Development of High Pressure Xenon Detectors for Dark Matter and Neutrino-less Double Beta Decay

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ABSTRACT

At present, some of the most sensitive dark matter and neutrino-less double beta decay search experiments use liquid xenon as the detection medium. However, at the expense of larger volumes and bulkier containment vessels, operation in the gas phase at room temperature and high pressure offers multiple important advantages and new opportunities. Molecules that enhance the performance (such as in-gas wavelength shifting for improved light measurement or columnar recombination enhancement for dark matter directionality measurement) can be easily added to the gas. Other advantages include the proven 6x (six times) better energy resolution and the demonstrated ability to do track imaging in pure high-pressure xenon and the potential of improved nuclear-recoil/electron-recoil discrimination with respect to the liquid.

At LBNL, as part of the NEXT Collaboration, we are measuring neutron-induced nuclear recoils and gamma-ray-induced electron recoils in pure gaseous xenon and its mixtures with neon and TMA in two dedicated R&D detectors to explore these prospects. In addition we have developed a detailed recombination simulation to assess the nuclear recoil directionality sensitivity in high-pressure xenon and its mixtures.

Proven Performance of High Pressure Xenon (HPXe)

Using prototype Time Projection Chambers (TPCs) with electroluminescent (EL) gain, excellent energy resolution was obtained at high pressure (10-15 atm) in pure xenon[1] . We expect 0.6% FWHM energy resolution at the ^{136}Xe double beta decay endpoint (2458 keV), thus enabling a powerful search for the neutrino-less peak at the endpoint. In addition, the extended ionization tracks of the two betas of O(10cm) length can be fiducialized and imaged in the TPC [2] providing rejection against gamma rays and other background events.

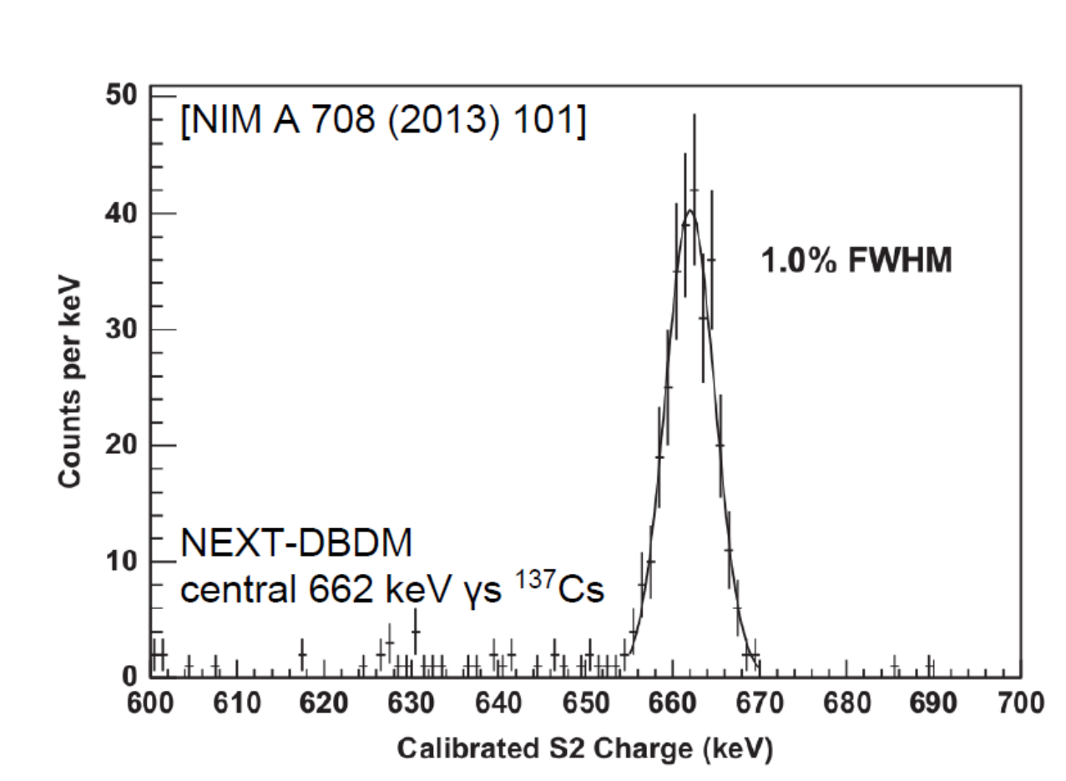

Fig.1: Measured energy resolution in high pressure xenon at 10 atm for 662 keV gamma calibration source

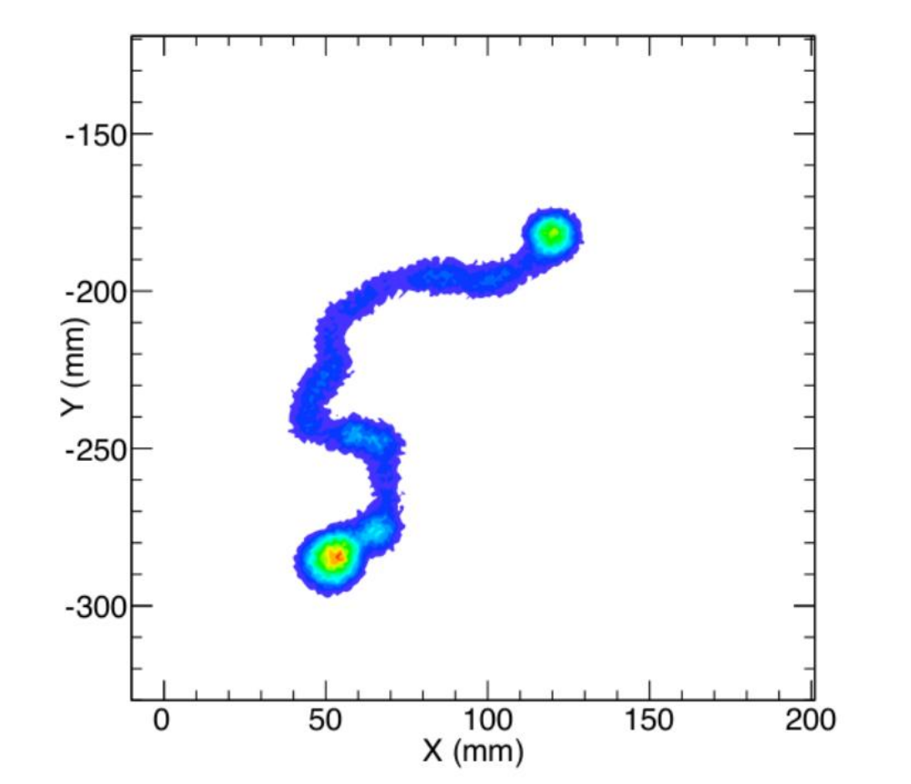

Fig.2: Simulated tracks from a neutrino-less double beta decay in 10 atm of xenon

Opportunities with HPXe & Gas Additives

- ❖ Reduction of diffusion
- ❖ Penning transfer: Super-intrinsic resolution
- ❖ Change light from Xe's VUV (170 nm) to UV (~300 nm):
  - ❖ x10 increase in light collection (with WLB bars)
- ❖ Improved electron/nuclear recoil discrimination for background suppression in Dark Matter search
- ❖ Use Columnar Recombination to determine direction of Nuclear Recoil from Dark Matter interaction [3]
- ❖ TMA, TEA, CH4 and CF4 being considered/tested

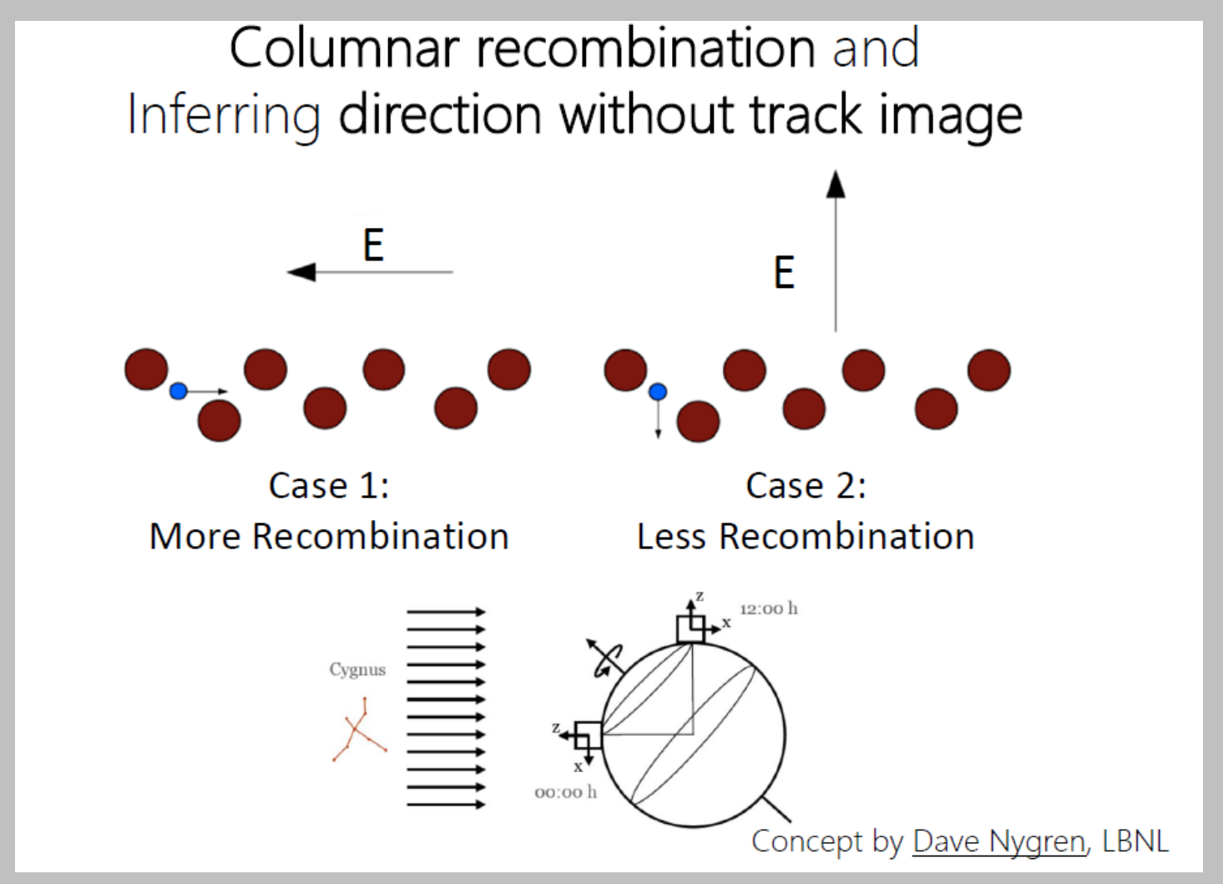

Fig.3: Dark Matter (Nuclear Recoils) directionality sensitivity through columnar recombination in HPXe

Nuclear Recoils: Light & Charge Yields in Pure Xenon @ 14 atm

Using a Pu/Be source of 2-6 MeV neutrons (externally tagged with 4 MeV coincident gamma ray), the O(50-100) keV xenon nuclear recoils (NR) were measured with the prototype TPC [4]. S1 signals (~5-20 photoelctrons) measure the excitations produced by the NR while the S2 signals (~2,000-20,000 photoelectrons) measure the ionizations (through electroluminescent gain).

As in liquid xenon, in HPXe the slope of the S2 vs S1 band is larger for electron recoils than for NRs, thus providing discrimination for gamma ray backgrounds.

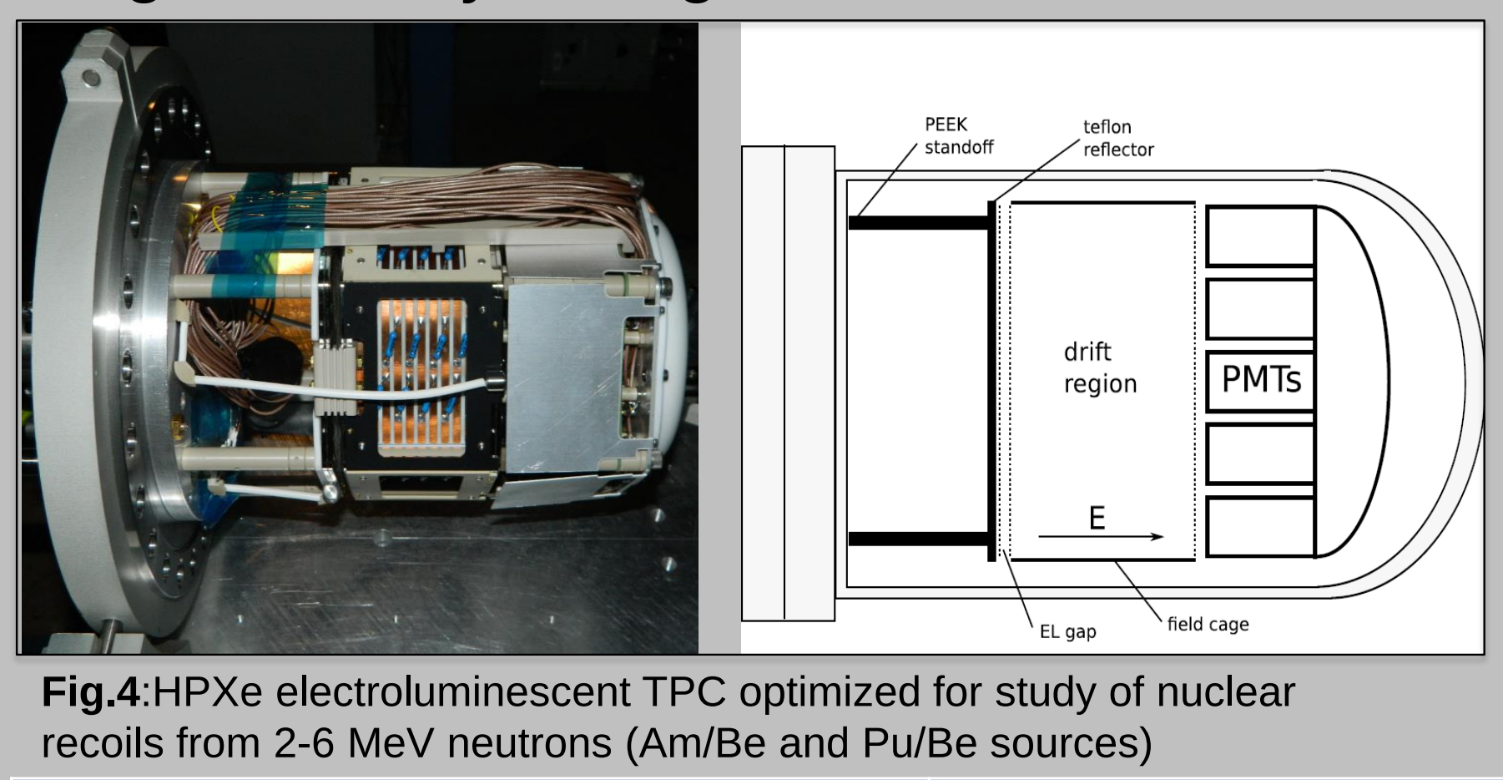

Fig.4:HPXe electroluminescent TPC optimized for study of nuclear recoils from 2-6 MeV neutrons (Am/Be and Pu/Be sources)

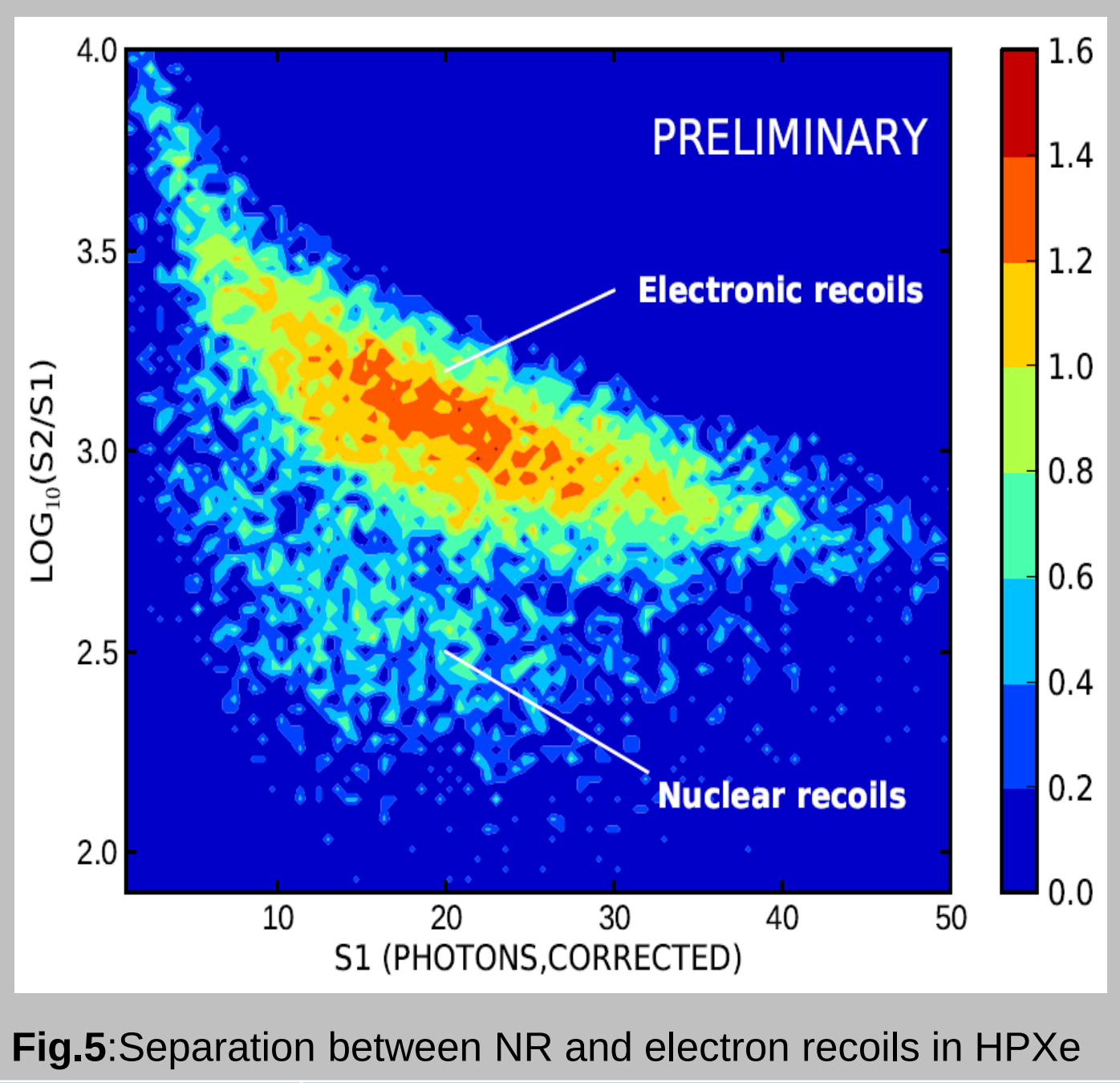

Fig.5:Separation between NR and electron recoils in HPXe

Table for 80 keV NRs	HPXe (14 Atm, 370 V/cm)	LXe (370 V/cm) [5]
NR S1 yield (photons/keV)	9.5	12.4
NR S2 yield (electrons/keV)	6.4	2.5
$(S2/S1)_{e-}/(S2/S1)_{NR}$	3	5

Light & Charge Yields of electrons in Xenon + TMA @ 1-5 atm

Trimethylamine (TMA) is the first additive under study. Its ionization potential is slightly lower than the first excitation energy of xenon making it a Penning-mixture candidate. It is known to fluoresce in the ~300 nm wavelengths and reduces electron diffusion [6] through its inelastic collisions with low energy electrons. A dedicated setup (the "TeaPot") was built to study the charge and light yield of the Xe+TMA mixtures for a range of pressures (1-8 atm), TMA fractions (0-1%), and electric fields. Using an intense and collimated ^{241}Am source of 60 keV gamma rays, DC measurements of the electrode and 4 photomultipliers (with different optical filters) currents are made with picoammeters.

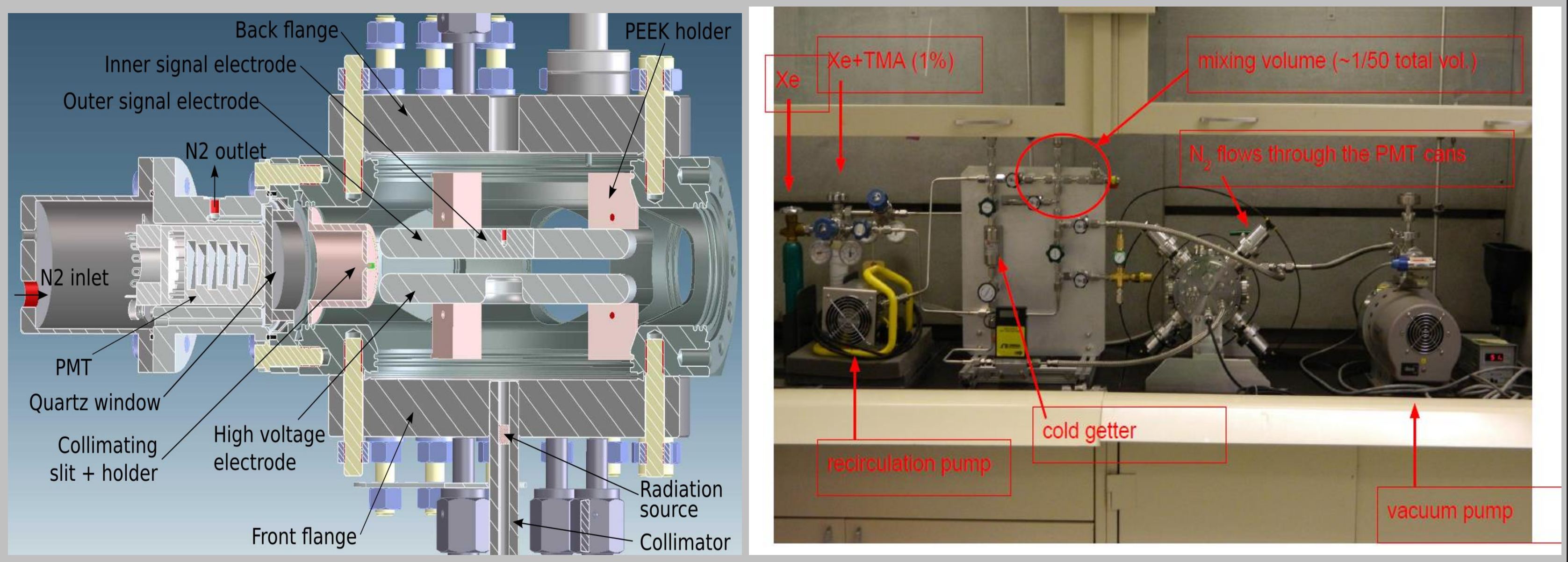

Fig.6: (Left) Schematic view of the "TeaPot". The solid electrodes around the central gap gap are 0.5 cm apart. The gap is viewed from the side by 4 PMTs. (Right) Picture of the setup with gas purification loop for the Xe+TMA mixture and N_2 flushing of the PMT enclosures.

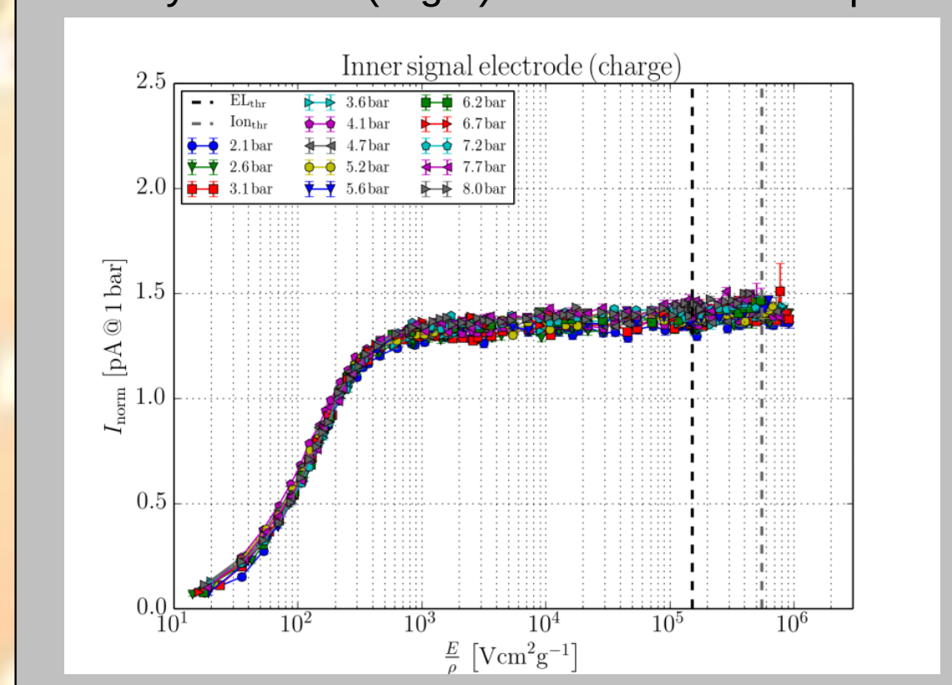

Fig.7: Pressure normalized electrode current for pure xenon.

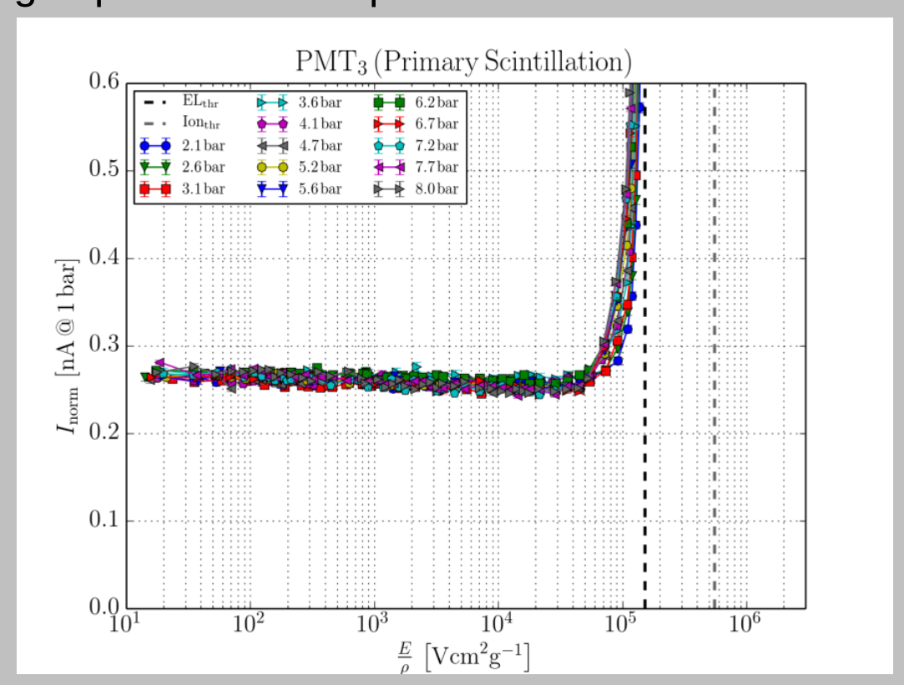

Fig.8: pressure normalized PMT current (xenon light) in the region until the EL onset.

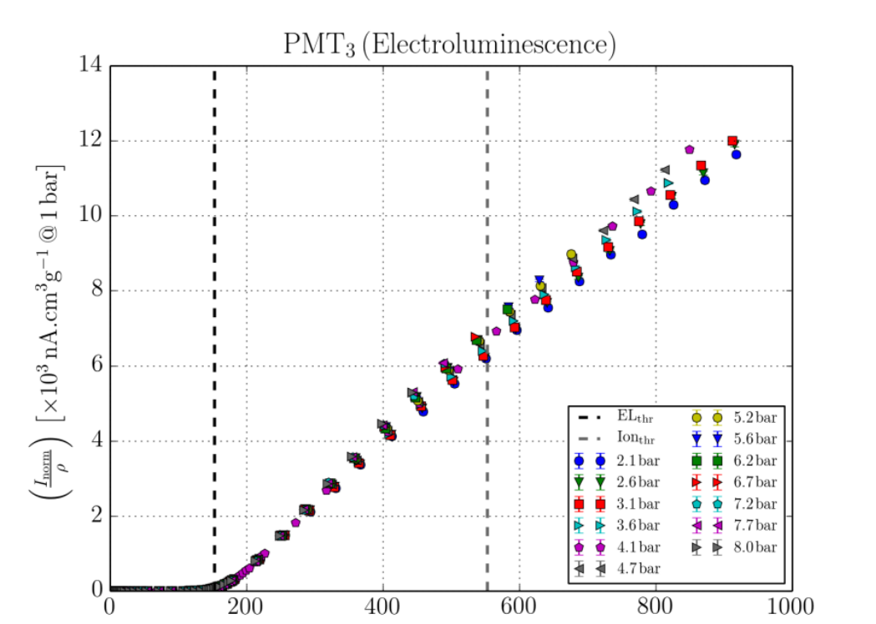

Fig.9: normalized PMT current (xenon light) in the linear electroluminescence region.

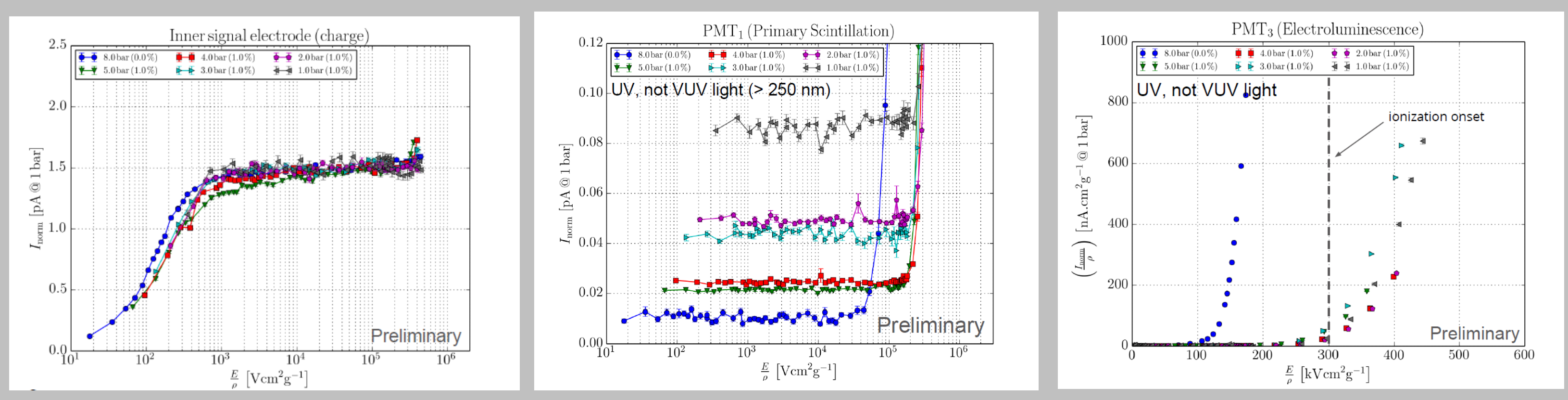

Fig.10-12: : Same as above plots but for various mixtures of Xe+TMA. The PMT currents correspond to TMA-light with xenon light filtered out.

Pure xenon (top three plots) behaves as expected and serves as a benchmark and verification of the experiment. These preliminary data for Xe+1% TMA (bottom plots) show no evidence of Penning transfer (lower left) and no significant electroluminescent yield of TMA before the onset of ionization(lower right). As expected TMA absorbs Xenon VUV light and S1 light is produced by direct excitations of the TMA molecules. These data show no evidence of TMA-light upon recombination (lower middle)

e^--ion Recombination Simulations

The concept for DM directionality measurement uses columnar electron-ion recombination along the short (few microns) ionization tracks of nuclear recoils. To study this idea a modified version of Garfield++ using with Magboltz cross sections [7][8] was developed. Electrostatic interactions between all charges (ions and electrons) are included. Nuclear recoils are simulated as ionization tracks with equidistant ions at the expected linear density (~1 ion/10nm at 10 atm). A recombination condition requires negative total energy of the electron in the potential of all the charges. We use the large Carver cluster (NERSC) of computers.

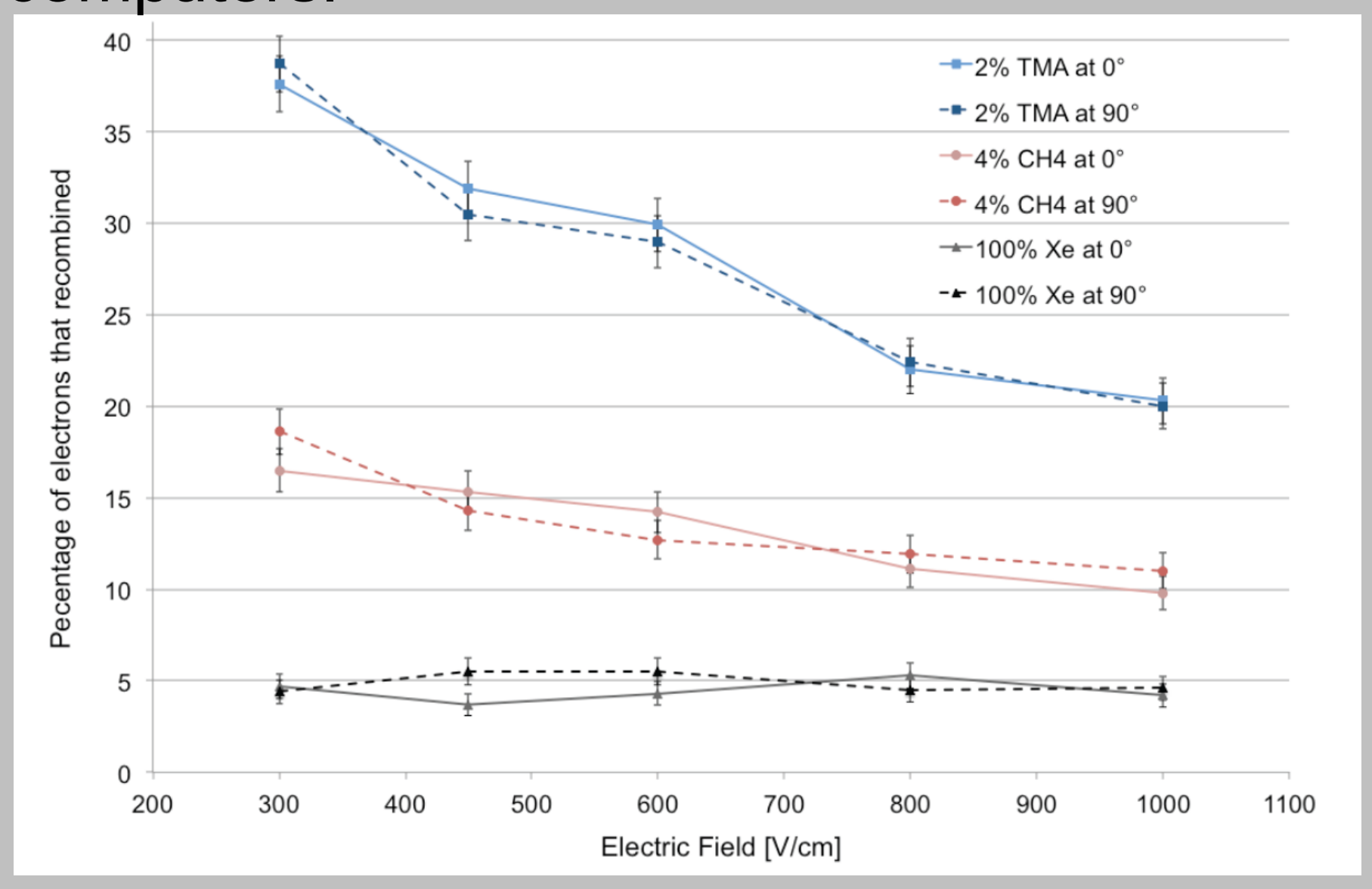

Fig.13: Monte Carlo calculation of the fraction of electrons recombining along a 1 micron long track with 100 equidistant ionization sites [proxy for a O(20) keV nuclear recoil in 10 atm xenon] as a function of the external drift field and for the two extreme relative orientations between the field and the track.

Conclusions

1. Nuclear recoils in pure high pressure xenon can be discriminated from electron recoils using S2/S1: separation is slightly better in liquid. With our data (low light collection efficiency) we could not test the expectation that there is less overlap between the bands in HPXe due to reduced recombination (and thus less fluctuations).

2. Preliminary data with Xe+TMA(1%) show no sign of Penning transfer and no TMA-light upon electron-ion recombination. No linear region of TMA electroluminescence is observed before onset of ionization and avalanche. Other gas mixtures are being considered.

3. Microscopic simulations of recombination along idealized nuclear recoil ionization tracks in high pressure Xe+TMA (2%) show no dependence on the angle between the drift field and the track. This is likely due to the large (~micron) distance traveled by ionization electrons before their first collisions. Other mixtures/pressures regions being considered for the Dark Matter directionality sensitivity.

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[7] R. Veenhof, September 2010. http://garfield.web.cern.ch/garfield/
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