LXe calorimeter prototype(s) for PIONEER
Status update & future plans

- LXe calorimetry
- R&D setup : LoLX
- Status of preparations for a large prototype
  - simulations (NEST, optimal simulations)
  - mechanical work
  - remaining work
  - timeline
- Physics (Doug's presentation)

LXe calorimeter option for PIONEER

- high density ~3g/cm3
- high light yield (~NaI)
- fast response
- transparent to its emission (long absorption length)
- highly homogeneous response
- emission in the VUV (~175 nm)
- purities can be removed
- detector can be "reshaped" (LXe is a commodity)
- "expensive" (currently quotes from China are OK -> see procurement talk)

✓ high energy resolution

✓ fast timing

✓ homogeneous response

Material Properties	Value & Unit	Conditions	Ref.
Atomic Number	54		
Atomic Weight A	131.29 g/mole		[3]
Boiling point T_b	165.1 K	1 atm	[3]
Melting point T_m	161.4 K	1 atm	[3]
Density ρ_{liq}	2.98 g/cm^3	161.35 K	[4]
Volume ratio $\rho_{\text{gas}}/\rho_{\text{liq}}$	550	15 °C, 1 bar	[5]
Critical point T_c, P_c	289.7 K, 58.4 bar		[5]
Triple point T_3, P_3	161.3 K, 0.816 bar		[5]
Radiation length X_0	2.77 cm	in liquid	[6]
	8.48 g/cm^2		
Molière radius R_M	5.6 cm		[6]
Critical Energy	10.4 MeV		[6]
$-(\mathrm{d}E/\mathrm{d}x)_{\text{mip}}$	1.255 MeV cm^2/g		[6]
Refractive index	1.6 ÷ 1.72	in liquid at 178 nm	[7, 26][a]
Fano Factor	0.041	theoretical	[9]
	unknown	experimental	
Energy/scint. photon W_{ph}	(23.7 ± 2.4) eV	electrons	[10]
	(19.6 ± 2.0) eV	α-particles	[10]
Lifetime singlet τ_s	22 ns		[10]
Lifetime triplet τ_t	4.2 ns		[10]
Recombination time τ_r	45 ns	dominant for e, γ	[10]
Peak emission wavelength λ_{scint}	178 nm		[11, 12]
Spectral width (FWHM)	~ 14 nm		[11, 12]
Scint. Absorption length λ_{abs}	> 100 cm		[1]
Rayleigh scattering length λ_R	(29 ± 2) cm		[13]
Thermal neutron σ_{tot}	(23.9 ± 1.2) barn	Natural composition	[14]

[a]Discrepancies are present among the measured values. Refractive index in [7] was determined at 180

from https://arxiv.org/pdf/physics/0401072.pdf

LXe calorimeter option for PIONEER

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

LXe calorimeter option for PIONEER

- triple point at 161K, 0.82 bar
- narrow temperature range for liquid operation
- normal operation : T~167 K, P~1.2 bar (“easy" cryogenics)
- scintillation light mechanism

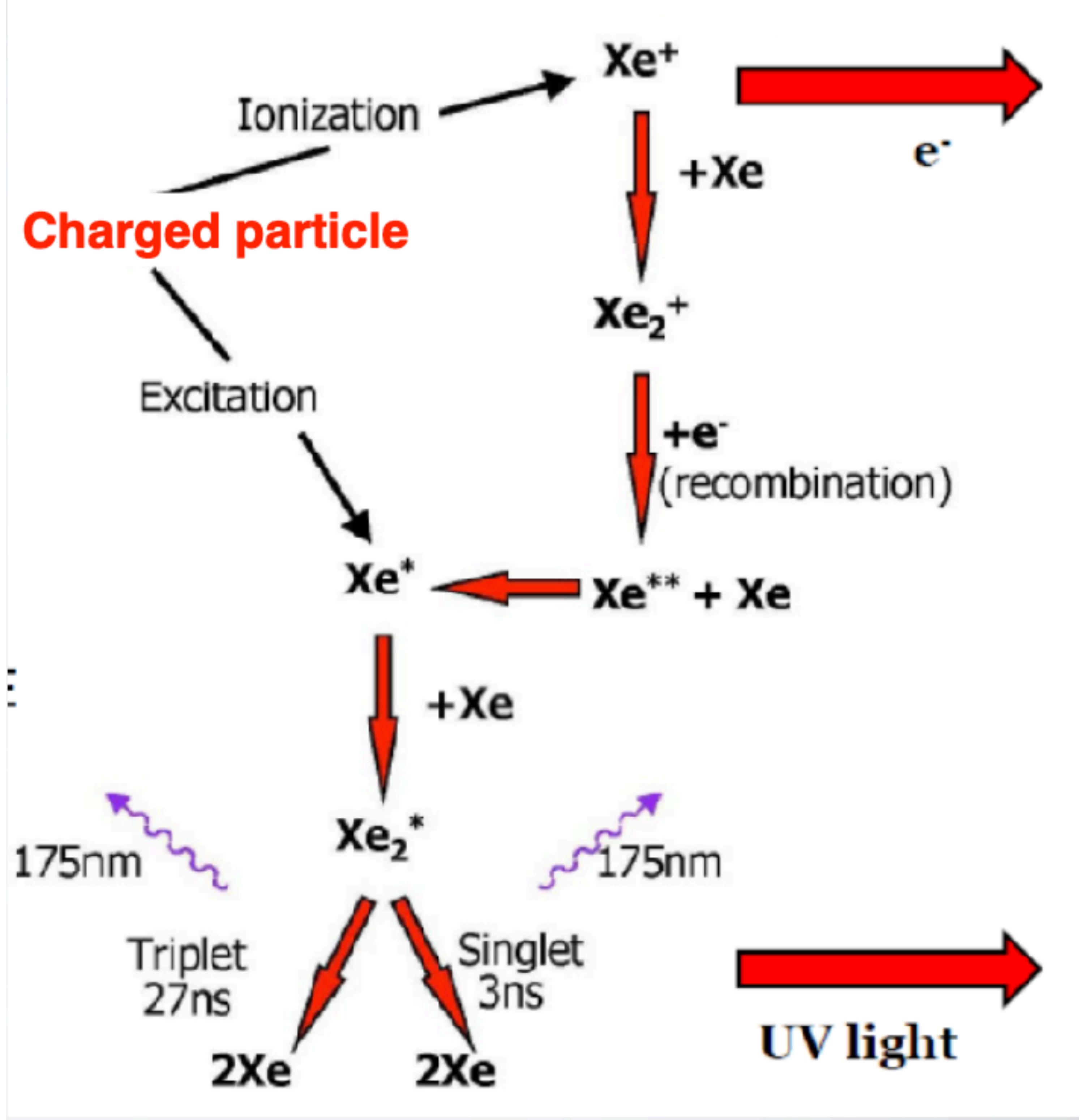
Excitation $Xe + Xe^{*} \rightarrow 2Xe + h\nu$

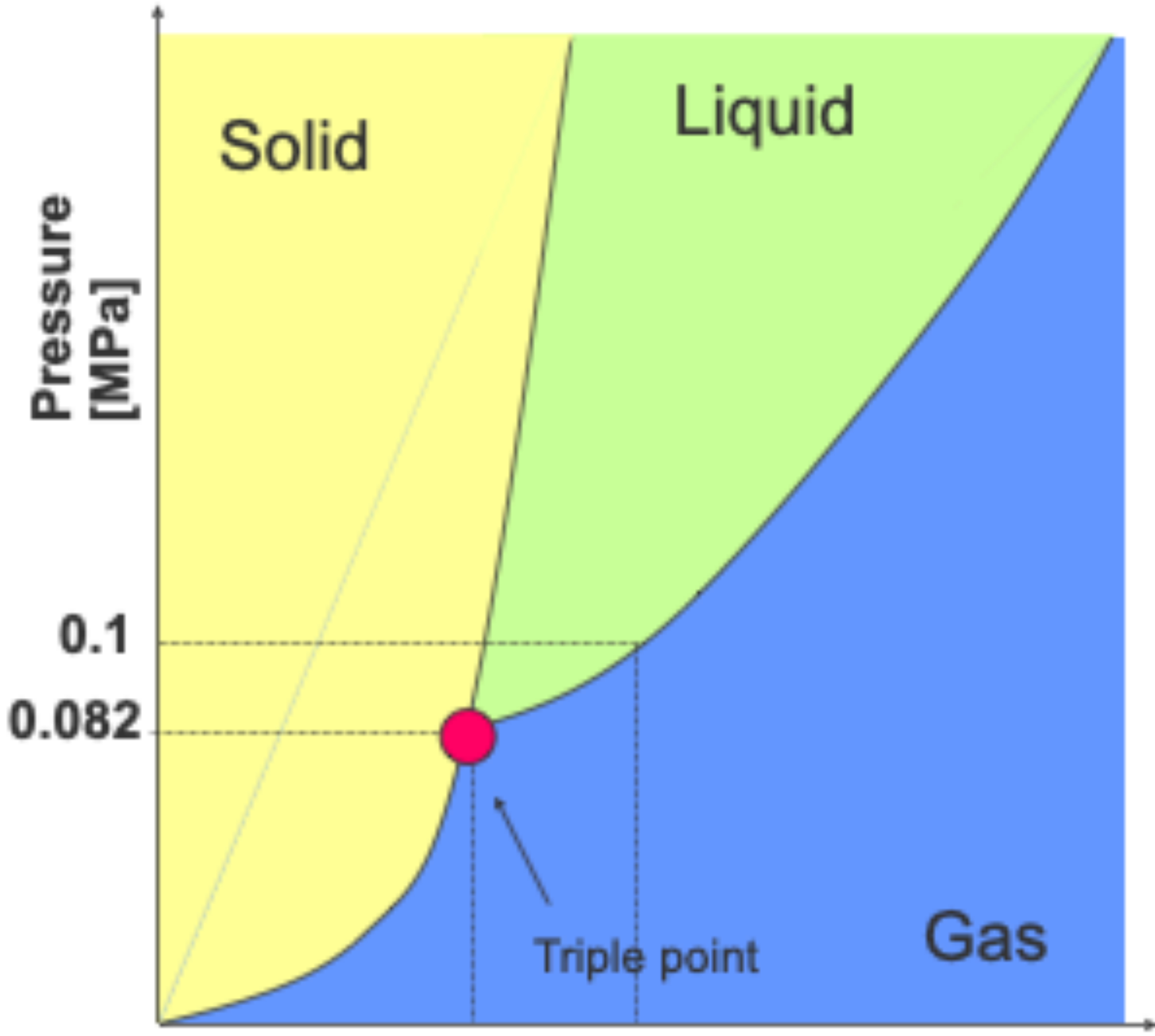
Recombination $Xe^{+} + Xe \rightarrow Xe_2^{+}$

$Xe_2^{+} + e \rightarrow Xe^{**} + Xe$

$Xe^{**} \rightarrow Xe^{*}$

$Xe + Xe^{*} \rightarrow Xe_2^{*} \rightarrow 2Xe + h\nu$



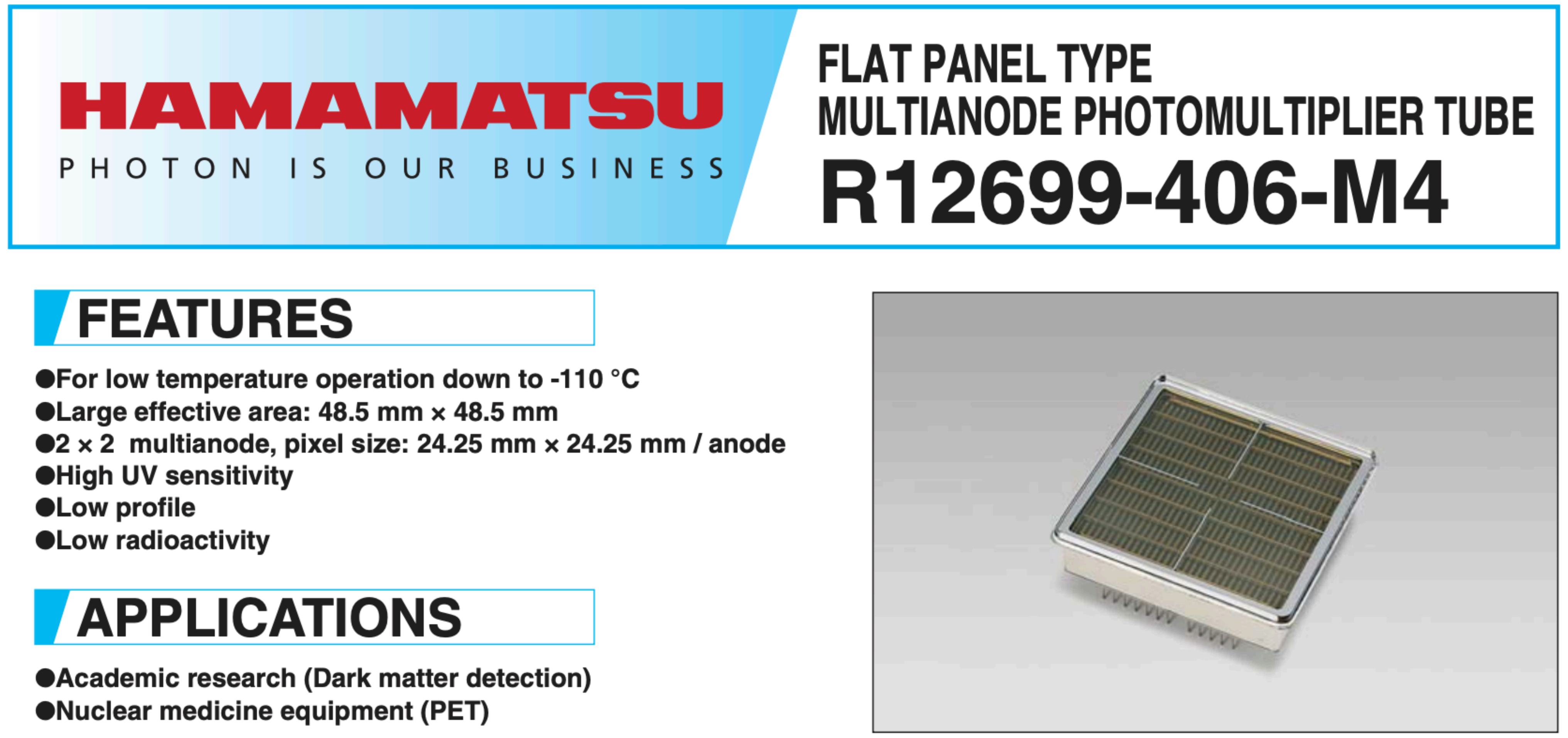


- Excitation/Ionization ratio depends on the incident particles
- Recombination speed depends on dE/dx (very fast for high dE/dx , e.g. alpha)

- 4ns/22ns for alpha
- 45ns for e/gamma (recombination)
- PID with PSD possible

VUV light collection in LXe

- VUV sensitive SiPMs
- Cryogenic PMTs with fused silica windows
- Other options:
  - WLS (TPB others) deposited on PMT/SiPM
  - WLS coated on reflective detector wall
  - other (light guide etc)


HAMAMATSU
PHOTON IS OUR BUSINESS
FLAT PANEL TYPE
MULTIANODE PHOTOMULTIPLIER TUBE
R12699-406-M4

FEATURES
- For low temperature operation down to -110 °C
- Large effective area: 48.5 mm × 48.5 mm
- 2 × 2 multianode, pixel size: 24.25 mm × 24.25 mm / anode
- High UV sensitivity
- Low profile
- Low radioactivity

APPLICATIONS
- Academic research (Dark matter detection)
- Nuclear medicine equipment (PET)

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/R12699-406-M4_TPMH1368E.pdf

Developed for PandaX : fast, QE=33%
$k8/tube!


HAMAMATSU
PHOTON IS OUR BUSINESS
PHOTOMULTIPLIER TUBE
R8520-406/R8520-506

FEATURES
- For low temperature operation
  down to -110 °C: R8520-406
  down to -186 °C: R8520-506
- Low radioactivity 26 mm (1 Inch) square
- High UV sensitivity by synthetic silica window

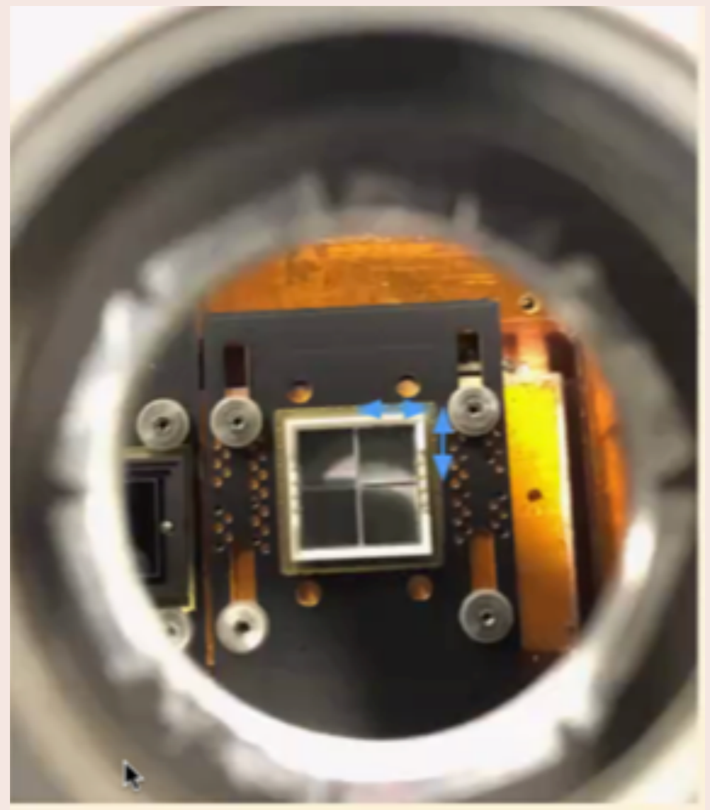
APPLICATIONS
- High energy physics
- Astrophysics
- Academic research

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/R8520-406_TPMH1342E.pdf

1 inch, fast, QE=30%

VuV SiPM : HPK / FBK

HPK VUV4-Q-50
Quad device
50um pitch



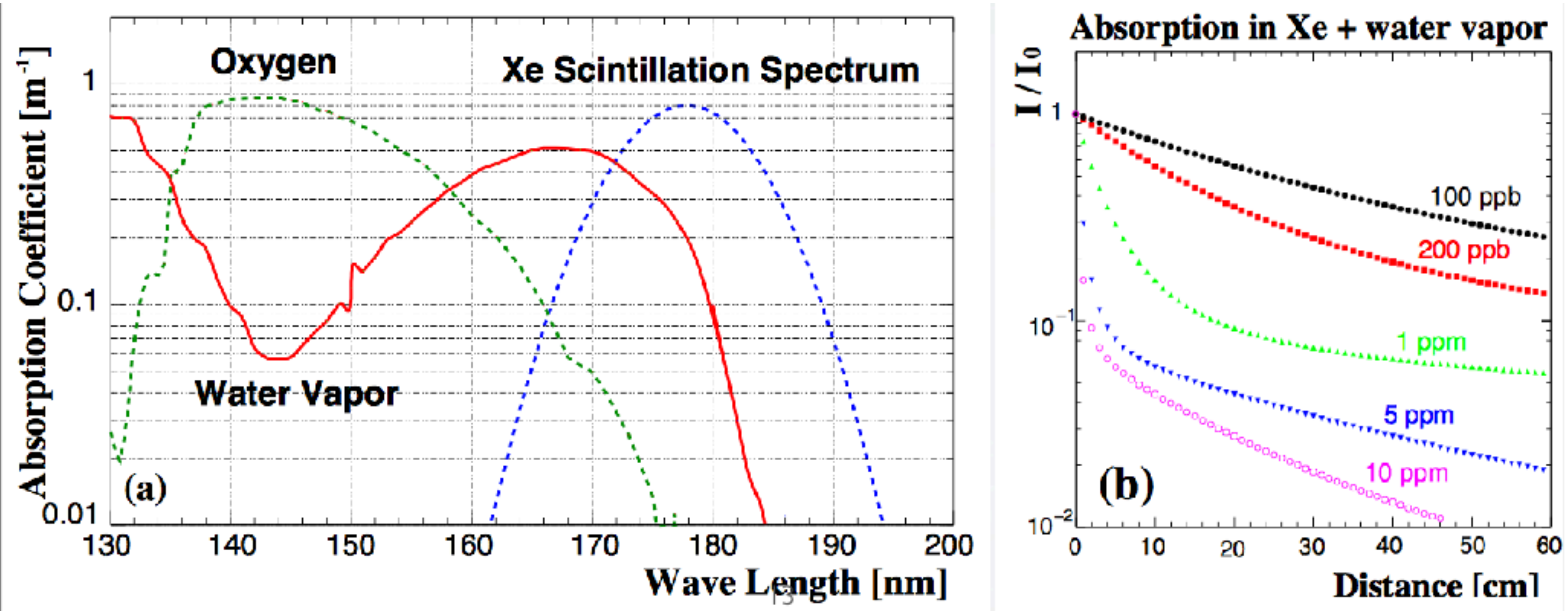
BEING CONCOMITANTLY TESTED in LOLX

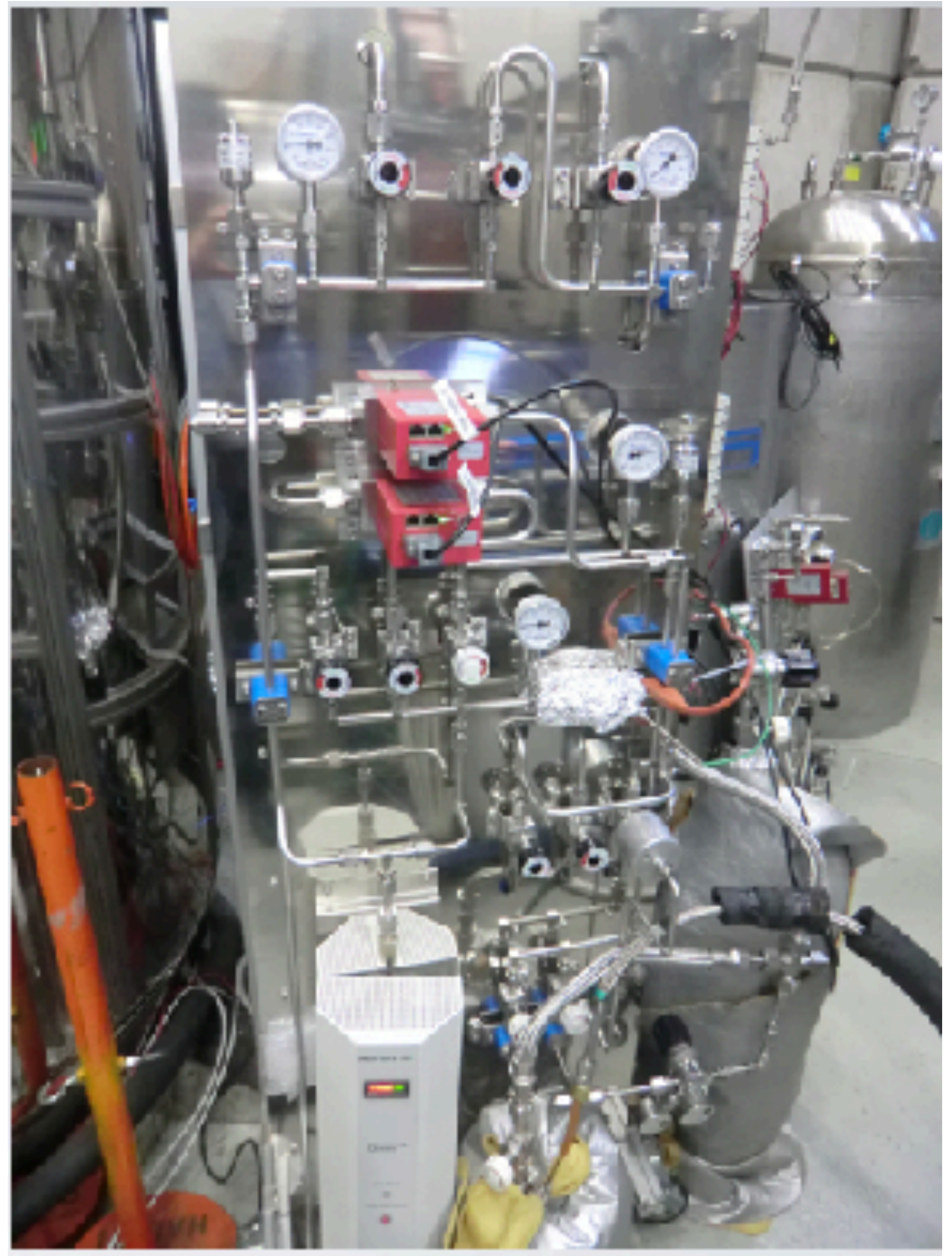
FBK VUVHD3

Xenon purification needed

- Xenon purchased is graded for 10 ppm impurities
- Impurities (water, 02 etc) dissolve in the liquid and absorb UV photons -> drastic effect

from Ozone PhD





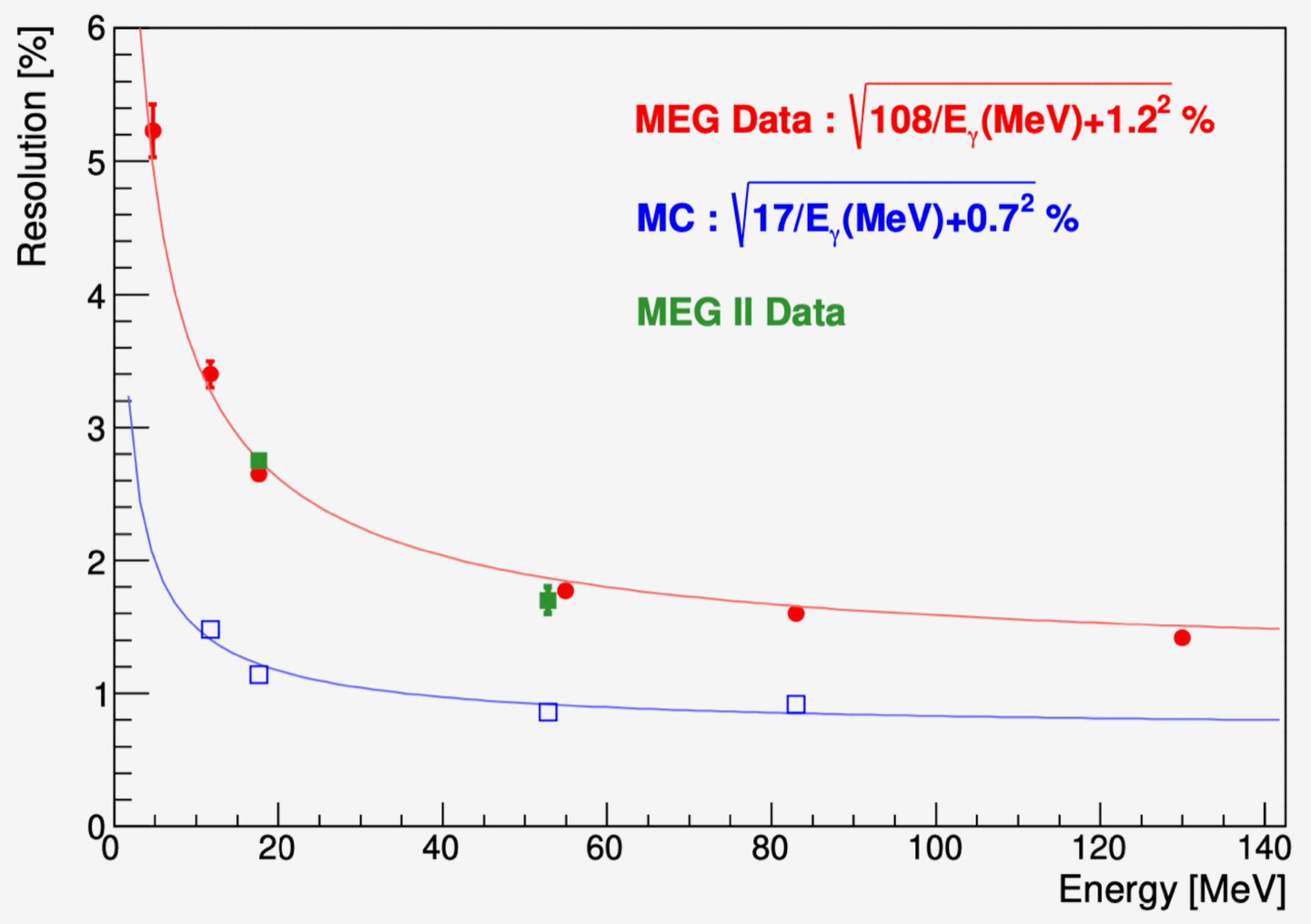
- presence of photosensors precludes high temperature baking (alternative: slow and long baking)
- Gaseous purification (metal getter purifier) slow ~4L/h (in MEG)
- Liquid purification (molecular sieves) fast ~40L/h
- Purity measured by light attenuation OR separate purity monitor (see slide)

LXe calorimeter option for PIONEER

- LXe - open questions

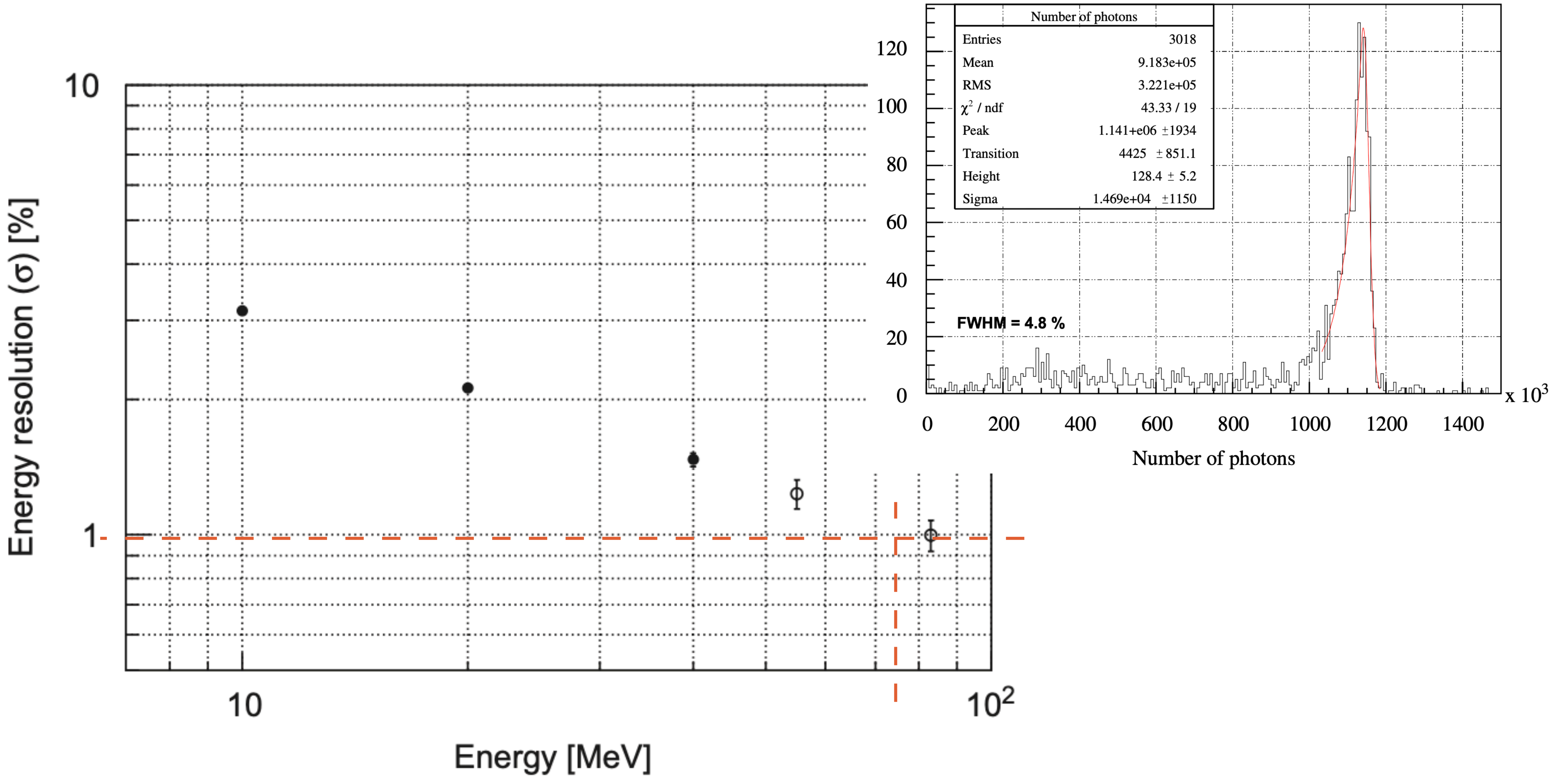
- **Energy resolution**

MEG data/MC disagreement



Shinji's Ph.D thesis
(Figure 9.15 https://meg.web.psi.ch/docs/theses/ogawa_phd.pdf).

MEG results for impinging γ in the LXe large prototype



In our proposal: "The baseline energy resolution goal for PIONEER at 70 MeV is 1.5%". Needs depends on physics goals. Higher is Better. But independently of the value, to trust our MC extracted sensitivity we need to understand the discrepancy

- **Pile-up**: Simulations needed to assess feasibility of 1st phase without segmentation
  i.e. relying on pulse shape separation (5-10ns)
  + knowledge of beam contamination needed

LXe calorimeter option for PIONEER

- **Energy resolution**

Resolution does not seem limited by intrinsic light yield

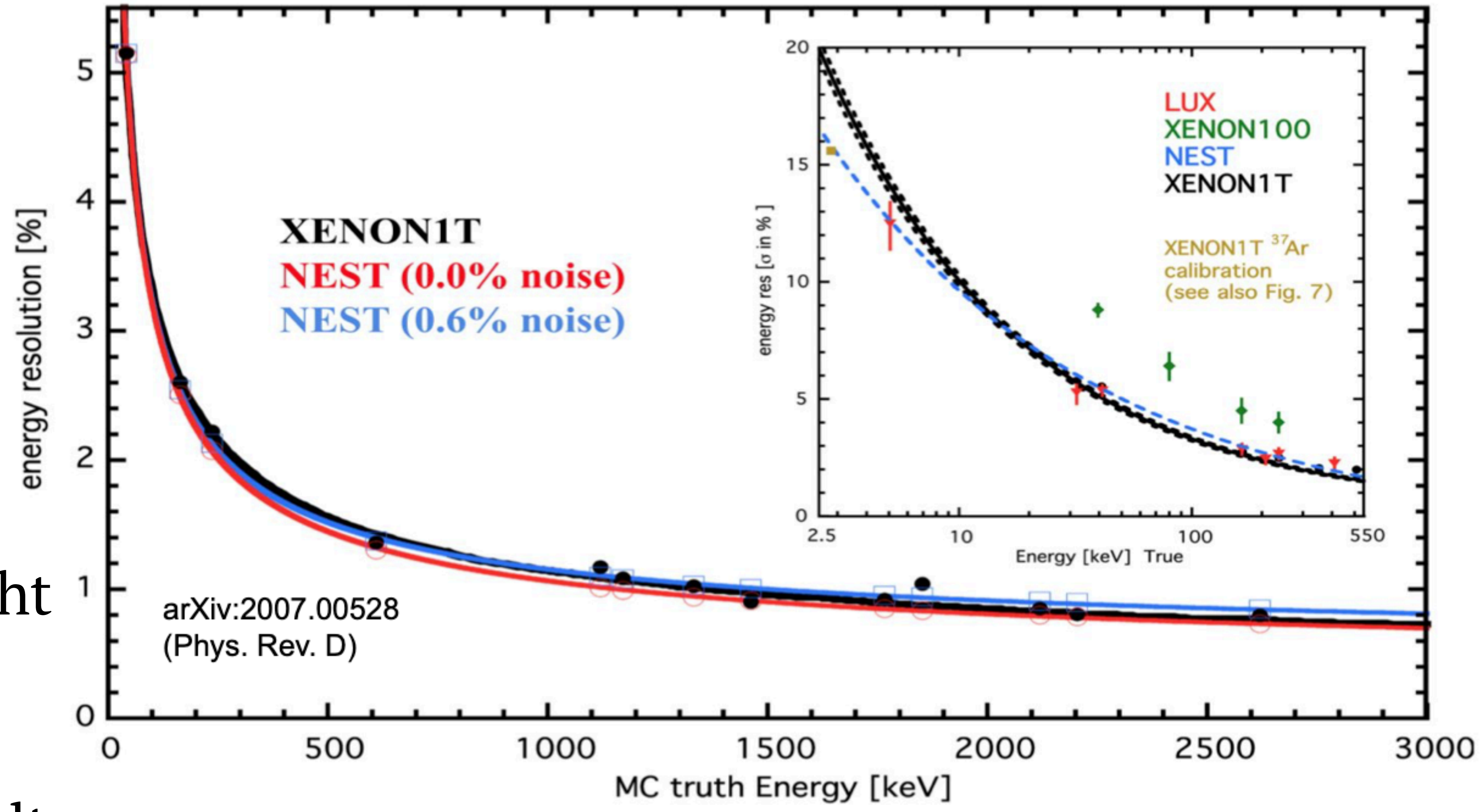
Can the fluctuations of dE/dx within the EM "shower" cause changes in light output and worsening the energy resolution
-> NEST
Also includes fluctuations in the recombination

==> Compare MEG data with MC with/wo NEST

- NEST studies based on MEG calorimeter geometry
  Conclusion: Resolution discrepancy (after equalizing the light yields). But resolution is highly dependent on E-field

  NEST has potential for tuning and matching simulation results to data, but reliable data is required for this effort to be successful.

Work by Aleksey



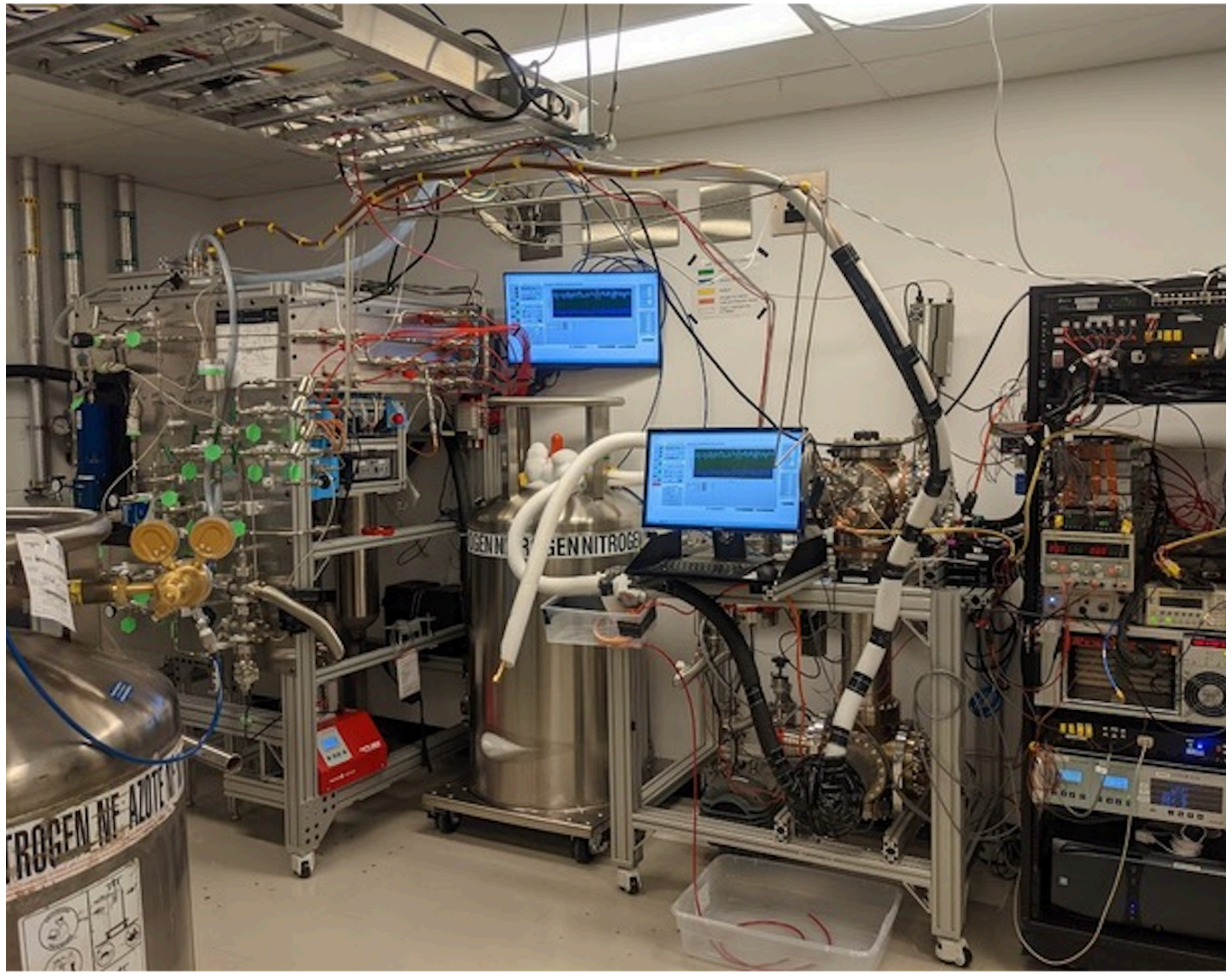
talk by K. Ni UCSD @ LIDINE2022

Very good agreement between NEST and available TPC low energy data

Need for R&D and large prototype

- **SMALL SETUP : LoLX @ McGill**
- few liters (~2L)
- offers flexibility of operation
- simple geometry

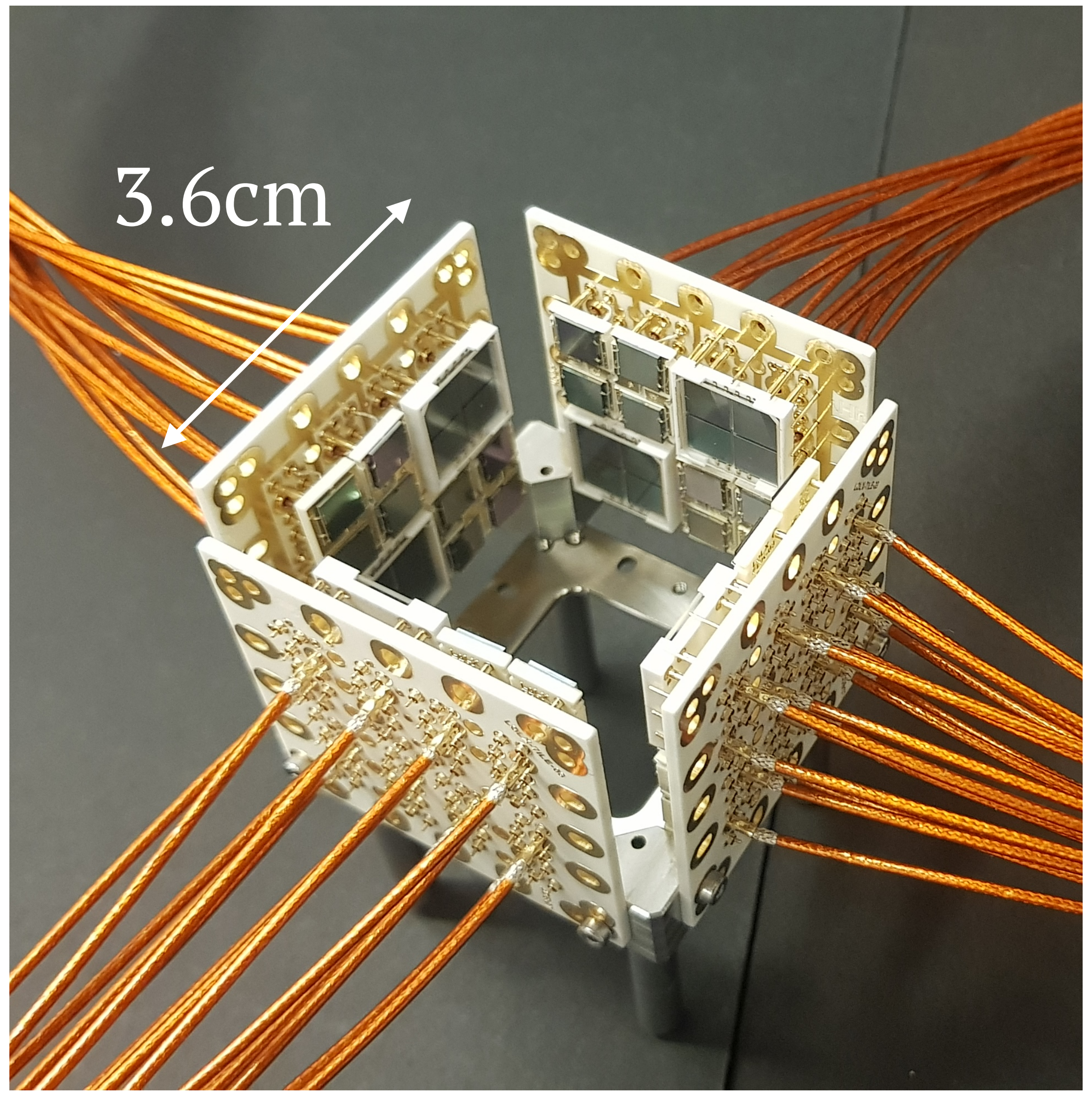
1. test and characterize photosensor technologies (PDE, response after high irradiation, stability etc)
2. benchmark simulations (G4 with and w/o NEST and optical simulations (Chroma))
3. LXe scintillation properties (IR emission, Cerenkov)
4. measure energy resolution at low energies (compare to simulations)
5. data input to NEST at zero-field
6. material test (reflectivity, different coatings, WLS) etc

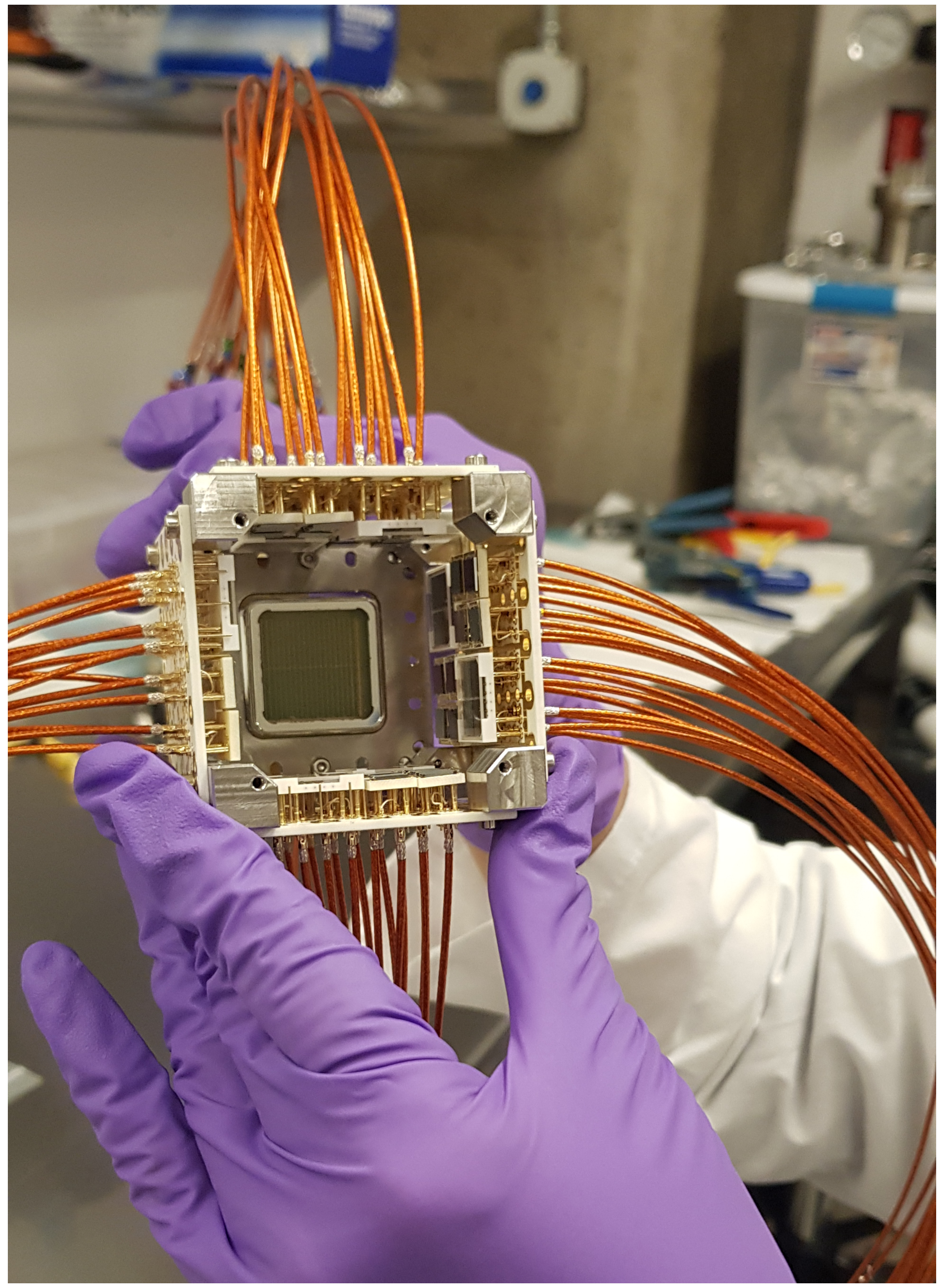


LoLX setup at McGill

Need for R&D and large prototype

- SMALL SETUP : LOLX @ McGill





LoLX detector built at TRIUMF

40 FBK VUV HD3

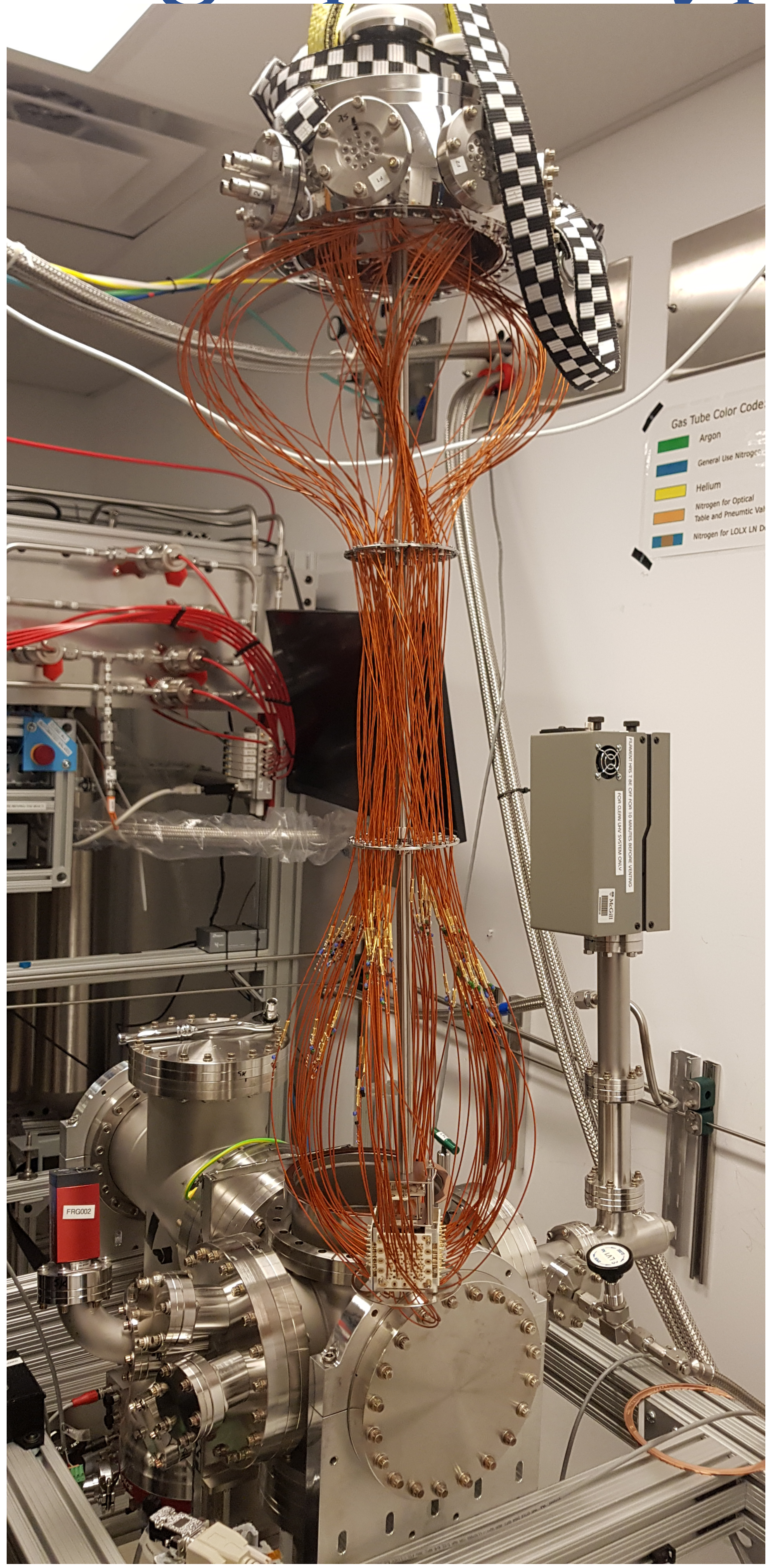
40 Hamamatsu VUV4

1 PMT R8520-406

All press-fit and crimp connectors, Kapton insulated coax cables, hydrocarbon ceramic PCB

shipped to McGill, assembled and **inserted in the cryostat in March**

Work by Khurshid, Colin, Stéphanie, Austin, Peter, Alex, Nicolas and others



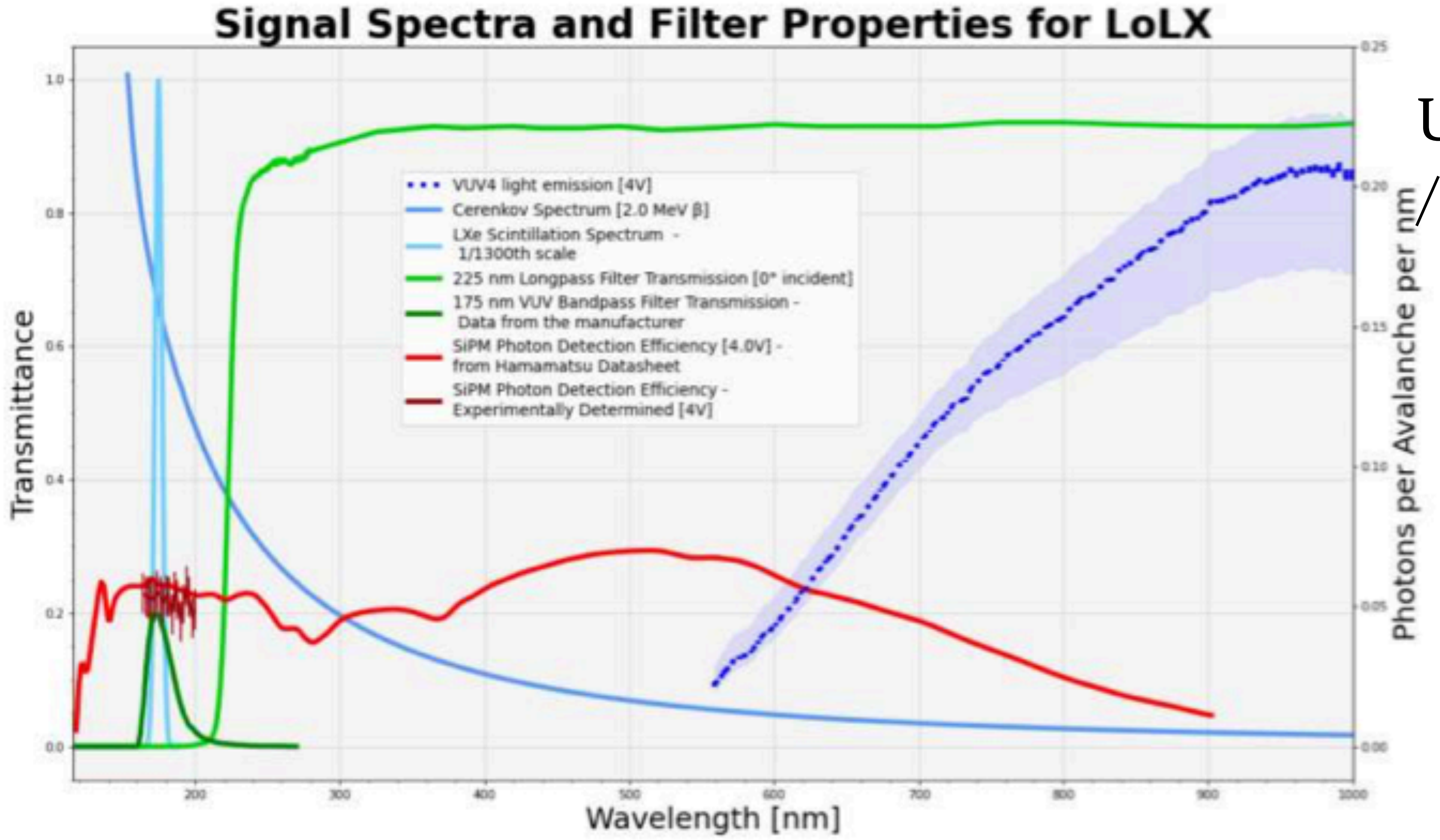
First run (2 days) with LXe mid August

- delayed by issues on compressor
- Successful run - analysis ongoing
- Several external gamma sources used (Ba133, Na22, Cs137)
- PicoQuant pulsed diode laser for calibration
- Likely problem of purity (presence of N2)

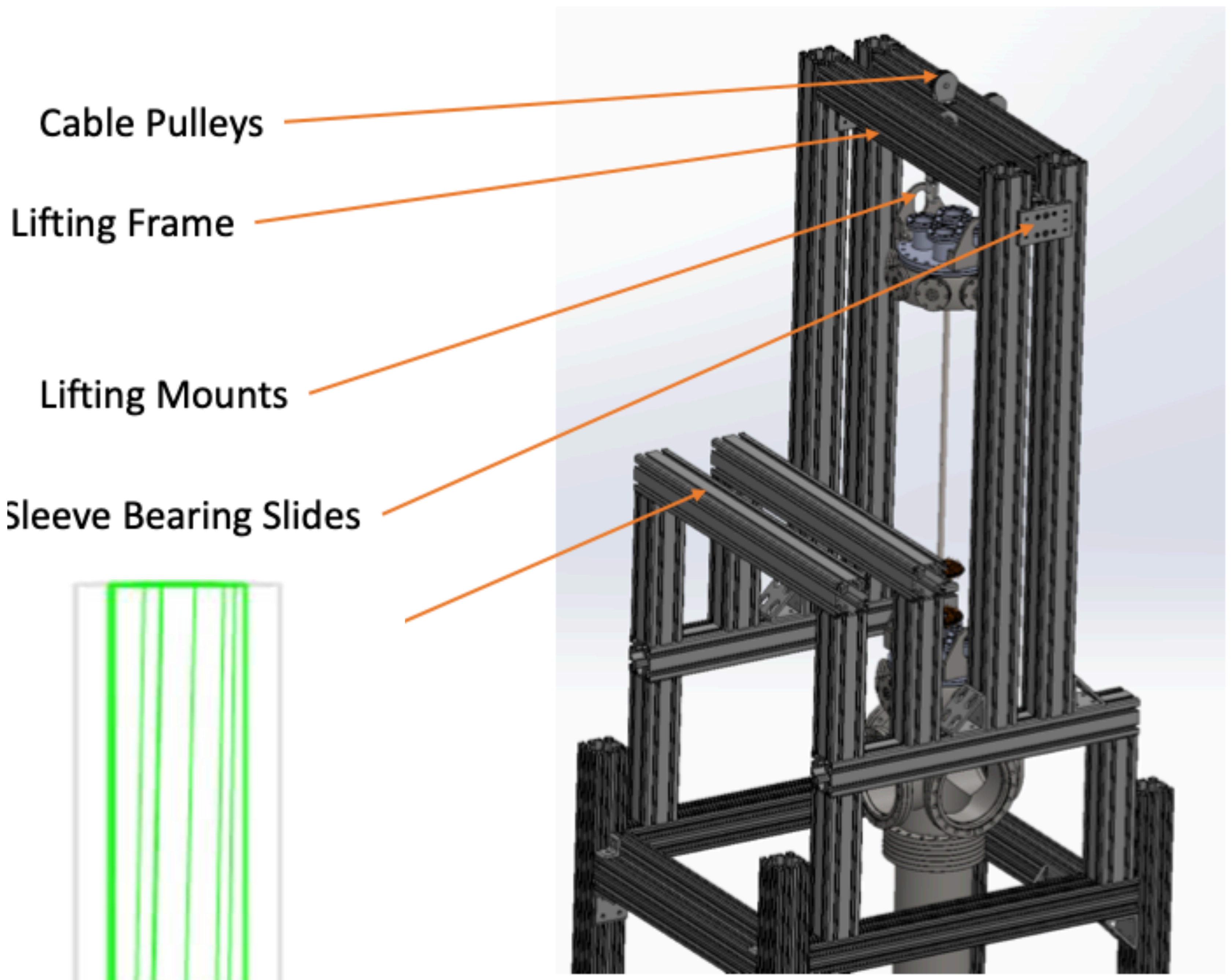
Need for R&D and large prototype

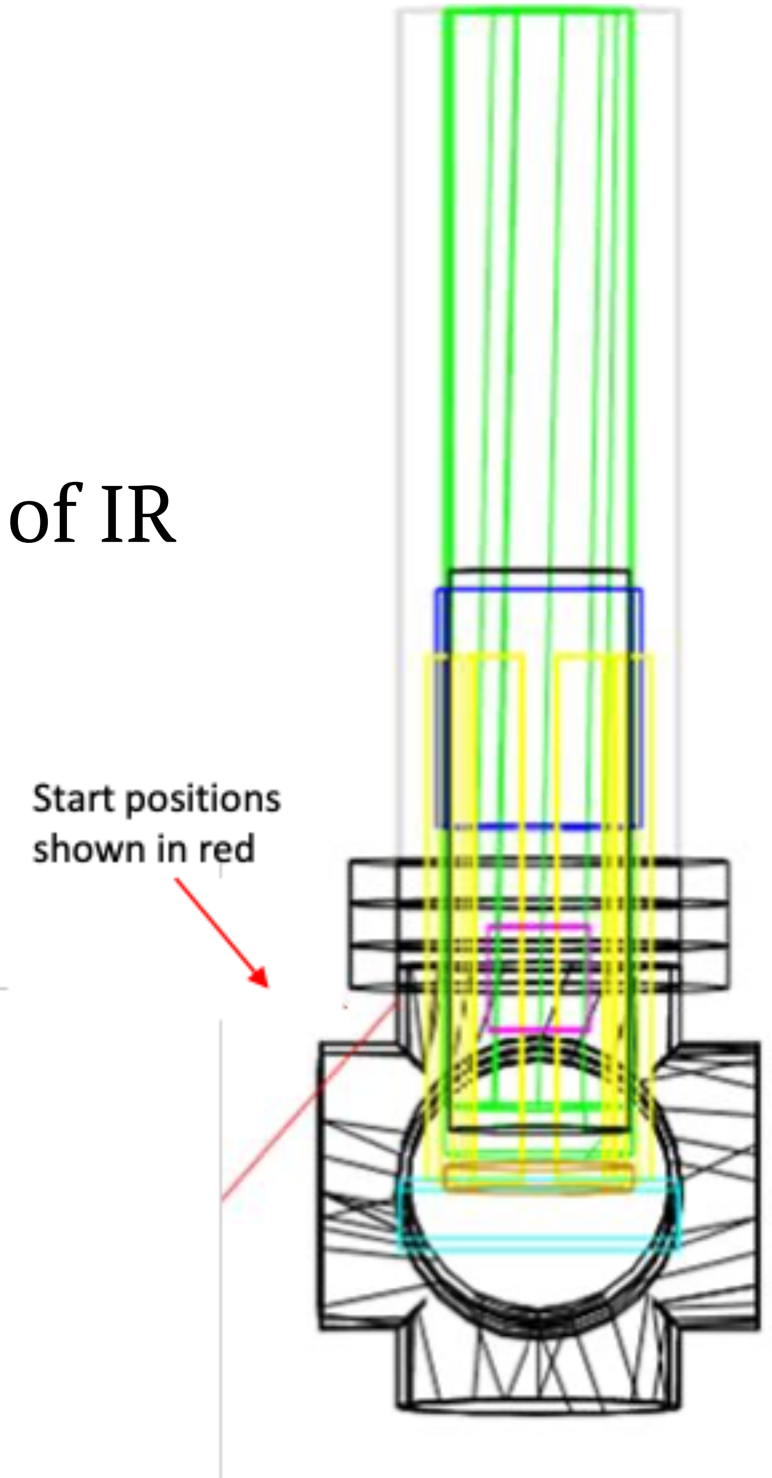
Until next run (likely in a couple of months) working on a number of improvements

- add internal source
- addition of UPS system and other operation-safety hardware
- addition of a gantry system for easier manipulation
- add optical filters
- **purity monitor (see next slide - prototype monitor for large LXe prototype)**
- recirculation pump for continuous purification
- some DAQ and electronics improvements



Using filters for detection of IR /Cerenkov light



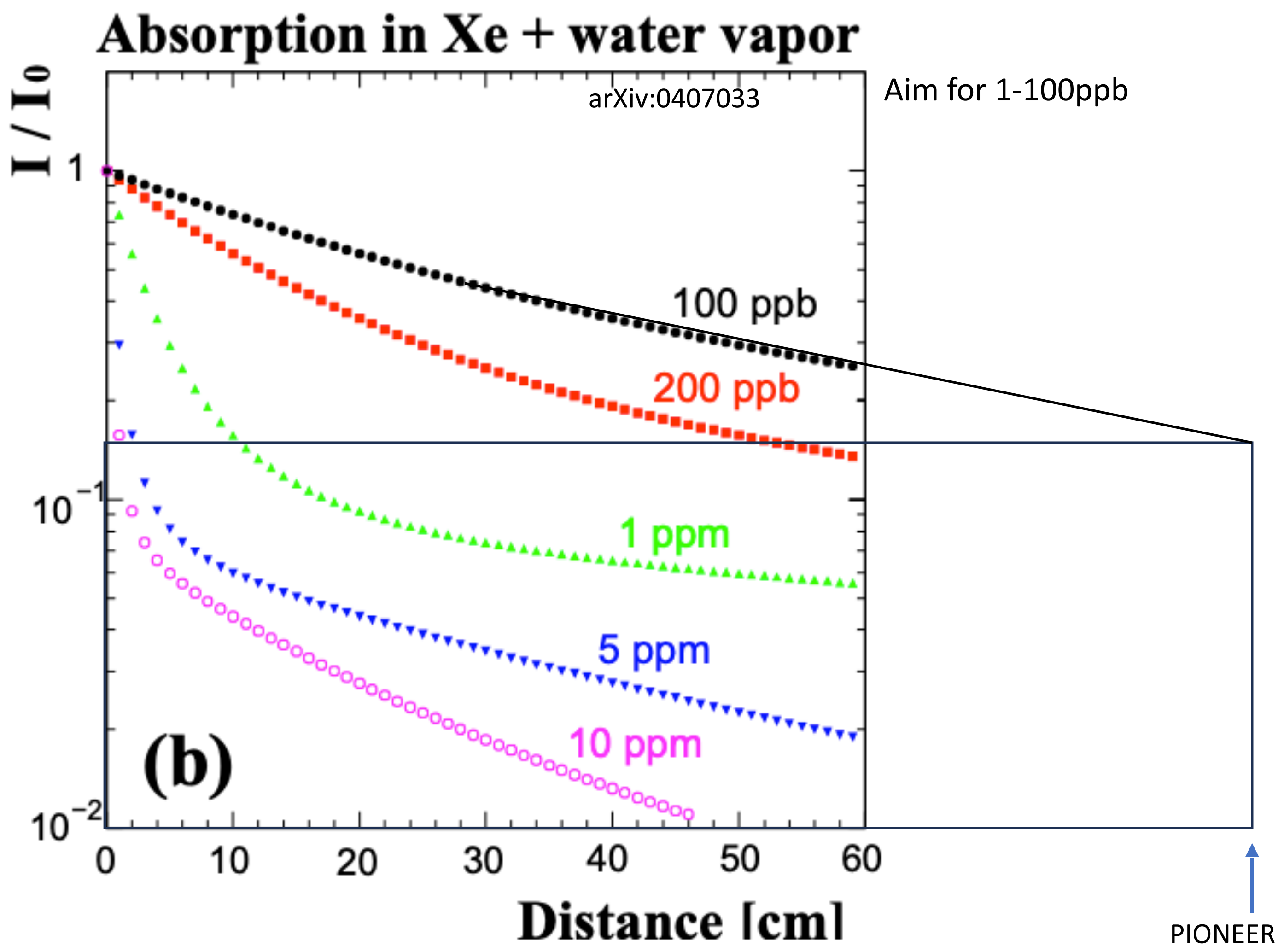


G4 simulations of energy deposit from external gamma source
Input to chroma for simulation of optical photons

Purity monitor for LoLX and large prototype

<u>Motivation</u>

- Impurities in LXe absorb VUV light and can degrade energy resolution
- electronegative impurities affect e- lifetime during drift in LXe
- e- lifetime is a sensitive measurement of impurities contamination in LXe
-



Work by Claire, Bob, Leonid, Irena, Nicolas and others

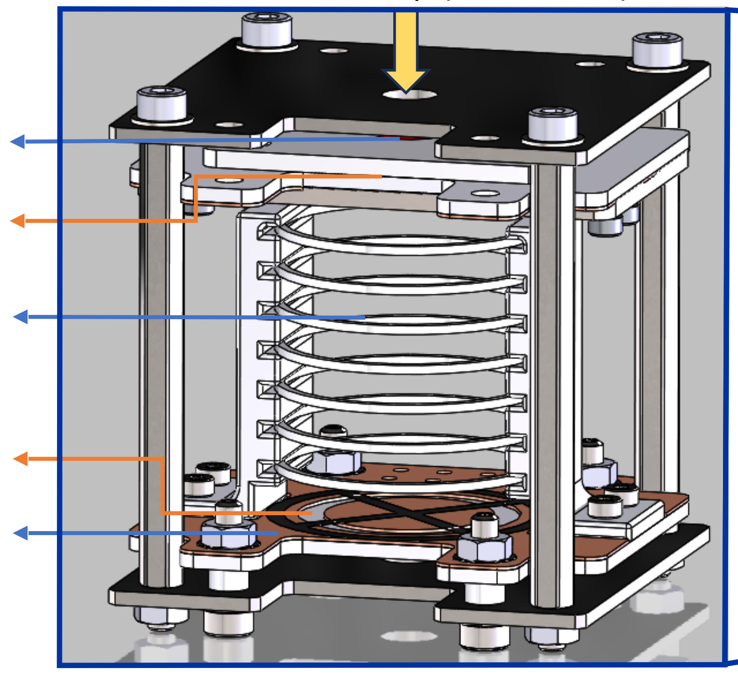
<u>Theory</u>

- Measure electron lifetime (τ) . Impurities will attenuate charge (Q) over the time of drift (t):

$$Q_{anode} = Q_{cathode} e^{-t/\tau}$$

- Relate τ to rate attachment constants (k) and concentration of impurities (n): $\tau = \frac{1}{\sum_i k_i n_i}$

Xe Flashlamp (or UV laser)

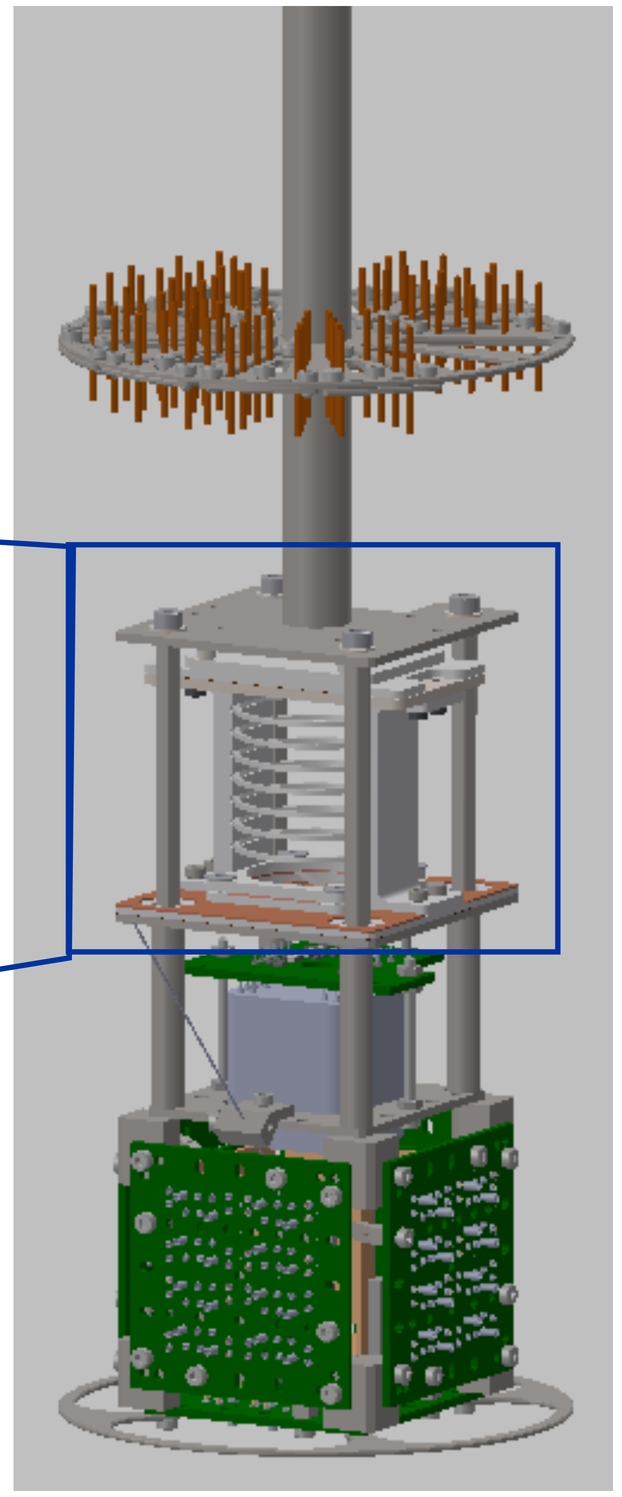


Electrons generated at cathode drift down to anode

<u>Basic Design Information:</u>
5cm drift length
1cm electrode
400V/mm drift field
~50us electron lifetime

*Grid may not be used in final design

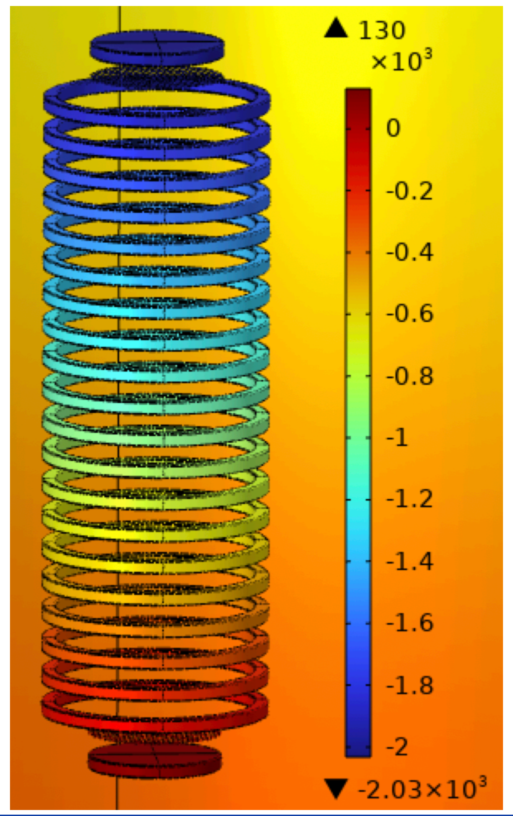
View in LoLX



<u>Simulations:</u>

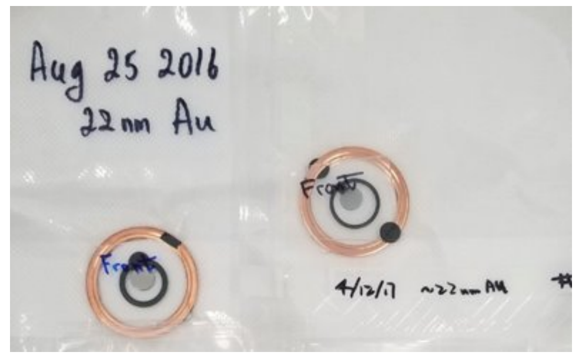
- COMSOL to optimize ring spacing to find most homogenous electric field in drift region
- Import COMSOL geometry into Garfield++ to measure grid transparency
- Grid transparency: ratio of the number of electrons at the anode to the number of electrons generated in cathode

Electric potential [V] of purity monitor in COMSOL

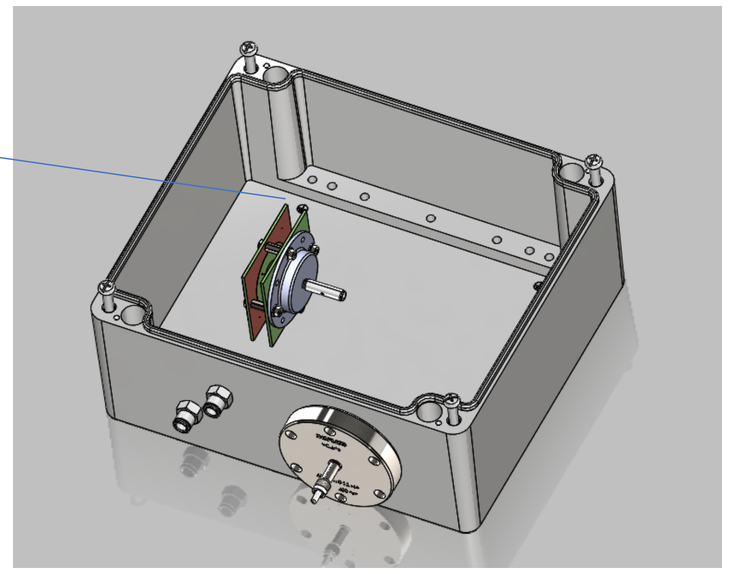


<u>Test Box: Next Steps</u>

- Determine how many electrons are produced by the flashlamp to decide whether to use grids in the purity monitor



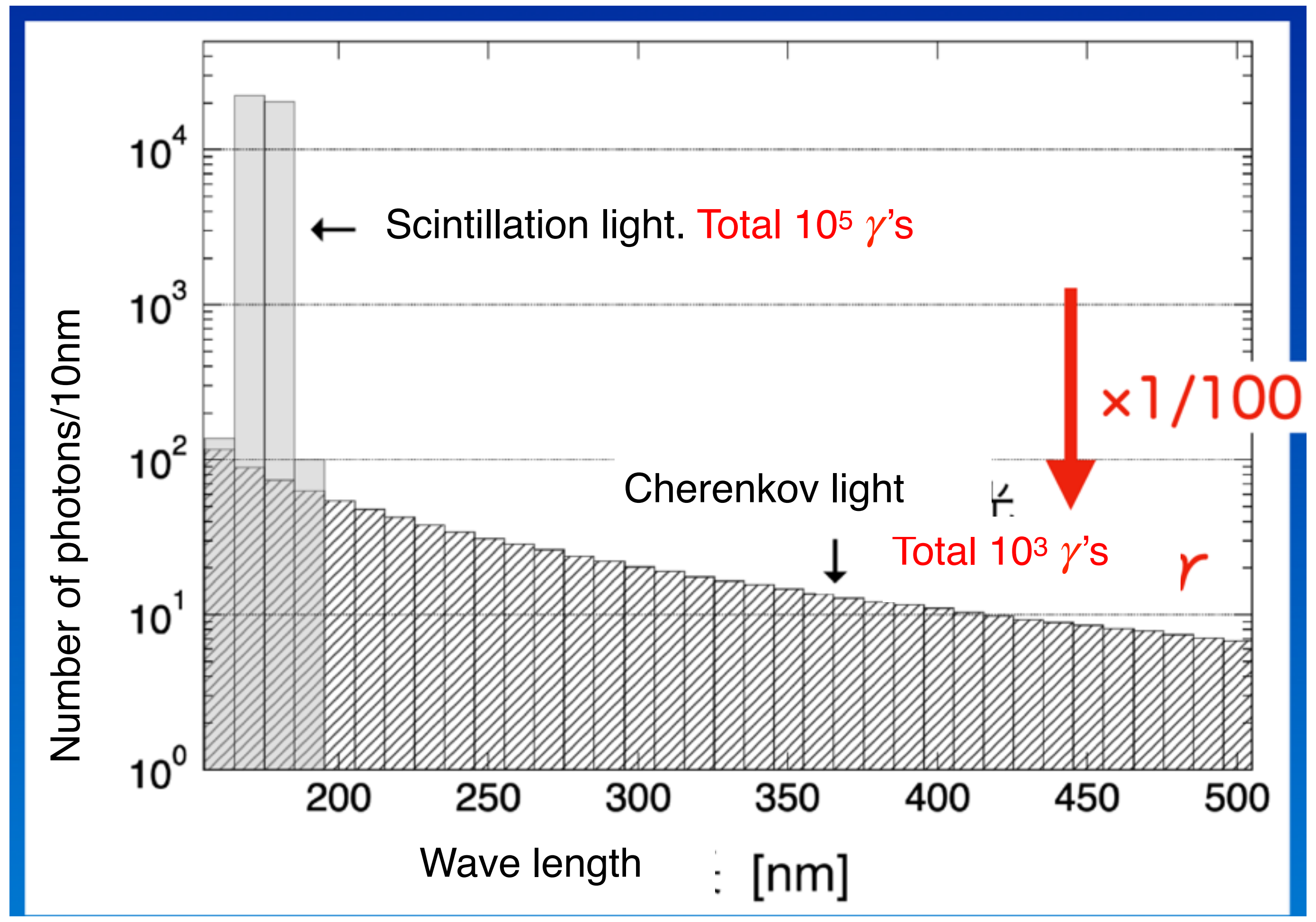
Photocathodes sent by BNL



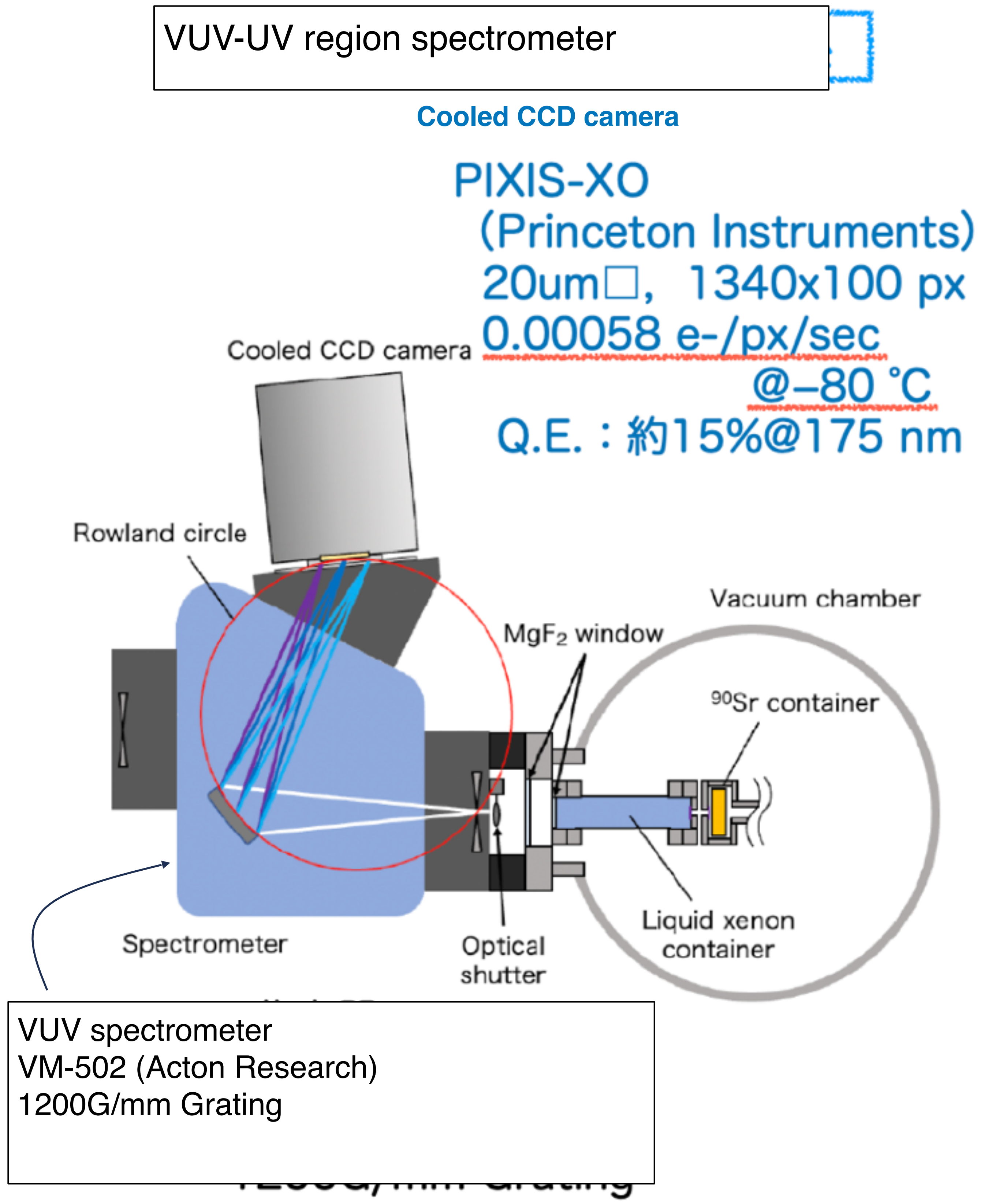
Other LXe related R&D setup by other groups

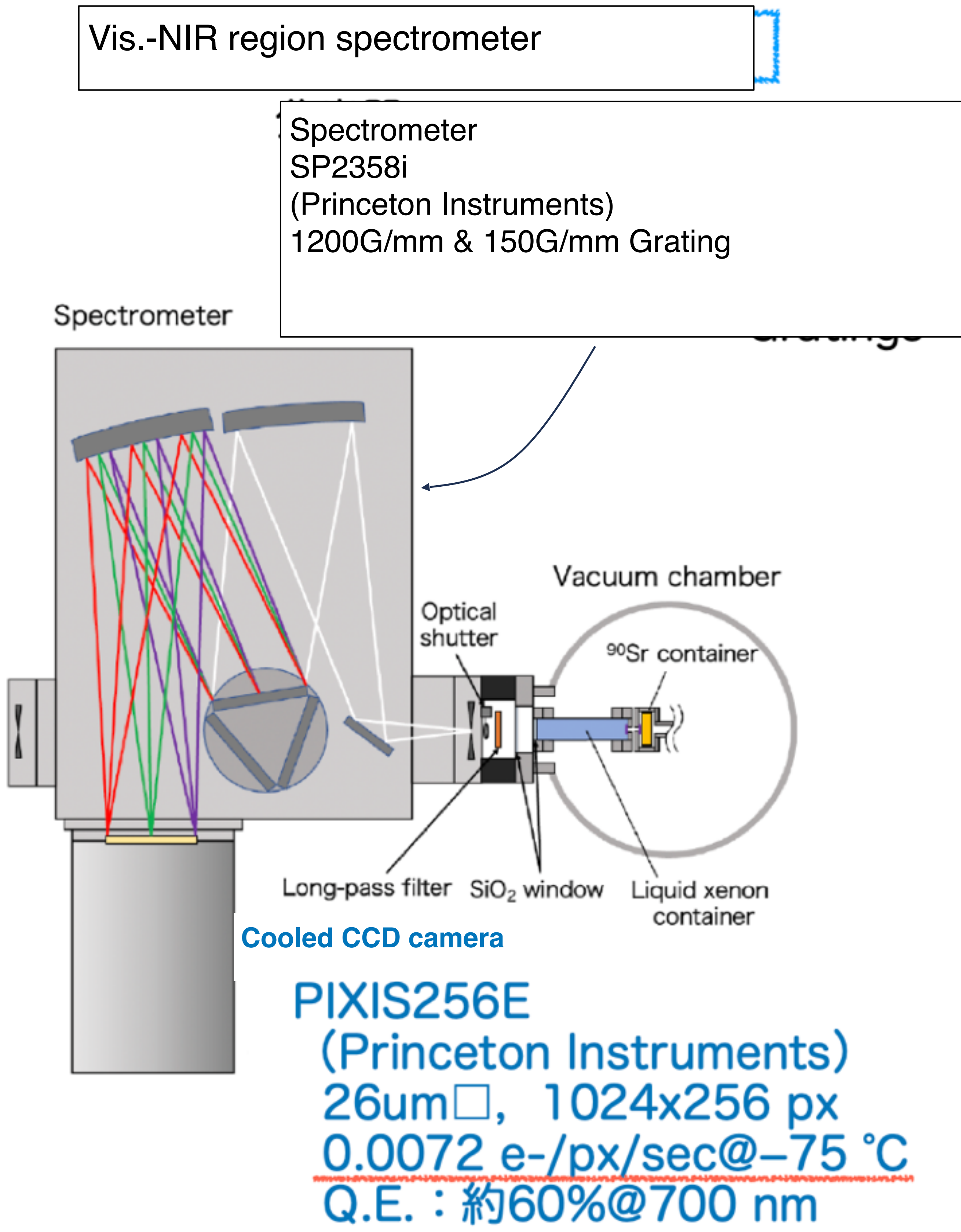
Slide by Satoshi

- Cherenkov light spectroscopy by the Yokohama National Univ. group (SM is in the collaboration)
- Measurement is in preparation. 1st test in 2023.



Simulation
$^{90}Sr/^{90}Y$ source
2.28MeV electron
1% of scintillation light yield





S. Nakamura in JPS meeting Sep. 2023

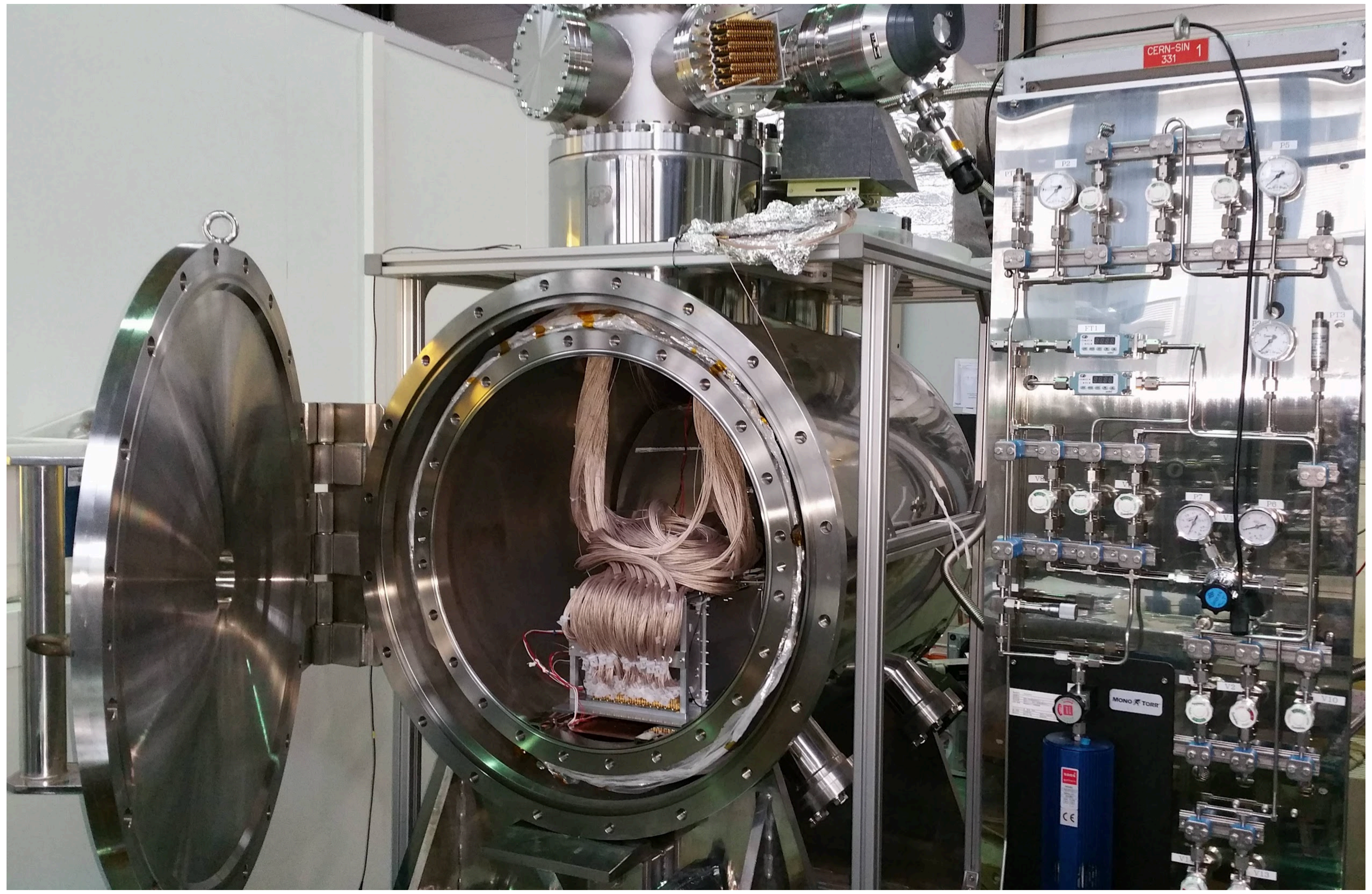
Need for R&D and large prototype

PIONEER needs a technology choice for the calorimeter - Given open questions listed before cannot rely entirely on MC without data validation
The MEG prototype is a good-sized prototype. Minimal additional design work - gas handling already existing
Axial length of the cryostat is up to 28 X_0 = baseline radius for the PIONEER LXe "ball" is 25 X0 (slice of the full detector)
Resolution and tail is limited by radius

Objectives

- Benchmark/Validate simulations to allow us to scale to PIONEER full calorimeter

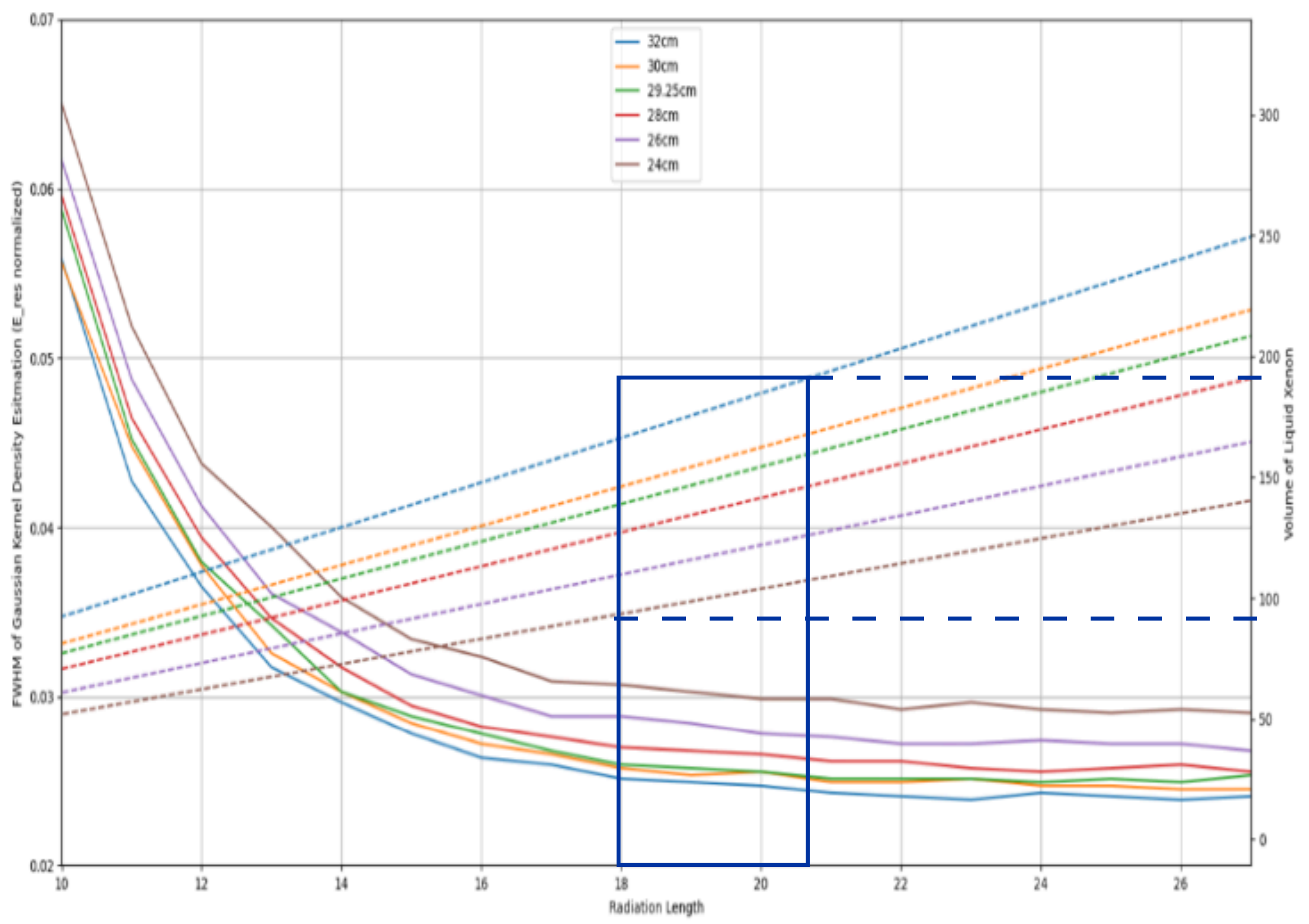
Using a high momentum resolution 70 MeV e^+ beam et PSI:
- **Measure energy resolution at our energies, with e+**
- Measure detector lineshape including contribution of photonuclear reactions
- Study shower leakages (resolution versus angle)
- Test of entrance window
- Technological upgrades test (cabling, choice of material for PMT PCBs, purity monitor)
- Training of the collaboration on LXe handling
- R&D : effect of optical coating on energy resolution, optical segmentation, Cerenkov, test of new generation photosensors
- PHYSICS! (see Doug's slides at the end)

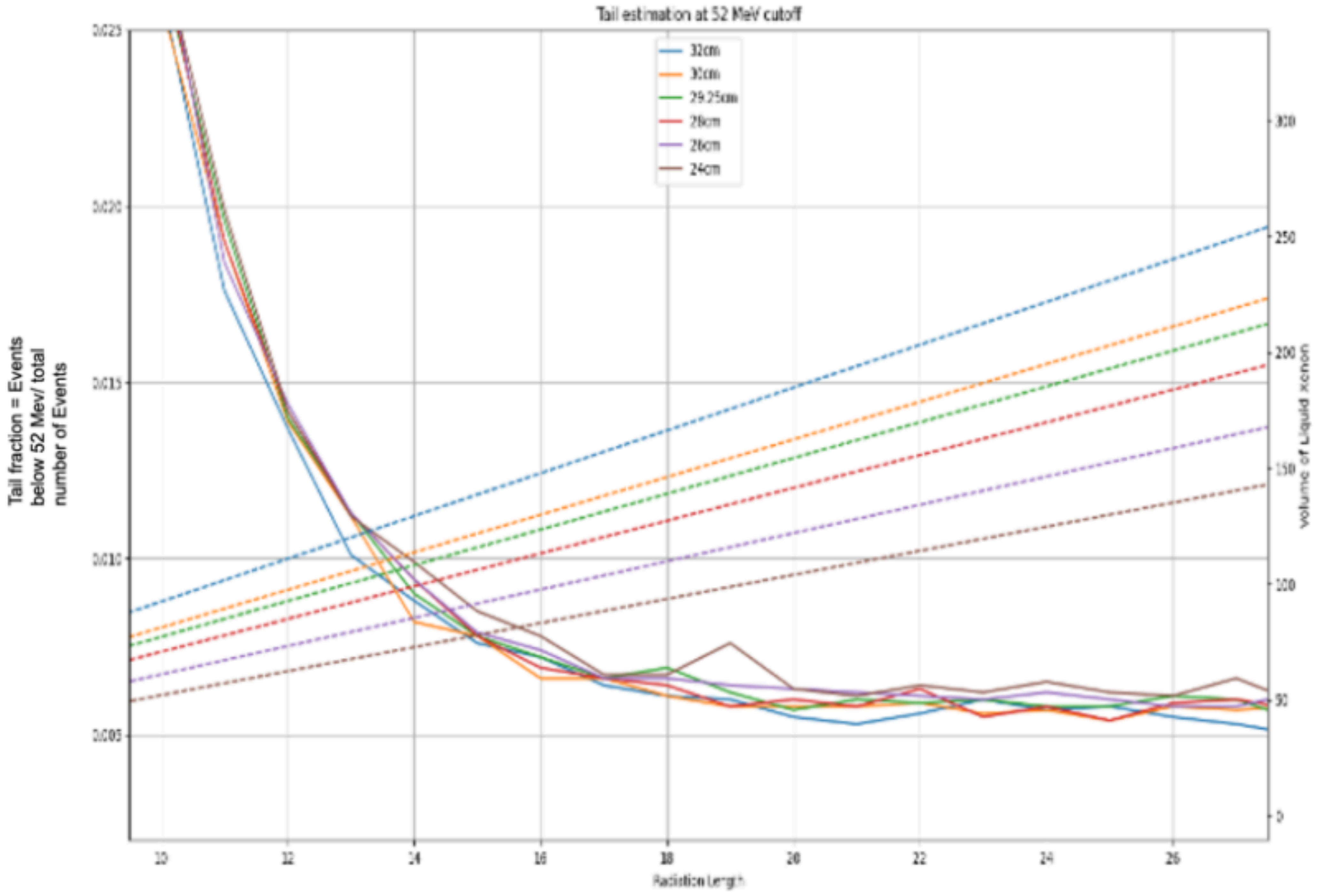


Simulations for prototype

- Energy deposit studies : limited by radius of cryostat but good performance with 100- 120 L

Work by Colin, Kolja





- Optical studies to determine optimal photosensor and calibration sources placement, evaluate expected energy resolution

Work by Emma

PMT for prototype

~142 VUV PMTs were sent from PSI to TRIUMF (Thanks to MEG)
Arrived mid-September

Mostly those (→ 2nd generation R9288TB)

1st generation R6041Q	2nd generation R9288TB	3rd generation R9869
		
228 in the LP (2003 CEX and TERAS) 127 in the LP (2004 CEX)	111 In the LP (2004 CEX)	Used in the final detector
Rb-Sc-Sb Mn layer to keep surface resistance at low temp.	K-Sc-Sb Al strip to fit with the dynode pattern to keep surface resistance at low temp.	K-Sc-Sb Al strip density is doubled. 4% loss of the effective area.
1st compact version QE~4-6% Under high rate background, PMT output reduced by 10-20% with a time constant of order of 10min.	Higher QE ~12-14% Good performance in high rate BG Still slight reduction of output in very high BG	Higher QE~12-14% Much better performance in very high BG

Inner assembly design

<u>Next steps</u>

✓Inventory (different types, some PMTs are potted)

- Test individual PMTs with flash lamp : about to start - test box prepared

- Design new base (use ceramic instead of G10), crimp wherever possible, connector directly on base

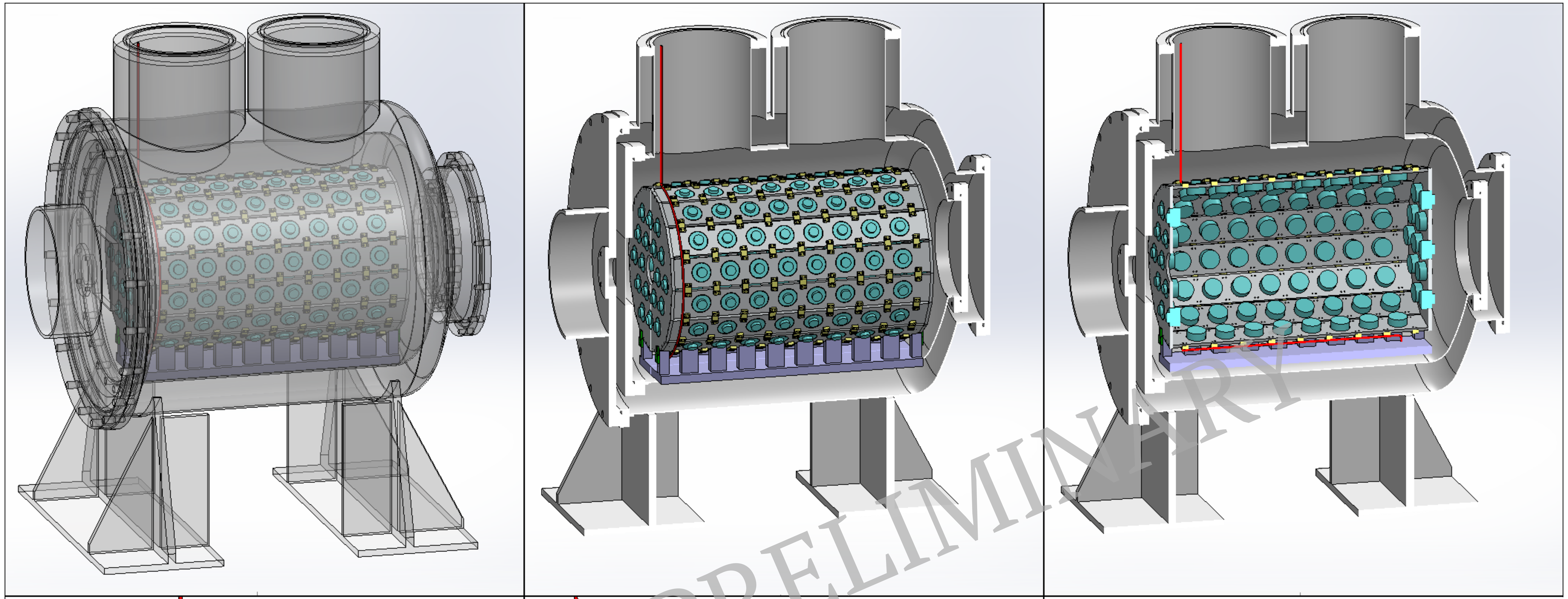
- Use kapton cables (~300 m of cables!)

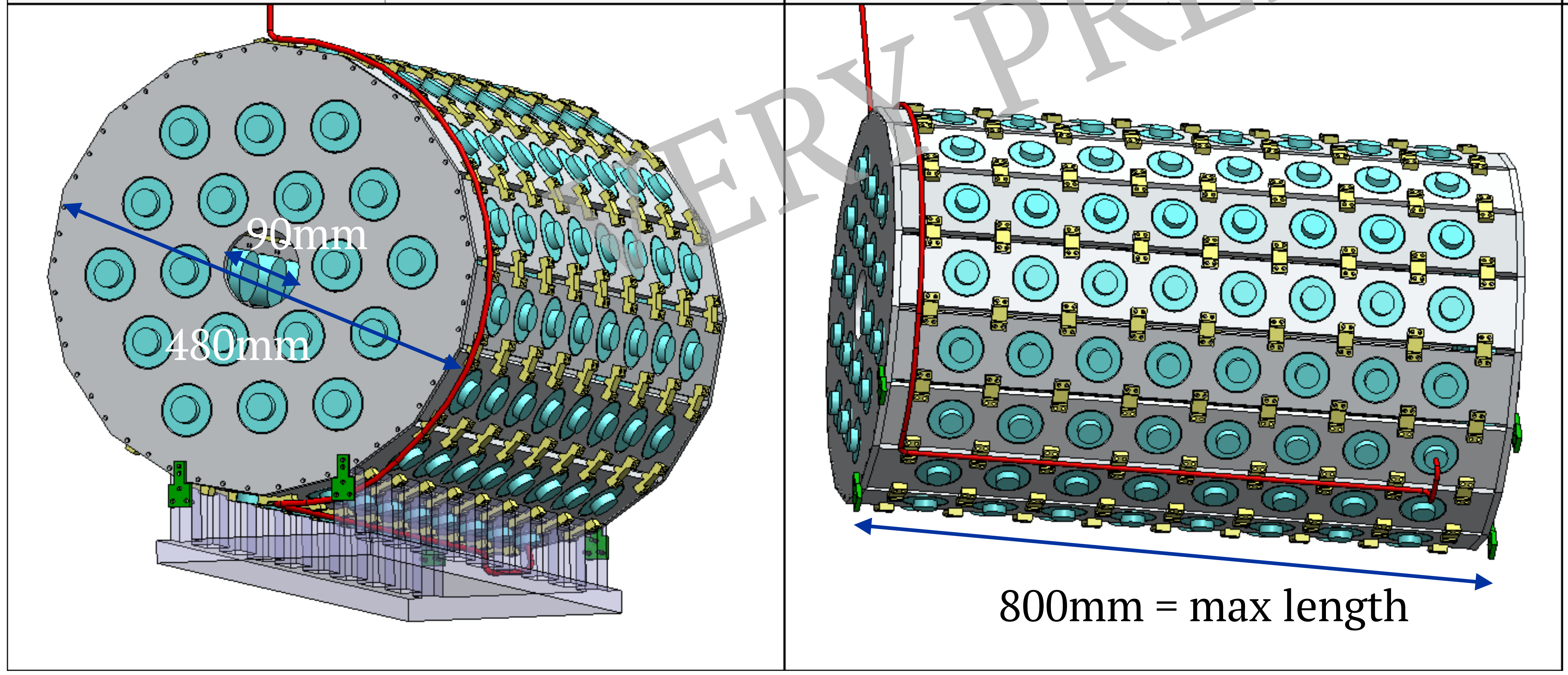
- Get HV and signal feedthrough

✓>140 HV channels (Lecroy power supply tested - working on the MIDAS frontend)

- cable routing

- work out connection to DAQ (DAQ planned to be shipped in the next weeks)





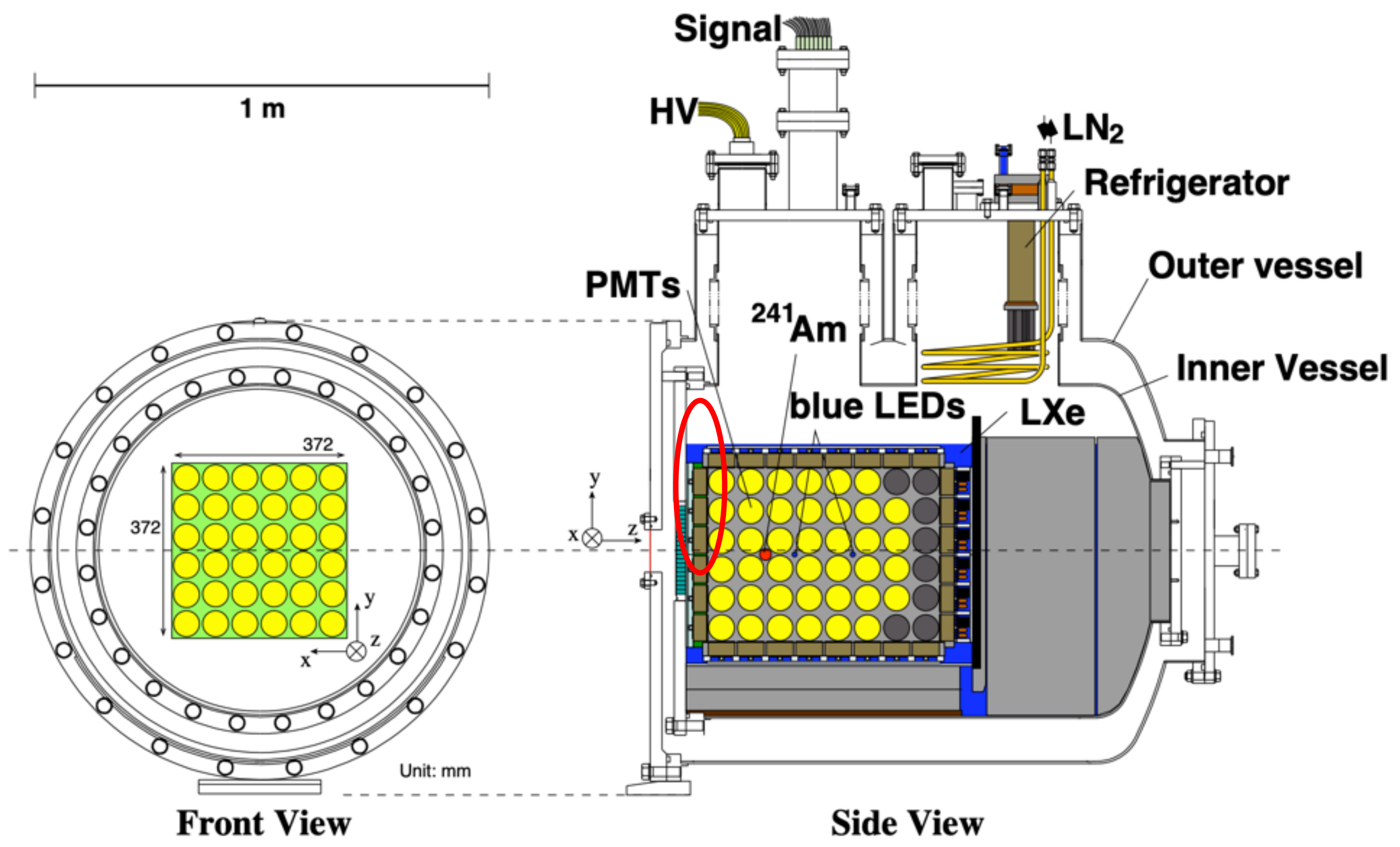
in this design: 165 2” PMTs

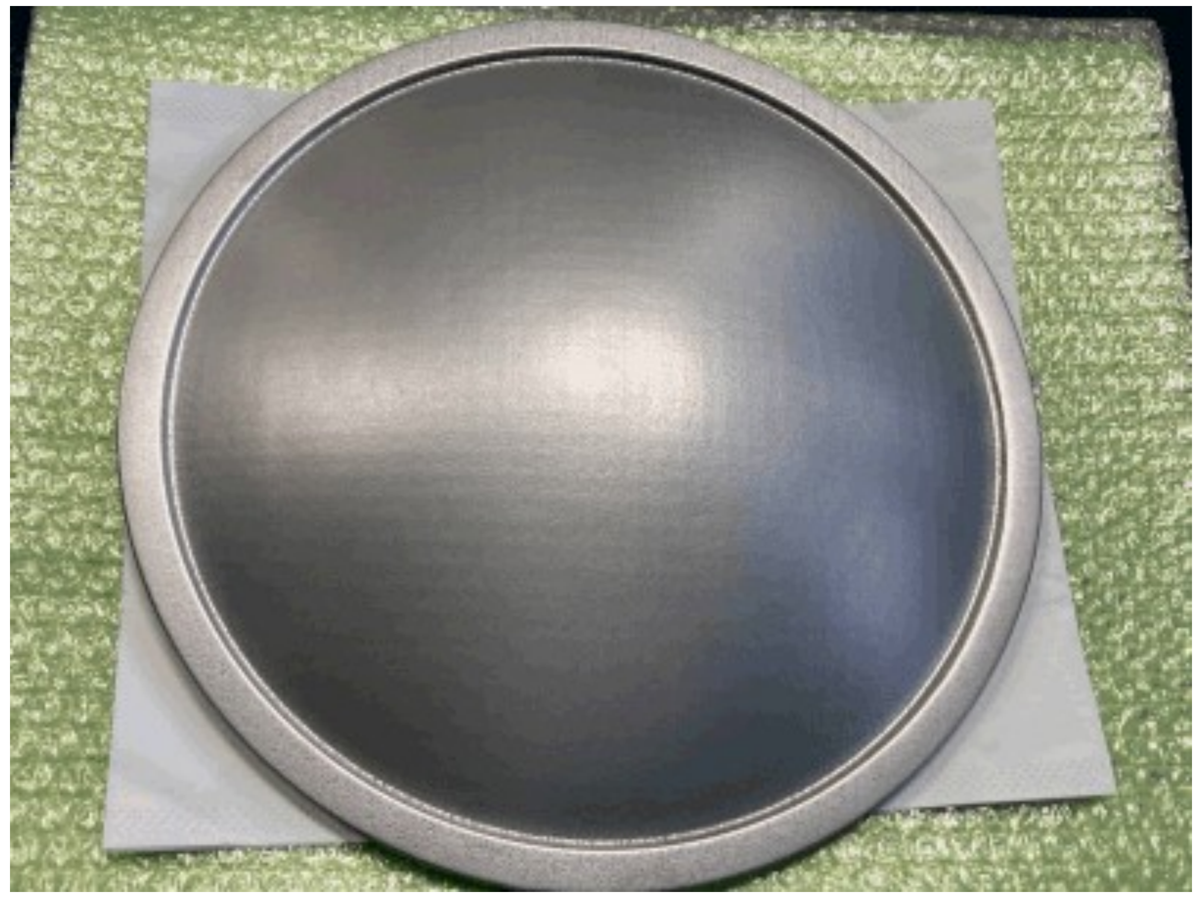
MISSING: LED and radioactive sources distributed on the surface

Entrance window R&D for prototype

Slide by Satoshi

- Metal honeycomb panel used in MEG R&D
  - Steel
- Recent KEK R&D for beam vacuum window
  - Ti-6AL-4V 3d-printed window
    - 6wt% Al (X_0=8.9cm) and 4wt% Vanadium (X_0=2.6 cm) is added to Ti (X_0=3.6cm)
    - 4.43 g/cm^3
    - 0.2mm, grinded down from ~0.5mm, OK for 3 bar. Technically not feasible to grind down more.
  - Al 3d-printed window is also possible, grinded down to 0.2mm
  - **[New!] Rupture disk Al 0.15mm is strong enough for 3 bar pressure difference!**
    - Need R&D to fix the window on the cover
    - Indium sealing should work





0.5mm 64Ti window

0.15mm Al Rapture disk

PIONEER overall timeline *(assuming approval stages and external funding decisions are positive and proceed expeditiously)*

Timeline (agressive!)

decision should be made on beamtime request (contingent on LXe procurement)

earliest possible beamtime

Proposal sent out 21st July 2023

TASKS & RESPONSIBILITIES - LXe PROTOTYPE

INSTALLATION AT PSI

PSI liaison	Anna
Beamline setup	?Anna
Experimental platform at PSI	Anna/Peter

CRYOSTAT MECHANICS

Simulations	Chloé / Anna
New windows design	Satoshi (KEK)
Cryostat inner modifications	Toshiyuki / Anna?
Inner assembly structure construction	Chloé (TRIUMF)

READOUT

PMT shipment	Toshiyuki
PMT & HV testing	Chloé (TRIUMF)
Electronics & cabling	Chloé (TRIUMF)
DAQ	Lawrence / Tim (Chloé)
Beam instrumentation	Jaydeep
Trigger	Lawrence/Jaydeep/Chloé

LXe & CRYOGENICS

LXe procurement and transport	all (Xin, Aleksey, Satoshi, Doug, Chloé)
LXe storage	Julien from Subatech/ others?
LXe gas handling & recovery system	Julien (SUBATECH)/ Toshiyuki/Anna coordination with PSI safety
Cryogenics and purification system	Toshiyuki/Satoshi?
Calibration (LED/alpha/cosmic-ray counter)	Sei/Toshiyuki/others (other calibrations)
Purity monitor & light attenuation monitor	Chloé/Doug/Bob (TRIUMF)

<u>At TRIUMF</u>

- Finalize simulations
- Test of ~140 PMTs (purchase new ones?)
- Design and production of new PMT base
- Design and construction of inner mechanical structure holding the PMTs and light sources
- gain matching with light sources
- Cabling and connections to DAQ
- Test overall assembly with DAQ
- production and test of purity monitor
- shipment

——> 6-8 MONTHS

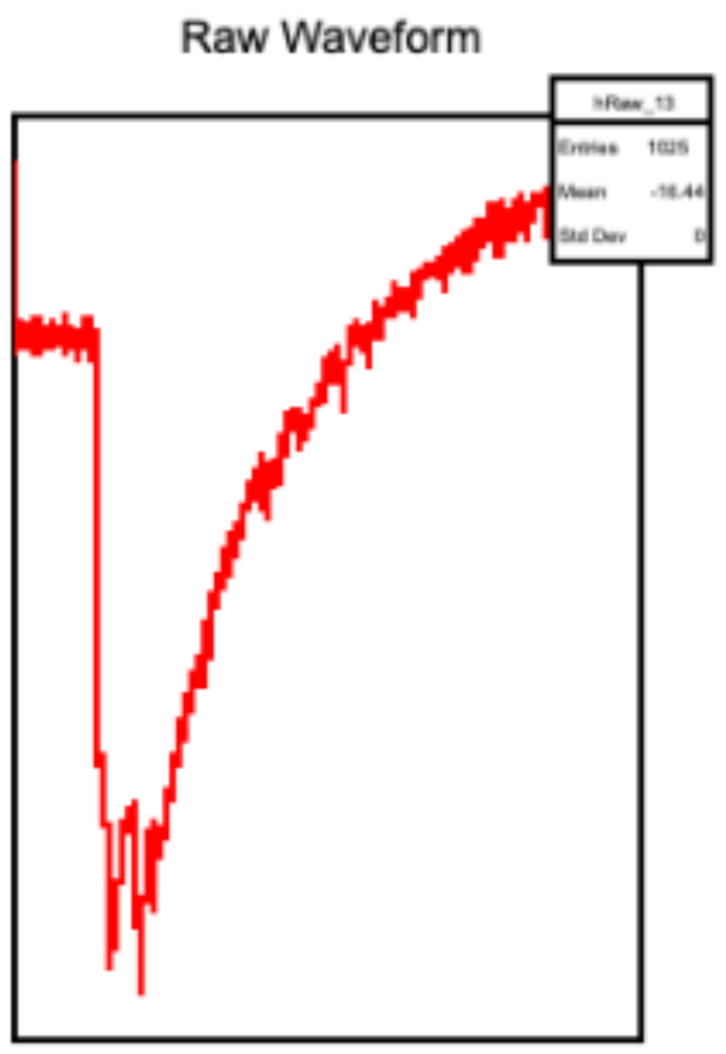
<u>At PSI/KEK</u>

- Production of window + new flange
- Find/Procure storage vessel & N2 double wall cylinder (CERN?)
- Beam instrumentation
- Find/Procure Cryocooler
- Procure purification system (new cartridge, include liquid purification?)
- radioactive source calibration. Other calibration?
- Modify inner of cryostat
- Procure pumps (vacuum and recirculation)

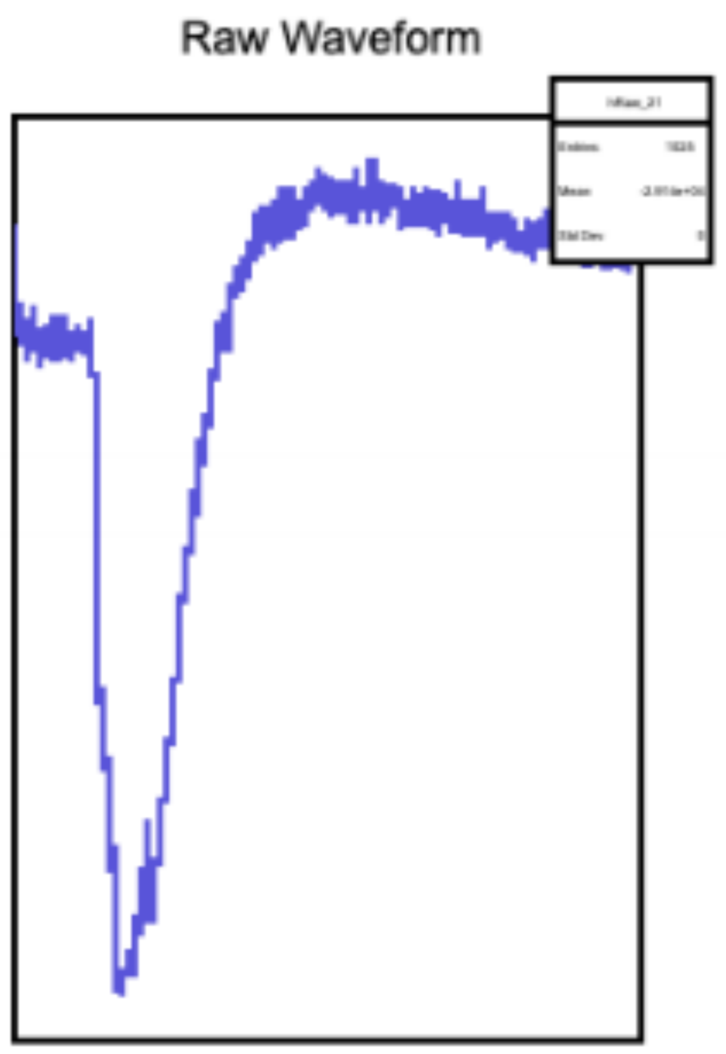
——> 4-6 MONTHS

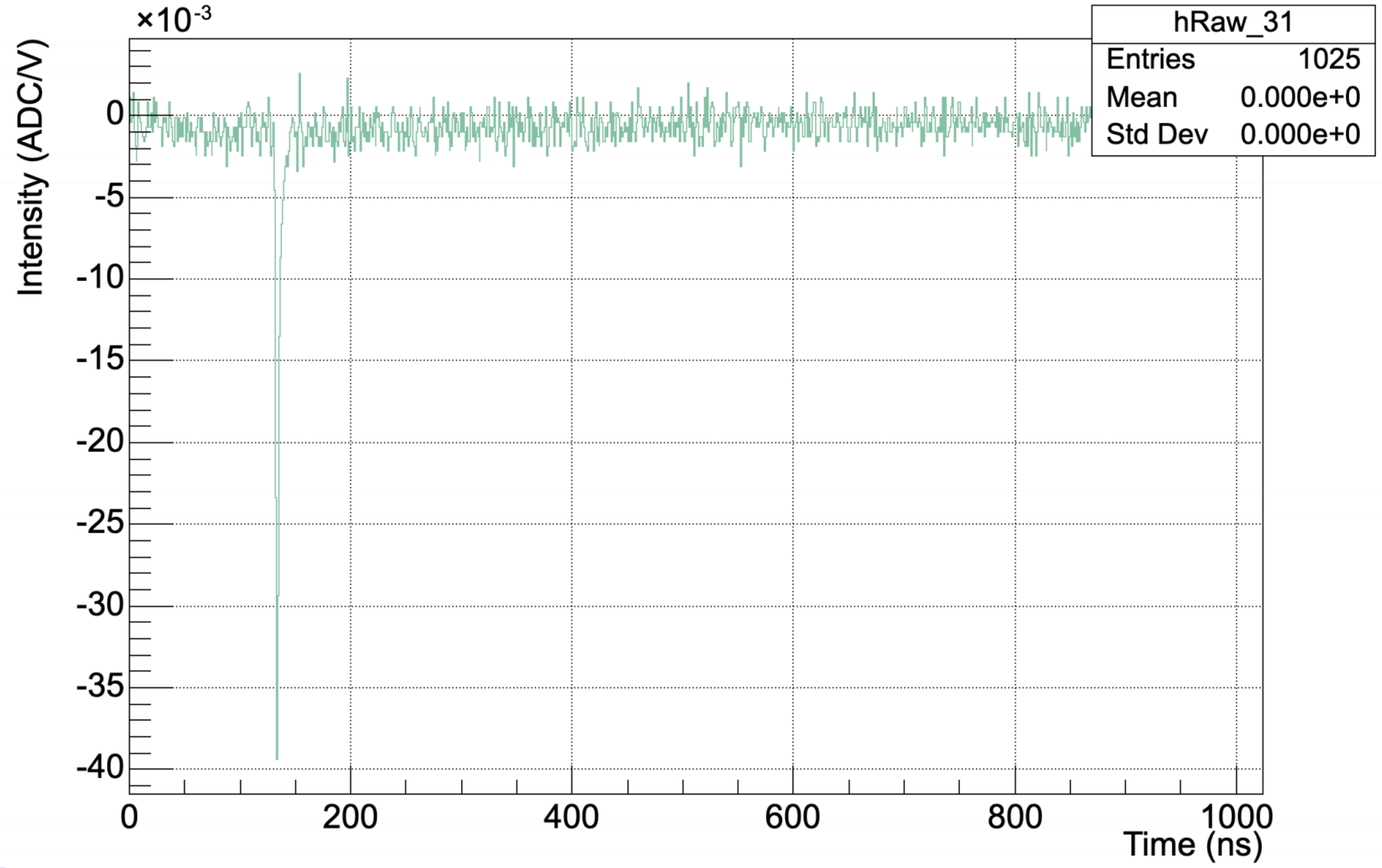
BACKUP - LOLX

FBK

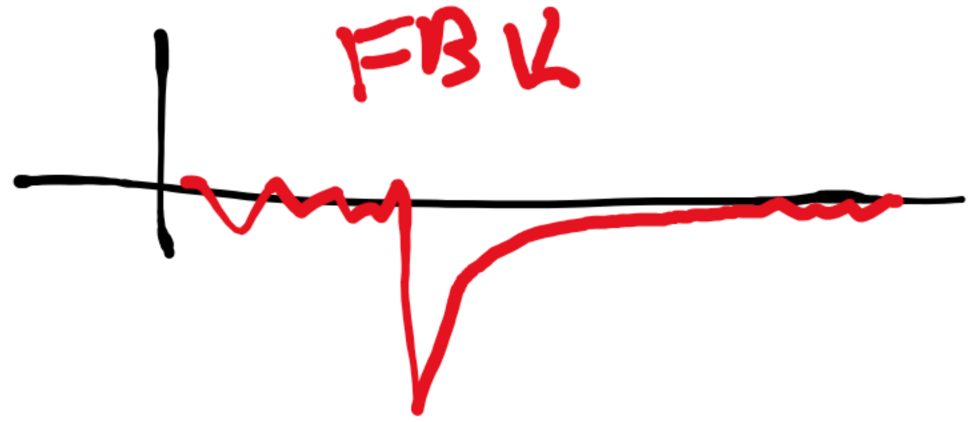


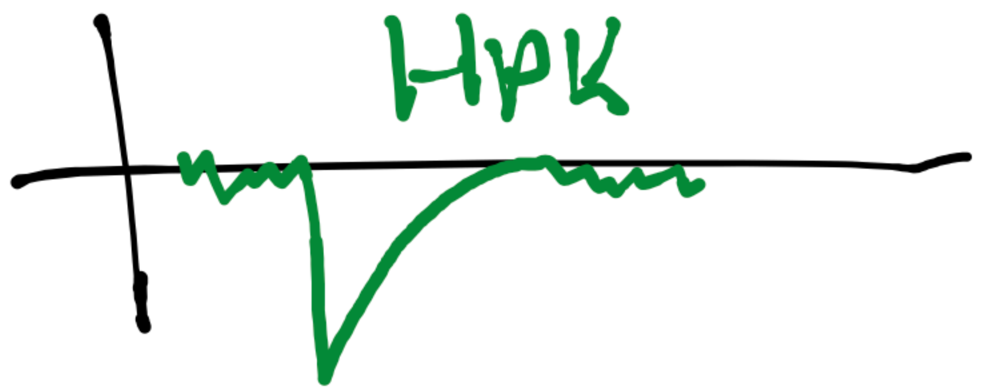
HPK





PMT





BACKUP - LOLX

Sources

Source	Photoabsorption Peak	SiPM Integrated Charge [V*ns]
Ba133	356 keV	1000
Na22	511 keV (+1275 keV?)	1700 + (3100?)
Cs137	662 keV	2000

PRELIMINARY

Ba133

γ without initial level have not been placed in the level schema
γ without intensity are expected but not observed

Gamma CSV Data API

#	E_γ [keV]	I_γ(abs) [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	53.1622 *6*	2.14 *3*	437.0113 *9*	1/2+	383.8491	3/2+	M1+E2	0.08 *3*	5.66 *10*		
2	79.6142 *12*	2.65 *5*	160.6121 *9*	5/2+	80.9979	5/2+	M1+E2(+E0)	0.124 *15*	1.77 *3*		
3	80.9979 *11*	32.9 *3*	80.9979 *8*	5/2+	0.0	7/2+	M1+E2	0.158 *5*	1.703		
4	160.6120 *16*	0.638 *5*	160.6121 *9*	5/2+	0.0	7/2+	M1+E2	0.96 *5*	0.294 *6*		
5	223.2368 *13*	0.453 *3*	383.8491 *8*	3/2+	160.6121	5/2+	M1+E2	-0.114 *14*	0.0975		
6	276.3989 *12*	7.16 *5*	437.0113 *9*	1/2+	160.6121	5/2+	E2		0.0566		
7	302.8508 *5*	18.34 *13*	383.8491 *8*	3/2+	80.9979	5/2+	M1+E2	0.022 *20*	0.0434		
8	356.0129 *7*	**62.05 *19***	437.0113 *9*	1/2+	80.9979	5/2+	E2		0.0254		
9	383.8485 *12*	8.94 *6*	383.8491 *8*	3/2+	0.0	7/2+	E2		0.0202		

Na22

Electron Capture and Beta+ CSV Data API

#	<$E_{\beta+}$> [keV]	$I_{\beta+}$(abs) [%]	E_{EC} [keV]	I_{EC}(abs) [%]	Daughter level [keV]	J^π	Log*ft*	Transition type	Comments
1	216.01 *8*	**89.90 *9***	(1568.63)	10.04 *9*	1274.53 *7*	2+	7.41	allowed	
2	835.46	0.055 *14*	(2843.13)	0.0010 *3*	0	0+	14.92 *11*	2nd unique	

Warning
γ without initial level have not been placed in the level schema
γ without intensity are expected but not observed

Gamma CSV Data API

#	E_γ [keV]	I_γ(abs) [%]	I_γ(abs) β^+ [%] ⚠	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	1274.537 *7*	99.940 *14*	89.90 *19*	1274.53 *7*	2+	0	0+	E2		2.8E-05 *3*		

Cs137

Warning
γ without initial level have not been placed in the level schema
γ without intensity are expected but not observed

Gamma CSV Data API

#	E_γ [keV]	I_γ(abs) [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	283.5 *1*	0.00058 *8*	283.50 *10*	1/2+	0.0	3/2+					
2	661.657 *3*	**85.1 *2***	661.659 *3*	11/2-	0.0	3/2+	M4		0.1124		

Main lines (Above 10% BR):

- 80 keV [Ba133]
- 302 keV [Ba133]
- 356 keV [Ba 133]
- 511 keV [Na22 e+ annihilation]
- 662 keV [Cs137]
- 1275 keV [Na22]
- 1275 keV + 511 keV [Na22 Pileup]

Use for 4-point light yield calibration to compare to simulations

Update on Physics Opportunities with the Calorimeter prototype: $\mu \to 5e$

Doug Bryman

October 13, 2023

New physics in multi-electron muon decays

Hostert et al. arXiv:2306.15631v1 [hep-ph] 27 Jun 2023

Matheus Hostert,[a,b,c] Tony Menzo,[d] Maxim Pospelov,[b,c] Jure Zupan,[d]

Muon decay to on-shell dark Higgs h_d

$$\mu^+ \to e^+ h_d ; h_d \to \gamma_d \gamma_d \to 2(e^+ e^-)$$

$$\mu^+ \to e^+ e^+ e^- e^+ e^-$$

$$\mathrm{Br}(\mu \to 5\mathrm{e}) \sim 10^{-12} \Longleftrightarrow \text{ Mass scale } \Lambda \sim 10^{15} GeV$$

$$\text{Current limit: } \mathrm{Br}(\mu \to 5\mathrm{e}) < 4\mathrm{x}10^{-6}$$

New Calculation of the intrinsic background: <10^{-12} to 10^{-11}

Integrated $B_{10}(\mu \to e\nu\nu\gamma)$ vs. E_{miss} for $E_\gamma < 10\,MeV$.

$$E_{miss} = m_\mu - E_e - E_\gamma$$

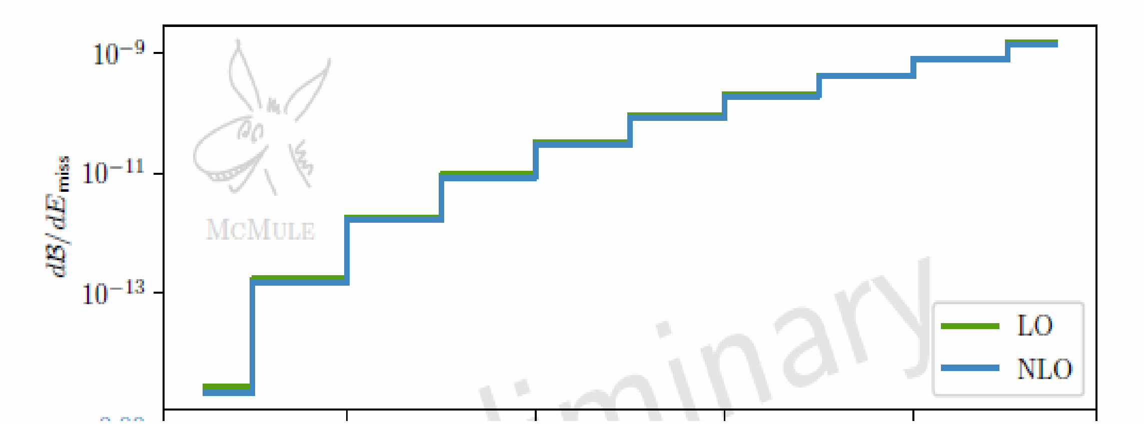


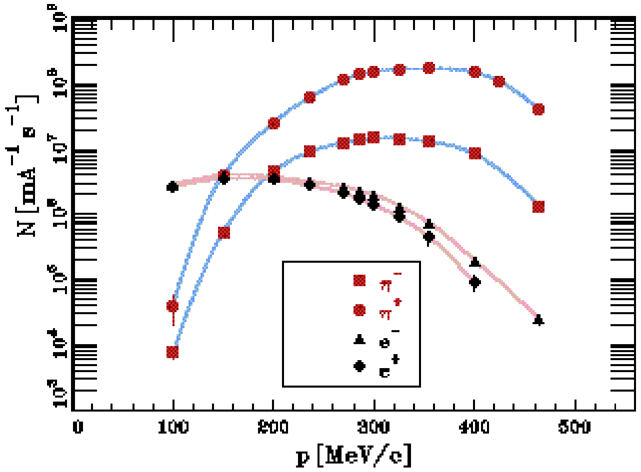
Figure 2: Differential branching ratio w.r.t. E_{miss} up to 10 MeV.

$\mathcal{B}_{10}^{incl}(E_{miss} < E_{max})$ integrated up to E_{max}

E_{max}	$\mathcal{B}_{10}^{incl}\|_{LO}$	$\mathcal{B}_{10}^{incl}\|_{NLO}$
1 MeV	$2.72(2) \cdot 10^{-15}$	$2.23(3) \cdot 10^{-15}$
2 MeV	$1.76(1) \cdot 10^{-13}$	$1.54(3) \cdot 10^{-13}$
3 MeV	$2.03(1) \cdot 10^{-12}$	$1.83(2) \cdot 10^{-12}$
4 MeV	$1.160 \cdot 10^{-11}$	$1.06(1) \cdot 10^{-11}$
5 MeV	$4.488 \cdot 10^{-11}$	$4.12(1) \cdot 10^{-11}$
6 MeV	$1.360 \cdot 10^{-10}$	$1.26(1) \cdot 10^{-10}$
7 MeV	$3.484 \cdot 10^{-10}$	$3.23(1) \cdot 10^{-10}$
8 MeV	$7.888 \cdot 10^{-10}$	$7.35(1) \cdot 10^{-10}$
9 MeV	$1.626 \cdot 10^{-9}$	$1.52(1) \cdot 10^{-9}$
10 MeV	$3.111 \cdot 10^{-9}$	$2.91(1) \cdot 10^{-9}$

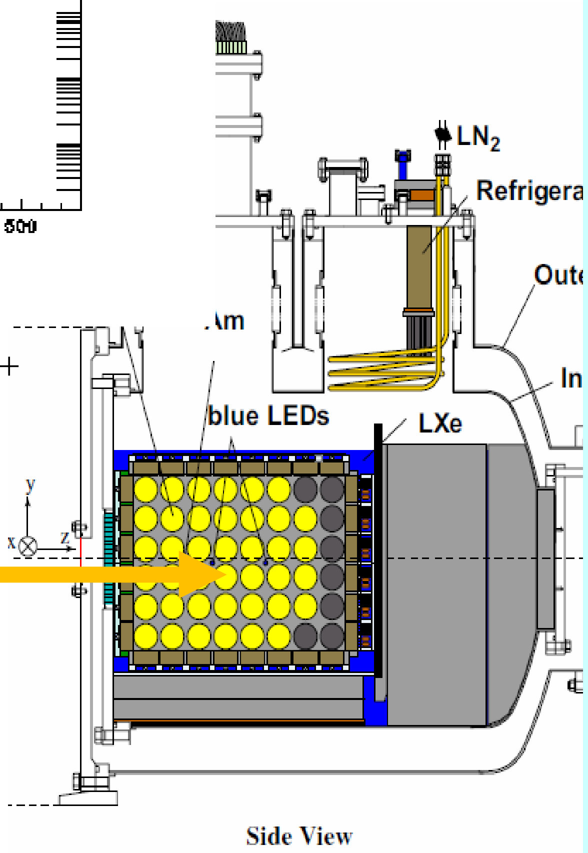
Experiment likely to be limited by random pile-up effects.

PIONEER Calo Prototypes for $\mu \to 5e$ (LXe or LYSO)



$\pi M1$: 300 MeV/c μ^+

$50 kHz$



Compared to the previous experiment: the PIONEER prototype can improve by $\sim O(10^4 - 10^6)x$ in a 10 day run

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Energy resolution 2%: 5x

Scint. Decay time : 5x

Timing resolution 100 ps : (50 x)

Pile-up recognition: 10x

Beam rate 50 kHz : 30 x

Run time 10 days: 10 x

Analysis improvement factor: 3 x

Efficiency factor: 2x