Neutrino-less double beta decay with gas-phase xenon

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Perspective

- NLDBD search seems to have entered a new era:

  "Maybe not big/good enough to succeed,
  but too costly to fail"
- Failure: *background-limited result: B ~ 1 event/ton/year*
- Success: *$B \leq 0.1$ event/ton/year*
- Energy resolution, extreme radio-purity, and shielding have been insufficient (to date) to achieve sensitivity at ton-scale
- Very difficult to produce background estimates based on measurements of materials/environment

Xenon: Energy resolution depends <u>strongly</u> on density!

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

<u>Fano factor</u>

F = 0.15

Unfolded resolution:

δE/E ~0.6% FWHM

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

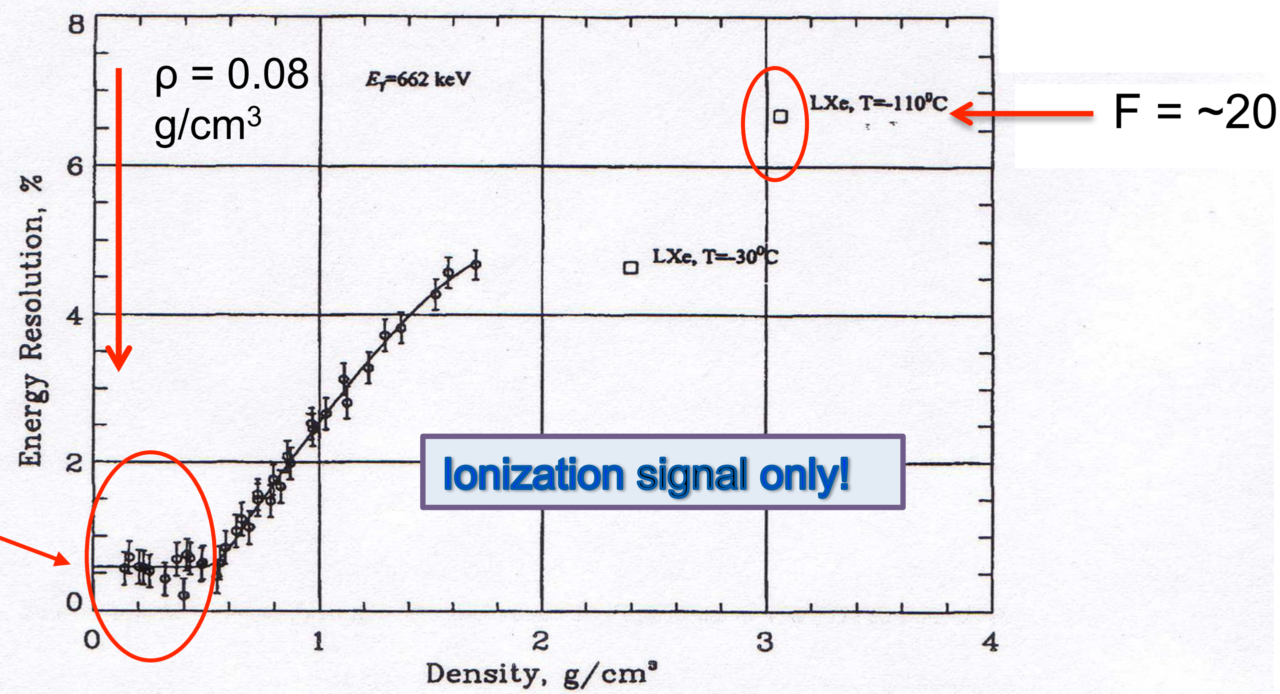


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For ρ <0.55 g/cm³, ionization energy resolution is “intrinsic”

What is occurring, as ρ increases?

- Critical temperature of xenon is room temp
- Increasing density → more "liquid phase"
- Energetic electrons create δ-rays
  - LXe + δ-rays → high ionization density
  - High ionization density → recombination
  - Recombination → scintillation
  - δ-ray spectrum → non-Gaussian behavior

→ Large energy partition fluctuations between Ionization and scintillation in LXe, but not in gas

Impact of fluctuations

- Signal fluctuations: $\sigma_N = (F \cdot N)^{1/2}$
- F = Fano factor:
  - Gas phase: F = 0.15 ± 0.03
  - Liquid phase: F ≈ 20
- A weighted sum of ionization I and scintillation S signals, E = aI + bS, can, in principle, entirely recover near-intrinsic energy resolution
- But: typical overall QDE < 20%
  → statistically impoverished corrections in LXe
- In gas phase, the ionization signal alone is sufficient

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

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

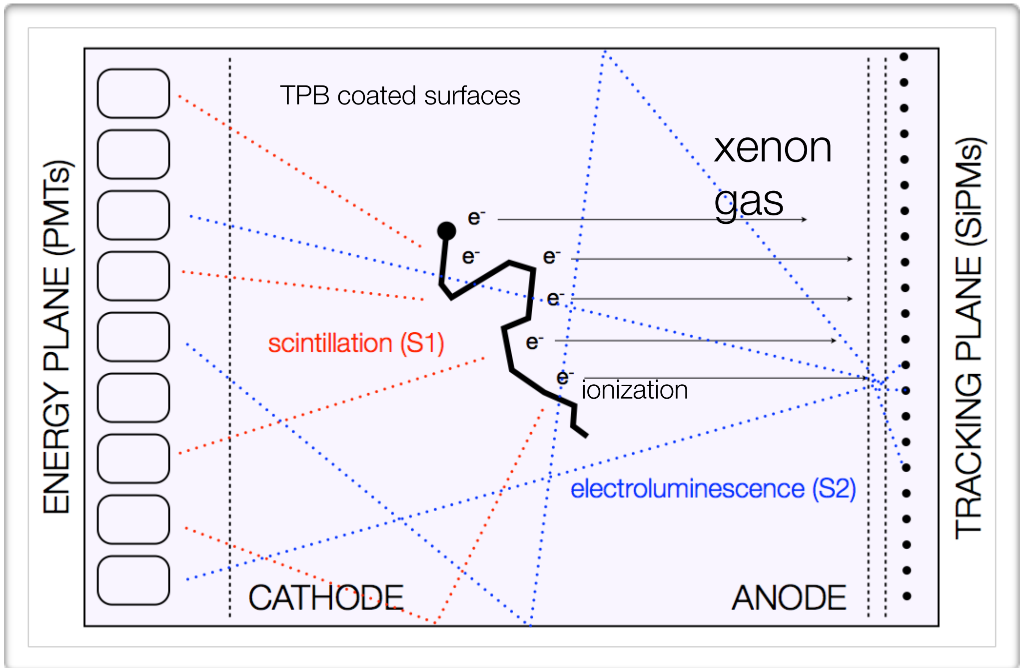
- F ≡ Fano factor (HPXe) : F = 0.15
- w ≡ Average energy per ion pair: w ~ 25 eV
- Q ≡ Energy deposited from $^{136}Xe \rightarrow ^{136}Ba$:

N = Q/w ~100,000 primary electrons

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

δE/E = 0.3% FWHM intrinsic HPXe

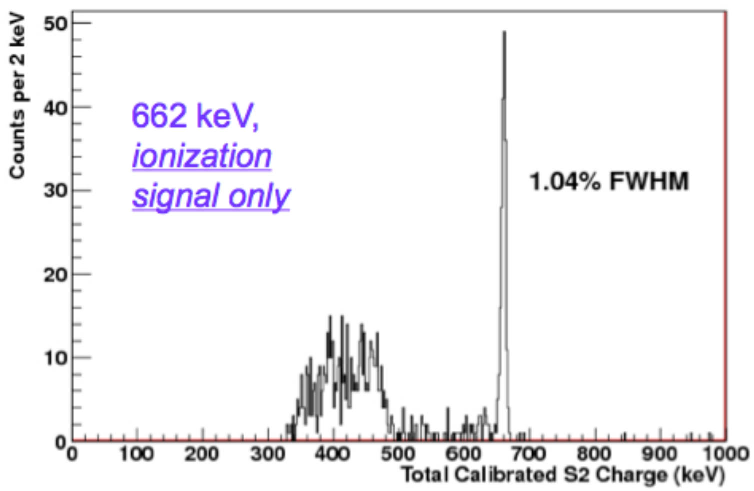
NEXT-XX: A series of photonic TPCs

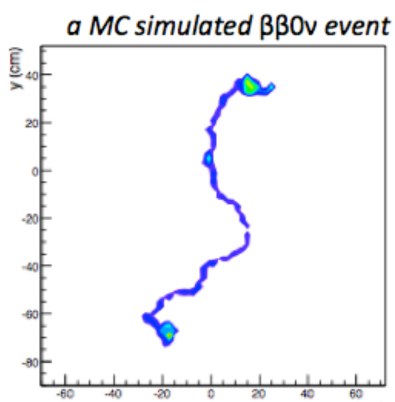


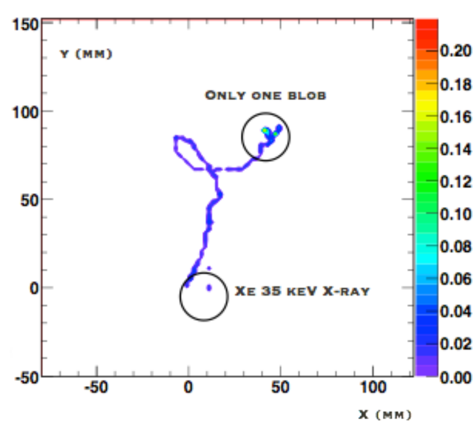
EL mode is essential to obtain linear gain; avalanche fluctuations are avoided, and the excellent Fano factor in gas is not lost

- NEXT: High Pressure Xenon (HPXe) TPC operating in electroluminescent (EL) mode.
- NEXT-100: 100 kg of Xenon enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane),
- PMTs also provide t_0 – essential for the z coordinate and fiducialization.
- The event topology is reconstructed by a plane of radiopure silicon pixels (SiPMs) (tracking plane).

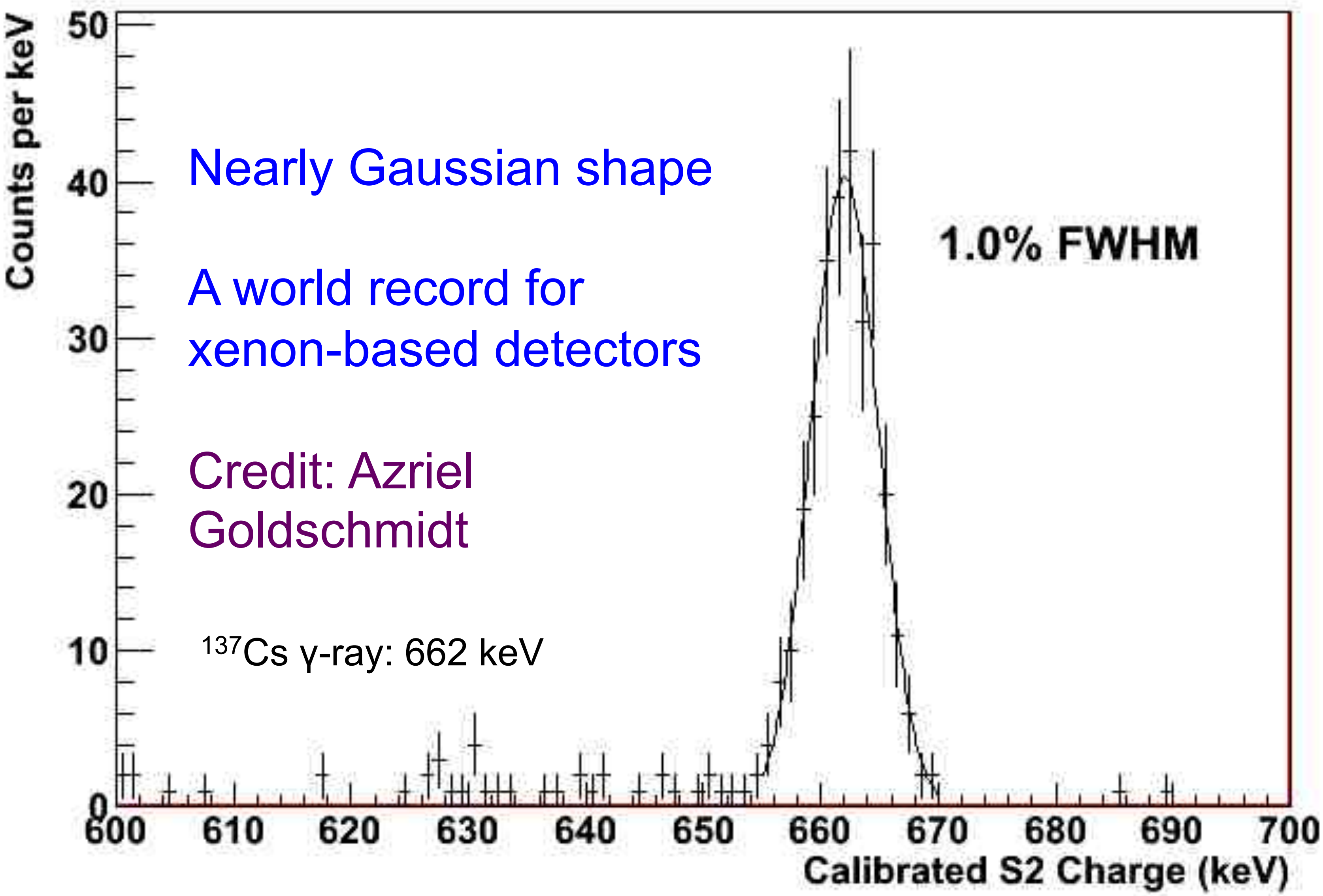
NEXT: Salient features







- Excellent resolution (~1% FWHM measured at 662 keV by NEXT prototypes, extrapolates to 0.5 % FWHM at Qbb if all systematics are well controlled
- Topological signature (TS) is the ability to distinguish between signal ("double electrons") and background ("single electrons"); evidence exists that this works well.
- Target = detector. Tracking establishes fiducial region, away from surfaces.
- TPC: generally scalable. Economies of scale; V/S ratio increases linearly with L.
- Xenon: the cheapest isotope to enrich in the market (NEXT owns 100 kg of enriched xenon, ~1 ton exists worldwide).

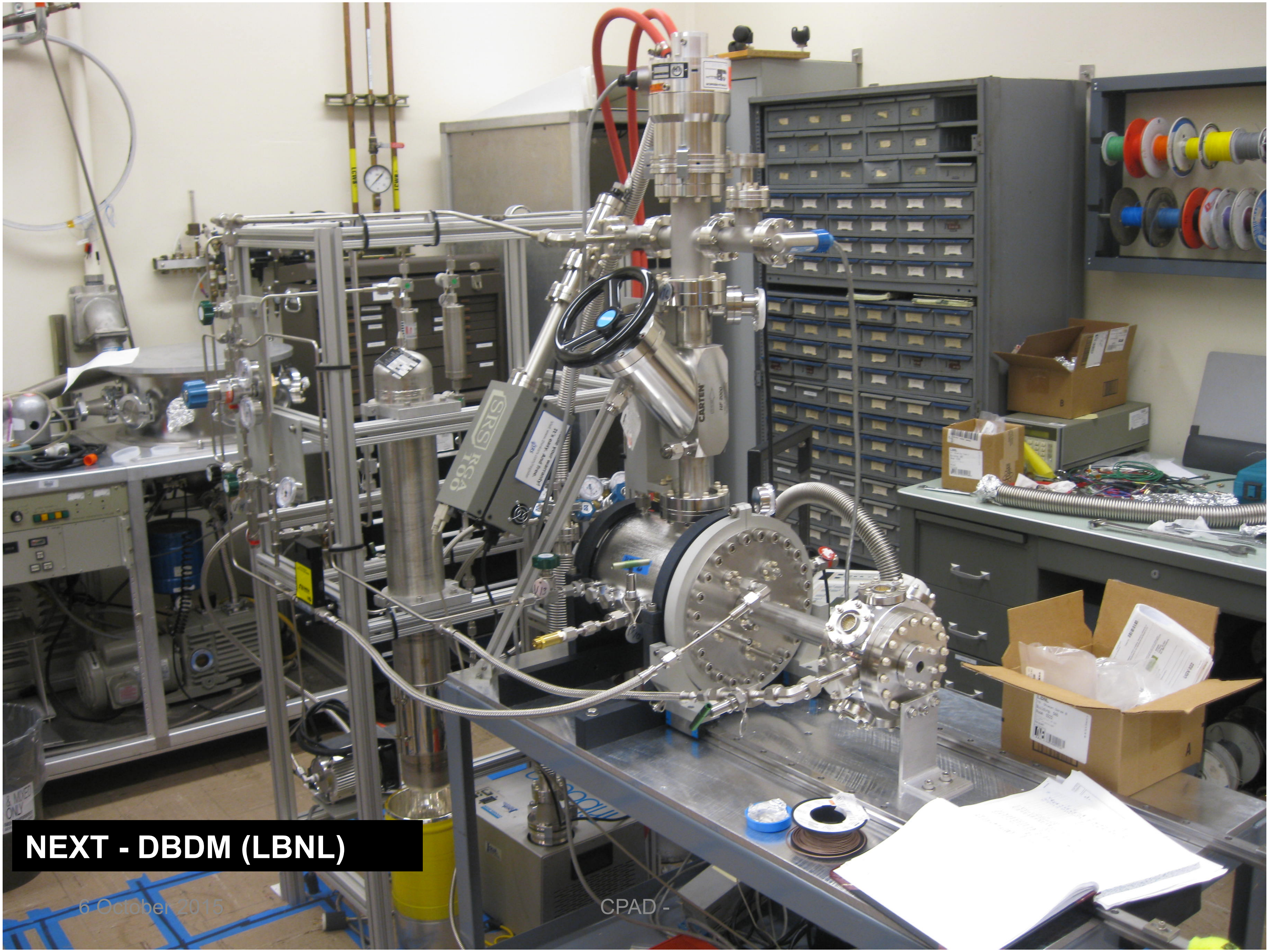


Nearly Gaussian shape

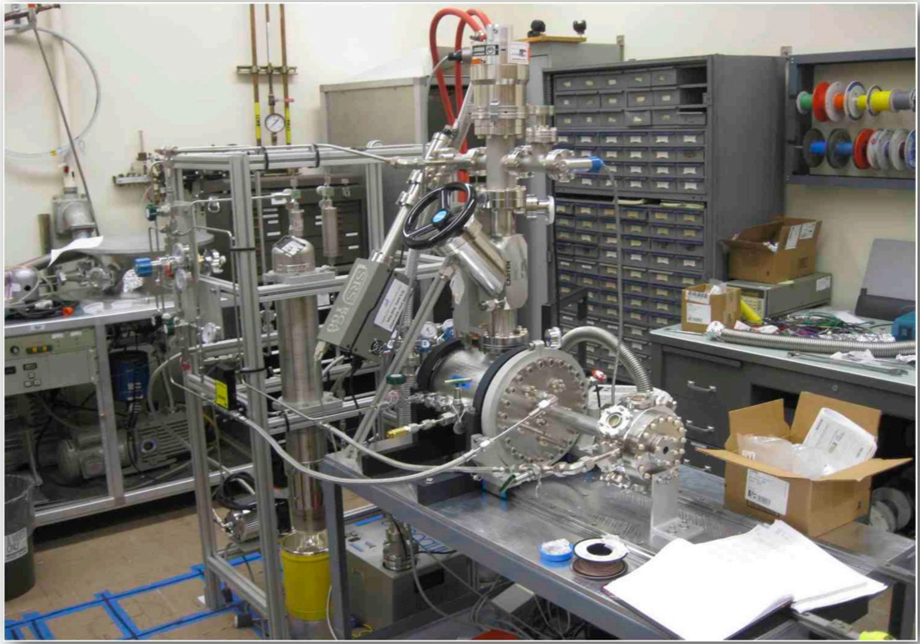
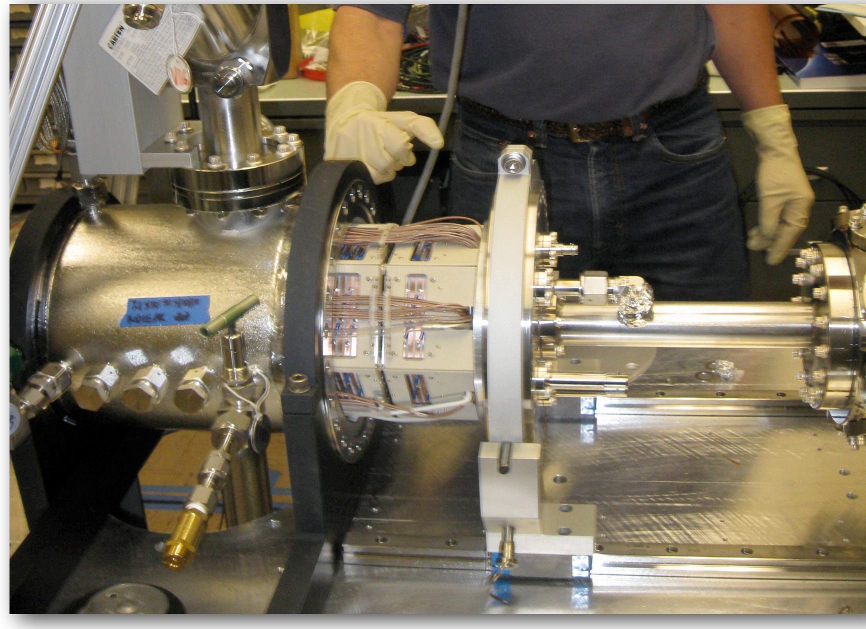
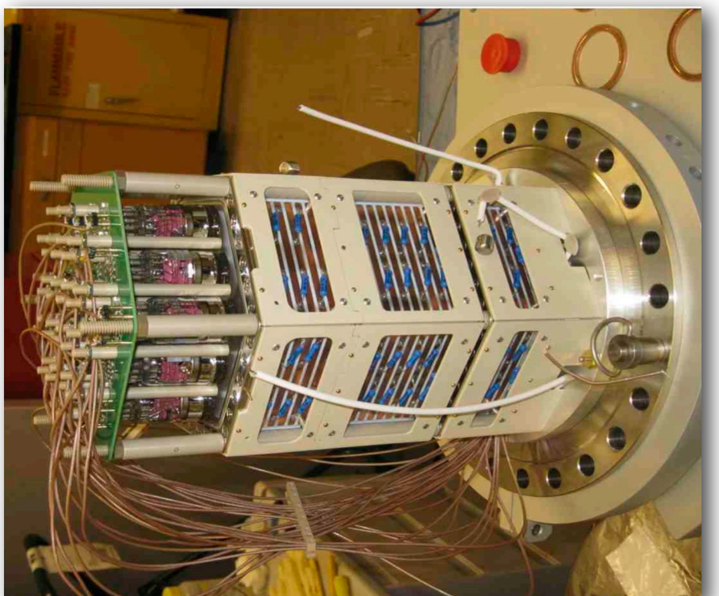
A world record for xenon-based detectors

Credit: Azriel Goldschmidt

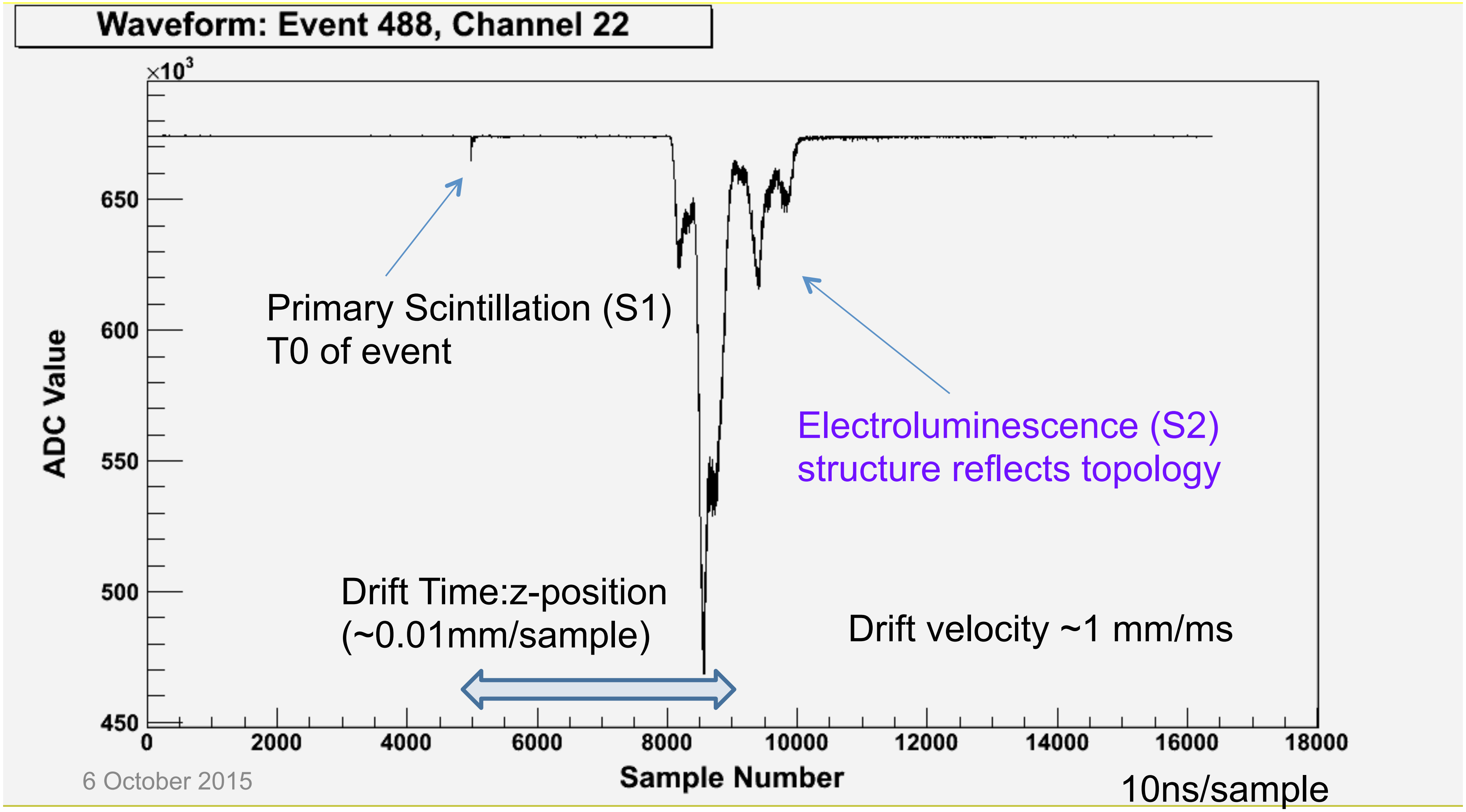
^{137}Cs γ-ray: 662 keV

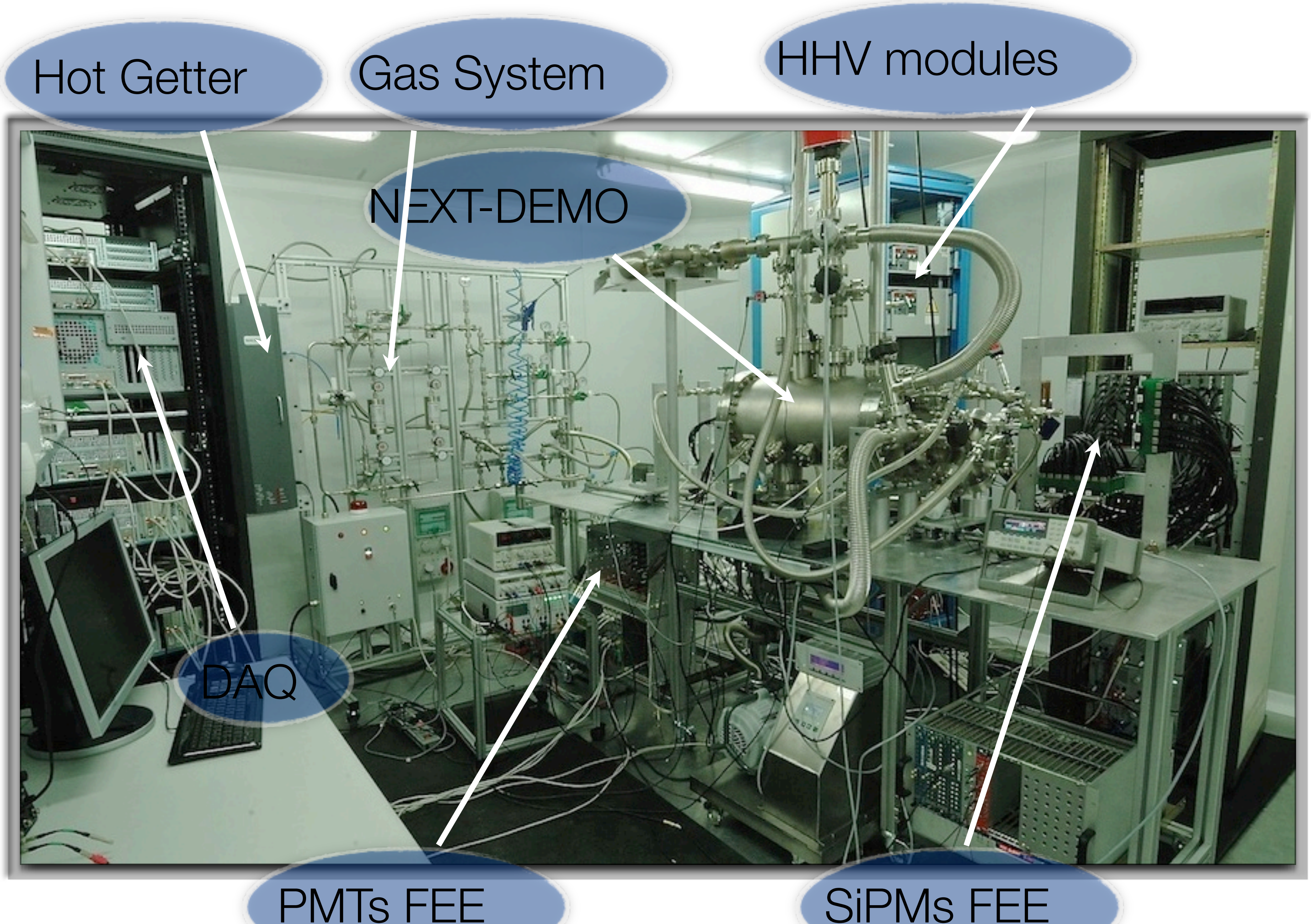


NEXT - DBDM (LBNL)

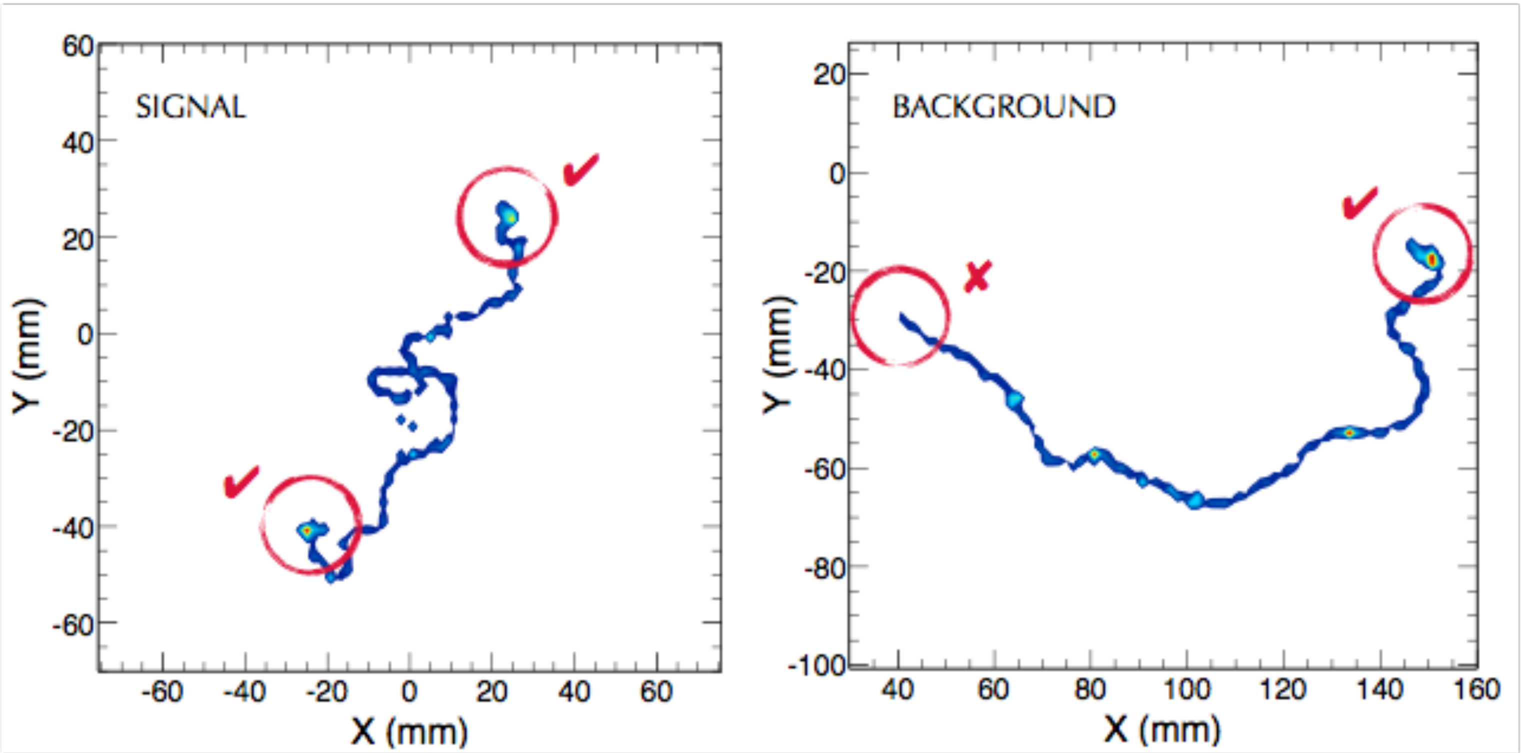




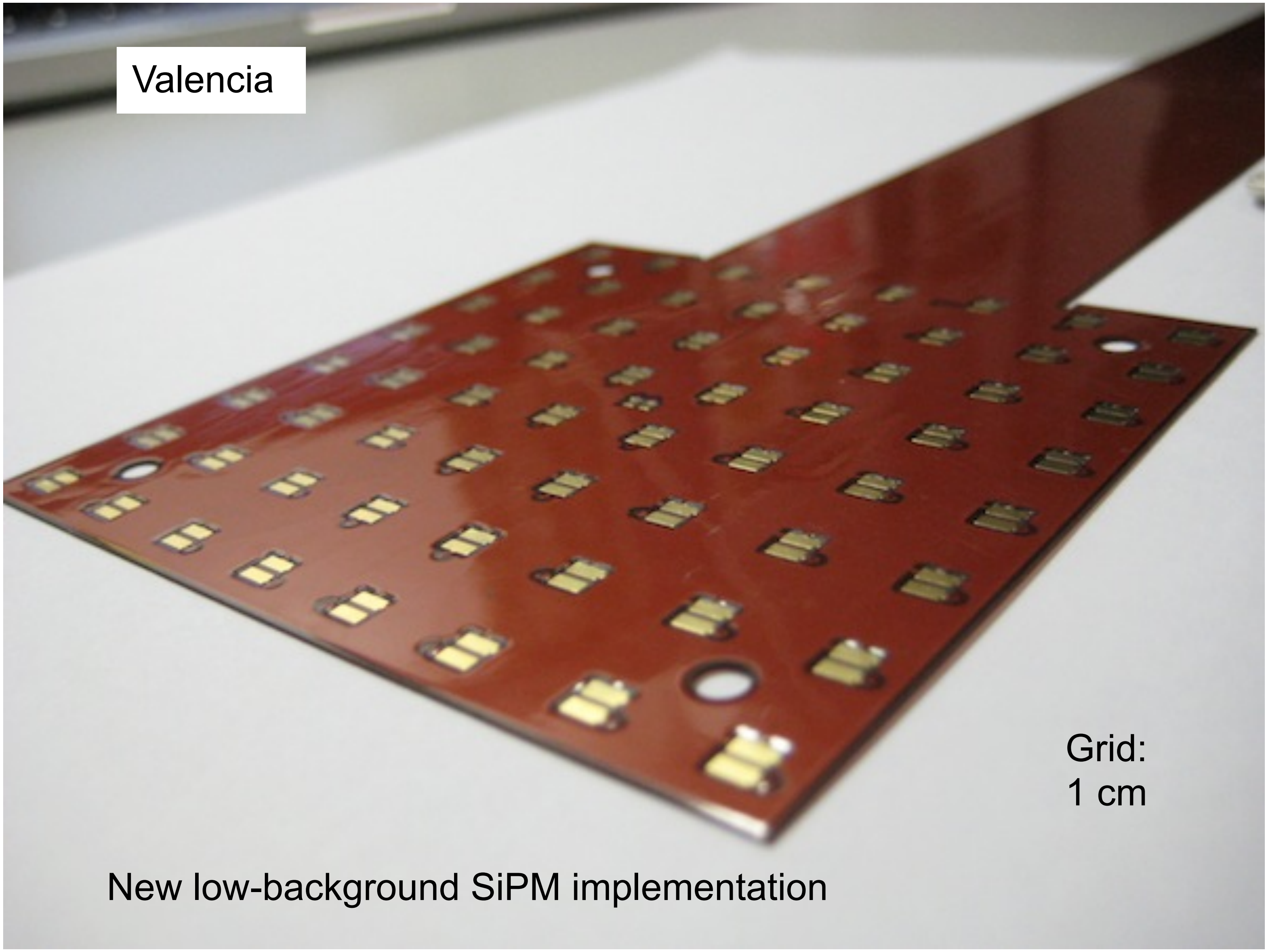

A typical ^{137}Cs γ waveform (sum of 19 PMTs)
~300,000 detected photoelectrons



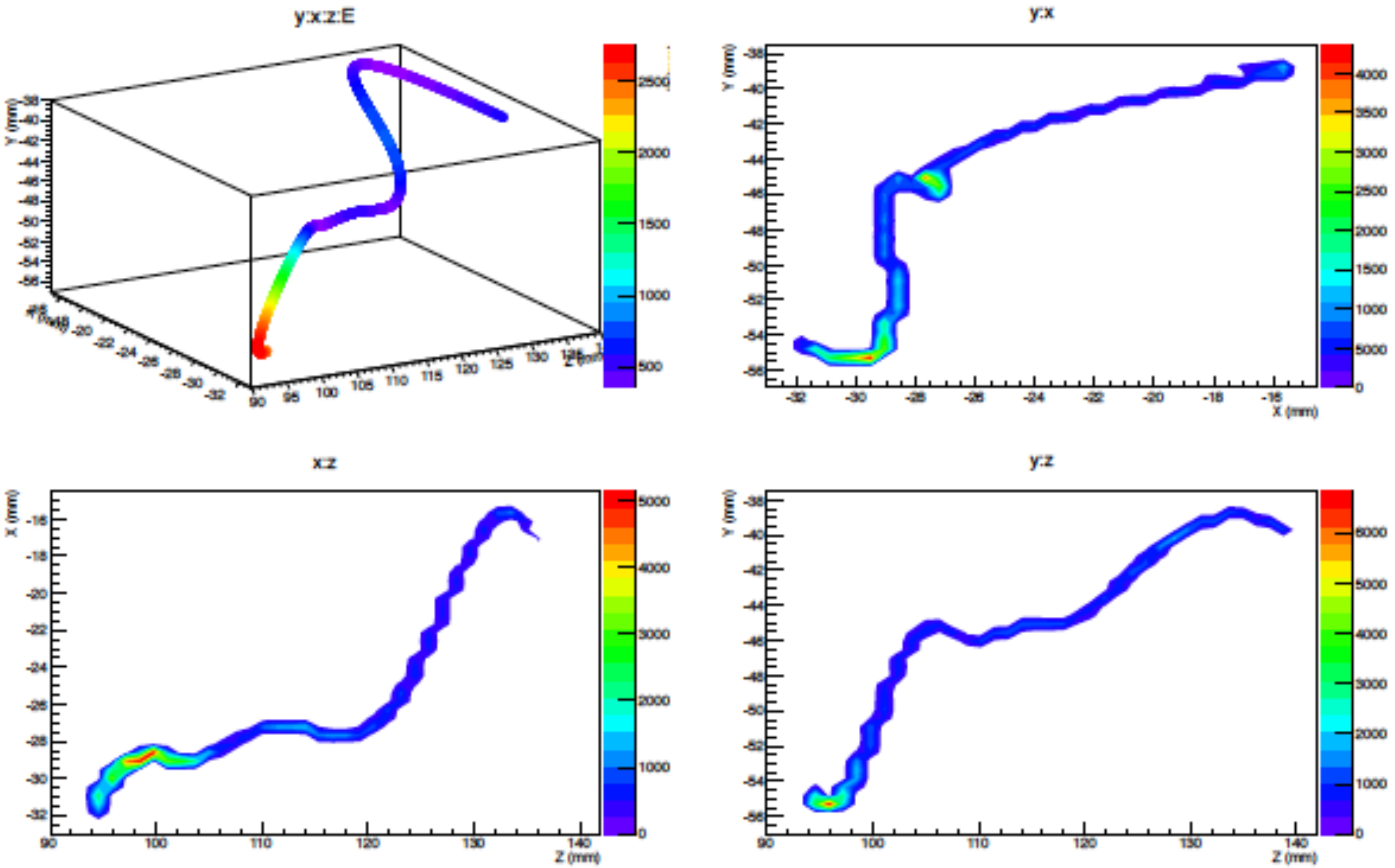

Hot Getter
Gas System
HHV modules
NEXT-DEMO
DAQ
PMTs FEE
SiPMs FEE

Topological signature - simulation

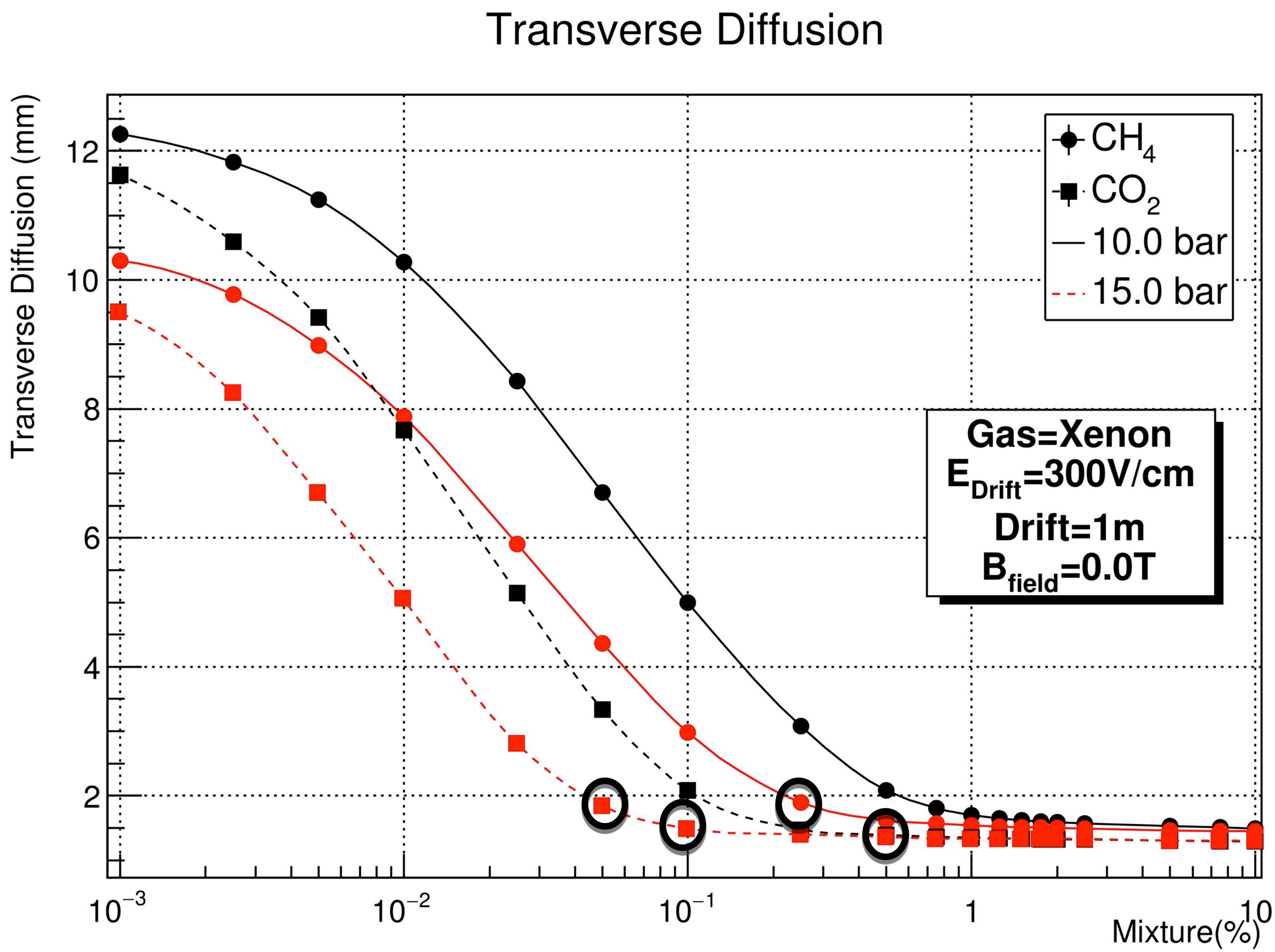



Valencia
Grid:
1 cm
New low-background SiPM implementation

DATA: Real track from ^{137}Cs γ-ray – reconstructed with SiPMs



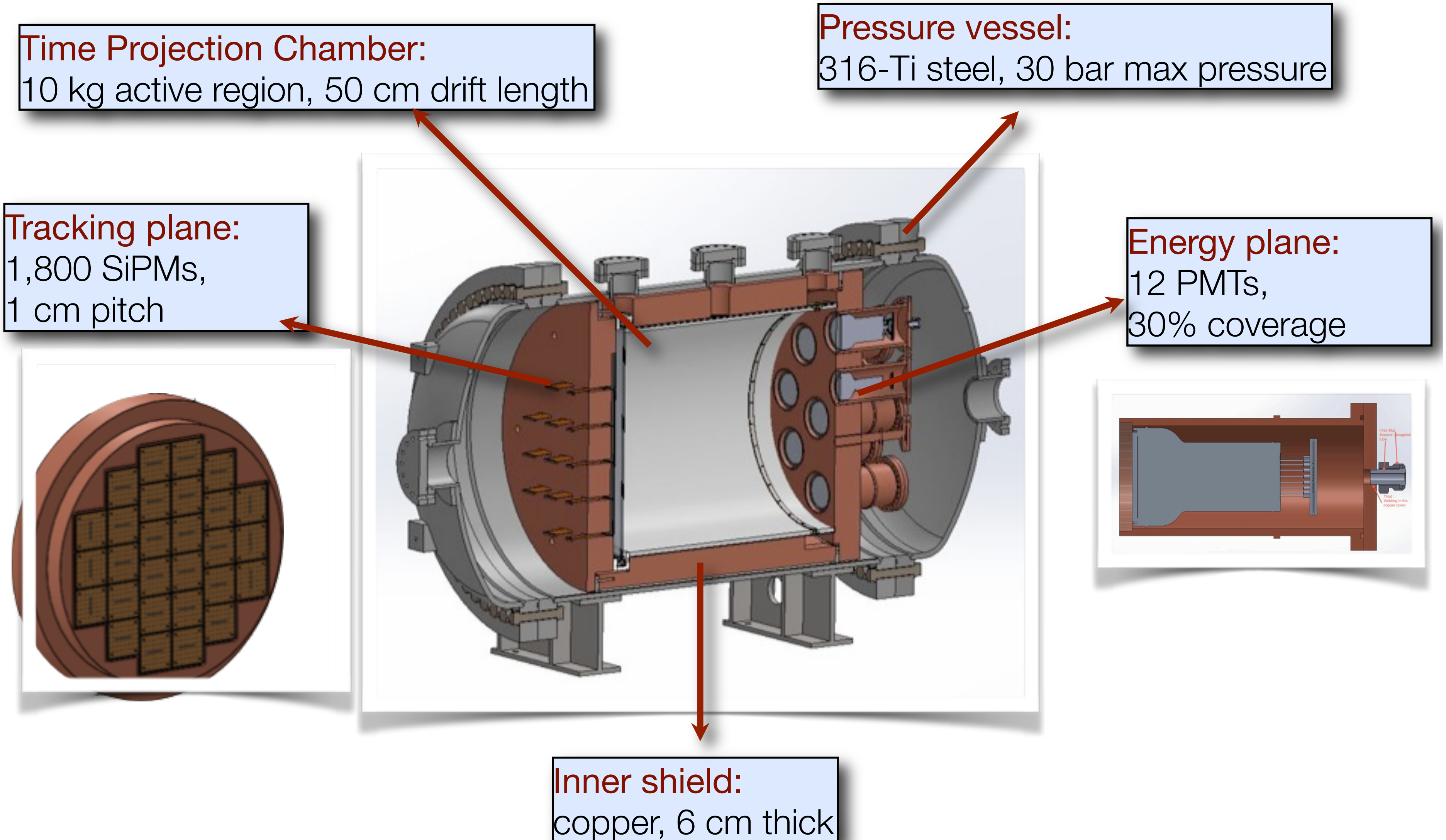
DATA from NEXT-DEMO   IFIC, Valencia



CO2: 0.1 % (CH4: 0.5 %) —> DT < 1.5 mm

CO2: 0.05 % (CH4: 0.25 %) —> DT < 2 mm

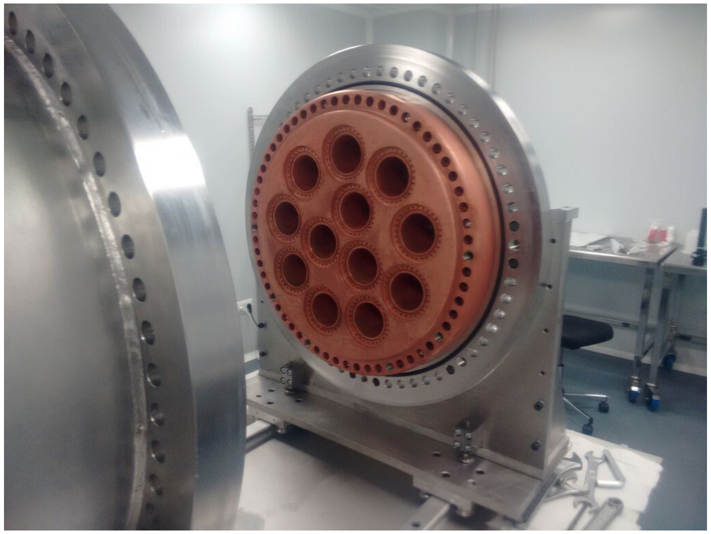
NEXT-10 at a glance

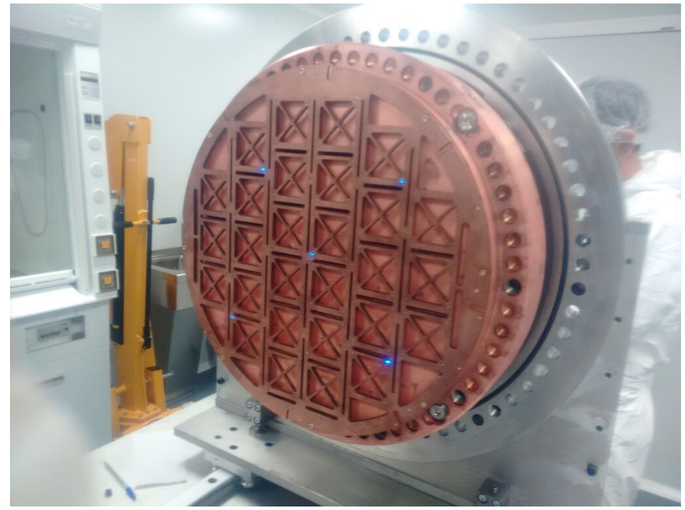


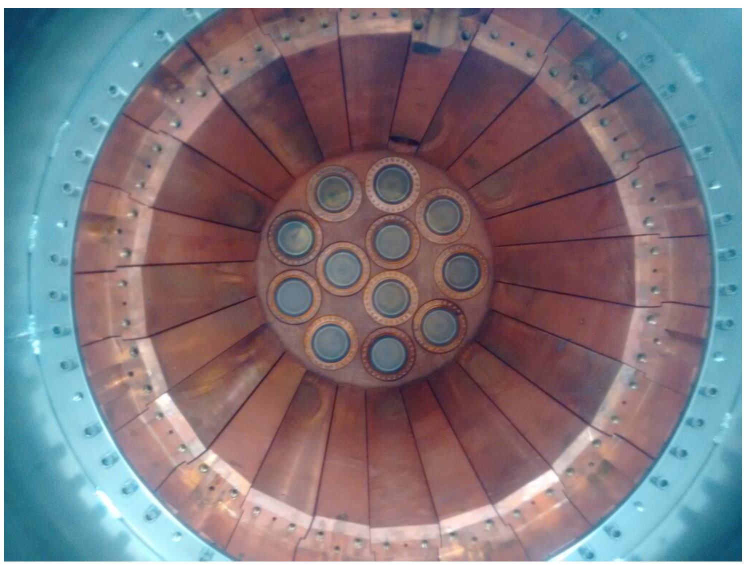
Inner copper shield

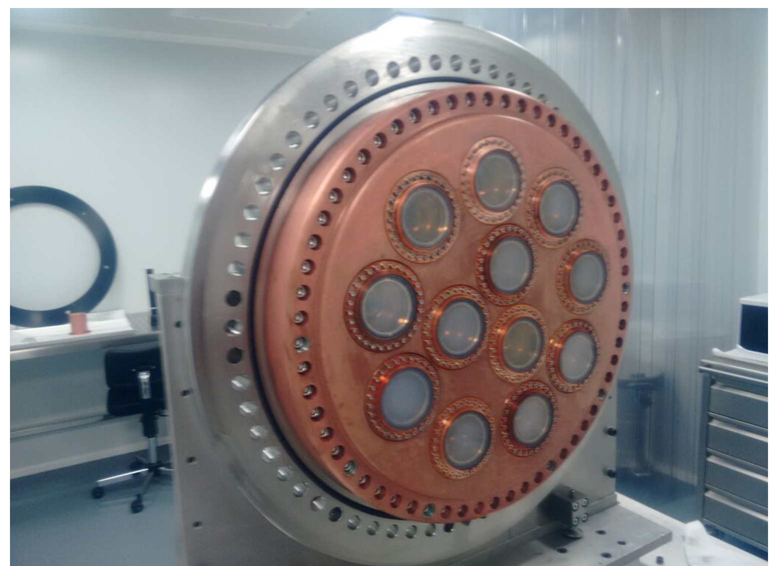
Inner Copper Shield made of low-background copper (< 10 muBq/kg)
Barrel ICS thickness is 6 cm (12 cm in NEXT-100). End-cup ICS is 12 cm (12 cm in NEXT-100)

Energy Plane installation (July 2015)

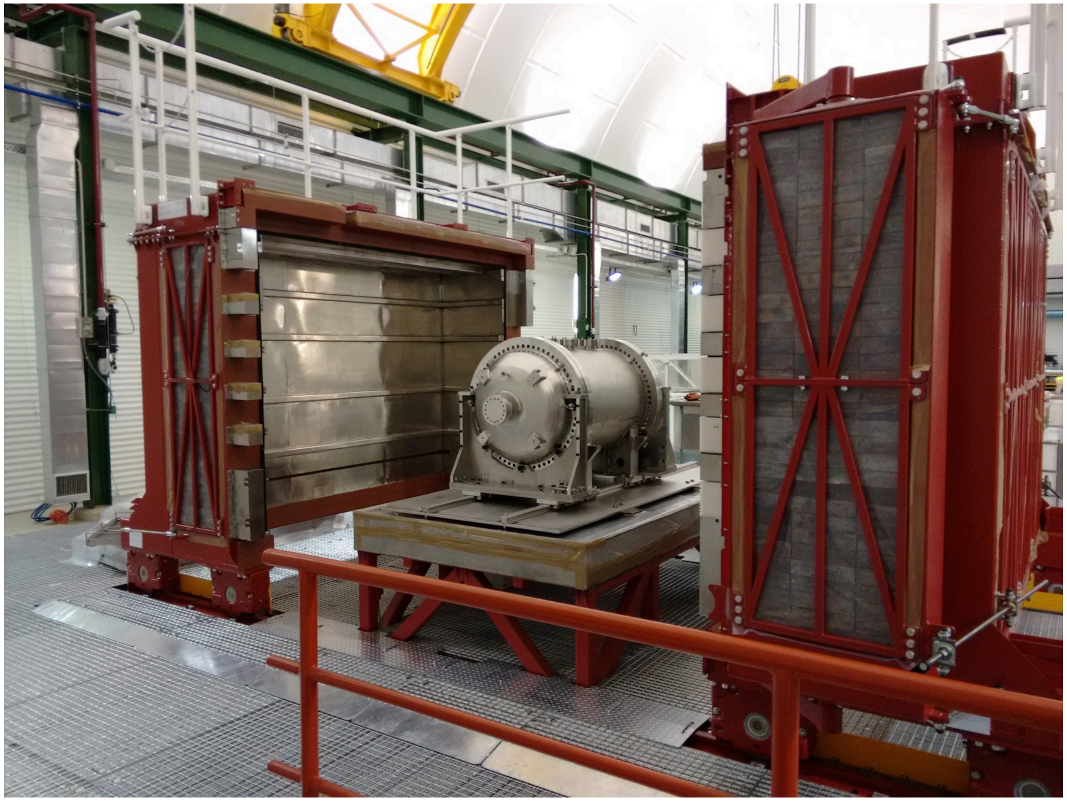








NEXT-10 at the LSC



NEXT-10 on the seismic support table, inside the Lead Castle at the LSC

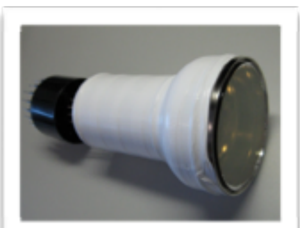
NEXT-100 Pressure Vessel

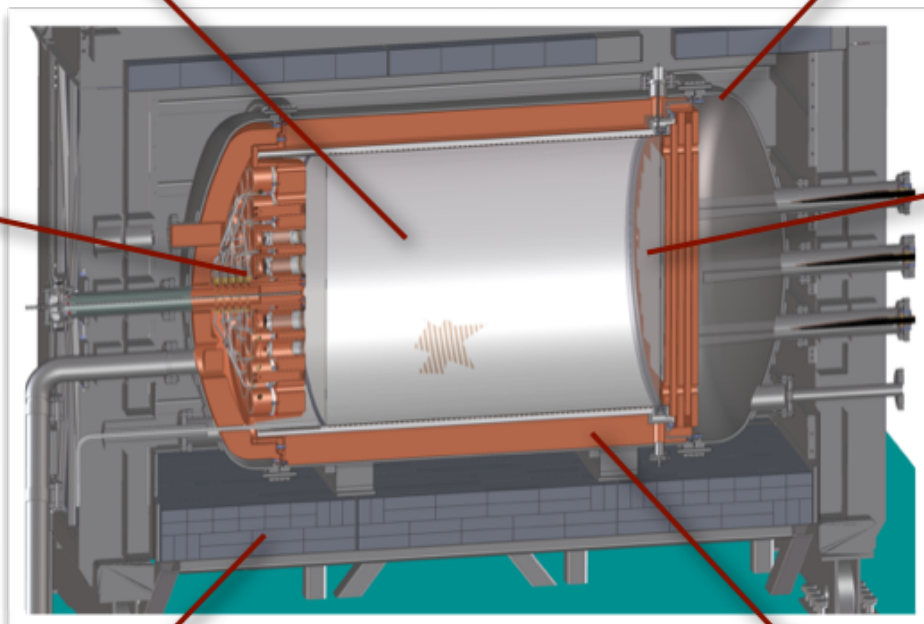
NEXT 100 kg detector at LSC: main features

Time Projection Chamber:
100 kg active region, 130 cm drift length

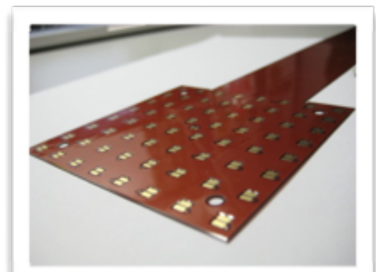
Pressure vessel:
stainless steel,15 bar max pressure

Energy plane:
60 PMTs,
30% coverage





Tracking plane:
7,000 SiPMs,
1 cm pitch



Outer shield:
lead, 20 cm thick

Inner shield:
copper, 12 cm thick

About Xenon in Gas Phase

- **Excellent <u>intrinsic</u> energy resolution in gas phase:**

  $\delta E/E < 3 \times 10^{-3}$ FWHM at ^{136}Xe $Q_{\beta\beta}$ (2457 KeV)

  Hard to realize, but maybe $\delta E/E < 5 \times 10^{-3}$ FWHM

- **Topology available for background rejection**

  Single electrons (γ-rays) create one endpoint blob

  Double-beta decay events create two endpoint blobs

- **electroluminescence → noiseless, linear gain**

- **non-cryogenic → flexibility, new approaches**

“Tagging” the barium daughter atom

- **The Reward:**
  - normal backgrounds do not make barium
  - → a (possibly) background-free experiment!
- **The Situation:**
  - Suppose ~10^{28} atoms in your fiducial volume
  - 2v ββ decays are occurring fairly often
- **The Challenge:**
  - Ideally, detect the **birth** of the barium daughter:
    - **Time window**: a few milliseconds
    - **Spatial window**: ~ 1000 mm^3 (within locus of decay electrons)

Xenon's barium daughter

- In the decay xenon → barium, the daughter atom is strongly ionized by the nascent electrons emerging from the nucleus and by shell relaxation

- Partial neutralization of barium occurs by electron capture from nearby neutral xenon atoms (ionization potential 12.14 eV)

- Process stops at Ba^{++} because the ionization potential of Ba^{++} is 10.04 eV; it can't take another electron from a neutral xenon atom

- **Ba^{++}** is the expected outcome in pure xenon, gas or liquid

Ba^{+} or Ba^{++} ??

- **Ba^{+}** ?
  - Barium must be transported out of LXe to a low-pressure trap
  - As ++ or + or neutral ??
  - For Ba^{+} spectroscopy, must ensure that barium is in Ba^{+} state
  - Must show that this ion is really associated with the event

- **Ba^{++}** ?
  - Can this natural state be exploited ***in situ*?**

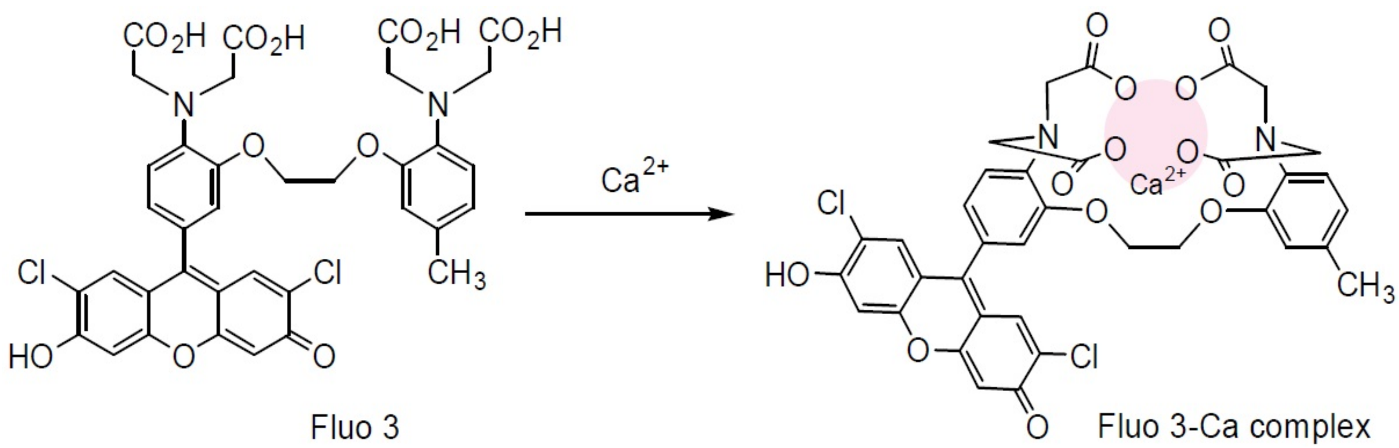
There might be a way to use Ba^{++}

- The technique of **Single Molecule Fluorescent Imaging** may be adaptable here.

- My idea is to exploit a remarkable chemical effect: the transformation of non-fluorescent molecular precursors into a robust fluorescent state by capture (chelation) of doubly ionized alkaline earth elements, such as Ca^{++}

- Maybe Ba^{++} too!
- Calcium and Barium are congeners → similar chemistry…

Fluo-3 converts from non-fluorescent to a fluorescent state by chelation!

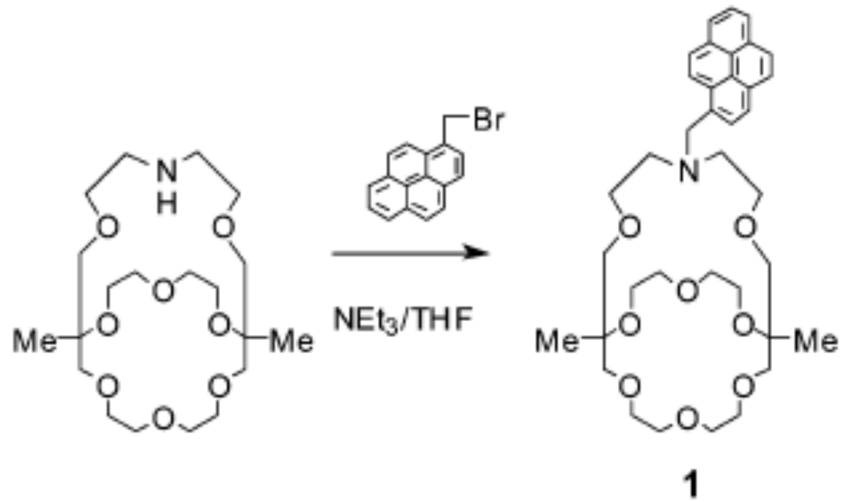


Once Ca^{++} is captured by Fluo-3, its responsiveness to external excitation increases by a factor of 60 -80. Two-photon excitation with IR is also possible

This might work for Barium as well since barium and calcium are congeners. Fluorophores exist for for Pb^{++}, Hg^{++}, Cu…)

2014 Nobel Prize in Chemistry awarded to three physicists for developing SMFI

A Fluorescent indicator specific to Ba^{++}!

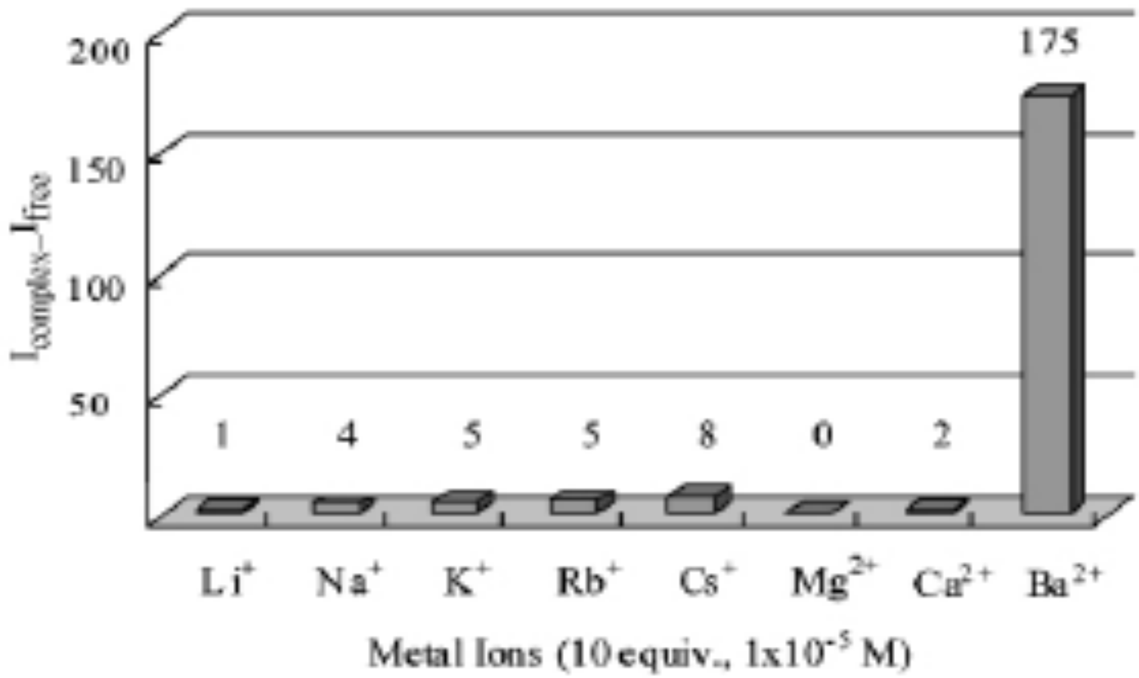


Scheme 1

"Monoazacryptand **1**"

Y. Nakahara, T. Kida, Y. Nakatasuji, M. Akashi, Chem. Comm., Roy. Soc. of Chem., 2004, p224-225

Highly specific to Ba^{++} !



The highly selective and sensitive fluorescence detection of Ba^{2+} among alkali metal and alkaline earth metal cations was successfully achieved in aqueous media by the combination of a novel monoazacryptand type of fluorophore and micelles of Triton X-100.

A TPC with a fluorescent cathode?

- One can imagine a cathode surface coated with untransformed molecules, waiting to respond strongly after capture of one Ba^{++}.

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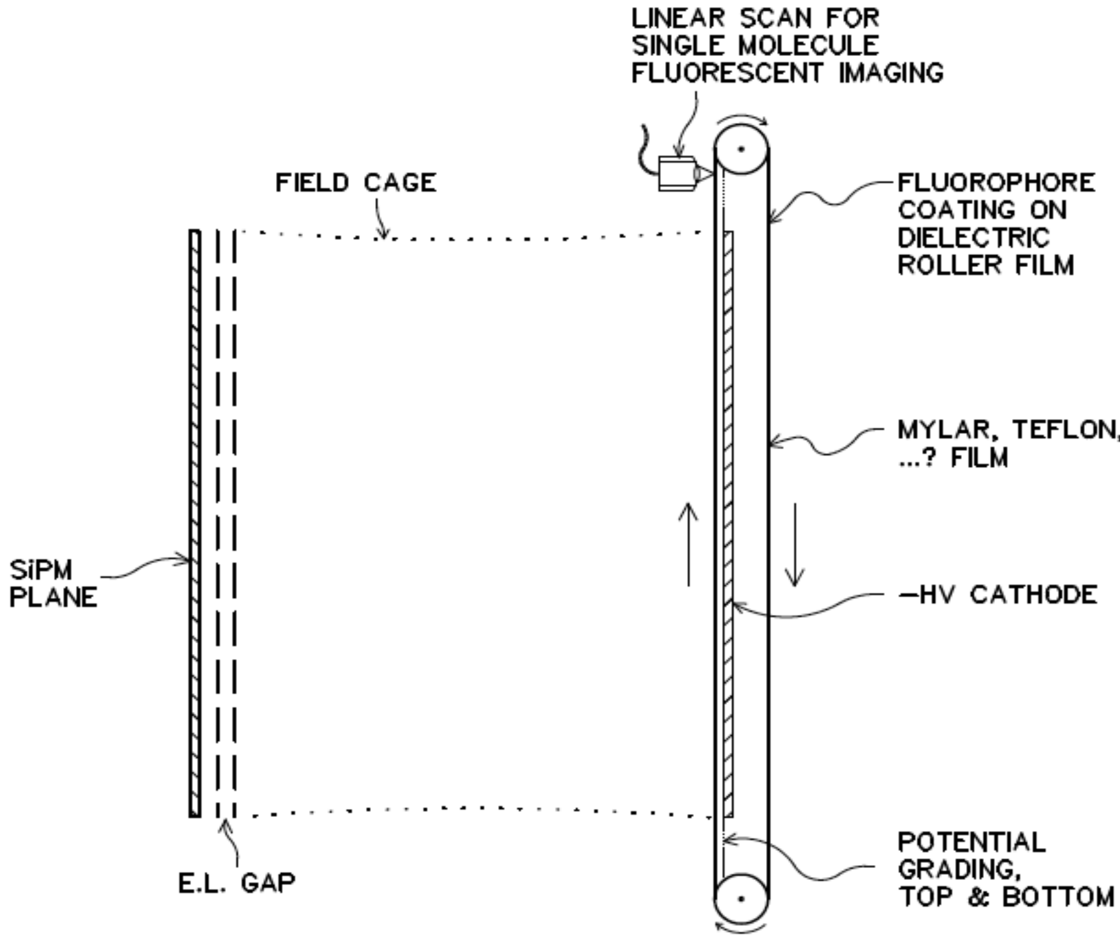
A TPC with a fluorescent cathode?

- One can imagine a cathode surface coated with untransformed molecules, waiting to respond strongly after capture of one Ba^{++}.
- One can imagine that the cathode surface is a dielectric belt that transports at a few mm/s the latent image to a molecular-ionic imager.
- Ionization electrons liberated by the decay electrons provide a 3-D image of the event, and also the needed energy resolution, *a la* NEXT



HIGH PRESSURE XENON GAS ELECTROLUMINESCENT TPC
WITH SINGLE MOLECULE FLUORESCENT IMAGING OF BARIUM DAUGHTER

Not quite right…

- Molecular coating may not be stable on belt?
  - Leave belt uncoated…
  - Transfer ion to a coated roller by electrostatics
  - Chelation occurs on roller

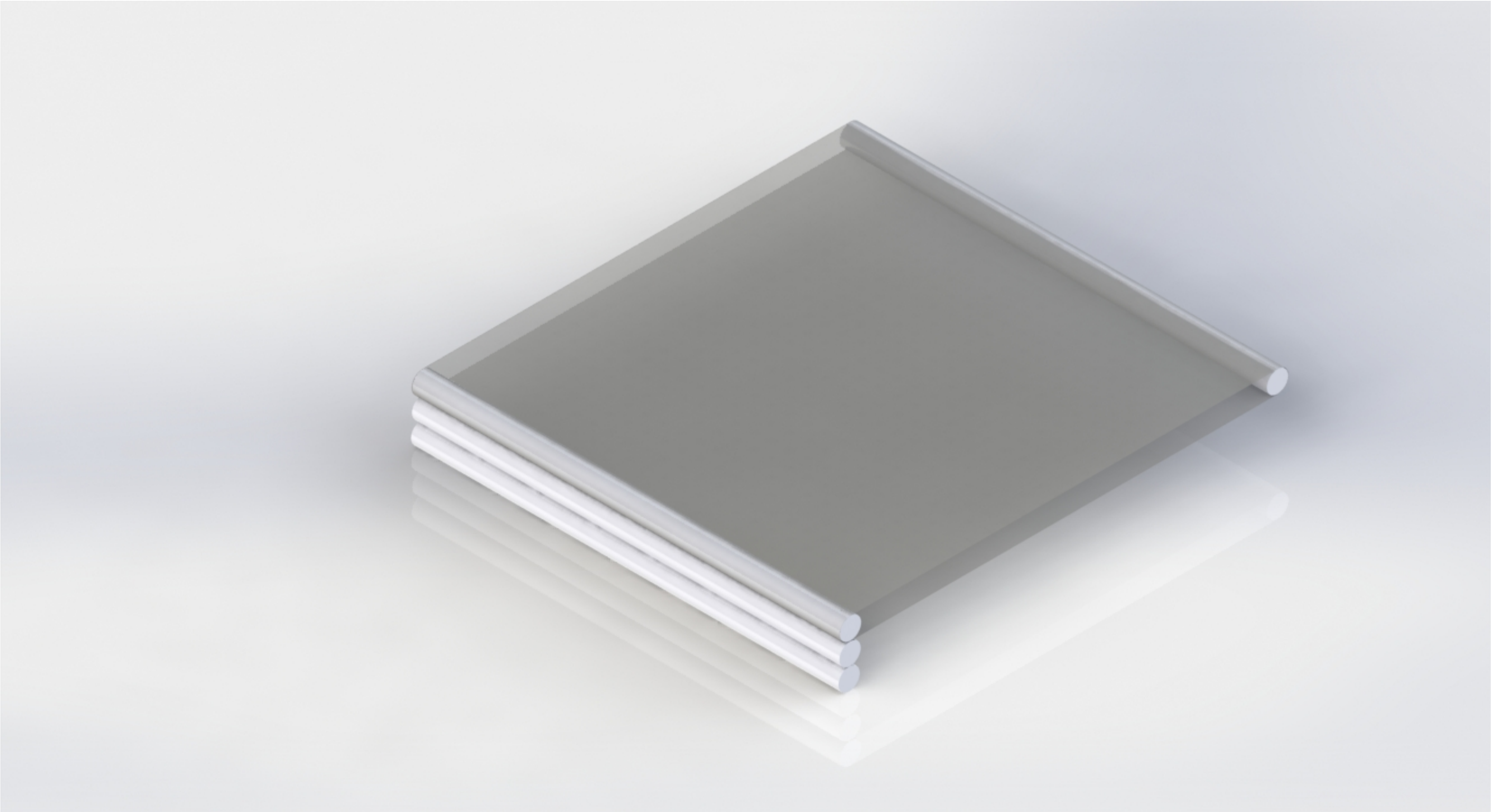
Not quite right…

- Molecular coating may not be stable on belt?
  - Leave belt uncoated…
  - Transfer ion to a coated roller by electrostatics
  - Chelation occurs on roller
- The non-fluorescent molecular precursors may still contaminate the scan:
  - Extract the chelated ion to a second roller
  - Only chelated ions exist on second roller

Not quite right…

- Molecular coating may not be stable on belt?
  - Leave belt uncoated…
  - Transfer ion to a coated roller by electrostatics
  - Chelation occurs on roller
- The non-fluorescent molecular precursors may still contaminate the scan:
  - Extract the chelated ion to a second roller
  - Only chelated ions exist on second roller
- Do SMFI scans on second roller
  - Discovery of new ions is automatic
  - Repeated verification scans are automatic

The belt + rollers scenario



Transform appearance of new Ba++ chelate back into TPC volume

Clearly, an out-of-the-box idea!

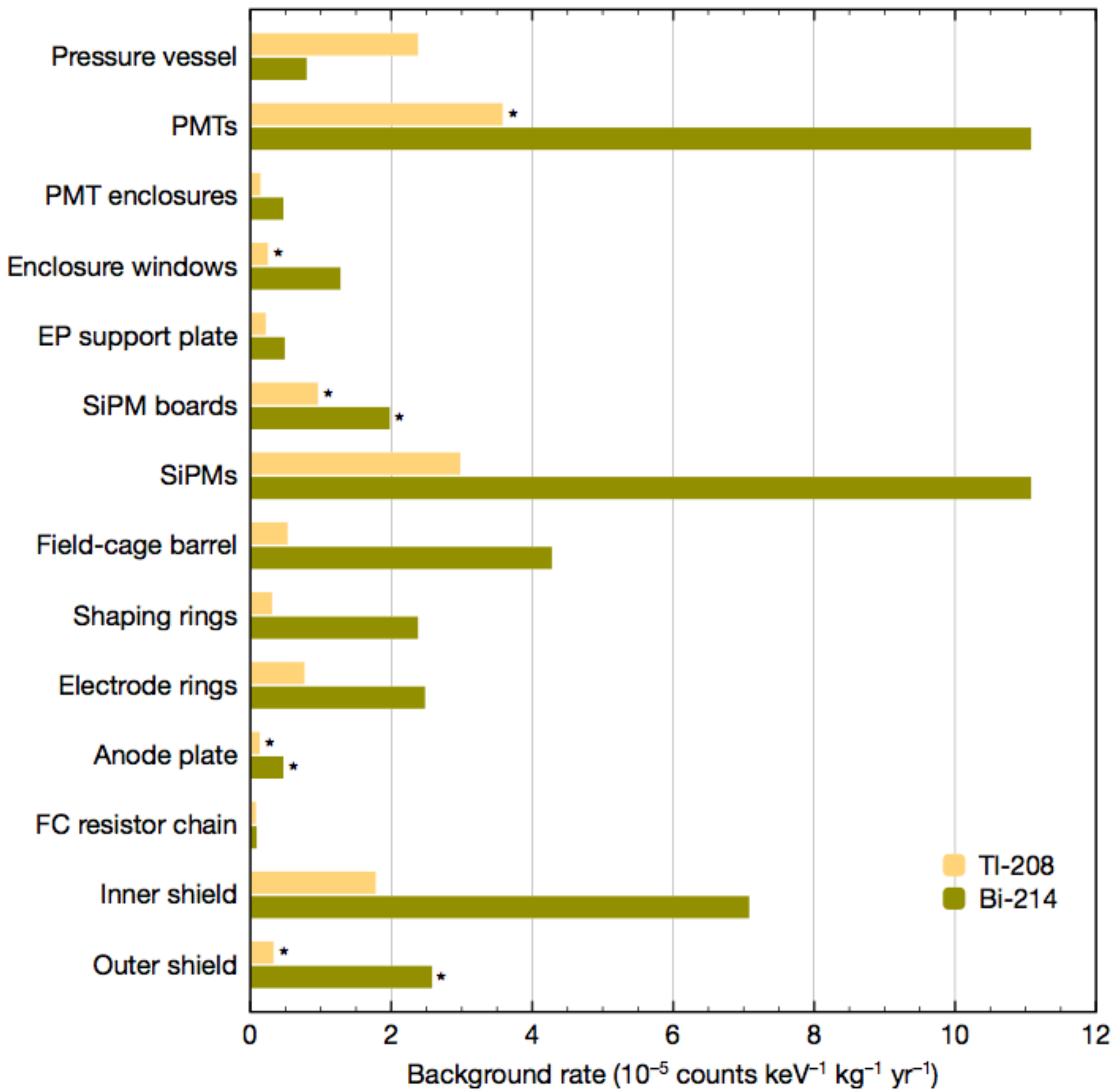
- Not clear if this idea can really work!
  - many unfamiliar but plausible steps must be efficient
- Current issues include:
  - How to make a Ba^{++} source for test setups
  - impact of neutral xenon atoms clustering around Ba^{++}
  - Transfers, molecular coatings, single molecule sensitivity…
- The idea serves to stretch our imagination!
- If any practical barium-tagging solution exists, it is unlikely to have a conventional nature.

Outlook

- NEXT-10:
  - Demonstrate power of topological signature using 2-ν decays; explore benefits of diffusion reduction; tracking density; optimize algorithmic approaches
- NEXT-100:
  - Demonstrate scalability; energy resolution; tracking; calibration; stability; limit on 0-ν decay
- NEXT-XXX ??
  - perhaps: a set of N 300 – 400 kg modules; both enriched and depleted xenon running possible
  - Ba^{++} tagging *in situ* may permit background free result

Thank you

Backup slides

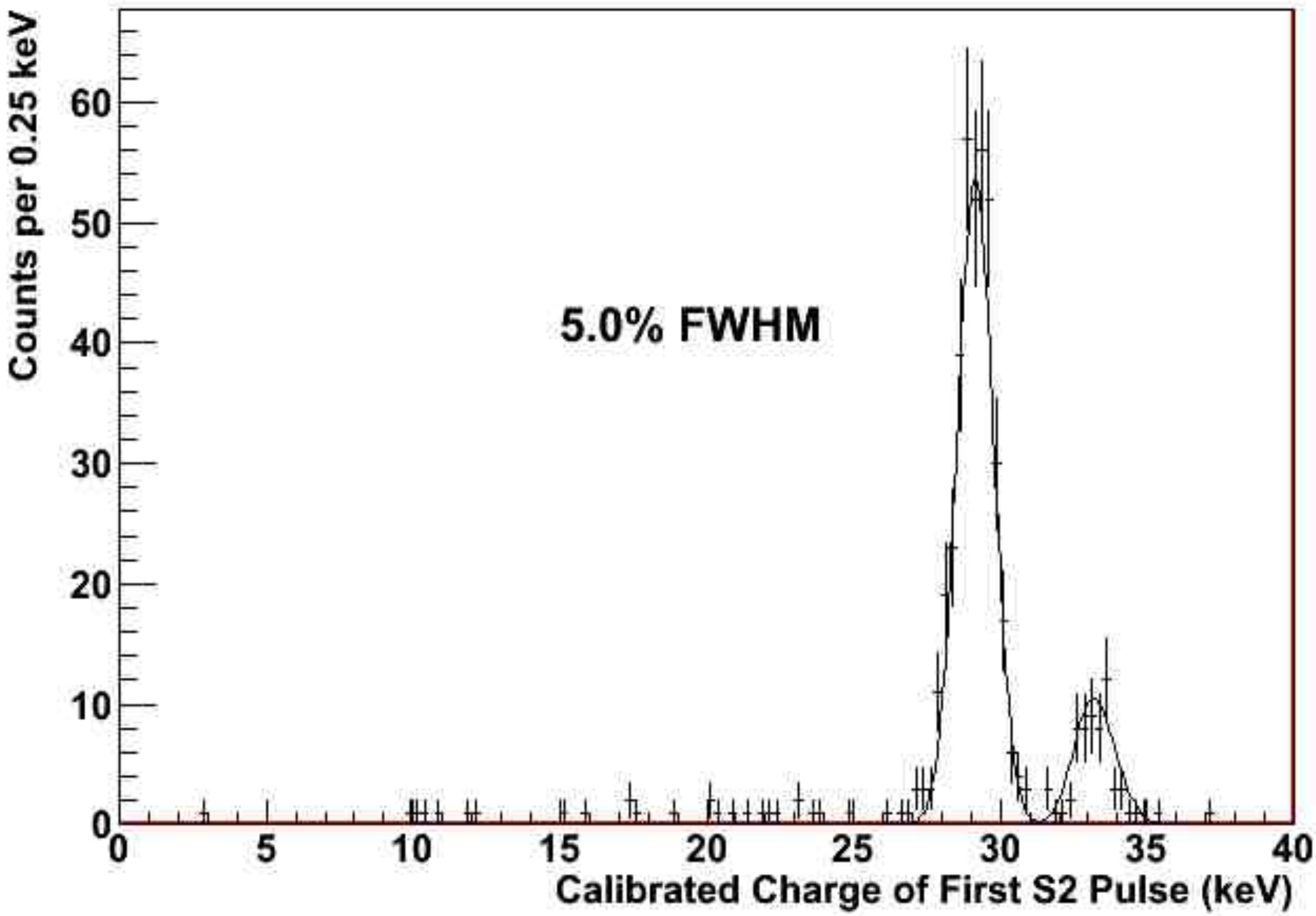


Background model dominated by limits rather than by actual values

Background Limit:
5.8 x 10^{-4} ckky

measured *
otherwise, a limit

The x-ray peaks at ~30 keV are captured precisely



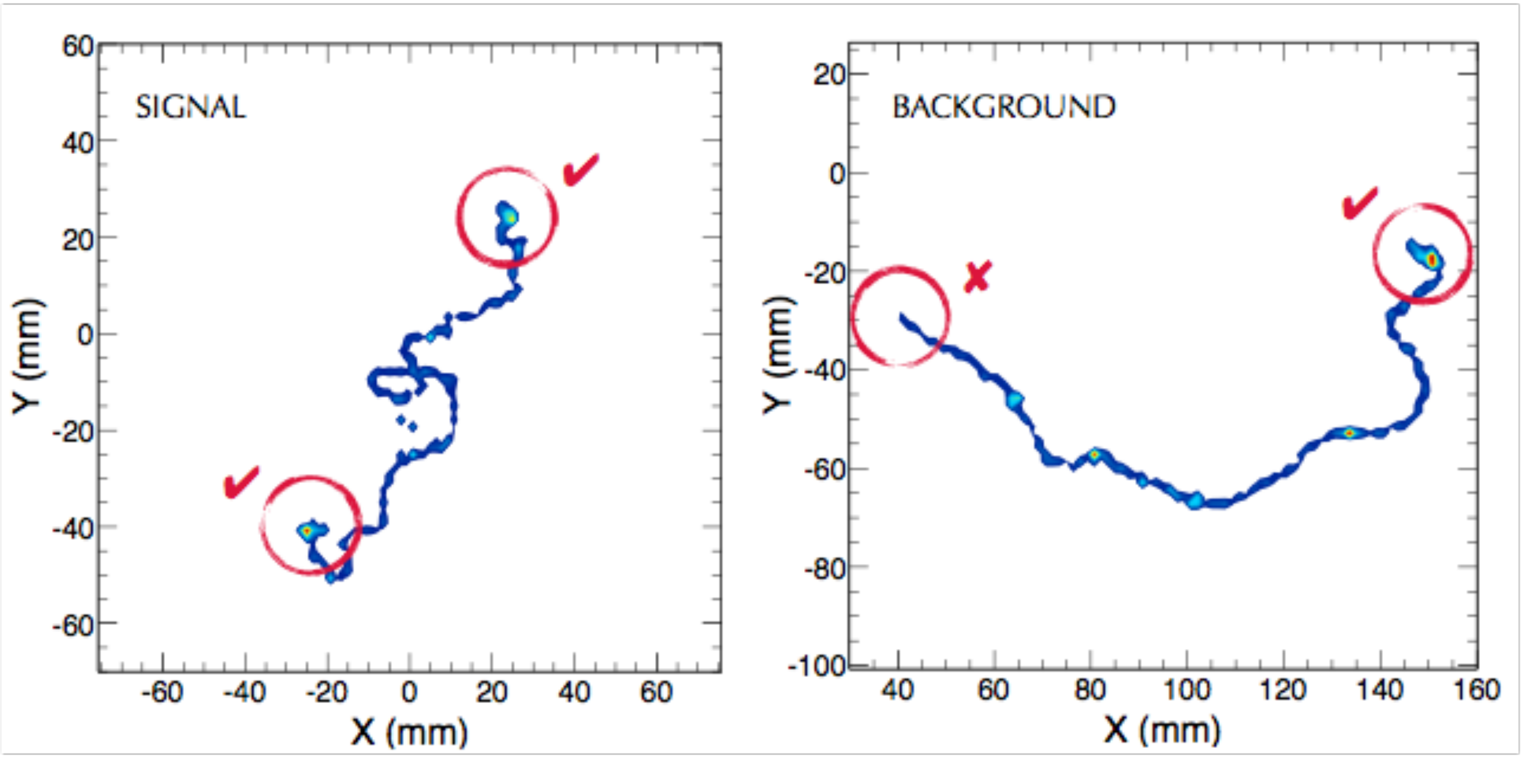
NEXT Expected Performance

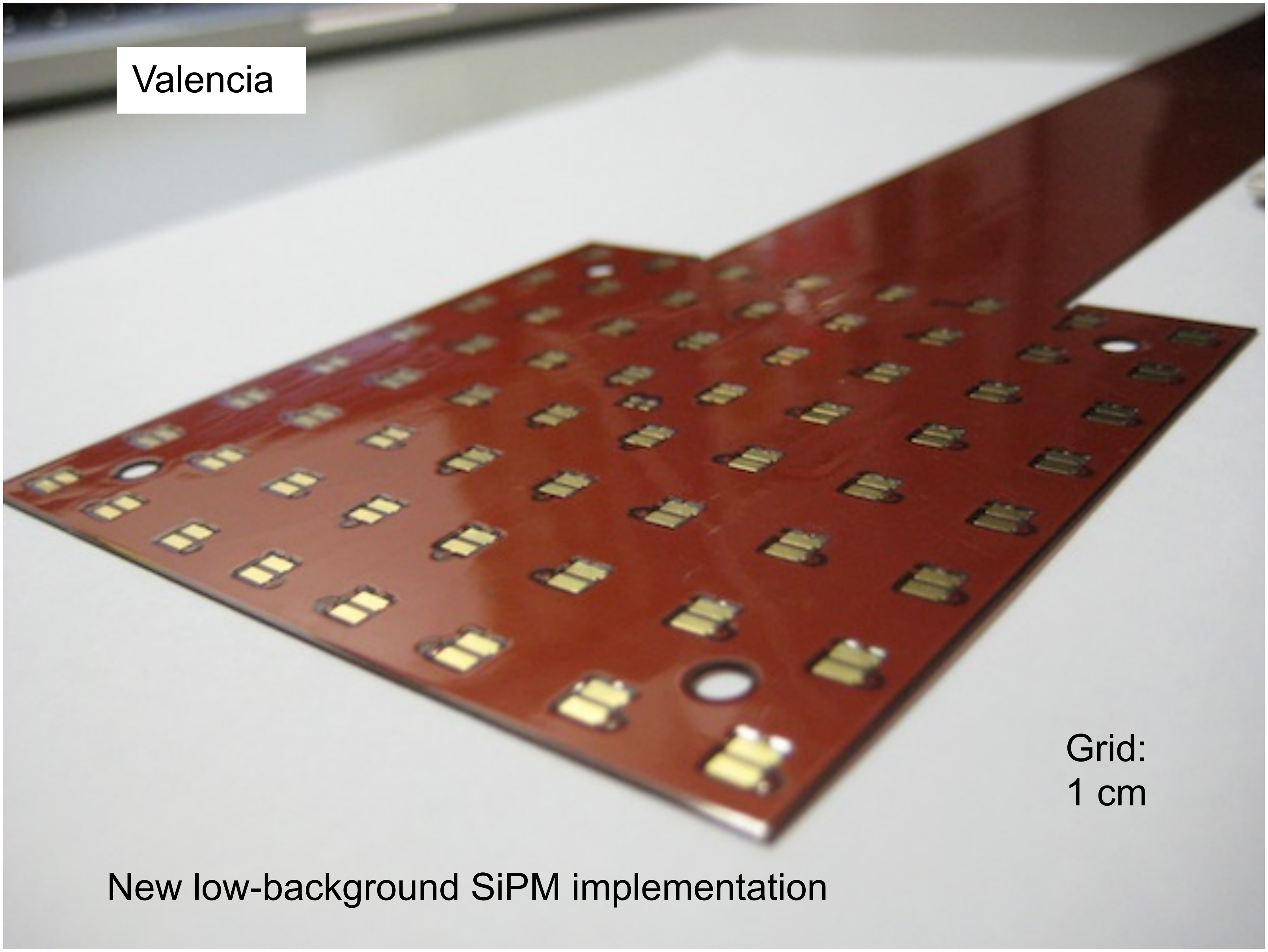
Systematic assay of ALL detector components at the LSC HPGe facility
Development of full MonteCarlo simulations

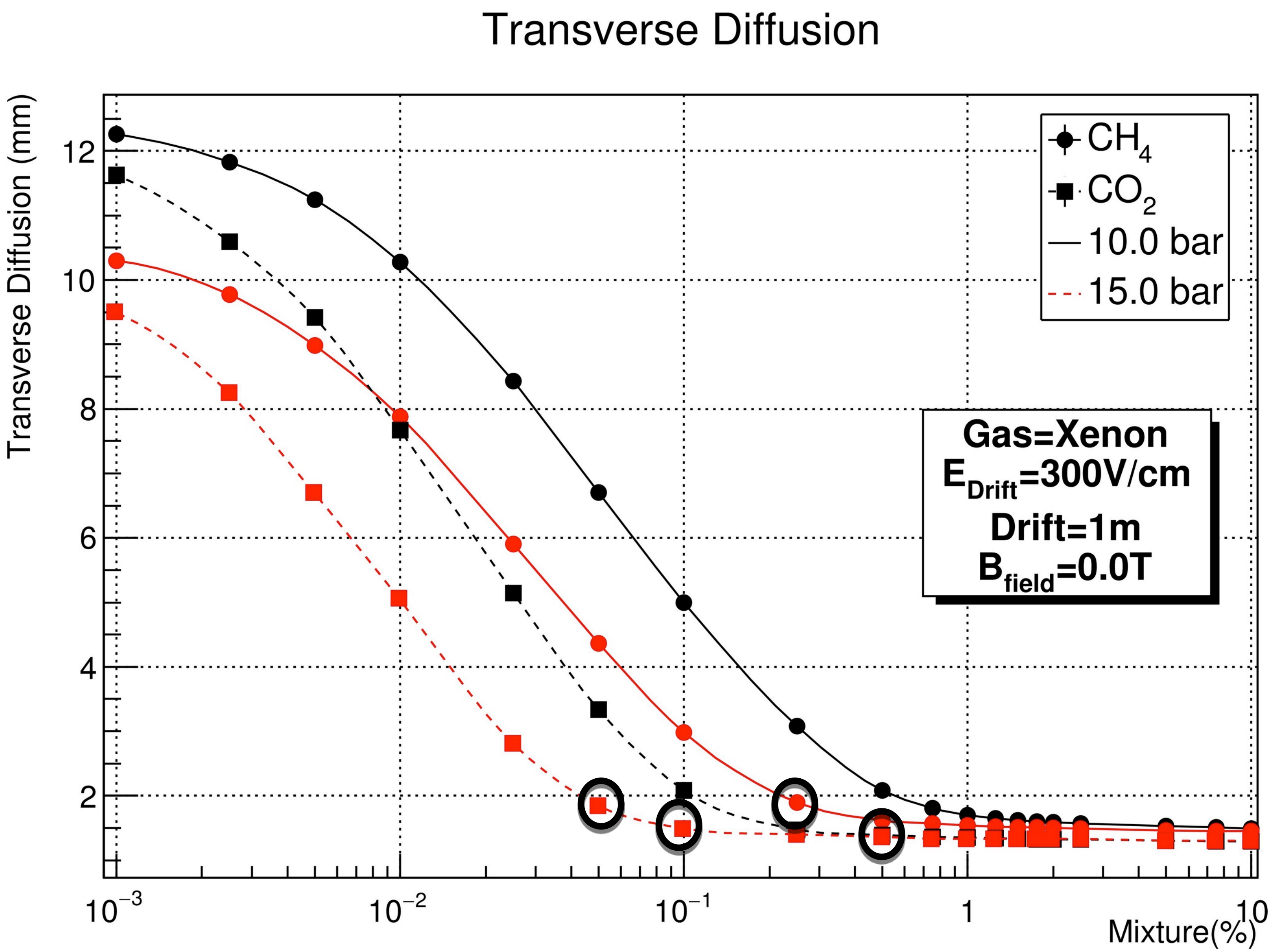
Selection criterion	$\beta\beta0\nu$	$\beta\beta2\nu$	^{208}Tl	^{214}Bi
Fiducial, single track $E \in [2.4, 2.5]$ MeV	0.4759	8.06×10^{-9}	2.83×10^{-5}	1.04×10^{-5}
Track with 2 blobs	0.6851	0.6851	0.1141	0.105
Energy ROI	0.8661	3.89×10^{-5}	0.150	0.457
Total	0.2824	2.15×10^{-13}	4.9×10^{-7}	4.9×10^{-7}

Detector subsystem	^{208}Tl	^{214}Bi	*Total*
Pressure vessel	< 0.23	< 0.06	< 0.29
Energy plane	< 0.57	< 2.10	< 2.67
Tracking plane	< 0.40	< 0.50	< 0.90
Electric-field cage	< 0.15	< 0.81	< 0.96
Inner shielding	< 0.05	< 0.7	< 0.75
Outer shielding	0.027(13)	0.25(14)	0.28(14)
Total	< 1.43	< 4.42	< 5.85 10^{-4} /(keV kg yr)

Topological signature - simulation




Valencia
Grid:
1 cm
New low-background SiPM implementation



CO_2: 0.1 % (CH_4: 0.5 %) —> DT < 1.5 mm

CO_2: 0.05 % (CH_4: 0.25 %) —> DT < 2 mm

Original tagging idea:
1980 - 1991

Identify the barium daughter by optical spectroscopy

(M.Moe PRC44 (1991) 931)

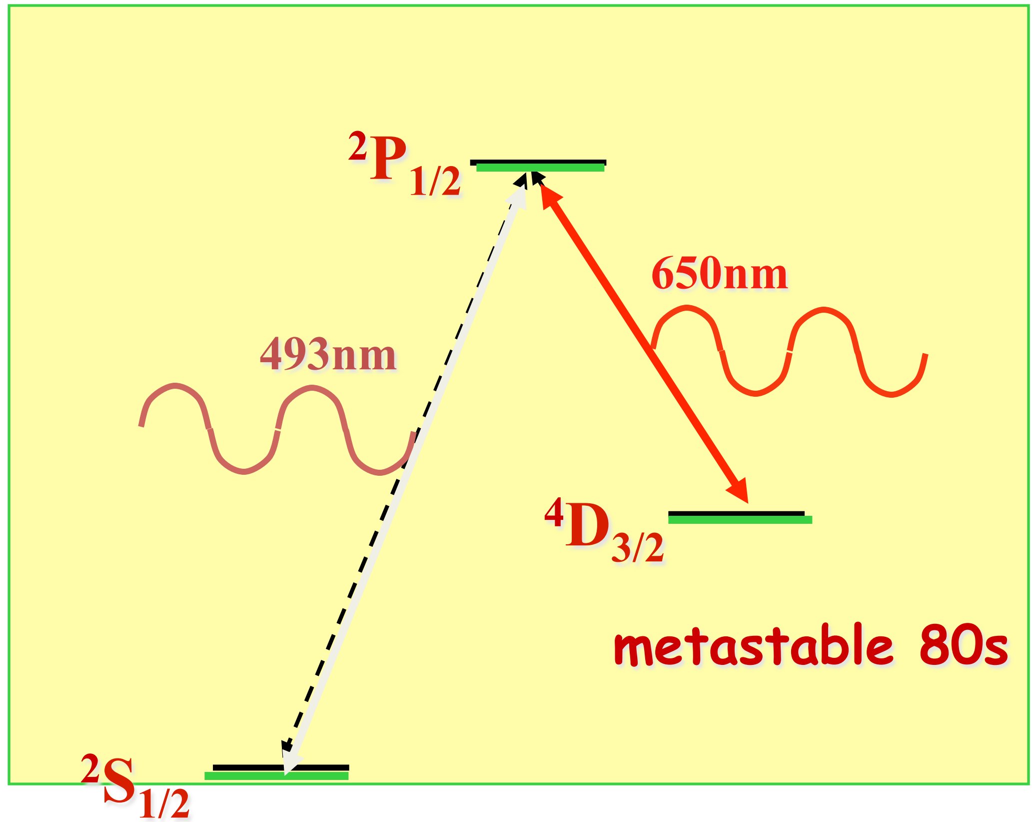
Ba^+ system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)

Single ions can be detected from a photon rate of 10^7/s

Pursued by EXO…

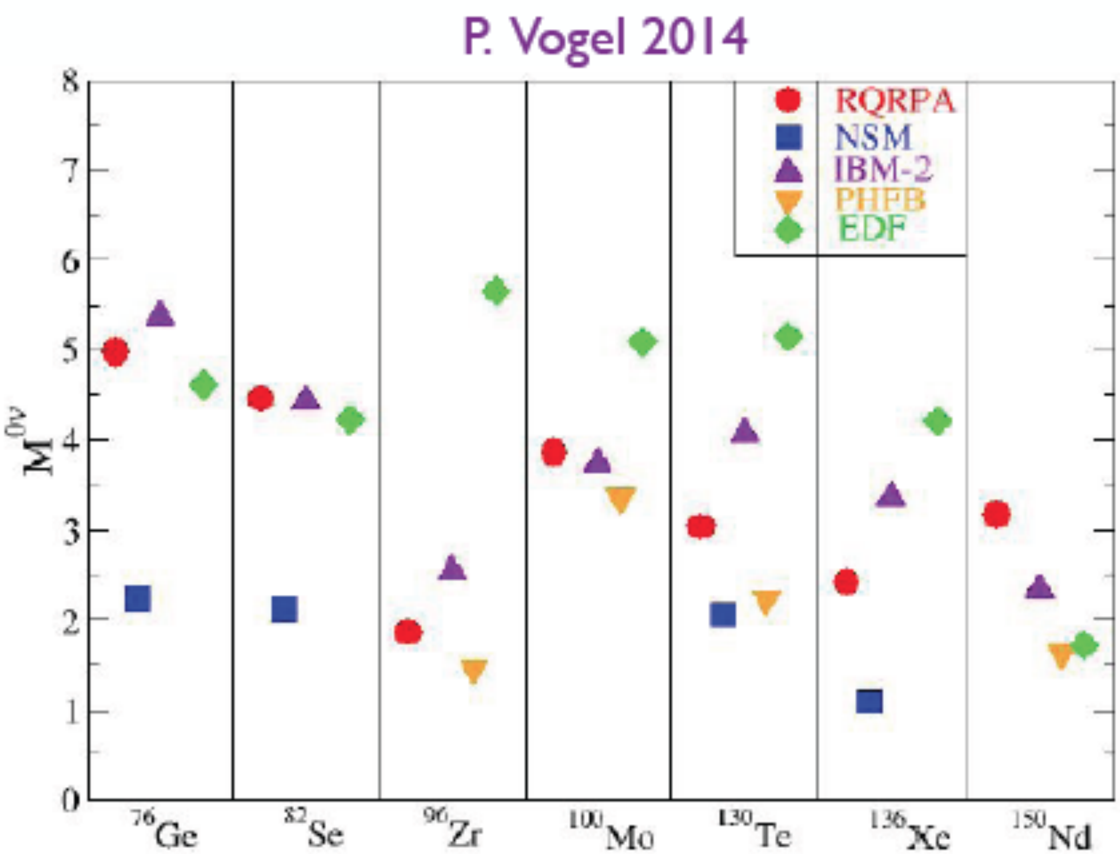
But:
Triplet state is quenched in dense gas!

Can excite with blue, look only for red



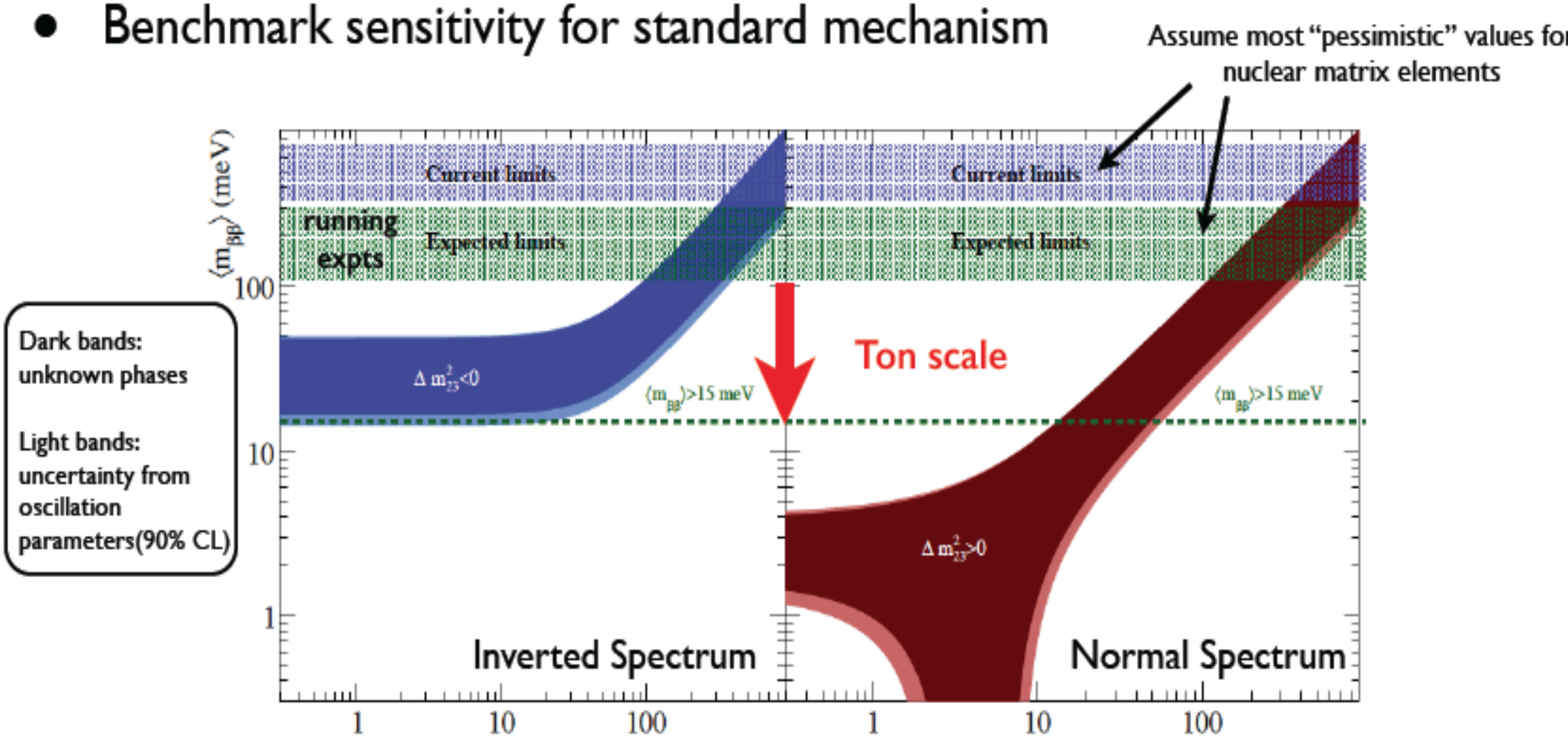
No scheme for extraction from LXe to vacuum has been successful, as yet

The nuclear matrix element picture



Matrix elements for "standard mechanism"

- Benchmark sensitivity for standard mechanism



- Ton-scale experiment will make a discovery if spectrum has
  1. inverted ordering *or*
  2. $m_{lightest}$ > 50 meV (irrespective of ordering)