Some Recent Progress on Searches for Sub-GeV Dark Matter

Rouven Essig

Yang Institute for Theoretical Physics

Stony Brook University

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Outline

- Overview of Some Recent Progress
  - Theory
  - Experiment
- Sources & Implications of Low-Energy Backgrounds
- Diurnal Modulation of Sub-GeV DM (if time)

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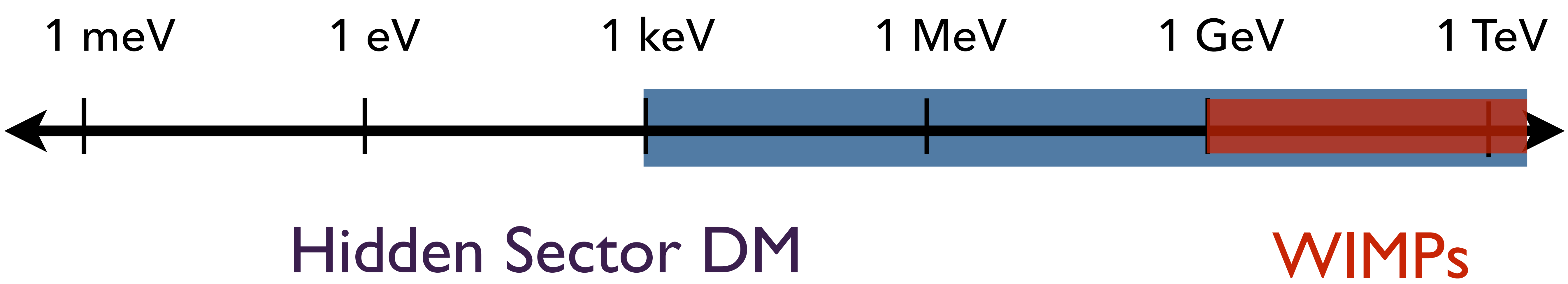
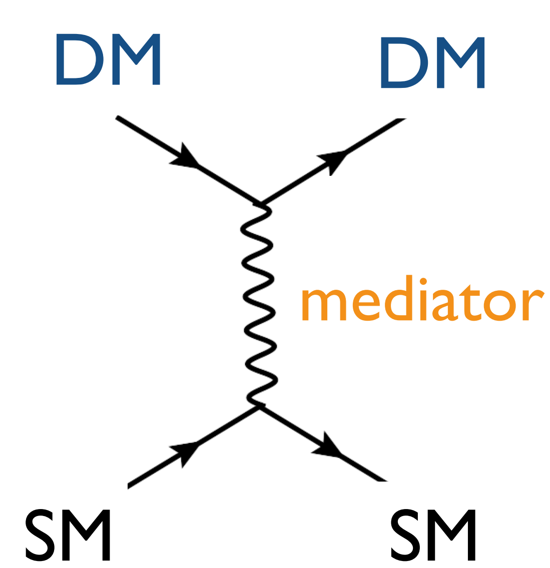
WIMPs

see e.g. Rick Gaitskell's talk



DM Scattering

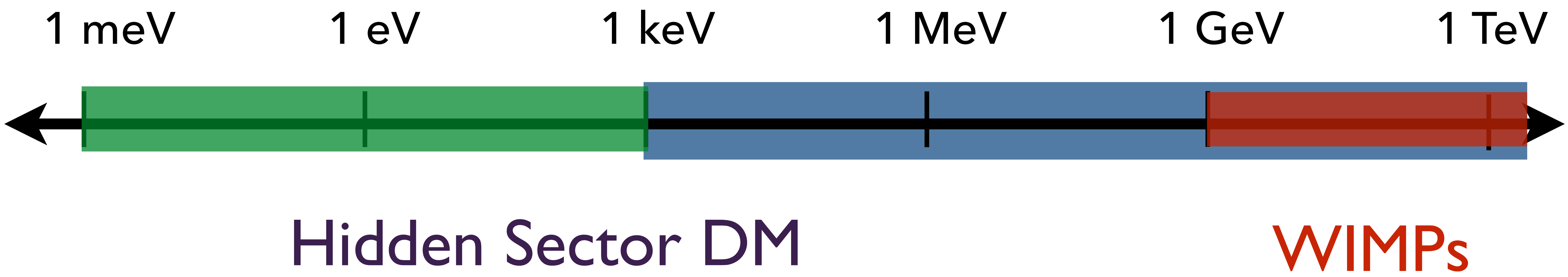


need to probe nuclear <u>and</u> electron interactions

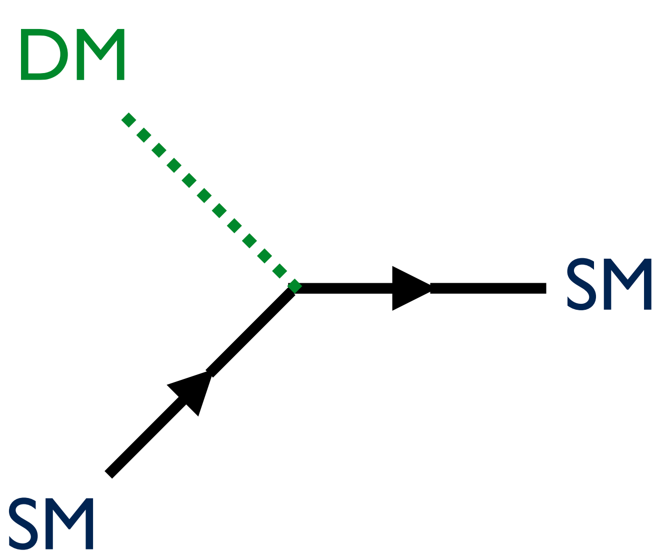
see e.g. Boehm & Fayet; Borodatchenkova, Choudhury, Drees; Kaplan, Luty, Zurek; Falkowski, Ruderman, Volansky; Hochberg, Kuflik, Volansky, Wacker; +Murayama; Izaguirre, Krnjaic, Schuster, Toro; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; Kuflik, Lorier, Perelstein, Tsai; Farina, Pappadopulo, Ruderman,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

see also Josh Ruderman's talk

several DM production scenarios
(e.g. freeze-out, asymmetric, freeze-in, SIMP, ELDER)



DM Absorption
(bosons)



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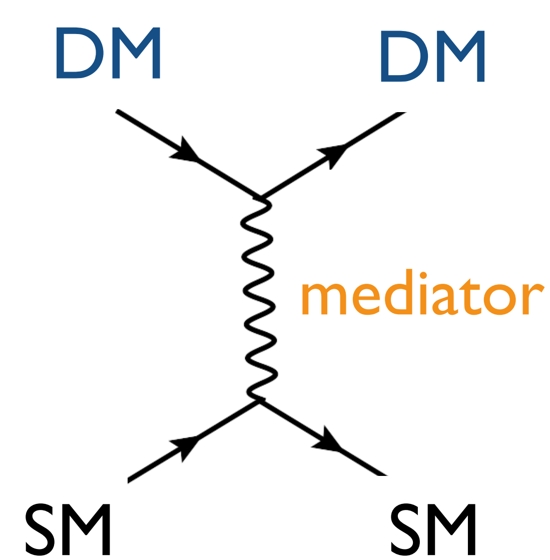

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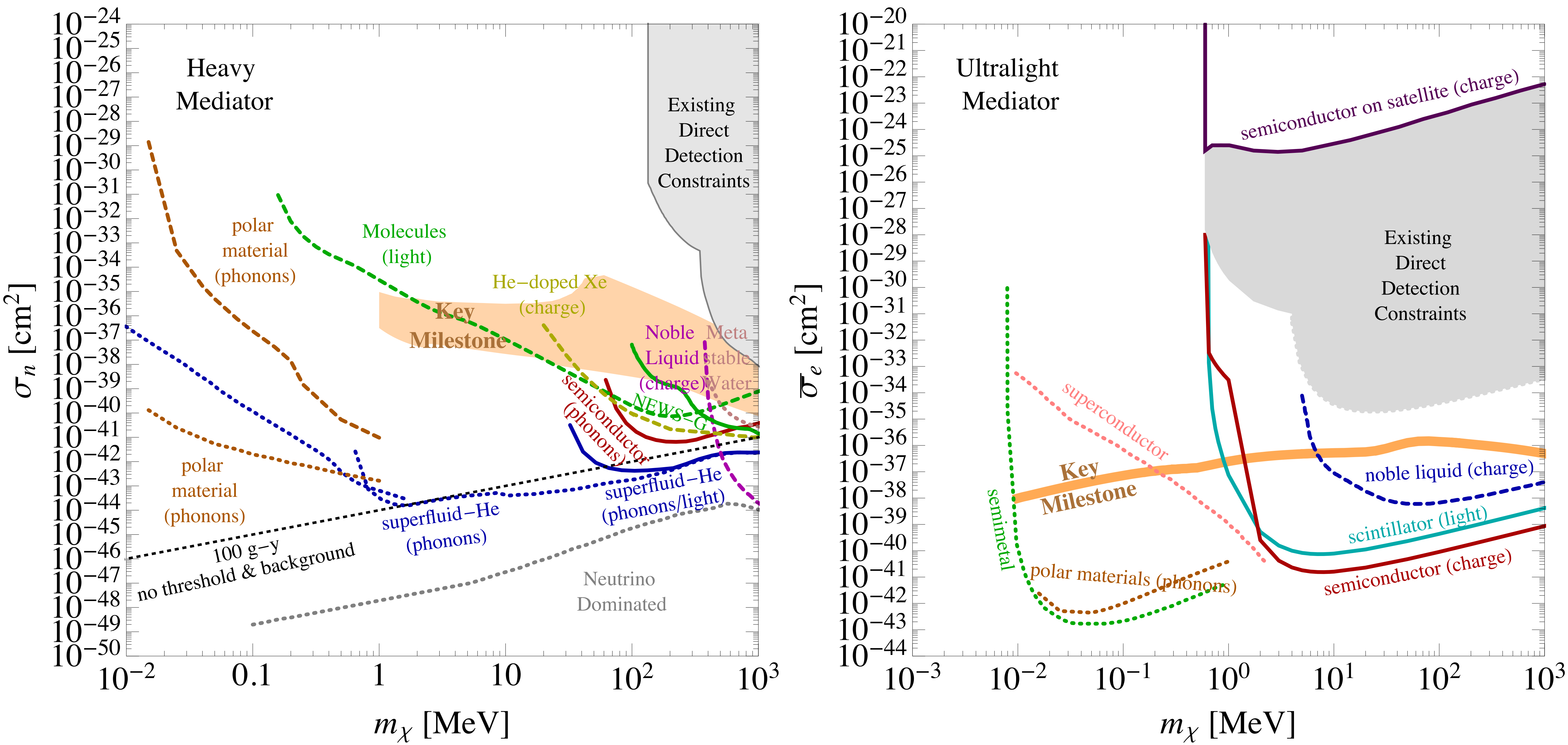
several DM production scenarios
(e.g. freeze-out, asymmetric, freeze-in, SIMP, ELDER)

Significant progress in probing sub-GeV dark matter

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

Many Detection Concepts

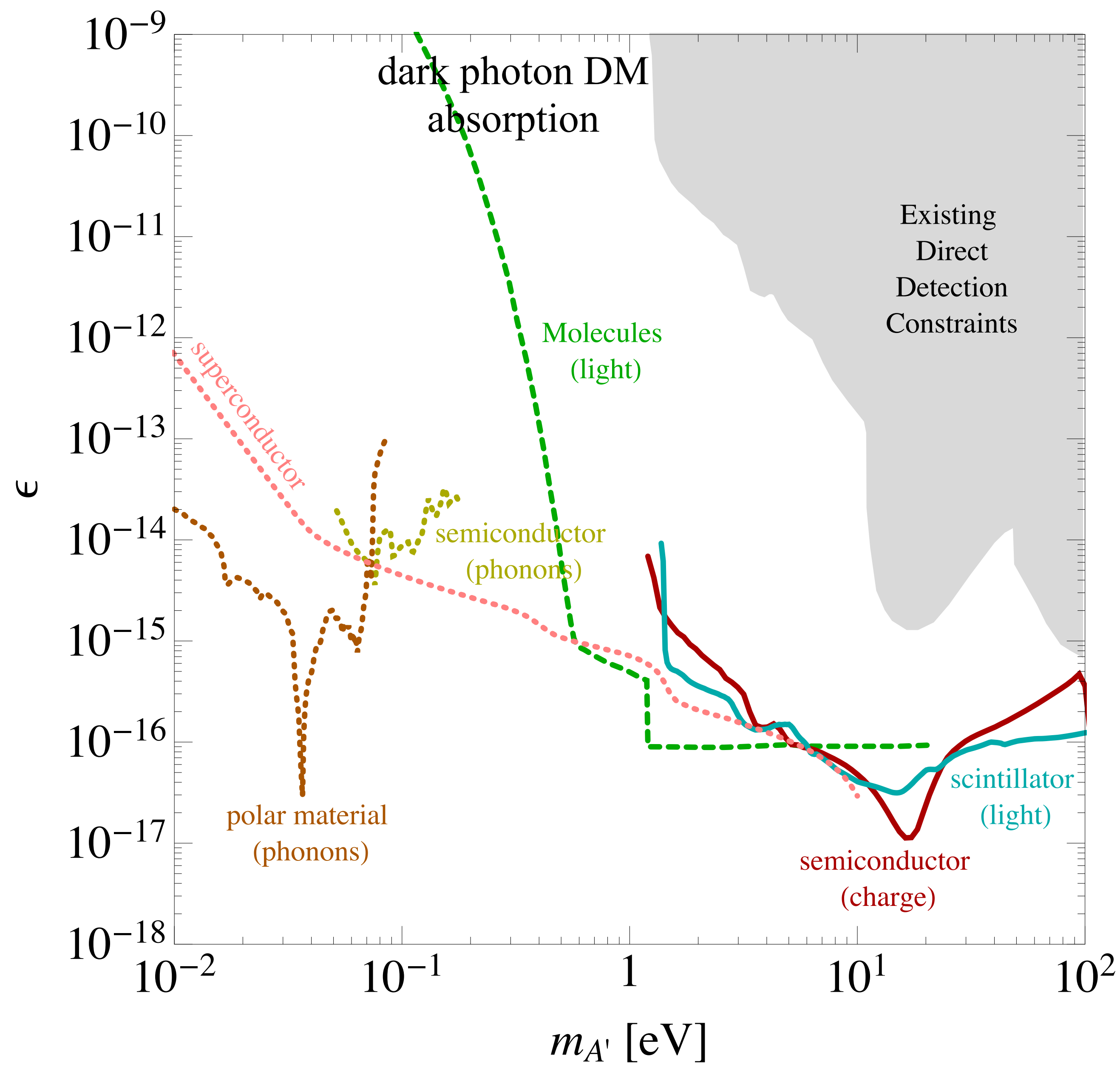
- DM scattering: $m_\chi \gtrsim \mathrm{keV}$



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

Many Detection Concepts

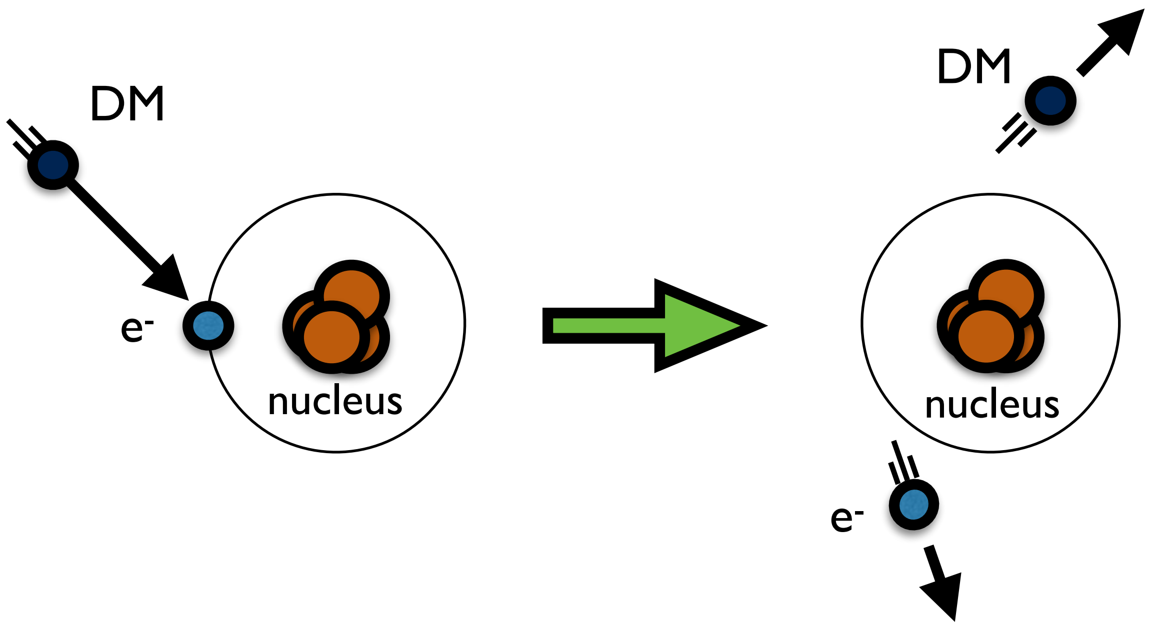
- DM scattering: $m_\chi \gtrsim \mathrm{keV}$
- (bosonic) DM absorption: $m_\chi \gtrsim \mathrm{meV}$



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

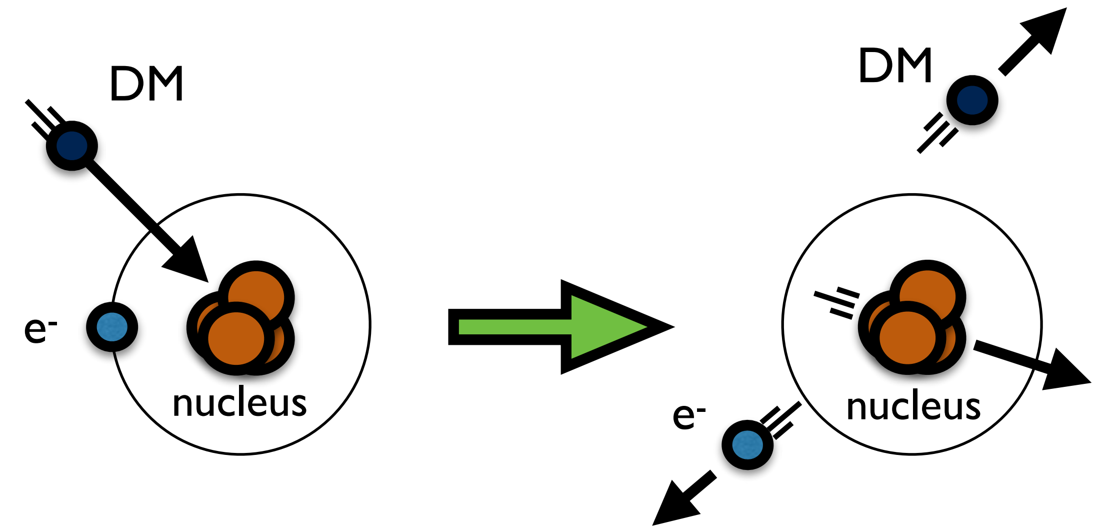
Main concepts (currently used) to probe DM $\ll$ GeV

- DM-e scattering:



RE, Mardon, Volansky

- DM-N scattering, Migdal effect:



Ibe, Nakano, Shoji, Suzuki

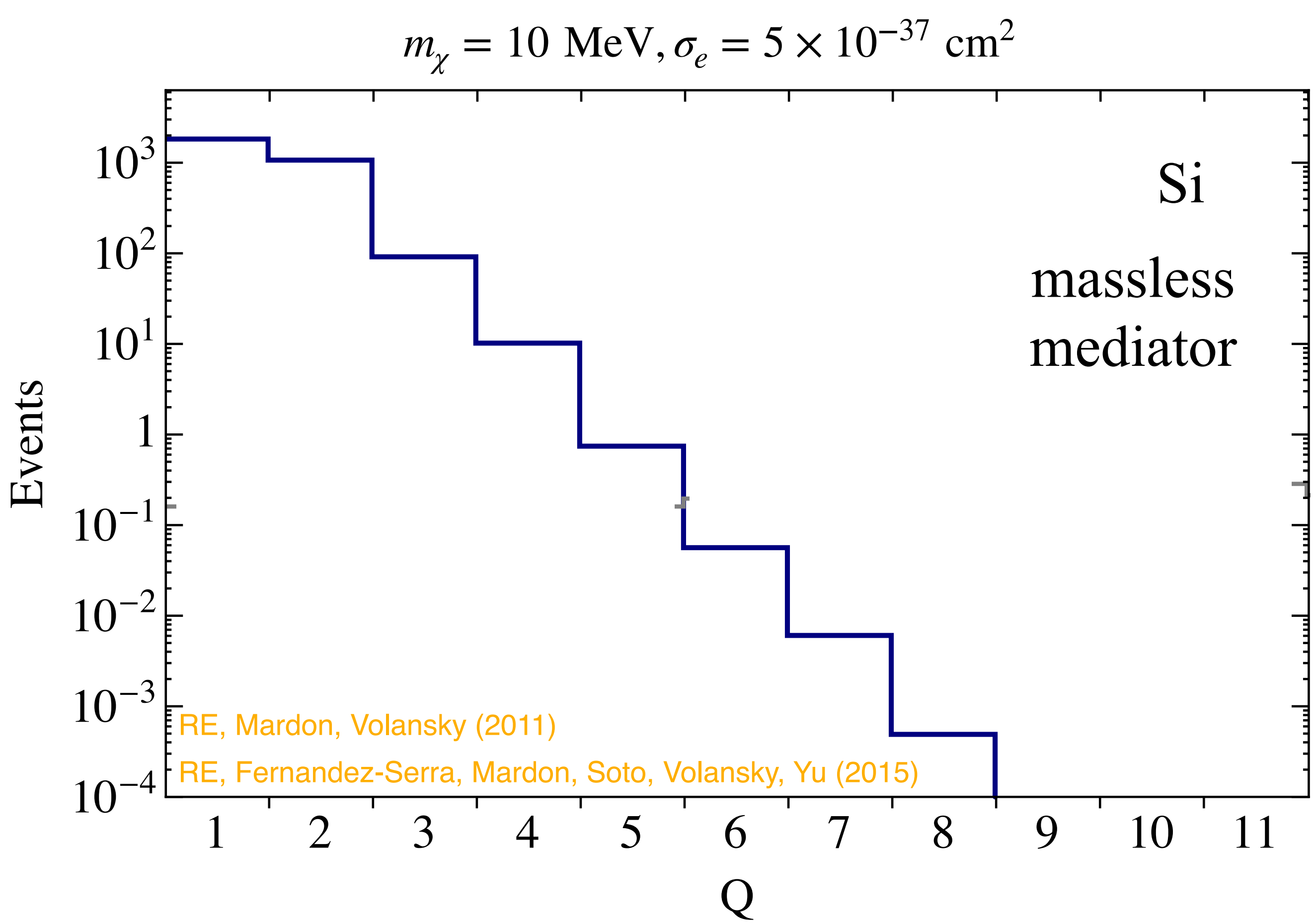
Allows transfer of O(1) amount of DM kinetic energy

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

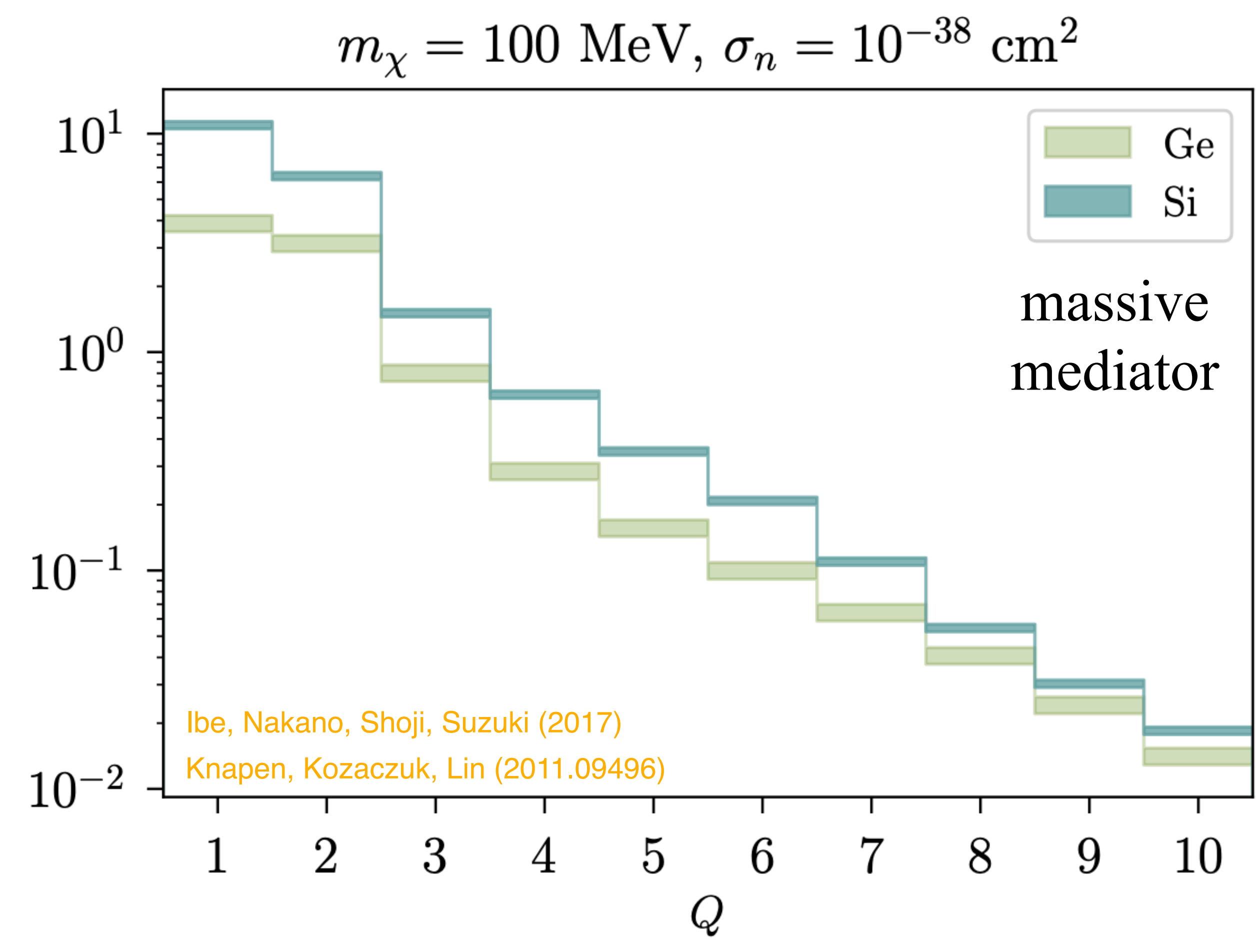
Typically produces a signal of only <u>one</u> to a <u>few</u> <u>electrons</u>

Spectrum of electrons produced by DM scattering

DM-electron scattering



DM-nucleus scattering (Migdal)



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

relate rates to dielectric 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 (in progress)

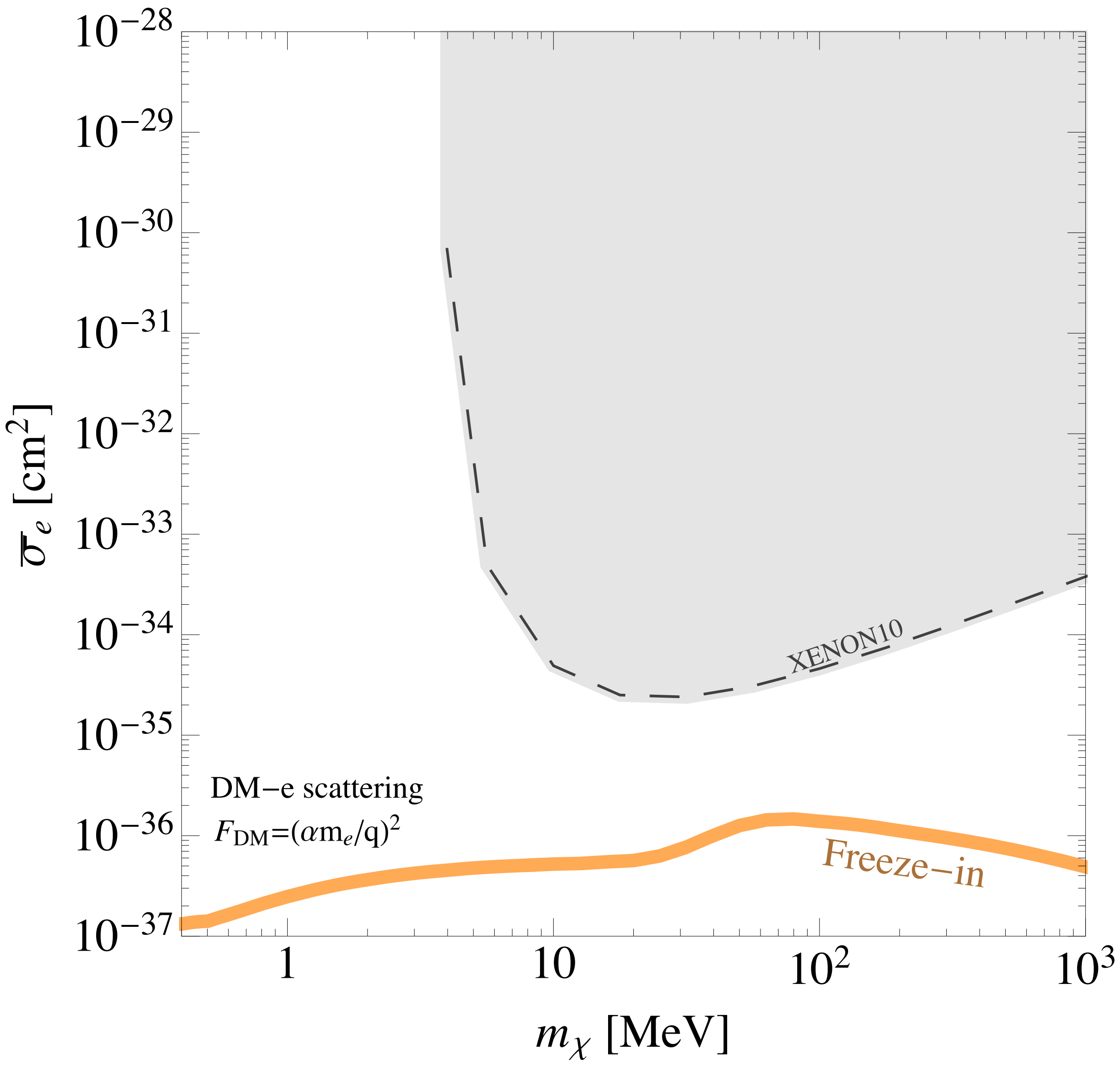
in both cases, have a sharply rising spectrum towards lower energies:
single/few-electron sensitivity is crucial for capturing more potential DM events

Significant progress in probing sub-GeV dark matter

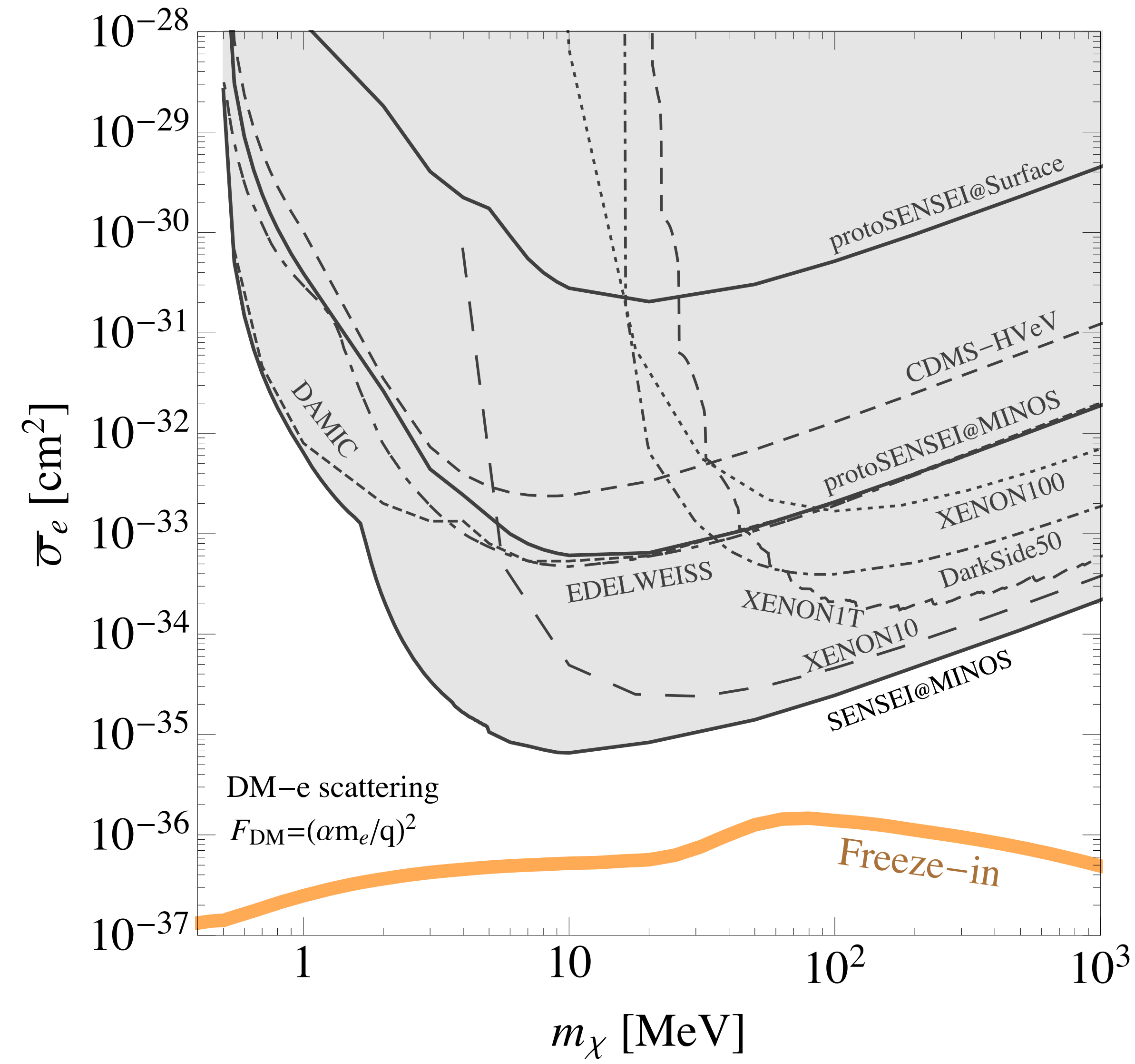
- Theory:
    - several detection concepts, using variety of target materials
    - improved calculations of DM scattering in crystals
    - improved understanding of low-energy backgrounds
- Experiments: multiple technologies can measure small signals, e.g.
    - Xe/Ar 2-phase TPC (XENON10/100/1T/nT,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

Exciting experimental progress

2012



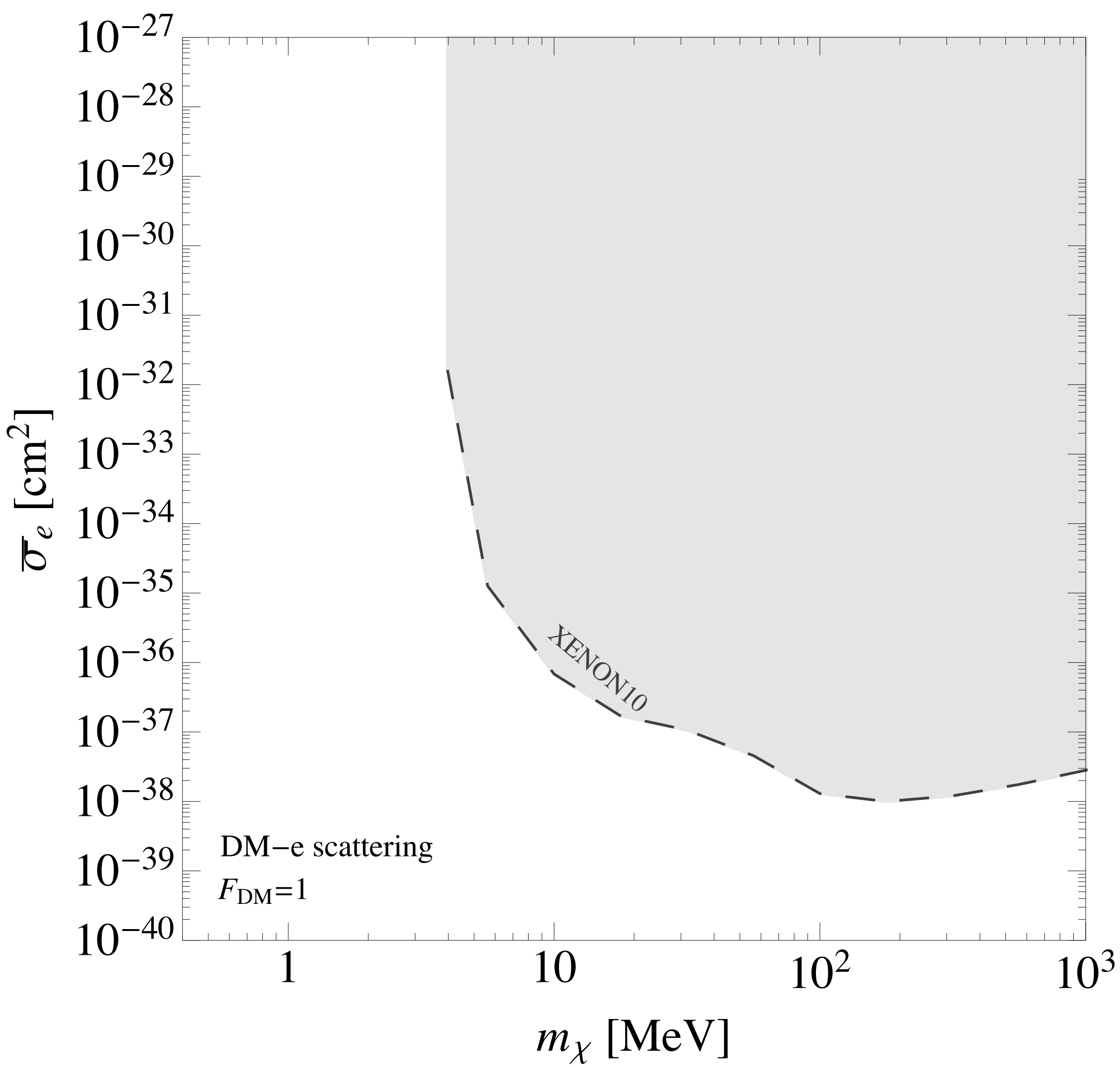
2021



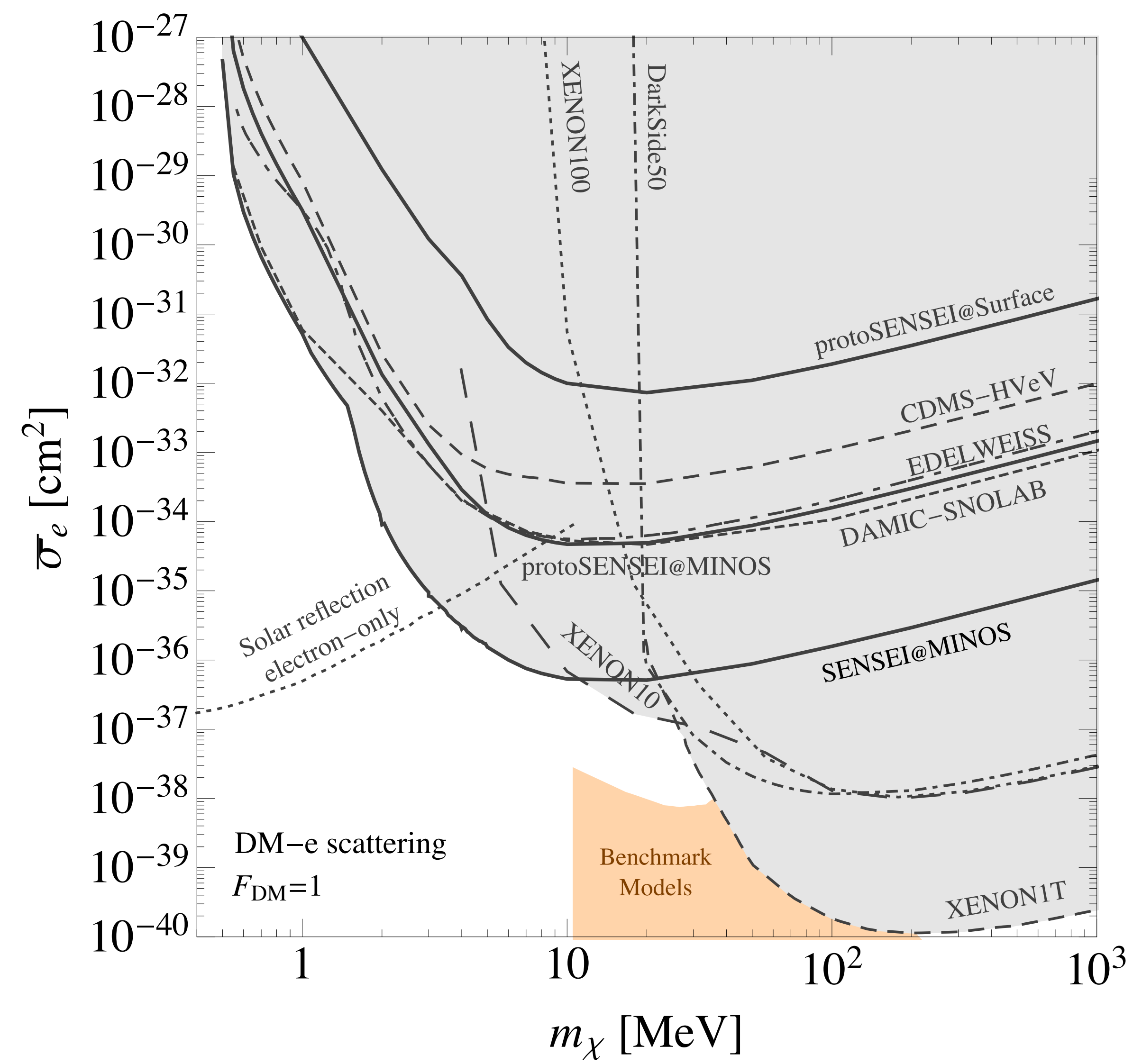
ultralight mediator

Exciting experimental progress

2012

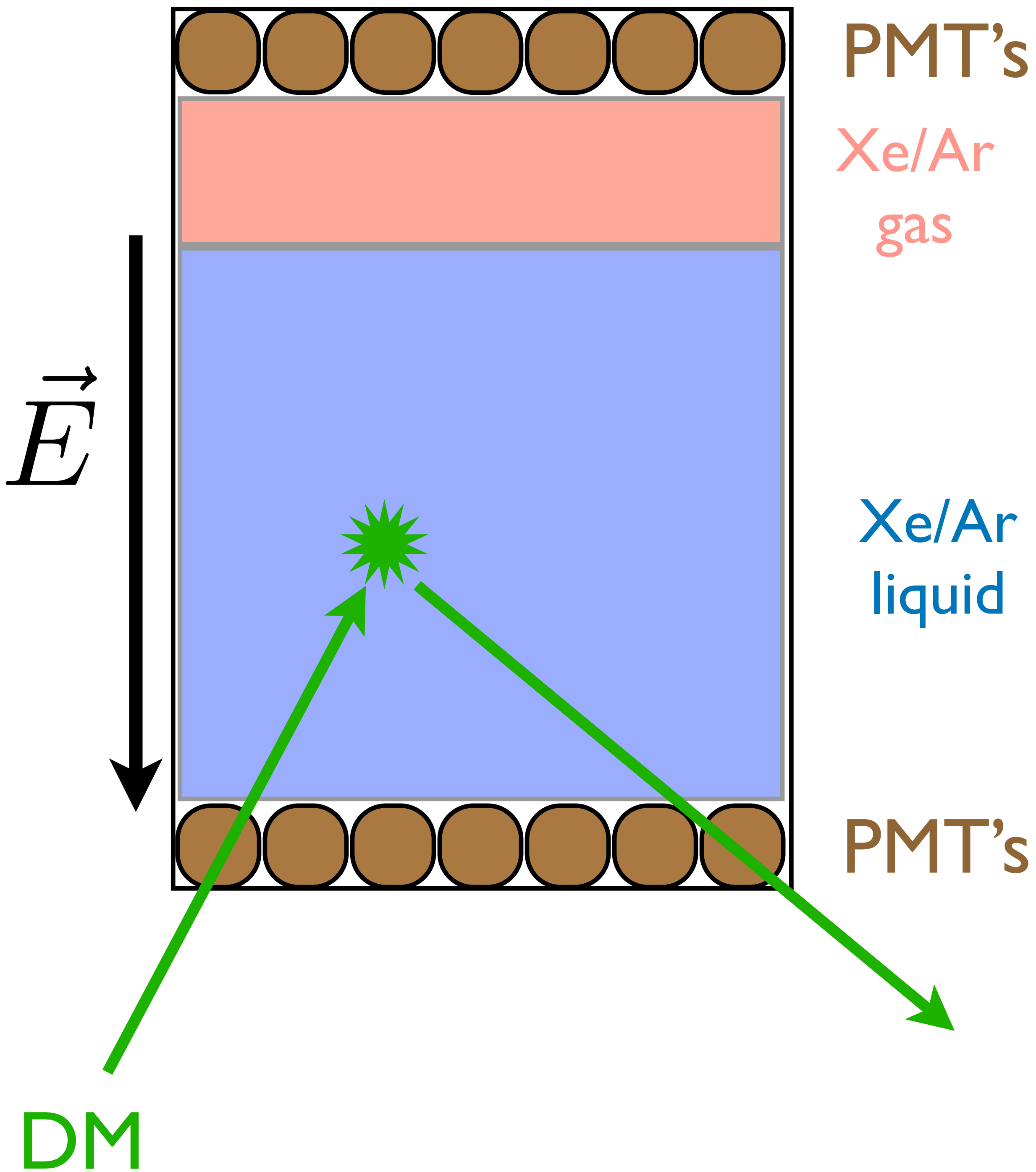


2021



heavy mediator

Two-phase TPCs (Xe, Ar)



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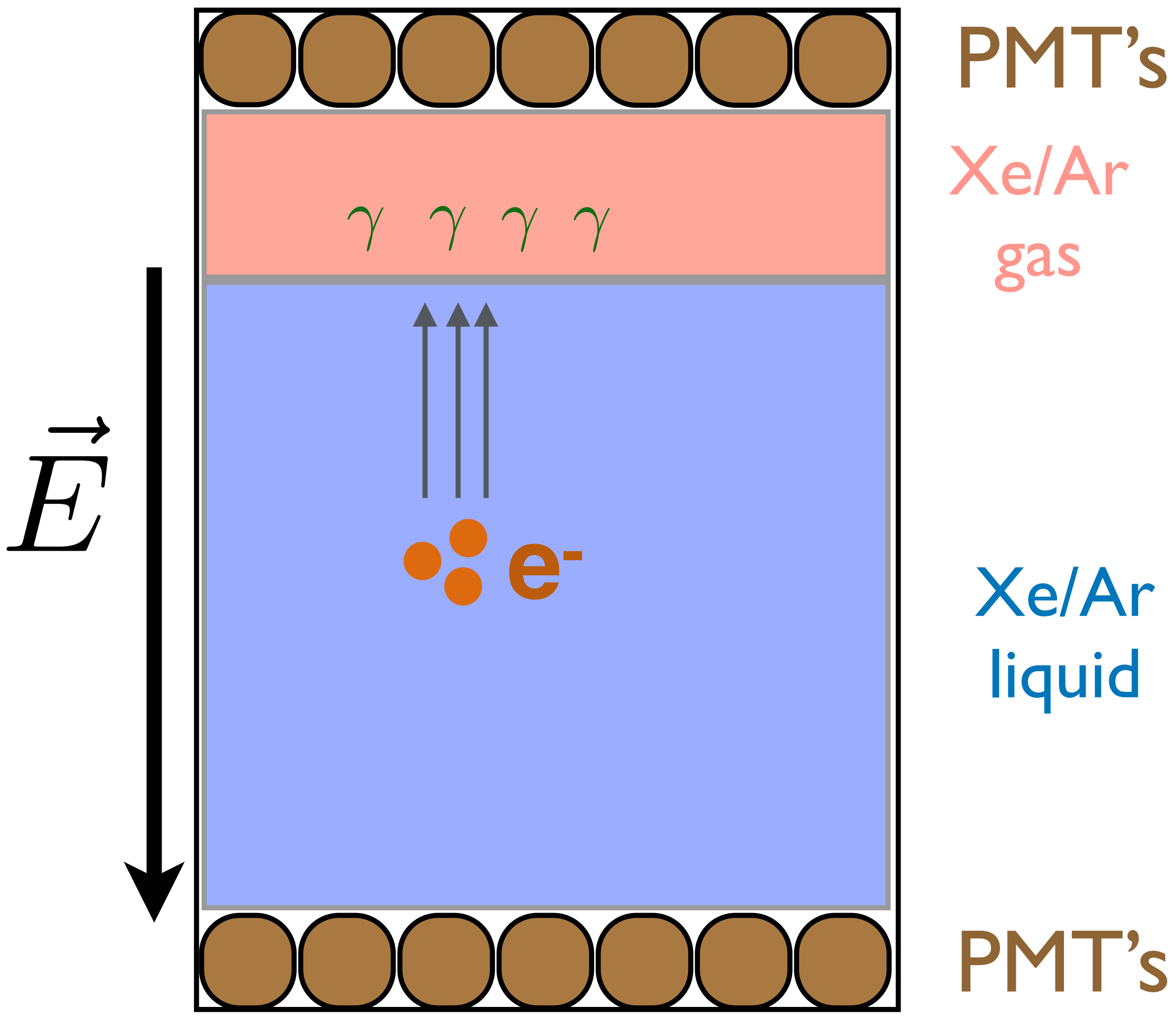
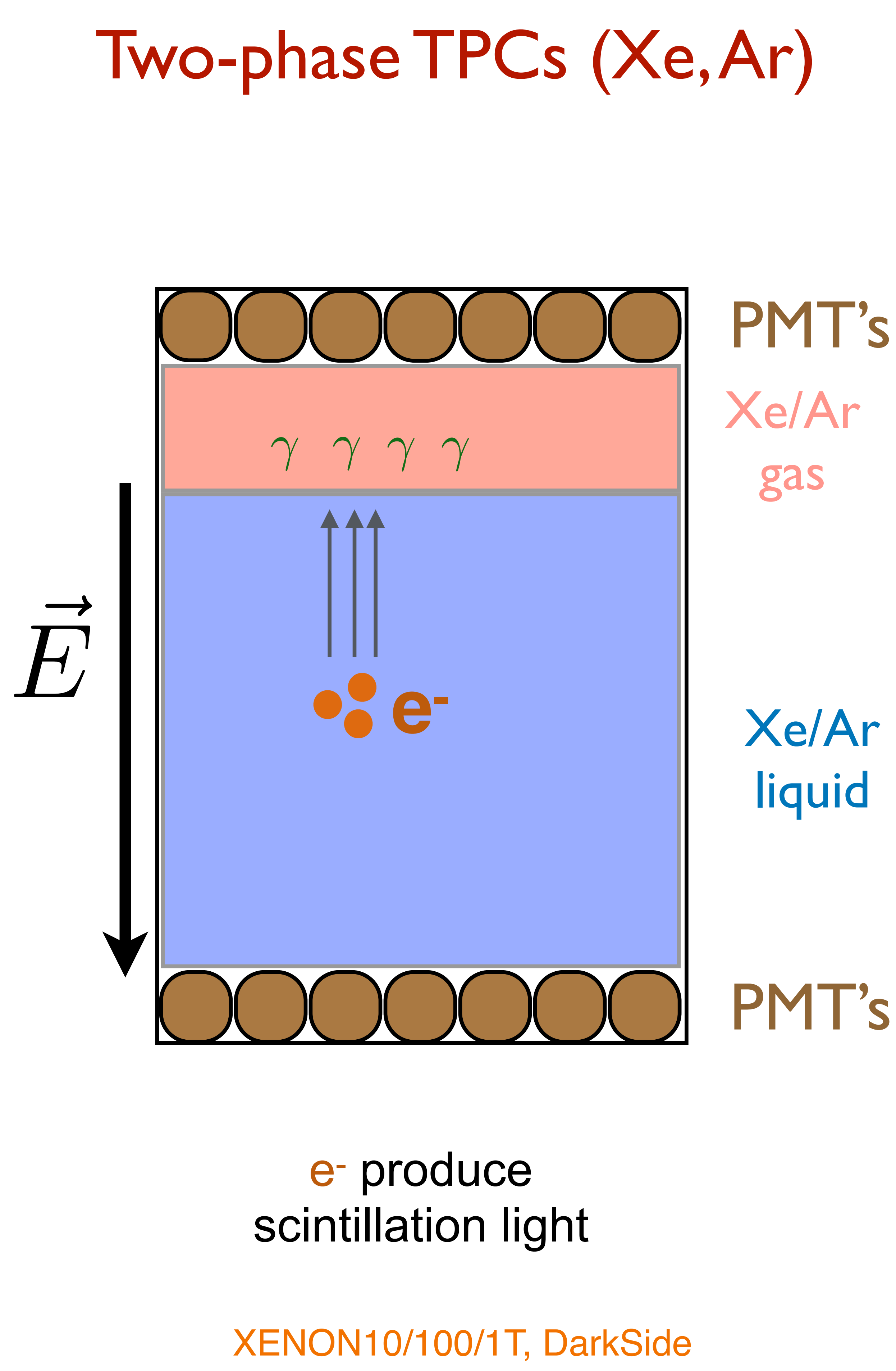
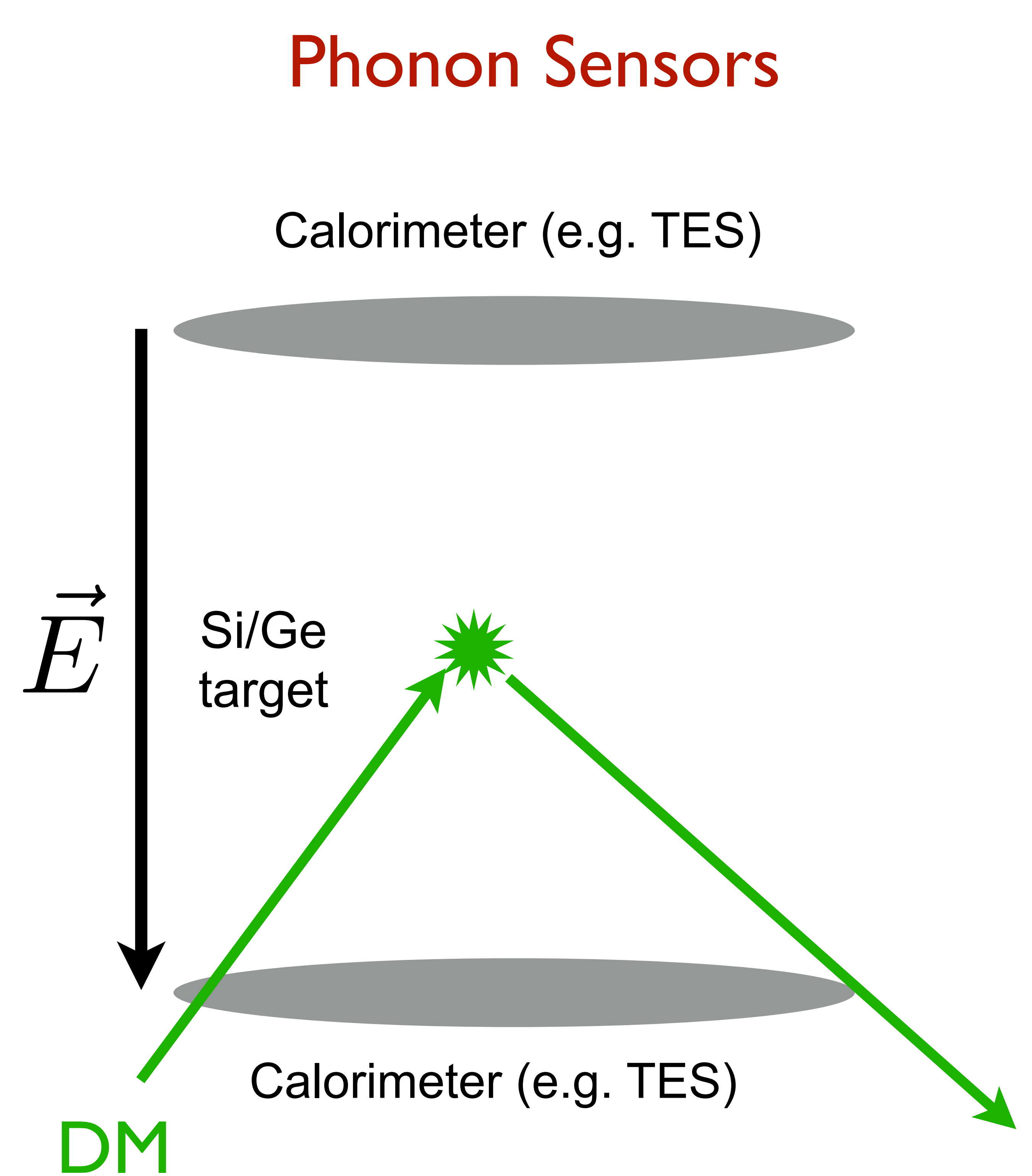


e- produce
scintillation light

XENON10/100/1T, DarkSide



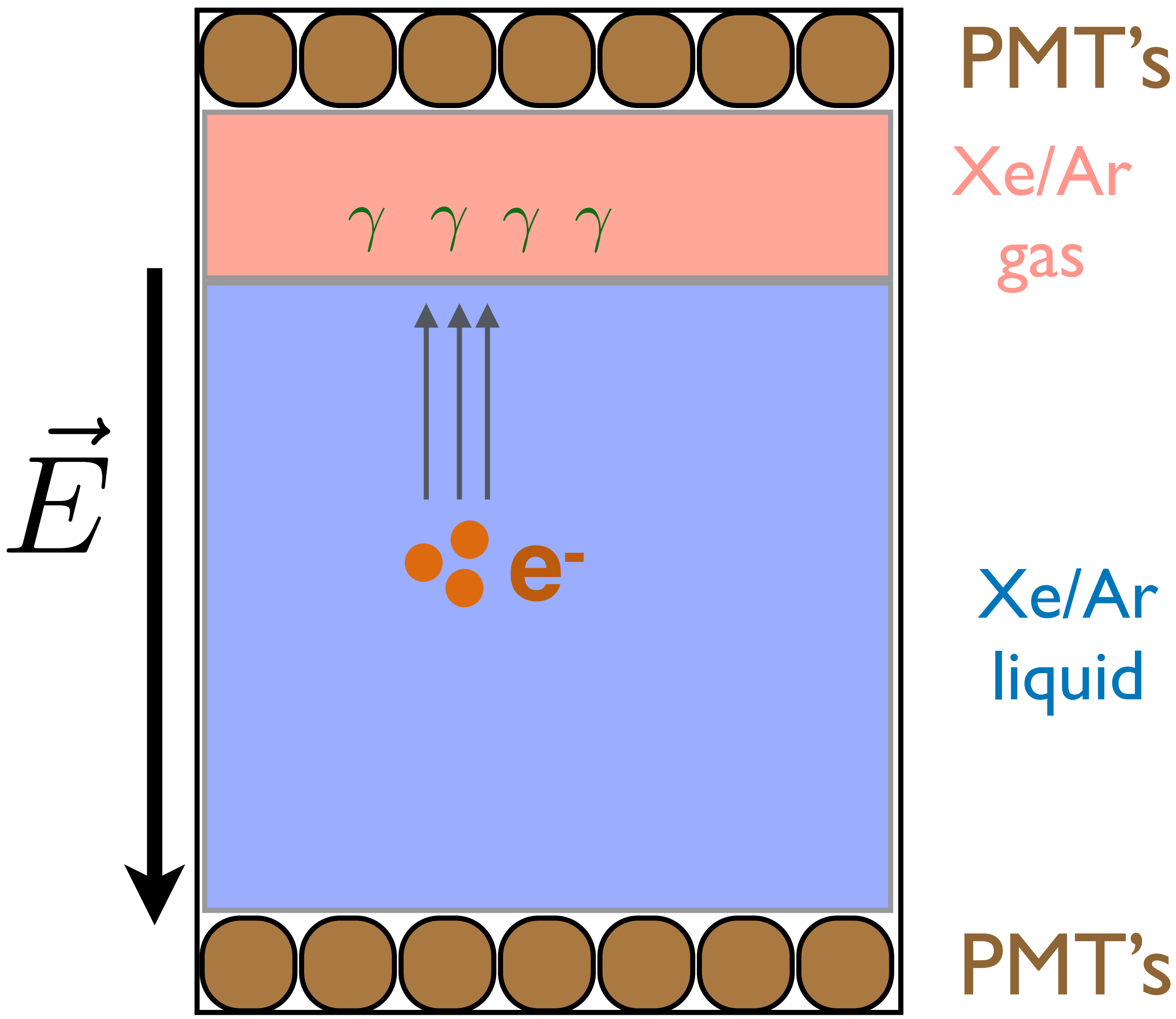
Two-phase TPCs (Xe, Ar)
PMT's
Xe/Ar
gas
γ γ γ γ
$\vec{E}$
e-
Xe/Ar
liquid
PMT's
e- produce
scintillation light
XENON10/100/1T, DarkSide

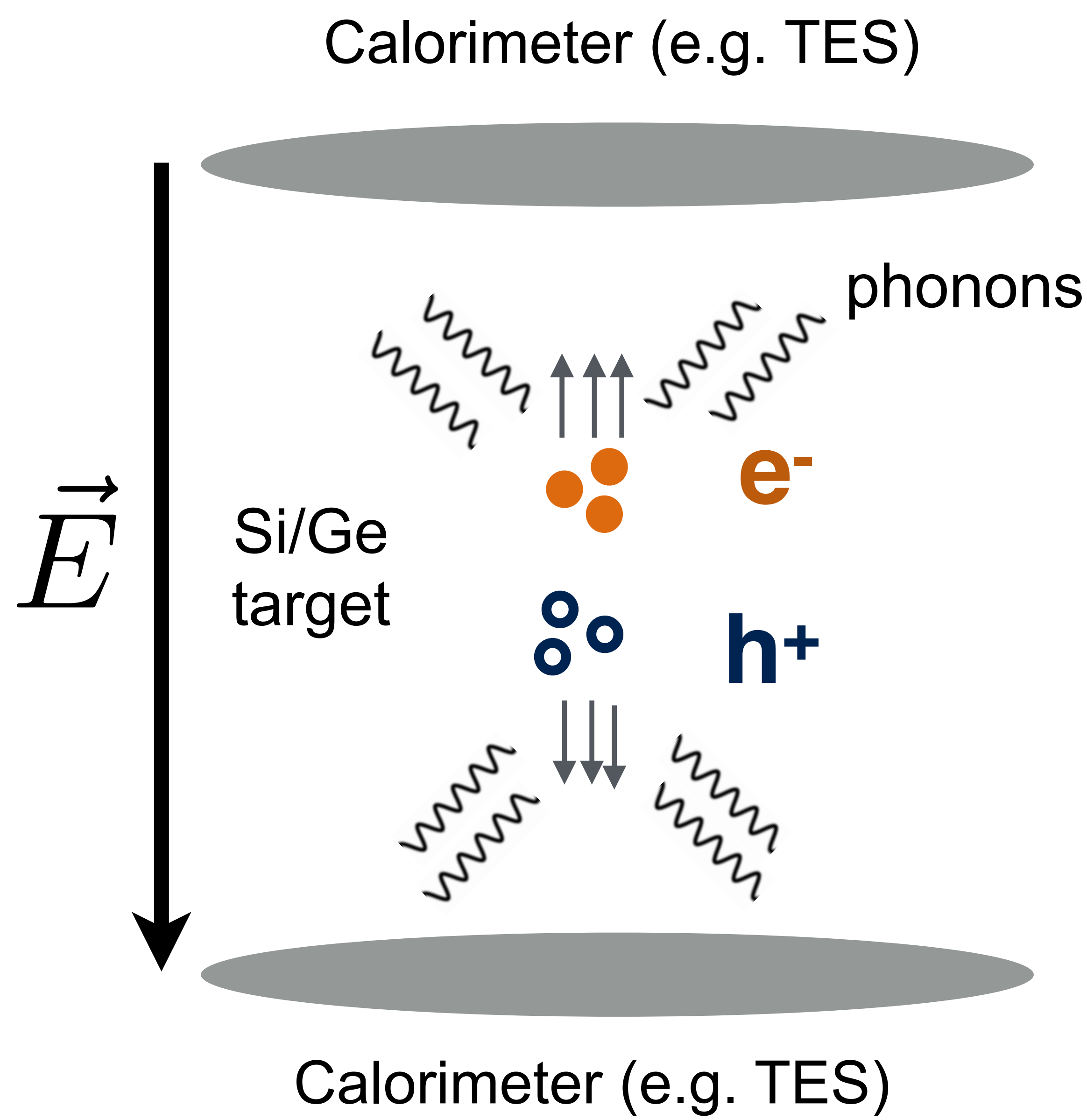


Phonon Sensors
Calorimeter (e.g. TES)
$\vec{E}$
Si/Ge
target
Calorimeter (e.g. TES)
DM

Two-phase TPCs (Xe, Ar)

Phonon Sensors





e^- produce
scintillation light

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

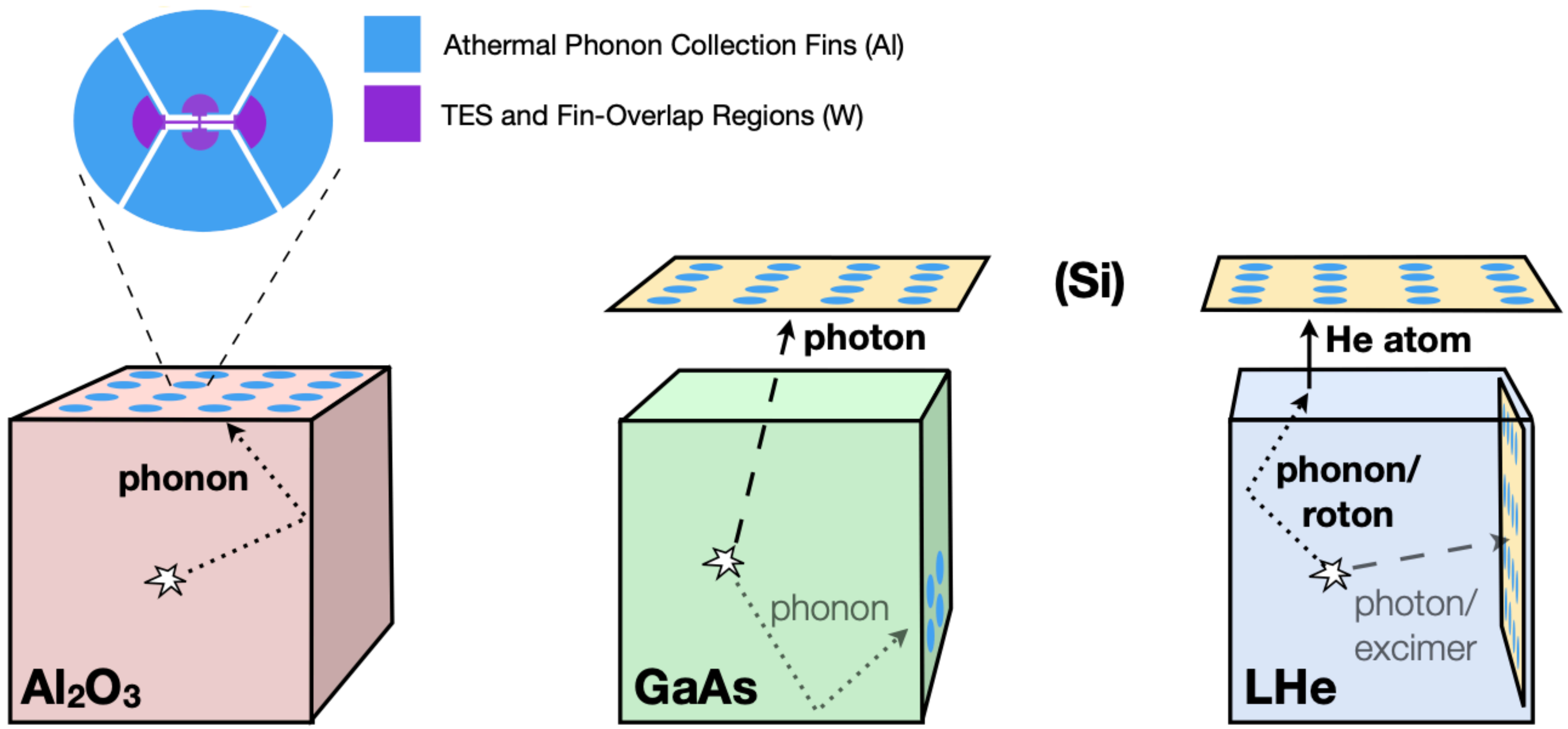
XENON10/100/1T, DarkSide

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

Skipper-CCD operation (SENSEI)

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

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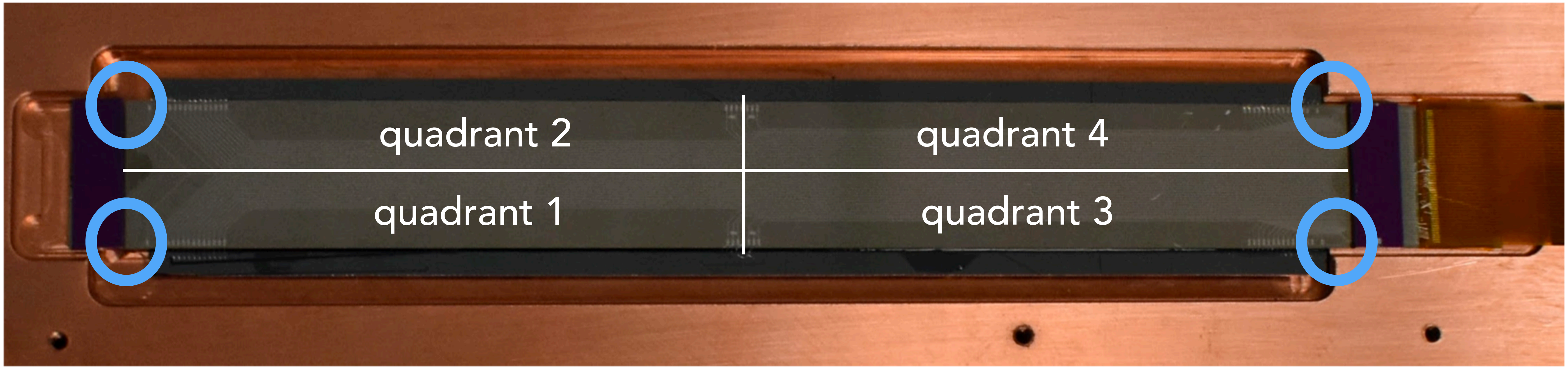
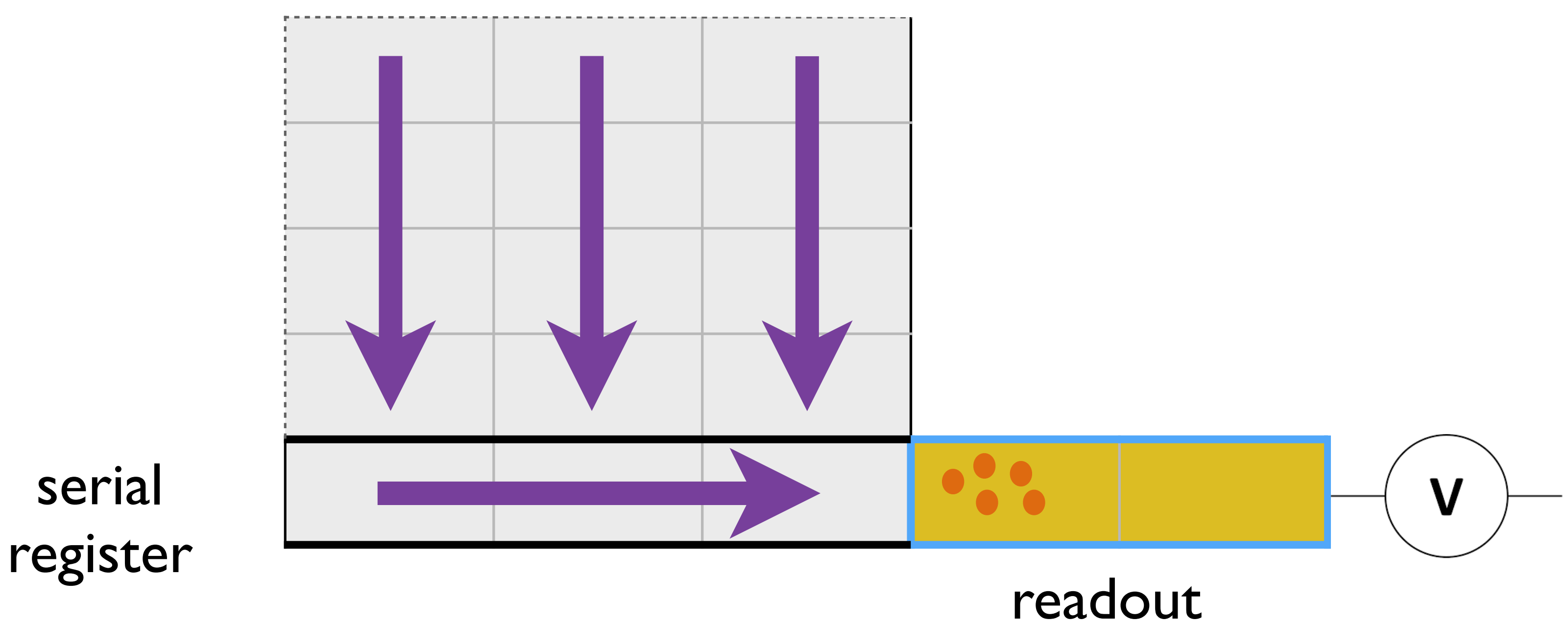


$\sim 2\text{ cm} \times 10\text{ cm, } 5.4\text{ Mpix}$



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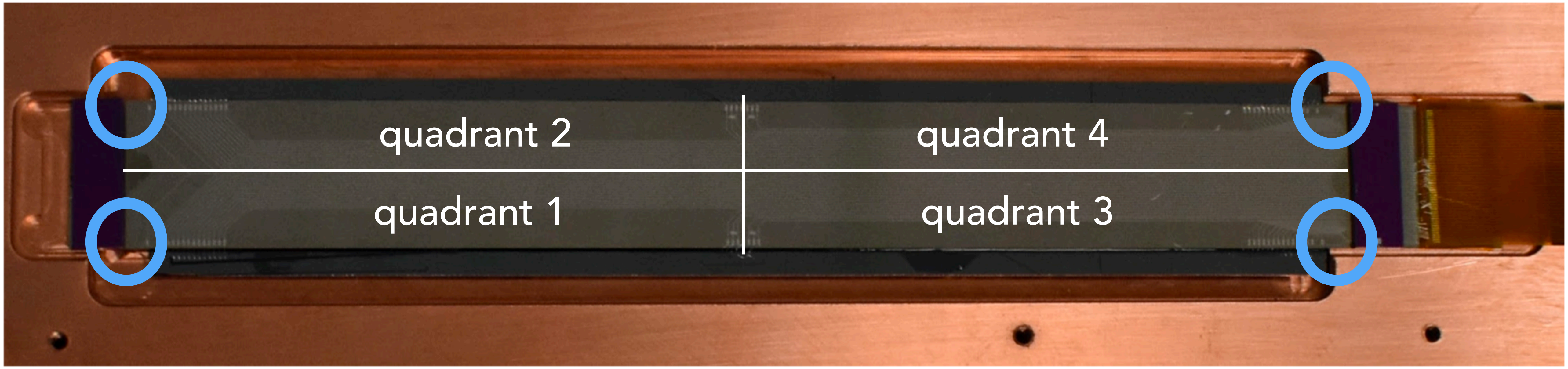

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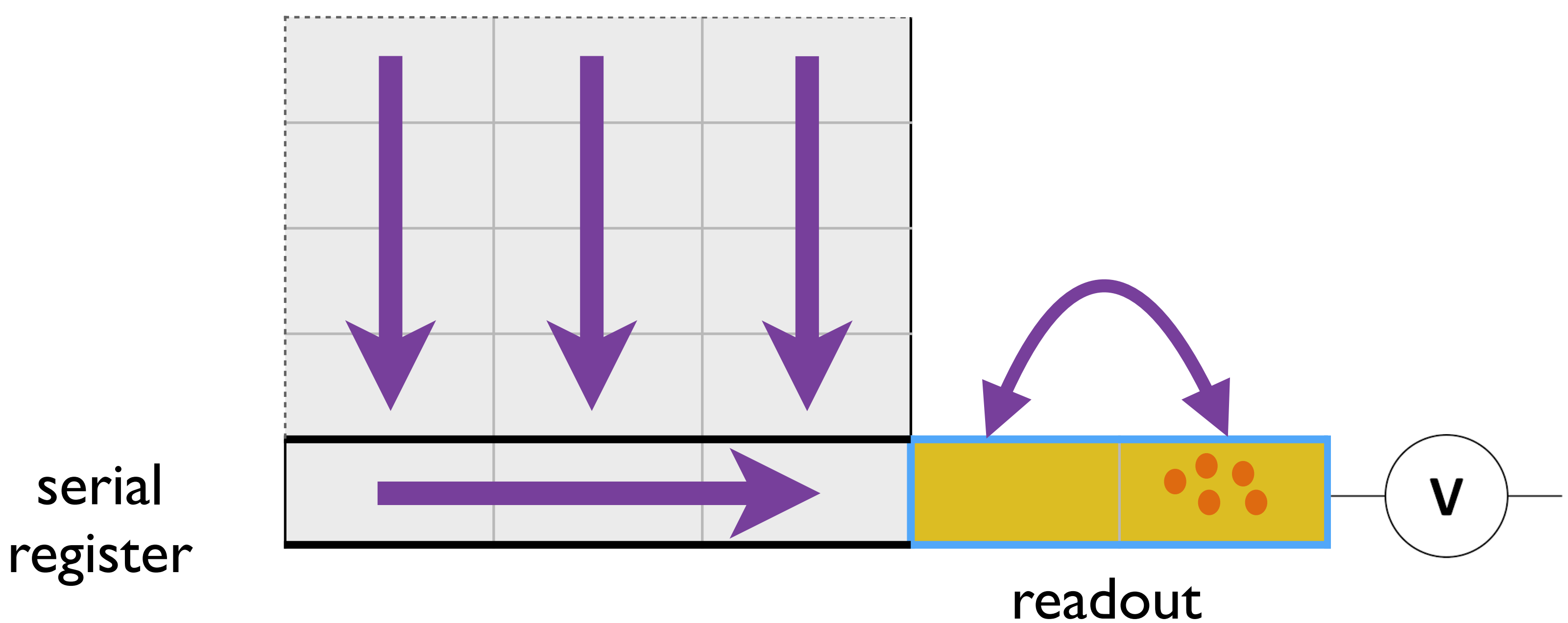

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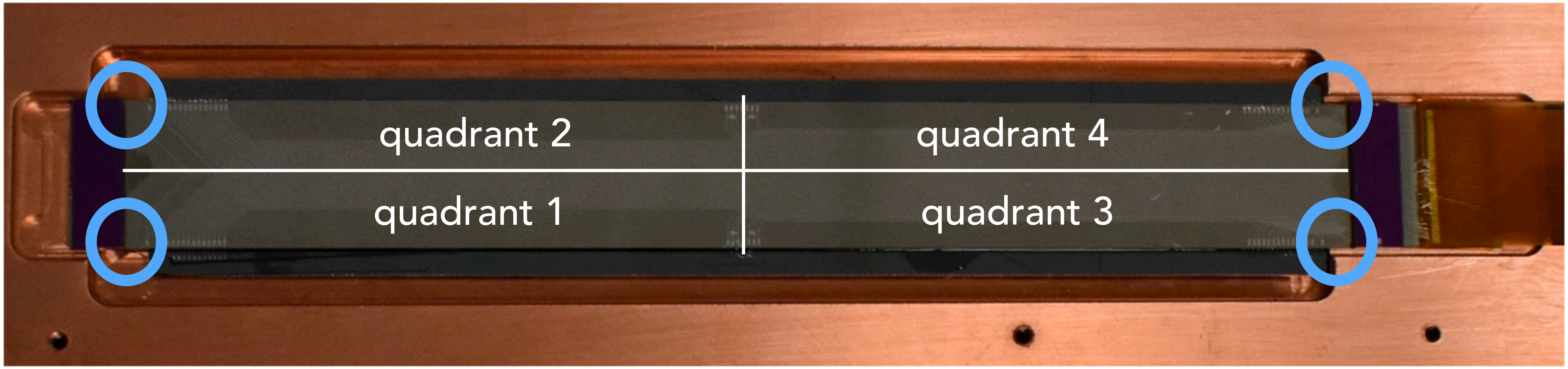

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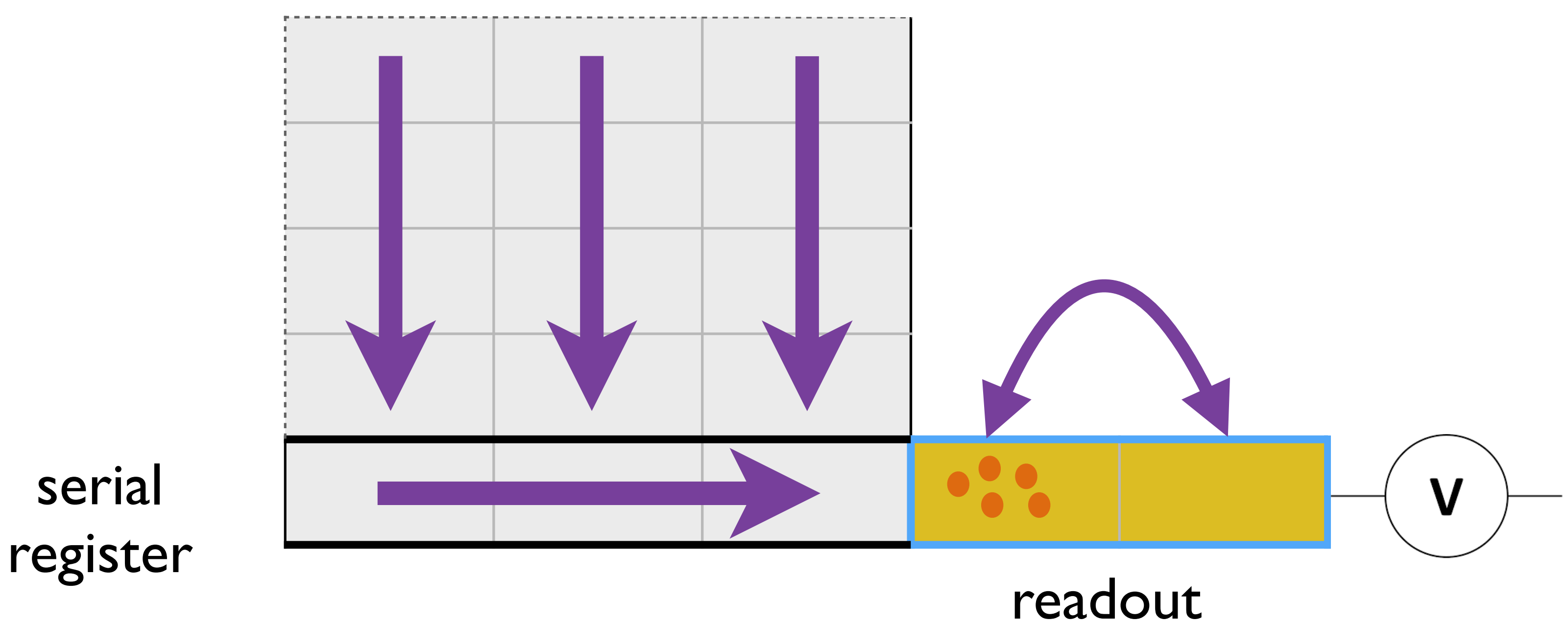

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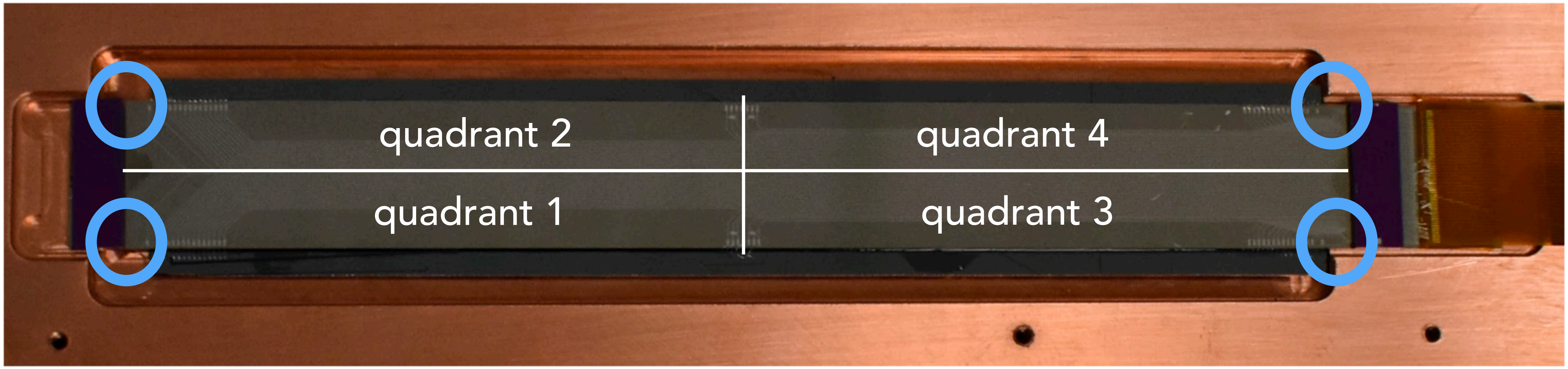

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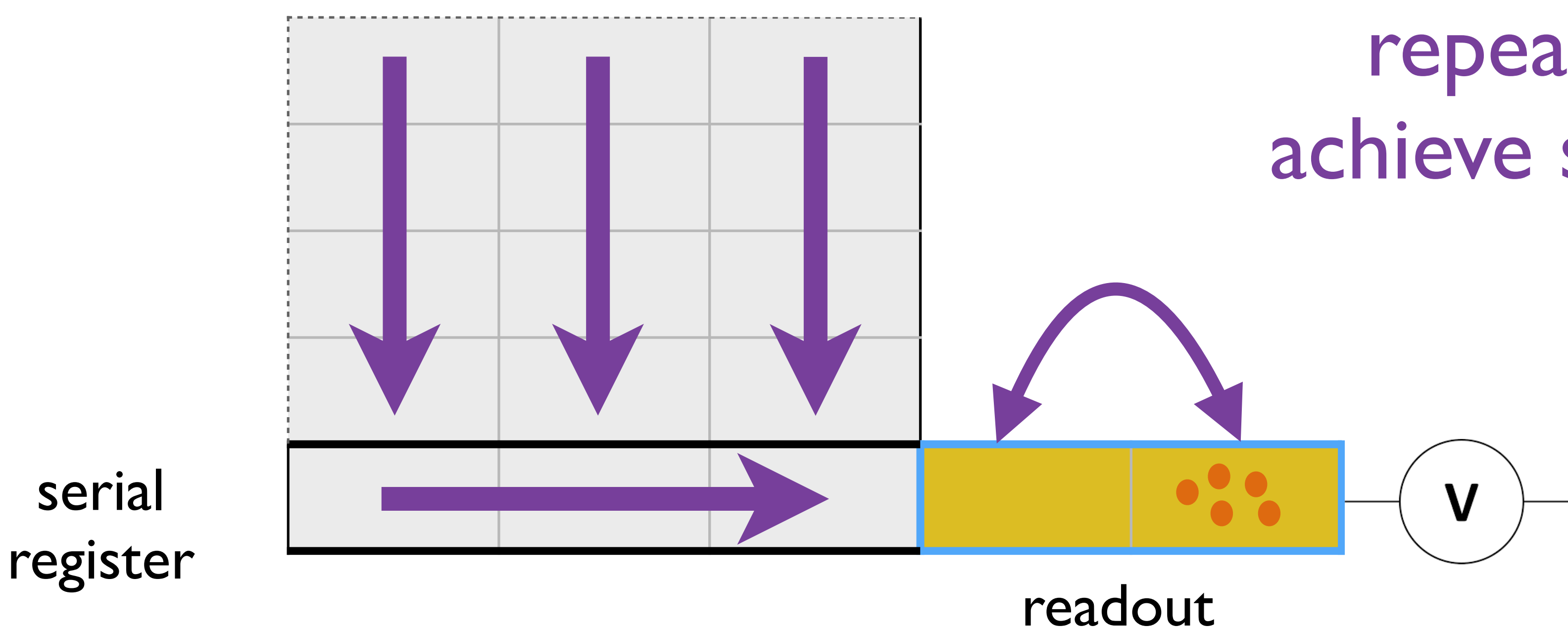

repeatedly measure charge to achieve sub-electron readout noise

Tiffenberg et.al. 2017

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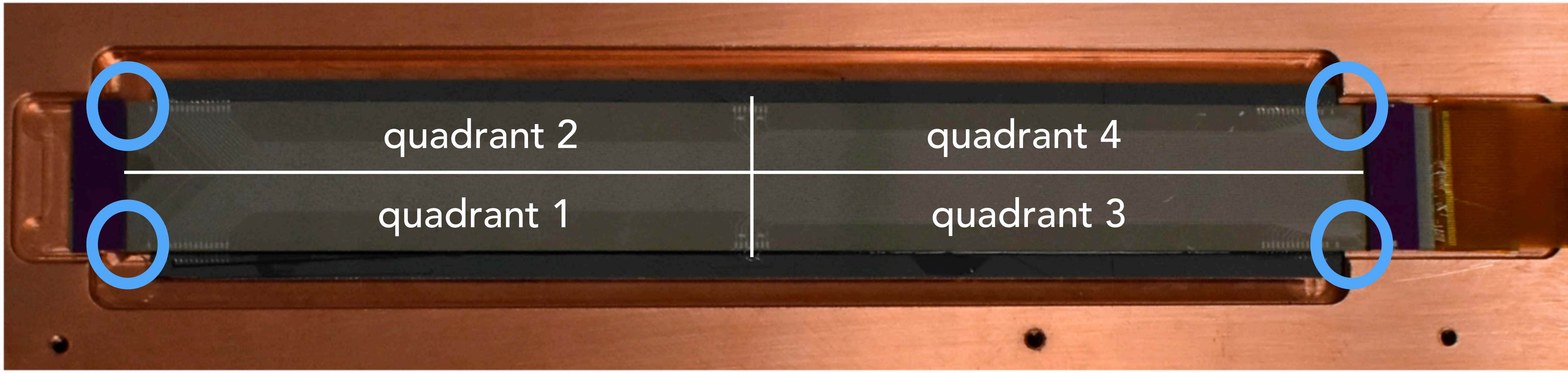

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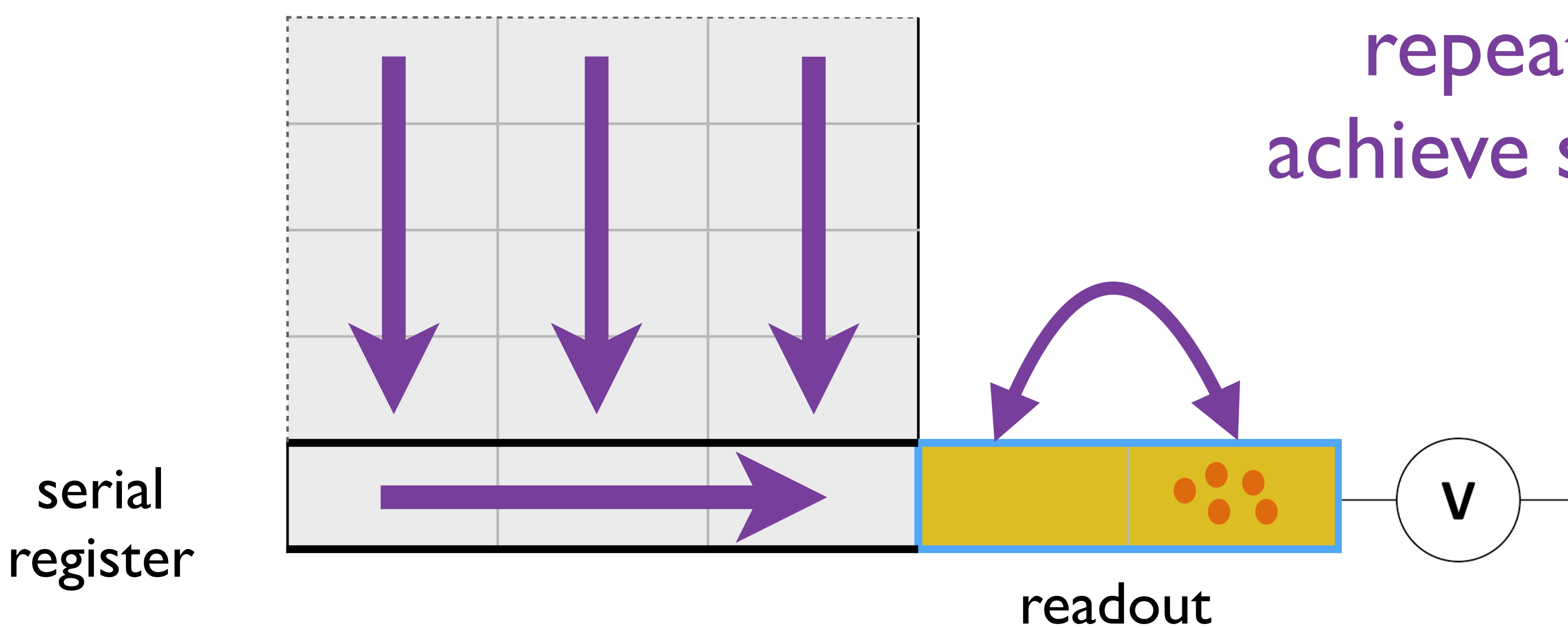
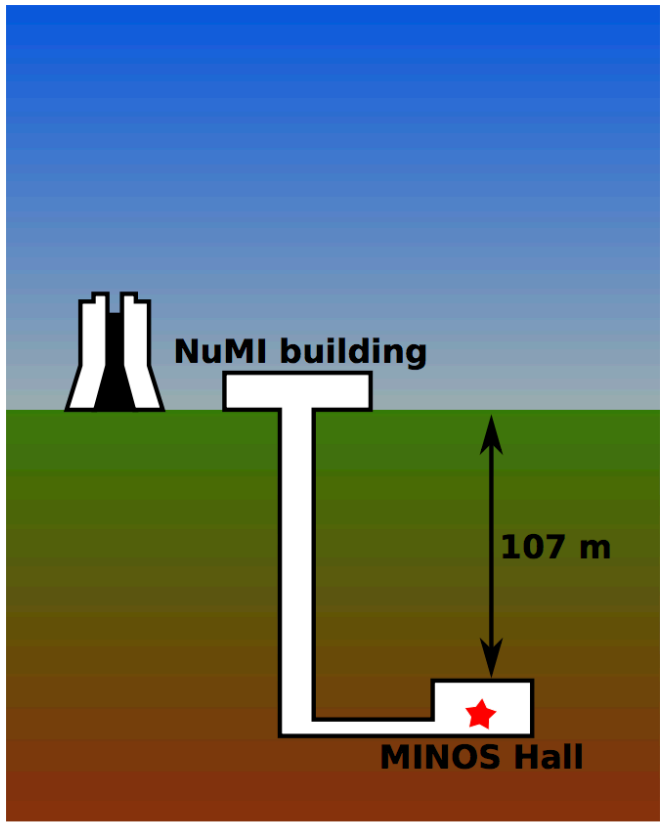


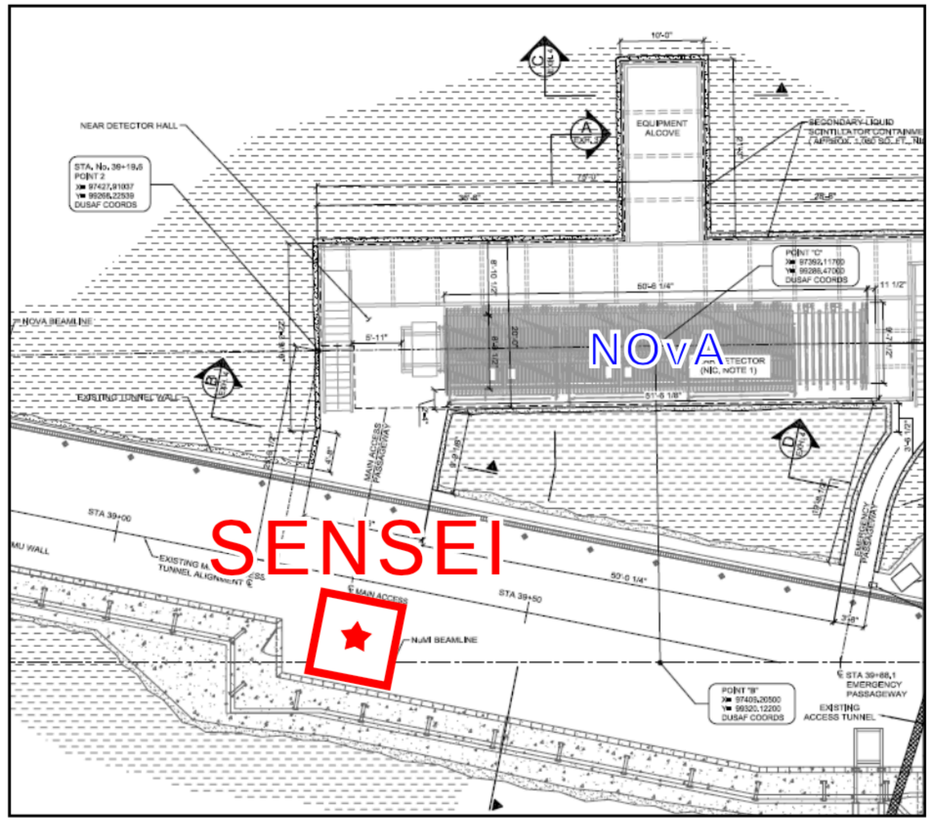
repeatedly measure charge to achieve sub-electron readout noise

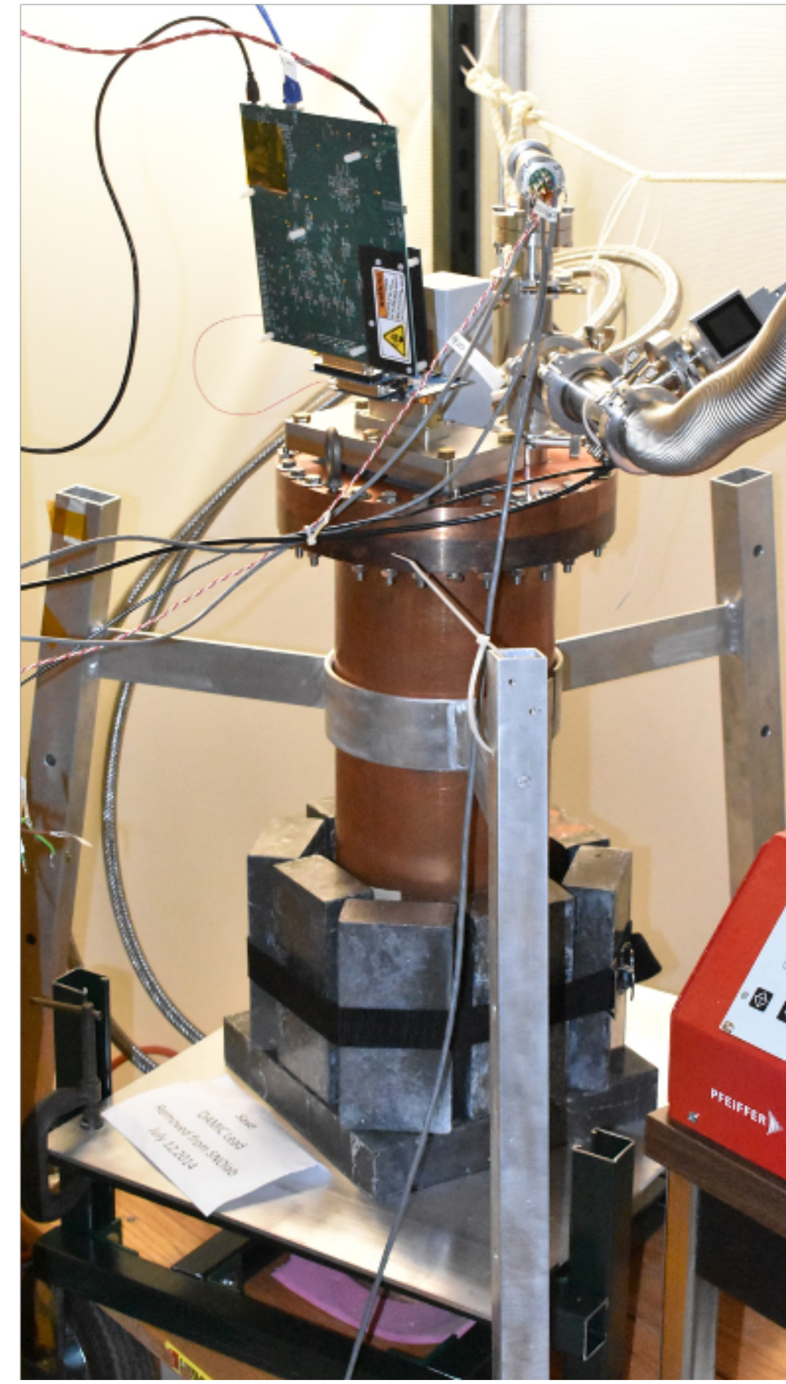
Tiffenberg et.al. 2017

designed at LBNL and fabricated at
Teledyne DALSA Semiconductor

SENSEI 2020 Detector Setup @ Fermilab

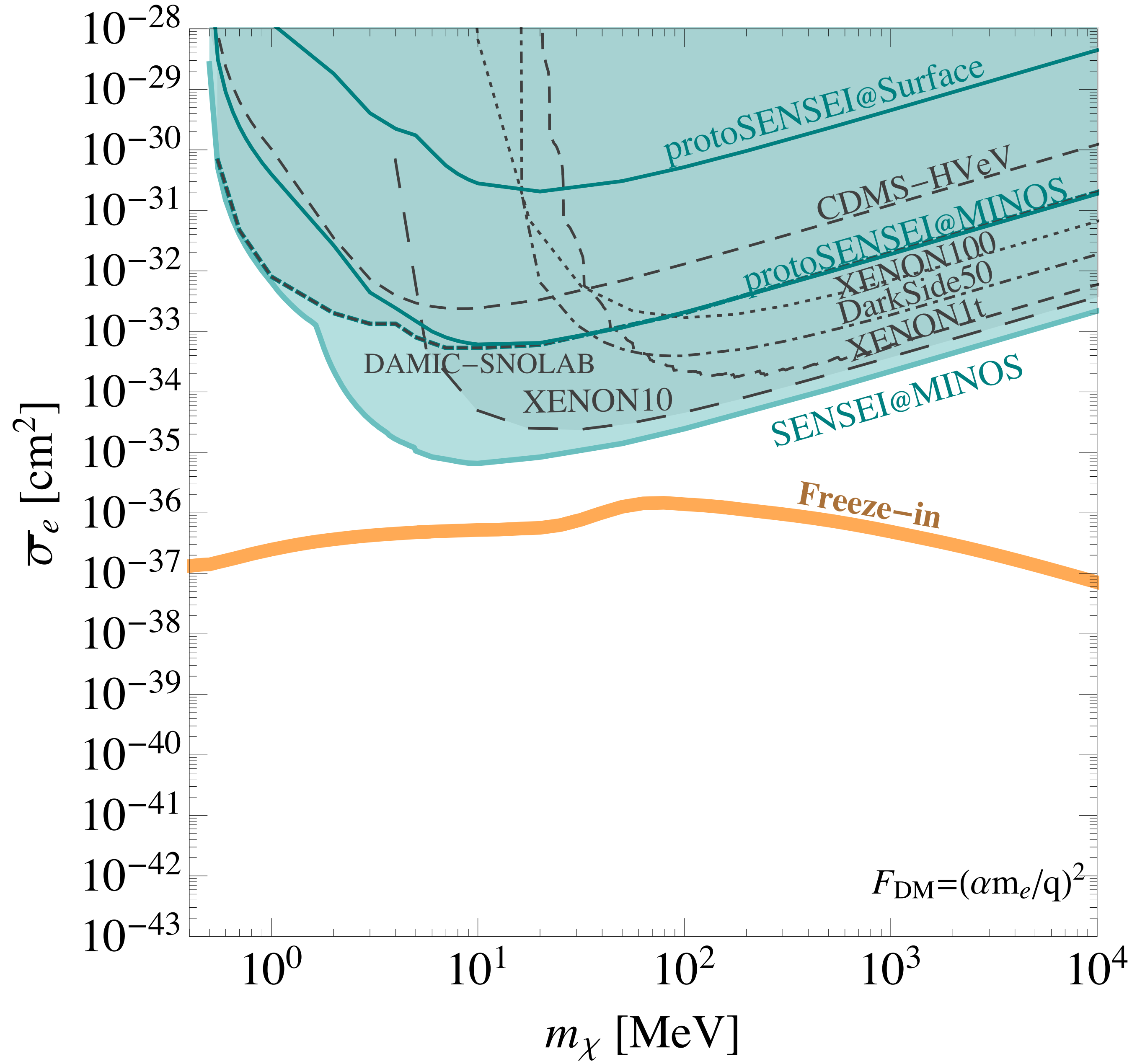






- ~100 m underground to reduce muons
- some extra lead shielding to reduce radiation

SENSEI Limits



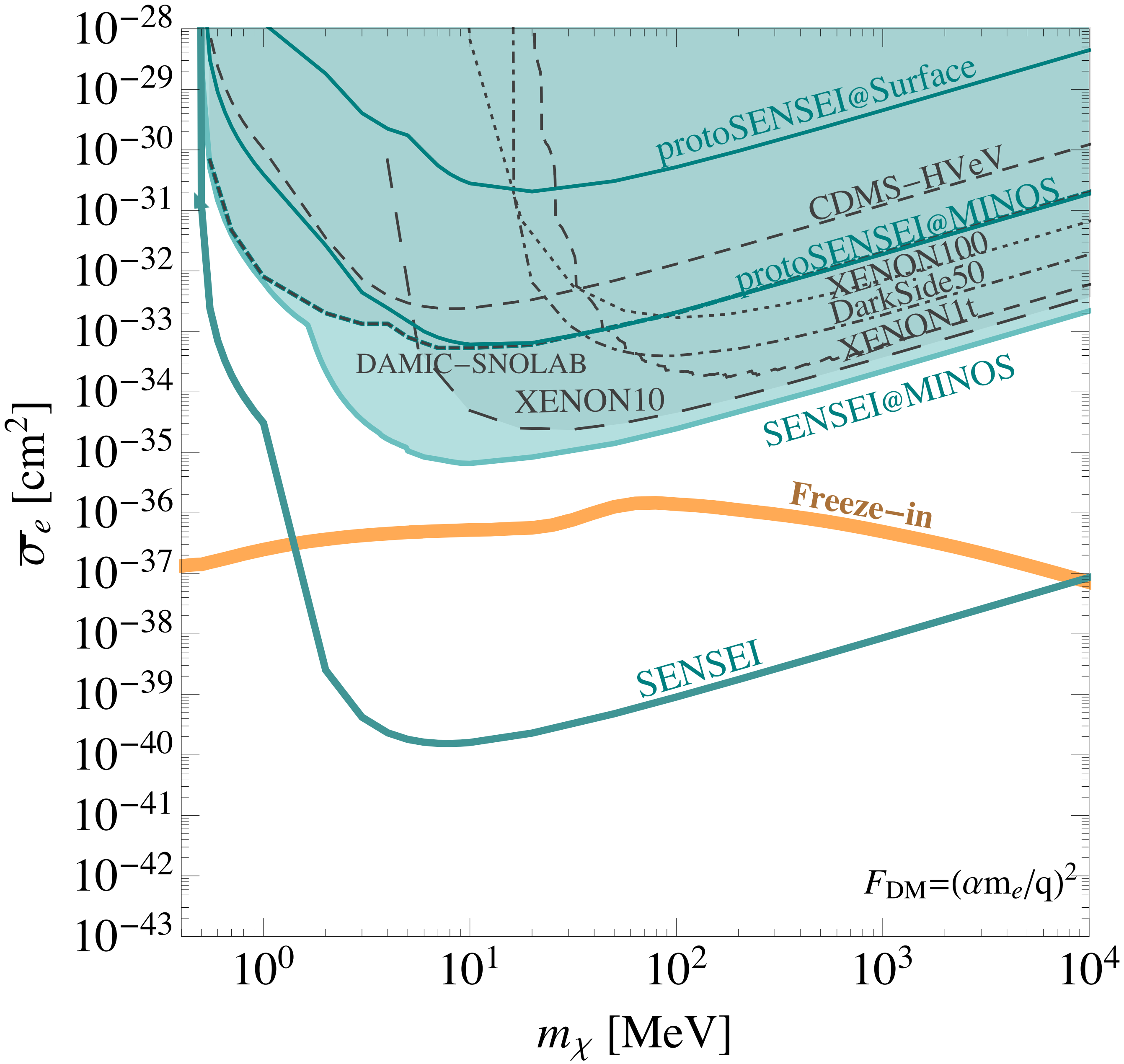
- 3 science results, using a prototype or science-grade Skipper-CCD

1804.00088, PRL

1901.10478, PRL

2004.11378, PRL

Projections



- SENSEI: ~100 gram (2021, SNOLAB)

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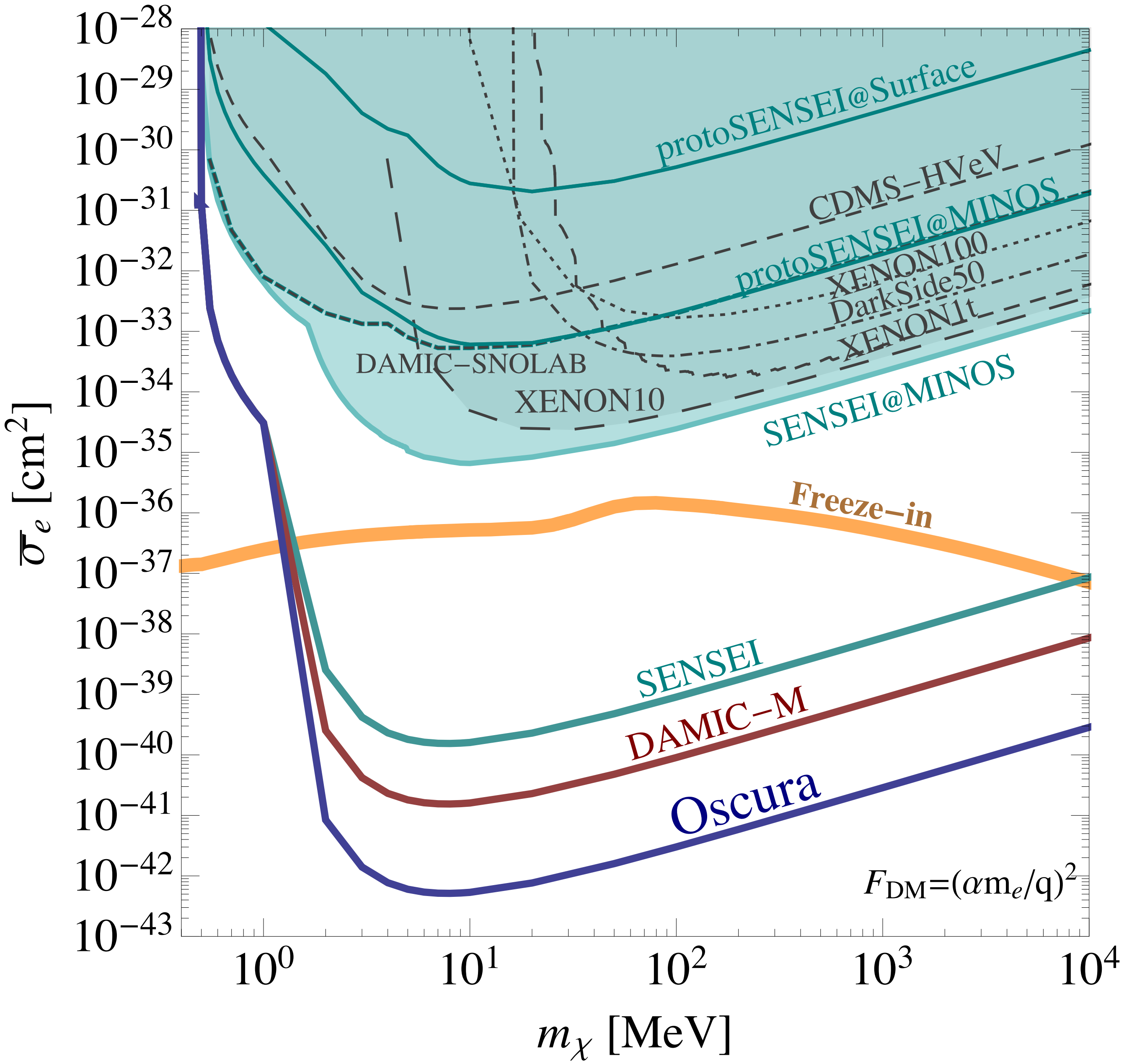


- SENSEI: ~100 gram (2021, SNOLAB)
- DAMIC-M: ~1 kg (2023, Modane)
- Oscura: 10 kg (R&D funded)

Rapid progress in probing many hidden-sector DM models!

The challenges ahead for low-mass DD

Significant recent progress, but much remains to be done

Over next 5-10 years, there are at least 5 major goals:

[order does not imply relative importance]

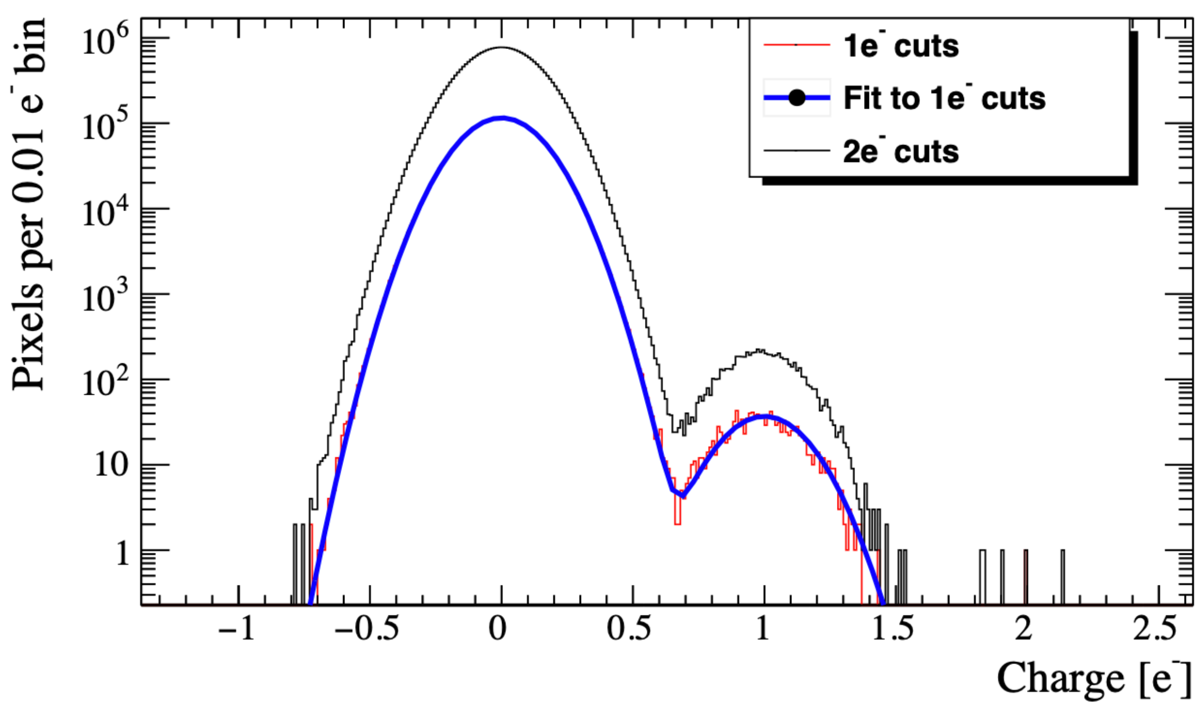
1. Sharpen theory predictions for DM signals
2. Calibrate low-energy signals and backgrounds
3. Increase target mass of “proven” detector technologies
4. Lower energy thresholds to probe even lower DM masses
5. Understand, characterize, and mitigate low-energy backgrounds

Outline

- Overview of Some Recent Progress
  - Theory
  - Experiment
- Sources & Implications of Low-Energy Backgrounds
- Diurnal Modulation of Sub-GeV DM (if time)

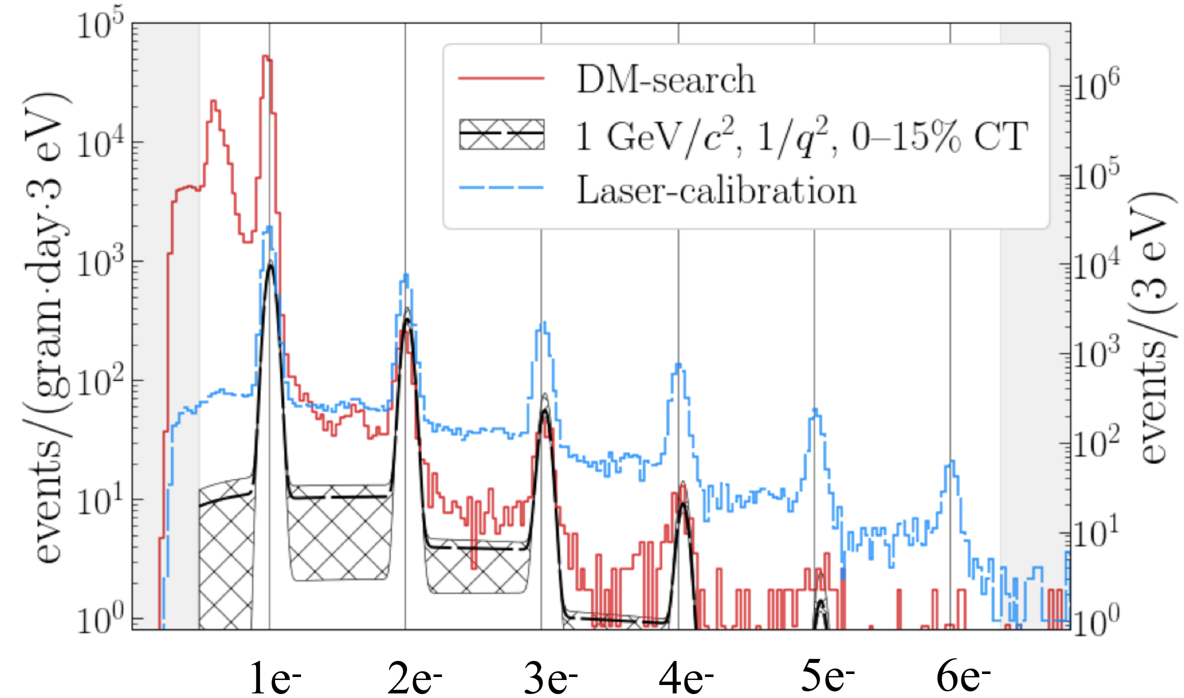
All sub-GeV DM experiments see "excess" low-energy events

e.g. SENSEI



SENSEI, 2004.11378

e.g. SuperCDMS HVeV



SuperCDMS, 2005.14067

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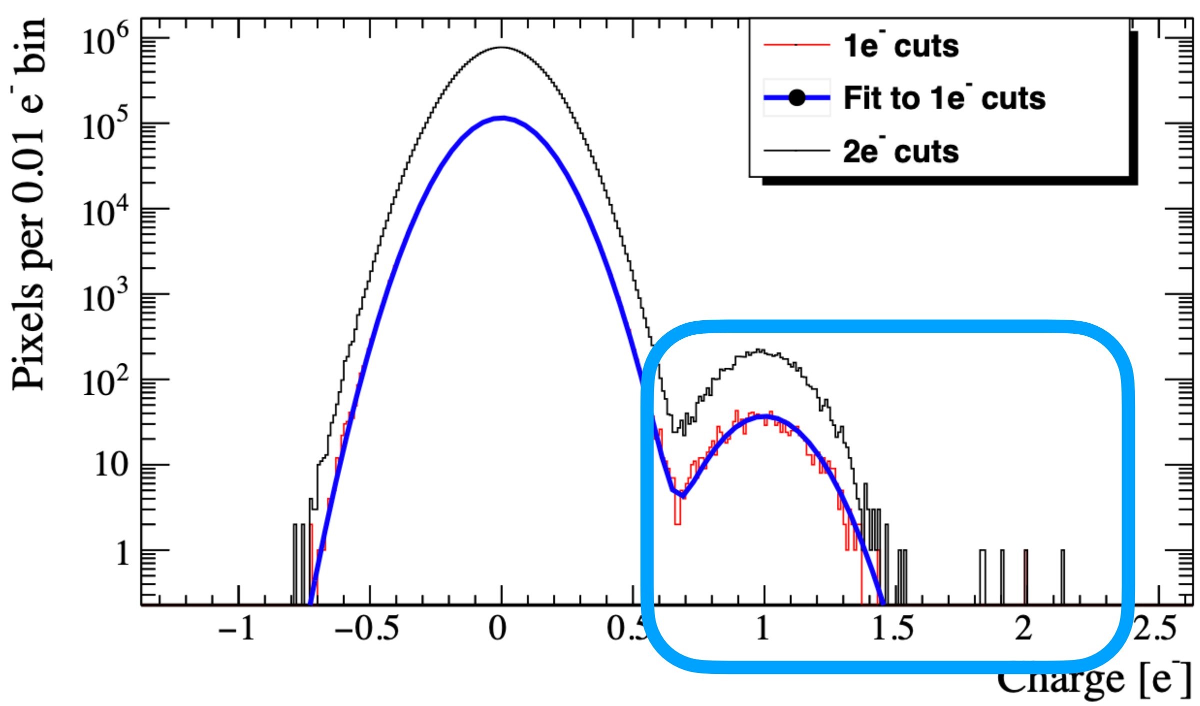

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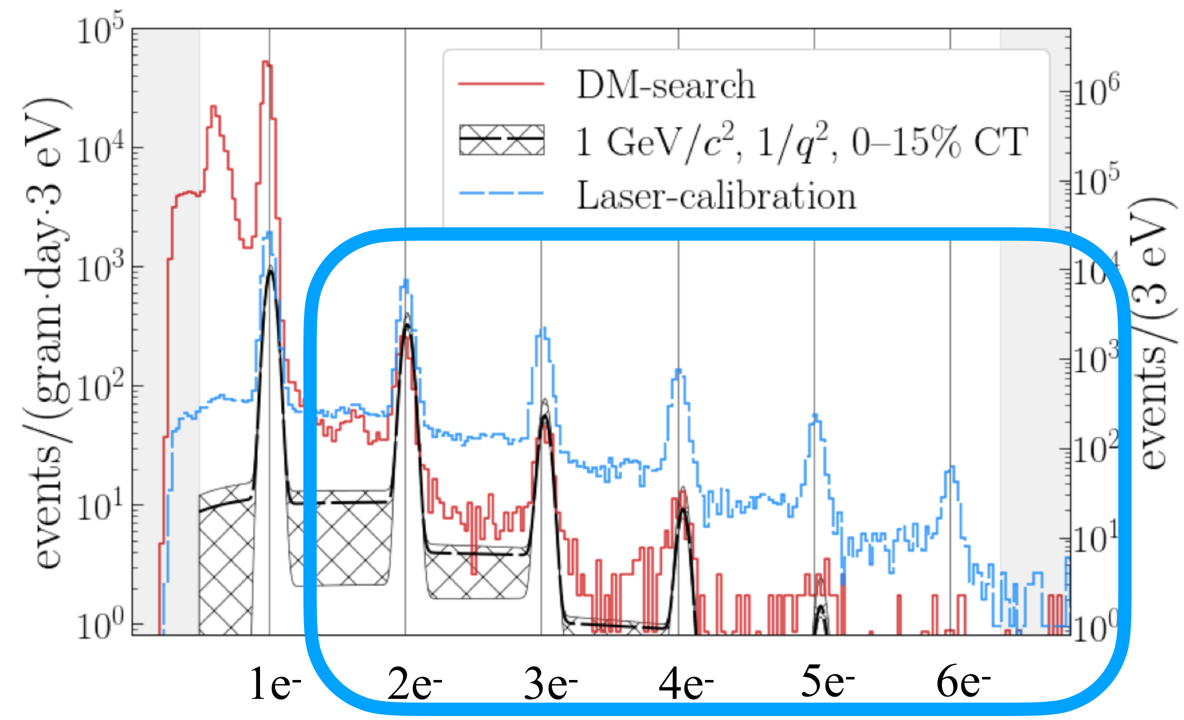

SuperCDMS, 2005.14067

Origin of these events has been a mystery for several years

(radioactive backgrounds expected to be ~flat)

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

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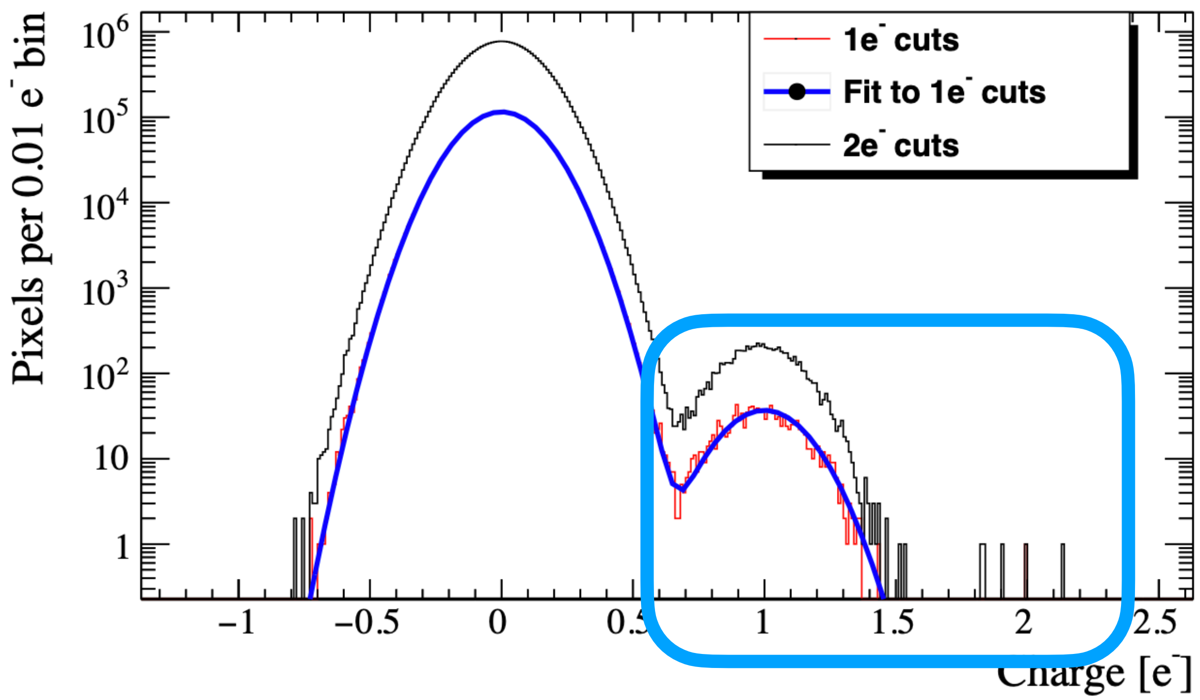

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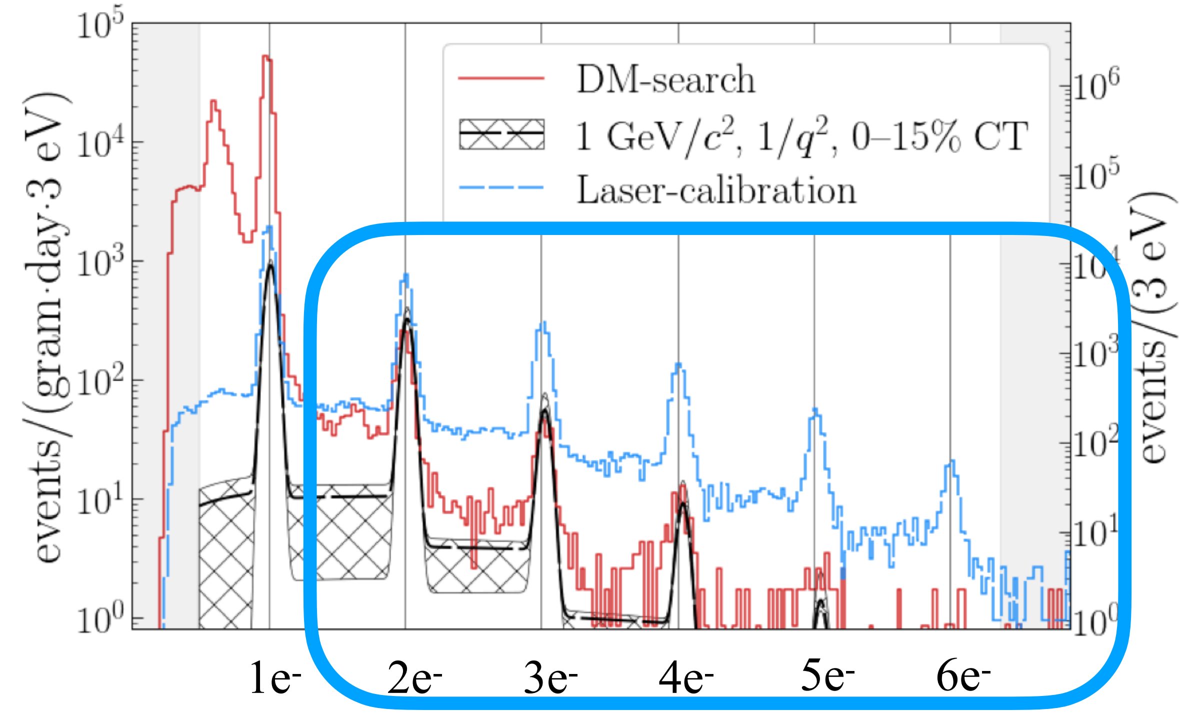


SuperCDMS, 2005.14067

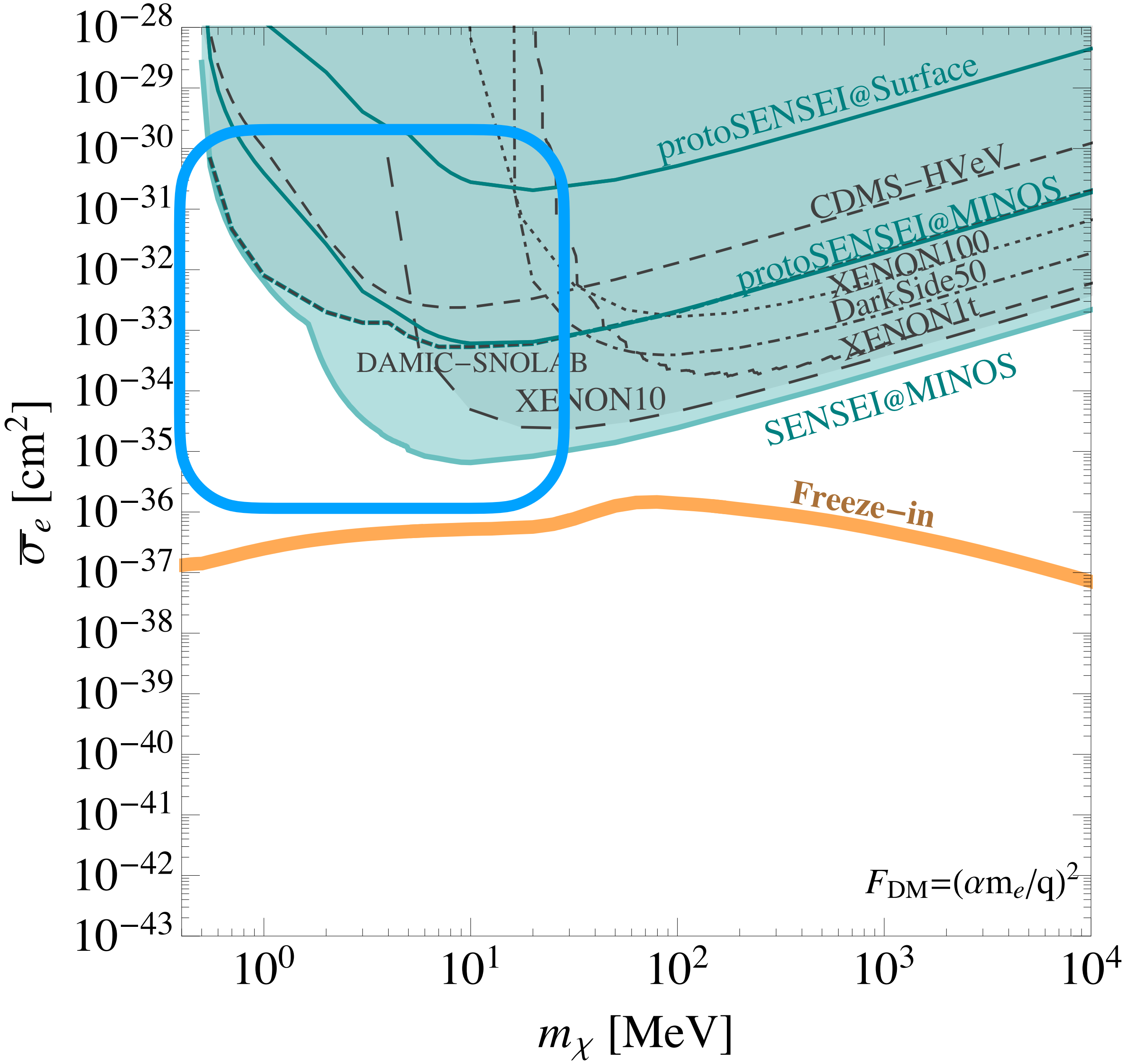
Origin of these events has been a mystery for several years

(radioactive backgrounds expected to be ~flat)

We have now identified the likely origin of these "excesses" at SENSEI and SuperCDMS HVeV

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

Understanding these events greatly improves sensitivity, especially at low masses



and that it makes sense to keep building larger experiments (with appropriate mitigation strategies)!

Image from SENSEI

- many $1e^-$ events

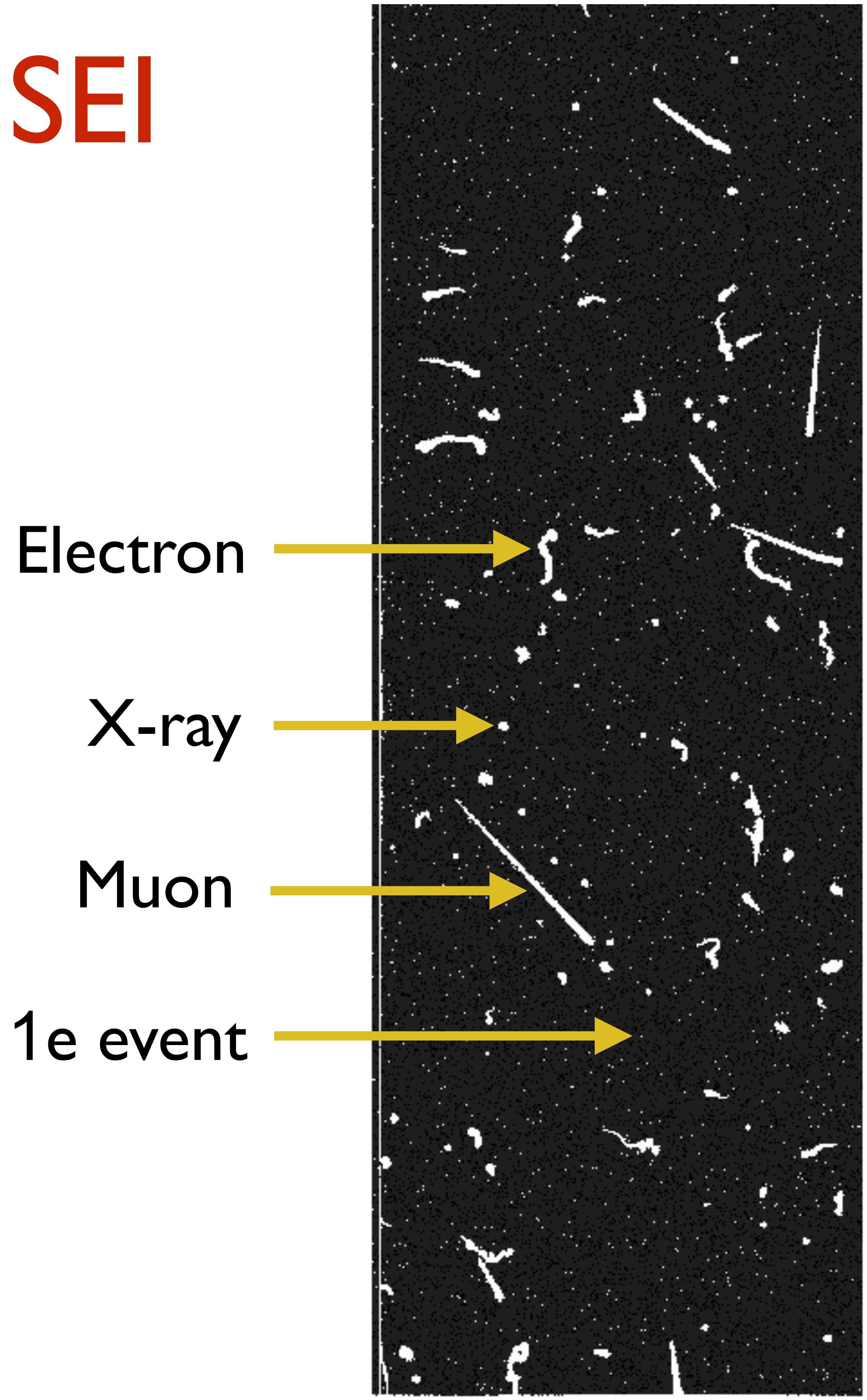


Image from SENSEI

- many $1e^-$ events

From data:

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

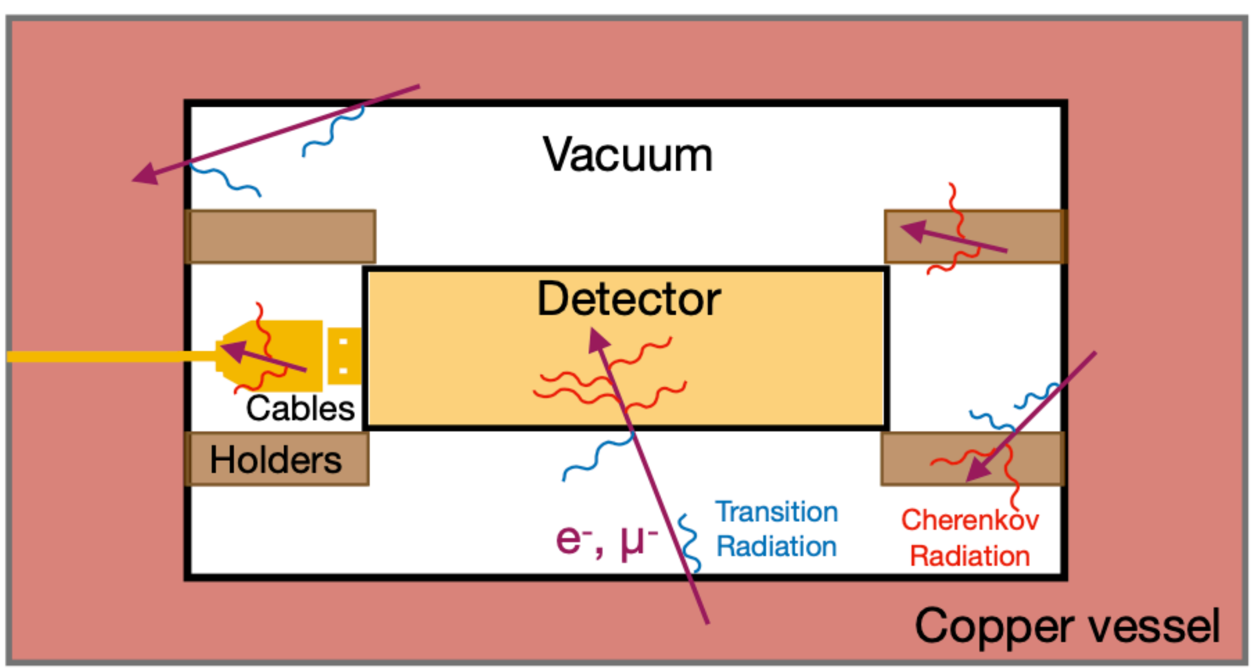
Sources of low-energy events

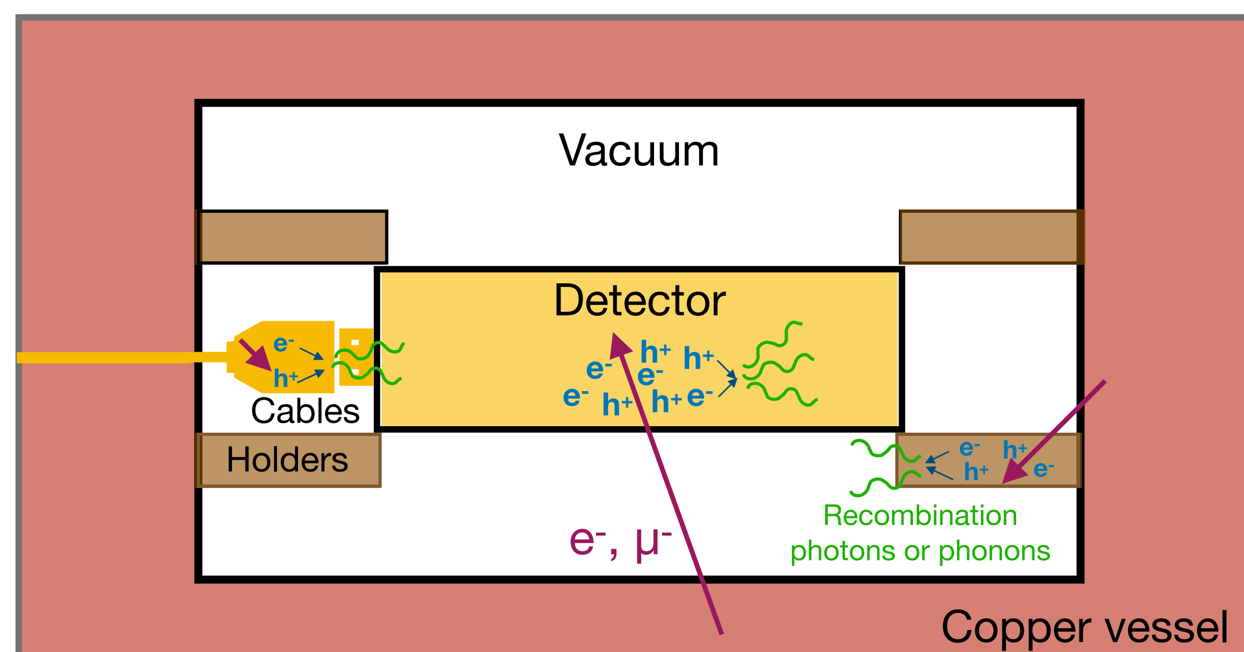
Peizhi Du, Daniel Egana-Ugrinovic, RE, Mukul Sholapurkar, 2011.13939

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

- Cherenkov radiation (many γ's)
- Transition radiation*
- Radiative recombination (many γ's)

Photons get absorbed in sensor to produce an electron





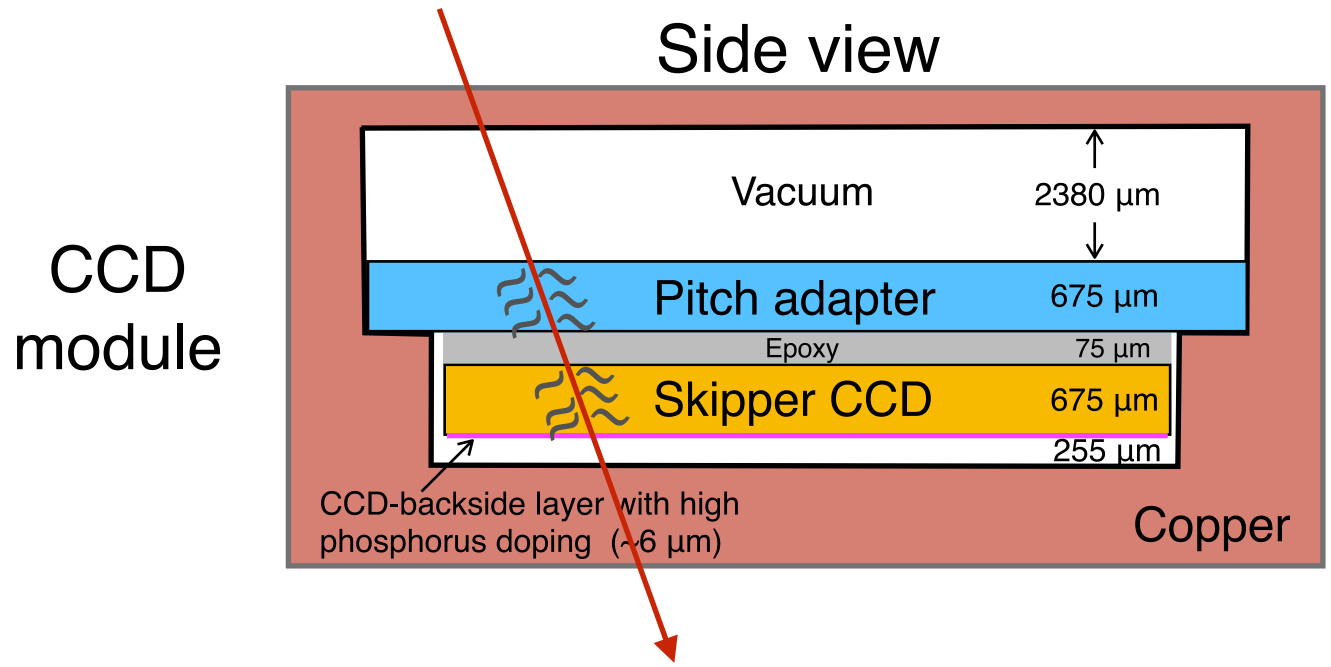
~100s of tracks/g*day at SENSEI, ~10 thousand /g*day at SuperCDMS HVeV

*see also Robinson, 2010.11043

SENSEI $1e^-$: likely dominated by Cherenkov & recombination

SENSEI, 2004.11378

Du, Egana-Ugrinovic, RE, Sholapurkar, 2011.13939



- Cherenkov from tracks in (mainly) CCD

SENSEI $1e^-$: likely dominated by Cherenkov & recombination

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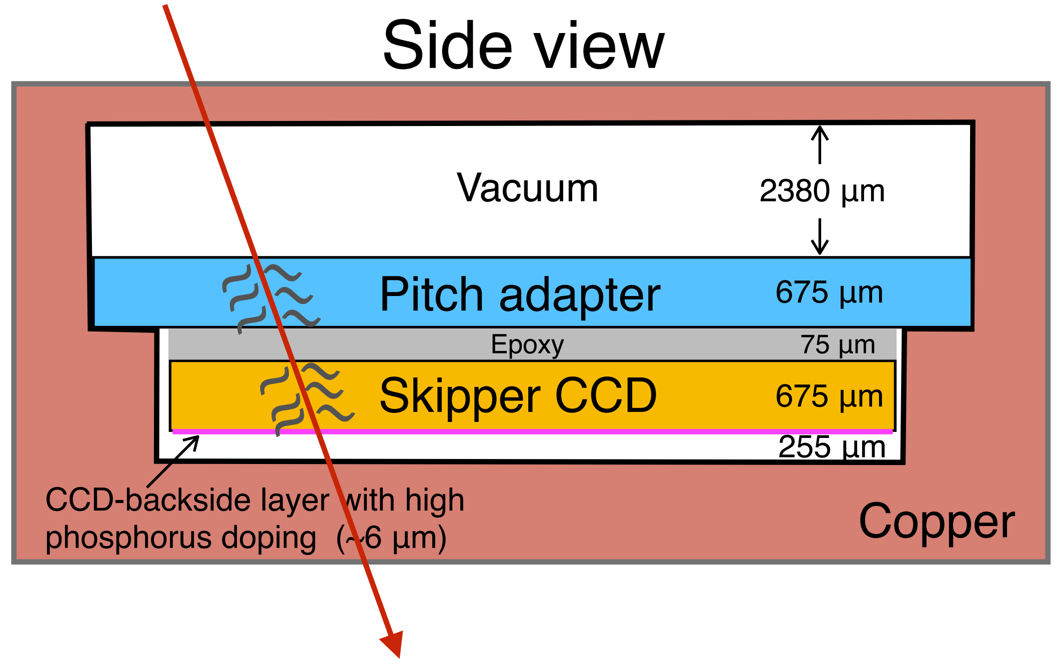
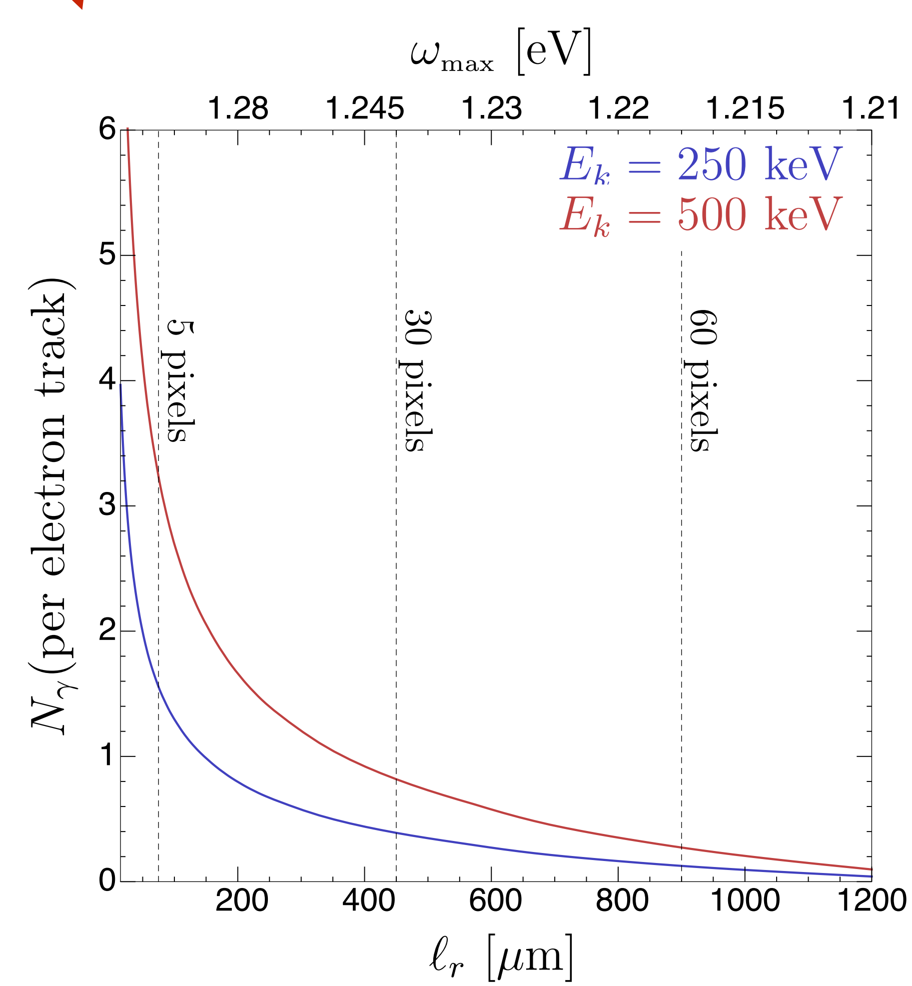
CCD module





- Cherenkov from tracks in (mainly) CCD
- Photons w/ energy closer to Si bandgap (~1.2 eV) travel further — explains correlation w/ high-energy tracks

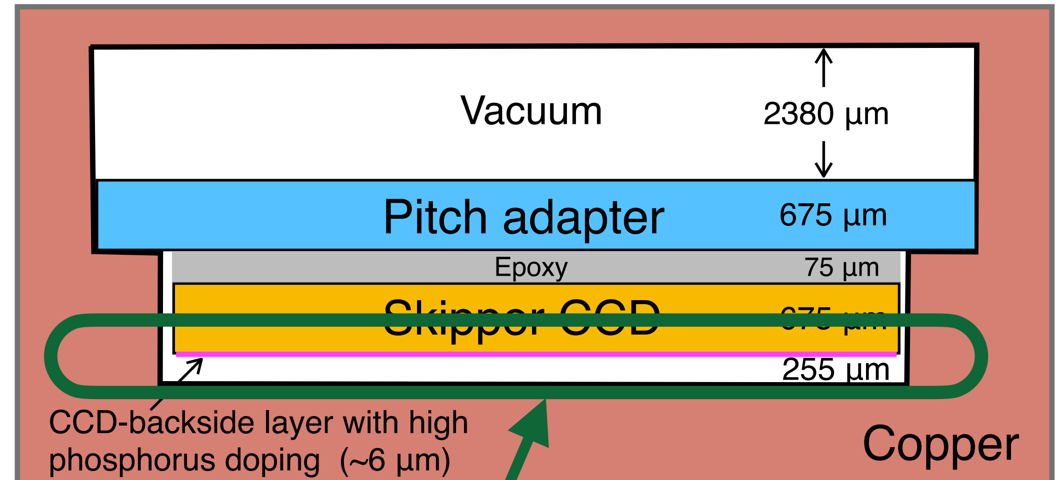
SENSEI $1e^-$: likely dominated by Cherenkov & recombination

Du, Egana-Ugrinovic, RE, Sholapurkar, 2011.13939

SENSEI, 2004.11378

CCD module

Side view



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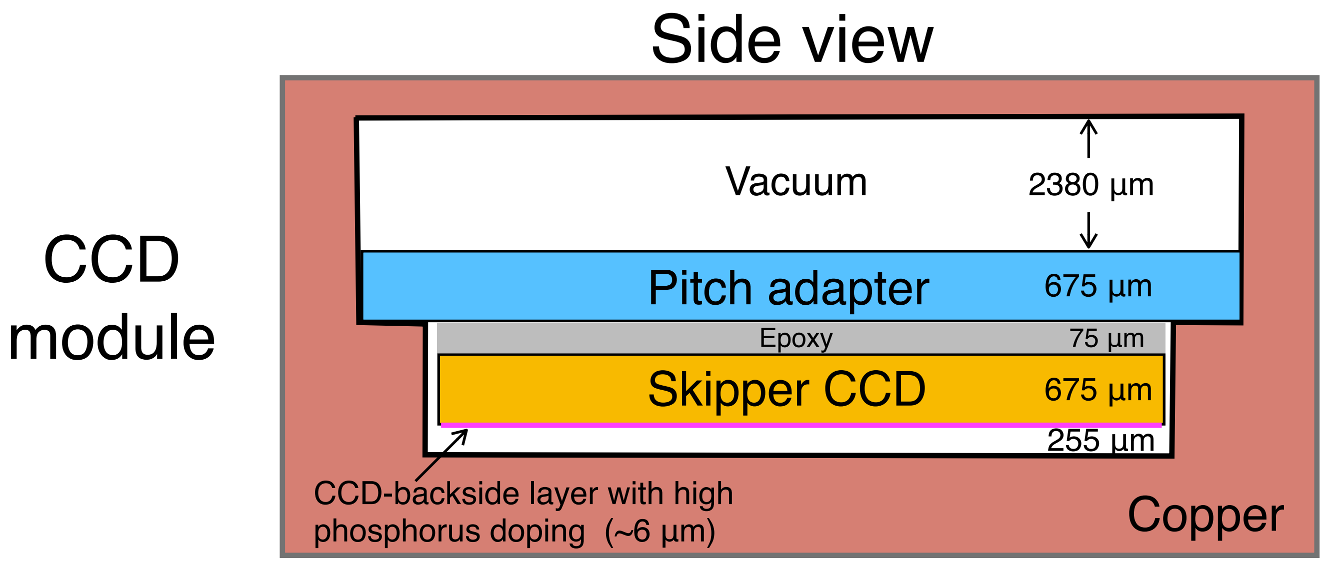

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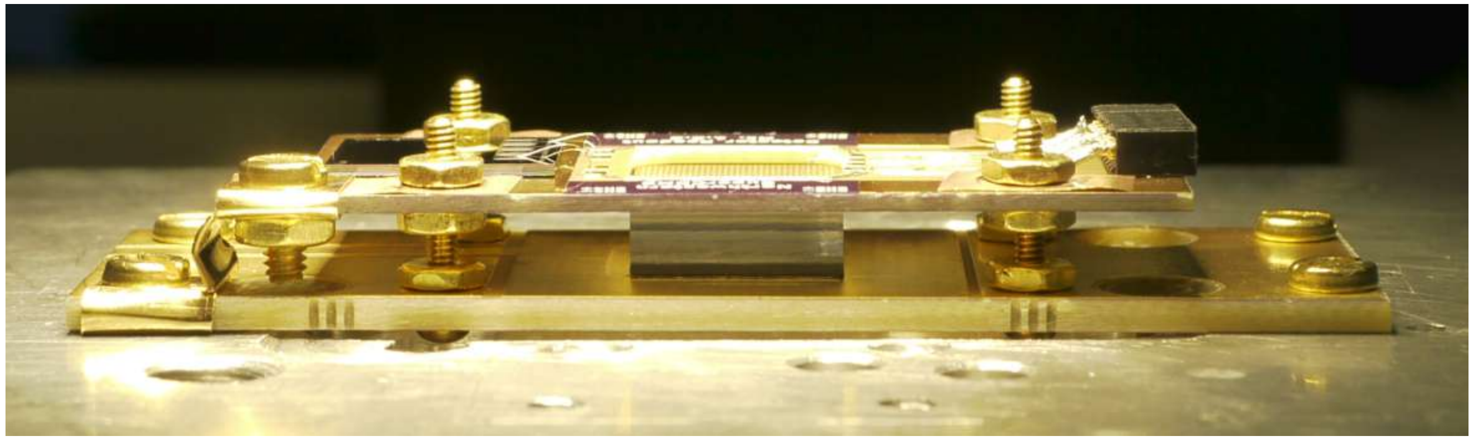
- detailed simulation is in progress

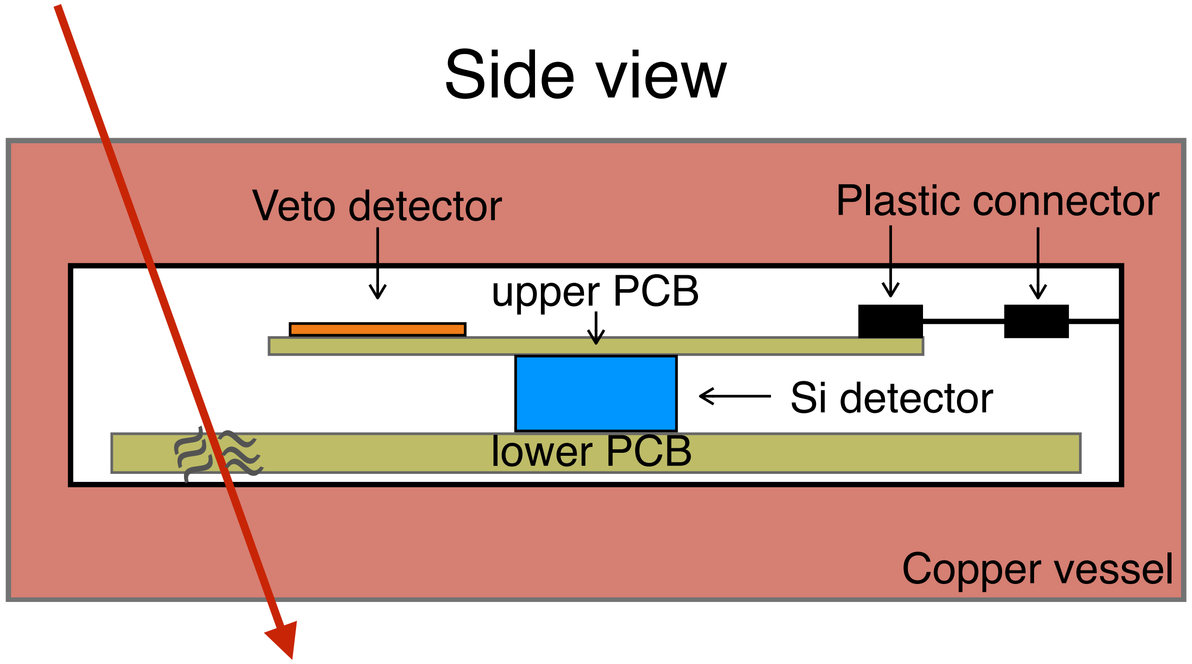
SuperCDMS $2e^-$ to $6e^-$ events: likely dominated by Cherenkov

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

SuperCDMS, 2005.14067



Side view



- Cherenkov from, e.g., "printed circuit board" ("PCB") produces *many* O(eV) photons

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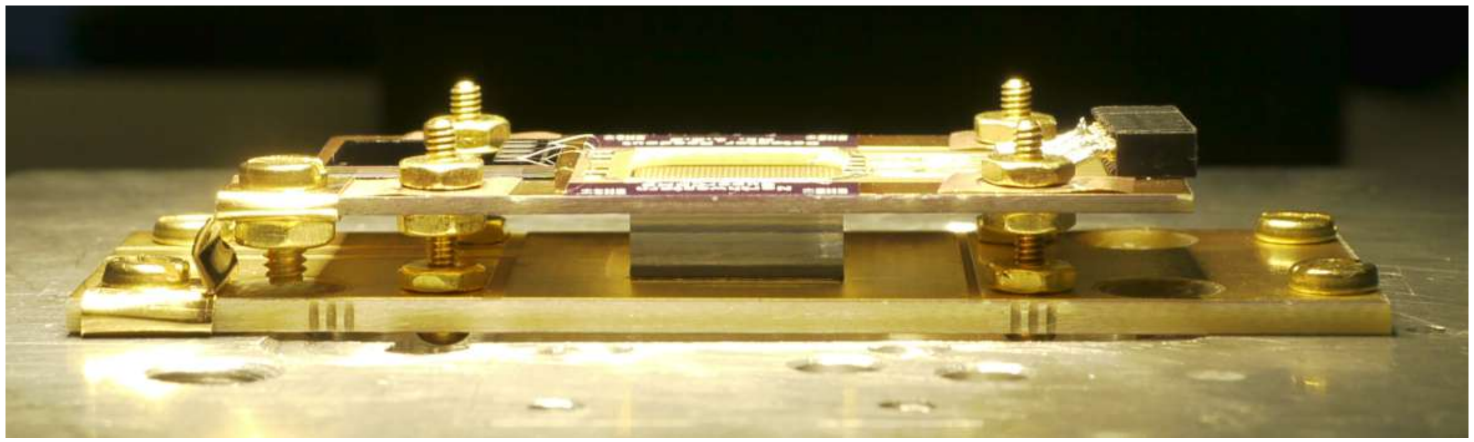

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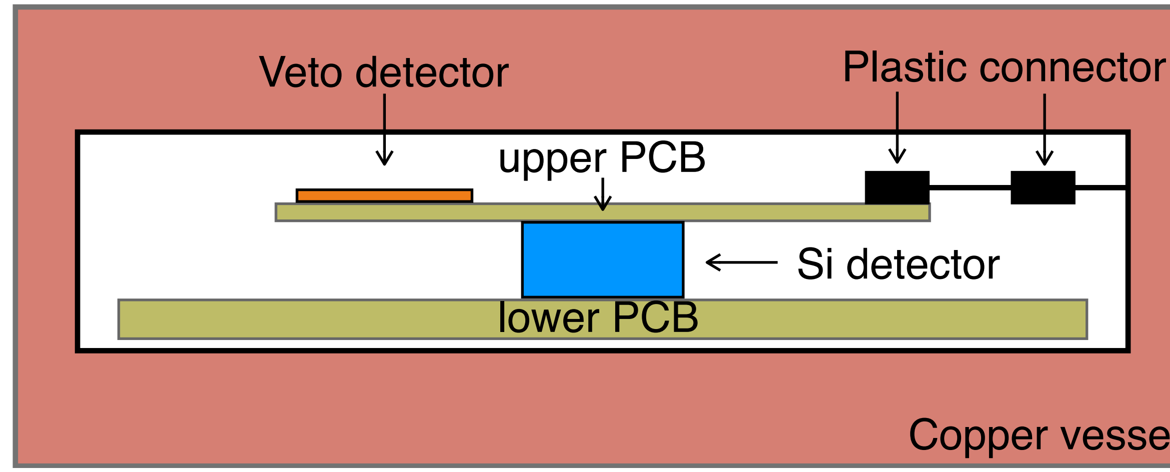
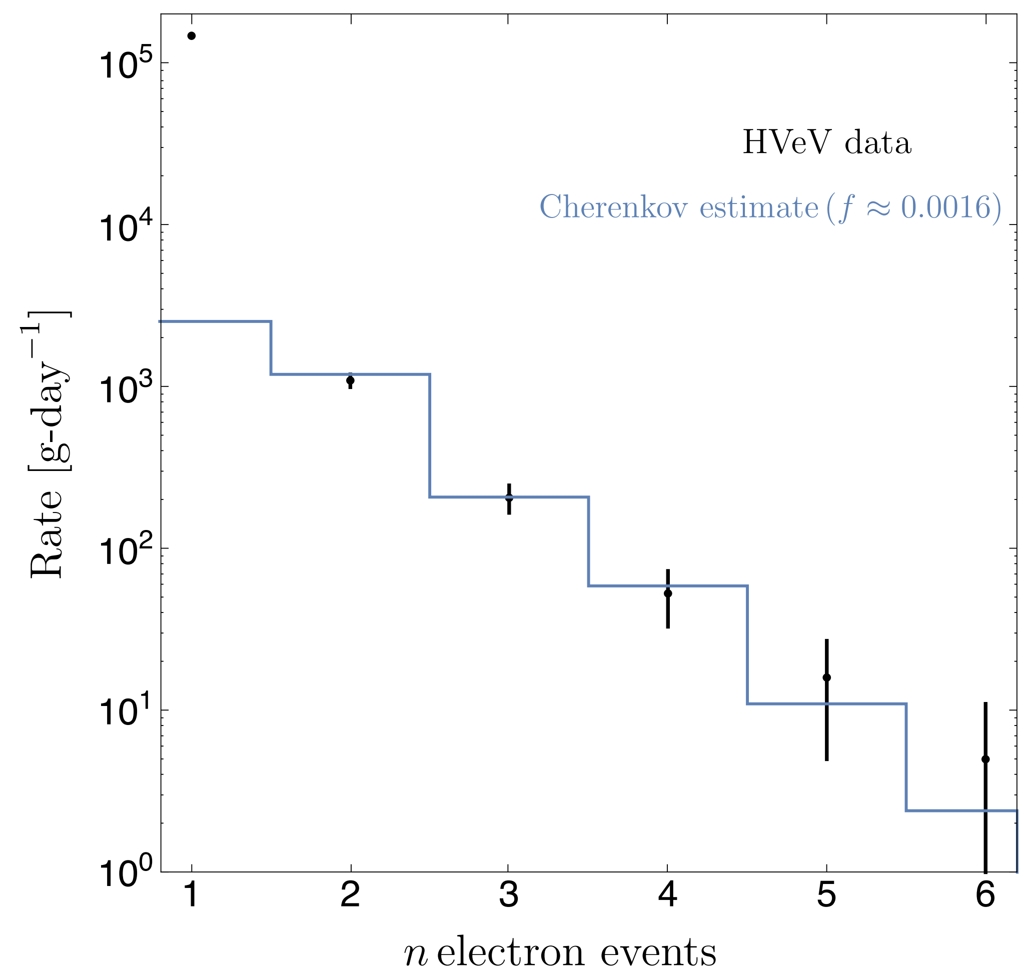


- Cherenkov from, e.g., "printed circuit board" ("PCB") produces *many* O(eV) photons

- 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…

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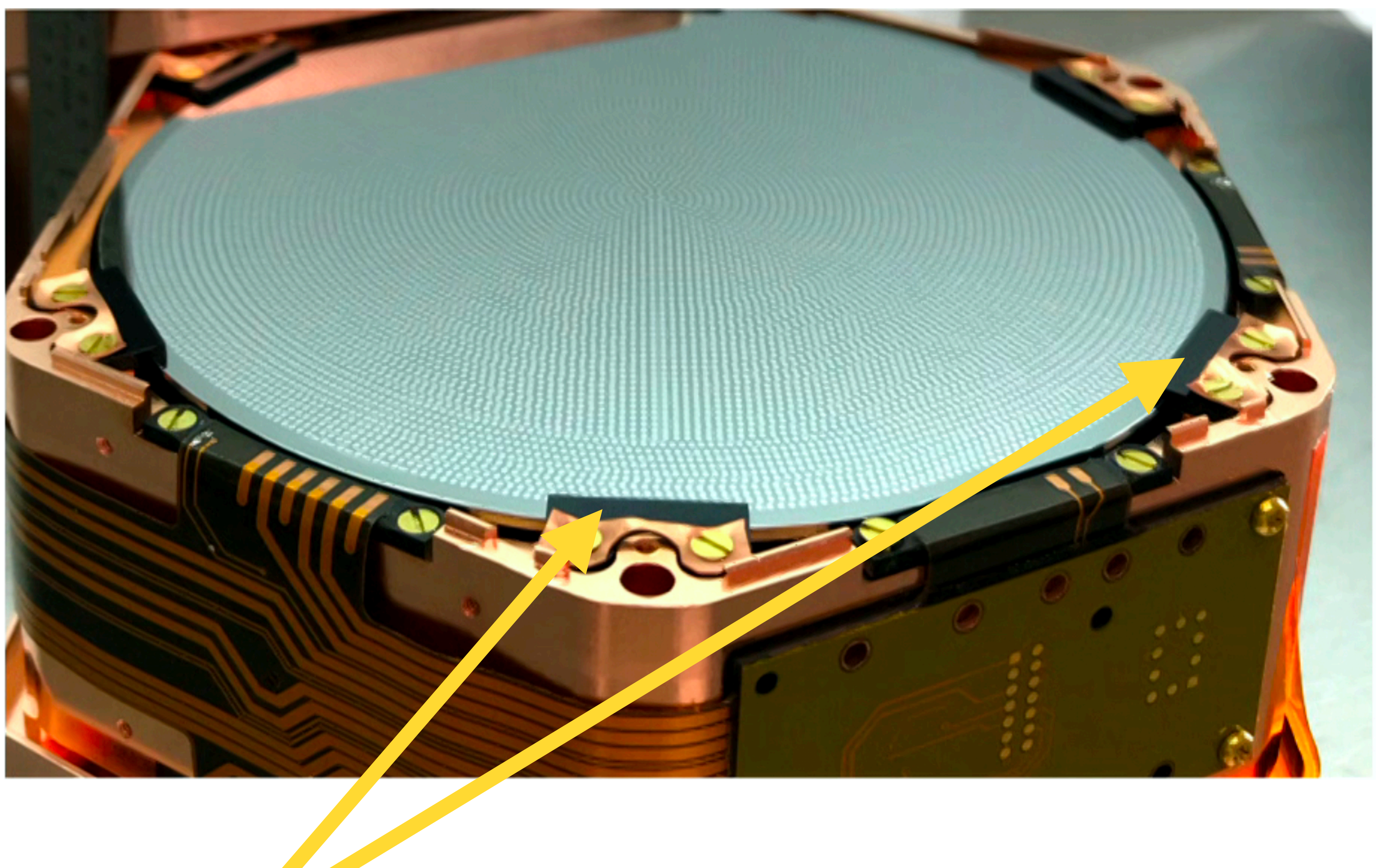

SuperCDMS SNOLAB detector

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

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- 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…
- Cherenkov/recombination will also produce sub-eV photons, which can be a background to proposed low-threshold phonon detectors
- 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)

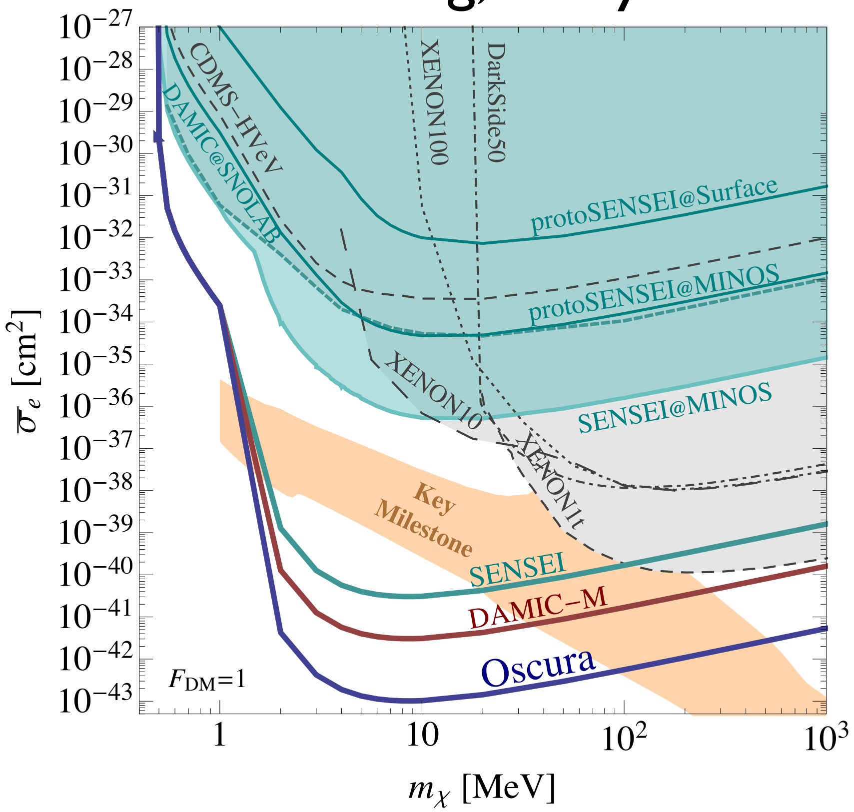
Summary

- Significant theory and experimental progress in direct detection of sub-GeV dark matter:
  - 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, with wide-ranging (<u>positive!</u>) implications

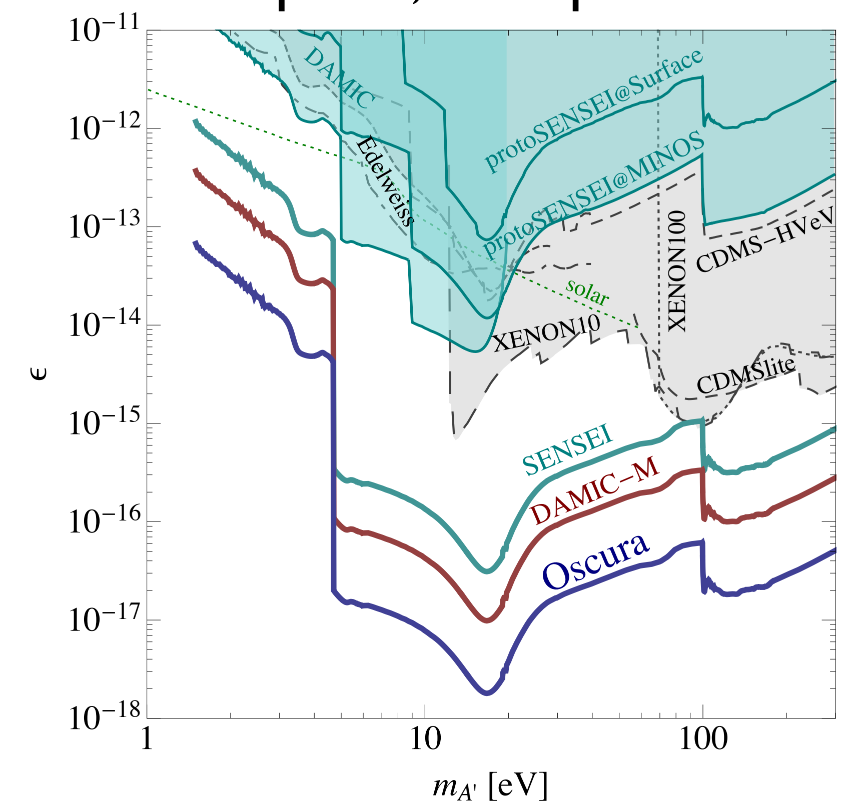
Backup

Projections for other models

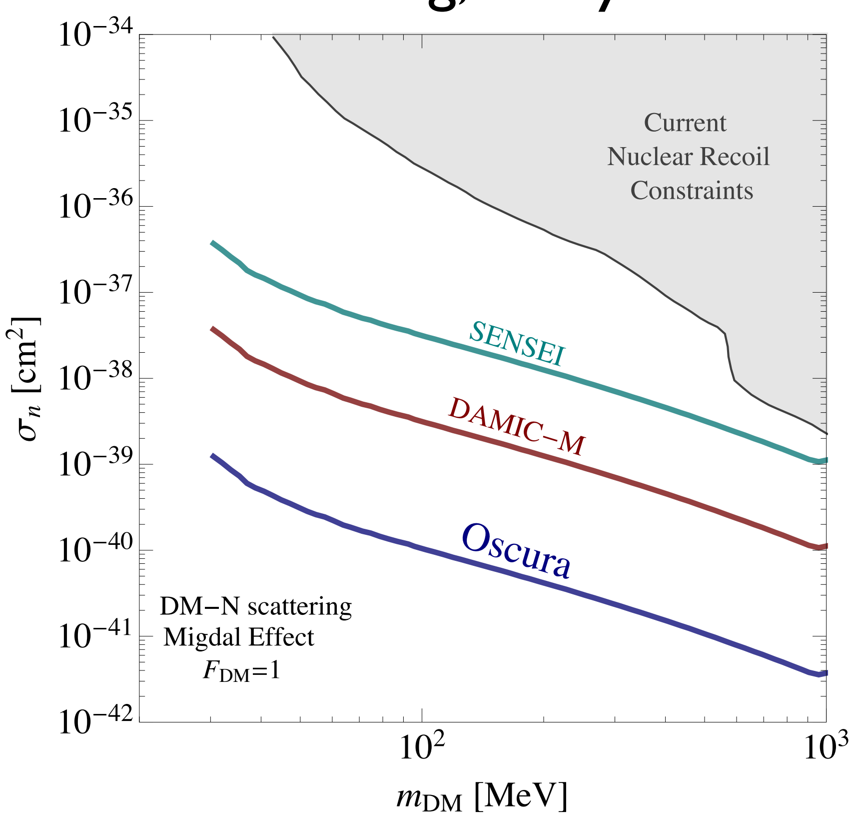
DM-e scattering, heavy mediator



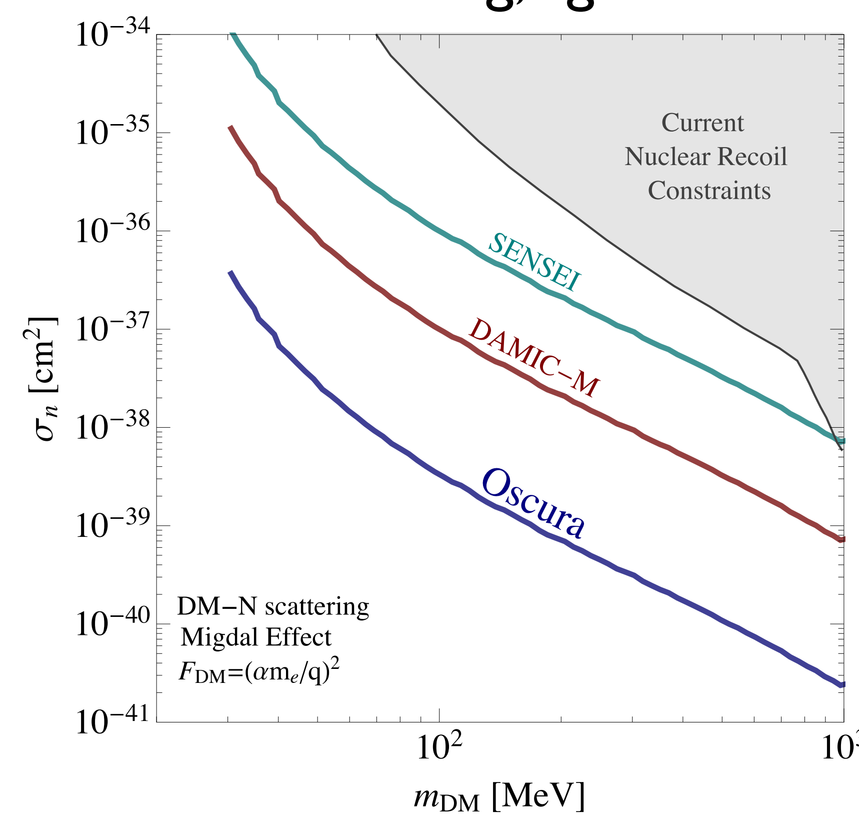
Absorption, dark photon DM



DM-N scattering, heavy mediator



DM-N scattering, light mediator



Mitigation Strategies

- passive shielding
- active shielding
- multiple sensors to veto coincident events
- minimize auxiliary dielectric materials
- thin CCD backside
- coat walls to absorb photons
- measure material properties, simulate, & subtract backgrounds