R&D for Solid Xenon Particle Detector

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Fermilab

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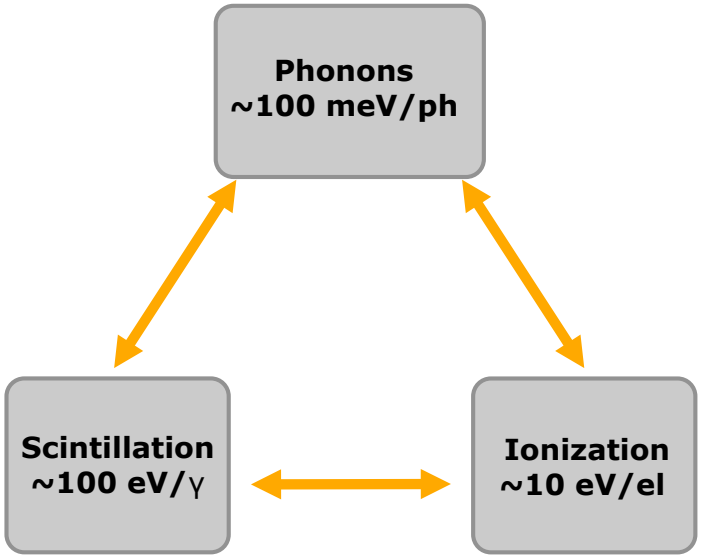
Fermilab Detector R&D Seminar

Contents

- Introduction
- Large scale Solid Xenon
- Signal Readout in the Solid Xenon
- Crystallography
- Summary

Solid Xenon



Why Xenon ?

- No long-lived Xe radio isotope (no intrinsic background)
- High yield of scintillation light
- Scintillation wavelength : 175nm (optically transparent)
- Relatively high melting point : T_m = 161K
- Simple crystal structure : *fcc* (same as Ge)
- Easy purification (distillation, etc)
- Self shielding : Z=54

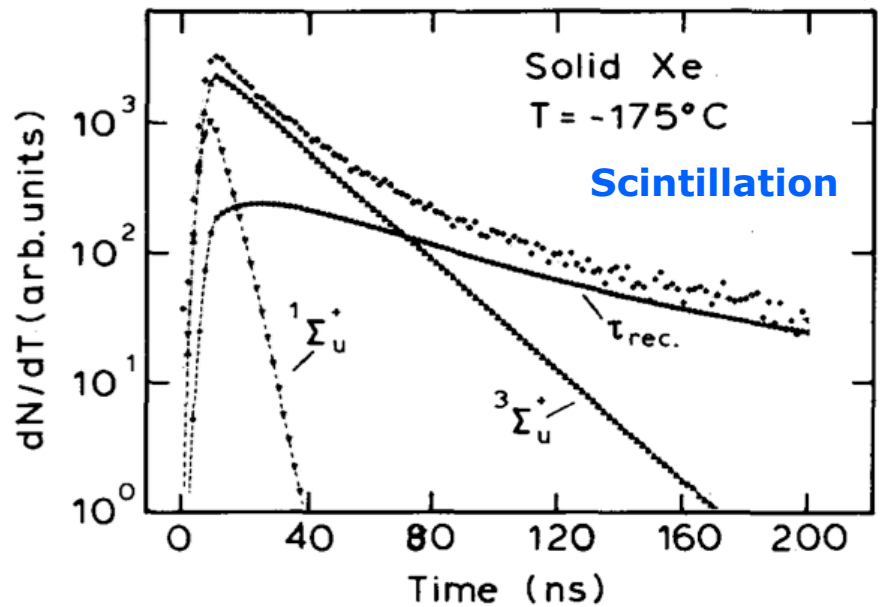
Why Solid?

- For solar axion search, being a crystal is crucial (Bragg scattering)
- More scintillation light readout than liquid phase is reported
- Drifting electrons faster in the crystal
- Superb low noise superconducting sensors are running at low temperature (mK ~ K)
- Phonon read out : largest number of quanta (~10,000 phonons / keV)
  - In principle best energy resolution can be achieved in phonon channel
  - Luke-phonon readout will provide ionization energy and position information
- No further background contamination through circulation loop (no convection mix)
- Optimal detector design for low background experiment
  - Possible container-free design
  - No outgassing issue -- backgrounds freeze out

Solid Xenon Property

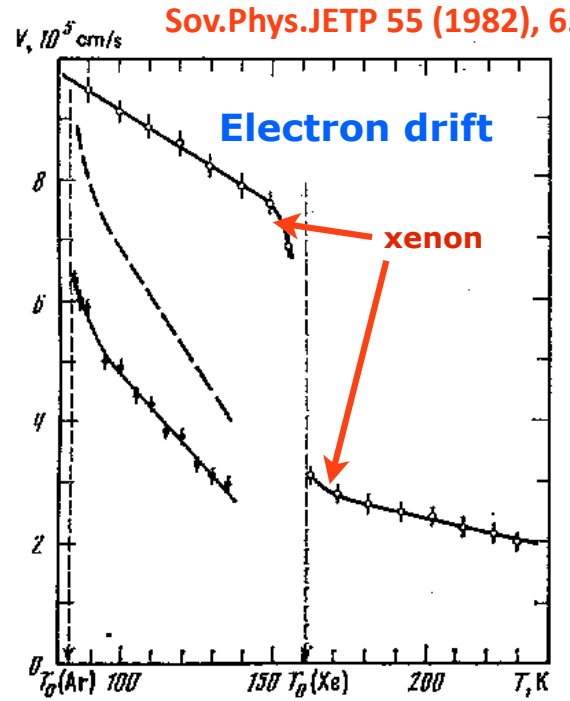
Atomic number :Z	54	
Boiling point (1 $[atm]$)	165	$[K]$
Melting point (1 $[atm]$)	161	$[K]$
Triple point properties		
Density		
Gas	8.18×10^{-3}	$[g/cm^3]$
Liquid	2.96	
Solid	3.40	
Temperature	161.391	$[K]$
Pressure	612.2	$[Torr]$

IEEE Transactionson Nuclear Science, Vol. 35,1 (1988)



	Gas	Liquid	Solid
W-value $[eV]$	21.5	15.6[1]	12.4[2] 19.5 [3]
Fano factor	< 0.17	0.0041 [1]	?
Electron drift velocity $[cm/sec]$	$\sim 10^5$ at $1[kV/cm]$	3.0×10^5[4] $> 5[kV/cm]$	5.0×10^5[4] $> 5[kV/cm]$
Ion or Hole drift velocity $[cm/sec]$	Positive ion 0.76 at $1[kV/cm]$	Positive ion 0.3 at $1[kV/cm]$	Hole 18[4] at $1[kV/cm]$

Sov.Phys.JETP 55 (1982), 650



Science

(1) Solar axion search: crystal

- scintillation / (ionization)

(2) Dark matter search : readout two(or three) signals

- scintillation / ionization / (phonon)

(3) Neutrinoless double beta decay (0v2b) : ^{136}Xe enriched

- scintillation / ionization / phonon

(4) pp-Solar neutrino measurement : ^{136}Xe depleted

(5) Supernova detection

(6) Neutrino coherent scattering

(7) Medical usage (MRI/NMR) : hyperpolarized ^{131}Xe

Full of science topics

- Strong motivation for R&D
- Does not mean we can initiate an experiment

→ We need a proven technology

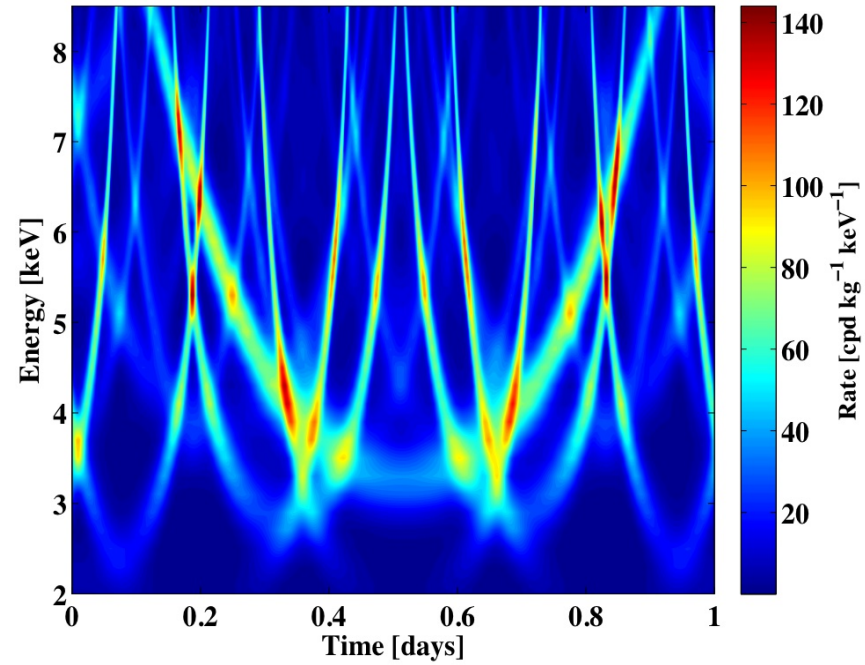
Axion Search

Coherent Scattering of Axion in Crystal

$$R(E) = \int 2c\frac{d^3q}{q^2} \cdot \frac{d\Phi}{dE} \cdot [\frac{g^2_{a\gamma\gamma}}{16\pi^2}|F(\vec{q})|^2 \sin^2(2\theta)]$$

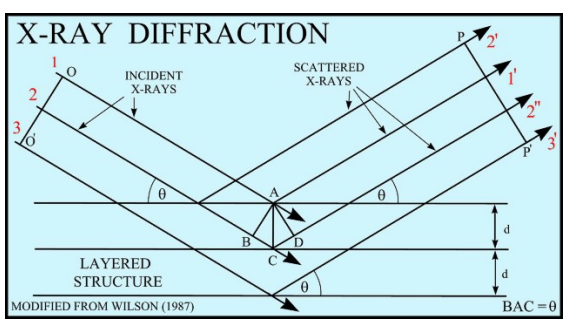
$$F(\vec{q}) = k^2 \int d^3x\ \phi(\vec{x})e^{i\vec{q}\cdot\vec{x}}$$

$$\phi(\vec{x}) = \sum_i \phi_i(\vec{x}) = \sum_i \frac{Ze}{4\pi|\vec{x}-\vec{x}_i|}e^{-\frac{|\vec{x}-\vec{x}_i|}{r}} = \sum_G n_G e^{i\vec{G}\cdot\vec{x}}$$



Time-energy plot of the expected event rate for finding photon-converted solar axions with a CDMS germanium crystal detector

Bragg Condition

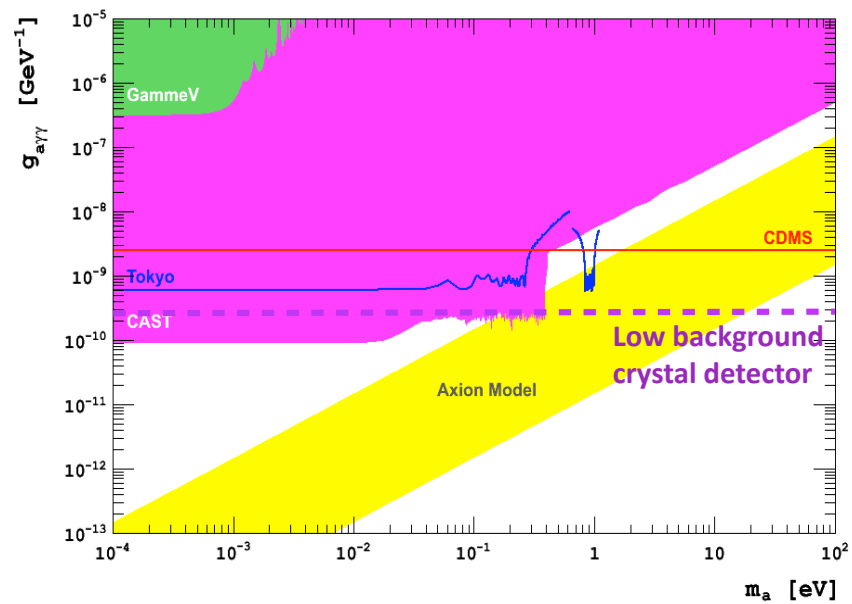


BRAGG LAW

$$2d(\sin\theta) = \lambda_o$$

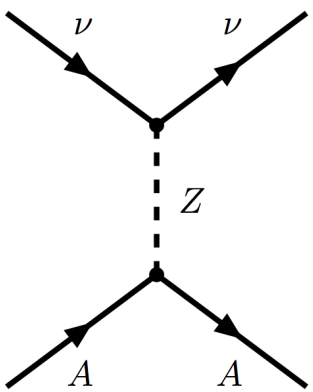
where:
d = lattice interplanar spacing of the crystal
θ = x-ray incidence angle (Bragg angle)
λ = wavelength of the characteristic x-rays

$$E_a = \hbar c\frac{|\vec{G}|^2}{2\hat{u}\cdot\vec{G}}$$



Community is Ready to Enjoy the Solar Axion

Coherent Elastic Neutrino Nucleus Scattering: CENNS



$$\sigma_{\nu N} \simeq \frac{4}{\pi} E_\nu^2 \left[Z\omega_p + (A-Z)\omega_n \right]^2$$

$$E_\nu < \frac{1}{R_N} \simeq 50 \text{ MeV}$$

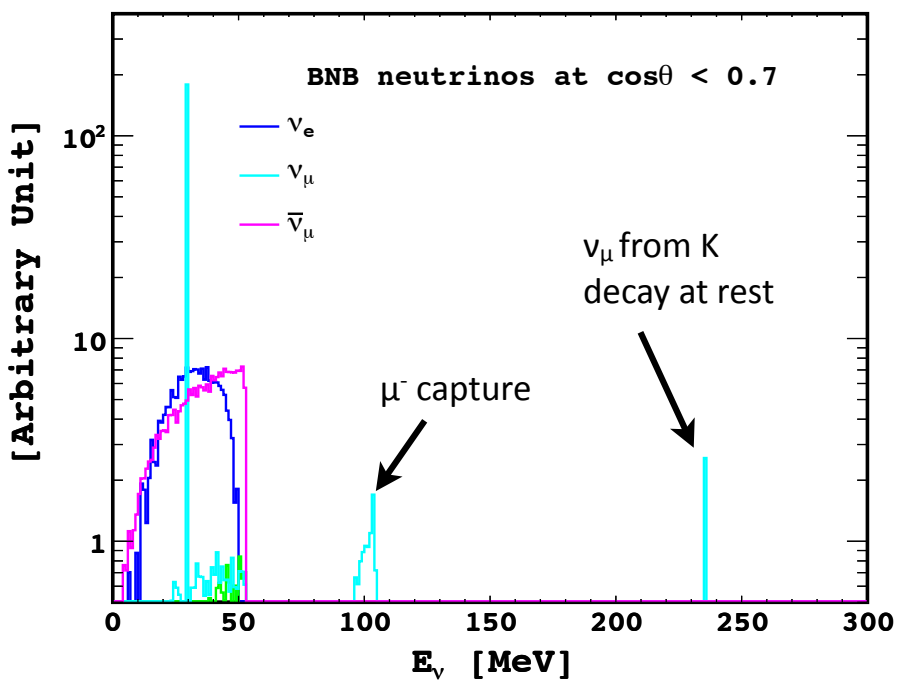
Never been observed!

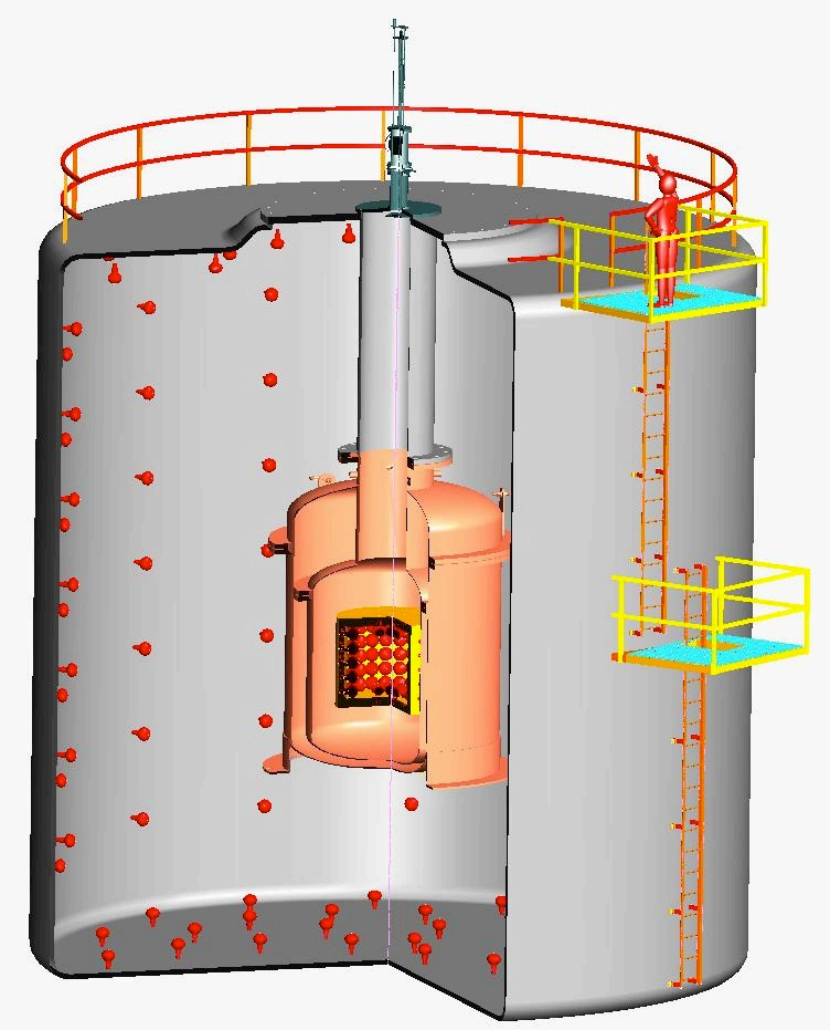
A lot of physics cases (arXiv:1311.5958)

Low energy threshold (~10s keV)

Fast response detector is required

Booster Neutrinos at the Far-Off-Axis are appropriate source to measure the CENNS





A ton-fiducial LAr detector may discover the CENNS

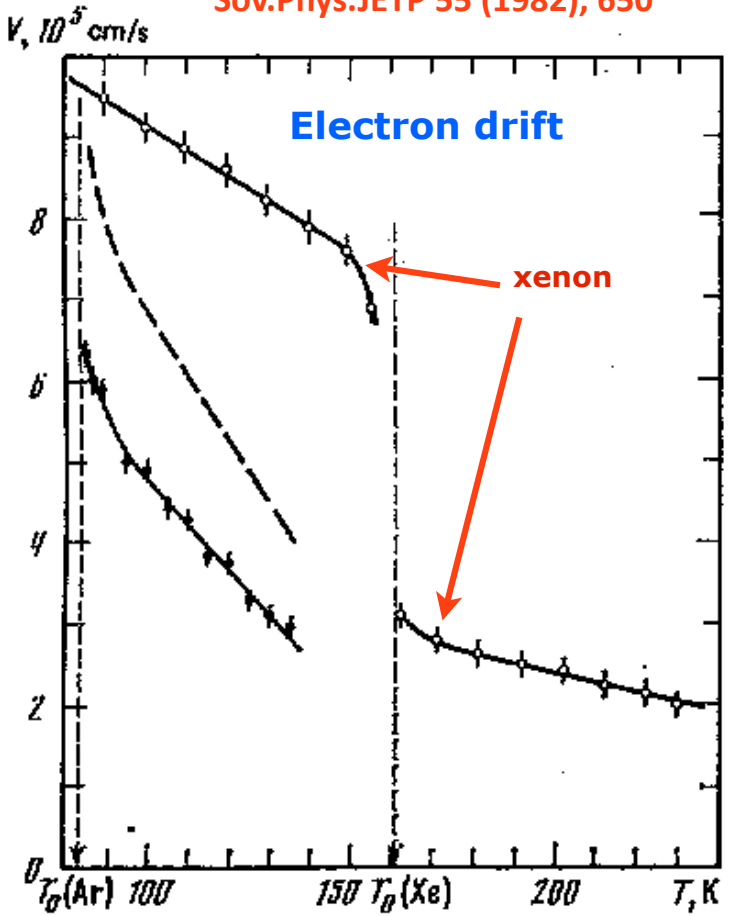
Solid Xenon CENNS Detector

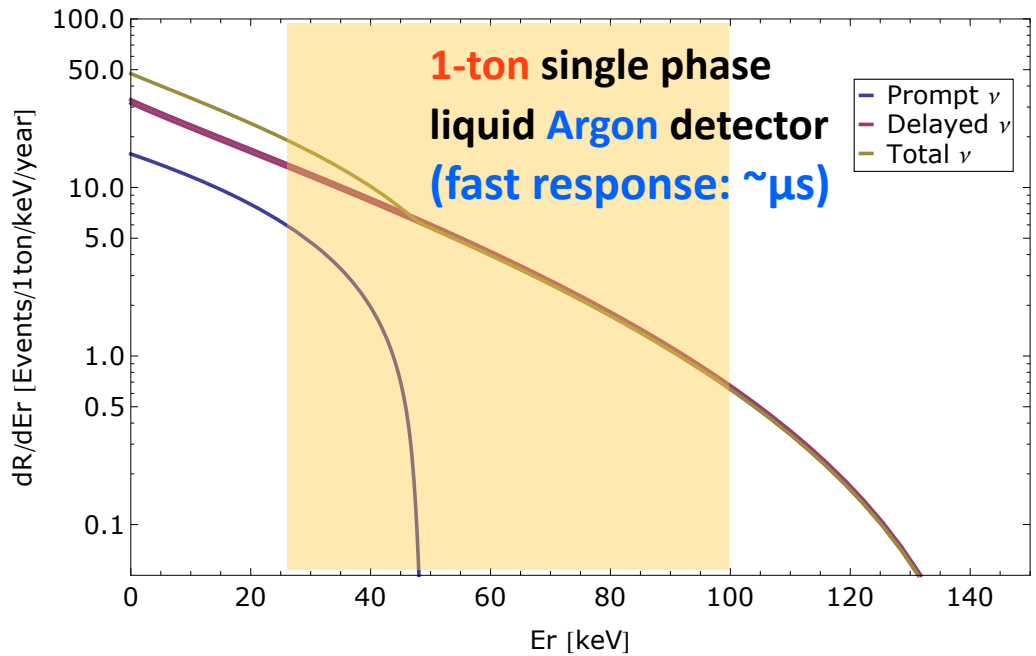
For example:

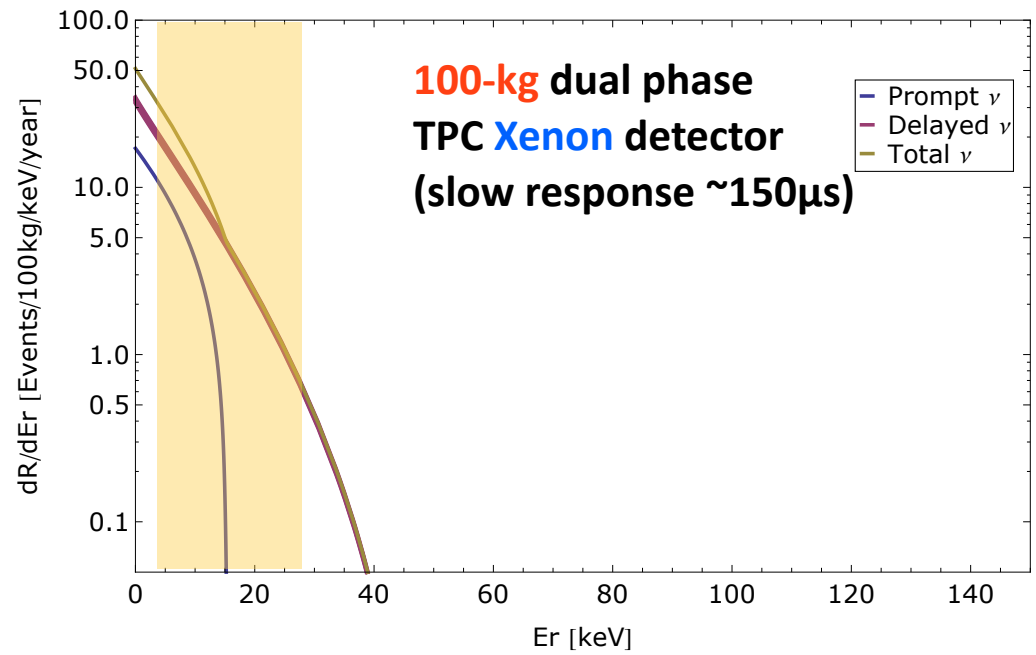
- **Drifting electrons in LXe: 150µs/30cm**
- **Drifting electrons in SXe: 30µs/30cm**

→ Steady state background reduction factor 5

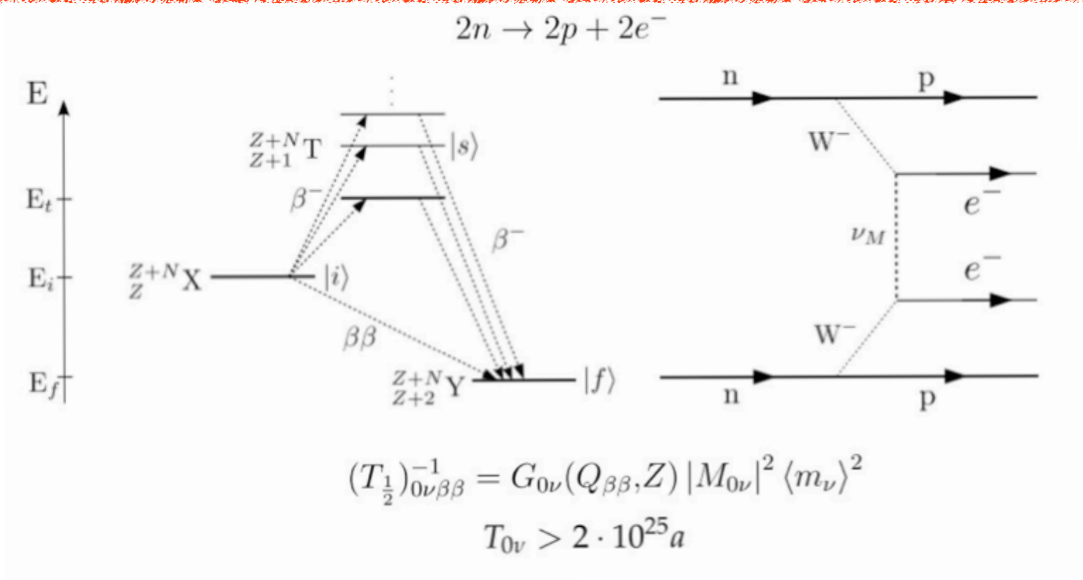
Sov.Phys.JETP 55 (1982), 650



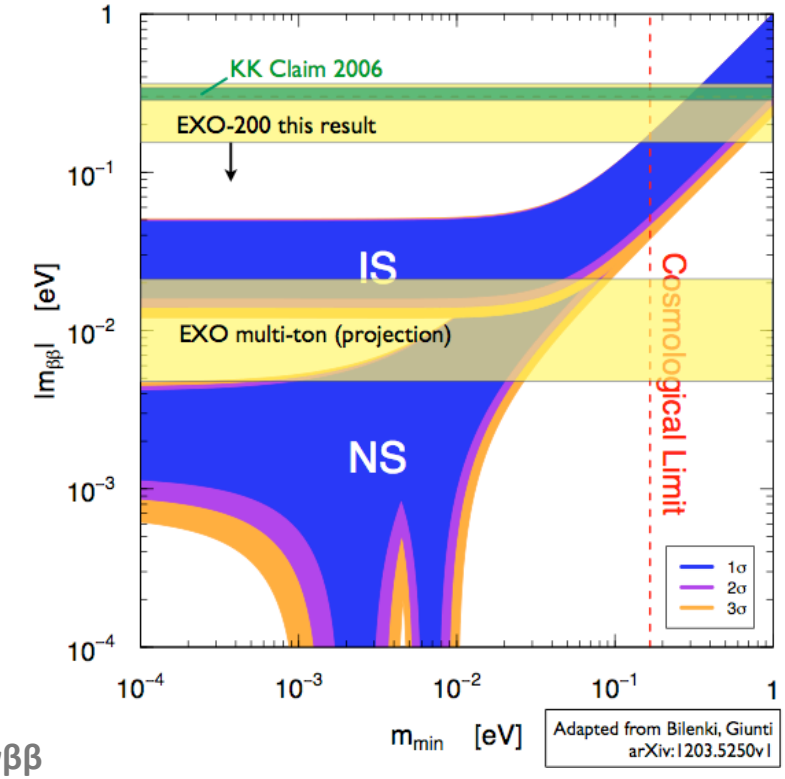


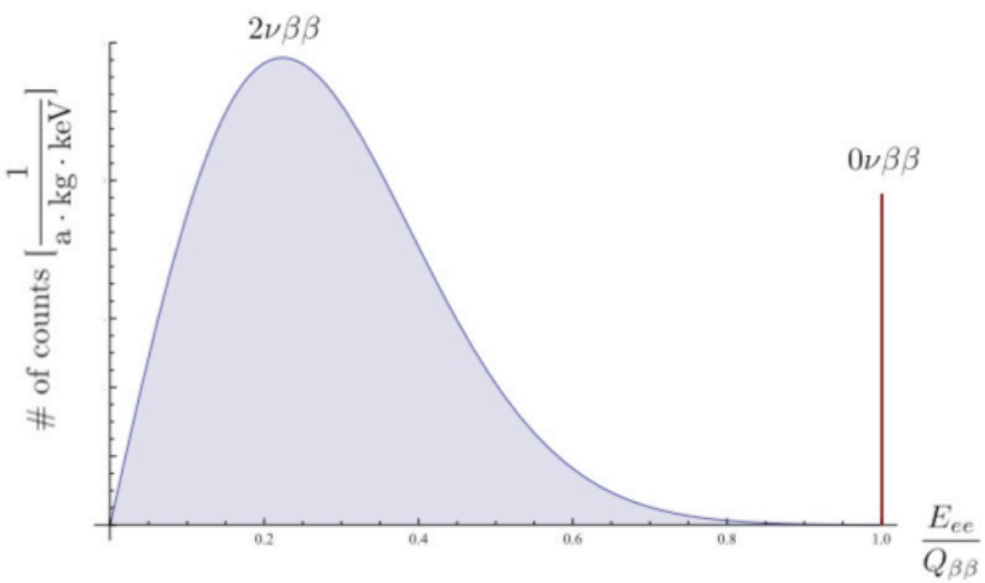


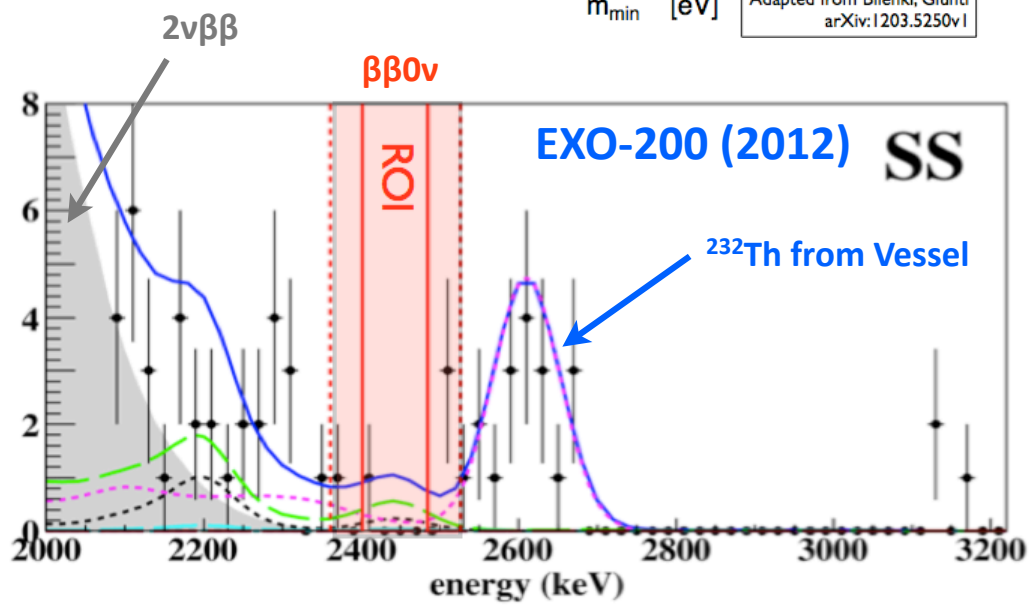
Neutrinoless Double Beta Decay



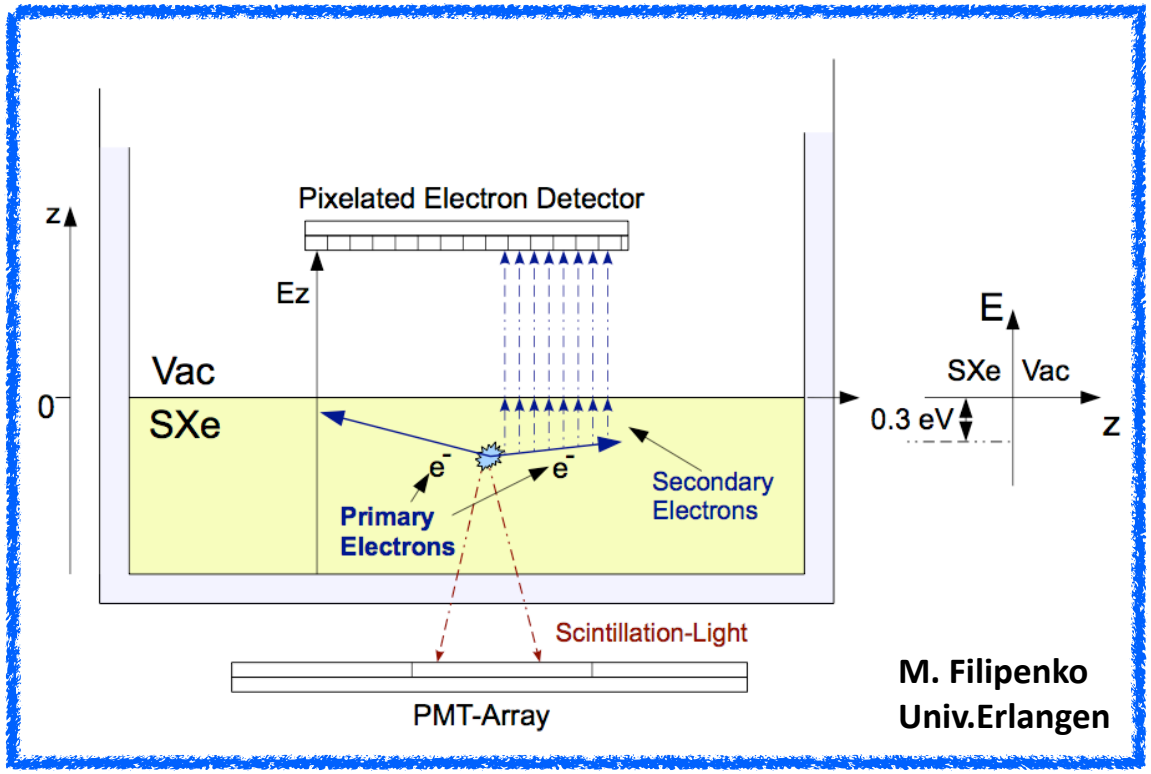
^{136}Xe: Q=2457.83 keV ± 0.37 keV



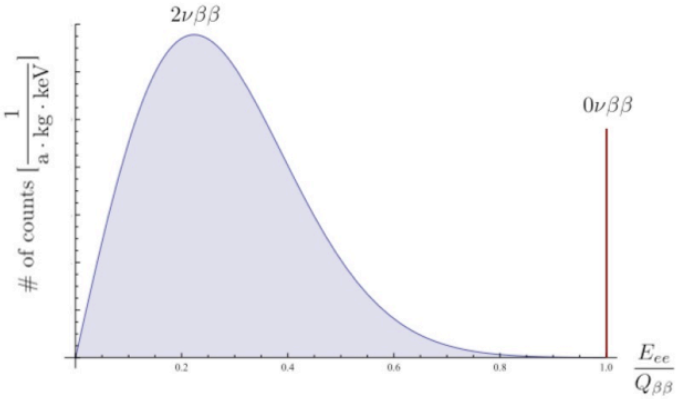




0νββ with Solid Xenon Tracking Detector

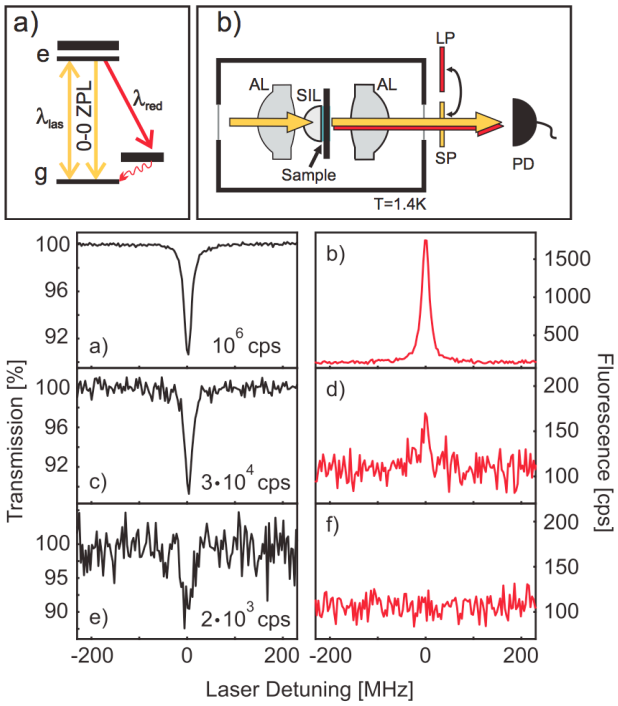


Energy Spectrum

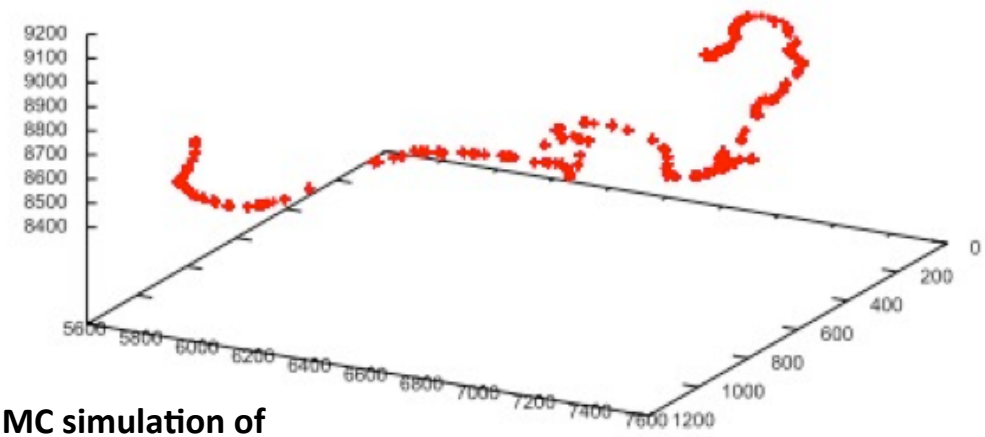


$^{136}Ba^{++}$ tagging

(ex:single atom tagging: arXiv0808.3300)



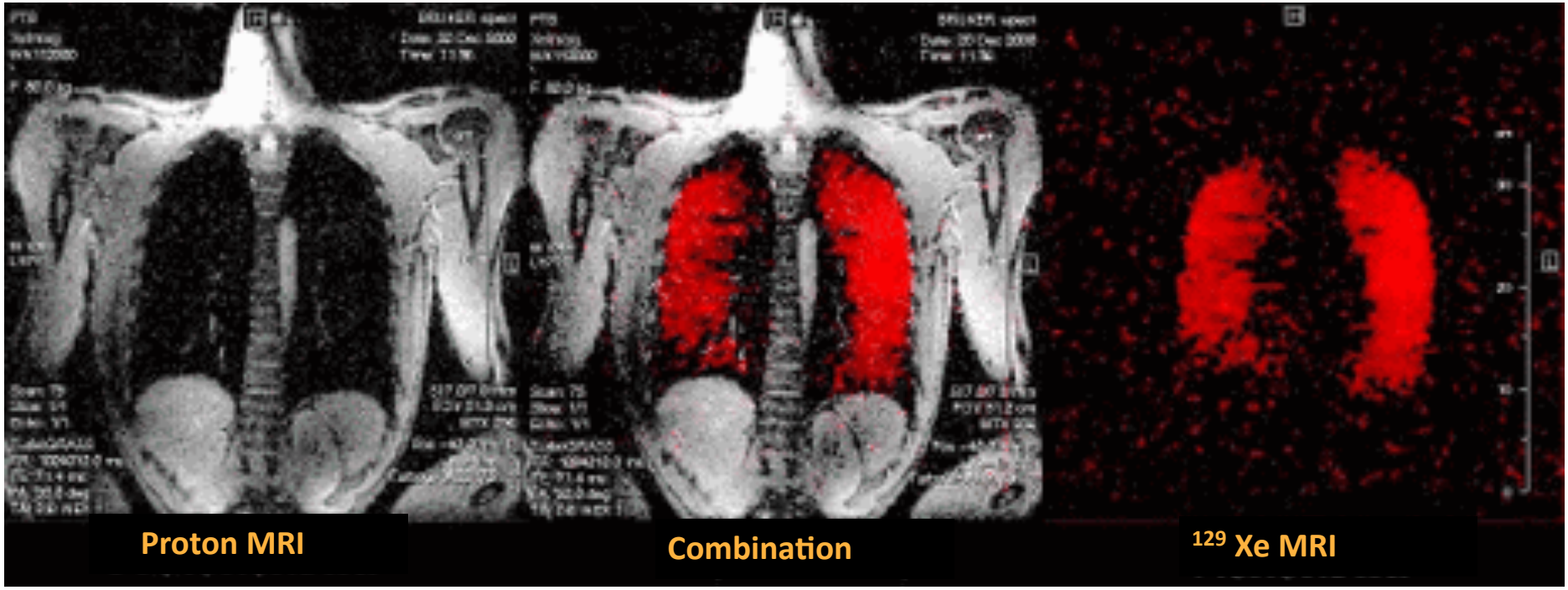
Tracking electron pair

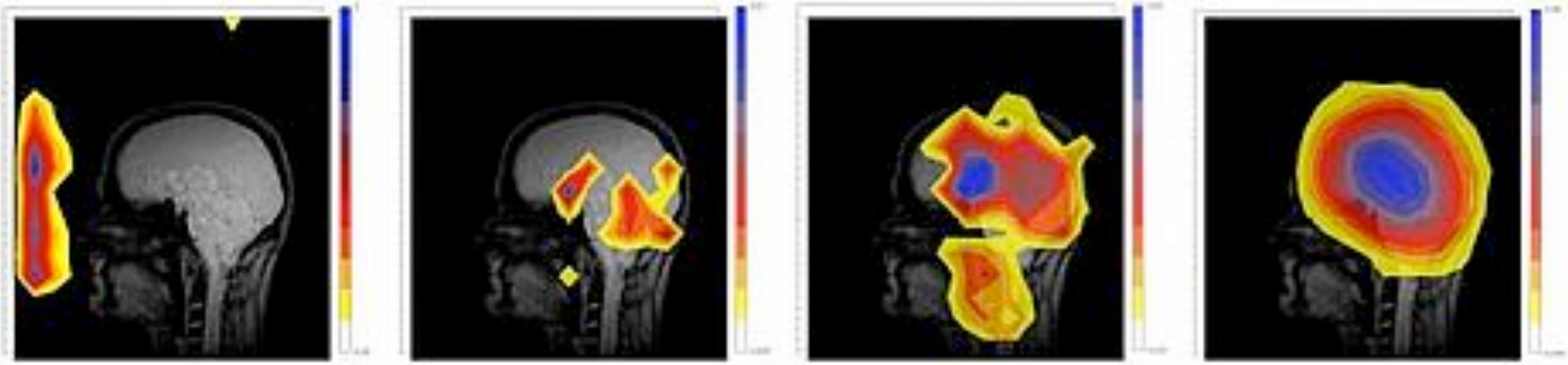


MC simulation of
0νββ decay

Medical Research

- **Hyperpolarized xenon MRI**
  - → **R&D for Hyperpolarized solid xenon (commercial application)**





(Images from www.ptb.de)

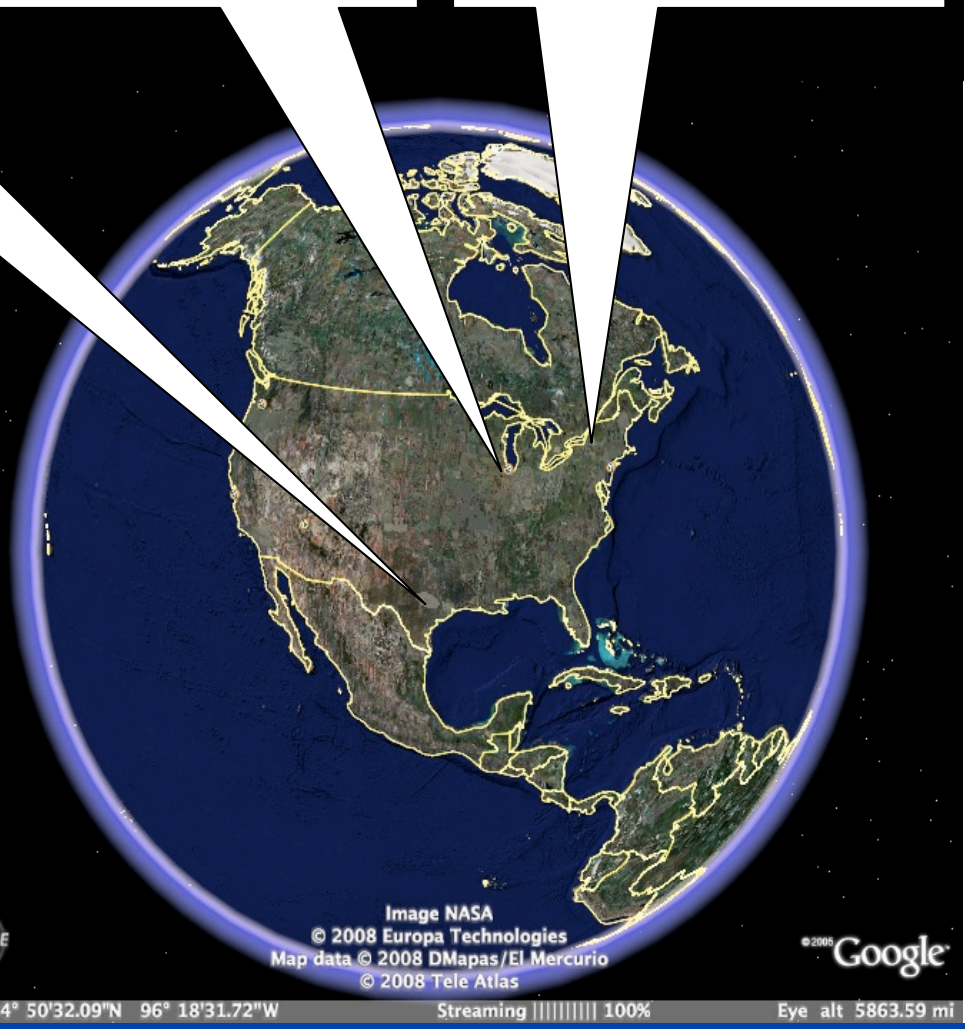
Solid Noble Element Detector R&D

1999@Japan
Successful grow of thin solid xenon to an ionization sensor using carbon graphite film

2004@TAMU
Ionization readout from solid Ar (not Xe). Failed to grow large crystals

1994@FNAL
Solid argon calorimeter detector wasn't successful

2004@Syracuse
A student grew large (~300g) scale xenon "*crystal*" everyday for medical research



Solid Xenon in Japan (1999)

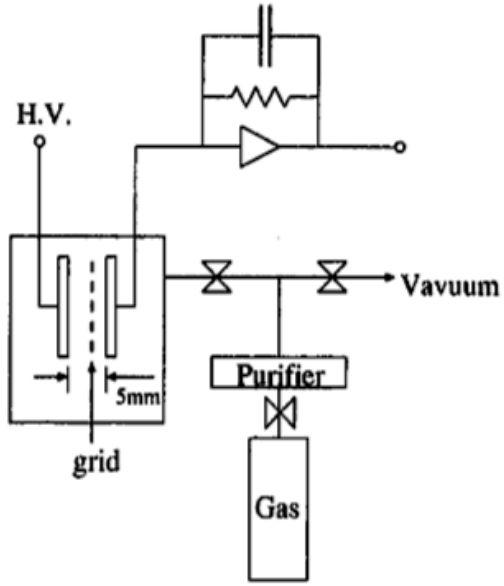
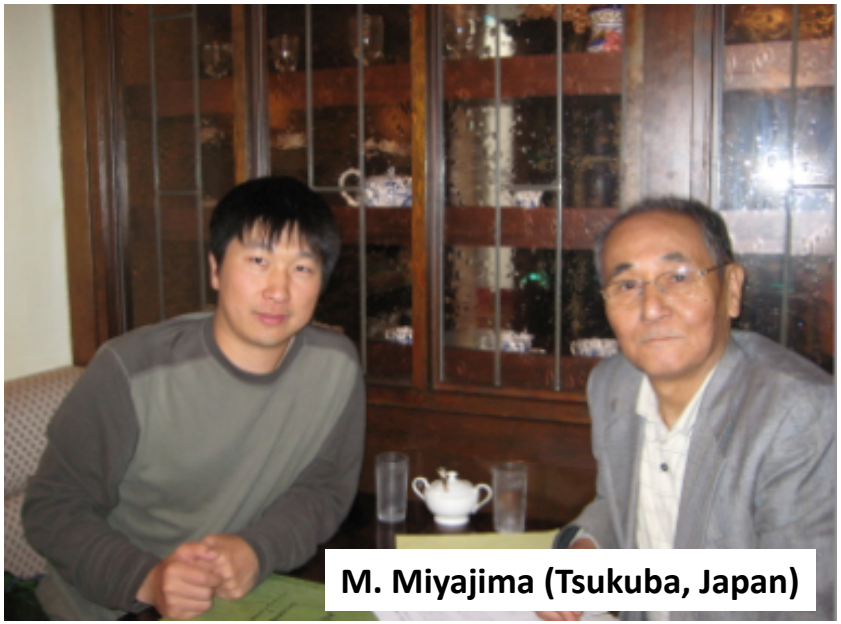


Figure 1: Schematic drawing for a solid xenon ionization chamber and a gas handling system



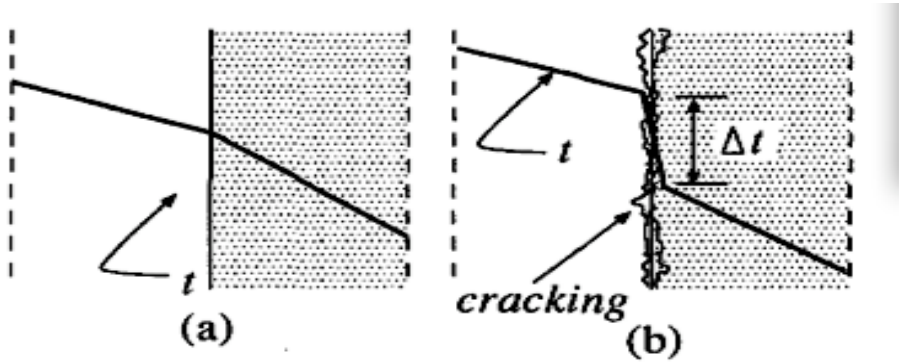


Figure 2: The temperature distribution near the contact surface of solid xenon and metal
(a).Perfect contact, (b).Imperfect contact

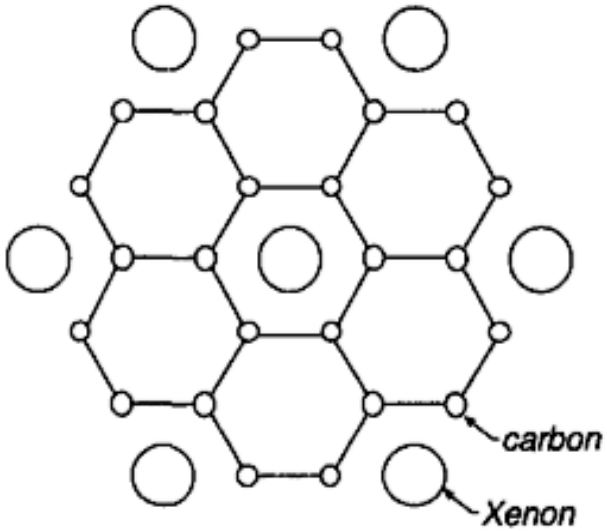
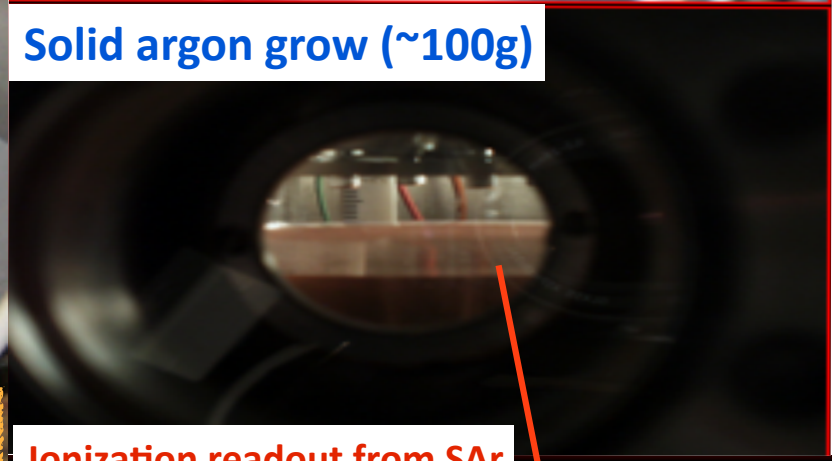


Figure 3: the first xenon layer grown on carbon graphite

Solid Xenon at Texas A&M (2004)

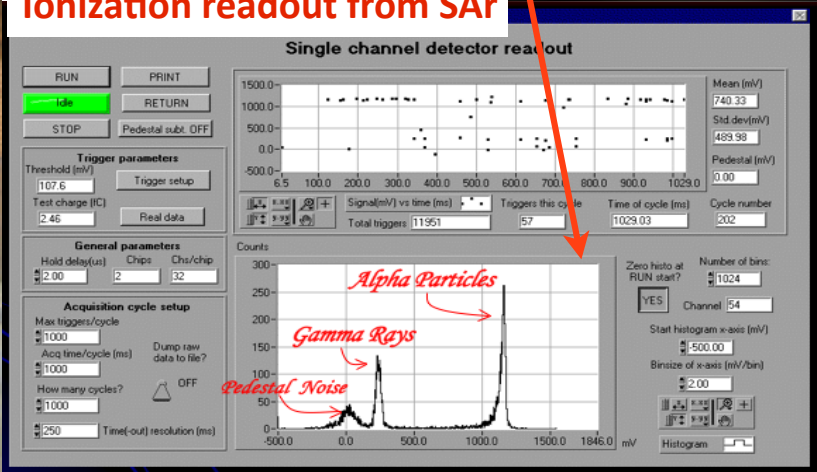
Solid xenon grow wasn't successful

Solid argon grow (~100g)



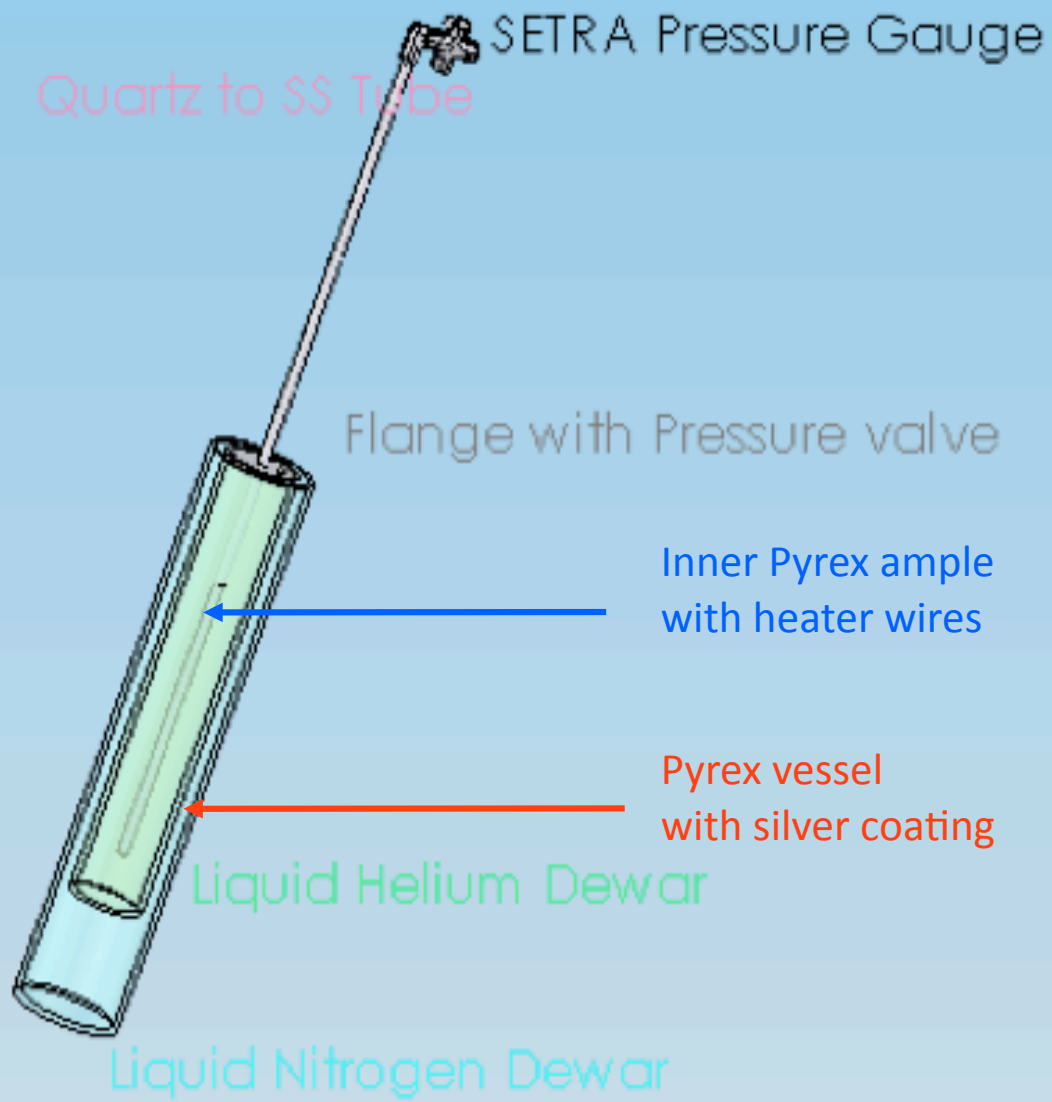
James White

Ionization readout from SAr



Americium-241 Energy Spectrum

Solid Xenon in Syracuse (2004)



- The purpose of the cryobath glass chamber was to grow hyperpolarized ^{129}Xe crystal for medical usage (MRI/NMR)

Pros

The cryobath has been used for years to grow Xe crystal
Most parts are commercially available

Cons

Syracuse decided to use the cryobath for cold fusion study

Xenon Crystal

Kramer 1976 : Epitaxial growth of xenon crystal on Carbon-graphite film

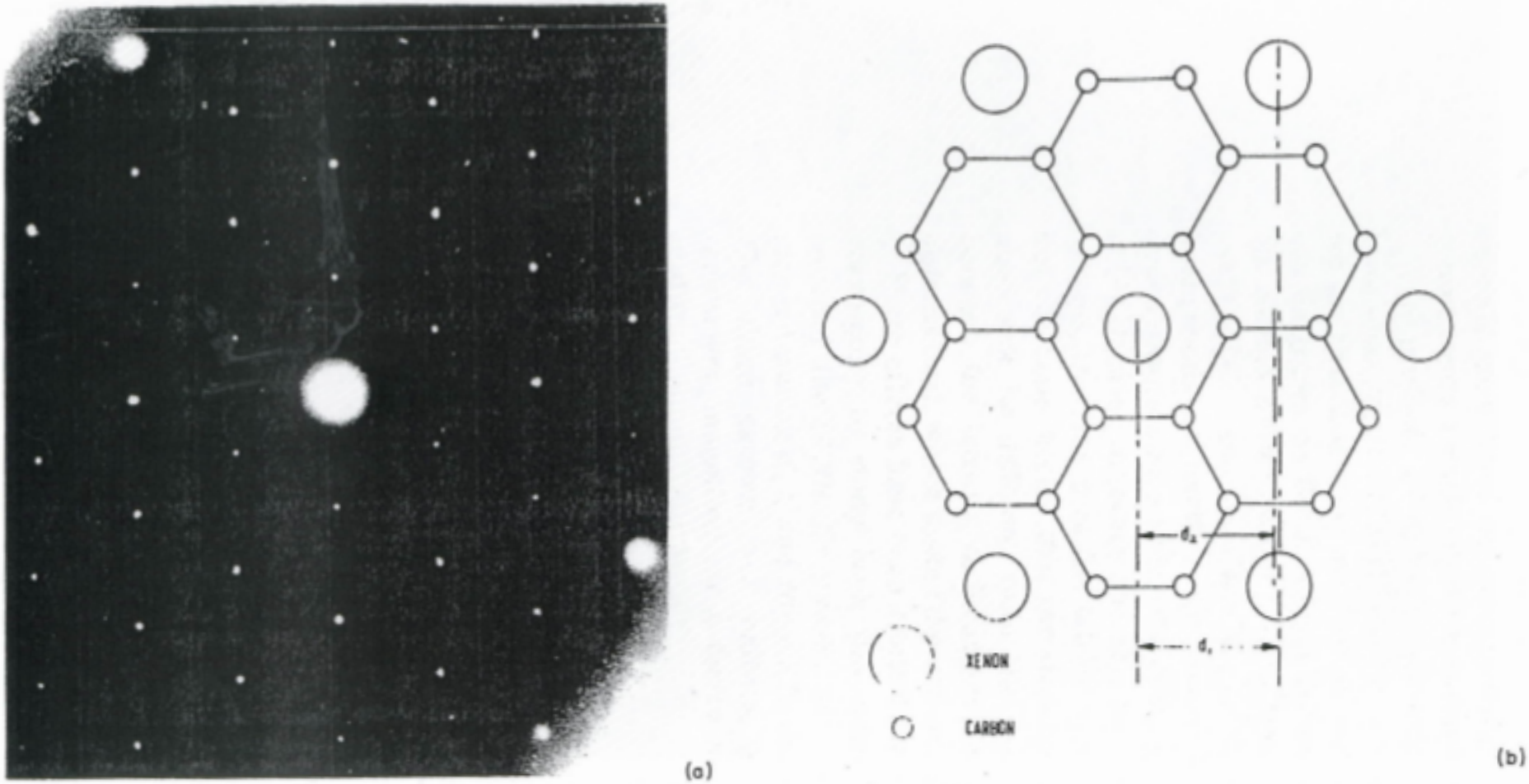


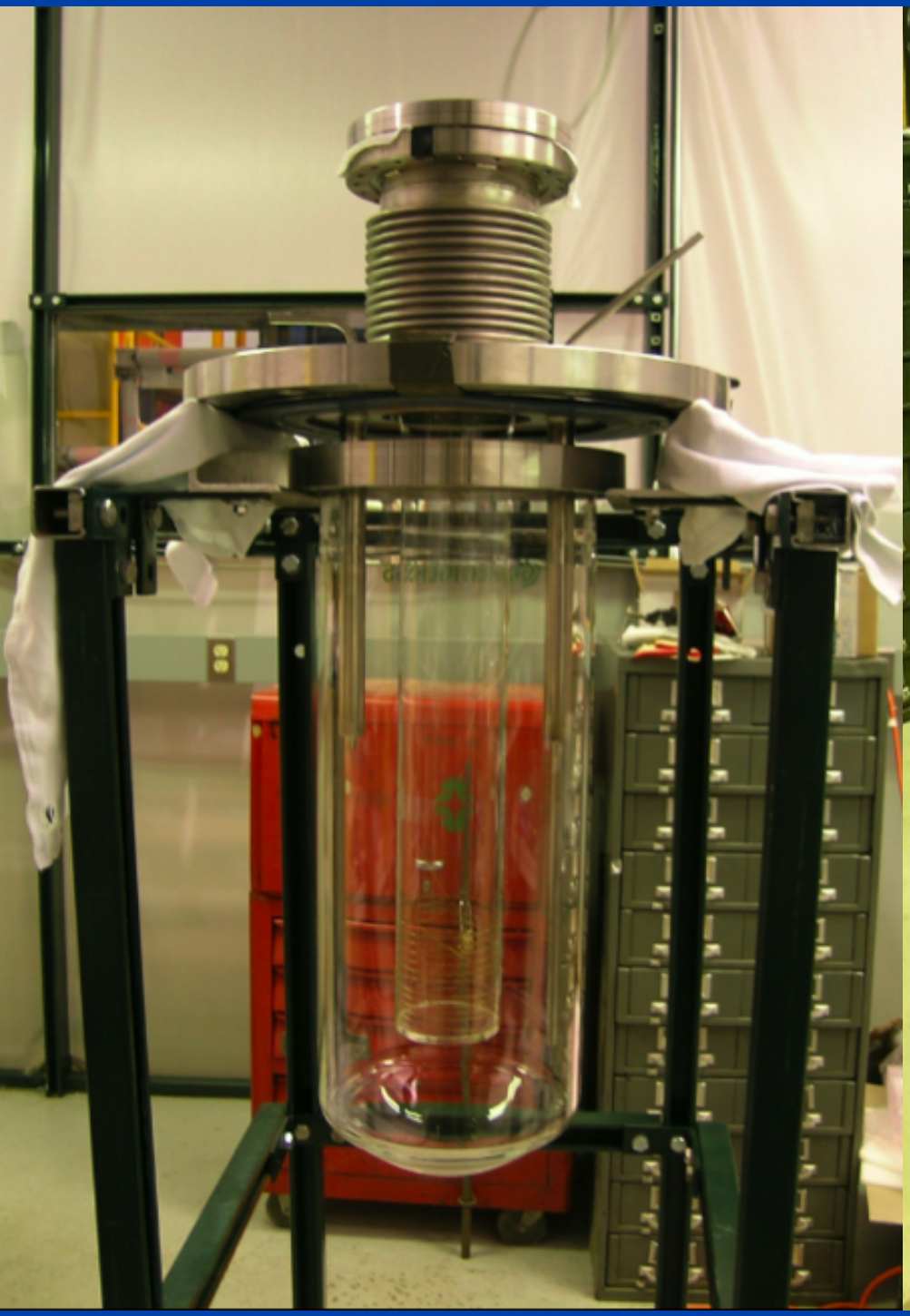
FIG. 17 (a) Electron diffraction pattern of epitaxial Xe on graphite, (b) orientation relationship between Xe and (0001) graphite, giving ($2\bar{2}0$) spacing of xenon, d_1, and (1010) spacing of graphite d_2 (Kramer, 1976).

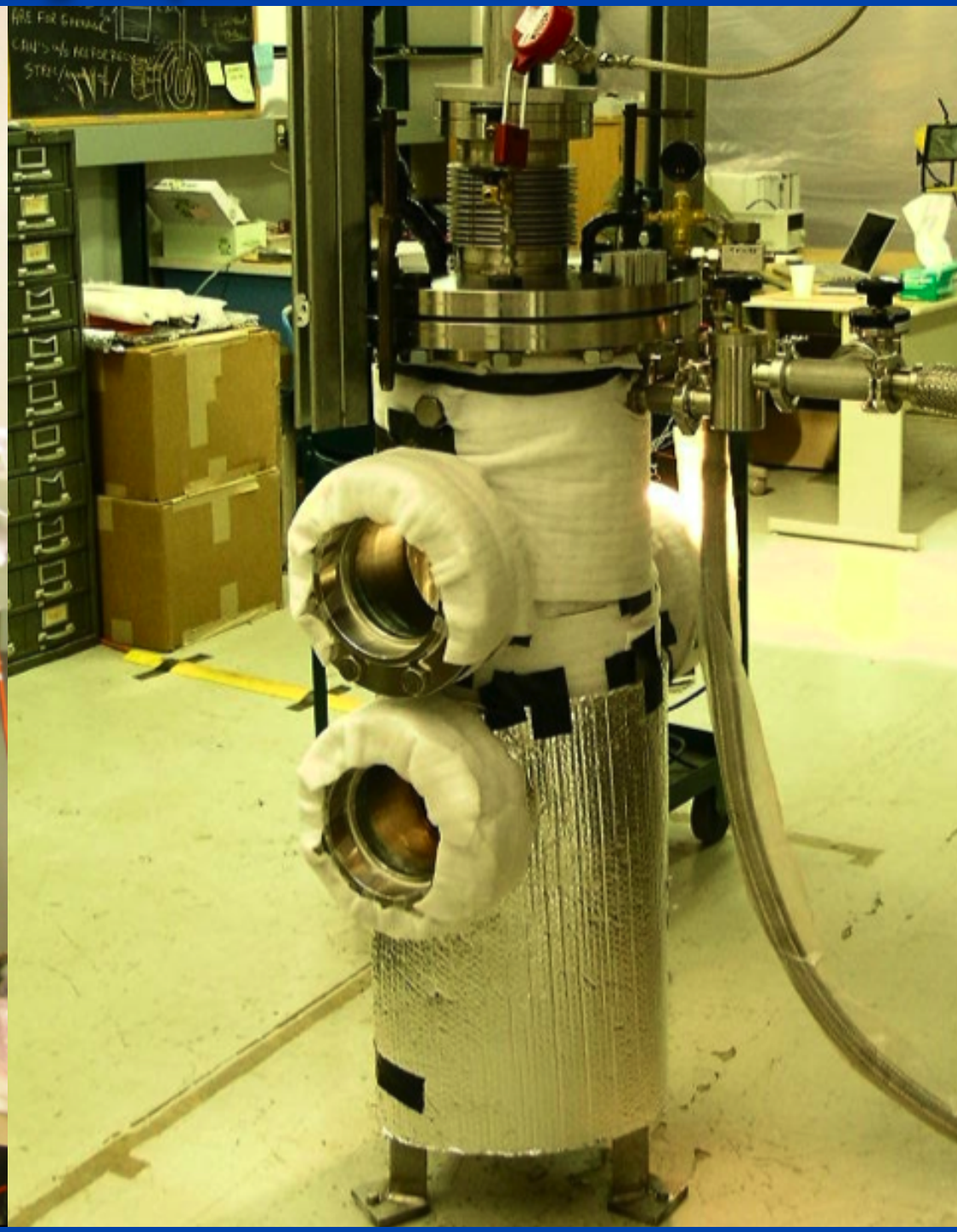
10. CRYSTAL GROWTH AND CRYSTAL DEFECTS

Solid Xenon at Fermilab

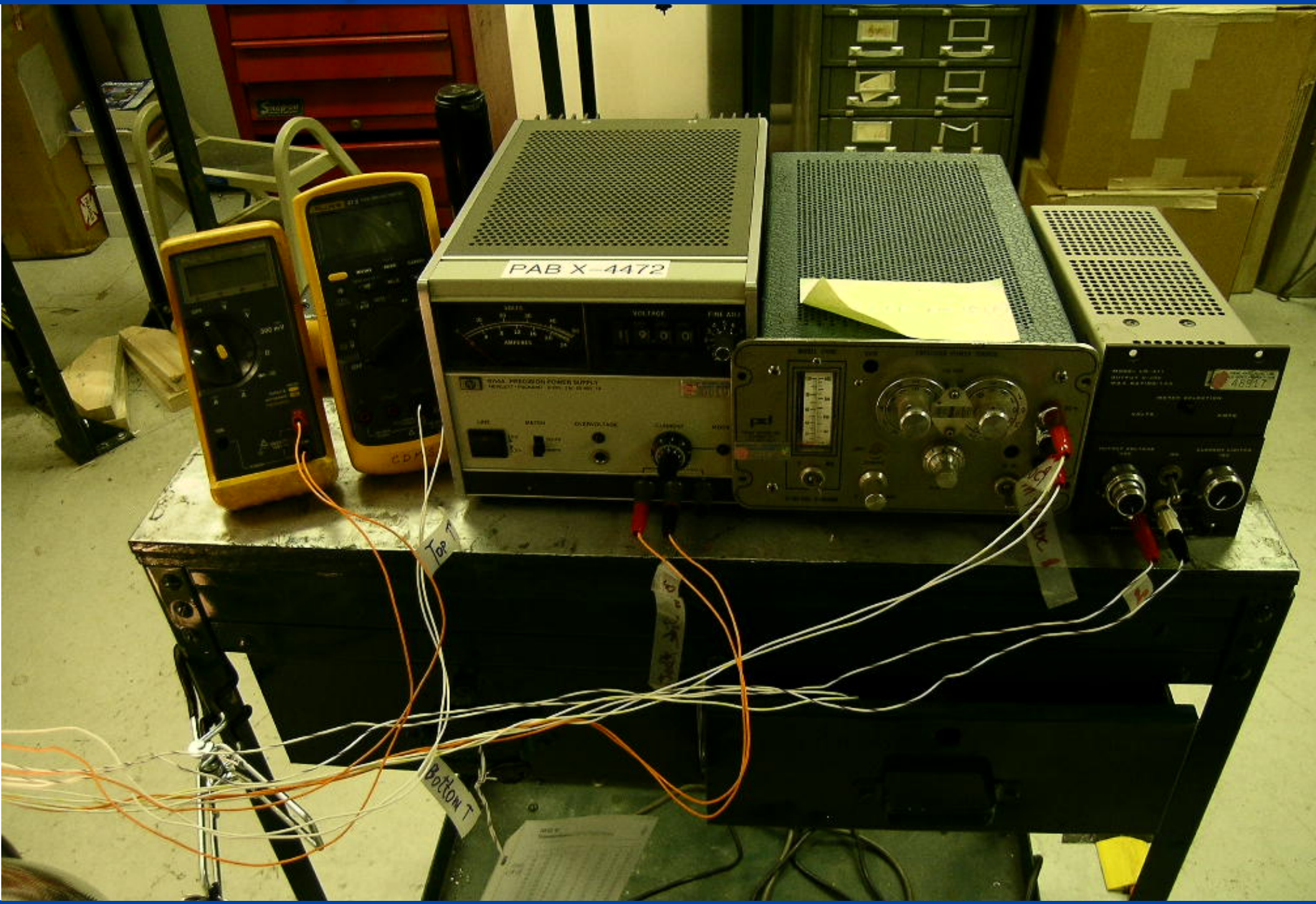
Solid Xenon Test Stand at Lab-F

Outer Glass Chamber: Cooling Liquid Volume

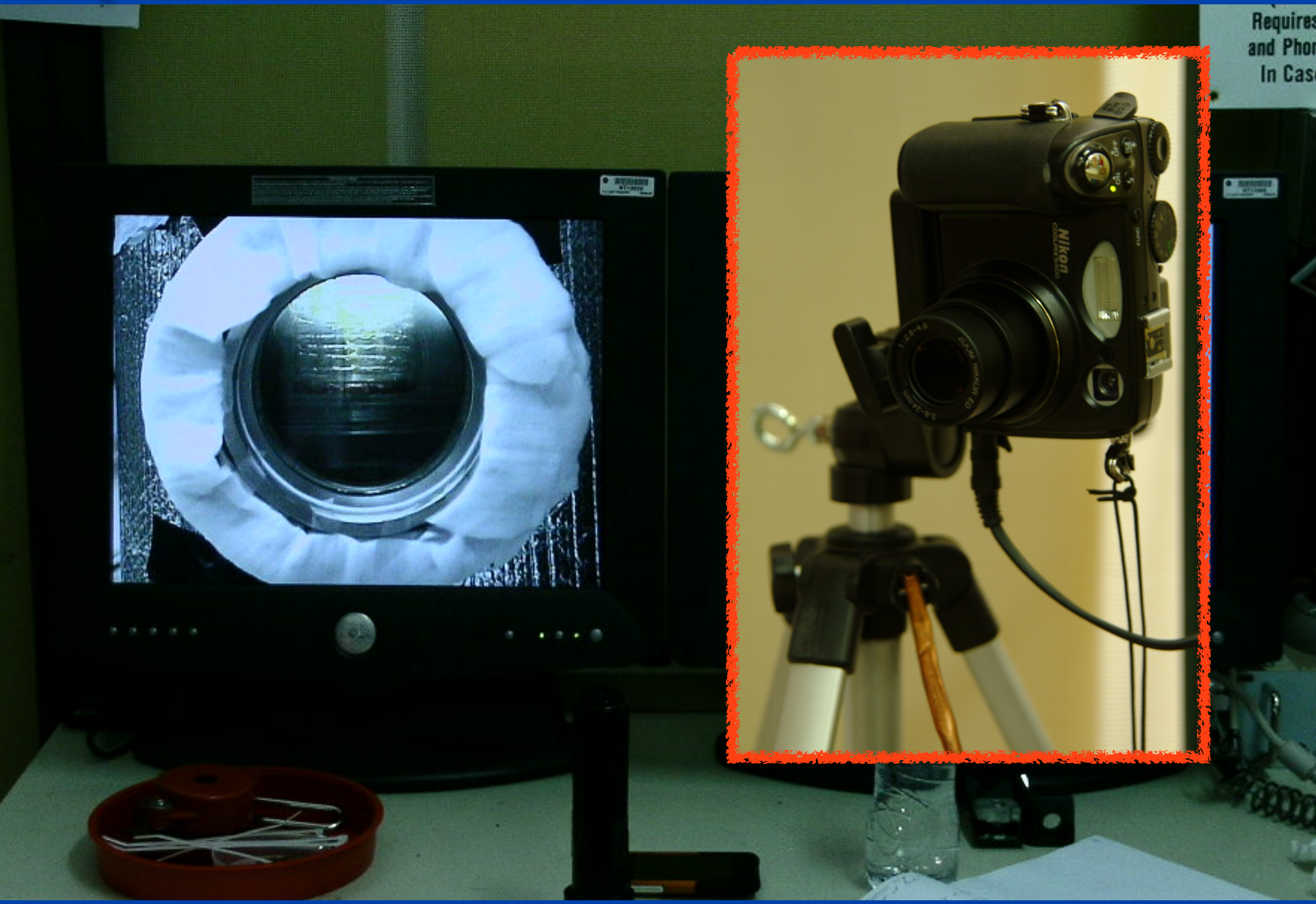




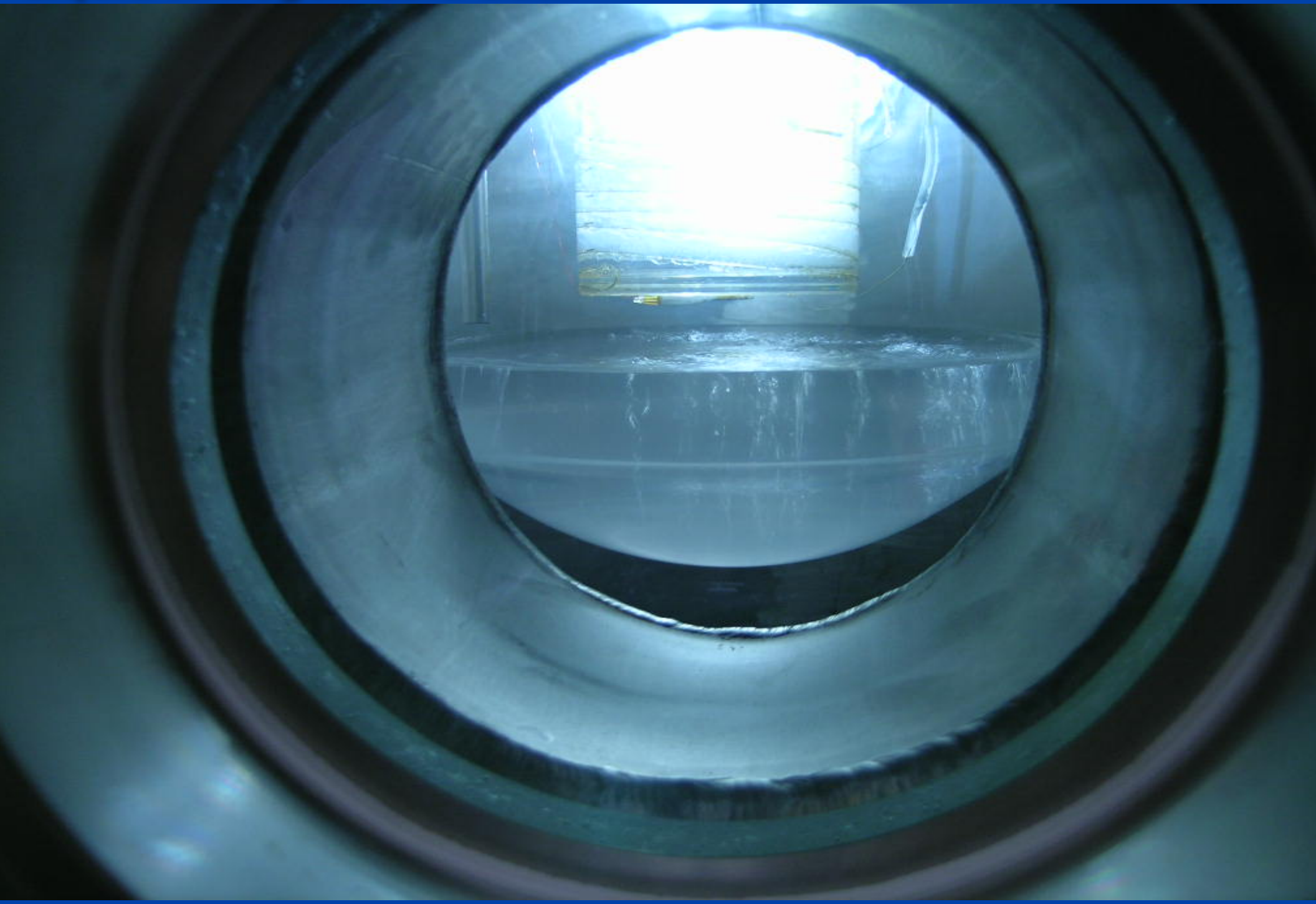
Slow Control System



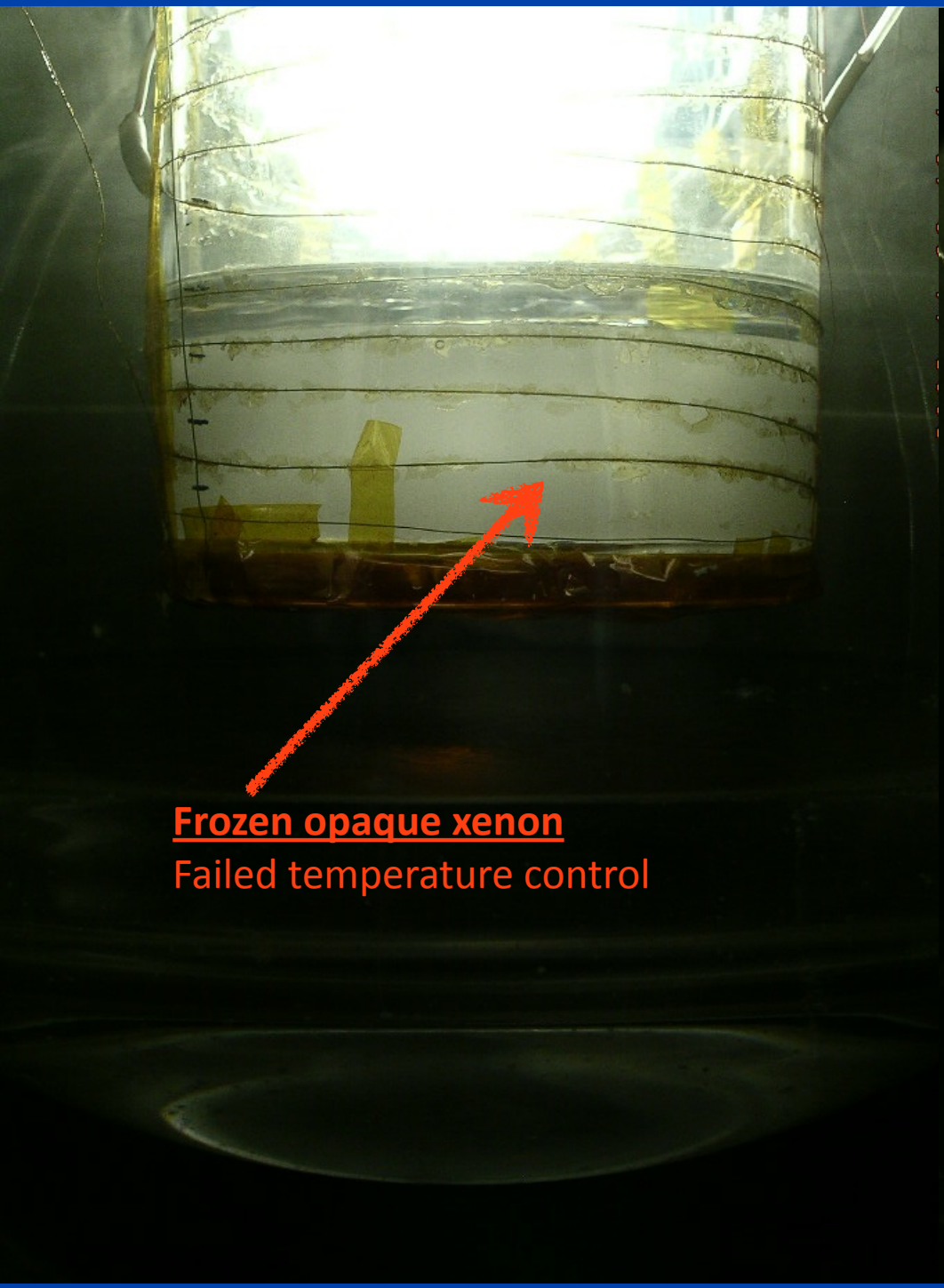
DAQ



Liquid Nitrogen Cold Bath



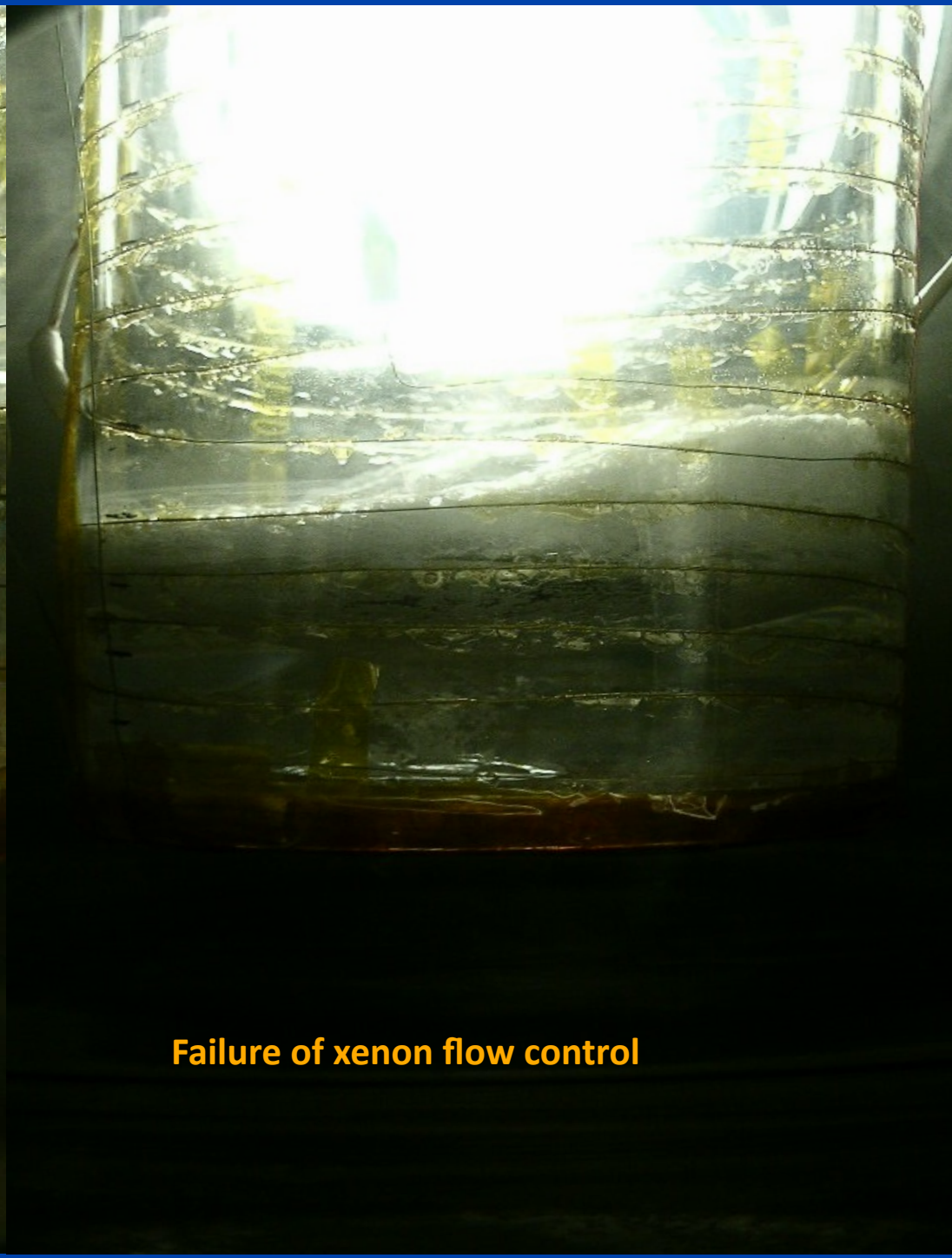
Failures


Frozen opaque xenon
Failed temperature control

Frost xenon layers
Failed pressure control

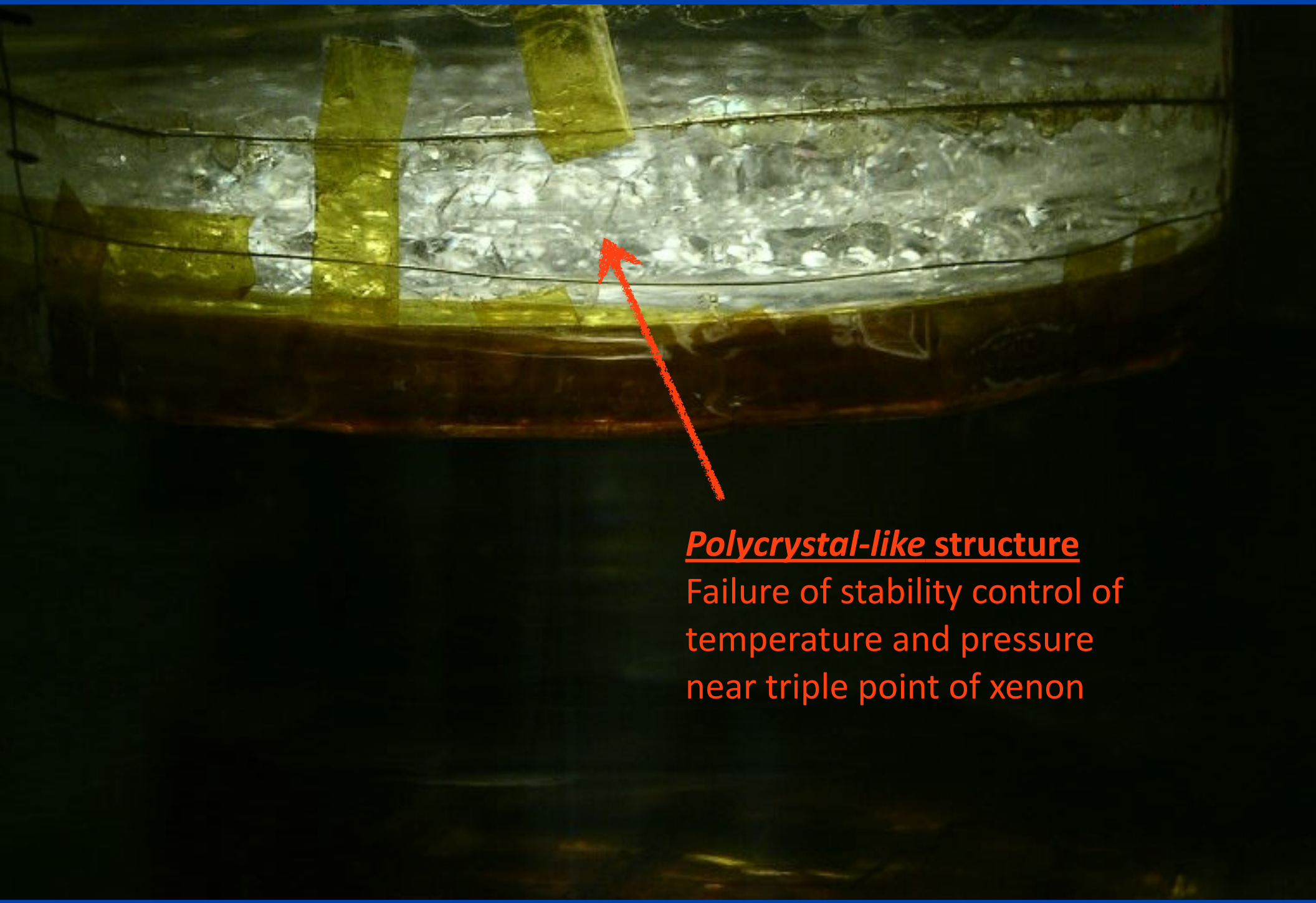
Failures

Failure of liquid nitrogen level control



Failure of xenon flow control

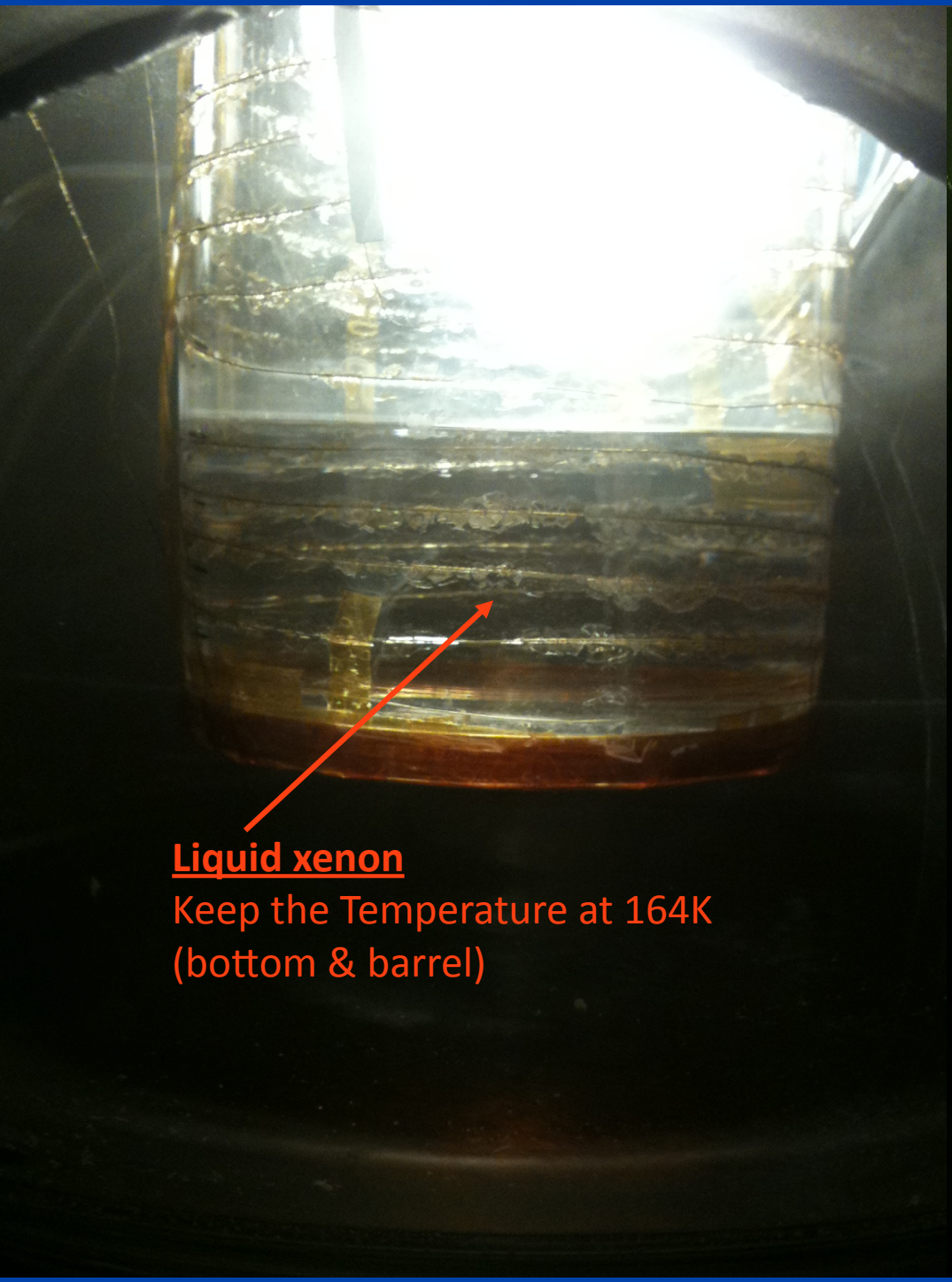
Failures



***Polycrystal-like* structure**

Failure of stability control of temperature and pressure near triple point of xenon

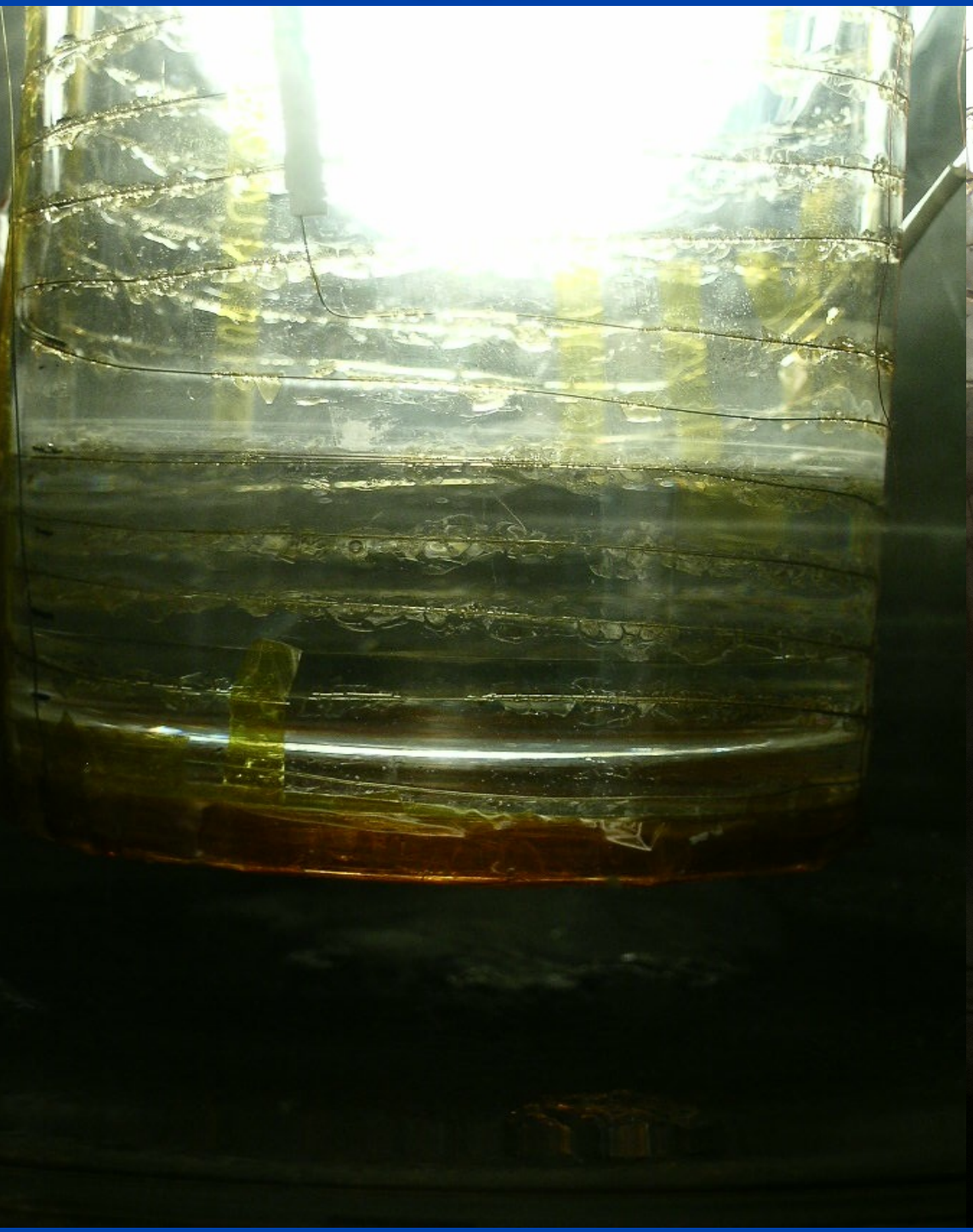
Solid Xenon Grow



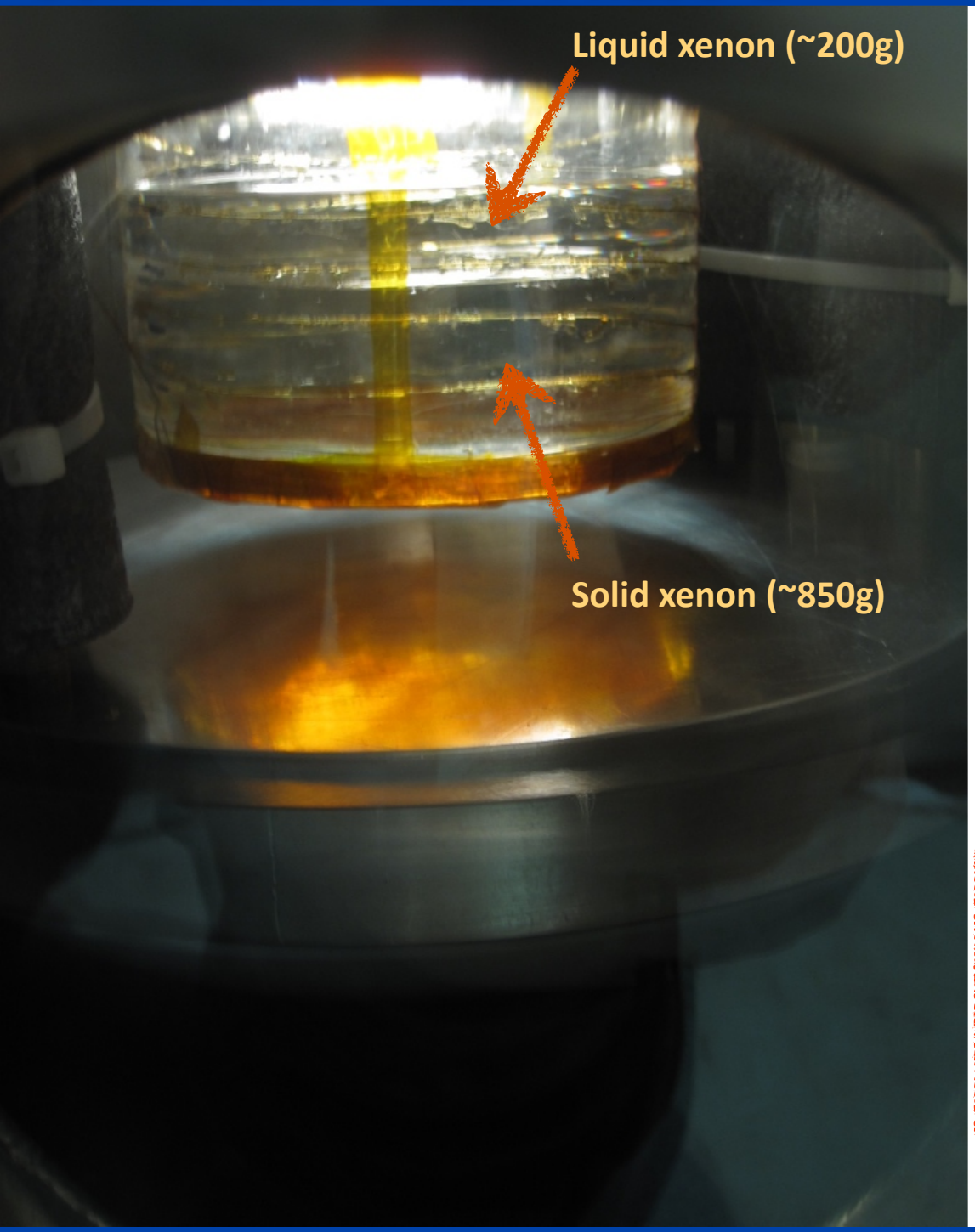
Liquid xenon
Keep the Temperature at 164K
(bottom & barrel)

Solid xenon grow!
Keep the temperature :
- @160K (top&barrel)
- @145K (bottom)

Solid Xenon Grow



Solid Xenon R&D Phase-1



Fermilab Center for Particle Astrophysics (FCPA)
New Initiative R&D Project

Phase-1 Goal: demonstrated ~1kg size of optically transparent solid phase of xenon

Collaboration with

T. Saab, D. Balakishiyeva (U.Florida)
R.Mahapatra (TAMU)

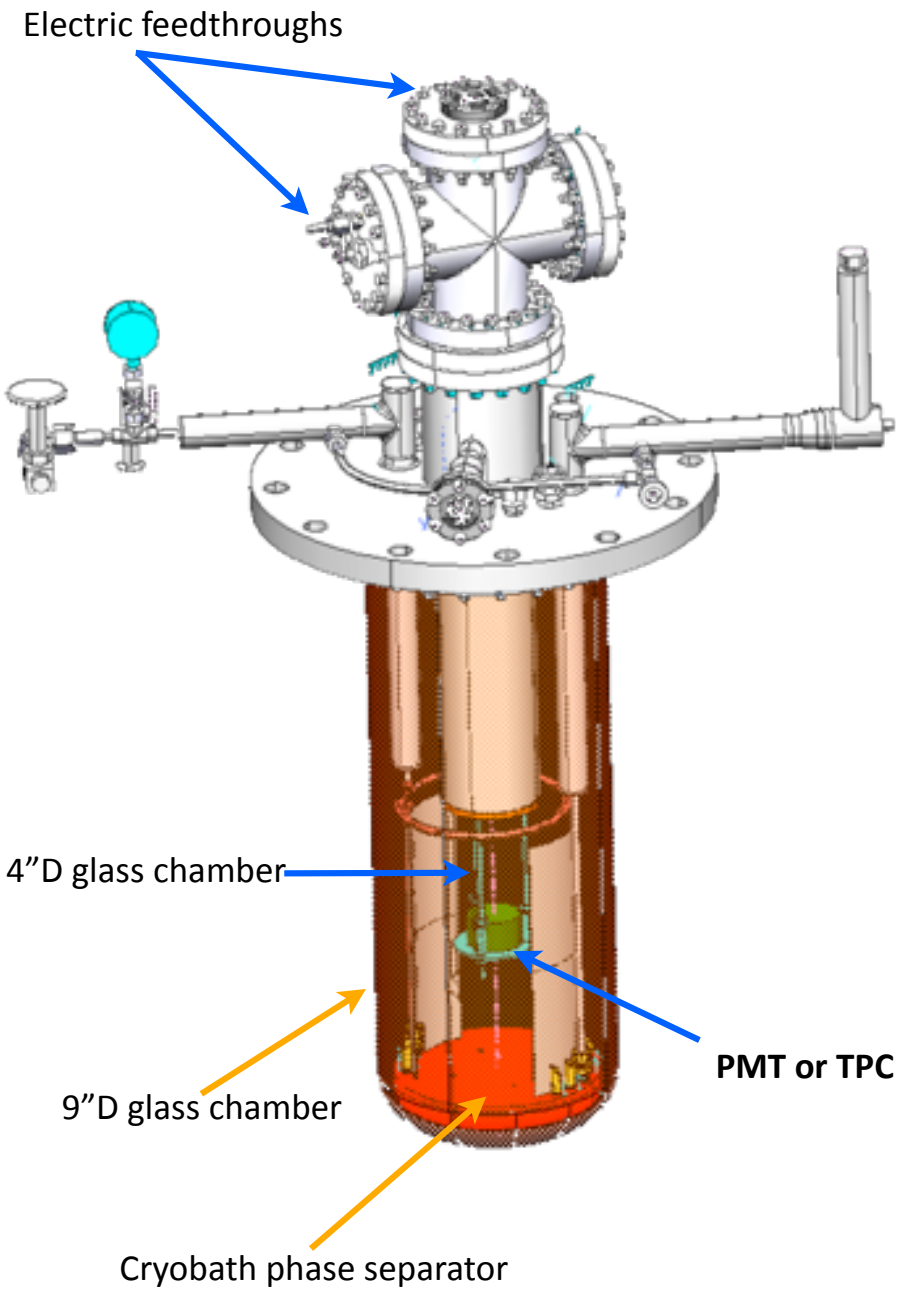
Established Recipe

Top T : 160 ± 0.5K
Bottom T : 145 ± 0.5K
Xenon gas pressure : 1.0 ± 0.1 atm
Patience : 3cm growth / 10 hours

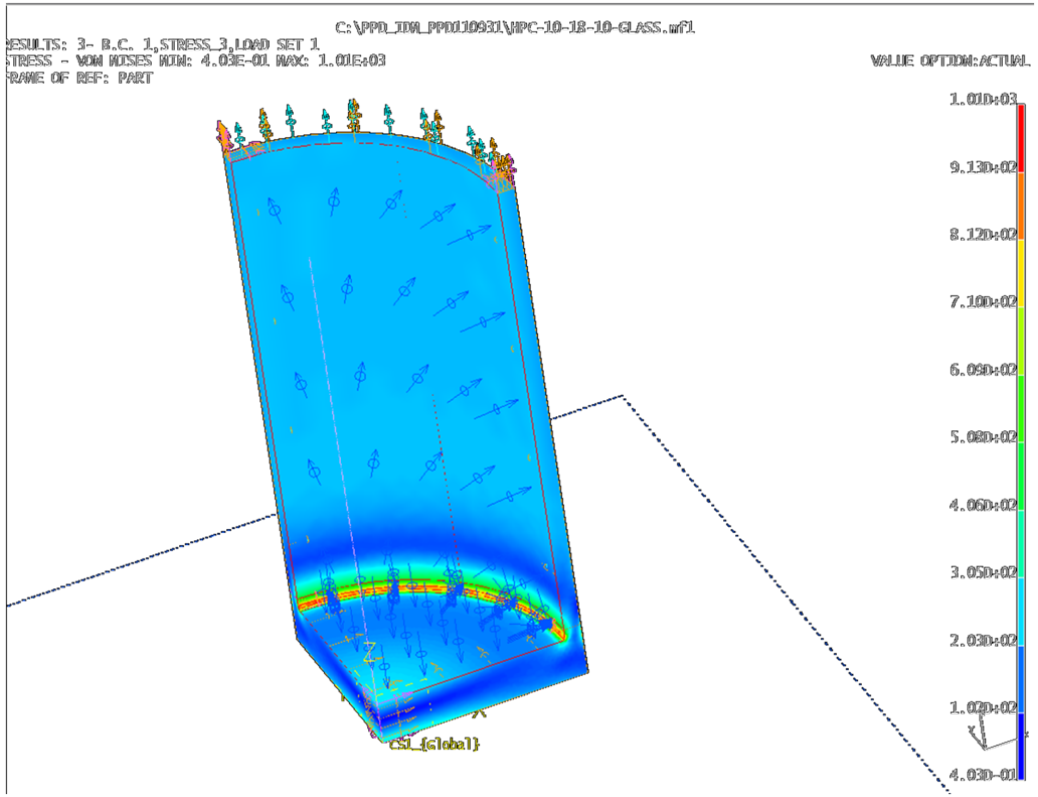
Phase-2

- Fermilab Particle Physics Division (PPD) review panel approved Phase-2 (2010)
  (1) Automate process
  (2) Scintillation & Ionization Readout

Solid Xenon R&D Phase-2



- New design of inner glass (xenon) chamber and electric/gas feed throughs
- Address safety concerns of using glass chamber system
- Engineering support from Fermilab PPD



Glass chamber pressure simulation (H.Cease)
Max. allowed pressure < 17.5 psig

Gas purification/analysis system

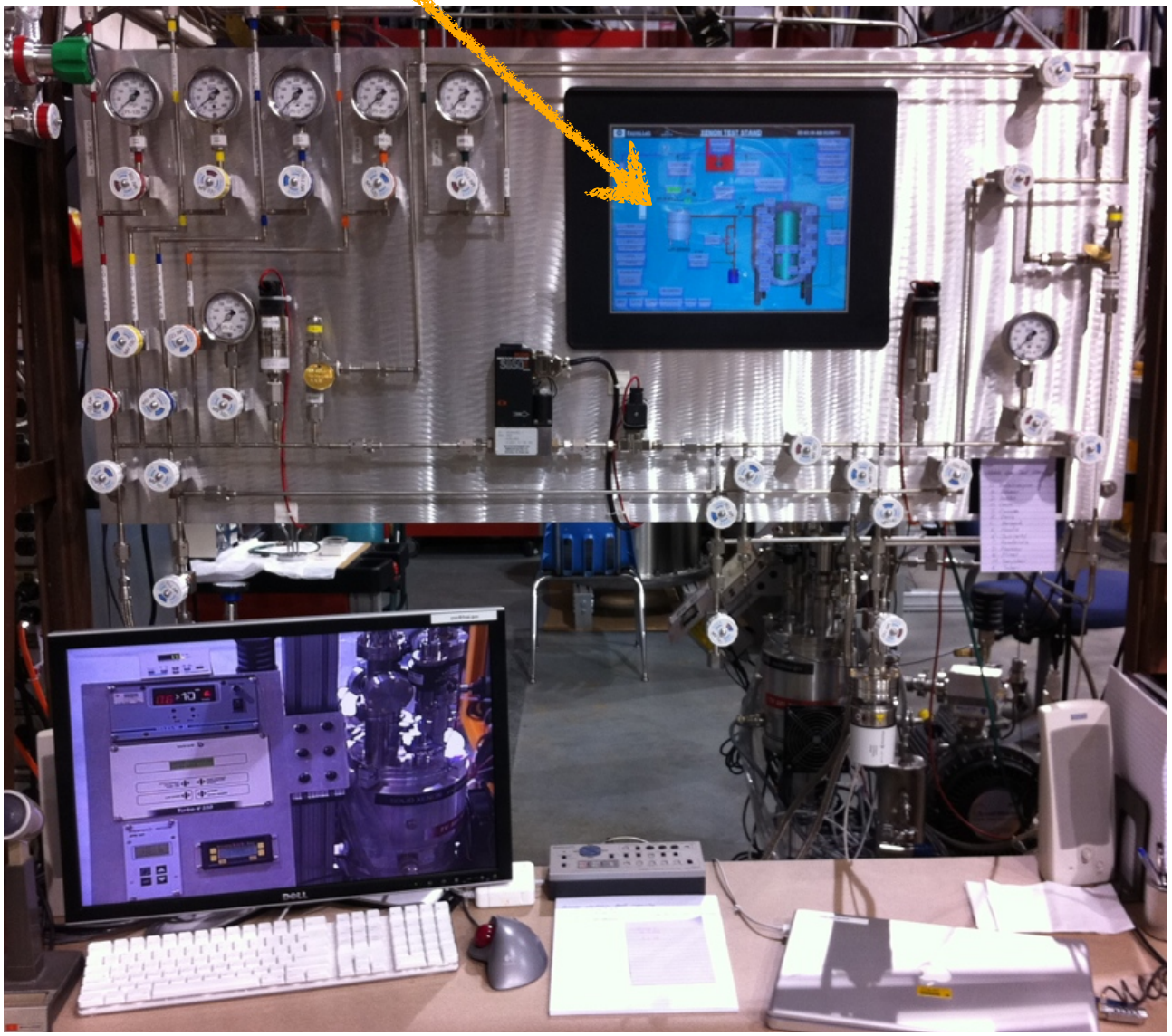
Noble Gas Purifier (U.Florida)

Residual Gas Analyzer (RGA)

Automatic control system

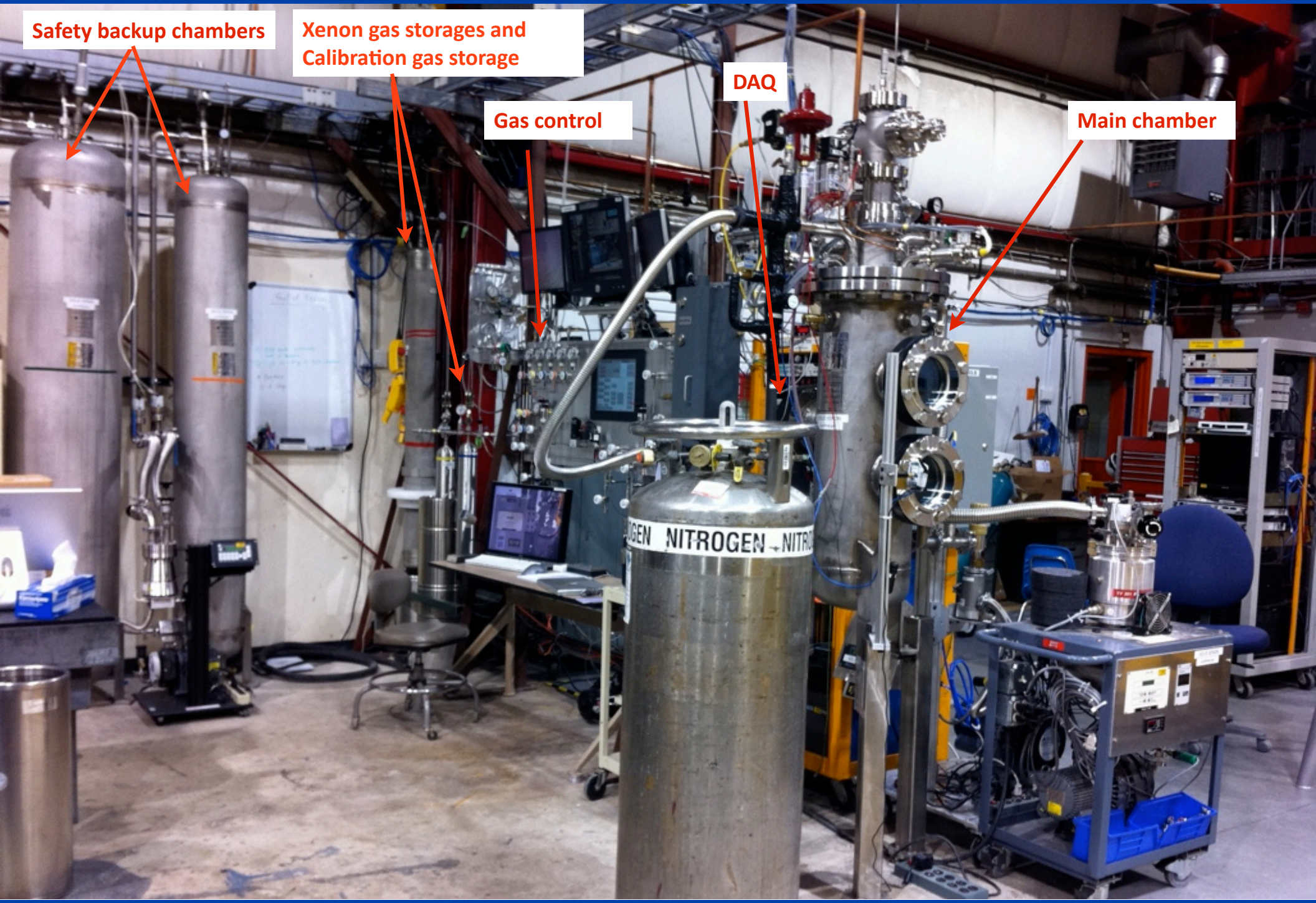
Touch screen control unit

Cryobath level, temperature, pressure and flow rates control
Monitoring (graph) tools, remote control (D.Markley)

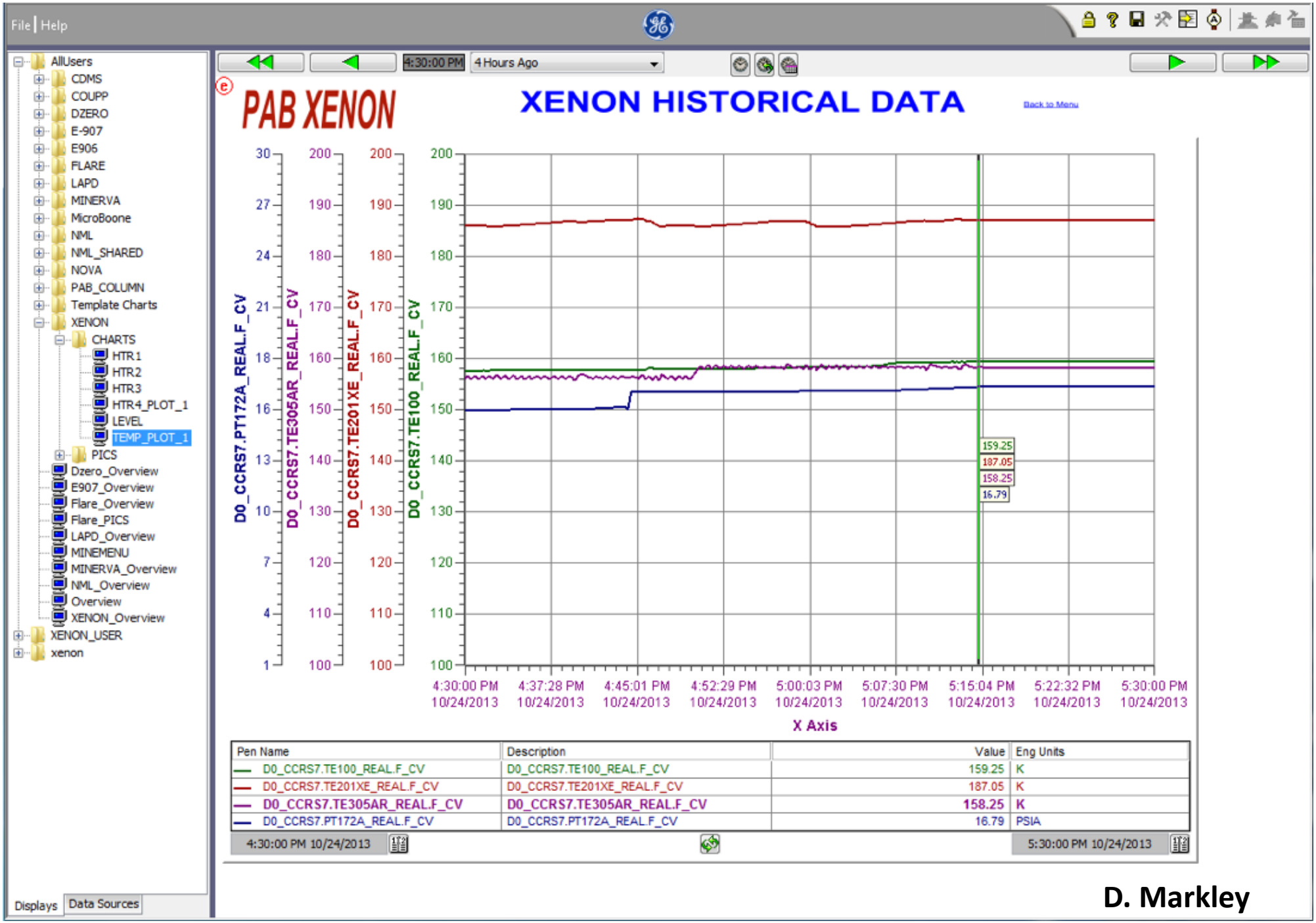


Programmable Logic Controller (PLC)

Solid Xenon Phase-2 Test Stand: Fermilab PAB

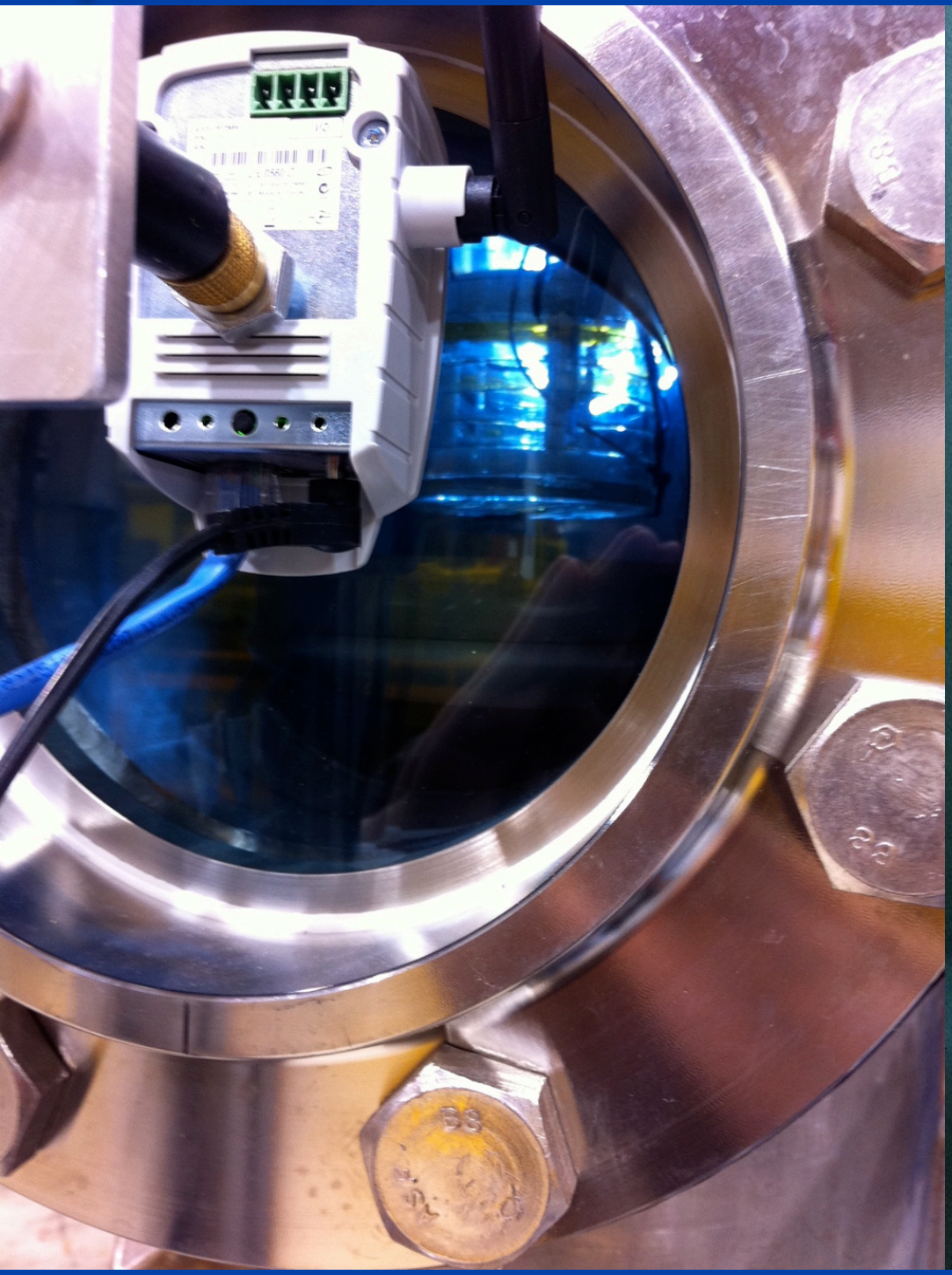


Slow Control Monitor



D. Markley

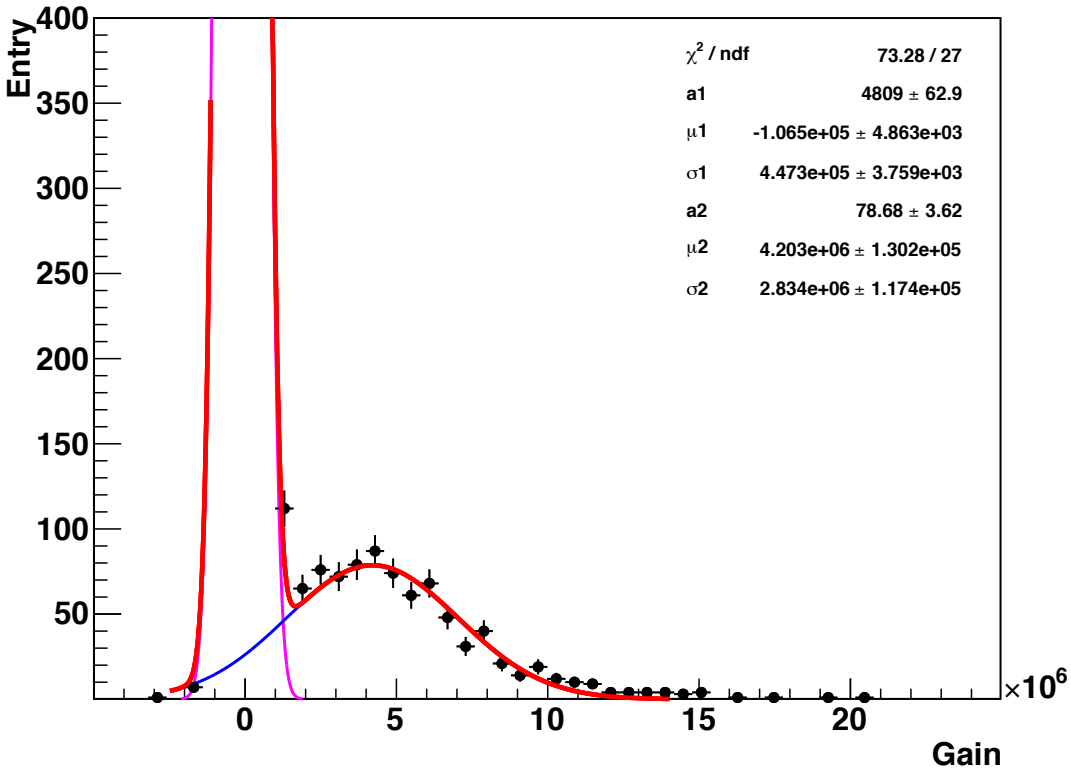
System Test

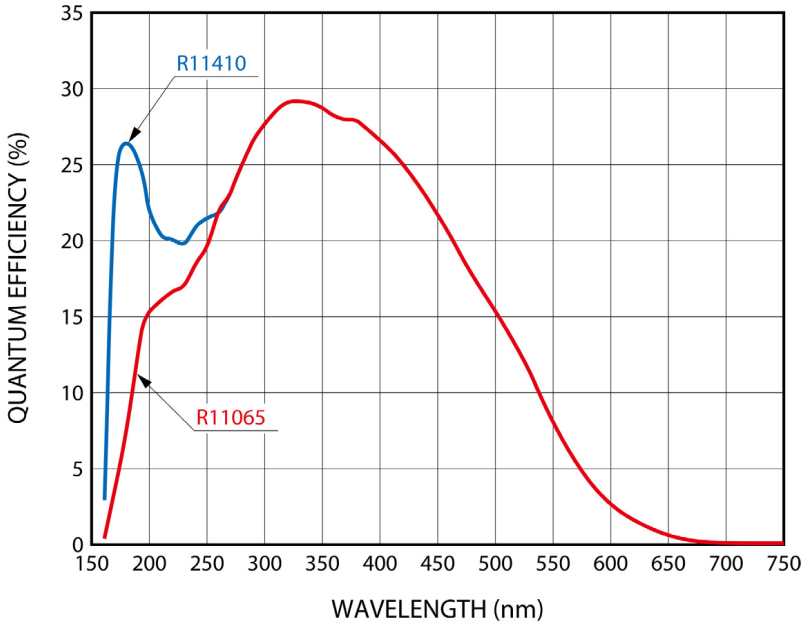


Photomultiplier

Hamamatsu R6041-06MOD

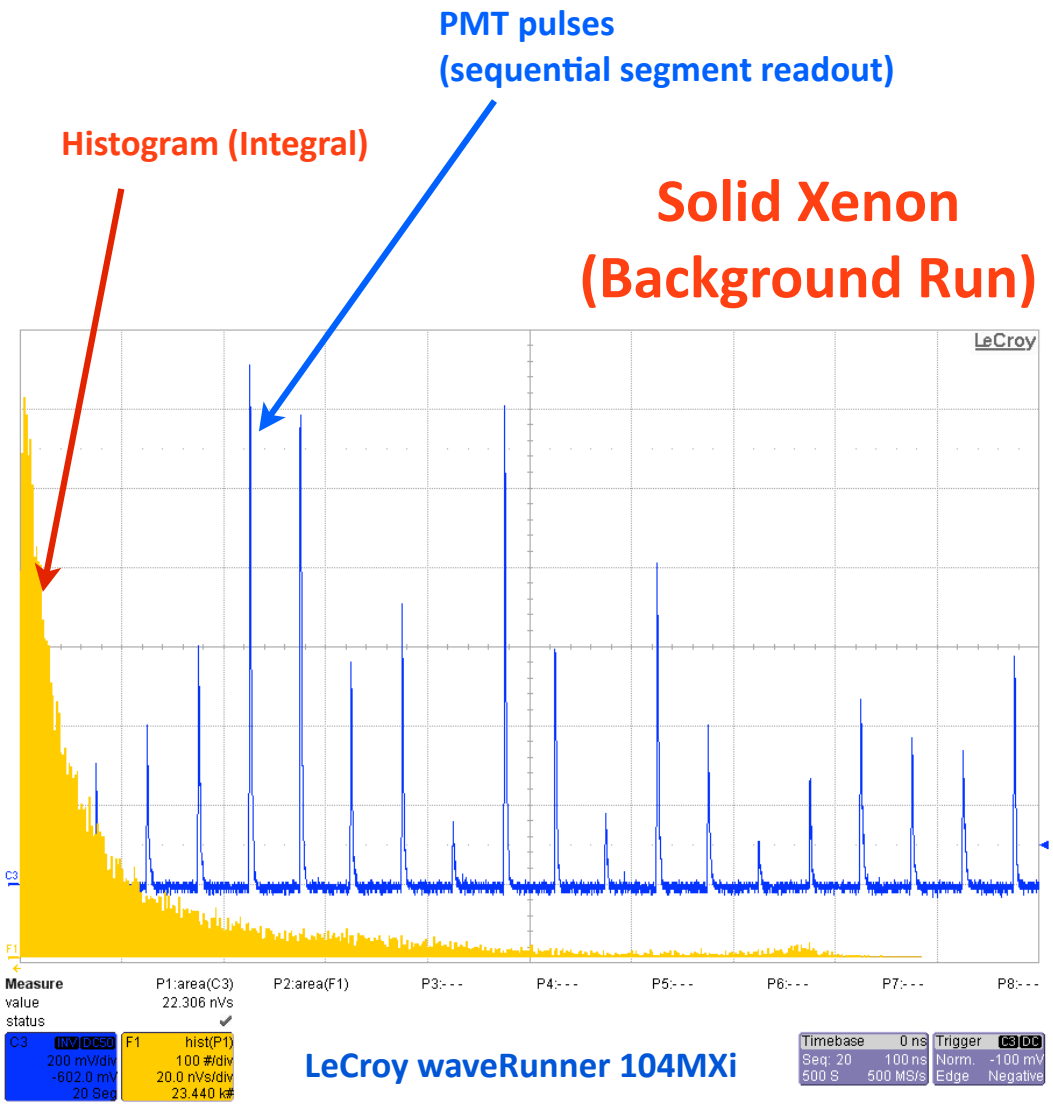
- Photocathode diameter: 2 inch
- Spectral response 169 ~ 650 nm
- Operating ambient temperature : 163K ~ 323K
- Quantum Efficiency at 175nm : ~20%
- Gain : ~10^6
- Anode pulse rise time : 2.3 nsec
- Weight : 95g
- Pressure resistance : 5 atm





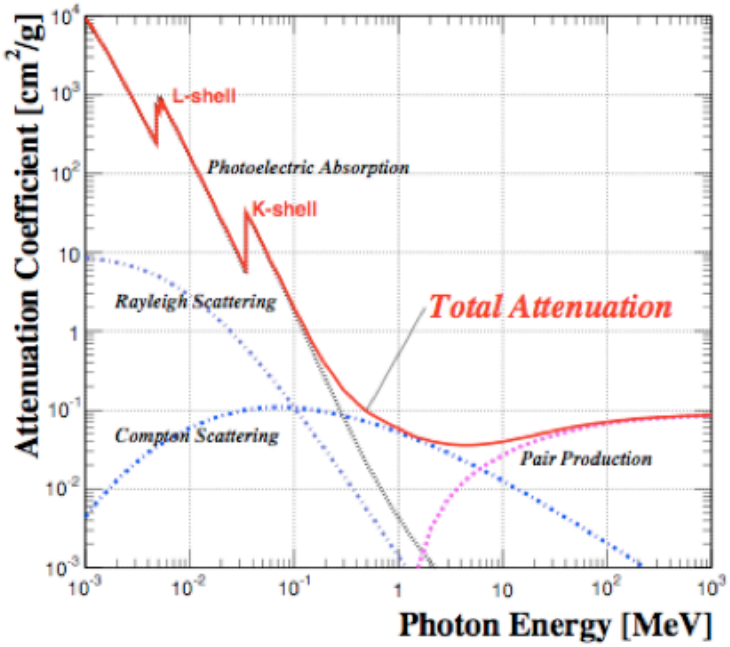
Single p.e. calibration (V. Anjur, IMSA)
in cold temperature
G = 4.2e6 (@860V, 160K)
or 33.6pVs at s.p.e

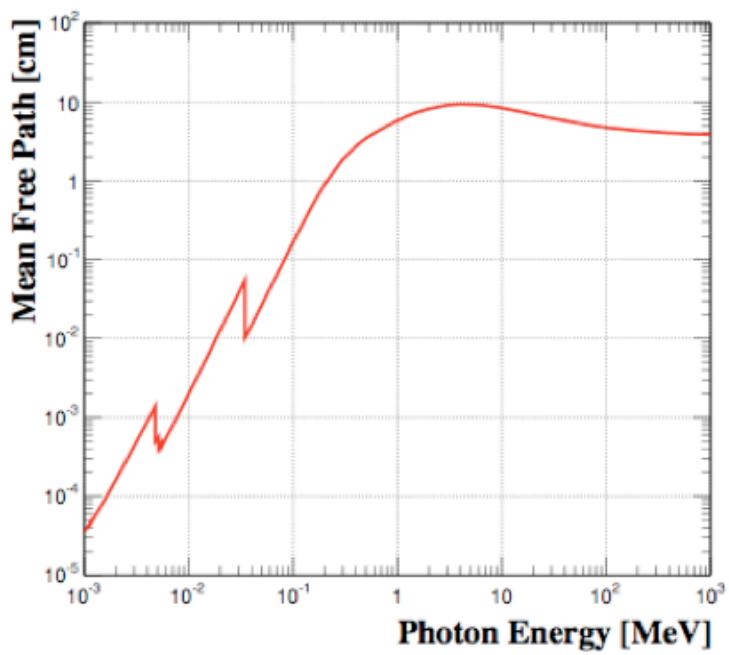
System test: Scintillation Light



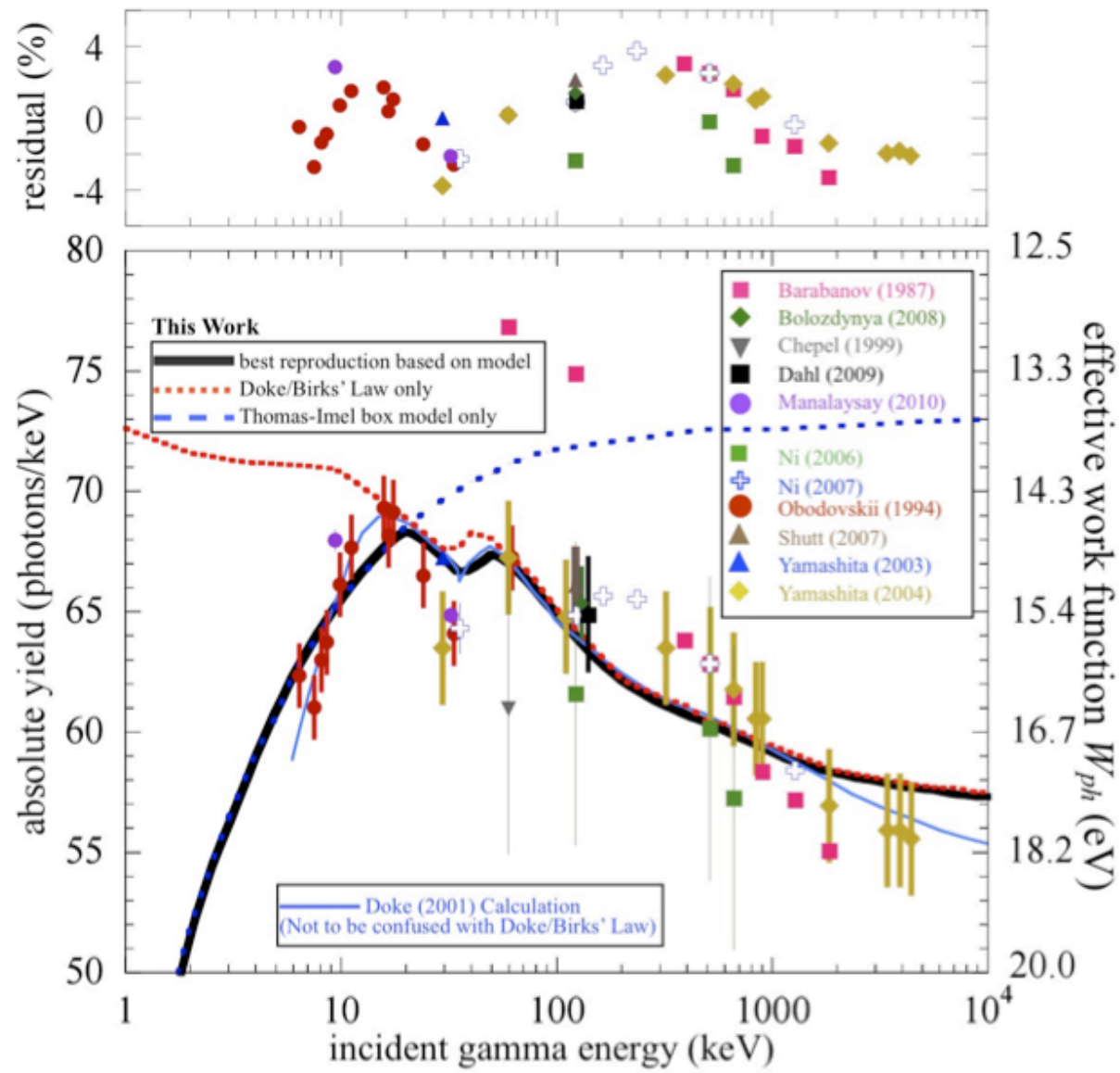
- Initial test of scintillation light readout
- Research grade xenon (<ppm for H_2O, O_2, N_2, …)

Attenuation Length and Light Yield



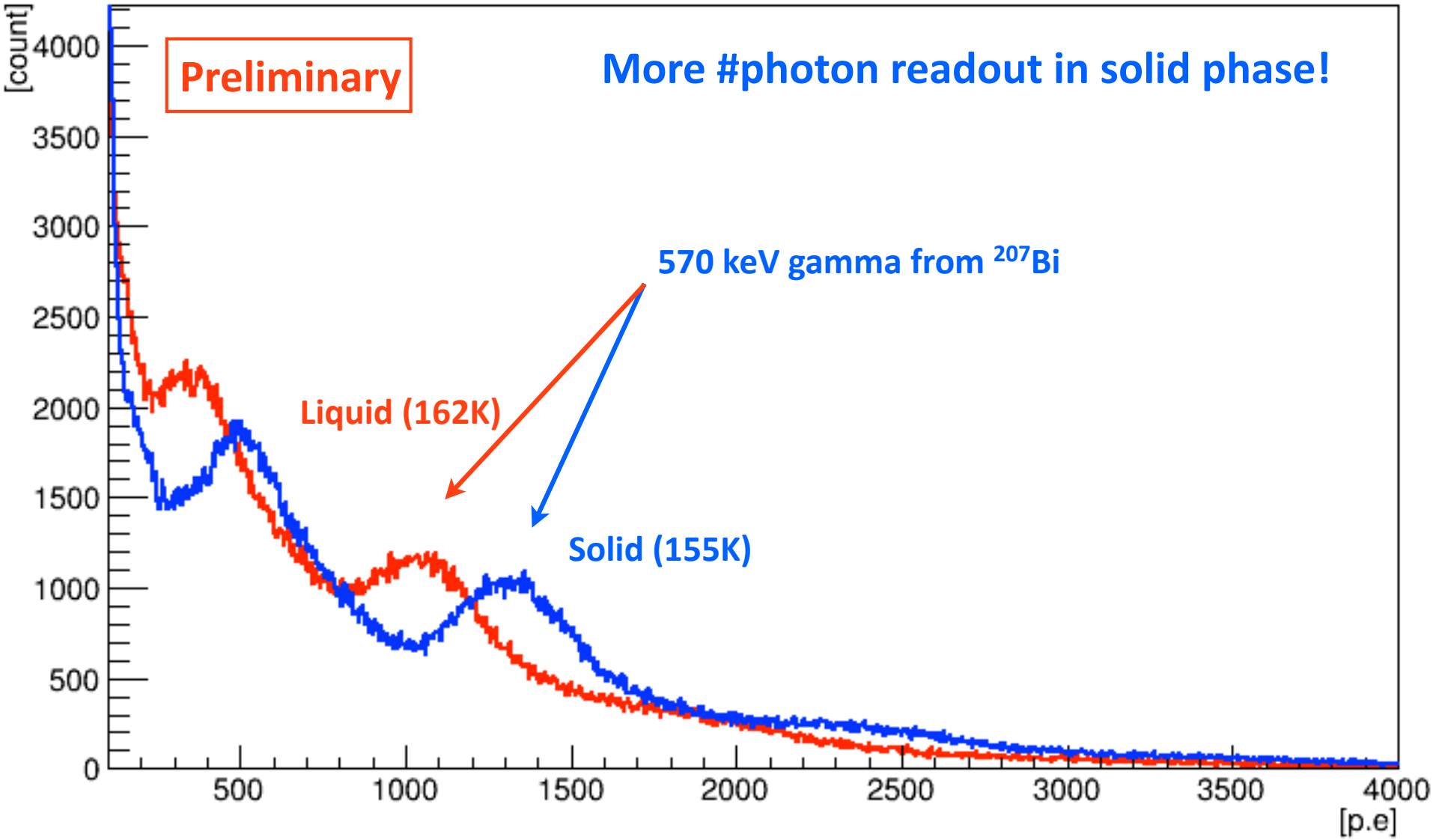


Light yield in *liquid xenon*



Scintillation Light Readout in Solid Xenon

Single PMT detector, 15psia



Does this mean more light yield in solid?

For example: Light Yield in Solid Neon

R.A. Michniak NIM A 482 (2002) 387–394

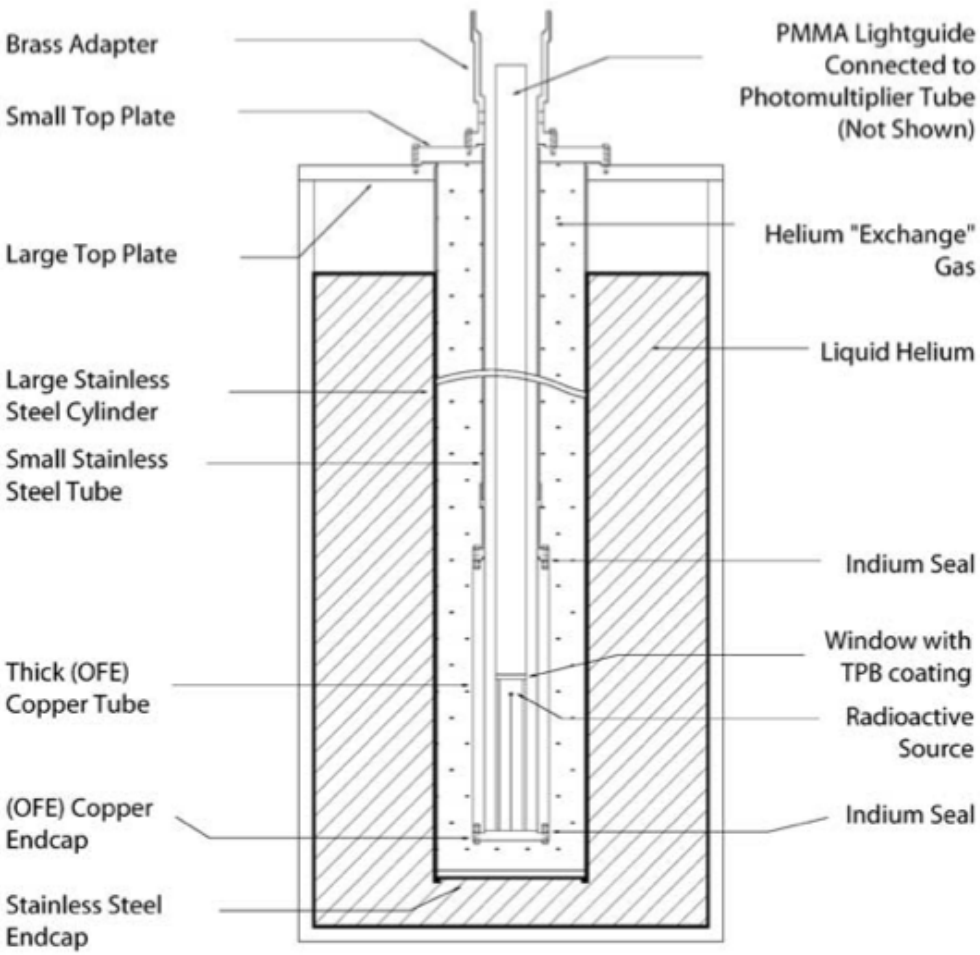


Fig. 1. Apparatus used to measure light yield from scintillations in helium and neon.

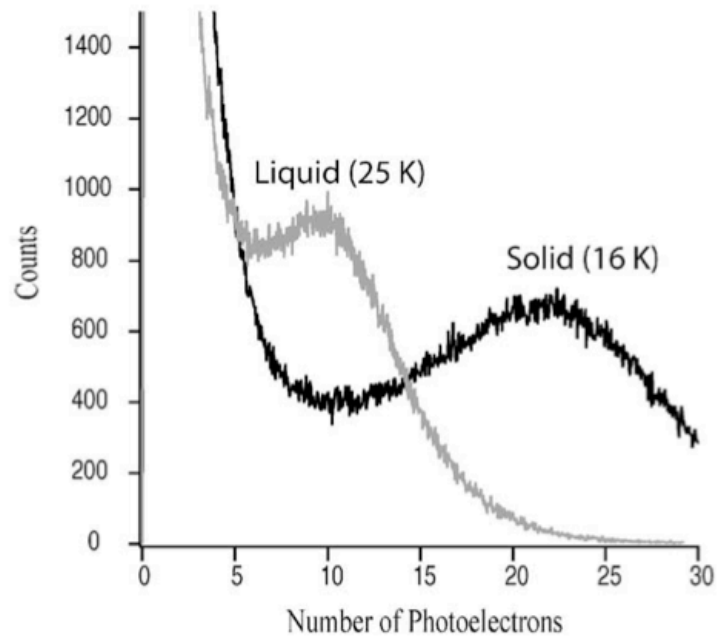
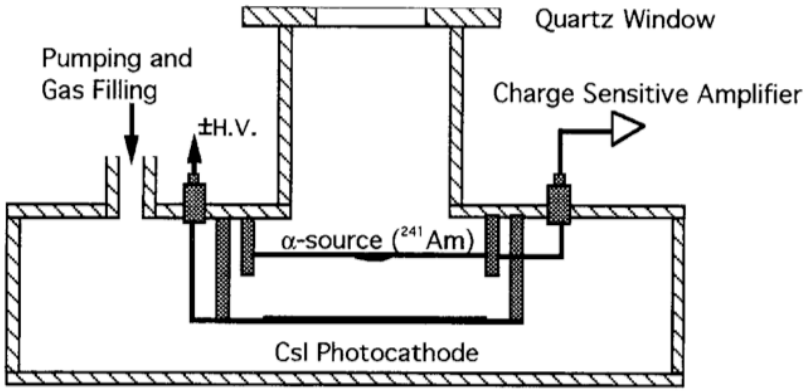


Fig. 4. Photoelectron peak from liquid neon (left) at 25 K and solid neon (right) at 16 K due to scintillations induced by a 0.5 kBq ^{113}Sn beta source (364 keV).

We might further speculate that the greater density of the liquid compared to the gas favors non-radiative quenching of the excited state. Perhaps the lower temperature and more regular structure of the solid make various quenching reactions less favorable compared to the liquid and thus account for the greater light yield observed in the solid. A more detailed study would be required to confirm or reject any of these speculations.

For example: Photoelectron Measurement in Solid Xenon

Aprile et al, NIM A 353 (1994) 55-58



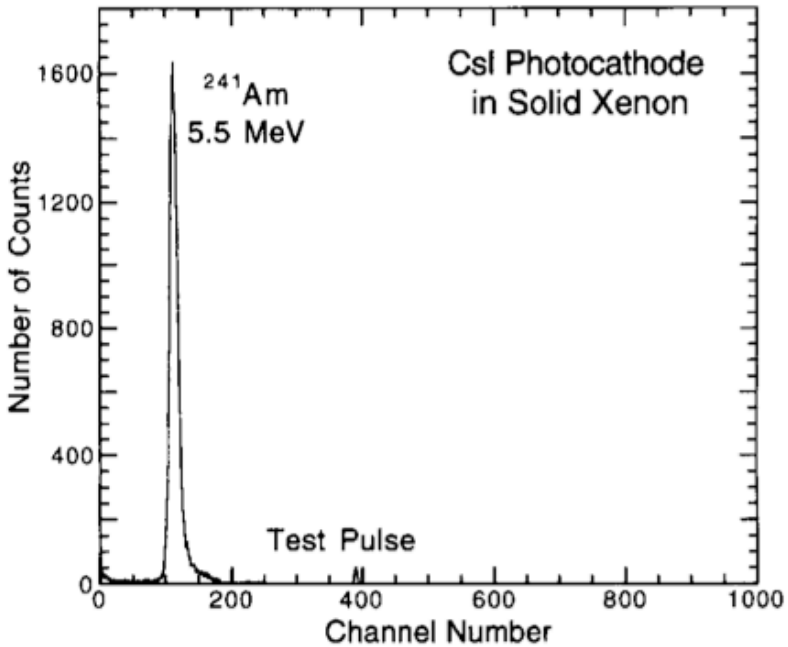


Fig. 2. Typical pulse height spectrum of the scintillation light from ^{241}Am 5.5 MeV α-particles in solid Xe.

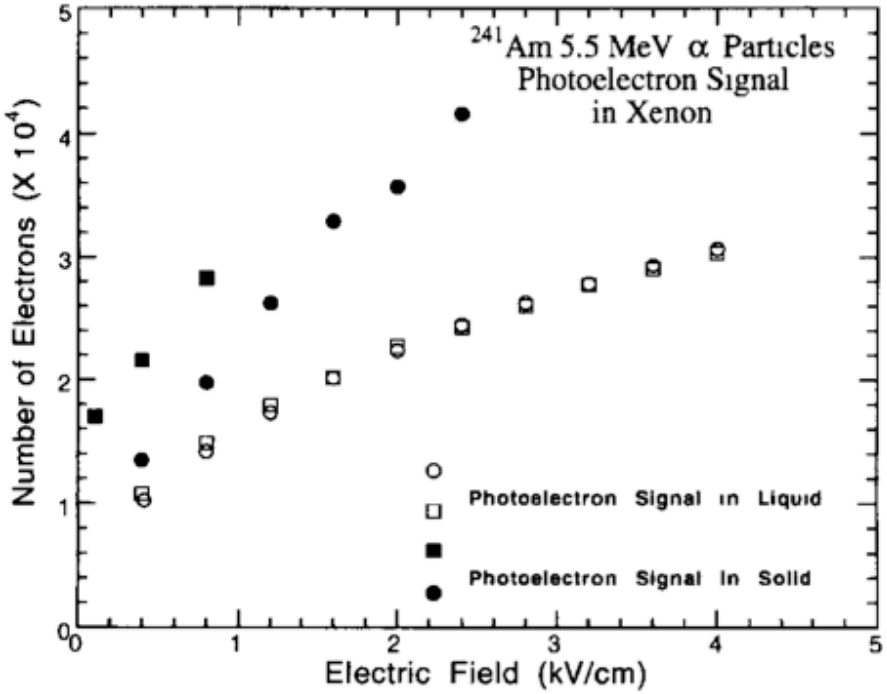
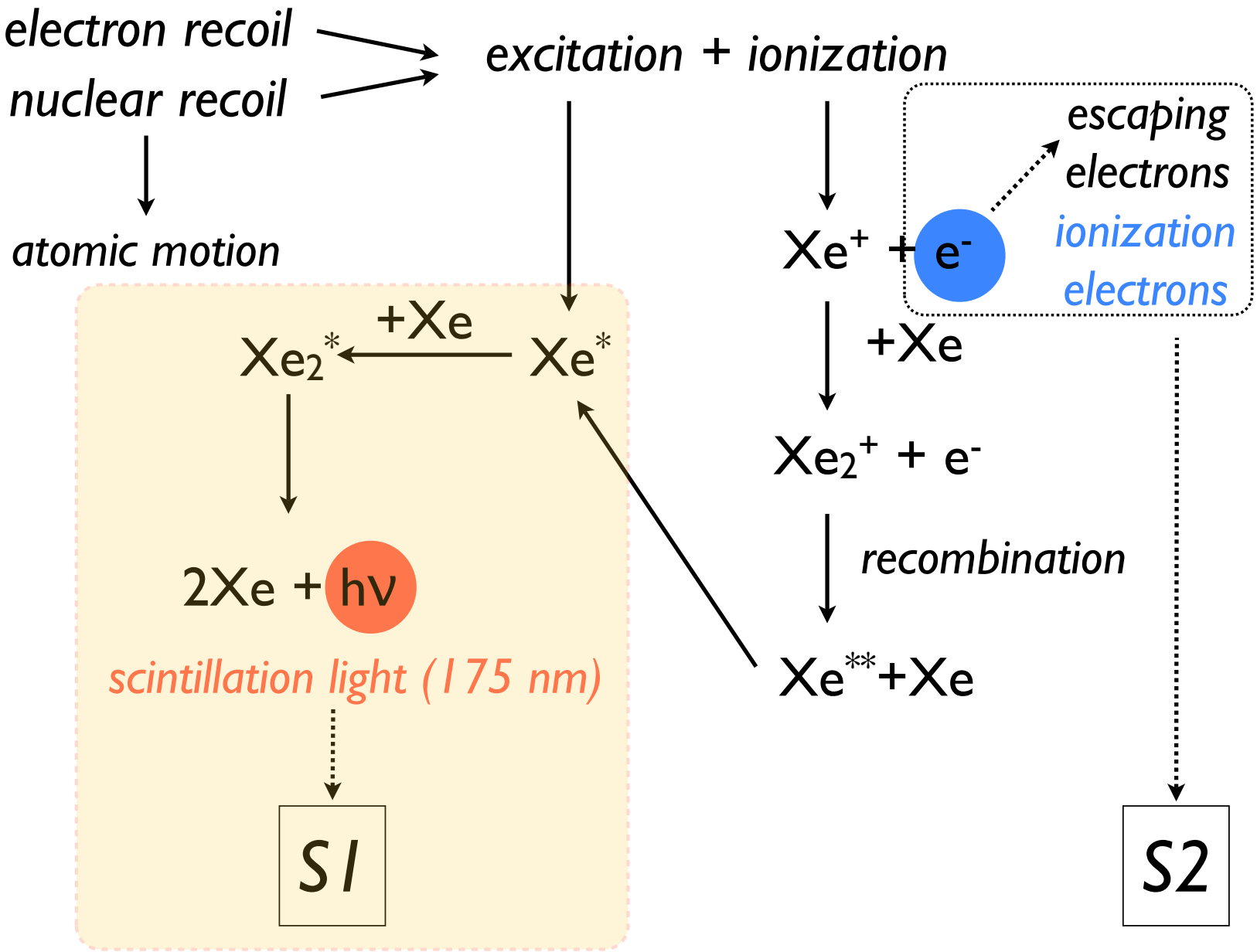


Fig. 3. Number of electrons collected as a function of the electric field from the CsI photocathode for 5.5 MeV ^{241}Am alpha particles in liquid and solid Xe.

The observed increase in the signal can be attributed to the following factors: 1) increase of the CsI QE, 2) increase in the intensity of the light produced by α-particles in solid rare gases because of the lower W_{ph} value in the solid phase. The W_{ph} value for solid rare gases has not been precisely measured. However it is expected that the W_{ph} value does not change significantly from the liquid to the solid phase.

Scintillation Mechanism in "*Liquid*" Xenon



Theory of Electron, Hole, Exciton Interaction with Phonon

Y. Toyozawa, Prog. Theor. Phys. 26, 29 (1961)

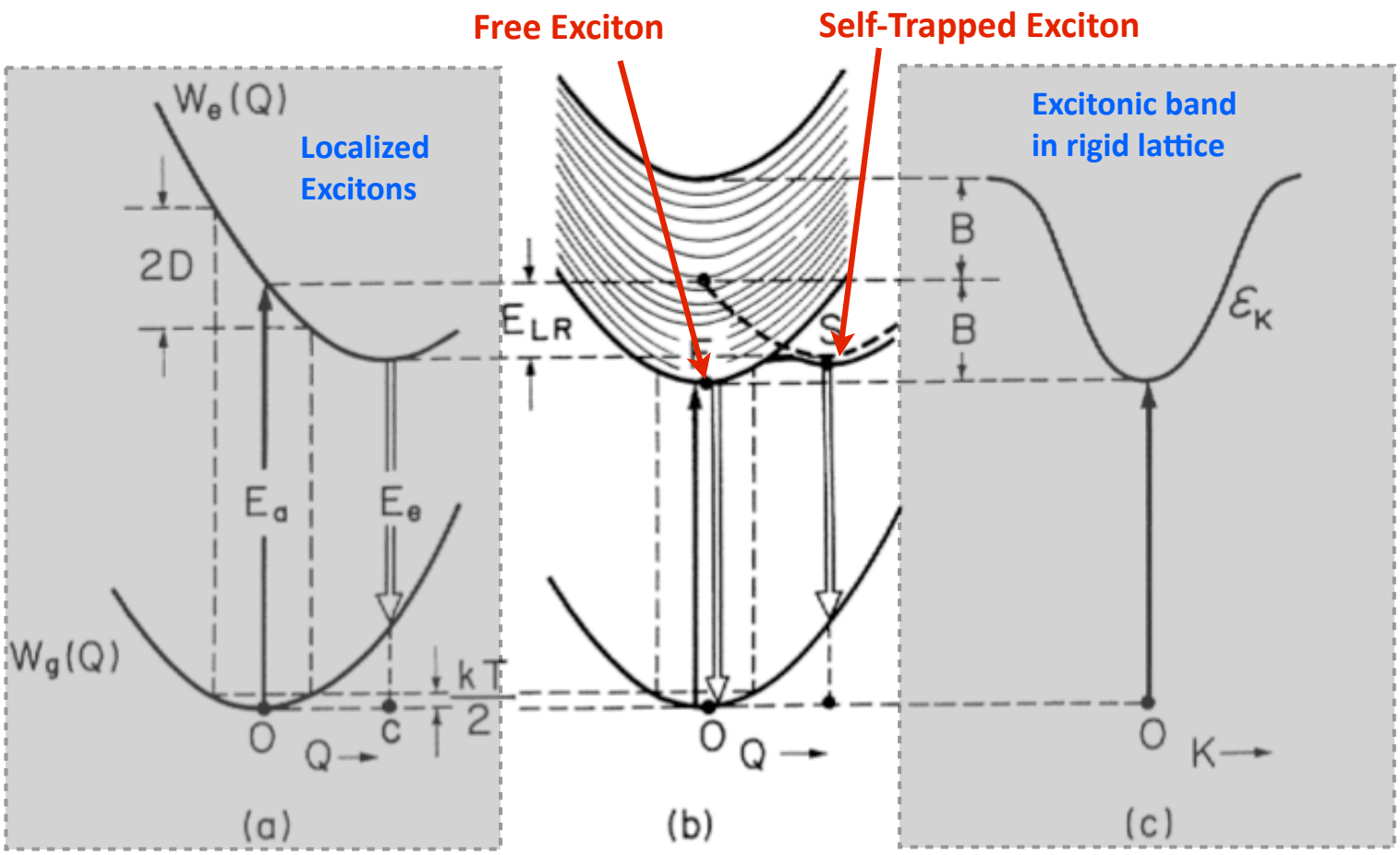
$$\mathcal{H} = \mathcal{H}_e + \mathcal{H}_{eL} + \mathcal{H}_{LL}$$

$$\mathcal{H}_e = \sum_n |n\rangle E_a \langle n| + \sum\sum_{n\neq m} |n\rangle T_{nm} \langle m|$$

$$\mathcal{H}_{eL} = -c\sum_n |n\rangle Qn \langle n|$$

$$\mathcal{H}_{LL} = U_{LL} + K_{LL} = \sum_n (Q_n^2 + \omega^2 P_n^2)/2$$

T_{nn}: nearest neighbor transfer energy
$B = |T_{nn}| \times (\#$ nearest neighbors$)$
D: fluctuation of site energy due to lattice vibrations
E_R: relaxation energy of the lattice due to the localized electron
Q_n: lattice distortion at the n-th site
ω: lattice vibrational frequency

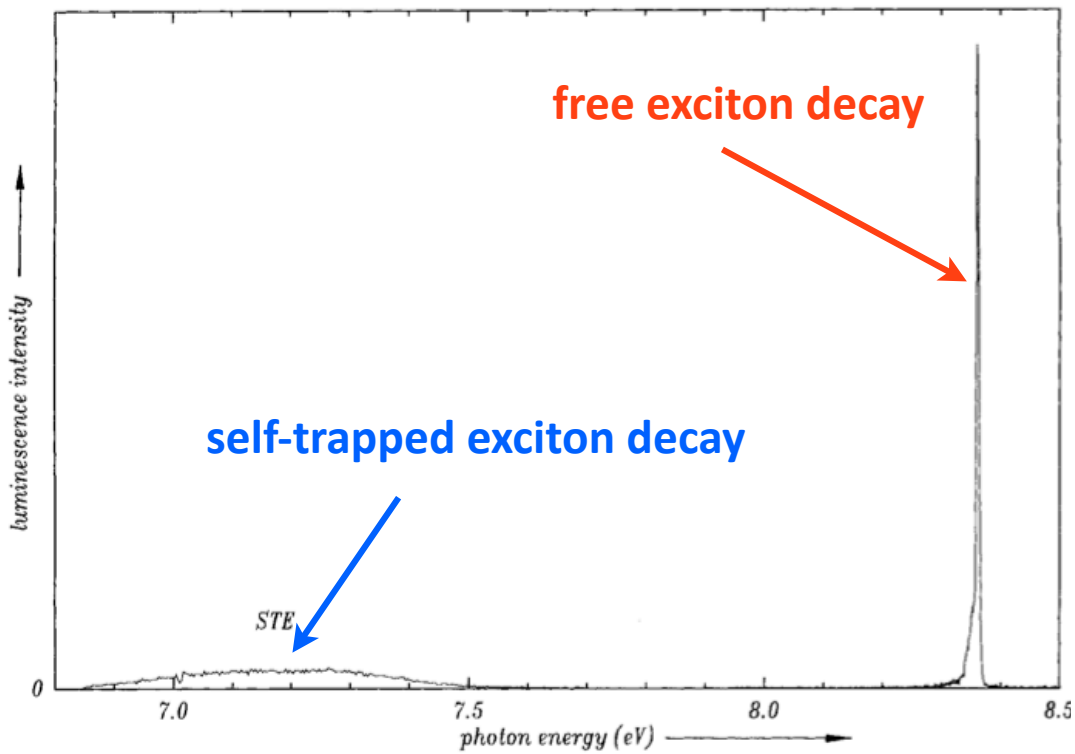


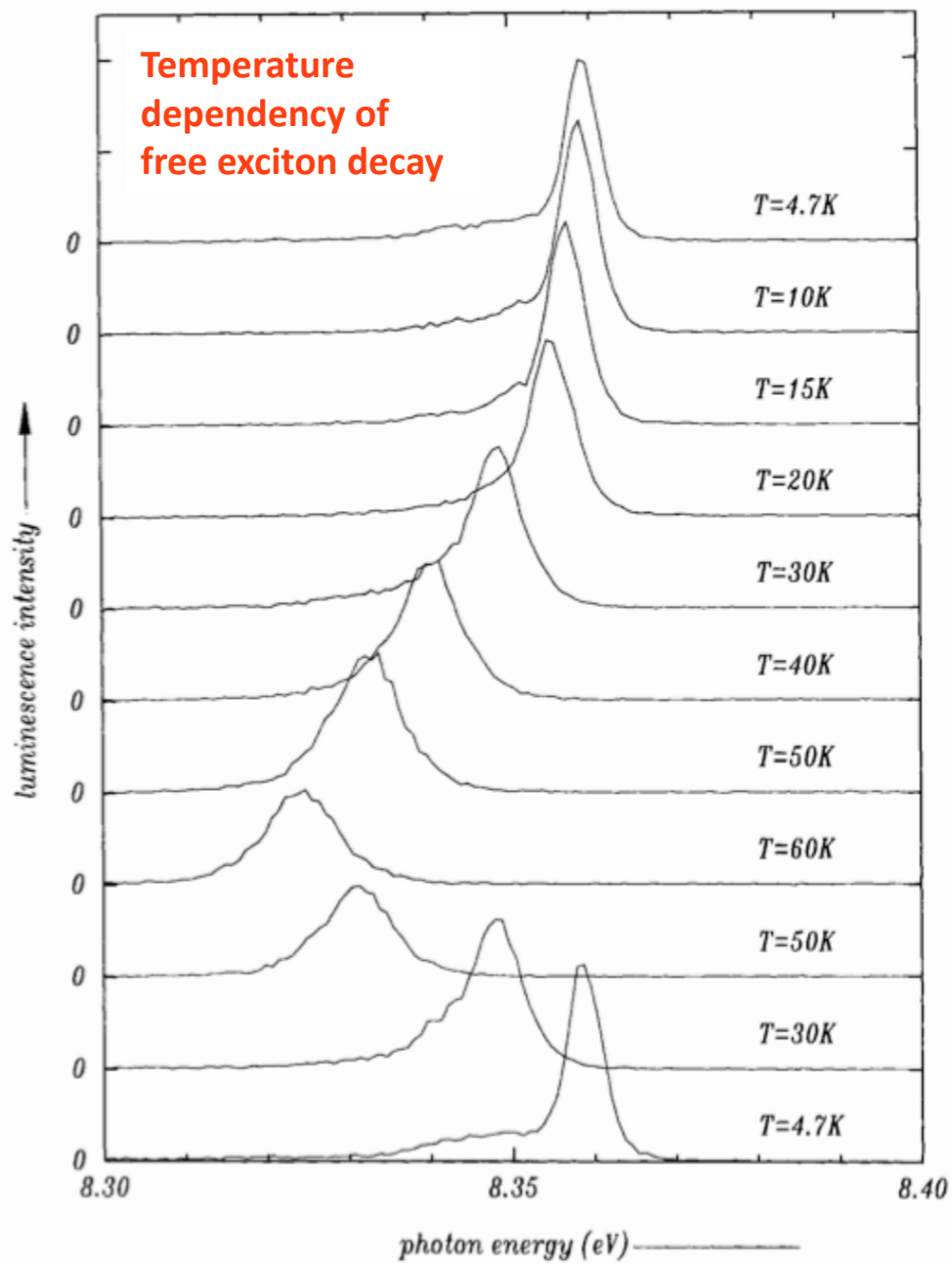
Excimer Decay Modes

D. Varding et al. Phys.Stat.Sol (b) 185, 301 (1994)

- Luminescence of free excitons exceeds the self-trapped exciton luminescence by a factor of 50 (peak-to-peak).
- Monte-Carlo simulations of the exciton-polariton transport model phonon scattering and trapping.

Solid Xenon @4.7K





Excimer Decay Luminescence Spectra

R.Kink et al Phys. Stat. Sol. (b) 139, 321 (1987)

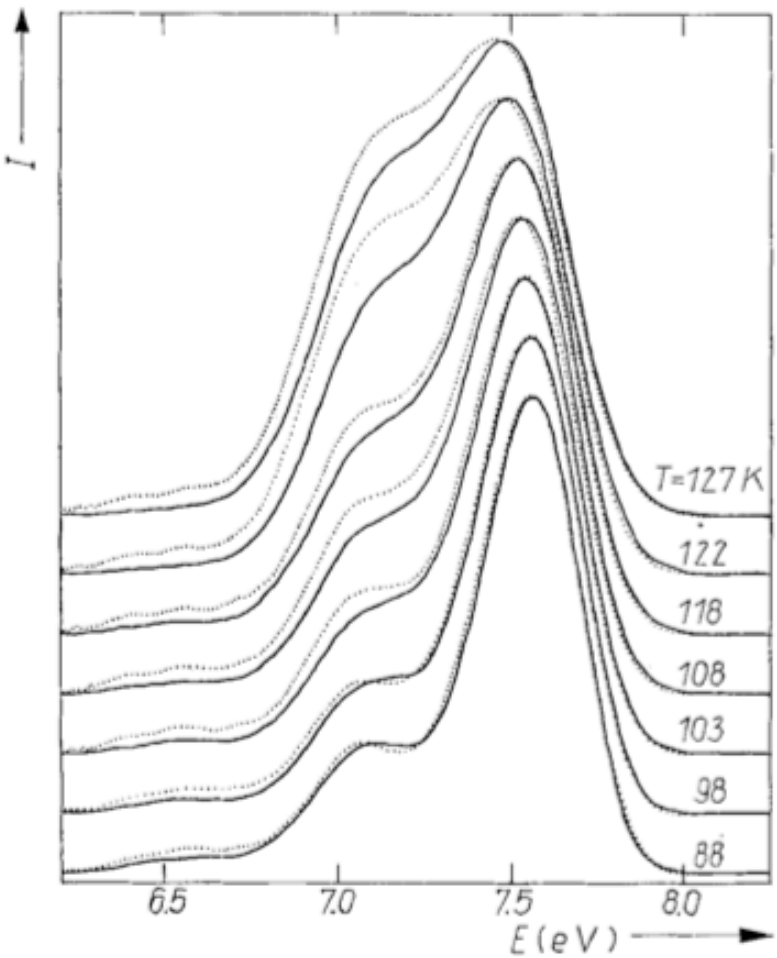
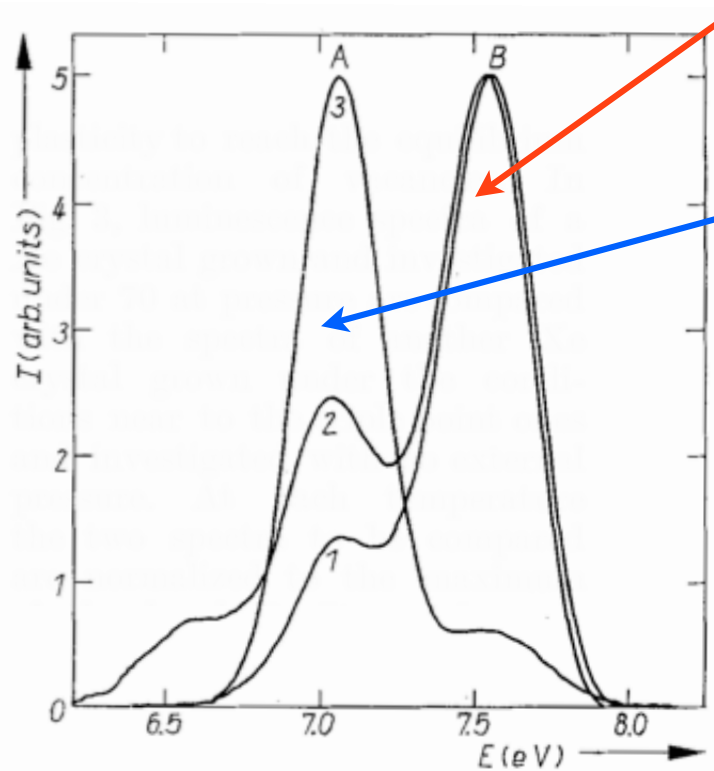


Fig. 3. Luminescence spectra of crystalline Xe at various temperatures. ——— Crystal grown and measured under 70 at pressure, ····· crystal grown with no excess pressure



Real self-trapped Xe_2^* decay (λ =165nm)

Xe_2^* decay which trapped in crystal vacancies (λ =172nm)

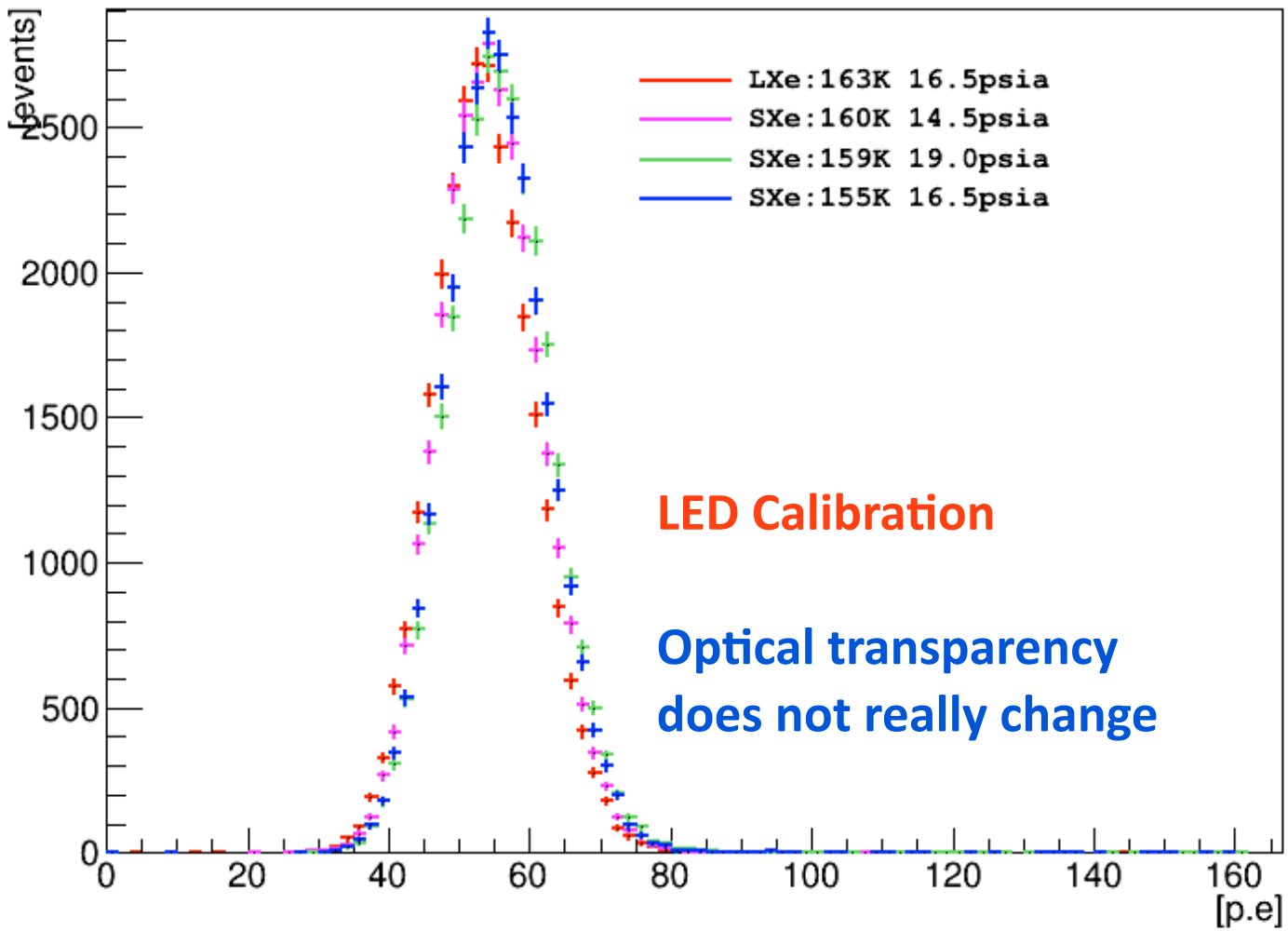
Solid Xenon at 80K

Fig. 2. Luminescence spectra of Xe under X-ray excitation at 80 K. (1) Bulk crystal slowly grown from the liquid, (2) bulk crystal quickly grown from the liquid, (3) film condensed from the vapour

2 PMT Setup

Optical fiber for s.p.e & m.p.e calibration

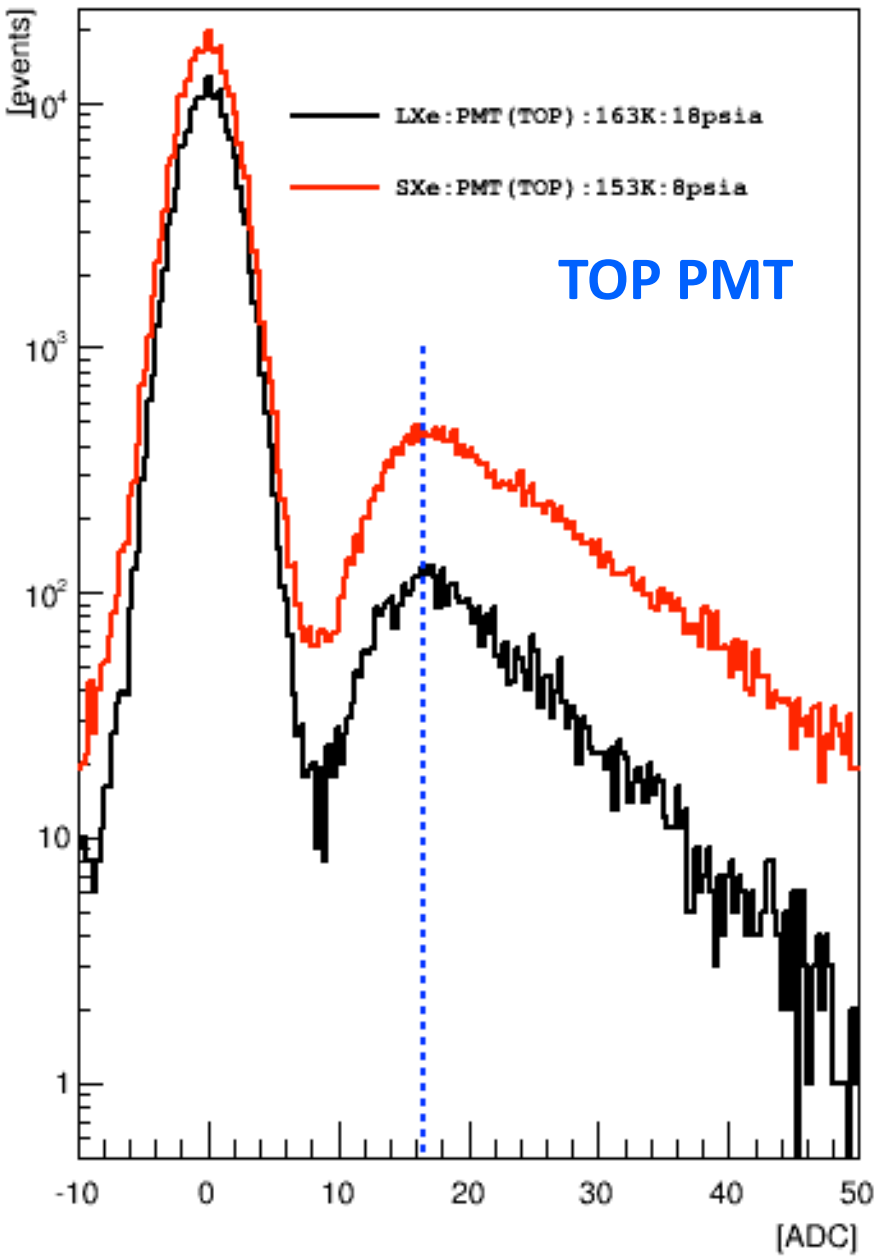
Internal heater and thermometer

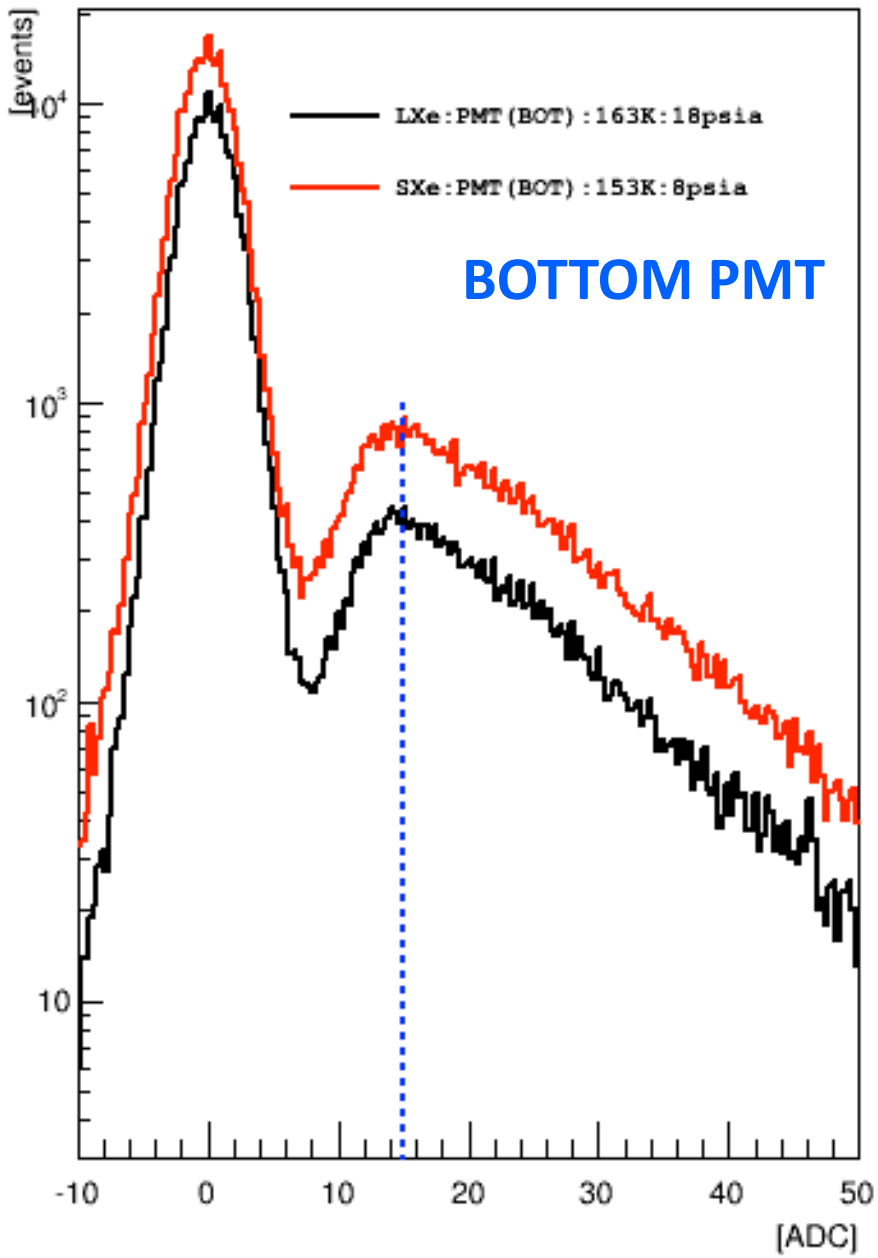


LED Calibration

Optical transparency does not really change

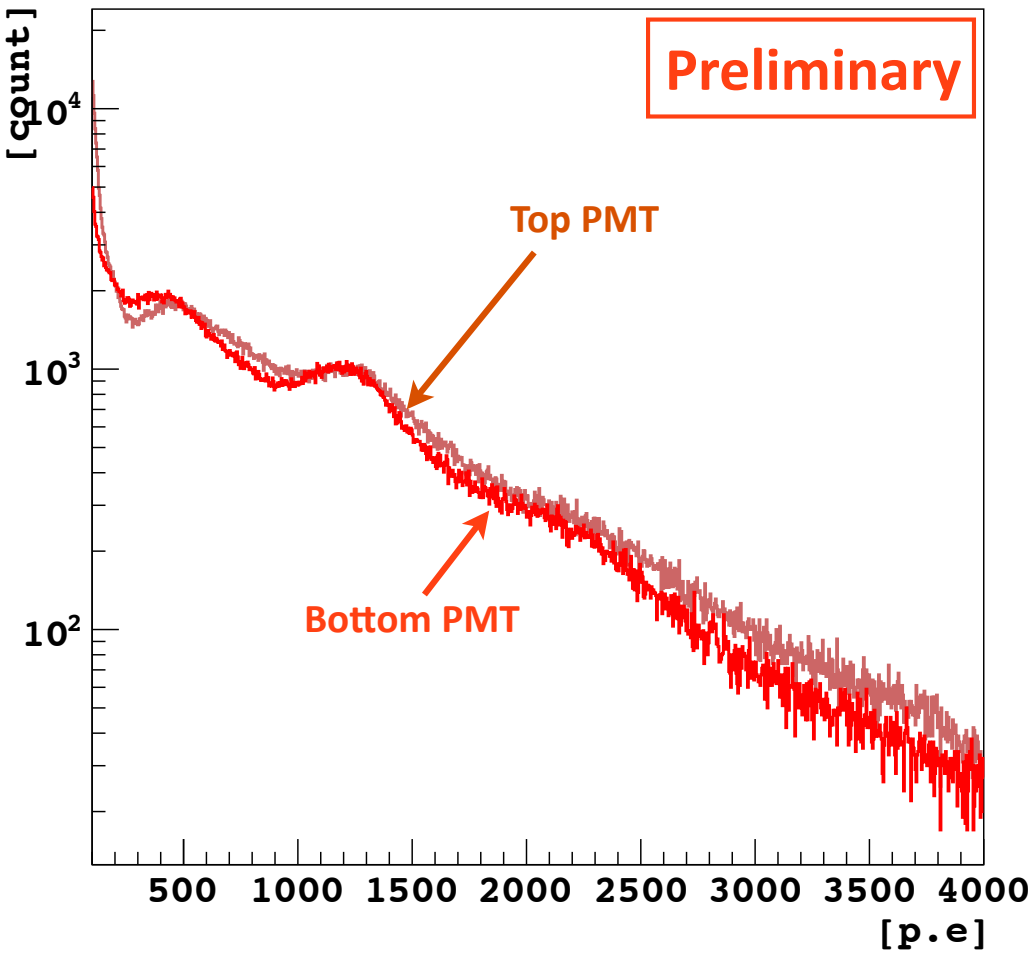
Single PE Response



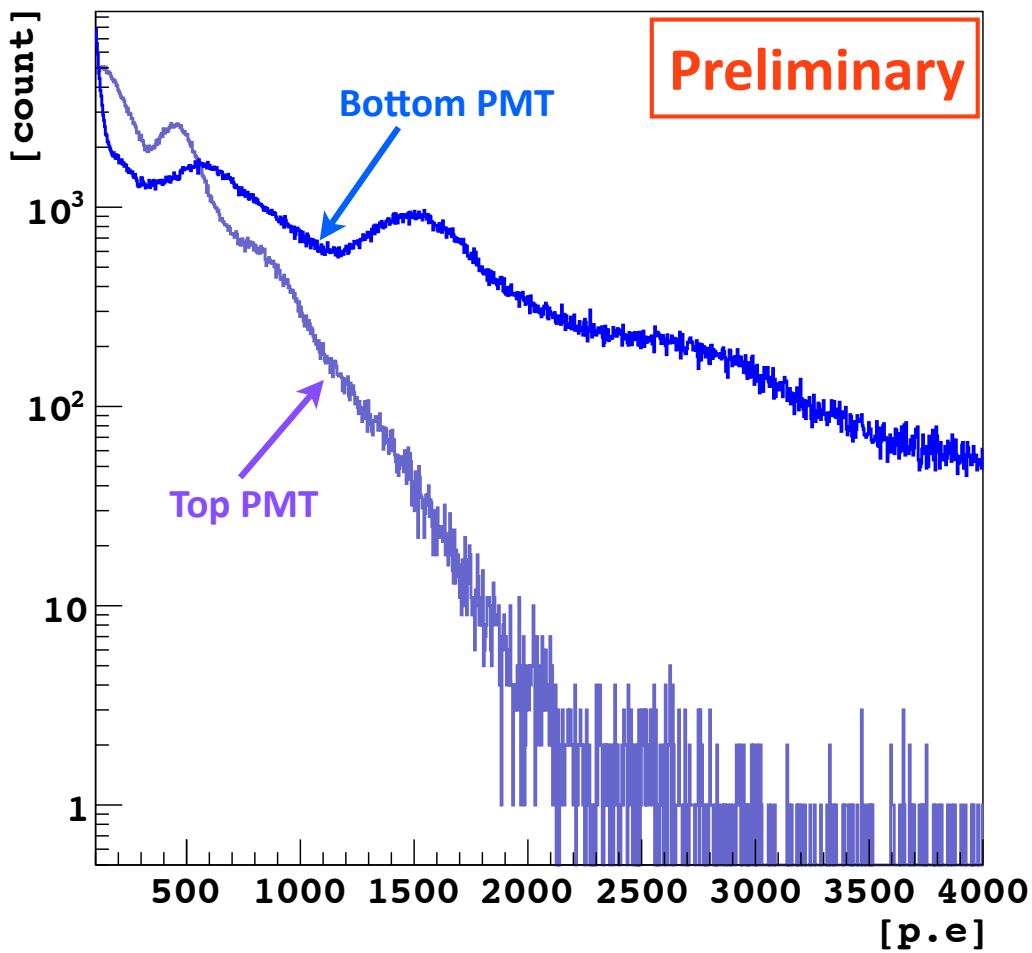


Photon Measurement

Liquid Xenon (165K@15psia)

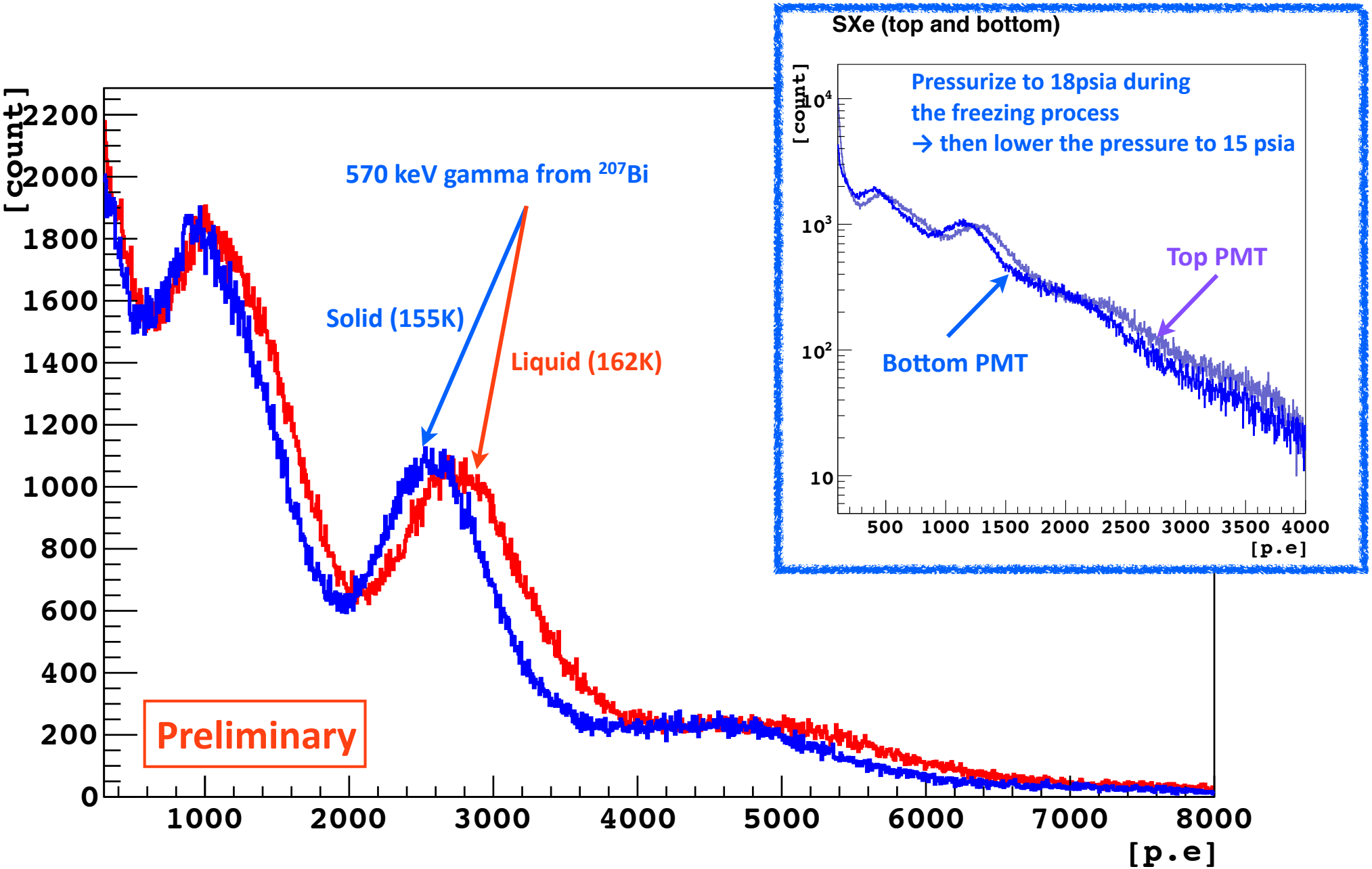


Solid Xenon (155K@15psia)



- Significant difference between top and bottom PMT readout
  - → Index of refraction changes (poor contact between PMT and bulk volume)
  - → This result is reproducible with careful control over pressure and temperature
  - → Can be fixed by refining the freezing process (pressurize)

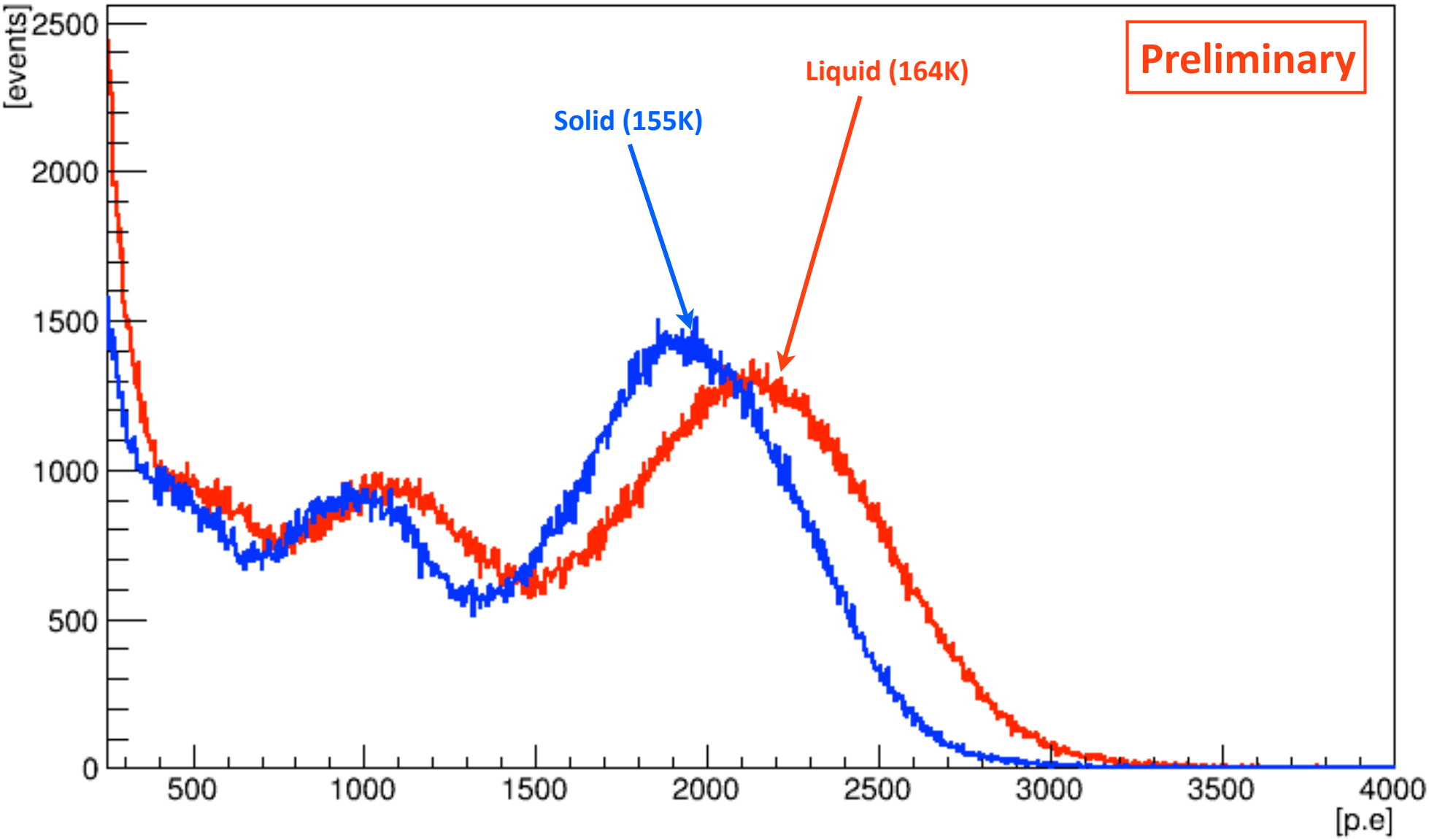
Photon Measurement



- 10% less photon readout (@570keV gamma) in solid phase

Photon Measurement

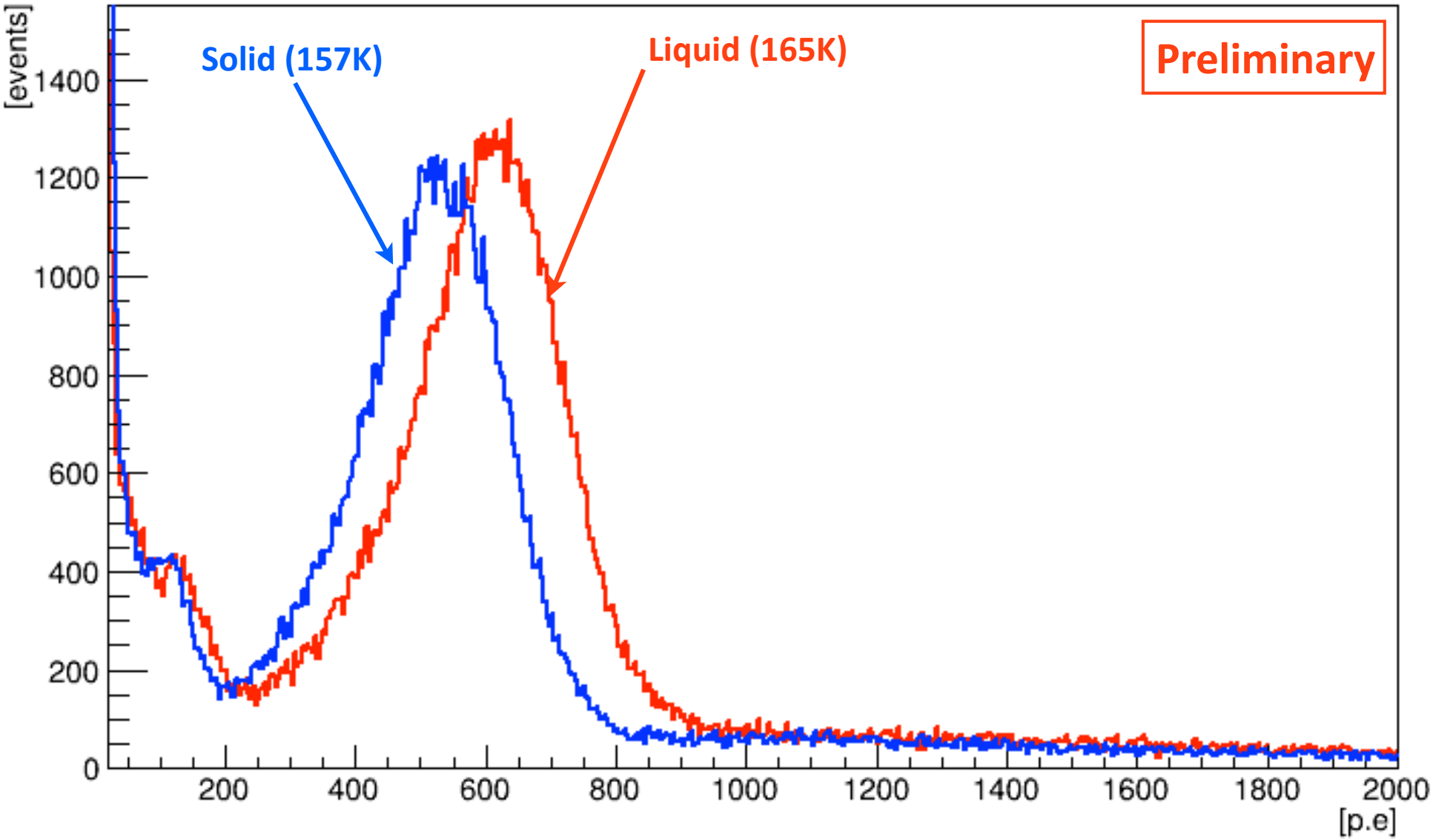
^{133}Ba source (276keV, 302keV, 356keV, 383keV)



- 12% less photon readout (@~300keV range gammas) in solid phase

Photon Measurement

^{57}Co (122keV 85%, 134keV 10%)

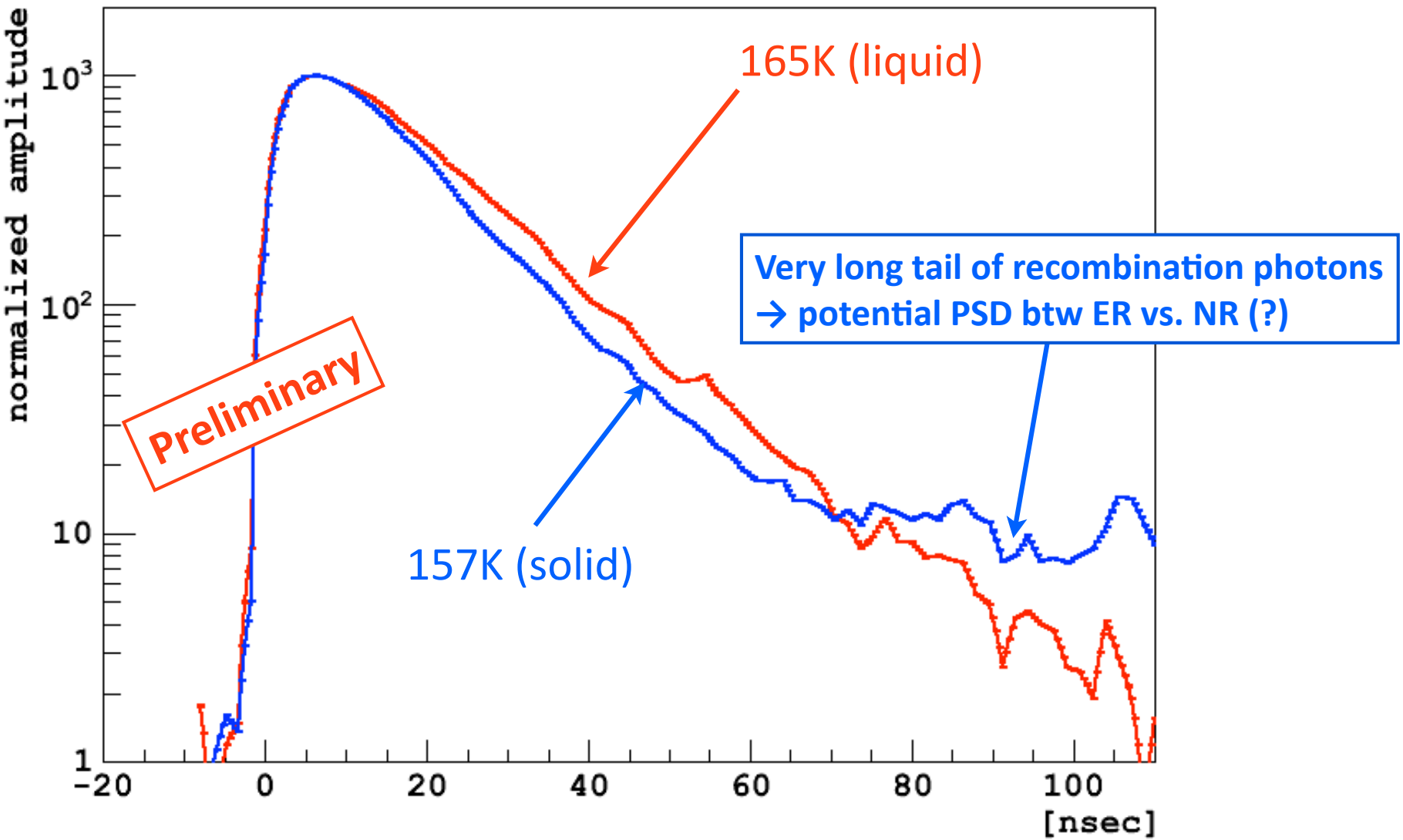


- 16% less photon readout (@122keV gamma) in solid phase

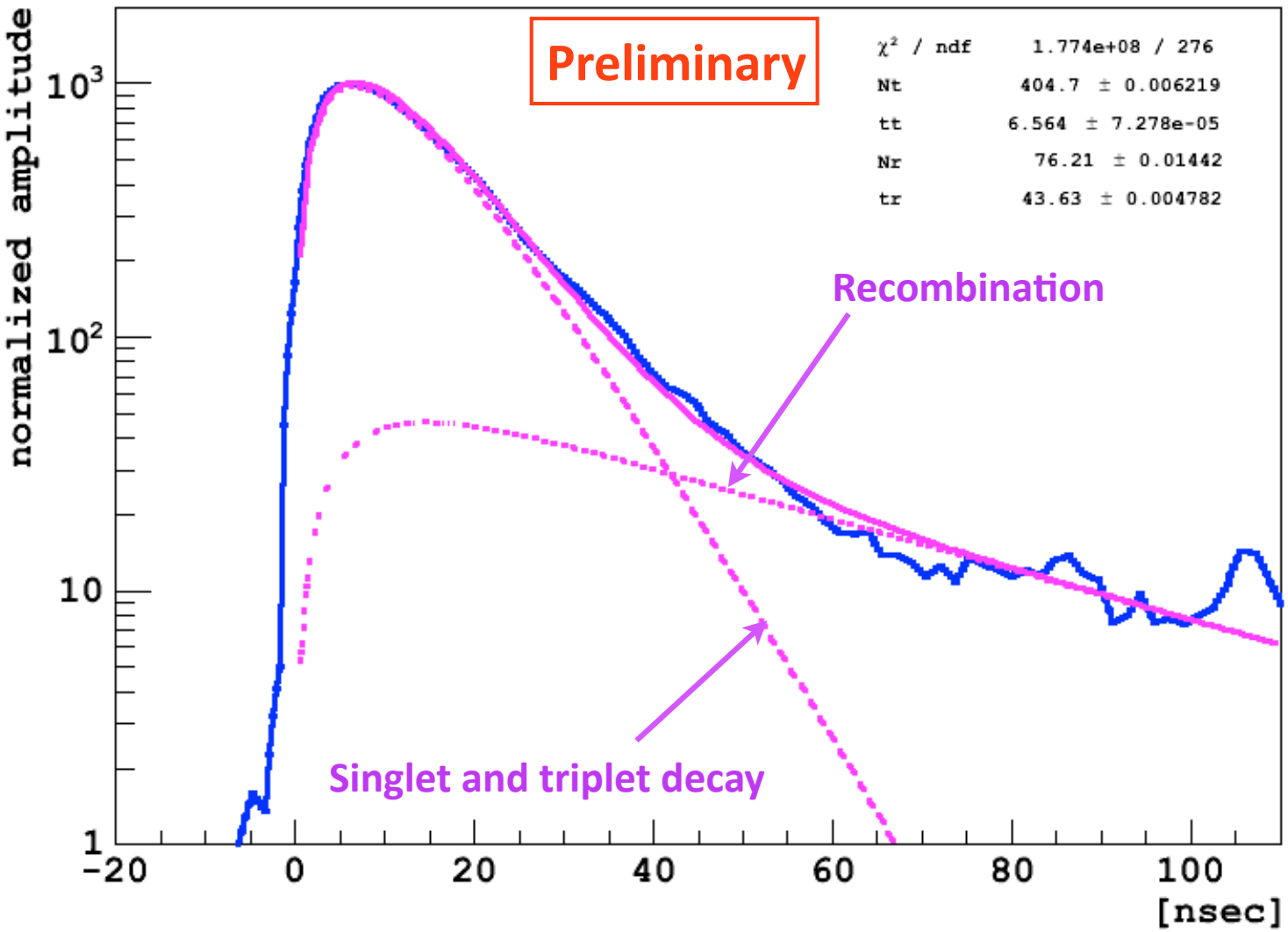
Scintillation Property

- Singlet ($^1\Sigma^+_u \rightarrow {}^1\Sigma^+_g$) and triplet ($^3\Sigma^+_u \rightarrow {}^1\Sigma^+_g$) decay are not quite separable in the current setup
- There is hint for less triplet decay but more recombination photons in solid phase

Scintillation time distribution at ^{57}Co (@122 keV peak)



Scintillation Property

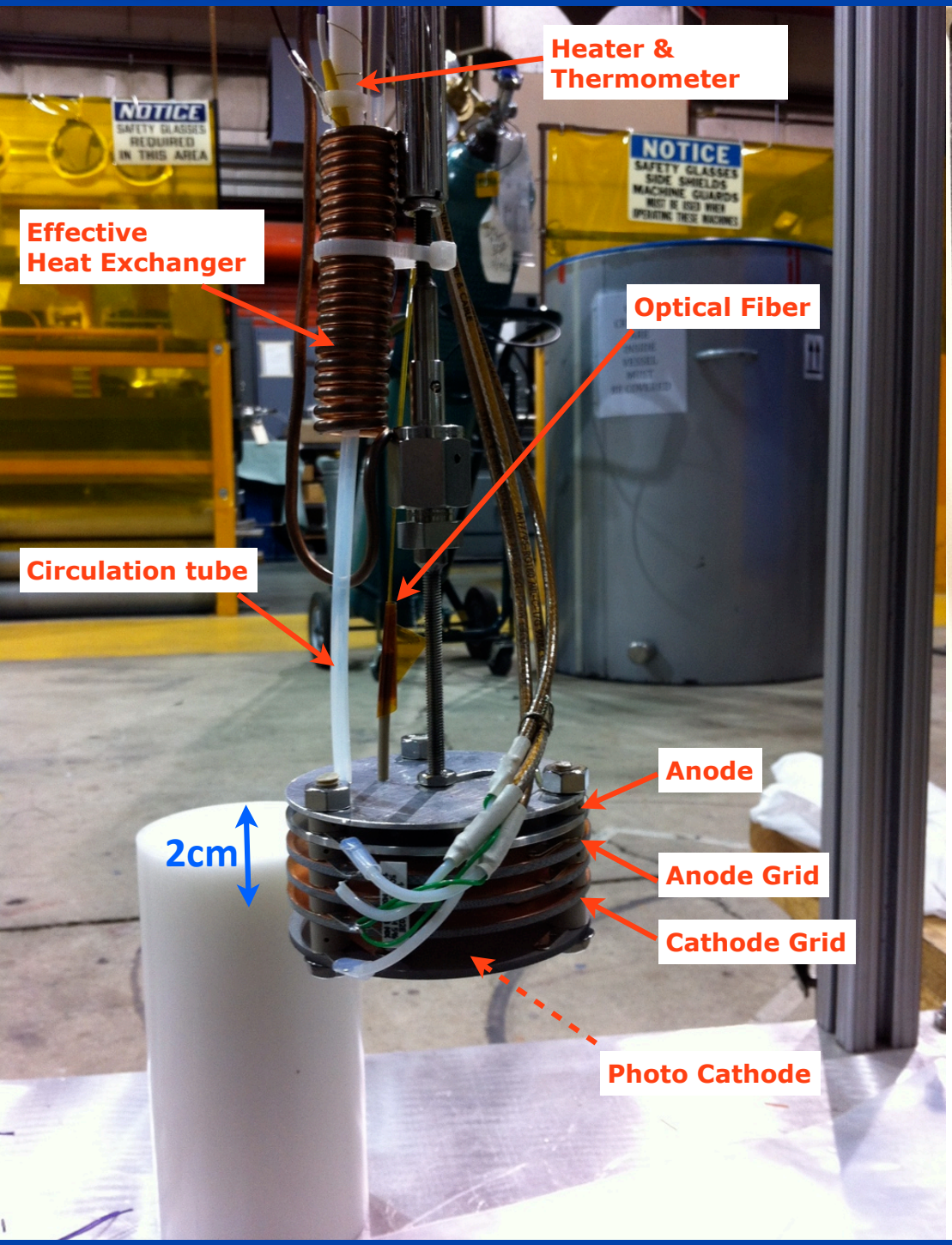


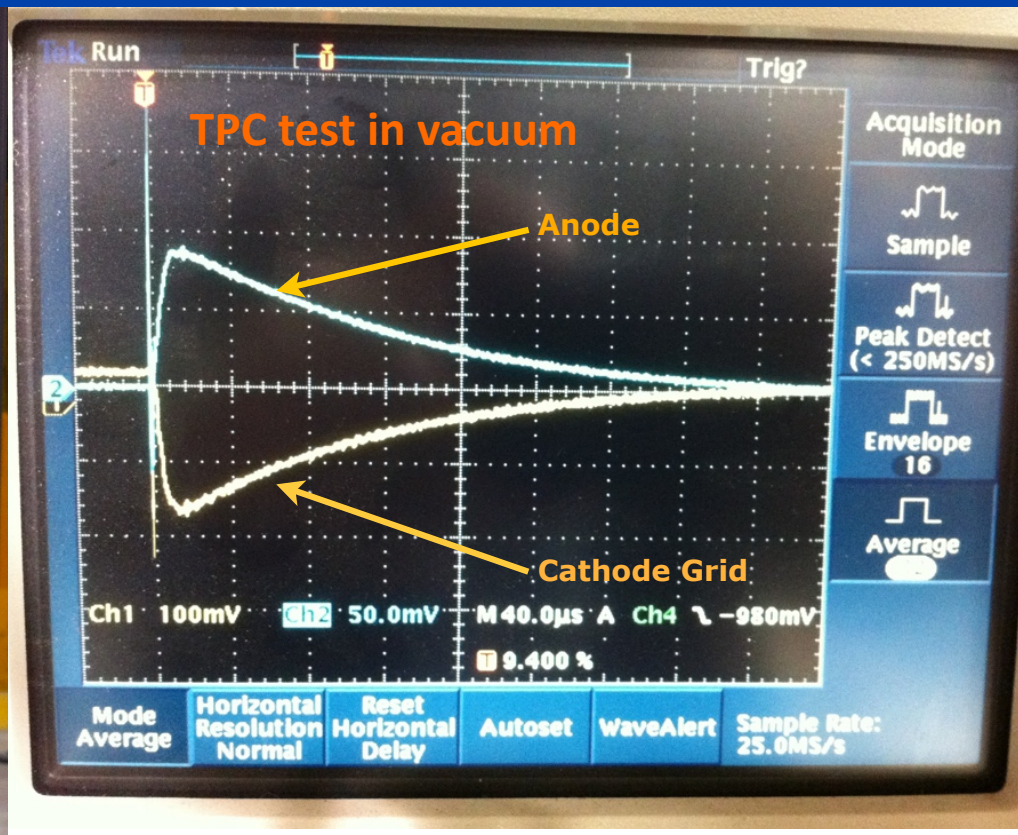
Two possible source of light loss in solid phase:

1. Shorter wavelength creation in crystal xenon
2. Photon loss due to slower recombination component in crystal xenon

→ yes, if it is crystal phase of xenon

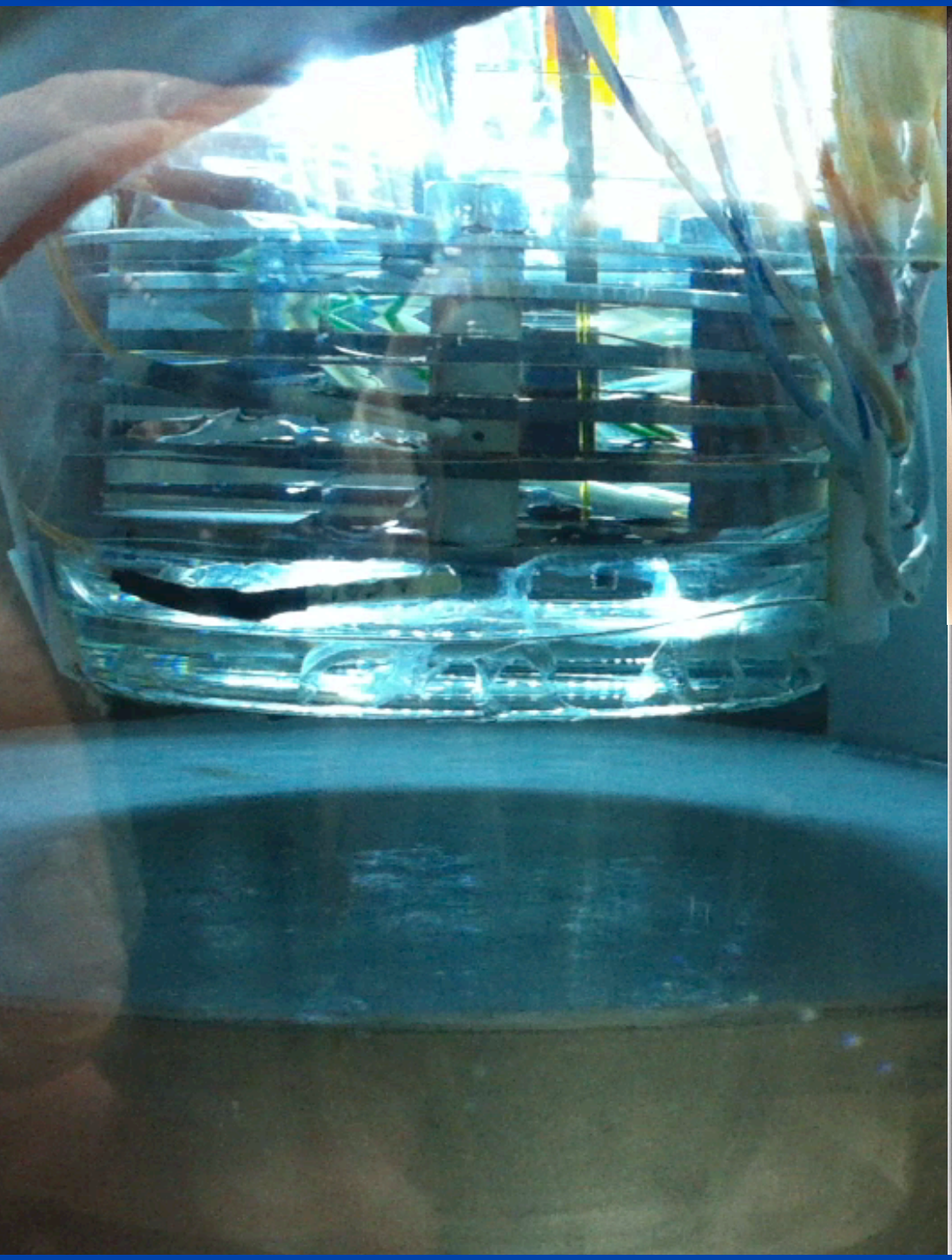
Electron Drift

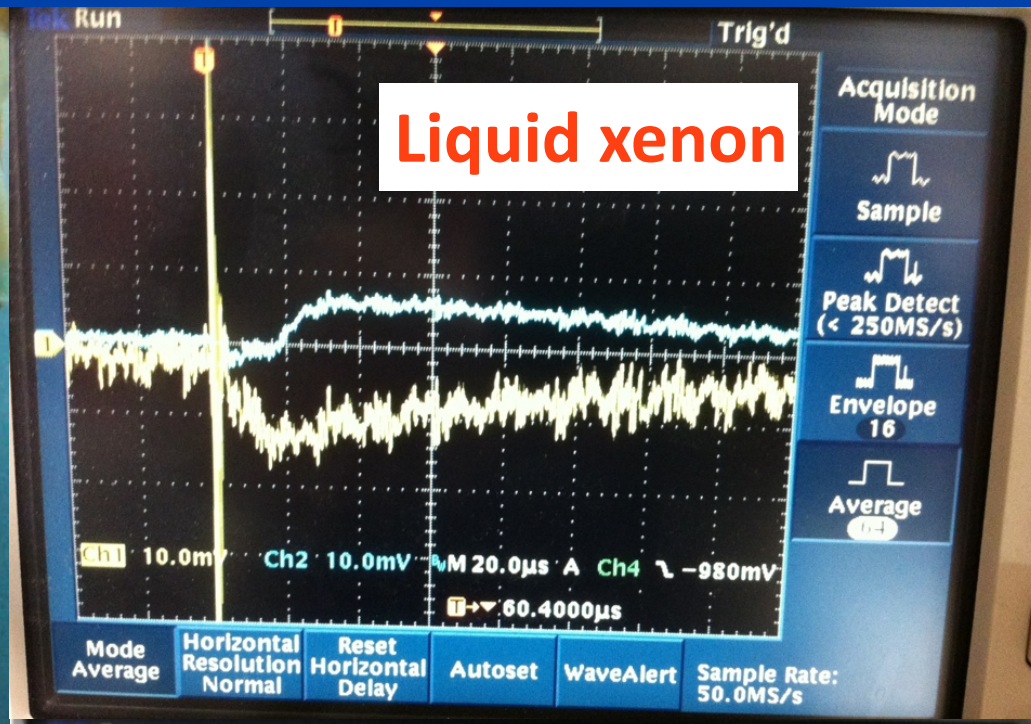


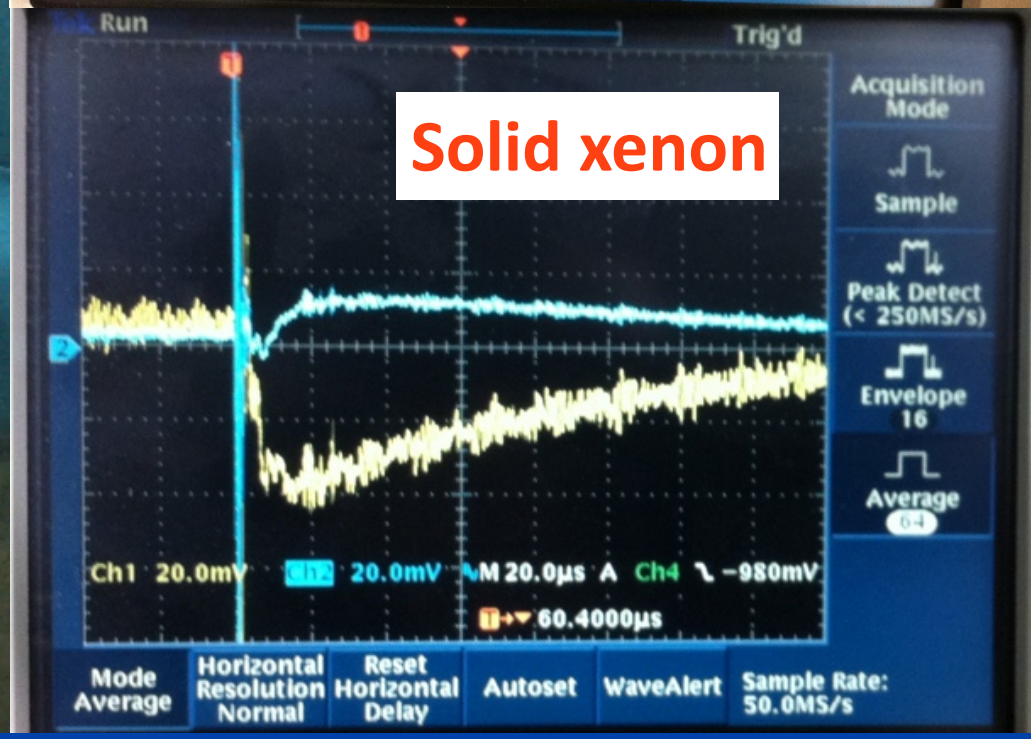


- Vertical setup helps to reduce test time
  → smaller effective xenon volume
- The effective heat exchanger prevents accidental pressure shock
- A week of Xe purification (circulation) in liquid phase : ~ 40 pass of total volume

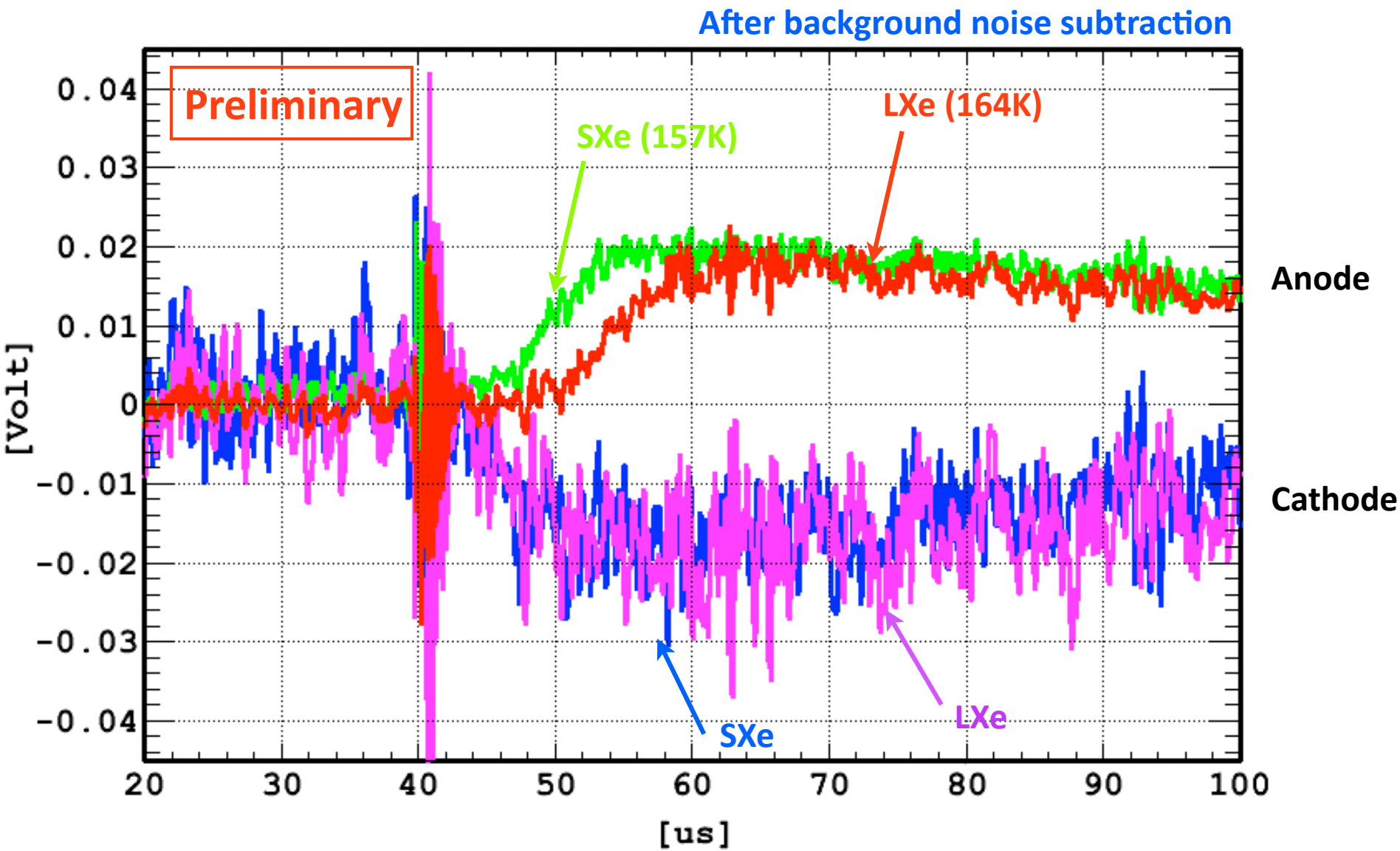
Electron Drift in Solid & Liquid Xenon





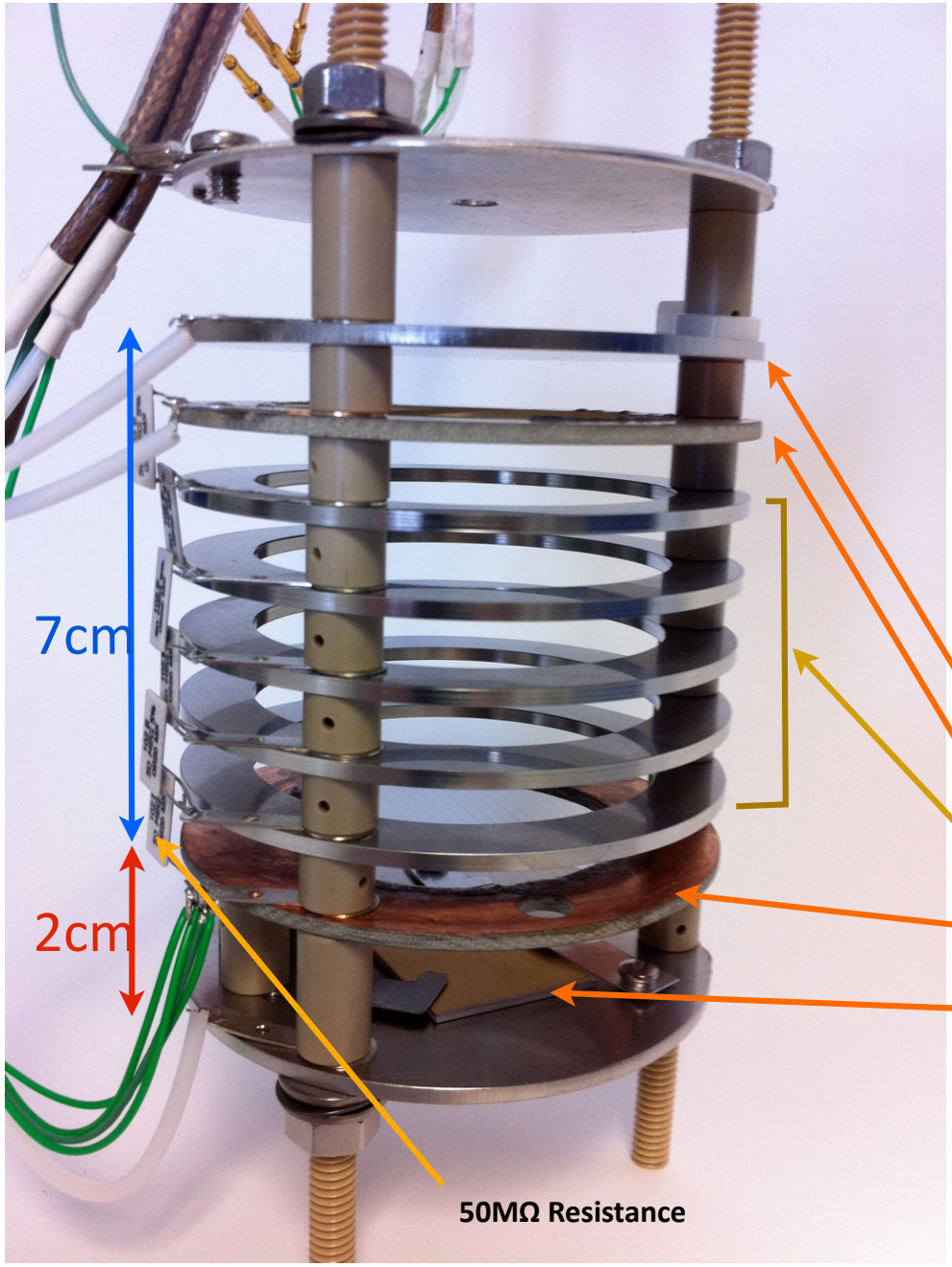


Electron Drift in Solid & Liquid Xenon

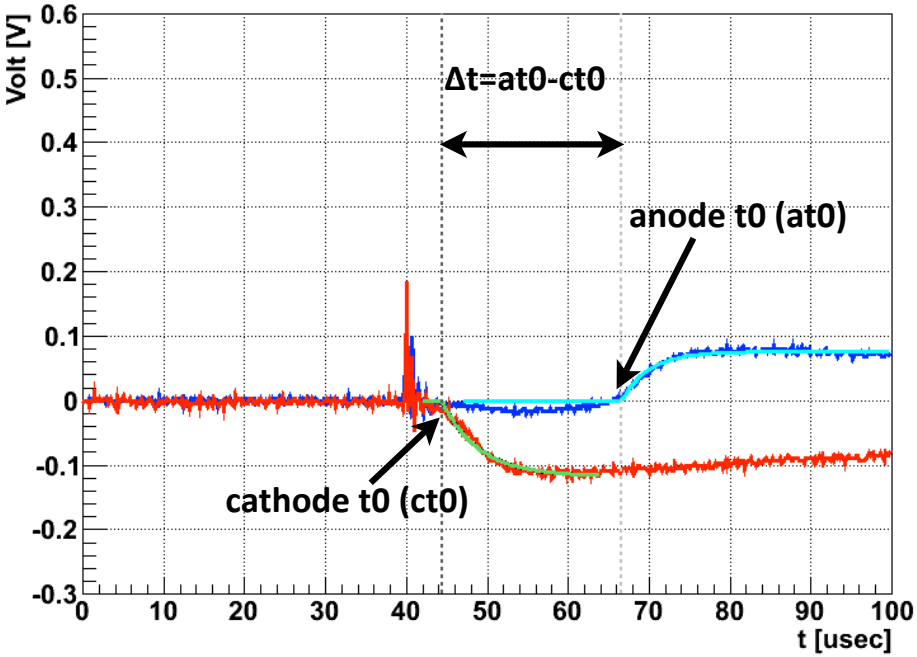


- Electric field: 1kV/cm
- Drift velocity : LXe (~2×10^5cm/s) and SXe (~4×10^5cm/s)
  - → Faster drift in large scale solid xenon!
  - → Refined measurement with longer drift length would provide better accuracy

Electron Drift: What Next?



TPC performance test done in gas Argon



Anode (+500V)

Anode Grid

Field shape rings

Ground Grid

Cathode(-215V)

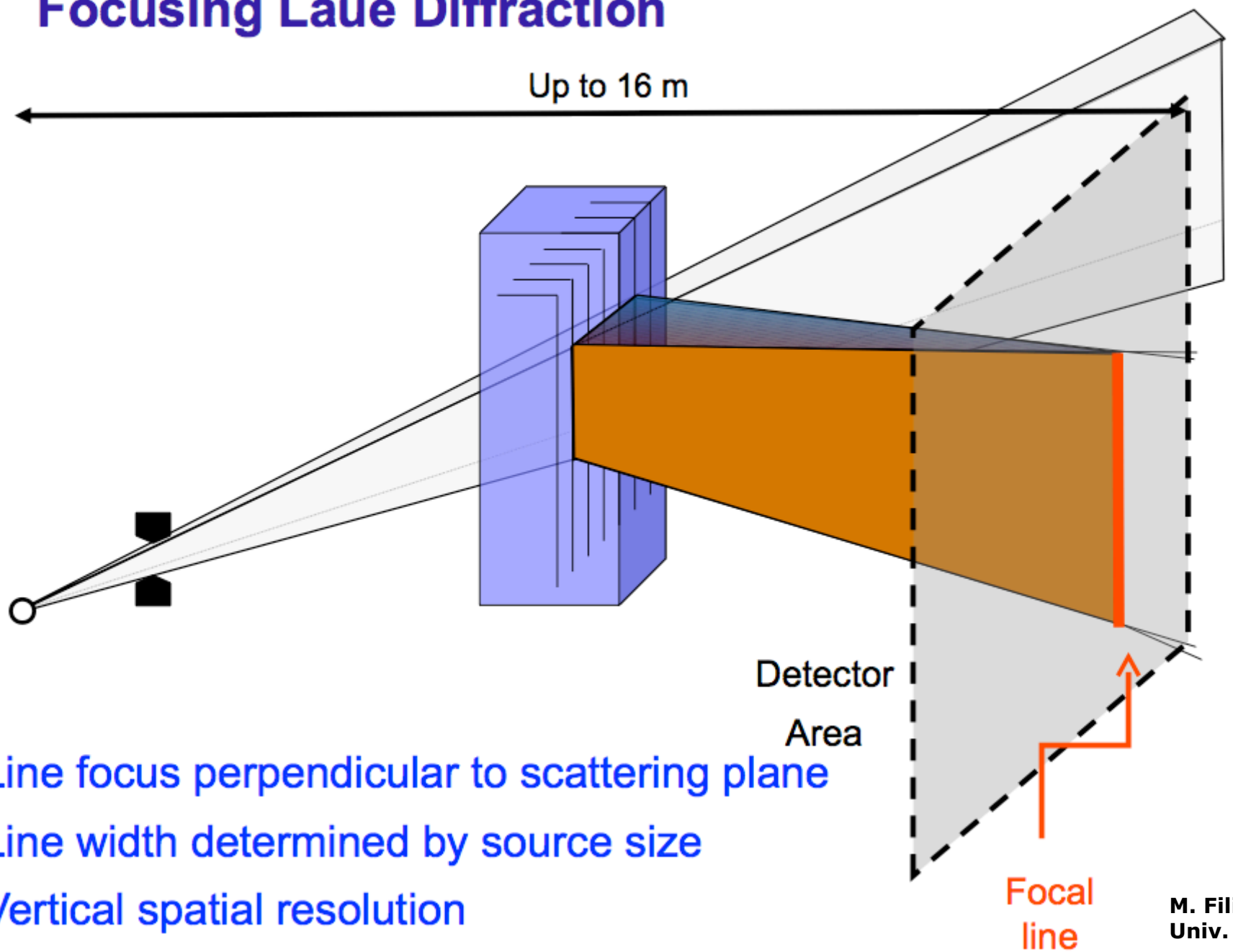
Photocathode: gold-coated on Al plate
Au 1000. Custom Al, PLATYPUS FC-2456

W.Jaskierny and E.Skup

TPC design is from LArTPC project at Fermilab

Crystallography of Solid Xenon?

Focusing Laue Diffraction



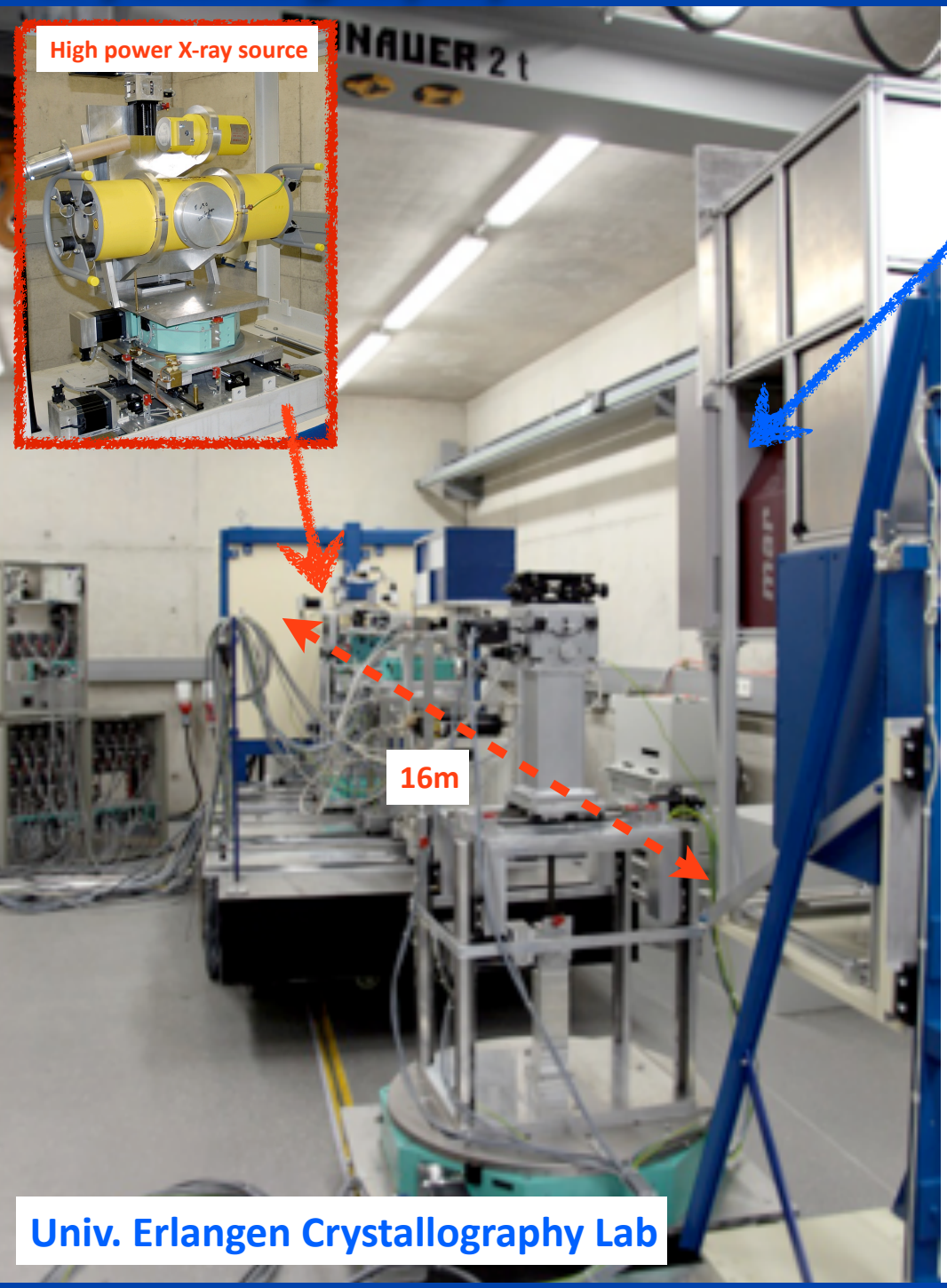
Line focus perpendicular to scattering plane

Line width determined by source size

Vertical spatial resolution

M. Filipenko
Univ. Erlangen

Crystallography



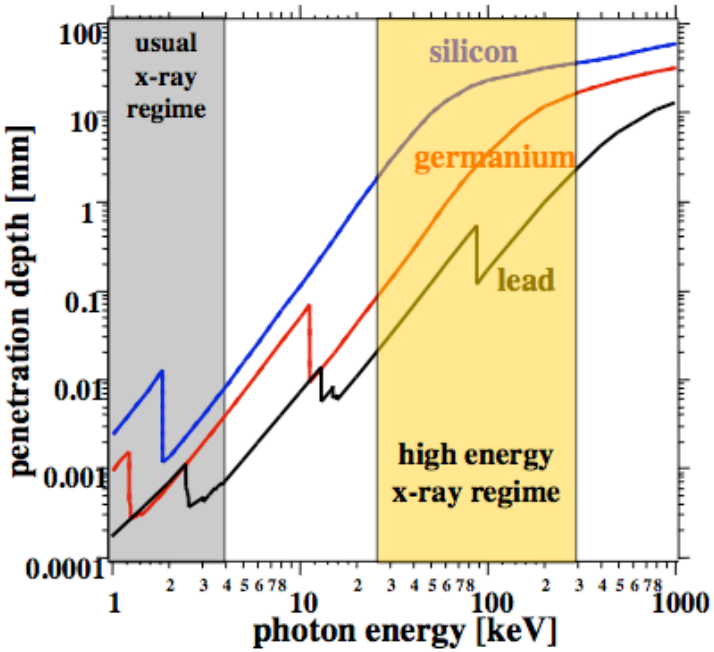
2 Area detectors:

Scintillator with a System of cooled CCD-Cameras

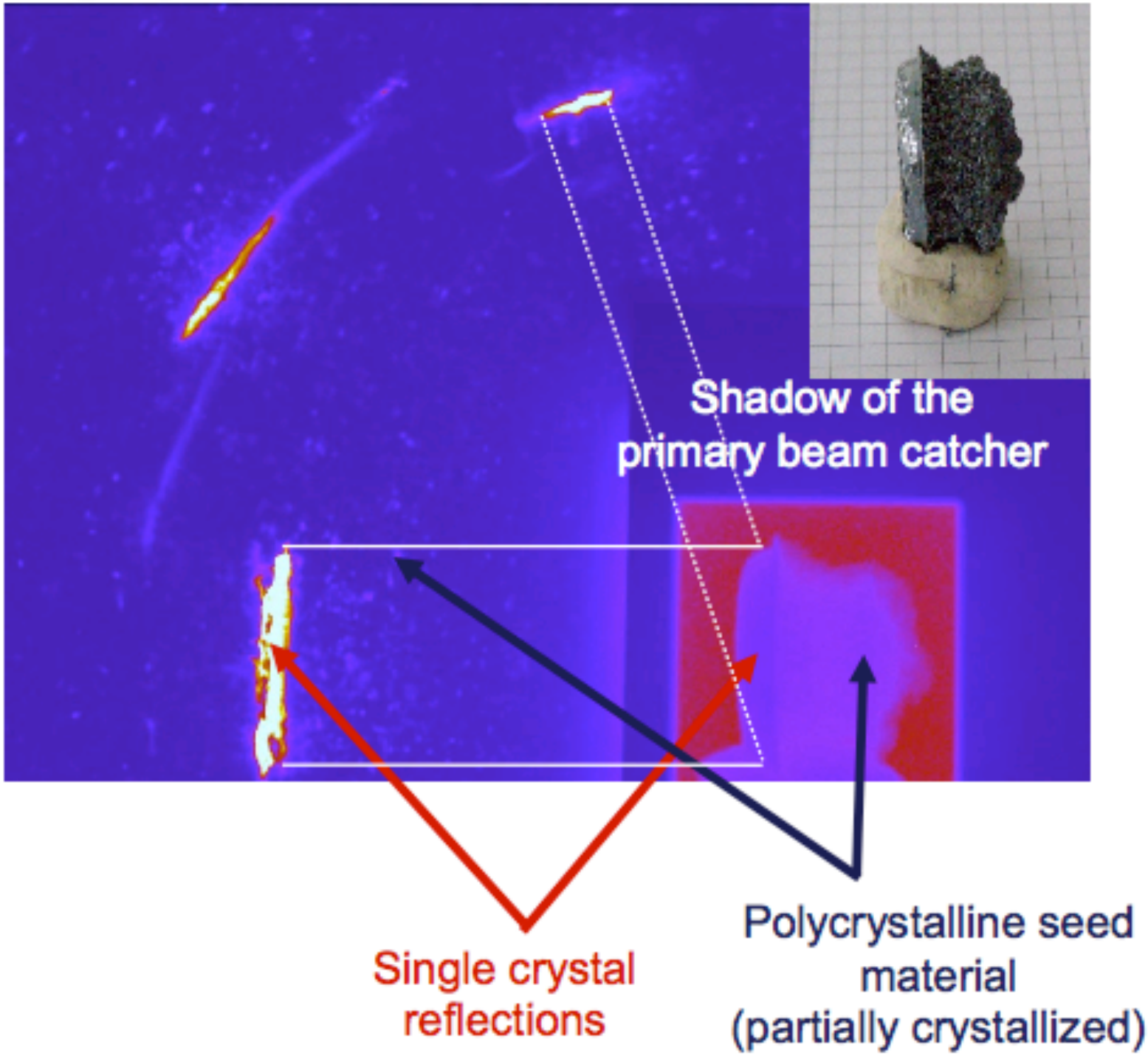
- Active area 30 x 20 cm2
- 2 x 14 bit CCD- with 1280 x 1024 pixel
- Resolution ~ 150 µm
- Read out = 125 ms

Image plate System MAR 345

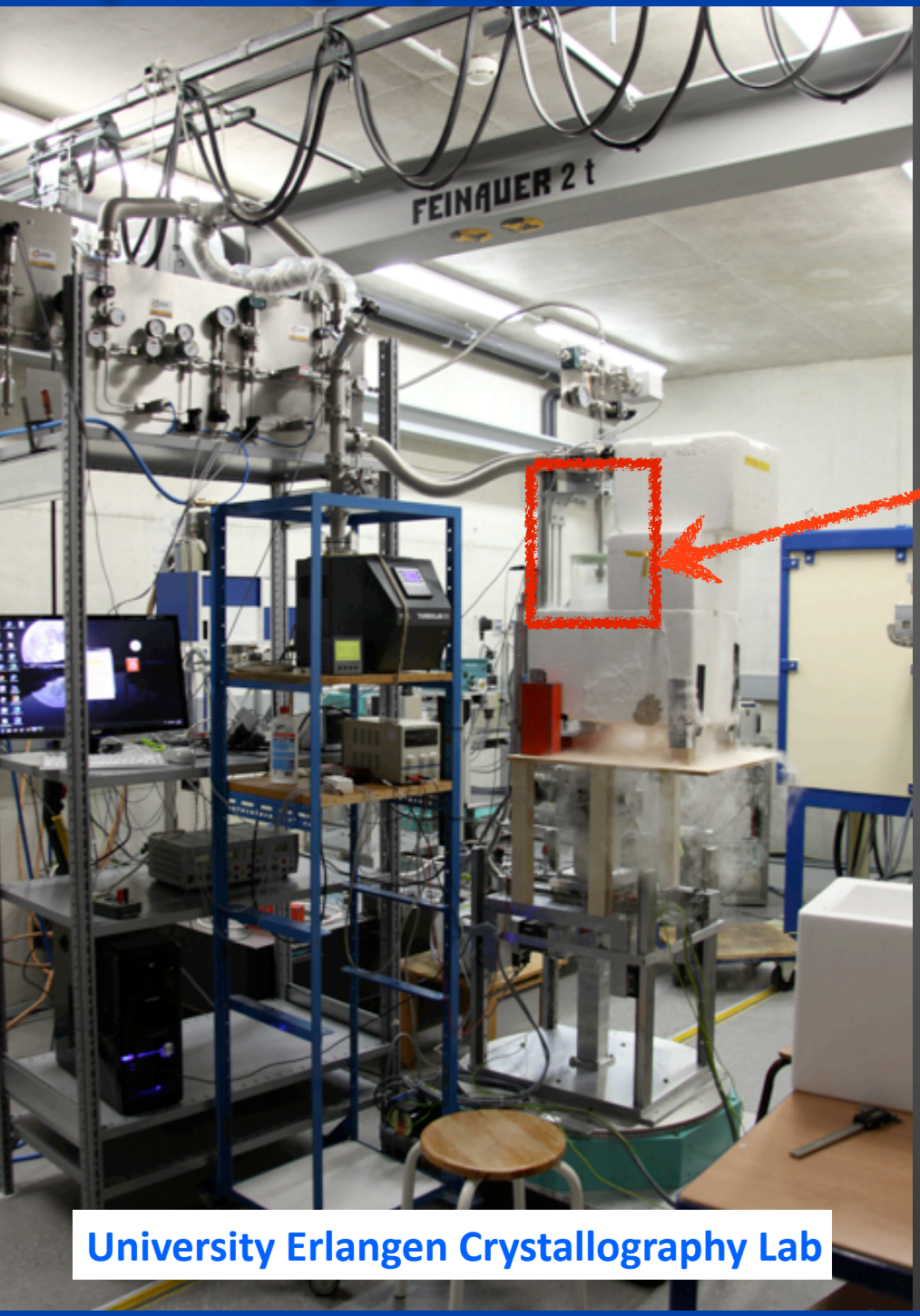
- Active area Ø 345 cm
- Resolution ~ 100 µm
- Read out incl. delay time = 2 min



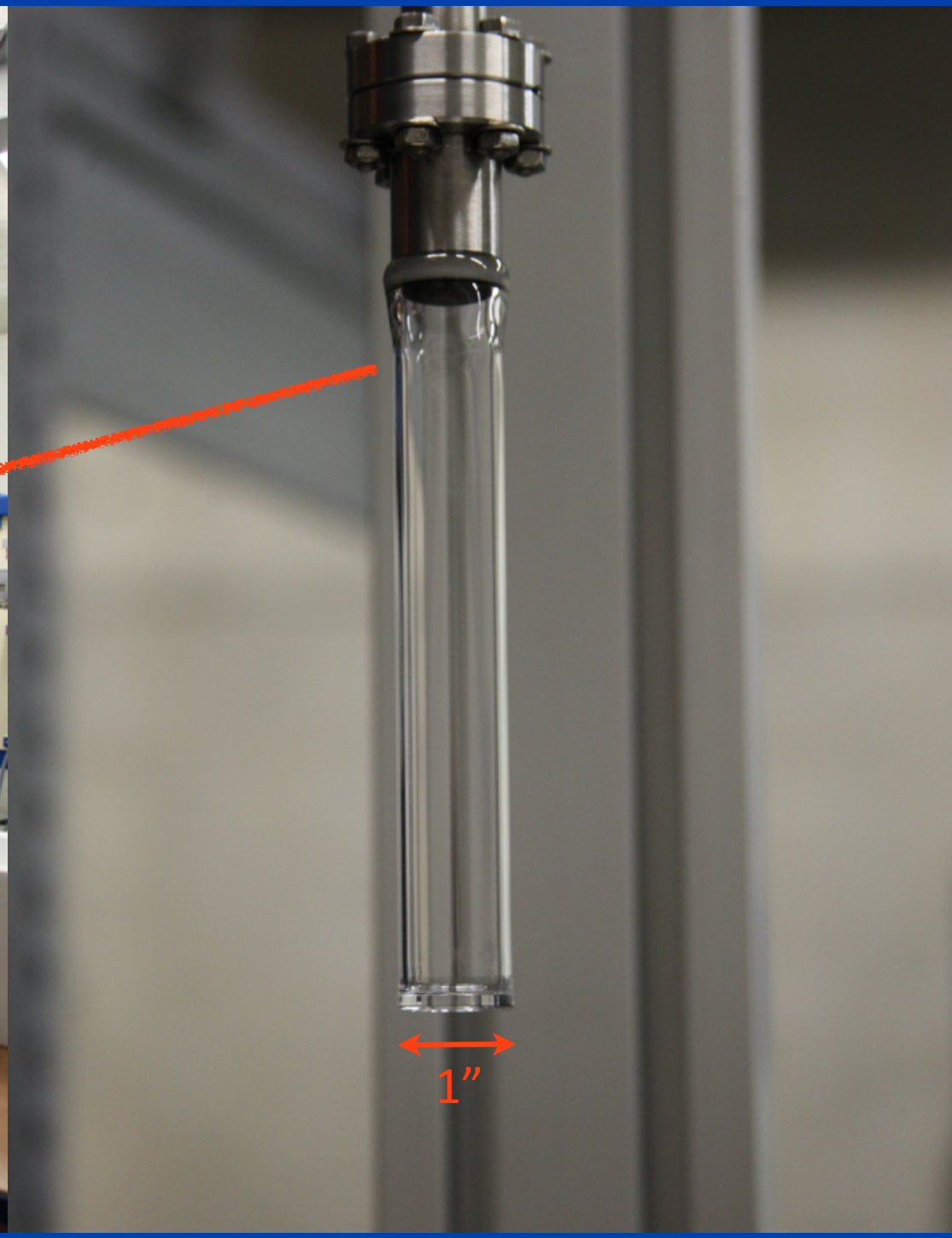
Crystallography



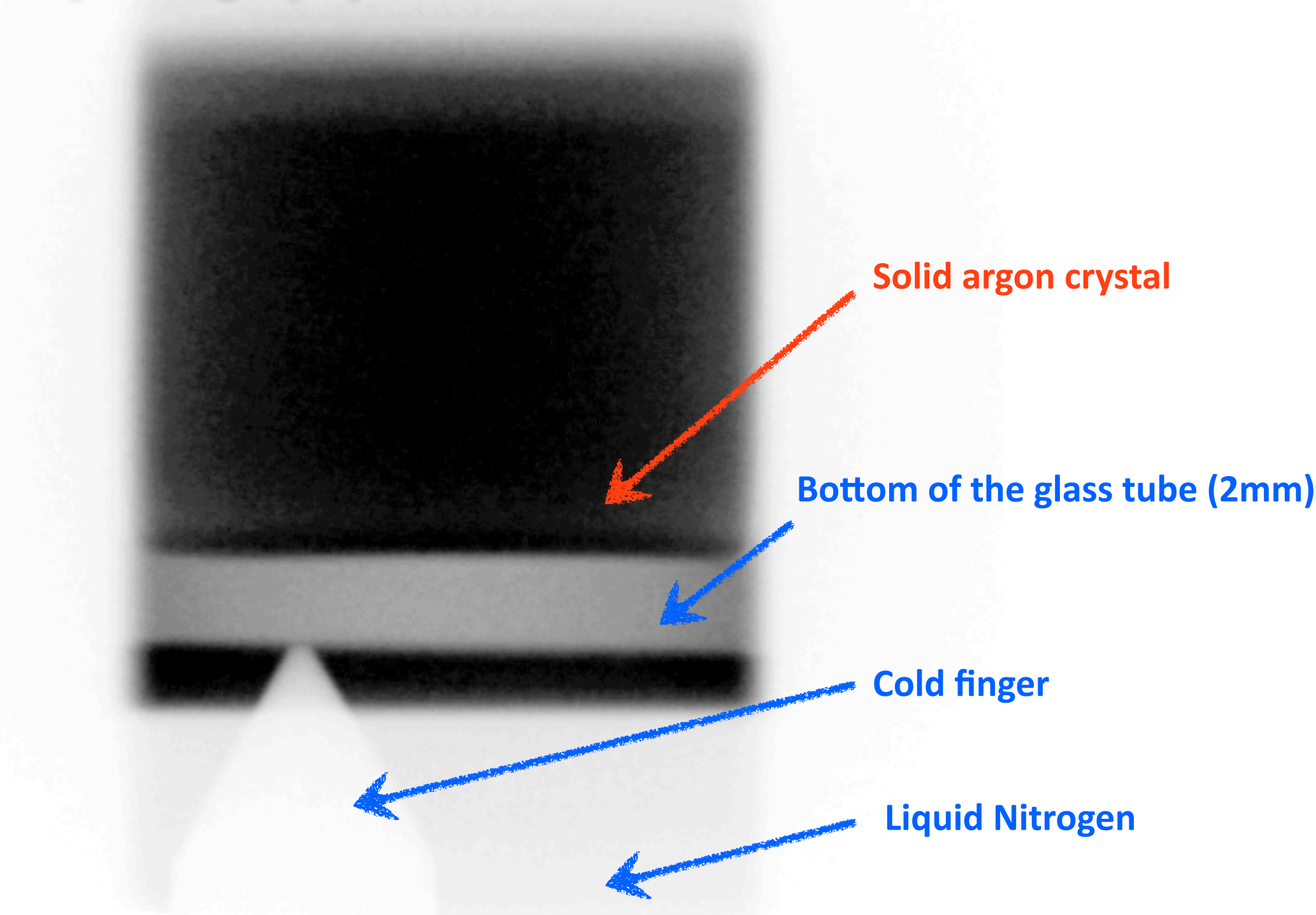
Crystallography of Solid Xenon?



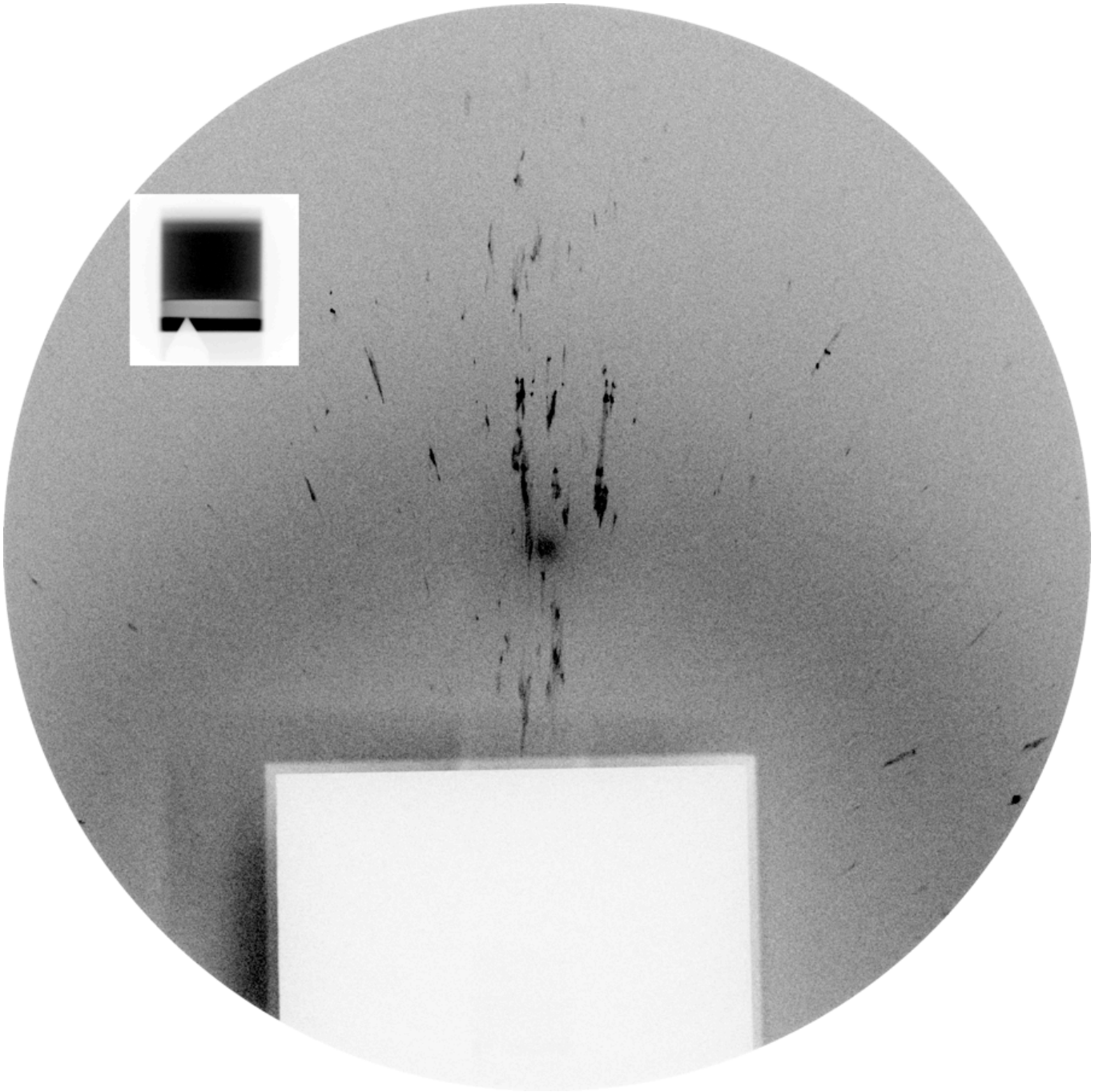
University Erlangen Crystallography Lab



Crystallography of Solid Xenon?



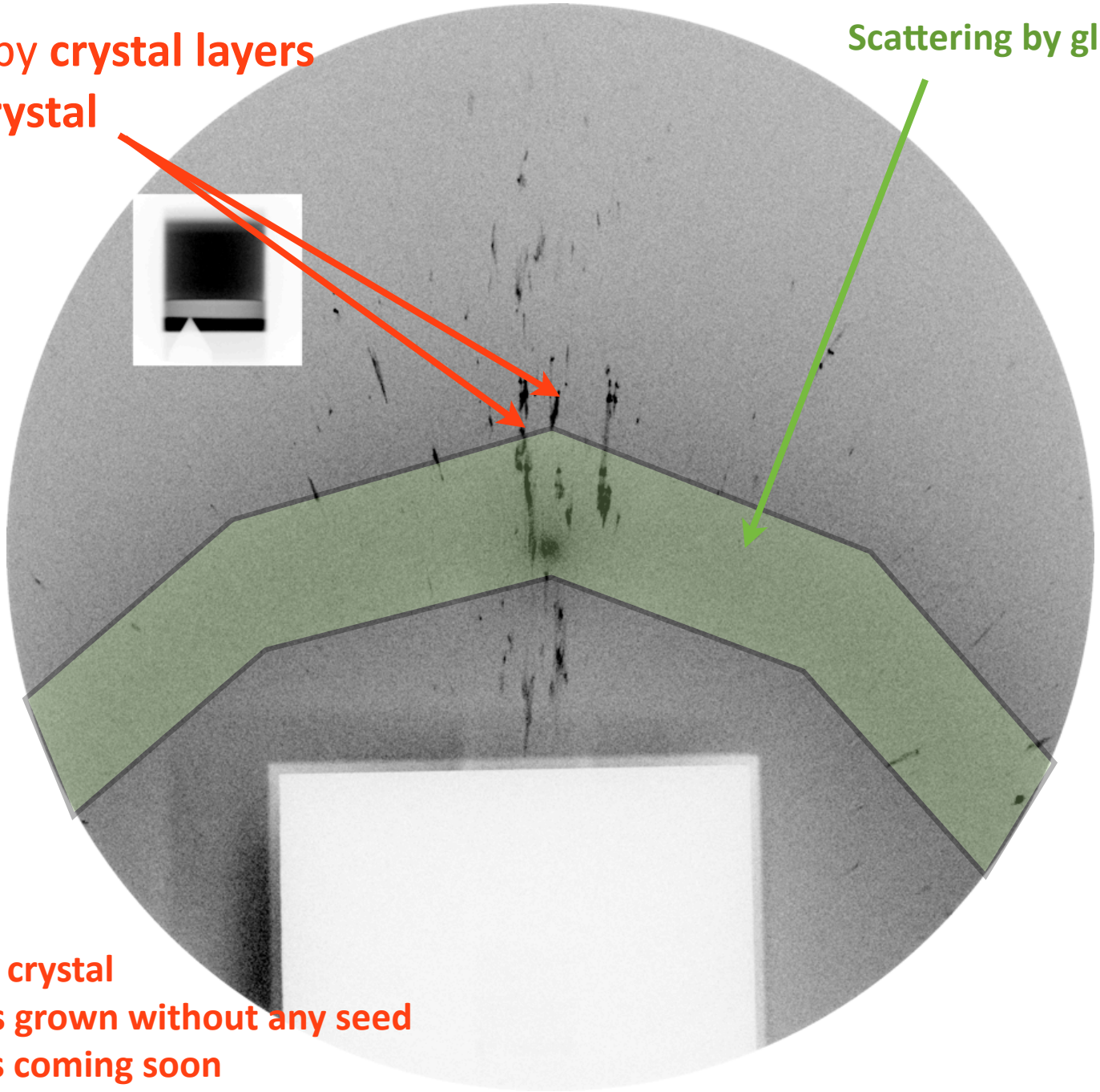
Crystallography of Solid Xenon?



Crystallography of Solid Xenon?

Scattering by **crystal layers**
→ **single crystal**

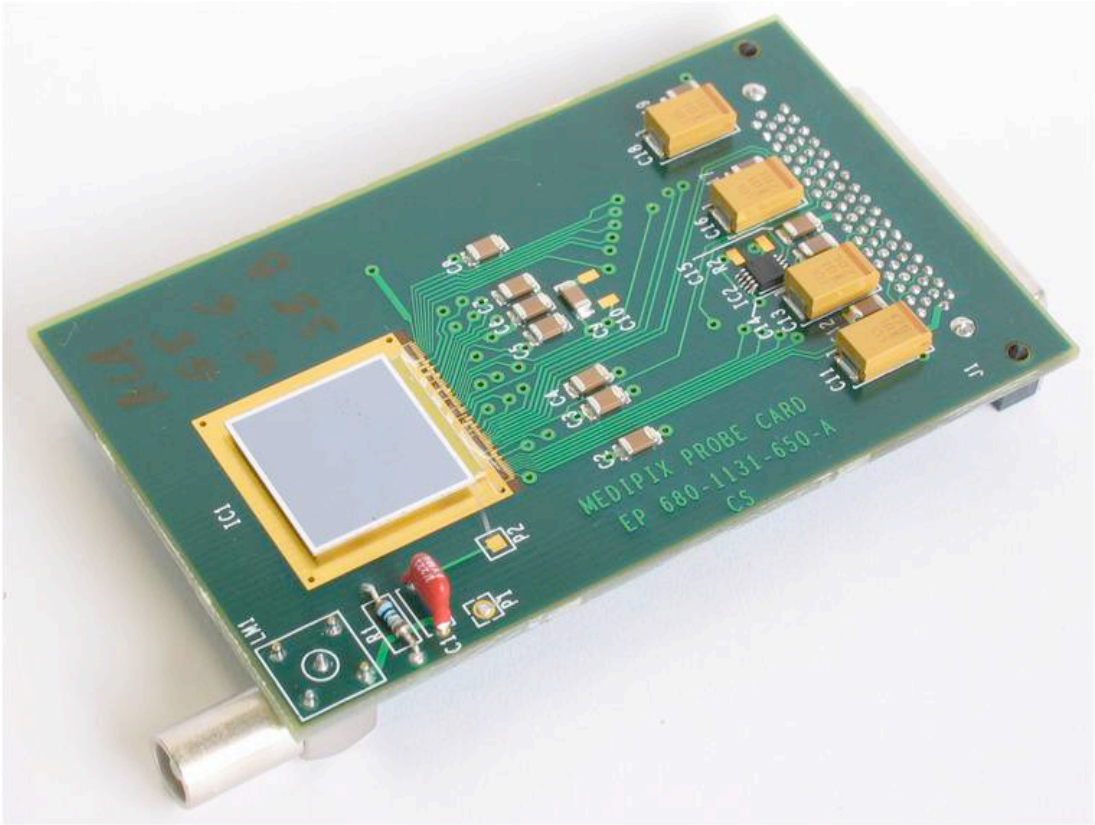
Scattering by glass (amorphous)

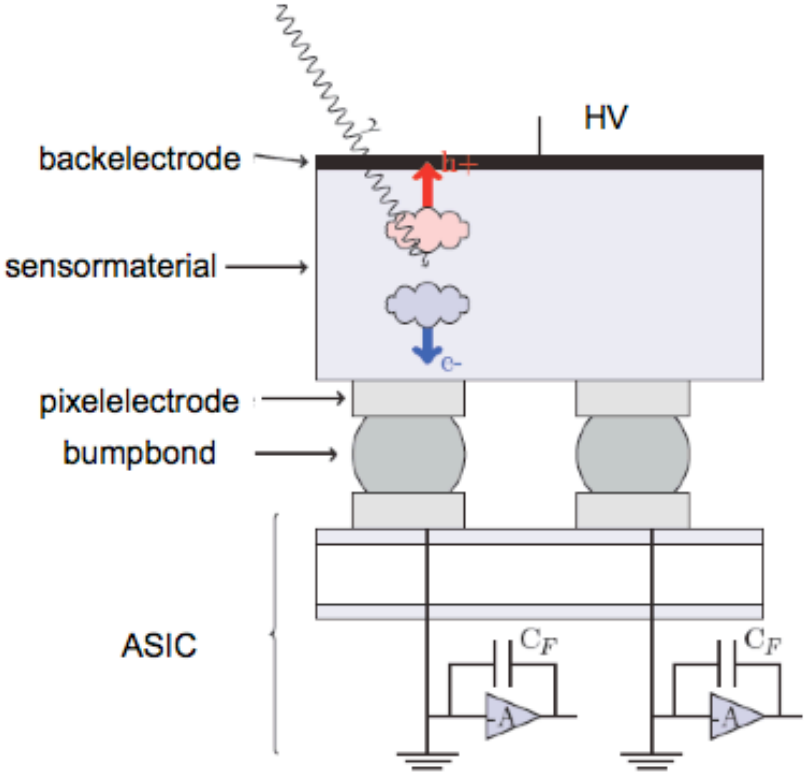


Note:
1. This is argon crystal
2. The crystal is grown without any seed
3. Xenon test is coming soon

Xenon Based Detector R&D at Fermilab

Fermilab & Univ.Erlangen





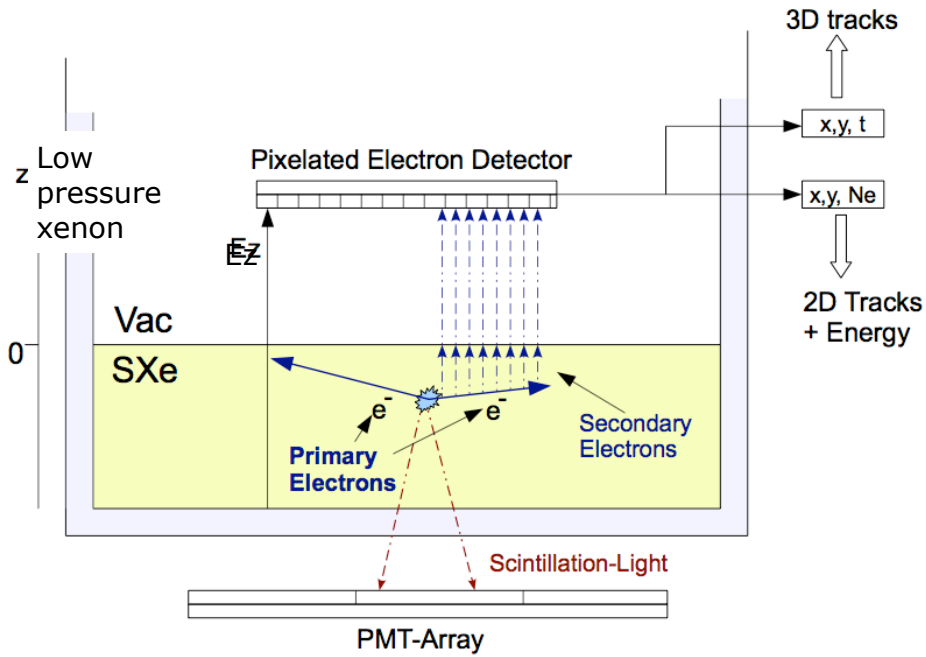
From E. Guni (Dissertation '12)

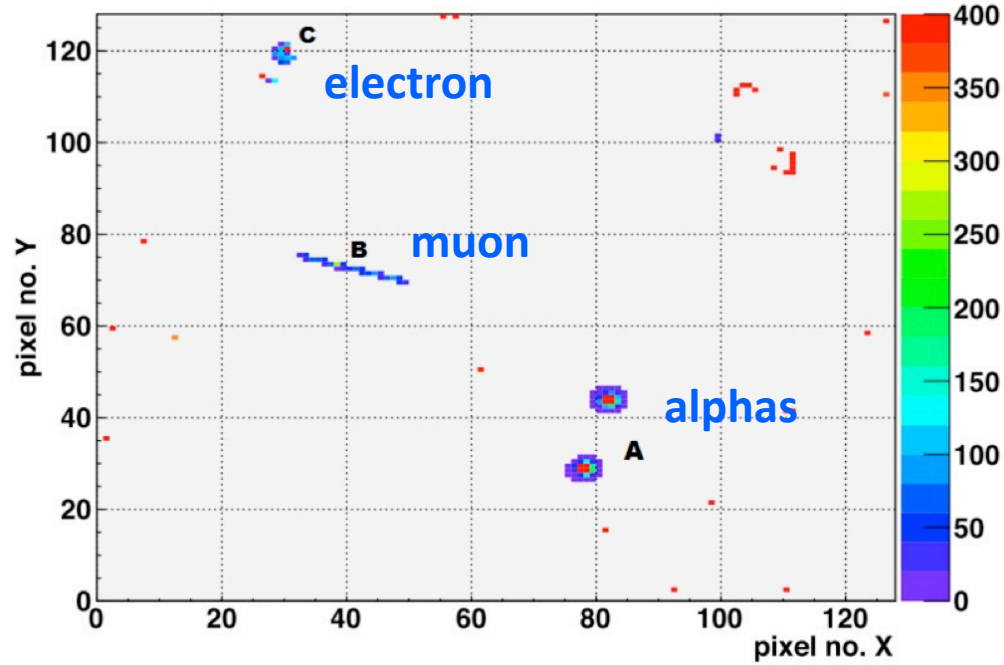
Timepix: Pixelated semiconductor X-ray imaging detector

- 256x256 pixels/chip
- 55µm, 110µm or 220 µm pixel size choices
- Si or CdTe sensors
- Energy threshold for each pixel is about 5 keV (current version)
- Timing resolution: 20ns

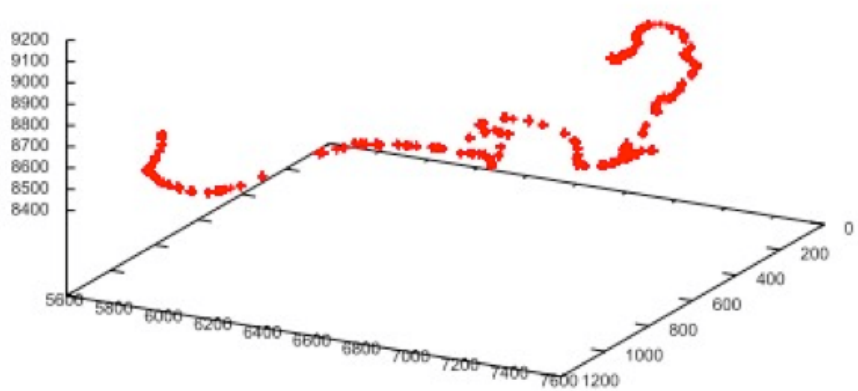
Xenon Based Detector R&D at Fermilab

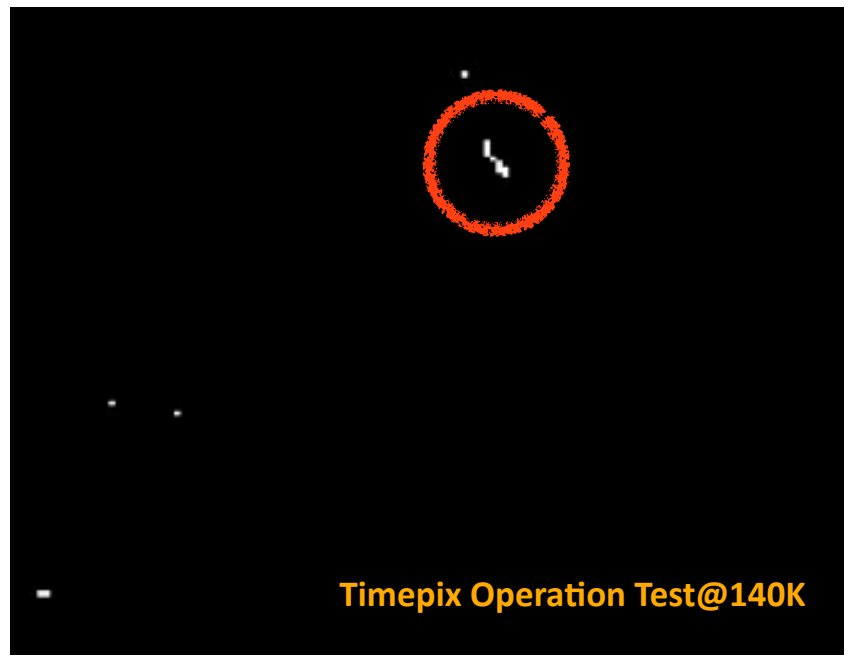
M. Filipenko



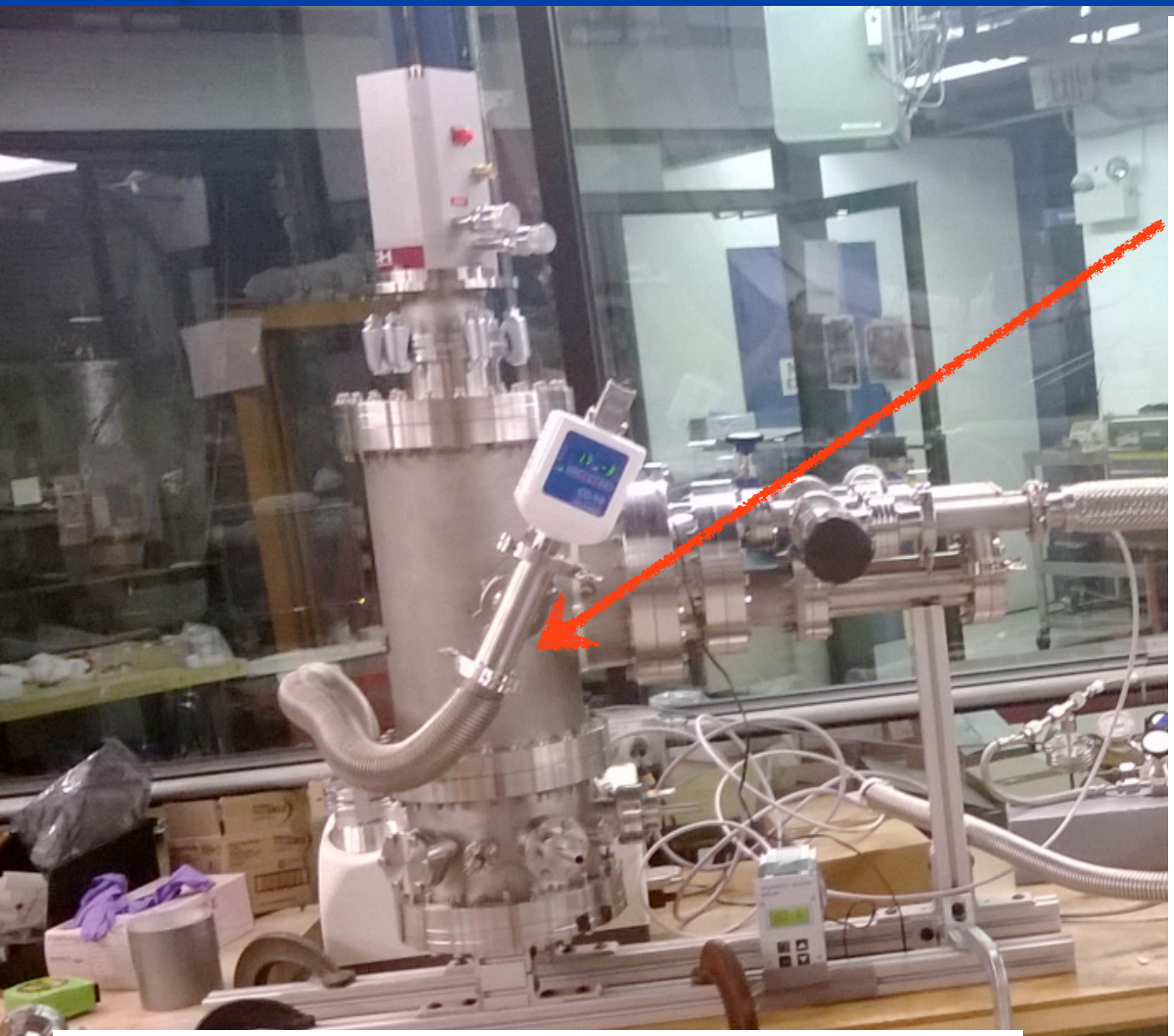


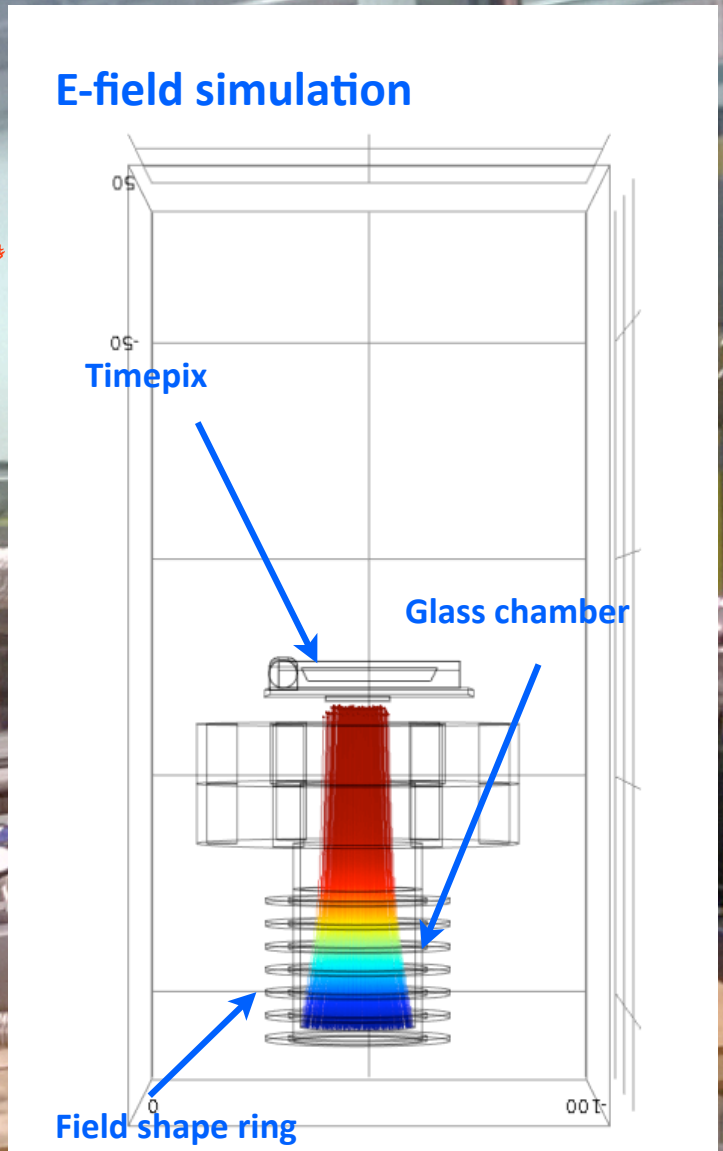
MC simulation of two electron tracks





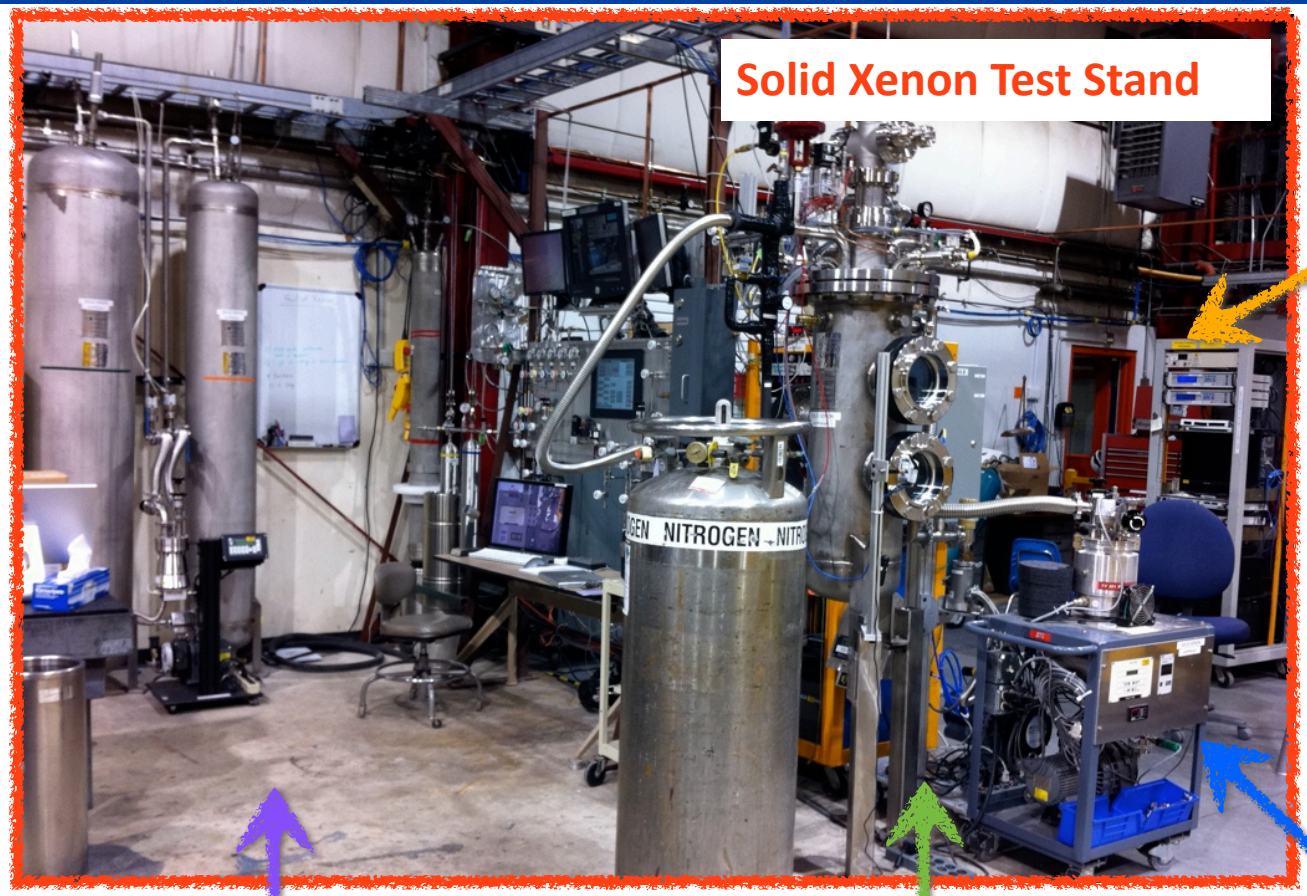
Timepix at Fermilab: Lab-A

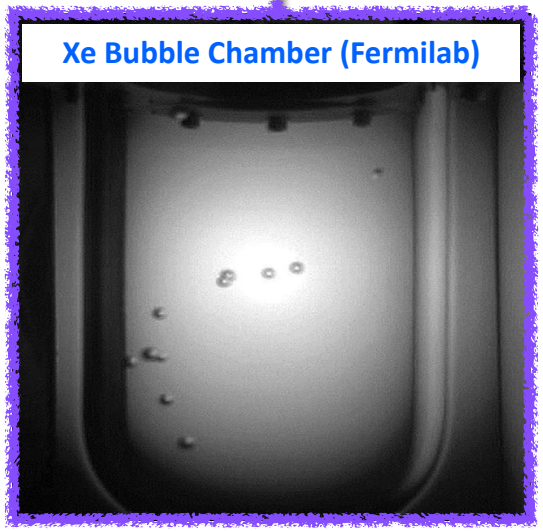


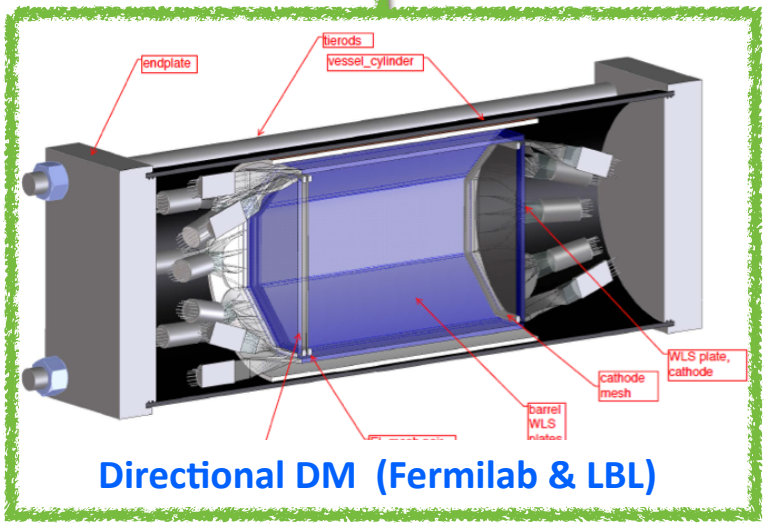


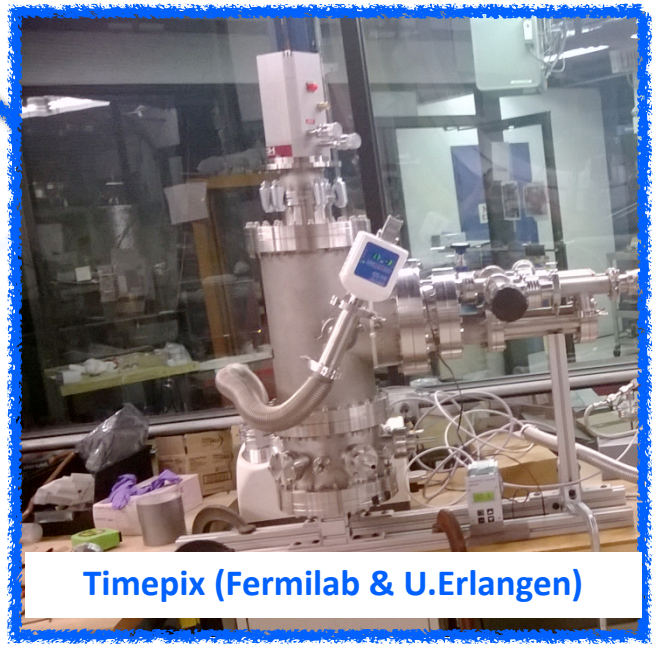
- Timepix operational test in cold temperature is done
- Cryocooler cooling test in progress
- The setup to be moved to PAB for the xenon test

Xenon Based Detector R&D at Fermilab









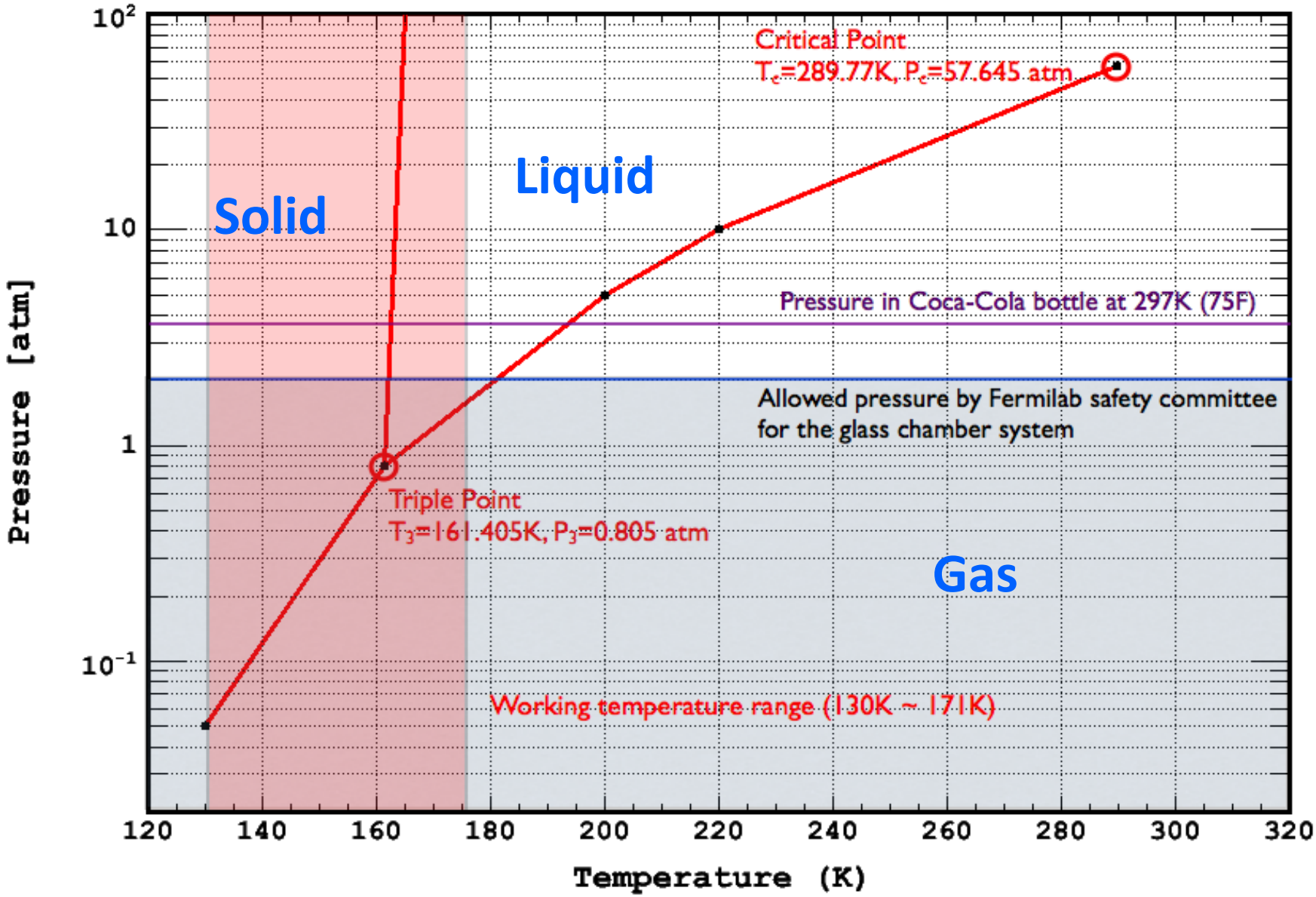
Summary

- **Solid Xenon is very attractive detector material**
  - Solid (crystal) phase of xenon is scalable
  - Scintillation light can be readout in large scale solid xenon
  - Electron drift is faster in solid xenon
  - Phonon readout (?.. milliKelvin Facility at Fermilab)
- **Fine tuning measurement to be continued**
  - Further characterize the scintillation property (focused on PSD)
  - Measure the electron drift velocity with better accuracy
  - Crystallography of solid xenon will be soon carried out (Univ. Erlangen)
- **Synergy of the infrastructure of the solid xenon test stand**
  - Timepix: SXe-based 0νββ detector R&D
  - XCD: LXe scintillation property measurement
  - Directional DM: detector R&D for columnar recombination in GXe
  - High pressure LXe Bubble Chamber: Dark matter search R&D

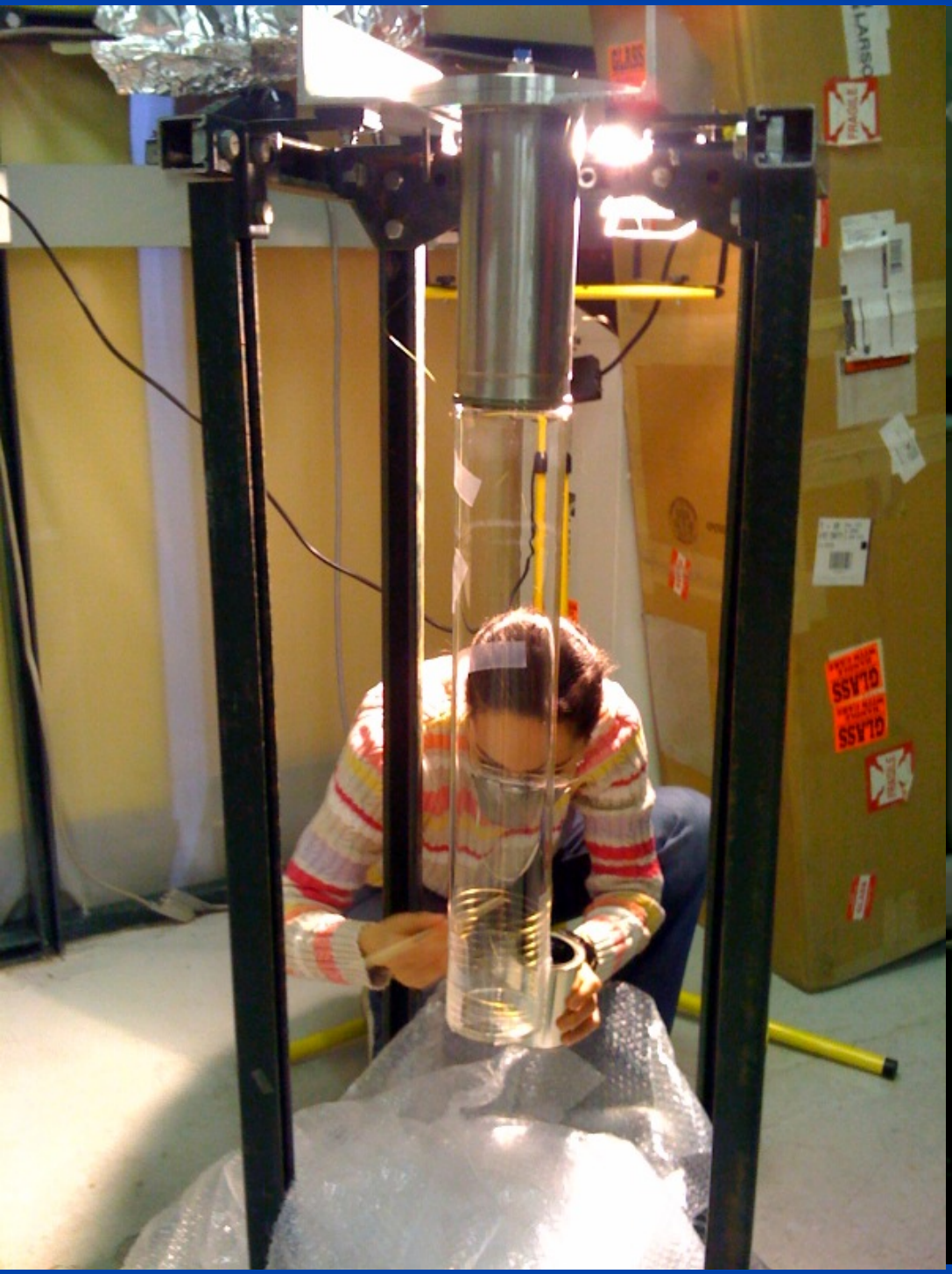
Thanks to technical and engineering crews at PAB, BEG, MAB, Lab-A, and Lab-F!

Backup Slides

Xenon Phase Diagram

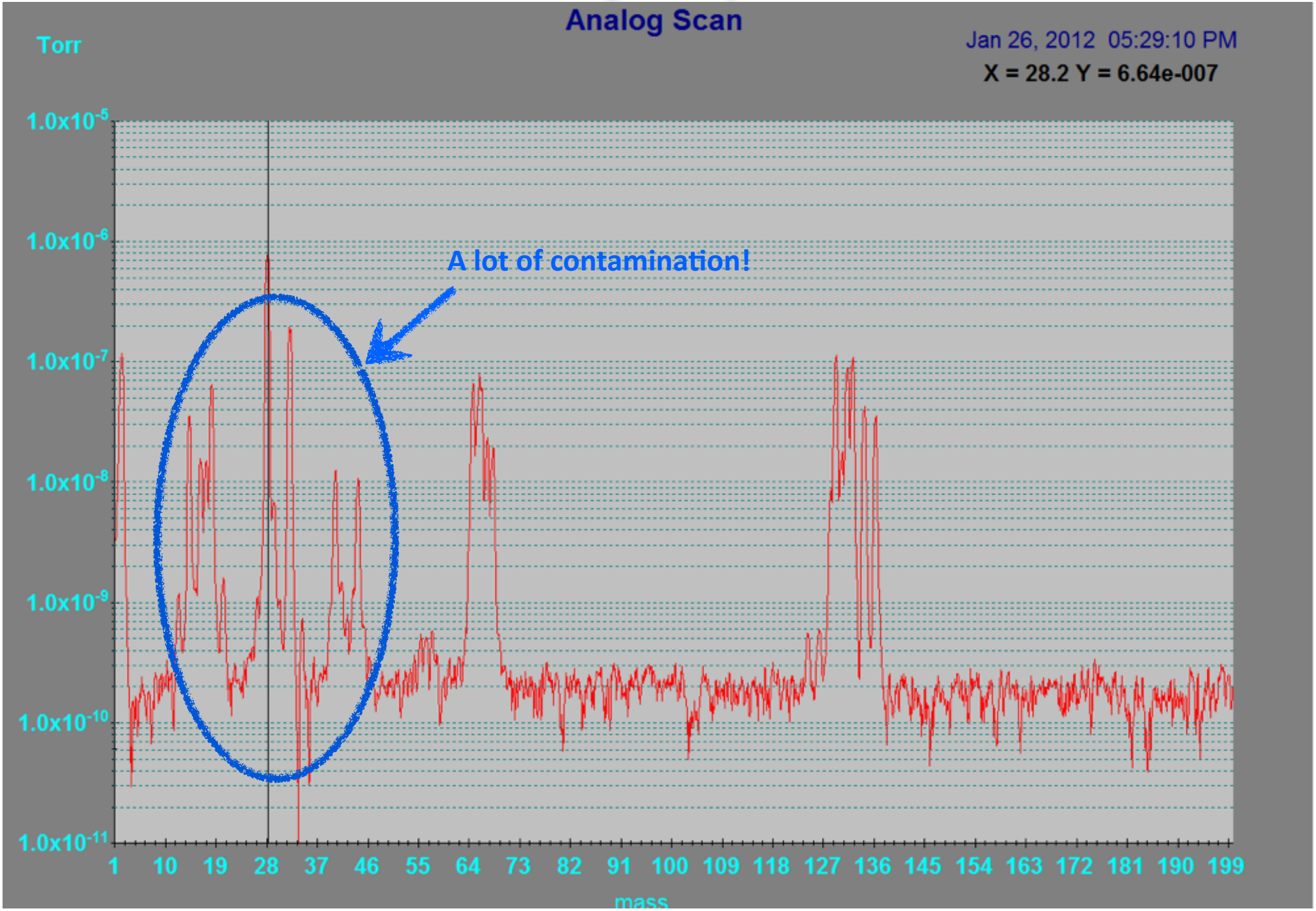


Inner Glass Chamber: Xenon Volume

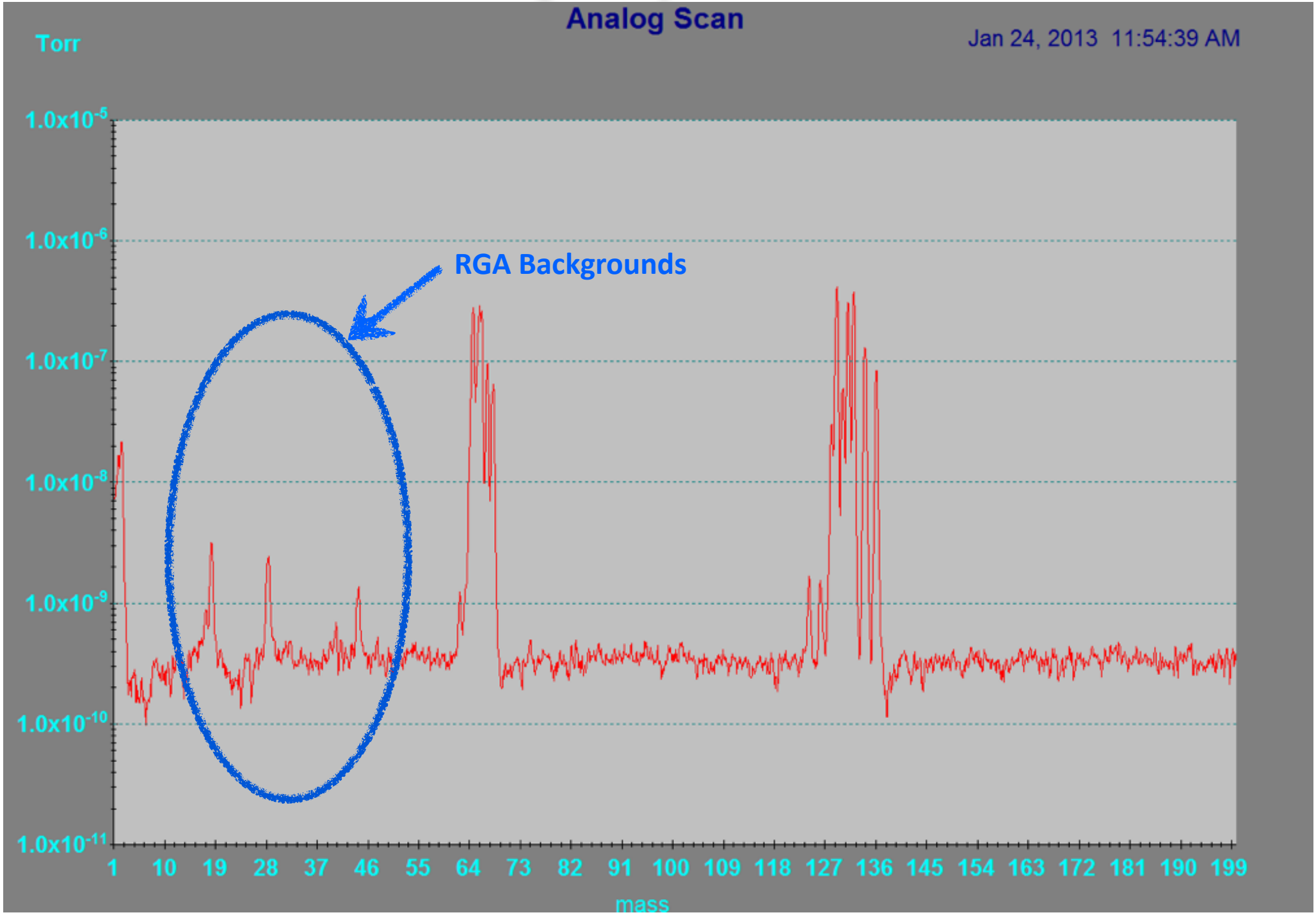


Xenon Gas at a Fermilab Shed

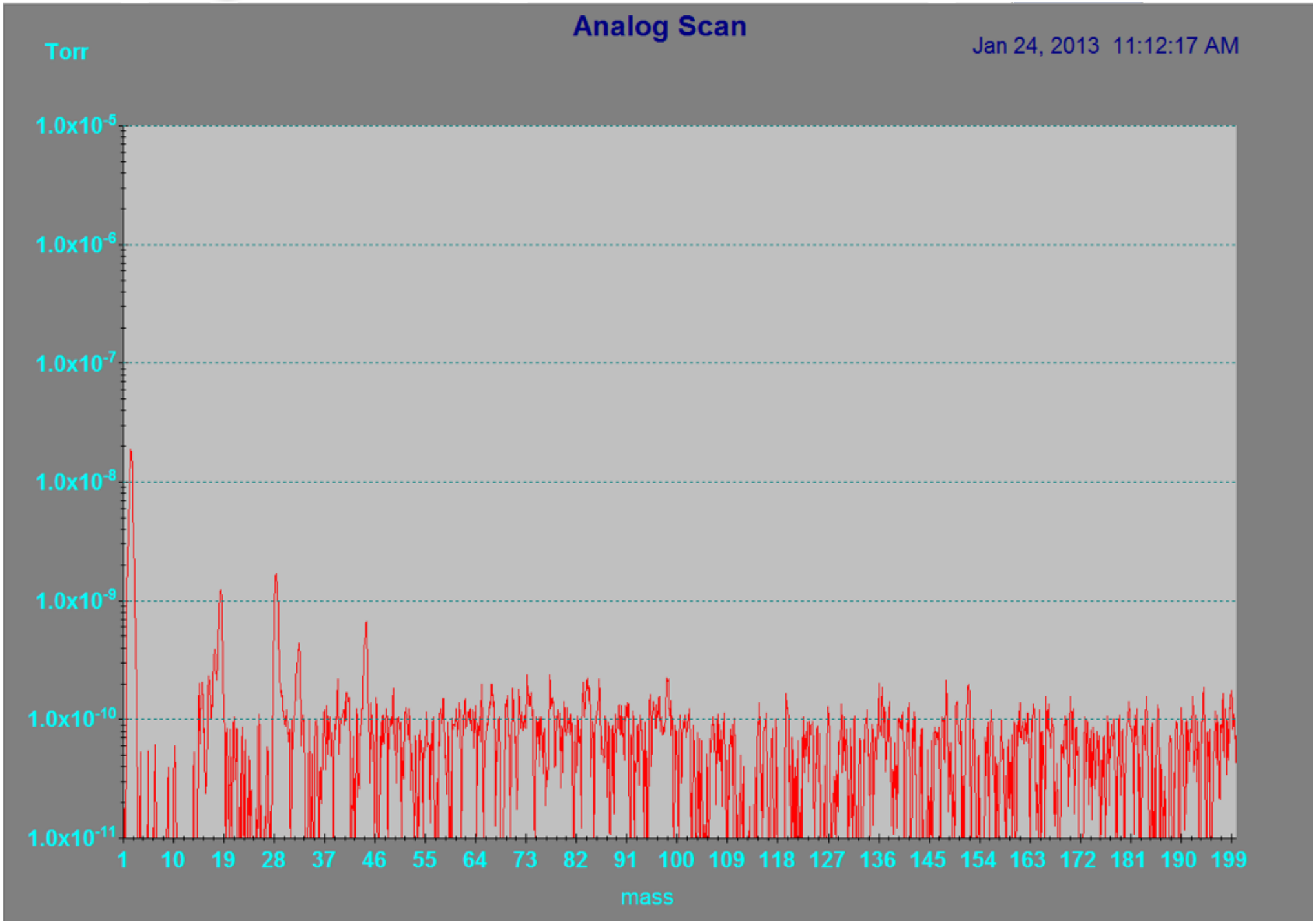
Fermilab Gas Shed Xenon Quality: RGA Readout



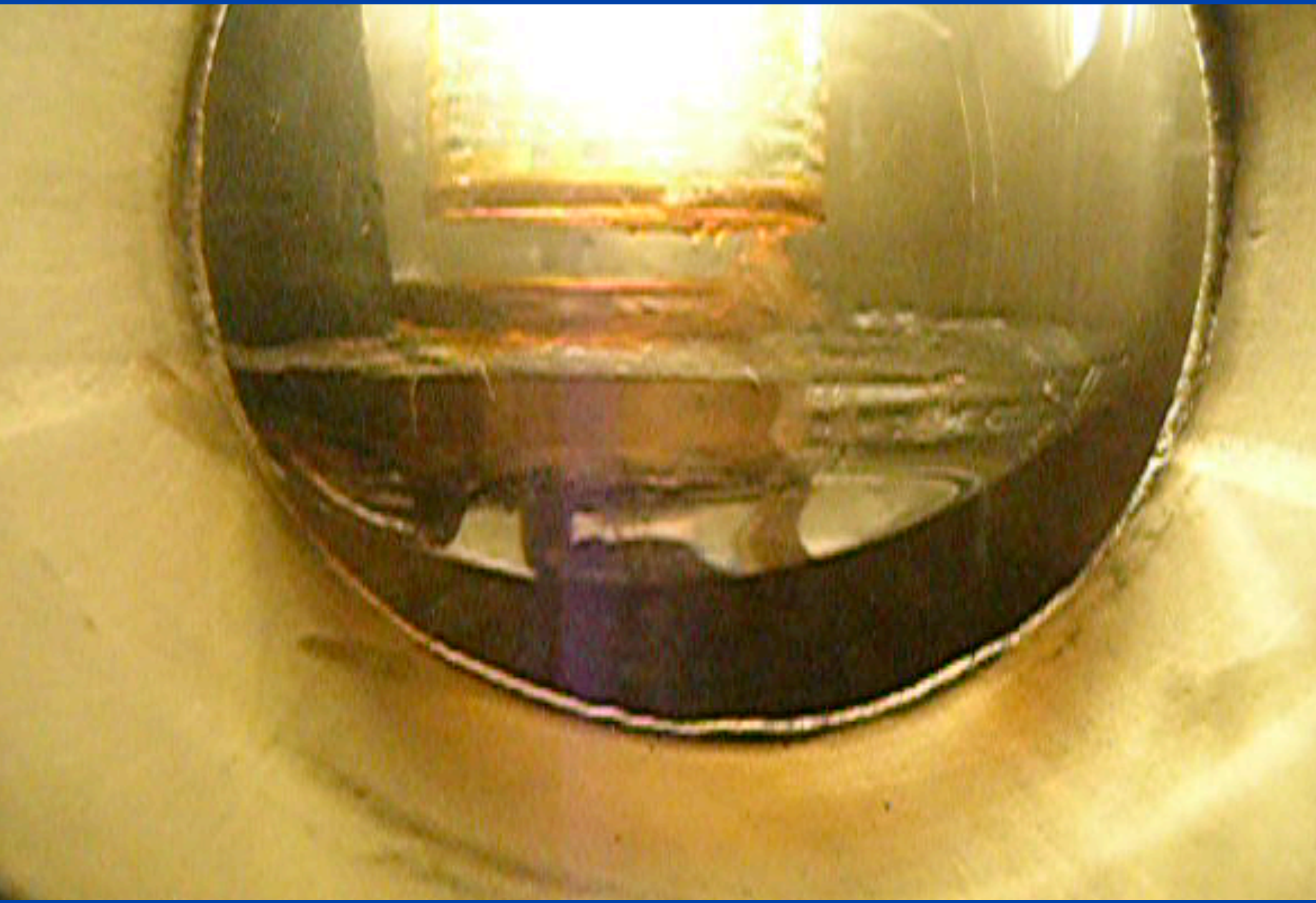
Research Grade Xenon Quality: RGA Readout



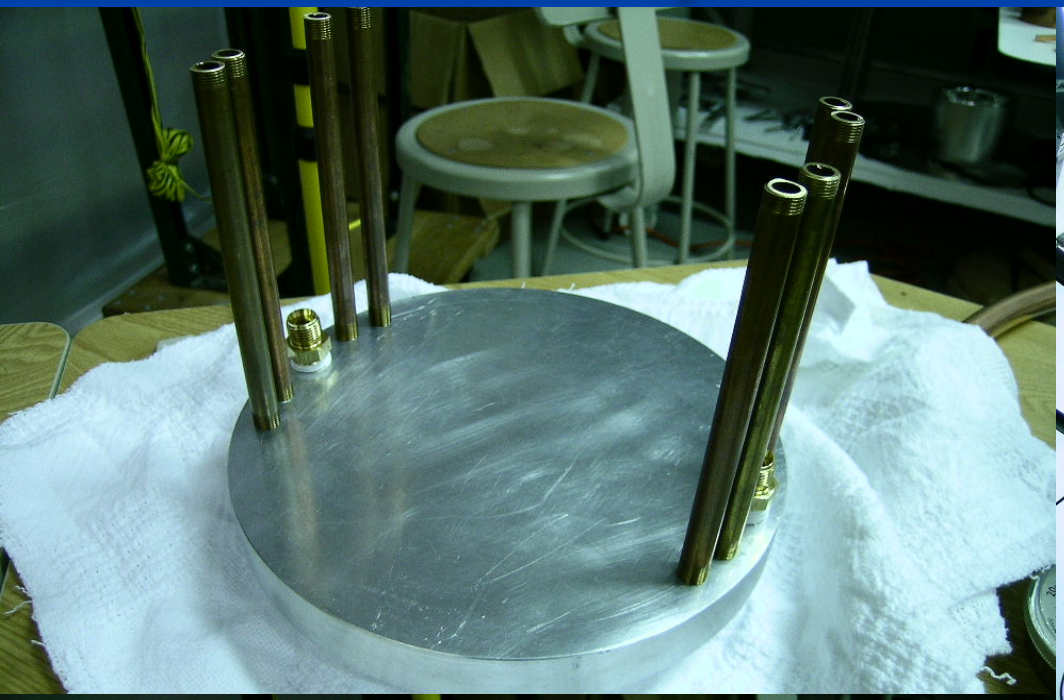
RGA Background

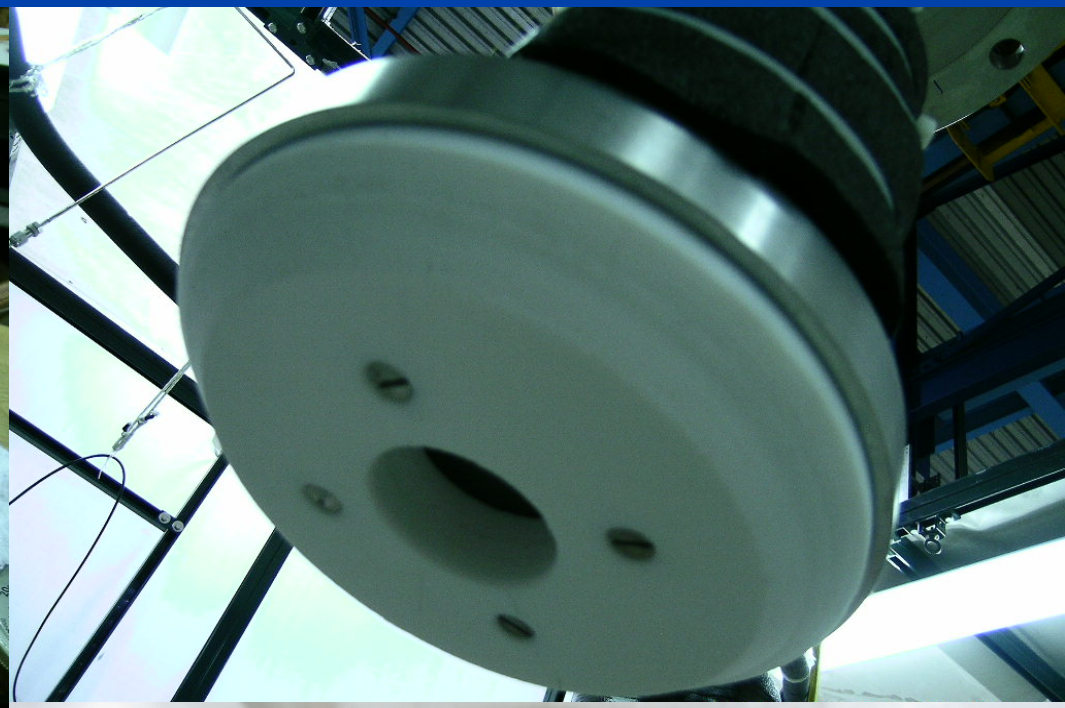


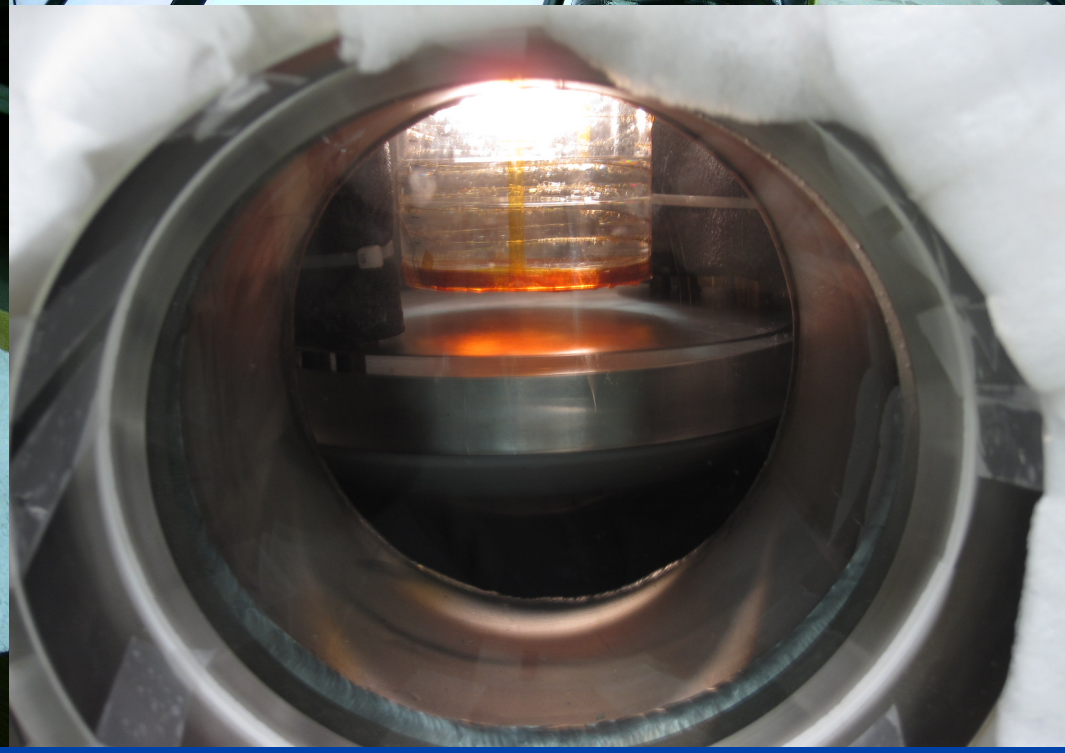
Cold Bath Control Trial



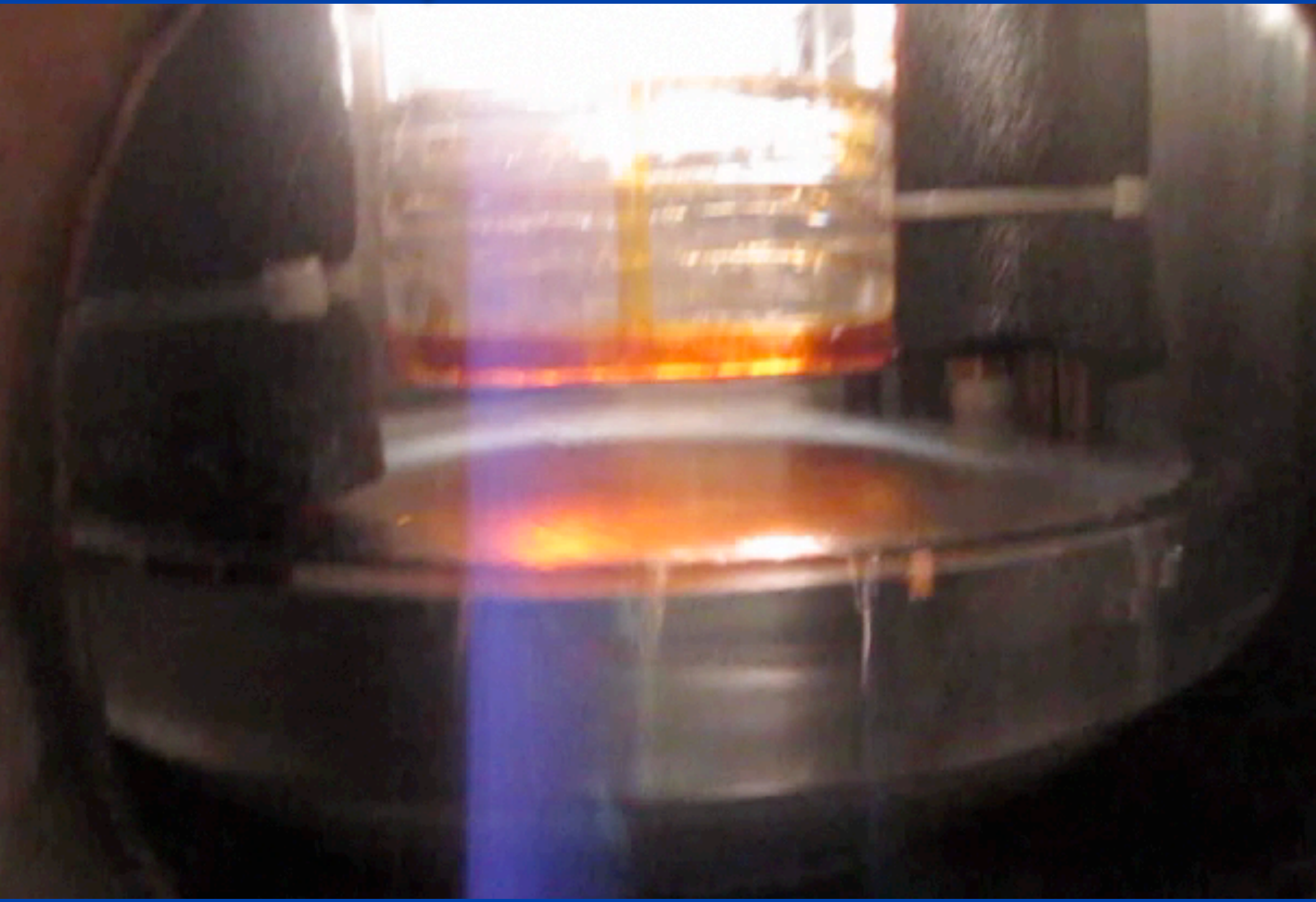
Effective Phase Separator



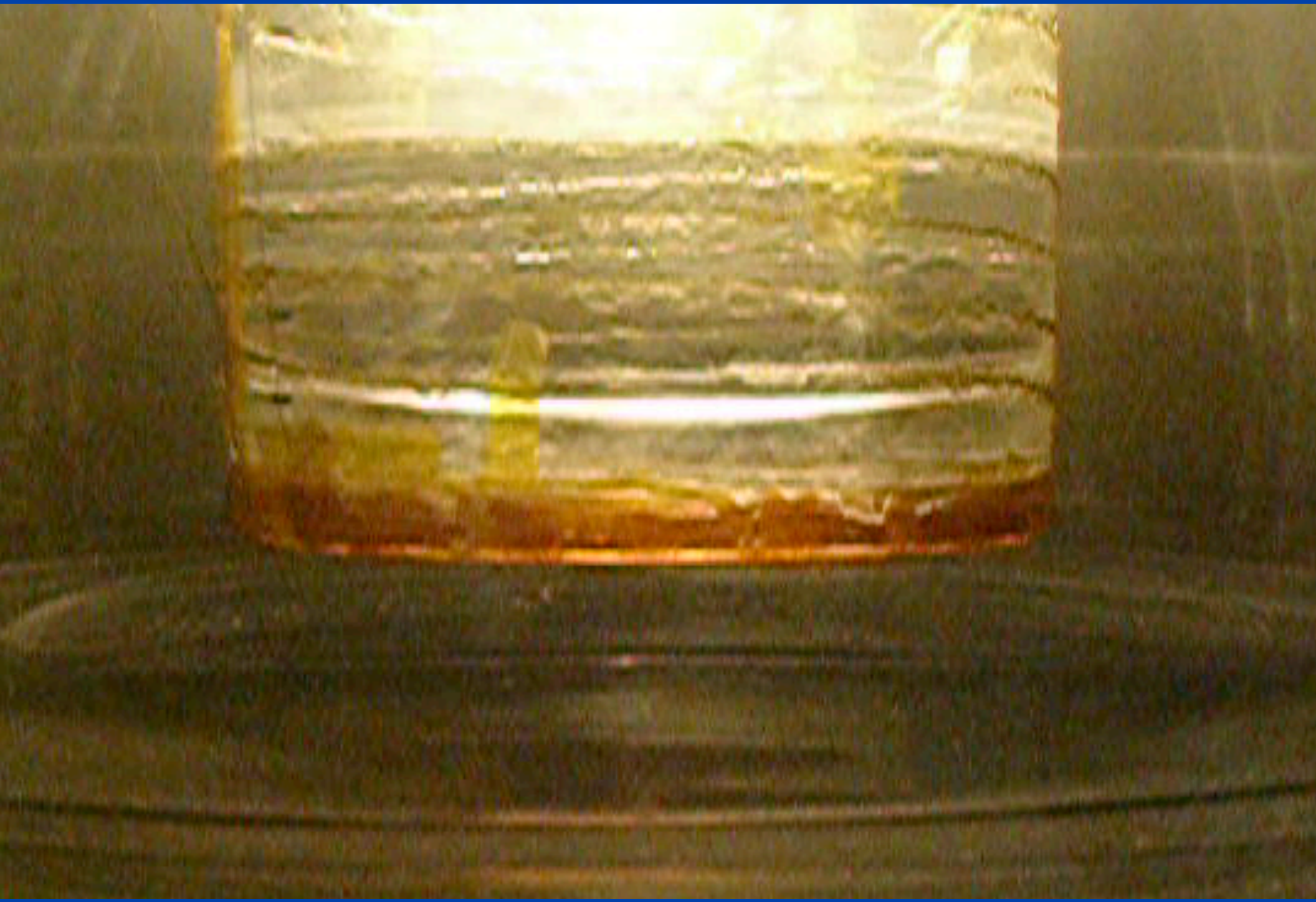




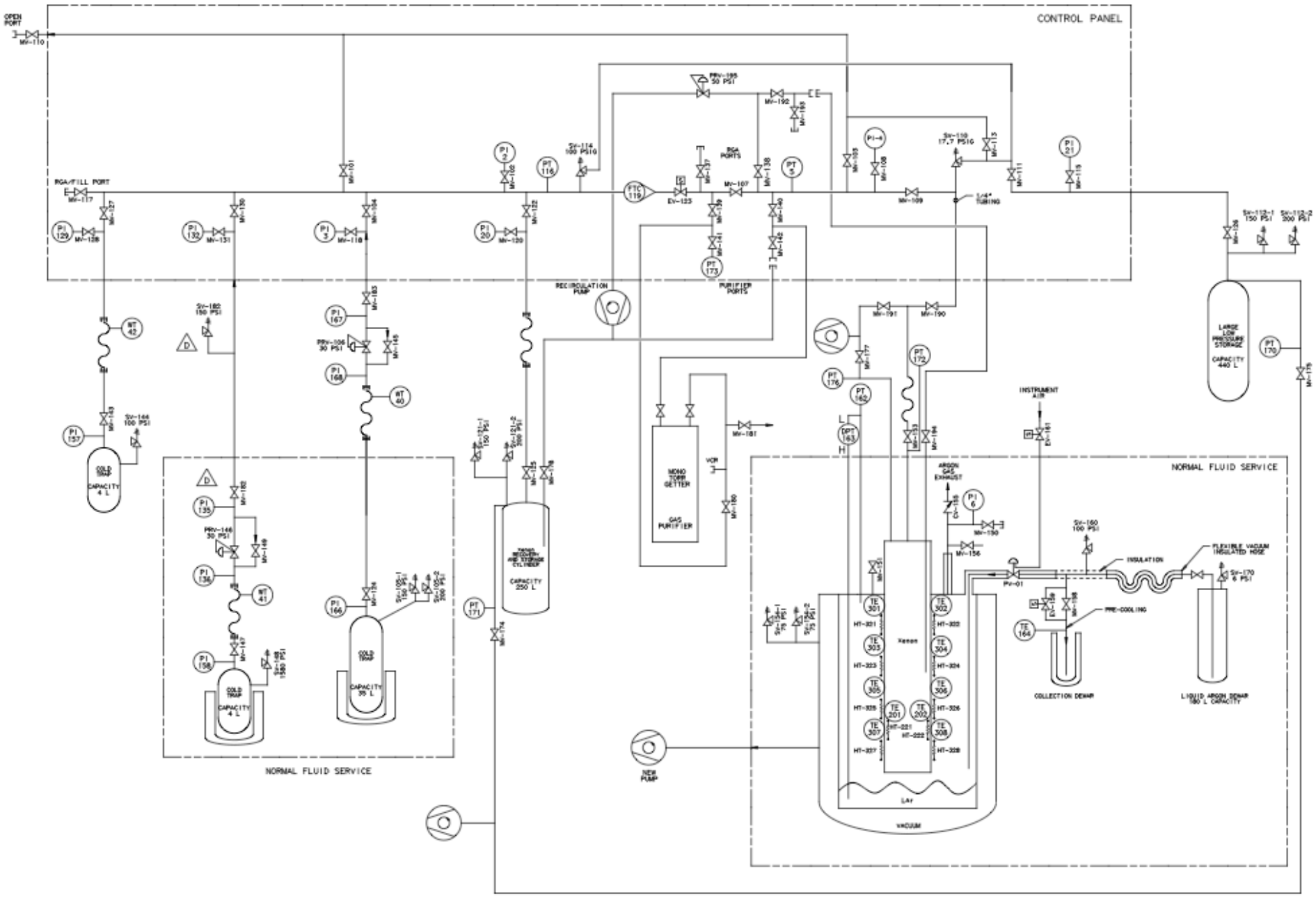
Effective Phase Separator



Solid Xenon: How do we know?



New Plumbing: Automate System Control



Excimer Potential in the Solid (Crystal) Noble Element

- **Weak van der Waals bonding of monoatomic solids**
- **Generally negligible chemical activity in the ground state.**

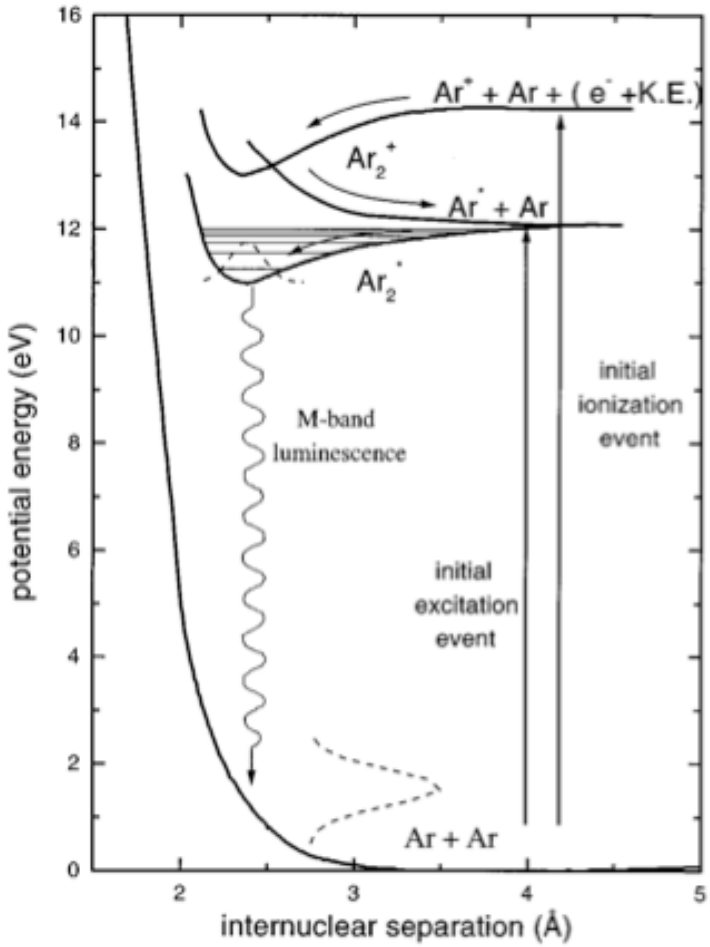


FIG. 1. Ar-Ar potential-energy curves in the solid state. The arrows indicate decay sequences. The decay of the Ar_2* gives rise to the *M* band.

Grosjean PRB 56 6975 (1997)

The *M* band as the major relaxation pathway for electronically deposited energy in solid Ar: decay of Ar_2^* is the major source

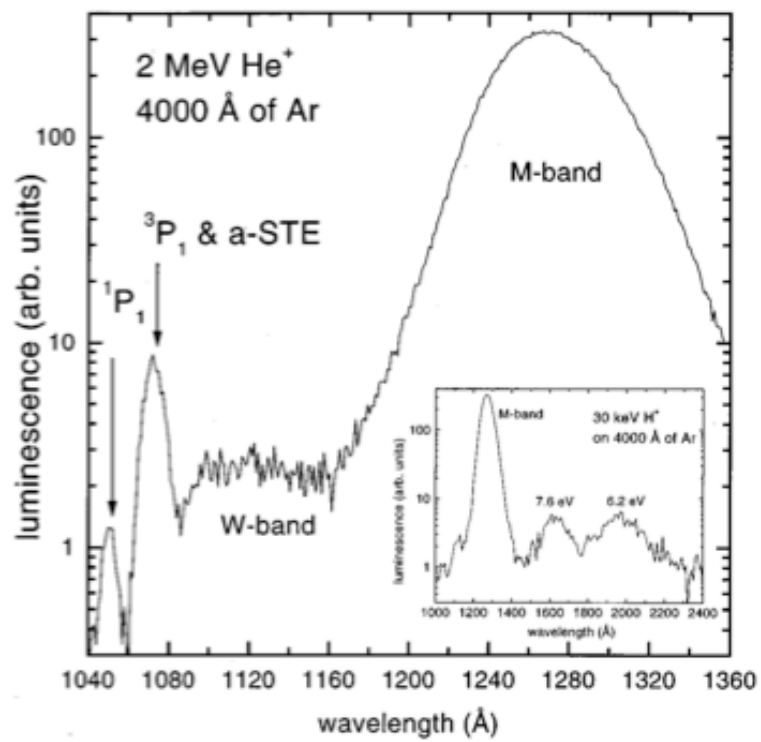


FIG. 3. UV luminescence spectrum of a 4000-Å solid Ar film bombarded by 2-MeV He^+. The inset shows a spectrum produced by 30-keV H^+ on a 4000-Å Ar film that includes lower-energy features. No luminescence features were seen in the range of 2200–5000 Å.

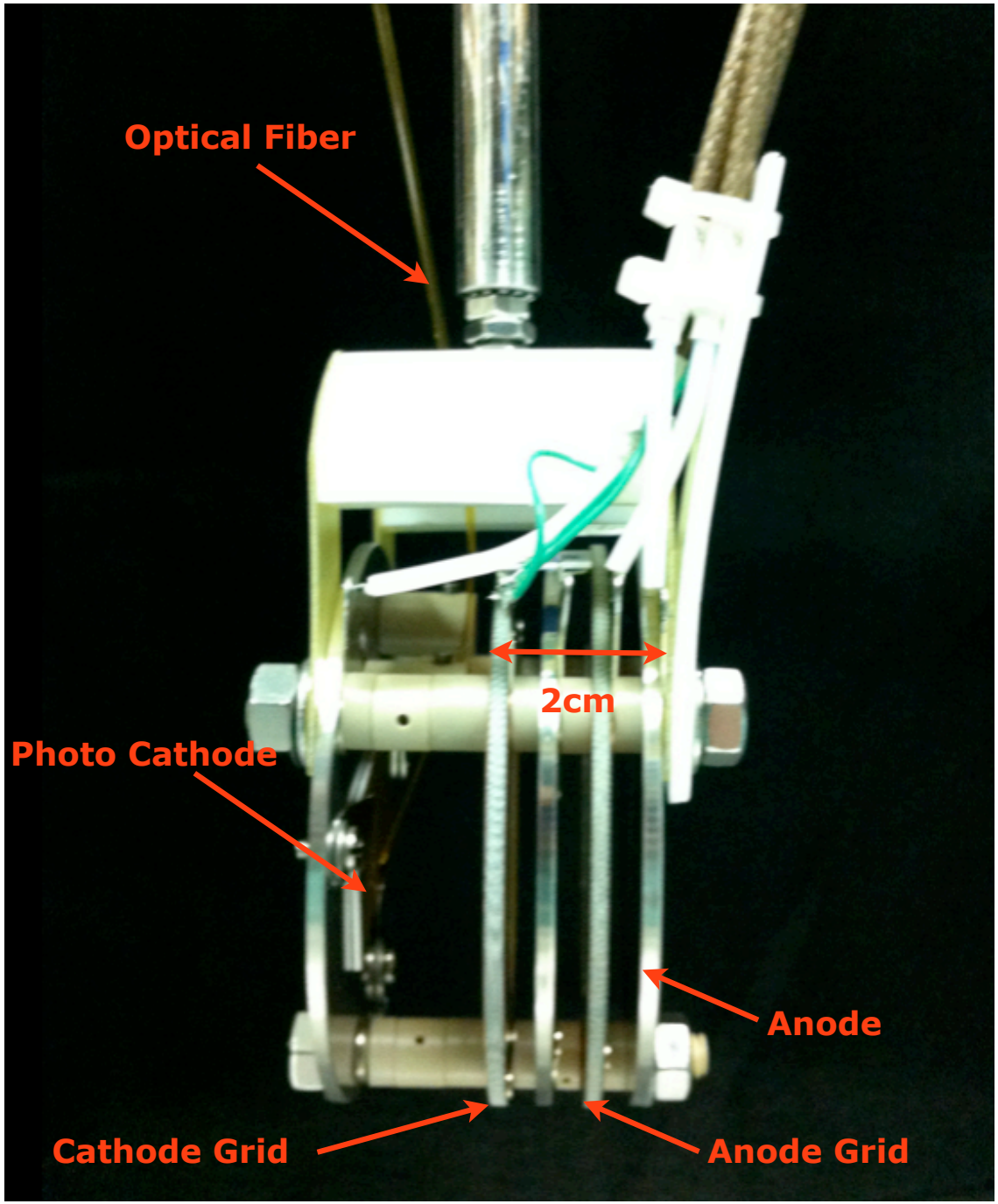
CAEN V1720B digitizer

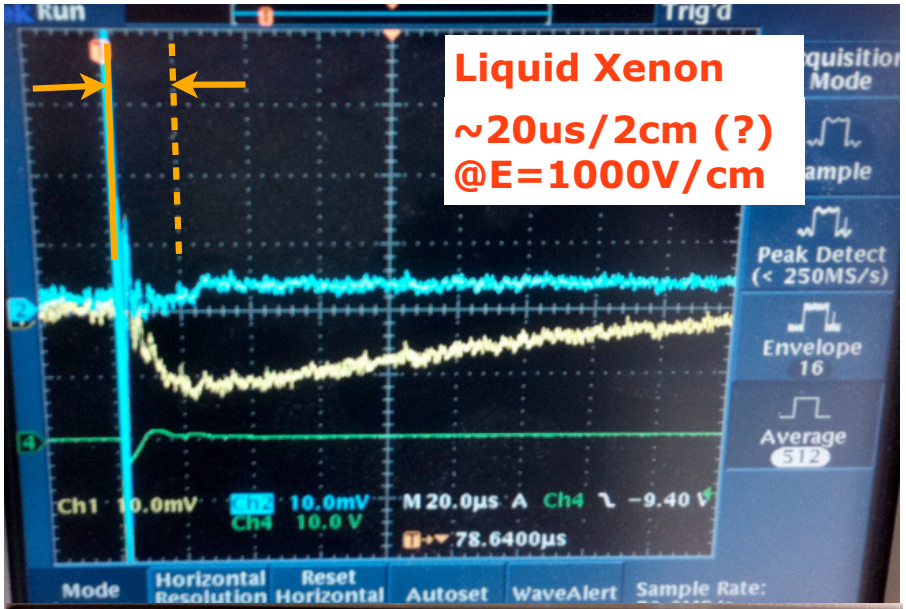
- VME module (optical Link CAEN protocol)
- 12 bit 250 MS/s ADC
- 8 channels
- 2 Vpp input range (single ended or differential)
- 16-bit programmable DC offset adjustment: ±1 V
- Trigger Time stamps
- Memory buffer: 10 MS/ch

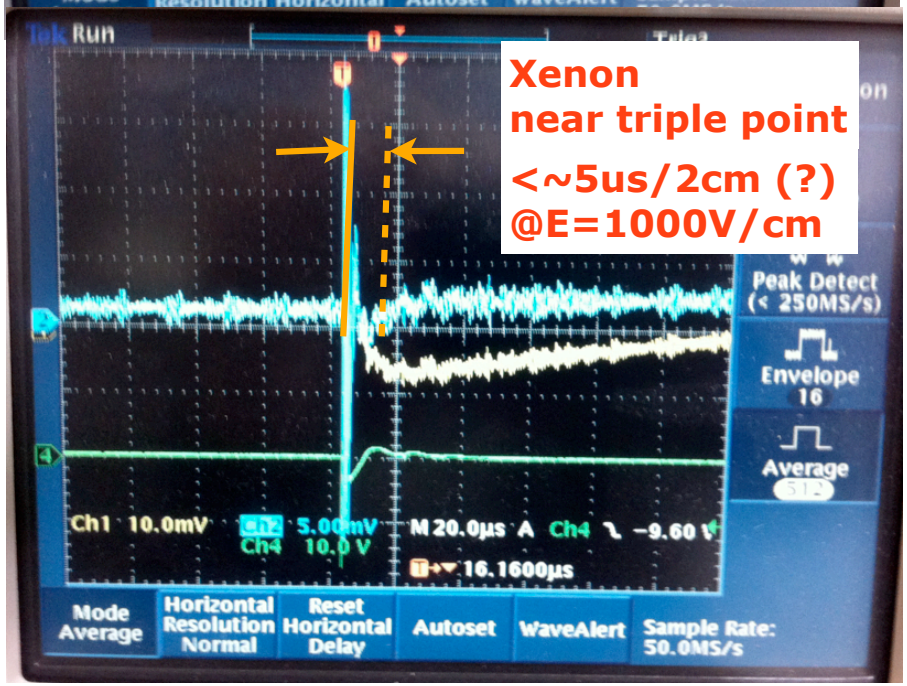
daqman software package (Ben Loer)

- Plug and Play
- Data acquisition / monitoring
- Convenient configuration setting
- Data processing → output ROOT trees
- Event display, analysis software tool set

Electron Drift Test



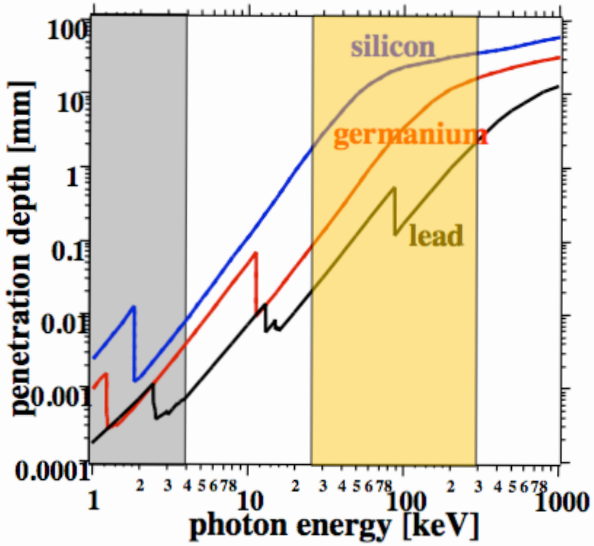




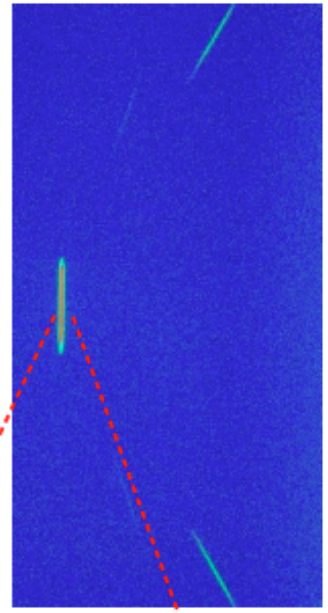
- Need to improve the purity of xenon

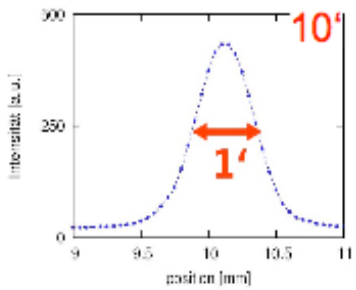
Crystallography Lab at Erlangen

HEXBay Lab



Ideal Si
CCD-detail: 20 x 10 cm²

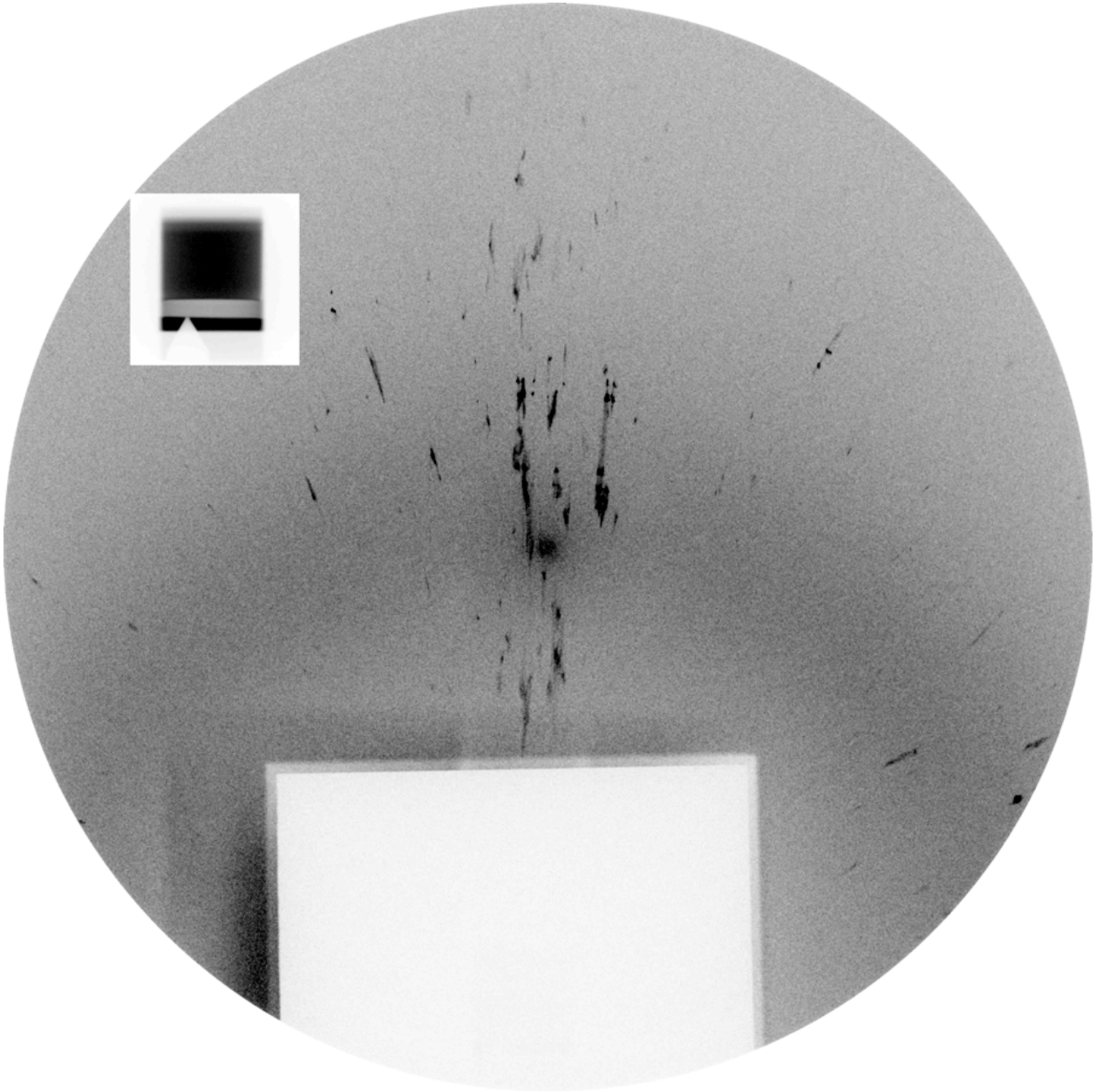




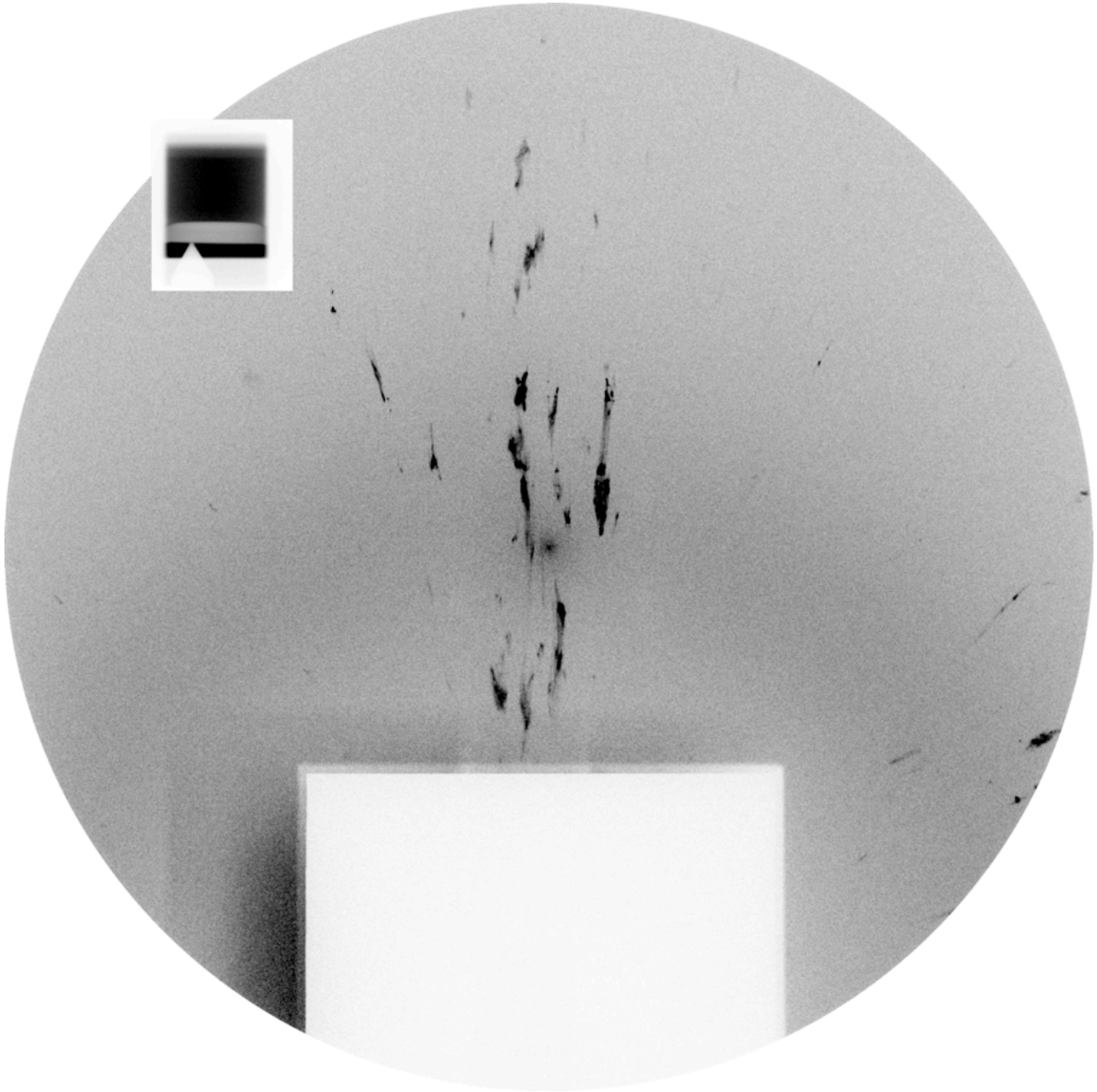
Instruments can be changed without loosing alignment of the beam-path

Erlangen group plans to pursue crystallography study of the solid xenon

Crystallography (SAr)



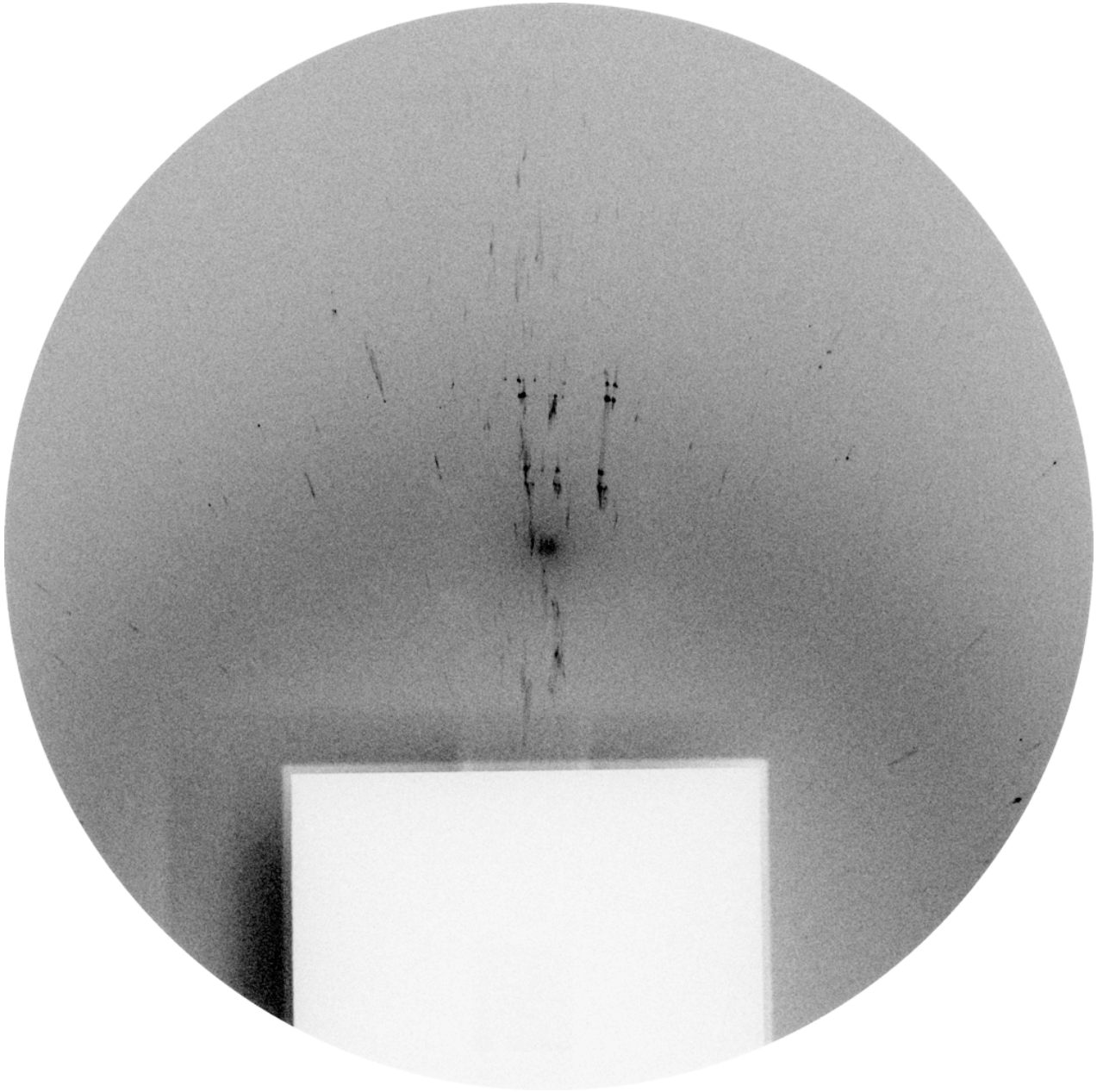
Crystallography (SAr)



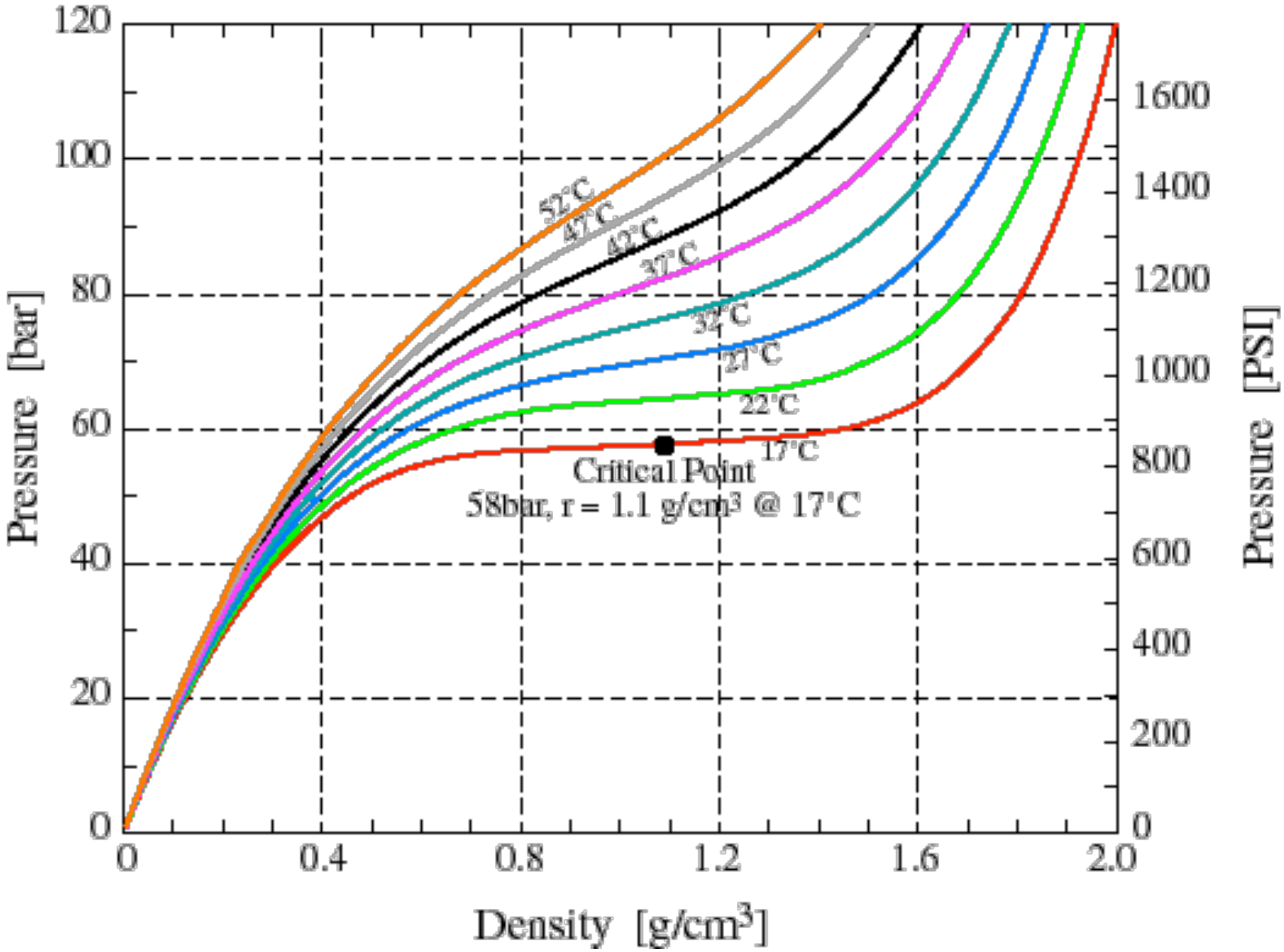
Crystallography (SAr)

Crystallography (SAr)

Crystallography (SAr)



Xenon Density vs. Pressure



Xenon Diffusion Coefficient

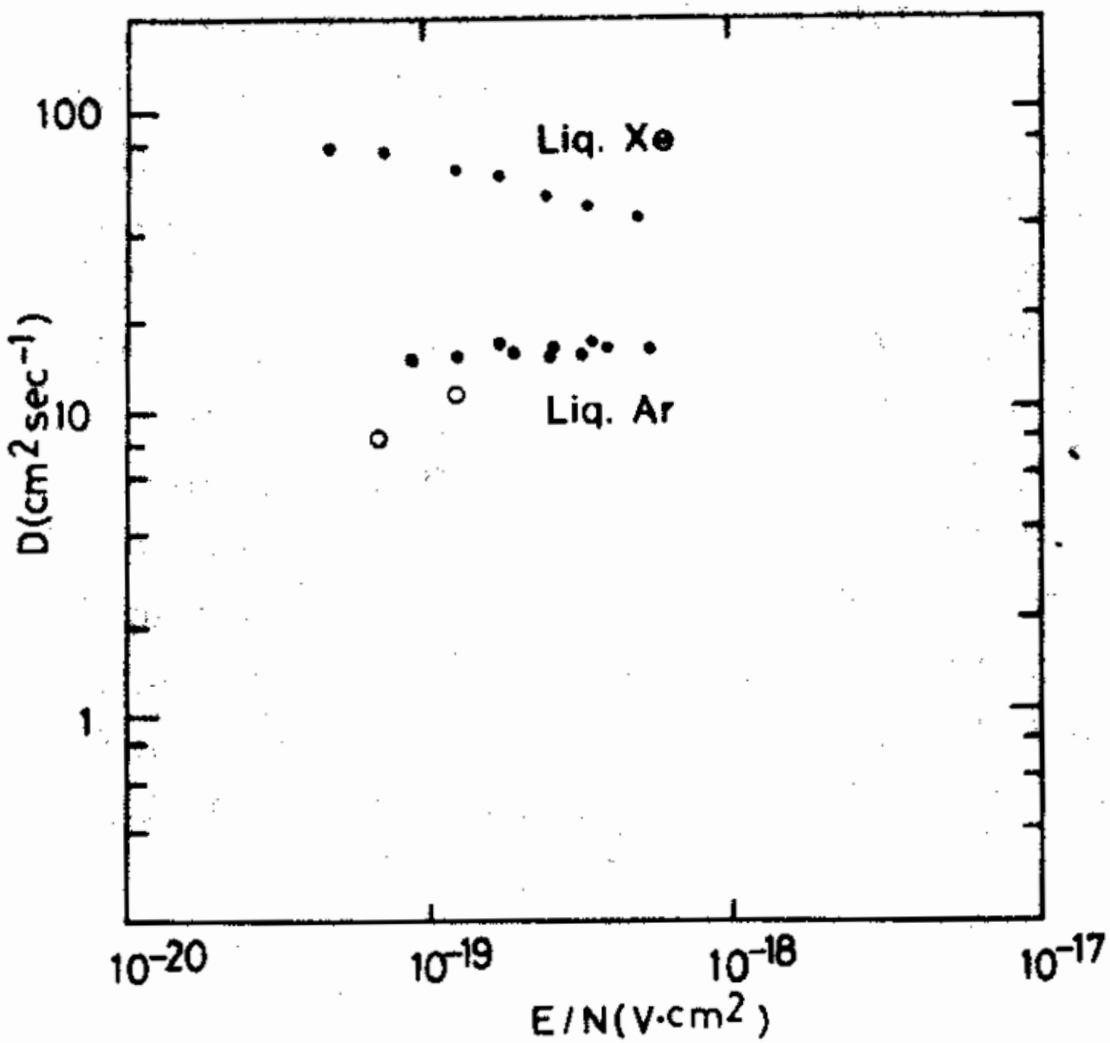
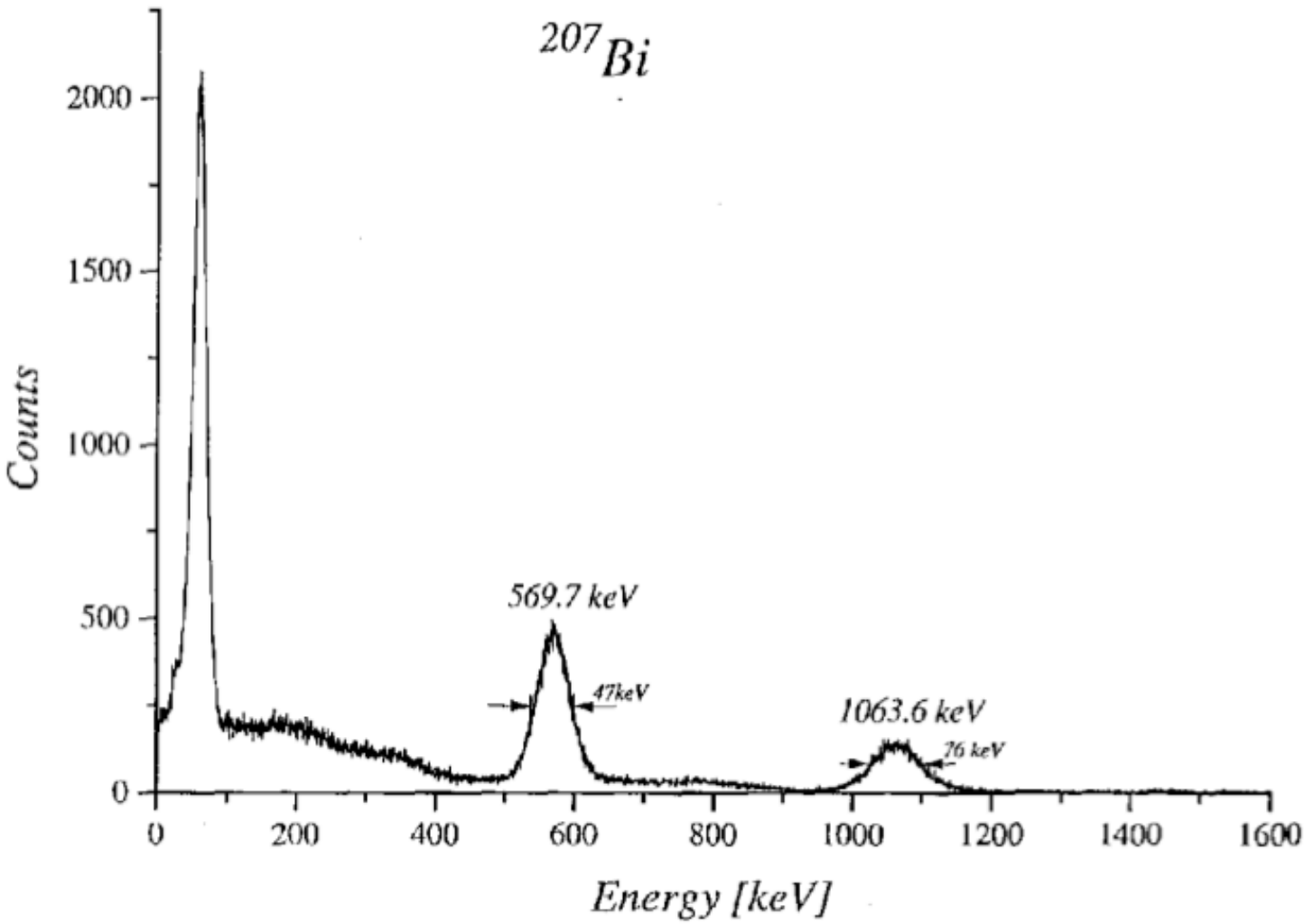


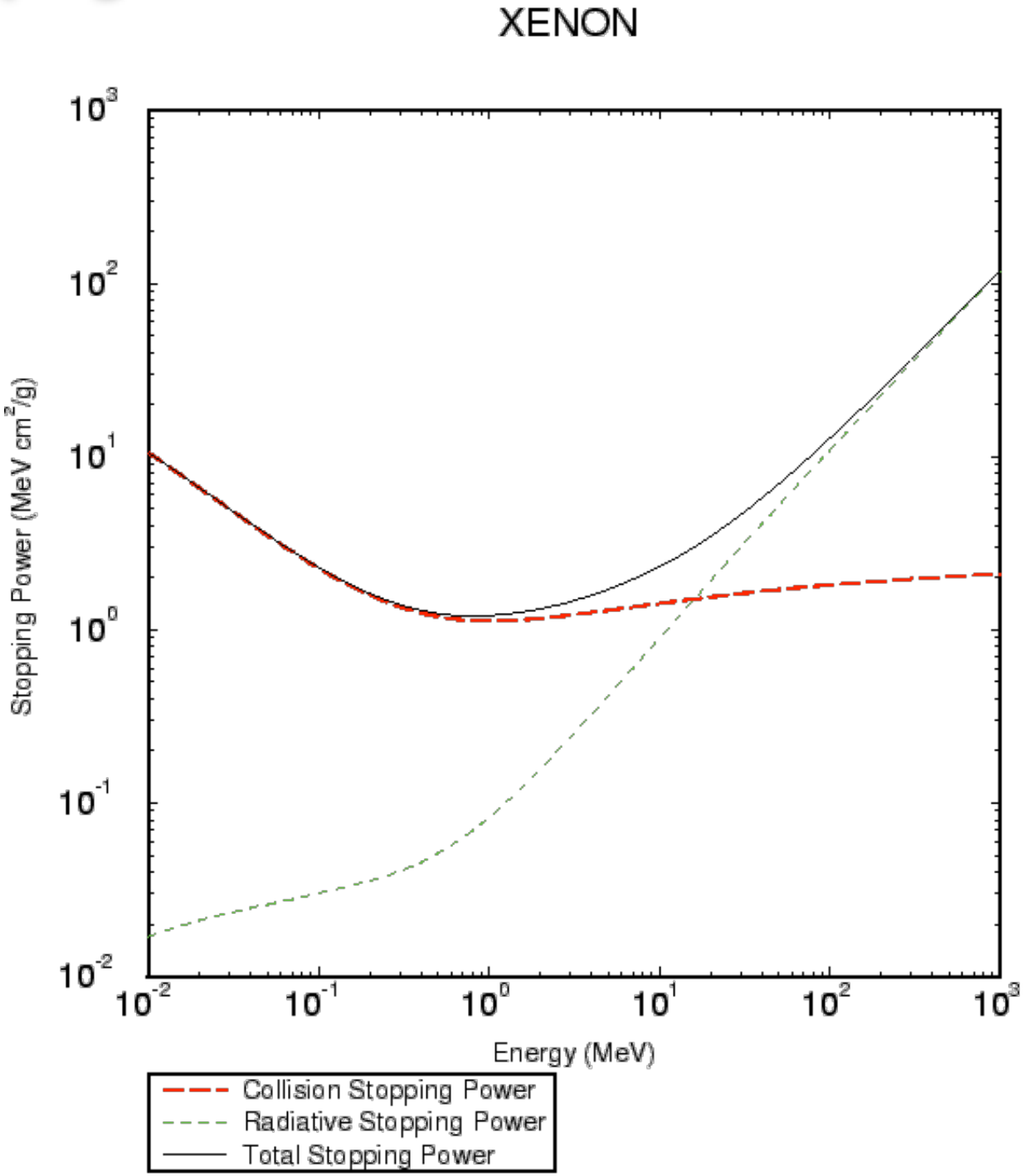
Fig. 1. Diffusion coefficients of electrons in liquid xenon and argon versus the density-normalized electric field. The full circles represent the authors' results and the open circles the results obtained by Derenzo [LBL, Group A Physics Note No. 786 (1974) unpublished].

^{207}Bi Gamma

Appendix 1. The gamma-ray spectrum of ^{207}Bi as measured with a scintillation detector.



Xenon Stopping Power



Solid Xenon DocDB

Document List by Group

http://projects-docdb.fnal.gov:8080/cgi-bin/ListBy?groupid=35

Fermilab | Projects Document Database

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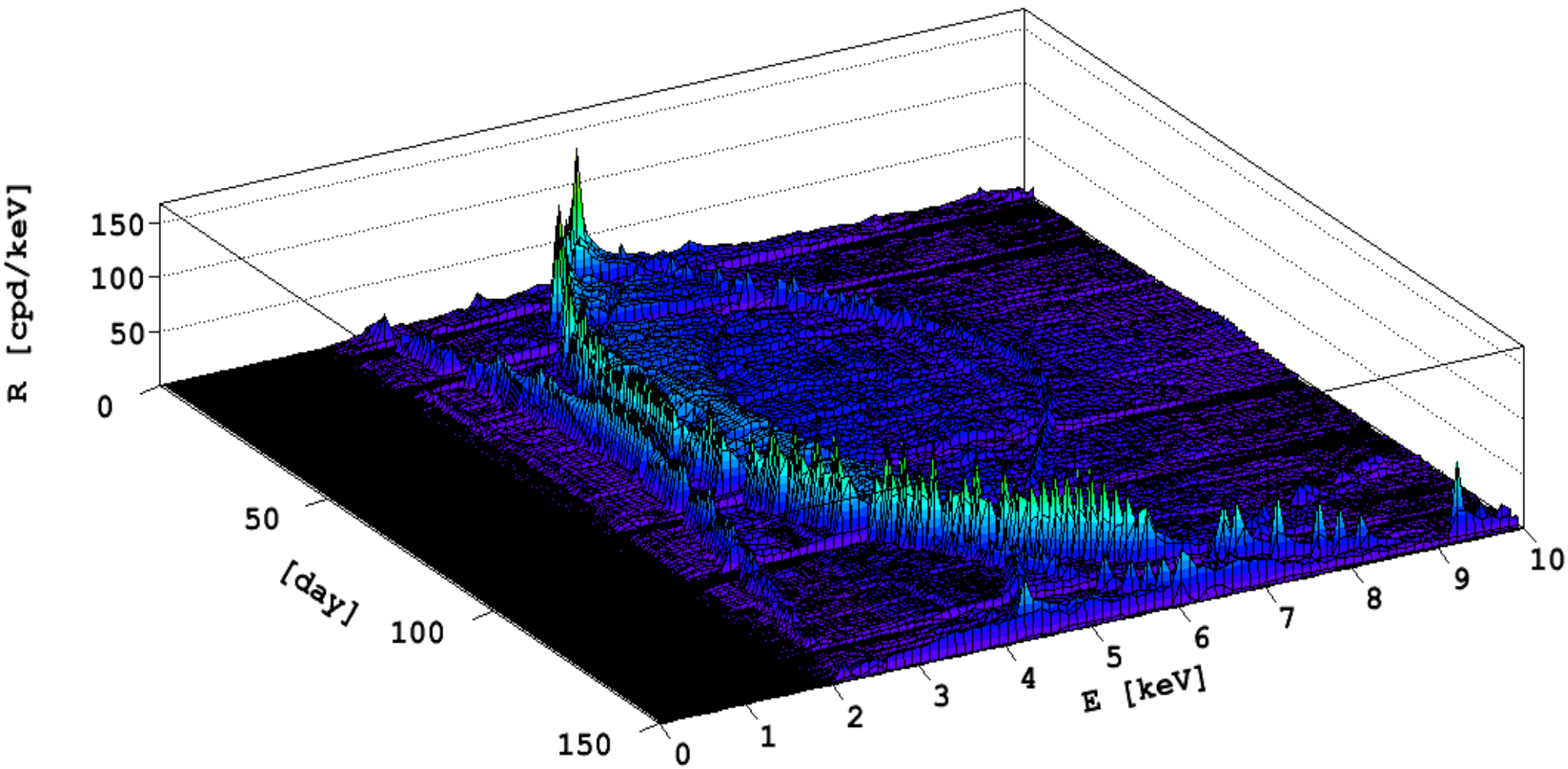
for physicists | Fermilab now | events | publications | Fermilab at work | jobs | press pass | help

Document List by Group

These documents for xenon are available:

Projects-doc-#	Title	Author(s)	Topic(s)	Last Updated
2722-v1	Hamamatsu PMT reference	Jonghee Yoo	Solid Xenon	28 Oct 2013
2632-v1	MgF2 window drawing w/ CF2.7 flange	Jonghee Yoo	Solid Xenon	05 Oct 2013
2685-v1	Xenon properties	Jonghee Yoo	Solid Xenon	05 Oct 2013
2432-v1	daqman manual (DAQ software guide)	Ben Loer	Solid Xenon	21 Aug 2013
2582-v1	Status of the Solid Xenon Project at Fermilab Proceedings	Benton Pahlka	Solid Xenon	21 Aug 2013
2622-v1	Xenon phase diagram	Jonghee Yoo	Solid Xenon	21 Aug 2013
2621-v1	First Results on Crystallography with Solid Argon	Mykhaylo Filipenko	Solid Xenon	20 Aug 2013
2620-v1	Xenon attenuation length	Jonghee Yoo	Solid Xenon	20 Aug 2013
2532-v1	Design with Cryocooler	Mykhaylo Filipenko	Solid Xenon	12 Jun 2013
2503-v1	New Design for Timepix Detector	Mykhaylo Filipenko	Solid Xenon	31 May 2013
2498-v2	Solid Xenon R&D (LIDINE talk)	Benton Pahlka	Solid Xenon	29 May 2013
2499-v1	Solid Xenon talk (ANL) 11-01-2013	Jonghee Yoo	Solid Xenon	29 May 2013
1478-v1	Solid Xenon Talk (UCLA2012)	Jonghee Yoo	Solid Xenon	28 May 2013
2496-v1	Alex Bolozdynya Fermilab Detector R&D seminar on RED detector	Jonghee Yoo	Solid Xenon	28 May 2013
2475-v1	AL10 cryocooler cooling test photos	Jonghee Yoo	Solid Xenon	22 May 2013
2438-v1	Near Fermilab Lodging	Jonghee Yoo	Solid Xenon	22 May 2013
2429-v1	Lodging near Fermilab	Jonghee Yoo	Solid Xenon	02 May 2013
2427-v1	Fermilab VPN connection	Jonghee Yoo	Solid Xenon	01 May 2013
2418-v1	Hamamatsu PMTs (R6041-406MOD)	Jonghee Yoo	Solid Xenon	30 Apr 2013
2393-v1	Newport Flash Lamp Power Supply 68826 Reset Procedure	Jonghee Yoo	Solid Xenon	11 Apr 2013
2307-v1	Absolute calibration of PMT (K.Arisaka)	Jonghee Yoo	Solid Xenon	12 Mar 2013
2306-v1	AFG 3000 series manual (Tektronix Arbitrary Function Generator)	Jonghee Yoo	Solid Xenon	12 Mar 2013

Expected Solar Axion Event Rate in a Germanium Crystal



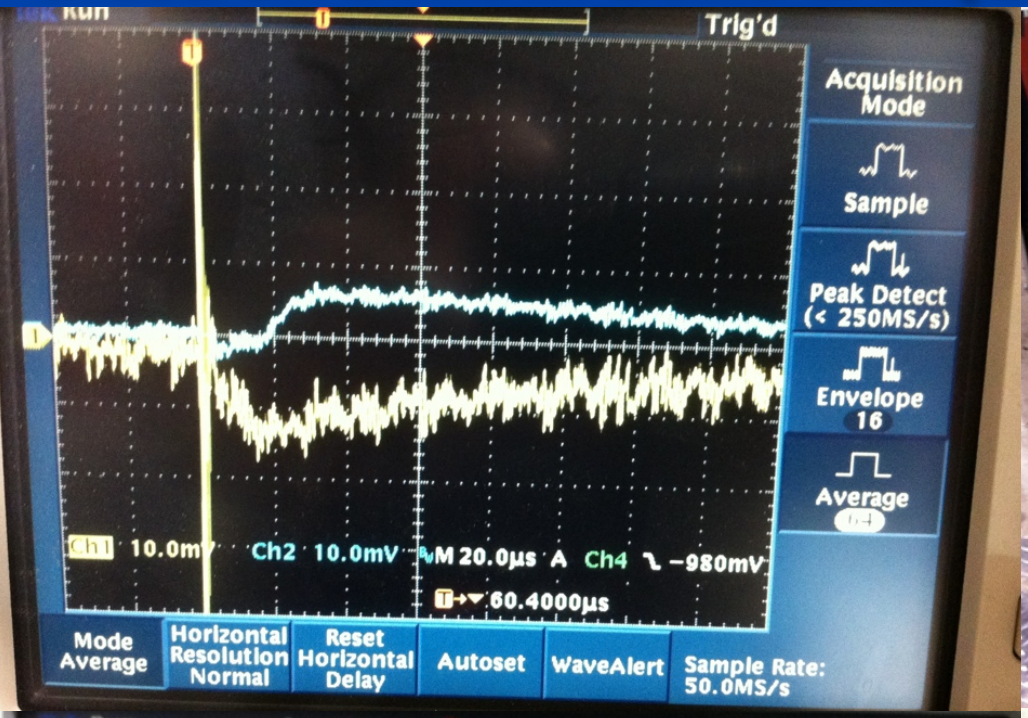
Electron Mobilities

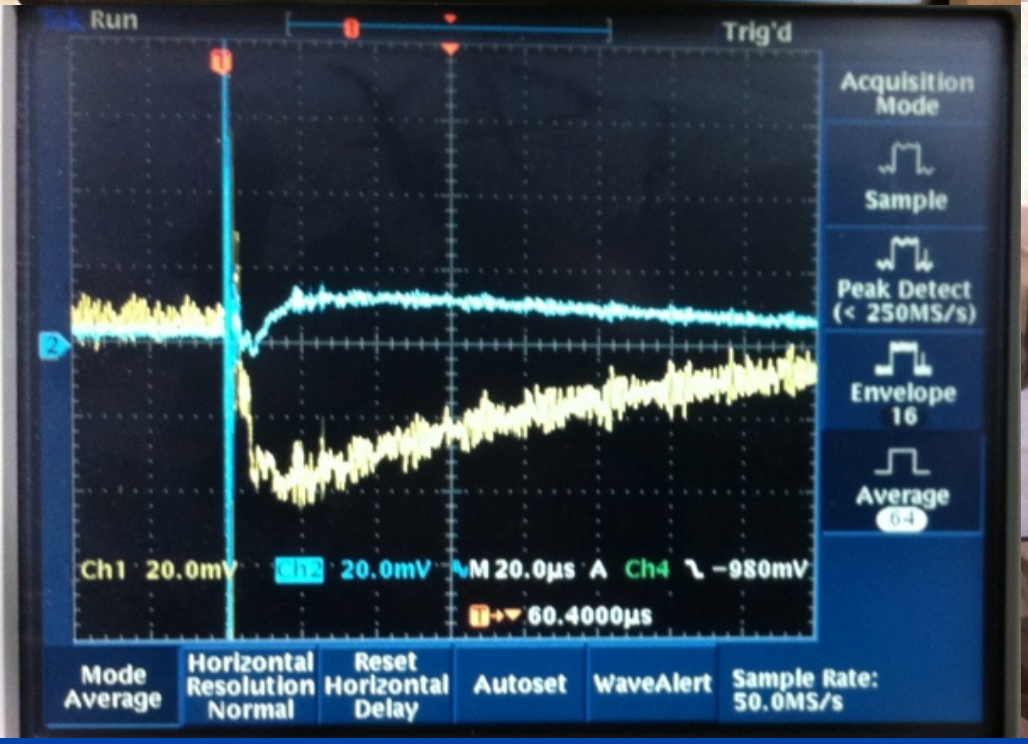
TABLE I. Low-field electron mobilities μ_0 for the rare-gas solids and liquids at a temperature close to their triple points. The velocity of sound is denoted by u and the last column lists the saturation values of the drift velocity in terms of u.

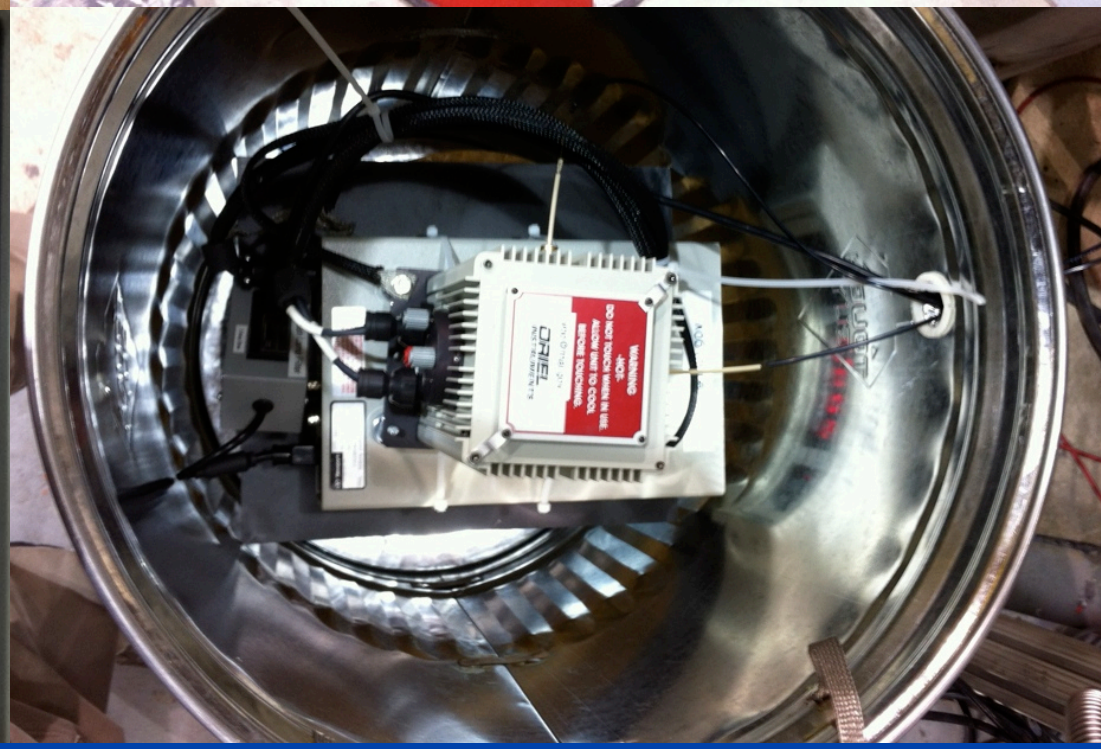
	T(°K)	μ_0 (cm^2 sec^{-1} V^{-1})	u (10^5 cm sec^{-1})	$(v/u)_{sat}$
Ar (solid)	82	1000	1.38[a]	10
Ar (liquid)	85	475	0.85[b]	9.4
Kr (solid)	113	3700	1.1[c]	8.0
Kr (liquid)	117	1800	0.7[d]	5.4
Xe (solid)	157	~4500	1.1[c]	5.0
Xe (liquid)	163	2200	0.65[d]	4.4

[a] D. J. Lawrence and F. E. Neale, Proc. Phys. Soc. (London) **85**, 1251 (1965).
[b] W. V. Dael *et al.*, Physica **32**, 611 (1966).
[c] Estimated from adiabatic compressibility (Ref. 1).
[d] C. C. Lim and R. A. Aziz, Can. J. Phys. **45**, 1275 (1967); and (private communication).

Electron Drift in Solid & Liquid Xenon

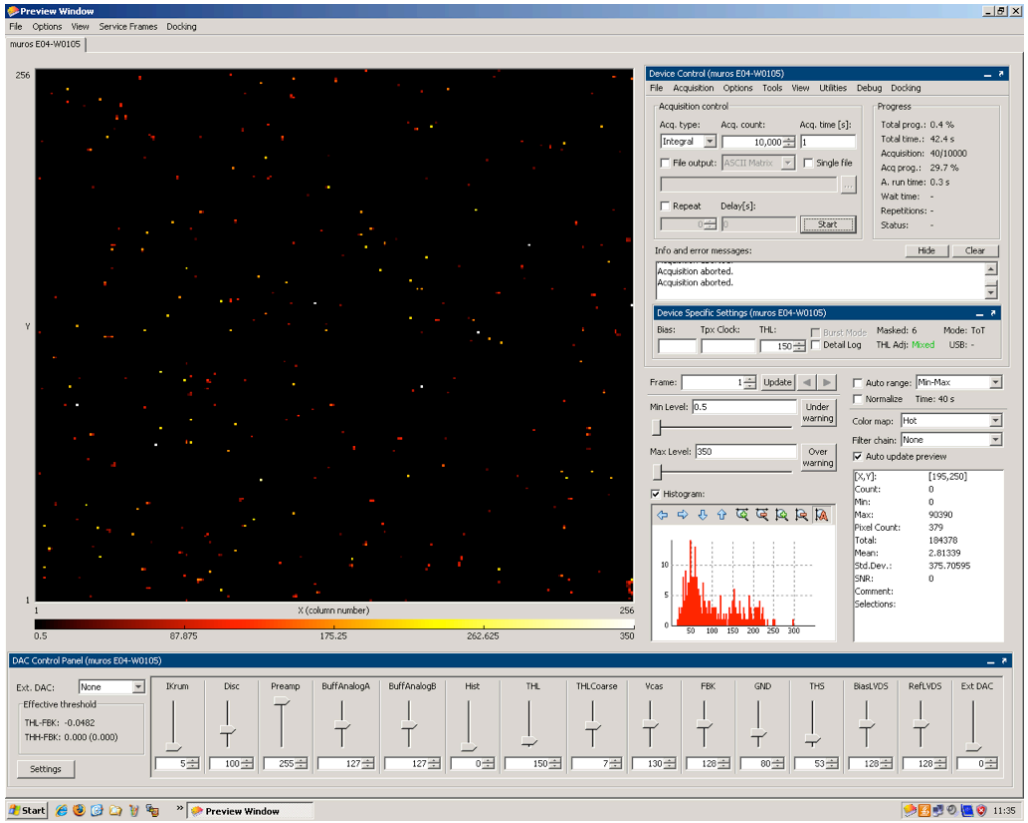


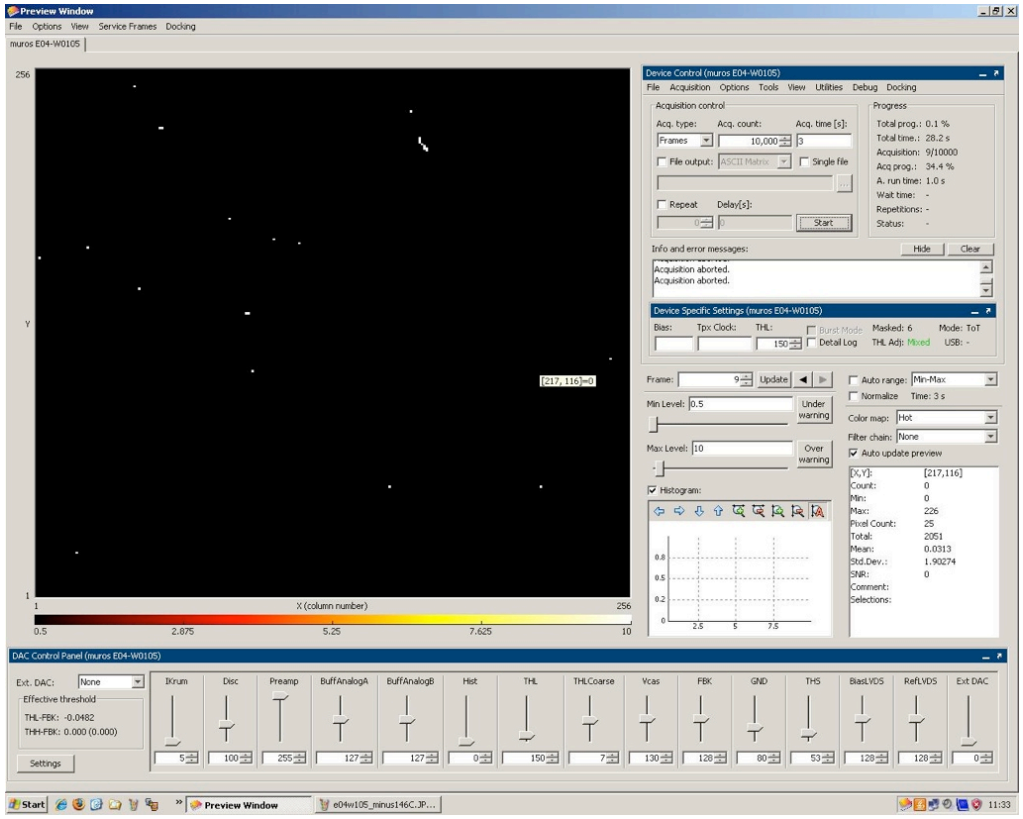




Timepix Test in Low Temperature

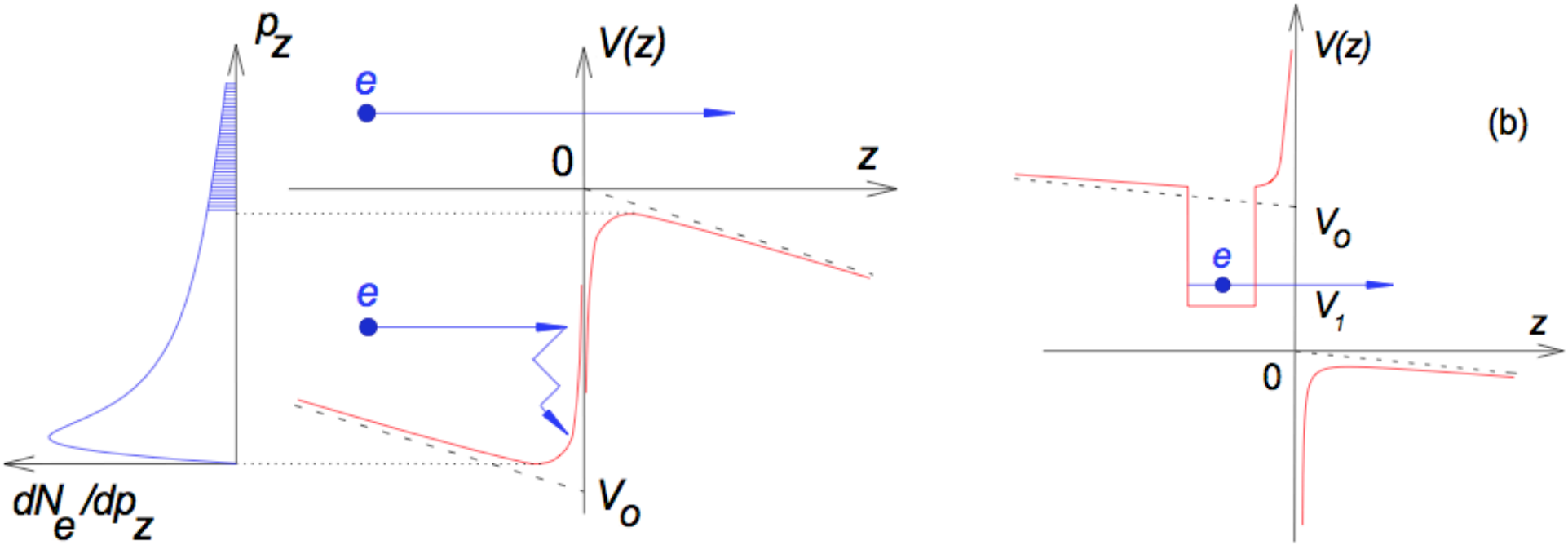
Timepix survived his first LN2 bath and was fully operative at -150C.
The muon/electron tracks are a definitive proof, that the device was operating as it should





Xenon Electric Potential

Quasi-free electron emission from nonpolar dielectrics



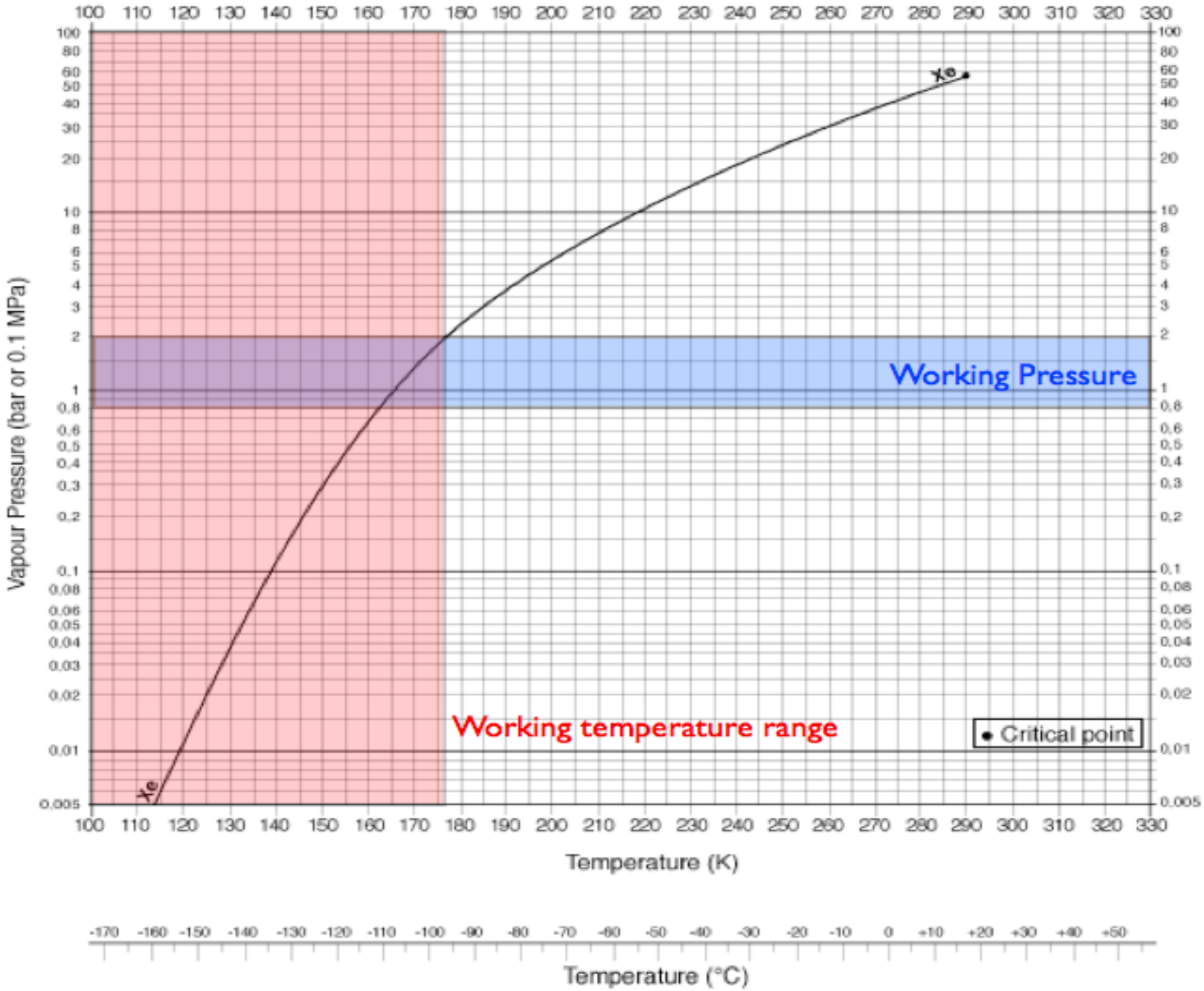
$$V_1(z) = V_0 - eF_1 z + eA_1, z < 0$$

$$V_2(z) = -eF_2 z + eA_2, z > 0$$

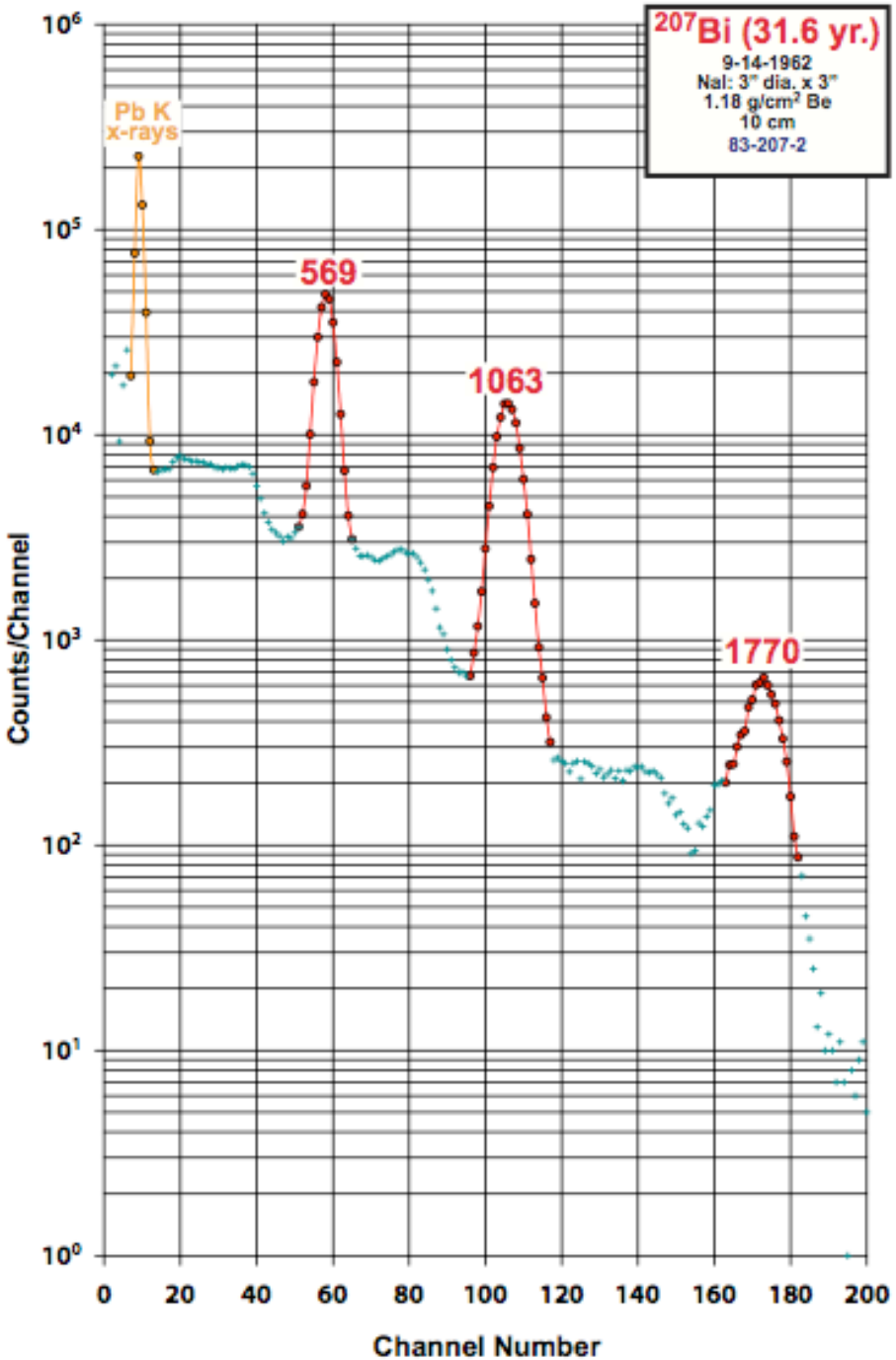
$$A_{1,2} = -e(\varepsilon_1 - \varepsilon_2) / \left[4\varepsilon_{1,2}(z + \xi z / |z|)(\varepsilon_1 + \varepsilon_2) \right]$$

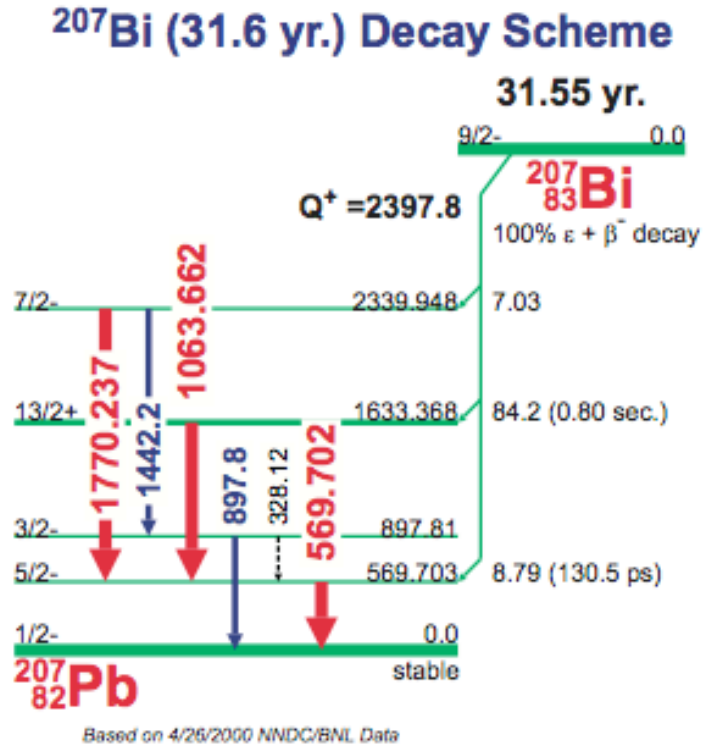
A. Bolozdynya

Xenon Vapor Pressure vs. Temperature



^{207}Bi Gamma





GAMMA-RAY ENERGIES AND INTENSITIES

Nuclide: ^{207}Bi Half Life: 31.55(5) yr.

E_γ (keV)	σE_γ	① I_γ	② σI_γ	Level	
328.12	0.10	0.000 67	0.000 08	897.81	ε
569.702	0.002	97.74	0.03	569.703	ε
897.8	0.1	0.121	0.008	897.81	ε
1,063.662	0.004	74.5	0.2	1,633.368	ε
1,442.2	0.2	0.130	0.003	2,339.948	ε
1,770.237	0.010	6.87	0.04	2,339.948	ε

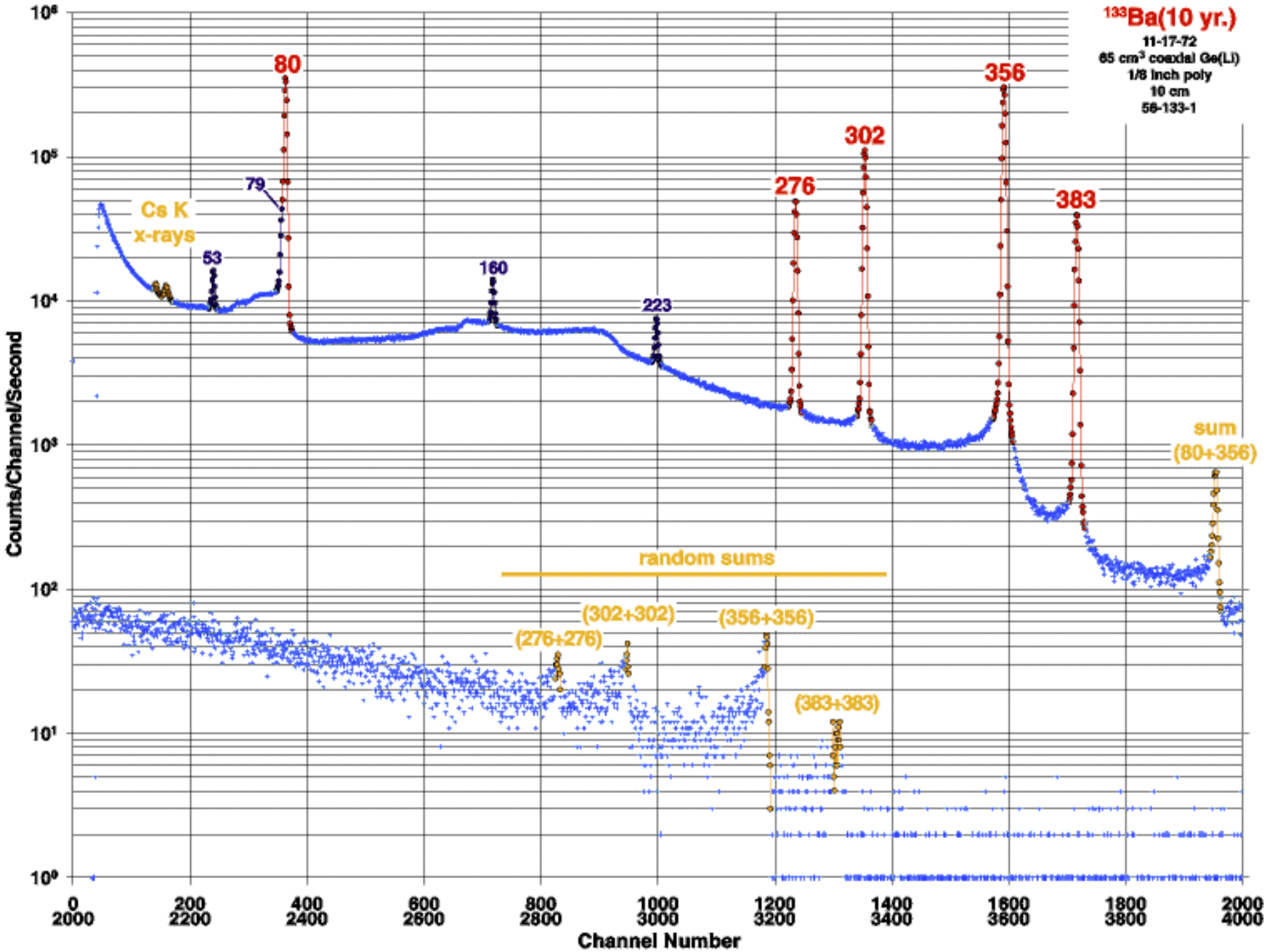
E_γ, σE_γ, I_γ, σI_γ Levels from ENSDF Database as of April 26, 2000

① These Iγ are per 100 Decays of ^{207}Bi.

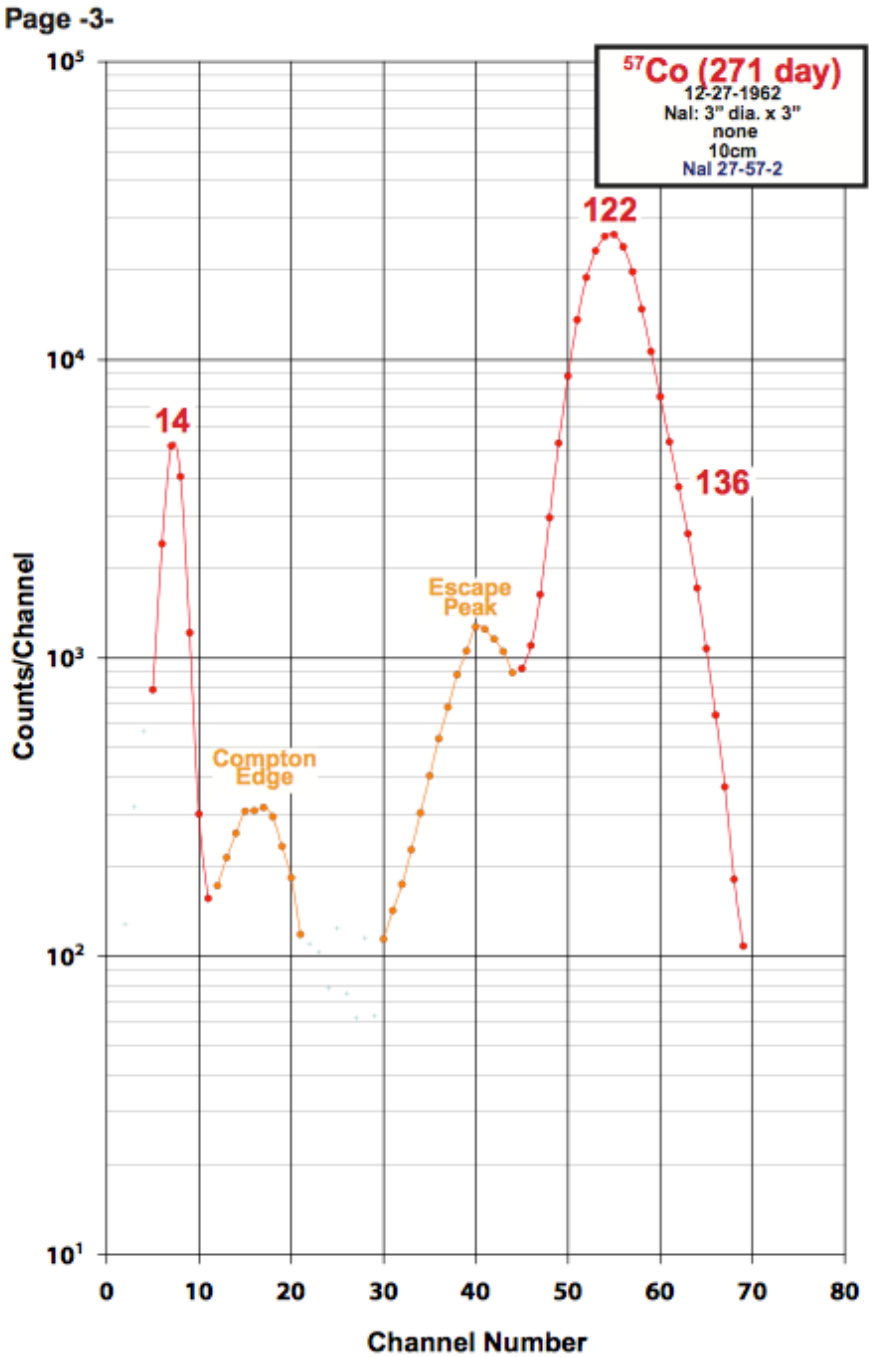
② Normalization factor is 1.0, and its uncertainty is taken to be 0.0

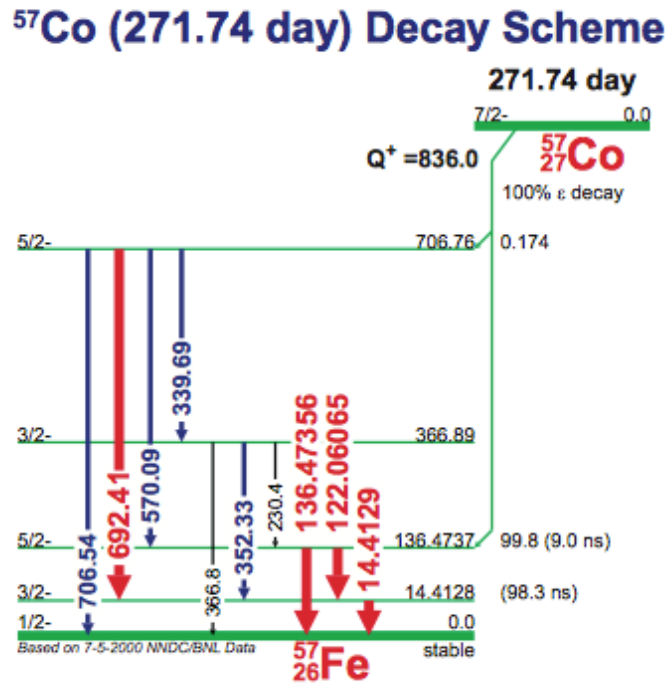
http://www.radiochemistry.org

133 Ba Source



133 Ba Source





GAMMA-RAY ENERGIES AND INTENSITIES

Nuclide: ^{57}Co Half Life: 271.74(6) day

E_γ (keV)	σE_γ	① I_γ	② σI_γ	Level	
14.412 9	0.000 6	9.16	0.15	14.412 8	ε
122.060 65	0.000 12	85.60	0.17	136.473 7	ε
136.473 56	0.000 29	10.68	0.08	136.473 7	ε
230.4	0.4	0.000 4	0.000 4	366.89	ε
339.69	0.21	0.003 7	0.000 3	706.76	ε
352.33	0.21	0.003 0	0.000 3	366.89	ε
366.8	0.3	0.001 2	0.000 3	366.89	ε
570.09	0.20	0.015 8	0.001 0	706.76	ε
692.41	0.07	0.149	0.010	706.76	ε
706.54	0.22	0.005 0	0.000 5	706.76	ε

E_γ, σE_γ, I_γ, σI_γ Levels from ENSDF Database as of July 5, 2000

① These $I\gamma$ are per 100 Decays of ^{57}Co.

② Normalization factor is 1.0, and its uncertainty is taken to be 0.0.

Refractive Indices

L.M.Barkov et al., NIM A379 (1996), 482

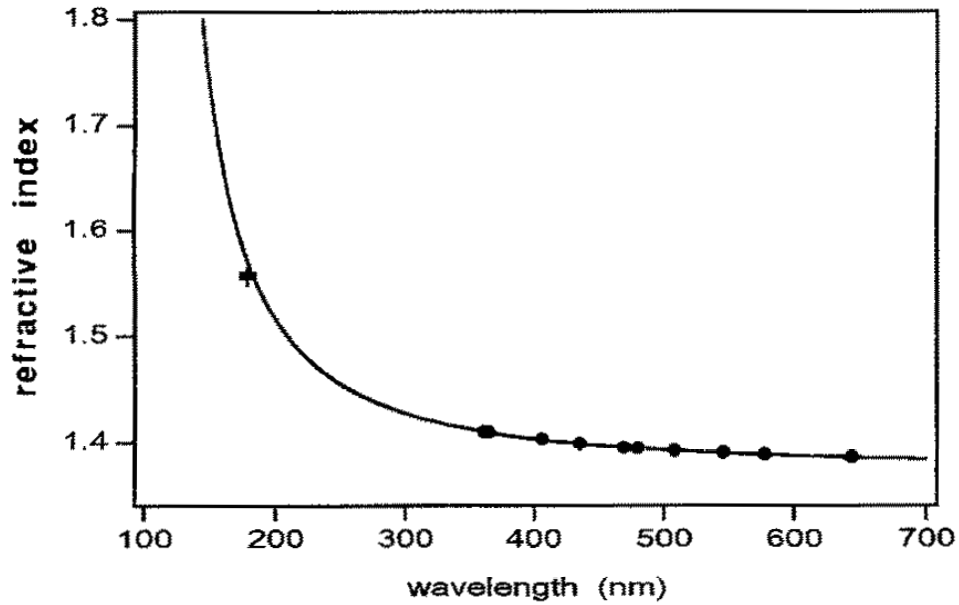


Fig. 2. LXe refractive index vs wavelength: circles indicate data from Ref. [2], the line indicates extrapolation of this data [3], and the square indicates the value obtained in this work.

- 1.69 +- 0.02 (@170K, 178nm)
  V.N.Solotov et al., NIM A516 (2004), 462
- 1.5655 +- 0.0024 +- 0.0078 (@161K, 180nm)
  NIM A379 (1996), 482

Sinnock et al. Phys.Rev 181 1297 (1969)

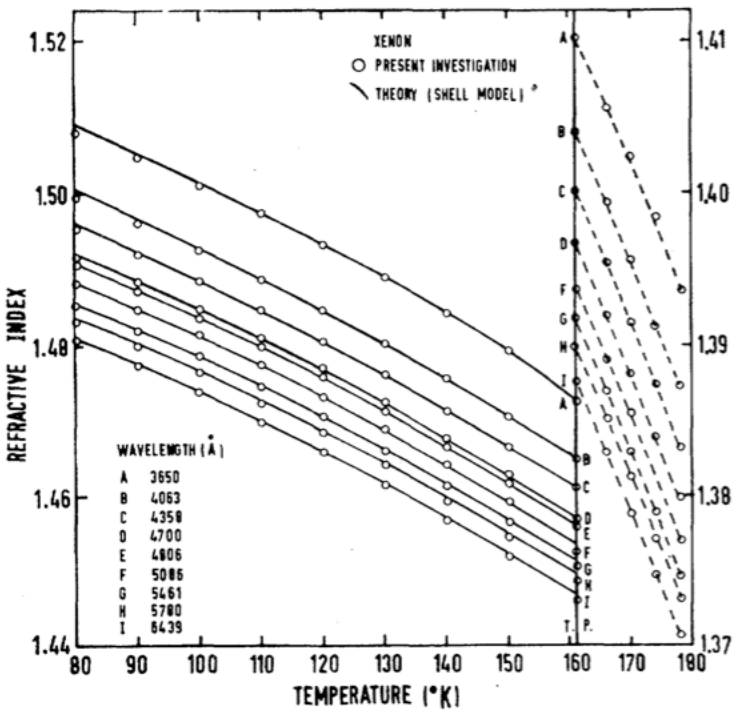


FIG. 5. Refractive indices of liquid and solid zenon. The continuous lines correspond to Eq. (12) with values $\omega_0 = 8.43$ eV, $\omega_p^2 = 23.145$ eV^2, $\mathcal{V}_0^3(\mathrm{TP}) = 3.35$ eV^2, $\chi_1 = 0.47425$, and $B_3 = 12$. To avoid confusion, not all data points are included in the figure.

For example: Light Yield in Solid Neon

R.A. Michniak NIM A 482 (2002) 387–394

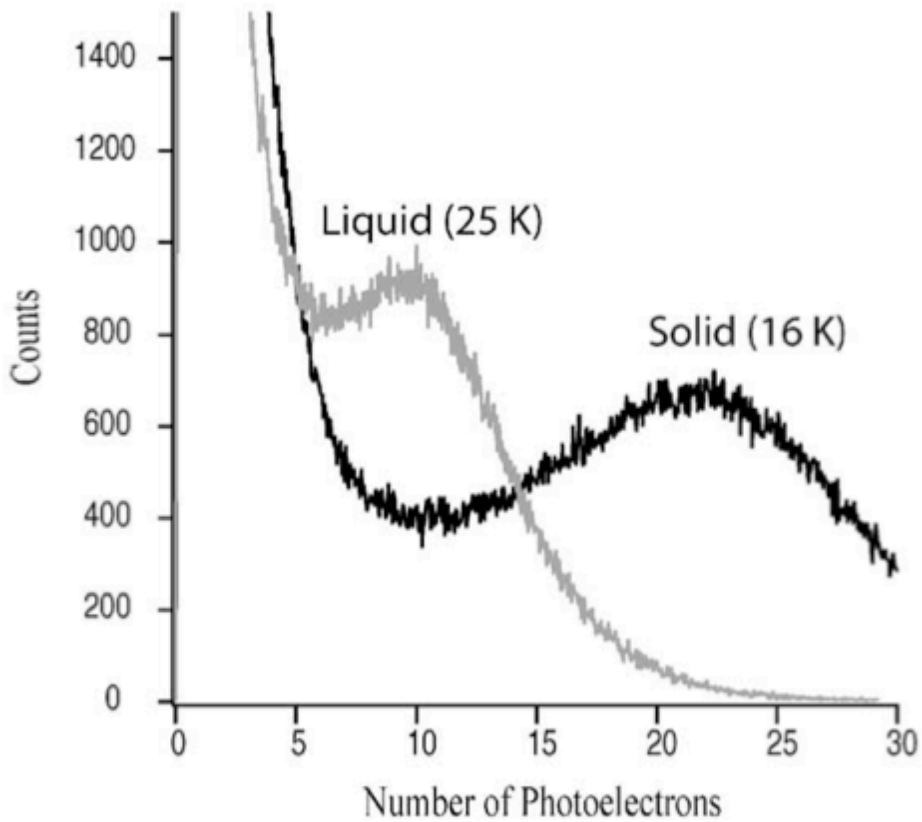


Fig. 4. Photoelectron peak from liquid neon (left) at 25 K and solid neon (right) at 16 K due to scintillations induced by a 0.5 kBq ^{113}Sn beta source (364 keV).

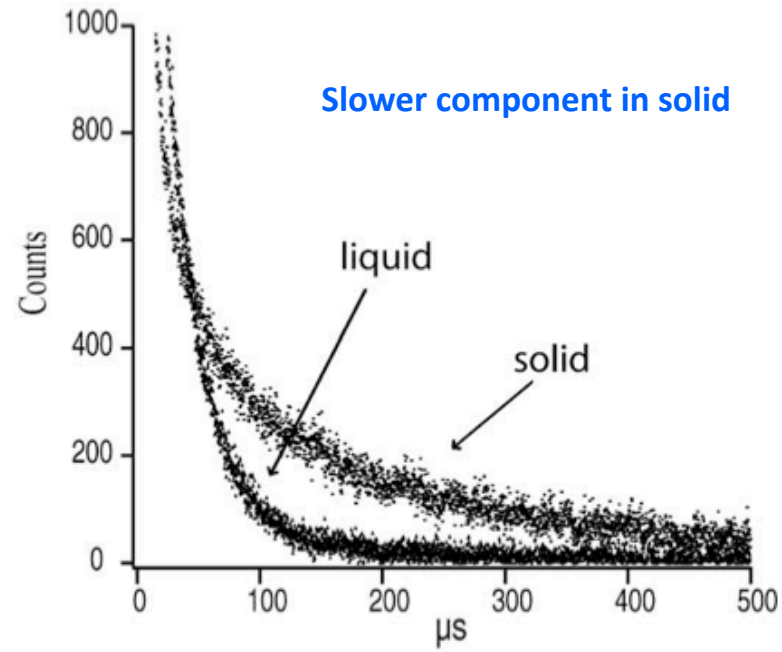


Fig. 6. Decay of fluorescence observed from 60,000 beta decays in liquid (25 K) and solid (16 K) neon.

We might further speculate that the greater density of the liquid compared to the gas favors non-radiative quenching of the excited state. Perhaps the lower temperature and more regular structure of the solid make various quenching reactions less favorable compared to the liquid and thus account for the greater light yield observed in the solid. A more detailed study would be required to confirm or reject any of these speculations.

Xenon Property

iso	NA	half-life	DM	DE (MeV)	DP
^{124}Xe	0.095%	^{124}Xe is stable with 70 neutrons			
^{125}Xe	syn	16.9 h	ε	1.652	^{125}I
^{126}Xe	0.089%	^{126}Xe is stable with 72 neutrons			
^{127}Xe	syn	36.345 d	ε	0.662	^{127}I
^{128}Xe	1.91%	^{128}Xe is stable with 74 neutrons			
^{129}Xe	26.4%	^{129}Xe is stable with 75 neutrons			
^{130}Xe	4.07%	^{130}Xe is stable with 76 neutrons			
^{131}Xe	21.2%	^{131}Xe is stable with 77 neutrons			
^{132}Xe	26.9%	^{132}Xe is stable with 78 neutrons			
^{133}Xe	syn	5.247 d	β^-	0.427	^{133}Cs
^{134}Xe	10.4%	^{134}Xe is stable with 80 neutrons			
^{135}Xe	syn	9.14 h	β^-	1.16	^{135}Cs
^{136}Xe	8.86%	^{136}Xe is stable with 82 neutrons			

- No long life radio isotpe
  → Intrinsic background free
- ^{85}Kr from natural air is a major concern
  ^{85}Kr → ^{85}Ru + β (Emax = 0.687MeV)
  $\tau_{1/2}$ = 10.75 year (99.57%)
- 0.1 ppm of Kr → ~ 1 cpd/kg/keV gamma
  XMASS achieved 3ppt (Kr/Xe) level using a gas distillation system
- External gamma source: U/Th/K/Co… need to be shielded out

Xenon Property

- **Gamma backgrounds: all high energy gammas (>39.58 keV)**

parent	abundunce(%)	σ (mb)	RI	half life	cross section(barn)	Energy(keV)
^{124}Xe	0.09	165	^{125m}Xe	57.0 sec	23.9 111.8(γ)	140.8(γ)
			^{125}Xe	16.9 hour	165 188.4(γ)	243.4(γ)
^{126}Xe	0.09	4.27	^{127m}Xe	69.2 sec	0.45 172.4(γ)	124.7(γ)
			^{127}Xe	36.4 day	4.27 202.9(γ)	375.0(γ)
^{128}Xe	1.92	8	^{129m}Xe	8.89 day	0.48 196.6(γ)	39.58(γ)
^{130}Xe	4.08	26	^{131m}Xe	11.8 day	0.45	163.9(γ)
^{132}Xe	26.89	85	^{133m}Xe	2.19 day	0.05	233.2(γ)
			^{133}Xe	5.24 day	0.45 81.0(γ)	346(β)
^{134}Xe	10.44	0.265	^{135m}Xe	15.3 min	3 (?)	526.6(γ)
			^{135}Xe	9.14 hour	0.265 249.8(γ)	910(β)
^{136}Xe	8.87	0.26	^{137}Xe	3.8 min	0.26 3720(β) 455.5(γ)	4170(β)

That was Expensive Test