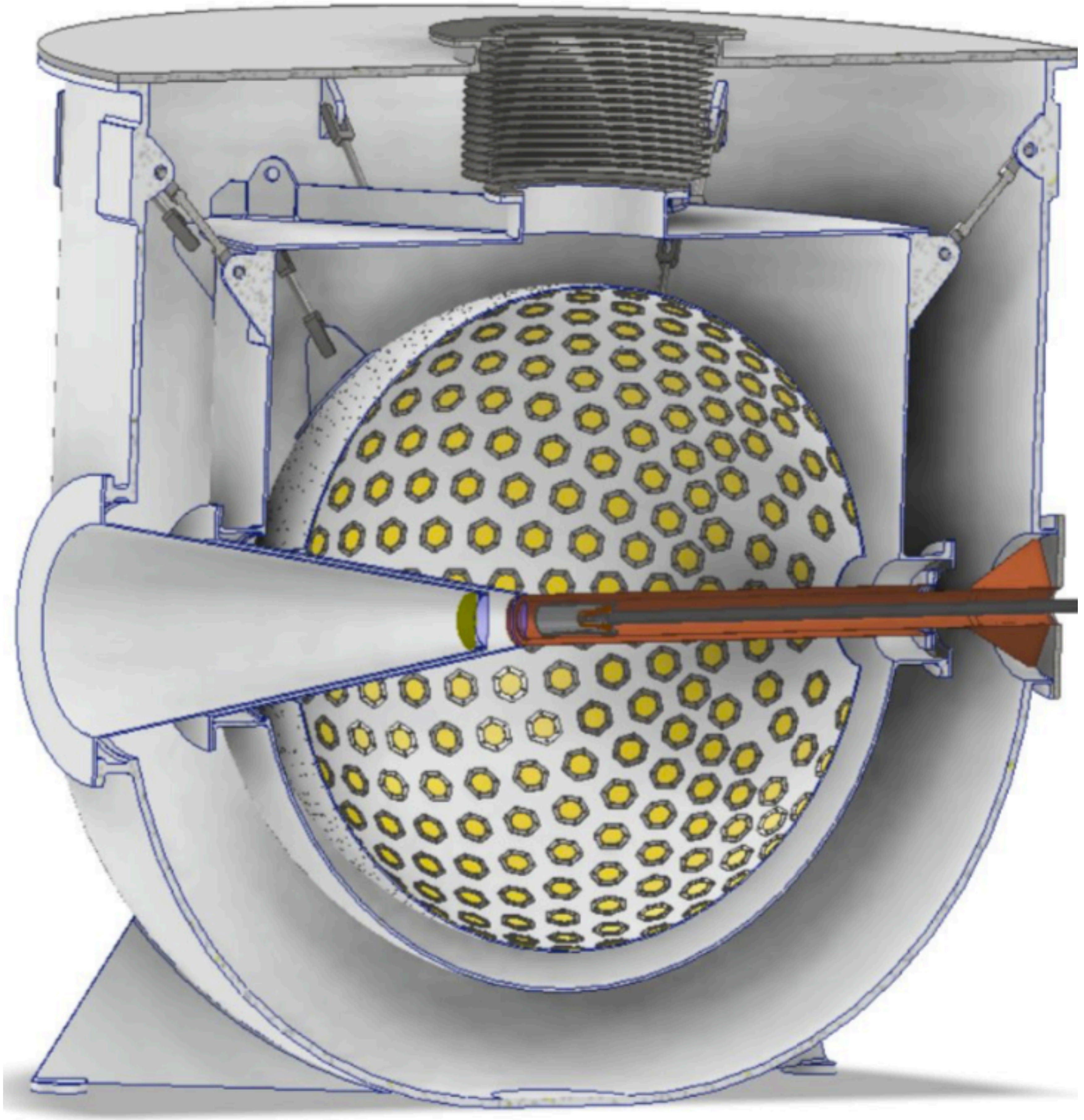
LXe calorimetry for PIONEER
Open questions/Simulation and R&D plans



https://triumf.wd10.myworkdayjobs.com/en-US/careers-at-triumf-job-postings/job/TRIUMF--Vancouver-BC/Postdoctoral-Researcher---Particle-Physics---Rare-Decay-group-at-TRIUMF_JR100269

LXe calorimeter option for PIONEER

- high density
- high light yield
- fast response
- transparent to its emission (long absorption length)
- highly homogeneous response
- emission in the VUV (~178nm)

✓ high energy resolution (<2% sigma at 70 MeV)

✓ fast timing

✓ homogeneous

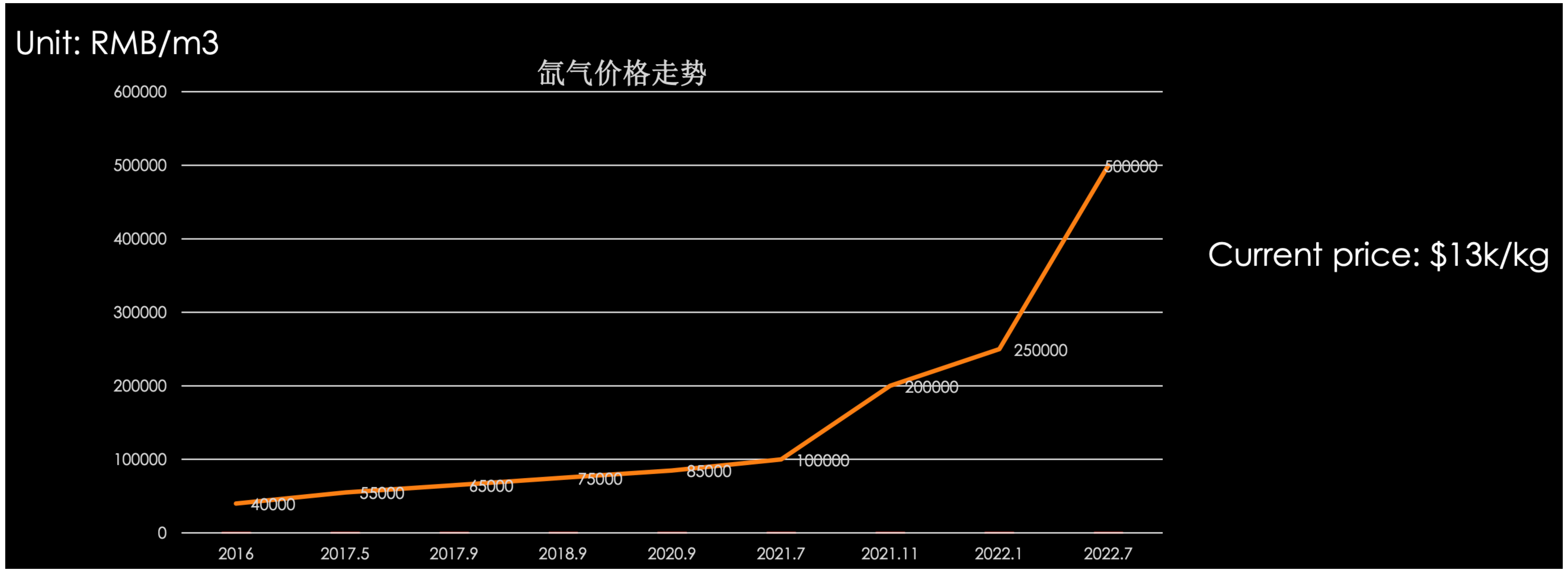
how much is high and how can we deviate from those ideal properties and still achieve PIONEER's goals should be studied carefully…

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	$1.6 \div 1.72$	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

Let's take the price aside…



from Jianglai Liu slides

un-favourable circumstances

Price cycle: "it will go down as new factories scale up their production to benefit from the high price"

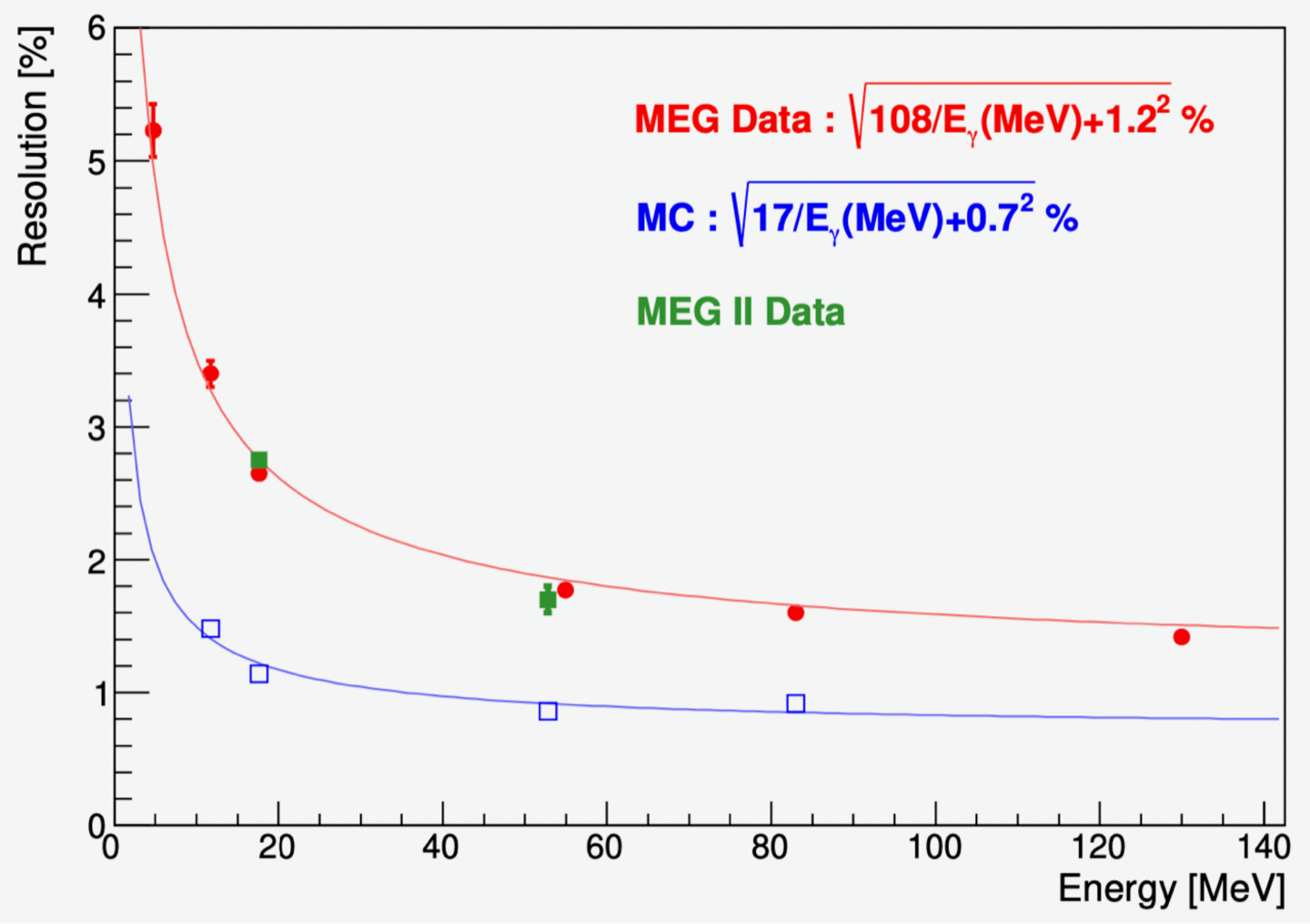
Updates from plants?

Advantage of Xe:
- it can be shared!
- it could be leased!
- it is reusable (if no leak)

LXe calorimeter option for PIONEER

✓ high energy resolution (<2% sigma at 70 MeV)
- important for the tail fraction
- observation of photonuclear events
- exotic searches (bump searches)

Energy resolution



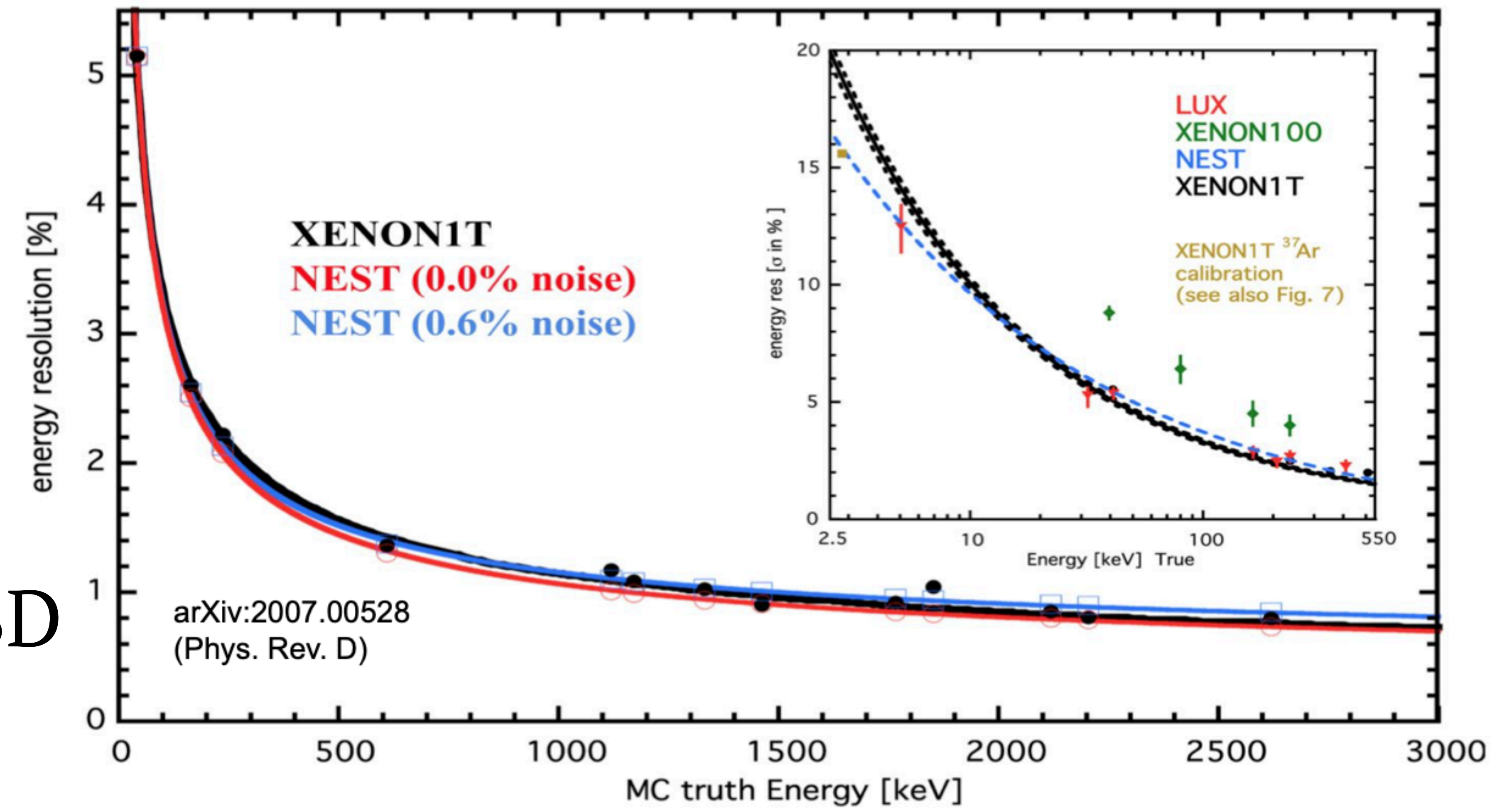
Shinji's Ph.D thesis
(Figure 9.15 https://meg.web.psi.ch/docs/theses/ogawa_phd.pdf).

Understand data/MC discrepancy

Resolution not 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 prototype data with MC with and without NEST



talk by K. Ni UCSD
@ LIDINE2022

In our proposal: "The baseline energy resolution goal for PIONEER at 70 MeV is 1.5%"

LXe calorimeter option for PIONEER

✓ high energy resolution (<2% sigma at 70 MeV)
- important for the tail fraction
- observation of photonuclear events
- exotic searches (bump searches)

✓ fast timing
- can cope with high rate
- better pile-up suppression (cf old muons etc) ~x5 improvement compared to PIENU NaI

LXe calorimeter option for PIONEER

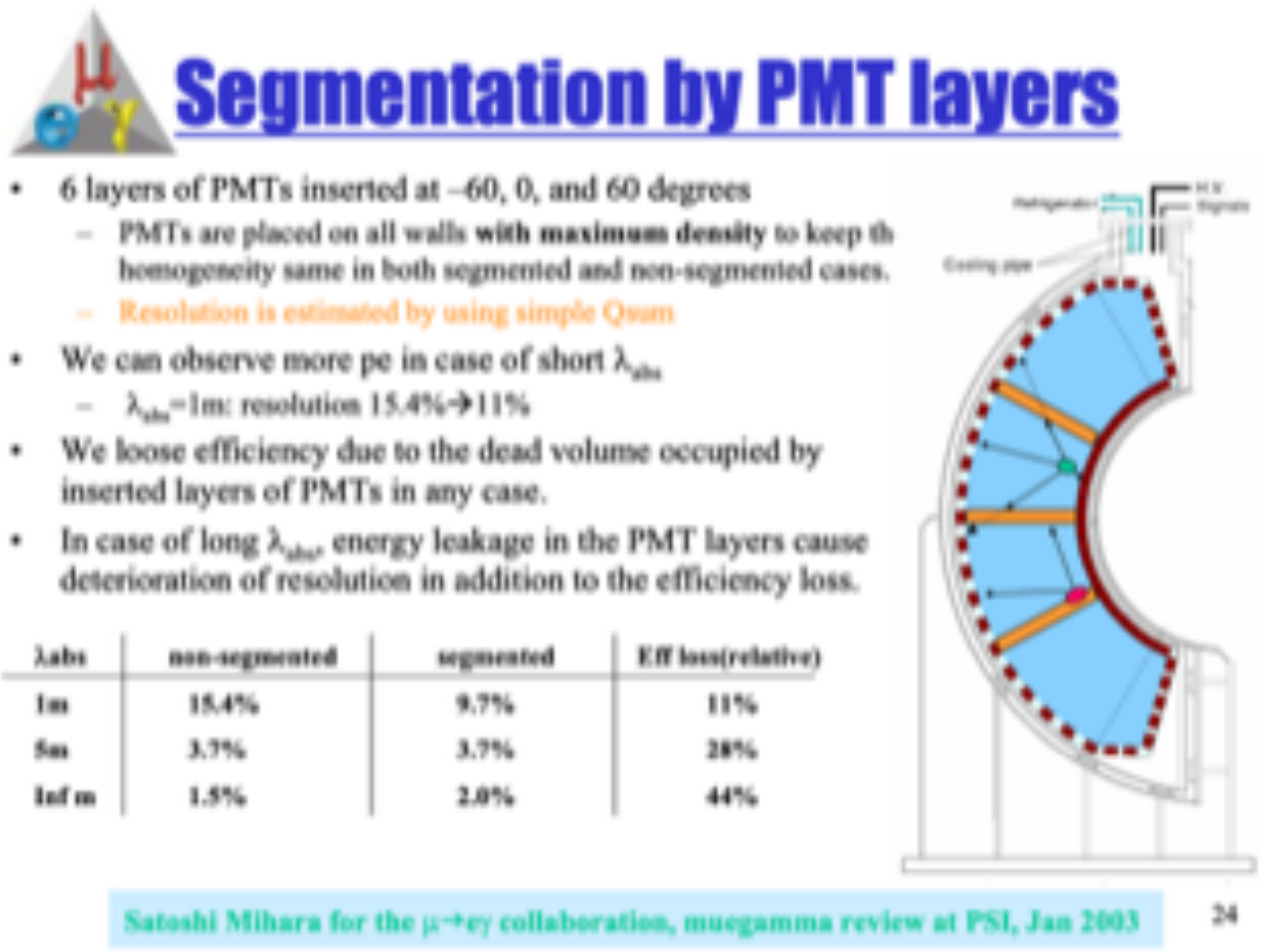
✓ high energy resolution (<2% sigma at 70 MeV)
- important for the tail fraction
- observation of photonuclear events
- exotic searches (bump searches)

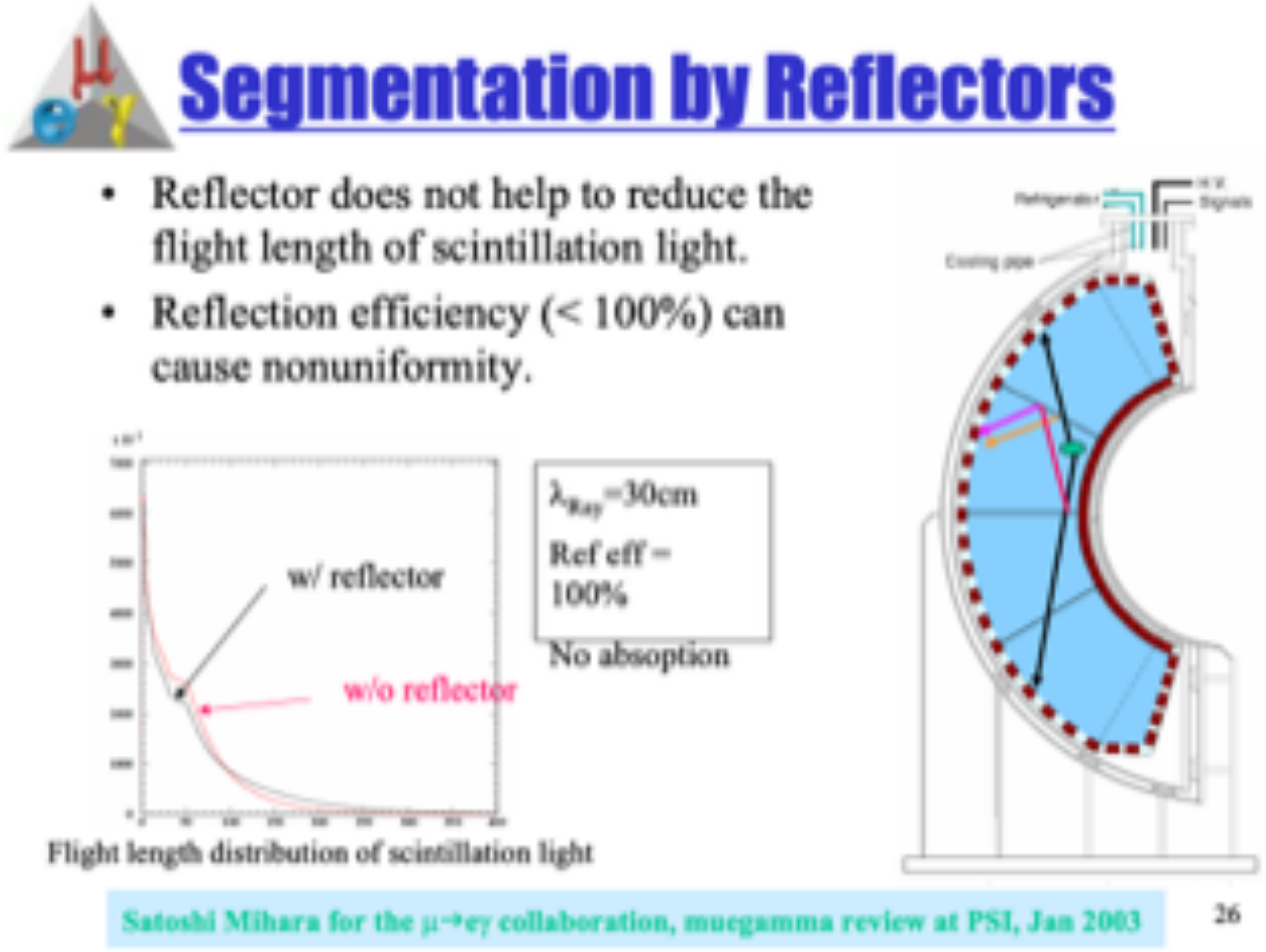
✓ fast timing

- can cope with high rate
- better pile-up suppression (cf old muons etc) ~x5 improvement compared to PIENU NaI

✓ homogeneous
- PIENU experience
- … but potentially not great when dealing with high rate ! Especially high rates of things we don't want (old muons, beam particles etc..)
- "best of both worlds" : segment the liquid!

Physical Optical Segmentation





Simulation studies done by MEG

PIONEER :

- “shafts” separating portions of the volume
- Possible material: MgF2 coated aluminum sheets, others. Optical simulation / optical measurements and tests

"Virtual" Segmentation

based on Cherenkov information?

- Cherenkov photons arrive earlier. Can serve as a trigger.

- They are directional. Could effectively define an area of interaction/ area of photodetectors to readout. How much would that affect the energy resolution?

to be studied in simulation and in a large prototype

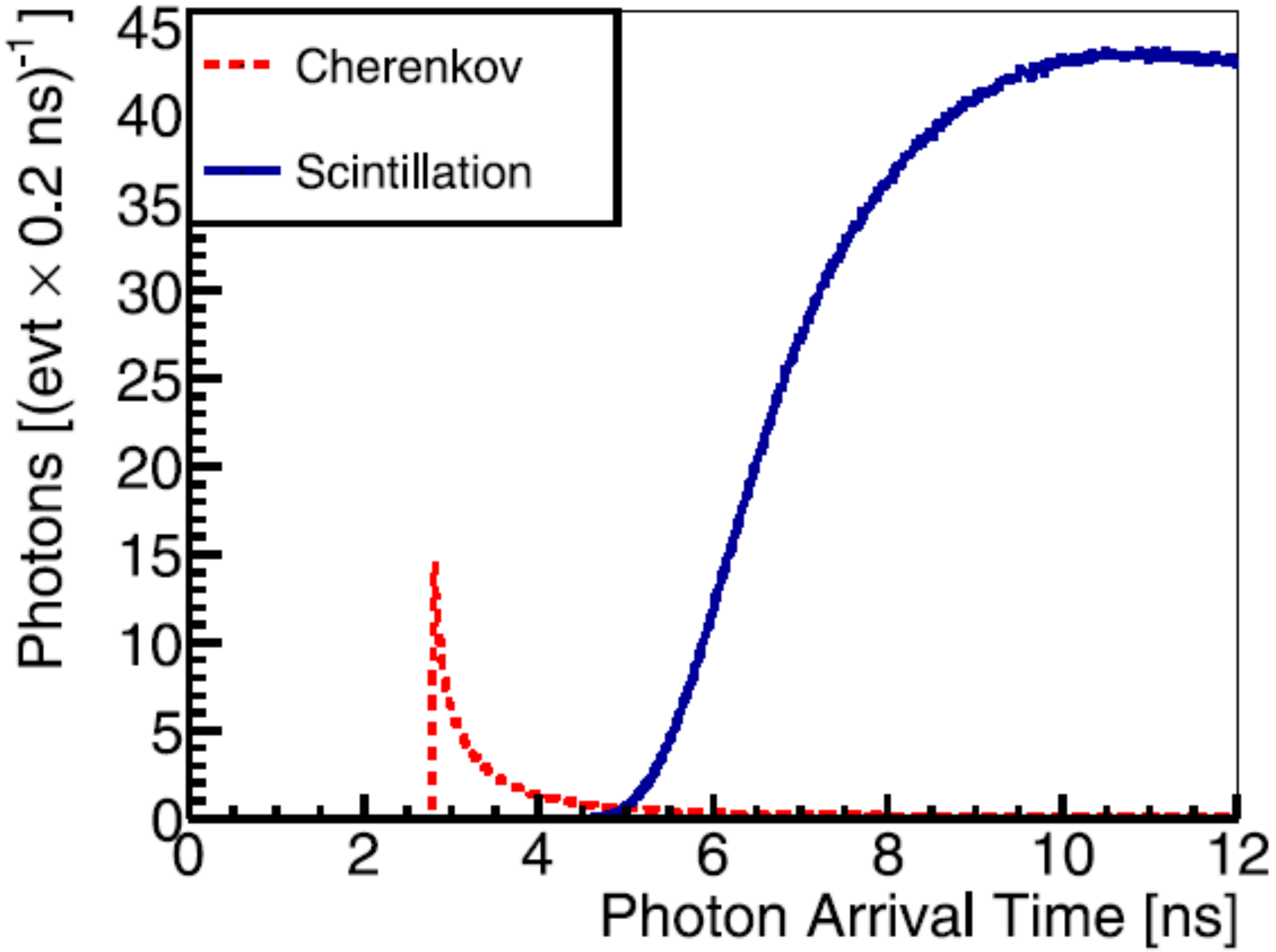


Fig. 5. Distribution of arrival times for Cherenkov and scintillation light traveling a distance of 60 cm, obtained from simulated $0\nu\beta\beta$ interactions in LXe.

Nucl.Instrum.Meth.A 922 (2019) 76-83 1812.05694 [physics.ins-det] (nEXO)

LXe calorimeter option for PIONEER

✓ high energy resolution (<2% sigma at 70 MeV)
- important for the tail fraction
- observation of photonuclear events
- exotic searches (bump searches)

✓ fast timing

- can cope with high rate
- better pile-up suppression (cf old muons etc) ~x5 improvement compared to PIENU NaI

✓ homogeneous
- PIENU experience
- … but potentially not great when dealing with high rate ! Especially high rates of things we don't want (old muons, beam particles etc..)
- "best of both worlds" : segment the liquid!

Scintillation wavelength in the **VUV**

- advantageous for the high transparency
- difficult for readout

LXe calorimeter option for PIONEER

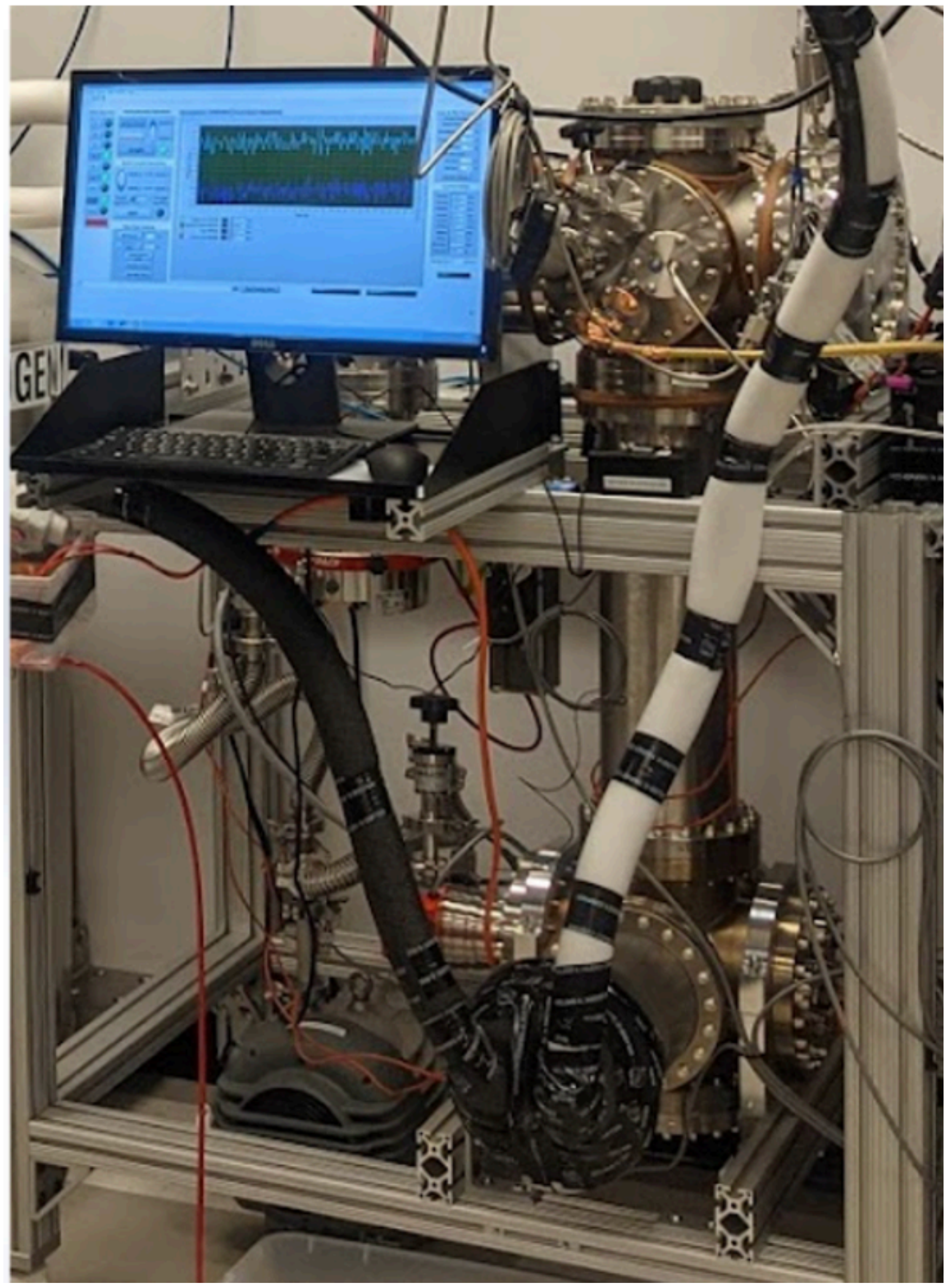
Scintillation wavelength in the **VUV**

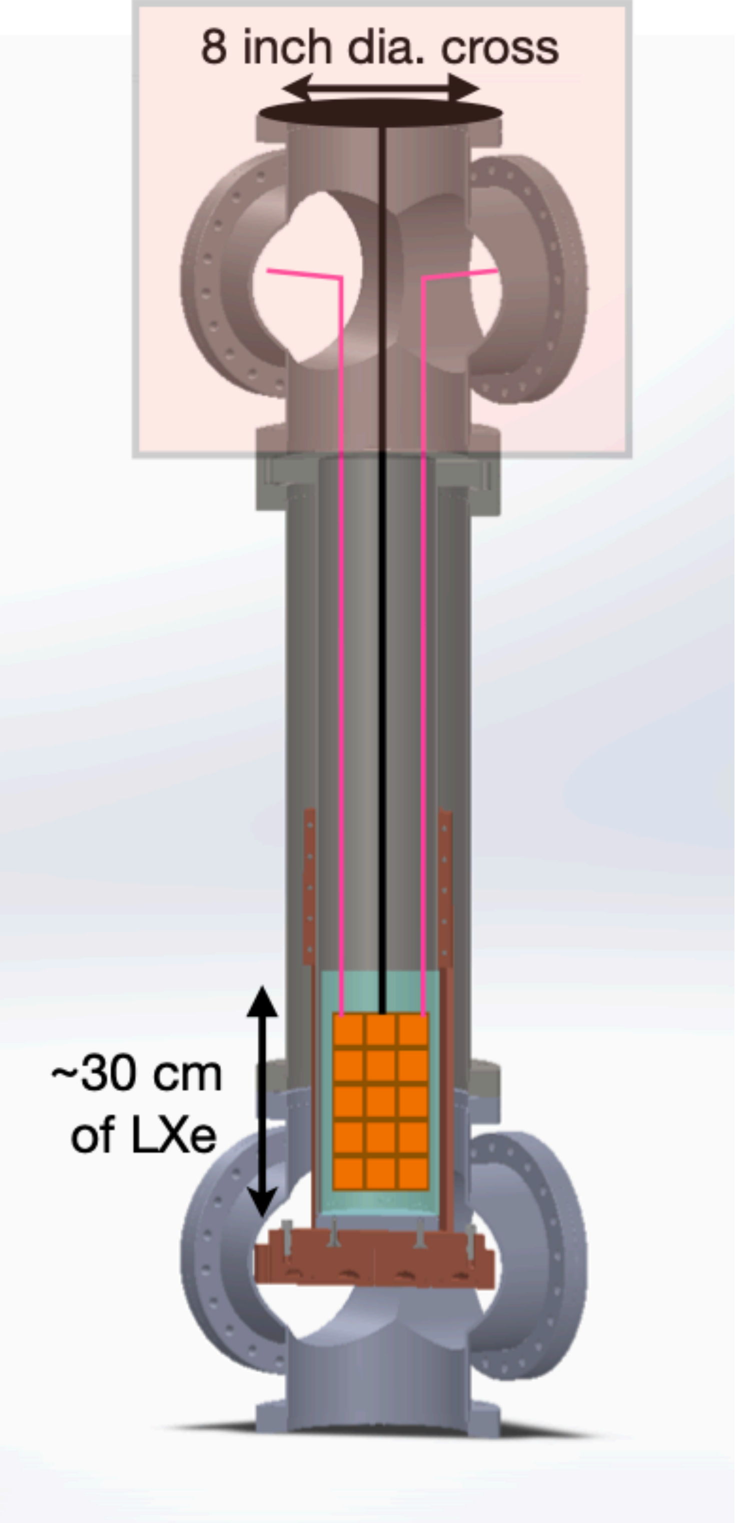
- advantageous for the high transparency
- difficult for readout

- VUV SiPM degradation observed by MEG in the MEG apparatus (not reproduced in other environments)
- Further tests can be done in a small LXe cryostat
  - high flux irradiation of MEG SiPM (VUV laser) immersed in LXe
  - tests of wls coated conventional SiPM
  - tests and comparison with VUV PMT

Overview of prototype and test facilities that could be used by PIONEER

1. small LXe cryostat facility at McGill University



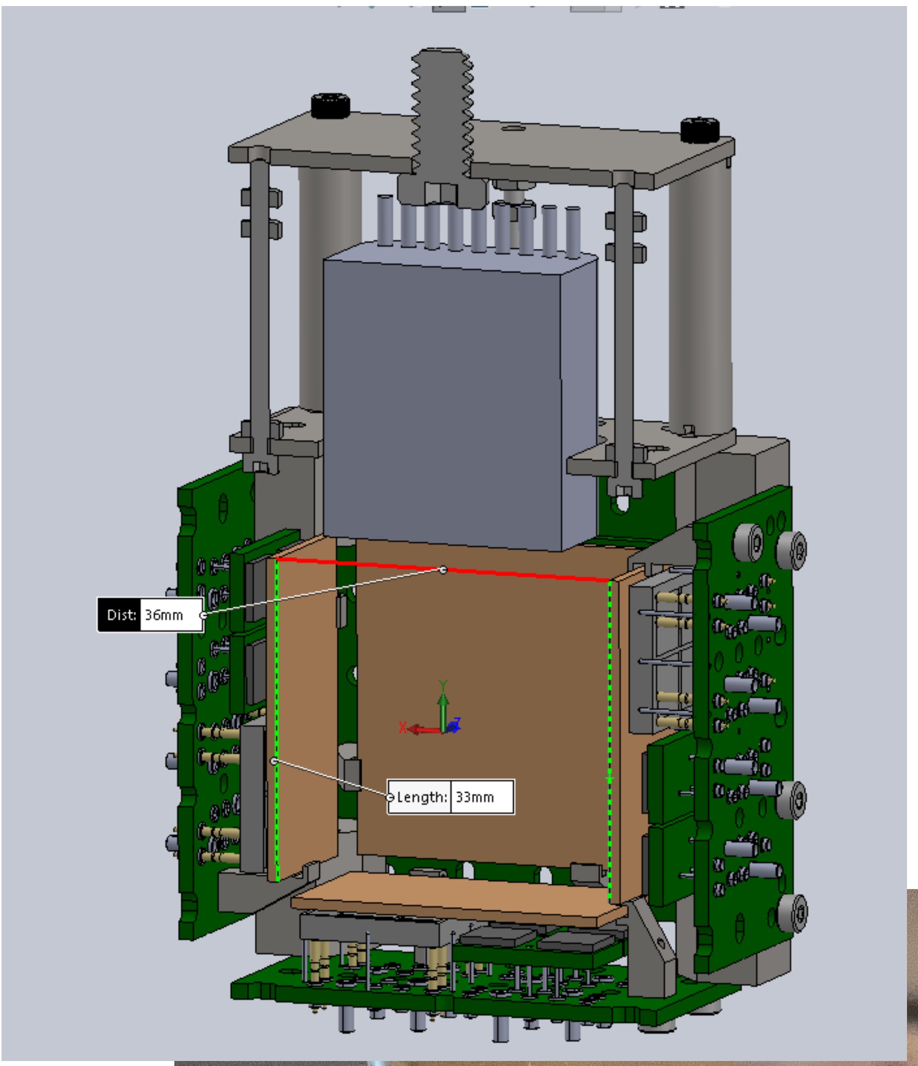


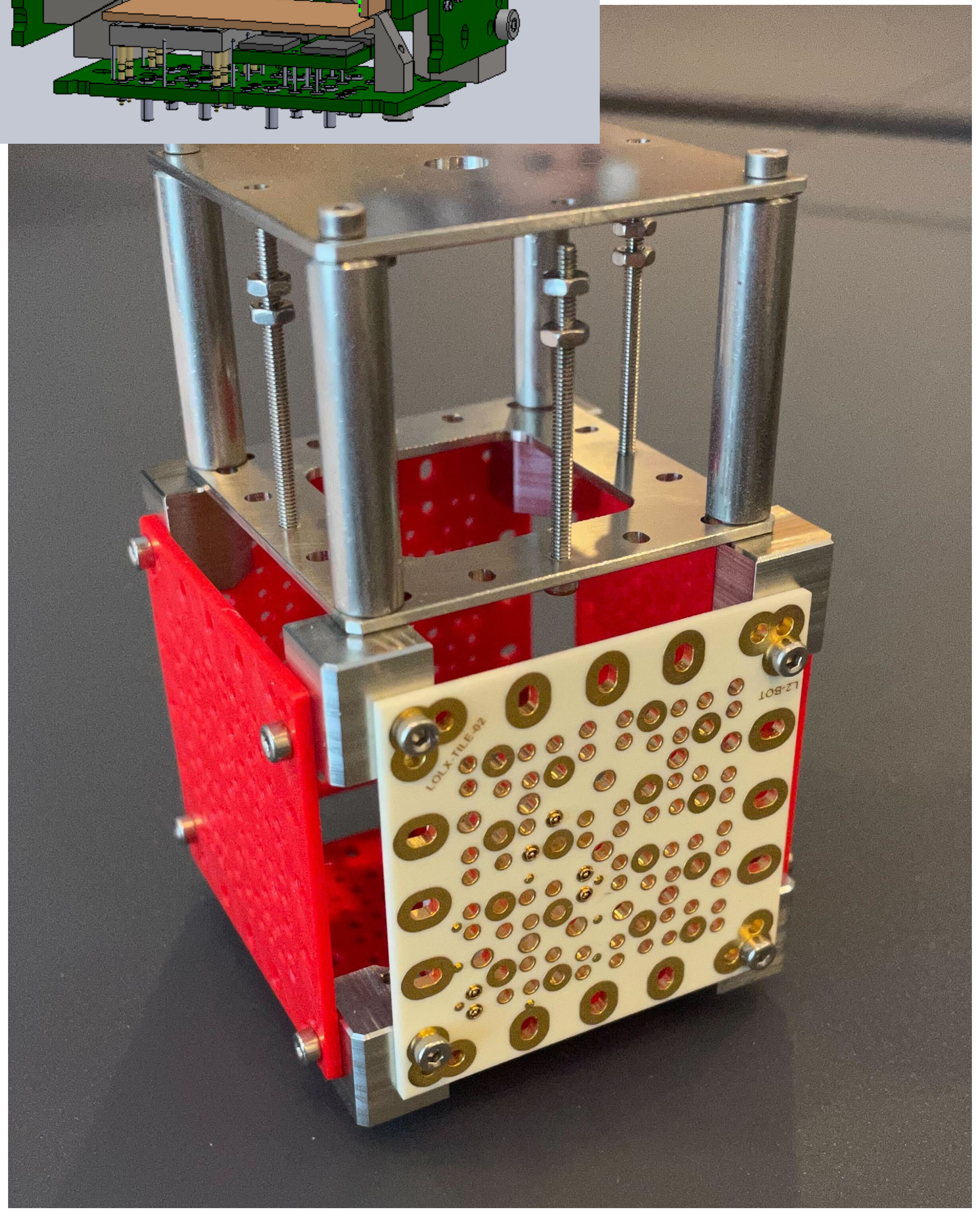
TRIUMF built the holder assembly for SiPM : assembly ongoing

5 faces covered with 16 SiPM (2 kinds FBK and Hamamatsu)

6th face equipped with 1 inch PMT for reference

Installation beginning of November.
Data taking start ~mid- November





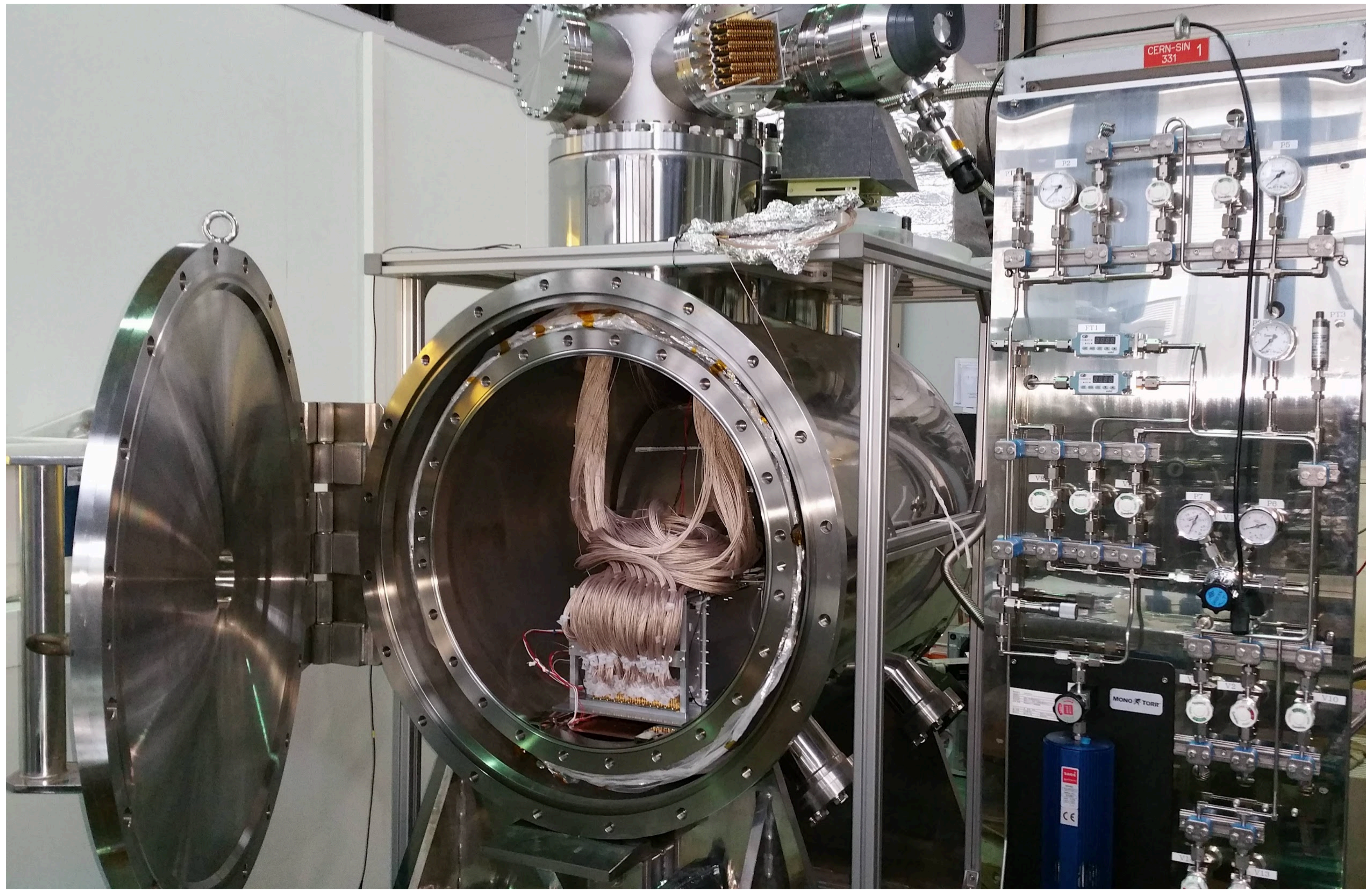
What we aim at doing in this cryostat:

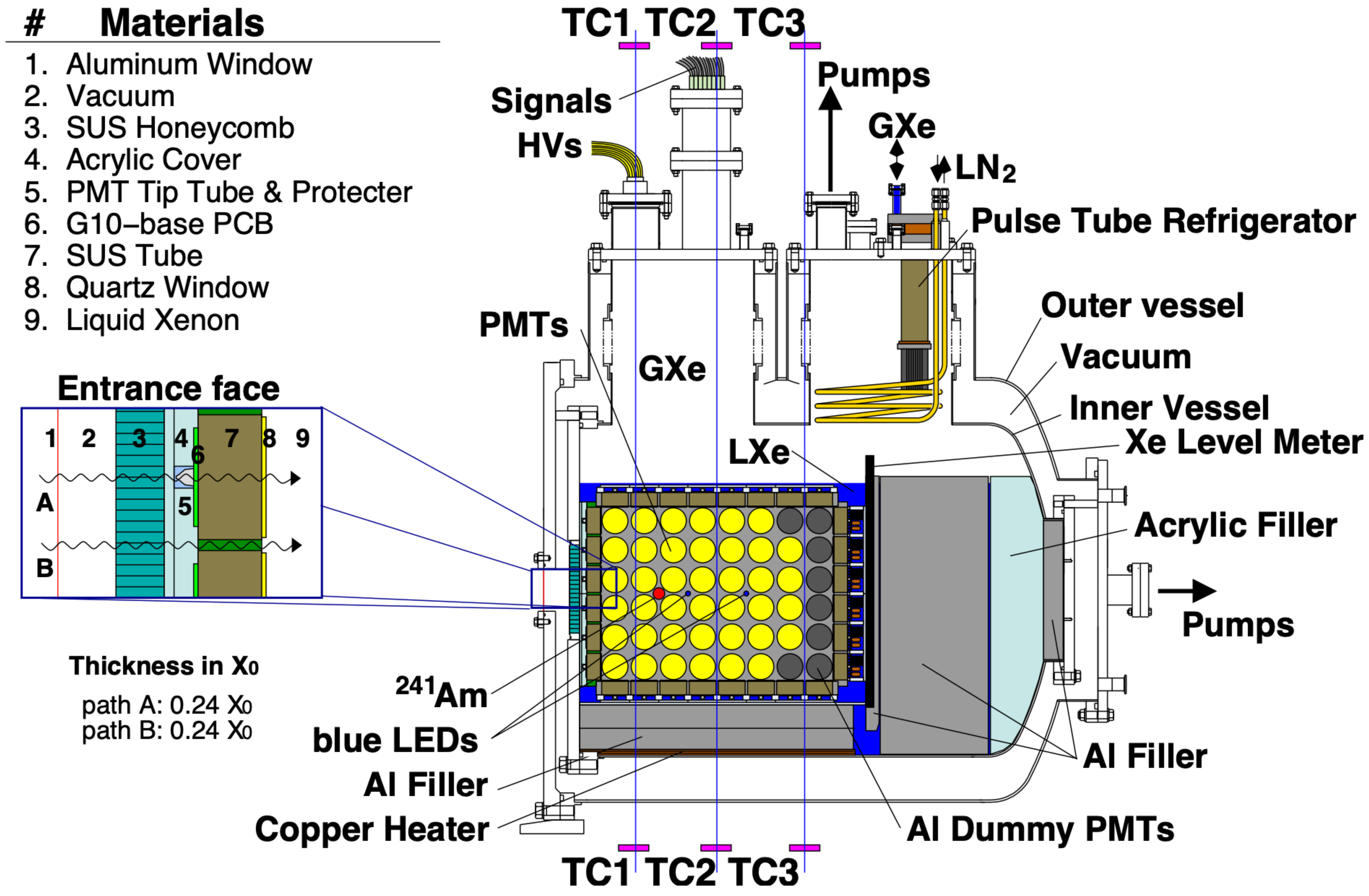
- test PDE of different VUV photosensor options
- look for Cerenkov signal (with filter)
- test conventional SiPM coated with wavelength shifting material
- high flux irradiation of SiPM

- test of reflective/ anti-reflecting material, segmentation material. Benchmark optical simulations
- NEST 0-field benchmarking (low energy)
- Development and test of a small ppb purity monitor for LXe
- ...

Timeline: 2023 and 2024

2. **MEG large prototype**
at PSI





~100L apparatus that can be available

https://arxiv.org/pdf/physics/0407033.pdf

Timeline? (where to get the Xenon from…)

What could we do in such a cryostat:

In a positron beam (modification of entrance window)

- energy resolution studies (resolution versus angle, versus MC prediction etc) (include purity monitor)
- segmentation and reconstruction studies (pileup studies)
- lineshape measurements. Assess and benchmark G4 wrt photo nuclear event. Need high momentum resolution beamline (PiE1?)
- Study Cherenkov
- large scale photosensor tests in LXe
- …

Could be used for a Run 0.5??

PIONEER GEOMETRY

Need to study with simulation (Josh already mentioned a lot of those - more from Patrick)

- Pacman versus open-ended geometry (importance of lineshape measurement at least to benchmark MC!)
- photosensor coverage
- pileup
- photonuclear
- segmentation

Others :

- calibration/monitoring etc