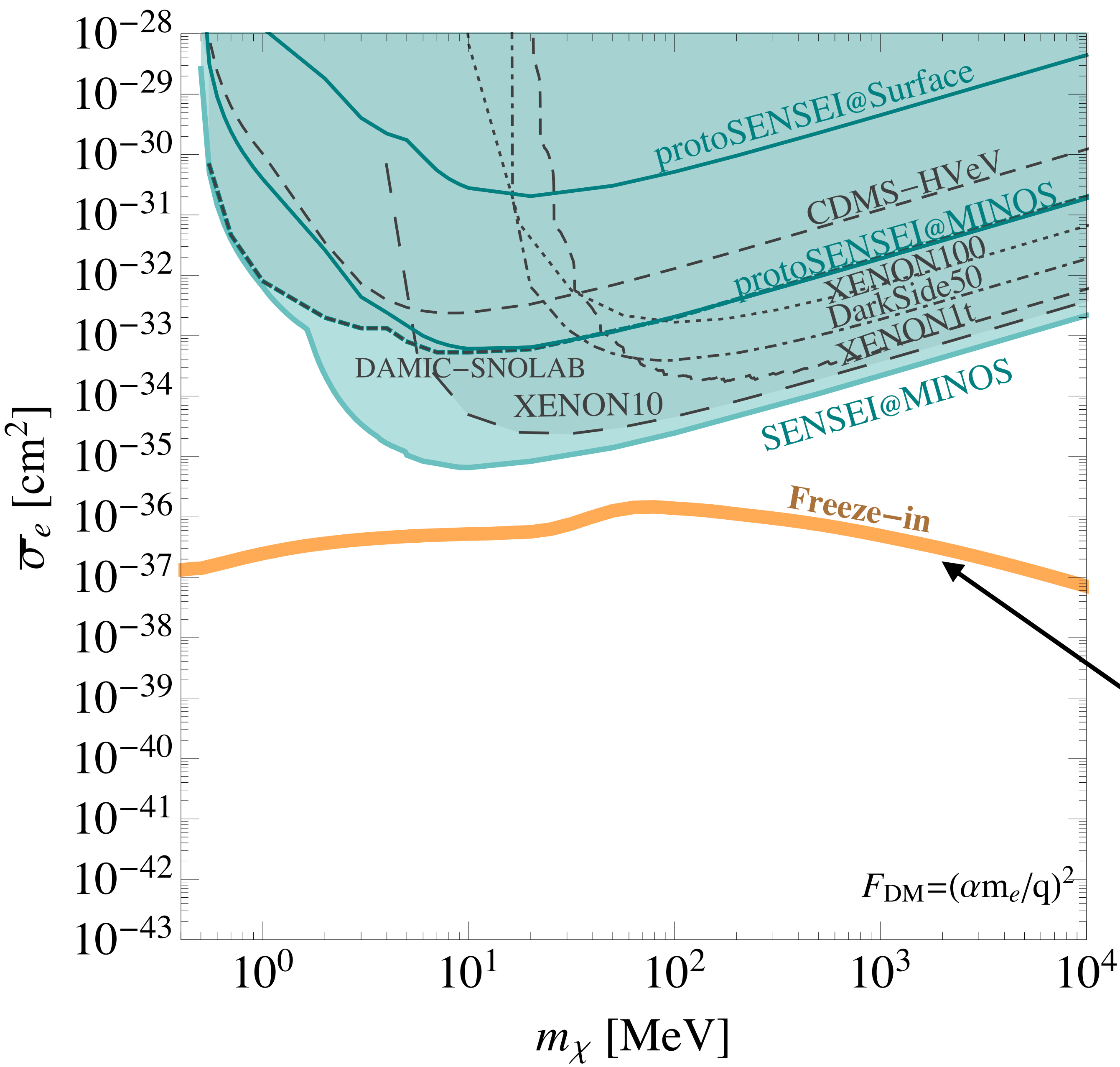






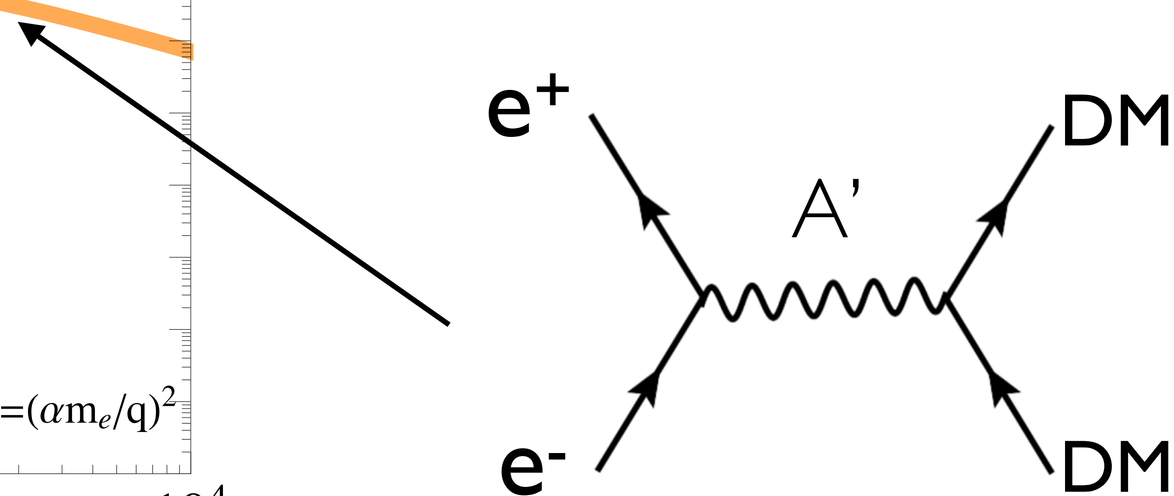
- ~100 m underground to reduce muons
- some extra lead shielding to reduce radiation

SENSEI Limits



- 3 science results, using a prototype or science-grade Skipper-CCD

1804.00088, PRL
1901.10478, PRL
2004.11378, PRL

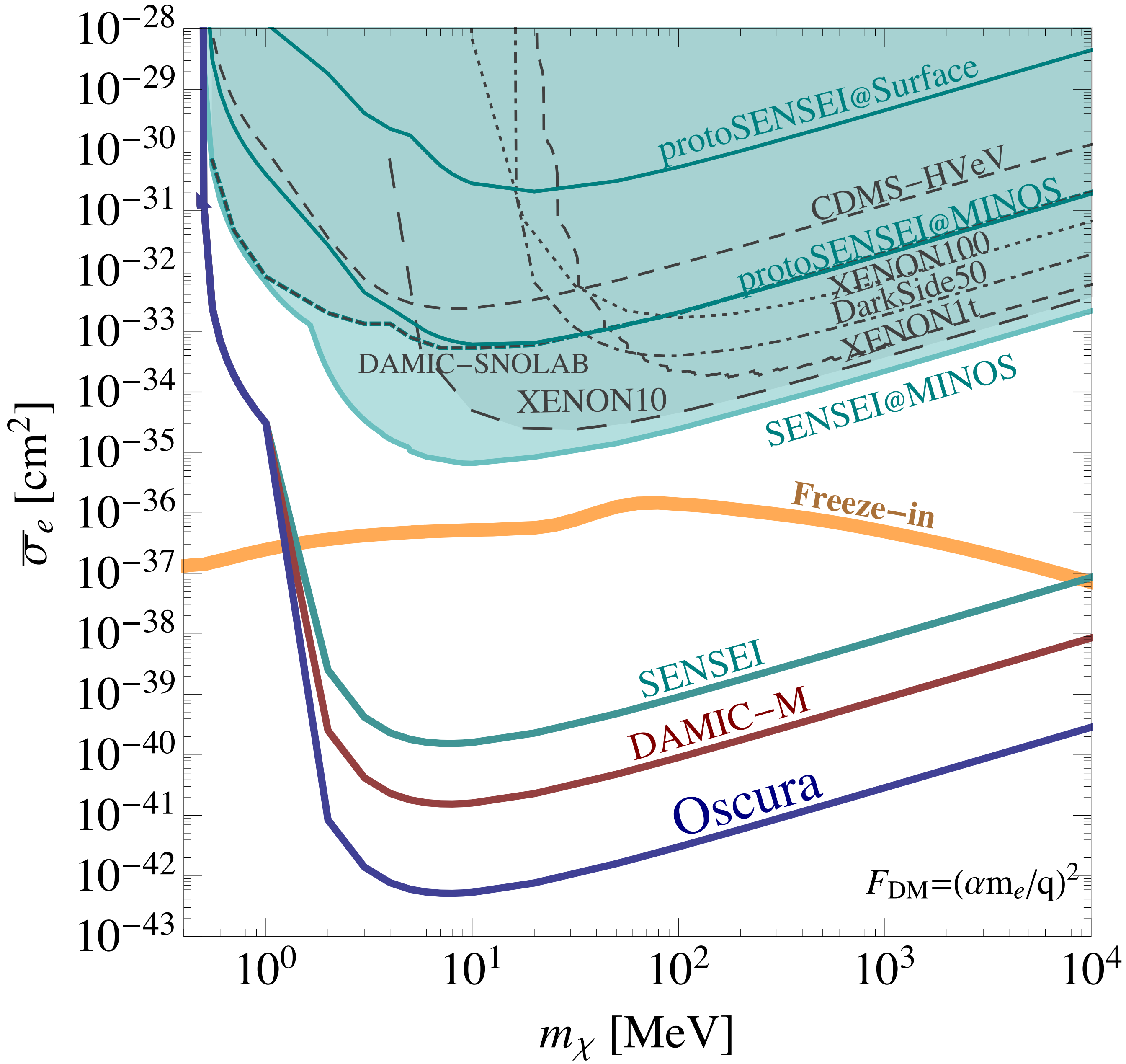


RE, Mardon, Volansky, 2011
Chu, Hambye, Tytgat, 2011
RE, Fernandez-Serra, Soto, Mardon, Volansky, Yu 2015
Dvorkin, Lin, Schutz, 2019

SENSEI@SNOLAB

- Phase 1 system taking data @ SNOLAB
- Current steps: understand data, build up detector mass to ~100 gram

Projections



- SENSEI: ~100 gram (SNOLAB)
- DAMIC-M: ~1 kg (Modane)
- Oscura: 10 kg (R&D funded)

Rapid progress in probing many hidden-sector DM models!

[projections for some other models in backup]

The challenges ahead for low-mass DD

Significant recent progress, but much remains to be done

[order does not imply relative importance]

1. Understand and mitigate (novel) low-energy backgrounds

   e.g., origin of few-electron events in SENSEI & SuperCDMS?

2. Develop new signals for DM

   e.g., diurnal modulation

3. Develop new DM detection concepts

   e.g., Quantum Dots, Doped Semiconductors

4. Calibrate DM signals and low-energy backgrounds

   e.g., observe & calibrate Migdal effect w/ neutrons

5. Sharpen theory predictions for DM signals (e.g., secondary ionization modeling)
6. Increase target mass of “proven” detector technologies
7. Lower energy thresholds to probe sub-MeV DM

Remainder of Talk

Outline

- Some Recent Progress
- Sources of Low-Energy Backgrounds
- Diurnal Modulation
- New Detection Concepts
- Calibrating the Migdal Effect w/ Neutrons

All sub-GeV DM experiments see "excess" low-energy events

e.g., detectors that measure ionization

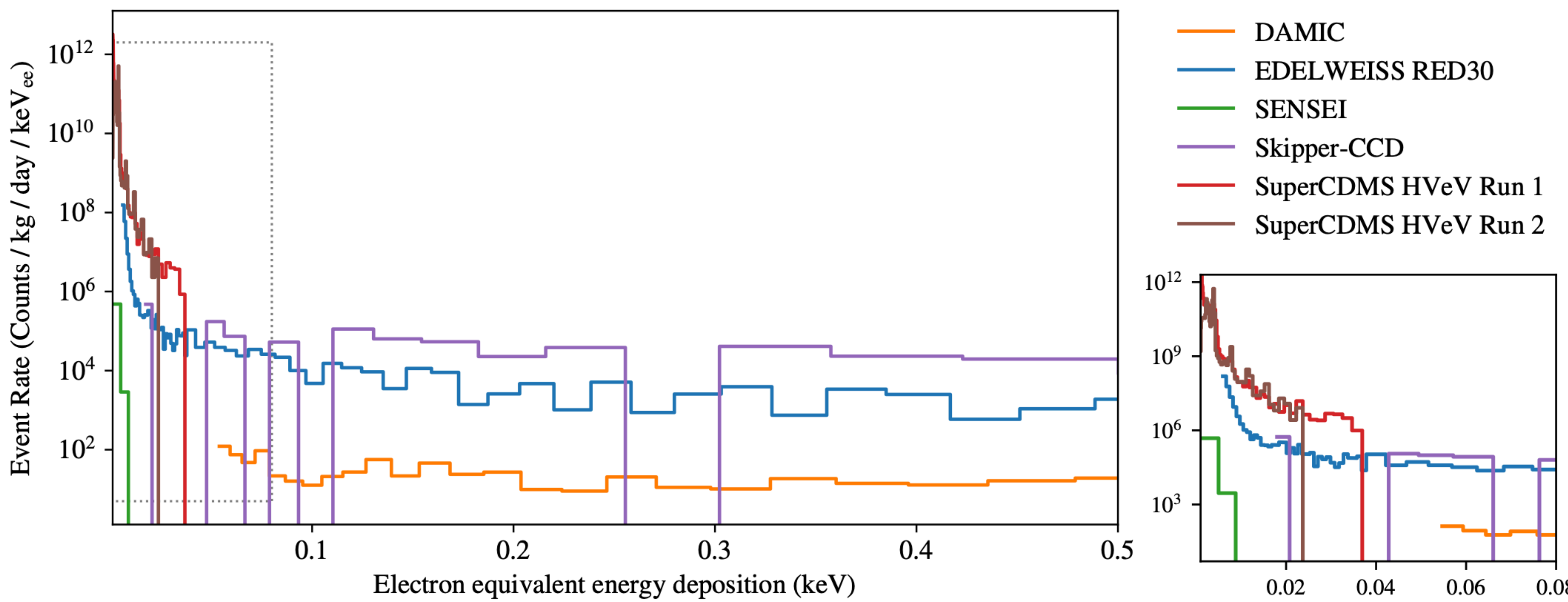


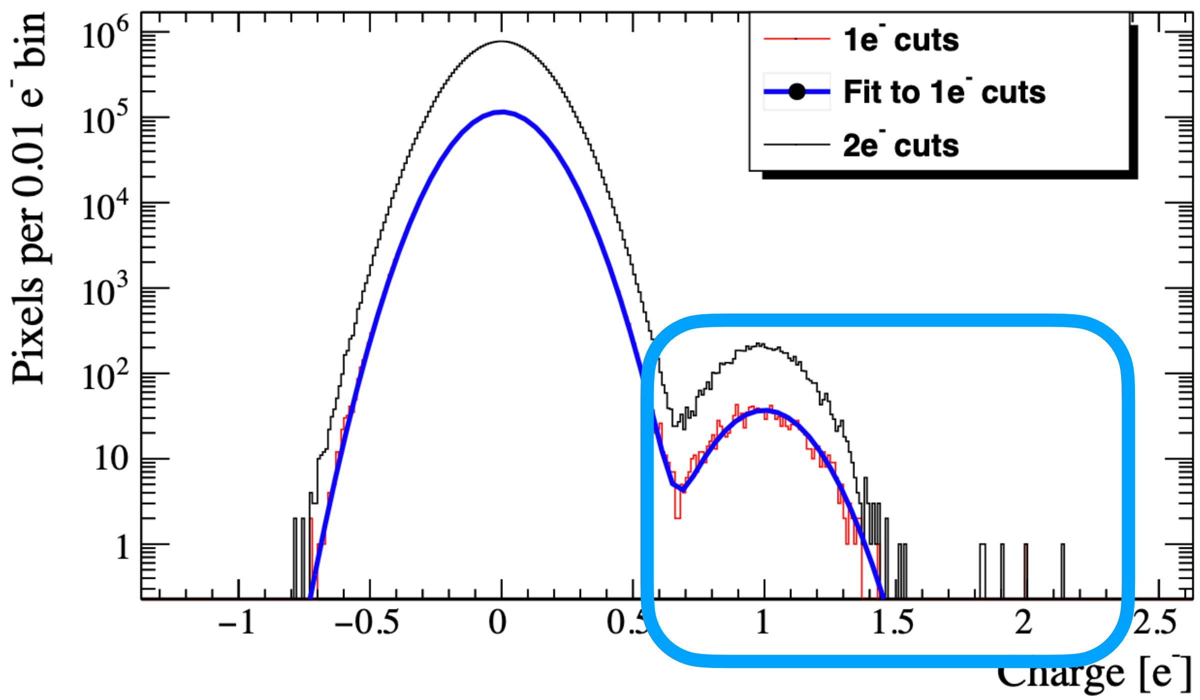
Fig from EXCESS workshop paper, 2202.05097

If origins of these events are not understood, it would severely limit sensitivity to sub-GeV DM

(radioactive backgrounds expected to be ~flat)

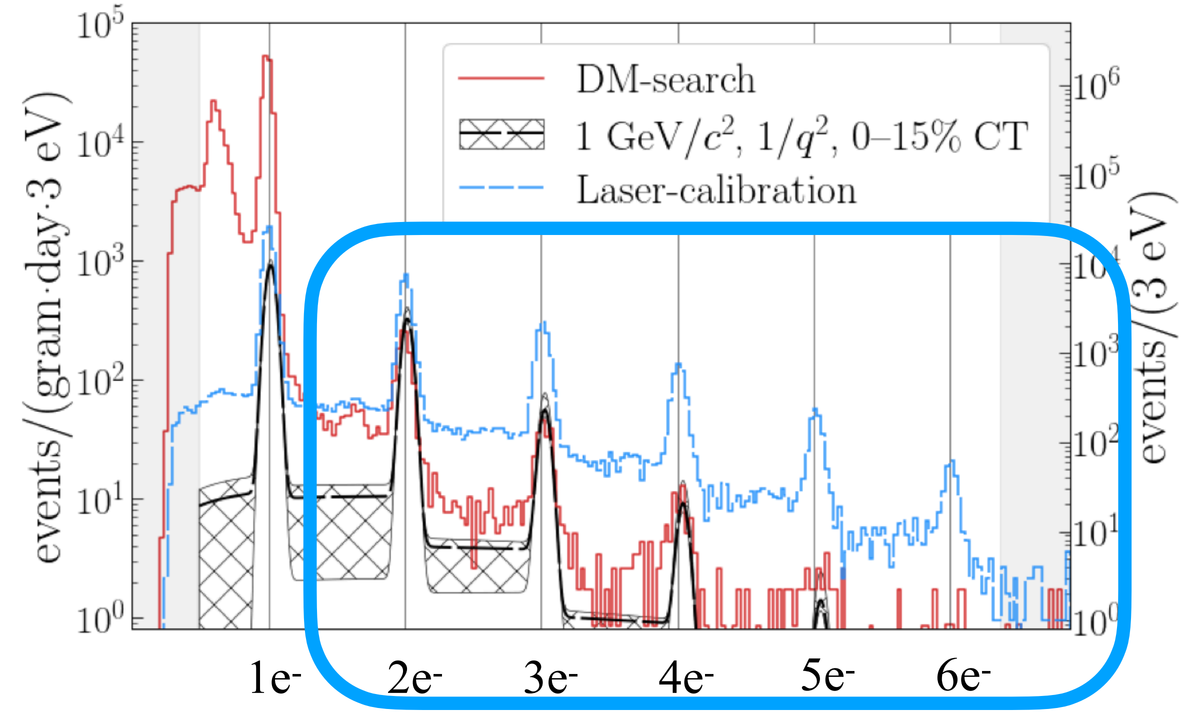
All sub-GeV DM experiments see "excess" low-energy events

e.g. SENSEI



SENSEI, 2004.11378

e.g. SuperCDMS HVeV



SuperCDMS, 2005.14067

We have now identified a major contribution to these "excesses" at SENSEI and SuperCDMS HVeV

Peizhi Du, Daniel Egana-Ugrinovic, RE, Mukul Sholapurkar, 2011.13939

Image from SENSEI

- many $1e^-$ events

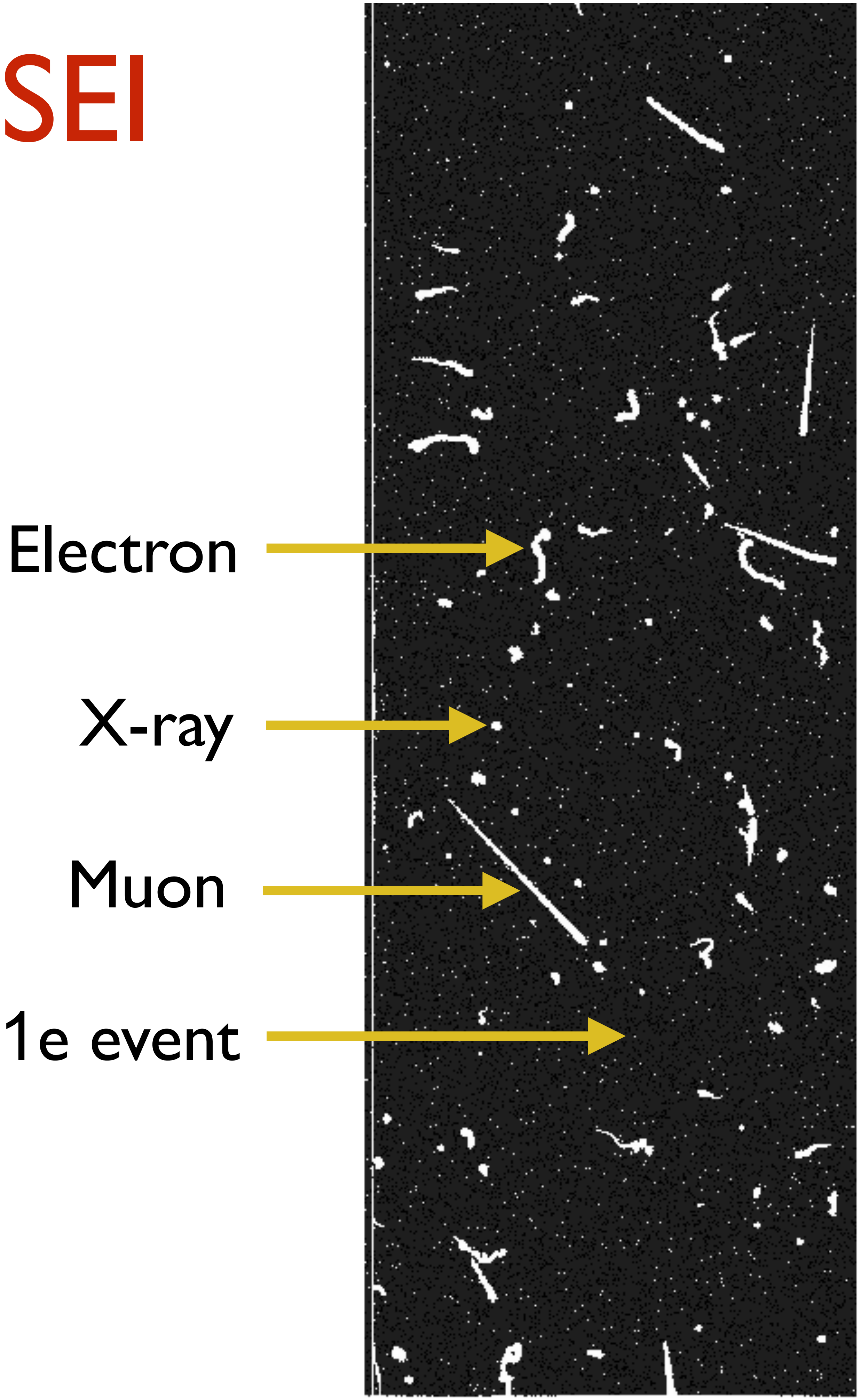


Image from SENSEI

- many $1e^-$ events

From data:

- $1e^-$ events are correlated in position w/ high-energy tracks
- rate correlated with shield thickness

Sources of low-energy events

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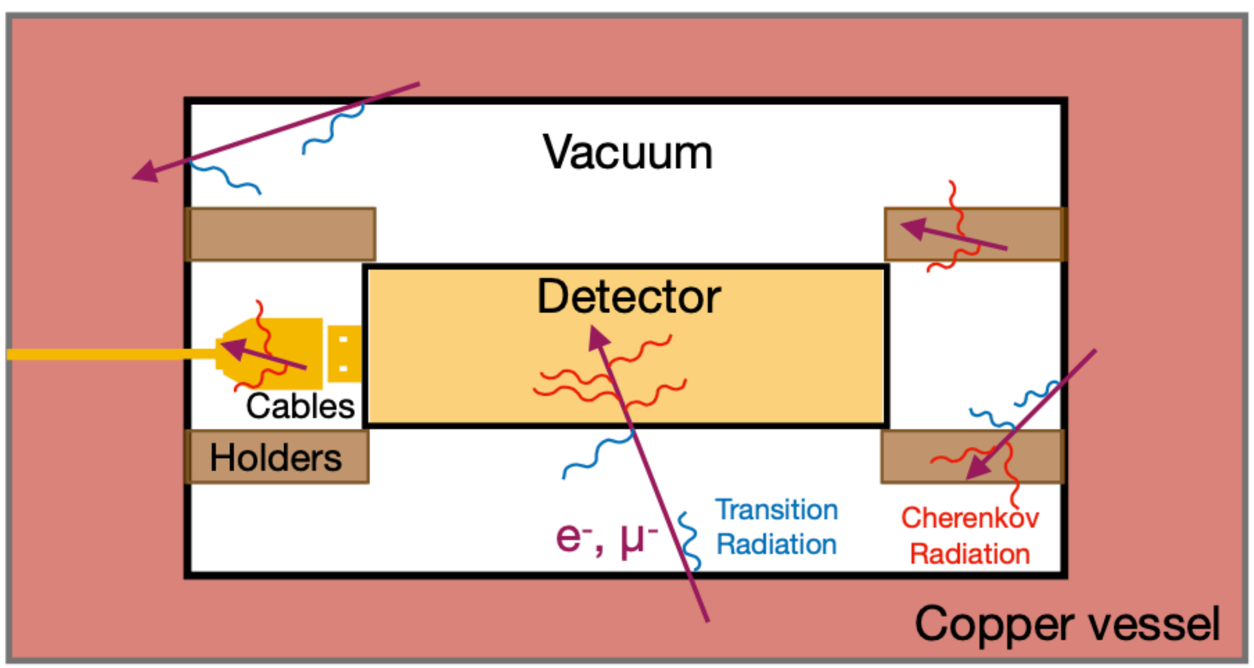
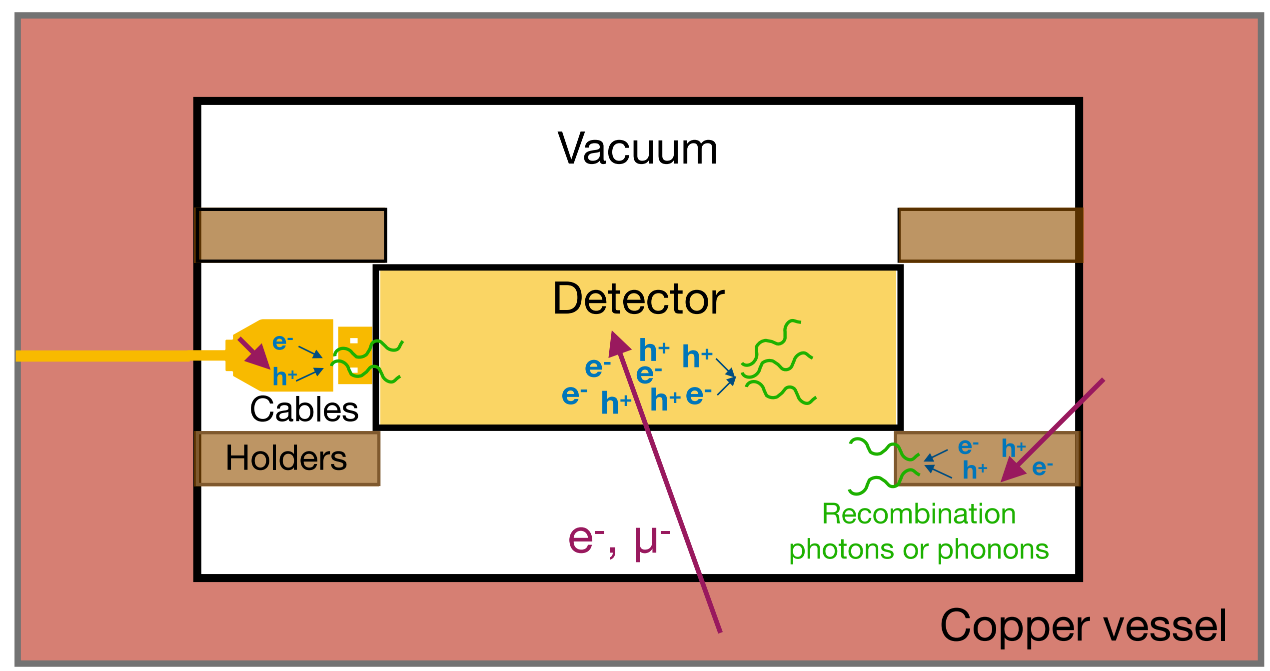
Radioactivity & cosmic-ray muons can produce *many* O(eV) photons, by e.g.

- Cherenkov radiation
- Radiative recombination
- Transition radiation*

Photons get absorbed in sensor to produce an electron





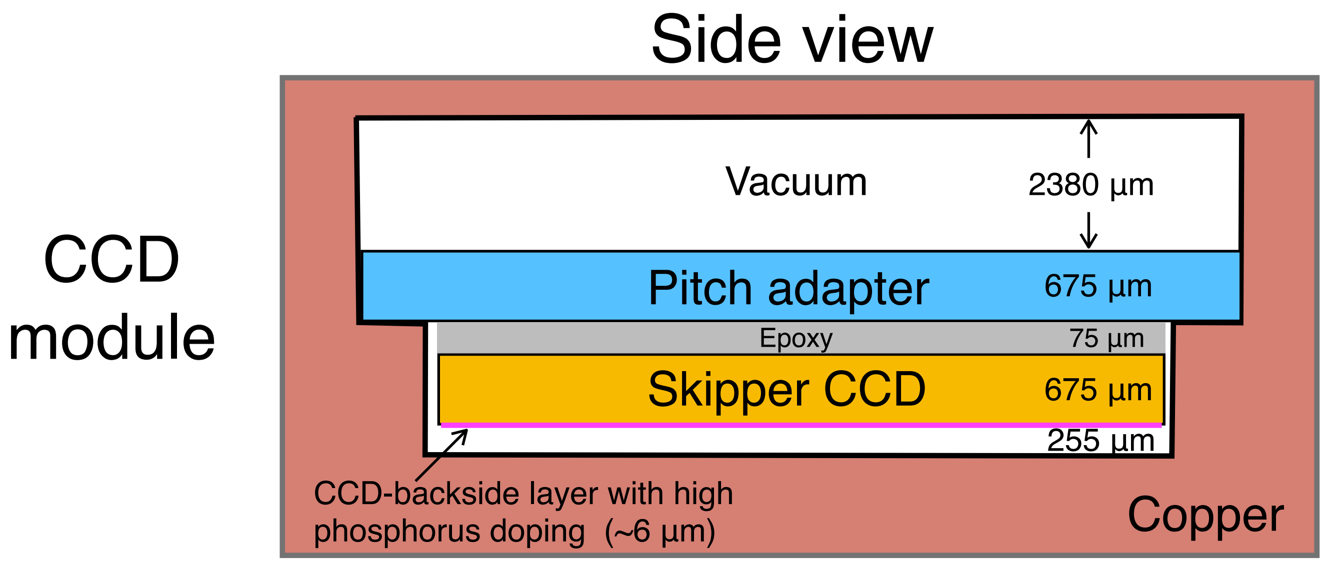
~100s of tracks/g-day at SENSEI, ~10 thousand /g-day at SuperCDMS HVeV

*see also Robinson, 2010.11043

SENSEI $1e^-$: contributions from Cherenkov & recombination

Du, Egana-Ugrinovic, RE, Sholapurkar, 2011.13939

SENSEI, 2004.11378

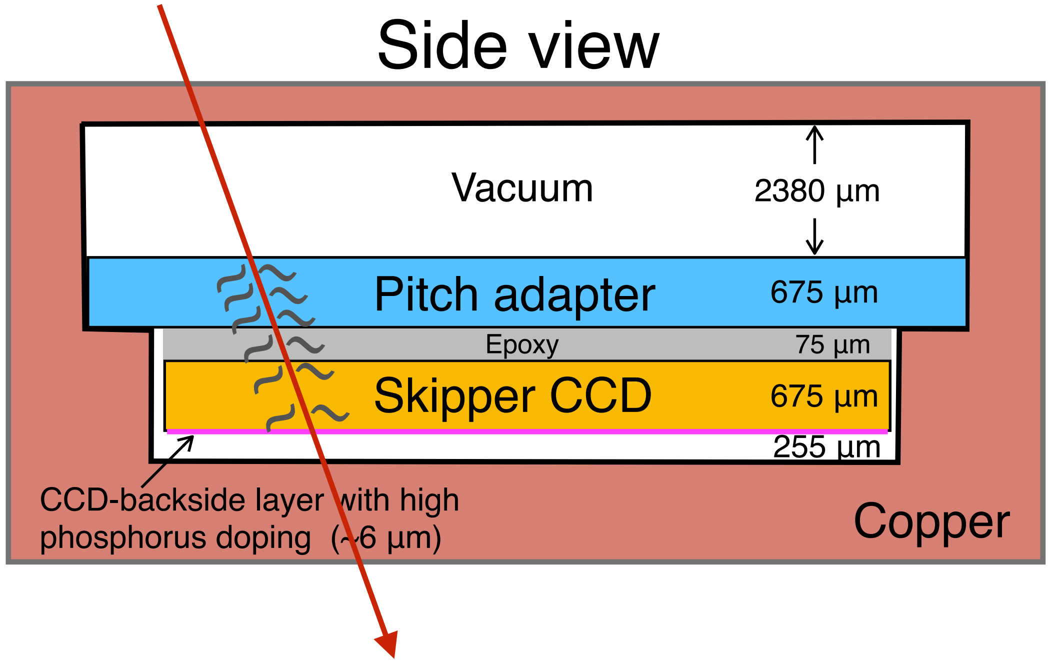


SENSEI $1e^-$: contributions from Cherenkov & recombination

SENSEI, 2004.11378

Du, Egana-Ugrinovic, RE, Sholapurkar, 2011.13939

CCD module

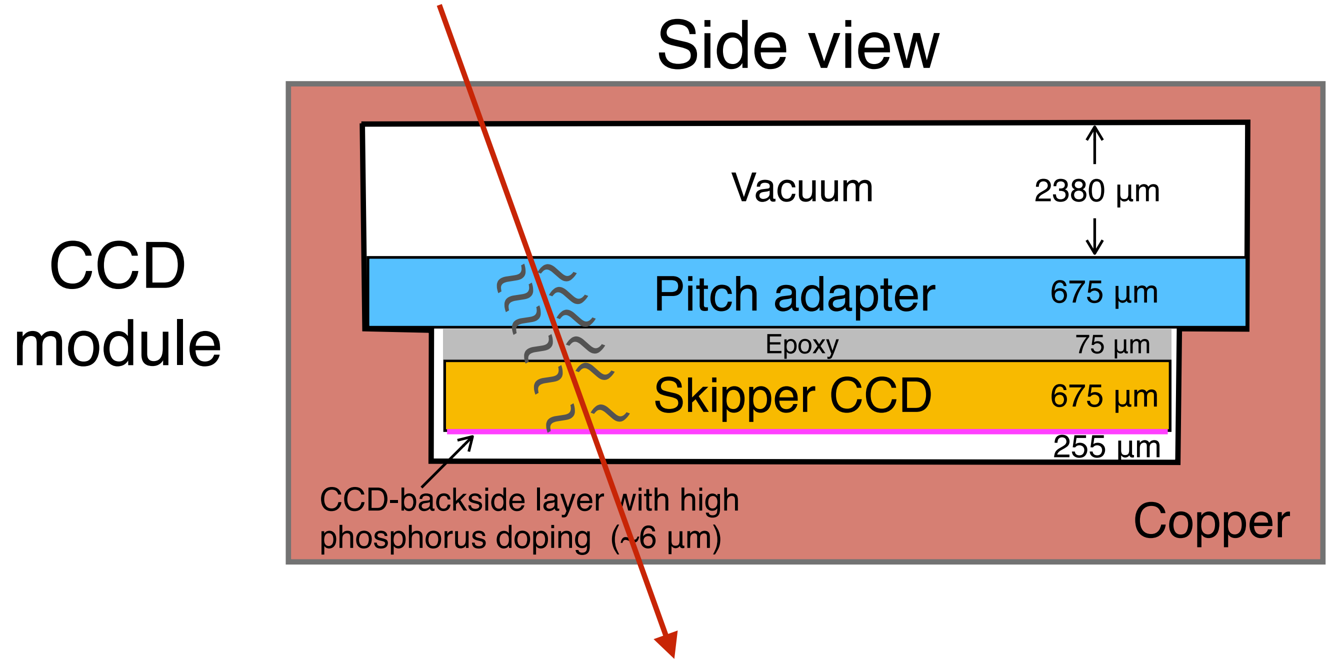


- Cherenkov from tracks produces photons w/ $E_\gamma \lesssim 4$ eV

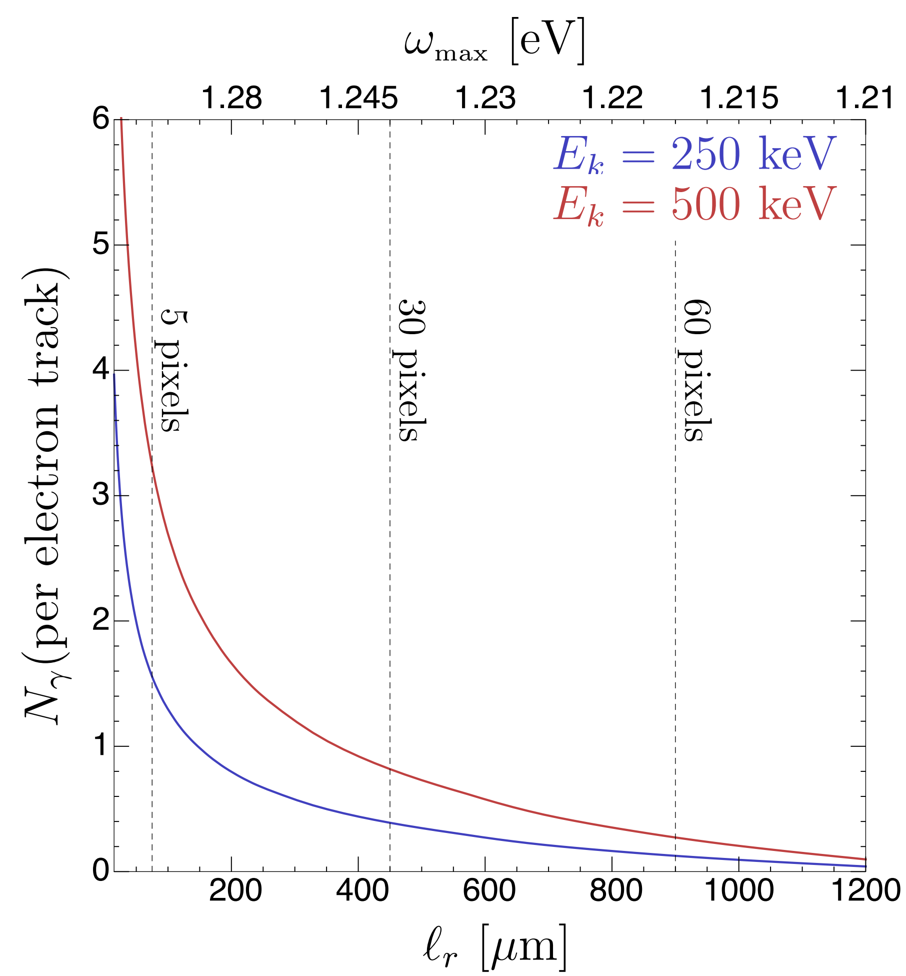
SENSEI $1e^{-}$: contributions from Cherenkov & recombination

SENSEI, 2004.11378

Du, Egana-Ugrinovic, RE, Sholapurkar, 2011.13939



- Cherenkov from tracks produces photons w/ $E_\gamma \lesssim 4$ eV
- Photons w/ energy closer to Si bandgap (~1.2 eV) travel further — explains correlation w/ high-energy tracks

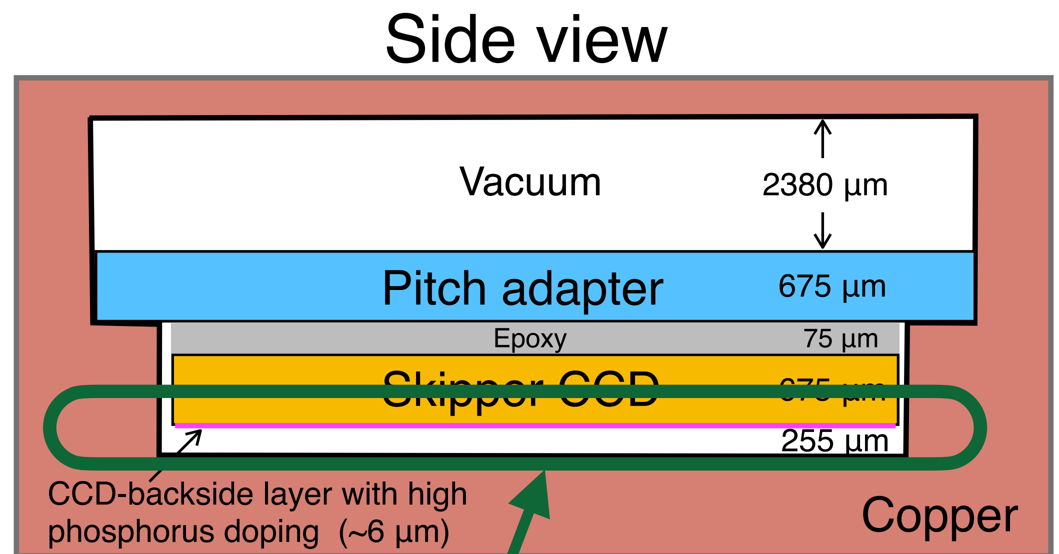


SENSEI $1e^-$: contributions from Cherenkov & recombination

SENSEI, 2004.11378

Du, Egana-Ugrinovic, RE, Sholapurkar, 2011.13939

CCD module



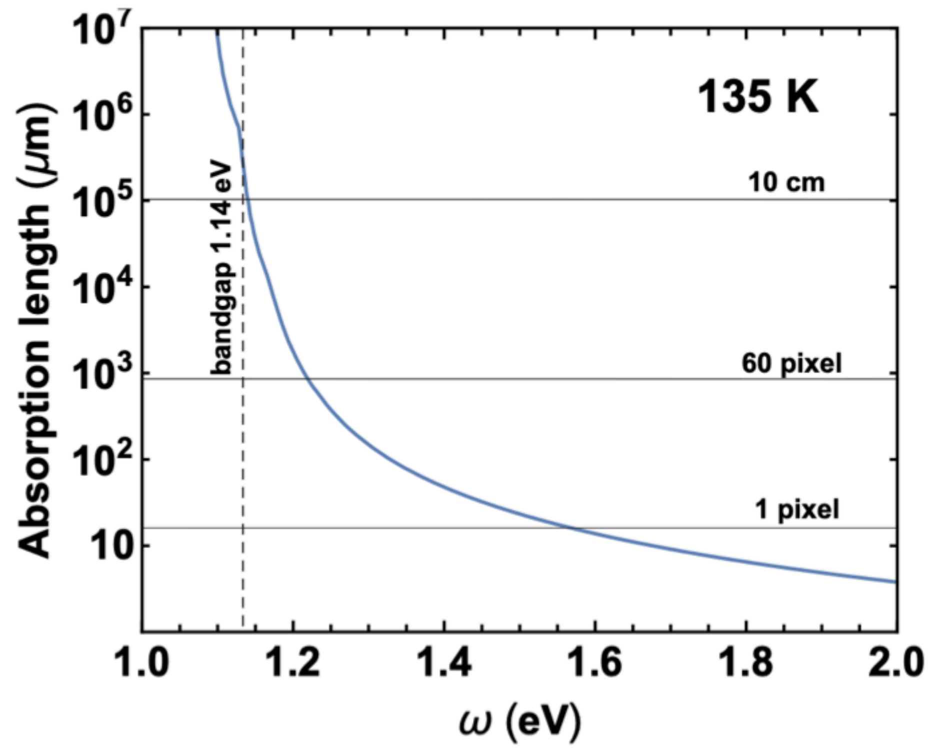
- Cherenkov from tracks produces photons w/ $E_\gamma \lesssim 4$ eV
- Photons w/ energy closer to Si bandgap (~1.2 eV) travel further — explains correlation w/ high-energy tracks
- Radiative recombination only important in a thin layer of highly-doped Si on CCD backside

Detailed simulation for SENSEI is in progress…

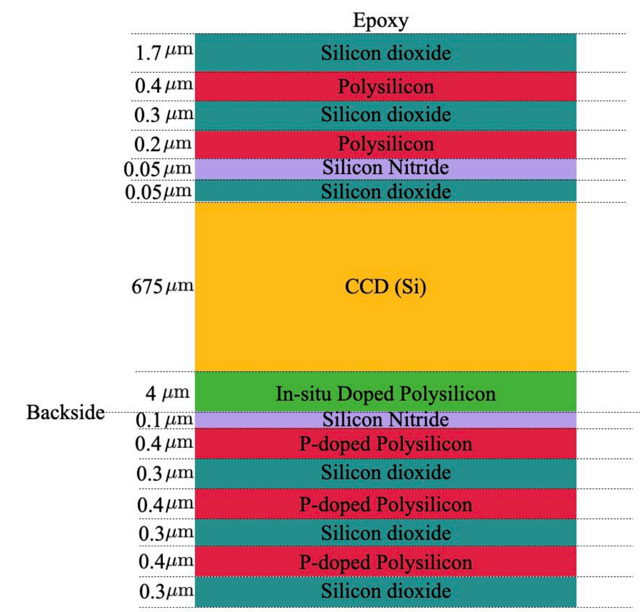
Peizhi Du, Daniel Egana-Ugrinovic, RE, Mukul Sholapurkar, to appear

Simulated tracks

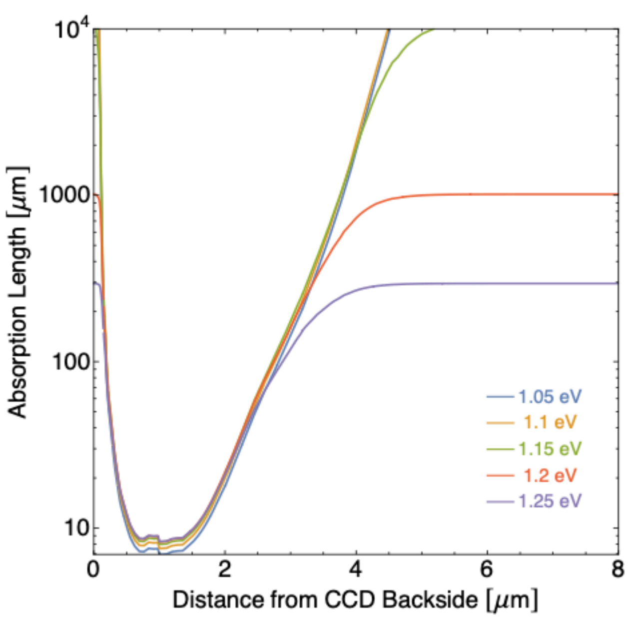
Photon absorption



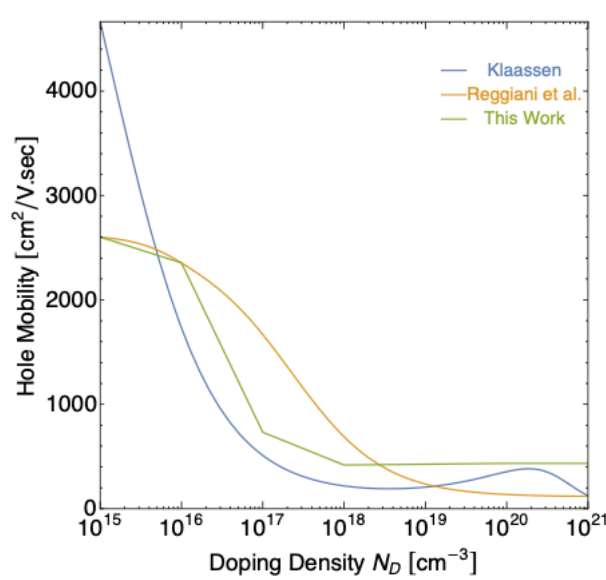
Reflection/refraction, thin-film interference



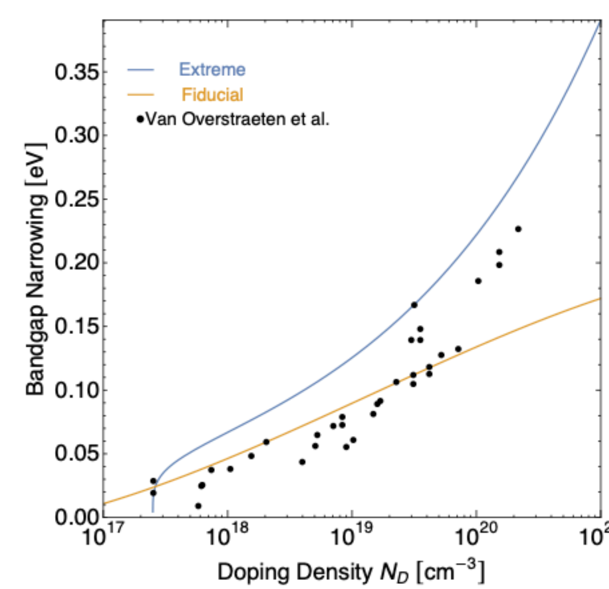
Backside absorption



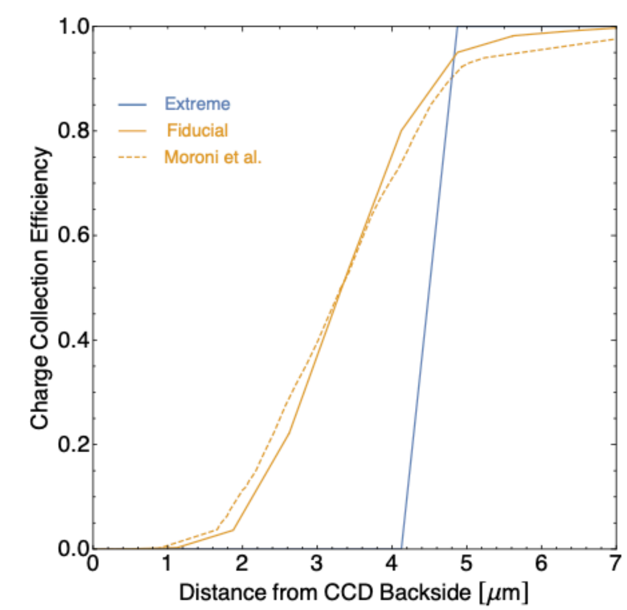
Mobility models



Bandgap gradients

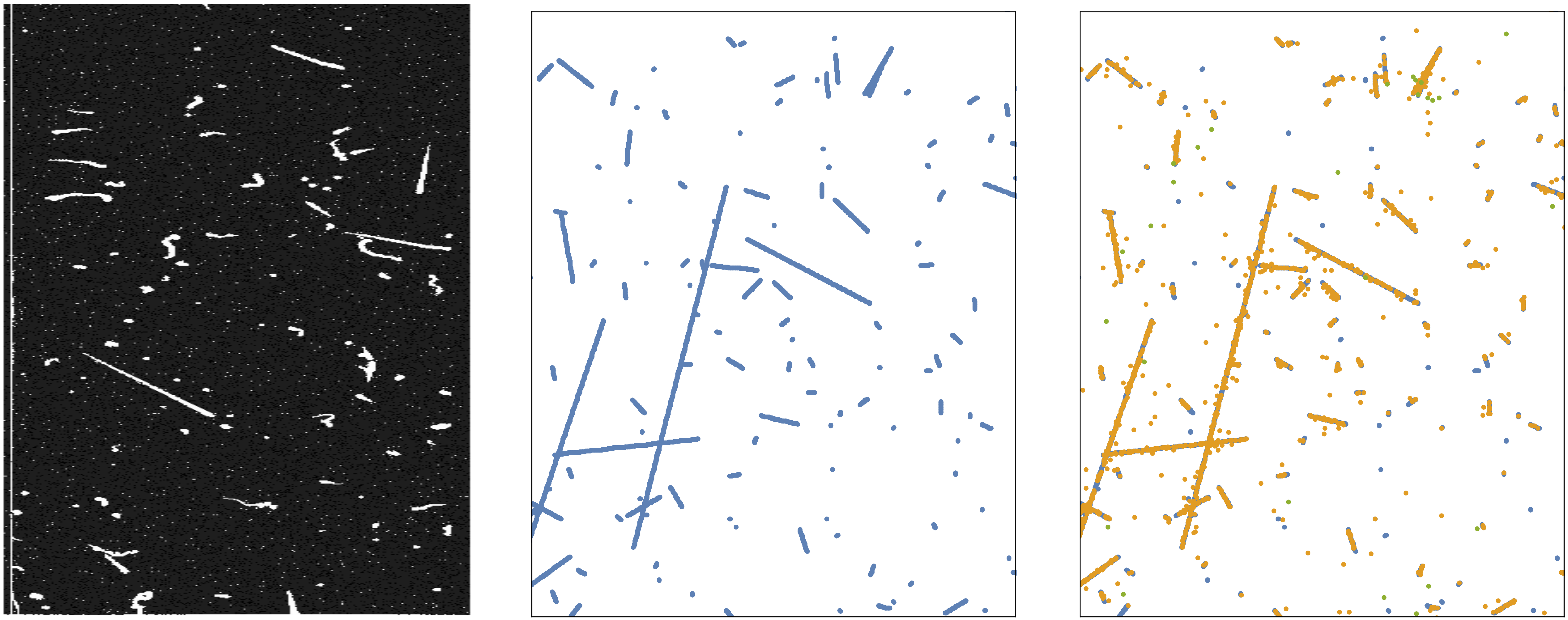


Partial charge collection



SENSEI simulation of $1e^-$ events (preliminary)

Peizhi Du, Daniel Egana-Ugrinovic, RE, Mukul Sholapurkar, to appear



SENSEI data

simulated
electron/muon tracks

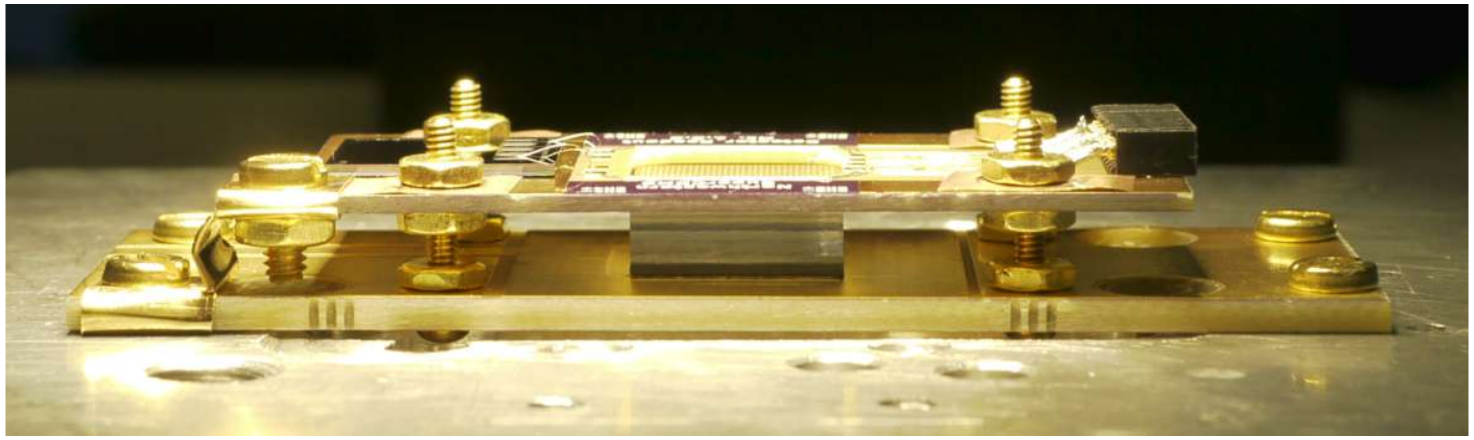
simulated
electron/muon tracks
+ Cherenkov +
Recombination

Current conclusion: Cherenkov dominates over recombination; contributes $\mathcal{O}(1)$ to observed 1e events, but does not explain all…

SuperCDMS $2e^-$ to $6e^-$events: likely dominated by Cherenkov

Peizhi Du, Daniel Egana-Ugrinovic, RE, Mukul Sholapurkar, 2011.13939

SuperCDMS, 2005.14067



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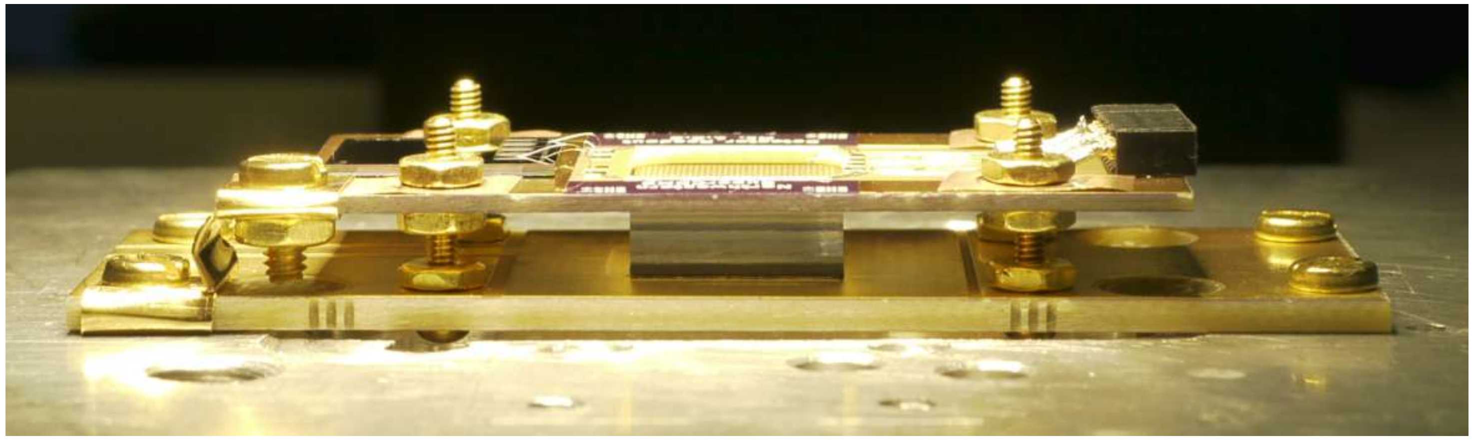
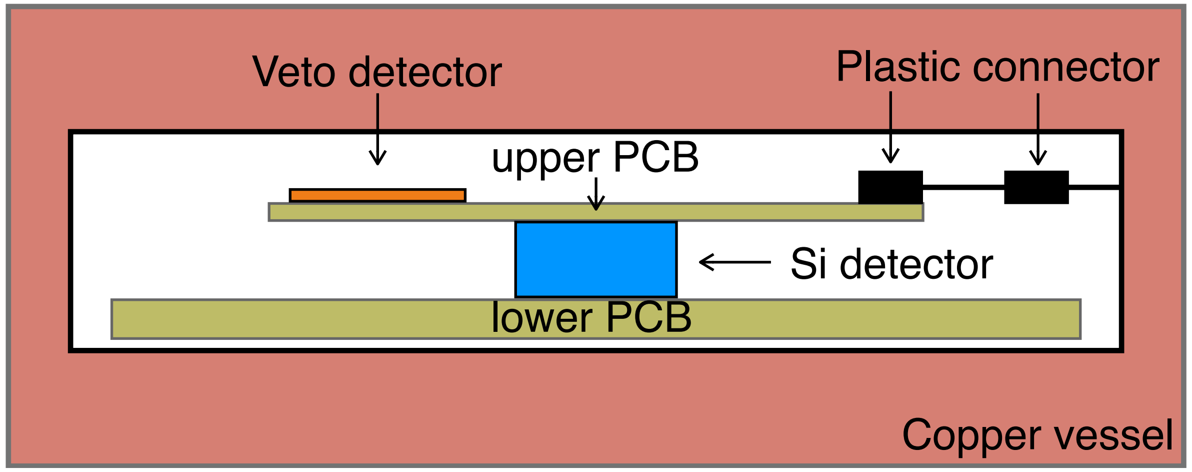
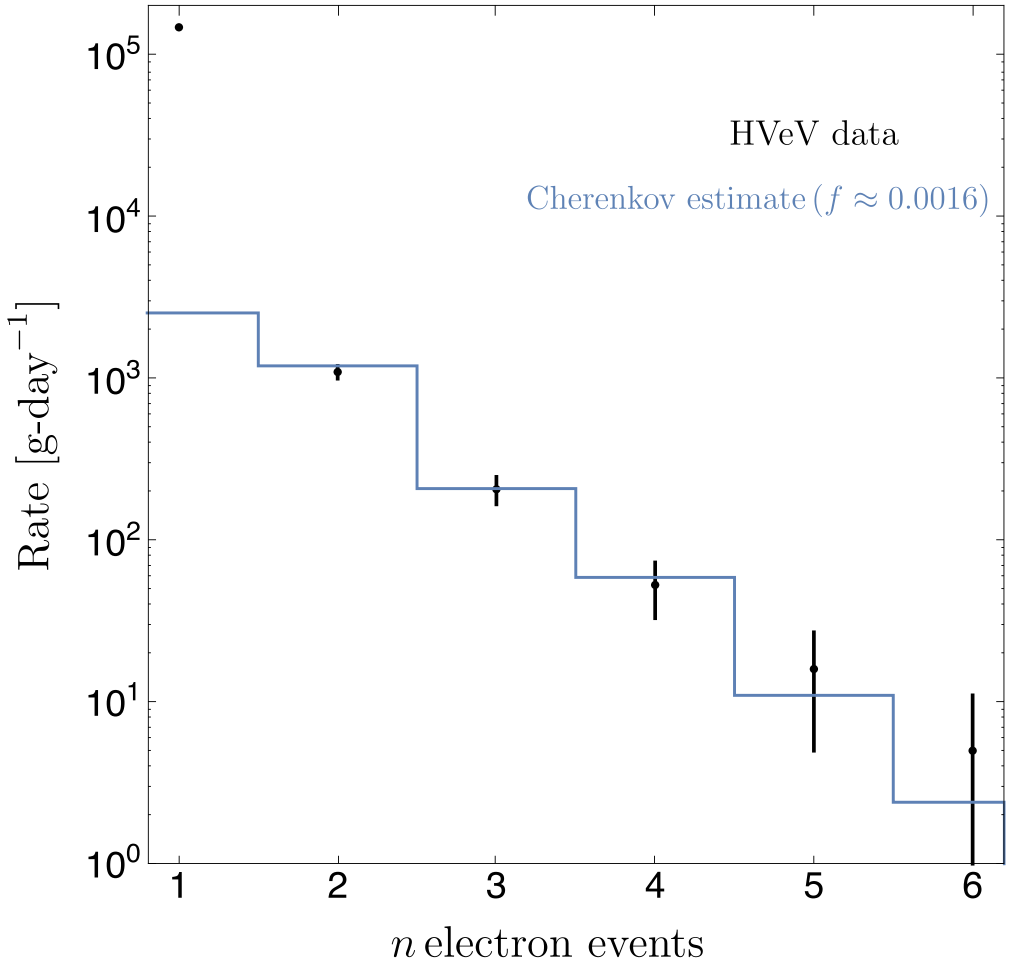
SuperCDMS, 2005.14067



Side view



- Cherenkov from, e.g., "printed circuit board" ("PCB") produces *many* O(eV) photons
- a simple model can explain spectrum & rate, assuming every photon is absorbed in detector with an efficiency $f \sim 0.0016$
- detailed sim is needed



Implications

Peizhi Du, Daniel Egana-Ugrinovic, RE, Mukul Sholapurkar, 2011.13939

- Dielectric materials in experiments are common (holders, cables etc): need careful evaluation of backgrounds!
  - important for SENSEI, DAMIC-M, Oscura, SuperCDMS-HVeV, SuperCDMS SNOLAB, optical haloscopes, scintillators…

Implications

Peizhi Du, Daniel Egana-Ugrinovic, RE, Mukul Sholapurkar, 2011.13939

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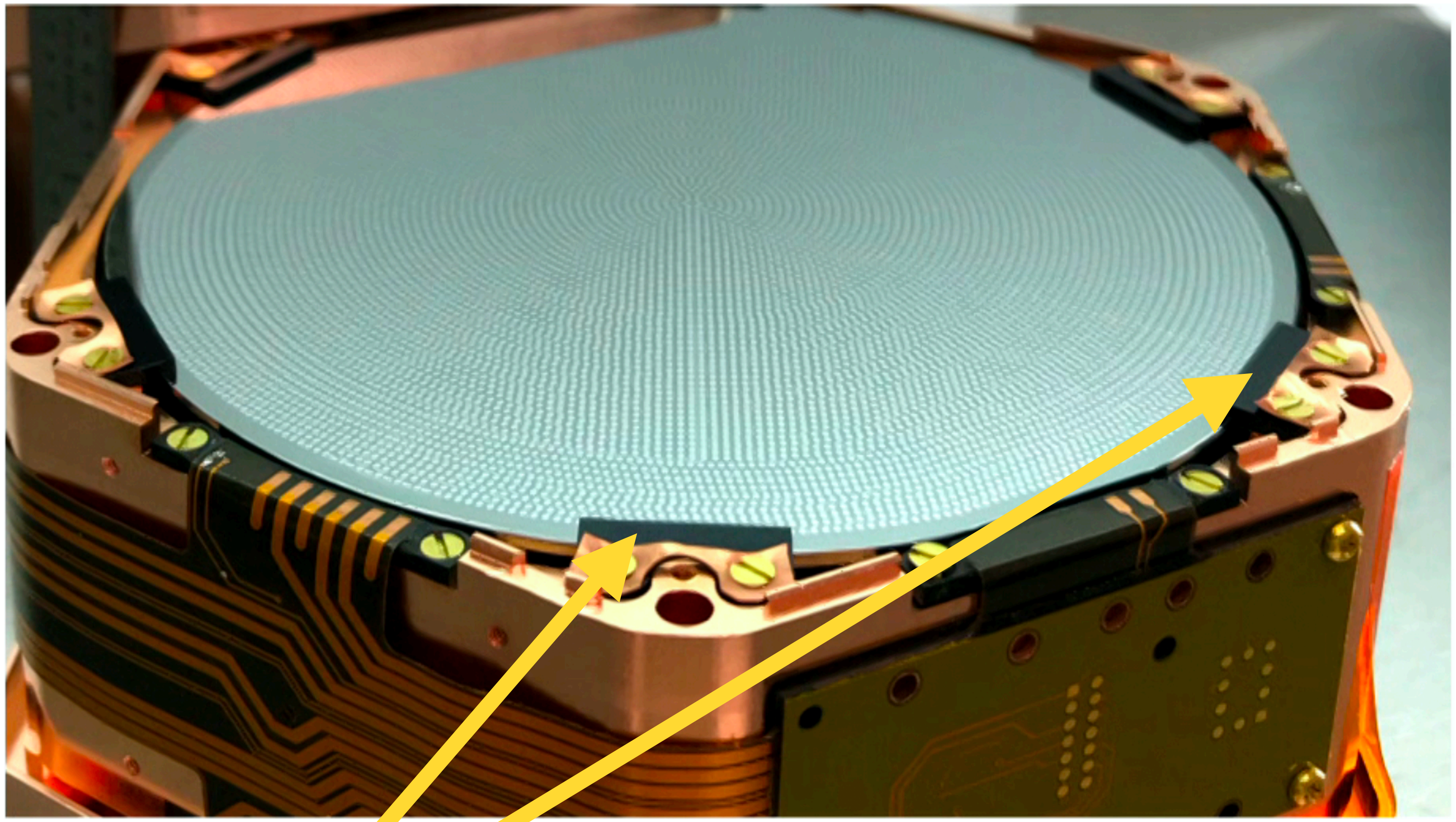

SuperCDMS SNOLAB detector

Radioactive impurities in Cirlex in SuperCDMS SNOLAB detectors produce ~50,000 β-decays/year that can produce Cherenkov… need careful simulation of how many can be vetoed

Implications

Peizhi Du, Daniel Egana-Ugrinovic, RE, Mukul Sholapurkar, 2011.13939

- Dielectric materials in experiments are common (holders, cables etc): need careful evaluation of backgrounds!
  - important for SENSEI, DAMIC-M, Oscura, SuperCDMS-HVeV, SuperCDMS SNOLAB, optical haloscopes, scintillators…
- Backgrounds could also limit coherence times of superconducting qubits
- Fortunately, can mitigate these backgrounds! [see backup slide; e.g., better shield reduces these backgrounds]

(Note: excesses at e.g. CRESST-III, EDELWEISS, SuperCDMS-CPD have another origin)

Outline

- Some Recent Progress
- Sources of Low-Energy Backgrounds
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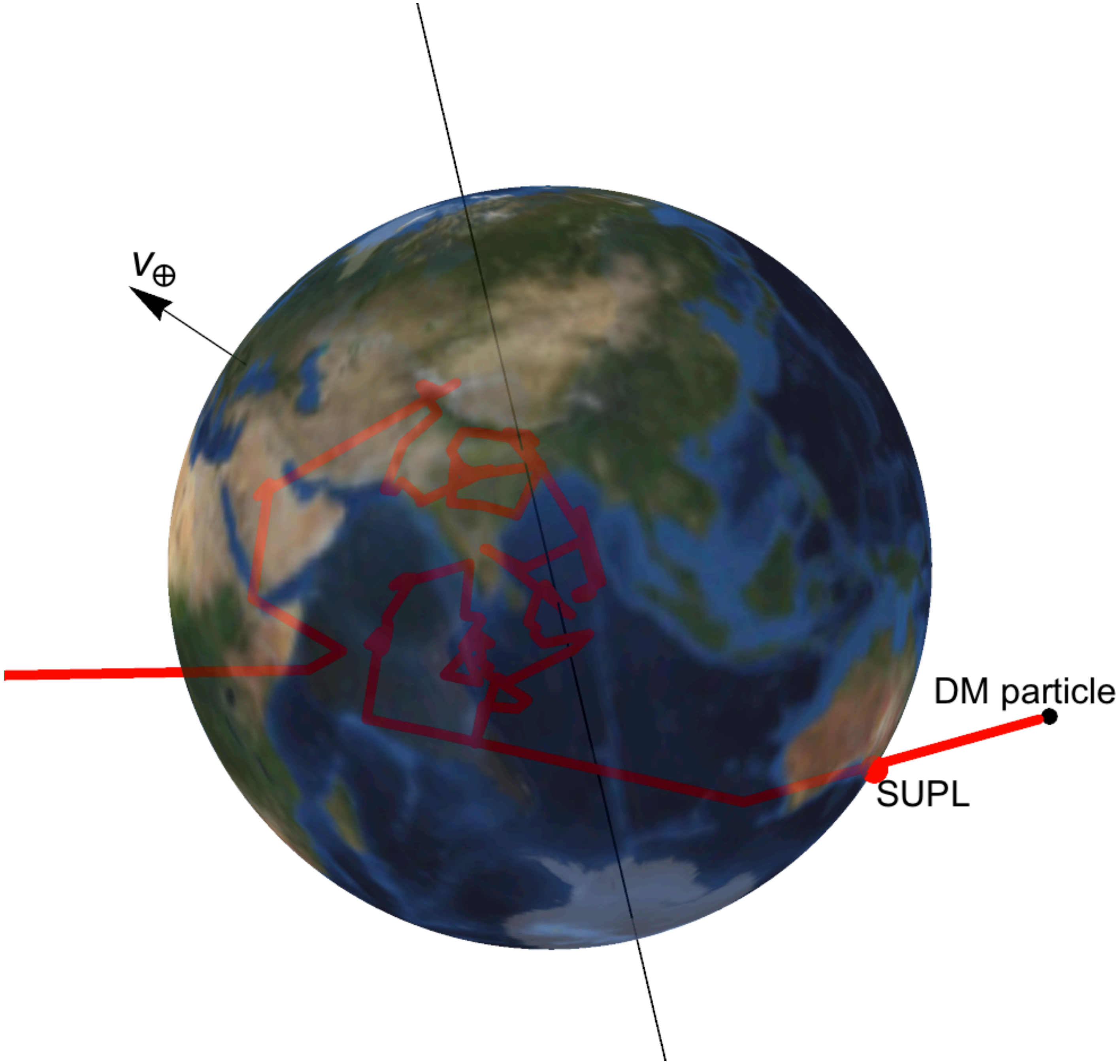
Effects from DM scattering in Earth



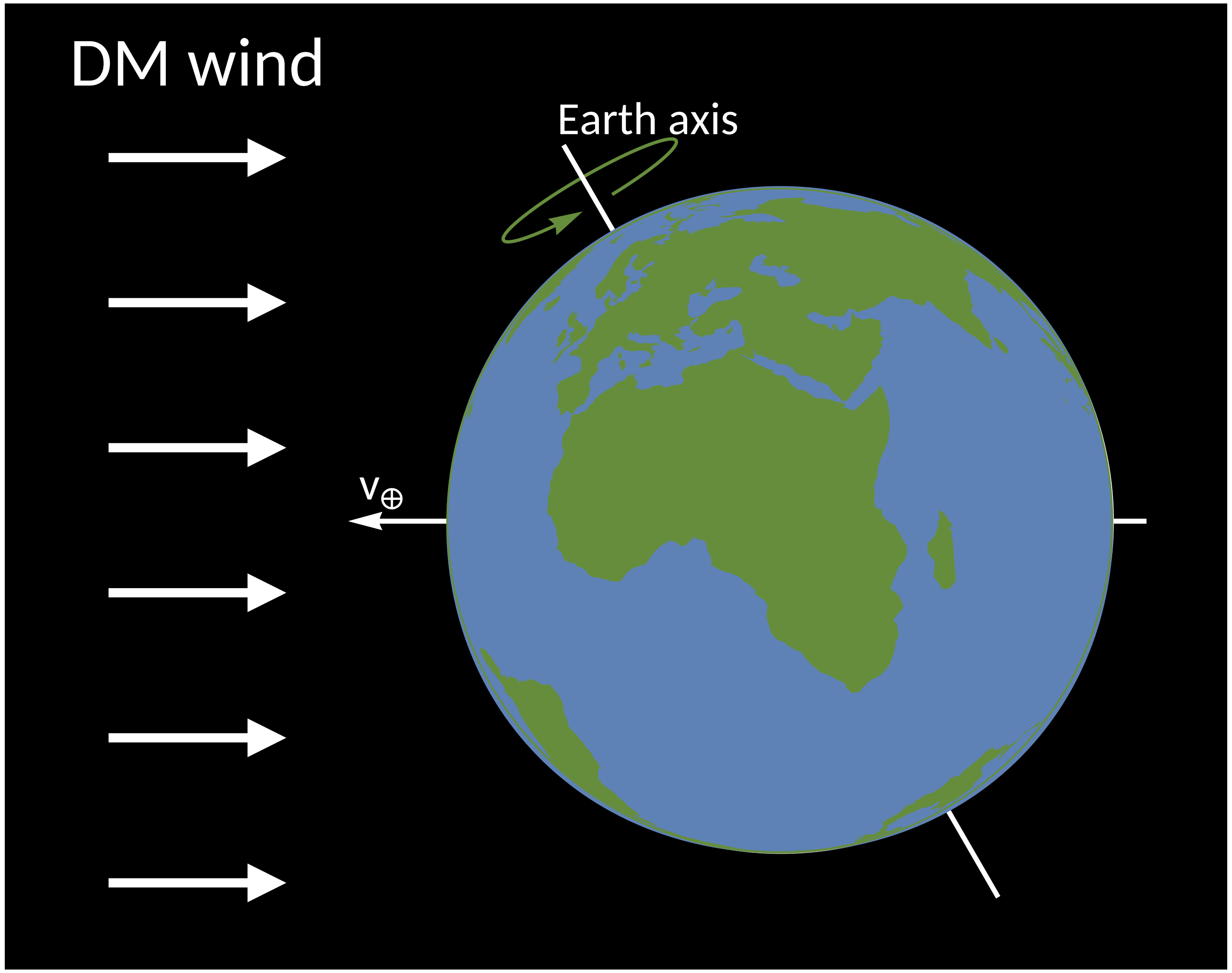
DM can scatter in Earth before reaching detector

affects velocity distribution of DM once it reaches detector

Fig. credit: Timon Emken

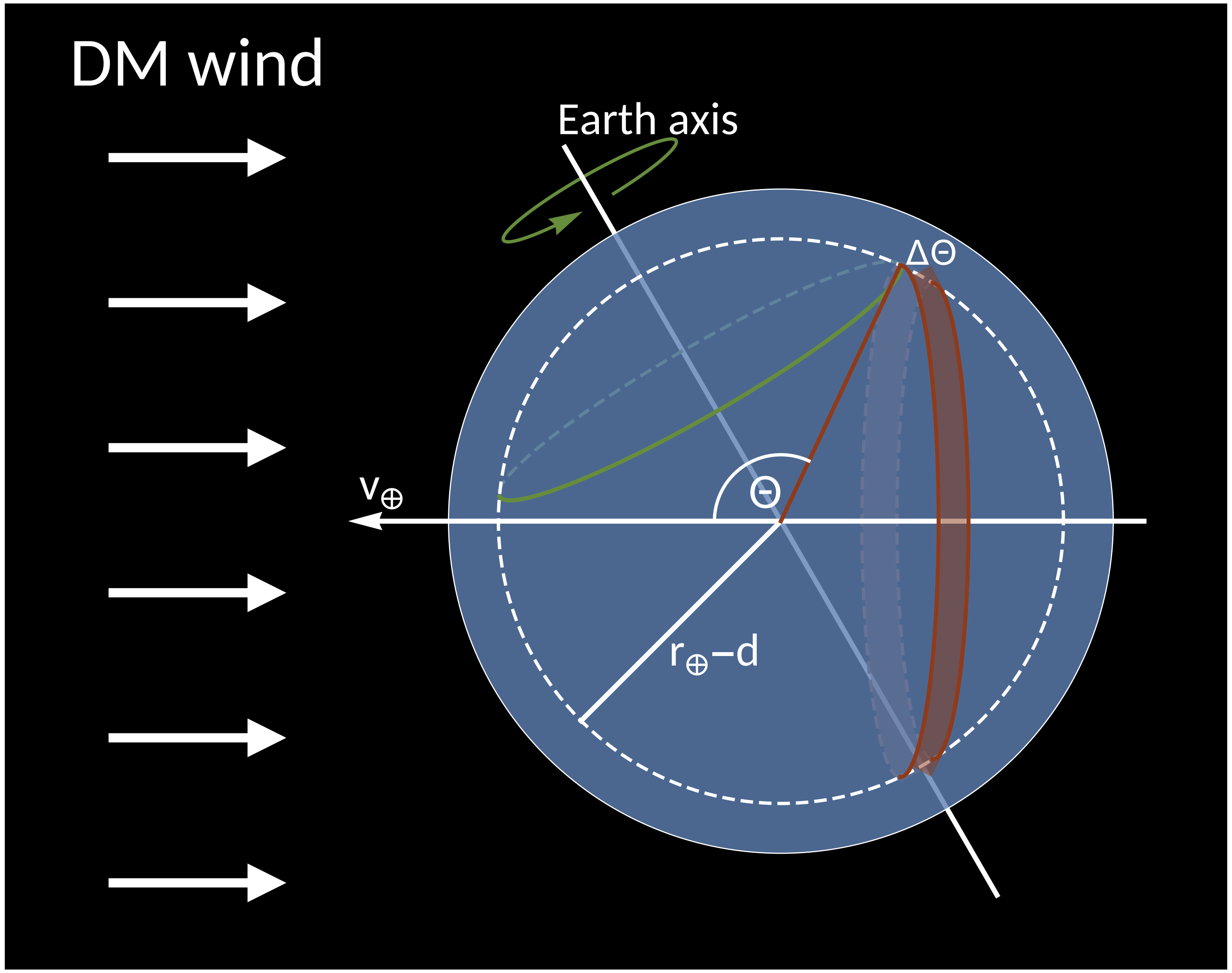
Effects from DM scattering in Earth

Diurnal modulation



Effects from DM scattering in Earth

Diurnal modulation



How deep is a laboratory in Earth's 'shadow'?

$$\Theta(t) = \arccos\left[\frac{\mathbf{v}_\oplus(t)\cdot\mathbf{x}^{(\mathrm{gal})}_{\mathrm{lab}}(t)}{v_\oplus(t)(r_\oplus - d)}\right]$$

$\Theta = 0^\circ \implies$ DM wind from above

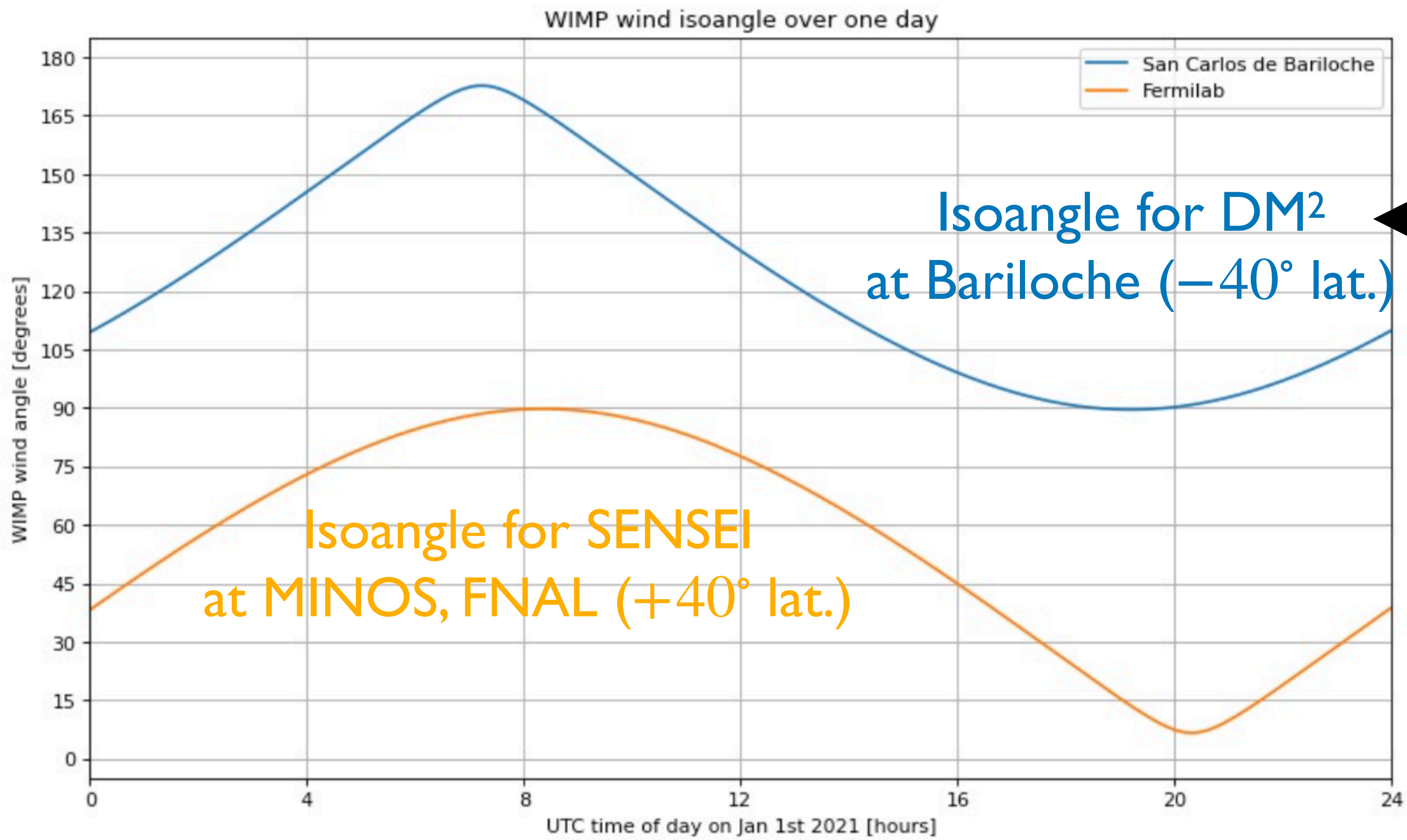
$\Theta = 180^\circ \implies$ Shadow

J.I. Collar, F.T. Avignone, Phys. Lett. B275 (1992), 181-185
J.I. Collar, F.T. Avignone, PRD 47 (1993), 5238-5246
Hasenbalg et al., PRD 55 (1997), 7350-7355

Diurnal modulation in current sub-GeV DM searches

Bertou, Emken, RE, Sofo-Haro, Tiffenberg, Volansky, Yu work in progress

consider two locations:
FNAL (USA) & Bariloche (Argentina)



DM² = DM Daily Modulation experiment

emerging effort, using Skipper-CCDs

more "stopping" at Bariloche than at FNAL

seeing a modulation at two different laboratories would be striking

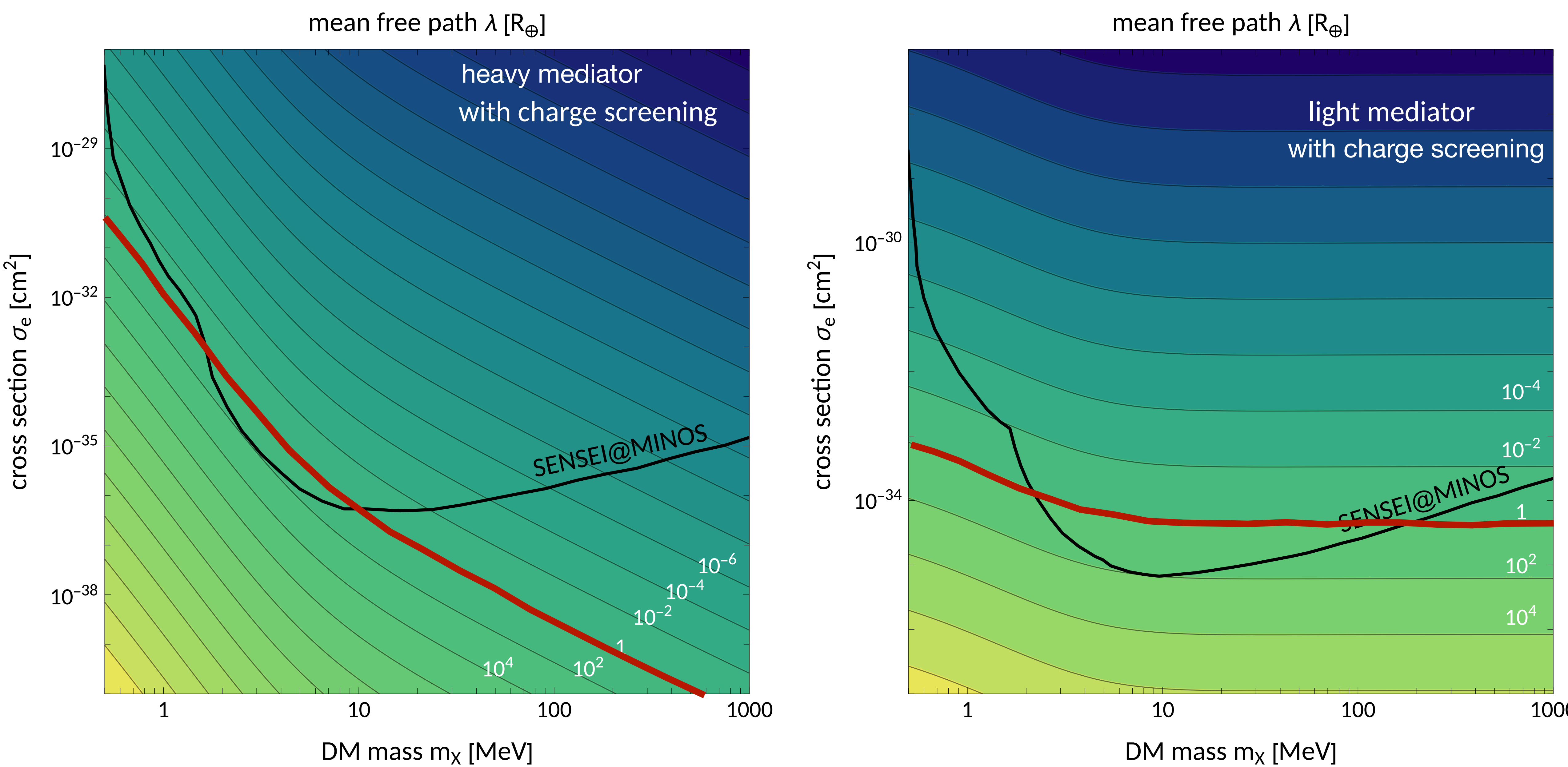
How important for current+upcoming Sub-GeV DM experiments?

- Consider DM interacting w/ a dark-photon
- Hierarchy between nuclear and electron scattering:

$$\frac{\sigma_p}{\sigma_e} = \left(\frac{\mu_{\chi p}}{\mu_{\chi e}}\right)^2 \approx \left(\frac{m_\chi}{m_e}\right)^2 \qquad \text{for } m_e \ll m_\chi \ll 1 \text{ GeV}$$

How important for current+upcoming experiments?

Bertou, Emken, RE, Volansky, Yu work in progress

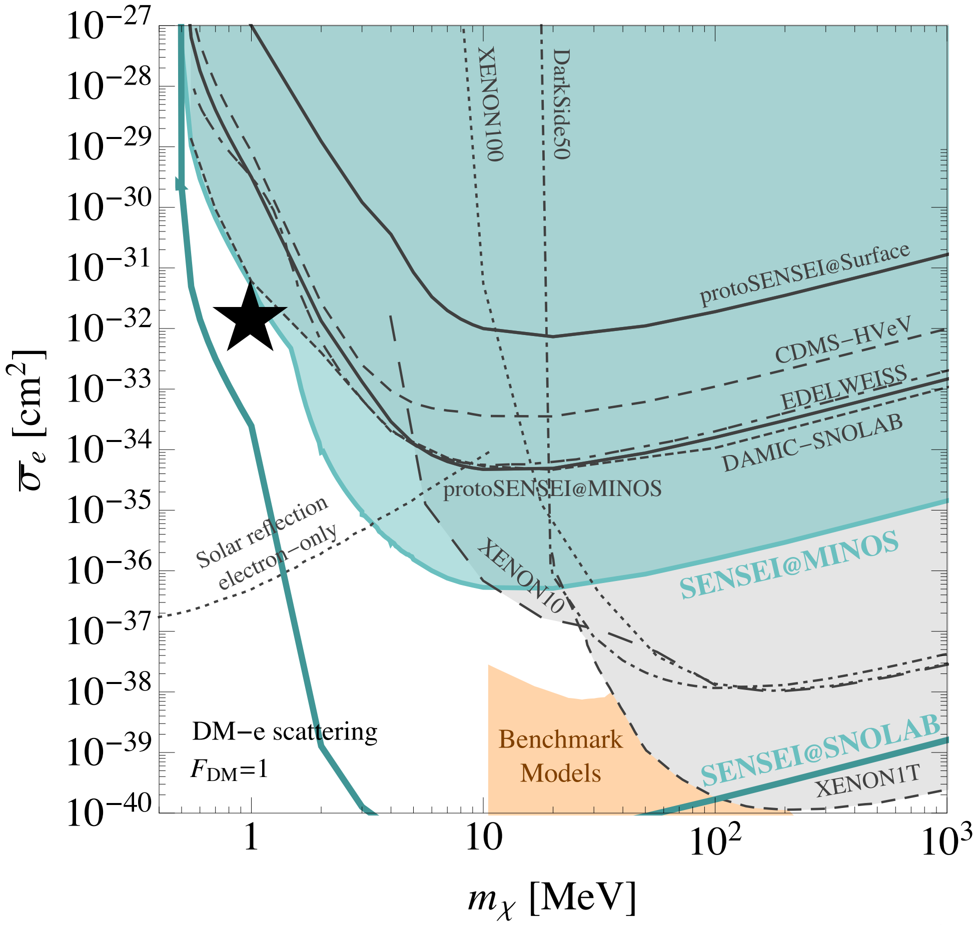


important for current results, especially at low DM masses

diurnal modulation provides discovery opportunity!
(or improved constraints)

Example of Diurnal Modulation in current searches

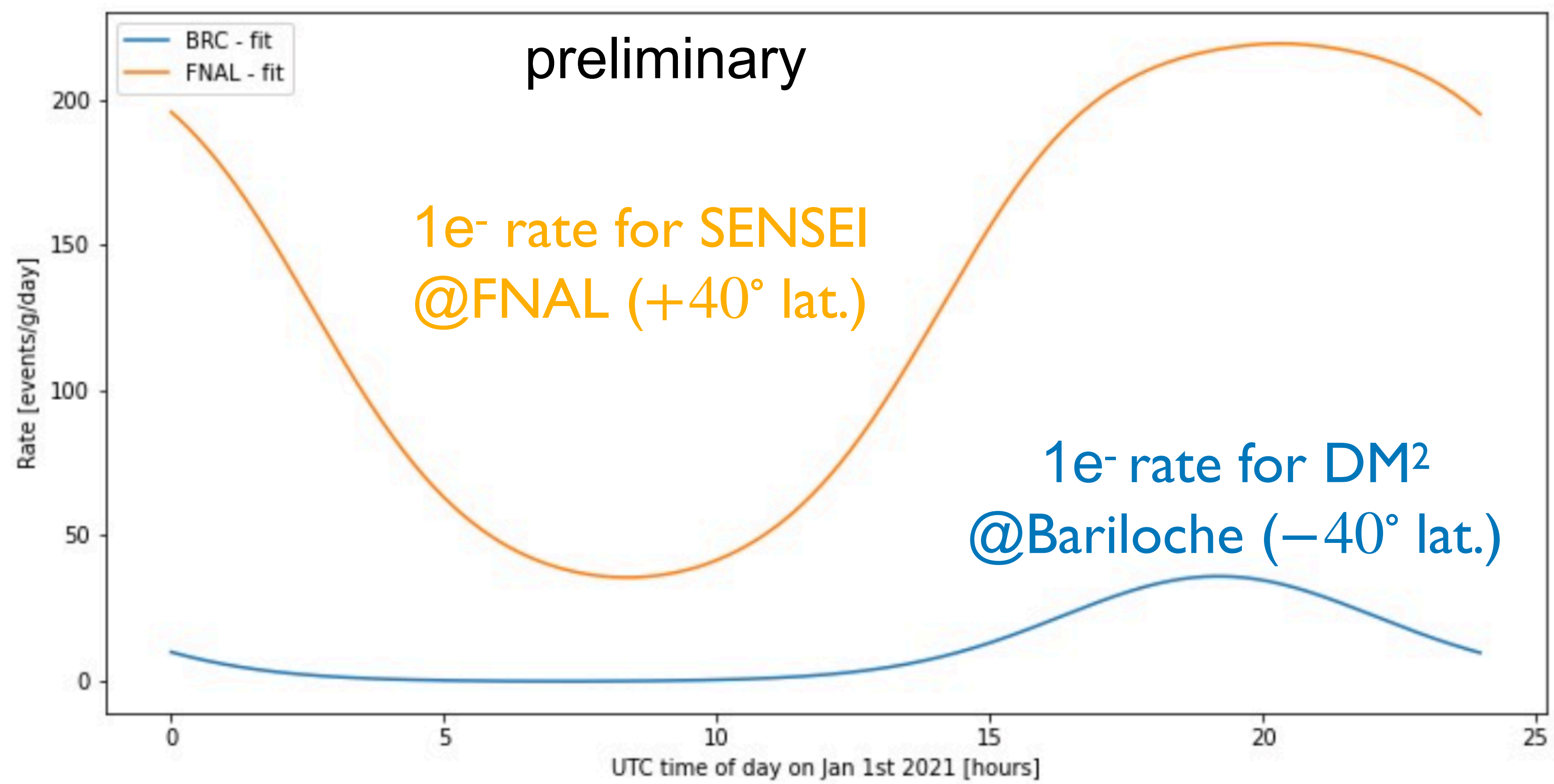
Bertou, Emken, RE, Volansky, Yu work in progress



could significantly improve search for low-mass DM, which is background-dominated

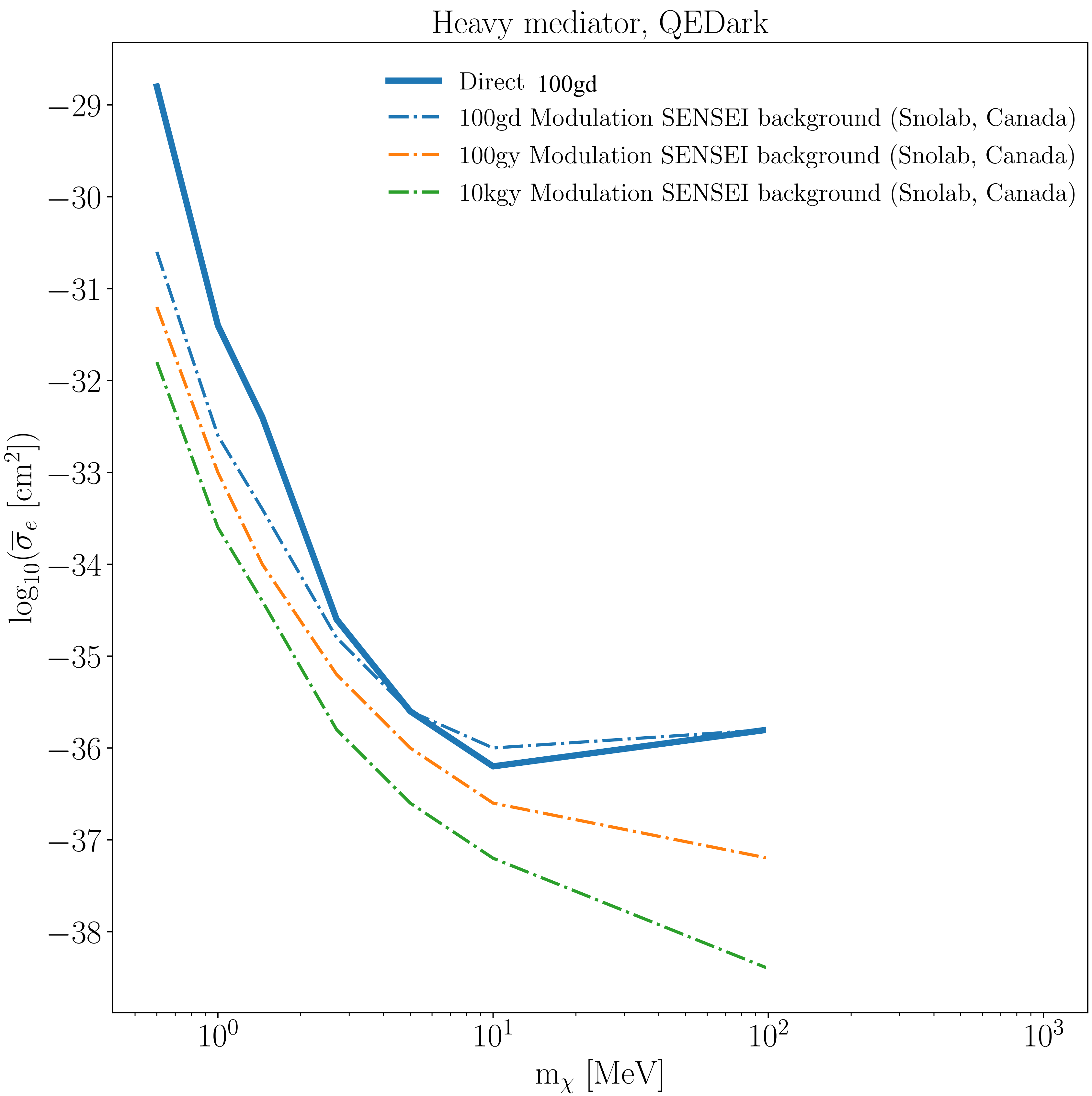
SENSEI modulation search is in progress

$$\sigma_e = 10^{-32}\ \mathrm{cm}^2,\ m_\chi = 1\ \mathrm{MeV}$$



Projected reach from modulation search

Bertou, Emken, RE, Volansky, Yu work in progress



preliminary

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Dark Matter Detection w/ Quantum Dots

Blanco, RE, Fernandez-Serra, Ramani, Slone, to appear soon

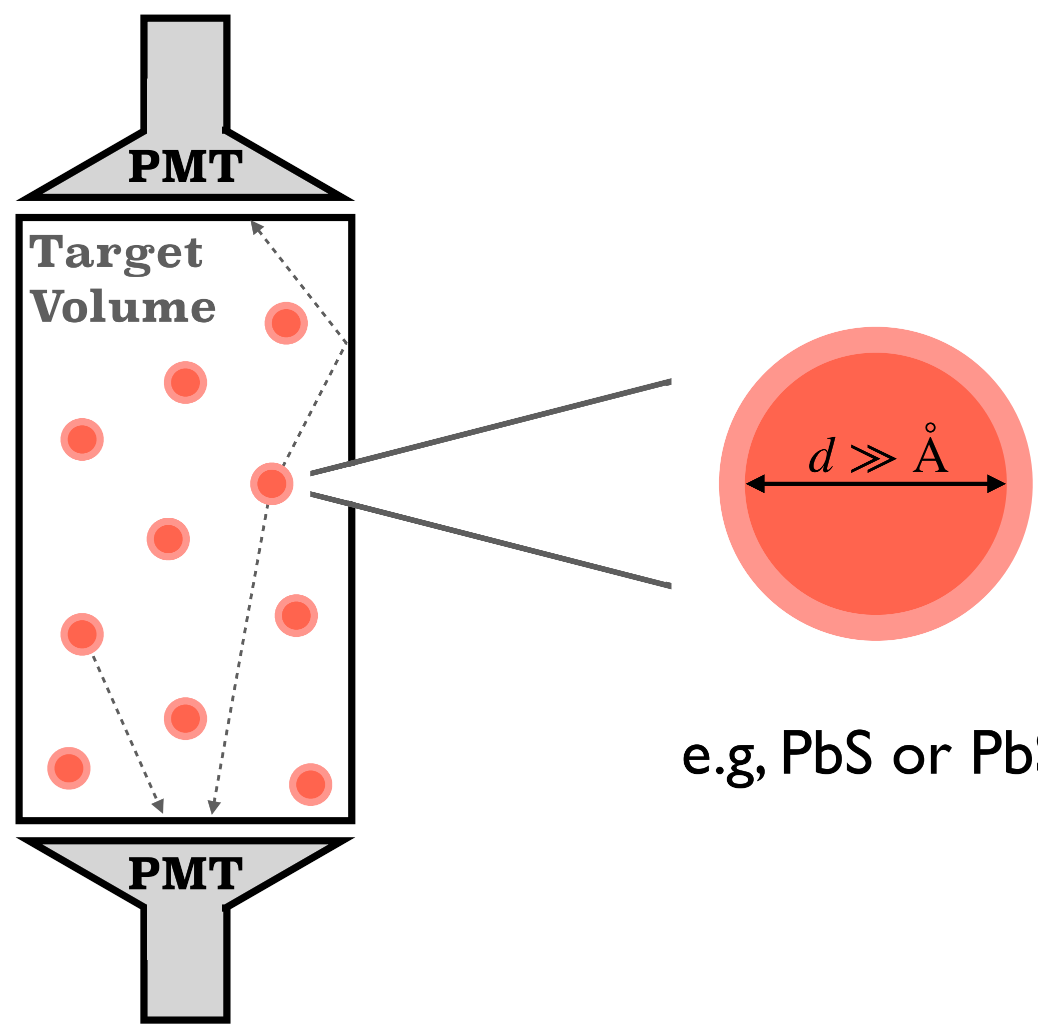
Quantum Dot: few-nm diameter semiconductor crystals (~100 to 100,000's of atoms), suspended in solution

DM-electron interaction in QD produces one or more excitons

Multi-exciton can decay via two-photon emission

low threshold, easily scalable

<u>Example setup</u>:
2 PMTs search for
two-photon coincident signal



e.g, PbS or PbSe

Dark Matter Detection w/ Quantum Dots

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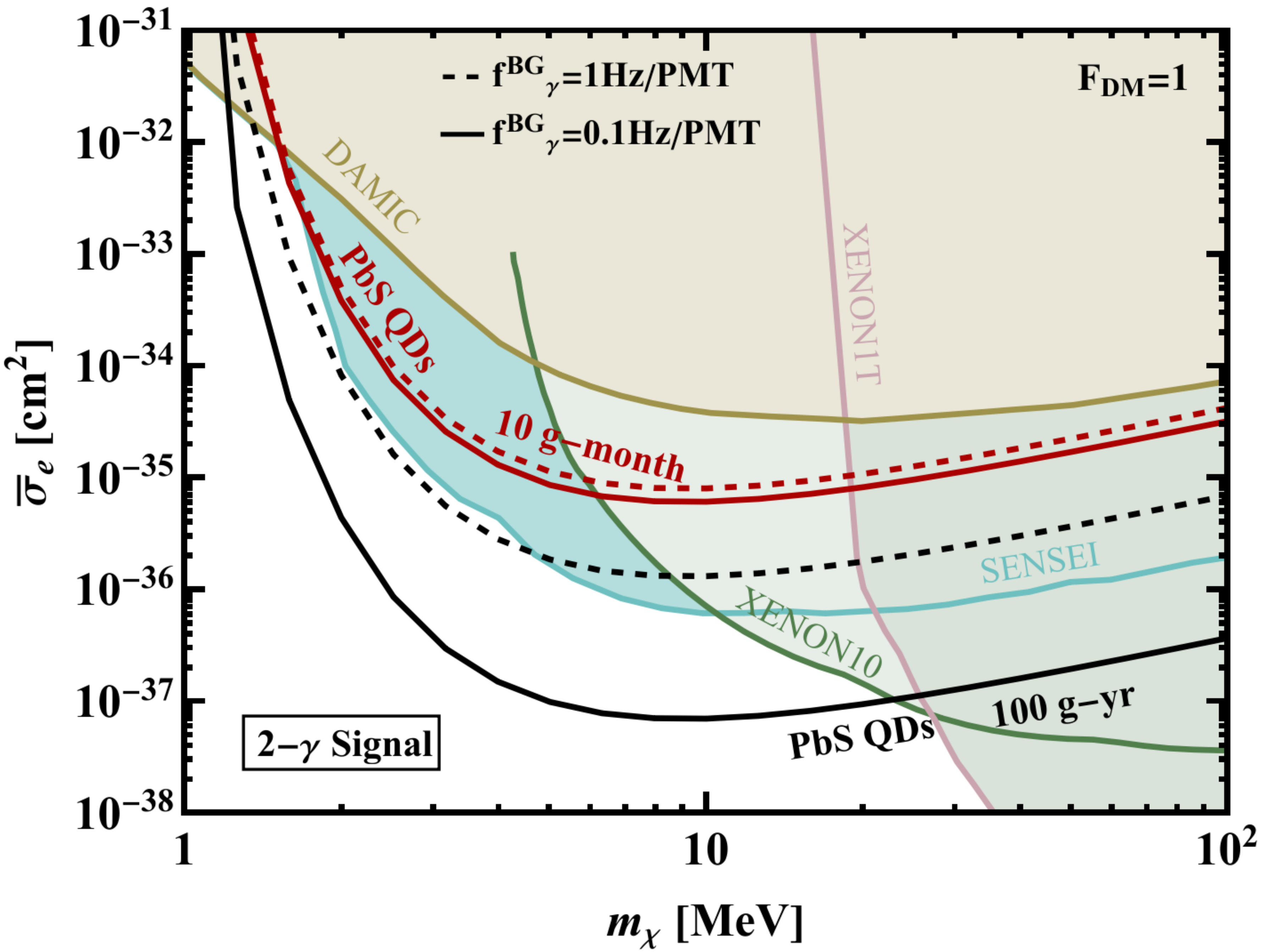


10 g: 1 L colloidal suspension
100g: 10 L colloidal suspension

even w/ "high" PMT background rate, can quickly achieve competitive sensitivity to other proposals

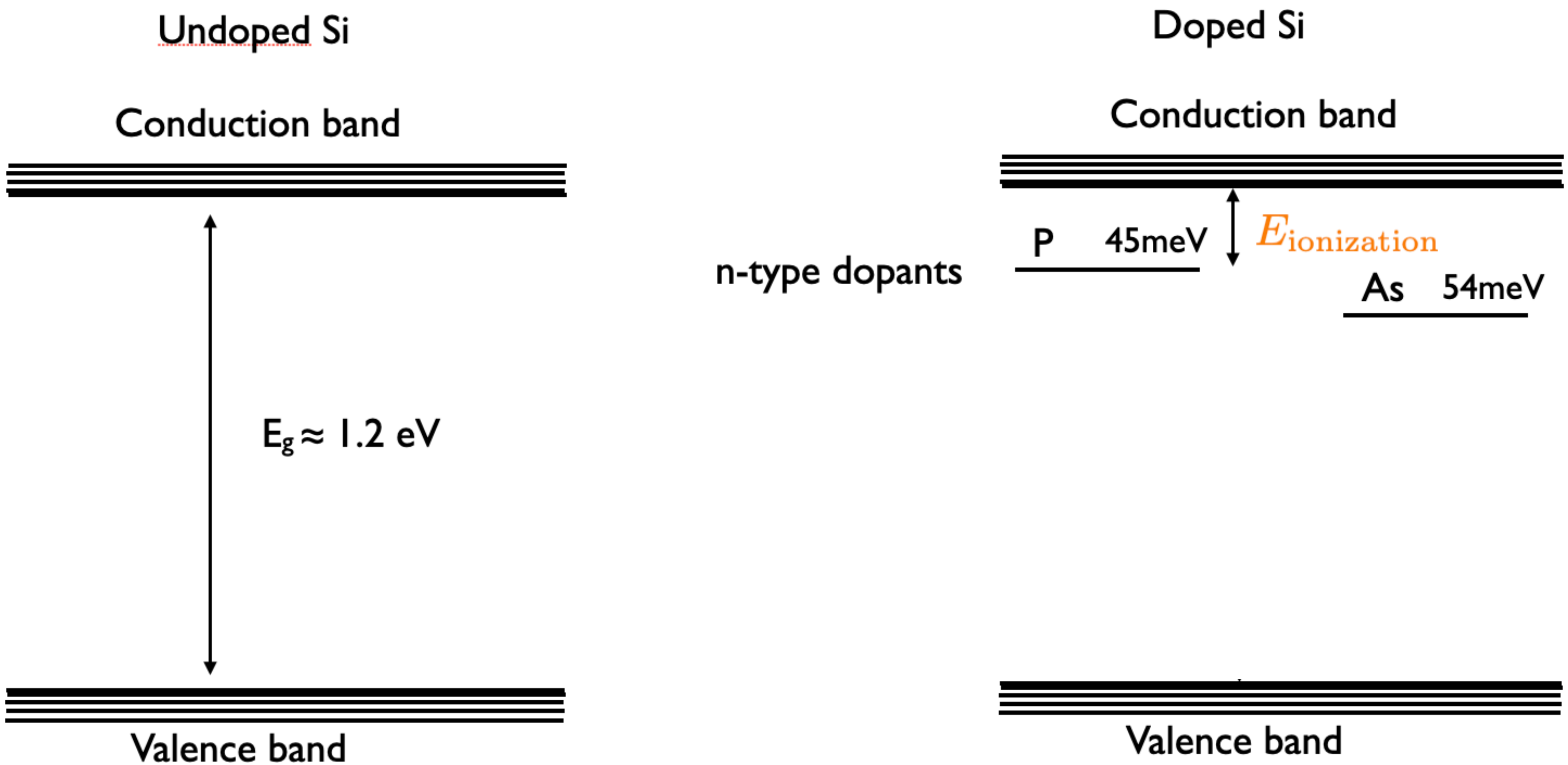
single-photon detectors w/ less background could do even better

discussions between Carlos and J. Collar have been encouraging!

ask Carlos and Oren for more details!

Dark Matter Detection w/ Doped Semiconductors

Du, Egana-Ugrinovic, RE, Sholapurkar, in progress



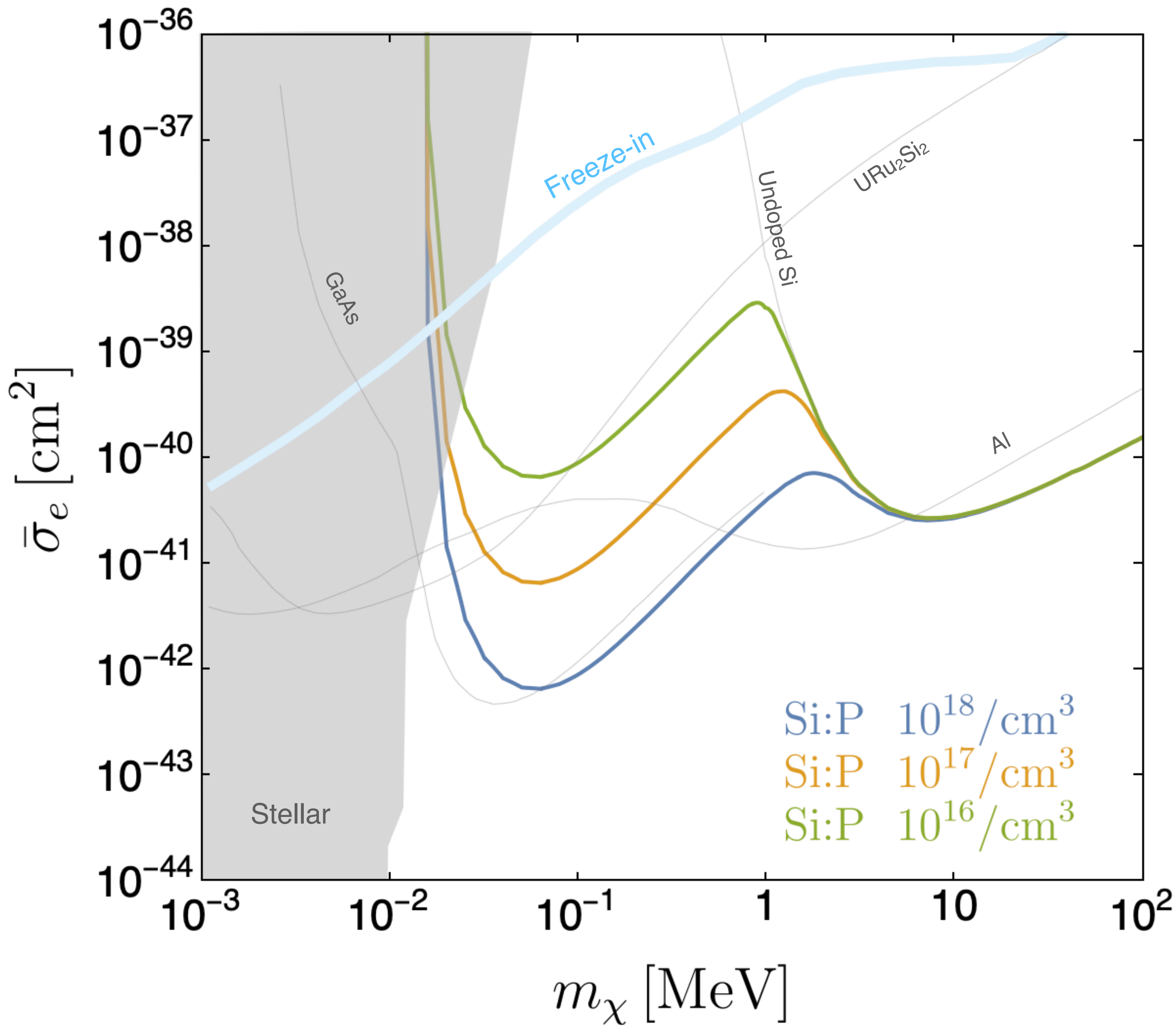
"usual" DM-electron scattering

new idea: DM scatters off loosely-bound electrons from dopant

can excite DM w/ masses $\gtrsim 10$ keV

Dark Matter Detection w/ Doped Semiconductors

Du, Egana-Ugrinovic, RE, Sholapurkar, in progress



like for other proposals, it will be important to control backgrounds

preliminary ideas for design include a CCD w/ a doped-semiconductor bulk, and which can read both holes and electrons

work in progress
Du, Egana-Ugrinovic, RE, Fernandez-Moroni, Sofo-Haro, Tiffenberg, Uemura

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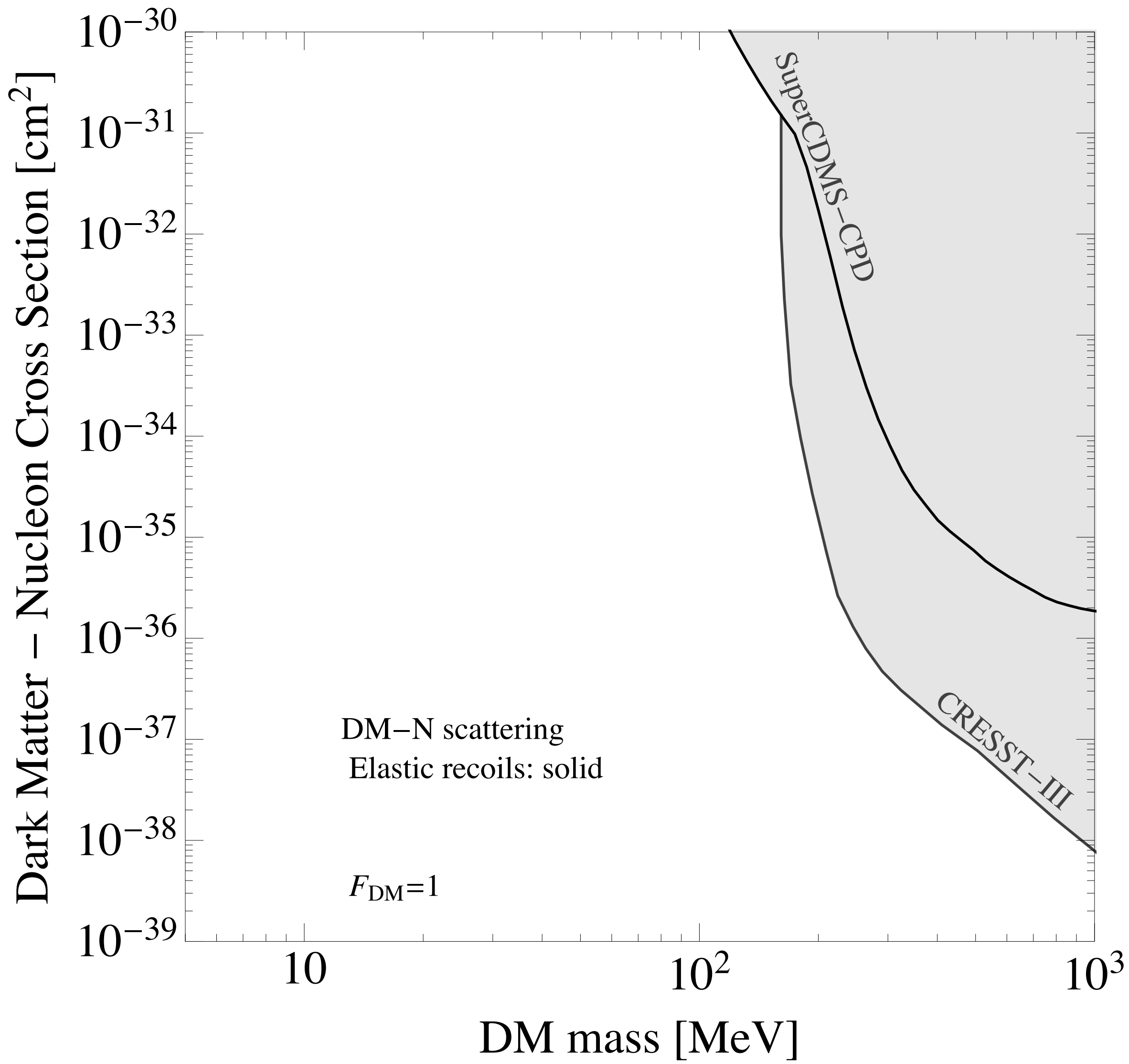
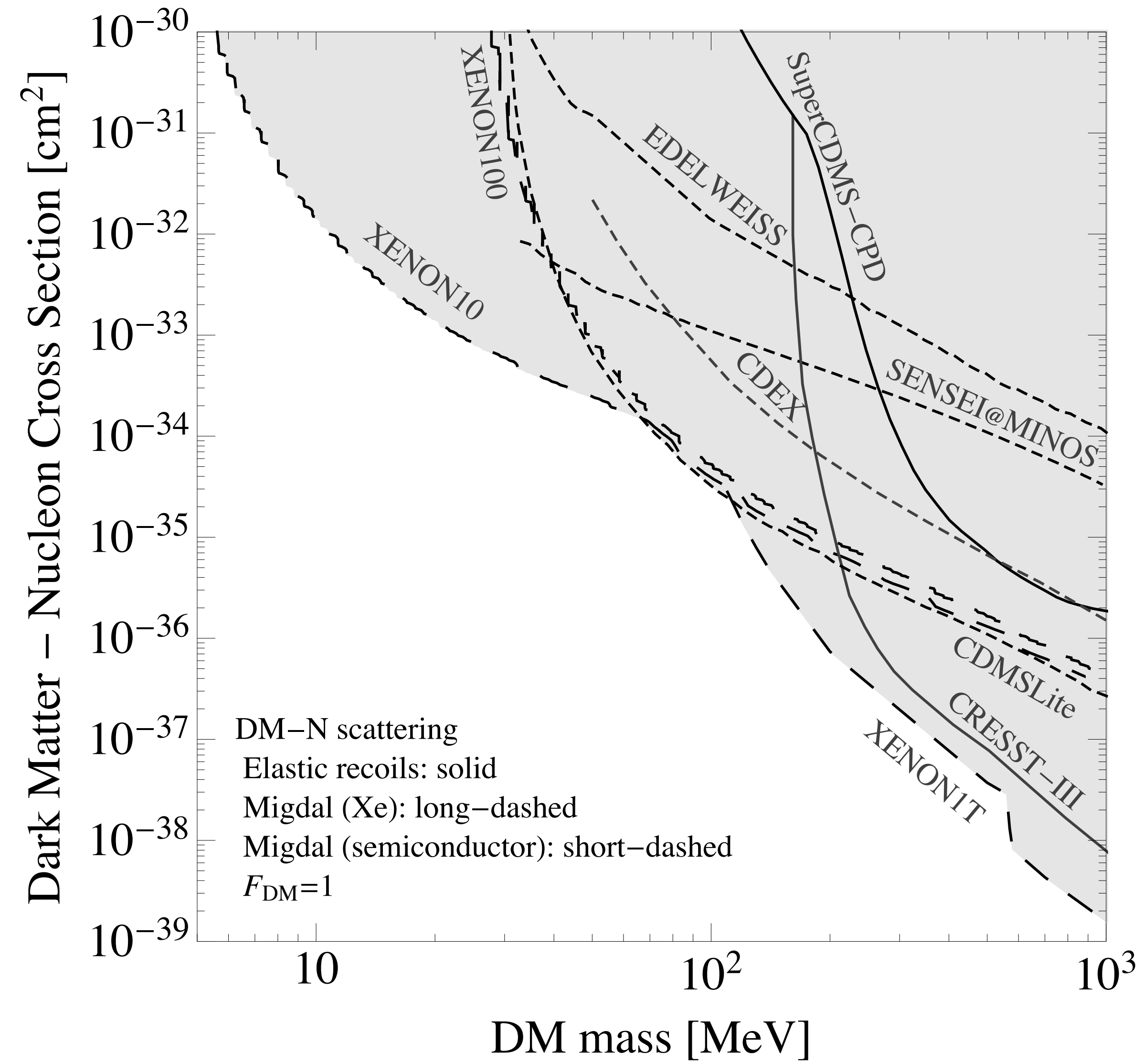
Constraints on sub-GeV DM-nucleus scattering dominated by Migdal effect

elastic DM-nucleus scattering



DM-nucleus scattering **w/ Migdal**

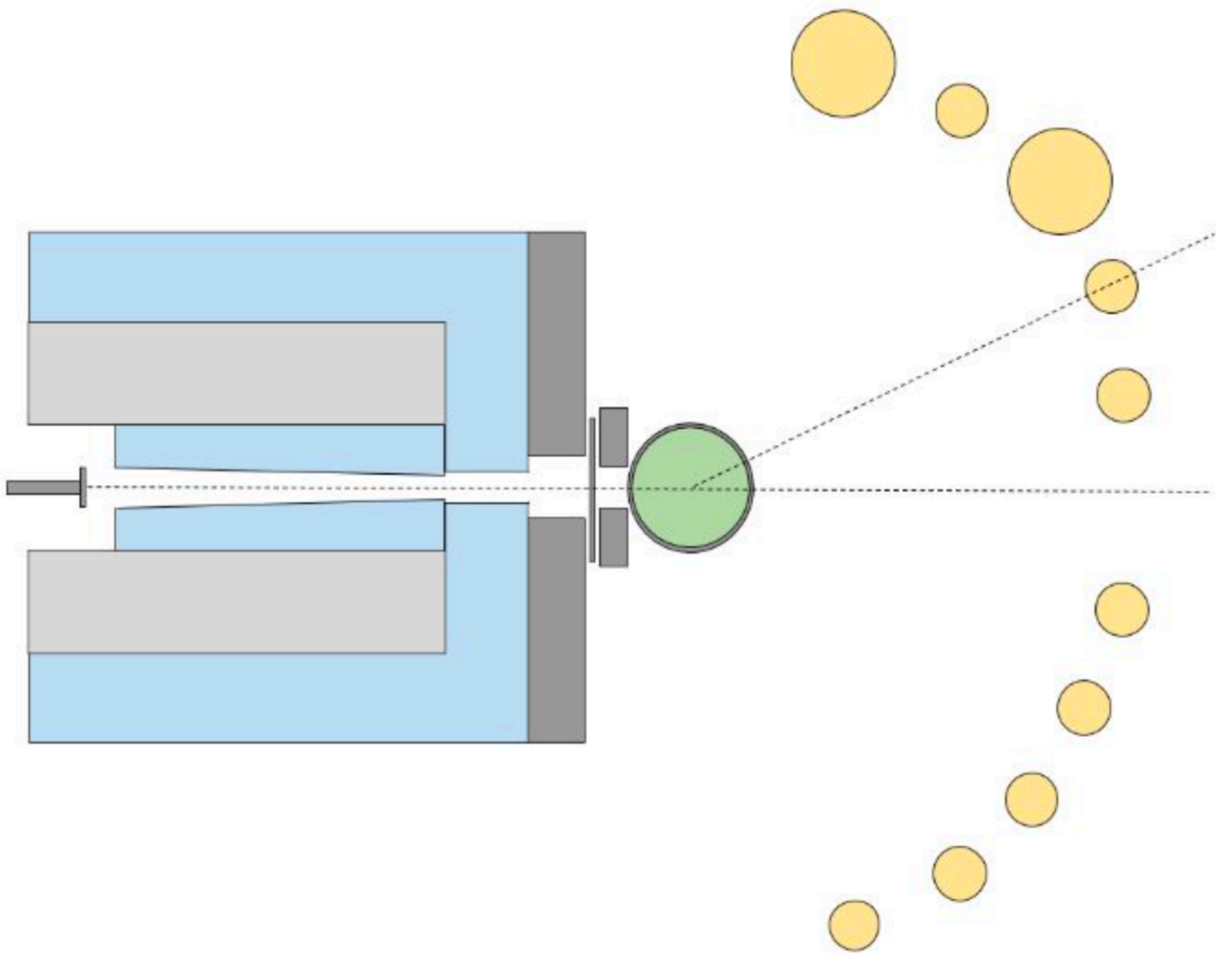


But Migdal effect has not been observed in the laboratory!

Measurements in a controlled setting crucial to validate DM searches

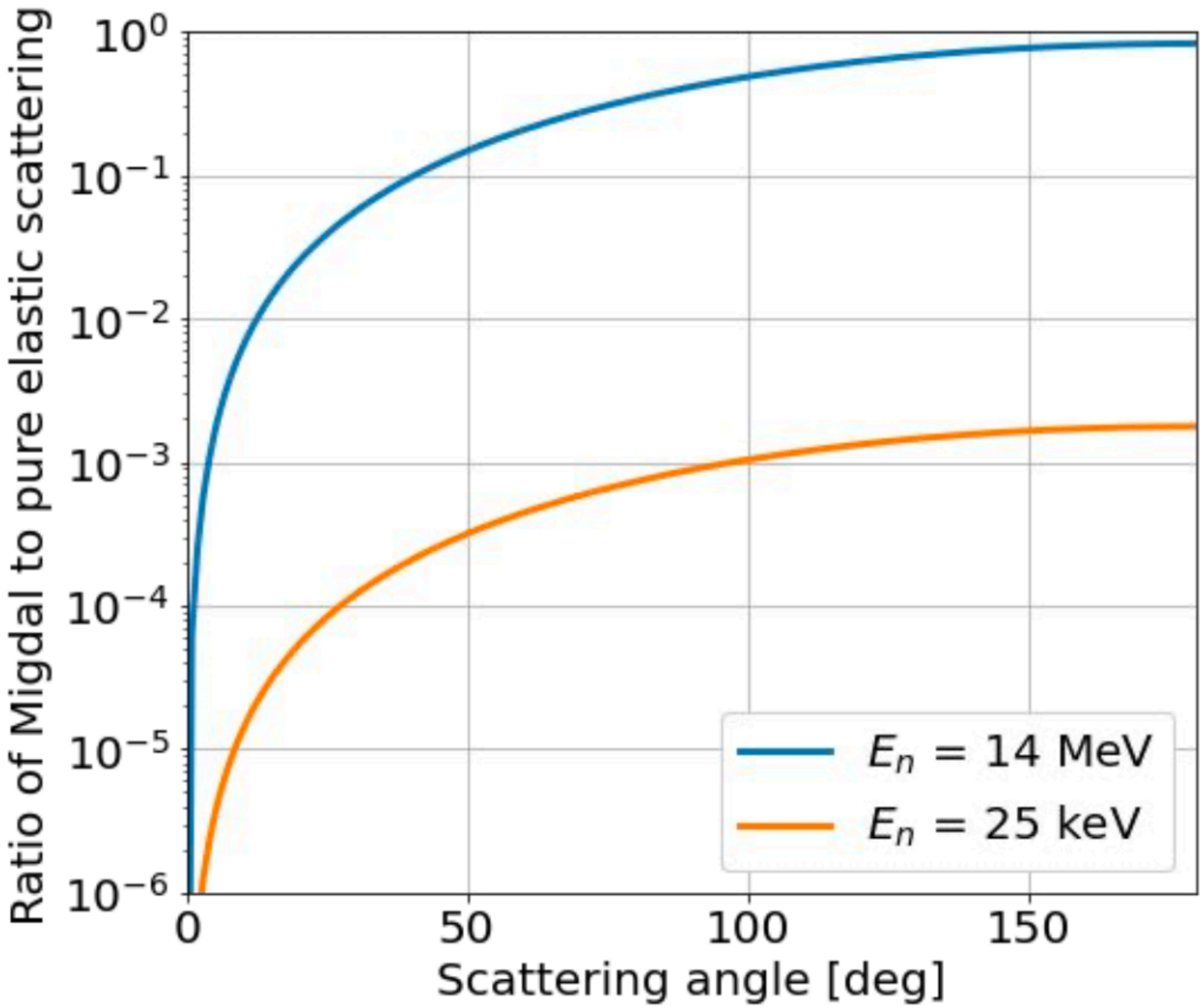
Migdal calibration in silicon and xenon

Idea: optimize neutron energies & scattering angles in setup usually used for measuring ionization efficiency



1908.00518

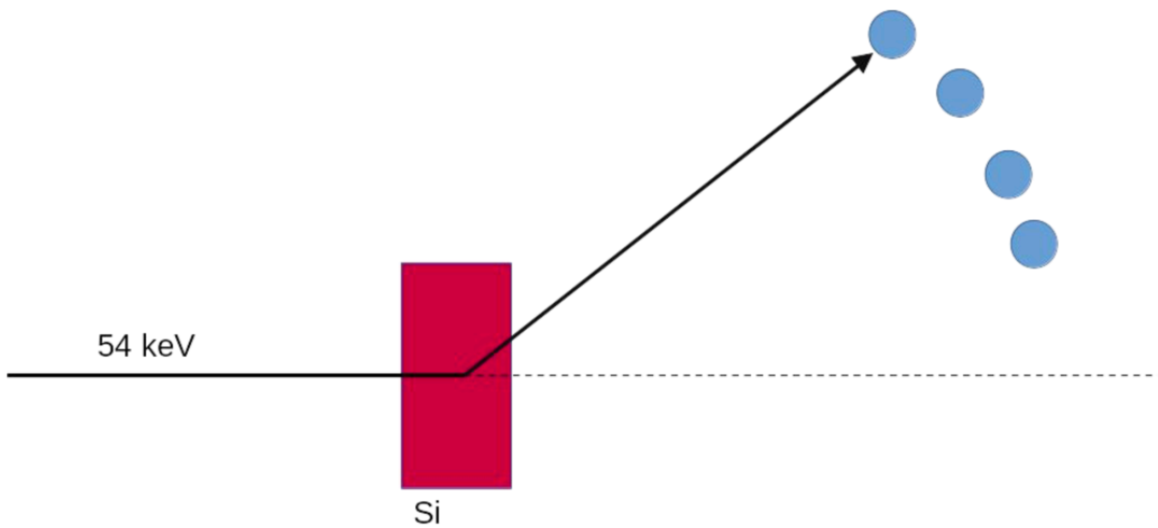
Challenge: Migdal signal is much smaller than signal from neutron elastic scattering



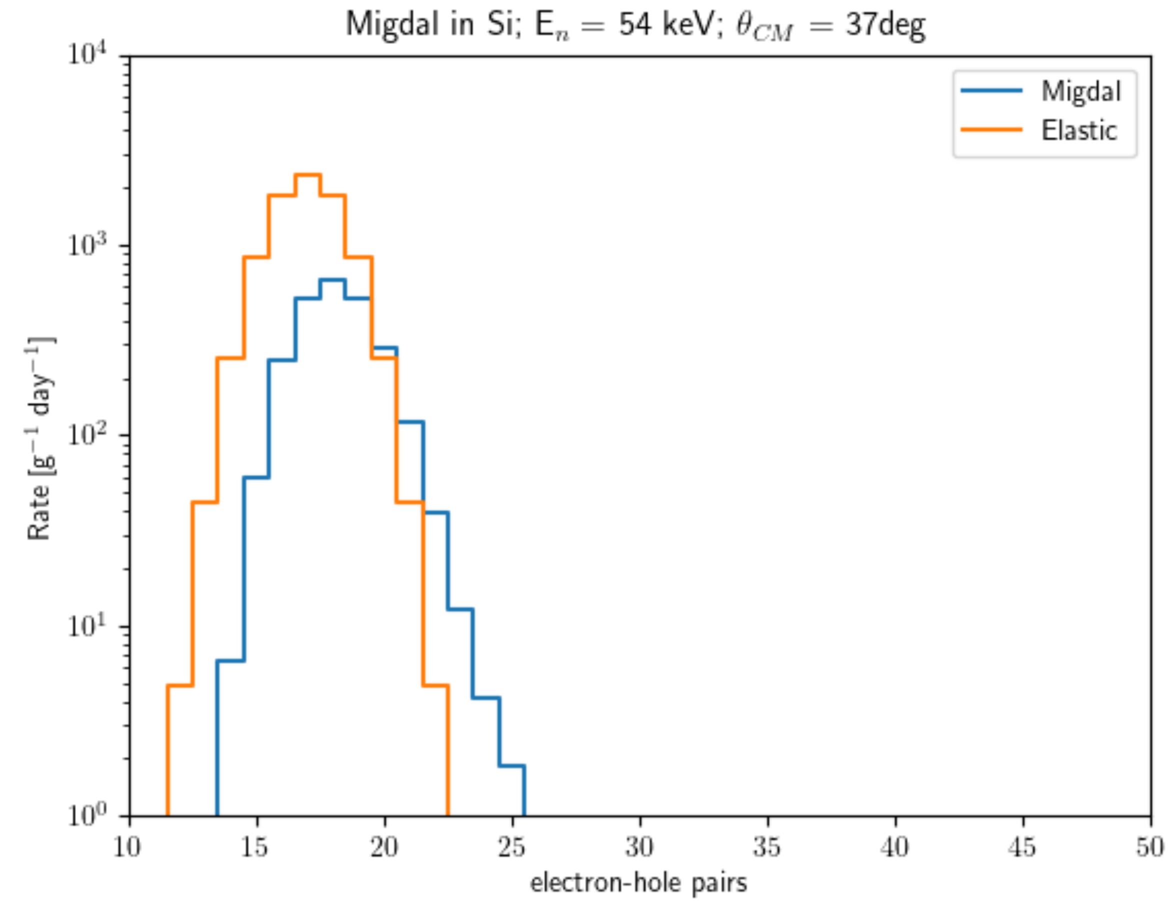
However, Migdal event produces a bit more ionization!

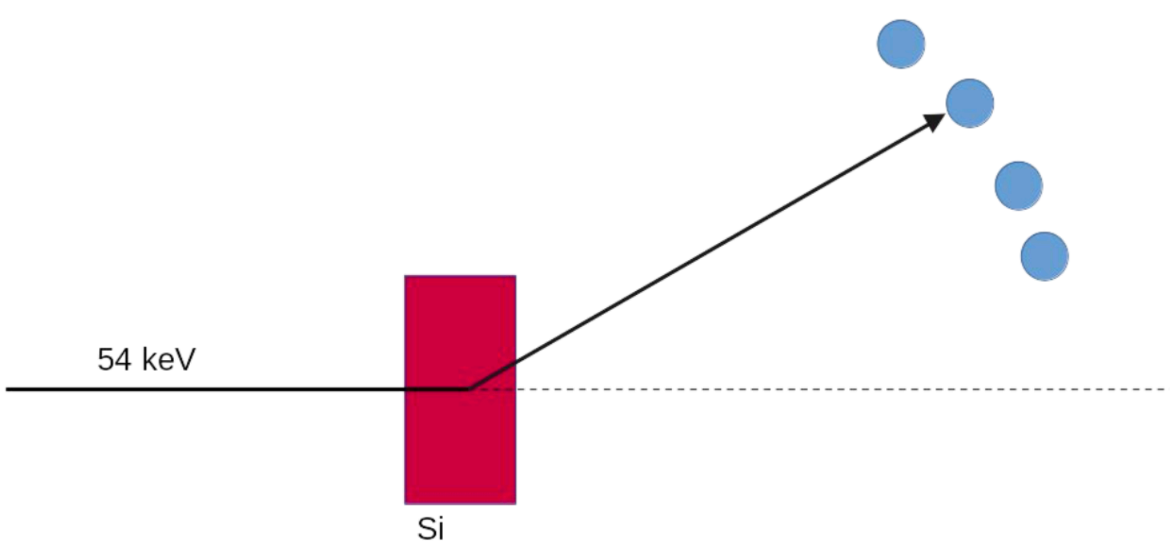
Migdal vs elastic in Si

Duncan Adams, D. Baxter, Hannah Day, RE, Y. Kahn in progress

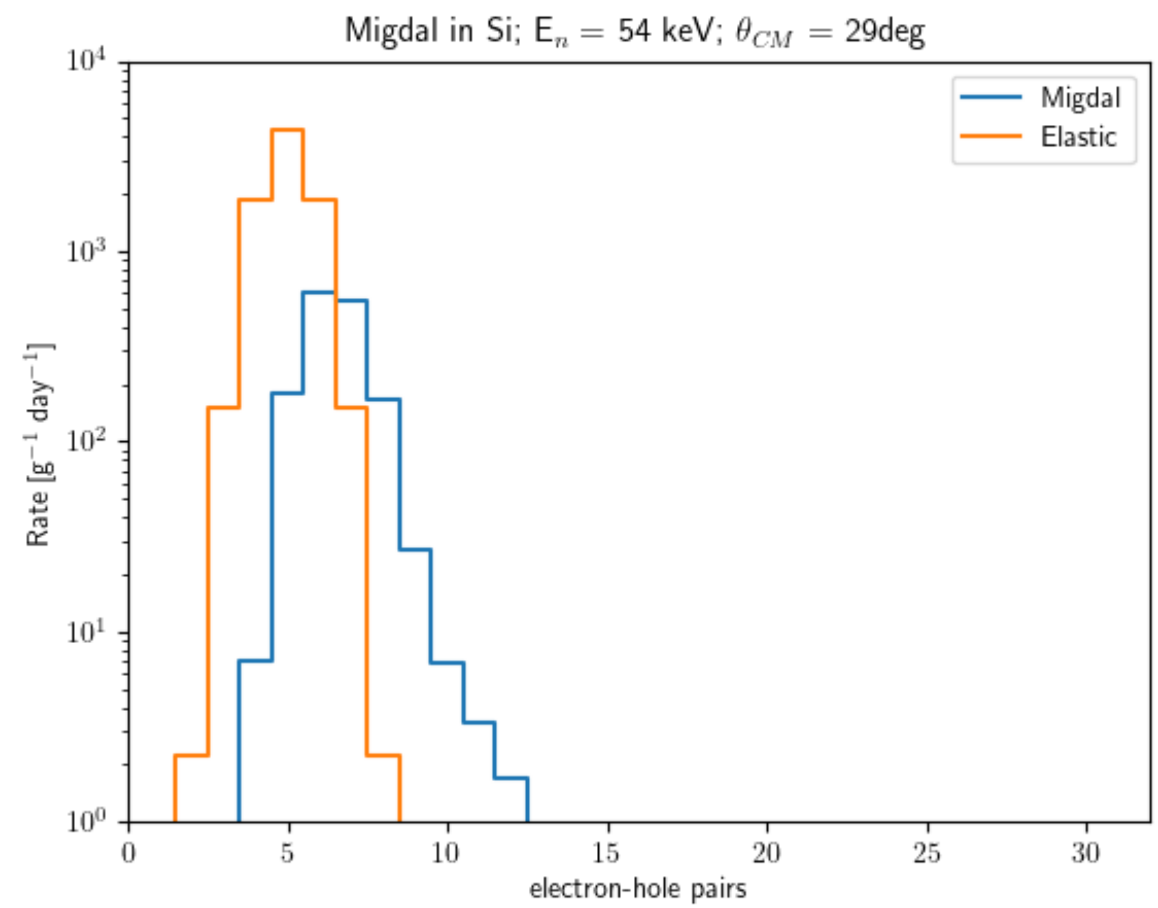


$$E_n = 54\ \text{keV},\quad 37°$$



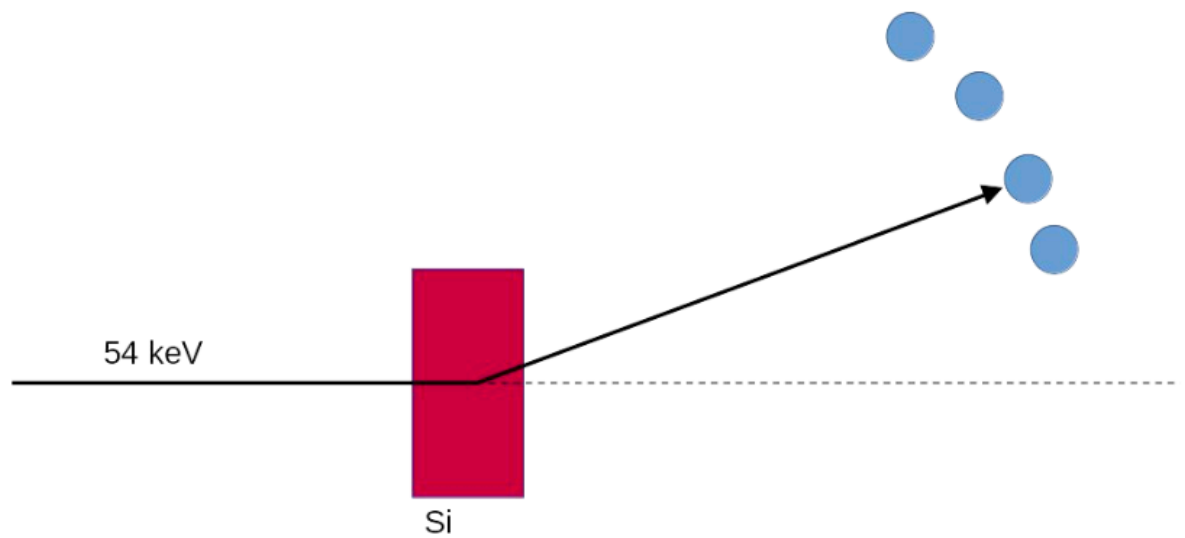


$$E_n = 54\ \text{keV},\quad 29°$$

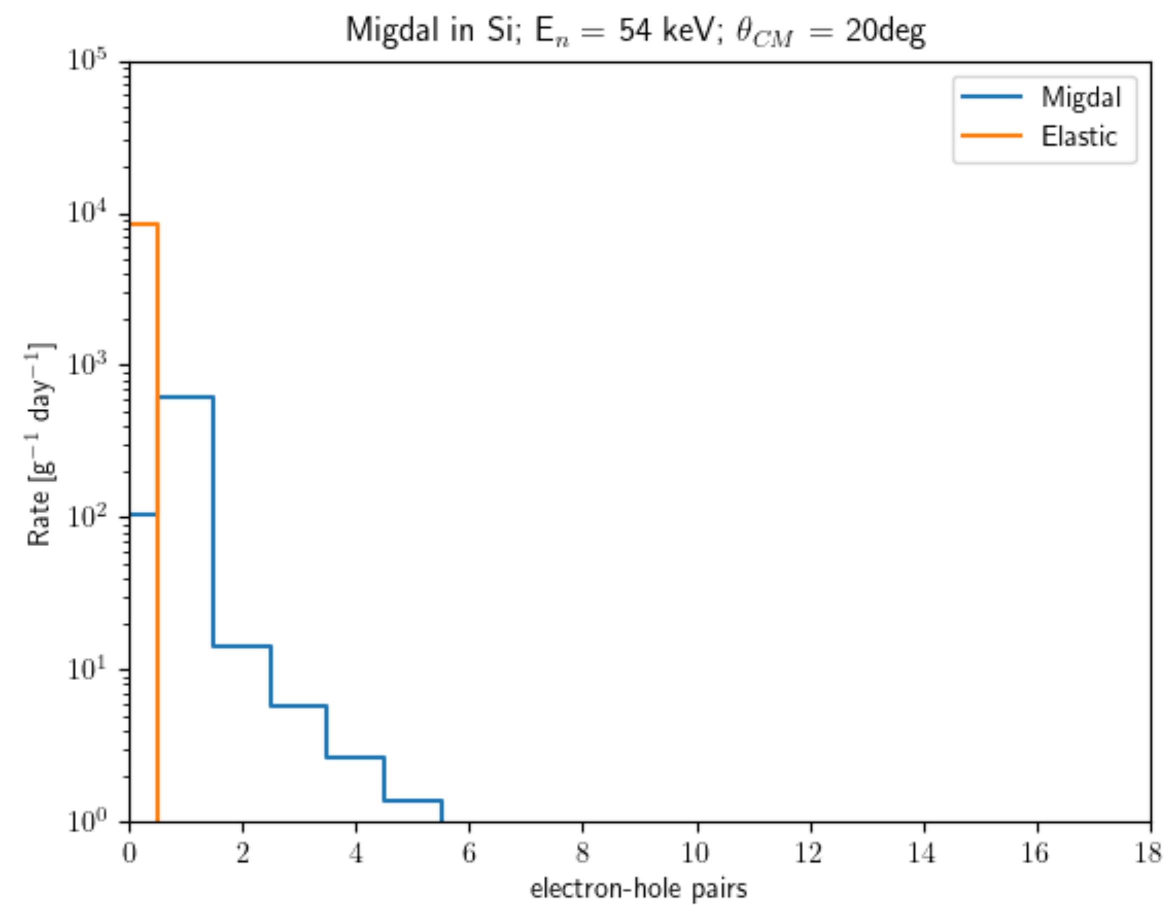


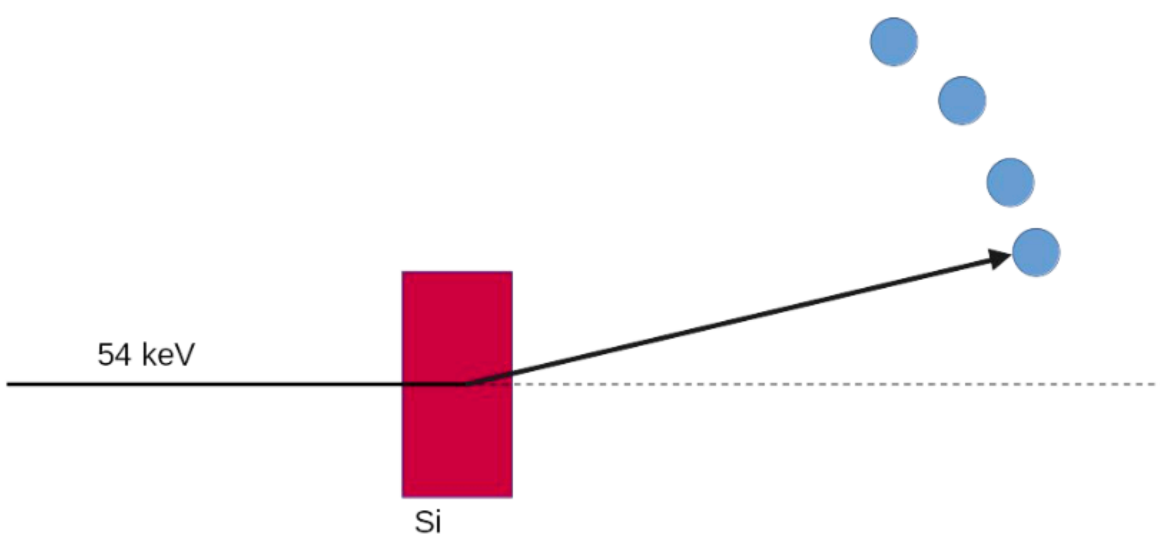
Migdal vs elastic in Si

Duncan Adams, D. Baxter, Hannah Day, RE, Y. Kahn in progress

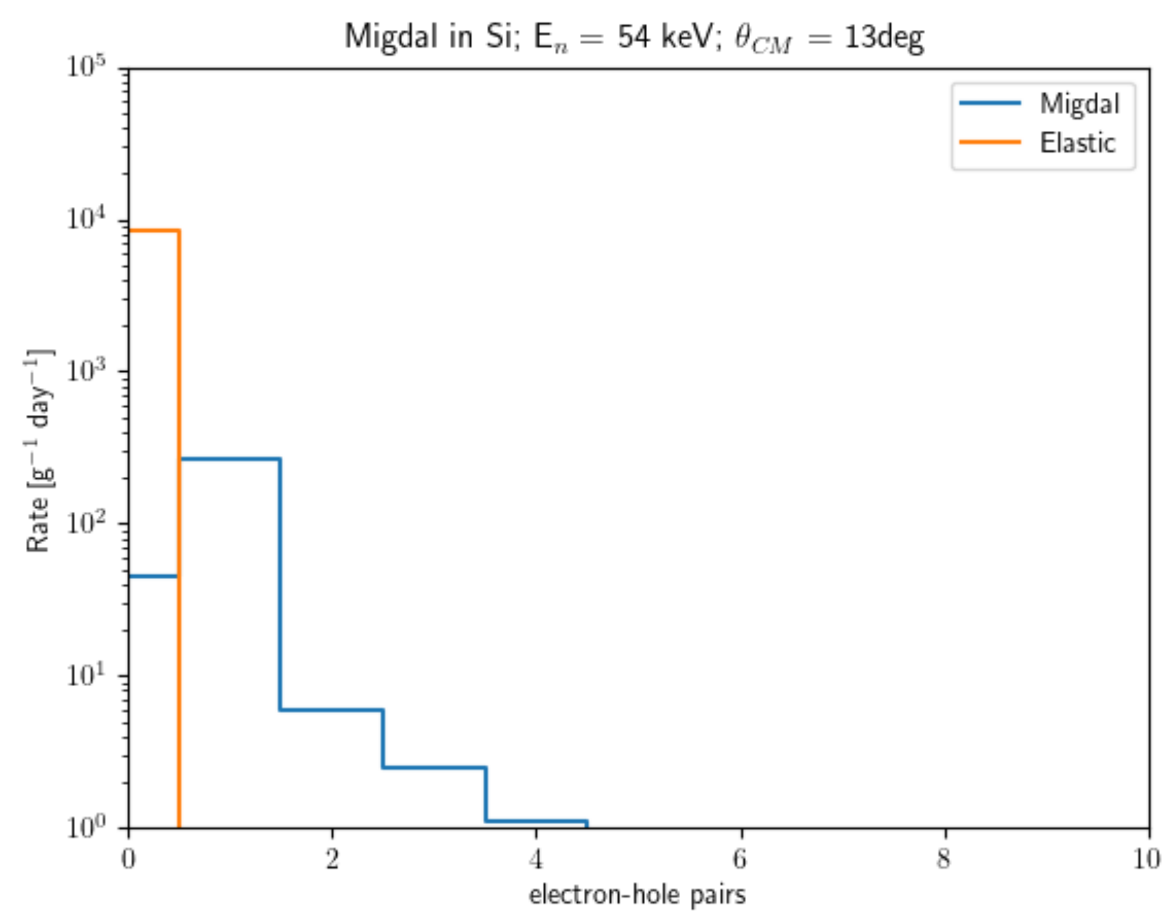


$$E_n = 54\ \text{keV},\quad 20°$$





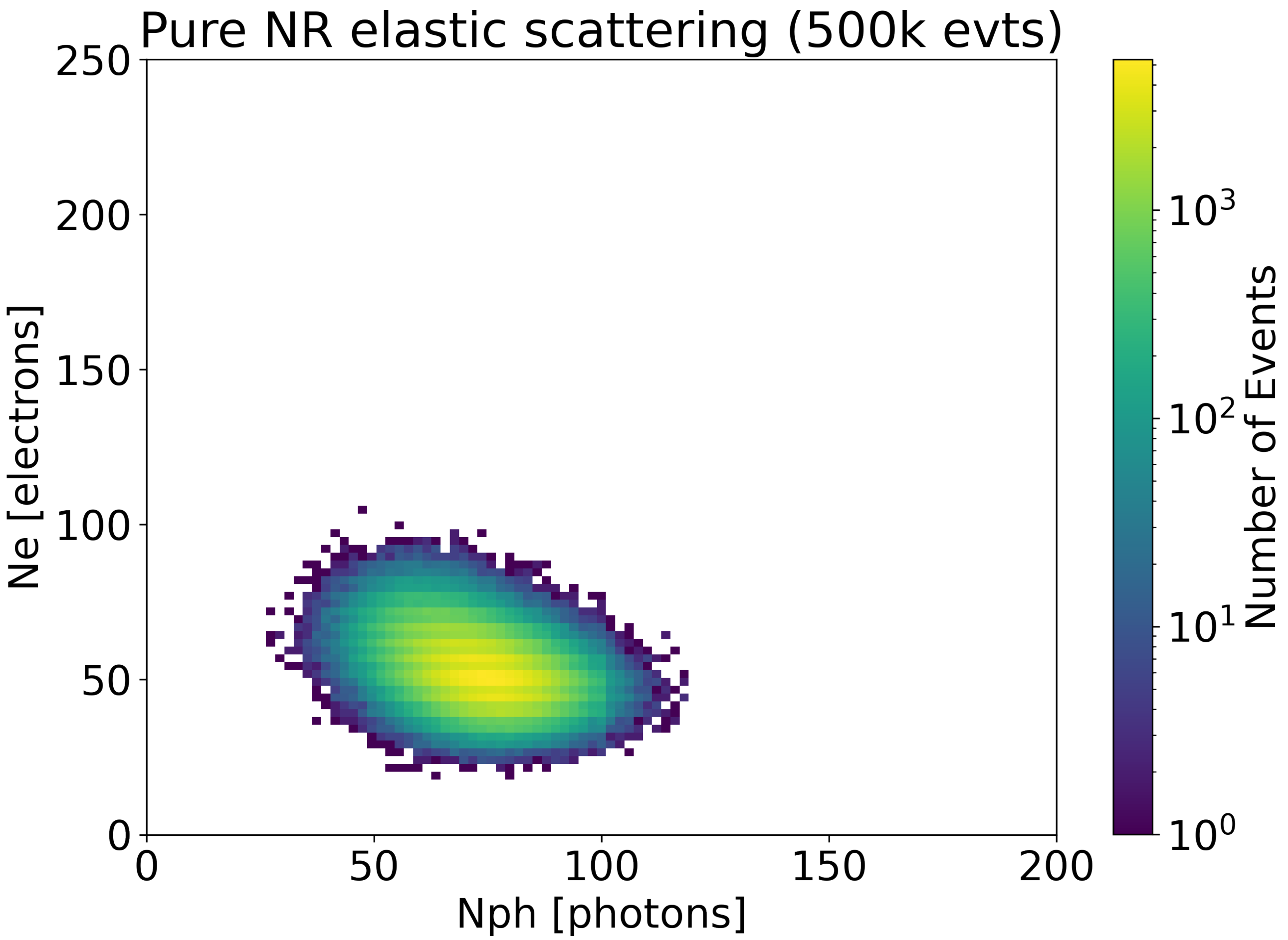
$$E_n = 54\ \text{keV},\quad 13°$$

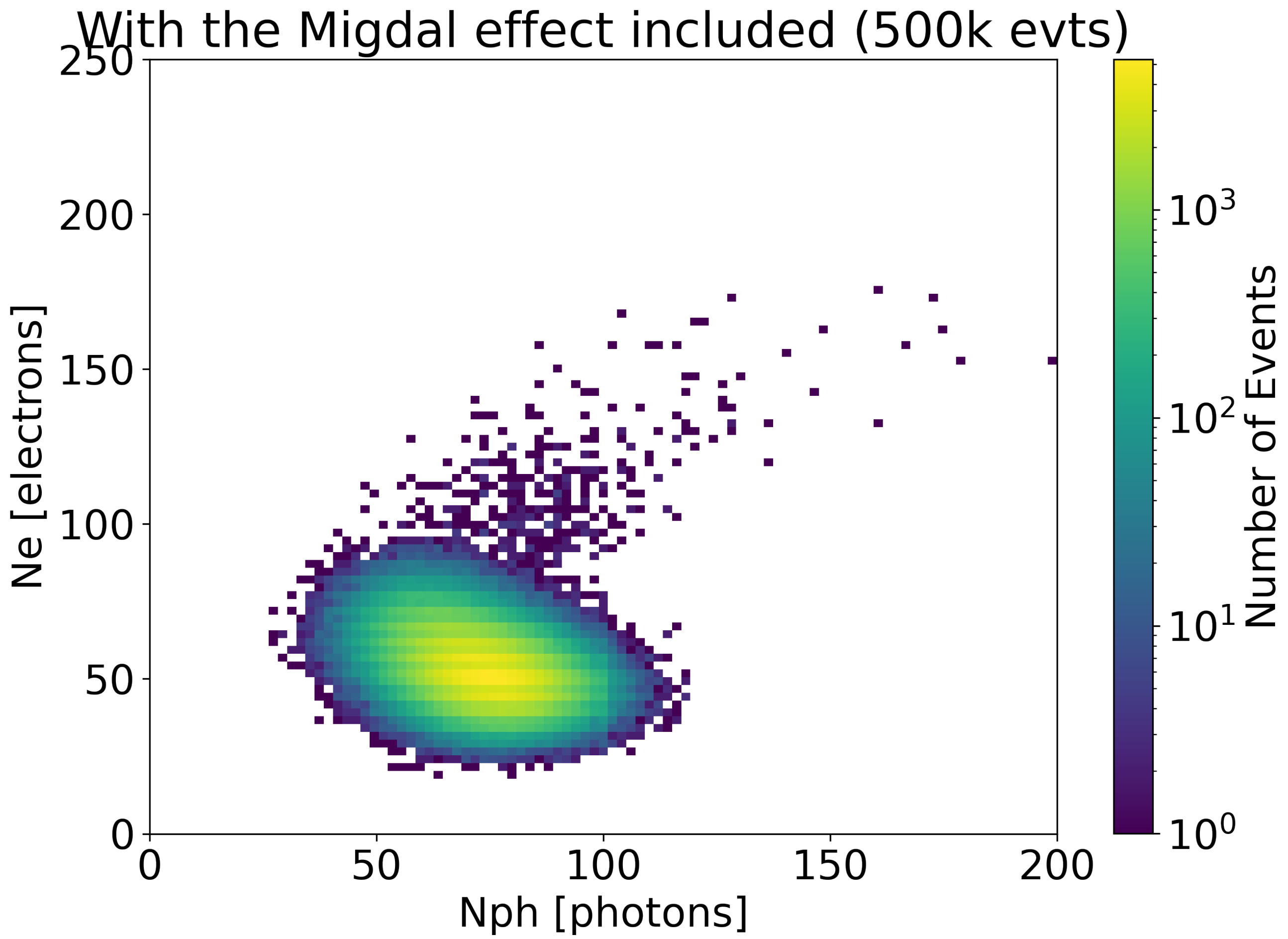


Migdal vs elastic in Xe

Duncan Adams, RE, B. Lenardo, J. Lin, R. Mannino, J. Xu
in progress

$$E_n = 14 \text{ MeV}, \quad 17^\circ$$





hoping for first measurements later this year…

Summary

- Significant theory and experimental progress:
  - many detection concepts w/ various targets
  - improved calculations of DM scattering in e.g. crystals
  - several experiments can now probe small DM signals
- Improved understanding of low-energy backgrounds
- Diurnal modulation is expected for current experiments in popular sub-GeV DM models
- Quantum dots and doped semiconductors are promising new targets to probe low-mass DM
- Expect Migdal effect calibration in Xe and Si in 1 to 2 years