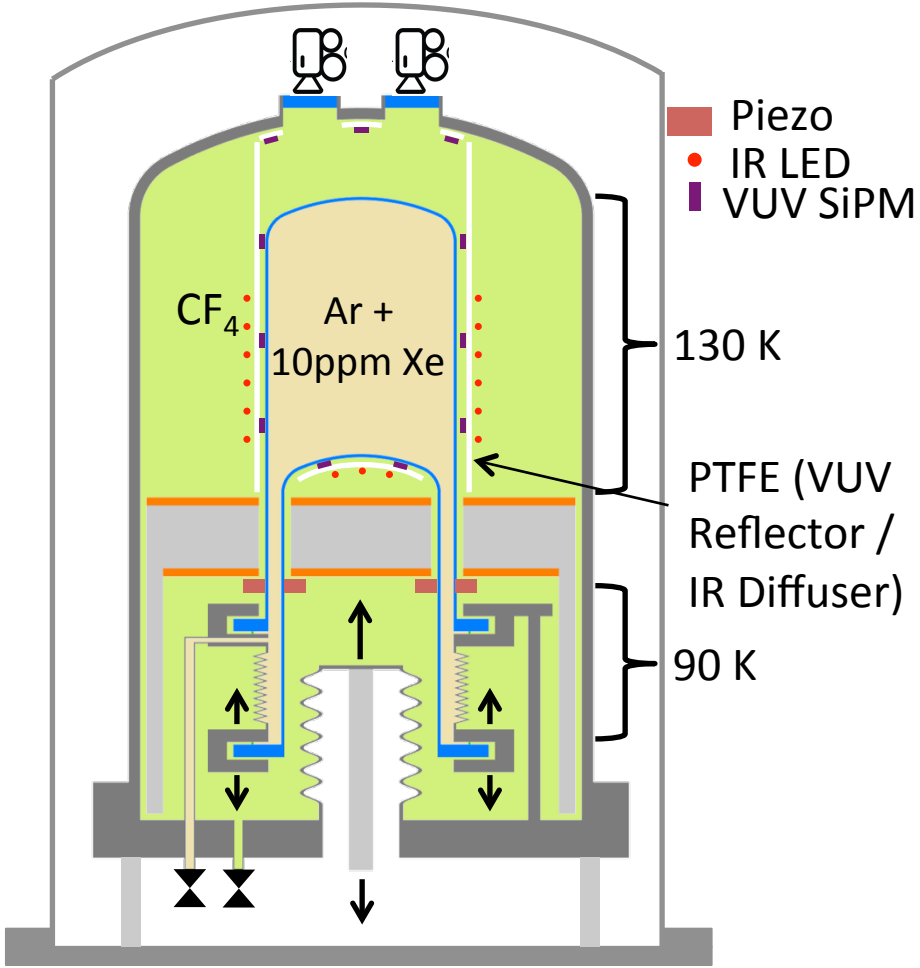
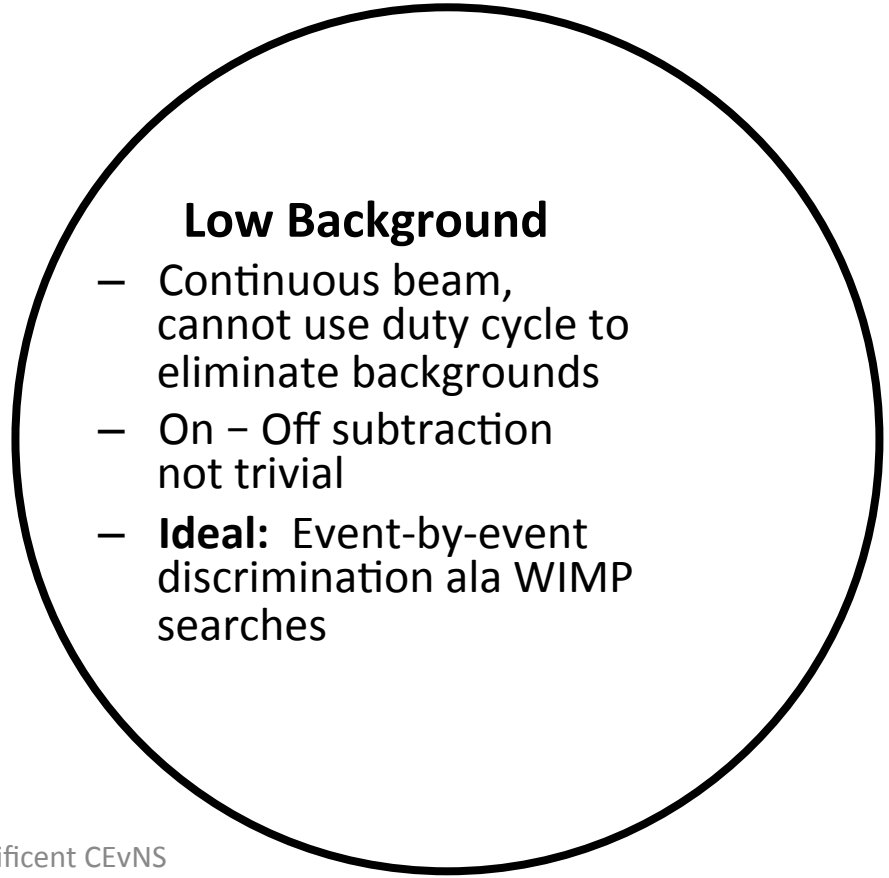
Scintillating Bubble Chambers for Reactor CEvNS

Eric Dahl
Northwestern University
Fermilab

The Magnificent CEvNS, Nov 2018



The Reactor CEvNS Detector Conundrum



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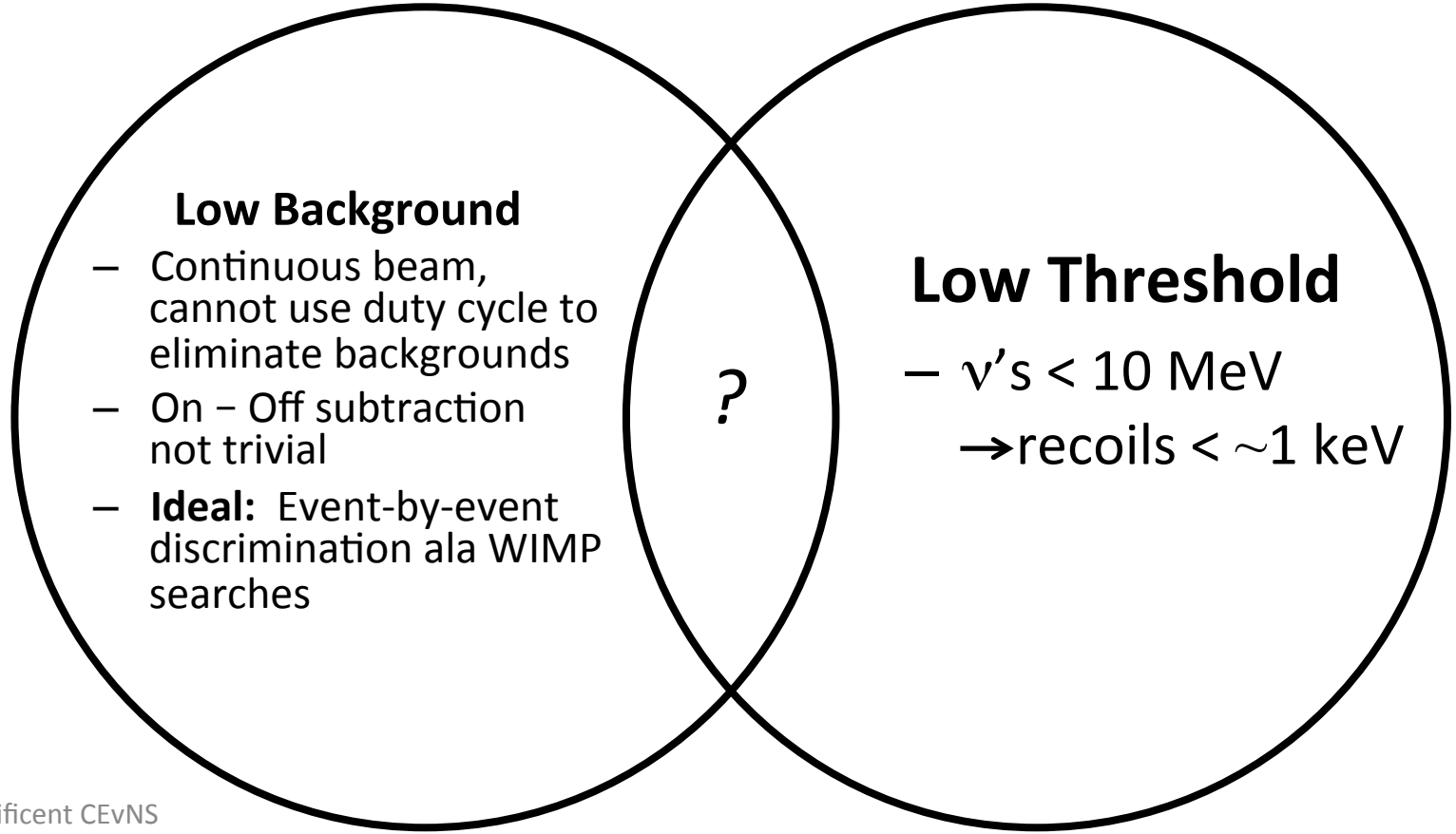
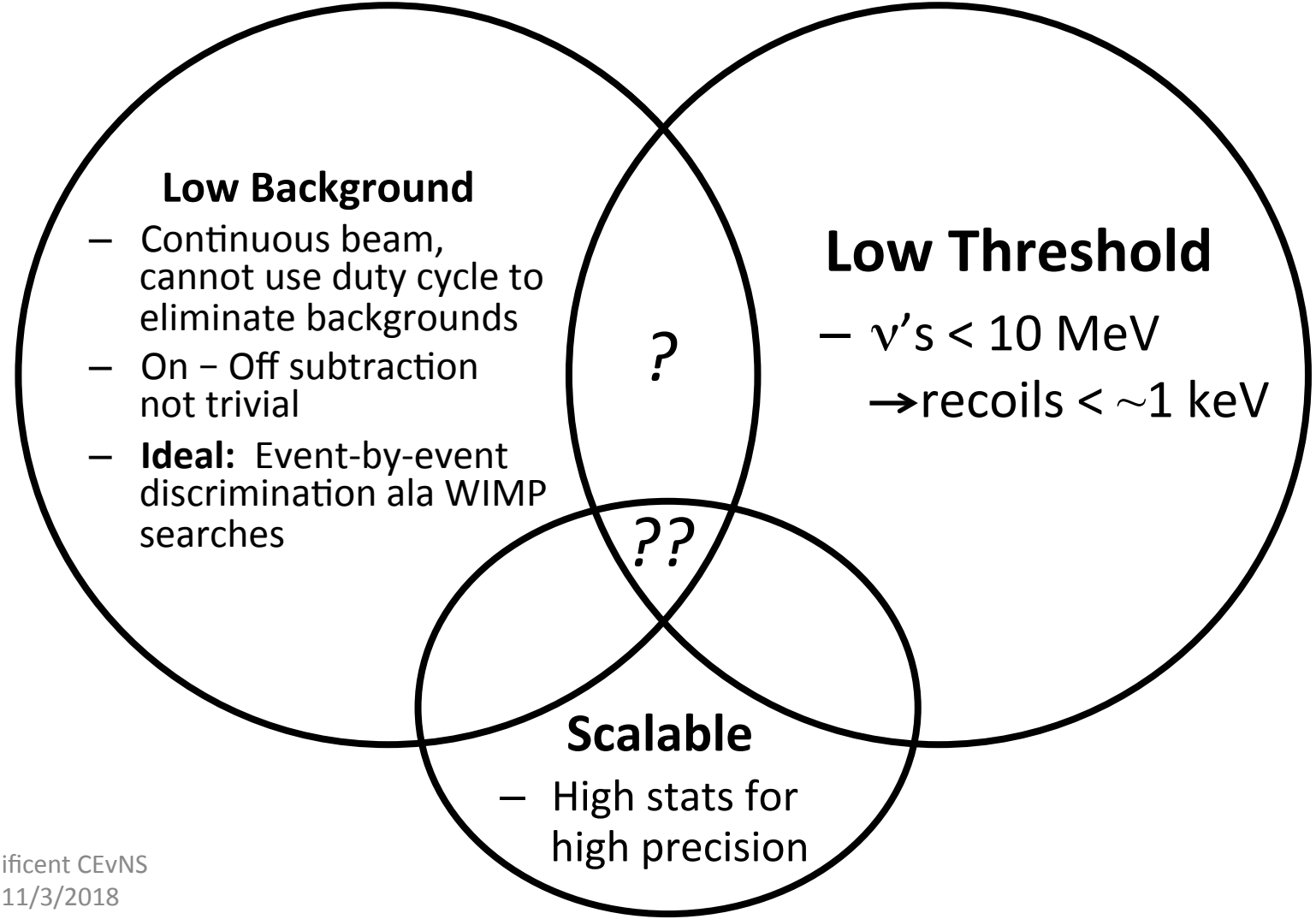
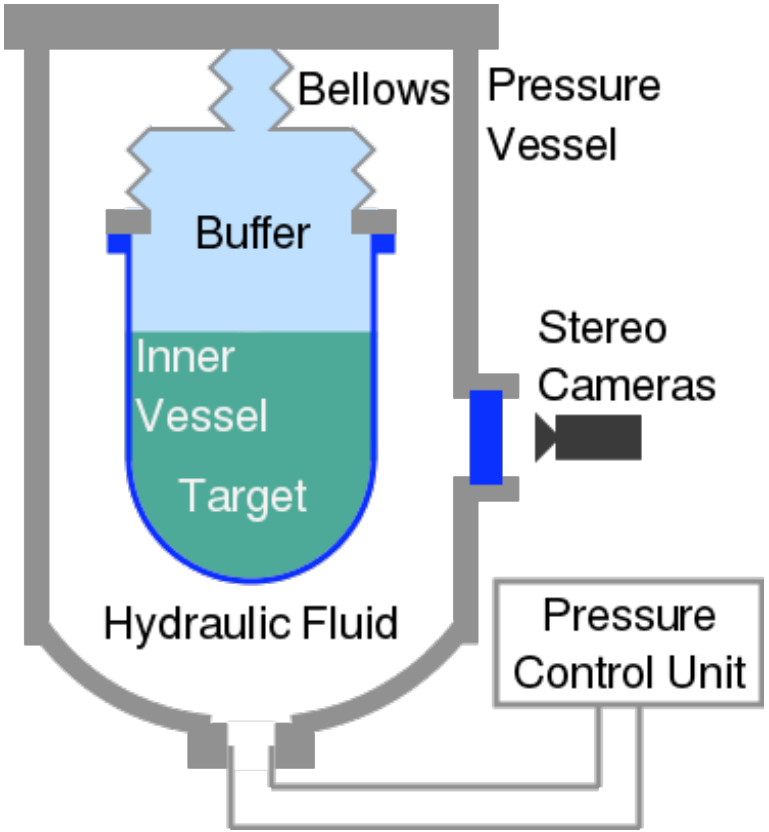



Low Background
– Continuous beam, cannot use duty cycle to eliminate backgrounds
– On – Off subtraction not trivial
– Ideal: Event-by-event discrimination ala WIMP searches
?
Low Threshold
– ν's < 10 MeV
→recoils < ~1 keV
??
Scalable
– High stats for high precision

Bubble Chambers

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



PICO

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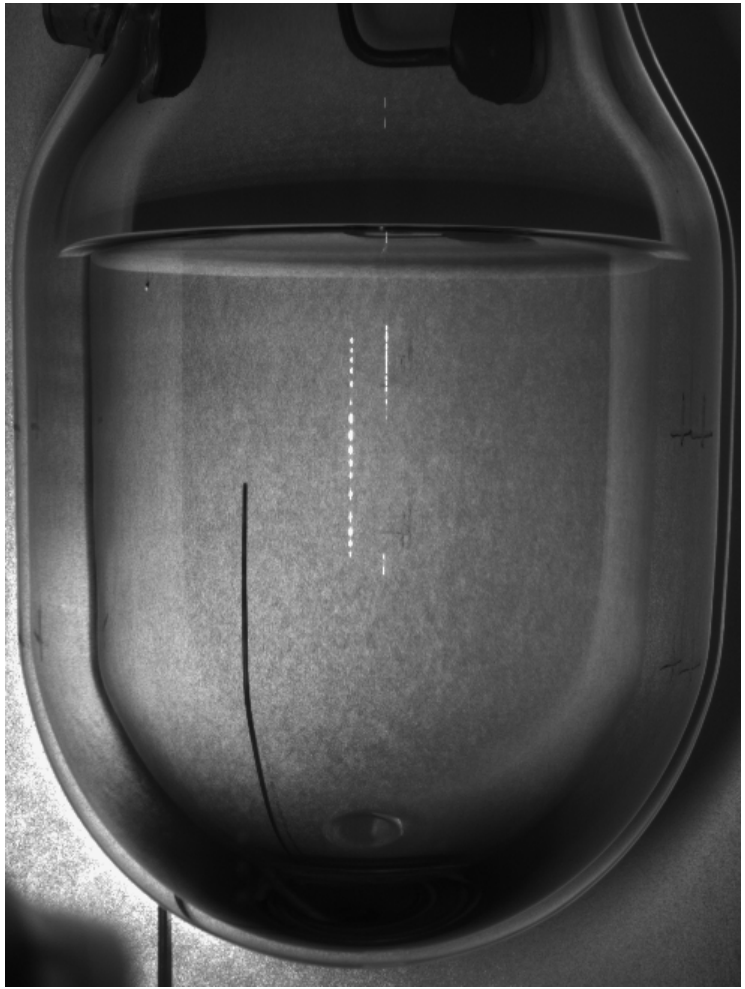

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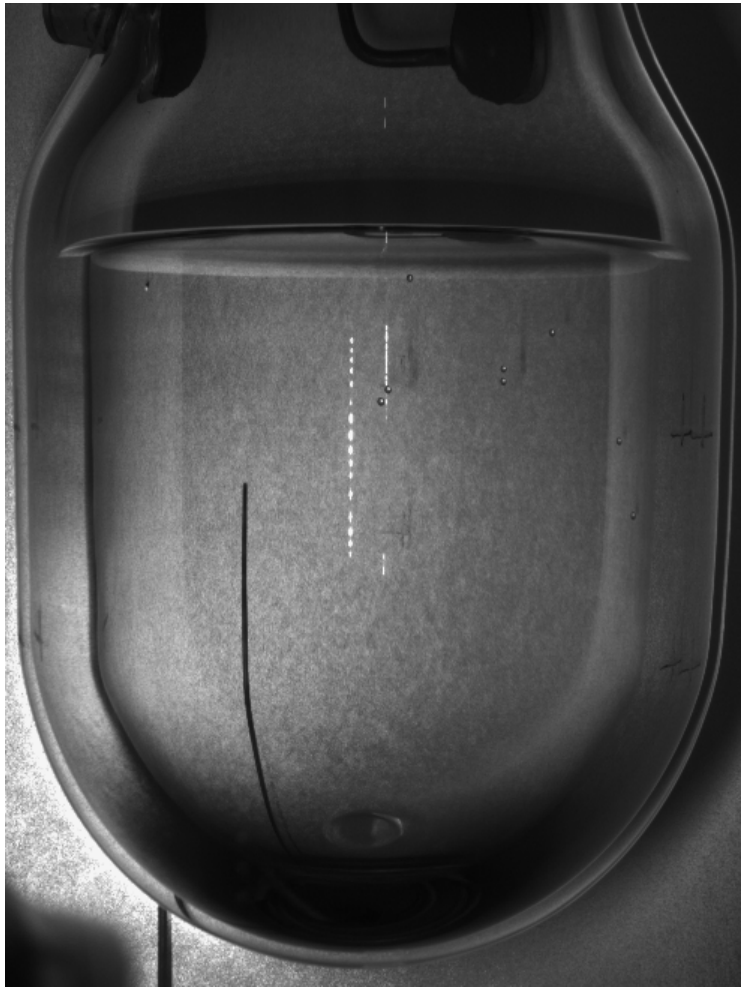

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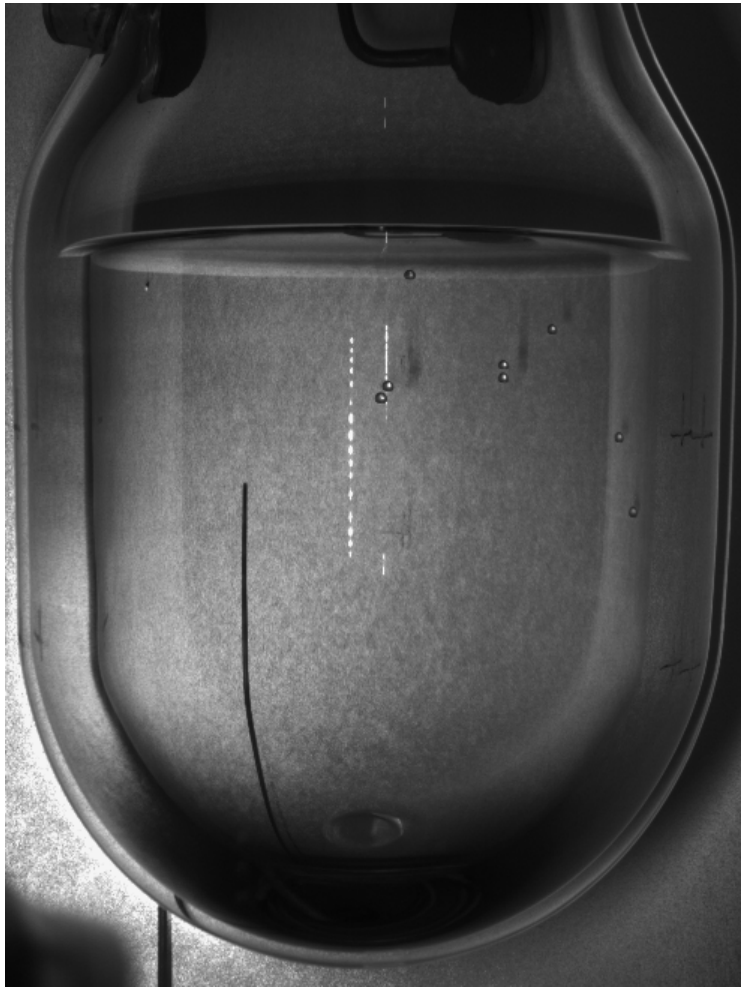

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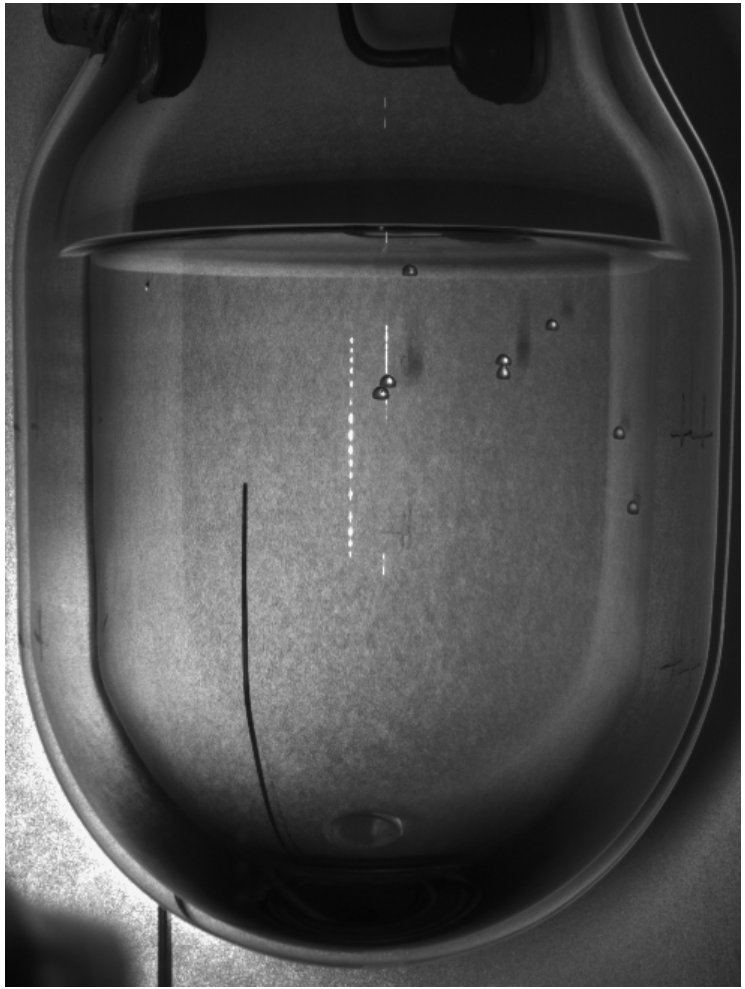

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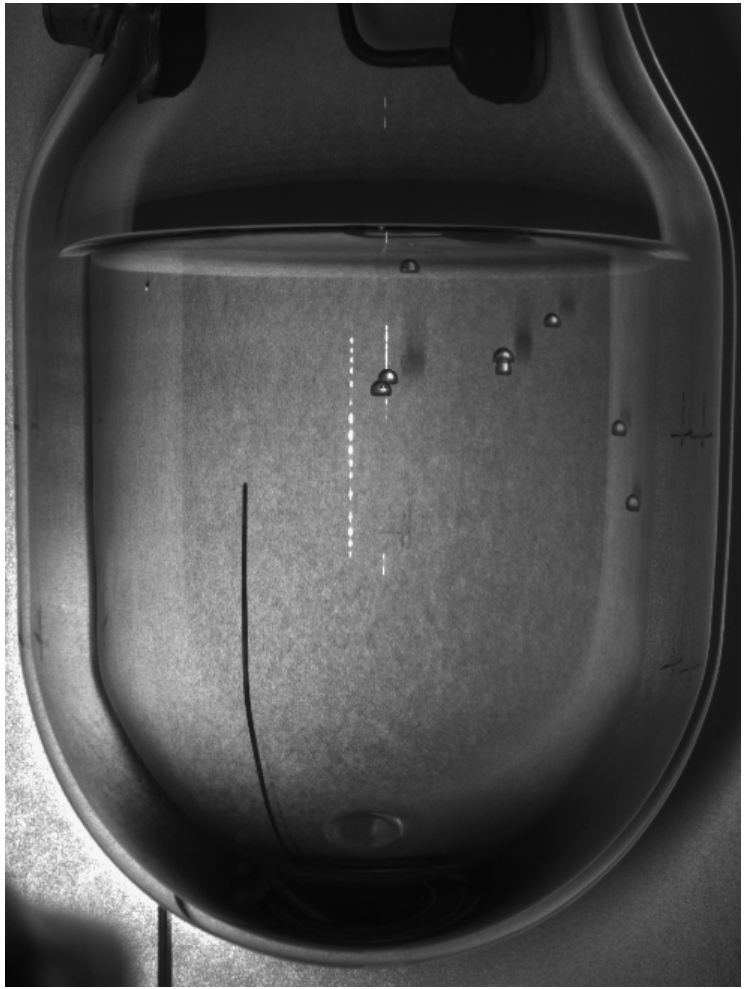

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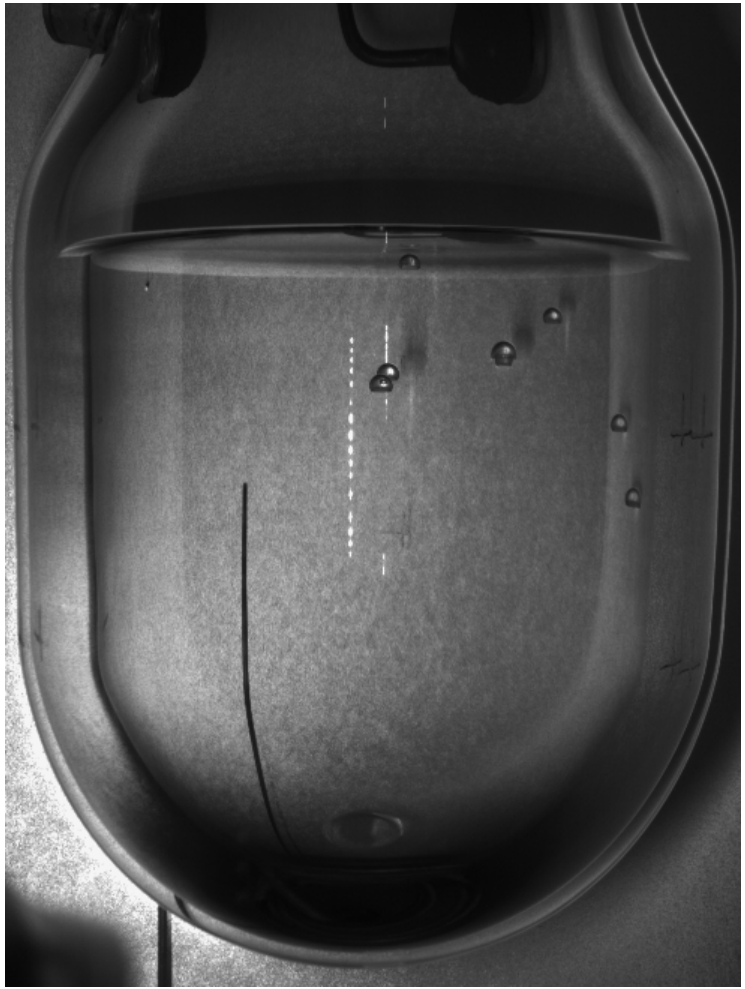

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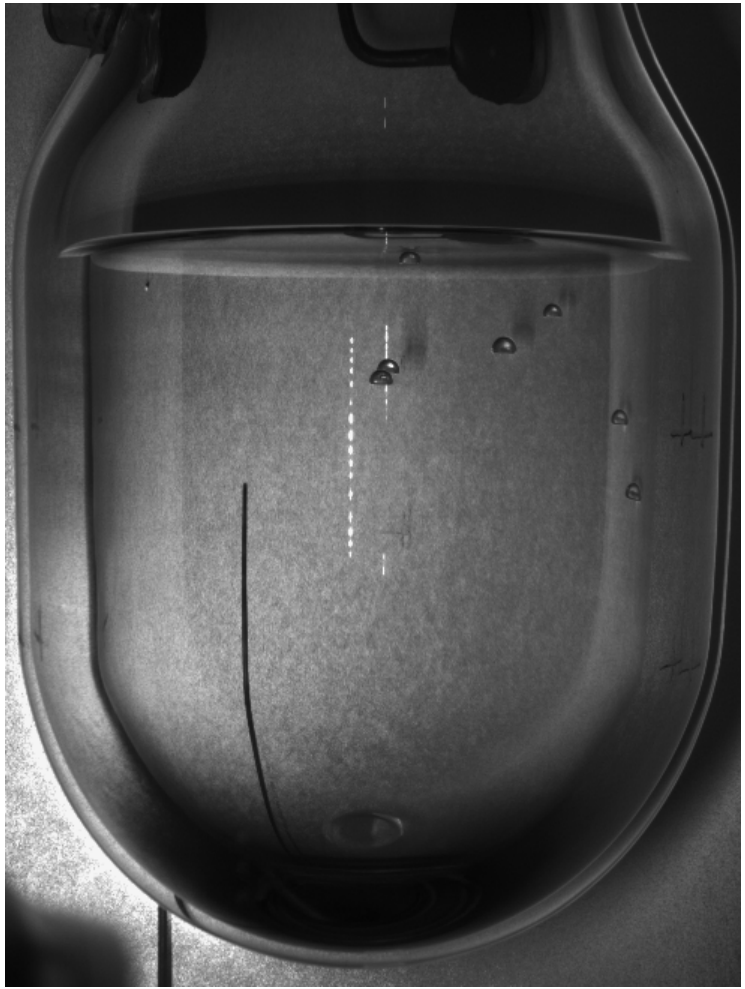

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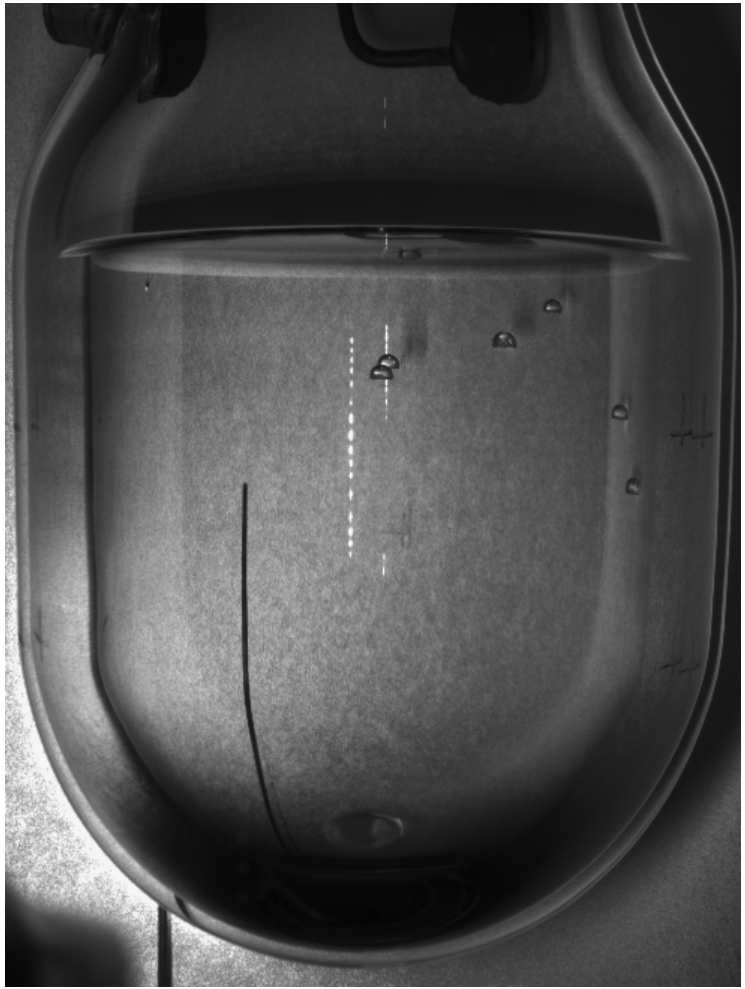

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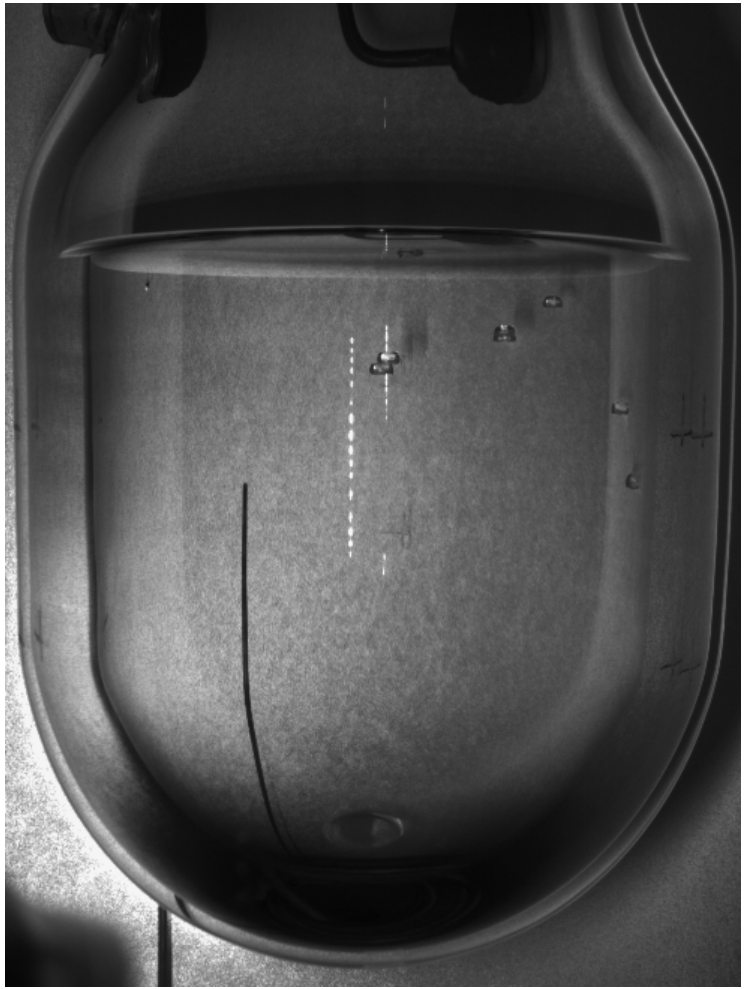

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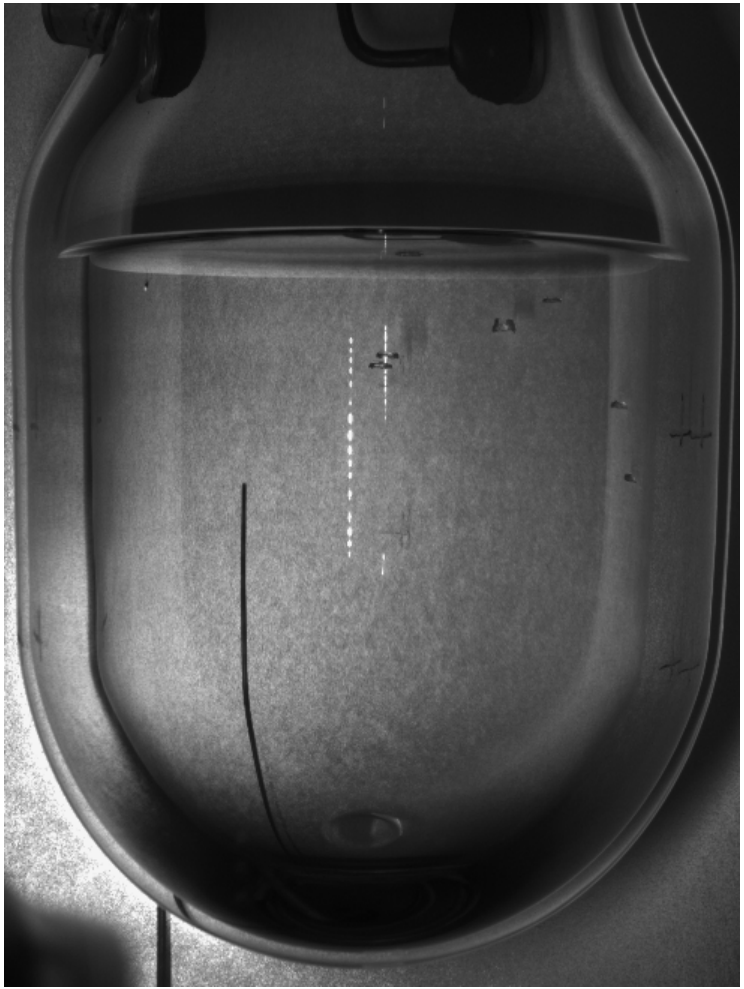

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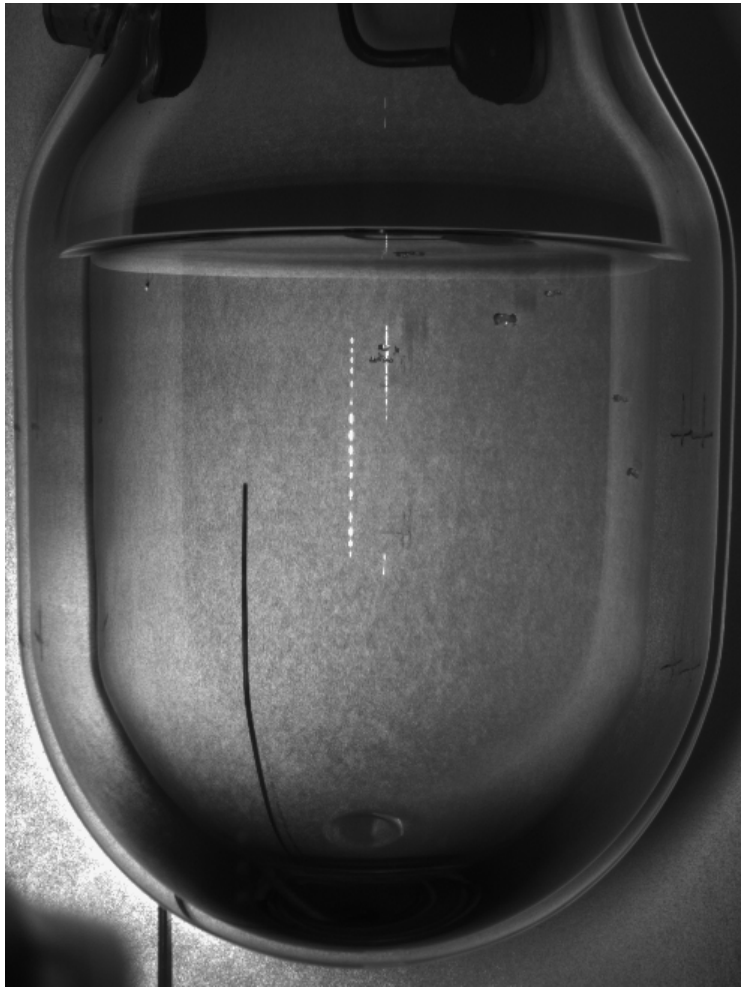

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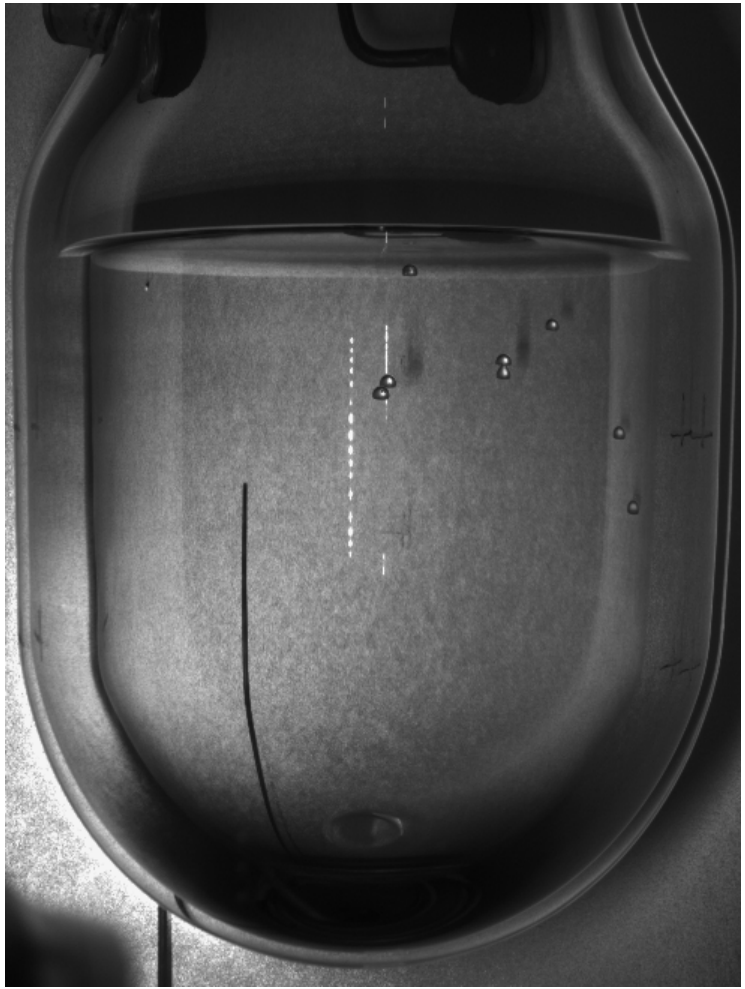
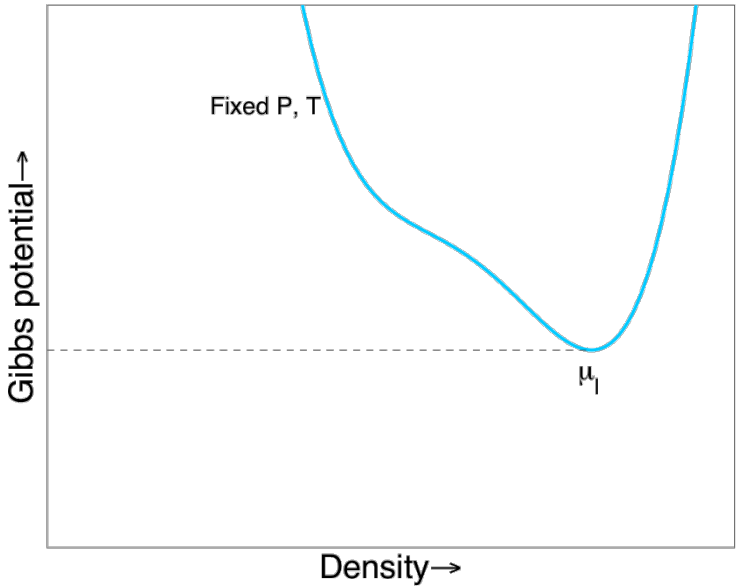
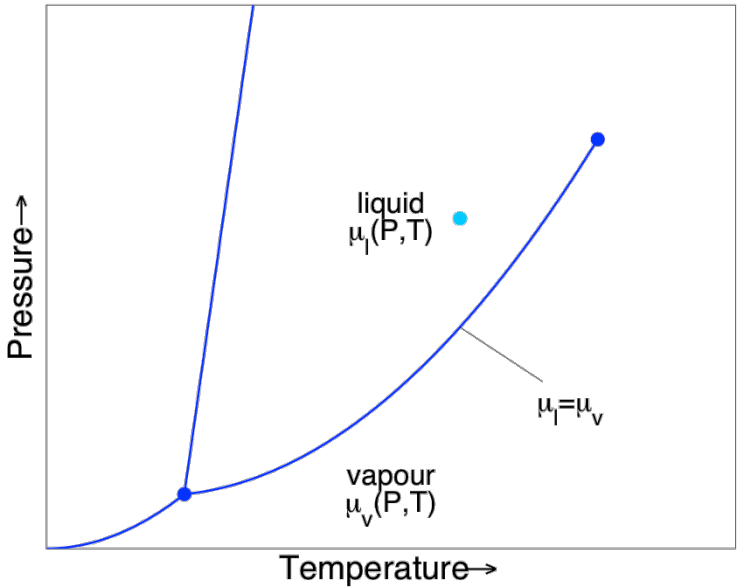


Bubble Chamber Thermodynamics

- What is a metastable state?





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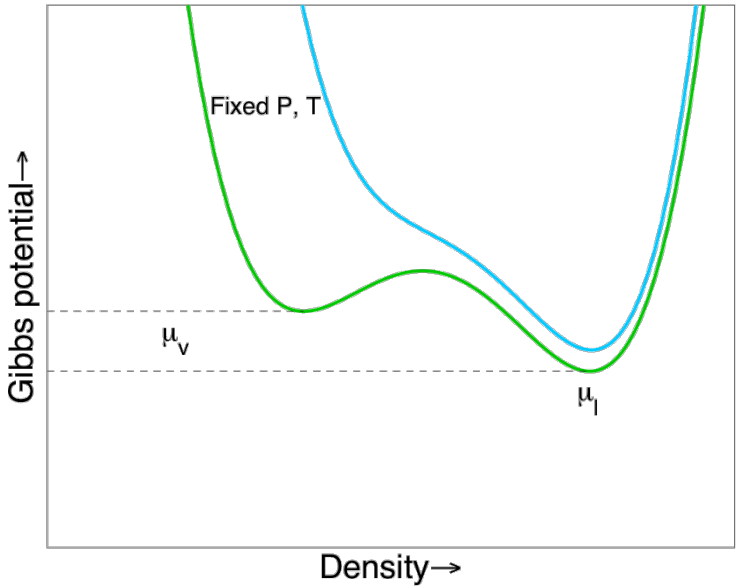

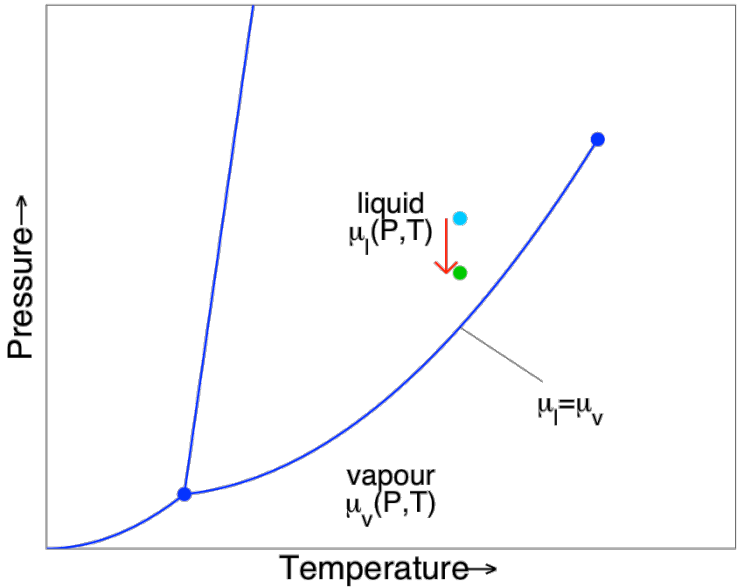

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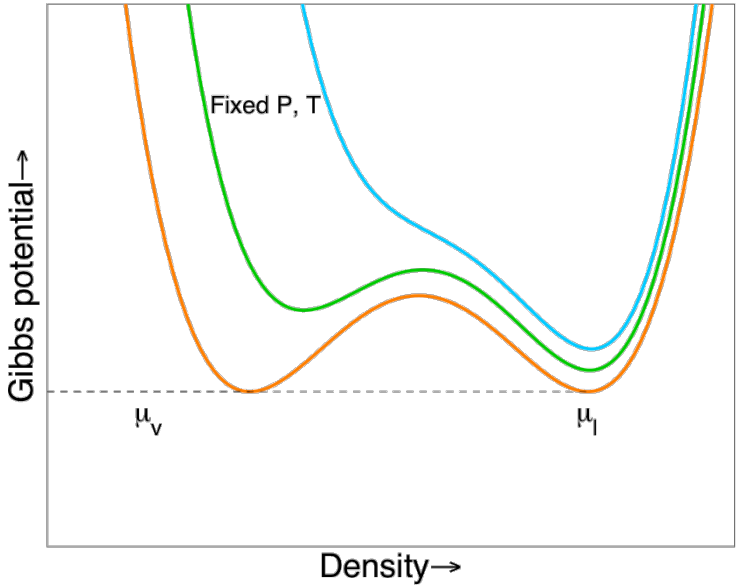

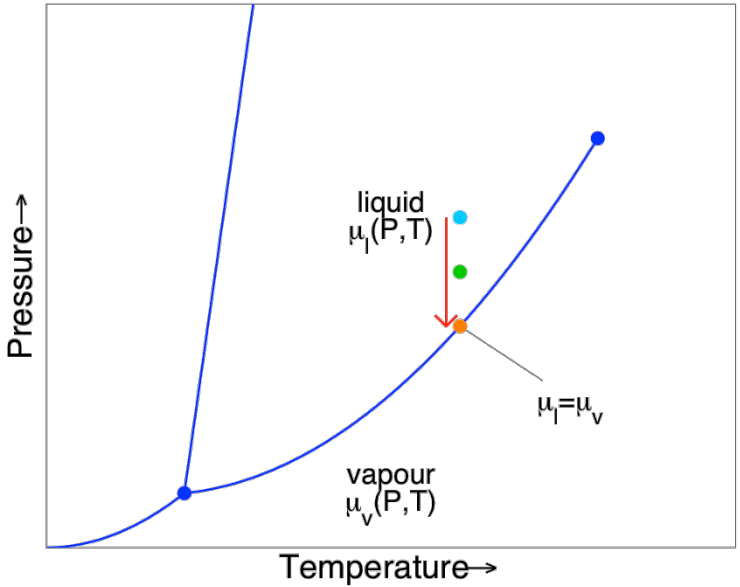

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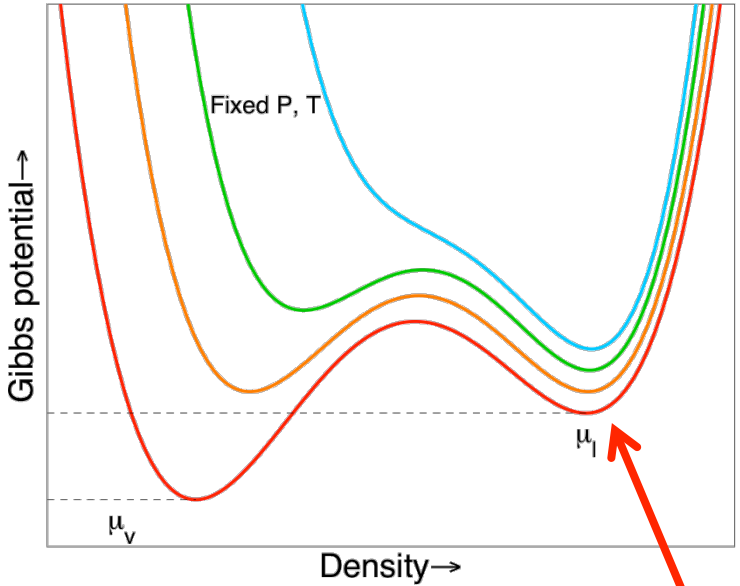

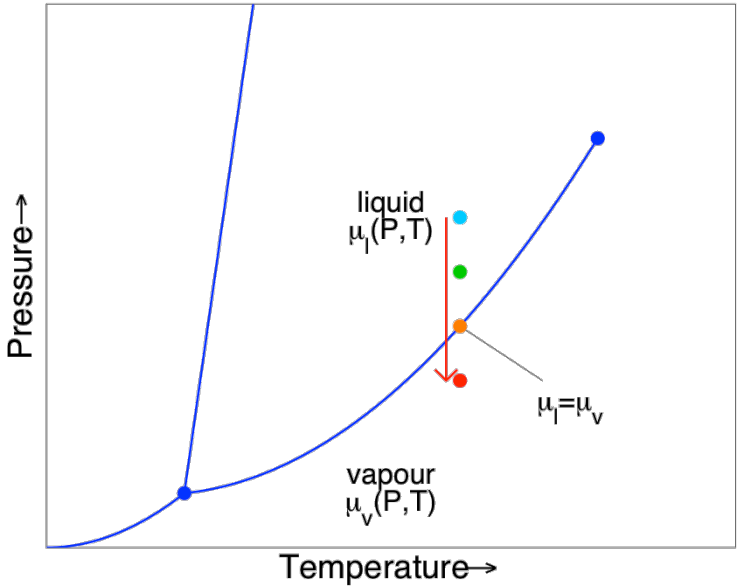

Superheated Liquid

Bubble Chamber Thermodynamics

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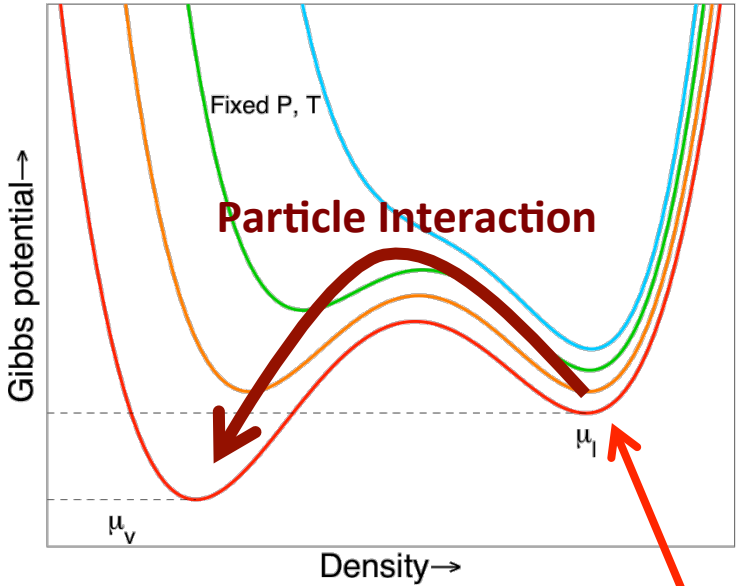

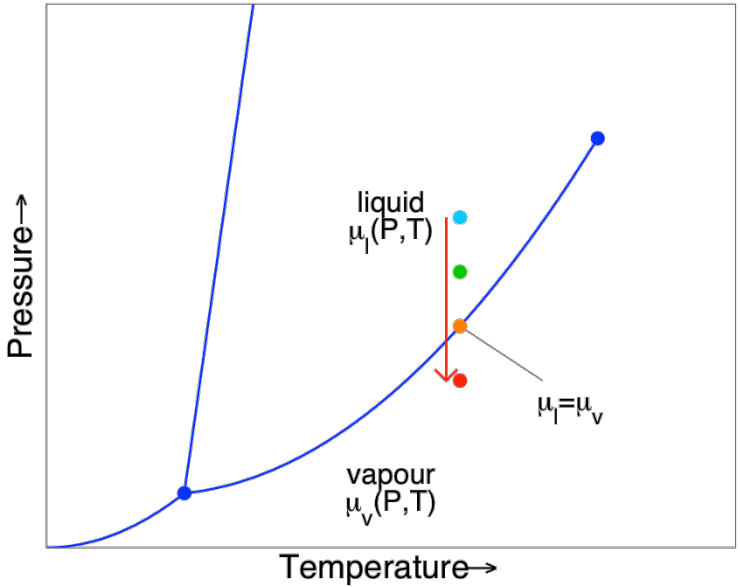

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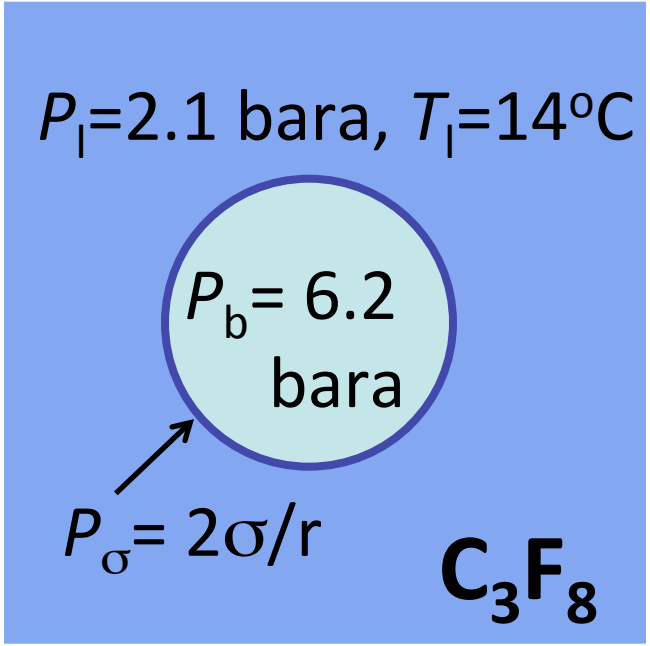
- What does it take to nucleate a bubble?



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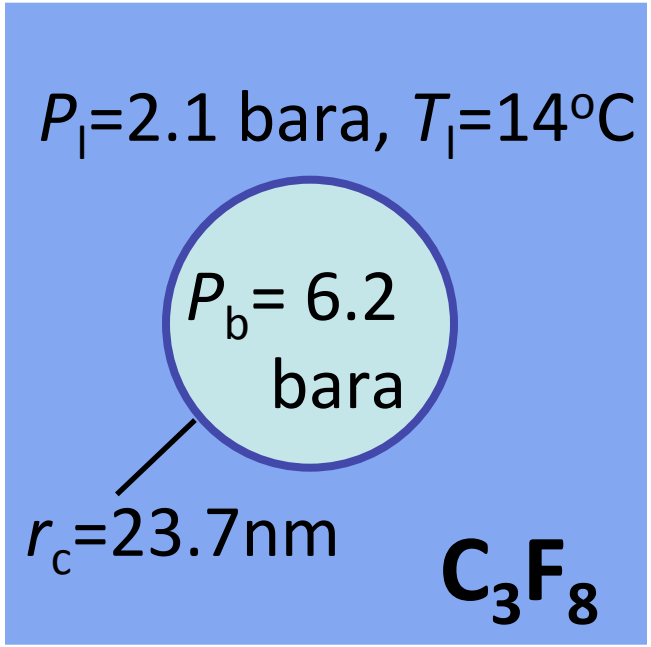


"Critical Radius"

Bubble Chamber Thermodynamics

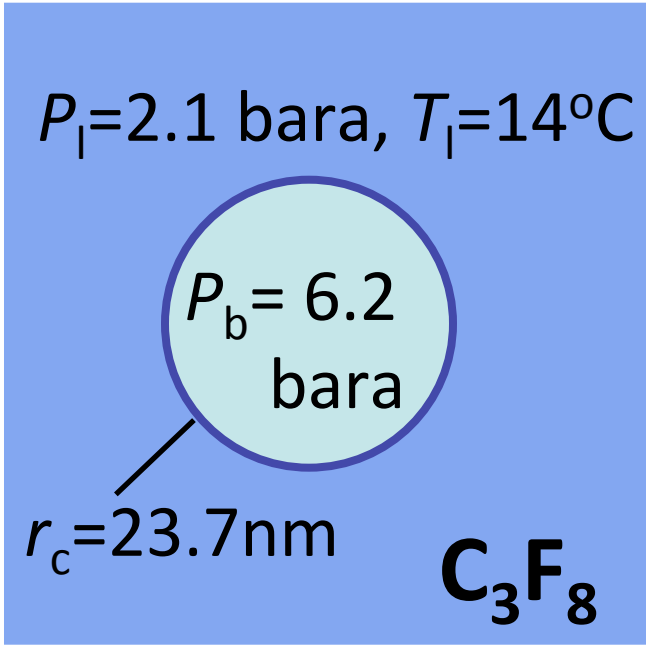
- What does it take to nucleate a bubble?

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

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

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

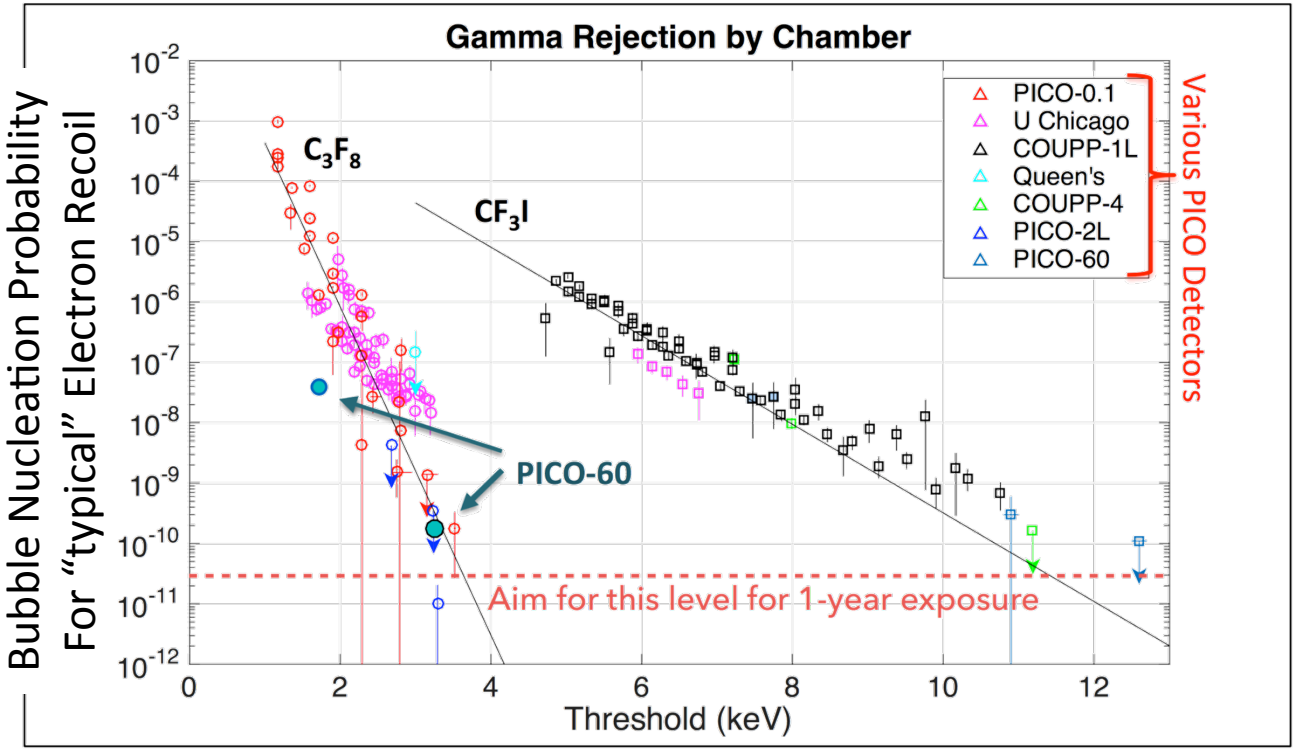
= 3.19 keV *"Thermodynamic Threshold"*



"Critical Radius"

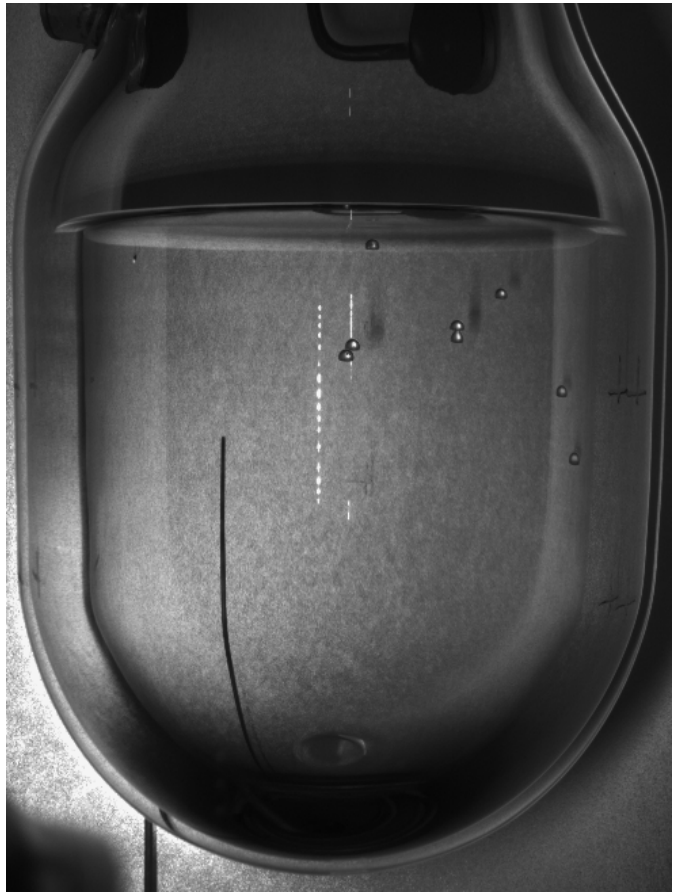
Electron Recoil Discrimination

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

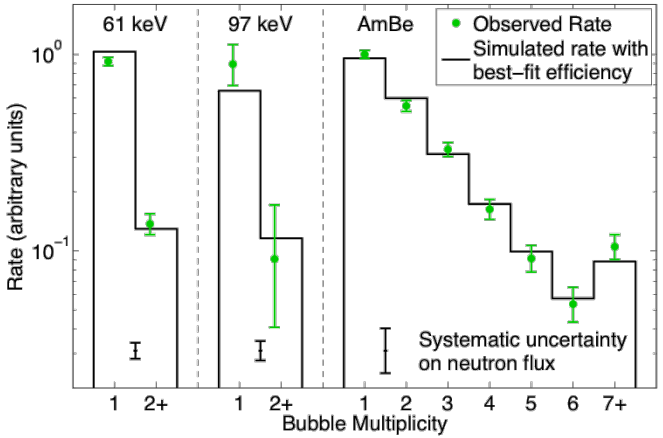


(Dan Baxter, Conference on Science at SURF, May 14, 2017)

Nuclear Recoil Response

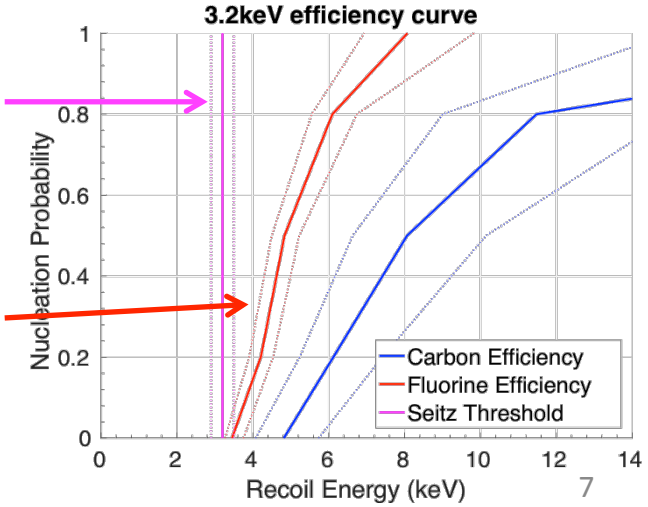


Multiple neutron sources used to constrain recoil detection efficiency



Calculated thermodynamic threshold

Calibrated fluorine recoil detection efficiency



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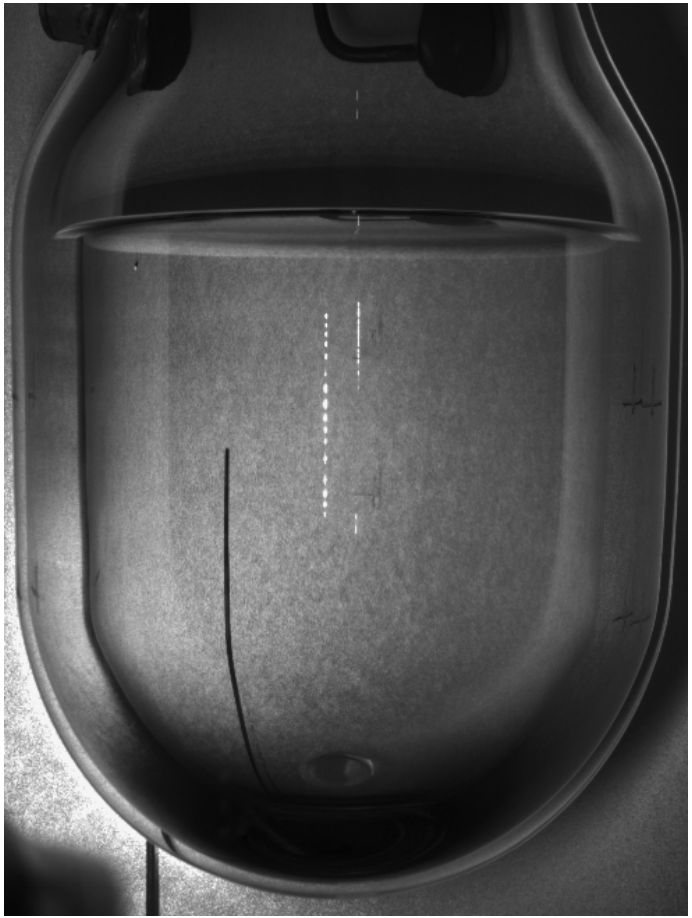
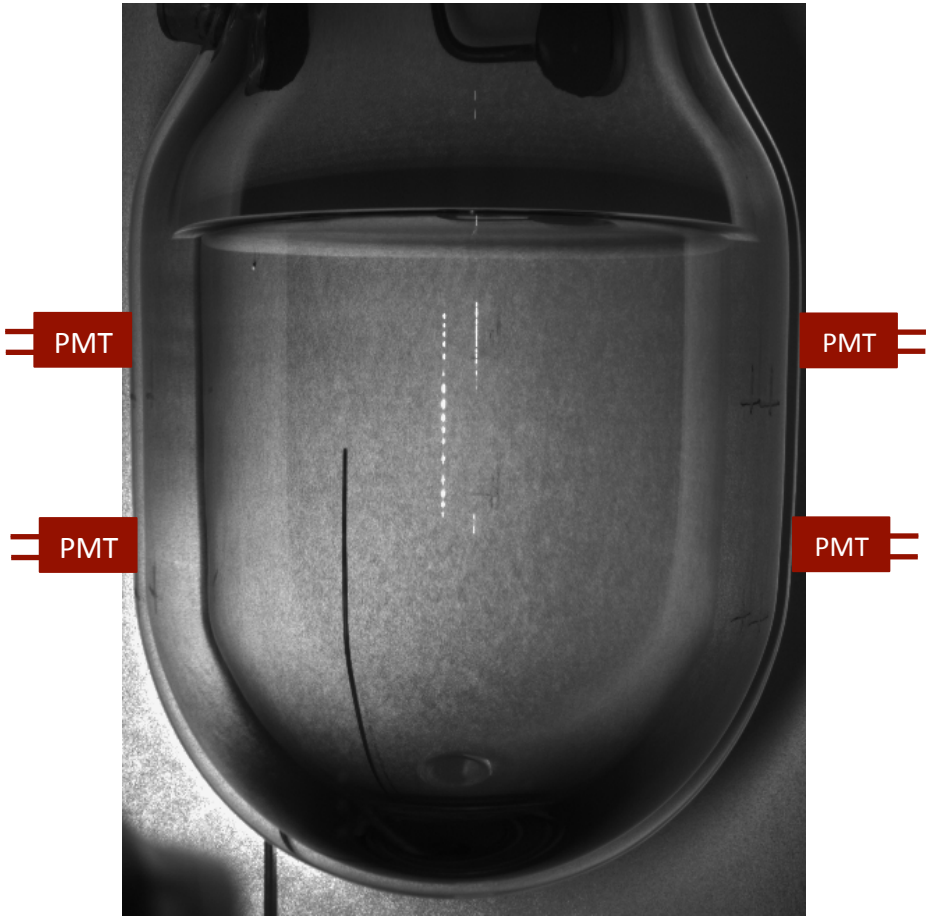


Scintillating Bubble Chambers

- 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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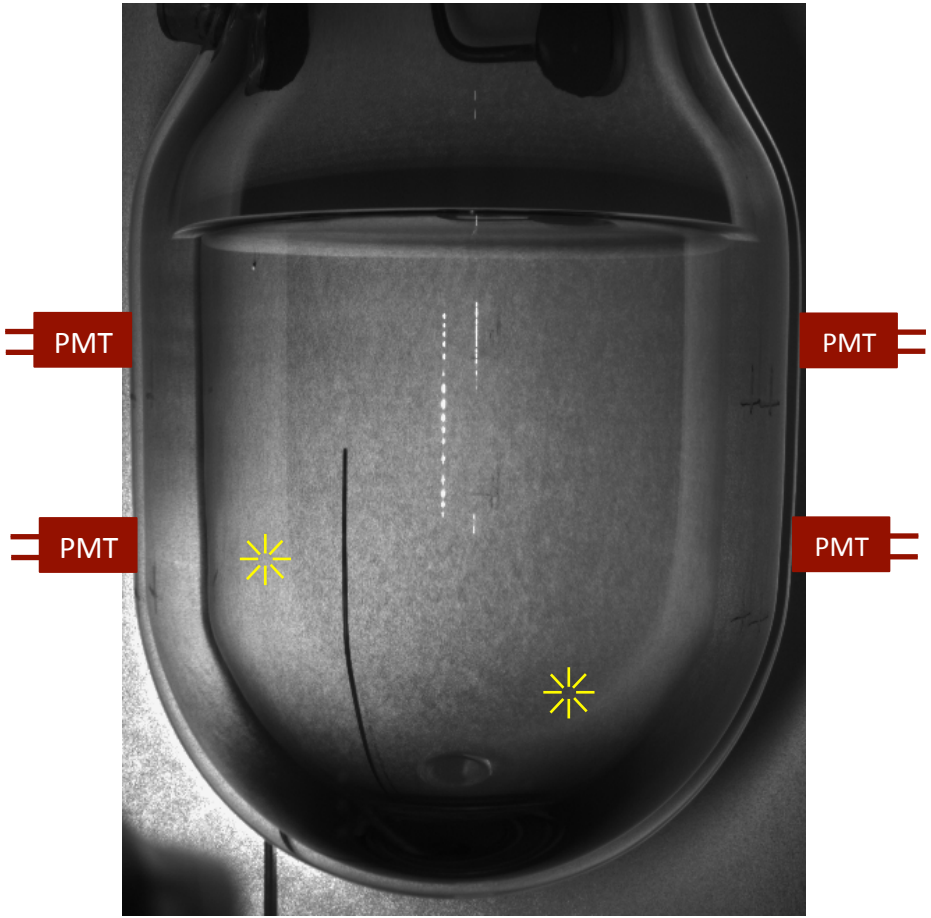

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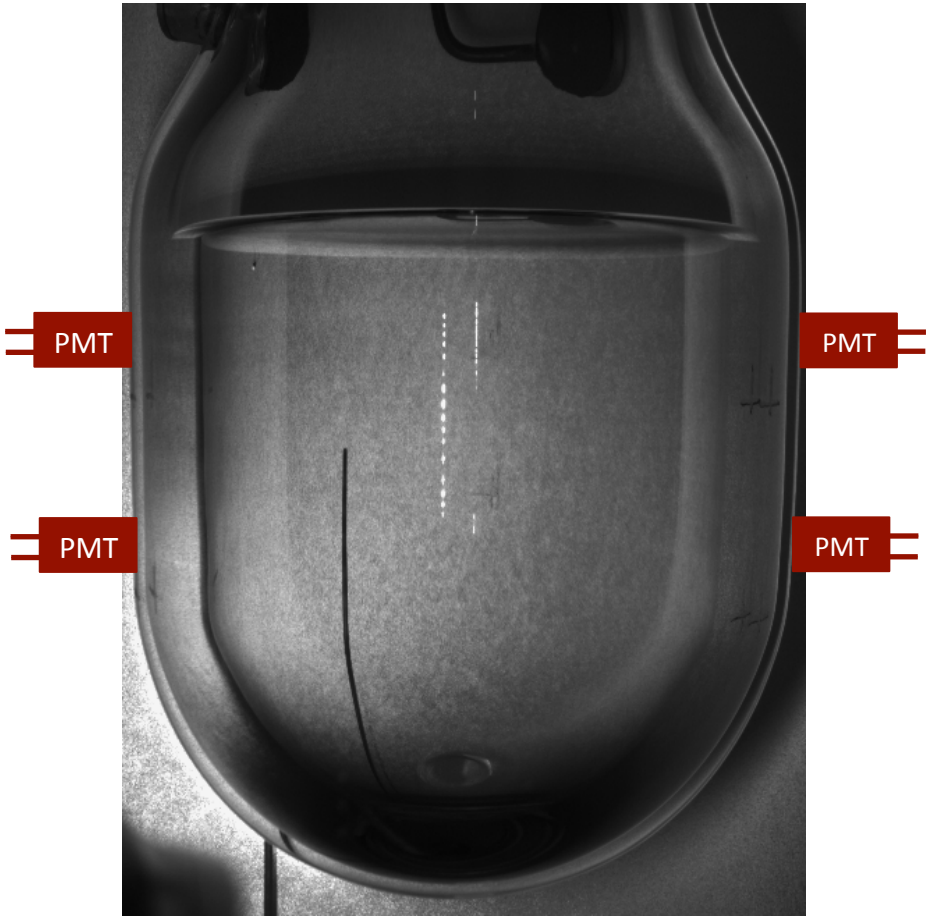

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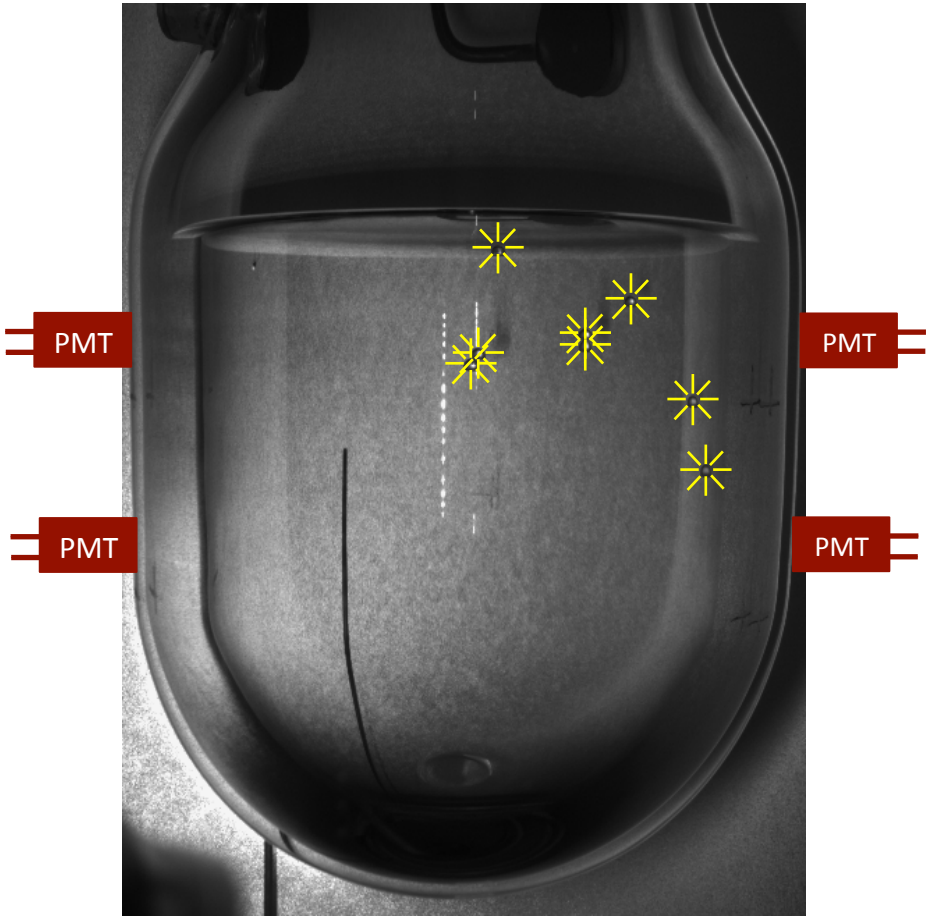

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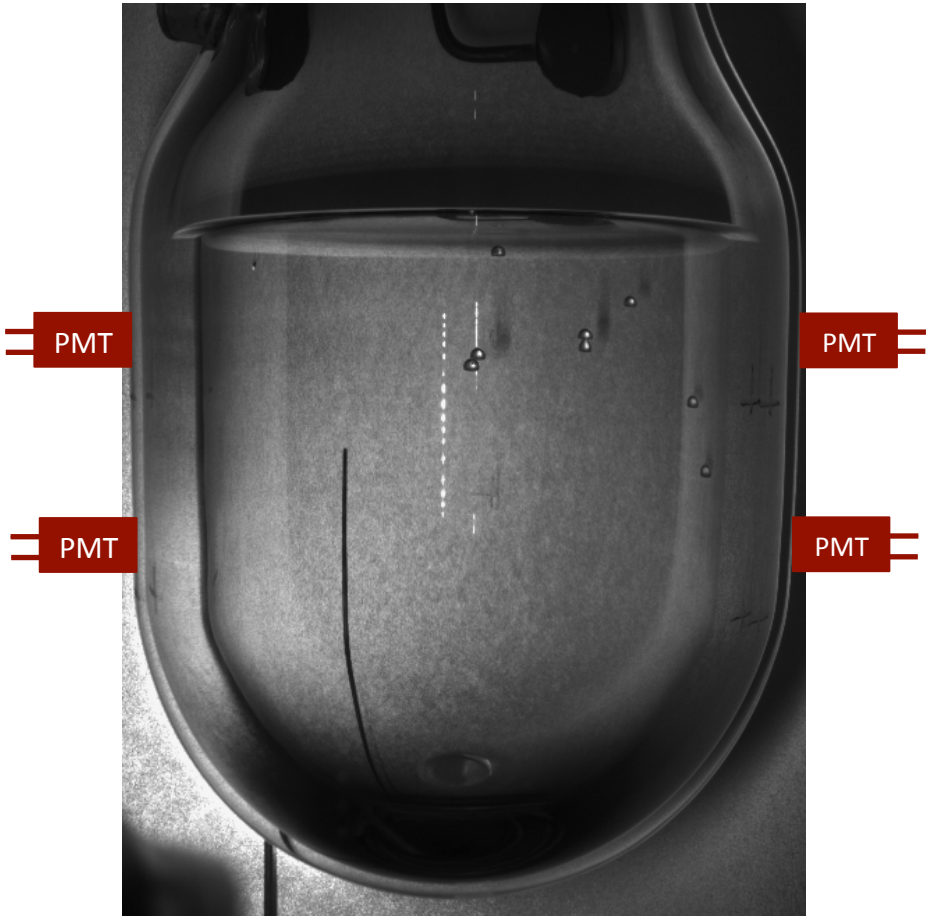
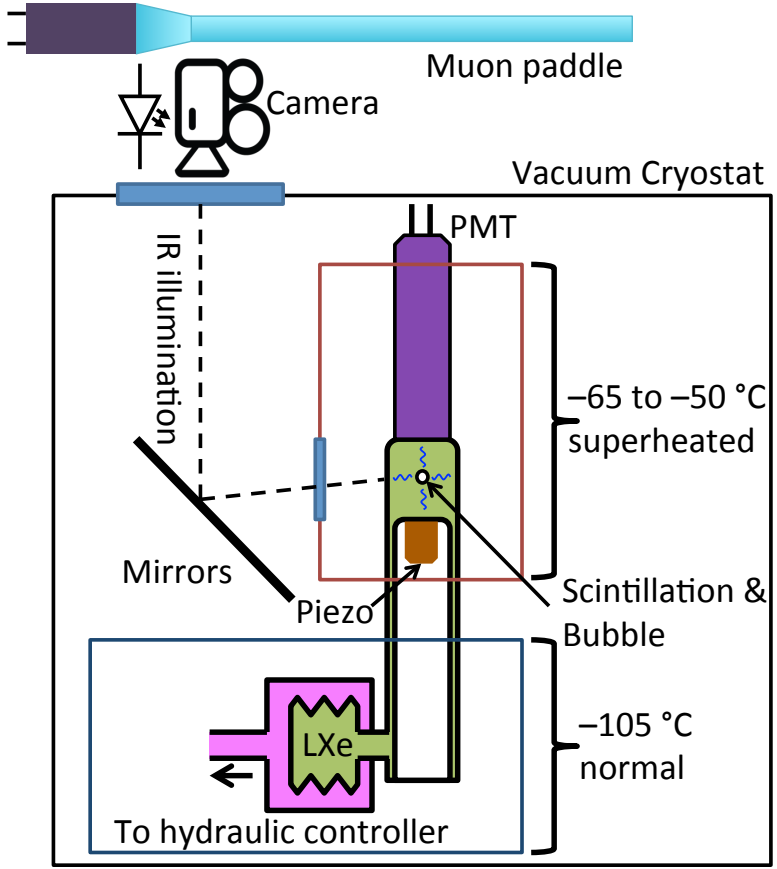


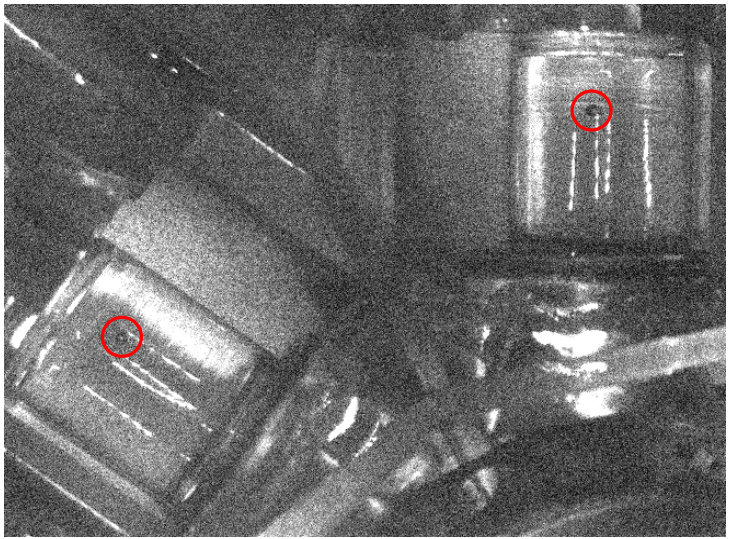
NU Xenon Bubble Chamber

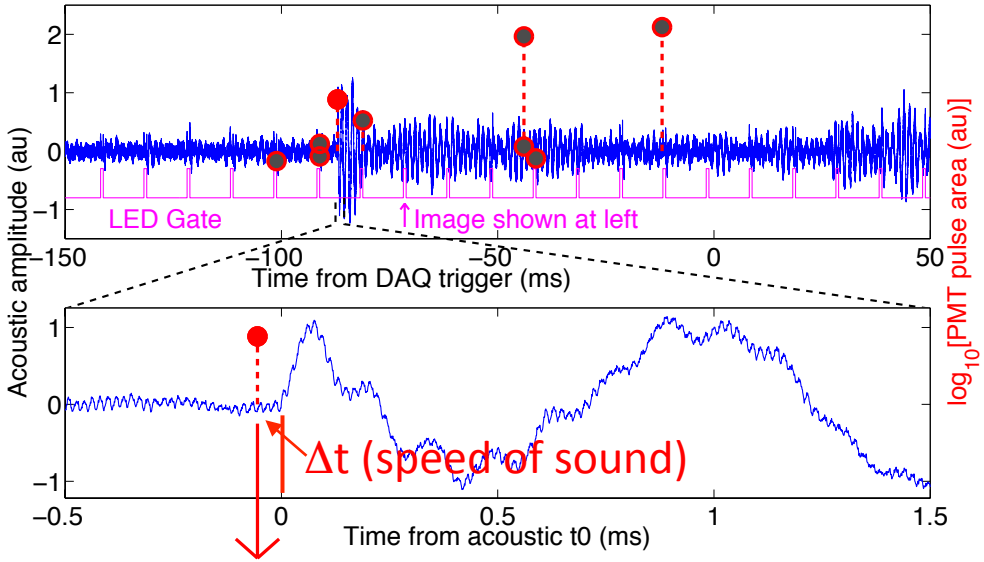
- 30-gram xenon target
- 25-psia, –38°C
  E_T = 0.5 keV
- Single fluid (no buffer)
- IR illumination for cameras
- IR-blind PMT (R6834) for 175nm scintillation

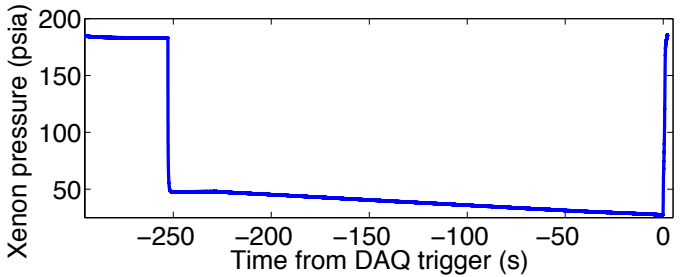


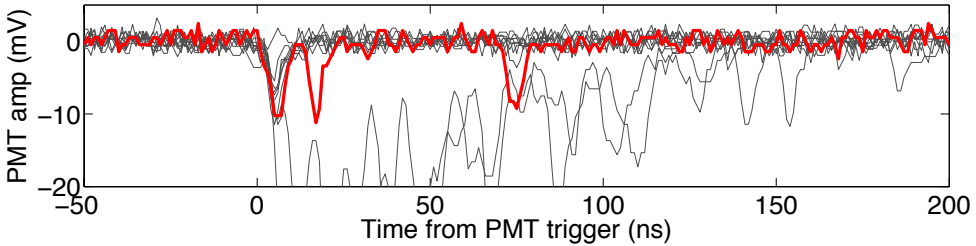
Nuclear Recoil Event

PRL 118, 231301 (2017)



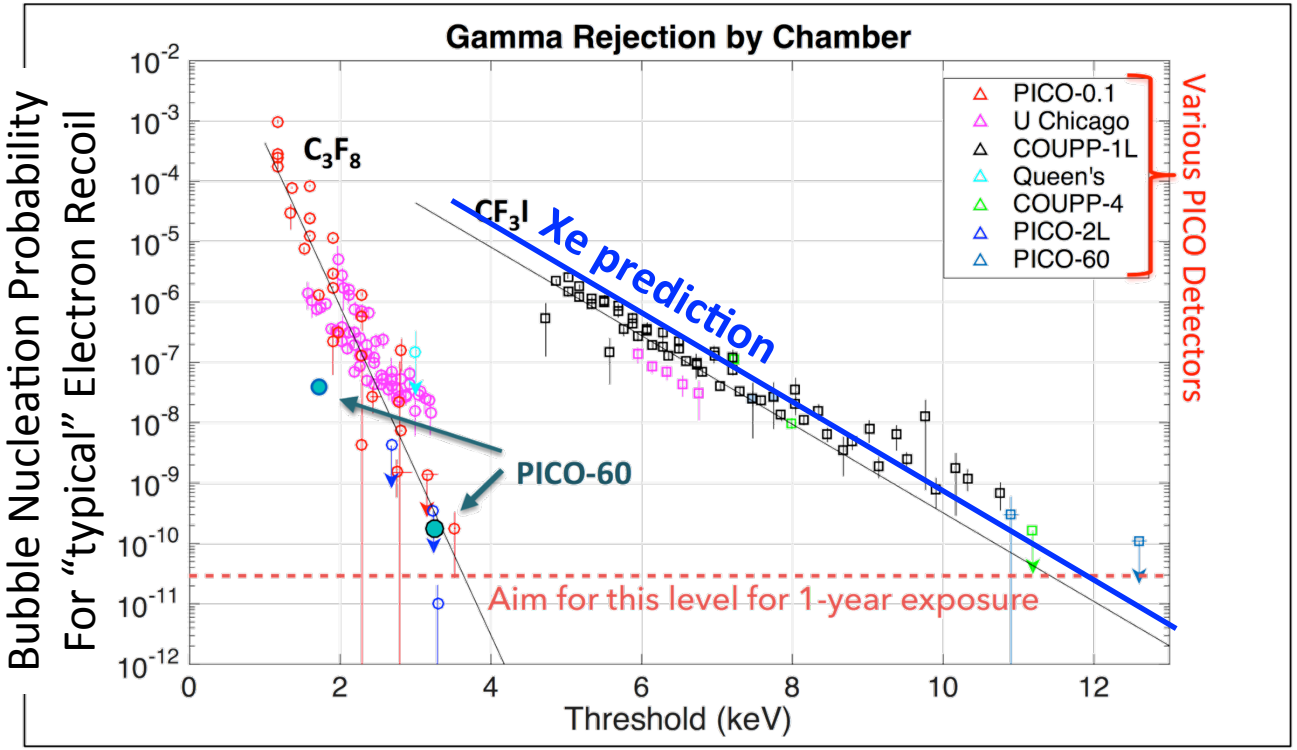






Electron Recoil Discrimination

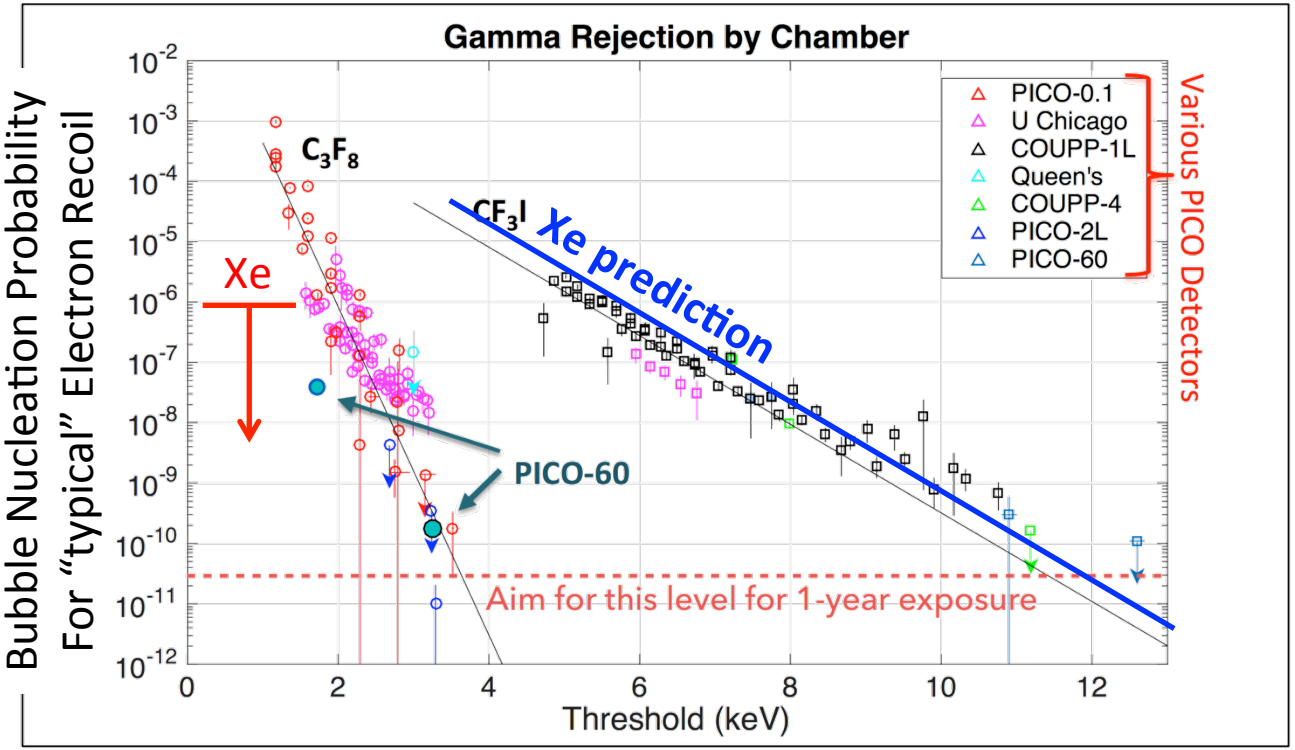
- Xenon predicted to have slightly worse ER discrimination than CF_3I
  - no good for CEvNS…



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

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



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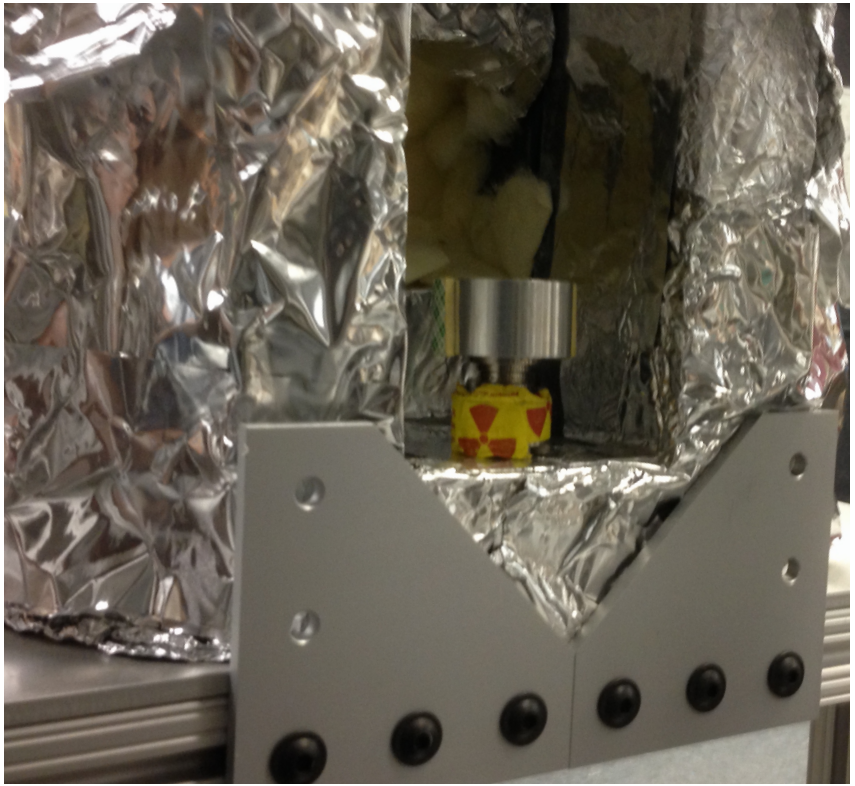
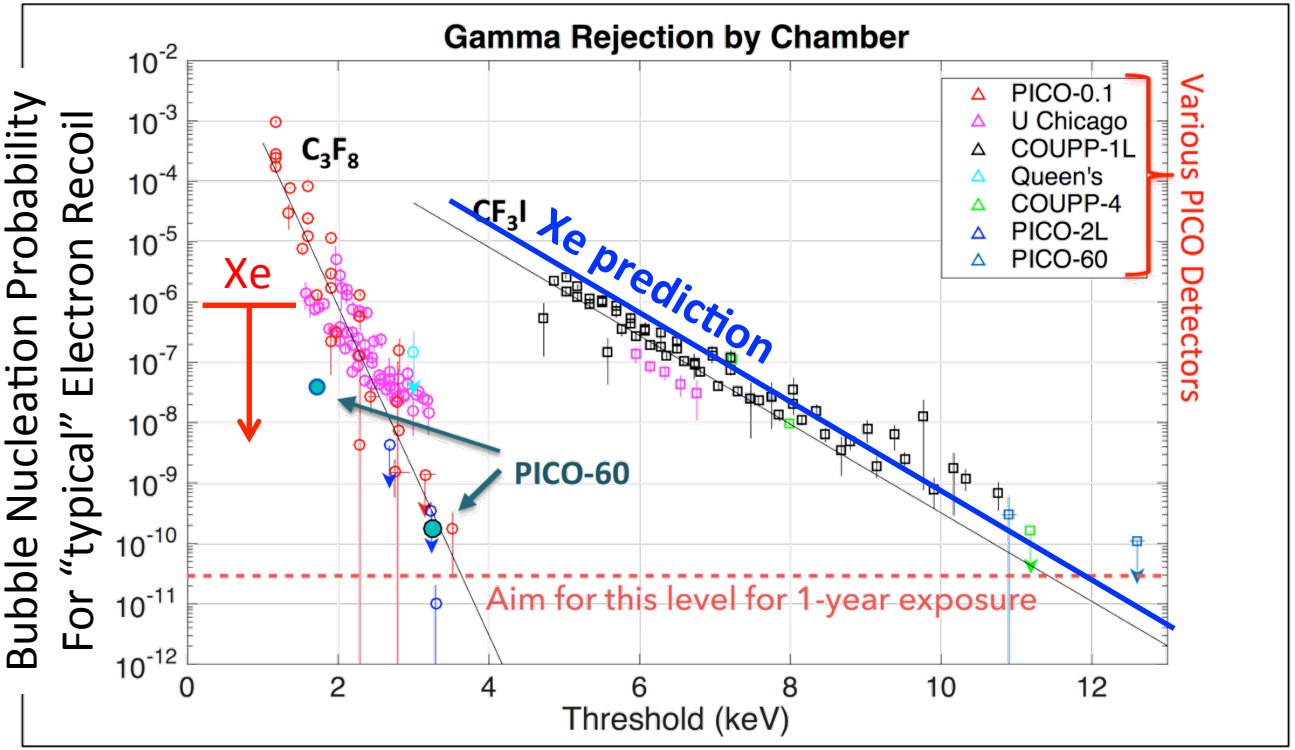
NR Threshold vs Thermodynamic Threshold



- ^{88}Y-Be(γ,n): 152 keV neutrons
  - Max 4.7 keV xenon recoil
  - Bubble nucleation by E_T = 2 keV
- ^{207}Bi-Be(γ,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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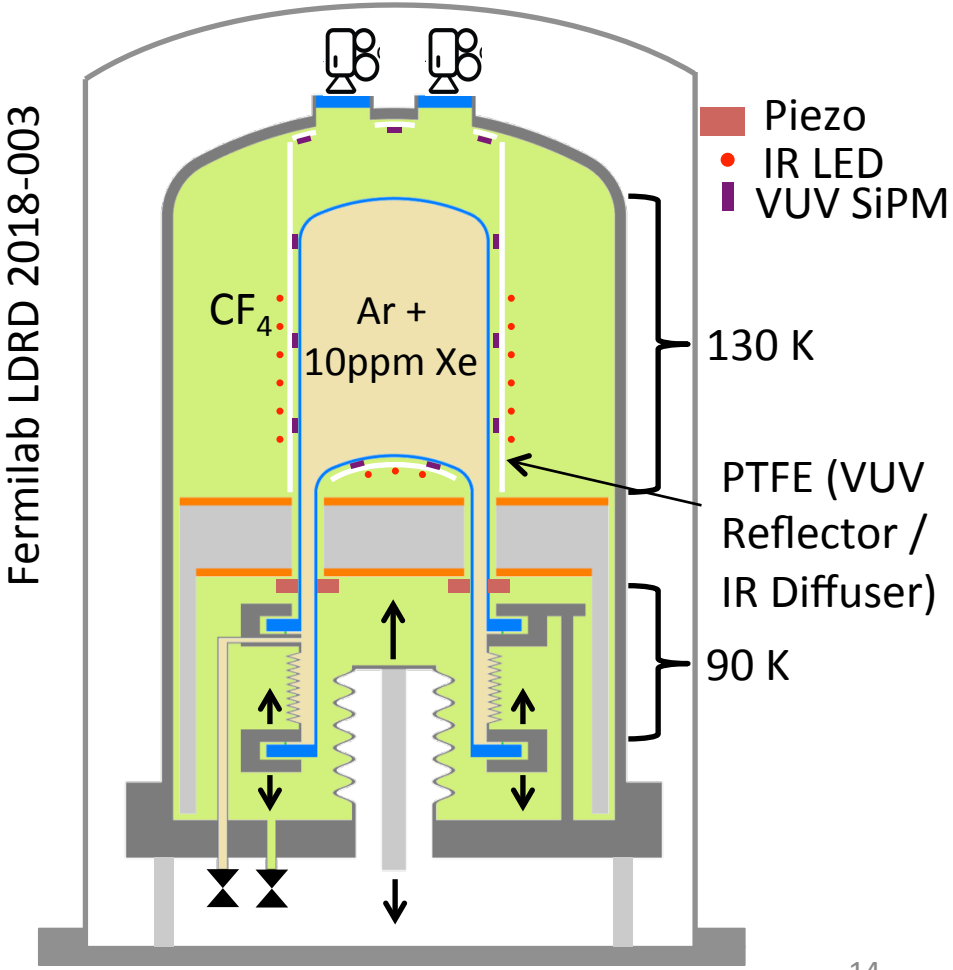
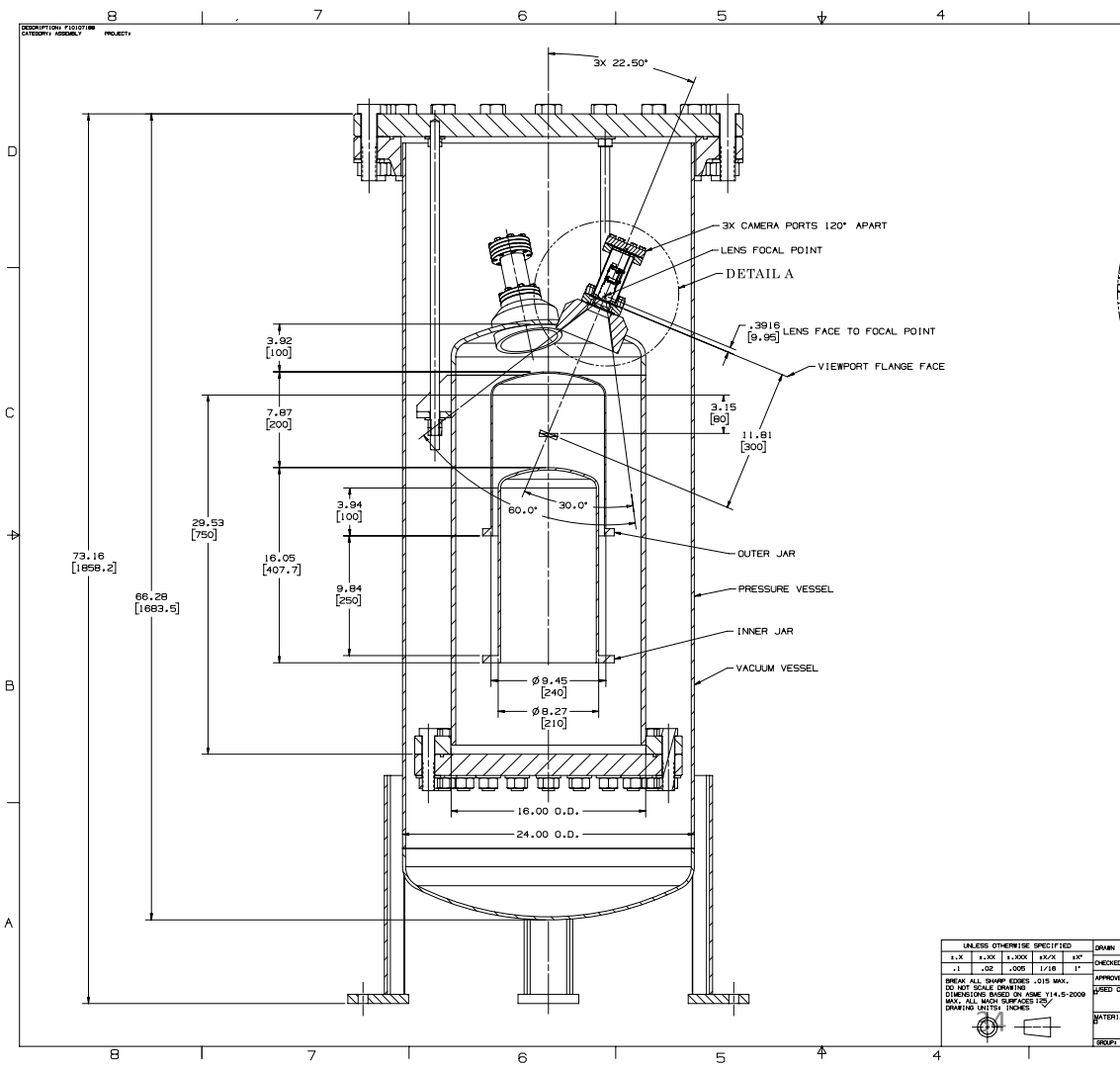
Scintillating Argon Bubble Chamber

- 10-kg Argon target
- Designed to reach E_T = 40 eV
  - 1 spontaneous bubble / ton-year
- Collaboration of 7 Institutions in US, Canada, Mexico

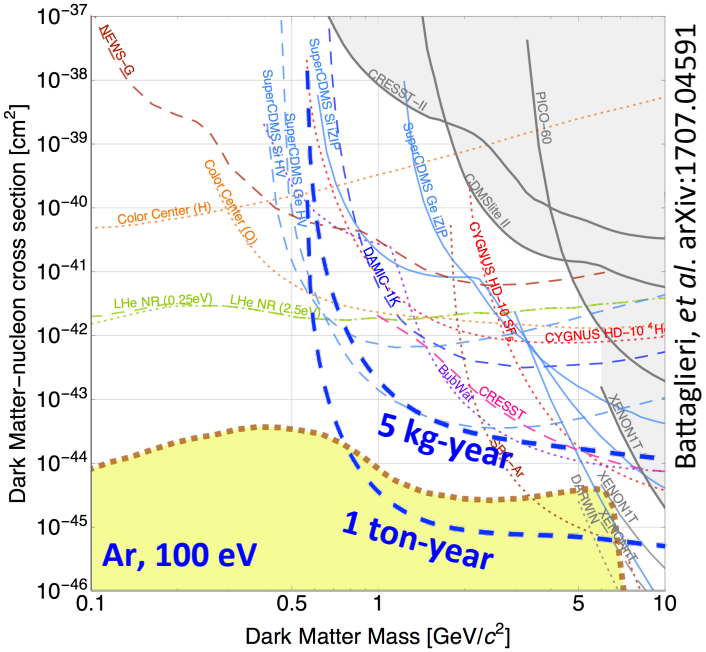


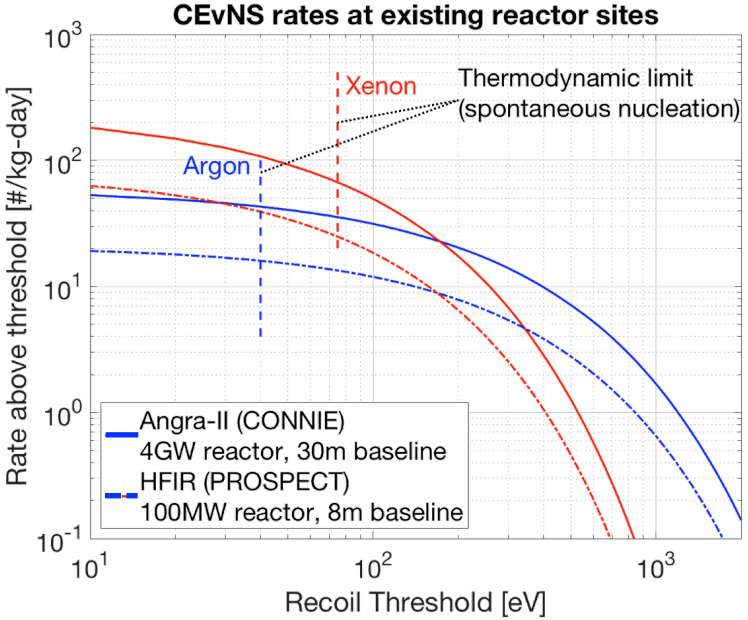
Scintillating Argon Bubble Chamber

- Critical parts arriving now
- Construction at FNAL in 2019
- Commissioning and ***Calibration*** in 2020



Physics with an Argon Bubble Chamber





- WIMP searches to solar ν-floor (1 – 7 GeV)
- *O*(10) CEvNS events / kg-day @ reactor ← **Follows Calibration @ FNAL**

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

*Scintillating Bubble Chamber PICO

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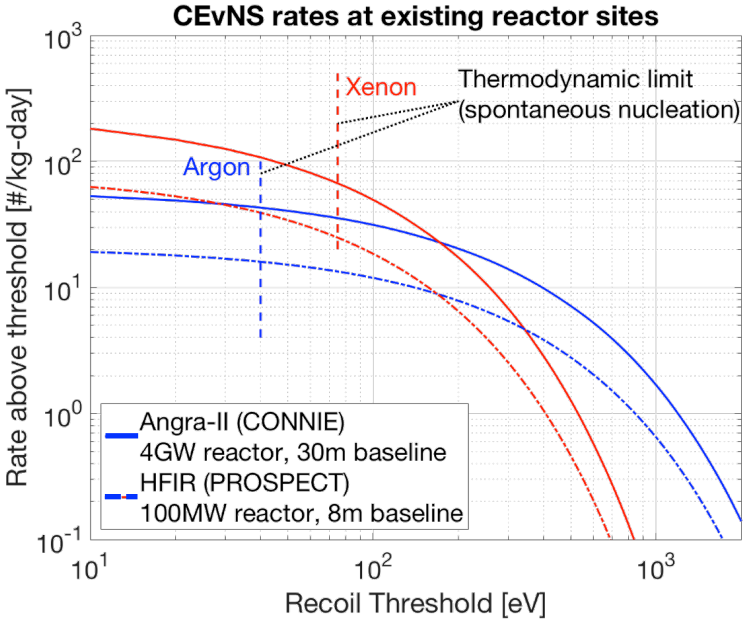
Summary

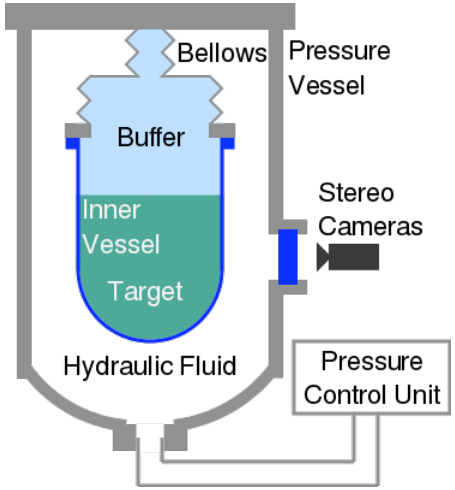
- Liquid Noble Bubble Chambers
  - Unique potential for background-free reactor CEvNS measurements
  - Stay tuned as story unfolds…

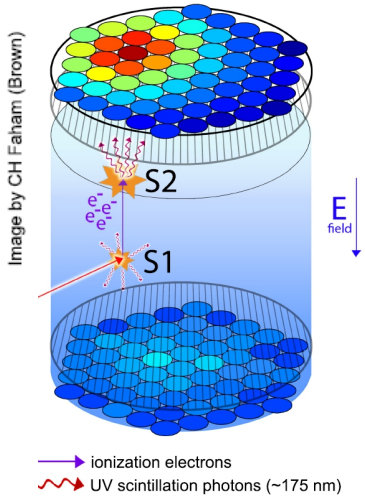


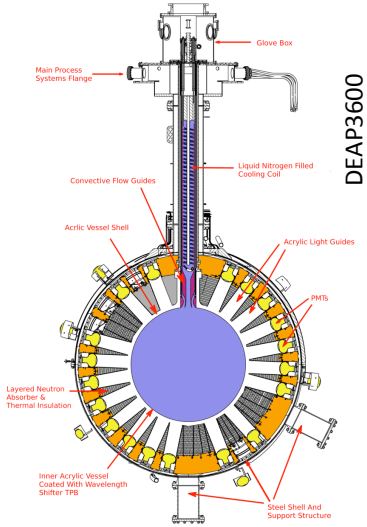
Funding acknowledgements:
- Fermilab LDRD 2018-003
- DOE Award DE-SC0012161

Backup

Why Liquid-noble Bubble Chambers

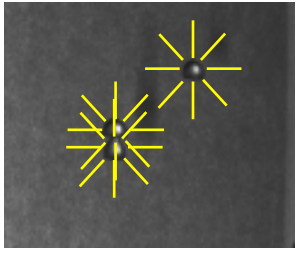






10^{-10} discrimination

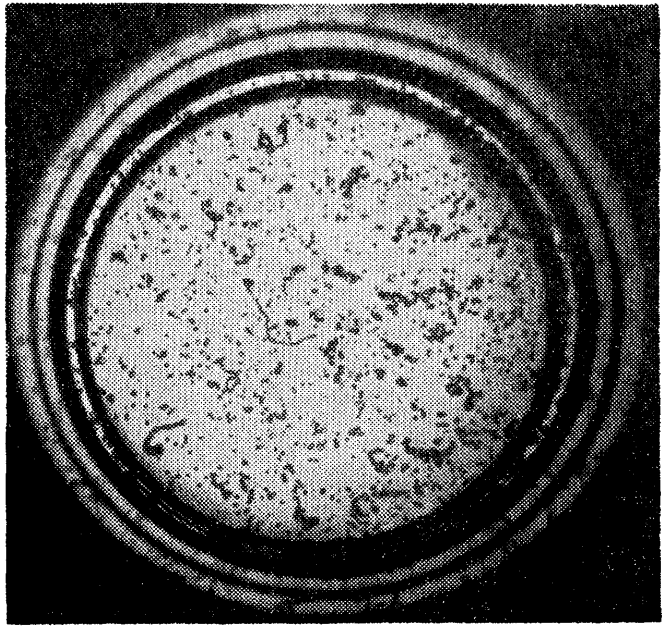
Event-by-event Energy



Low-threshold (< keV) ER discrimination

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

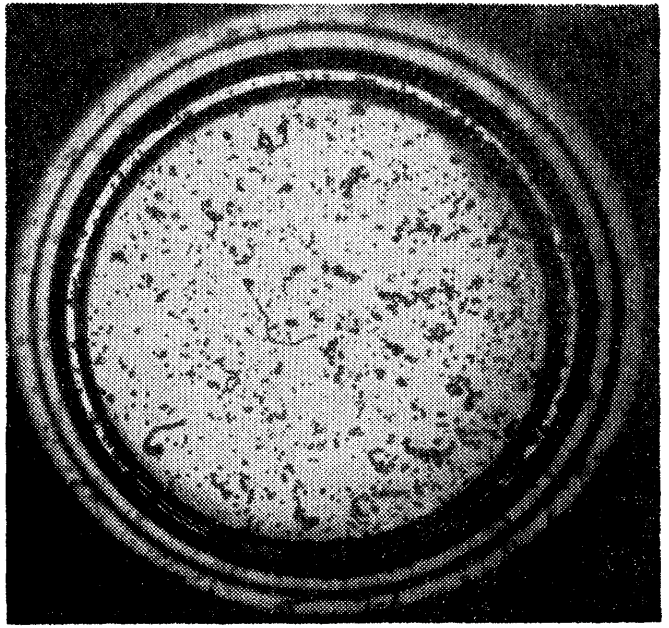
- Glaser built a xenon bubble chamber in 1956 and found:
  - **No bubbles** in pure xenon even at ~1 keV threshold (with gamma source)
  - Normal bubble nucleation in 98% xenon + 2% ethylene (scintillation completely quenched)



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

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

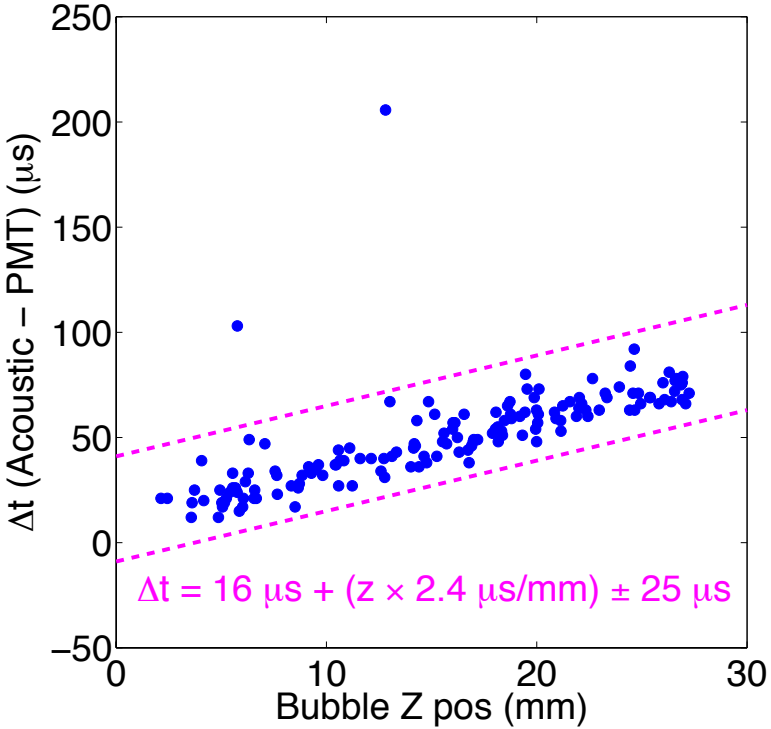
- Scintillation suppresses bubble nucleation?
  - **Electrons** should be even less likely to make bubbles than in freon chambers
  - Greater superheat (lower thresholds) possible
  - **Nuclear Recoils should be largely unaffected**, thanks to Lindhard Effect



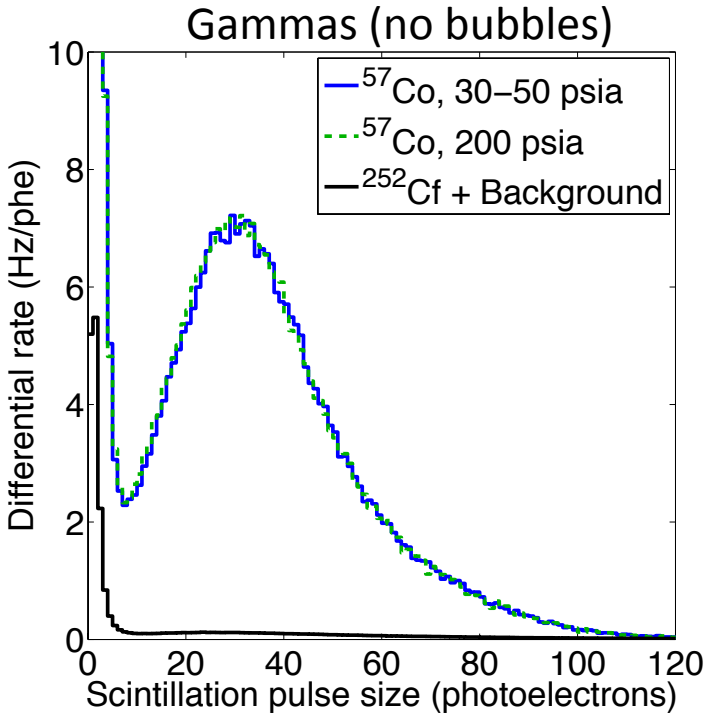
Phys.Rev. **102**, 586 (1956)

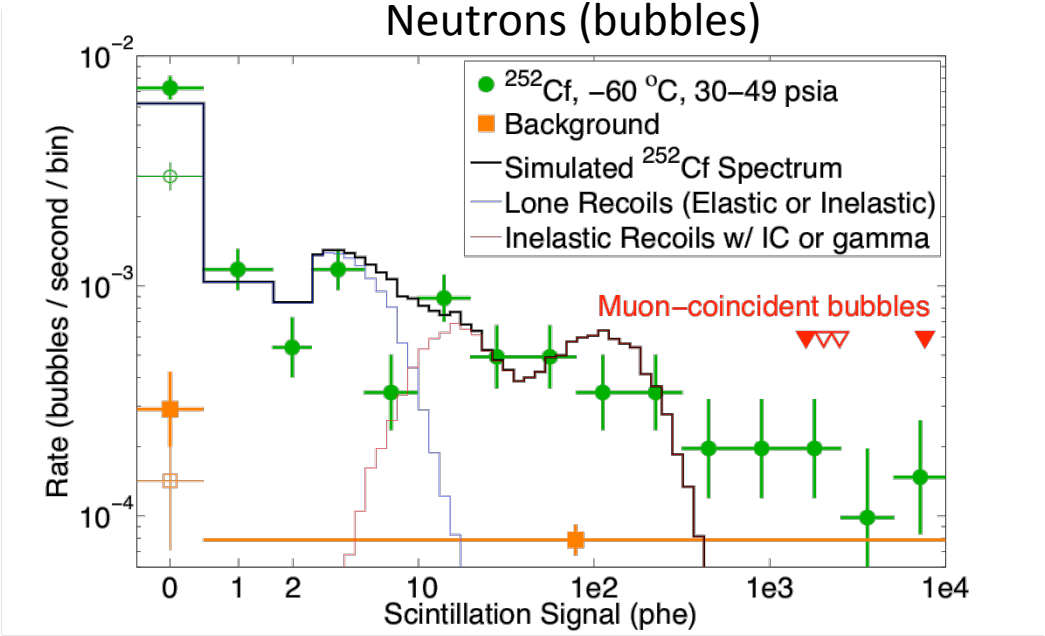
Acoustic – Scintillation Coincidence

- $< 1\%$ 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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LZ: Dylan Temples (GS)

Scintillating Bubble Chamber: Jianjie Zhang (PD), Jon Chen (UG), Trent Cwiok (UG), Jared Gupta (UG), Ricky Puig (UG), Allison Grimsted (HS), John Gresl (MS), Theo Baker (UG)

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– PRL 118, 251301 (2017), arXiv:1702.07666 (PICO-60)

– PRL 118, 231301 (2017), arXiv:1702.08861 (XeBC)