The way Forward in the Search for Neutrinoless Double Beta Decay TAUP 2025

A PERSONAL PERSPECTIVE ON LIQUID XENON PROSPECTS

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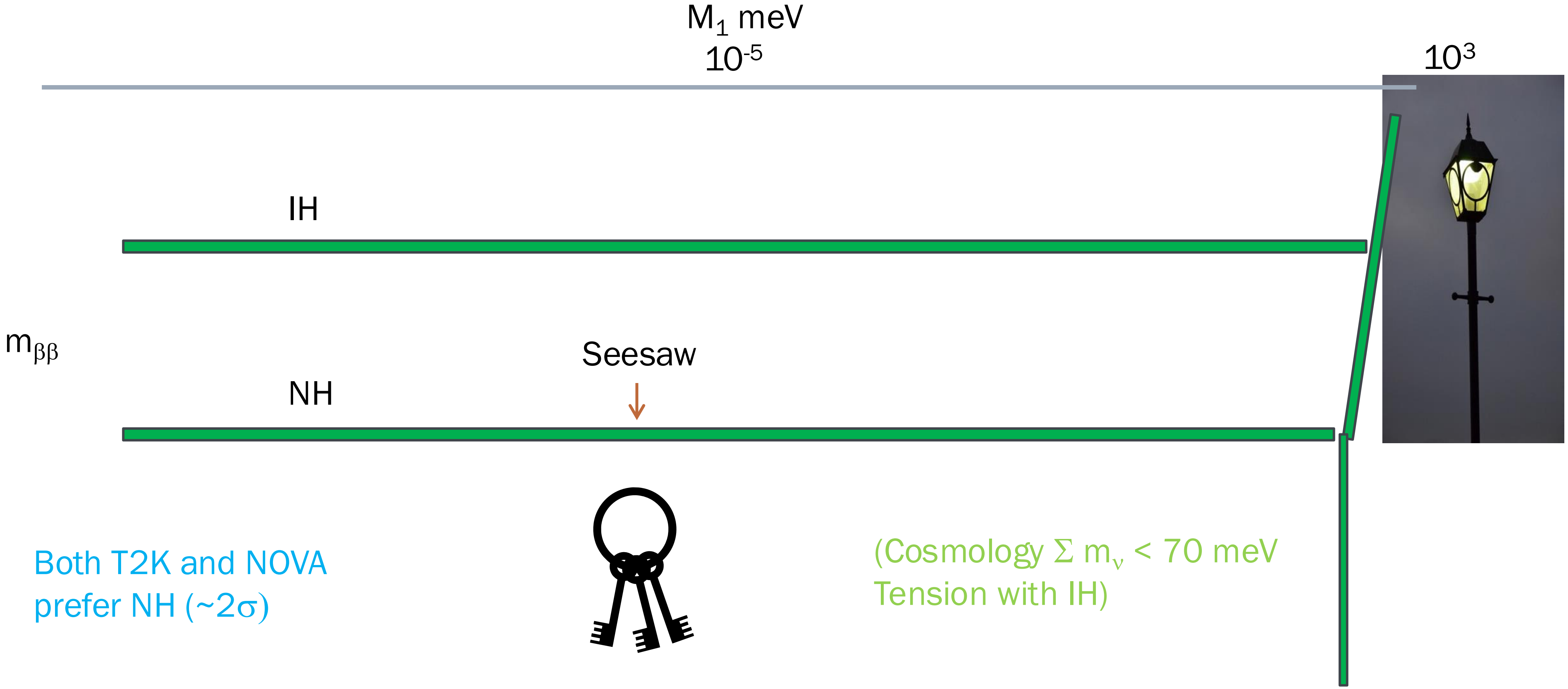
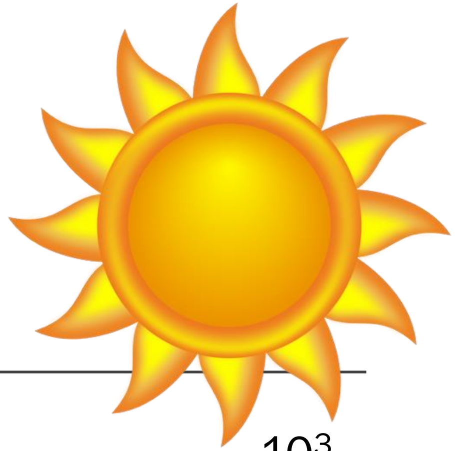
Talk Objectives

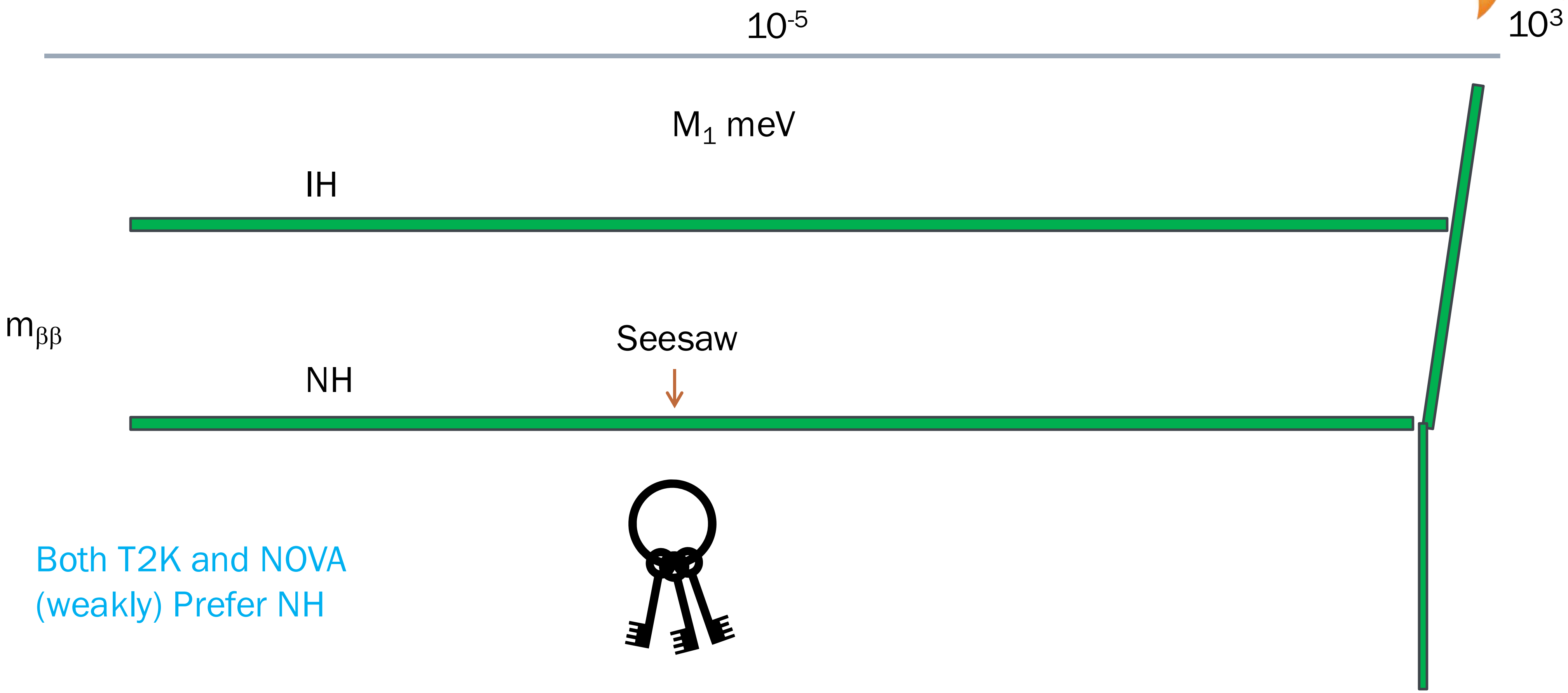
- Need to focus new ββ searchs on NH
- With a focus on liquid Xe
    - What is needed to reach NH
        - Technically
            - Some detector concepts for reaching NH
            - Ie I think we can get there!
        - Sociologically
- Action Plan

Mass dependence of NLBB process



Let's Search in the Daylight!





First look at Liquid Xenon for NH

- In a few years we expect measurements (DUNE, Hyper-K, JUNO) to provide guidance as to whether we have a Normal or Inverted hierarchy
- Present technology (eg XLZD, Pandax-xT, nEXO) promise a reach to 10 meV but do not scale easily to 1 meV
- If we have a Normal hierarchy we will need a detector with at least 50 T of ^{136}Xe (ie 500 T Xe)
- Only works if we can reduce the backgrounds by ~100 compared with current proposals
- Want to avoid the use of Xe as shielding (all of the above require self shielding)
- Solar neutrinos become an important background issue

Reaching NH with Liquid Xenon

- Need huge background reduction
  - Better energy resolution required (reduce $2\nu\beta\beta$ events and ^{214}Bi gammas)
    - Greatly improve scintillation detection efficiency
    - Better control of re-combination
  - Better discrimination against gamma and neutrino events required
    - Better single site selection
    - Better single/double electron cluster selection

Energy Resolution – (1) add TEA (following Doke)

- Adding a few ppm of Triethylamine (TEA) to liquid xenon converts 80% of scintillation photons to electrons
  - Electrons are detected with 100% efficiency while for photons it is ~15% so gain factor 5 in statistics
  - TPC signal now looks like a compact ionization track (~mm) surrounded by a halo of scintillation produced electrons
  - Both detected with the same device, so systematic effects reduced, only a small area of the detector is needed so noise reduced.
- Note:
- (a) TEA also fluoresces giving a possible trigger signal,
- (b) the use of TEA probably precludes a dual phase detector because of feedback concerns

Spatial resolution (2) Use pixelated Anode

- Modern HEP experiments moving to pixelated detectors
- ~50 μm resolution, ~1 electron noise
- Ability to identify low energy, close clusters
- Note: in EXO-200 single site selection gave ~6 fold rejection of gammas – should be 40!
- Reduced noise on charge and scintillation measurement
- Some ability to distinguish 2 electron clusters but limited by diffusion
- Some ability to measure track length on drift axis to estimate columnar recombination – first measure of recombination
- For 1 m drift, 1 kV/cm $\delta_L \sim 0.7$ mm, $\delta_T \sim 1.5$ mm

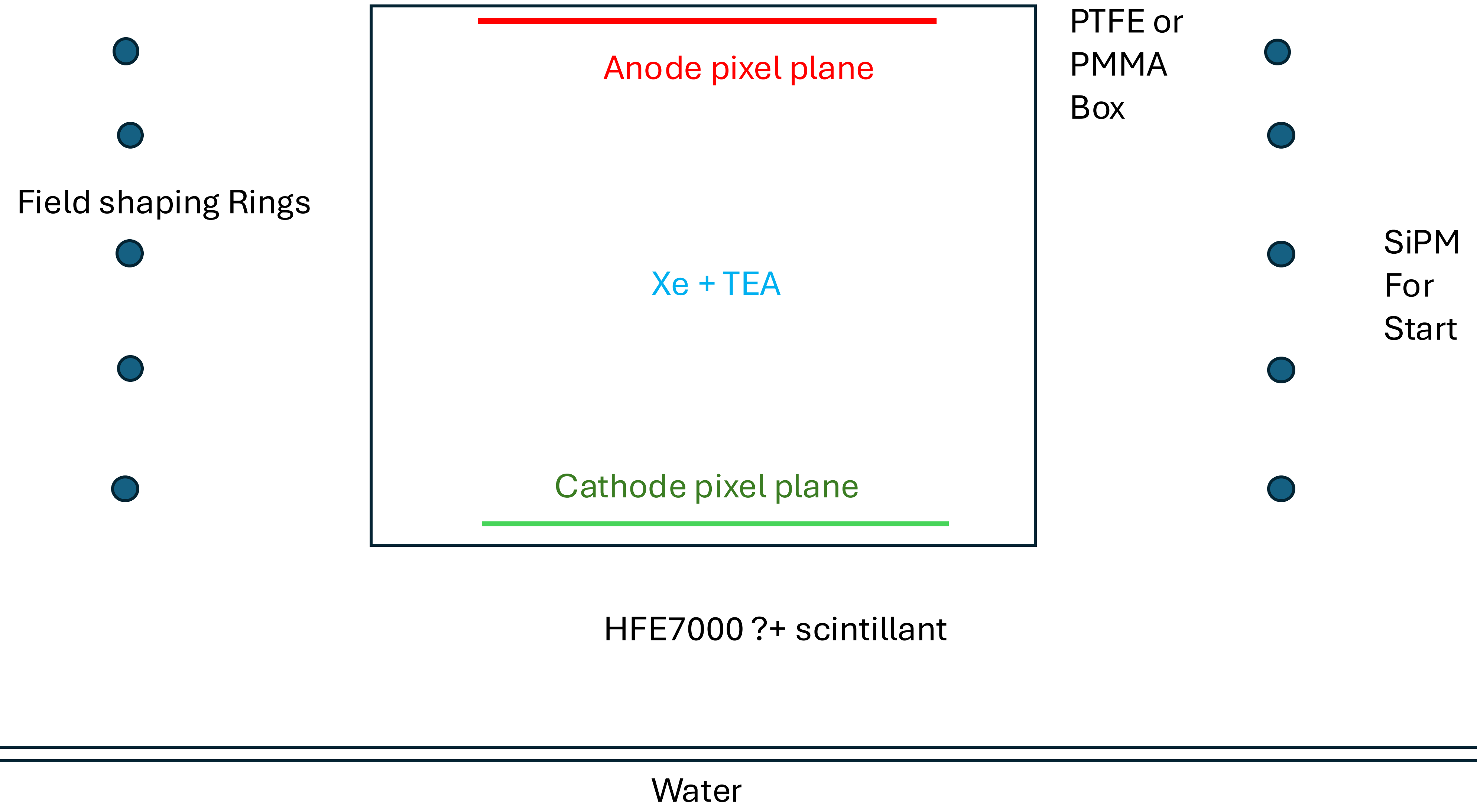
Bonus!

- With TEA and Pixels, we can measure the charge to light ratio for a single cluster. Expect higher light with 2 electron clusters due to higher mean charge density

Spatial Resolution (3) Detect positive ions

- Event reconstruction with electrons limited by high diffusion due to non-thermal electrons
- Using positive ions has potential for much higher resolution (EG Drift detector!)
- With TEA loading, all positive ions (Xe^+) will charge exchange to give TEA^+ in short distance
- All will drift to the cathode with similar speeds
- Use very low noise (but slow) pixel array at cathode
- At 10 kV/cm, 1m drift, $\delta \sim 100\ \mu m$
- Resolution is small compared with track length – implies 20 fold rejection of single electron clusters (ie Compton scatters or $\nu - e$ scatters)

Xe Strawperson NH Detector



Design Features

- Very clean Xe volume allows use of high voltages
- TEA is expected to fluoresce and this gives a start trigger
- Shield is HFE7000 or similar
  - High density
  - Very clean
  - Liquid at LXe temperatures
  - Might be made to scintillate to tag neutrons, gammas
- Operate at modest voltage until candidate seen, then turn up field and turn on cathode detector chip(s) below chosen event (need to keep the xenon free of turbulence)

Possible background reductions (Needs real simulation!!!)

Improvement	Possible Background reduction factor
Energy resolution	?5
Improved single site selection	6
Double electron cluster selection	20
Remove all metals	?5
Veto gamma, neutron in HFE	?
Total Perhaps	3000

Lots of work to put this on a solid foundation but prospects for success look good

Sociology

- Procurement of Xe is a challenge. Cannot have competition
- World should get together to do this
- By introducing these concepts at such an early stage, everyone can be involved in developing the final detector
- Without using self shielding, design could be modular
  - Each lab could host a module
  - Global ownership of the design
  - Shared data
  - Construction could be sequential to match Xe production

The way forward

- Lots of work to be done to design a real detector
- Let's get together and get Started!

Backup slides

EXO-200 was very successful

Two back to back time projection chambers provided a 3D reconstruction of events by drifting the electrons to sense wires and measuring the light with LAAPDs

Made the first measure of the 2 neutrino double beta decay rate in Xe

Rejection of gamma backgrounds was helped by looking for single site events (factor of 4 rejection initially, now factor of 6-7)

Gamma rejection should have been factor of 40 ($\sigma_C+\sigma_{pair}/\sigma_{pe}$) limited by noisy electronics and poor spatial resolution

EXO measured total light (both direct and recombination)

How to reduce the backgrounds?

Main backgrounds are gammas from the ^{238}U and ^{232}Th decay chains.

^{214}Bi (2448 keV) and ^{212}Po (2614 keV) give ~99% of background

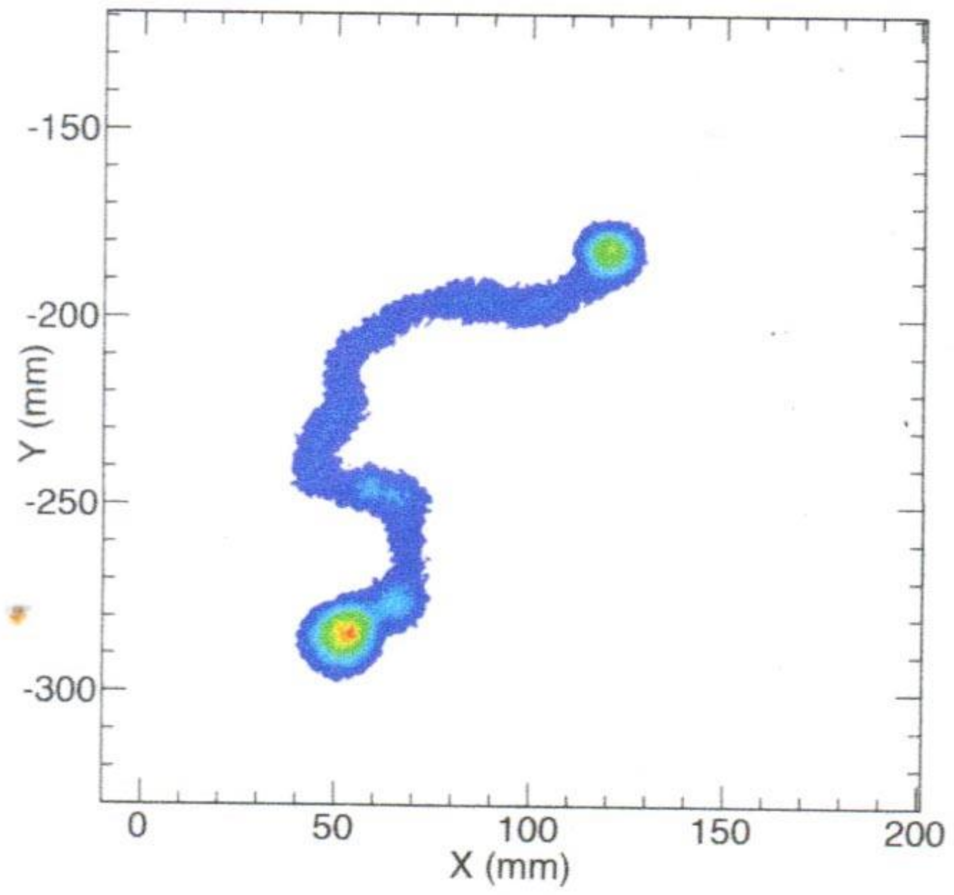
How to improve –

- Better energy resolution
- Lower noise
- Better resolution in x,y,z

I will try to show how each of these might be achieved

Critical to improve the energy resolution to separate the 2 νββ background

NEXT double beta simulated event (gas)



Structure in the direct ion cloud

(a) In gas, double beta events are seen with 2 blobs at ends of the electron tracks

Same should be true in liquid but much more compressed (10 cm -> 1.5 mm)

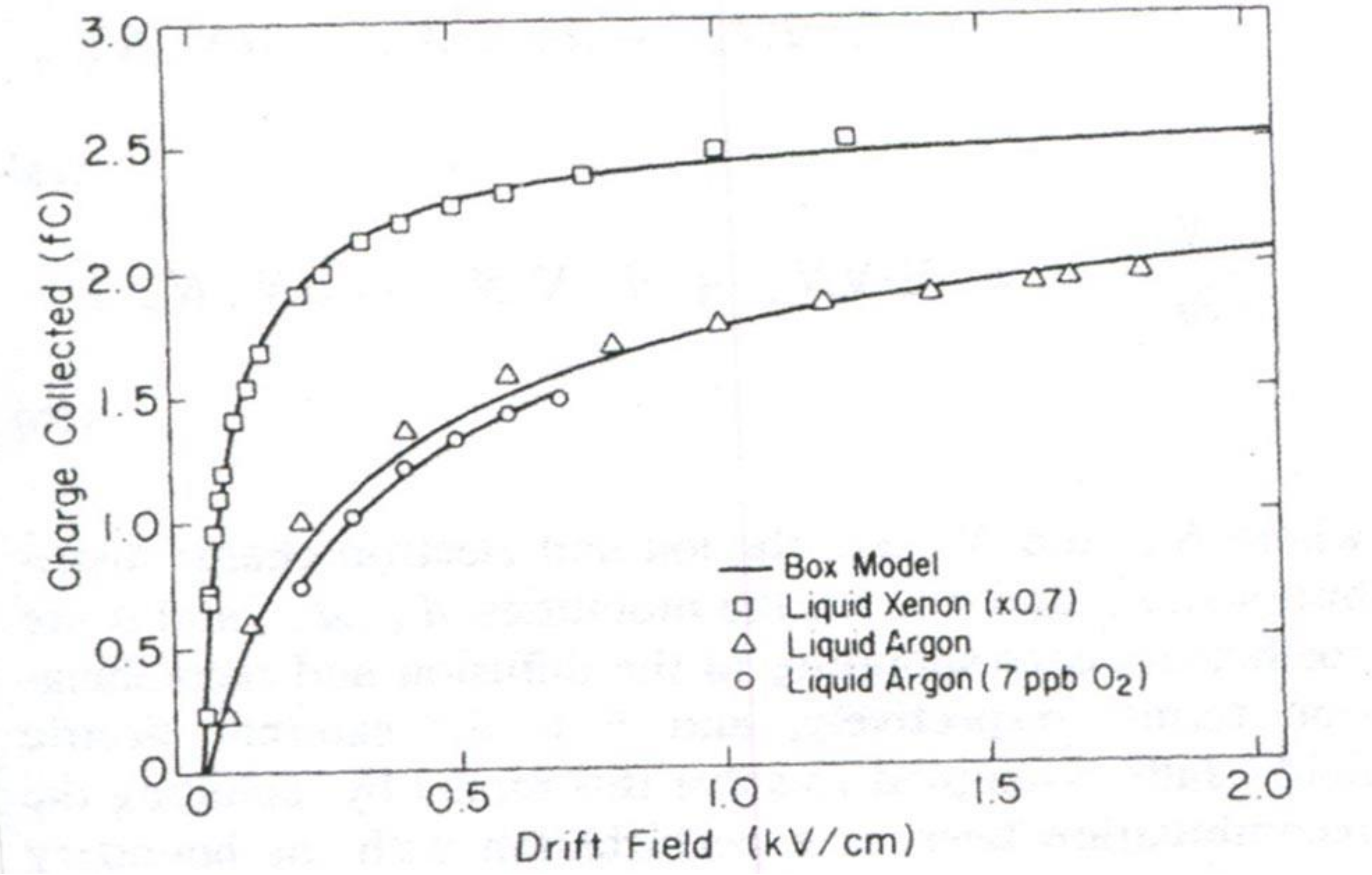
In gas this leads to factor 20 rejection of gamma events

Can we achieve this?

(b) If we can get the projection of the ionization tracks in the drift direction we can get an estimate of the recombination and hence improve the direct vs recombination light and hence energy resolution

(c) Note – even without resolving the structure, with Chocolate we should see a higher light/charge ratio for 2 electron clusters because more recombination in the dense clusters

High fields reduce the recombination light and should improve resolution



Thomas & Imel Phys Rev A 36 (1987) 614

Improve veto for nearby events

Self shielding can be critical for a large Xe detector. It would help if there were a veto detector inside the cryostat. Events in which gammas enter the Xe, scatter and leave the Xe are hard to remove by multi-site cuts. Similarly neutron events that scatter out are hard to eliminate.

LZ used Xe for shield – gets expensive!

There is a shield of HFE7000 in EXO – could it be made to scintillate? It is extremely transparent. Years ago I looked for attenuation in HFE using a Lamda-9 and could not detect any.

Perhaps the SNO+ experts could look at this.

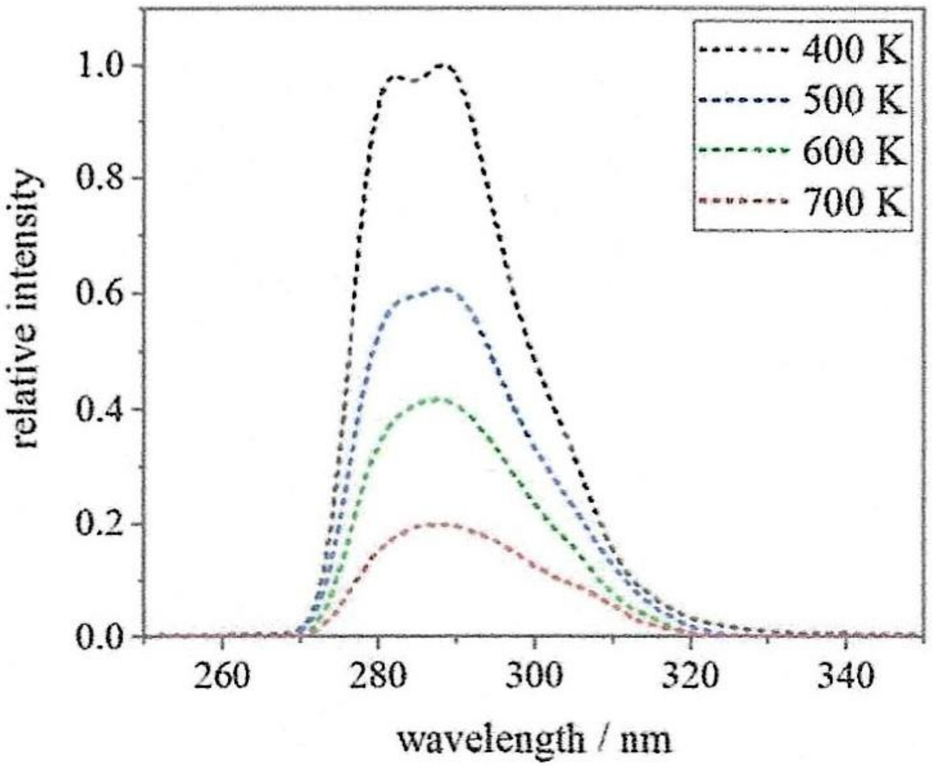


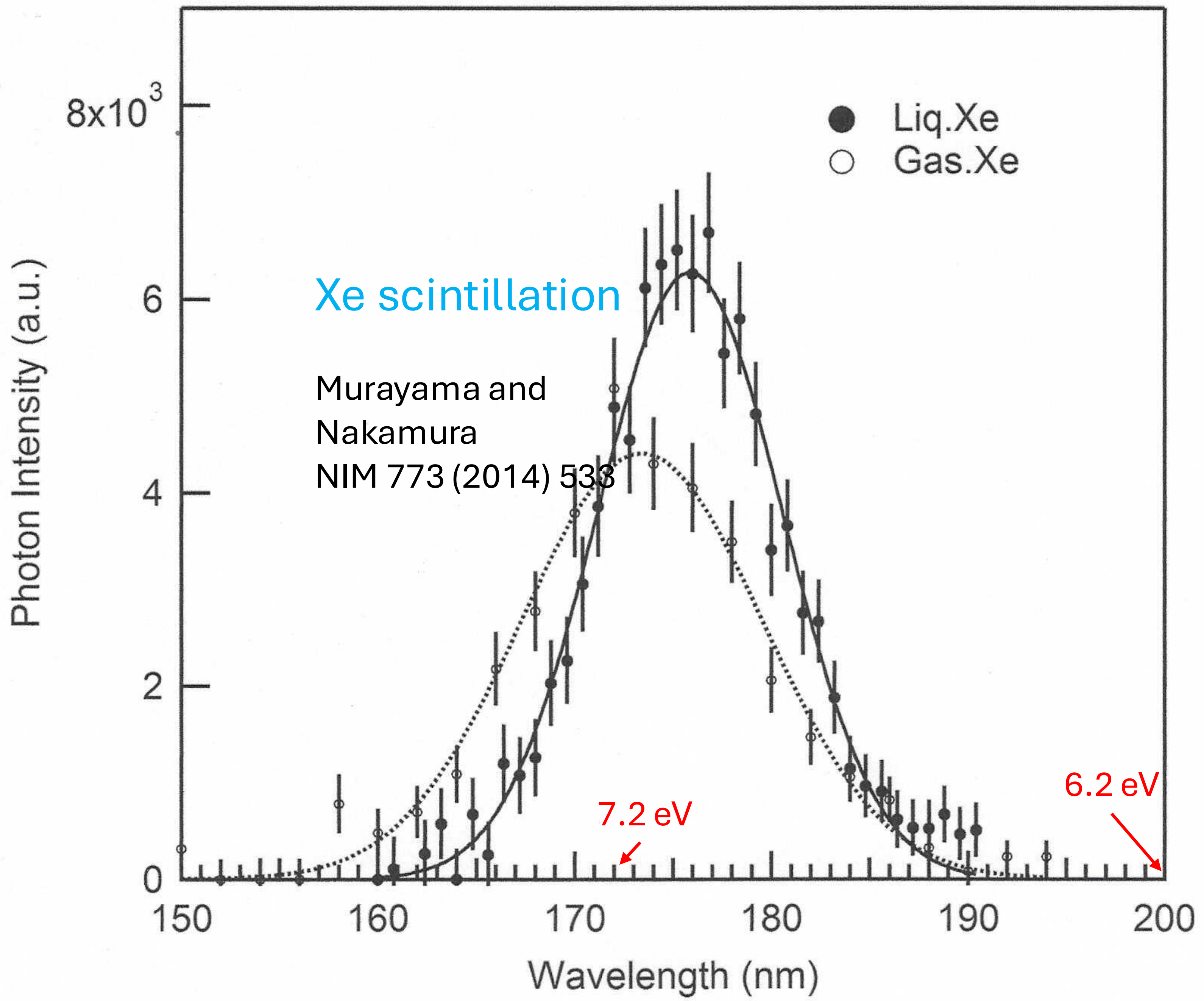
Fig. 5. Fluorescence emission spectra of triethylamine at 1 MPa and various temperatures normalized to maximum value of intensity at 400 K.

TEA fluoresces rather strongly
Only data is at high temperature but
Trend is to stronger yield at lower
Temperatures

Fluorescence time is increasing with
lower temperatures
Reaching ~20 ns at 400K

Larger Stokes shift may reduce yield
for Xe scint. Light (but it is much
smaller than TPB in Ar)

Fluorescence of TEA excited by 263 nm light, Susanne Lind et al



Threshold for ionization of TEA shifts from 7.2 eV (in gas) to 5.6 eV in Xe