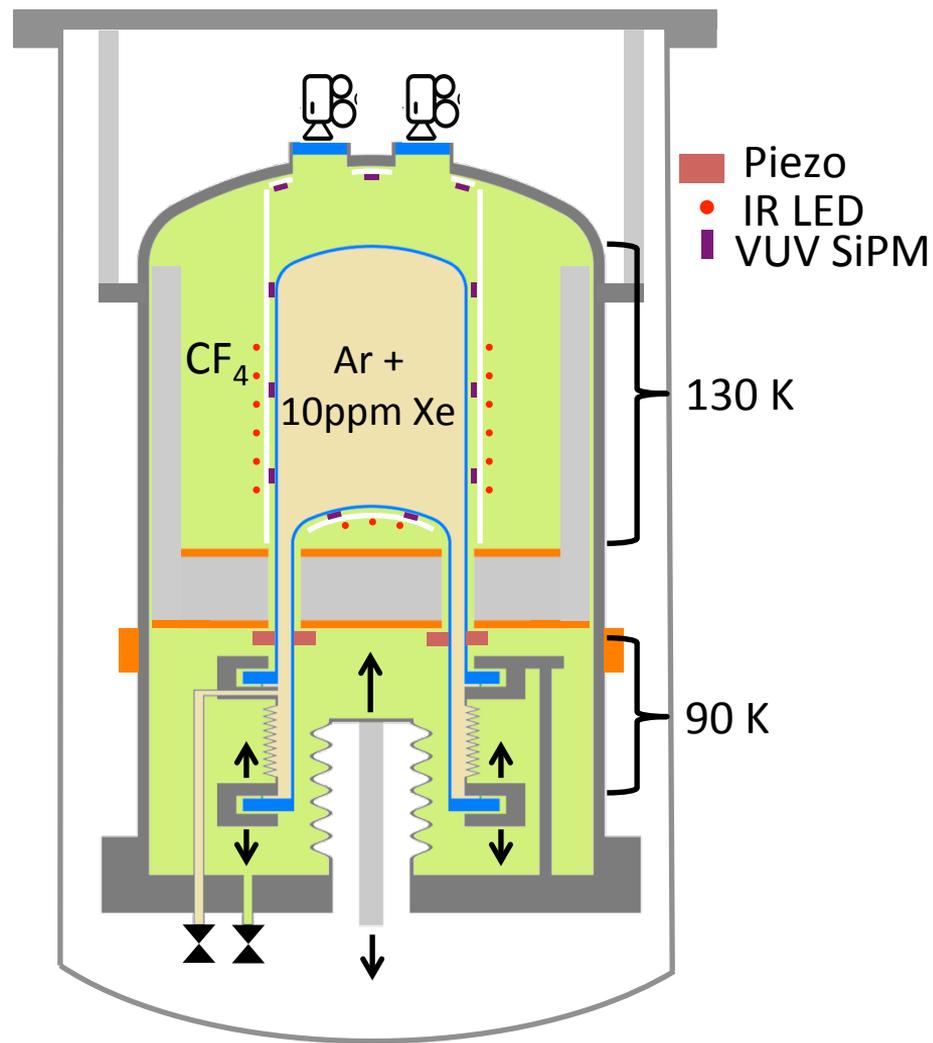


Scintillating Bubble Chambers for WIMPs and Reactor CEvNS

Eric Dahl
Northwestern University
Fermilab

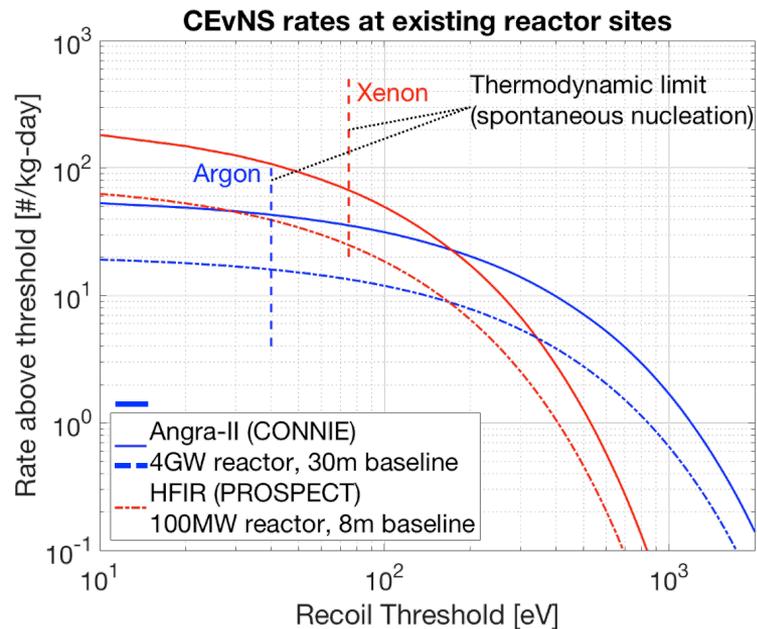
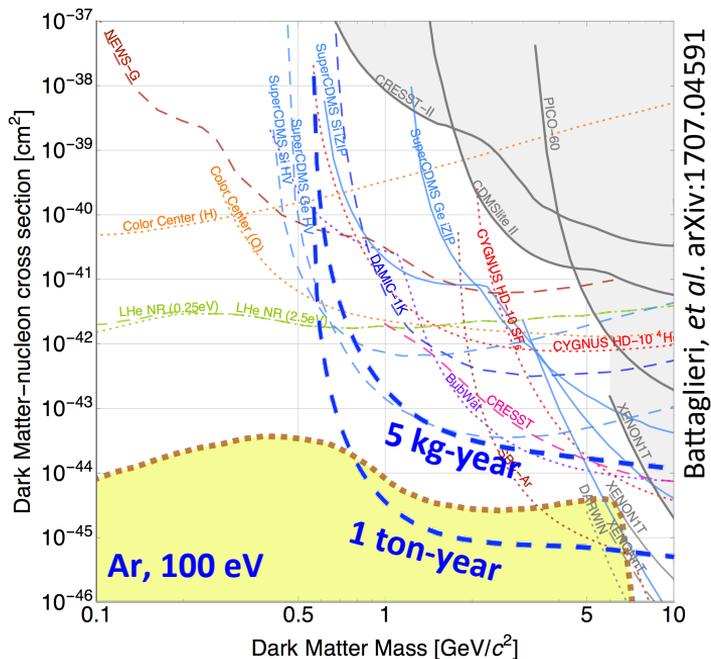
Novel Instrumentation for
Fundamental Physics, Nov 2018



Roadmap

- Nuclear recoil detection with bubble chambers (quick review)
- Why liquid-noble bubble chambers are different
- How to build and calibrate a kg-scale argon bubble chamber

If you can detect low-momentum nuclear recoils...



100eV Ar recoils
($p \approx 3 \text{ MeV}/c$)



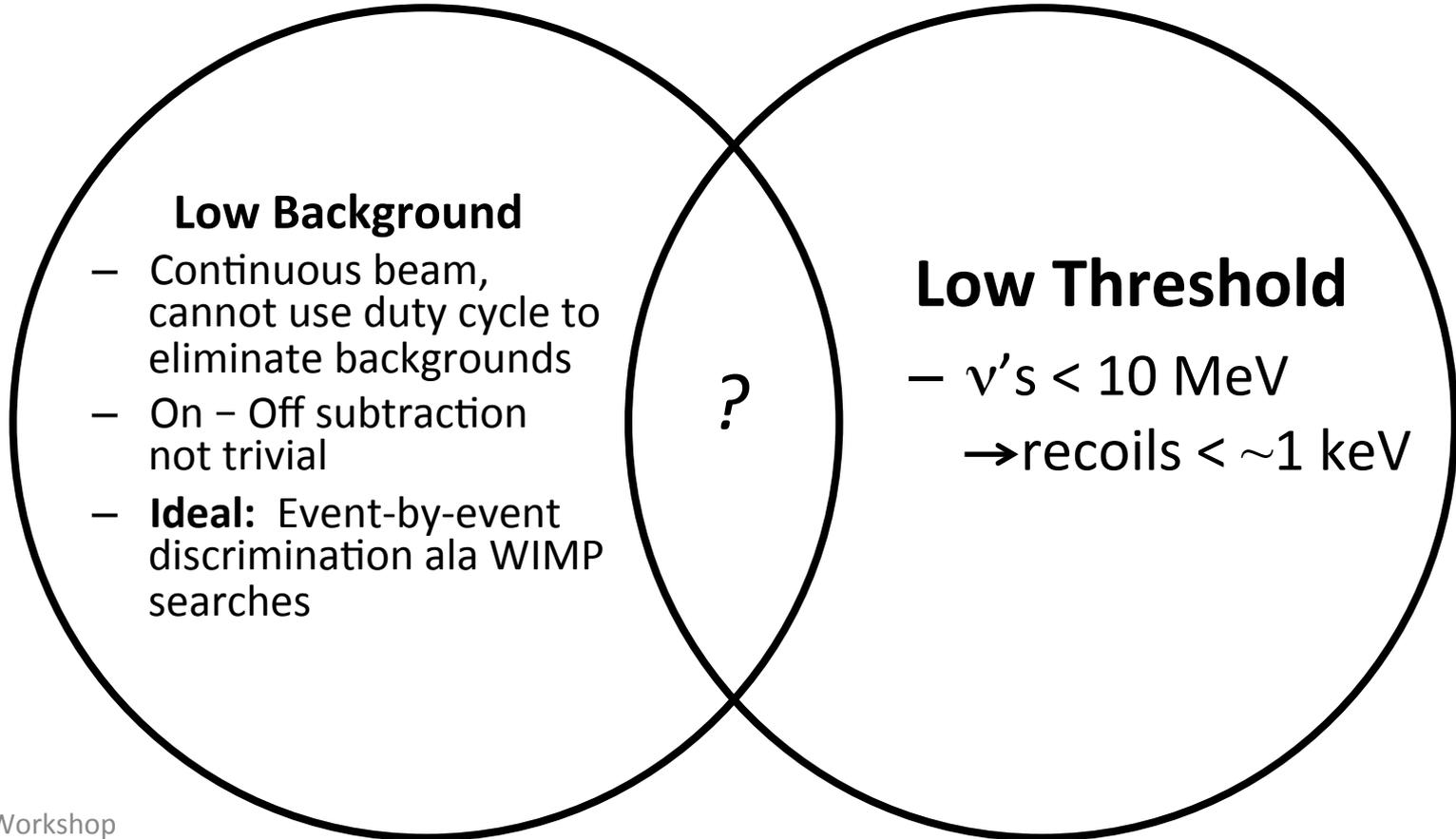
- WIMP searches to solar ν -floor (1 – 7 GeV)
- $O(10)$ CEvNS events / kg-day @ reactor

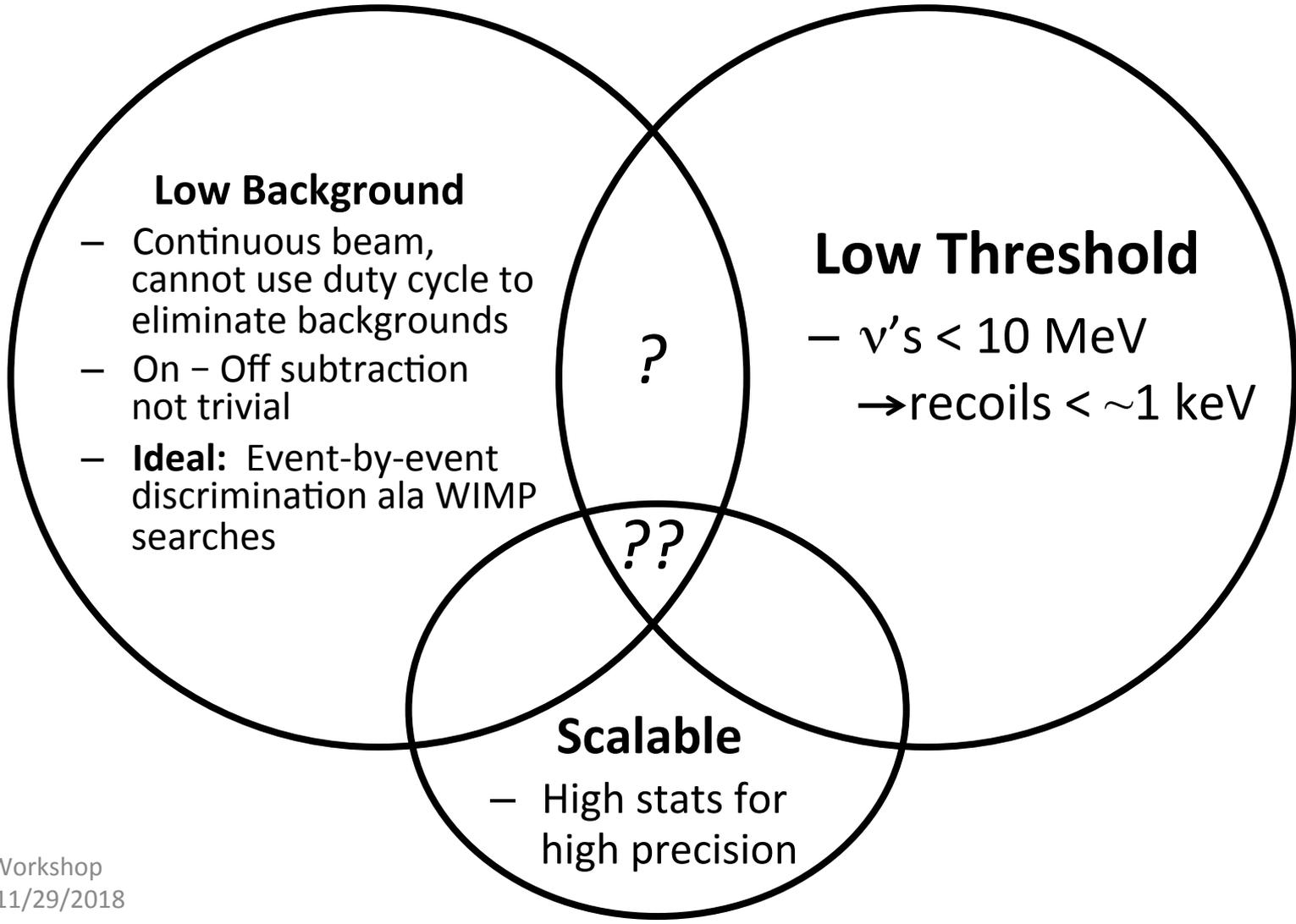
The Reactor CEvNS Detector Conundrum

Low Background

- Continuous beam, cannot use duty cycle to eliminate backgrounds
- On – Off subtraction not trivial
- **Ideal:** Event-by-event discrimination ala WIMP searches

The Reactor CEvNS Detector Conundrum

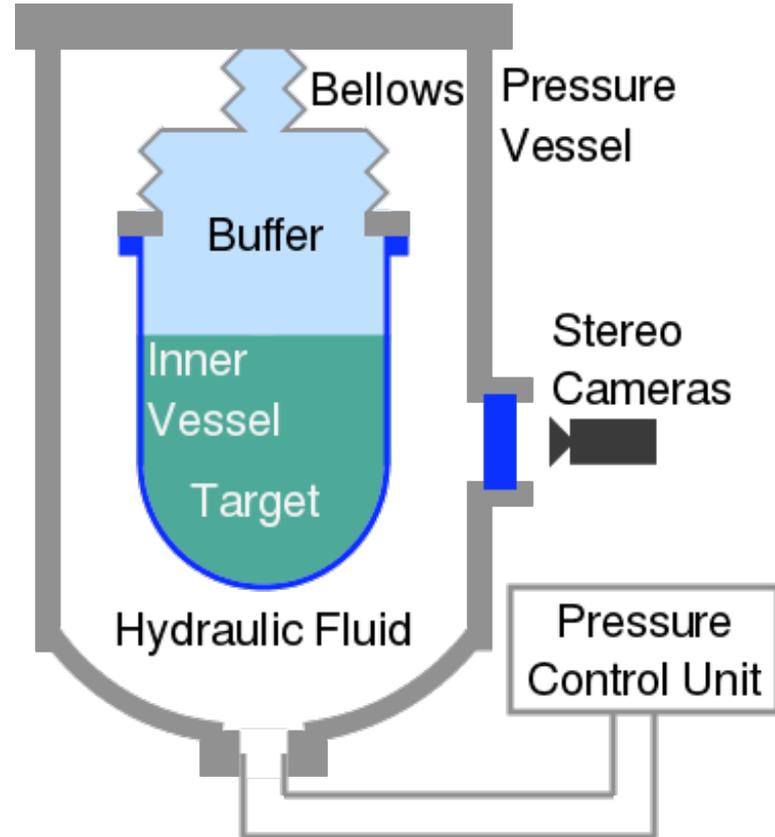


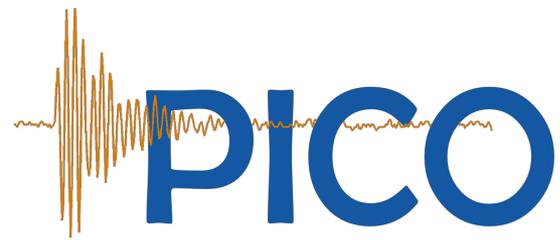


PICO

- Superheated Target
 - CF_3I , C_3F_8 , ...
- Particle interactions nucleate bubbles
- Cameras and acoustic sensors capture bubbles
- Chamber recompresses after each event

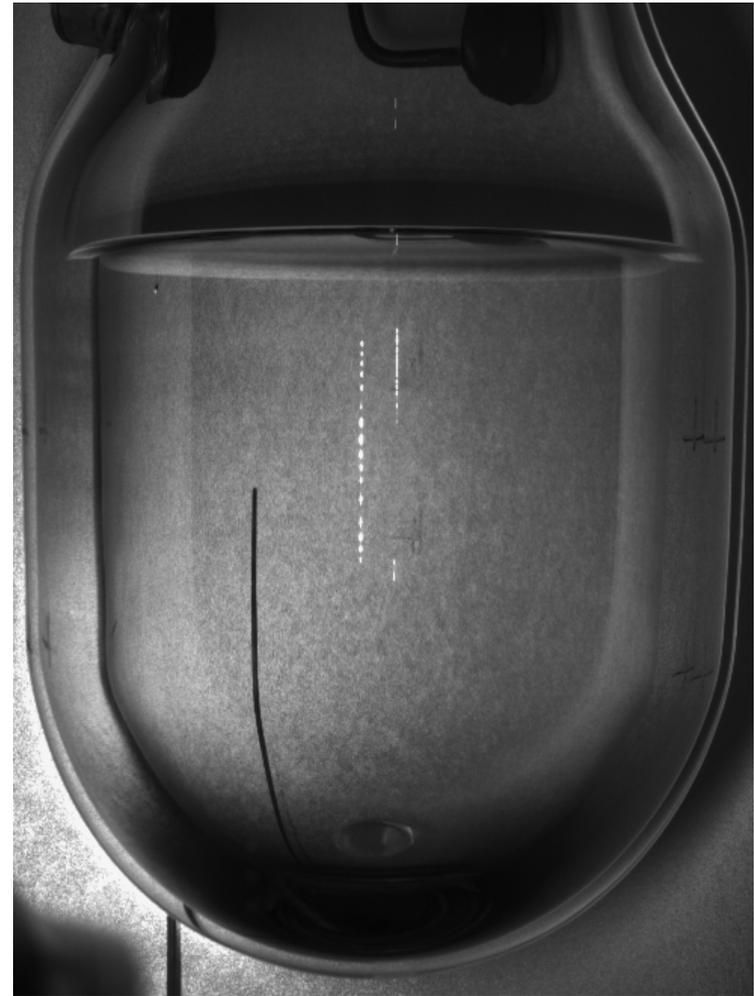
Bubble Chambers

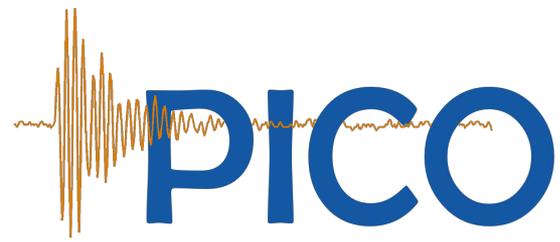




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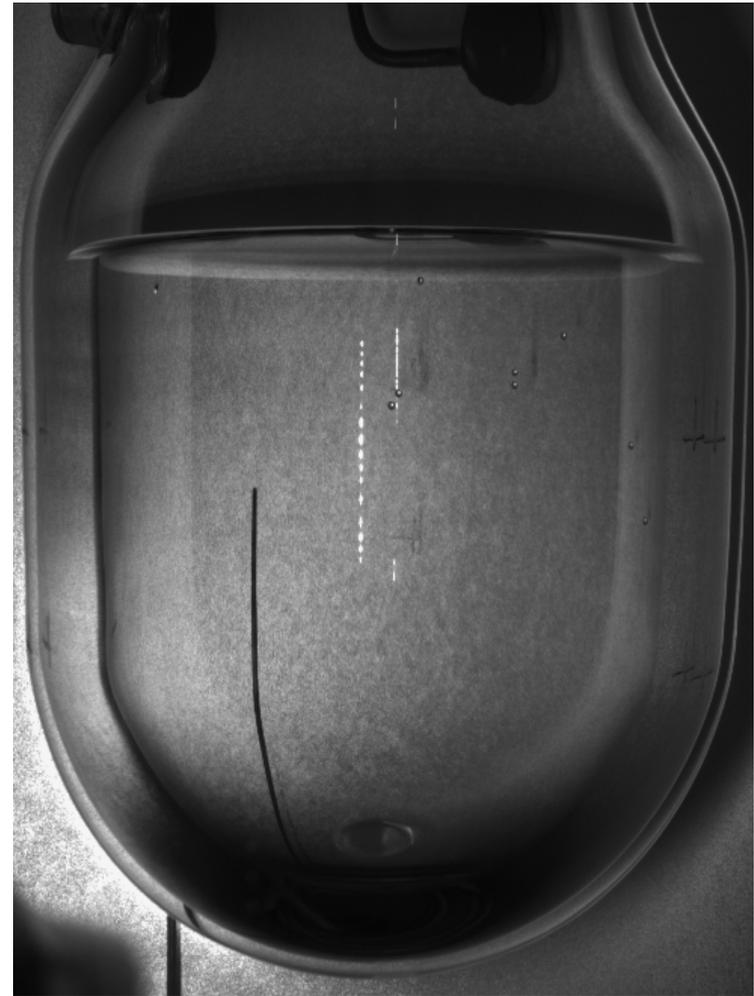
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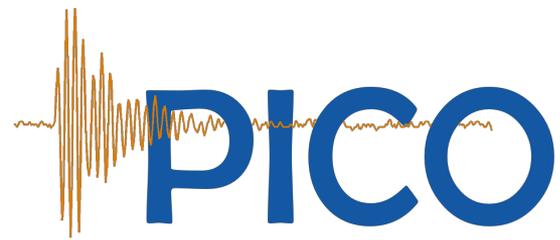




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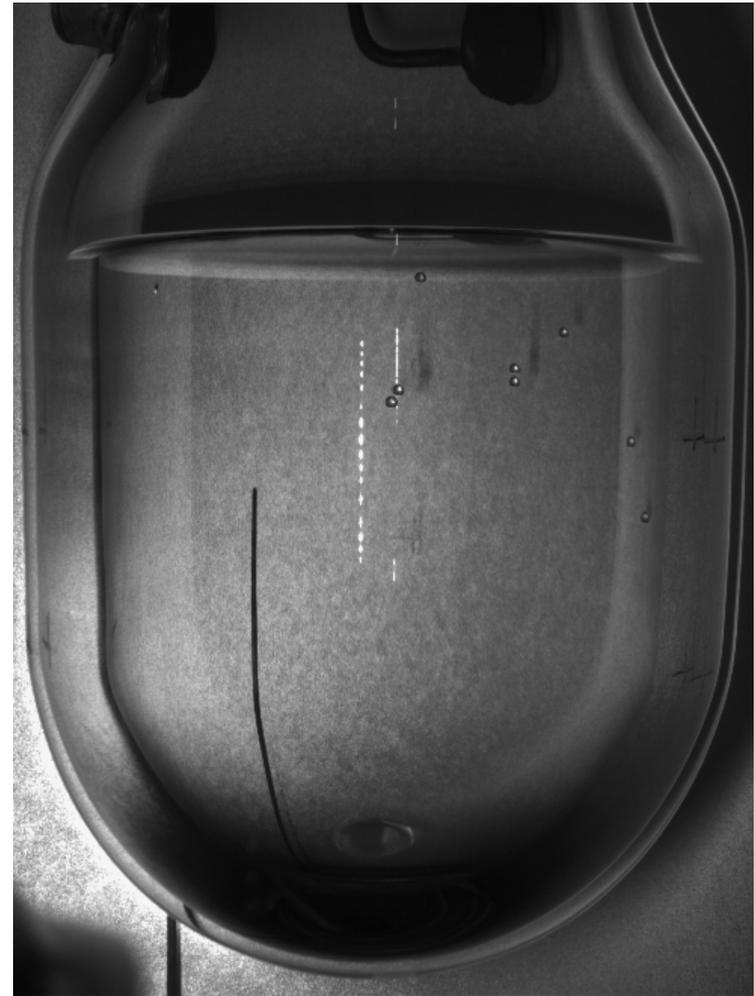
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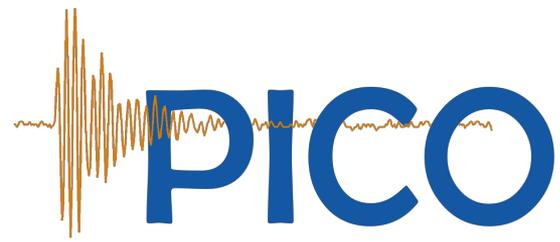




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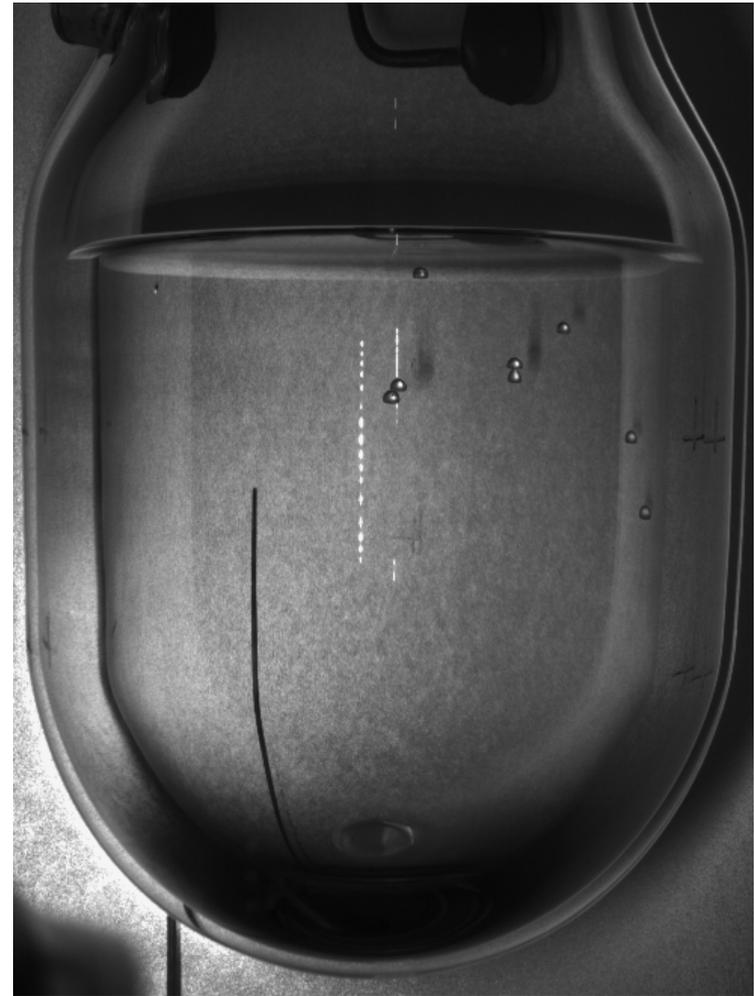
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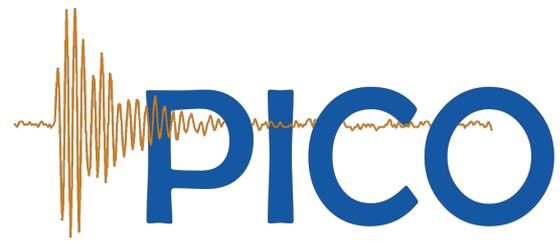




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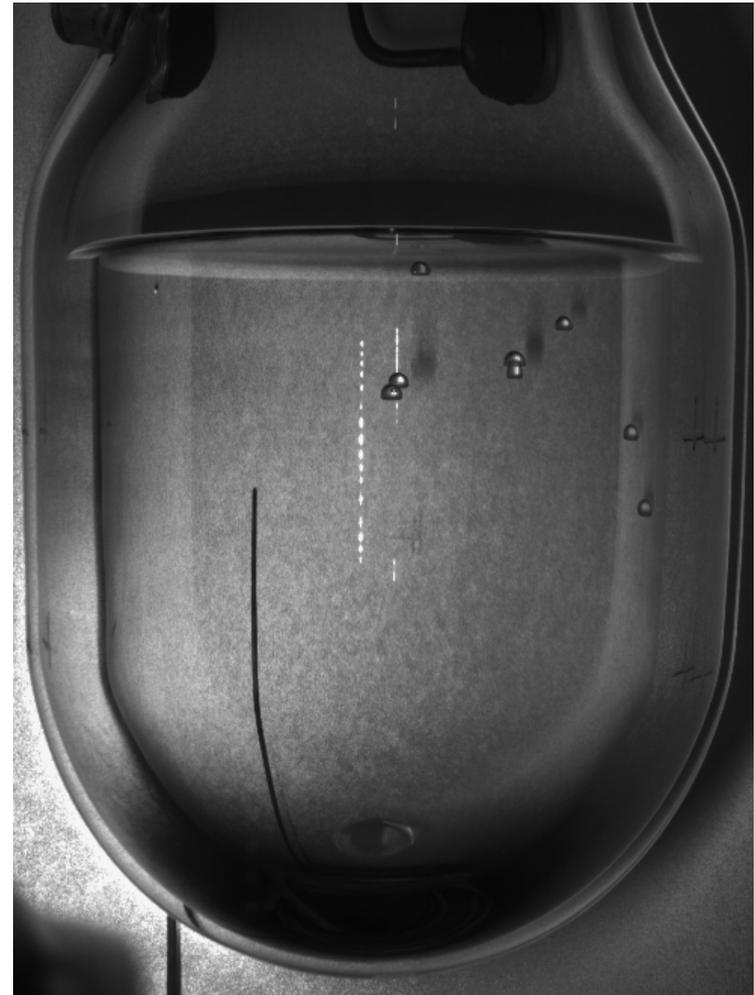
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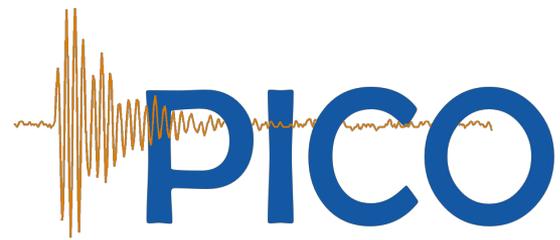




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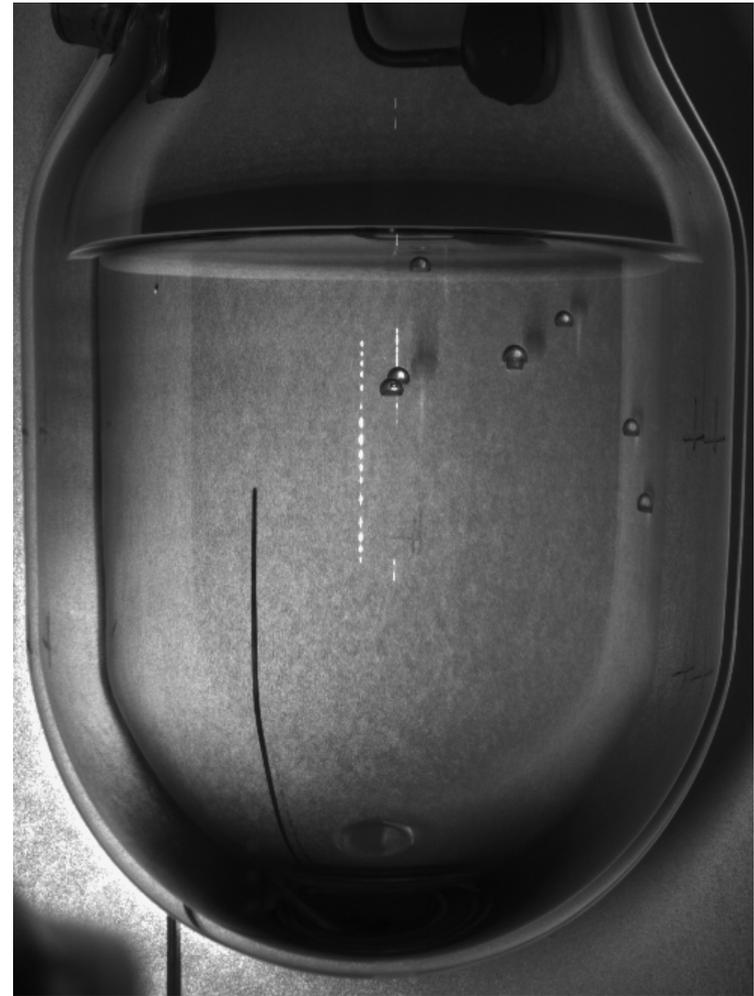
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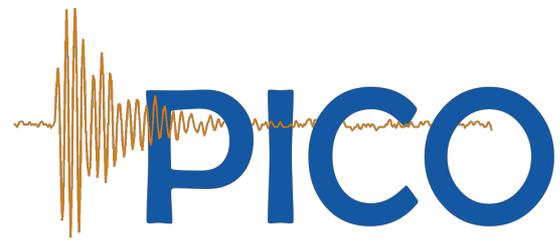




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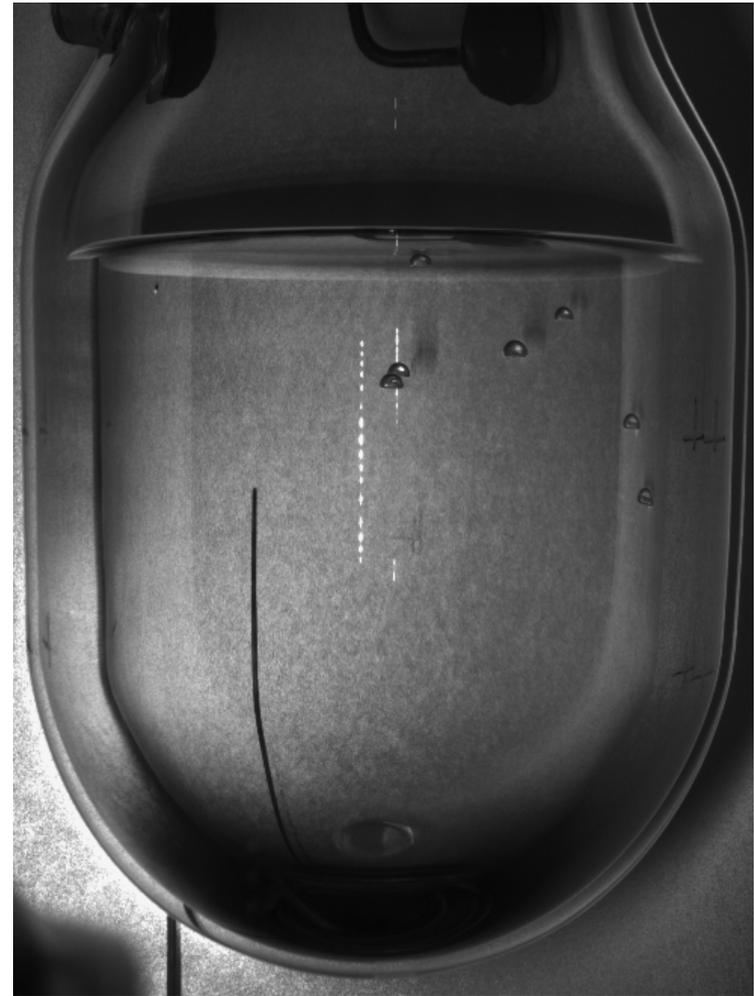
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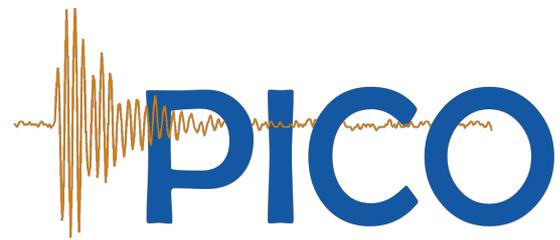




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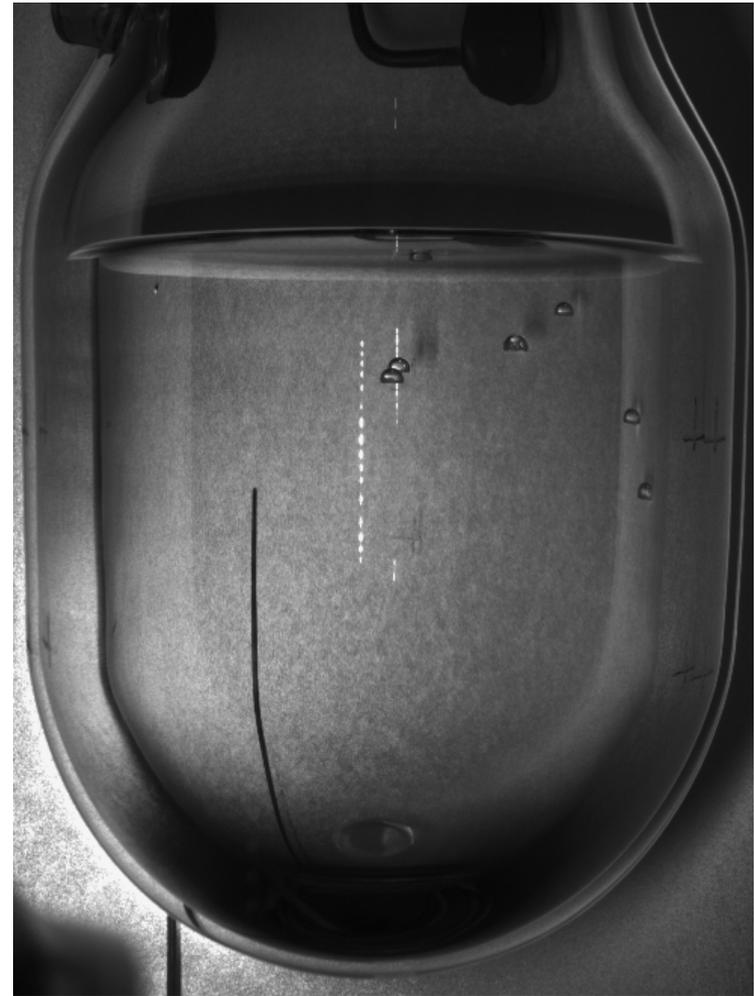
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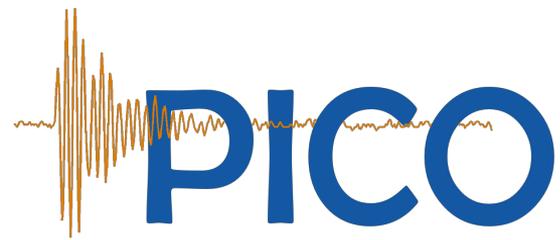




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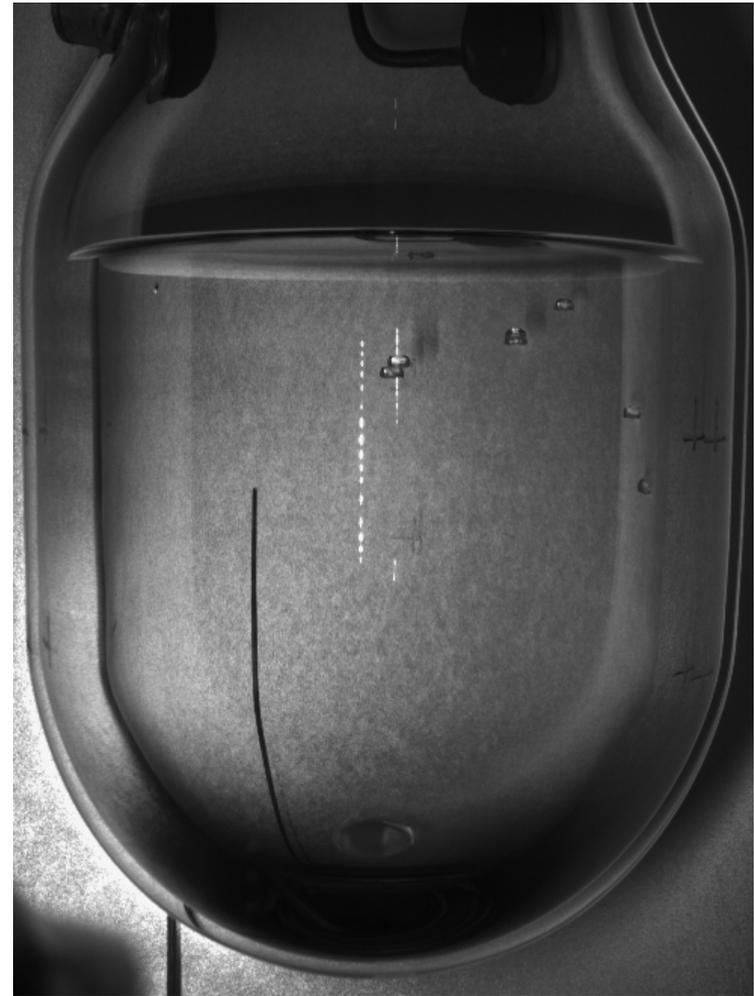
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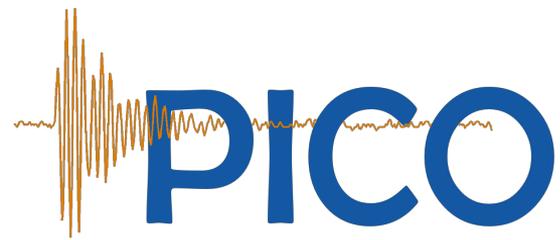




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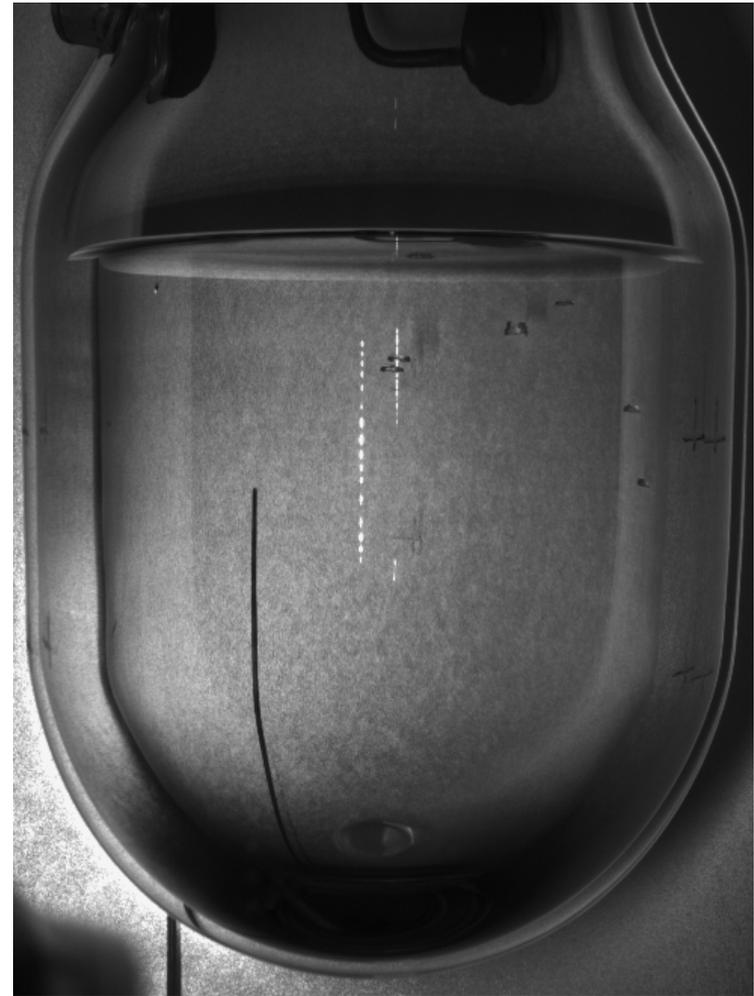
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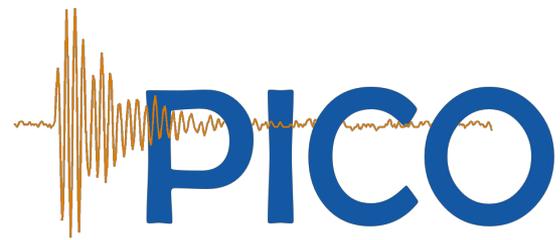




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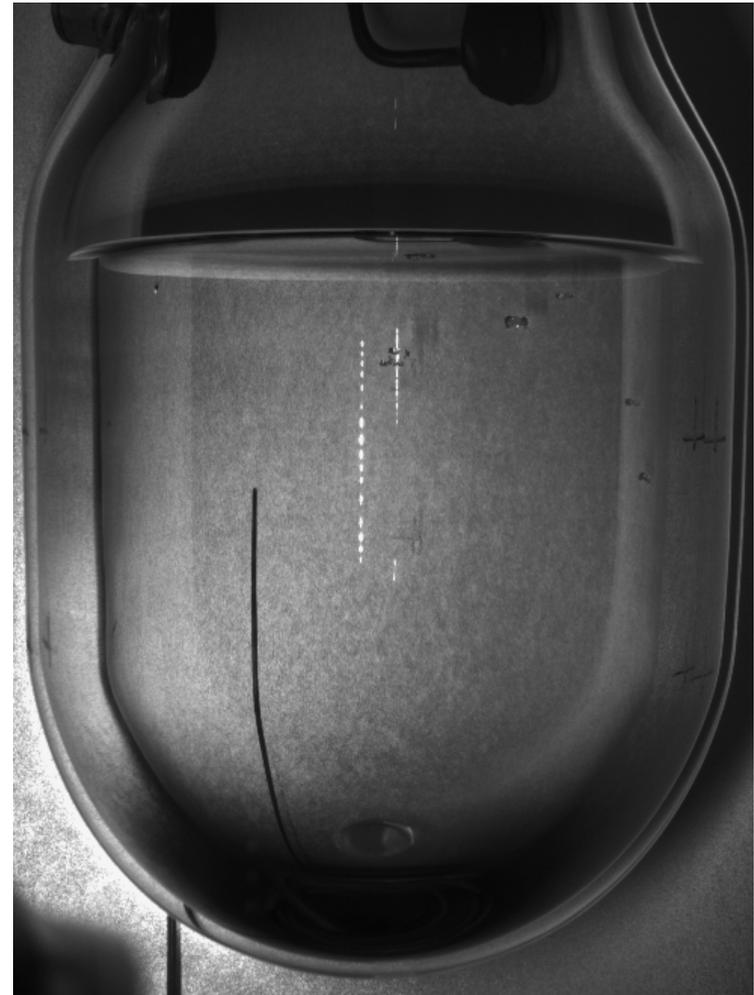
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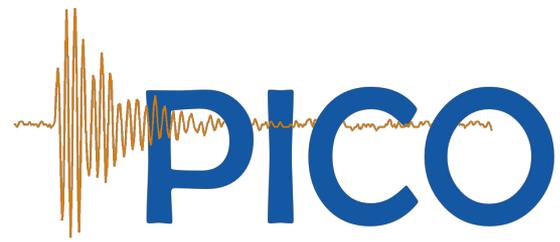




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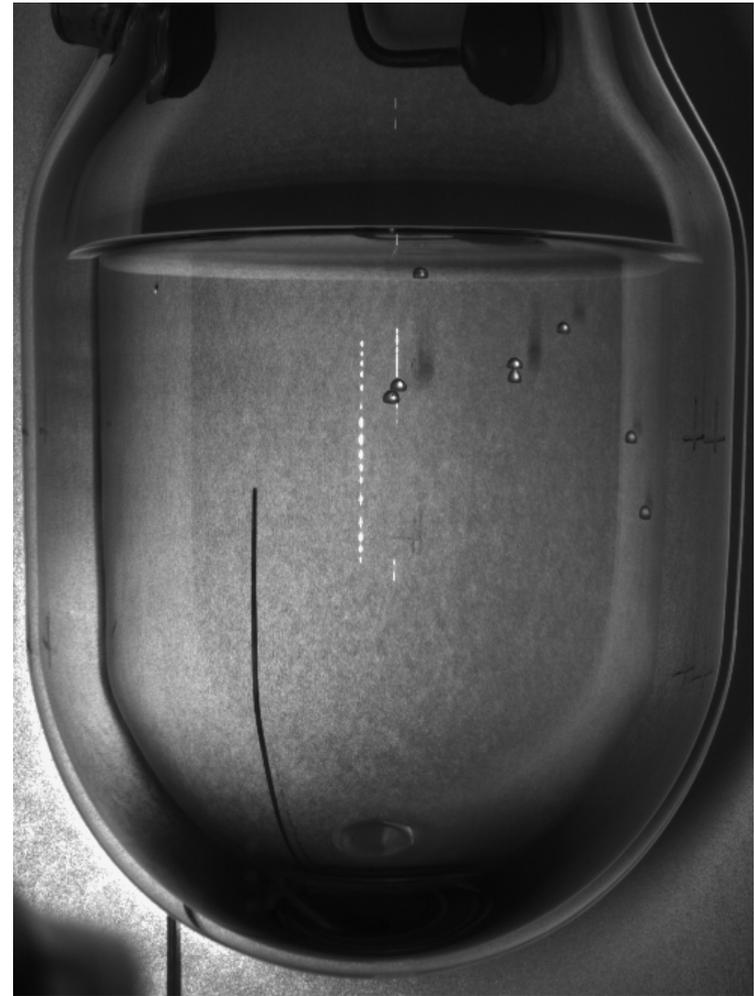
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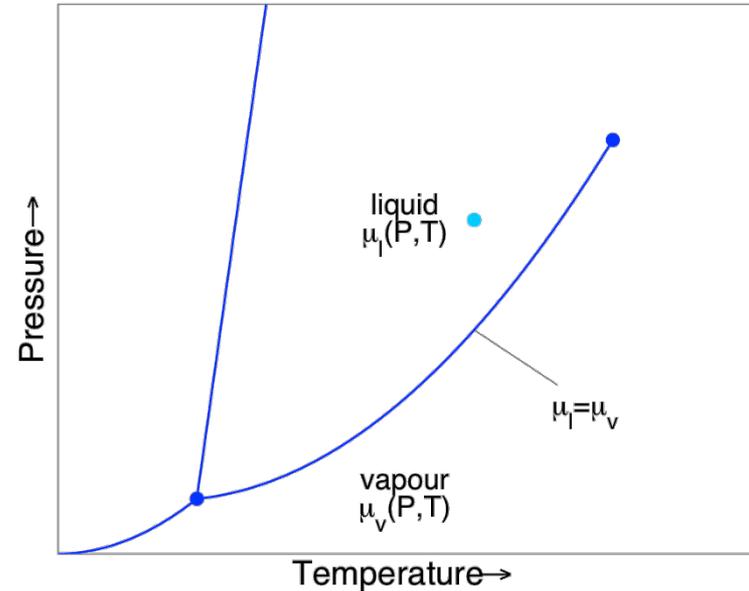
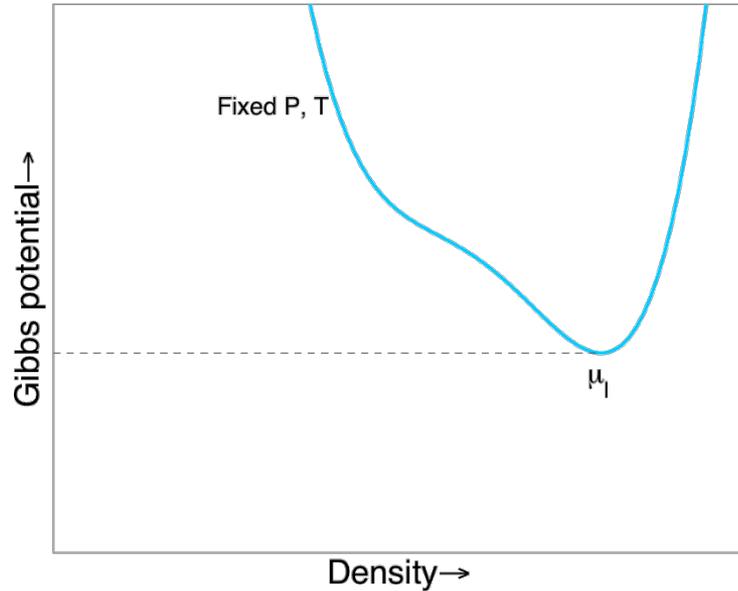
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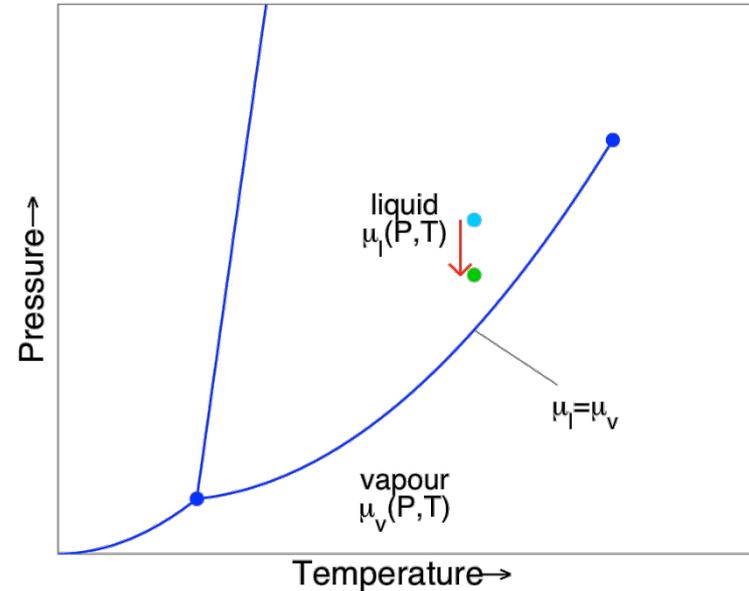
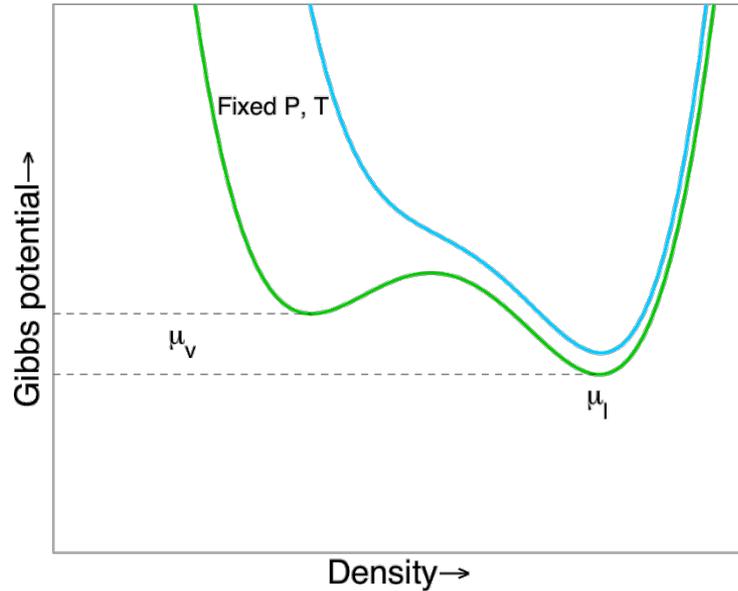
Bubble Chamber Thermodynamics

- What is a metastable state?



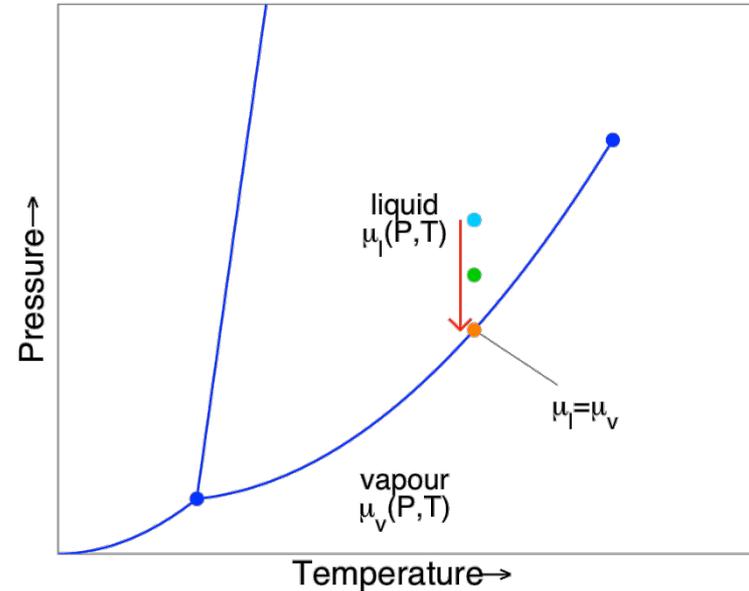
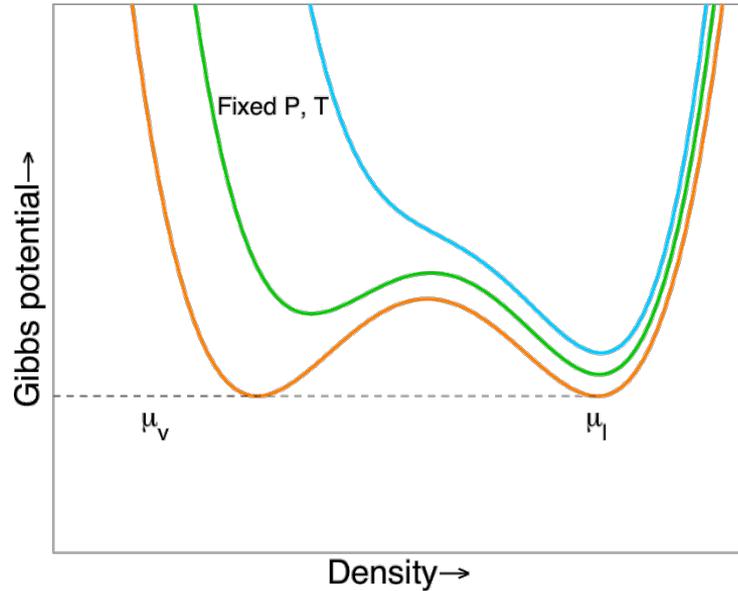
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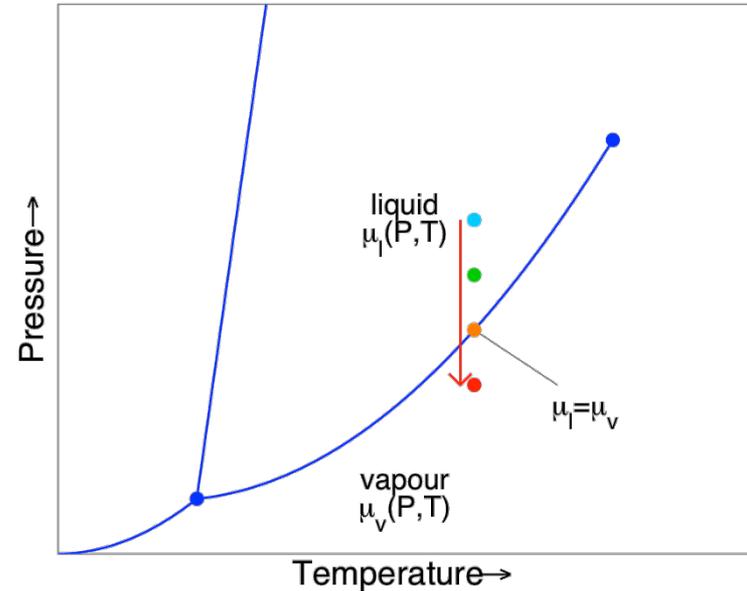
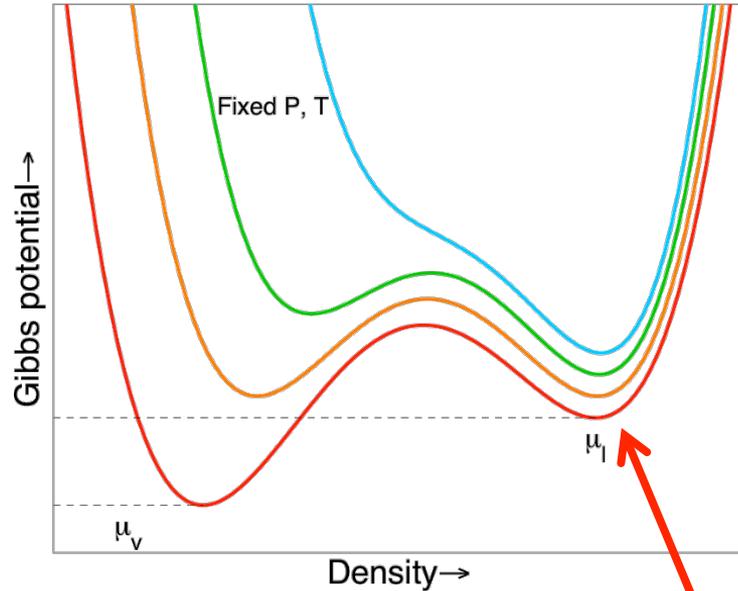
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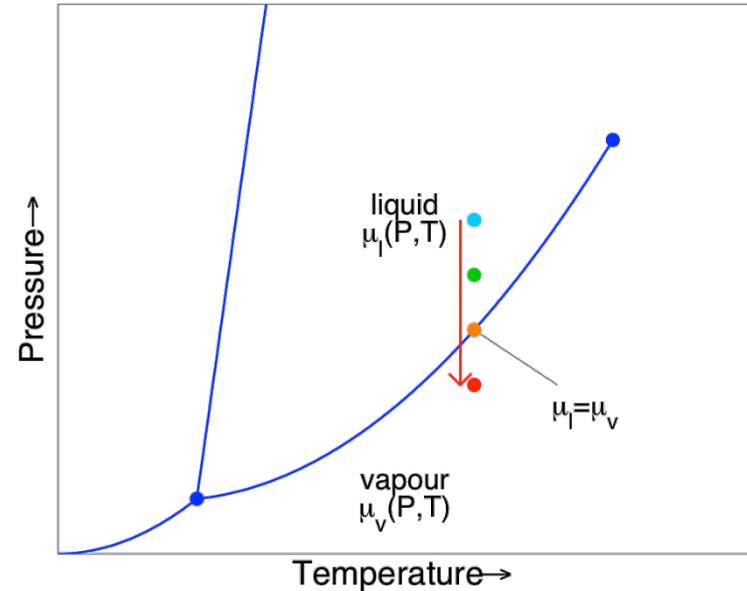
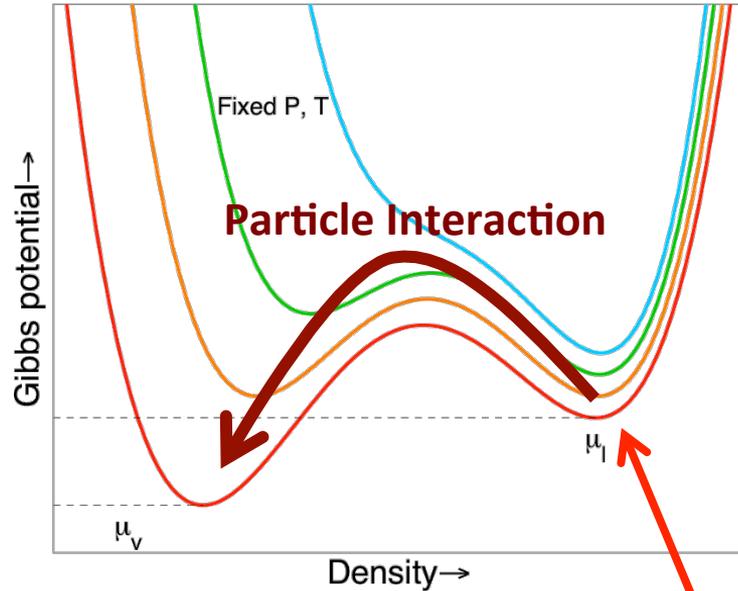
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Superheated Liquid

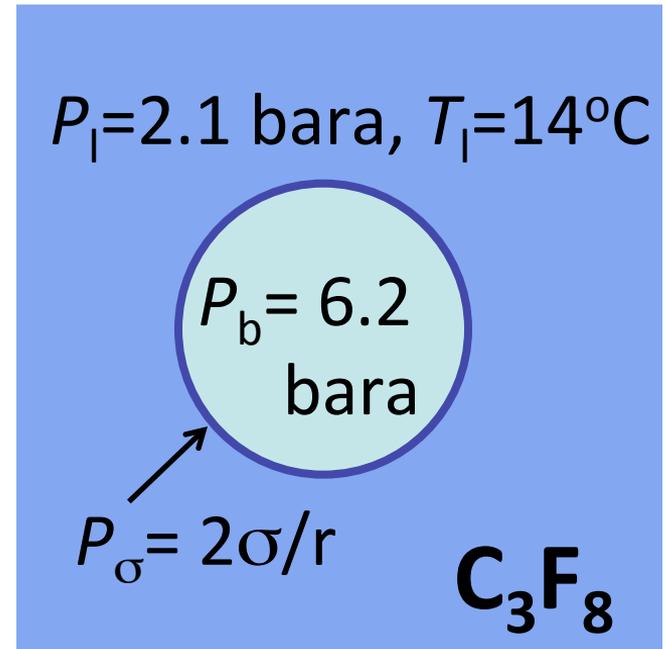
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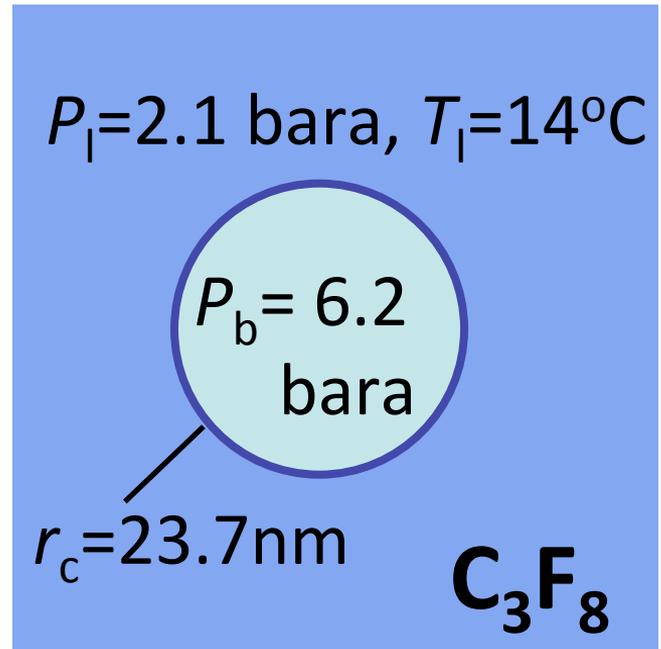
Bubble Chamber Thermodynamics

- What does it take to nucleate a bubble?



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- What does it take to nucleate a bubble?



Bubble Chamber Thermodynamics

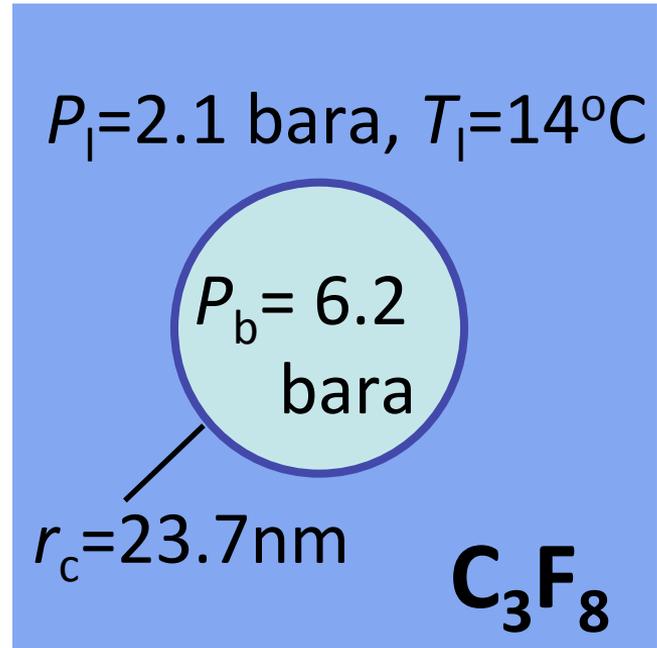
- What does it take to nucleate a bubble?

$$E_T = 4\pi r_c^2 \left(\sigma - T \left(\frac{\partial \sigma}{\partial T} \right)_\mu \right) \quad 1.53 \text{ keV}$$

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

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

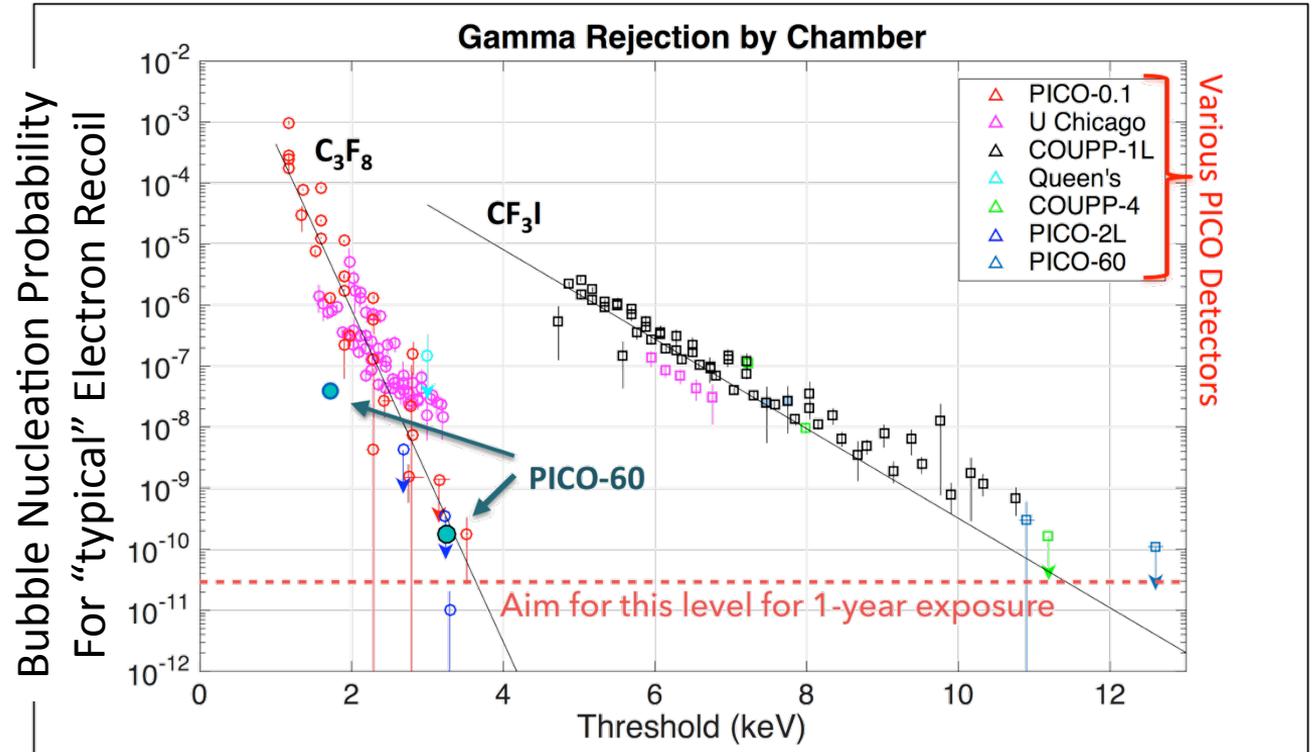
= 3.19 keV “*Thermodynamic Threshold*”



“*Critical Radius*”

Electron Recoil Discrimination

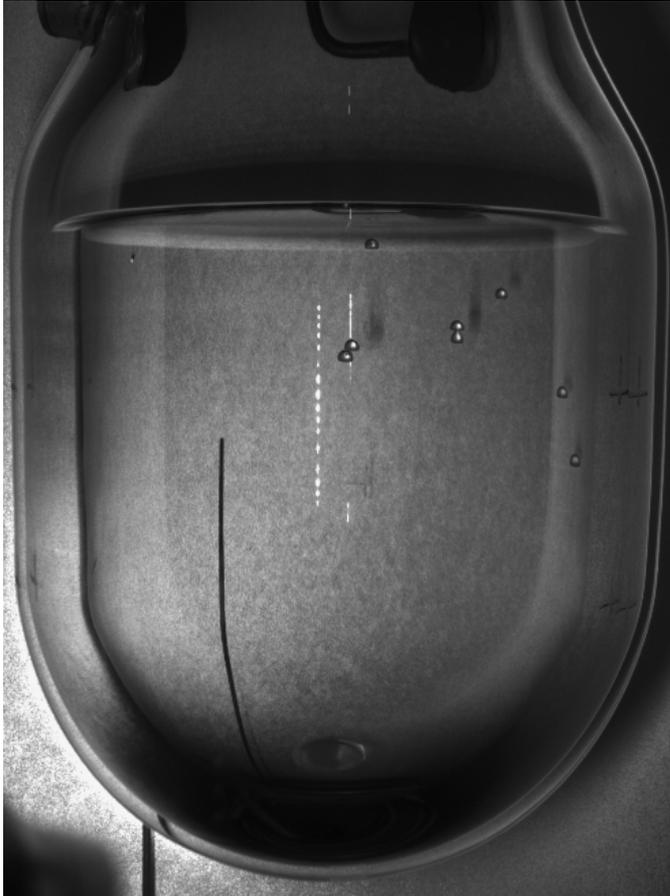
- Extreme discrimination against β , γ backgrounds
- β , γ sensitivity sets threshold for NR detection



(Dan Baxter, Conference on Science at SURF, May 14, 2017)

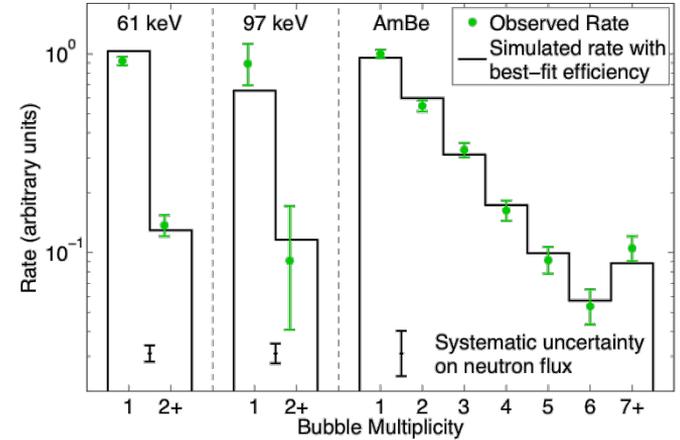
13

Nuclear Recoil Response



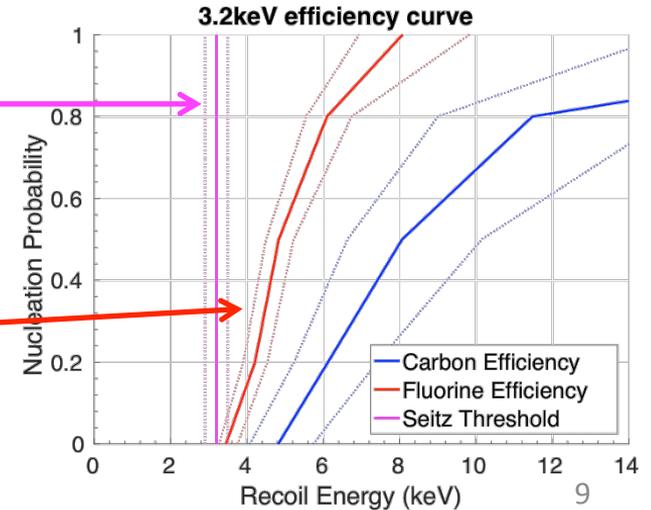
Dahl, 11/29/2018

Multiple neutron sources used to constrain recoil detection efficiency

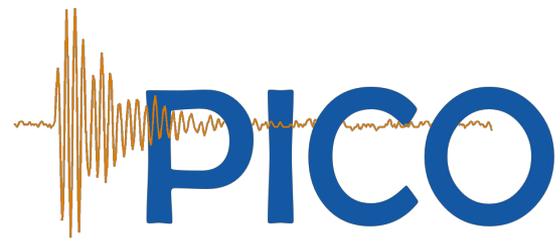


Calculated
thermodynamic
threshold

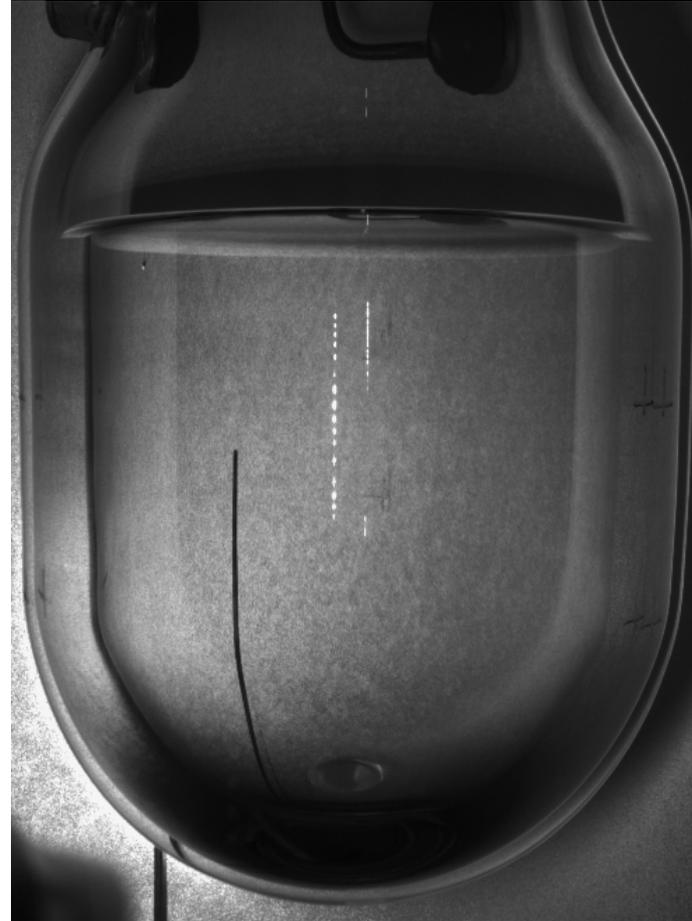
Calibrated
fluorine recoil
detection efficiency

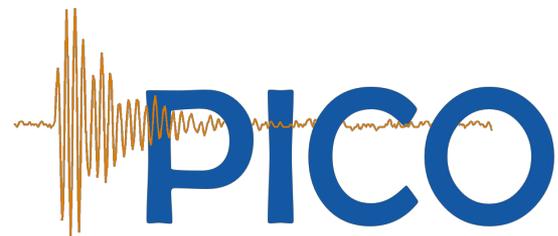


Bubble Chambers



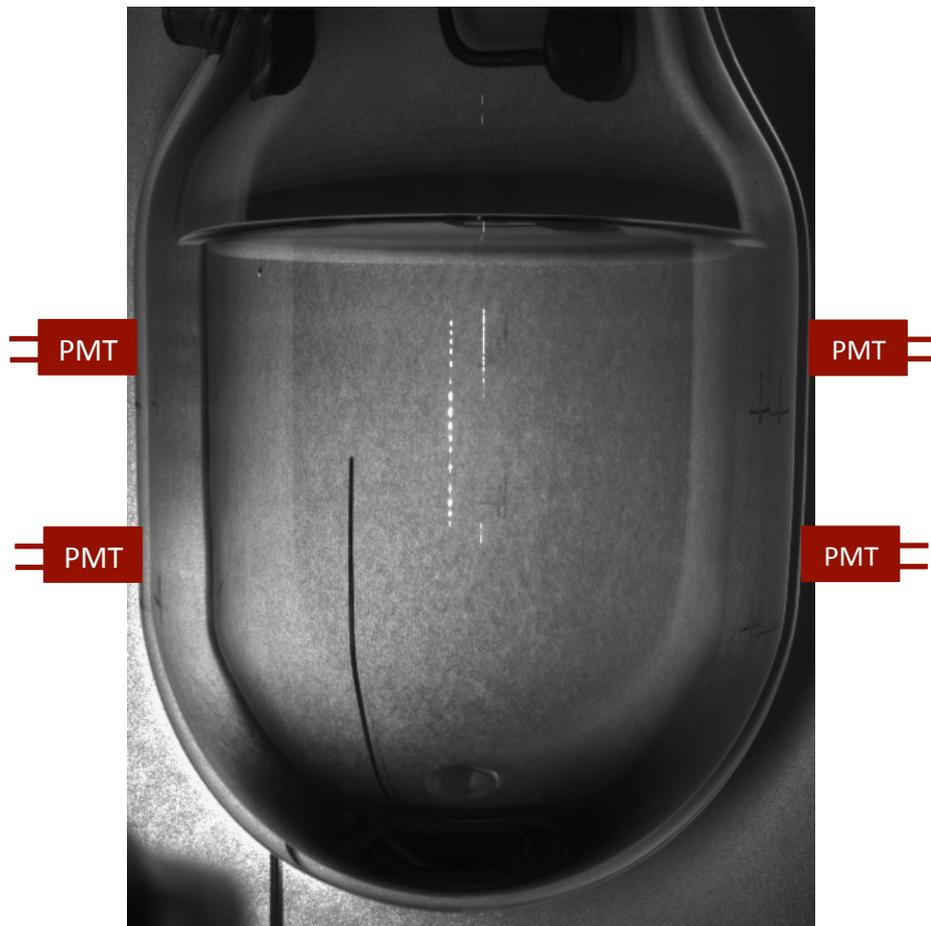
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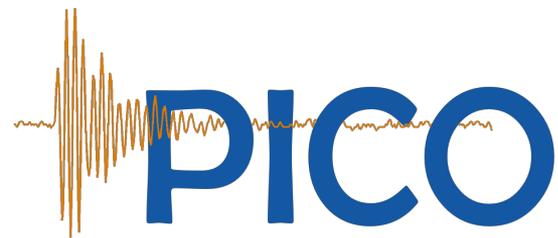




Scintillating Bubble Chambers

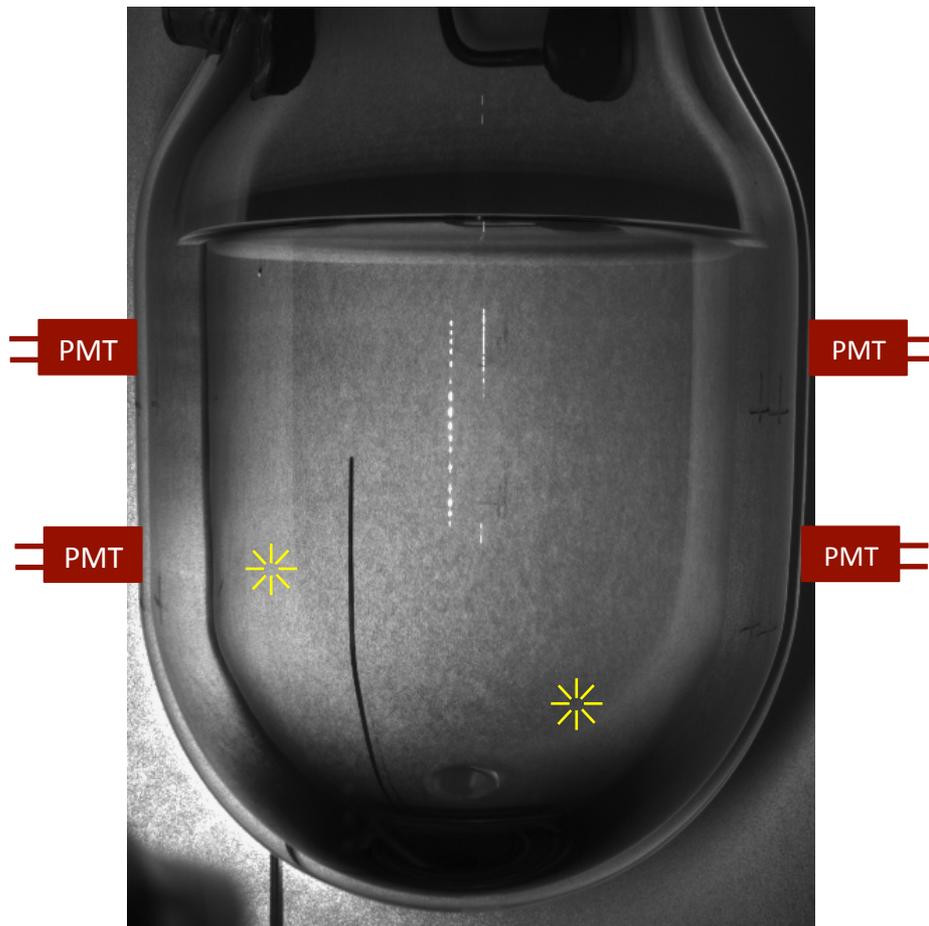
- Superheated **Scintillator**
 - Xe, Ar, C_6F_6 , ...
- Particle interactions nucleate bubbles **and produce scintillation**
- Cameras and acoustic sensors capture bubbles **and photo-detectors collect scintillation light**
- Chamber recompresses after each event

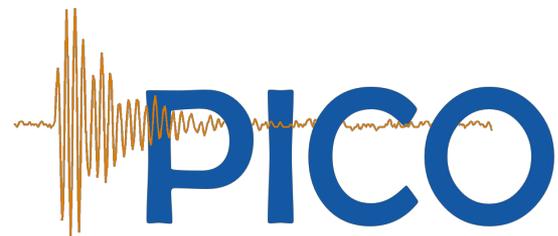




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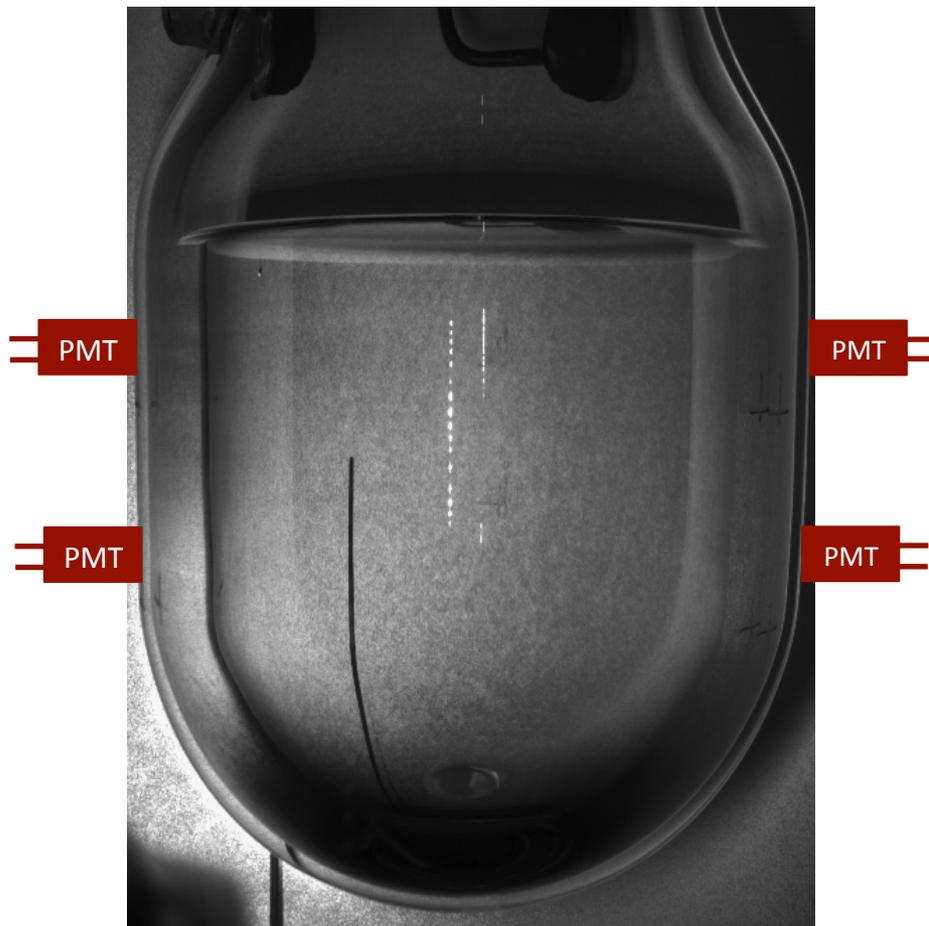
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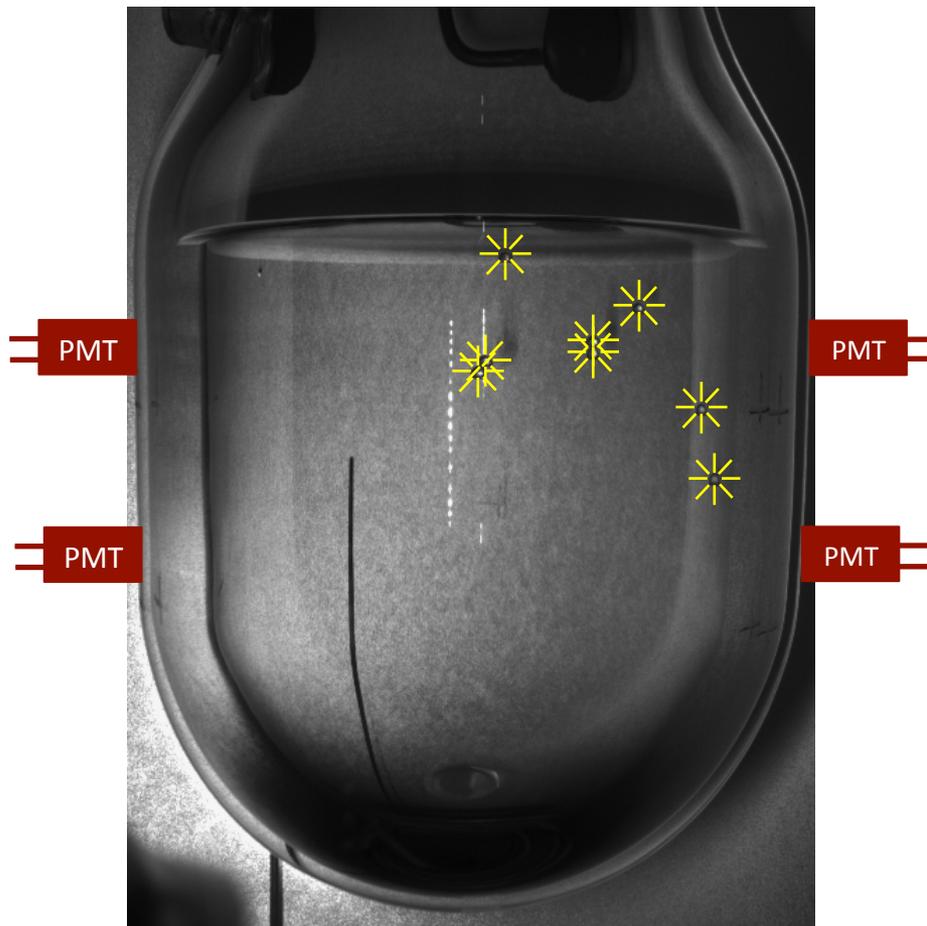


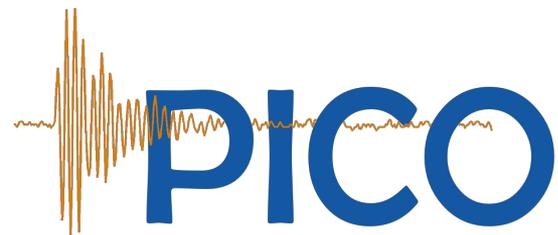
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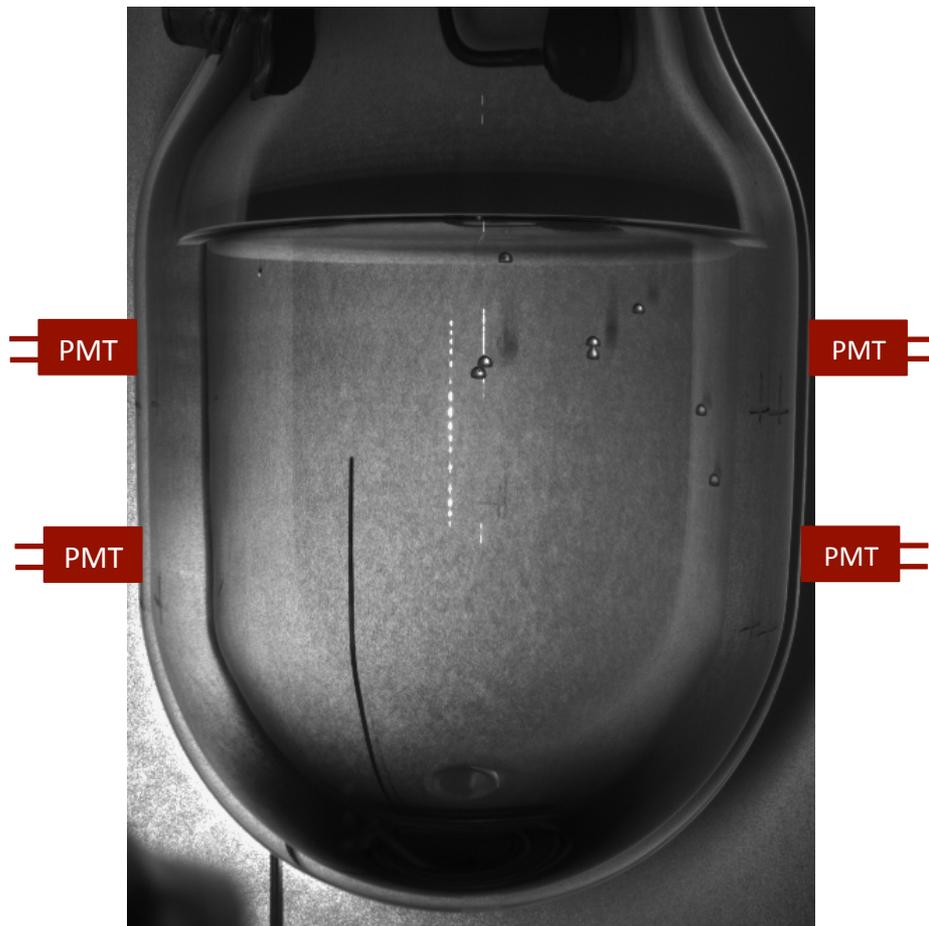
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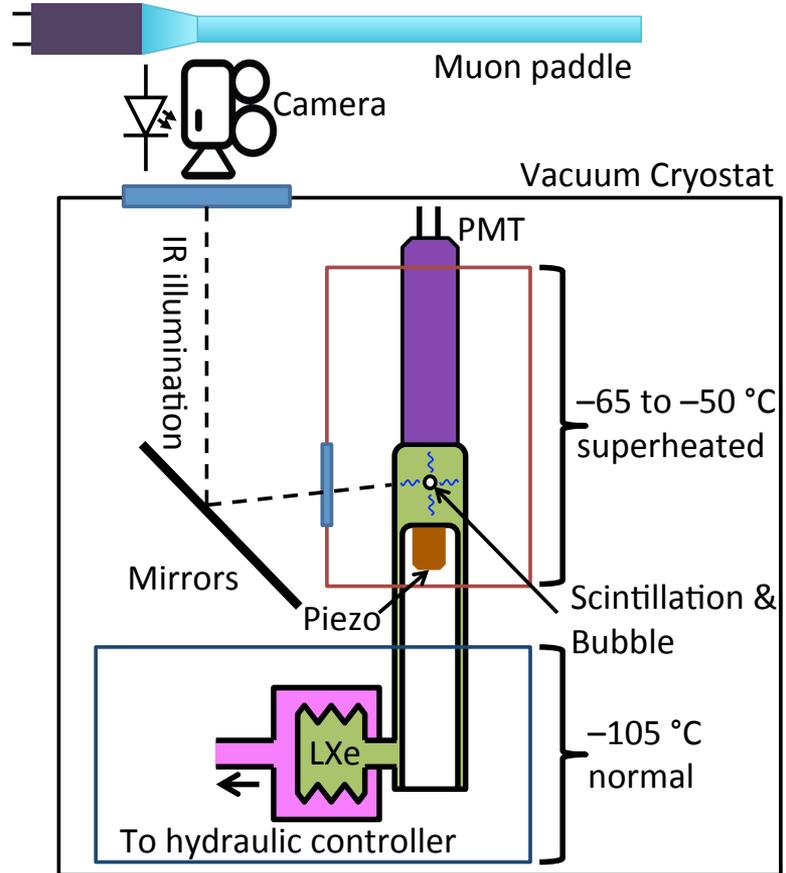
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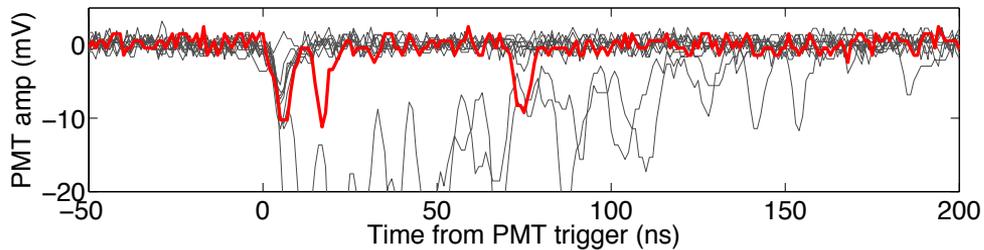
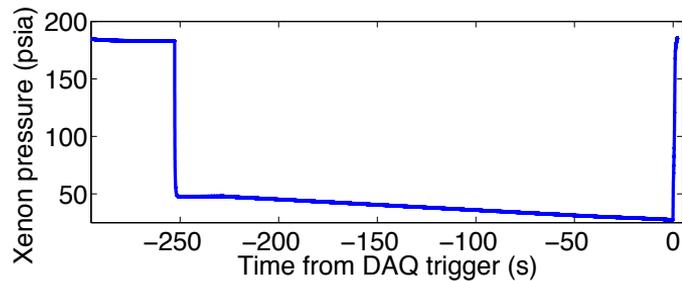
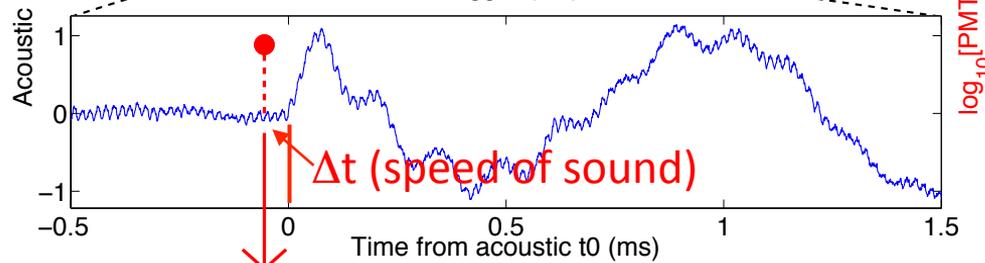
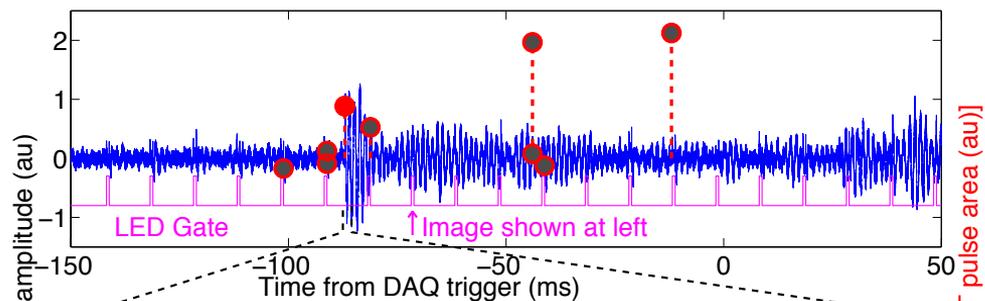
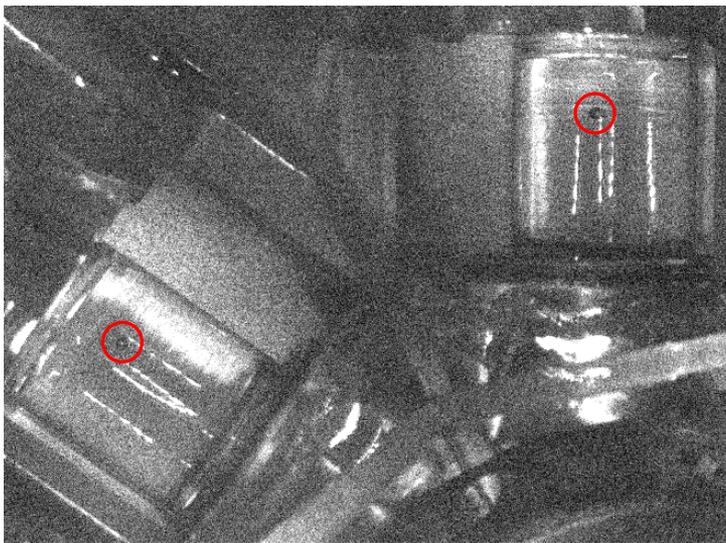
NU Xenon Bubble Chamber

- 30-gram xenon target
- 25-psia, -38°C
 $E_T = 0.5 \text{ keV}$
- Single fluid (no buffer)
- IR illumination for cameras
- IR-blind PMT (R6834) for 175nm scintillation



Nuclear Recoil Event

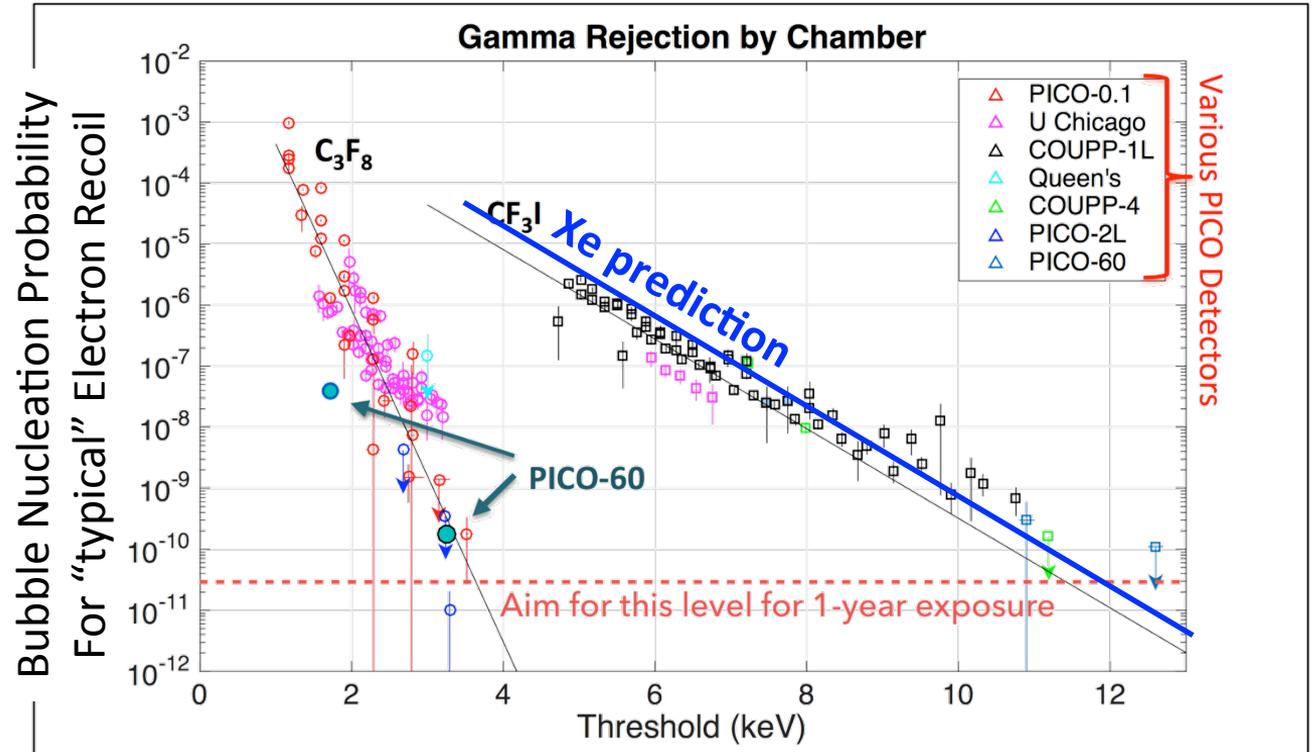
PRL 118, 231301 (2017)



\log_{10} [PMT pulse area (au)]

Electron Recoil Discrimination

- Xenon predicted to have slightly worse ER discrimination than CF_3I
 - no good for CEvNS...

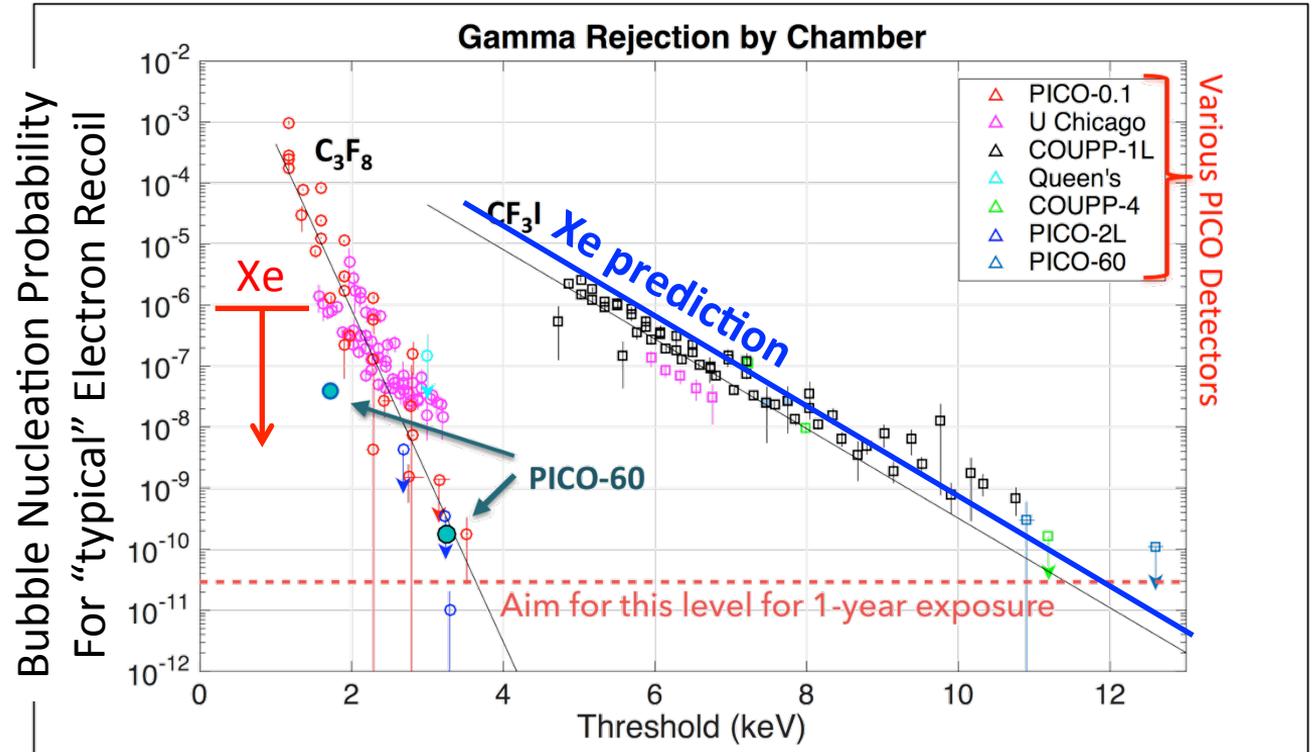


(Dan Baxter, Conference on Science at SURF, May 14, 2017)

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Electron Recoil Discrimination

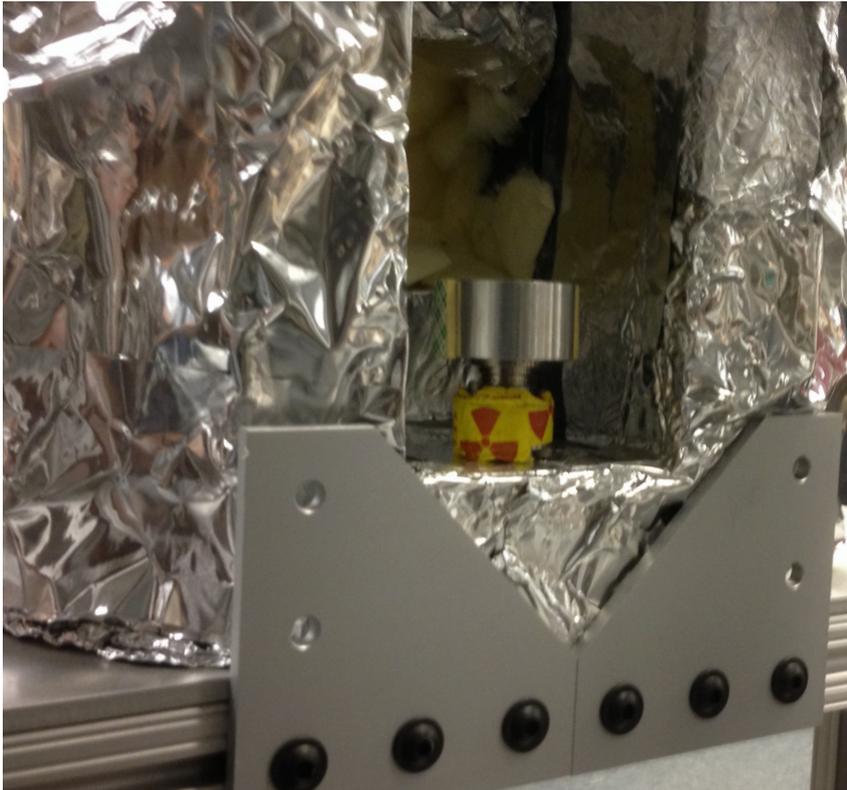
- Xenon *measured* to have phenomenal ER discrimination!
 - No observation so far of bubbles nucleated by gamma-rays
 - Explored thresholds down to 900 eV



(Dan Baxter, Conference on Science at SURF, May 14, 2017)

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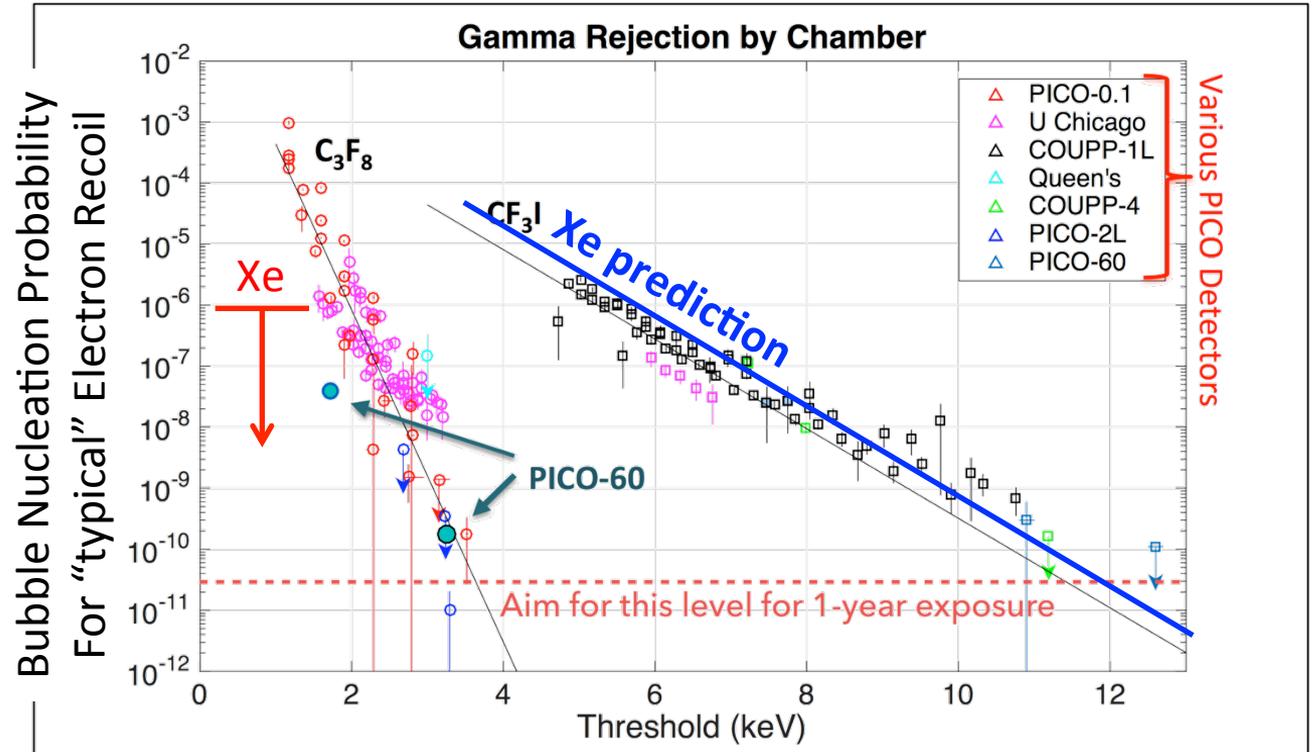
NR Threshold vs Thermodynamic Threshold



- $^{88}\text{Y}\text{-Be}(\gamma, n)$: 152 keV neutrons
 - Max 4.7 keV xenon recoil
 - Bubble nucleation by $E_T = 2$ keV
- $^{207}\text{Bi}\text{-Be}(\gamma, n)$: 94 keV neutrons
 - Max 2.9 keV xenon recoil
 - Bubble nucleation by $E_T = 1$ keV

Electron Recoil Discrimination

- Liquid nobles fundamentally different than molecular fluids!
 - No molecular bonds -> no efficient way to *locally* turn ER energy into heat

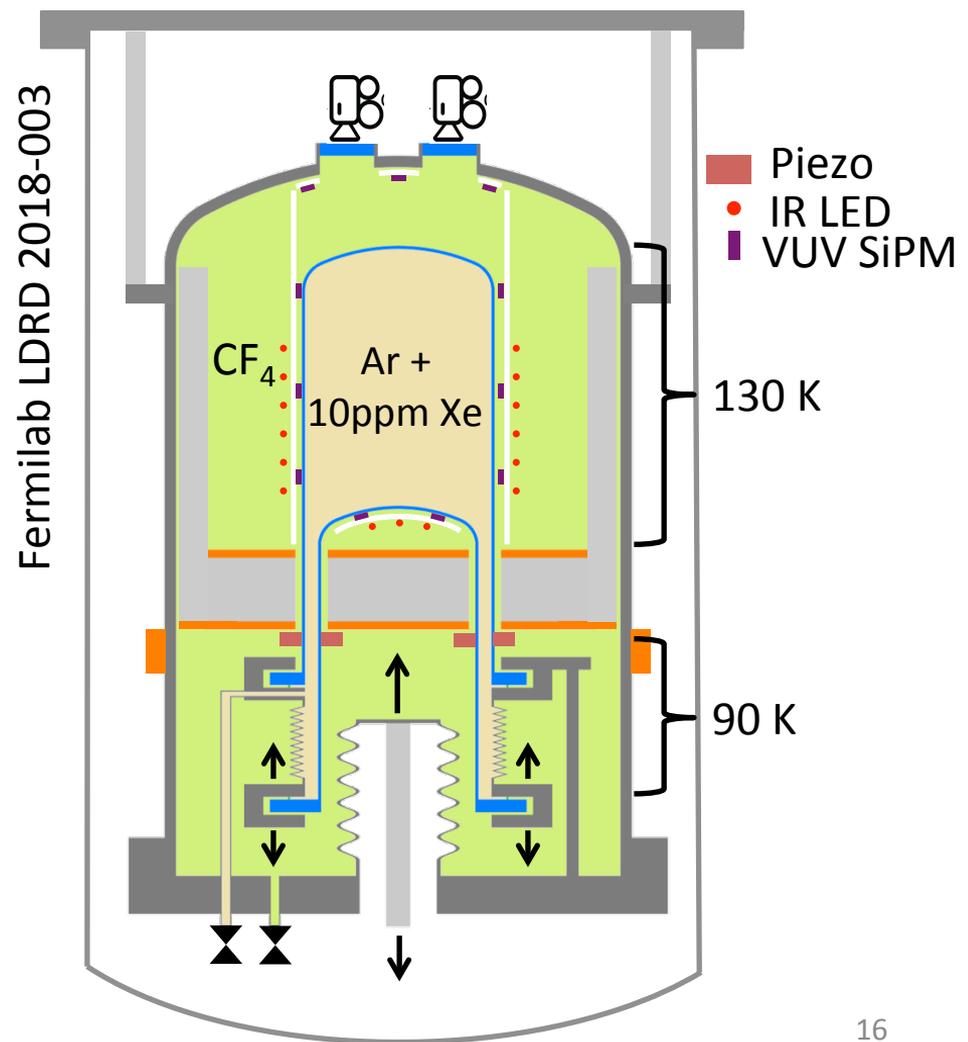


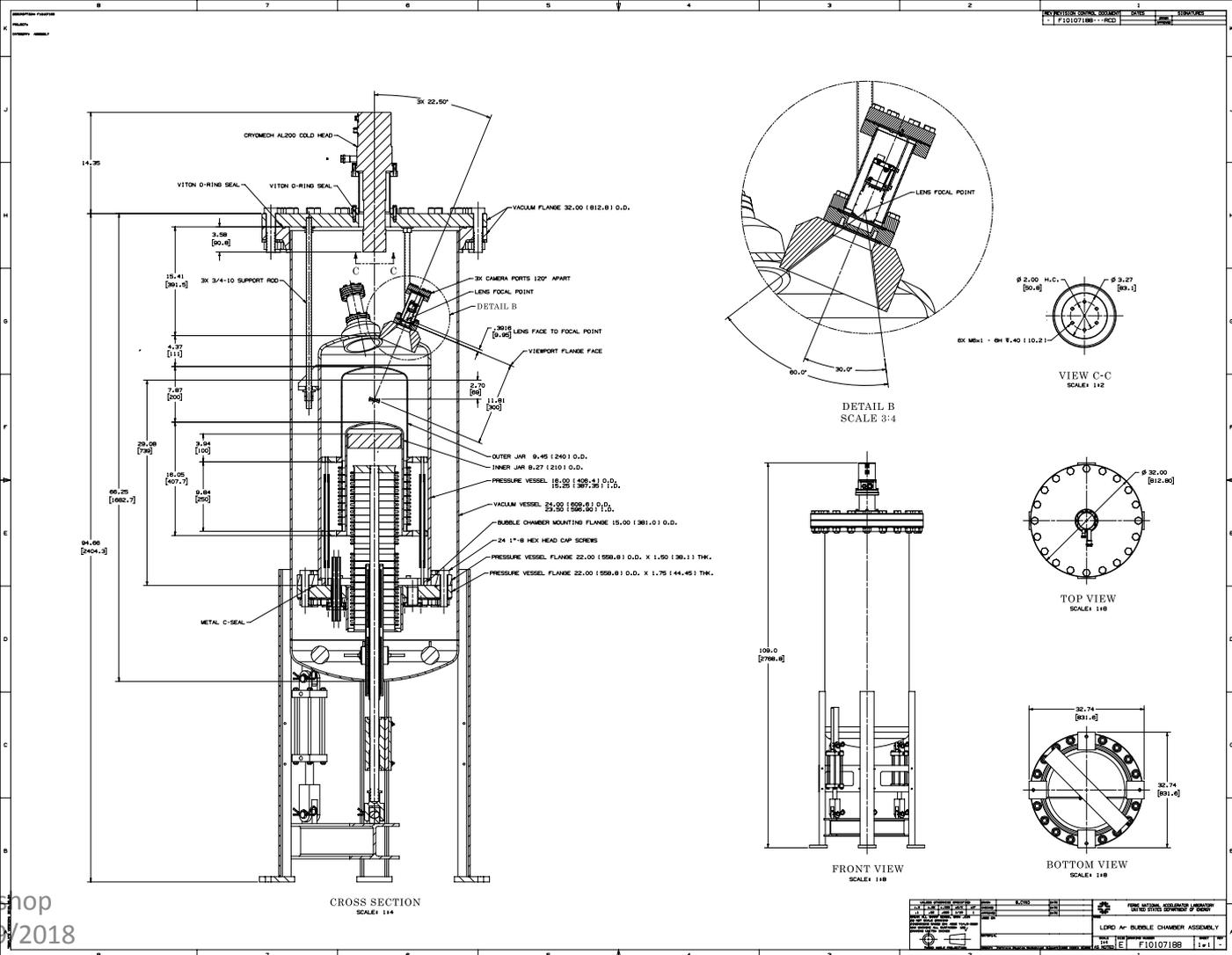
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Scintillating Argon Bubble Chamber

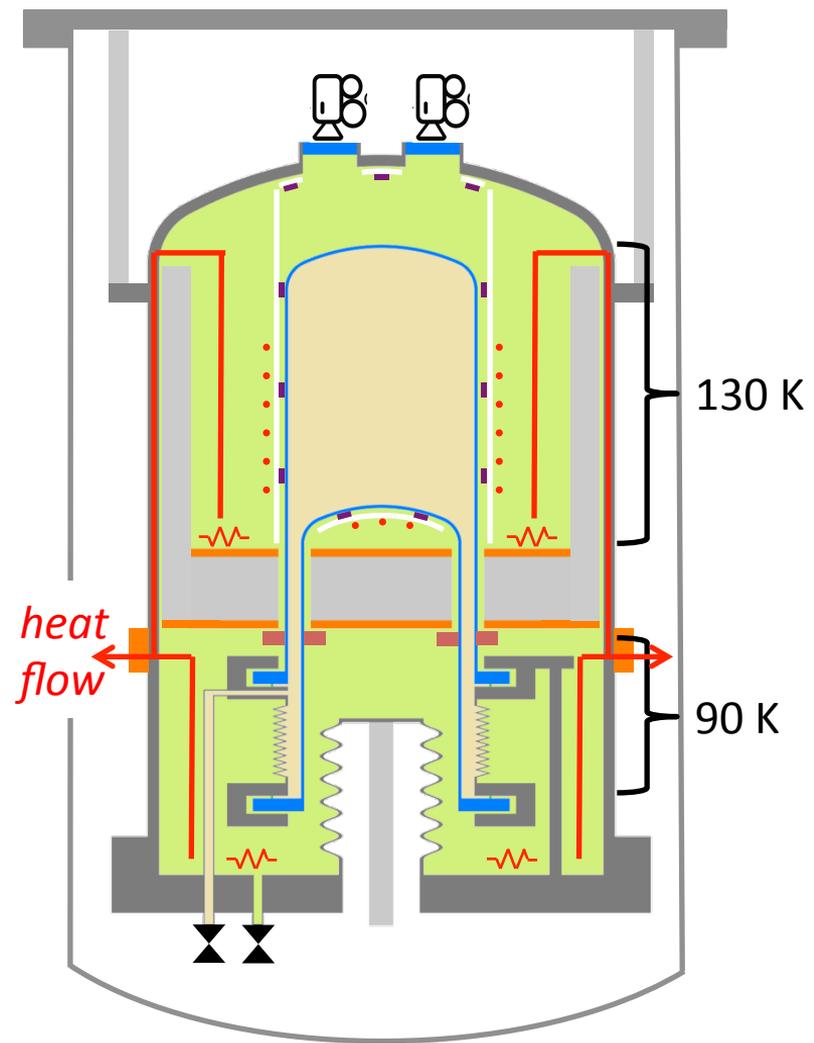
- 10-kg Argon target
- Designed to reach $E_T = 40$ eV
 - 90 – 130 K,
 - 1.5 – 26 bara
 - 1 spontaneous bubble / ton-year
- Collaboration of 7 Institutions in US, Canada, Mexico
 - Funding from FNAL LDRD, CFI, and COFI





Thermal Control

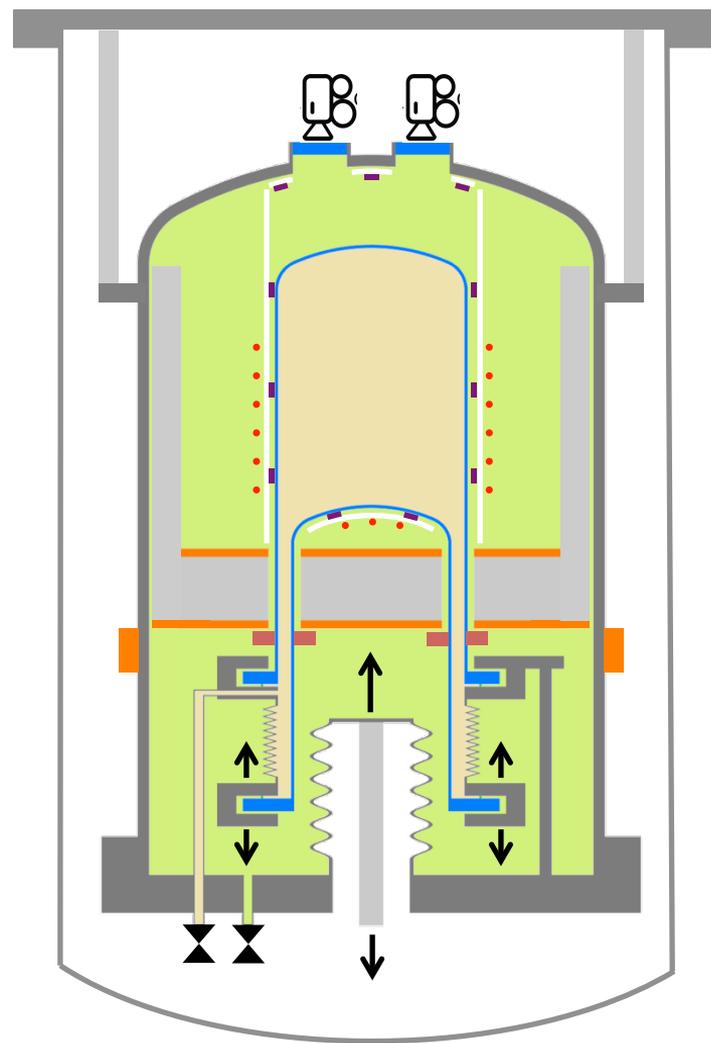
- Two thermal zones in hydraulic volume
 - Heaters drive convection in each zone
- Rely on conduction through silica jars to set target temperature
- Challenge: rising bubbles generate gradient in target fluid – keep bubbles small!



Pressure Control

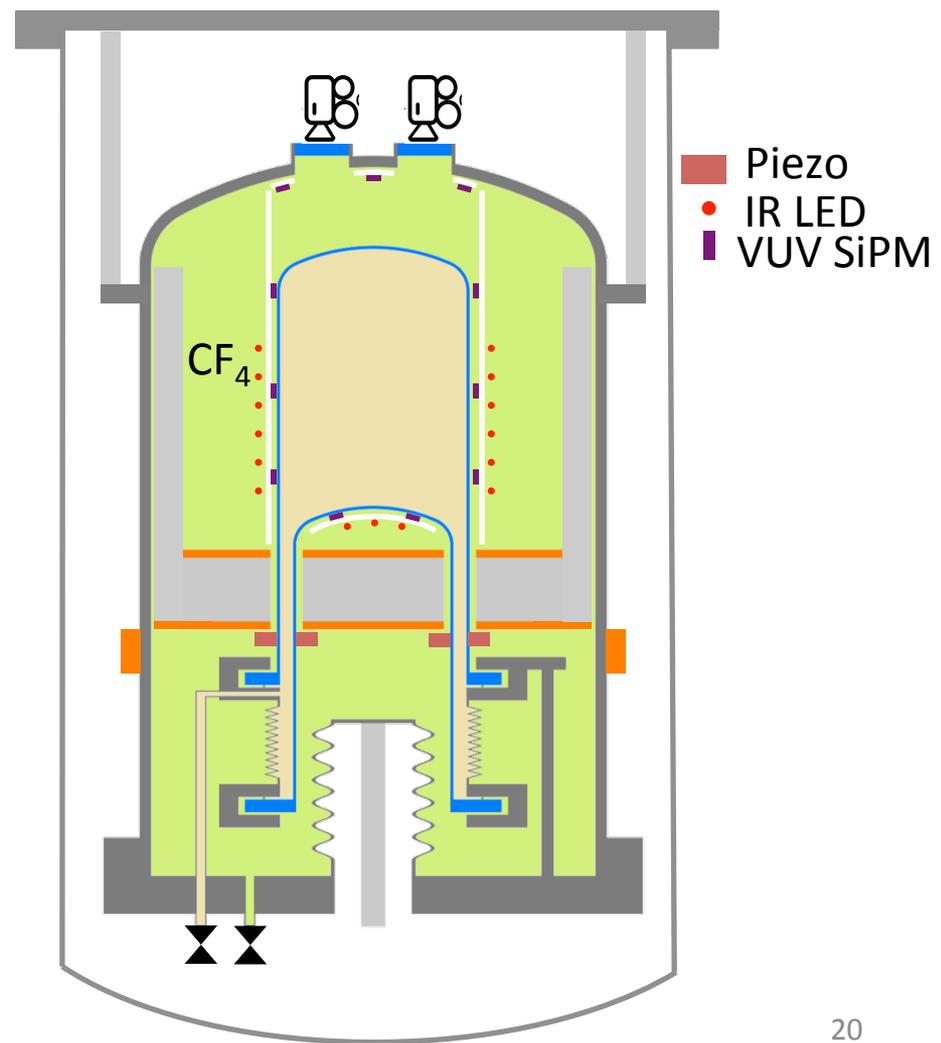
Requirements:

- Regulate pressure to 0.01 bar in superheated state
- Compress quickly to arrest bubble growth
 - 1.5 -> 6 bara in 100ms
 - 6 -> 26 bara in $O(1)$ second
- All achieved with single piston, driven by warm hydraulic system



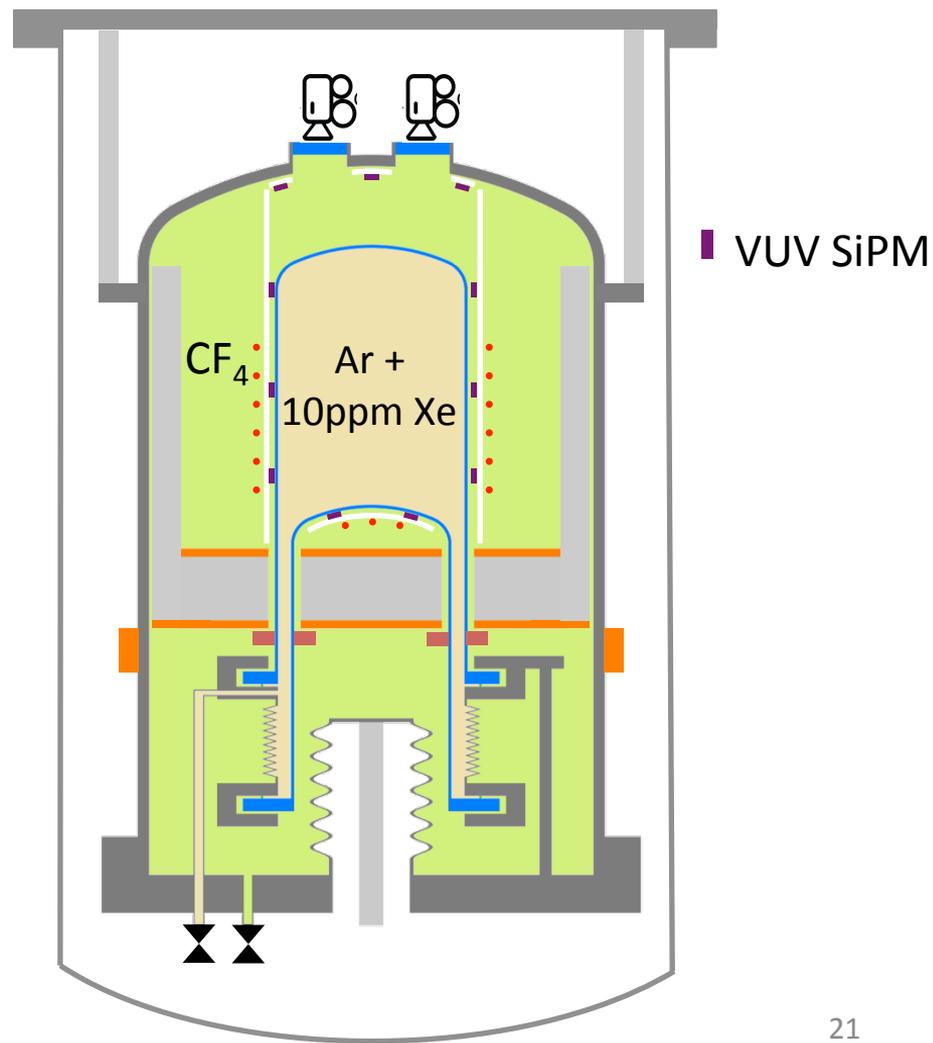
Instrumentation

- Unusual combination of pressure, temperature, and purity requirements
- Many custom and home-built parts
- Dedicated cryogenic pressure-cycling system to stress-test components



Scintillating Detection

- Xenon doping
 - Scintillation without xenon:
 $\text{Ar}_2^* \rightarrow 2\text{Ar} + \gamma$ (128 nm)
 - With 10 ppm xenon:
 $\text{Ar}_2^* + 2\text{Xe} \rightarrow 2\text{Ar} + \text{Xe}_2^*$
 $\text{Xe}_2^* \rightarrow 2\text{Xe} + \gamma$ (175nm)
- Lose pulse-shape discrimination
- Gain SiO_2 and CF_4 transparency
- Estimate 1 photon detected for 5 keV Ar recoil

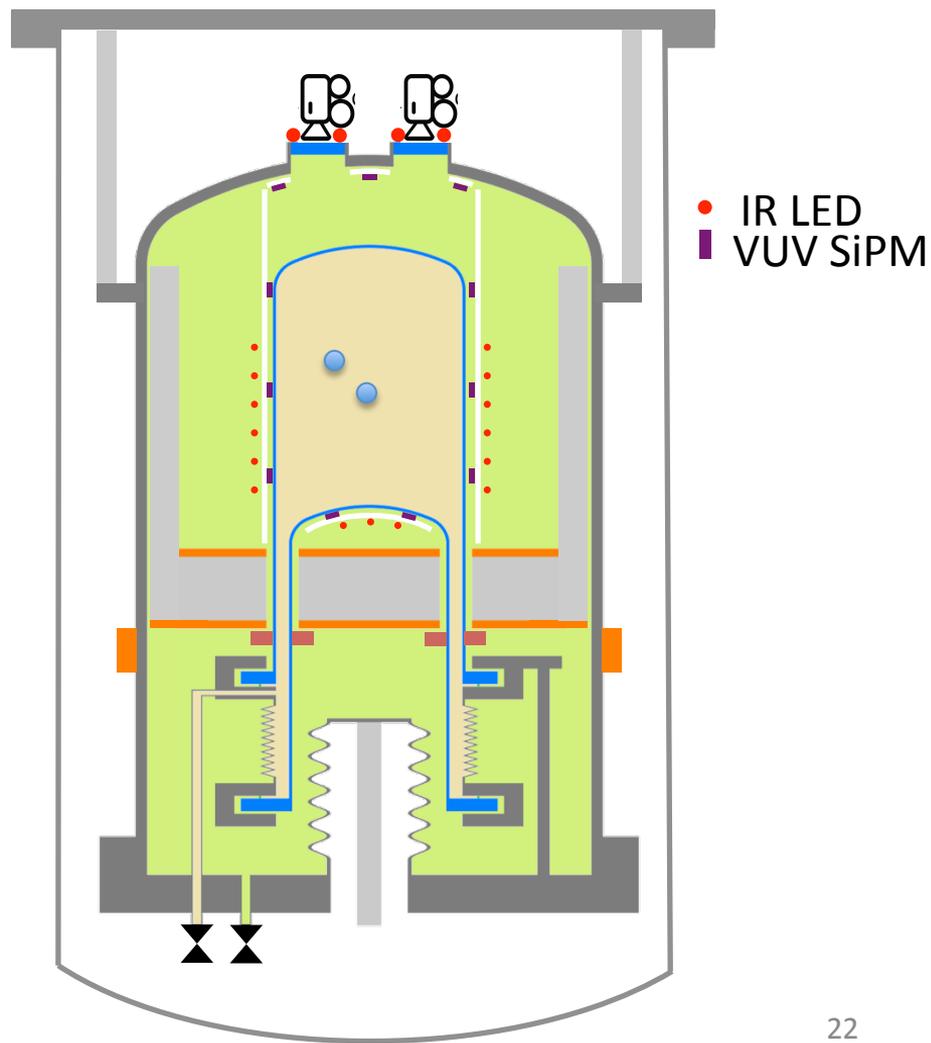


Bubble Imaging

- Flashed IR illumination for imaging

Challenge:

- Need white walls for scintillation detection
- But white walls give no contrast for images



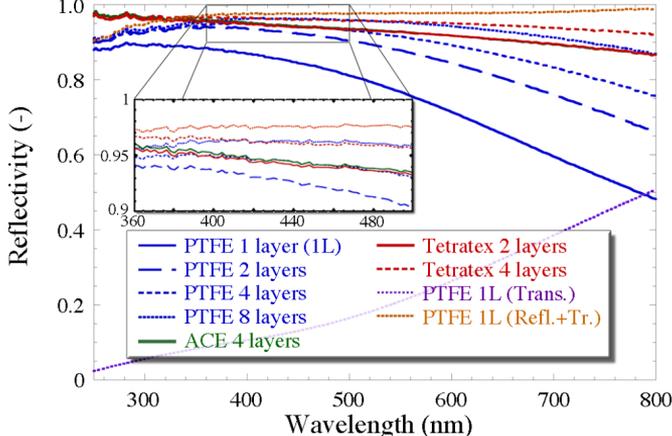
Bubble Imaging

- PTFE film reflectivity

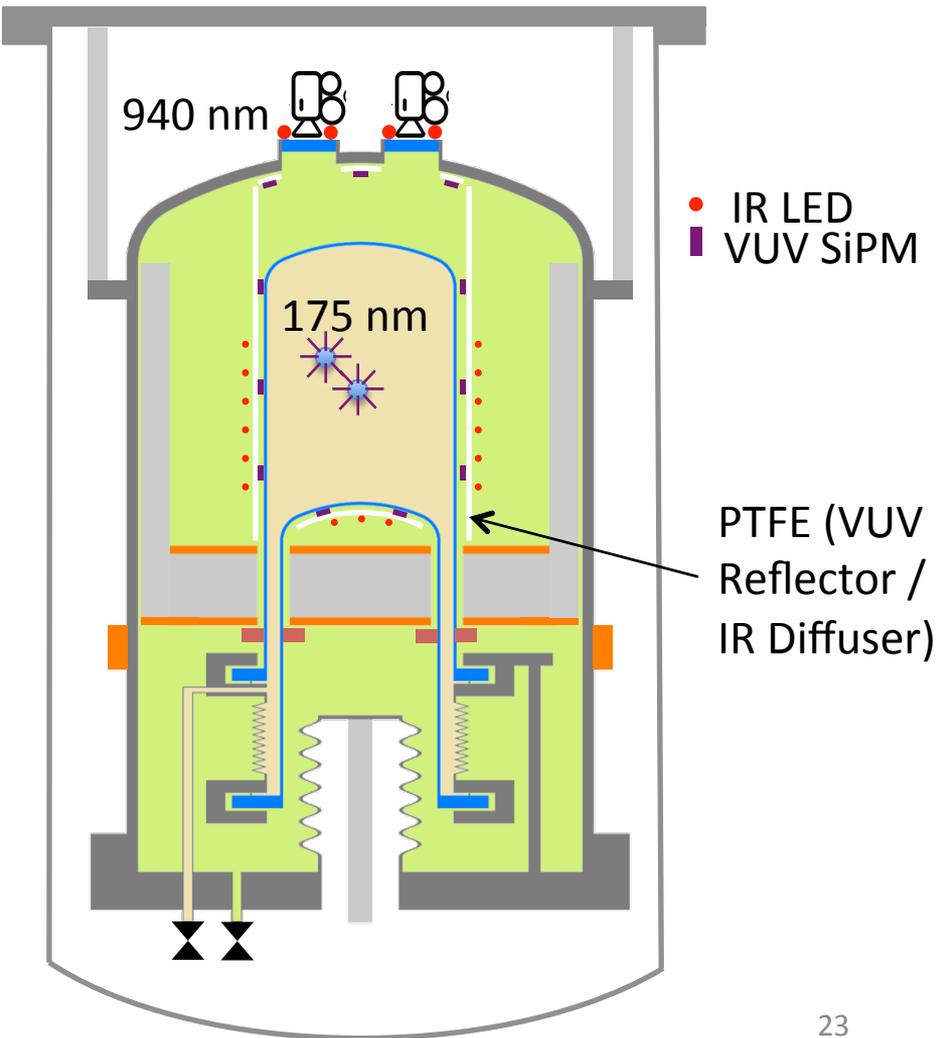
- crude model:

$$R \approx \frac{t}{t + 100\lambda}$$

- reality:



Janecek, IEEE Trans Nucl Sci
59(3):490-497 (2012)

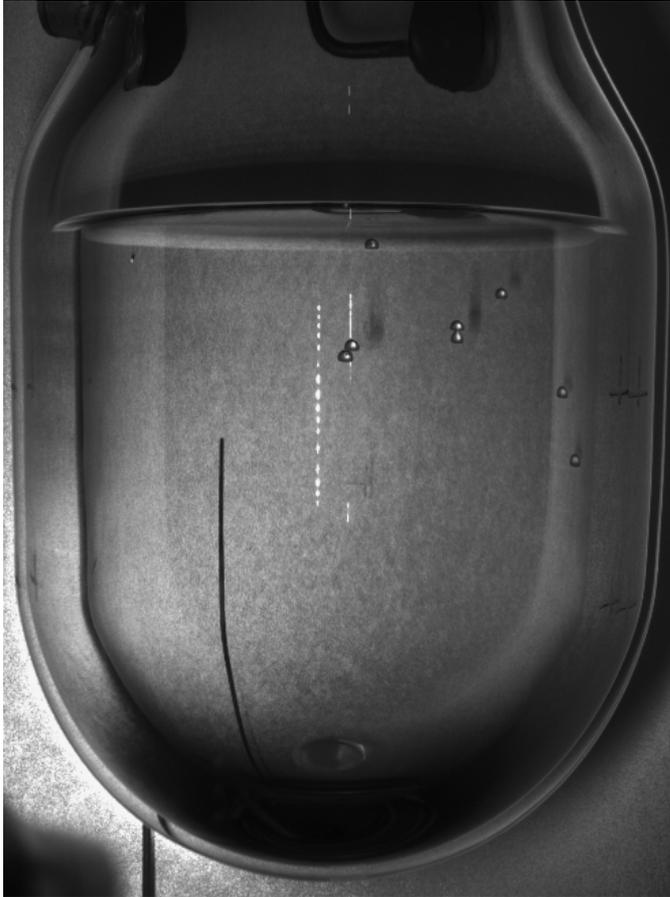


Big Challenge: Calibration

- How to measure a $O(100)$ eV bubble nucleation threshold?
 - Minimal: neutron scattering endpoint
 - $^{58}\text{Co} + \text{Be} \rightarrow 9 \text{ keV neutron} \rightarrow 860 \text{ eV maximum Ar recoil}$
 - Better: neutron scattering multiplicity measurement
 - Best: kinematically tagged neutron scatters

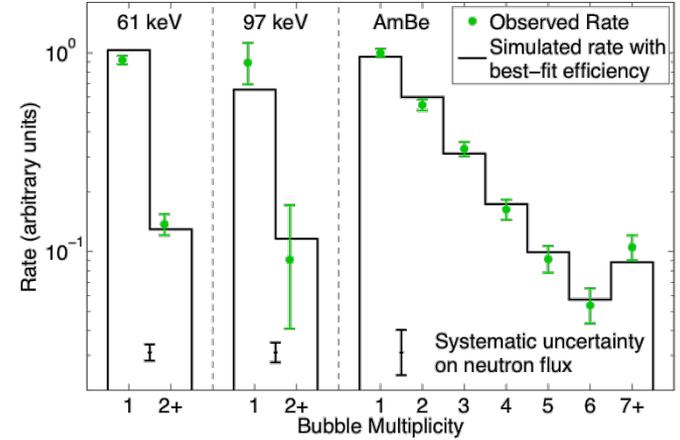
 - Challenge 1: Max $\sim 1,000$ bubbles per day (per detector)
 - Challenge 2: Much material between neutron source and superheated target

Nuclear Recoil Response



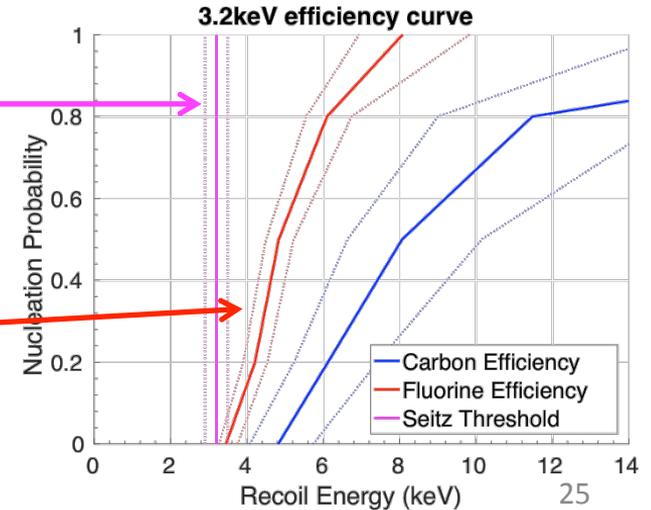
Dahl, 11/29/2018

Multiple neutron sources used to constrain recoil detection efficiency



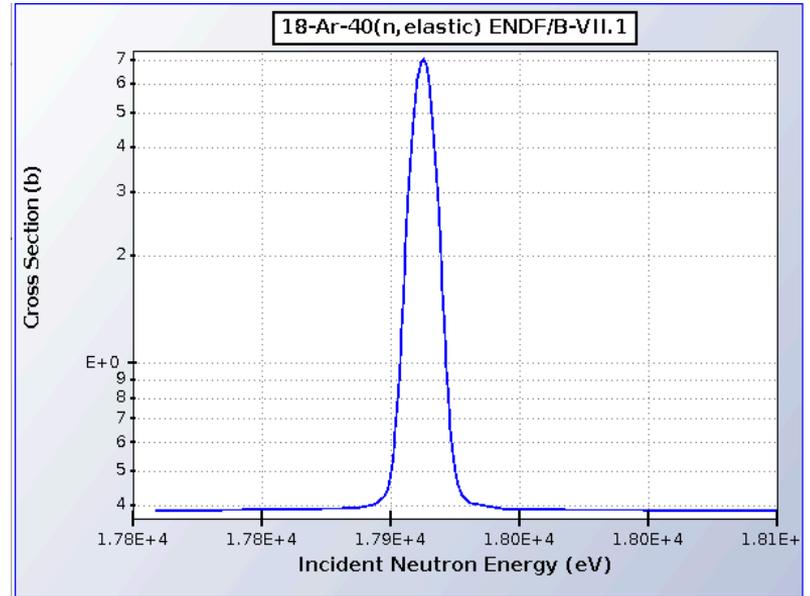
Calculated
thermodynamic
threshold

Calibrated
fluorine recoil
detection efficiency



Resonant scattering

- Argon has elastic neutron scattering resonances at 11.2, 17.9 keV
 - Use resonance to minimize impact of forward-scattered neutrons

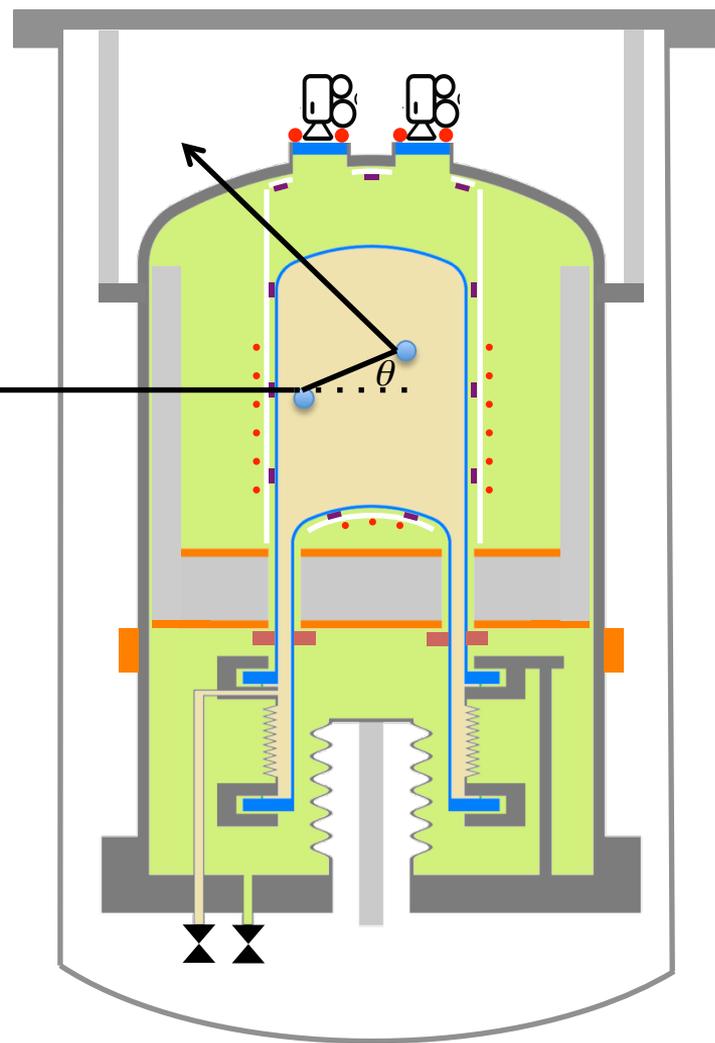


Neutron Scattering

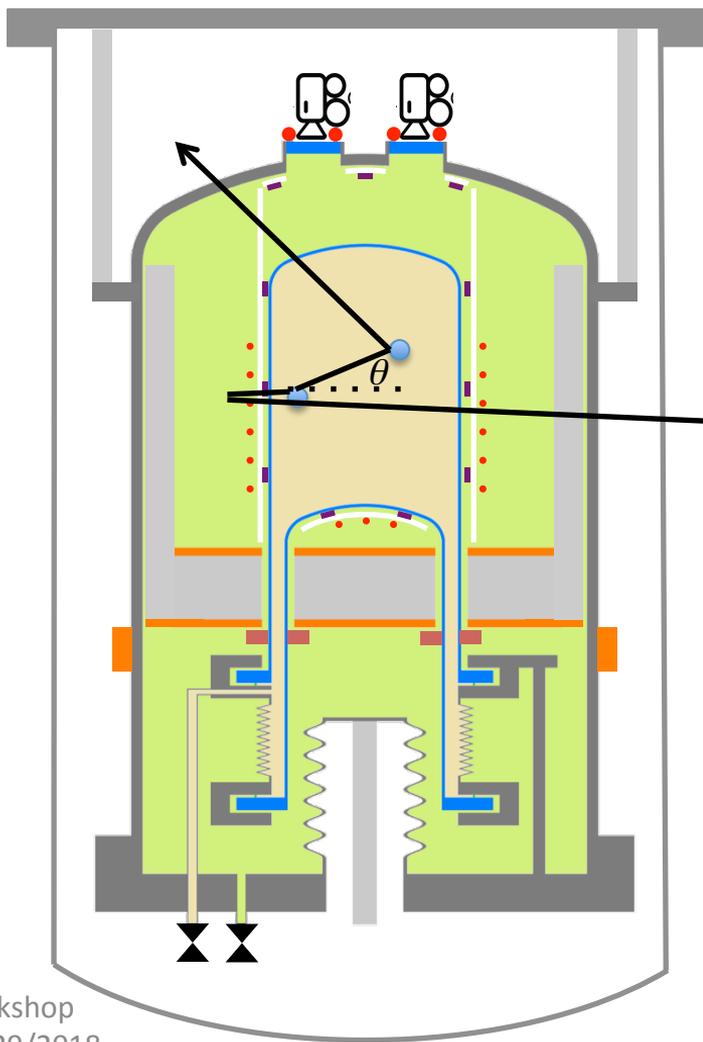
n

17.9 keV (on-resonance)
neutron beam

Non-trivial beam to make...



Neutron Scattering



Poor-researcher's 17.9 keV n source:

n

22.1 keV ^{124}Sb -Be neutron,
back-scattering from ^{19}F
lands on resonance

Simulations req'd to see
if this is useful.

*Scintillating Bubble Chamber



PICO



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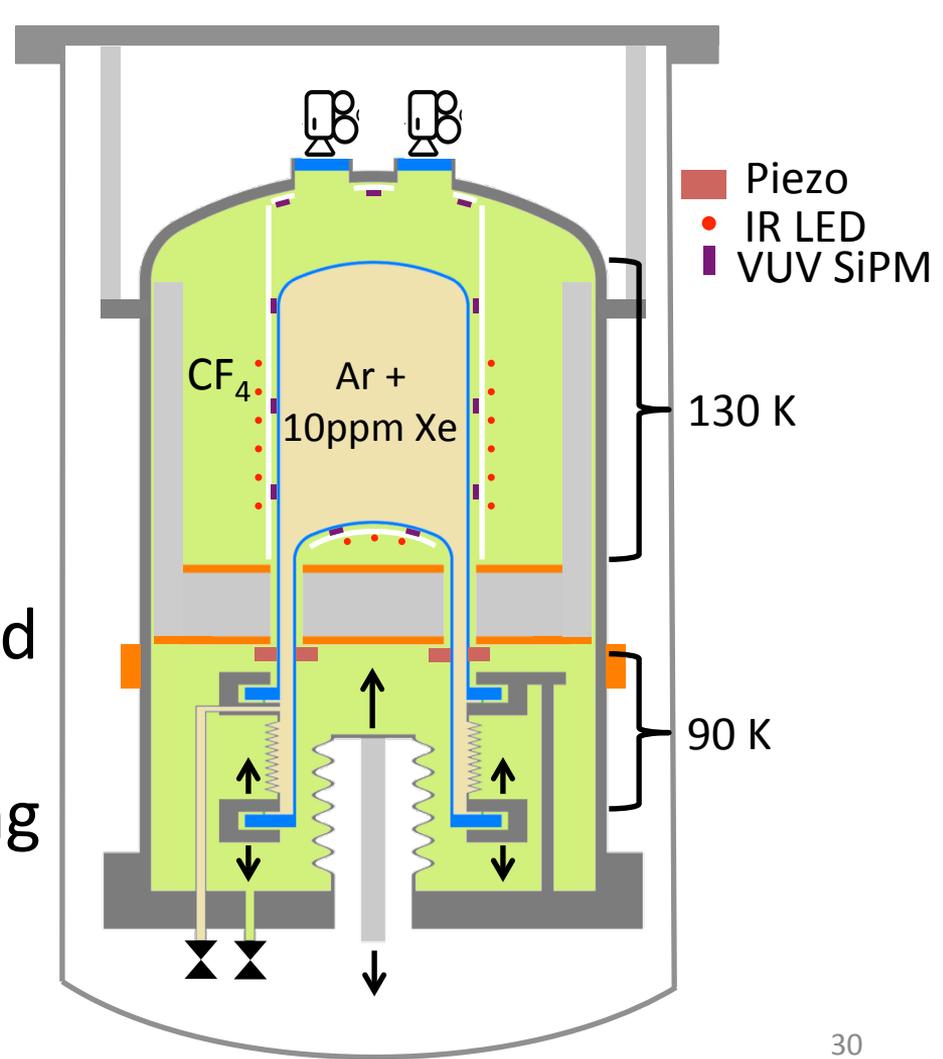
Fermilab LDRD 2018-003

DOE Award DE-SC0012161

COFI support for COFI Fellow Rocco Coppejans

Summary

- Liquid Noble Bubble Chambers
 - Unique potential for background-free reactor CEvNS measurements and GeV WIMP searches
 - Simple idea, many moving parts



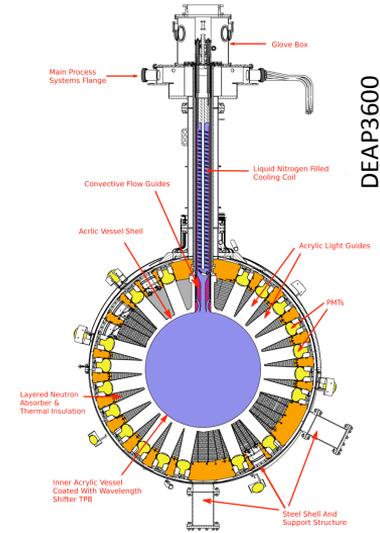
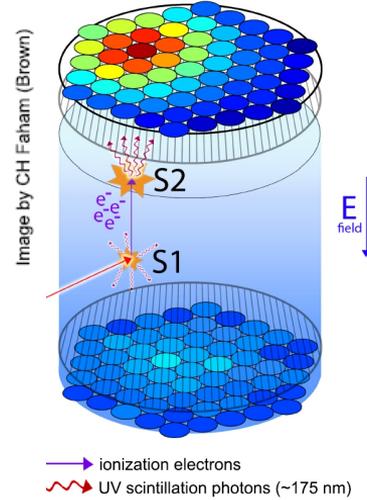
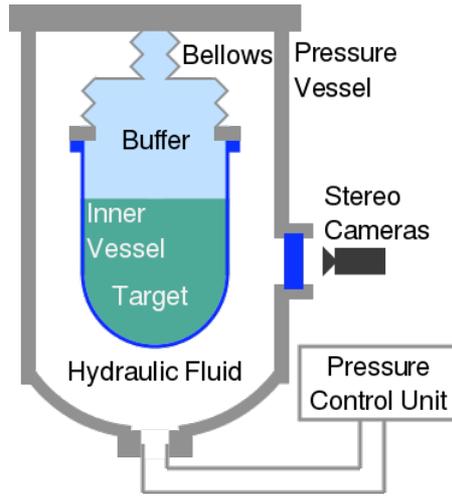
Backup

Potential SBC Specifications

Parameter	Value
Threshold (Bubble Nucleation)	100 eV _r (Argon recoil energy)
Resolution (Bubble Nucleation)	~100 eV _r (spectrum built by threshold scan)
“Quenching” (Bubble Nucleation)	1 – Lindhard ≈ 0.8
Threshold (Scintillation*)	5 keVr (single photon detected)
Resolution (Scintillation*)	Poisson on # photons detected
Quenching (Scintillation*)	Lindhard ≈ 0.2
Target Mass	10-kg being built now, scalable to 1-ton before ³⁹ Ar becomes concern
Background concerns	Neutrons only (and no Pb shield -> no NIN’s)
Other unique features	Event-by-event tagging of inelastic recoils

*Scintillation used primarily as veto and for sideband studies-
Most reactor CEvNS events will have zero scintillation signal

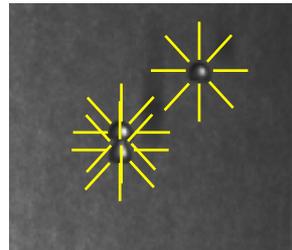
Why Liquid-noble Bubble Chambers



Event-by-event
Energy

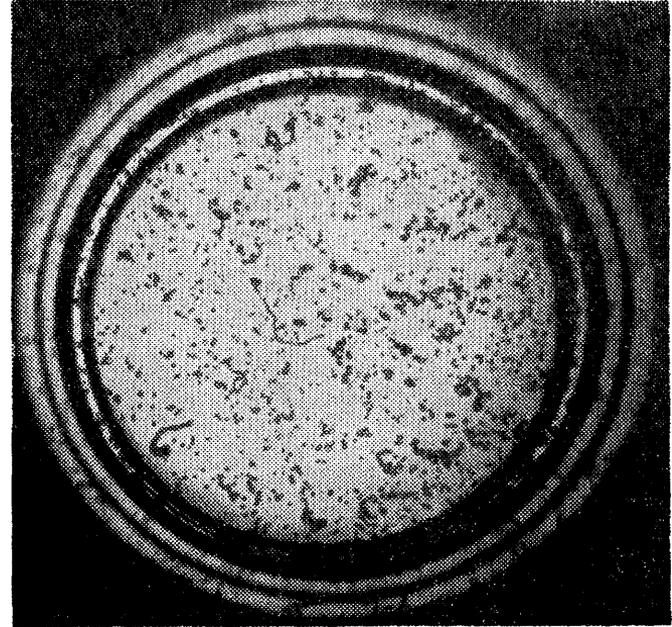
10^{-10} discrimination

Low-threshold (< keV)
ER discrimination



Scintillating Bubble Chamber History (Why they might not work...)

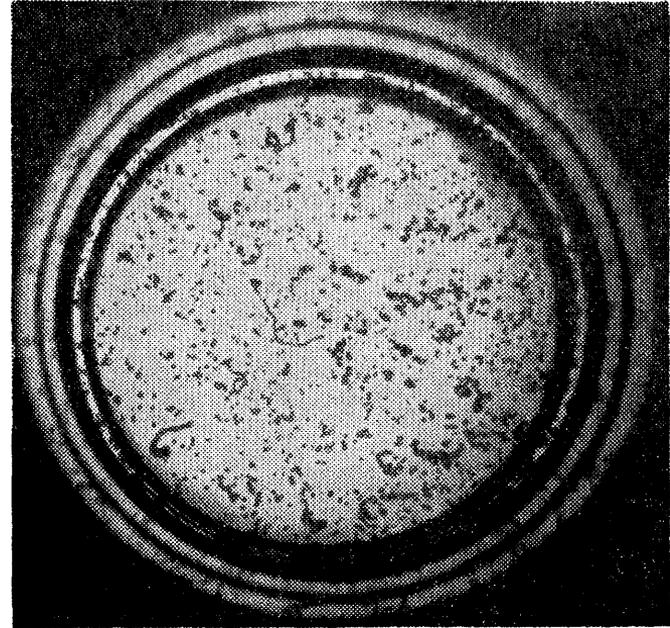
- Glaser built a xenon bubble chamber in 1956 and found:
 - **No bubbles** in pure xenon even at ~ 1 keV threshold (with gamma source)
 - Normal bubble nucleation in 98% xenon + 2% ethylene (scintillation completely quenched)



Phys.Rev. **102**, 586 (1956)

Scintillating Bubble Chamber History (...or why they might work *really* well)

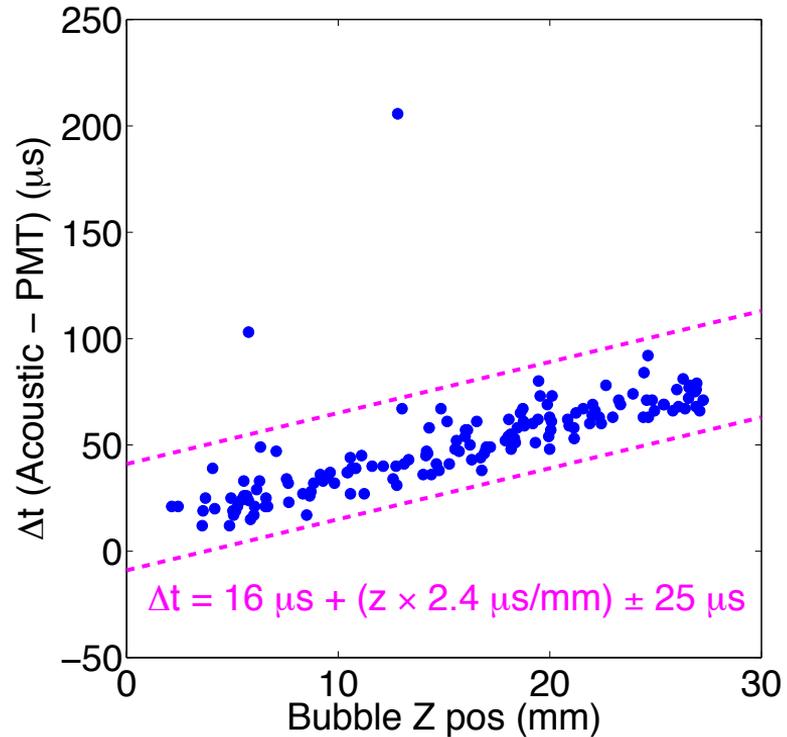
- Scintillation suppresses bubble nucleation?
 - **Electrons** should be even less likely to make bubbles than in freon chambers
 - Greater superheat (lower thresholds) possible
 - **Nuclear Recoils should be largely unaffected**, thanks to Lindhard Effect



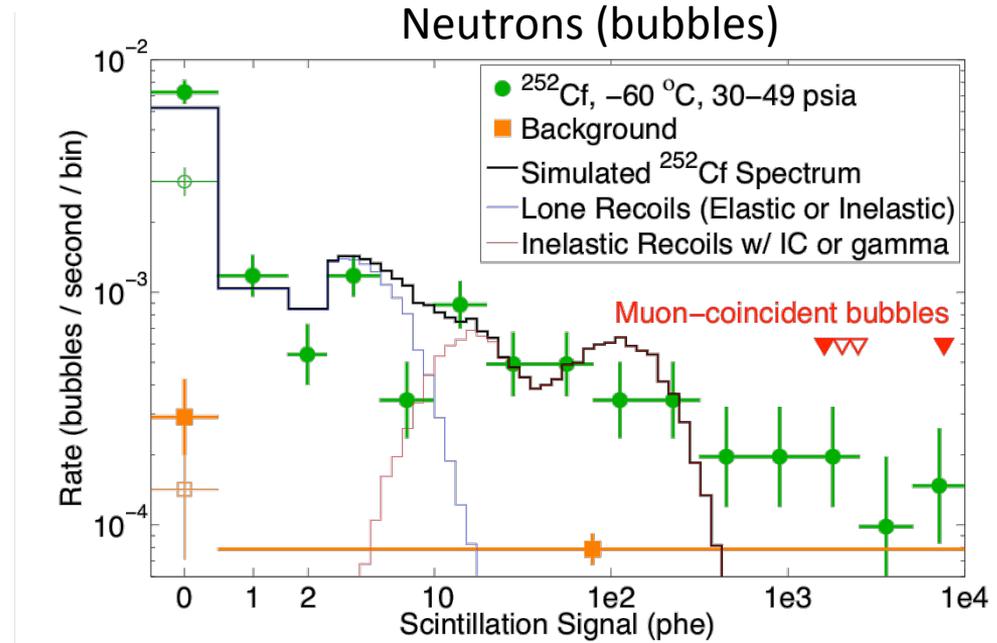
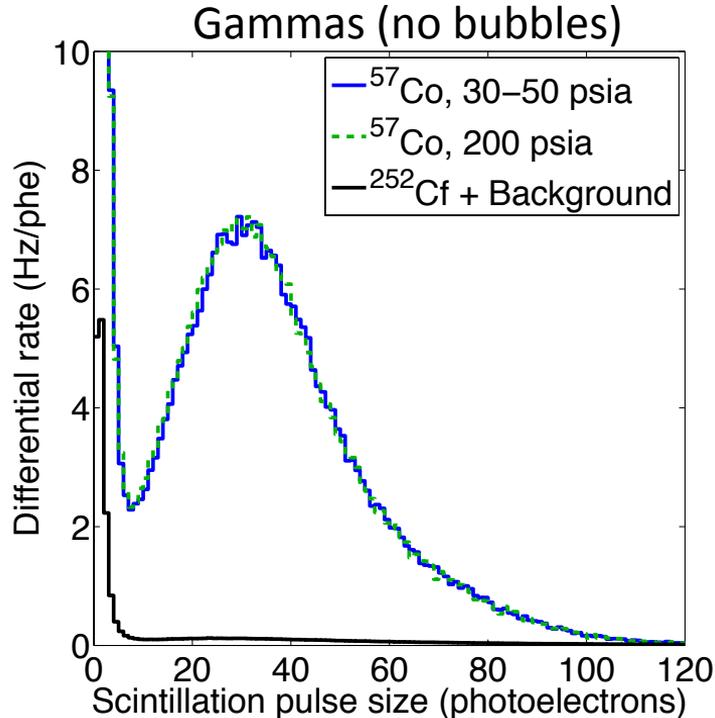
Phys.Rev. **102**, 586 (1956)

Acoustic – Scintillation Coincidence

- $< 1\%$ accidental coincidence rate in calibration data
- Slope = speed of sound in xenon (to 20%)



Scintillation Spectra



- Scintillation unaffected by superheated state



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Key Pubs:

- PRL 118, 251301 (2017), arXiv:1702.07666 (PICO-60)
- PRL 118, 231301 (2017), arXiv:1702.08861 (XeBC)