Detection of *Light* Particle Dark Matter

semiconductors and novel ideas

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QSFP school

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Overview

Introduction in lecture 1

Noble liquids in lecture 2

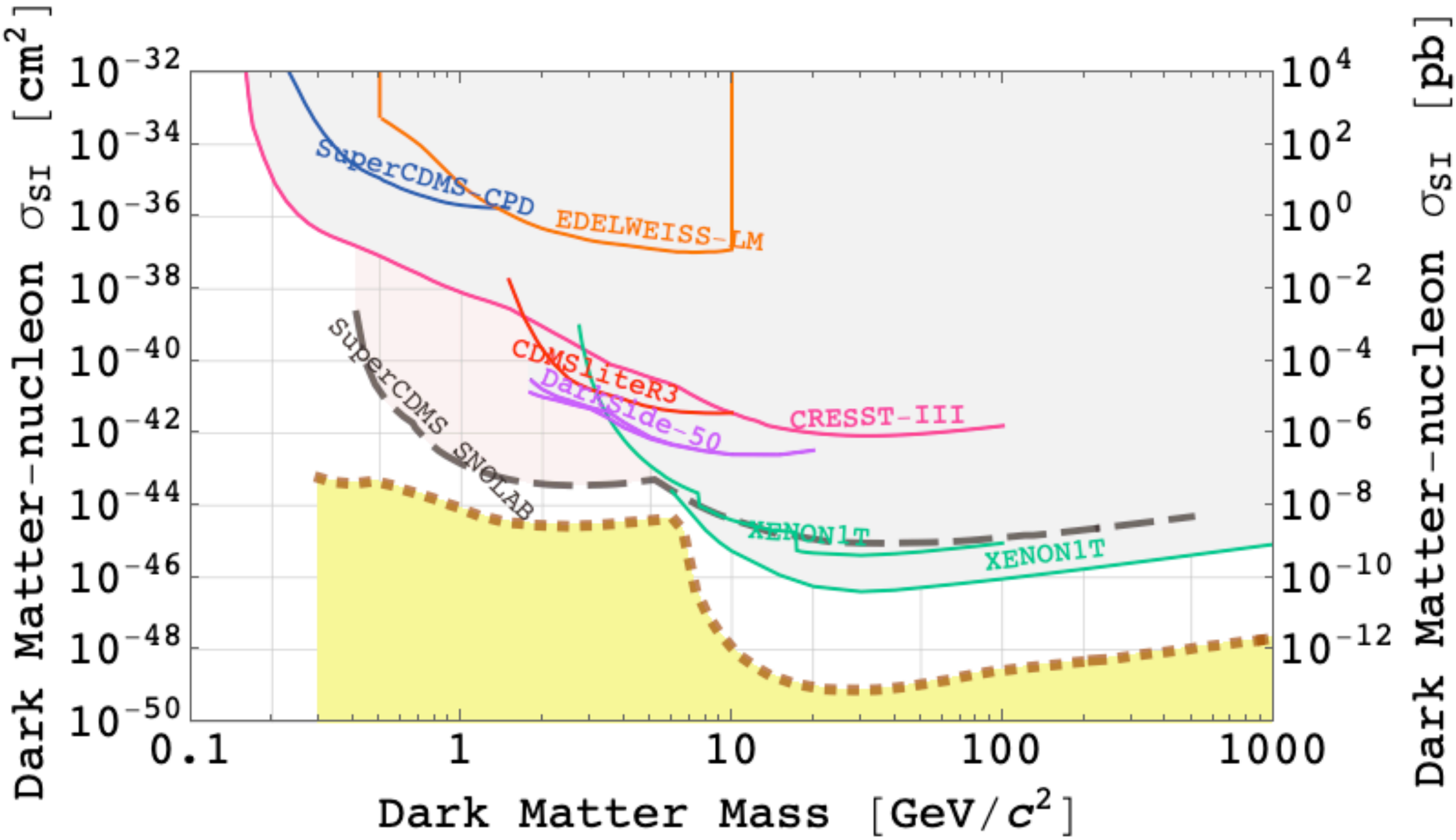
Plan for today:

- brief review of searches in semi-conductors
  SuperCDMS, DAMIC, SENSEI
- Novel ideas
  SiPMs, semi-conductors, super-conductors, super-fluids

References:

- SuperCDMS
- DAMIC-M
- SENSEI
-

Experimental status: 0.1 - 1 GeV



SuperCDMS at SNOLAB

These detectors consist of cylindrical crystals, 100mm in diameter and 33.3mm thick. Each Ge(Si) crystal has a mass of 1.39(0.61) kg.

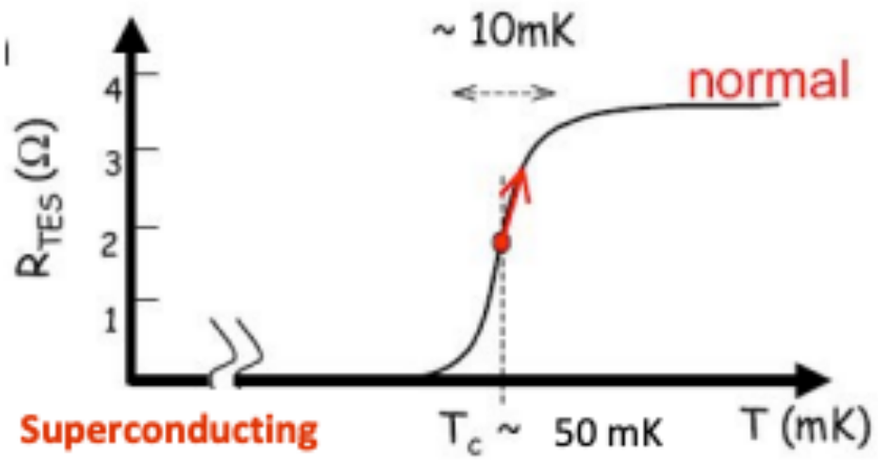
Two detector designs: HV / iZIP.

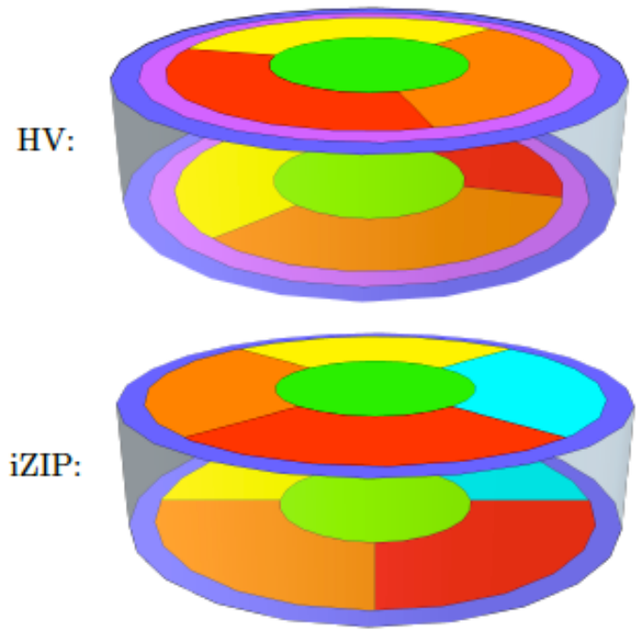
iZIP: interleaved Z-sensitive Ionization Phonon
+ ionization charge AND phonons —> NR/ER discrimination!
+ field configuration to reject surface events
==> nearly background-free

HV: high voltage (100 V), only phonons:
+ amplification by Neganov-Luke effect
==> better energy resolution
==> sensitivity to lower energy energy deposits

operated at 15-30 mK

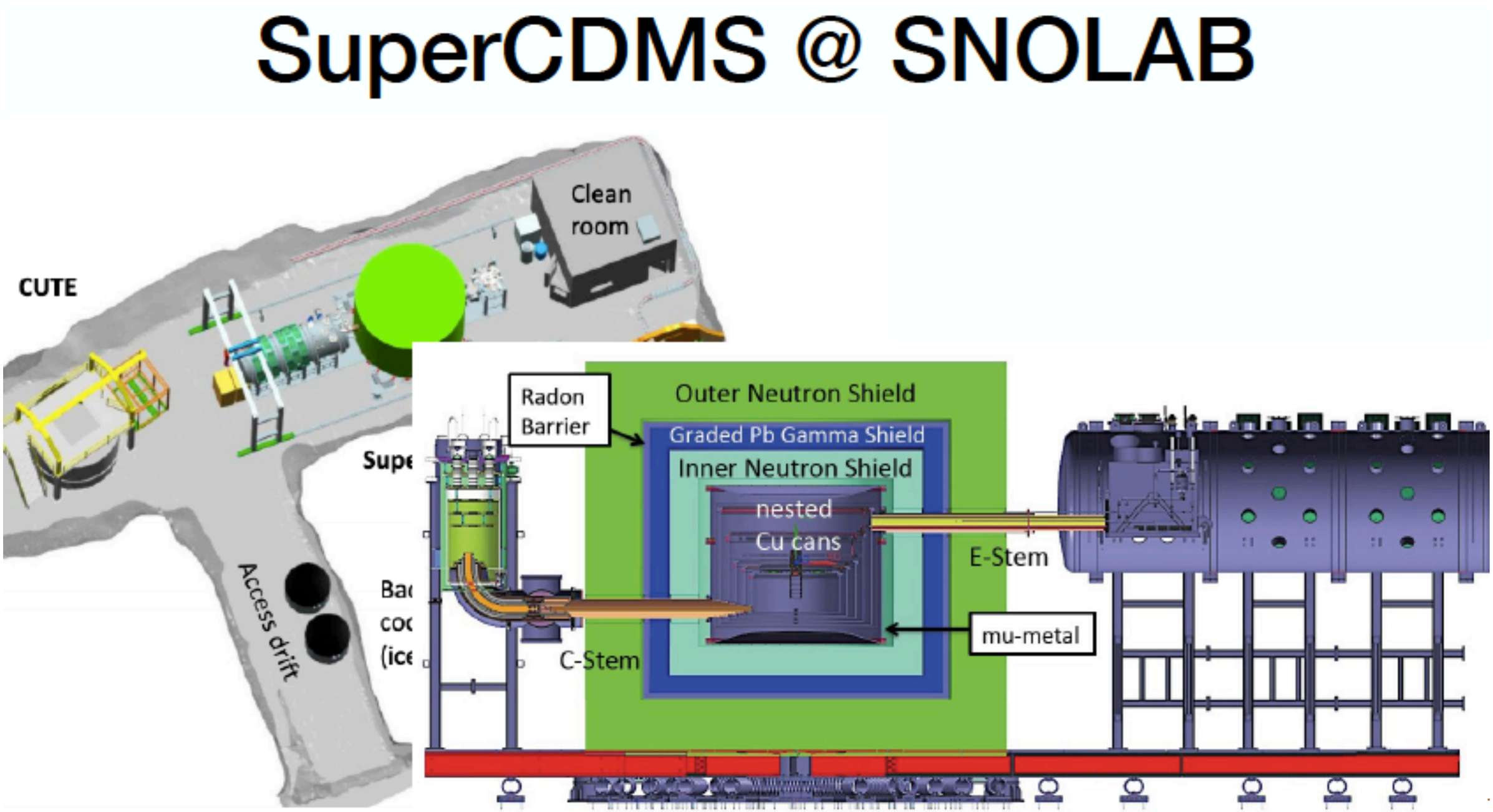
Phonons readout with TES:





https://arxiv.org/pdf/1610.00006.pdf

Installation site

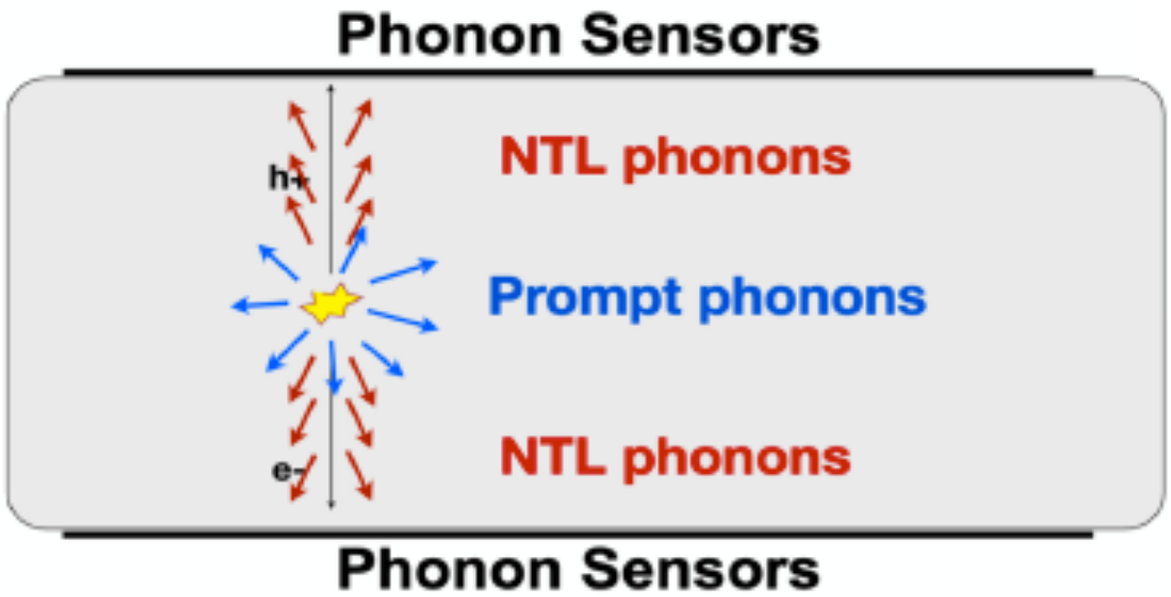


Luke-Naganov effect

==> phonons are produced when charges are drifted in an electric field

$$E_{phonon} = E_{recoil} + V * n_{eh}$$
$$= E_{recoil}\left[1 + V * \left(\frac{y(E_{recoil})}{\varepsilon_{eh}}\right)\right]$$

ε_{eh} ~ few eV



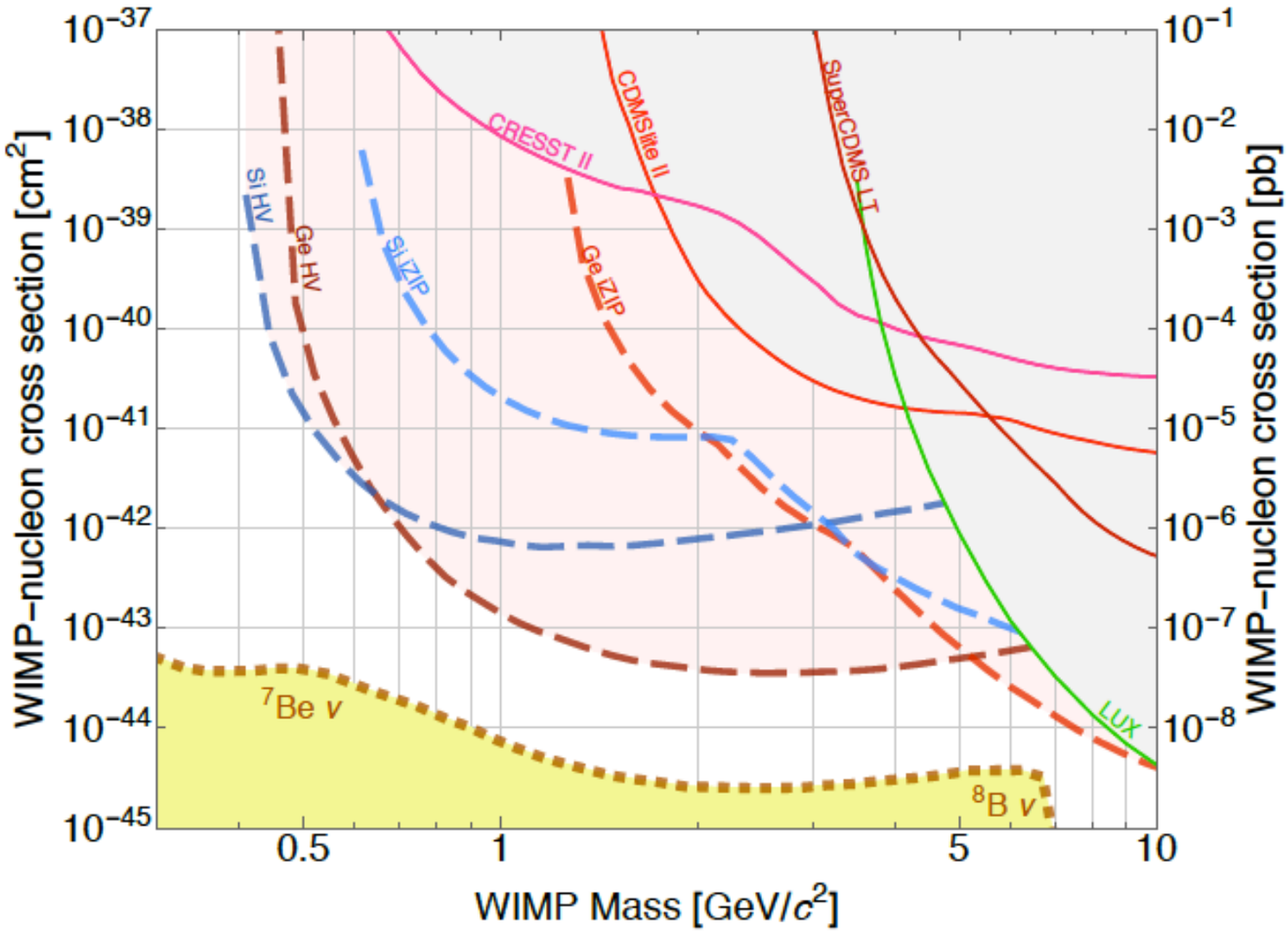
P. N. Luke, J. Appl. Phys. 64, 6858 (1988).
B. S. Neganov and V. N. Trofimov, Otkryt. Izobret. 146, 215 (1985).

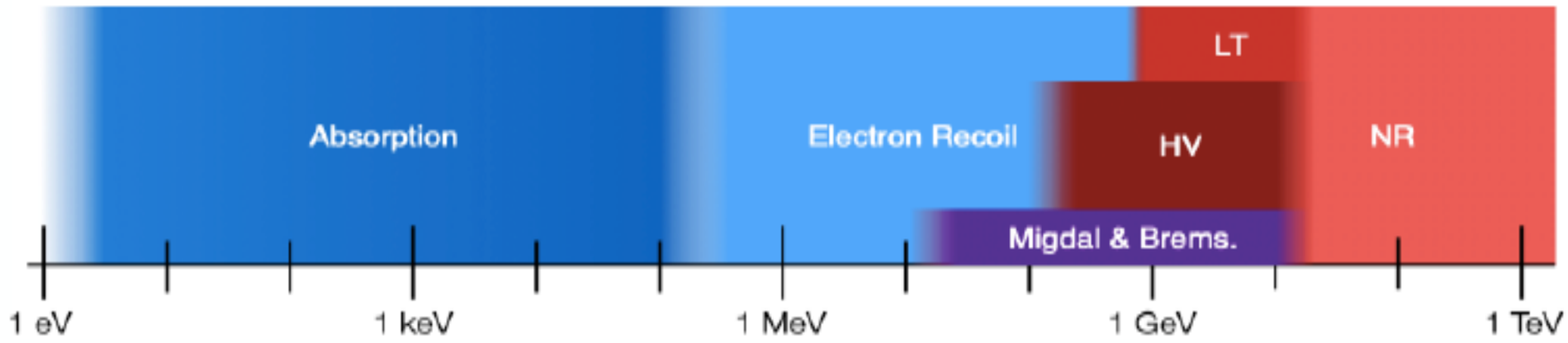
Thresholds and Backgrounds

Detector	$7\sigma_{Ph}$ (eV)	$e\Delta V$ (eV)	Analysis threshold (eV) E_{Ph}	E_{nr}
Si HV	35	100	100	78
Ge HV	70	100	100	40
Si iZIP	175	8	175	166
Ge iZIP	350	6	350	272

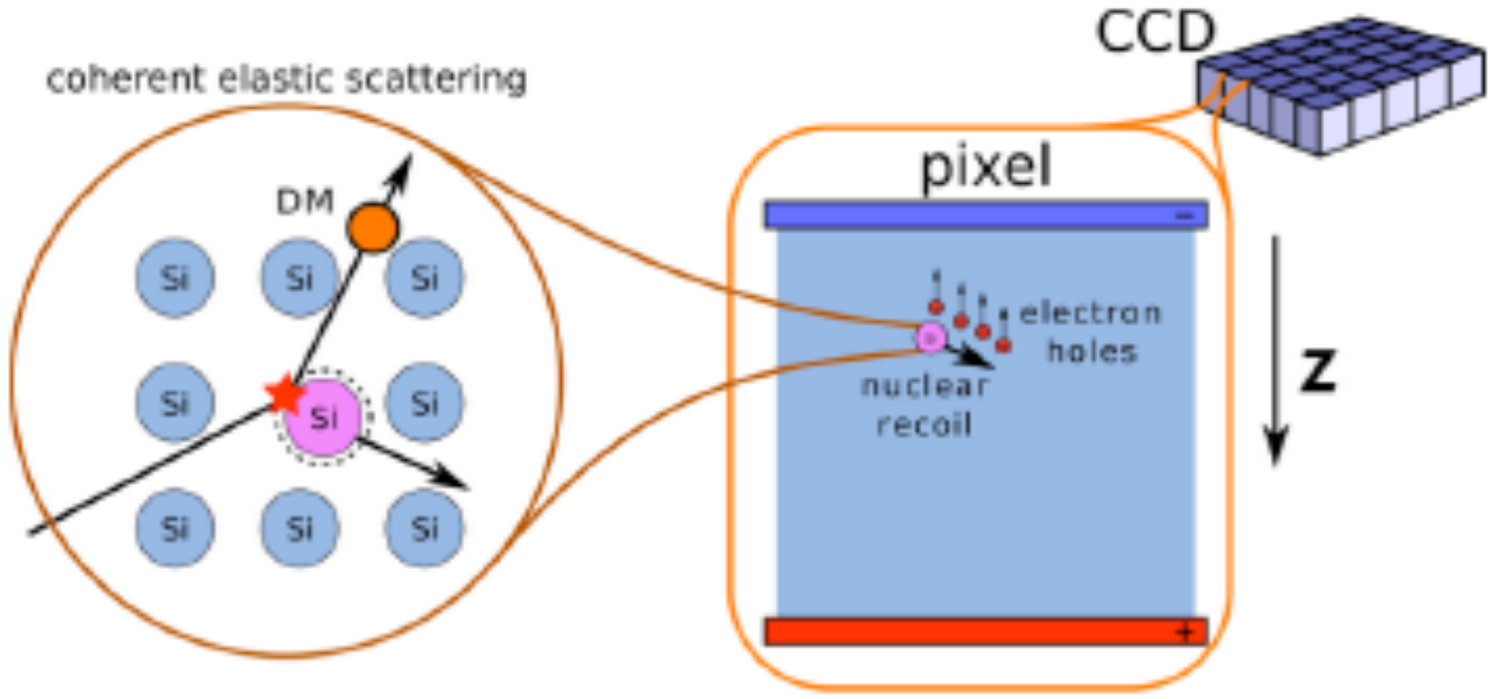
Total bg
Electron recoils (γ-rays, ^{3}H, ^{32}Si)
Surface β's
Surface α's
neutrons
neutrinos

DM - nucleon and complementary searches

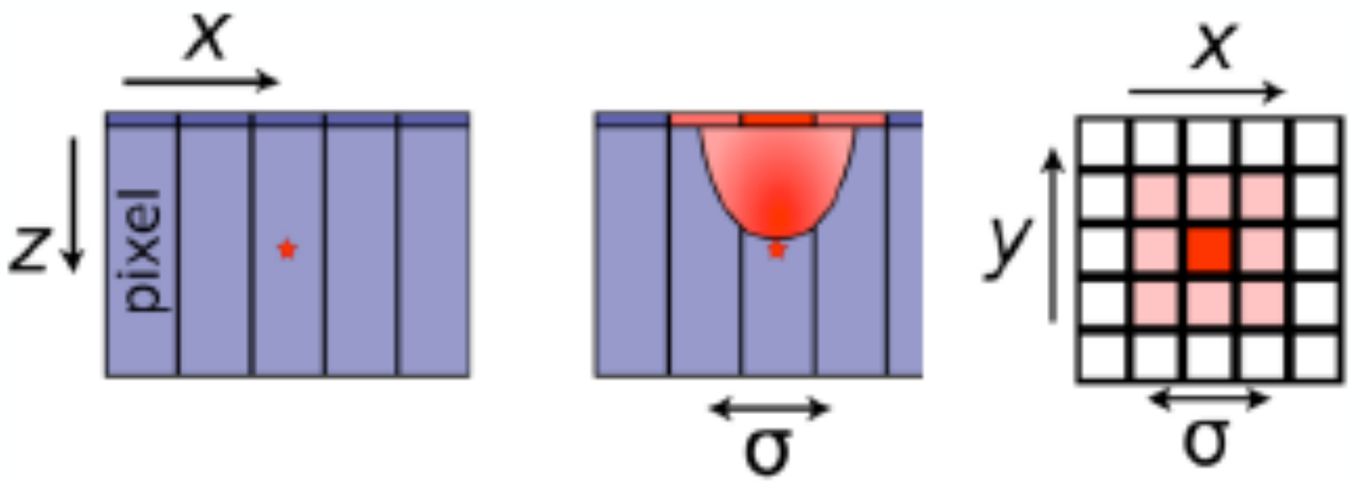




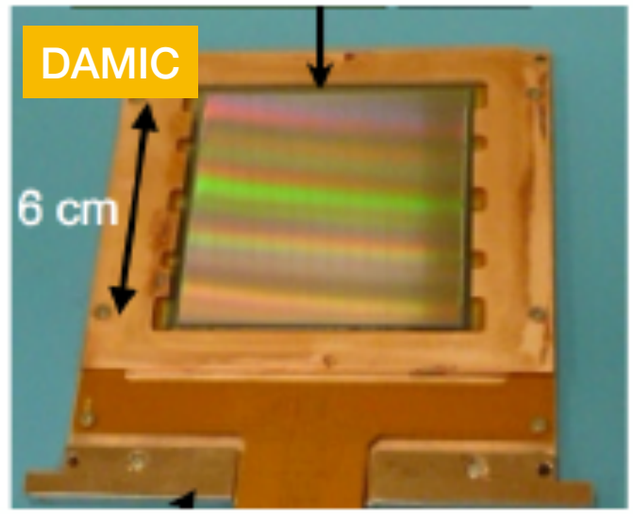
DAMIC - SENSEI



3.7 eV to create e-h pair



Charge-Coupled Device (CCD)

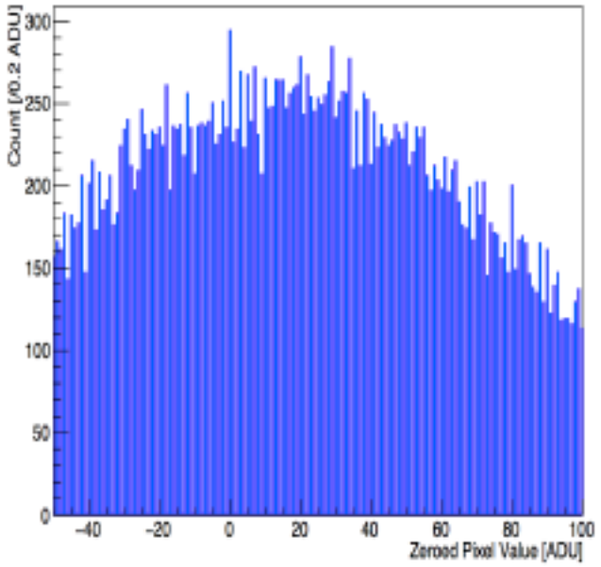


16 Mpix, 15 μm x15 μm,
675 μm thick, 5.9 g mass

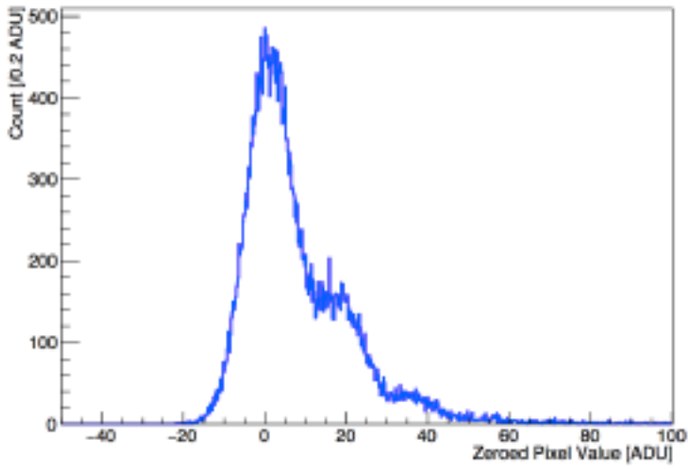
675 m thick, 1.59 x 9.42 cm^2, 2 g active

Skipper CCD

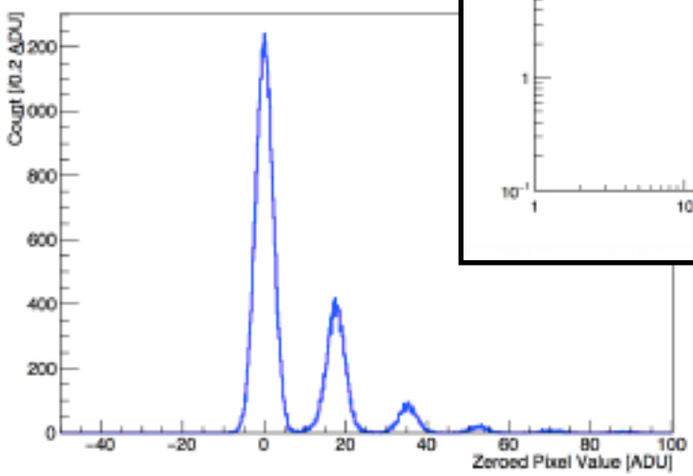
Enabling very low readout noise levels. Readout time ~ hr



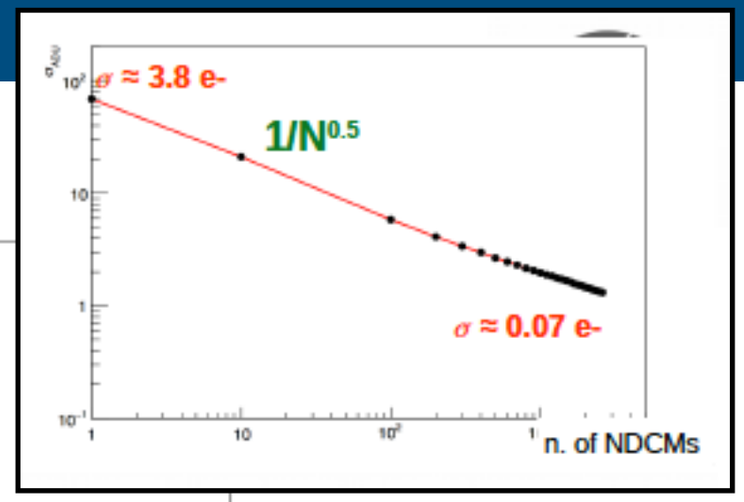
1 Non Destructive Charge Measurement

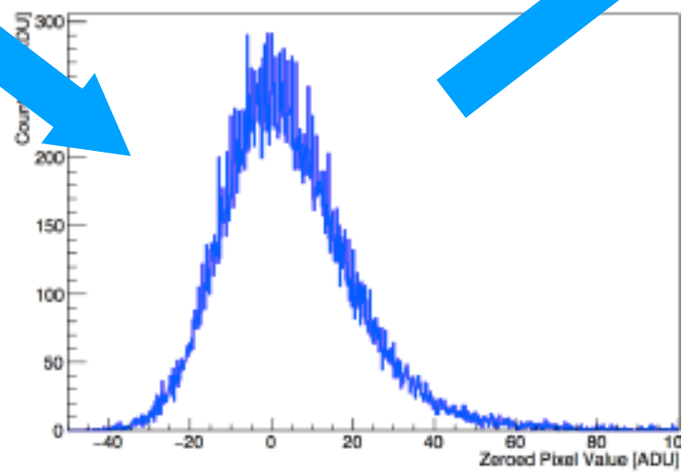


100 Non Destructive Charge Measurement

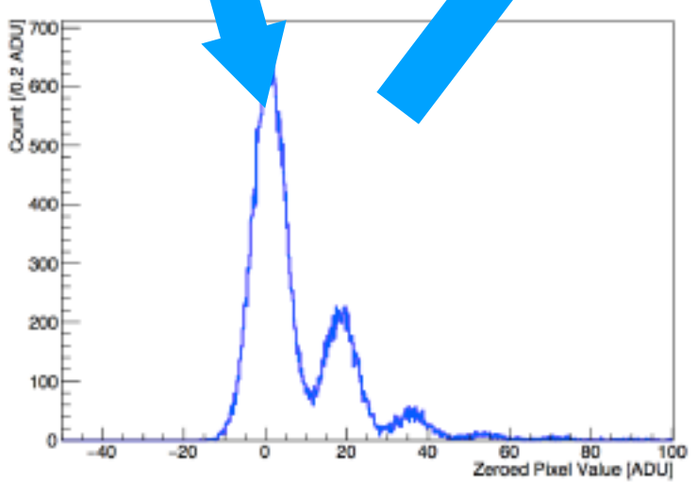


800 Non Destructive Charge Measurement

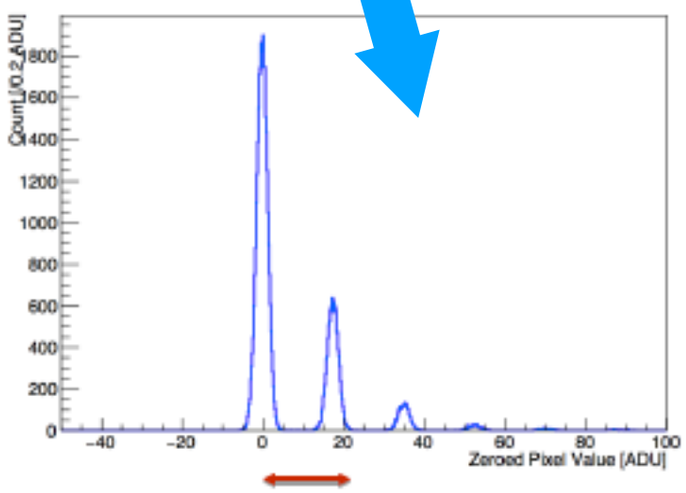




25 Non Destructive Charge Measurement



200 Non Destructive Charge Measurement



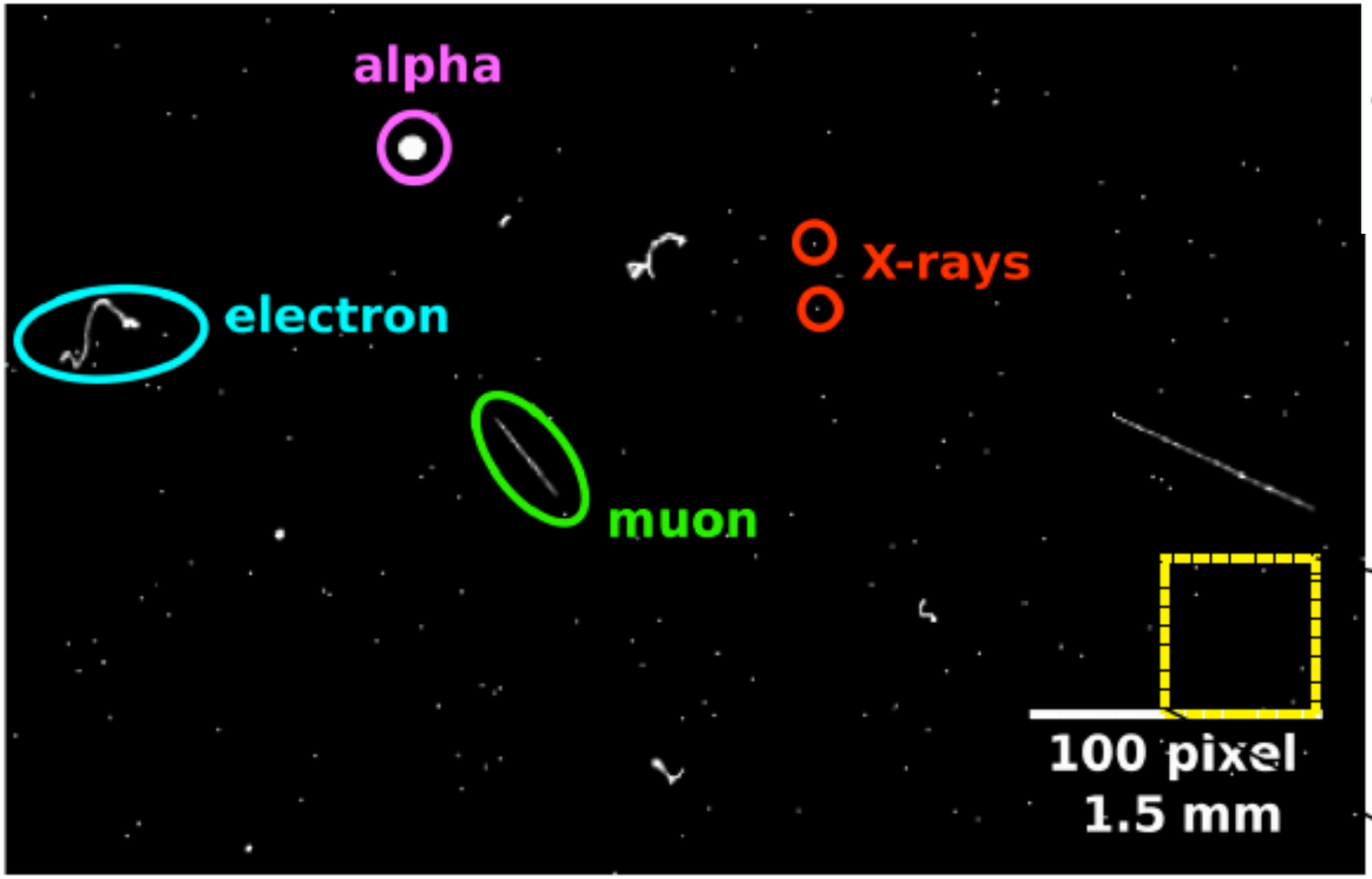
1 e- = 17.3 ADU
Direct calibration of ADU to charge (^{57}Co)

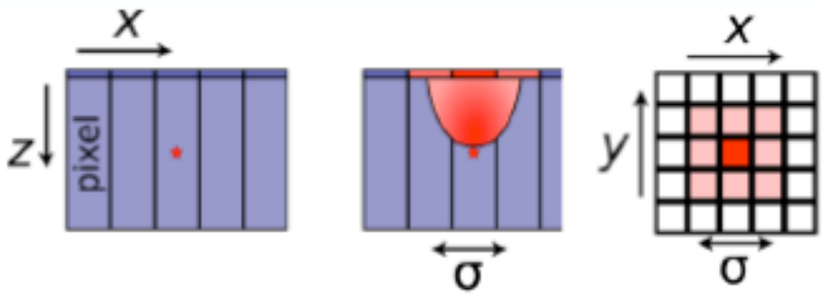
2500 Non Destructive Charge Measurement

https://www.spiedigitallibrary.org/conference-proceedings-of-spie/1242/0000/New-advancements-in-charge-coupled-device-technology--subelectron-noise/10.1117/12.19452.short?SSO=1

Event topology

Long exposures: 8 to 20 hrs. No event timing information





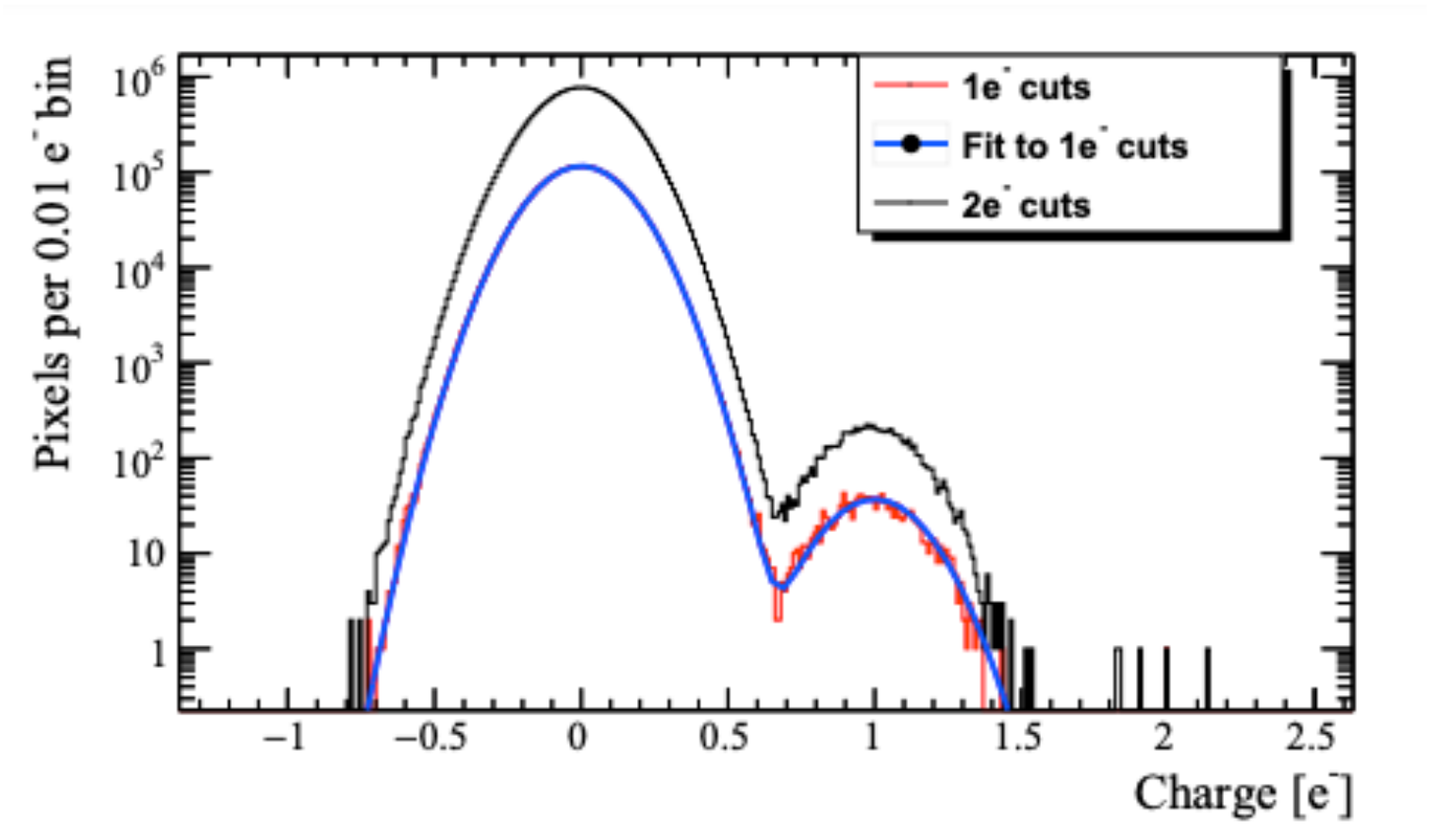
Background rates - low energy

https://arxiv.org/pdf/2004.11378.pdf

Rate of single electrons (spurious charge: charge generated during readout Intrinsic dark current: charge generated during exposure by thermal excitation):

after readout component subtraction: **1.59(16) 10^{-4} $e_{?}$/pixel/day**

10x larger than what expected from thermal dark counts



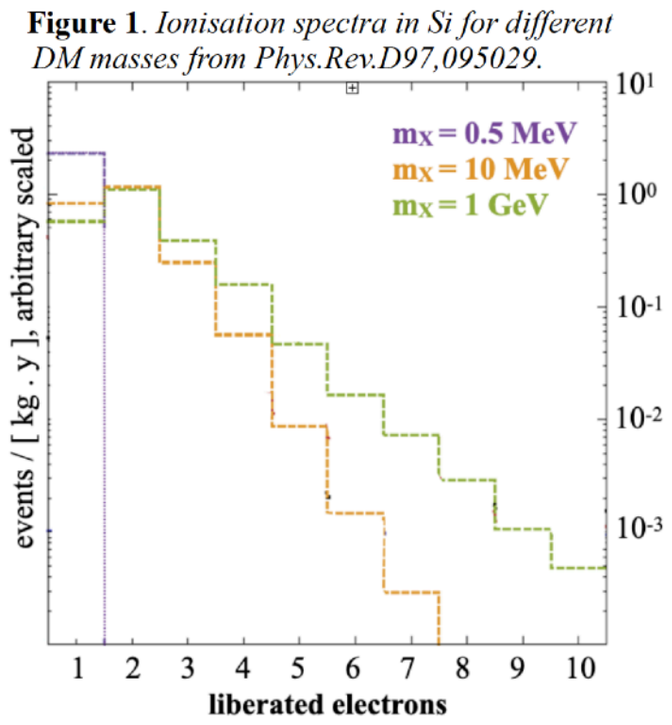


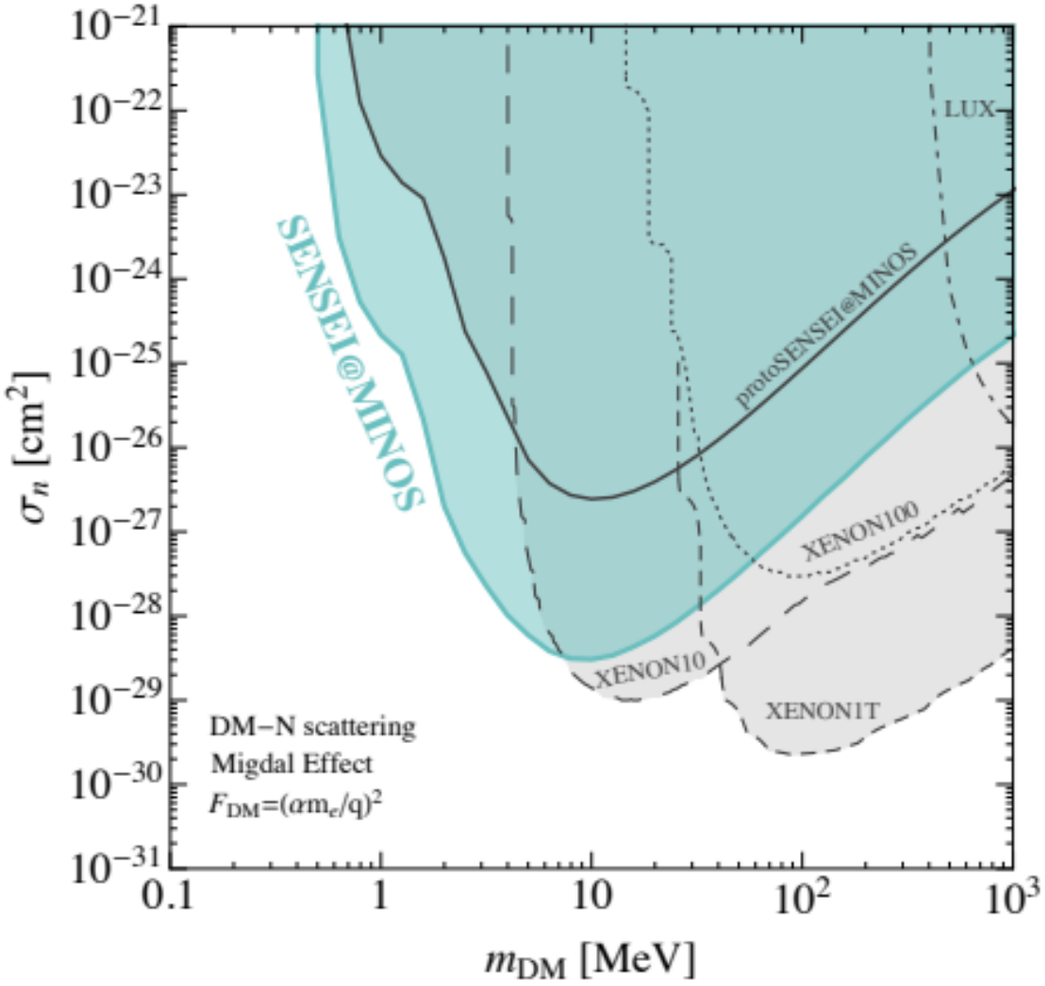
Figure 1. *Ionisation spectra in Si for different DM masses from Phys.Rev.D97,095029.*

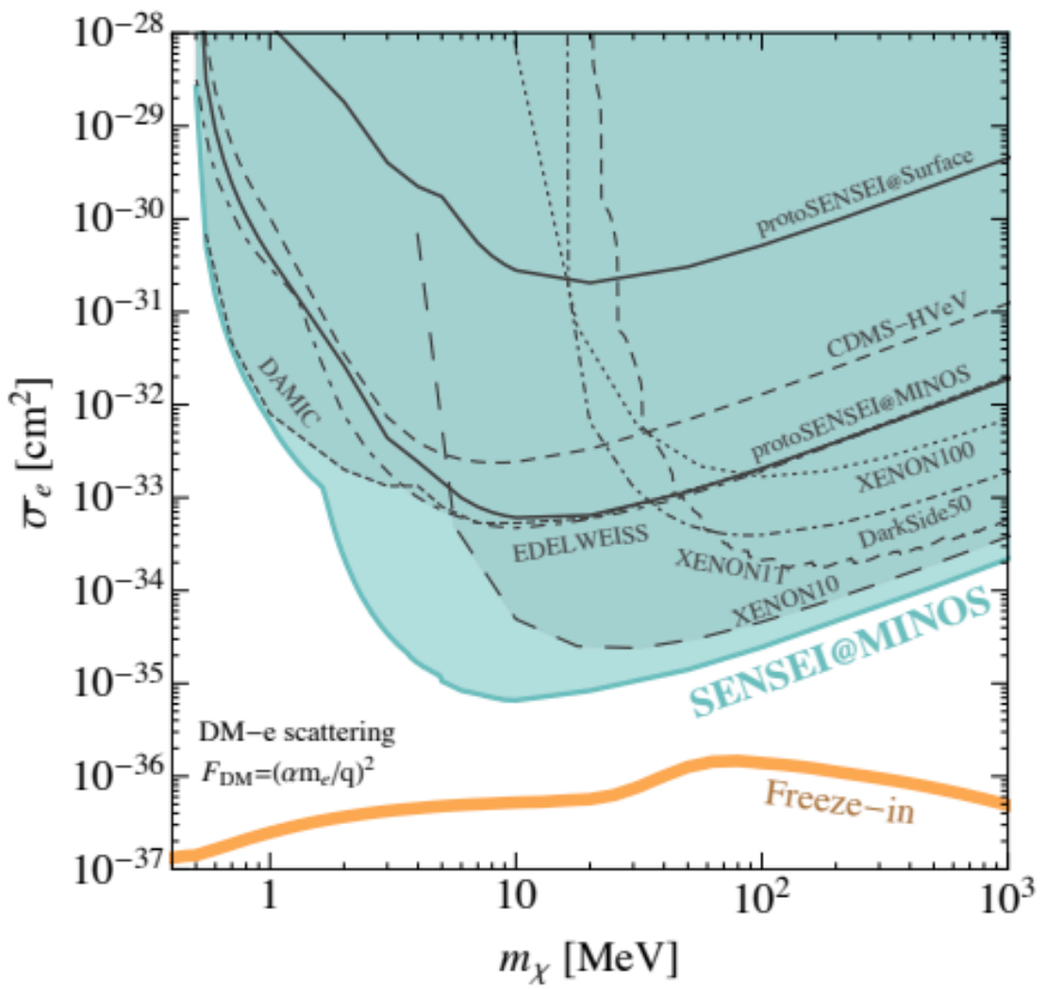
What dominates the single electron bg? — 3x reduction with Pb shield

Cerenkov radiation in neighbouring materials? https://arxiv.org/pdf/2011.13939.pdf

Exclusion and Projections

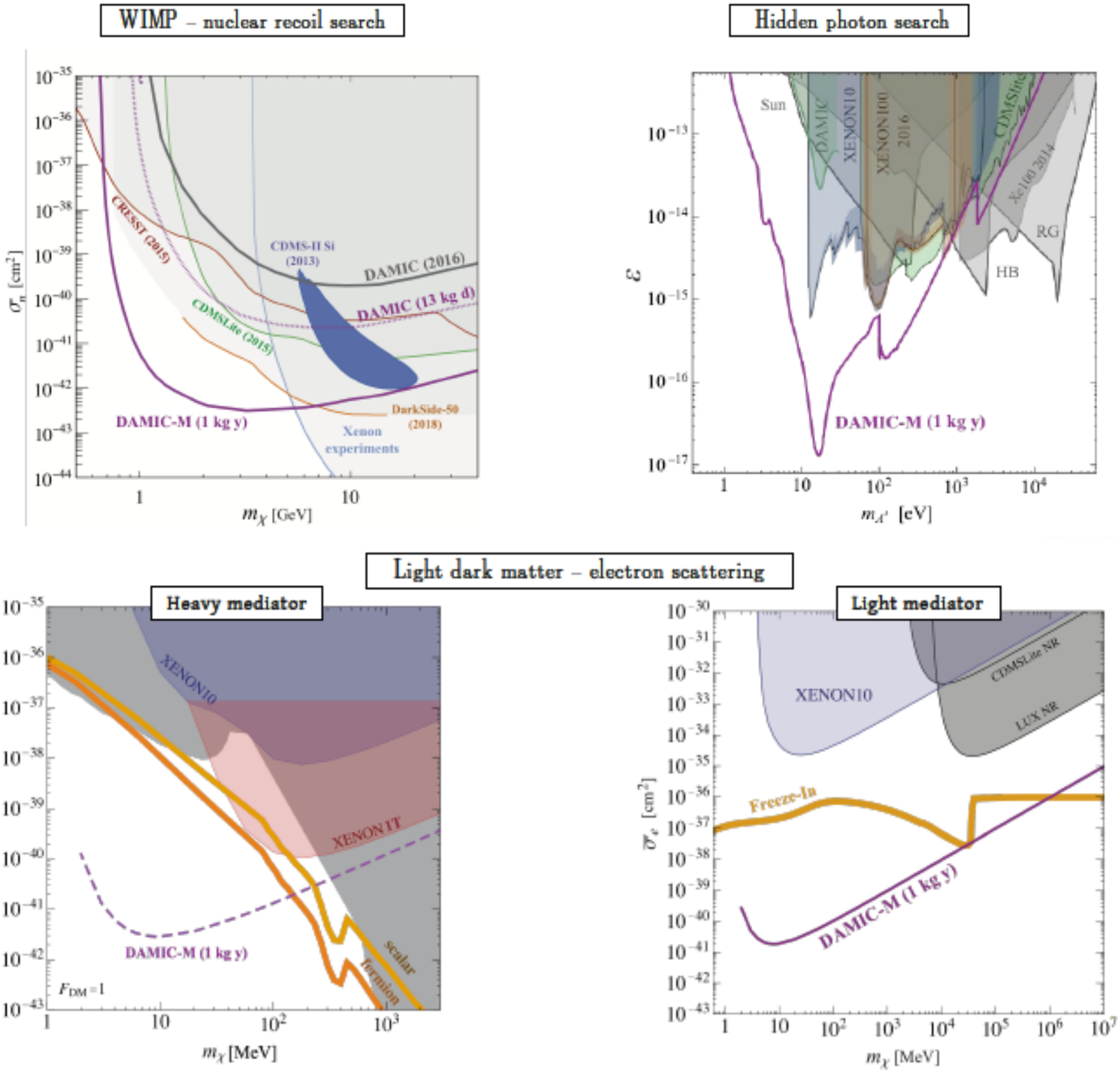
https://arxiv.org/pdf/2004.11378.pdf





50 g day exposure

Exclusion and Projections



Future developments

Lower DM candidates require:

low threshold

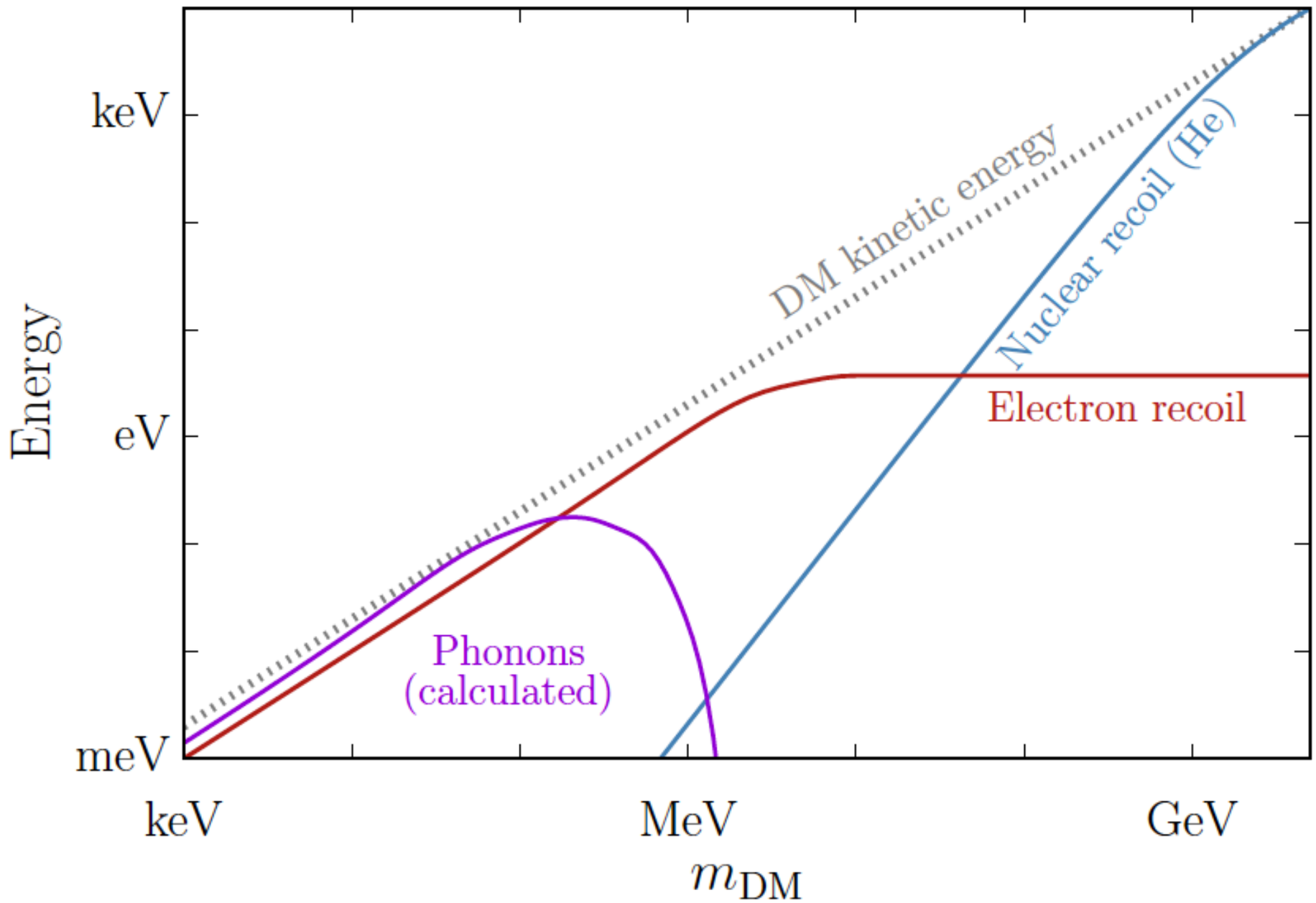
low readout noise

What WE need:

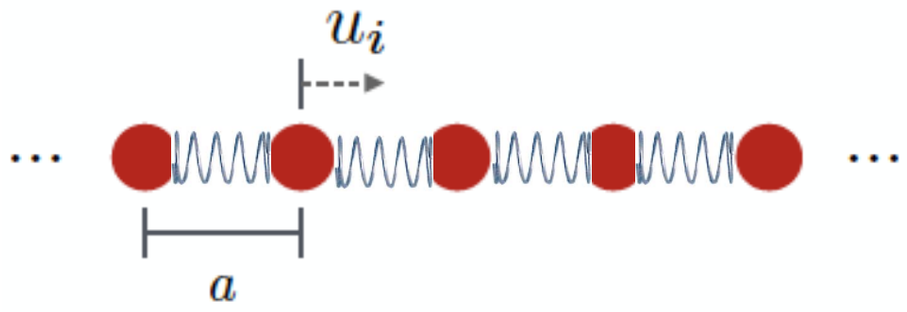
New ideas for feasible detector technology

calibration

backgrounds !


keV
eV
meV
Energy
DM kinetic energy
Nuclear recoil (He)
Electron recoil
Phonons
(calculated)
keV
MeV
GeV
m_{DM}

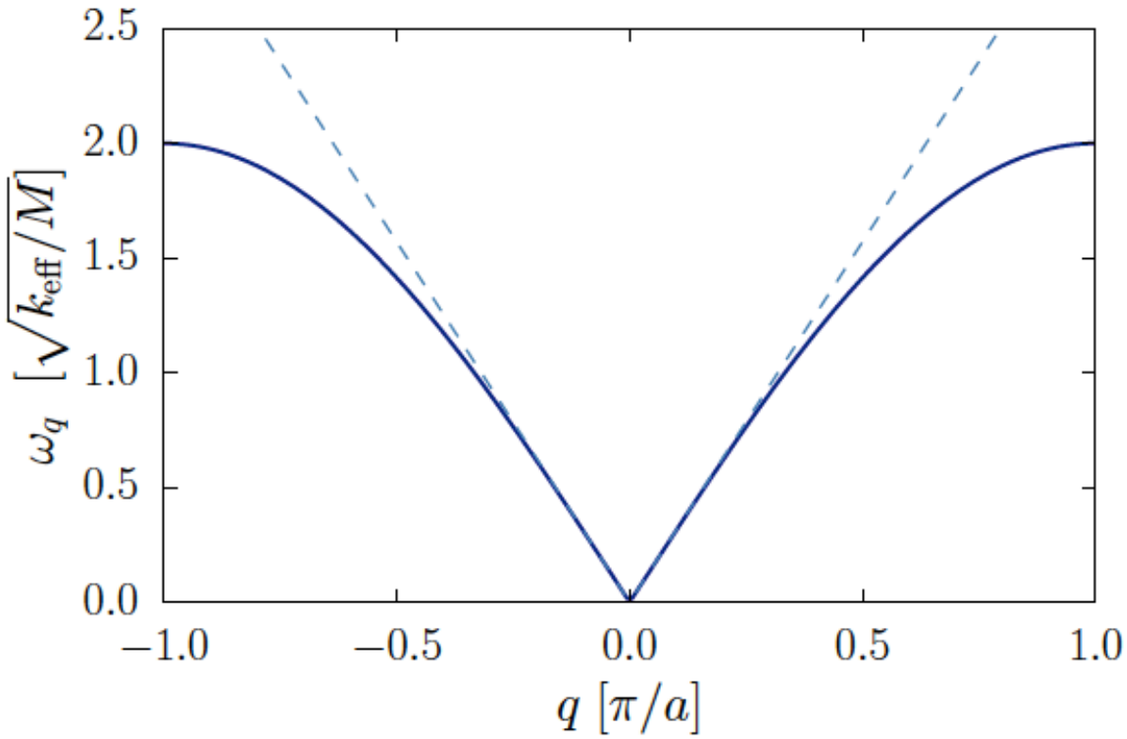
Single phonon detection



a = inter-atom distance
~ 10^{-10} m
~ 10^5 eV

u_i : displacement

For ~MeV DM:
Edep ~ 0.1 eV
=> q << 1



q = amplitude of wave vector

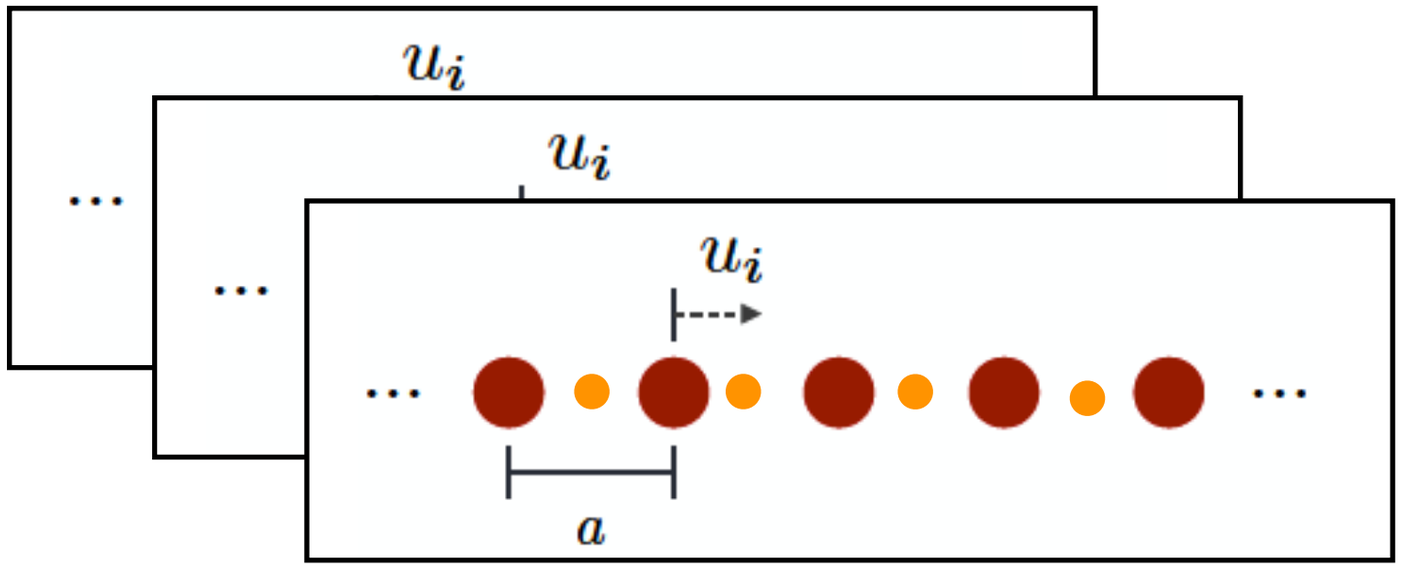
q ~ 0 : low frequency oscillations
q ~ π/a : perfectly out of phase

ω_q : energy of the vibration mode

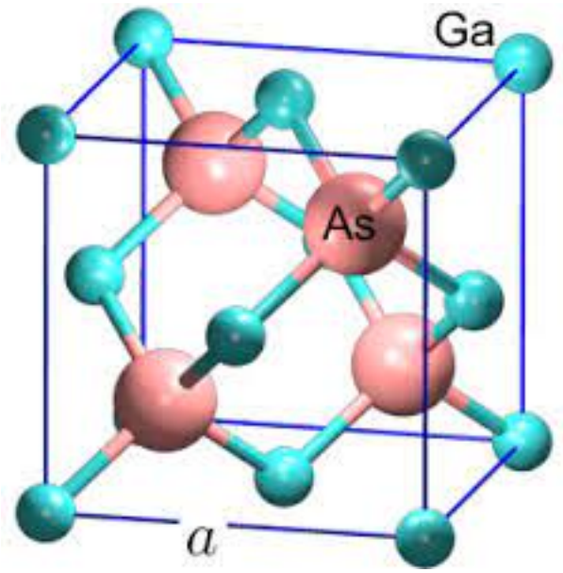
slope: sound speed (10^{-5})

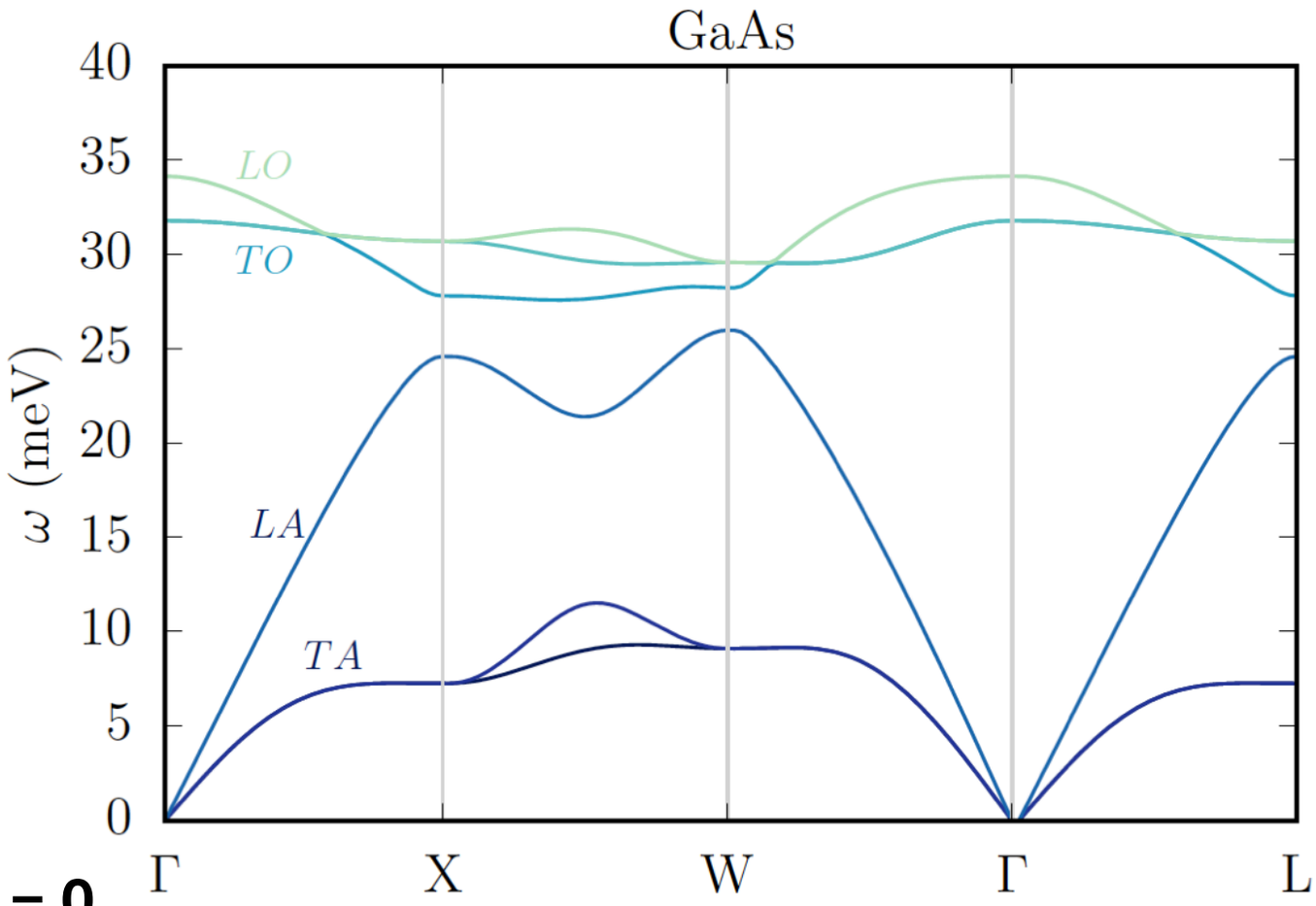
https://arxiv.org/pdf/1712.06598.pdf

Single phonon detection

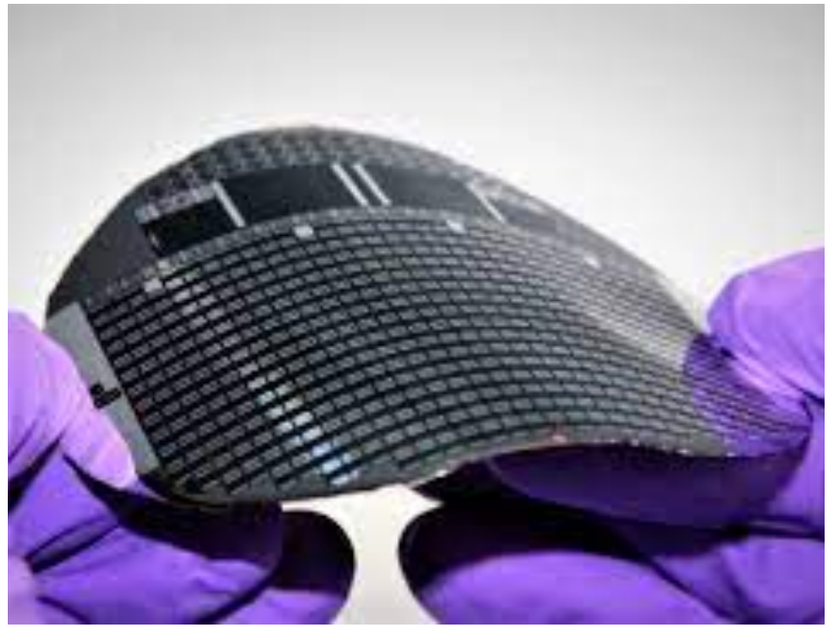


3D



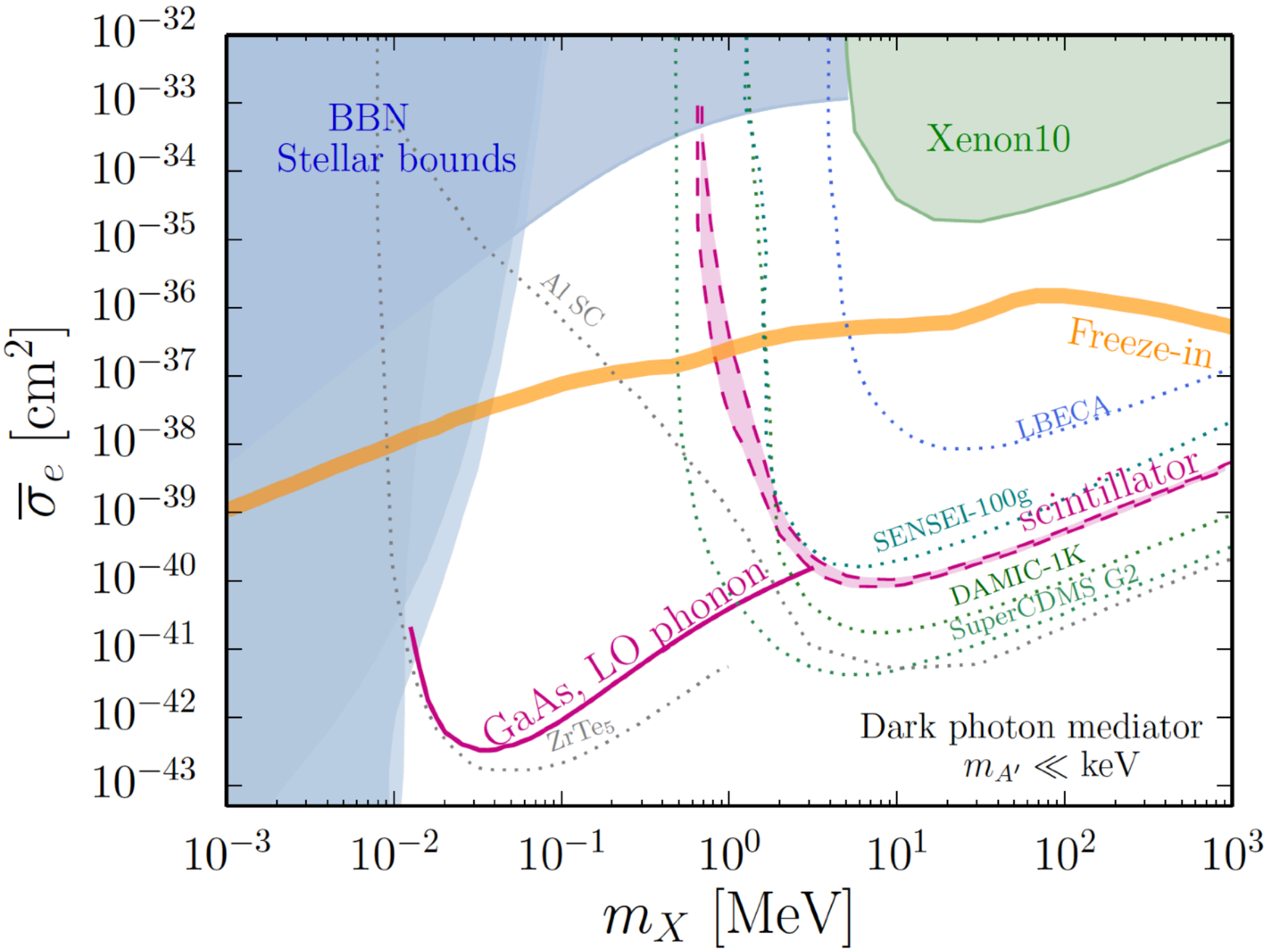


q = 0



https://arxiv.org/pdf/1712.06598.pdf

Projections



https://arxiv.org/pdf/1712.06598.pdf

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

Superconductor targets

Superconducting Nanowire
Single Photon Detectors (SNSPDs)

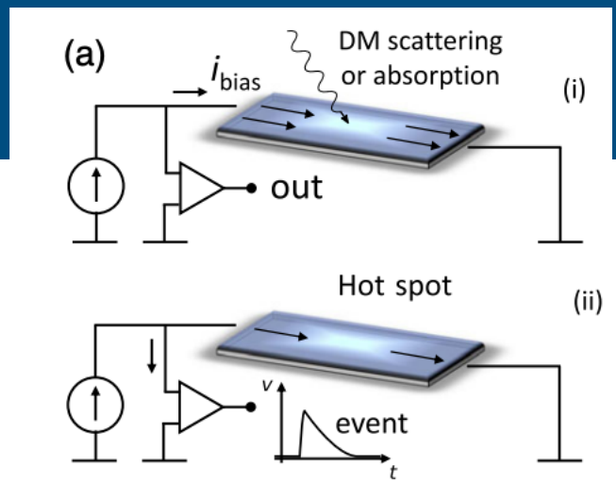
Measure resistance across the wire
==> use sensor as target

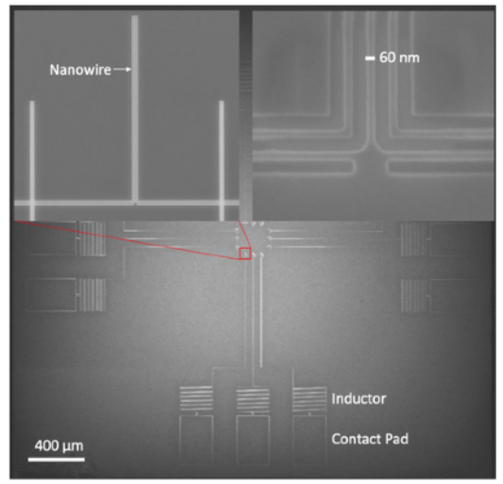
Examples
NbN (niobium nitride) —> SC at 8 K;
proven sensitivity down to $\lambda \sim 3$ μm

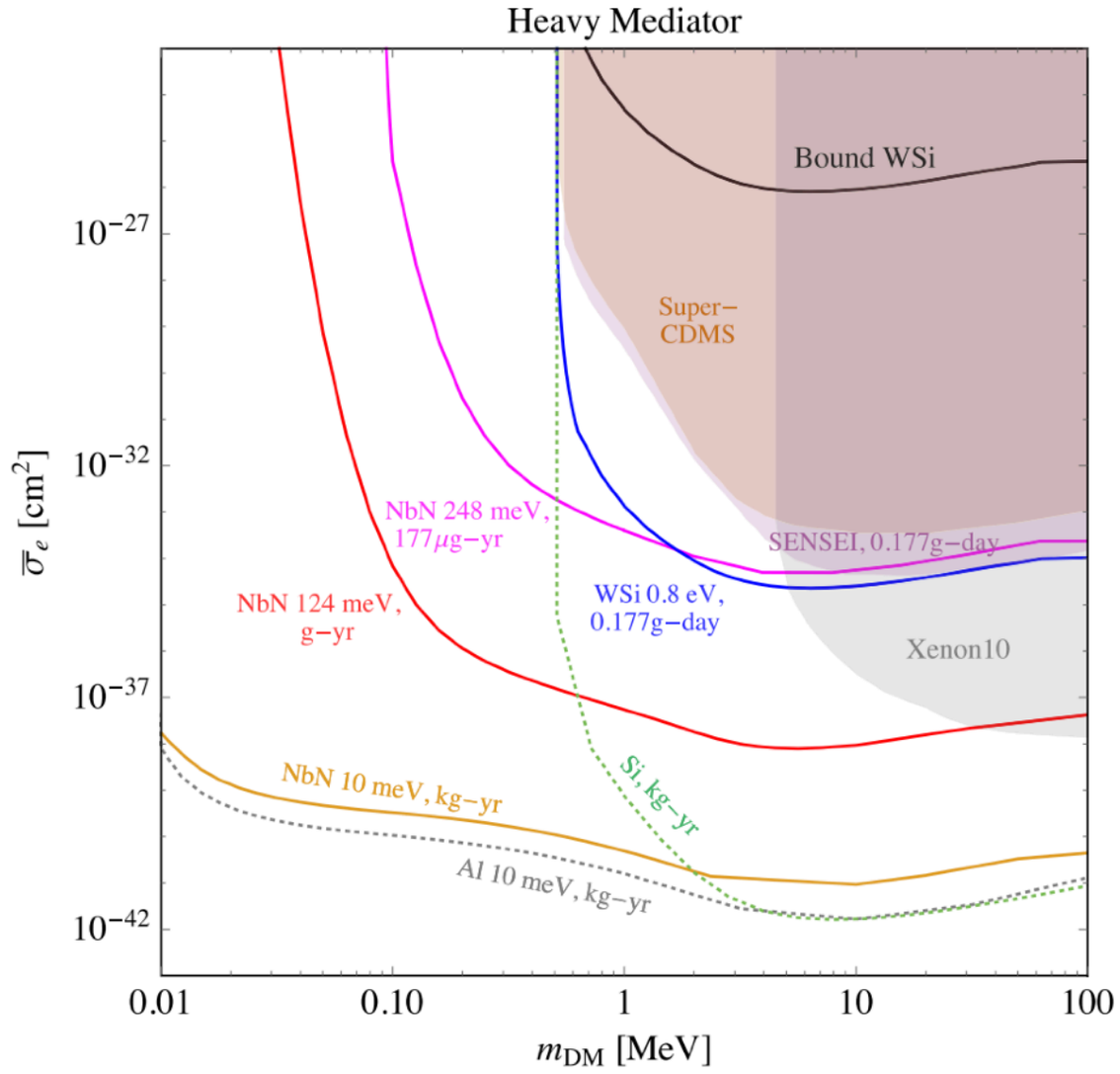
WSi (prototypes) —> SC at ~ K;
sensitivity down to $\lambda \sim 10$ μm, **0.125 meV**

PRL.123.151802

https://arxiv.org/pdf/2012.09979.pdf







Superfluid ^{3}He and ^{4}He

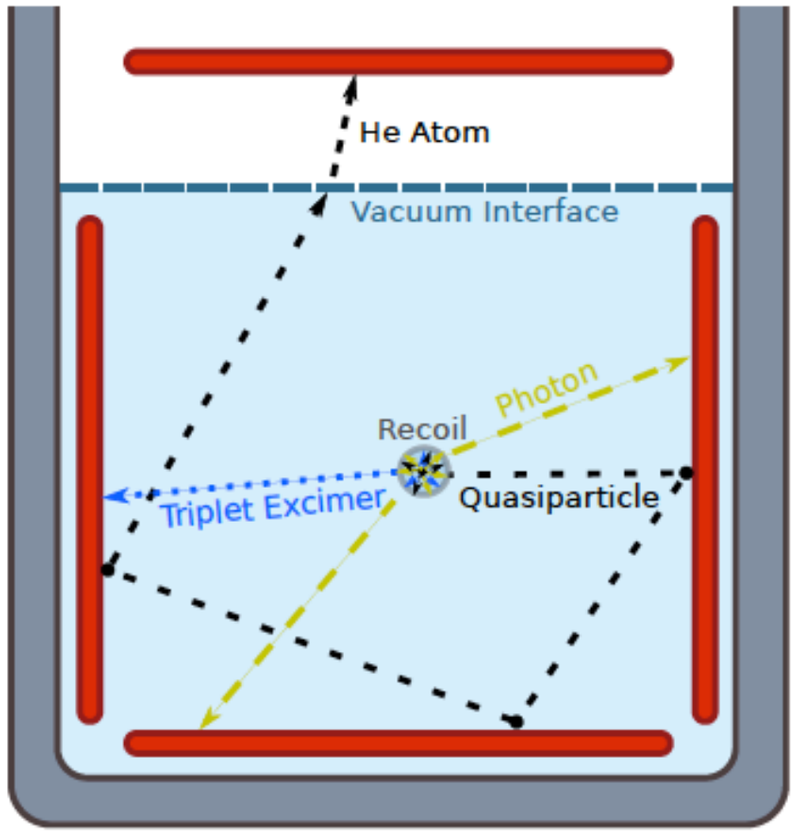
- Radiopure
- no electron bg below 20 eV (W)
- 3 channels: scintillation (singlet/triplet) and quasiparticles/phonons

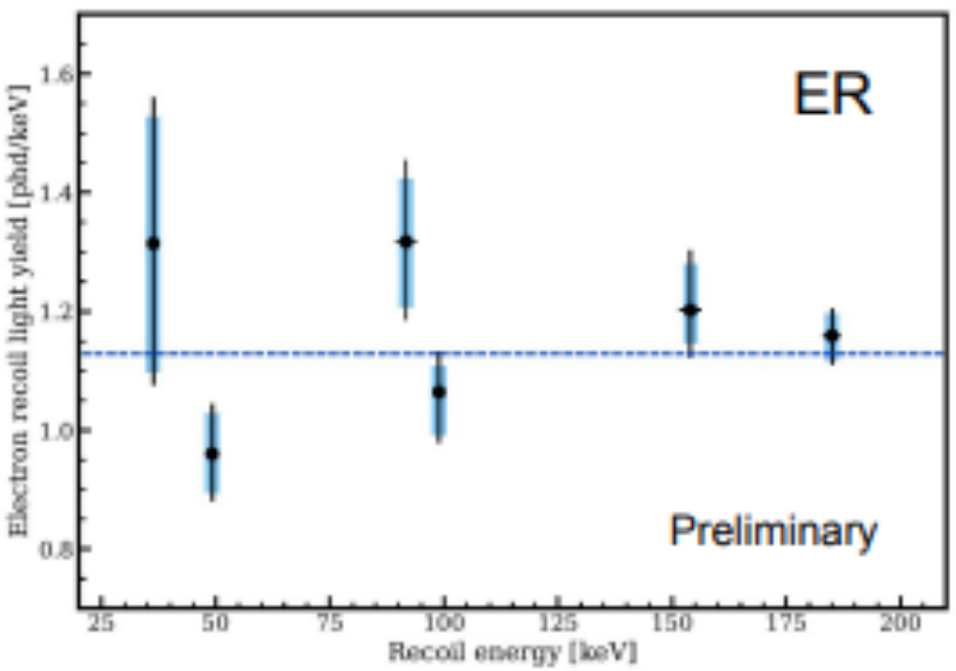
==> discrimination

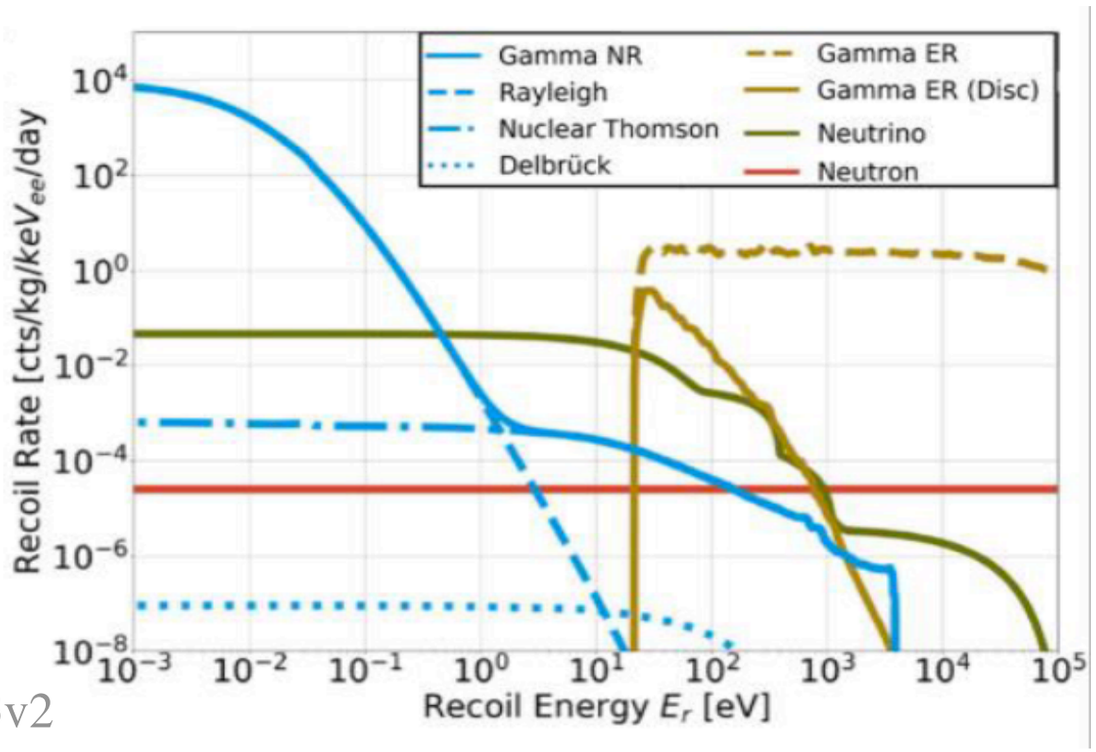
- quasiparticles detected via quantum evaporation of He atoms

Light measurements at 1.75 K

HeRALD



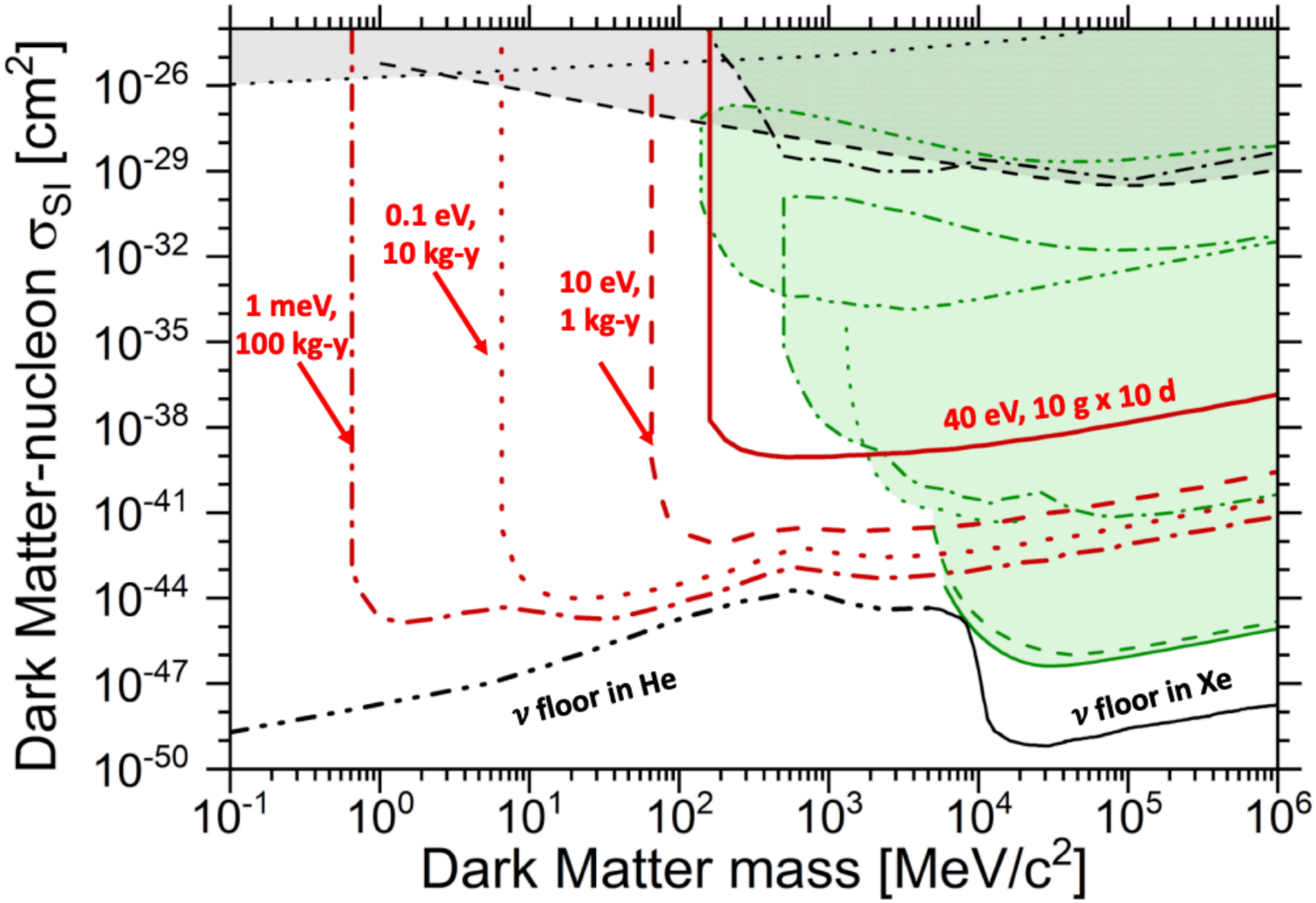




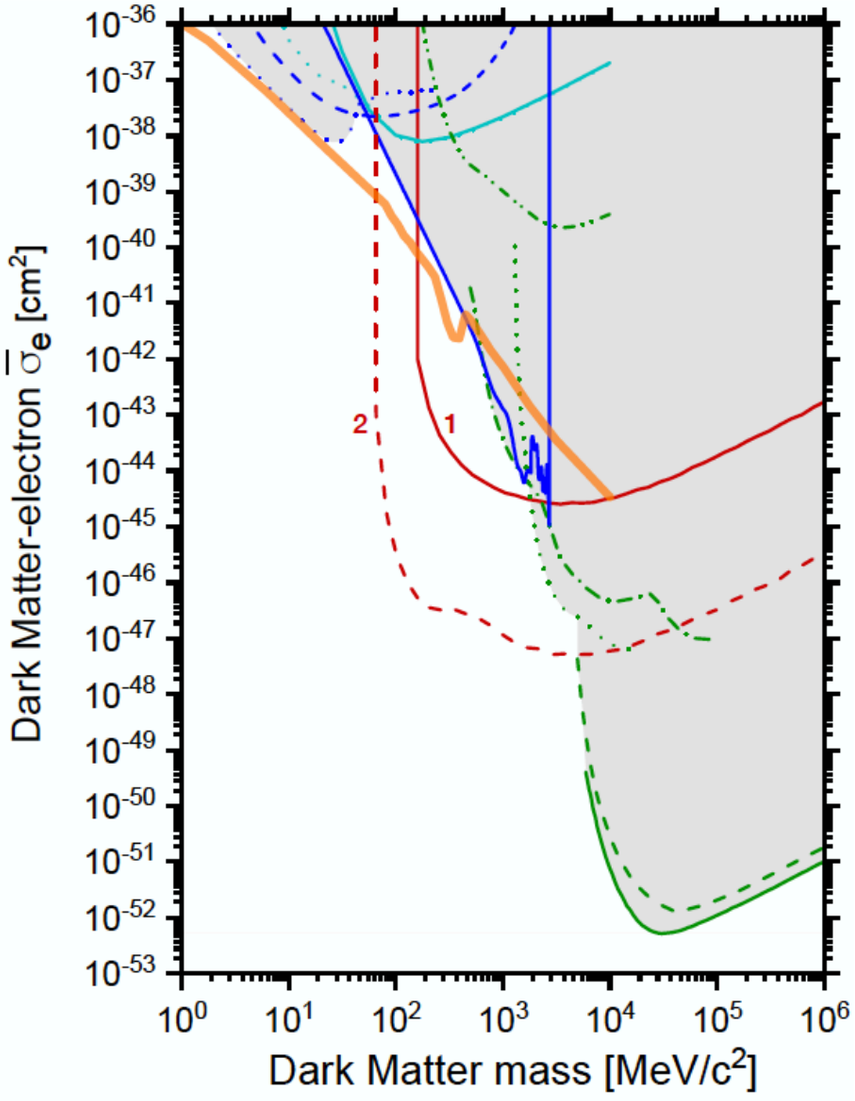
arXiv:1810.06283v2

Superfluid ^{3}He and ^{4}He

DM - nucleon



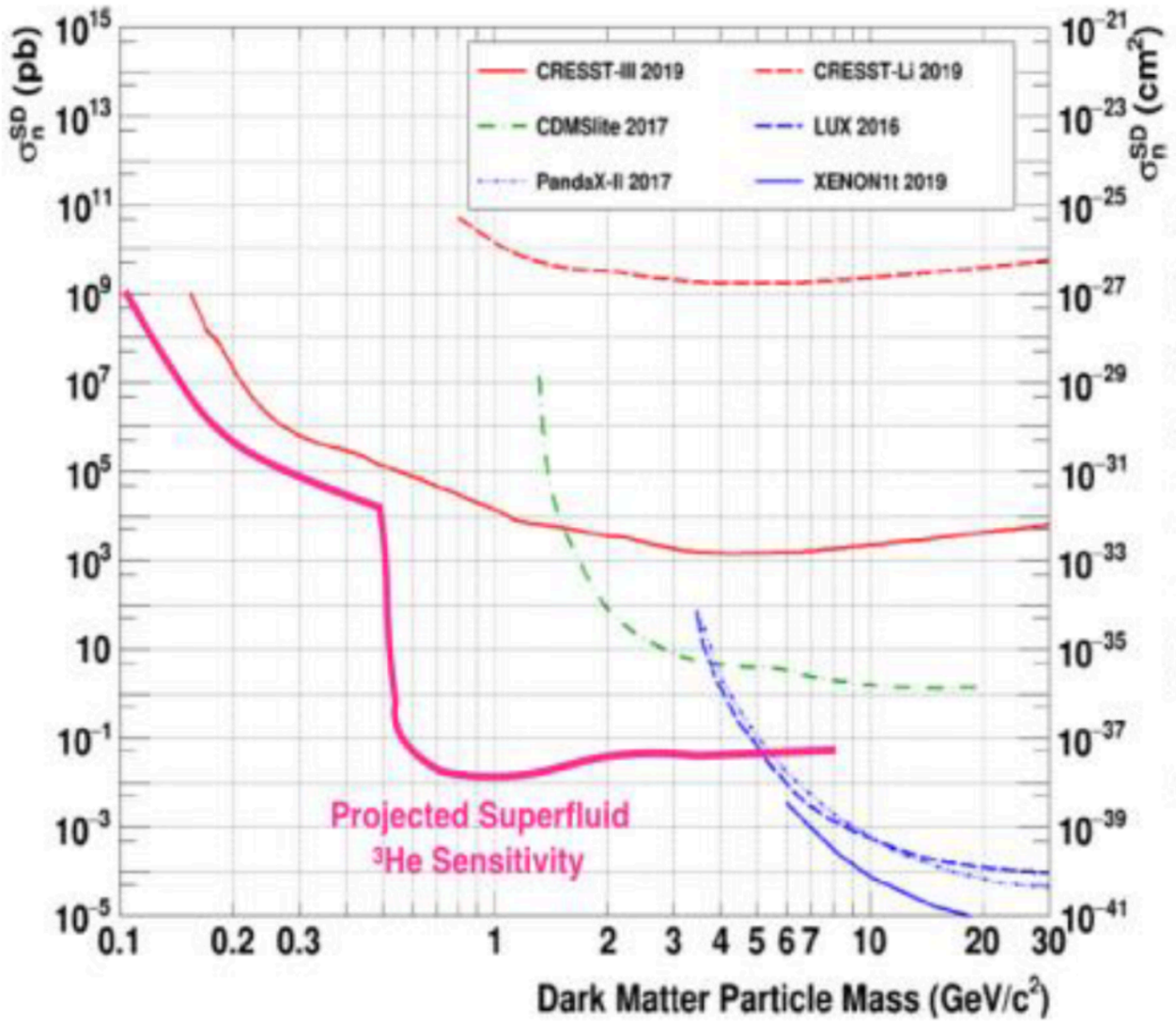
DM - electron



https://www.mpi-hd.mpg.de/lin/seminar_theory/talks/Talk_McKinsey_070721.pdf

Superfluid ^{3}He and ^{4}He

^{3}He —> Spin-Dependent DM-nucleon interaction



5 cm^3 cells, in a ^{3}He bath

- TES to readout scintillation
- Sensitivity of **nanobeam** oscillators extrapolated at 80 μK, may reach recoil energy sensitivity of ~10 eV

QUEST @

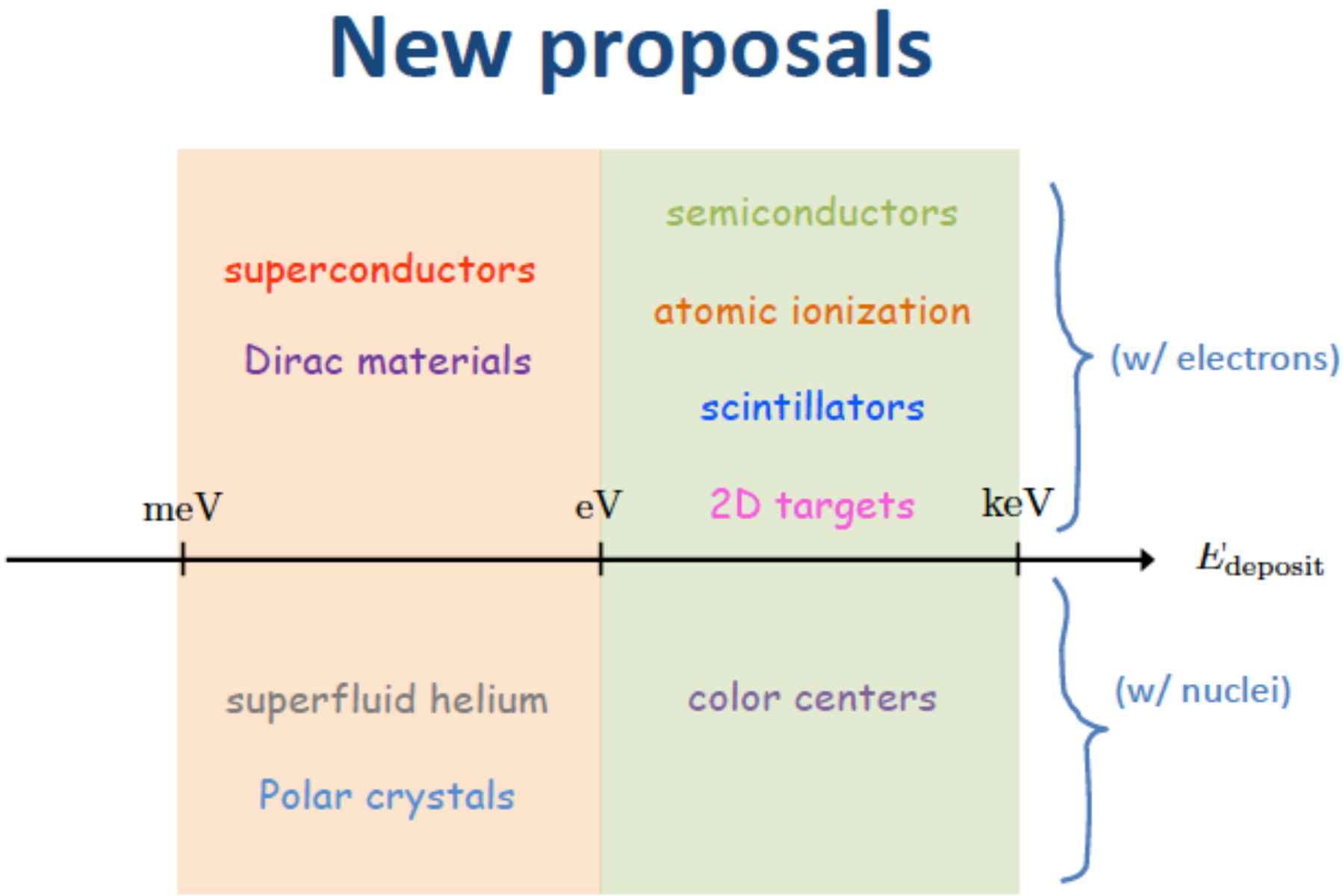
ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

University of Sussex

UNIVERSITY OF OXFORD

Looking for new ideas?



summary slide from Y Hochberg at Invisibles 21 (she will be here on Tuesday)

Conclusions

Evidence for DM, no evidence for standard WIMP candidates

Increasing interest for new candidates at sub-GeV scale

Light DM candidates require sensitivity to low energy deposit (low detection threshold)

Addressed existing technology (noble liquids, semi-conductors) and what is the potential for lower thresholds and limitations imposed by backgrounds

Introduced partial list of future projects and interesting ideas

Some of them at early stage of development / prototyping, exciting time ahead

Thanks!

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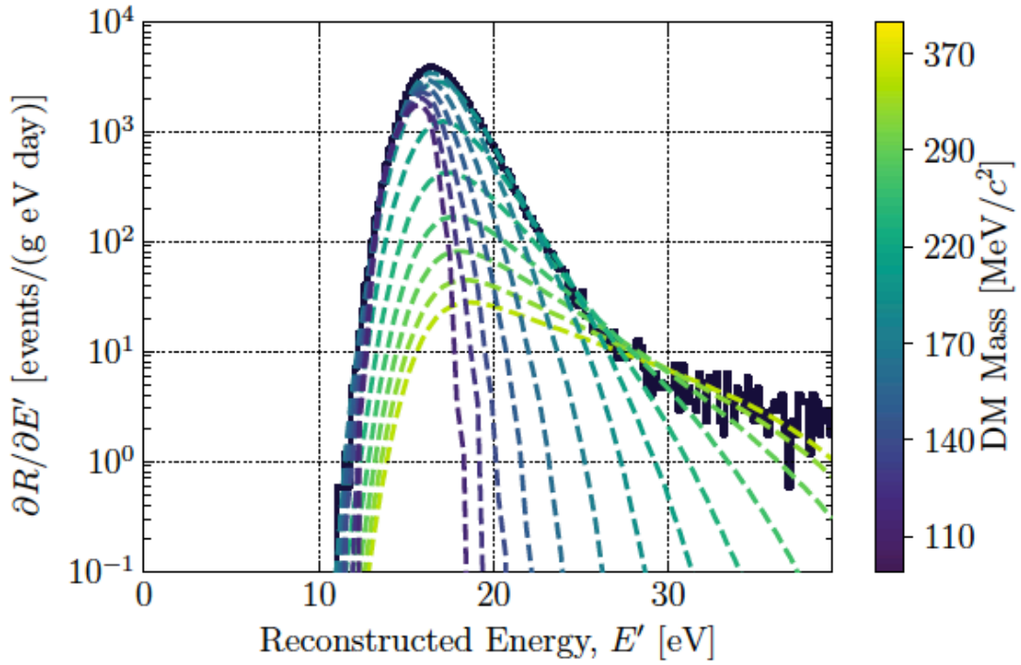
Extra slides

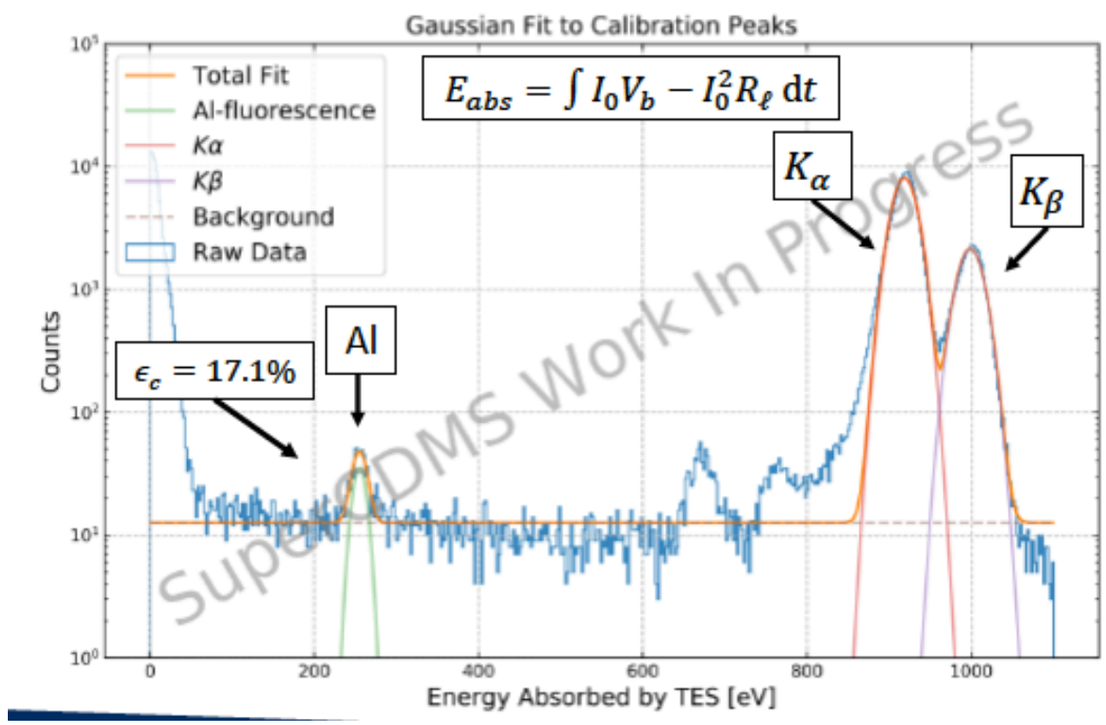
SuperCDMS + CPD

The CPD substrate is a 1 mm thick Si wafer with a radius of 3.81 cm and a mass of 10.6 g. It is instrumented on one side with ~1000 Quasiparticle-trap-assisted Electrothermal feedback Transition-edge sensors (QETs) [20, 21] distributed over the surface and connected in parallel to a single readout channel. The opposite side of the wafer is unpolished and not instrumented

For the sensor readout, a direct-current superconducting quantum interference device (SQUID) array–based amplifier was used, s



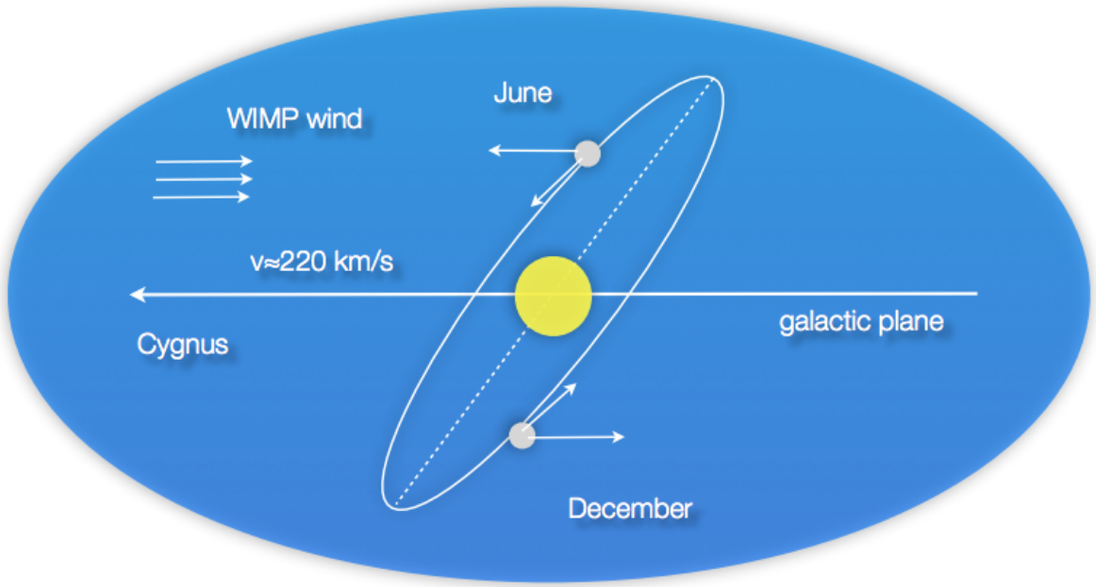
- We have a collimated Fe-55 calibration source
  - K-α and K-β peaks are visible (5.9 keV and 6.5 keV)
  - Used aluminum foil for attenuation, resulting in a collimated aluminum fluorescence line at 1.5 keV



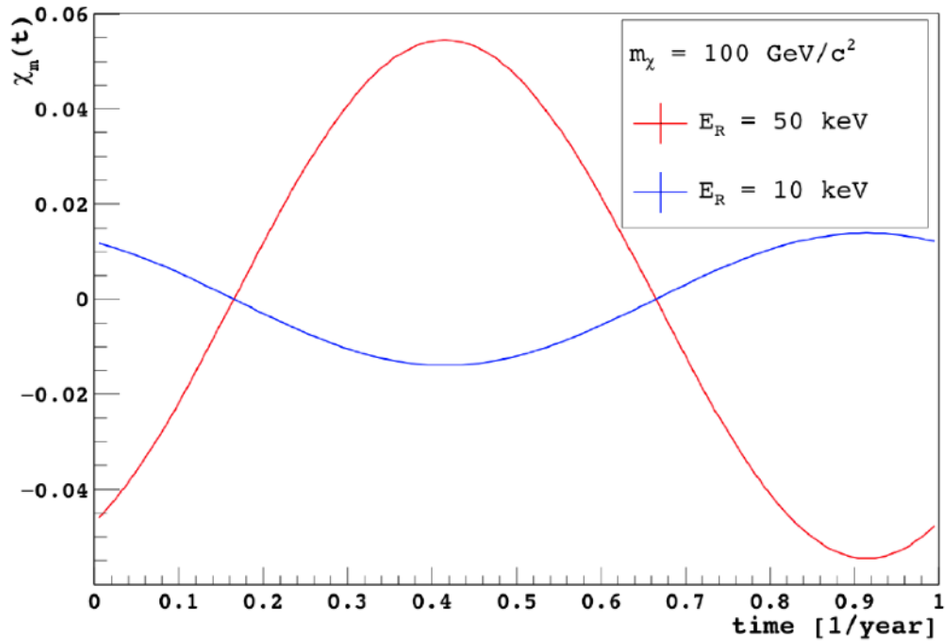
$$\sigma_E = 3.9 \pm 0.1(\text{stat.}) \pm 0.18(\text{sys.})\ \text{eV}$$

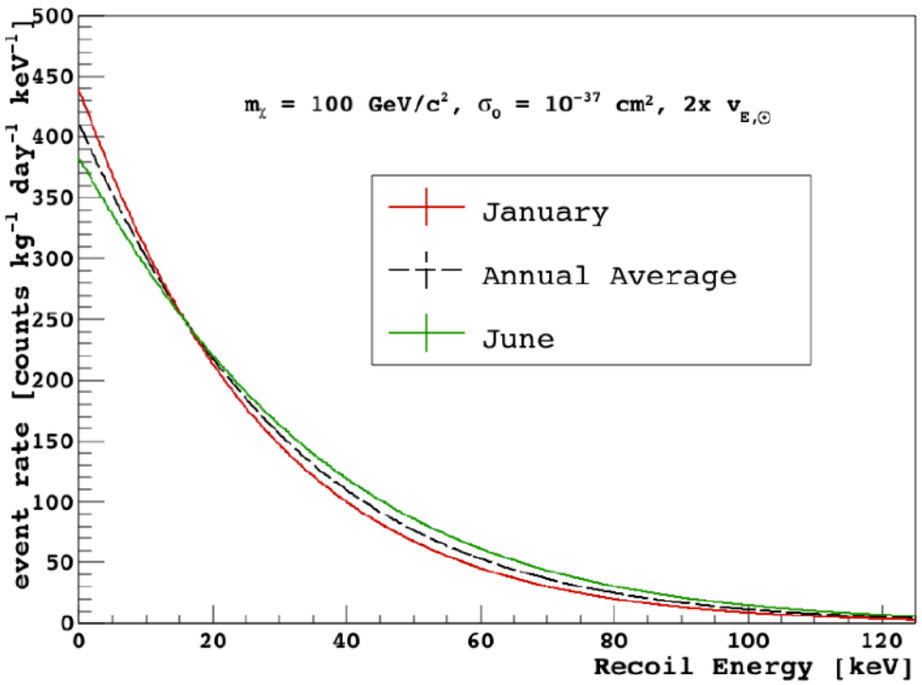
Annual (and diurnal) modulation signature

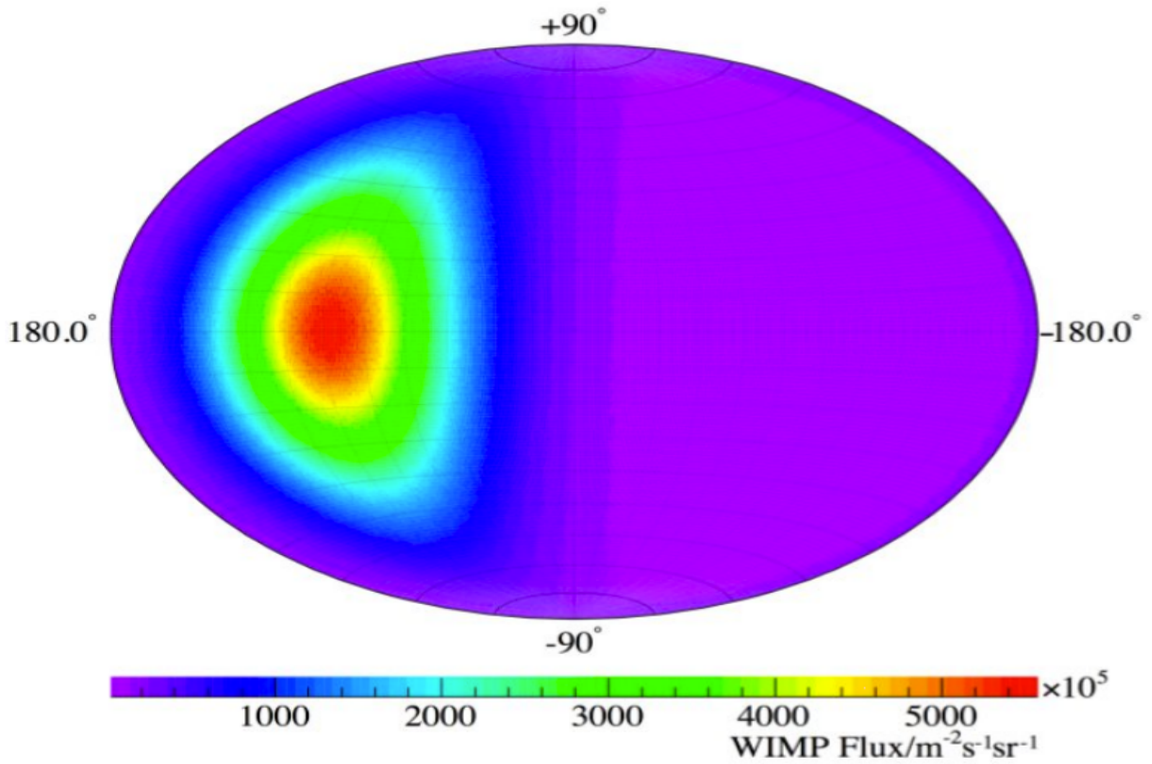
Additional signatures to be considered in case of positive detection



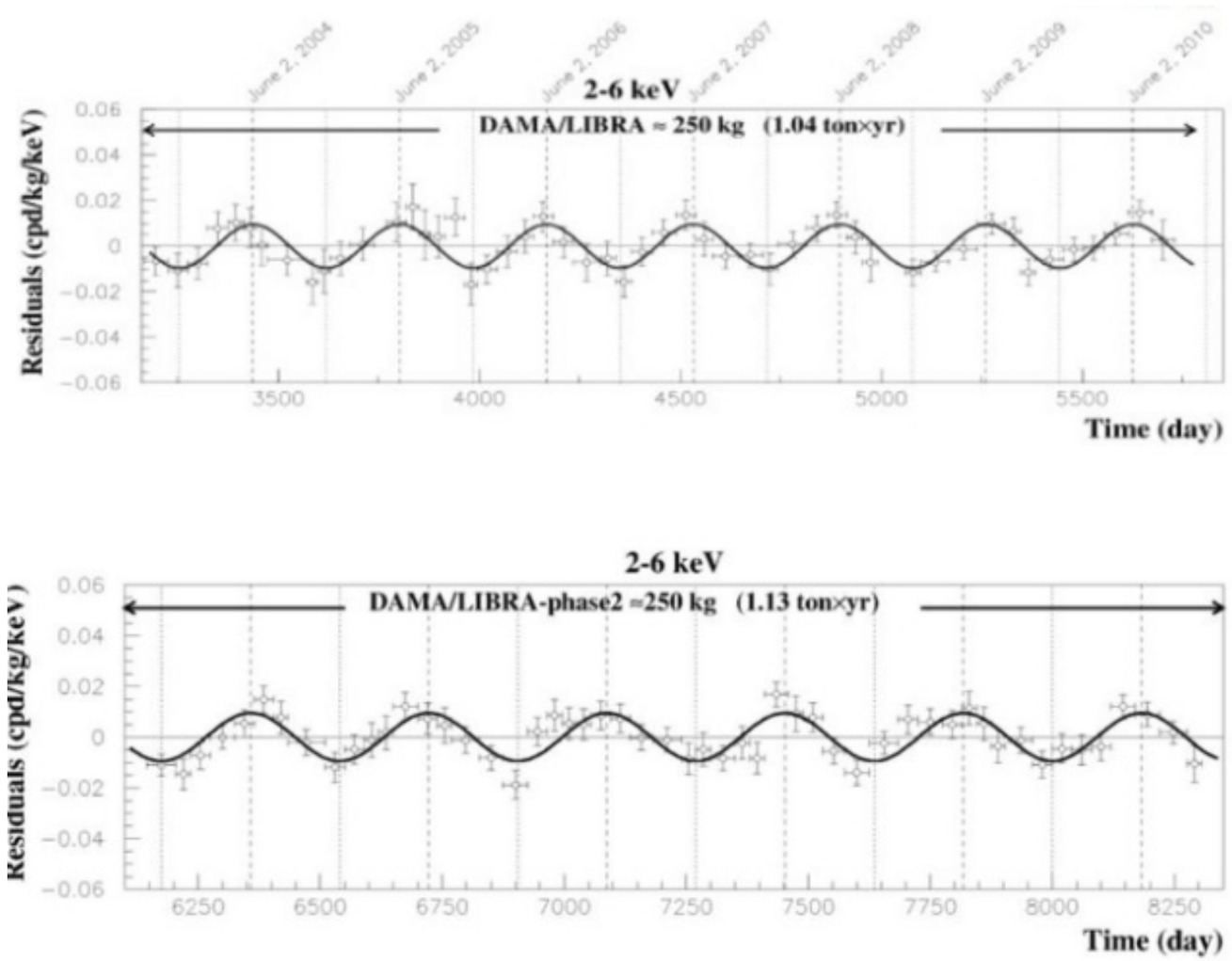
Drukier, Freese, Spergel, PRD 33,1986







DAMA



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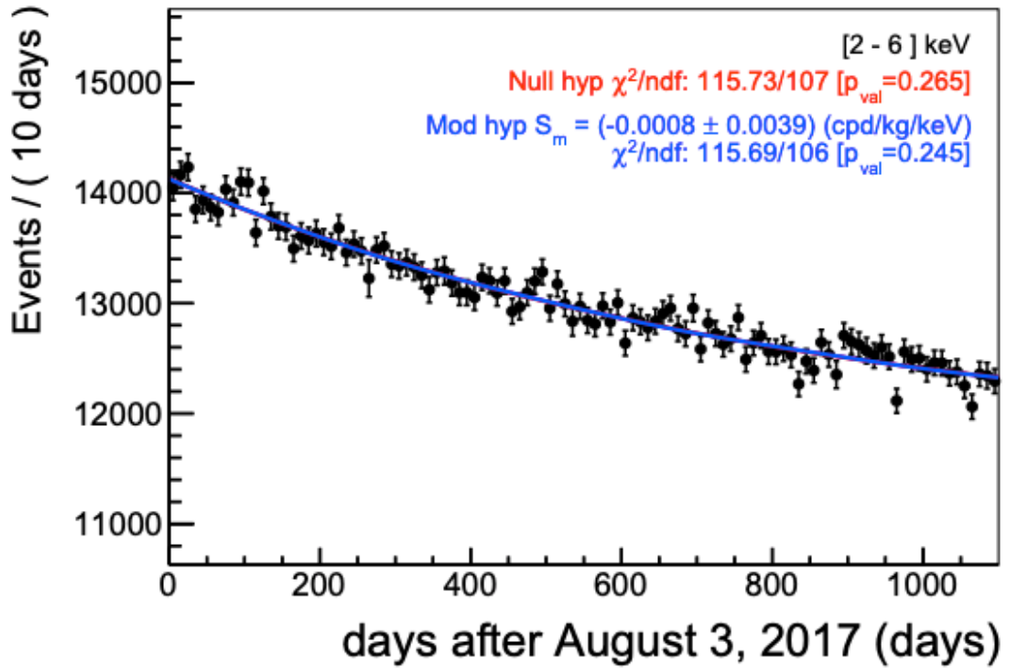

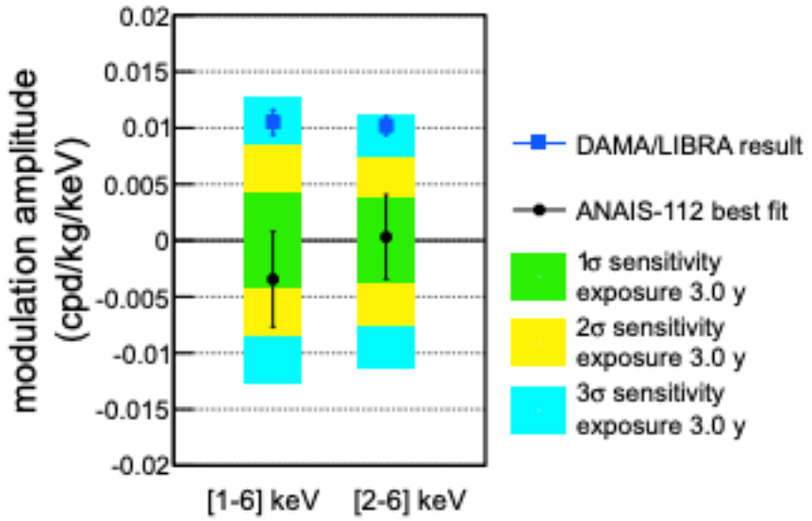

https://arxiv.org/pdf/2103.01175.pdf

DarkSide-20k SiPMs