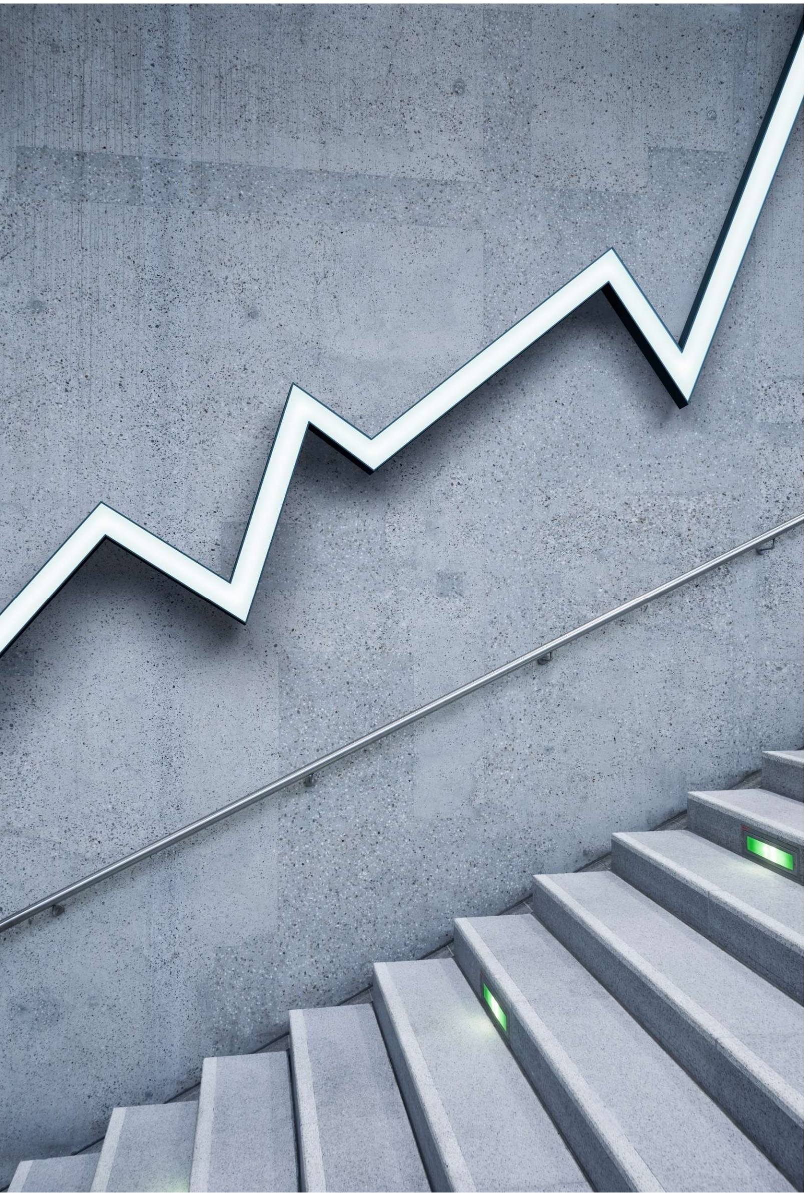

The way Forward in the Search for Neutrinoless Double Beta Decay

A PERSONAL PERSPECTIVE FOCUSED ON XENON

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Neutrino Mass

From SNO we know that neutrinos have mass and are strongly mixed

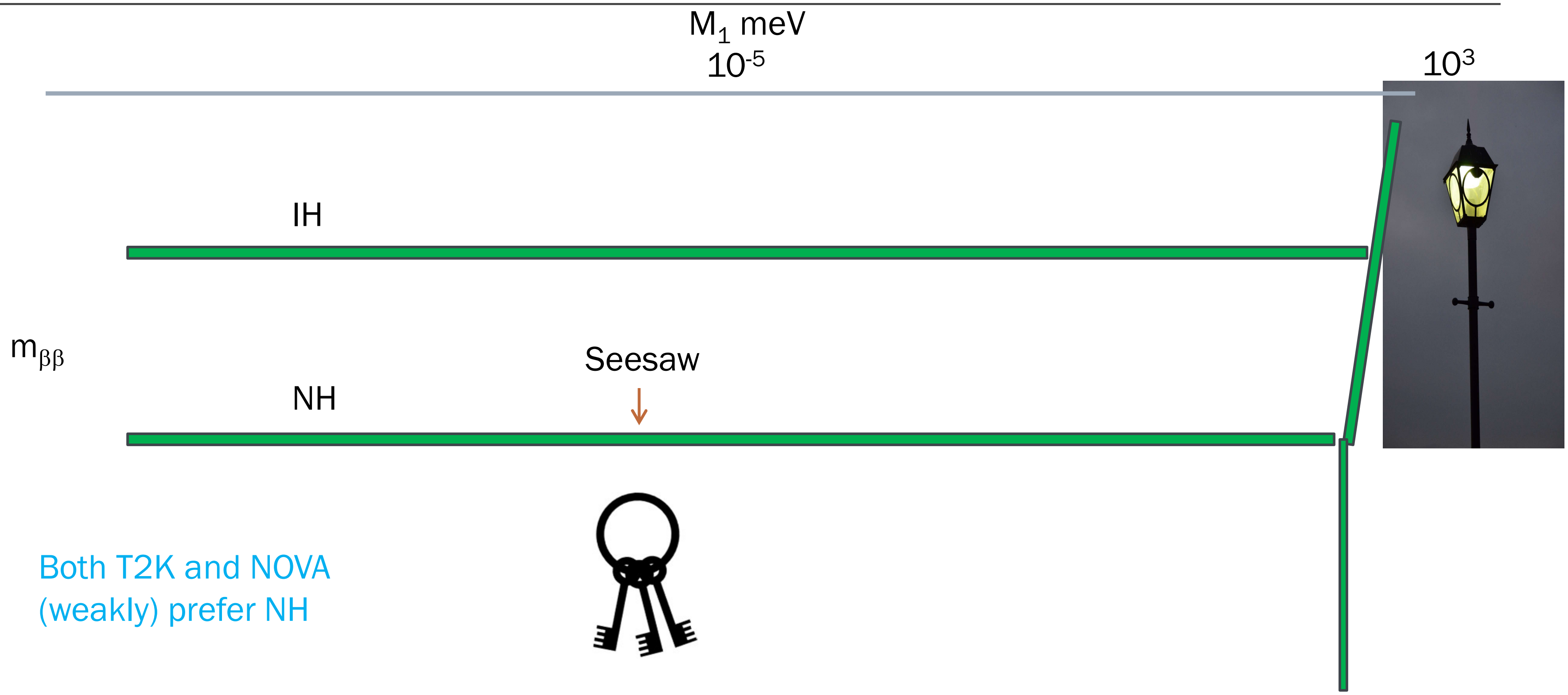
Actual masses not yet known but mass differences have been measured and upper bounds established – $M < \sim 200$ meV – i.e. at least 6 orders of magnitude smaller than the electron mass

Is there a new mechanism for producing mass?

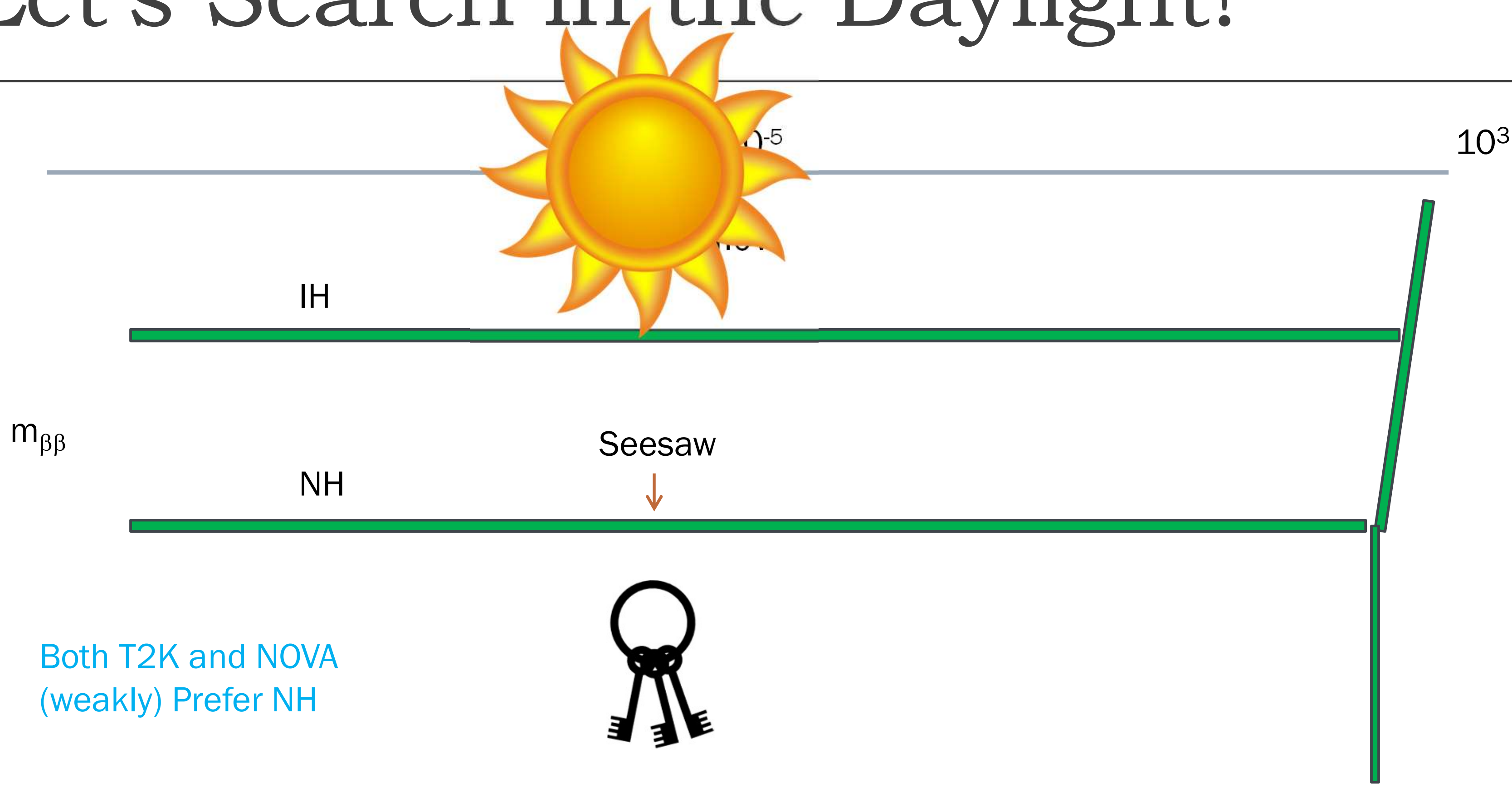
Could neutrino properties allow an explanation for the dominance of matter over antimatter in the universe (leptogenesis)?

Observation of neutrinoless double beta decay would demonstrate the Majorana nature of neutrino mass and shed light on the cosmological problem

Mass dependence of NLBB process



Let’s Search in the Daylight!



First look at the future

In about 3 years we expect measurements (DUNE and Hyper-K) to provide guidance as to whether we have a Normal or Inverted hierarchy

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 EXO/ early nEXO

This talk will look at how this might be accomplished

If we have an Inverted hierarchy, then R&D to investigate these ideas could lead to a much less expensive detector

Detection in liquid Xe

Ionizing radiation in noble liquids releases electrons (1) but also excites dimers which decay giving light (2)

The directly excited dimers decay with a mean life of 33 ns

With an electric field applied the electrons will drift towards the anode

If electrons meet a Xe+ ion, they can re-combine to form a neutral dimer state. These normally decay with either a 4 ns or 33 ns mean life (3)

Tracks aligned with the drift direction will have higher re-combination rates compared with tracks more perpendicular to the field (Columnar recombination)

In order to fully determine the primary energy we need to measure (separately) all of these processes (1, 2 & 3) (Note – EXO assumes w values for 2 & 3 are the same but one expects 1&3 should be the same)

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 $\nu\beta\beta$ background

Step 1 – Do something about energy resolution!

EXO-200 demonstrated an energy resolution of about 1.4% (σ/E). The competition (Legend) gets 0.05%. Fano factor should favour Xe

It is even more important for Xe because there is a strong gamma line from the decay of ^{214}Bi almost degenerate with $Q_{\beta\beta}$ In nEXO this line is about 80% of the total background

In addition, as one goes to lower 0νDB rates, the 2ν rate becomes more significant and only energy resolution can help

Change 1 - the CHOCOLATE detector

We heard a lot recently about the LOLX proposal. There are many lessons to be learned but I would focus here on changing the first letter

The CHarge Only,CerenkOv Light Assisted, Test Experiment

Why charge only?

(a) We can detect charge with almost 100% efficiency. For light we can get about 15%

(b) When we detect charge, we know where it came from

Many years ago, Doke showed that, with a simple liquid Xe ion chamber, he could convert 85% of the light into electrons by introducing a few ppm of triethylamine (TEA) ($(C_2H_5)_3N$) and thus improve the energy resolution. With a TPC we can do much better because we can separate the direct ionization electrons from the electrons from photoionization.

This would improve photon energy resolution by sqrt(6) which would be huge!

Similar ideas being looked at elsewhere

CHOCOLATE - 2

If TEA were introduced into a NEXO like detector, one could form an image of an event with the direct ionization at the centre and a halo of electrons coming from around it. Radius of the halo would be depend on the concentration of TEA but might be a couple of cm. The size of the ionization is 1-2 mm. Both groups would have about 10^5 hits.

Many additives would introduce new traps for the drifting electrons. We do not expect TEA to form negative ions and it did not appear to be a problem for Doke. One group claimed to have seen negative ions when they hit liquid Xe + TEA with an excimer laser but production depended on the square of the laser power and seems to have been a 2 step process. This paper seems to have been withdrawn.

No Free Lunch!

There are 2 obvious issues with introducing TEA

1) We lose our start signal (from the light). Possibly Cerenkov light saves us as much of it is below the energy threshold for photoionization of TEA. Also in gas, Xe has strong lines in the IR and some light in the green region. These are suppressed in liquid but we may be left with a few more photons. Needs an experiment! LOLX MC suggests about 30 hits could come from Cerenkov light.

2) For some of the following ideas we would benefit from a dual phase approach. This is complicated with TEA because the EL photons will ionize the TEA leading to a large +ve feedback. It may be possible to find a quench that would control this (hydrogen might work) but needs study

Step 2 Do something about spatial resolution

In EXO-200 events are located in the drift direction (z) by timing the arrival of electrons at the anode. The perpendicular directions (x&y) are determined by crossed induction and charge collection wires. In nEXO, the wires are replaced by strips. Both systems are very slow (~ few μs) Timing is set by the characteristic size of the collecting pads and the drift speed of the electrons. Both systems are noisy because there is no intrinsic gain in the system and the pads/wires have relatively high capacitance. Spatial resolution is also (poor several mm) because the large size of the pads.

Solution 1- Replace Pad Systems

Change the pad system to an array of pixel detectors.

Recent workshop (International Workshop on Semiconductor Pixel detectors for particle and imaging. Nov 18-22 2024. To be published in JINST). State of art is about 0.3 e rms noise compared with a few hundred e for pads.

Timing goes from few μs – few ns

Spatial resolution improved to ~ 50 μm

In principle reconstruction voxel reduced in volume by 10^7

Several concepts available. Not clear which might work in liquid xenon

We would like Q(x,y,t) but current state of art may limit us to Q(x,y) integrated over time + Q(t) integrated over x,y

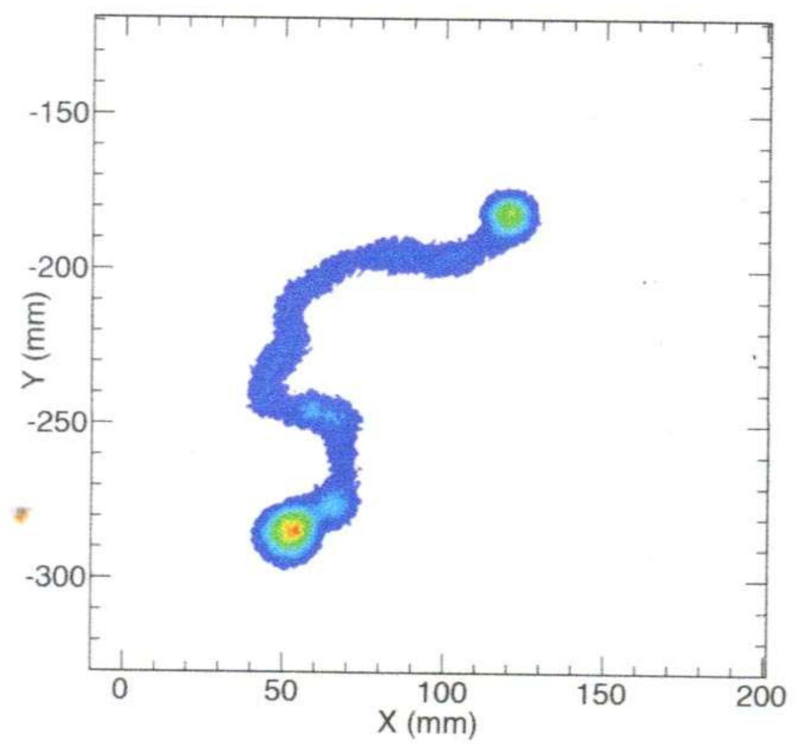
This would be very workable

Physics gains

1) We get excellent identification of low-energy clusters and clusters close to the main peak. This should lead to much better gamma discrimination. (factor of 7 available)

2) We can start to look at the ionization structure within the clusters. Gas counters such as NEXT give us guidance on what to look for

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

Solution 2

Change to a dual phase detector

Use a fine mesh grid anode in front of an array of digital SiPMs

Operate at low EL voltage so most light is produced at the grids where field is enhanced.

Gain – very fast timing, transvers resolutions of order 50 μm – similar to Sol. 1 but now noise level down to single electron.

Solution 3

Use a dual phase detector mode, again with low or no EL gain

At the anode use Medipix + micromegas units to measure the electrons

Single electron sensitivity, excellent timing and spatial resolution

Interest in the Carleton HEP group in developing this concept for a CERN experiment

Need to look at possible quench gas etc but very low gain required (Medipix noise ~ 80 electrons)

No Free Lunch –pixel detectors

To fully exploit the improved spatial resolution we need to learn how to work with diffusion

With high resolution detectors, possible techniques are deconvolution and AI (Working on this at Carleton)

Diffusion not well understood in Xe. May be driven by trapping of electrons by dimer states followed by release as the dimer breaks up?

Do pixelated counters work at liquid Xe temperatures or in liquid Xe? Needs some study, do they work in electric fields? All needs study!

Solution 4 Measure +ve ions

Some years ago the DRIFT detector was developed to look at short tracks (in gas) from dark matter scattering. Because diffusion of electrons is high (they have temperatures much higher than thermal in the electric fields), Martoff et al chose instead to trap electrons on CS_2 and drift these molecular ions towards a sense wire. In the high field of the wire the electrons would be released and give proportional gain.

In a detector with TEA all of the positive ions will be TEA+ (one makes Xe+ but I expect this will quickly charge exchange with TEA). TEA will drift towards the cathode and might be detected by some techniques. Development of CCD techniques might be relevant here. Again, possible pixel cmos detectors?

No Free Lunch

Ions in liquid Xe drift 'slow as old boots'! (but stay cold – known as dirty snowballs) Event rate very low so that is not an issue but turbulence in the Xe could be a problem. Bill Fairbank looked at a number of + ions and found μ~2-3 x 10^{-4} $cm^2/(V\text{-}s)$

BUT

We note from the Einstein relation,

$D=\mu\, k_B T / q$

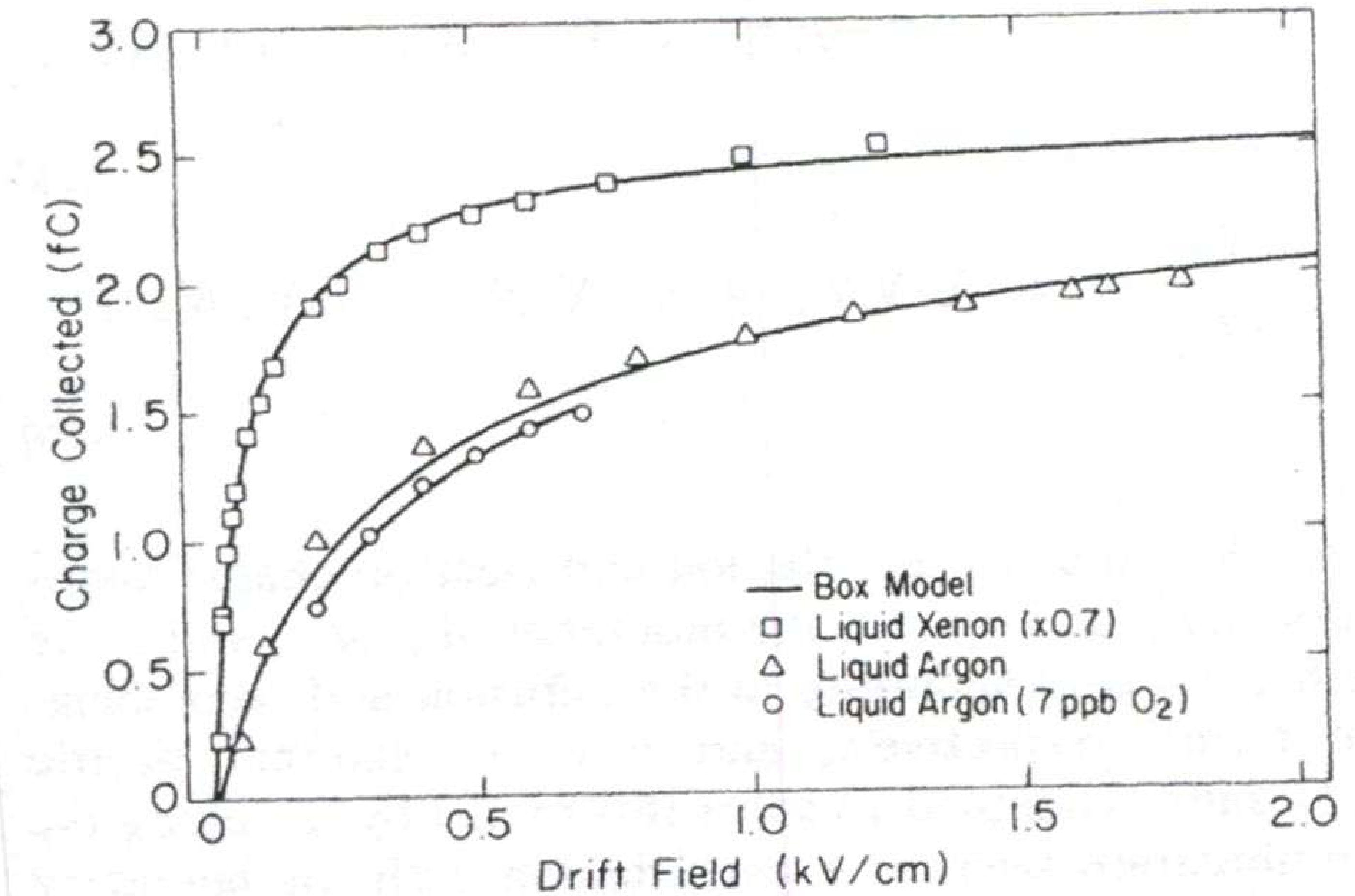
slow drift speed leads to low diffusion so drift time may not be critical to maintain information

We could look for designs of a detector with minimal turbulence (which would be good for other reasons as well!). Reynolds number about 1500 so should be laminar if we do not force turbulence

Need to operate at high drift fields (but this helps in other ways – lower electron loss and reduction in recombination light) (no need to exceed peak field in EXO-200)

No need for a light-based start signal as +ve ion drift times fix the z location

High fields reduce the recombination light and should improve resolution



Thomas & Imel Phys Rev A 36 (1987) 614

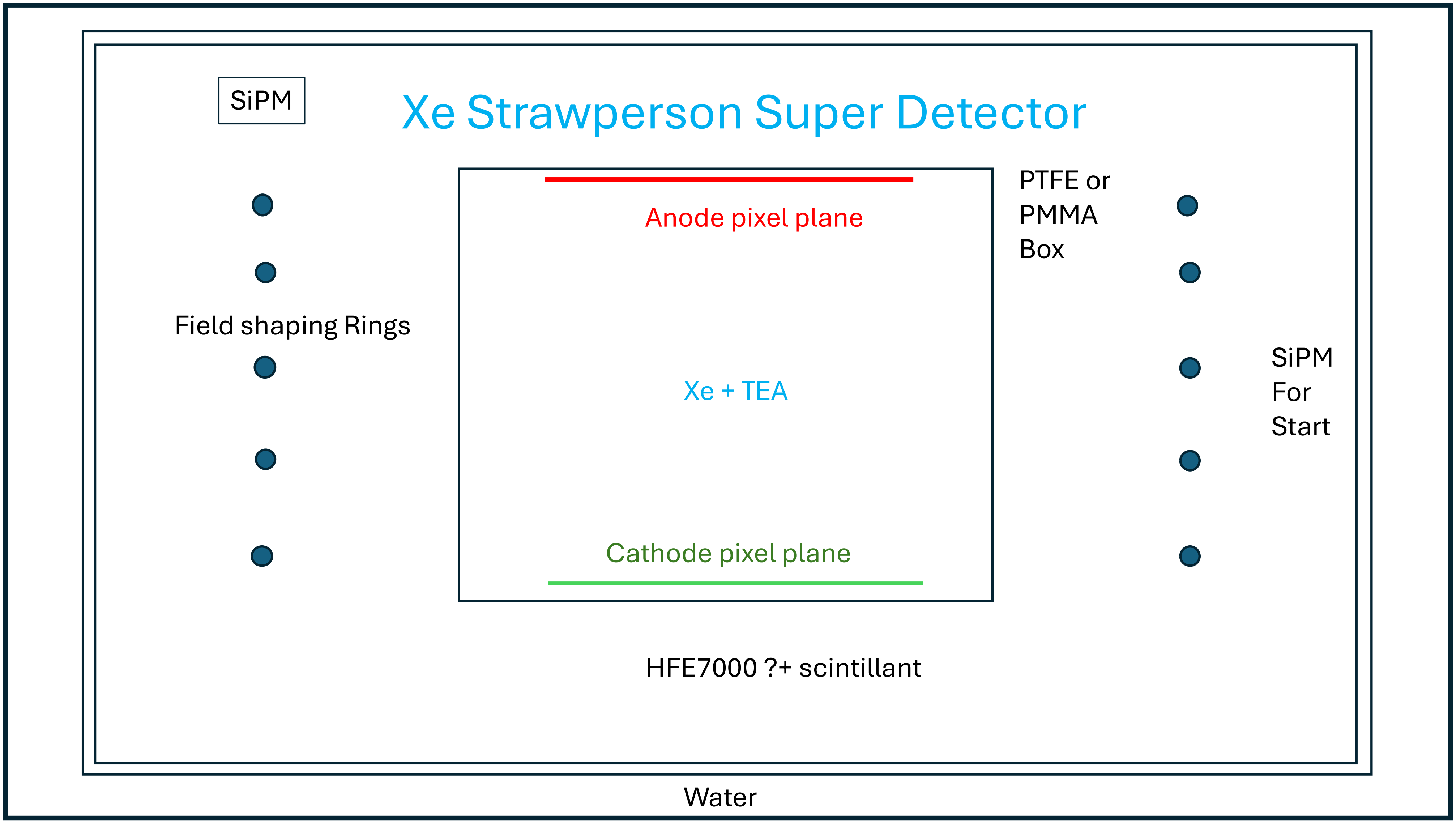
Improve veto for nearby events

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.



SiPM
Xe Strawperson Super Detector
Anode pixel plane
PTFE or
PMMA
Box
Field shaping Rings
Xe + TEA
SiPM
For
Start
Cathode pixel plane
HFE7000 ?+ scintillant
Water

Strawperson Xe Superdetector

- All HV parts outside Xe. Design using good HV practice and to avoid any damage if sparking occurs
- Rings are PMMA coated with Clevios
- Almost no metal in the HFE or Xe -> most background gone
- HFE thick enough to provide all needed shielding
- 100% usage of Xe (ie little need for self shielding)
- Can operate to high fields so +ve ions drift, little recombination, high resolution
- SiPMs in the HFE if it can scintillate, or to detect start signal

Summary of possible background reduction

- Single site/multisite selection 6
- Single electron vs 2 electron cluster 20
- Removing background sources 10
- Energy resolution improvements ?5
- Our target to reach the NH is an overall factor of 100. Does not seem totally unrealistic!

Further thought

If the self shielding is not so important, it might be possible to use a modular approach. Could have a global project with modules in different countries. Could sequence modules to match a xenon production schedule.

The way forward

- Start to build an international collaboration where everyone can bring new ideas
- Plan and start R&D program to focus the design
- Develop an analysis framework so all concepts can be evaluated in consistent way. Also study dependence on enrichment
- Plan one or more prototypes that could reach the inverted hierarchy if this is nature's solution
- If needed plan for a globally supported effort to reach the normal hierarchy