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

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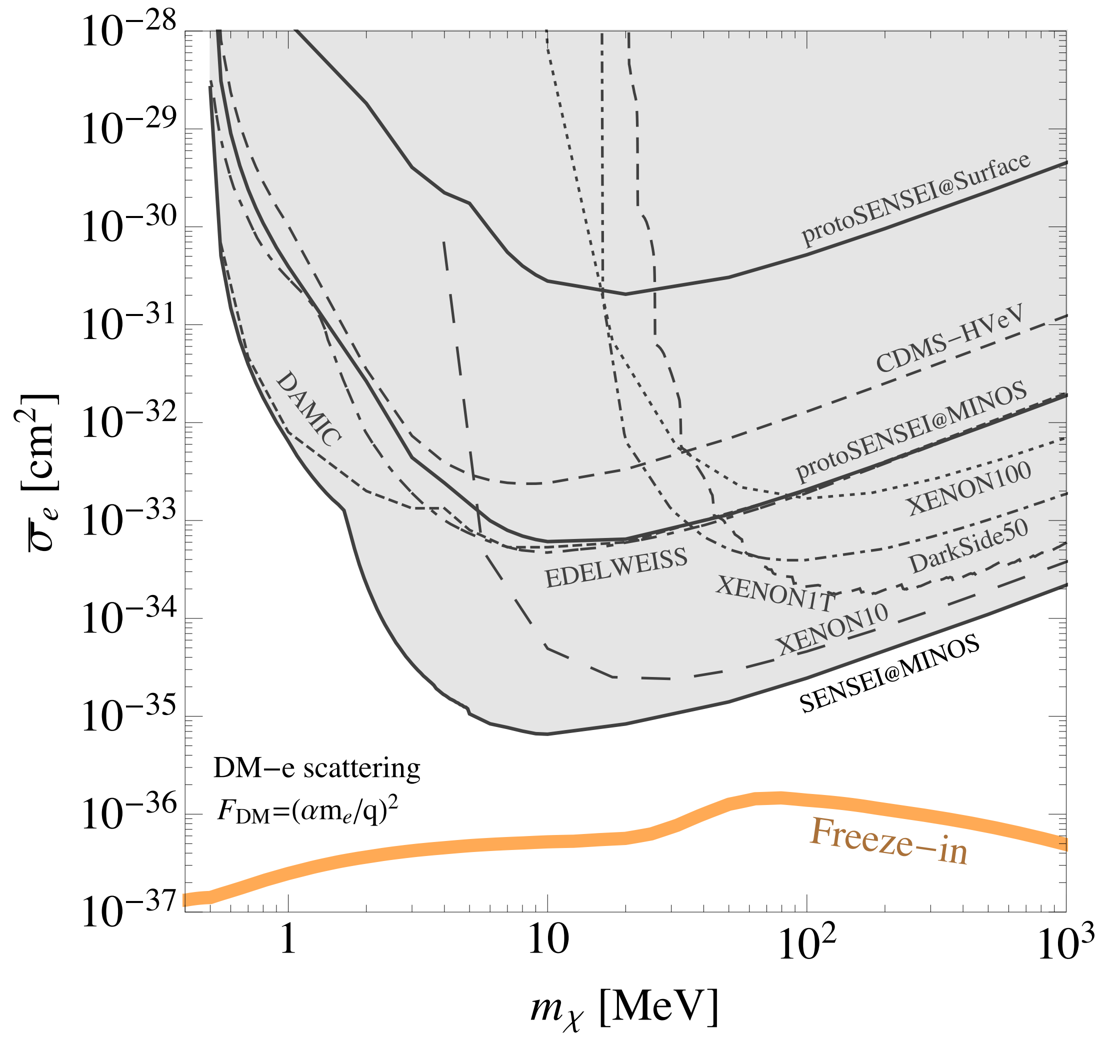
BSM Pandemic Seminar

*two papers in preparation with Peizhi Du, Daniel Egana-Ugrinovic and Rouven Essig

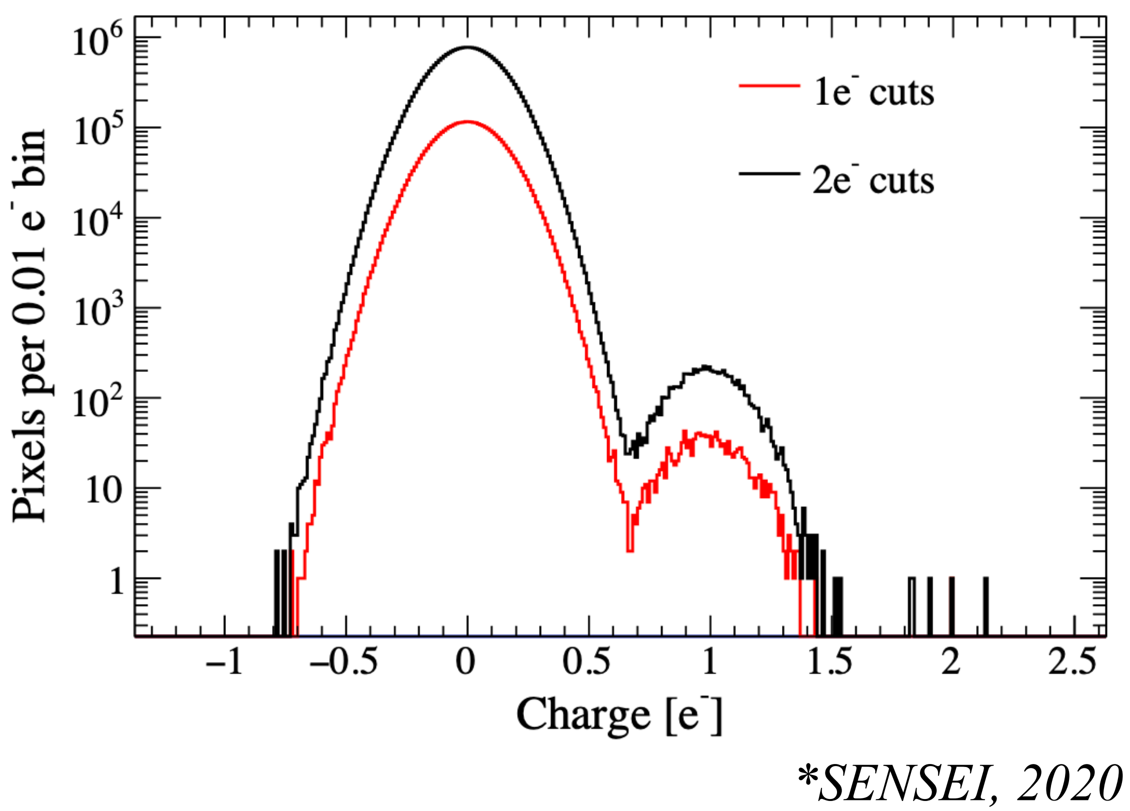
Sub-GeV Dark Matter Direct Detection

- Conventionally, direct-detection experiments search for nuclear recoils produced by WIMPs
- Recently, low-threshold experiments are probing sub-GeV DM by looking for ionization or phonons produced by the interactions of DM with electrons or nuclei
- Several new challenges, e.g. identifying, characterizing, and mitigating new low-energy backgrounds

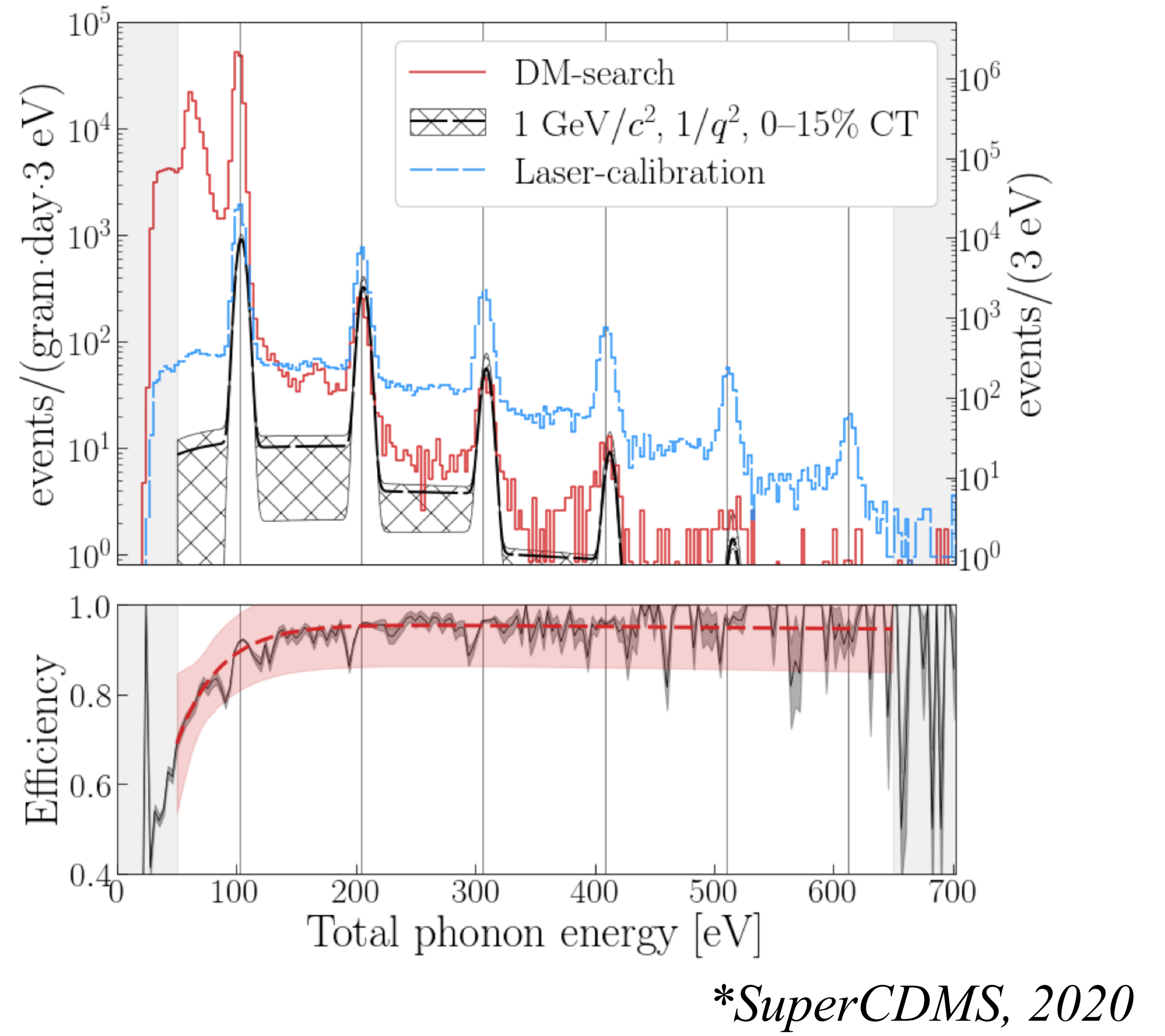


Excesses in Low-Threshold Dark Matter Searches

- Several experiments observe a sizable number of low-energy events
- For example, searches for electron recoils:



SENSEI
(Si, Skipper-CCD)



SuperCDMS HVeV
(Si, TES detector)

Our Hypothesis

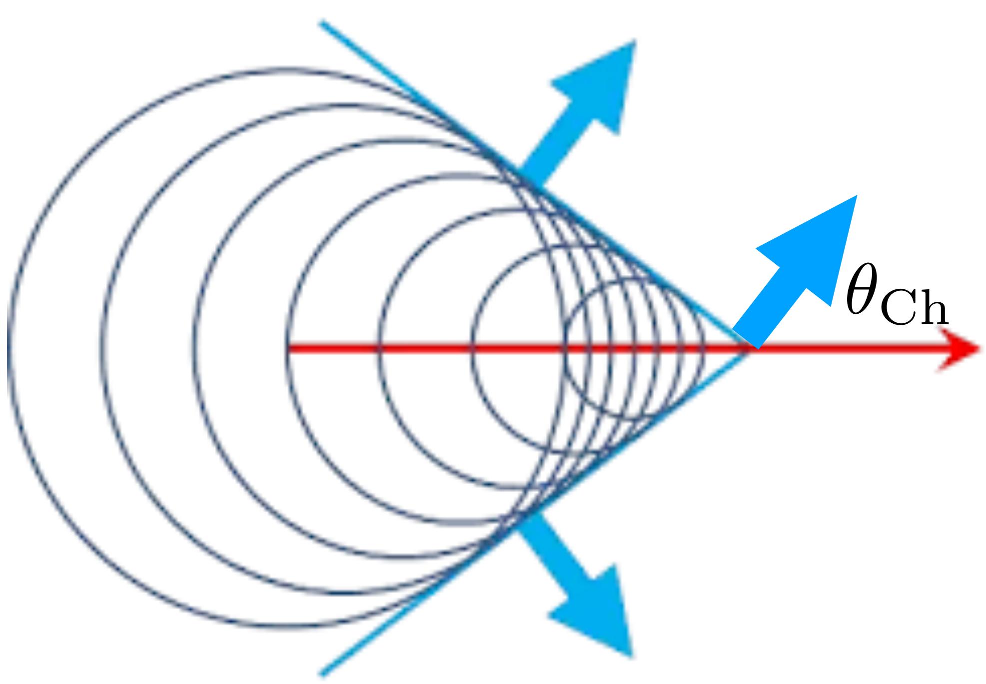
- Several unexplored radiative backgrounds exist; in this talk, will focus only on Cherenkov radiation
- **Cherenkov radiation** emitted by **sufficiently energetic** charged particles interacting with any **non-conducting material** in the detector can be absorbed to produce one- or a few-electron event
- Can account for a large fraction of events observed in some current experiments
- Can be mitigated, and has important implications for the design of future low-threshold DM experiments

Cherenkov Radiation

- Cherenkov radiation is the spontaneous emission of radiation by a charged particle passing through a dielectric material, when the speed of the particle exceeds the speed of light in the material

$\epsilon(\omega)$: Dielectric Function as a function of photon frequency ω

$$v^2 \mathrm{Re}\ \epsilon(\omega) > 1$$



$$\cos\theta_{\mathrm{Ch}} = \frac{\sqrt{\mathrm{Re}\ \epsilon(\omega)}}{v|\epsilon(\omega)|}$$

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

Cherenkov Radiation in DM Detectors

- Any **insulator** or **semi-conducting** material in the detector target or the material surrounding the detector will emit Cherenkov radiation when a **sufficiently energetic** charged particle passes through it:

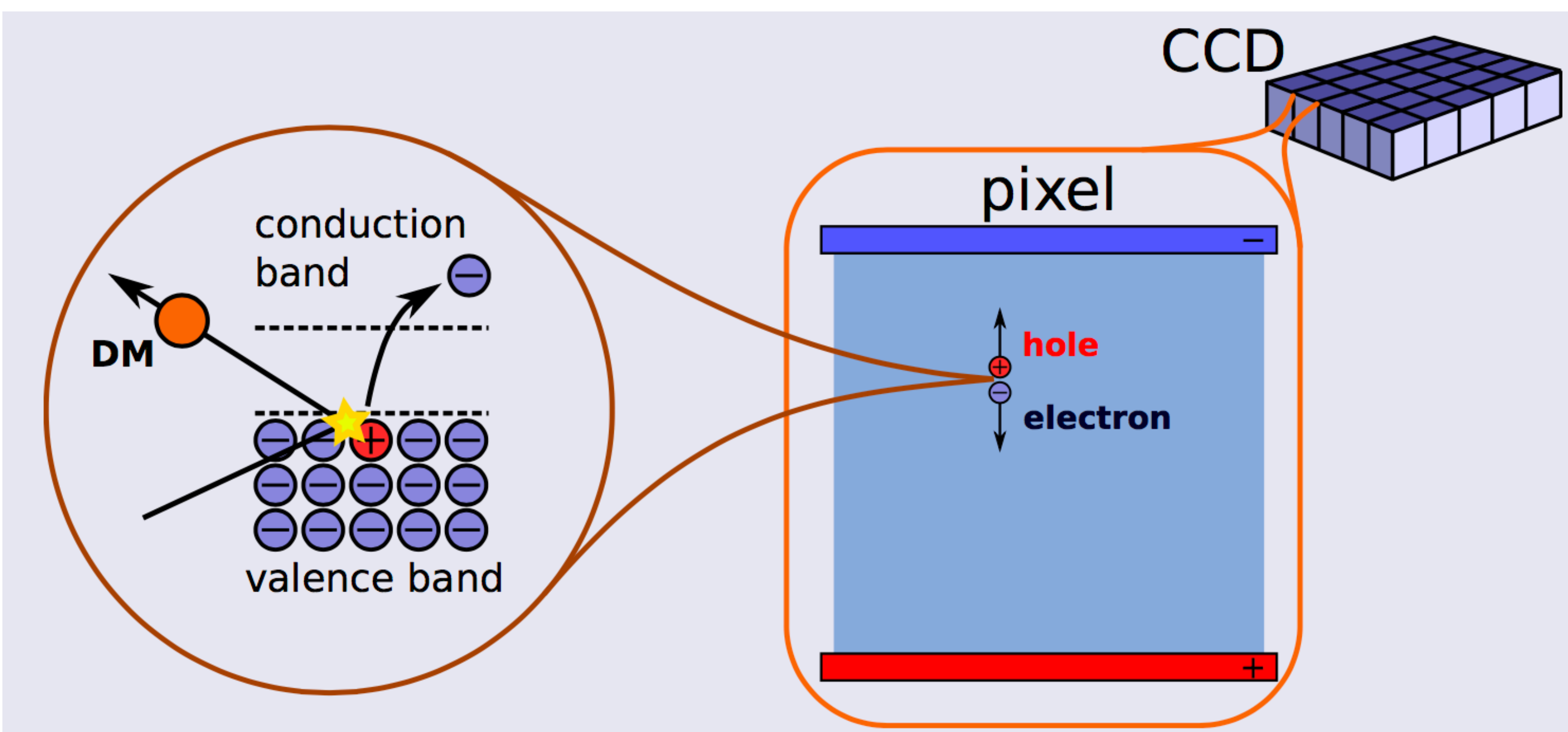
Detector materials
Si, Ge, GaAs (Semiconductor targets)
SiO_2, Al_2O_3 (Insulator targets)
Epoxy glue, Insulators to cover cables, Printed Circuit Boards, Holders and Connectors

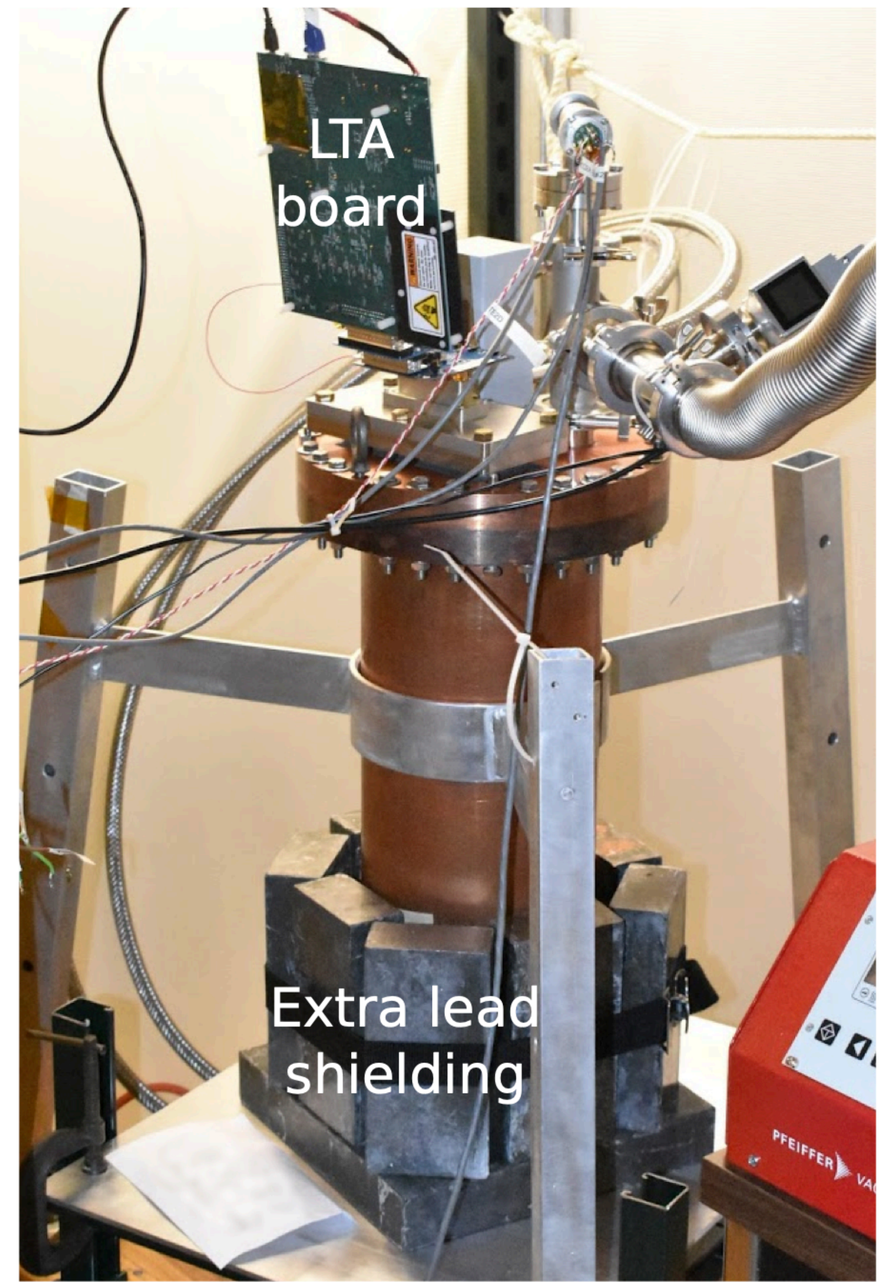
Typical high-energy particle sources
Cosmic Muon Flux
Electrons ejected by gammas and X-rays
Beta particles from radioactive impurities

Concrete Example: SENSEI at MINOS

SENSEI overview:

- Uses silicon Skipper-CCDs to probe sub-GeV DM by precisely measuring ionization





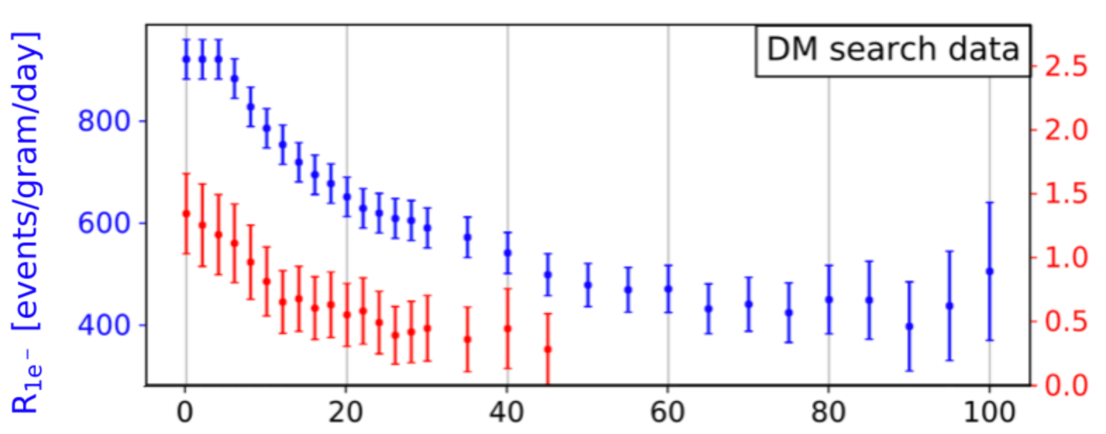
**SENSEI, 2020*

SENSEI at MINOS

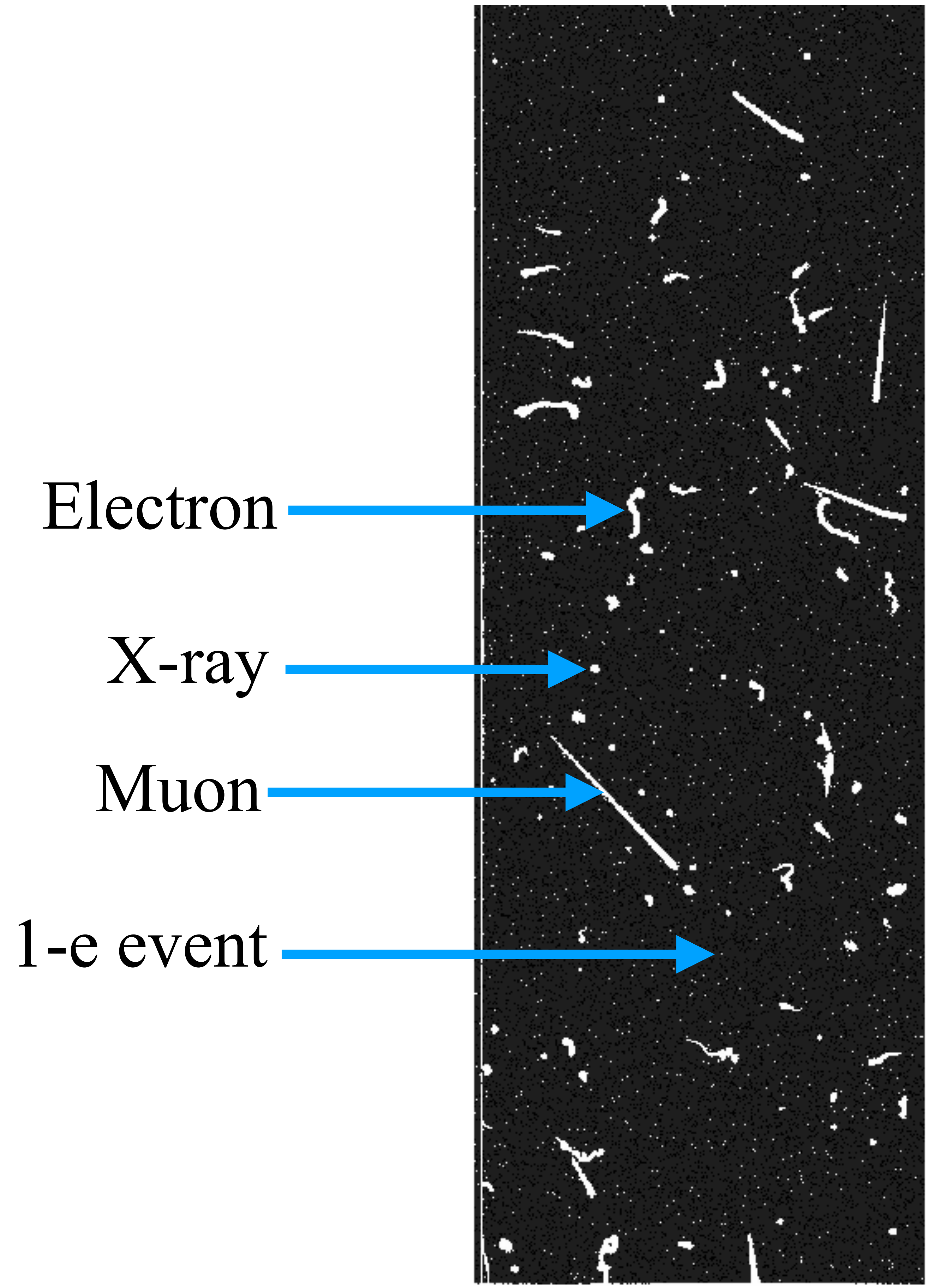
SENSEI data:

- **Excellent spatial resolution:** Can place cuts based on the position of events relative to the positions of high-energy tracks

- Observed ~ 450 1-e events per (gram*day) after applying a 60-pixel (~900 μm) halo-mask cut



**SENSEI, 2020*

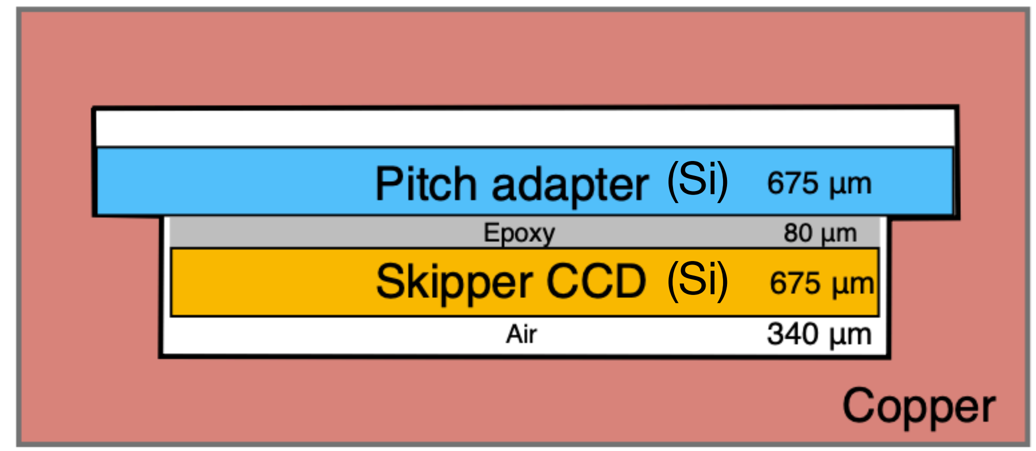


Cherenkov Radiation as a Background in SENSEI

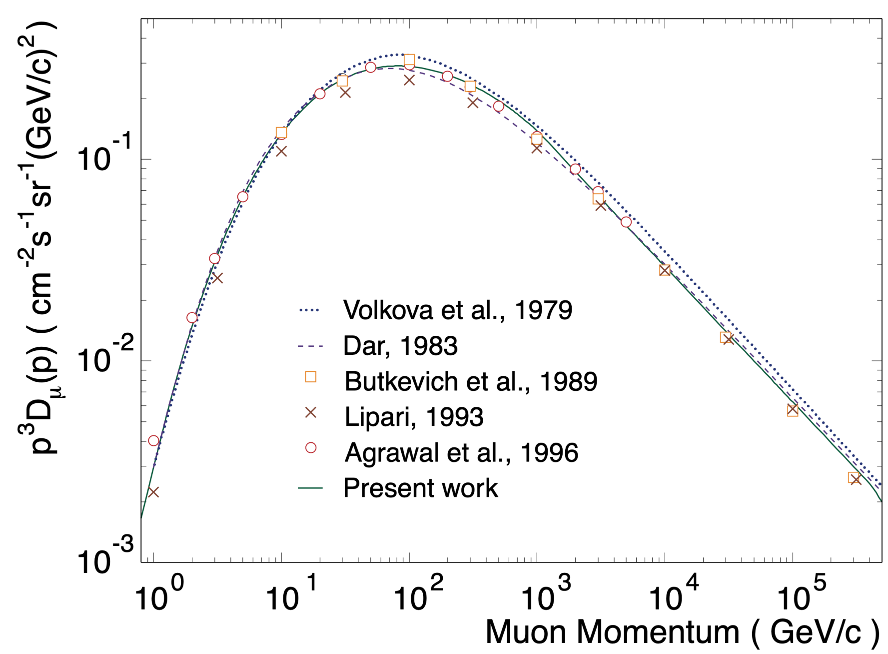
Materials that can emit Cherenkov:

- **Silicon CCD (675 µm)**
- **Silicon in pitch adapter (675 µm)**
- Epoxy-glue (80 µm)

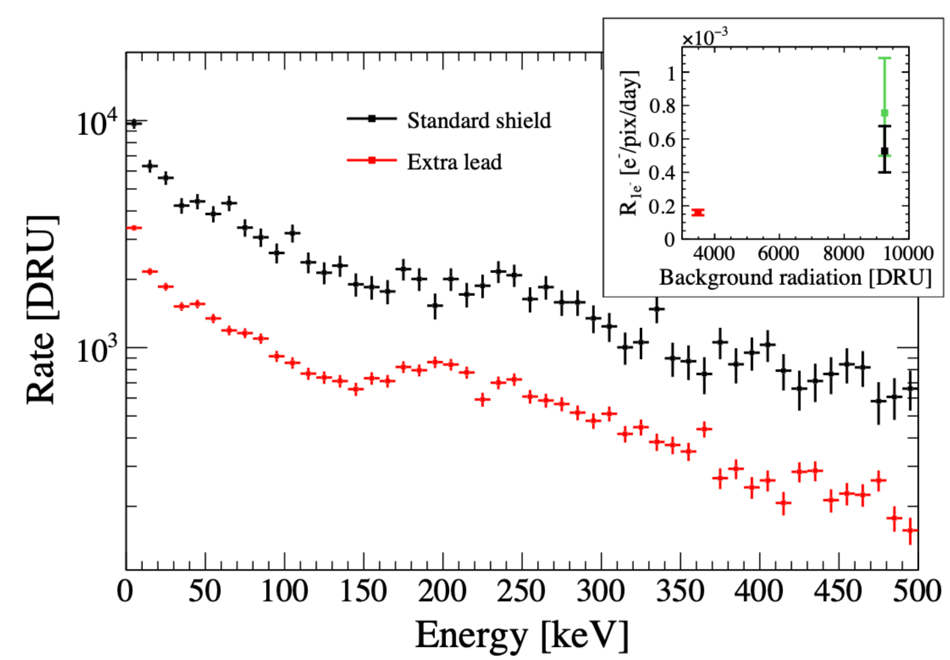
Side view



High-energy Particles	Cherenkov Energy Threshold (Si)
Electrons	20 keV
Muons	4.1 MeV



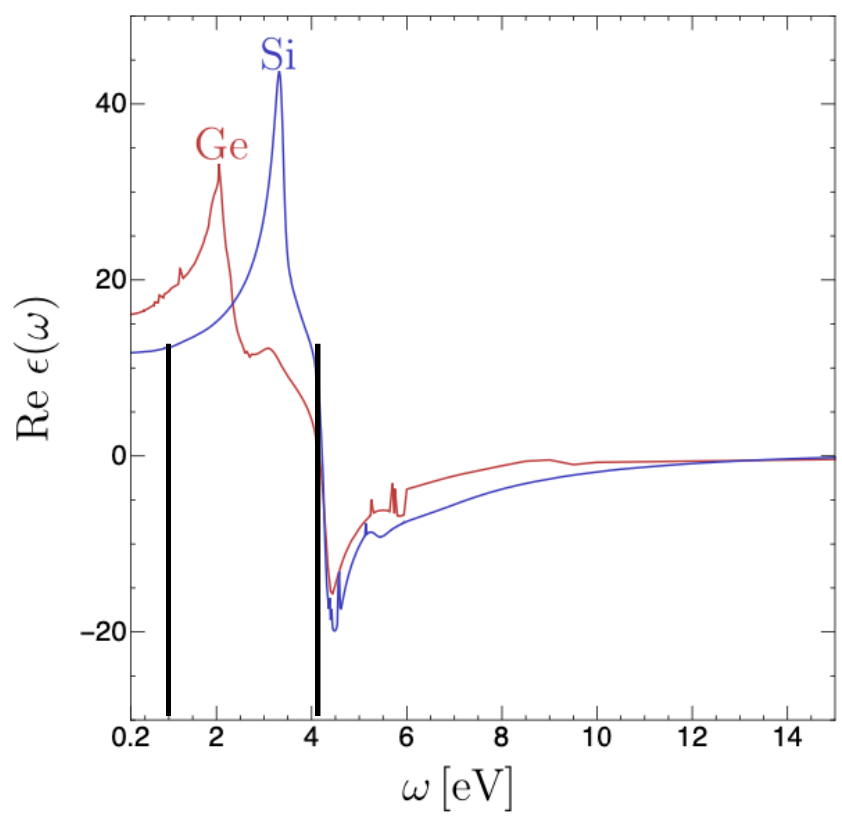
Bugaev et.al., 1998



SENSEI, 2020

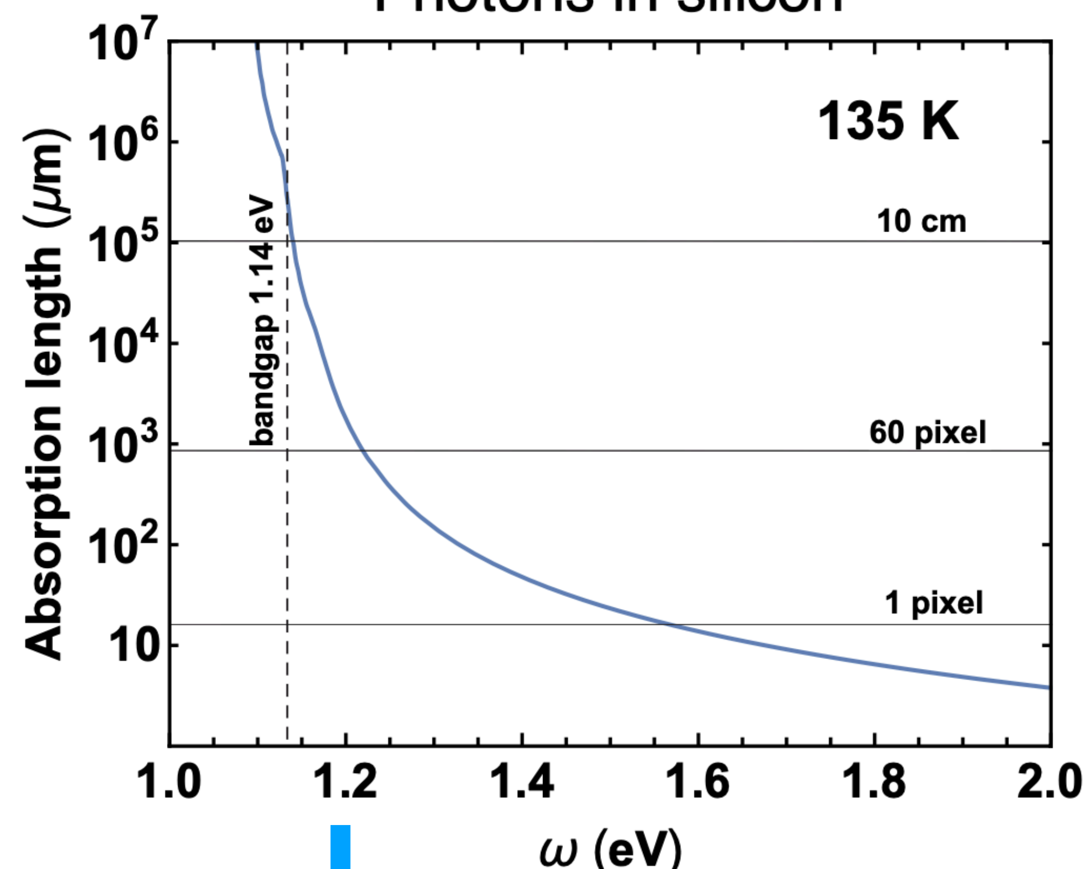
Cherenkov Radiation as a Background in SENSEI

Dielectric function



Emitted Cherenkov photons can be absorbed to produce 1-e event

*Rajkanan, Singh, Shewchun, 1978

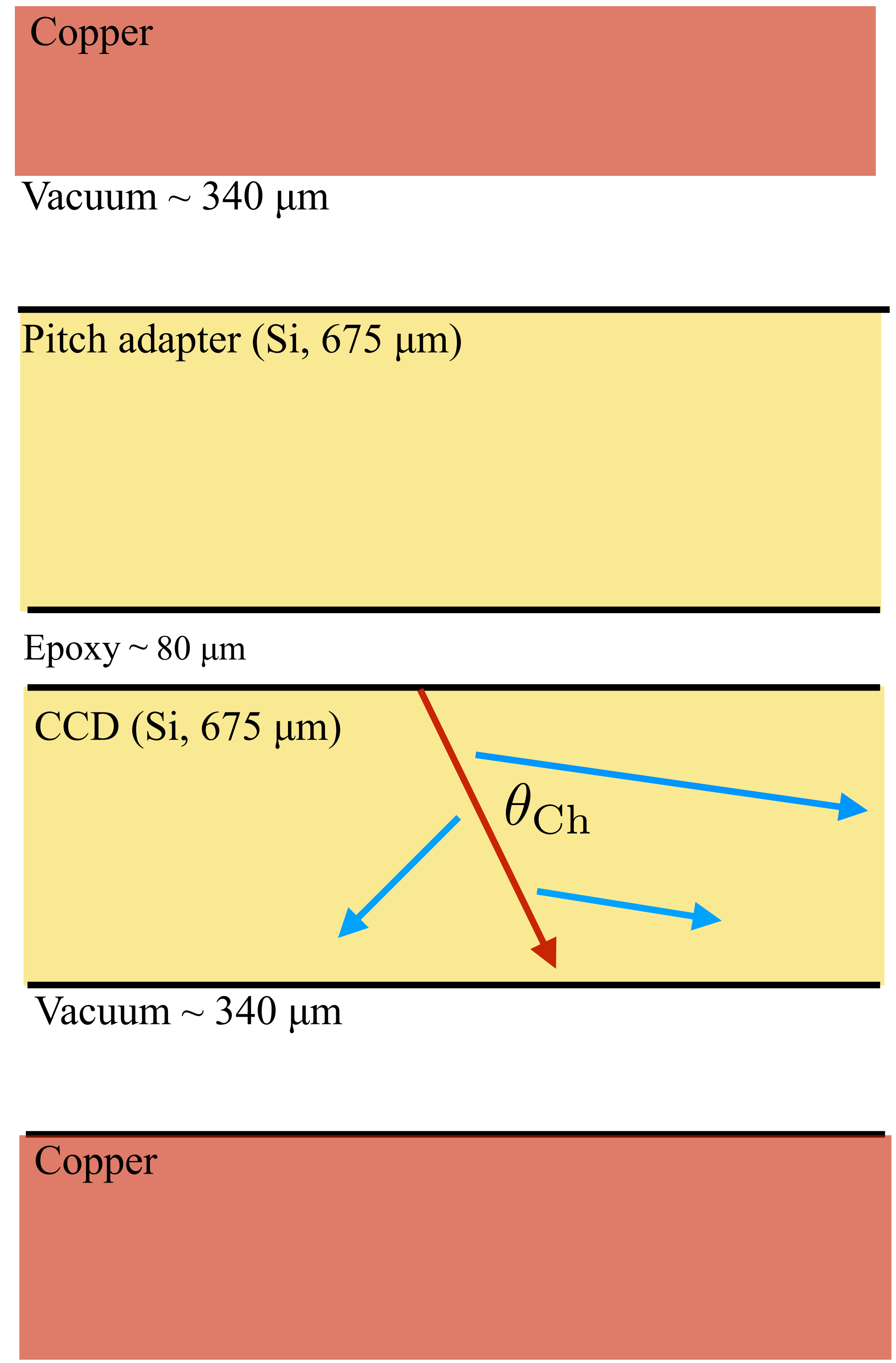


Can evade 60-pixel halo-mask if energy is close to bandgap

Cherenkov Radiation as a Background in SENSEI

Simulate Cherenkov background:

- Simulate high-energy particle tracks
- Tracks in CCD or pitch-adapter will emit Cherenkov photons
- Include reflections, refractions, and thin-film interference at interfaces, and reflections from copper housing



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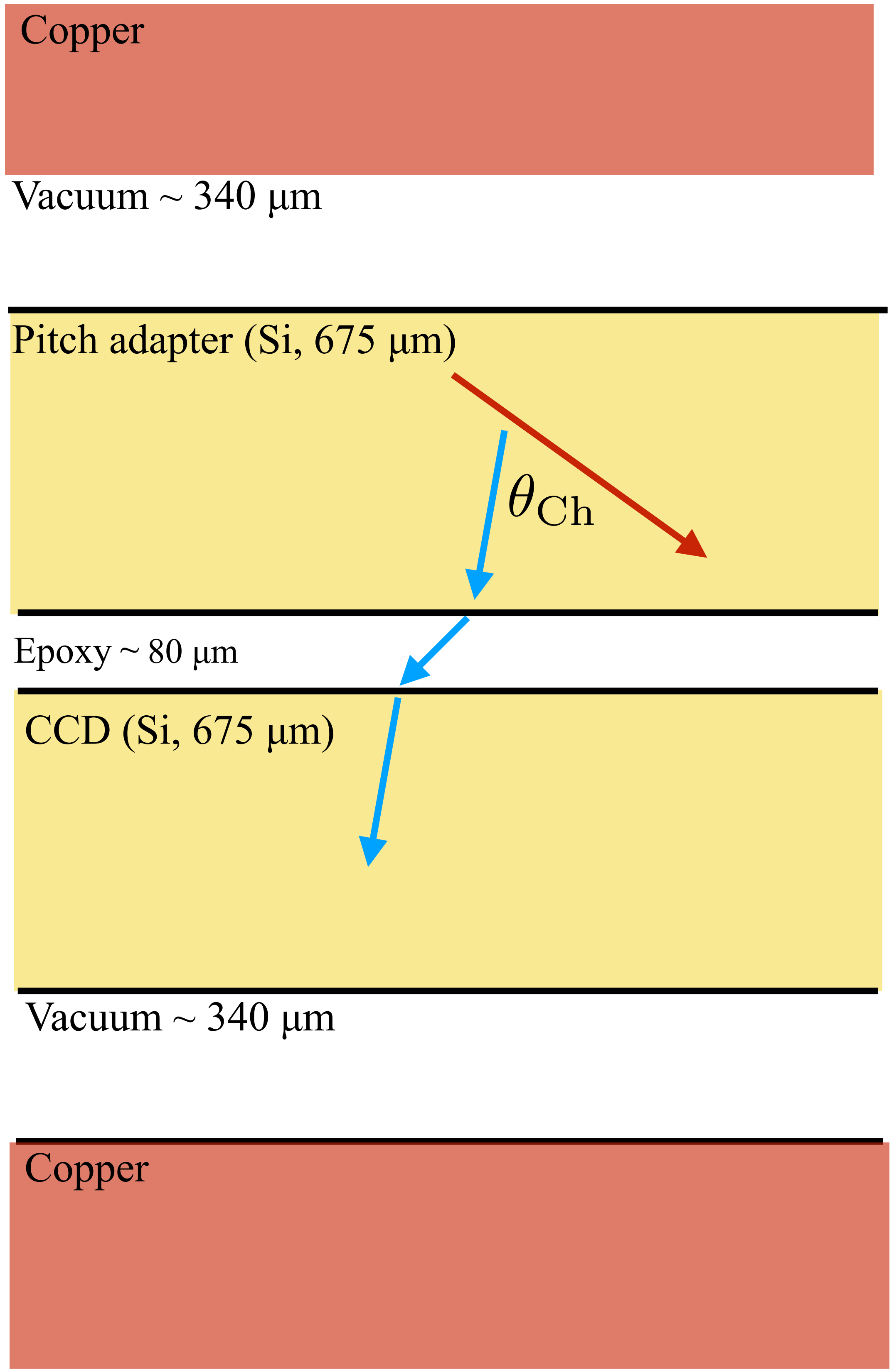

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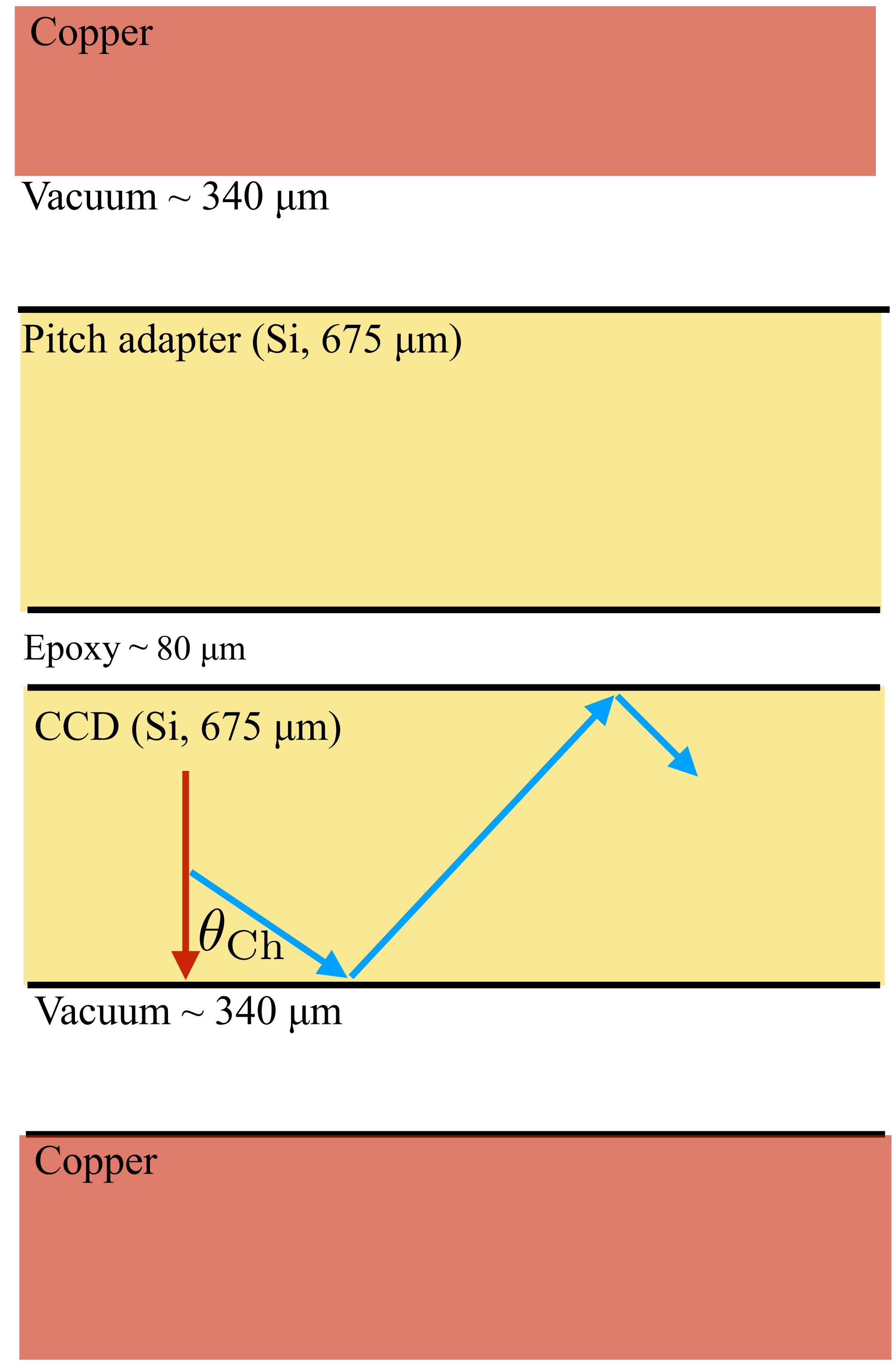
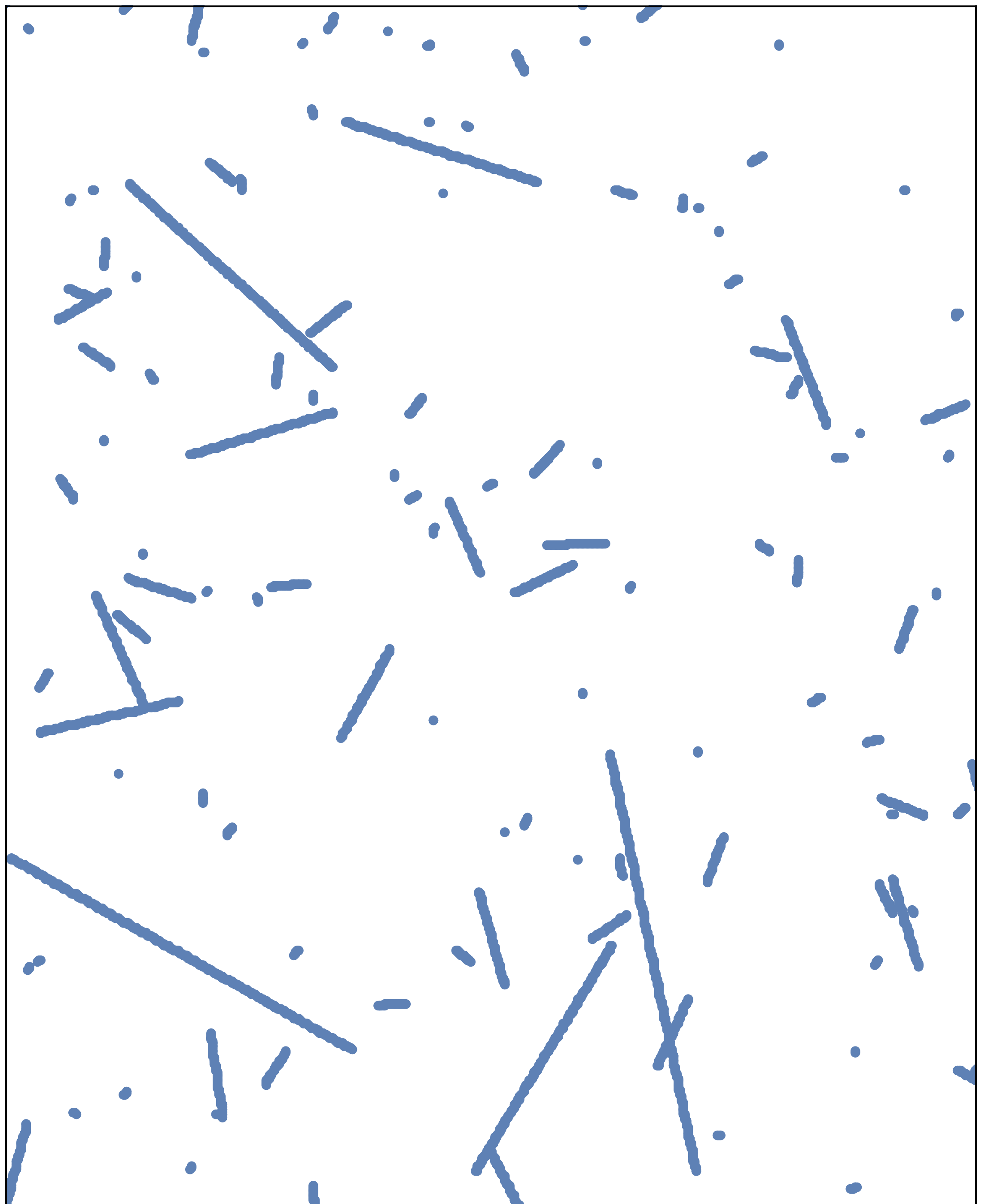
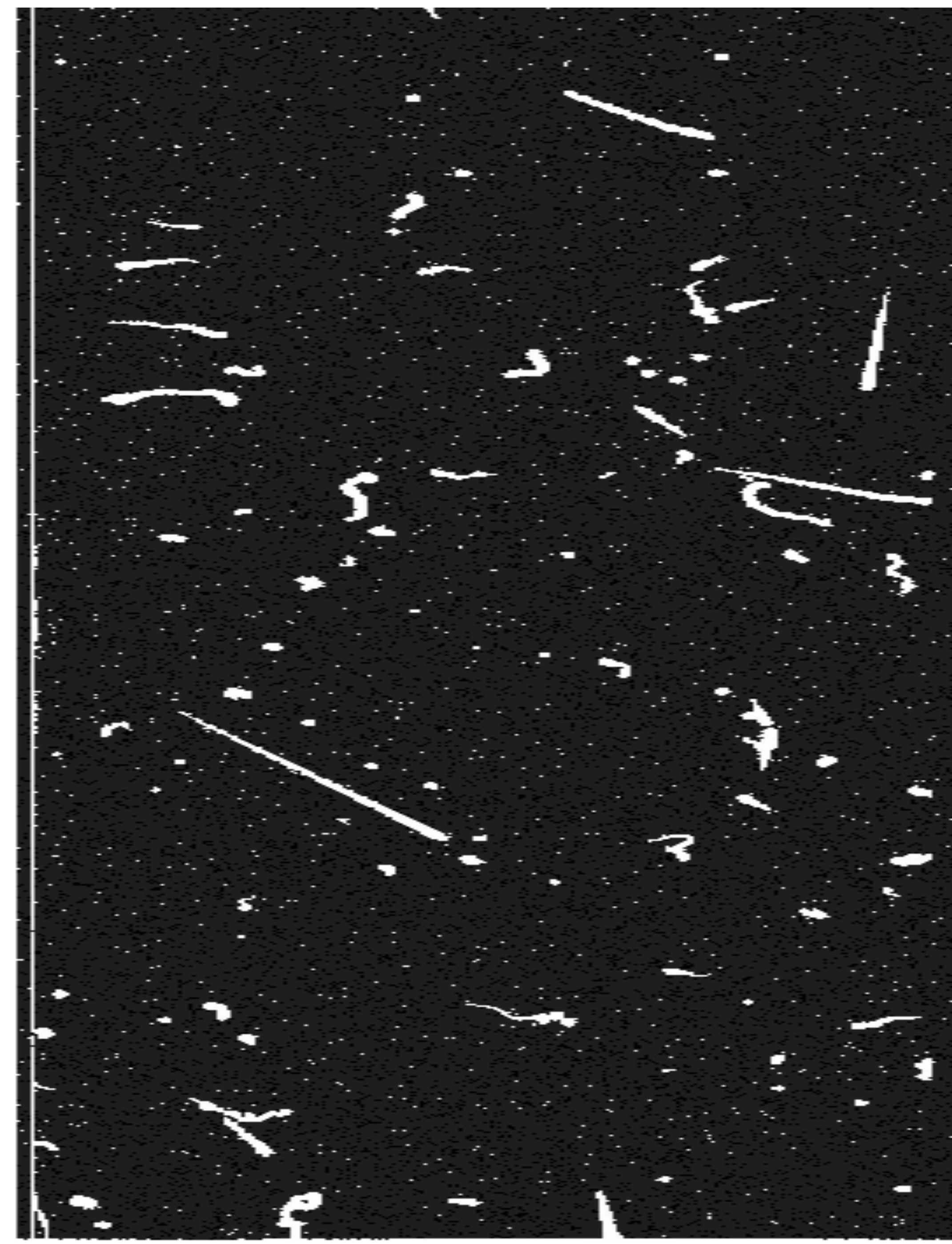


SENSEI Images

Simulated Tracks

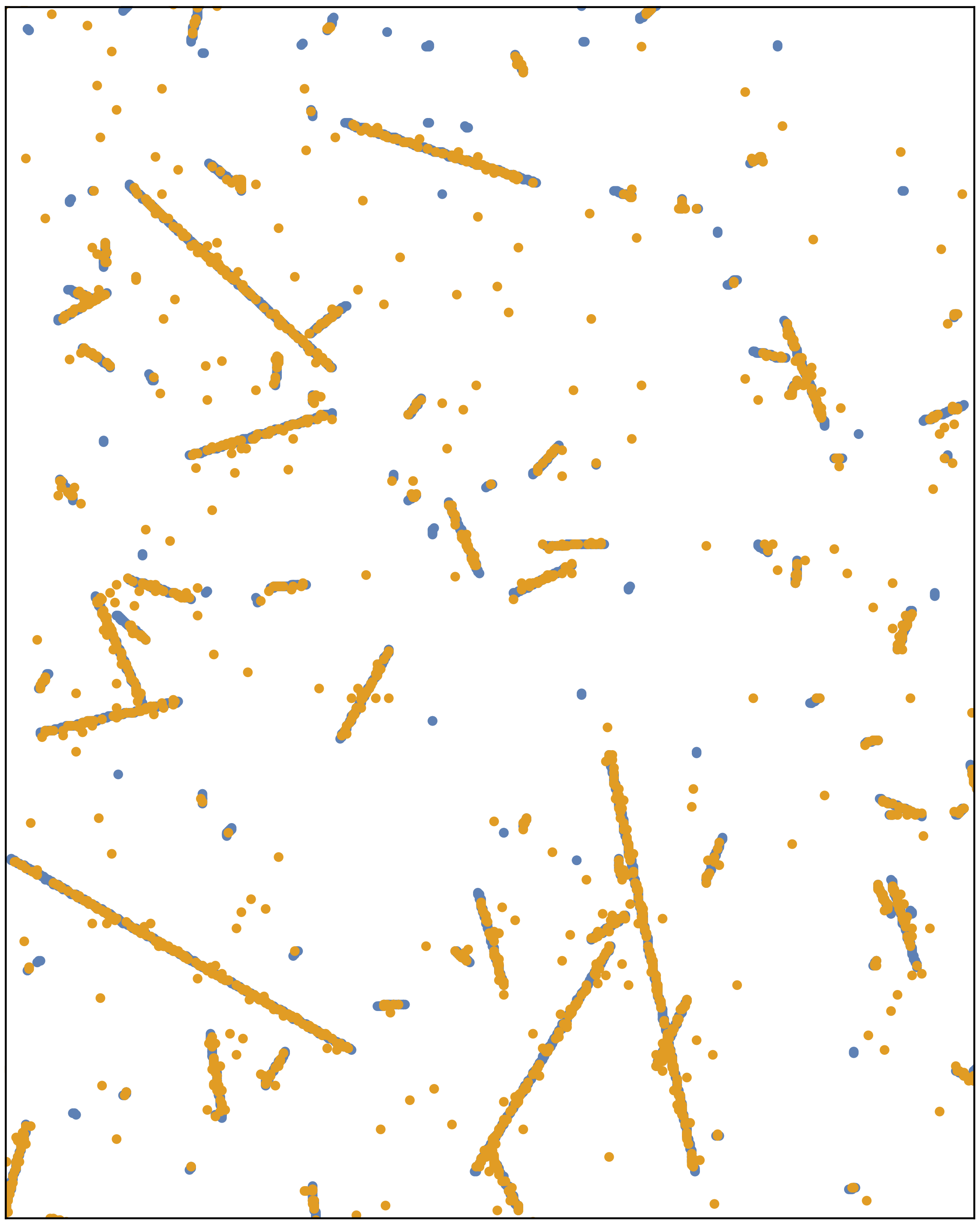


SENSEI data



SENSEI Images

Simulated Tracks + Cherenkov



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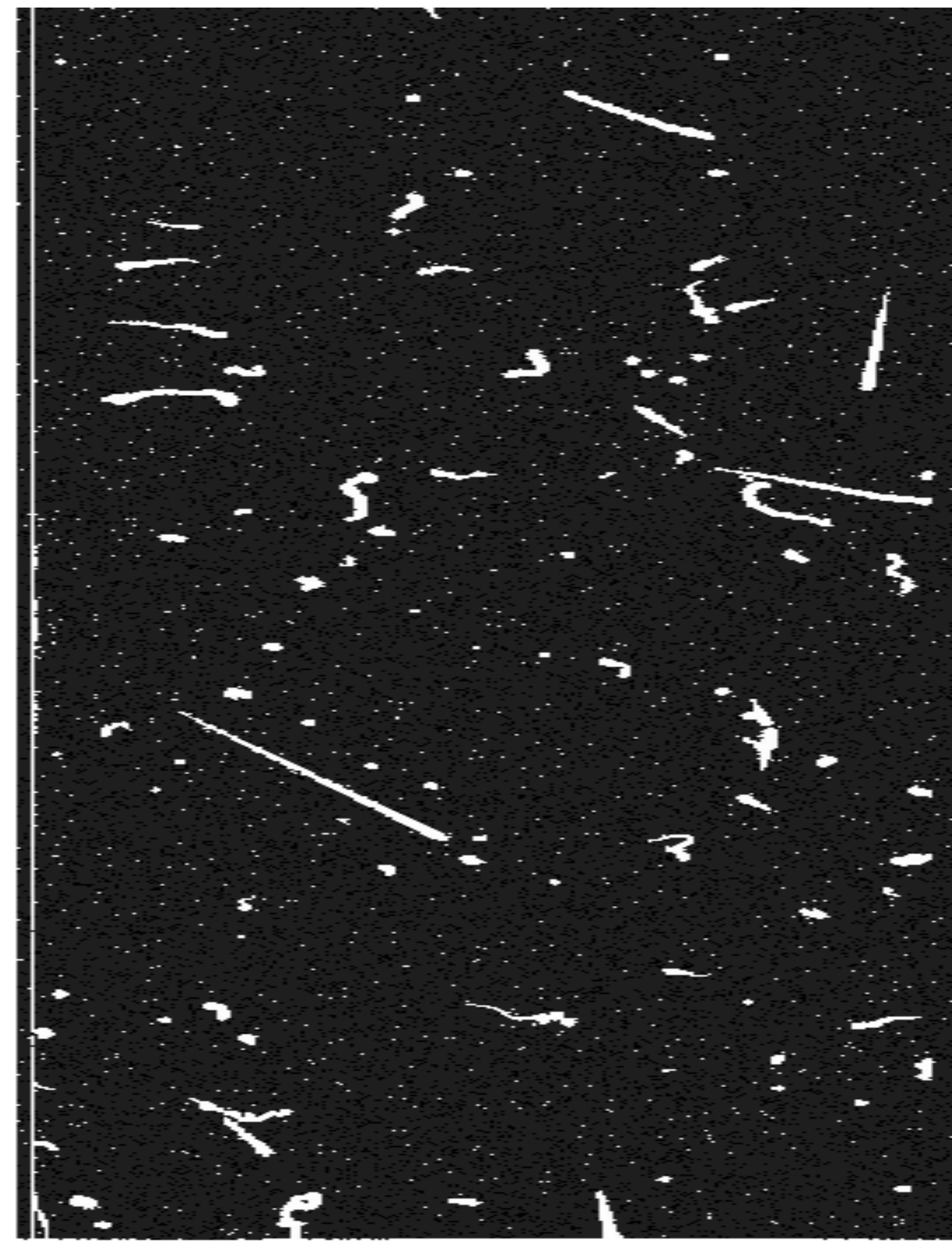
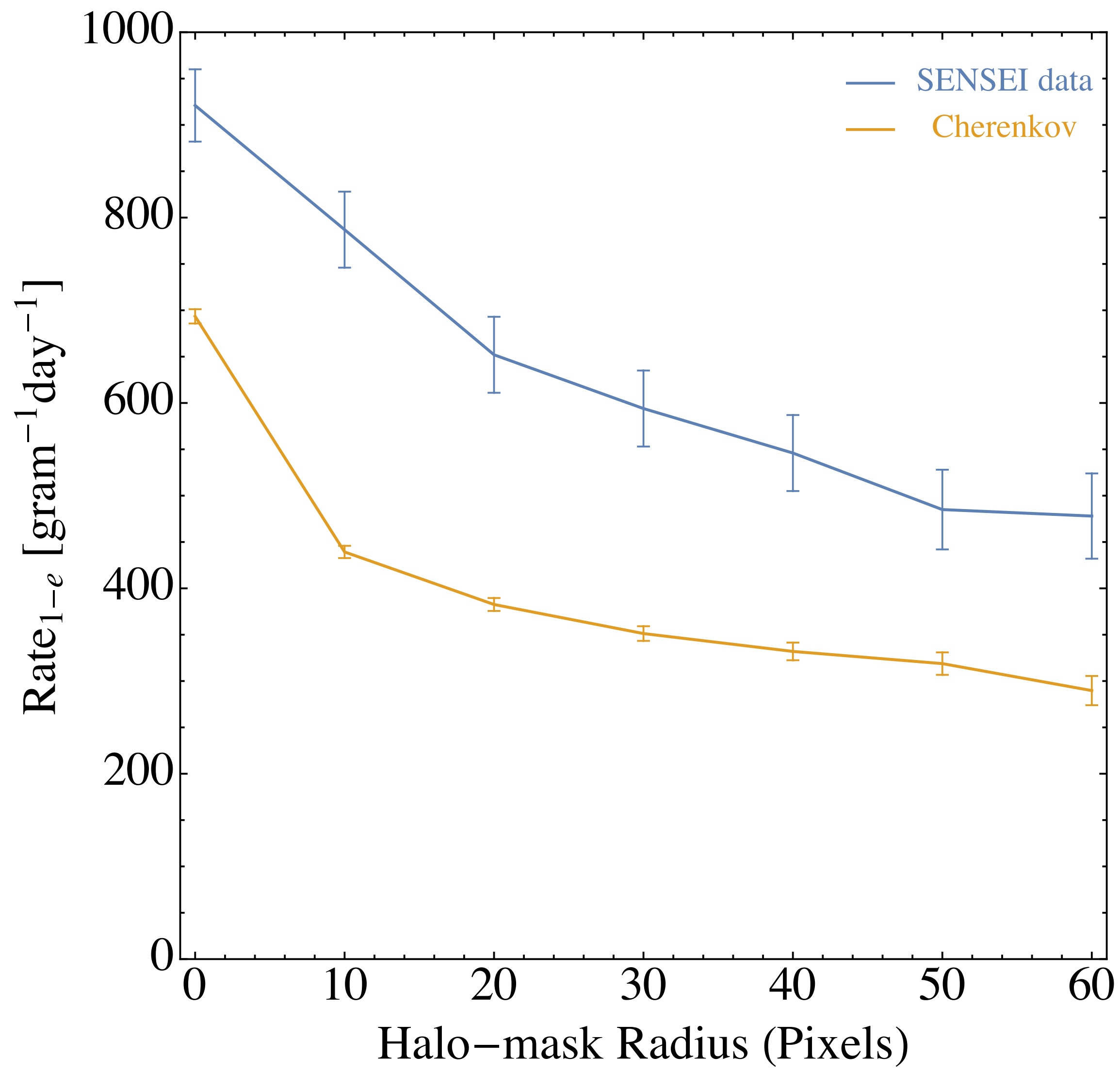


Cherenkov Radiation as a Background in SENSEI

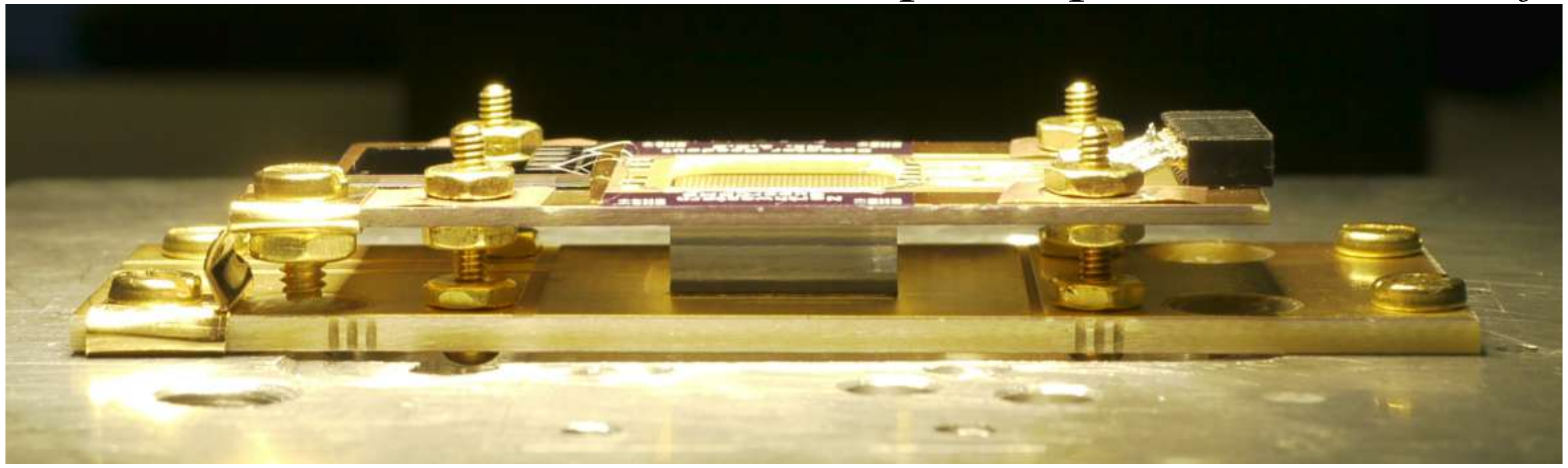
Preliminary Results:

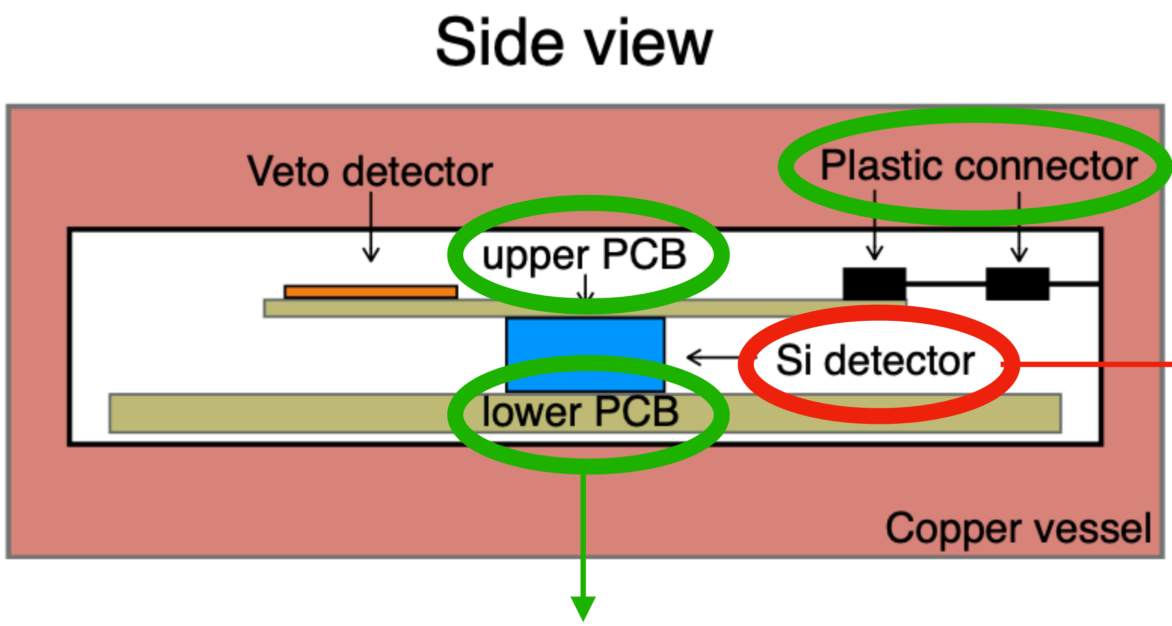
- SENSEI rate after a 60-pixel halo-mask cut: **450 $\pm$ 45 / (gram*day)**
- Estimated Cherenkov contribution: **290 $\pm$ 16 / (gram*day)**
- Rate vs Halo-radius plot (evaluation of systematic error in progress):



Cherenkov radiation in SuperCDMS HVeV

*https://supercdms.slac.stanford.edu/hvevr2-0





Can produce Cherenkov,
but part of high-energy track
and easy to veto

Two PCBs and plastic connectors
can produce Cherenkov that cannot be vetoed
because the accompanying high-energy track is missed

- We find this can easily produce sizable fraction of observed events w/ 2 to 6 electrons
- Need detailed simulation + precise optical properties of materials

Implications for Sub-GeV DM Searches

- Any non-conductive materials near detectors can produce Cherenkov
- Need careful evaluation of Cherenkov background in upcoming searches (e.g. SuperCDMS at SNOLAB, SENSEI at SNOLAB, DAMIC-M at Modane, OSCURA…)
- Even sub-gap Cherenkov photons can be absorbed to produce a phonon (could be important for proposed DM searches using single phonons and e.g. sapphire)

Several Mitigation Strategies Exist

- Increase passive shielding
- Active shielding
- Minimize non-conductive materials near detector
- Radiopure materials
- Multiple Nearby Detectors

Summary and Conclusions

- We have identified an important and unexplored background for low-threshold DM detectors: Cherenkov radiation
- Likely explains a sizable fraction of low-energy events observed in some experiments looking for electron-recoils (SENSEI, SuperCDMS HVeV)
- Important design implications for future searches
- Consideration of other unexplored backgrounds is in progress