Nano-tracking detector for neutrinoless double beta decay characterization

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Mille feuille = 1000 leaves in French
How to stack 1000 leaves in a nano-structure for a novel detector

LR Symmetric Model and 0νββ Decay

- Many mass mechanisms exist
- Consider the left-right symmetric model
- Multiple contributions to the 0νββ half life
  - η model – W_R W_L mixing term
  - λ model – W_R W_L mass term

$$\nu'_{eL} = \sum_k^{light} U_{ek}\nu_{kL} + \sum_k^{heavy} S_{ek}N^c_{kR}$$

$$\nu'_{eR} = \sum_k^{light} T^*_{ek}\nu^c_{kL} + \sum_k^{heavy} V^*_{ek}N_{kR}$$

Negligible for type I seesaw with mass > 1 GeV

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}_{01} g_A^4 \left| M^{0\nu}\left(\eta_\nu + M^{0N}\left(\eta^L_{N_R} + \eta^R_{N_R}\right)\right) + \eta_\lambda X_\lambda + \eta_\eta X_\eta + \ldots \right|^2$$

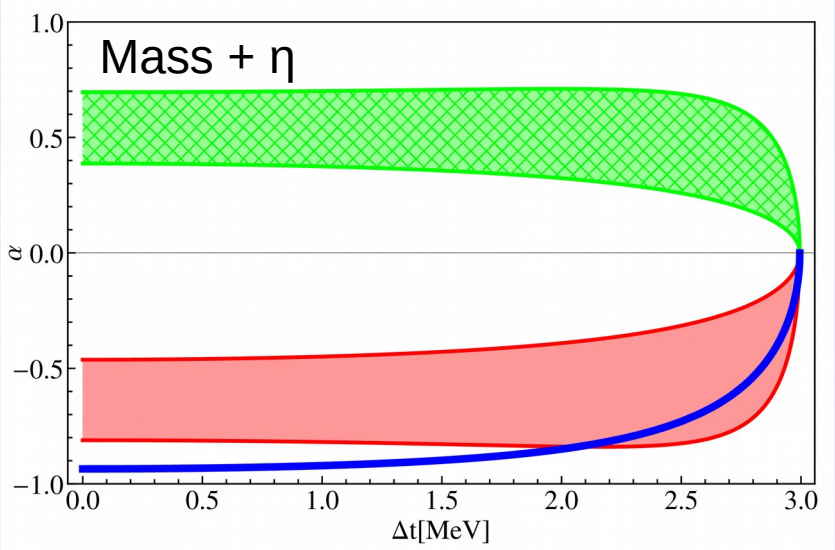
Effective electron neutrino mass term

Constrain with multi-isotopes (mass term for heavy neutrinos)

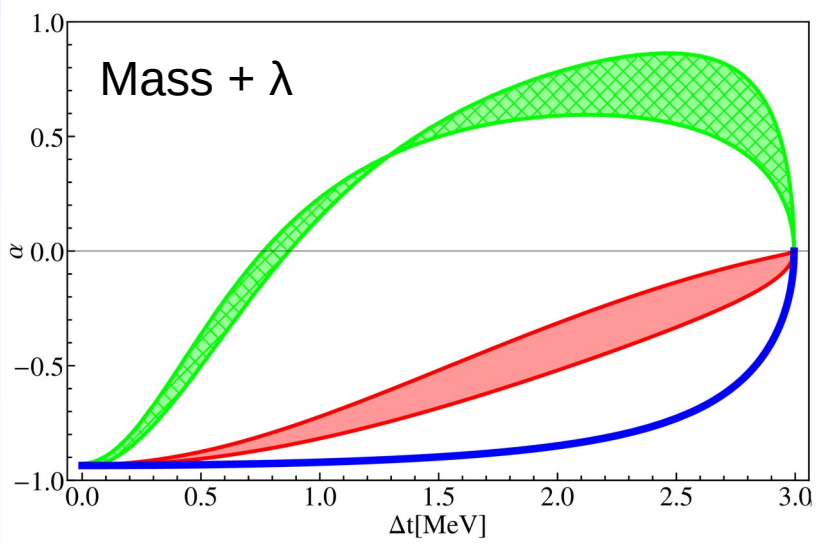
Constrain with energy and angular correlations

Disentangling η and λ Models

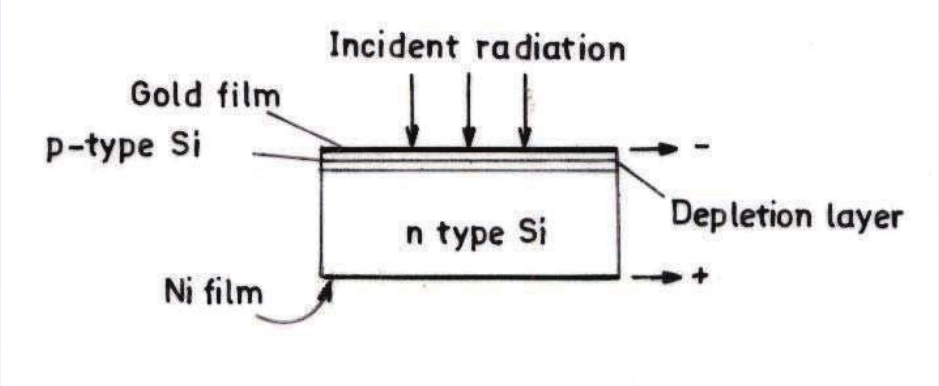
- Example of angular correlation coefficient α vs kinetic energy difference between two electrons Δt
  - Shown here for ^{84}Se
  - Taken from Horoi et al, Phys. Rev. D 93, 113014 (2016)
- Pure mass mechanism shown in blue
- Min/max values of η and λ shown in red/green



- Need to resolve beta tracks
- Measure energy and angle of both betas
  - Super NEMO aims to do this
    - Thin foil source
    - Sandwiched between
  - NEXT also uses tracking in high pressure gas

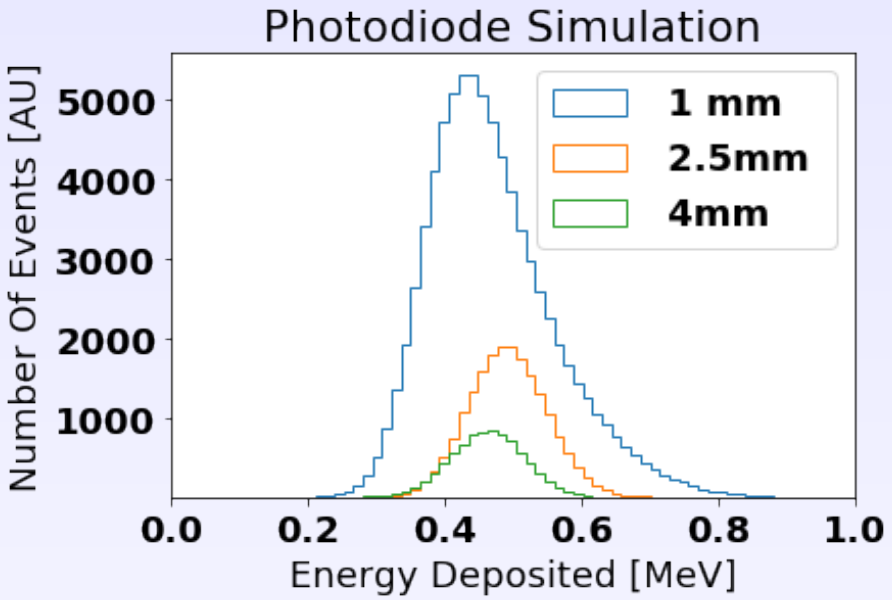


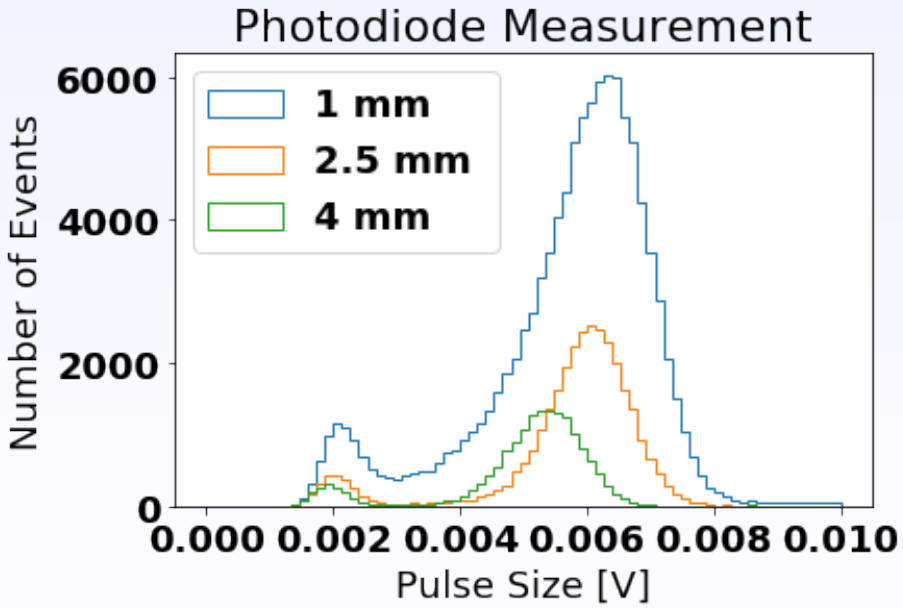
Surface Barrier Detectors



- Radiation induces electron hole pair liberation
- Current proportional to energy
- PN junction with small depletion layer
  - Can use PIN diodes as well
- Few 10s of nm thick
- Alpha and beta spectroscopy and counting

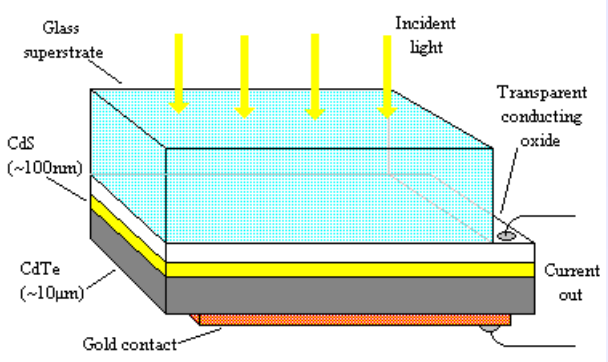
- Measurement of ^{241}Am alphas with commercial PIN photodiode
- Can reverse engineer depletion layer based on peak location

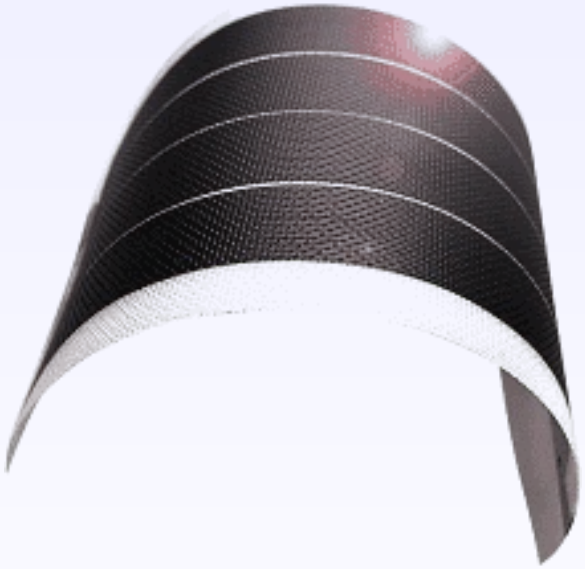




Thin Film CdTe Devices

- Epitaxial growth of CdTe devices
  - Macroscopic single crystals
  - Controlled growth on many substrates (e.g. GaAs)
- Extensive use in solar cell and x-ray detection
  - Micron-sized CdTe crystals
- Naturally high purity
  - Must avoid crystal defects for performance
  - Use chemical process (e.g. CVD) rather than evaporation
    - Additional radiogenic suppression



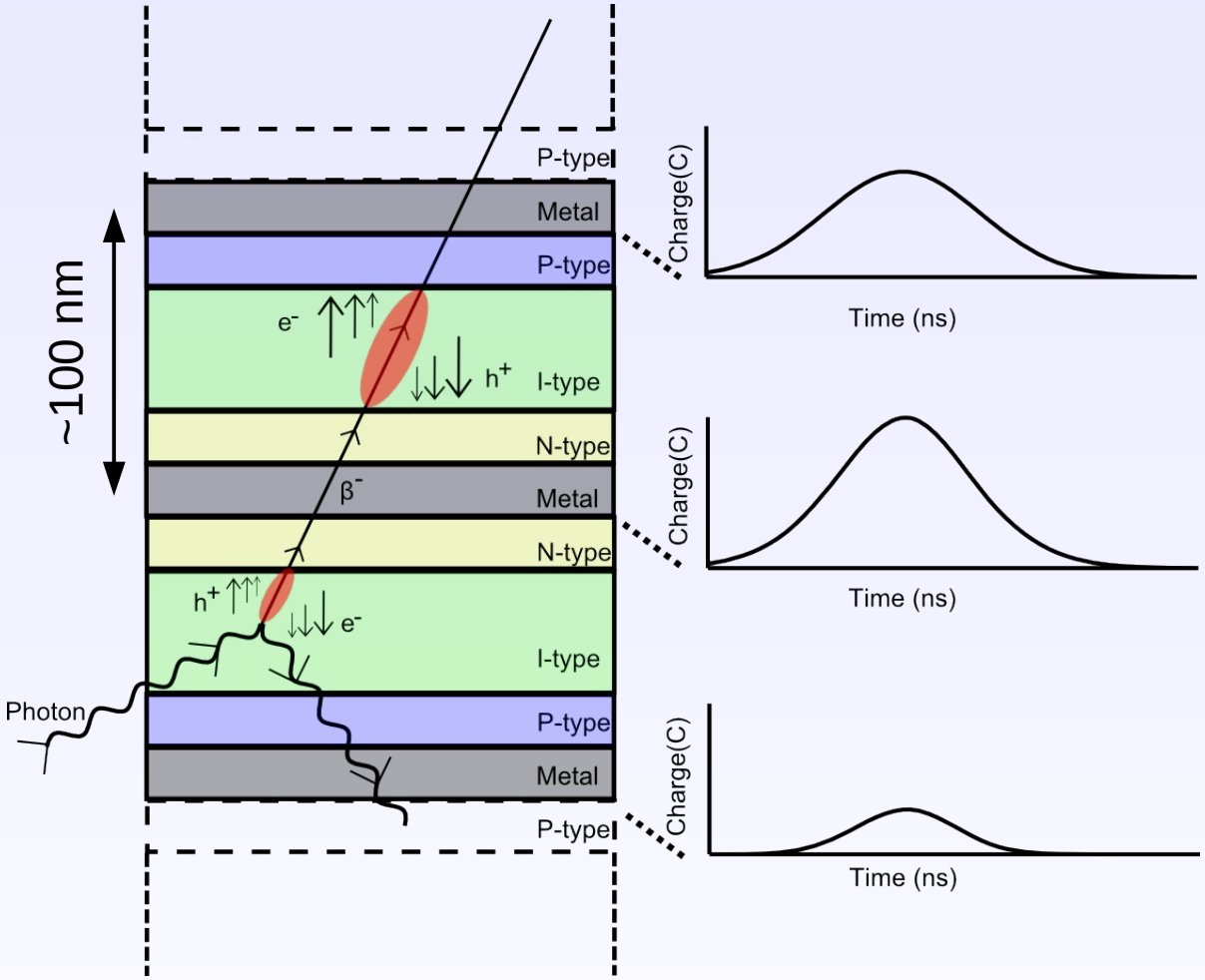


Thin film CdTe solar cell

- Biasing and readout
  - P and N doped for junctions
  - Use highly doped layer and/or metal contacts
  - Can tune design based on performance specs

Nano-Tracker Detector Concept

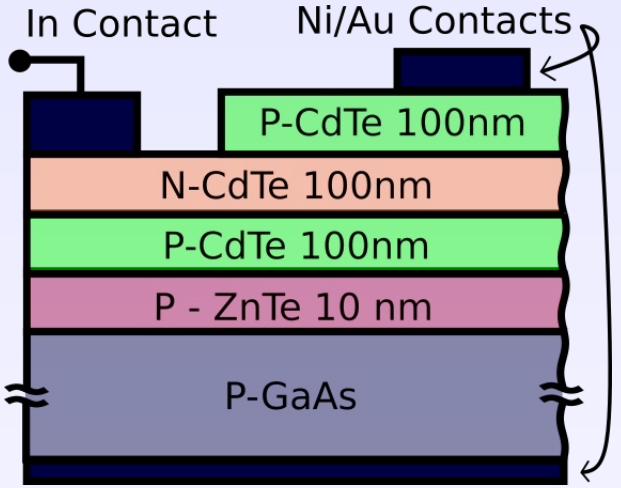
- Stacked PIN diode structure
  - PIN – NIP – PIN …
  - Metal contacts for biasing and readout in between
- Electrons and holes read out at each layer
  - Signal proportional to E deposition
  - Use CCD for large scale device
- Nano-scale
- 2D tracker
  - Average energy per channel function of incidence angle
  - Use machine learning algorithms to reconstruct particle tracks



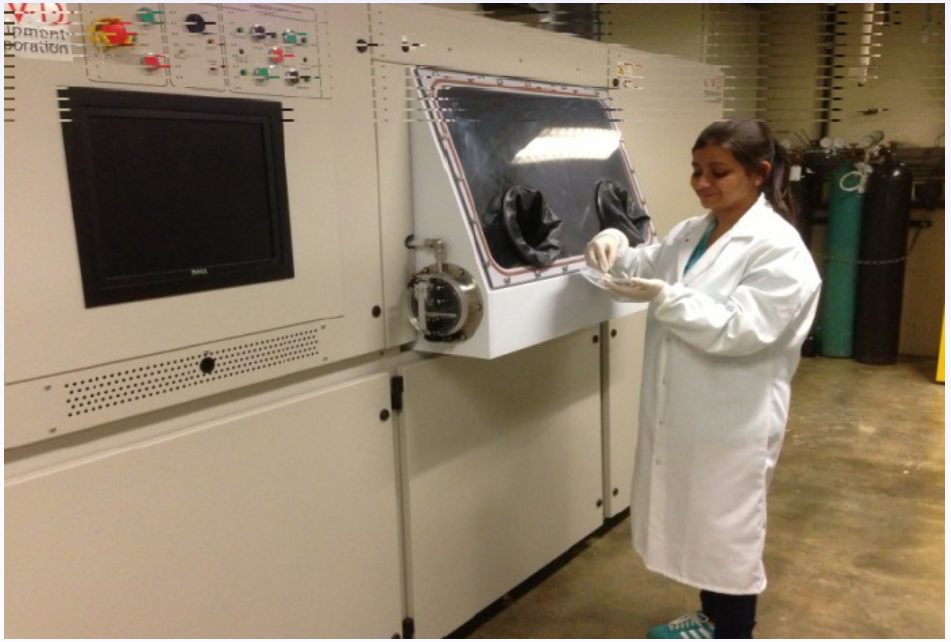
U.S. Pat. Appl. No. 62/878,960

Prototyping

- Collaborate with ECSE faculty I. Bhat at RPI
  - World expert on epitaxial CdTe devices
- Build stacked diodes from 2-20 layers
  - Start with PN junctions
  - Add I layer in advanced prototyping phase
- P-GaAs substrate
- P and N type CdTe layers
- In and Ni/Au contacts

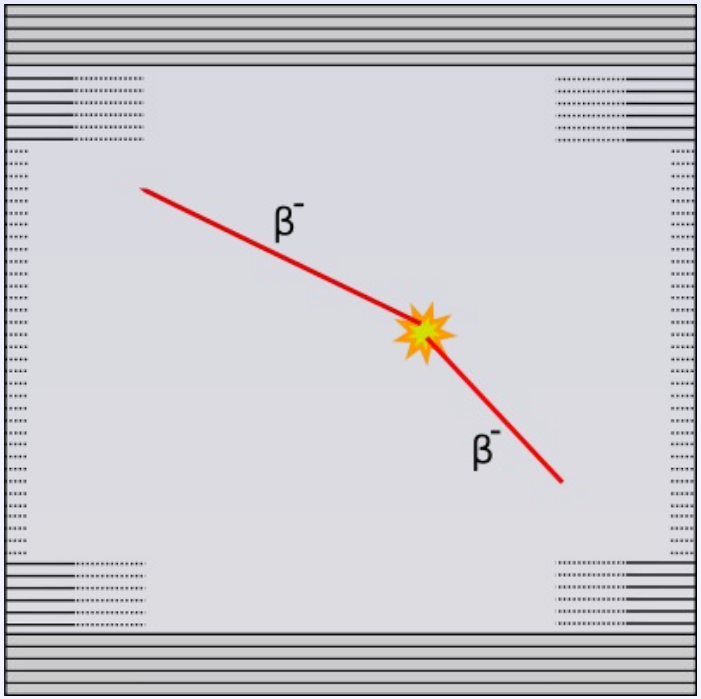


- Metal-organic chemical vapor deposition (MOCDV)
  - Metal-organic precursor to inject Cd and Te
- Routine production of epitaxial CdTe devices
- Custom system at RPI for CdTe
- Prototyping ready to begin



CdTe Detector for 0νββ Decay

- 4 ββ emitting isotopes
  - ^{114}Cd, ^{116}Cd, ^{128}Te, ^{132}Te
  - (29%, 8%, 32%, 34%) natural abundance
- Measure angular and energy correlations with multi-isotopes
  - Probe all (kind of...) parameters of left-right symmetric models
- Similar to Super NEMO but with array of monolithic detectors
  - Source and tracker combined in one device
  - Compactness wins…
  - … if we can build it



- Need ~1000 layers
  - Major engineering feat
  - Prototype layout planned around eventual upgrade
- Serial production will be a challenge
  - In-house probably impractical

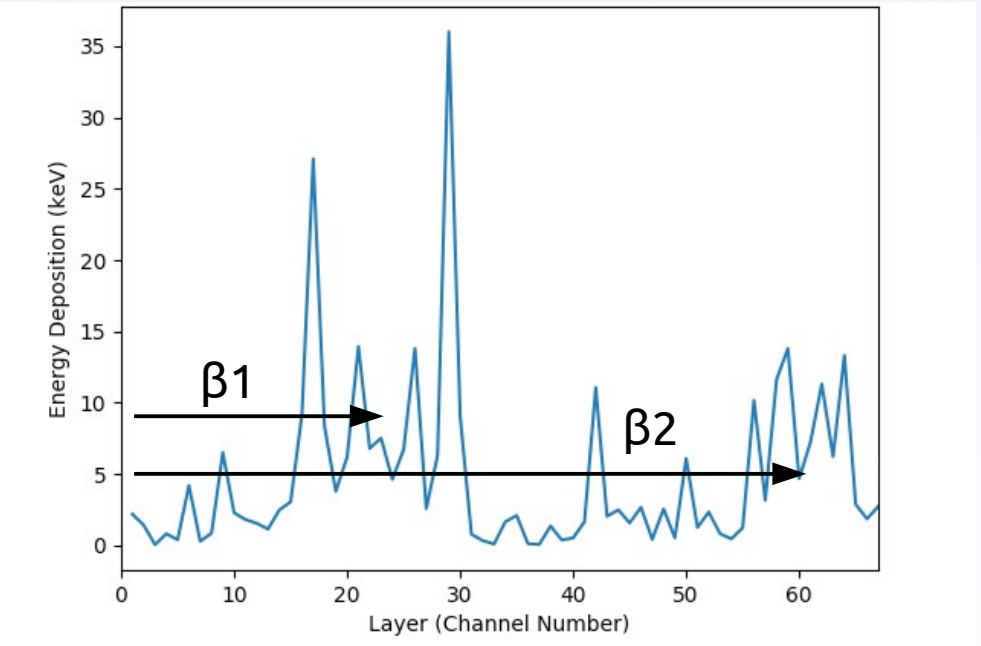
<u>Ideal as a post-discovery experiment</u>

- Scenario 1: Tonne-scale experiments discover 0νββ decay
  - Follow up with characterization measurements
- Scenario 2: Tonne-scale experiments set limits beyond inverted hierarchy
  - Background-free search of the normal hierarchy

Signal Reconstruction

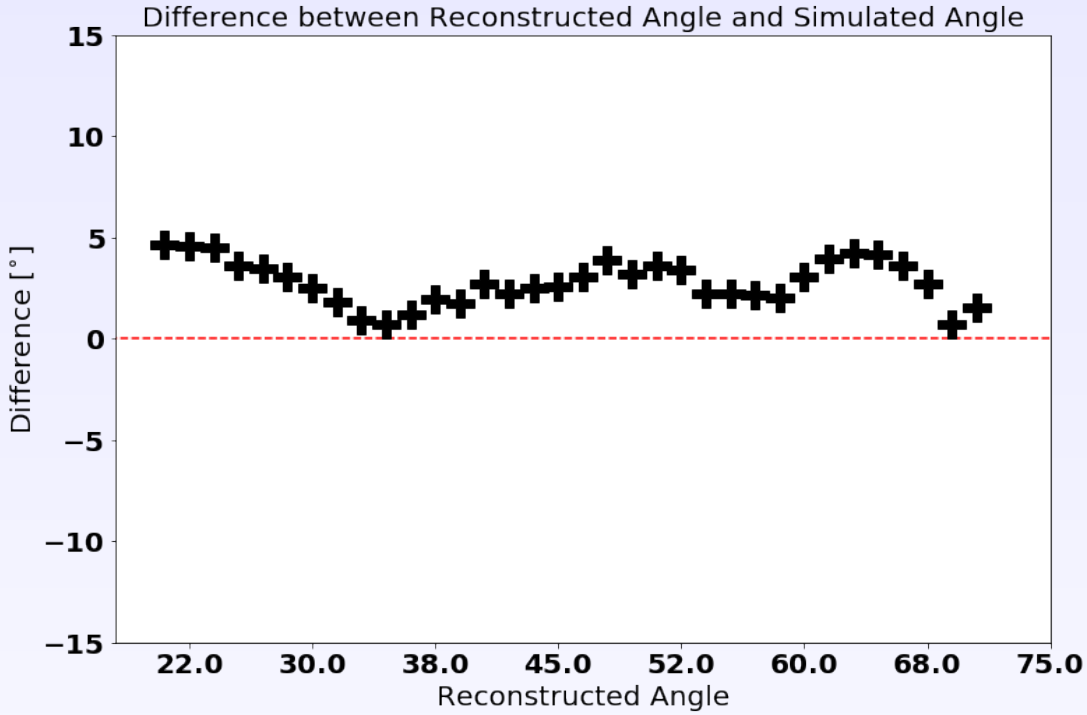
- Take advantage of Bragg peak
  - High energy deposition at end of tracks
- Back to back vs parallel double betas
  - Longer track
  - Double vs single spike at end of track
- Full signal reconstruction uses **deep learning**
  - Vertex localization will be challenging
    - Not necessarily needed
    - Can find best estimate for relative and total energy and angles
    - Angular and energy resolution must be optimized

- Example waveform for ^{128}Te 0νββ
  - Two βs each at E=Q/2
  - Both isotropic
- Use Bragg peak to tag ends
  - Track that passes more channels has lower amplitude



Energy and Angular Correlation

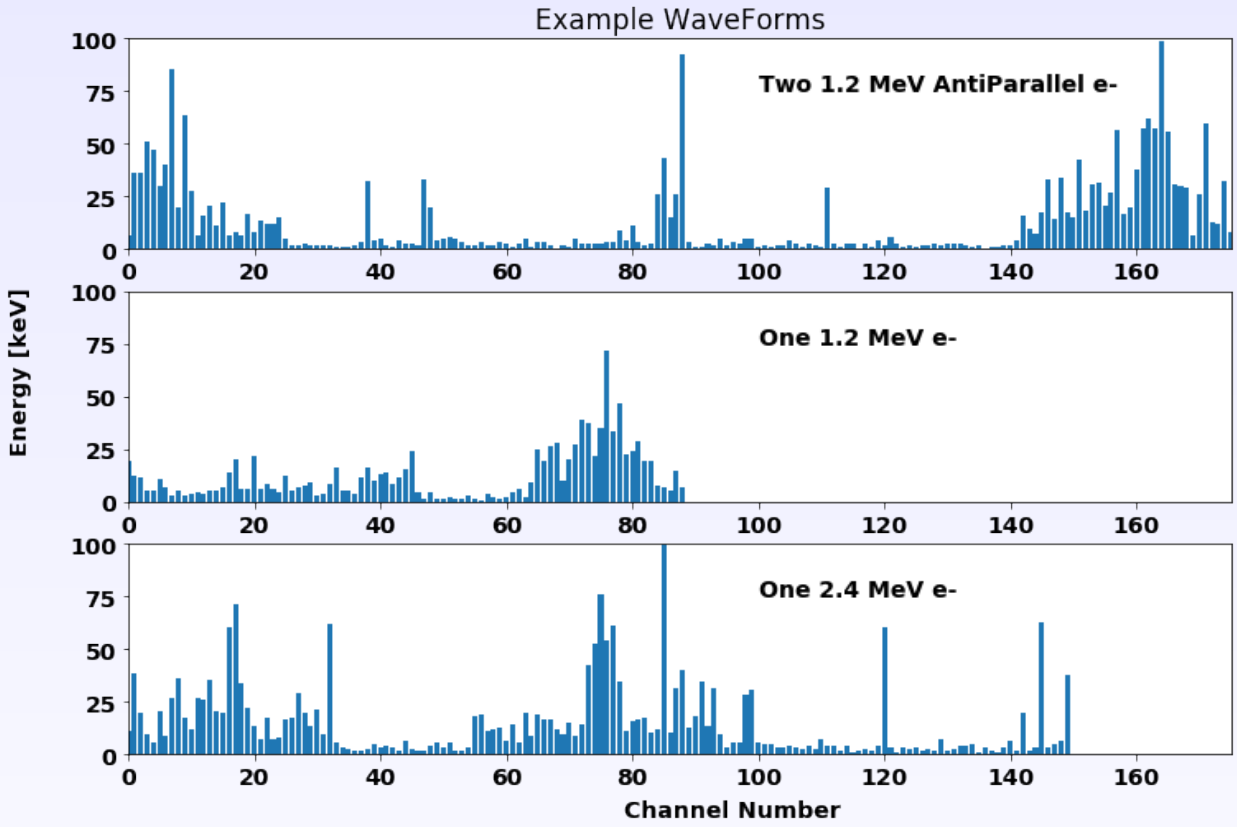
- Developing sophisticated reconstruction algorithm
  - Neural nets and other machine learning algorithms
  - Identify event multiplicity
  - Locate decay vertex
- Extensive MC campaign underway to train algorithms
  - Concept paper in development
- Reconstruct energy and angle simultaneously
  - Along with event/particle type
- Resolution requrements:
  - Few degree angular resolution
    - Care most about distinguishing 90 and 180 degree events
  - Few percent energy resolution (compared to <1% for tonne scale experiments)
    - Get away with this because of background discrimination



- Example of deep learning reconstruction algorithm performance (here for single recoils)
  - Average performance angular reconstruction with deep neural net
  - Reconstruct polar angle within a few degrees

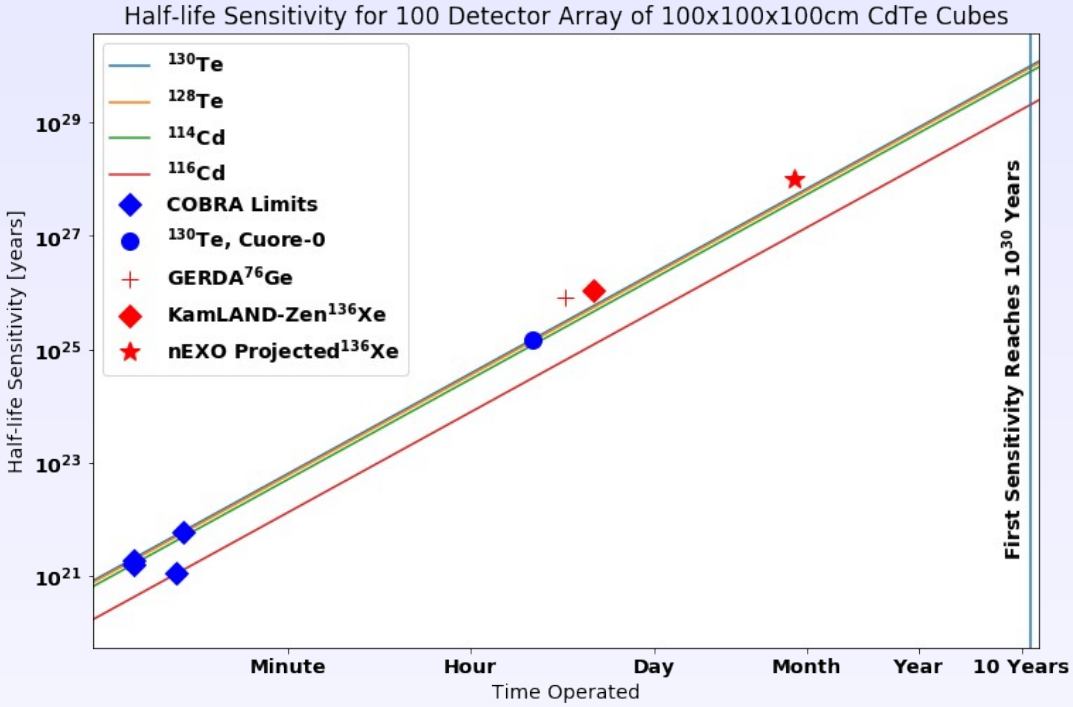
Background Suppression

- Unique suppression of non double-beta signals
  - Summed energy plus track features
  - Classify event types using machine learning algorithms
  - All single beta and gamma backgrounds effectively removed
    - Gammas have additional multi-scatter feature
- External backgrounds
  - Use outer most layers as veto
  - Further suppress with external shielding and/or veto
- Effectively a zero-background experiment!



Since BG can be tagged, production challenges will be slightly alleviated!

0vBB Sensitivity



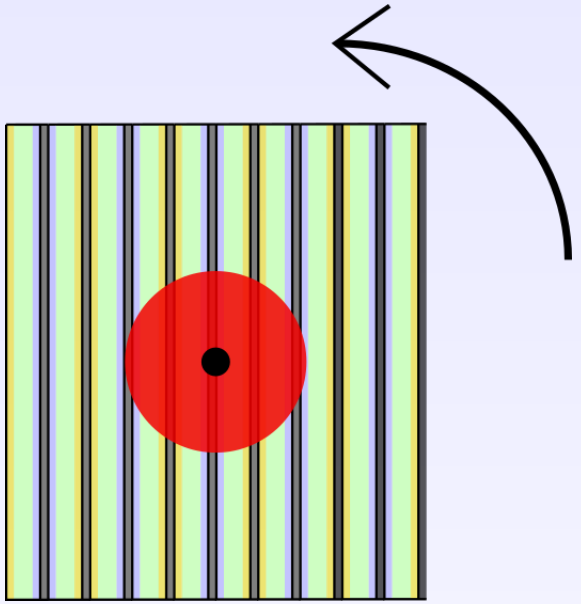
<u>How to reach competitive 0vββ sensitivity</u>

- What would it take to reach 10^{30} year half-life?
  - Largest detector possible
  - ~100 cm dimensions
  - Array of up to 100 detectors
    - Capitalize on monolithic nature of detector
    - But probably segmented design to avoid huge capacitance
- Why such a lofty goal?
  - Probe normal hierarchy
  - High stats measurement of inverted/degenerate discovery
- More conservative fallback
  - Missing target by a factor of 100 still complements tonne scale sensitivity
  - Phased approach can start data in ~decade

- Time to start prototyping is <u>now</u>
  - 20 layer prototype: ~3 yrs
  - 100 layer demonstrator: ~6 yrs
  - 1000 layer phase 1 detector: ~10 yrs
  - Serial production and scaling to follow
- On track to follow tonne-scale experiments

Other Applications

Side-on illumination applications
- Beam imaging (SEM/TEM) with nano-scale resolution
  - Resolve single dimension
  - Rotate to get 2D diffraction profile
- Spatially resolved x-ray imaging



Full tracking applications
- Gamma tracking
  - Use multi-scatter ER tracking to reconstruct incident gamma
  - Unique particle ID allows gamma detection with minimal shielding
    - Potential space deployment
- Alpha, beta, fission fragment screening
  - Compact devices for remote radiation monitoring
  - Potential NNSA/DHS applications
- Directional dark matter detection
  - Need to push spatial resolution to few nm

- Highly versatile detector
- Countless applications in physics and technology
- So much more potential than just 0vBB physics

Summary

- Nano-tracker based on stacking thin film PIN diodes
  - 2D track reconstruction with 10-100 nm spatial resolution
  - Capable of resolving radio-decay tracks
- Apply for 0νββ decay
  - Array of monolithic nano-trackers
  - Sensitivity as high as 10^{30} years
  - Ideal for post-discovery characterization
  - Probe left-right symmetric models with
    - Angular and energy correlation
    - Multi-isotope measurement
- Essentially background-free
  - High purity construction
  - Machine learning to classify signal and background based on event topology