The Selena Neutrino Experiment

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Outline

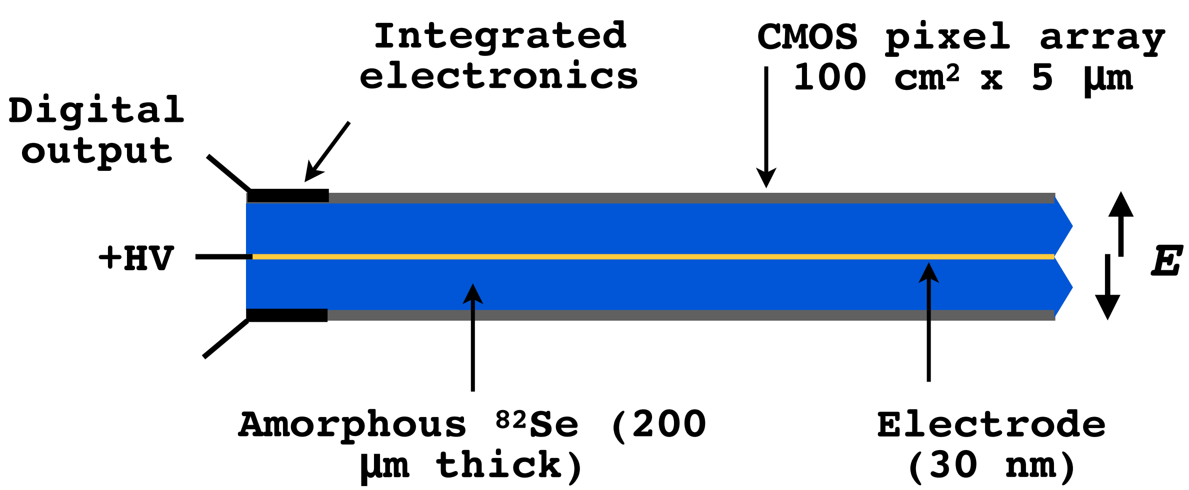
- The Selena neutrino experiment.
- Neutrinoless $\beta\beta$ decay.
- Solar neutrinos.
- Sterile neutrinos.

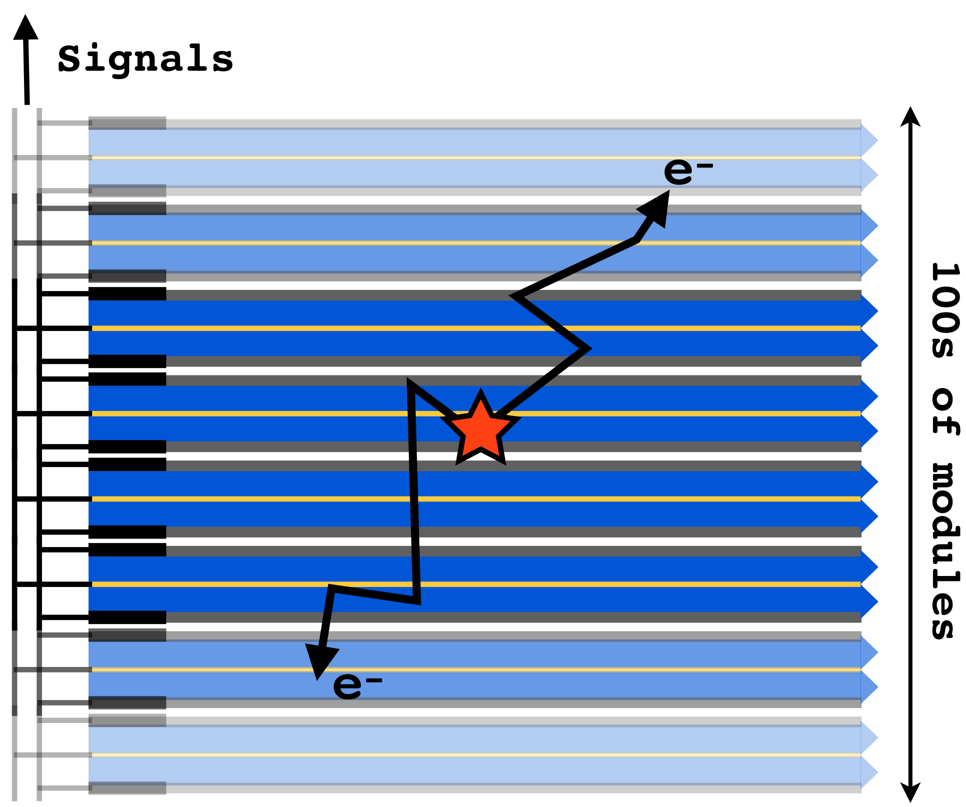
Broad neutrino science program!

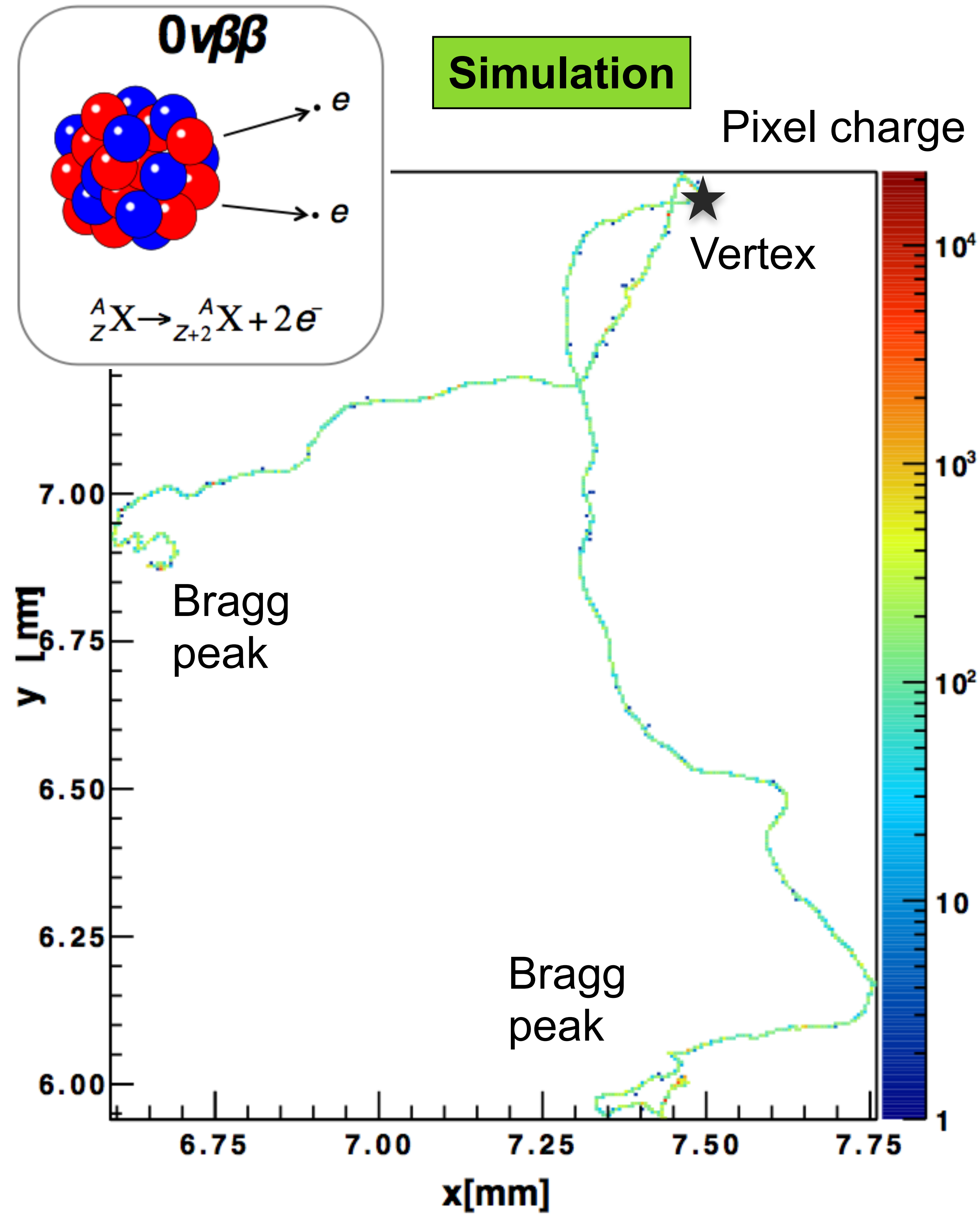
- Detector technology: hybrid **aSe/CMOS** pixelated devices.
- Toward a large detector.
- Conclusion.

Selena detector concept

JINST12(2017)P03022







Detector goals

- Excellent *energy resolution* to perform precision spectroscopy, e.g., distinguish 0ν signal from $2\nu\ \beta\beta$ decay background.
- Excellent *spatial resolution* to suppress backgrounds by event topology, e.g., number of Bragg peaks, decay sequences, etc.
- *Easy to build*: room temperature operation, not very stringent radio purity requirements or fiducialization, etc.
- *Scalable*: standard CMOS foundry process (300 mm diameter wafers) and industrial aSe deposition.

2022 →	**2025** →	**2029** →	**2040**
Small prototypes	Large detector module (2 kg)	100 kg (50 modules) demonstrator	10-ton detector underground

Background suppression

High resolution imaging in a solid-state target provides unique opportunities for signal/background discrimination!

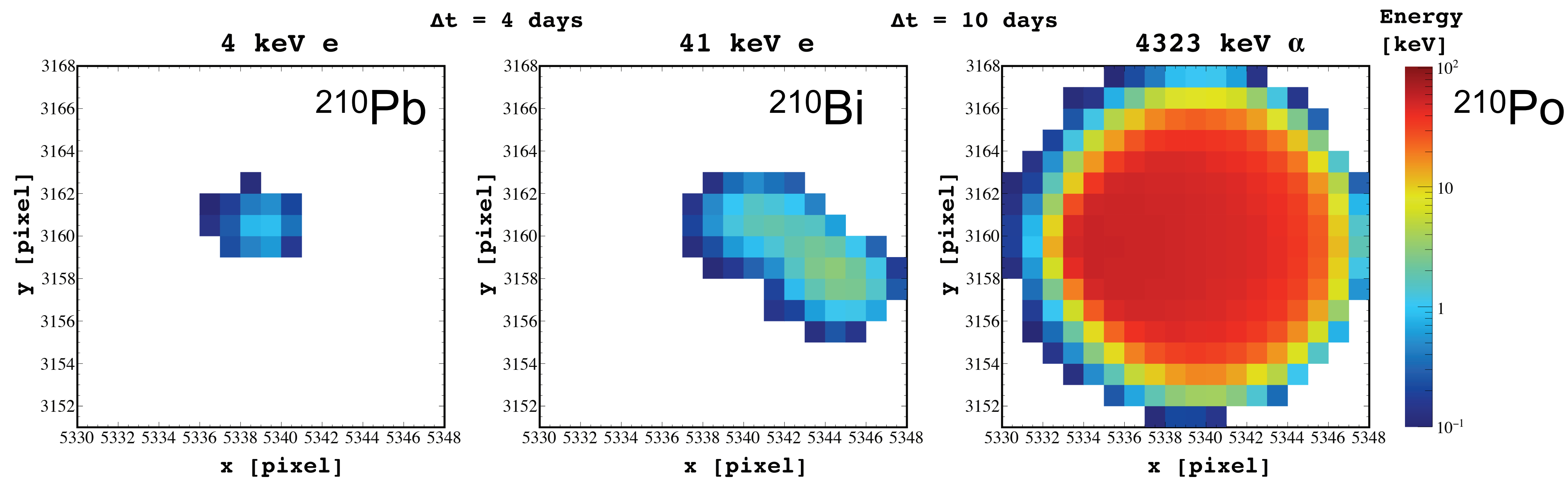
- Determine the number and types of particles (β, α, etc.).
- Determine the end-point of β tracks by identifying the Bragg peak.
- Since atoms remain immobile in the solid target, we can identify radioactive decay sequences with time separations of up to weeks!
- DAMIC uses this strategy to constraint the decay rates of every β in the U and Th chains.

JINST16(2021)P06019

Spatial correlations

Data from DAMIC

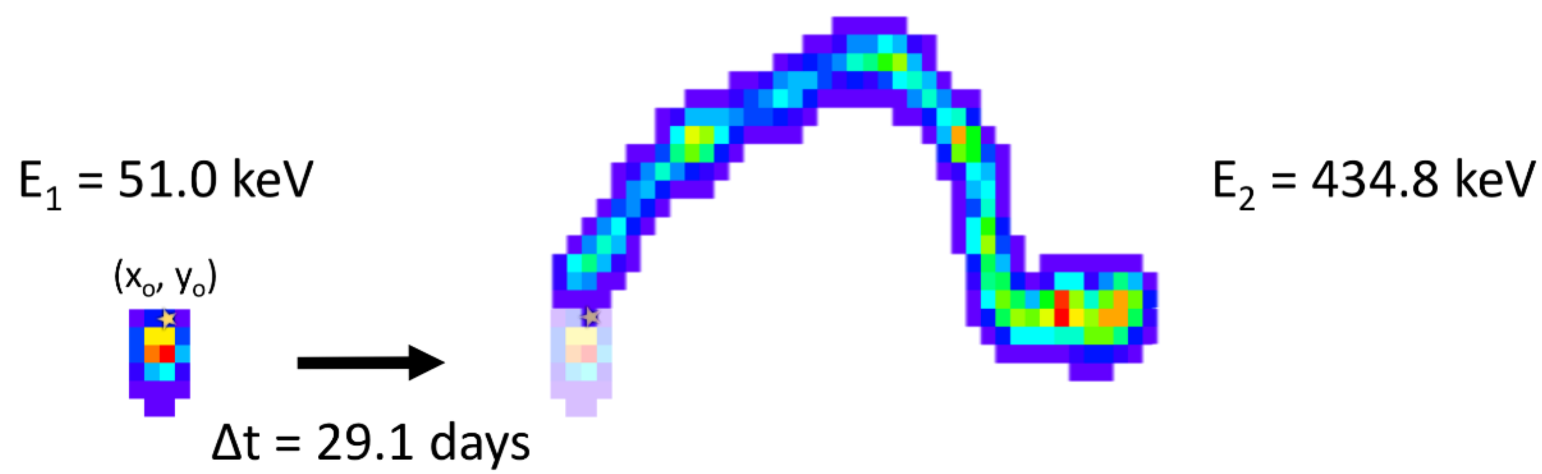
- **^{210}Pb surface background:**



- **Cosmogenic ^{32}Si:**

  Search for spatially correlated beta decays. Sensitivity with current data is few Bq/kg.

^{32}Si ($T_{1/2}$= 150 y, β) → ^{32}P ($T_{1/2}$= 14 days, β)



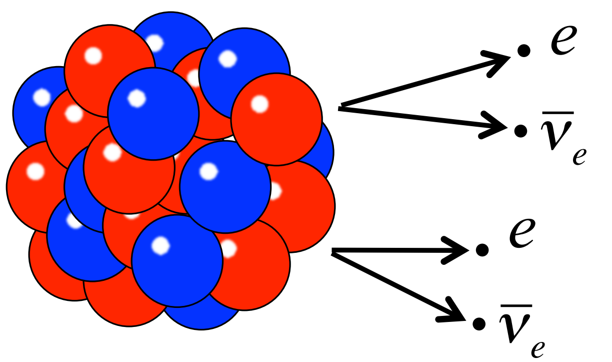
Science case

With a 10-ton detector (100 ton-year exposure)

$0\nu\beta\beta$ decay

Standard process

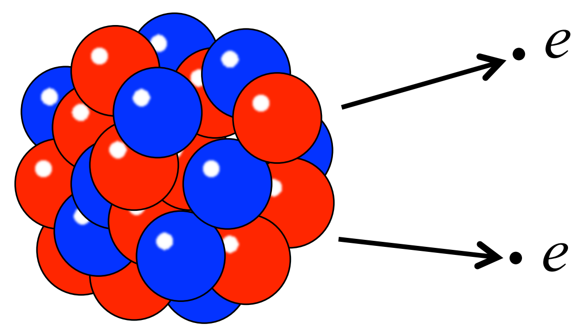
$2\nu\beta\beta$



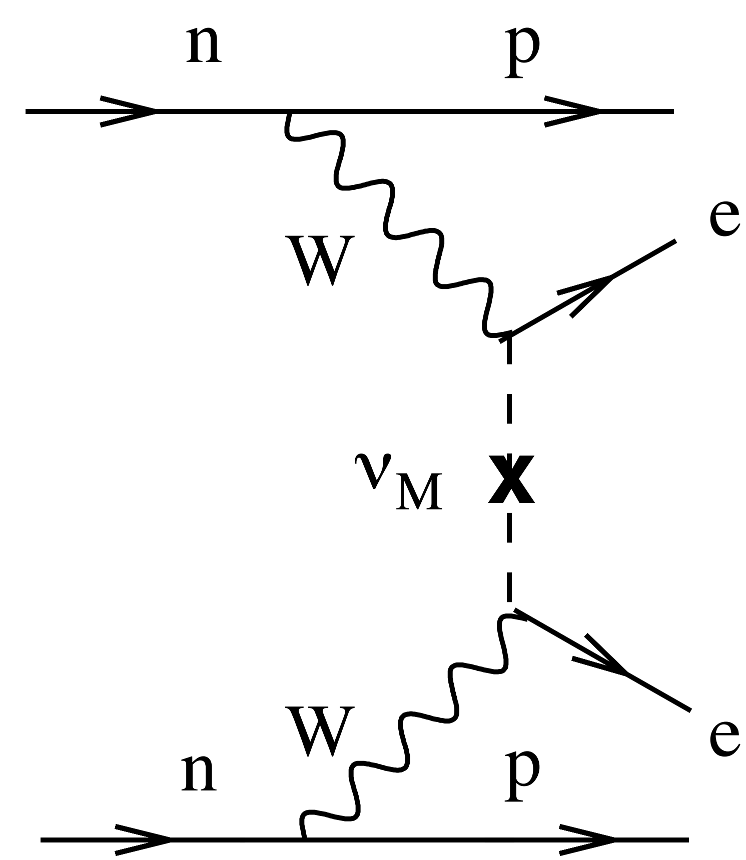
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-} + 2\bar{\nu}_e$$

BSM: **Majorana νs**

$0\nu\beta\beta$



$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-}$$



Decay rate

Phase space factor

$$\Gamma_{0\nu} = G_{0\nu}\mathcal{M}^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

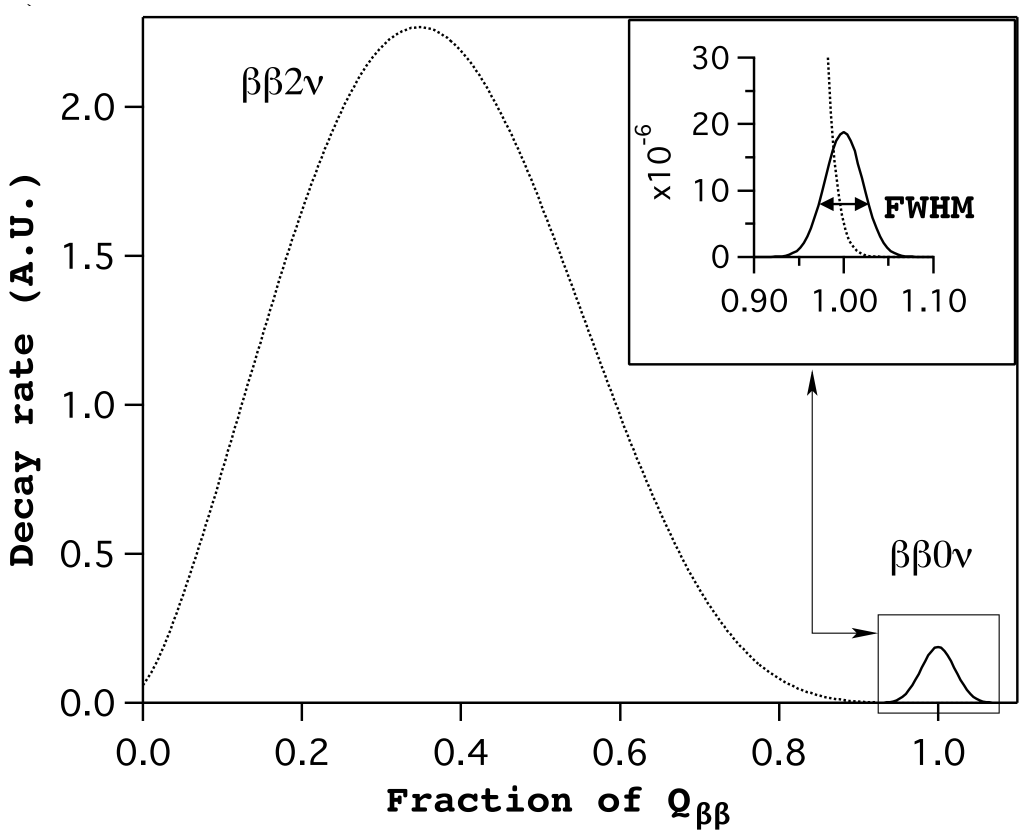
Nuclear matrix element (NME)

Particle physics:

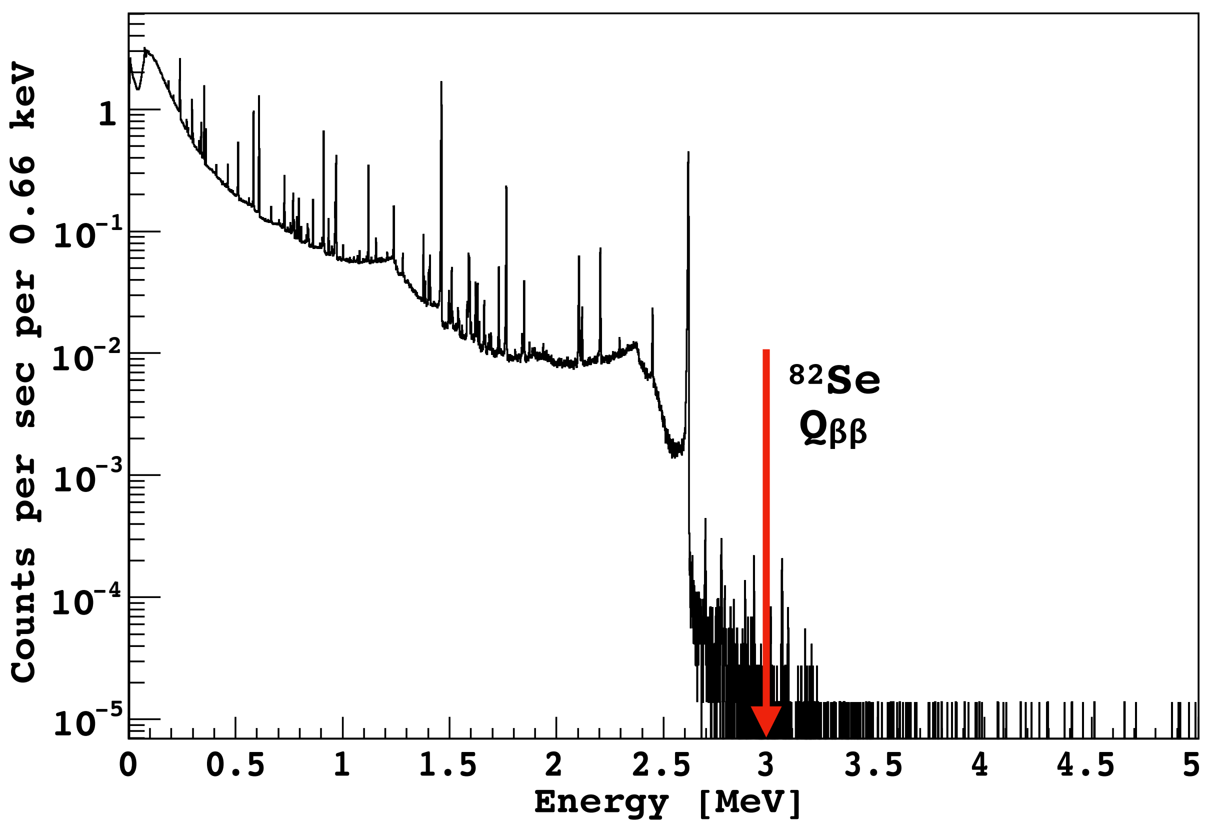
$$m_{\beta\beta} \equiv \left|\sum_{i=1,2,3} U_{ei}^2\, m_i\right|$$

Strategy

Excellent energy resolution to distinguish neutrinoless decay



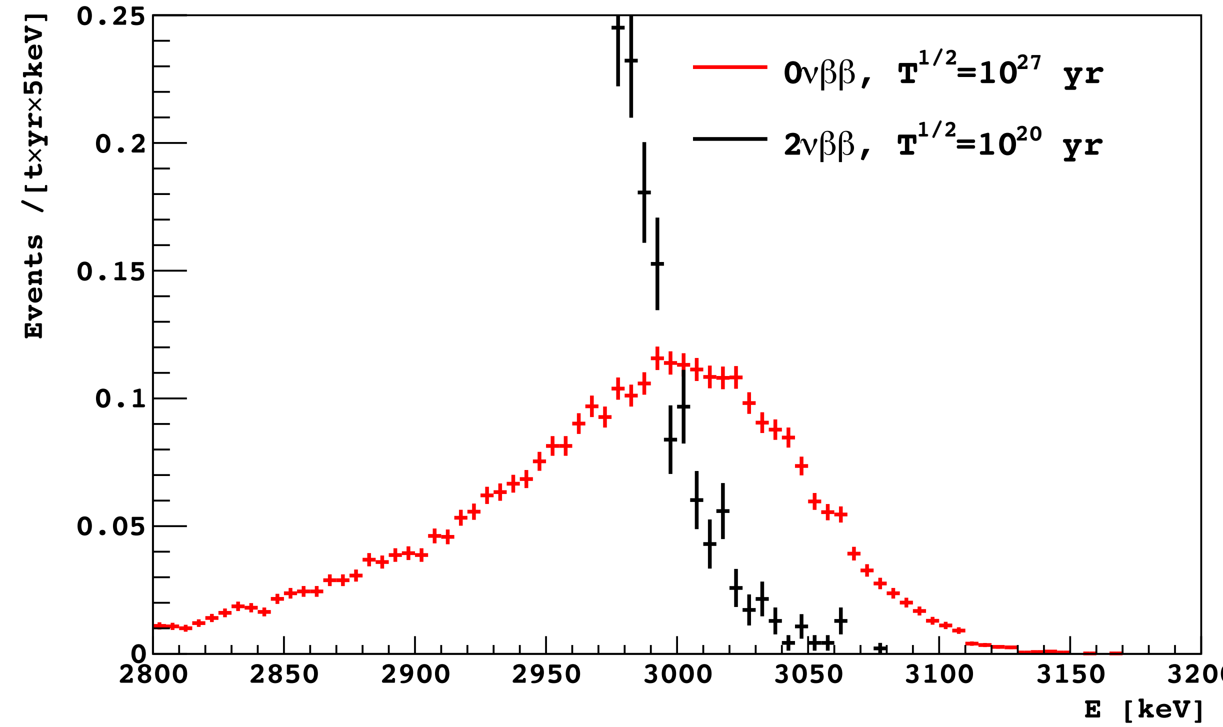
High Q-value to avoid background from U+Th



Bonus: Identify the ββ decay in an event-by-event basis by measuring the event topology (two electrons vs. one).

Selena $\beta\beta$

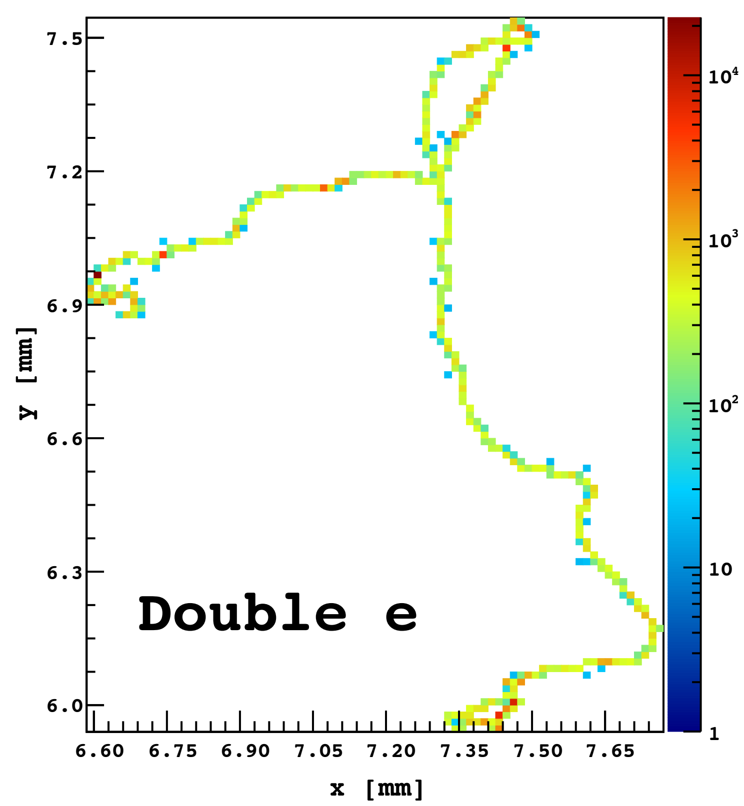
- By identification of Bragg peak we can achieve 10^{-3} suppression of single electron background, with 50% signal acceptance.
- Bulk backgrounds suppressed by α/β particle ID, spatial correlations.

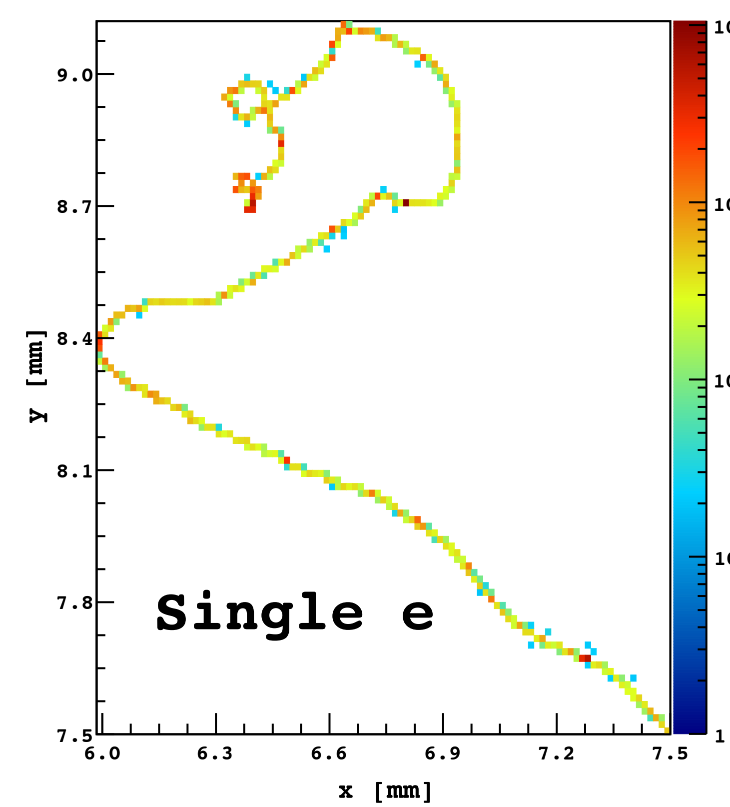


Background rate <6 x 10^{-5} /keV/ton/year!

JINST12(2017)P03022

$T_{1/2}$ > **10^{28} years** limit on ^{82}Se $0\nu\beta\beta$





ν_e detection

Triple sequence:

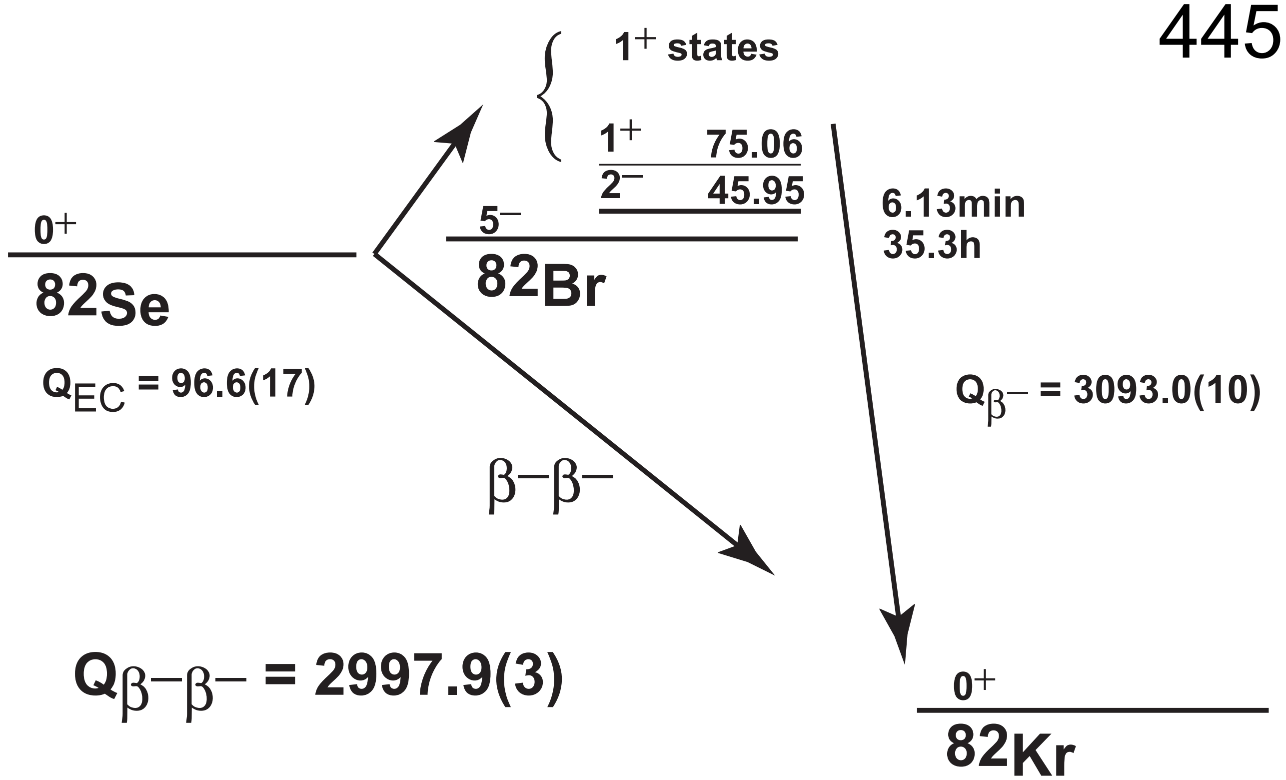
$$\nu_e + {}^{82}\mathrm{Se} \longrightarrow {}^{82}\mathrm{Br}^* + \overset{\substack{E_\nu - 172\ \mathrm{keV} \\ \downarrow}}{e^-} + \mathrm{C.E.}\ (29\ \mathrm{keV})$$

“prompt”

$${}^{82}\mathrm{Br}^* \longrightarrow {}^{82}\mathrm{Br} + \mathrm{C.E.}\ (46\ \mathrm{keV}) \qquad \tau_{1/2} = 6.1\ \mathrm{min}$$

$${}^{82}\mathrm{Br} \longrightarrow {}^{82}\mathrm{Kr} + \gamma + \beta^- \qquad \tau_{1/2} = 35\ \mathrm{hours}$$

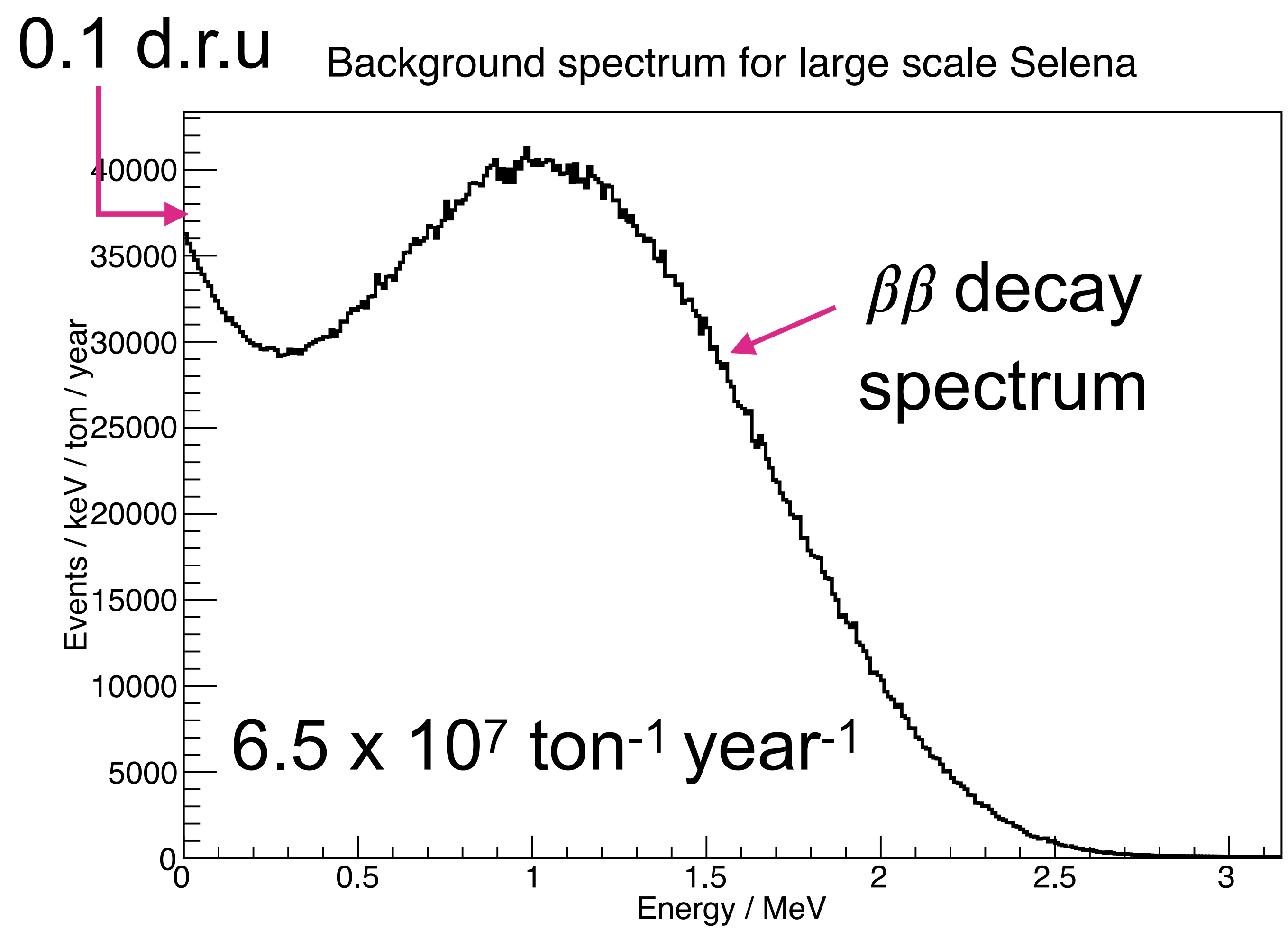
445 keV end-point



We can use the prompt events to perform ν_e spectroscopy!

Backgrounds

- Expected number of three accidental events in 100 μm^2 (22 μg) is **<10^{-4} in 100 ton year**.
- Other α, *p*, or *n* reactions that make $^{82}Br^*$ have a different prompt event topology.
- No cosmogenic isotope starts a decay chain that mimics the triple coincidence.

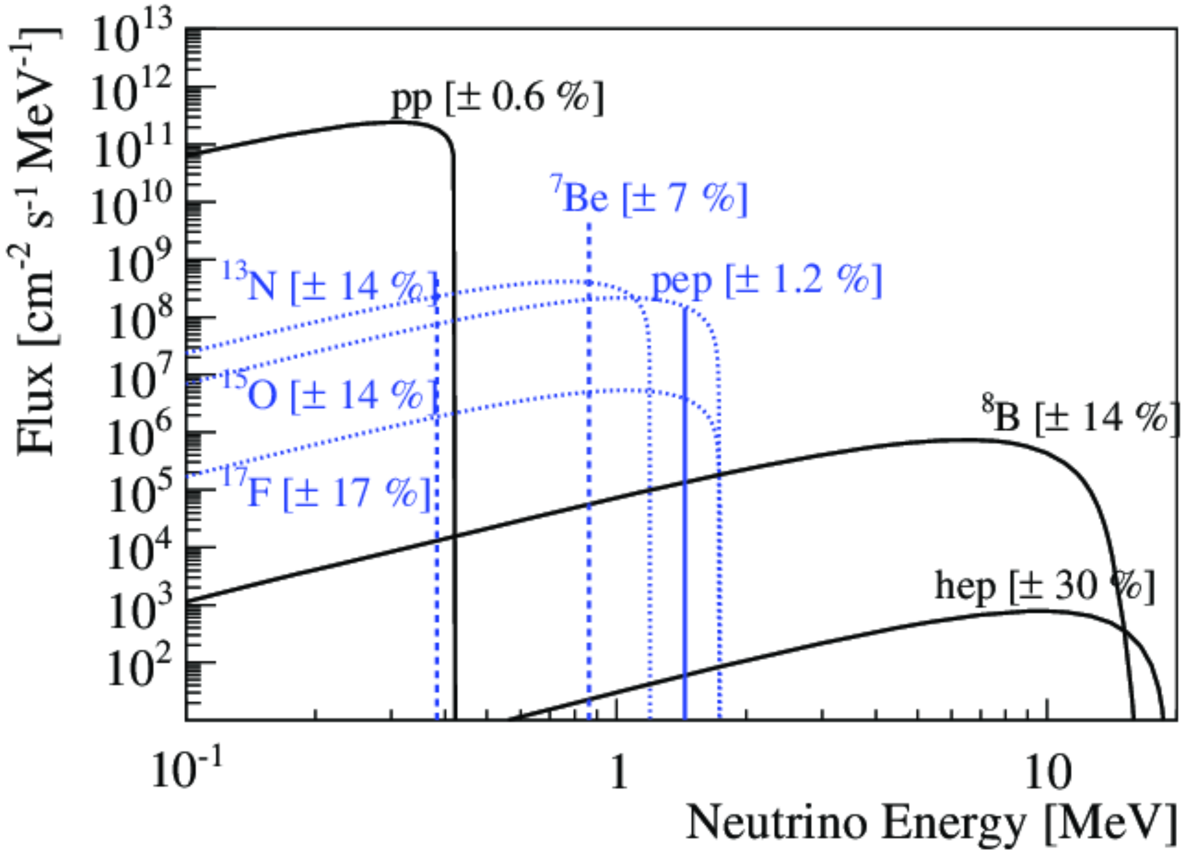


- Some neutron captures on Se isotopes can give triple coincidences but their event topologies are also very different.

No identified background to mimic the triple coincidence.
Possibility of zero background υ spectroscopy!

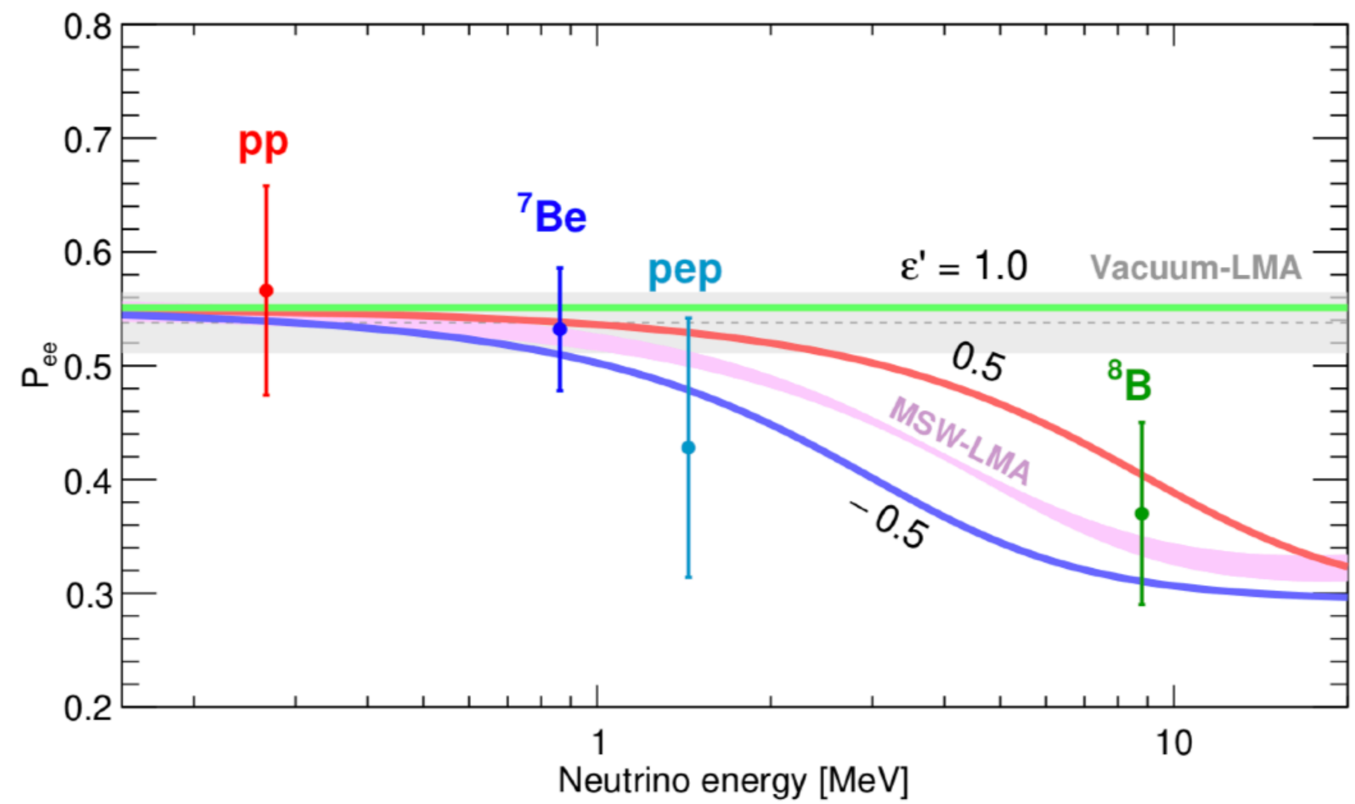
Solar neutrinos

Solar fluxes



- Nuclear reactions in the sun.
- *pp* + CNO cycles.
- Predicted by solar models.

Survival probability



- Vacuum oscillations, matter effects.
- Precise prediction by MSW-LMA (parameters from PMNS matrix).

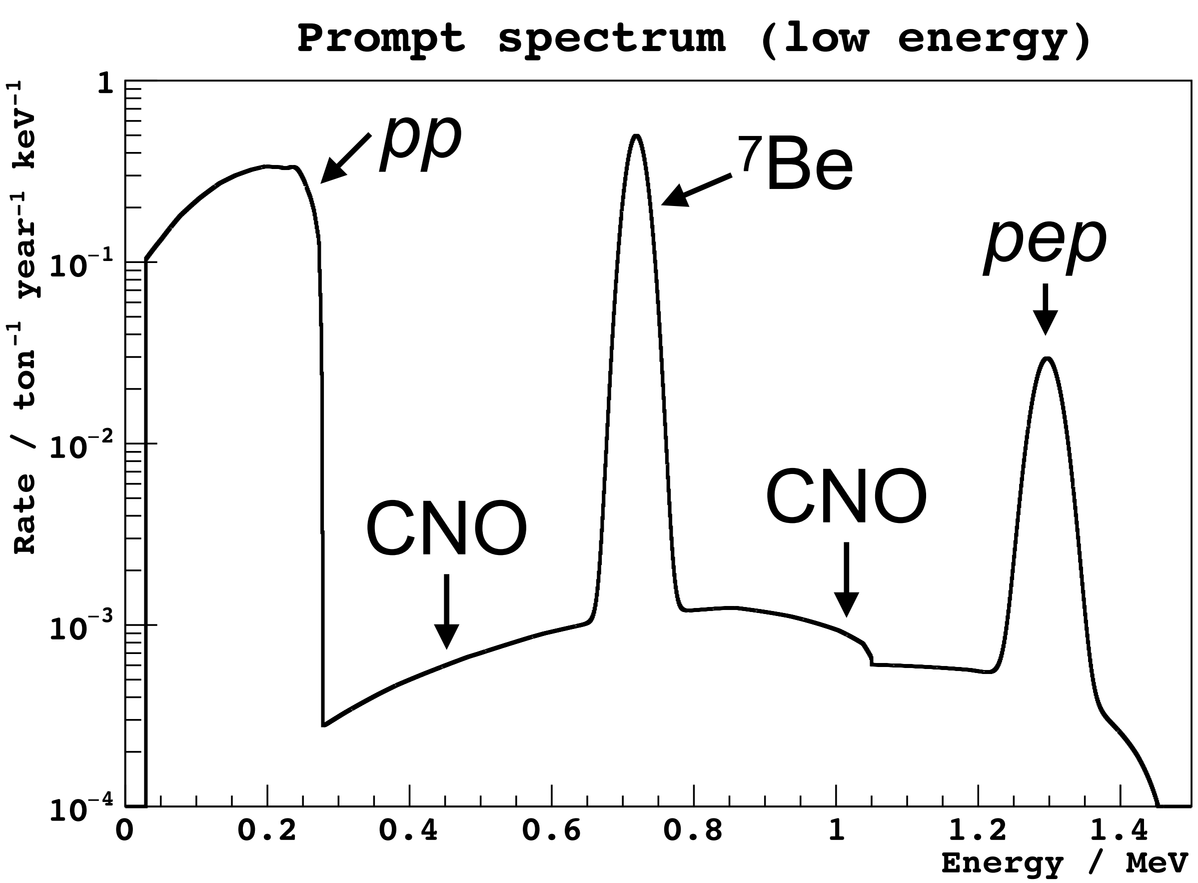
Prompt spectrum

$$\nu_e + {}^{82}\text{Se} \longrightarrow {}^{82}\text{Br}^* + e^- + \text{C.E. (29 keV)}$$

$E_\nu - 172$ keV

Capture $\sigma(E)$ from

PRC 94, 014614 (2016)



100 ton-year

Species	E range (keV)	N	$1/\sqrt{N}$
pp	29 - 278	6170	**1.3%**
^{7}Be	665 - 775	1850	**2.3%**
pep	1230 - 1360	151	**8.1%**
CNO	278 - 655 785 - 1220	63	**12.6%**
^{8}B	(1.5 - 15) x 10^3	209	**6.9%**

Solar Physics

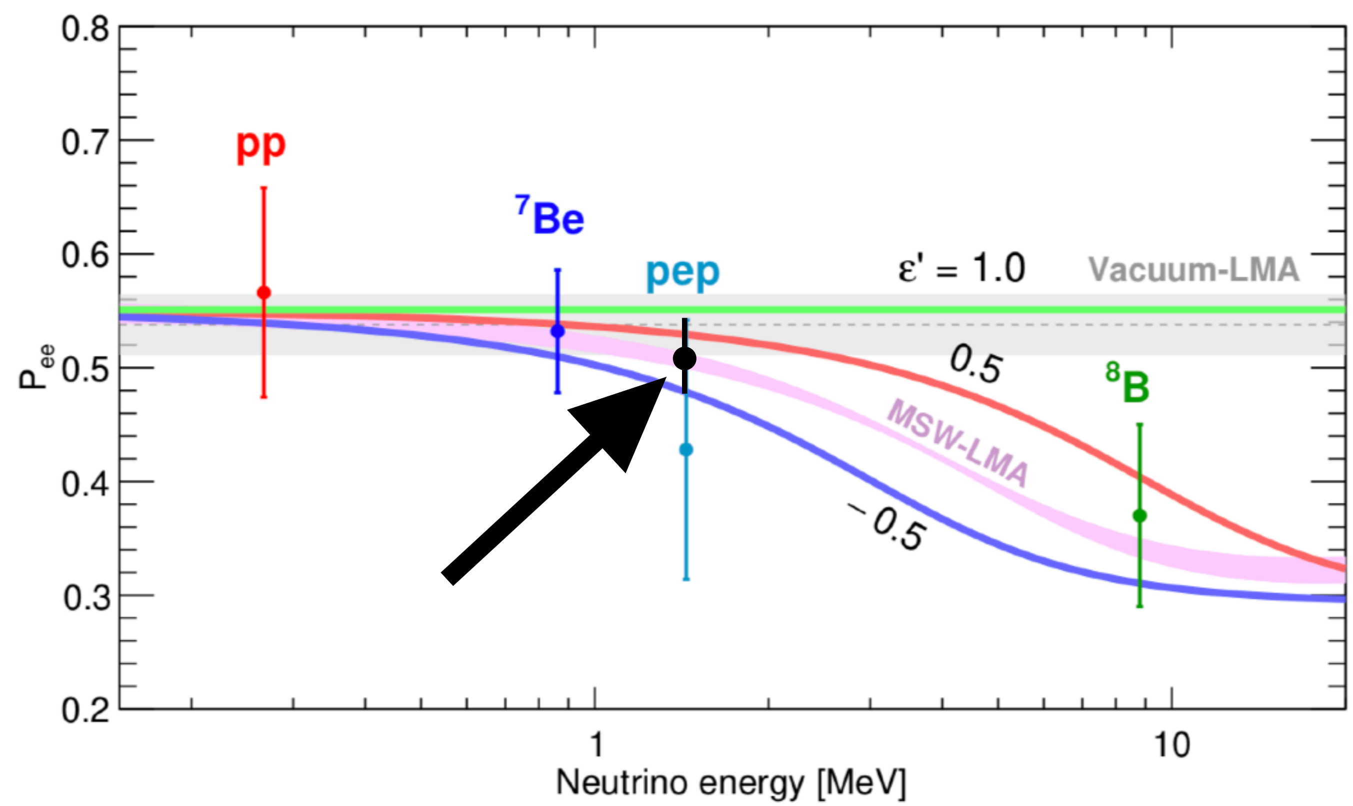
- **Solar luminosity:** *pp* rate unc. improved to **1.3%** (currently ~10% by BX). Flux measurement uncertainty depends on uncertainty on ν_e capture σ. If calibrated to ν-e scattering σ by comparing measured ^{7}Be rate with BX, sys. unc. = **3.5%**.
- **Solar metallicity:** CNO flux measured to **~10%**. Difference between high- and low-metallicity solar model predictions: **28%**.
- **Solar core temperature:**

PRD 49, 3923 (1994)

Species	RMS width (keV)	Mean unc. (keV)	Line diff. (keV)	Fraction
^{7}Be	14.8	0.34	1.29	26%
pep	19.8	1.60	7.59	21%

Neutrino physics

- **Onset of matter effects in ν oscillations:** *pep/pp* rate ratio measured to **8%**. Flux ratio very well predicted by SSM, MSW effect should suppress *pep* ν_e flux by **7%**. NSI could increase this.

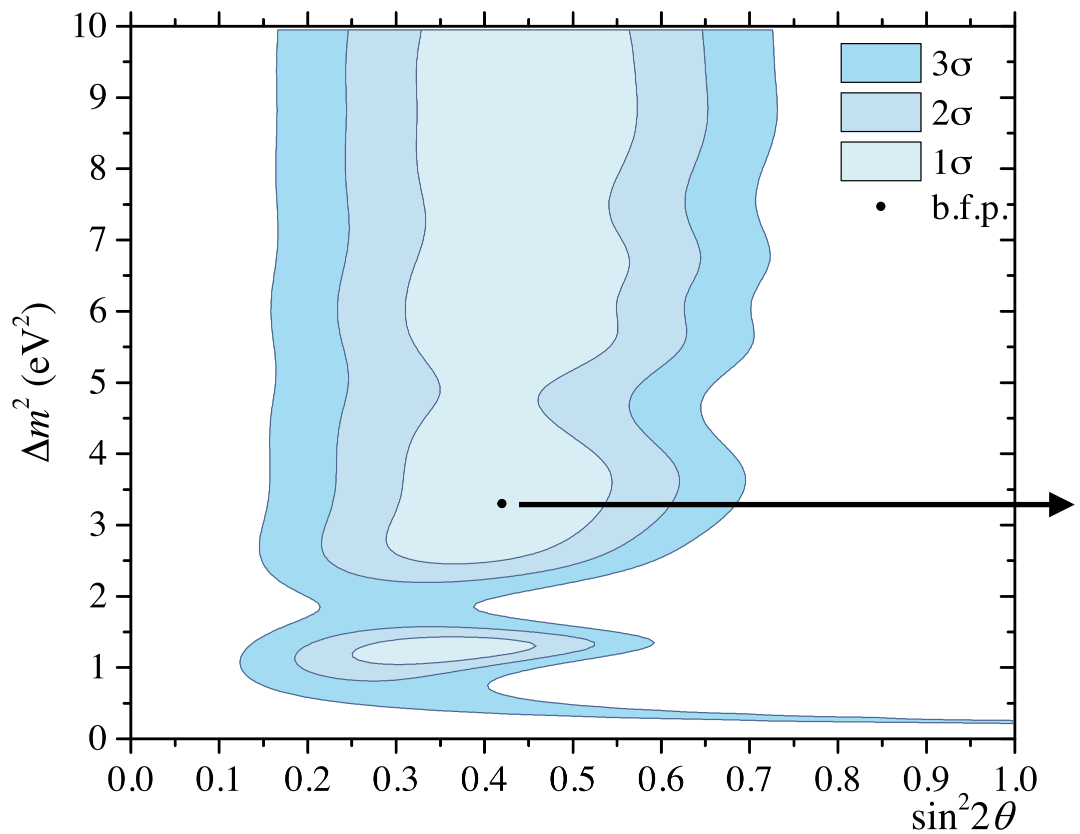


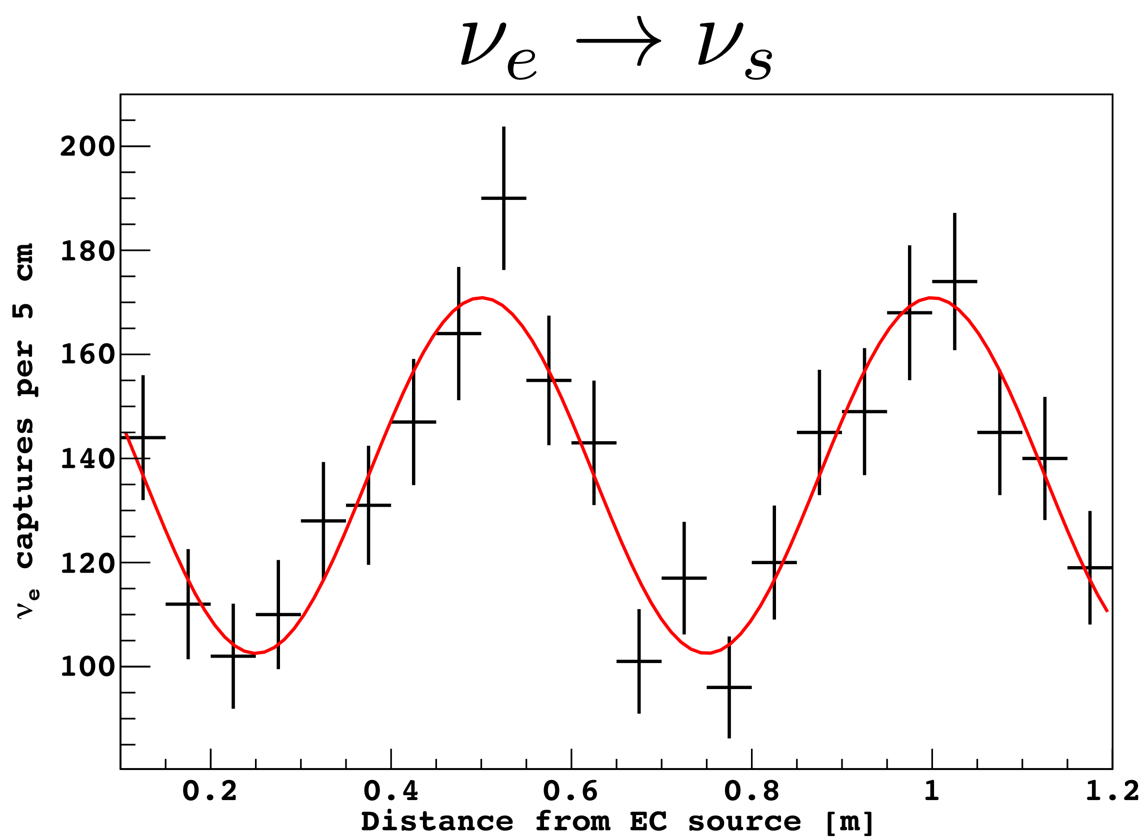
Sensitive probe for neutrino transport in the Sun

Sterile ν

arXiv:2109.11482 (2021)

- The *gallium anomaly*: Observed ν_e capture rate from sub-MeV EC sources is 80±5% of expected. Recently confirmed by BEST.
- We expect ~3000 ν_e captures from a 3.5 MCi ^{51}Cr source at the center of a 10 ton Selena detector, in a similar configuration to BEST.



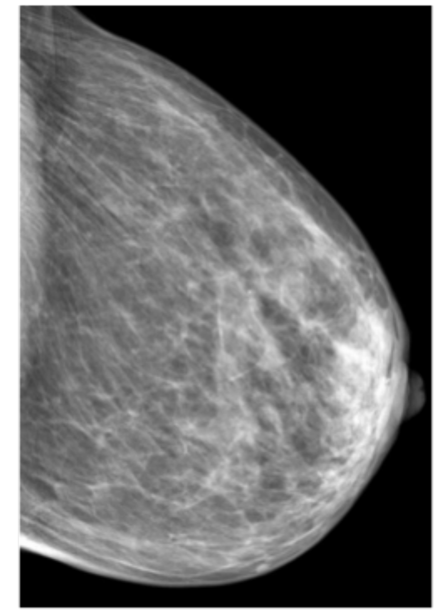


Selena could confirm oscillations into sterile neutrinos as the explanation!

Detector technology

Amorphous Se detectors

aSe X-ray detectors are used in medical imaging.
720 cm^2, 1 mm-thick.
Pixel size: 85 μm x 85 μm.



Operated at high electric fields (~10s V/μm) and ~50 e-h pair per keV for 140 keV X-rays.

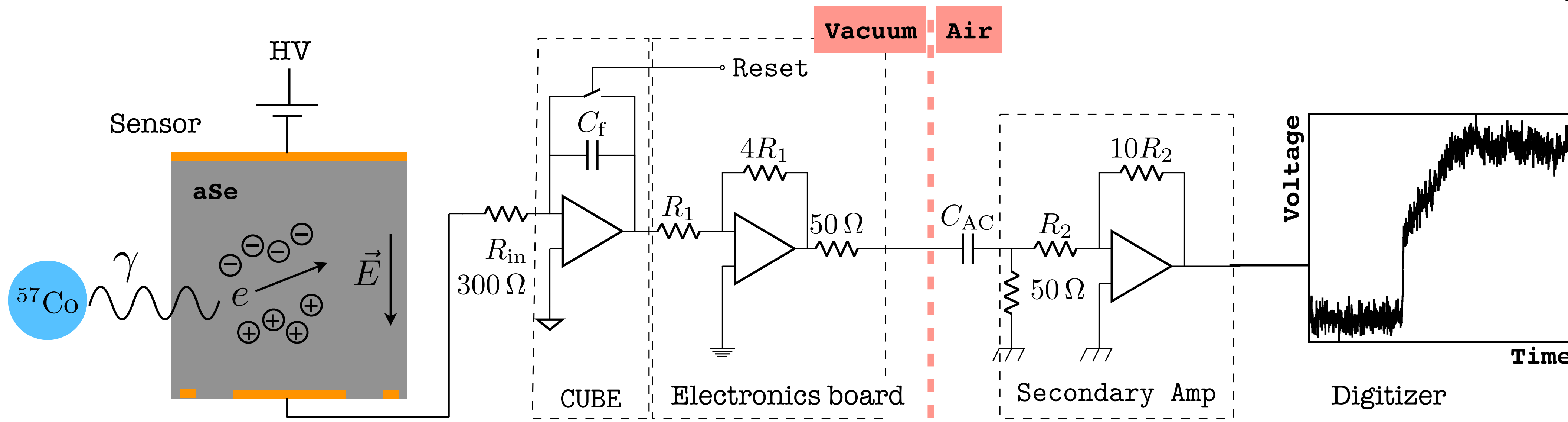
Large band gap: ~pA/cm^2 dark current at room temperature.

Present limitation: 1000 e-h RMS noise per pixel (from readout and leakage current).

R&D: Single pixel

JINST16(2021)P06018

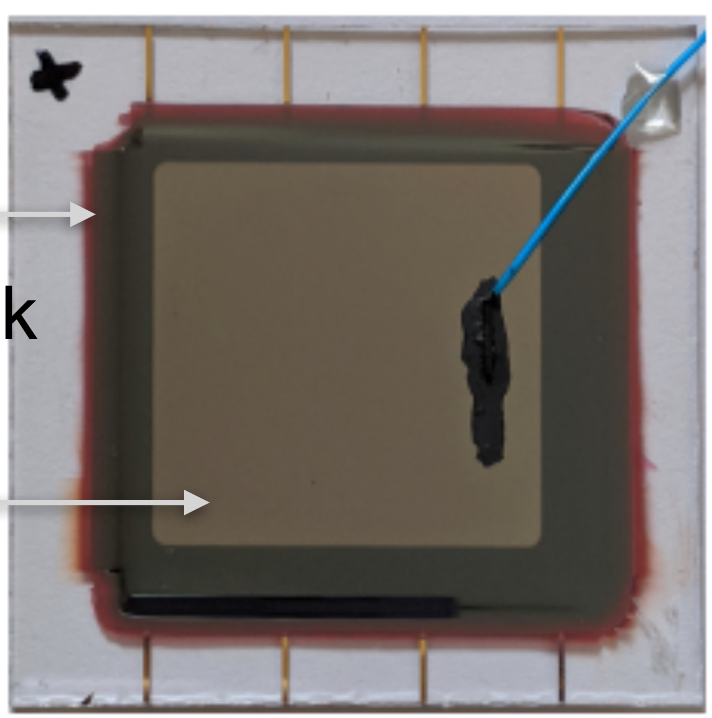
X. Li

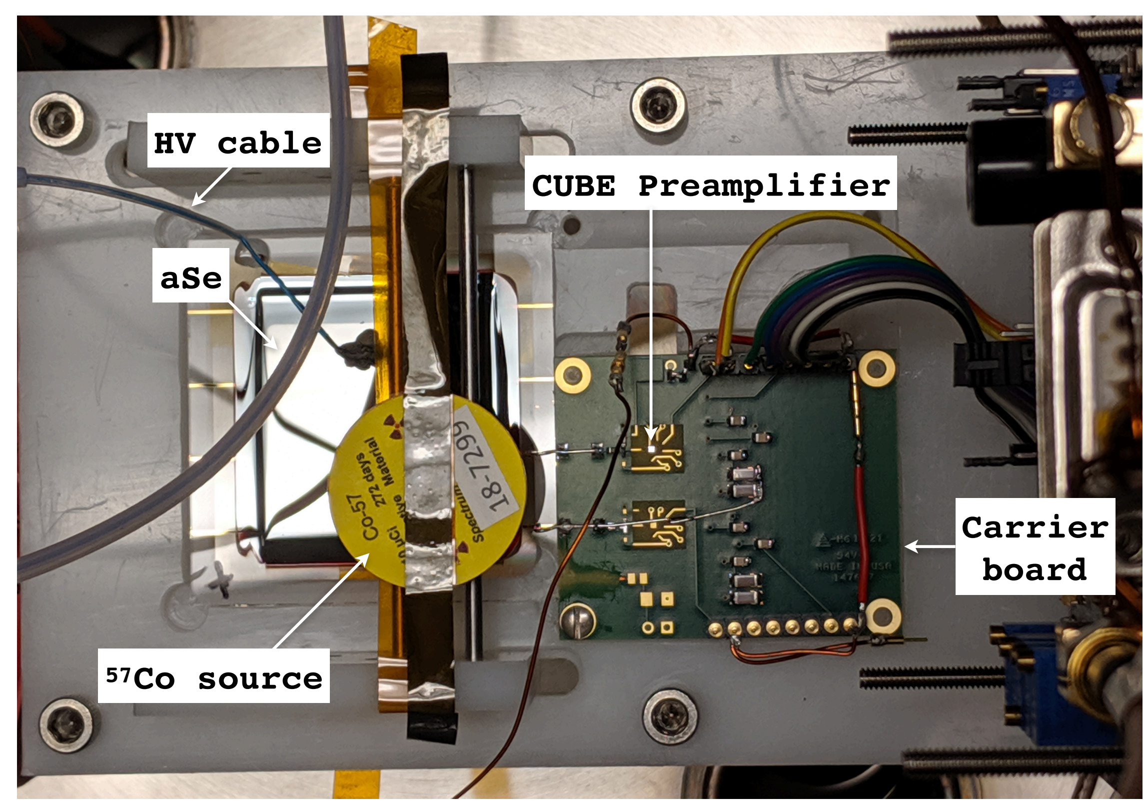


aSe

200 μm thick

HV contact





R&D: Single pixel

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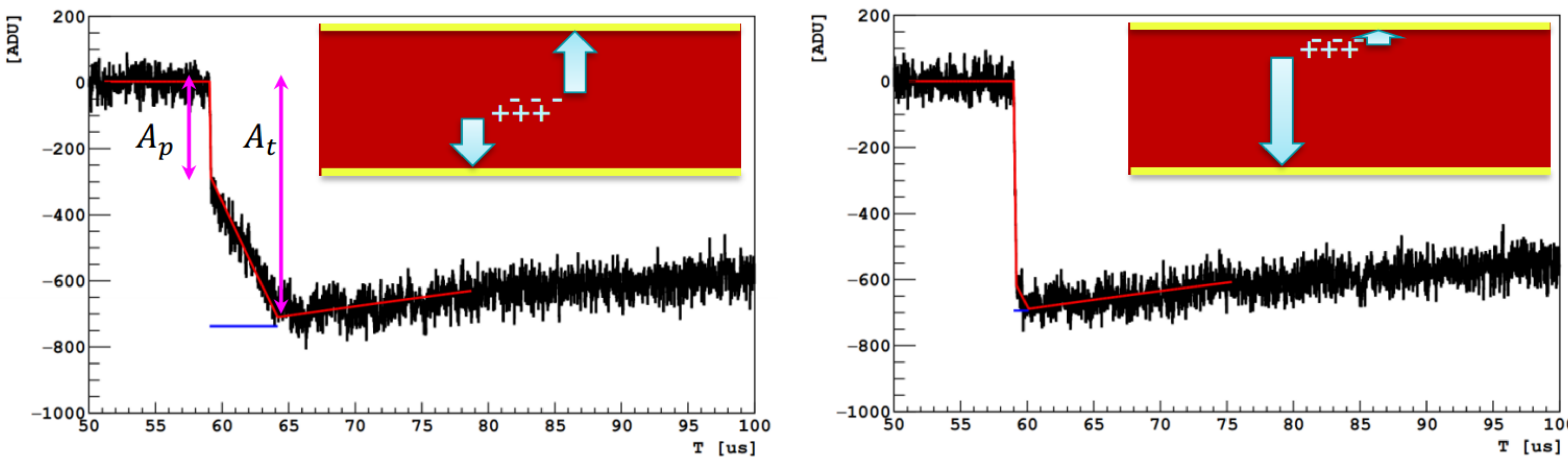
High S/N pulses from photo absorption of 122 keV γ rays



HV: 6 kV, Signal: ~5000 e^-, Baseline noise: 270 e^- RMS

- μ_h is significantly higher than the μ_e in aSe (measured in Ref.).
- Pulse shape depends on the depth of the interaction.

Demonstrated depth reconstruction from pulse shape for the first time!

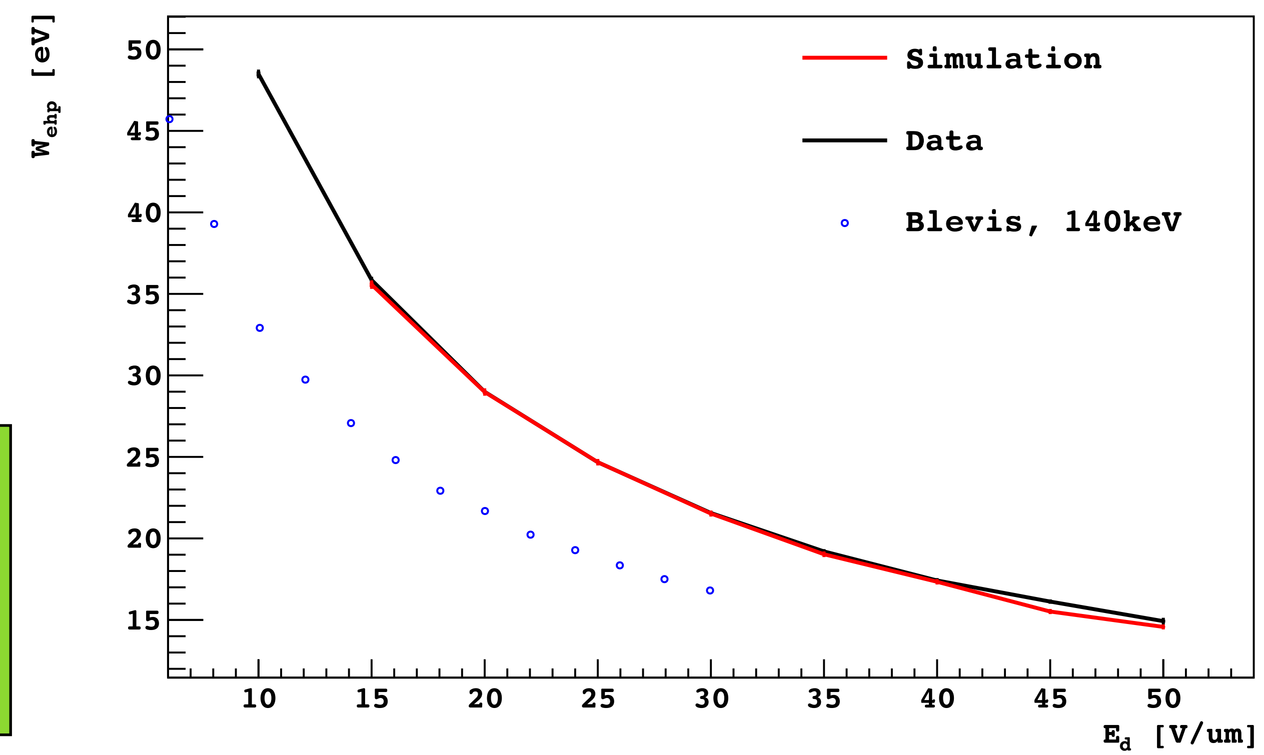
R&D: Single pixel

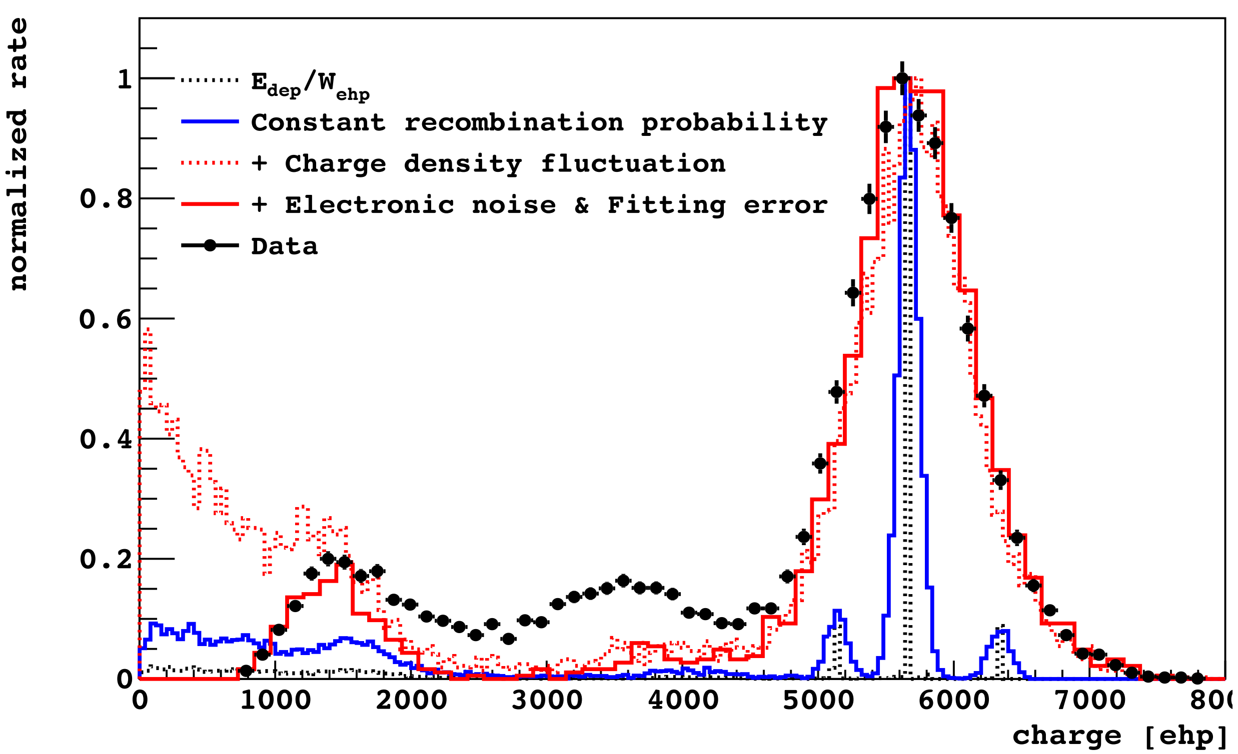
JINST16(2021)P06018

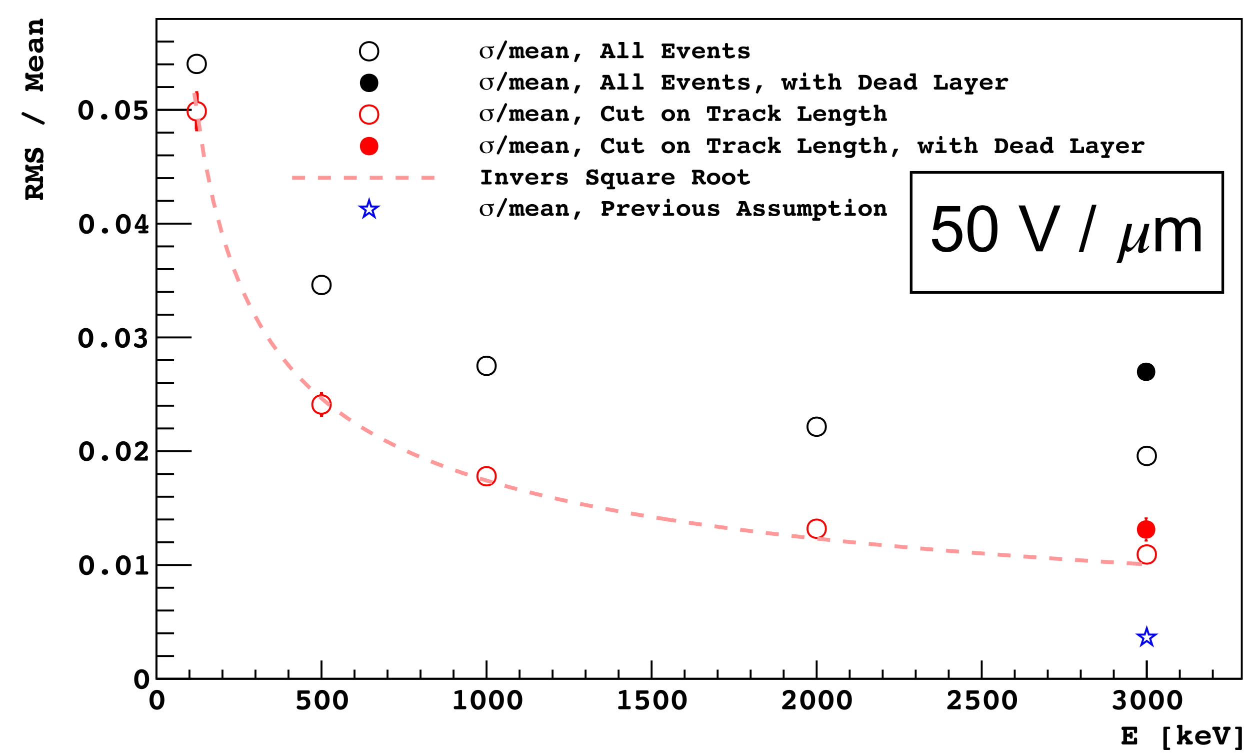
From ^{57}Co photo absorption peak:

- Charge yield vs. HV
- Line width vs. HV

Ab initio Monte Carlo to extrapolate energy resolution to $Q_{\beta\beta}$: **1.1%** after track-length correction.

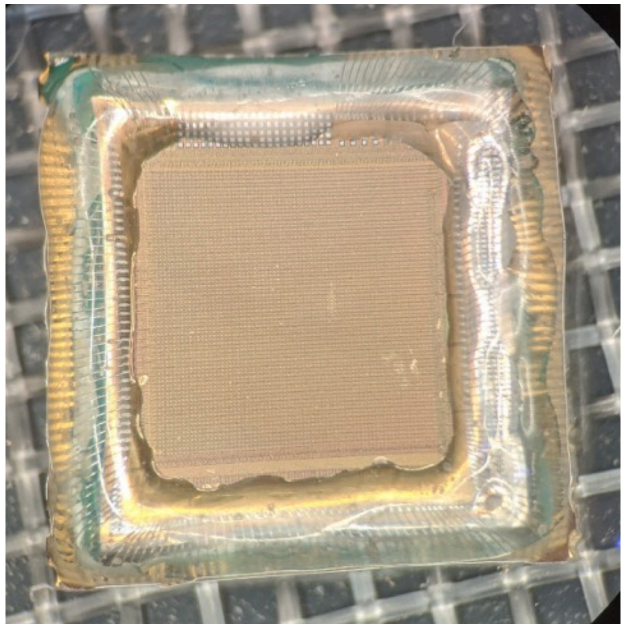




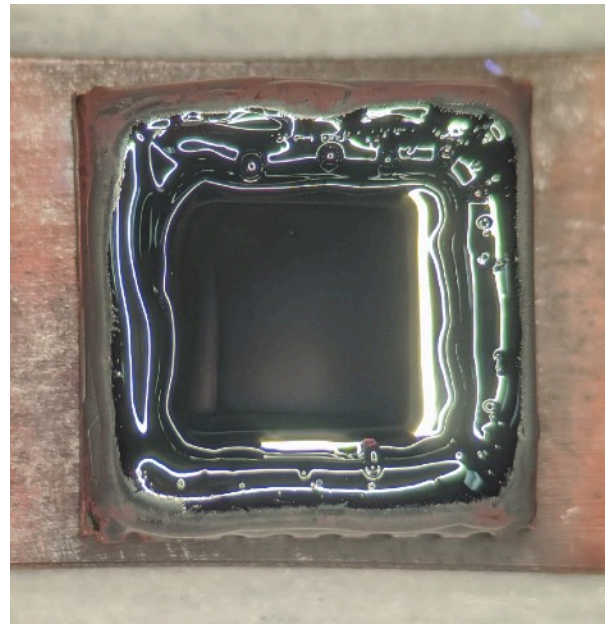


R&D: Topmetal-II⁻

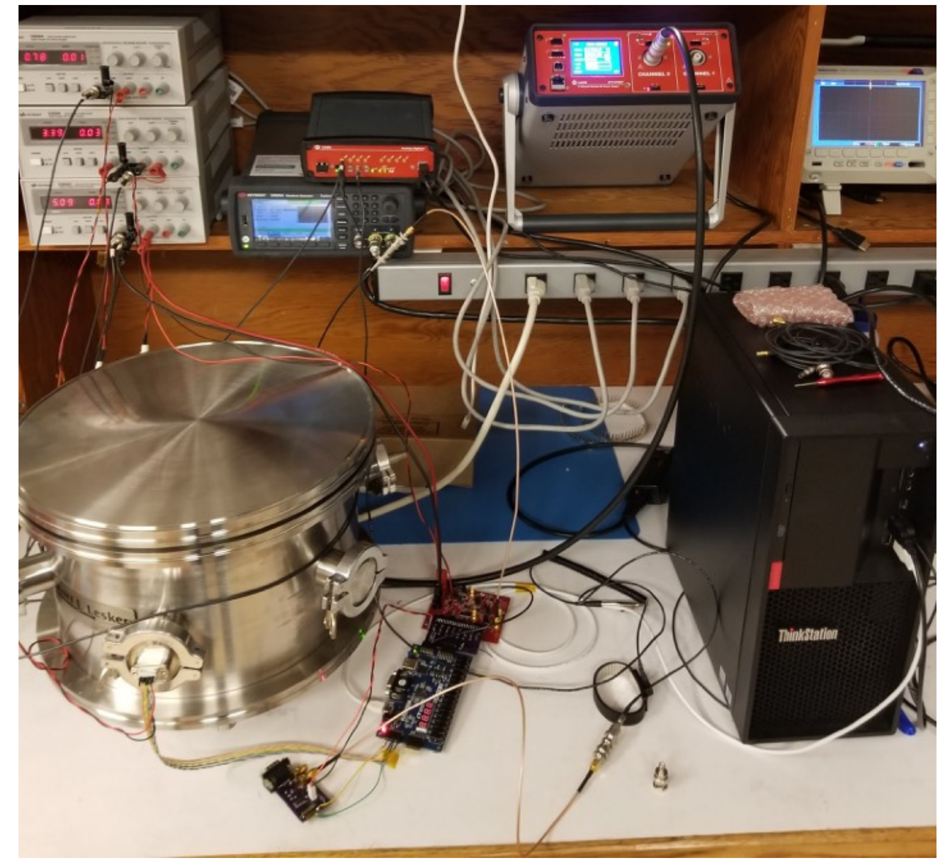
Before aSe



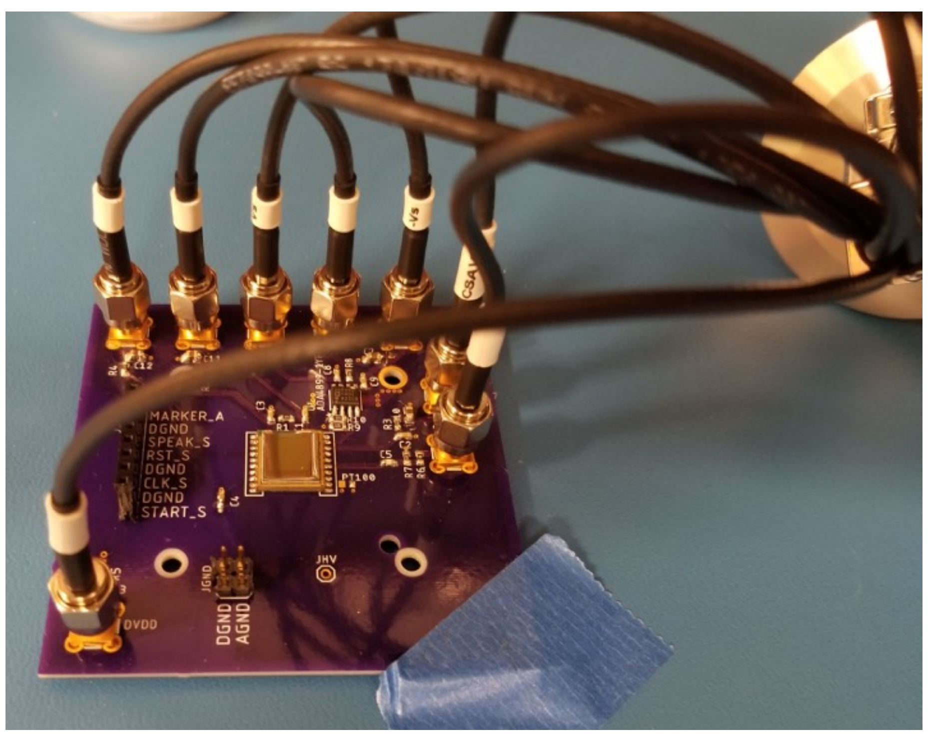
After aSe



Setup at CENPA



Test board



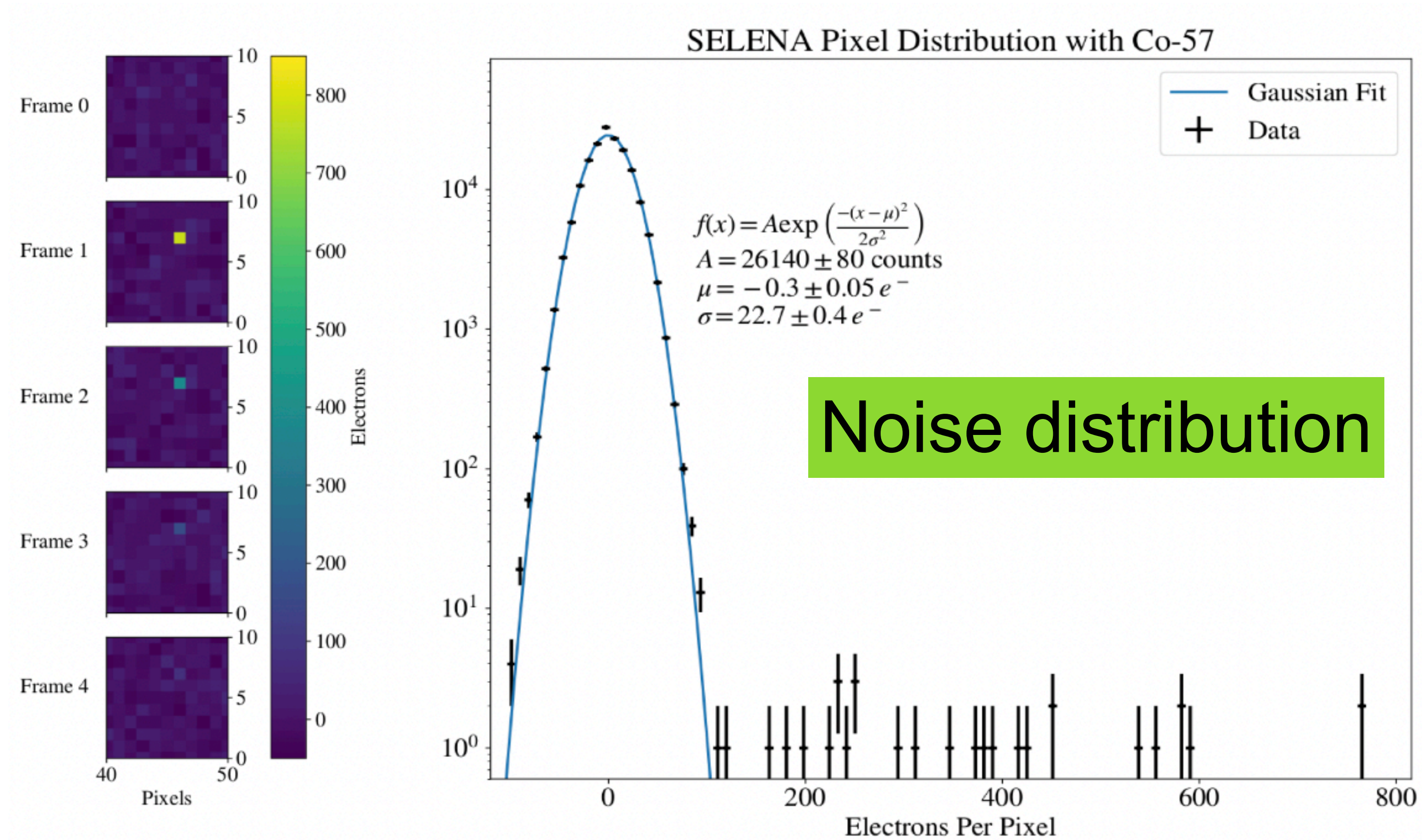
- From Berkeley Lab.
- CMOS pixel array with exposed metal electrodes.
- 83 μm pixel pitch.
- 15 e^- pixel noise.

Topmetal II⁻

NIMA810(2016)144

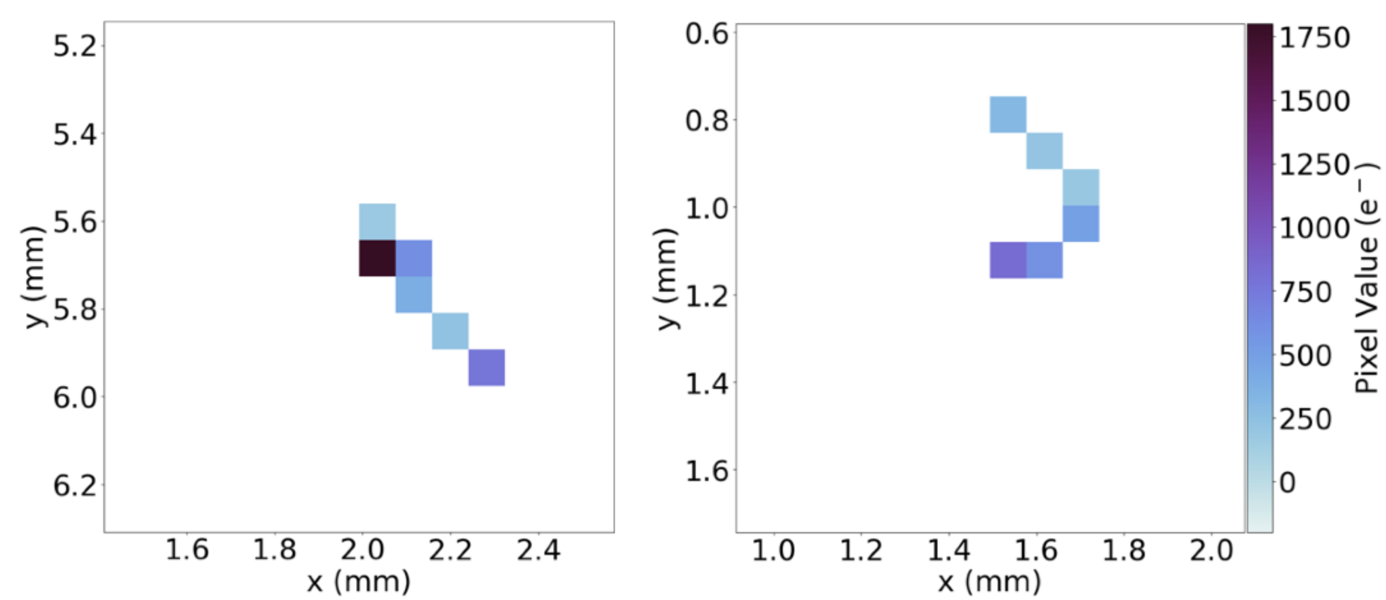
R&D: Topmetal-II-

- Improved noise by 50x relative to commercial detector.
- Imaged electron tracks in amorphous selenium (at room temperature!) for the first time.



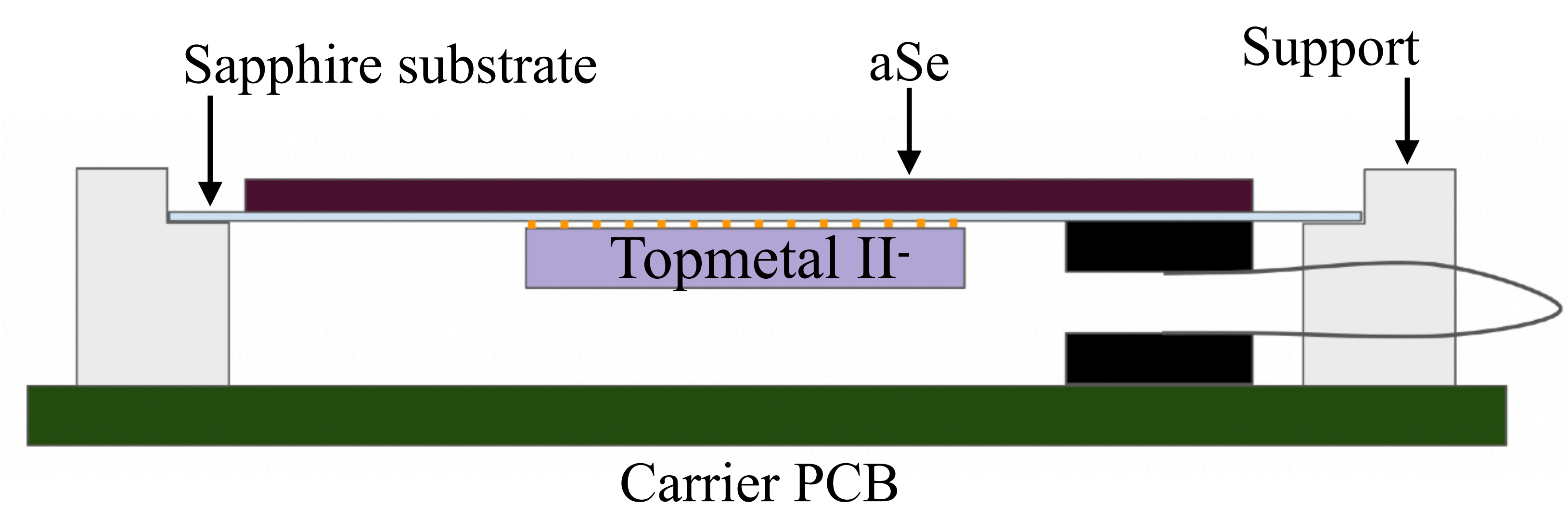
Technological breakthrough!

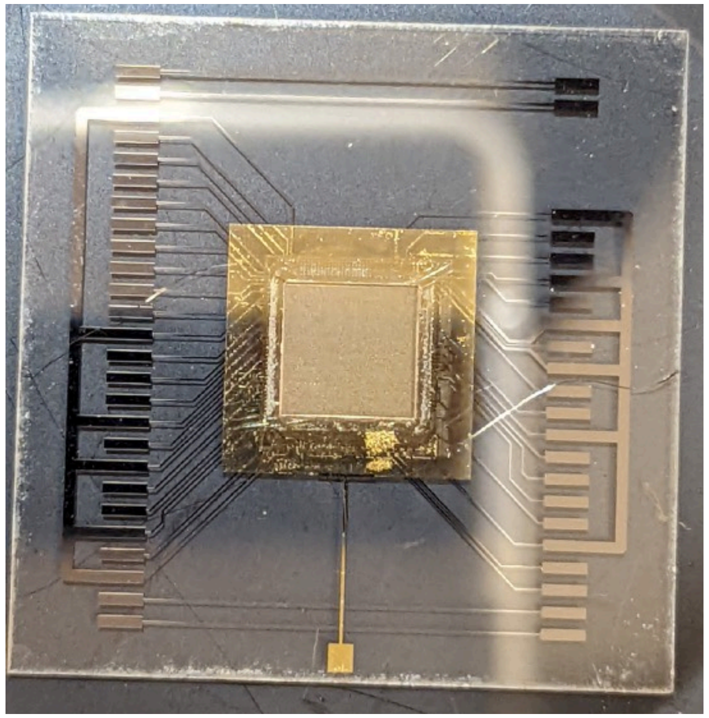
^{90}Sr-Y source:



R&D: Package

- Current aSe/CMOS device tested was an already-packaged *Topmetal-II⁻* with aSe deposited on top.
- HV electrode is smaller than pixel array and aSe tapers off within the pixel array.
- We are developing new package so that device is the same size as standard test devices at Hologic (4x4 cm^2).
- Expect much more uniform electric field within pixel array and higher HV can be applied.

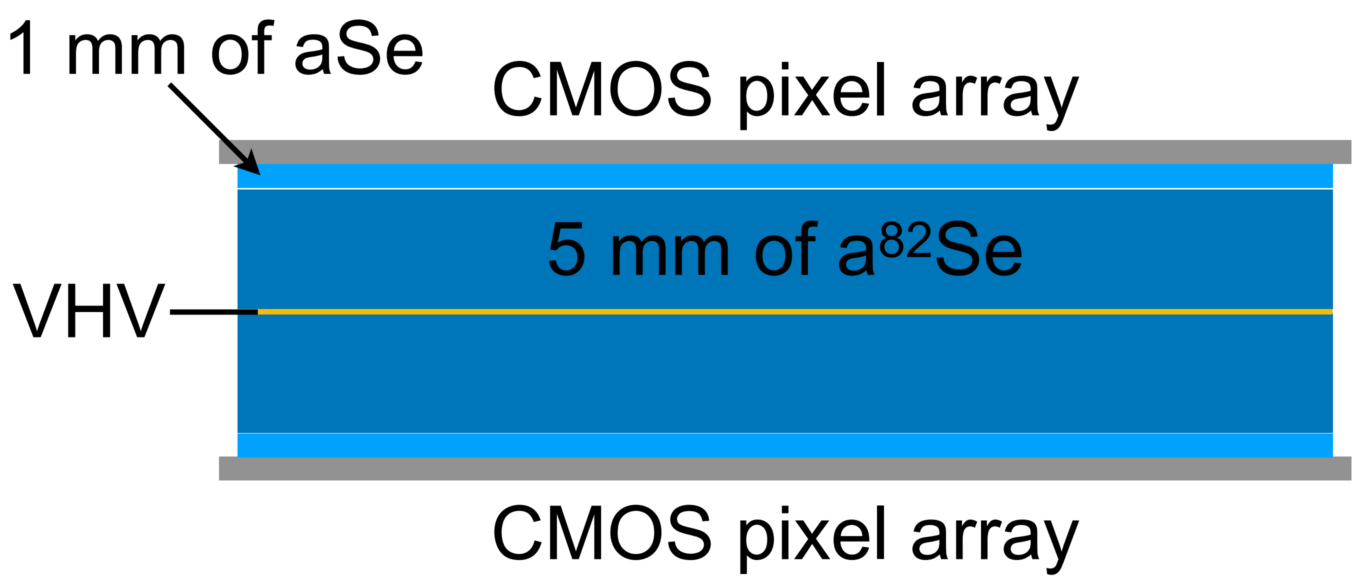




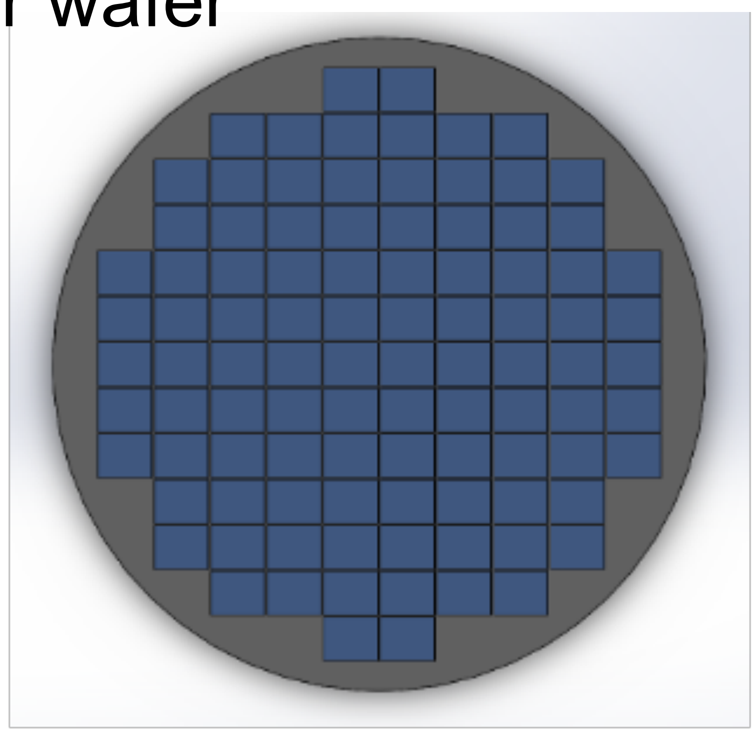
Toward a large detector

Selena module

- Module design has evolved beyond original proposal.
- Now we plan for thick aSe to fully contain electron tracks.
- Back-to-back imagers with ~2 kg of active ^{82}Se per module.
- More functionality on CMOS pixel array: time-of-arrival (TOA) of charge for 3D reconstruction, signal processing.

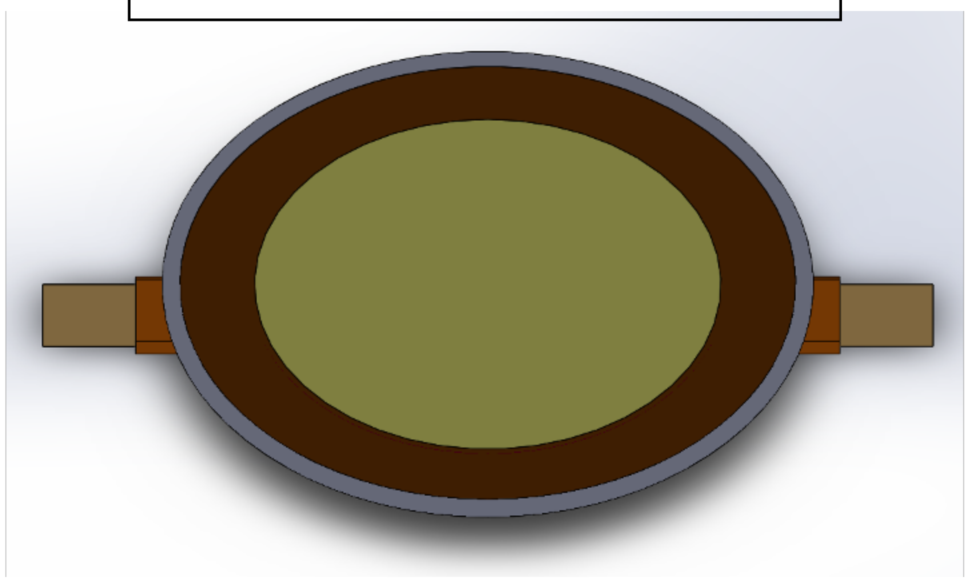


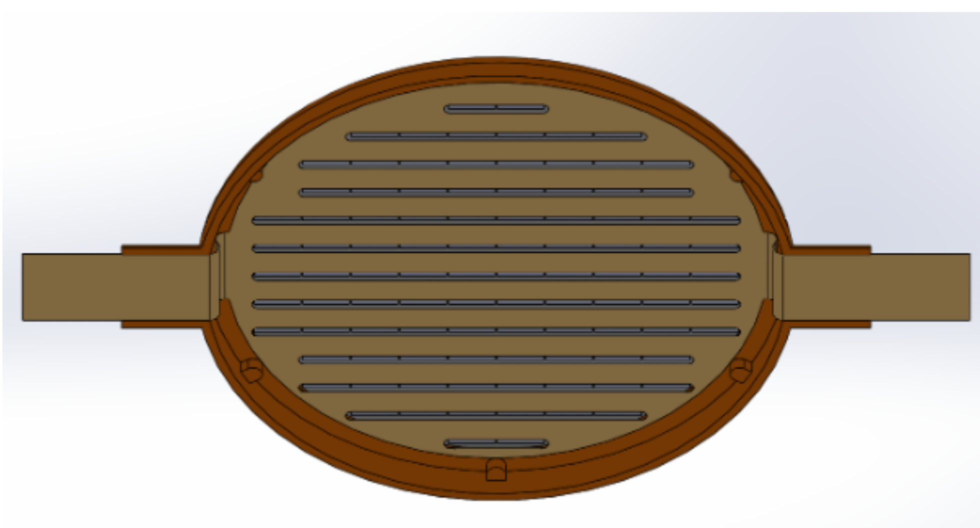
300-mm diameter wafer



Selena module

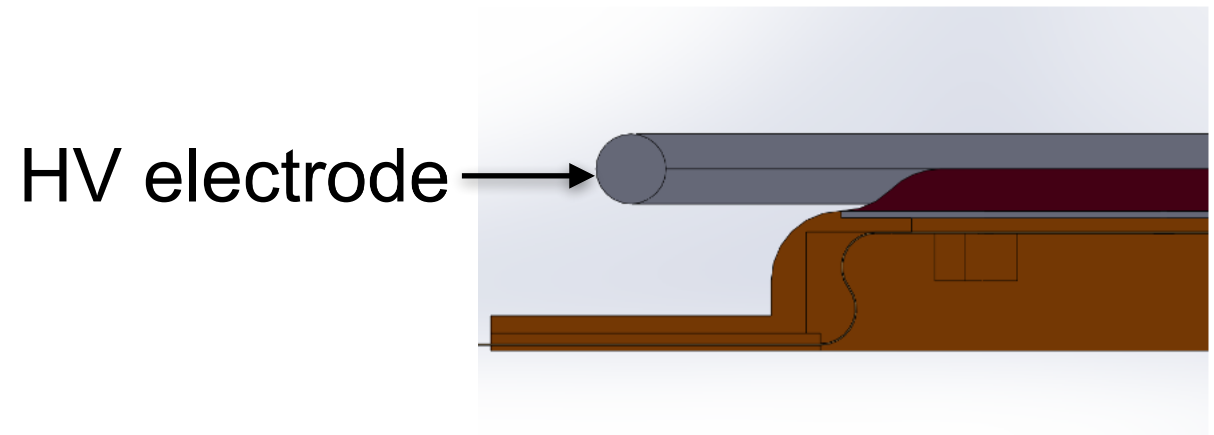
Front wafer with aSe





Back wafer with vias

Cross section of edge

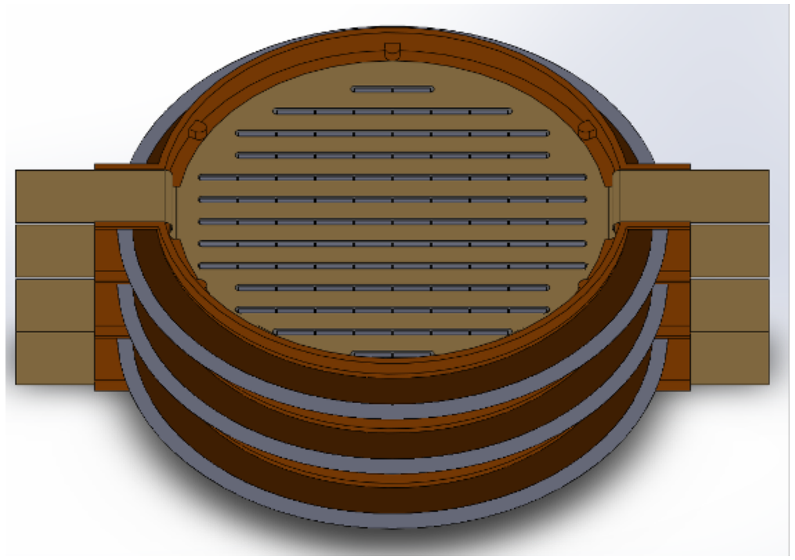


Pixel array specs:

- 15 μm pixel pitch.
- 15 e^- pixel noise.
- Pixel charge measurement accurate to ~10 e^-.
- 5 ns TOA resolution.
- 50 mW/cm^2.

100 kg Demonstrator

- 50 modules for 100 kg of a^{82}Se.
- ^{82}Se from cryogenic distillation of H_2Se?
- Dedicated aSe deposition chamber with recovery.
- Our partners at Hologic deposit 1 ton of aSe per year.



The demonstrator would detect 5 *pp* neutrinos and 15,000 $\beta\beta$ decay events > 2 MeV with zero background after one year of operation

- Demonstrate detector response (esp. energy resolution) to events with energies up to $Q_{\beta\beta}$.
- Demonstrate background suppression capabilities.

Conclusion

- Selena is a proposed neutrino experiment to perform zero-background spectroscopy of $\beta\beta$ decay and low-energy neutrinos.
- High resolution imagers with a target layer of a^{82}Se.
- Technology development stage.
- Early R&D milestones: *i)* measurement of energy response, *ii)* first electron tracks in a CMOS/aSe device.
- Next steps: finalize R&D to develop a large-area module.
- Building block for a 100 kg demonstrator and beyond!

Thank you!

White paper authors and collaborators:

- University of **Washington**: Alvaro E. Chavarria, Alex Piers, Harry Ni.
- **Berkeley** Lab: Yuan Mei, Xinran Li.
- Cristiano Galbiati (**Princeton** U.) and Hanguo Wang (**UCLA**).
- Carlos Peña Garay (**LSC**) and Aldo Ianni (**LNGS**).
- **Hologic** Coporation: Brad Polischuk, Snezana Bogdanovich.

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