0νββ search with CMOS pixel charge plane in gain-less high-pressure gas Time Projection Chamber

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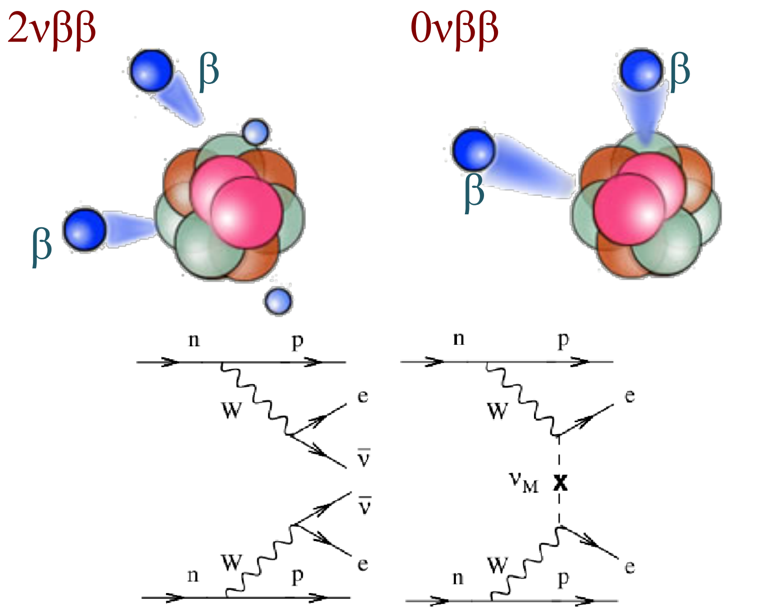
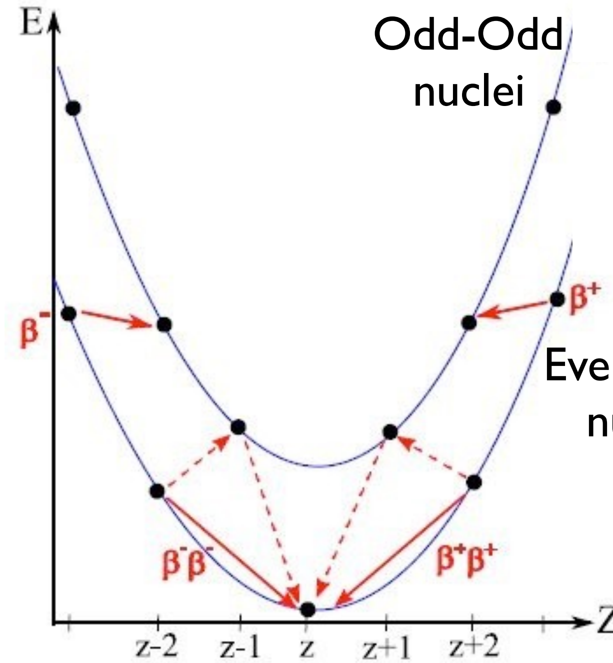
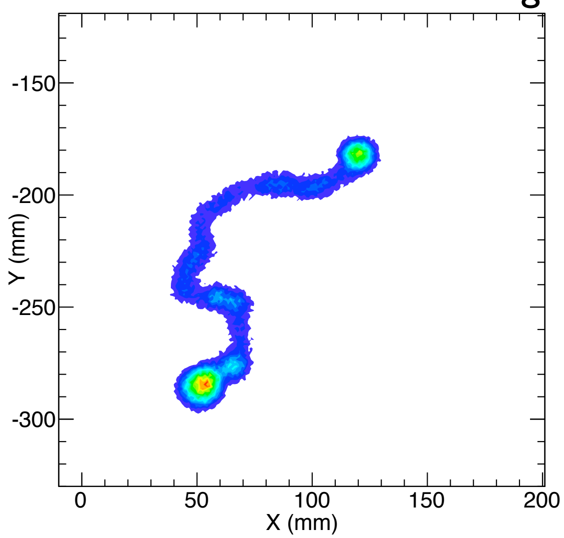
Physics Motivation: Neutrinoless Double-Beta Decay

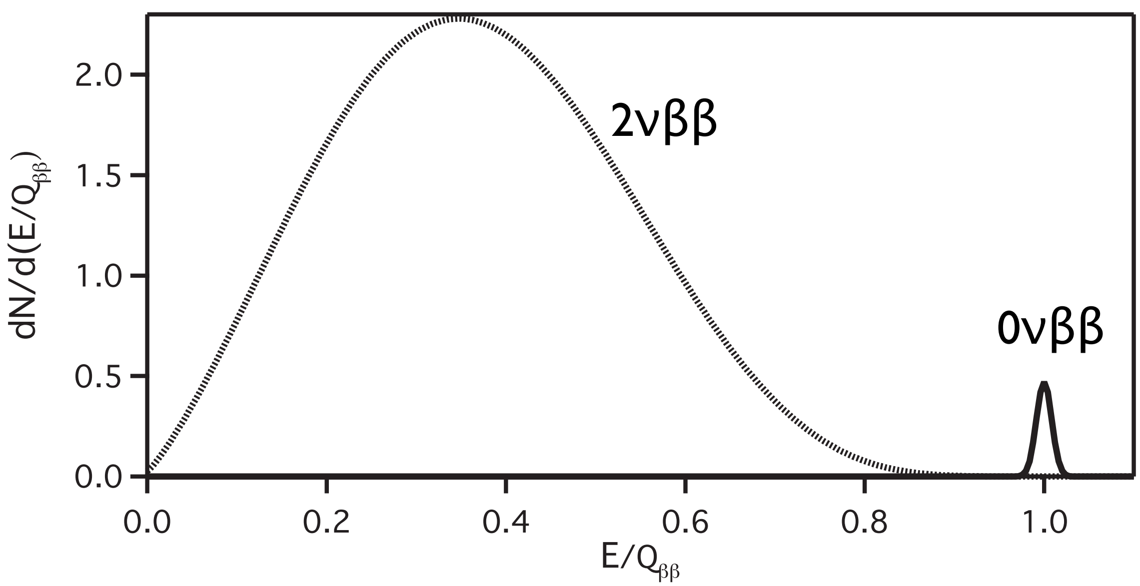


half-life sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$



Simulated ^{136}Xe 0νββ event, ionization track in10bar Xe gas

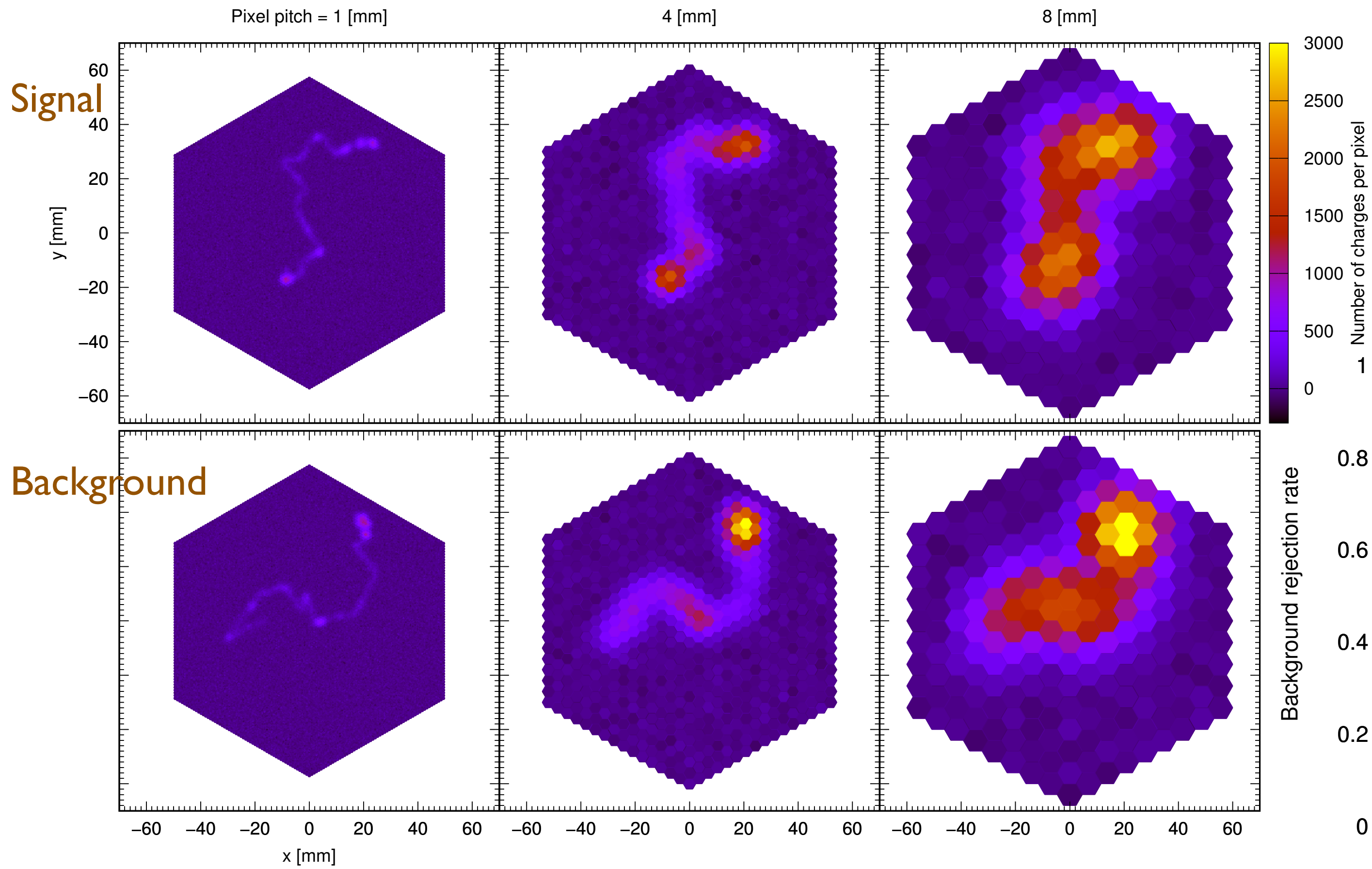




Assumes BR 0ν/2ν = 1% and detector energy resolution is 2%

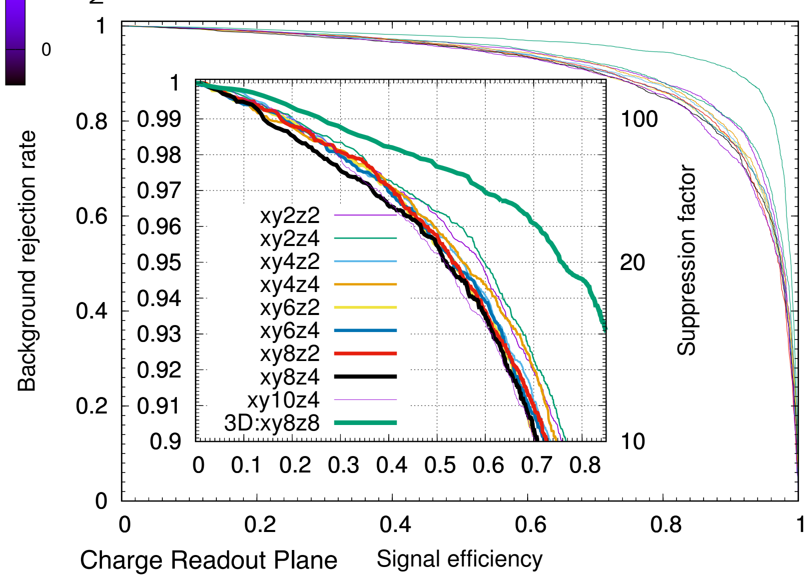
Ionization imaging (3D) for 0νββ

Simulated events in ^{136}Xe 0νββ energy region, ionization track in10bar Xe gas

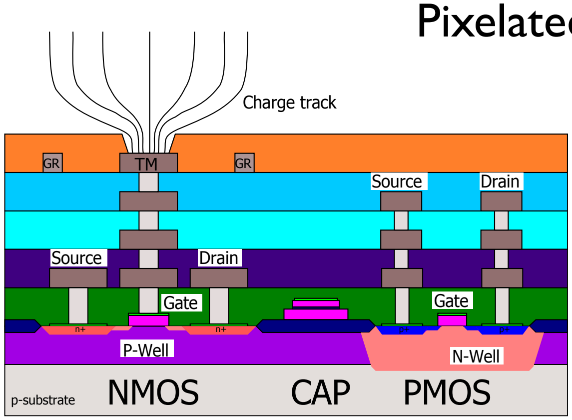


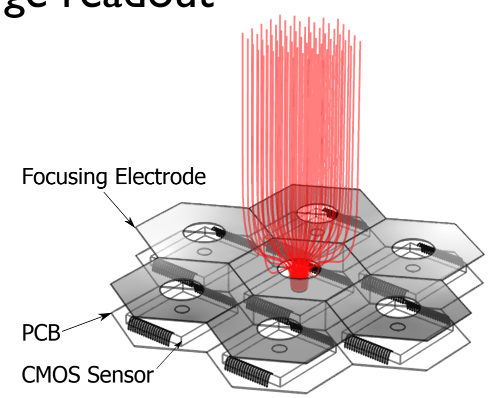
Background discrimination using 3D track pattern information

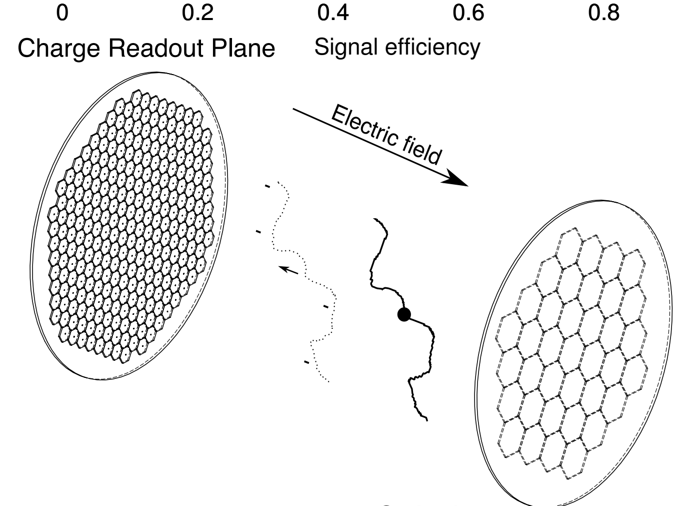
Application of machine learning methods:



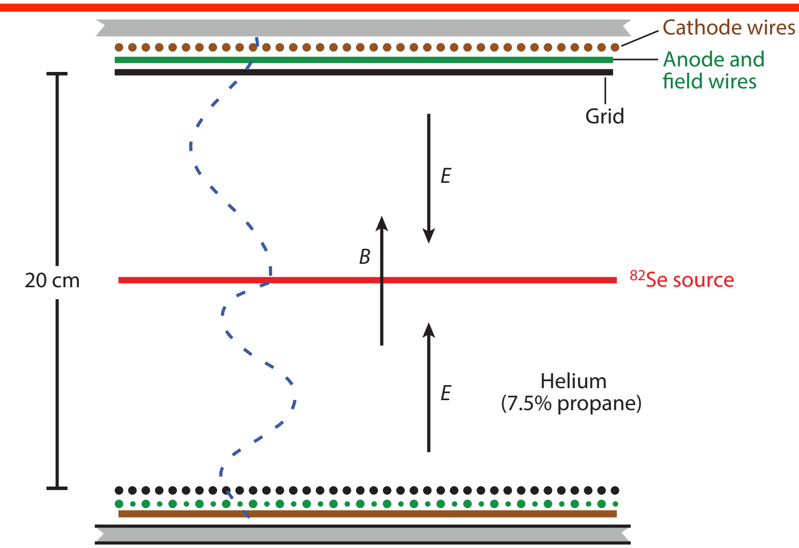
Pixelated charge readout

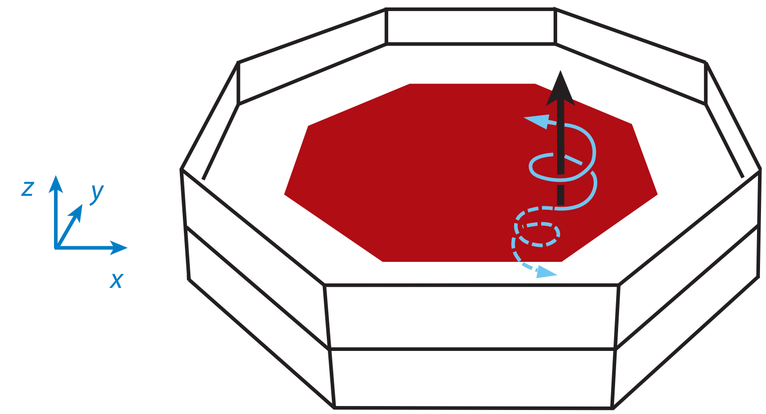


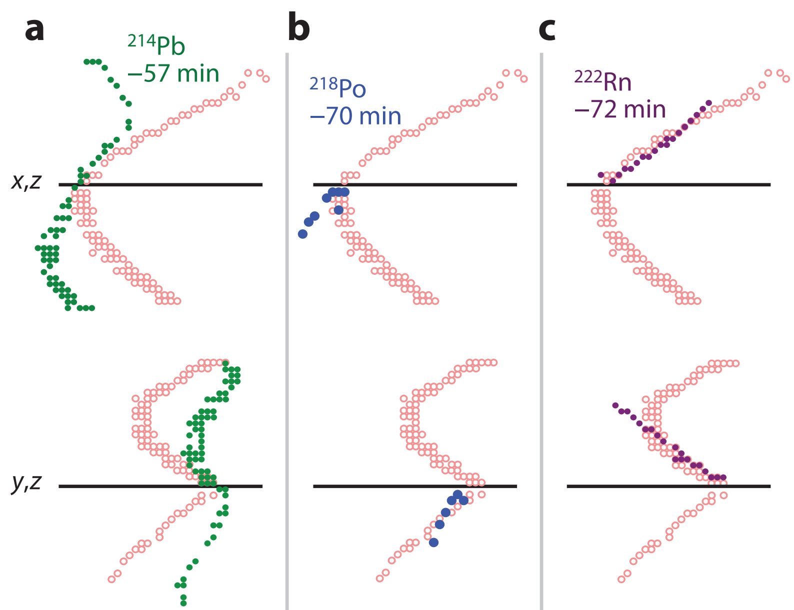


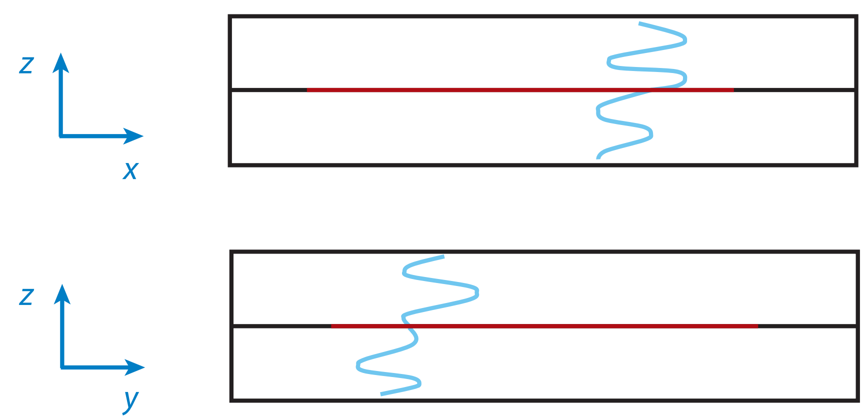


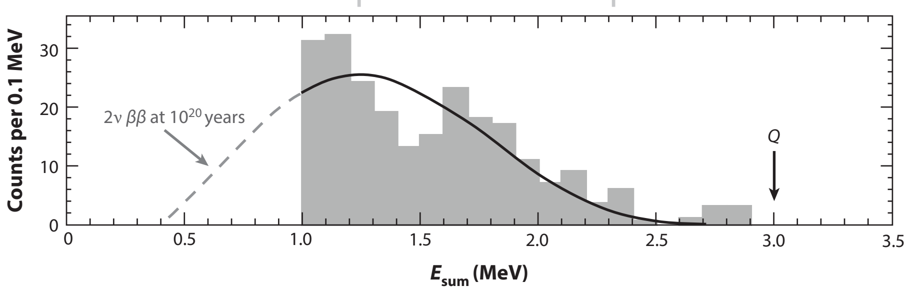
^{82}Se 2ν double-beta decay











- Michael Moe et. al. circa 1980s
- Thin ^{82}Se source (~7g, 97% enriched) in He gas TPC
- ^{214}Bi background suppression at 96%

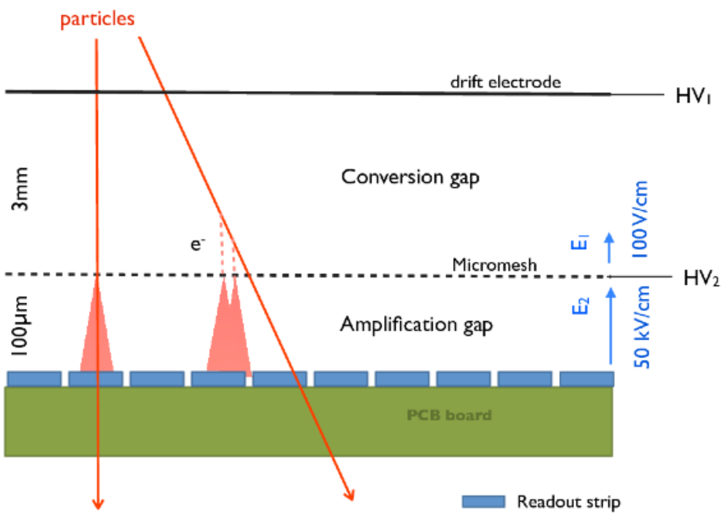
Annu. Rev. Nucl. Part. Sci. 2014. 64:247–67

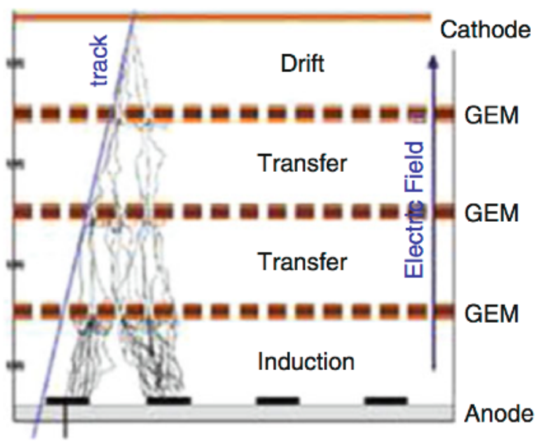
Challenges and solutions

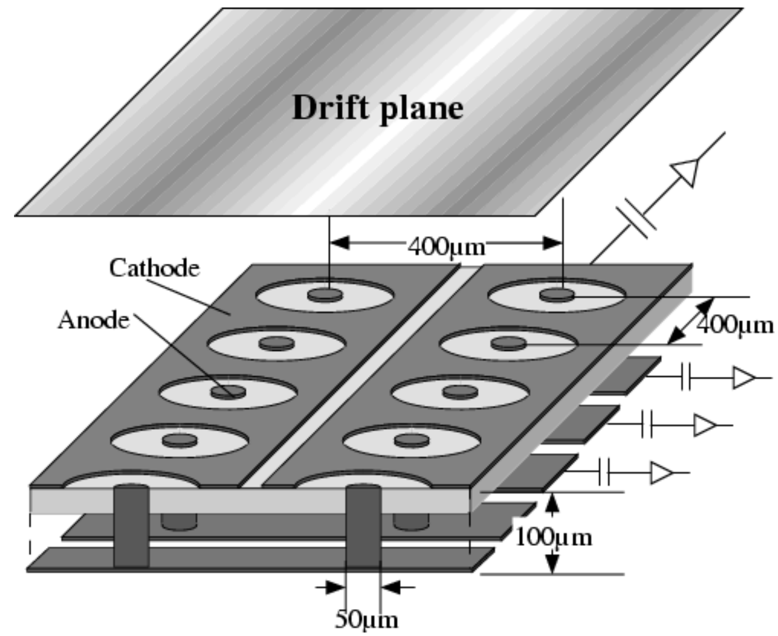
To do a definitive experiment

- Scalable to large mass while retaining:
  - Excellent energy resolution at $Q_{\beta\beta}$
  - Background control: pure material and active discrimination
  - Geometrical signature of decay (positive signal identification)
  - Leverage industry to scale
- High pressure gaseous TPC
  - HP Xe has been proven to have excellent intrinsic energy resolution (ionization charge statistics)
  - PandaX-III and NEXT employ Micromegas and electroluminescence techniques to achieve high energy resolution and charge tracking

Gas-electron multiplication, stability?







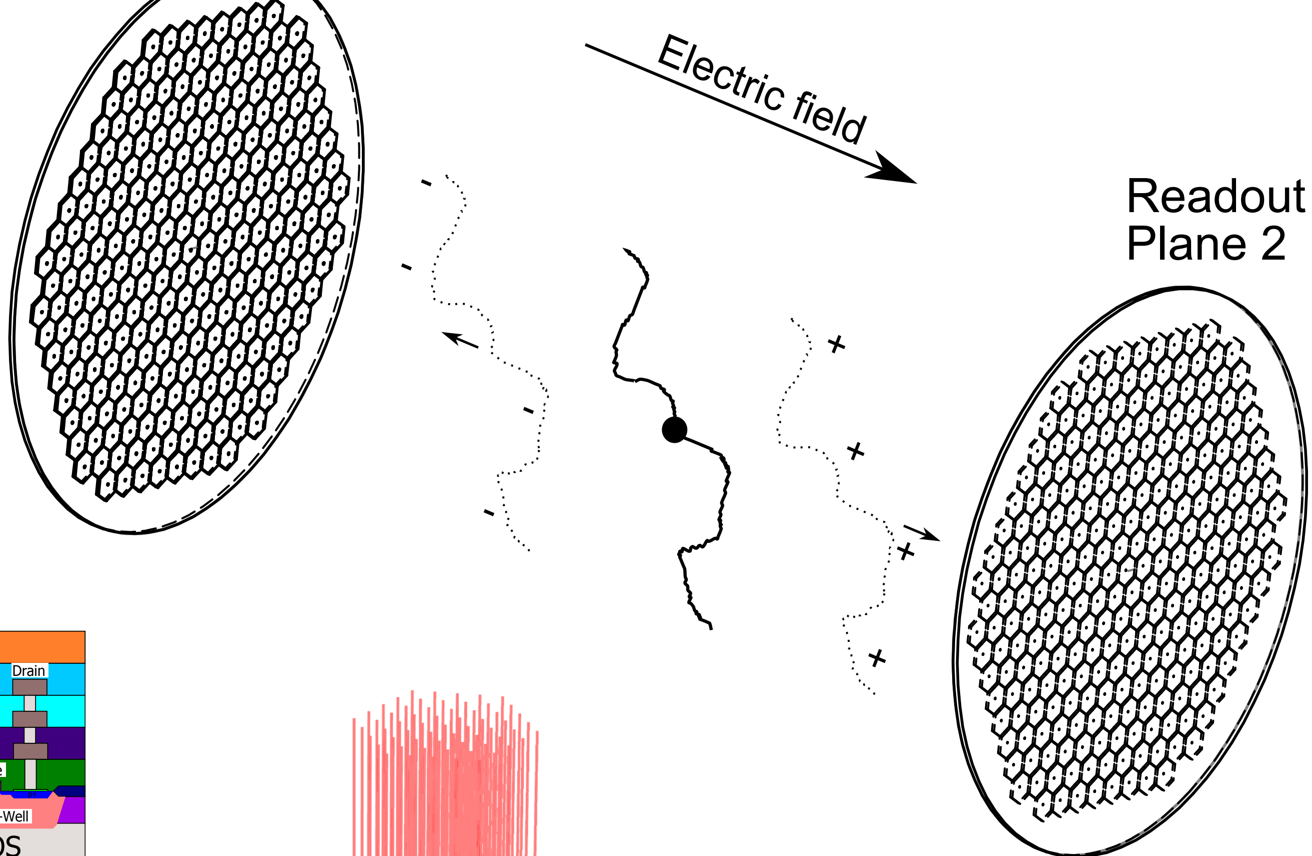
- MicroMegas
- Micromesh placed (very) close to readout PCB

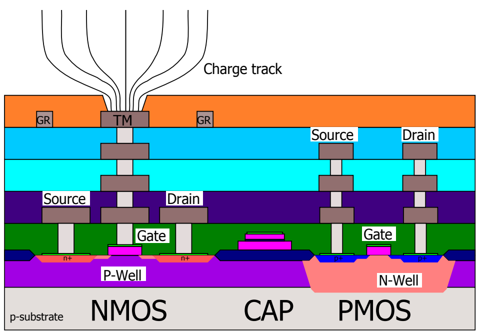
- GEM
- Array of micro-holes in thin foils with conductor cladding on both sides

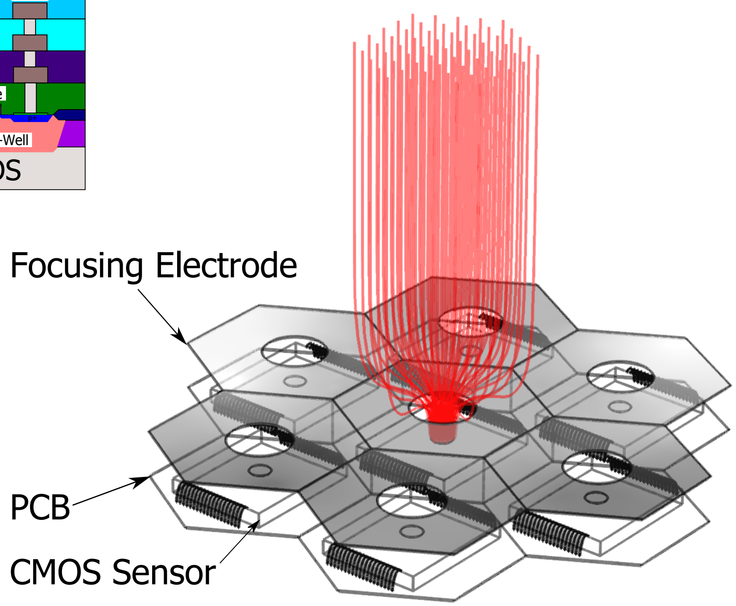
- μ-PIC (Micro Pixel Chamber)
- Printed Circuit Board technology

CMOS charge sensor array for TPC

No electron avalanche gain!







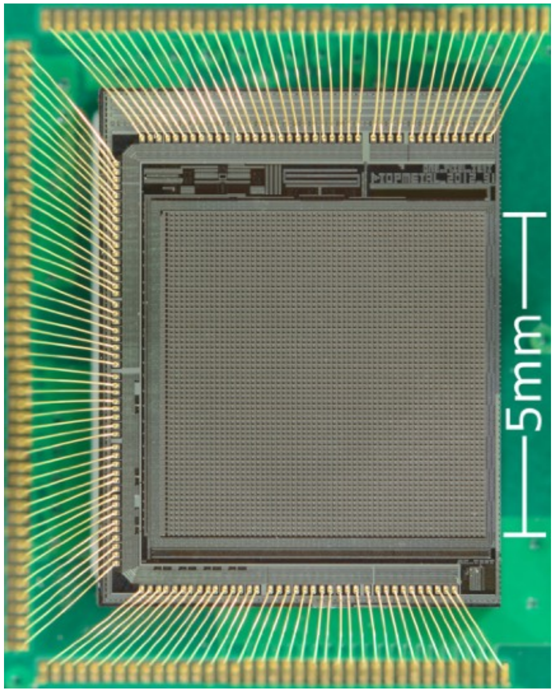
- Eliminate charge amplification
- Focusing electrode 100% coll. eff.
- Direct charge collection in X-Y
- In-sensor digitization
- Inter-sensor network for data readout

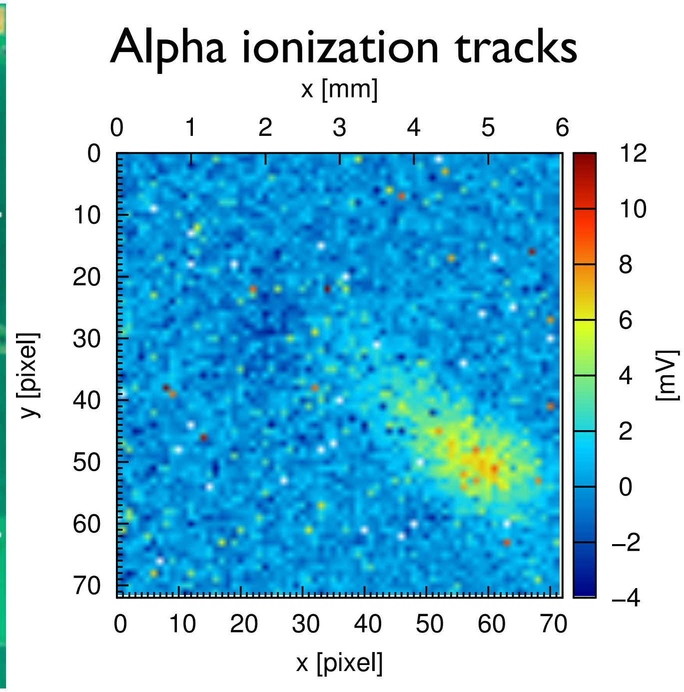
Numbers

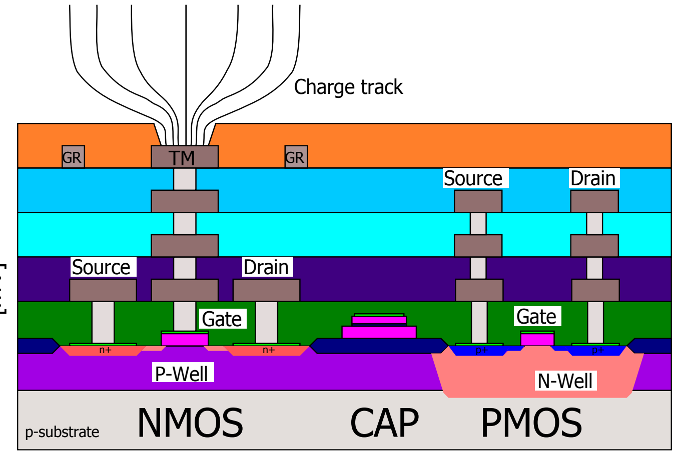
High pressure Xenon TPC as an example

- ~50 free ions/electrons per keV energy deposition
- ^{136}Xe $Q_{\beta\beta}$=2.458MeV → 100k charges
- 10bar Xe intrinsic energy resolution: 0.3% FWHM at $Q_{\beta\beta}$
  → 130 e^- total fluctuation (σ, detection medium contribution)
- 1% FWHM energy resolution at $Q_{\beta\beta}$ → 420 e^- fluctuation (σ)
  → 400 e^- electronic noise allowed (sum of all pixels)
- Track length 20~30cm → 300 pixels see charge if pitch 5~10mm
  → <30 e^- per pixel noise required
- 100% charge collection efficiency
  loss of efficiency is equivalent to increasing noise
- 10cm diameter array: ~100 chips
- 1m diameter array: ~10k chips
- Charge drifting speed (sets the sampling rate requirement)
  - Electron: mm/μs
  - Ion: mm/ms

Topmetal





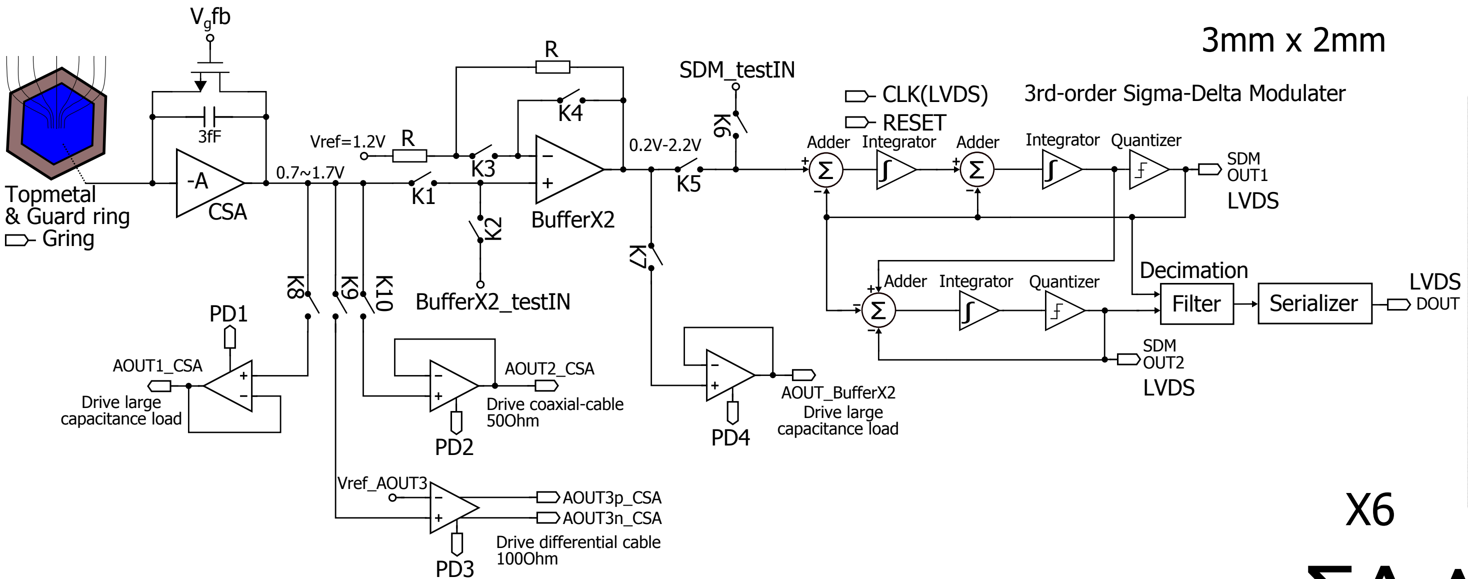


<u>Xiangming Sun</u>
Former LBNL RNC postdoc,
STAR HFT development until 2013
Now Professor, Director of Pixel Lab (PLAC)
Central China Normal University (CCNU)

<u>Yuan Mei</u>
LBNL NSD weak interactions
Postdoc (2011–2015)
Staff (2016–)

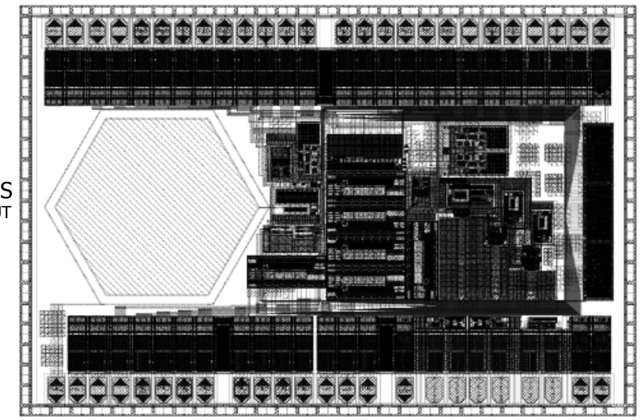
- 80×80μm pixel size
- Direct charge collection
- Standard 0.35μm CMOS process, no post-processing
- First version (2012), high noise & high bandwidth
- Second version (2014), <15e- noise on each pixel. In-chip signal processing, good for large scale array
- Third version (2016), specialized design for 0νββ

Topmetal-S (2016)



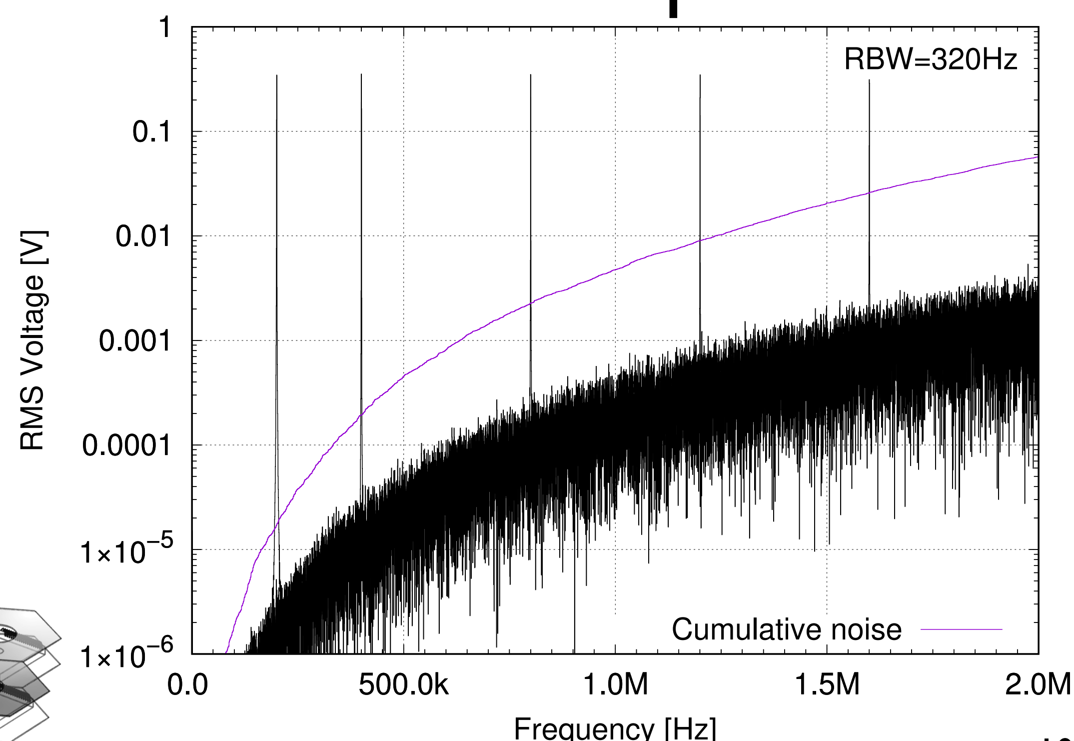
3mm x 2mm

chip layout



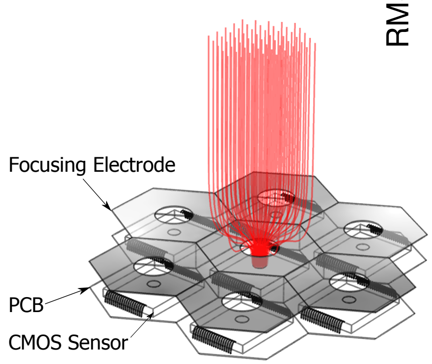
X6

ΣΔ ADC spectrum



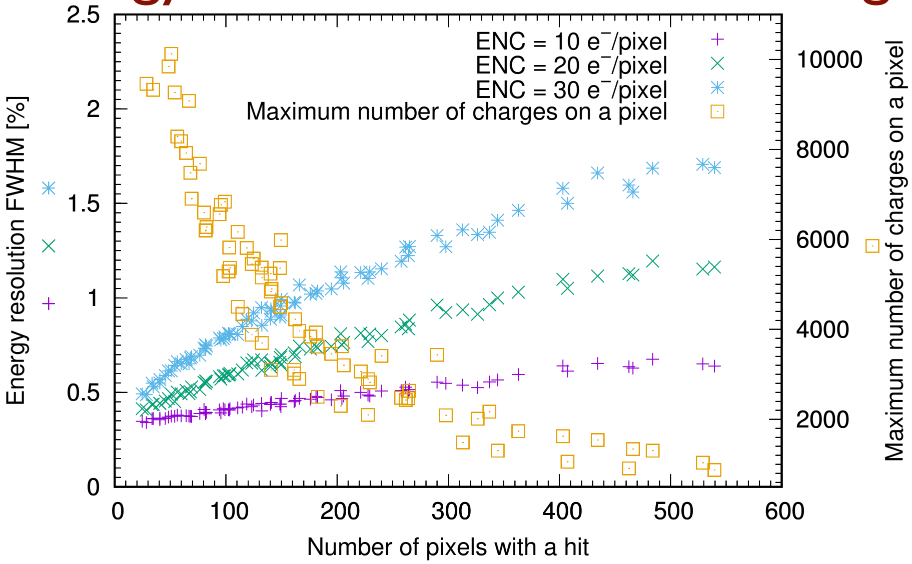
- Single electrode: 1mm dia. *Topmetal* or smaller electrode with externally `grown' structure
- Distance between chips: 5~10mm
- CSA: C_{in}~2pF, ENC<30e^-, tunable biases through DACs
- Tunable feedback RC decay constant
- Directly accessible analog output
- Analog output (X2) feeds into a Sigma-Delta ADC

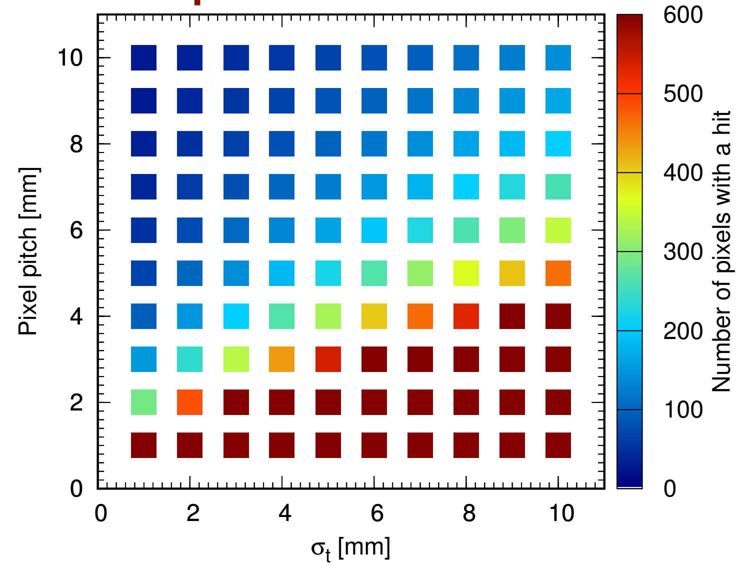
- 3rd-order Sigma-Delta Modulator
- 25.6MHz clock
- X64 over sampling rate
- SINC4 decimation filter
- 200kHz signal bandwidth
- Equivalent of a 400ksps 16bit ADC
- Raw modulator output
- LVDS I/O



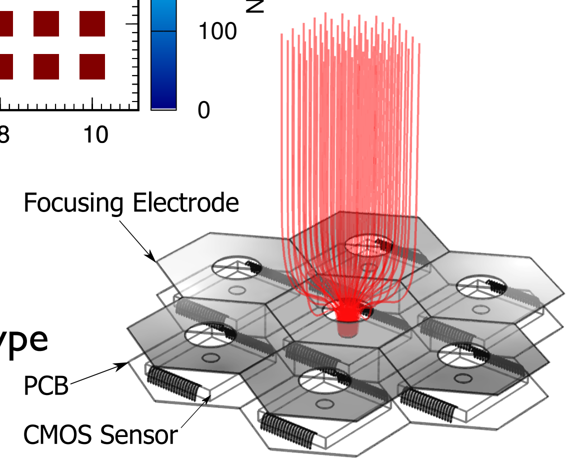
Design optimization (prototype)

Energy resolution: tradeoff among diffusion, pixel size and noise

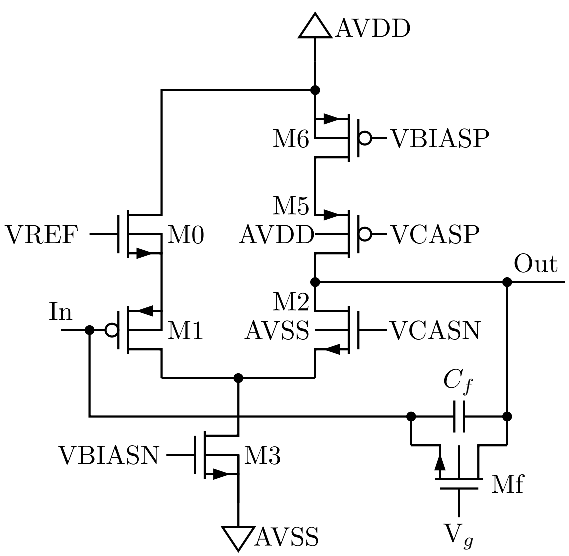


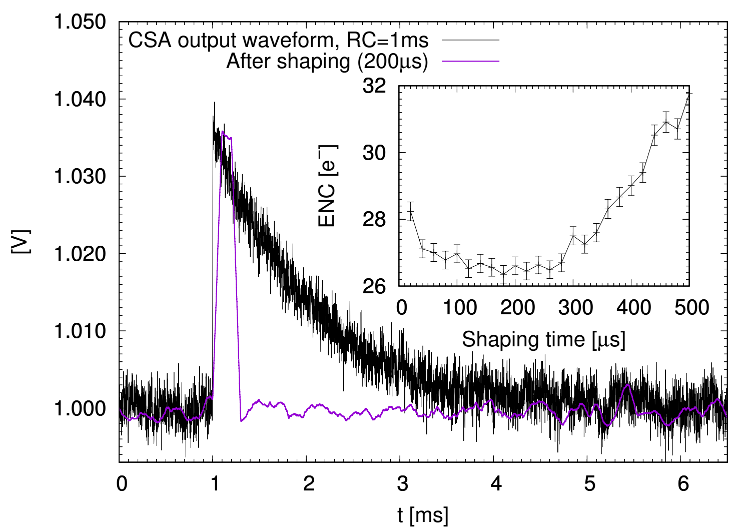


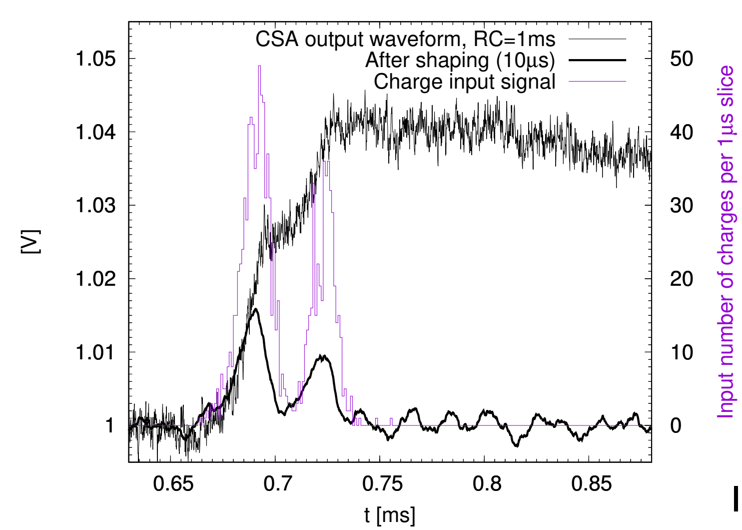
- 1mm dia. electrode
- 8mm pitch
- 127 chips on prototype



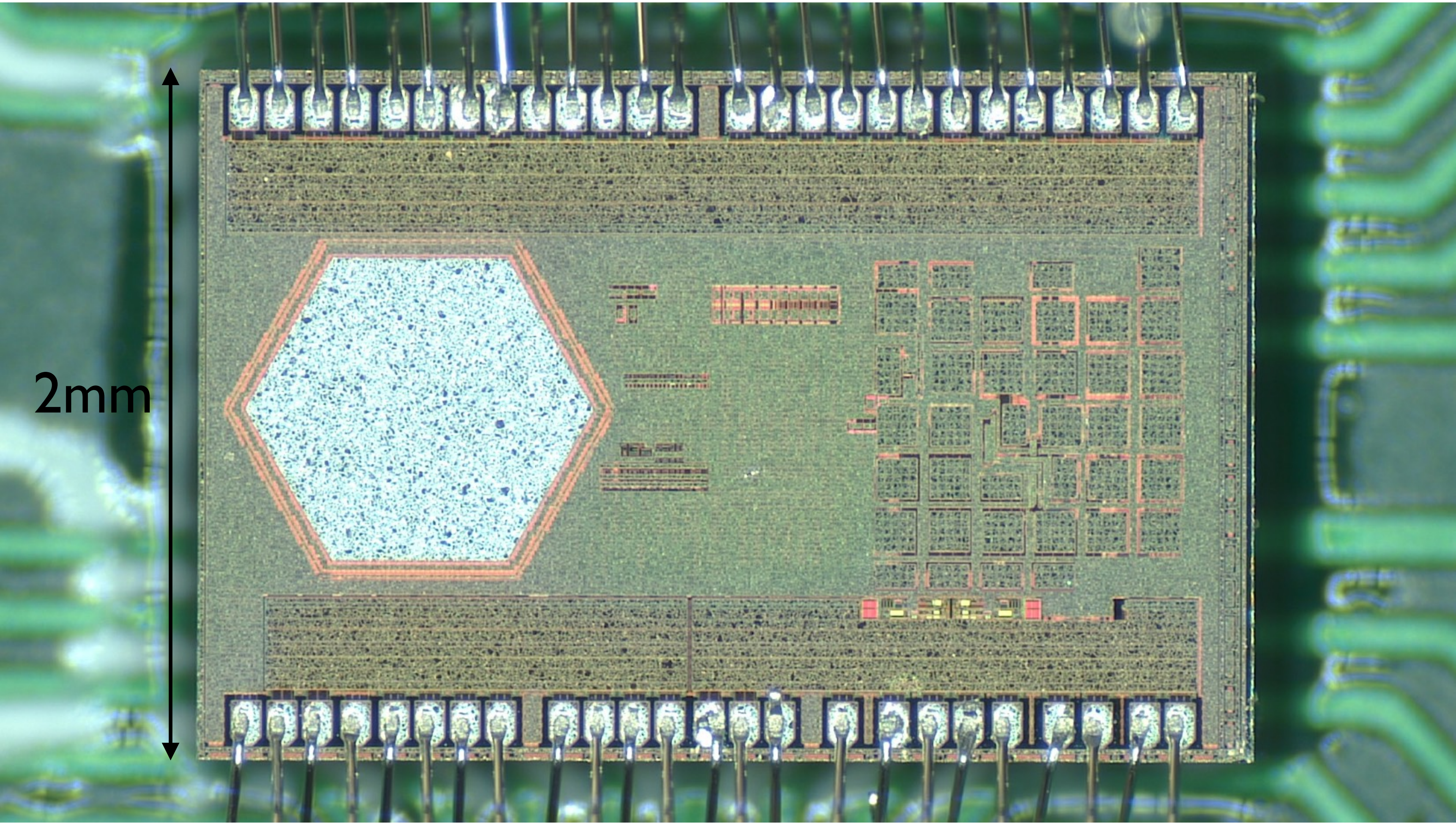
Charge measurement, noise, and signal recovery







Topmetal-S with 1mm electrode

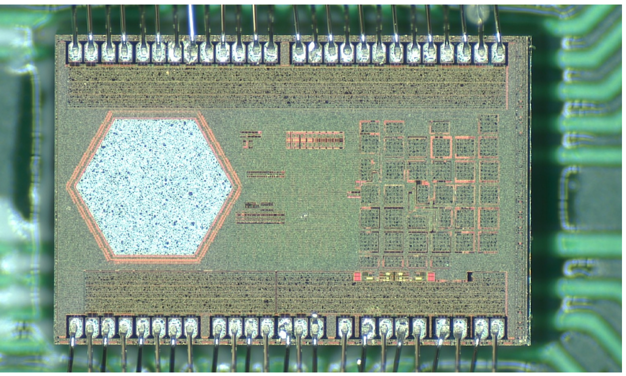


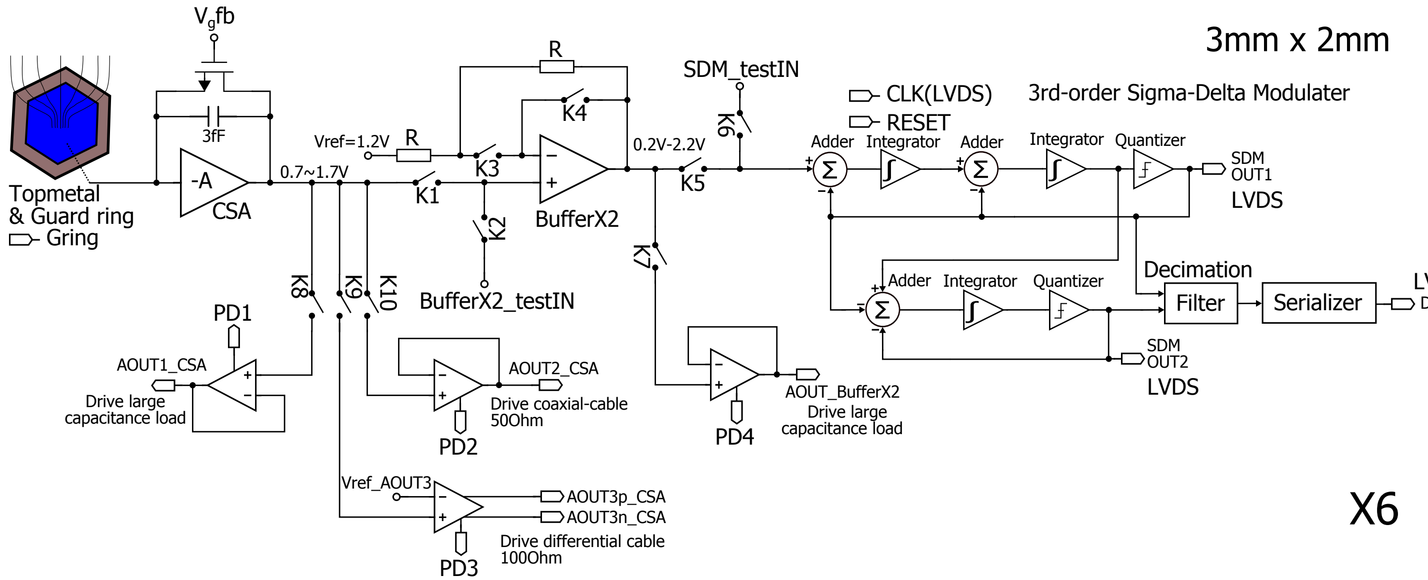
2mm

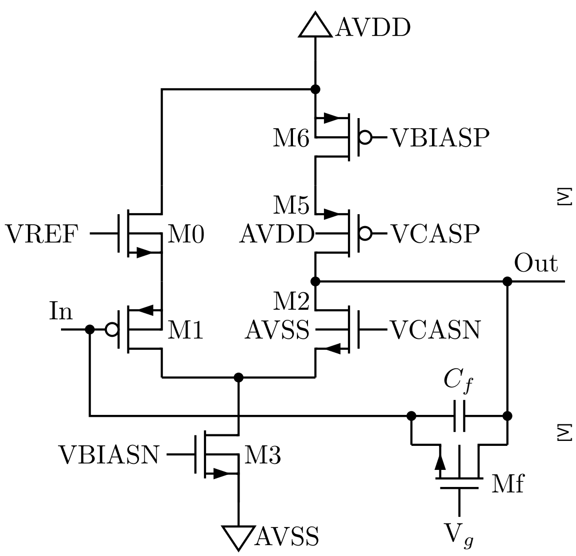
3mm

Topmetal-S Performance

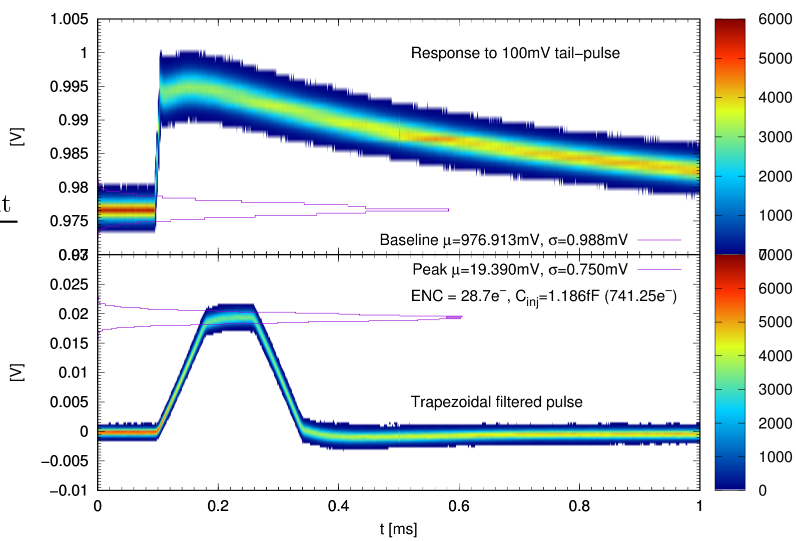
A working *Topmetal-S* sensor



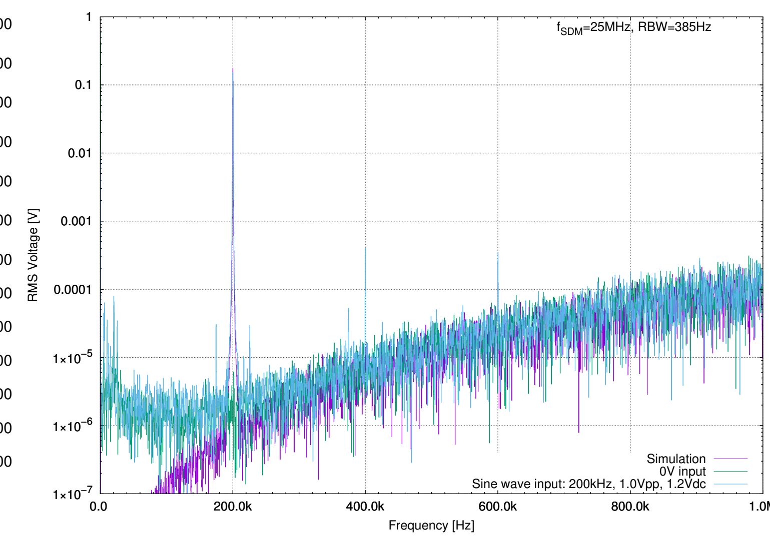




$< 30e^-$ noise CSA

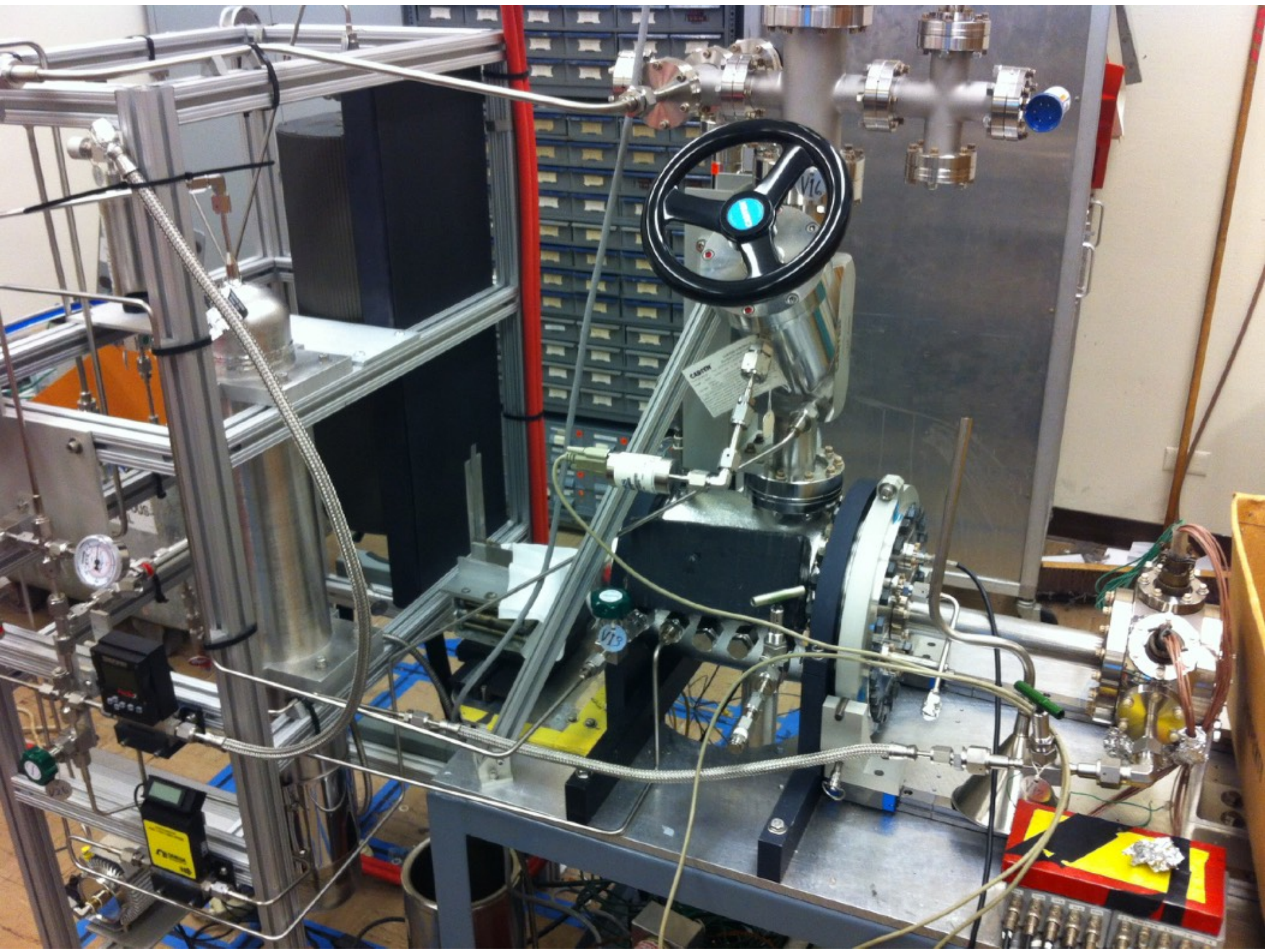


Working ΣΔ ADC

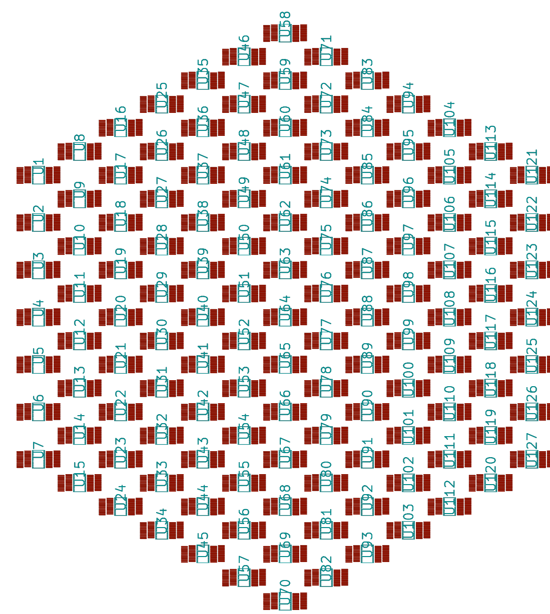


High pressure gas TPC prototype

Gas system

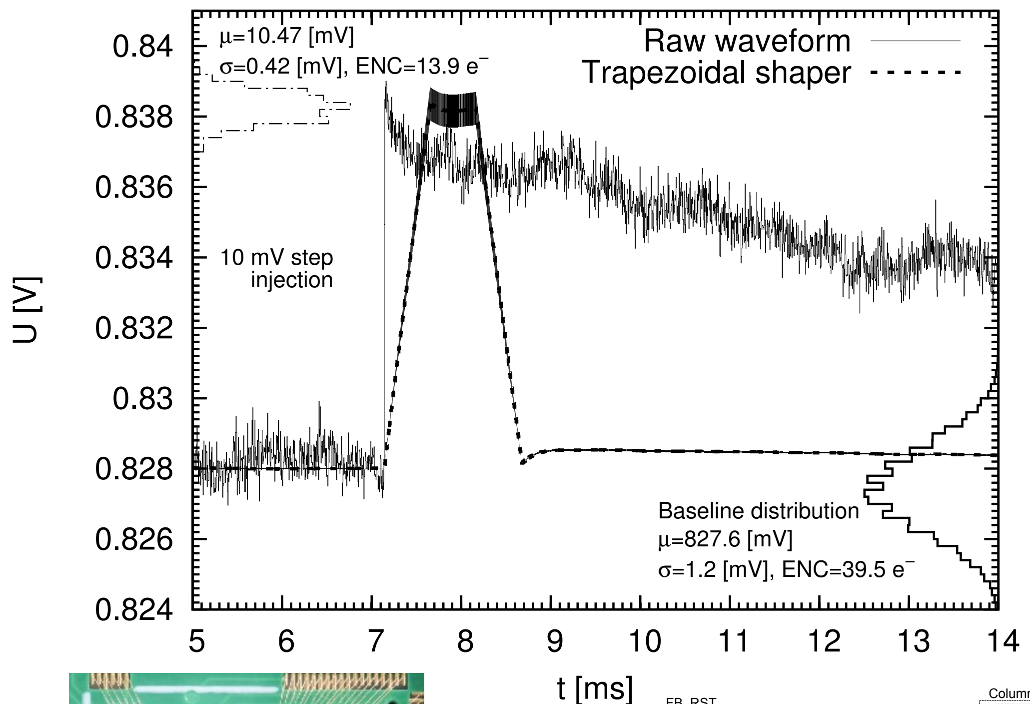


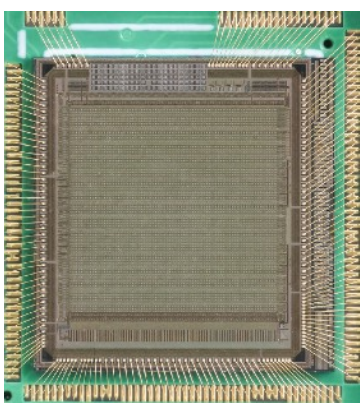
Charge plane:
127 chips, Φ10cm

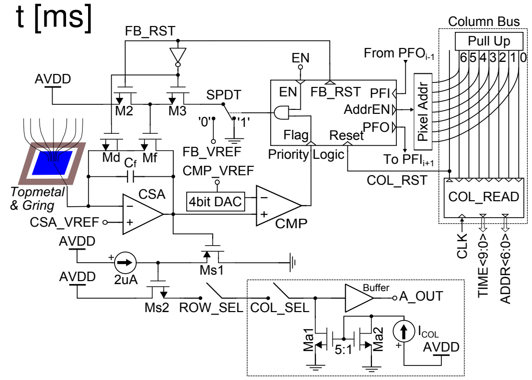


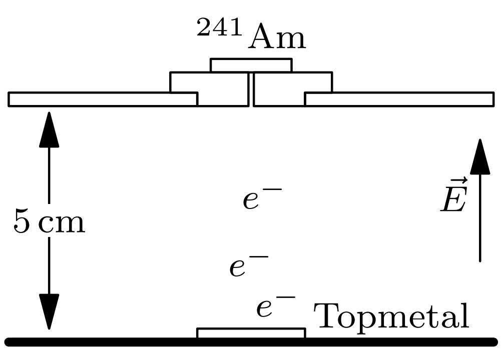
- 1mm dia. electrode
- 8mm pitch
- 127 chips on prototype

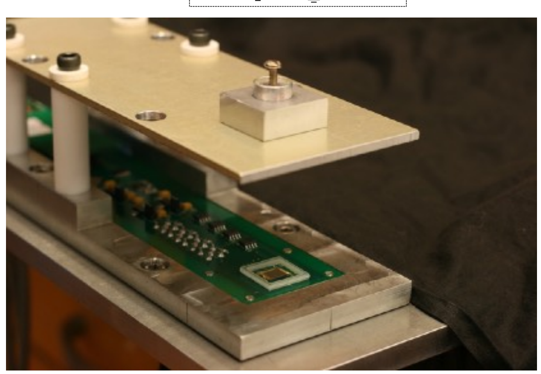
Topmetal-II⁻ seeing alpha (ion) tracks in air

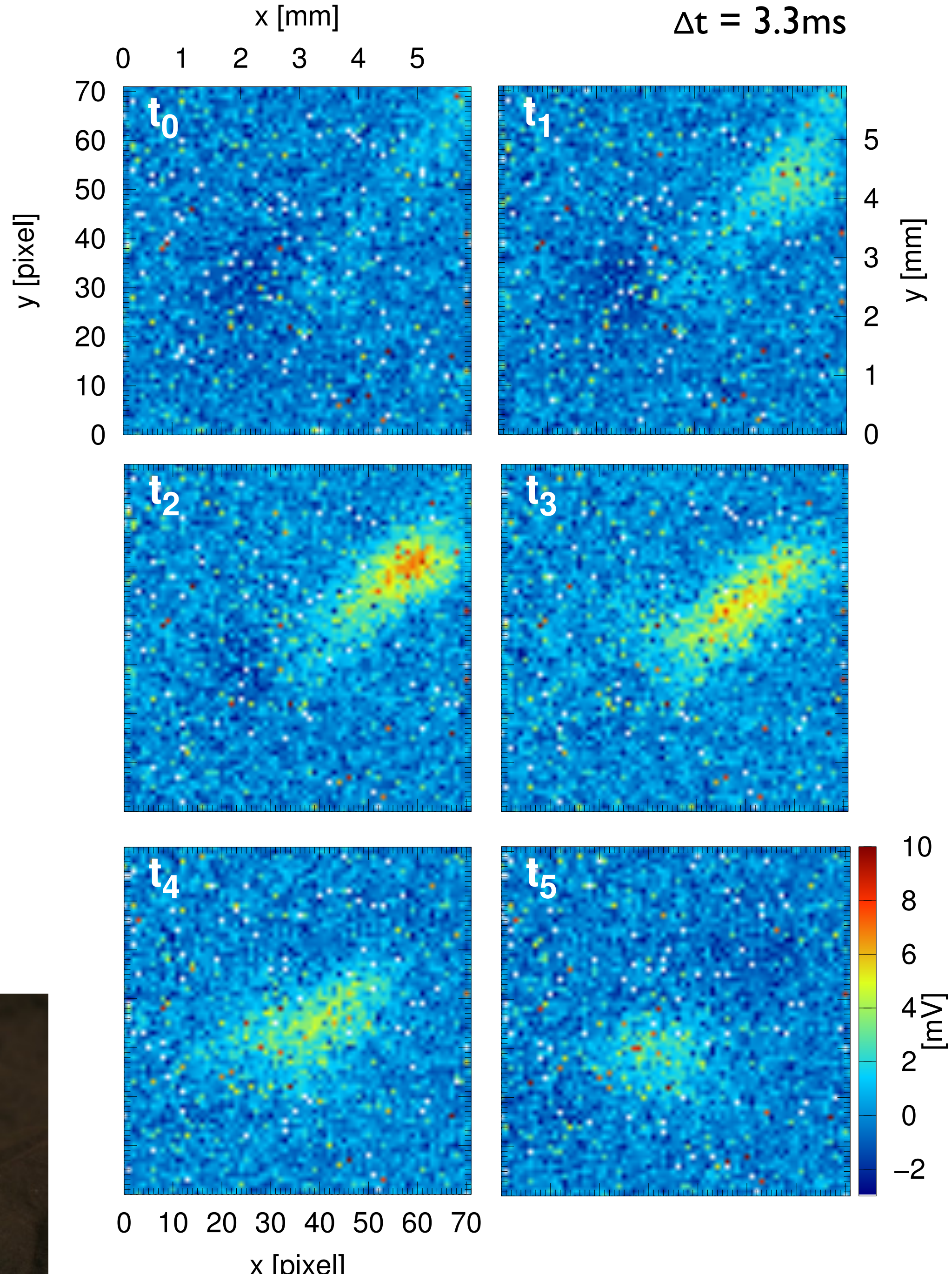












NIMA 810, 144, 2016

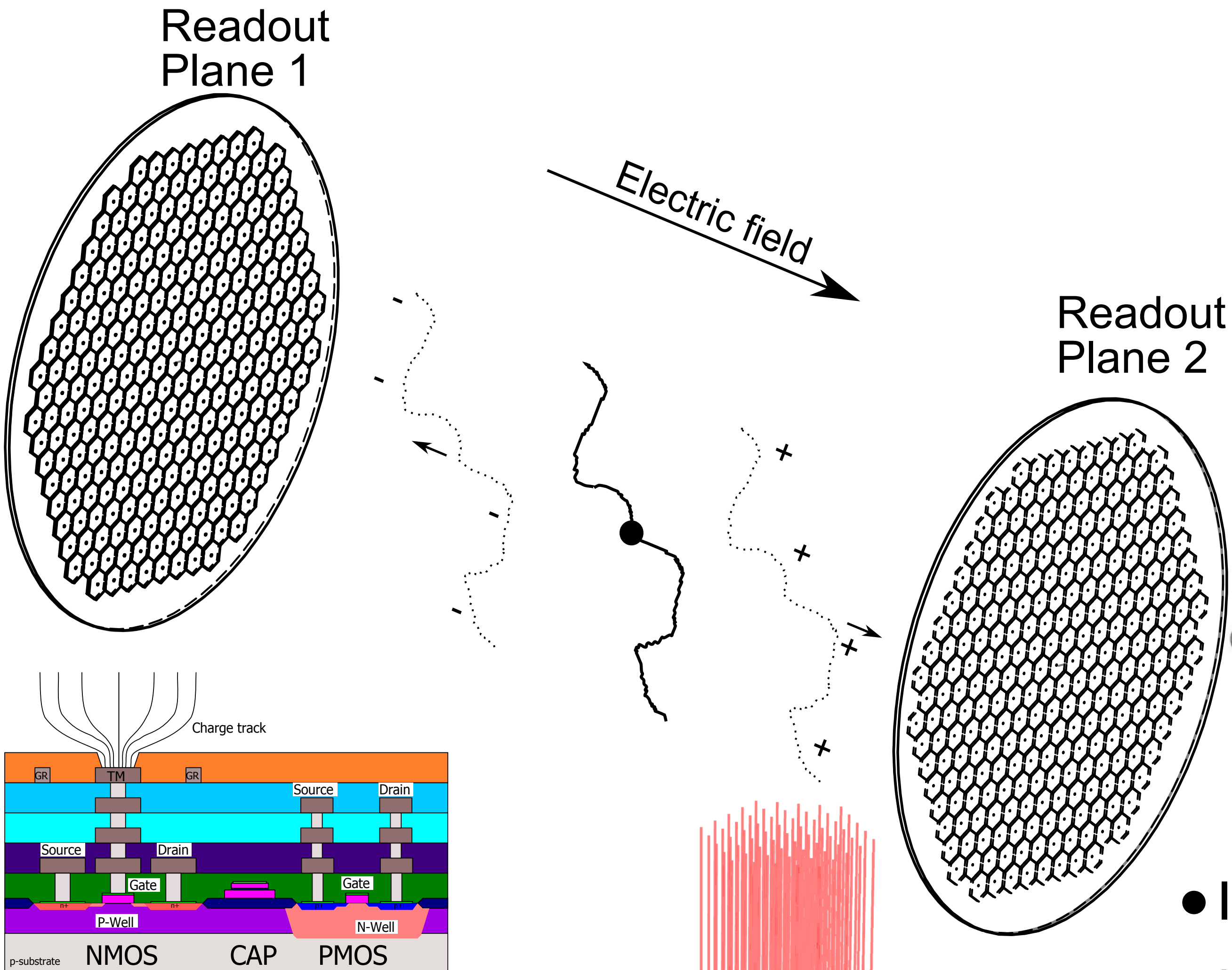
SeF_6 gas for 0νββ in ^{82}Se

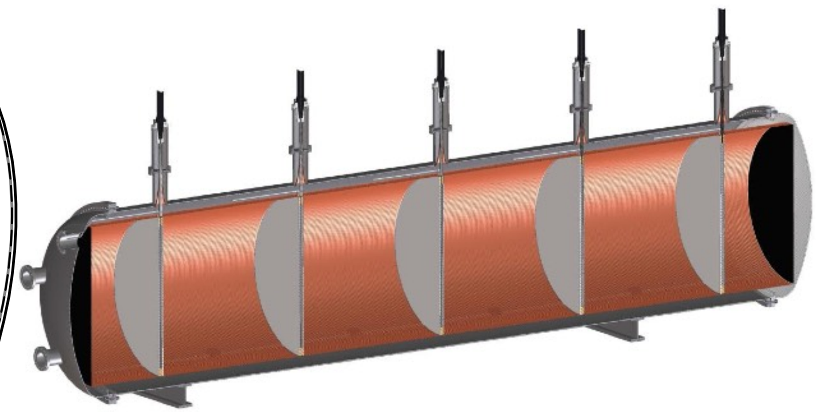
- ^{82}Se
  - High $Q_{\beta\beta} \approx 2995.5$keV
    - $Q_{\beta\beta}$ for ^{136}Xe is 2458keV
  - A sharp drop in γ-ray backgrounds occurs above the ^{208}Tl (2615keV) line
- SeF_6
  - Used in early days of HV electrical insulation
  - Easy to enrich ^{82}Se (9% natural abundance)
  - Low effective Z : straighter tracks – better tracking
  - Highly electronegative – ion drifting only
  - Cannot sustain well-behaved avalanche gain

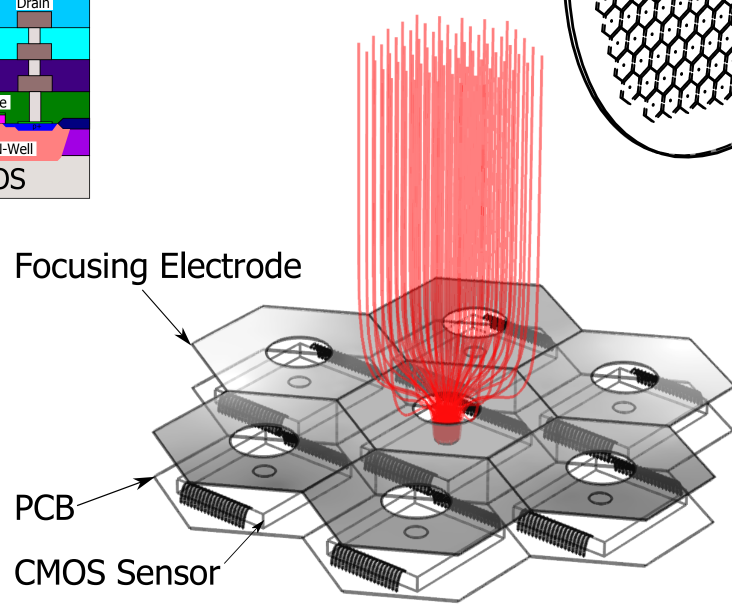
Must detect ions directly in gas

Credit: D. Nygren

Topmetal gain-less charge readout for 0νββ in $^{82}SeF_6$







- Ion drifting
- No charge amplification
- Direct charge collection in X-Y
- Z is determined by the +/- charge arrival time difference
- Tandem TPC

Summary

- *Topmetal* direct charge sensor, without gas avalanche gain:
  - 1% FWHM energy resolution charge readout in HP Xe gas without sacrificing tracking
  - Very scalable leveraging electronics industry
  - Upgrade to PandaX-III, NEXT etc.
- Direct ion detection enables the use of SeF_6 gas
  - Provide an alternative isotope ^{82}Se.
  - Higher $Q_{\beta\beta}$ and better signal identification
  - Potential Xe/SeF_6 gas swap without modifying the rest of the system