# Sources of Low-energy Events in Sub-GeV Dark Matter Detectors

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In collaboration with Daniel Egana-Ugrinovic, Rouven Essig and Mukul Sholapurkar
(arXiv2011.13939)

# Sub-GeV dark matter detections with semiconductors

General idea: Look for electron-hole pairs in semiconductors

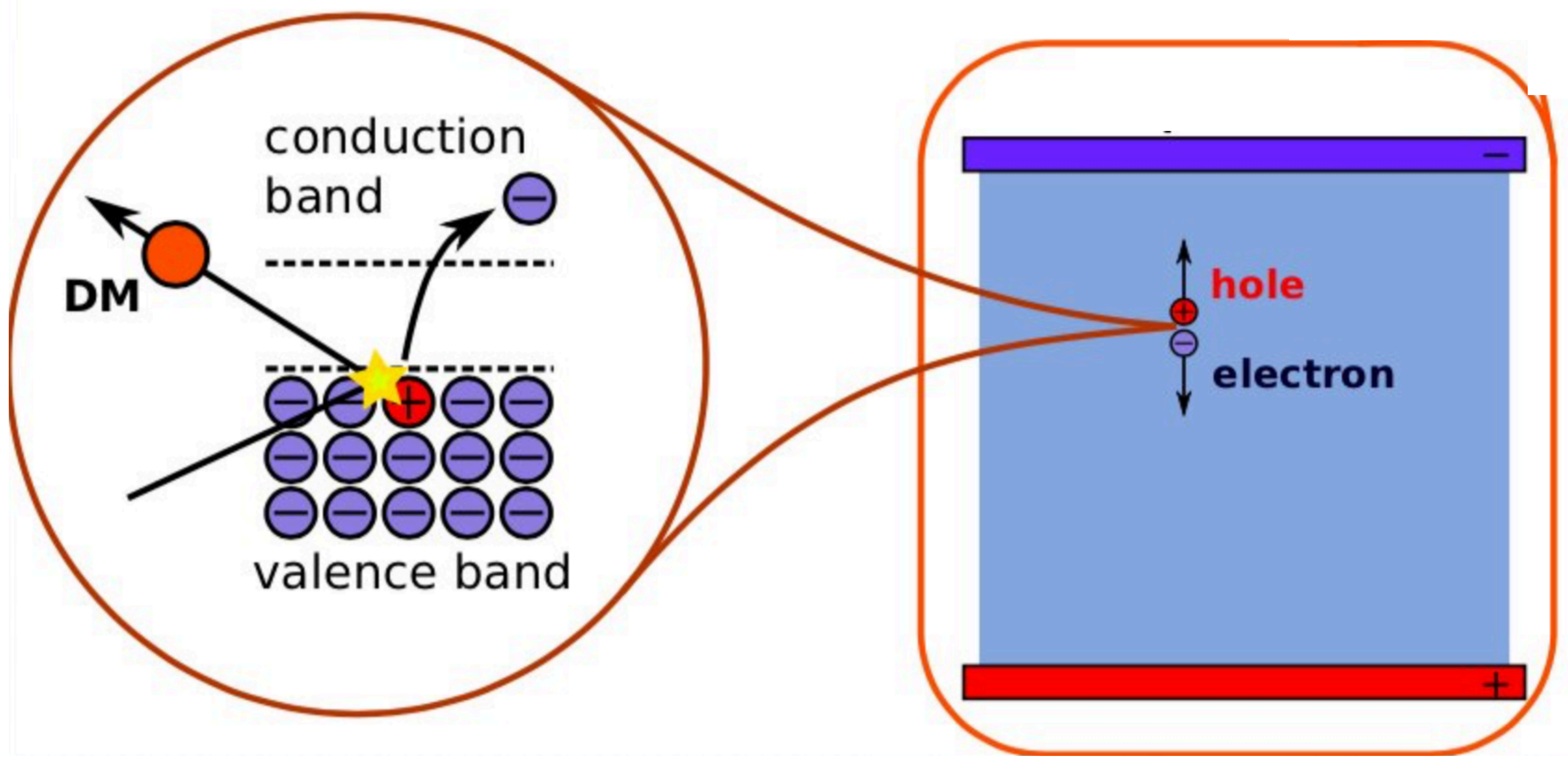


Figure from Sho Uemura

Bandgap of semiconductors ~eV

**Can probe sub-GeV dark matter:**

$$E_{\rm ER} \lesssim \frac{1}{2} m_\chi v^2 \approx 1\,\mathrm{eV} \left[\frac{m_\chi}{2\,\mathrm{MeV}}\right]$$

# Sub-GeV dark matter detections with semiconductors

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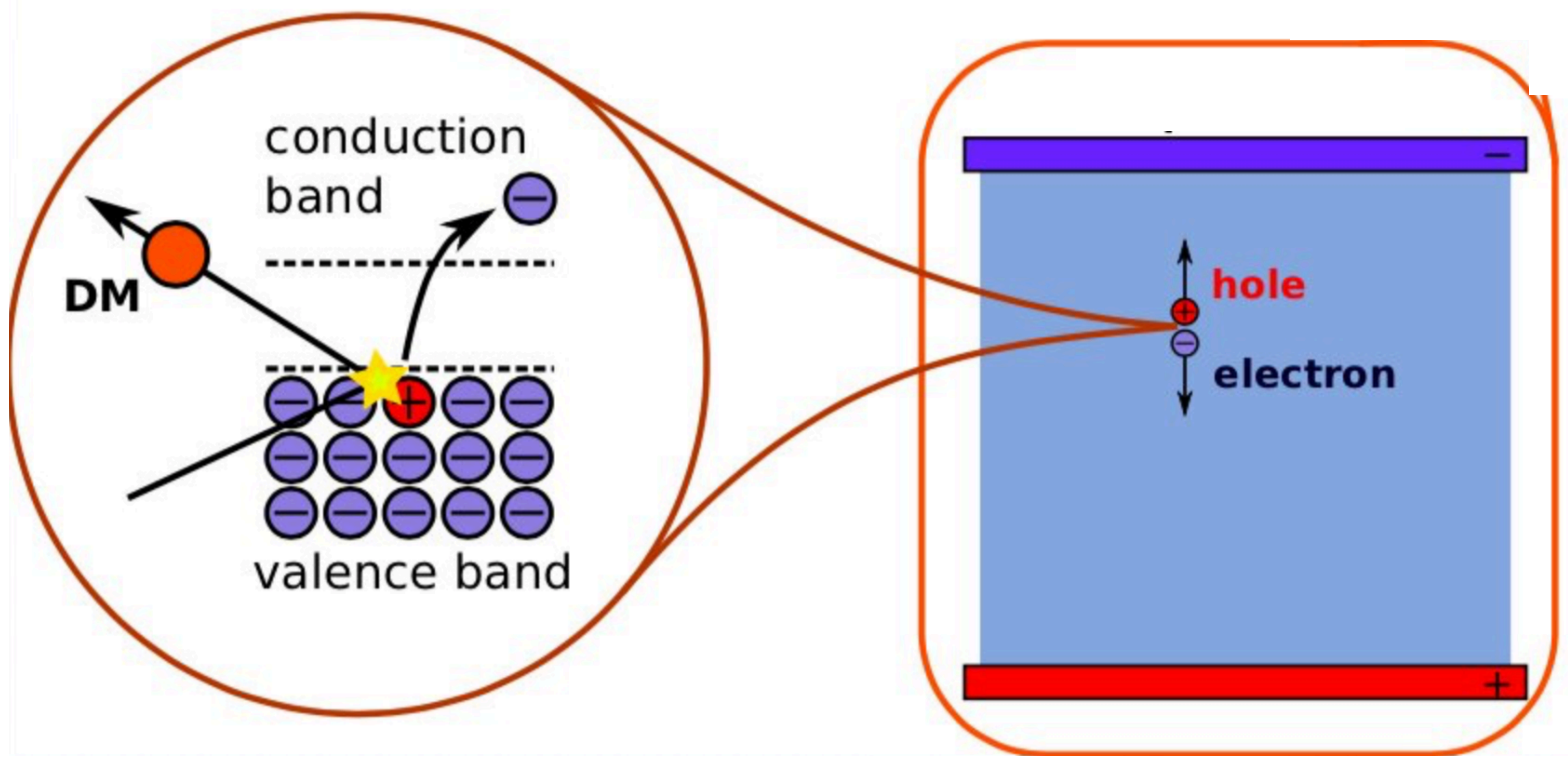


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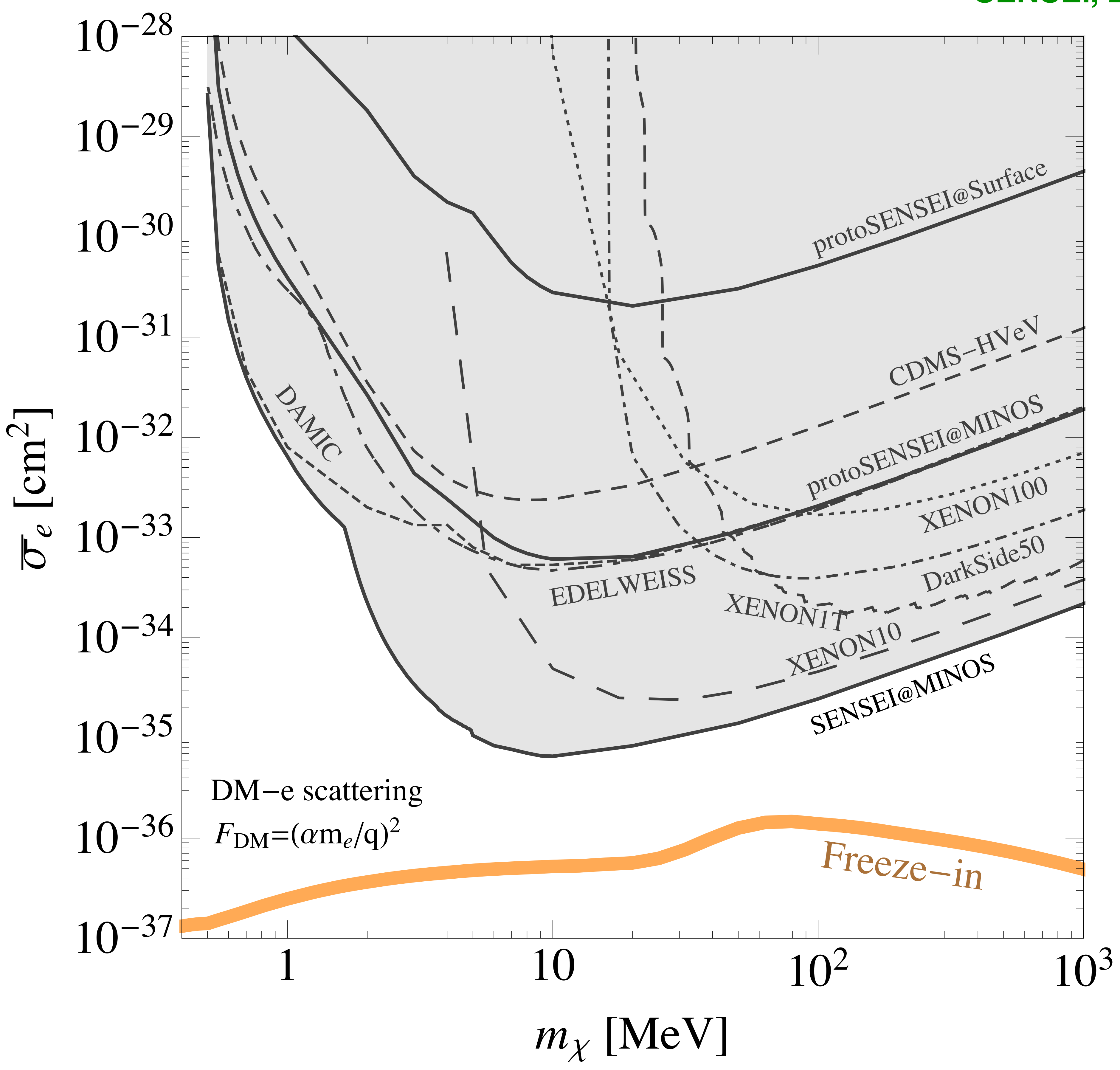
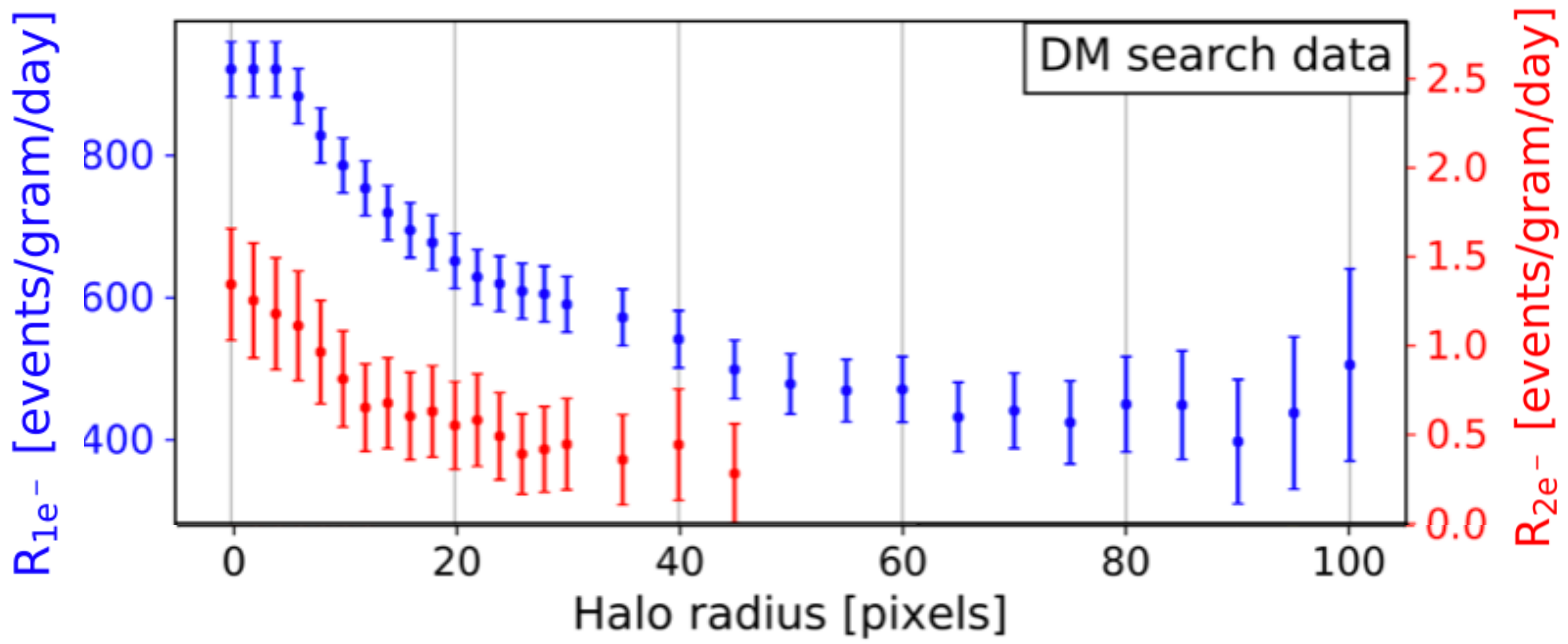
SENSEI, 2020



# Excess in Sub-GeV dark matter detectors

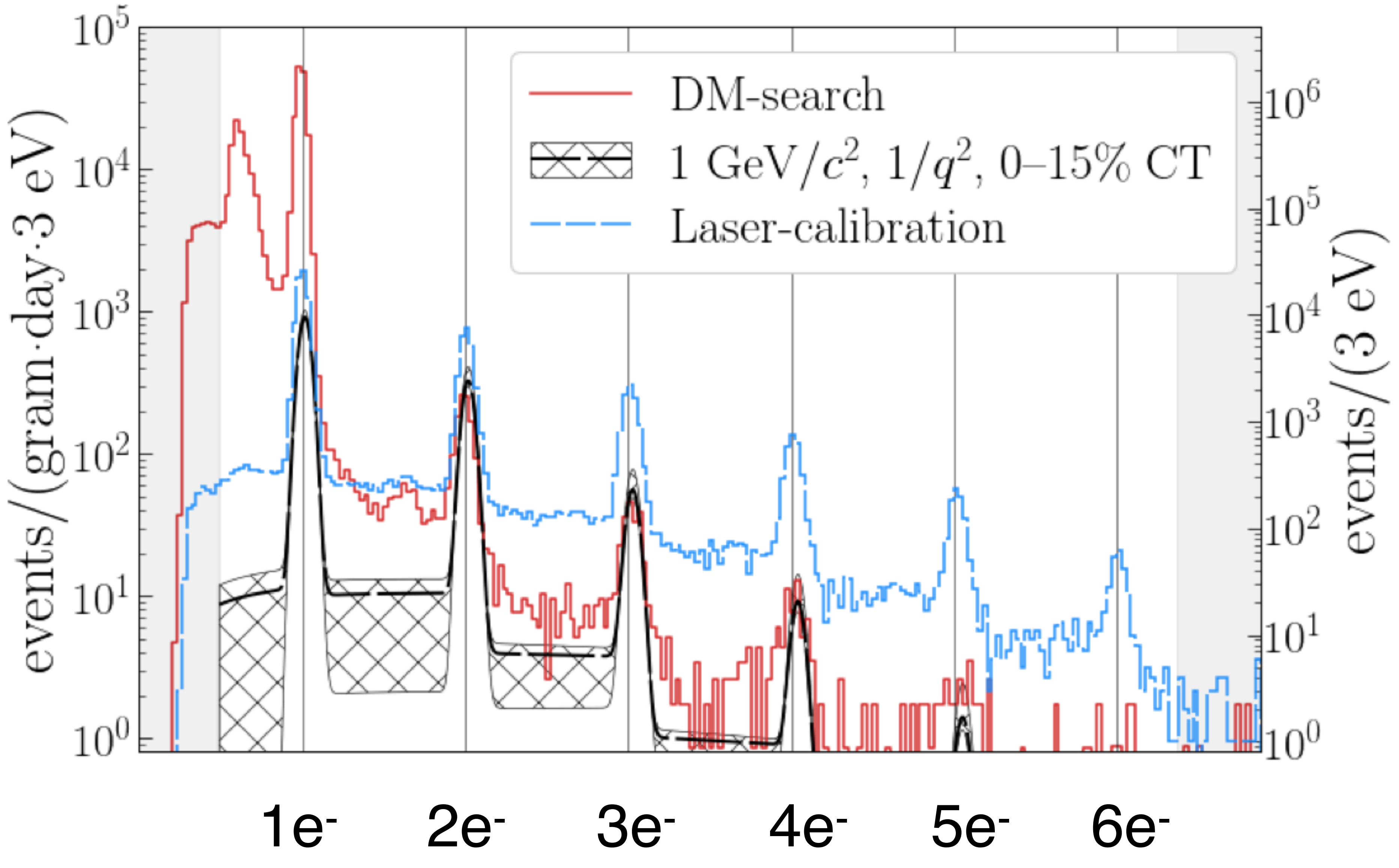
*SENSEI*

SENSEI, 2020




*SuperCDMS HVeV*

SuperCDMS, 2020

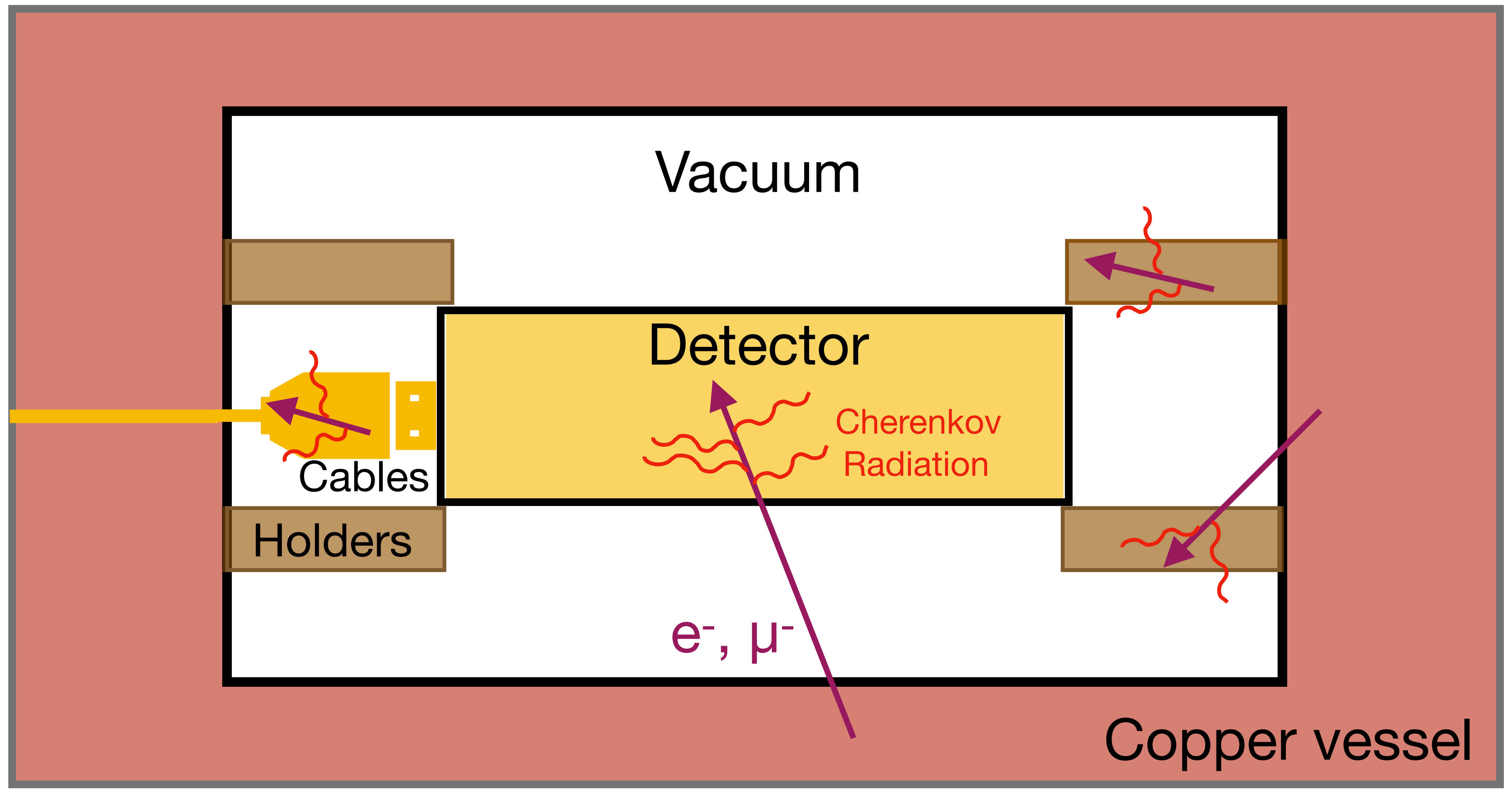


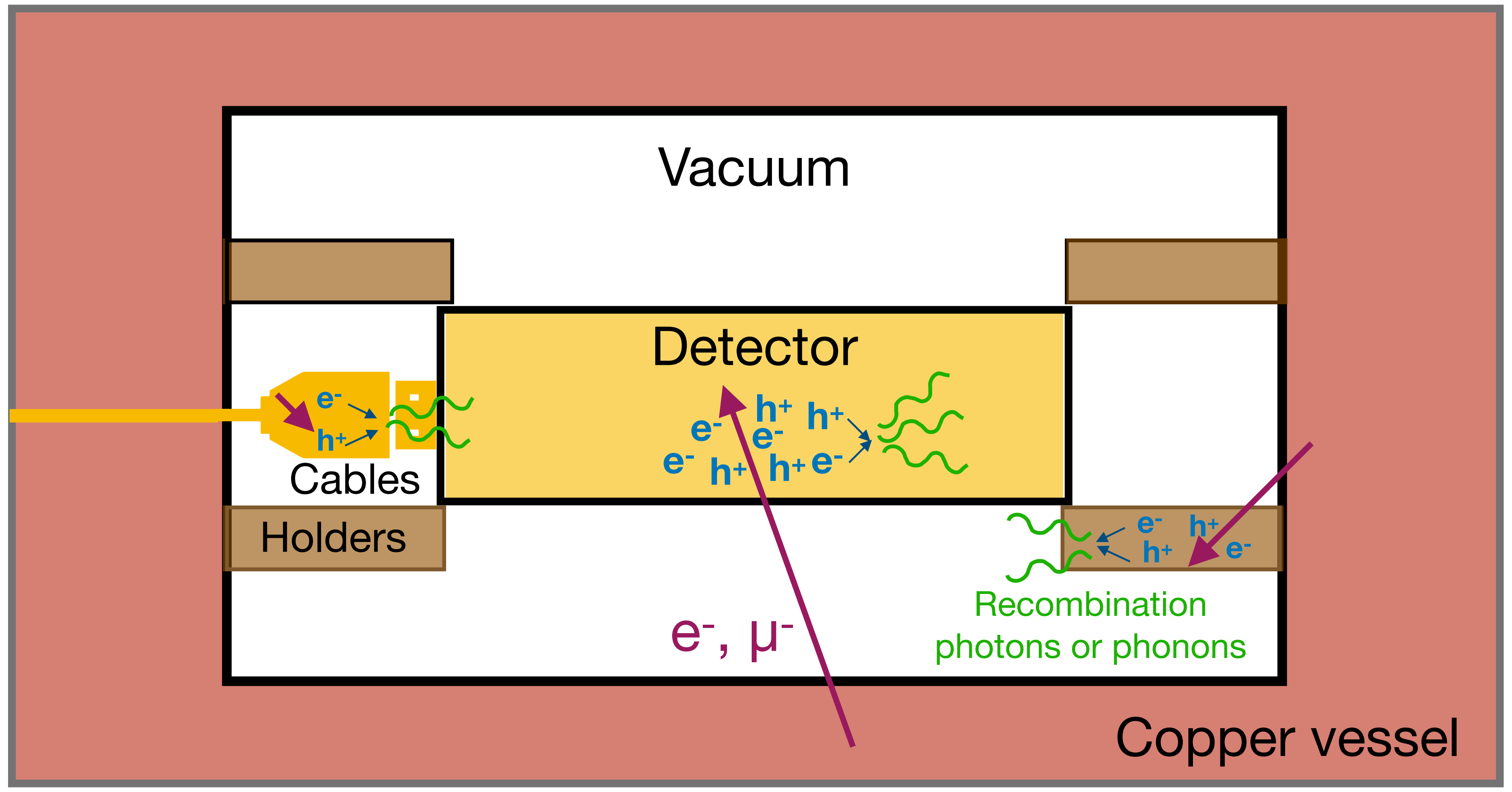

- Excess events are near the threshold
- Cannot be explained by known sources
- Limit the sensitivity for dark matter detection

# Sources of low energy backgrounds

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020

*Cherenkov radiation and radiative recombination are unexplored sources of low-energy backgrounds at sub-GeV dark matter detectors*




In this talk:

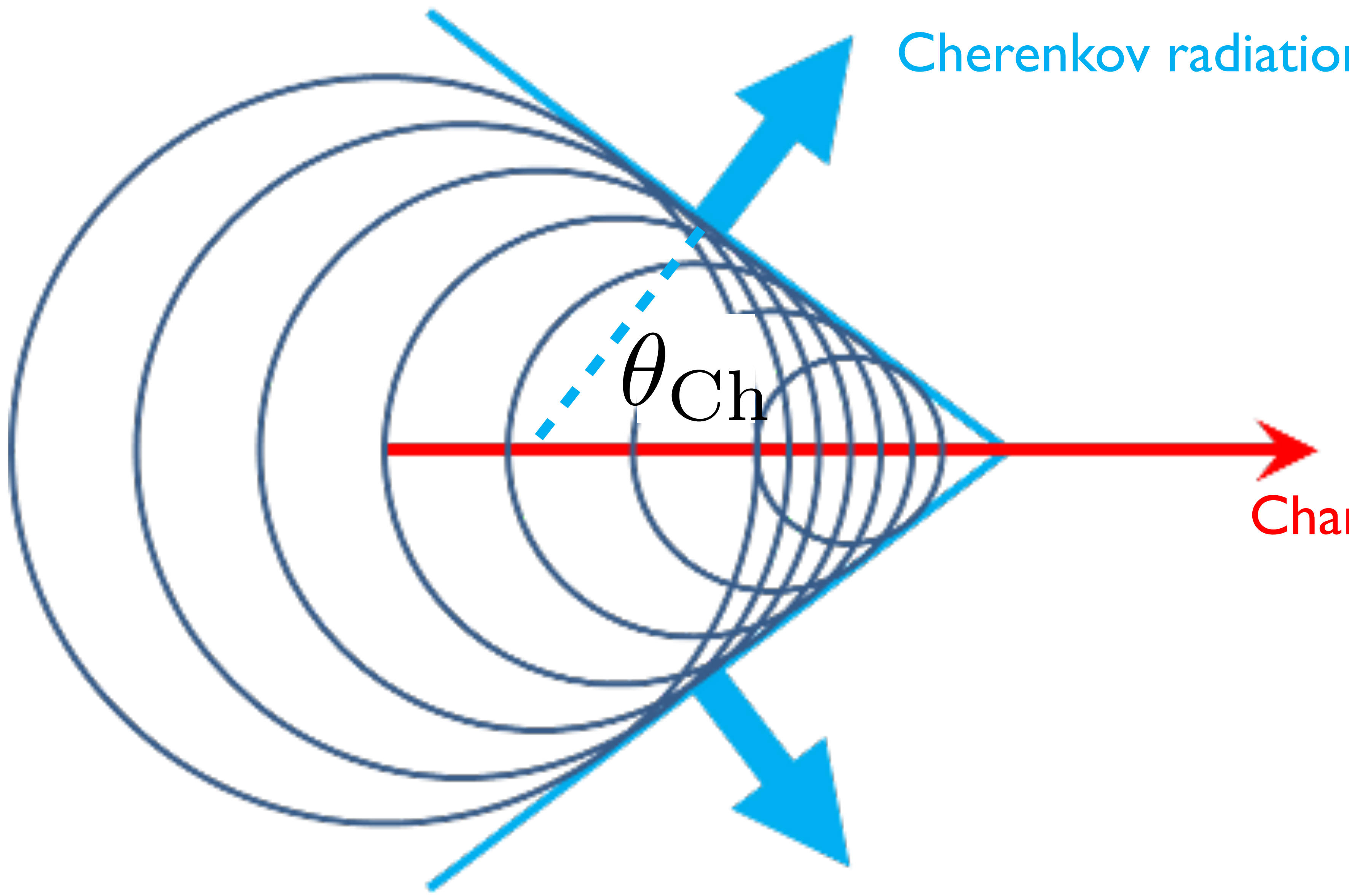
Cherenkov radiation inside detector ⇒ SENSEI excess

Cherenkov radiation from holders ⇒ SuperCDMS HVeV excess

# Cherenkov radiation

Jackson, Classical Electrodynamics

Incident charge is moving faster than the speed of light inside the medium



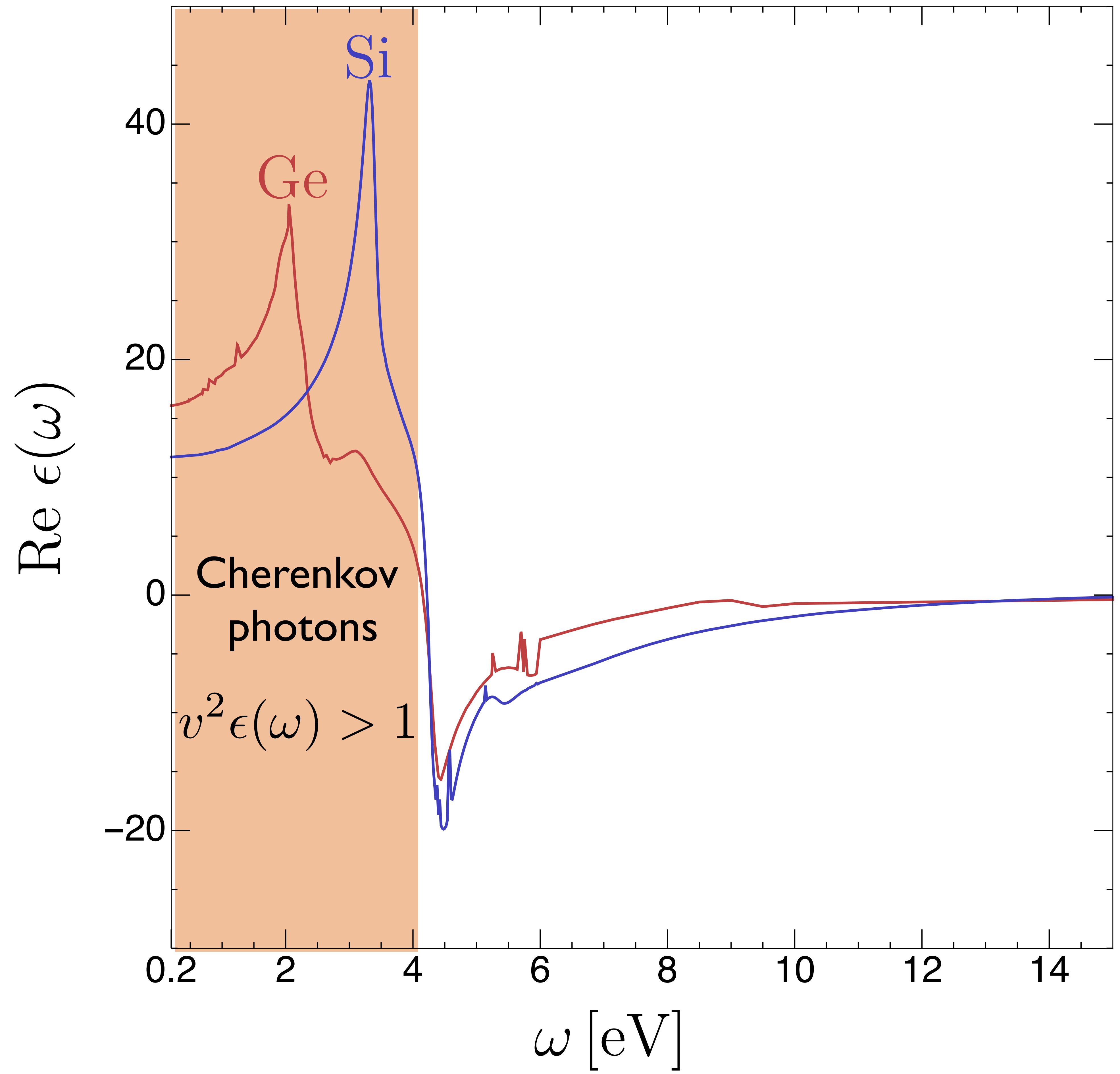

Condition:

$$v^2\epsilon(\omega) > 1$$

$$\frac{d^2N}{d\omega dx} = \alpha\left(1 - \frac{1}{v^2\epsilon(\omega)}\right)$$

$$\cos\theta_{\rm Ch} = \frac{1}{v\sqrt{\epsilon(\omega)}}$$

# Cherenkov radiation in semiconductor target




*Cherenkov spectrum:*

$$\omega \lesssim 4\,\mathrm{eV}$$

Near bandgap/detection threshold

Typical rate:

$$\frac{d^2N}{d\omega dx} \sim \alpha \quad (\text{for}\,\epsilon(\omega) \gg 1)$$

$$N \sim 40 \left[\frac{\Delta\omega}{1\,\mathrm{eV}}\right] \left[\frac{\Delta x}{1\,\mathrm{mm}}\right]$$

Significant rate for dark matter detection

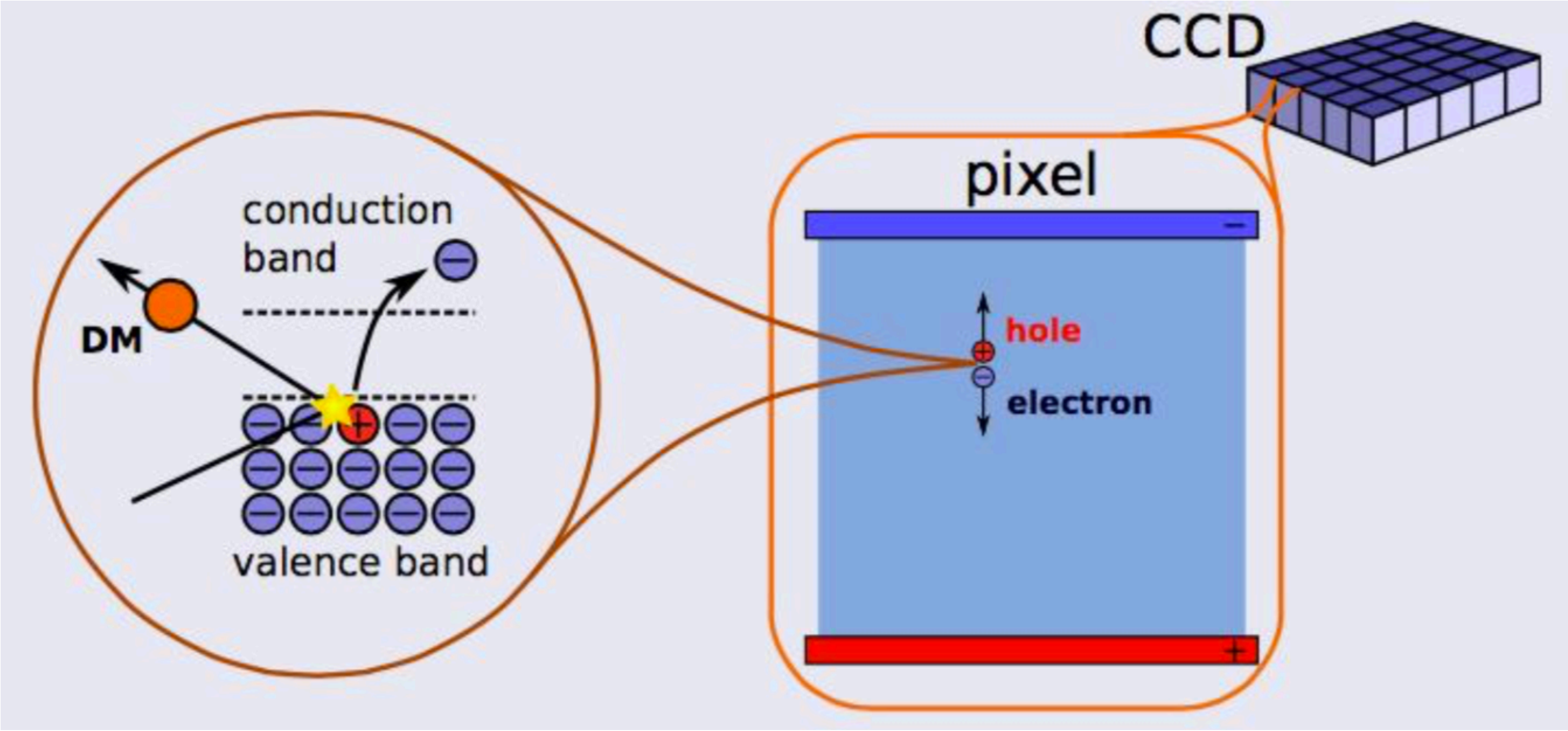
# Experiments: SENSEI

# SENSEI experiment

SENSEI, 2020

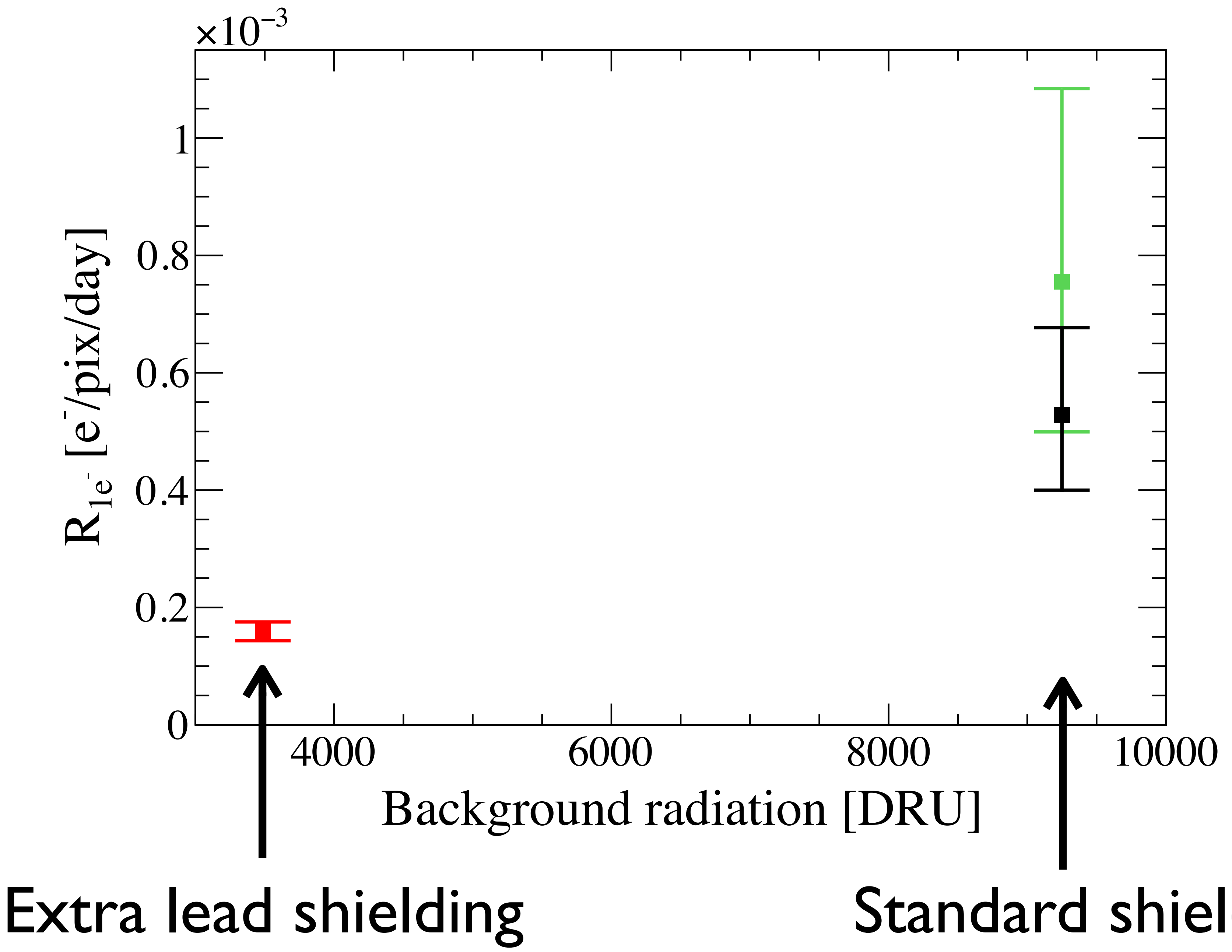
- Look for electron-hole pairs in skipper CCD, ~0.1 $e^-$ resolution
- Location: MINOS cavern at Fermilab, 104 m underground
- CCD: 1.329 × 9.216× 0.0675 $cm^3$ ,1.926 gram active mass

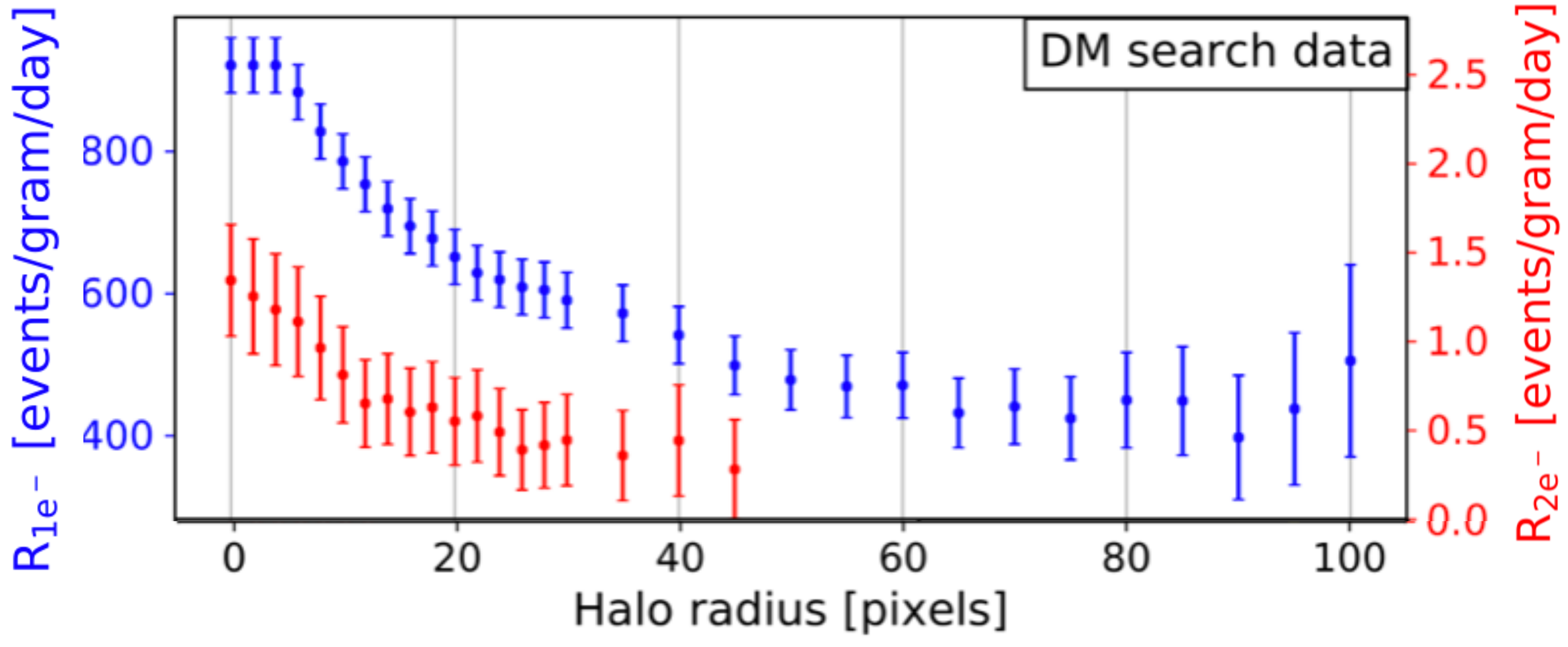
Nice spatial resolution but limited timing resolution



# Single electron rate excess in SENSEI

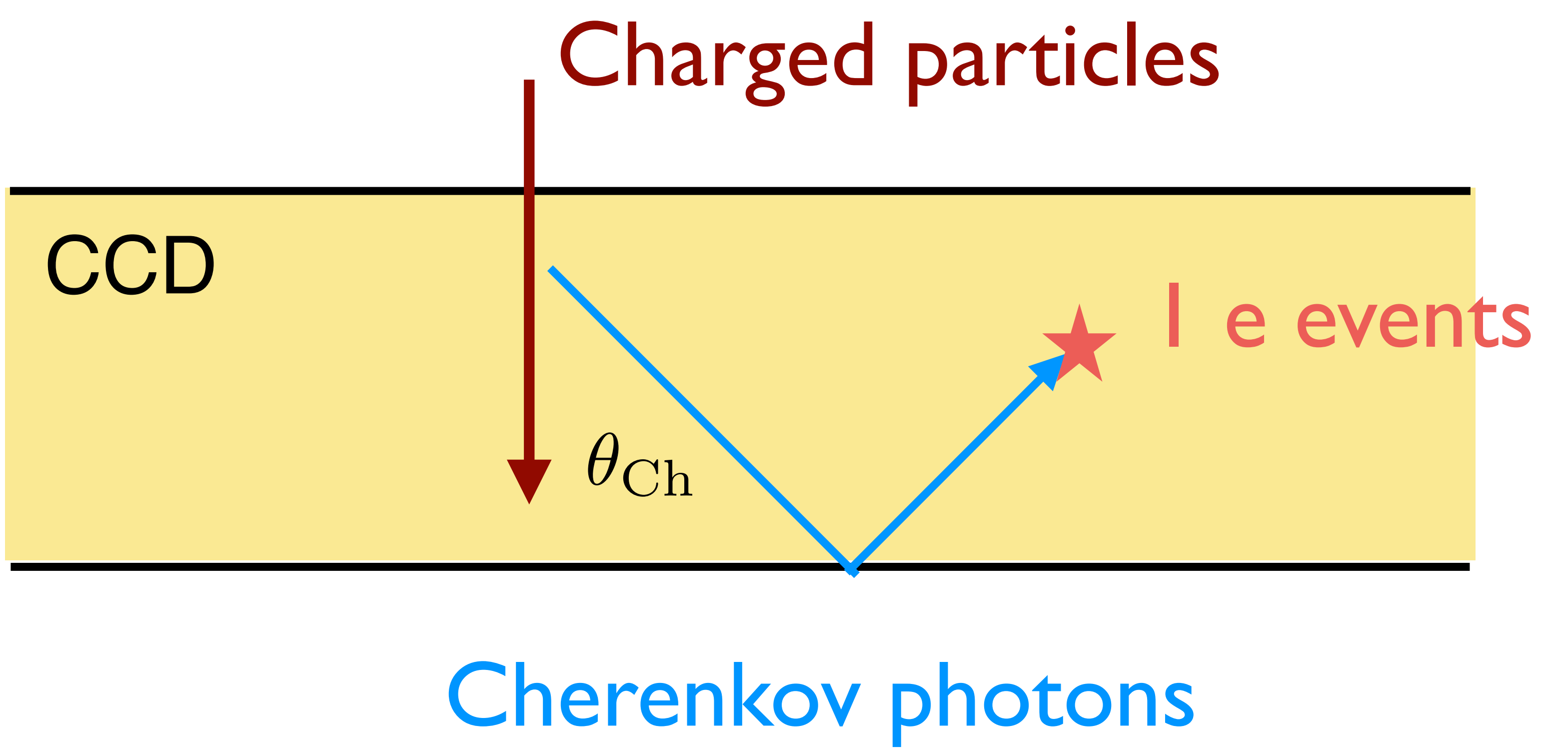
SENSEI, 2020



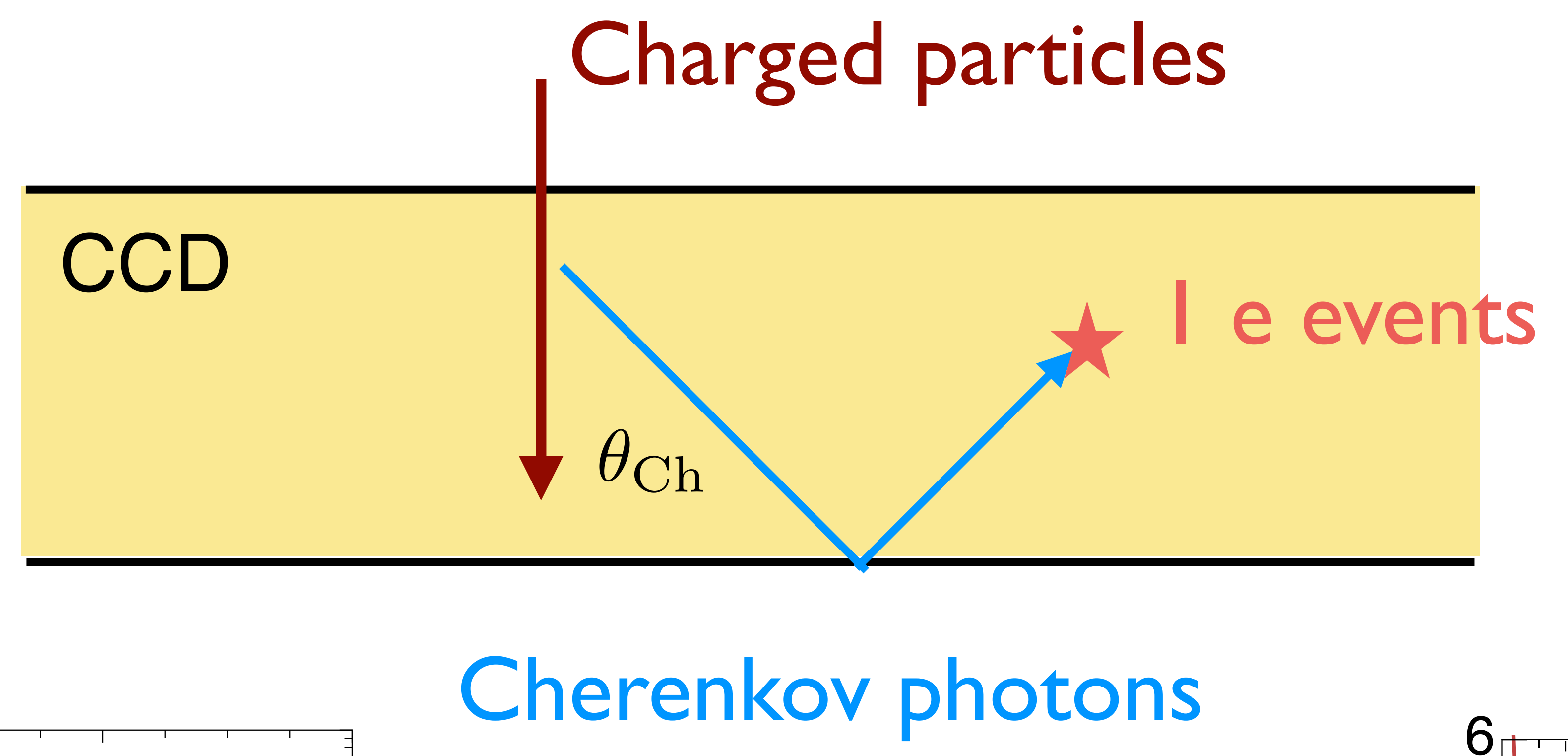



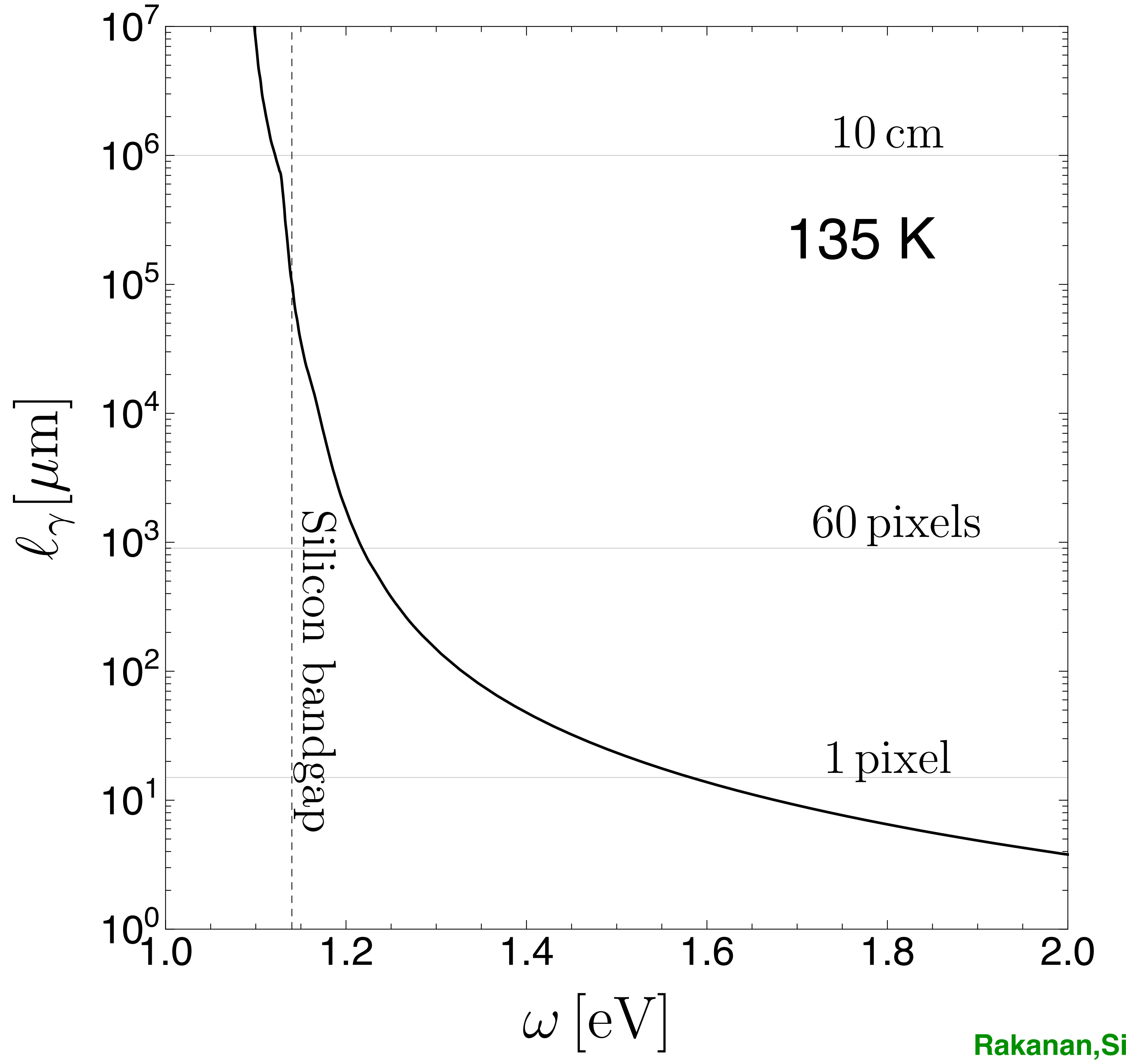

- The rate is correlated with high energy background event rate
- Has spatial correlation with high energy events
- Extends to 60 pixels away and the rate becomes flat

# Cherenkov radiation in SENSEI

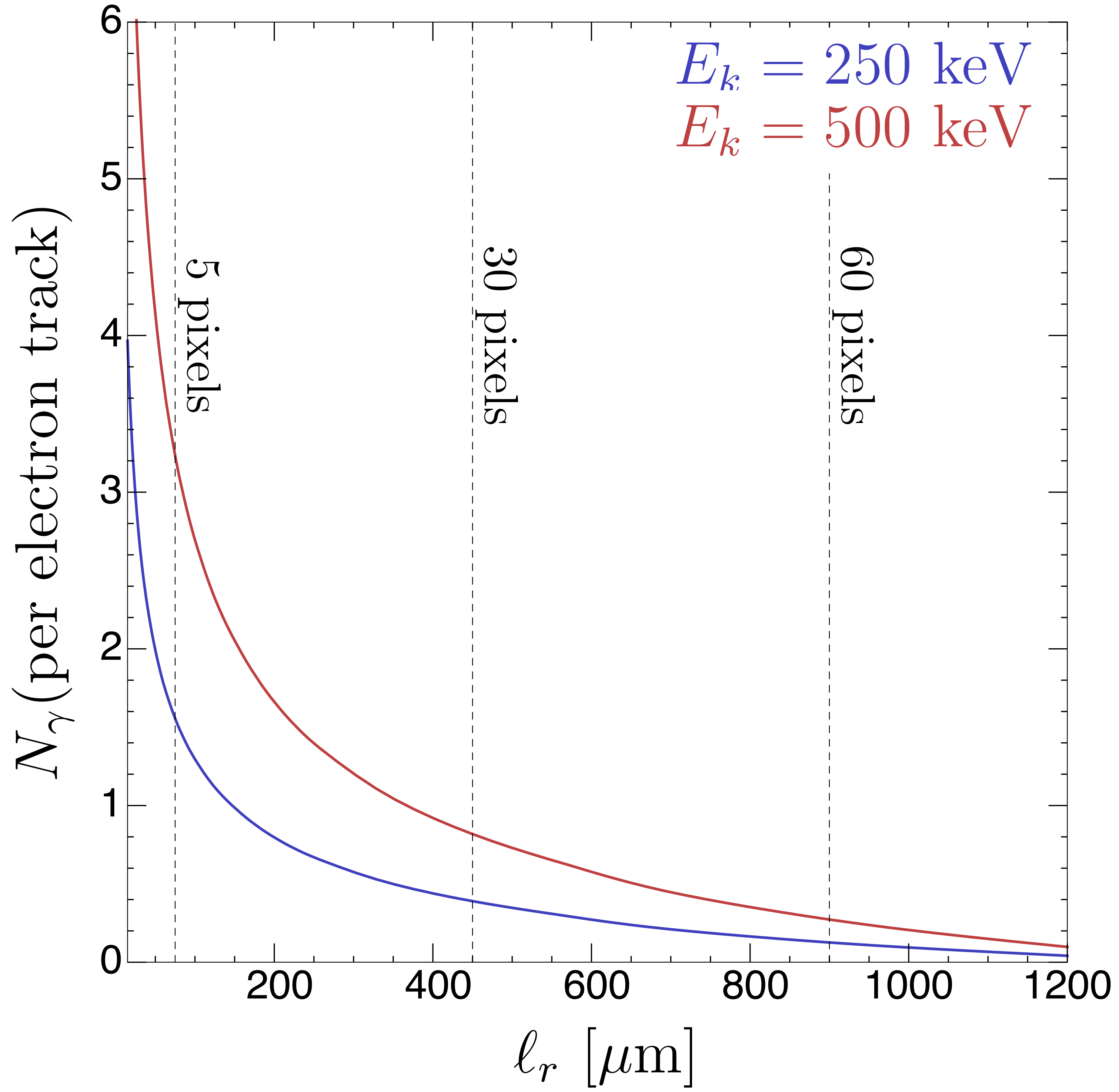


# Cherenkov radiation in SENSEI




Rakanan,Sinhg,Shewchun, 1979



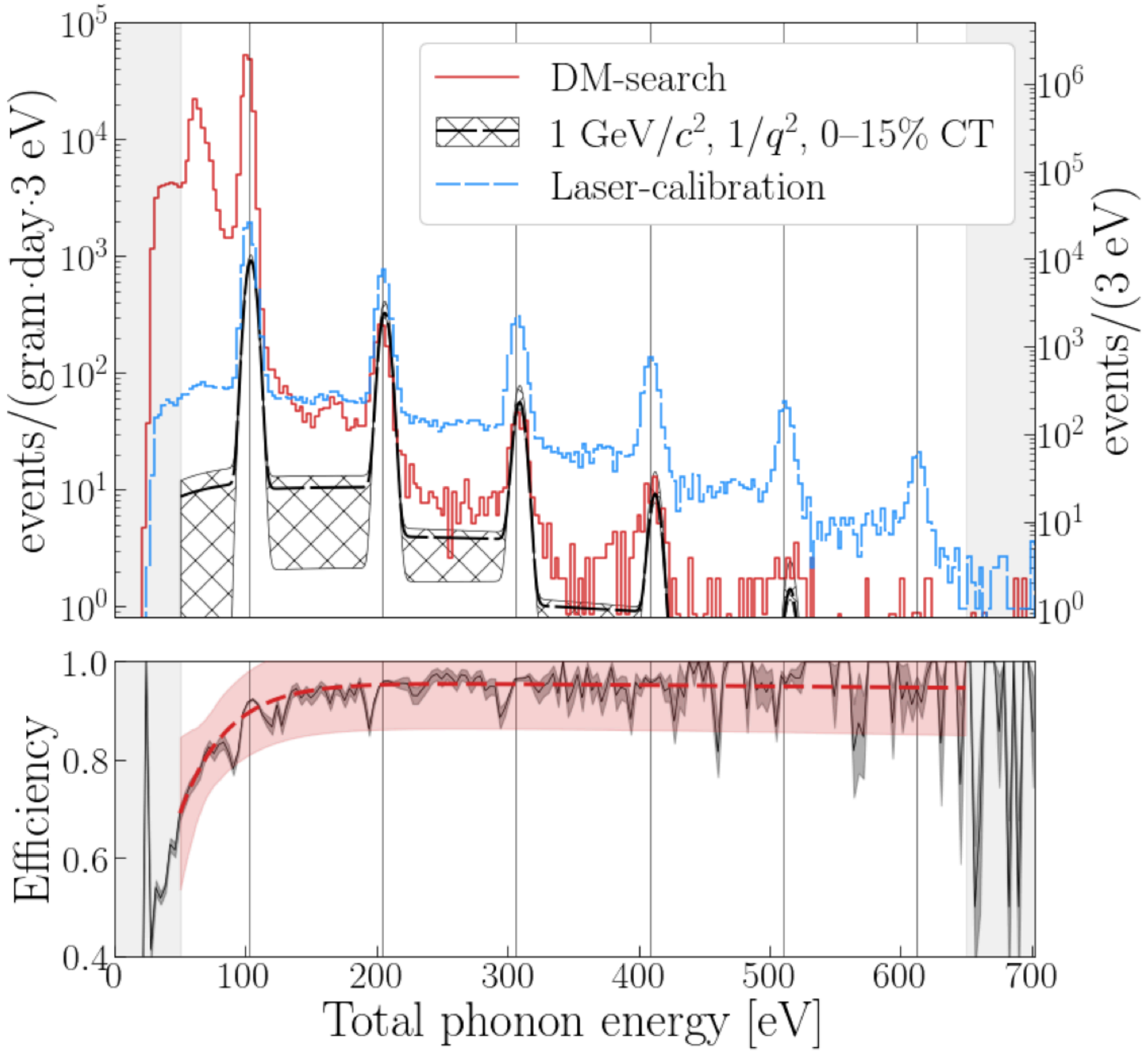

Simulation of Cherenkov events at SENSEI will be presented in Mukul Sholapurkar's talk

# Experiments: SuperCDMS

# Excess in SuperCDMS HVeV

SuperCDMS, 2020

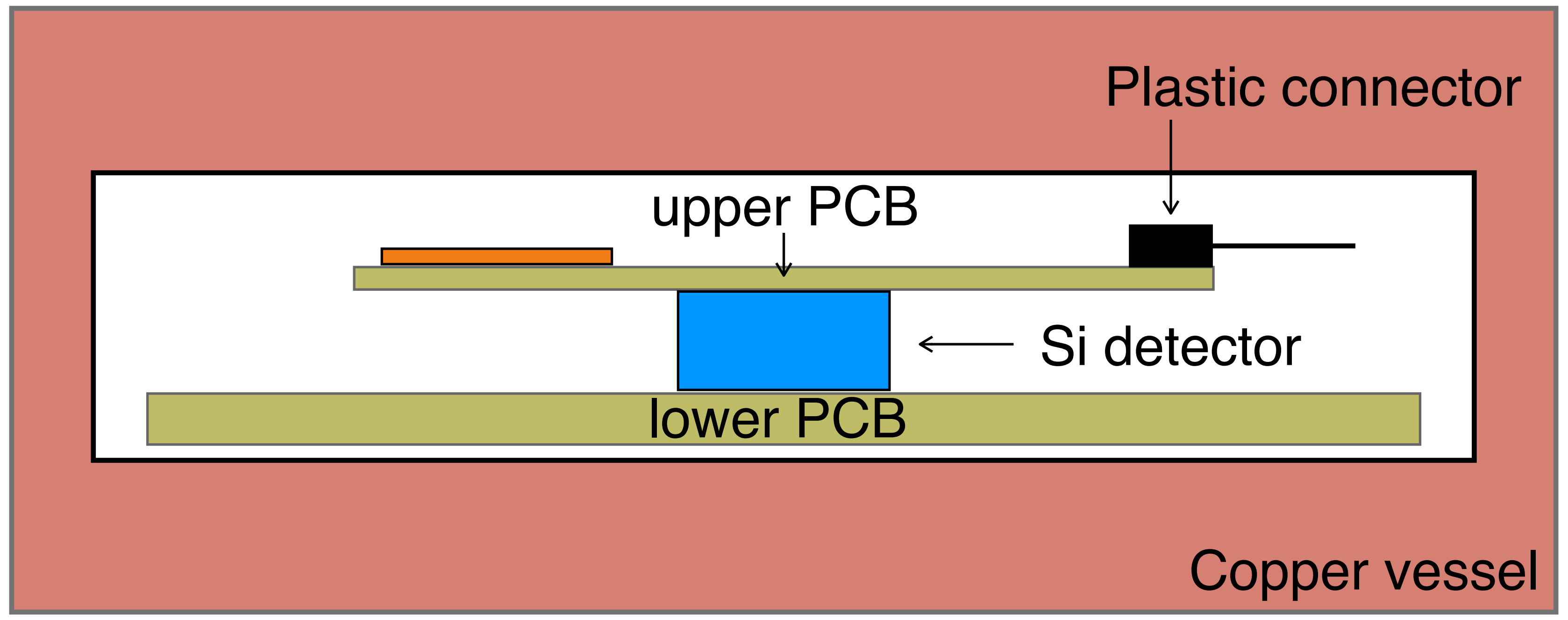
- HVeV detector measures electron-hole pairs via phonons (Neganov–Trofimov-Luke effect)
- Si detector: 1×1×0.4 cm³ , 0.93 gram active mass
- HVeV detector has 0.03 e- resolution, excellent time resolution




| | HVeV Rates $(\text{g-day})^{-1}$ | |
|---|---|---|
| | 100 V | 60 V |
| $R_1$ | $(149 \pm 1)10^3$ | $(165 \pm 2)10^3$ |
| $R_2$ | $(1.1 \pm 0.1)10^3$ | $(1.2 \pm 0.2)10^3$ |
| $R_3$ | $207 \pm 40$ | $245 \pm 86$ |
| $R_4$ | $53 \pm 20$ | $77 \pm 48$ |
| $R_5$ | $16 \pm 11$ | $20 \pm 25$ |
| $R_6$ | $5 \pm 6$ | $10 \pm 17$ |

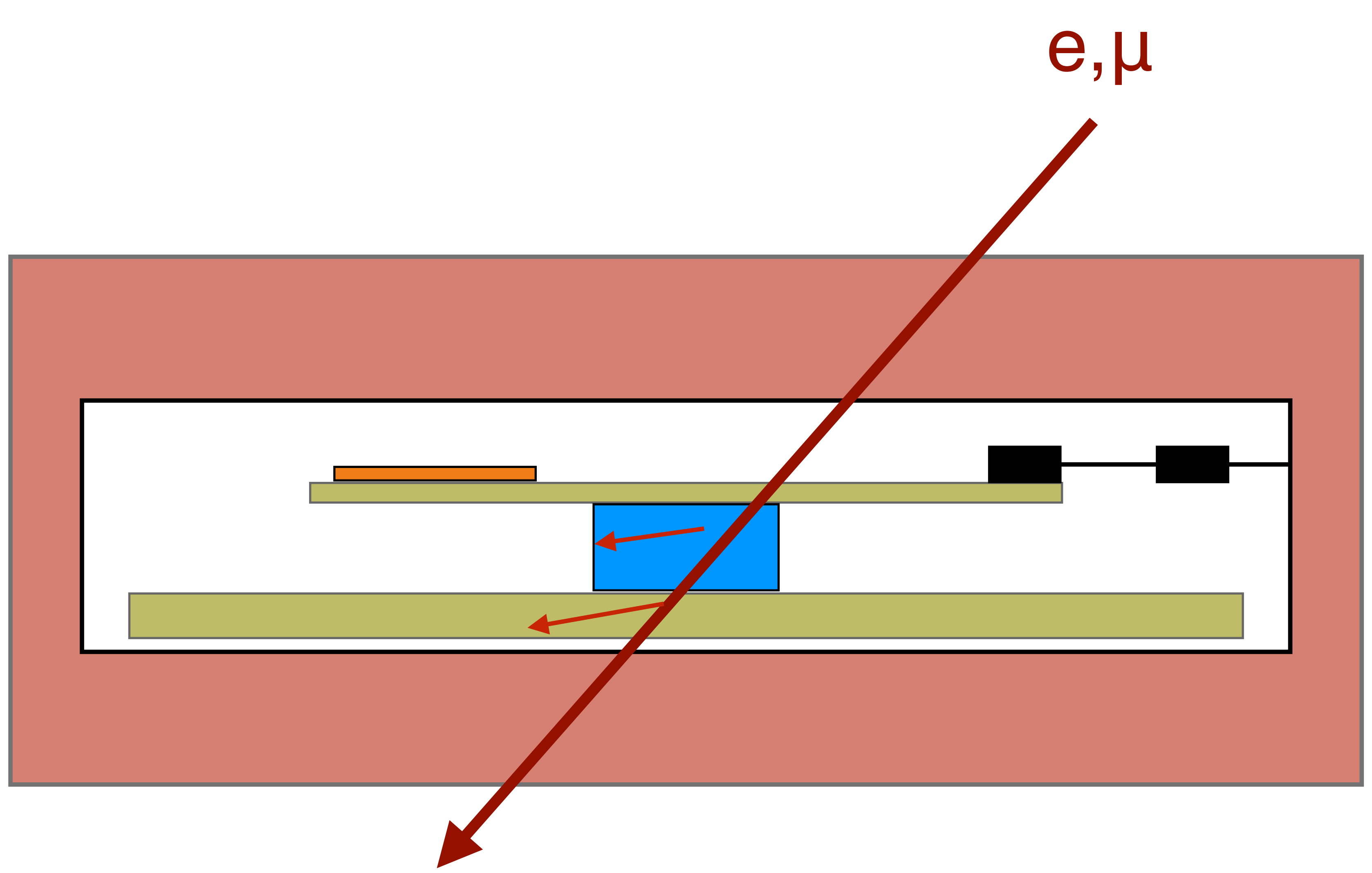
- Independent of voltage
- Single electron events are likely to come from leakage current

# Cherenkov radiation in SuperCDMS HVeV



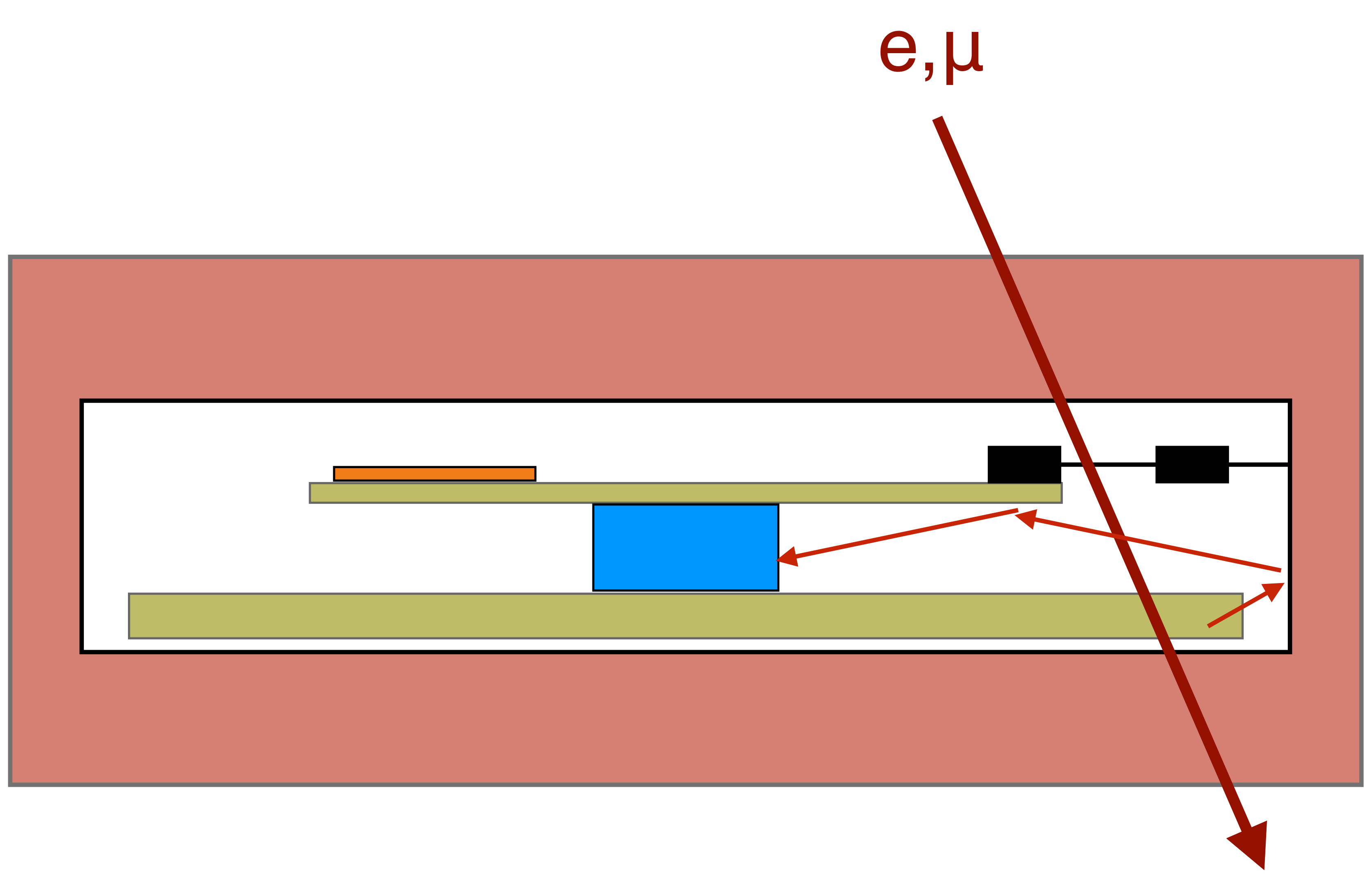
# Cherenkov radiation in SuperCDMS HVeV

Tracks hitting detectors




Can be vetoed by timing information

Tracks hitting PCBs, connectors




Cannot be vetoed

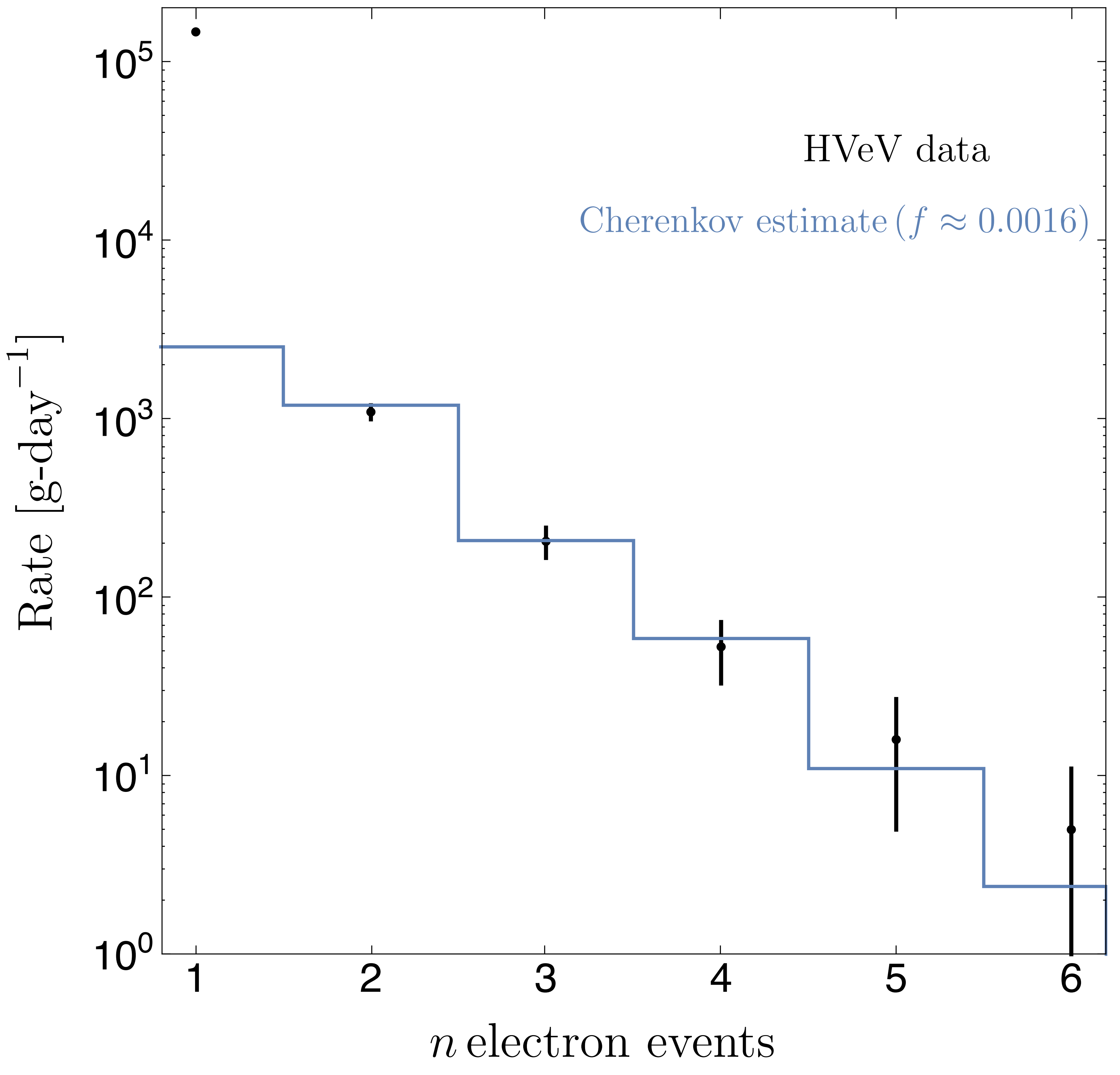
# Estimation of Cherenkov events

PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020

$f$ : efficiency of a Cherenkov photon being recorded at the detector

Best fit: $f \approx 1.6 \times 10^{-3}$

- Small $f$ indicates a lot of Cherenkov photons generated
- One parameter fits the spectrum for 2-6 electron events

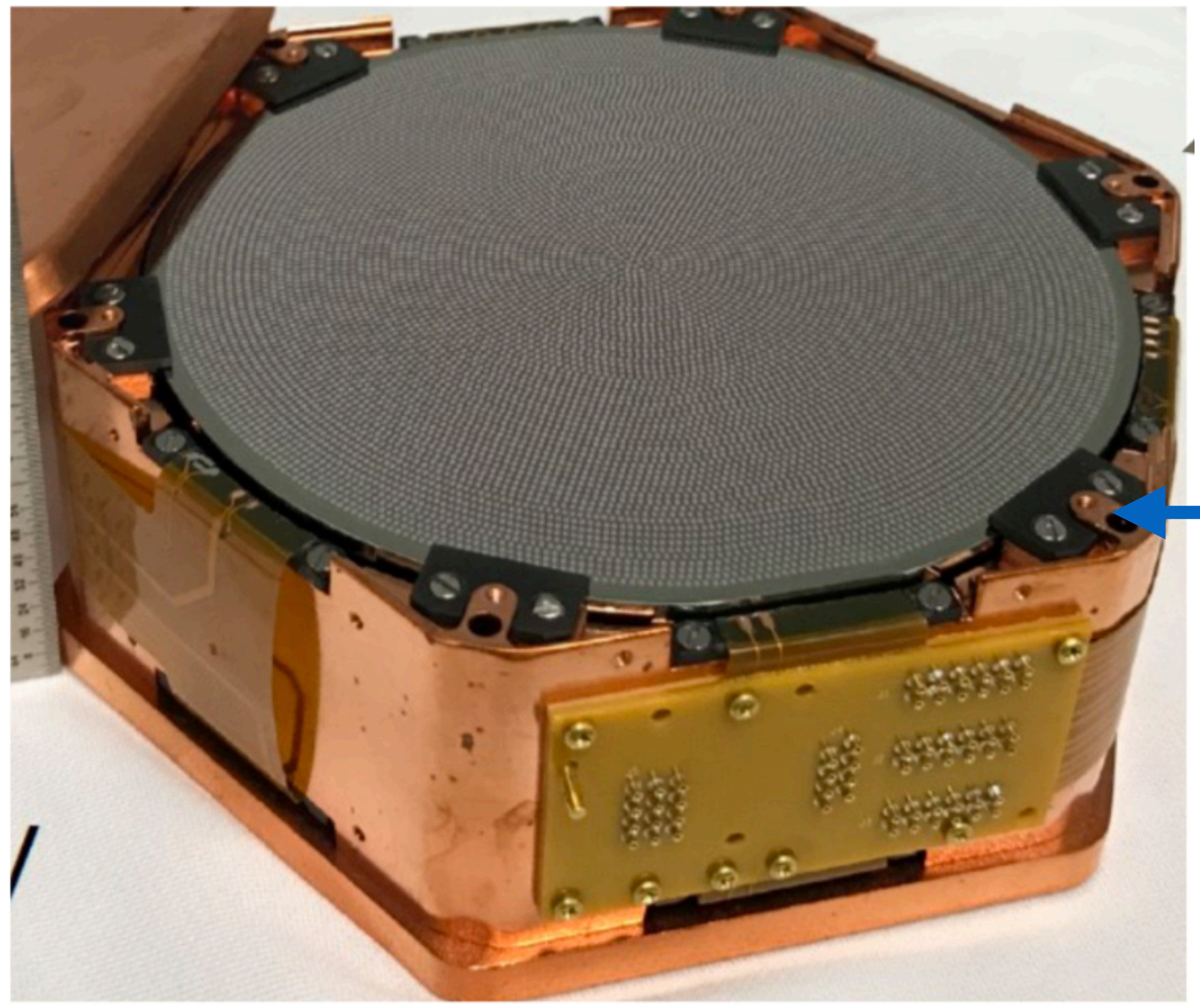


# Cherenkov events at future experiments

*SuperCDMS @SNOLAB*

**SuperCDMS SNOLAB, 2016**

Cherenkov radiation from beta decays of impurities in holders



Cirlex clamps

**Figure from Ben Loer, DM 2018**

Cherenkov event rate: $N_{\rm events}^{\rm Cirlex} \sim 130/{\rm day}/{\rm tower}$

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SuperCDMS SNOLAB, 2016

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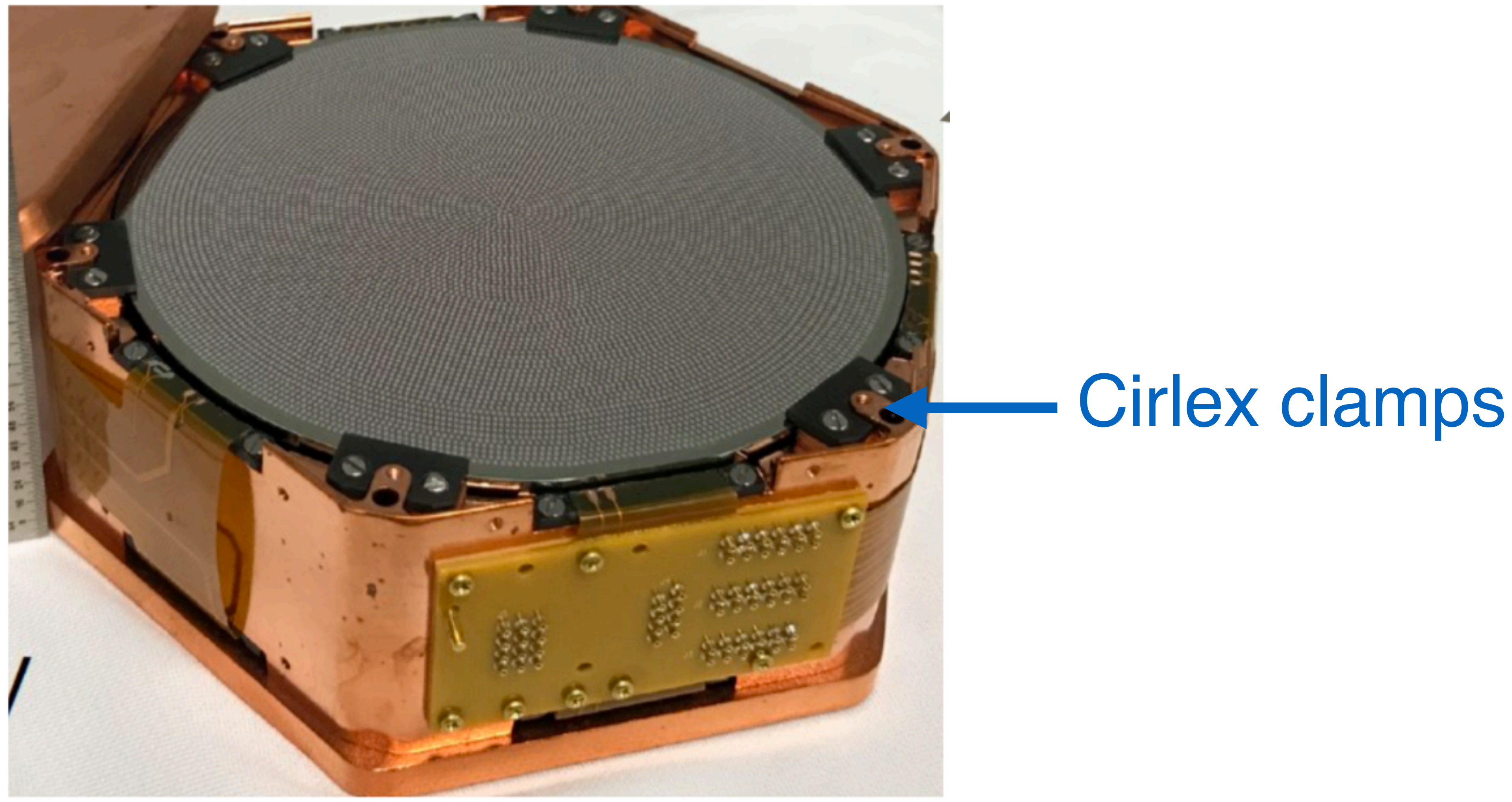



Figure from Ben Loer, DM 2018

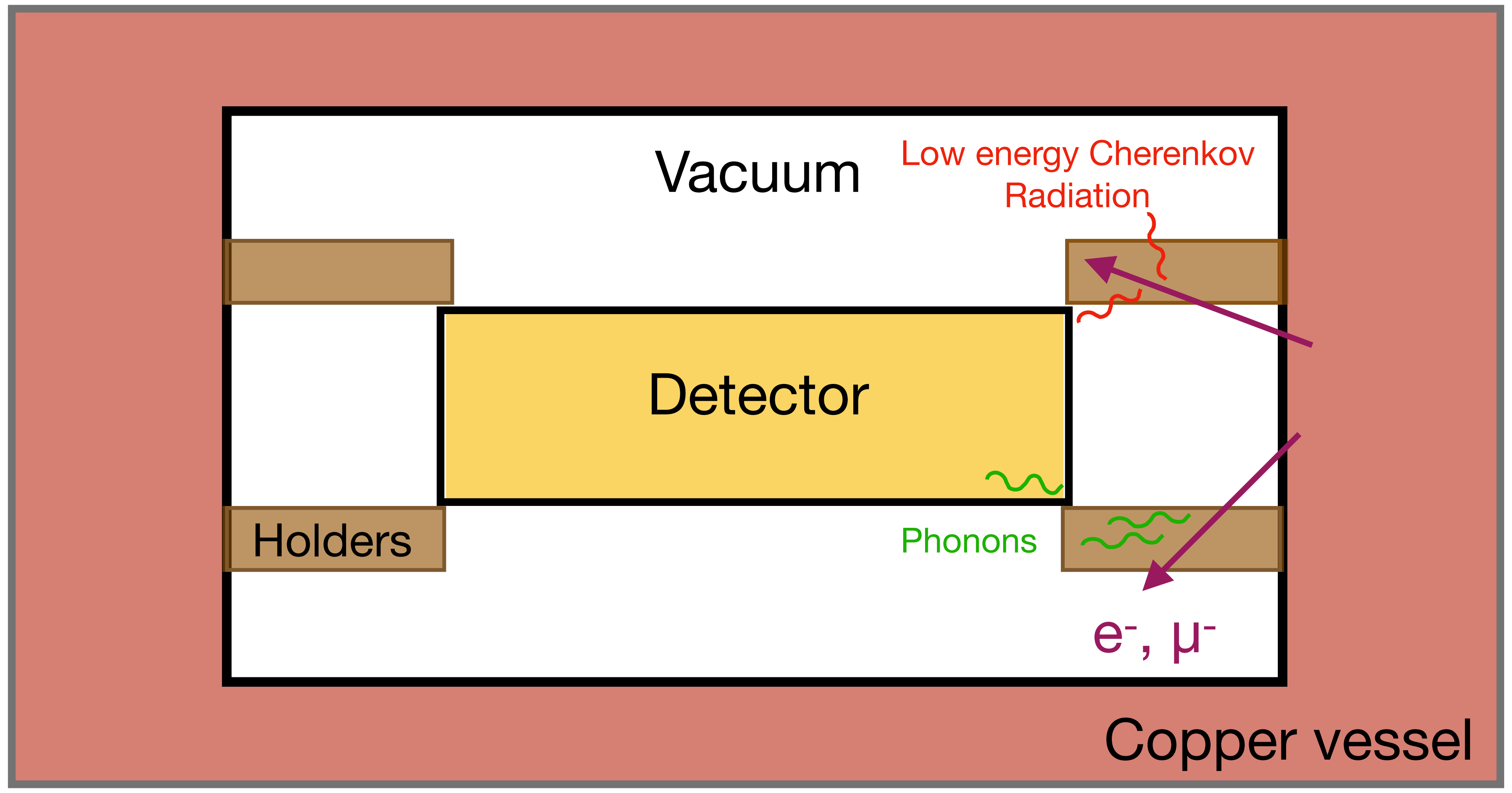
Cherenkov event rate: $N^{\text{Cirlex}}_{\text{events}} \sim 130/\text{day}/\text{tower}$

## *Single phonon detector*

Knapen, Lin, Pyle, Zurek, 2017

Low energy Cherenkov photons from holders

Phonons from holders leak into the detector



# Mitigation strategies

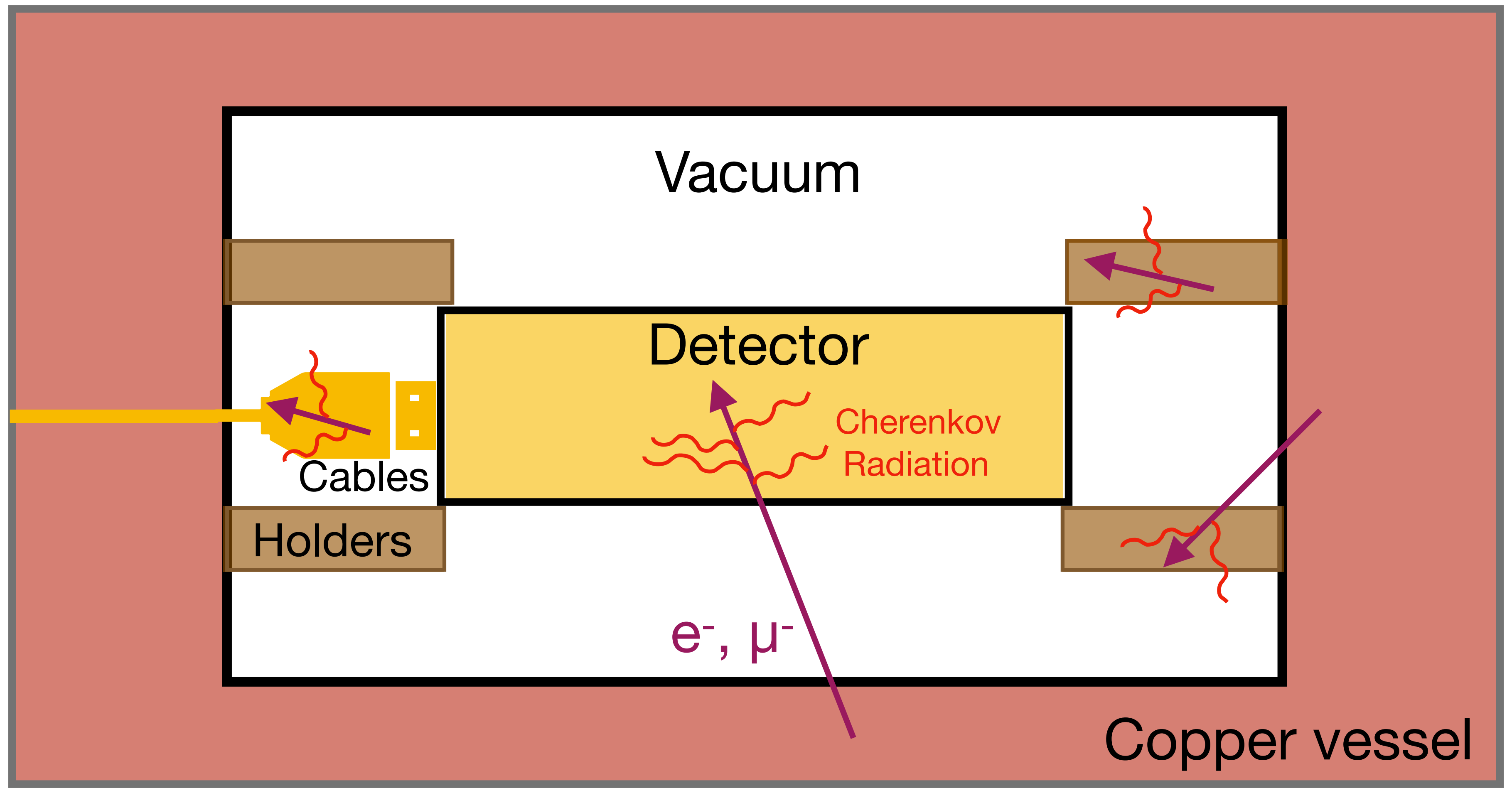
PD, Egana-Ugrinovic, Essig, Sholapurkar, 2020

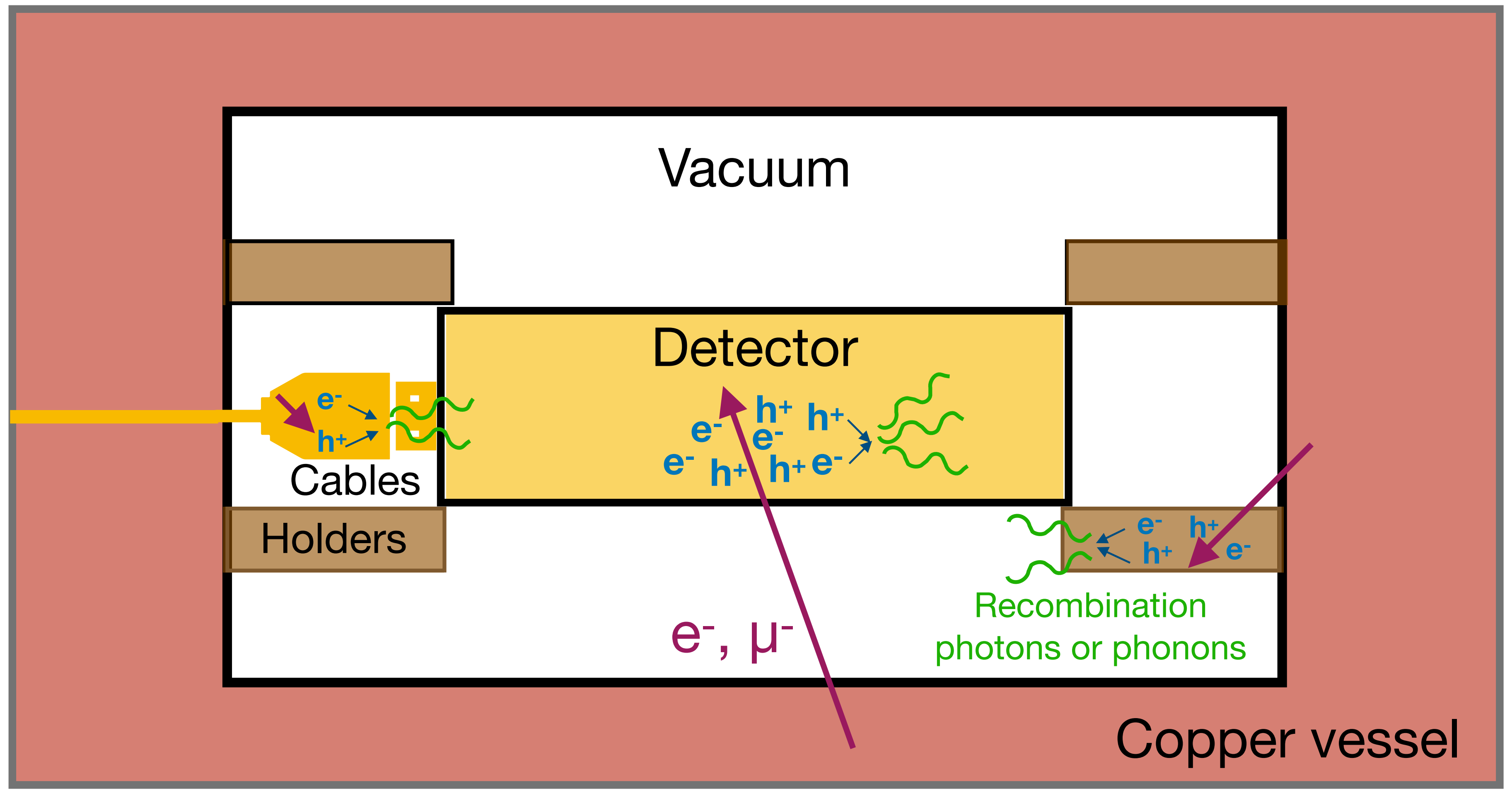
- Active and passive shielding
- Radio-pure materials
- Multiple detectors
- Minimizing non-conductive materials near detector
- Reduce the reflectivity of inner copper wall

First proposed in our work

# Conclusions

- Many sub-GeV dark matter experiments observed excess events
- Cherenkov radiation and radiative recombination are unexplored sources of backgrounds
- Cherenkov radiation contributes to the excess in SENSEI and SuperCDMS HVeV
- These backgrounds will also be important for future dark matter detectors
- Several mitigation strategies can be applied to reduce these backgrounds



***Thank you***