Simultaneous Searches for WIMP Dark Matter and 0-ν ββ decay at the ton-scale with a high-pressure xenon gas TPC

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For the NEXT collaboration

See also talk on NEXT by David Lorca Galindo

Xenon:
a popular choice for both
0-ν ββ and WIMP search

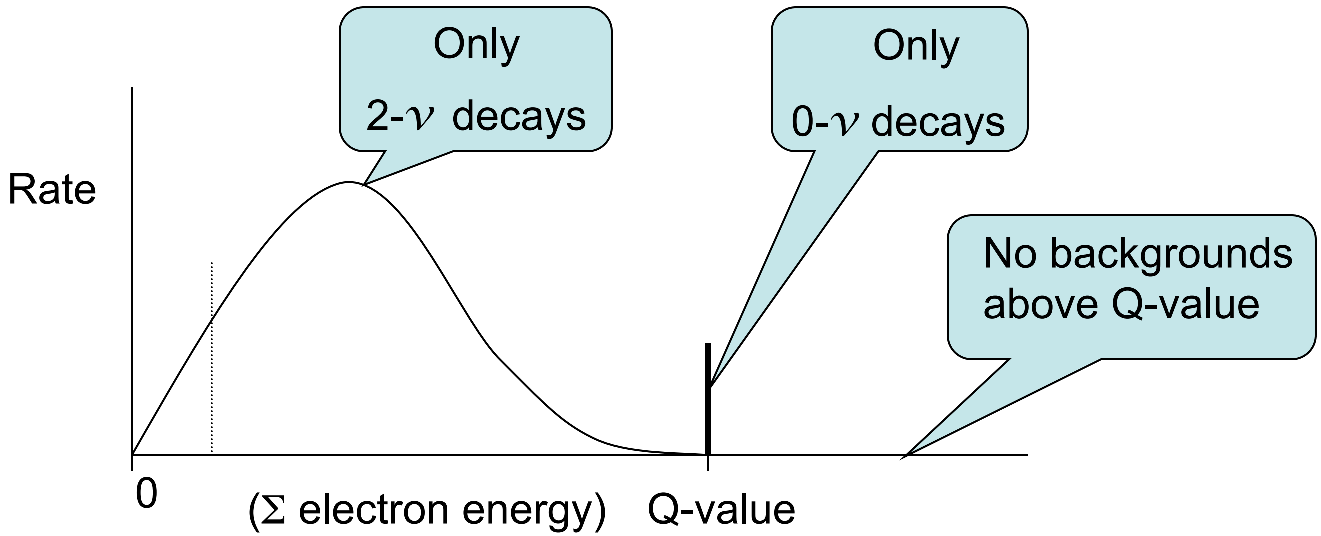
But not in the same detector!

Xenon: a popular choice for both 0-ν ββ and WIMP search

- Both searches require very low backgrounds
- Simultaneous searches could save $$$,…
- I present a case that both could be done, with little or no compromise, in a xenon gas electroluminescent TPC, perhaps at ton-scale

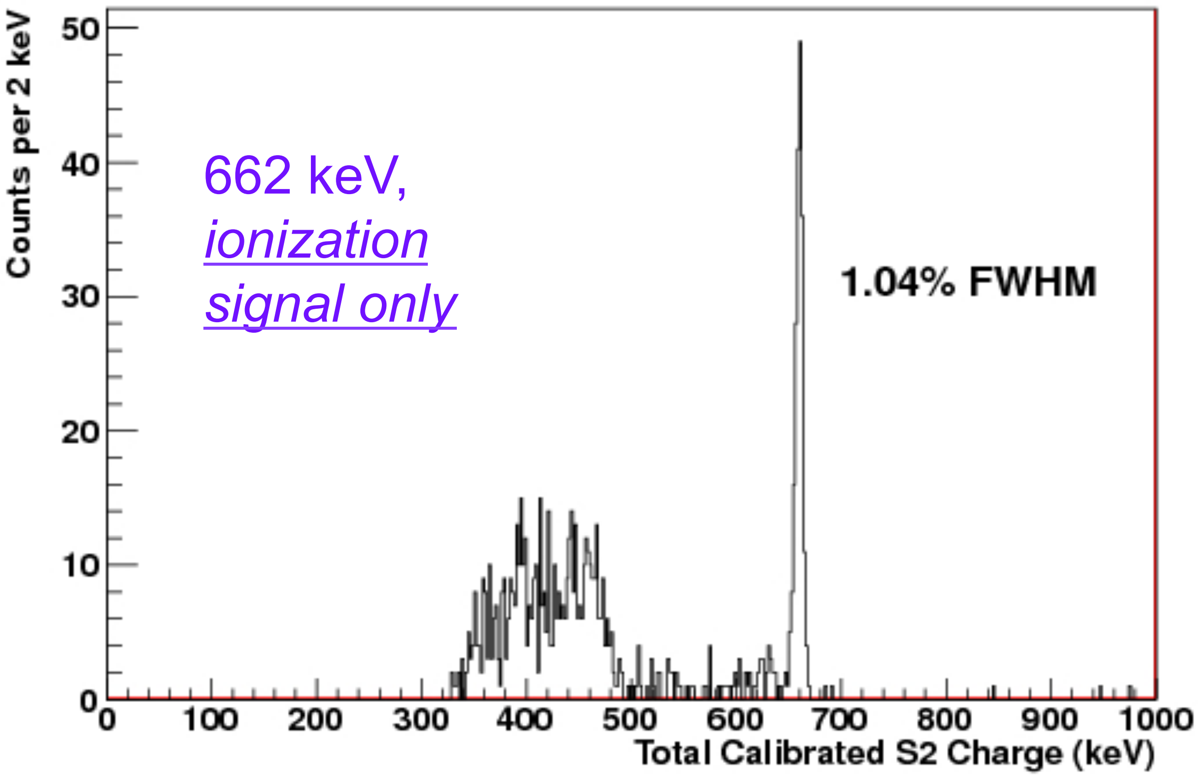
0-ν ββ: Energy resolution is important!

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

New: 1% FWHM energy resolution for ^{137}Cs 662 keV γ-rays in xenon!



Data from LBNL-TAMU HP Xe TPC

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

Resolution: ^{137}Cs γ-ray (662 keV)

$$\sigma_N = (F \cdot N)^{1/2}$$

$F \equiv$ Fano factor: $F = 0.15$ (xenon gas)

$N = Q/w = 662{,}000/25 \sim 26{,}500$ primary electrons

$\sigma_N = 63$, a very small number of electrons!

$\delta E/E = 2.35 \bullet \sigma_N/N = 0.6\%$ FWHM (intrinsic)

Our 1.04% FWHM result is ~1.6 x intrinsic resolution

How does gas deliver such good performance?

Energy resolution in Xenon depends strongly on density

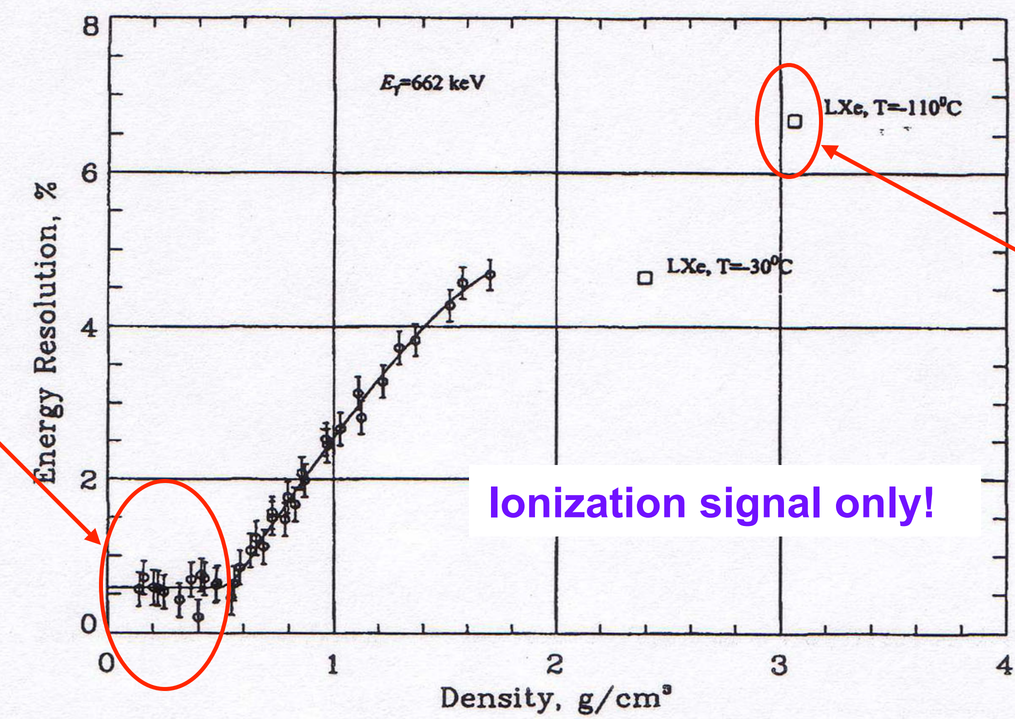
A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370

Here, the fluctuations are normal

F = 0.15

Unfolded resolution:

$\delta E/E$ ~0.6% FWHM



...sity dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

Very large fluctuations between light/charge!

F ~ 20 !!

WIMPs:

S2/S1 suffers!

For ρ <0.55 g/cm^3, ionization energy resolution is "intrinsic"

Energy Partitioning in LXe

Anomalously large fluctuations in energy partition between **ionization** and **scintillation** appear in Lxe, and generate a **Fano factor F ~ 20**

The large fluctuations in LXe are caused by ***delta-rays***, few in number, but with “Landau” fluctuations toward high local ionization density

A conduction band exists in LXe, **promoting** high recombination in regions of high ionization density – delta rays

The recombination process **amplifies** the non-Poisson statistics of the energy loss process of electrons in LXe, leading to large fluctuations

But not for xenon gas!

Energy resolution at $Q_{\beta\beta}$ = 2457 keV

$$\delta E/E = 2.35 \cdot (F \cdot W/Q)^{1/2}$$

- F ≡ Fano factor (HPXe) : F = 0.15
  - w ≡ Average energy per ion pair: w ~ 25 eV
  - Q ≡ Energy deposited from ^{136}Xe --> ^{136}Ba:

N = Q/w ~100,000 primary electrons

$\sigma_N = (F \cdot N)^{1/2}$ ~124 electrons rms!

δE/E = 0.28% FWHM intrinsic HPXe

Only about x3 worse than Ge diodes!

Energy resolution at $Q_{\beta\beta}$ = 2457 keV

$\delta E/E$ = 0.28% FWHM intrinsic HPXe!

How can this performance be preserved through the detection process?

Let "G" represent noise/fluctuations in EL gain
Uncorrelated fluctuations can add in quadrature

Gain, noise & resolution

$$\sigma_n = ((F + G)\cdot N)^{1/2}$$

Require that $G \leq F = 0.15$

Only electroluminescence can provide this performance

EL: $G = J_{CP}/N_{UV} + (1 + \sigma^2_{PMT})^2/N_{pe}$

N_{pe} = number of photo-electrons per primary electron

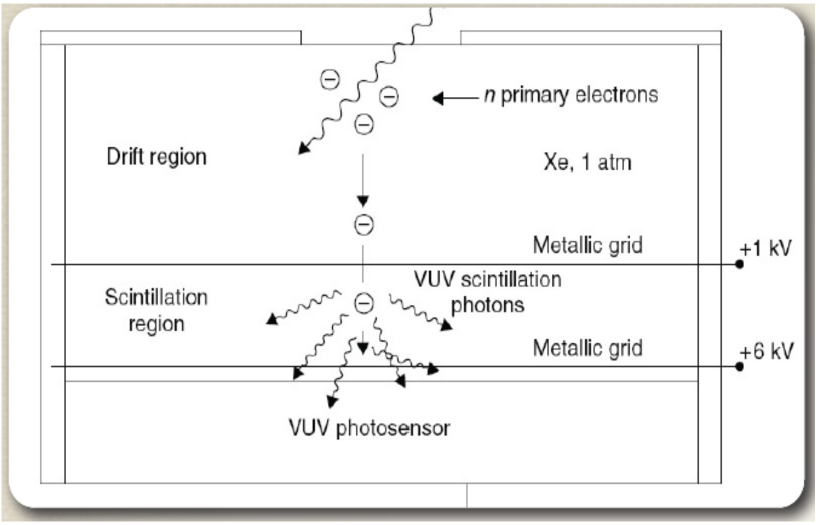
$\sigma^2_{PMT} \approx 2$ (due to after-pulsing !!)

$G \approx 3/N_{pe}$

$\Rightarrow N_{pe} > 20$ **per** electron so that $G \leq F = 0.15$

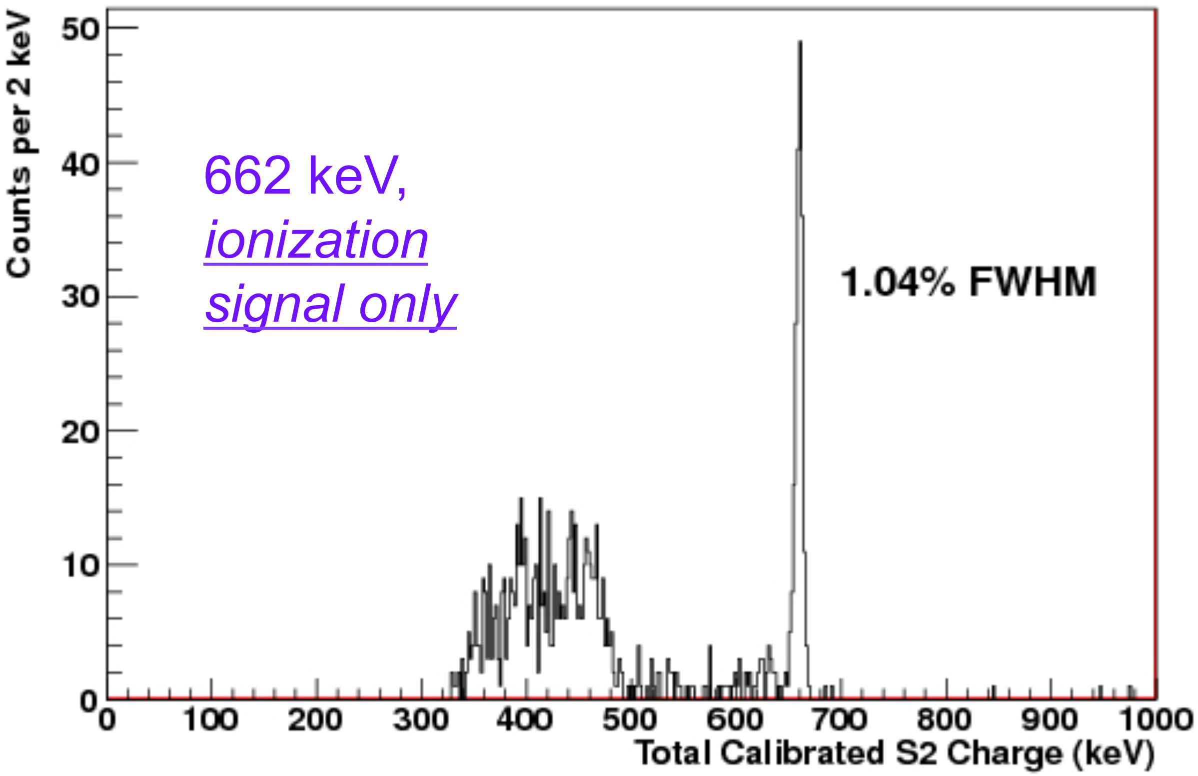
Electro-Luminescence (EL) is the key
(aka: Gas Proportional Scintillation)

- Physics process generates ionization signal
- Electrons drift in low electric field region
- Electrons enter a high electric field region
- Electrons gain energy, excite xenon: 8.32 eV
- Xenon radiates VUV (≈175 nm, 7.5 eV)
- Electron starts over, gaining energy again
- Linear growth of signal with voltage
- Photon generation up to >1000/e, but no ionization



- Sequential gain; no exponential growth ⇒ **fluctuations are very small**
- $\delta N_{UV} = (J_{CP} \bullet N_{UV})^{1/2}$ (Poisson: $J_{CP} = 1$)
- Optimal EL conditions: $J_{CP} = 0.01$

How was this 1% result obtained?



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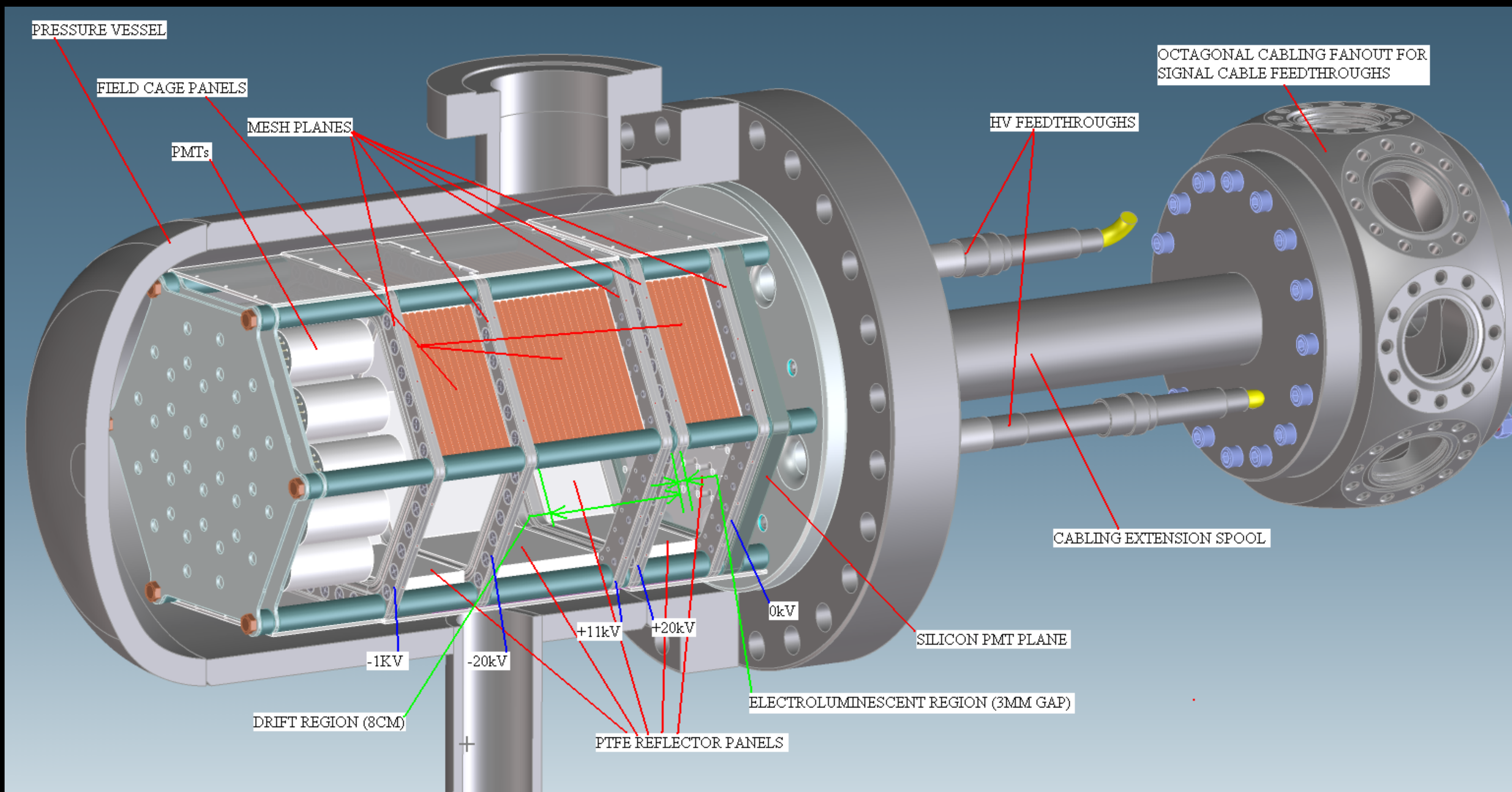
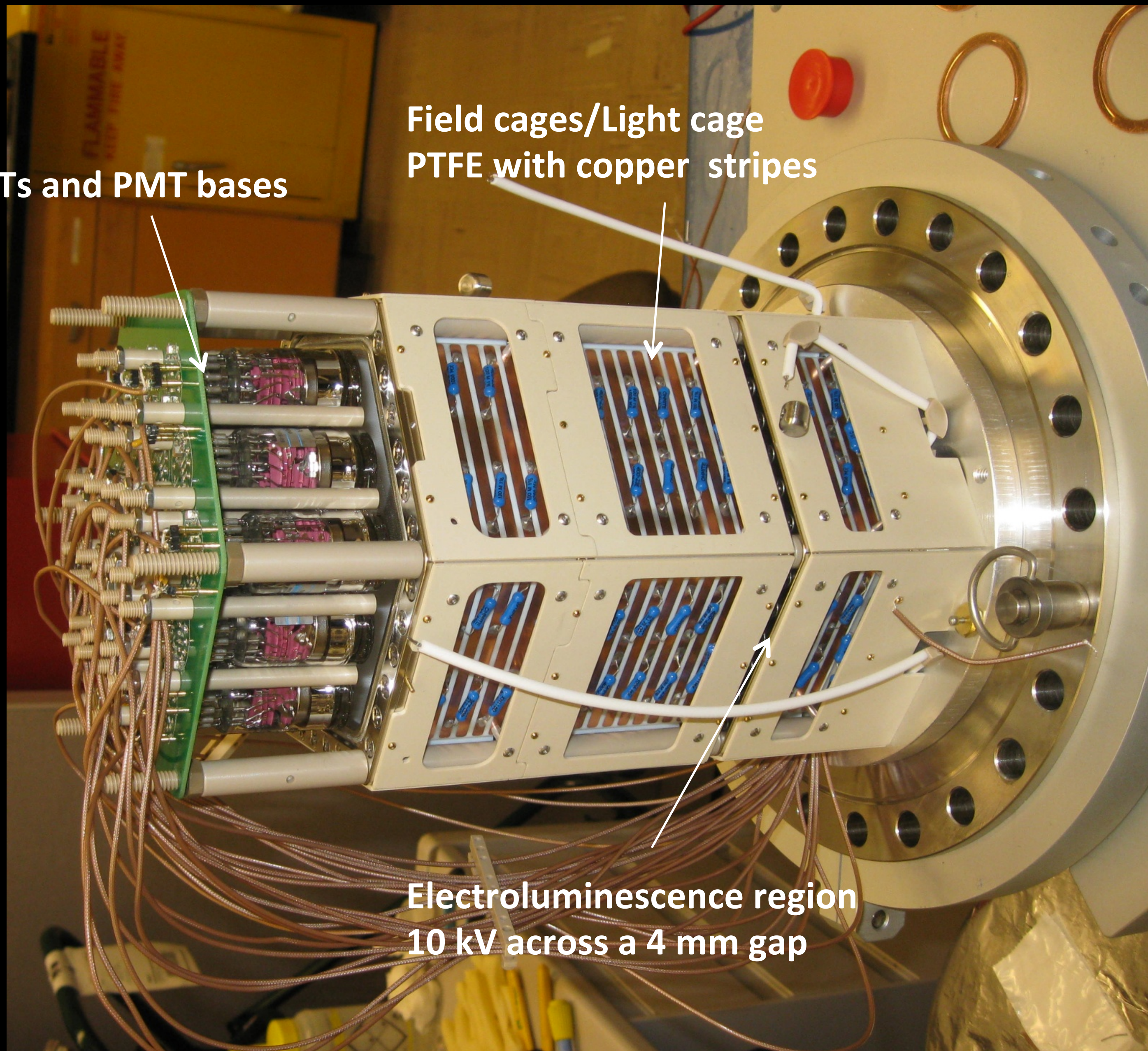
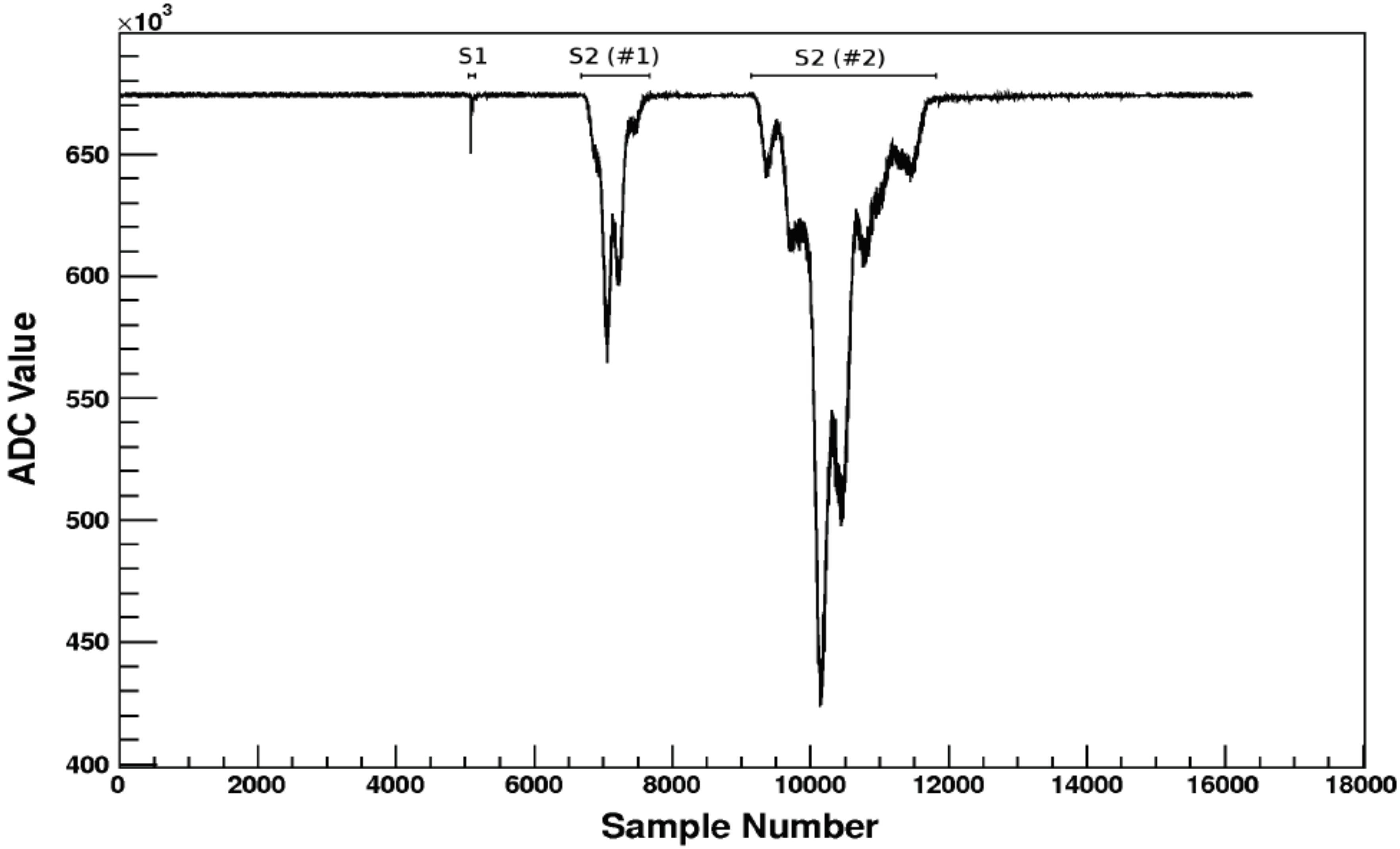
LBNL-TAMU TPC Prototype



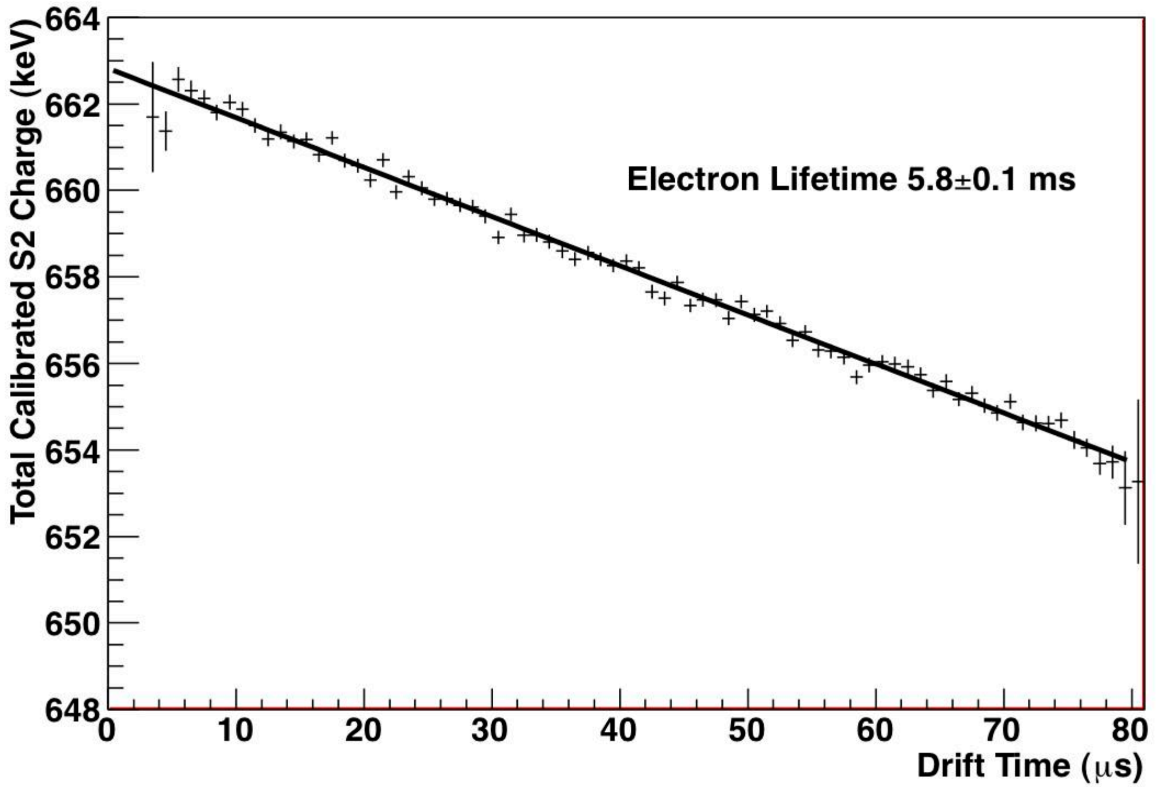

19 PMTs and PMT bases
Field cages/Light cage
PTFE with copper stripes
Electroluminescence region
10 kV across a 4 mm gap

PMT Array: inside the pressure vessel
Quartz window 2.54 cm diameter PMTs

Complex topologies are common!



Attenuation of electrons during drift is very small



correction for attenuation is modest, but must be done with care for minimal error to energy

*“**N**eutrino **E**xperiment **X**enon **T**PC”*

NEXT

Is based on high-pressure xenon gas (HPXe) TPC ideas

Is optimized for 0-v ββ becay

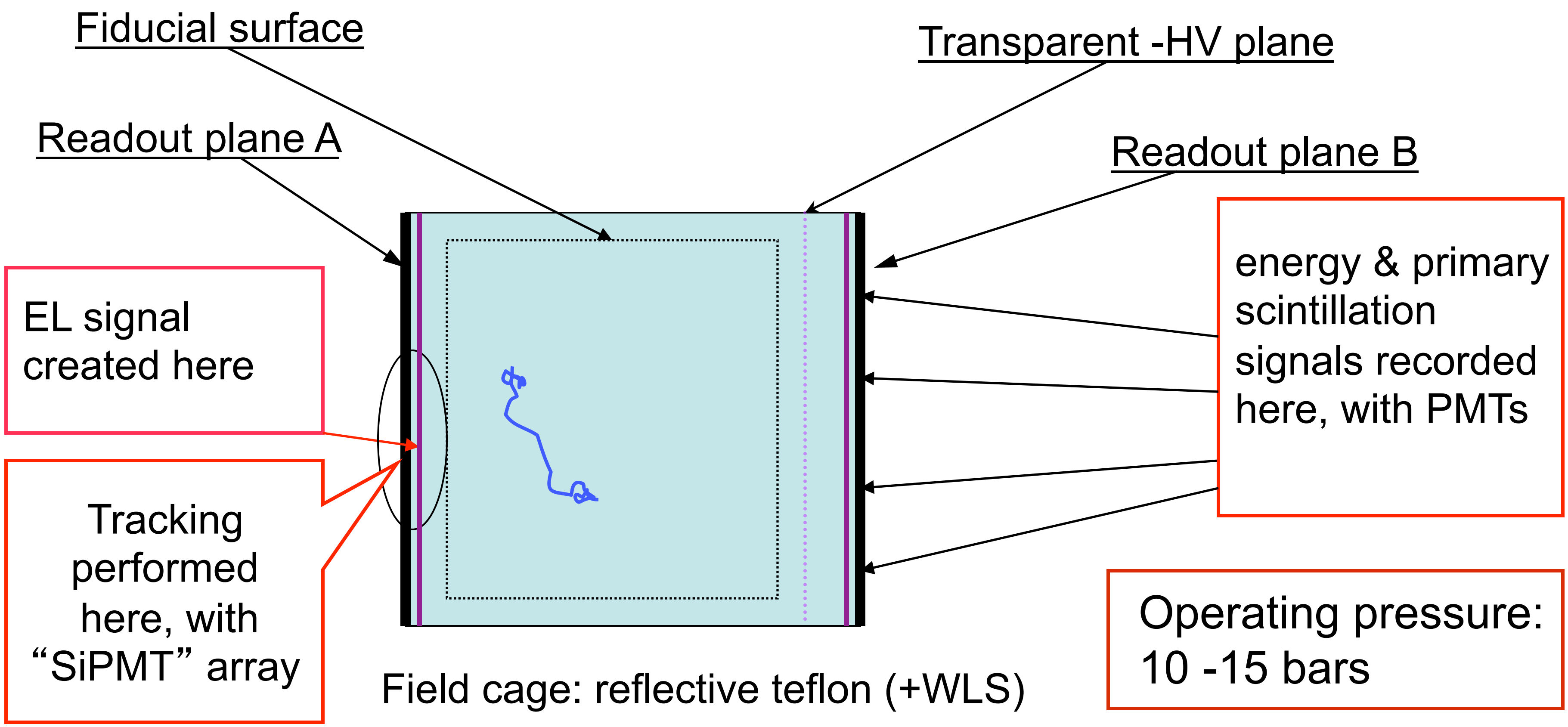
has 100 kg of enriched xenon (85% ^{136}Xe)

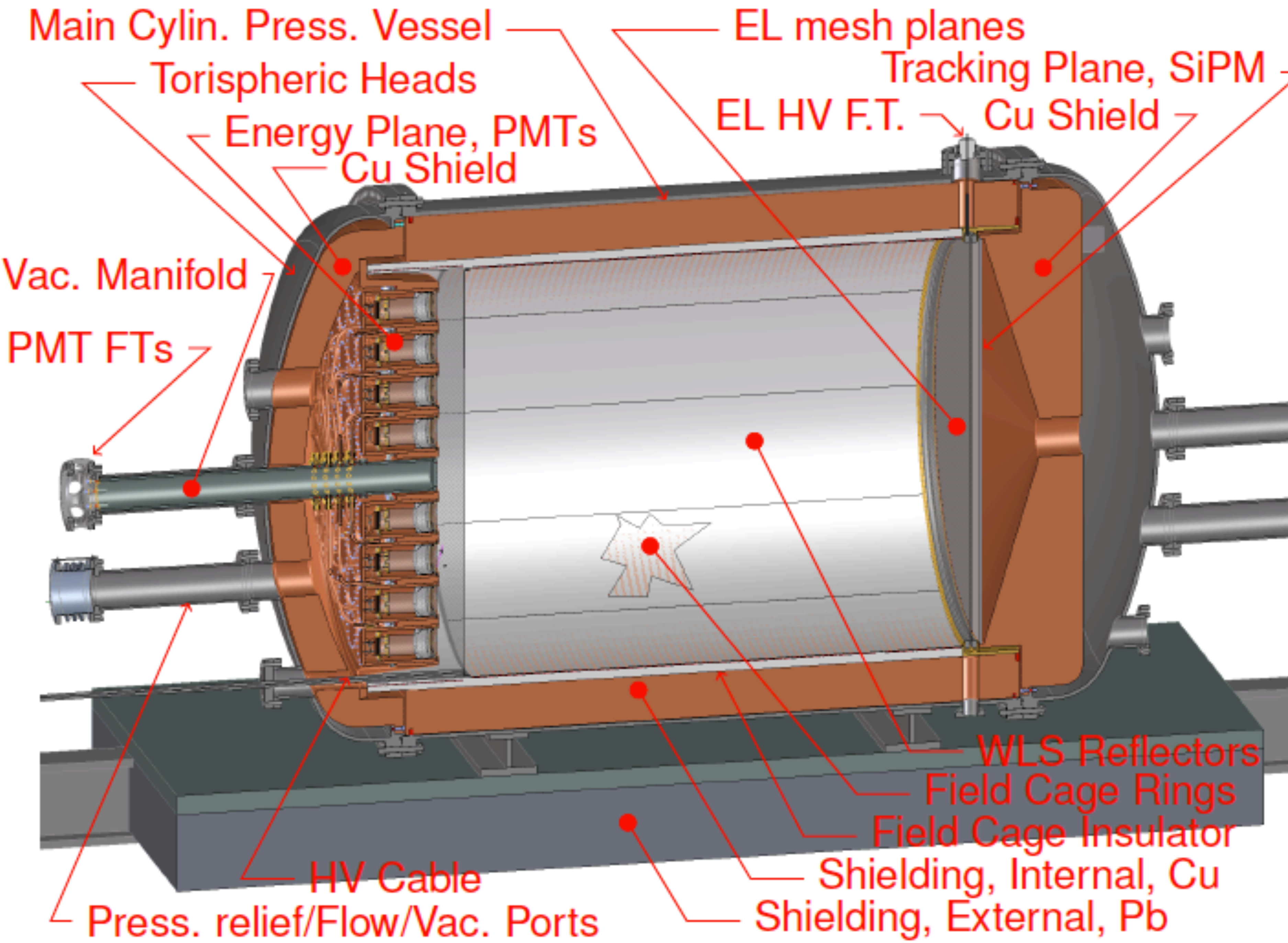
is located in Canfranc Underground Laboratory

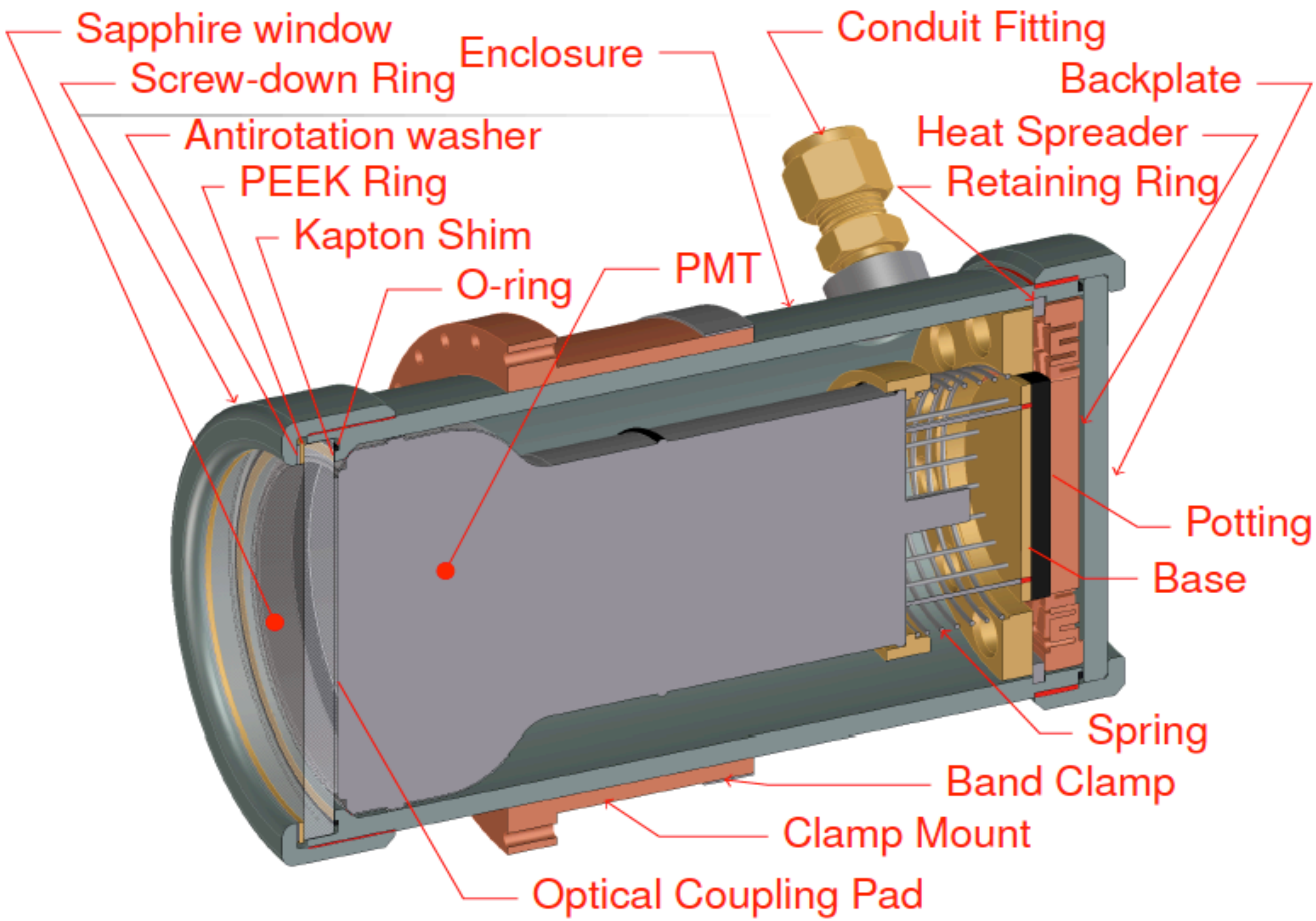
funding by Spanish Funding Agencies: **€ 6M+**

NEXT Asymmetric TPC

"Separated function"




Main Cylin. Press. Vessel
EL mesh planes
Tracking Plane, SiPM
Torispheric Heads
EL HV F.T.
Cu Shield
Energy Plane, PMTs
Cu Shield
Vac. Manifold
PMT FTs
WLS Reflectors
Field Cage Rings
Field Cage Insulator
HV Cable
Shielding, Internal, Cu
Press. relief/Flow/Vac. Ports
Shielding, External, Pb


Sapphire window
Screw-down Ring
Enclosure
Antirotation washer
PEEK Ring
Kapton Shim
O-ring
PMT
Conduit Fitting
Backplate
Heat Spreader
Retaining Ring
Potting
Base
Spring
Band Clamp
Clamp Mount
Optical Coupling Pad

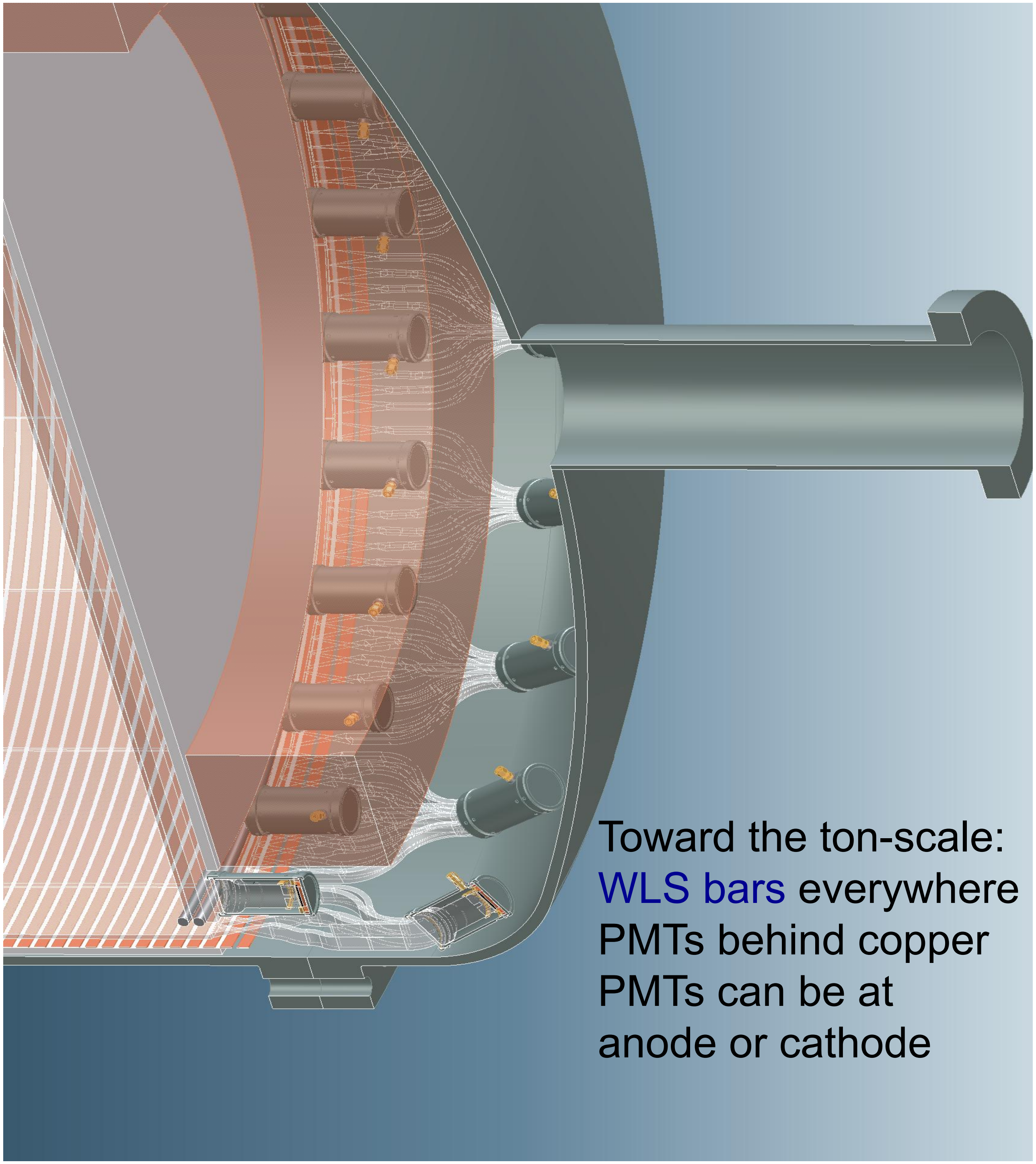
Direct Dark Matter Search?

- NEXT-100 not optimized for Dark Matter search, but will serve as a spring board to understand potential
  - S1 detection efficiency determines recoil energy threshold
- Normal fluctuations in S2/S1 in HPXe should offer a huge benefit in electron/nuclear recoil discrimination.
  - F factor ratio of 11 in enters exponentially in overlap of gaussian

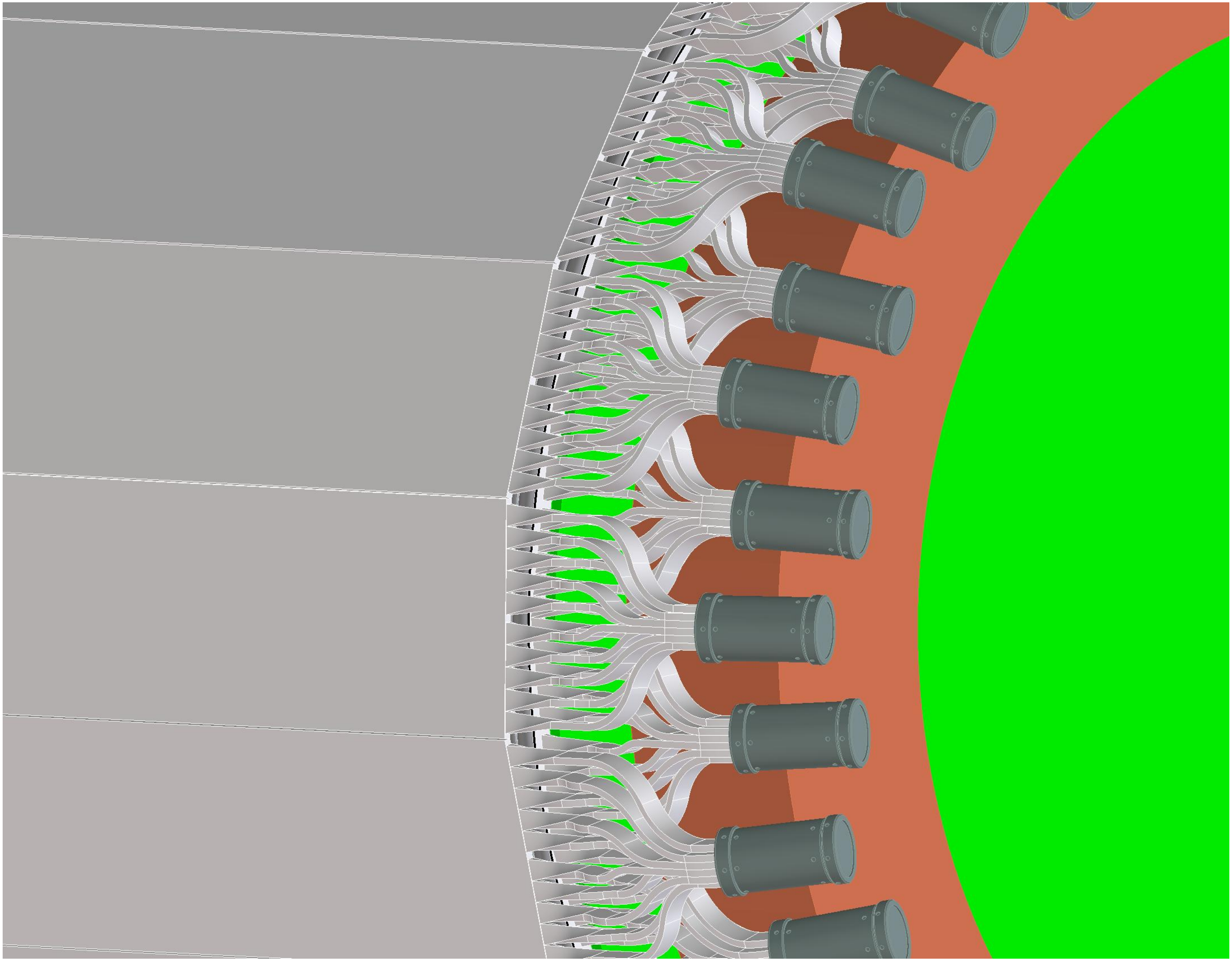
Ton-scale concept: DM + 0ν-ββ

- The number of PMTs should remain small, or smaller.
- The optical detection efficiency should be maximized to increase sensitivity to low-energy nuclear recoils.

- Approach: use wavelength shifting (WLS) plastic
  - cover the TPC interior completely
  - pipe light to remote PMTs, shielded by copper



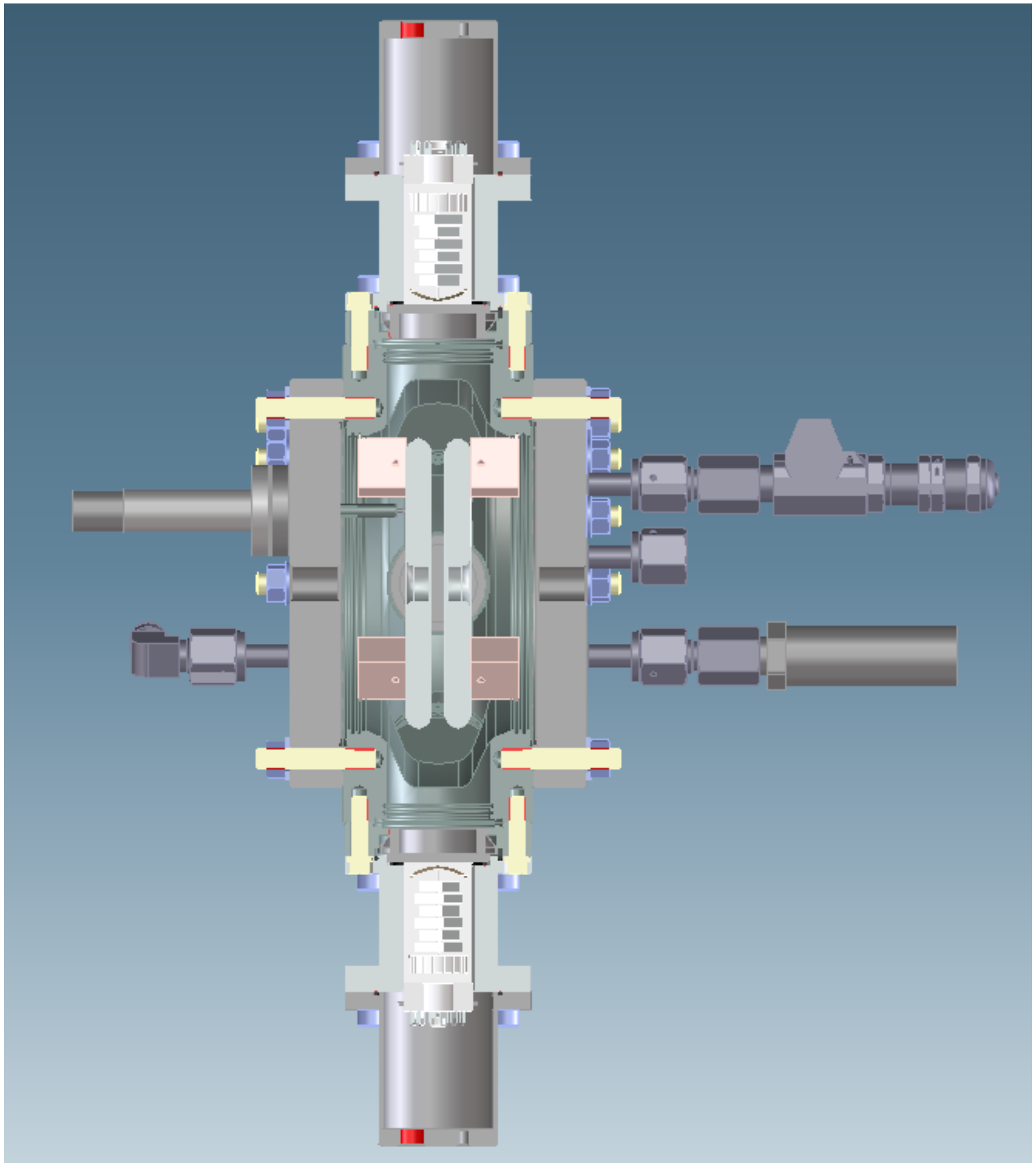
Toward the ton-scale:
WLS bars everywhere
PMTs behind copper
PMTs can be at
anode or cathode



Ton-scale concept...

- Problem: xenon light is in VUV - 173 nm
  - WLS plastic response maximum is at 300 nm
  - WLS plastic response at 173 nm is ~zero !!
  - What to do?

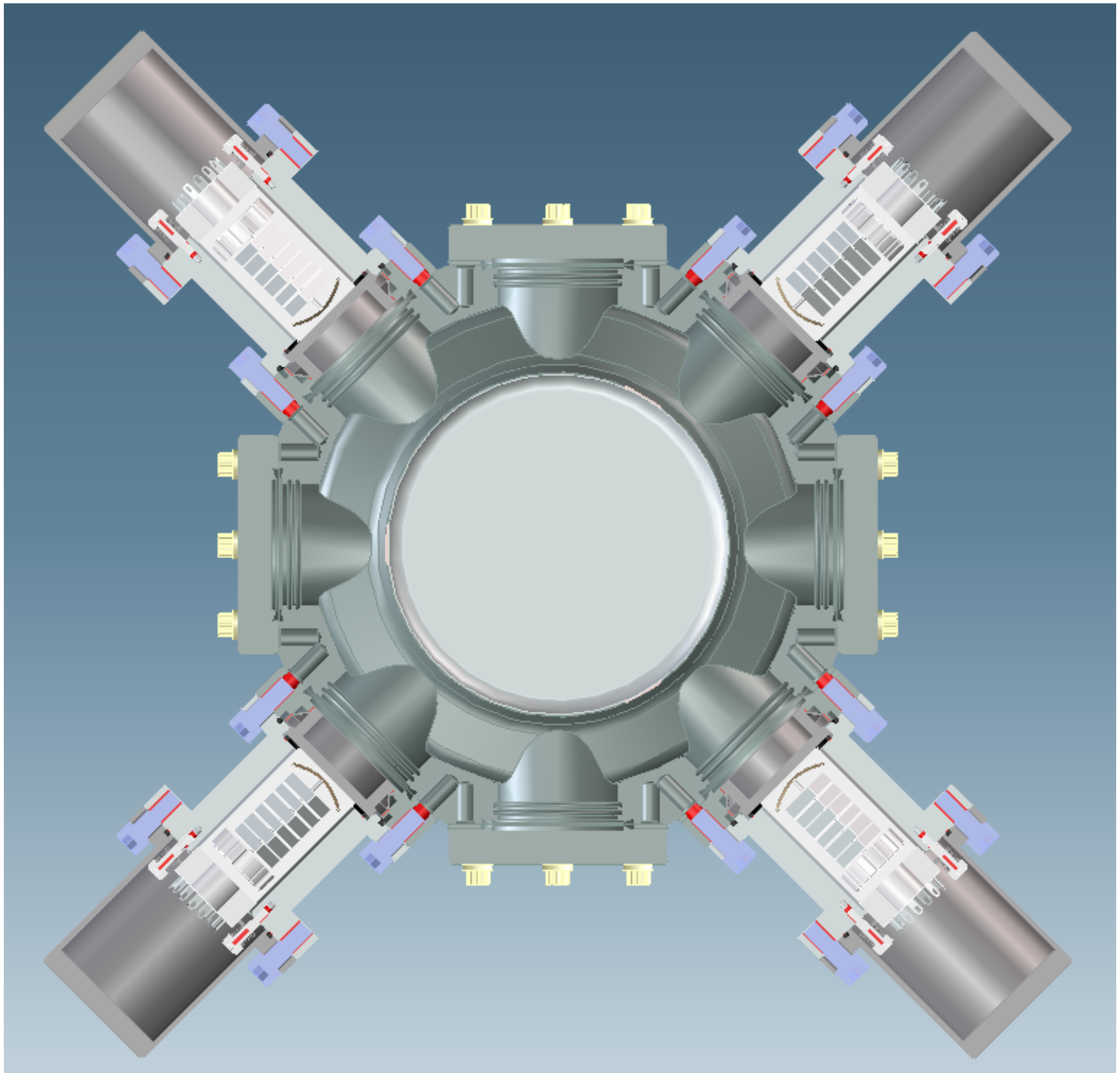
- Use gaseous molecular wavelength shifters
  - Trimethylamine (TMA) and/or Triethylamine (TEA)
  - TMA and TEA fluoresce efficiently in bands 285 – 310 nm
  - TMA and TEA may also display Penning effect in xenon
  - Complex behavior expected with density and fraction!



Back to Basics

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

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



We can have eight PMTs if useful to do so.

We may modify the cathode and convert to TPC mode to study energy resolution and EL range

Perspective

- Gas phase offers superb energy resolution, event visualization and flexibility in operation
- Electroluminescent gain stage is the key element for near-intrinsic energy resolution for 0ν-$\beta\beta$ search
- Energy resolution may provide superb discrimination between electron and nuclear recoils through S2/S1
- Can switch easily from enriched to depleted xenon, with real benefits to both searches

Conclusion...

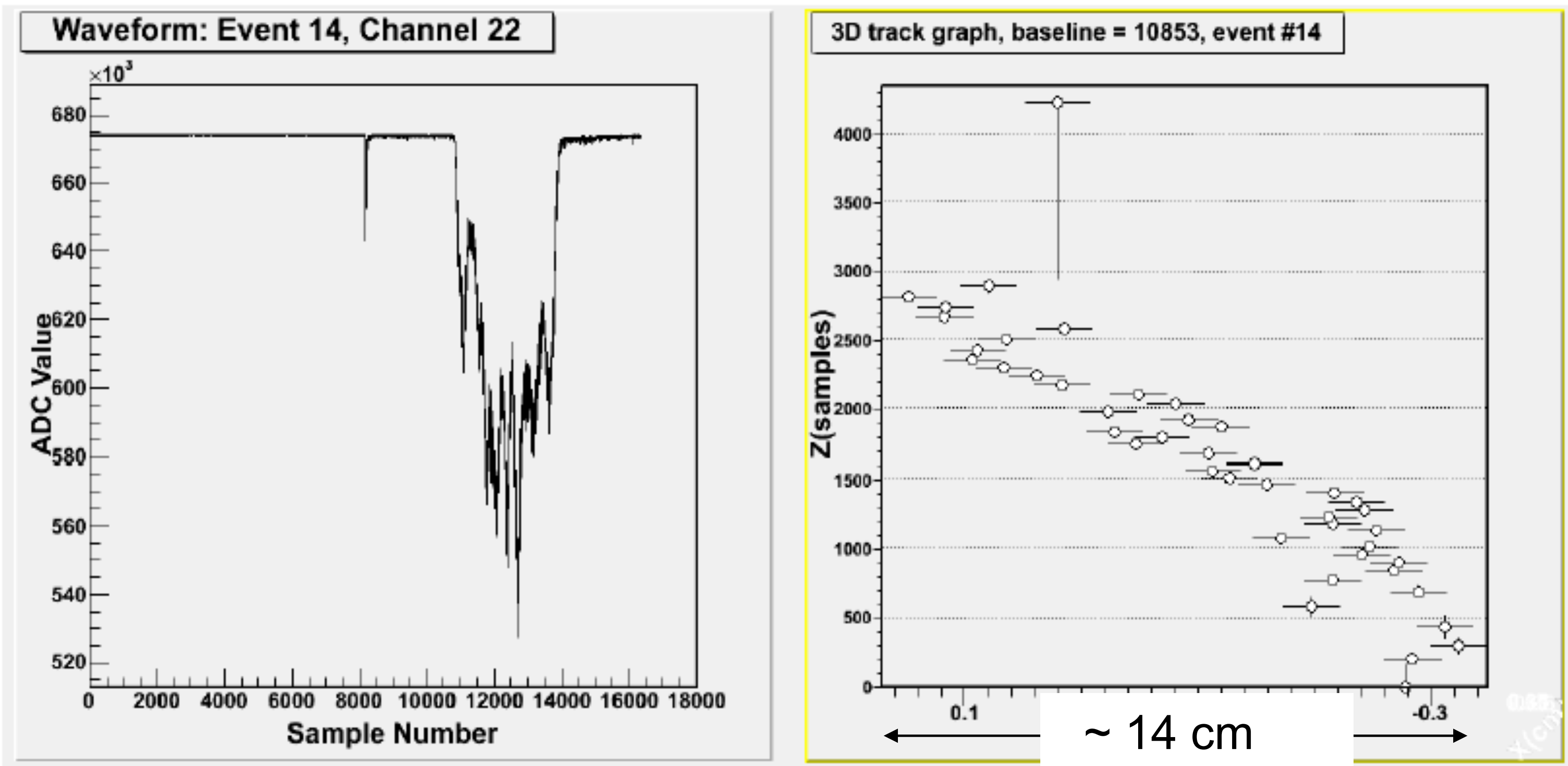
- Is this a true story or a fairy-tale?
  - We should know which in less than a year

Conclusion...

- Is this a true story or a fairy-tale?
  - We should know which in less than a year...
- Gas detectors continue to offer surprises!
  - "You can see a lot by looking" – Yogi Berra

Thank you

A Diagonal Muon Track - "reconstructed"; Signal depends on radius in chamber



Virtues of Electro-Luminescence in HPXe

- Linearity of gain versus pressure, HV
- Immunity to microphonics
- Tolerant of losses due to impurities
- Absence of positive ion space charge
- Absence of ageing, quenching of signal
- Isotropic signal dispersion in space
- Trigger, energy, and tracking functions are accomplished with optical detectors

WIMP search, with xenon

Xenon10 data

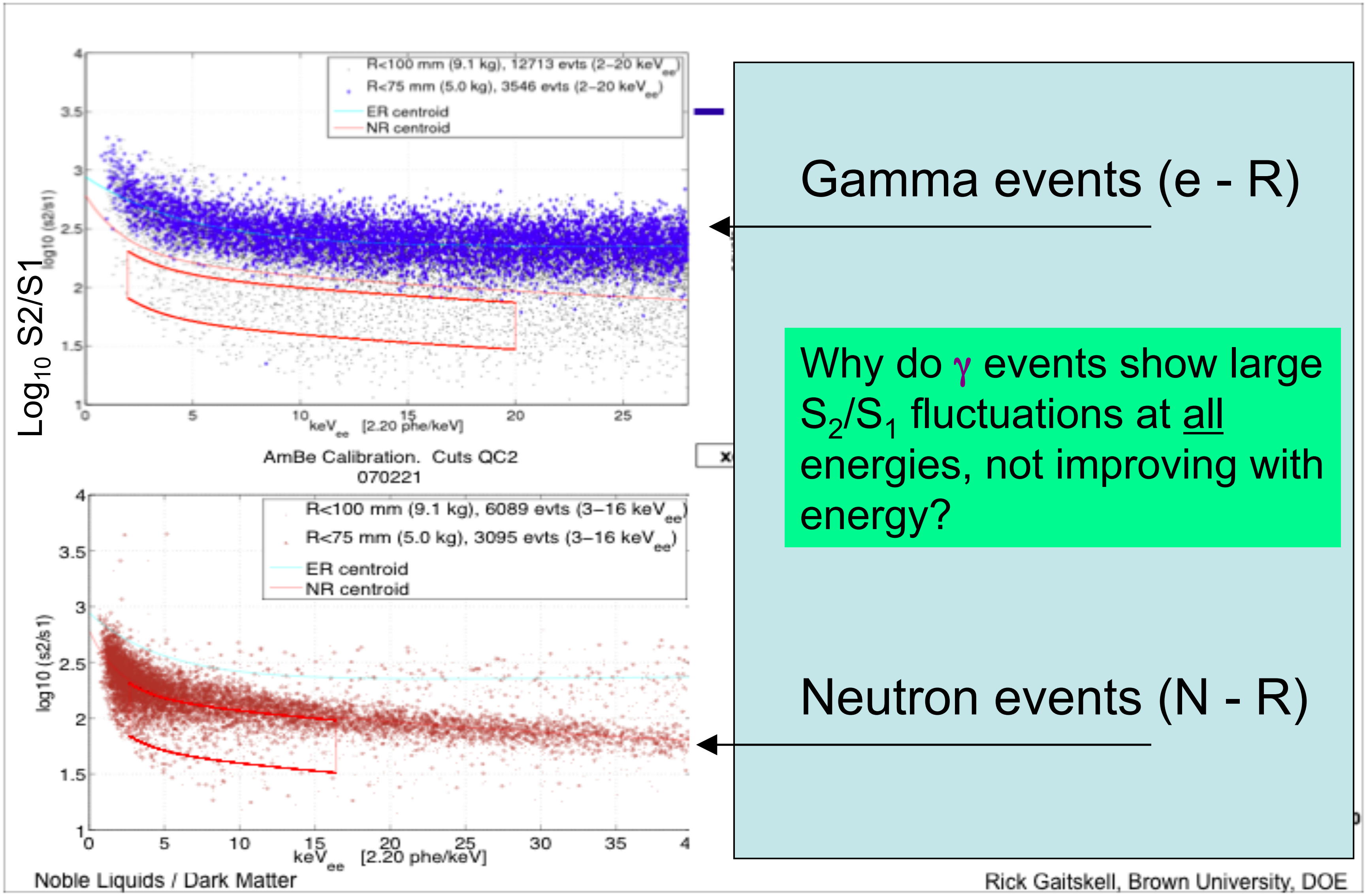


Photo-Luminescence of PMMA

Different WLS nature observed for two PMMA Samples