Experimental searches for sub-GeV Dark Matter

Francisco Vazquez de Sola
EDSU, November 2022

Subatech

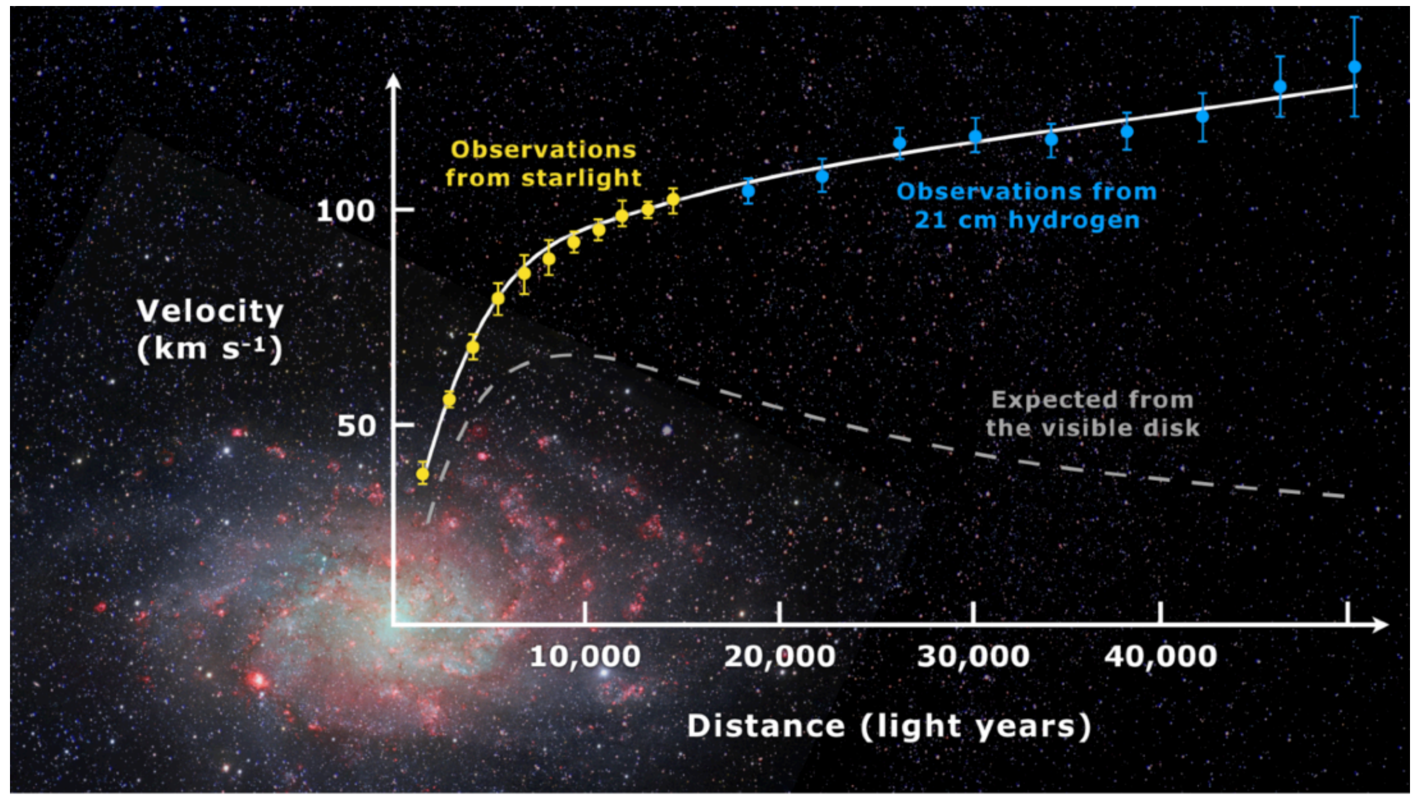
CNRS IN2P3 Les deux infinis

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

Nantes Université

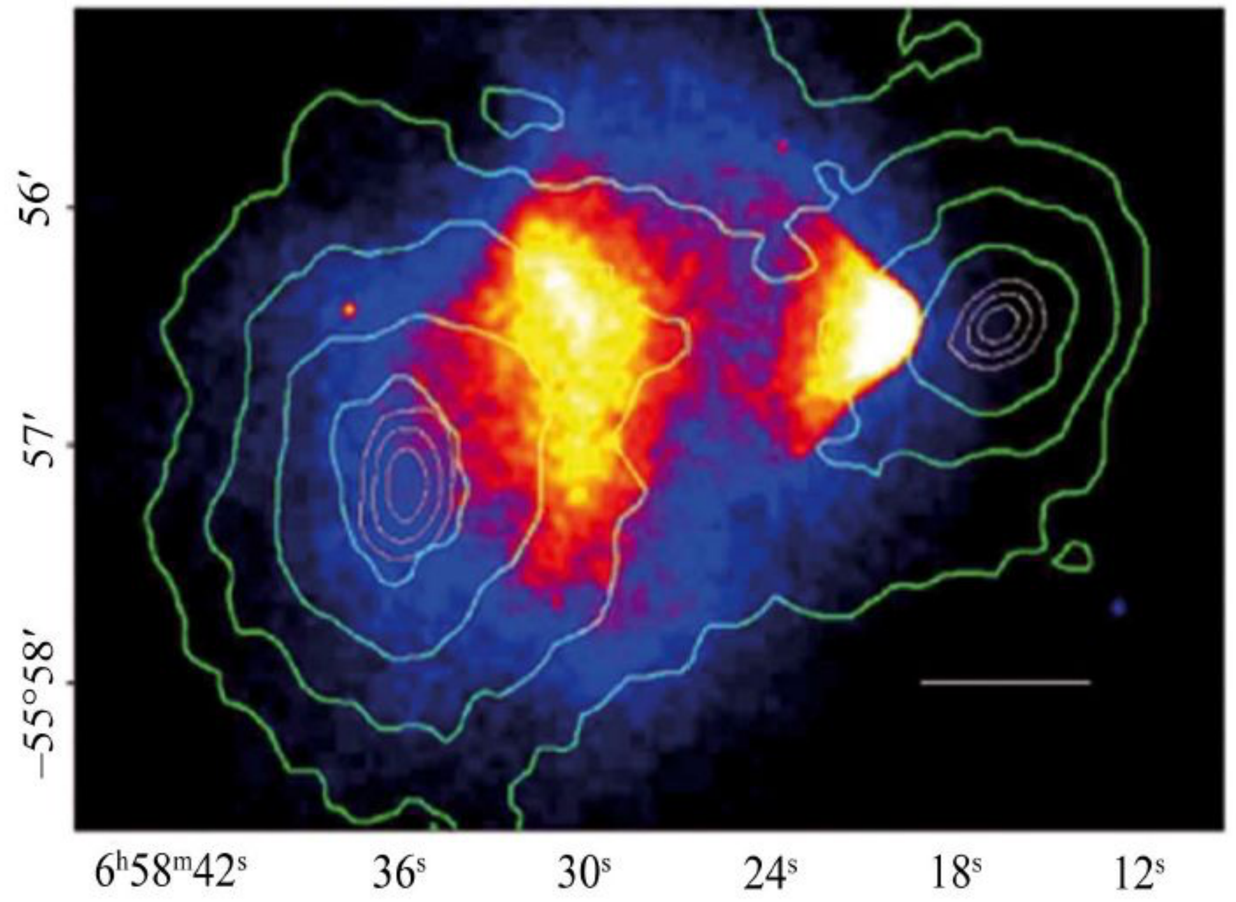
- Why look for Sub-GeV Dark Matter?
- Down to ~100 MeV/c^2 : Cryogenic detectors
- Down to ~10s MeV/c^2 : H/He detectors
  - interlude : the Migdal effect
- Down to ~0.5 MeV/c^2 : CCDs and recoils on electrons

Galaxy Rotation Curves



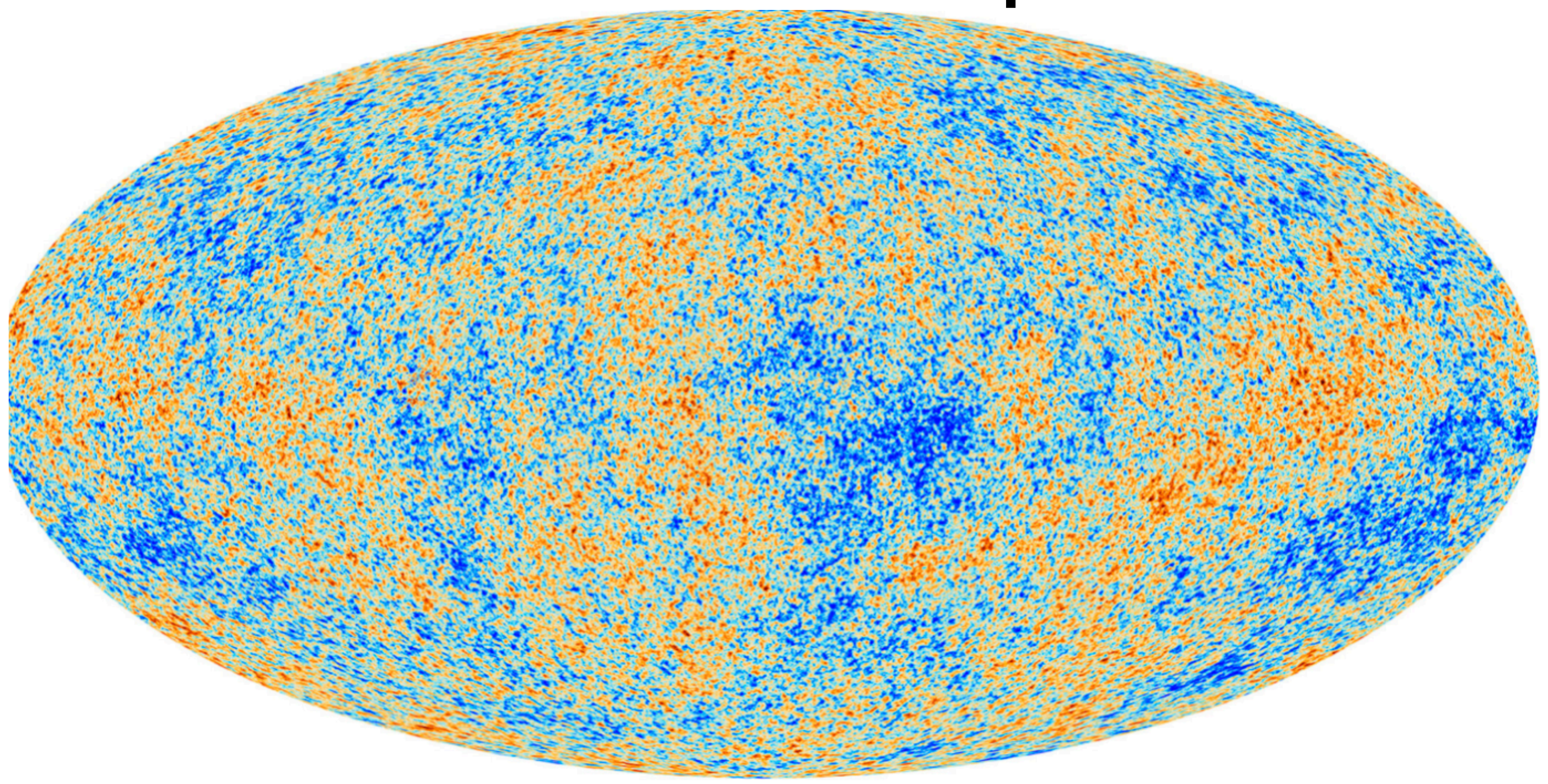
Galaxy scale

Bullet Cluster

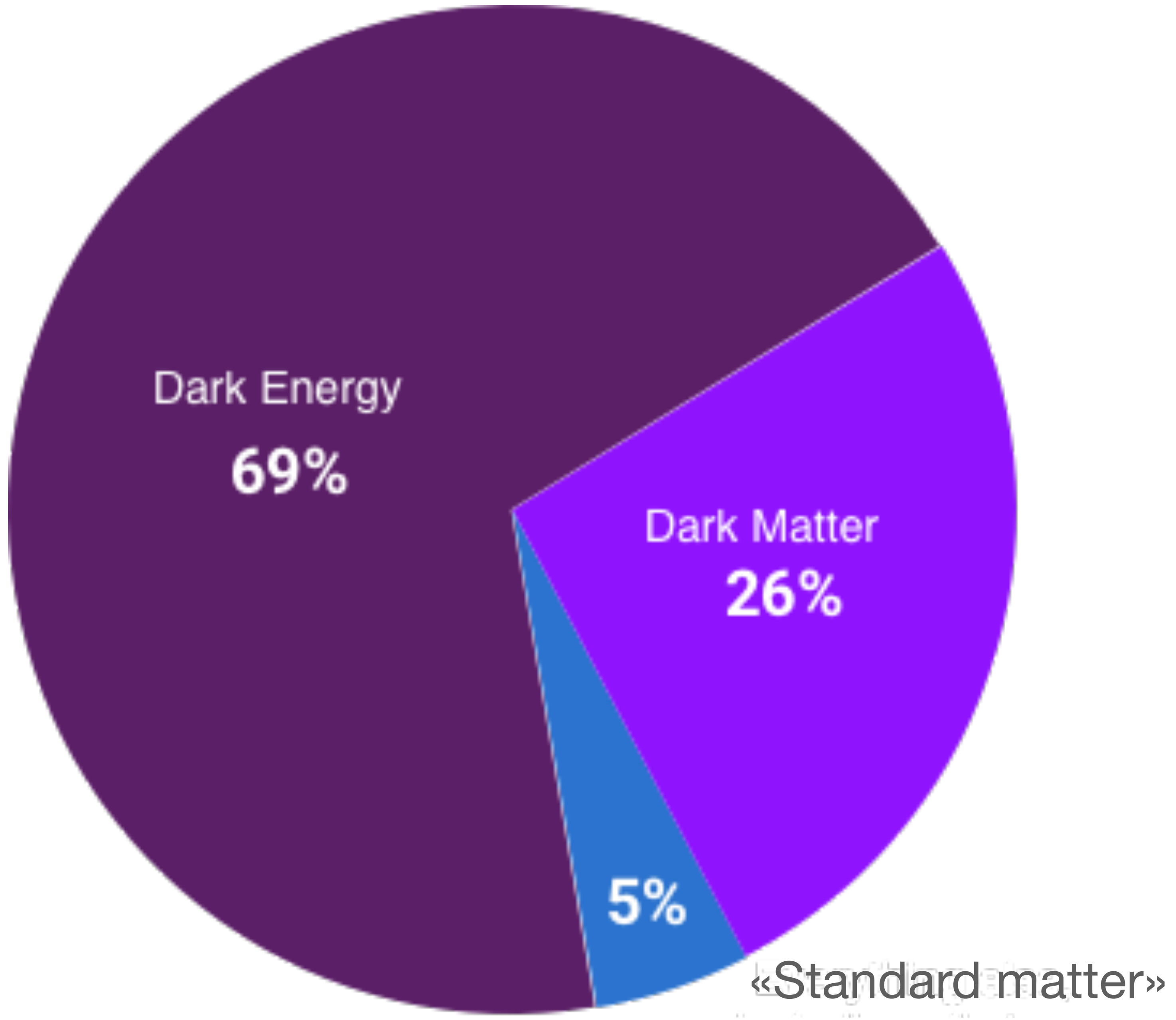


Cluster scale

CMB anisotropies

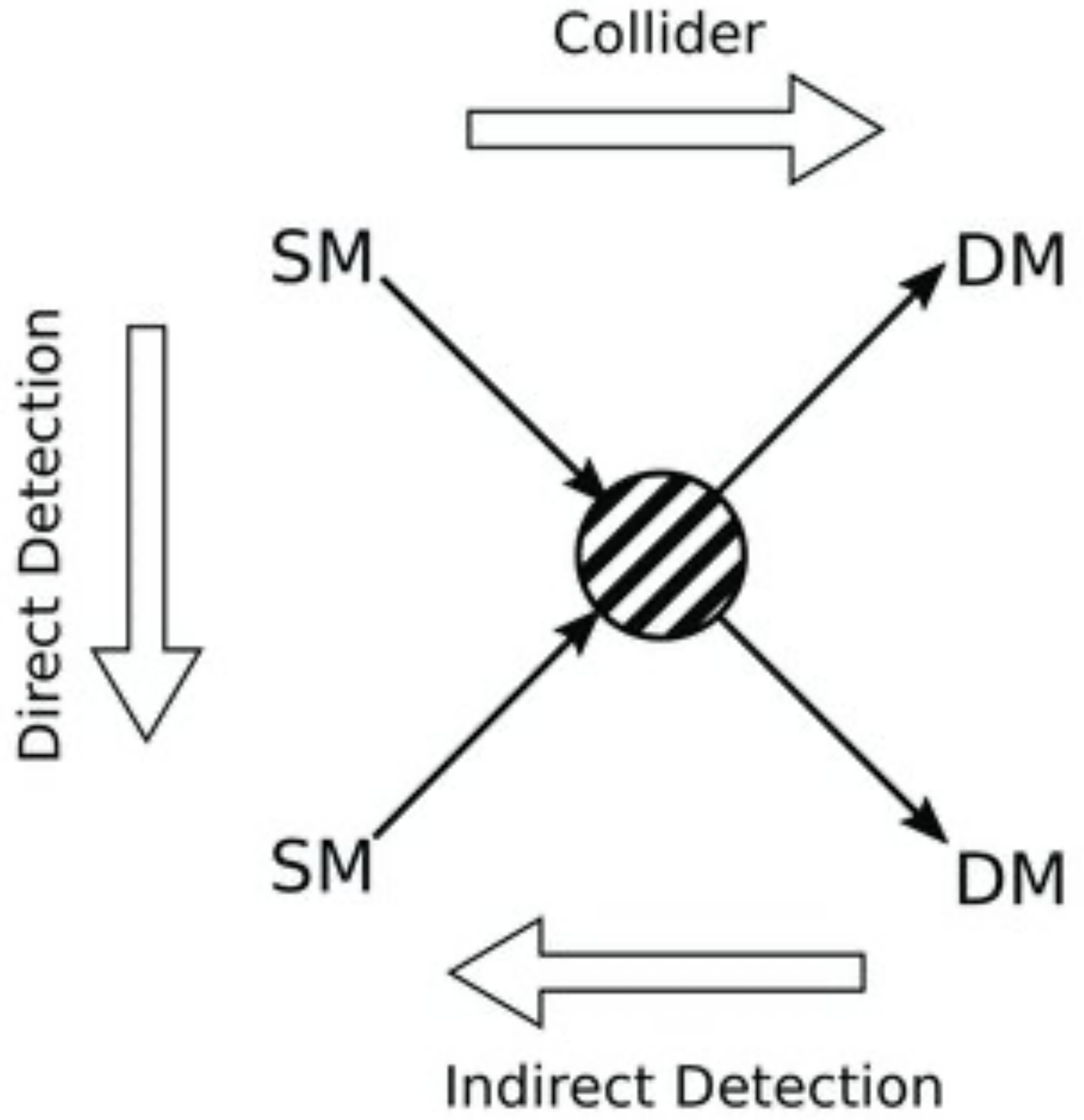


Cosmic scale



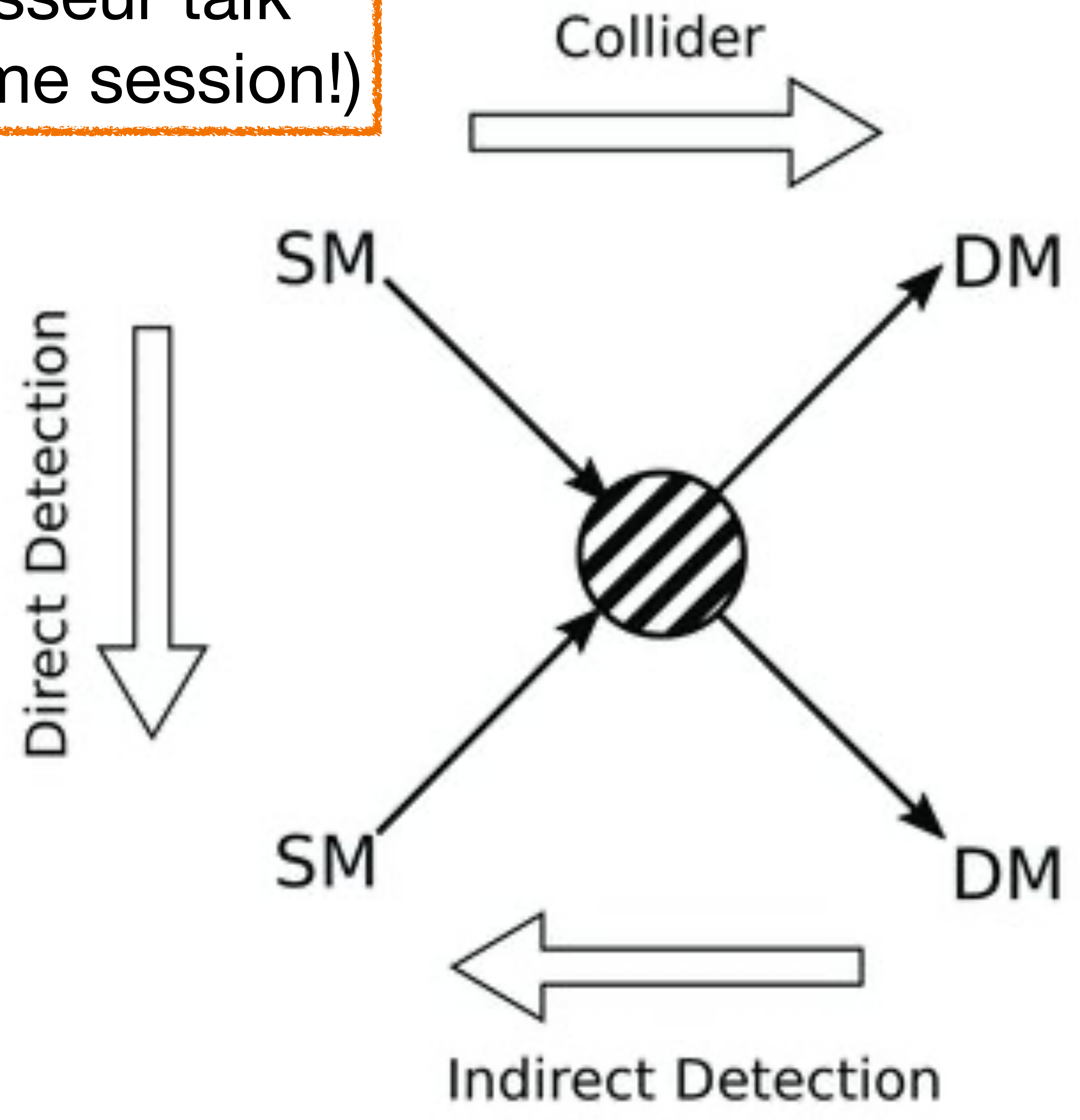
- Postulated for the first time a century ago. Now have evidence for Dark Matter at multiple scales!
- DM composition of Universe measured precisely. But nature remains unknown.

- Assume Dark Matter is some kind of (new) particle:



- Assume Dark Matter is some kind of (new) particle:
  - Can create it in colliders from Standard Model particles

G. Vasseur talk
(this same session!)



- Assume Dark Matter is some kind of (new) particle:
  - Can create it in colliders from Standard Model particles
  - Can study its annihilation products coming coming from regions with high density of DM (indirect detection)

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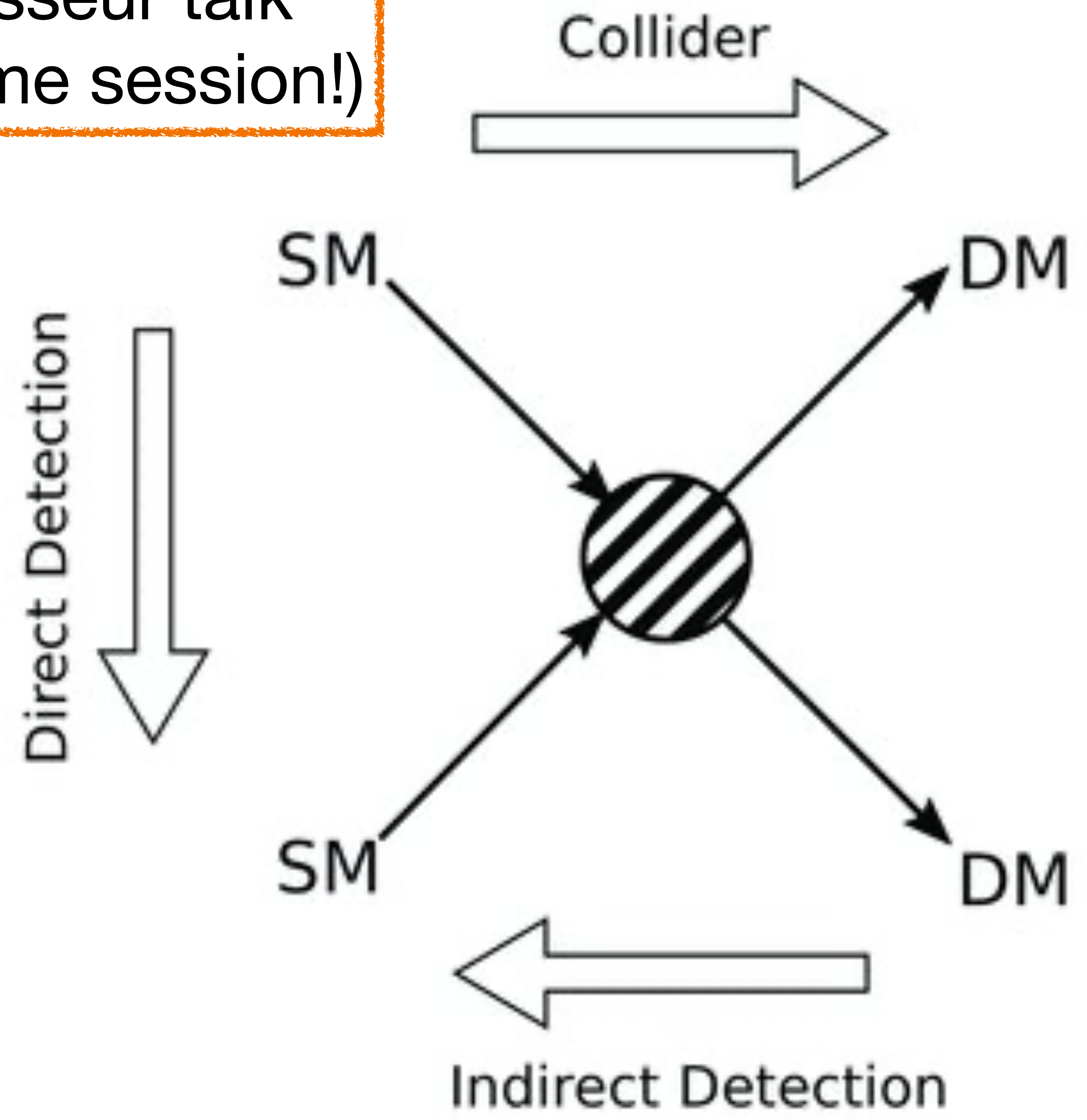
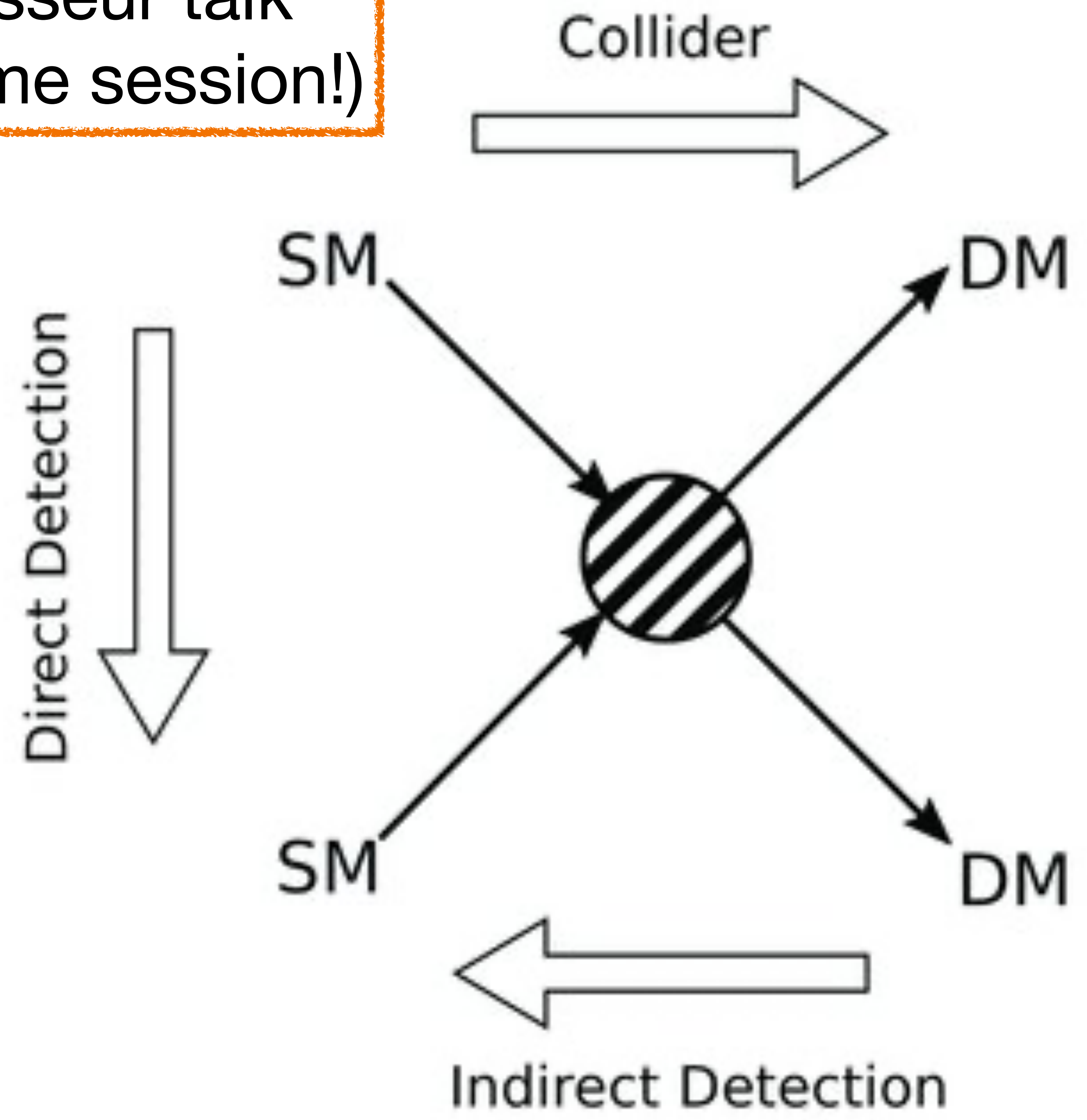


D. Kerszberg talk (this same session!)

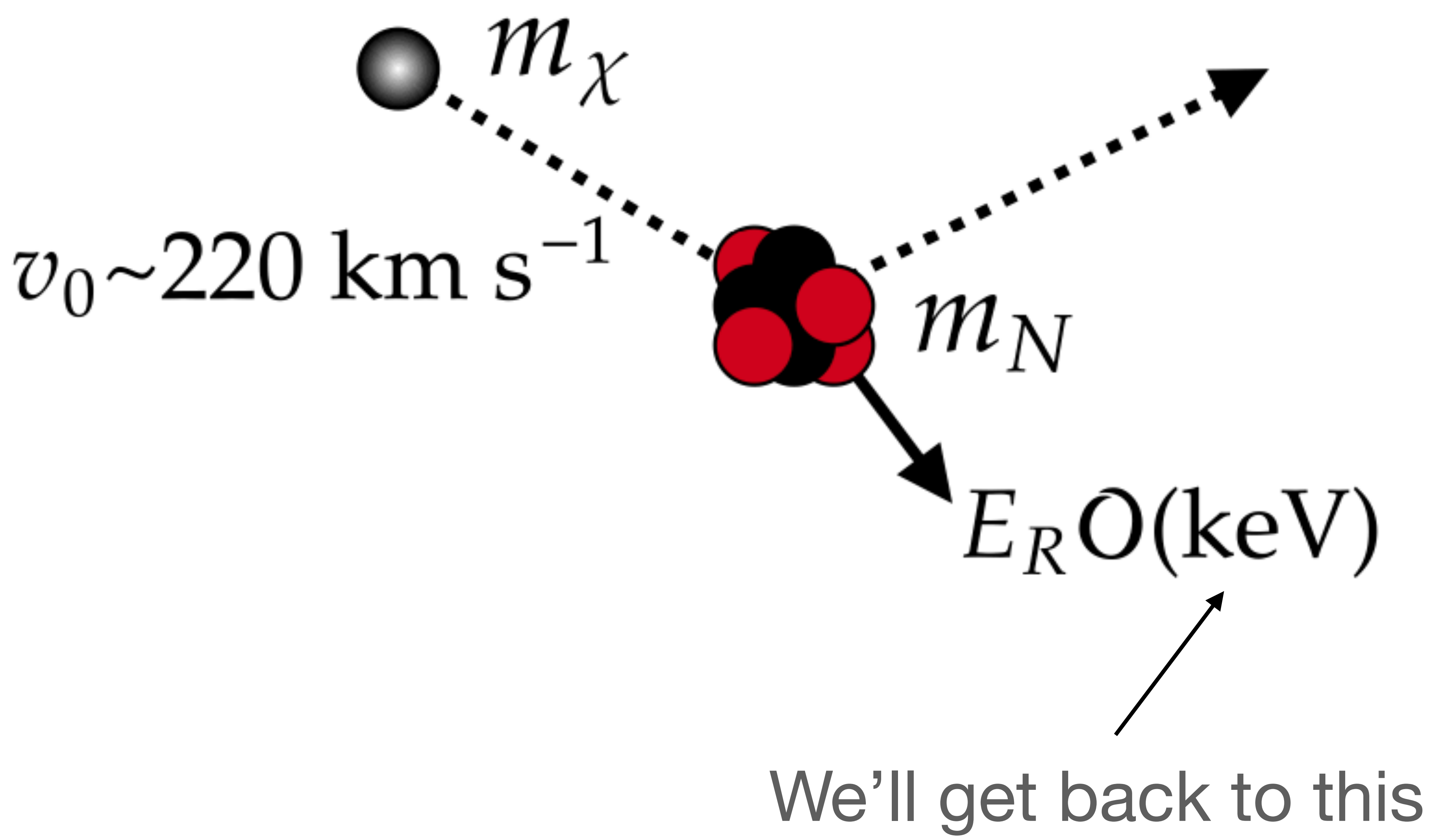
- Assume Dark Matter is some kind of (new) particle:
  - Can create it in colliders from Standard Model particles
  - Can study its annihilation products coming coming from regions with high density of DM (indirect detection)
  - **Can observe recoils of DM from galactic halo on Standard Model particles (direct detection)**
- **This talks focuses on the latter.**

G. Vasseur talk (this same session!)



D. Kerszberg talk (this same session!)

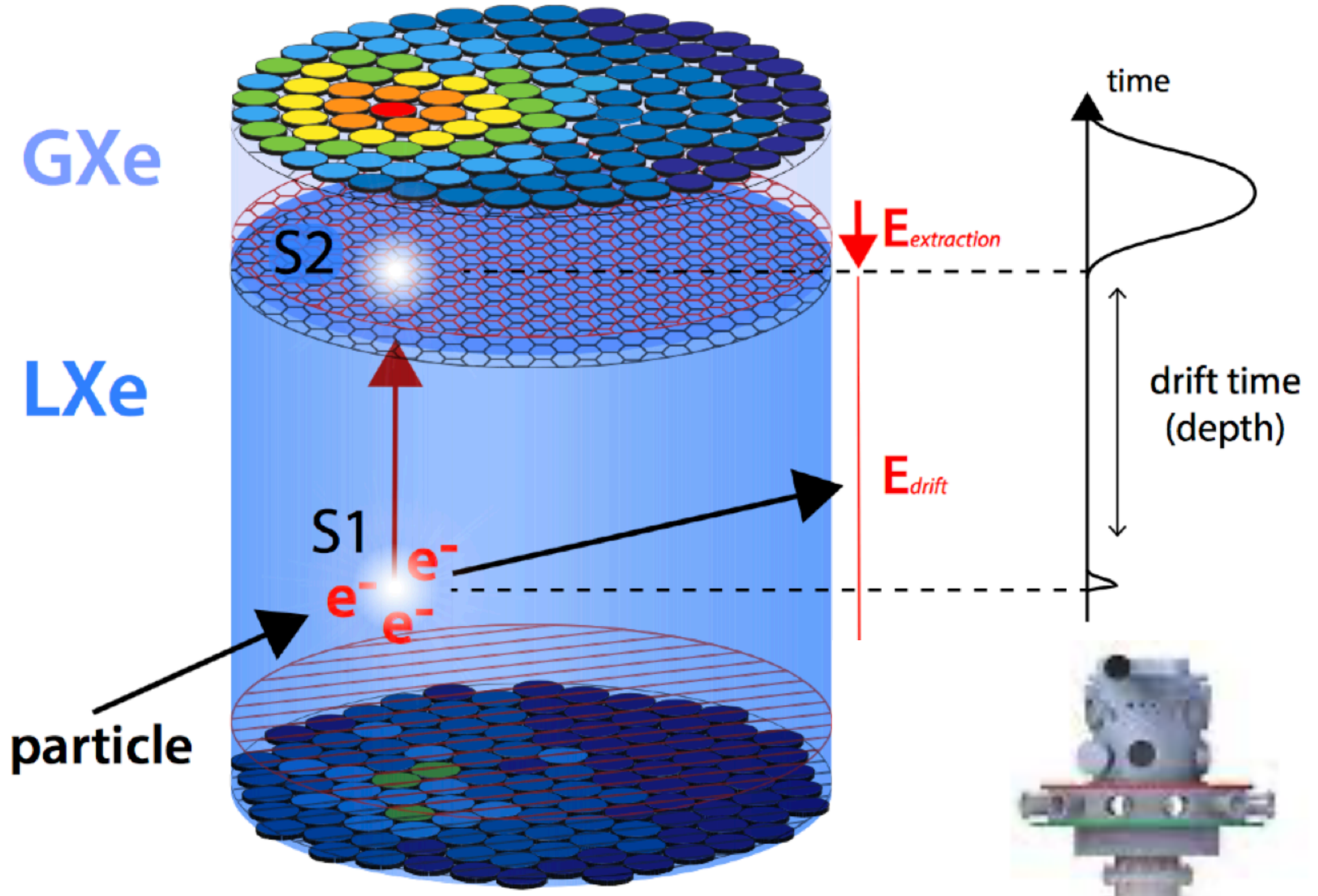
- DM-induced recoils are very rare:
  - Need large detectors that run for a long time
- To claim discovery of DM, need to observe recoils unexplained by other sources
  - Need to protect detectors from natural radioactivity, cosmic backgrounds, etc
  - Need to reject recoils that aren't produced by DM



- Weakly Interacting Massive Particles (WIMPs), with masses in ~10 GeV/c^2 - TeV/c^2 range, were first class of privileged DM candidates.

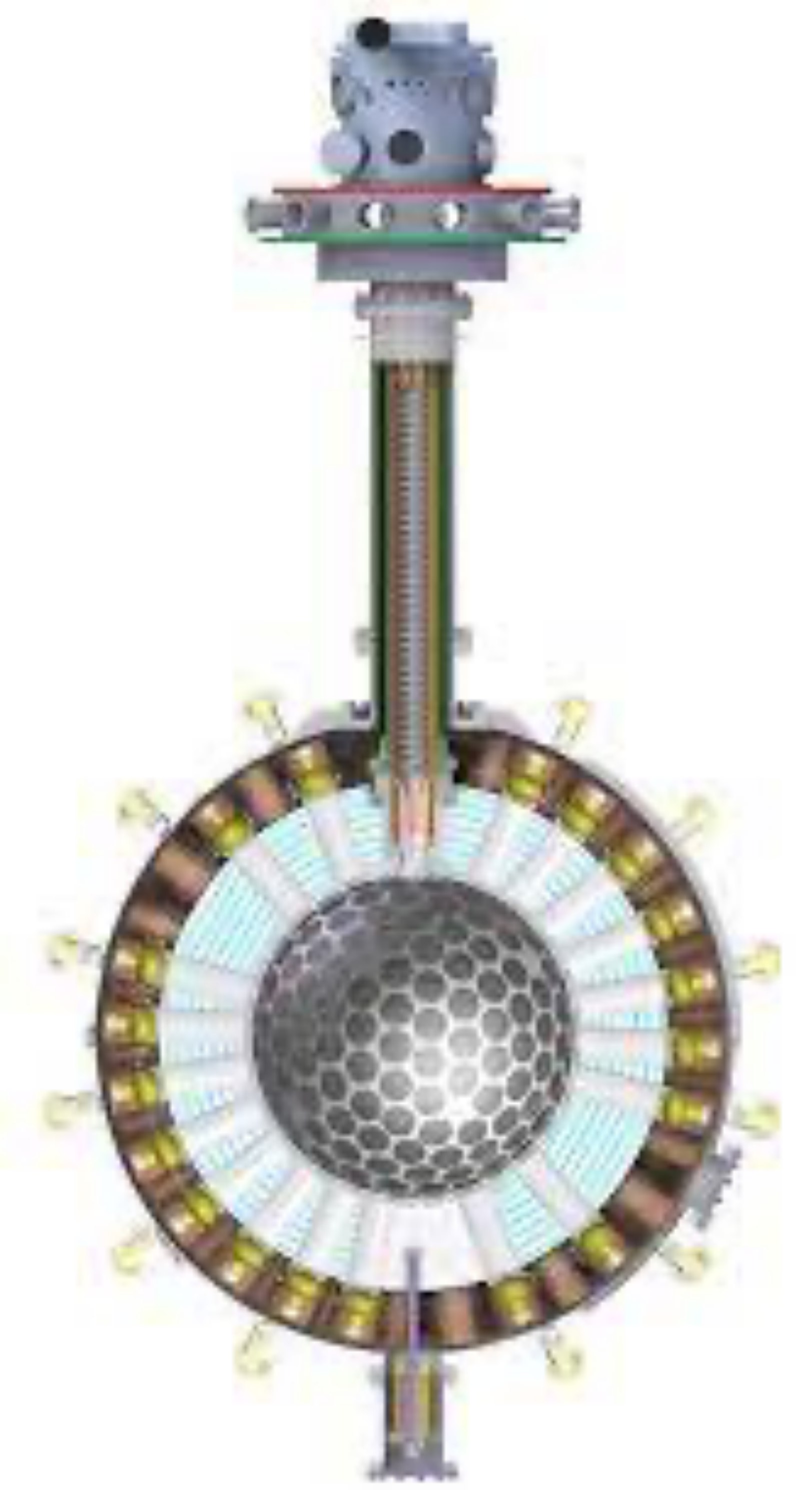
- Liquid noble (Xenon/Argon) detectors lead the charge:
  - Massive exposures ~1 ton.year
  - WIMP-nucleus interaction rate boosted for heavy atom targets
  - Excellent background rejection, leading to backgrounds of ~100 evt/ton.year (and aiming even lower!)

- However, no signal observed yet, and soon(TM) to reach neutrino fog



XENON1T

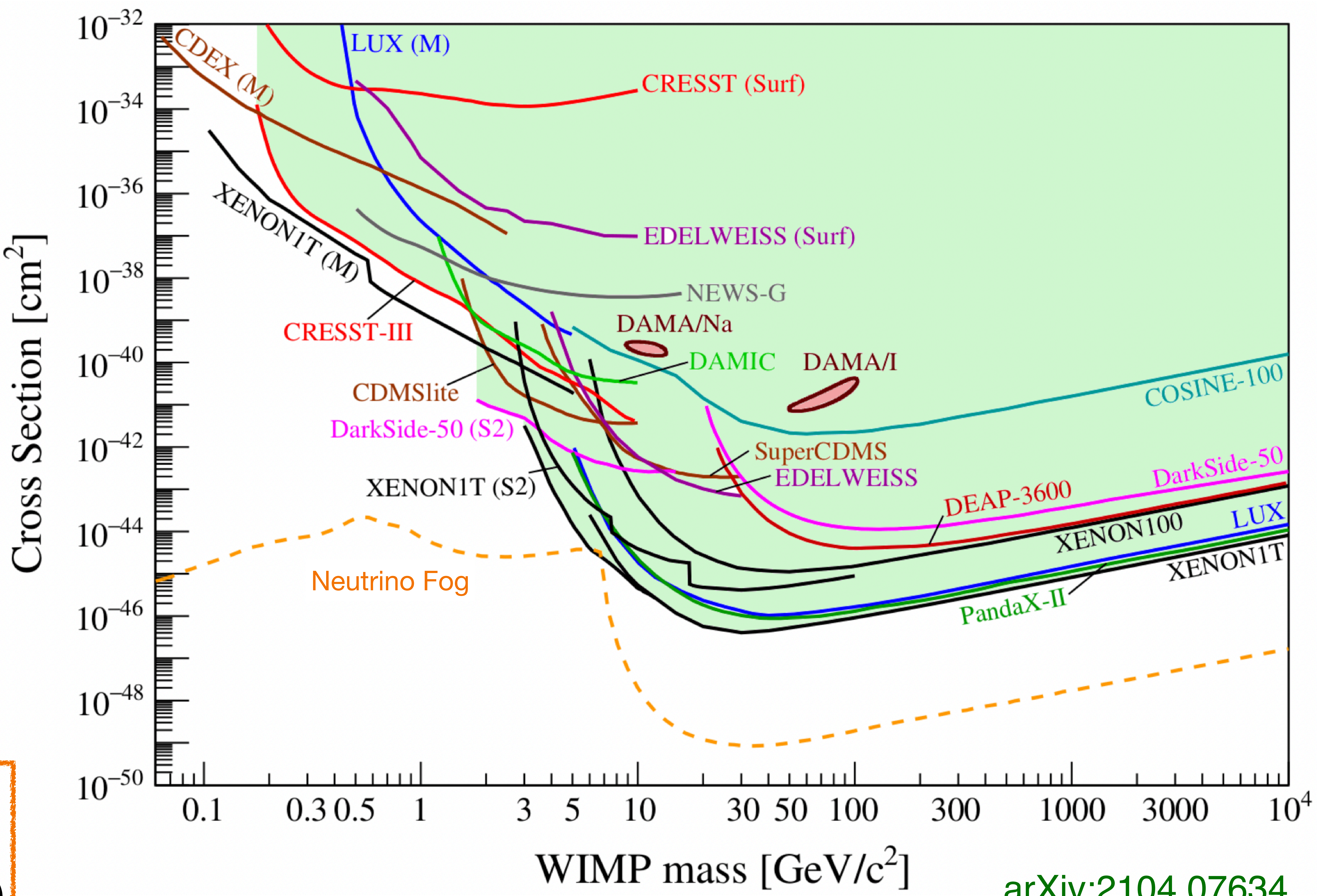
DEAP3600



(also LUX-ZEPLIN, DARWIN, PANDA-X, DarkSide)

Review with G. Rieschbieter talk (Friday afternoon session)

- Dominance above O(1 GeV/c²)
- Preferred parameter space for many WIMP candidates already covered, neutrino fog looms.
- What to do?



arXiv:2104.07634

A. Kamaha &
D. Ramírez García talks
(Thursday morning session)

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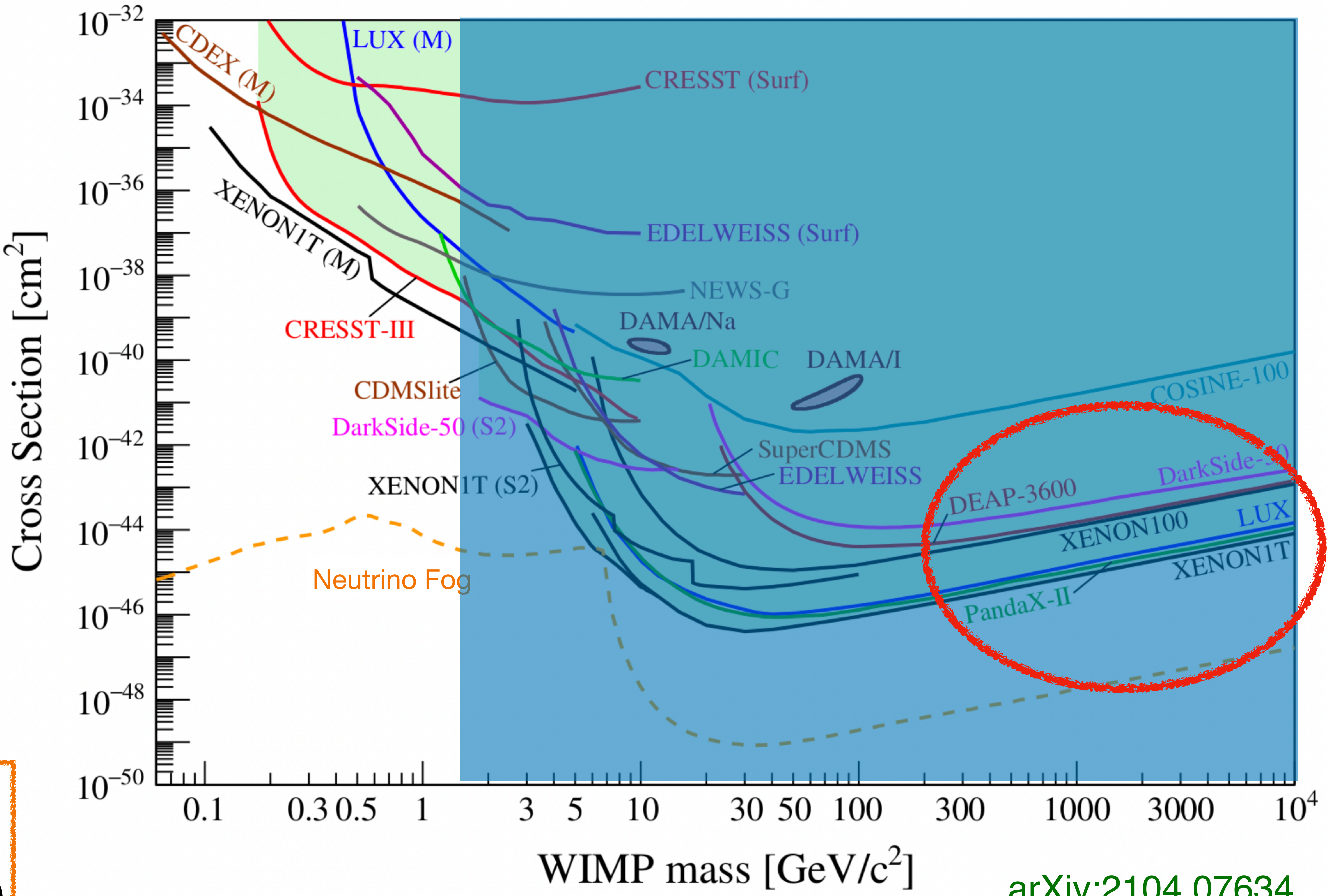

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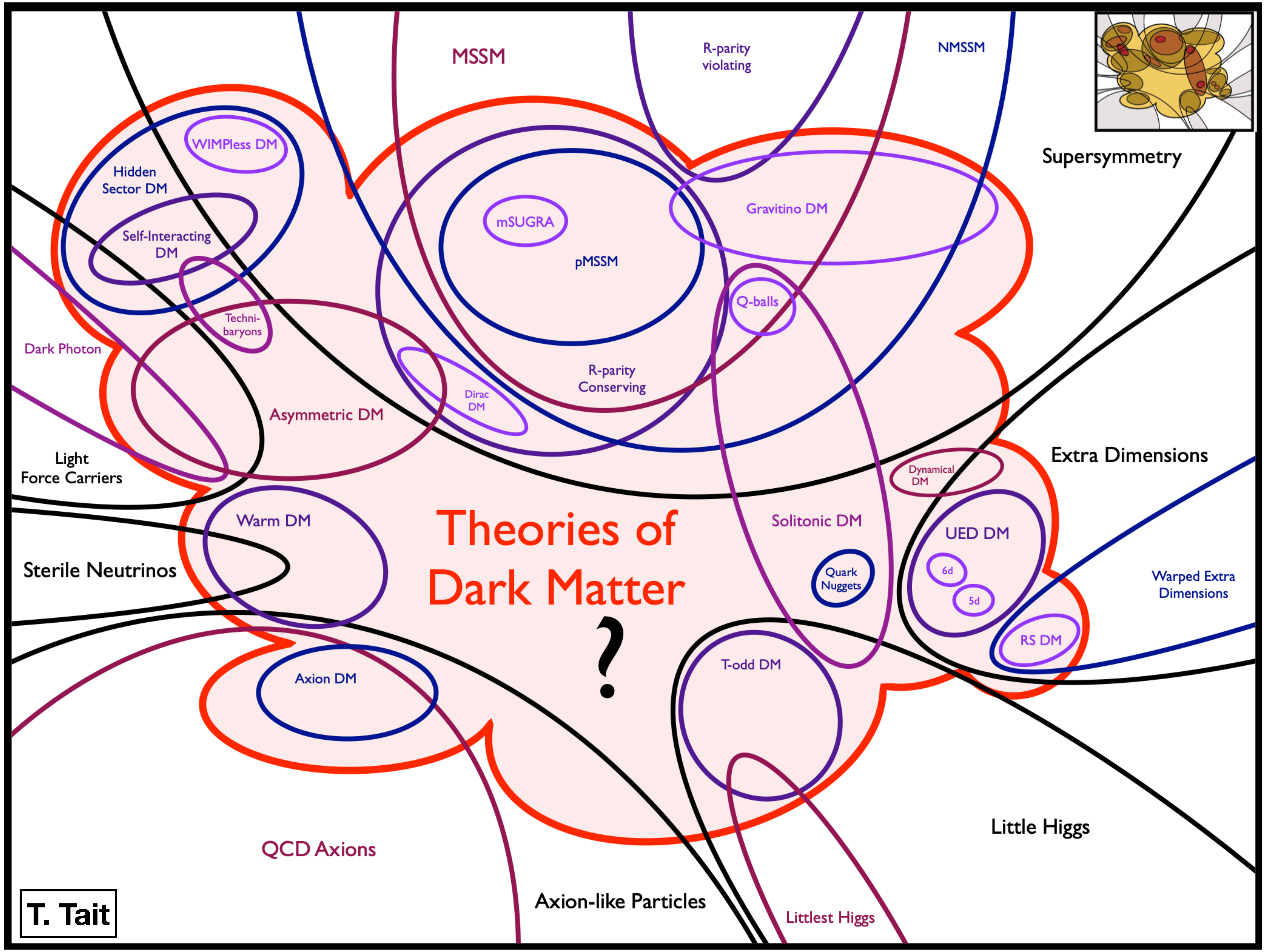
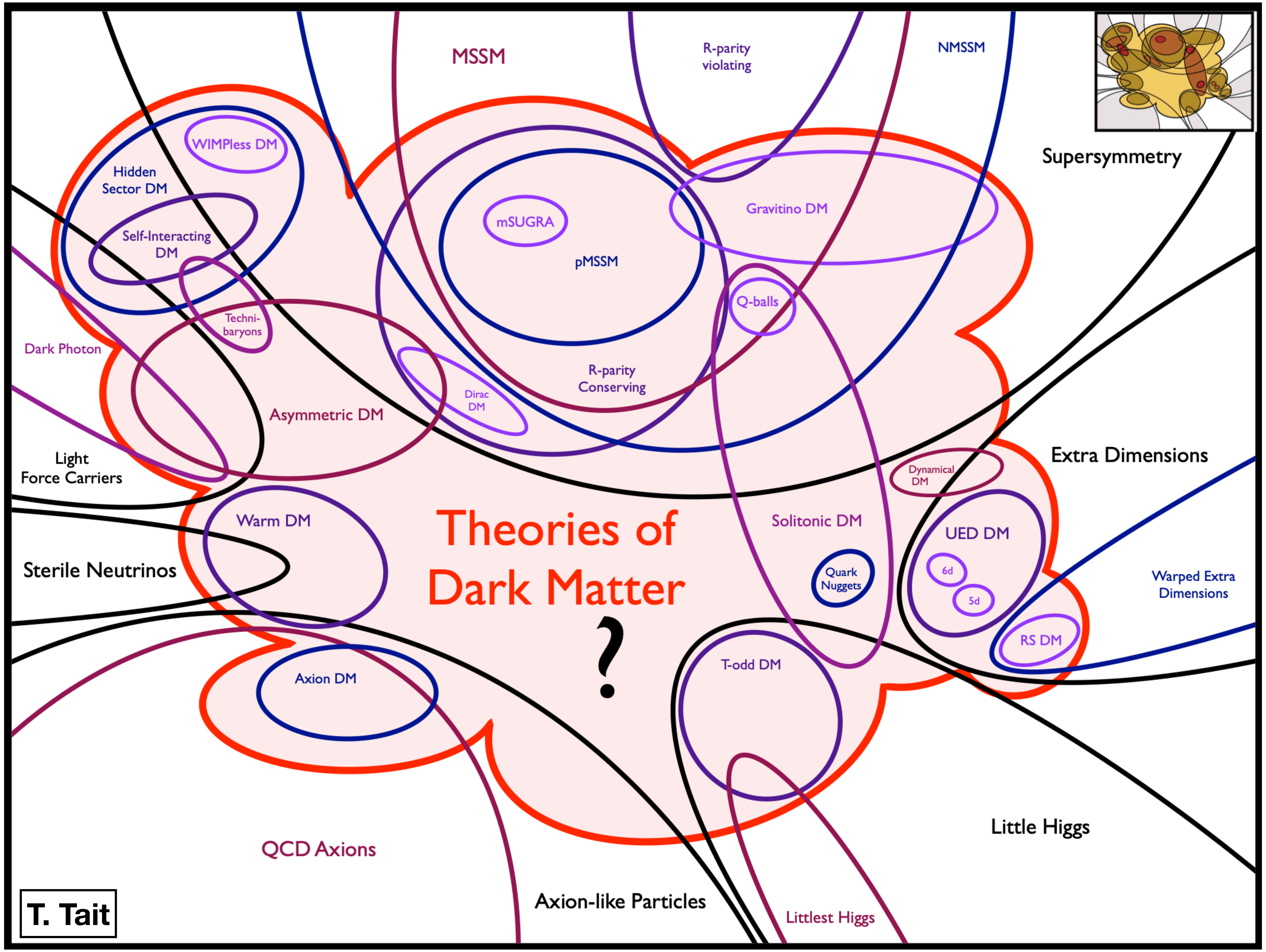
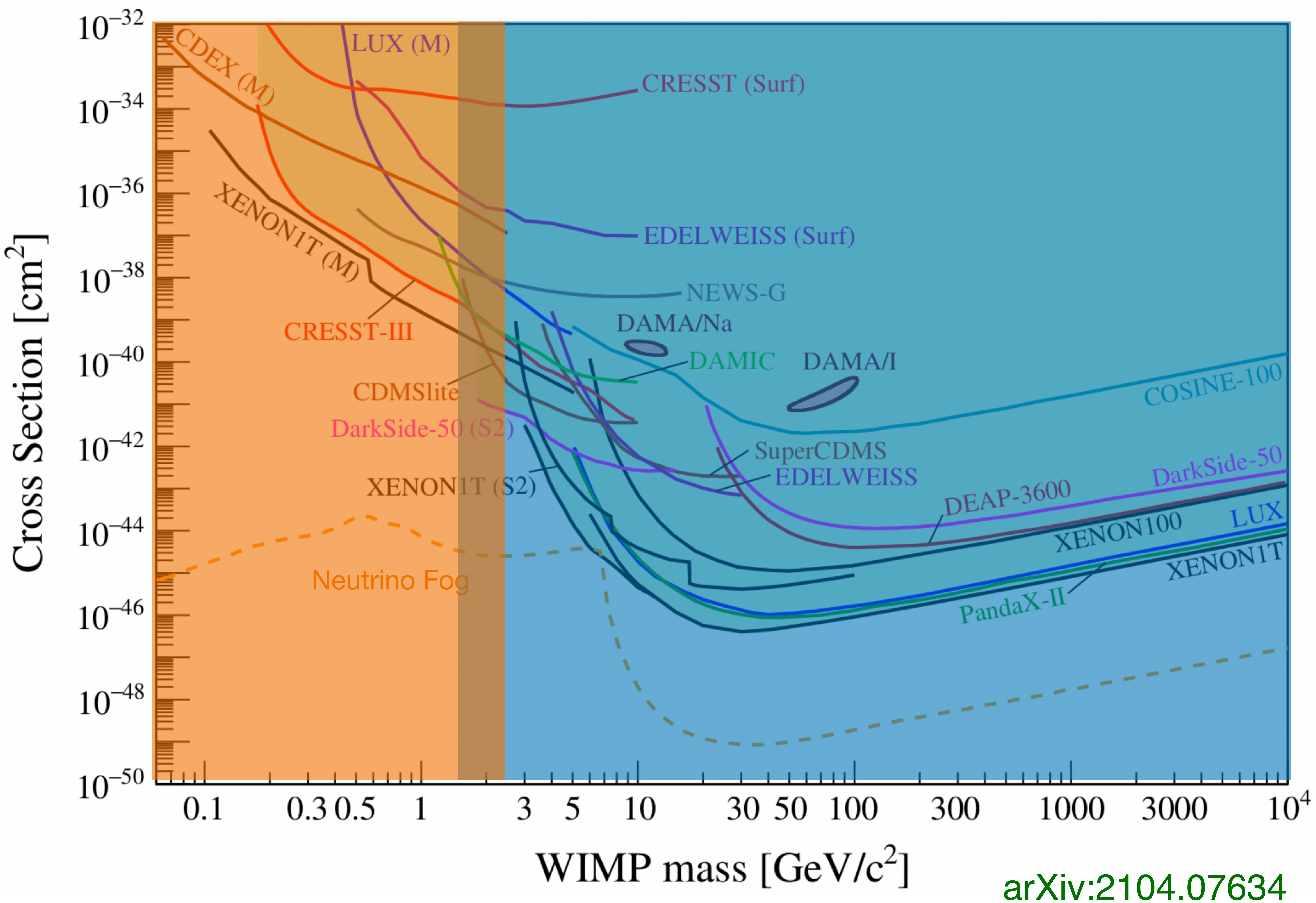

MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T. Tait



- I don’t understand this diagram
- But I can tell you where we’ve been looking!

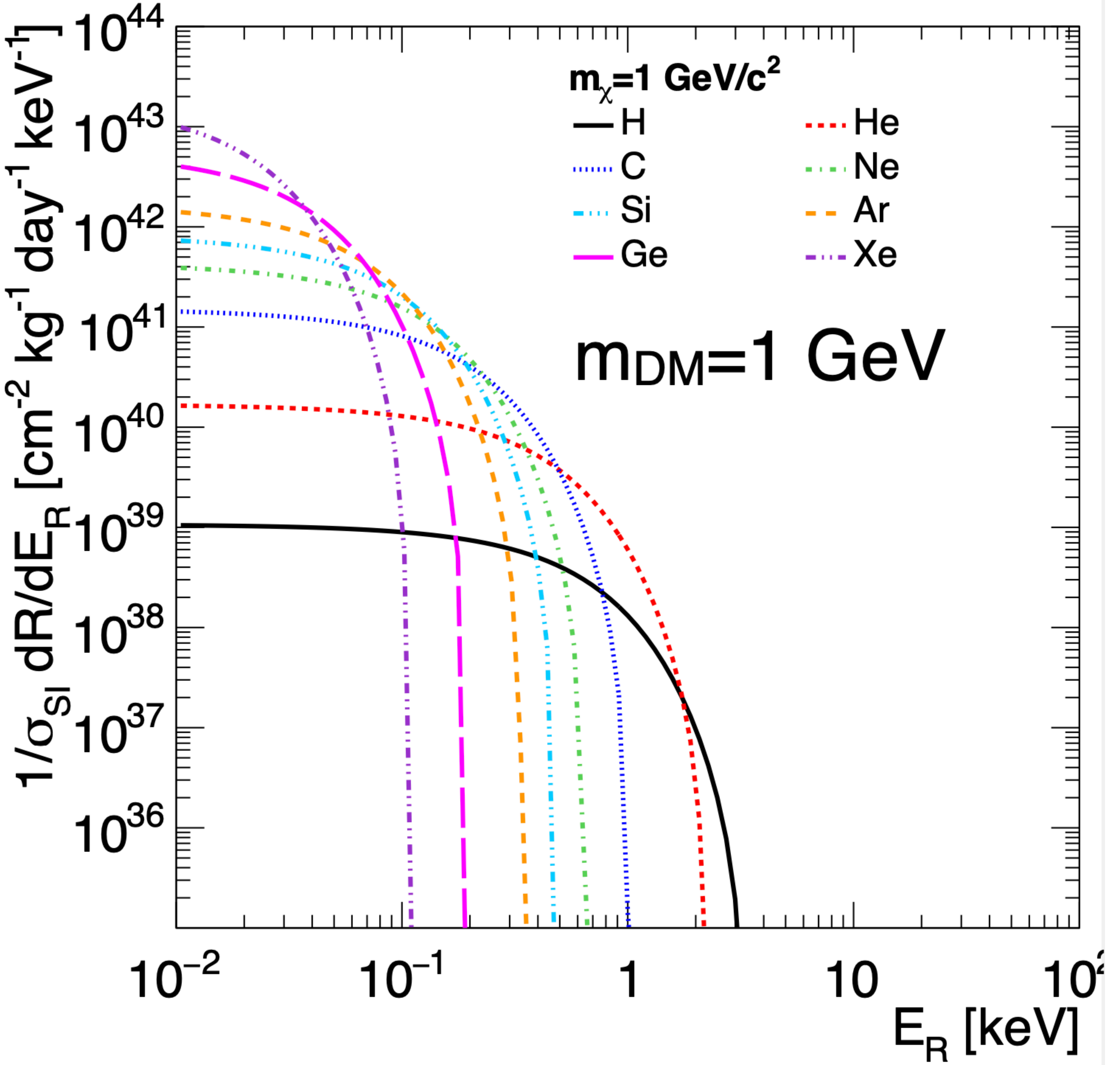
Let's look for SubGeV «WIMPs»!

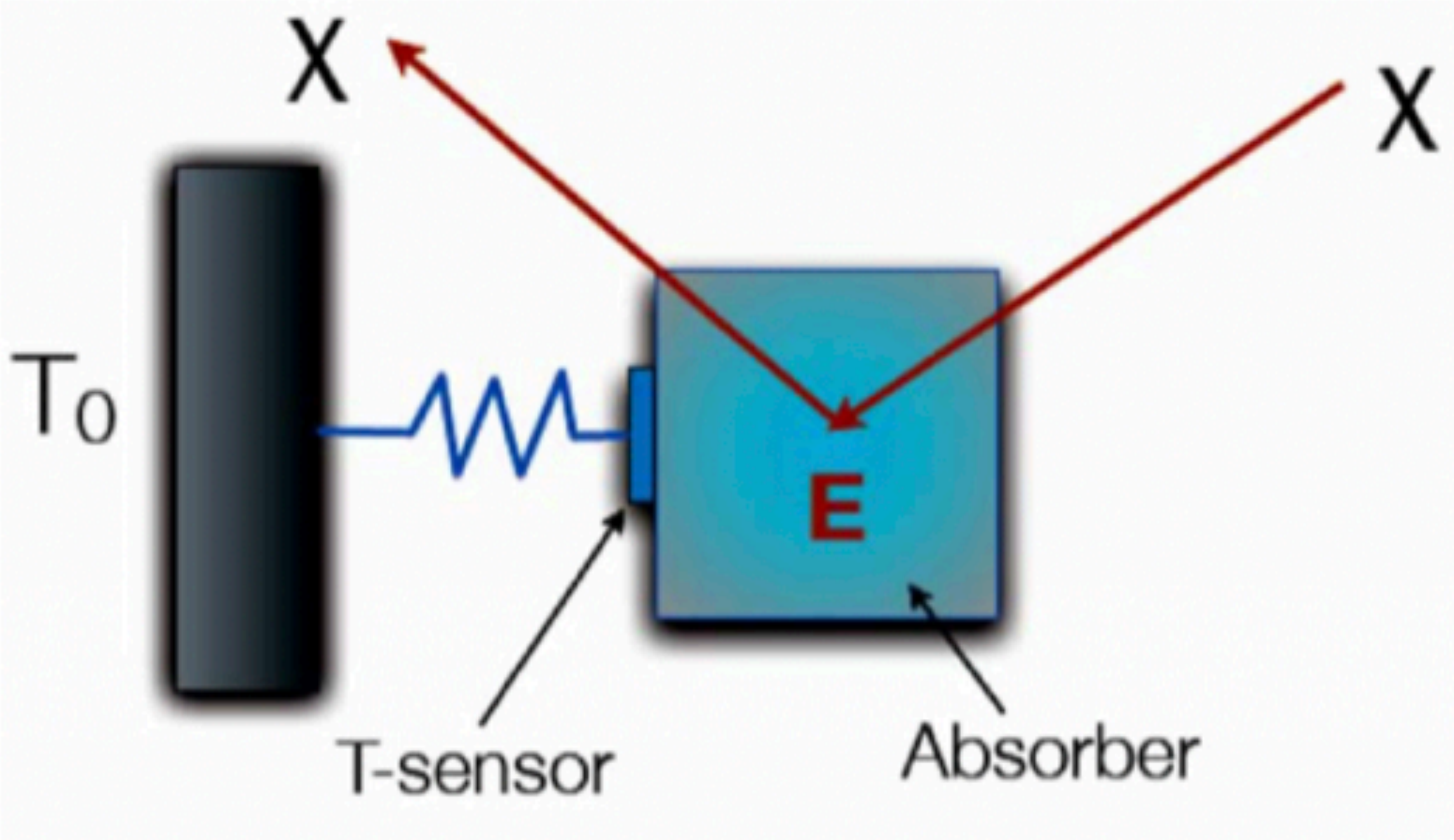
…How?



arXiv:2104.07634

- Maximum WIMP-nucleus energy transfer in elastic recoil when they have the same mass («kinematic match»)
- Liquid noble detectors have ~1 keV energy tresholds, limiting sensitivity to low WIMP masses
- To go under 1 GeV/c^2 masses, need:
  - **lower atomic mass target**
  - **low energy threshold**



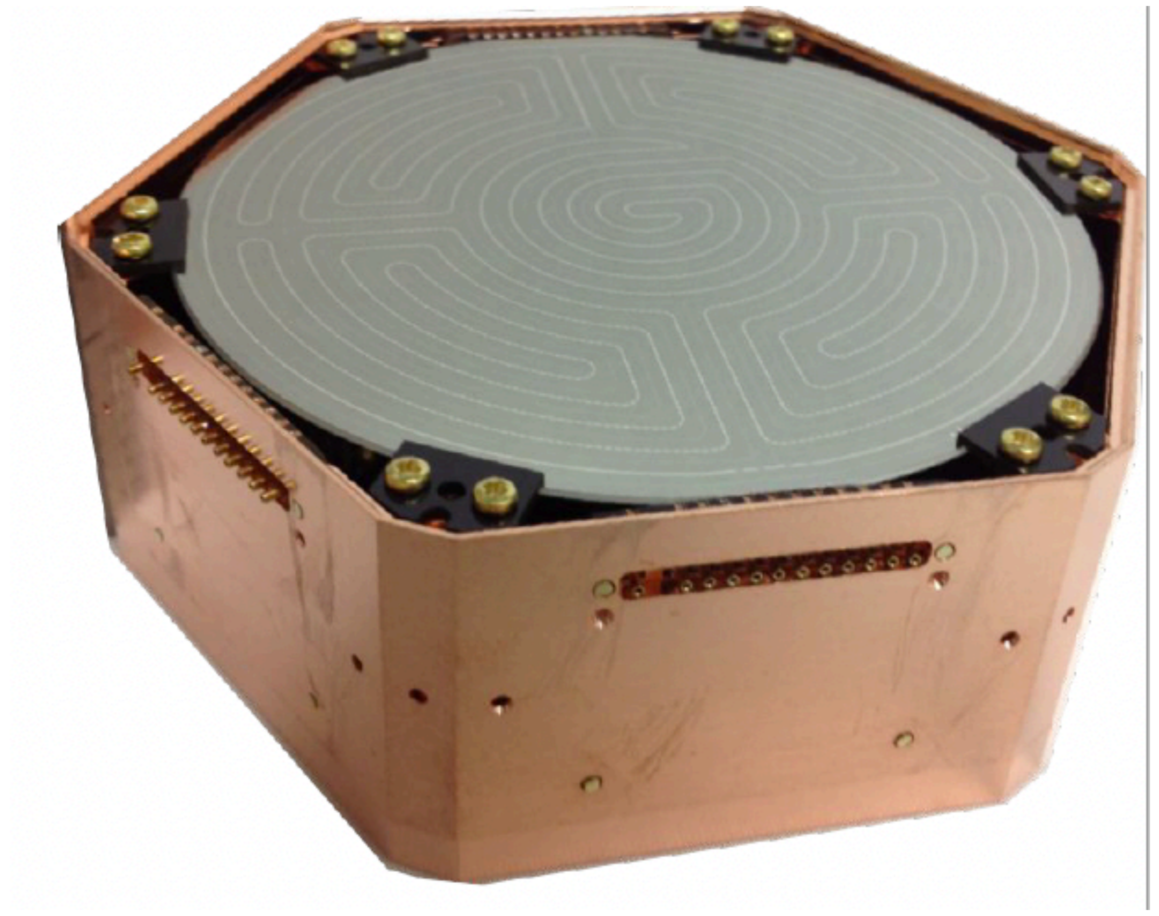


$$C(T) = \frac{\Delta E}{\Delta T} \propto T^3$$

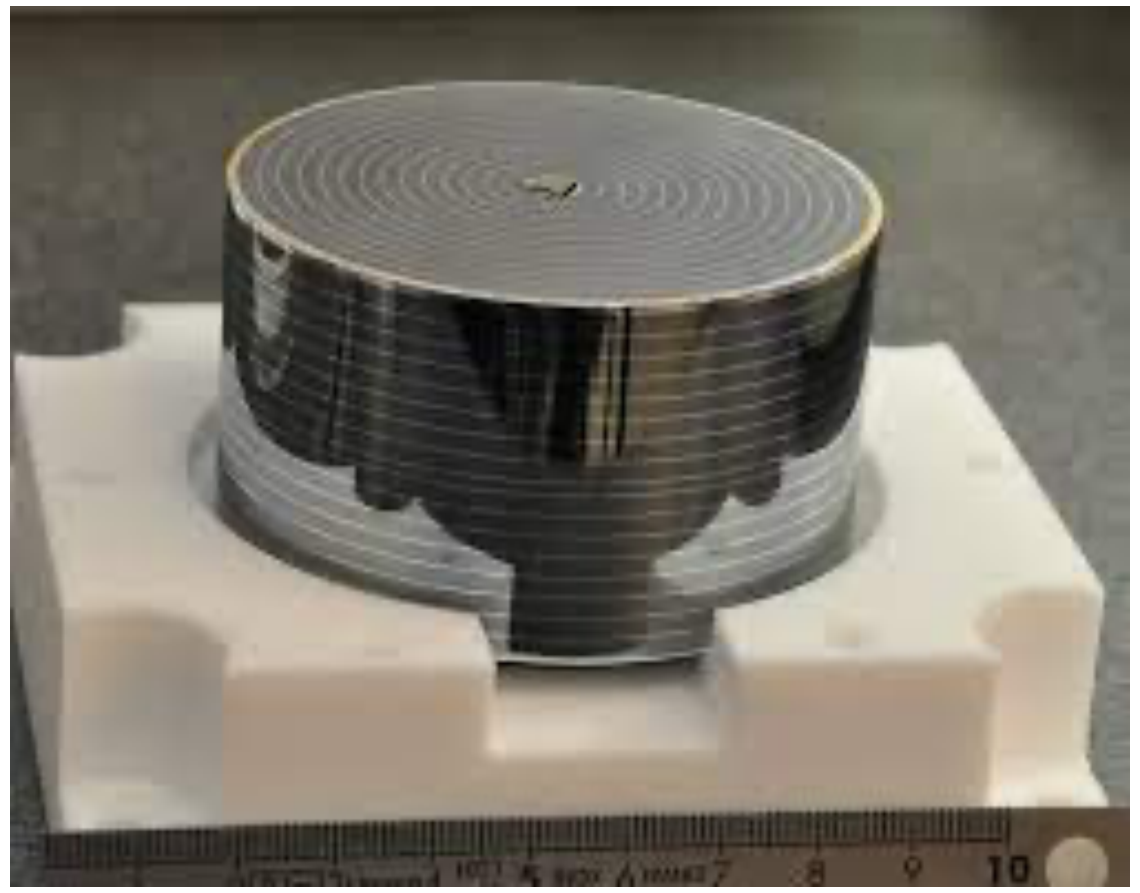
Need small heat capacity!
Need small temperature (mK)

Section based on R. Strauss review at IDM'22
https://indico.cern.ch/event/922783/contributions/4897442/

SuperCDMS
Silicon&Germanium



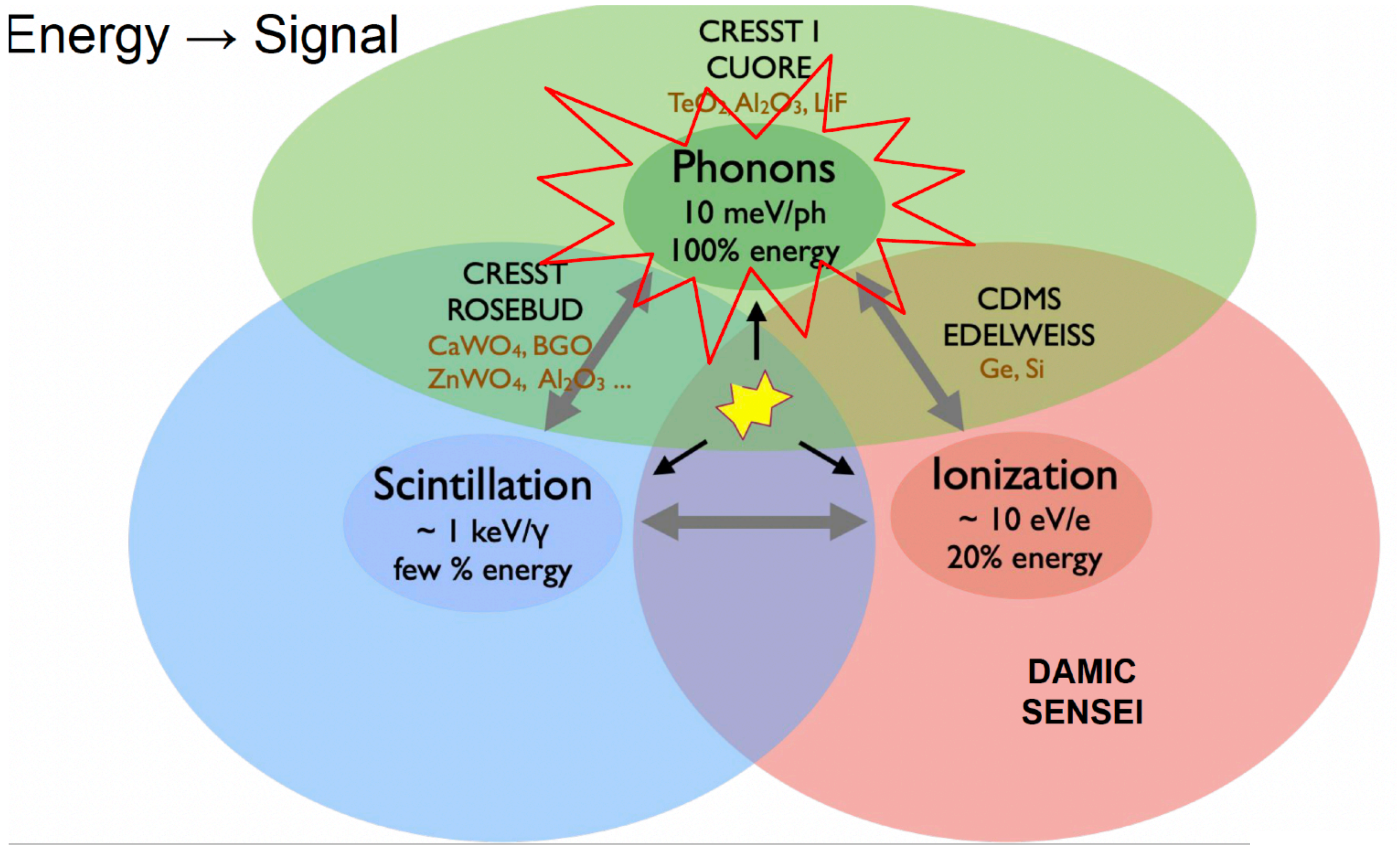
EDELWEISS
Germanium



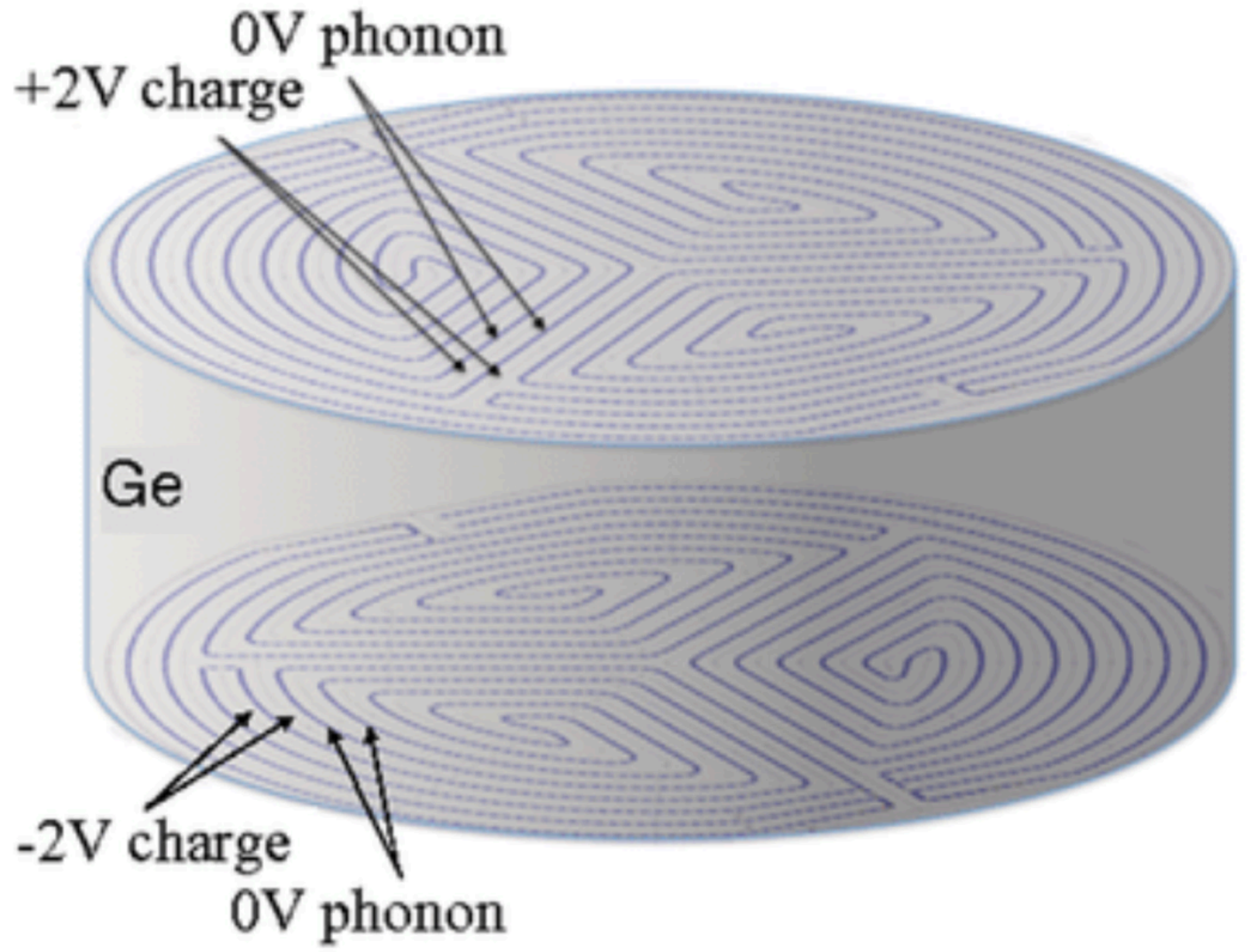
Use material at cryogenic temperatures (10-40mK) with «thermometer» (NTD or TES) to measure energy depositions from nuclear recoils

Main players : SuperCDMS, EDELWEISS, CRESST

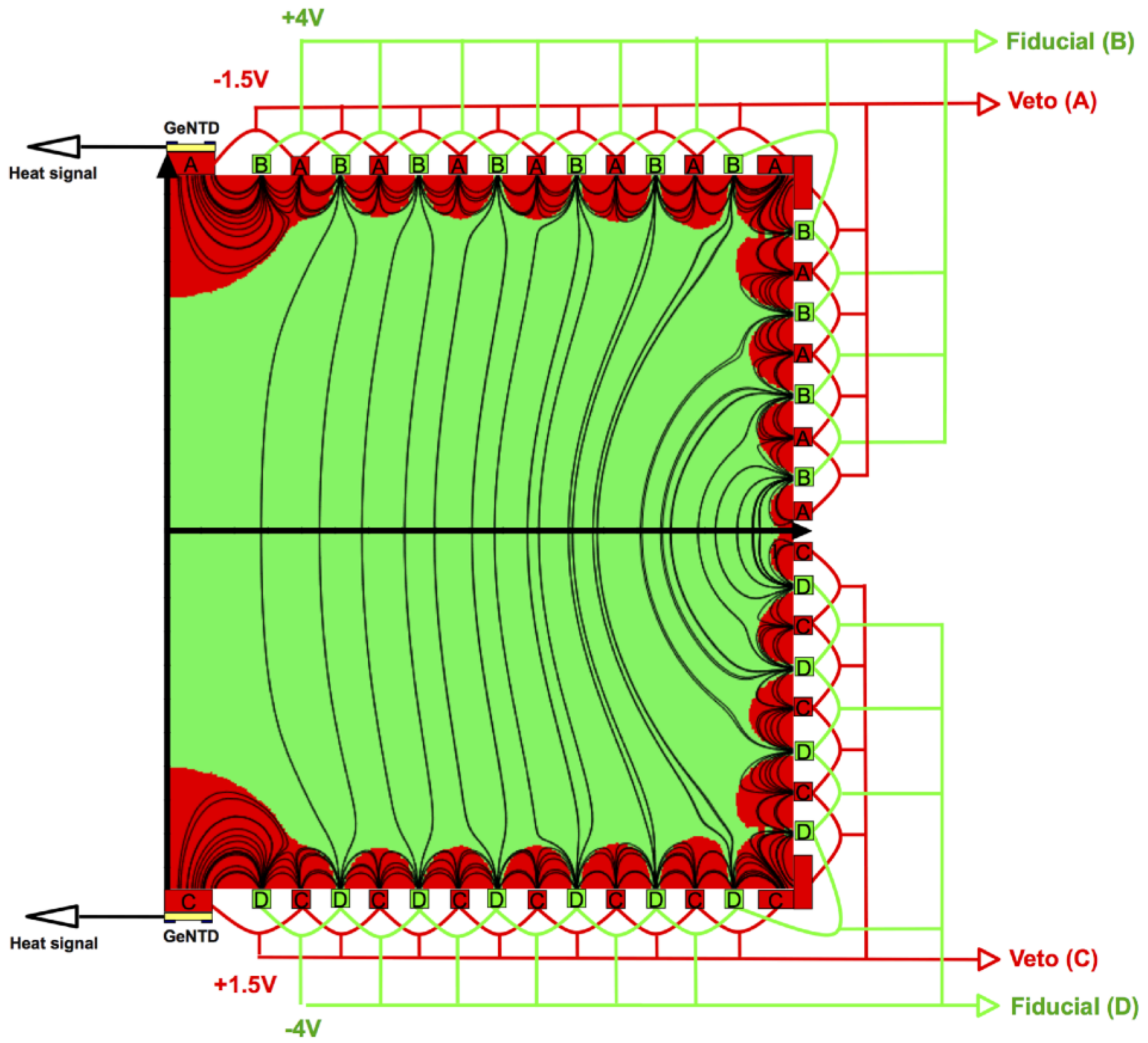
CRESST
$CaWO_4$ (&others)



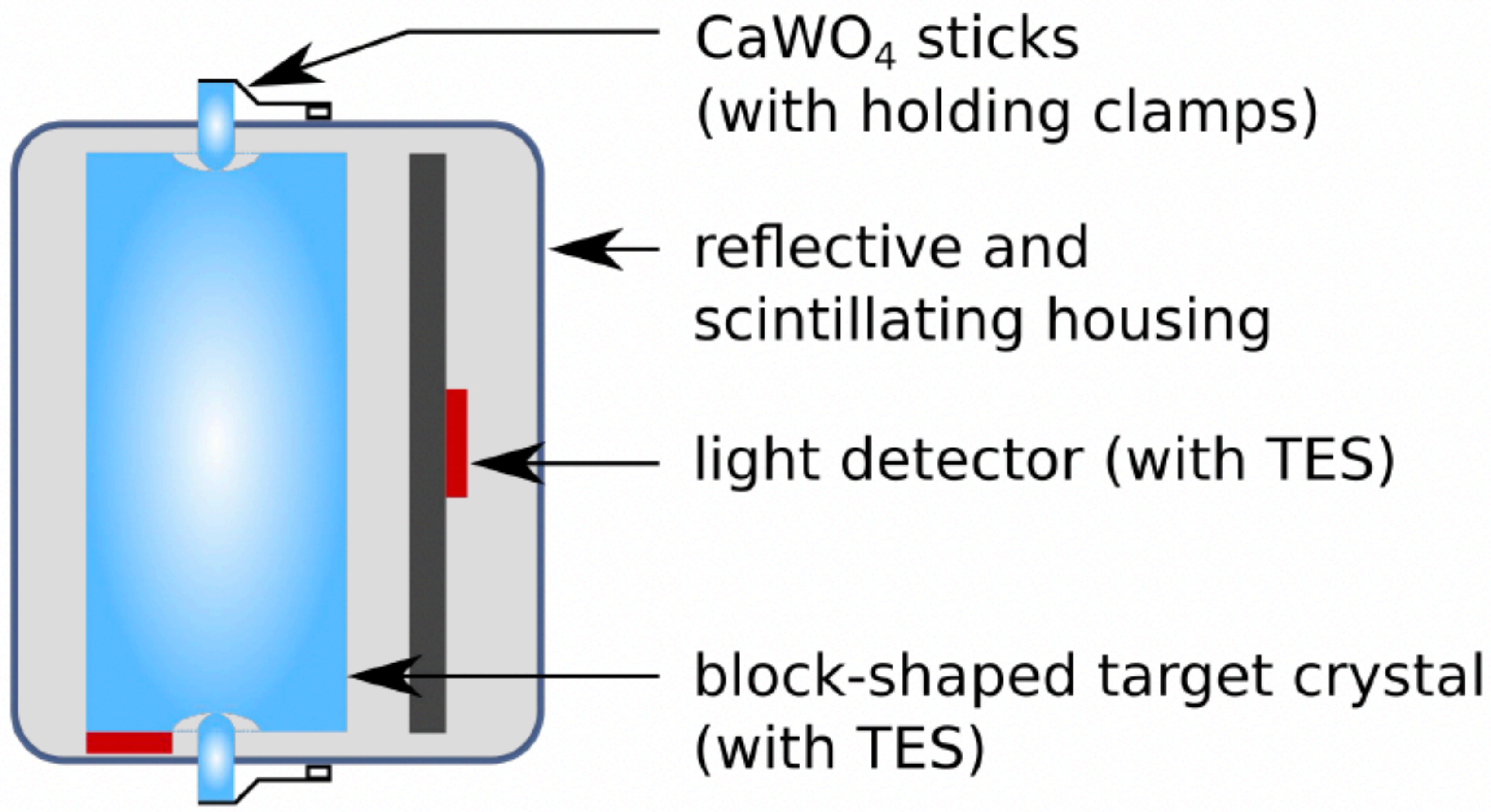
- Phonon/thermal channel for energy measurement of recoil
- Secondary channel (CDMS, EDELWEISS: ionization; CRESST: Scintillation) for background rejection



SuperCDMS

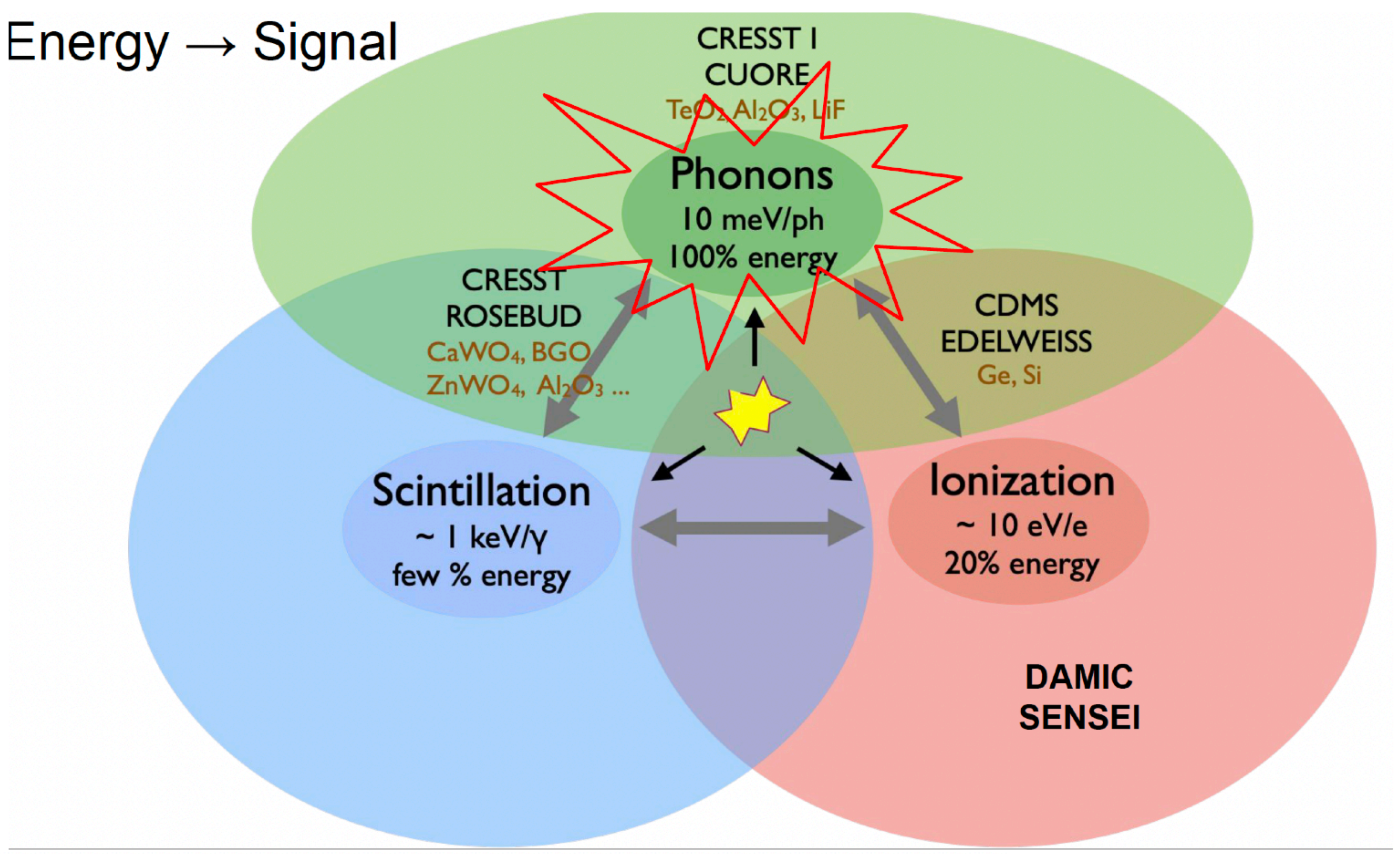


EDELWEISS



J. Phys.: Conf. Ser. 1342 012076

CRESST-III



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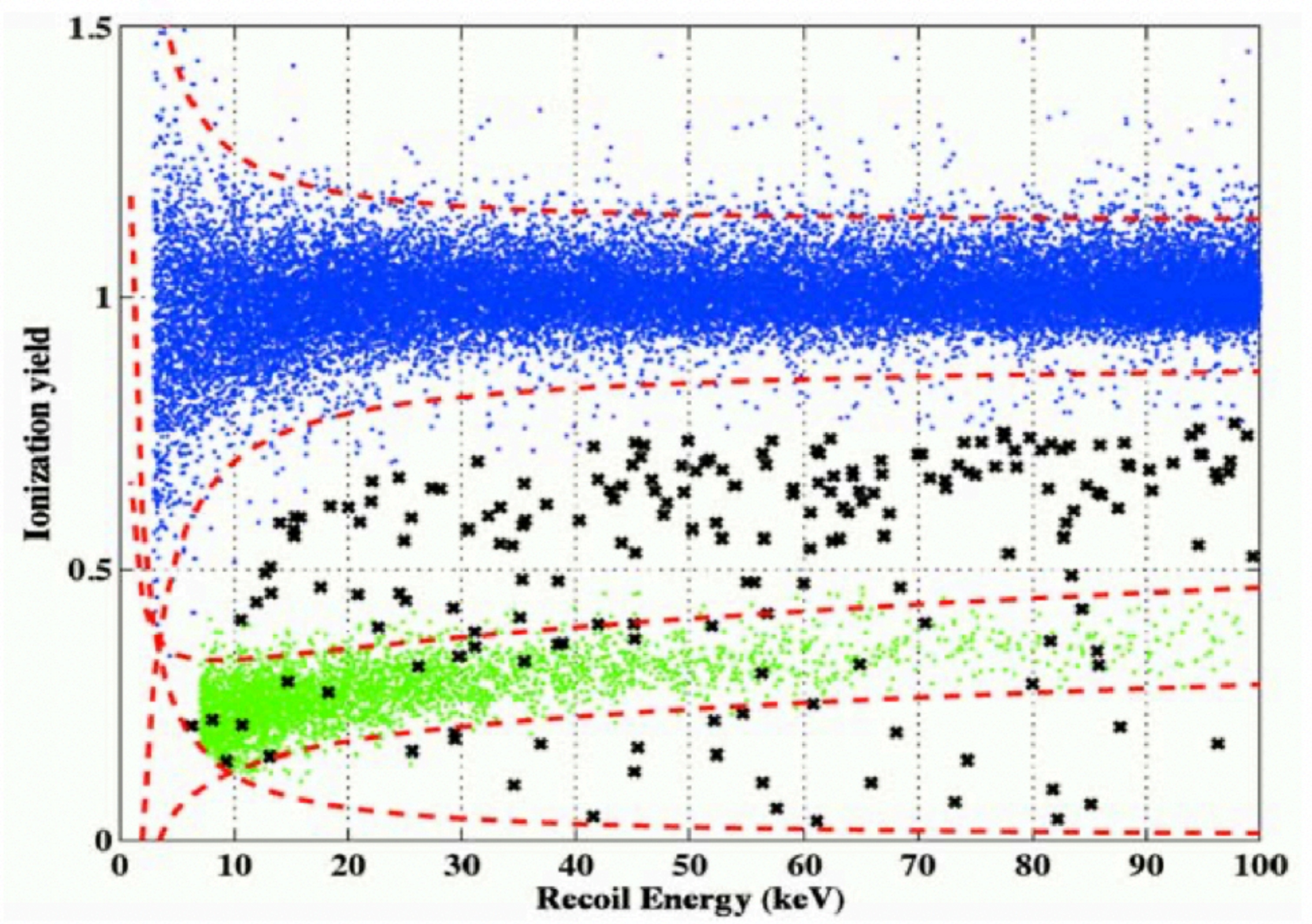
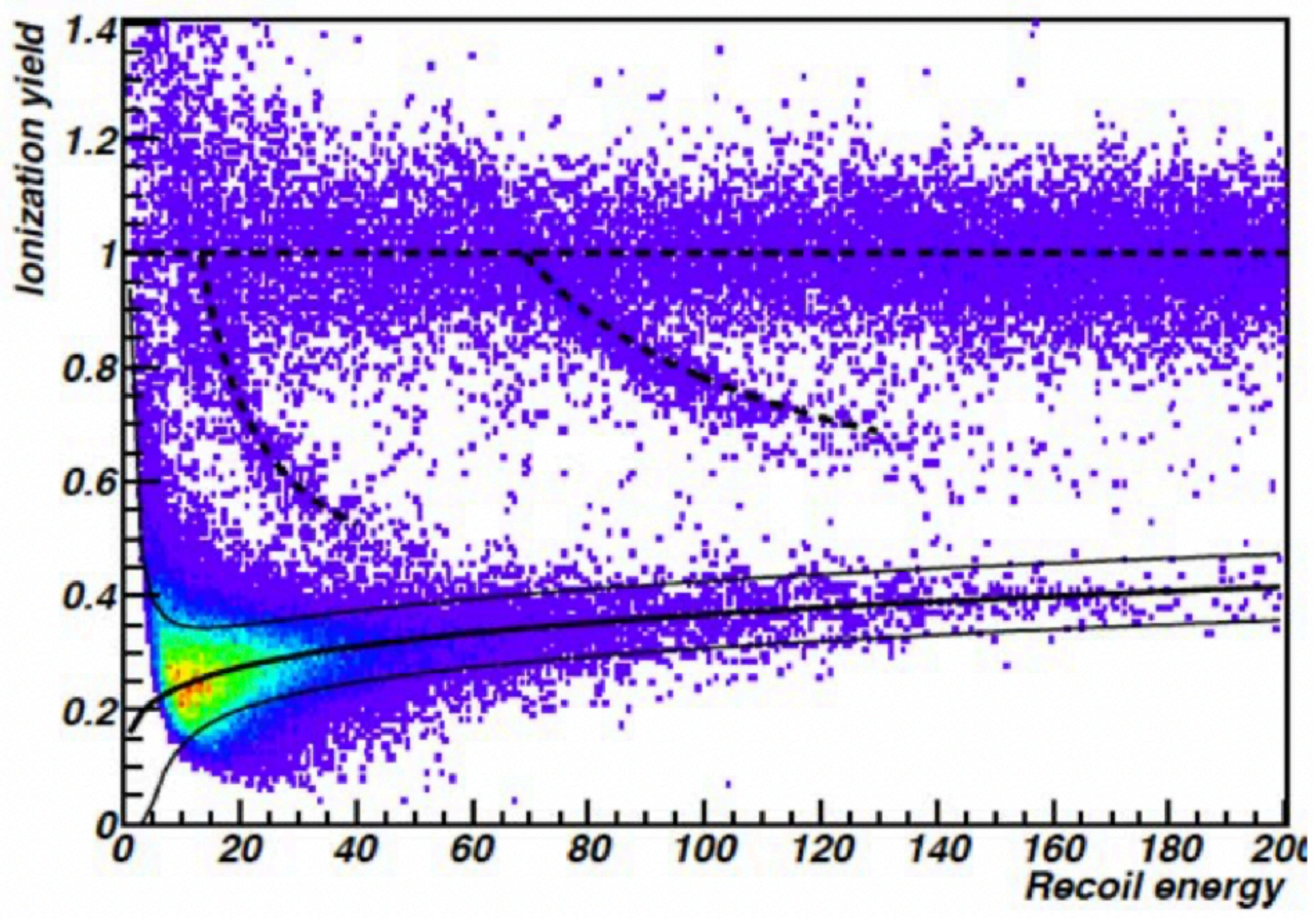
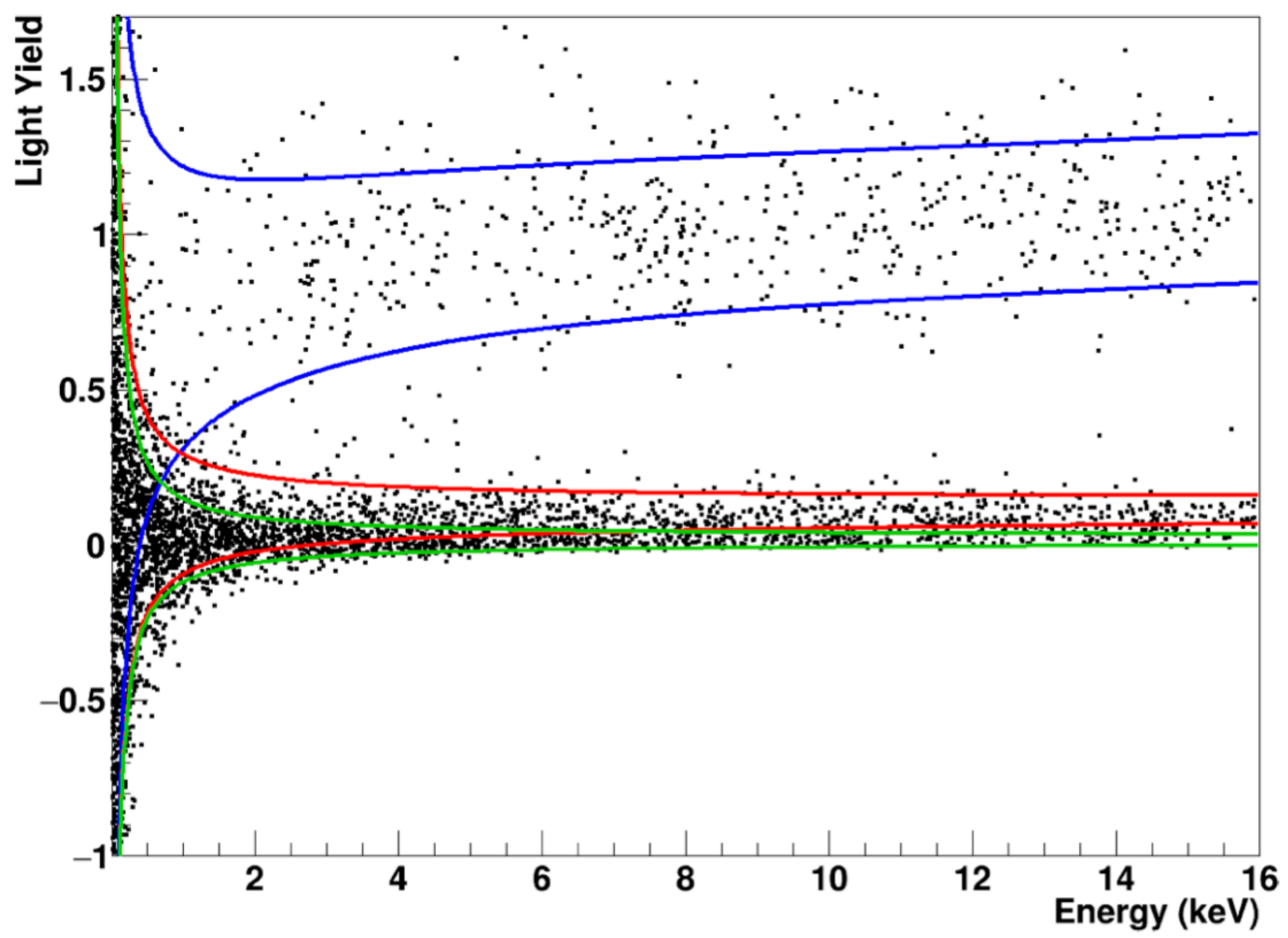


SuperCDMS



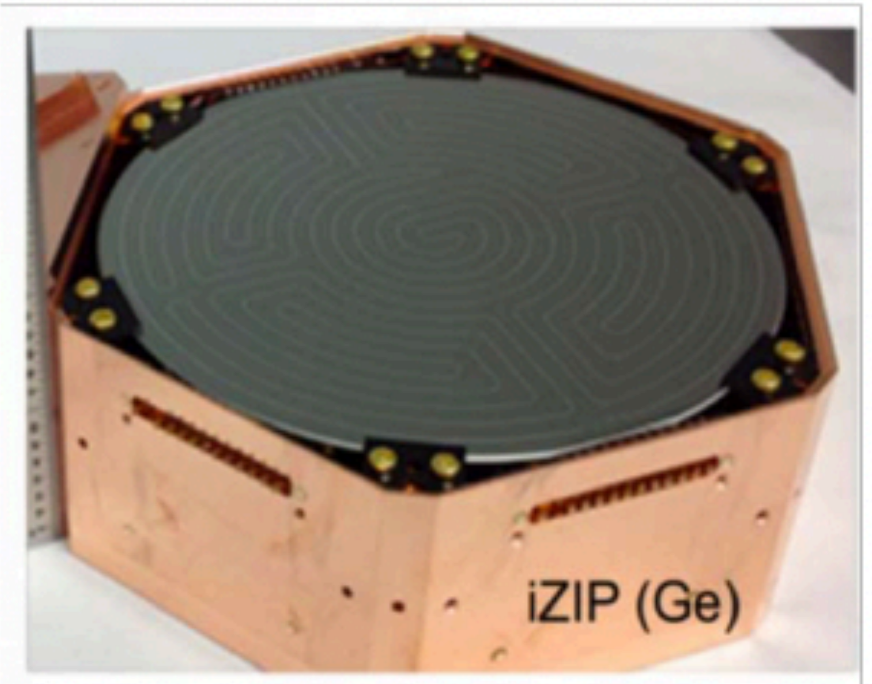
EDELWEISS



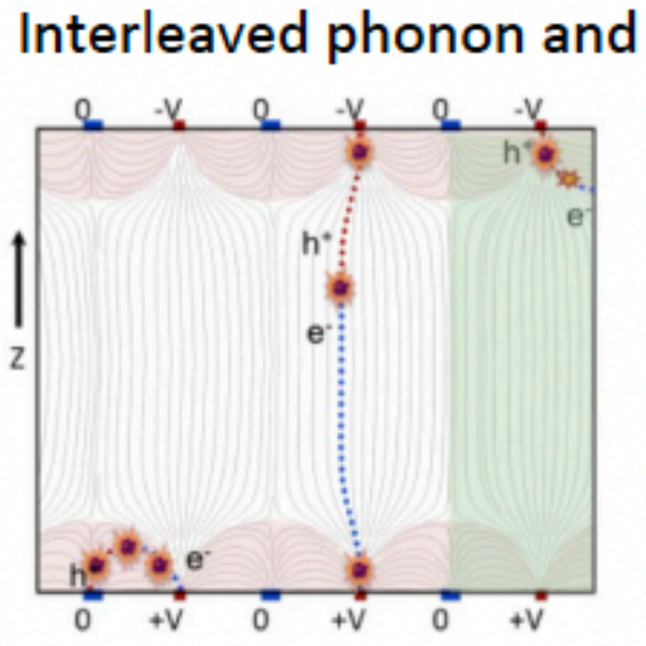
CRESST-III

SuperCDMS

Phys. Rev. D 97 (2018)



1.4kg Ge

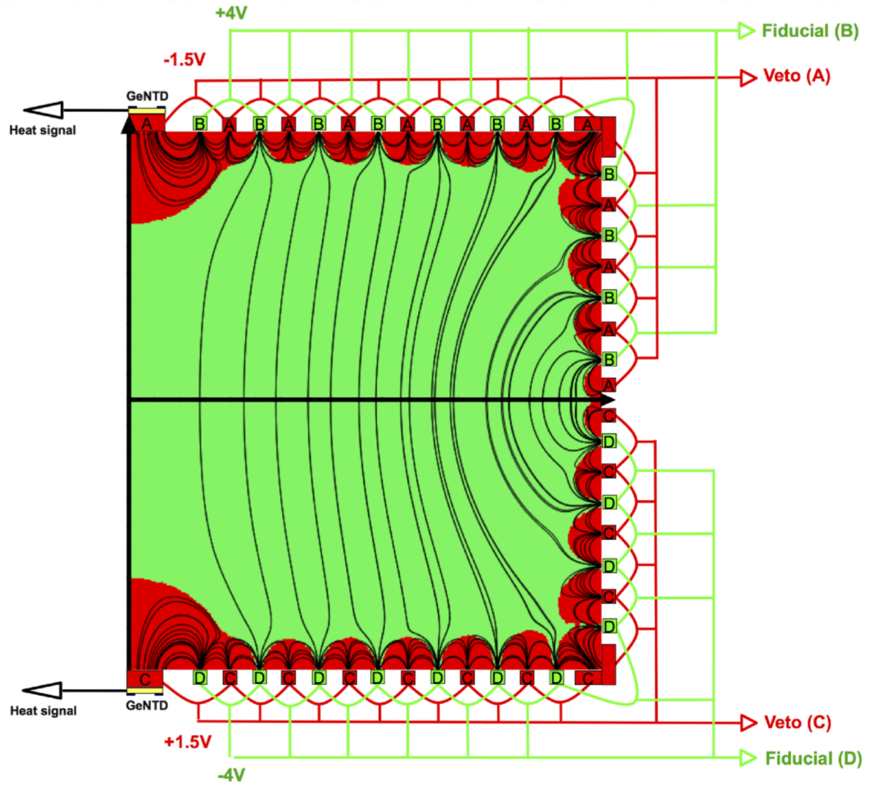


→ Particle discrimination

→ E_{th} ~ 150 eV_{nr}

EDELWEISS

JCAP05(2016)019

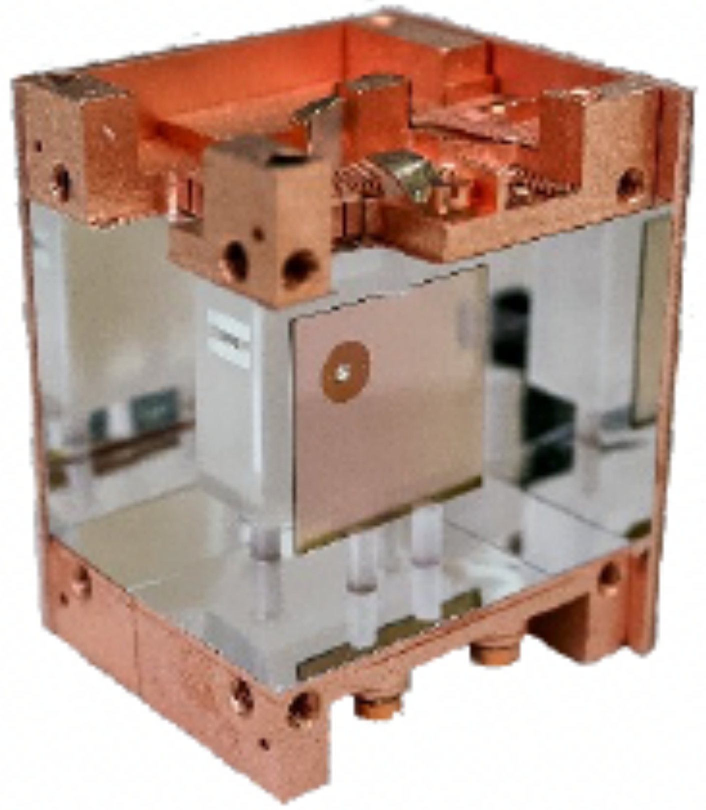


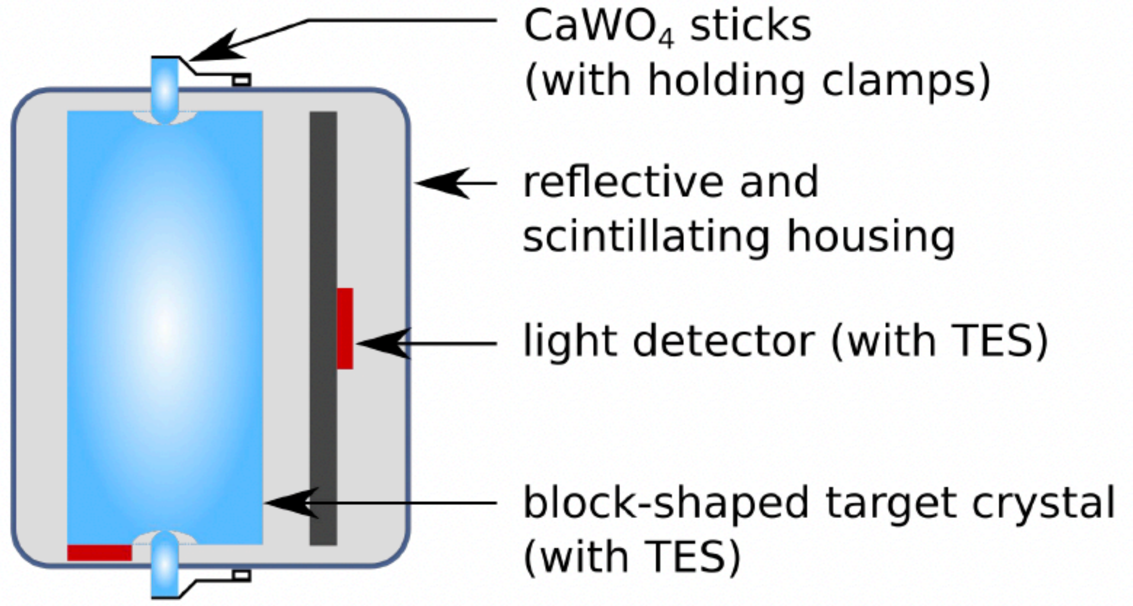
Particle discrimination

E_{th} ~ 1 keV_{nr}

CRESST-III

PRD 100 102002 (2019)



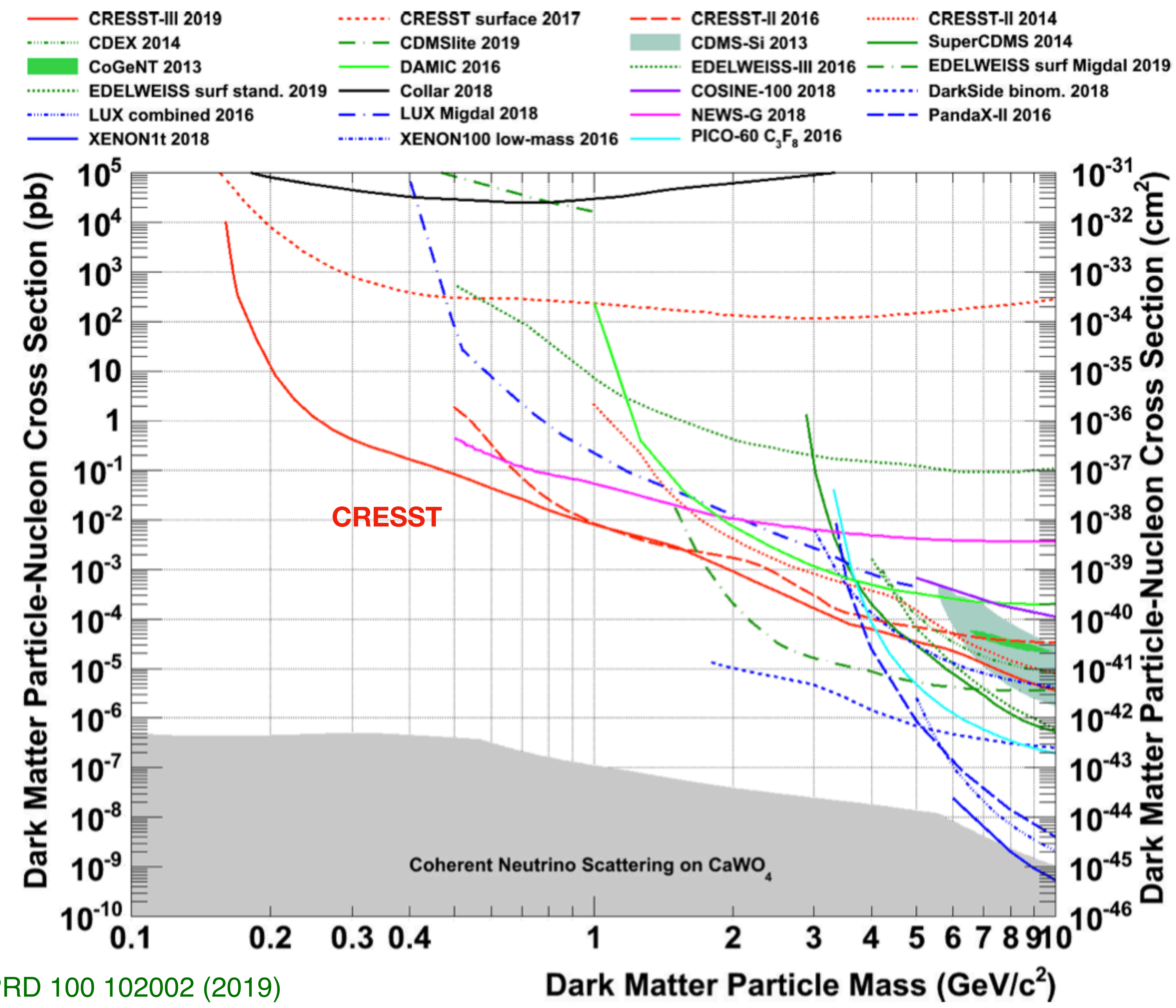


J. Phys.: Conf. Ser. 1342 012076

Particle discrimination

E_{th} = 30.1eV_{nr}

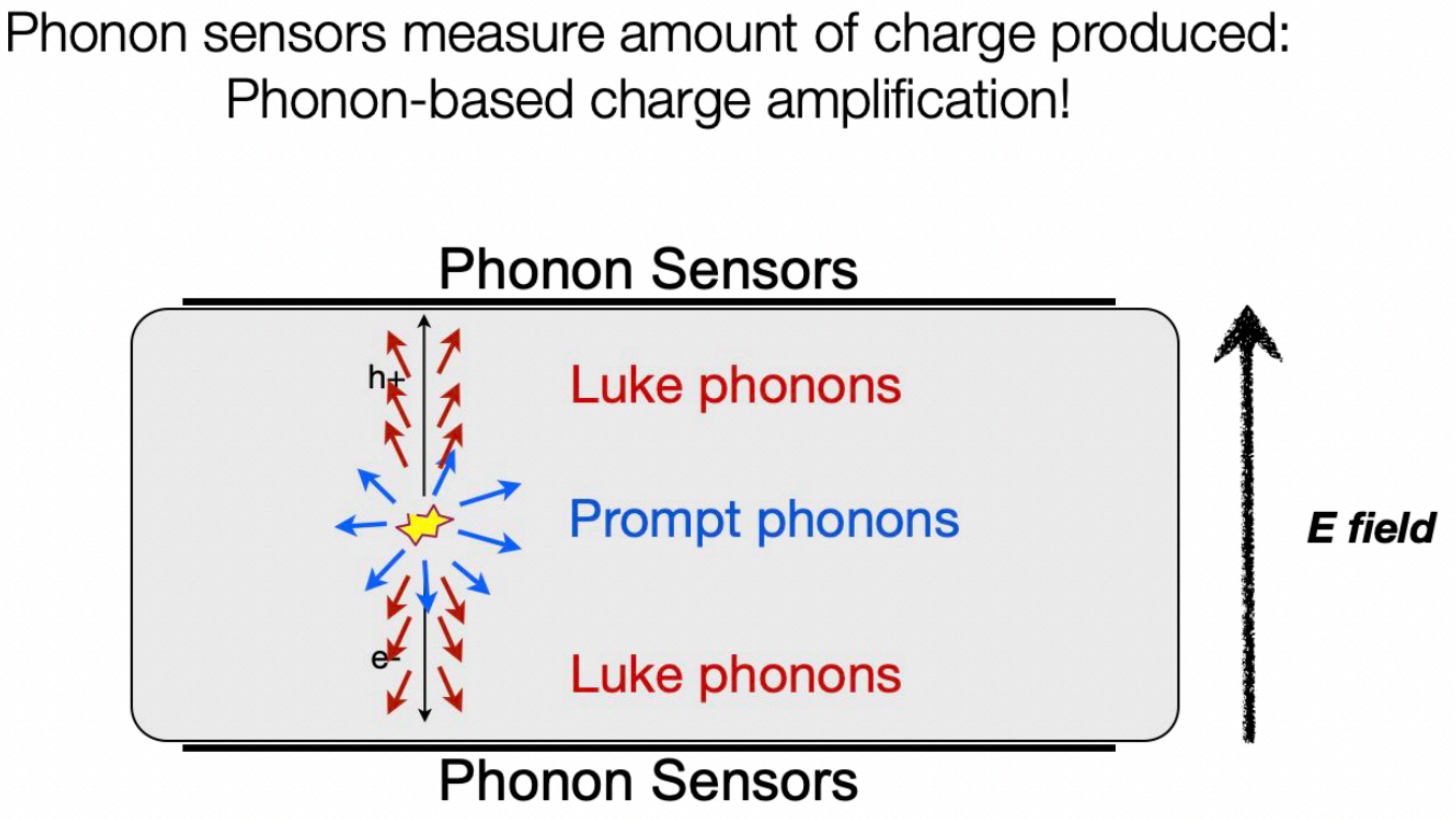
Leading SI limit down to 150 MeV/c^2



PRD 100 102002 (2019)

Reach down to 150 MeV/c²!

More CRESST-III news at A. Kinast talk (Friday afternoon session)

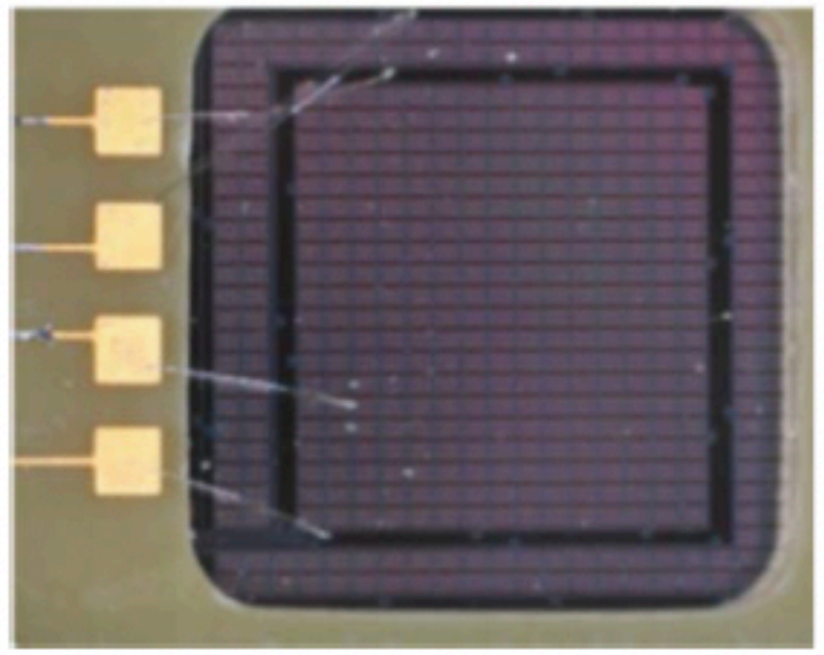


$$\text{Phonon energy} = E_{recoil} + E_{Luke} = E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

For phonon-ionisation detectors, boost ionisation signal by increasing the voltage applied on bolometer

- Advantage : much lower threshold
- Disadvantage : lose particle discrimination

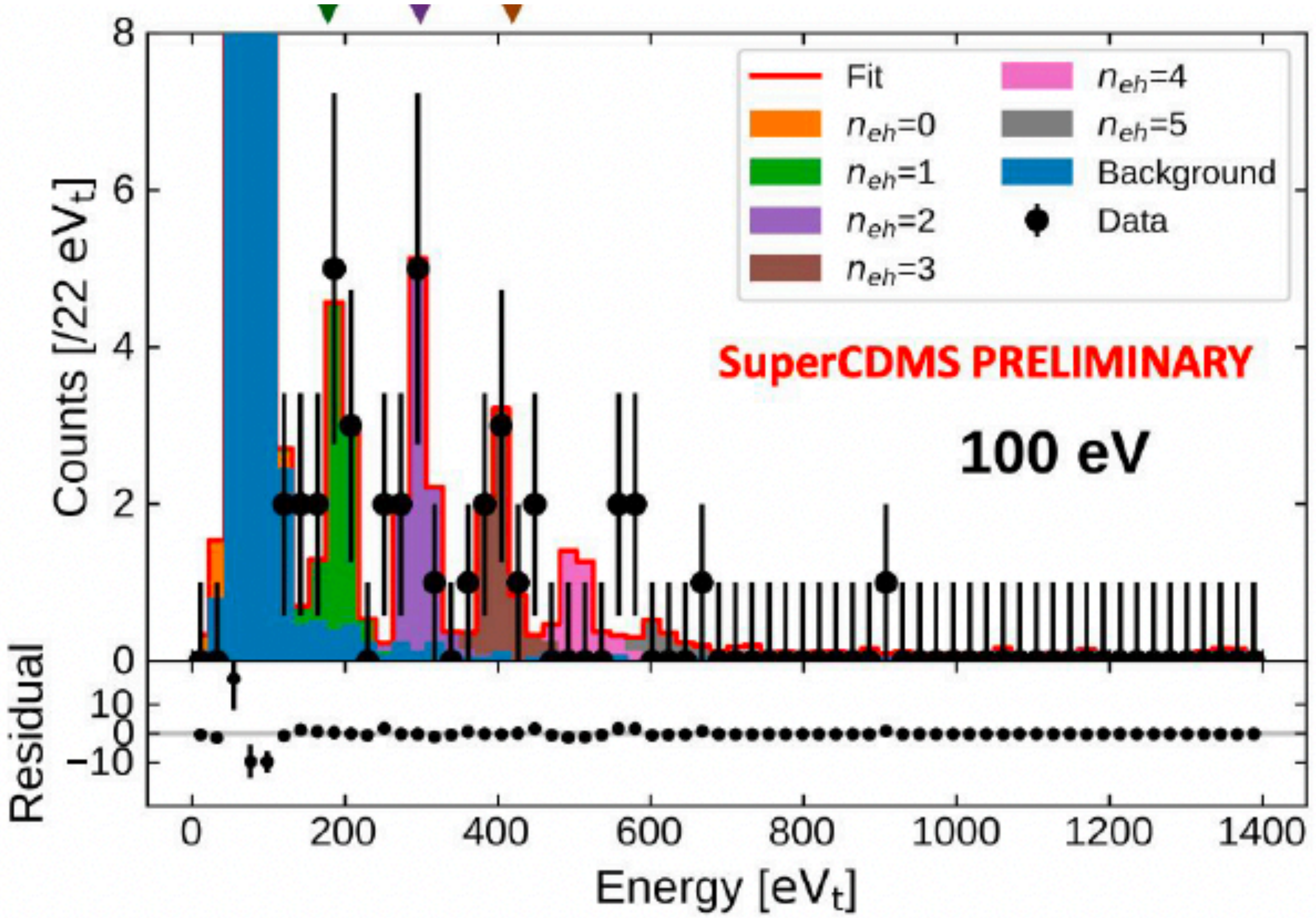
SuperCDMS @ Surface



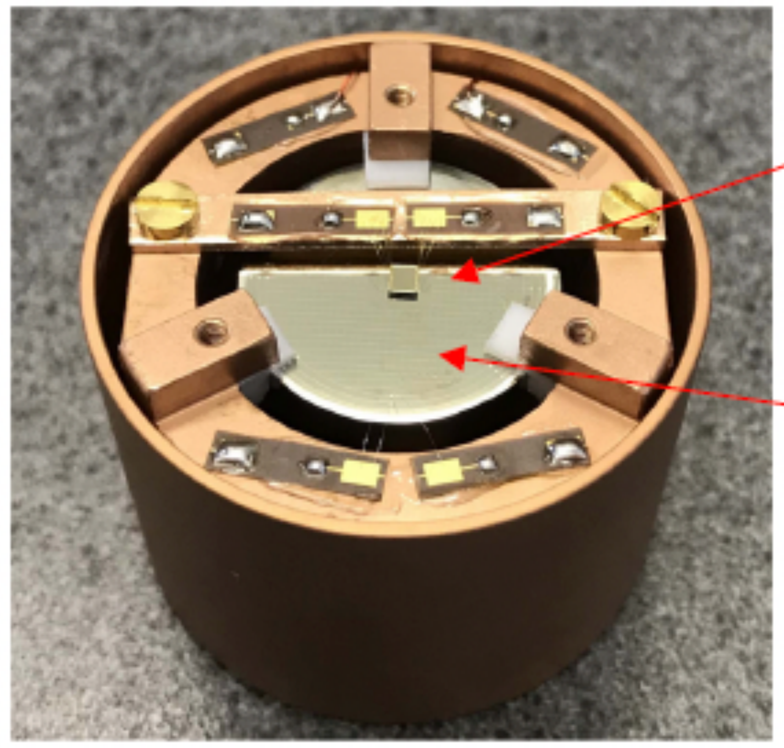
HVeV detector
Phys. Rev. Lett. **121**, 051301
1cm^2 x 4mm Si wafer

→ Single e-h resolution
E_{th} = 9.2 eV_{nr}

(& CPD detector : E_{th} = 16.3eV_{nr})
Phys. Rev. Lett. **127**, 061801 (2021)



EDELWEISS @ Surface

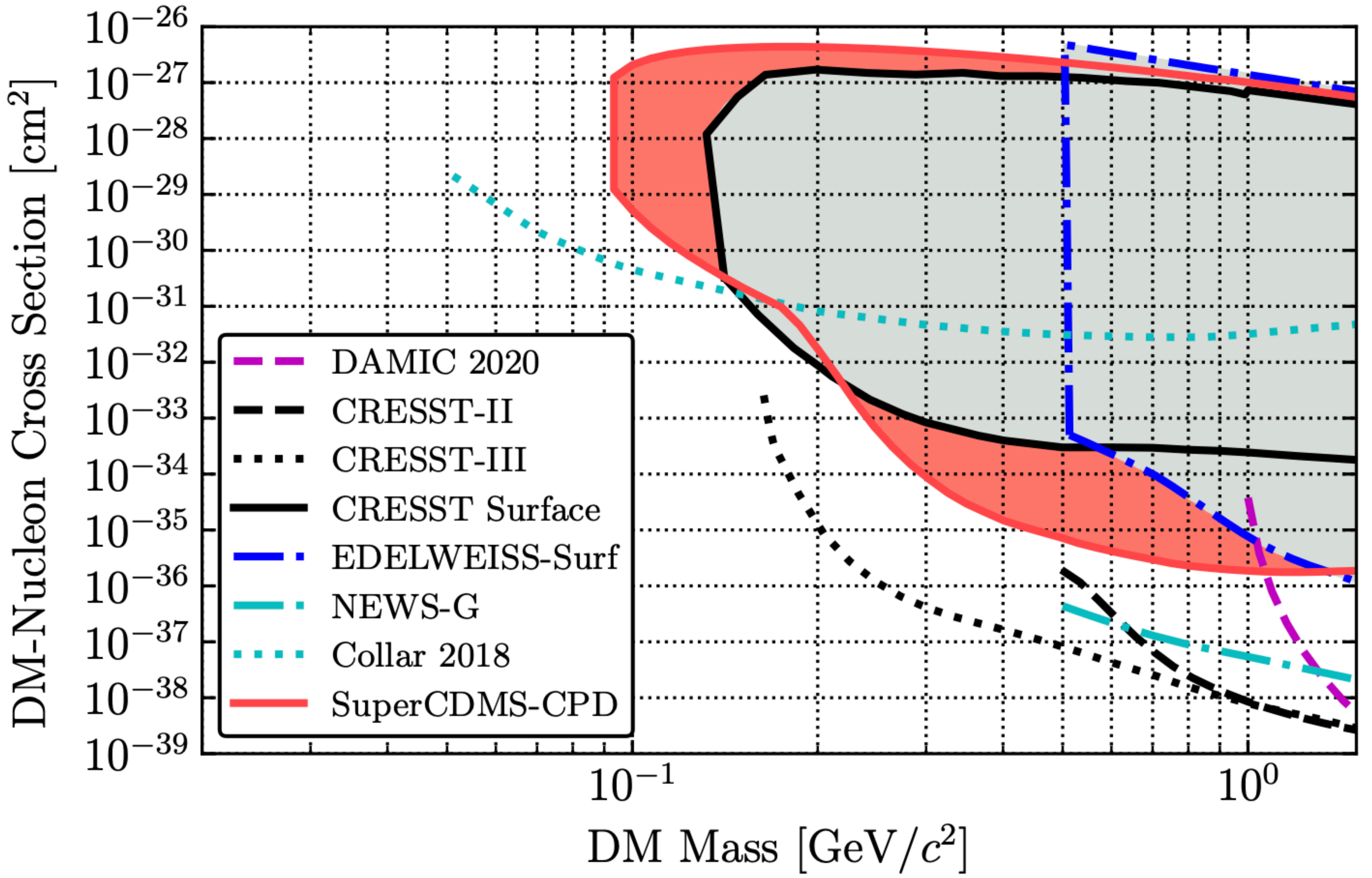


E_{th} = 60eV_{nr}

33g Ge   PRD 99 082013 (2019)

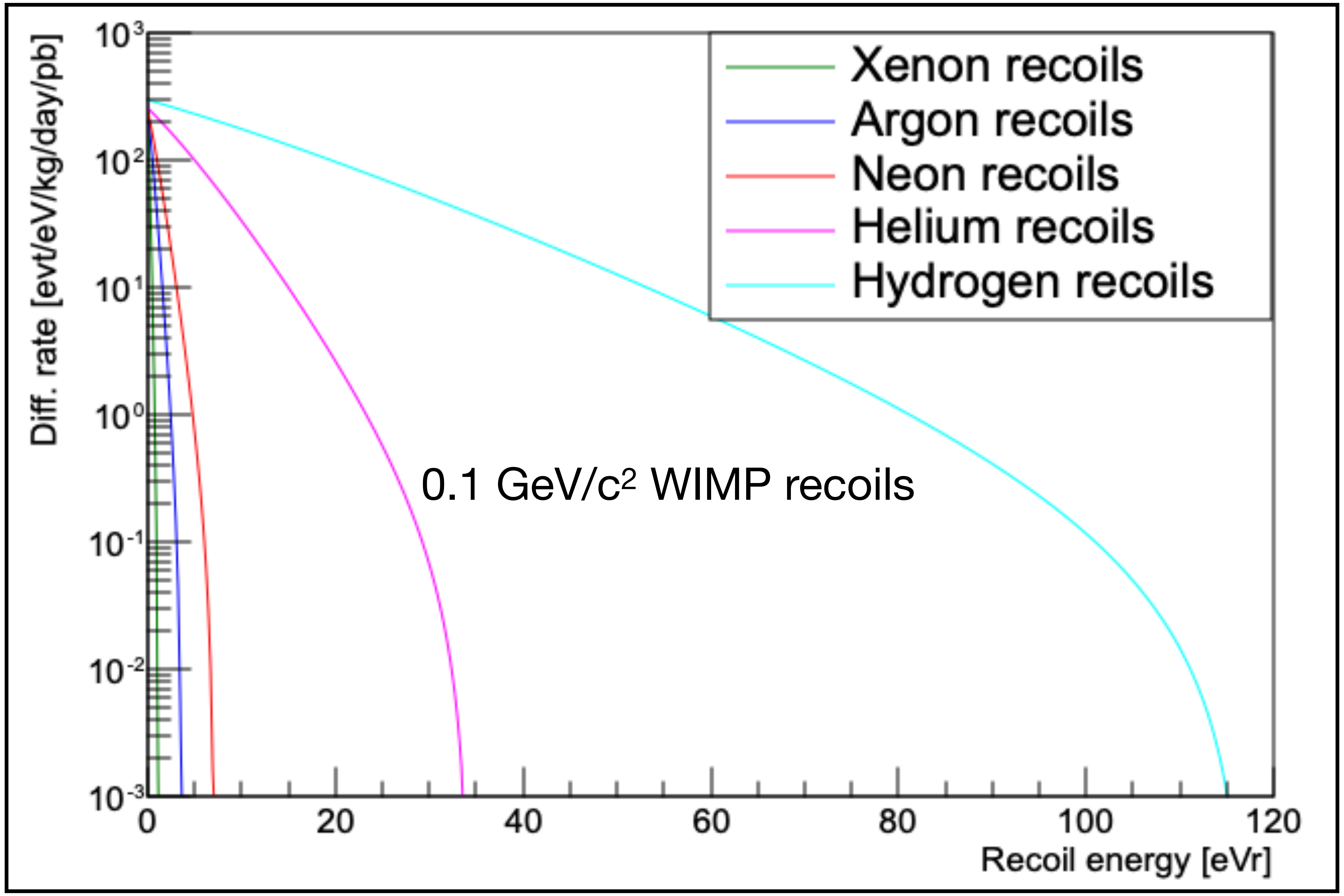
SuperCDMS HVeV can count primary electrons (demonstration with neutron-induced recoils down to 100eV)

Reach down to 93 MeV/c²!



Phys. Rev. Lett. **127**, 061801 (2021)

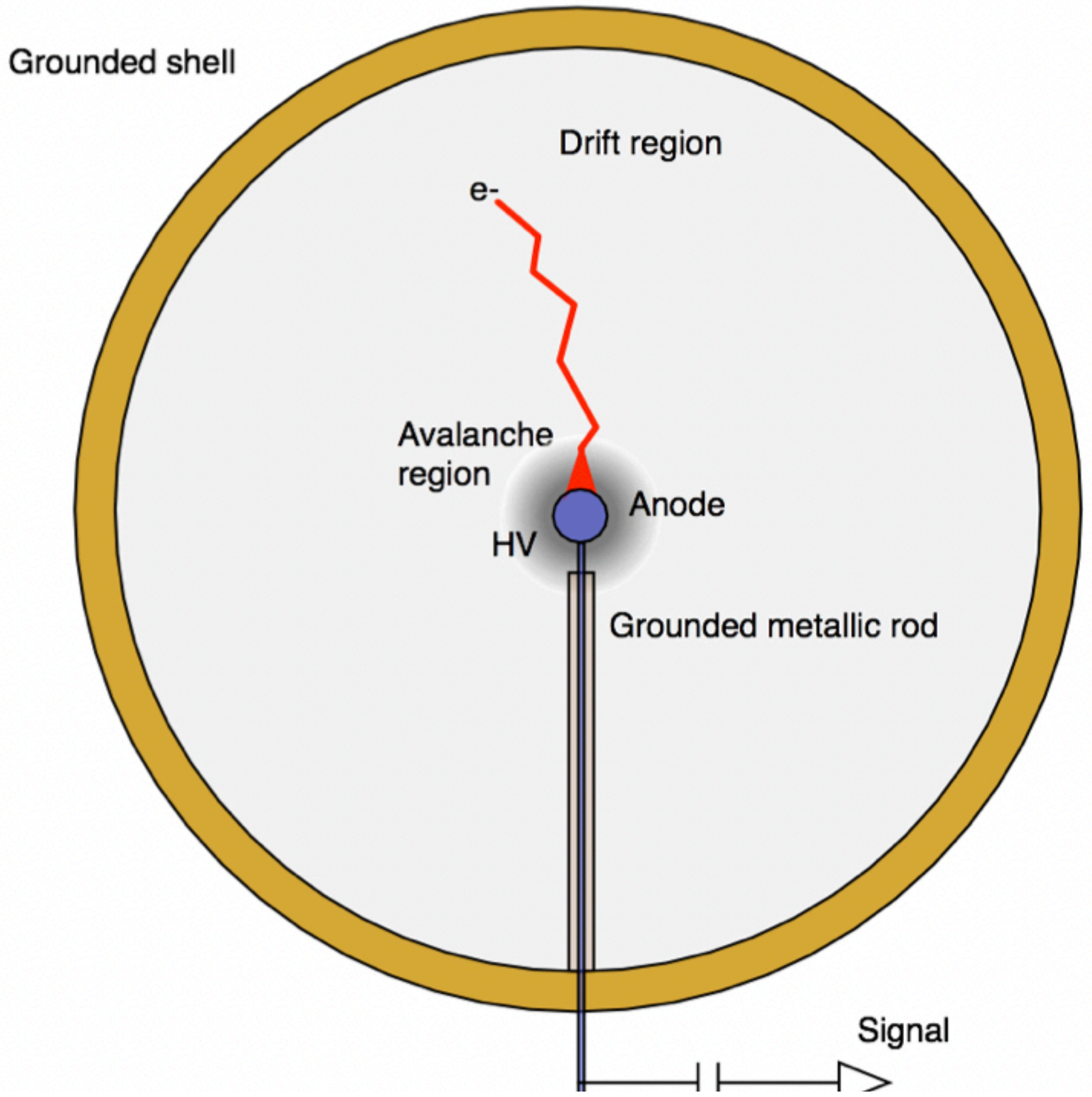
(also see arxiv:2203.08463 for future goals)

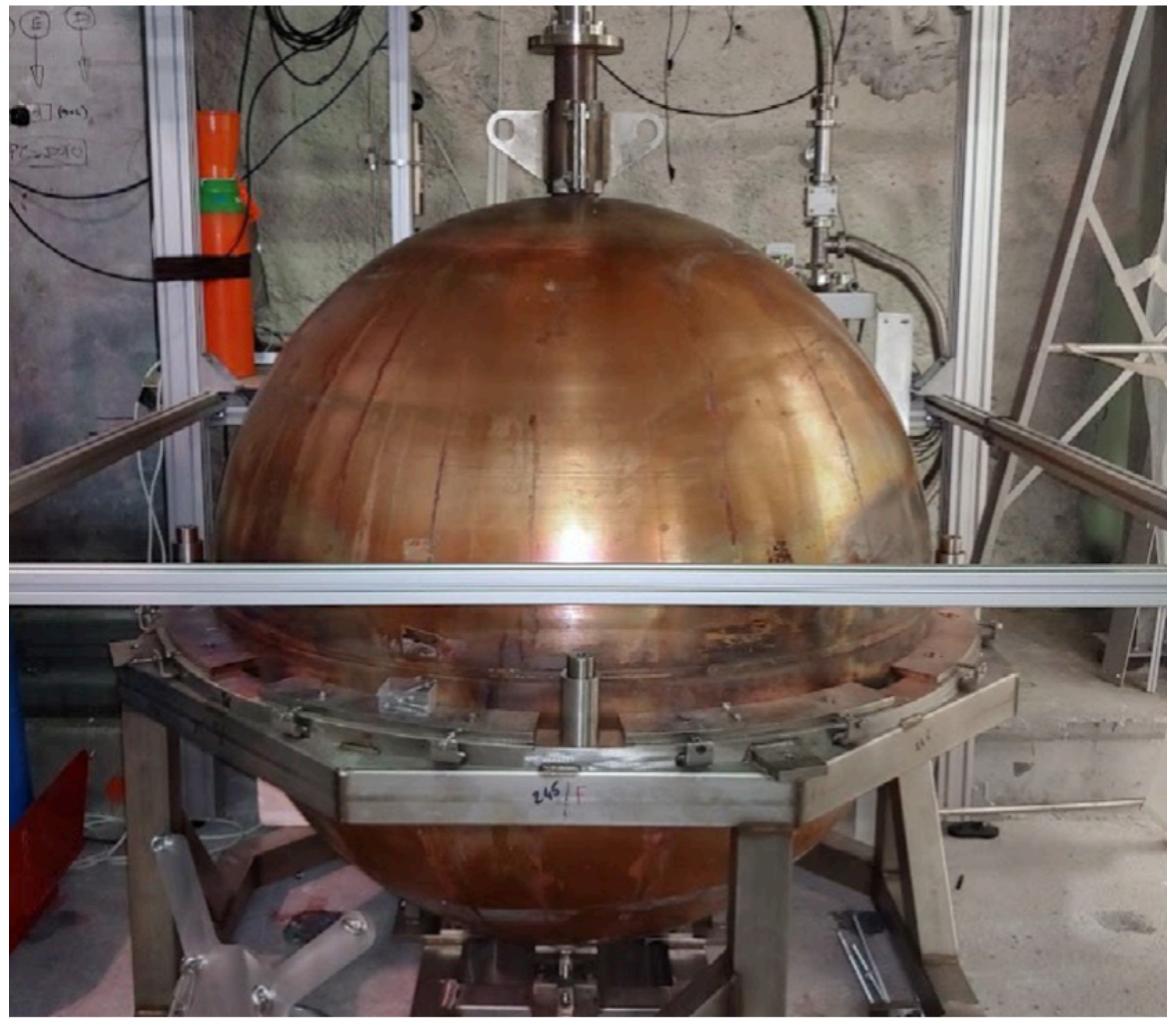


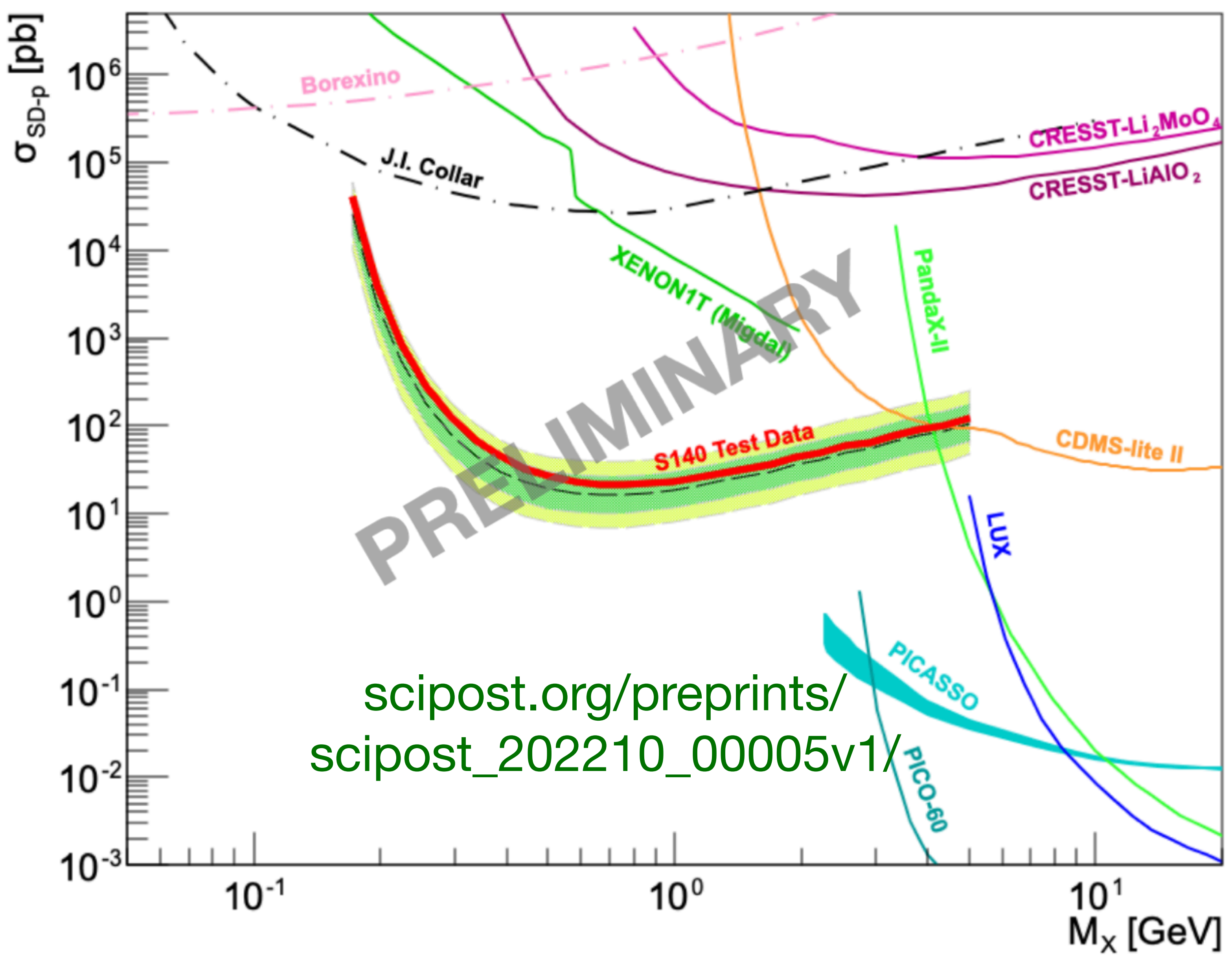
- To go under 0.1 GeV/c^2 masses, we need:
  - **even lower atomic mass target**
  - **even lower energy threshold**

Preliminary results from new generation S140 detector filled with CH_4 at Modane:

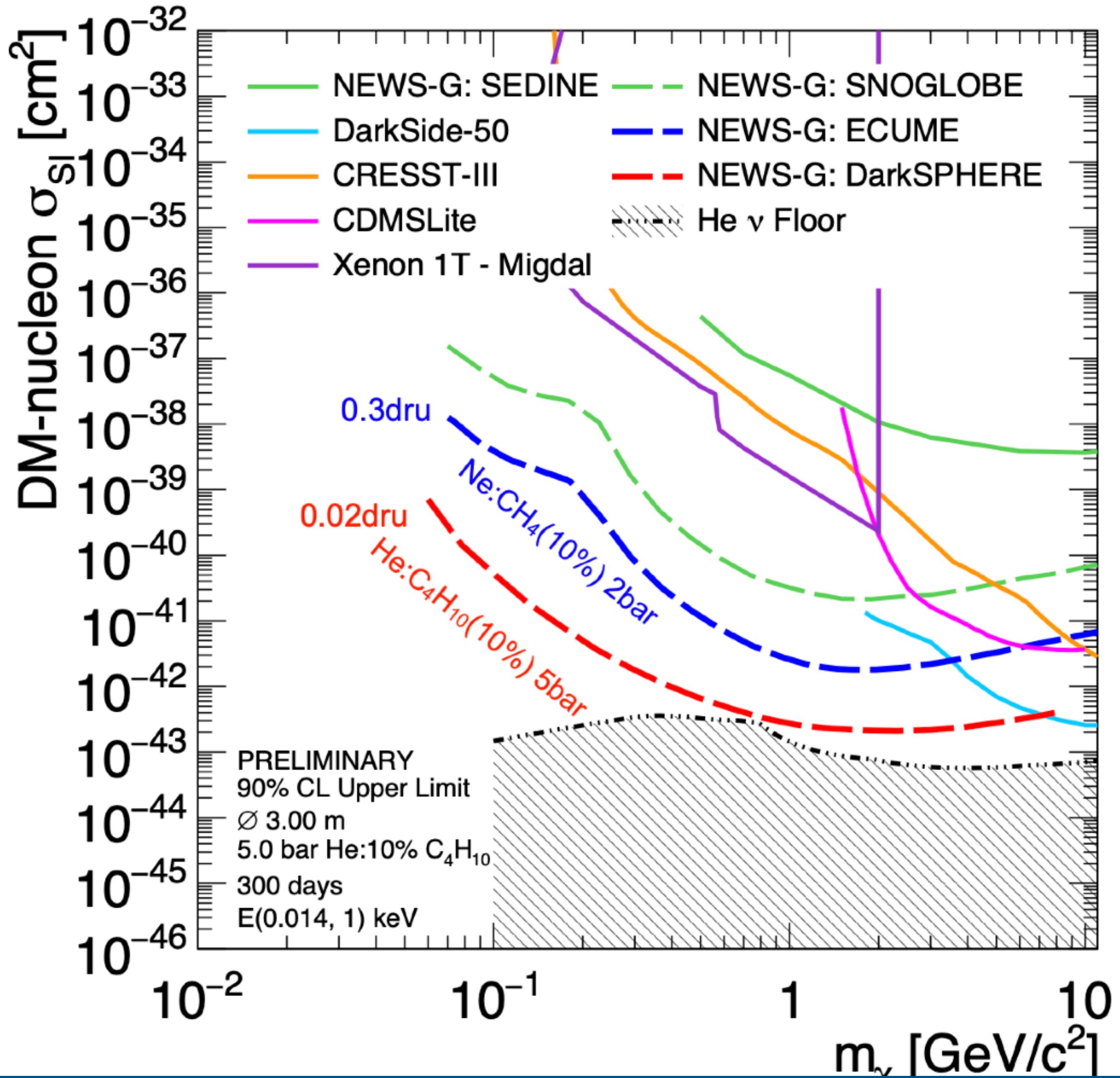
- primary electron reconstruction (~20eV_{ee} threshold)
- Sensitivity down to below 200 MeV/c^2 (preliminary)







scipost.org/preprints/
scipost_202210_00005v1/



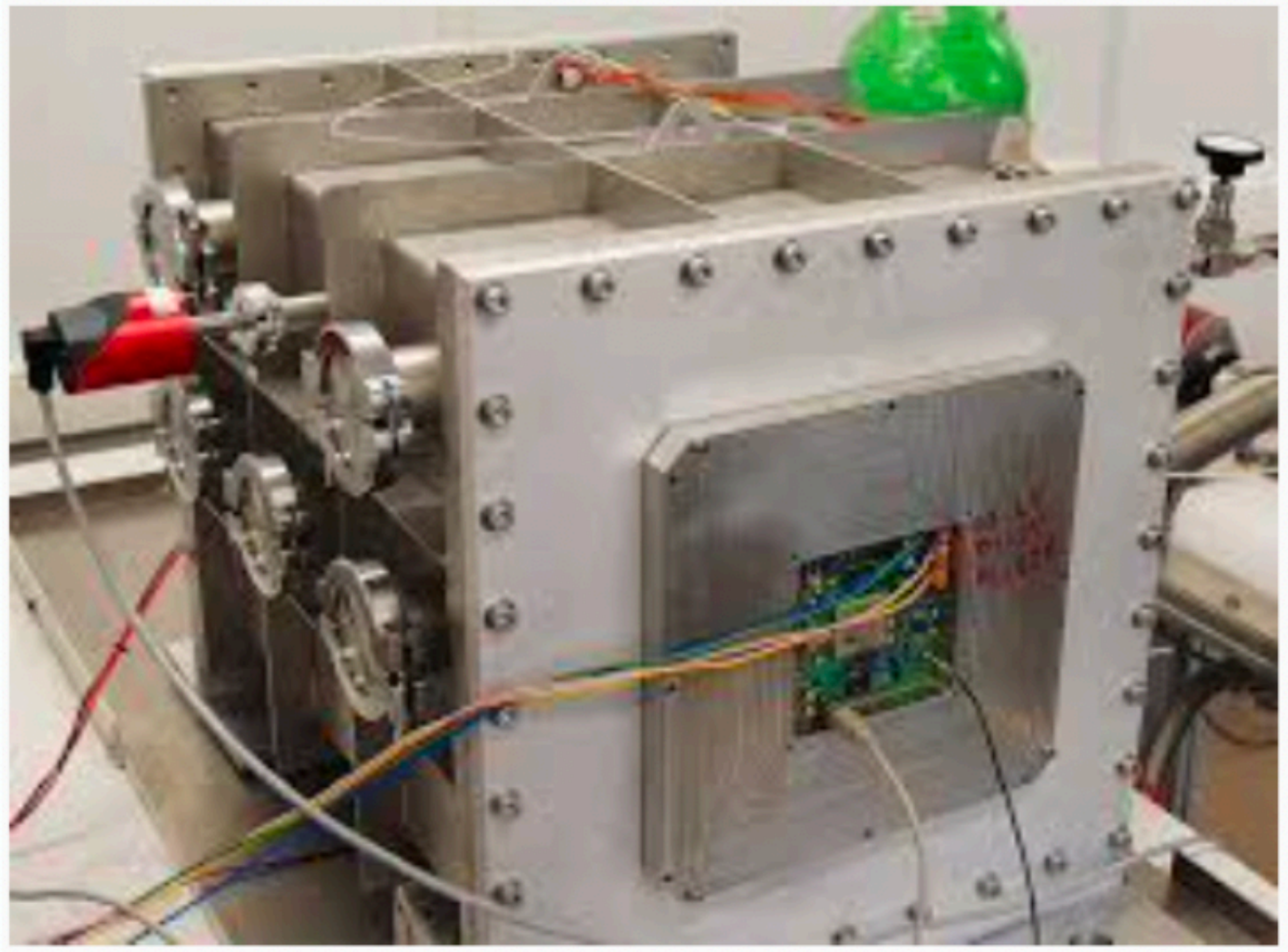
Directionality: lets DM detectors distinguish signal coming in the same direction as DM wind!

MIMAC:

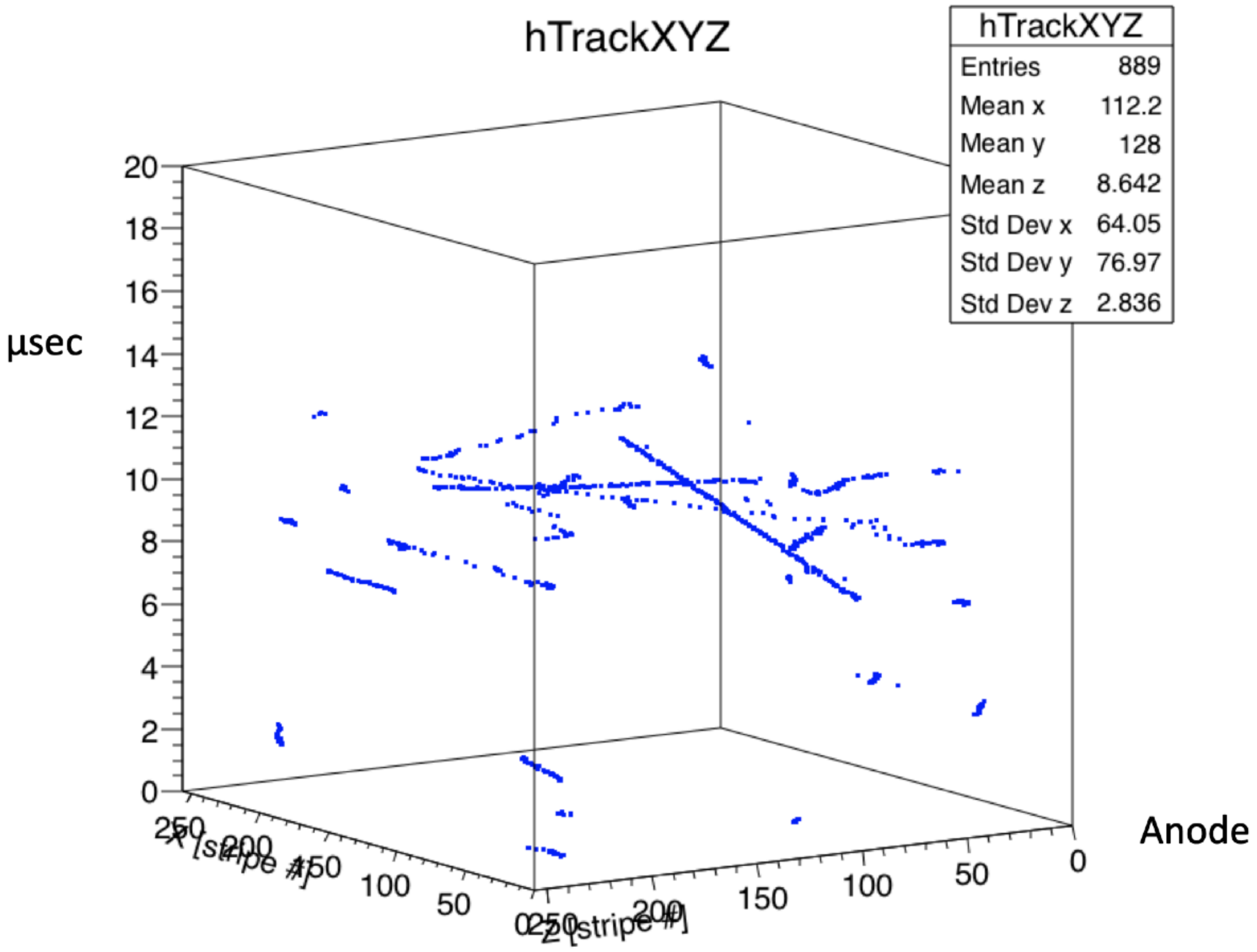
- Low-pressure gaseous TPC based on a Micromegas with a pixelated anode
- 50%i-C_4H_{10}+ 50%CHF_3 at 30 mbar : DM recoils leave tracks!
- 15deg track reconstruction at 8 keV!

arxiv.org:2112.12469

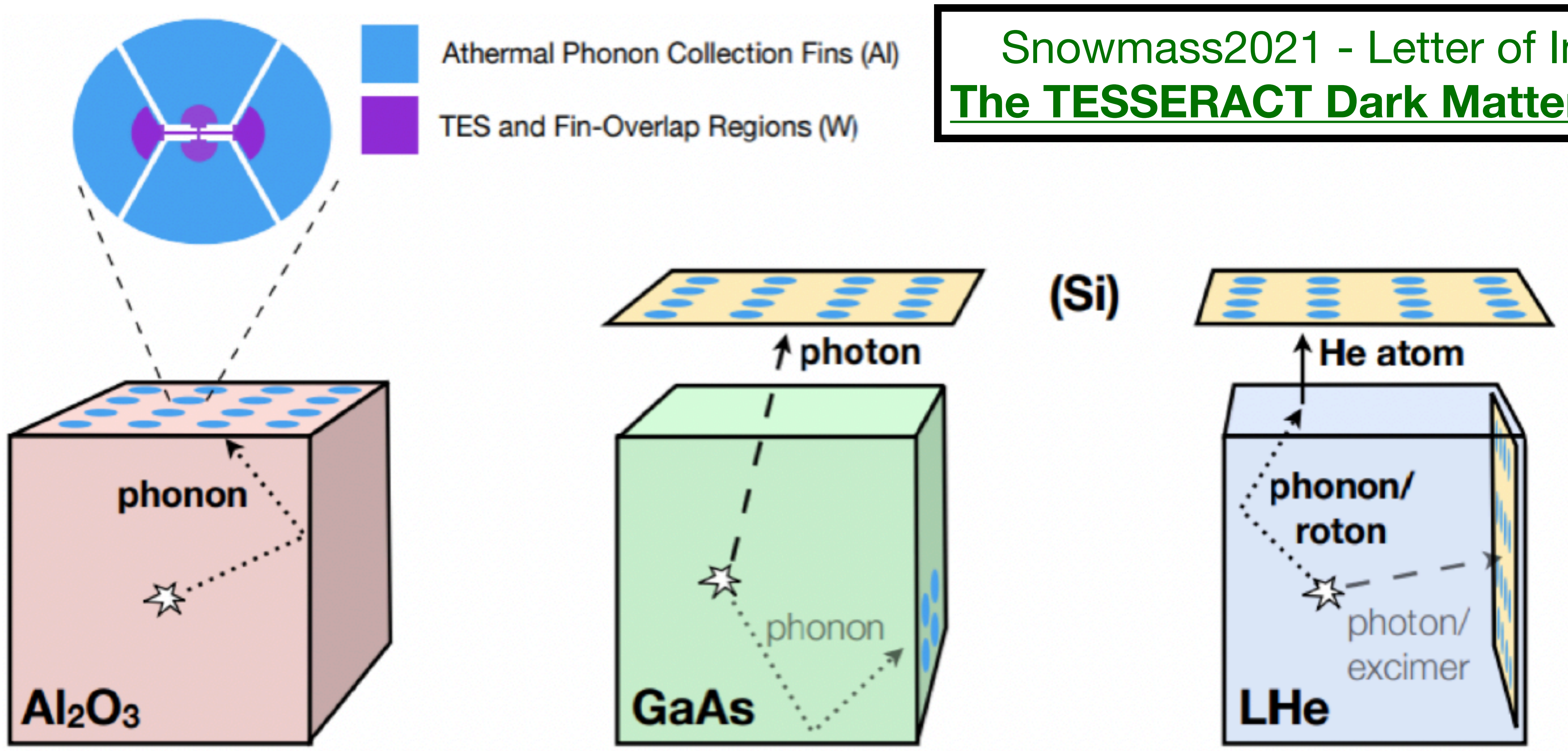
Many other projects for directionality with gas TPCs: DRIFT, NEWAGE, New Mexico, CYGNO, CYGNUS… Topic for another time!



3D event-localization in MIMAC by means of the cathode-signal



Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project

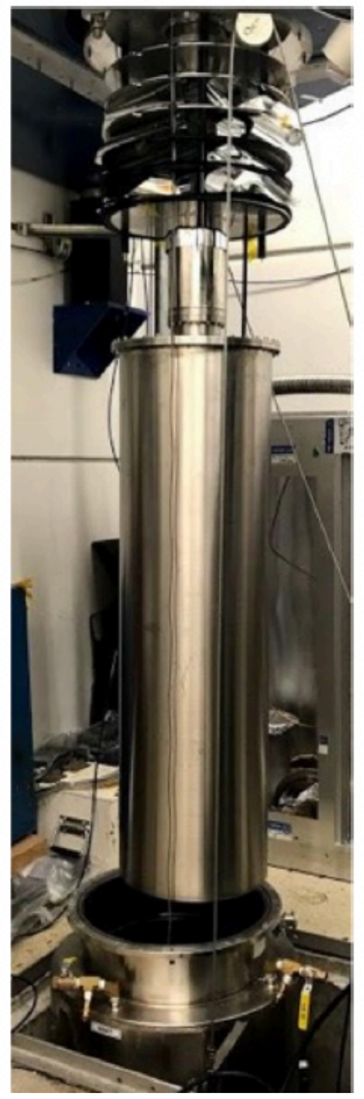


- TESSERACT: Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets

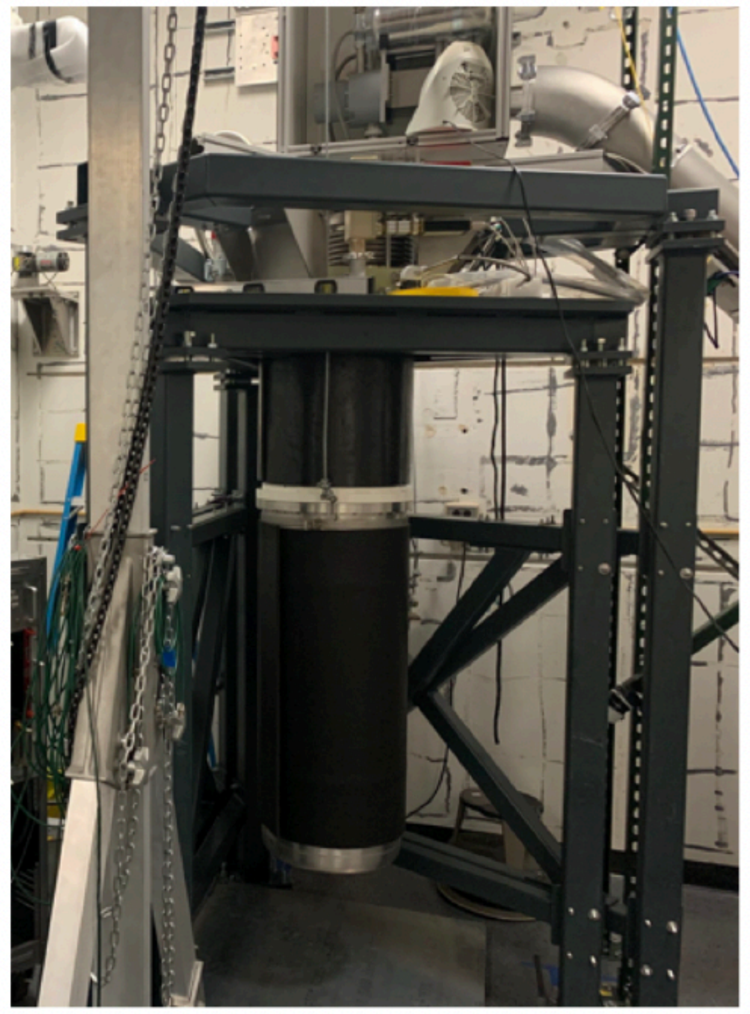
- Project development began in June 2020.

- Just stick TES to different targets:
  - SPICE (polar crystals)
  - HeRALD (superfluid Helium)

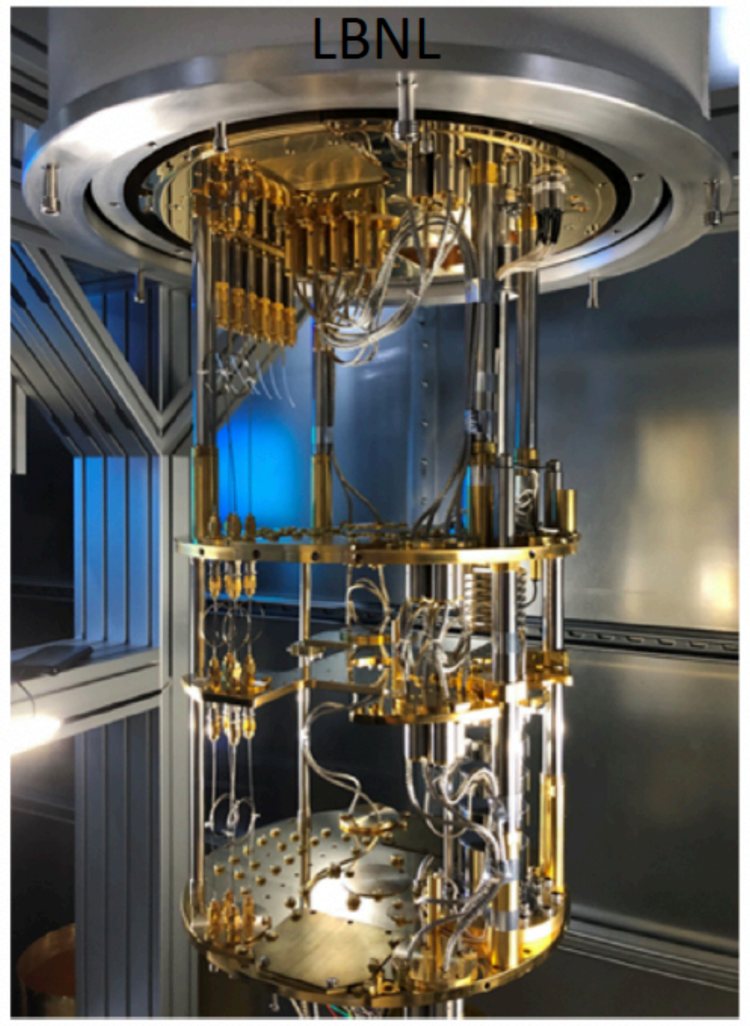
Leiden MNK126-500
McKinsey Group @ UCB



CryoConcept UQT-B 200
Pyle Group @ UCB



BlueFors LD-400
Detector Group @ LBNL

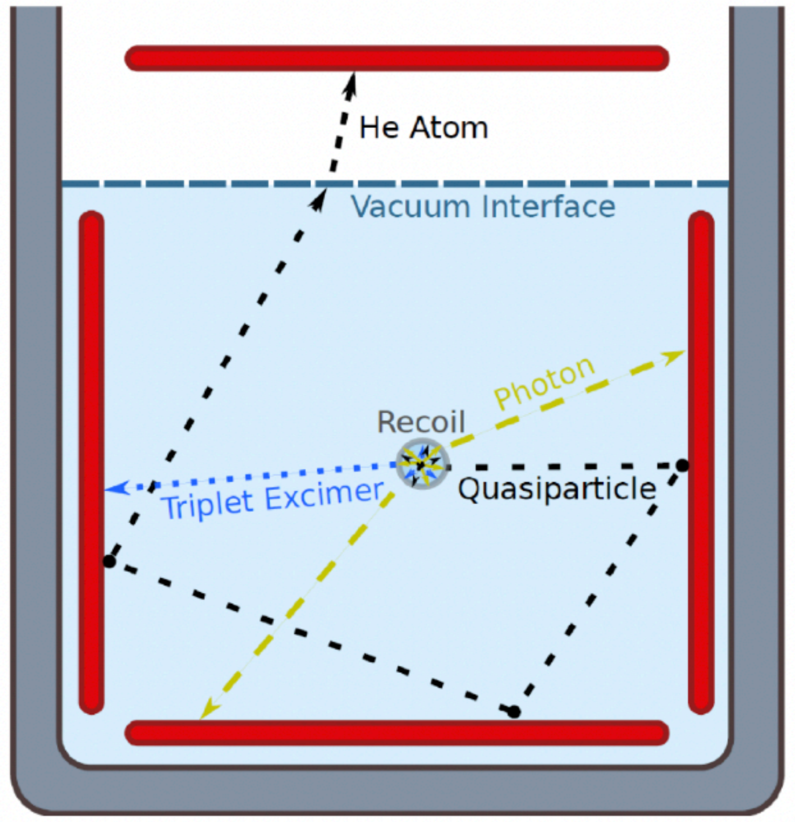


CryoConcept HEXADRY UQT-B 400
Hertel Group @ UMass

Helium Roton Apparatus for Light Dark matter (HeRALD)

Phys. Rev. D **100**, 092007

Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project



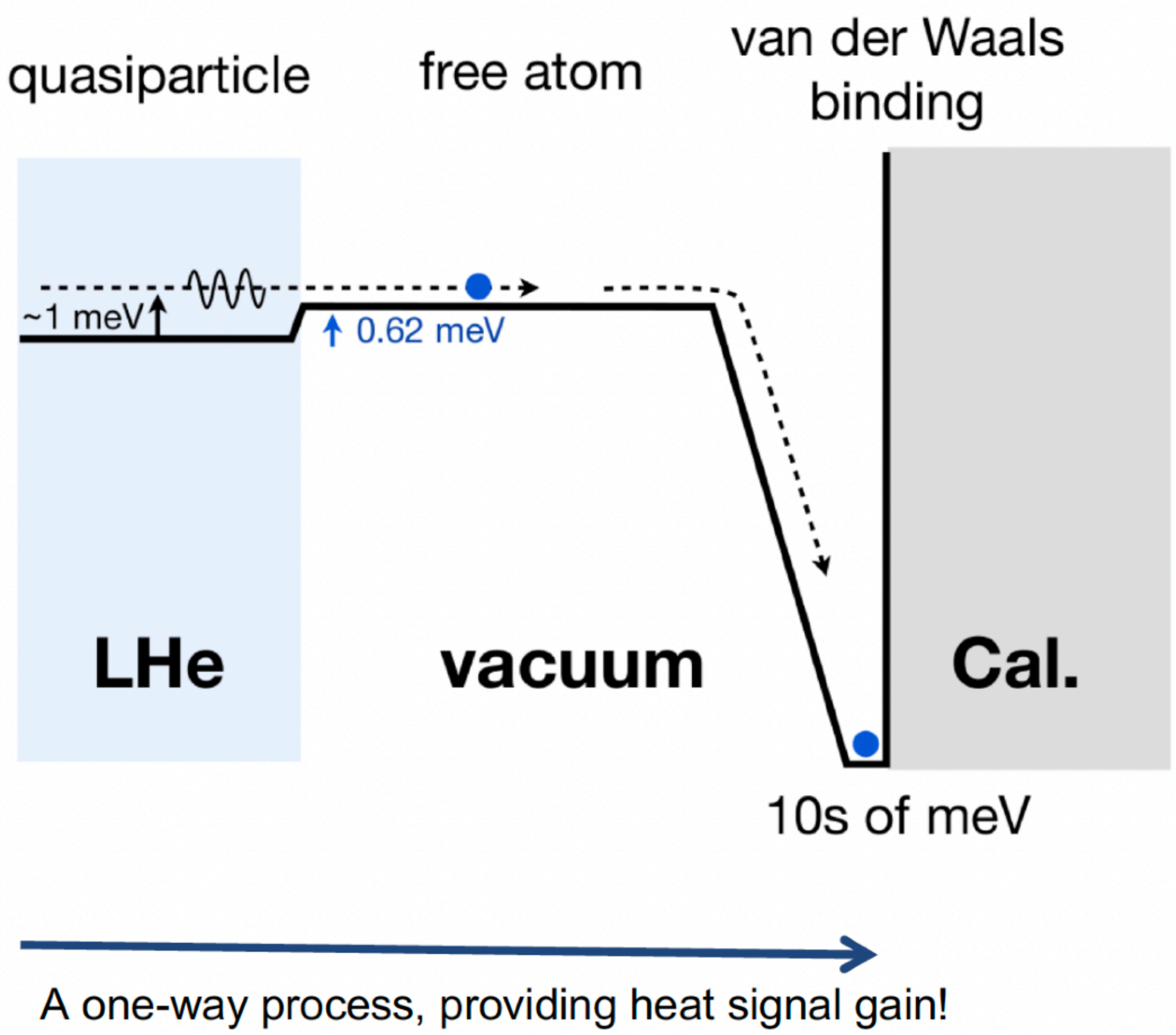
- Operated at ~20-50 mK
- Calorimeters with TES readout
  - submerged in liquid
    - Detect **UV photons**, **triplet molecules** and **IR photons**
  - suspended in vacuum
    - Detect UV photons, IR photons and **He atoms** (evaporated by quasiparticles)

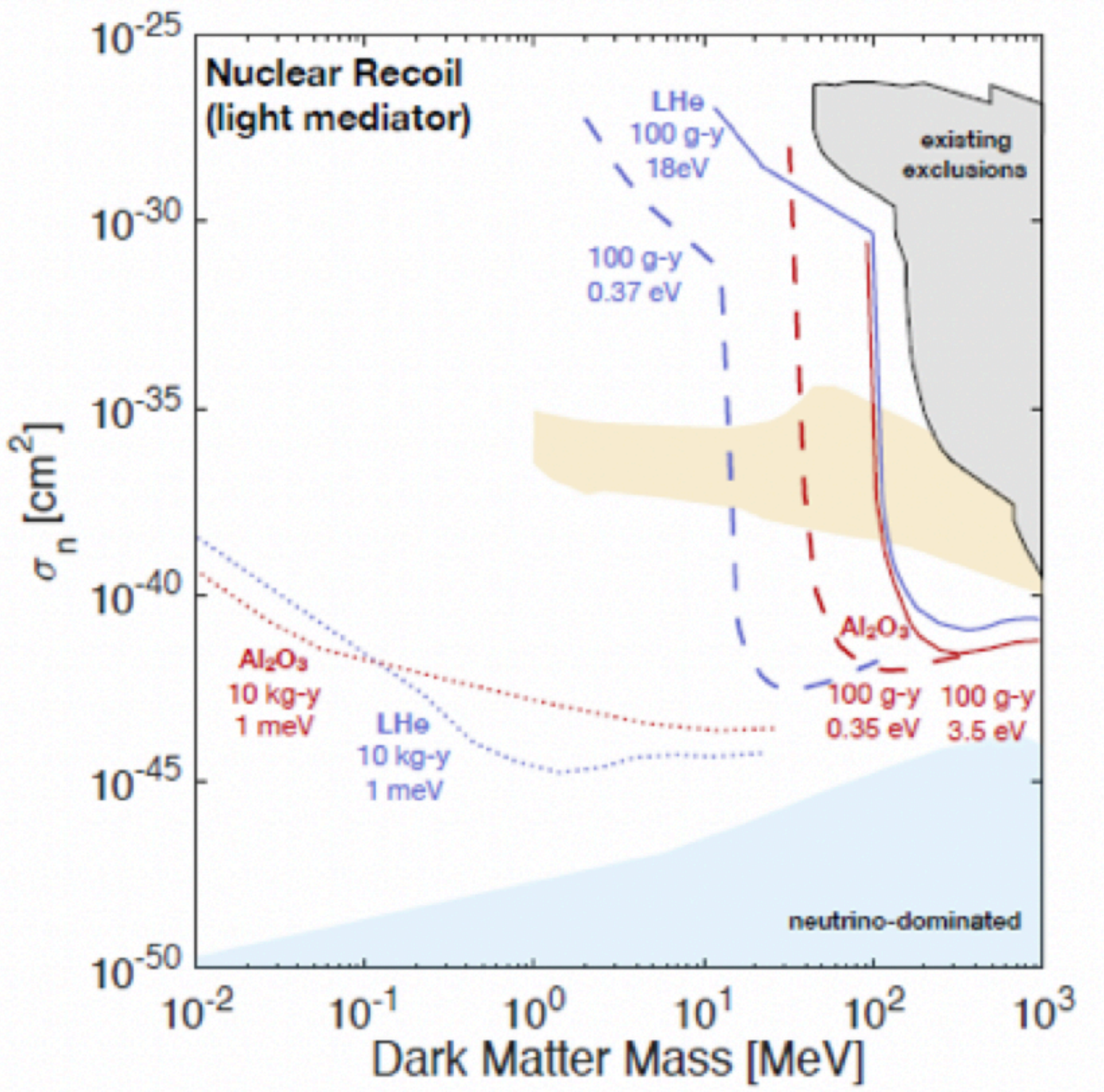
Binding energy between helium and solid amplifies signal

1 meV recoil energy → up to 40 meV detectable energy

Thermal energy negligible (μeV)

Film burner to remove helium from calorimeter



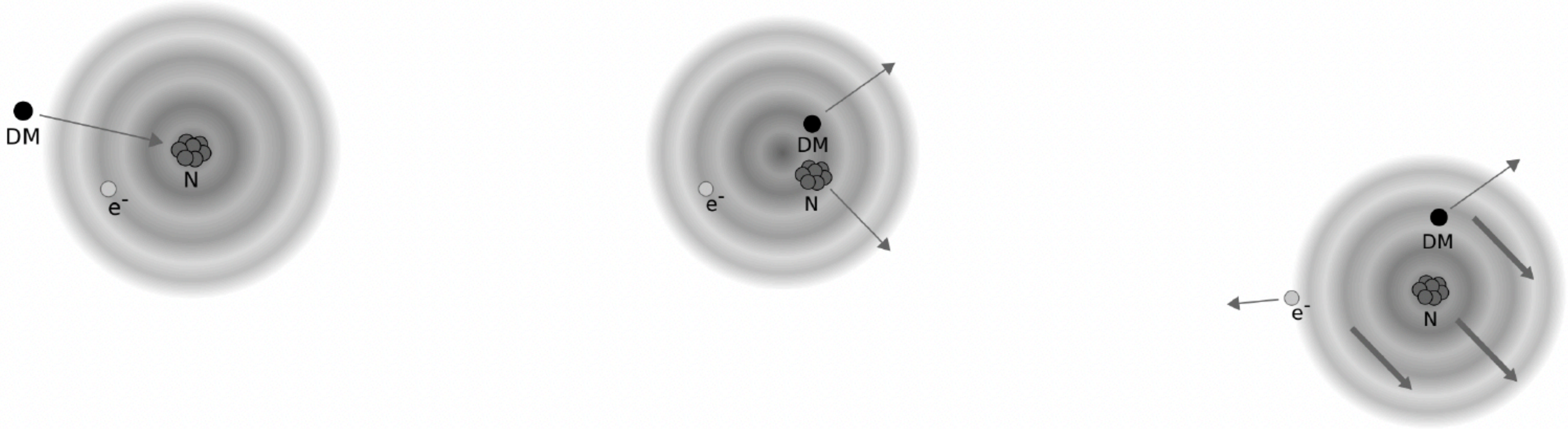


Slides shamelessly stolen from D. McKinsey

Migdal effect

Migdal 1939

- Ionisation/excitation due to displacement of nucleus after nuclear recoil



- Migdal effect observed in $\alpha, \beta^{\pm}$ decays
- Yet to be observed in neutron scattering

Elastic DM-nucleus scattering:

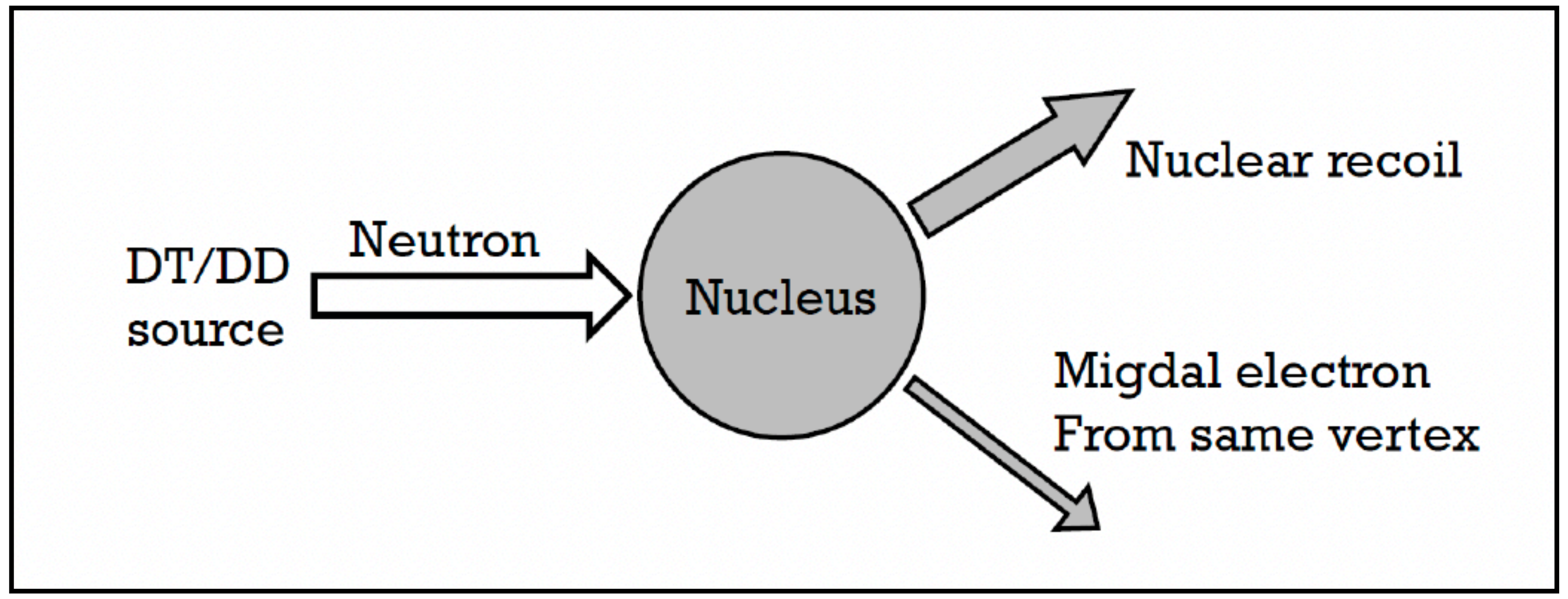
$$E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu^2 v_\chi^2}{m_N}$$

$$E_{NR}^{\max} \sim \underline{0.1\,\mathrm{keV}} \left(\frac{131}{A}\right)\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

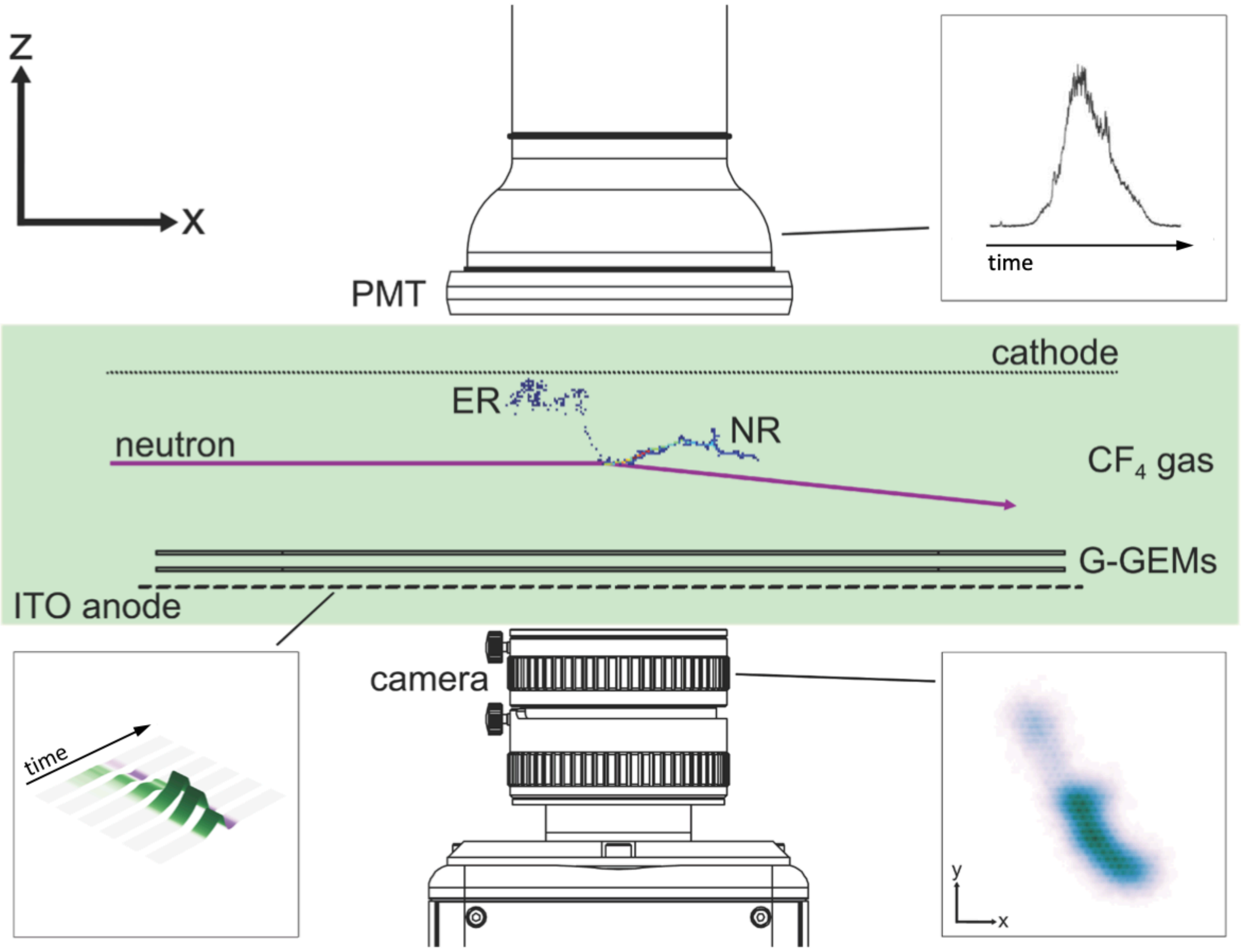
Migdal (inelastic):

$$\omega = \boldsymbol{v} \cdot \boldsymbol{q} - \frac{q^2}{2m_\chi} \leq \frac{1}{2}\mu v_\chi^2$$

$$\omega_{\max} \sim \underline{3\,\mathrm{keV}} \left(\frac{m_\chi}{\mathrm{GeV}}\right)$$



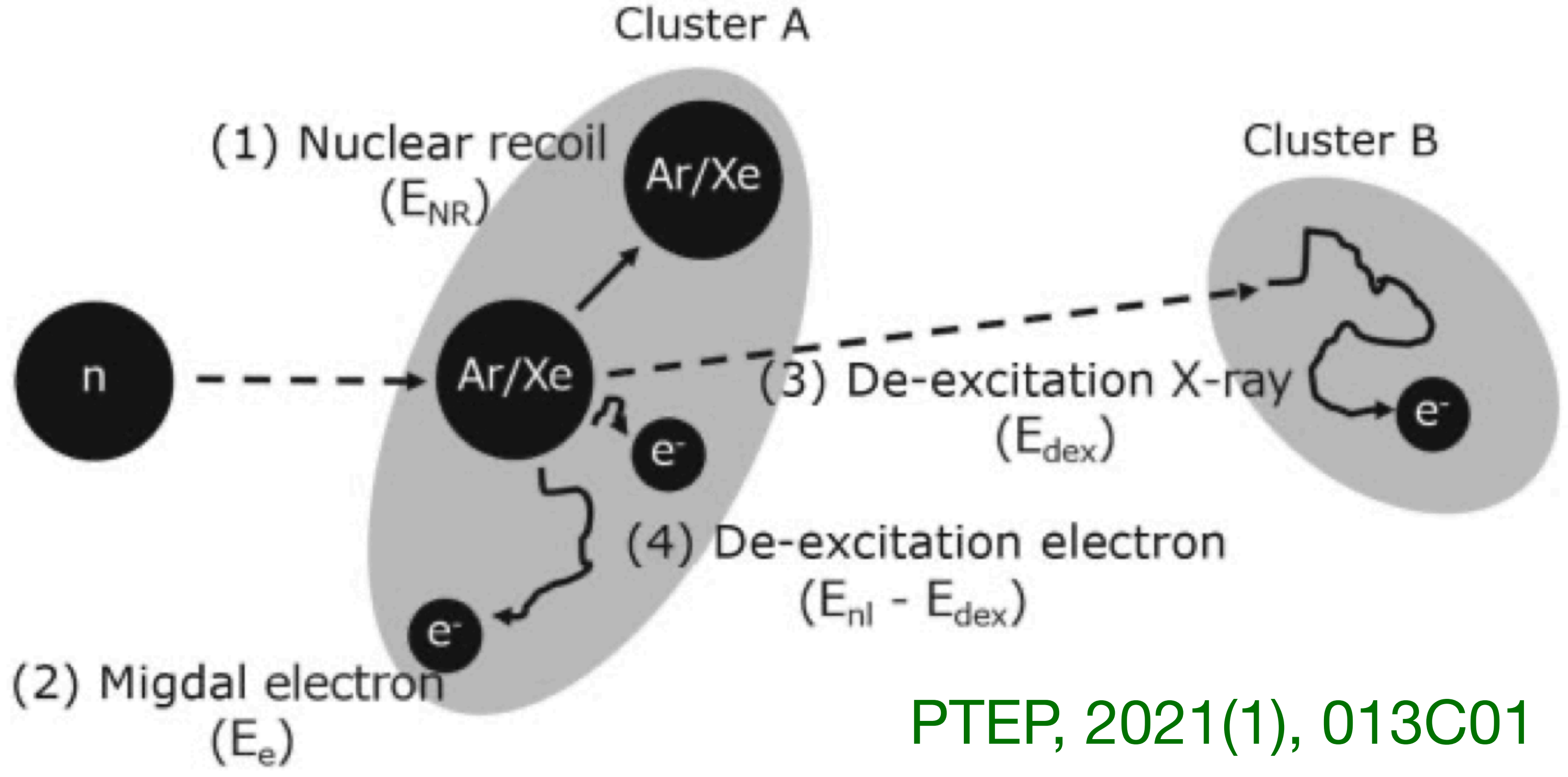
MIGDAL experiment (vertex reconstruction)



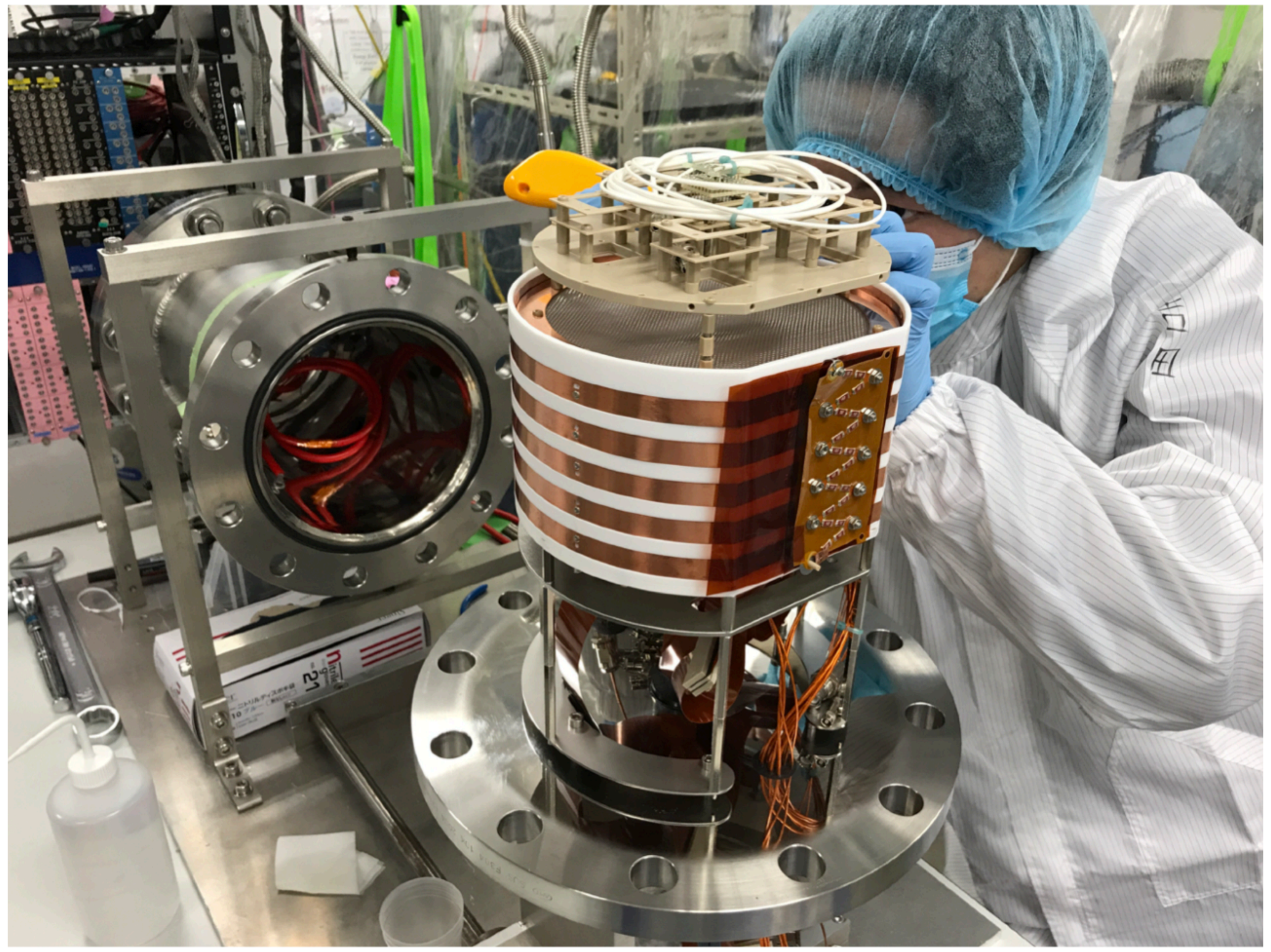
arxiv.org:2207.08284

Also see
arxiv.org:2112.08514
for project without event-by-event discrimination

MIRACLUE experiment (Xe/Ar characteristic X-ray)



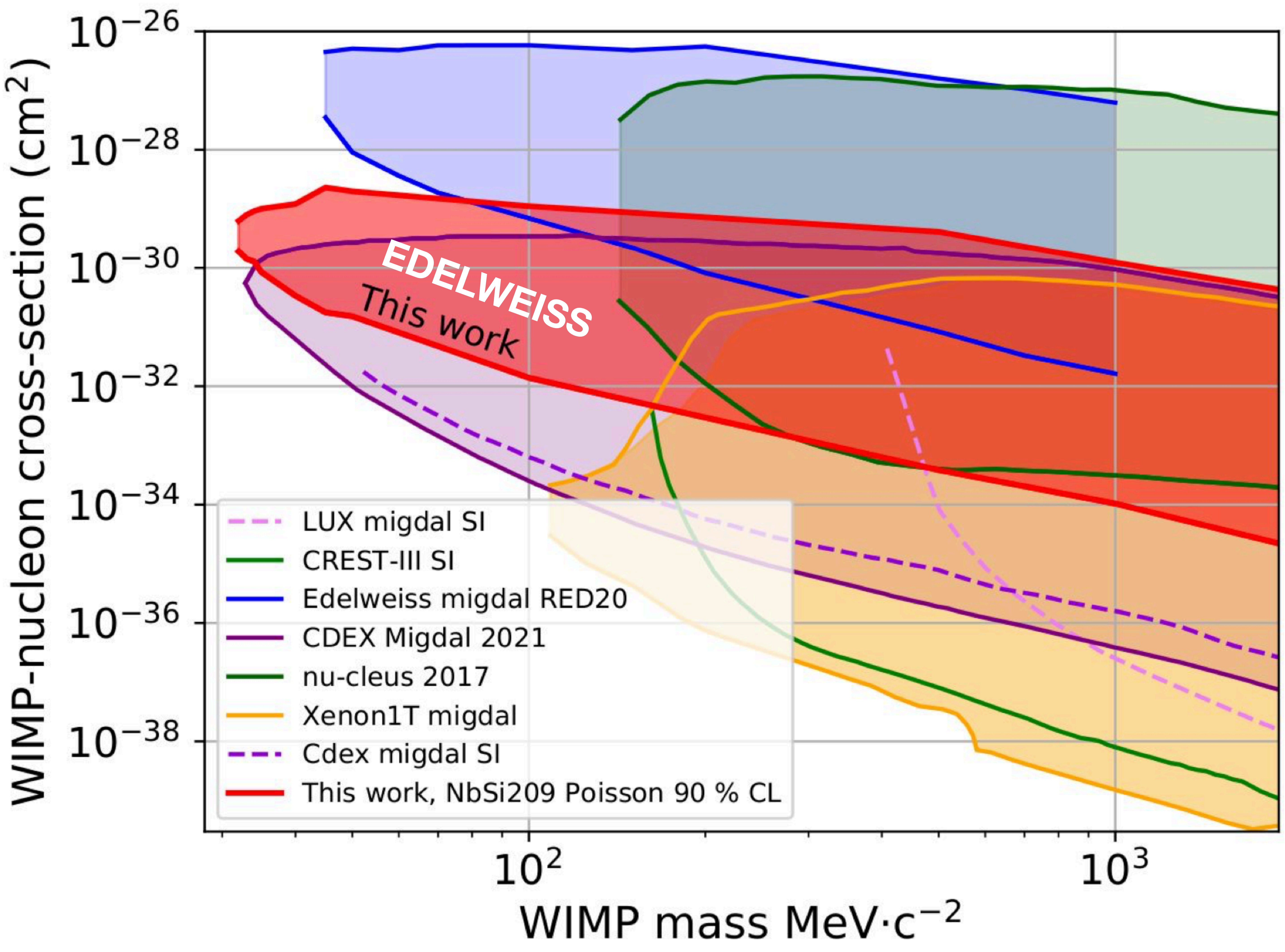
PTEP, 2021(1), 013C01



Reach down to 32 MeV/c²!

XENON1T becomes strongest constraint down to ~100 MeV/c²

arXiv:220303993



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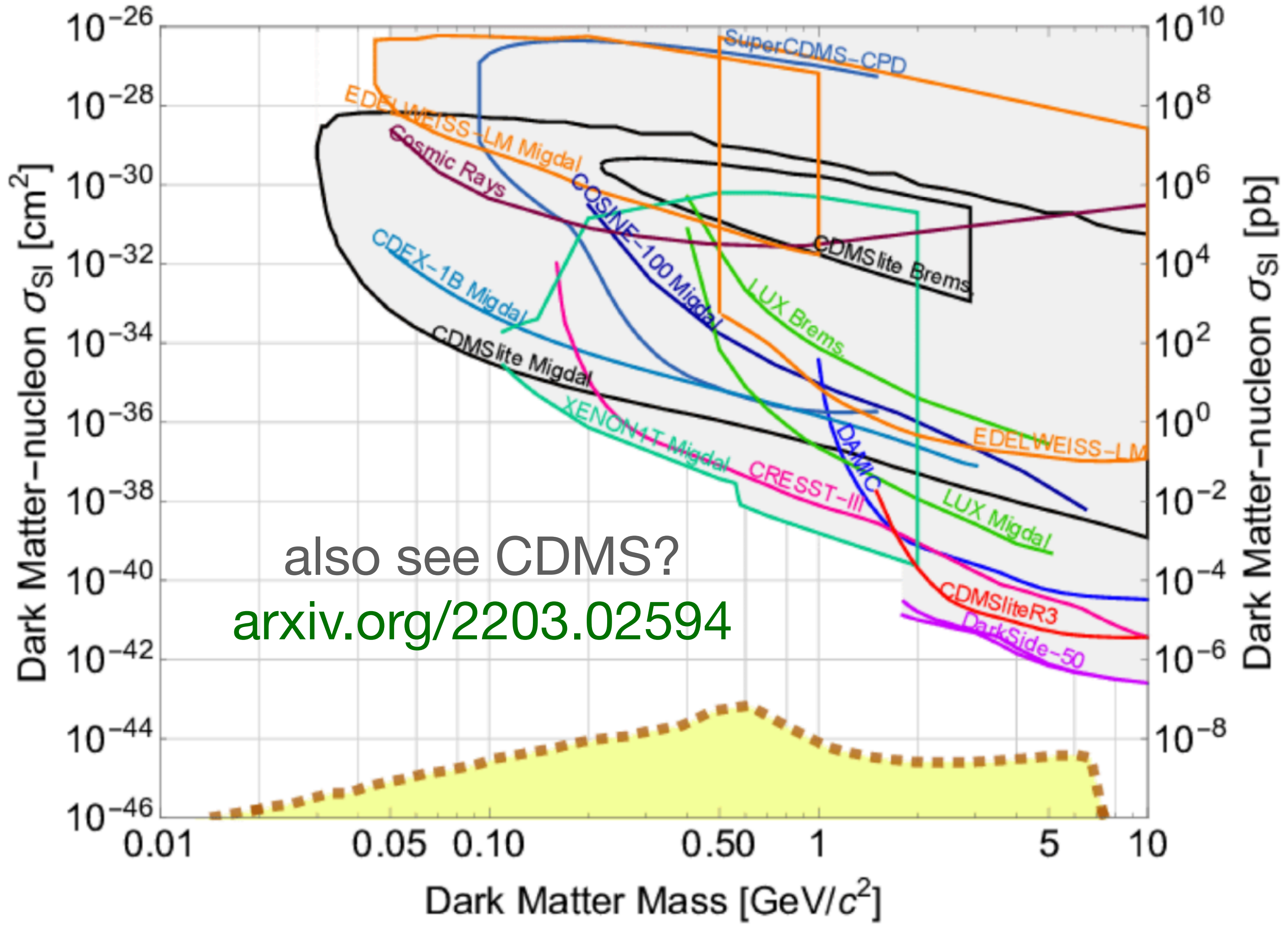
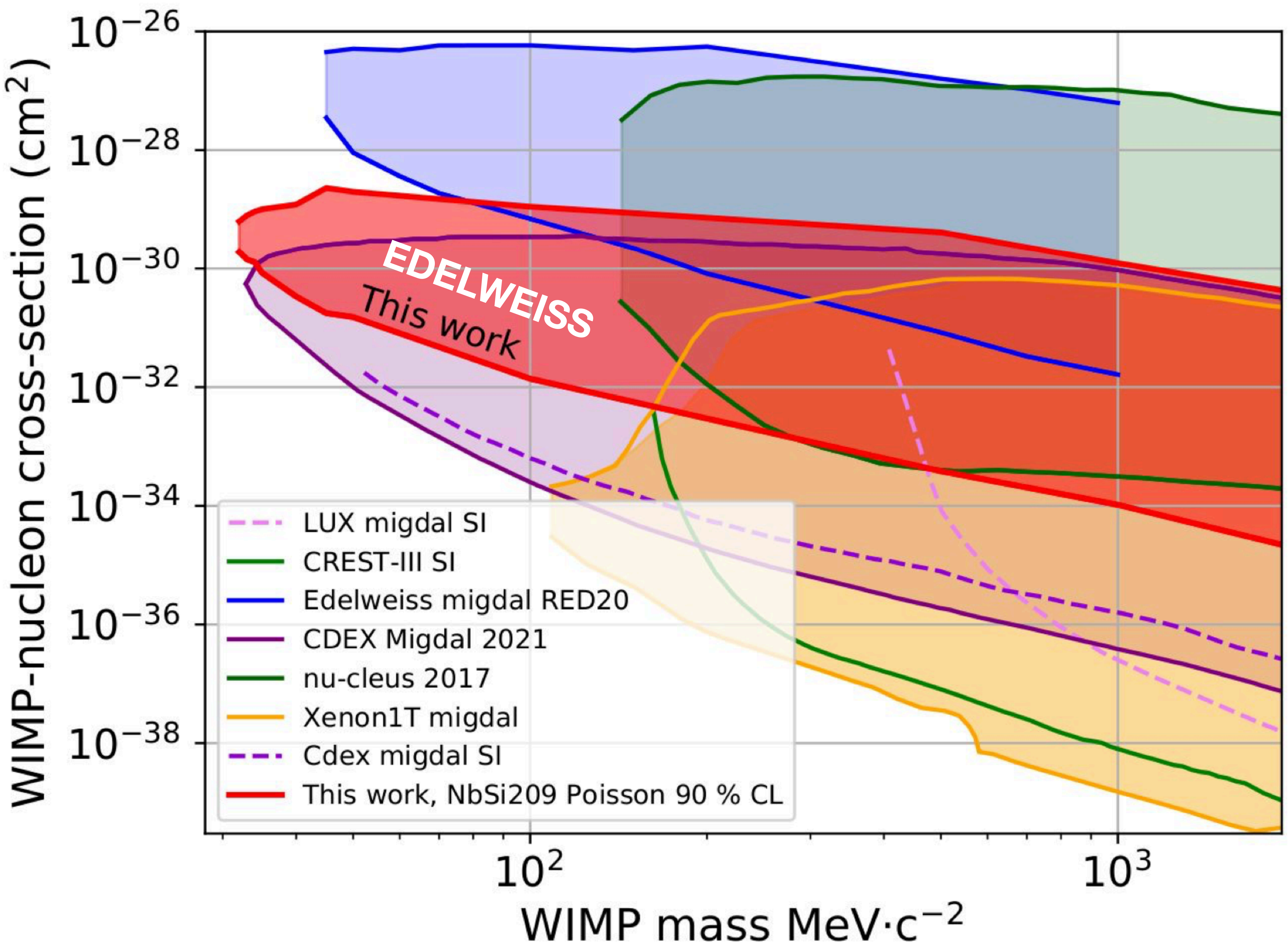
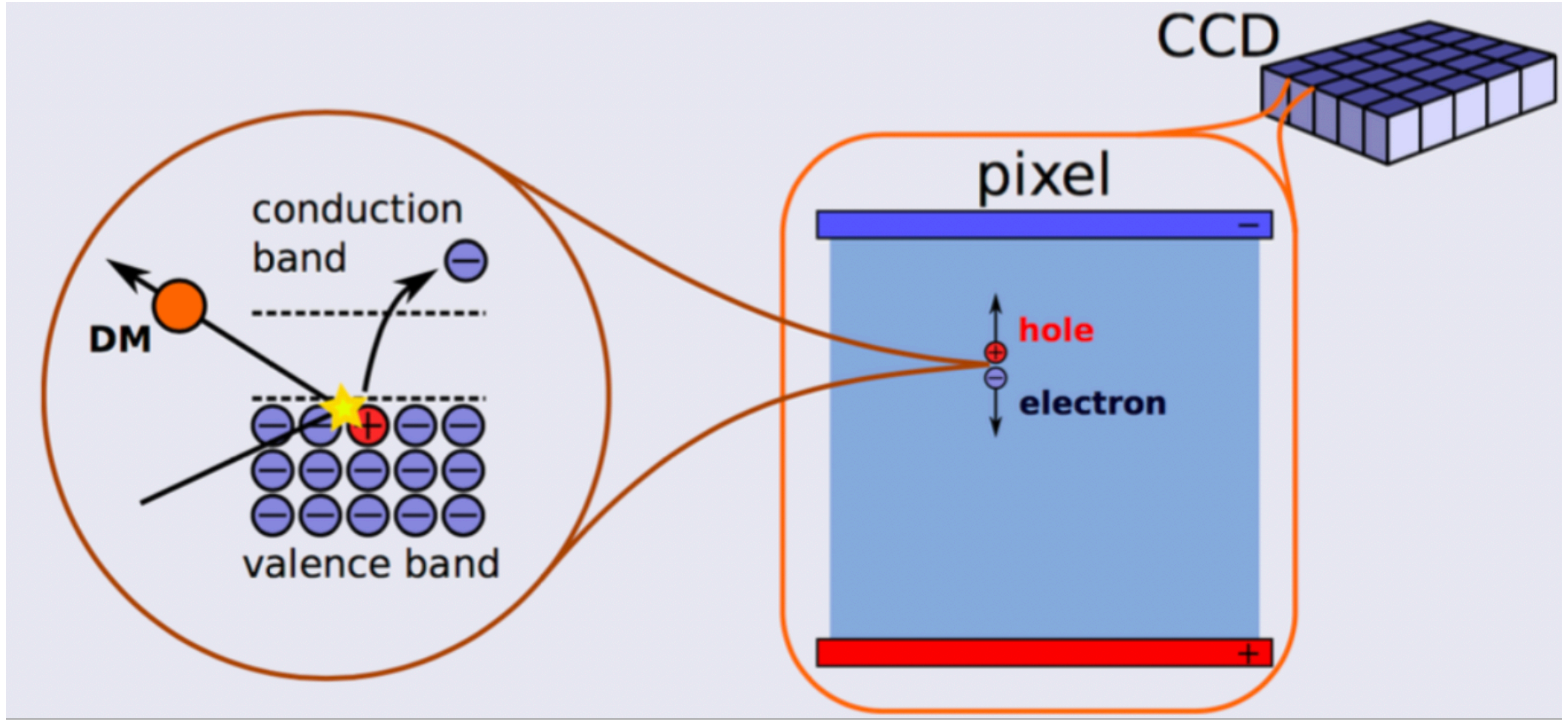
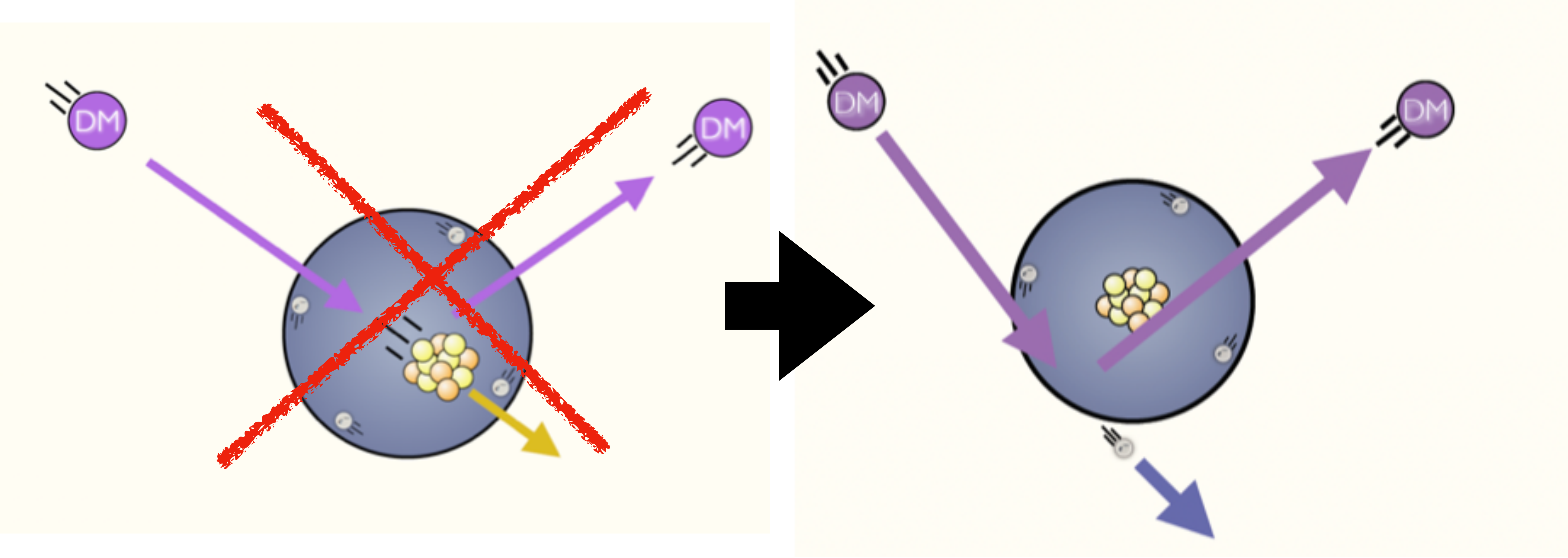


arXiv:220303993



- We cannot look for DM much further below ~0.1 GeV/c2 through recoils on nucleus
- Look for recoils on electrons? Atomic mass not relevant anymore
  - CCD detectors: DAMIC, SENSEI
  - Cooled to «only» ~100K

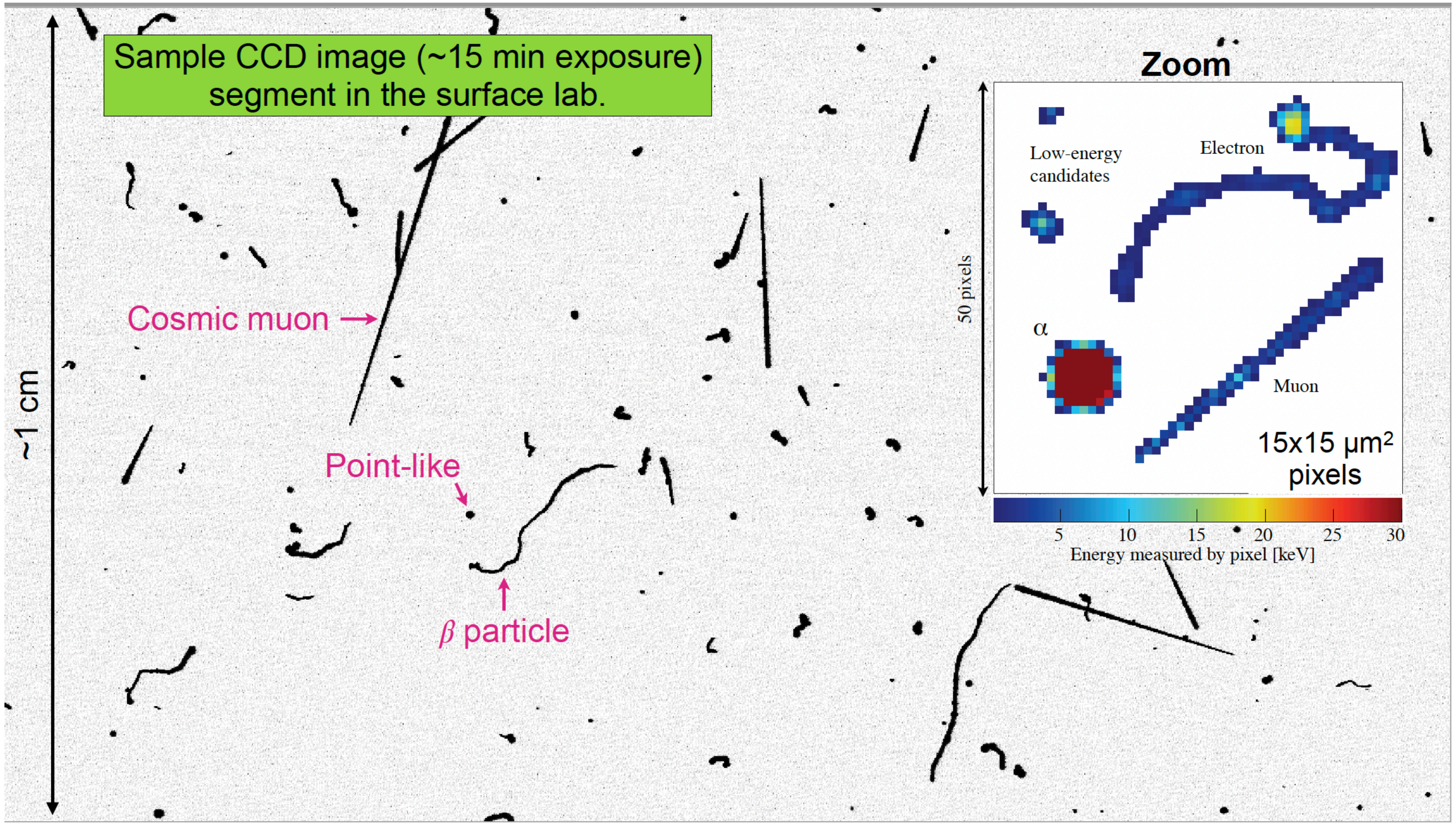




Silicon band-gap: 1.2 eV.
Mean energy for 1 e-h pair: 3.8 eV.

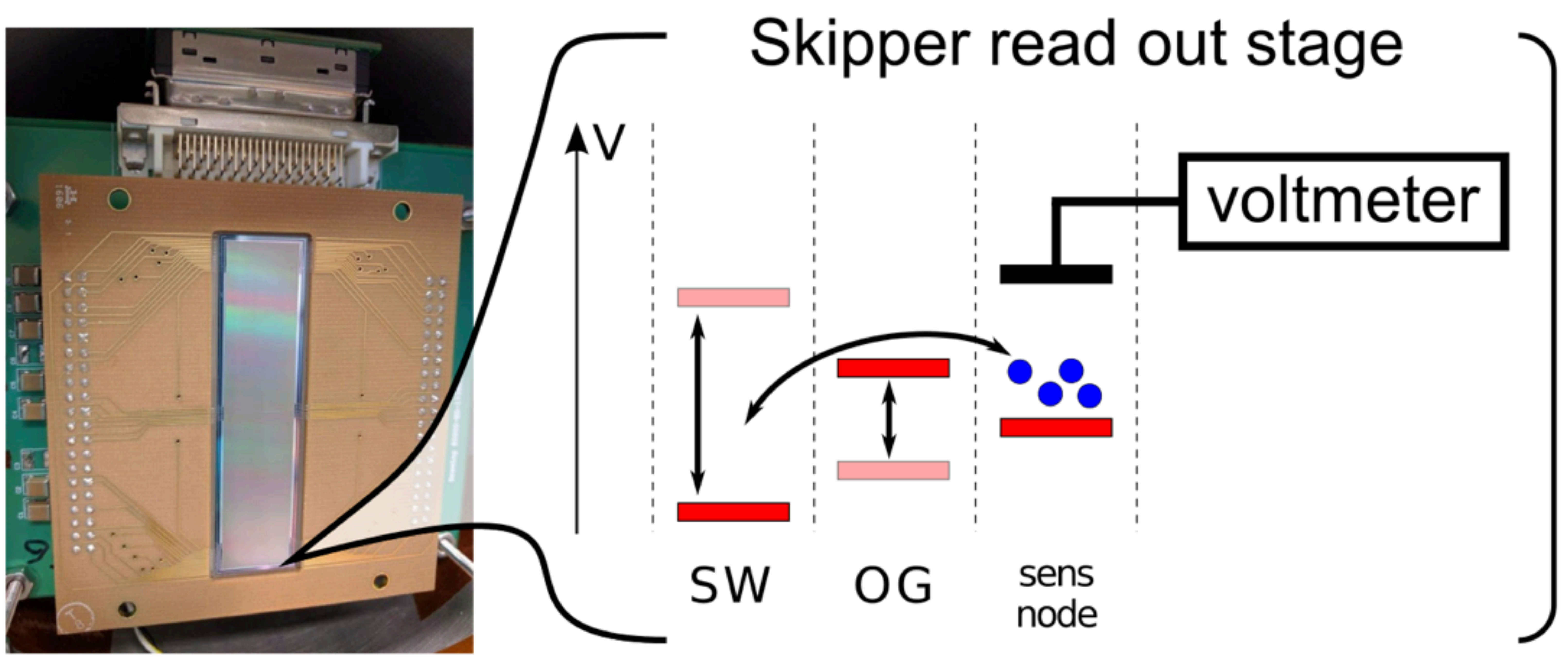
Section based on A. Chavarria review at IDM'22 https://indico.cern.ch/event/922783/contributions/4908964/

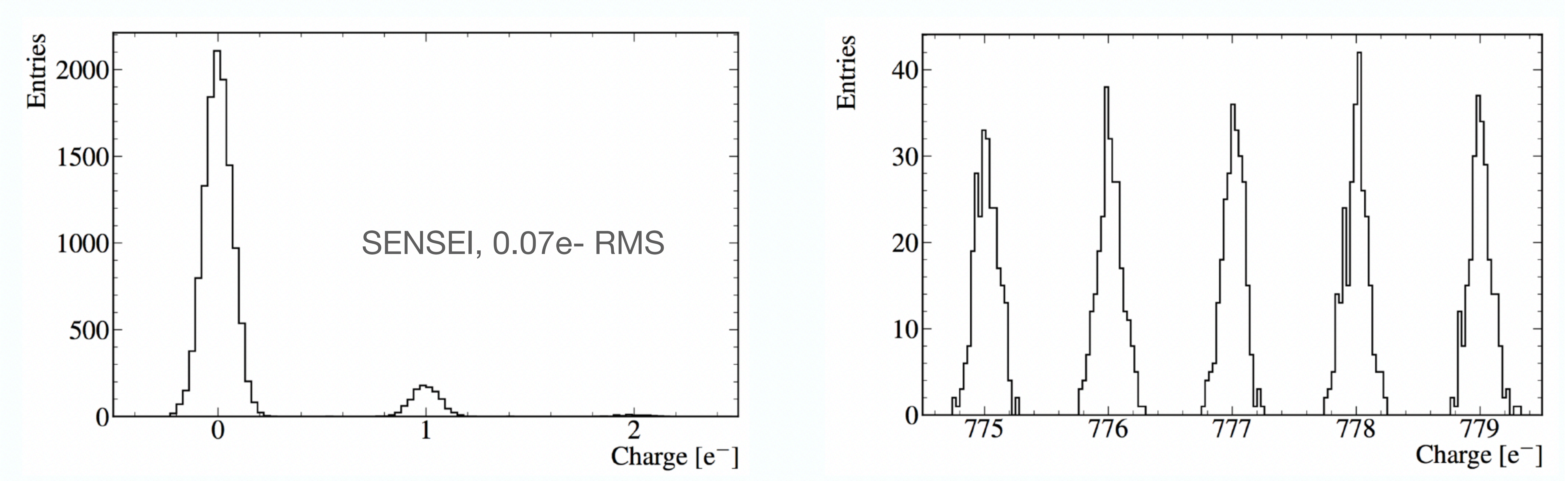
- Detector is literally a camera. Keep running for a few hours before readout, then clear and start again.
- 2D track reconstruction from pixels, Z-coordinate reconstruction from electron dispersion.
- Can identify nature of individual events



- Skipper CCD innovation : read each charge packet multiple times. Reduce electronic noise to almost nothing!
- Need to balance with dark current, which increases with readout time
- Can count primary electrons up to hundreds!!

PRL **119**, 131802 (2017)





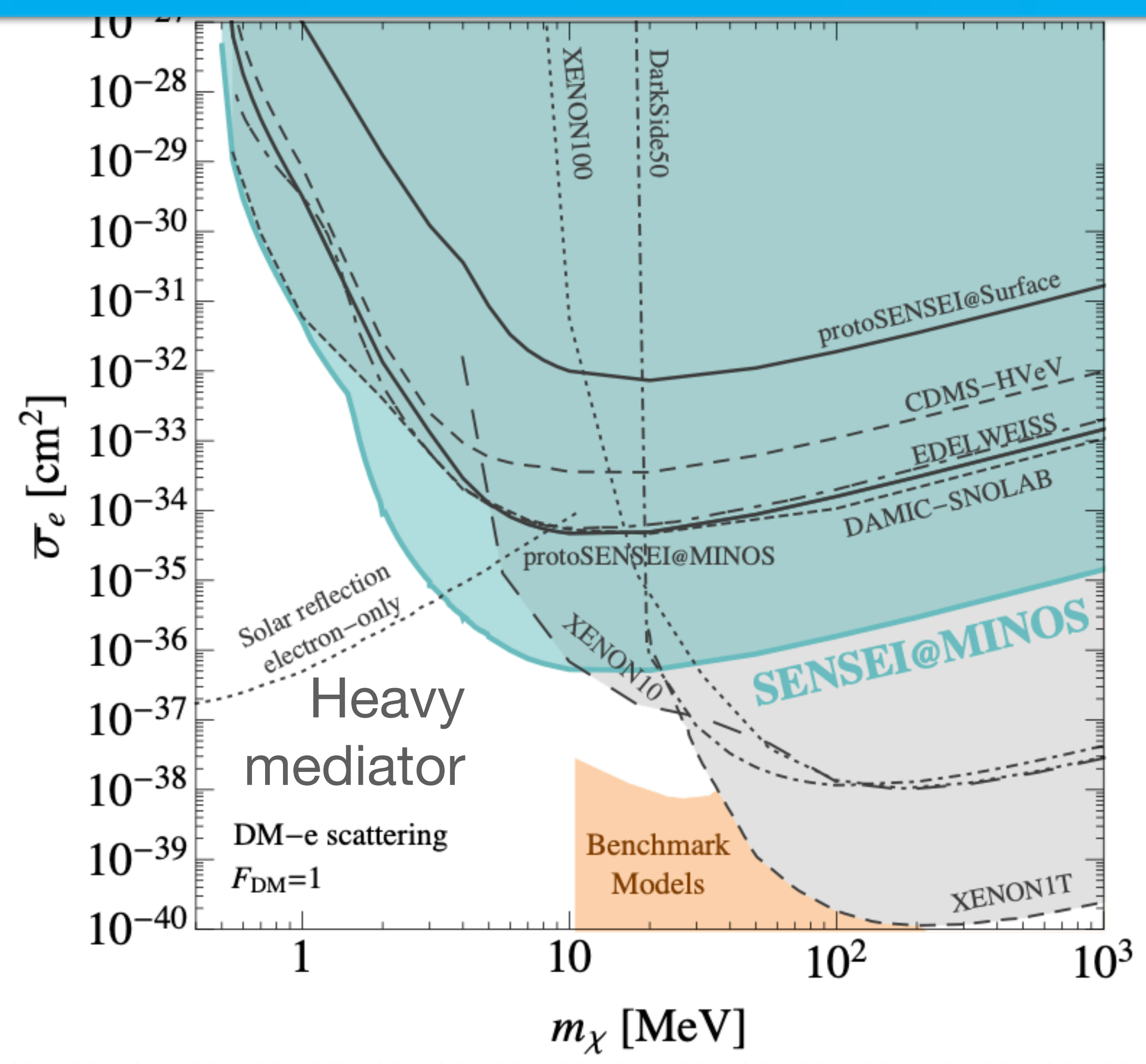
- First DM search with Skipper CCDs, at Fermilab. **Reached ~0.5 MeV/c² DM masses!**

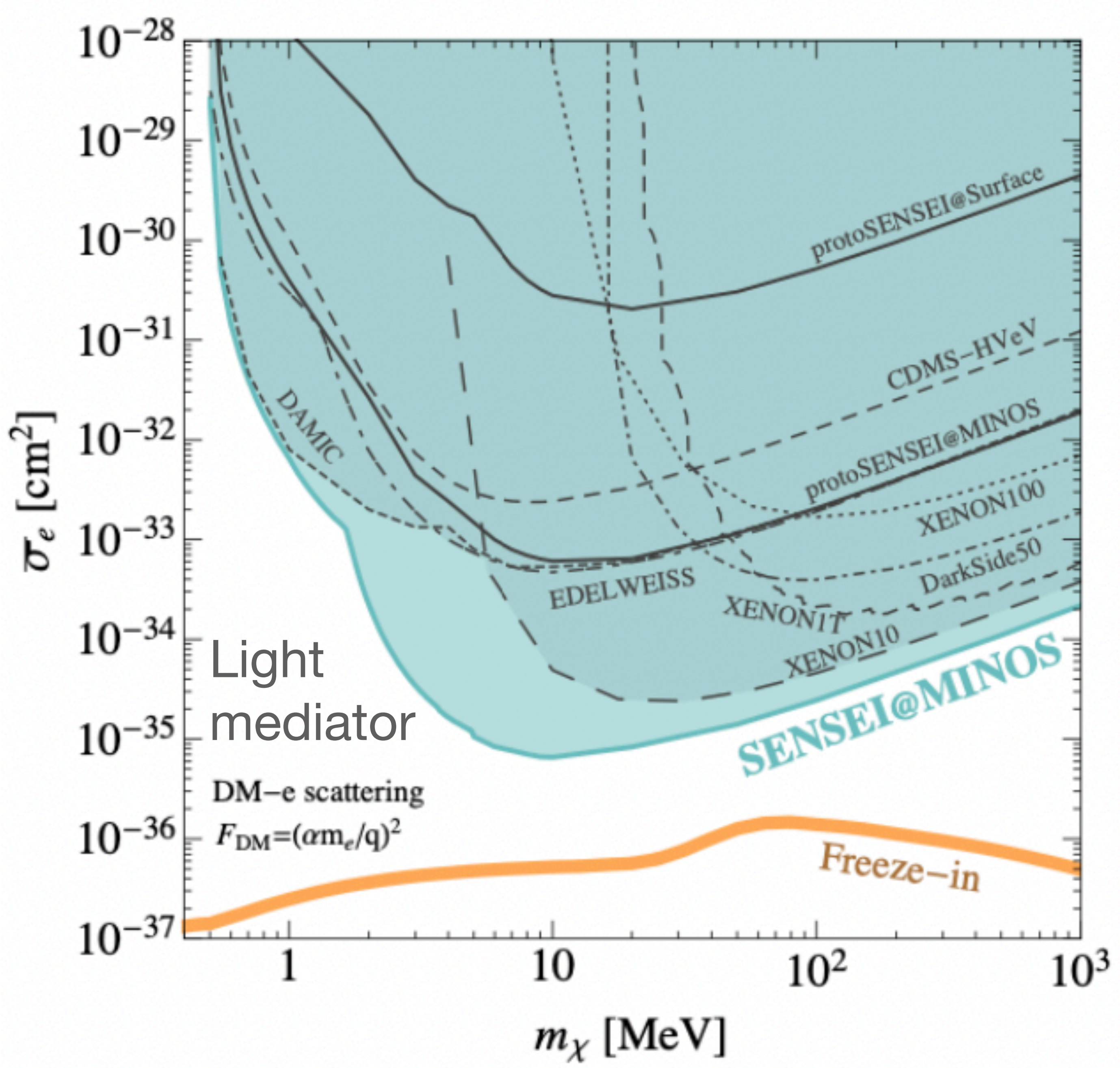
PRL125(2020)171802

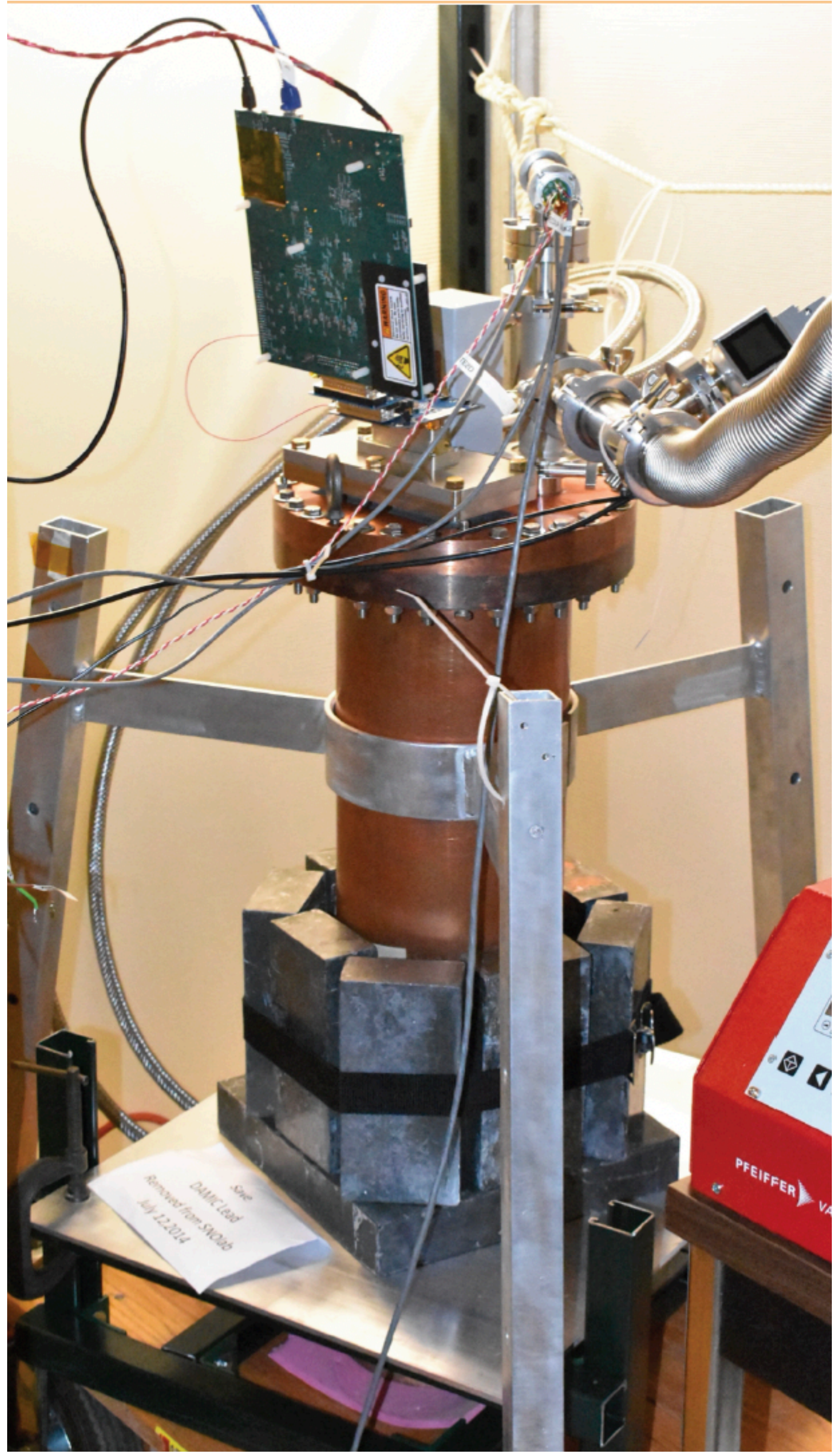
- Observed large single-electron background, under study.

PRX12(2022)011009

- New generation detector search at SNOLAB with 10 CCDs (goal 100g)

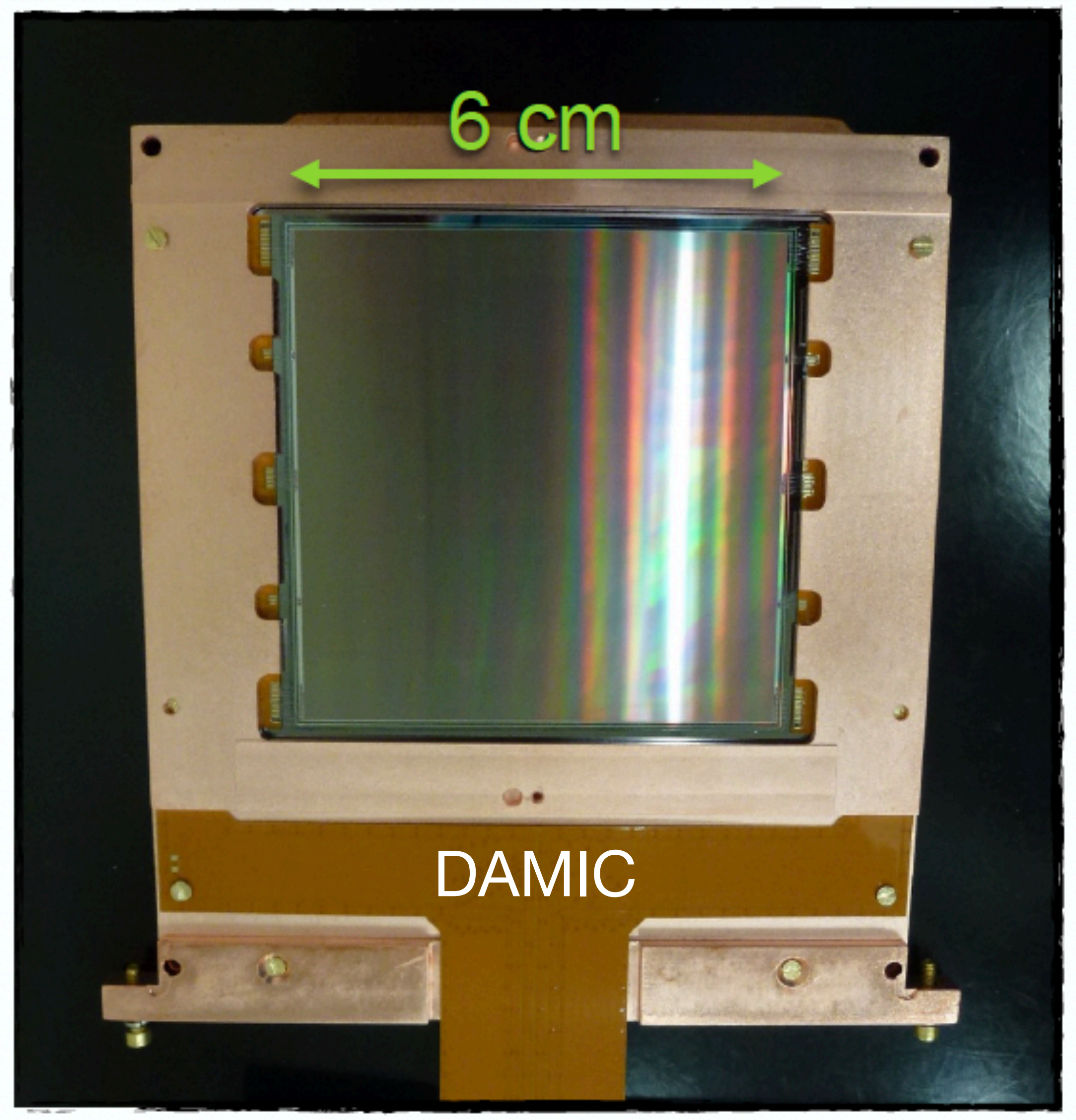






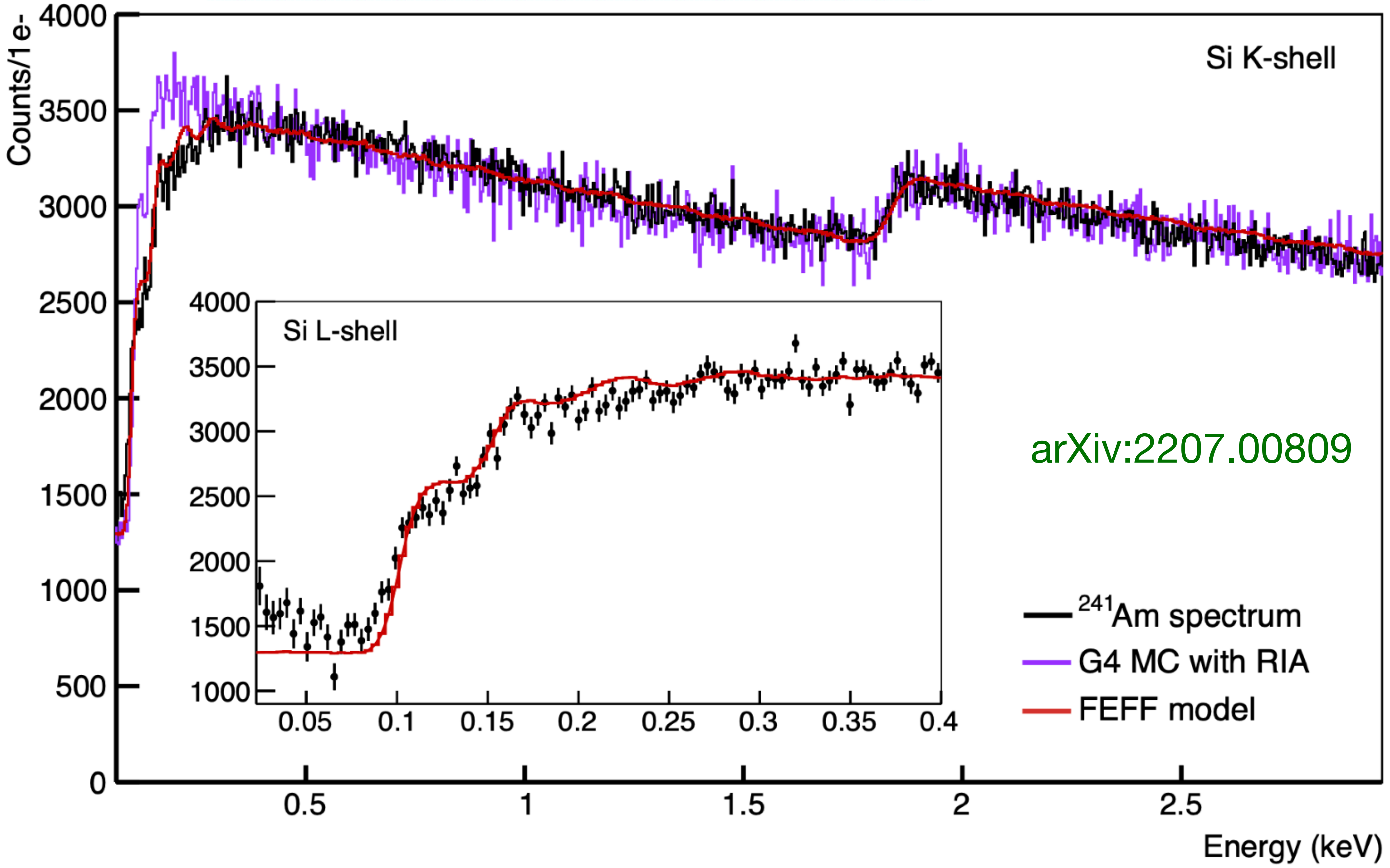
- First array of CCDs operated underground (SNOLAB) for DM search, since 2012. 11kg-year exposure. 1.6e- noise with conventional readout.

- New generation search with DAMIC-M at Modane with Skipper CCDs (0.07e- RMS), aiming for kg-year exposures with most massive CCDs ever built. First tests ongoing (threshold of 23eV$_{ee}$, Compton edge study)



PRL123(2019)181802

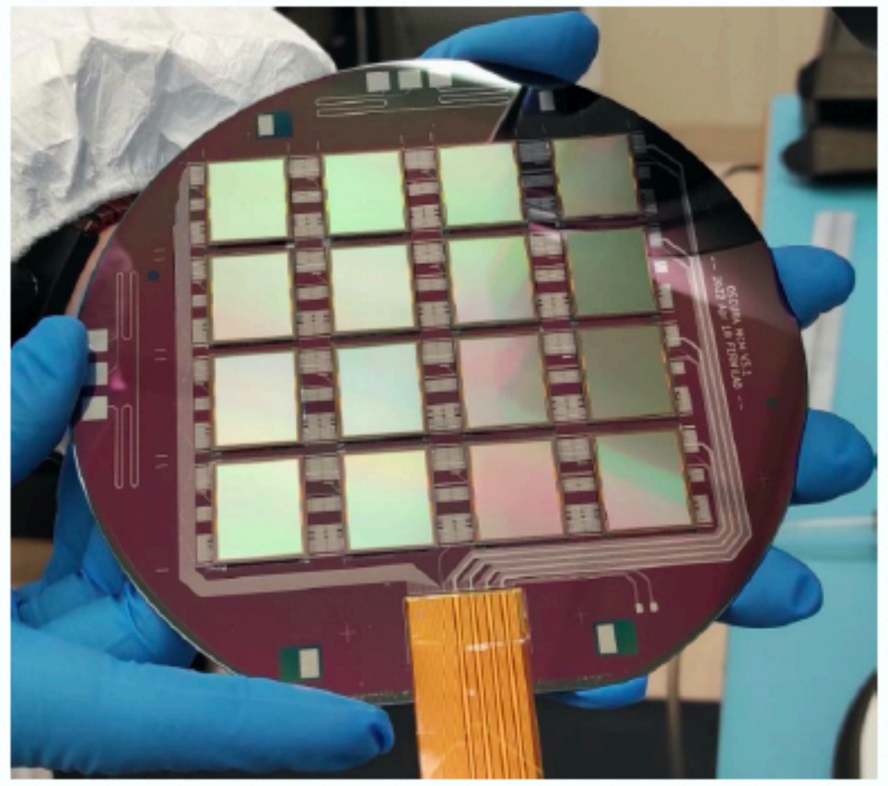
PRL125(2020)241803



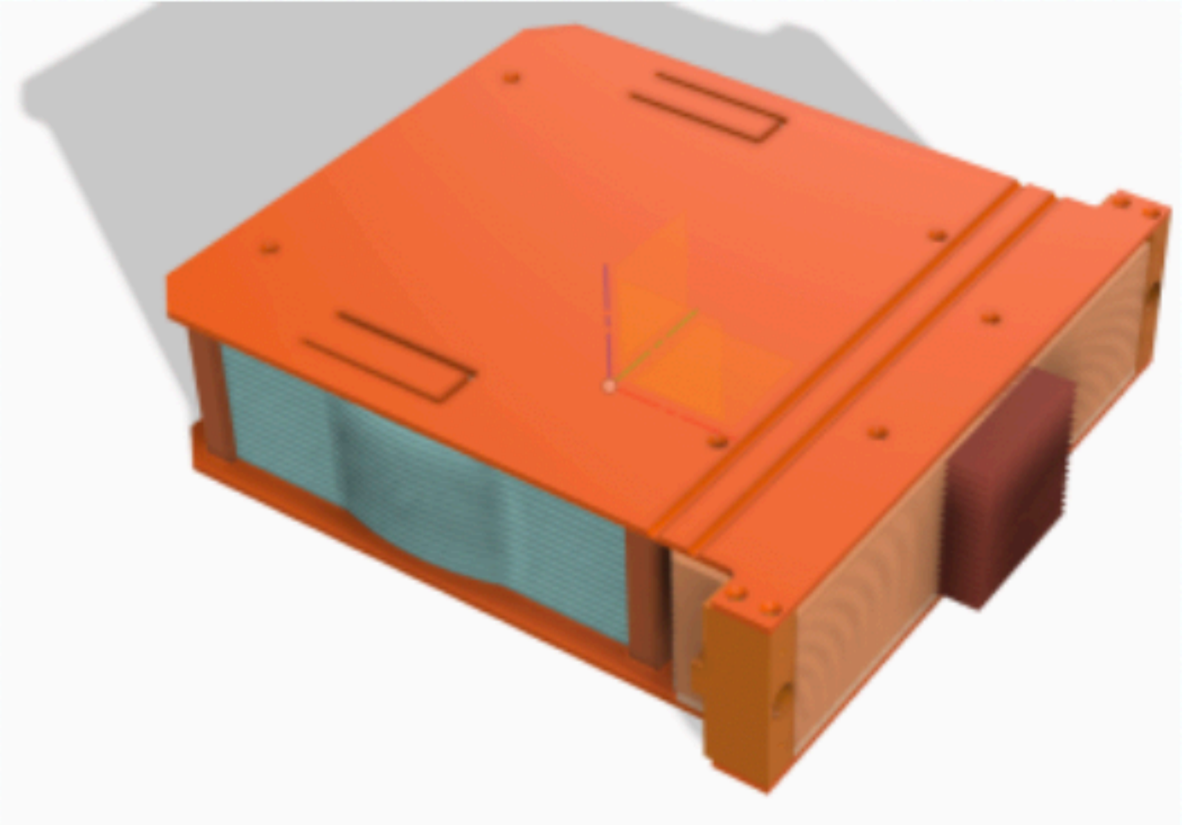
arXiv:2207.00809

- **R&D**: scale the existing technology towards a 10 kg experiment.
- **Goal**: 30 kg-yr exposure with background level of 0.01 d.r.u.
- 28 Gpix in full Oscura instrument! c.f. LSST camera's 3.2 Gpix.

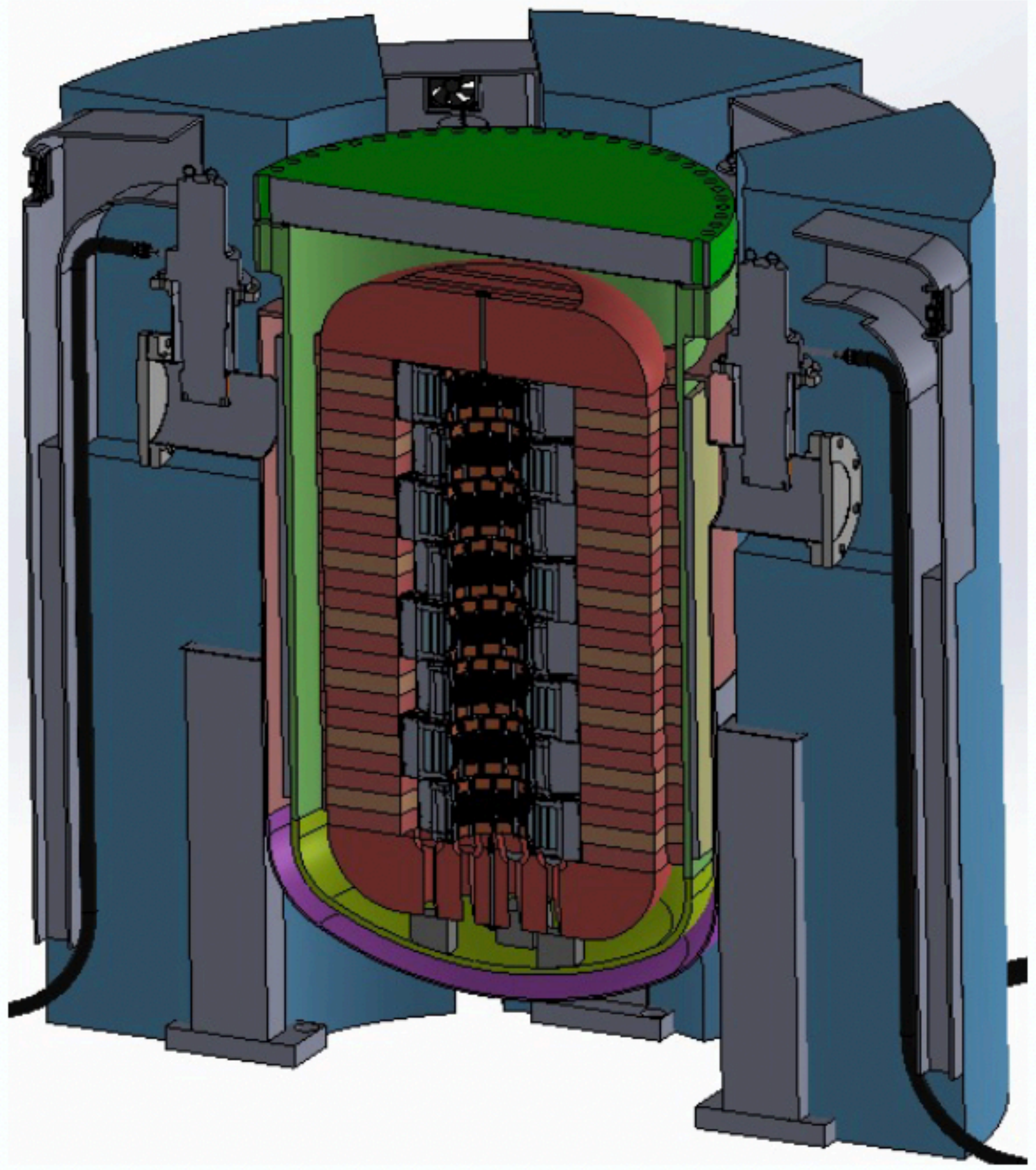
arXiv:2202.10518



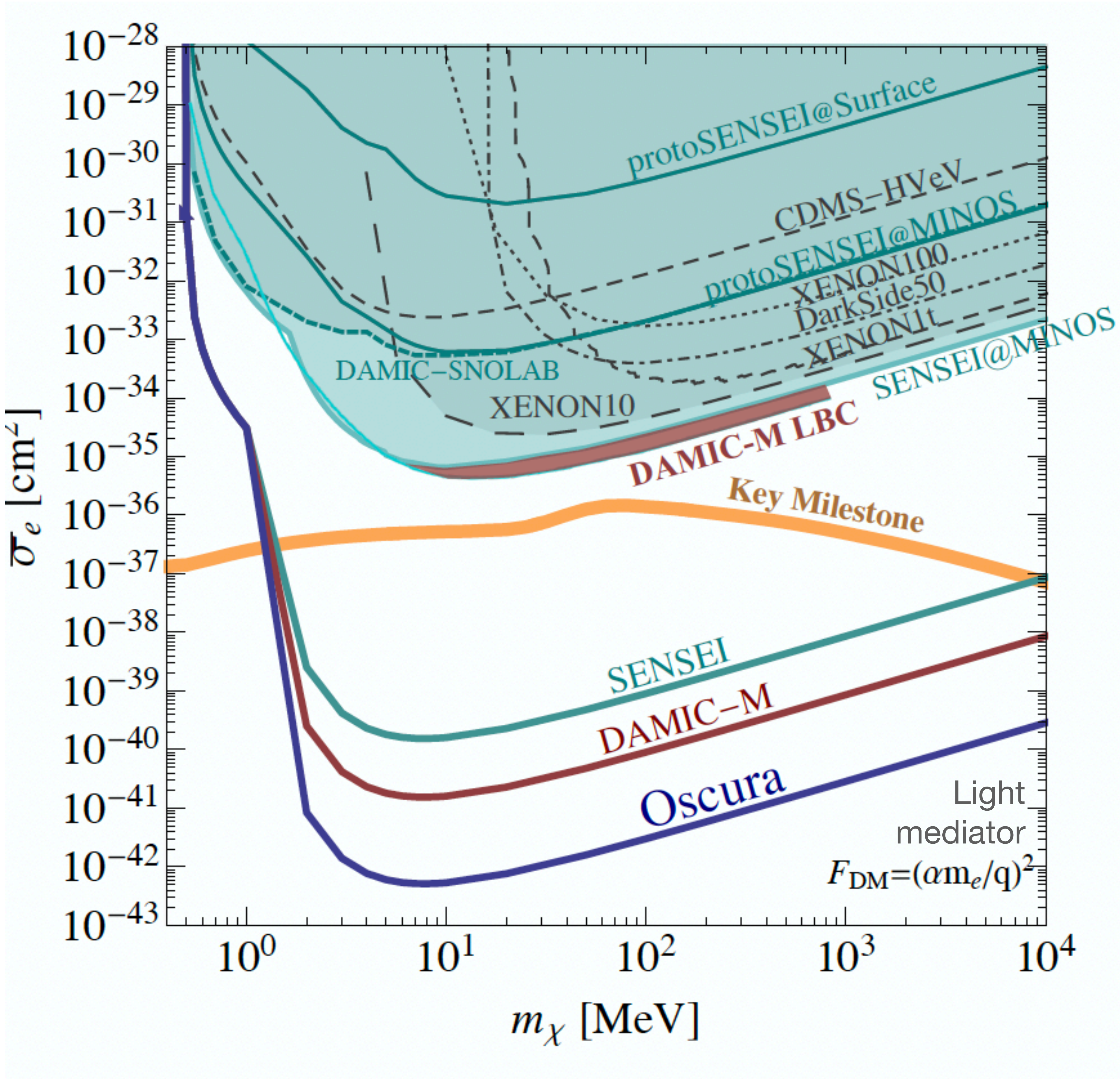
16-CCD Multi Chip Module (MCM)

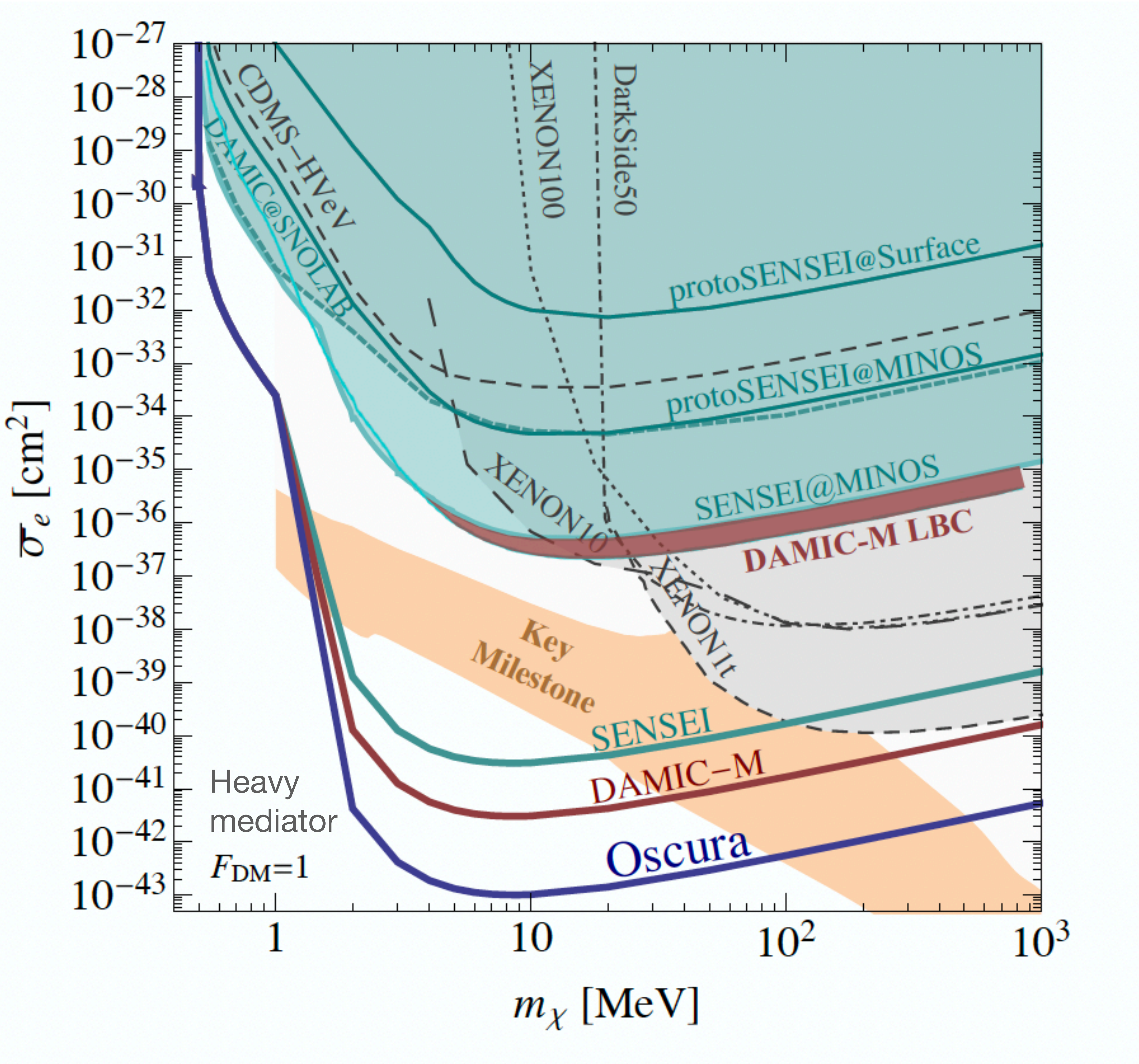


Super Module (SM): 16 MCMs in EFCu



Full payload 100 SMs: 10 kg!


protoSENSEI@Surface
CDMS-HVeV
protoSENSEI@MINOS
XENON100
DarkSide50
XENON1t
SENSEI@MINOS
DAMIC-SNOLAB
XENON10
DAMIC-M LBC
Key Milestone
SENSEI
DAMIC-M
Oscura
Light mediator
$F_{DM}=(\alpha m_e/q)^2$
$\bar{\sigma}_e$ [cm^2]
m_χ [MeV]


CDMS-HVeV
DAMIC@SNOLAB
XENON100
DarkSide50
protoSENSEI@Surface
protoSENSEI@MINOS
XENON10
SENSEI@MINOS
DAMIC-M LBC
XENON1t
Key Milestone
SENSEI
DAMIC-M
Oscura
Heavy mediator
$F_{DM}=1$
$\bar{\sigma}_e$ [cm^2]
m_χ [MeV]

Summary

- Liquid Noble detectors dominate down to ~2 GeV/c2 masses.
- Cryogenic detectors are become ever more competitive at lower WIMP masses (down to ~100 MeV/c2) by improving their threshold.
- Lighter targets (He, H) are required for seeing lighter WIMPs interacting with nucleons
  - Gas detectors can employ directionality for conclusive proof of DM detection
  - TESSERACT/HeRALD has extremely ambitious goal of 10 keV/c2 sensitivity
- Migdal effect, if experimentally proven for nuclear recoils, could radically alter the regions that DM-nucleon detectors are sensitive to.
- DM interactions on electrons detected with (skipper) CCDs give sensitivities down to ~300 keV/c2.
- Other models for DM required to probe below that (hint: axion).

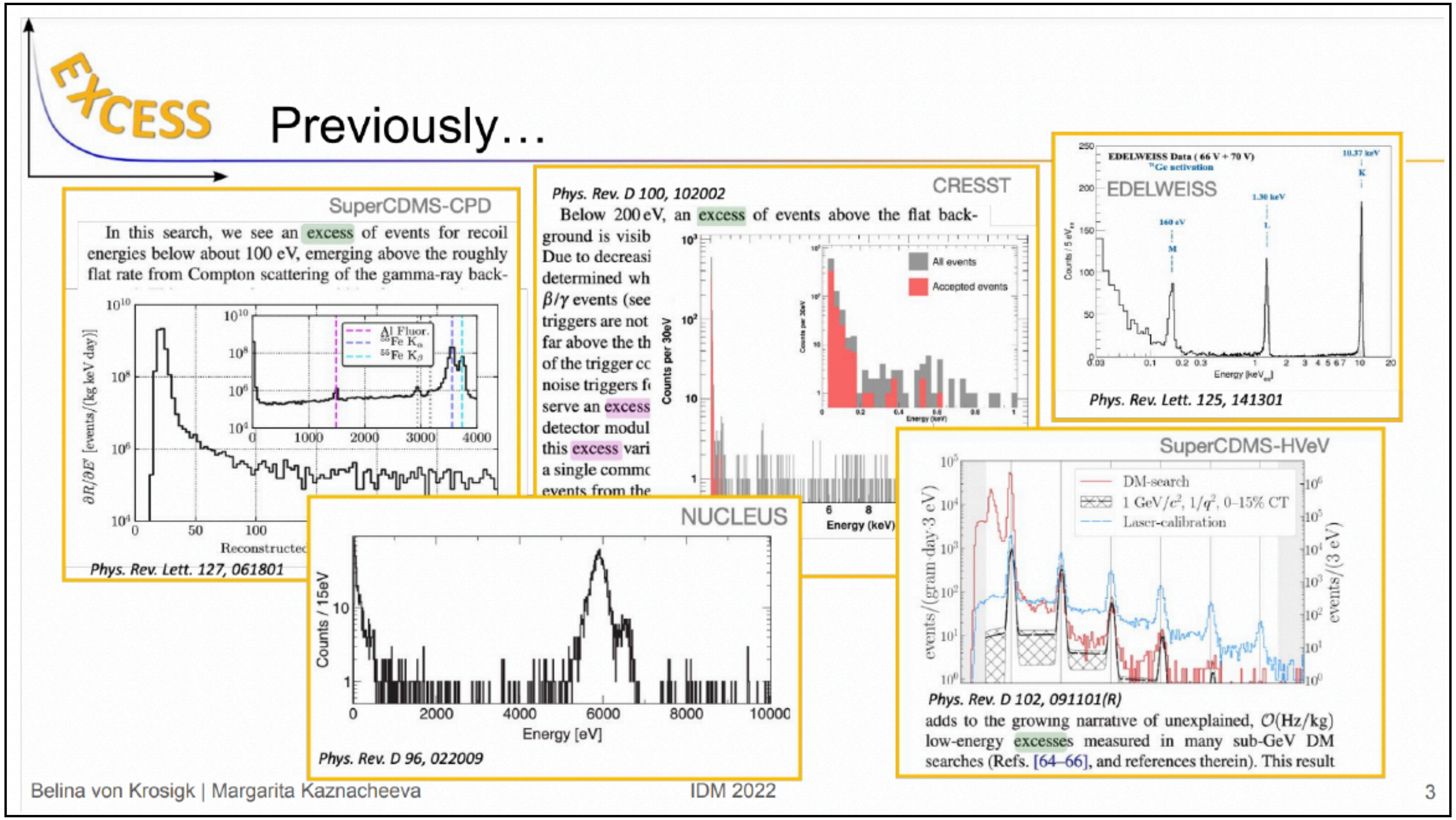
B. Majorovits talk (right after this one!)

Not mentioned

- Calibration efforts (especially for Quenching Factor)
- Spin-dependent DM-nucleus interactions
- Effect of halo DM velocity distribution or cosmic-ray boosted DM on detector sensitivity
- CEvNS offshoots
- DM absorption (dark photons, etc)
- …Other stuff I forgot about

Thank you for your attention!

Extra slides



Observed event excesses in cryogenic detectors. EXCESS initiative to try to find (common?) origin.

doi: 10.21468/SciPostPhysProc.9.001

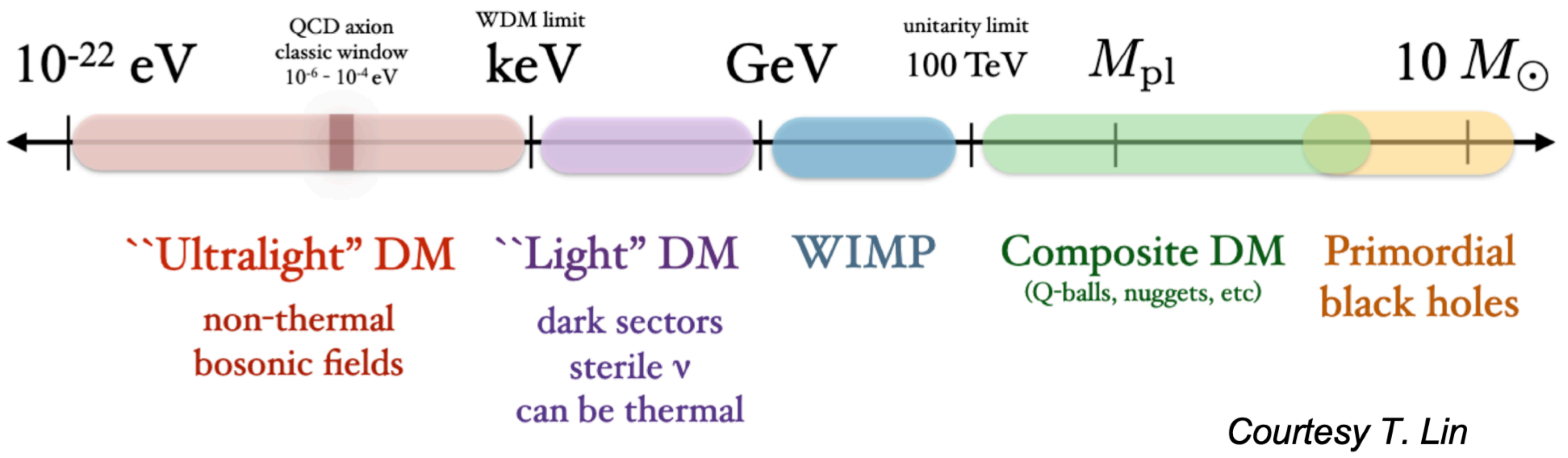
Leading theory: stresses/ microfractures

Summary at IDM'22:
https://indico.cern.ch/event/922783/contributions/4883379/

- Under ~keV/c² masses for Dark Matter, it behaves more wave-like : boson

- QCD axion possible candidate. Searches for axion (and Axion-Like-Particles) through Primakoff effect : conversion axion-photon in presence of magnetic field.

- Topic for other talks!



B. Majorovits talk
(right after this one!)