Columnar Recombination: a tool for nuclear recoil directional sensitivity in dense xenon gas

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Topics

- How Columnar Recombination may display a sensitivity to the angle between nuclear recoil direction and drift field $\underline{E}$ in a gaseous TPC
- How Fluorescent Penning Molecules may optimize Columnar Recombination sensitivity
- How to extrapolate this idea to ton-scale
- How this idea can also serve 0-ν ββ search

Excellent energy resolution in Xenon Gas

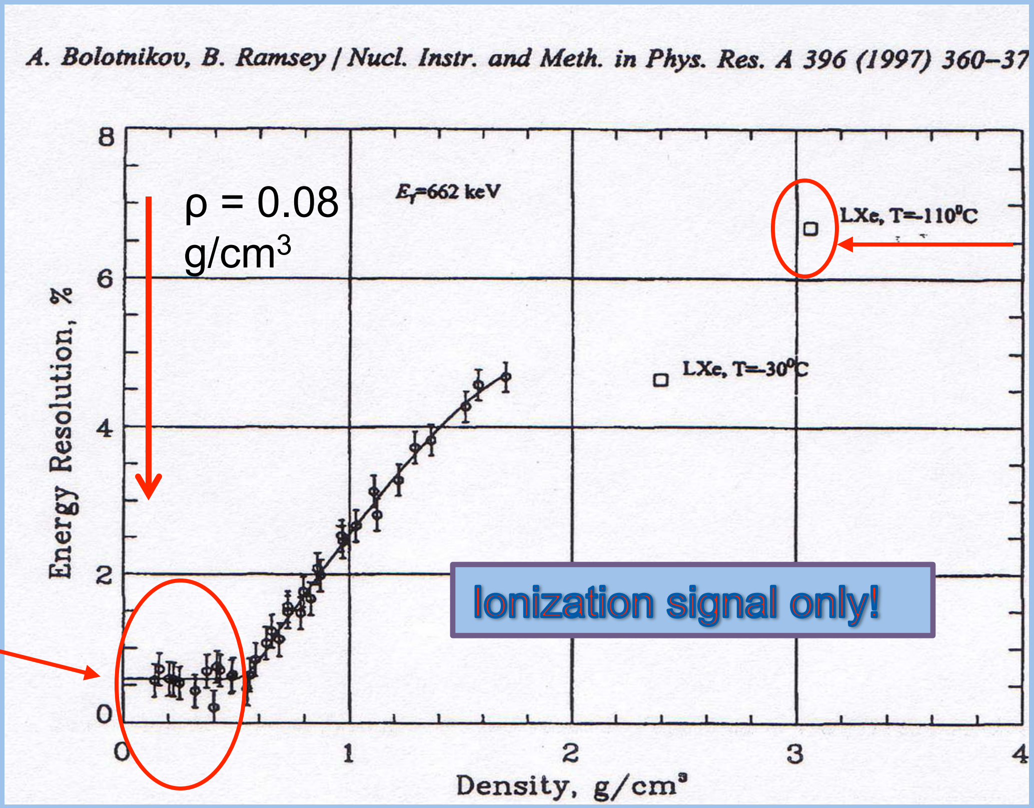
Here, the fluctuations are <u>normal</u>

<u>Fano factor</u>

F = 0.15

Unfolded resolution:

$\delta E/E$ ~0.6% FWHM



Very large fluctuations between light/ charge!

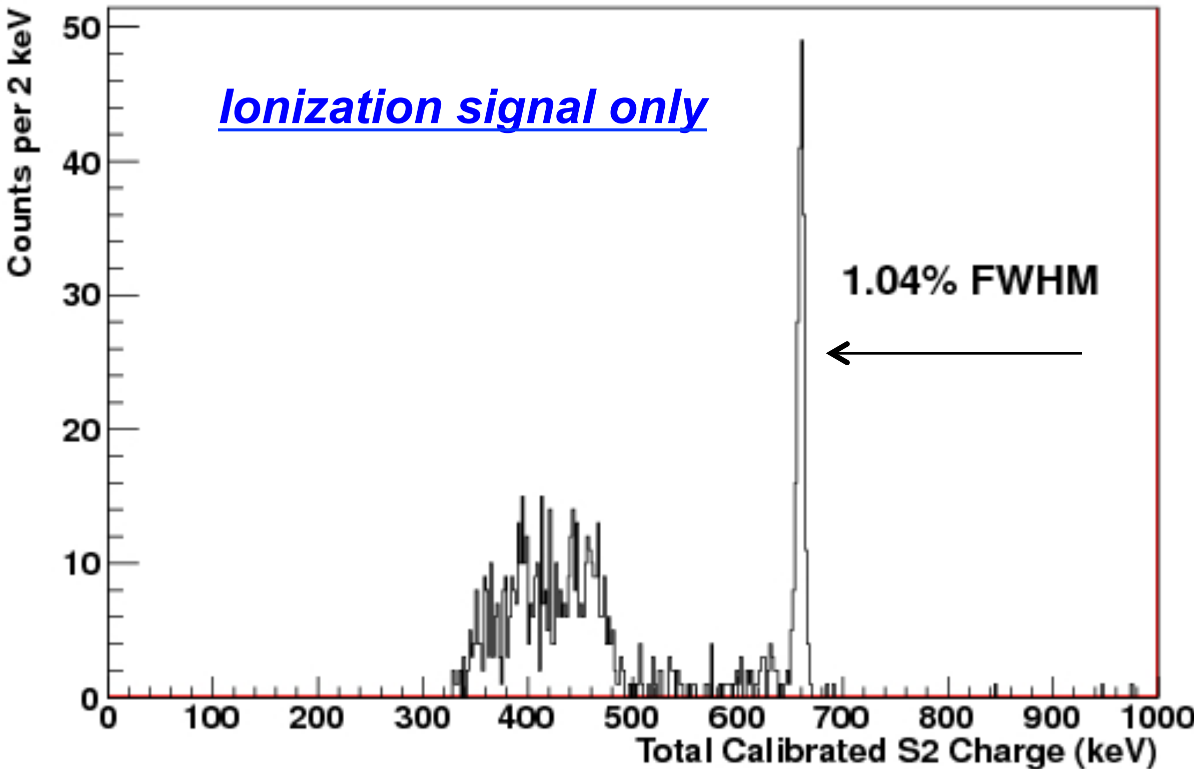
F ~ 20 !!

WIMPs:

electron/ nuclear recoils mix!

For ρ <0.55 g/cm³, energy resolution from ionization is ¨intrinsic˝

New result: Energy resolution δE/E = 1% FWHM for ^{137}Cs 662 keV γ-rays in xenon!



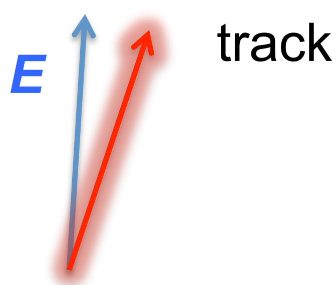
Data from LBNL-TAMU HPXe TPC

This result is important for both 0-νββ & WIMP searches

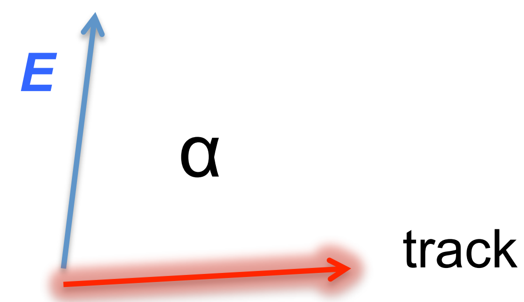
This result shows that fluctuations are “normal” in HPXe

What is Columnar Recombination?

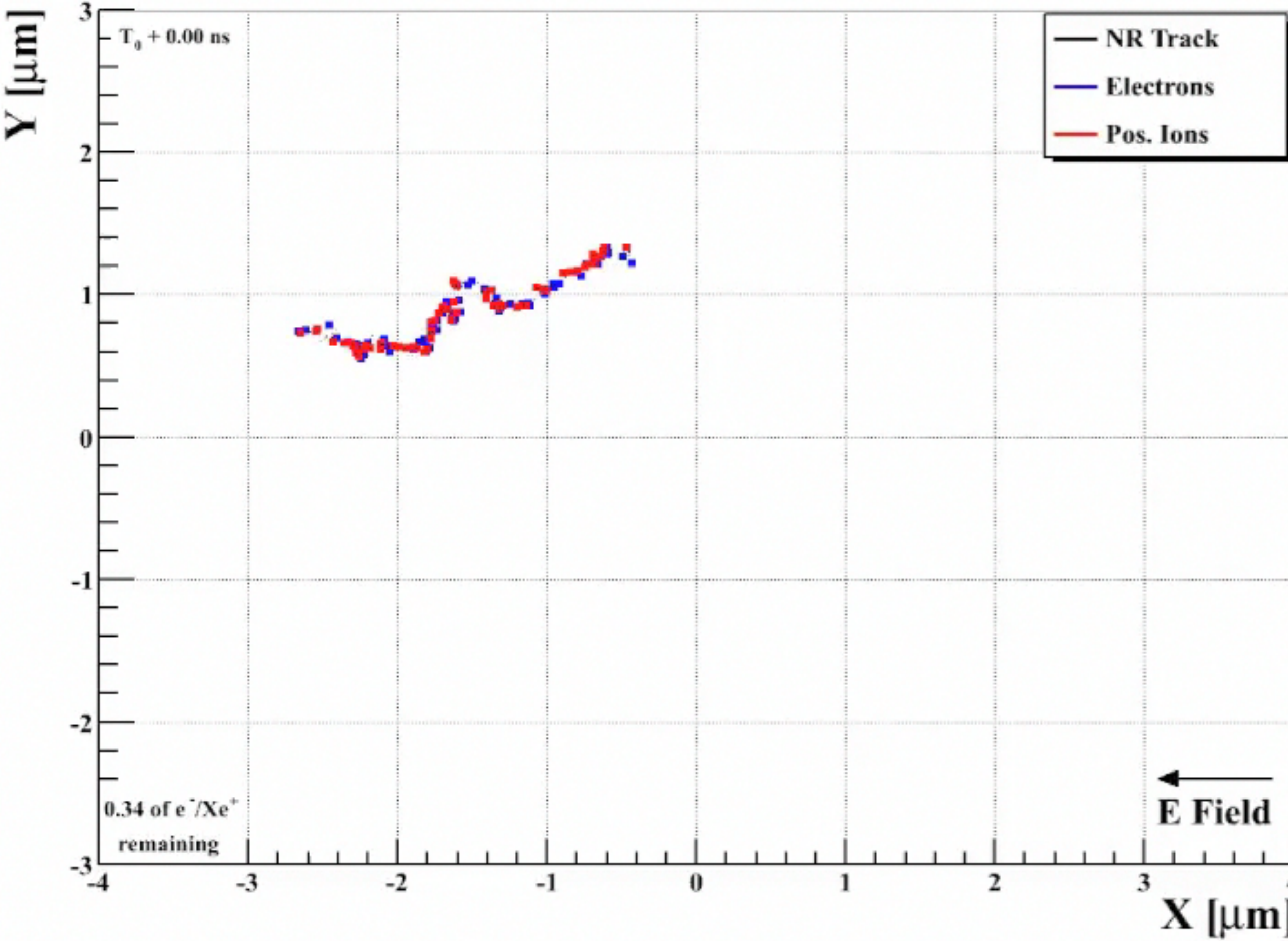
- Columnar Recombination (CR) occurs when:
  - A drift electric field ***E*** exists;
  - Tracks are highly ionizing;
  - Tracks display an approximately linear character;
  - The angle α between ***E*** and track is small:
  - **Recombination** ≈ dot-product of vectors E and “track”

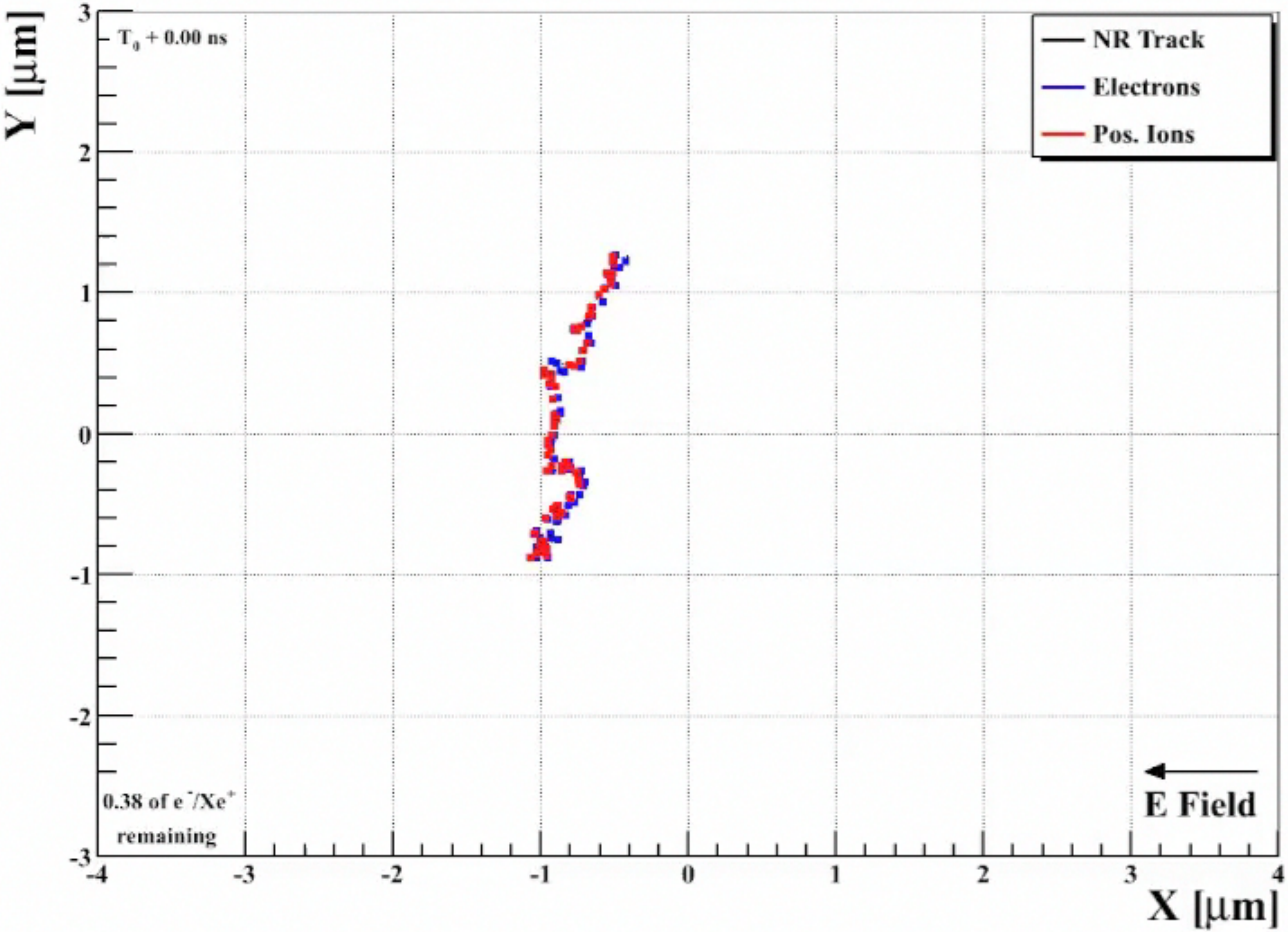


Substantial CR



~No CR


T0 + 0.00 ns
NR Track
Electrons
Pos. Ions
Y [μm]
X [μm]
E Field
0.34 of e-/Xe+
remaining
3
2
1
0
-1
-2
-3
-4
-3
-2
-1
0
1
2
3
4



Y [μm]
X [μm]
T0 + 0.00 ns
NR Track
Electrons
Pos. Ions
E Field
0.38 of e-/Xe+
remaining

CR Exists!

Evidence for columnar recombination in **α-particle** tracks in dense xenon gas.

FWHM depends on E-field and density!

Bolotnikov & Ramsey
NIM **A 428** (1999)
pp 391-402

G. C. Jaffe:
Annalen der Physik,
42, p 303, (1913)

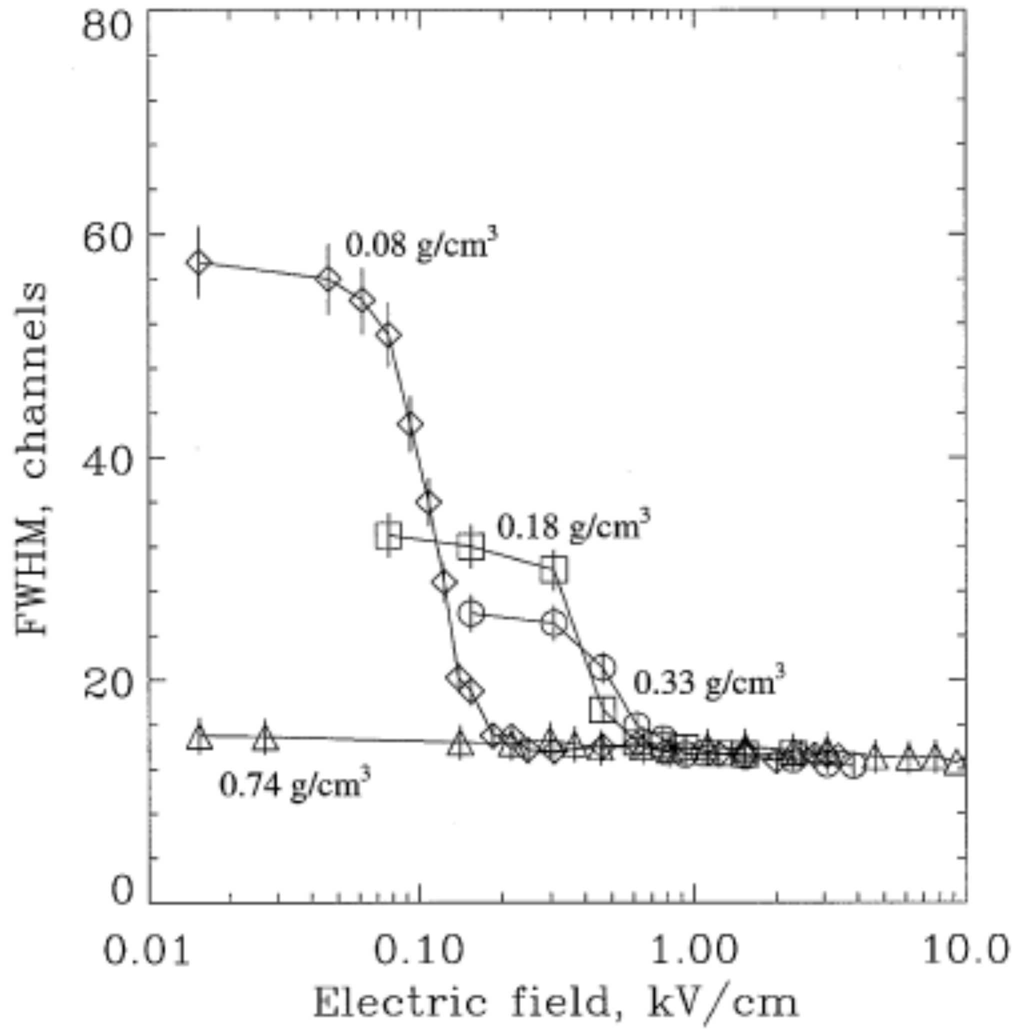
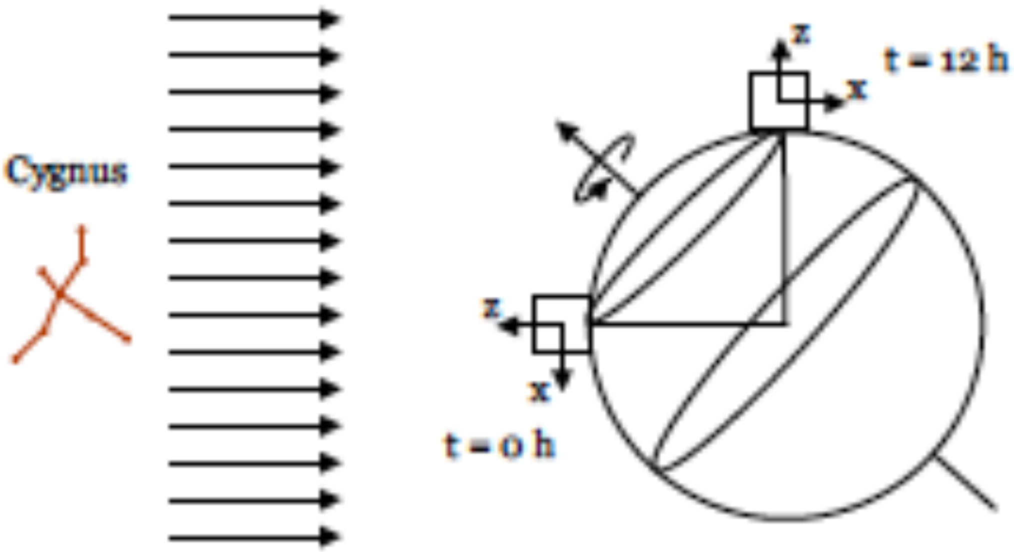


Fig. 5. FWHM of the peaks in pulse-height spectra of the amplitude of the light signals versus the electric field strength measured at 0.08 g/cm³ (diamonds), 0.18 g/cm³ (squares), 0.33 g/cm³ (circles), and 0.74 g/cm³ (triangles).

Sidereal variation of directionality signal



Two Vectors:

1. Nuclear recoil

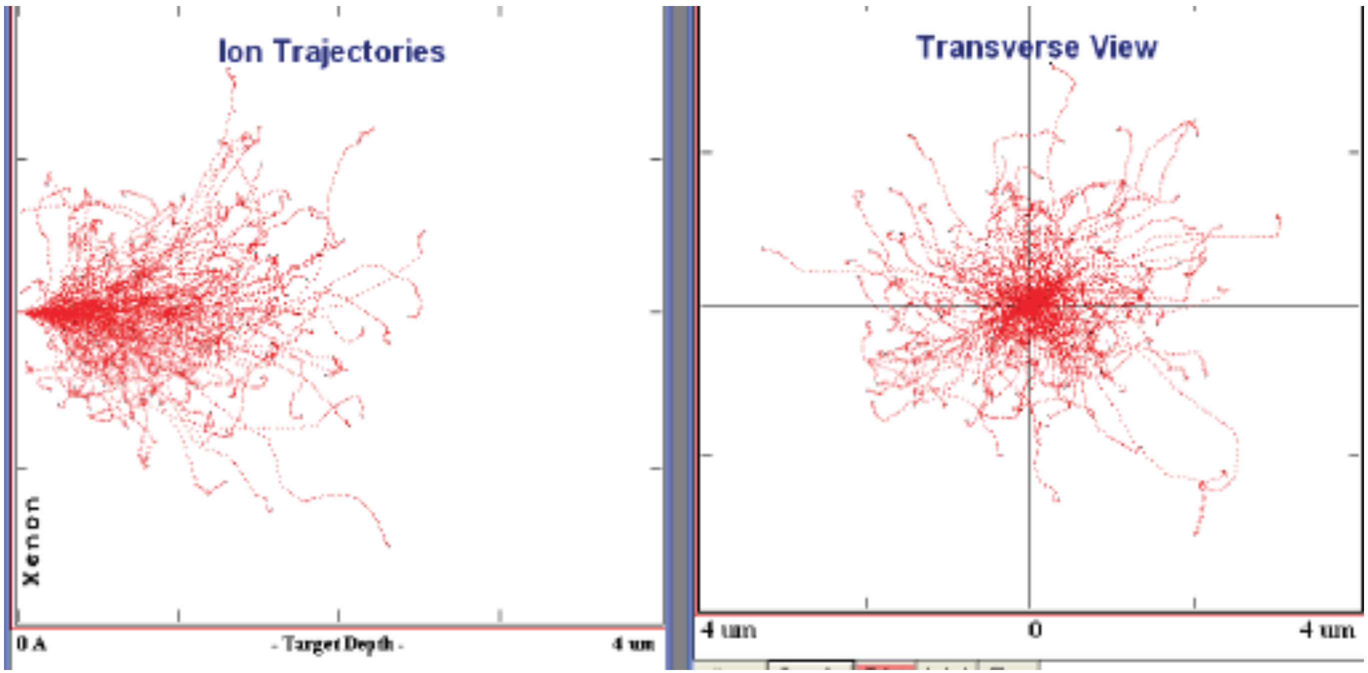
Galactic flux direction is “fixed”

2. TPC electric field:

Sidereal rotation

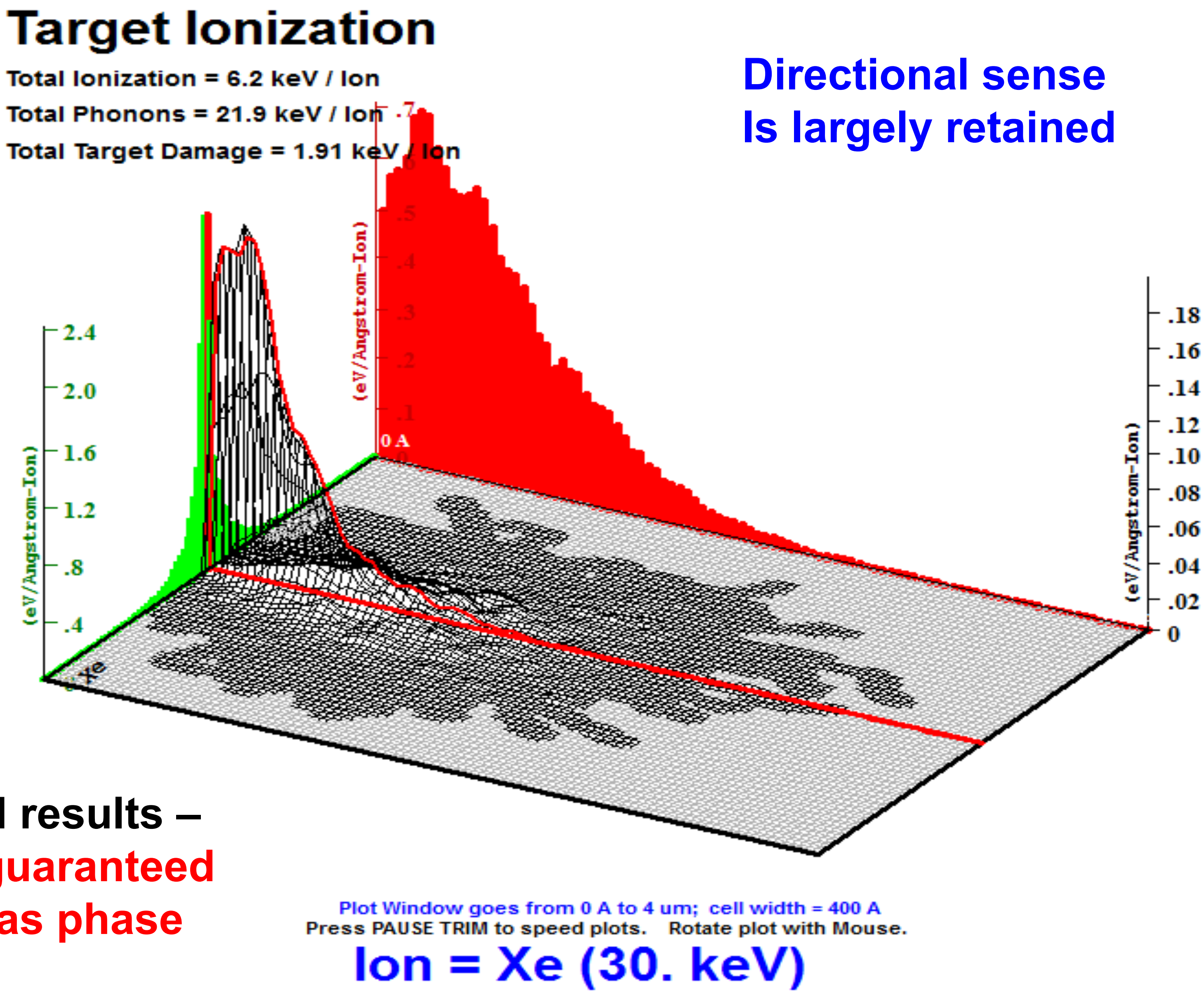
No signal if flux is aligned with polar axis of rotation!

Nuclear recoils:
Vector or... ??



SRIM: 200 Xenon 30 keV nuclear recoil events in HPXe Xenon – unweighted by energy loss

Directional sense Is largely retained



SRIM results – not guaranteed for gas phase

What is the optimum Xe density?

- Define (*electrostatic) **Columnarity "C"***
- ***C*** = $\mathcal{R}/r_0$
  - $\mathcal{R}$ = the nuclear recoil track *range*
  - r_0 = Onsager radius $r_0 = e^2/\varepsilon\,\mathcal{E}$, where $\mathcal{E}$ is electron energy (usually taken as kT)
  - in xenon gas for $\rho \approx 0.05$ g/ cm^3:
    - $r_0 \sim 70$ nm
    - $\mathcal{R} \sim 2100$ nm for 30 keV nuclear recoil (SRIM result)
    - ***C ≈ 30*** in this example

Columnarity "C" is key

- **But:** ***Onsager spheres overlap at this density, so we should consider an "Onsager tube" of larger radius:***

$$r \approx (3 - 5) \times r_0$$

We want C to be fairly large, i.e. C > 10

- This condition is probably met for KE ≥ 20 keV in xenon gas for $\rho \approx 0.05$ g/ cm^3, or less
  - ~2% of LXe density
  - Hopeless for LXe density: $\rho = 3.1$ g/ cm^3 → C<1

Recombination Signal: R

- The signal **R** is fluorescence (scintillation)
  - Observed in noble gases and some molecules
  - Noble gas: VUV (85 – 173 nm) – difficult,…
  - *Desired: Recombination signal is UV, not VUV*
  - Molecular fluorescence: 280 - 500 nm
  - Very few gaseous molecular candidates:
    - *Trimethylamine (TMA)*
    - *Triethylamine (TEA)*
    - *Tetrakis-dimethylamino-ethylene (TMAE)*
    - *Others?*

Nuclear Recoils: extracting directionality

- Rapidly falling energy spectrum of recoils
  - Kinetic Energies < 40 keV for xenon
  - But, Head-on collisions have more energy
- Substantial scattering along trajectory
  - But, where directionality is retained, energy loss high
  - Majority of energy lost to “heat” – quench factor ~5
- Ambipolar diffusion holds most of the electron population
  - A few primary electrons wander off and are lost
- Excitations outnumber ionizations by large factor
- Primary excitations contain no directional information!

What to do! ?

Exploit Atomic/Molecular Dynamics

- **Primary Xe excitations**: these must be converted to ionization – to serve as recombination sites!
  - Use Penning effect: excitations → ionization
  - Xenon: TMA (and maybe TEA) are candidates
- **Primary Xe ions:** Xe^+ are rapidly neutralized by charge exchange with Penning molecules
  - Ionization potential of TMA ≤ first excited state of Xe*
  - Ionic image transformed to TMA^+ molecular image
- Columnar recombination occurs on TMA^+ ions

Atomic/Molecular Gymnastics

Xe_{nr} + Xe → Xe + heat
→ Xe^*
→ $Xe^+ + e^-$

Xe^* + TMA → Xe + $TMA^+ + e^-$ (Penning effect)
Xe^+ + TMA → Xe^* + TMA^+ (Charge exchange)

$TMA^+ + e^-$ → TMA^* → TMA + photon (~300nm)

Fluorescence spectrum of tertiary amines

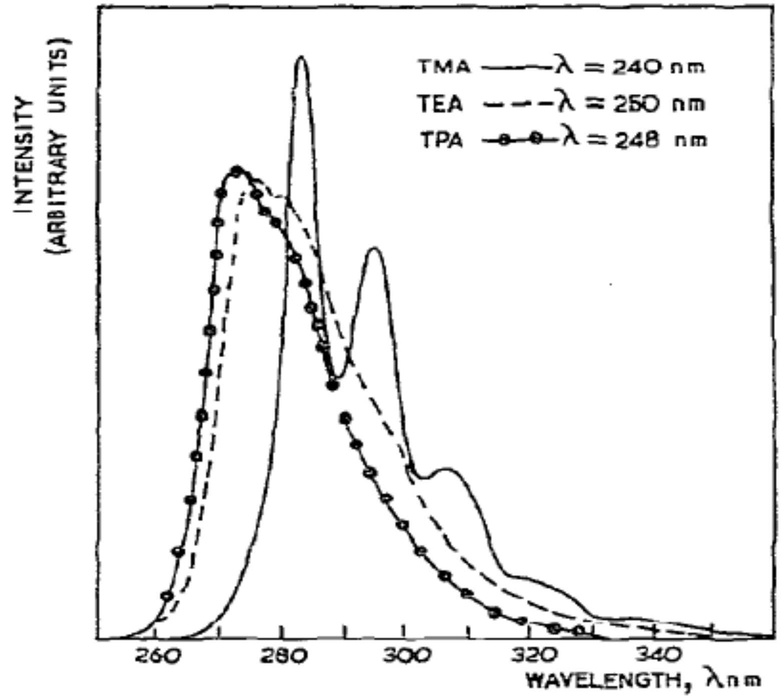


Fig. 4. Vapour-phase fluorescence spectra of TMA, TEA and TPA at excitation wavelengths indicated.

TMA in xenon retains same fluorescence spectrum up to at least 10 bars

Detecting Directionality

- Columnar Recombination with TMA leads to UV
  - TMA, TEA, fluoresce strongly in 280 – 330 nm band
- **The Directionality signal is contained in the ratio of recombination/ionization = R/I**
  - More recombination implies less ionization & vice versa
- R signal is intrinsically optical
  - Convert I signal to scintillation by electroluminescence
- All signals detected optically
  - I signal is separated in time by drift interval

Conceptual Advantage

– **No track visualization required !**
  - **R/I** determined <u>before</u> drift
  - Simplified readout plane possible
  - TPC scale can be arbitrarily large

Figure of Merit: $\mathcal{M} = V_{det}/V_{track}$

$\mathcal{M} \sim 10m^3/10\mu m^3 \sim 10^{18}$ for CR-based system

Efficient detection of the R signal

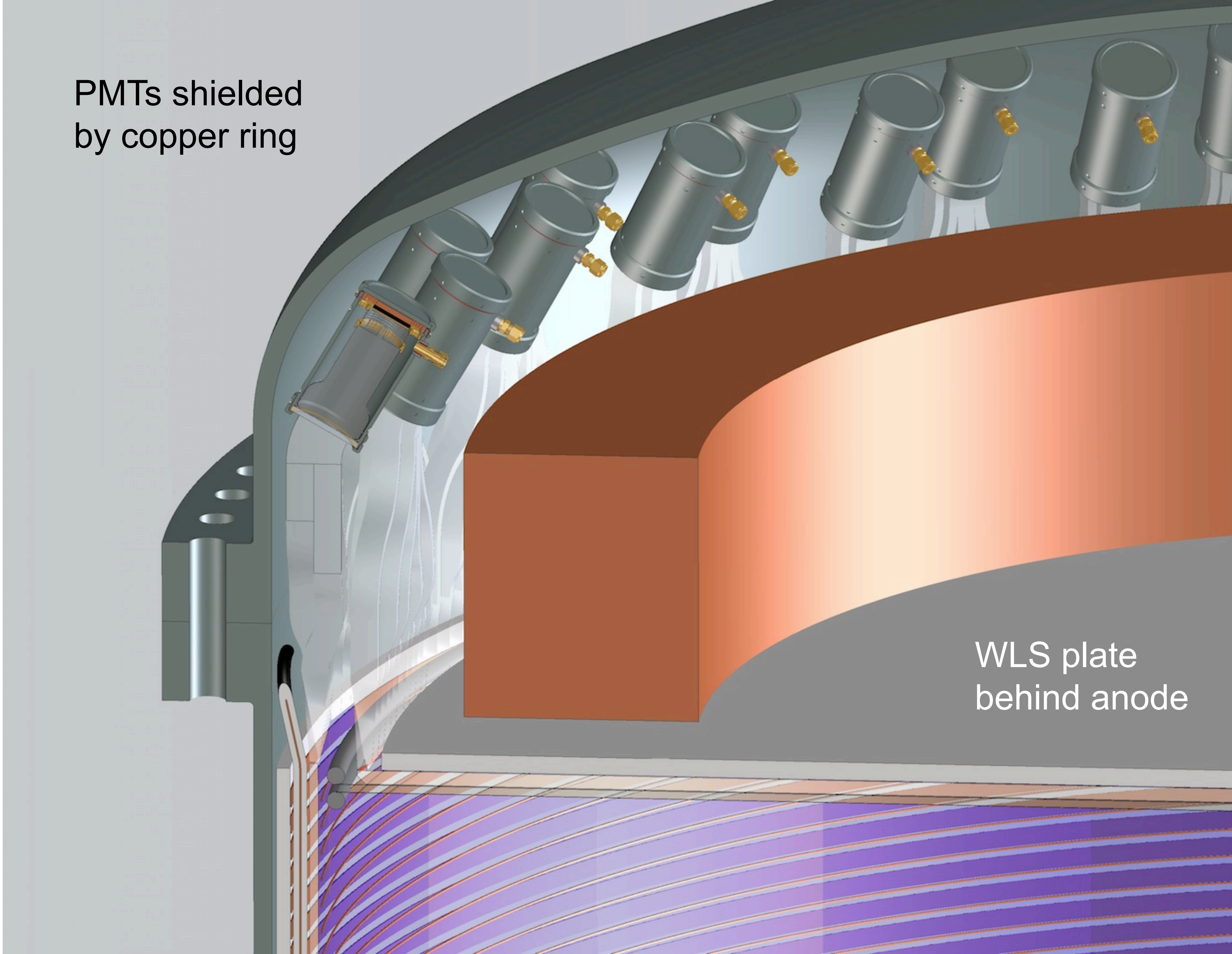
- Gas-phase TPC is very large…
- Use wavelength-shifting (WLS) plastic

  – Cover the TPC interior completely with WLS
  – Maximum efficiency of WLS occurs at 300 nm
  – TMA UV matches WLS optimum wavelength!

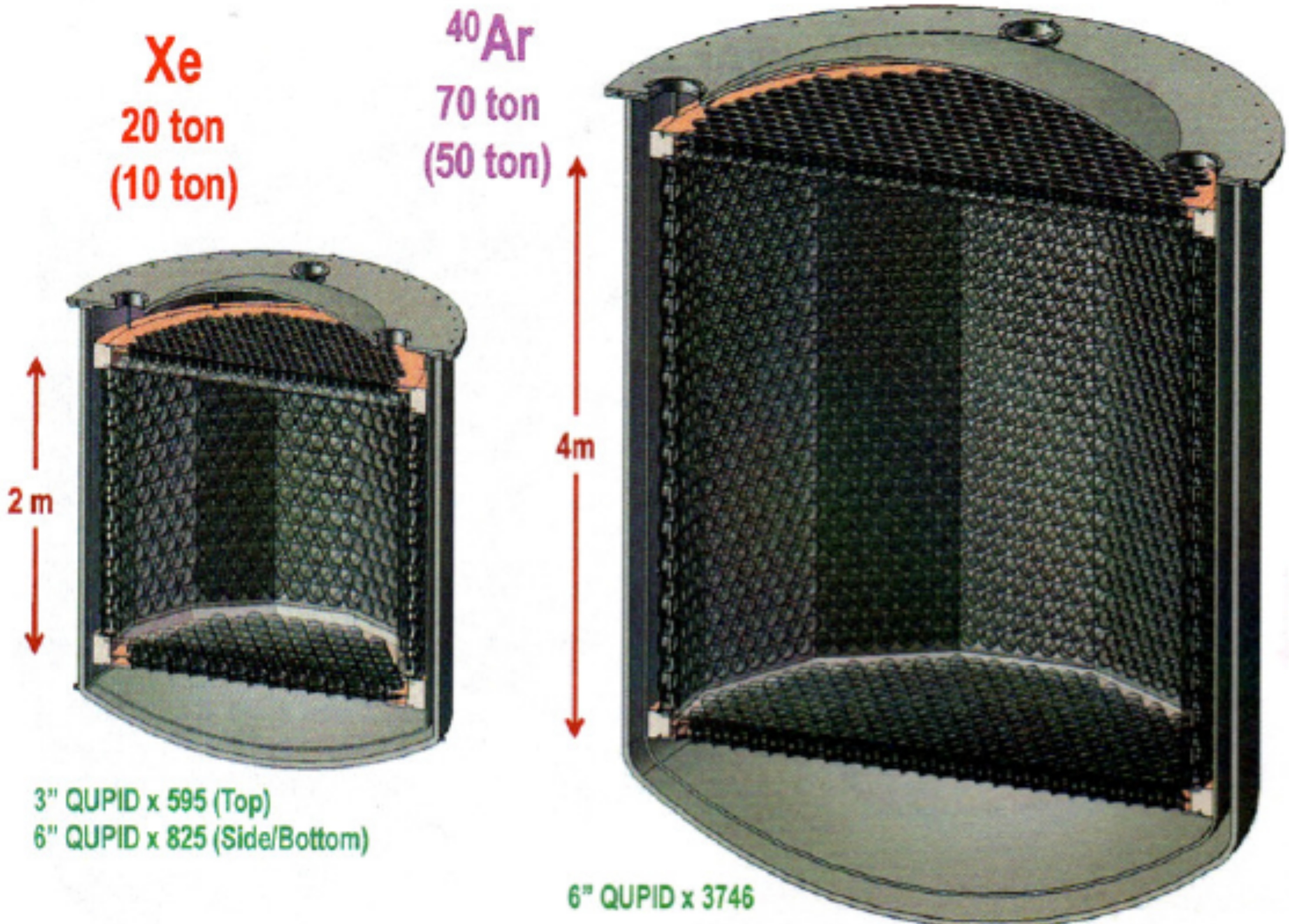
  – More than 50% is internally captured in gas interface

  – Pipe light to small # of PMTs, shielded by copper

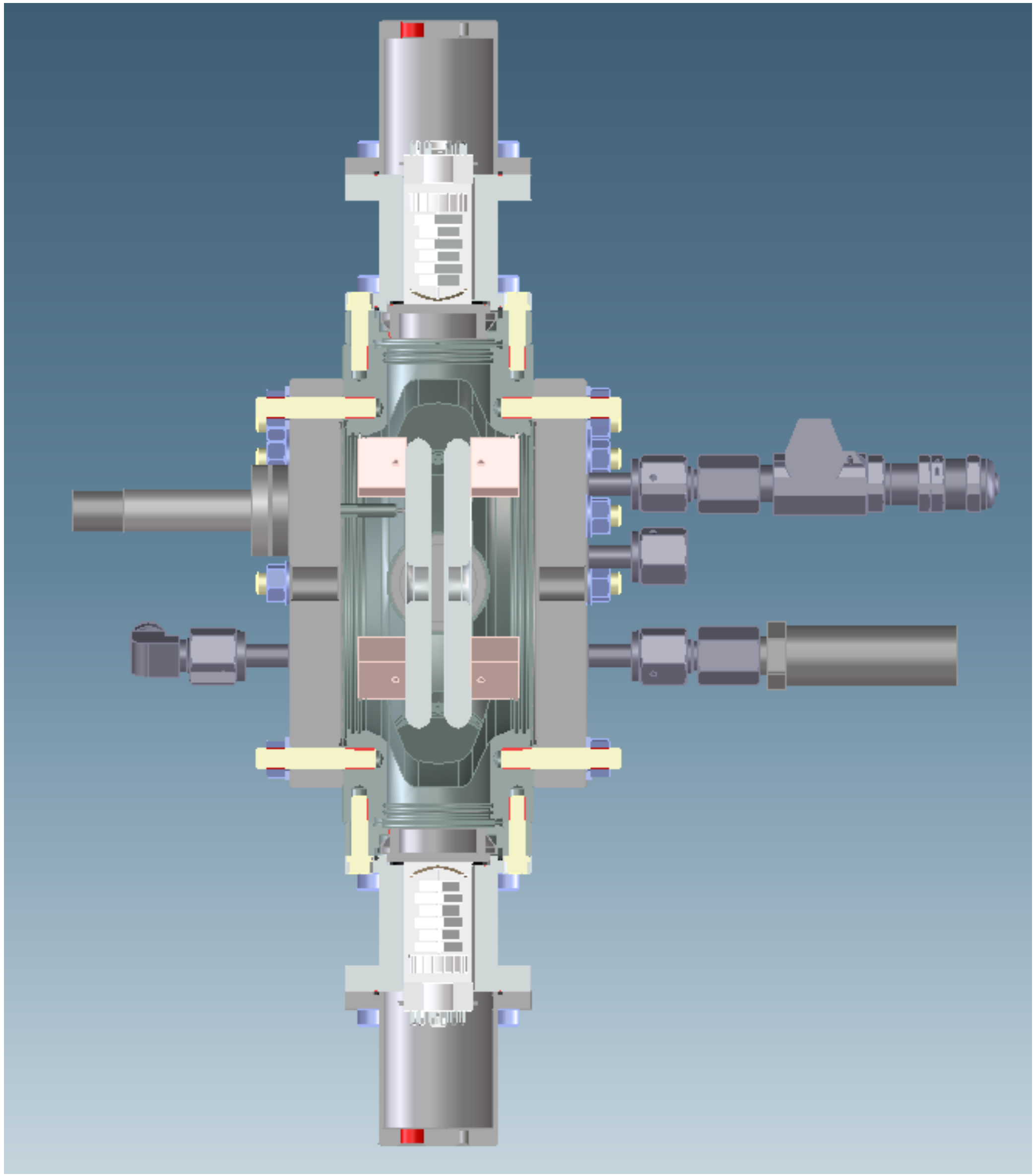
“Ton-scale” HPXe TPC with WLS on all surfaces, except HV cathode plane


PMTs shielded
by copper ring
WLS plate
behind anode

Arisaka *et al*



arXiv1107.1295v3



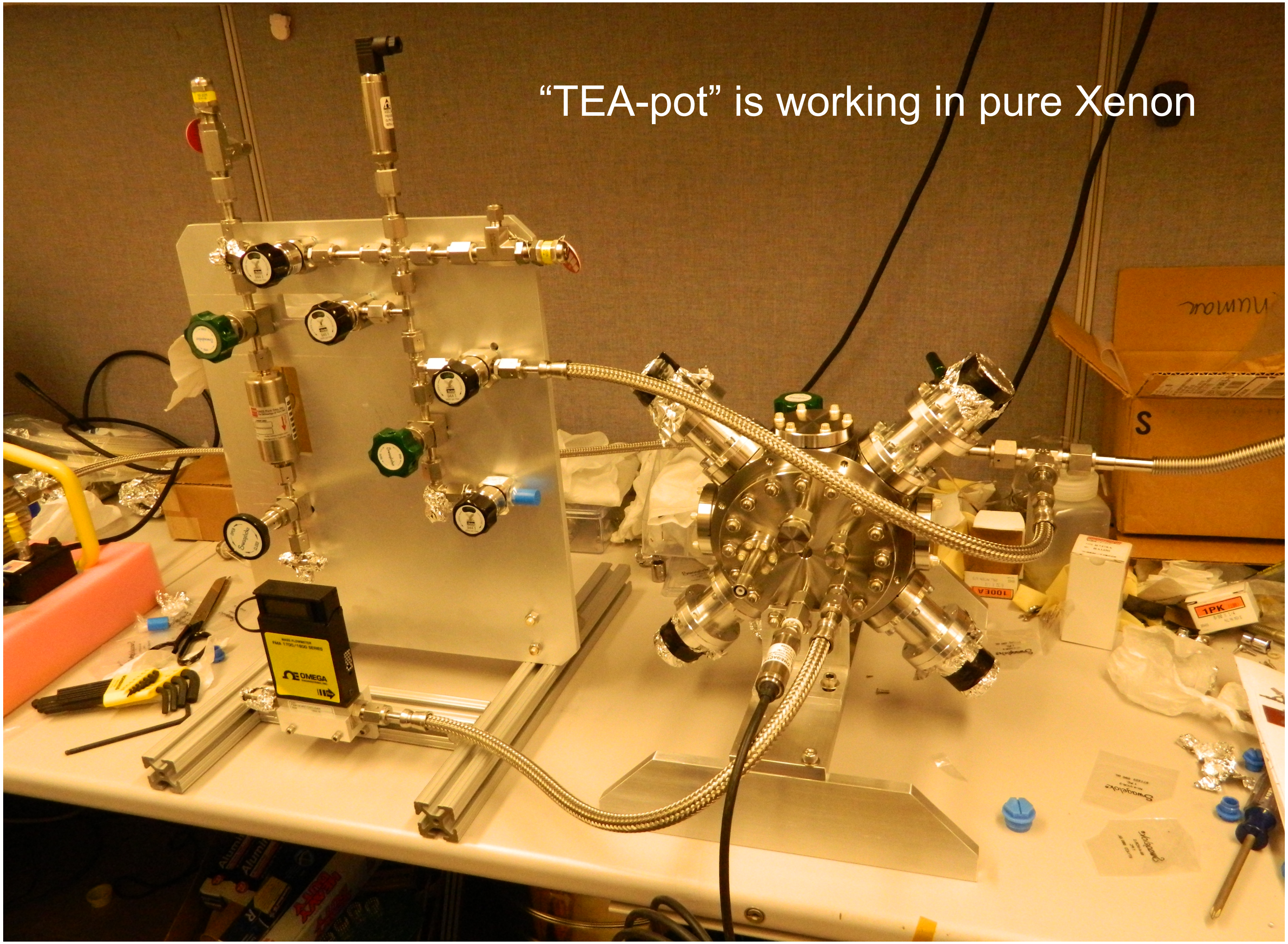
the "TEA-pot"

Basic responses measurements:

A parallel-plate ionization chamber with optical sensing, using 4 PMTs that look at the gap from the sides

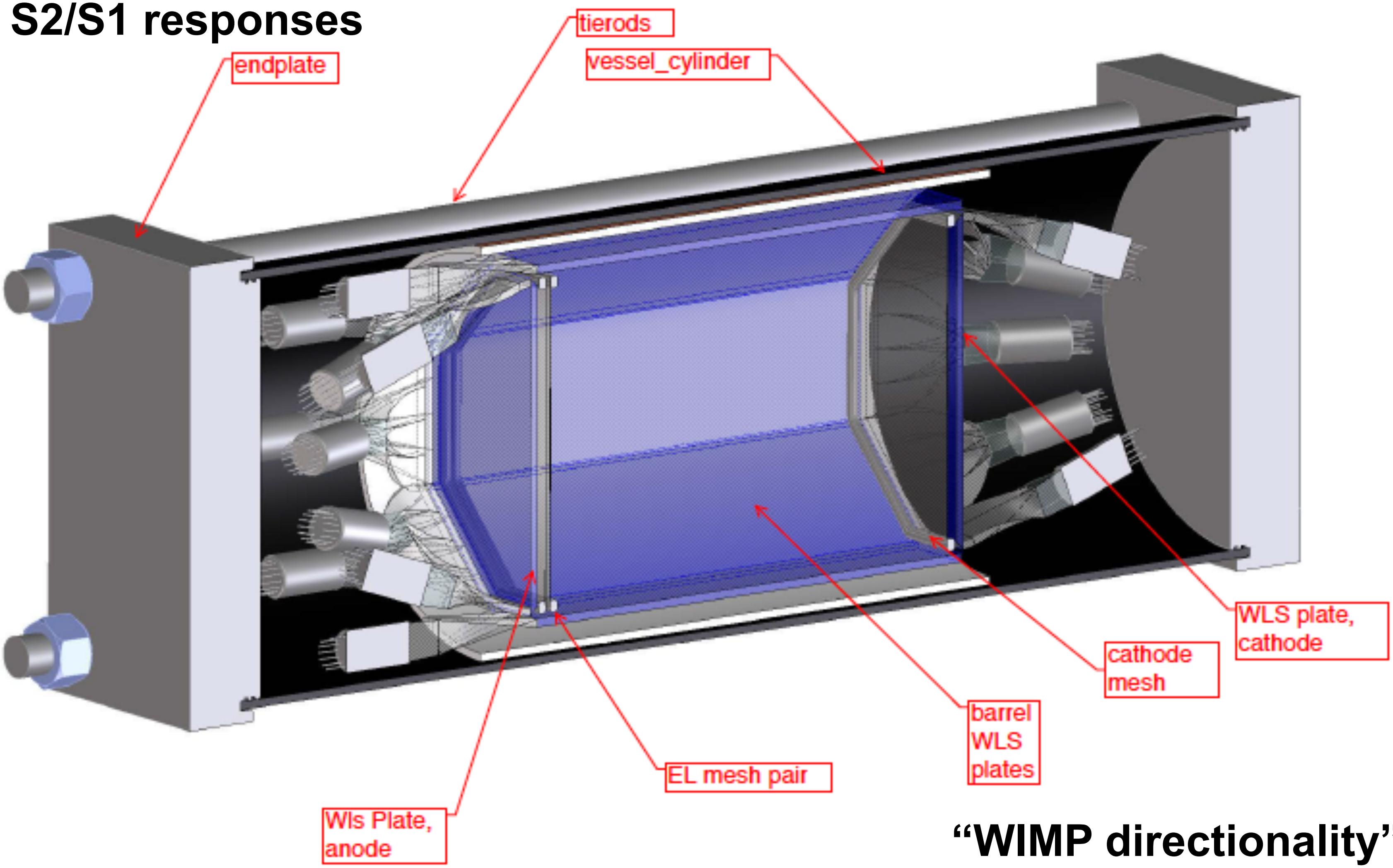
We measure both light and charge as functions of density, electric field, and fraction of TMA/TEA,

“TEA-pot” is working in pure Xenon



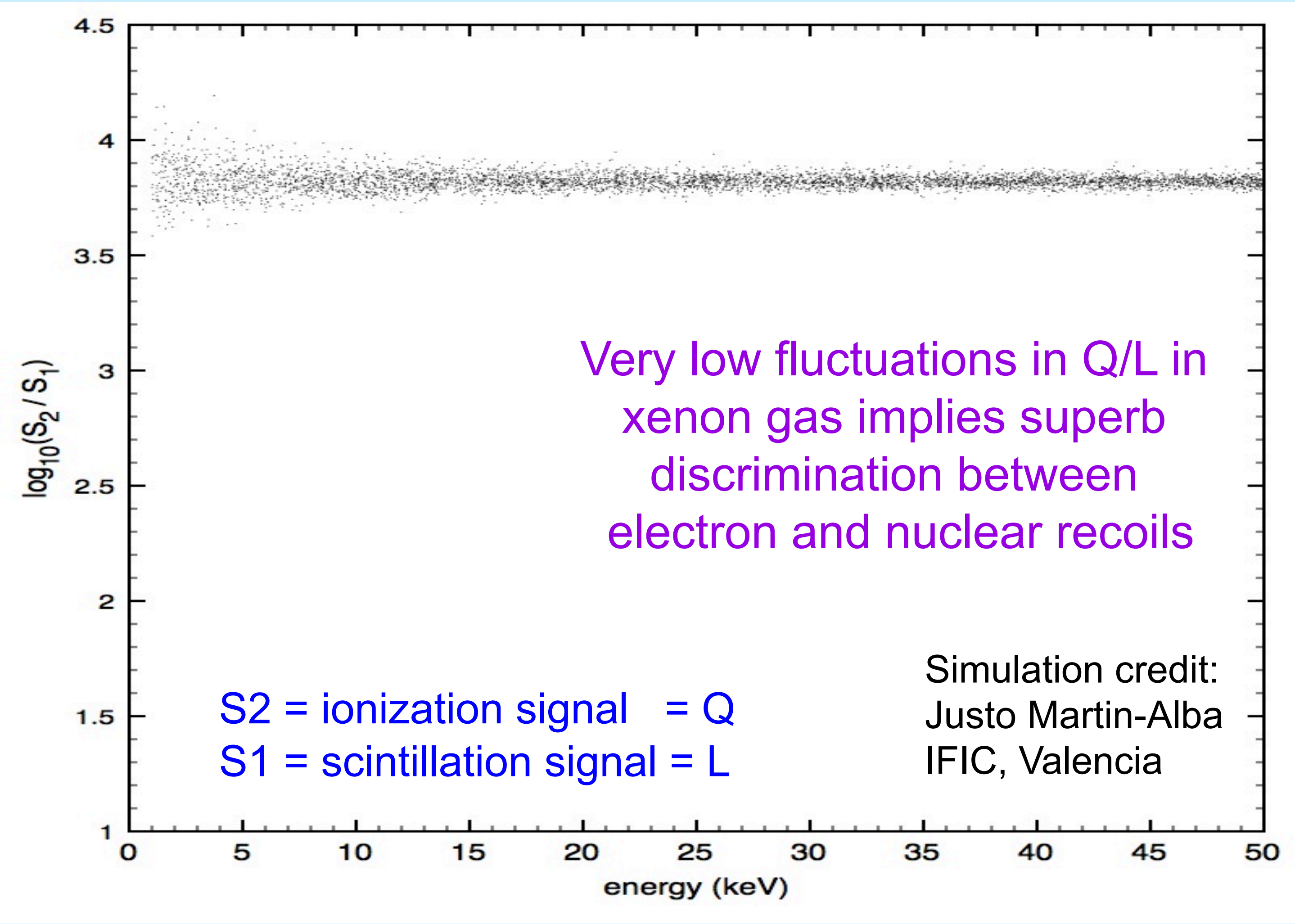
OSPREY: "*Opportunities for Superior Performance in Rare Event Yields*"

S2/S1 responses



"WIMP directionality"

Simulation: electron recoils in pure HPXe, F = 0.15, !0% optical efficiency



Uncertainties

- WIMPs exist with mass 50 – 300 GeV? Not sure...
- Head-tail effect? Not sure...
- Penning efficiency? Not sure...
- Reduction of Fano factor? Not sure...
- How much drift field? Not sure...
- How much TMA? Not sure...
- Do transfers happen quickly enough? Not sure...
- Behavior of TMA in large system? Not sure...
- Optimal conditions:
  - Identical for both WIMP and 0-ν ββ? Not sure...

Summary

- The exploitation of columnar recombination and atomic/ molecular processes in xenon-TMA may permit a substantial directionality signal in a massive TPC

- No visualization of nuclear recoils is necessary

- Superb energy resolution for electron recoils
  - Unsurpassed electron/nuclear recoil discrimination?
  - Intrinsic resolution at ^{136}Xe $Q_{\beta\beta}$: 0.28% FWHM?

- Simultaneous searches may be possible!

Thanks to LBNL HP Xe TPC Group:

Vic Gehman (PD), Azriel Goldschmidt (NSD), Tom Miller (ME TECH), Carlos Oliveira (Post-doc), Josh Renner (GSRA), Derek Shuman (ME), Jim Siegrist (part-time – now at DOE) + Visitors & Undergrads

And many Colleagues in *NEXT-100*

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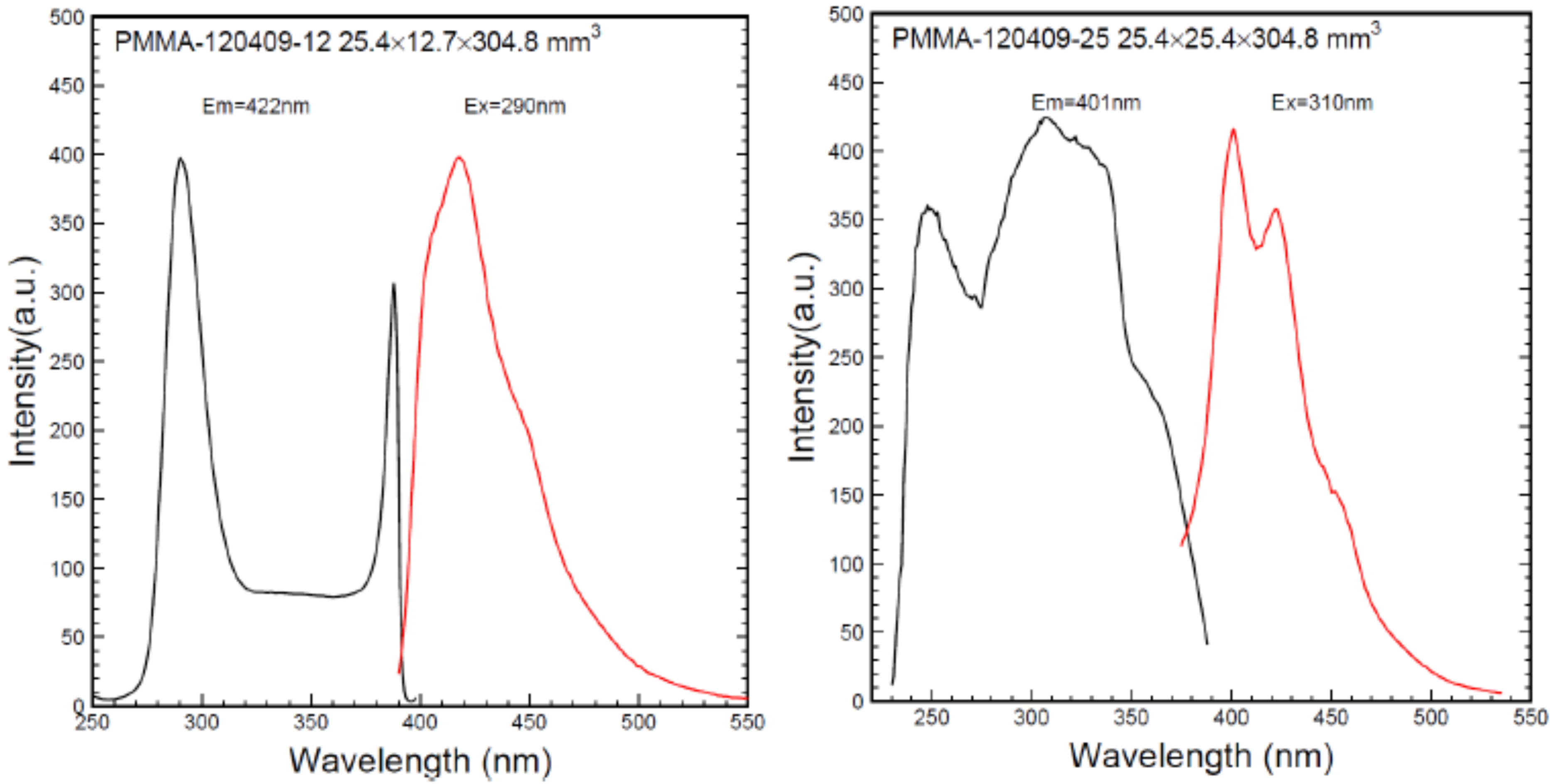
Thank you

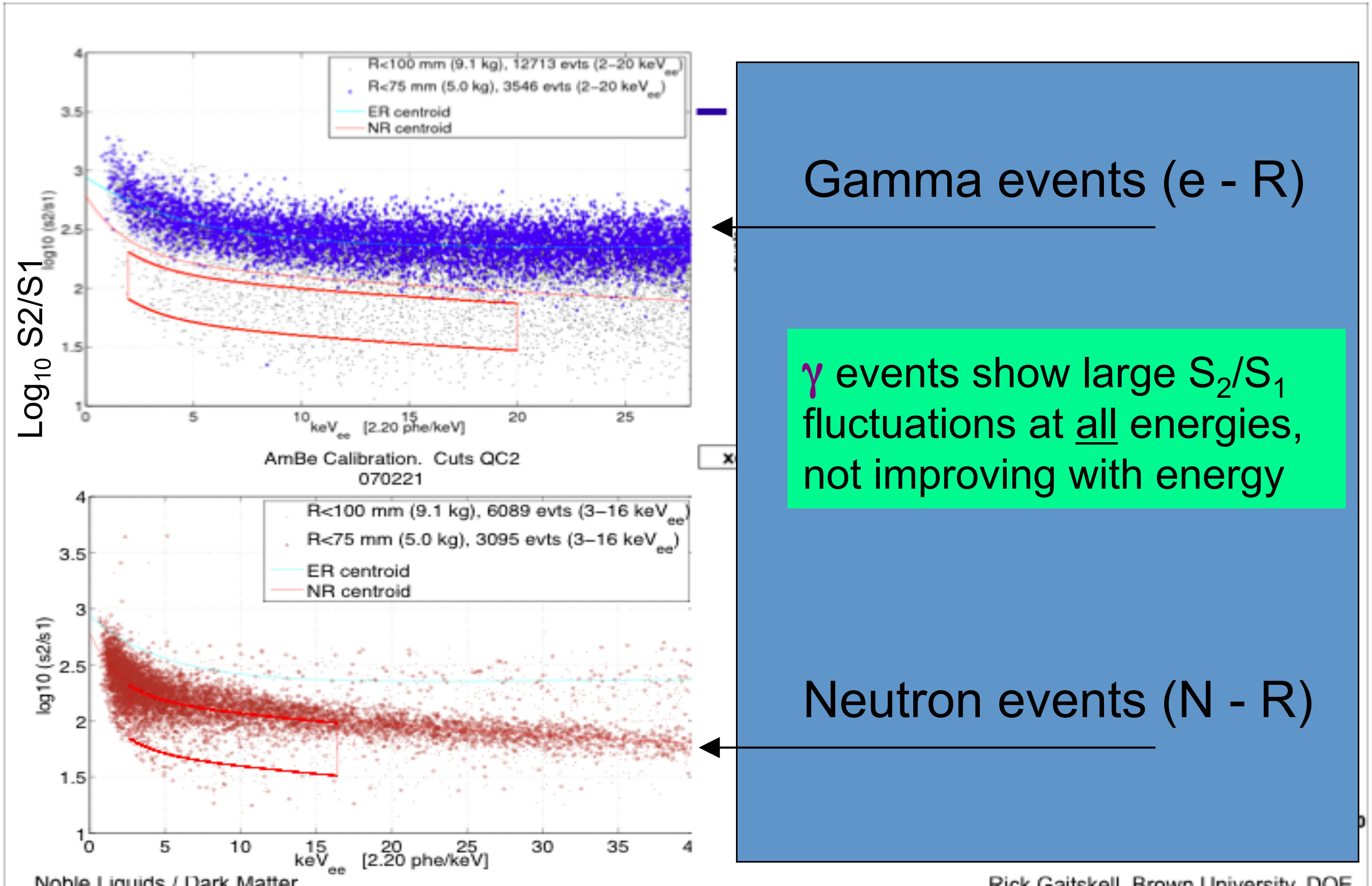
Photo-Luminescence of PMMA

Different WLS nature observed for two PMMA Samples

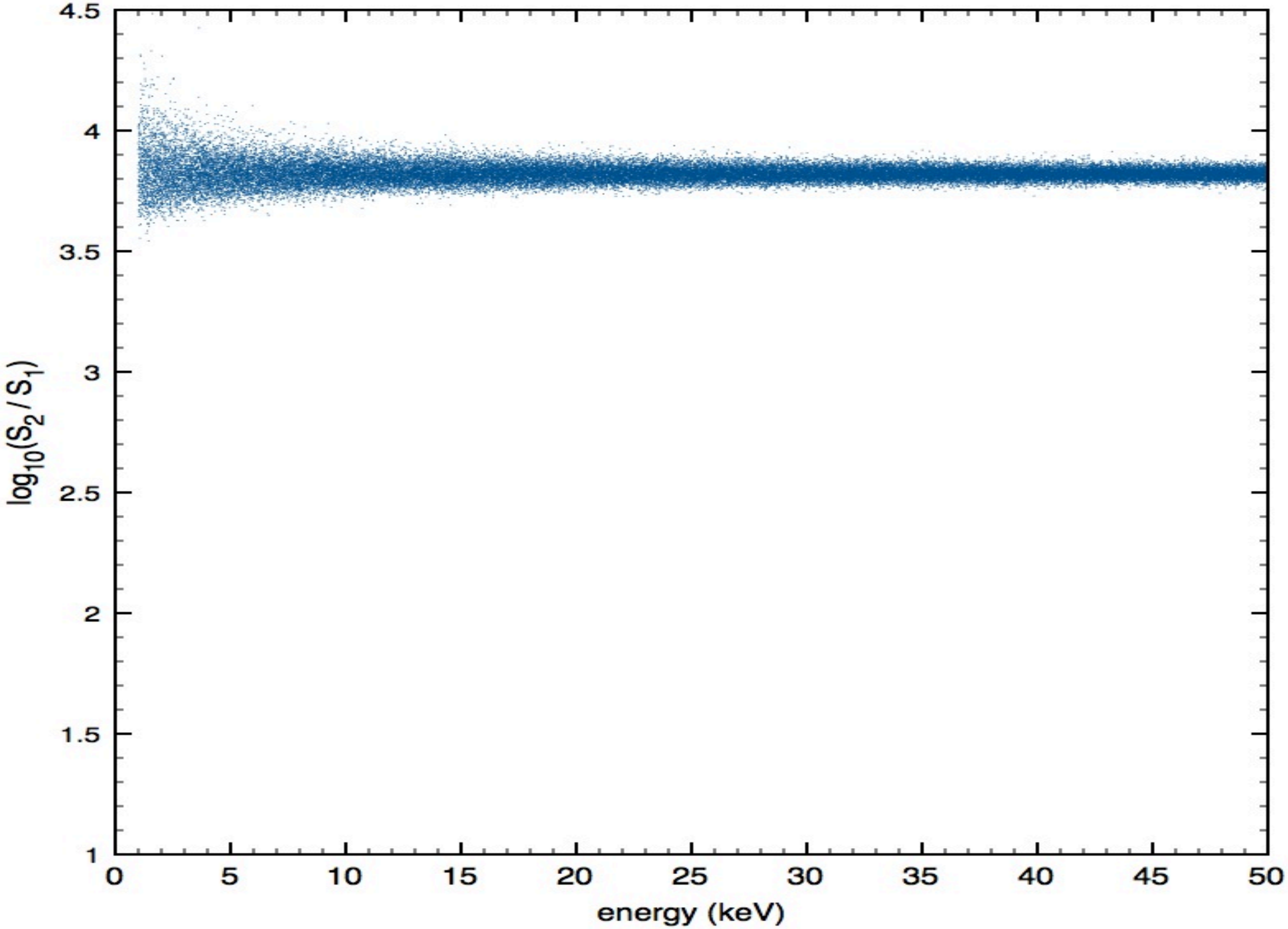


S2 = Primary ionization signal
S1 = Primary scintillation signal

Xenon10 WIMP search - data



<u>Gaussian behavior persists</u> at x10 number of events



Enemy: TMA Geminate Recombination

Xe_{nr} + Xe → Xe + heat
→ Xe*
→ Xe^{+} + e^{-}

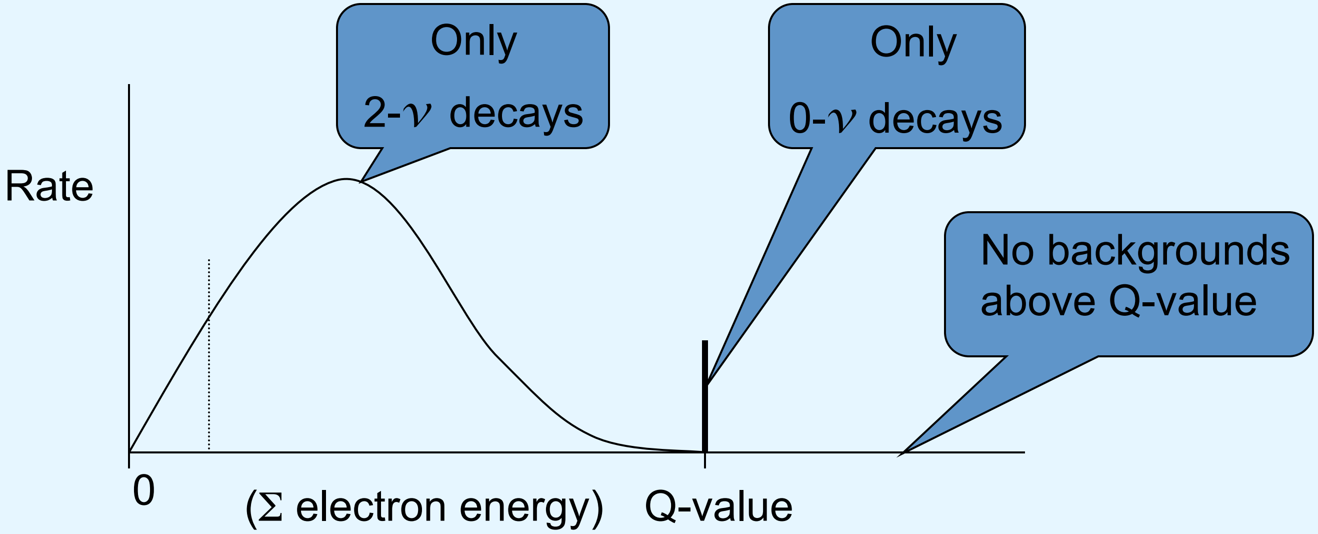
Xe* + TMA → Xe + TMA^{+} + e^{-} (Penning effect)

Xe^{+} + TMA → Xe* + TMA^{+} (Charge exchange)

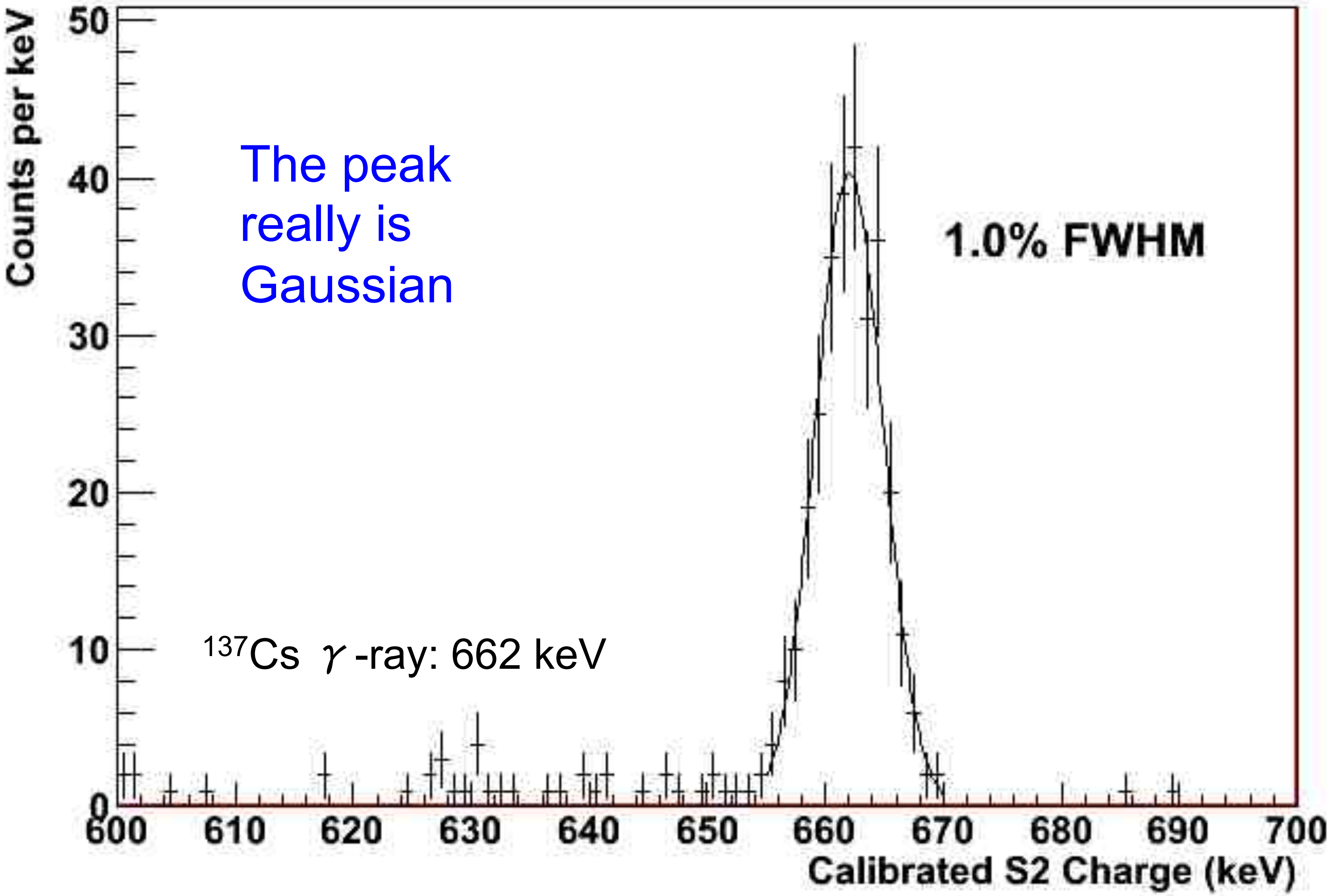
TMA^{+} + e^{-} → TMA* → TMA + photon (~300nm)

0-ν ββ: Energy resolution is critical!

Ideal case: 0-ν signal appears as a narrow peak



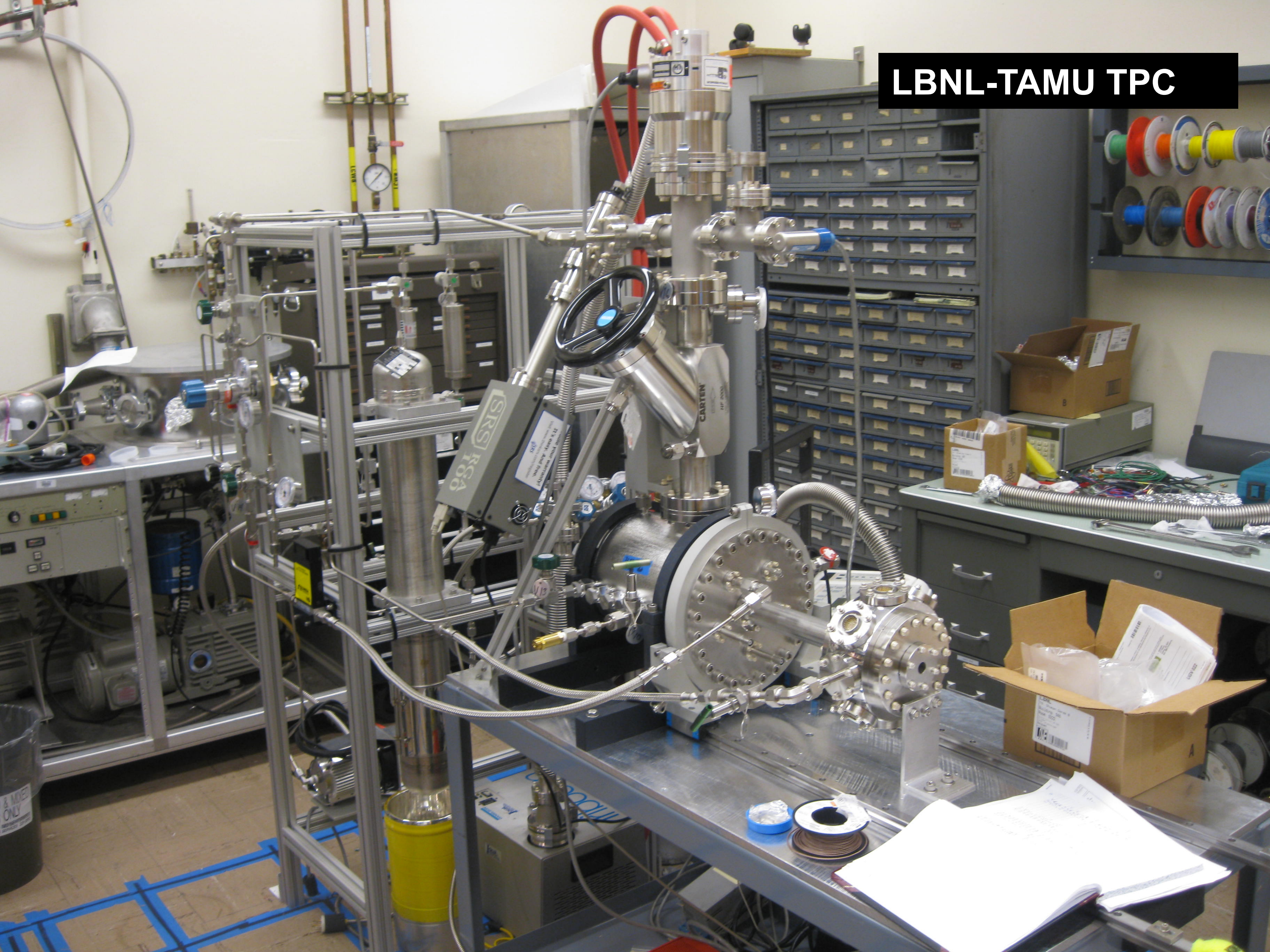
δE/E <1% FWHM is needed for separation from 2-ν background, and to avoid nearby γ-ray lines such as from ^{214}Bi



The peak really is Gaussian

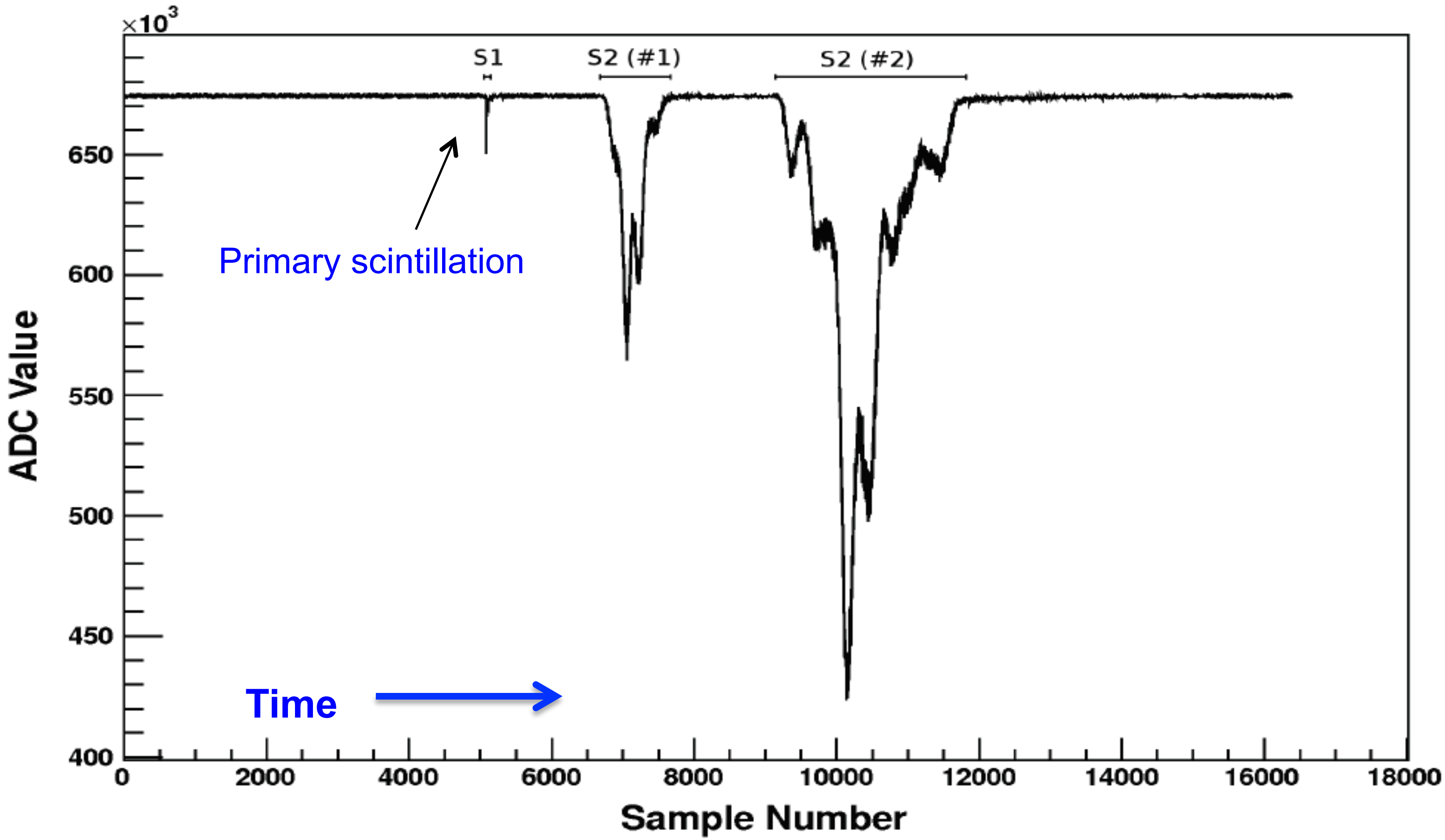
^{137}Cs γ-ray: 662 keV

LBNL-TAMU TPC

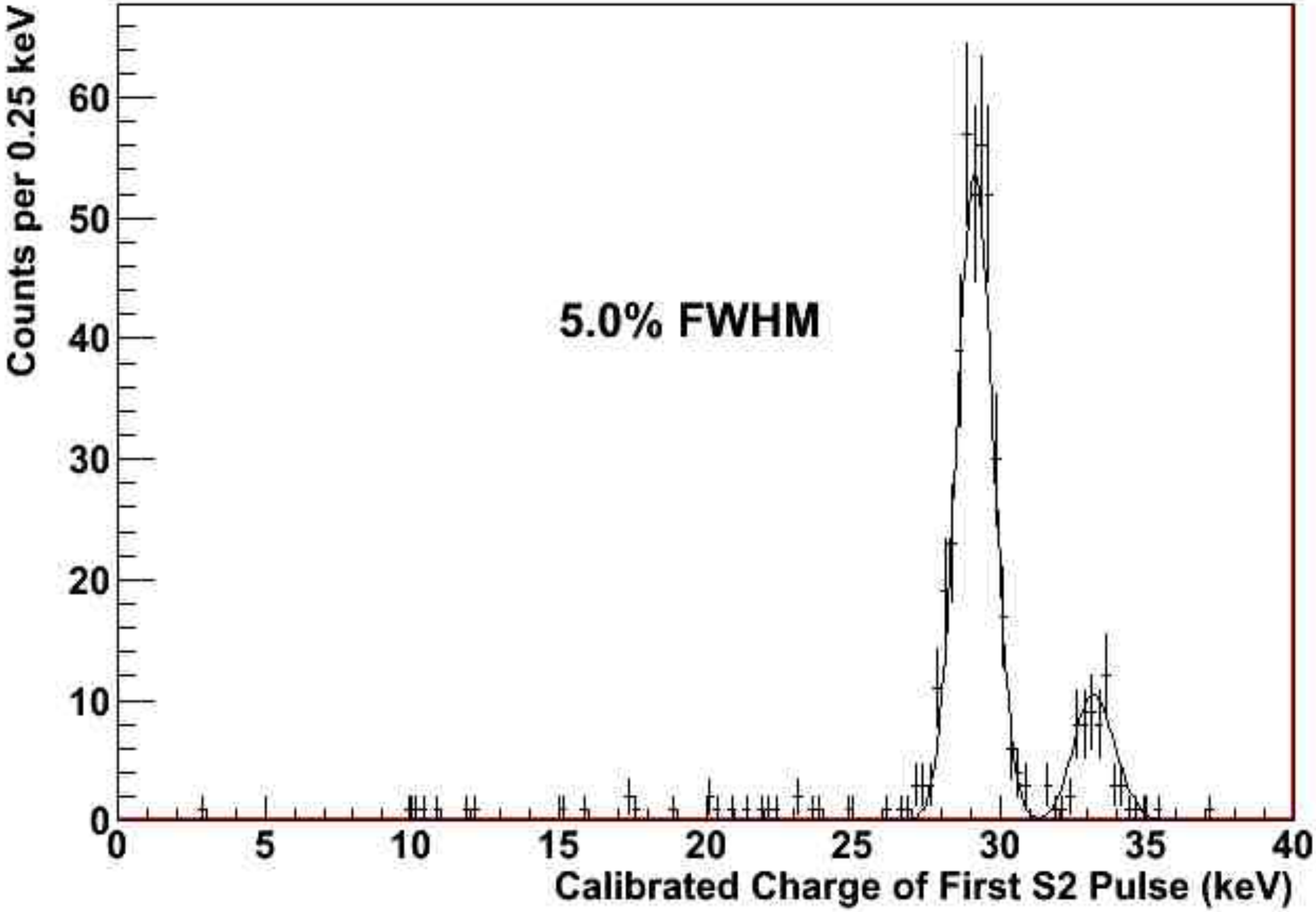


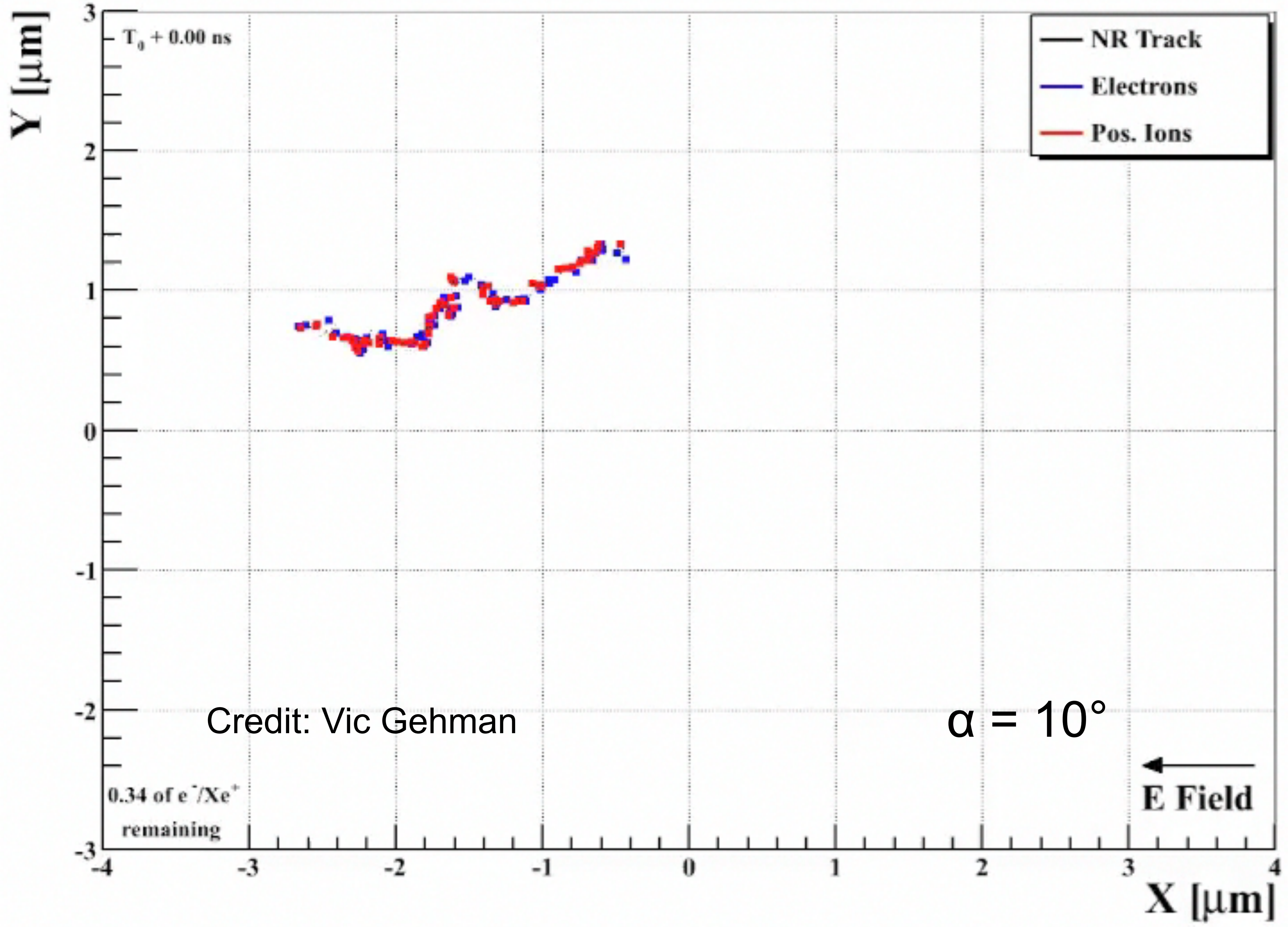
Complex topologies are common:

multiple Compton scatters, followed by a photoelectric event



The x-ray peaks around ~30 keV





Y [μm]
X [μm]
T₀ + 0.00 ns
NR Track
Electrons
Pos. Ions
Credit: Vic Gehman
α = 10°
E Field
0.34 of e⁻/Xe⁺ remaining
3
2
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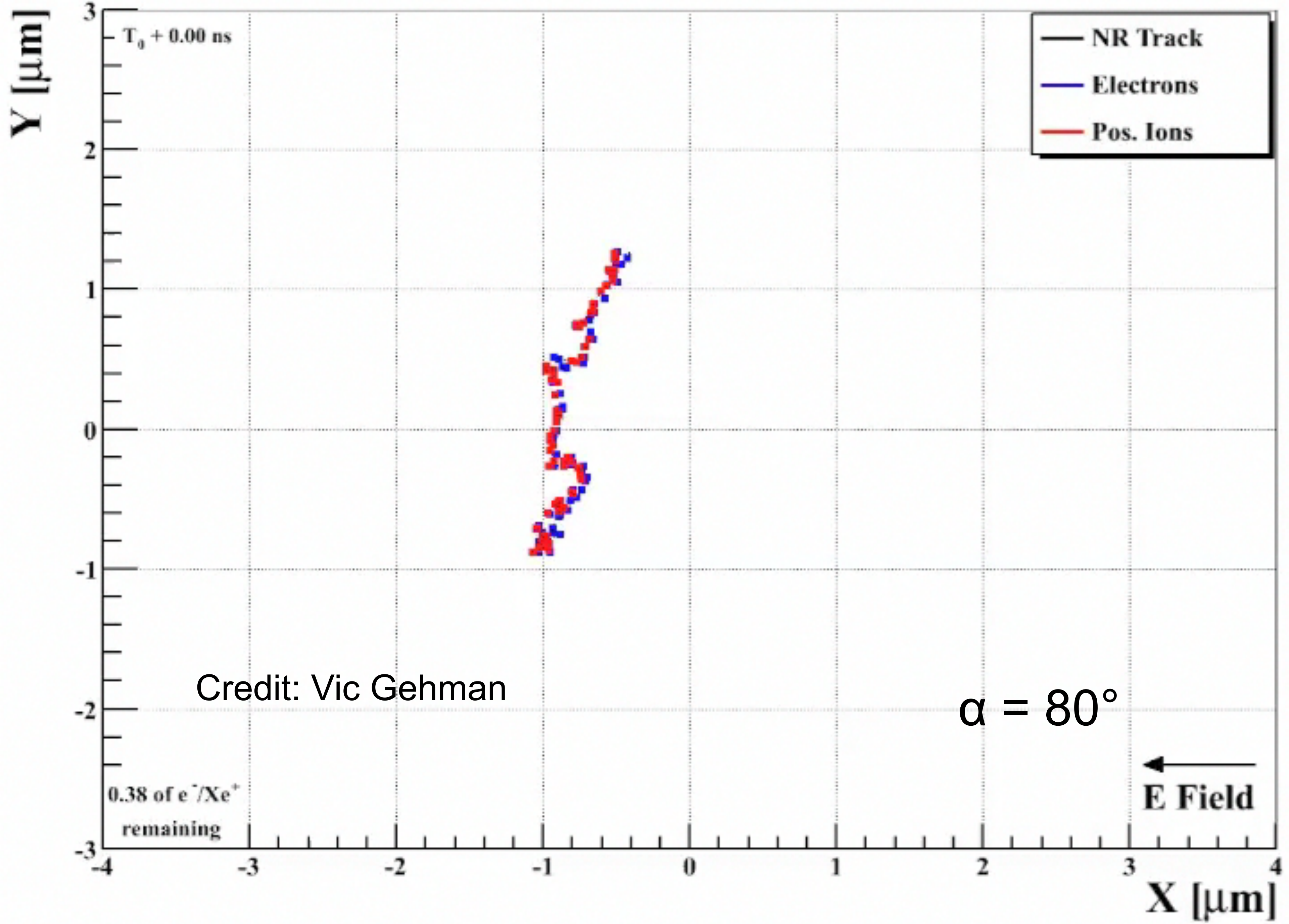

Y [μm]
T₀ + 0.00 ns
NR Track
Electrons
Pos. Ions
Credit: Vic Gehman
α = 80°
E Field
0.38 of e⁻/Xe⁺
remaining
X [μm]