Title: A high-resolution CMOS imaging detector for the search of neutrinoless double beta decay in Se-82

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Abstract:

An imaging detector for the search of neutrinoless ββ decay

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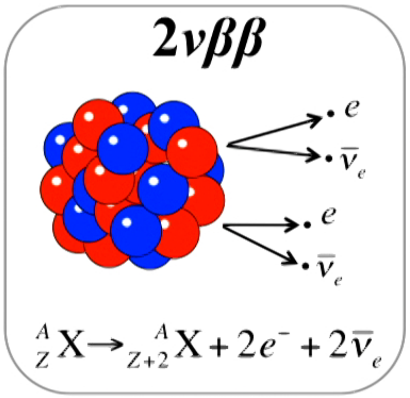
Outline

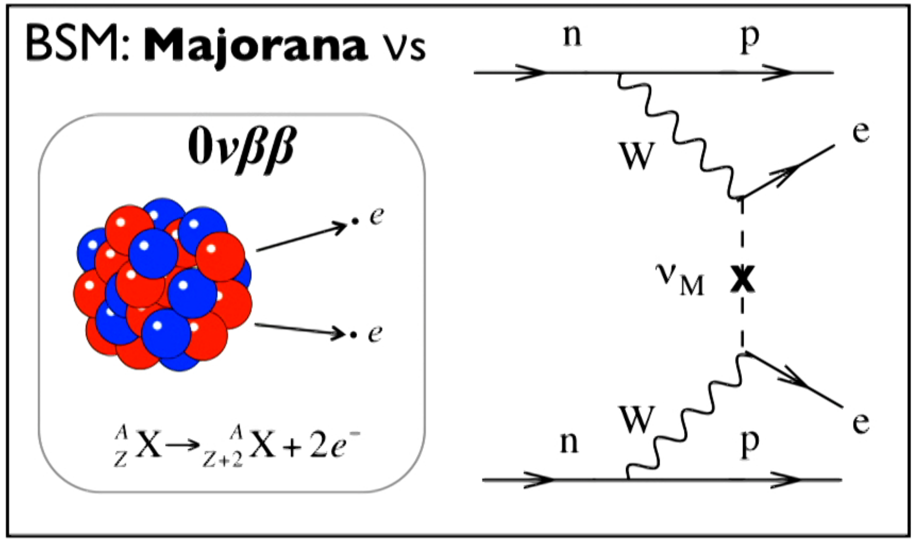
- The search for neutrinoless ββ decay.
- Particle detection in an imaging device.
- Current amorphous Se (aSe) imaging technology.
- Background estimates for a large CMOS / ^{82}Se imaging array.
- Near term R&D efforts and prospects.


Se

0νββ decay

Standard process





Decay rate

Phase space factor

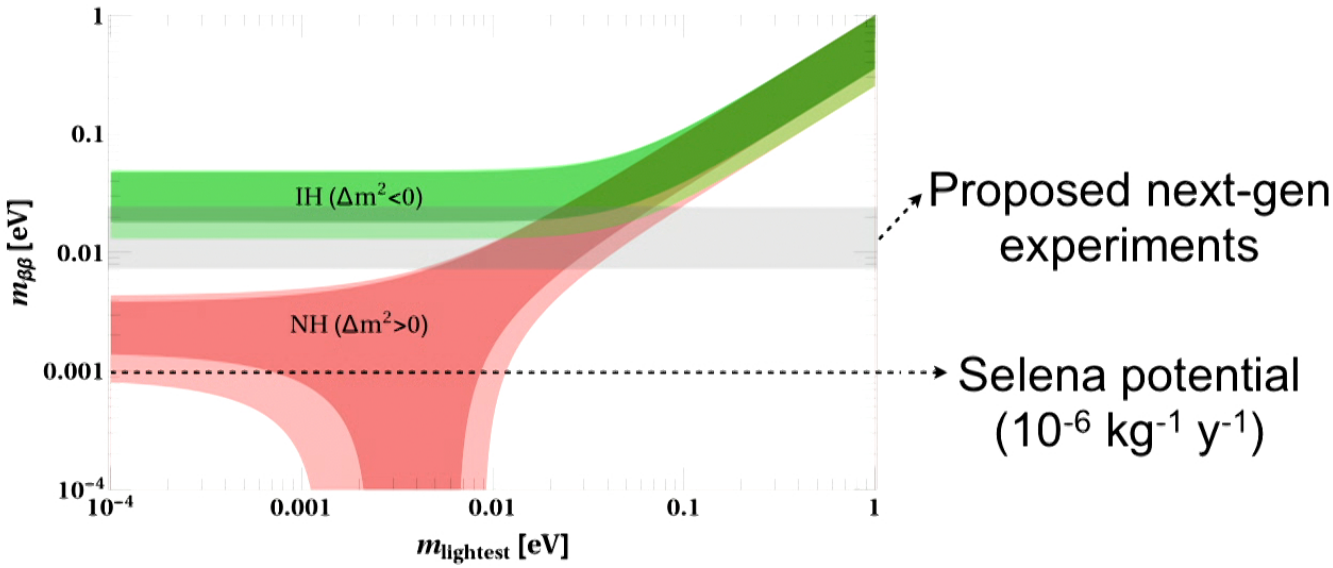
$$\Gamma_{0\nu} = G_{0\nu}\mathcal{M}^2 \left| \frac{m_{\beta\beta}}{m_e} \right|^2$$

Nuclear matrix element (NME)

Particle physics:

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

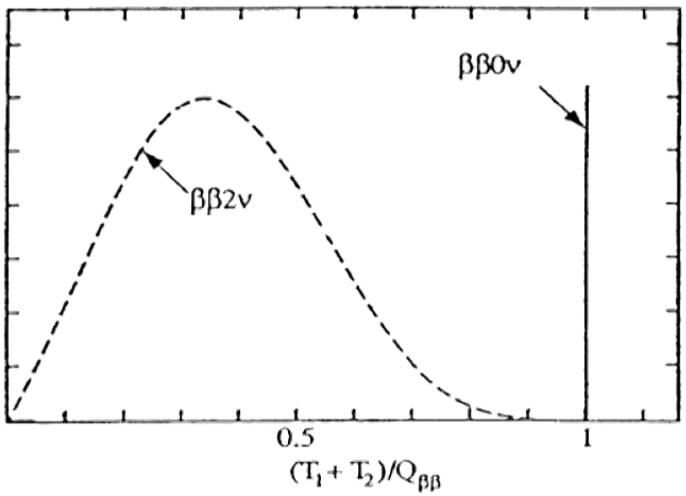
Parameter space

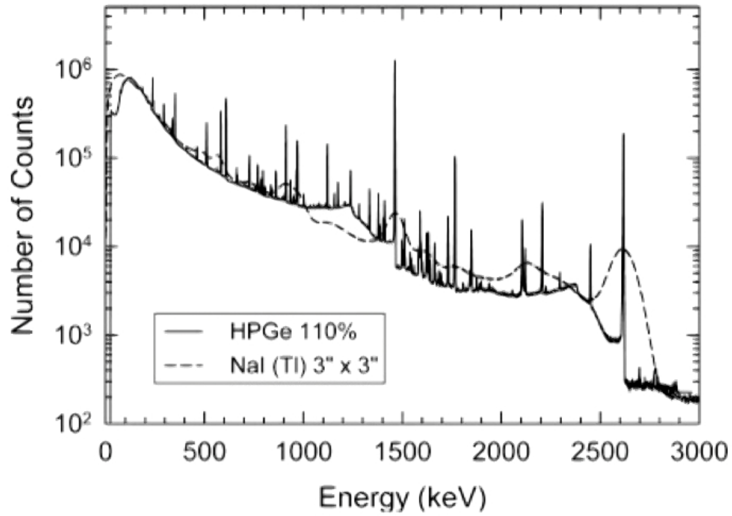


The field is crowded... with experimental proposals that won't answer the question if the neutrino mass hierarchy is normal.

Strategy

Good energy resolution to distinguish neutrinoless decay





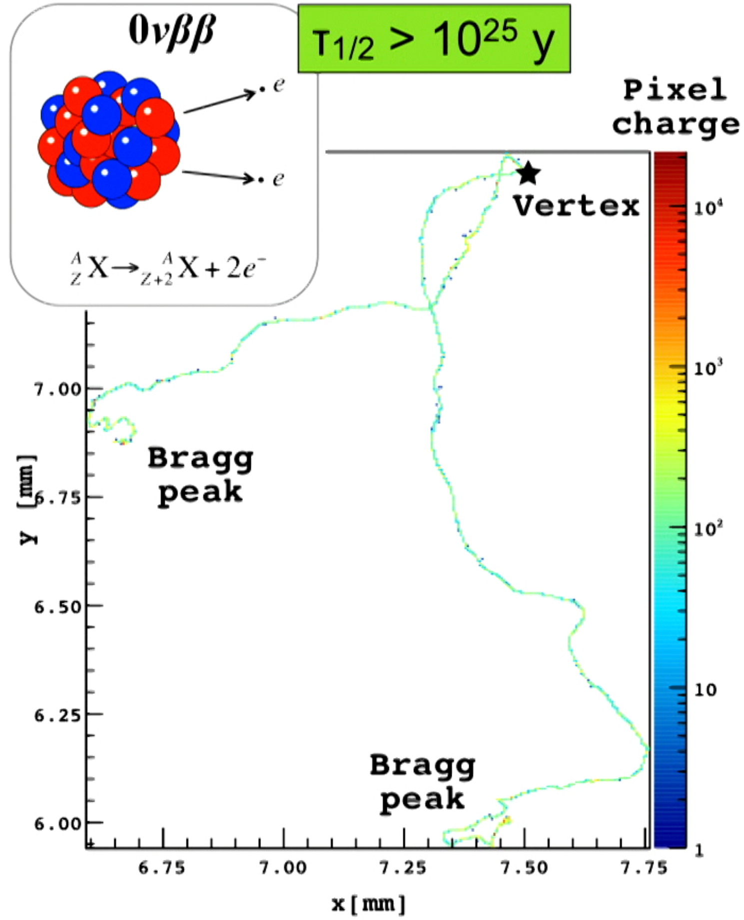
High Q-value to avoid background from U+Th

Not all isotopes are equal: phase-space factors, NMEs and number densities vary between ββ isotopes. E.g. for the same $m_{\beta\beta}$, decay rate is 2.5x higher in ^{82}Se than ^{136}Xe.

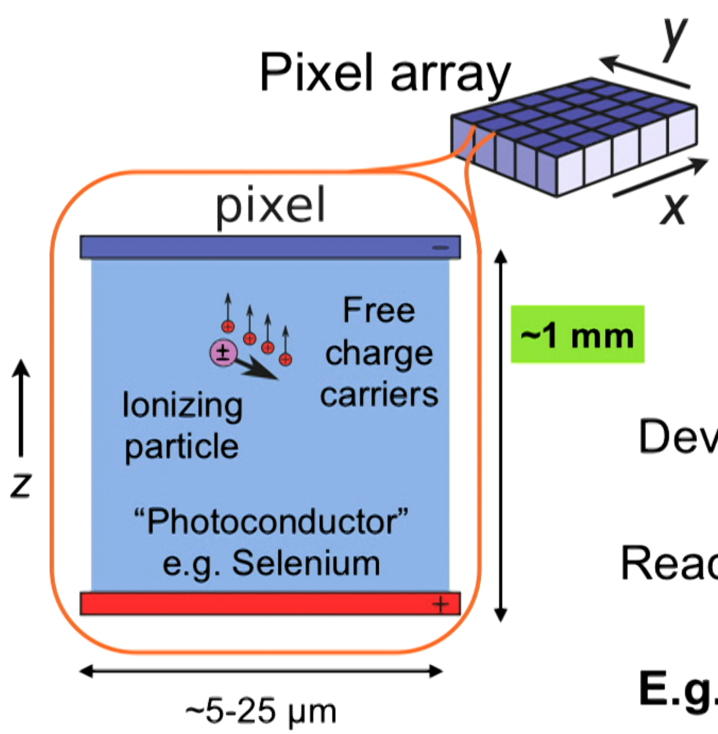
0νββ decay in ^{82}Se

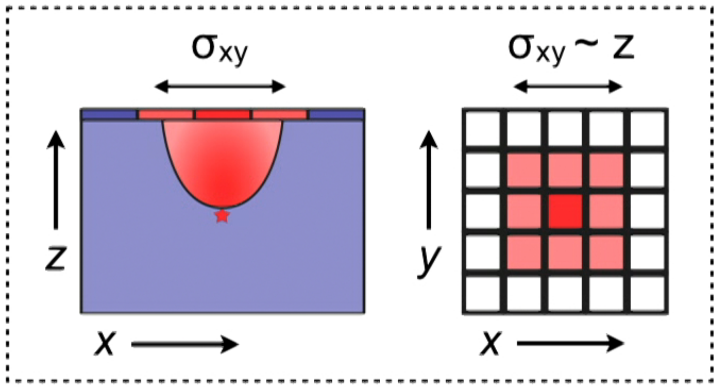
An amorphous ^{82}Se / CMOS active pixel array to image, with high spatial and energy resolution, the two electrons with energy $Q_{\beta\beta}$ from the neutrinoless ββ decay of ^{82}Se.

Potential to achieve the low backgrounds necessary **<10^{-6} $kg^{-1}y^{-1}$** to test if neutrinos are Majorana if the hierarchy of neutrino masses is normal.



Imaging detector



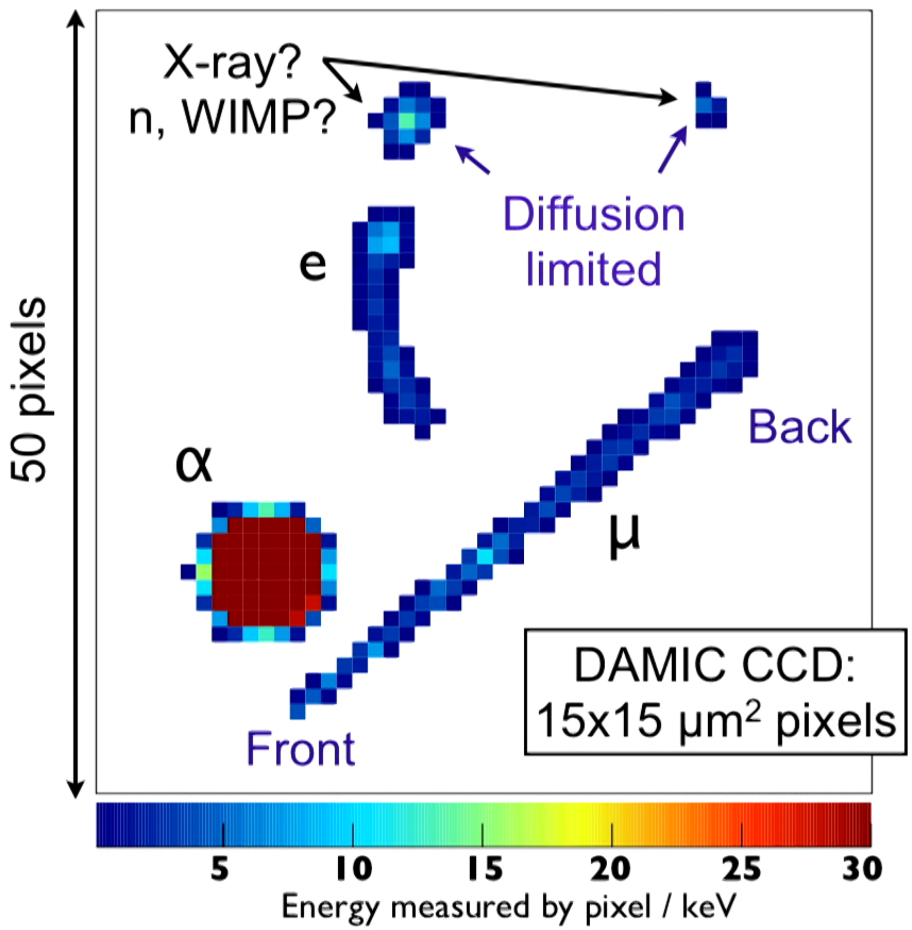


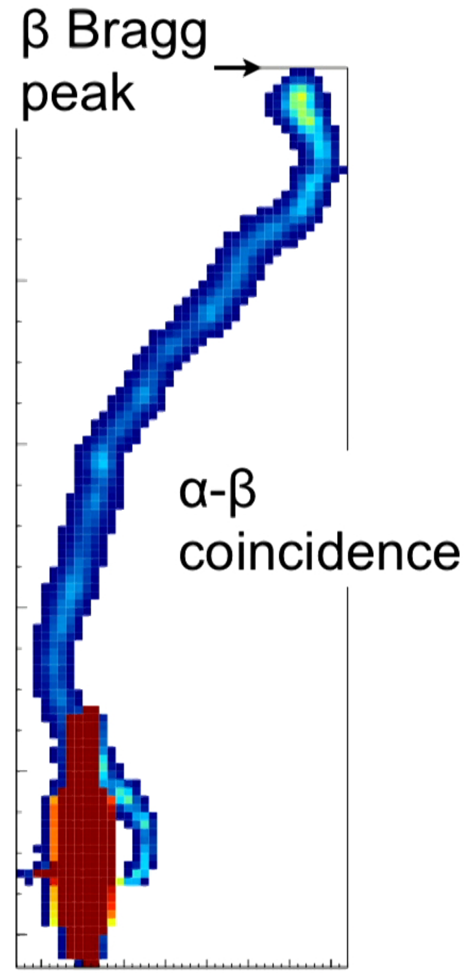
Device is "exposed," collecting charge until user commands readout.

Readout can be slow / non-destructive : **very low noise (few e⁻).**

E.g. Charge-coupled devices (CCDs), CMOS active pixel arrays.

Particle tracks





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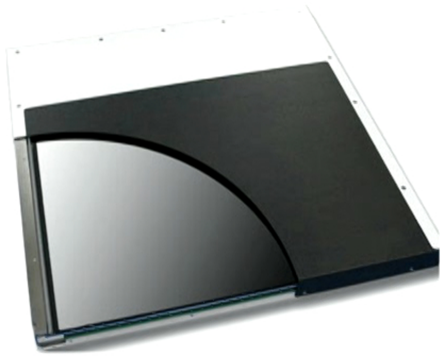
Amorphous Se detectors

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

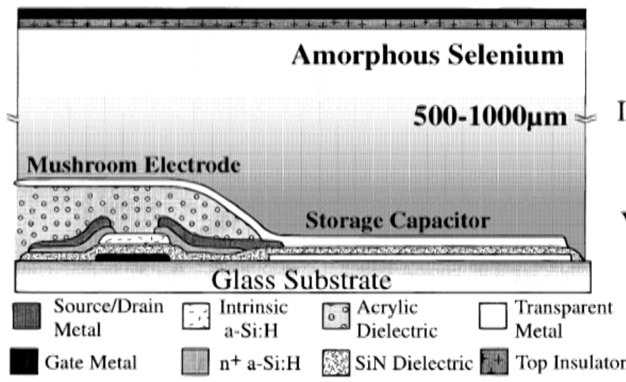


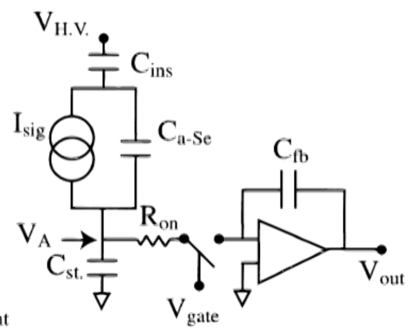
Operated at high electric fields (~10s V/μm) and ~50 e-h pair per keV for 140 keV X-rays.

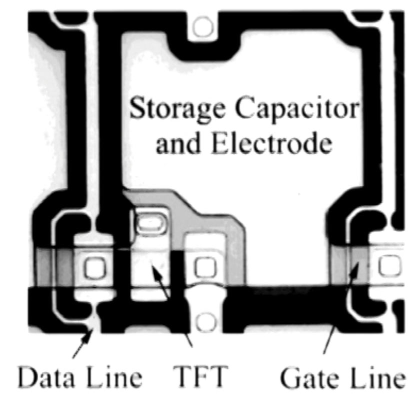
Large band gap: Negligible bulk dark current at room temperature.

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

Existing technology



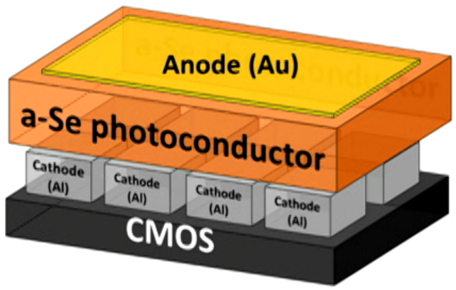




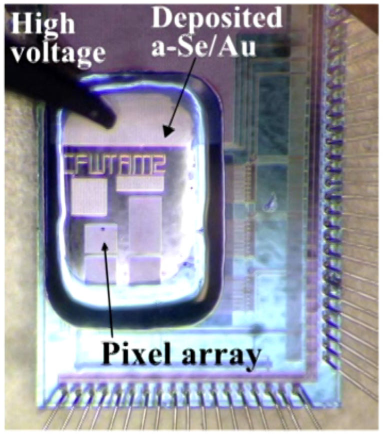
Replace current TFT pixel array on glass substrate for CMOS active pixel array on silicon substrate for lower-noise and more functionality.

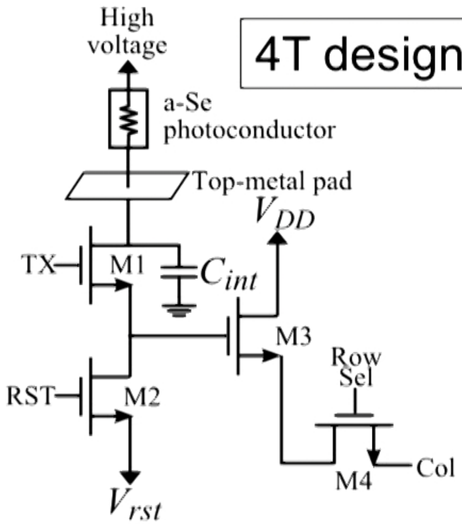
Other requirement: Storage electrode / pixel structure must be a few μm thick.

CMOS aSe imager



DOI: 10.1109/IEDM.2015.7409803
DOI: 10.1109/LED.2015.2410304

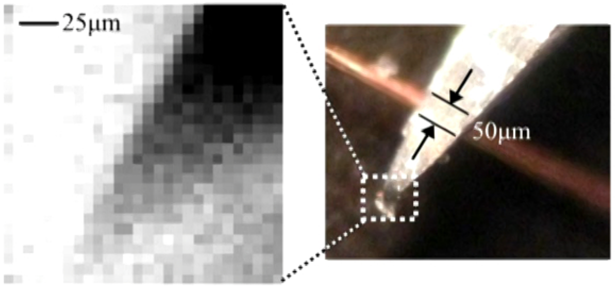




4T design

Already implemented for small test arrays with 50 µm-thick aSe.
Down to 6x6 μm^2, 20 e^- noise. Up to 22 s integration time.

Low cost, scalable technology.
Possible functionality: A/D conversion
and zero suppression on board.

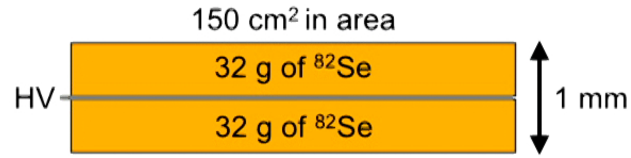


Selenium-82

- High Q-value (3 MeV, above most γs from uranium and thorium), 10^{20} y 2ν half-life, and 9% natural abundance.
- Se can form many gaseous compounds: e.g. selenium hexafluoride, hydrogen selenide, dimethyl selenide.
- Thus, isotopic separation by centrifugation or distillation are possible (Data hints at significant isotopic separation in hydrogen selenide with a meter-long column).
- Elemental selenium has been successfully purified by float-zone process (can be very radio-pure).

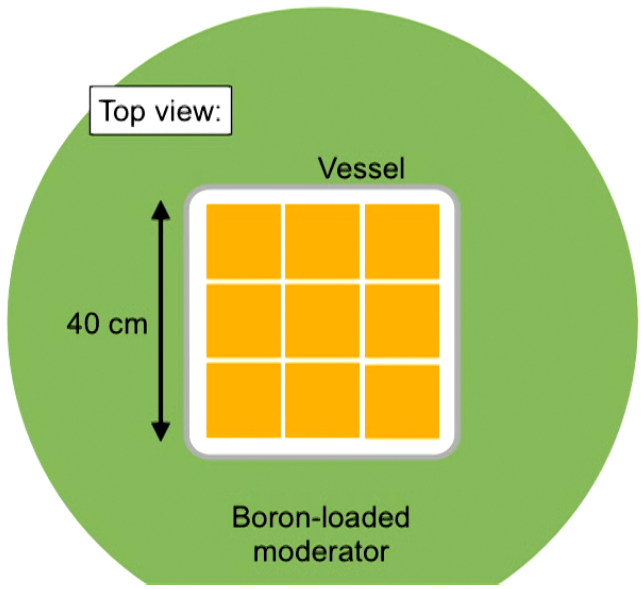
Detector array e.g.

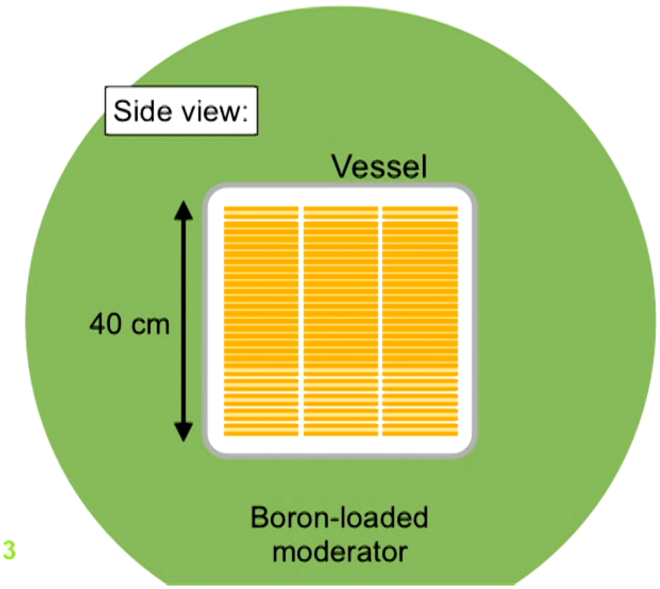
Rectangular CMOS pixel arrays with ^{82}Se evaporated on pixel structure.



Starting from 200 mm Si wafers. Digitization and zero-suppression on board.

~160 kg target **~2500** modules **~75 m²** imaging area





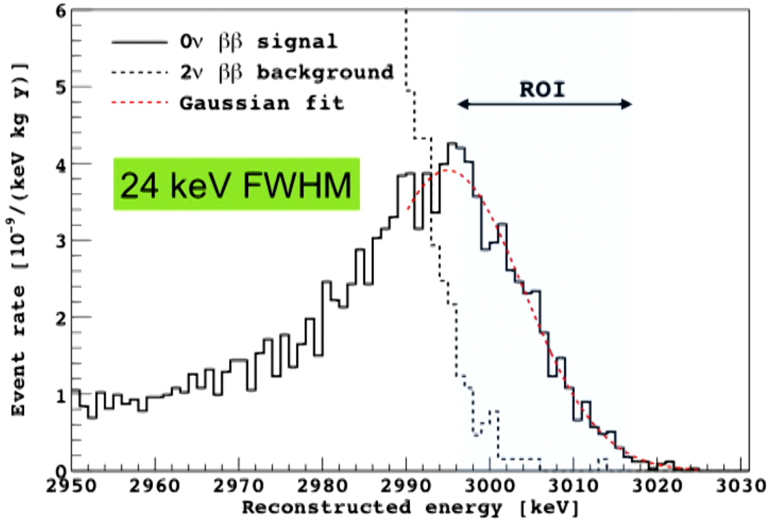
2ν background

<u>Full simulation:</u>

CMOS properties:
10 e^- noise
70 dB dynamic range
15x15 μm^2
5 μm-thick pixel array

Amorphous Se:
200 μm thick
15 eV per e-h pair
Fano = 0.6

For $m_{\beta\beta}$ = 1 meV/c^2 and $g_{phen.}$
(most unfavorable case)



For $m_{\beta\beta}$ = 1 meV/c^2 and $g_{phen.}$ ($g_{nucl.}$):
0νββ decay signal: 4 (160) x 10^{-8} /(kg y)

2νββ decay background: 5 x 10^{-9} /(kg y)

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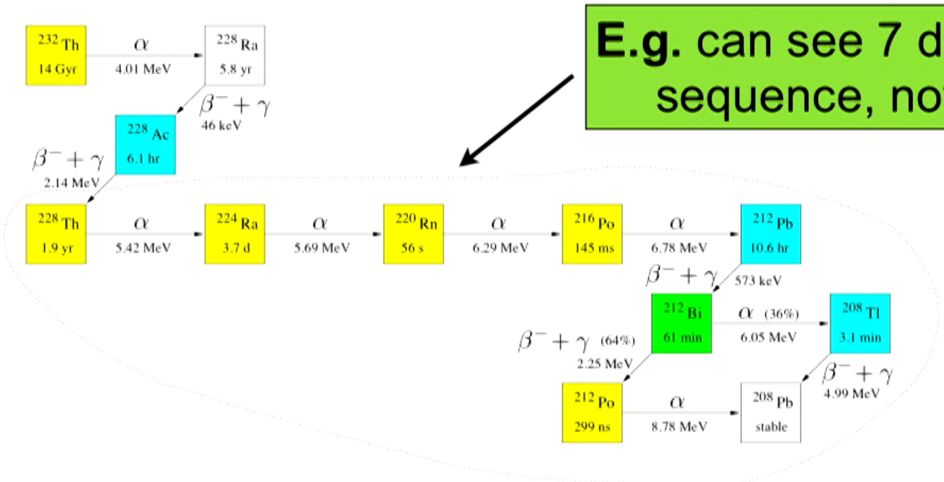
Background suppression

- The high spatial resolution of imaging devices allows for particle identification based on the topology of the ionization track.
- Precise determination of a radioactive decay site (+ solid-state device) allows for superb efficiency in the identification of radioactive decay sequences.

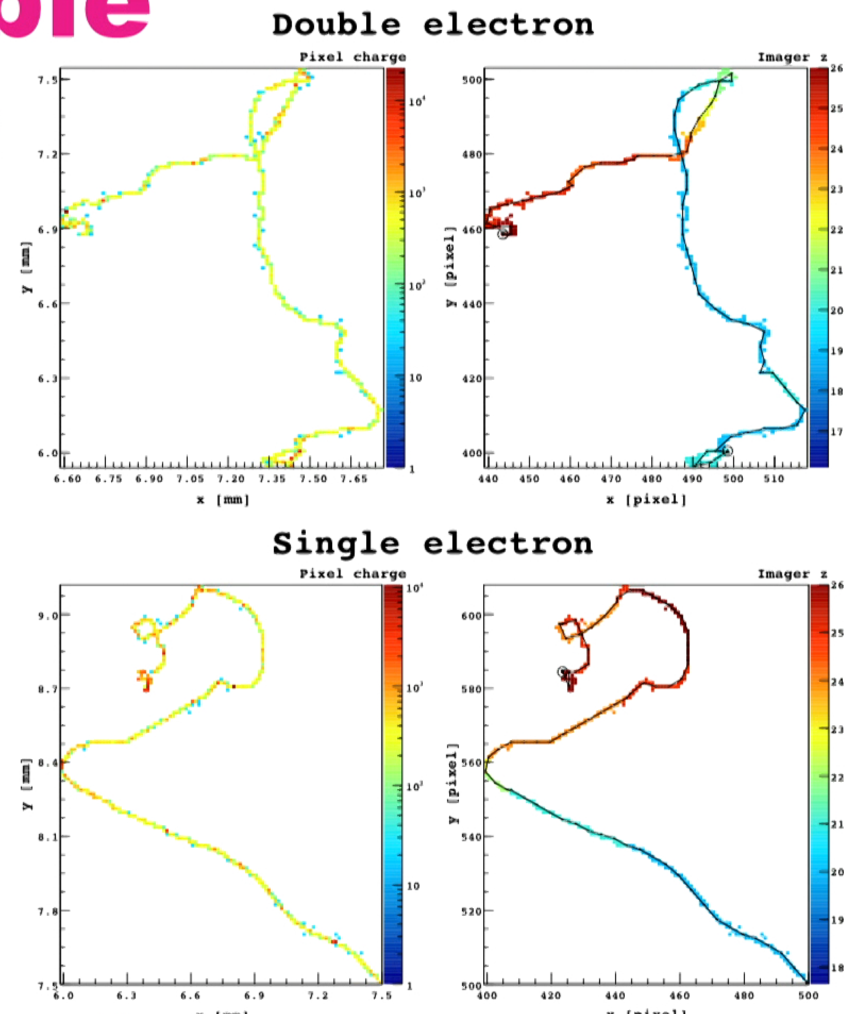


E.g. can see 7 decays in a sequence, not just 2.

Single/double electron

From simulation:
By identification of Bragg peak have achieved 10^{-3} suppression of single electron background, with 50% signal acceptance.

Strongly suppresses γ-ray and single β backgrounds



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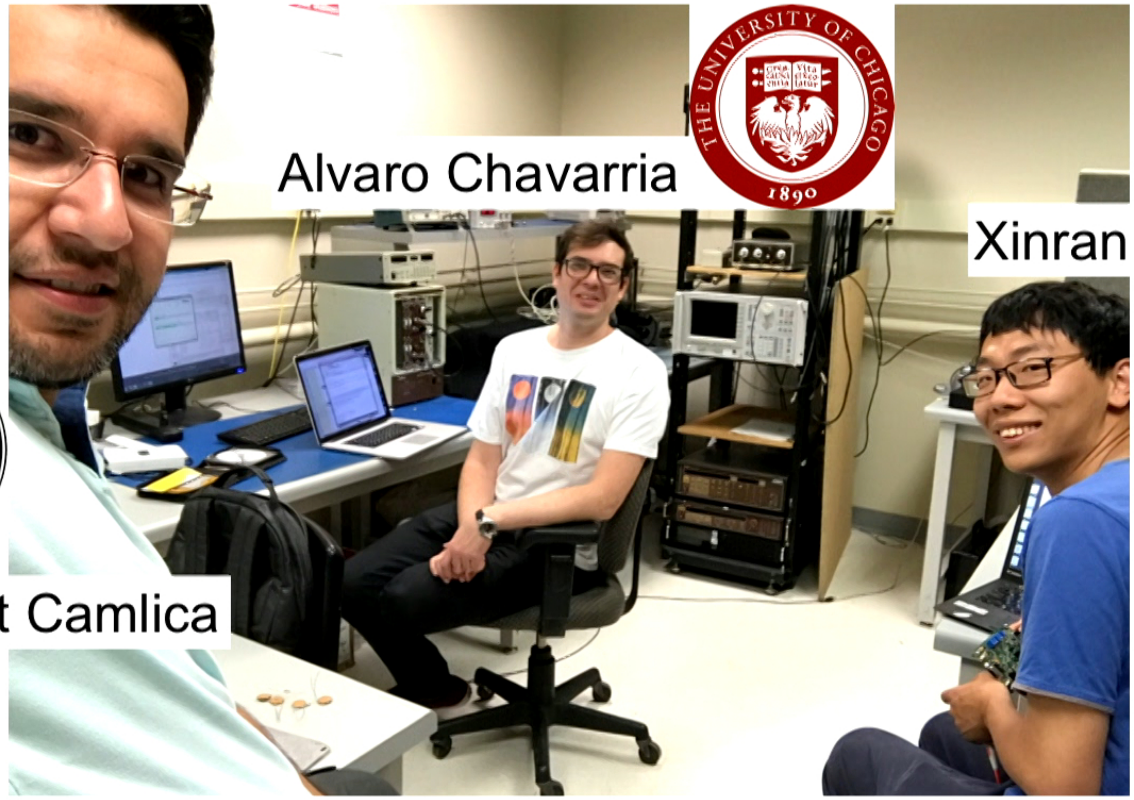
Radioactive backgrounds

In ROI Source	Raw background rate / $kg^{-1}y^{-1}$	After discrimination / $kg^{-1}y^{-1}$
β-decay (bulk)	$< 3.3 \times 10^{-1}$	$< 3.7 \times 10^{-9}$
β-decay (surface)	$< 4.1 \times 10^{-1}$	$< 1.2 \times 10^{-8}$
β-decay (cosmo.)	$< 9.9 \times 10^{-5}$	$< 1.5 \times 10^{-7}$
γ-ray (photo-elec.)	$< 7.2 \times 10^{-4}$	$< 7.2 \times 10^{-7}$
γ-ray (Compton)	$< 1.6 \times 10^{-3}$	$< 4.1 \times 10^{-7}$
γ-ray (pair prod.)	$< 1.9 \times 10^{-6}$	$< 1.9 \times 10^{-7}$
Total	$\mathbf{< 7.4 \times 10^{-1}}$	$\mathbf{< 1.5 \times 10^{-6}}$

Bulk backgrounds suppressed by α/β particle ID and spatial coincidences.

Also applied multiple scattering cut, limited to 10^{-1} suppression of nearby scatters.

R&D



Not Pictured: C. Galbiati, K.S. Karim, P. Privitera

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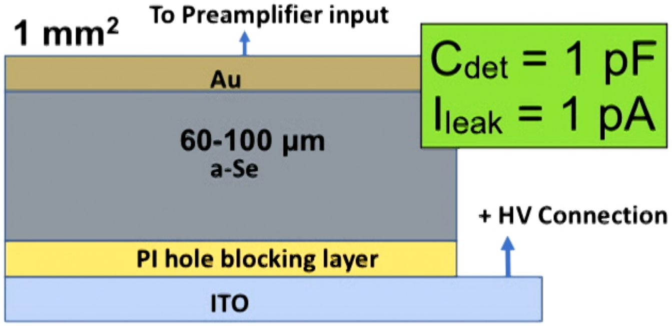
Establish E response

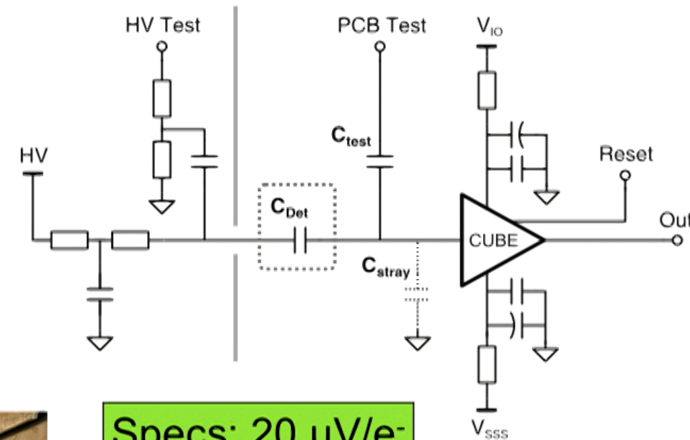
Detector:



C_{det} = 1 pF
I_{leak} = 1 pA

ITO Size= 25x50x0.5 mm

Front-end from XGLab:



Specs: 20 µV/e^-
20 e^- noise

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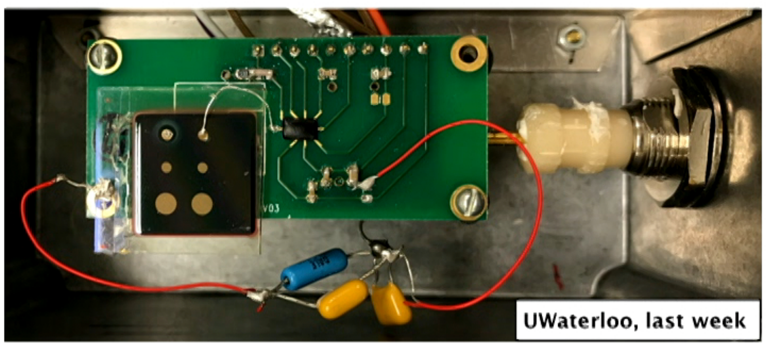
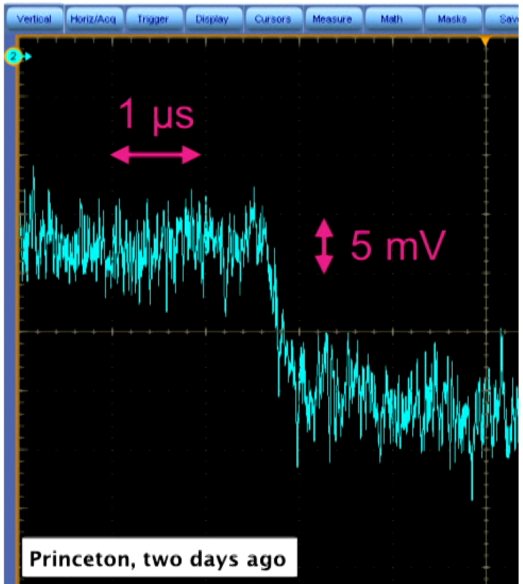


← Components distributed for setups in Waterloo, Princeton and Chicago.

First single x ray pulse!



^{241}Am 60 keV x-ray
E = 10 V/μm
~1000 e^-

Goal: decrease noise further to do measure signal pulses with high resolution.

Perform calibration campaign with x rays of increasing energy.

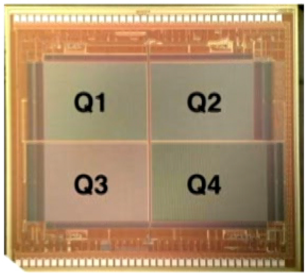
Size of step $\propto$ charge generated.

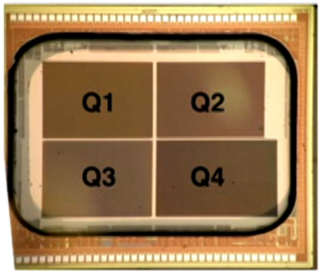
Decay time dependent on drift and trapping of charge carriers.

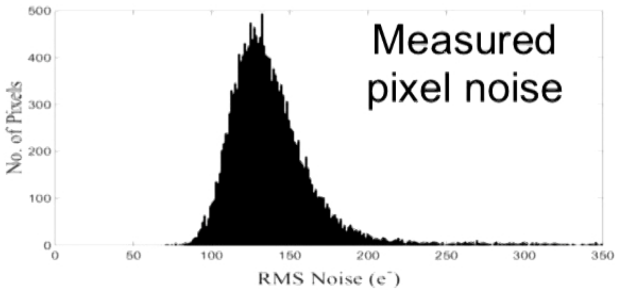
Pulse analysis to understand the properties of charge generation and transport in aSe.

CMOS implementation

Prof. Karim and Prof. Levine at UWaterloo have already been characterizing CMOS/aSe devices for imaging.







Will collaborate to test these devices for particle detection (starting with x rays).

As we understand aSe better from pulse shape analysis we will be able to evaluate the aSe/CMOS implementation and provide insight for pixel array design.

CMOS device test

KA Imaging will release the Libra prototype for evaluation this fall:

Feature	Libra (1M)	Units
Pixel Pitch	7.8 x 7.8	μm^2
Array Resolution	1000 x 1000	pixels
Chip dimension	11 x 9	mm^2
Detector node Cap	58.4	fF
Conversion gain	2.74	µV/e-
Operating Speed	≤ 10	fps
Input referred Noise	< 150 (@ t_{line} = 100ms)	e-
Fill Factor	100	%
ADC	14	Bit
Full Well Pixel Capacitance	>876	Kelectrons
DQE (RQA5 beam)	>15% upto 40 lp/mm	%
A-Se Thickness	100 +/- 15	µm
Selenium HV Voltage	1500 max	Vdc
Conversion Gain	<35 @ 1500V (i.e. 15V/um)	eV/electron
A-Se dark current	<100 (nominally 10)	pA/mm^2
Included Software	GUI executable, optional Verilog code for custom timing and control modification	

KA IMAGING

Also a **15x15 cm²** device with 50x50 µm² pixels next year.

We plan to test and optimize these devices for particle detection in the lab.

Conclusions

- CMOS/aSe technology could have the capability to reach backgrounds at the level of 10^{-6} kg^{-1} y^{-1} in $0\nu\beta\beta$ ROI.
- Most of the required specifications for the devices can be met in the next few years.
- Existing capabilities in industry will help with scalability.
- Ongoing **R&D** to determine the intrinsic response of aSe to radiation.
- Near-term **R&D** to characterize CMOS/aSe device implementation for particle detection.