GammaTPC: a powerful new MeV gamma ray instrument concept

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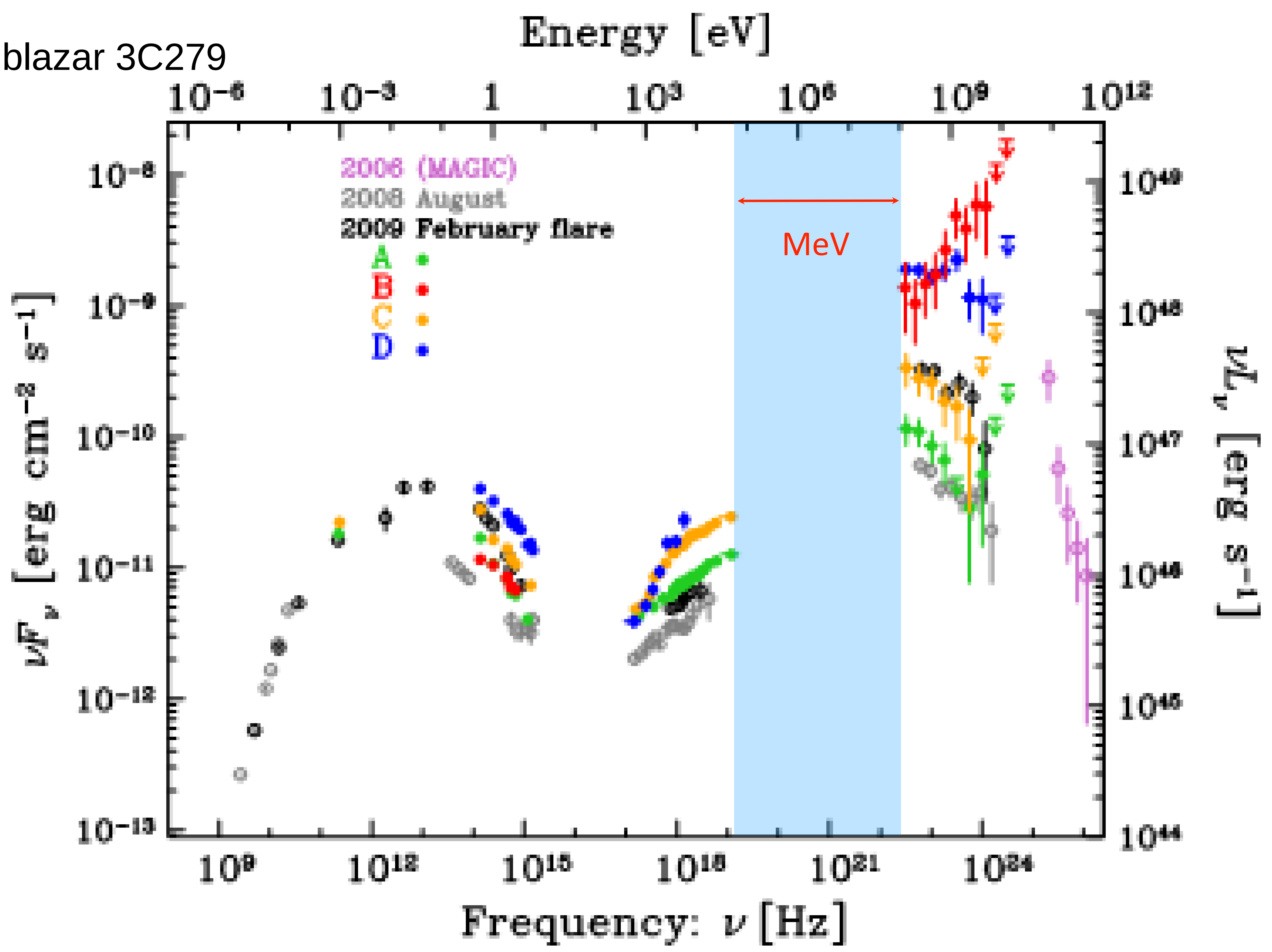
17th Marcel Grossmann Meeting

The unexplored MeV Gamma Ray Sky

blazar 3C279

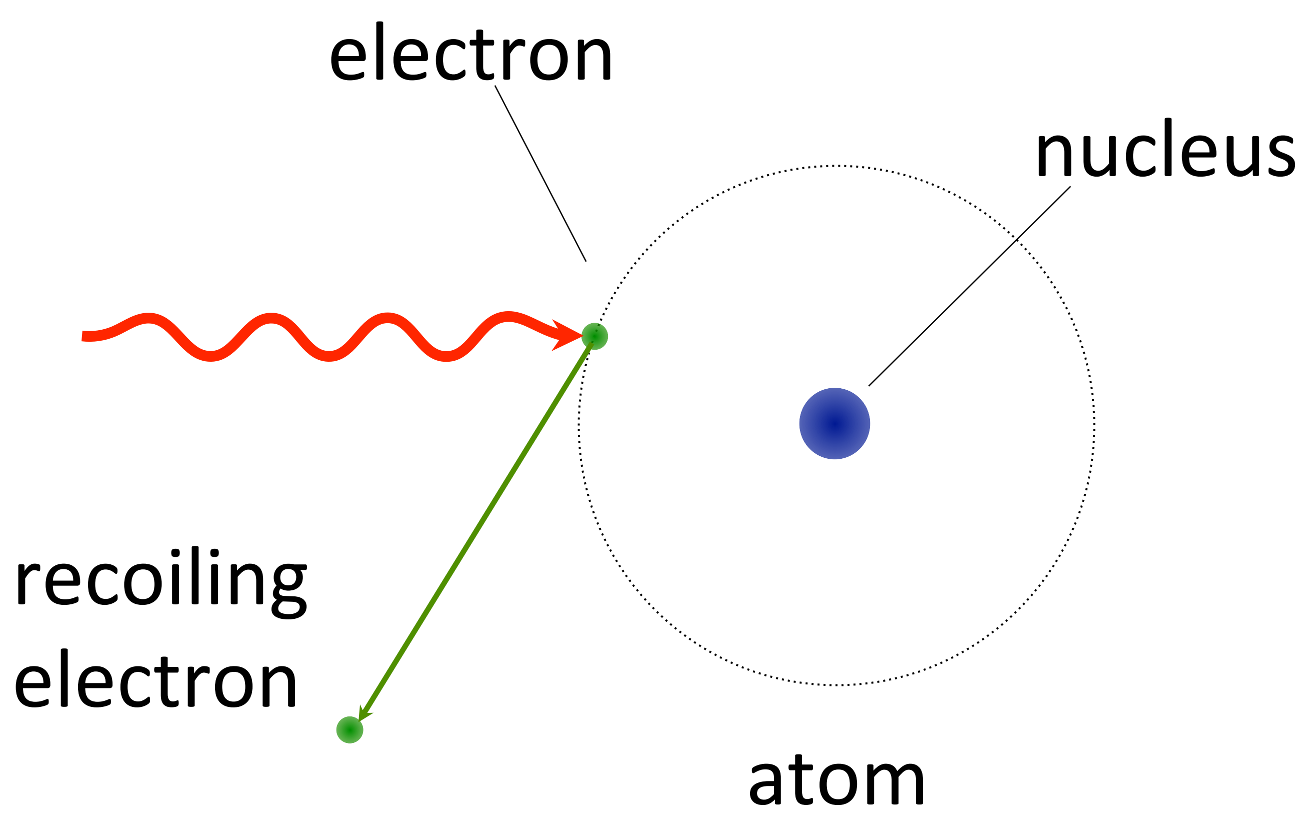


Astrophysics Opportunities

- Millisecond Pulsar Timing Array - Gravity Waves, H_o
- Excellent transients, multi-messenger
- GW NS mergers - bright at MeV
  - Possibly: r-process in real time with nuclear lines
- Huge population of Gamma Ray bursts.
- AGNs
- Acceleration mechanism: transition from synchrotron radiation to inverse Compton
- Good polarization sensitivity: magnetic fields
- Nuclear lines

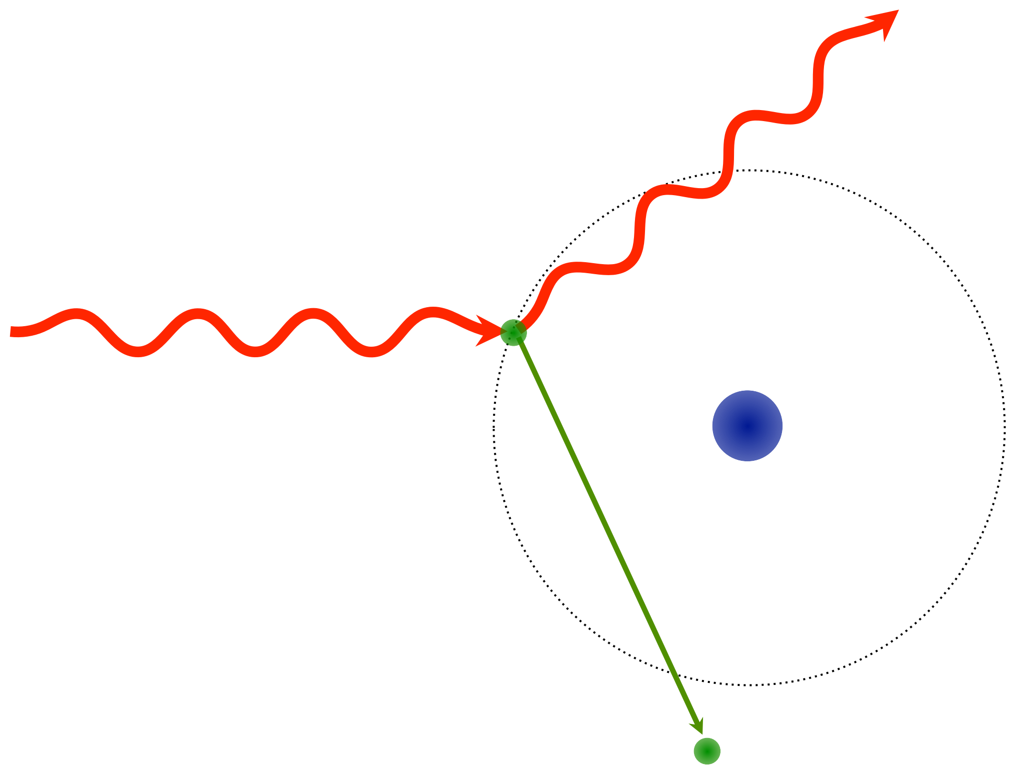
photo-absorption

$E_{\gamma} \lesssim E_{atomicbinding}$



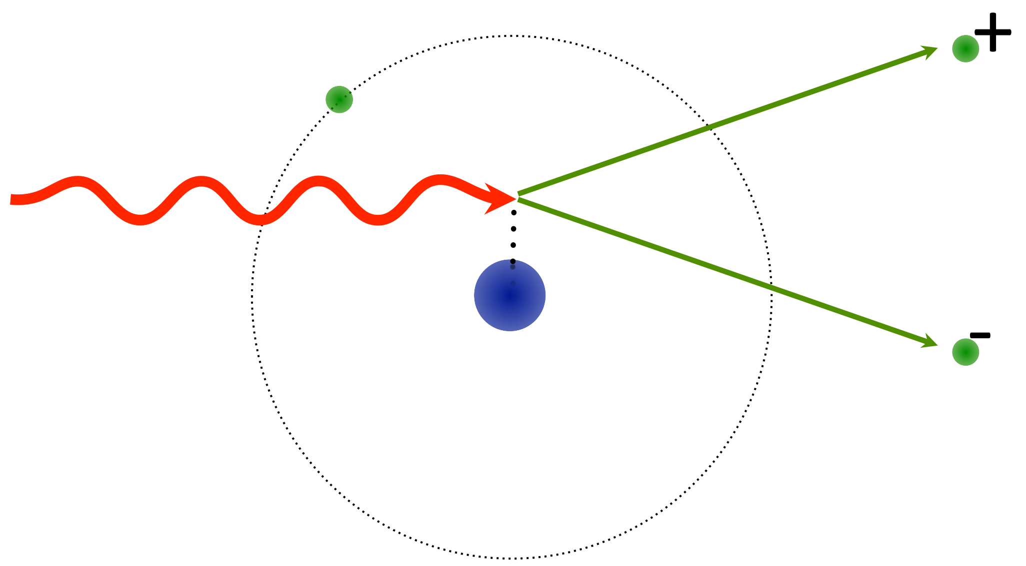
Compton scattering

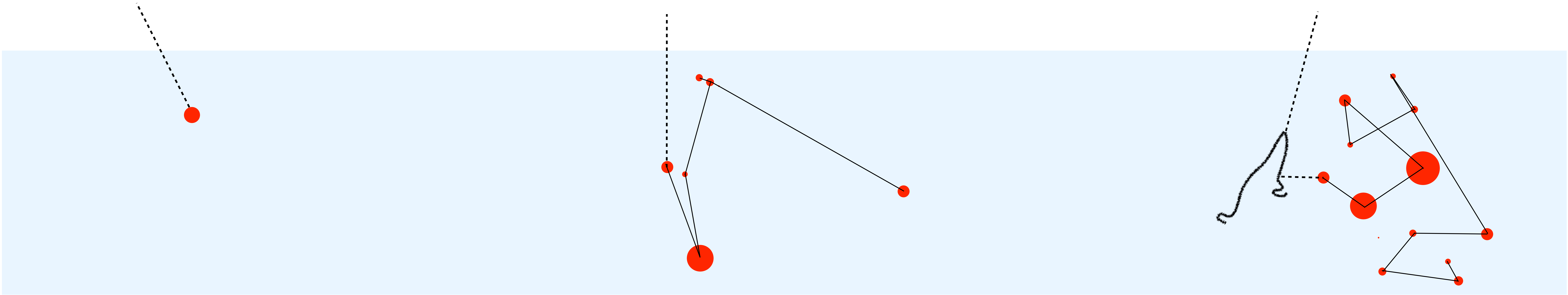
$E_{atomicbinding} < E_{\gamma} < 2m_{e}c^{2}$



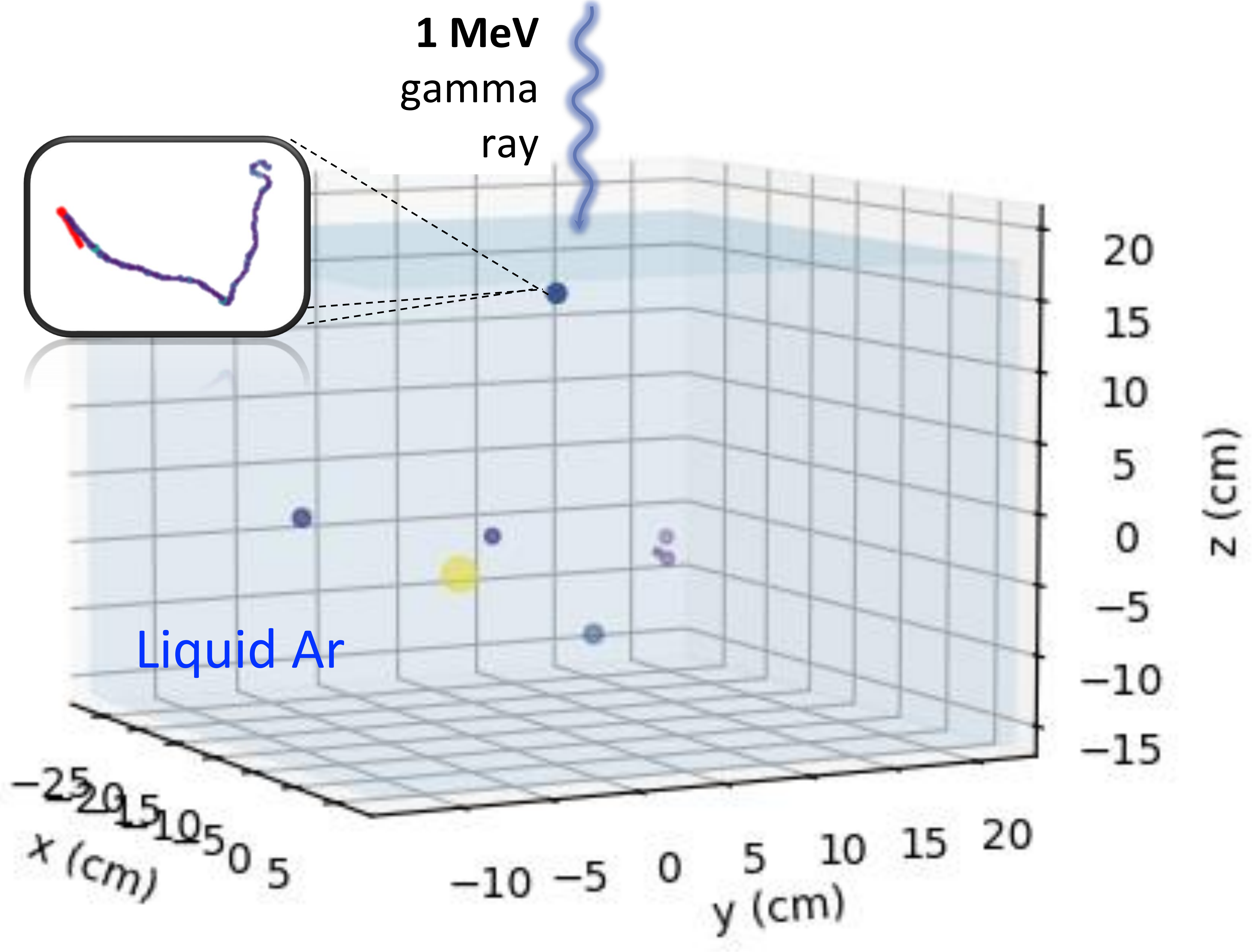
electron-positron pair production

$E_{\gamma} \gg 2m_{e}c^{2}$





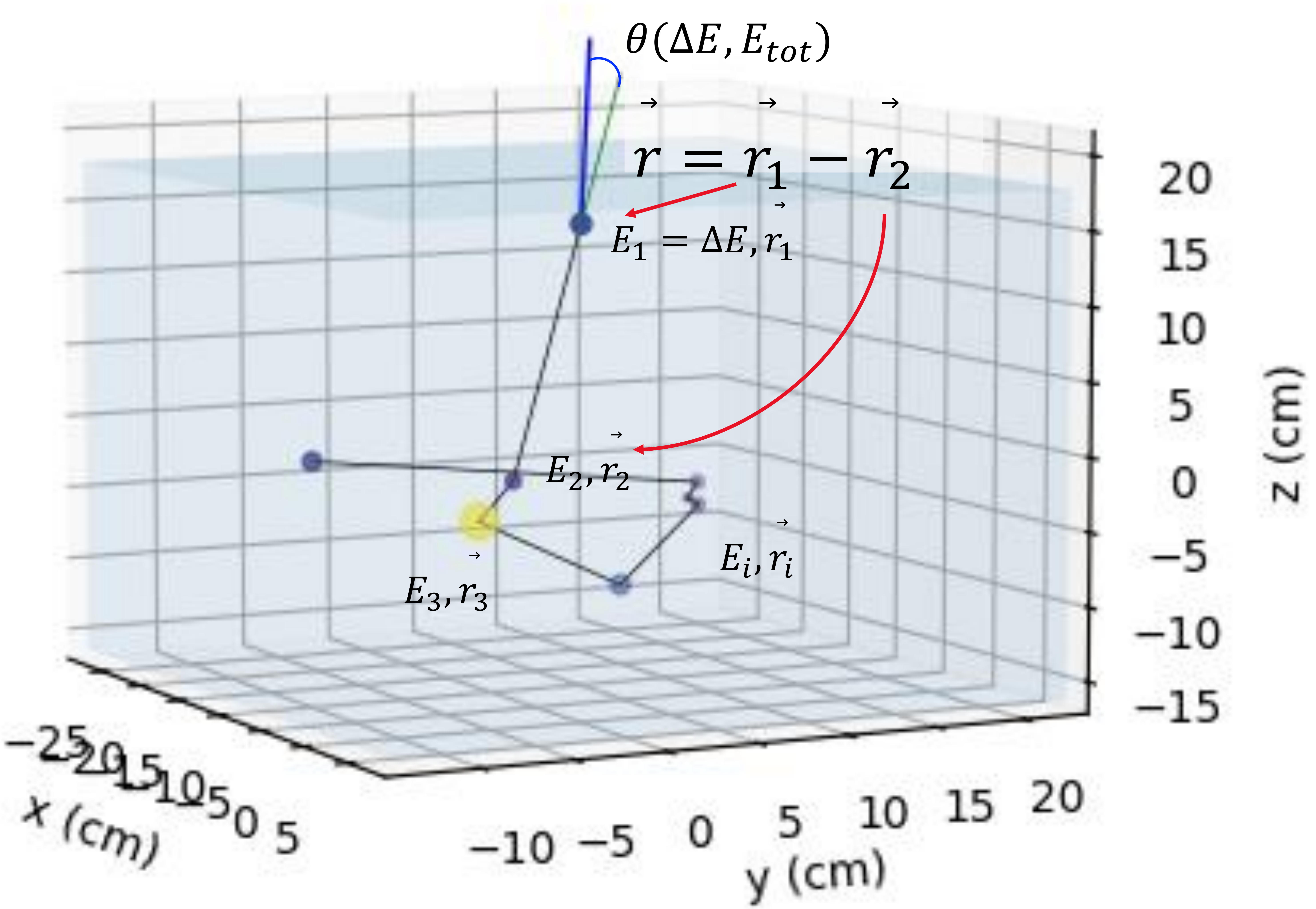
MeV gamma ray measurement



- Gamma ray with multiple Compton scatters, final absorption.
- Each creates recoiling electron track.
- Circle sizes indicate recoil energies.

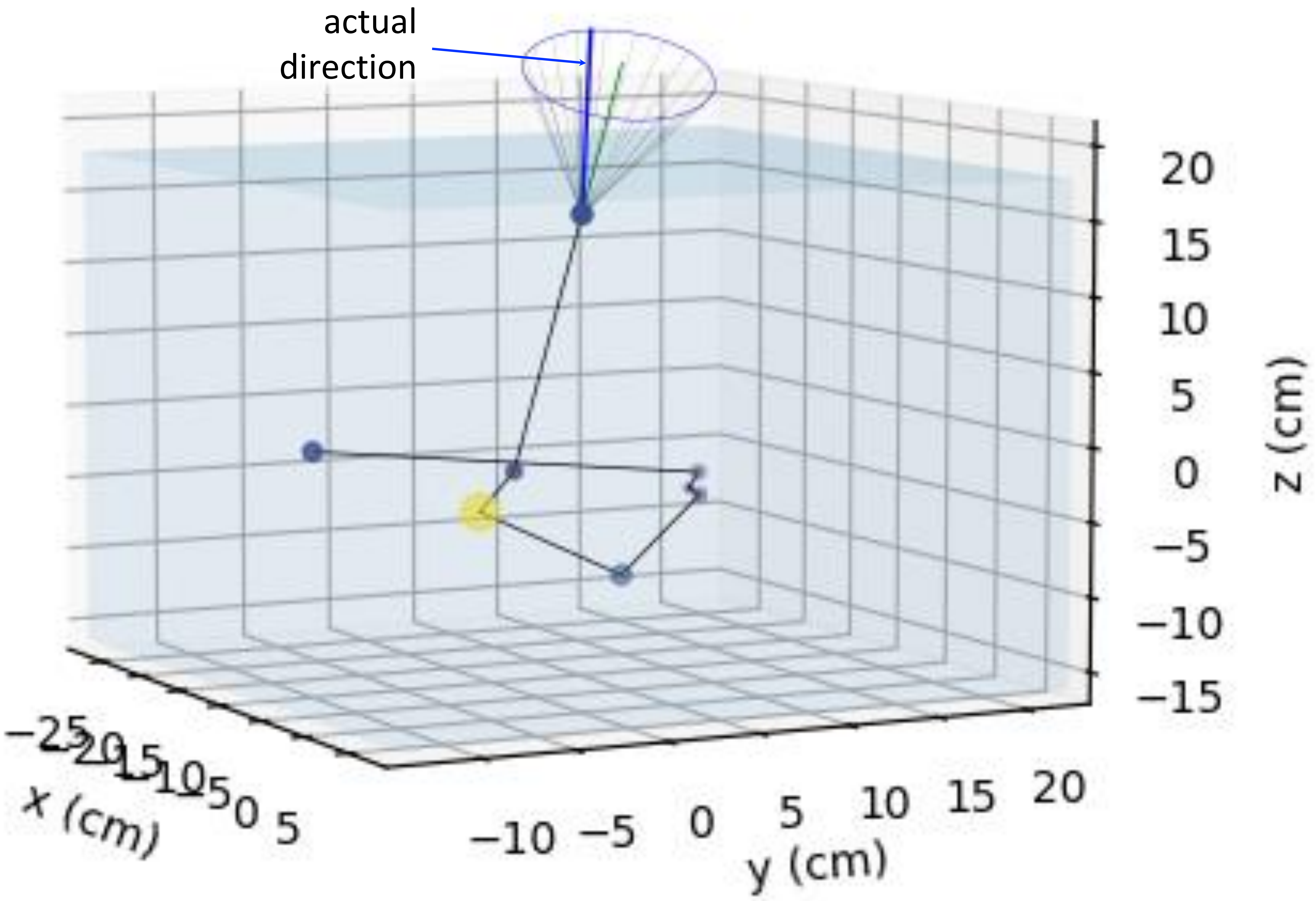
A difficult problem

MeV gamma ray measurement



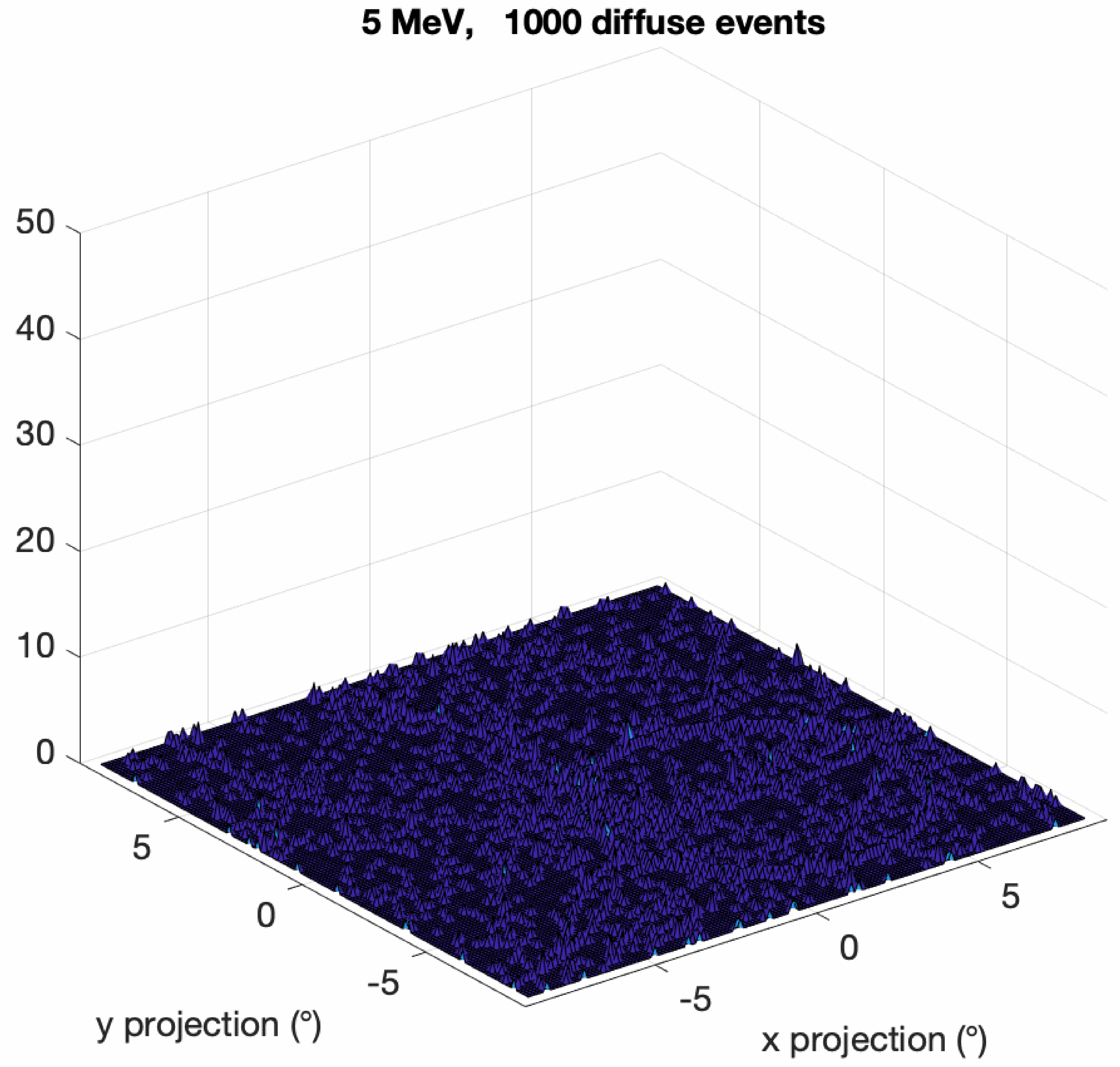
- Measure all $\{E_i, \vec{r}_i\}$
- Deduce sequence
- Now have $\vec{r}$, and θ.

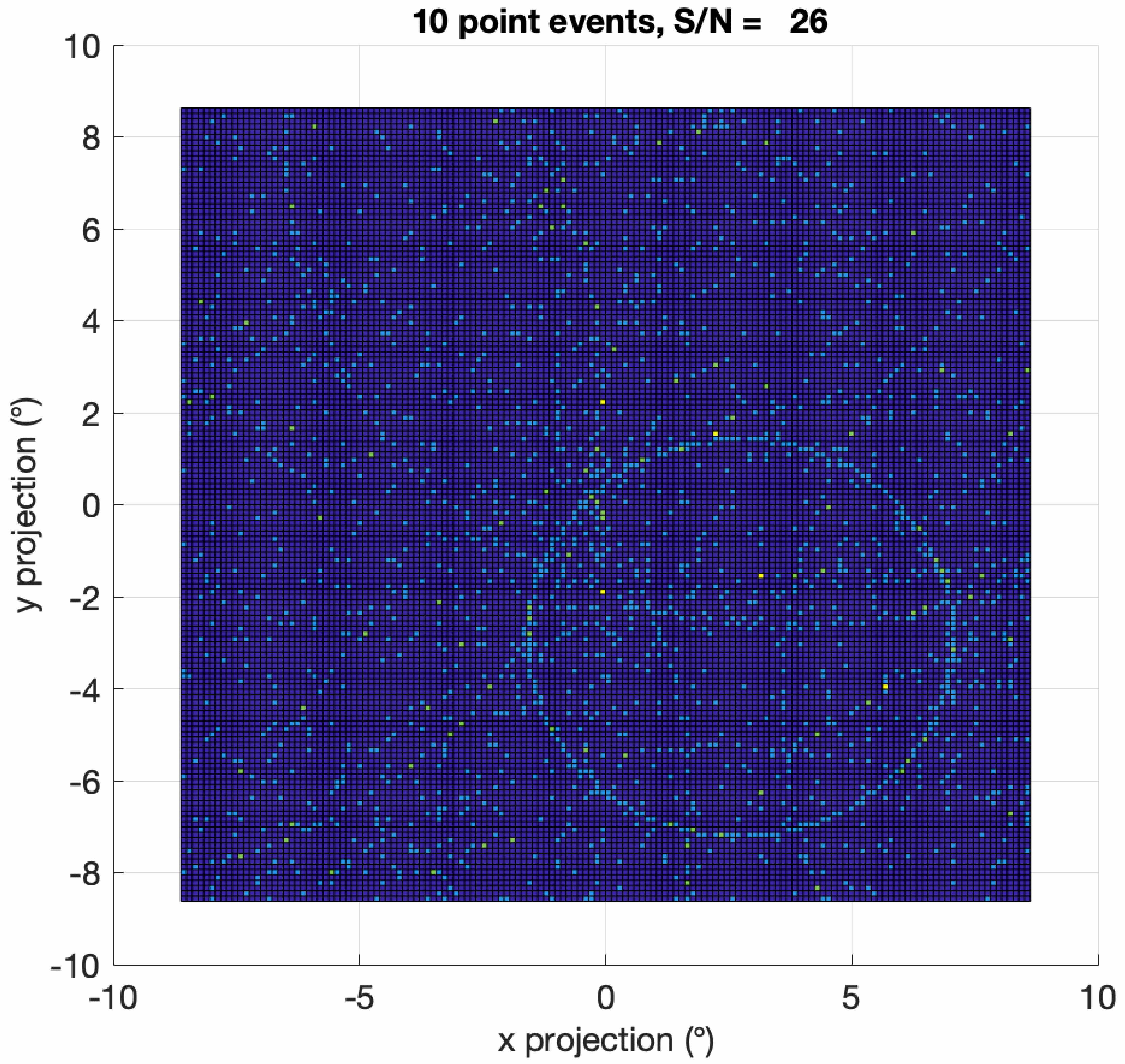
MeV gamma ray measurement



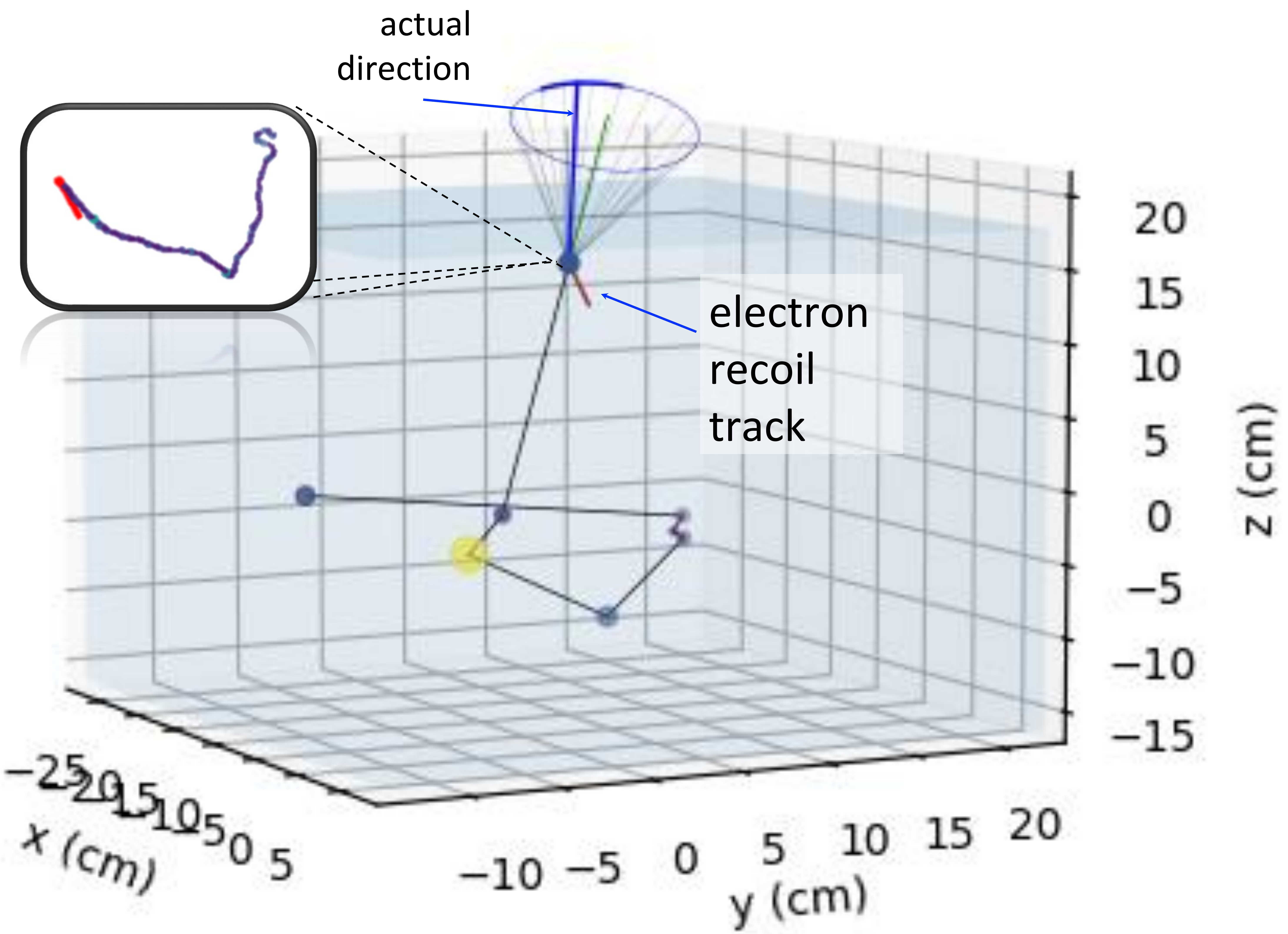
Circle of possible gamma ray directions. 😡

Sky map from point source with some background

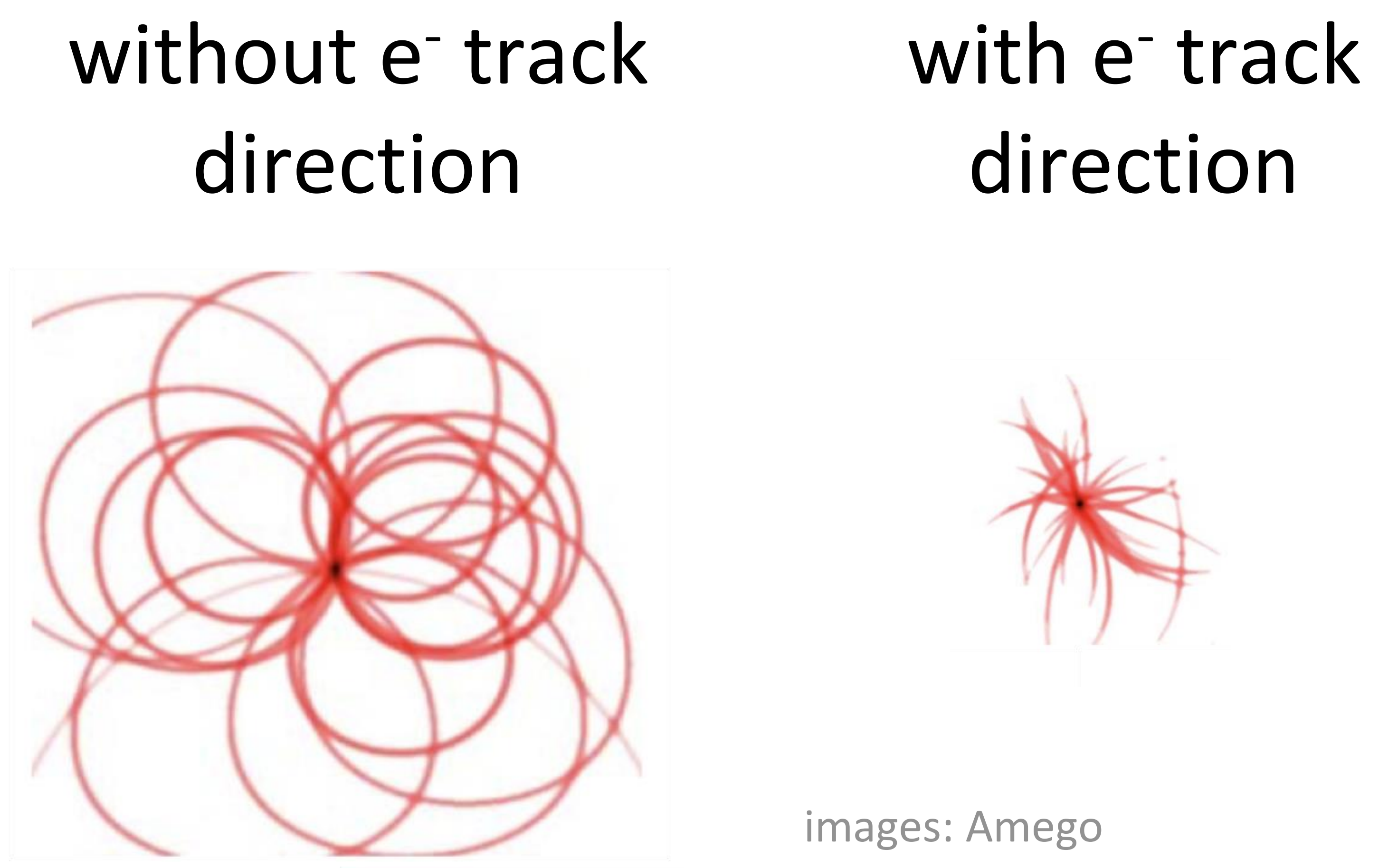




If the initial electron recoil direction is measured



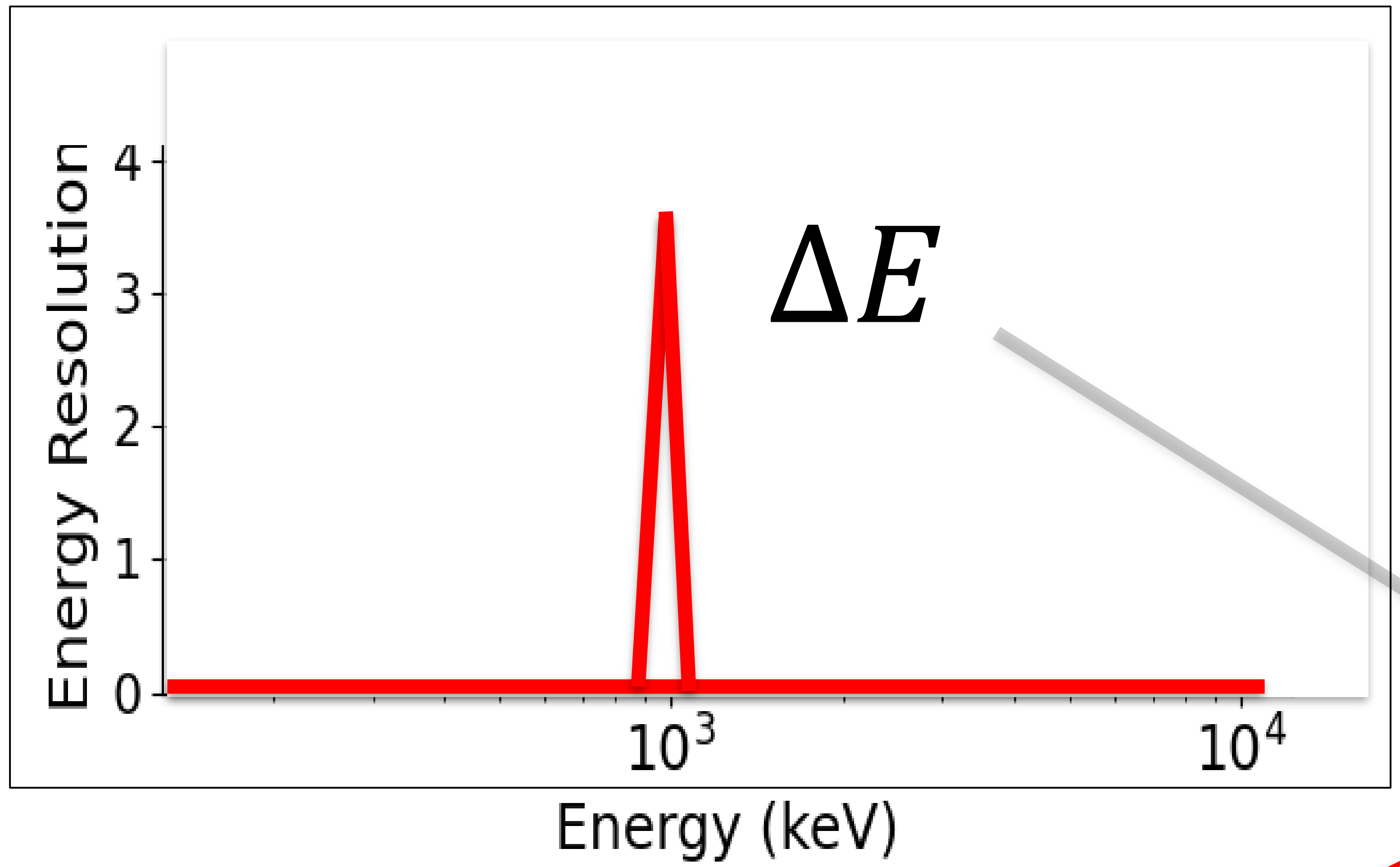
- Reduces circle to an arc
- Significant reduction in confusion



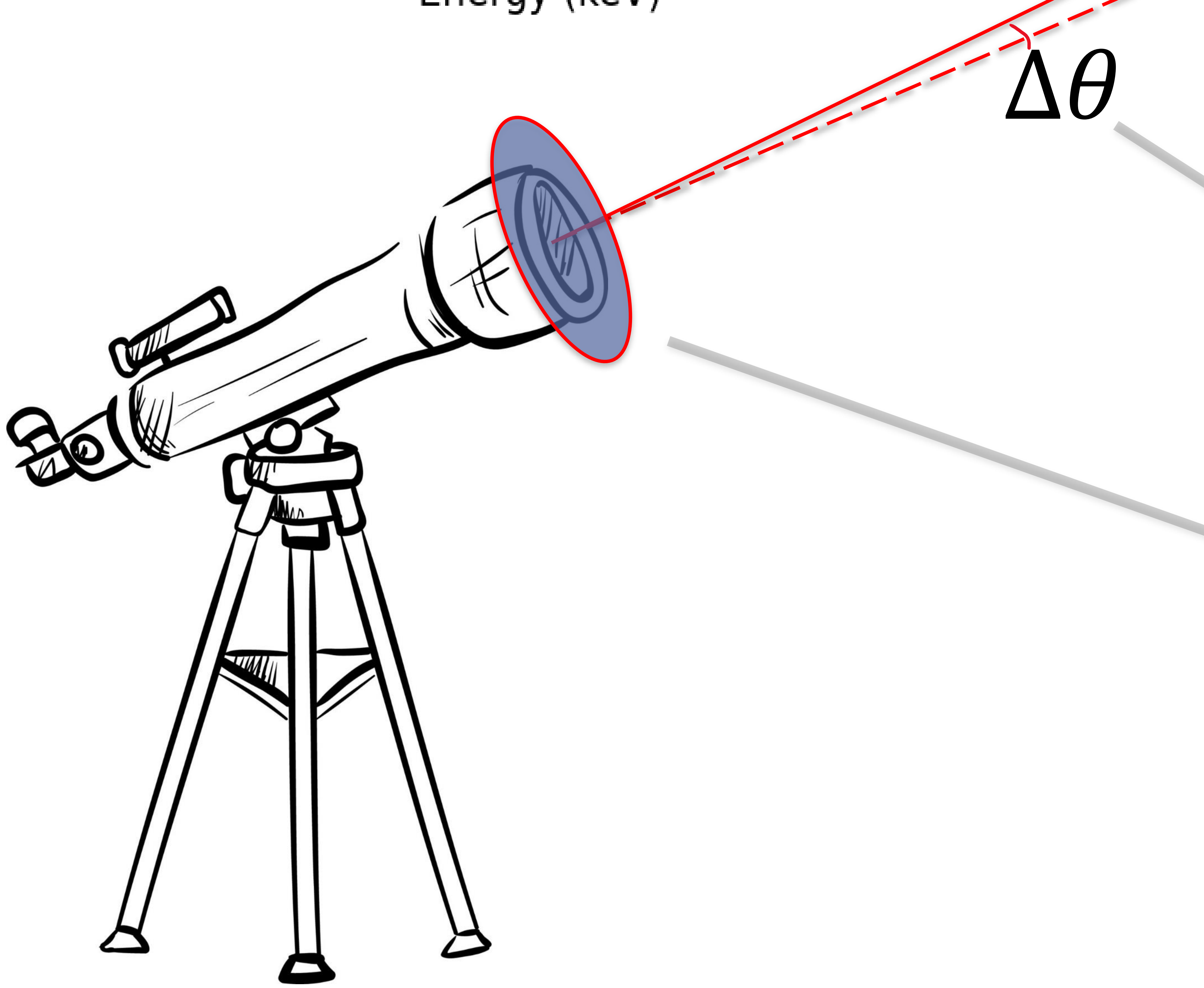
images: Amego

- More on this later

Telescope Performance



Far Field **Monoenergetic Point** Source



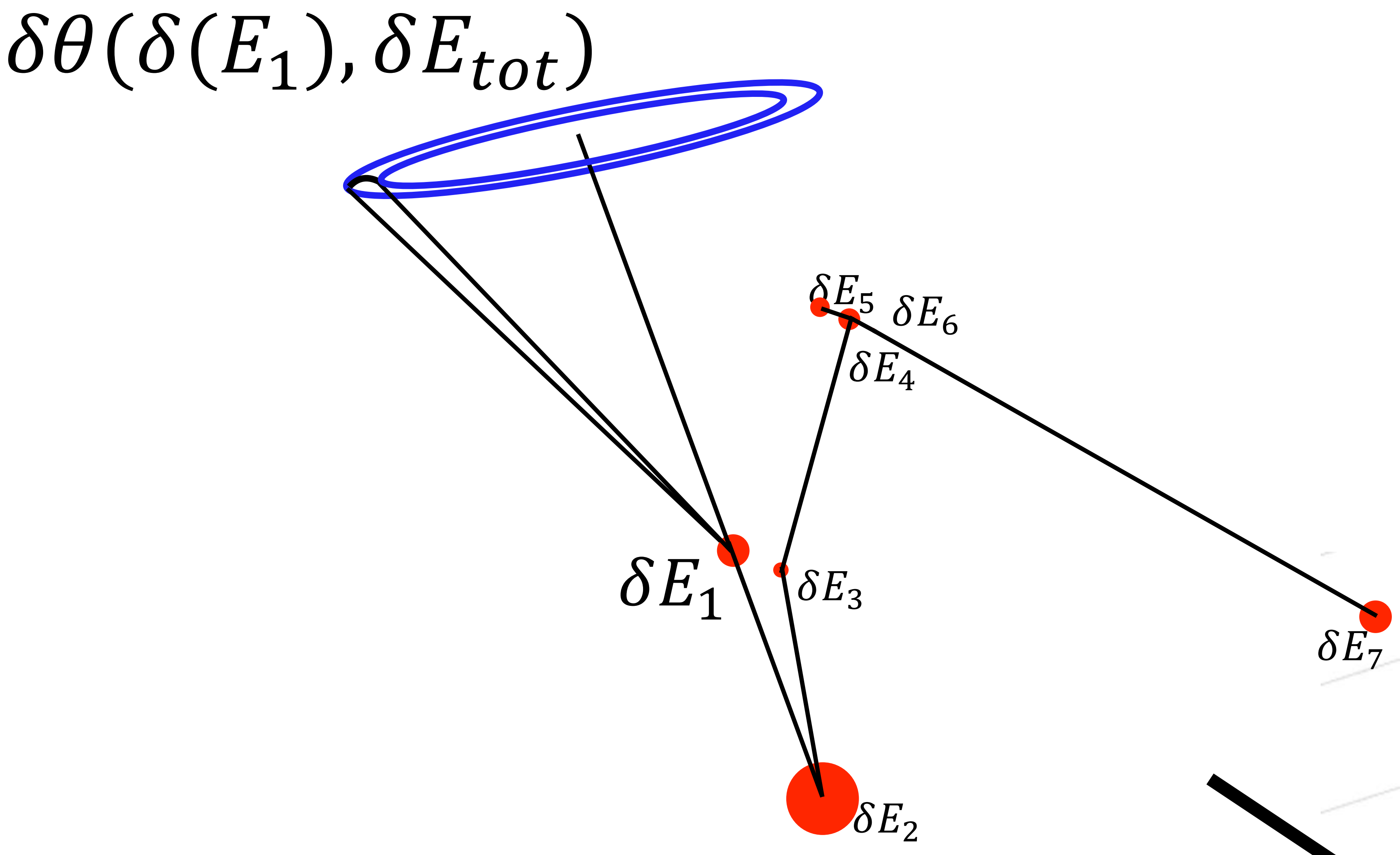
1. Energy Resolution
2. Angular Resolution
3. Effective Area
4. Background Signal

Sensitivity

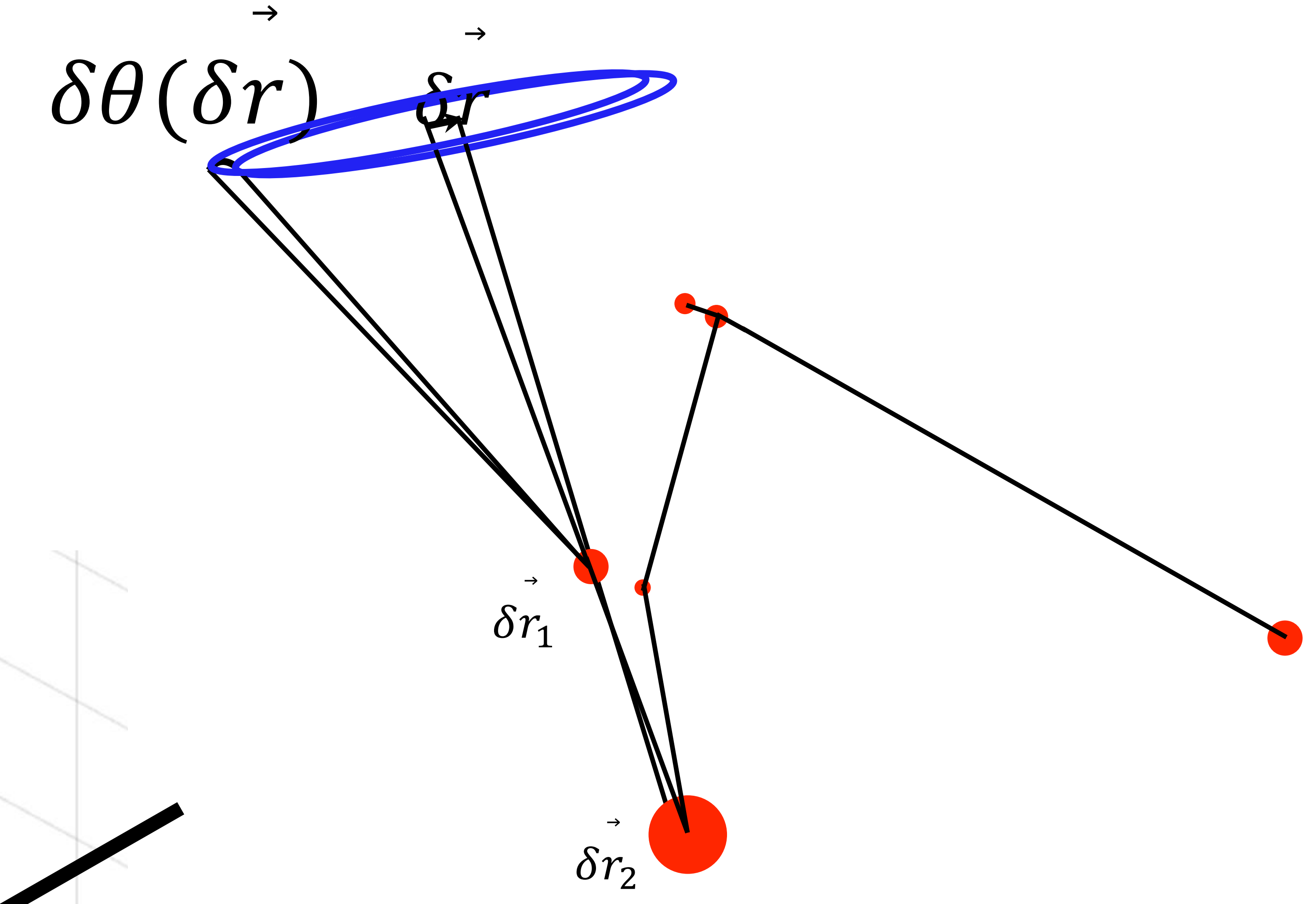
The minimum brightness of the source that can be detected

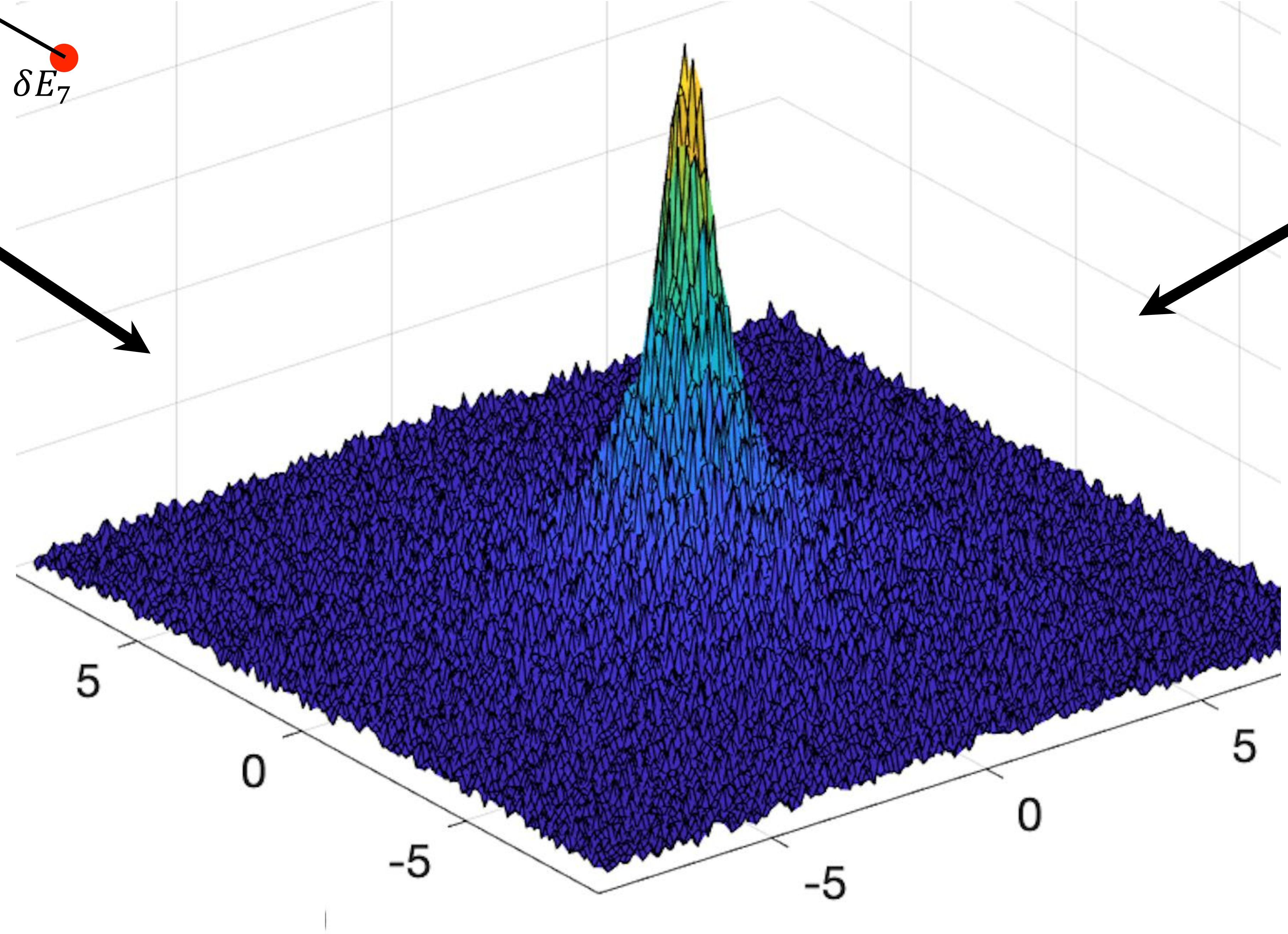
Angular resolution

Energy error



Geometry error





Non dominant when:

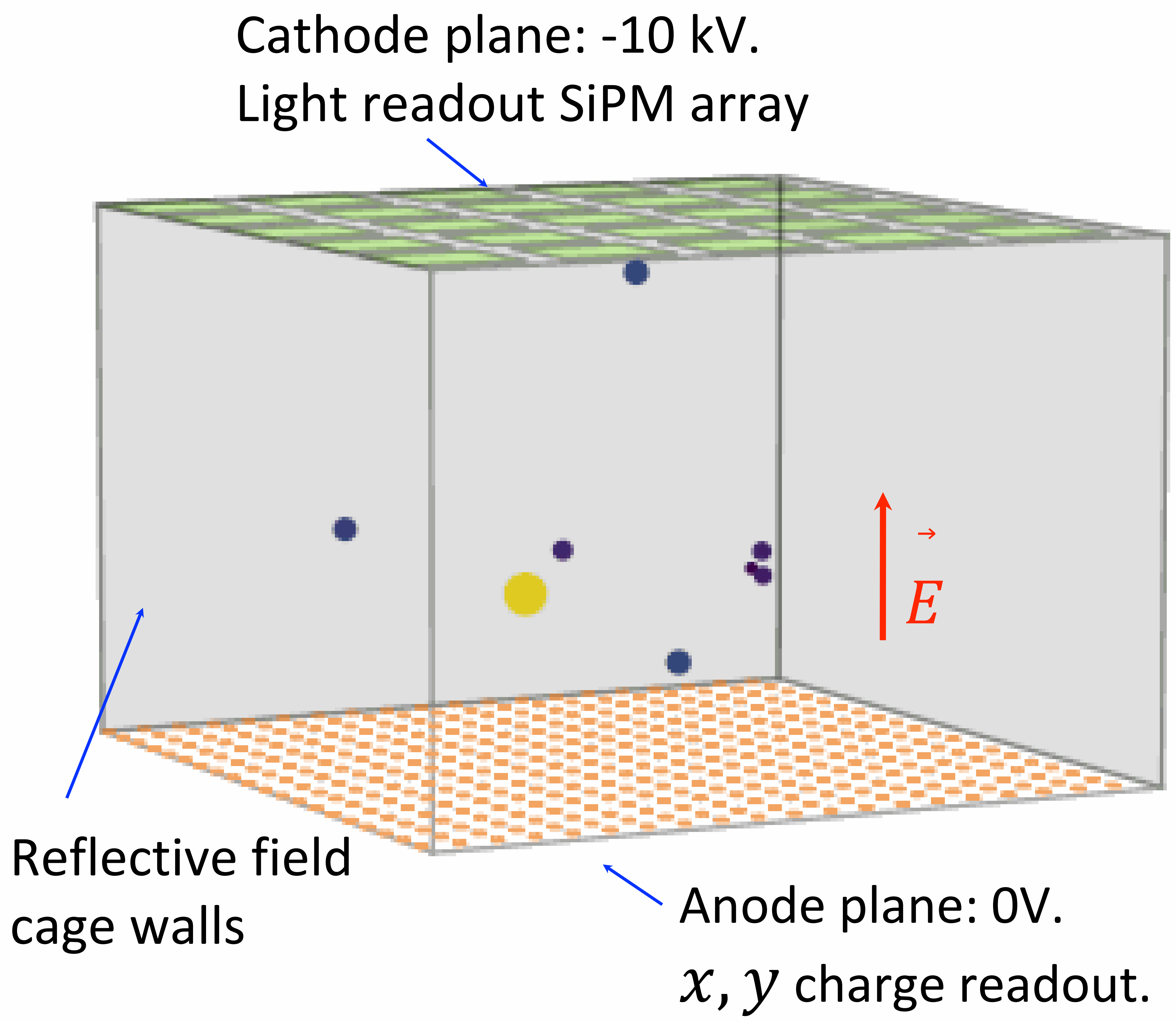
$\sigma_{xyz} < 1mm$

REQUIREMENTS

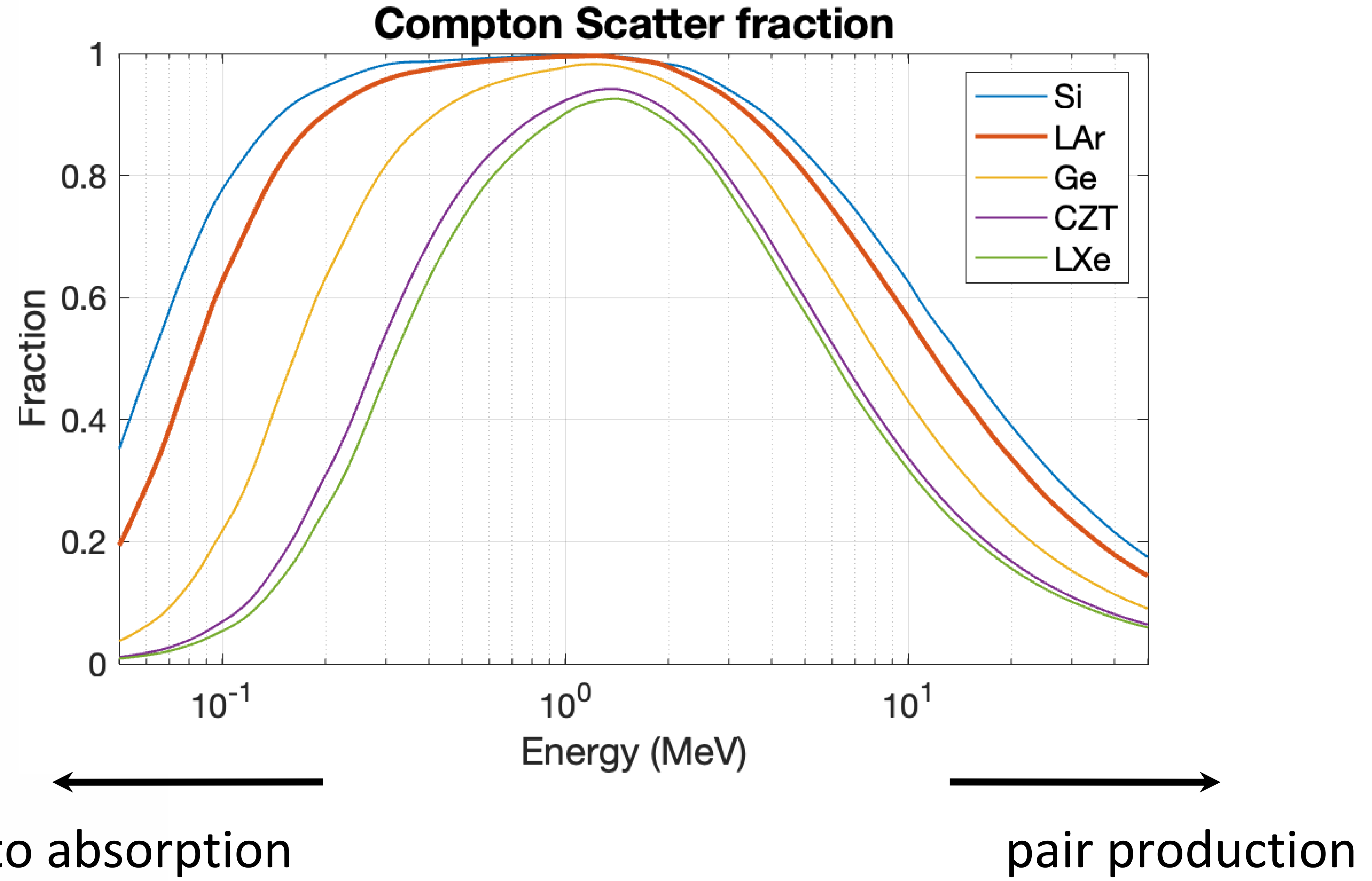
- Precise 3D readout over a **large** volume
- Minimal energy error

Better point also gives better (sequence) reconstruction

Time Projection Chamber – TPC & LAr

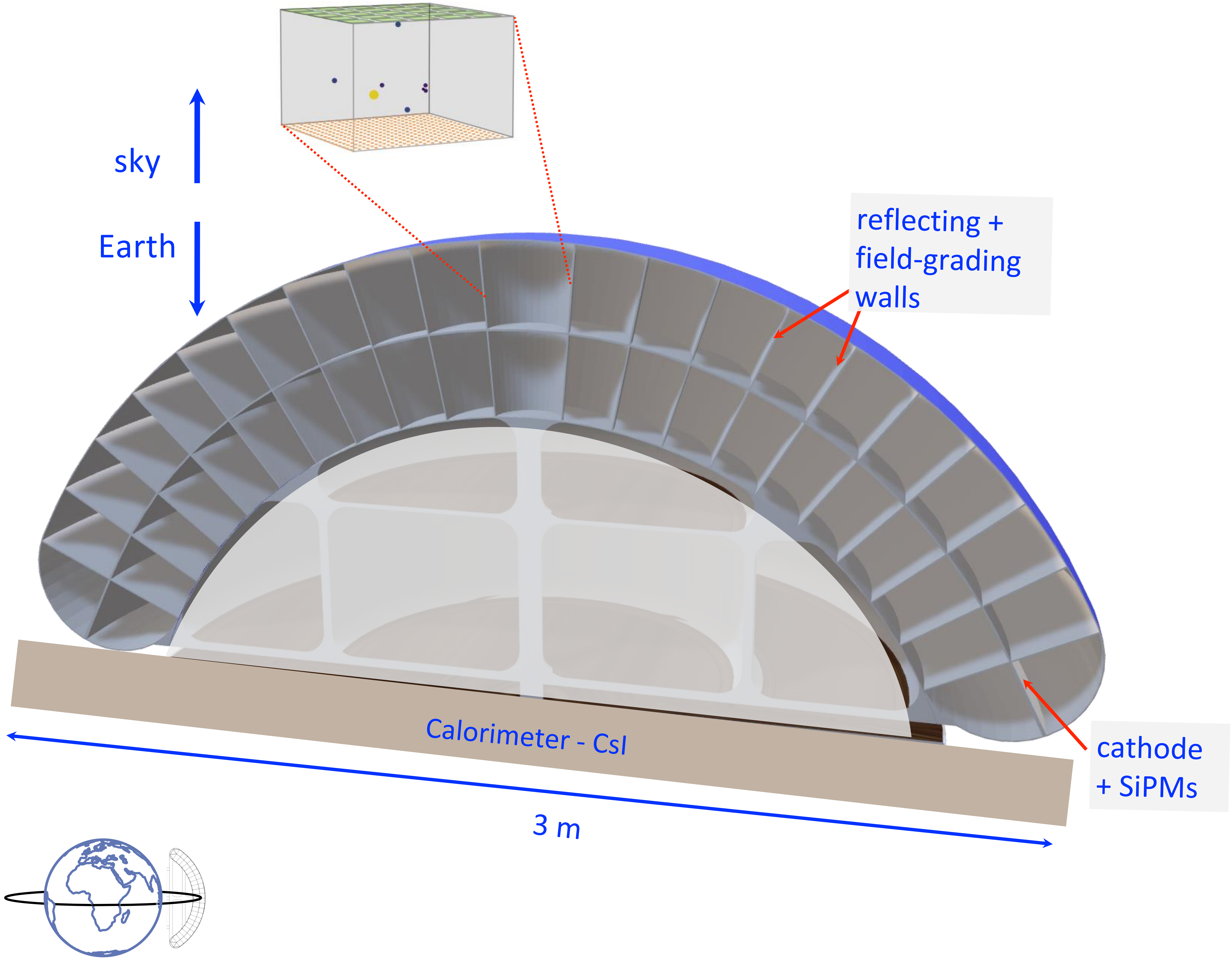


- 3D readout with 2D instrumentation
  - Allows scaling to large mass
- Uniform detection volume and response
- Fine grained readout possible



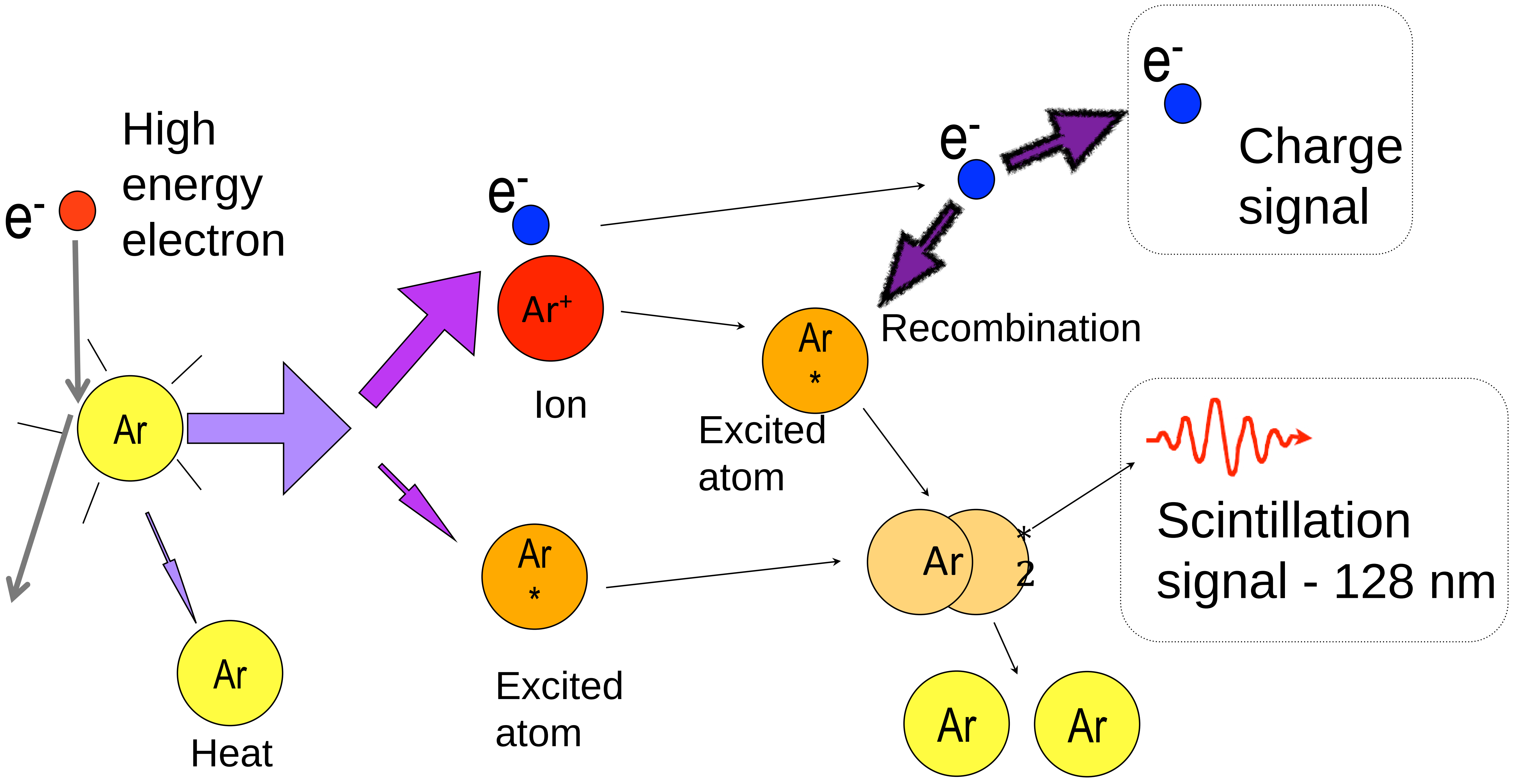
- Ar low Z maximizes Compton energy window
- Low density -> Larger Mean Free Path

GammaTPC Concept

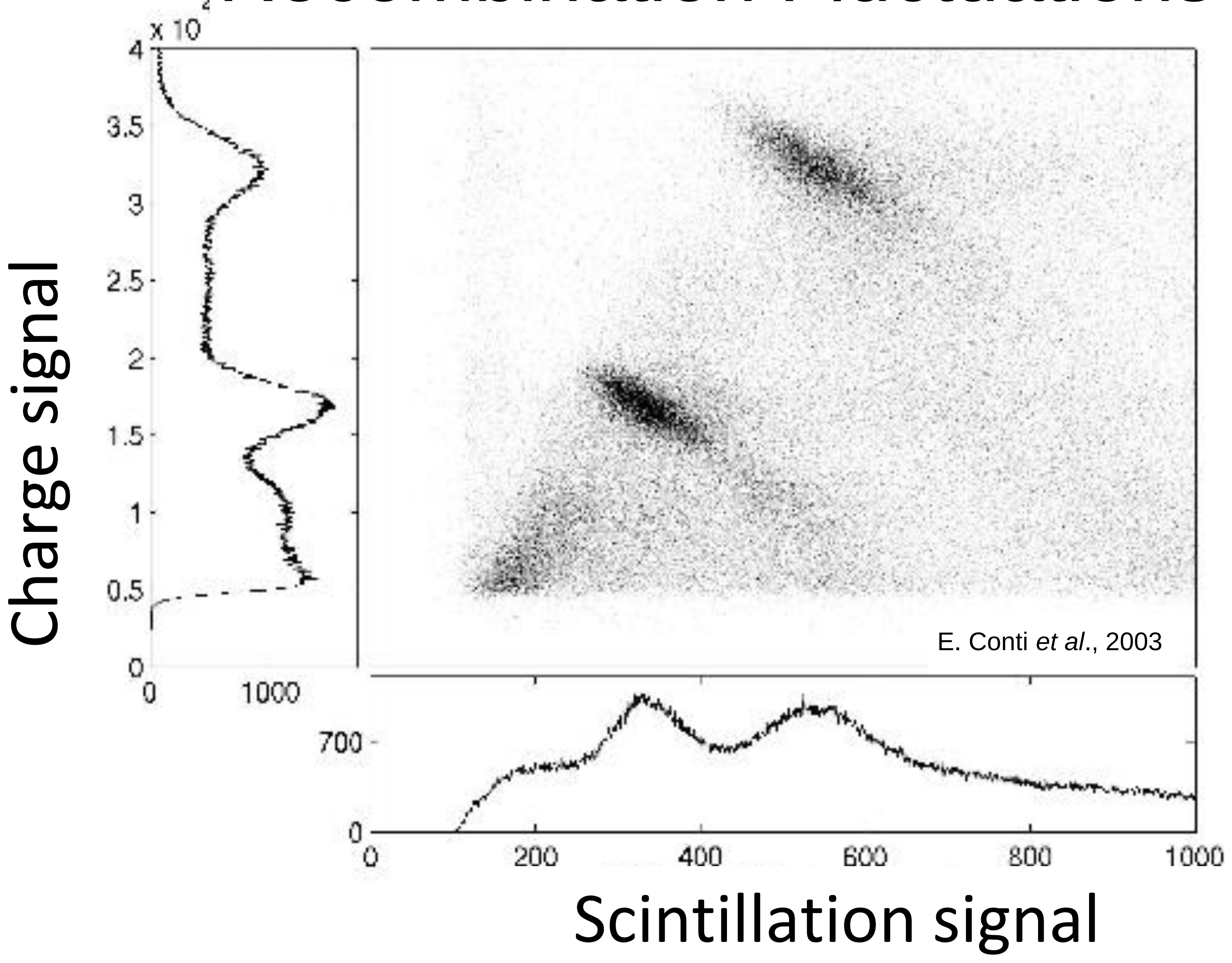


- LAr at ~120 K, carbon fiber vessel
- ~20 cm segmentation for pile up
- 10 m^2, 4 ton configuration shown
  - Readout + vessel mass ~300 kg
  - Readout cost ~\$1.2M /m^2
- Calorimeter needed for high energy Compton and pairs
- Tracker thickness and area optimized for ~1 MeV
- Hemispherical pressure vessel: 2π FOV

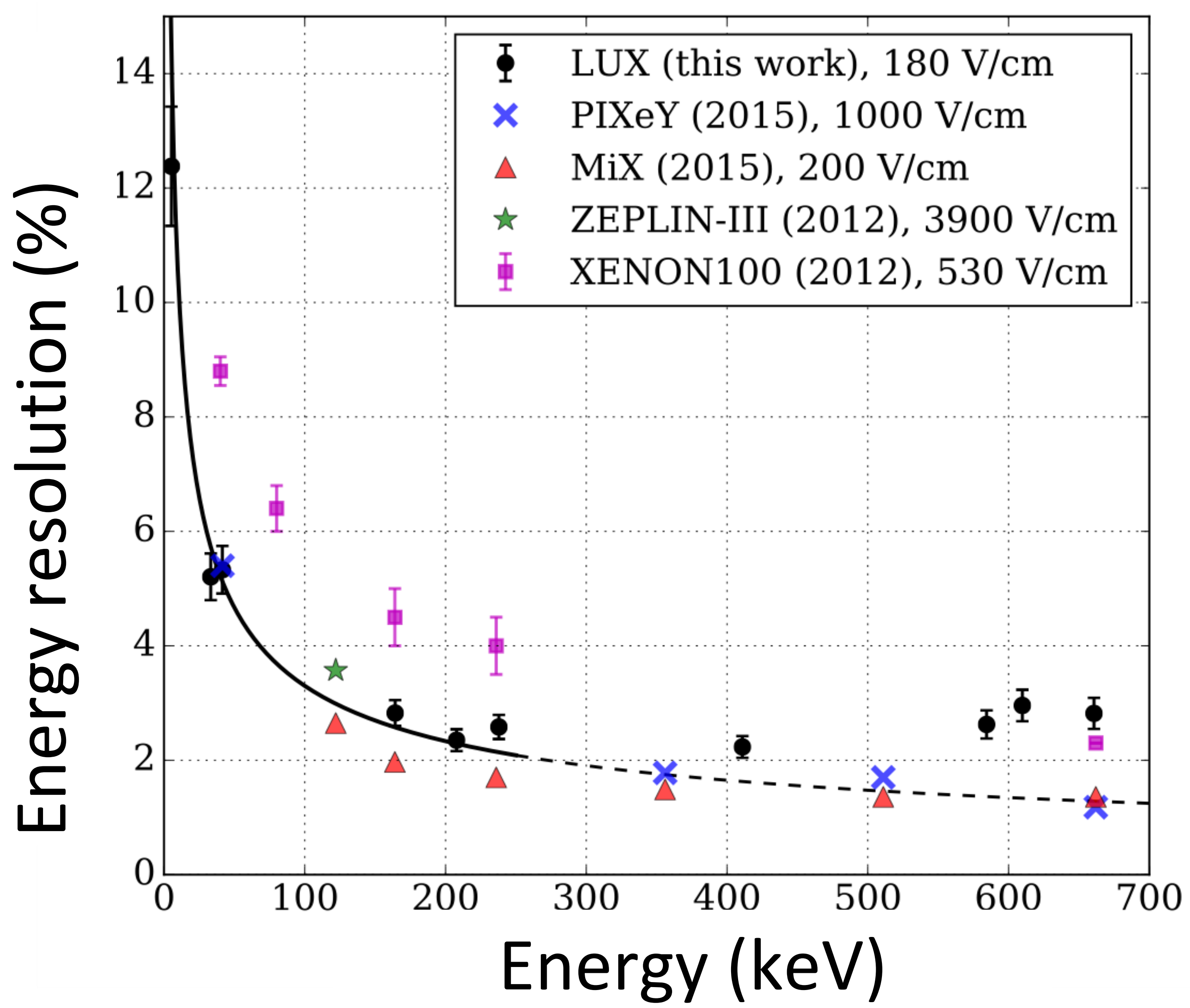
Energy Resolution



Recombination Fluctuations



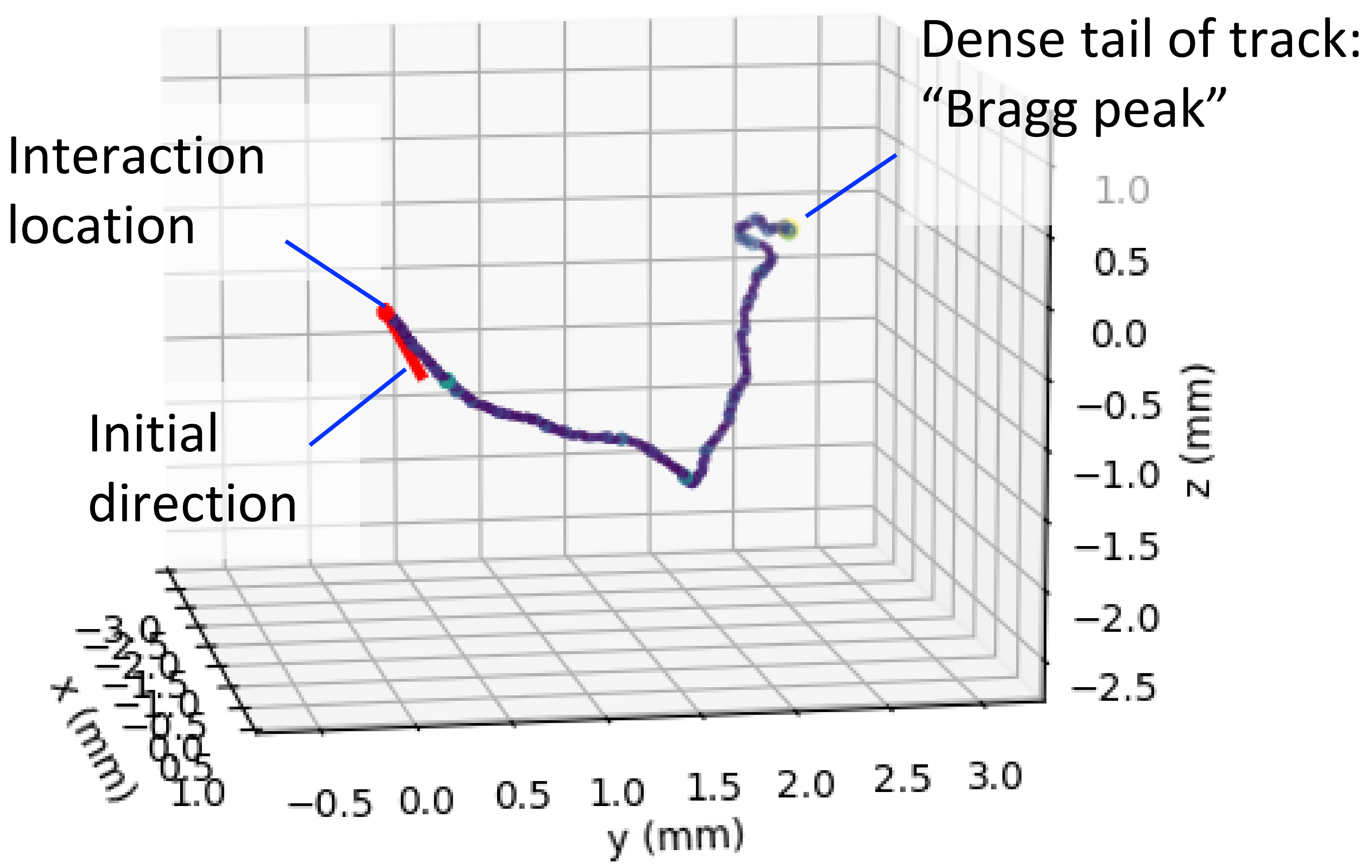
Energy = Charge + light in LXe



- Complicated process results in charge and light
- Recombination fluctuations smears these signals
- Combined signal should have respectable energy resolution, comparable to Si, worse than Ge or CZT.
- Light measurement with SiPM array + wave shifter

Interaction Locations

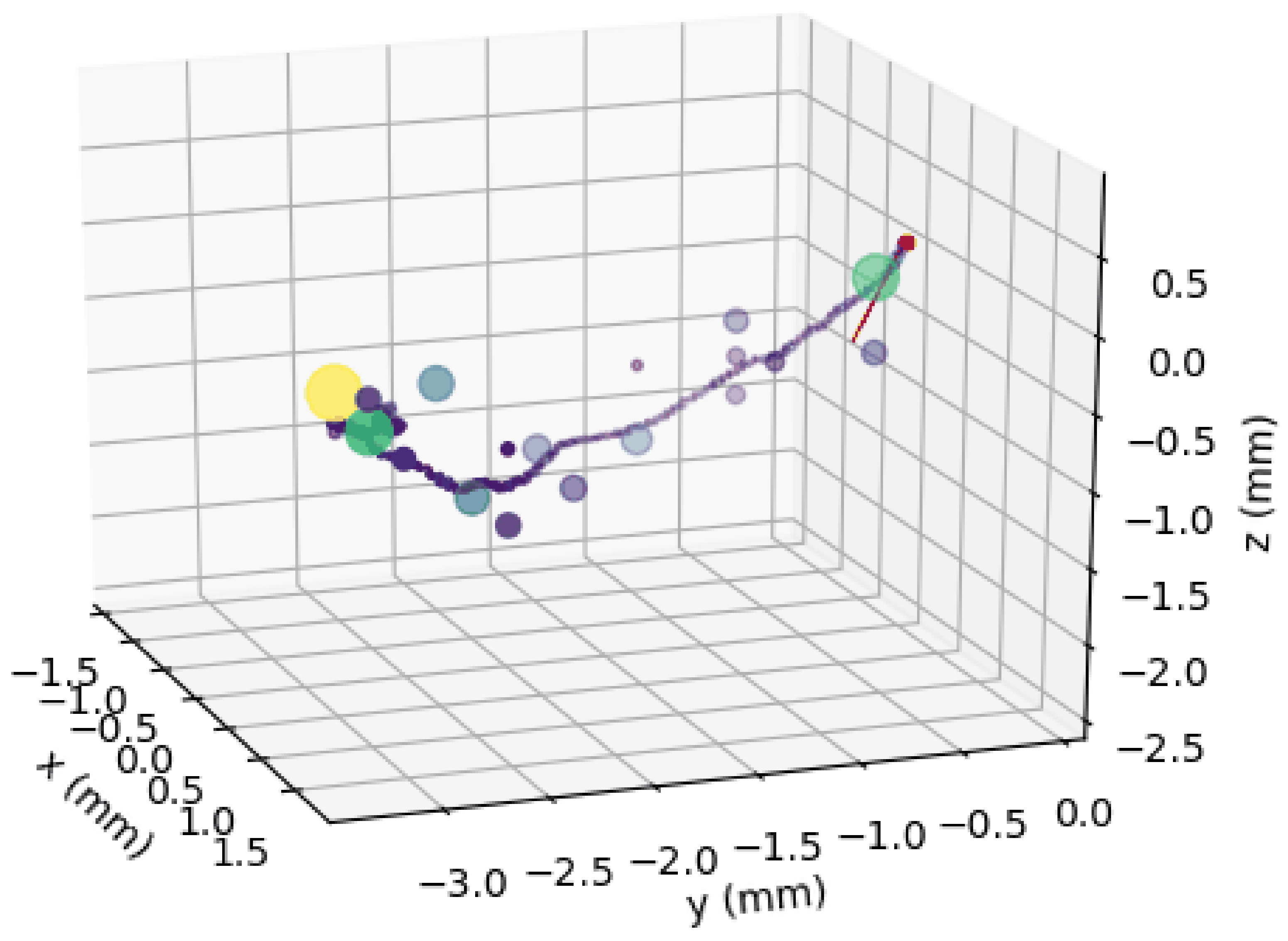
1 MeV electron track, 21K e-



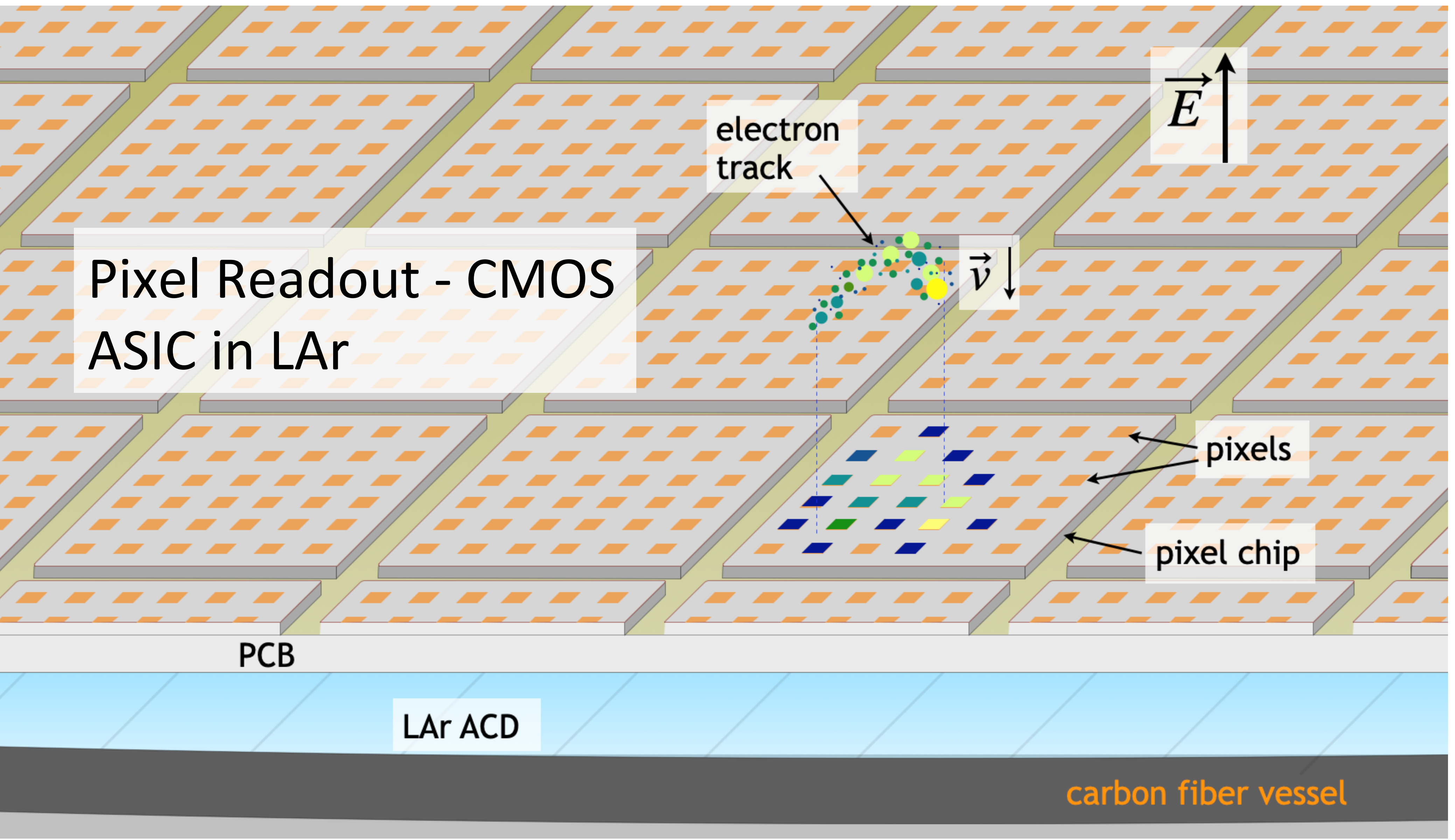
High fidelity simulation with PENELOPE

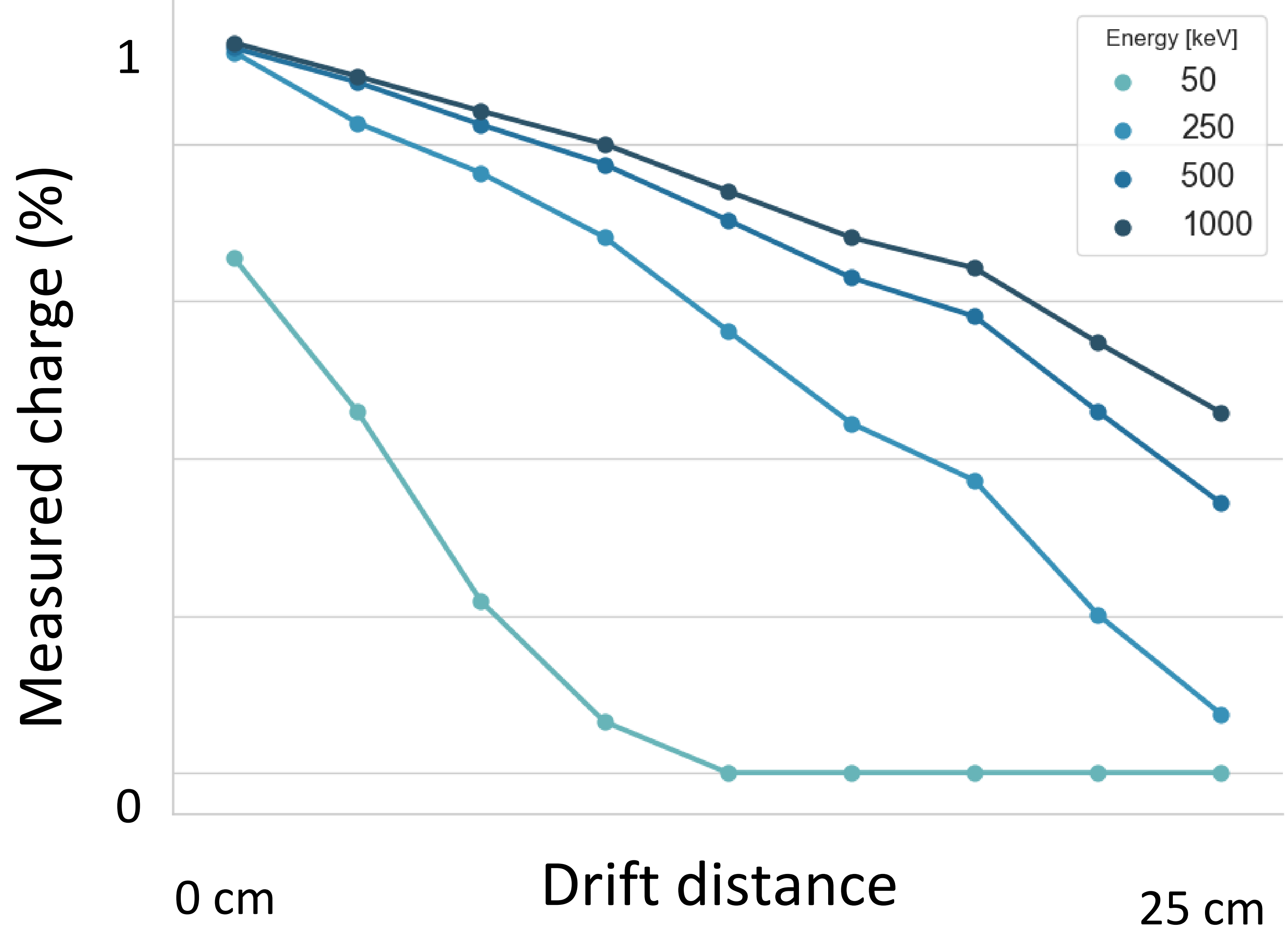
- Tracks bigger than required $\sigma < \sim 1$ mm resolution: must image and find head. Also measure initial direction, pair tracks

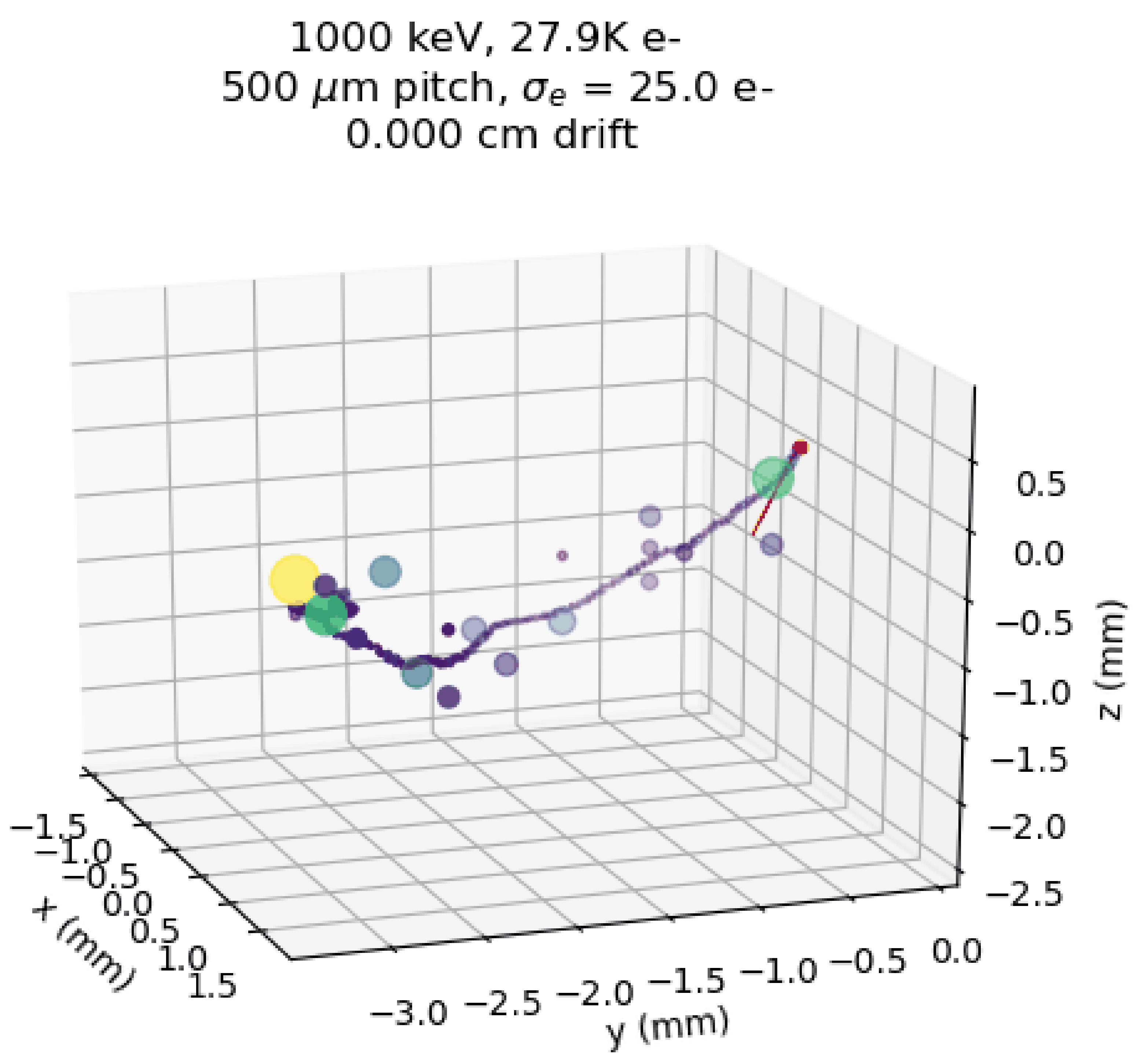
Pixel Readout

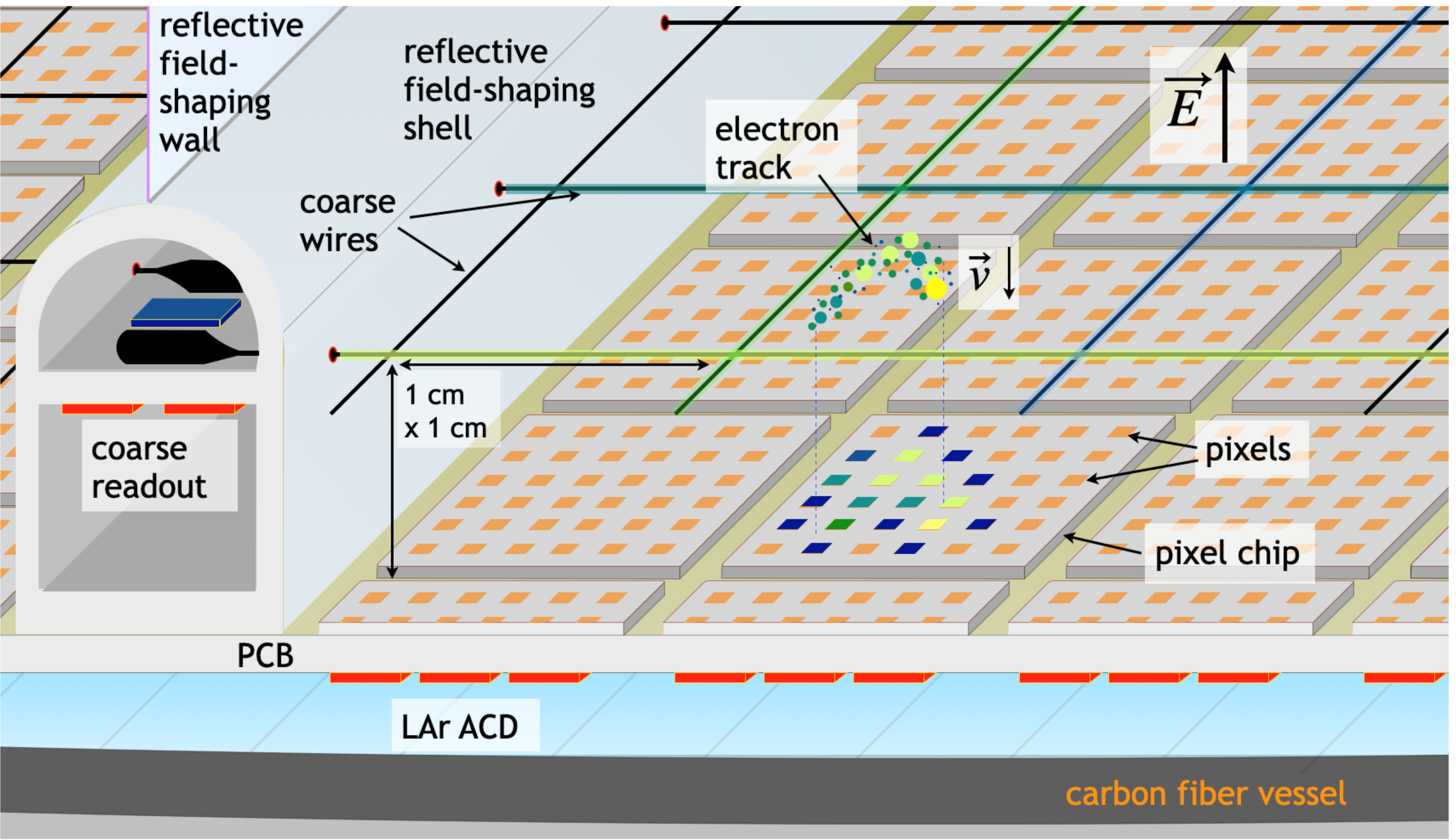


- Tracks bigger than required σ < ~1 mm resolution: must image and find head. Also measure initial direction, pair tracks
- Two problems:
  - *Power:* ~100 μW/ch with low noise; space power budget 10^3 higher at ~W/m^2
  - *Diffusion:* tails of charge lost when pitch ≃ diffusion







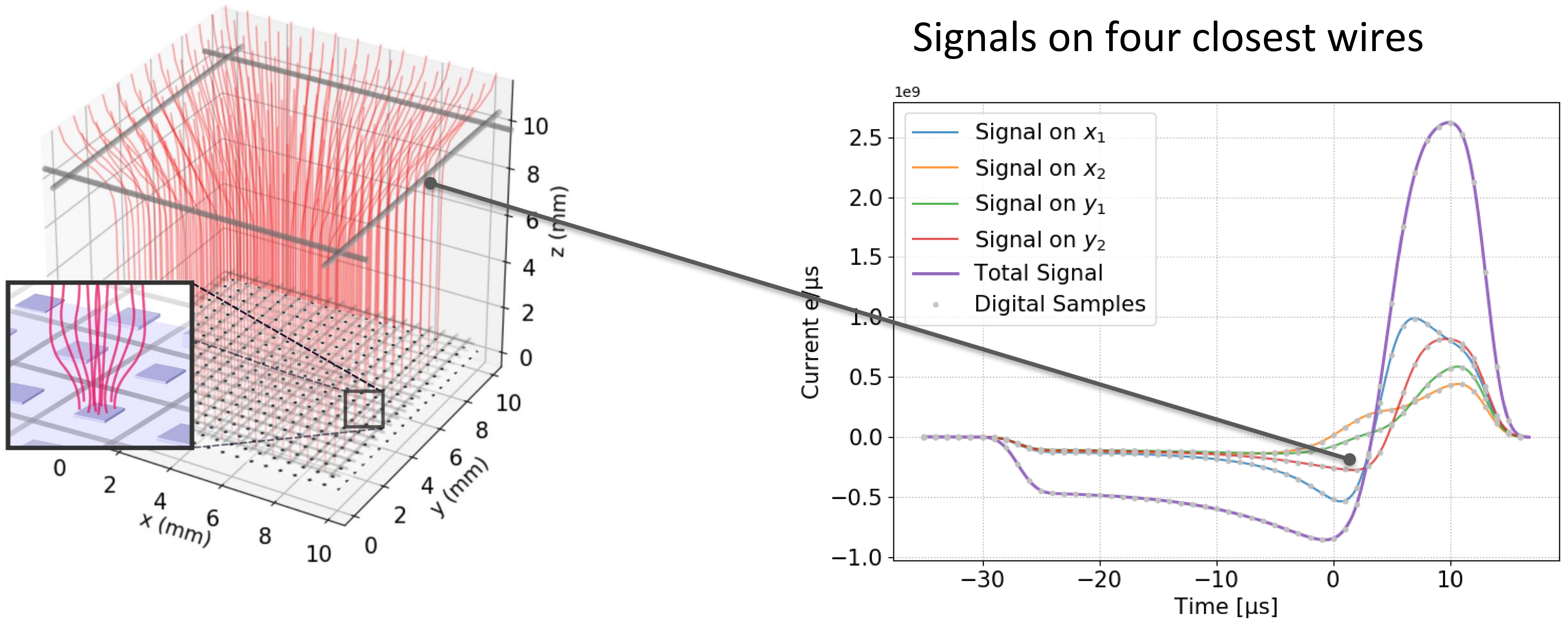


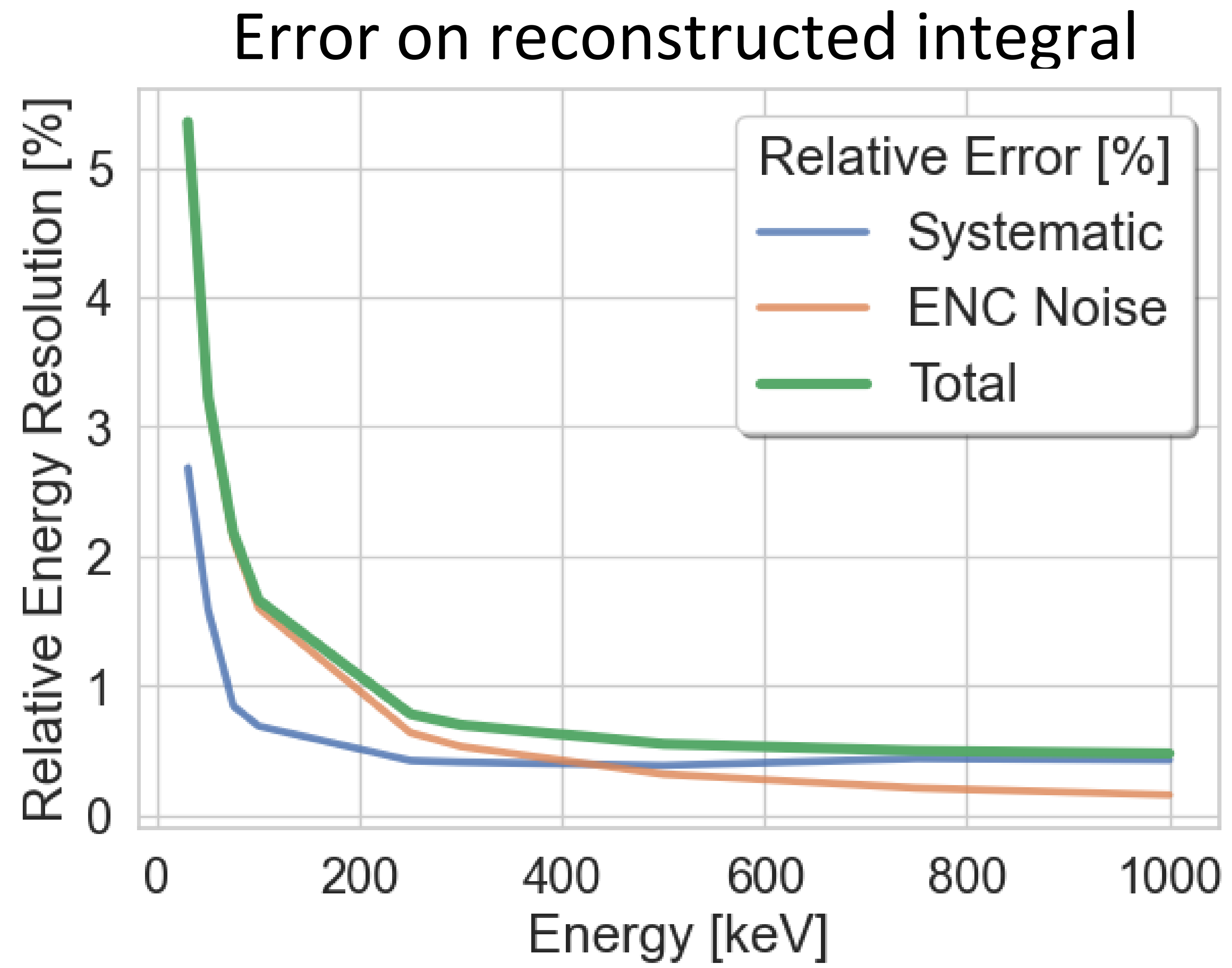
GAMPix

ArXiv:2402.00902

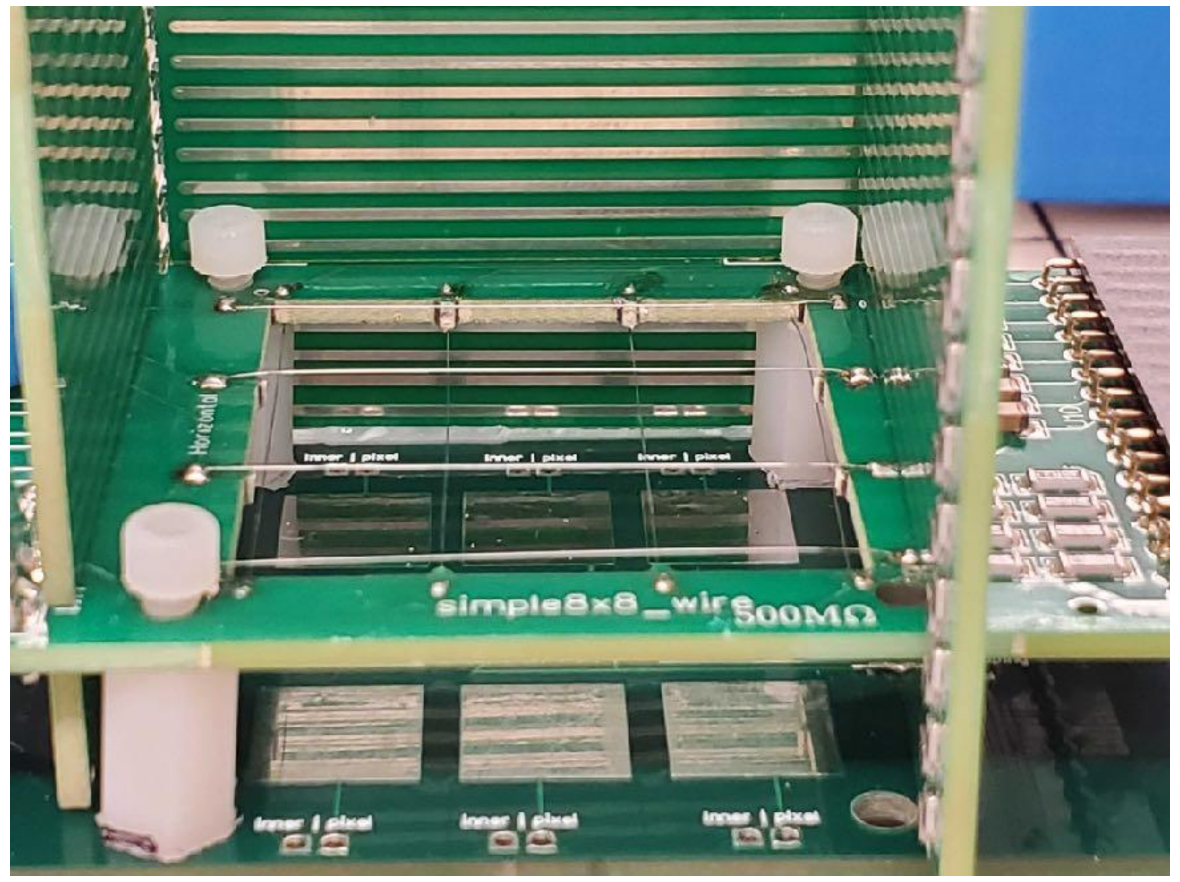
- Tracks bigger than required σ < ~1 mm resolution: must image and find head. Also measure initial direction, pair tracks
- Two problems:
  - *Power:* ~100 μW/ch with low noise; space power budget 10^3 higher at ~W/m^2
  - *Diffusion:* tails of charge lost when pitch ≃ diffusion
- Grid Activated Multi-Scale Pixel readout - GAMPix
- Measure charge *twice*
  - Coarse inductance grid insensitive to diffusion
  - Pixels image track
- Power cycle pixels based on coarse signal, reduces power and data, by ~10^3

Recovery of Charge Integral



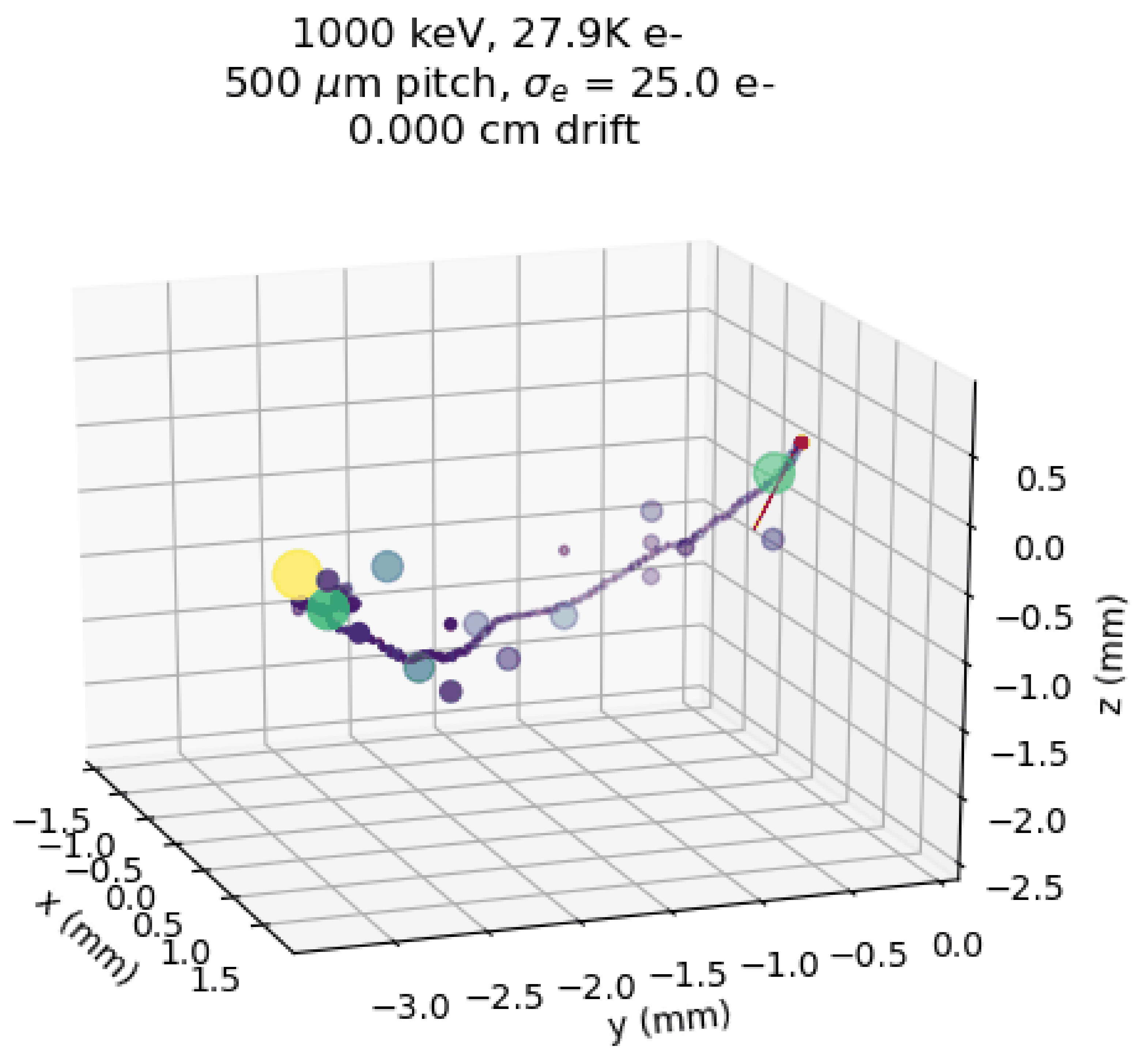


- Coarse grid induction signals highly position dependent
- Detailed simulation: COMSOL, Garfield++ Ramo's theorem, full electronics chain
- Pixel spatial information corrects coarse grid integral to <1%, meeting requirements.

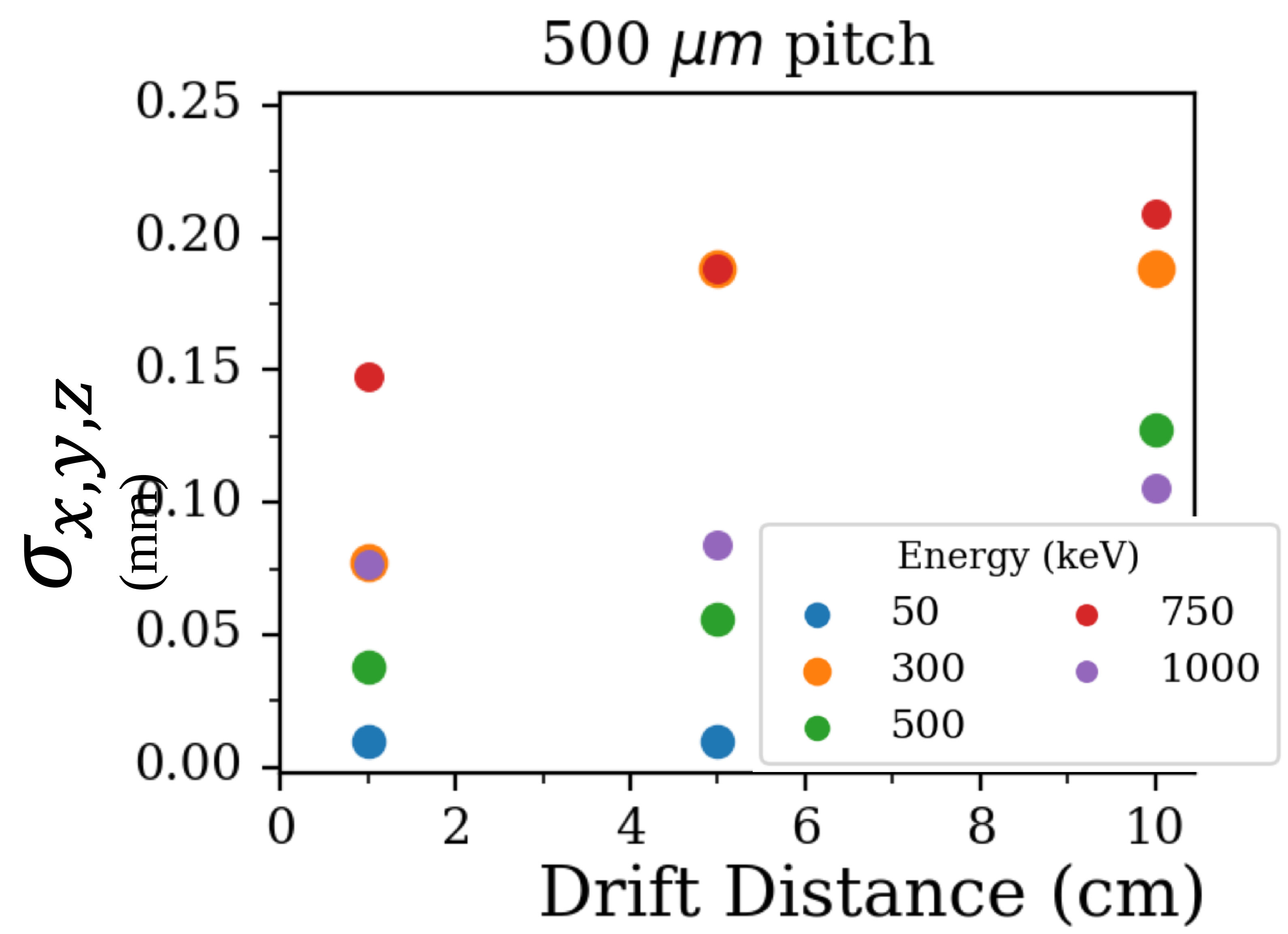


Upcoming test with CRYO (σ_e~100e-) readout

Excellent track reconstruction

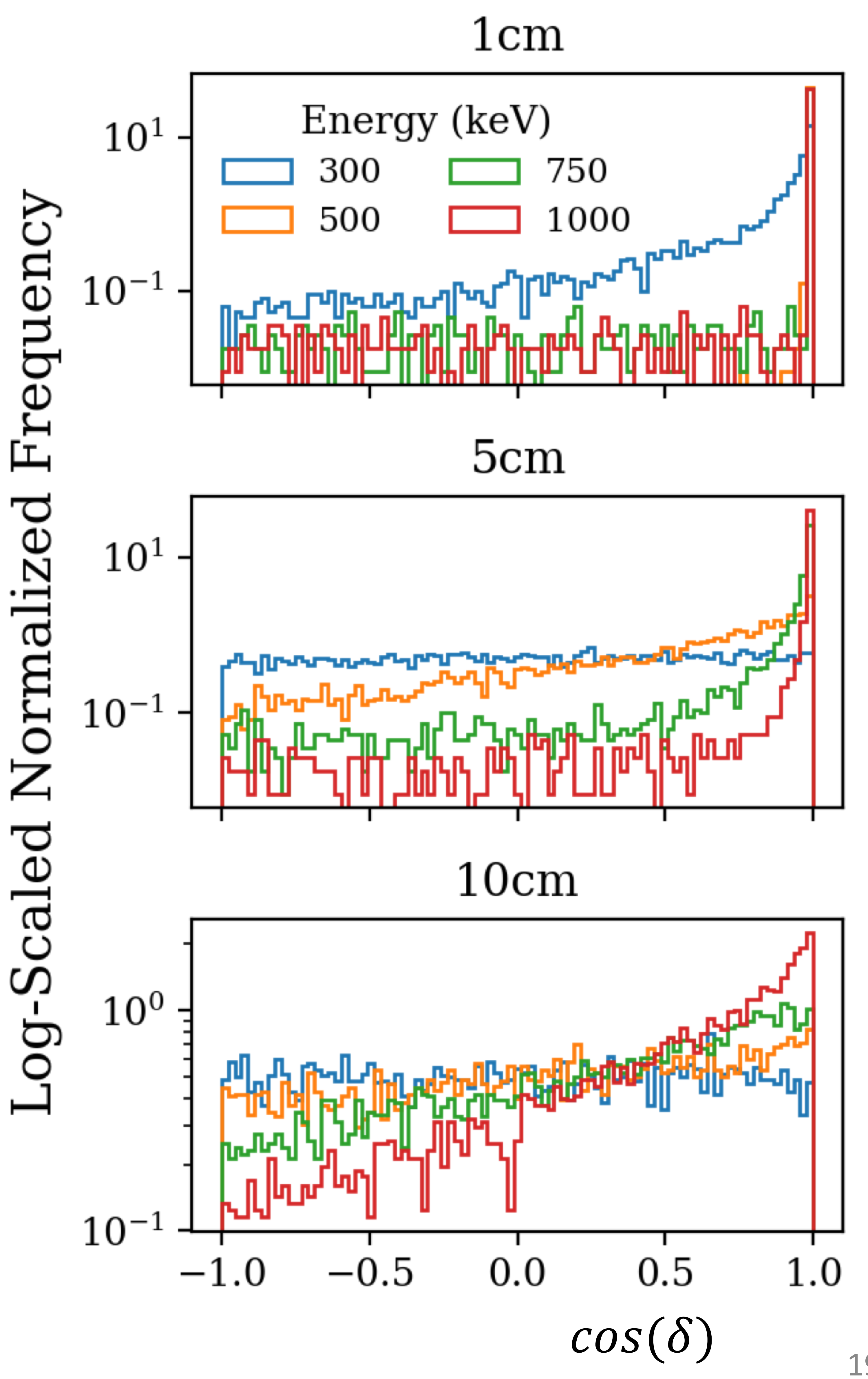


Interaction location



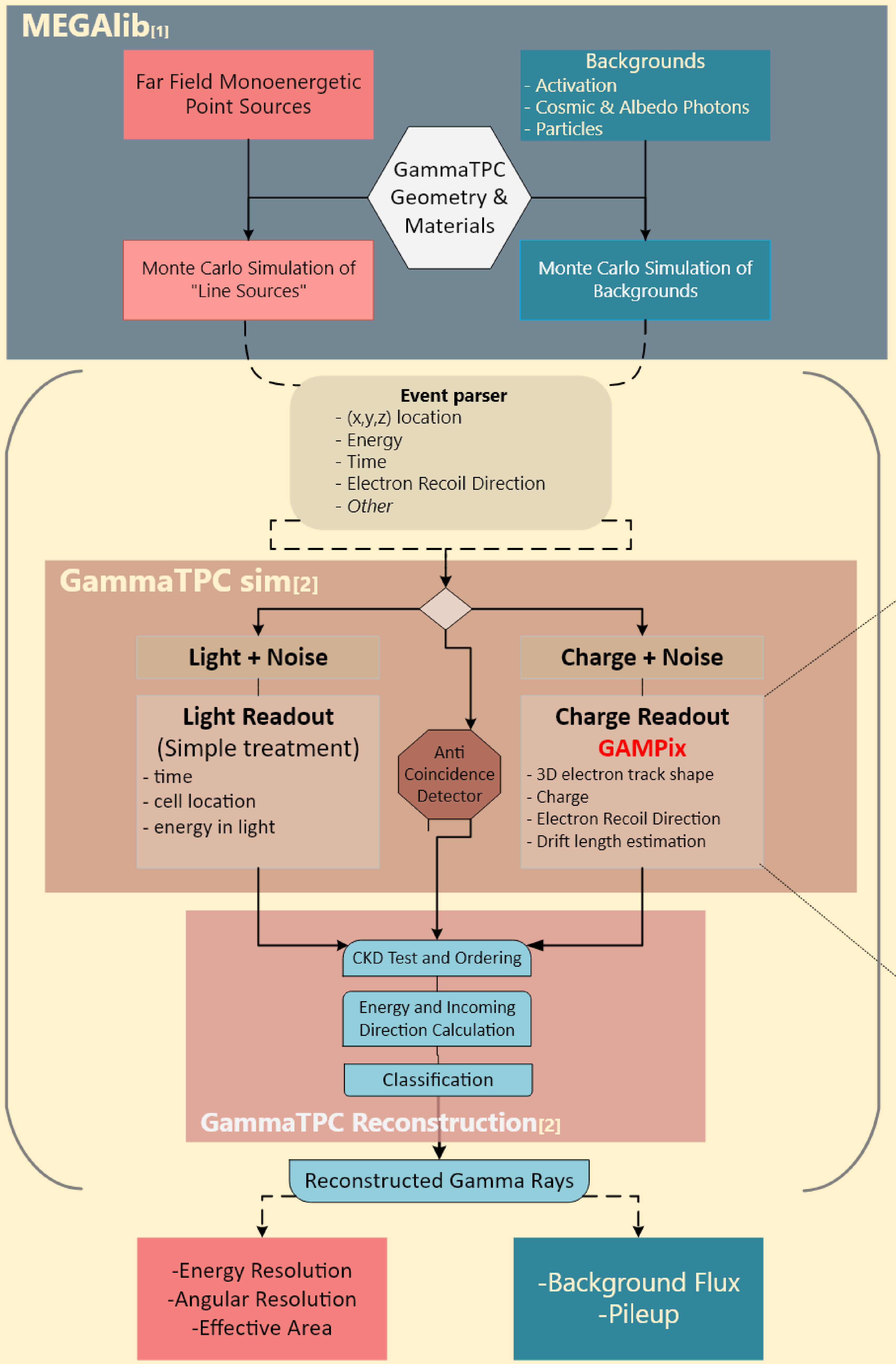
ArXiv/2207.07805

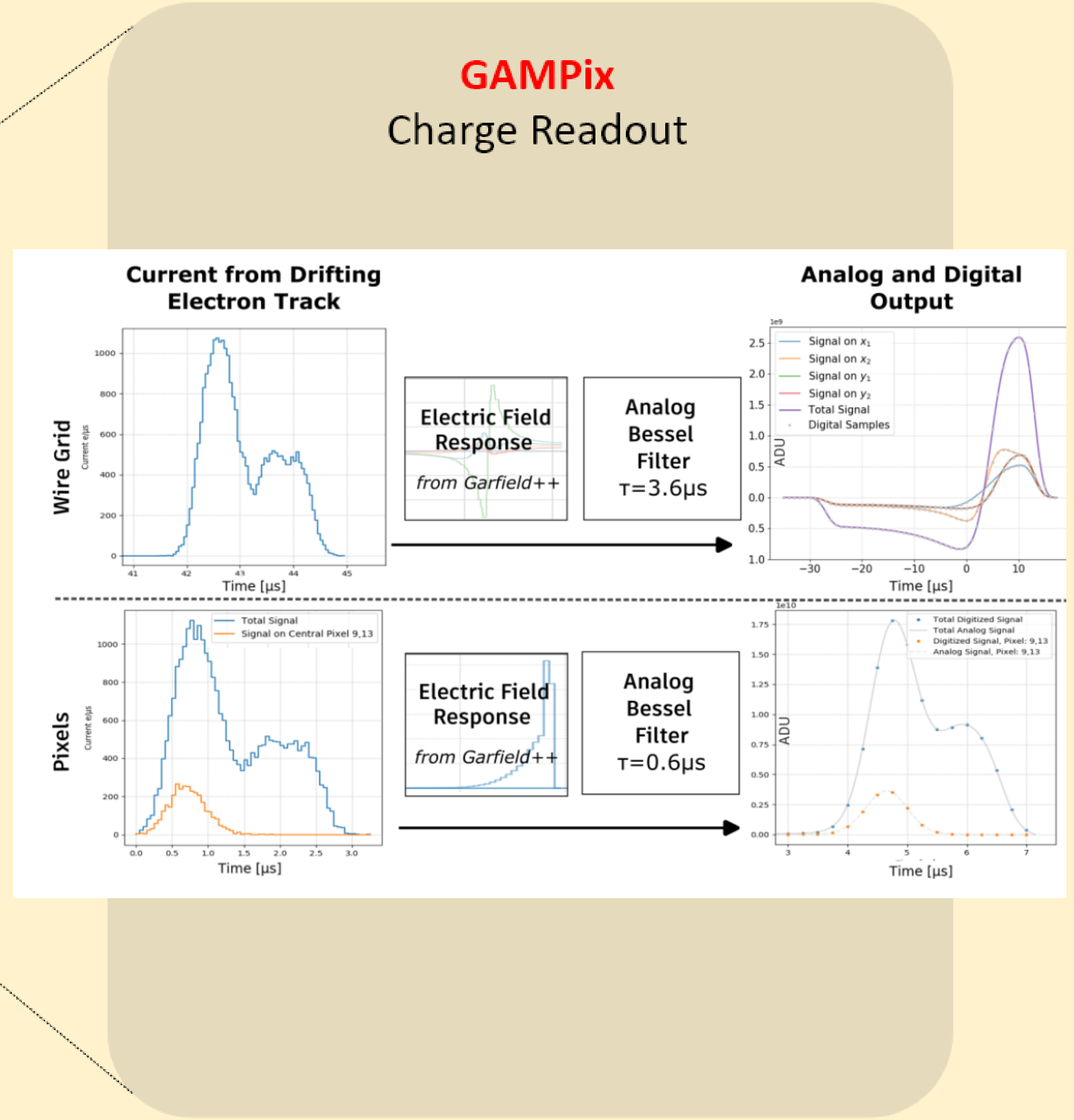
Initial direction

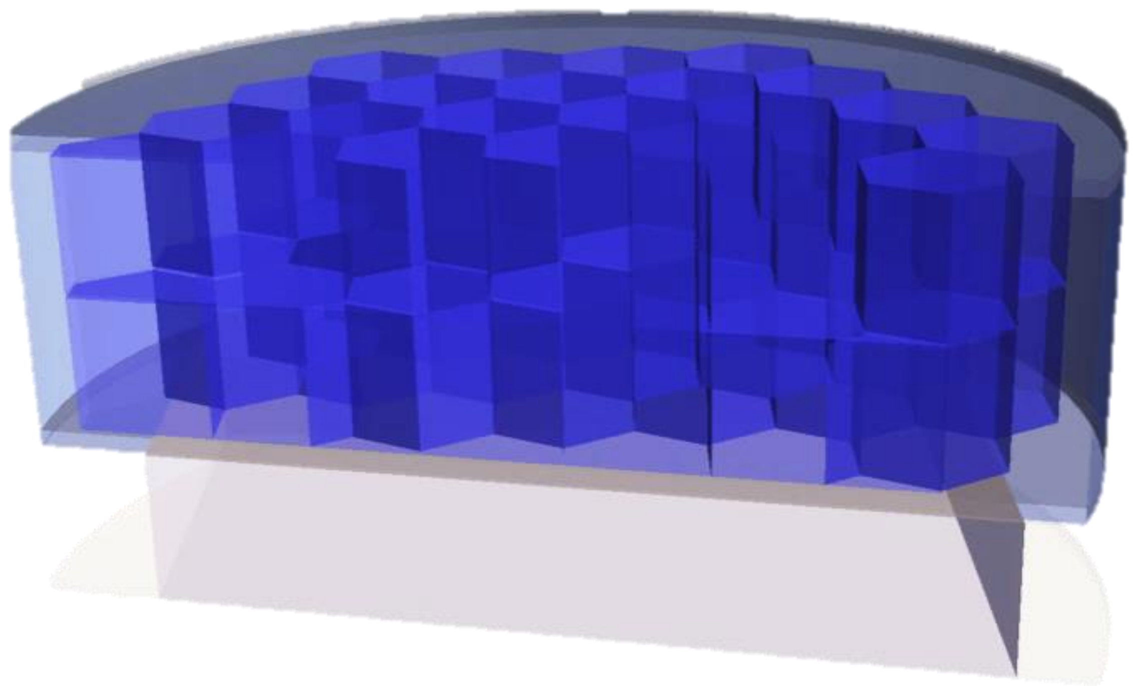


- $\sigma_{xyx} \leq 200\mu m$
- Initial direction well measured at short drift

GammaTPC Simulation Chain







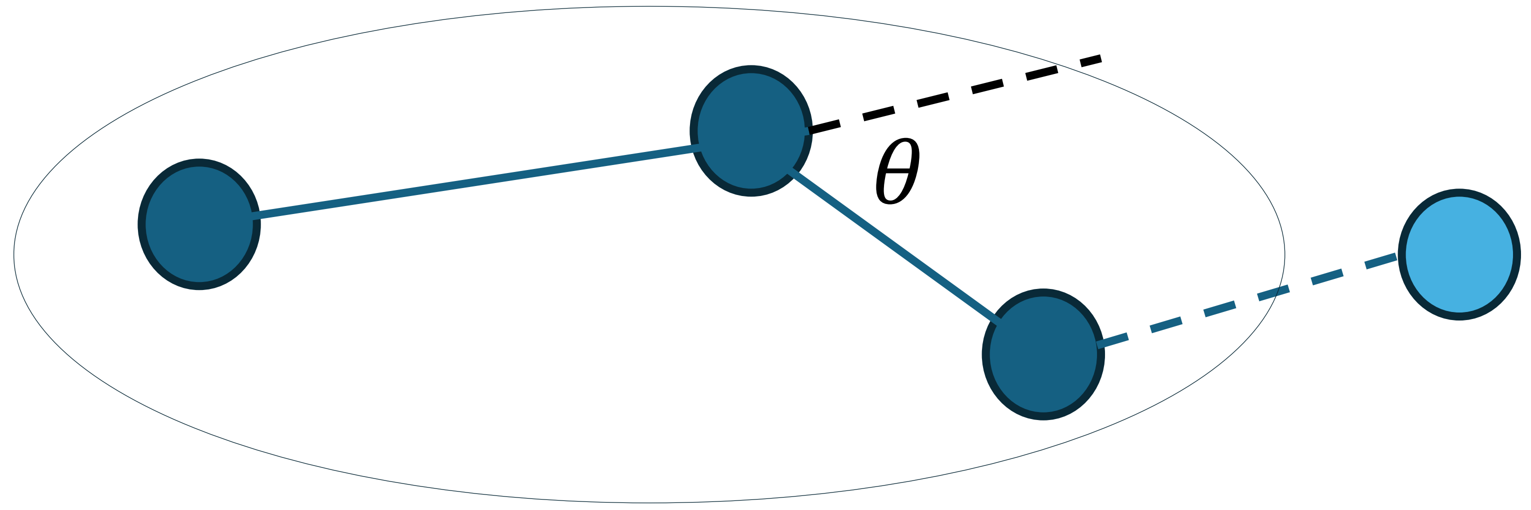
References

[1] https://megalibtoolkit.com/home.html
[2] https://github.com/tashutt/Gampy/

Event Reconstruction

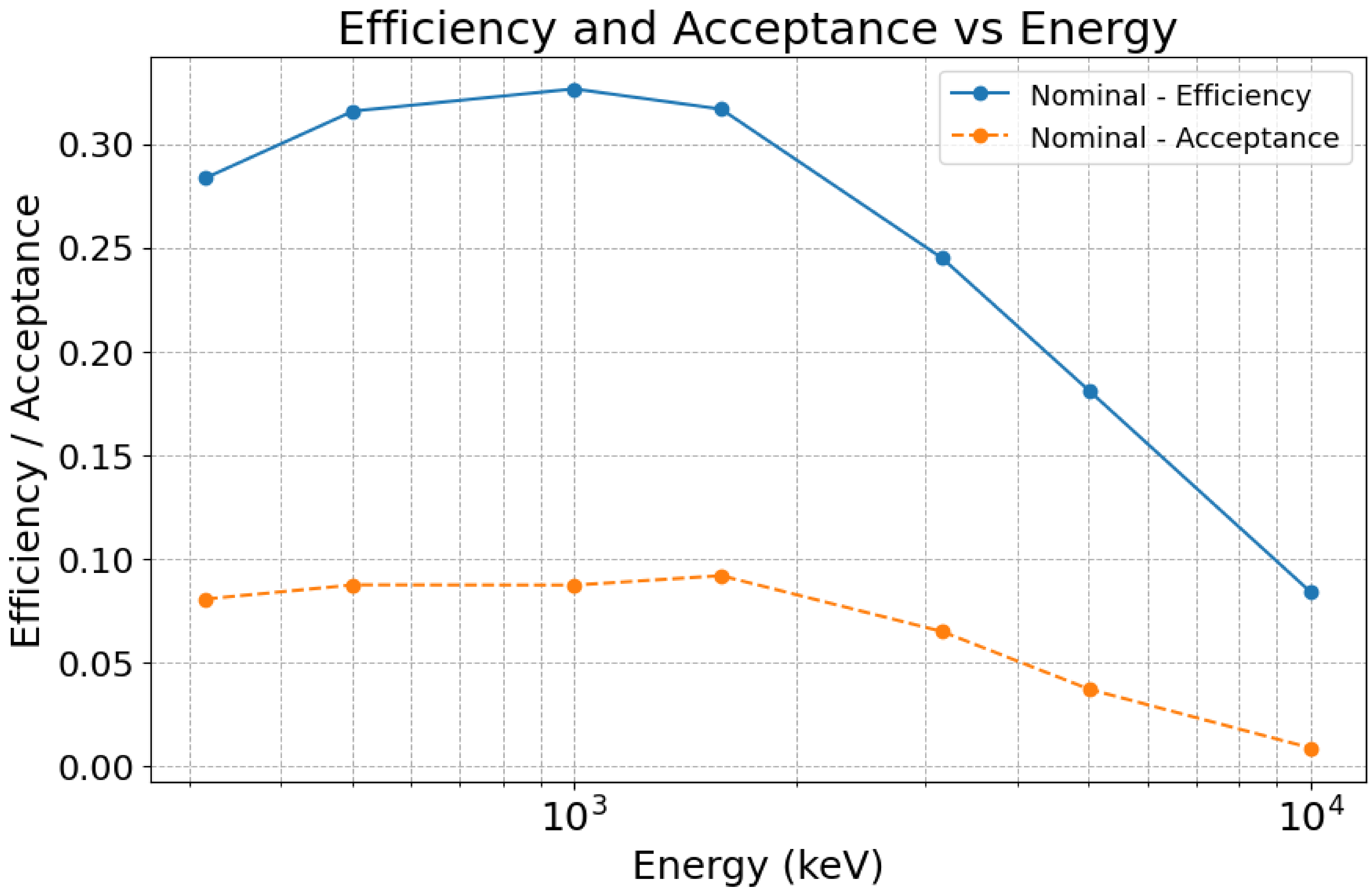
RandomTreeClassifier

	Feature	Importance
3	calc_to_sum_ene	0.221334
5	compton_angle	0.163330
2	kn_probability	0.158314
6	energy_from_sum	0.143044
1	min_hit_distance	0.141768
0	e_out_CKD	0.124048
4	num_of_hits	0.048163

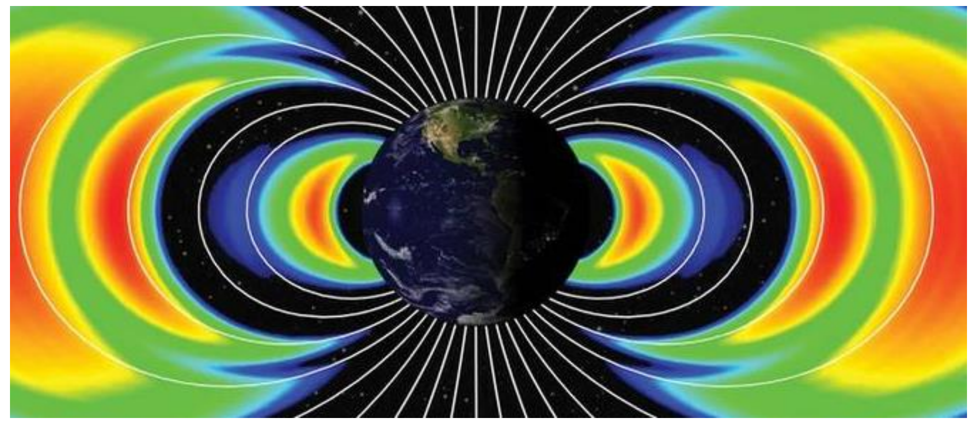


$E_{sum} = \sum E_i$

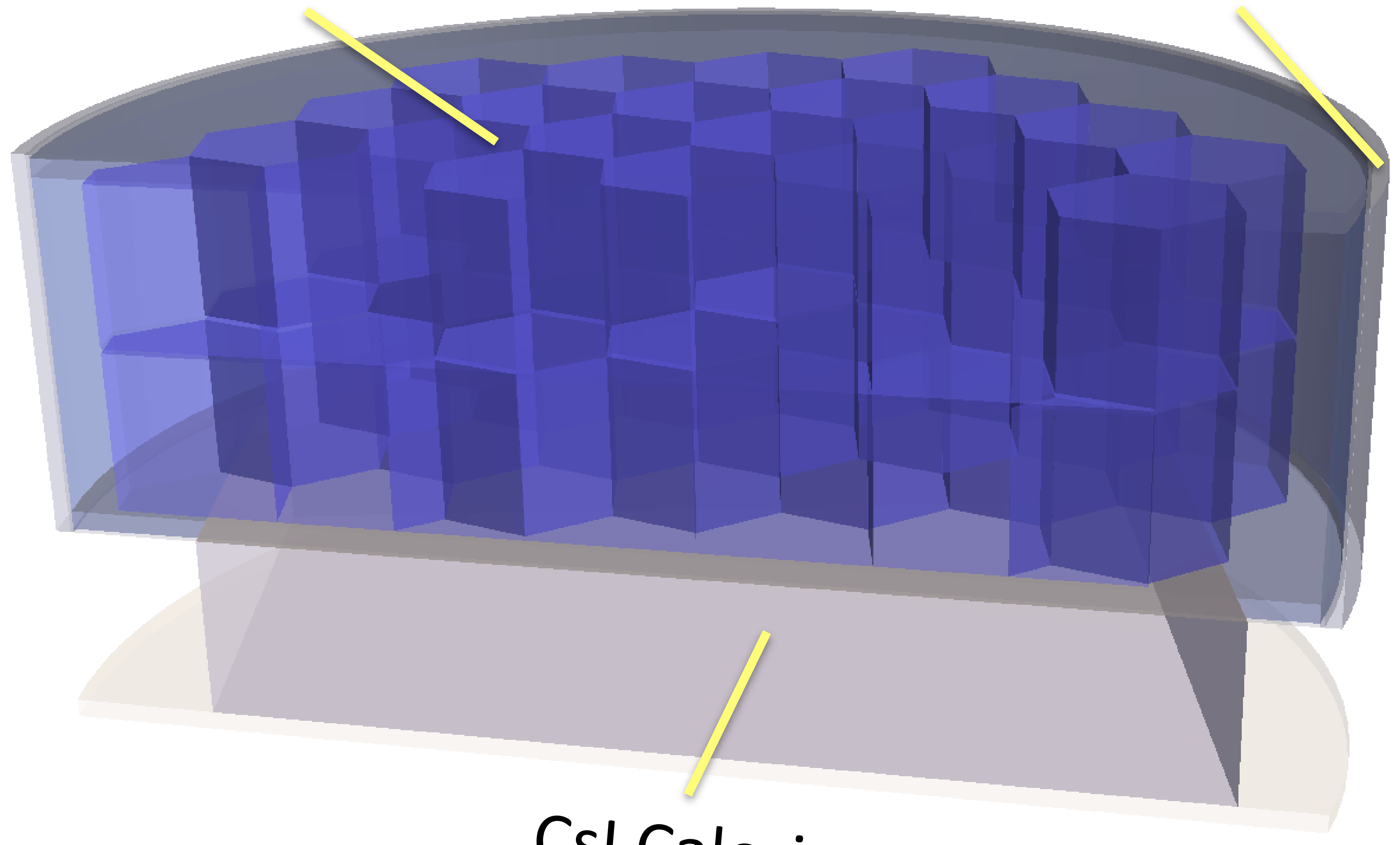
- 3% bad contamination
- 4% good mis-classified

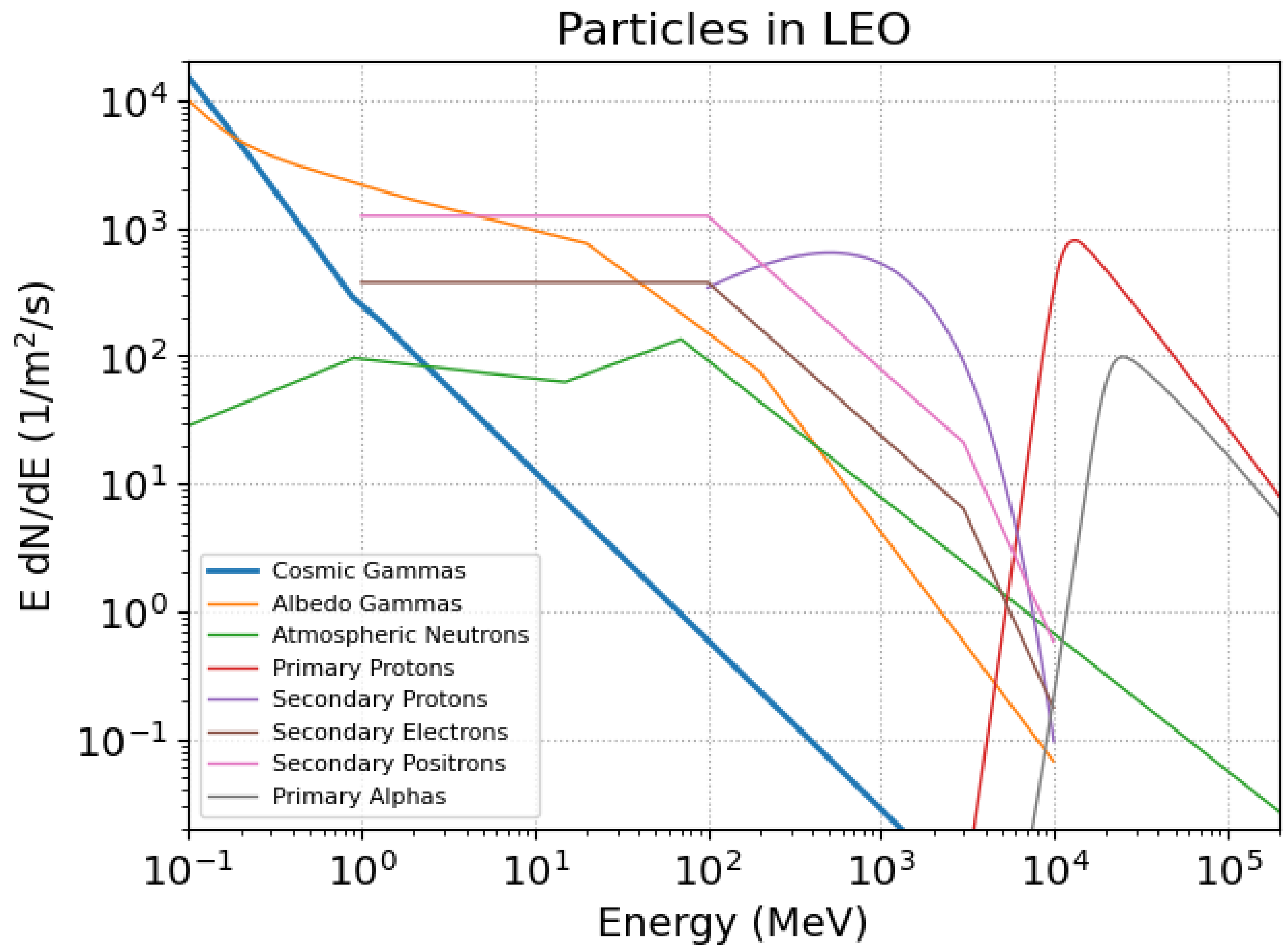


Backgrounds

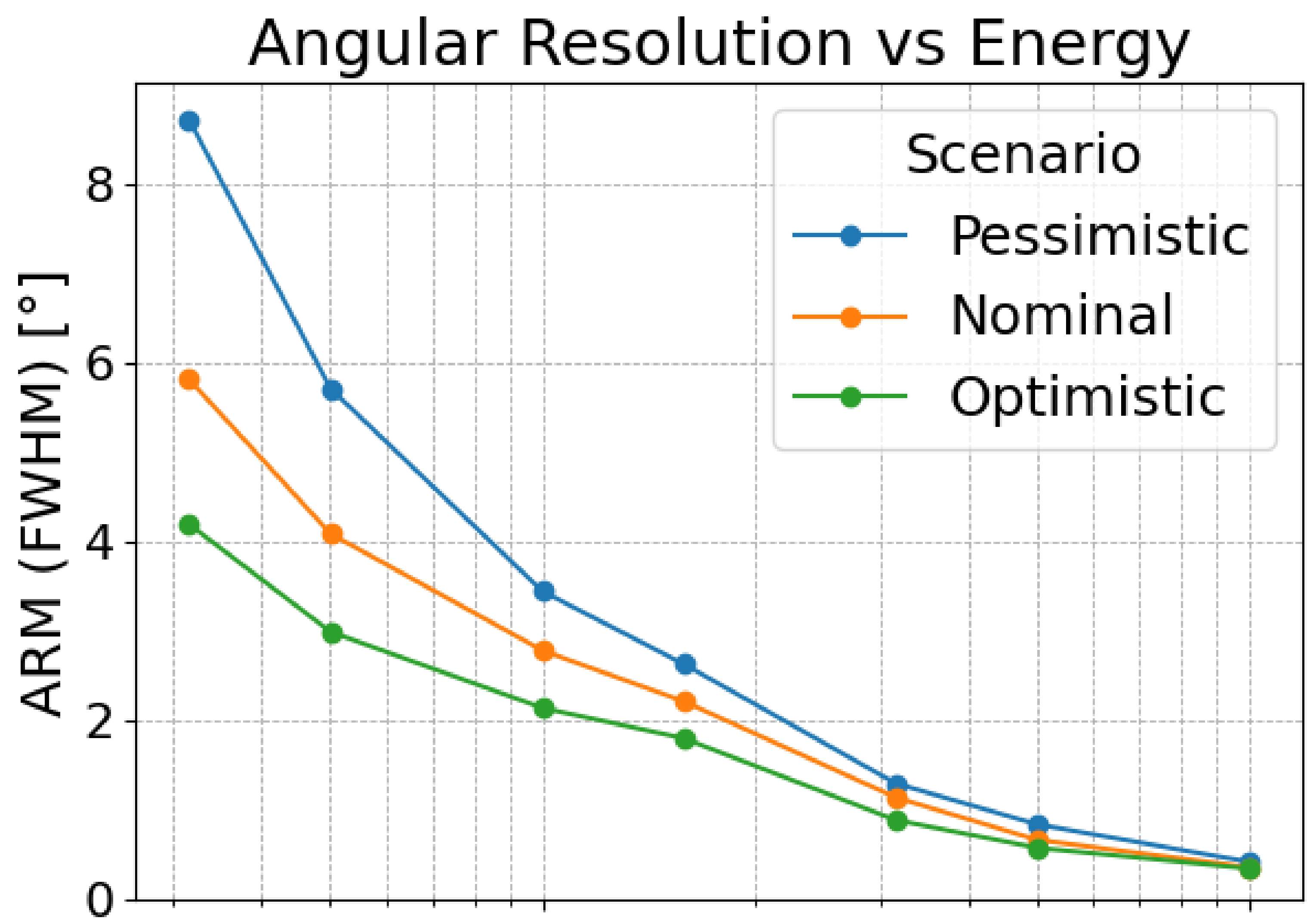


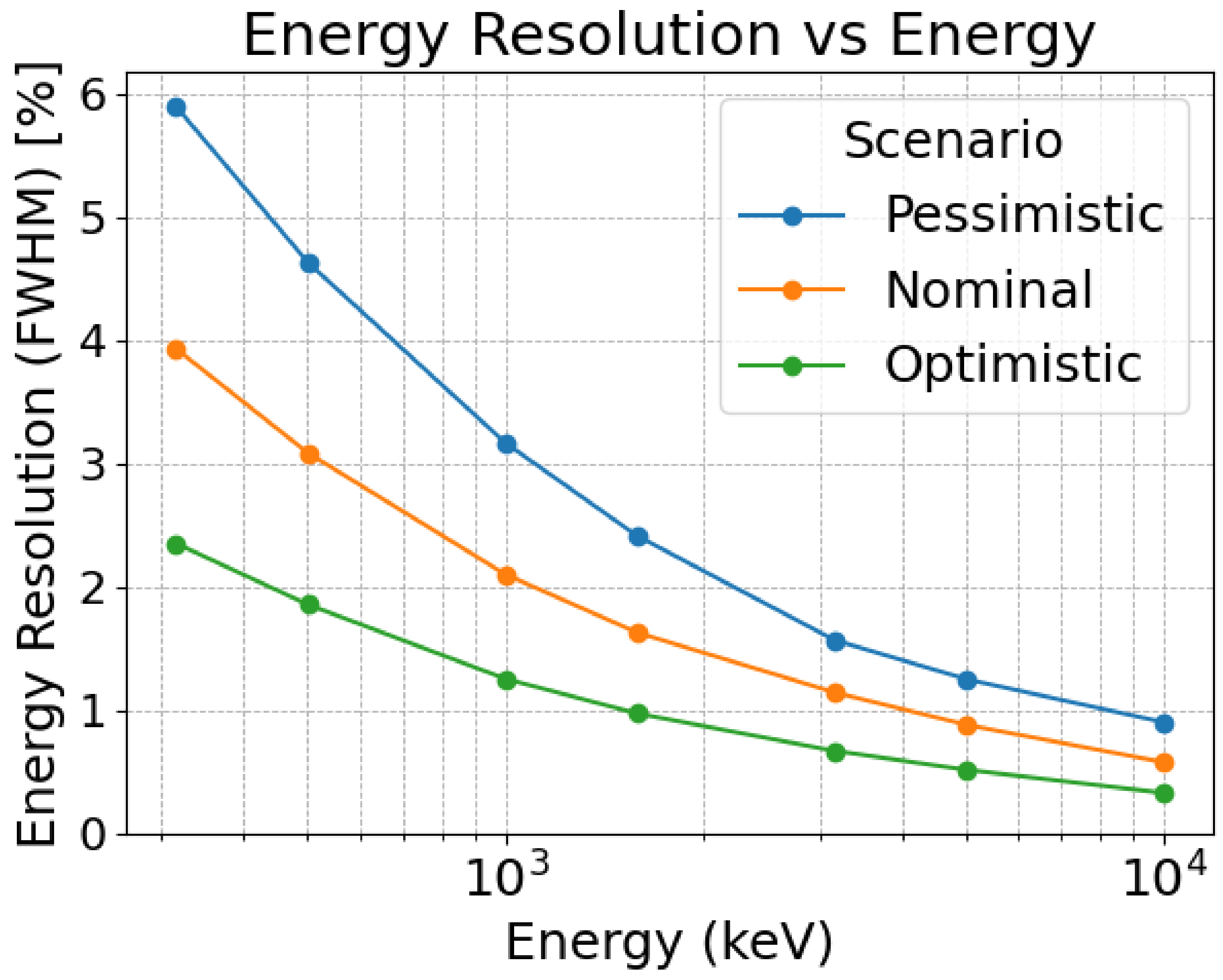
- Equatorial LEO
- Pile-up < 5% for ~17.5 cm segments
- Backgrounds in sensitivity estimates:
  - Cosmic photons
  - Ar activation - modest due to low Z
    - ^{39}Cl, ^{38}Cl, ^{41}Ar, ^{37}S, ^{38}S, ^{40}Cl, …
  - CsI activation - high rate, but tagged + reconstructed
  - Albedo photons - mostly eliminated by CsI calorimeter + reconstruction.
  - Charged particles tagged by ACD

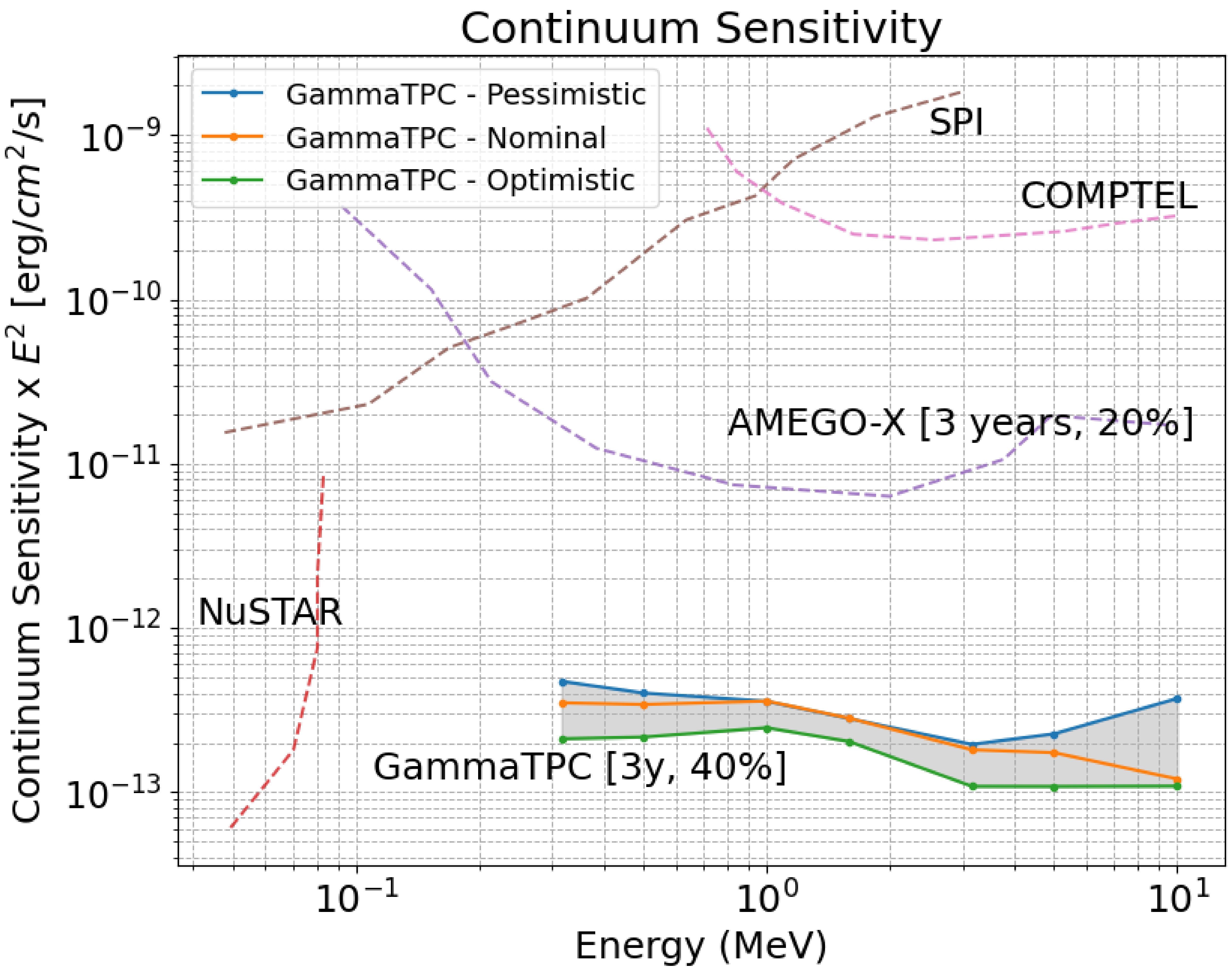




Preliminary Compton Sensitivity

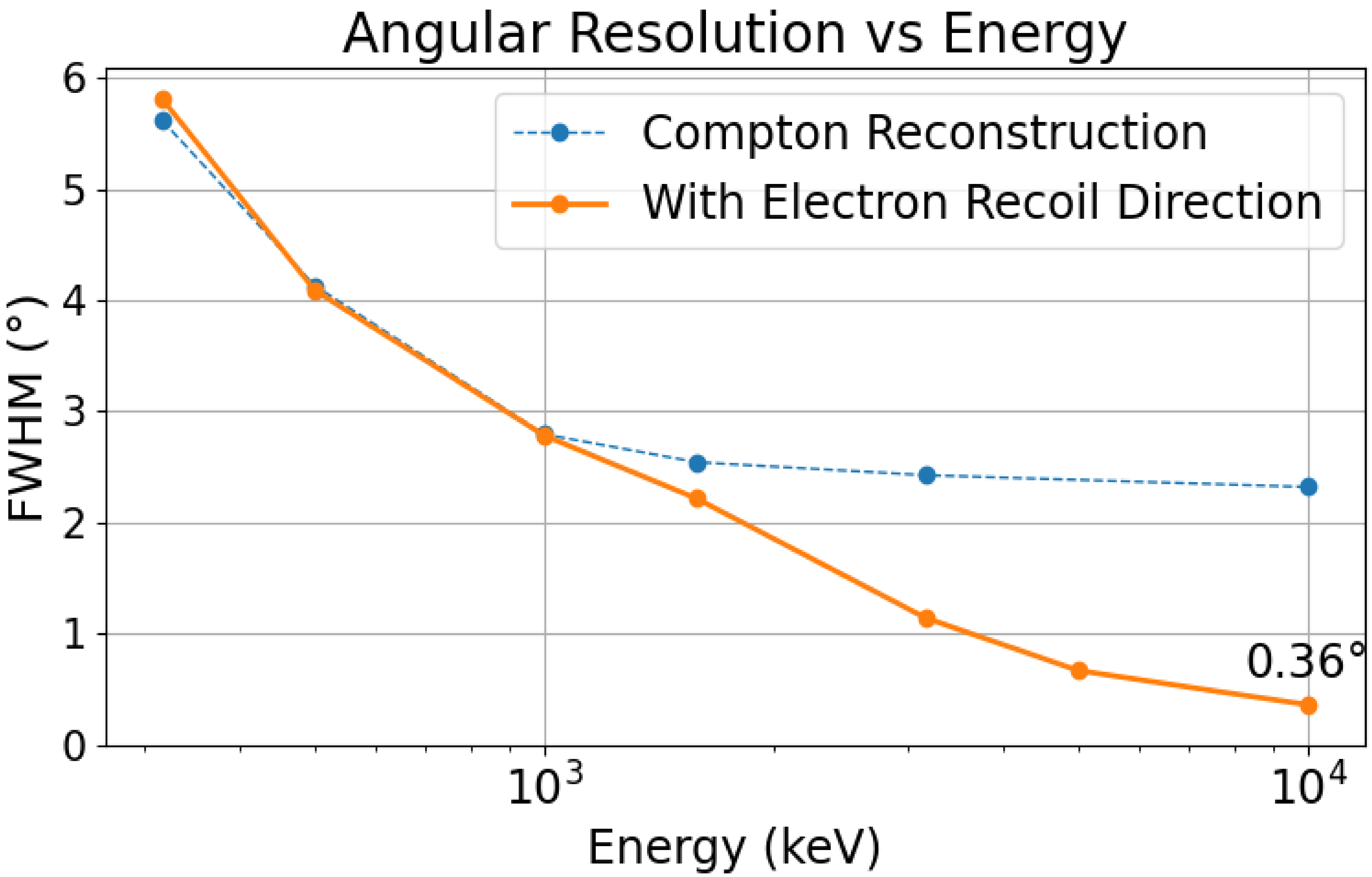


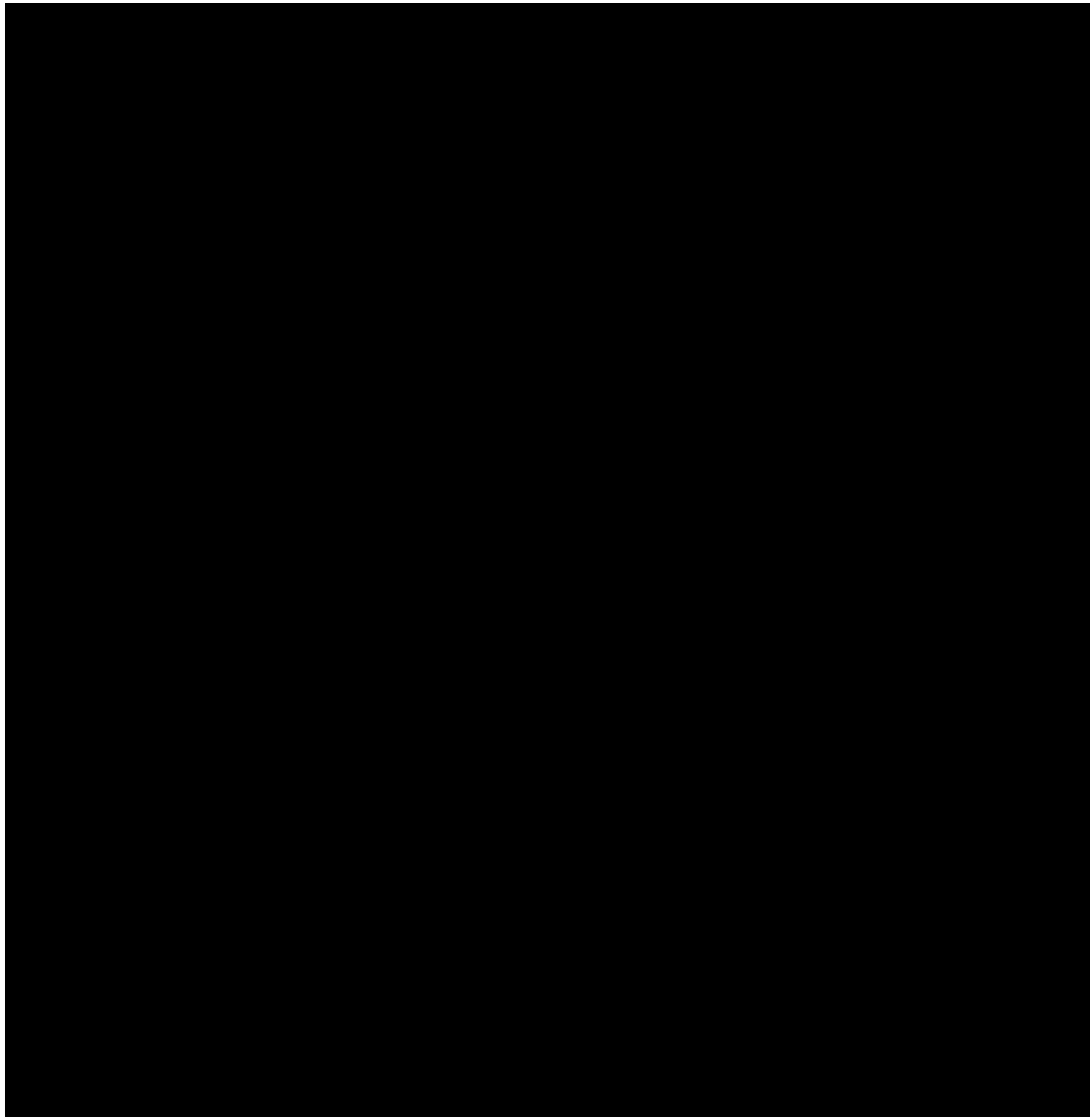




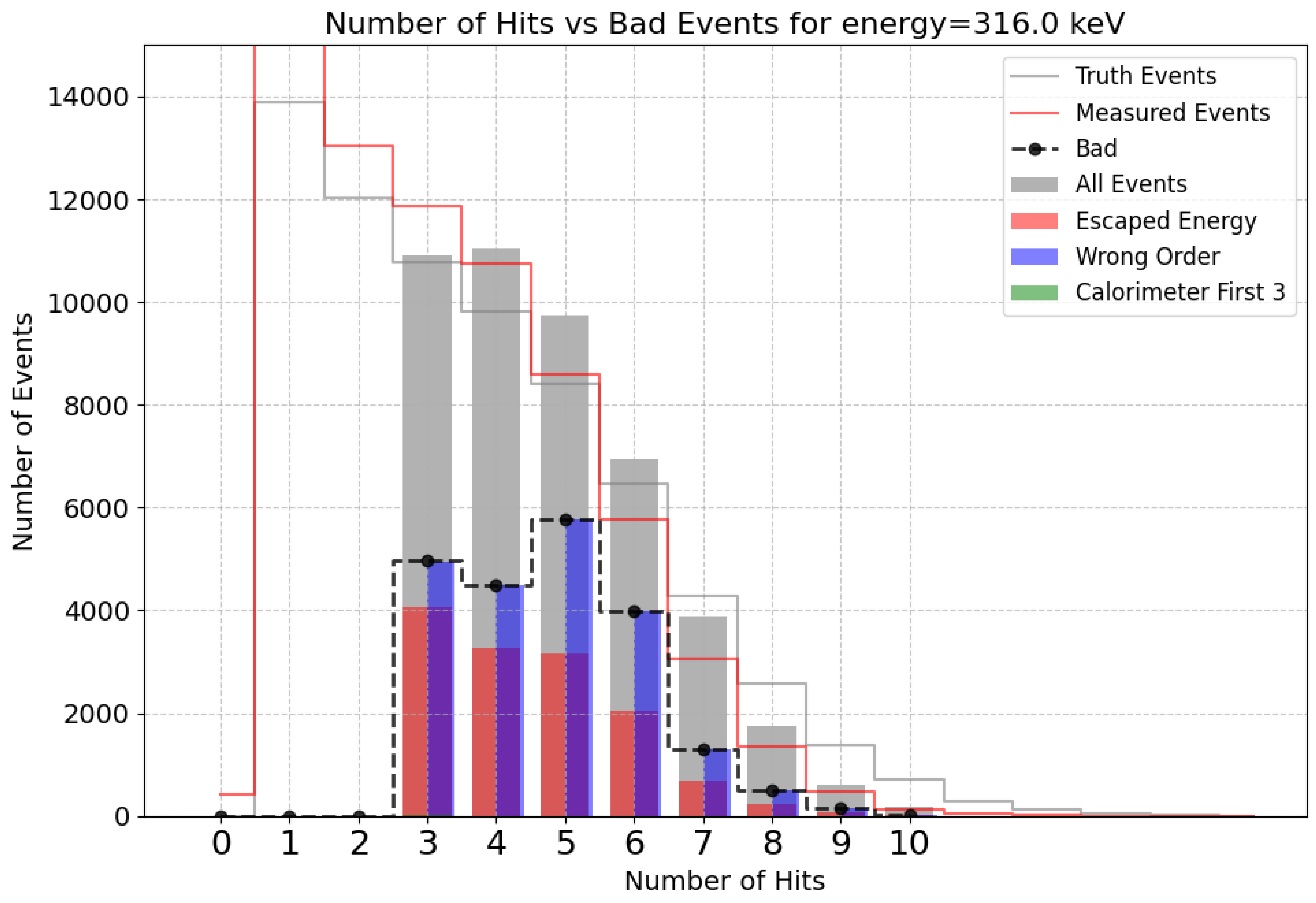
- 7 m^2 instrument, 35 cm LAr, 10 cm CsI
- Only include 3-10 hits

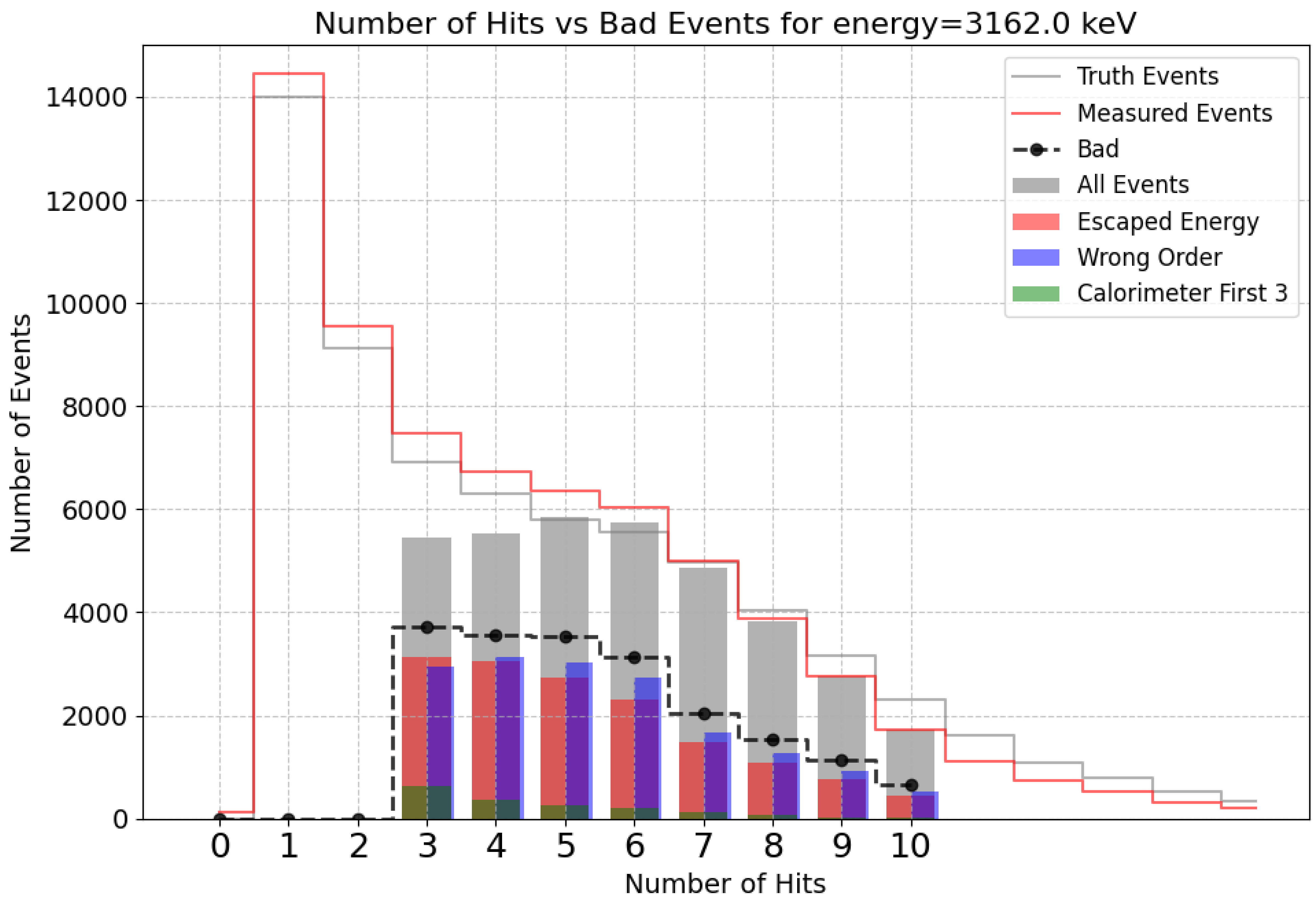
Angular Resolution and Efficiency





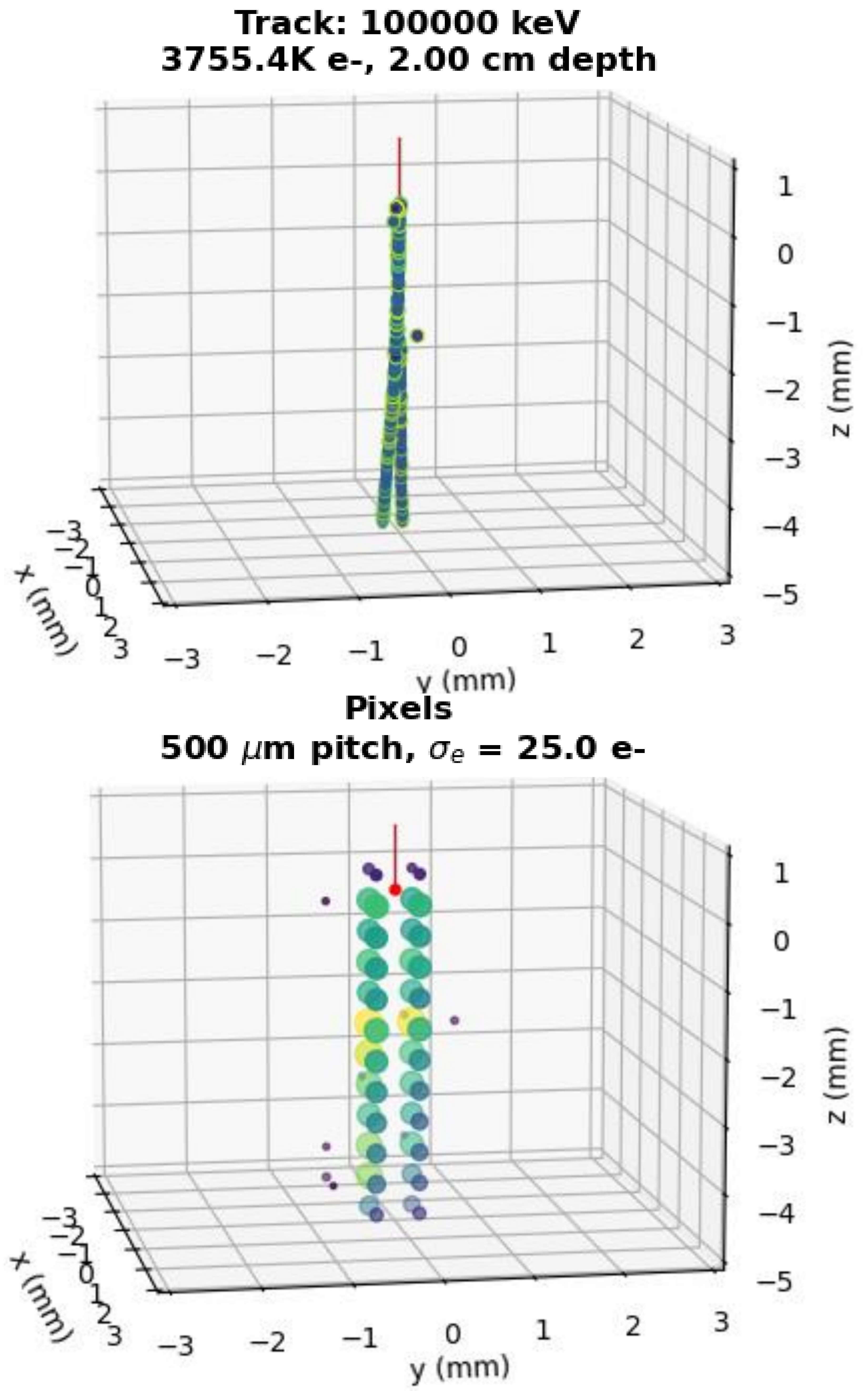
Angular Resolution and Efficiency





Pair Sensitivity

- Not yet studied
- Tracker highly efficient at 2 radiation lengths
- Low Moliére scattering in LAr may compensate lack of layers with gaps
- 100 MeV example shown, $\Delta\theta \sim 1°$ with crude PCA treatment.
- Upper energy range set by calorimeter



Summary

- LAr TPCs are powerful new technology, especially in era of low launch costs. Combines large mass, and sensitive readout.

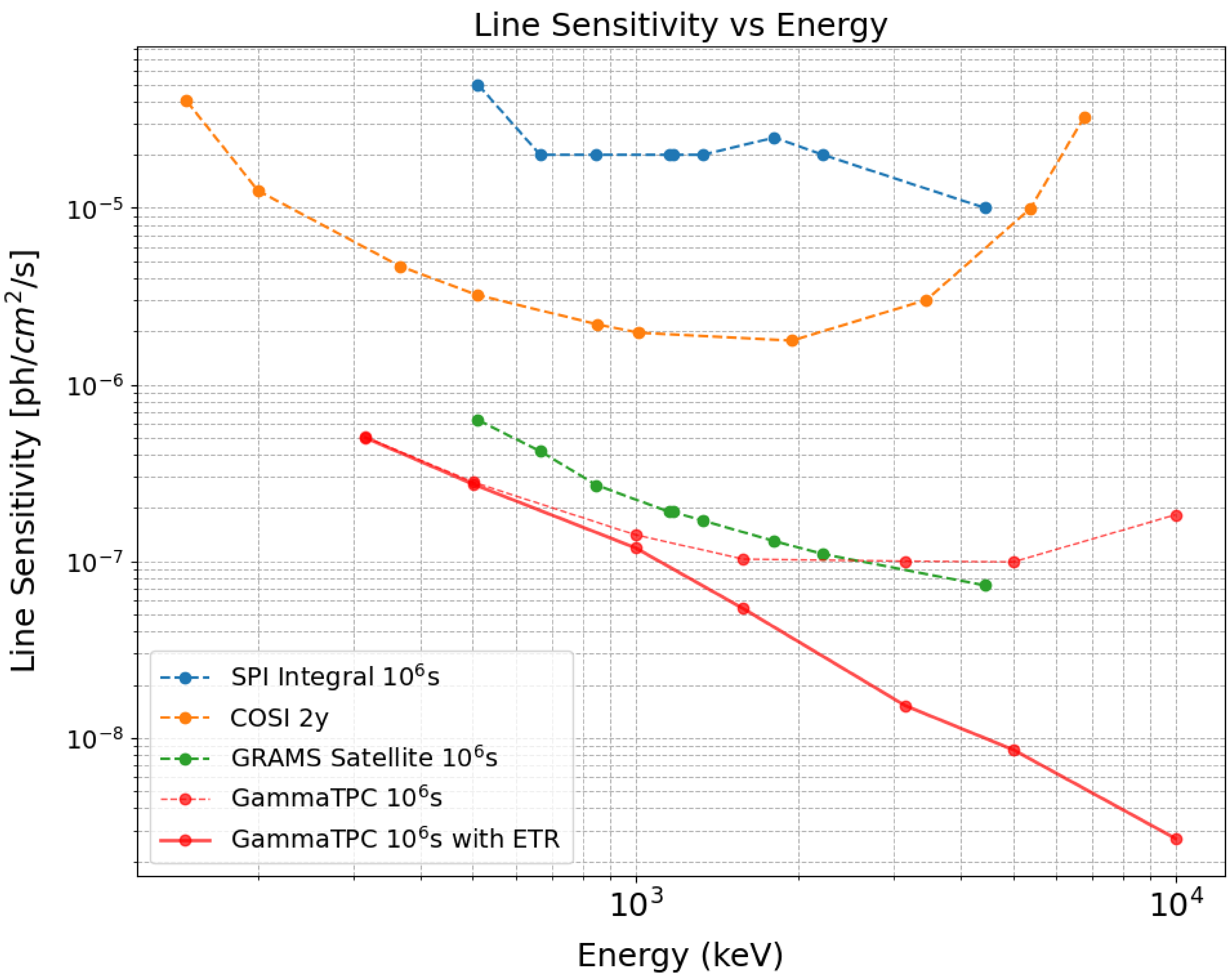
- Substantial development remains, but we are making progress on core challenges

- Plenty of work to go around!

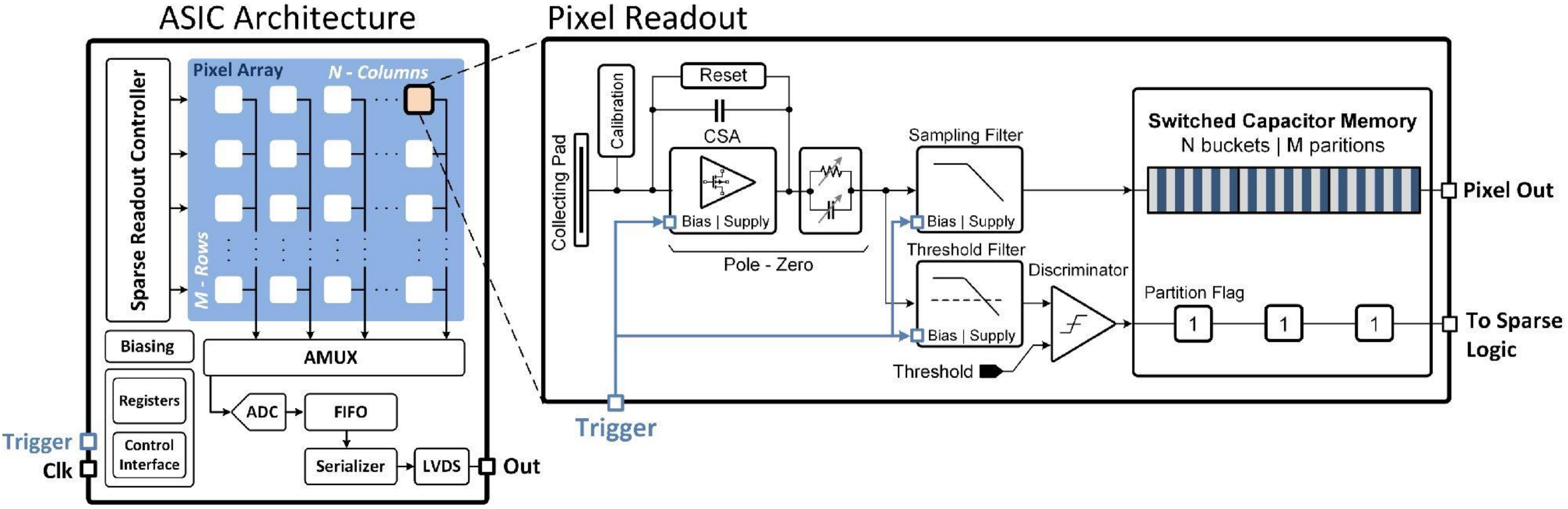
Paper or ArXiv ☺

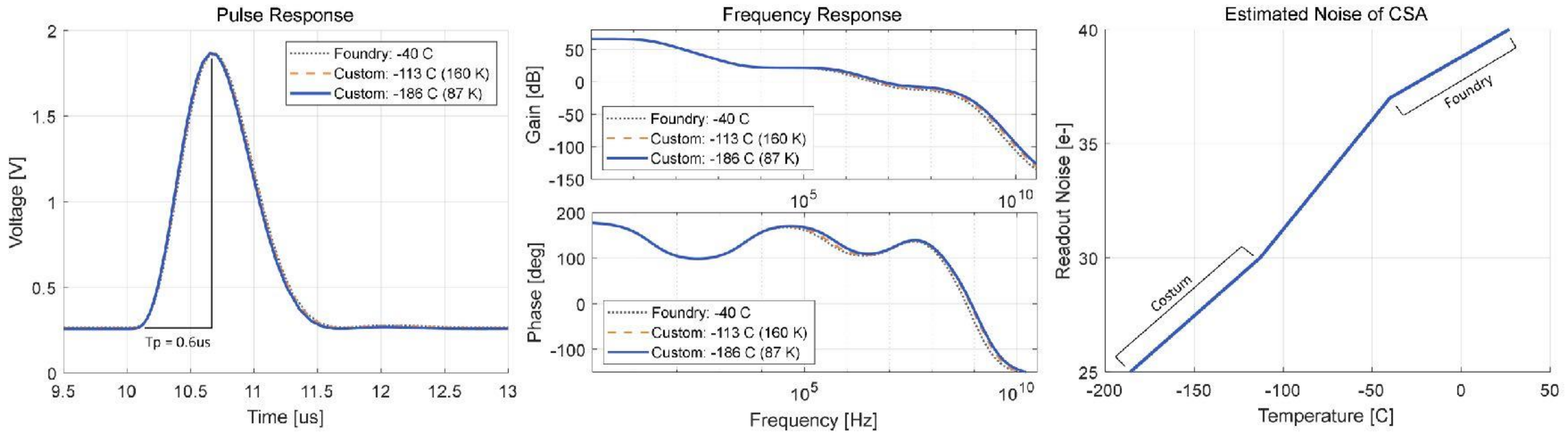
Backup

Line Sensitivity



GAMPix fast power cycle ASIC





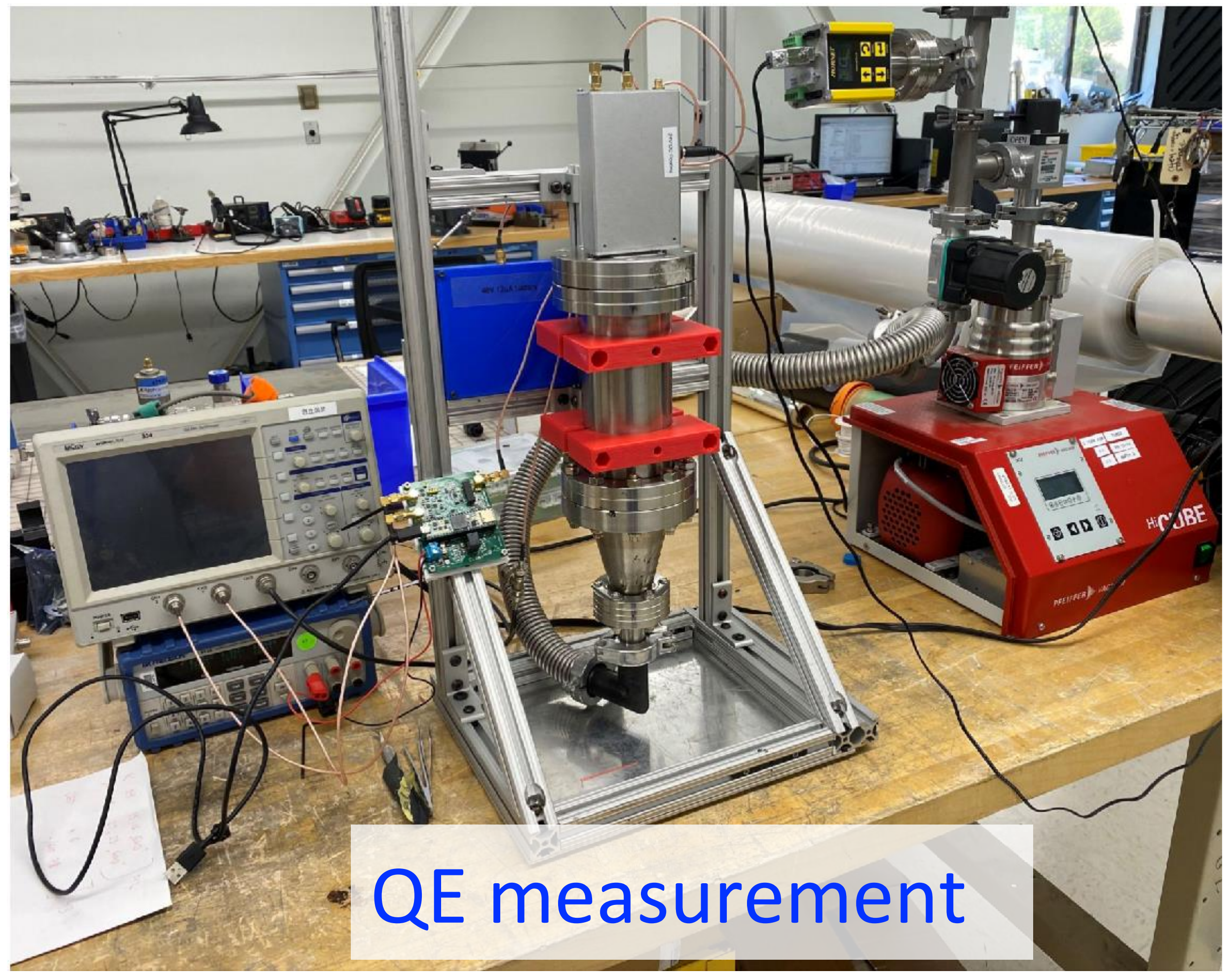
- Builds on cryogenic ASIC development for DUNE, quantum instrumentation.
- Transistor-level modeling of power switching front end (TSMC + SLAC data): ΔT_{on}~500 ns, $\sigma_e \sim 15e-$
- Switched capacitor storage + slow multiplexed sparse sampling to be adapted from other designs

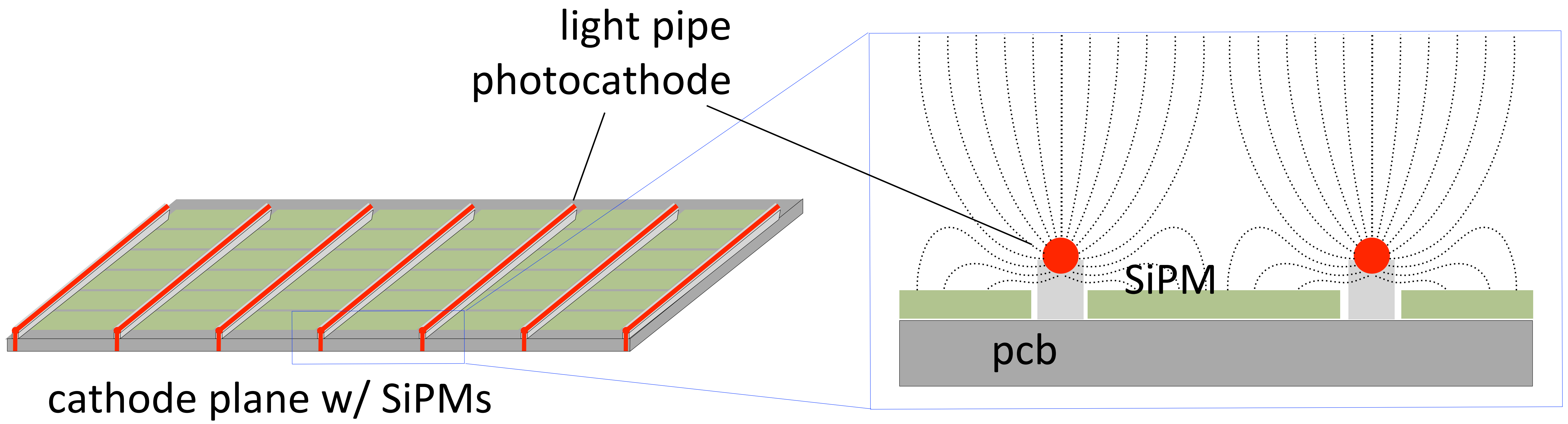
Aldo Peña Perez

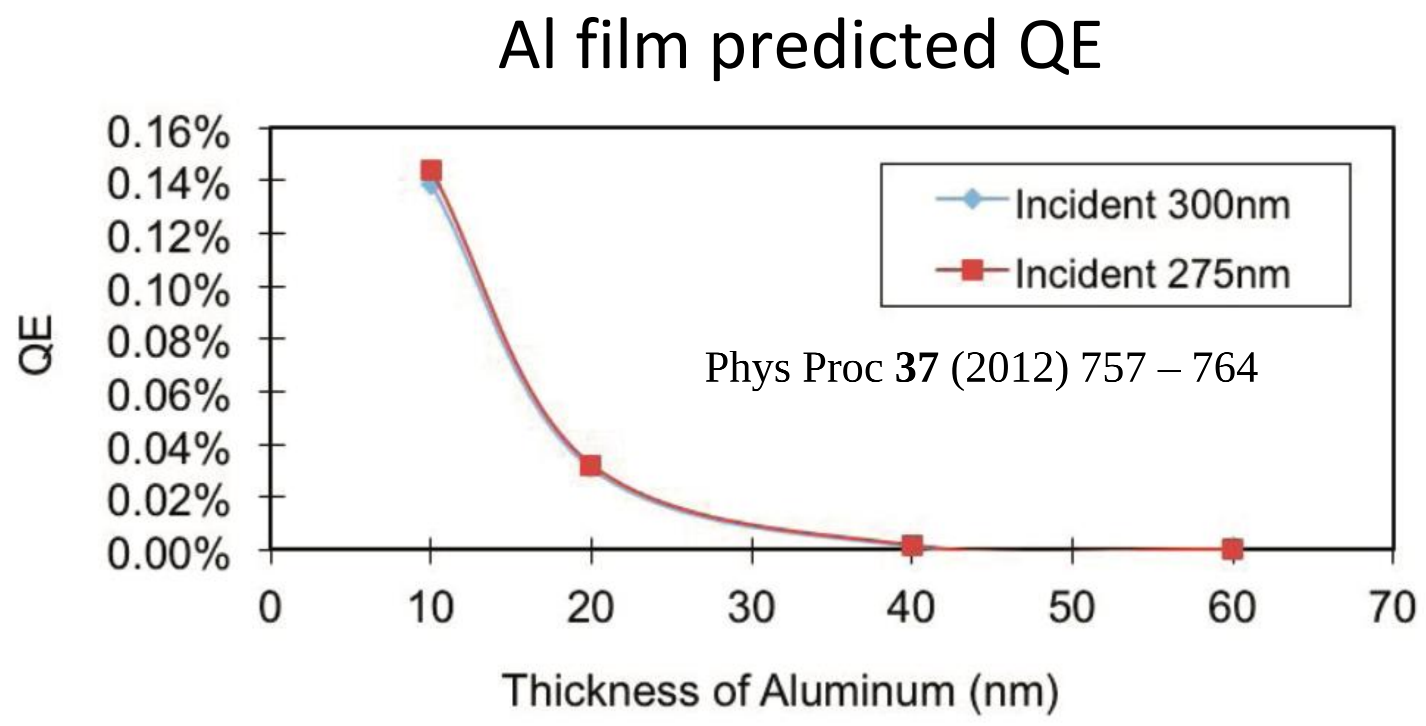
Charge neutralization

- Slow drifting Ar^+ ions create space charge
- Field distorted by few %; traps charge
- Perhaps ok? Calibrate?
- Neutralization concept: photocathode on lossy light pipes, pulsed with 275 nm light. QE ~10^{-4} needed
- Needs work
- Synergy with DUNE calibration, Michigan St. and Hawaii groups.

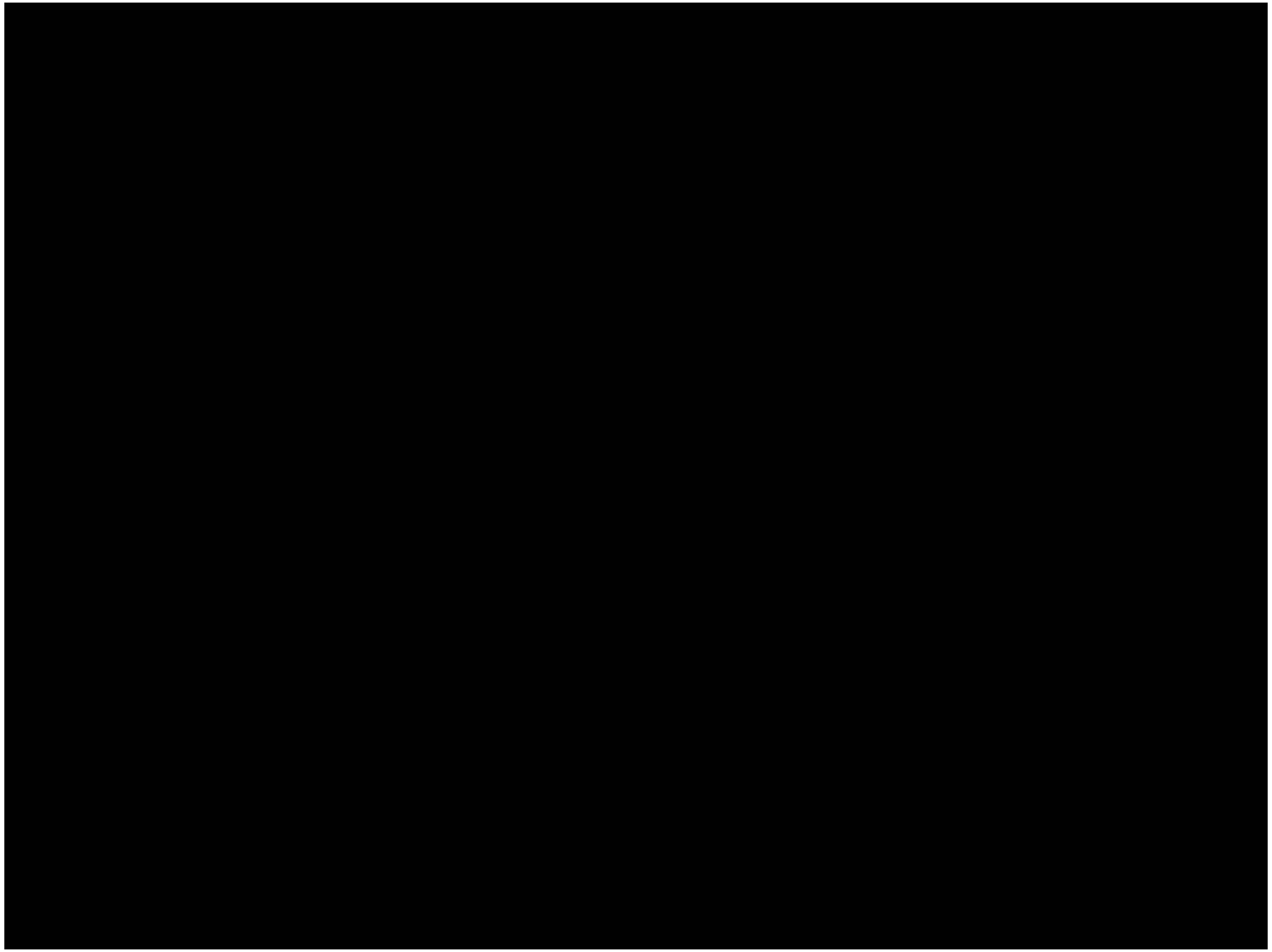
Steffen Luitz





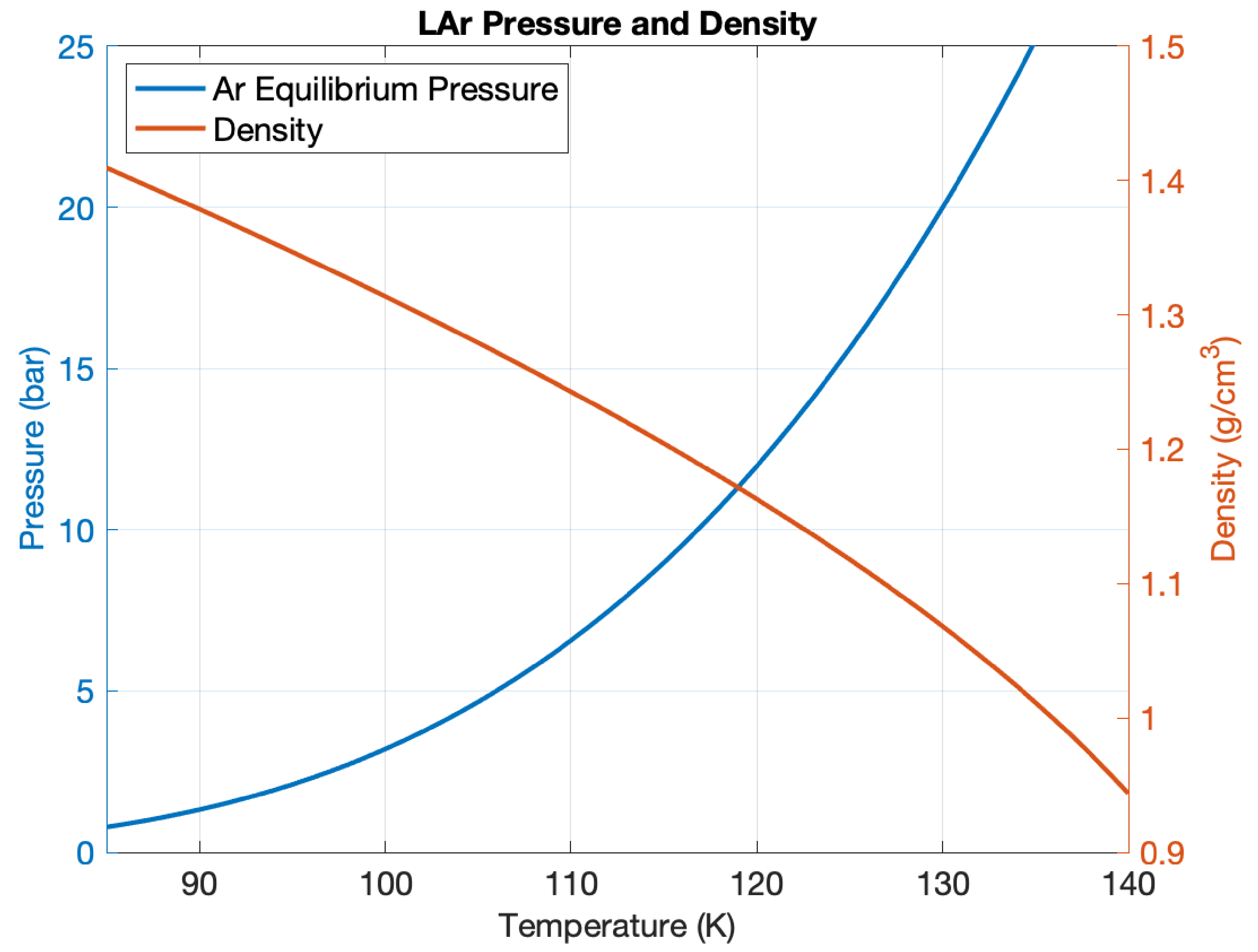


Electron track direction

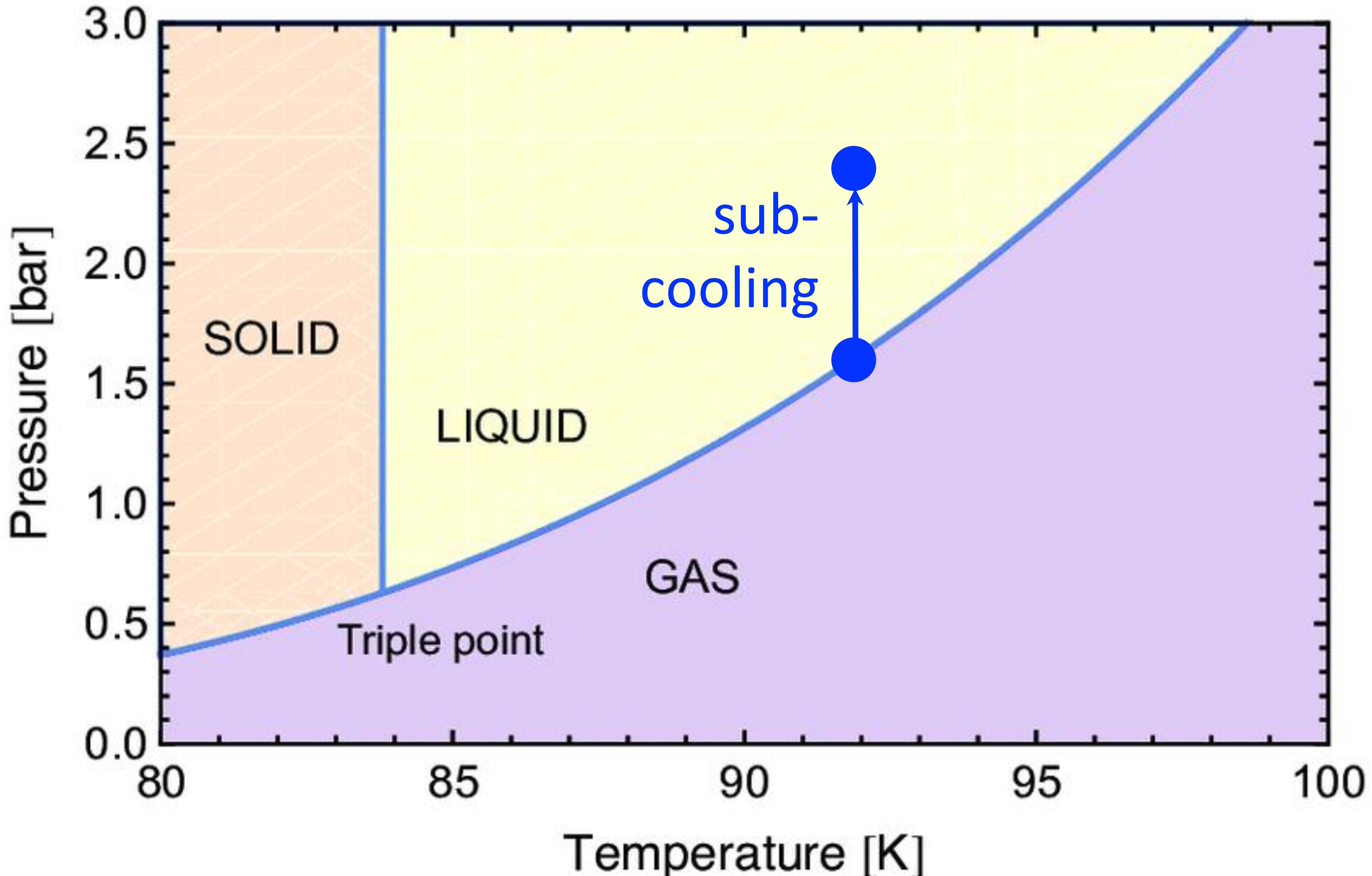


LAr in space

- Passive cooling would require untenable Sun + Earth shield
- Cryocooler should work
  - Smaller "heat lift" at ~120 K, 10 bar.
  - Few W/m^2 power budget
- Need single phase Ar + sub-cooling.
  - Control of volumes + displacement element (e.g., piston) to create overpressure.
  - Spin spacecraft?



4 mm carbon fiber shell holds 20-30 bar!

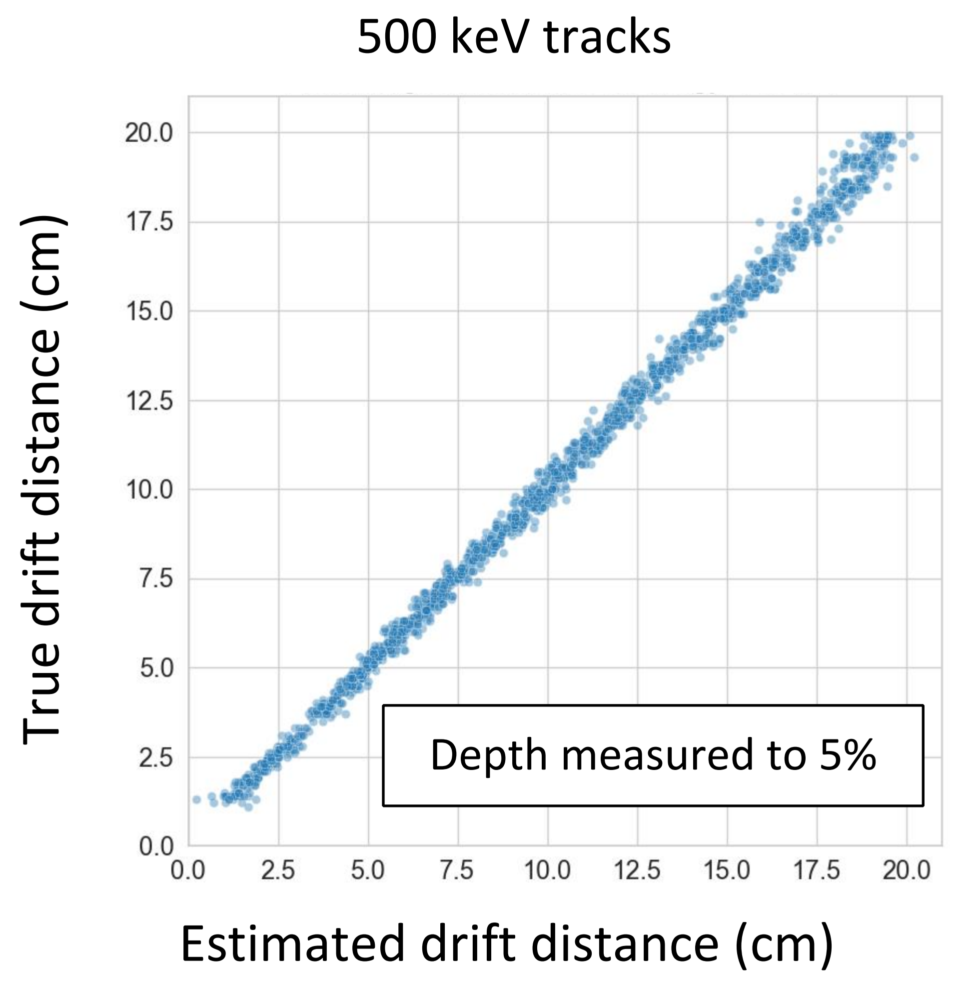


More on GAMPix

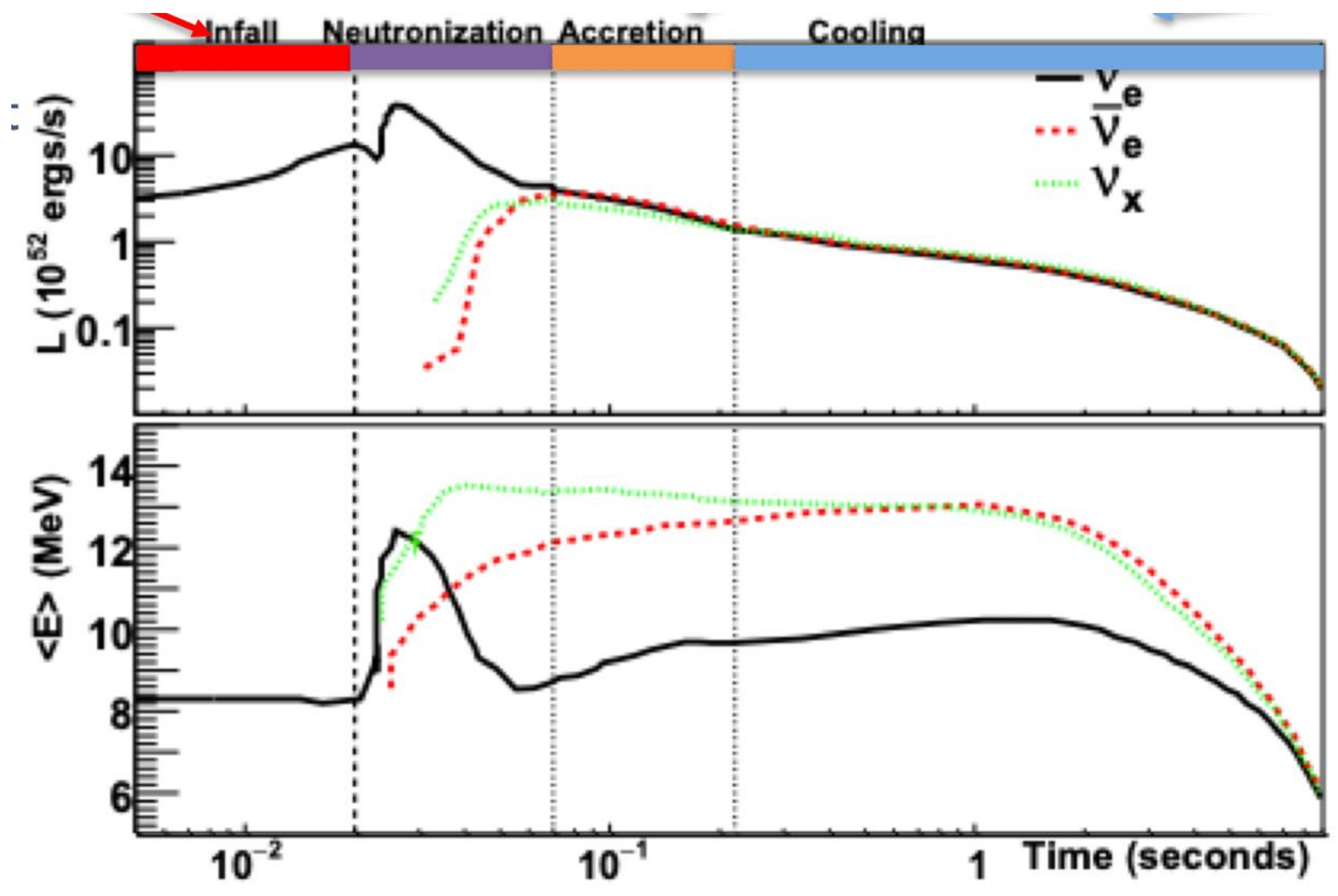
- Coarse + fine measures diffusion; hence depth; hence pile-up rejection

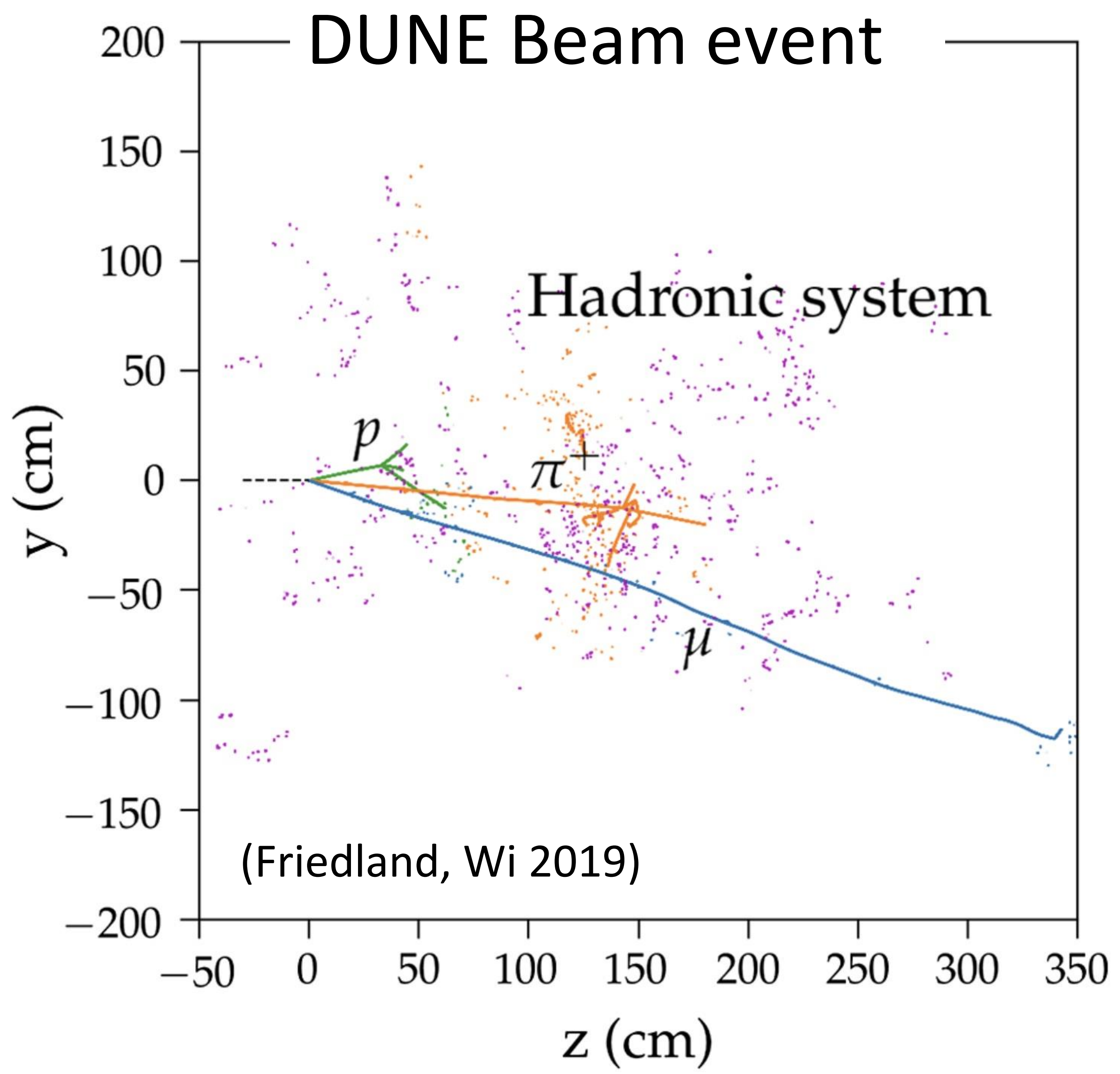
- Two possible DUNE application:
  - Galactic SN signal.
  - Beam ν energy resolution, reconstruction.

- *GAMPix powerful whenever imaging at diffusion limit*

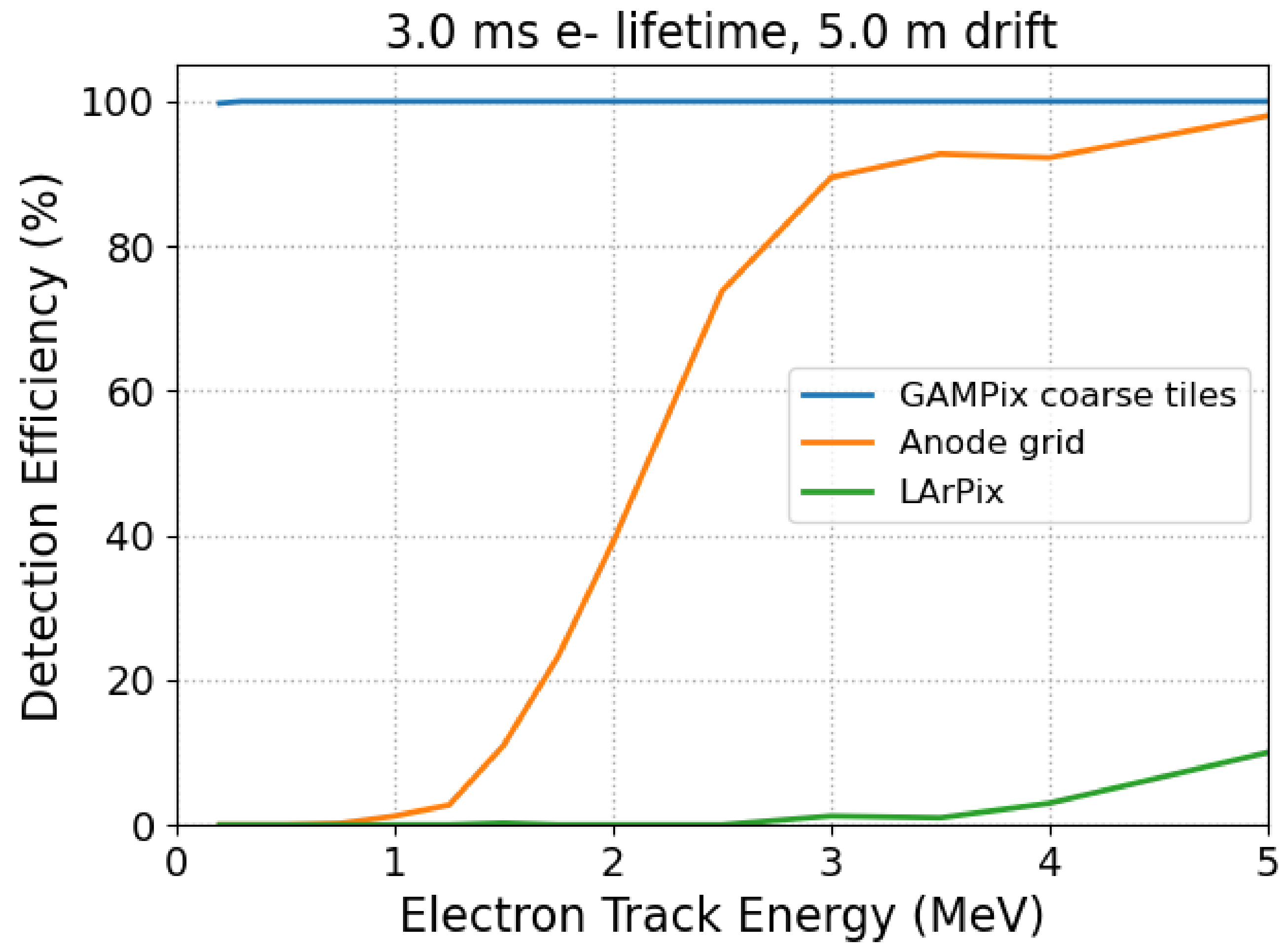


Galactic SN neutrinos

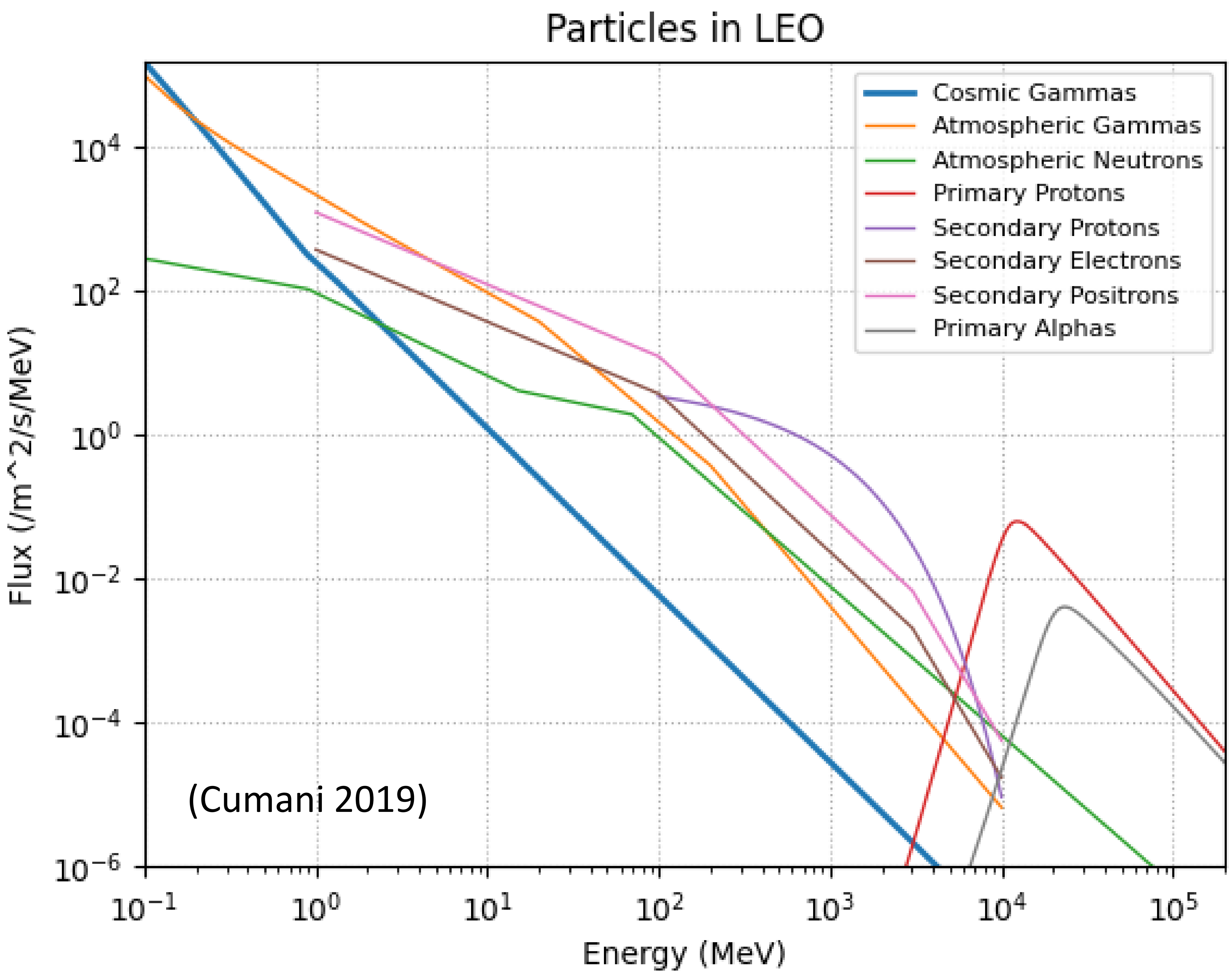




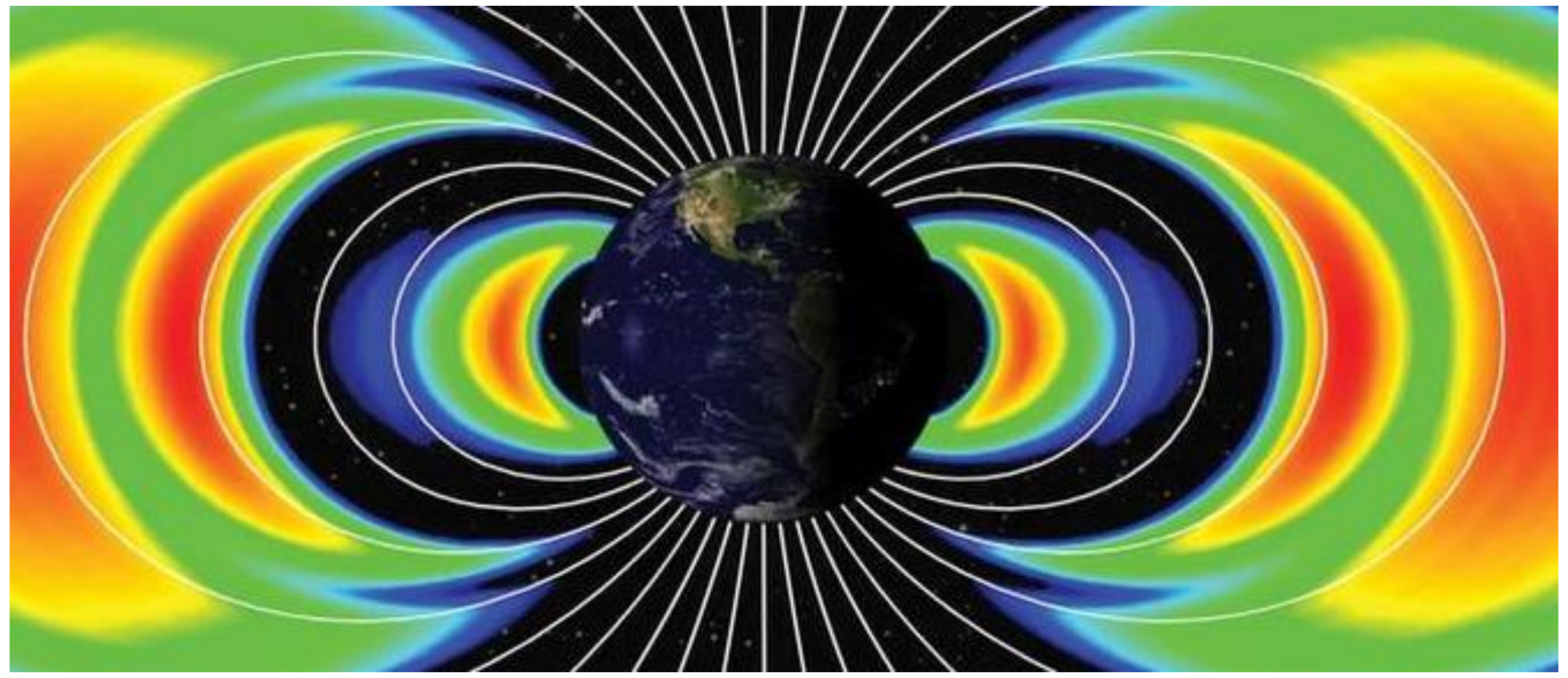
DUNE 'blip' response



Particle rate in space is challenge



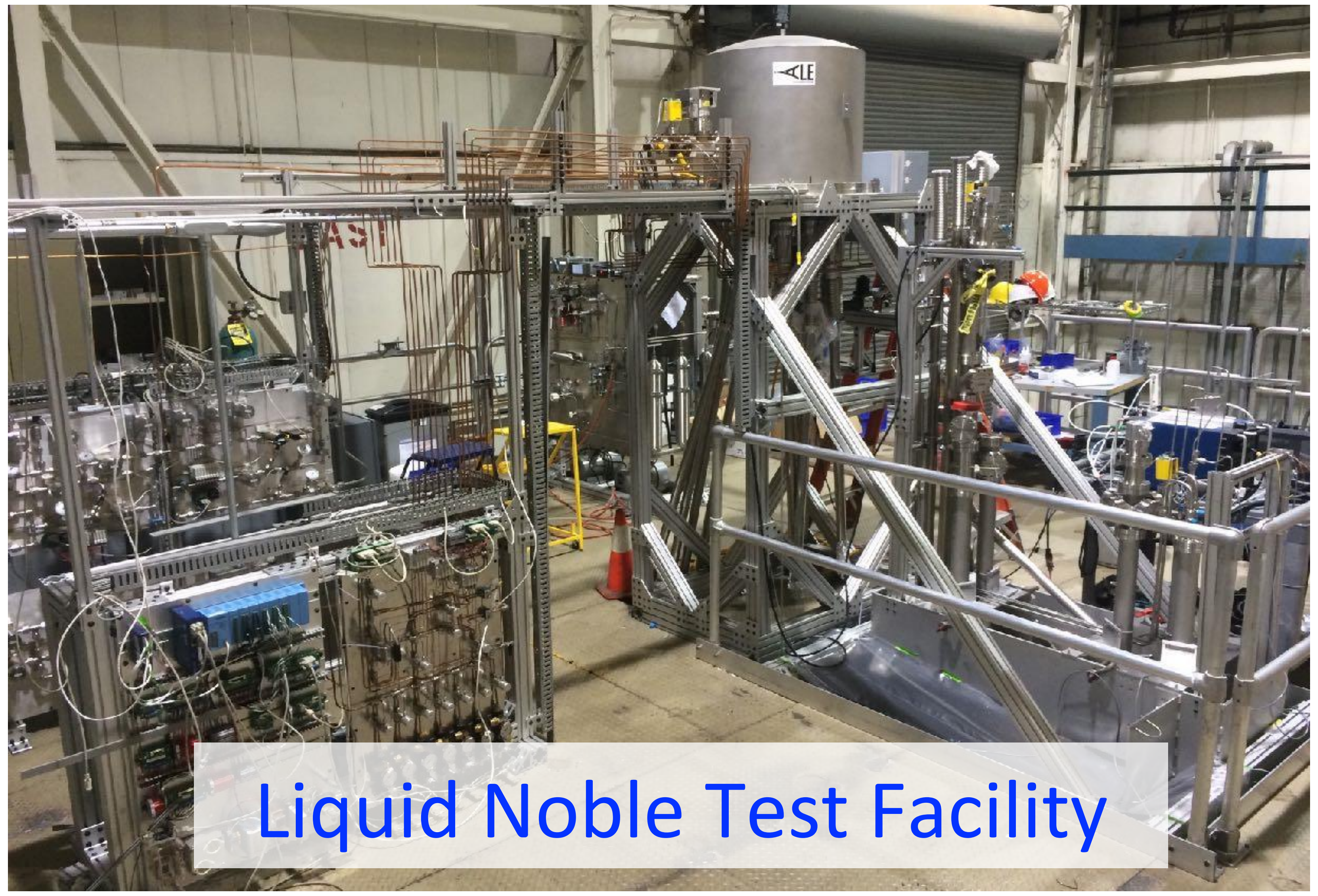
Equatorial low earth orbit required



- Lowest background orbit required
- Pile-up, after segmentation < 10%
- Backgrounds
- Space charge

GammaTPC Development

- Modest funding to date - internal, APRA
- Significant leveraging of DUNE program overall, and group at SLAC.
  - Joint TPC development with R&D for SN neutrino calibration
- SLAC Liquid Noble Test Facility - LNTF
  - Initially LZ system test, now hosts R&D for XLZD, DUNE, nEXO, GammaTPC, cryogenic ASICs
- Possible synergy with GRAMS balloon program?
- Small zero-g prototype needed

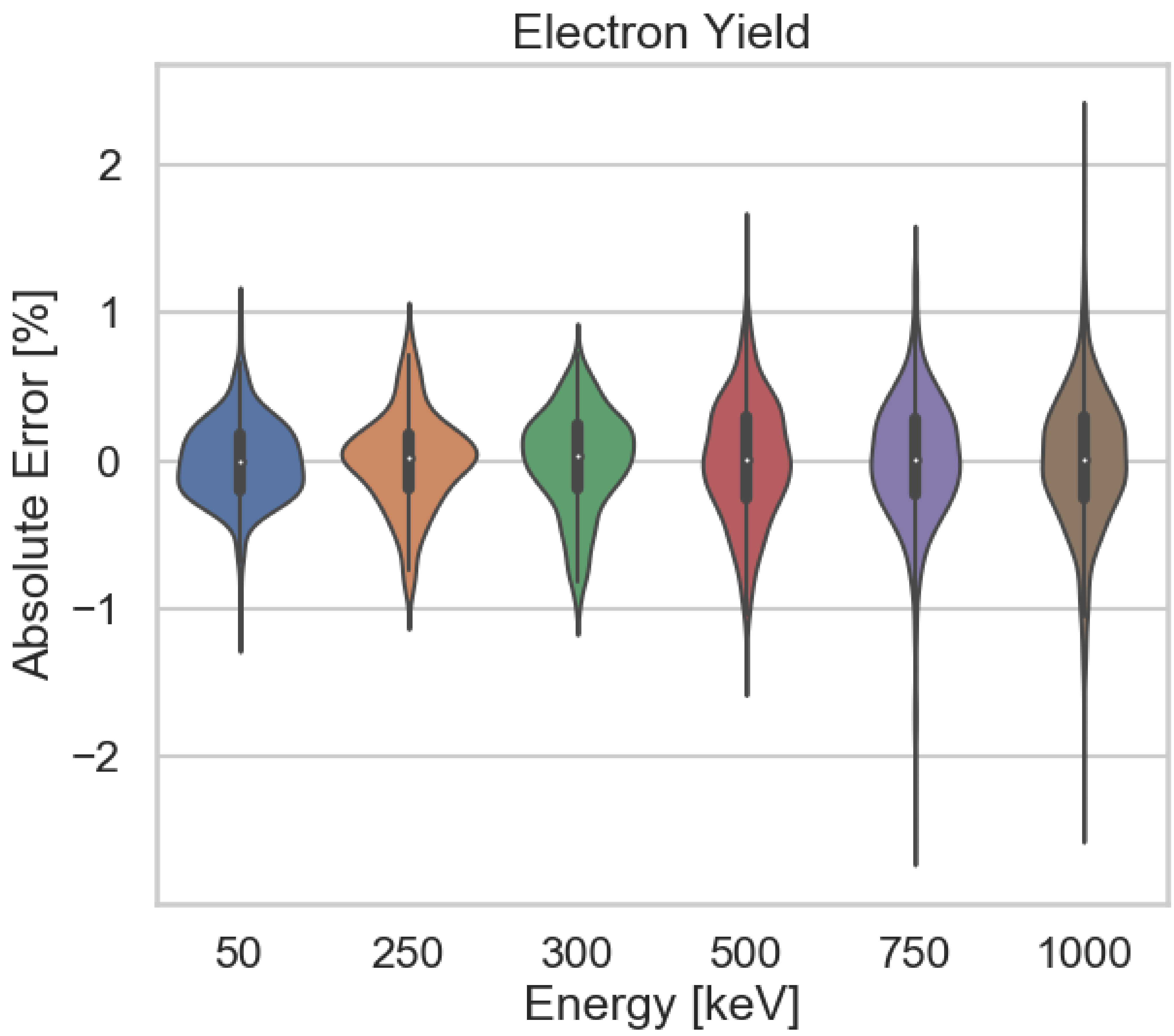


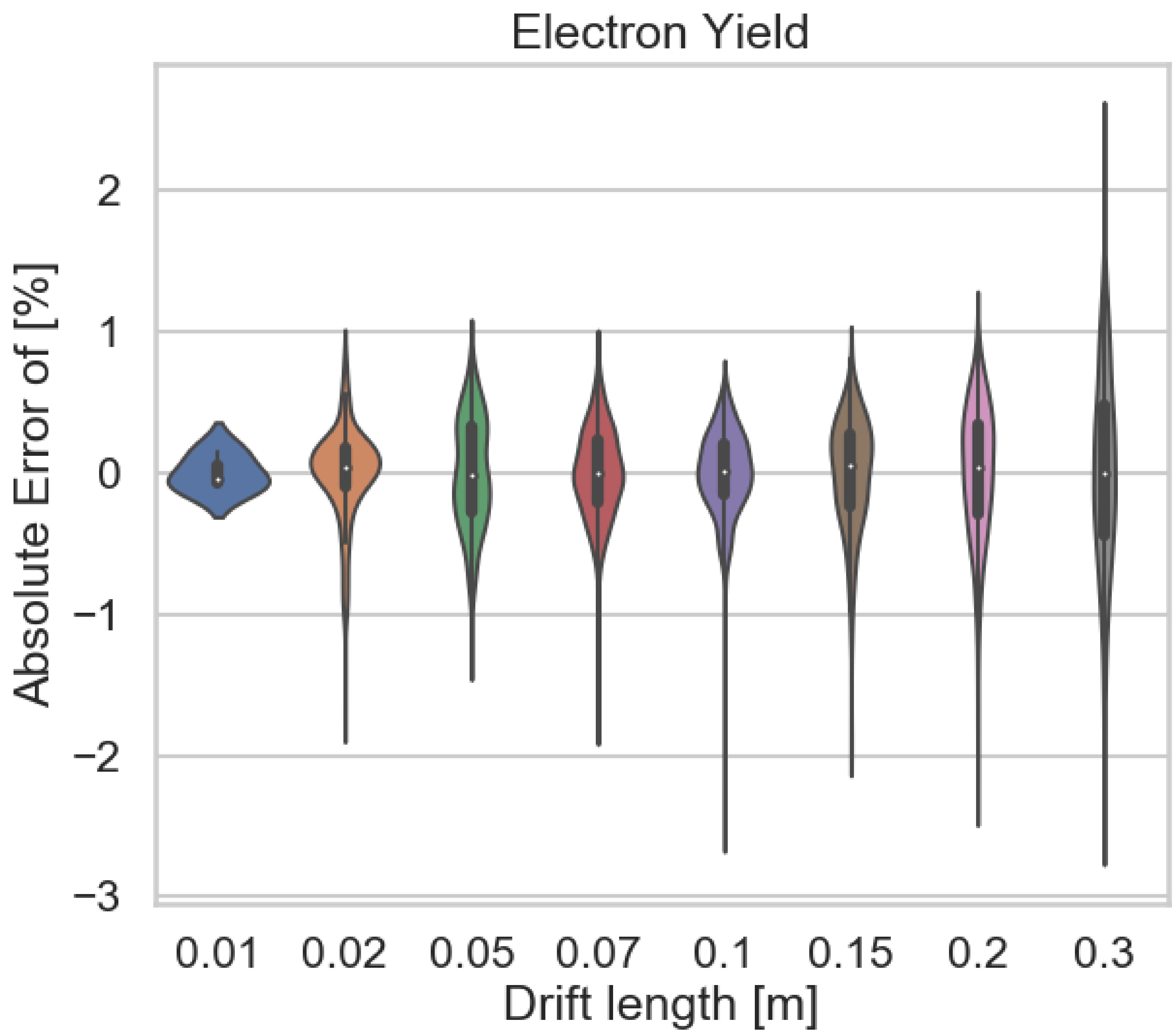
Liquid Noble Test Facility

LAr systems in LNTF

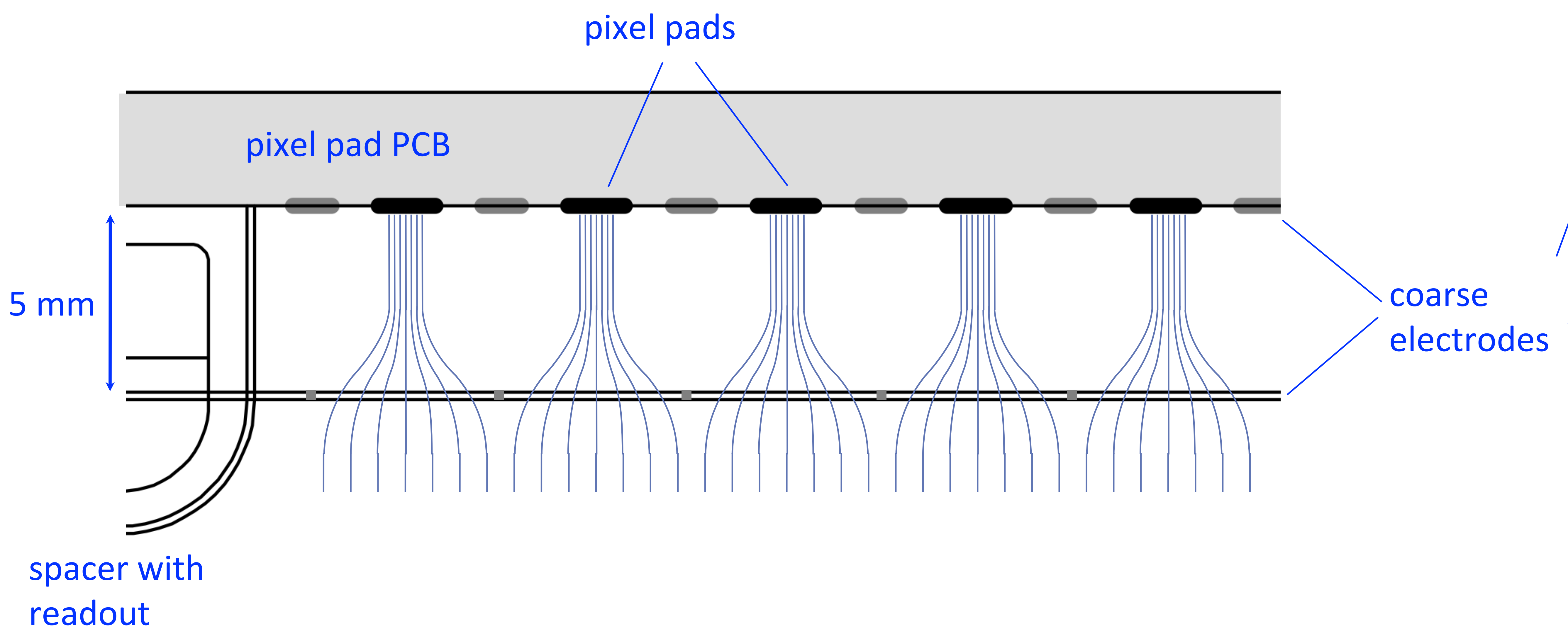
IV. Accuracy of the algorithm

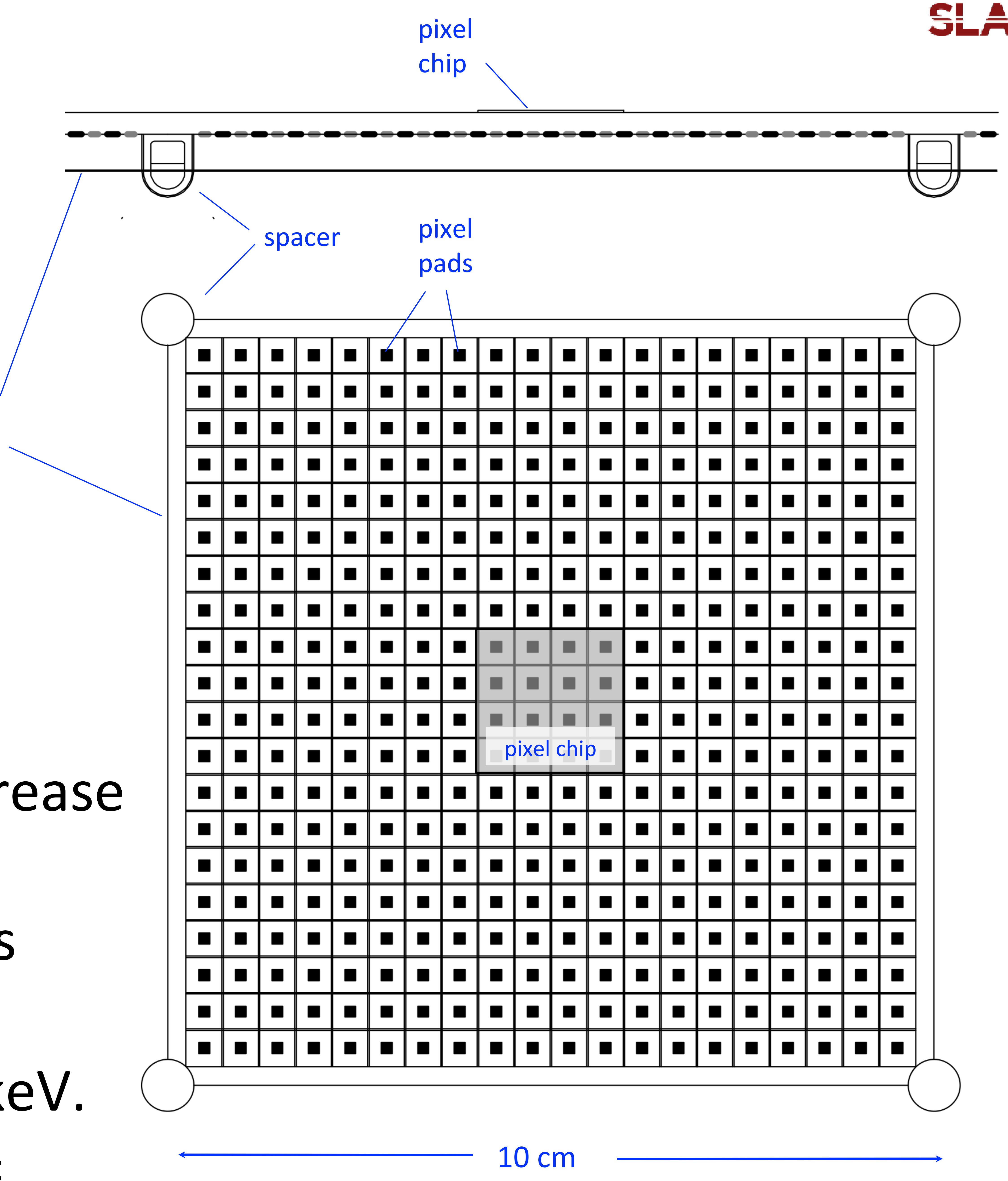
With this procedure we achieve amazing positional and charge readout accuracy.





DUNE implementation





- Pixel pitch should roughly match diffusion: increase pitch from 0.5 mm to 3-5 mm
- No coarse grids. Read out focussing electrodes instead
- Initial study: pixel noise ENC σ_e~50 e-, or 2.5 keV.
  - Coarse electrode similar or higher, depending on dynamic range.