The NEXT-100 Double Beta Decay Experiment - Progress and Perspectives for the Ton-scale

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Dual-purpose Concept

1. 0½ **ββ search**:

NEXT-100 experiment at Canfranc is based on a high-pressure Xe gas TPC for better performance

- Spring-board for dual-purpose ton-scale system

2. **WIMP search**:

Novel approach for *directional* sensitivity in WIMP nuclear recoils exploits columnar recombination

- If successful, active mass → ton-scale is possible

Simultaneous searches?

- **Next generation projects will be expensive!**
  - A dual-purpose detector should be considered… *if it truly saves money and truly is dual-purpose*

- Xenon is an attractive choice for both searches
  - No long-lived isotopes
  - Relatively cheap, and easy to enrich
  - Can exchange: enriched ←→ depleted
  - Scales well as monolithic source = detector

Xenon in Gas Phase?

- Gas phase offers attractive possibilities:
  - Normal energy partition fluctuations: F = 0.15
    - Excellent correlation of ionization with deposited energy
      - » **Remarkably good energy resolution (0ν-ββ)**
    - Much better discrimination between electron/nuclear recoils
      - » **Small S2/S1 fluctuations (WIMPs)**
  - Visualization of event topology (0ν-ββ & WIMPs)
    - Must try to evade background dominant $(Mt)^{1/4}$ regime
  - Nuclear recoil <u>directional</u> sensing possibility
    - *Optimal density? Maybe 10 bars! → x1000 advance?*

Why Xenon Gas?
Energy resolution in Xenon depends very strongly on density

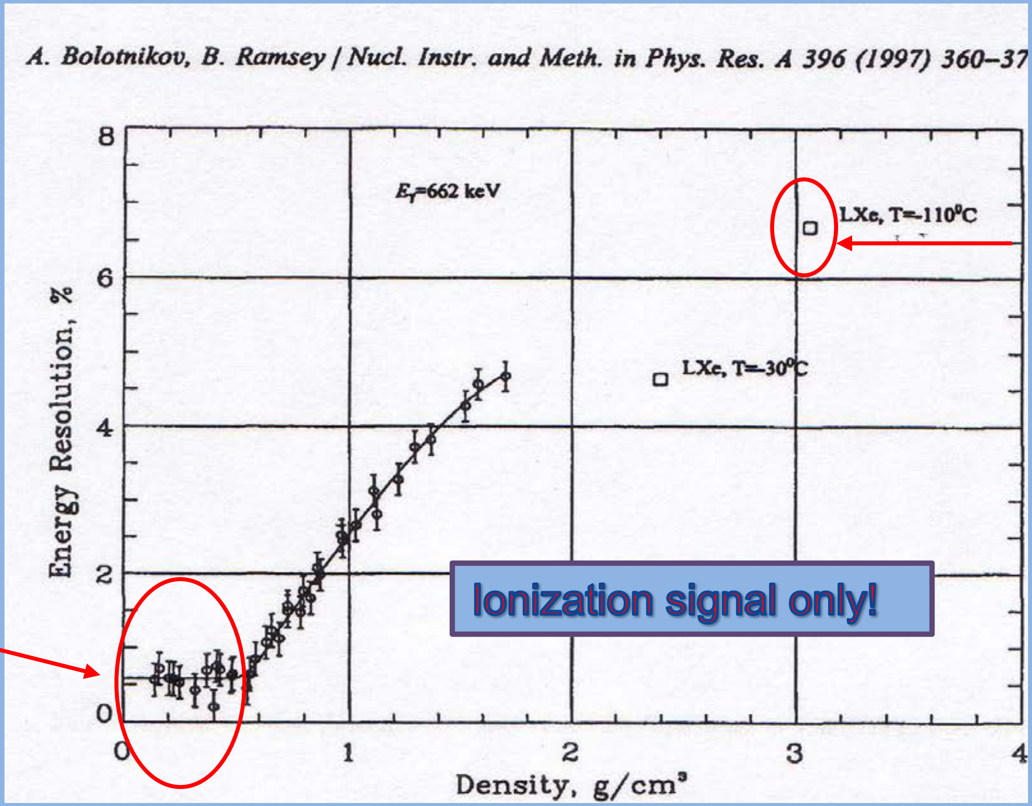
Here, the fluctuations are normal

Fano factor

F = 0.15

Unfolded resolution:

δE/E ~0.6% FWHM



Very large fluctuations between light/charge!

F ~ 20 !!

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

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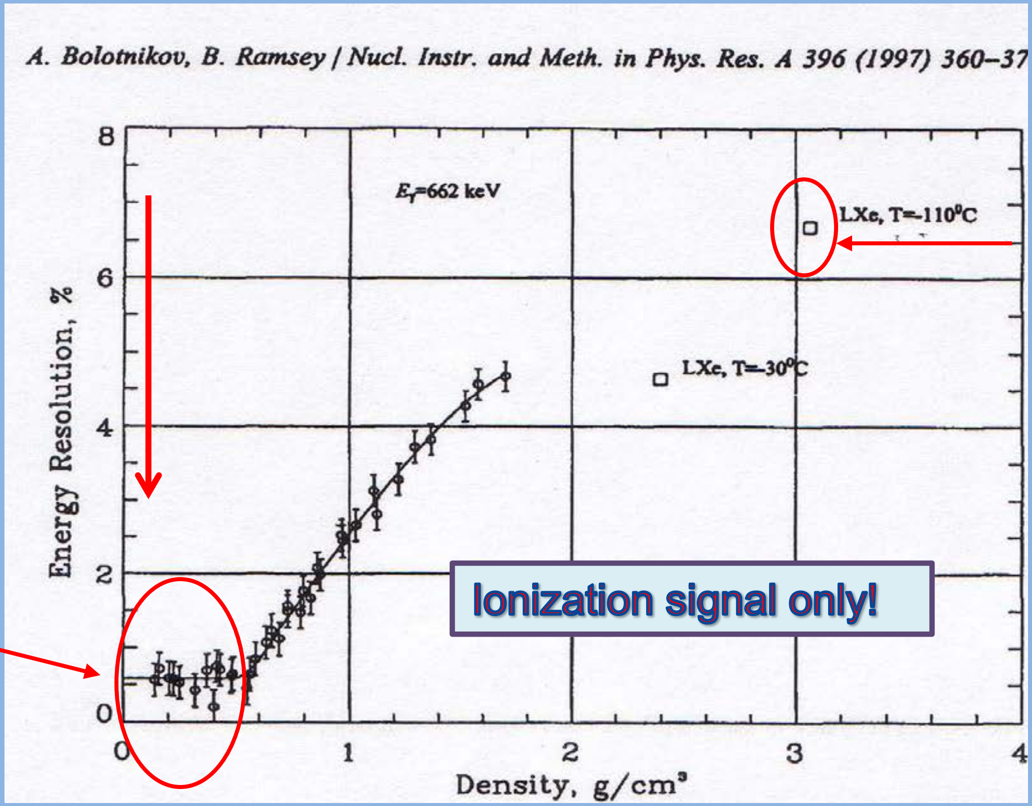

Very large fluctuations between light/charge!

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WIMPs:

Large S2/S1 fluctuations

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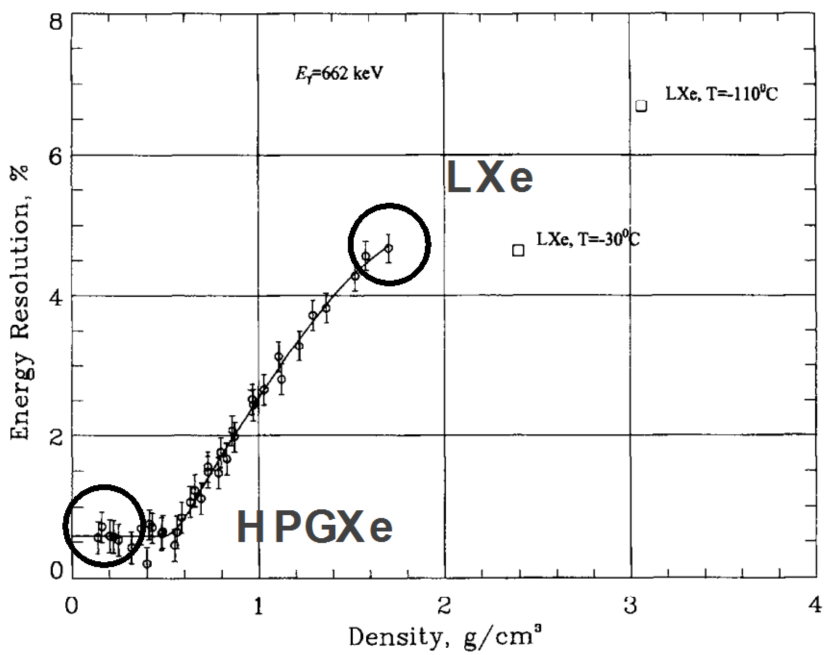
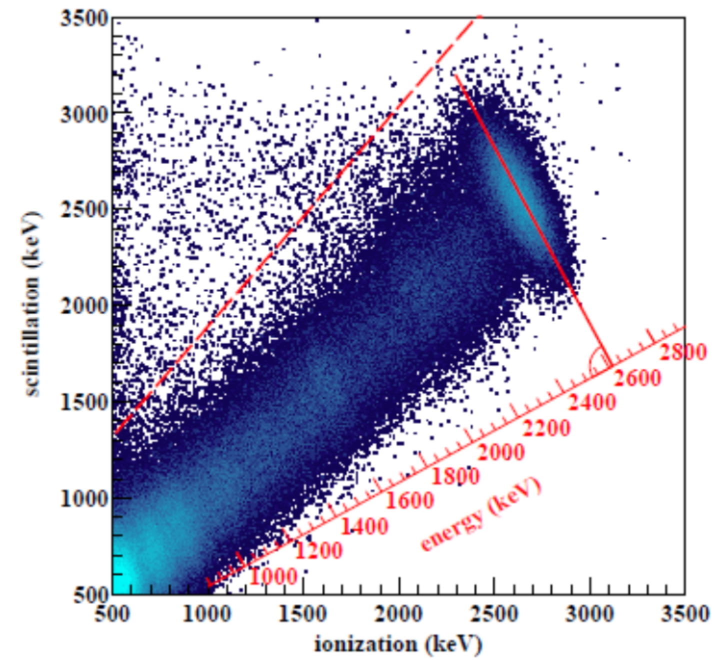
LXe: Energy resolution

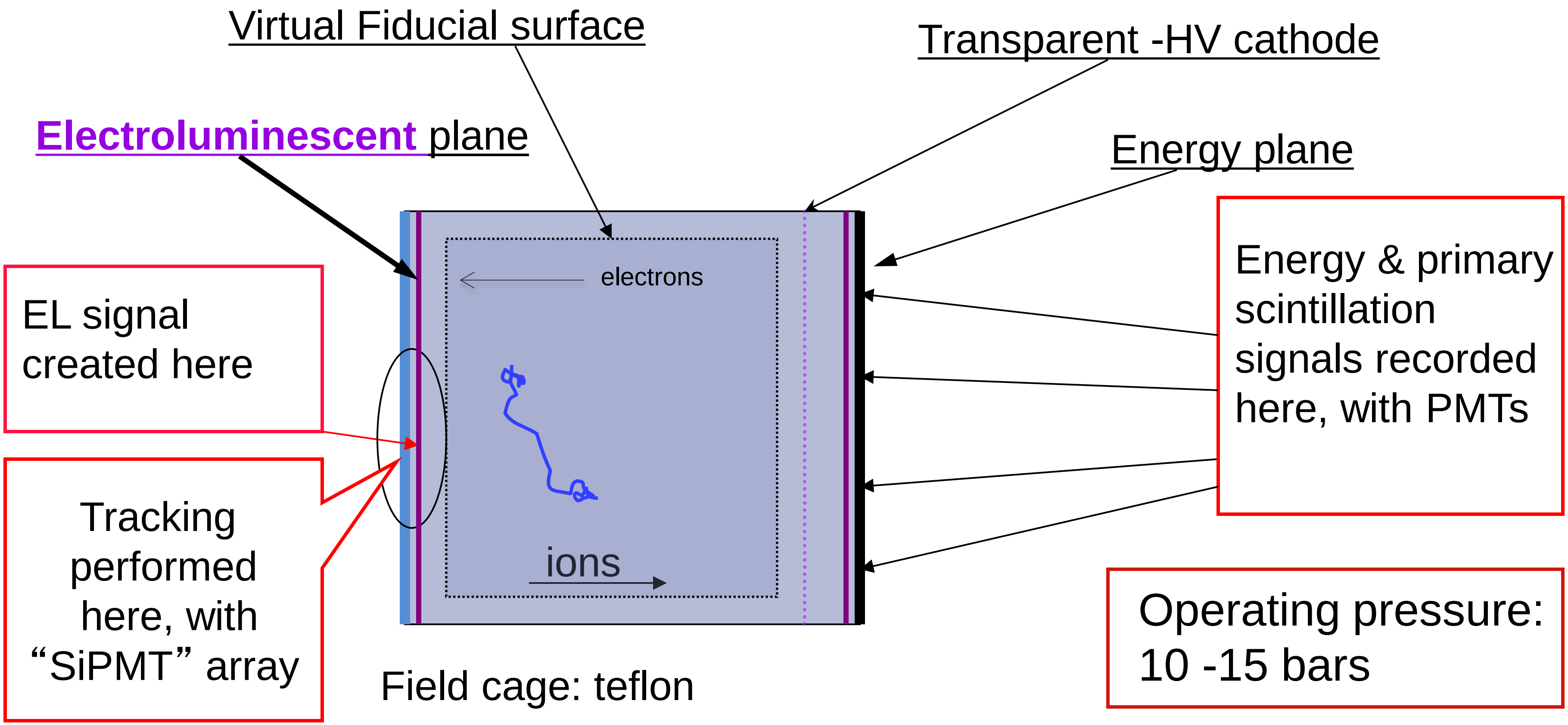


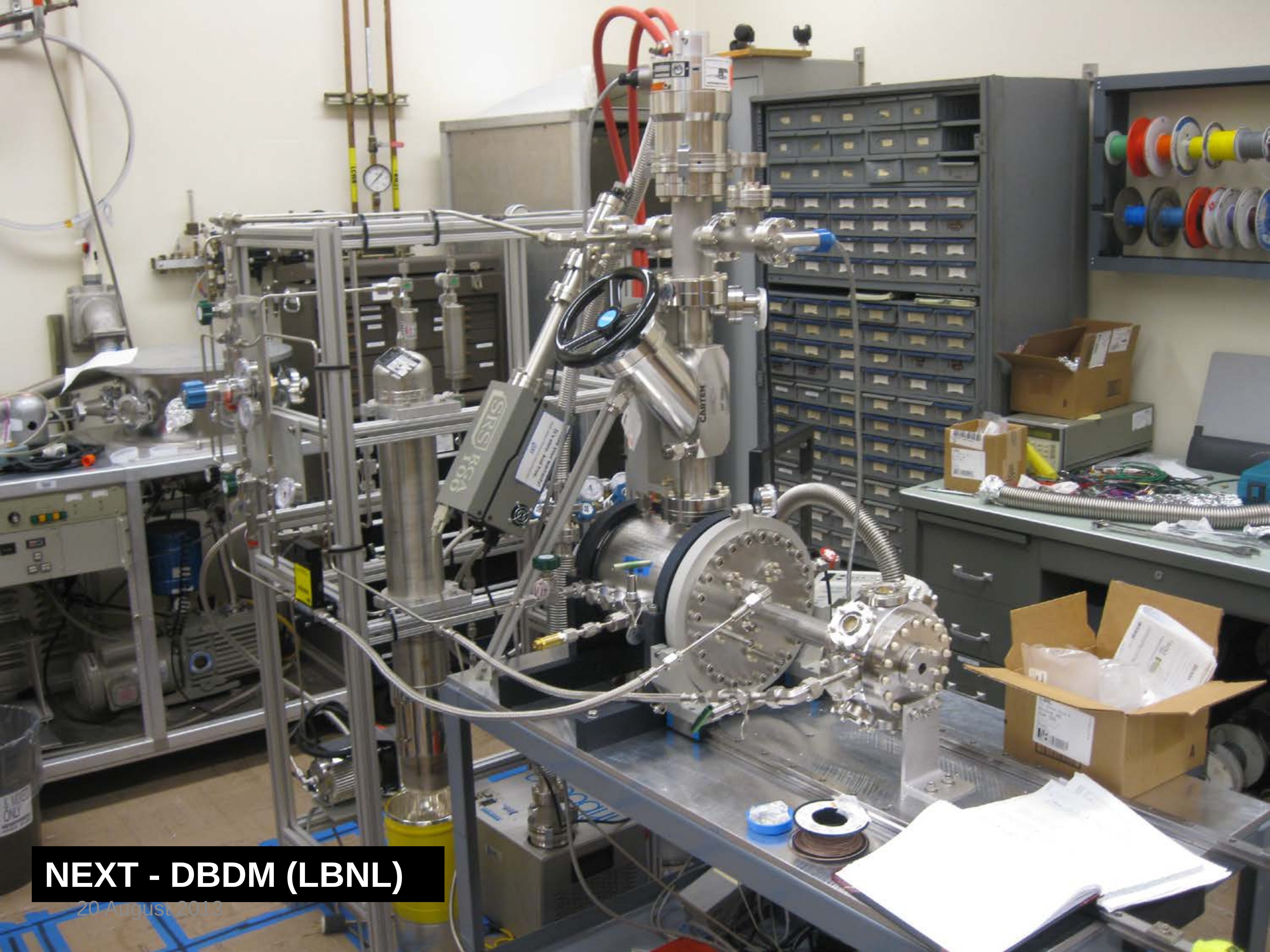


Energy resolution: Anomalous in LXe. Much worse than in HPXe.

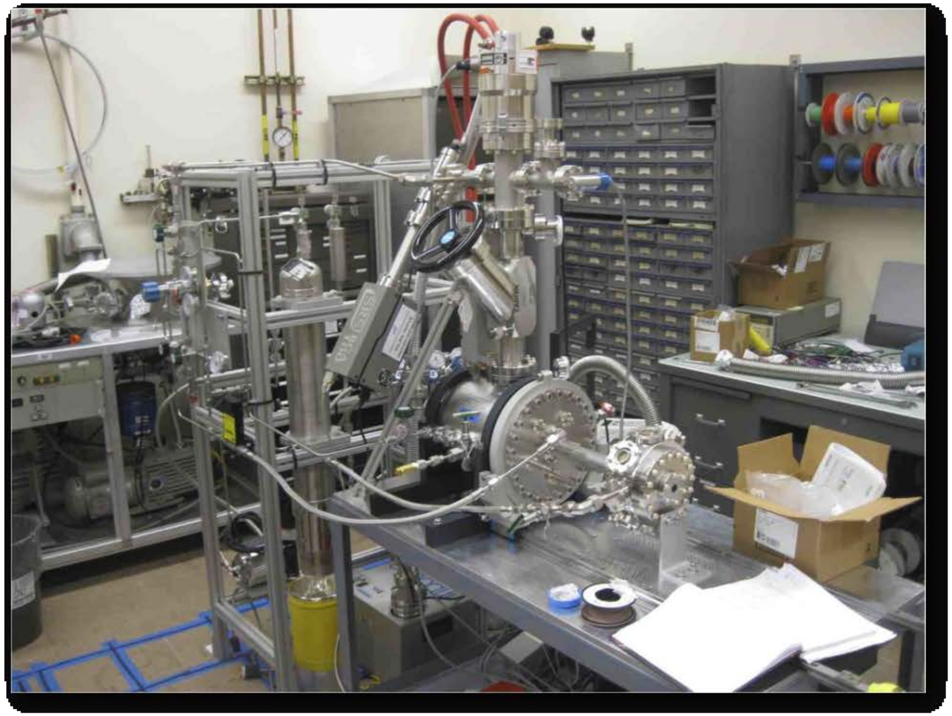
Energy resolution: 4% FWHM at Q, using anti-correlation between scintillation and ionization

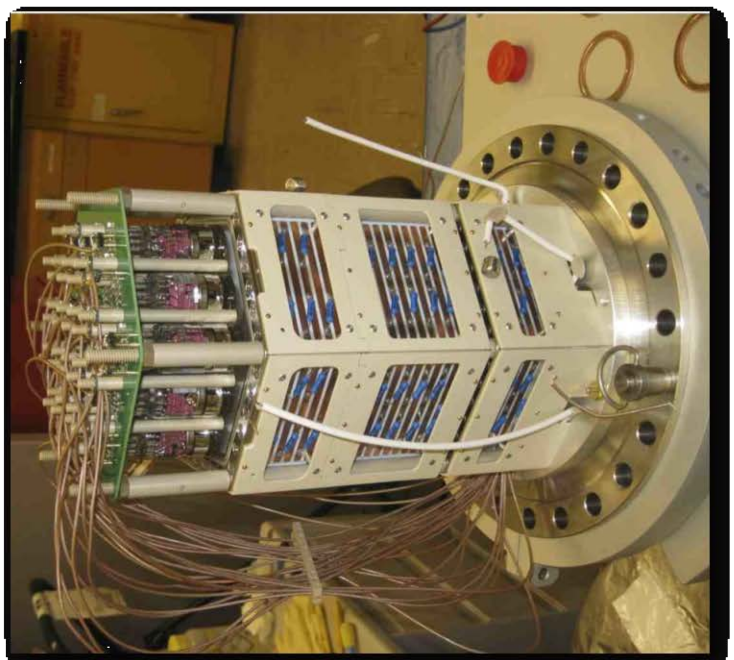
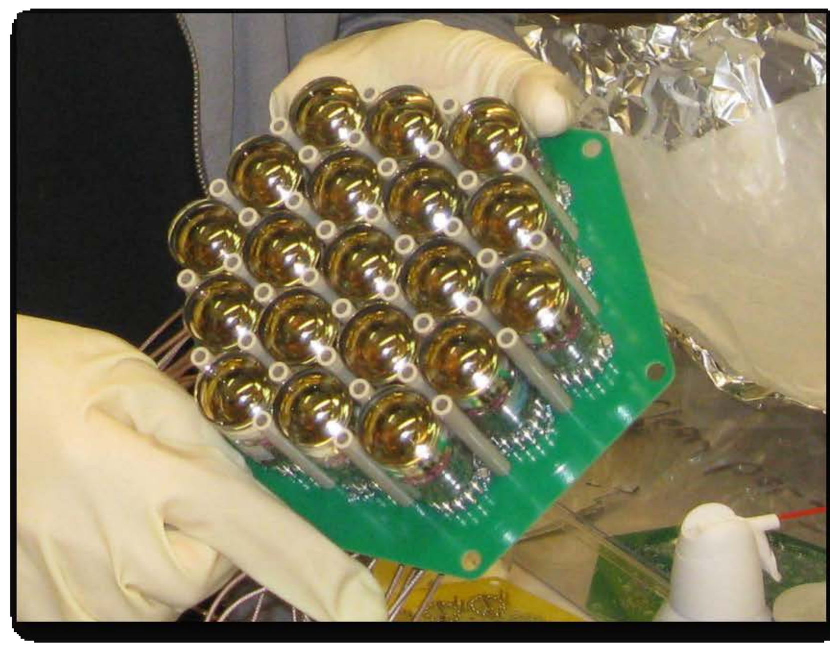
Asymmetric TPC *with "Separated functions"*



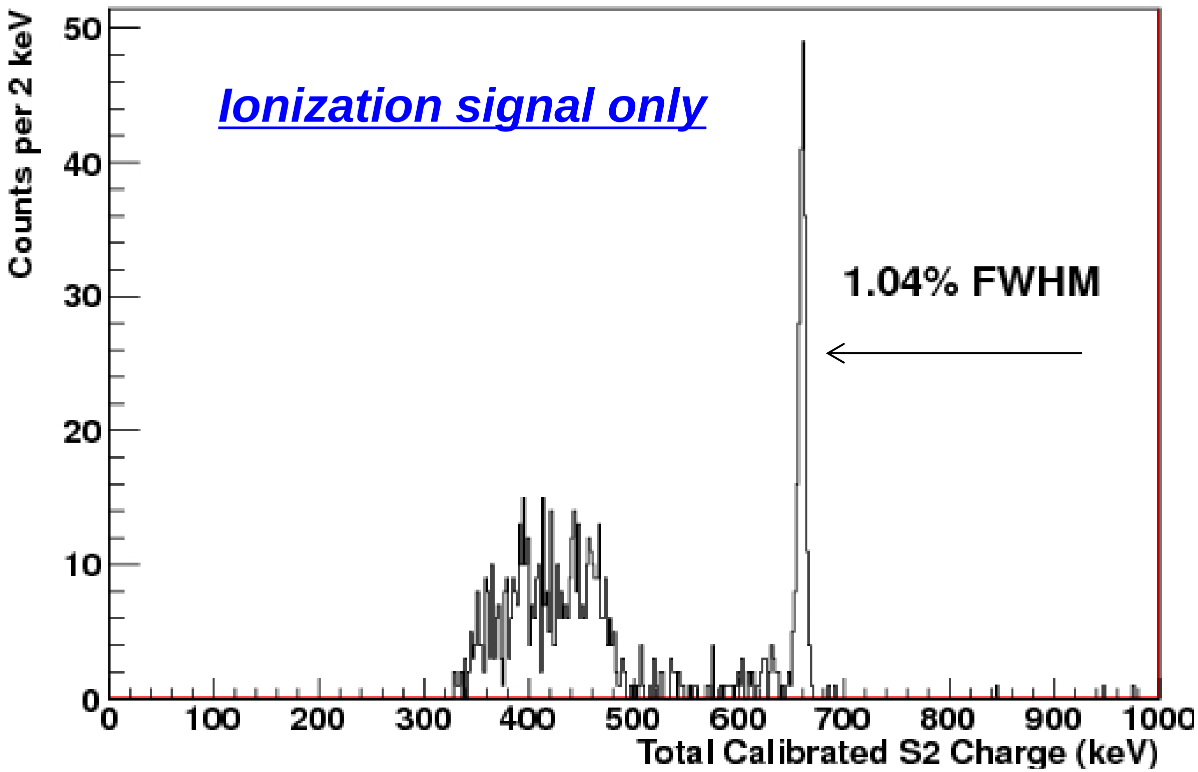


NEXT - DBDM (LBNL)



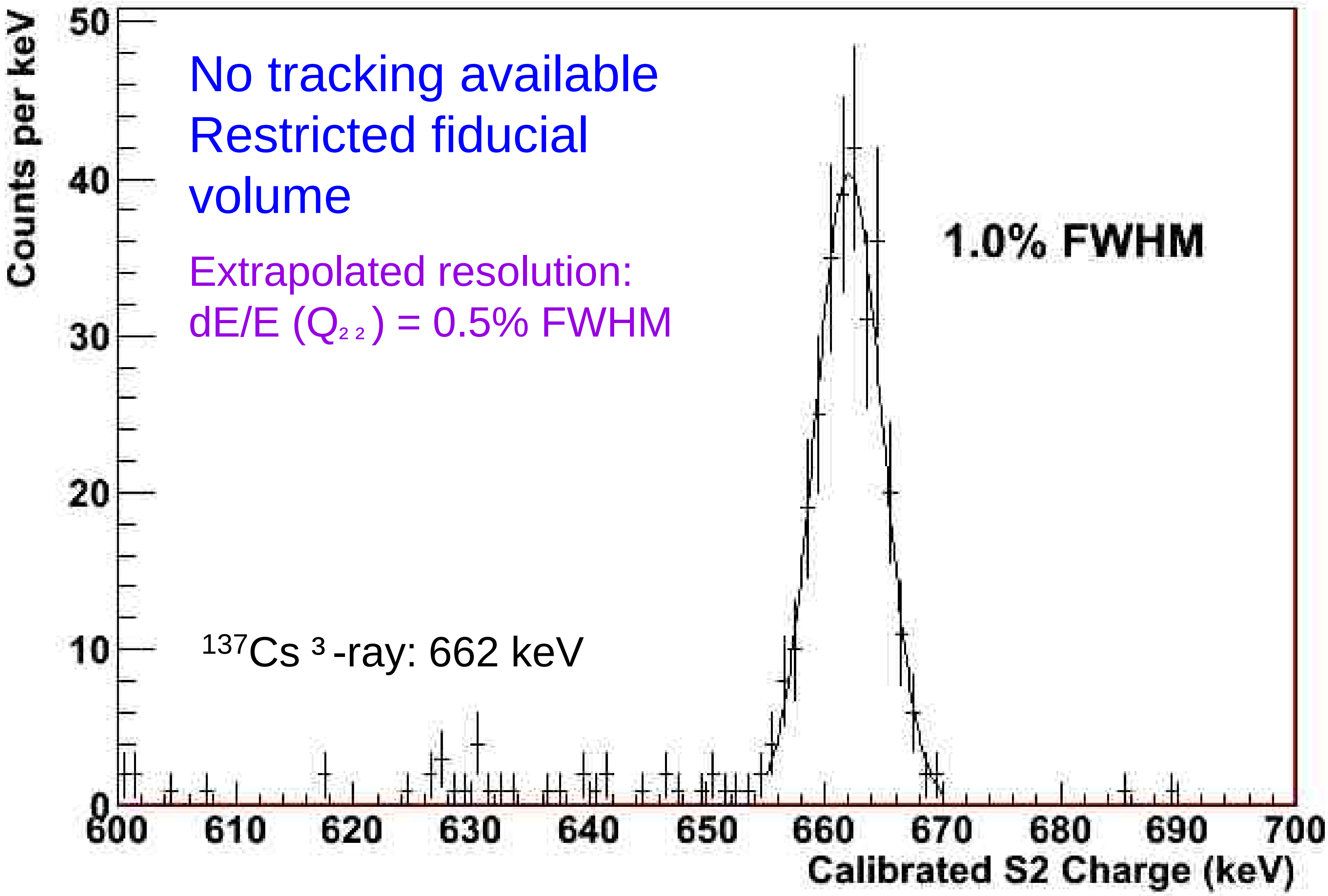
World record: Energy resolution ´ E/E = 1% FWHM for ^{137}Cs 662 keV γ-rays in xenon!

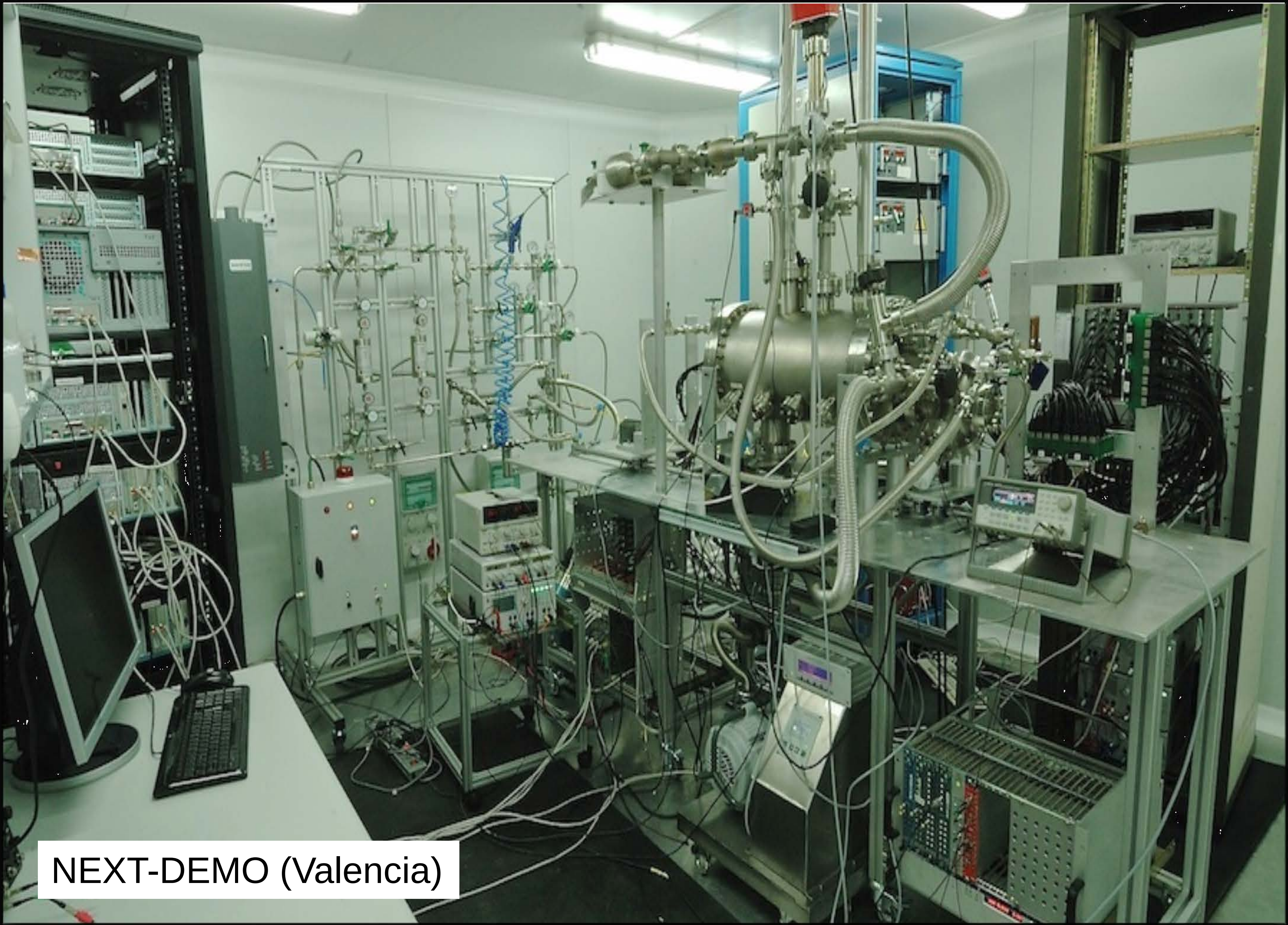


Data from LBNL-TAMU HPXe TPC

This result is important for both 0-½ ² & WIMP searches

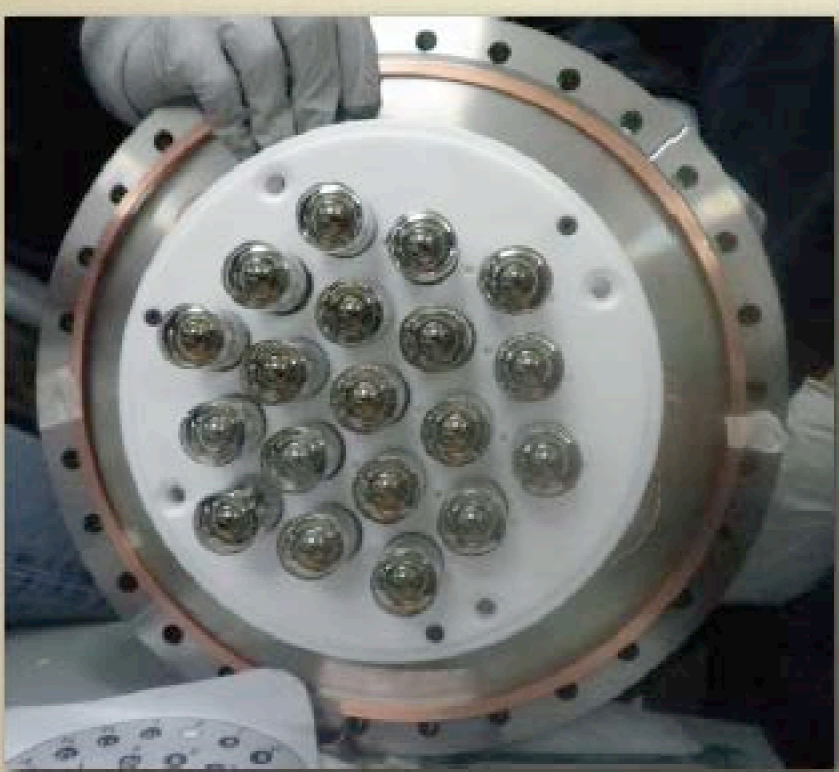
This result shows that fluctuations are “normal” in HPXe


No tracking available
Restricted fiducial volume
Extrapolated resolution:
dE/E (Q_{22}) = 0.5% FWHM
1.0% FWHM
^{137}Cs 3 -ray: 662 keV
Counts per keV
0
10
20
30
40
50
600
610
620
630
640
650
660
670
680
690
700
Calibrated S2 Charge (keV)

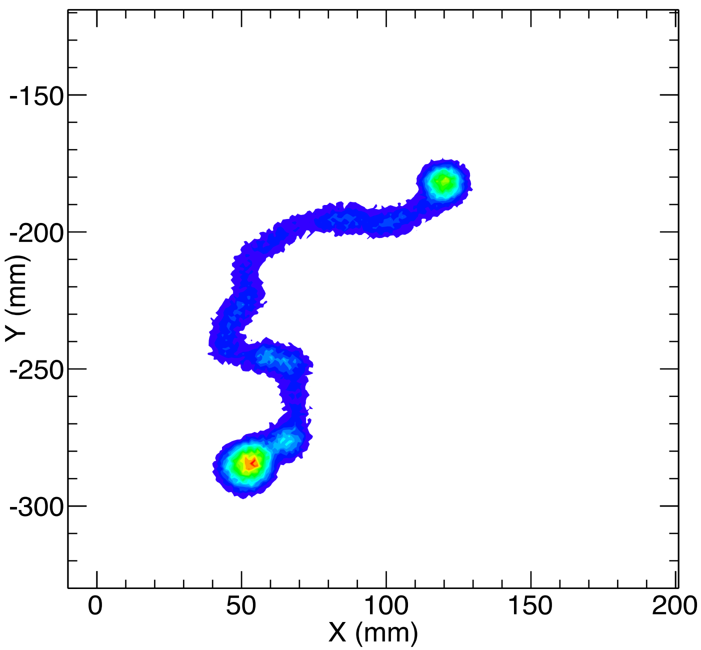


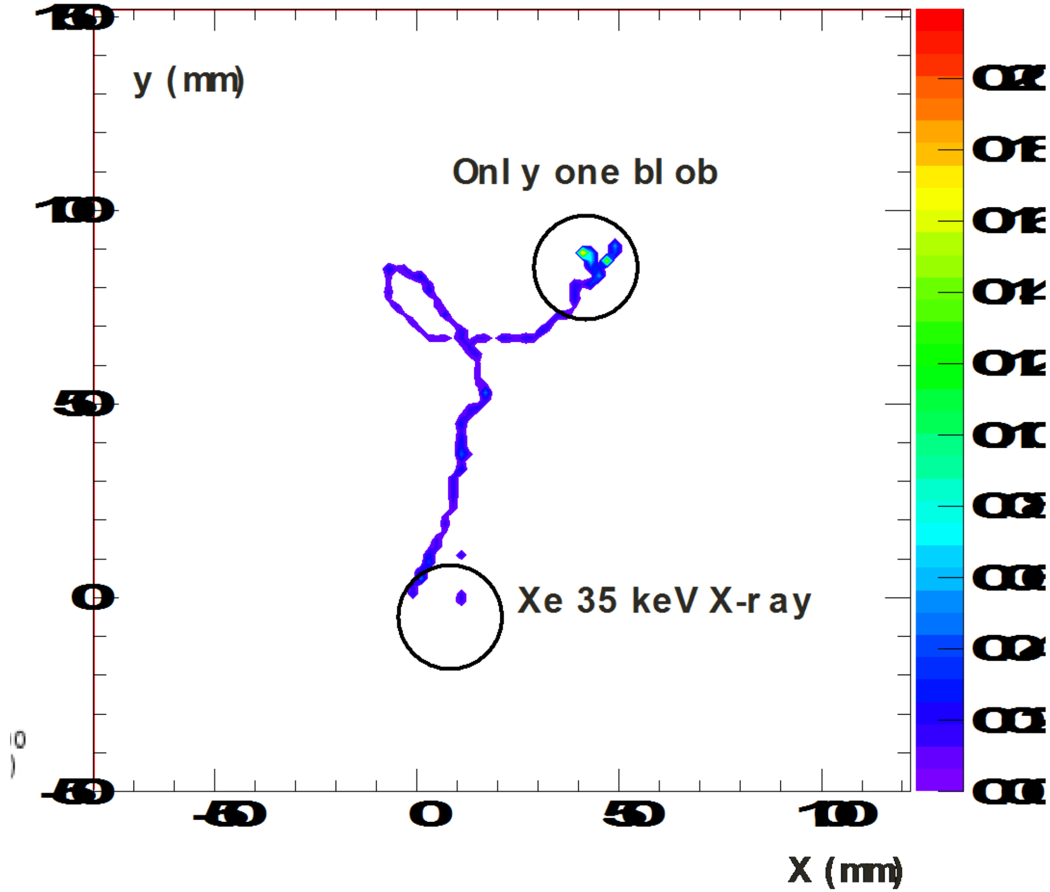
NEXT-DEMO (Valencia)

Tracking: PMTs → SiPMs



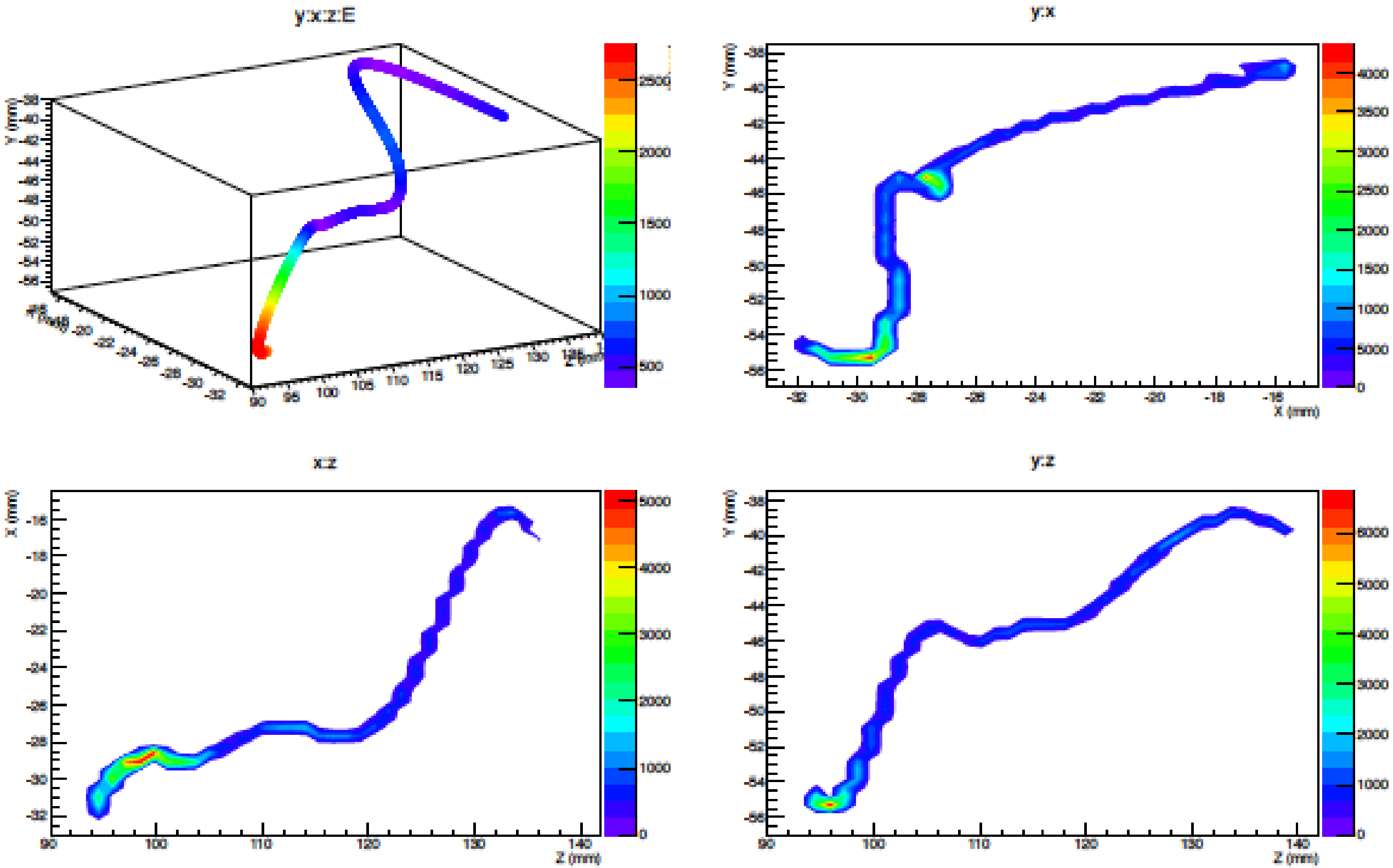
NEXT-DEMO (IFIC, Valencia)





Simulations!

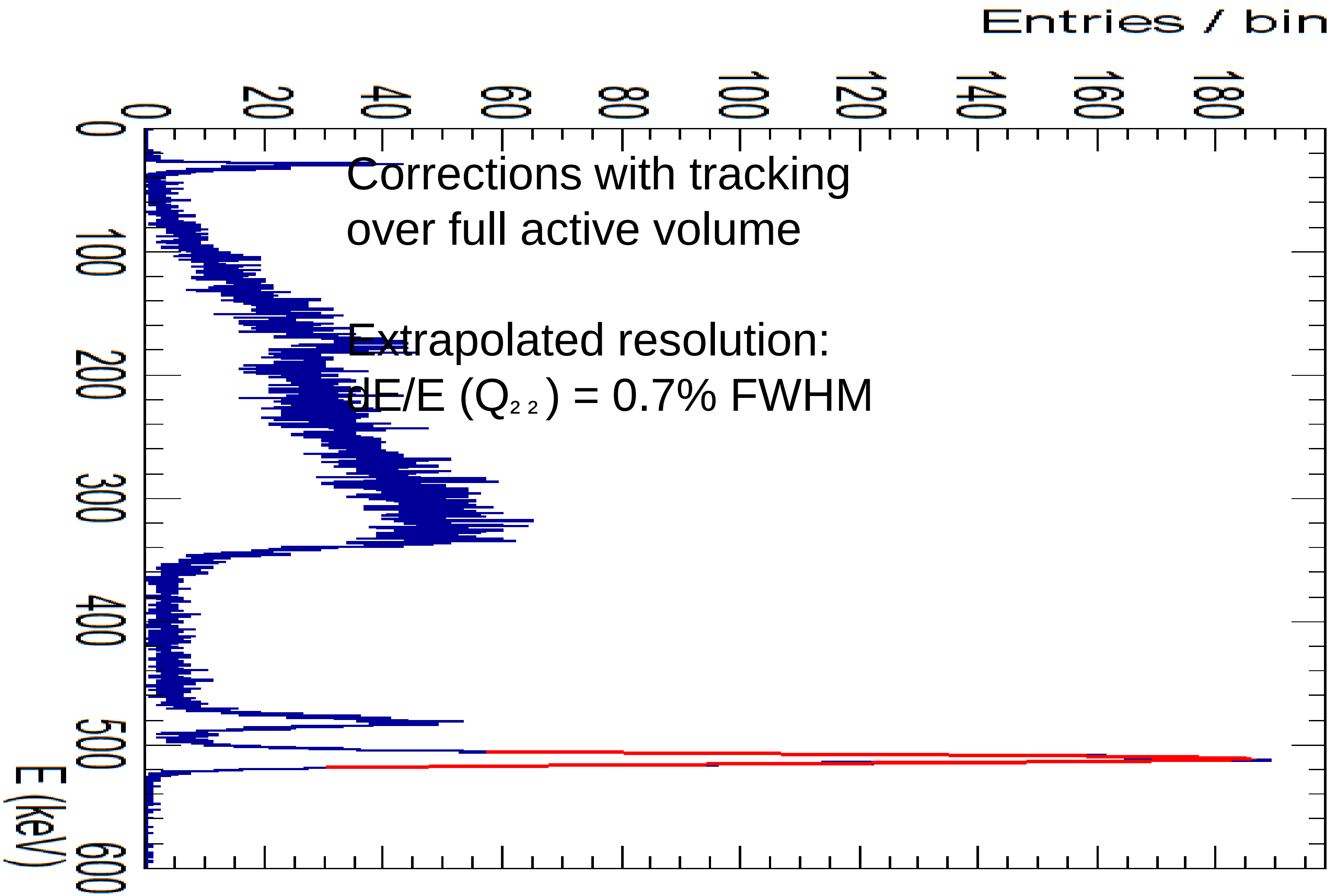
Real track from ^{137}Cs ^{3}-ray – reconstructed with SiPMs

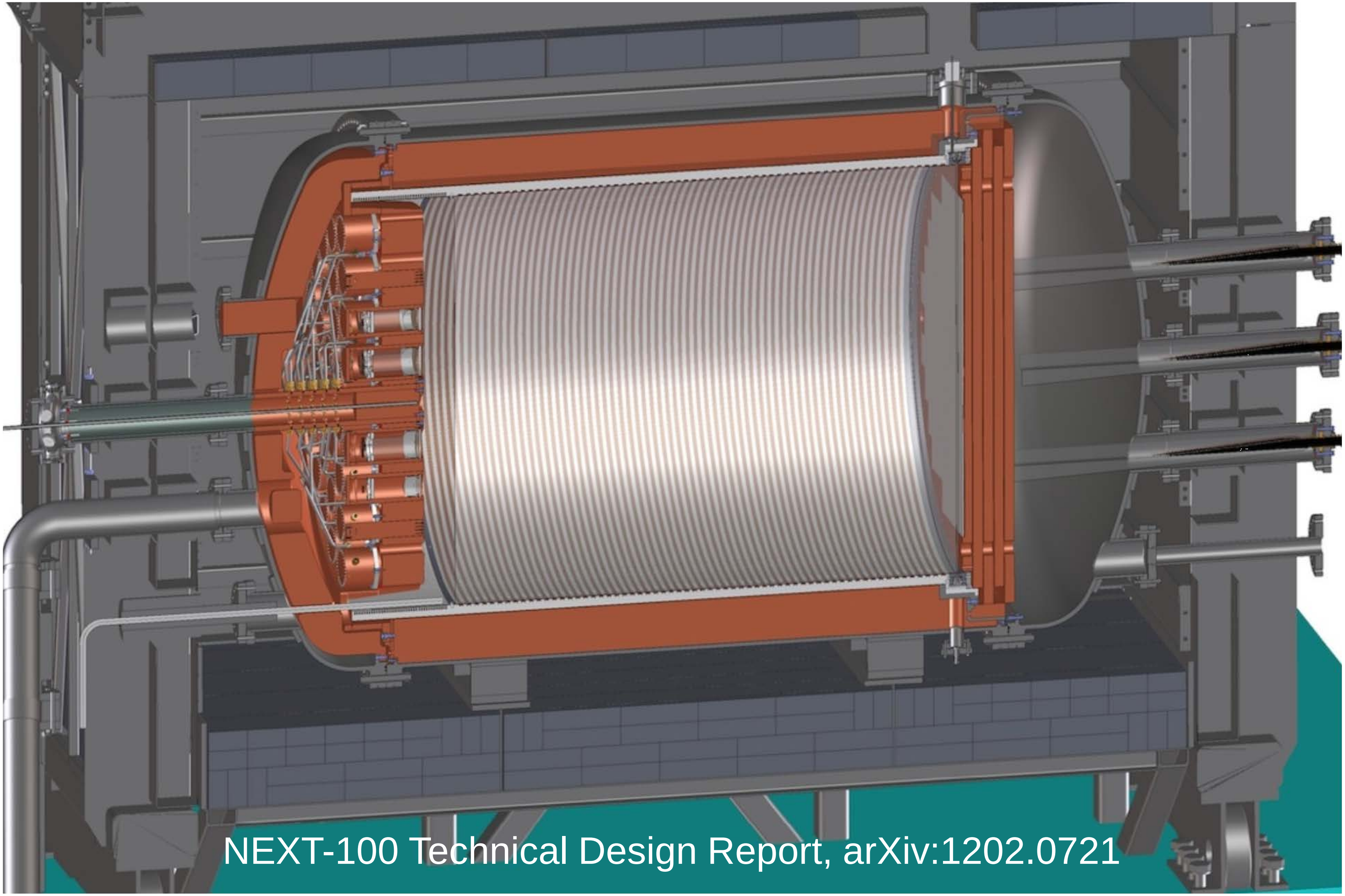


DATA!

NEXT-DEMO IFIC, Valencia

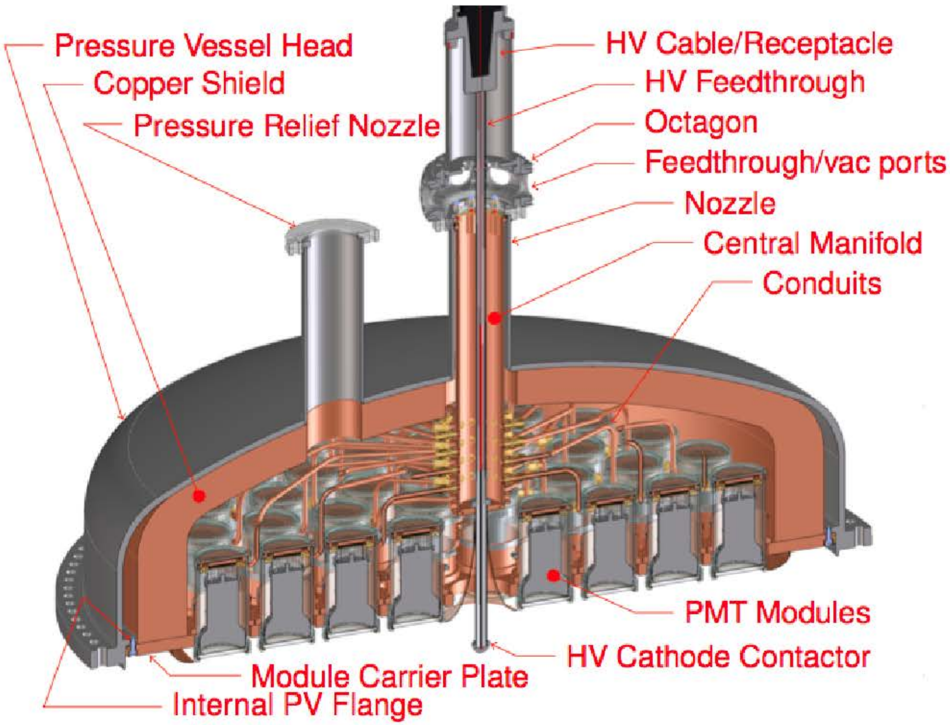
Energy resolution @ 511 keV: NEXT-DEMO (Valencia)

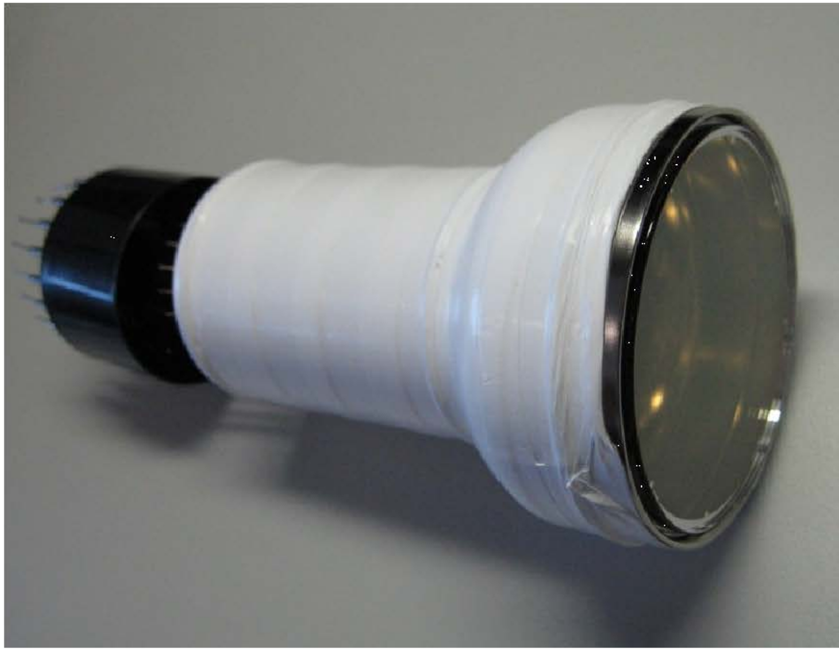


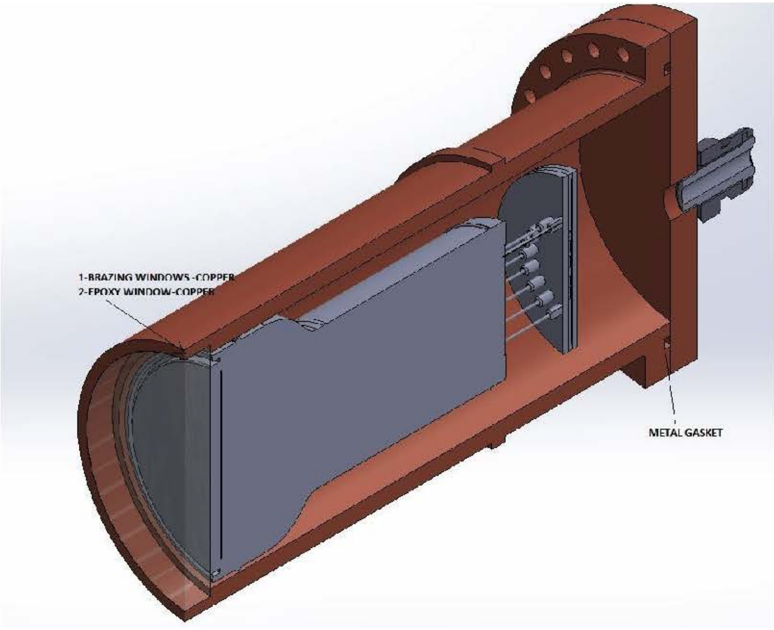


NEXT-100 Technical Design Report, arXiv:1202.0721

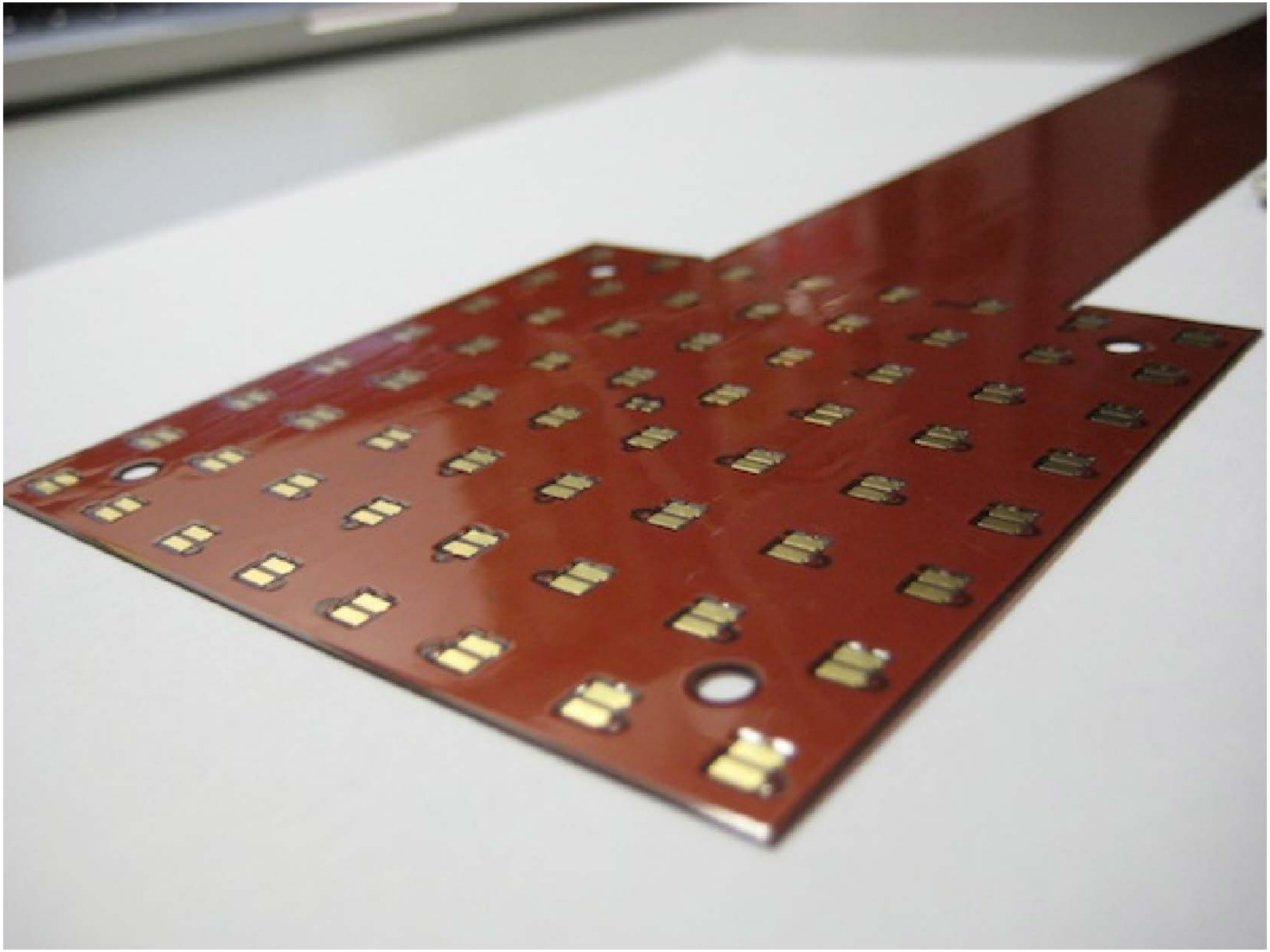
Energy plane





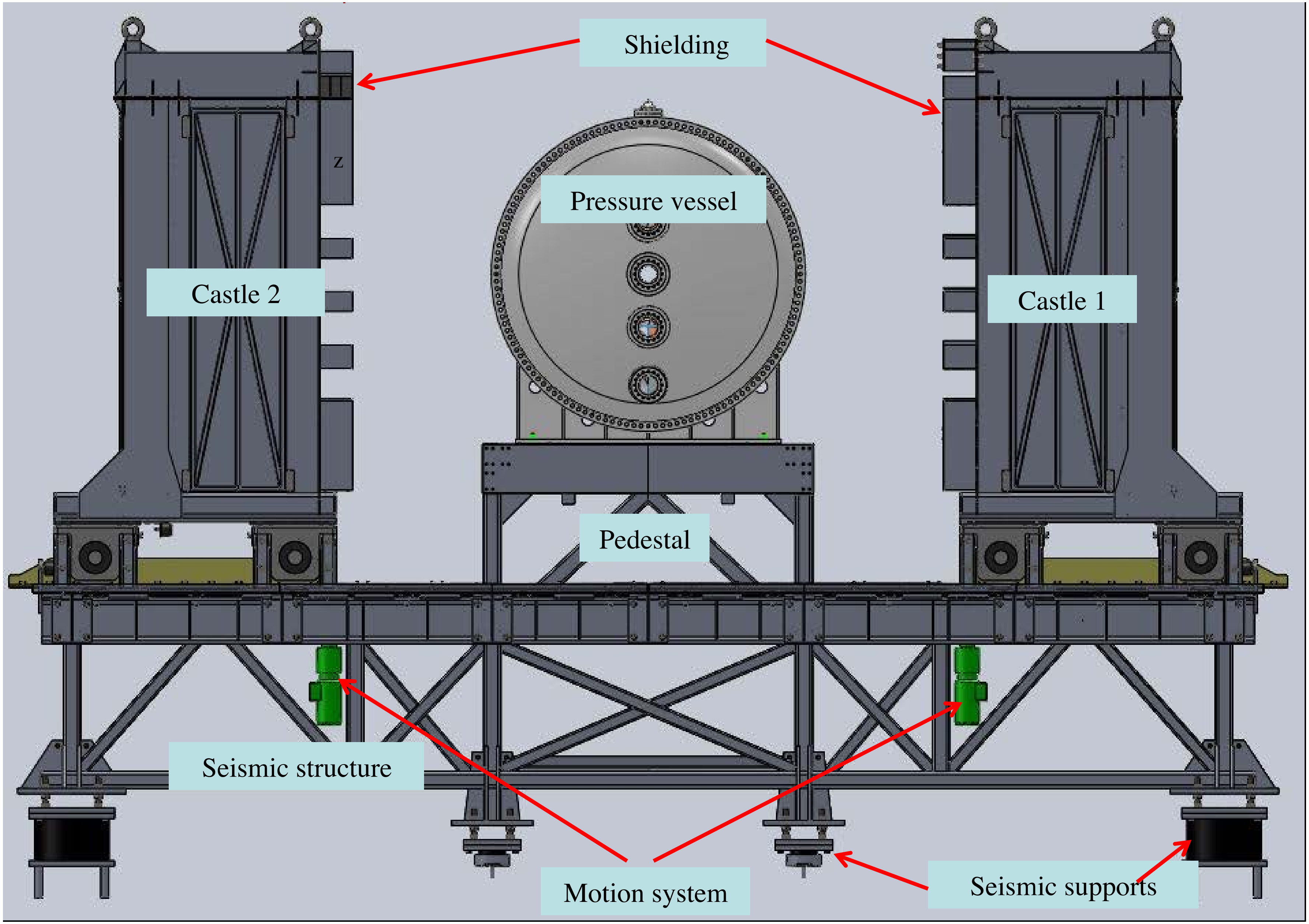



NEXT-100 Pressure Vessel



NEXT at Laboratorio Subteranneo de Canfranc (LSC), Spain

The experiment will be located at Hall A at the LSC. Working platform and basic gas system already in place.


Shielding
Pressure vessel
Castle 2
Castle 1
z
Pedestal
Seismic structure
Motion system
Seismic supports

Pure xenon gas: 0½ ββ :

- 1% FWHM energy resolution verified by NEXT-DBDM at 662 keV → 0.5% FWHM @ Q-value
  - Dangerous ^{214}Bi γ-ray at 2448 keV
- Track reconstruction with SiPMs verified; confirms x 30 – 50 background rejection
  - Background rate: 4×10^{-4} counts/keV/kg/year
- NEXT-100, with 100 kg enriched ^{136}Xe, should "touch" inverted hierarchy if backgrounds are as low as measurements + simulations

Criteria for “**Discovery**”

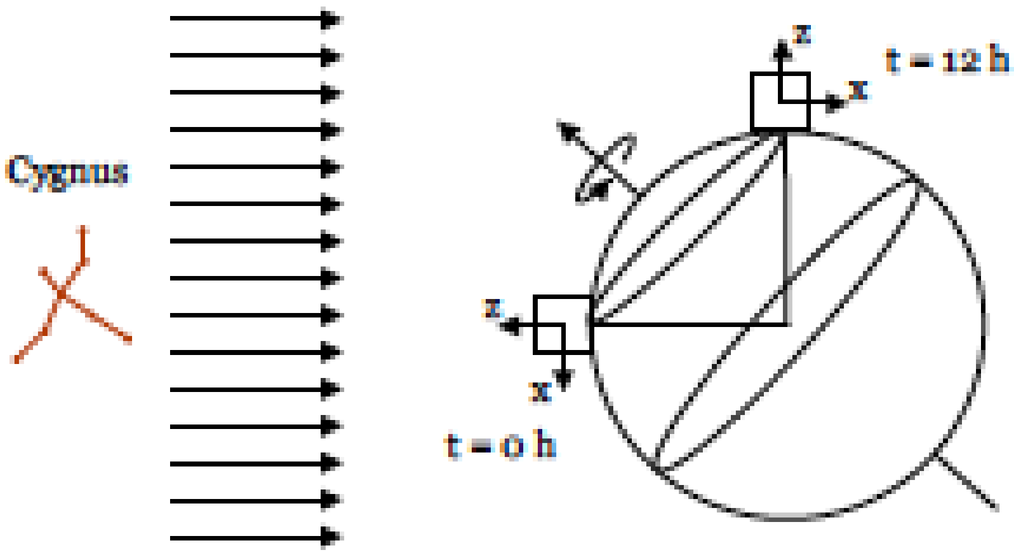
- What criteria should be established and met for a claim of “discovery” of 0ν-ββ decay?
  - Excellent energy resolution has been insufficient…
  - Is *event topology* an essential component?

- What criteria should be established and met for “discovery” of WIMP dark matter?
  - Backgrounds lurk everywhere at keV energies…
  - Is “recoil directionality” an essential criterion?

Directional sensing for nuclear recoils?

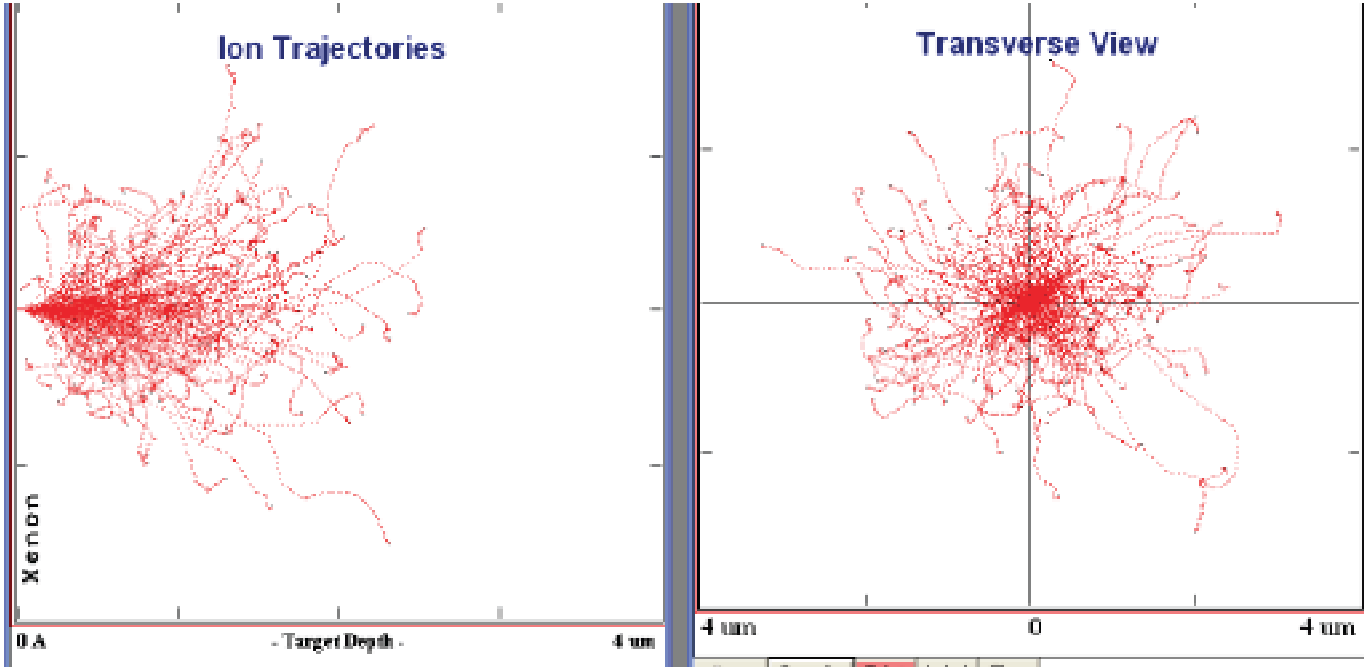
A *sidereal* variation of “WIMP wind from Cygnus”

WIMP <V> comparable to earth’s velocity: ~230 km/s



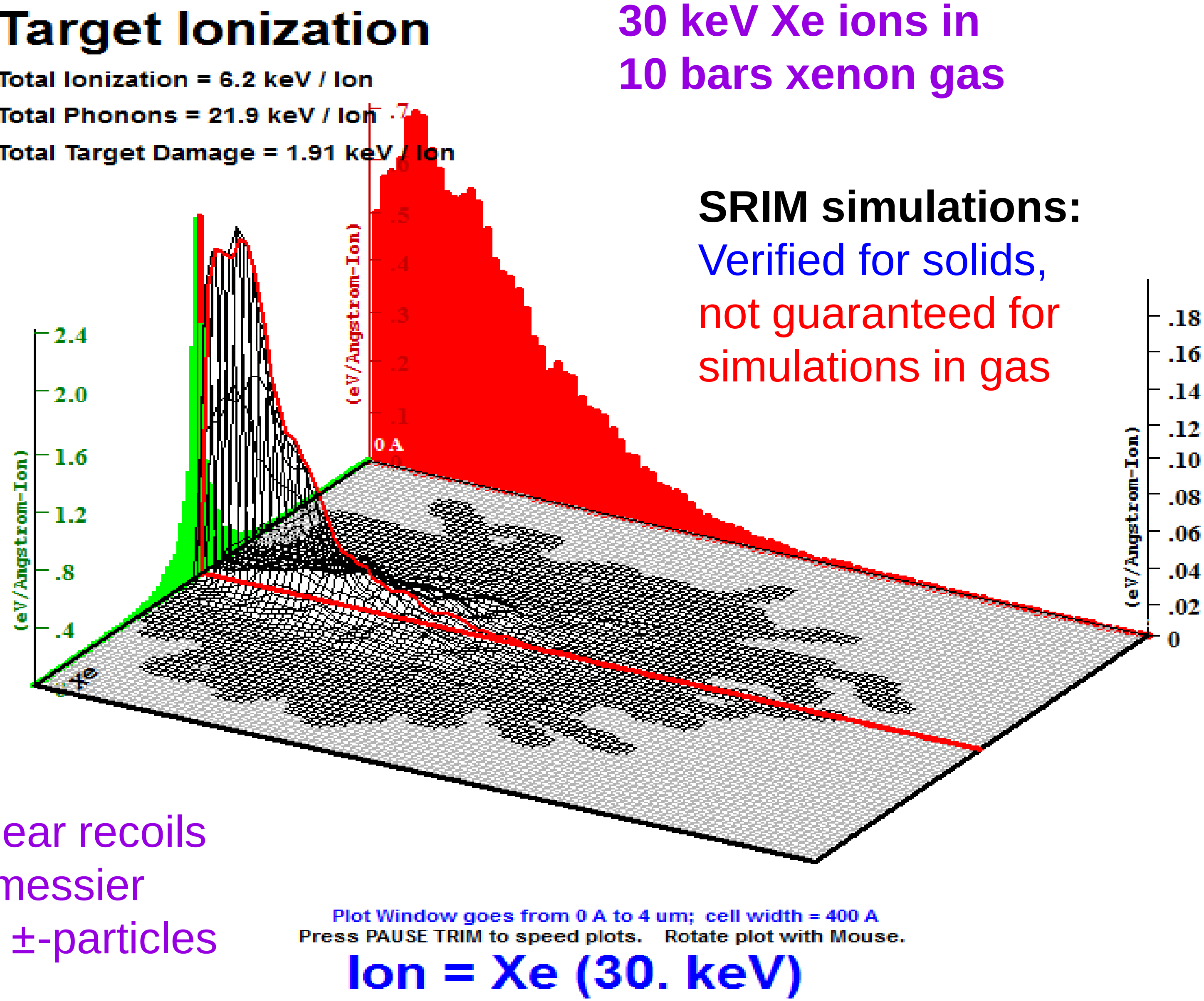
A substantial anisotropy in nuclear recoils should be observable

Do nuclear recoils retain directionality?



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

30 keV Xe ions in 10 bars xenon gas



SRIM simulations:

Verified for solids,
not guaranteed for simulations in gas

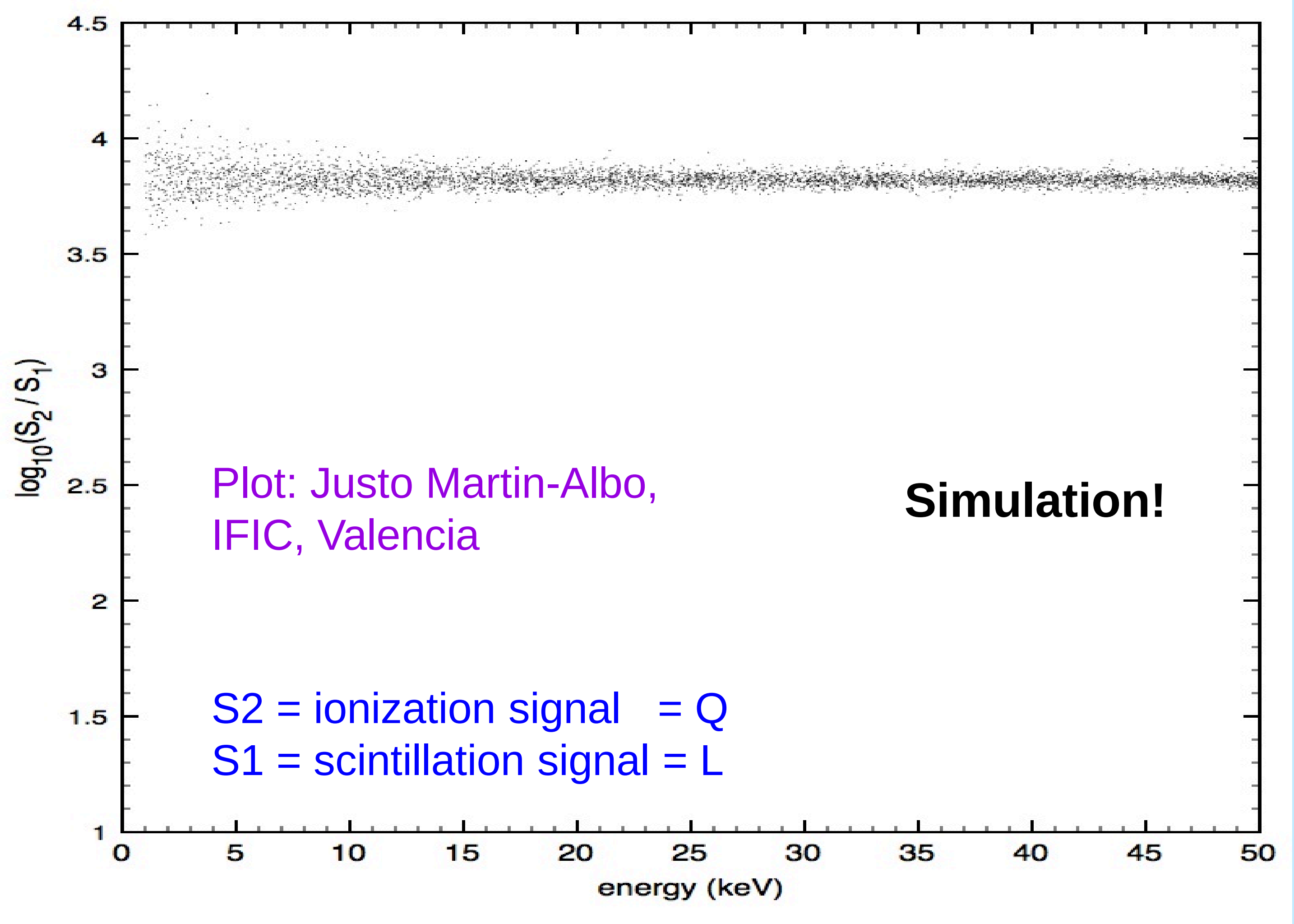
Nuclear recoils are messier than ±-particles

Dark Matter Search with HPXe

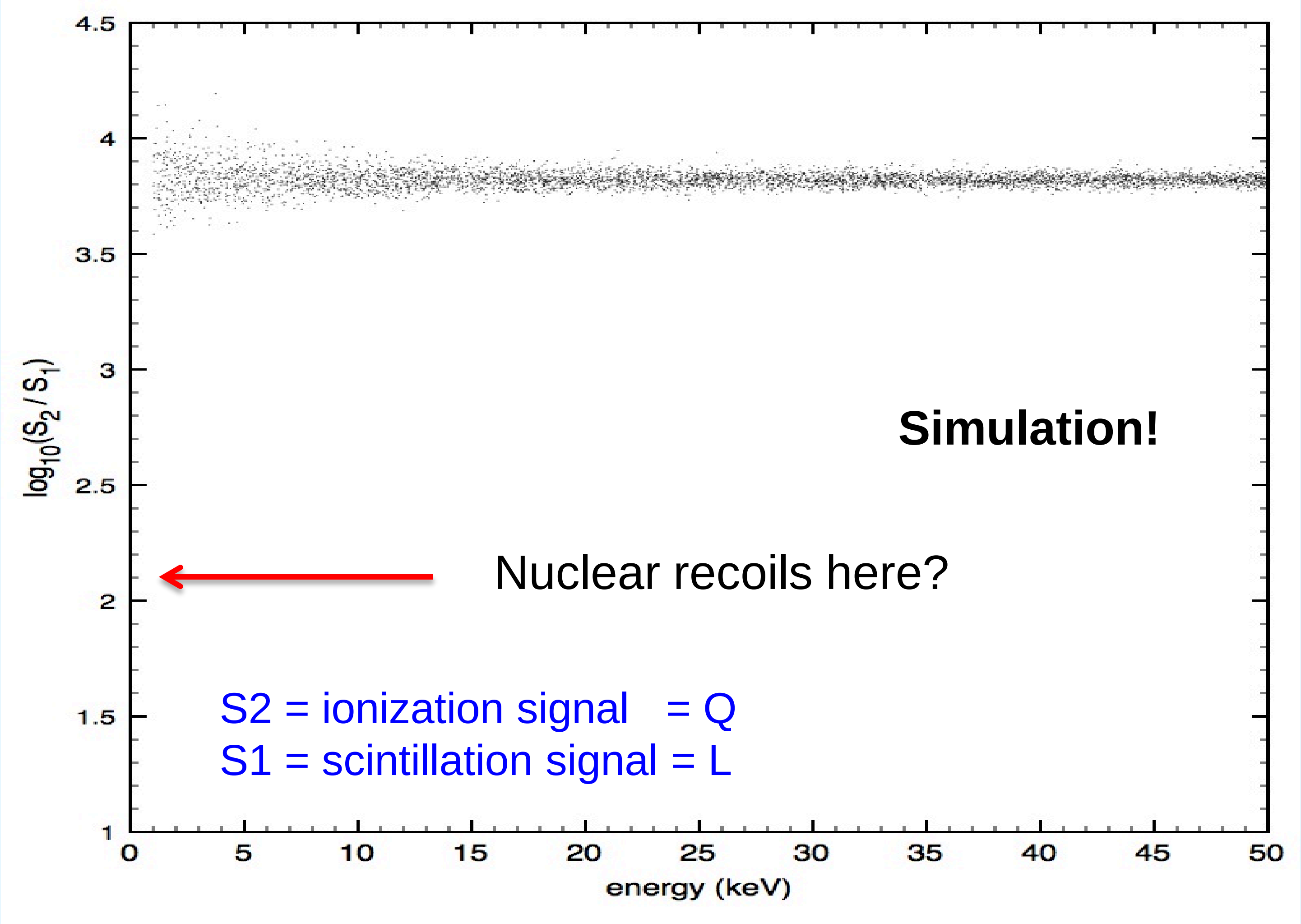
- The superb energy resolution available, in principle, also helps the WIMP search
  - Intrinsic S2/S1 fluctuations are much smaller

- Gas phase permits molecular additives that offer remarkable performance opportunities
  - Beneficial for 0ν-ββ, too, but no time to discuss

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



Simulation: electron recoils in pure HPXe, F = 0.15, 10% optical efficiency

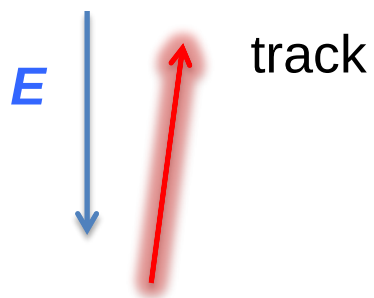


Today's techniques

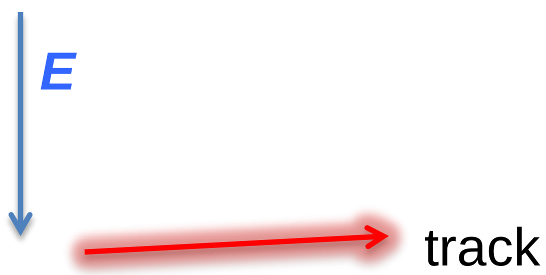
- All current approaches attempt to **visualize** the nuclear recoil track:
    - Nuclear Emulsions (expanded optical readout !!)
  - Low-pressure TPCs (~50 g/detector)
    - D^3 (GEM + pixel ASIC)
    - DMTPC (CF_4 optical CCD)
    - DRIFT (CS_2^-, CF_4, MWPC)
    - MIMAC (CF_4 + µMegas)
    - NEWAGE (Gem, µ-dots)

Columnar Recombination: a nuisance? - or a new way to "see" directionality?

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



Substantial CR: more light, less charge



CR small: less light, more charge

Columnar recombination and Directionality sensing in nuclear recoils

- **Columnar recombination** (CR) can be quite sensitive to the angle between a highly ionizing track and an electric field $\boldsymbol{E}$;

- For a given event energy, more recombination would yield more scintillation, less ionization

- Therefore, a comparison – event by event – of scintillation/ionization is a measure of CR

CR Exists!

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

FWHM depends on E-field and density!

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

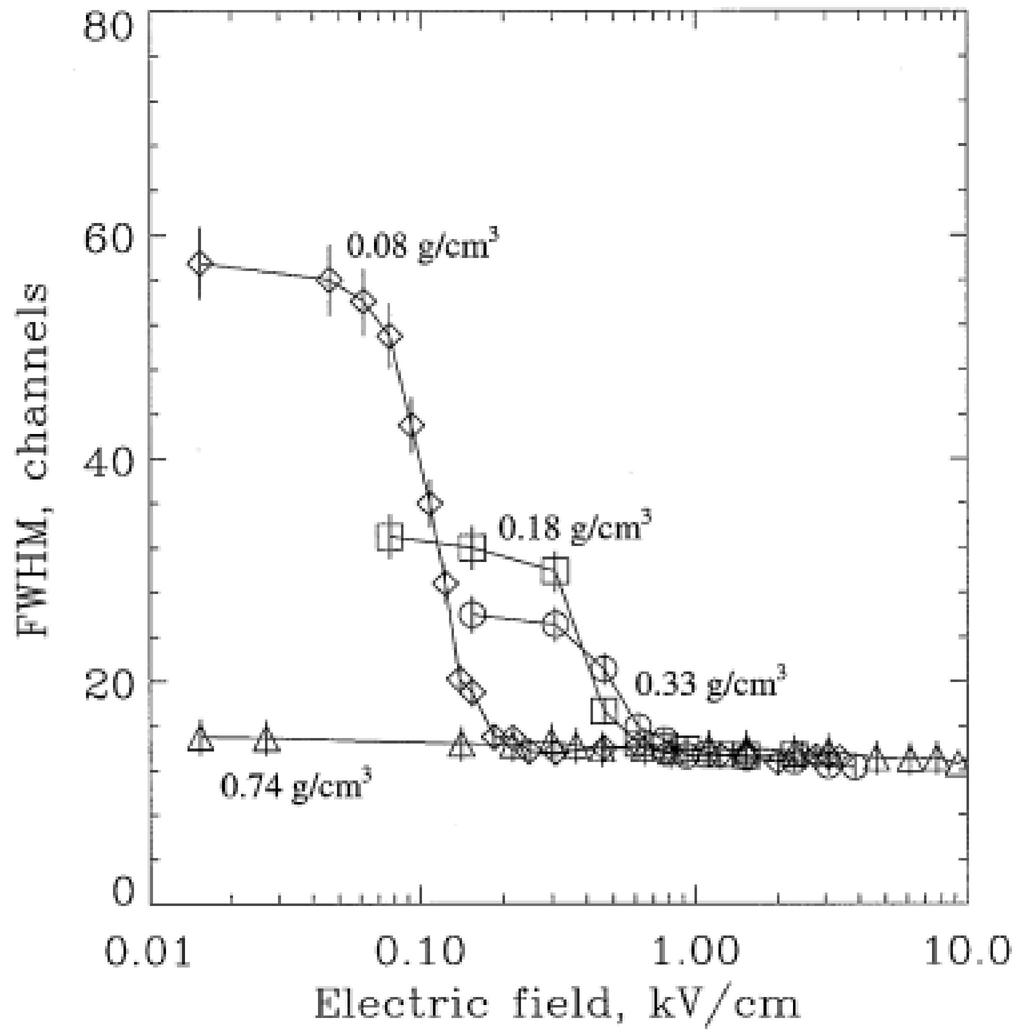


Fig. 5. FWHM of the peaks in pulse-height spectra of the amplitude of the light signals versus the electric field strength measured at 0.08 g/cm^3 (diamonds), 0.18 g/cm^3 (squares), 0.33 g/cm^3 (circles), and 0.74 g/cm^3 (triangles).

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 **ρ ≈ 0.05 g/ cm³**:
    - R_0 ~ 70 nm
    - $\mathcal{R}$ ~ 2100 nm for 30 keV nuclear recoil
    - ***C ≈ 30*** in this example
  - Hopeless for liquid density: C < 1

Columnarity is key

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

- Figure of Merit **M** = V_{det}/V_{track} **= 10^{17}** per m^3
- CR **M** is better than low-density TPC by x10^9

Molecular gymnastics can help

- Primary excitations ~ ionization
  - Excitations carry no directional information!
    - Convert excitations to ionization by **Penning effect**
      - Use appropriate molecular additive – which one?
      - **Trimethylamine** (TMA) displays a strong Penning effect in Xe
    - Molecular additive:
      - will cool electrons – facilitates CR
      - Neutralizes xenon ions by charge exchange
      - Track "image" transformed to molecular ion image
      - Molecular ions recombine with electrons → "light"

How to maximize a CR signal…

- Large size of gas-phase TPC requires optical detection by wavelength-shifting plastic (WLS)
  - WLS: maximum efficiency at 300 nm
  - WLS: negligible efficiency at 173 nm VUV of xenon
- Miracle needed: Penning molecule must display efficient UV fluorescence at ~300 nm
- Providence: **trimethylamine** is known to fluoresce very efficiently at ~300 nm !!!

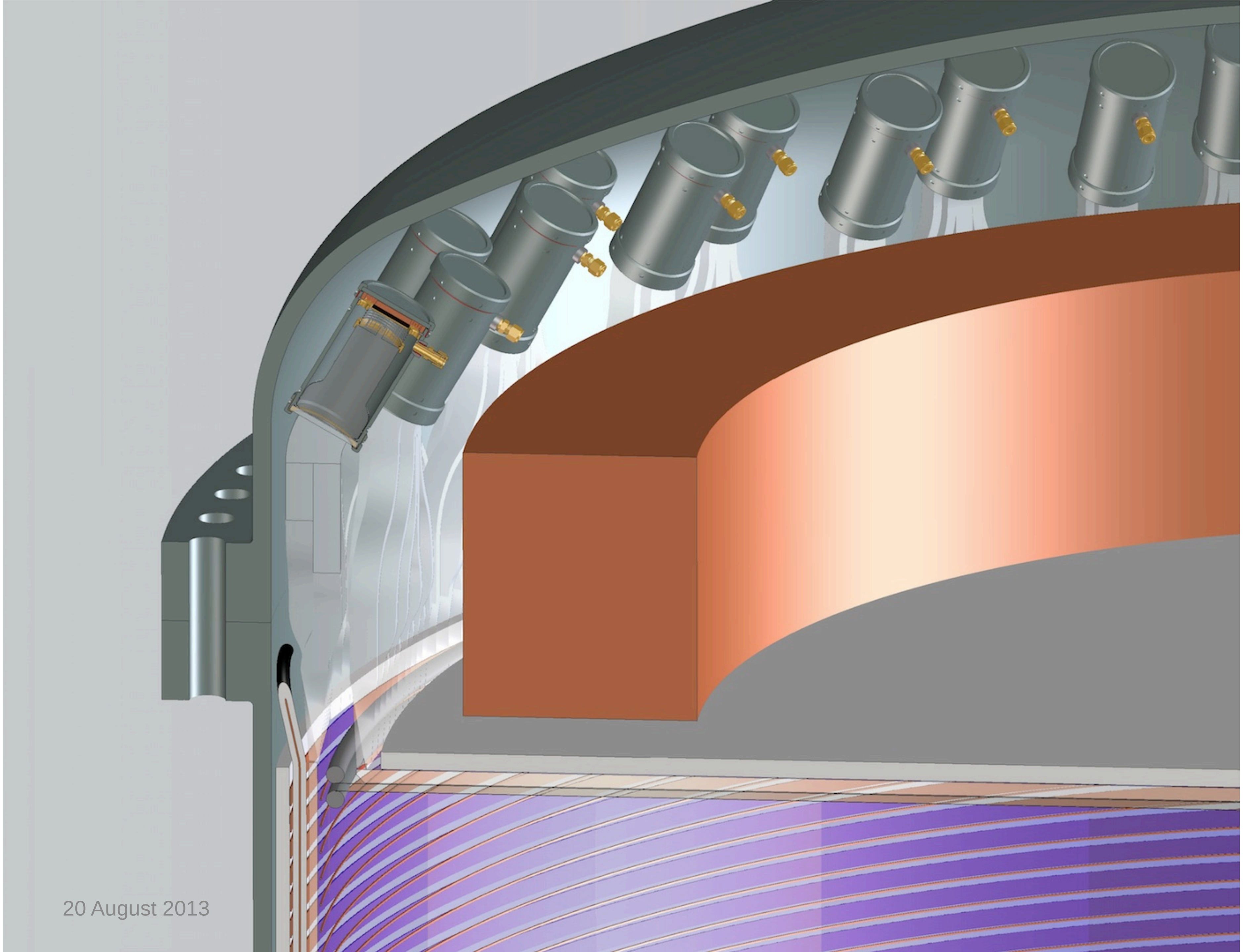
Scenario

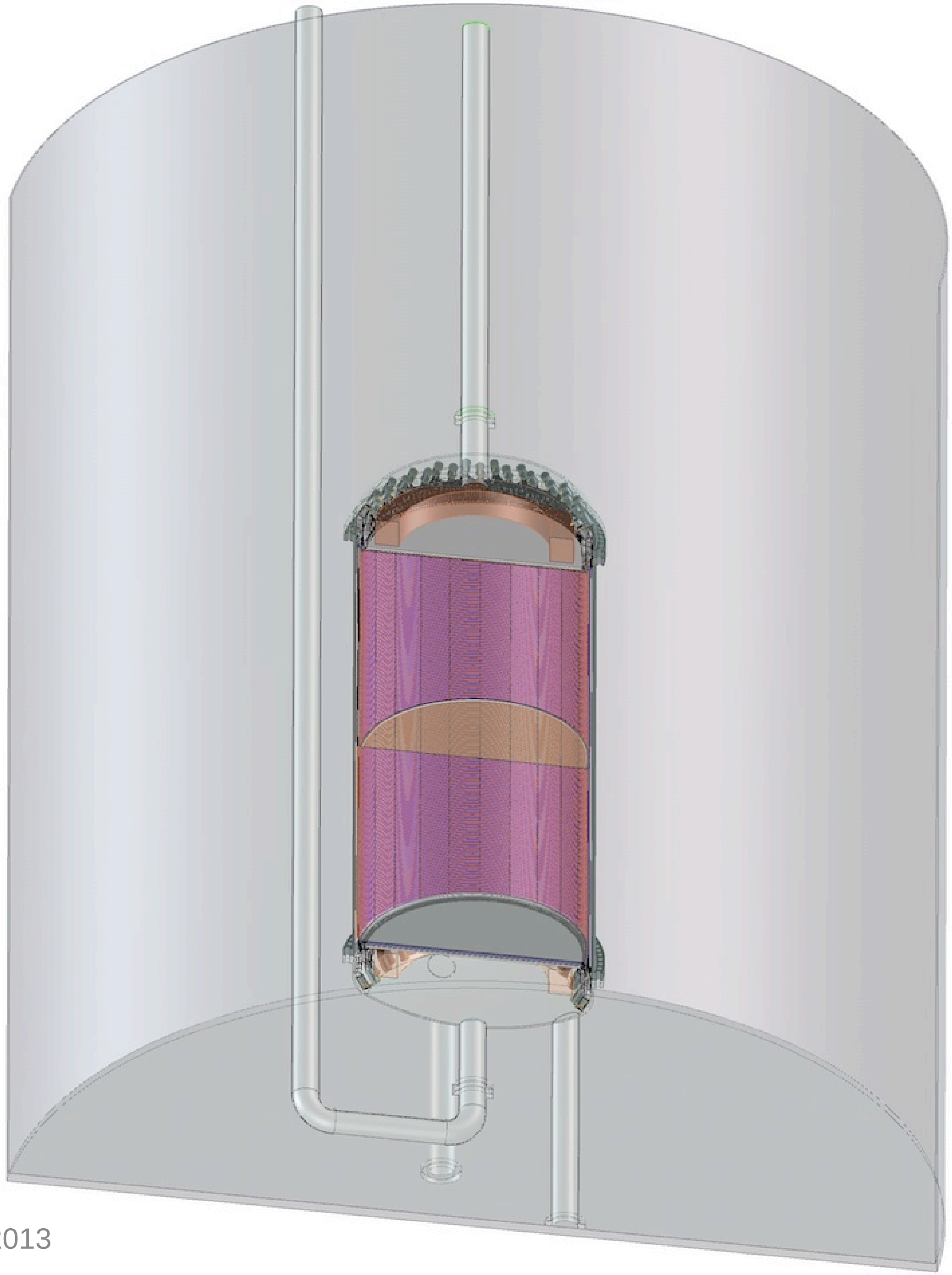
- "S1" signal may display strong *columnar recombination*
  - A substantial effect for nuclear recoils (~100x minimum ionizing)
  - A negligible effect for electron recoils
- This may provide a way to "see" WIMP directionality without direct imaging of nuclear recoil tracks
  - Density restriction on gas is moved to ~10 bars
  - X100 increase relative to low density TPC concept
  - Drift length restriction due to diffusion is removed
  - Simpler spatial detection requirements at anode plane
  - Larger monolithic detector possible, x10 – 100 volume
- Several hundred kg active mass possible, if true!

Size: 2.3 meter diameter
2 x 3 meter drift length

With WLS, only a few dozen PMTs are needed

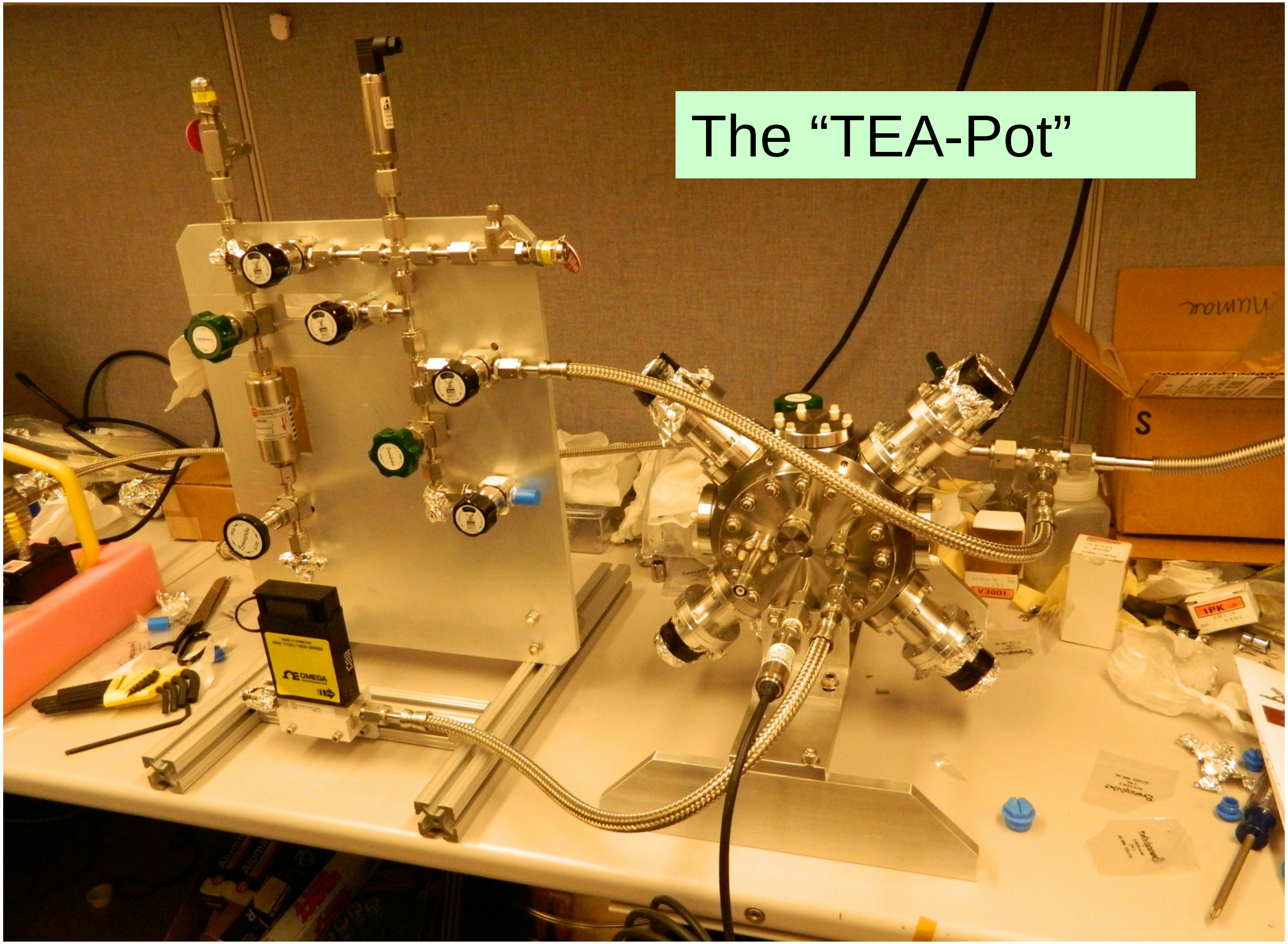
With E-field in opposing directions, a “head-tail” effect might show up





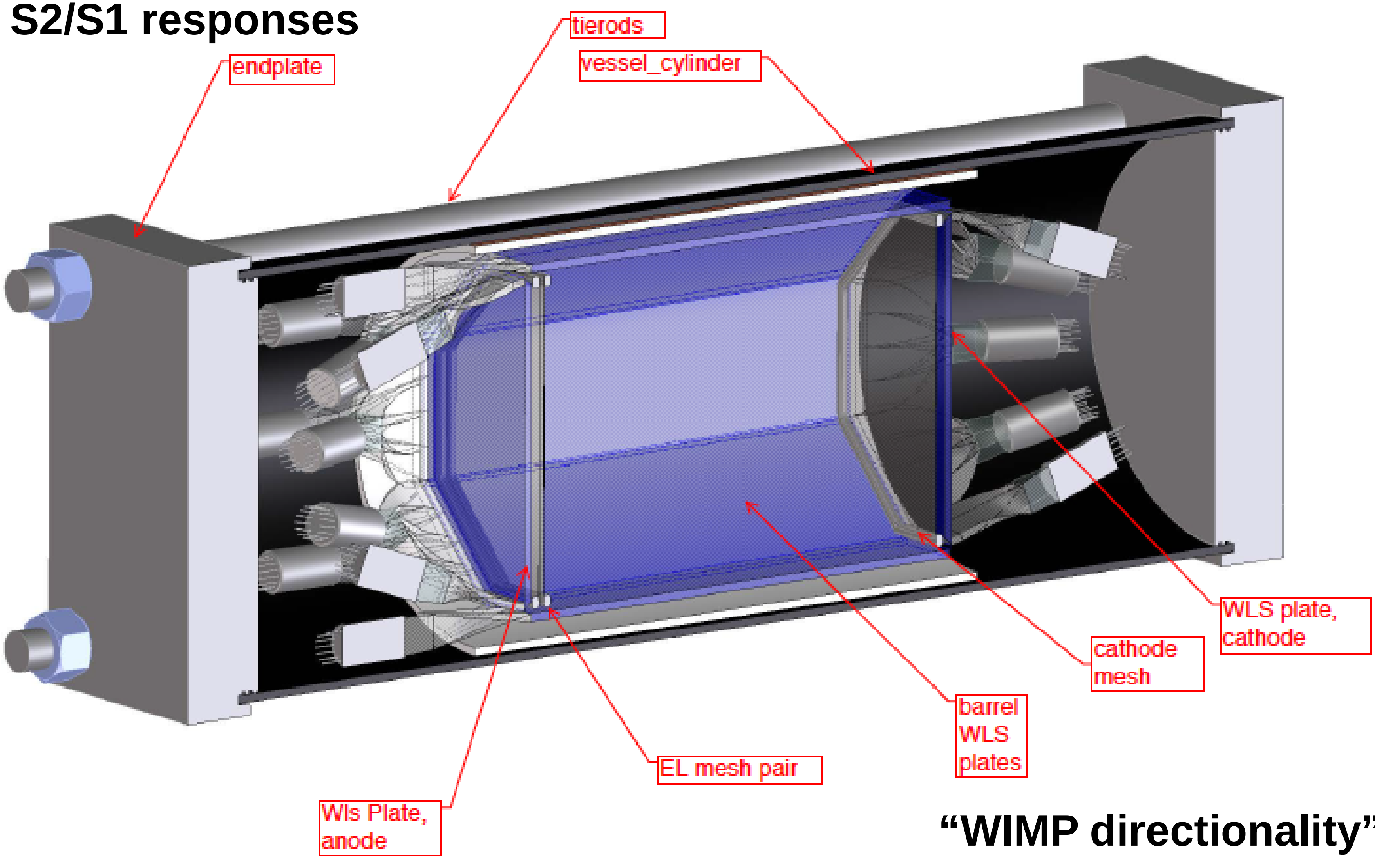
Large, but
maybe not
too large…

The “TEA-Pot”



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

S2/S1 responses



"WIMP directionality"

Perspective

- Is this a true story, or a fairy tale?
  - At least, serves as imagination stretcher…
- Plausible at each step, but unknowns exist:
  - Has Nature chosen WIMP mass: 50 – 350 Gev?
  - Penning efficiency of TMA?
  - Fluorescence efficiency of TMA in recombination?
  - Rate of ionic charge exchange?
  - Cooling rate of electrons after ionization?
  - Head-Tail sensitivity?
- Simulation and experimental effort starting…

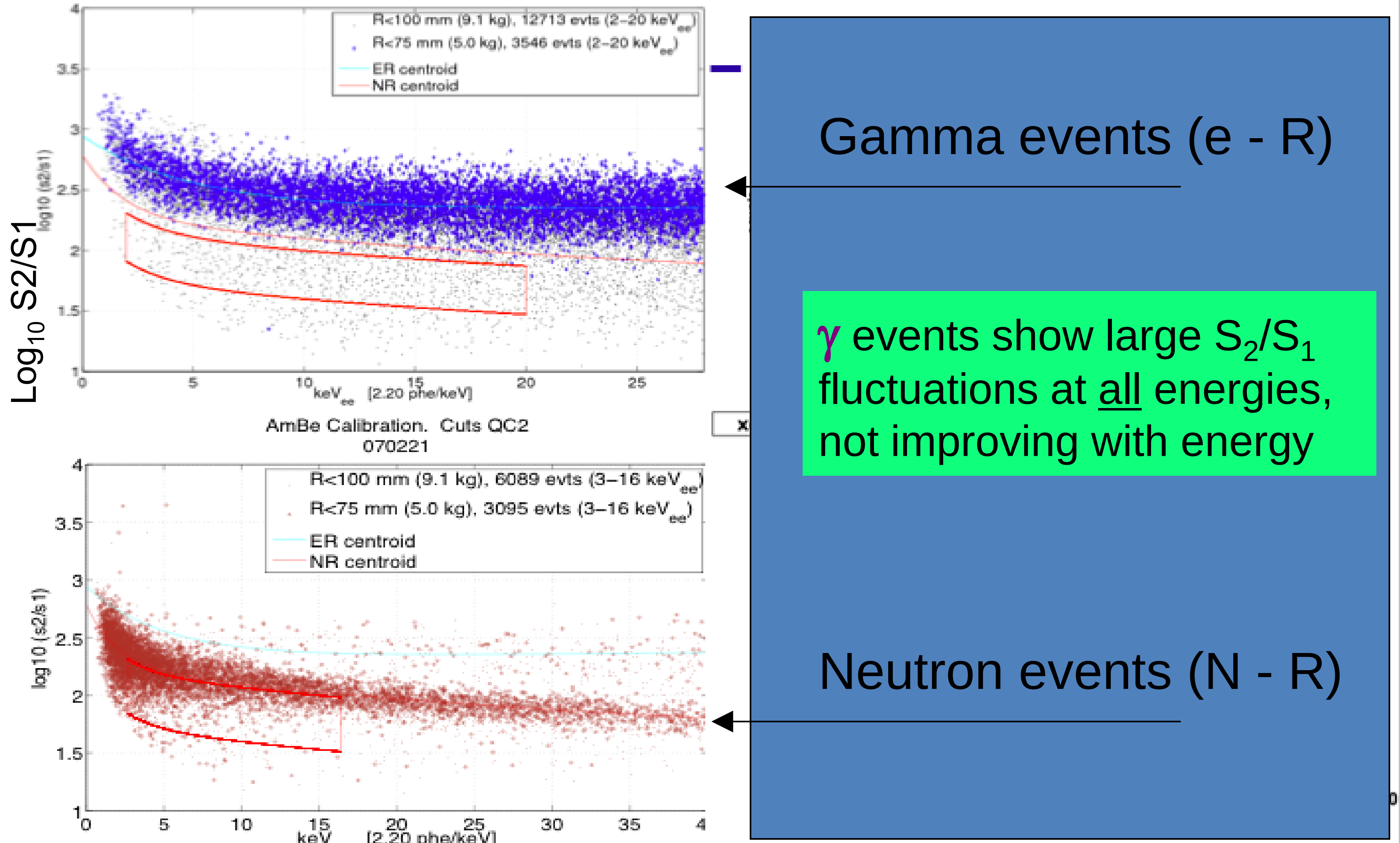
Perspective

- Gas phase offers superb energy resolution, event visualization, and flexibility in operation
- **EL** gain stage is a key element for near-intrinsic energy resolution for 0½² ² search and low energy signals
- Small energy partition fluctuations imply superb S2/S1 discrimination between electron and nuclear recoils
- Directionality signal for WIMP search at 100's of kg in monolithic TPC would exceed current reach by >1000

Thank you

S2 = Primary ionization signal
S1 = Primary scintillation signal

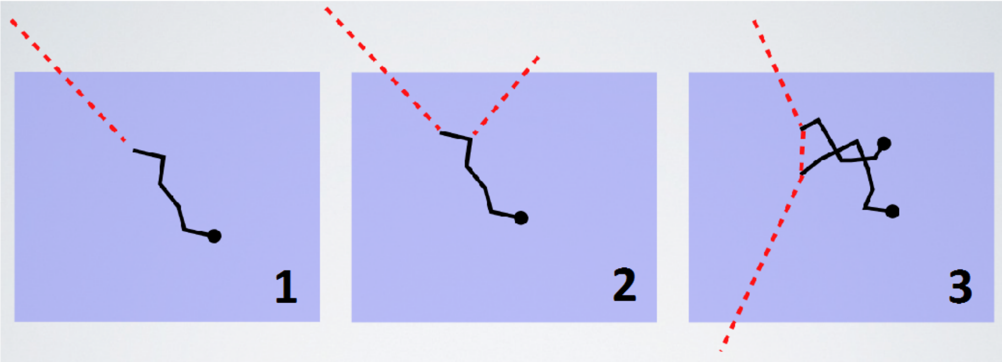
Xenon10 – LXe data



γ events show large S_2/S_1 fluctuations at <u>all</u> energies, not improving with energy

Radiopurity: BACKGROUND MODEL

Simulations made with **NEXUS**, a GEANT4 based software developed by NEXT



Example 1: Electron photo-produced by 2448 keV gamma from ^{214}Bi decay

Example 2: Electron photo-produced by 2448 keV gamma from ^{214}Bi decay that undergoes Bremsstrahlung

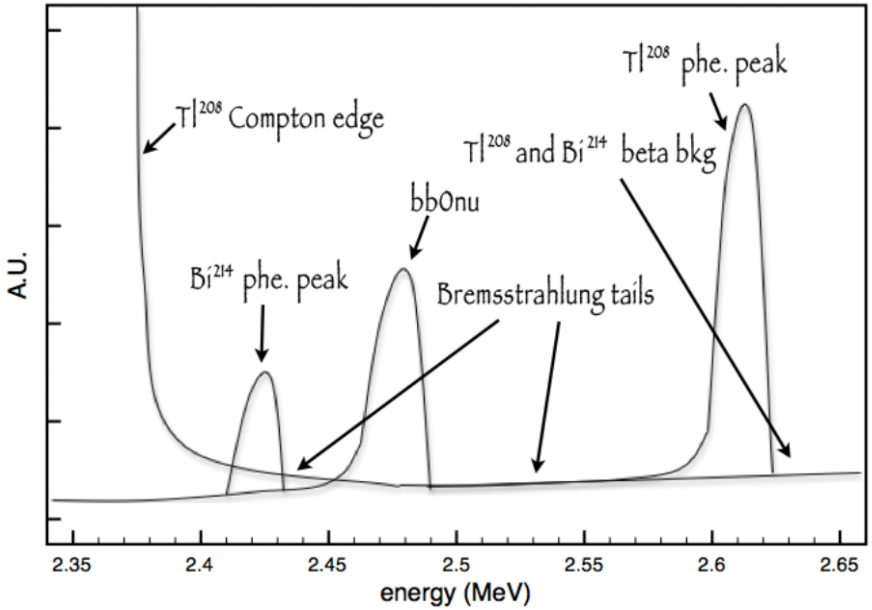
Example 3: Two electron Compton scattered from 2615 keV gamma from ^{208}Tl decay

requirements from Background Model *(counts/kg/keV/year)*

^{214}Bi: 0.18 - 0.40 e^{-3}

^{208}Tl: 0.21 - 0.48 e^{-3}

Total: 0.38 - 0.88 e^{-3}



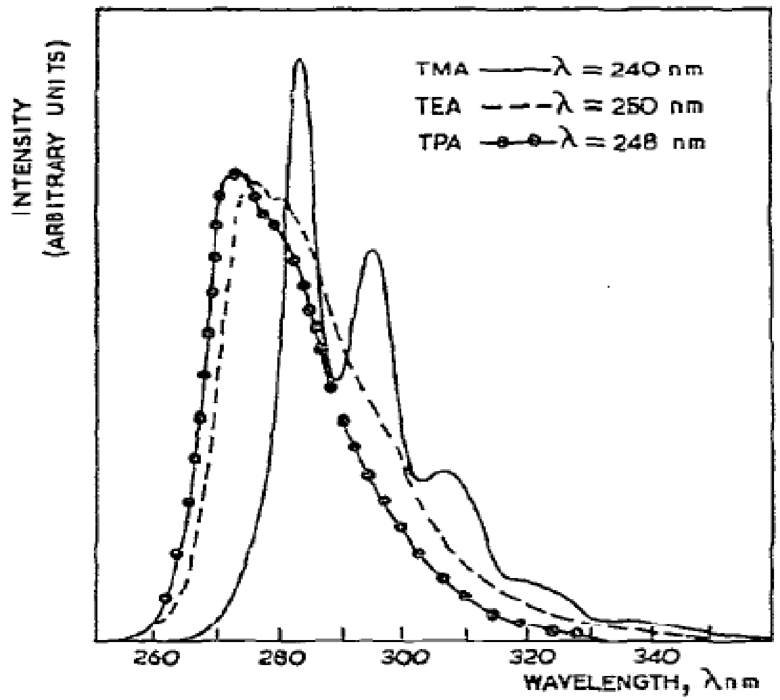
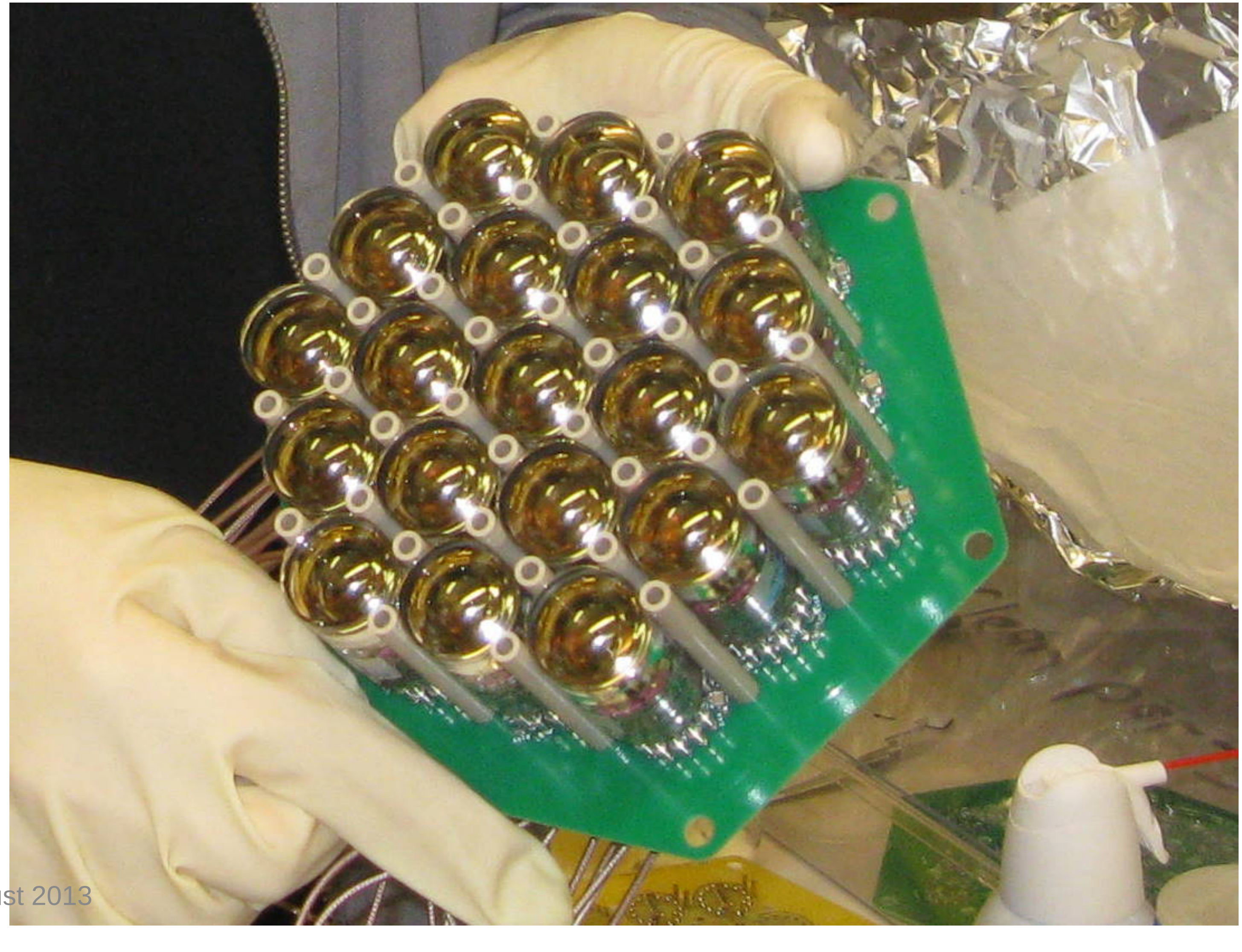


Fig. 4. Vapour-phase fluorescence spectra of TMA, TEA and TPA at excitation wavelengths indicated.

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



A typical ^{137}Cs γ waveform (sum of 19 PMTs)
~300,000 detected photoelectrons

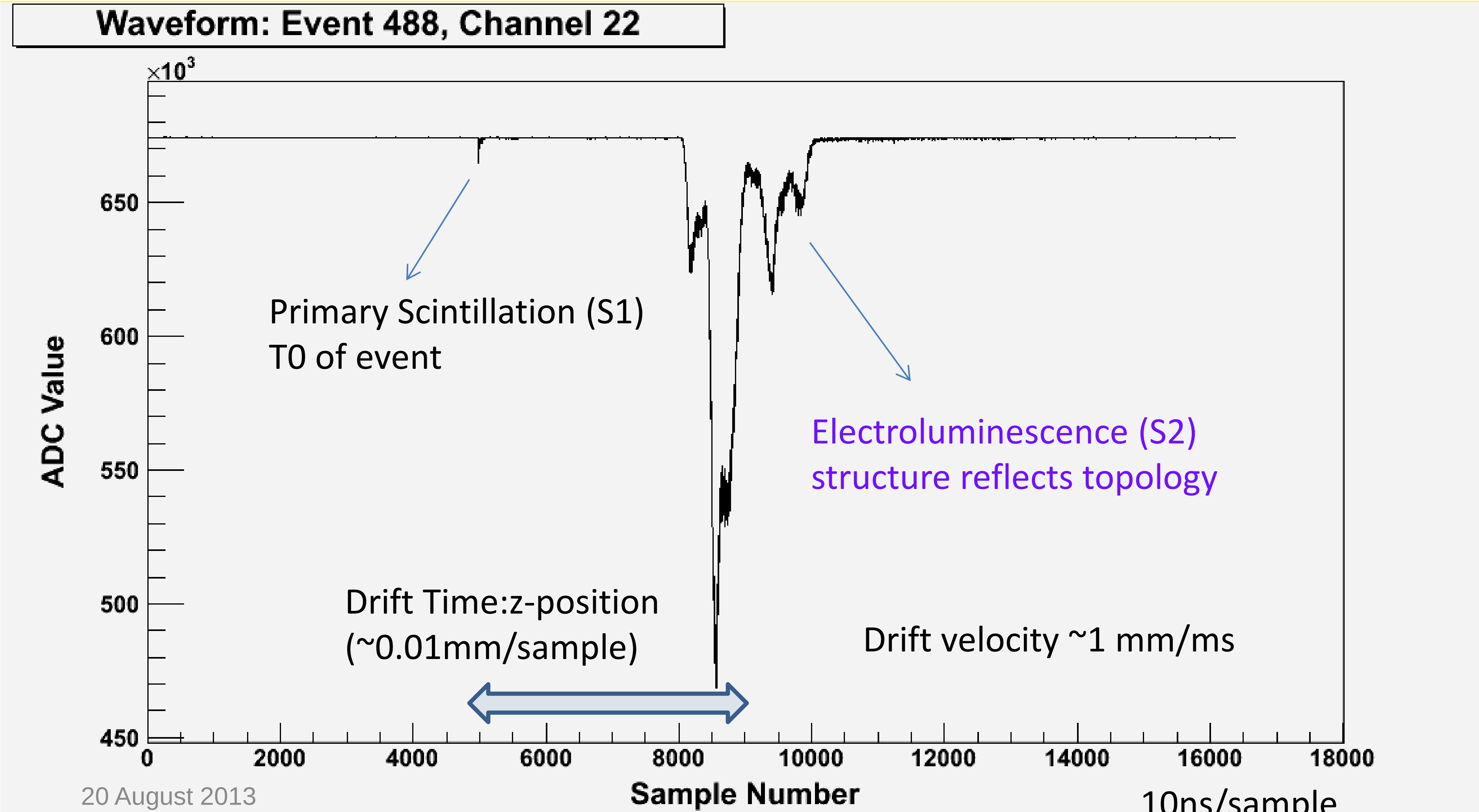
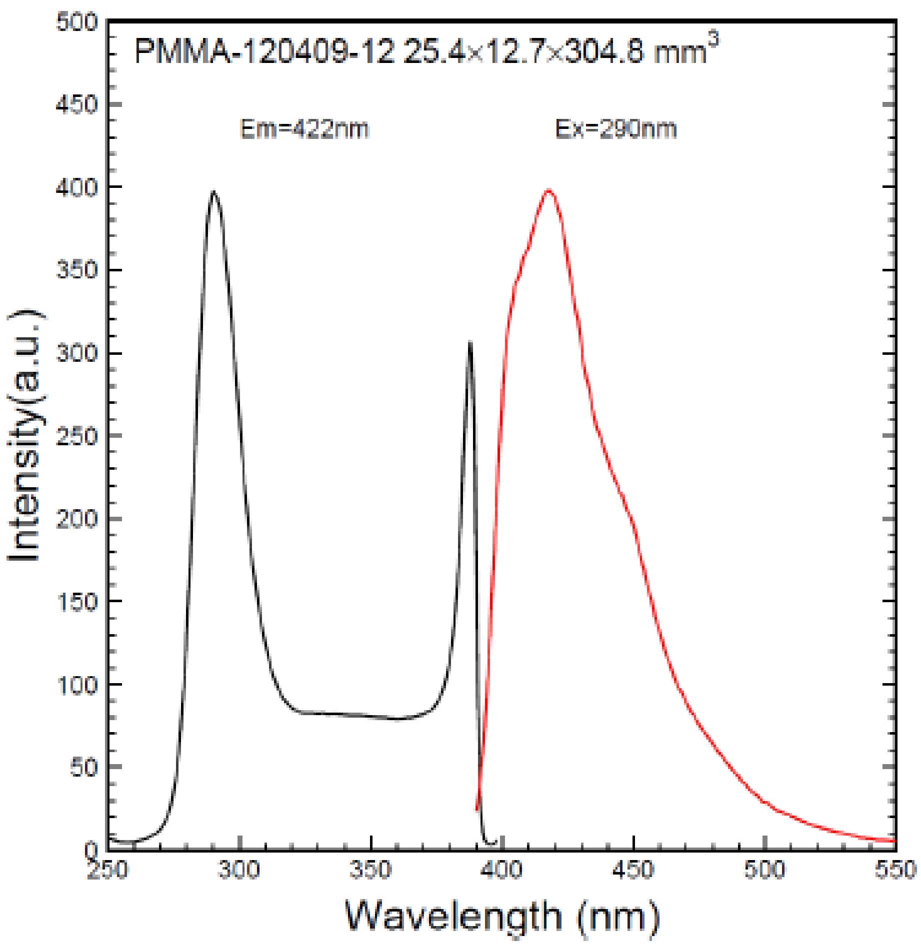
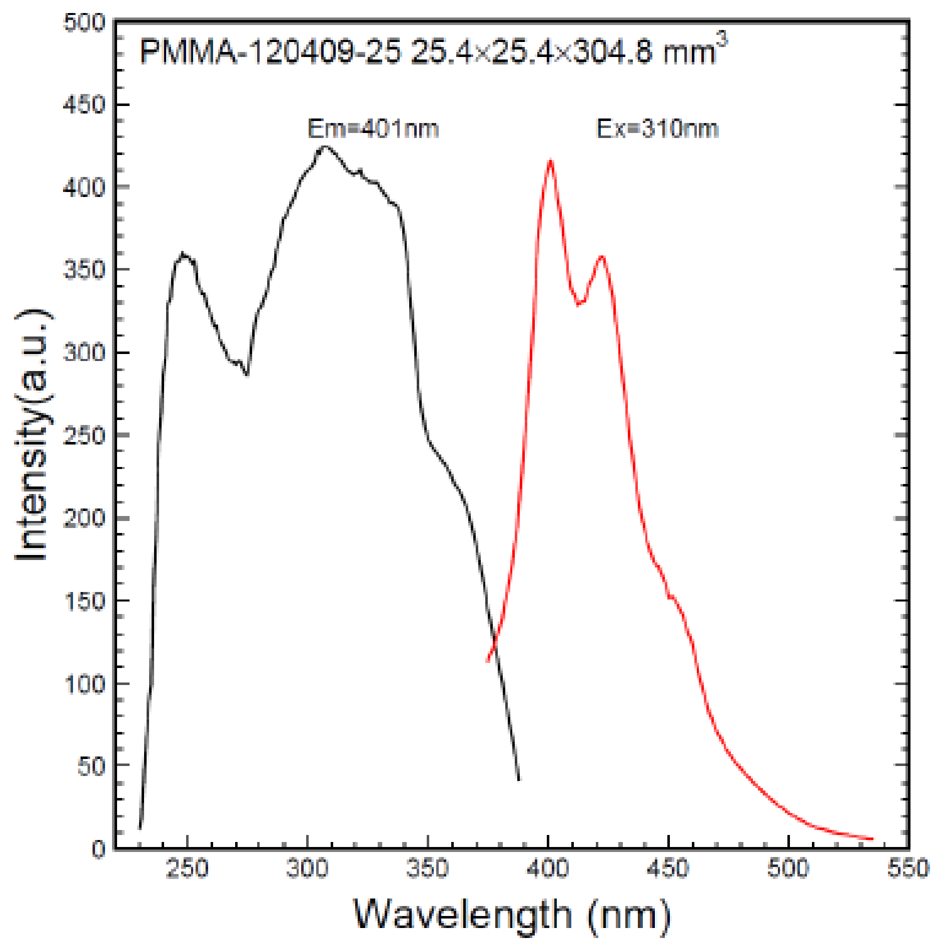


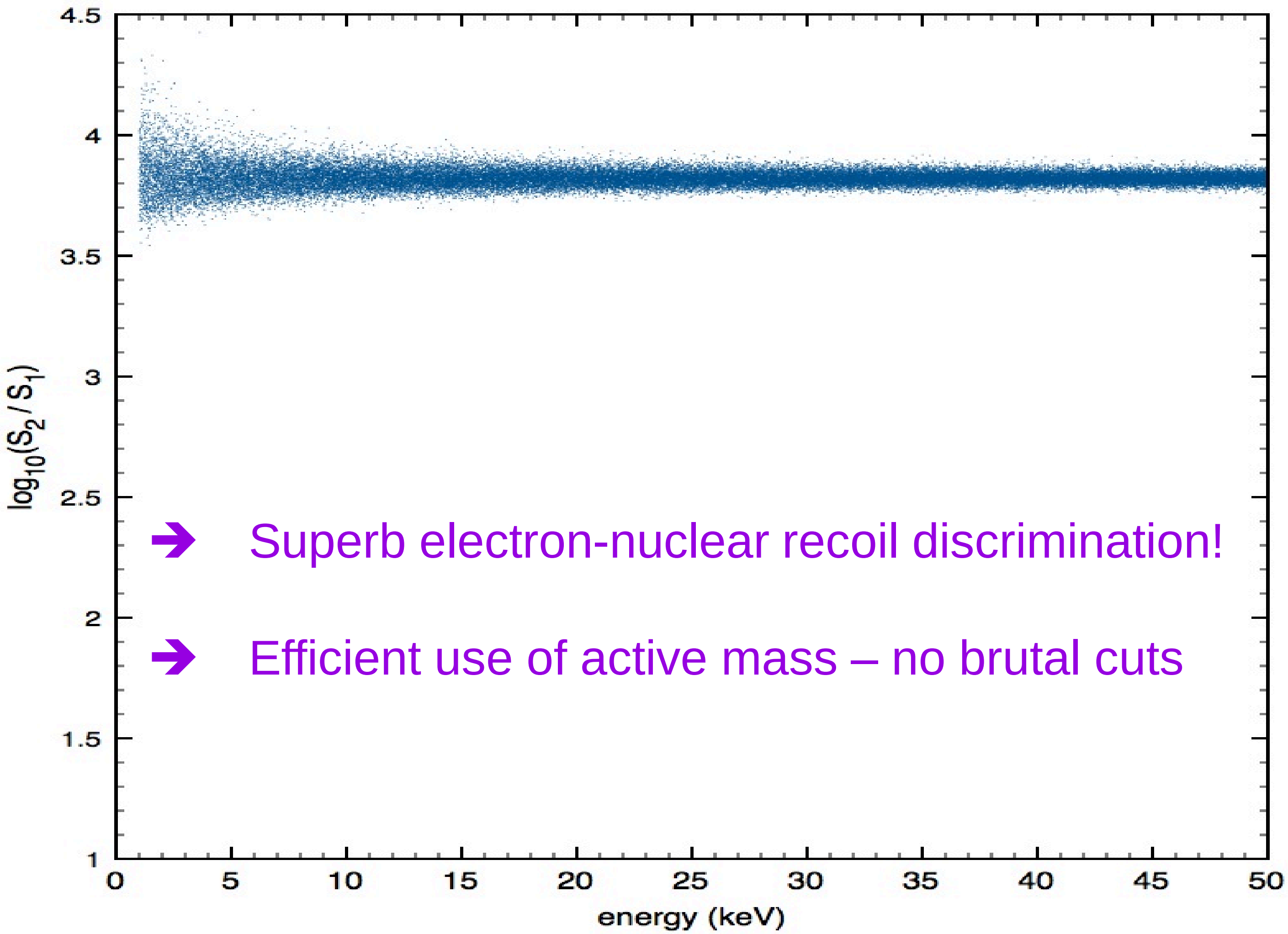
Photo-Luminescence of PMMA

Different WLS nature observed for two PMMA Samples



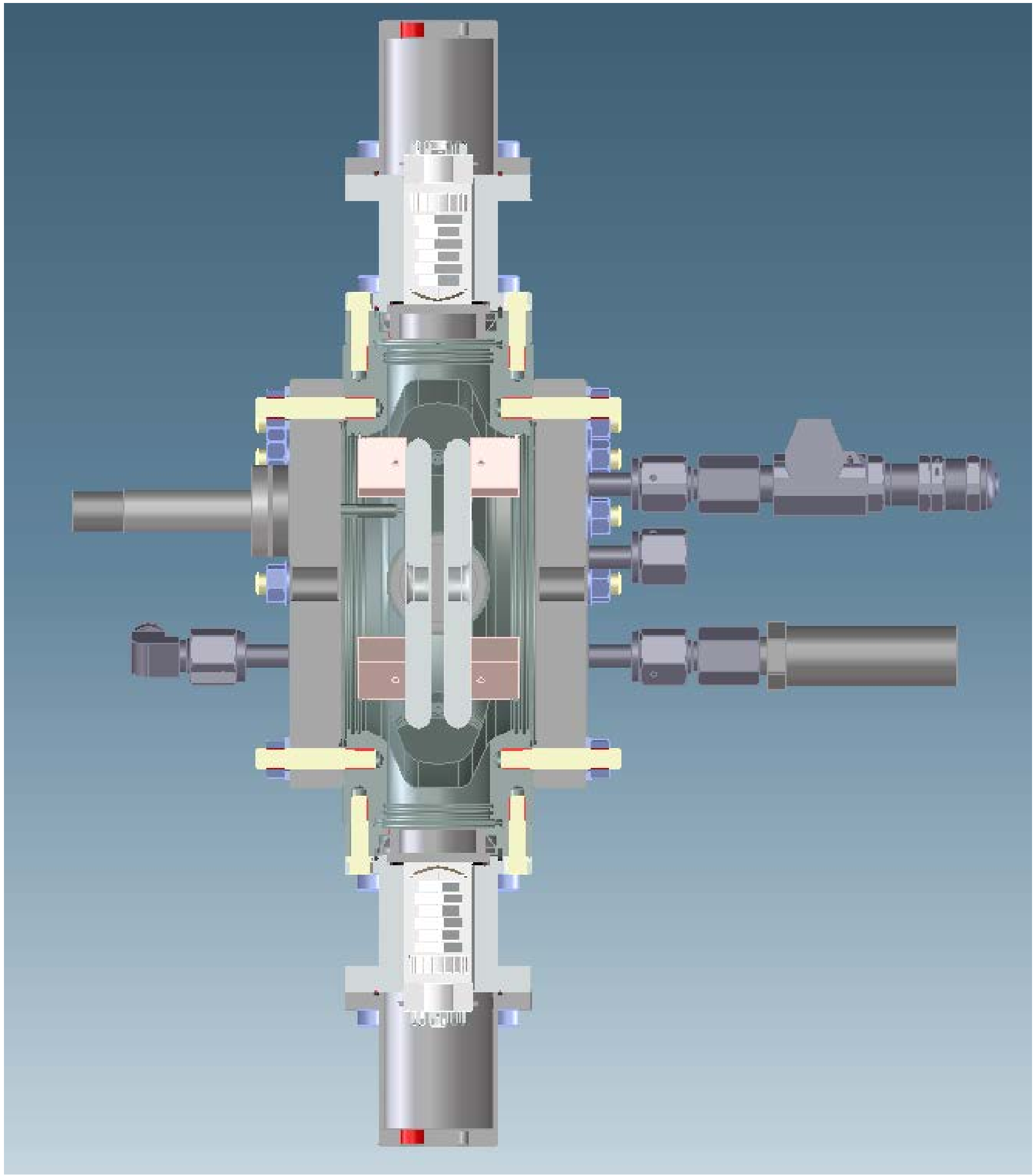


Gaussian behavior persists at x10 number of events



➔ Superb electron-nuclear recoil discrimination!

➔ Efficient use of active mass – no brutal cuts



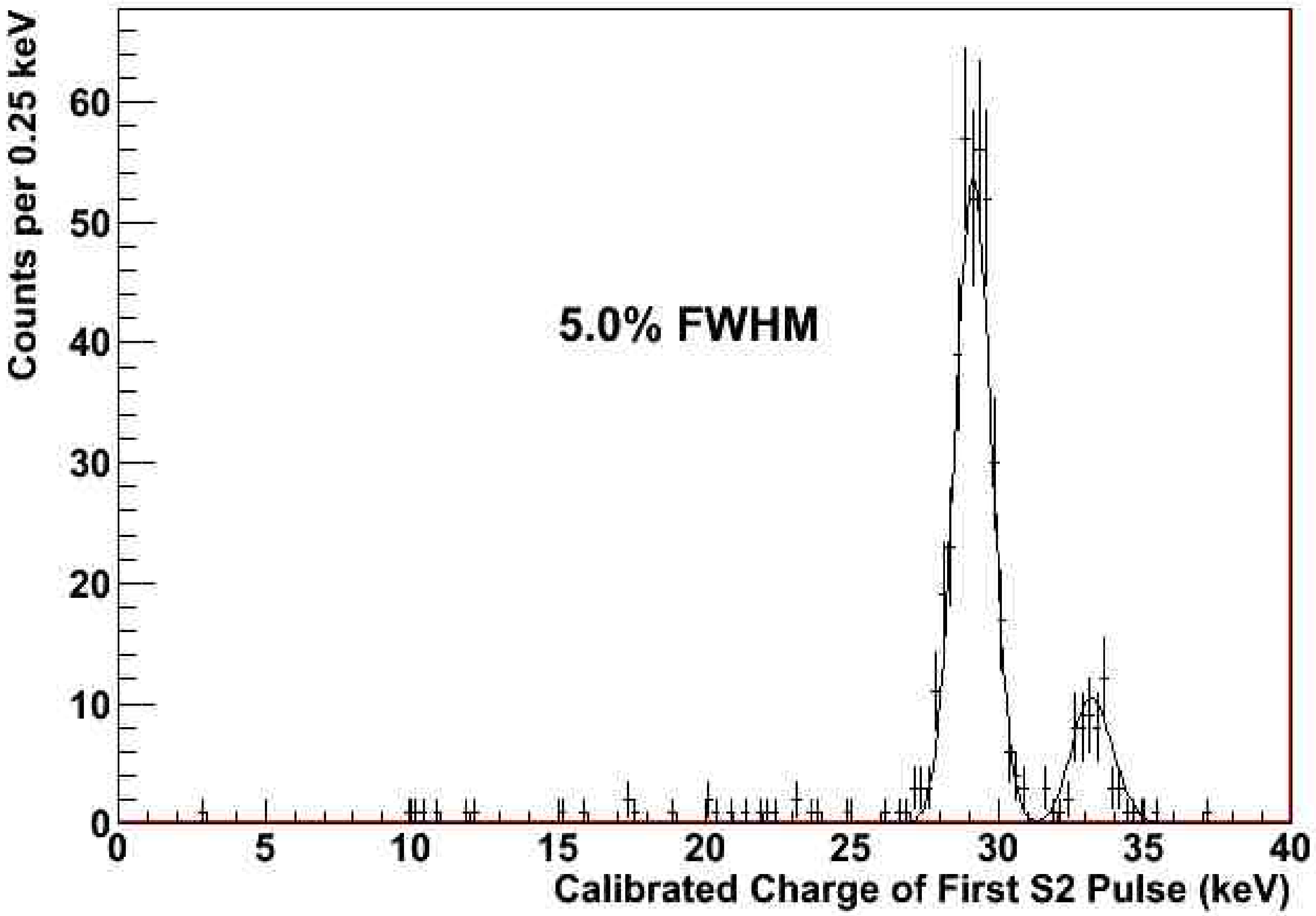
the “TEA-pot”

Basic responses measurements:

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

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

The x-ray peaks around ~30 keV



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

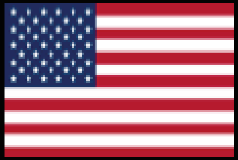
$\sigma_N = (F \cdot N)^{1/2}$ ~124 electrons rms!

δE/E = 0.28% FWHM intrinsic HPXe

Scaling our result: **δE/E H0.5% FWHM @ $Q_{2\,2}$**

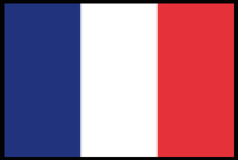
NEXT Collaboration

~~CIEMAT~~ (Madrid) • U. Girona • ~~IFAE (Barcelona)~~ •
IFIC (Valencia) • U. Santiago • U.P. Valencia • U. Zaragoza



LBNL • Texas A&M • ISU • UNM

U. Aveiro • U. Coimbra



CEA (Saclay)

JINR (Dubna)

UAN (Bogota)

Spain provides:

Most of the collaborators

Most secured funding

Host Laboratory - LSC

Key contributions from international groups

Engineering and integration

TPC expertise

high-pressure gas detectors

Xenon supply & enrichment