

Quest for $0-\nu\beta\beta$ Decay: Is there a better way?

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$0-\nu \beta\beta$ Decay

- If $0-\nu$ decays occur, then:
 - Neutrino mass $\neq 0$ (we know this...)
 - Decay rate measures effective mass $\langle m_\nu \rangle$
 - Neutrinos are Majorana particles
 - Lepton number is not conserved
- Because the physics impact is so great, the experimental result must be **robust**.

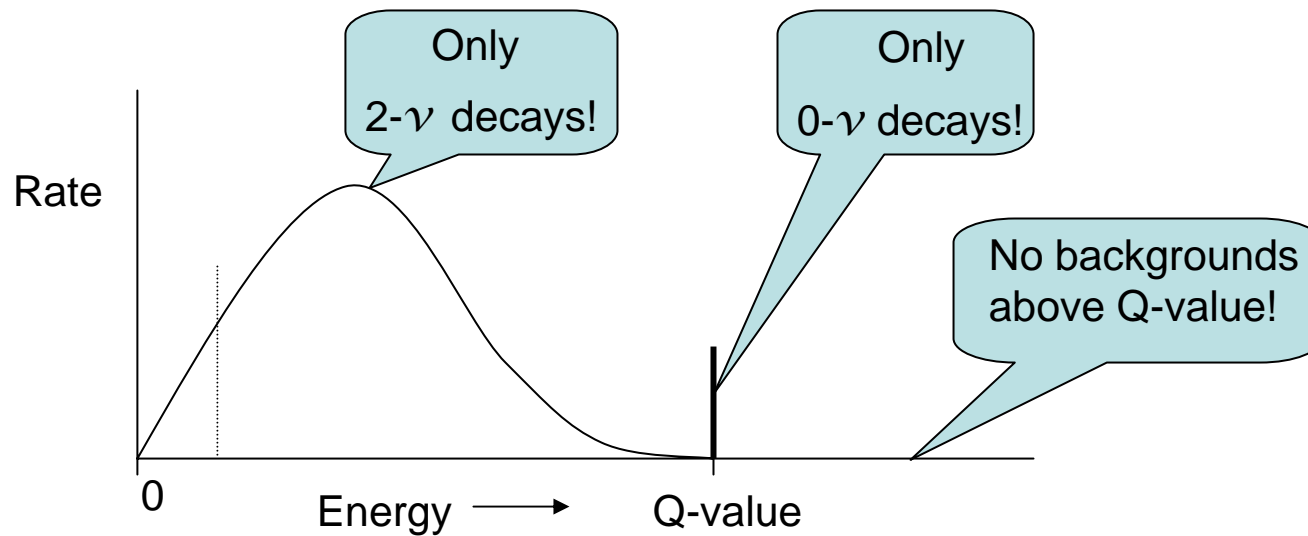
Obvious Requirements:

- Provides the needed level of sensitivity
 - Active mass $\sim 1/\langle m_\nu \rangle^2$ (1000 kg may be necessary)
 - True events detected with high efficiency
 - Excellent energy resolution essential
- Rejects conventional backgrounds effectively
 - Surface of fiducial volume completely active
 - Distinctive $\beta\beta$ decay topology can be imaged
 - Conventional processes can mimic $\beta\beta$ decay:
 - Photoelectric conversion of γ with auger electron
 - Nuclear de-excitation with internal conversion

A robust experiment:

- Selects $0-\nu\beta\beta$ and $2-\nu\beta\beta$ events identically
 - Does not depend solely on end-point energy!
- Detects birth of daughter nucleus ($\Delta Z = 2$)
 - Birth detection \neq Daughter tagging!
- Small overlap of $0-\nu$ events by $2-\nu$ events
 - excellent energy resolution is essential!

A “Robust” Experiment:



The experimental result is a **spectrum of all $\beta\beta$ events**, with very small or negligible backgrounds.

Energy Resolution...

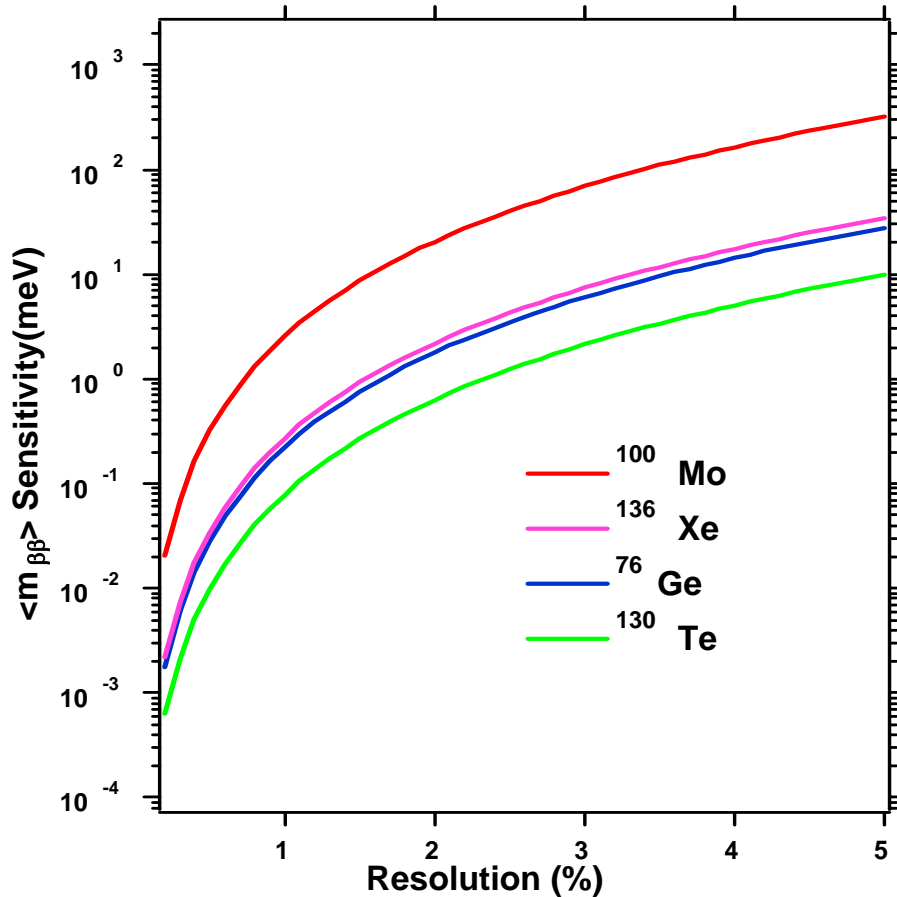


Figure of Merit for 0ν decay - 2ν background under 0ν peak

$$\frac{S}{B} = \frac{m_e}{7Q} \frac{\tau_{1/2}^{2\nu}}{\tau_{1/2}^{0\nu}} \delta^6$$

δ is the energy resolution of the detector.

Most important considerations:

Backgrounds

Good energy resolution

(required to observe $0\nu\beta\beta$ peak on $2\nu\beta\beta$ background)

Energy Resolution

“To address the mass scale around $\langle m_\nu \rangle \sim 50$ meV may require that energy resolution approaches the limit imposed by underlying physical processes.”

“To realize an energy resolution near the limit imposed by physical processes, the detector and target must be the same thing.”

The Gold Standard:

Energy resolution with Germanium detector:

$$\delta E/E \sim 1.25 \times 10^{-3} \text{ FWHM at } 2.6 \text{ MeV}$$

Present Status

- Heidelberg-Moscow claim:

$$\langle m_\nu \rangle = 0.44^{+0.14}_{-0.20} \text{ eV (best value) } \textit{disputed!}$$

$$\tau^{0\nu}_{1/2} = (8 \text{ --- } 18.3) \times 10^{25} \text{ y (95\% c.l.)}$$

Scale: ~11 kg of ^{76}Ge , for ~7 years

Present Perspective...

- Cuoricino is also background-limited
 - $\delta E/E$ only \Rightarrow Cuore may be vulnerable
 - “Surface contamination can be reduced”
- Majorana (^{76}Ge):
 - $\delta E/E$ + multi-site rejection (x10)
 - Large rejection factor needed for success
- EXO (^{136}Xe):
 - Will barium daughter tagging work?
 - Will energy resolution be adequate?

Uncertainties...

- Hierarchy uncertain
 - Determines needed sensitivity
- Matrix element calculations uncertain
 - Order of magnitude in rate
- Effective mass uncertain
 - Phases enter: $\langle m_\nu \rangle = \sum \varepsilon_i m_i U_{ei}^2$
- Direct tests by ^3H kinematics uncertain
 - For $\langle m_\nu \rangle \ll 1$ eV, technically very difficult!
- Best experimental approach: uncertain!

NUSAG Recommendations:

- “...support research in two or more $0-\nu\beta\beta$ experiments to explore the region of degenerate neutrino masses ($\langle m_\nu \rangle > 100$ meV)...”
- “The knowledge gained and the technology developed in the first phase should then be used in a second phase to extend exploration into the inverted hierarchy region of ($\langle m_\nu \rangle > 10 - 20$ meV) with a single experiment.”

Is There Nothing New?

NUSAG did not explicitly recognize the possibility or importance of new ideas.

This is unfortunate, but we persist...

Experimental Approach

“We believe that an
Imaging Ionization Chamber
is most likely to meet all criteria imposed
for a robust experiment.”

An Imaging Ionization Chamber (IIC) is
a TPC without gain at the readout plane

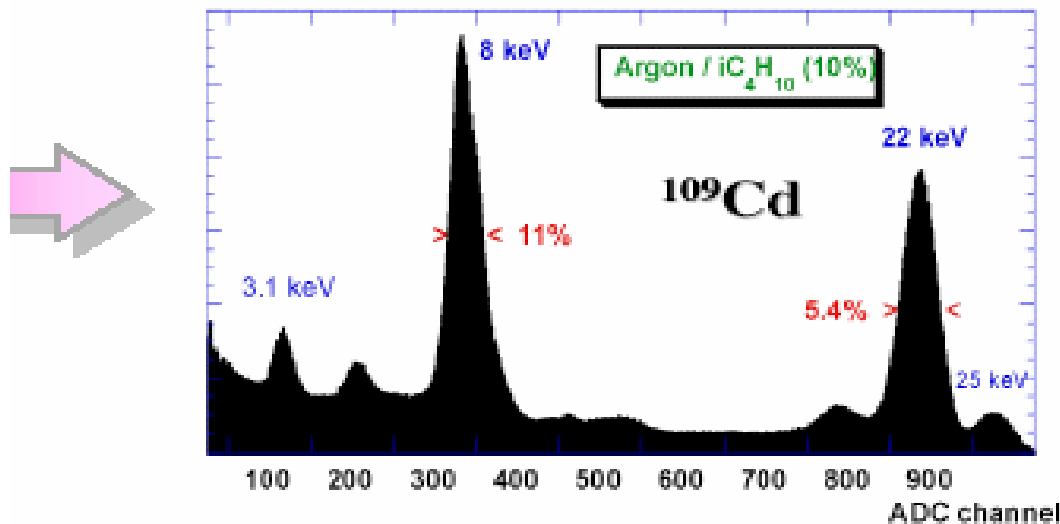
No Proportional Gain - Why?

Reason #1:

- MWPC, Micromegas, and GEM offer:
 - excellent resolution for ^{55}Fe x-rays...
 - but: poor resolution for extended tracks
- Causes (?):
 - Ballistic deficit in signal processing
 - Impact of space charge on gain
 - High sensitivity to density variations

MicroMEGAS Detectors: Energy Resolution and 2-D Readout

Good energy resolution for a gaseous detector



Ref: A. Delbart et al, NIM A461, p84 (2001)

Imaging Ionization Chamber

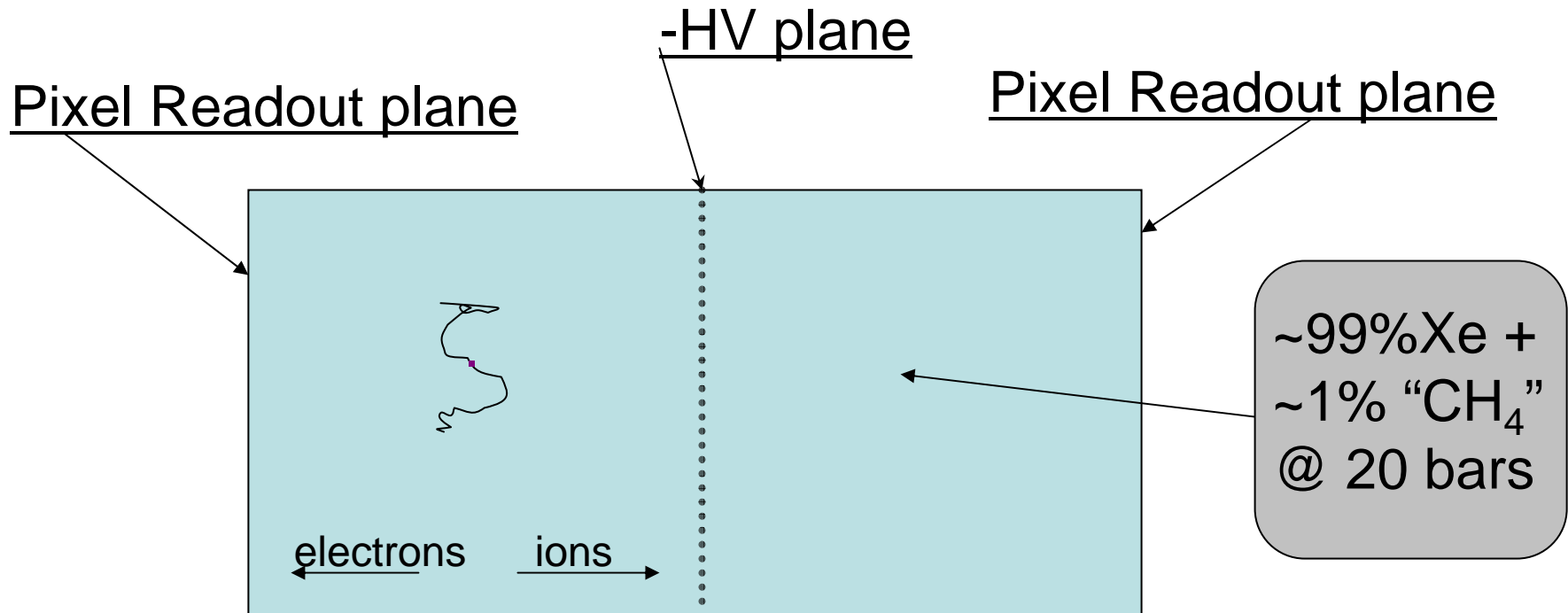
IIC is filled with ^{136}Xe gas

- Pressure: 20 - 40 bars?
- Xe is relatively safe and easy to enrich
- density provides 1000 kg in $\sim 10 \text{ m}^3$
- provides adequate S/N for good tracking
- Small admixture of “ CH_4 ” may be useful
- “Xe may offer an opportunity for novel daughter atom detection and identification”

Event Characteristics in IIC

- High density of xenon constrains $\beta\beta$ event:
 - total track length ~20 cm max
- Multiple scattering will be prominent in xenon
 - Unclear if B-field would help identification
- True $\beta\beta$ events will have two “blobby” ends
 - Shown to reject background by ~30 in Gotthard TPC
- Bremsstrahlung and fluorescence γ 's
 - distinct satellite “blobs”
- UV scintillation can provide an event “start”
(Could double electron signal with photoionization)

Imaging Ionization Chamber



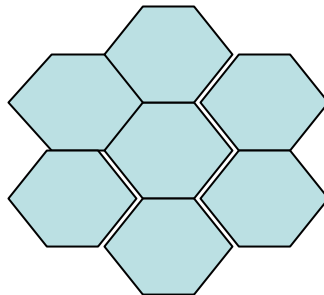
Imaging Ionization Chamber

has a fully “decorated” pixel readout plane

- pixel size is 5 mm x 5 mm (4×10^4 /m²)
 - ~ 40 - 80 contiguous “hit” pixels for $E = Q$
 - $dn/dx = \sim 2900$ electrons/(5mm)
- ultra-low noise readout electronics - BNL ASIC?
 - $\langle n \rangle = \sim 27$ e⁻ rms for bare input, 1.2 μ s shaping time
 - Other noise terms must be included $\Rightarrow \langle n \rangle = 75$ e⁻ rms?
- “waveform capture” essential for extended tracks
- no grids or wires: eliminates microphonics

Pixel geometry

A low capacitance solution: a 7-pixel hexagonal sub-module:



Or, a 16 channel 4x4 rectangular array...

Imaging Ionization Chamber

collects electrons on pixel readout plane

- all energy information is derived from $q = \int I dt$
- current is very small until electrons approach pixel
- pixels with no net charge have bipolar signals
- drift velocity is small, $0.1 < V_d < 0.5 \text{ cm}/\mu\text{s}$
- diffusion after 1.5 m drift is 1 - 2 mm rms
- event is reconstructed from contiguous hit pixels
- noise adds only from hit pixels + some neighbors

Energy Resolution...

Q-value of $^{136}\text{Xe} = 2.48 \text{ MeV}$

$W = \Delta E$ per ion/electron pair = 21.5 eV

$N =$ number of ion pairs = Q/W

$N \approx 2.48 \times 10^6 \text{ eV} / 21.5 \text{ eV} = 115,350$

$\sigma_N^2 = FN$ ($0.05 < F < 0.17$)

$F = 0.17$ for pure noble gases

\Rightarrow

$\sigma_N = (FN)^{1/2} \sim 140$ electrons rms

Geminate and Volume Recombination

- Reduces the yield of free ionization
- Degrades the energy resolution.
 - Recombination rate depends on ionization density, carrier mobility, relative orientation of track & **E** field.
 - Occurs in gases, liquids, solids, semiconductors.

Electrons that scatter and thermalize, or meander, within the Onsager radius $r_o = e_o^2 / (4\pi\epsilon_o\epsilon_r k_B T)$ of an ion will recombine

$$r_o \sim 60 \text{ nm in gases}$$

Should not be a significant effect for 20 bar Xe

Energy Resolution...

- If ionization were the only issue:

$$\delta E/E = 2.9 \times 10^{-3} \text{ FWHM}$$

- Other contributions:

- electronic noise from $N = 49$ pixels in event
 - $N^{1/2} \times \langle n \rangle$ if noise is gaussian $\sim 7 \times 75 = 525 e^-$
- ballistic deficit in signal processing
- “locked” charge caused by slow-moving ions

$$\delta E/E \sim 10.0 \times 10^{-3} \text{ FWHM}$$

Barium Daughter Atom

- In a volume of $\sim 10^{27}$ xenon atoms, a $\beta\beta$ event creates **one** barium atomic ion.
- The Ba ion drifts out to the HV plane, and in ~ 1 second, the ion will be lost!
- In xenon/CH₄, the Ba⁺⁺ ion will survive, but becomes Ba⁺ if low-IP impurities exist
 - IP(Xe) = 12 eV, IP(CH₄) = 13 eV
 - First IP(Ba⁺) = 5 eV
 - Second IP(Ba⁺⁺) = 10 eV

Ion Mobilities

Is there a straightforward way to detect and identify the barium daughter?

- Ba and Xe ion masses are ~identical...
- Ba⁺ and Xe⁺ ion charges are identical...
- Ion mobilities should be the ~same,
Right??

Ion Mobilities...

- But: **ion mobilities are quite different!**
 - The cause is **resonant charge exchange**
 - RCE is macroscopic quantum mechanics
 - occurs only for ions in their parent gases
 - no energy barrier exists for Xe^+ in xenon
 - energy barrier exists for Ba ions in xenon
 - resonant charge exchange is a long-range process; glancing collisions = back-scatter
 - RCE increases viscosity of ions

Ion Mobilities in Xenon

- Mobility differences have been measured at low pressures, where clustering effects are small:
 - $\mu(\text{Xe}^+) = 0.6 \text{ cm}^2/\text{V-sec}$
 - $\mu(\text{Cs}^+) = 0.88 \text{ cm}^2/\text{V-sec}$ (Cs is between Ba and Xe)
- So, the barium ion should move faster by ~50%! (maybe even faster if Ba^{++} is stable)

RCE can provide a way to detect Ba daughter!

Ion mobility in dense gases?

- Ion mobility data at high pressure does not apparently exist in the literature.
 - Clustering may be prominent at 20 bars.
 - Clustering phenomena are complex, and may introduce very different behavior
 - Not clear whether this will help or hurt!
 - Low pressure measurements not adaptable to high pressures like 20 bars - **need new method**

Complexity in Transport

- Electron mobility in dense xenon gas displays unexpected behavior:

At constant E field, μ_e increases with density!

Possible explanation:

Onset of conduction band in Xe clusters, in concert with RCE...?

Ba Daughter Detection

- If we assume that barium ion mobility is not identical to xenon ion mobility, then:
 - A barium ion will arrive at the HV plane at a **different time** than the Xe⁺ ion track image.
 - If event time origin and mobilities of the barium and xenon ions are known, an **arrival time for the barium daughter at HV plane is predicted**.
 - The unique Δt between Xe⁺ and Ba⁺ ions is a **robust signature** for a true $\beta\beta$ event.

Arrival Time Separation

- Assume low-pressure data...
 - Assume drift distance: $L = \mu T = 250$ mm
 - Thermal transport diffusion: $\sigma \sim .25$ mm
 - $\sigma/L = 0.25/250 = 1/1000$
 - $\sigma/(\Delta L) = 2^{1/2}/(\mu_{\text{Ba}} - \mu_{\text{Xe}})T \sim 1/235$
- Arrival times are very precisely determined

Detection of Ion Arrival

- Detection of ion arrival may be possible:
 - Ions drift at thermal energies to HV plane...

Then:

- Ions are attracted to enter a “blind GEM”
 - Very high electric field inside GEM pore
 - Ions can enter, but electrons are blocked
 - High energy tail of M-B distribution relevant
 - Ba⁺⁺ may be critical for desired outcome
 - Hoped-for outcome: ≥ 1 electron appears

Blind GEM or “Microwell”

Drift region:
Low E-field

ions →

HV plane

Resistive
back side
blocked to
electrons

Very High E-field inside pore;
low work-function surface?

The barium daughter “Echo”

- If a single electron appears, high E-field in blind GEM causes **electron avalanche**.
- Electron avalanche will saturate, producing a **large pulse** of electrons, more than 10^3 .
- Electron pulse returns to pixel plane, at a **spot** on the projected event track.
- This spot on the projected track is very **close to origin** of the barium daughter.

An Echo Implication

- Reason #2 for no-gain (ionization only) at the readout plane:

Because gain exists at the HV plane, the presence of gain at the readout plane would create positive feedback

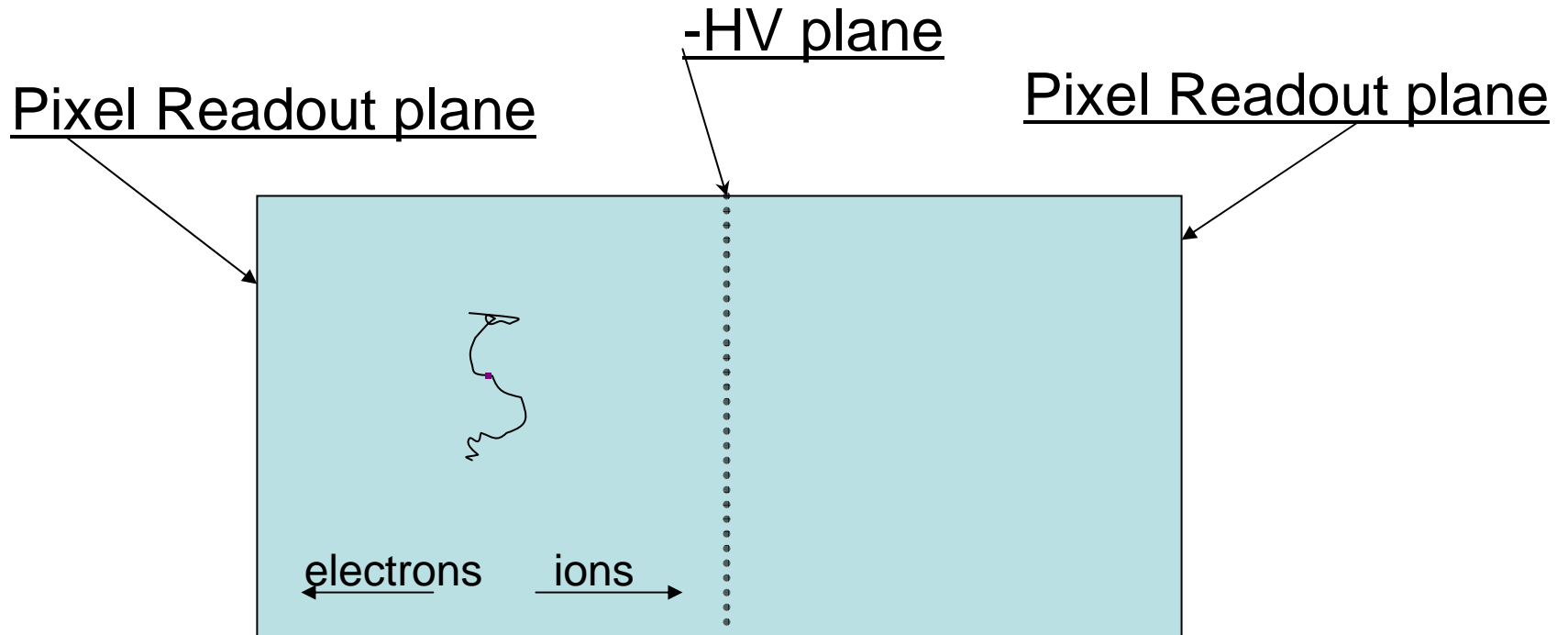
The Return Image Echo

- The Xe^+ ions will also enter blind GEM pores, producing an “echo” of the track.
- The track echo time will (must) be distinct from the pulse due to the barium daughter.
- Maybe: transfer charge to C_2H_6 : IP = 11.6 eV
 - Complex organic molecule is much less likely to liberate electrons than Ba^{++} ,

Event Quality

- strong primary UV scintillation gives t_0
 - May be quenched by organic additive
- electron track image provides topology
 - Energy resolution limited by electronic noise
- ion track echo also places event in space
 - Don't need all 115,000 echoes from HV plane
- barium daughter echo is elegant tag method
 - Can efficiency be made high enough?
- an over-constrained reconstruction possible.

Imaging Ionization Chamber



What to do?

- An R&D (and library) effort is needed to:
 - Optimize S/N with practical electronics
 - Measure $\delta E/E$ in HPXe IIC with γ rays
 - Investigate benefits of organic additives
 - Determine ion mobilities in HPXe.
 - Explore ion-induced avalanche processes

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 - Investigate benefits of organic additives
 - Determine ion mobilities in HPXe.
 - Explore ion-induced avalanche processes
- A proposal has been rejected by DOE!

Summary

- A novel, but incomplete, approach for a robust $0-\nu \beta\beta$ decay search is proposed:
 - $\delta E/E \sim 1\%$ FWHM
 - Detailed & constrained 3-D event topology
 - Active, variable fiducial boundaries
 - Identification of Ba daughter possible, in principle, by exploitation of macroscopic quantum mechanical phenomenon, RCE