Development
of
Large Area Cryogenic Gaseous Photo Multipliers
for
Dark Matter Search

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Direct Dark Matter Search is one of the most interesting topics in physics. Worldwide there are many experiments in deep underground labs, planned, under construction, data taking, or completed.

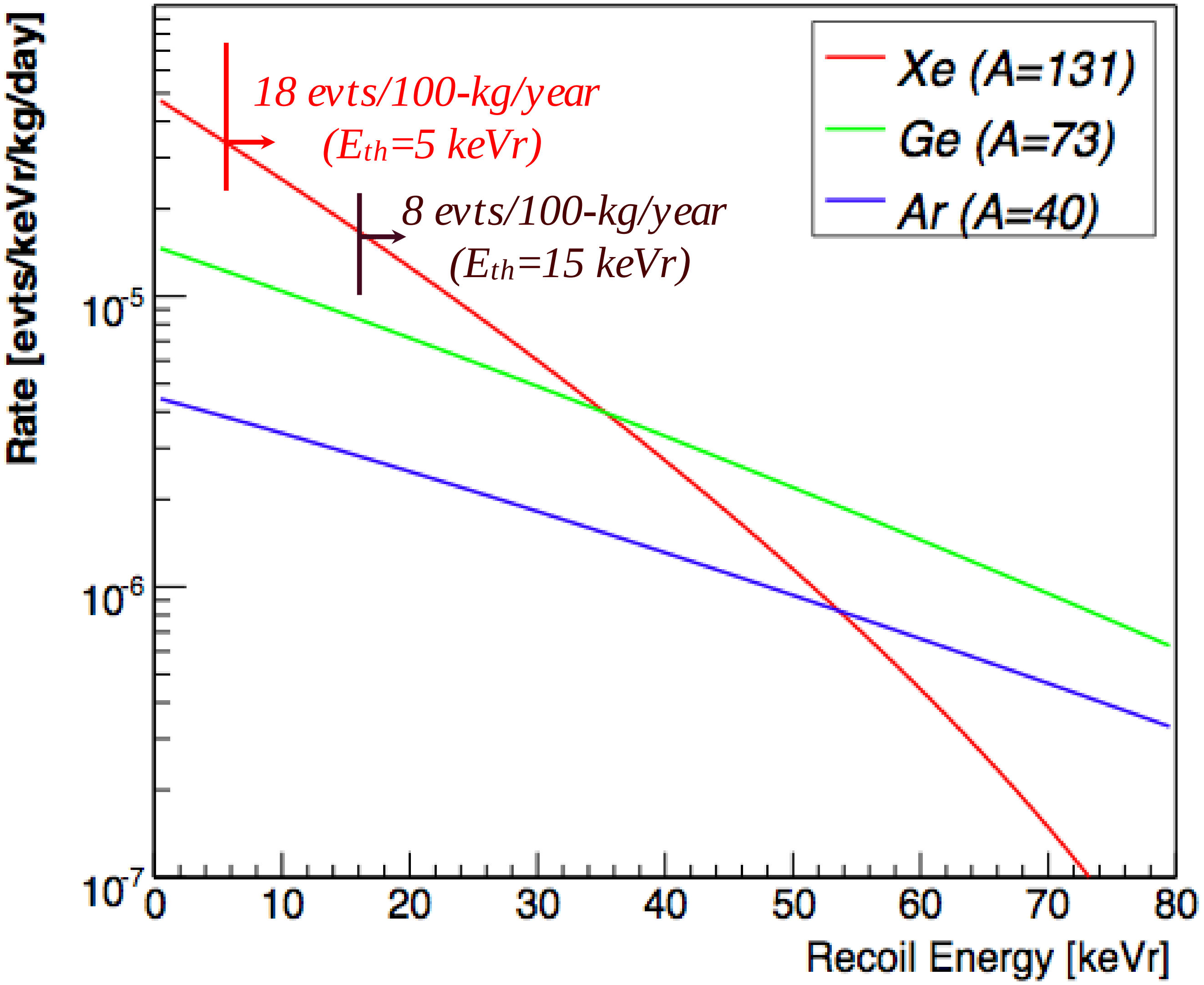
Direct detection is complementary to production at the LHC

Common to all Dark Matter Detectors are very small energy transfer, small cross sections and the radioactive background from the environment. This requires ever more massive detectors with enhanced sensitivity and better control of background radioactivity. And a deep underground lab with extra shielding.

Specially attractive are LAr and LXe detectors. Let’s focus on LXe, but there are many synergies to LAr experiments

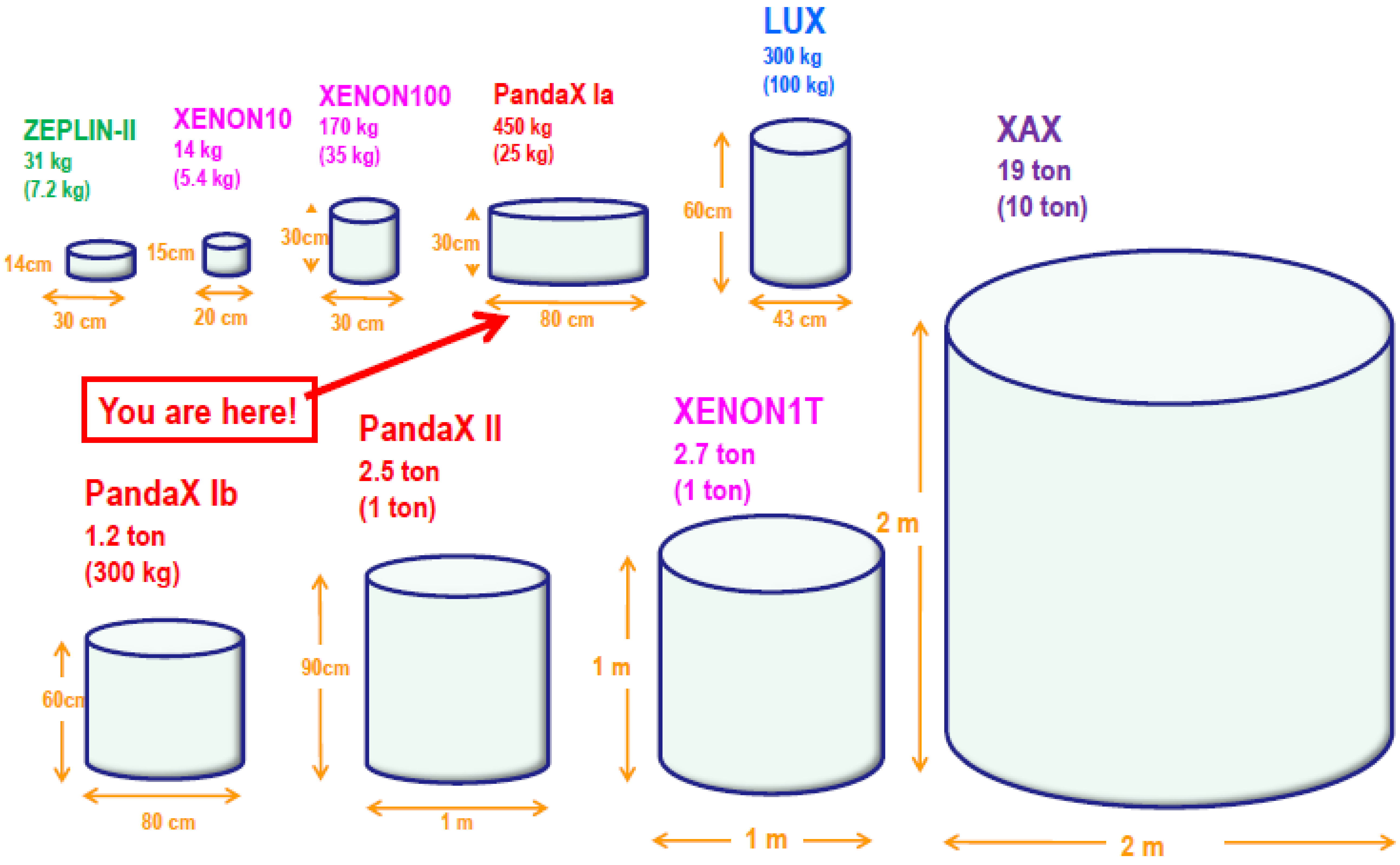
Why liquid xenon for Dark Matter detection ?

WIMP Scattering Rates



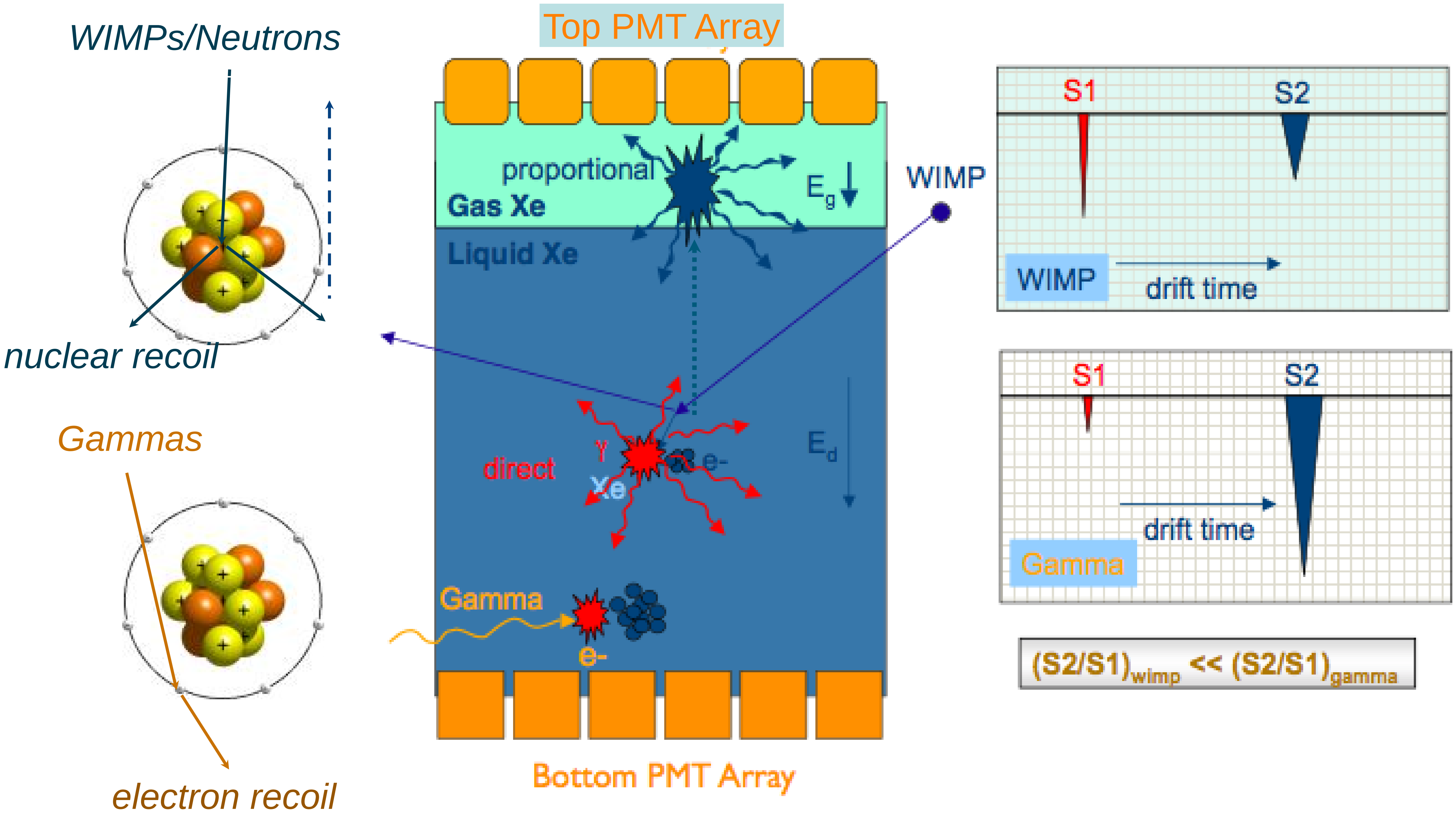
- Large A (~ 131)
- No radioactive isotopes
- High stopping power
- Efficient and fast scintillator
- Good ionization yield
- Modest quenching factor for NR
- Background Rejection: Charge and Light detection (> 99.5%), 3D localization, self-shielding, and Pulse Shape Discrimnation
- Scalable to very large targets
- Spin dependent and independent measurement with different isotopes

Road Map of LXe Dark Matter Detectors



A XENON detector can measure two quantities for each interaction: the free drifting charges and the primary scintillation light

However, the number of drifting electrons for low energy events is too small for direct measurement. Therefore the two phase scheme is adopted.



$(S2/S1)_{wimp} << (S2/S1)_{gamma}$

The Light Collection Efficiency (LCE) determines the Trigger Threshold, i.e. the sensitivity of the detector

Normally, the light is detected with two PMT arrays (Top and Bottom). The light emitted to the sides is reflected on PTFE panels and finally may hit one of the PMTs.

The reflectivity of PTFE is not specular, but into all space. It was measured between 65 % and 95 % at 178 nm, with the difference not well understood.

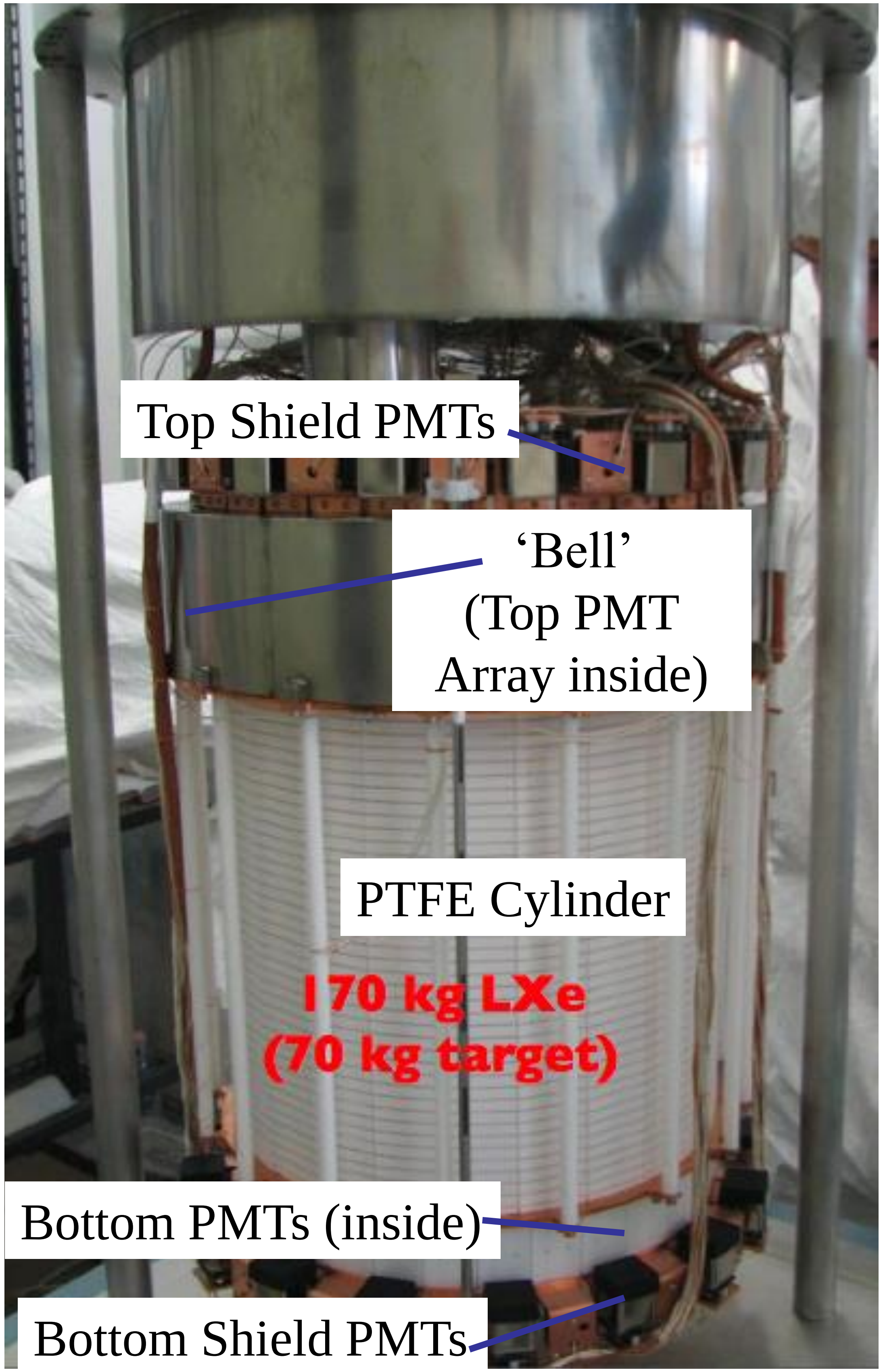
PTFE contributes to α - N reactions

An increase of the LCE by replacing PTFE side panels with PMTs is possible, but:

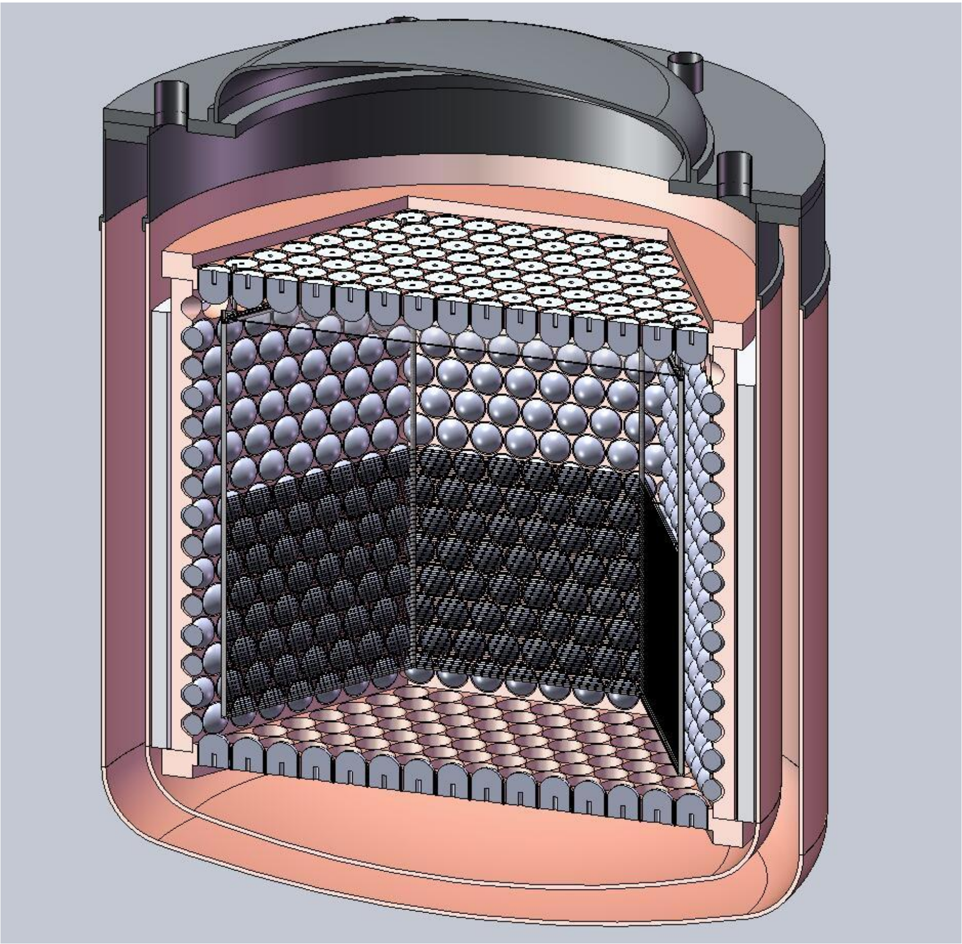
1. very expensive (1000 or more PMTs)
2. many channels even with 3” PMTs
3. Heat losses in cables
4. Radioactivity, even with low activity tubes
5. Large volumes of dead LXe around PMTs
6. Not very fast (TTS of 3” PMT: 5 nsec)
7. Large dead spaces between PMTs

Large area cryogenic GPMs would solve all these problems.

Geometry of XENON100 (182 1” square PMTs + 64 in shield)



Originally proposed XENON1T with Qupids all around the active volume



Order of 1000 QUPIDs (3” OD”)
No PTFE reflectors!

Coverage with PMT arrays:

XMASS	sphere	62.5 %	(Maximum PMT coverage!)
1” square	flat array	60 - 65 %	(1 mm between PMTs)
3” round	flat array	60 - 65 %	(Tight hexagonal array)

Light collection efficiency:

XMASS	14.3 pe / keV *
XENON10	4 pe / keV
XENON100	2.3 pe / keV

*No electric field. Field reduces the light by about 50 %

To improve coverage we have to reduce dead areas in arrays

Solution: **Large area homogeneous cryogenic GPMs (20 x 20 cm^2 min.)**

XMASS Detector: **Single Phase LXE**

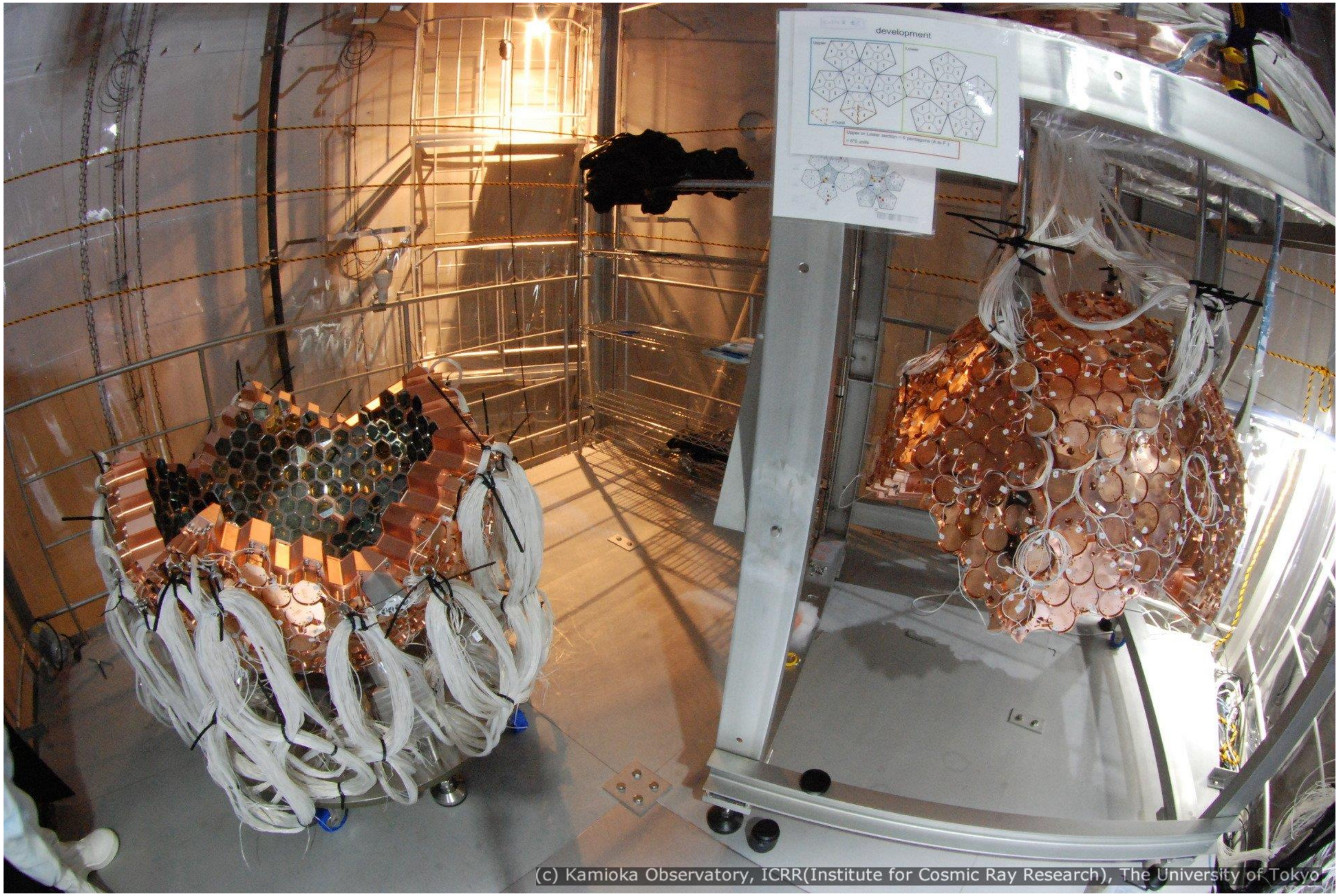
641 PMTs arranged around sphere

800 kg active volume (**100kg** fiducial)

High Q_e low activity 2” hexagonal PMT

Geometrical coverage with photo cathode surface: **62.5 %**

Trigger threshold: **0.3 keV**

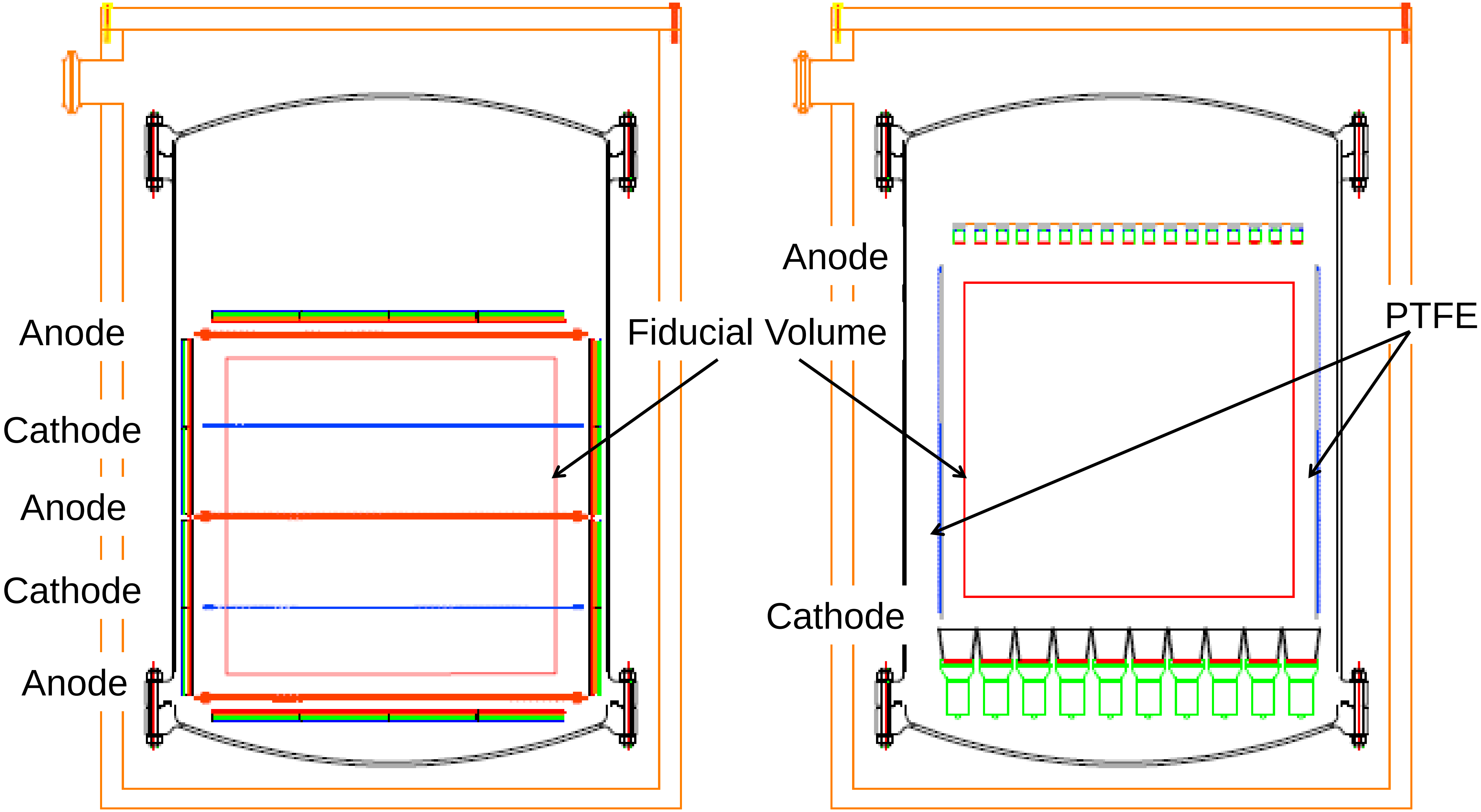


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Schematic comparison of the Panda-X detector with:

GPMs on all sides

PMTs and PTFE reflectors



Specification for ‘our’ GPMs:

Size: 20 cm x 20 cm min., better 40 cm x 40 cm
Envelope: UV quartz for 178 nm
Q_e above 30 %
Semi transparent photo cathode
Temperature: -100 C (immersed in liquid xenon)
Outside Pressure: 0 - 3.5 bar absolute
High gain
Granularity of Read Out: 1” x 1” fully sufficient
Very low dead volume at borders
Very compact design to improve TTS

Conclusions:

CsI Qe will not be sufficient, only for tests.
GPM must be in hermetically closed envelope
We have to defeat positive ions going back
We probably need commercial partner for Cathode

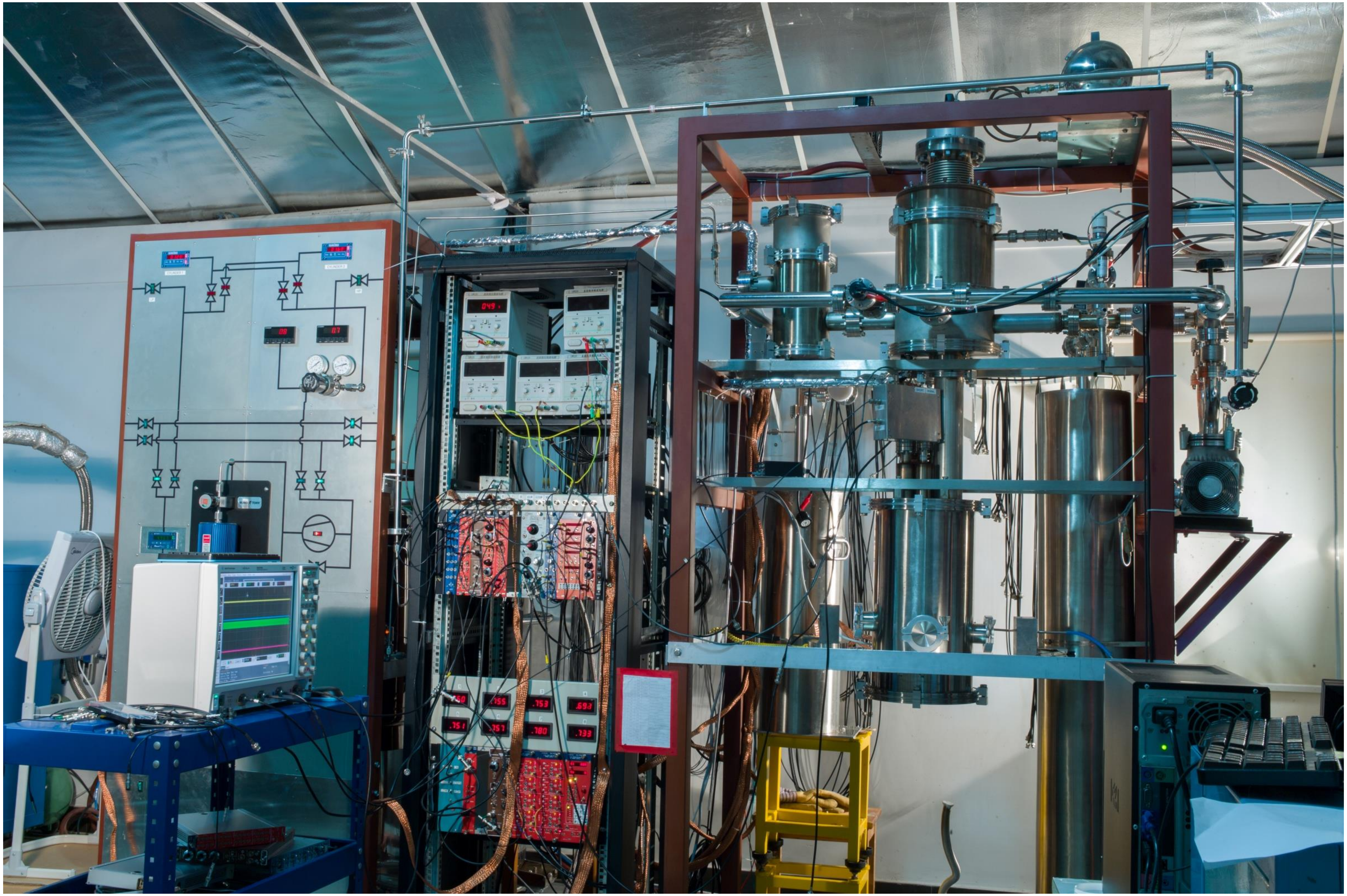
Present idea:

Hermetic quartz envelope
Double ThGEM low gain
MicroMega for amplification
Semi transparent photocatode
Ar + CH_4 gas mixture, no recirculation of gas
ThGEMs on CIRLEX for radioactivity
Bialkali photocathode for high Q_e
Assembly probably with Transfer-Technology

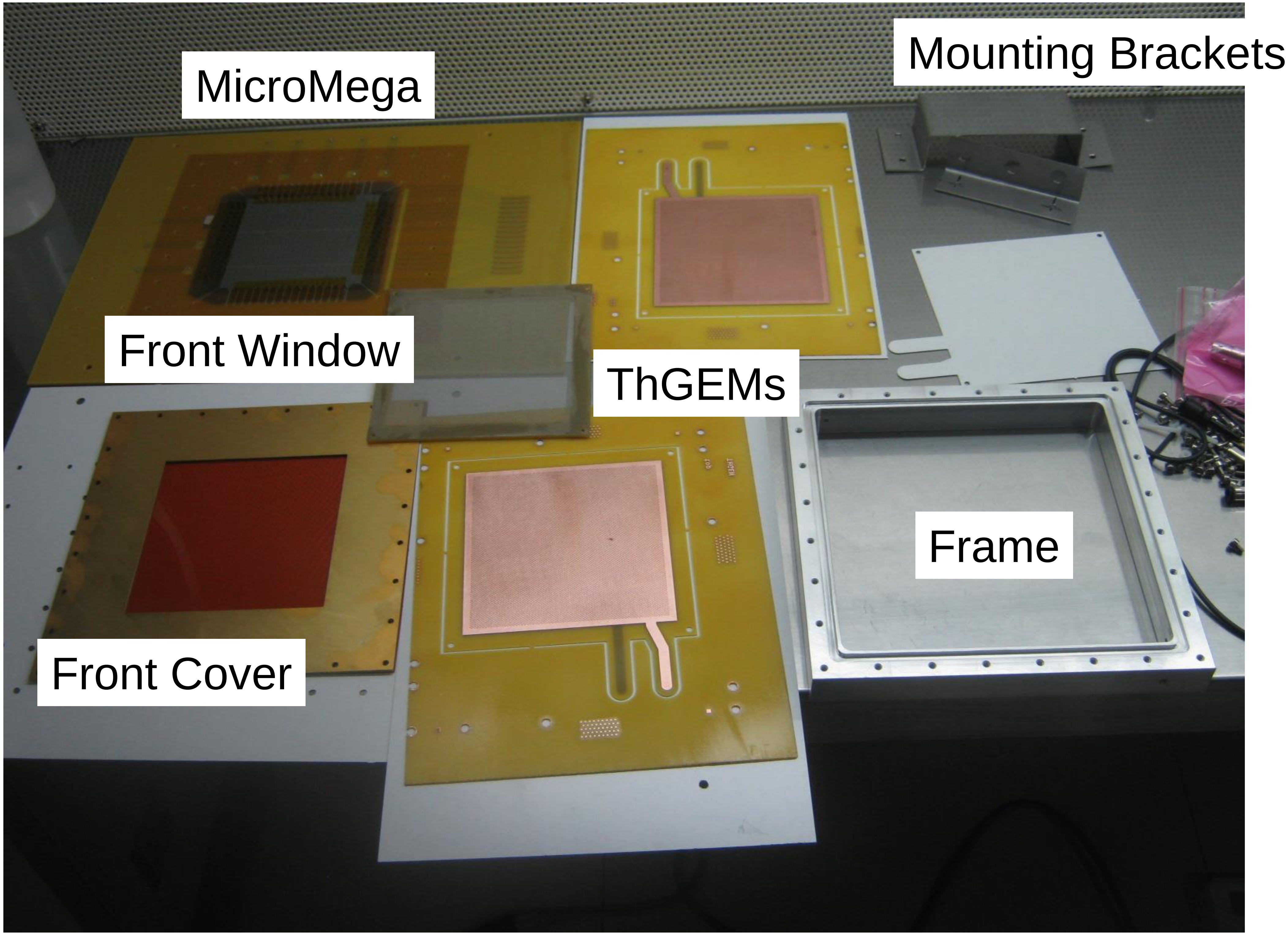
To start we acquired standard MicroMega kit and 2 ThGEMs (10 cm x 10 cm)

We are just building gas handling system
We need CsI evaporation station
We do have complete LXe test system

But, we can improve LXe detectors with GPMs even further



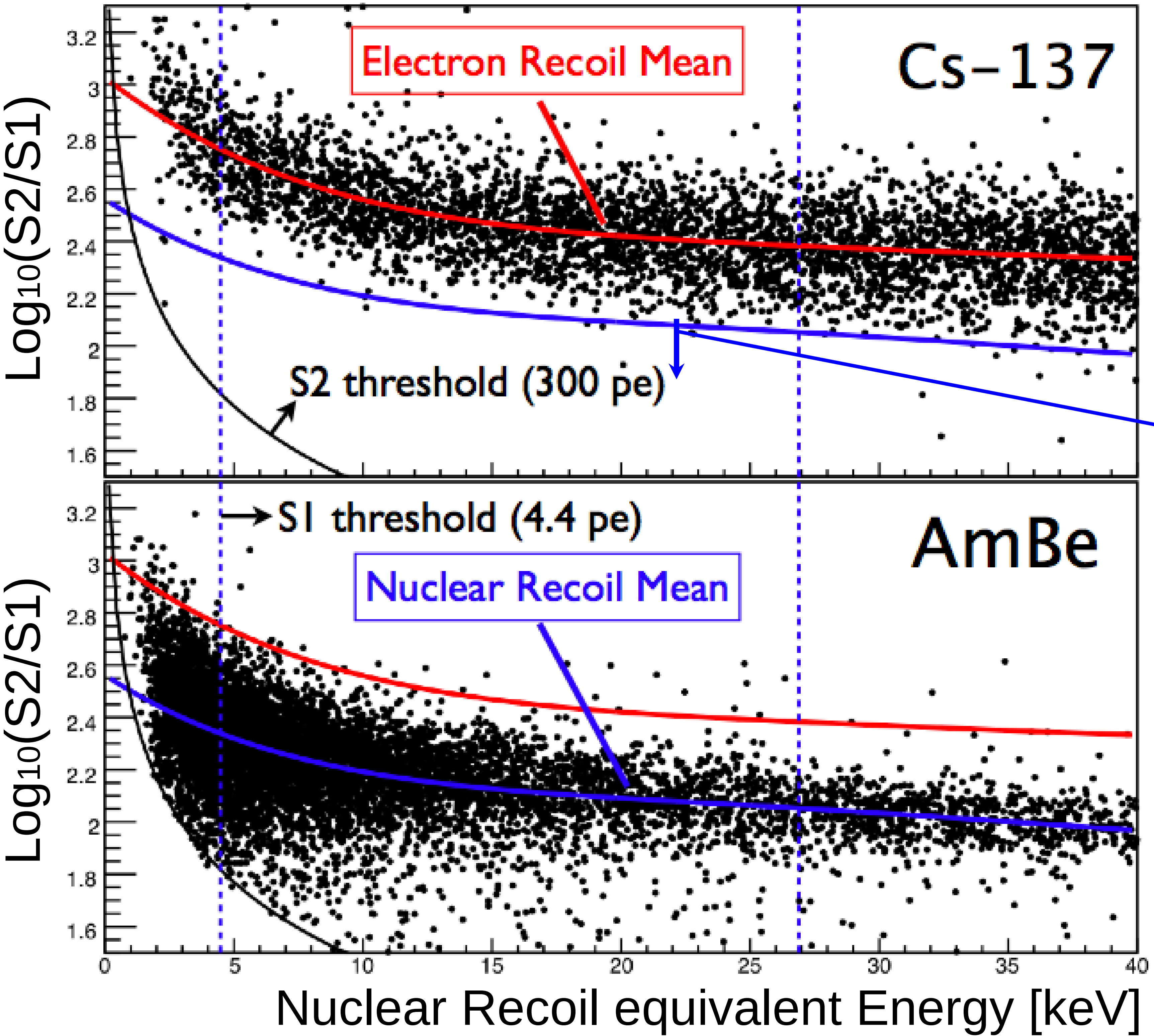
LXe test set up at SJTU



The standard kit (+ 2 ThGEMS). Not yet assembled!

The ratio of S2/S1 forms bands for Gamma rays and nuclear recoils.

This gives a high rejection ratio for gamma ray background



~ 99.5 % gamma events are rejected below the nuclear recoil mean

The width of a bands is Related to the energy resolution, i.e. related to the number of photo electrons.

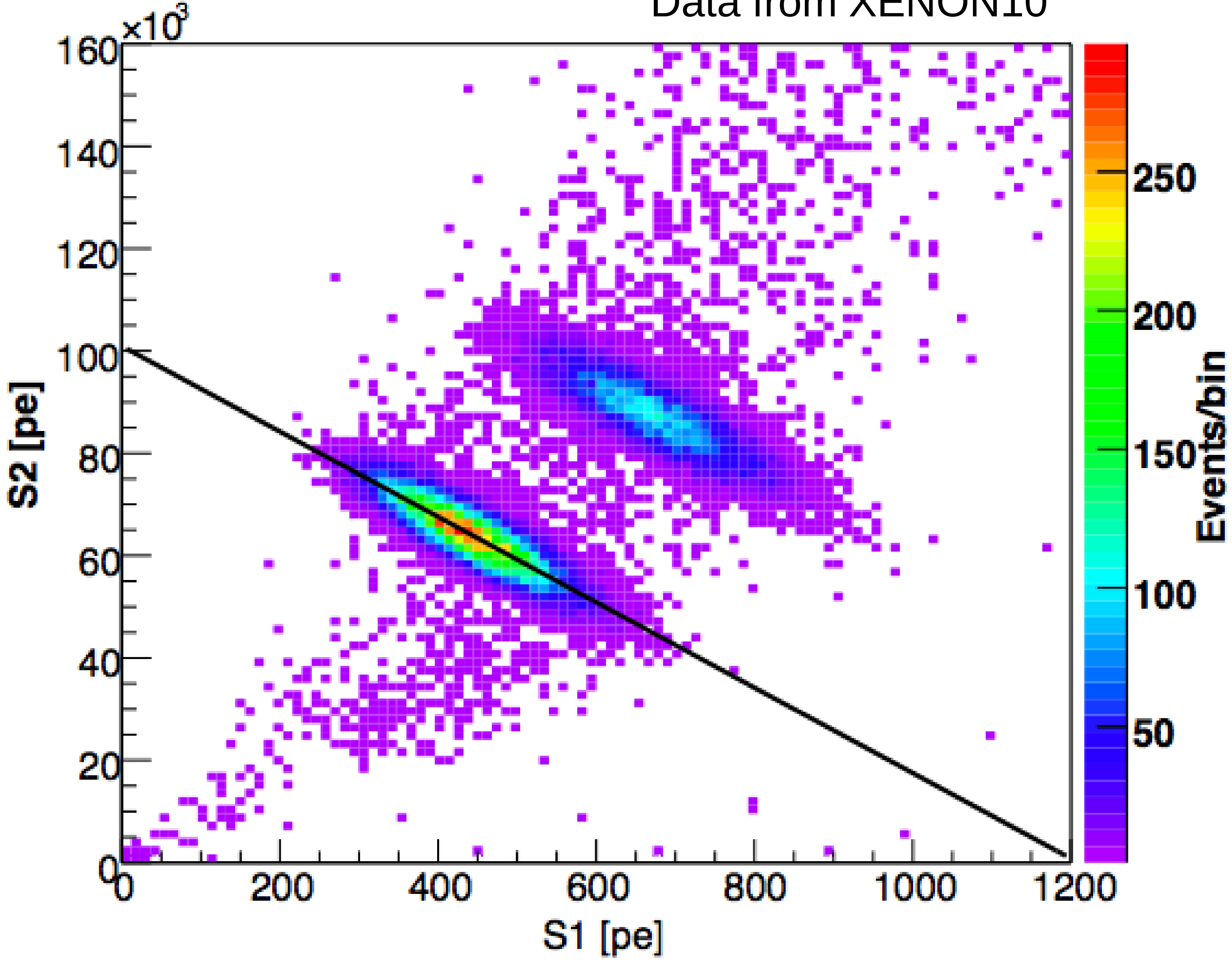
The signal strength is dependent on the number of photons for S2, and on the number of drifting electrons for S1.

S2 and S1 are not independent. There is an anti-correlation between light and charge, i.e. S2 and S1.

A linear combination has a much better resolution than S2 or S1 alone.

If transformed into a 2 D space with perpendicular coordinates there will be again bands for NR and gamma rays, but the bands will be much narrower. This means: The cut will have a higher gamma rejection while keeping more NR events.

Data from XENON10



The mixing constants are detector dependent, i.e. light collection efficiency.

The Light Collection Efficiency (LCE) determines not only the Threshold, but also the **energy resolution**, i.e. **Background Rejection Capability**)

With a maximum LCE the fluctuations on S1 are as small as possible, i.e. the contribution of S1 to the energy resolution is optimized.

S2 is often assumed to be easier to measure since there are more photo electrons. This is correct, if the **gain fluctuations** are sufficiently small.

The gain depends on E / P and the length L, the thickness of the gap. P is the pressure of the gas phase and normally quite stable. And E is the electric field strength which is assumed to be the applied voltage over the gap length, i.e. the distance of liquid level to the anode wires.

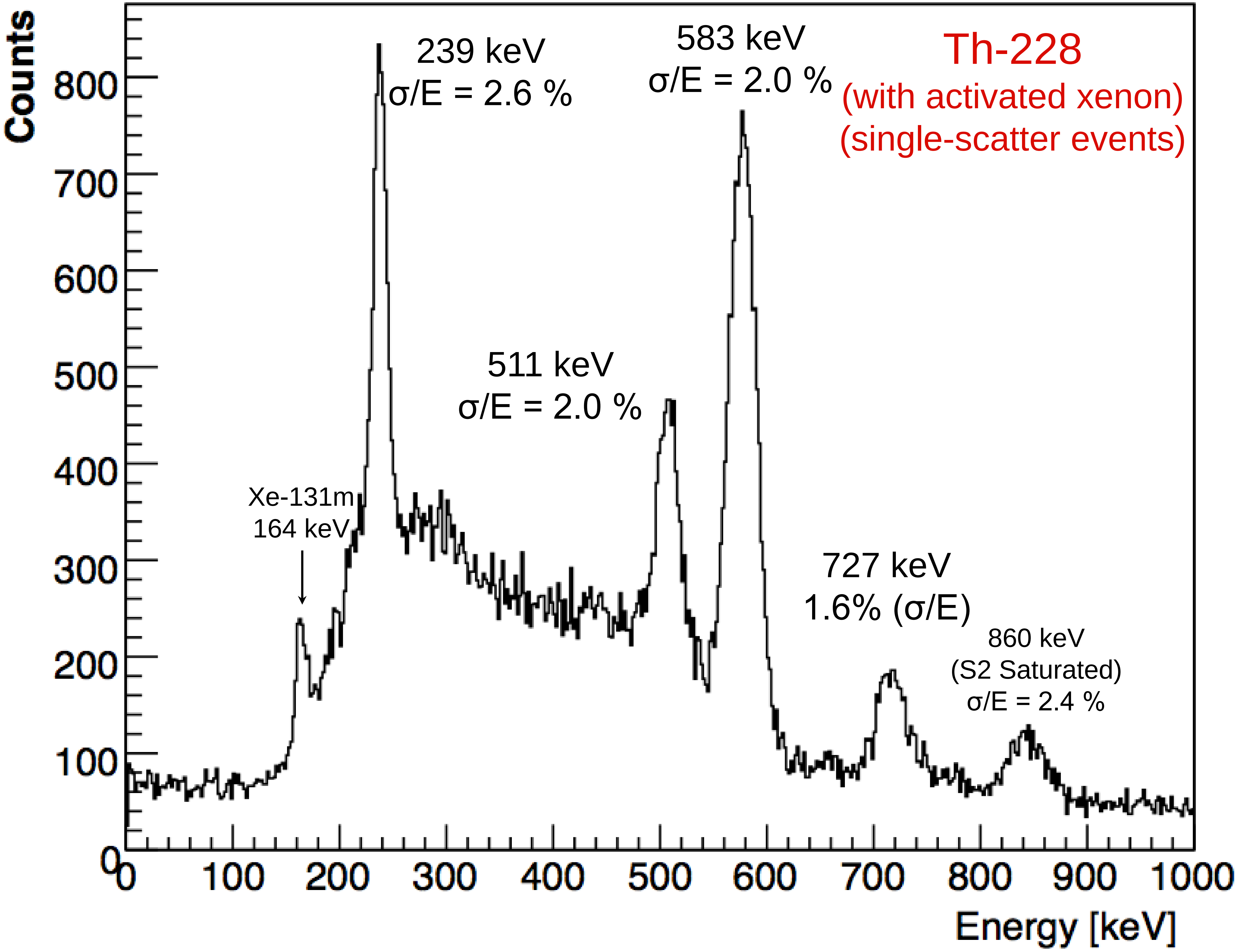
Variations of L and thus E can be kept low in small chambers, but this is very difficult in large detectors.

An very easy assumption is the geometry is a parallel plate capacitor between liquid level and anode plane.

It is not very easy to make a parallel plate geometry on large lengths (**more than 1 m**).
Especially when the opening in the meshes are kept large for enhanced light collection. Some regions might have a smaller gap because of sagging wires or mechanical tolerances. Also, some field lines might overshoot the anode plane and then return to an anode wire. The introduced fluctuations might be dominate the fluctuations from the number of drifting electrons.

The detector is leveled to give the optimum response in average. **But, what about the fluctuations**?

The Energy Resolution of the XENON10 TPC



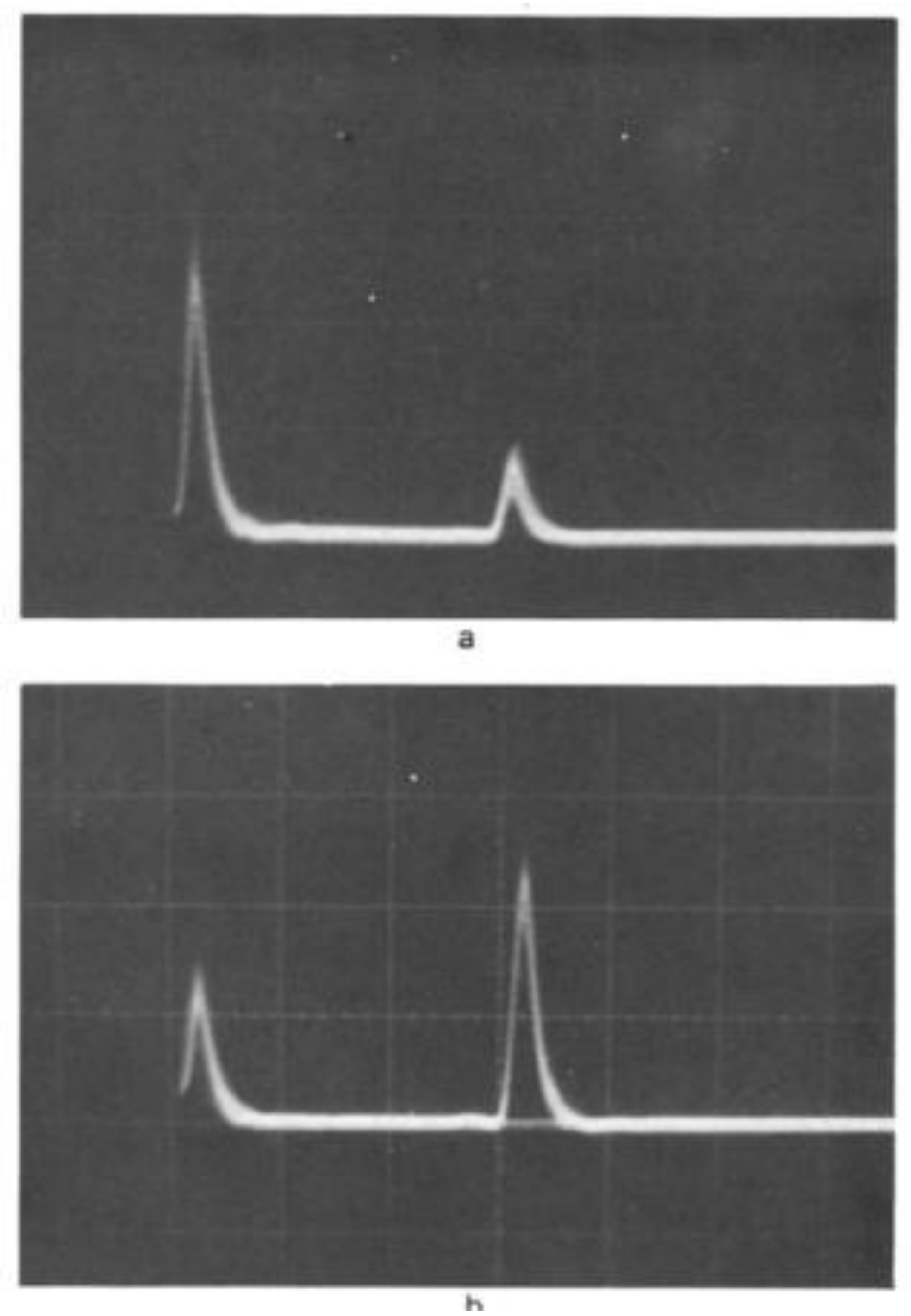
Solution to Problem:

Proportional Scintillation in Liquid Xenon.

Not really a new idea. Already demonstrated by the Doke group in **1979**! But, nearly forgotten afterwards.

Geometry similar to Multi Wire Drift Chamber Scintillation in high field around thin wires in the liquid. No more Double Phase!

Effectively no more dependence on, pressure, temperature, parallelism of wires, distance of anode wires to liquid level.

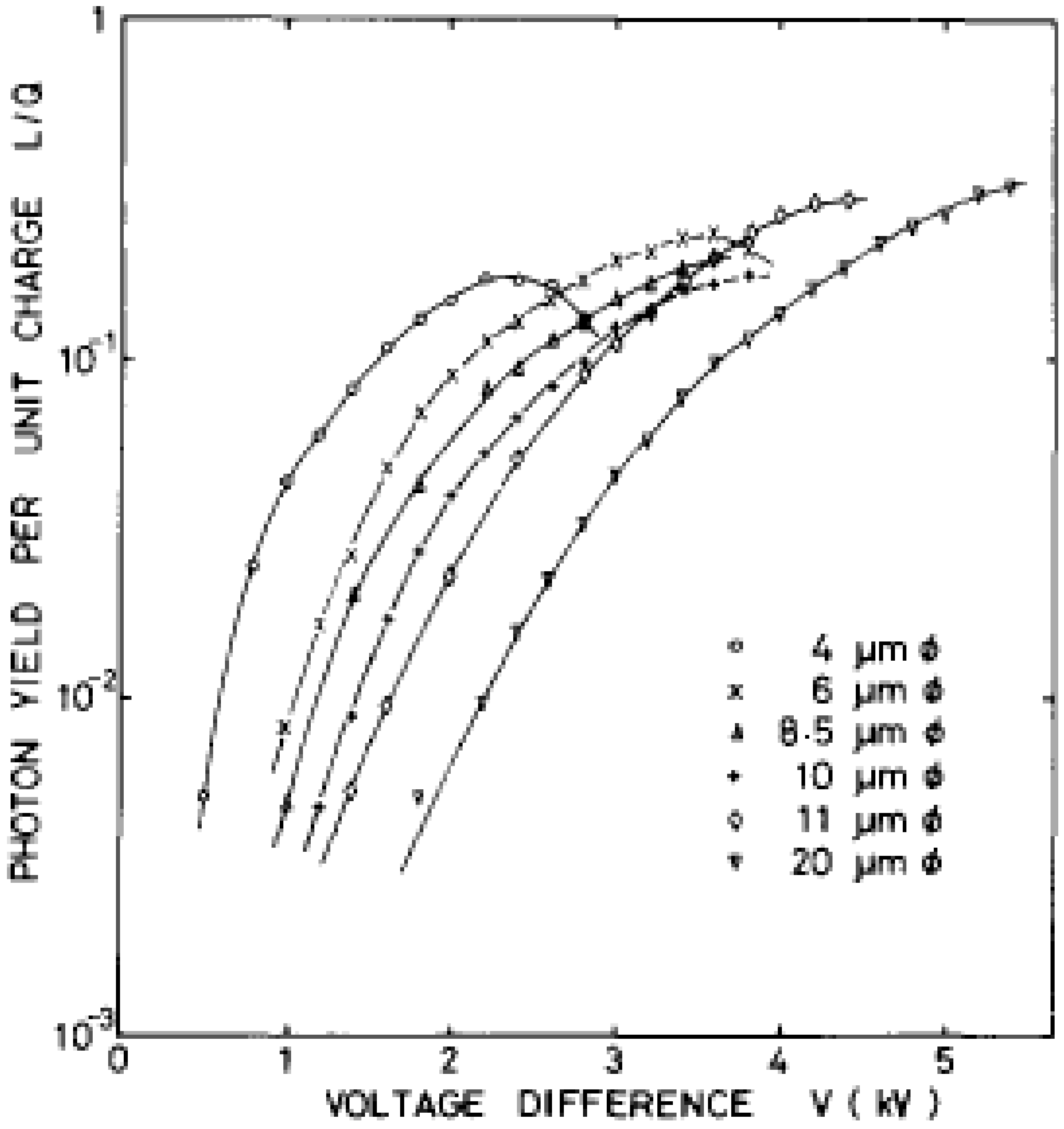


Miyajima et al. NIM160(1979)239

Additional advantage:

Charges drift up or down. If we split volume into 2,4, or 6) drift spaces, we can lower HV, get shorter drift time, less attachment, and lower amount of digitized data.

There are several more advantages implied.



Masuda et al. NIM160(1979)247

Conclusions

1. High sensitivity requires higher coverage of surface with photo cathode
2. PMTs could do the job, but too expensive, too slow, large dead spaces
3. PTFE reflectors should be avoided
4. GPMs seem to be the solution, but many problems to be solved
5. Proportional Scintillation in liquid is a must, not an option
6. We have to optimize the energy resolution
7. PSD might give an additional tool for background rejection
8. Probably there will be detector beyond the 1 ton scale
9. We are at the very beginning of the development, if anybody wants to help, let’s collaborate.