The Scintillating Bubble Chamber

Ken Clark
Queen's University & TRIUMF

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute
TRIUMF
Queen's University

History of bubble chambers

- Many bubble chambers were constructed

Table 1
Major bubble chambers used in high-energy physics[a].

	H_2	D_2	Ne/H_2	C_3H_8, Freon, LXe
US chambers (total > 50)				
Berkeley	2″, 4″, 6″, 10″, 15″, 25″, 72″			UM LXe LRL 50 cm, 10″
SLAC	15″, 40″			
BNL	30/31″, 80″, 84″, 7′ (3.9 Mpx)			15 cm, 170 l
Argonne	30″ (4.7 Mpx), 12′ (7 Mpx)		30″, 12′	UM 40″
Fermilab	15′ (2.9 Mpx) UW 30″ [Scotchlite]	15′	15′	Tohoku (Holographic)
European chambers (total > 50)				
German	85 cm (6.3 Mpx)	85 cm	85 cm	
French	80 cm (16 Mpx)			BP3, Gargamelle (4.7 M)
British	150 cm			Oxford He
Russian	Ludmilla		Ludmilla?	1 m, 2 m, SKAT ITEP He, 700 1 LXe
CERN	Mirabelle (3.3 Mpx) 30 cm, 2 m (40 Mpx) BEBC (6.3 Mpx) LEBC (5.2 Mpx triggered)	2 m BEBC	Mirabelle? BEBC	HOBC

BEBC: Big European Bubble Chamber; LEBC: Lexan Bubble Chamber; HOBC: Holographic Bubble Chamber; Gargamelle: Heavy Liquid Bubble Chamber; *Ludmilla*: Russian Heavy Liquid Bubble Chamber; *Mirabelle*: Bubble Chamber built in Saclay/France; Mpx: million pictures, UM: U. Michigan Heavy Liquid and Liquid Xe Bubble Chambers. Data in round brackets () give the number of pictures taken with a chamber, those in straight brackets special features of the chambers.

[a] Adopted from Gert G. Harigel, in "30 Years of Bubble Chamber Physics" (Bologna 2003); Ref. [38].

History of the bubble chamber and related active- and internal-target nuclear tracking detectors, F.D. Becchetti, NIMA 784 (2015) 518-523

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We'll come back to this…

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Physics using bubble chambers

- Using this type of detector, many discoveries were made

Particle	Source of Radiation	Instrument
e^+	Cosmic ray	Cloud chamber
$\mu^\pm$	Cosmic ray	Cloud chamber
$\pi^\pm$	Cosmic ray	Nuclear emulsion
π^0	Accelerator	Counters
$K^\pm$	Cosmic ray	Nuclear emulsion
K^0	Cosmic ray	Cloud chamber
Λ^0	Cosmic ray	Cloud chamber
Σ^+	Cosmic ray	Nuclear emulsion
		Cloud chamber
Σ^-	Accelerator	Cloud chamber
Σ^0	Accelerator	*Bubble chamber*
Ξ^-	Cosmic ray	Cloud chamber
Ξ^0	Accelerator	*Bubble chamber*
Ω^-	Accelerator	*Bubble chamber*
Λ_c^+	Accelerator	*Bubble chamber*
p, n	Accelerator	Counters
B (Σ^+, Ξ^+, Ω^+)	Accelerator	*Bubble chamber*

Gert G. Harigel, *Bubble Chambers, Technology and Impact on High Energy Physics*

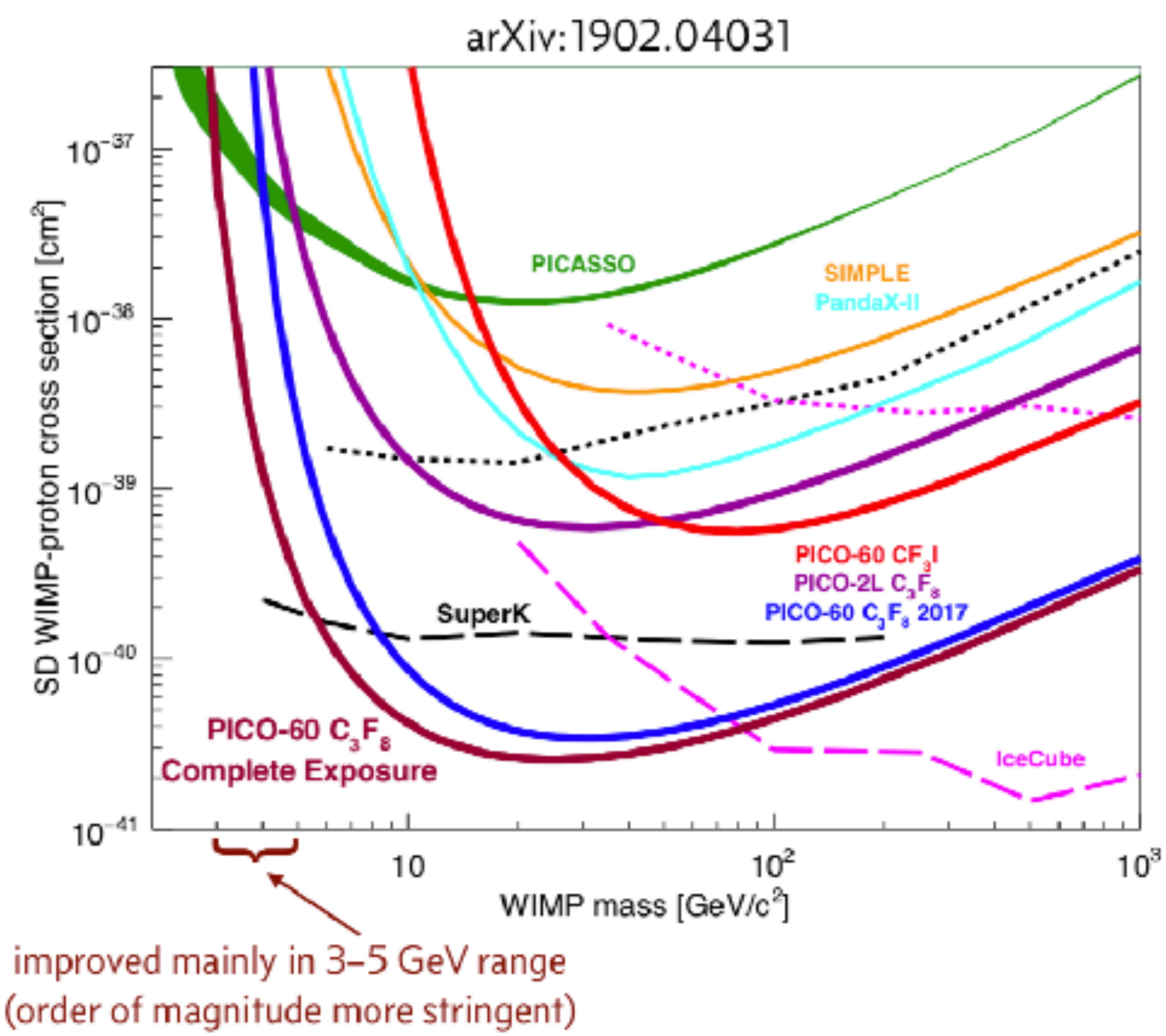
There was a real boom in bubble chamber physics for many years

Current Searches

- Currently there are projects that use these detectors to search for dark matter

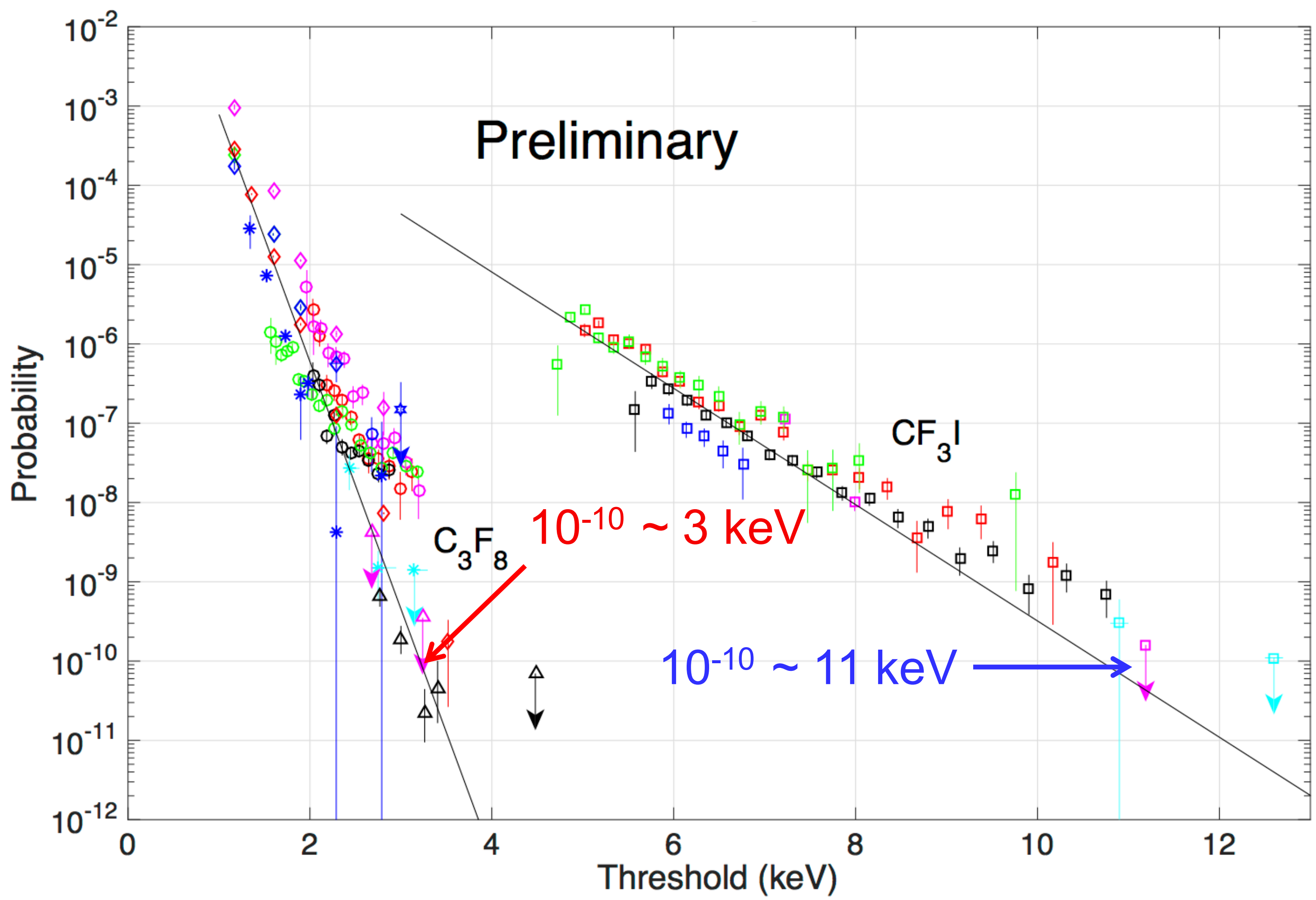
Current Searches

- Currently there are projects that use these detectors to search for dark matter
- These have had success… or as much as any DM search has



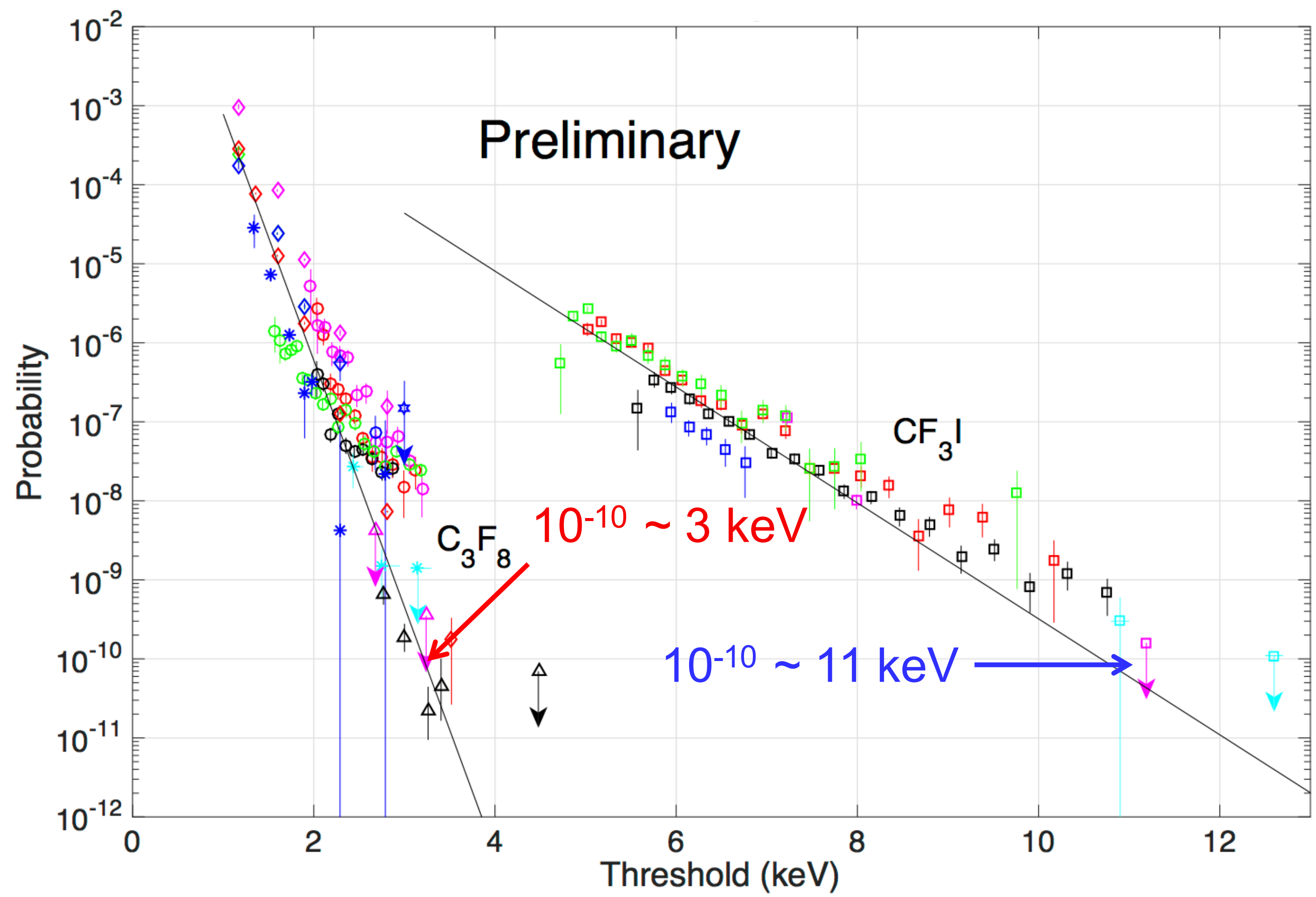
Bubble Chamber Advantages

- There are some unique aspects of the bubble chamber that make it attractive
    - Discrimination is one big one

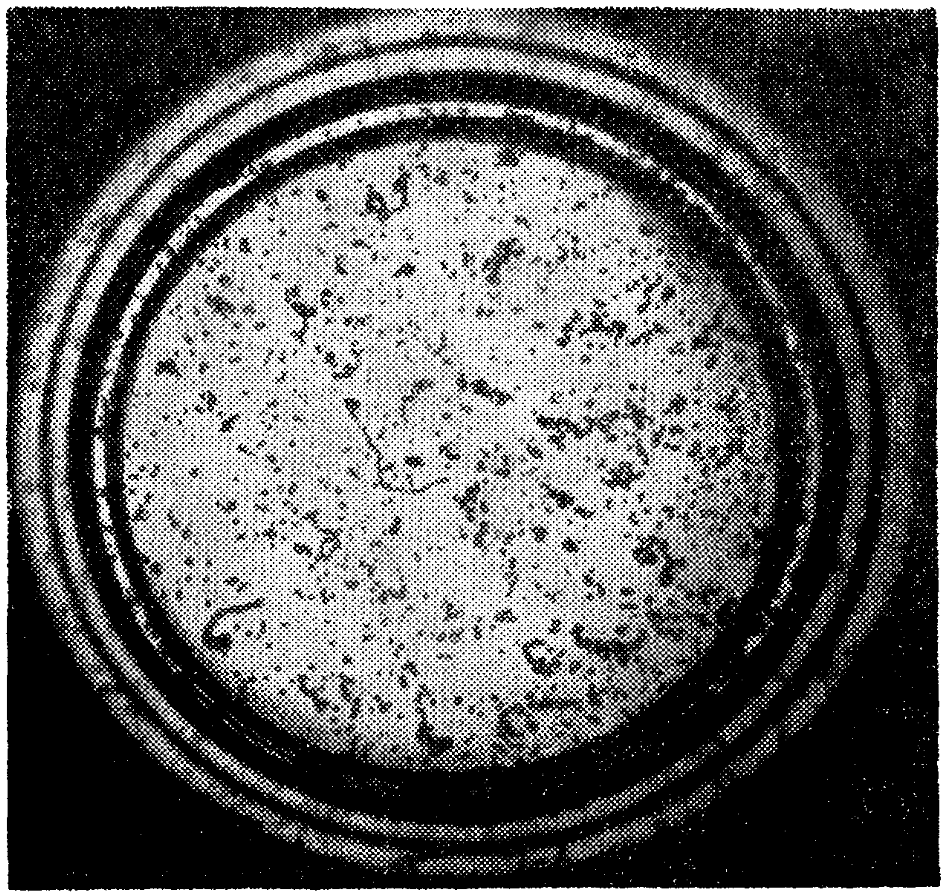


Bubble Chamber Challenges

- Searching for low mass dark matter requires a lowered threshold
    - This becomes an issue quickly…



Revisit a bit of history

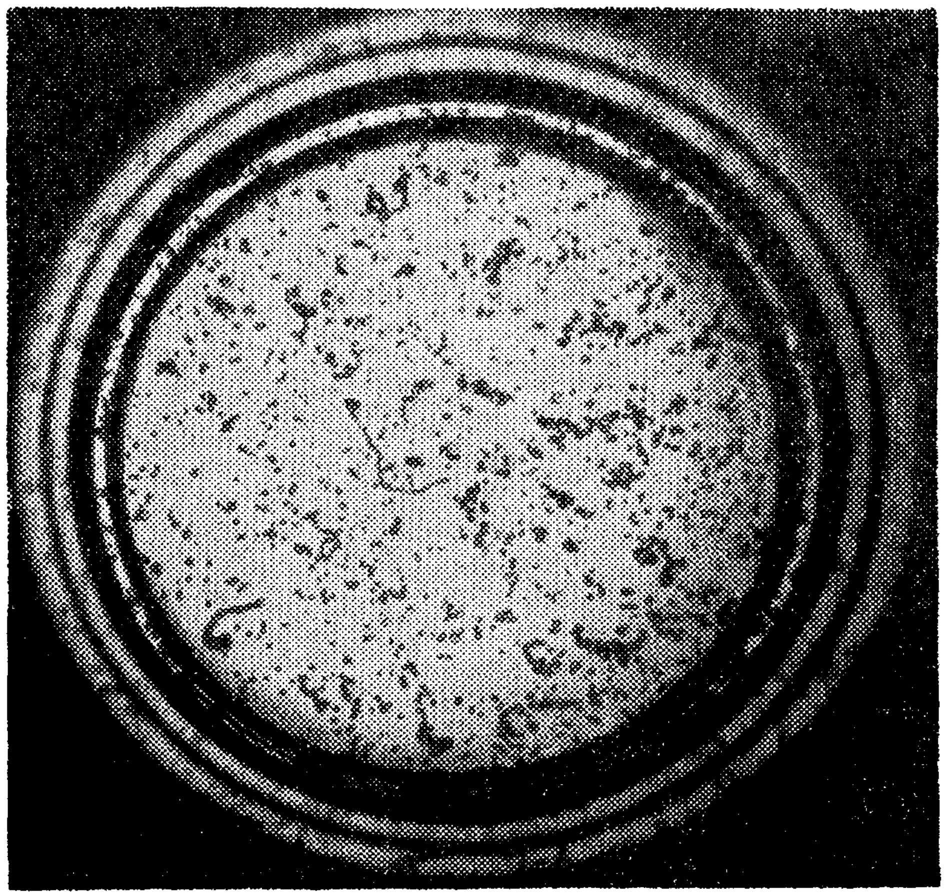


Phys. Rev. 102, 586 (1956)

- In 1956, Glaser made a xenon bubble chamber

Shortly after these failures to observe tracks, we learned[3] that gaseous xenon had been found to be an efficient scintillating material, so that some sizeable fraction of the energy lost by an ionizing particle in liquid xenon might escape in optical radiation instead of being deposited locally in the xenon itself.

Revisit a bit of history



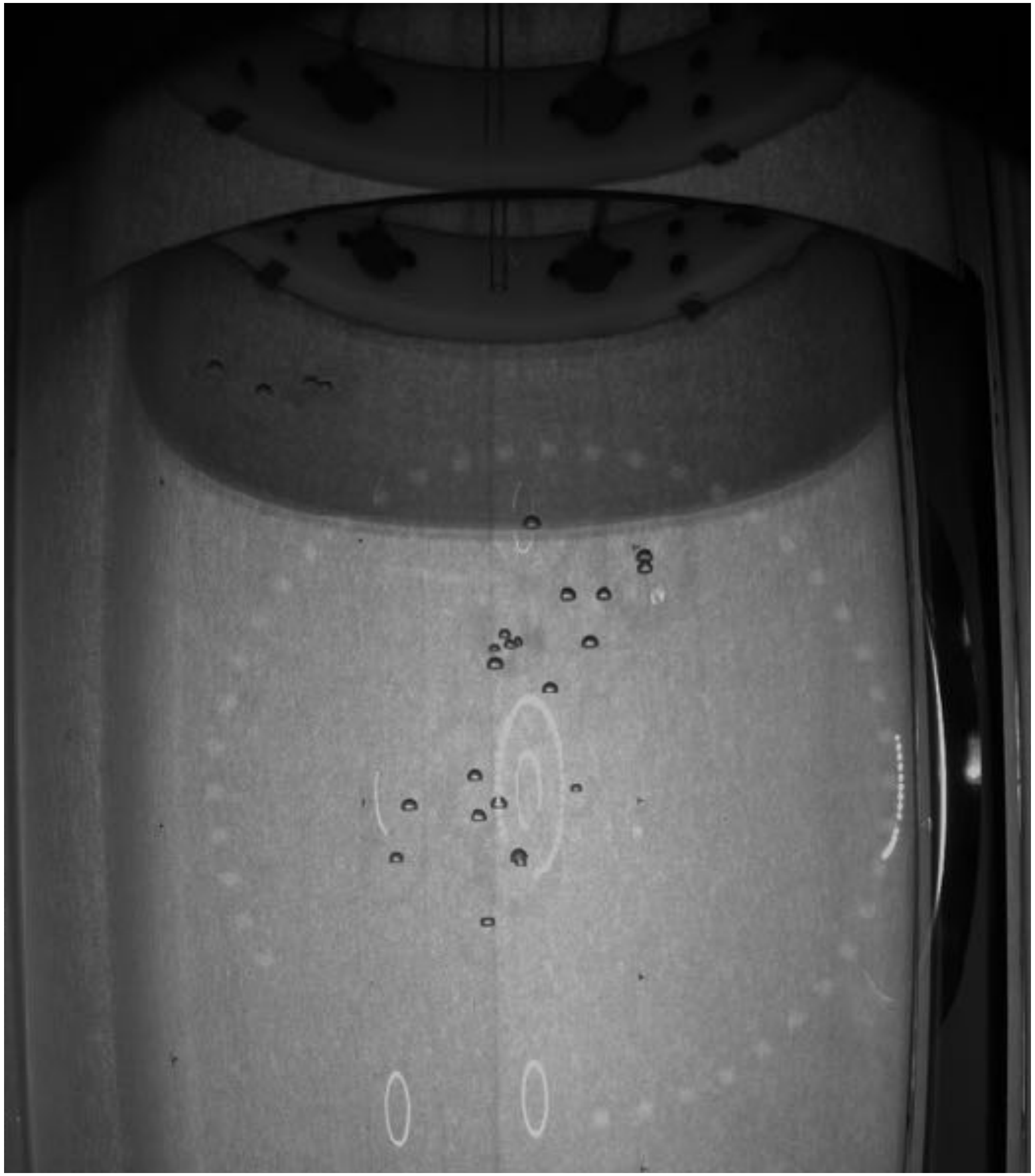
Phys. Rev. 102, 586 (1956)

- In 1956, Glaser made a xenon bubble chamber
    - Saw no bubbles in pure xenon even at 1keV threshold with gamma source
    - Also saw normal production in 98% xenon + 2% ethylene (scintillation completely quenched)
- Scintillation suppresses bubble nucleation (?)

Can we exploit this?

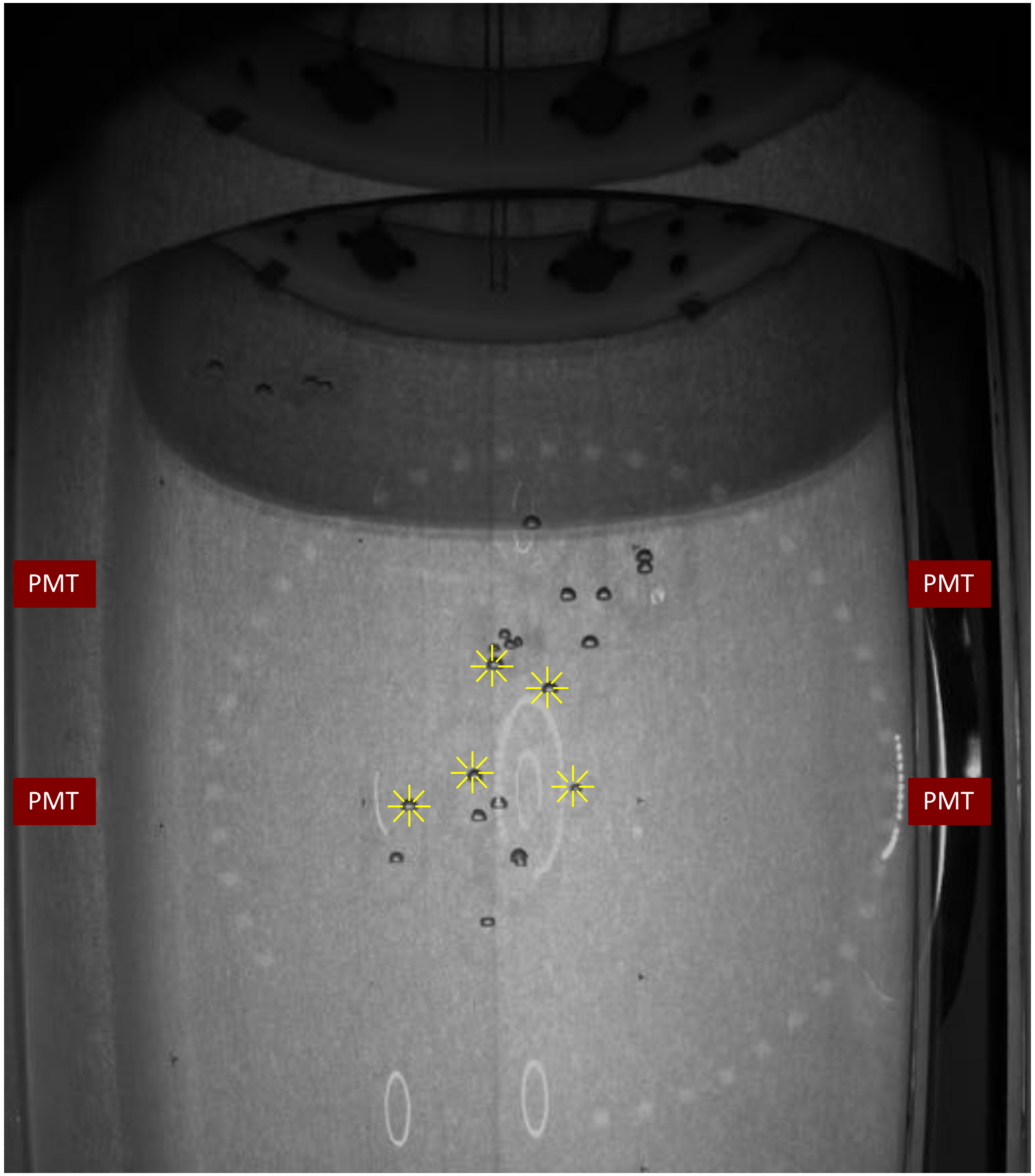
The “traditional” bubble chamber

- Superheated target (C_3F_8, CF_3I…)
- Particle interactions nucleate bubbles
- Cameras and acoustic sensors capture signals
- Chamber recompresses after each event



The "scintillating" bubble chamber

- Superheated scintillator (Xe, Ar…)
- Particle interactions nucleate bubbles and cause scintillation
- Cameras and acoustic sensors capture signals, photodetectors collect scintillation light
- Chamber recompresses after each event



Potential Benefits

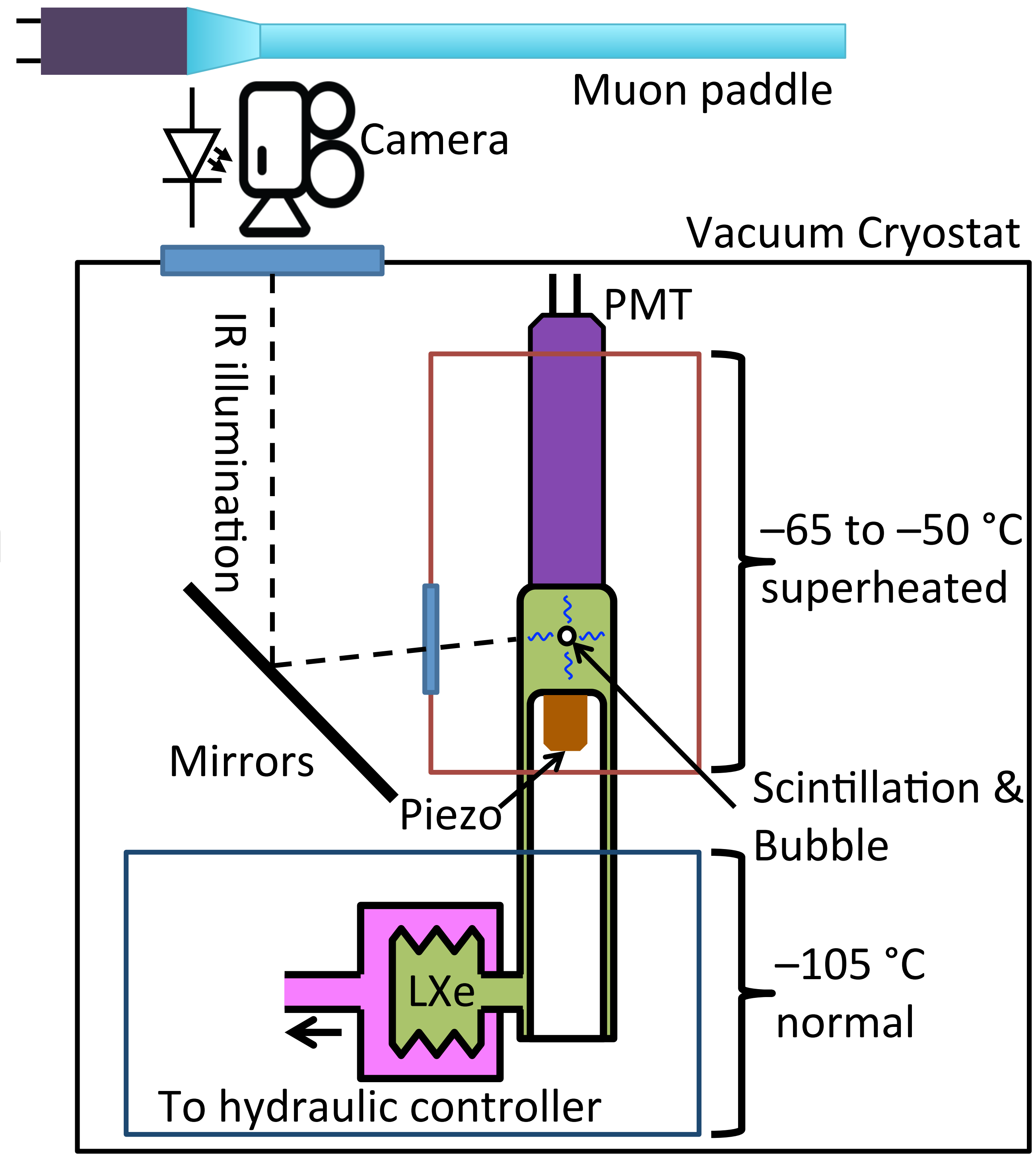
- Better background rejection compared to PICO, particularly at low thresholds
    - Improve on 10^{10} gamma rejection
- Improved information for rejection compared to usual xenon detectors
- Maintain the position reconstruction from PICO

Questions to be answered

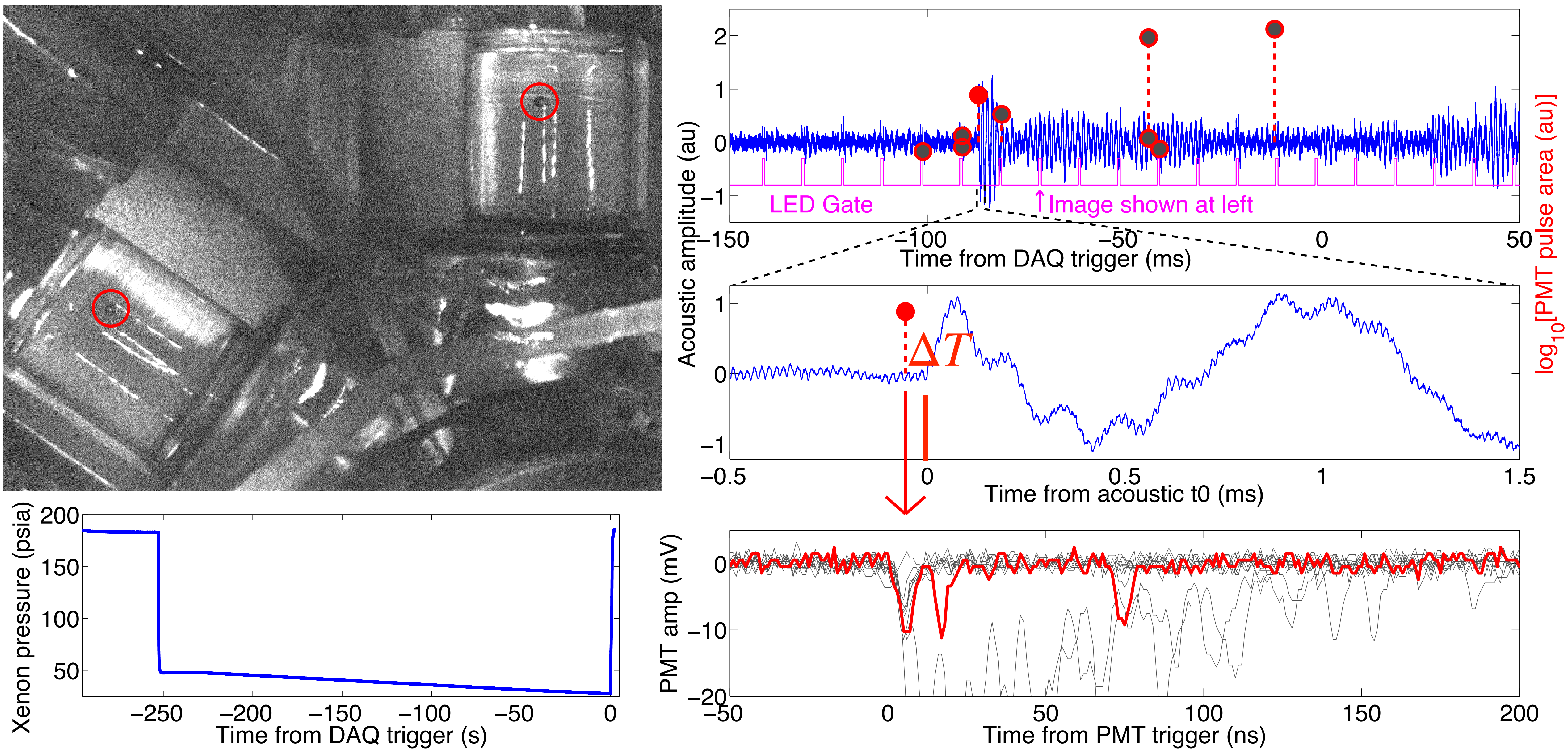
- Can this style detector be operated for a DM search?
- Can the ~1keV (or lower) threshold be reached in xenon?
  - What's the nuclear recoil efficiency at that threshold?
  - What is the low threshold behaviour?

Northwestern Chamber

- Operated at 4keV threshold
- Camera ported through sapphire window
- Mirrors allow two angles on the bubble

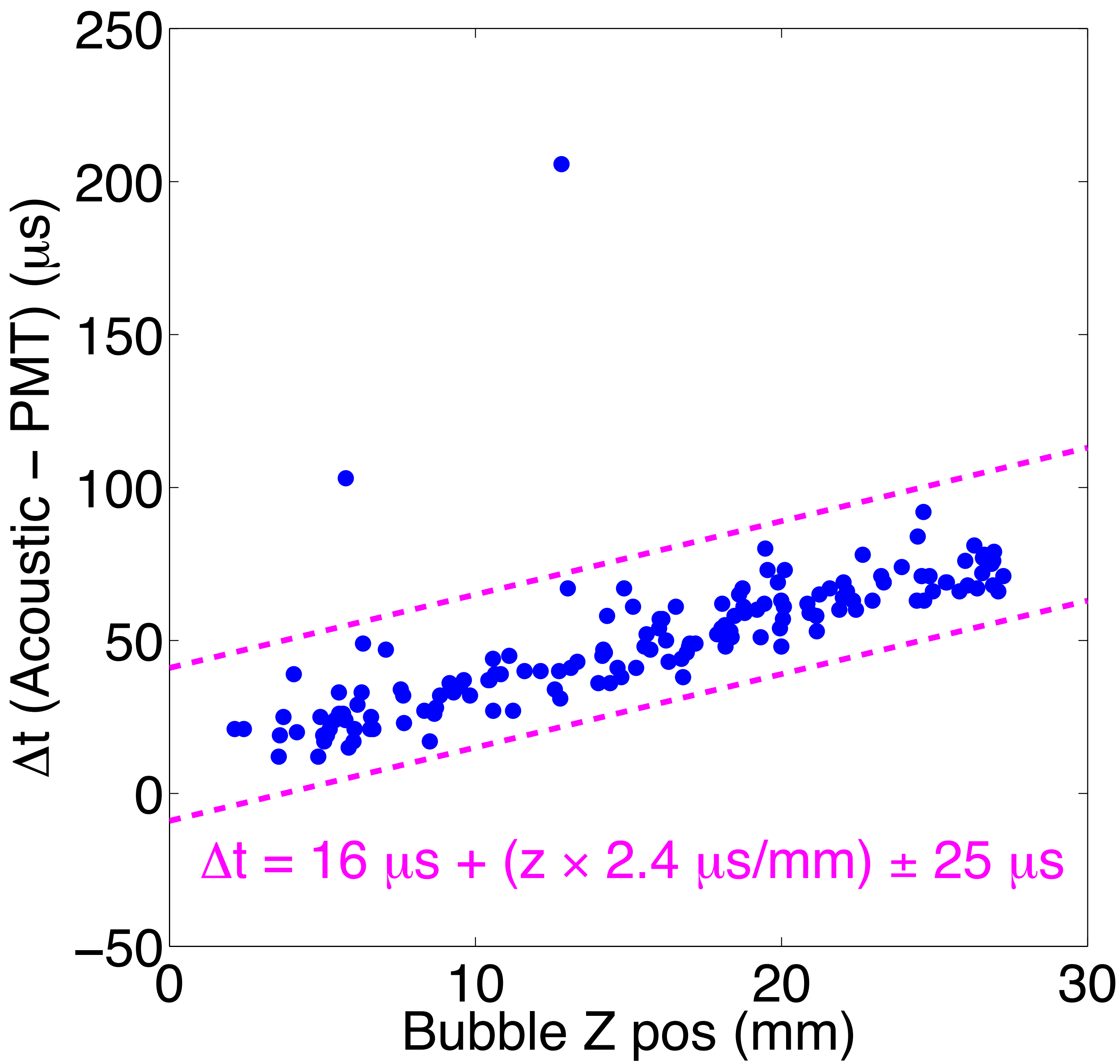


An event



Queen's University

Timing



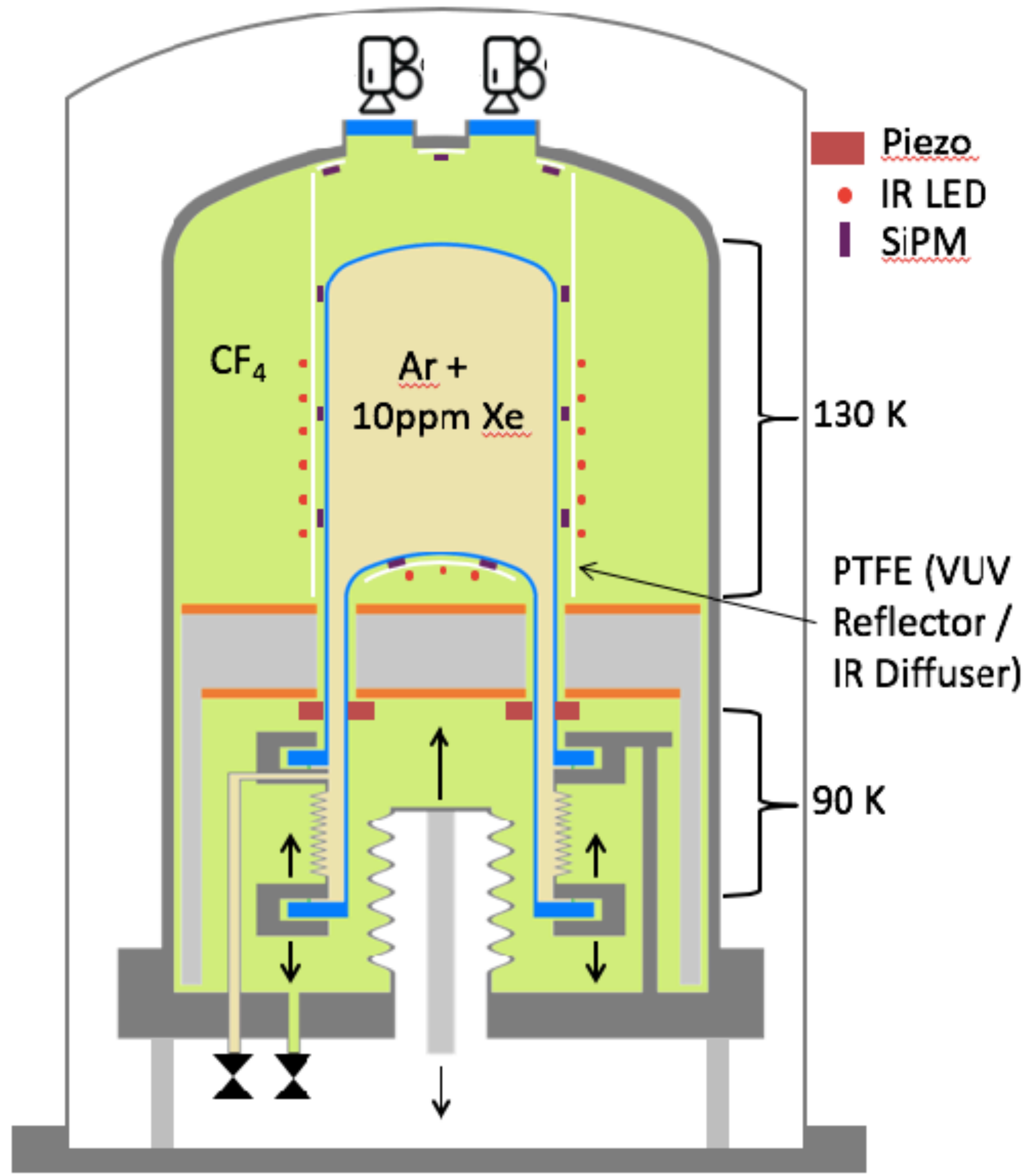
- Look at the time difference between scintillation and acoustics
- Derive the speed of sound in xenon (to ~20%)

Next Questions

- What other fluids work? Could, for example, Argon be usable?
    - UV scintillation probably means spiking it with a bit of xenon
- Are there good solutions for the scintillation light collection? SiPMs?
    - Need to be pressure tolerant, operate at LAr temperatures, be compatible with camera illumination…

The SBC Detector

- Roughly 10kg of Argon
- SiPMs used for detection
- Much of the internal detail modelled on PICO 500



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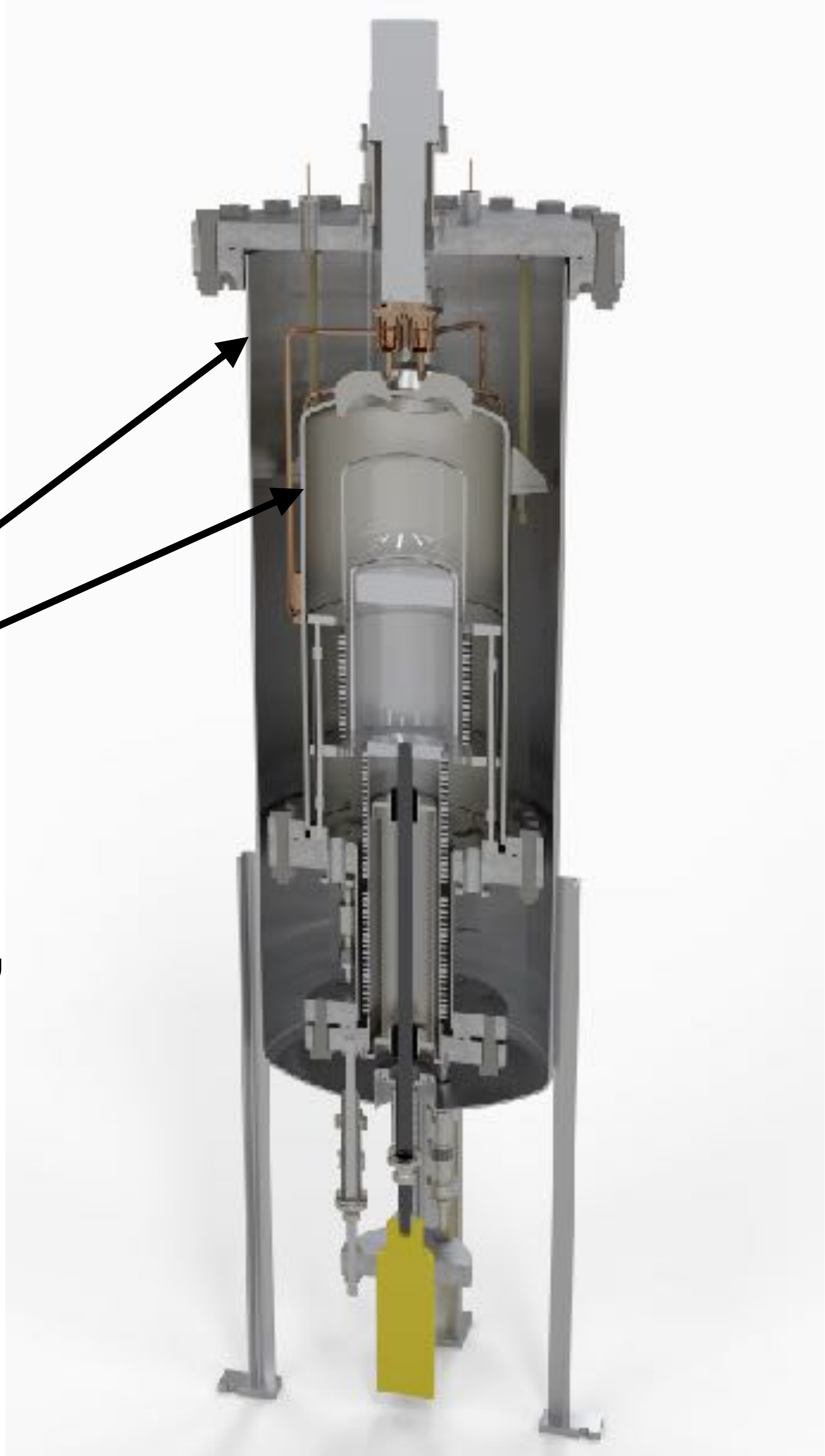
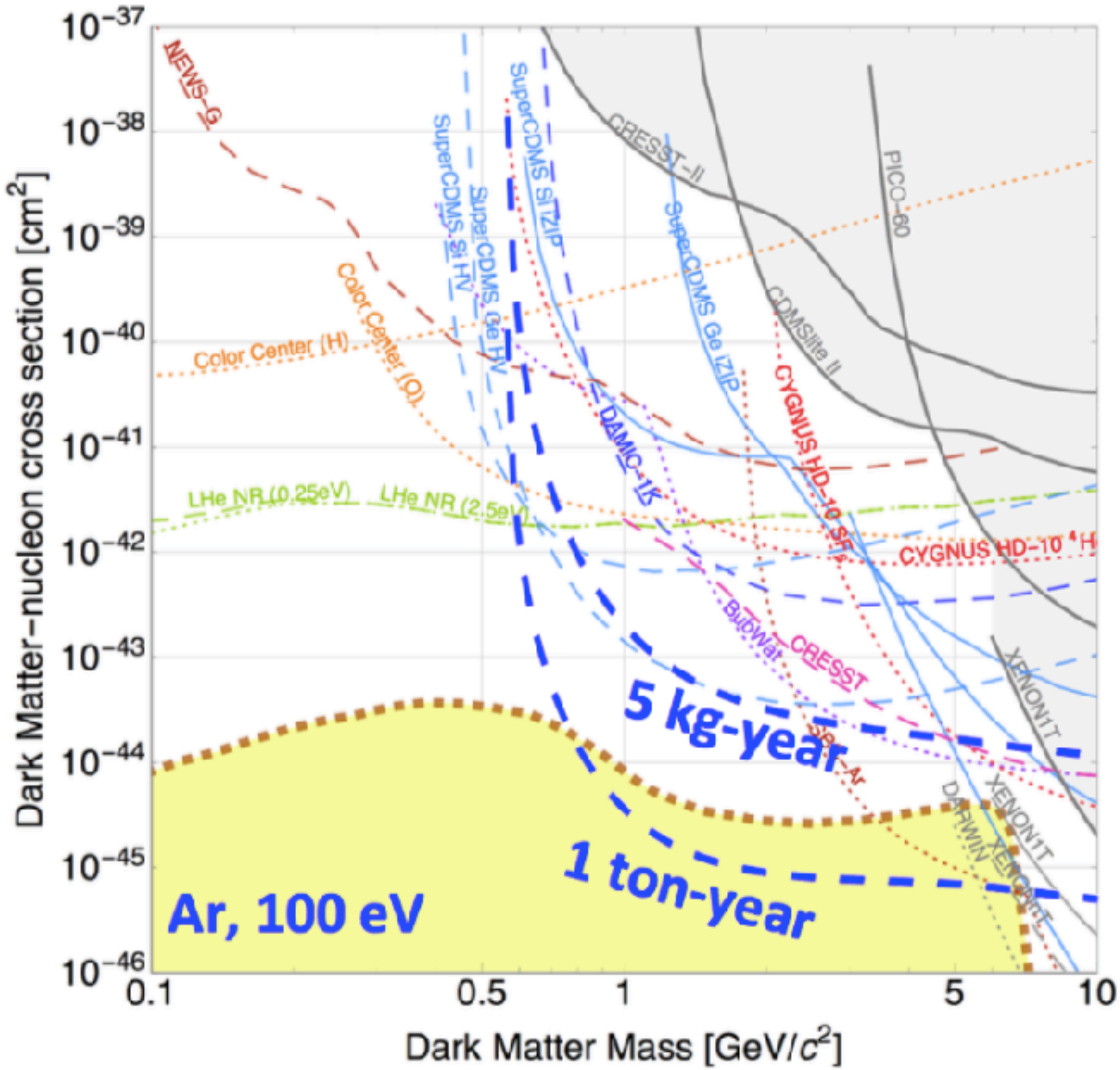


Pressure vessel and vacuum jacket manufacturer identified, bid accepted

Physics Goals

- Building two detectors for two different physics goals
- One for installation at SNOLAB
    - Look into low background response and feasibility for dark matter search
- One for installation at ORNL (?)
    - Look to further study coherent neutrino scattering

Physics Goals



SNOLAB Installation

- Currently past Gateway 0, anticipating Gateway 1 shortly
- Discussion of space is ongoing, although informally the space between SENSEI and DAMIC has been proposed

What's going on?

- Fermilab LDRD funding approved 2018
    - Primarily covering engineering so far, but money for construction and personnel
- CFI funds obtained in Canada
    - Mostly covering the construction of the chambers, as well as some infrastructure
- Construction of thermal system started, internal assembly also being built

Collaboration Building

- SBC Collaboration
  - U.S.: Fermilab, Northwestern, Drexel, IUSB
  - Canada: Queen's, Alberta, TRIUMF
  - Mexico: UNAM
- Responsibilities have been assigned

Timeline

- Technical design partially complete, wrapping up by August 2019
- Assembly and commissioning at Fermilab continues through 2020
    - Assembly of second detector may happen elsewhere
- Installation in the beginning of 2021

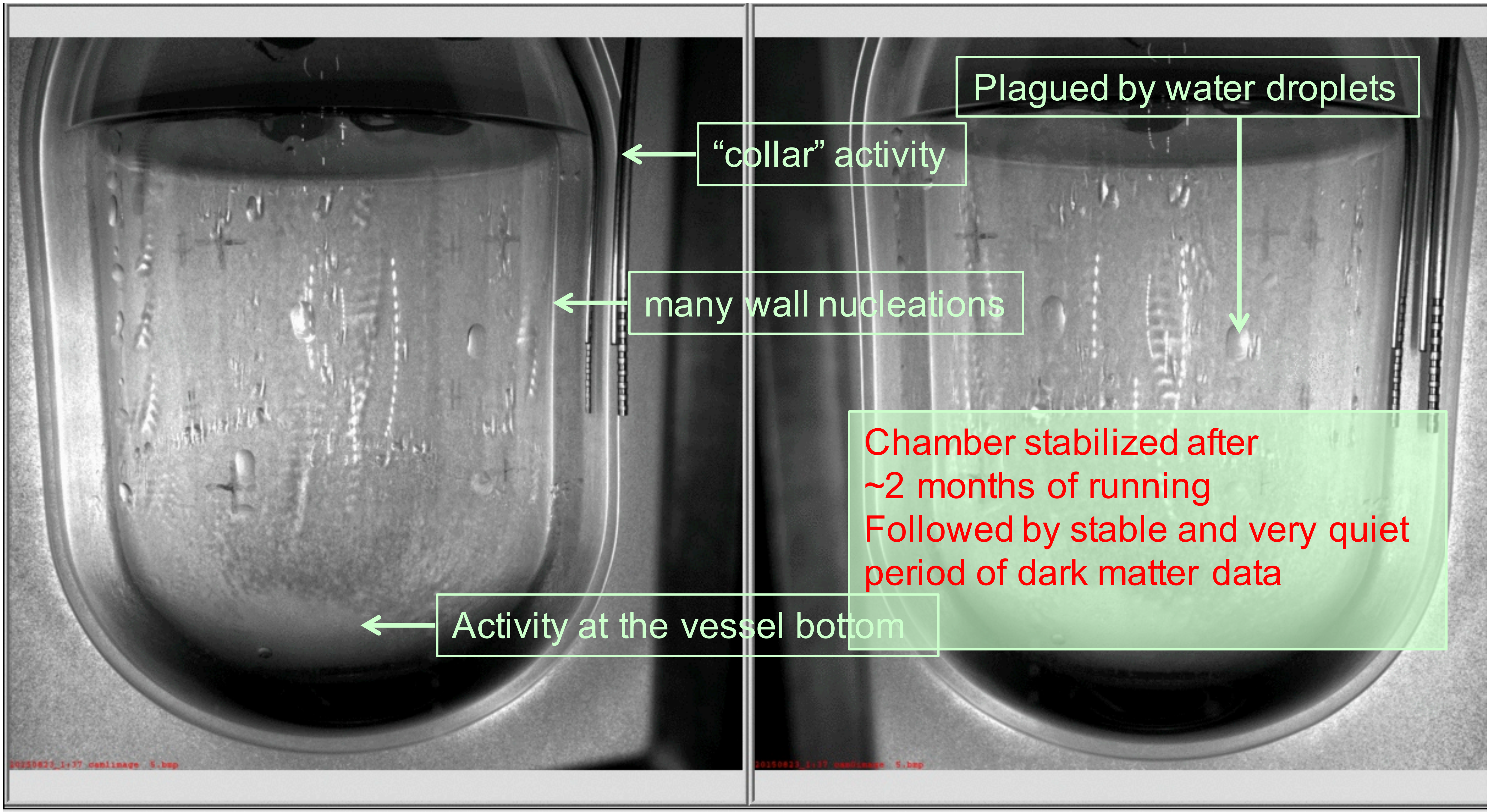
Conclusion

- Bubble chambers have had and continue to have a significant impact on the world of particle physics
- The Scintillating Bubble Chamber is the next step in the development of bubble chamber technology
- The SBC collaboration is steaming toward having a detector up and running

Events

Run 20160821_1 event 0

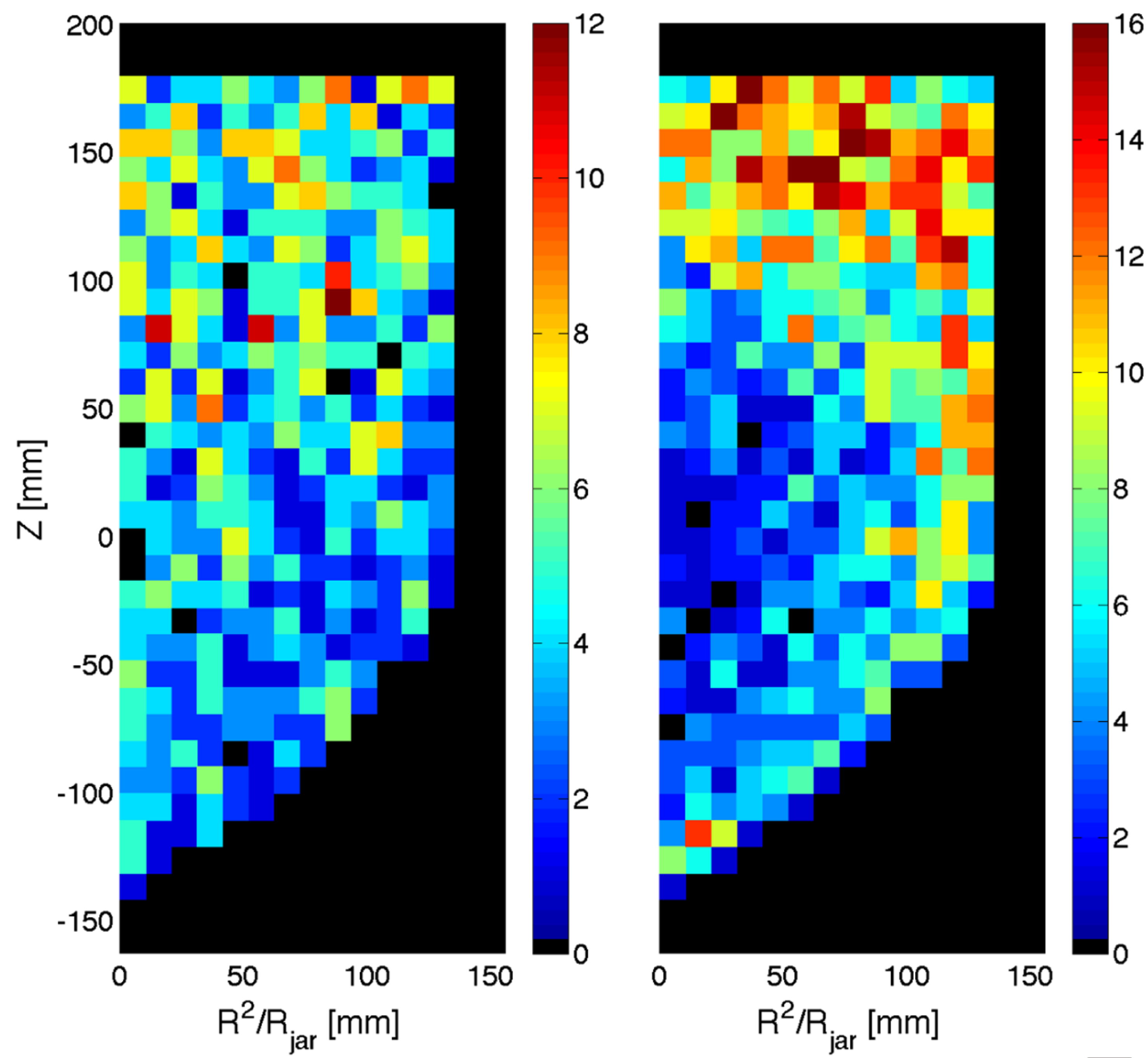
PICO-2L Run 2



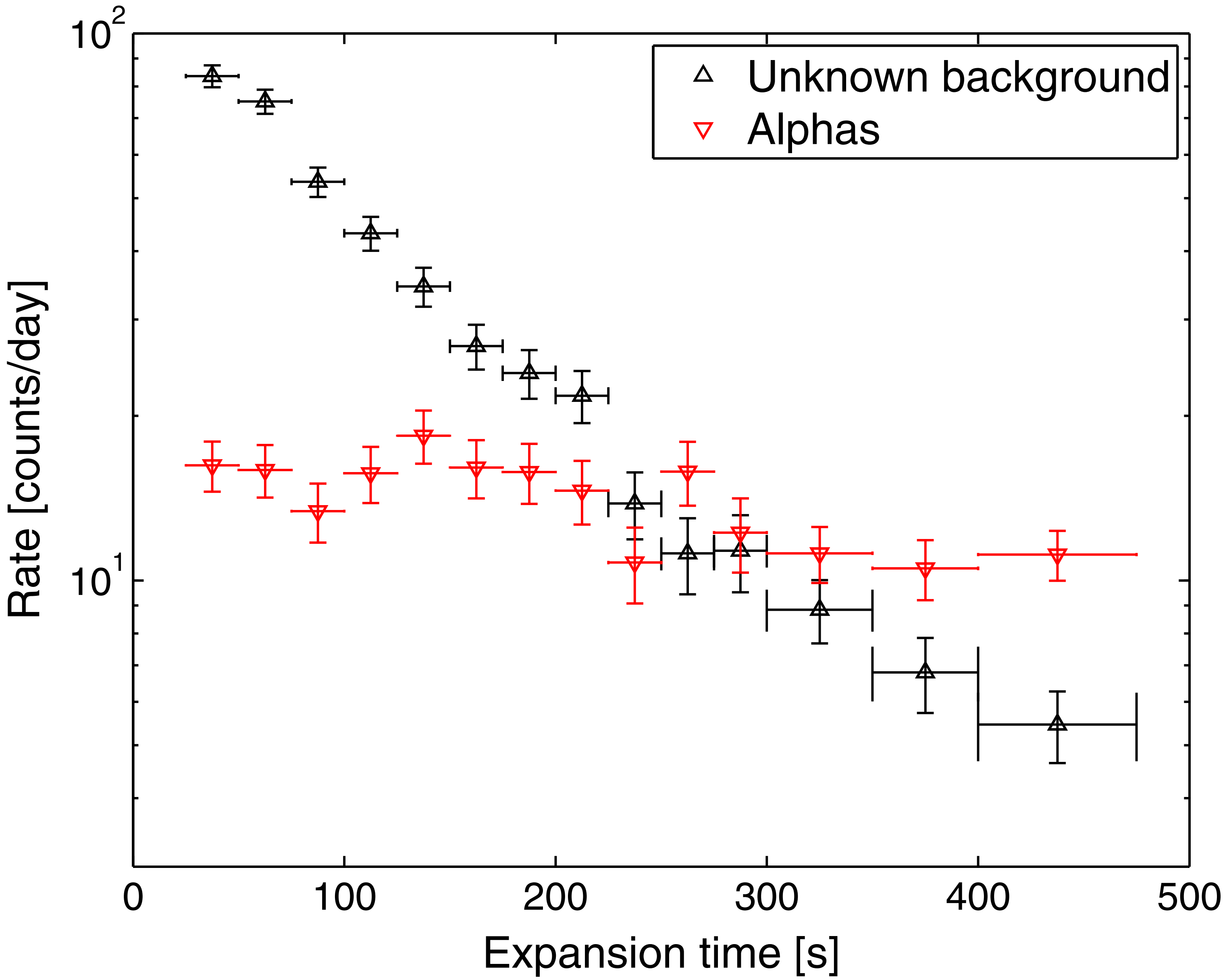
Chamber stabilized after ~2 months of running
Followed by stable and very quiet period of dark matter data

PICO-60 Background - Geographically

- These events were preferentially located at the surface
- Also some increase along the wall



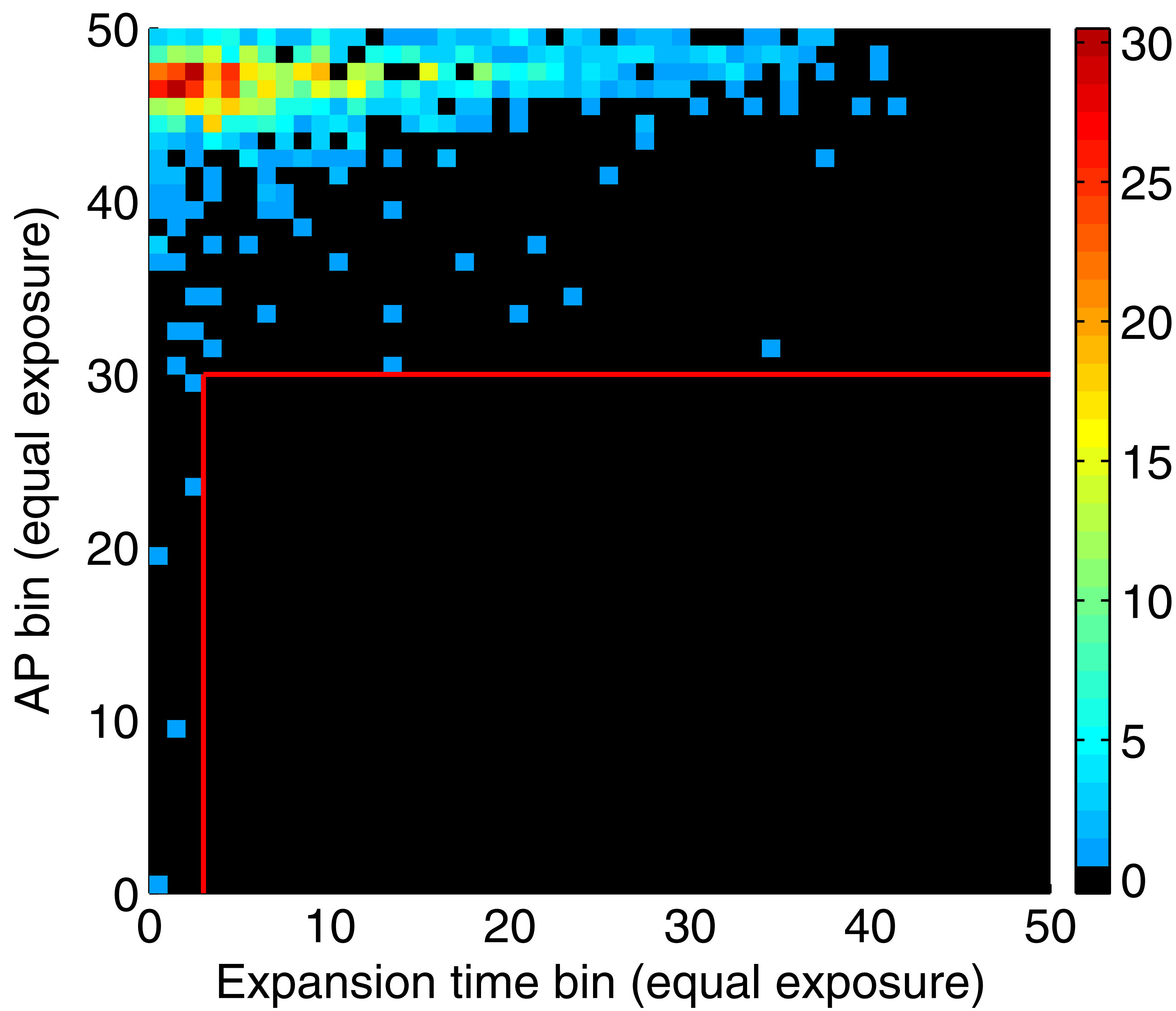
PICO-60 Background - Temporally



- Isolating low-AP events showed a time correlation with expansions

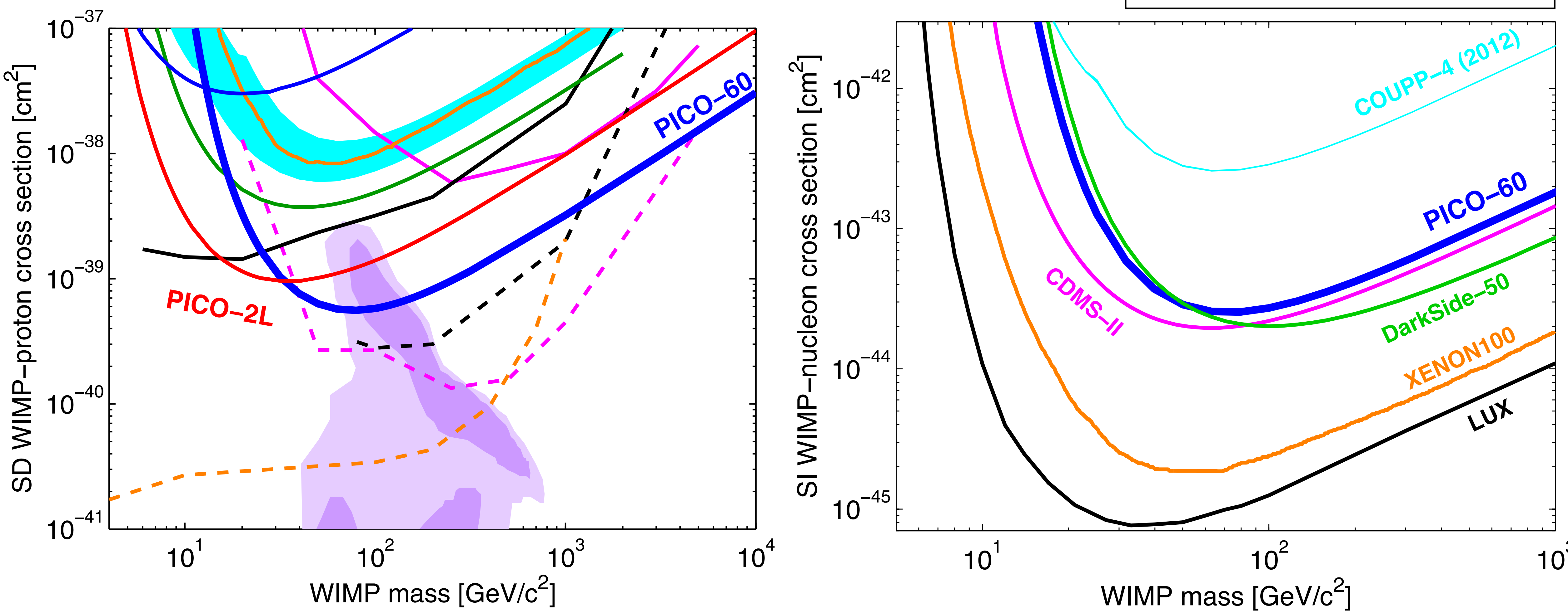
PICO-60 Run 1 Results

- Defined a “clean” region away from this class of events to produce a result



PICO-60 Run 1 Results

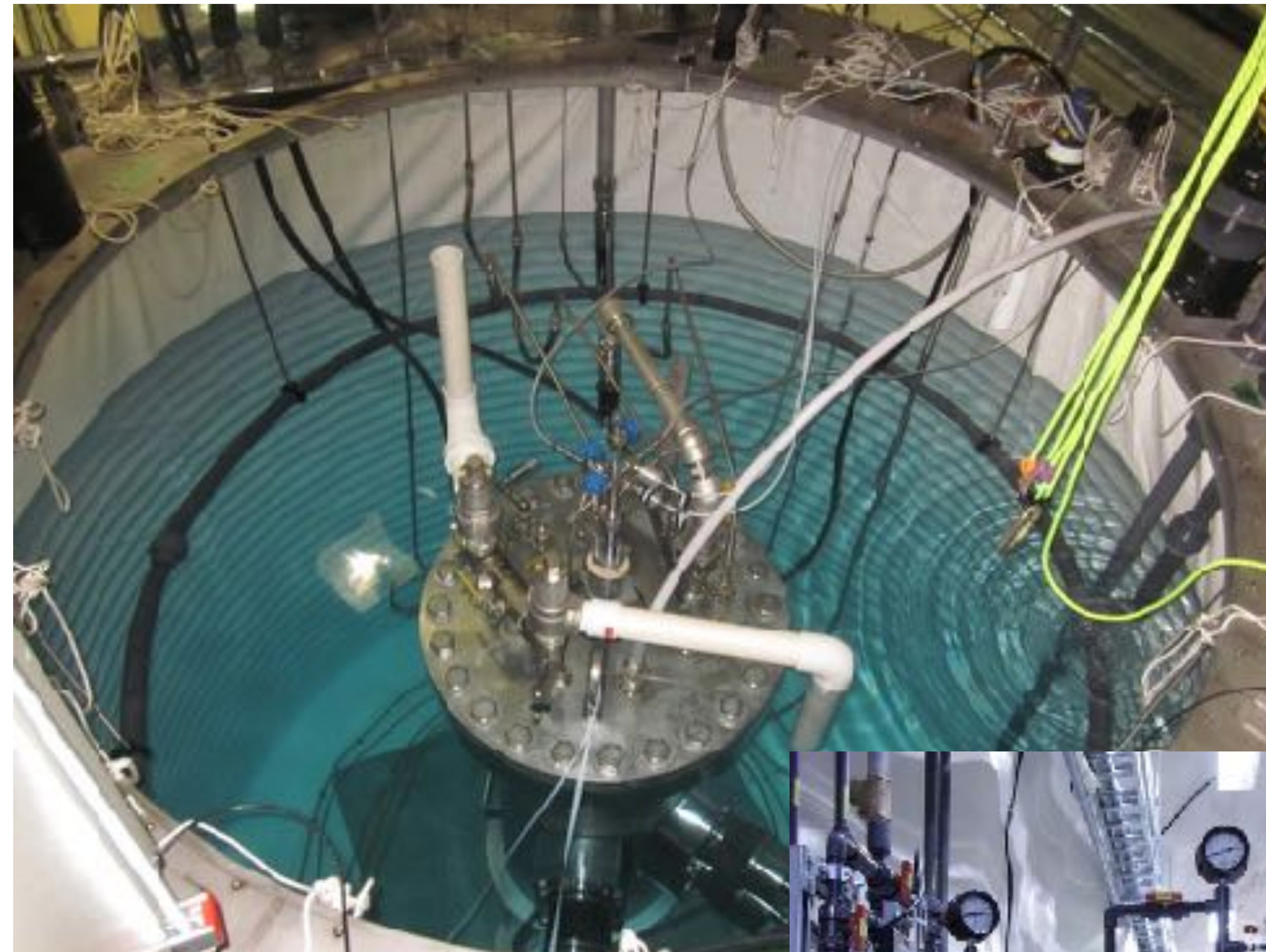
Phys. Rev. D 93, 052014 (2016)



- World-leading SD WIMP proton above 25GeV
- Statistical penalty for cutting data calculated via Monte Carlo

PICO-60 Run 2

- The water tank temperature control system also improved
- Significantly aids in the threshold setting



- A filtration system was also included to remove biological contaminants

So what was required?

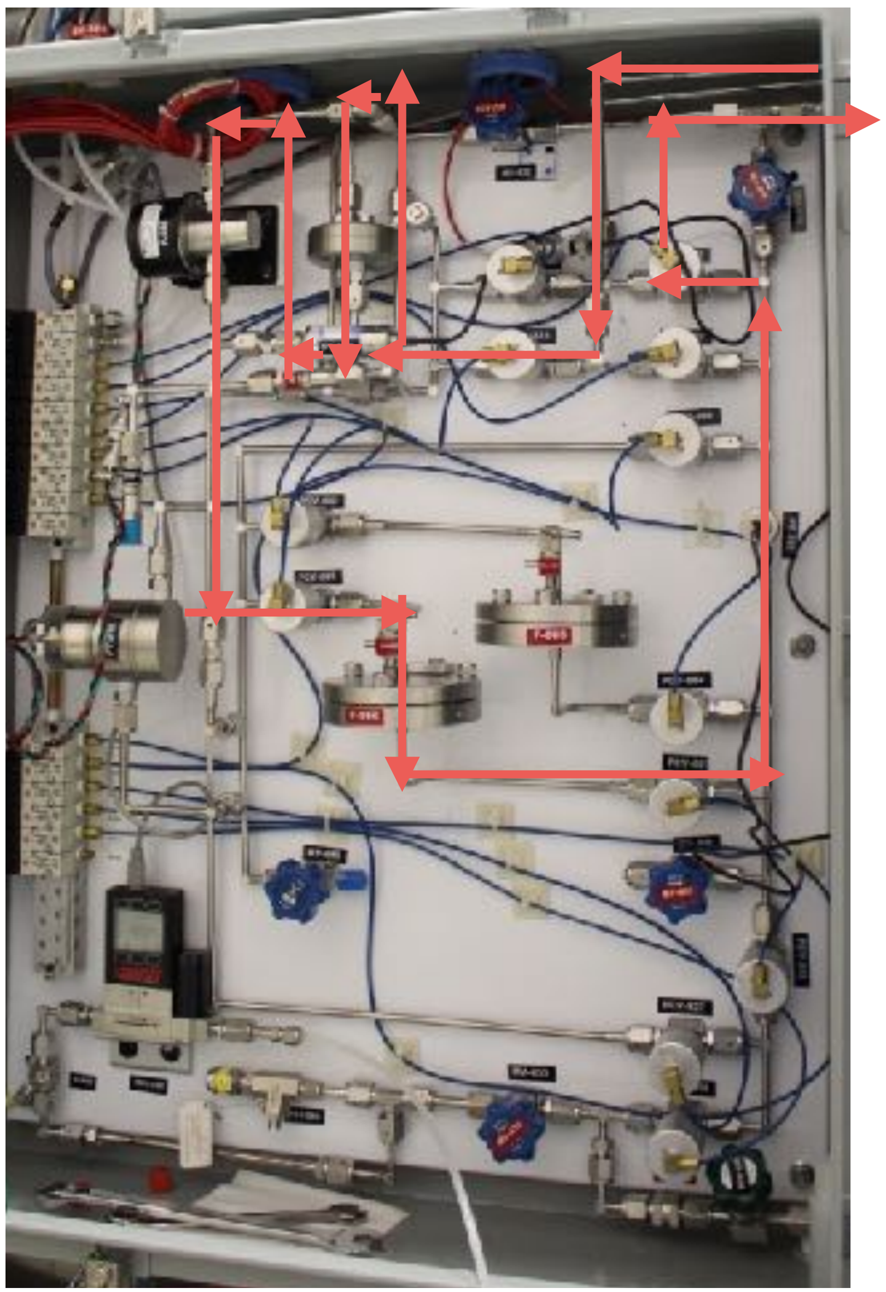
- Needed something that can be made sensitive quickly after an event
- Increased density would provide more events
- Easy readout of the detector would also be favourable
    - In cloud chambers, the event can be obscured by the large metal plates

Task Breakdown

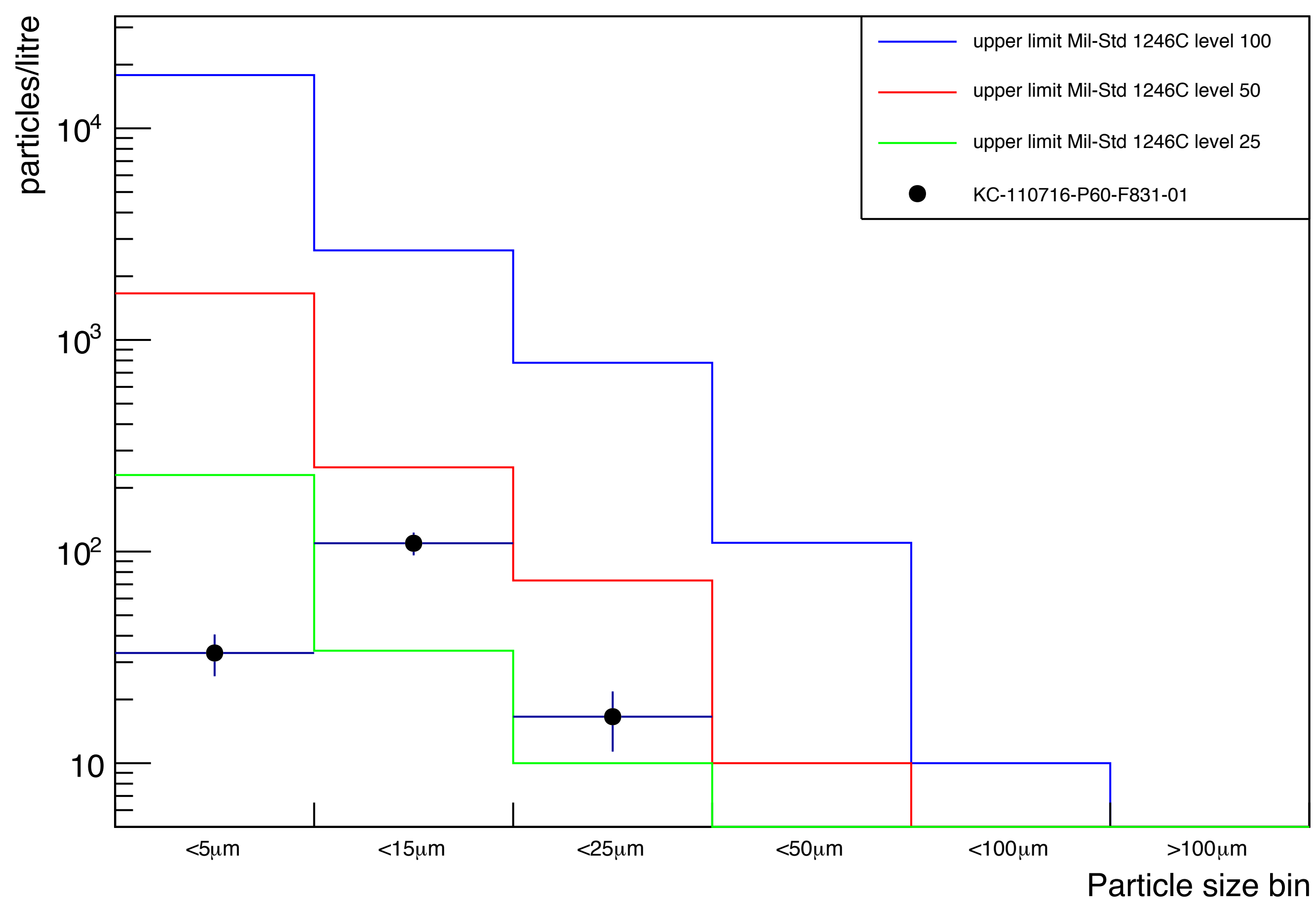
Task definition has happened, progress on all fronts

- WBS 1.1 Cryostat and Pressure Vessel (Fermilab / Dahl)
- WBS 1.2 Inner Assembly (Queen's / Clark)
- WBS 1.3 Fluid Systems (Alberta / Piro)
- WBS 1.4 Cryogenics (Fermilab / Lippincott)
- WBS 1.5 Optics and Imaging (Northwestern / Dahl)
- WBS 1.6 Scintillation Detection (Queen's / Clark)
- WBS 1.7 Acoustic Detection (IUSB / Levine)
- WBS 1.8 Shield Systems (UNAM / Vazquez Jauregui)
- WBS 1.9 Calibration (Drexel / Neilson)
- WBS 1.10 Online Computing (Northwestern / Dahl)
- WBS 1.11 Offline Computing (TBD)

PICO-60 Run 2



- Add a filtration system to remove the particulates
- This is monitored and has achieved military specifications

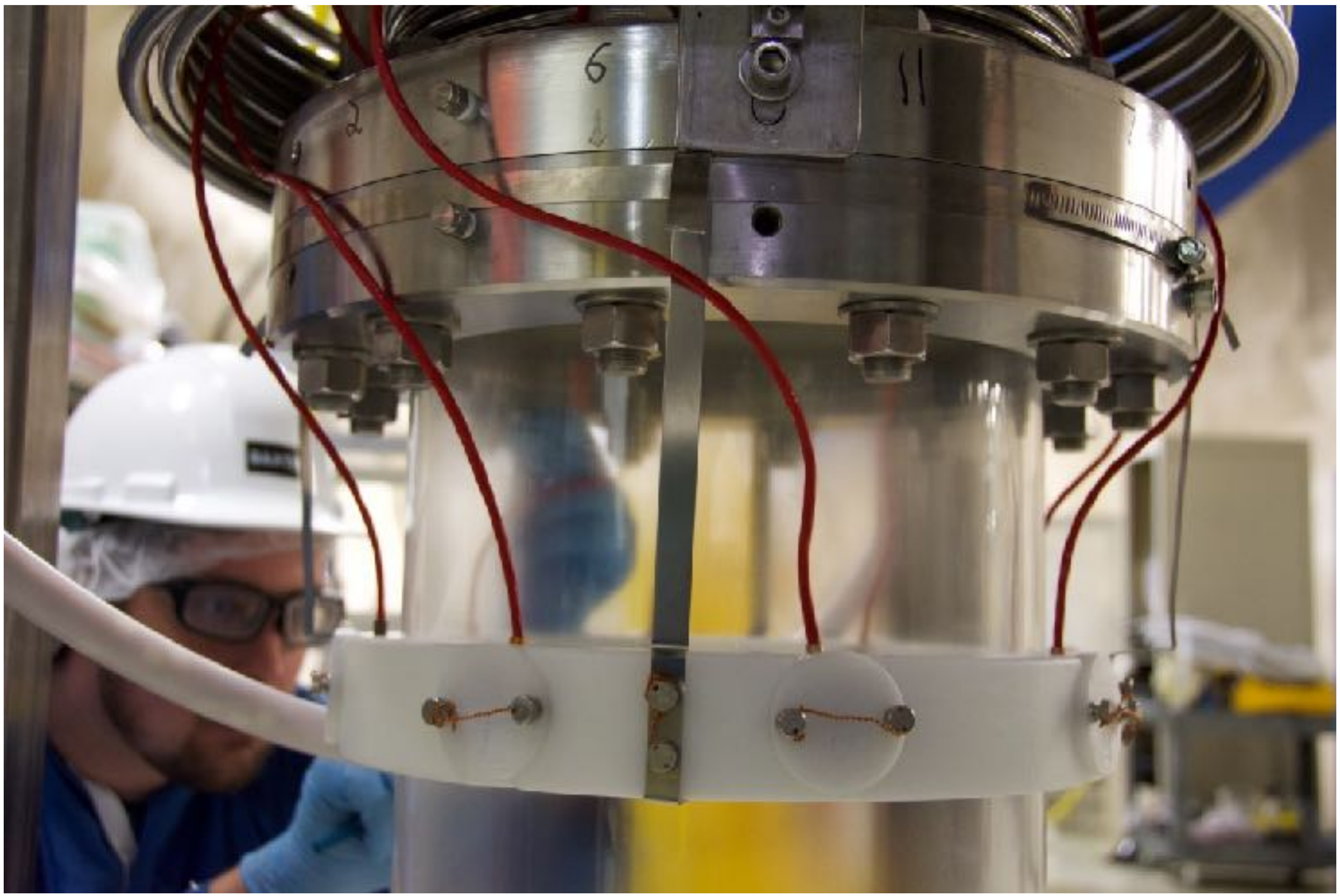


PICO-60 Run 2

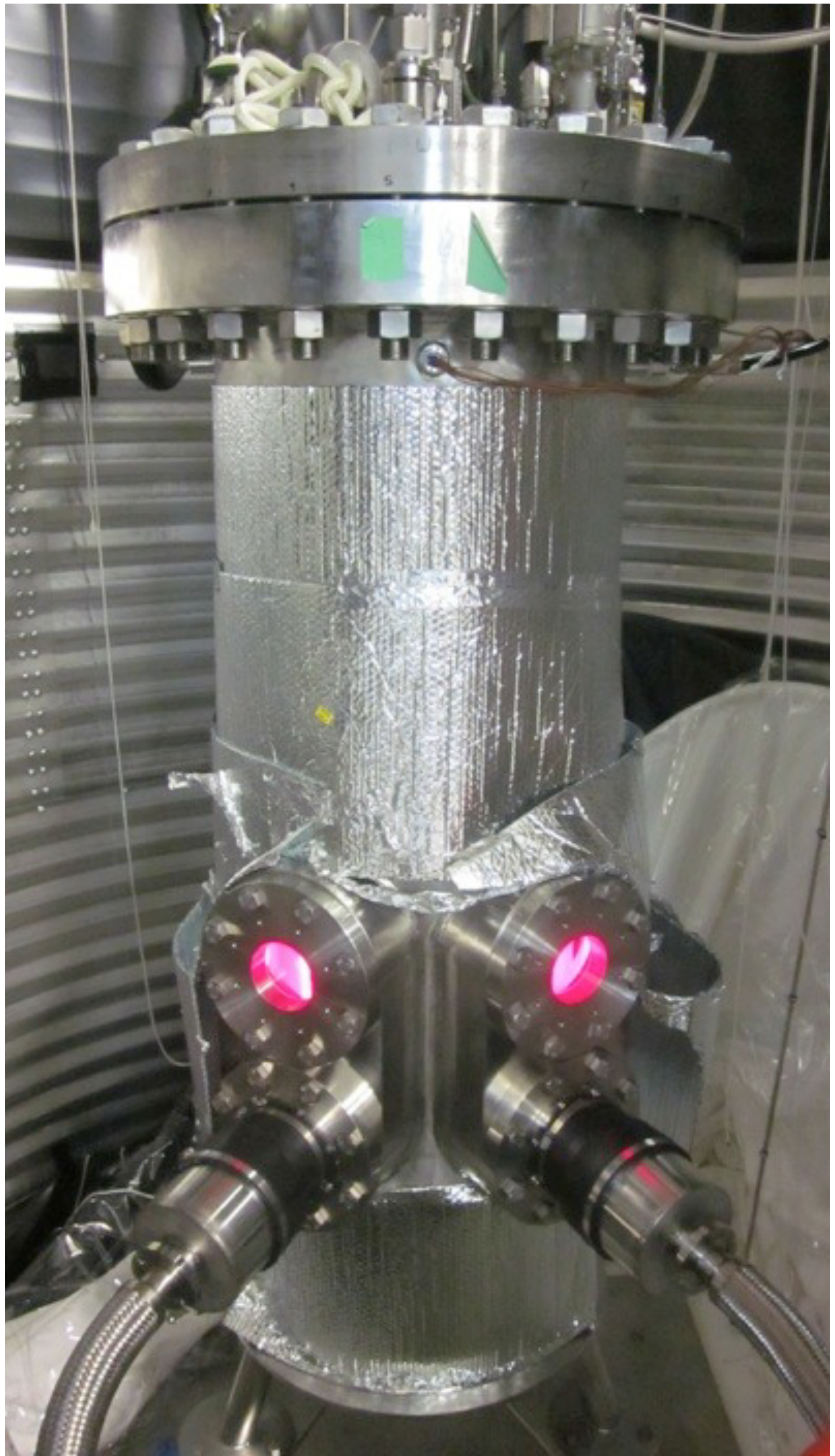
- Cleaning was even more stringent than previous runs
- A special rig was designed to clean the jar with heated surfactant

PICO-60 Run 2

- The number of piezos was increased and the mounting system upgraded



PICO-60 Run 2



- Double the number of cameras (from 2 to 4)
  - Doubles the active mass viewed
- Increase the rate to 340 frames per second

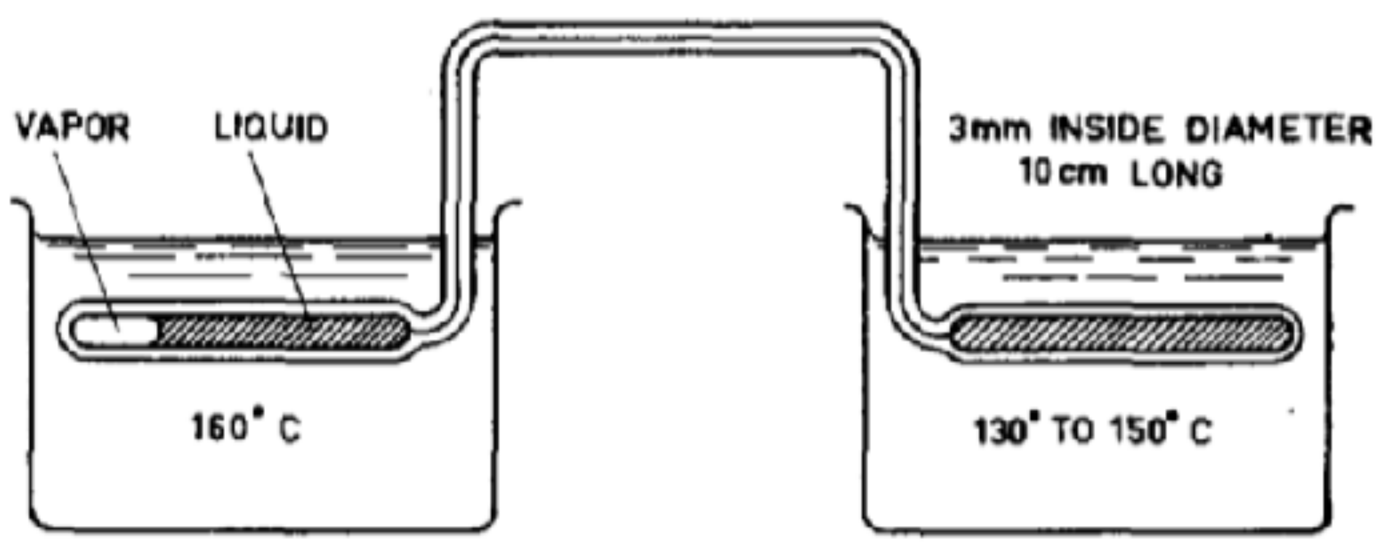
How did this start?

- Physicists needed to detect particles
  - Kind of one of the main things we do, or did…
- Cloud chambers existed, but had some issues:
  - low density
  - low rate

Accelerators started to outstrip the detection using these chambers

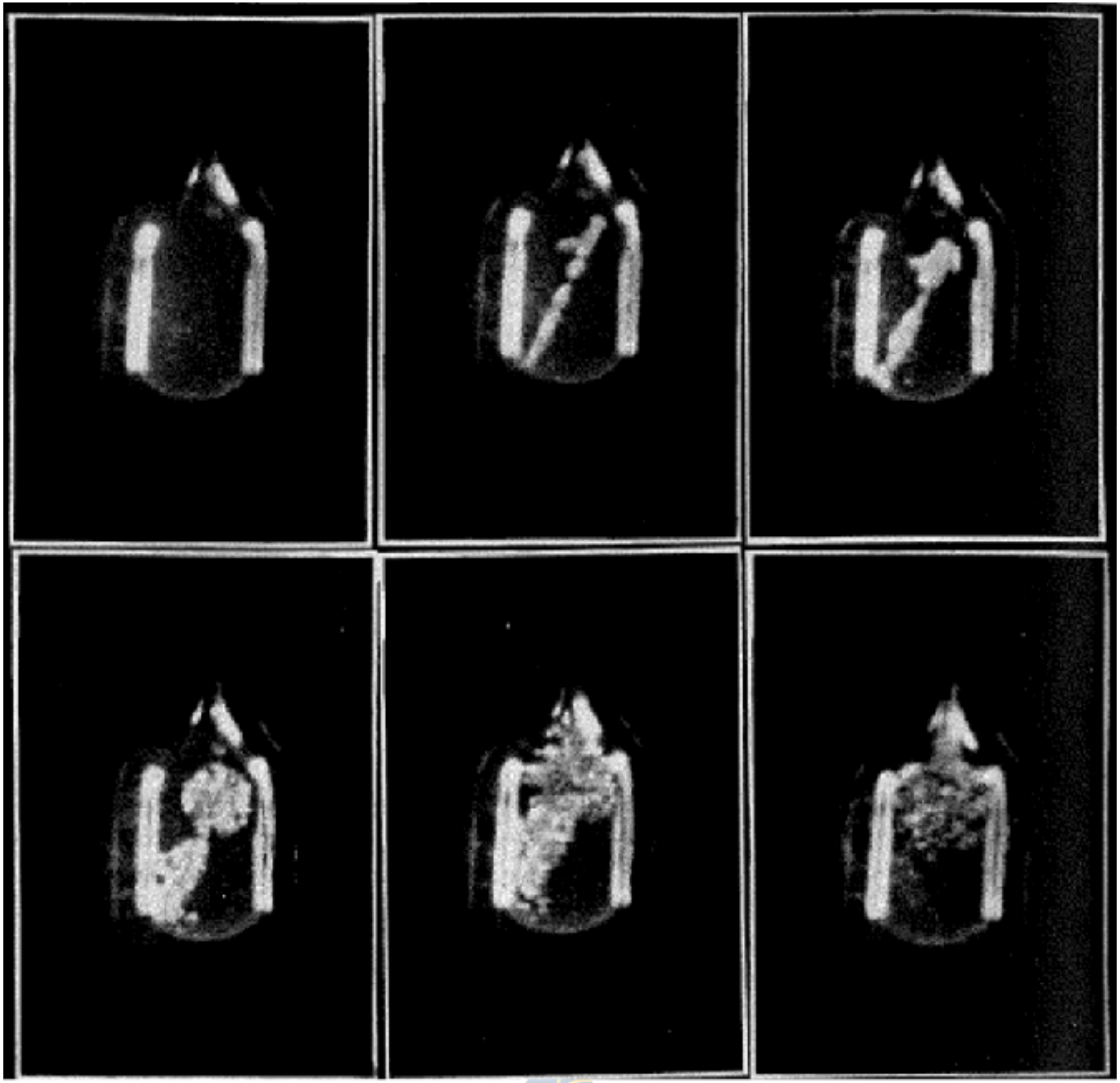
Glaser was inspired

- Donald Glaser saw these problems and worked on a solution
- He used superheated liquid to show the tracks
    - This allowed for a clear view and quick "reset" of the detector
- He has denied that he was inspired to do this by beer, but apparently did try it as an active fluid



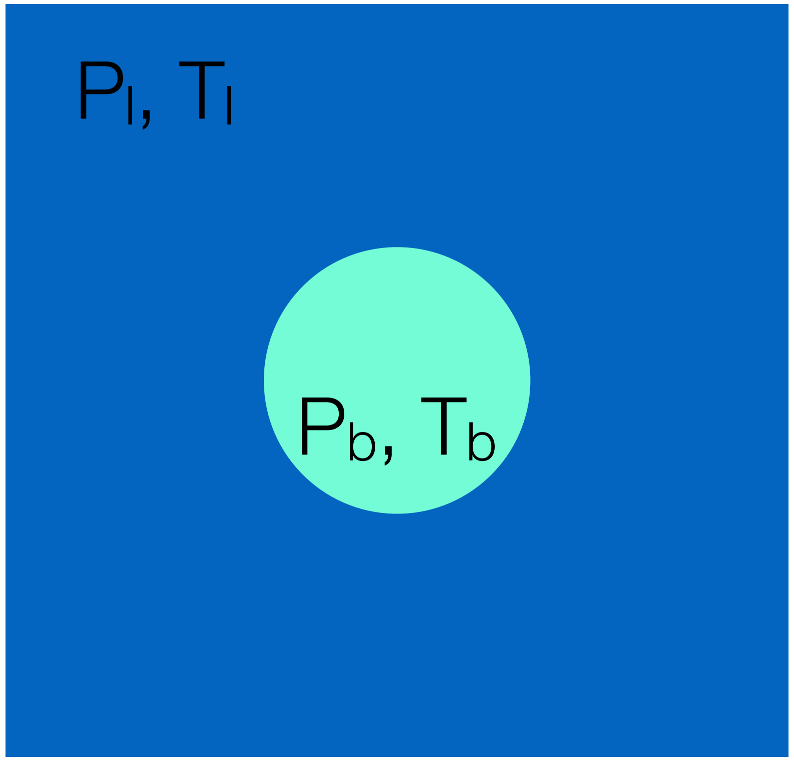
Glaser, Nuovo Cimento 11 (1954) 361

Glaser Images



How does this work?

- Start with a bubble in a liquid
- In thermal equilibrium, so $T_l = T_b$
- Also in chemical equilibrium, so $\mu_l = \mu_b$
- P_b is then roughly the vapour pressure at temperature T, and $P_b > P_l$, so the bubble should expand



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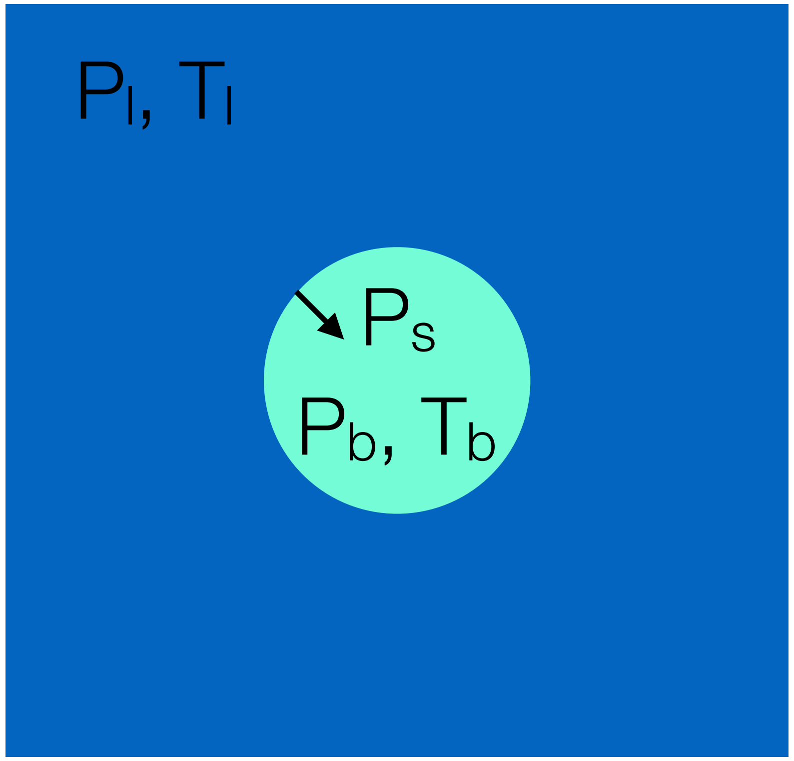


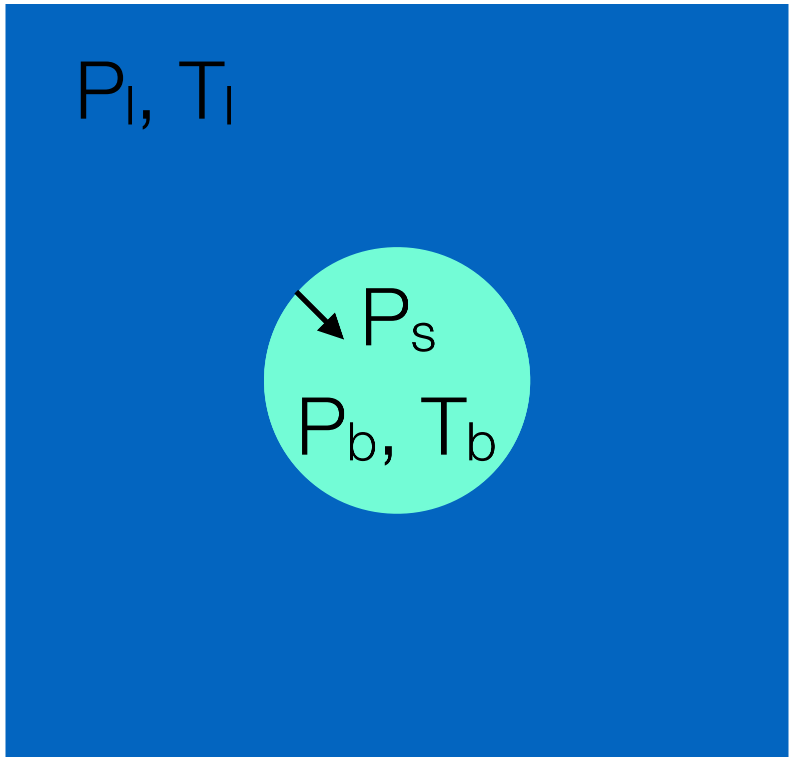
How does this work?

- Include pressure from surface tension $P_s = 2\sigma/r$
- This means the bubble will grow only if:

$$P_b > P_l + P_s$$

and

$$r > \frac{2\sigma}{P_b - P_l}$$



- Which we call the critical radius r_c

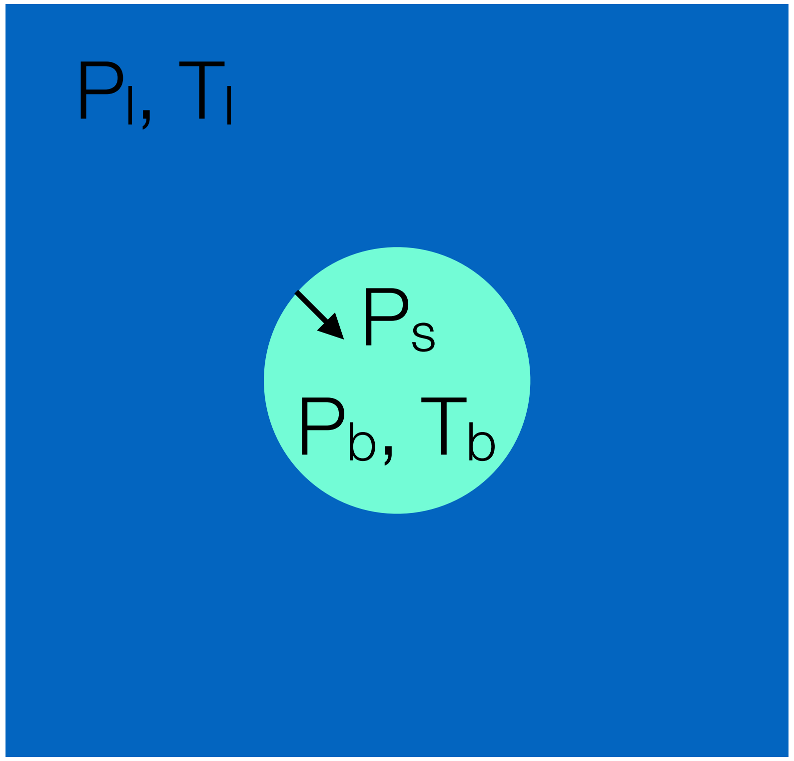
How does this work?

- Any bubbles which don't meet these conditions will collapse and re-condense

$$P_b > P_l + P_s$$

and

$$r > \frac{2\sigma}{P_b - P_l}$$



Calculation of Threshold

- So how is the threshold energy calculated?

$$E_T = 4\pi r_c^2 \left(\sigma - T \left[\frac{d\sigma}{dT} \right]_\mu \right)$$ Surface energy

$$+\frac{4\pi}{3} r_c^3 \rho_b (h_b - h_l)$$ Bulk energy

$$-\frac{4\pi}{3} r_c^3 (P_b - P_l)$$ Reversible work

- Where ρ is the density and h the specific enthalpy

Calculation of Threshold

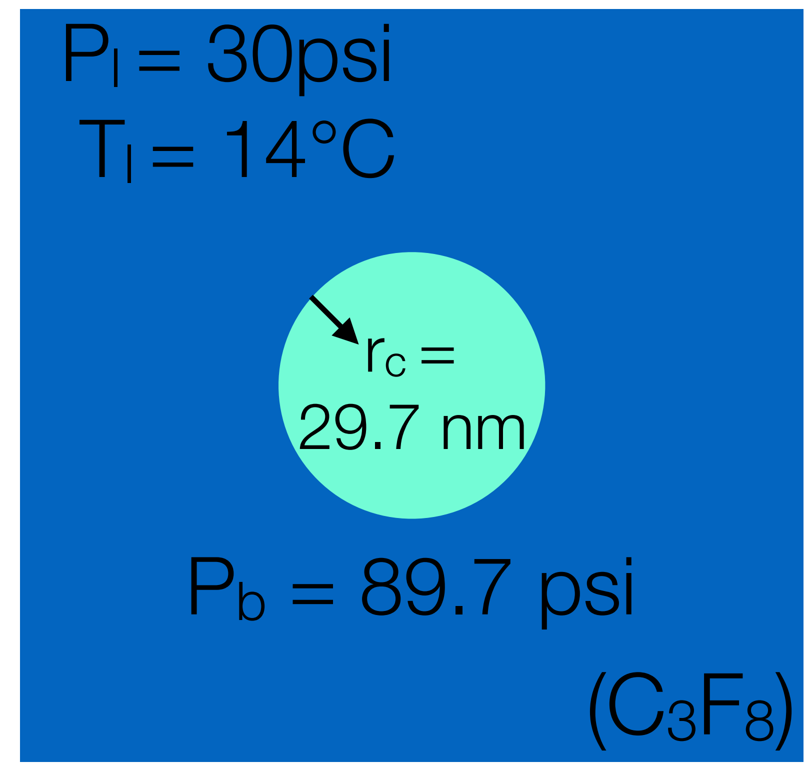
- So how is the threshold energy calculated?

$$E_T = 4\pi r_c^2\left(\sigma - T\left[\frac{d\sigma}{dT}\right]_\mu\right)$$ 1.53 keV

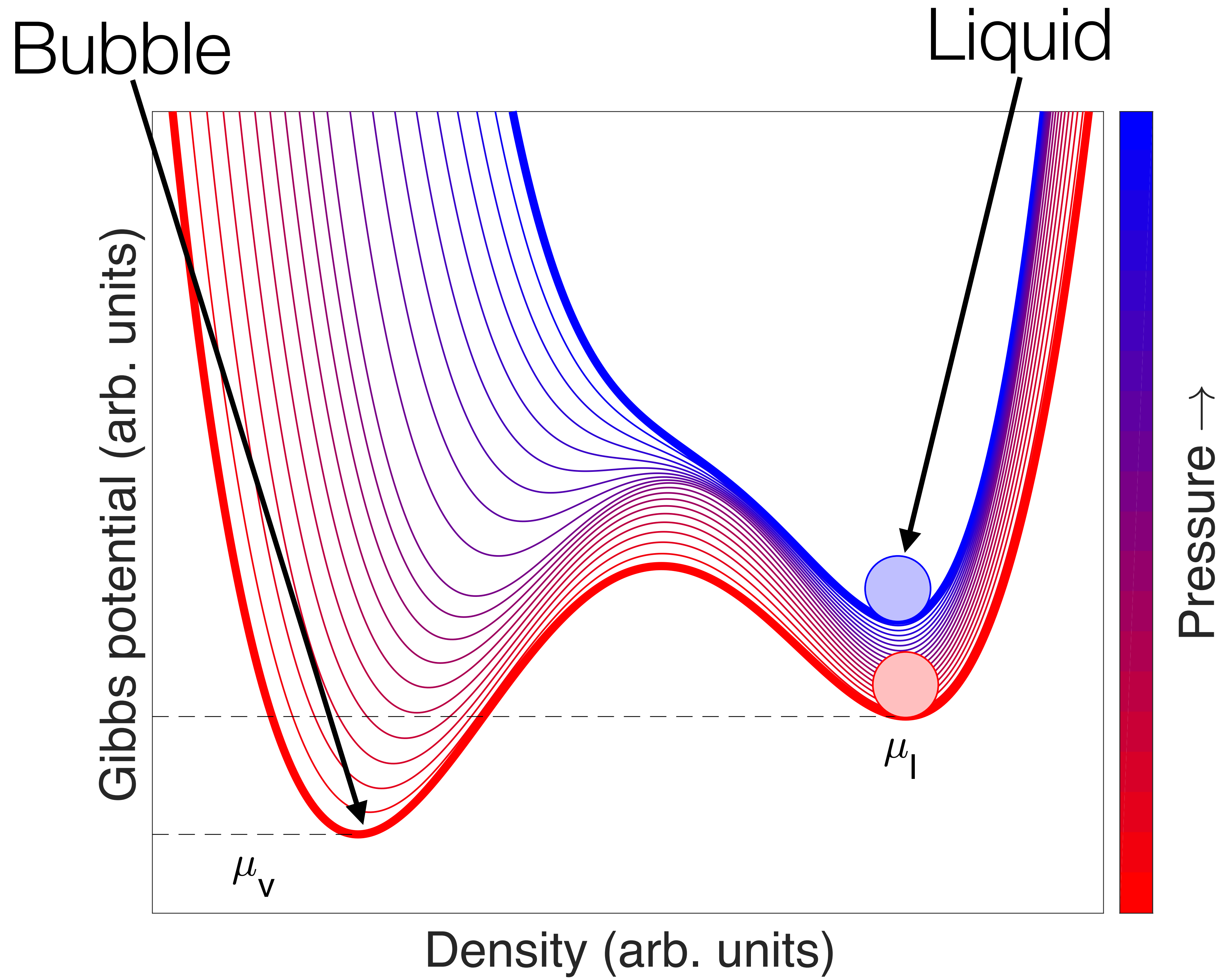
$$+\frac{4\pi}{3}r_c^3\rho_b(h_b - h_l)$$ 1.81 keV

$$-\frac{4\pi}{3}r_c^3(P_b - P_l)$$ 0.15 keV

3.19 keV



Graphically



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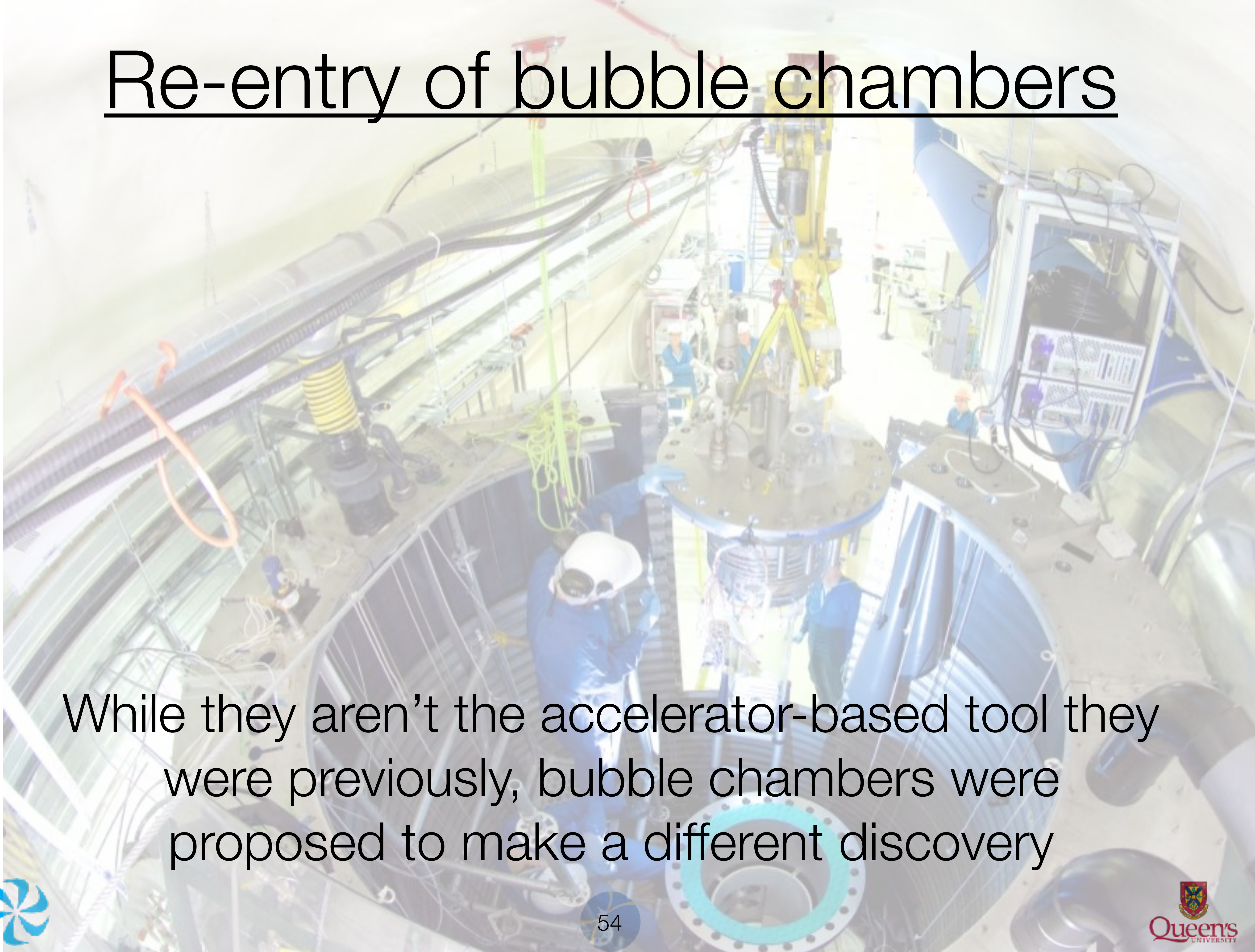
History of the bubble chamber and related active- and internal-target nuclear tracking detectors, F.D. Becchetti, NIMA 784 (2015) 518-523

Exit the bubble chamber

- This technology worked solidly for decades, making lots of contributions to physics
- Unfortunately the use of hydrogen as a target had some associated dangers
- New detectors with more convenient readout started to supplant the bubble chamber, at least for some uses

15’ bubble chamber at Fermilab

Re-entry of bubble chambers

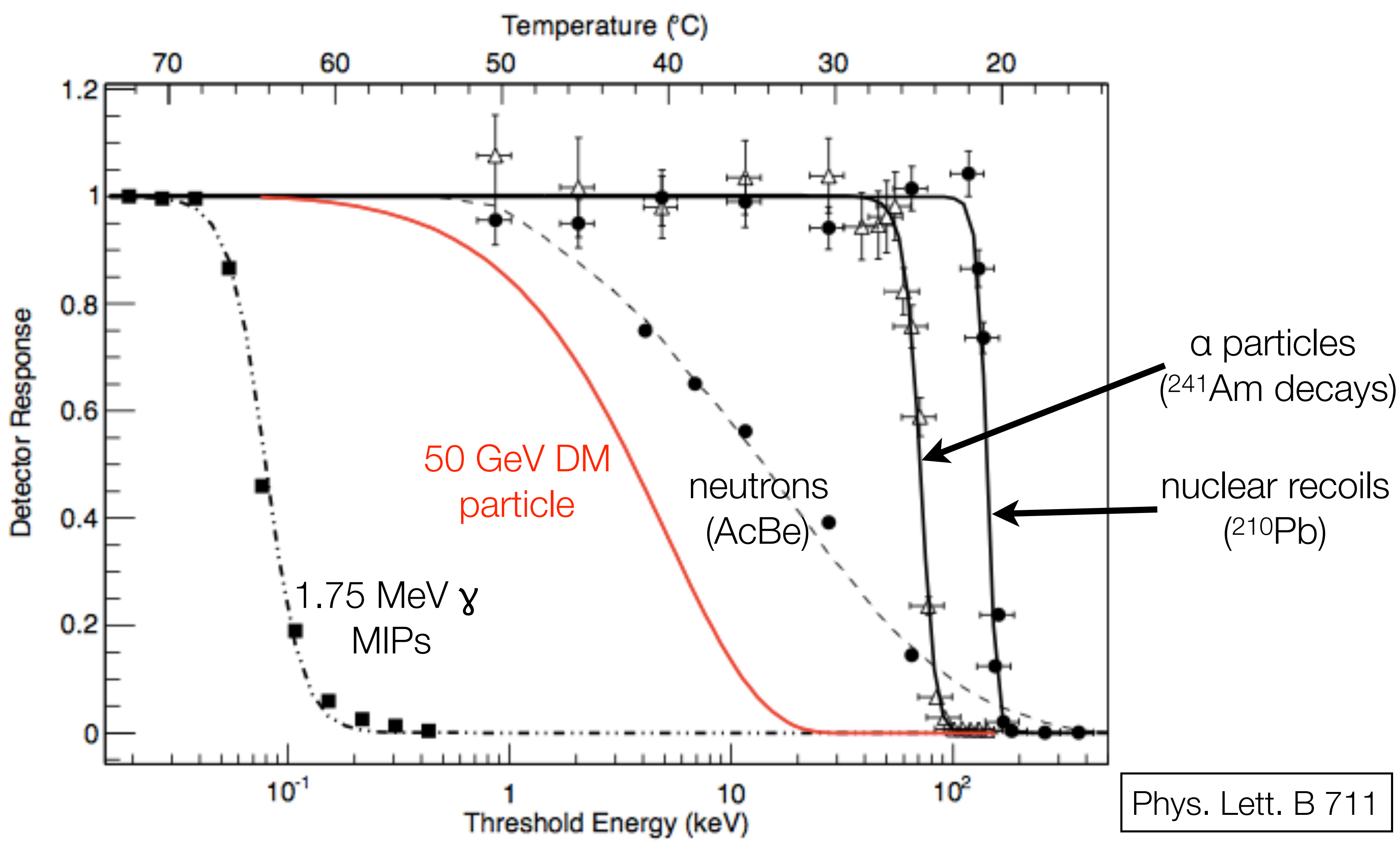


While they aren't the accelerator-based tool they were previously, bubble chambers were proposed to make a different discovery

Queen's UNIVERSITY

Bubble Chamber Advantages

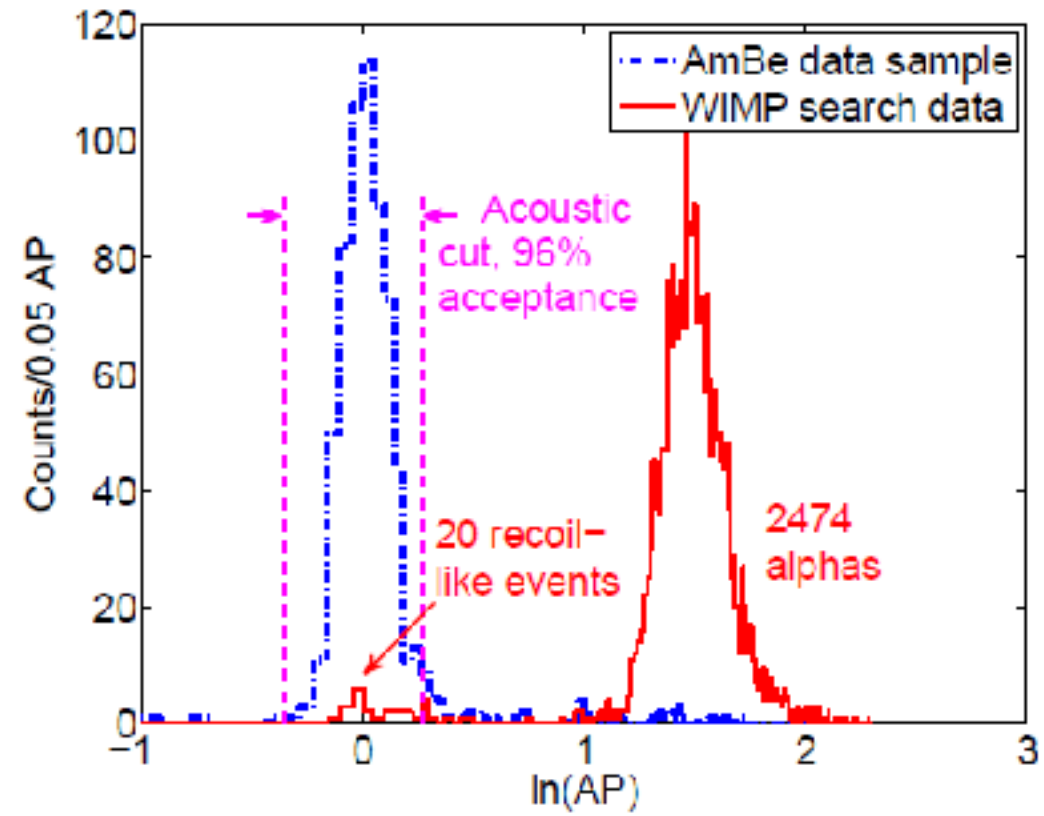
- There are some unique aspects of the bubble chamber that make it attractive
  - Discrimination is one big one

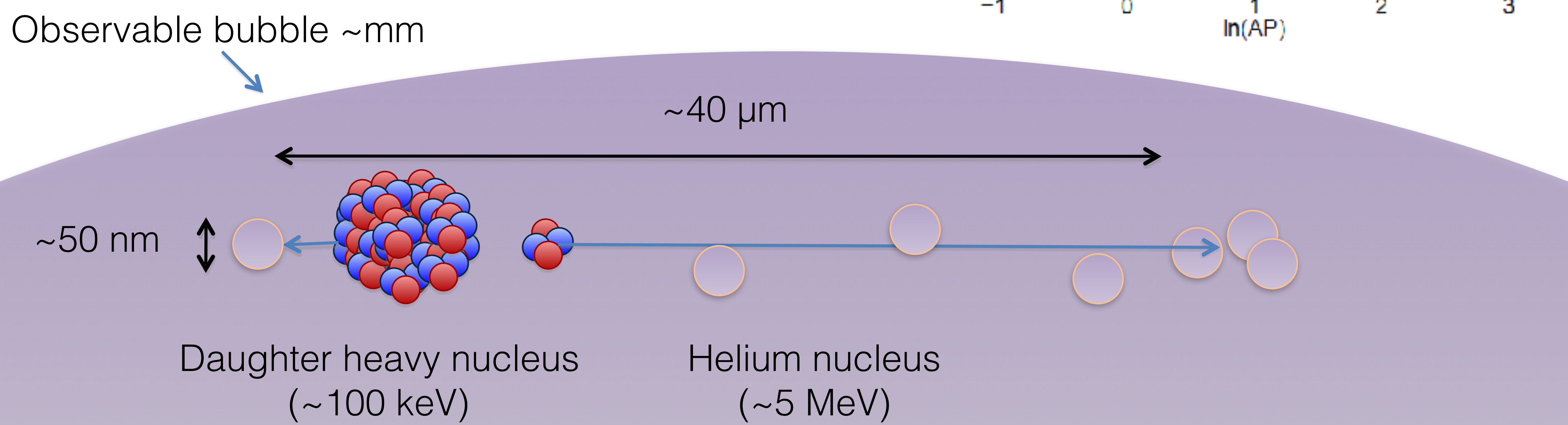


Phys. Lett. B 711

Acoustic Discrimination

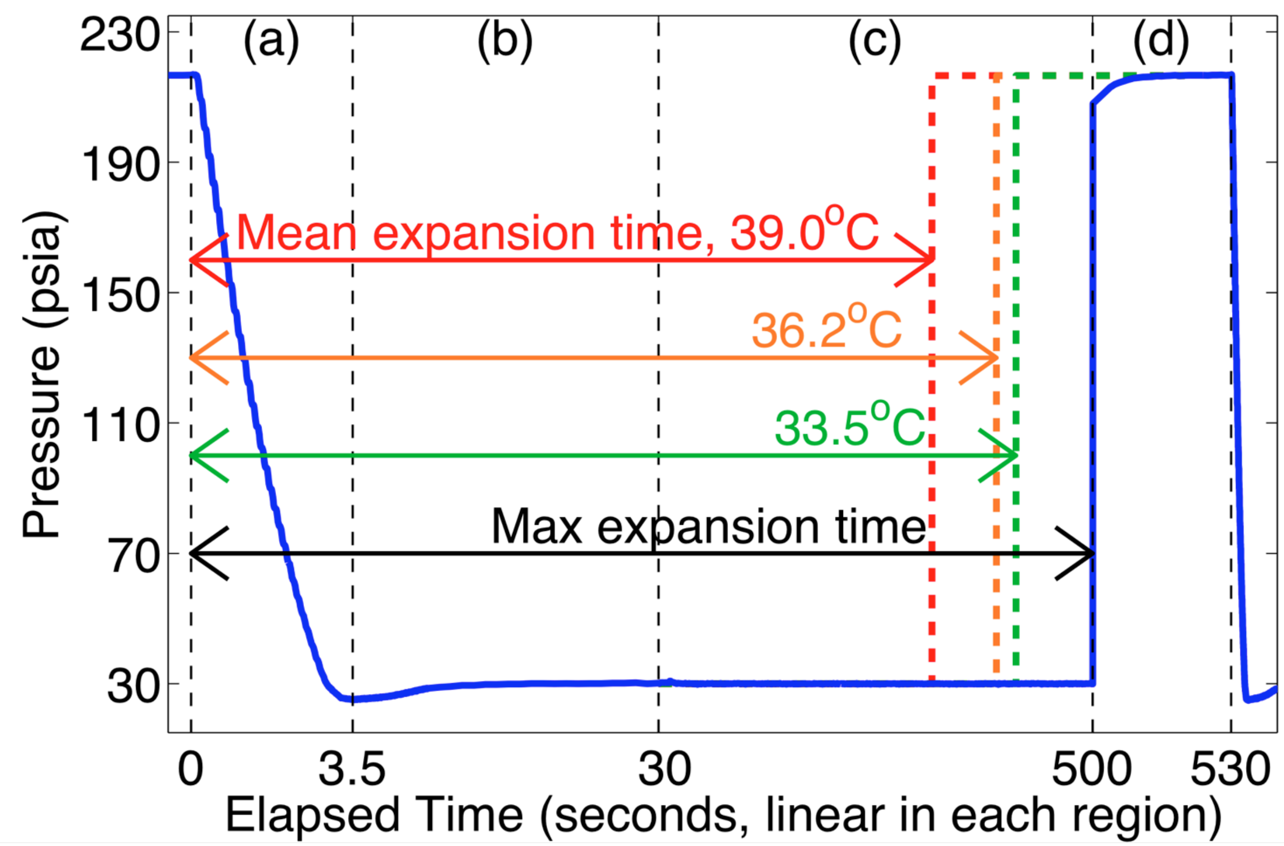
- Alphas deposit their energy over tens of microns
- Nuclear recoils deposit theirs over tens of nanometers

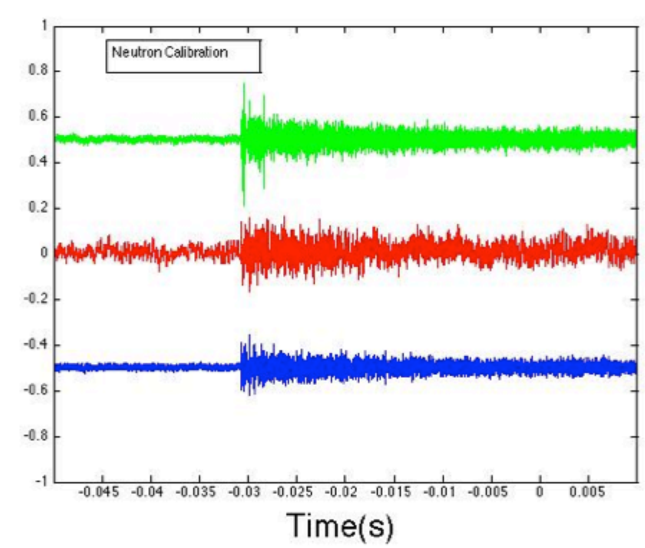


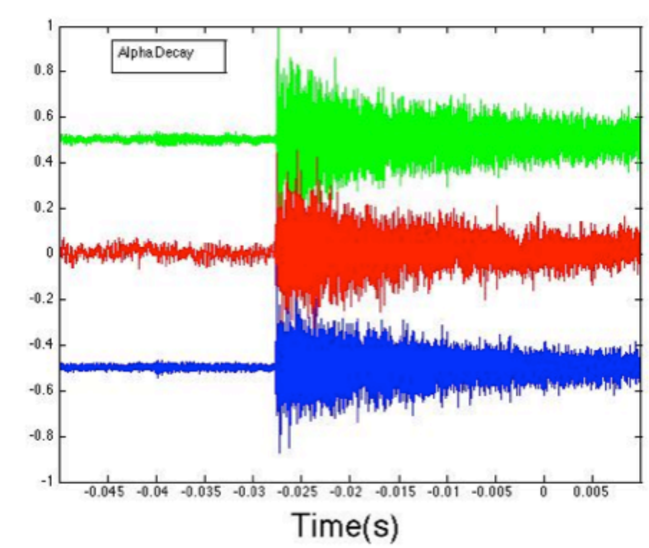


Chamber Operation

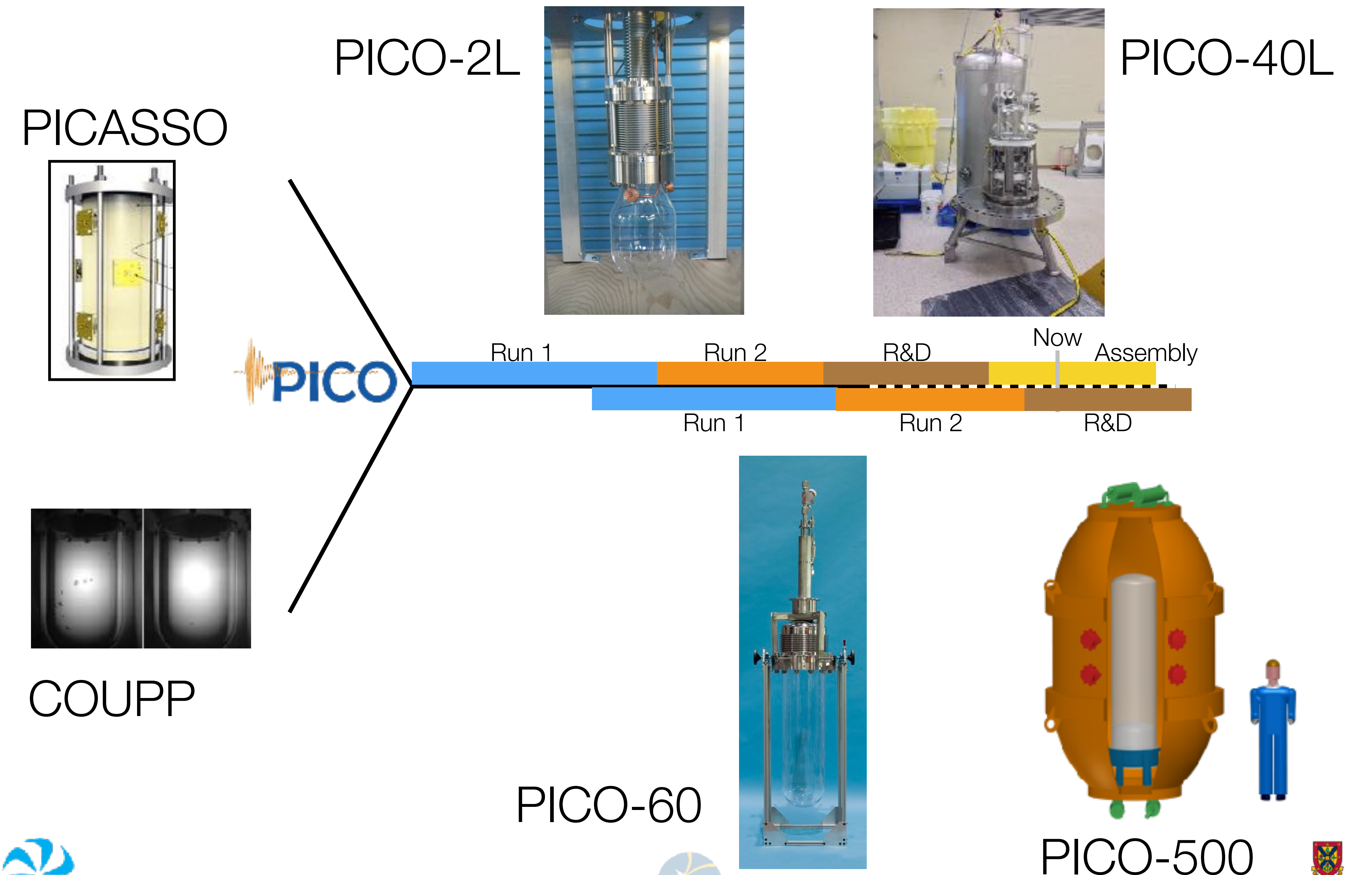
- Detector is made sensitive by depressurizing chamber
- Use video for trigger, acoustically monitor as well
- A trigger causes pressurization to force back into liquid state



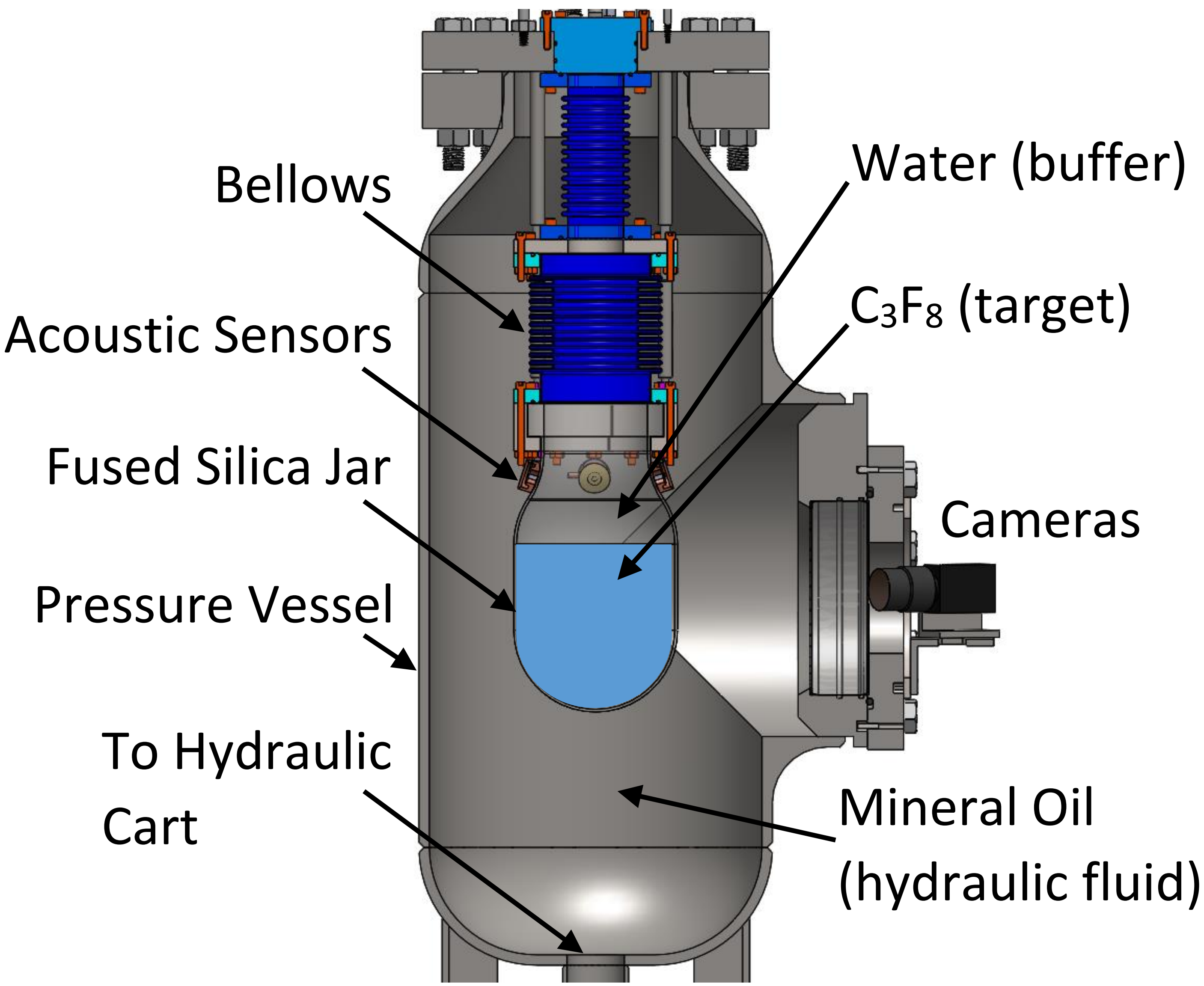




PICO Timeline



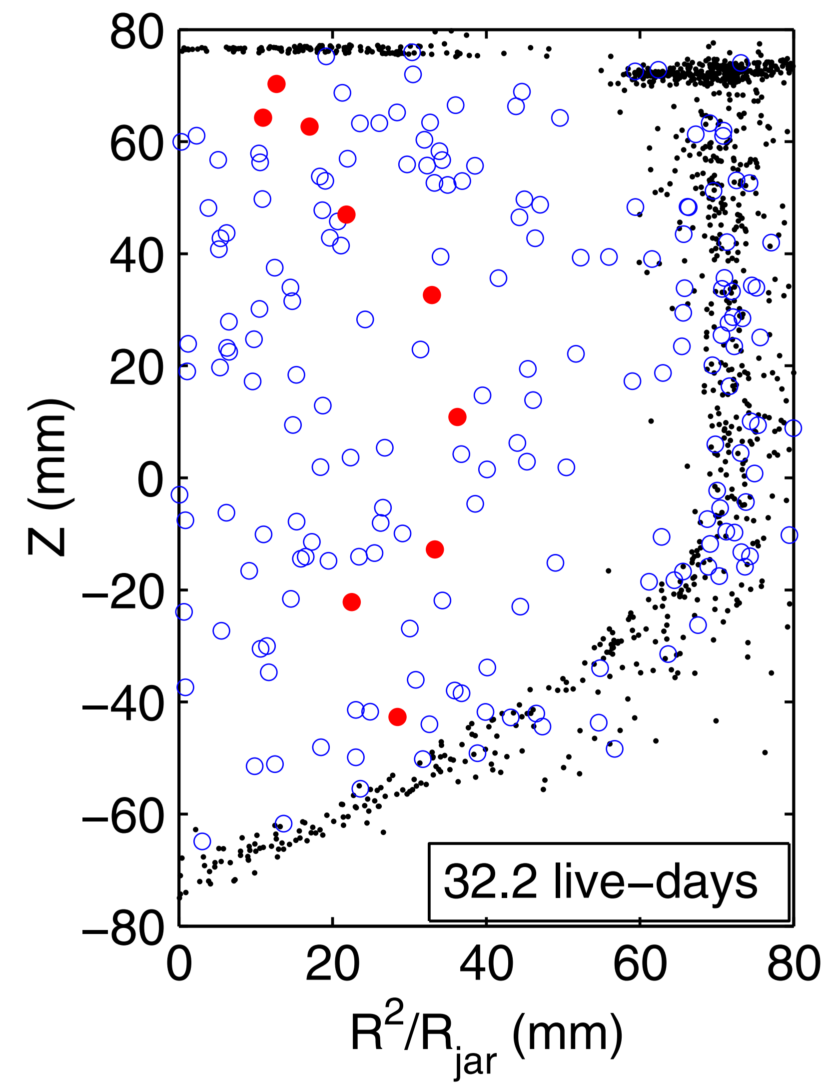
PICO-2L



- 2L (2.9kg) active mass of C_3F_8
- Change from CF_3I gives better gamma rejection, more active mass for proton-interaction search

PICO-2L Run 1

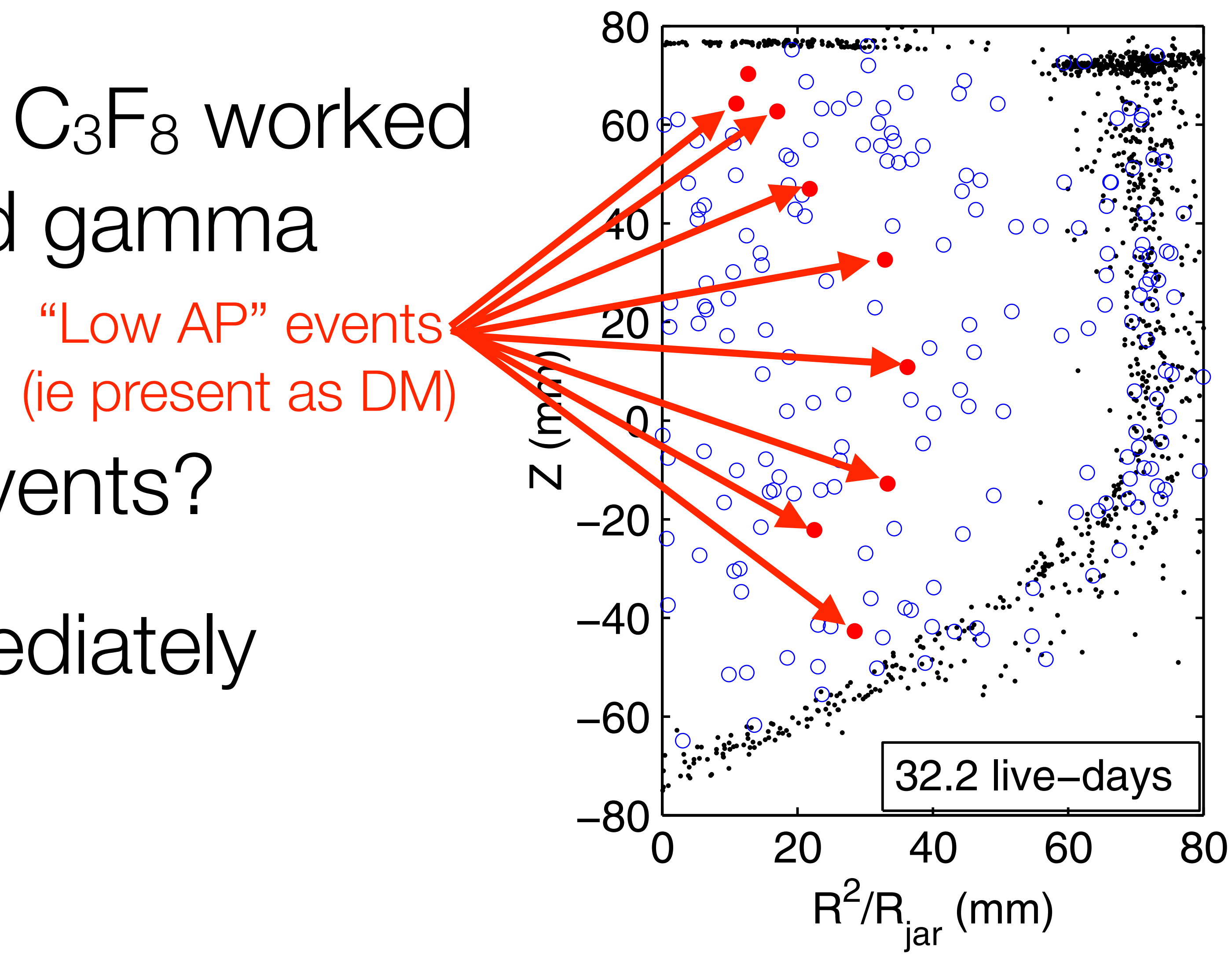
- First run showed that C_3F_8 worked and had the expected gamma rejection



Neutron expectation: $0.6^{+0.2}_{-0.4}$

PICO-2L Run 1

- First run showed that C_3F_8 worked and had the expected gamma rejection
- But what are those events?
- Cleanliness was immediately suspected

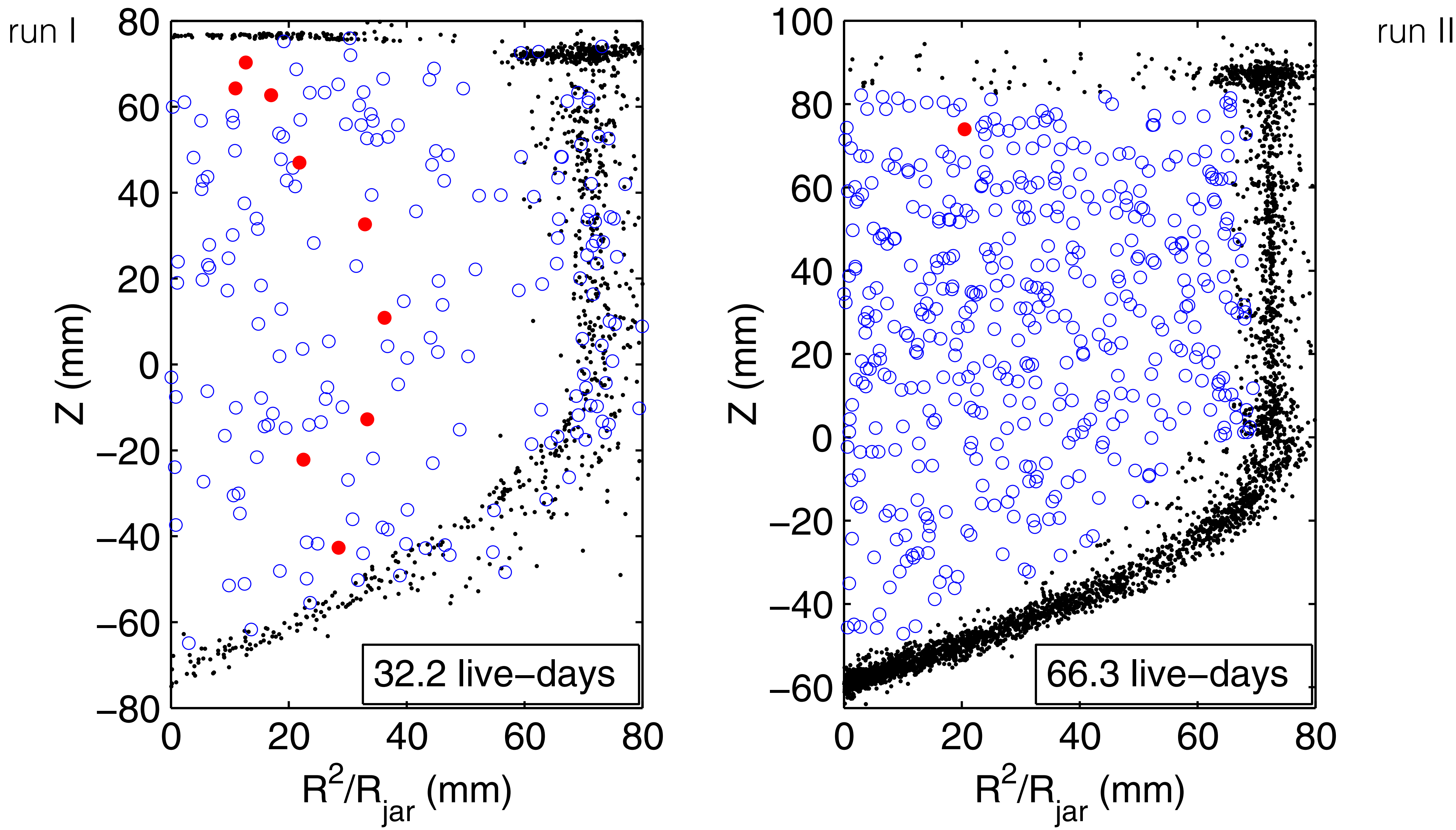


Neutron expectation: $0.6^{+0.2}_{-0.4}$

PICO-2L Results

- ALL candidates seen were within 1000 seconds of a previous expansion
- Also noted to cluster near the surface and the walls
- Some particulate was seen with an indication that it was quartz
- Fused silica replaced the quartz jar
- Extensive cleaning undertaken

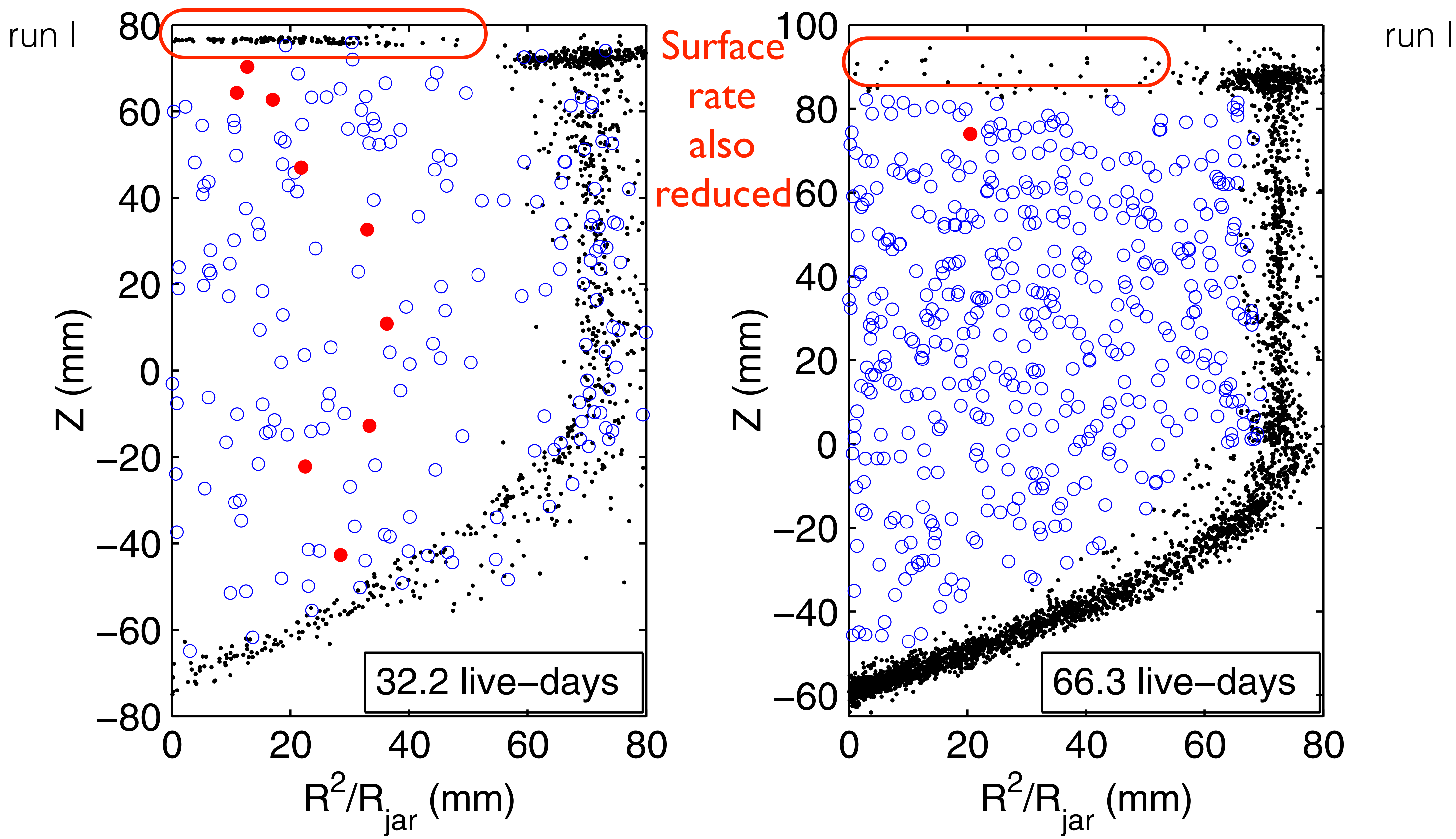
PICO-2L Results



Neutron expectation: $0.6^{+0.2}_{-0.4}$

Neutron expectation: $1.0^{+0.2}_{-0.7}$

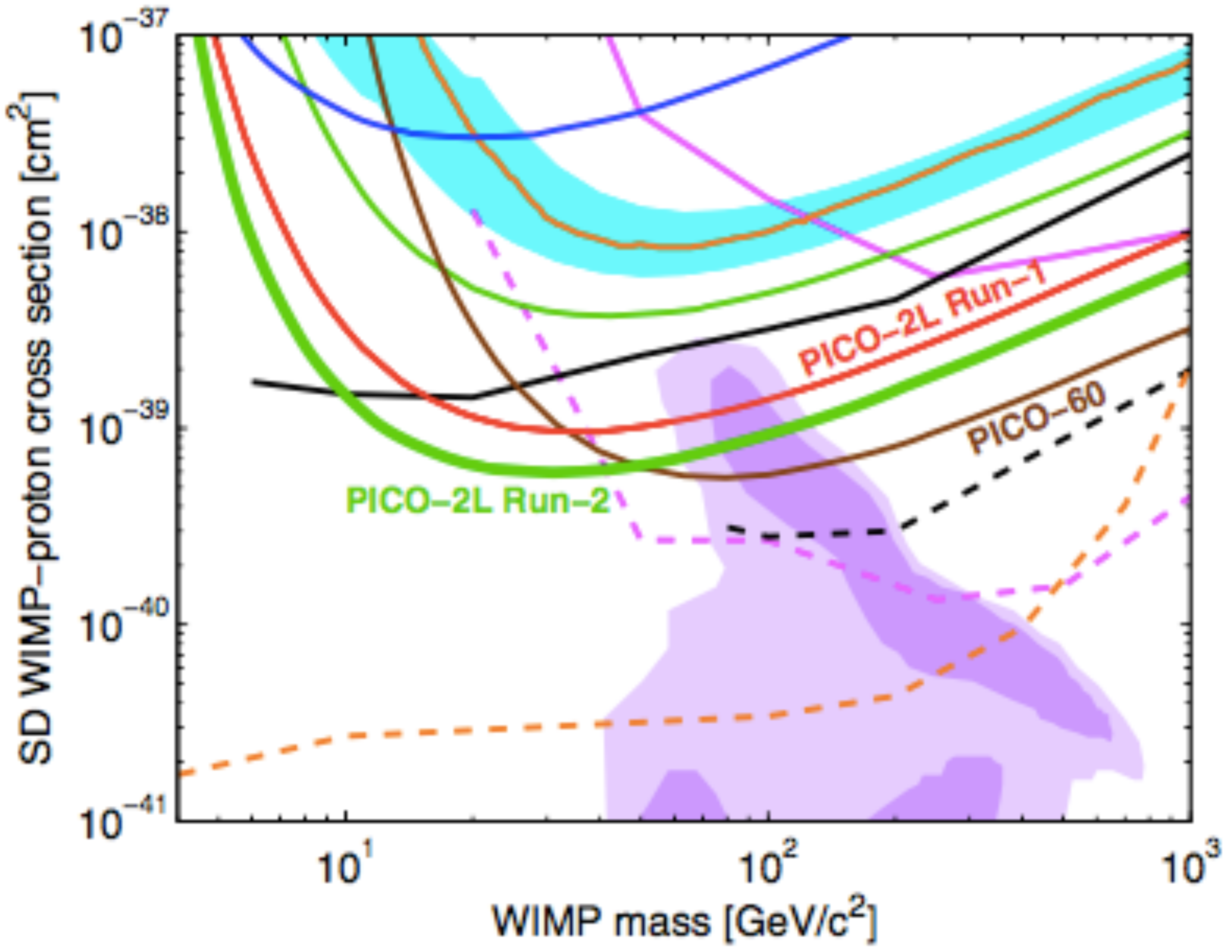
PICO-2L Results

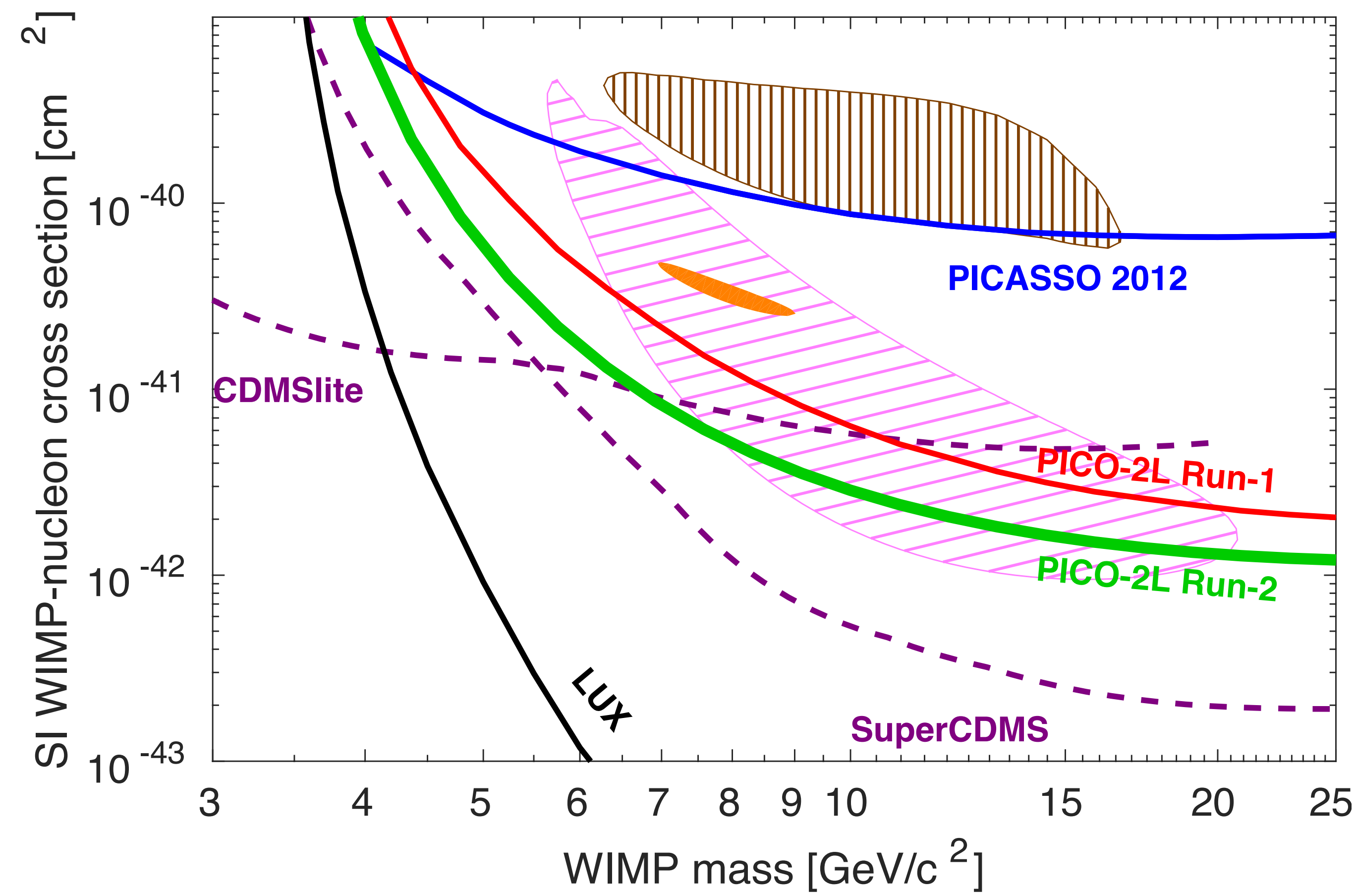


Neutron expectation: $0.6^{+0.2}_{-0.4}$

Neutron expectation: $1.0^{+0.2}_{-0.7}$

PICO-2L Results

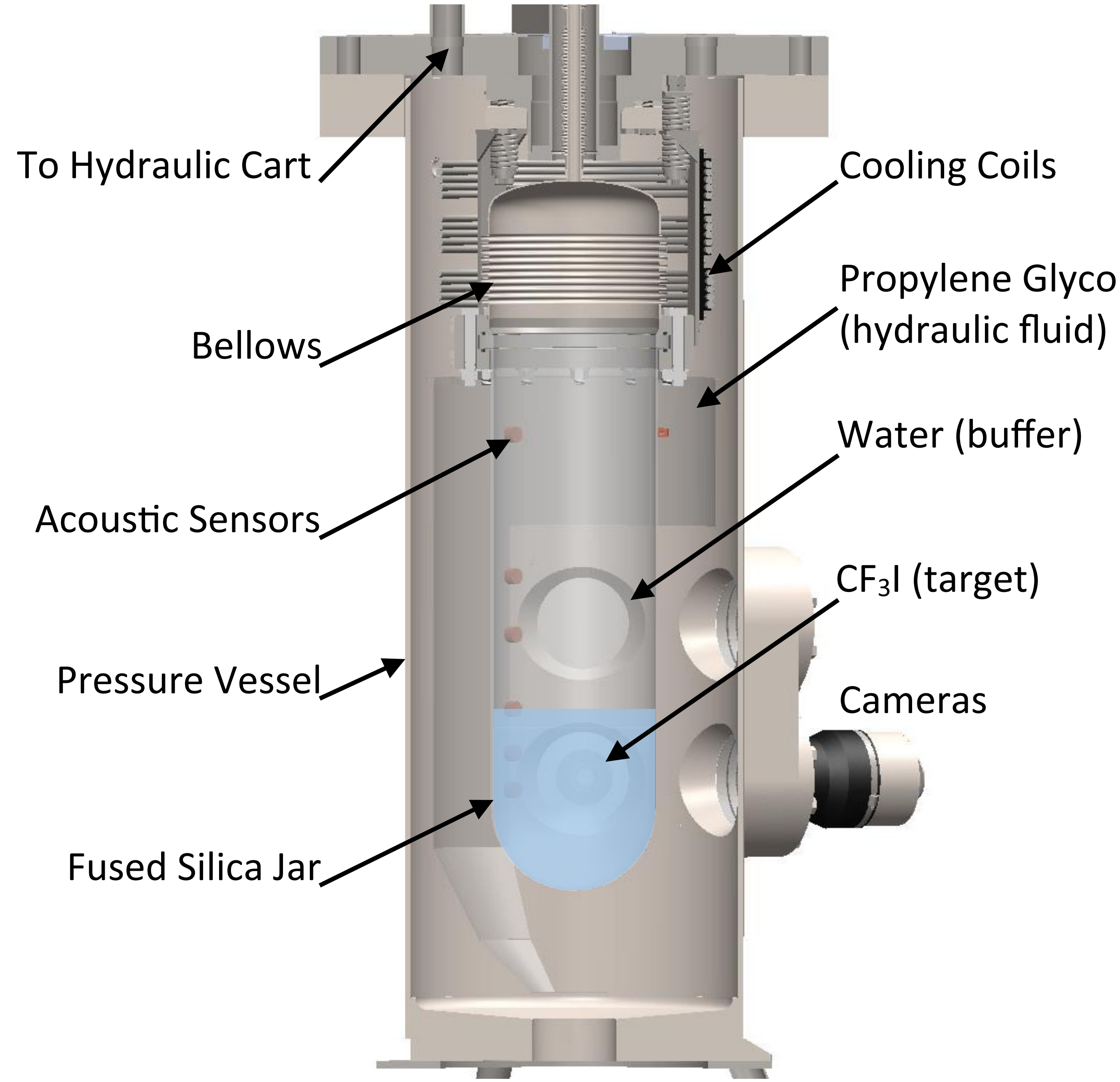




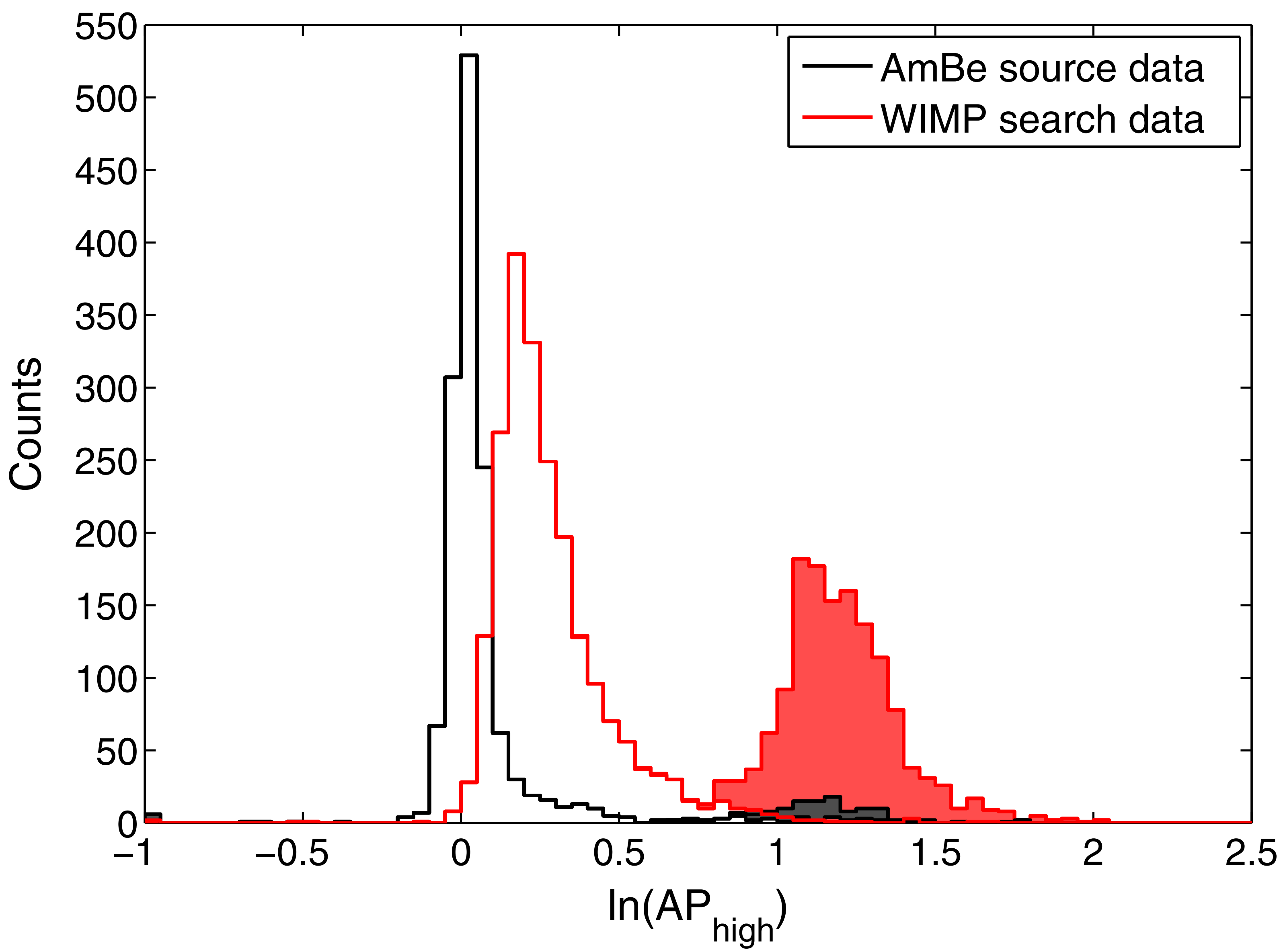
Run 1: Phys. Rev. Lett. 114, 231302 (2015)
Run 2: Phys. Rev. D 93, 061101 (2016)

PICO-60

- Active material: 36.8kg of C_3FI
- This is where we really dug into the anomalous background…



PICO-60 Background - Acoustically

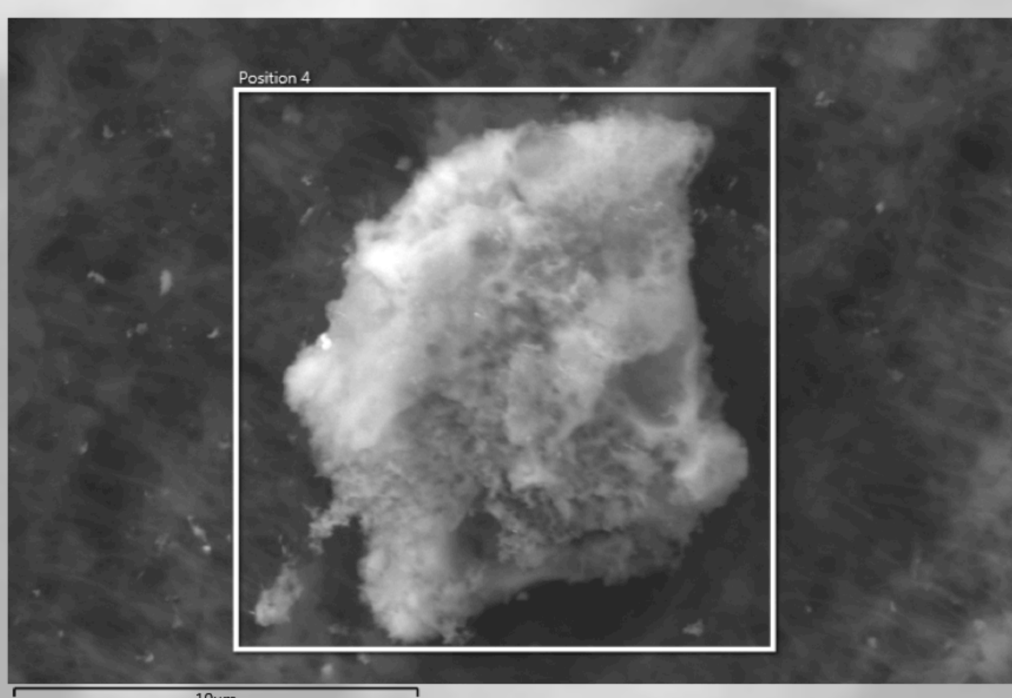


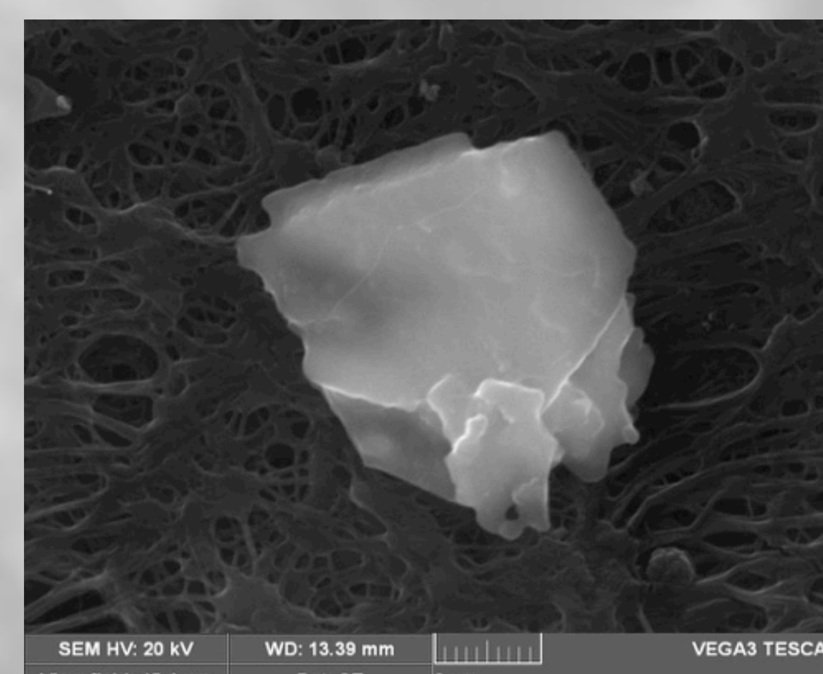
- Calibrations showed us a class of events which we did not understand

PICO-60 Assay

- Radioactive particulates were suspected to be part of the problem after run I ended. Careful assays of the liquids after the end of the fill revealed contamination with mostly steel and silica particulates

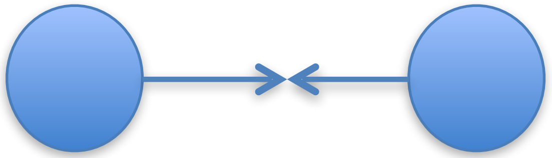
- The radioactivity of the material is not sufficient to explain the backgrounds observed



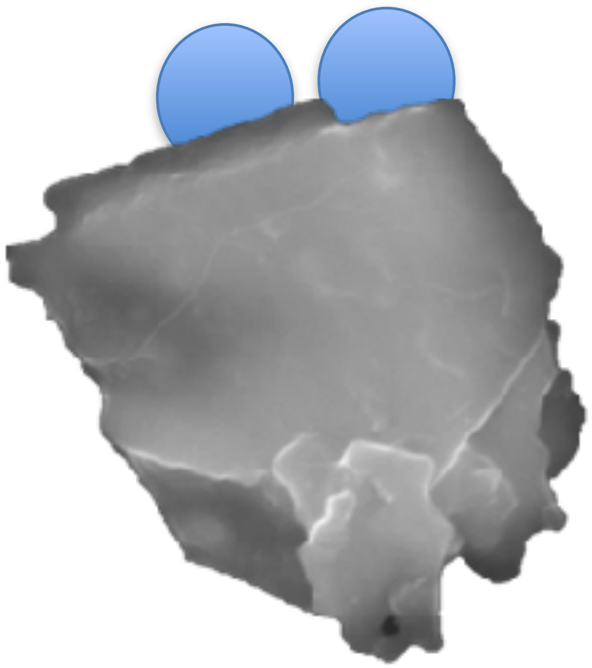


What's going on?

- Surface tension in a 50nm bubble ~3.5keV

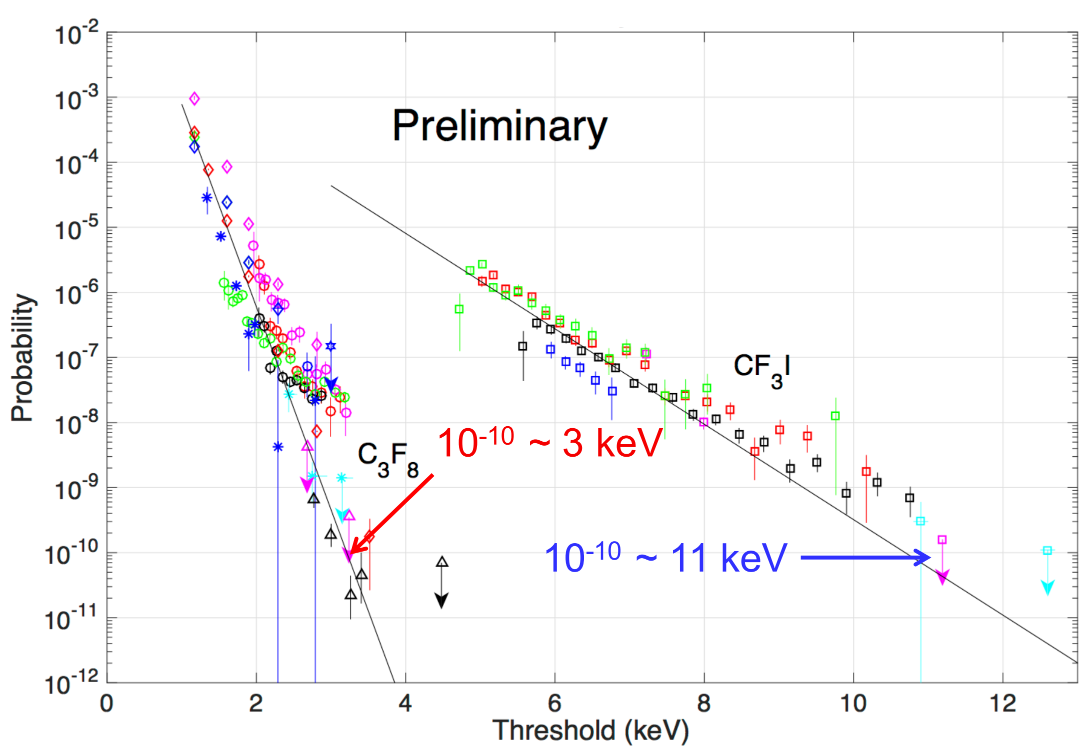


- Merging bubbles release a significant fraction of that energy
- The water also lowers the bubble nucleation threshold, so the released energy can nucleate bubbles at PICO operating thresholds of a few keV
- Solid particulate is a location for the bubbles to merge

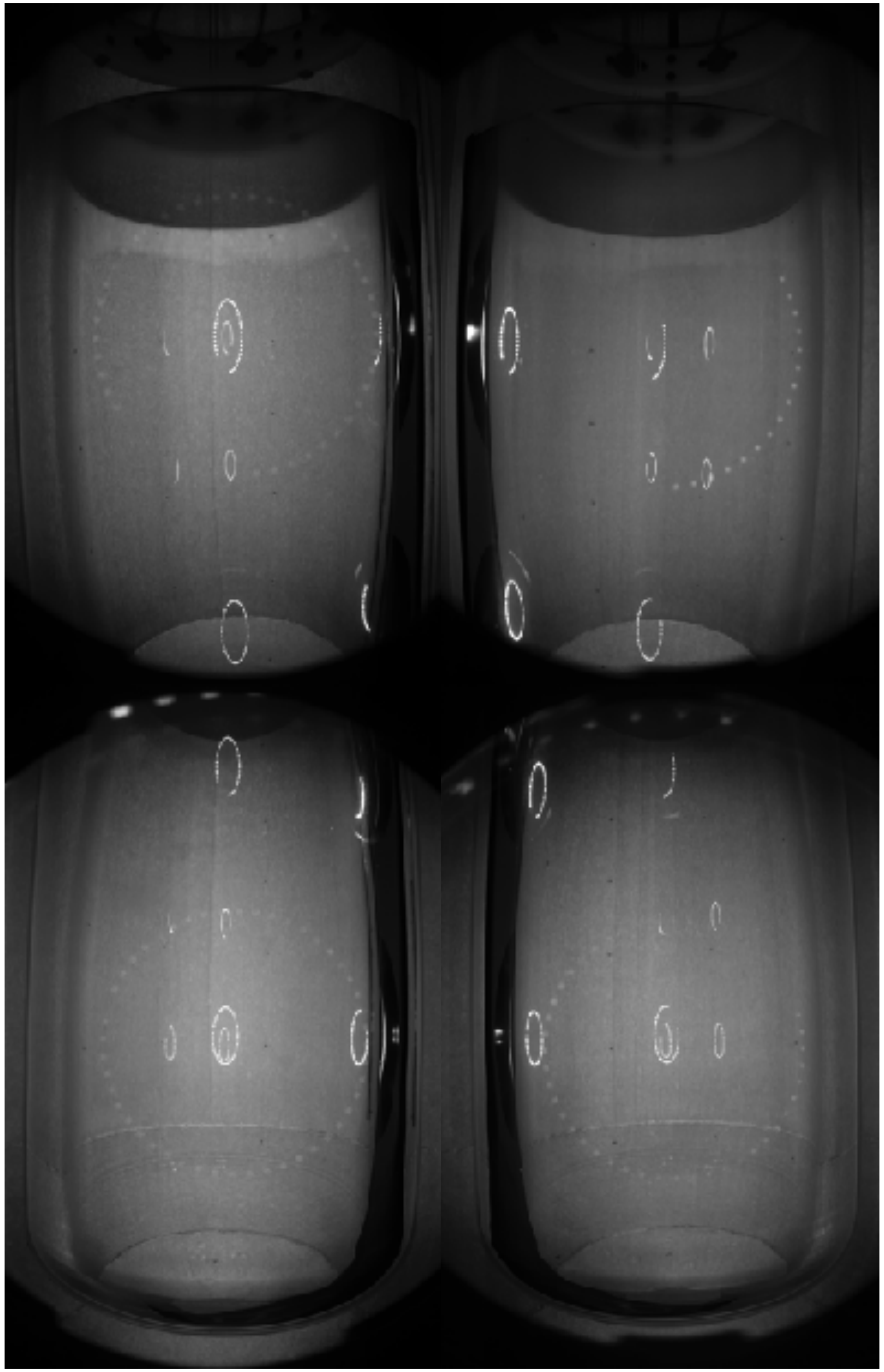


PICO-60 Run 2

- After our experience with PICO-2L, pretty confident we know what the issue is
- Since we are making changes, let's do everything we can with this detector
- Start by switching to C_3F_8 to increase gamma rejection

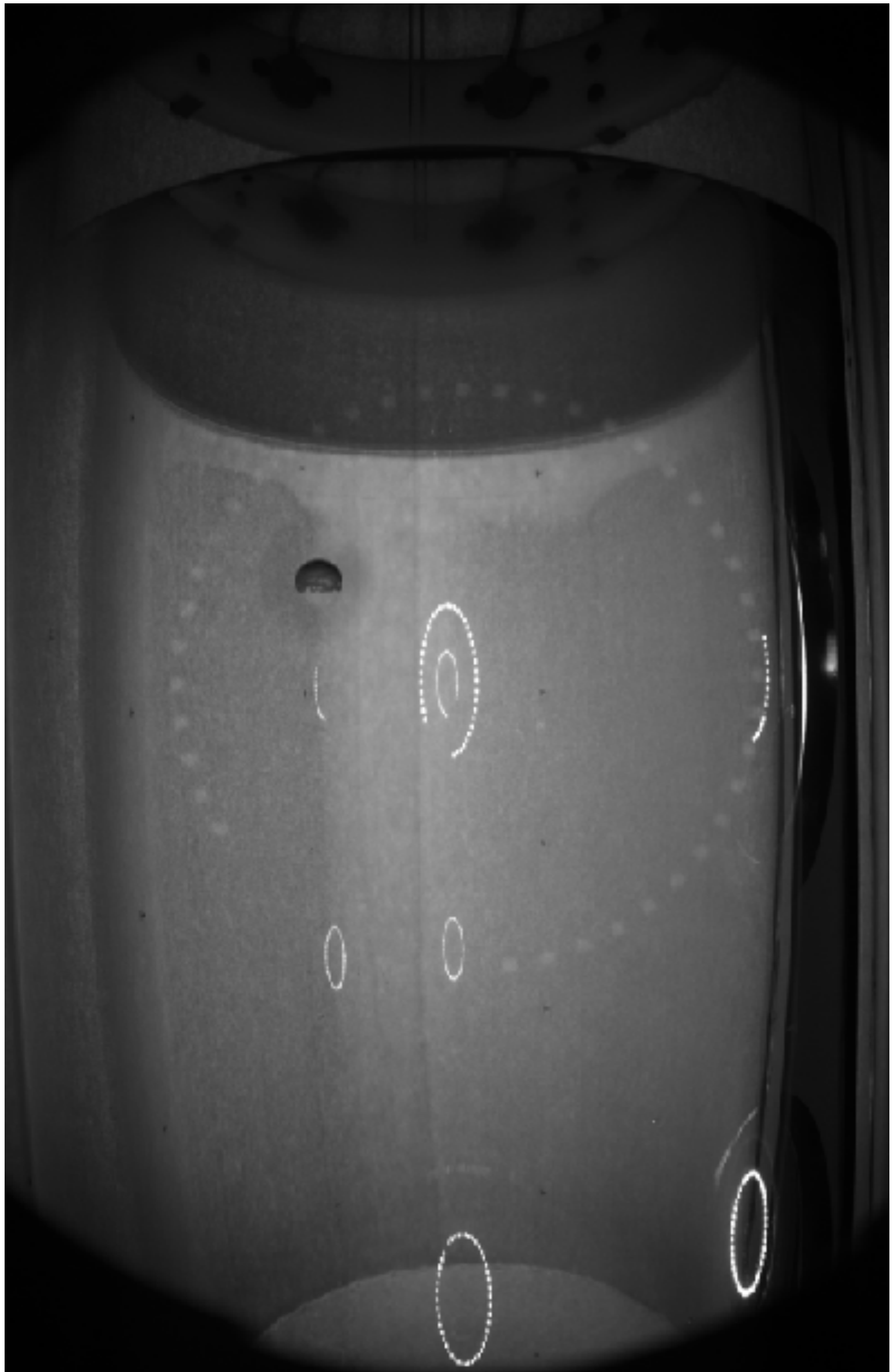


PICO-60 Run 2



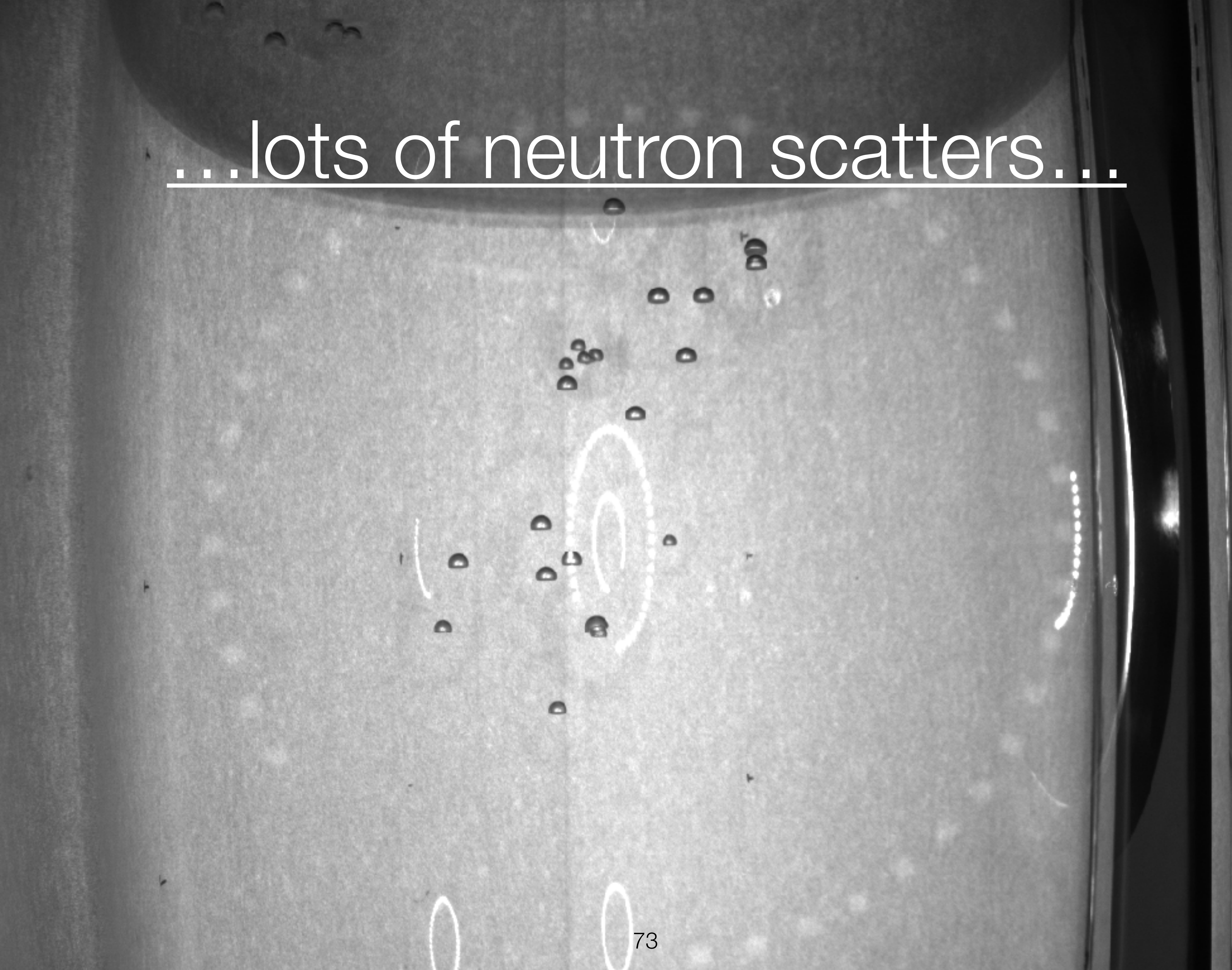
- Double the number of cameras (from 2 to 4)
  - Doubles the active mass viewed
- Increase the rate to 340 frames per second

PICO-60 Data!

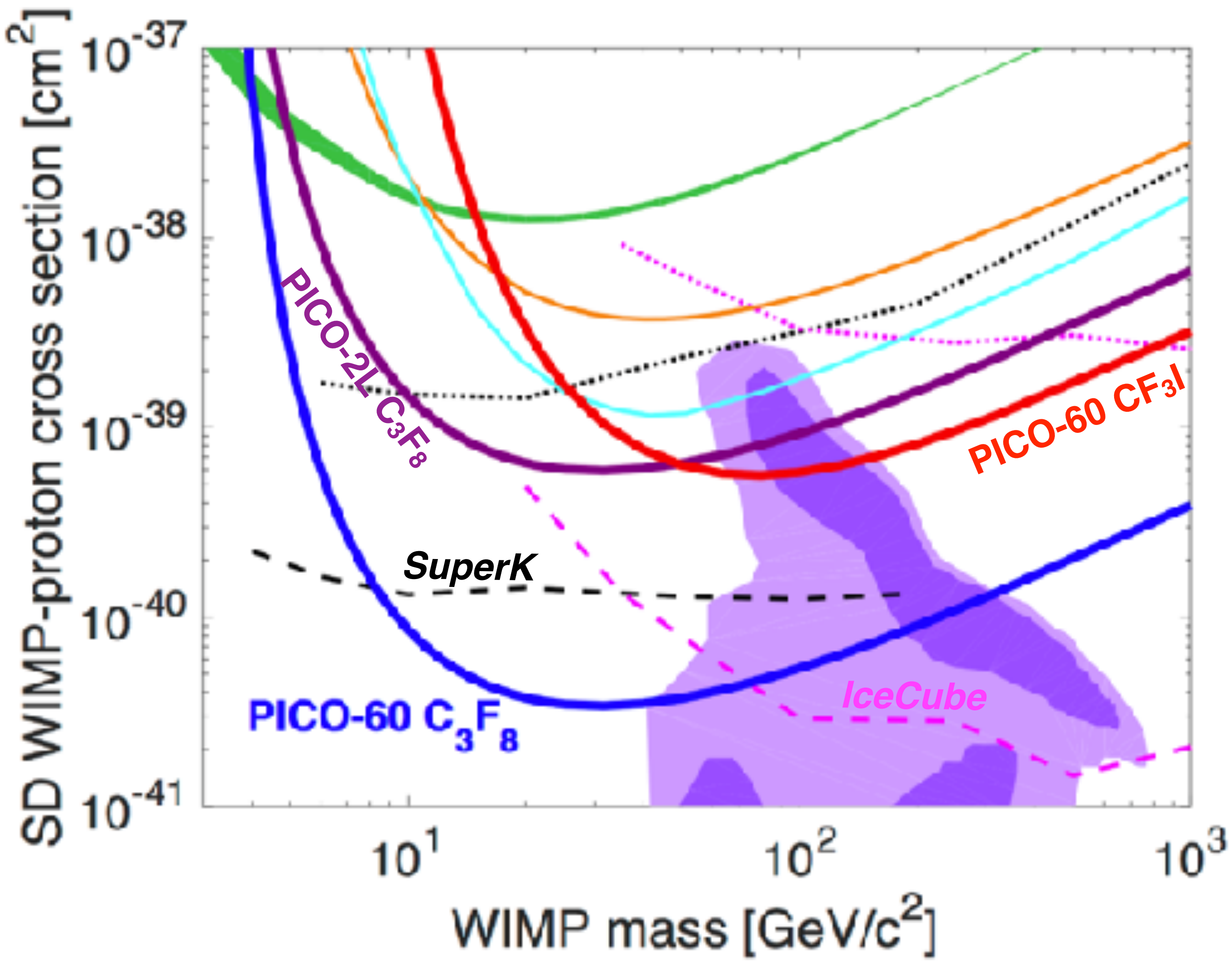


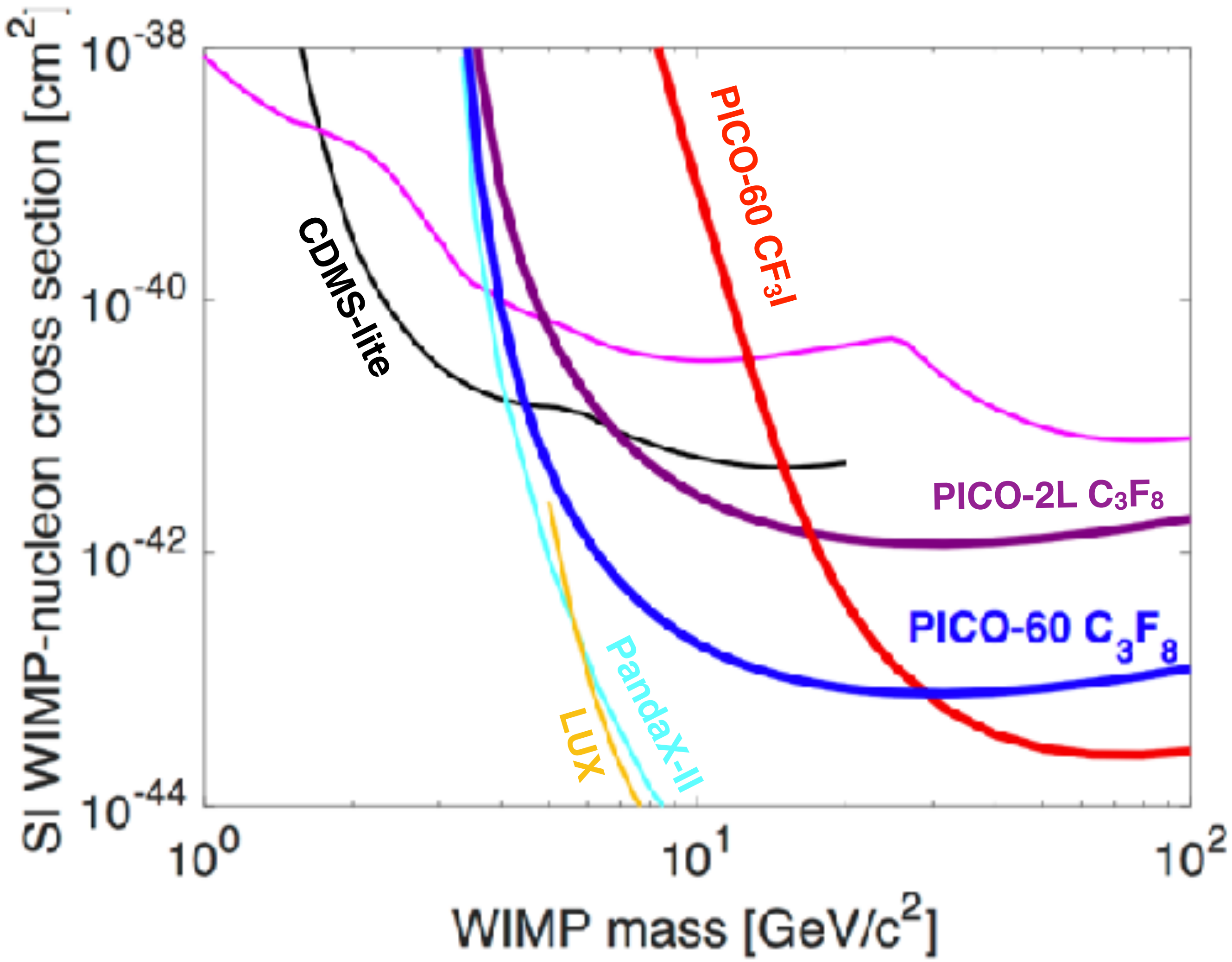
- The first bubble was seen August 1, 2016
- This was without the water shield, which was filled over the next week
- Lack of an active shield meant muons and many neutrons were seen…

…lots of neutron scatters…



PICO-60 Results

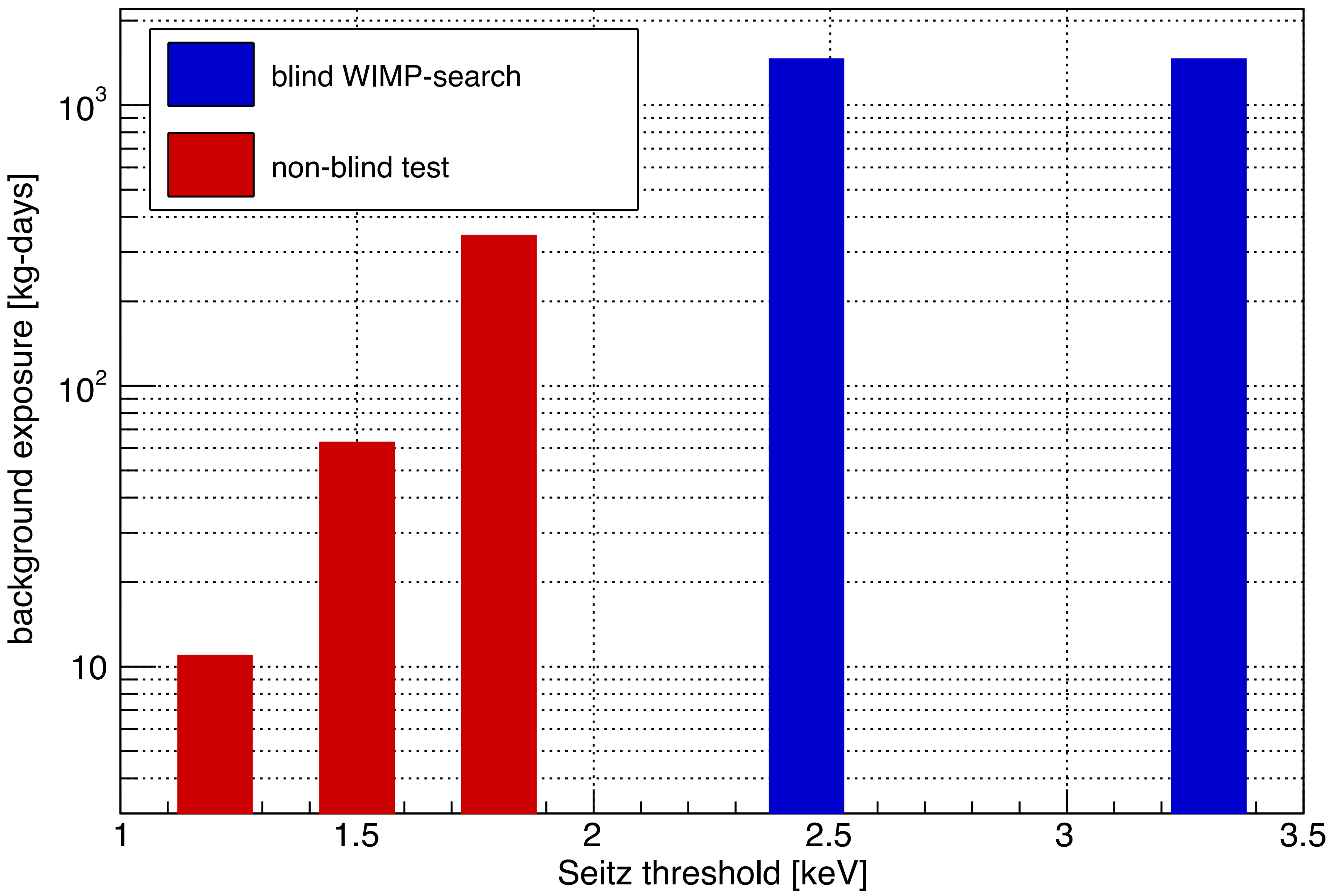




Phys. Rev. Lett. **118**, 251301 (2017)

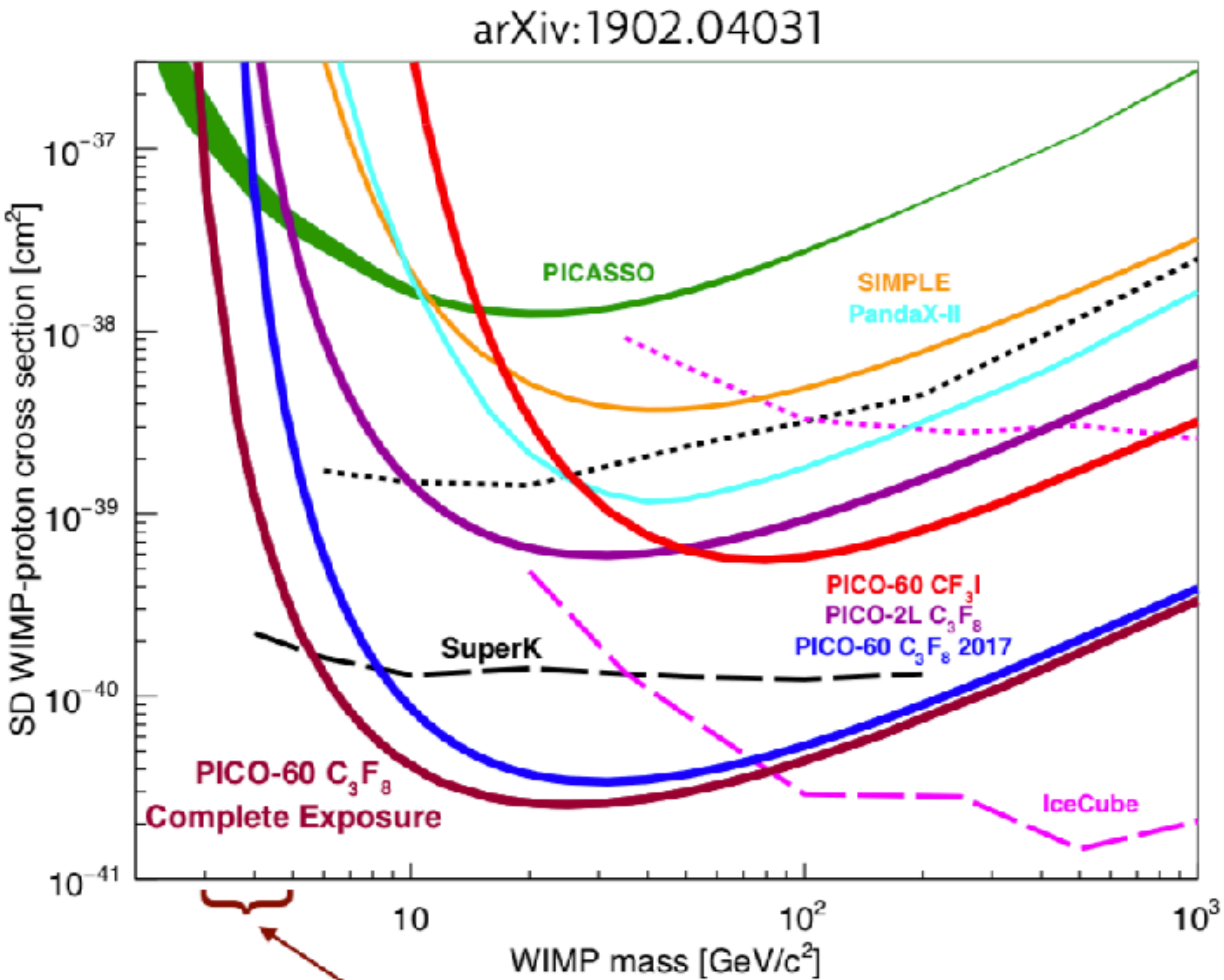
- World leading SD WIMP proton sensitivity for large range of WIMP masses

PICO-60 Lowered Threshold



- Stable operation was achieved at lower thresholds
- Analysis took slightly longer than expected…

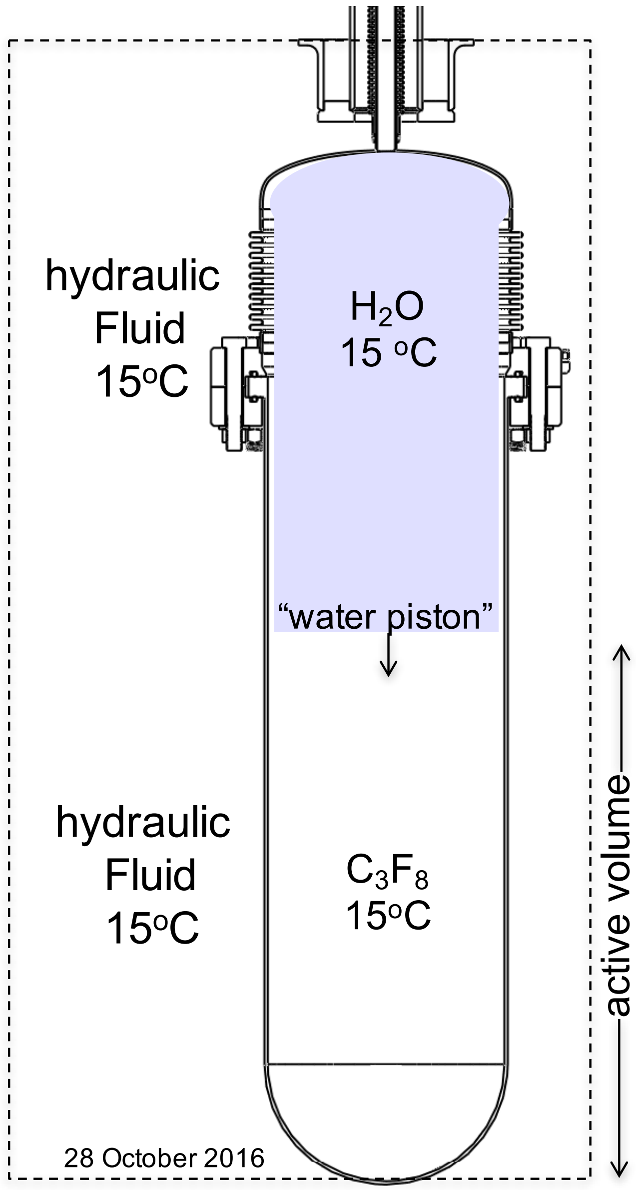
PICO-60 Full Exposure Results



improved mainly in 3–5 GeV range
(order of magnitude more stringent)

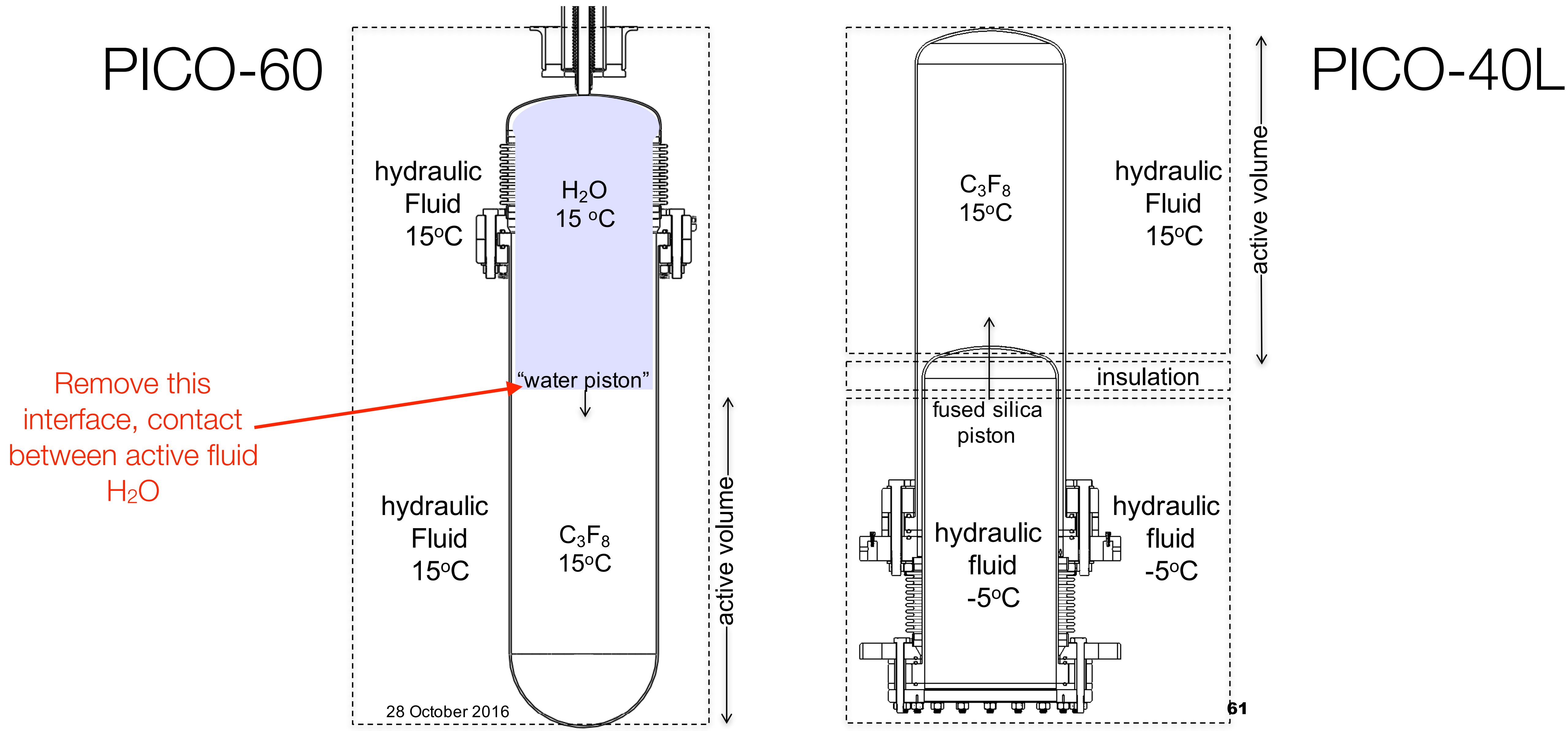
The Present

PICO-60



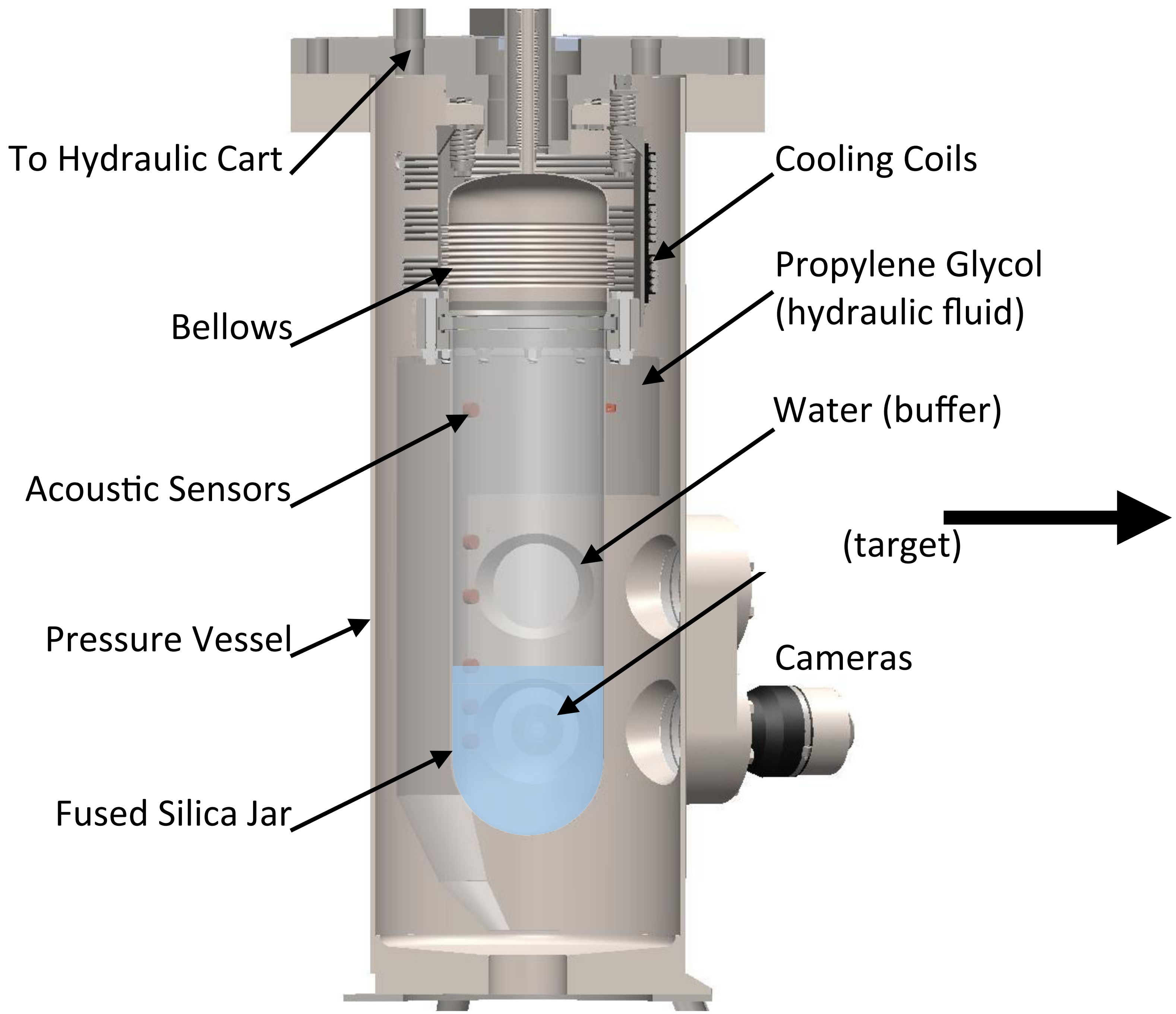
- Many problems seem connected to water/active fluid interface

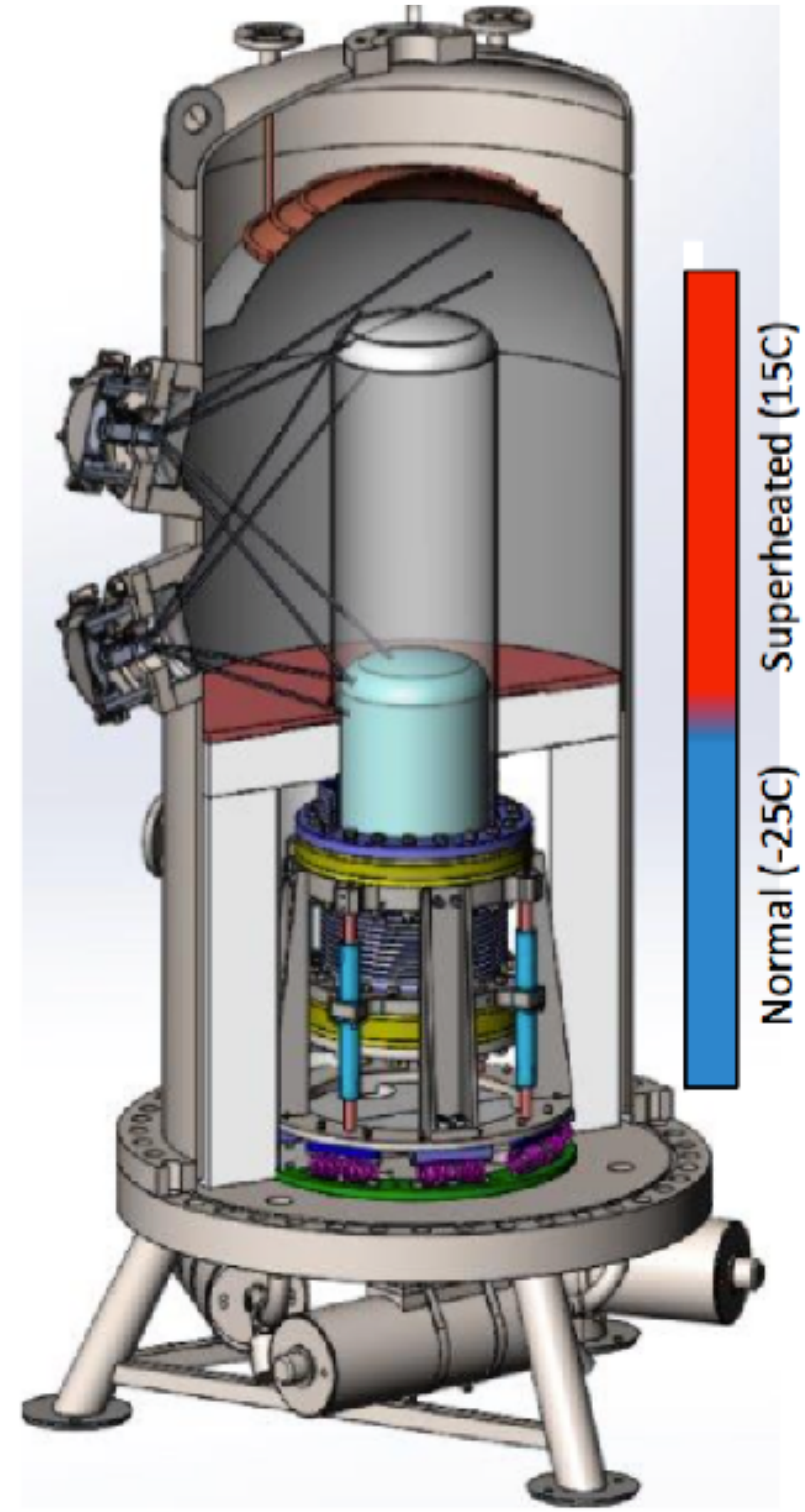
The Present



- Many problems seem connected to water/active fluid interface

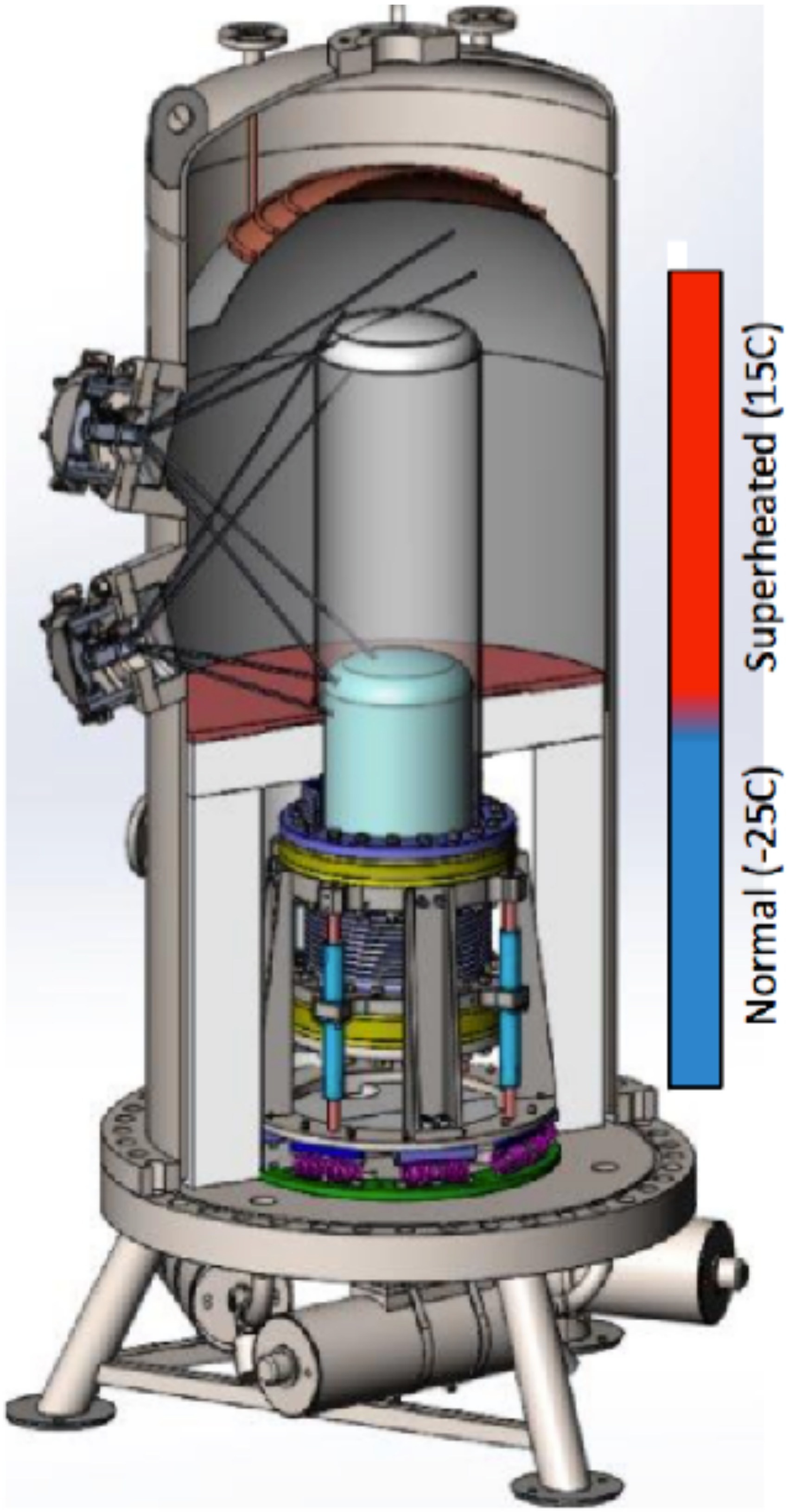
PICO-40L


To Hydraulic Cart
Cooling Coils
Propylene Glycol
(hydraulic fluid)
Bellows
Water (buffer)
Acoustic Sensors
(target)
Pressure Vessel
Cameras
Fused Silica Jar


Superheated (15C)
Normal (-25C)

PICO-40L

- Deployed at same location as PICO-60
- Target ~40L C_3F_8
- Synthetic fused silica piston removes water interface
- Larger stainless steel pressure vessel minimizes backgrounds

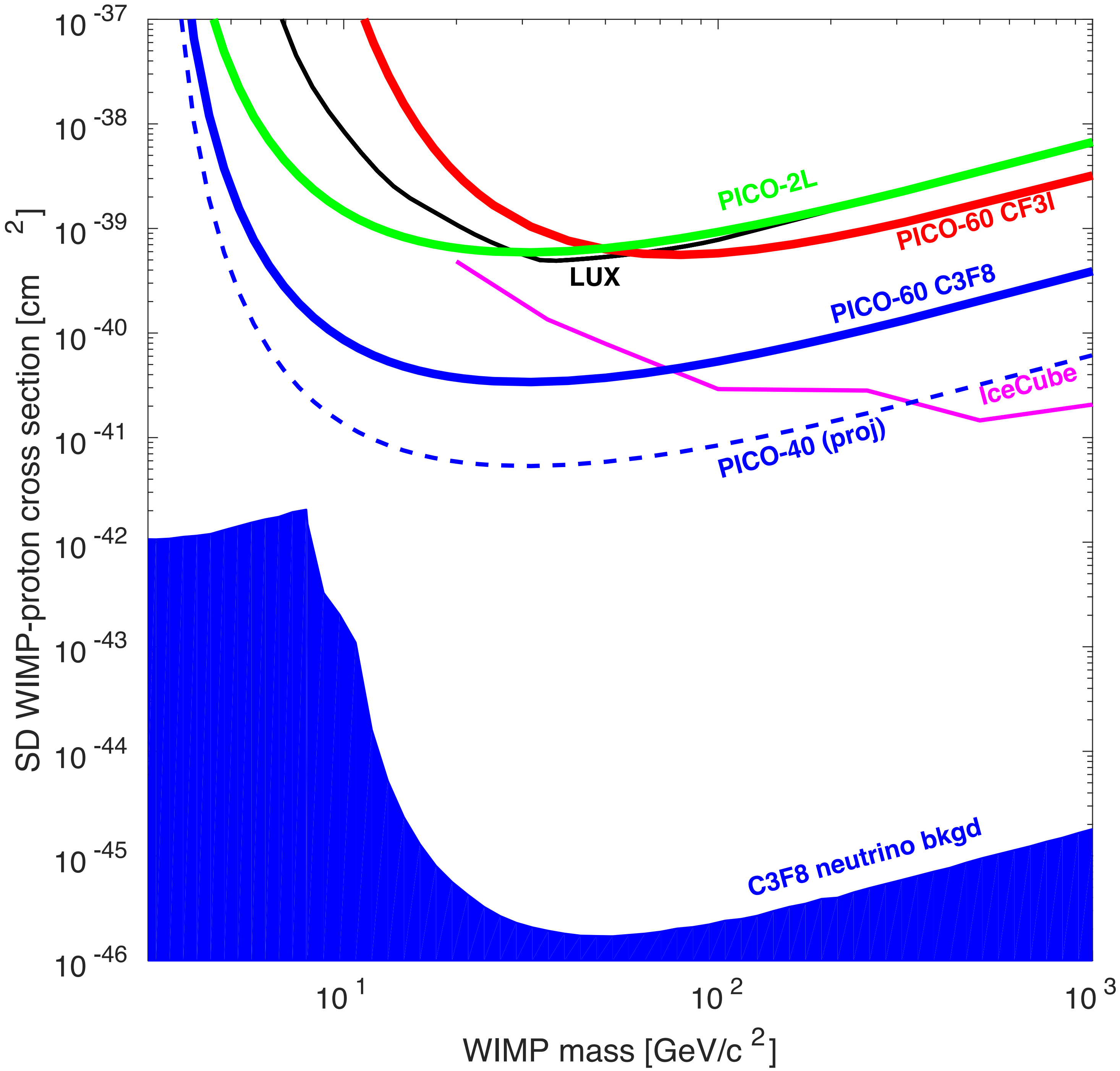


PICO-40L

- Currently assembling all major components underground at SNOLAB
- Completion of assembly in March 2019
- Commissioning to extend for a few months
- Data taking for ~a year

PICO-40L Sensitivity

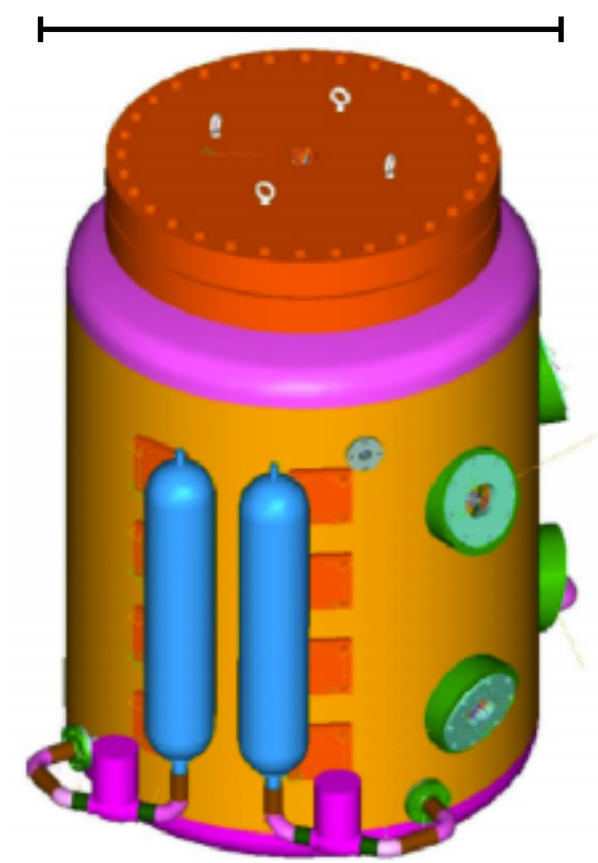
- One year of running with "traditional" threshold of 3.2 keV
- We now think that lower thresholds can be explored with PICO 40L, so this sensitivity limit now appears very conservative

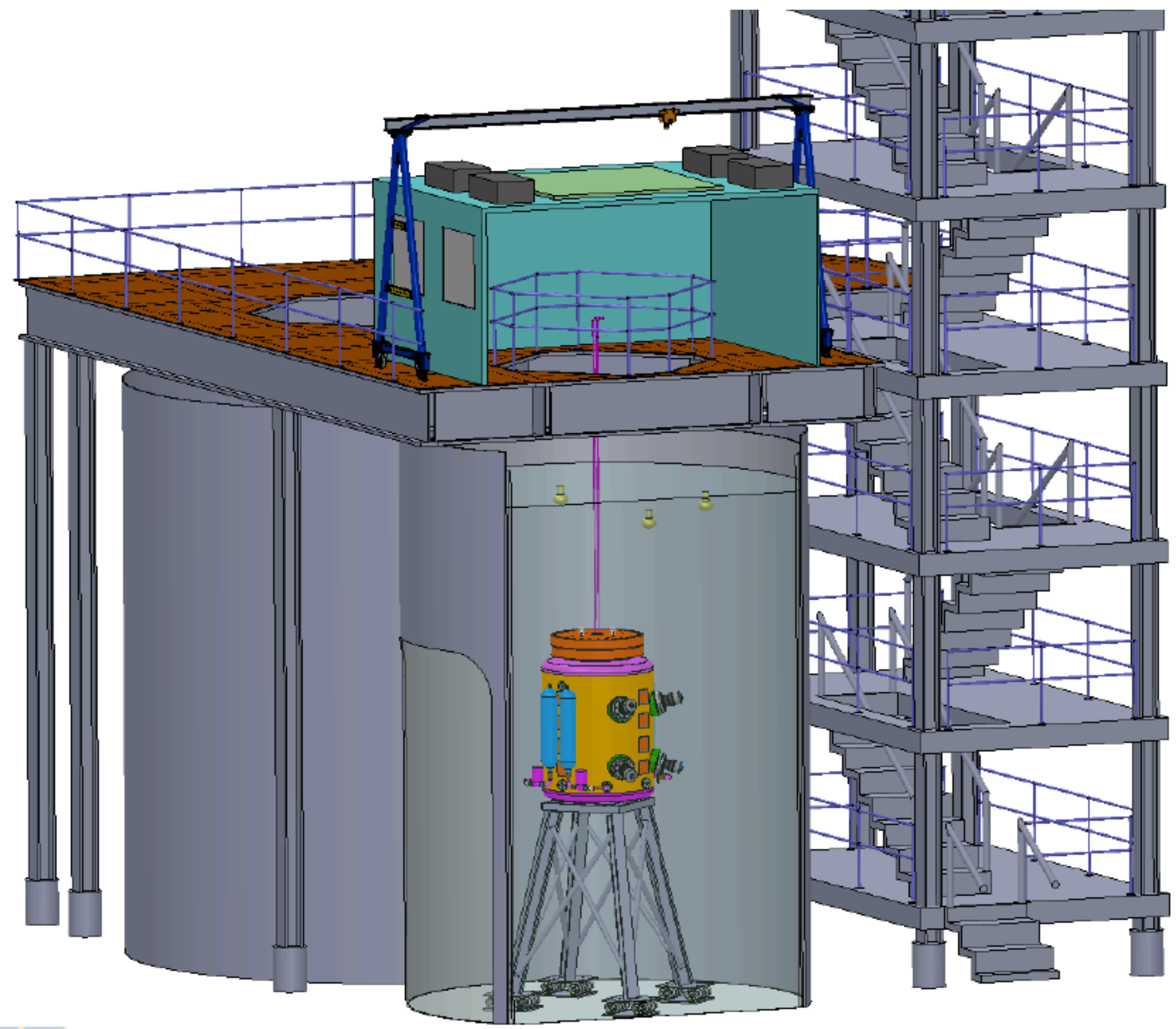


The Future - PICO 500

- Designed to increase sensitivity by an order of magnitude
- Could run C_3F_8 and/or CF_3I or other targets

SNOLAB cage width





The Future - PICO 500