dilute xenon in instrumentation: challenges and virtues

azriel goldschmidt, lbnl

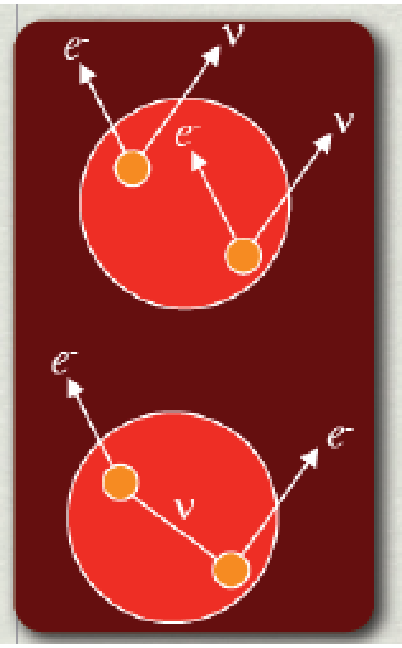
slac experimental seminar

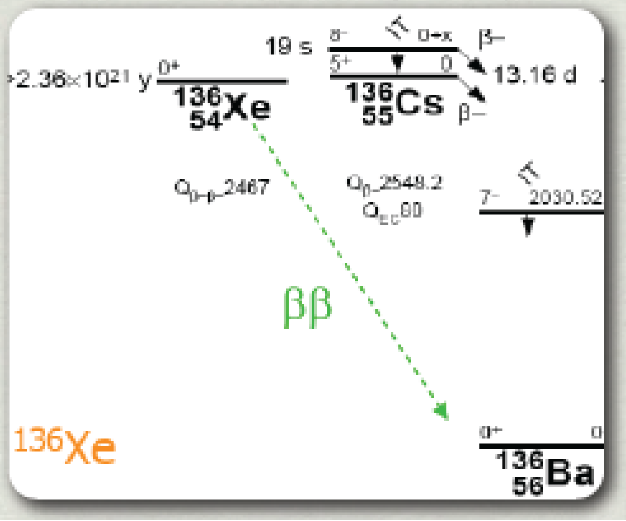
july 16 2015

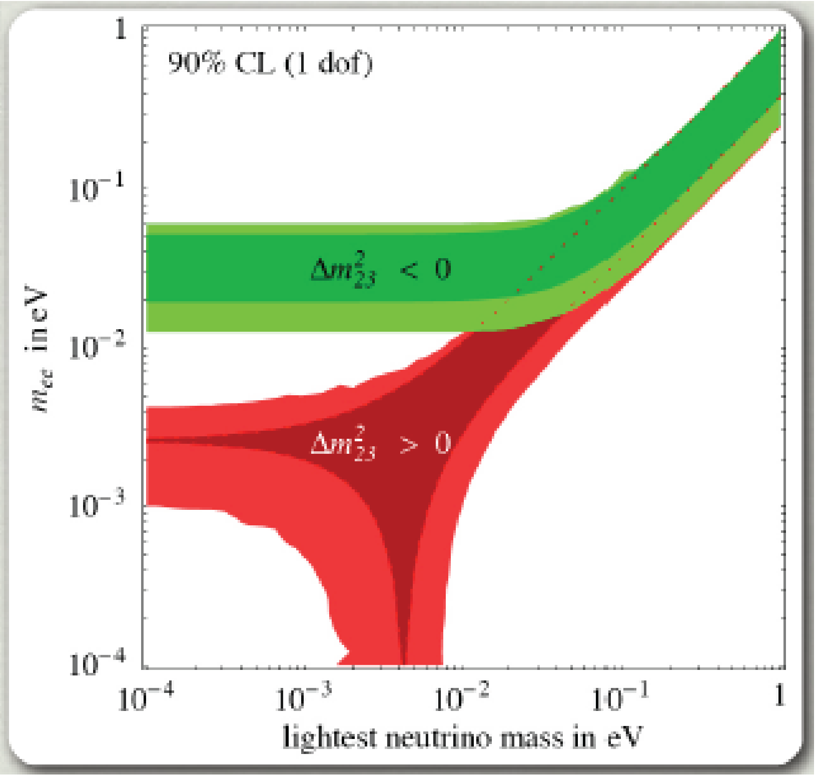
topics

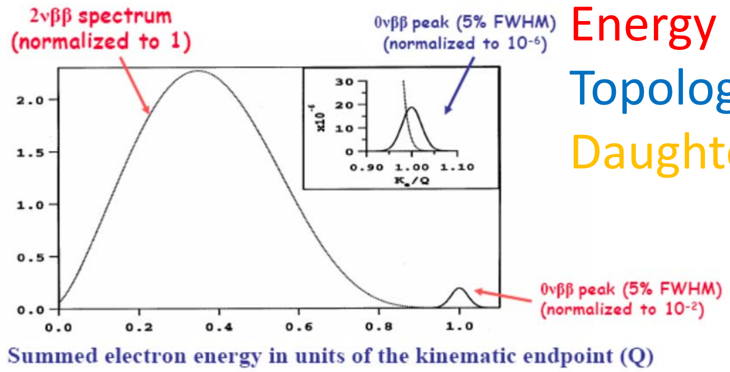
- physics drivers of xenon instrumentation
- electroluminescent tpc with high pressure xenon:
  - energy resolution
  - track imaging
- nuclear recoils: tpc response and discrimination
- study of xe + tma gas mixture (charge and light)
- recombination simulations (for dm directionality)
- concept for barium tagging in-gas testing (for $\beta\beta$)

neutrino-less double beta decay





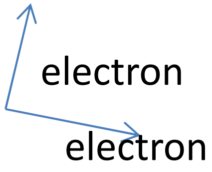




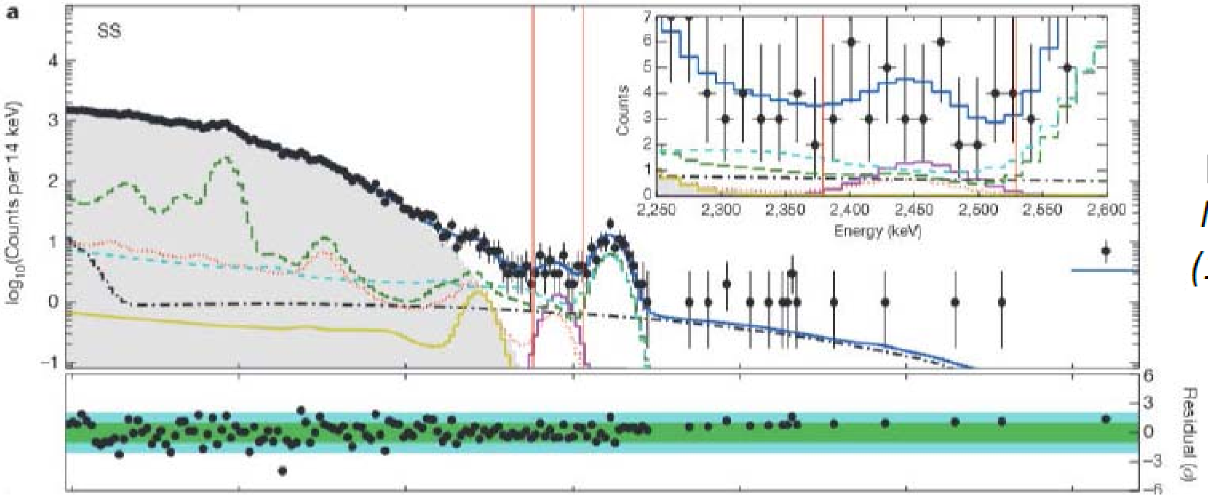
Energy peak at $Q_{\beta\beta}$

Topology of the 2 electrons from a point

Daughter identification



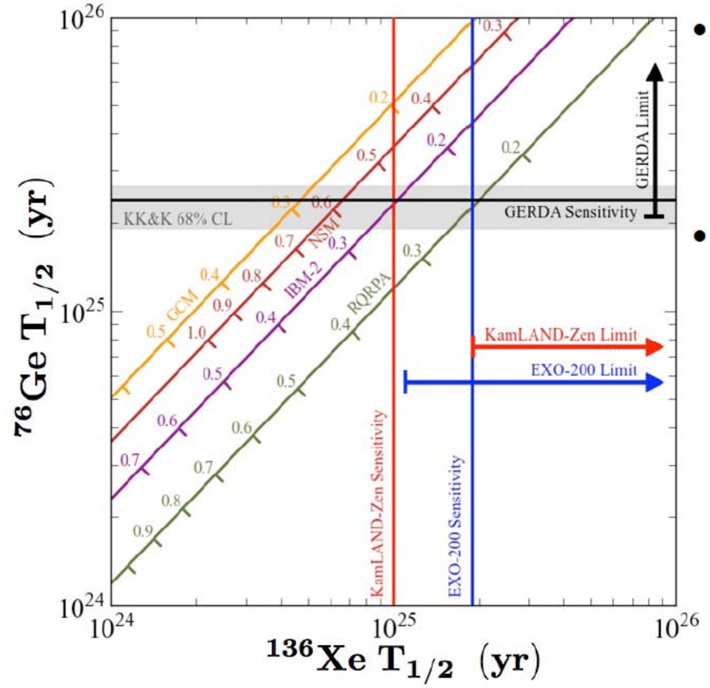
neutrino-less double beta decay: search status



EXO-200

Nature 510, 229–234

(12 June 2014)



- EXO-200 limit

$$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}\ \mathrm{yr}\ \ (90\%\ \mathrm{C.L.})$$

$$< m_{\beta\beta} >= 190 - 450\ \mathrm{meV}$$

- EXO-200 sensitivity

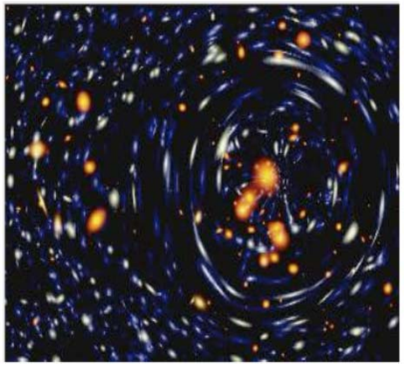
$$T_{1/2}^{0\nu\beta\beta} = 1.9 \times 10^{25}\ \mathrm{yr}$$

[Nature, 510, 229-234 (2014)]

[GERDA: PRL 111, 122503 (2013)]

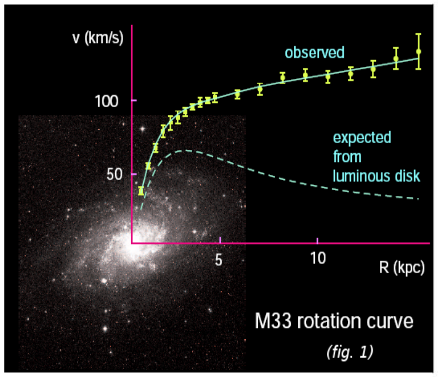
[KL-Zen: PRL 110, 062502 (2013)]

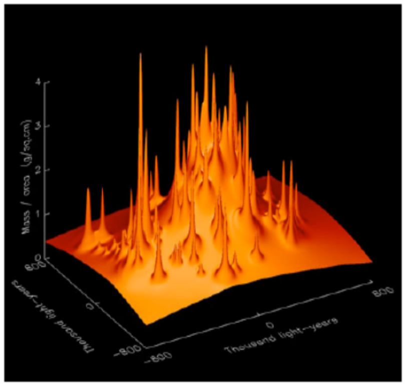
wimp dark matter



Solid evidence for the existence of invisible matter at:

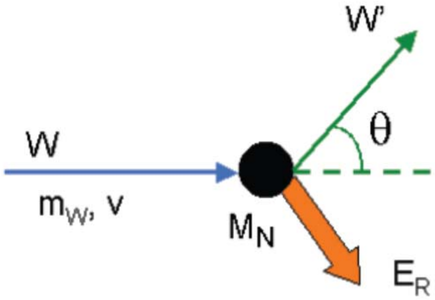
- Galactic scale (rotation curves)
- Clusters of galaxies scale (lensing)
- Cosmological scale





DM makes up about 23% of the total energy in the Universe.
Mostly non-relativistic to give rise to observed structure
Weakly Interacting Massive Particles WIMPs are a well motivated Dark Matter candidate

Directly detect the WIMPs by observing their elastic collisions with nuclei in the target/detector mass



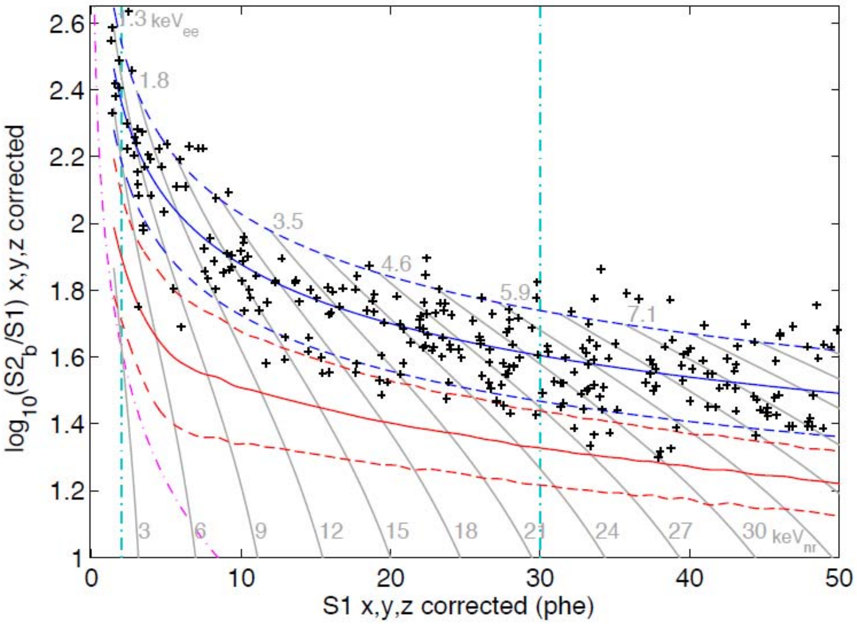
Annual modulation in rate ($v_{Sun} \pm v_{Earth}$)
Preferred direction (Sun motion in galaxy to Cygnus)
Directionality daily modulation (Earth rotating)

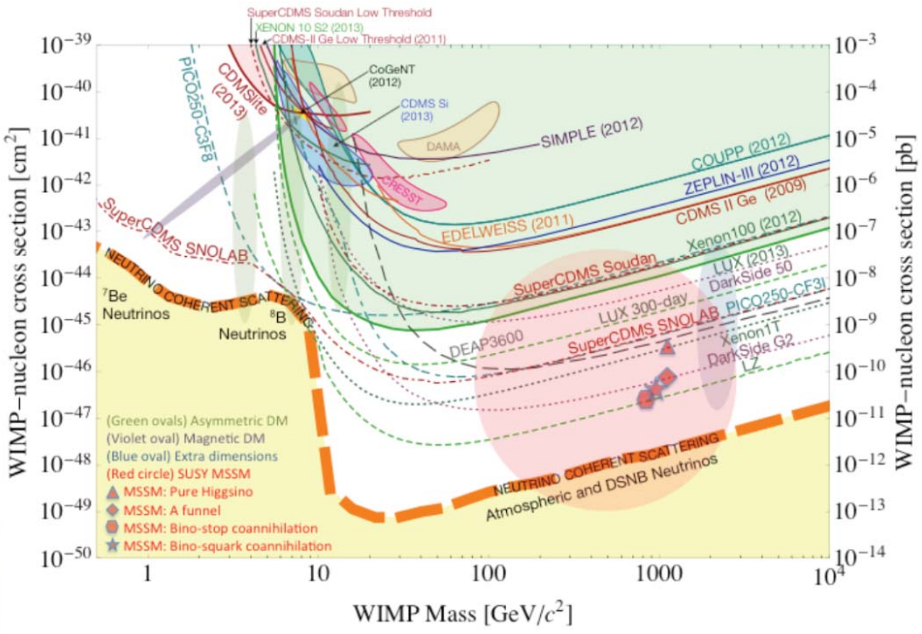
Small energy deposition -tens of keV- and very rare process -WIMPs interact weakly-:
Large detectors 100s kg-Tons underground and additional background rejection techniques

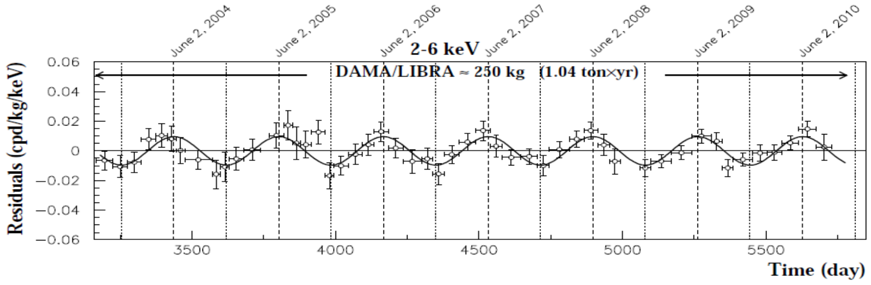
wimp dark matter: search status

Counting experiments: search for low energy nuclear recoils

LUX result:350 kg of Xenon, 10,000 kg-days







DAMA/LIBRA result:250 kg of NaI, 370,000 kg-days

gas vs liquid: general remarks

- liquid:
  - smaller volumes
  - self-shielding
  - scales more gracefully
- gas:
  - extended ionization tracks
  - optimum energy resolution
  - options for additives to improve performance
    - reduce diffusion
    - wavelength shifting
    - penning, enhanced recombination light, etc

prototype high-pressure xenon electroluminescent tpc
demonstrate excellent energy resolution for $0\nu\beta\beta$
scan operational parameters
develop corrections

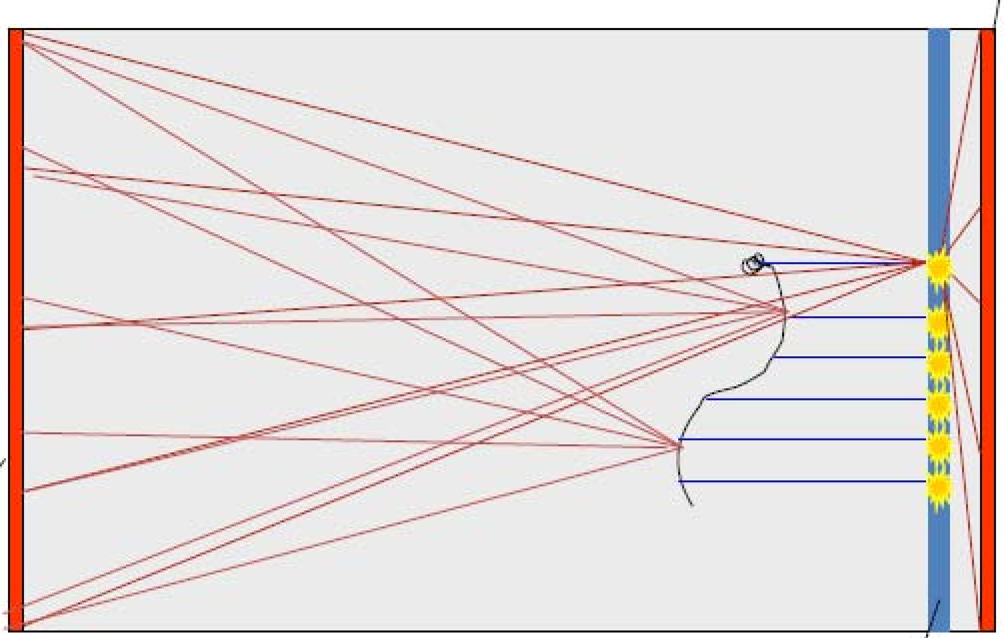
ENERGY RESOLUTION IN A XENON ELECTROLUMINESCENT TPC AT 10 ATM

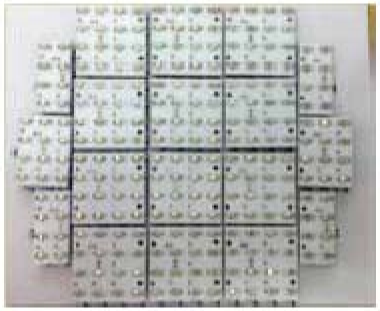
AG, Joshua Renner, David Nygren

Nucl.Instrum.Meth. A708 (2013) 101-114

TPC with Electroluminescence: Total Energy and Track Imaging

Readout
Plane A
- **position**



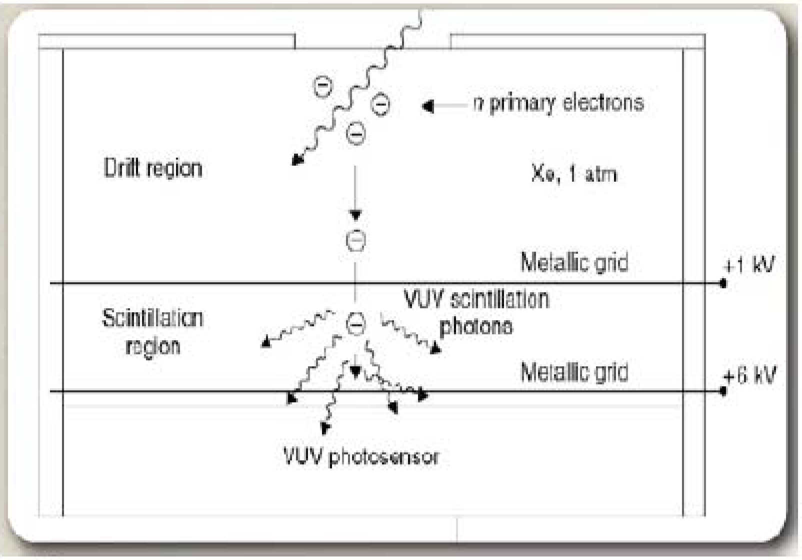


Readout
Plane B
- **energy**

Electroluminescent
Layer

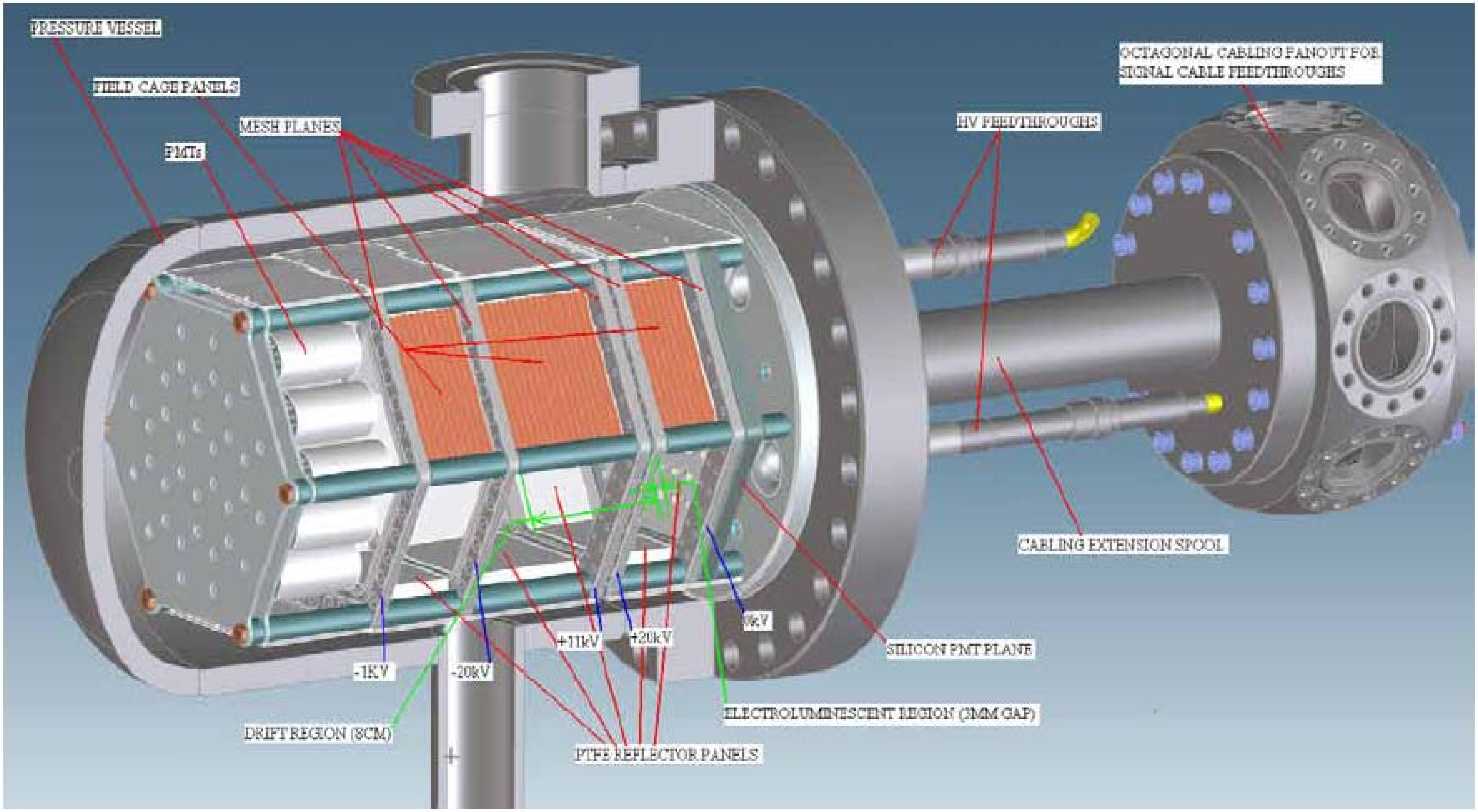
Electro-Luminescence (EL) is the key

(Gas Proportional Scintillation)

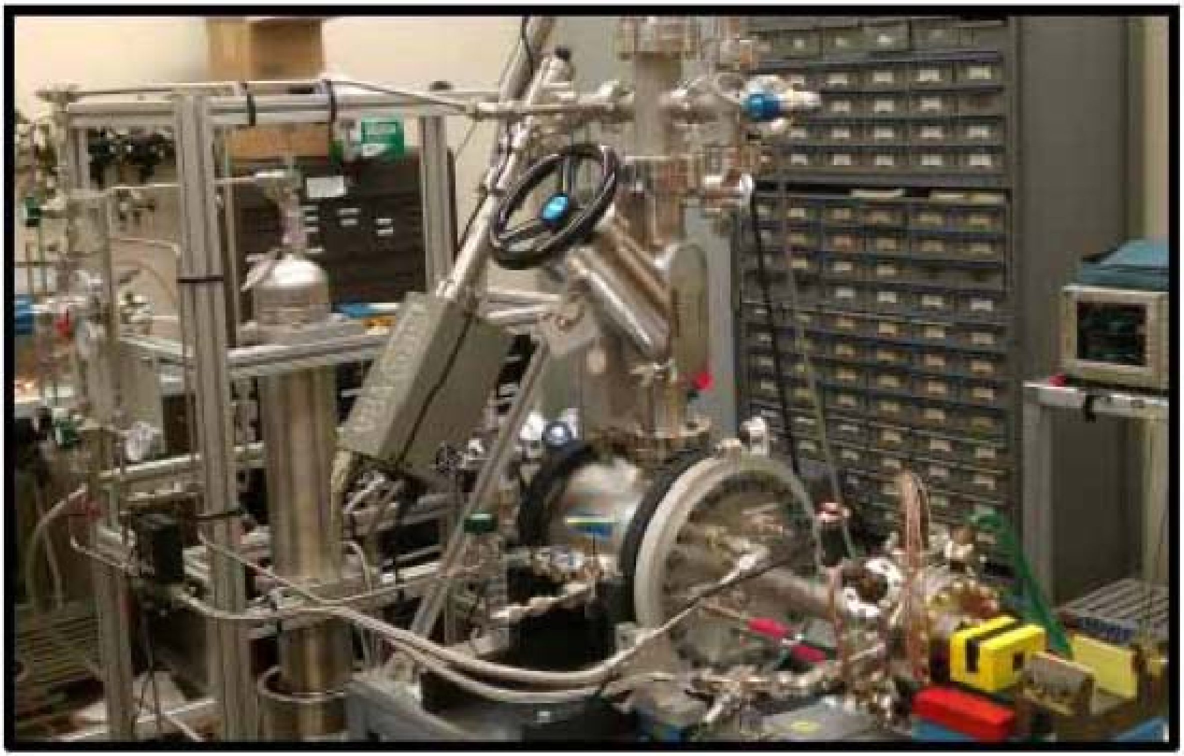


- Physics process generates ionization signal
- Electrons drift in low electric field region
- Electrons enter a high electric field region
- Electrons gain energy, excite xenon: 8.32 eV
- Xenon radiates VUV (≈175 nm, 7.5 eV)
- Electron starts over, gaining energy again
- Linear growth of signal with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

xenon electroluminescent tpc



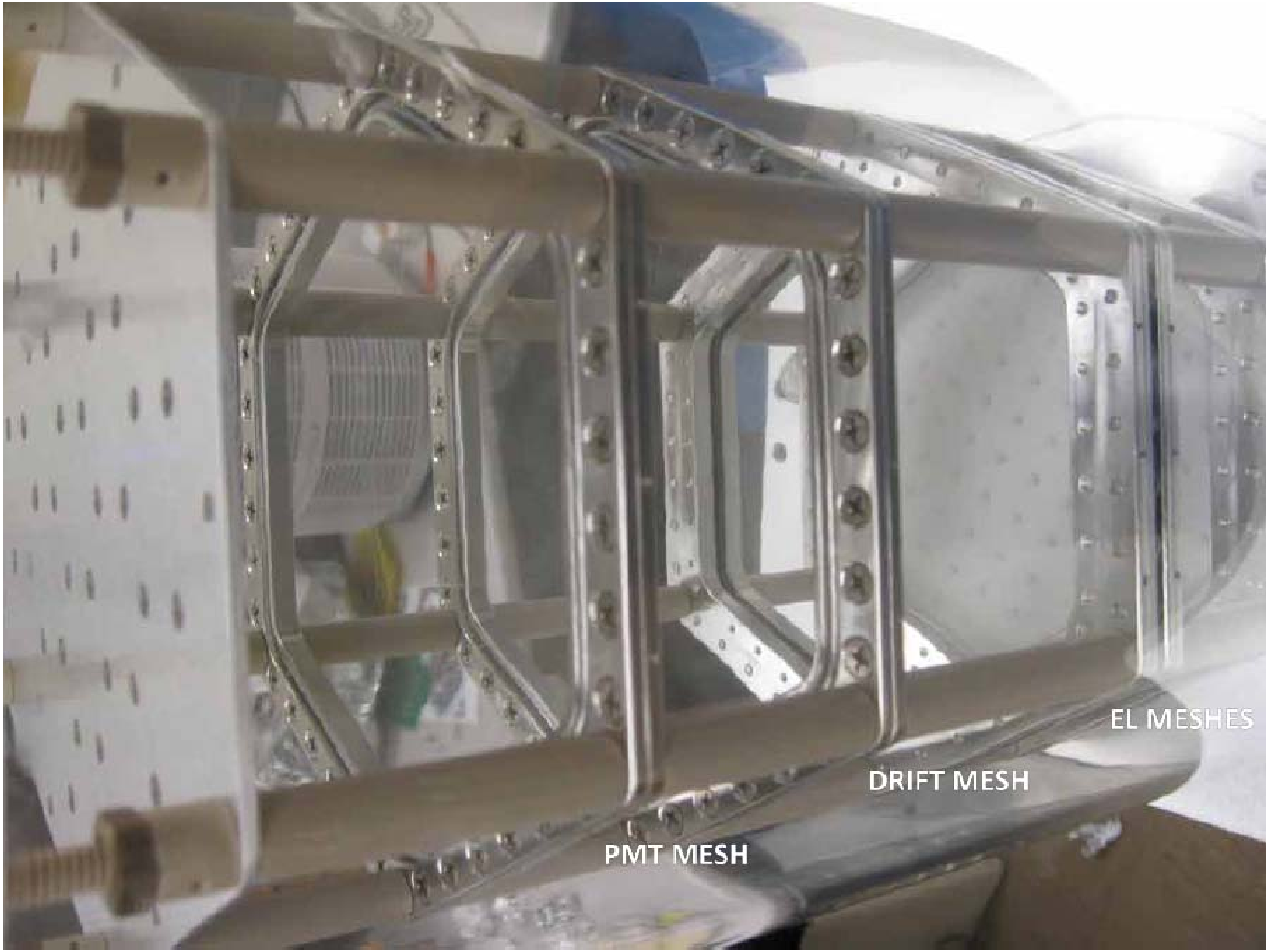
electroluminescent tpc: Setup

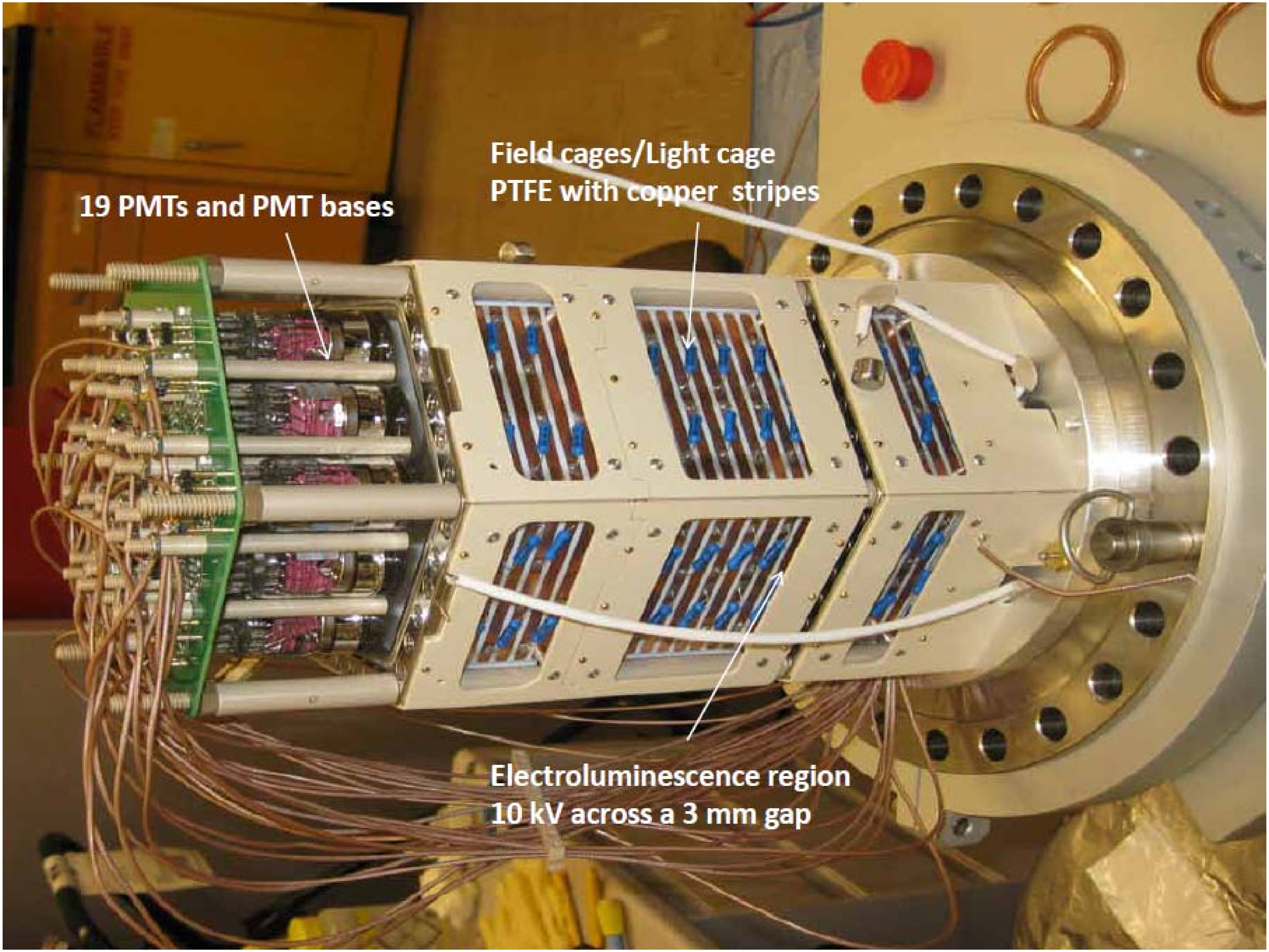


Full Chamber and Gas System

EL Grid

PMT Array


EL MESHES
DRIFT MESH
PMT MESH



19 PMTs and PMT bases

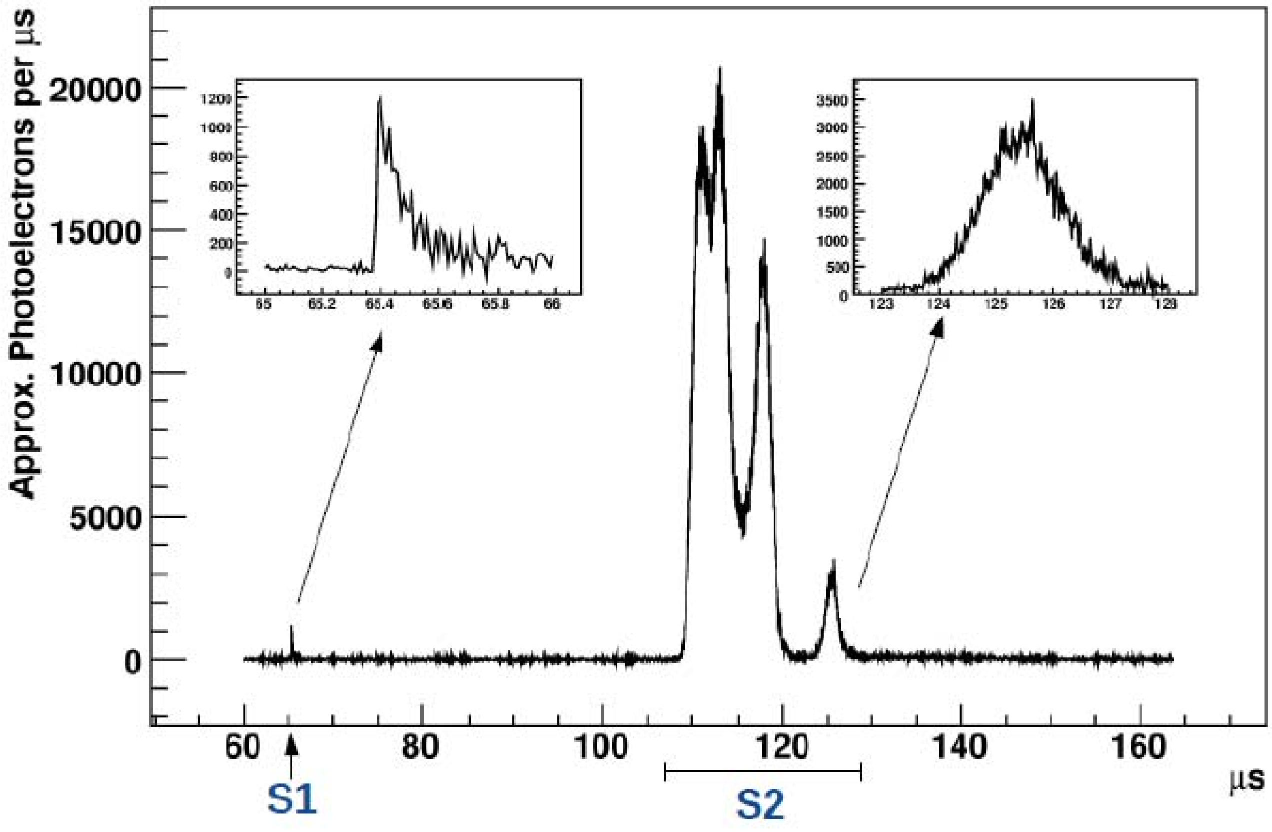
Field cages/Light cage
PTFE with copper stripes

Electroluminescence region
10 kV across a 3 mm gap

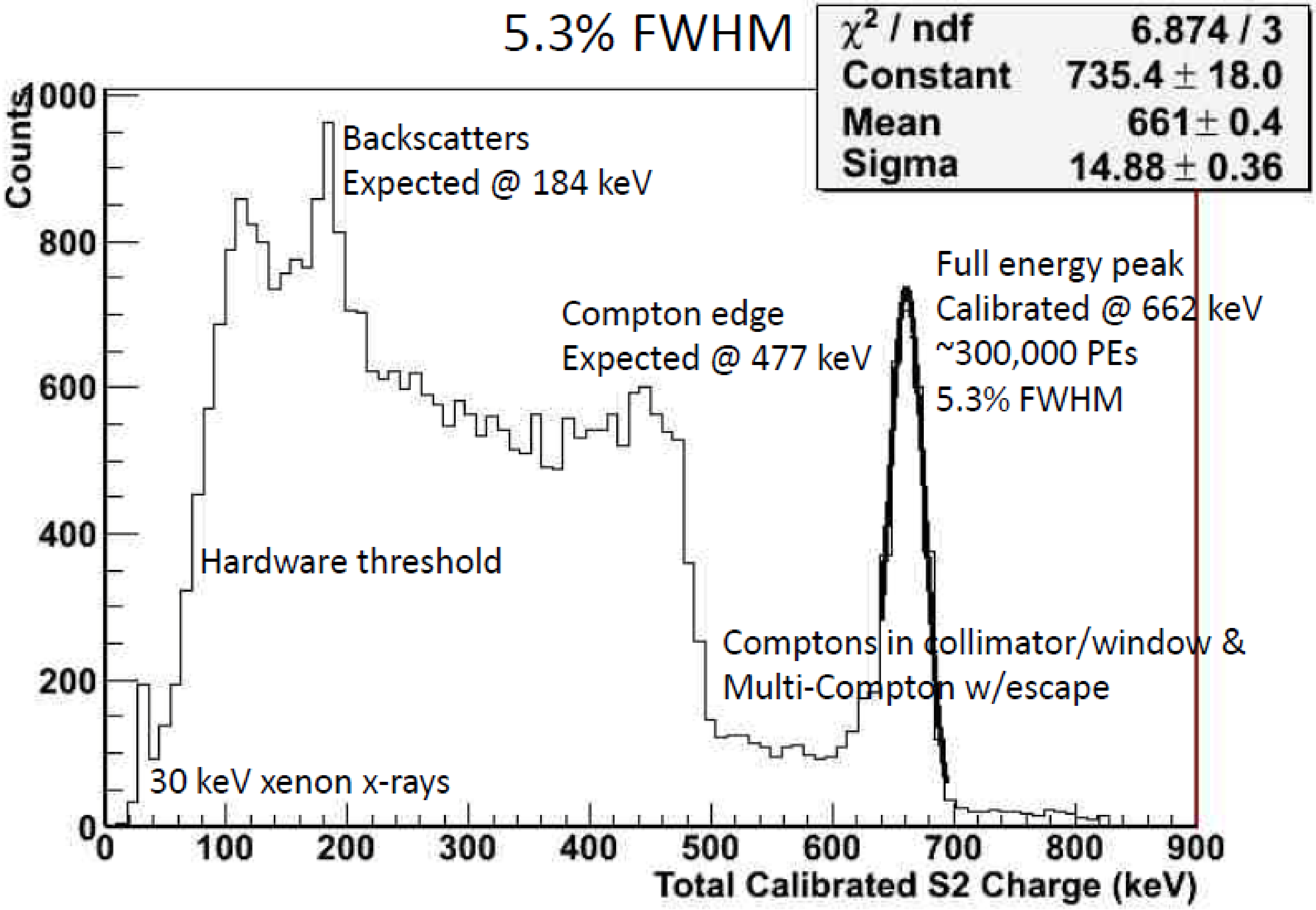
electroluminescent tpc: Typical waveforms

- for 662 keV:
- O(hundreds) S1 SPEs
- O(half million) S2 PEs

Waveforms



electroluminescent tpc: Raw 662 keV spectrum



5.3% FWHM

Backscatters
Expected @ 184 keV

Compton edge
Expected @ 477 keV

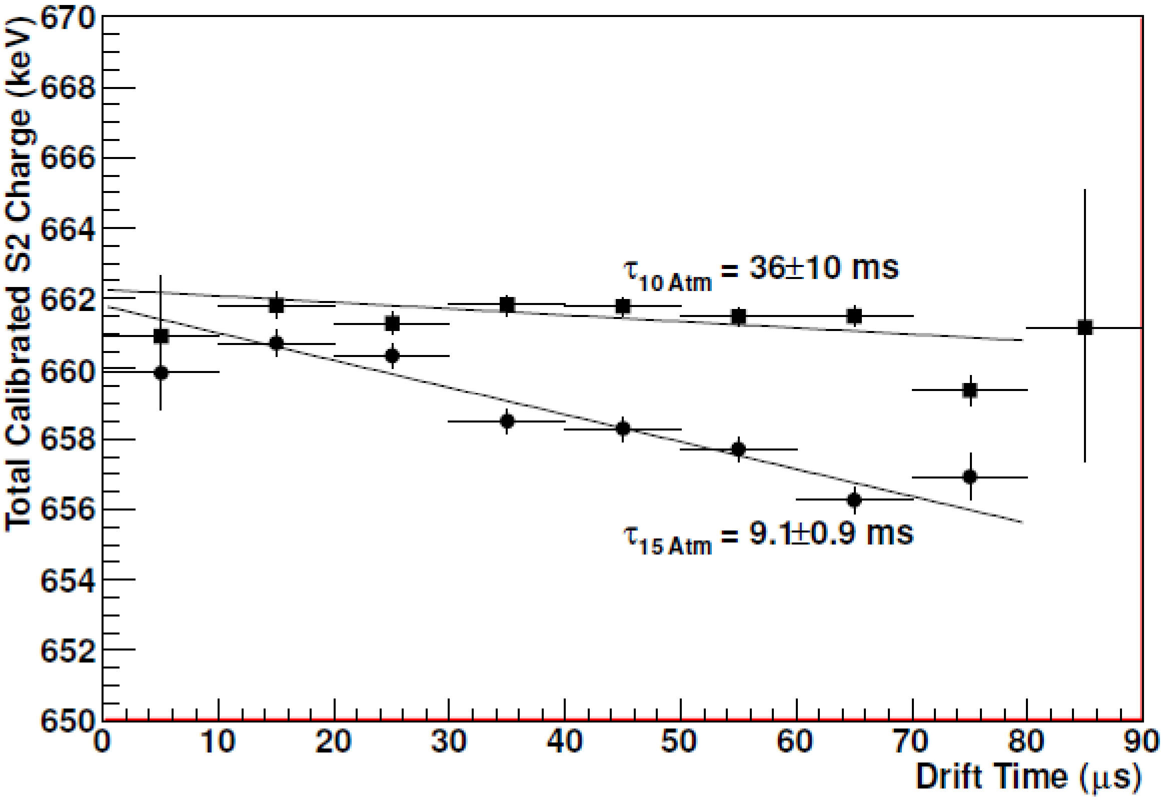
Full energy peak
Calibrated @ 662 keV
~300,000 PEs
5.3% FWHM

Hardware threshold

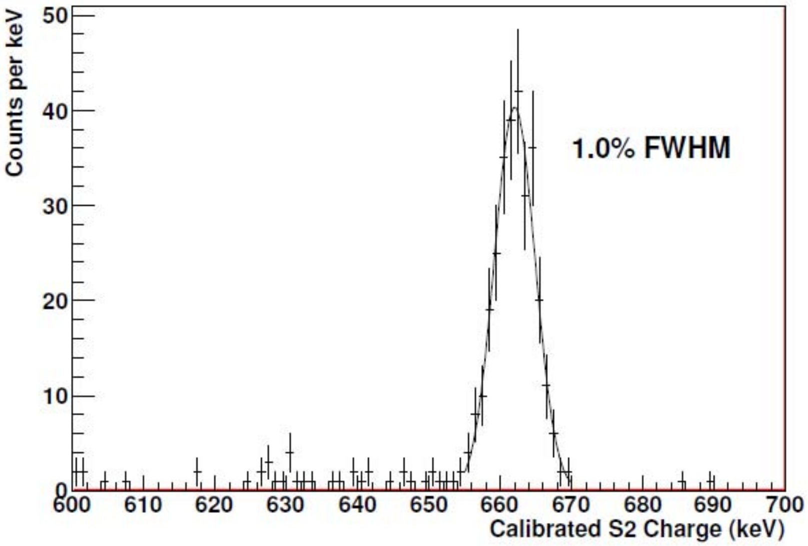
Comptons in collimator/window &
Multi-Compton w/escape

30 keV xenon x-rays

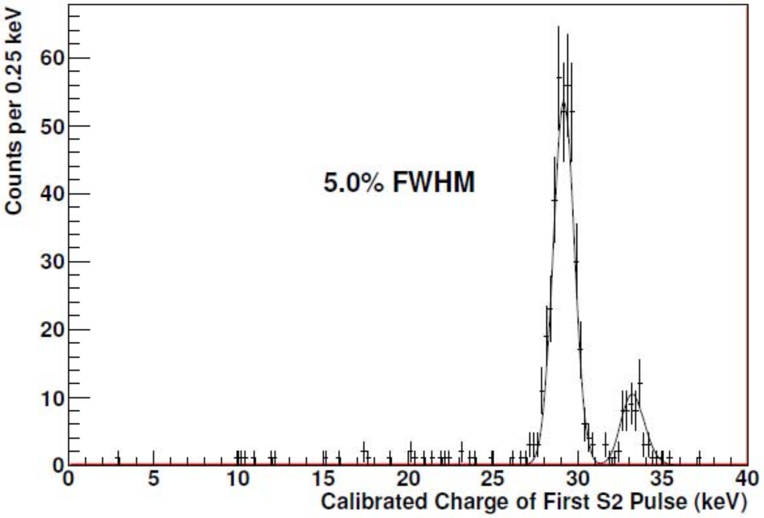
electroluminescent tpc: Electron attachment



electroluminescent tpc: 662 keV and 30 keV resolution



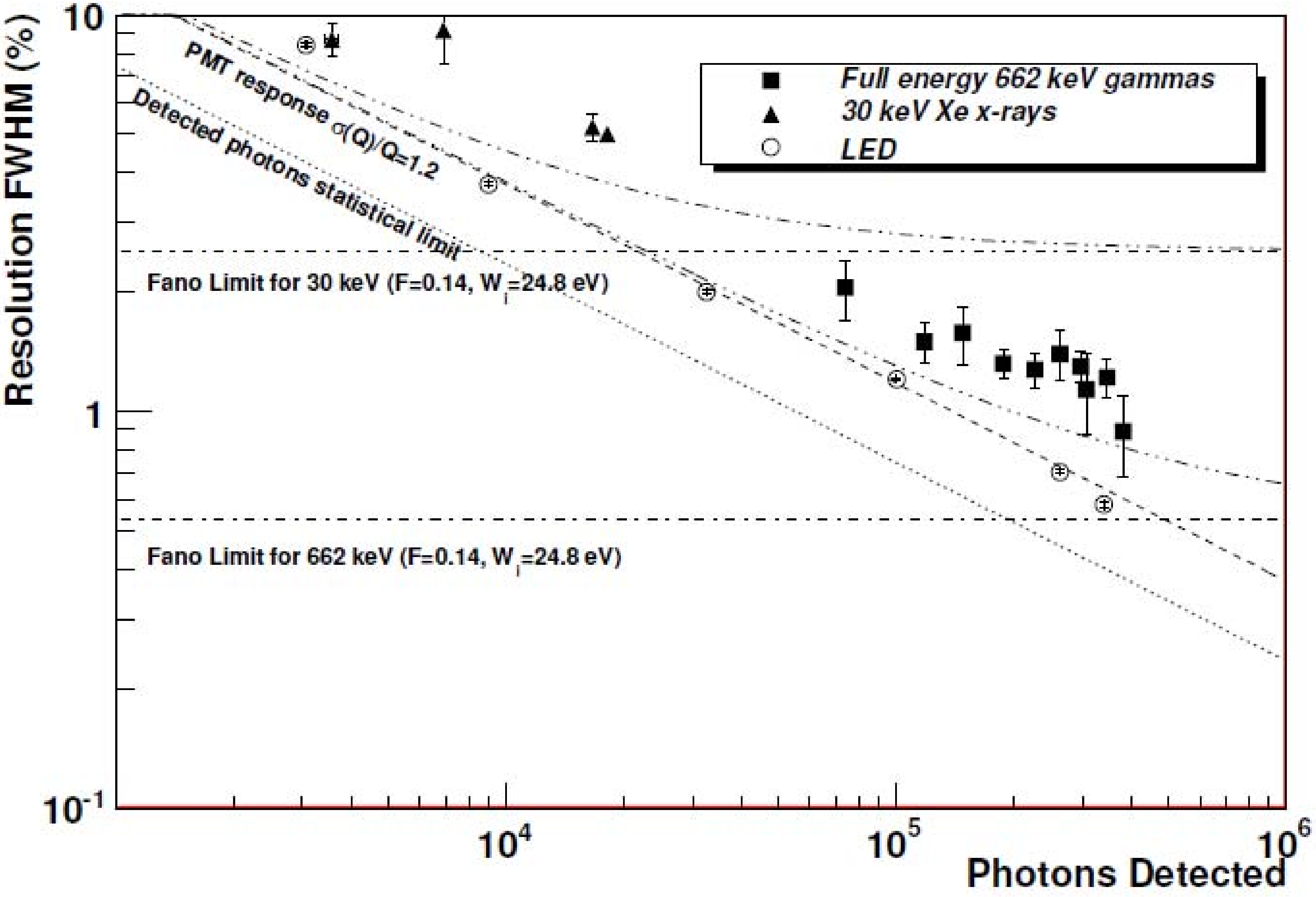
662 keV gammas
15 Atm
0.6 kV/cm dirft field
1.9 kV/(cm atm) EL field



Xenon X-rays
10 Atm (more isolated)
1.0 kV/cm dirft field
2.7 kV/(cm atm) EL field

Energy measured derived only from S2 with central fiducial cut and attachment correction

electroluminescent tpc: Energy Resolution Summary



develop track imaging system in xenon tpc with sipms
develop track reconstruction algorithms
springboard to “spaghetto with 2 meatballs” topology signature for $0\nu\beta\beta$

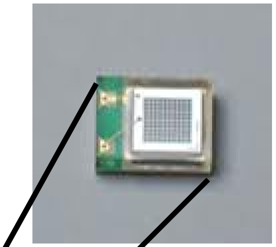
TRACK IMAGING WITH SIPMS IN AN ELECTROLUMINESCENT TPC AT 10 ATM

Max Egorov, AG, Joshua Renner
Nucl.Instrum.Meth. A708 (2013) 101-114

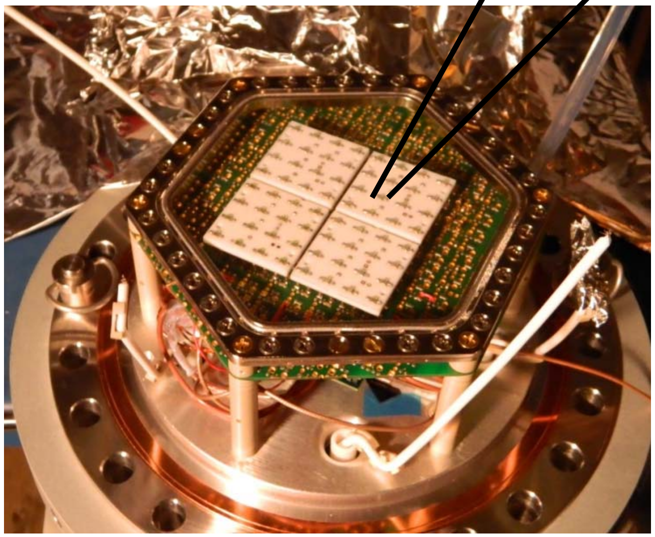
track imaging with sipms : Setup

Prototyped tracking with 64 SiPMs (**MPPCs**)
Imaged muons: 1.2 mm resolution x-y-z per point
Imaged extended tracks from~660 keV electrons and separated Xe x-rays

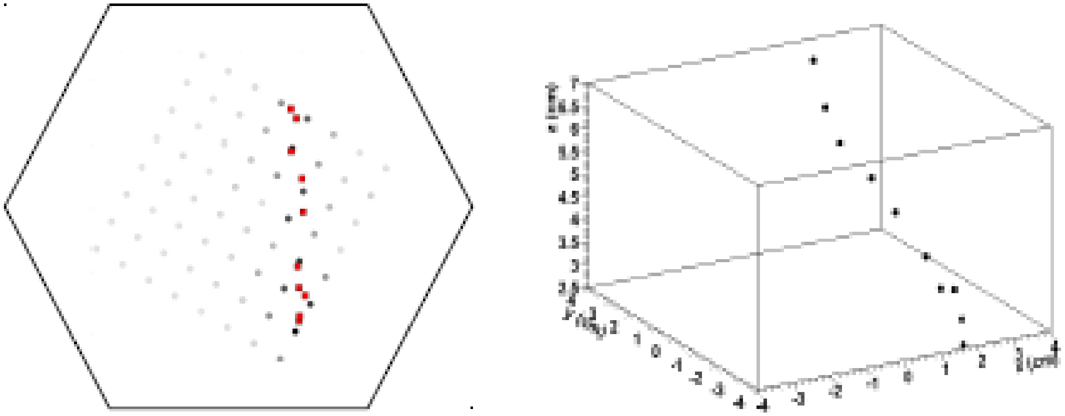
1 mm x 1 mm SiPM



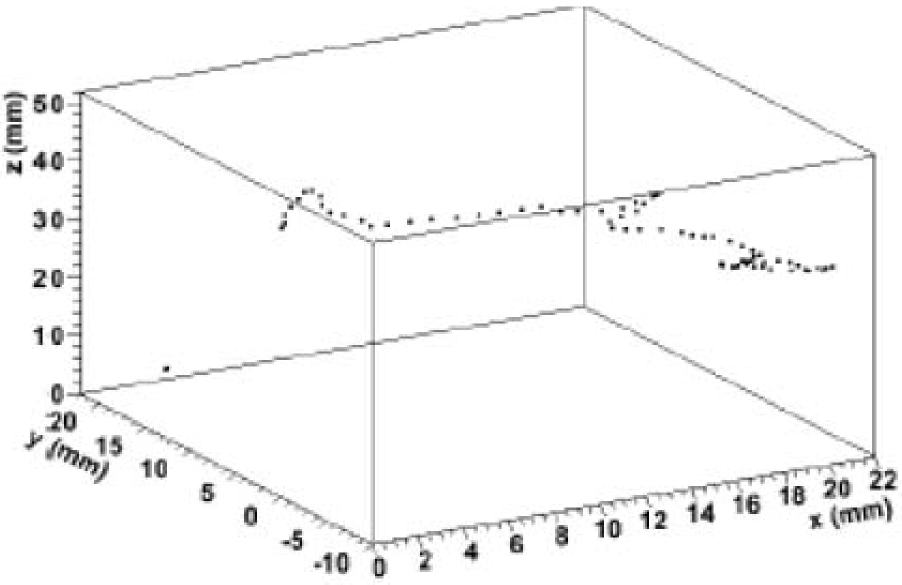
With TPB layer as WLS



μ in HPXe TPC



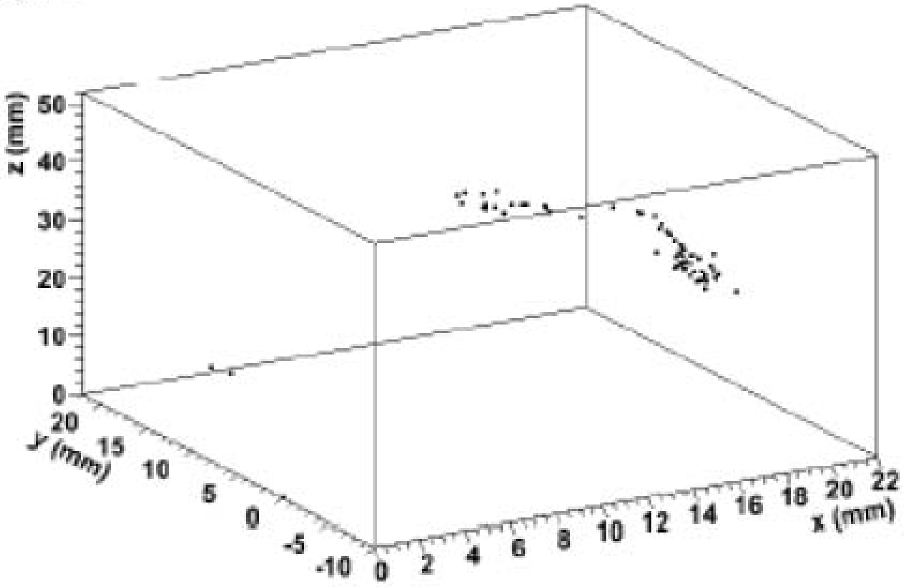
track imaging with sipms : Reconstruction



662 keV gamma in xenon 15 atm

← MC Truth

Reconstructed →



Joshua Renner (LBNL/UCB)

characterize xenon tpc response to nuclear recoils for dark matter search

study electron/nuclear recoil discrimination

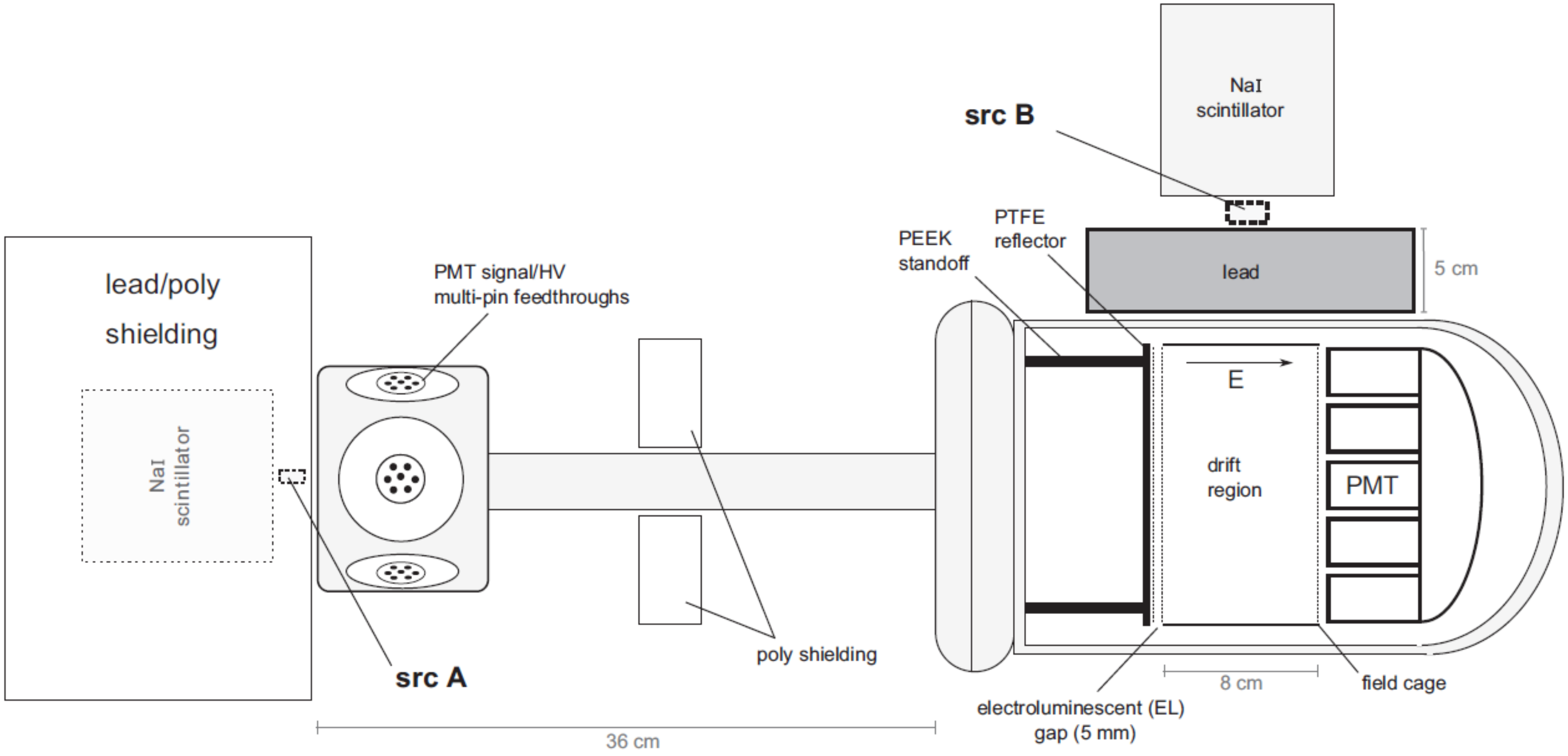
measure scintillation and ionization yields for nuclear recoils

NUCLEAR RECOIL / ELECTRON DISCRIMINATION IN XENON AT 14 ATM

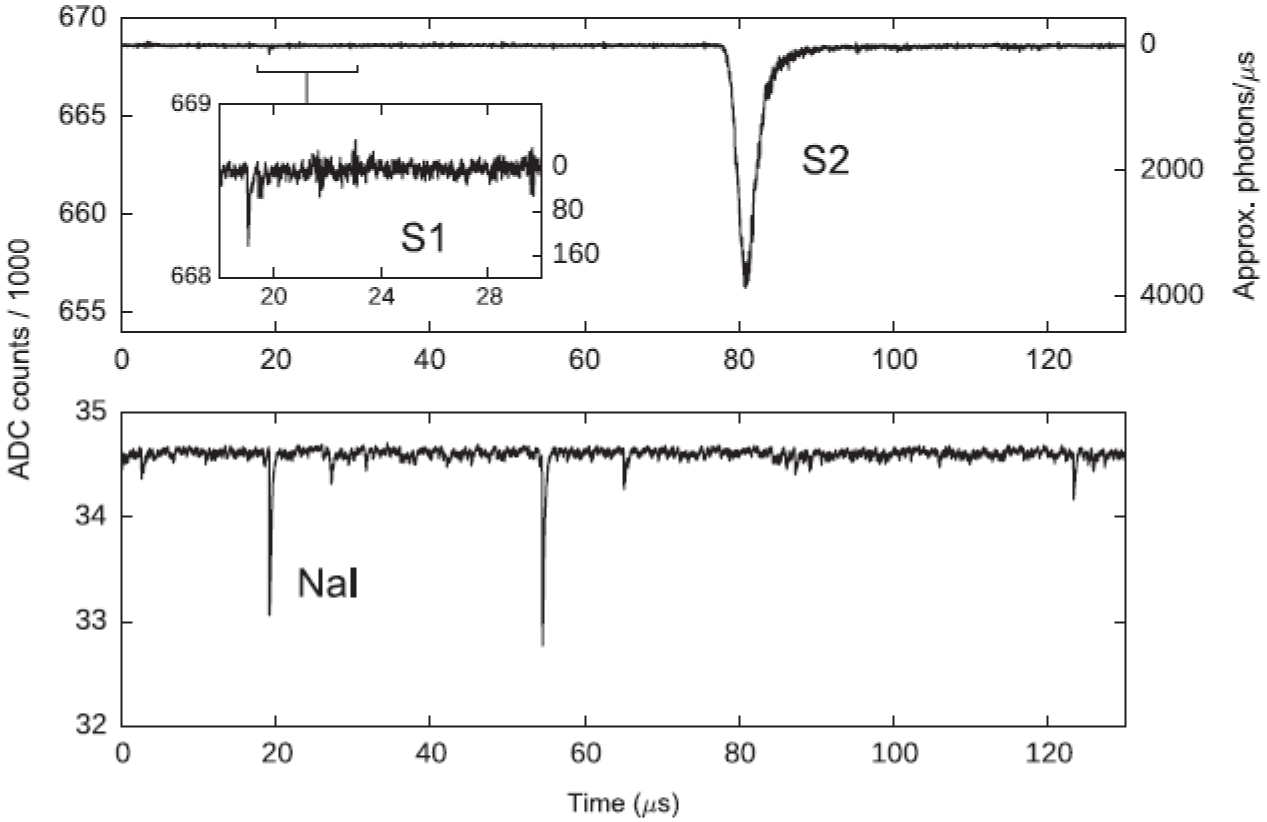
Joshua Renner, **AG**

Nucl.Instrum.Meth. A793 (2015) 62-74

nuclear recoils with neutrons: Setup

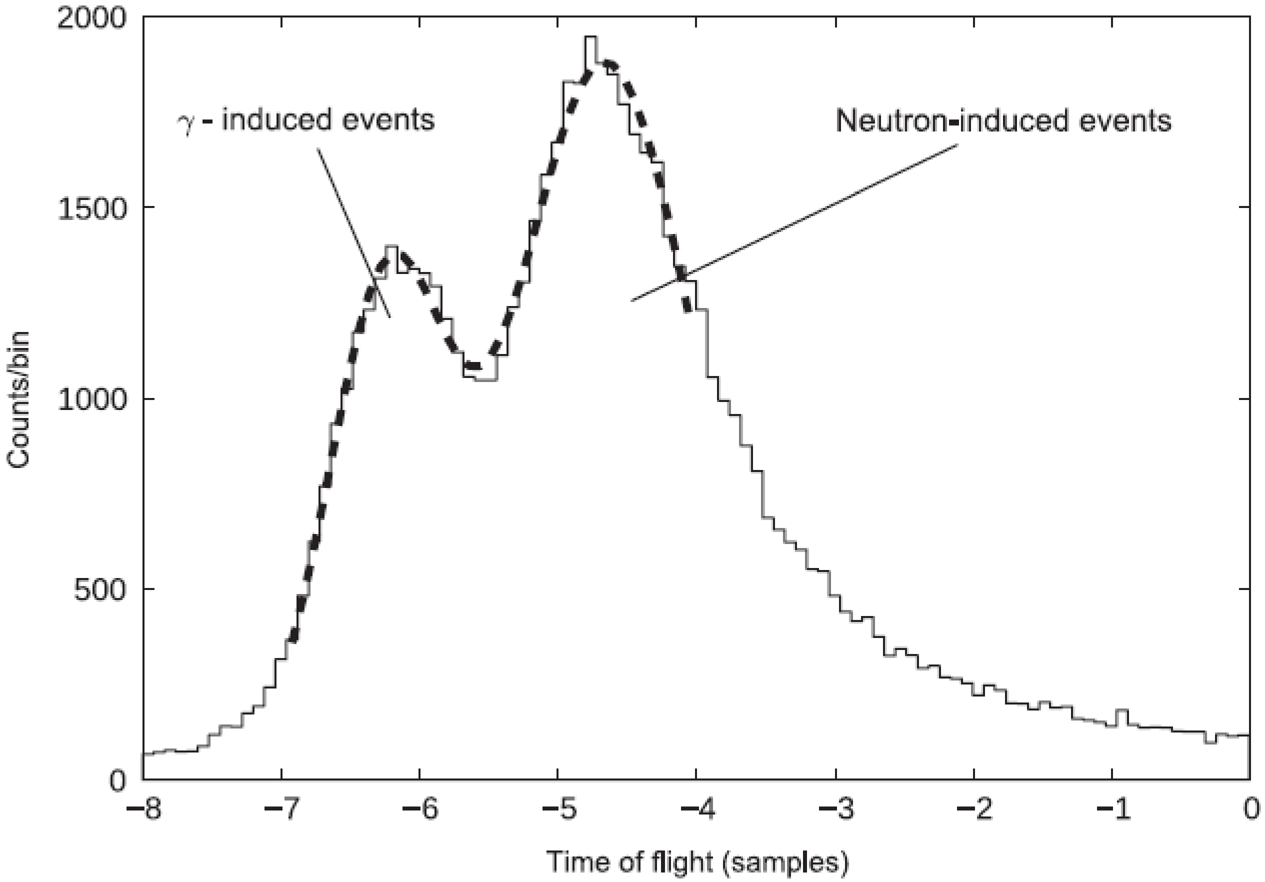


nuclear recoils with neutrons: Typical Waveforms



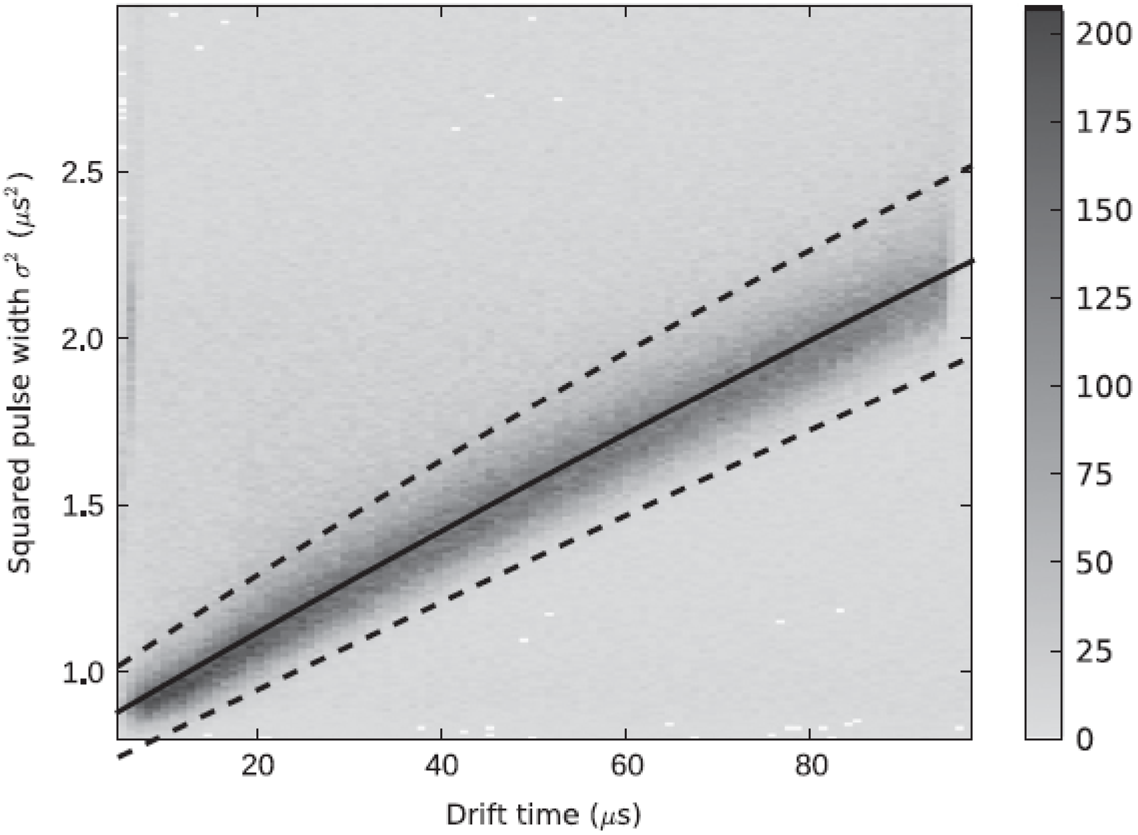
Time coincidence with external NaI detector for 4.4 MeV gamma

nuclear recoils with neutrons: Time of Flight



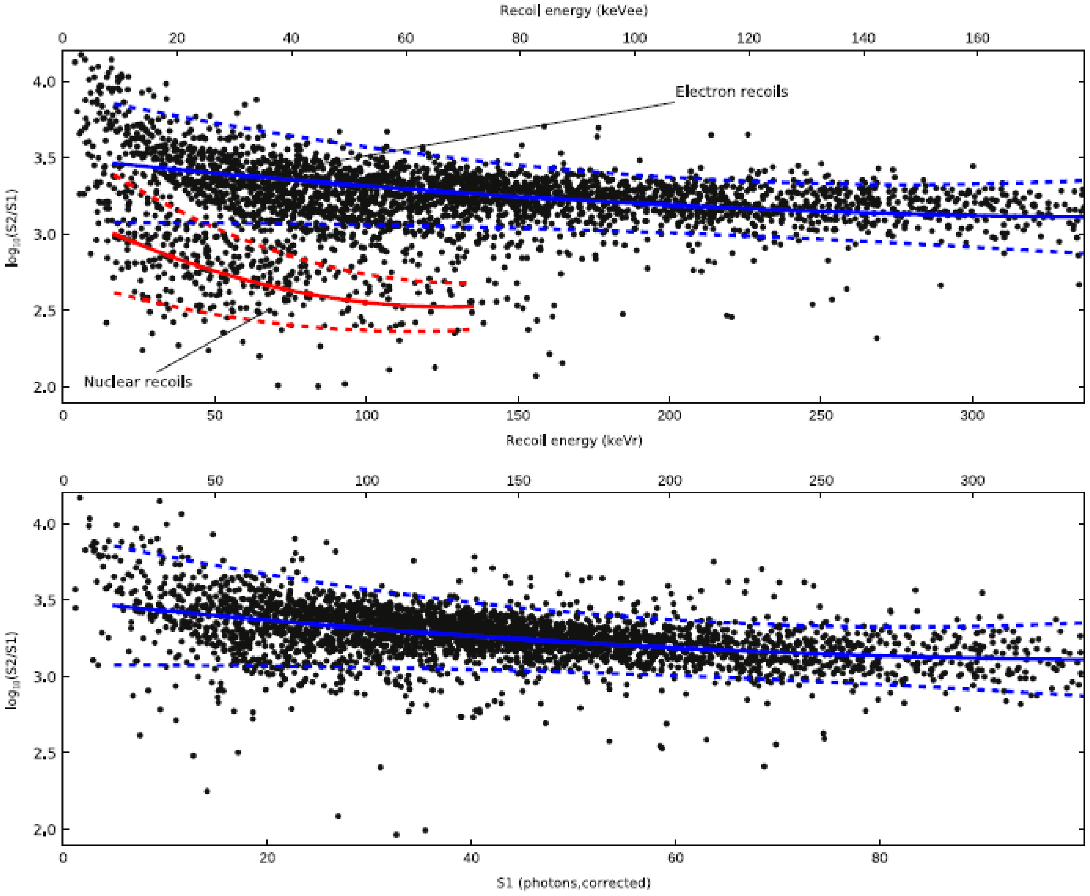
1 sample = 10 ns. These events are selected for higher energy (S2) where gamma peek is more prominent

nuclear recoils with neutrons: Diffusion-Drift



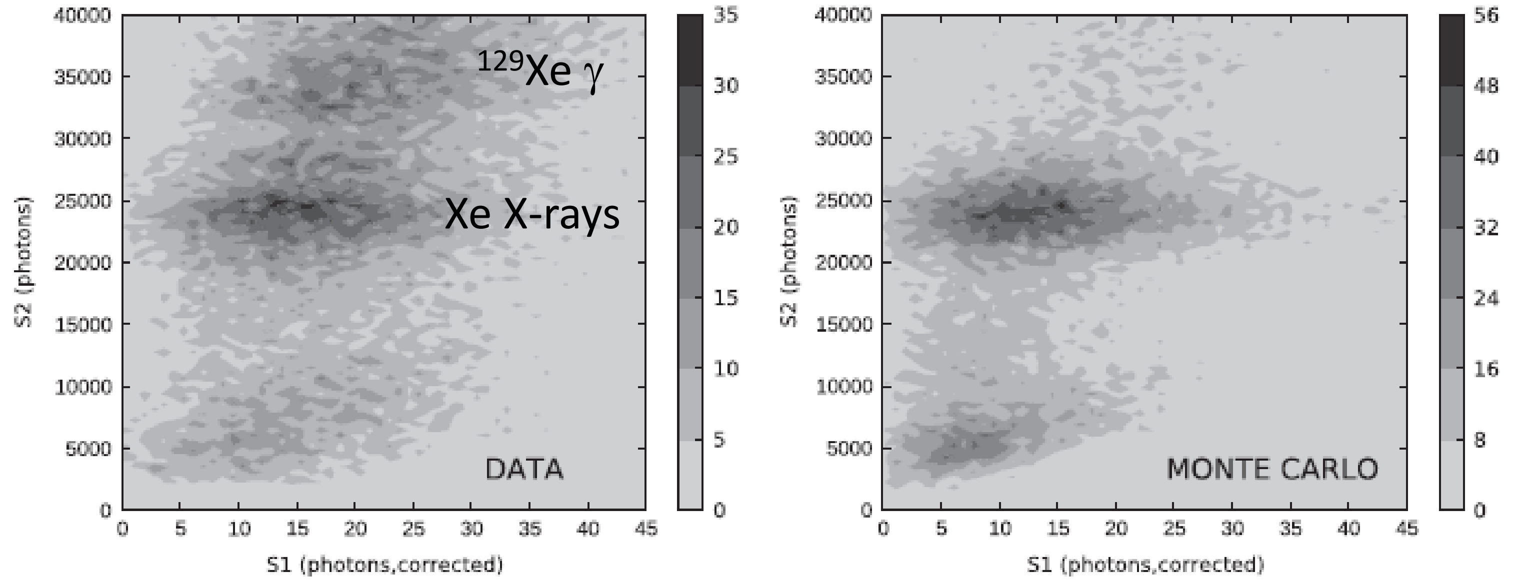
Events with a single S1 and single S2 pulse show a clear diffusion(L) drifttime correlation that is used to further eliminate background from misassignment

nuclear recoils with neutrons: S2-S1 discrimination



Electron recoils calibrated (S1 and S2) with 662 keV line. Quenching factors estimates (not statistically significant to be a measurement) for nuclear recoils were derived from neutron backscattering spectrum feature.

nuclear recoils with neutrons: Simulation comparison



Using quenching factors for nuclear recoils consistent with neutron backscatter spectral feature. Simulation does not include lower energy neutrons (with 7.7 MeV gamma) that produce most Xe+n -> ^{129}Xe. Overall, reasonably good agreement.

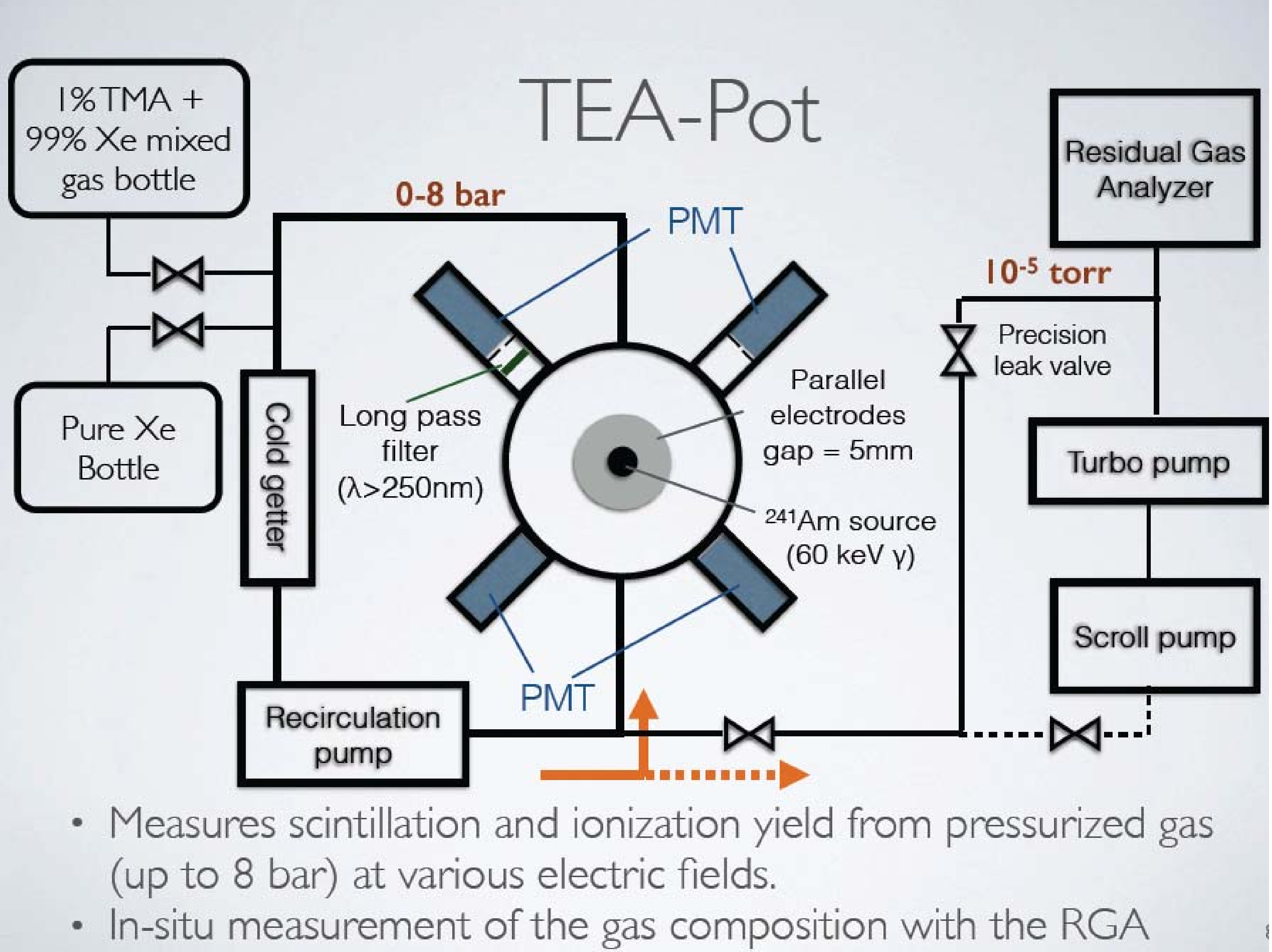
is xe + tma a good penning mixture?
is there recombination light from $tma^+ + e$?
what is the electroluminescence yield of the mixture?
is there primary scintillation?

CHARGE AND LIGHT YIELD IN XENON + TMA MIXTURES AT 1-8 ATM

Yasuhiro Nakajima, Carlos Oliveira, **AG**, David Nygren

e-Print: **arXiv:1505.03585**

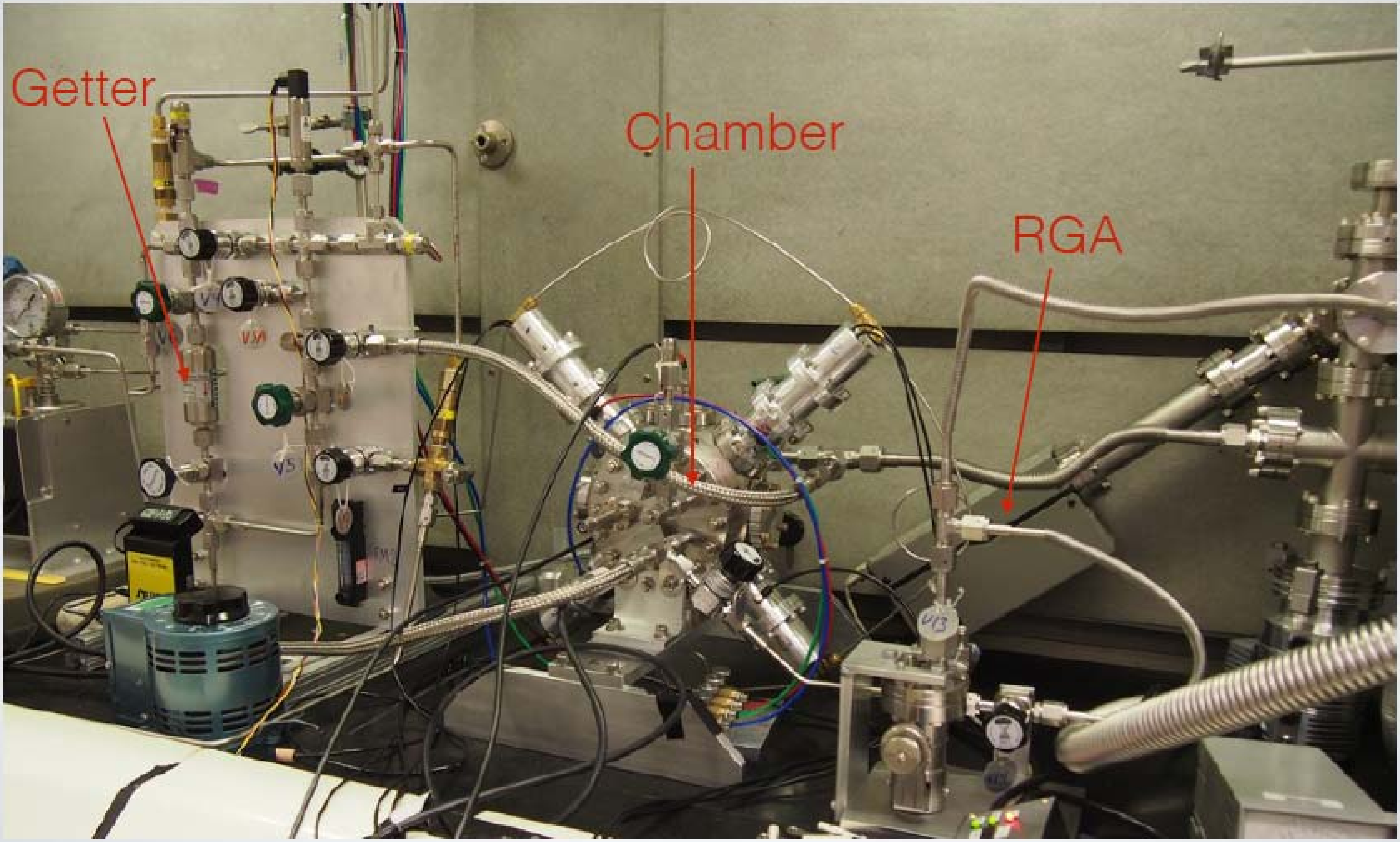
xe+tma charge and light yield: Scheme



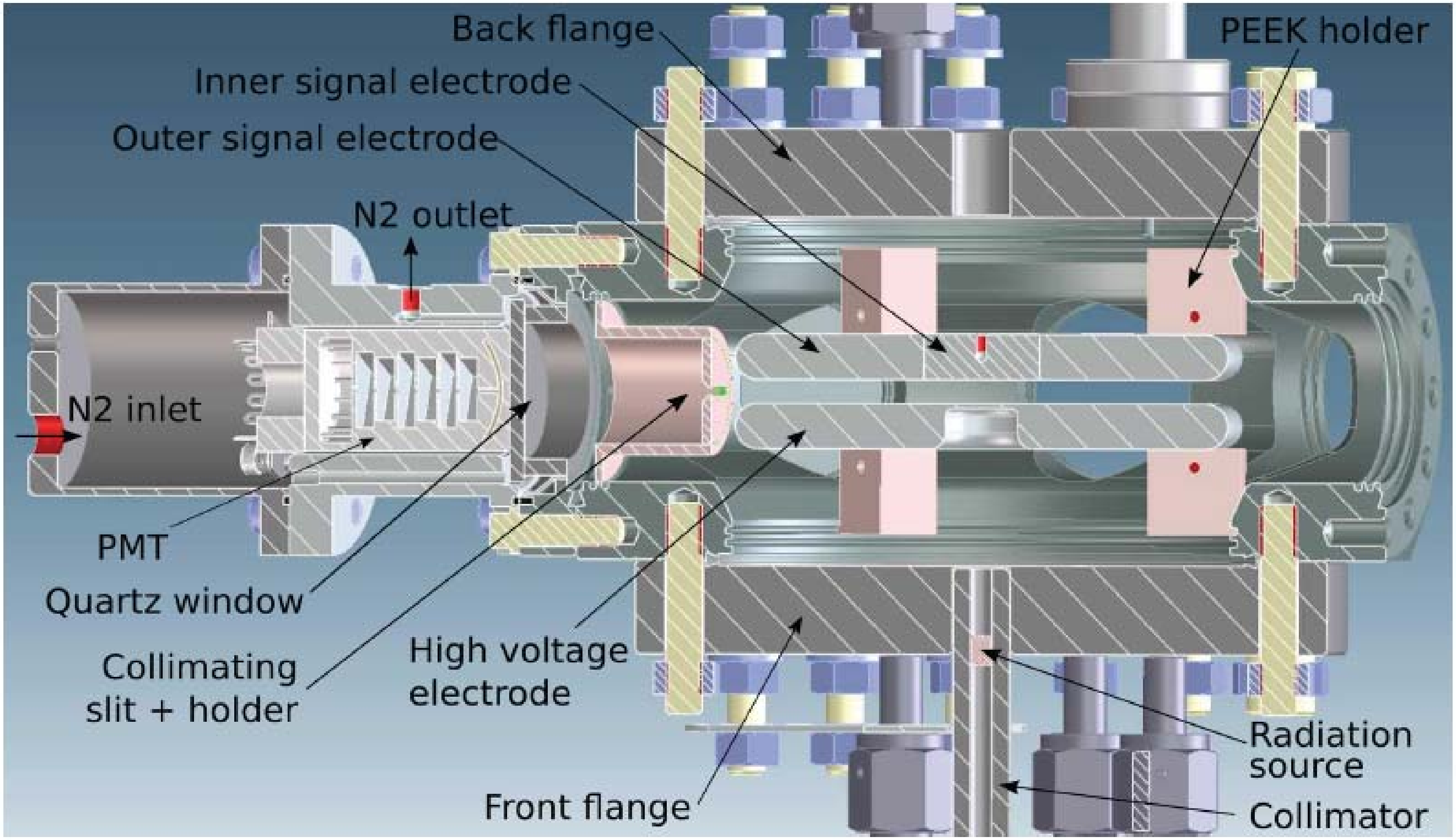
TEA-Pot

- Measures scintillation and ionization yield from pressurized gas (up to 8 bar) at various electric fields.
- In-situ measurement of the gas composition with the RGA

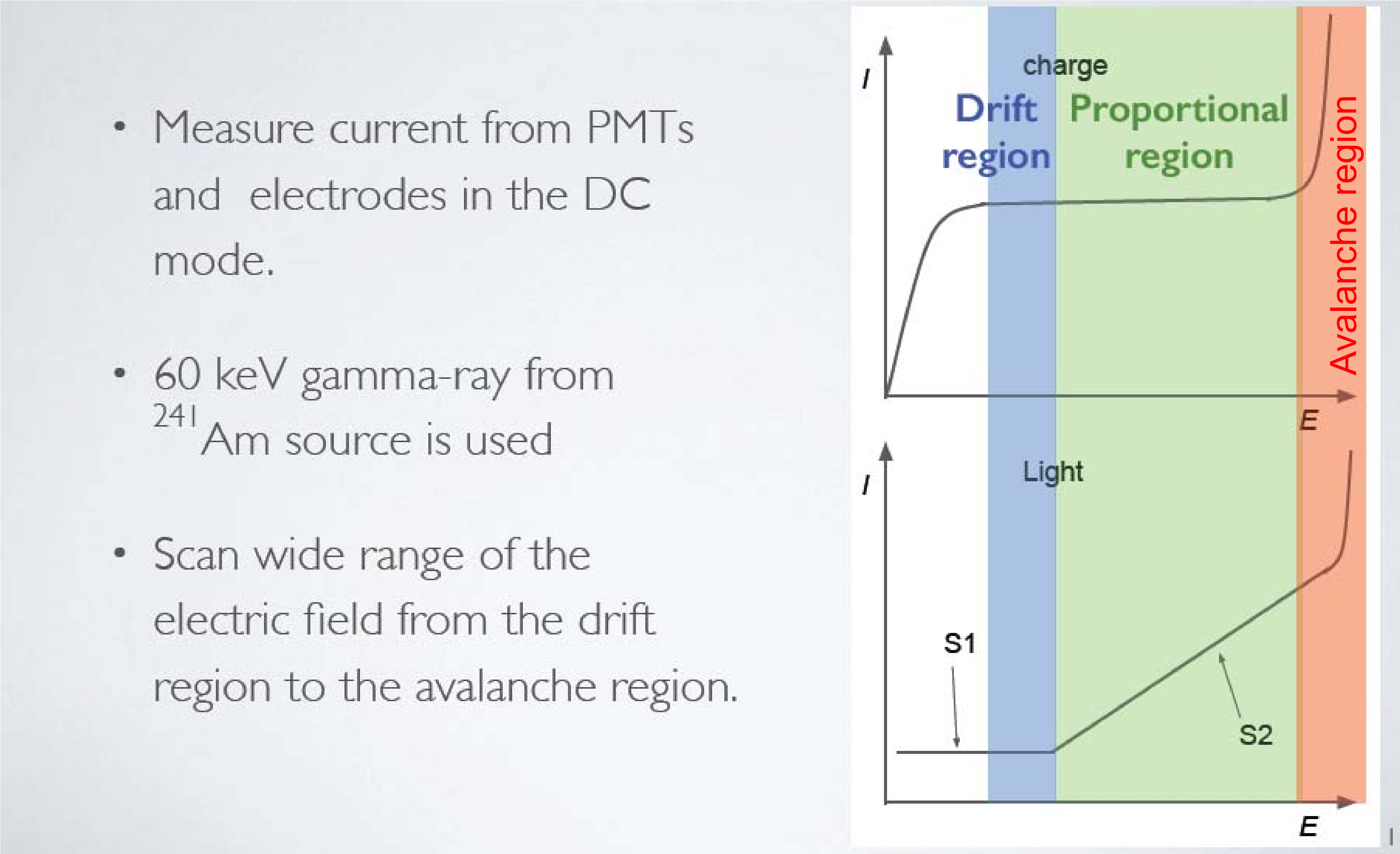
xe+tma charge and light yield: Setup



xe+tma charge and light yield: Setup details



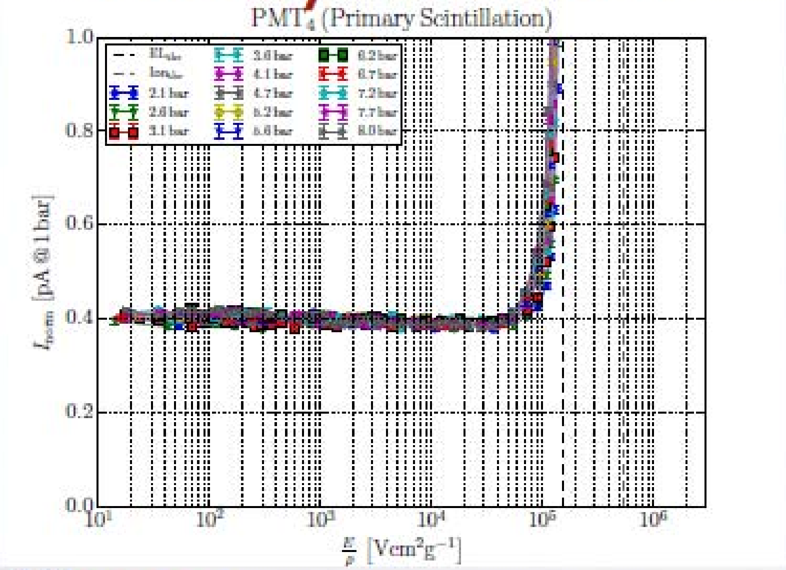
xe+tma charge and light yield: As field changes…



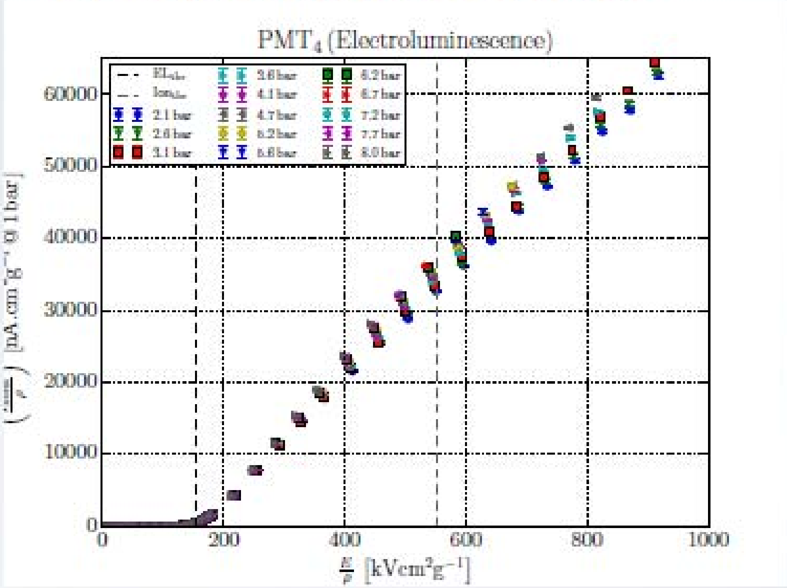
- Measure current from PMTs and electrodes in the DC mode.
- 60 keV gamma-ray from ^{241}Am source is used
- Scan wide range of the electric field from the drift region to the avalanche region.

xe+tma charge and light yield: Pure xenon

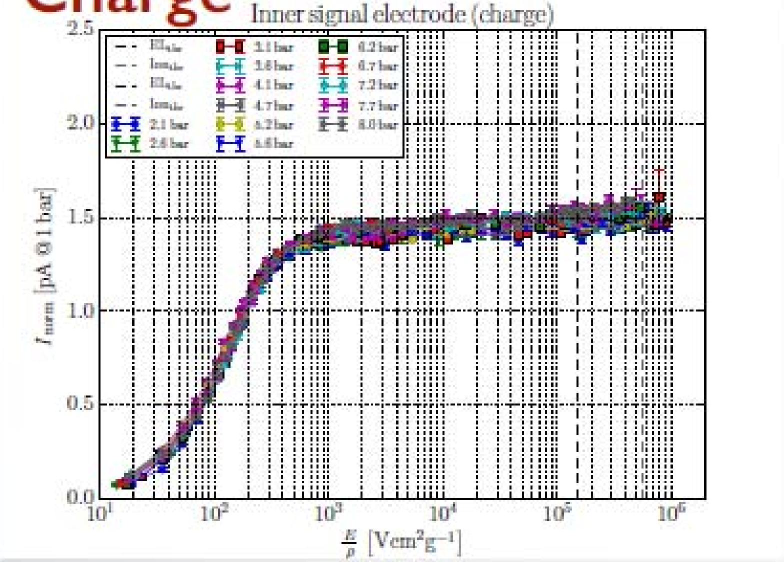
Primary scintillation



Electroluminescence

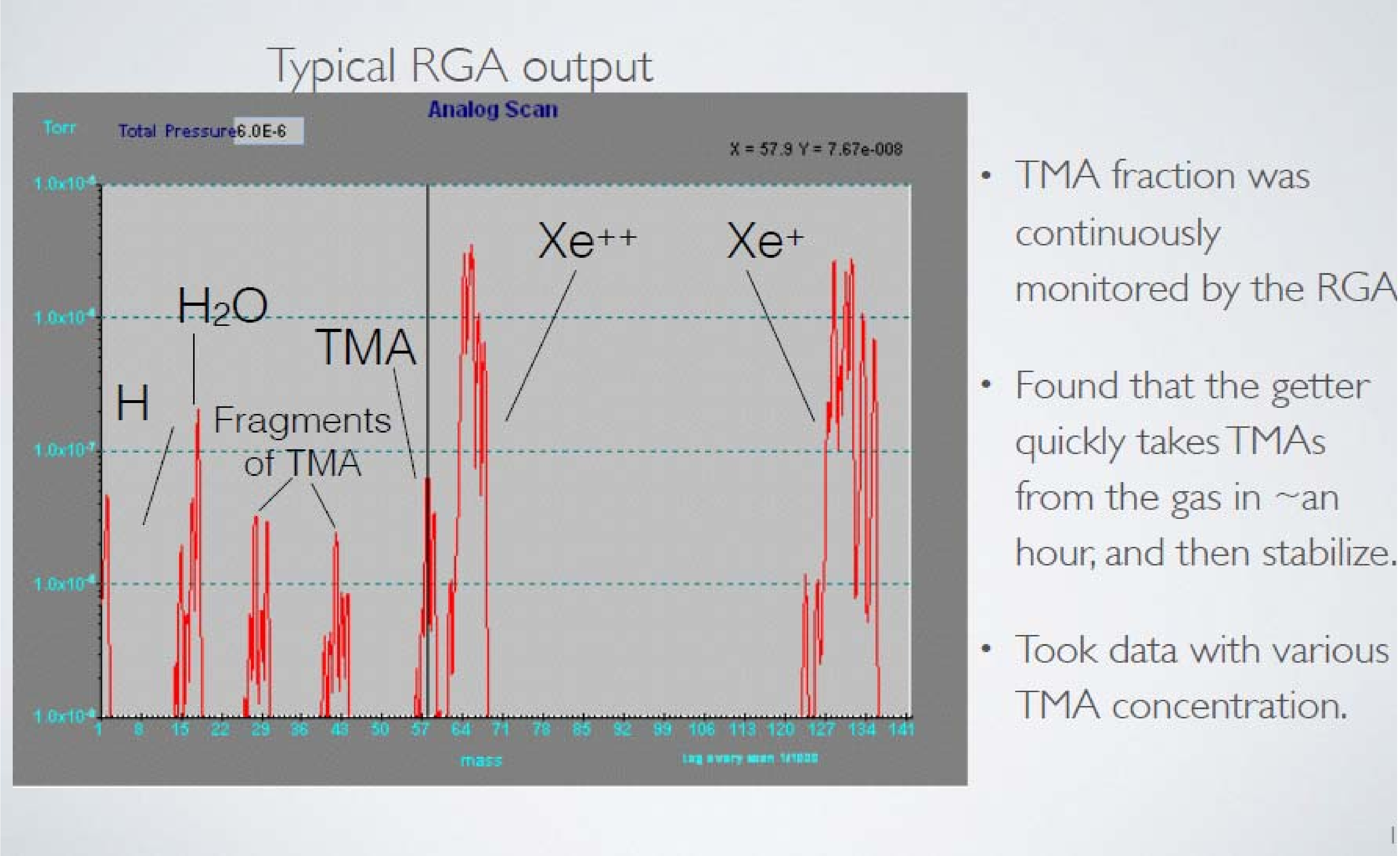


Charge



- Very high quality data, consistent between different pressures
- Difference of energy deposition in the active region is corrected using Geant4 simulation

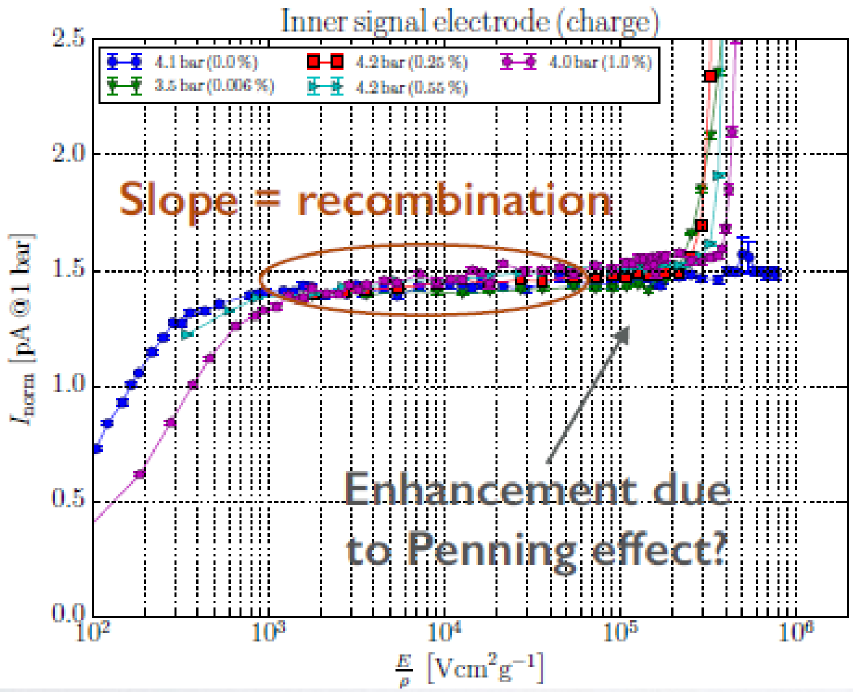
xe+tma charge and light yield: Adding tma



Typical RGA output

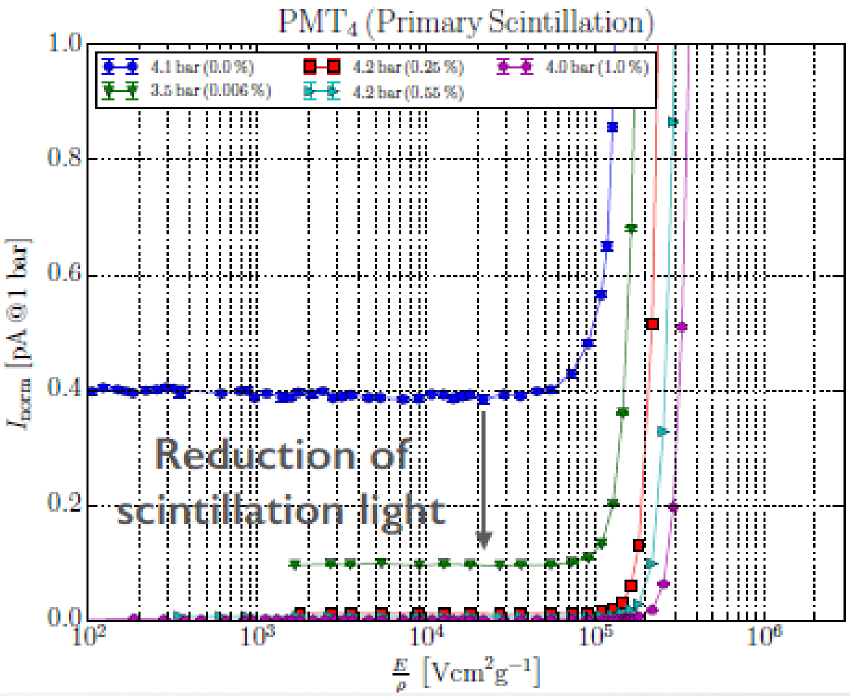
- TMA fraction was continuously monitored by the RGA
- Found that the getter quickly takes TMAs from the gas in ~an hour, and then stabilize.
- Took data with various TMA concentration.

xe+tma charge and light yield: Results with tma



Slope = recombination

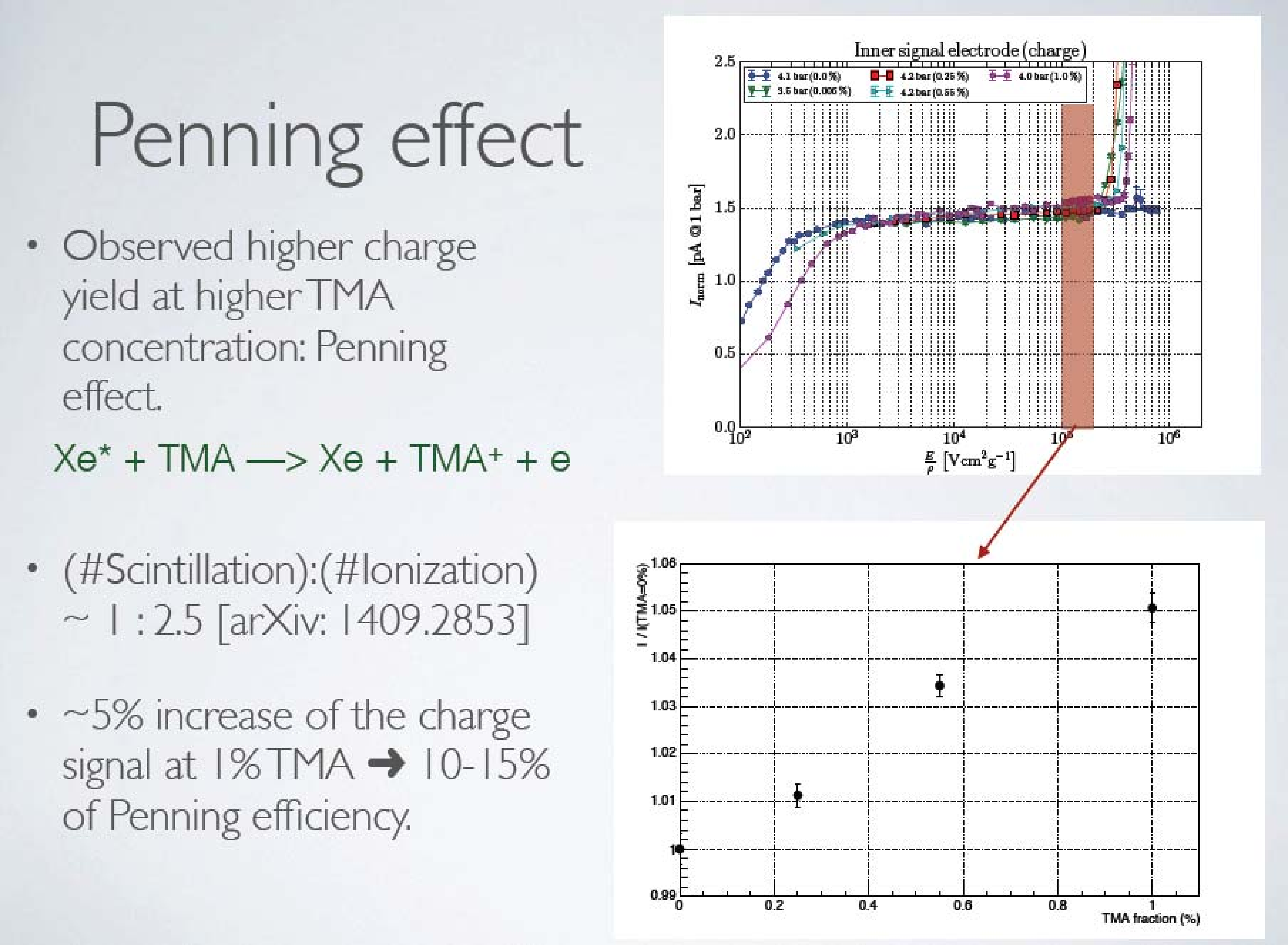
Enhancement due to Penning effect?



Reduction of scintillation light

- Enhanced recombination and slight hint of Penning effect (will come back later)
- Charge multiplication happens at lower field due to lower ionization energy of TMA and the Penning effect
- Big reduction of scintillation light.
    - Most of Xe scintillation light seems to be absorbed by TMA at >0.1% level

xe+tma charge and light yield: Penning measurement



Penning effect

- Observed higher charge yield at higher TMA concentration: Penning effect.

Xe* + TMA —> Xe + TMA⁺ + e

- (#Scintillation):(#Ionization) ~ 1 : 2.5 [arXiv: 1409.2853]
- ~5% increase of the charge signal at 1% TMA ➜ 10-15% of Penning efficiency.

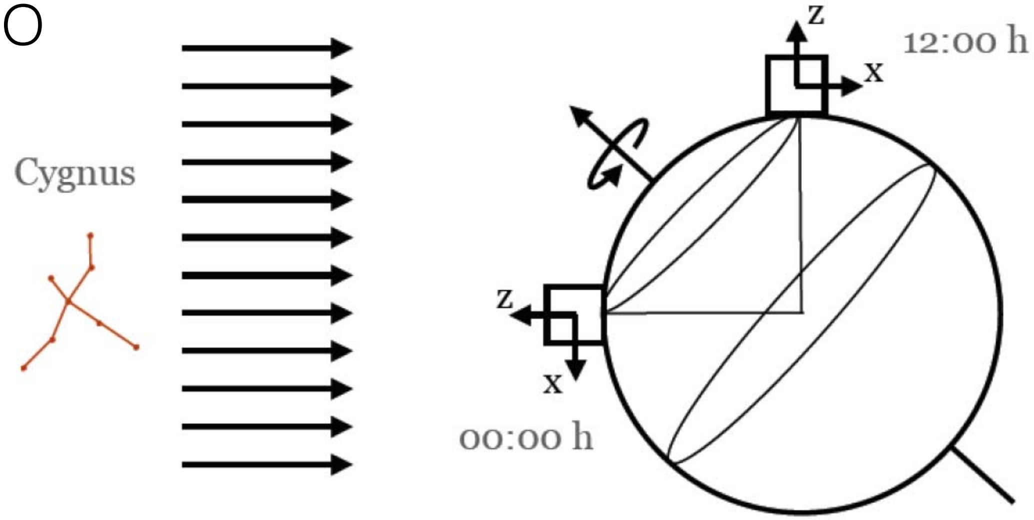
test in simulation concept to derive direction of dm recoil from recombination
use gas additive (tma) to reduce diffusion and enhance recombination

RECOMBINATION SIMULATION FOR DARK MATTER DIRECTIONALITY IN XENON AT 10-20 ATM

Megan Long, Yasuhiro Nakajima, AG
e-Print: **arXiv:1505.03586**

recombination simulation: Motivation

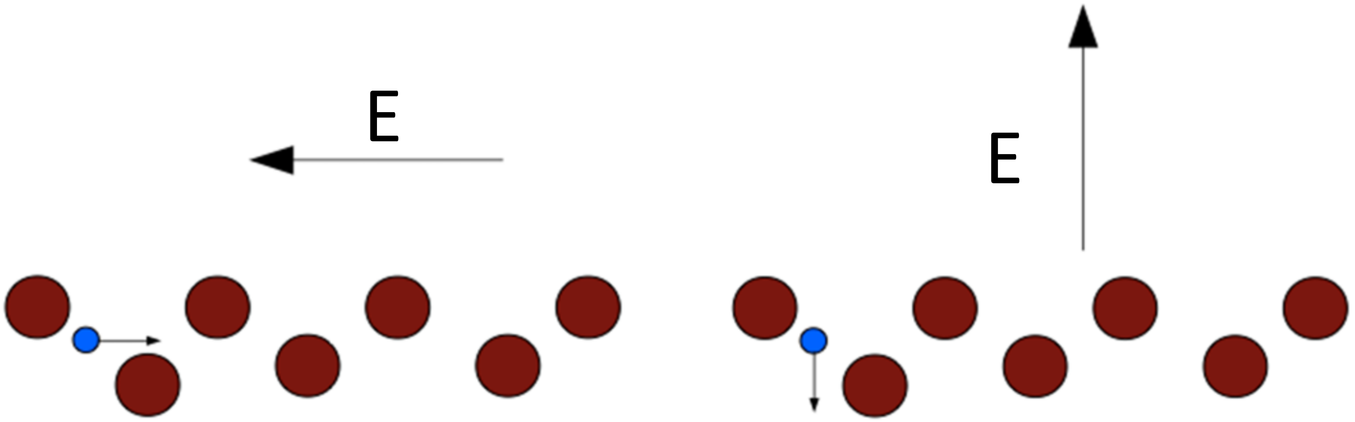
A preferred direction: From galaxy rotation (and thus Sun & Earth) in a non co-rotating Dark Matter halo



$$\frac{dR}{dRd\cos\psi} \approx \frac{1}{2}\frac{R_0}{E_0 r}\exp\left[-\left(\frac{v_E\cos\psi - v_{\min}}{v_0}\right)^2\right]$$

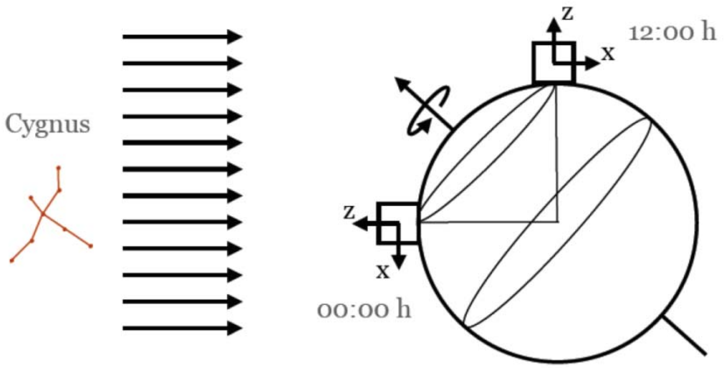
Sidereal-day modulation quickly goes out of phase with the day-night cycle

recombination simulation: Recombination for directionality



Case 1:
More Recombination

Case 2:
Less Recombination



Concept by Dave Nygren, LBNL

recombination simulation: Intended effect of tma

- Enhance intrinsic columnar recombination signal by:
  - Reduction in electron diffusion
  - Transferring xenon excitations to TMA ionizations through Penning
- Enhance measured columnar recombination signal:
  - Increase ten-fold light collection efficiency (with less PMTs): expected/hoped for TMA recombination light at ~300 nm converted in WLS bars

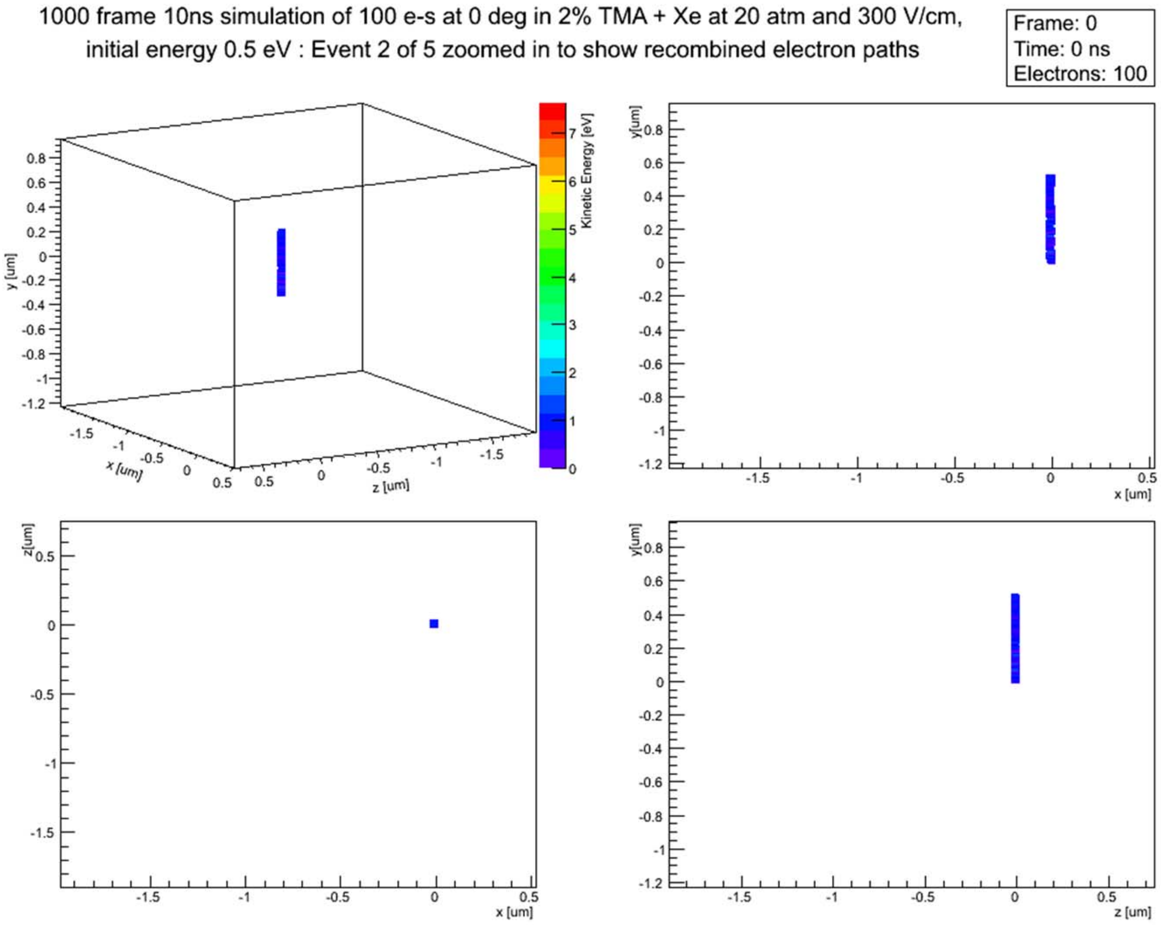
recombination simulation: Simulation elements

- Garfield++ with Magboltz cross sections for Xe and TMA
- Electrostatic interactions between all charges (ions and electrons)
- Define energy spectrum of ionization electrons
- Simplified nuclear recoil ionization tracks (equidistant ions at expected linear density)
- Recombination condition (negative total energy of electron)
- Use large Carver cluster (NERSC) of computers

Megan Long and AG, LBNL

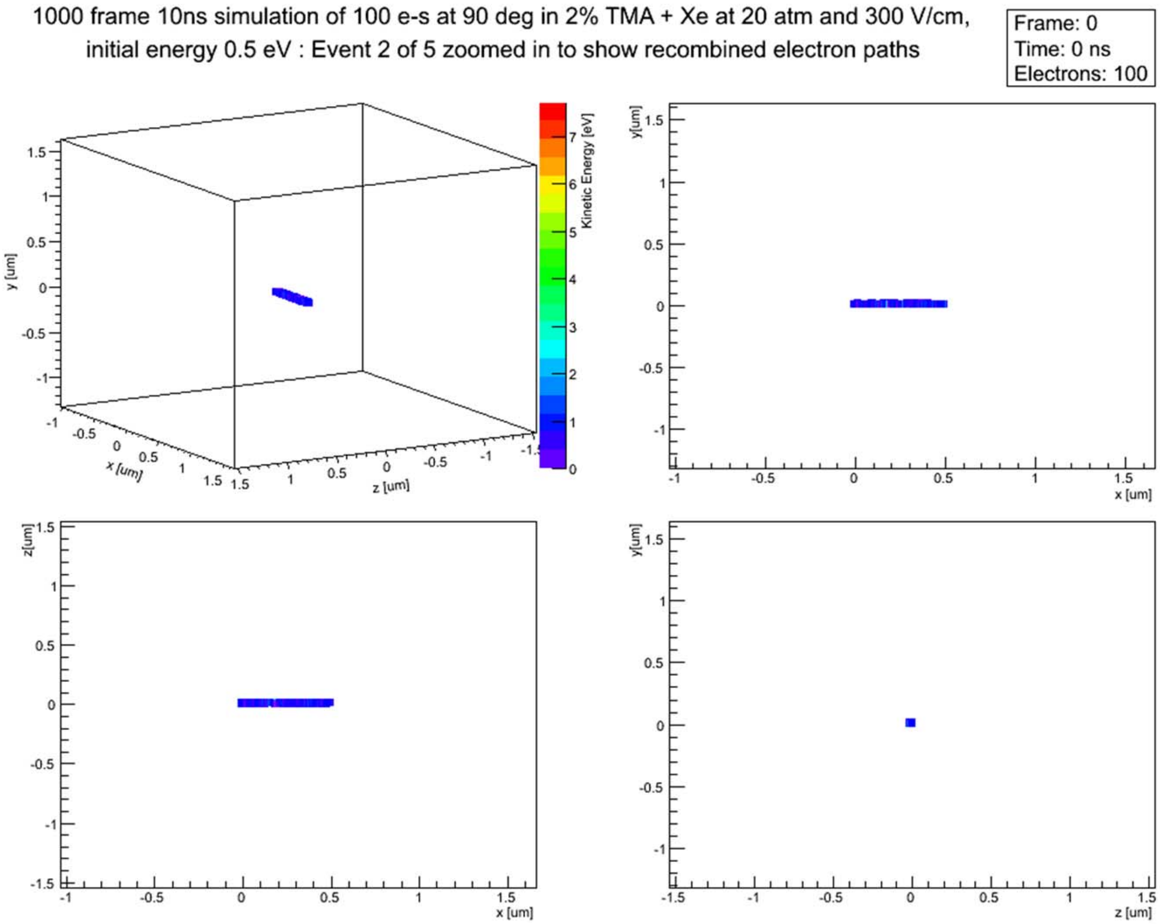
recombination simulation: Movie #1 parallel

Xe + 2% TMA: Field and Track Parallel



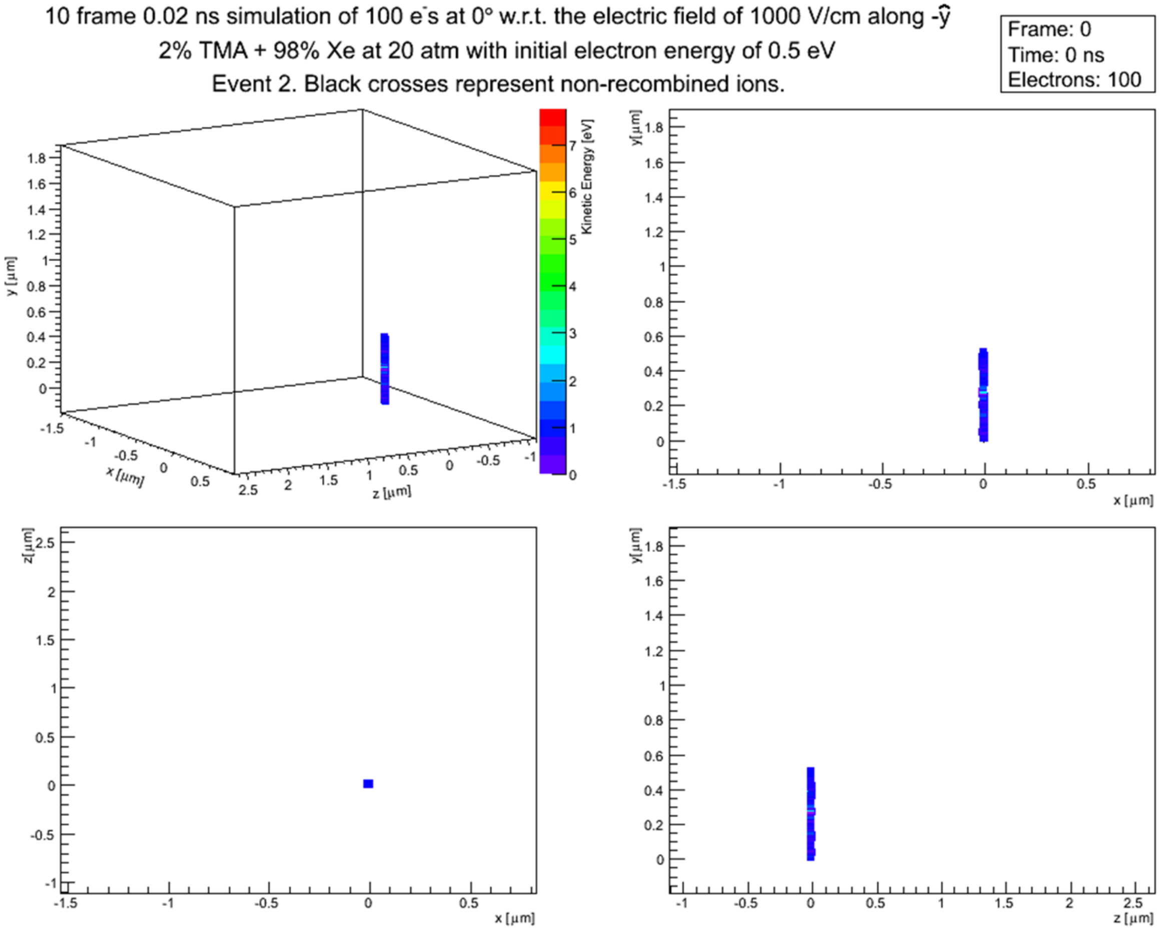
Megan Long, LBNL

recombination simulation: Movie #1 perpendicular

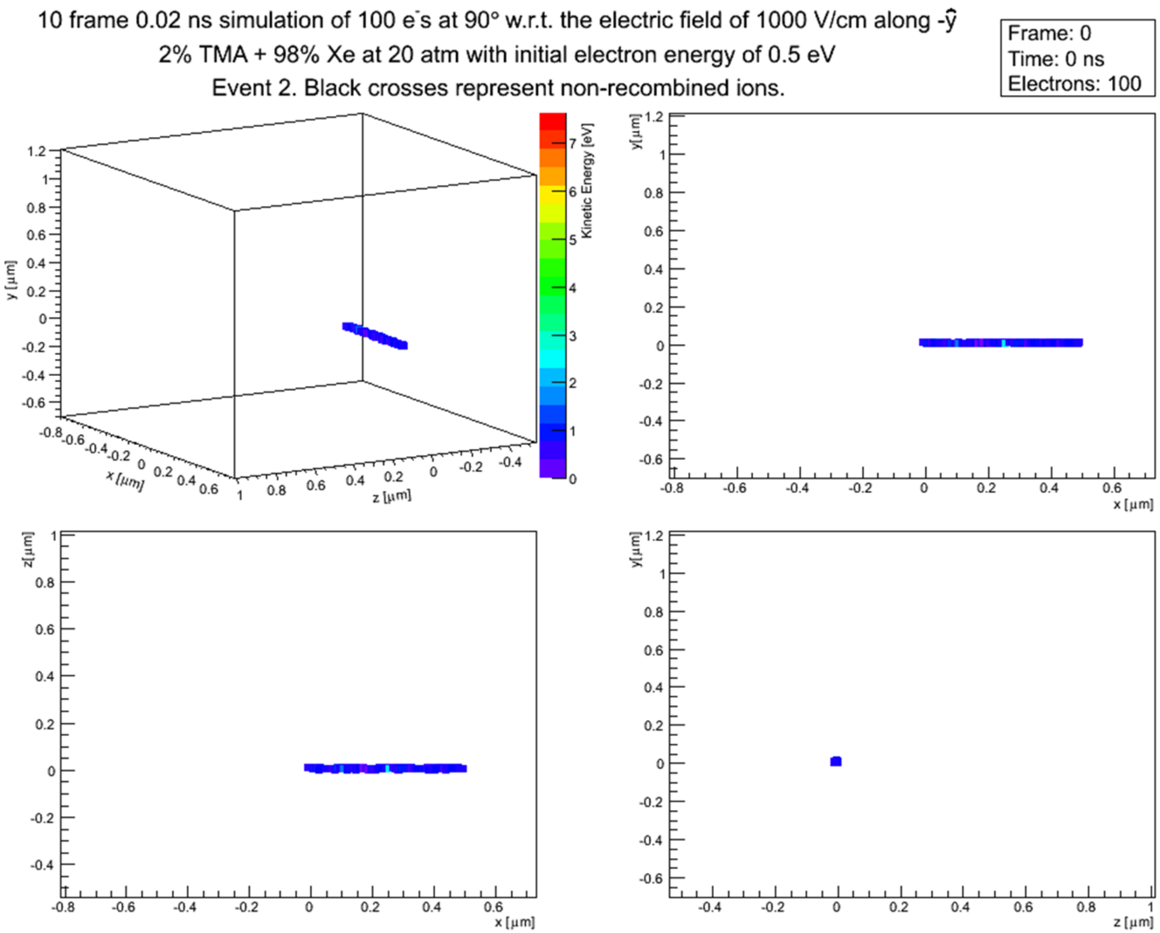

1000 frame 10ns simulation of 100 e-s at 90 deg in 2% TMA + Xe at 20 atm and 300 V/cm, initial energy 0.5 eV : Event 2 of 5 zoomed in to show recombined electron paths

Frame: 0
Time: 0 ns
Electrons: 100

recombination simulation: First 20 psec parellel

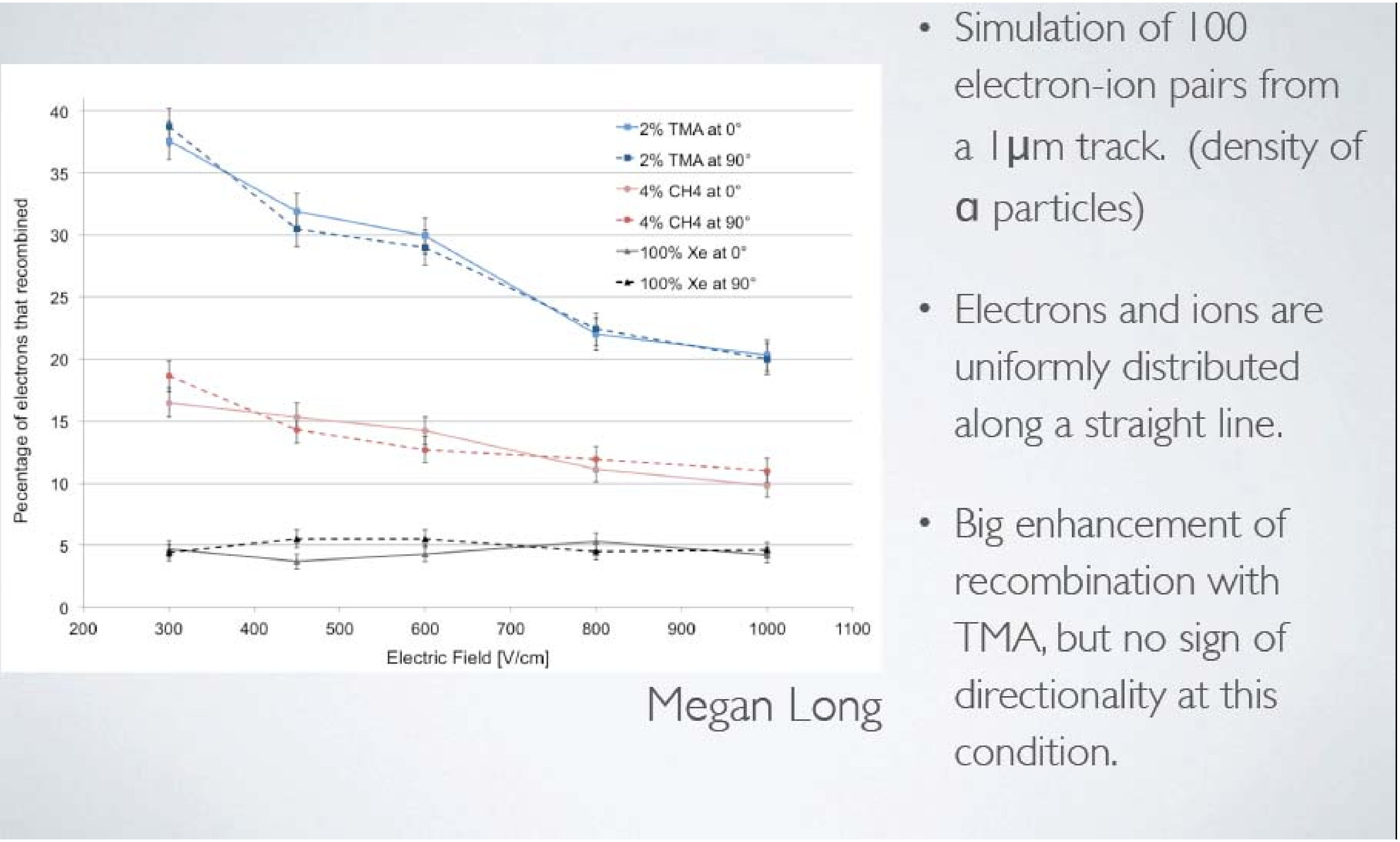


recombination simulation: First 20 psec perpendicular



10 frame 0.02 ns simulation of 100 e⁻s at 90° w.r.t. the electric field of 1000 V/cm along -ŷ
2% TMA + 98% Xe at 20 atm with initial electron energy of 0.5 eV
Event 2. Black crosses represent non-recombined ions.

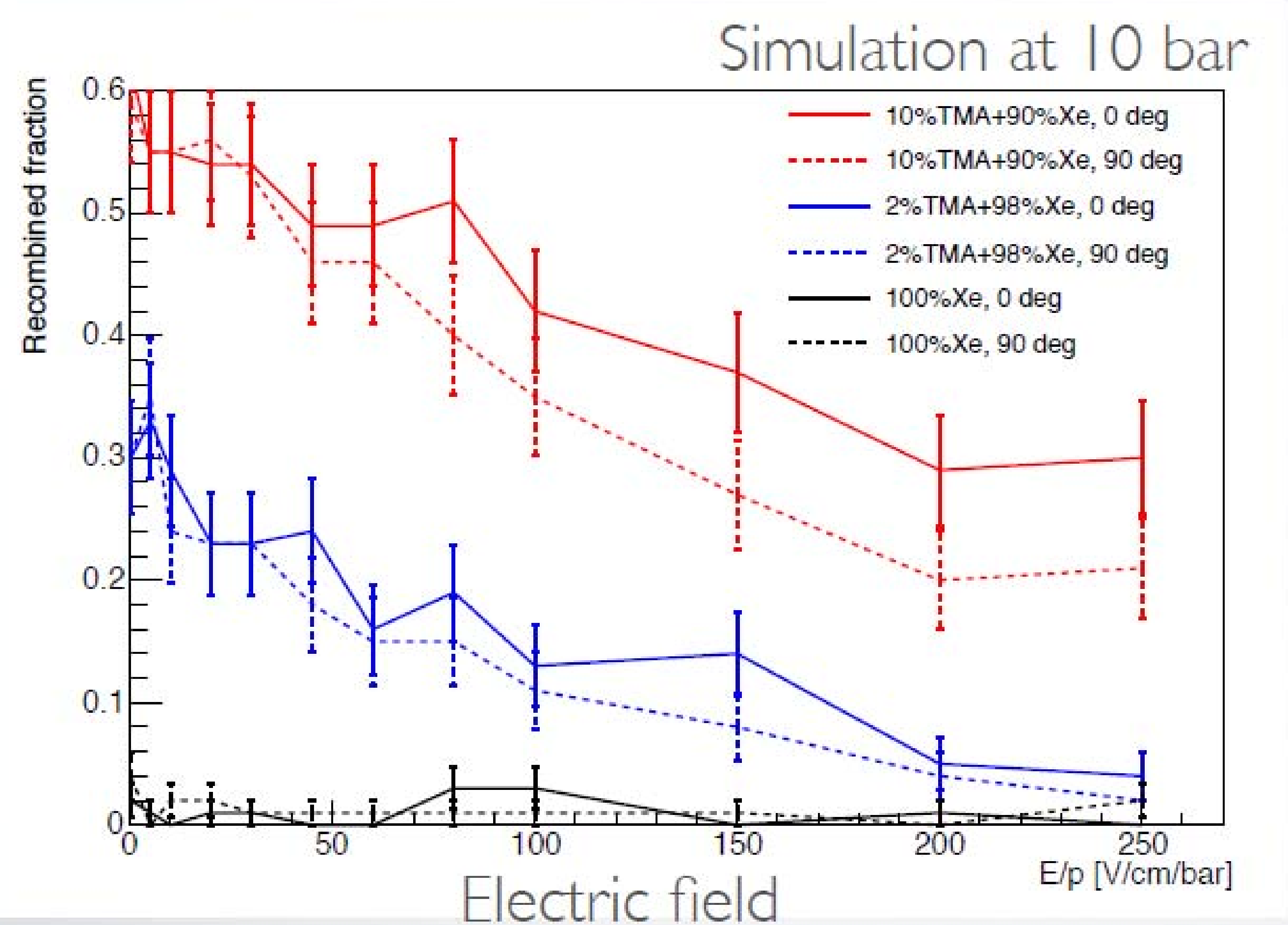
recombination simulation: Directional sensitivity (1)



Megan Long

- Simulation of 100 electron-ion pairs from a 1 μm track. (density of α particles)
- Electrons and ions are uniformly distributed along a straight line.
- Big enhancement of recombination with TMA, but no sign of directionality at this condition.

recombination simulation: Directional sensitivity (2)



Simulation at 10 bar

Electric field

- Stretched the track from 1 μm to 4μm

10% TMA: σ_R ~ 2 μm

2% TMA: σ_R ~ 4 μm

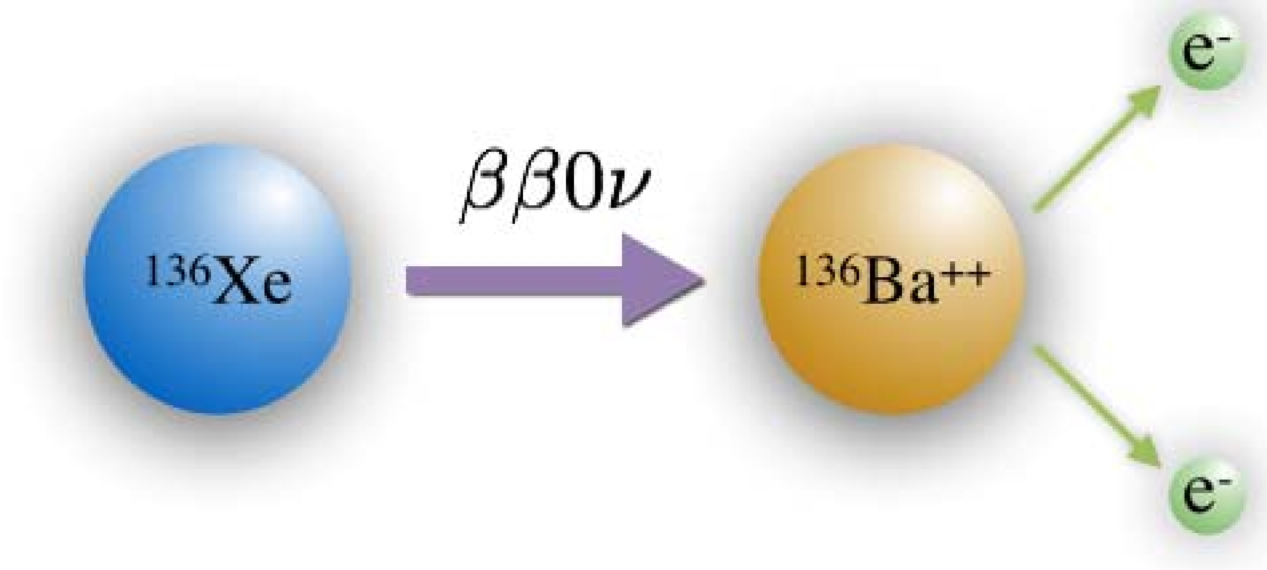
- Simulation predicts difference of recombination probability!

is it really a Ba^{++} that drifts in xenon gas after a $\beta\beta$ decay?

NOTIONS ON BARIUM TAGGING IN HIGH PRESSURE XENON FOR $0\nu\beta\beta$

AG
Internal funding proposal 2015 (LDRD) from LBNL’s NSD

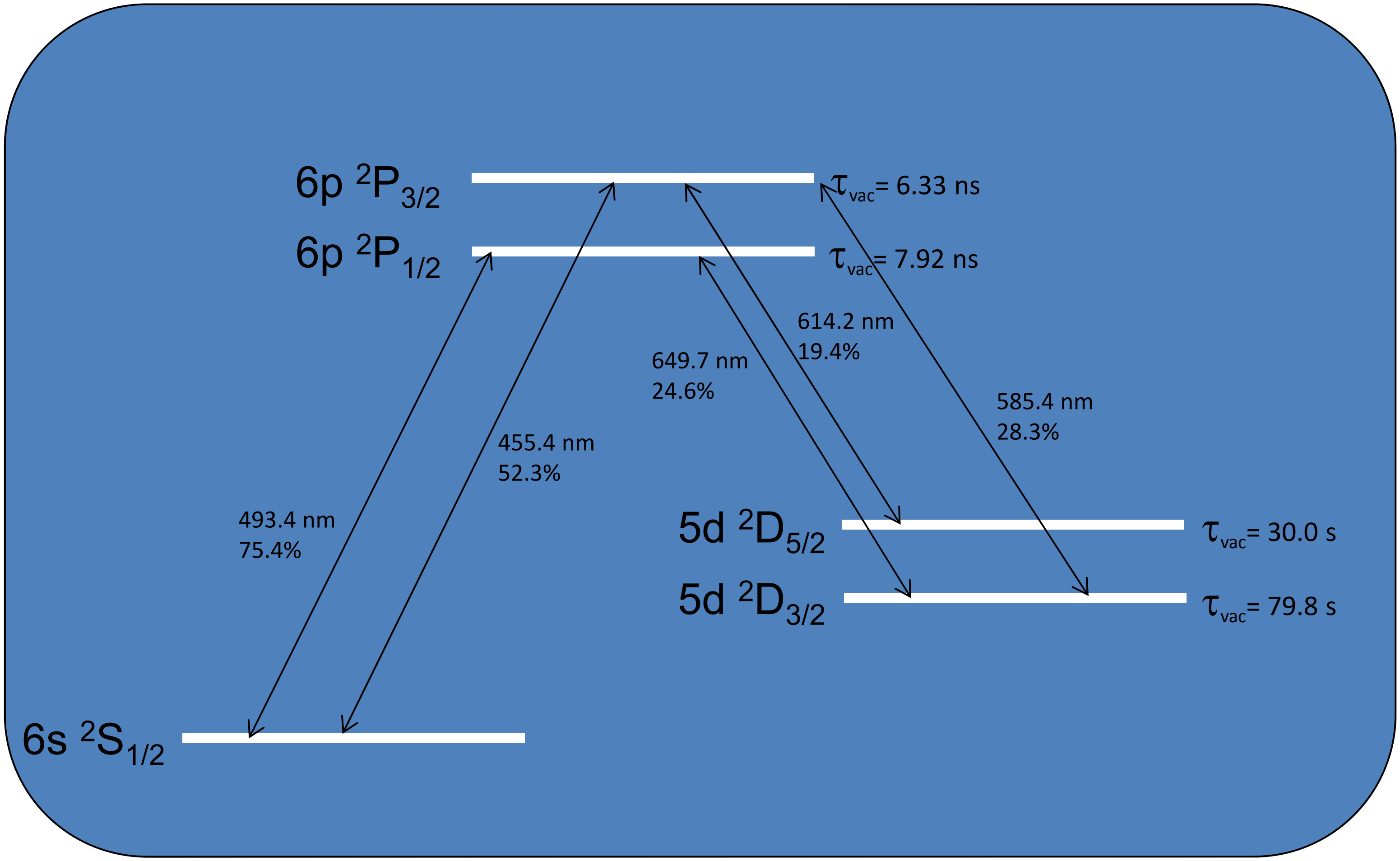
barium tagging in gas: The challenge



M.Moe PRC44 (1991) 931

Can the presence of a single barium ion be efficiently identified from/within $4x10^{27}$ xenon atoms and 10^5 xenon ions?

barium tagging in gas: Positive identification

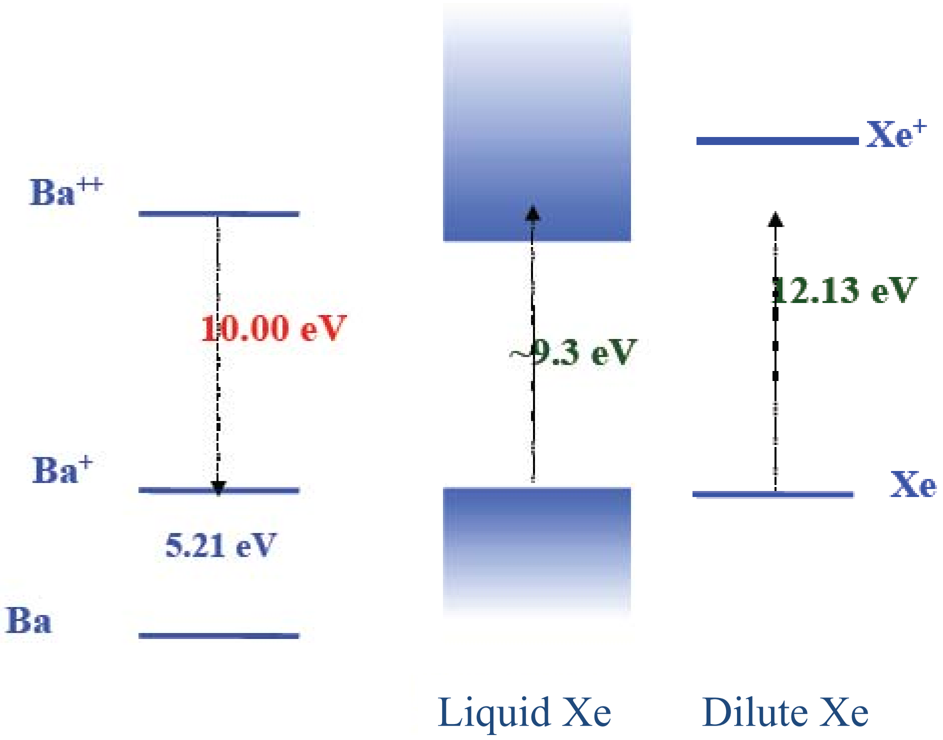


Light Induced Fluorescence (LIF)

Ba^+ Level Scheme

Method does not work for Ba^{++}

barium tagging in gas: Ba^{++} or Ba^{+}?



Naively, expect:

Ba^{+} in liquid xenon (from charge transfer)
Ba^{++} in gaseous xenon

But…

barium tagging in gas: Van Der Walls clusters

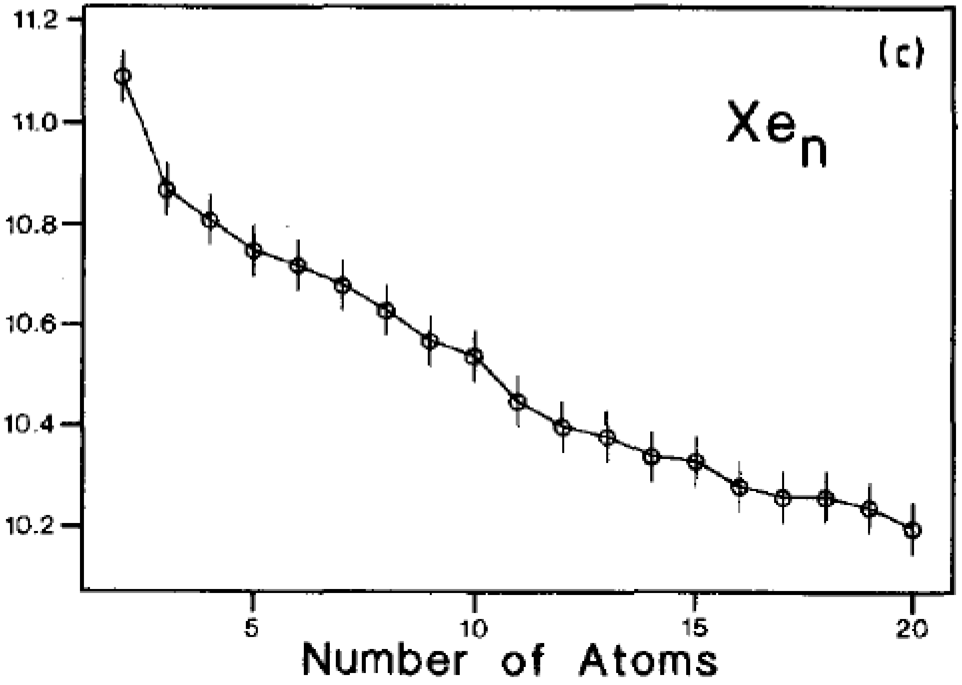


FIG. 4. Ionization potentials of argon (a), krypton (b), and xenon (c) clusters. The values of Ar_3 (Refs. 22 and 23), Kr_2 (Ref. 24), and Xe_3 (Ref. 25) serve as a calibration of the measured relative IP's shifts.

Ganteför *et al.*: Photoionization of rare gas clusters
J. Chem. Phys., Vol. 91, No. 12, 15 December 1989

Naturally occurring clusters in high pressure xenon <u>may</u> look "locally" as liquid and thus transfer charge to $Ba^{++} \rightarrow Ba^{+}$

barium tagging in gas: Ba^{++} will nucleate a cluster

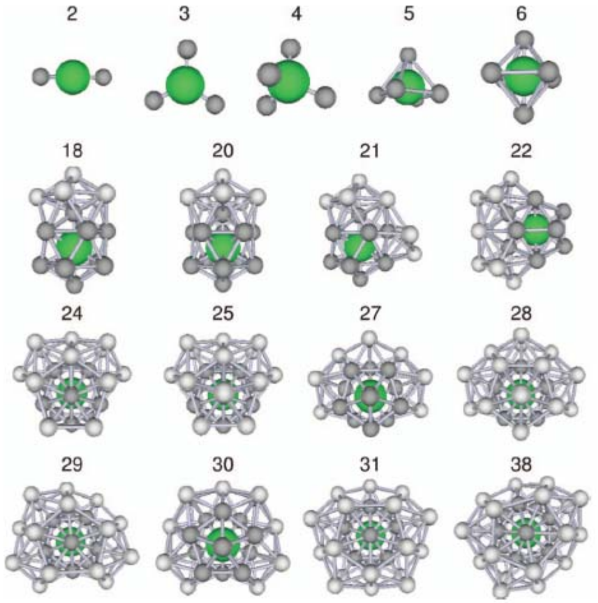


FIG. 2. Selected global minima of Ba^{2+}Xe$_n$ clusters in the many-body polarizable model. The xenon atoms from the first solvation shell of the barium cation (green sphere) are depicted by grey spheres, more distant atoms being shown by lighter grey spheres.

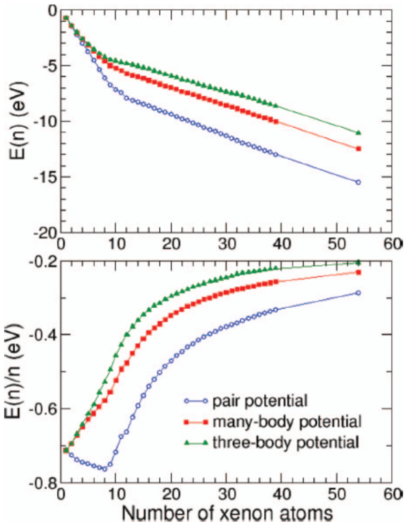


FIG. 3. Total binding energy (upper panel) and binding energy per number of xenon atoms (lower panel) of Ba^{2+}Xe$_n$ clusters obtained for the pairwise and many-body potentials. The binding energies obtained within the three-body approximation are also indicated.

Abdessalem et al. J. Chem. Phys. 141, 154308 (2014)

- Ba^{++} is in a xenon cluster, maybe enables charge transfer (CT) between Xe & Ba^{++}
- Conditions are dynamic with collisions between the Ba^{++}-nucleated cluster and the medium (with clusters of xenon atoms)
- CT is irreversible (medium is largely neutral), so if CT happens we end up with what we need: Ba^{+}
- Possible issue: second ionization energy of Ba may also be lowered by the medium

barium tagging in gas: LIF of Ba⁺ in xenon

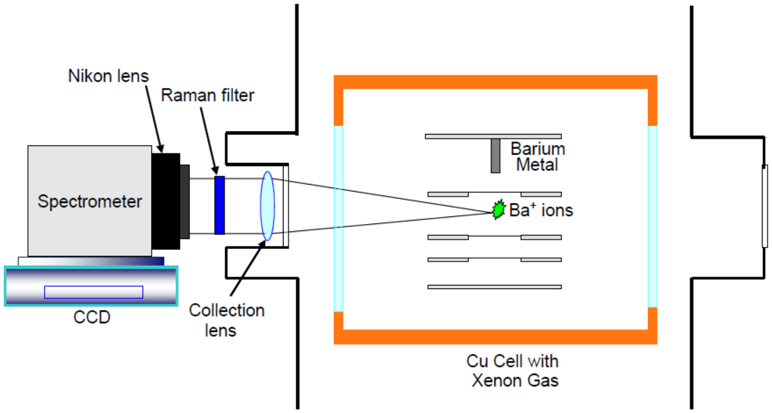


Figure 3.35: Schematic diagram of the fluorescence detection setup

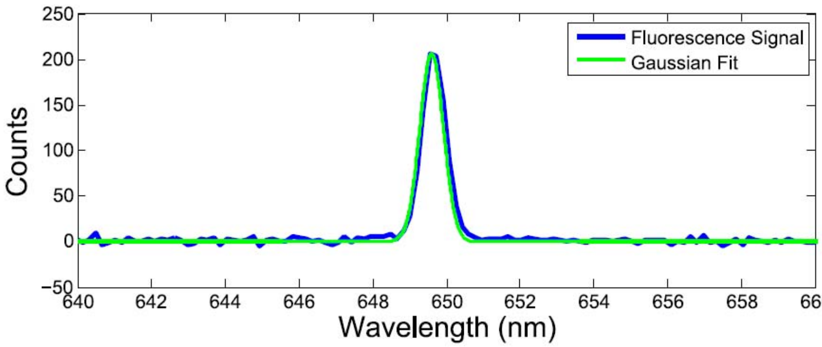
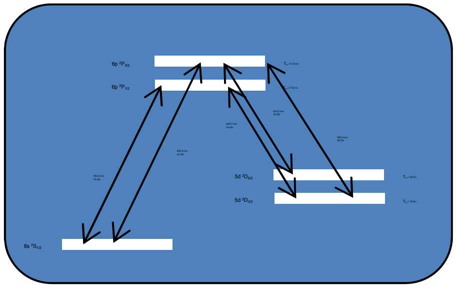


Figure 4.29: Background subtracted fluorescence spectrum of Ba^+ in xenon gas from the transition ($6p\ ^2P_{1/2} - 5d\ ^2D_{3/2}$) with excitation at 493.4 nm. The average charge per shot is 3 pC and the xenon gas pressure is 55 Torr.

Ph.D. dissertation by J. C. Benitez Medina, CSU (EXO Collaboration) 2014

- Demonstrated LIF in xenon at 40-800 Torr (with many Ba⁺ ions from laser ablation blast)
- Inferred the (predicted) creation of BaXe⁺ VDW molecules from ion mobility
- Expected D-state de-shelving rate from collisions with xenon atoms



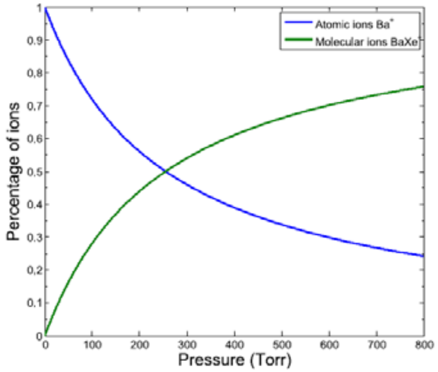
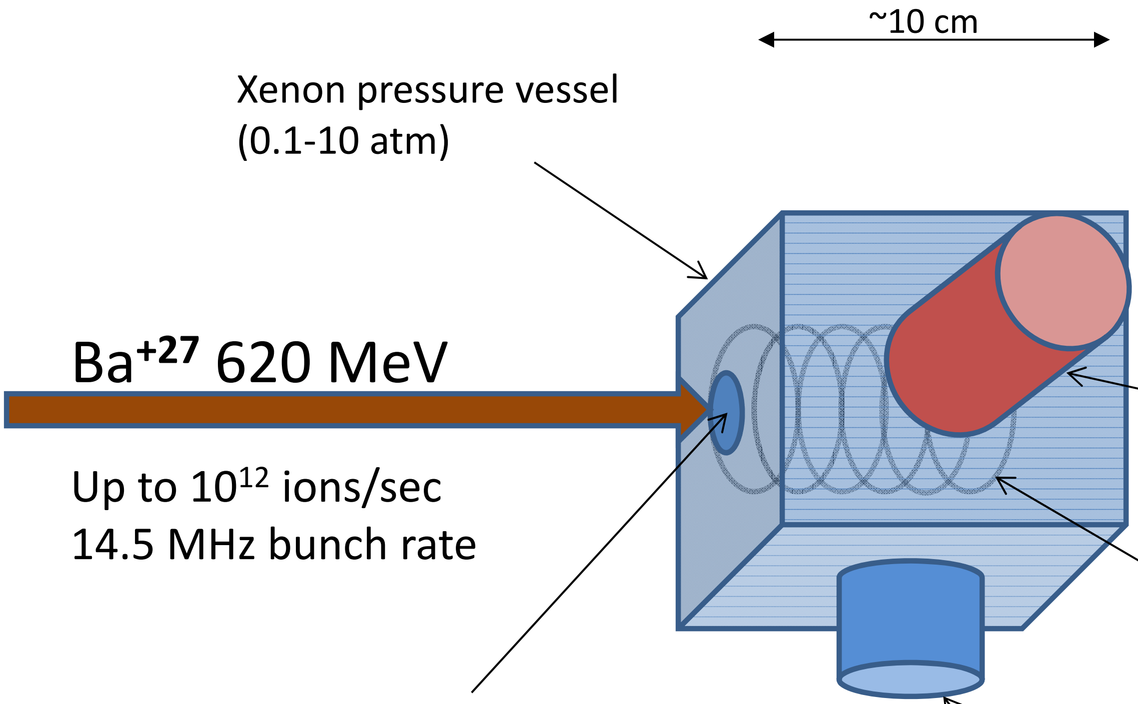


Figure 4.22: Percentage of Ba^+ and $BaXe^+$ ions in xenon gas as a function of xenon pressure.

barium tagging in gas: Yield of Ba^{++} to Ba^{+} in Xe?

Proposal to use Lbnl 88” cyclotron’s Barium ions to measure Ba^{+} <u>yield</u> in xenon



~10 cm

Xenon pressure vessel
(0.1-10 atm)

Ba^{+27} 620 MeV

Up to 10^{12} ions/sec
14.5 MHz bunch rate

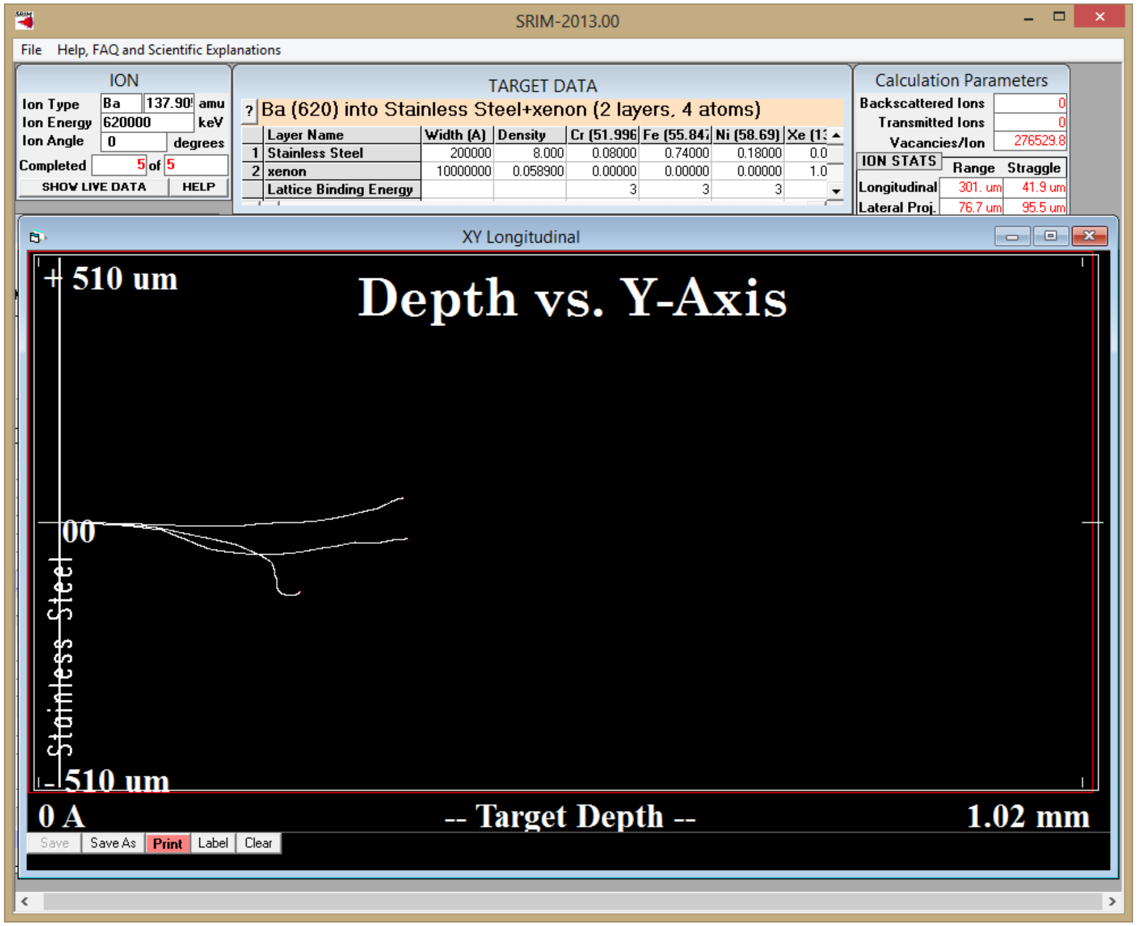
PMT with filter for
580nm or 650 nm

Field rings remove
electrons and drift ions
to center

Entrance window
SS 15 micron, 1 cm diam.

Excitation LED (455nm or 493nm)

barium tagging in gas: Ion trajectories (SRIM MC)



Ion Type: Ba 137.90 amu
Ion Energy: 620000 keV
Ion Angle: 0 degrees
Completed: 5 of 5

Ba (620) into Stainless Steel+xenon (2 layers, 4 atoms)

	Layer Name	Width (A)	Density	Cr (51.996	Fe (55.847	Ni (58.69)	Xe (13
1	Stainless Steel	200000	8.000	0.08000	0.74000	0.18000	0.0
2	xenon	10000000	0.058900	0.00000	0.00000	0.00000	1.0
	Lattice Binding Energy			3	3	3	

Backscattered Ions: 0
Transmitted Ions: 0
Vacancies/Ion: 276529.8

ION STATS	Range	Straggle
Longitudinal	301. um	41.9 um
Lateral Proj.	76.7 um	95.5 um

- Ions lose most of the energy in window
- Ions range out depositing 10 MeV in the xenon
- As it slows picks up electrons from medium
- Thus Ba^{+27} at the end of the trajectory is a good proxy for Ba^{++}

SUMMARY

- liquid xenon’s better scalability (volume and self shielding) is a clear advantage for dm and double beta searches
- liquid xenon is also clearly ahead in the development, now moving to the ton scale
- gaseous xenon with its better energy resolution and track imaging will be tested in the next few years at a scale of EXO-200 by NEXT in Spain and maybe a chinese project as well
- recombination to determine dm directionality seems insufficient according to simulations.
- the xe + tma mixture has been characterized in a range of concentrations and pressures and fell short of the educated-hopes for enhancement of recombination light, etc.
- the question of whether is Ba^{++} or Ba^{+} that drifts after the bb decay may be addressed with a dedicated experiment at a cyclotron

thanks for your attention!