R&D Status of Selena

The Selena Neutrino Experiment

A.E. Chavarria,[1] C. Galbiati,[2,3,4] B. Hernandez-Molinero,[5] Al. Ianni,[3] X. Li,[6] Y. Mei,[7] D. Montanino,[8,9] X. Ni,[1] C. Peña Garay,[5,10] A. Piers,[1] and H. Wang[11]

White paper: arXiv:2203.08779
Backgrounds in imaging detectors: arXiv:2212.05012
Original paper: arXiv:1609.03887

CENPA
Center for Experimental Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON
BERKELEY LAB
HOLOGIC
LSC
Laboratorio Subterráneo Canfranc
INFN

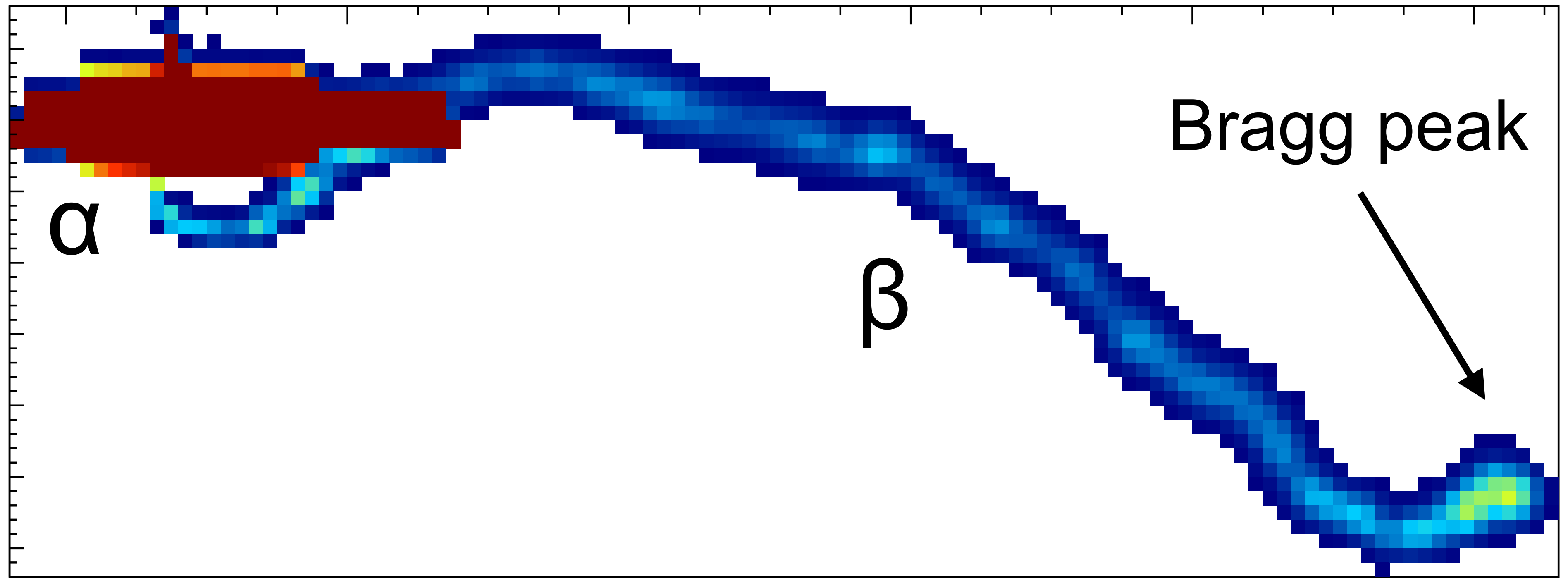
Outline

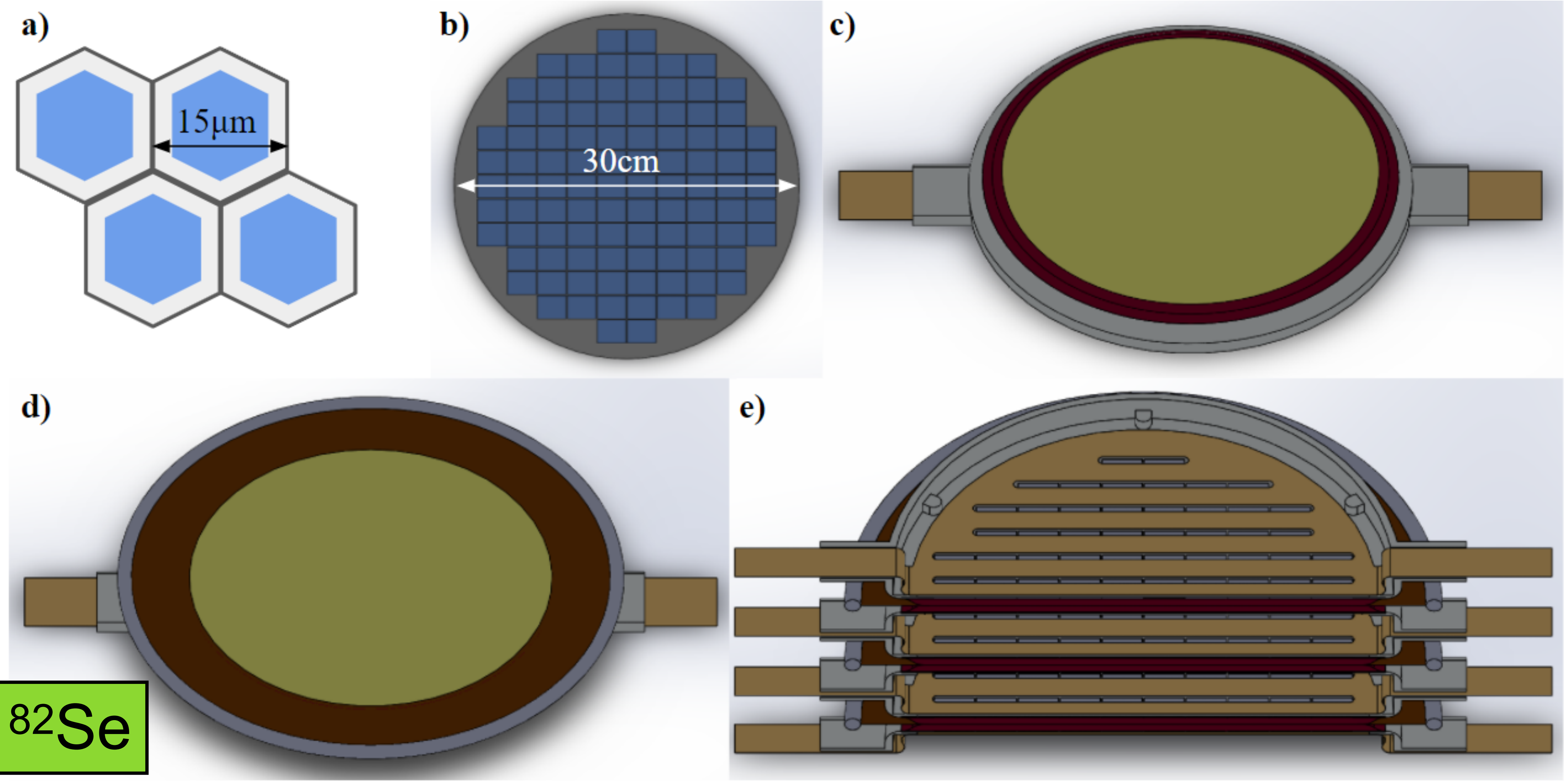
- Selena concept.
- Neutrinoless $\beta\beta$ decay.
- R&D goals.
- Past R&D results.
- Upcoming developments.

Selena

- 10-ton enriched ^{82}Se active target with exquisite spatial resolution for signal identification.
- Large-area hybrid CMOS imagers with ~5-mm thick layers of amorphous ^{82}Se (a^{82}Se).
- Leverages the existing industrial capabilities on CMOS fabrication and aSe deposition for scalability.
- Zero-background $\beta\beta$ decay and solar neutrino spectroscopy in 100-ton year exposure.

α-β sequence in DAMIC (silicon CCD) data





Each module: 3 kg of ^{82}Se

Selena $\beta\beta$

JINST12 (2017) P03022

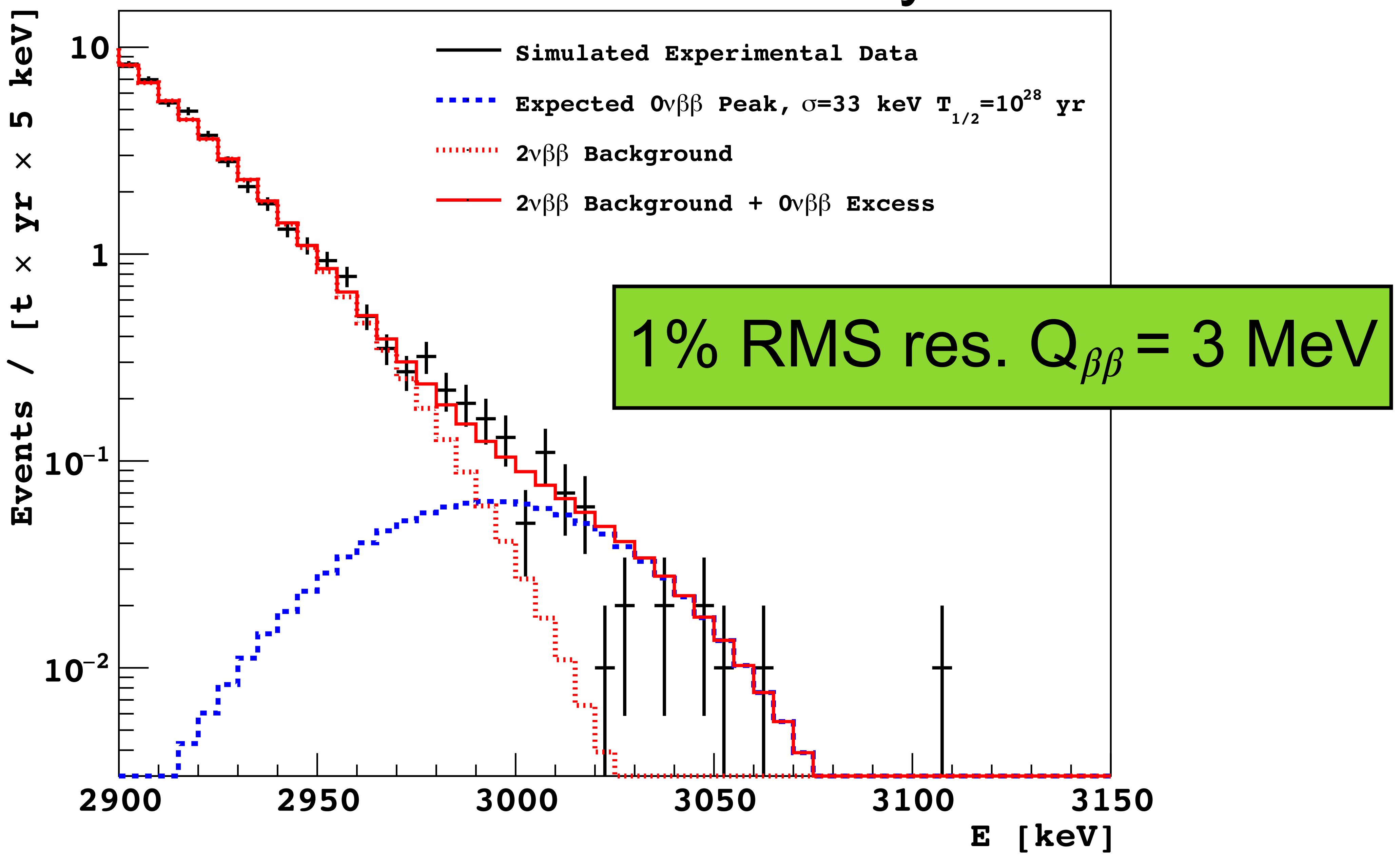
- By identification of Bragg peaks, can achieve 10^{-3} suppression of single electron background, with 50% signal acceptance.
- Bulk backgrounds suppressed by α/β particle ID, spatial correlations.

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

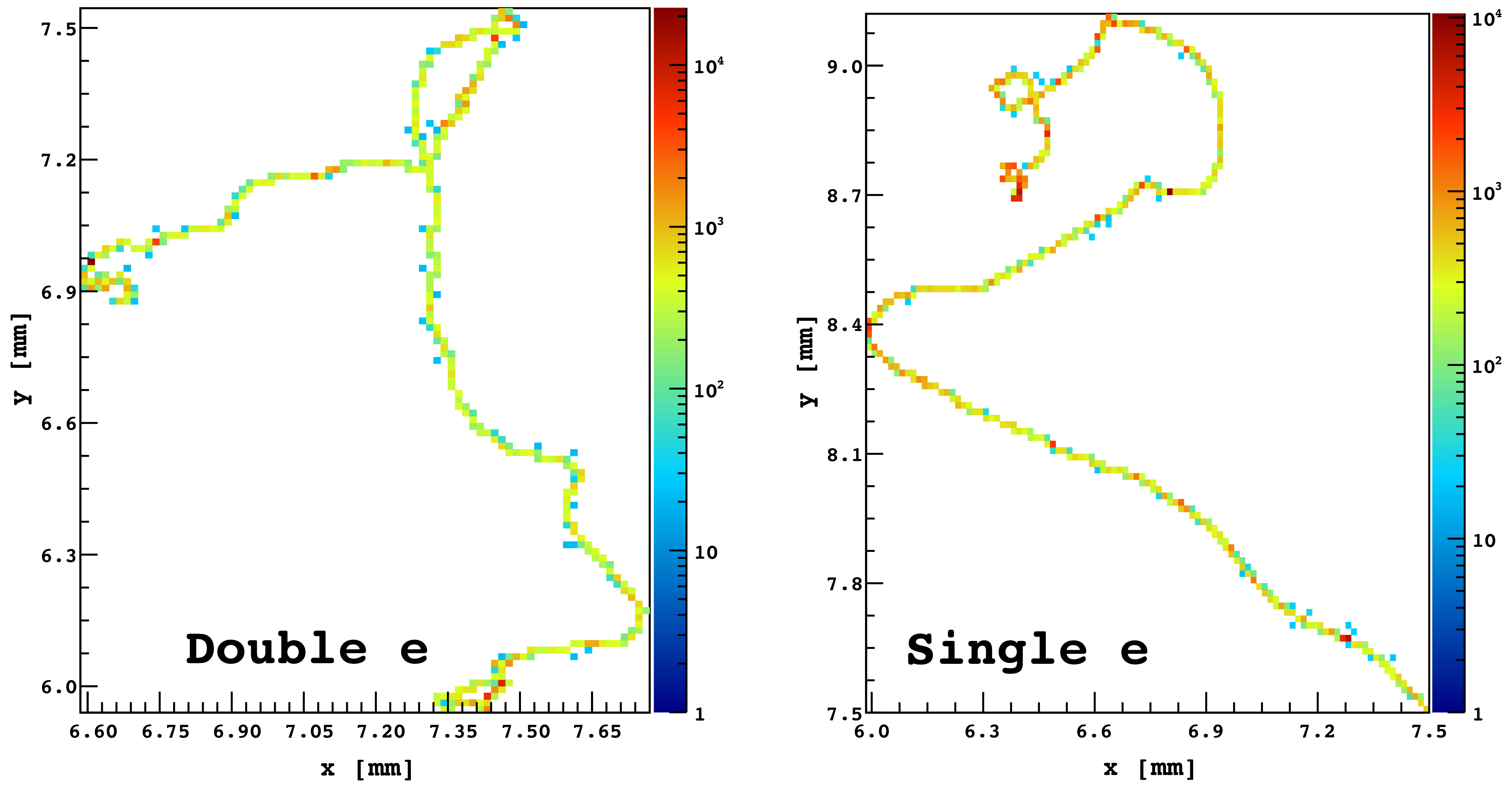
3σ discovery for $T_{1/2}$ = **2 x 10^{28} y** in ^{82}Se

Or study $0\nu\beta\beta$ mechanism after ton-scale discovery!

100 ton-year simulation



Simulation:



$\beta\beta$ backgrounds

Background source	Raw rate / (keV ton y)$^{-1}$	After disc.
β-decay (bulk)	5.8	6.4 x 10^{-8}
β-decay (surface)	7.1	2.1 x 10^{-7}
β-decay (cosmogenic)	1.7 x 10^{-3}	2.6 x 10^{-6}
γ-ray (photoelectric)	1.3 x 10^{-2}	1.3 x 10^{-5}
γ-ray (Compton)	2.8 x 10^{-2}	7.1 x 10^{-6}
γ-ray (pair production)	3.3 x 10^{-5}	3.3 x 10^{-6}

JINST12 (2017) P03022

Background challenges very different from other experiments

$Q_{\beta\beta} = 3\,\mathrm{MeV}$

- **Example U+Th γ:**

^{214}Bi

3000.0 *2*	0.0086 % *9*	
3053.9 *2*	0.0209 % *23*	← Photoelectric absorption
3081.79 *25*	0.0059 % *18*	
3094.0 *4*	5.9E-4 % *18*	
3142.6 *4*	0.00123 % *14*	
3149.0 *5*	8.6E-5 % *9*	
3160.7 *6*	5.5E-4 % *14*	
3183.6 *4*	0.00136 % *23*	

^{208}Tl

3475.1	0.0015 % *15*
3708.4	0.0020 % *20*
3960.9	0.0015 % *15*

← Compton scattering

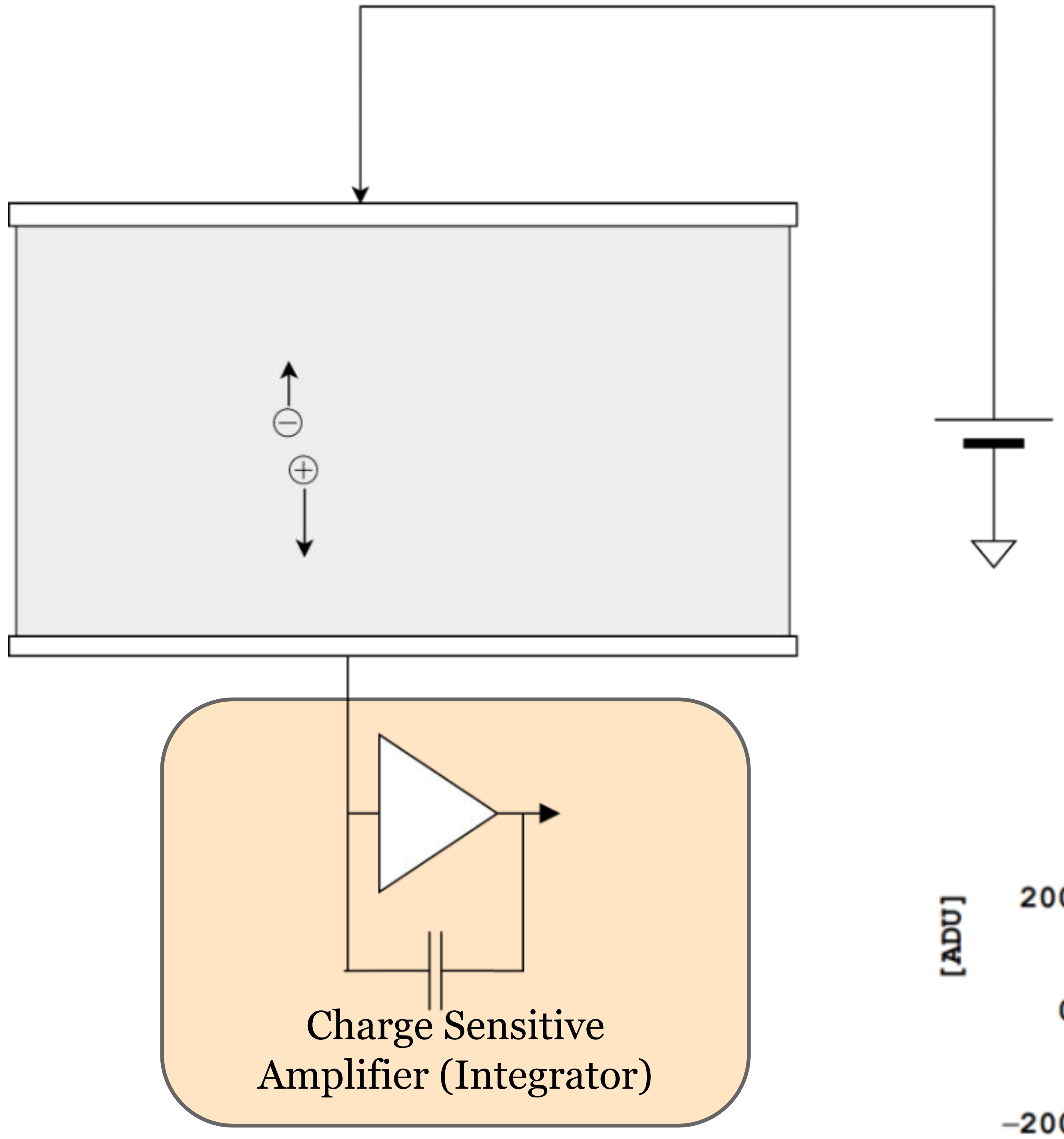
U+Th γ rays contribute <1 background in ROI every 10^9 decays (<1 in 100 ton year at 10 ppt)

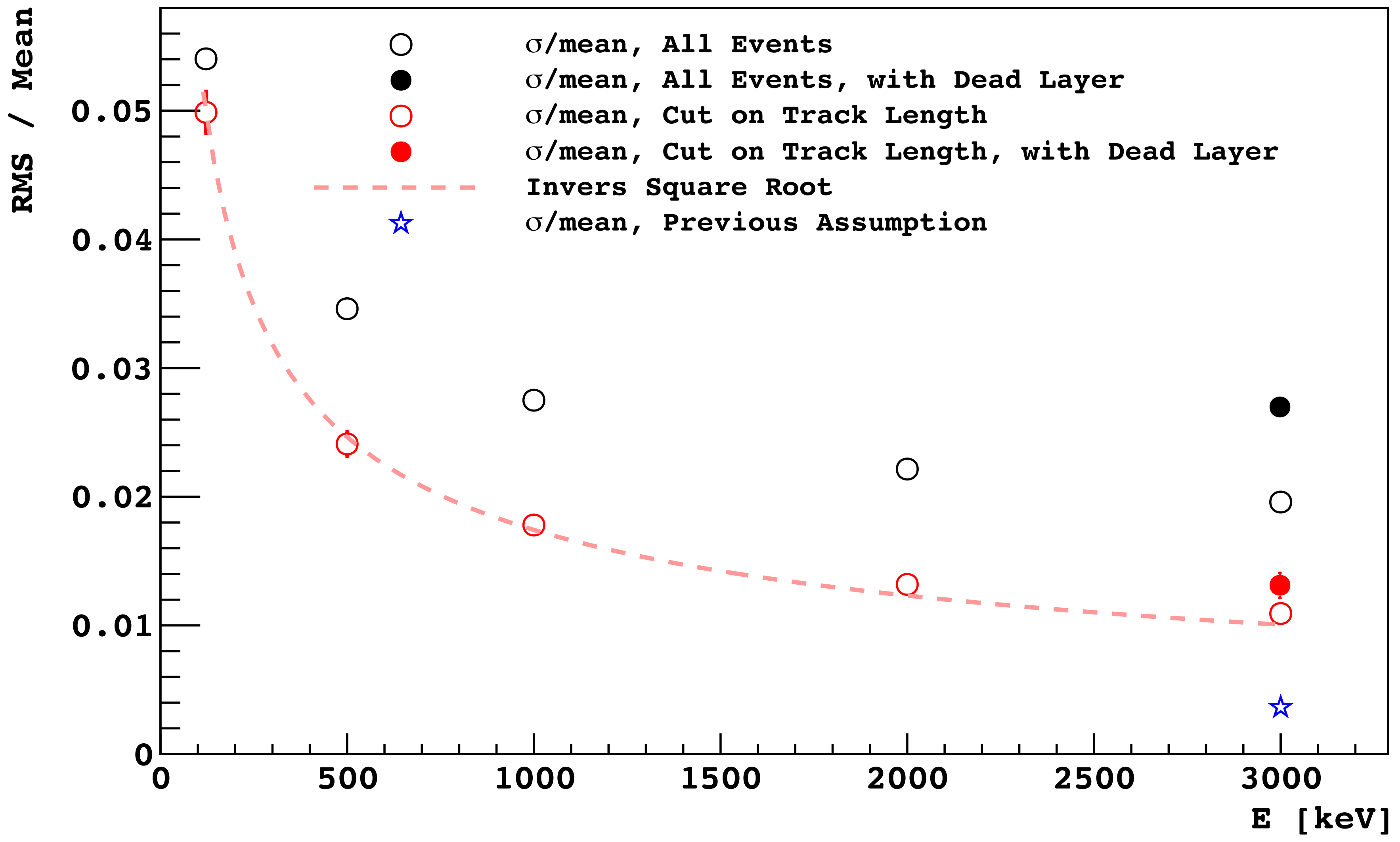
R&D Goals

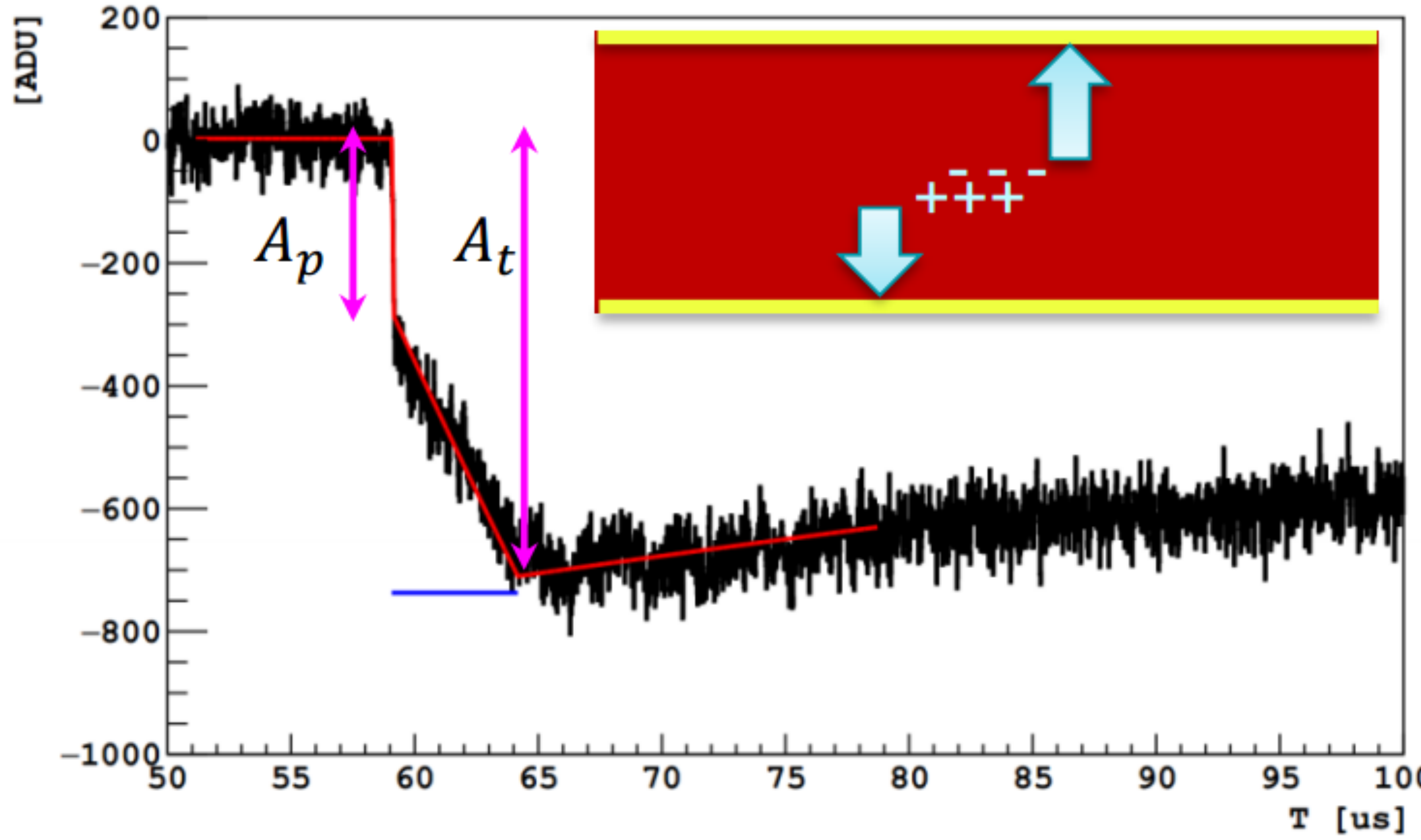
• Measure ionization response of aSe.	Done!
• Demonstrate aSe can be successfully coupled to CMOS pixel array.	Done!
• Optimize CMOS pixel design for Selena: low pixel noise, full charge collection, low power consumption.	In progress
• Optimize CMOS readout for scalability: in-pixel digitization.	In progress
• Possible: measurement of time of arrival (TOA) of charge.	Upcoming
• Demonstrate large area module with performance for Selena.	Upcoming

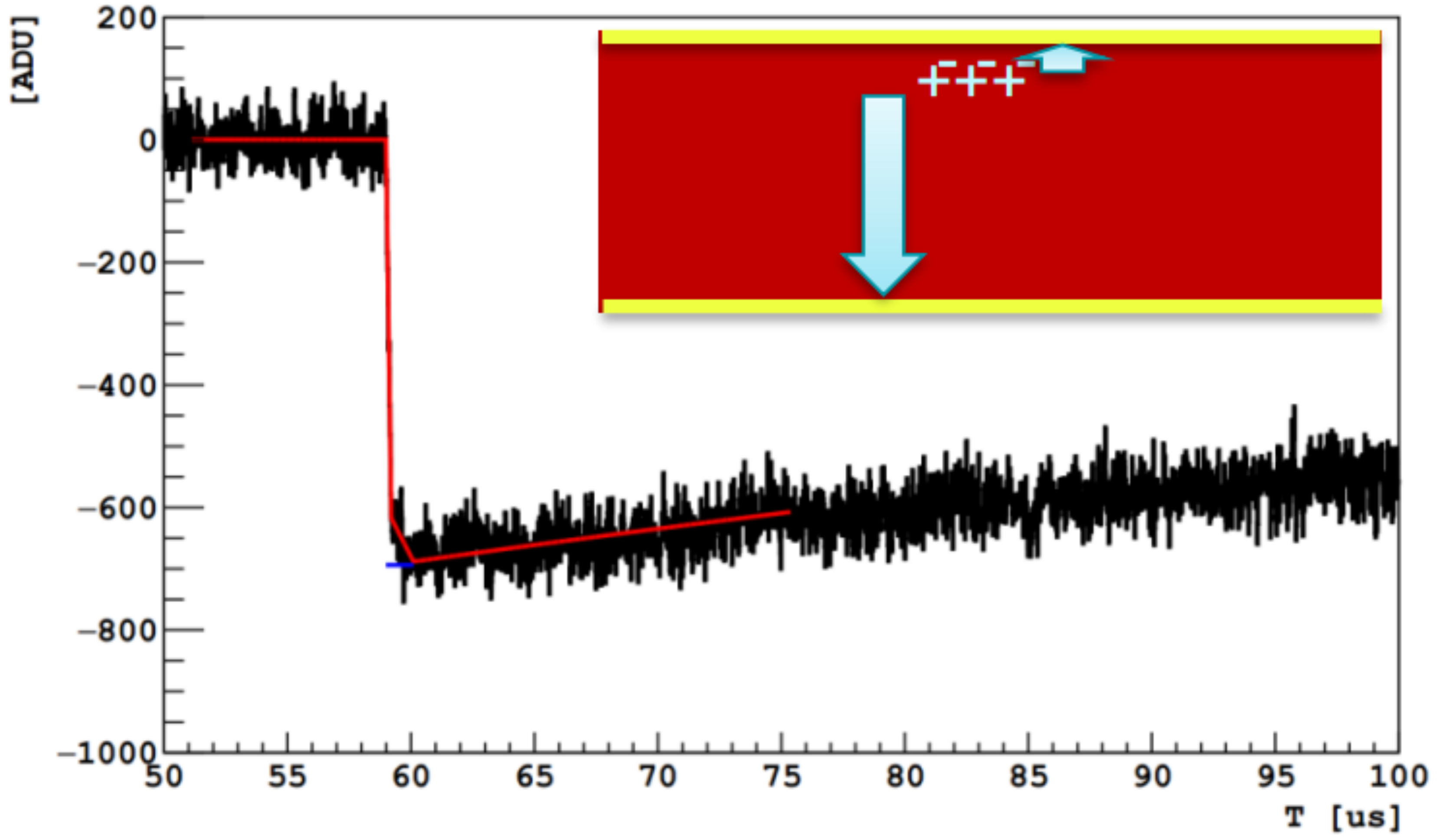
aSe response

JINST16(2021)P06018





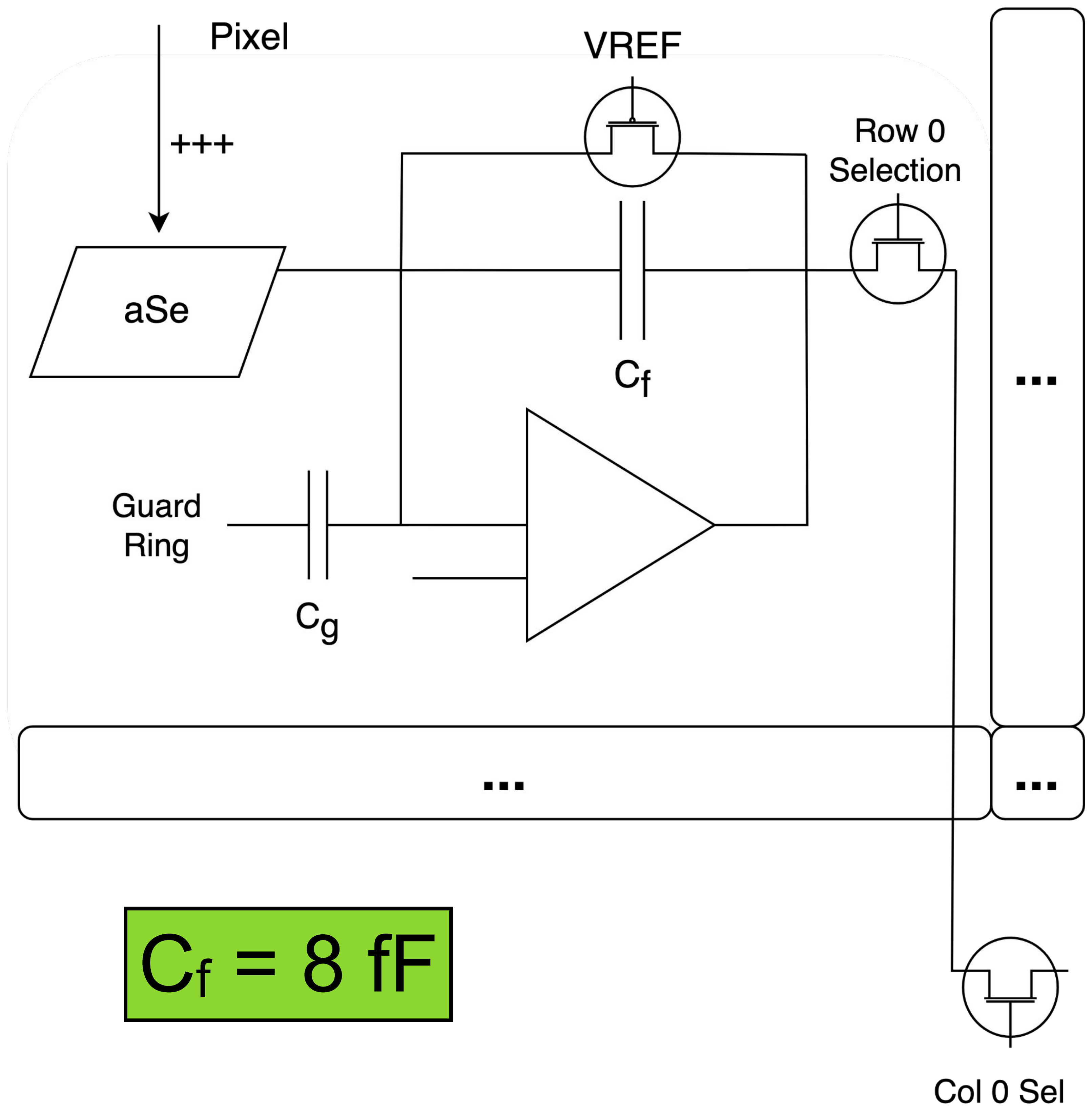




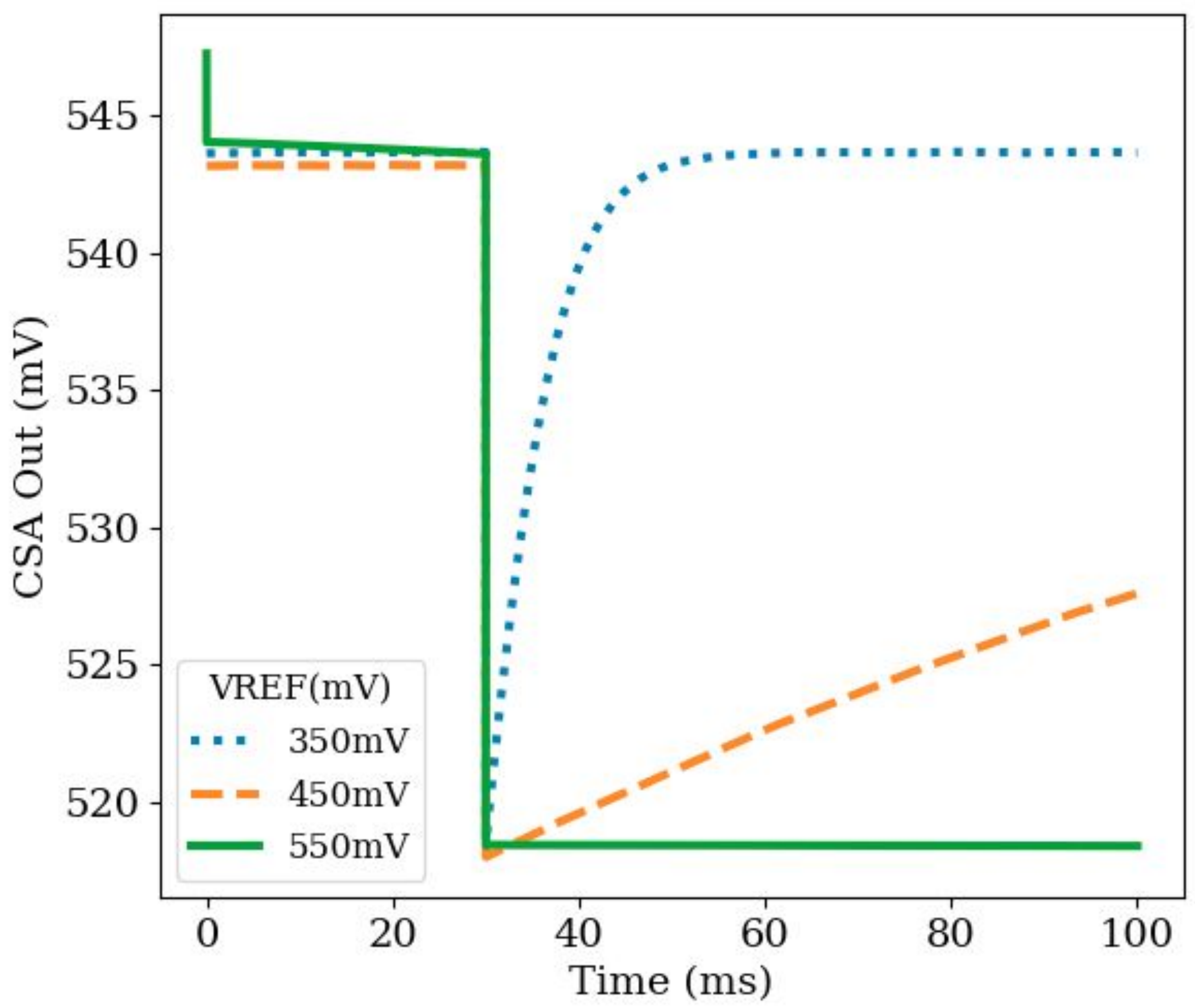
Exposed to ^{57}Co radioactive source

65 e$^-$ per keV at 50 V/μm

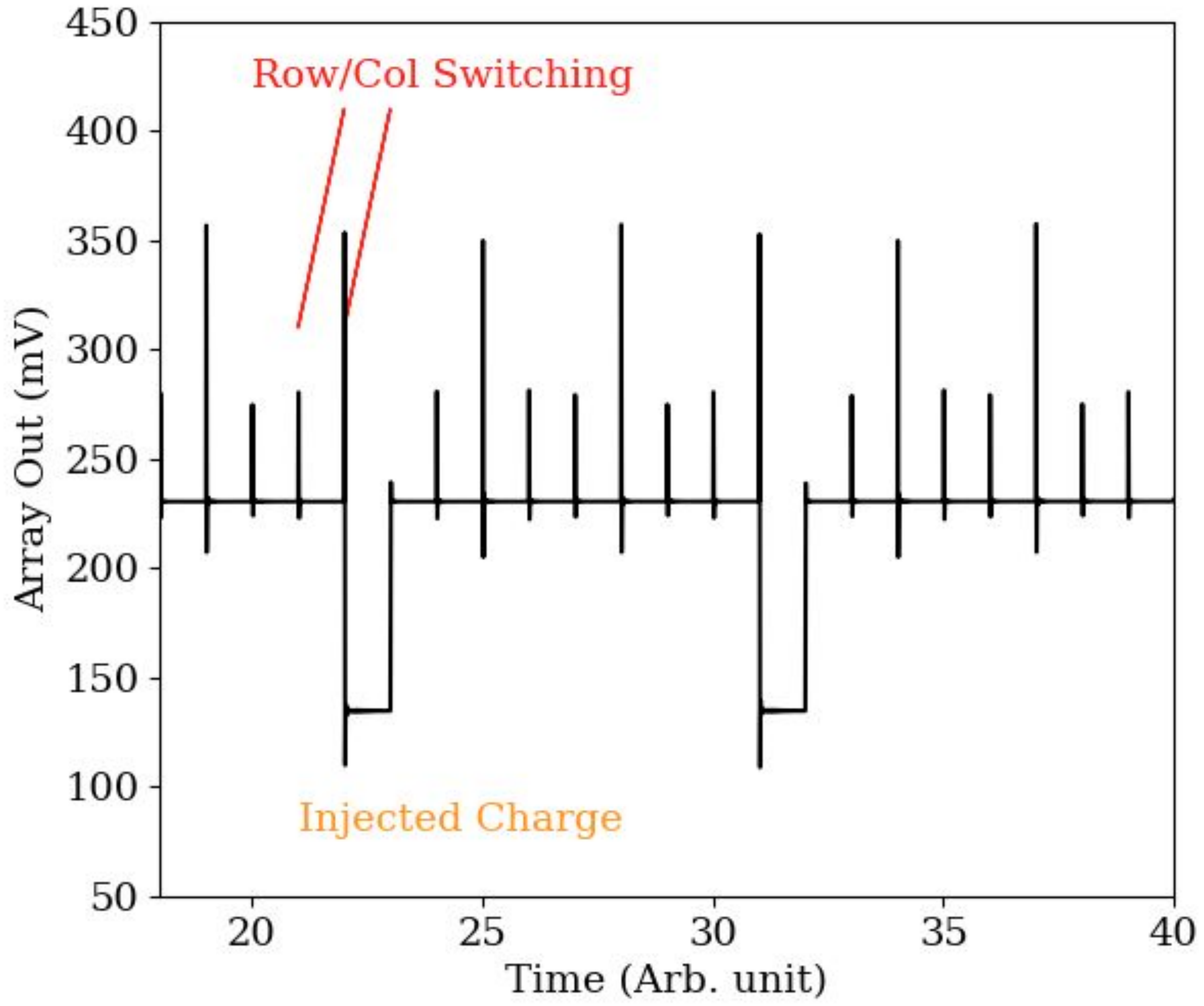
Pixel Array Readout



C_f = 8 fF



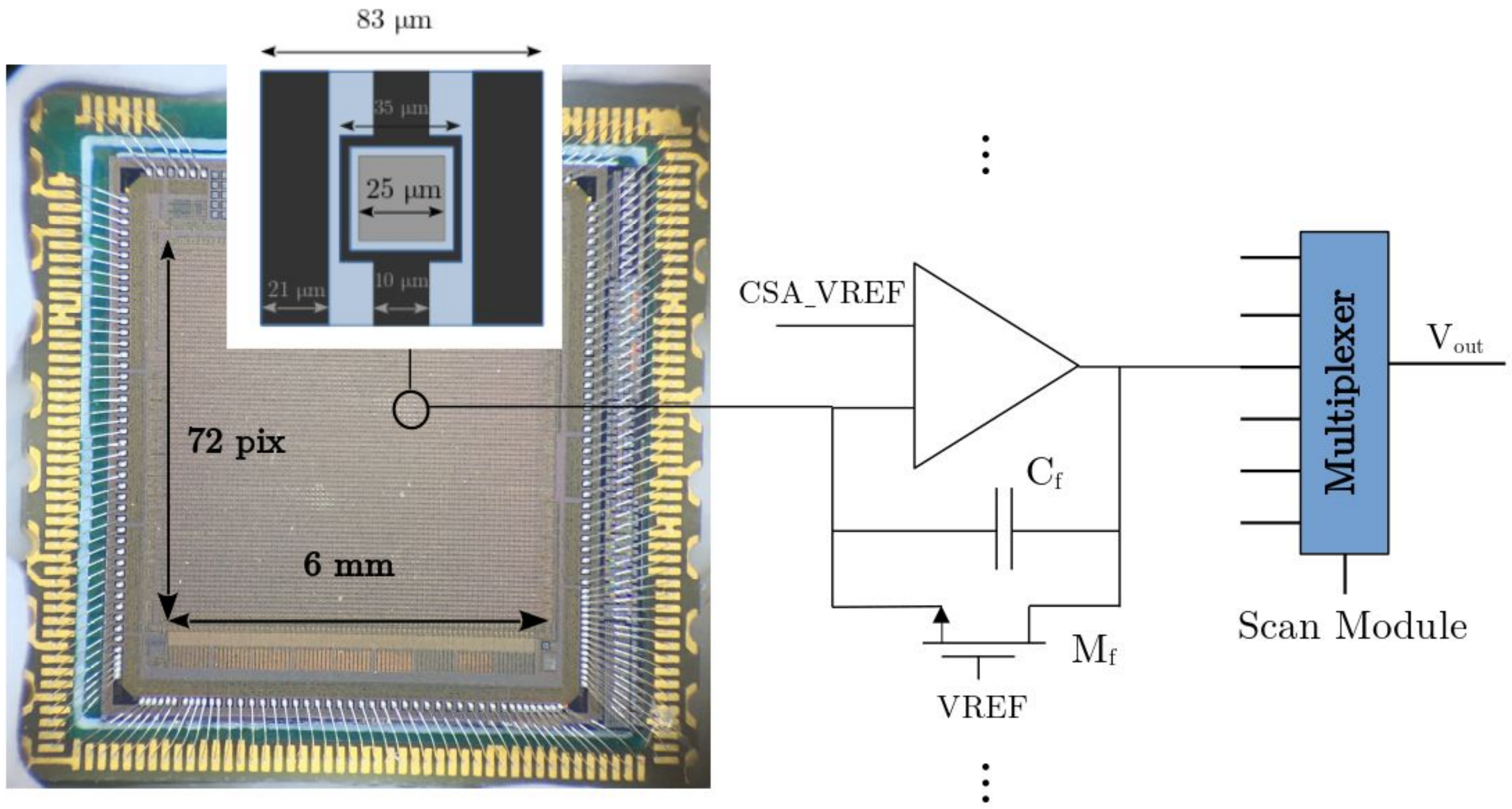
Charge Injection Single Pixel Response

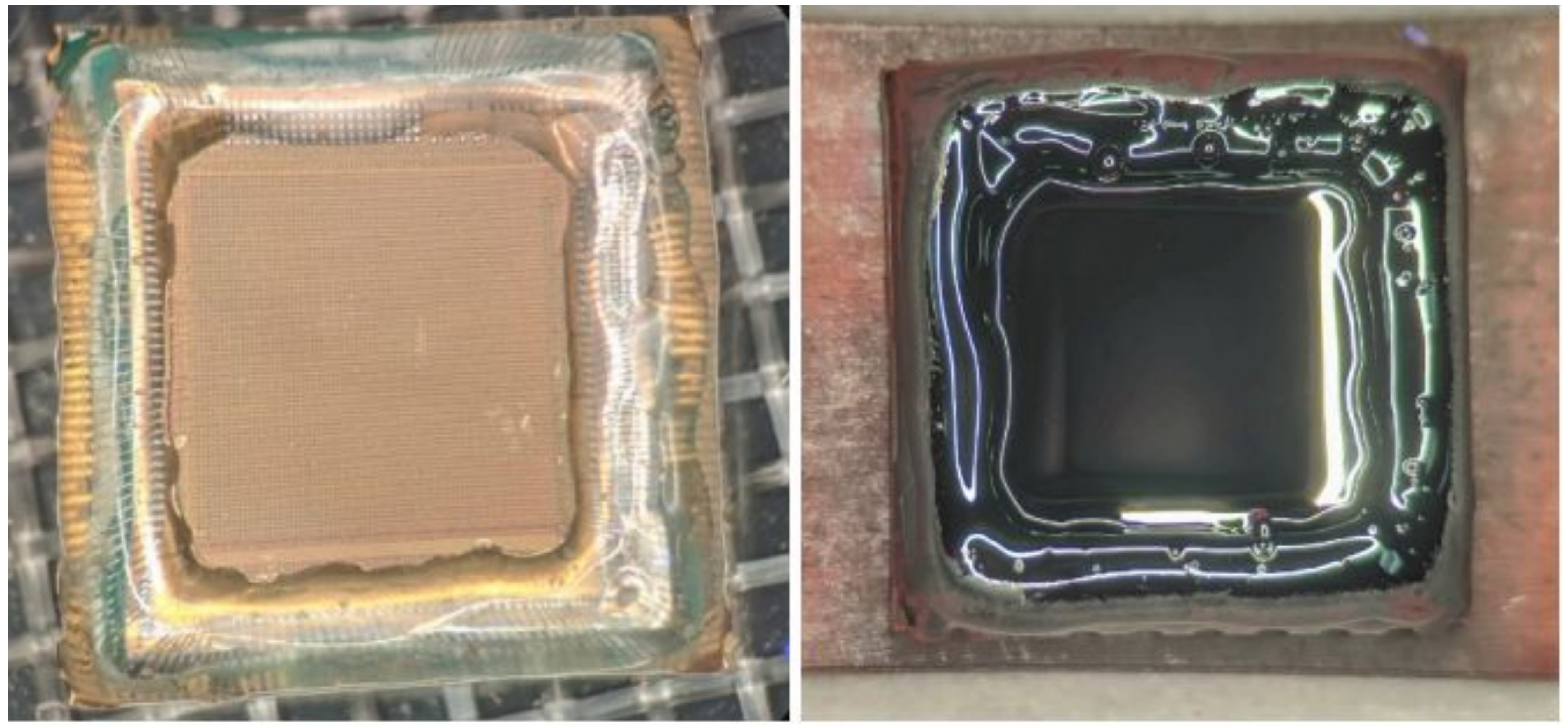


Example of 3x3 Rolling Shutter Array

Each pixel has its own charge-sensitive amp (CSA) that can be selected for readout

Topmetal II^{-}





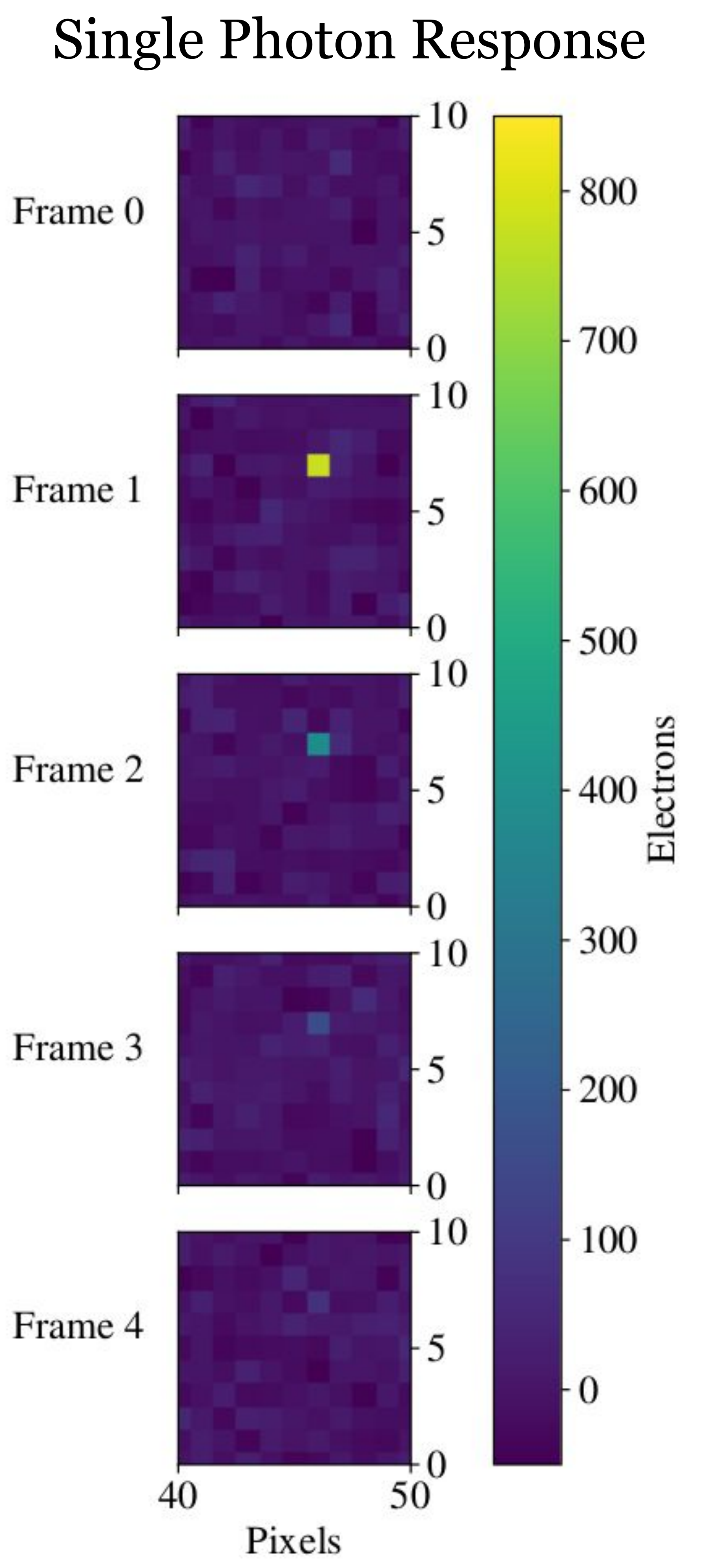
Before/After 500um aSe deposition by Hologic Inc.

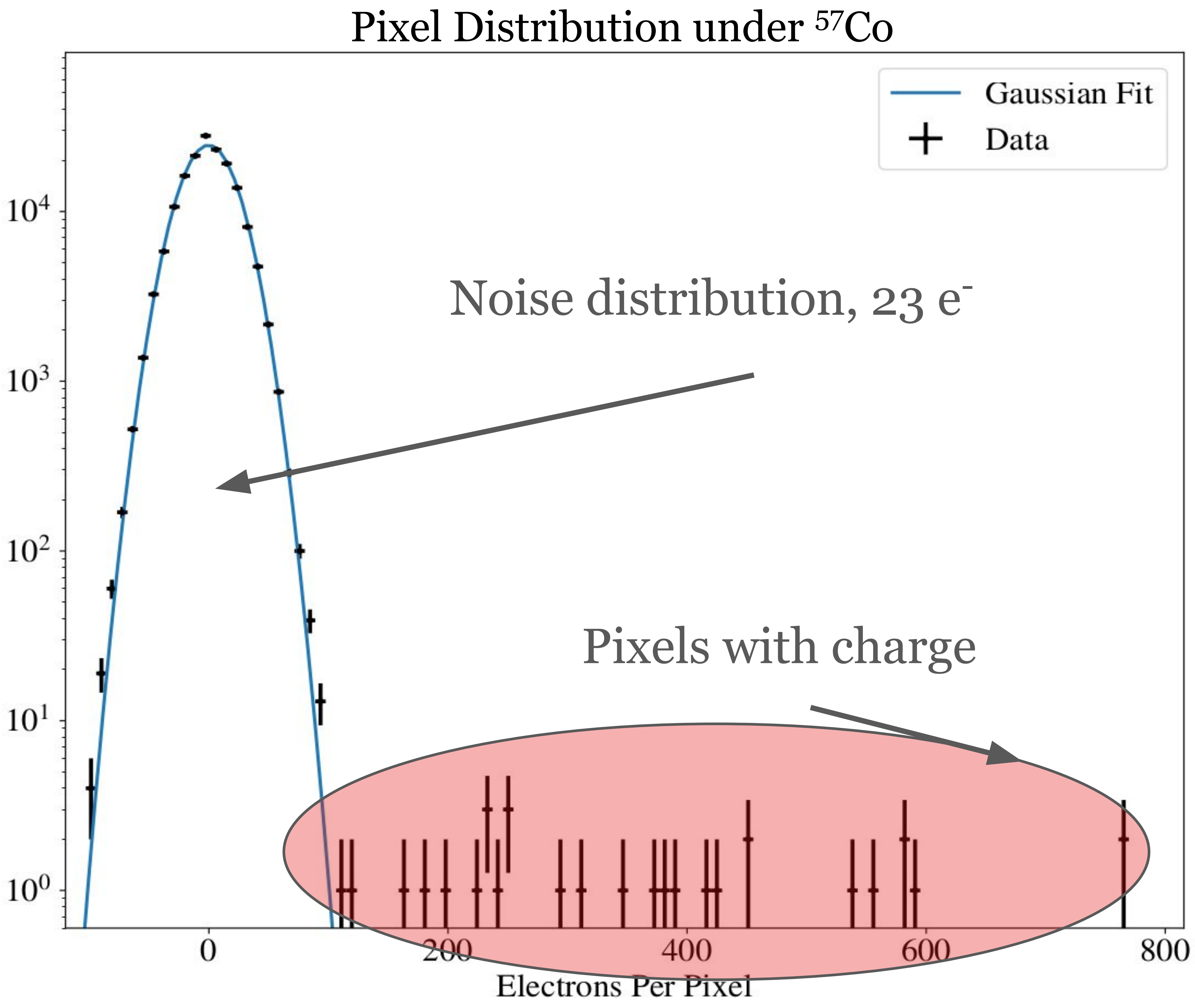
- Start with existing sensor Topmetal II^{-} from LBNL.
- CMOS pixel array with exposed metal electrodes.

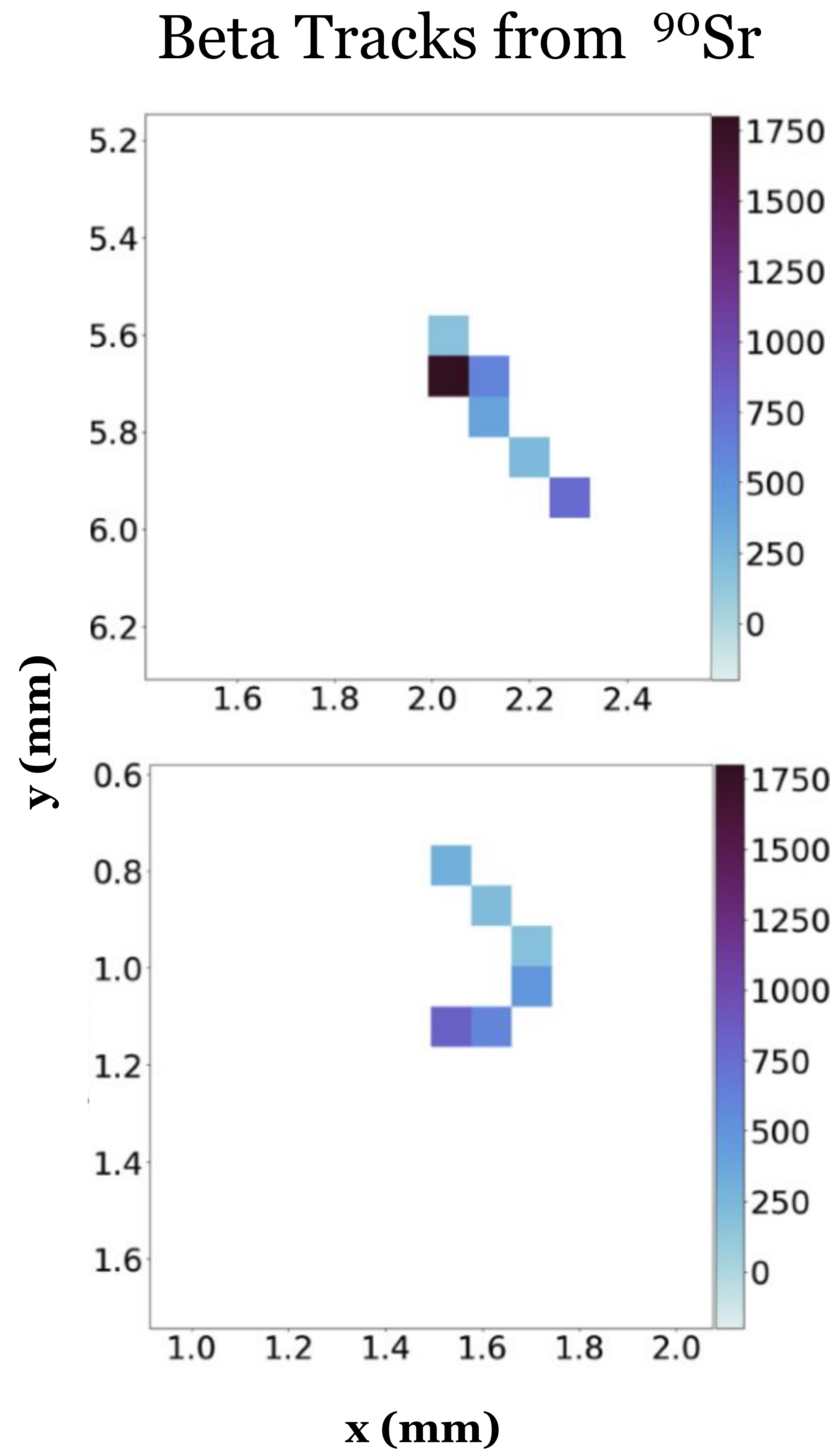
- 83 μm pixel pitch.
- 15 e^{-} pixel noise.

NIMA810(2016)144

Performance

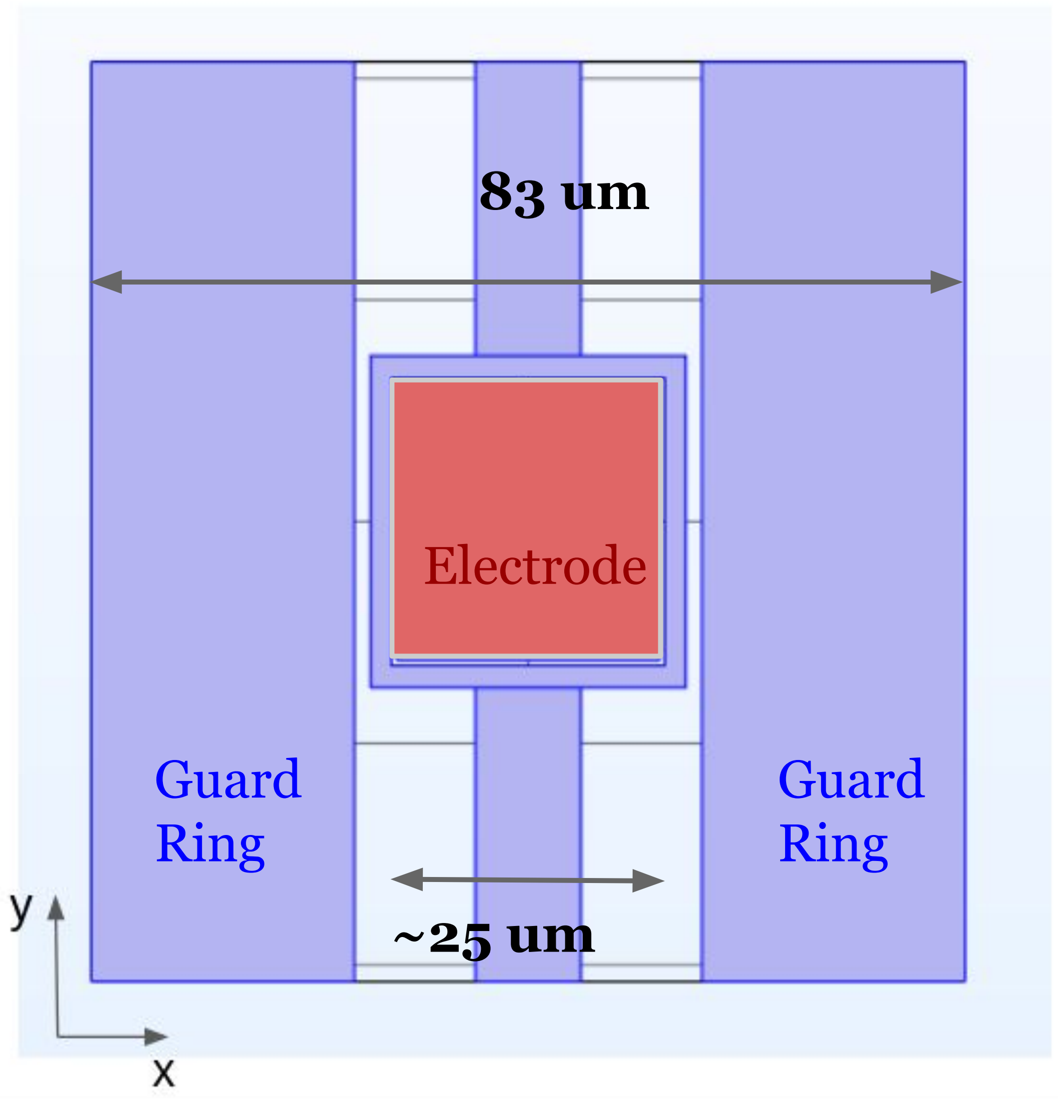


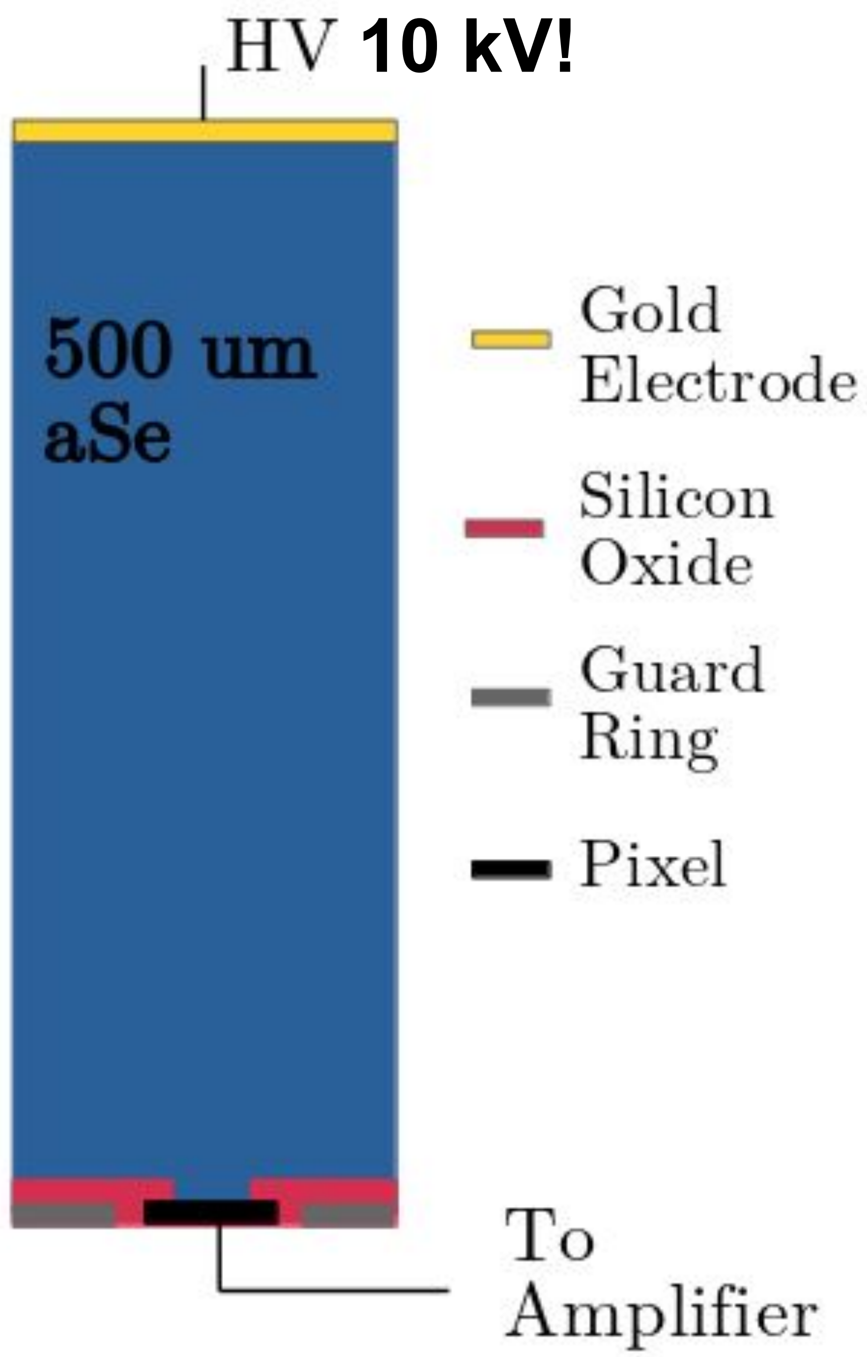


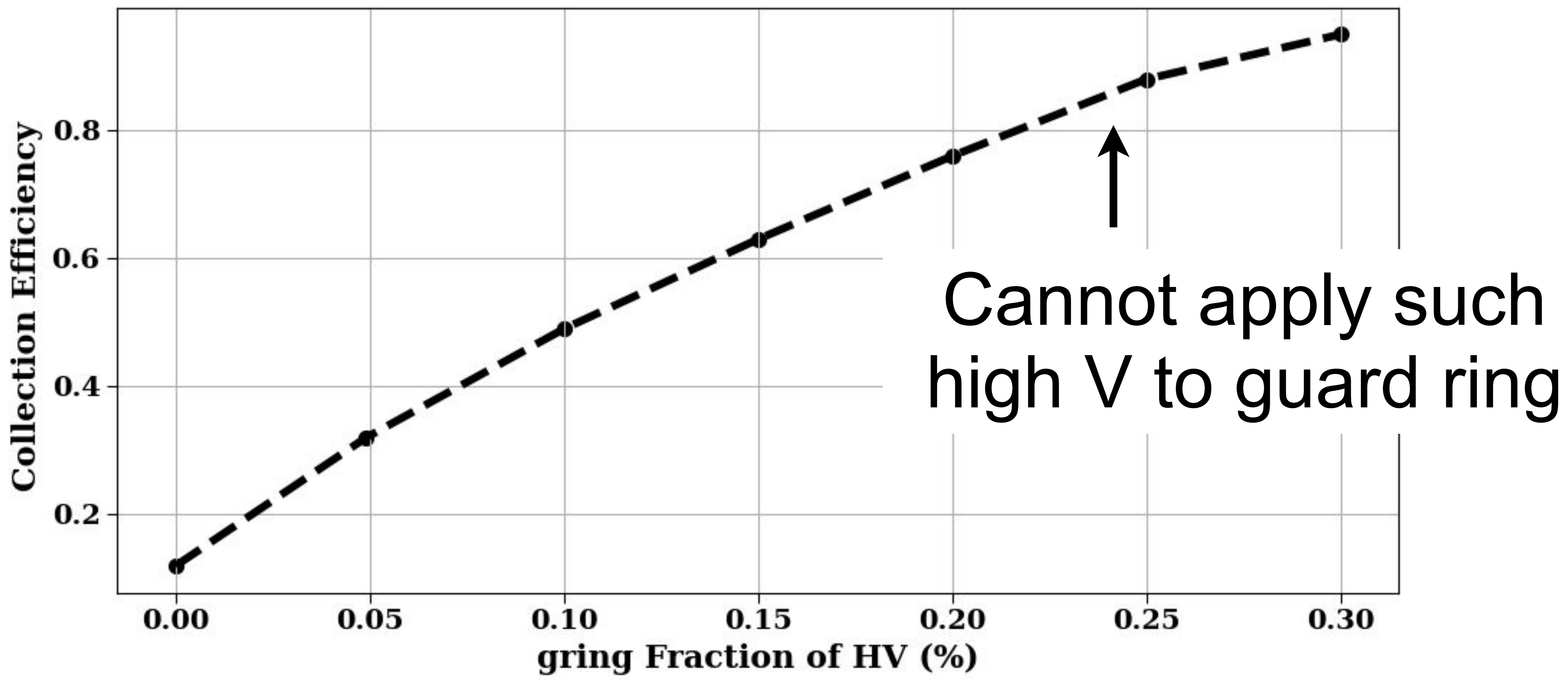


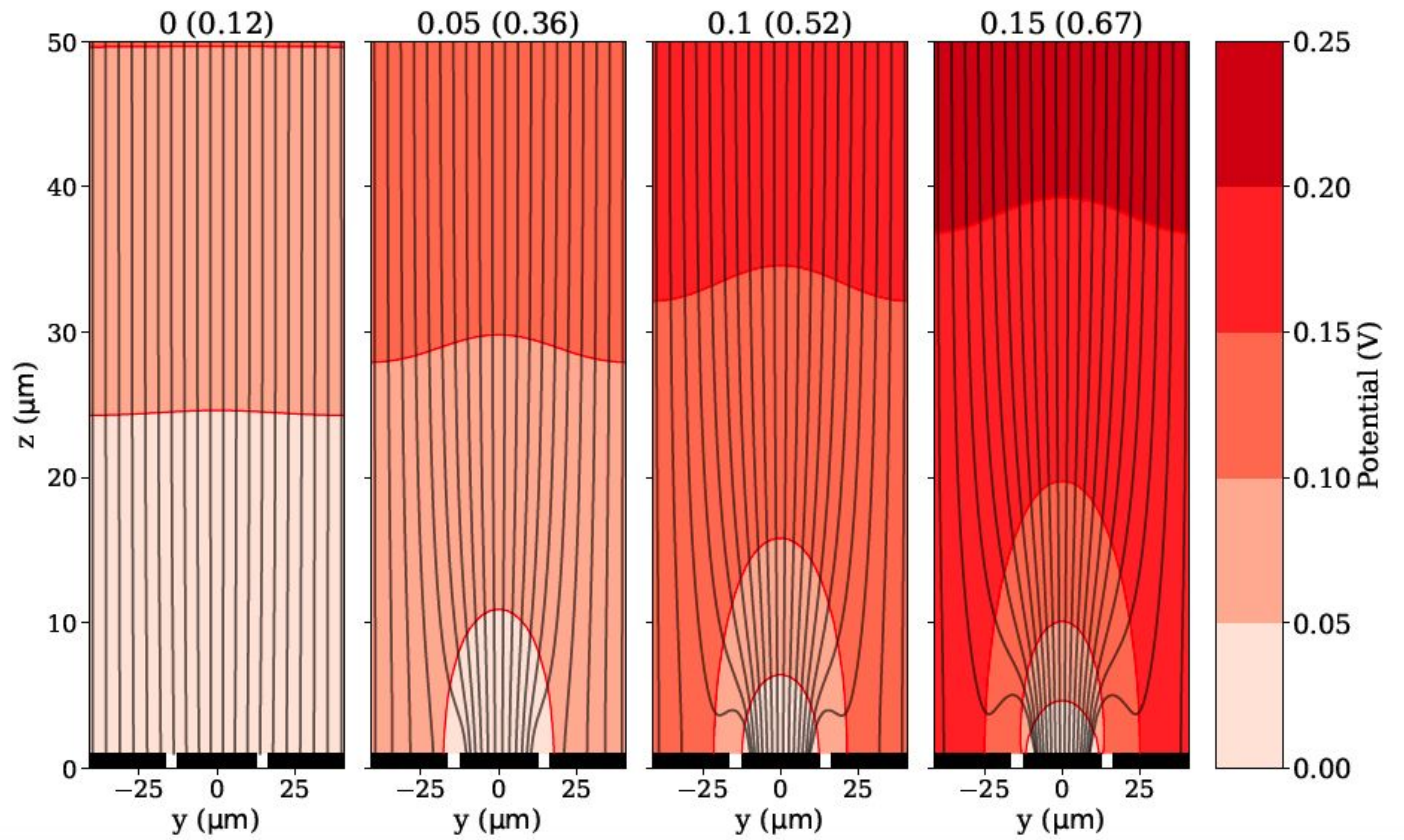
Limitations

Pixel Structure & Collection Efficiency:

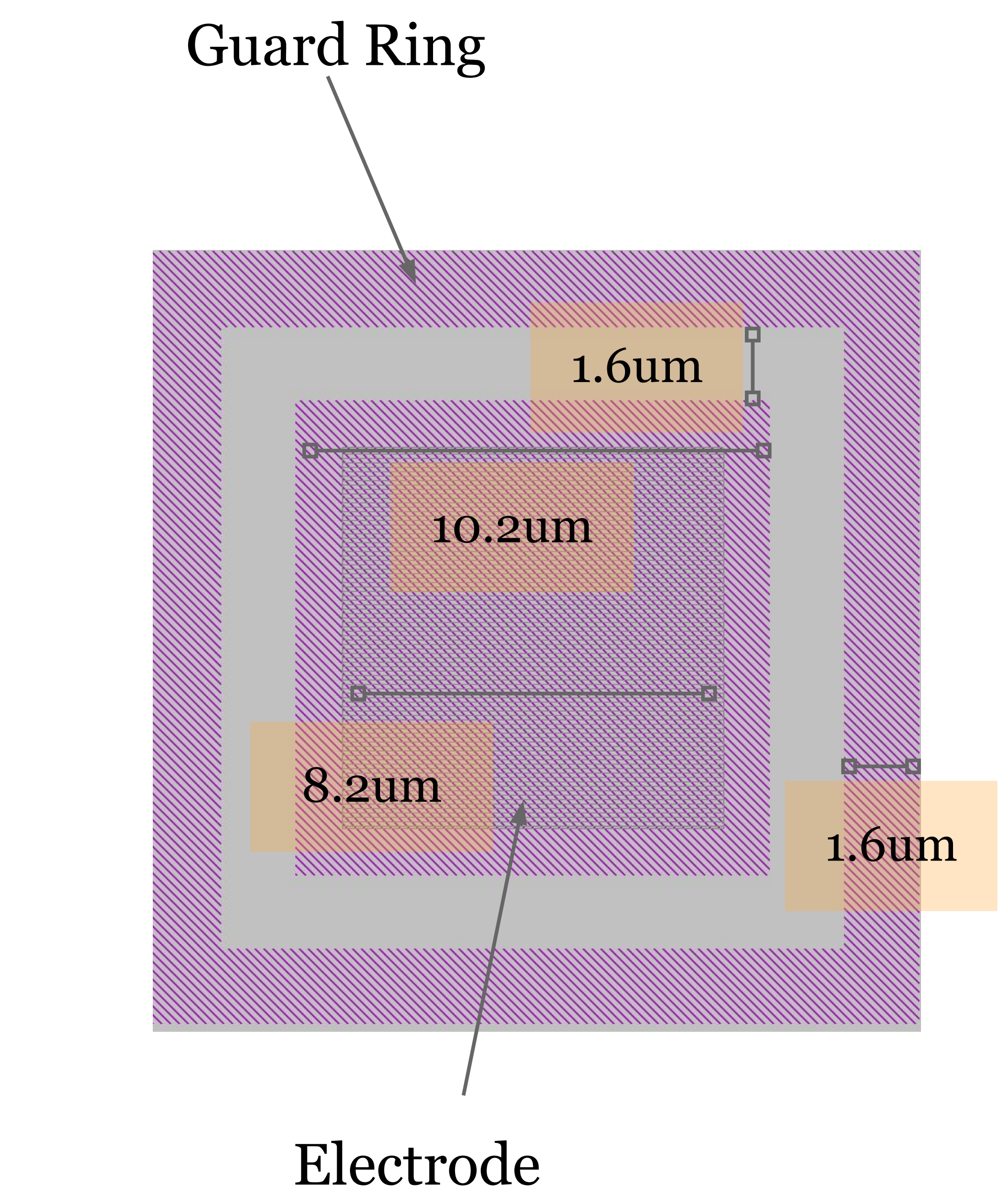








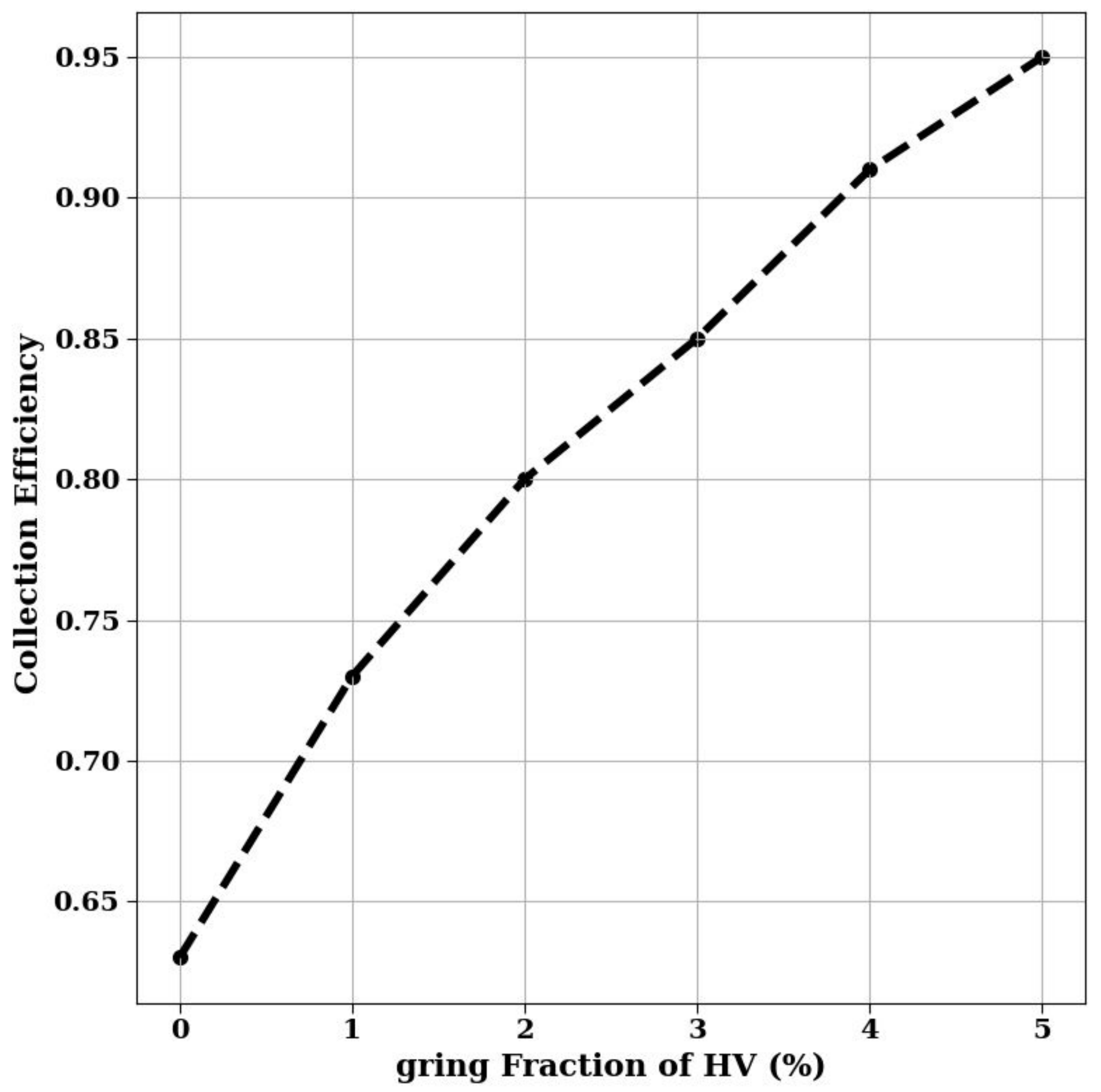
Solution: Build our own CMOS pixel array for aSe!



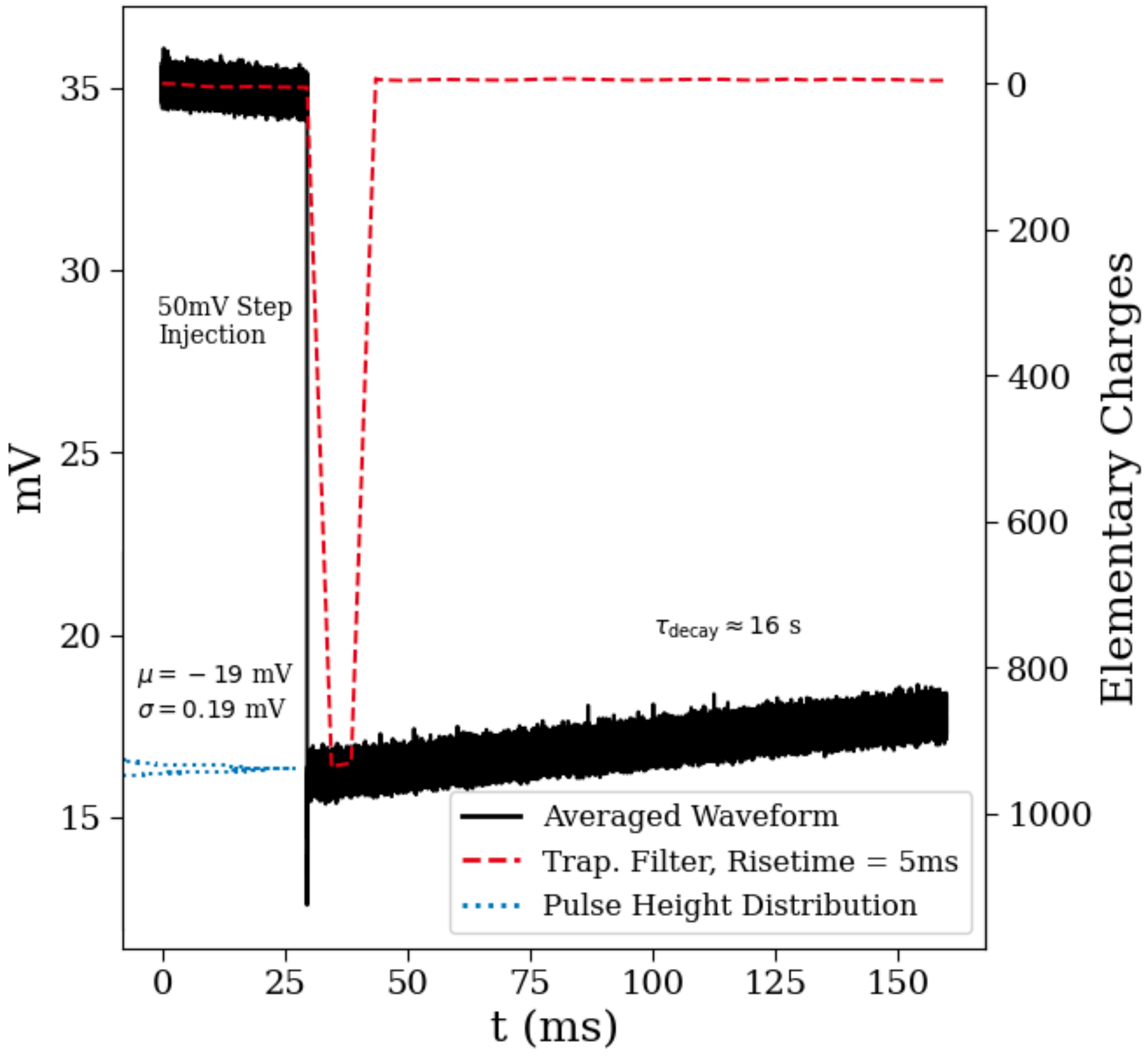
TopmetalSe

First chips arrived this summer!

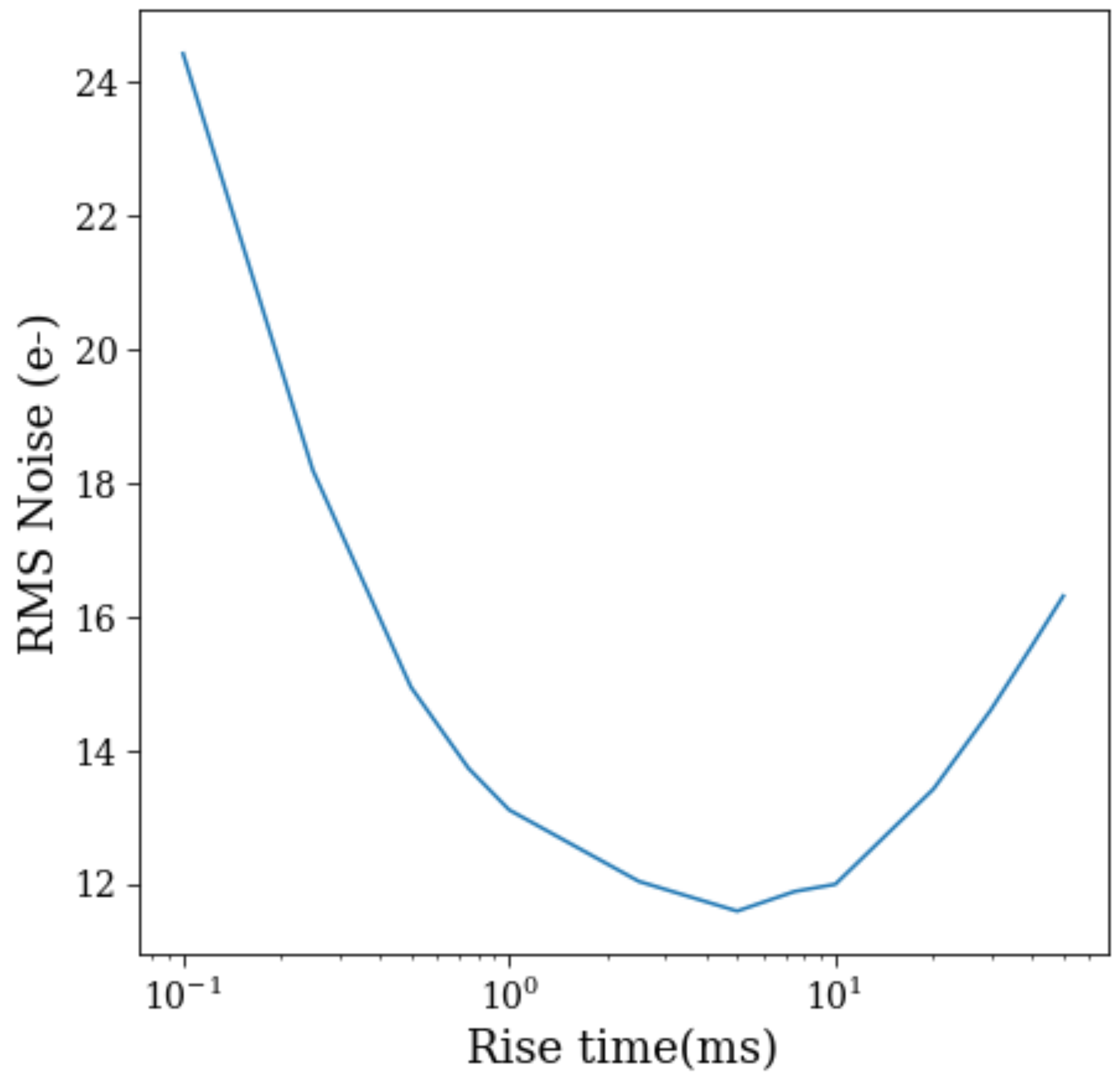
- Open source design by student Harry Ni on Skywater PDK.
- 15 μm pitch, high collection efficiency, low power ($< 1\mu W$), low noise.



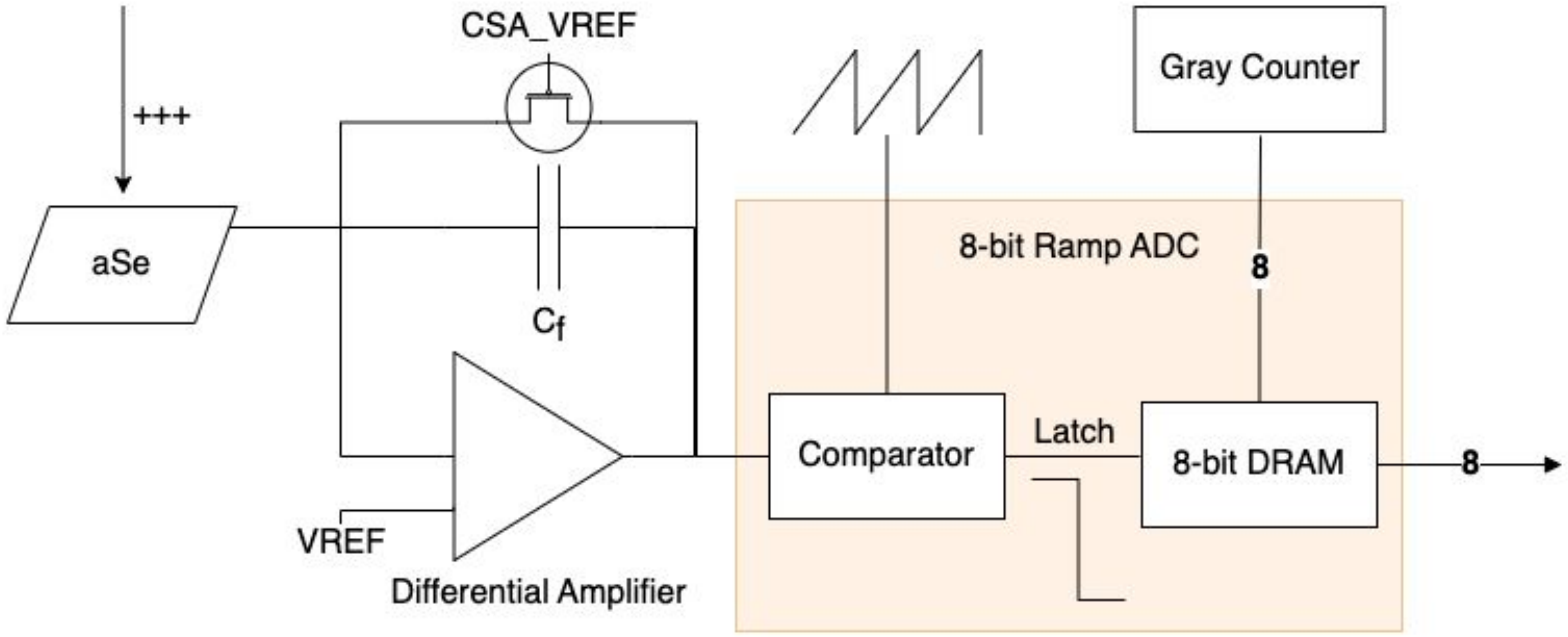
FEA Simulated Collection Efficiency

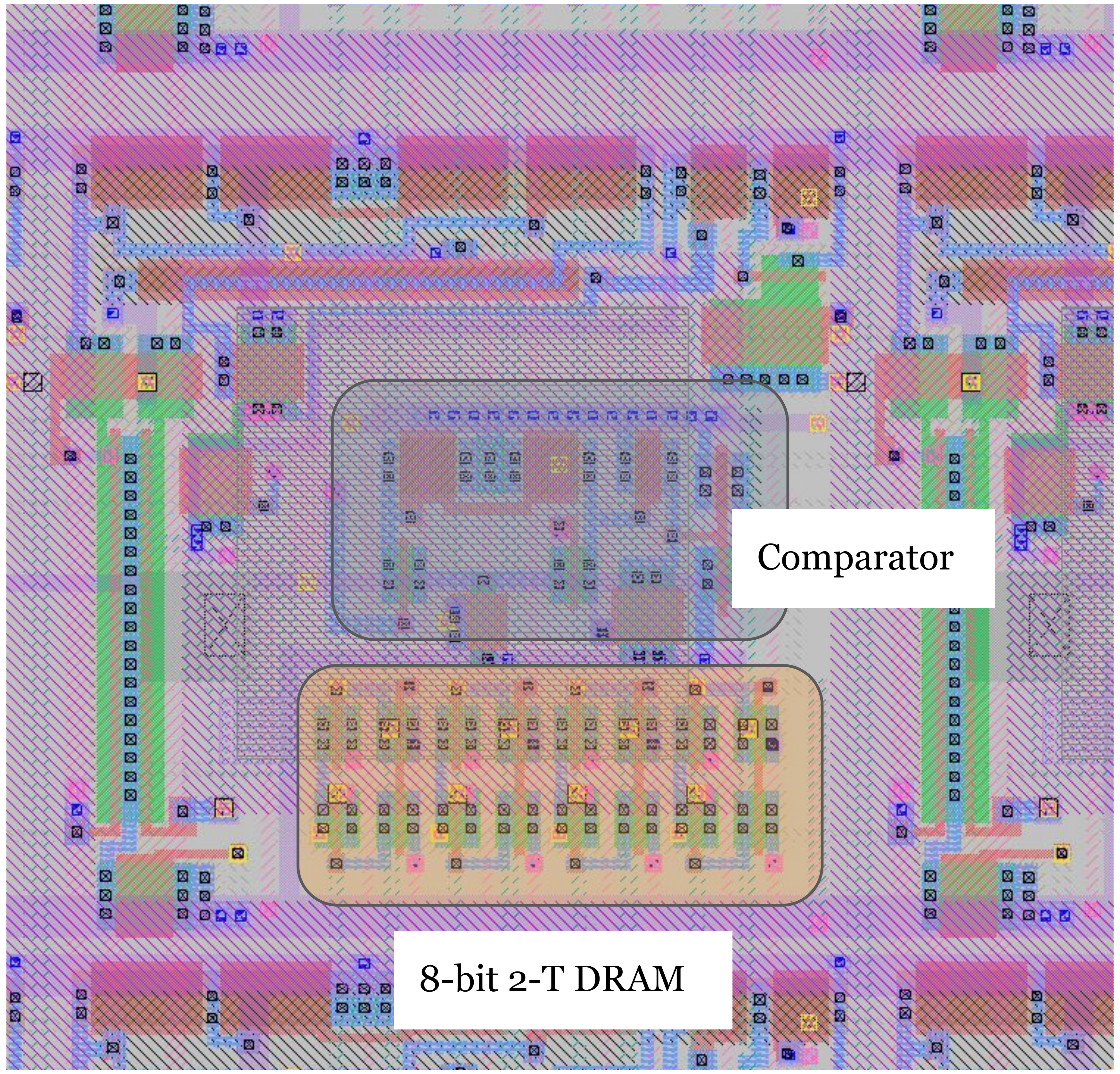


Already demonstrated noise performance!



TopmetalSe-DPS





- Test structure for in-pixel digitization.
- First chips arrive later this year.

Conclusion

- A 10-ton Selena detector has the potential for background-free search for $0\nu\beta\beta$ decay and solar ν spectroscopy.
- Neutrinoless $\beta\beta$ decay sensitivity of **$m_{\beta\beta}$ = 4 to 8 meV (3σ)** in 100-ton year.
- We already fabricated and operated the lowest noise single-pixel and pixelated aSe sensors capable of detecting individual electrons!
- Our own CMOS pixelated sensor *TopmetalSe* has met all design specifications.
- Steadfast CMOS development to scale up to wafer-size devices.

Thank you!

Backups

ν_e detection

Triple sequence:

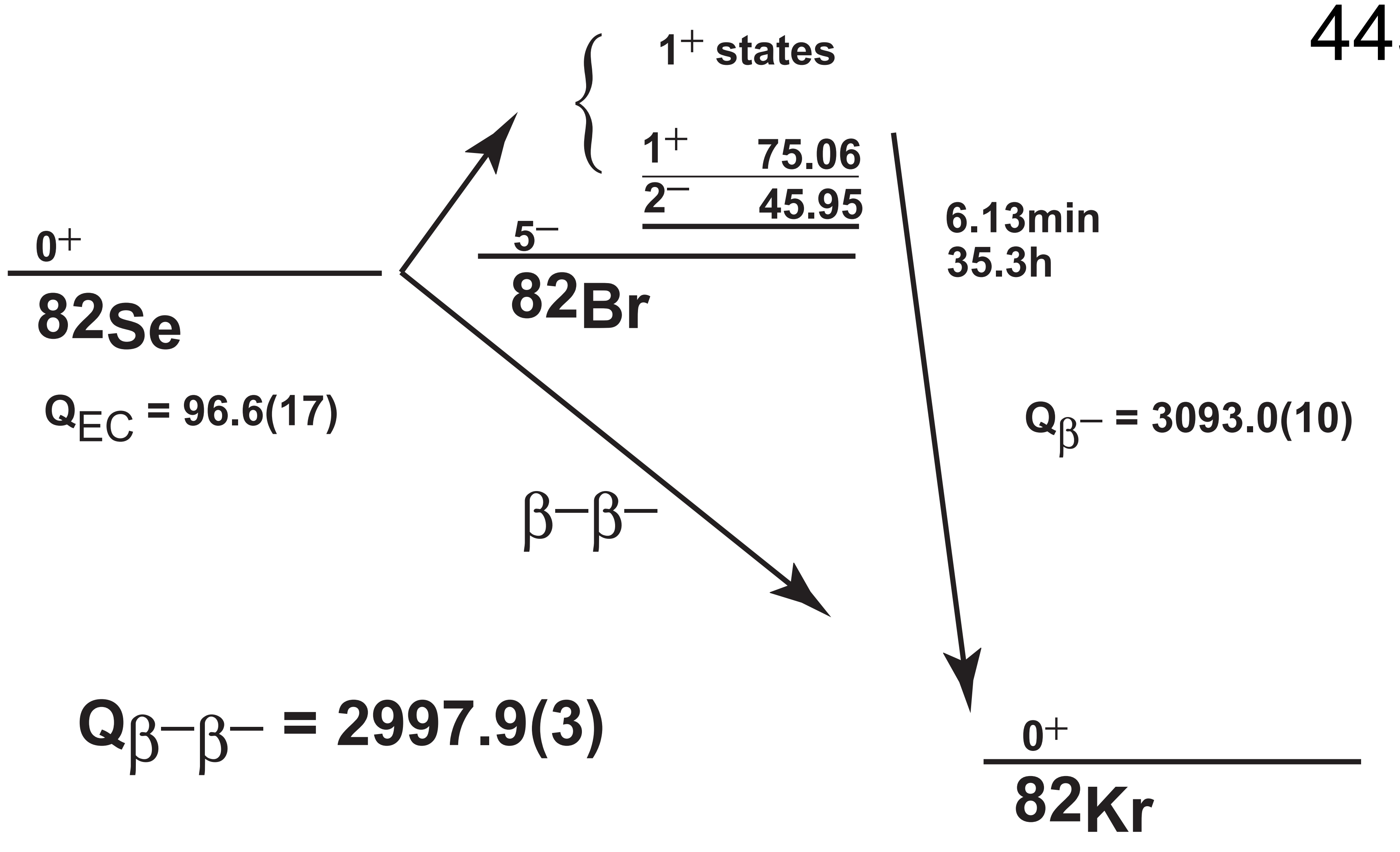
$E_\nu - 172$ keV

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

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

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

445 keV end-point

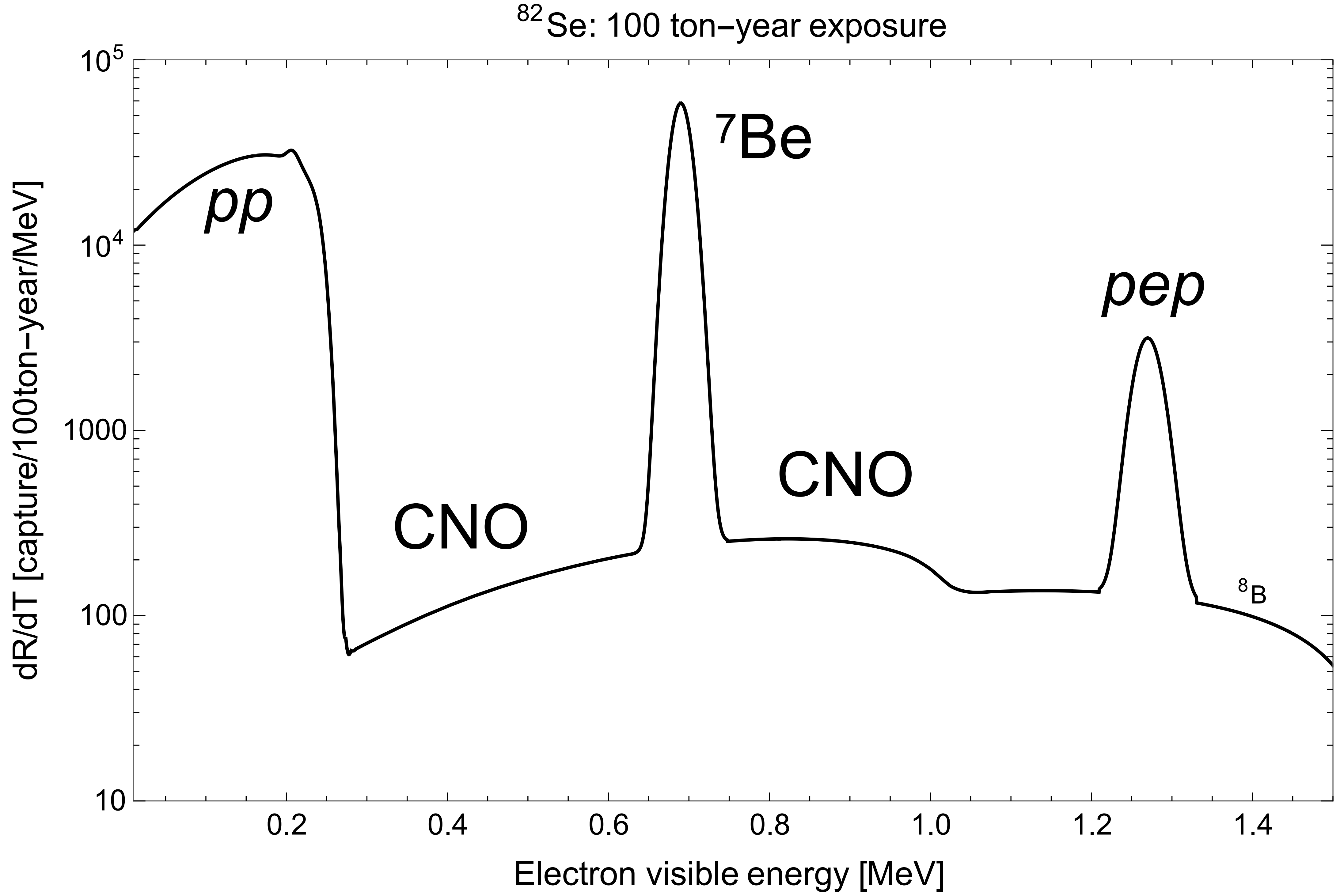


We can use the prompt events to perform solar ν spectroscopy!

Solar ν spectrum

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

↑ E_ν – 172 keV



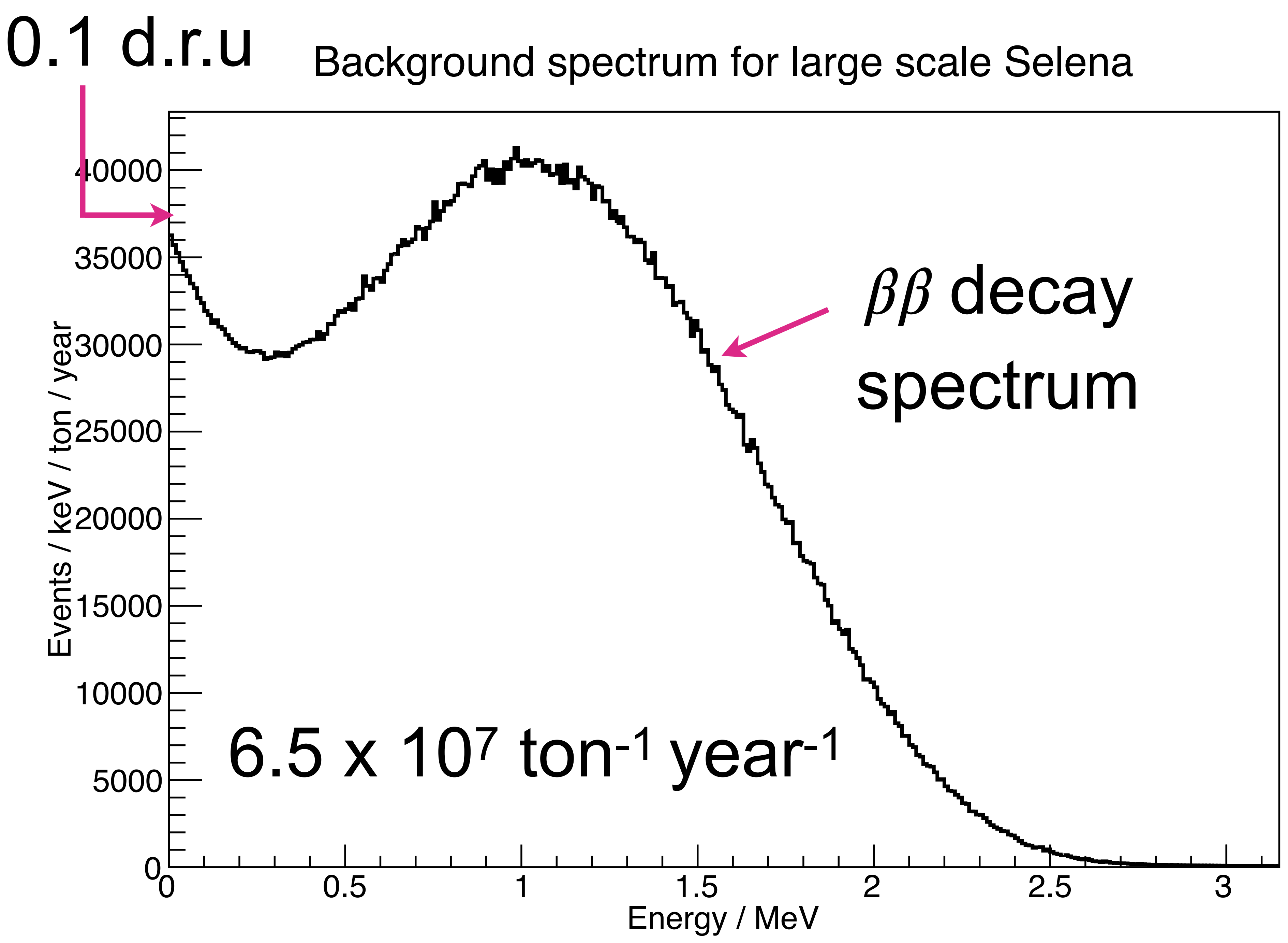
100 ton-year

Species	E range (keV)	N	1/√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%**

Constraints on solar luminosity, solar metallicity, solar core temperature, onset of matter effects in ν oscillations, etc.

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



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