Bubble Chambers for WIMP and CEvNS detection

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Northwestern University

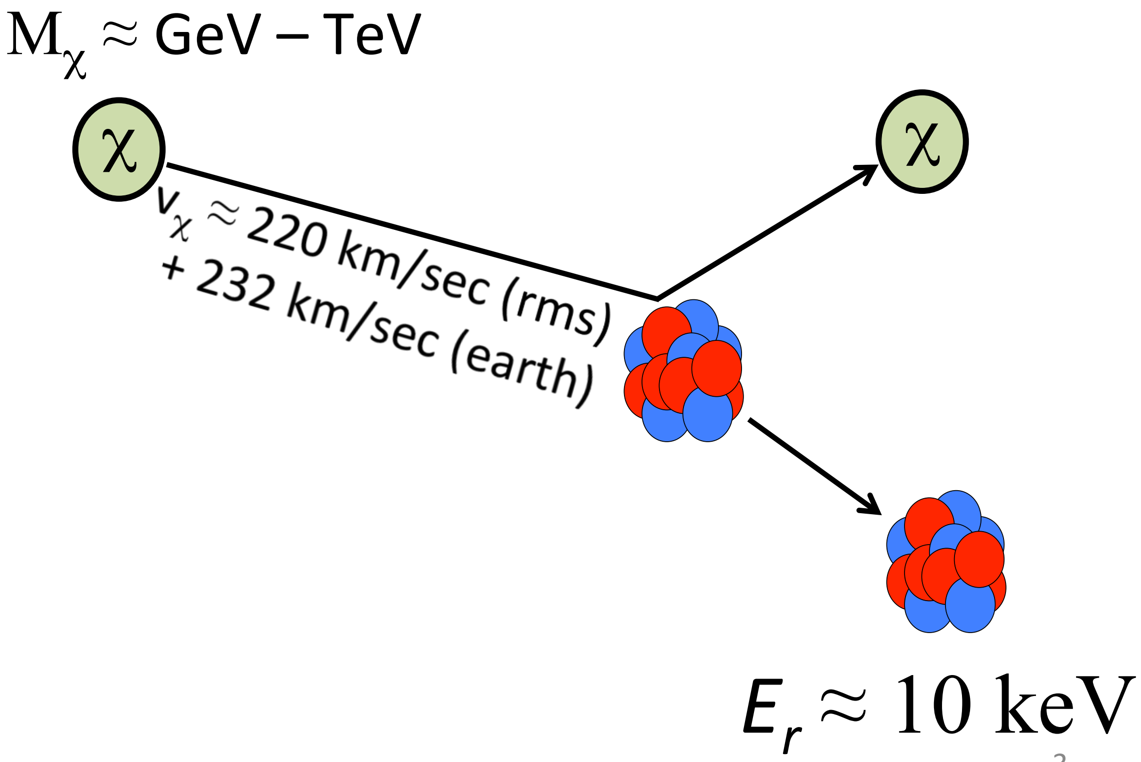
INT-18-2a Workshop, 2018

Roadmap

- Motivation
  - WIMP hunting with elements besides xenon
- Bubble Chamber Basics
  - Background discrimination in superheated fluids
- PICO Progress
  - Backgrounds discovered, backgrounds eliminated
- New Developments in Bubble Chambers
  - Future PICO detectors
  - Liquid-noble bubble chambers

State-of-the-art WIMP Hunting

- Signal: WIMP-nucleus elastic scattering
- Irreducible Background: ν-nucleus elastic scattering, a.k.a. "neutrino floor"



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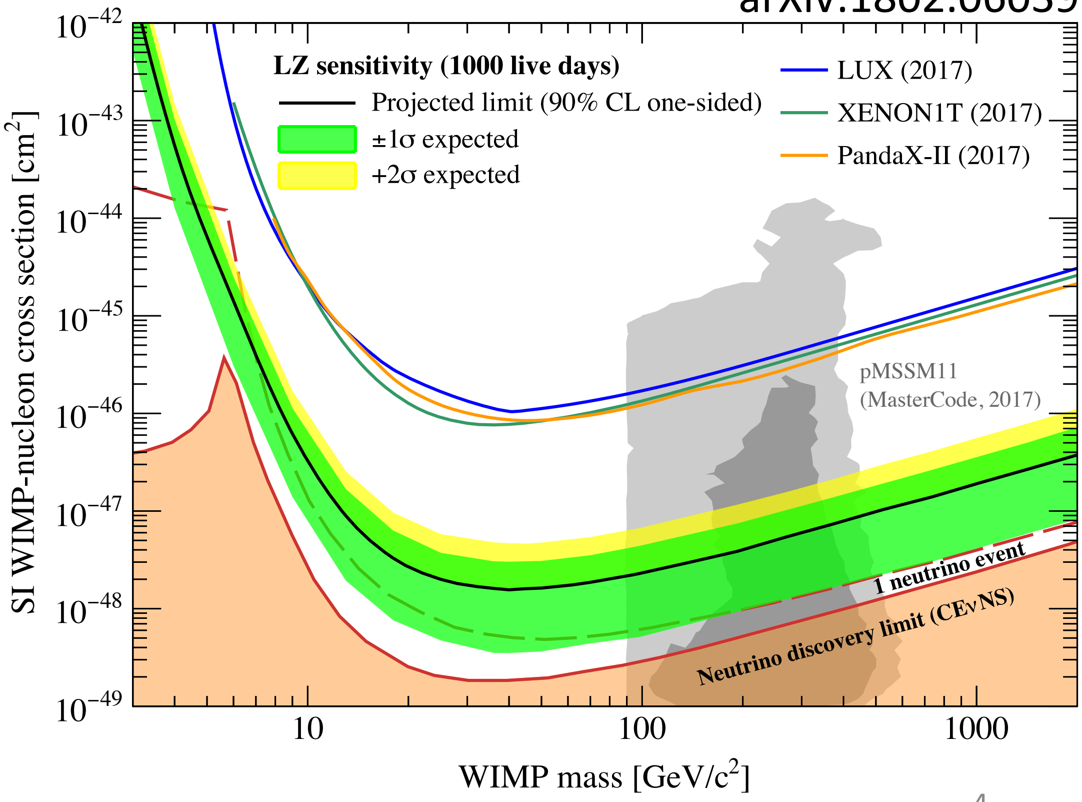
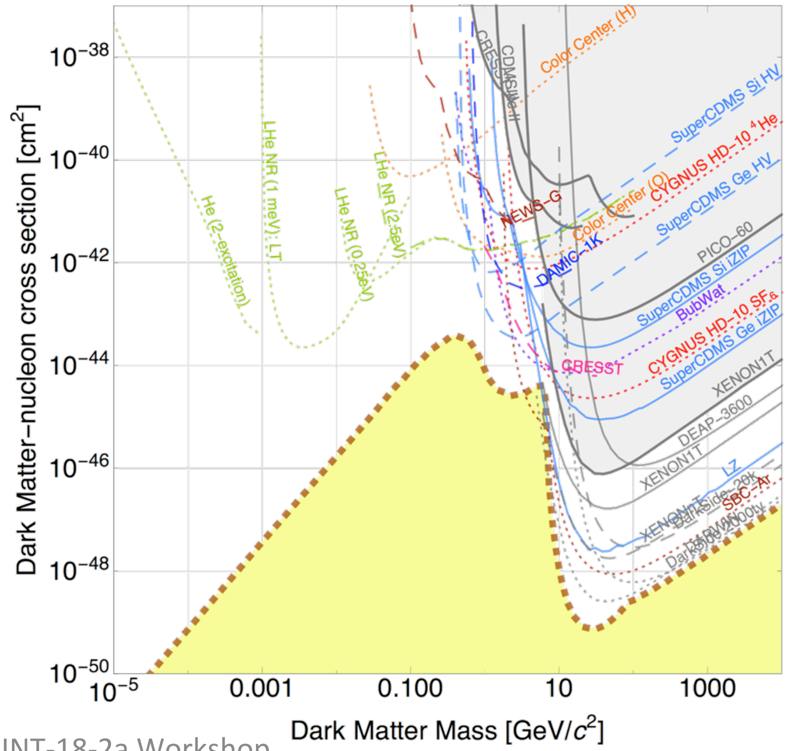
arXiv:1802.06039



Where LXe TPC's can't go…

Spin-Independent: $\sigma \propto A^2$



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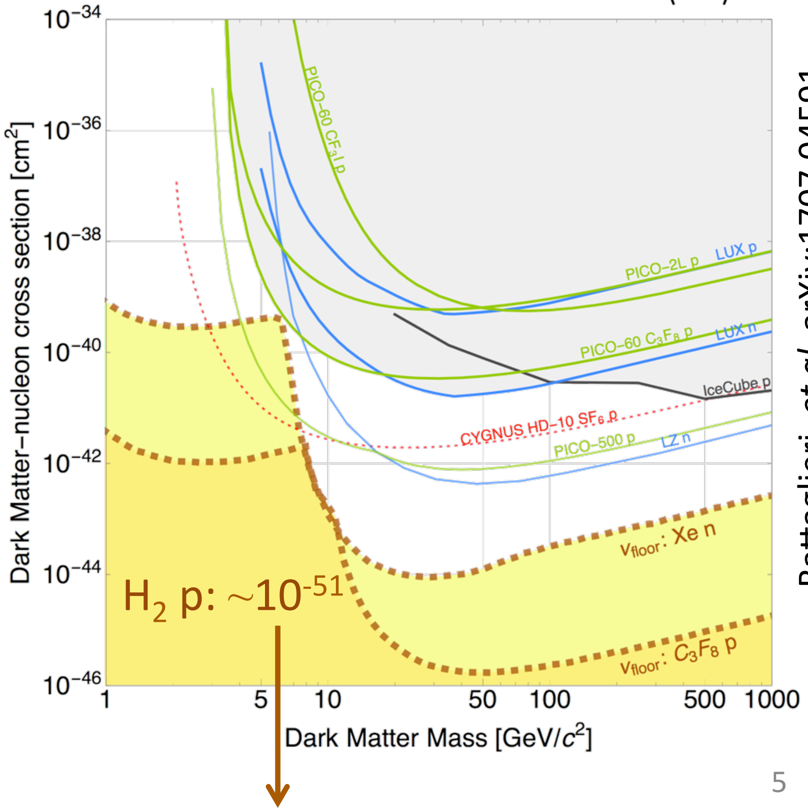
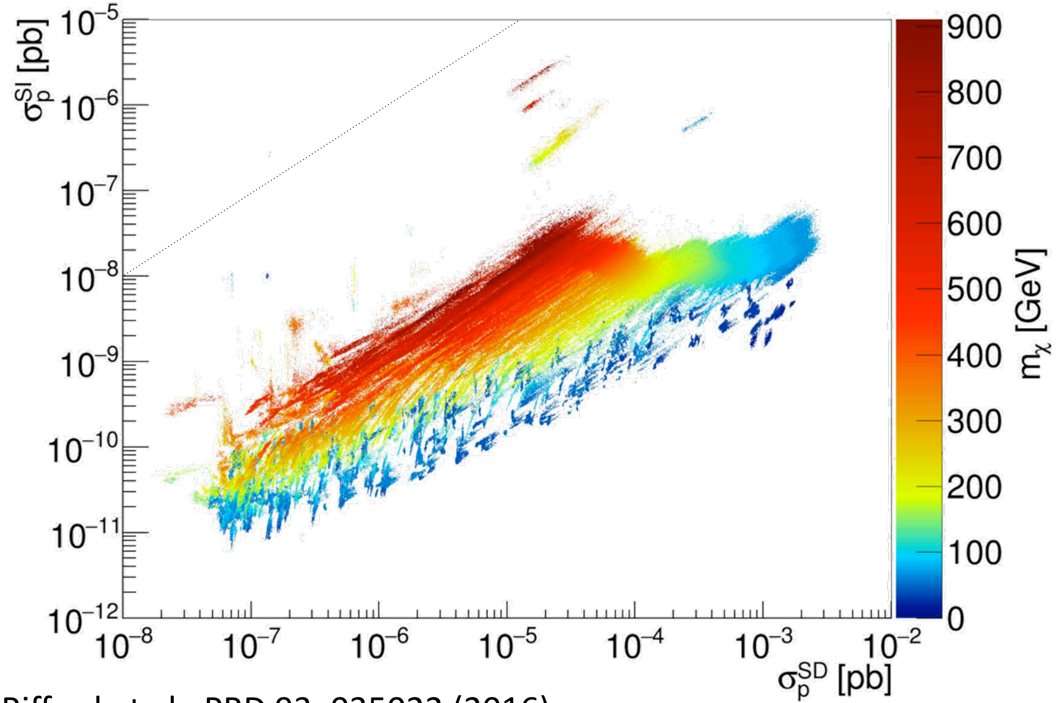


Battaglieri, *et al*. arXiv:1707.04591

What LXe TPC's can't tell you…



Riffard et al., PRD 93, 035022 (2016)

- Even in xenon (A=128–136) detection may come via SD channel
- Xenon is sensitive to *both* SI and SD couplings…
- But other target nuclei needed to determine which coupling matters

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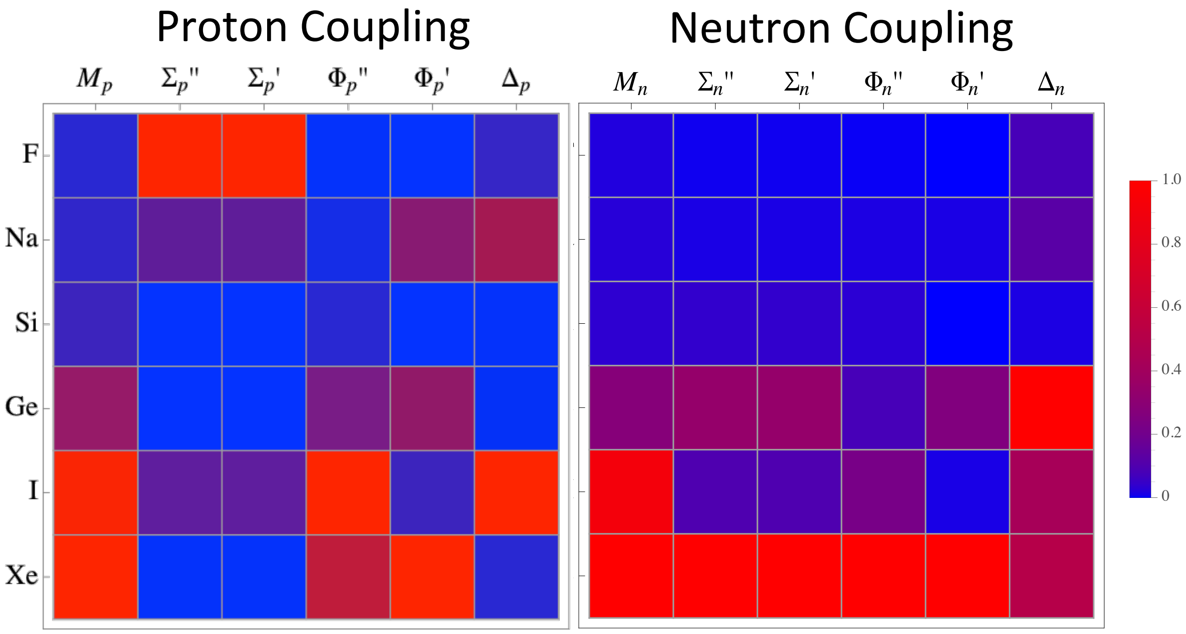

A. Liam Fitzpatrick, INT-14-57w Workshop

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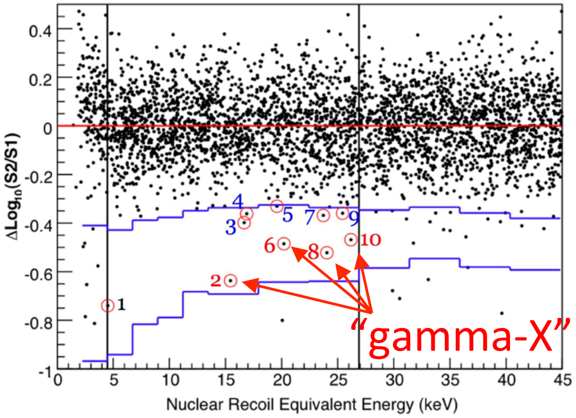
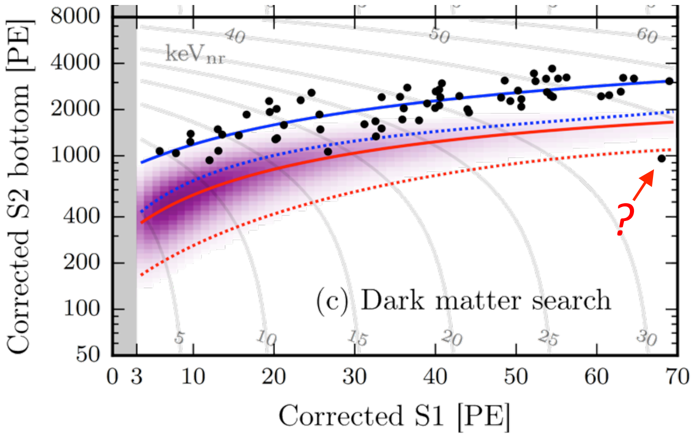
But other target nuclei needed to determine which coupling matters

Signal? Or Anomalous Background?

XENON10 (2008)
PRL **100**, 021303



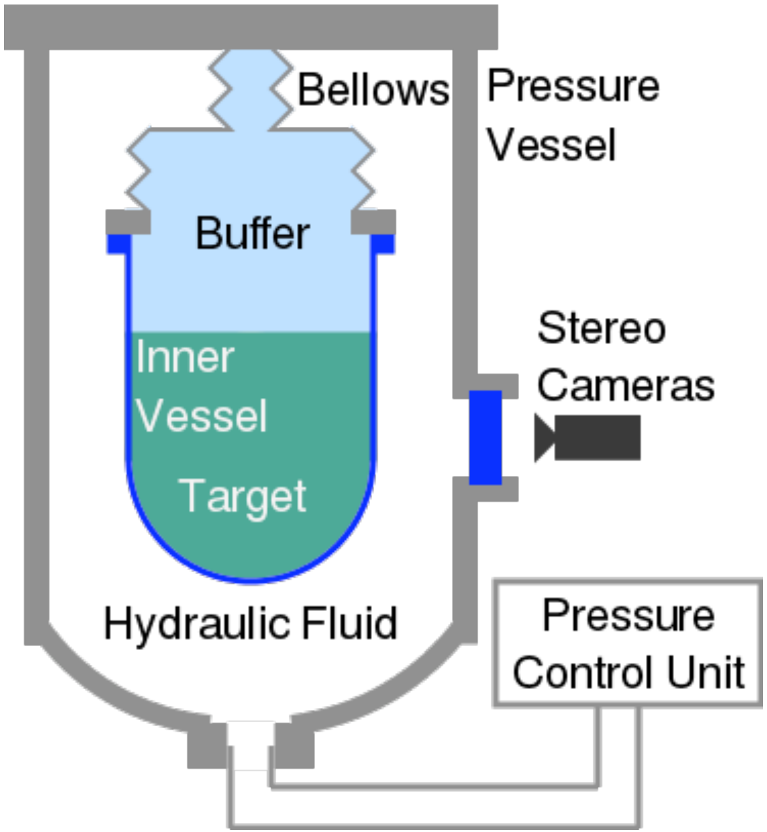


XENON1T (2017)
PRL **119**, 181301

- ***Every*** detection technique has the potential for anomalous backgrounds:
  - Ways discrimination may be systematically fooled
  - Backgrounds we weren't creative enough to think of *a priori*…
- The dark matter signal might not be what we expect!
- Confirmation from a different technology, with different anomalous backgrounds, will be crucial

Bubble Chambers

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



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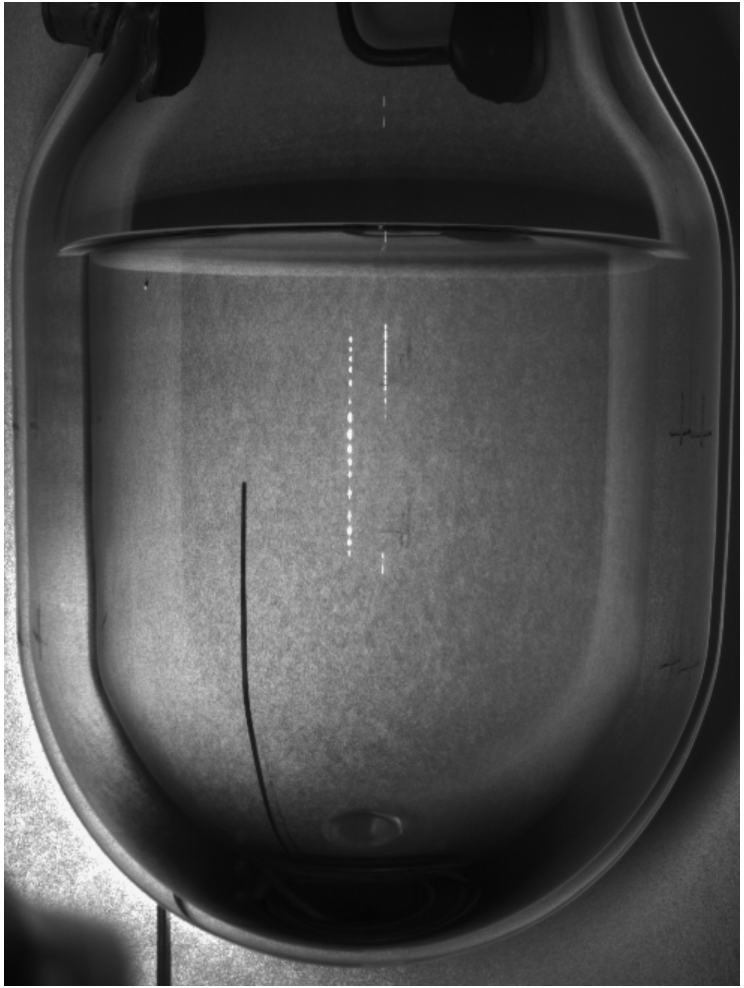

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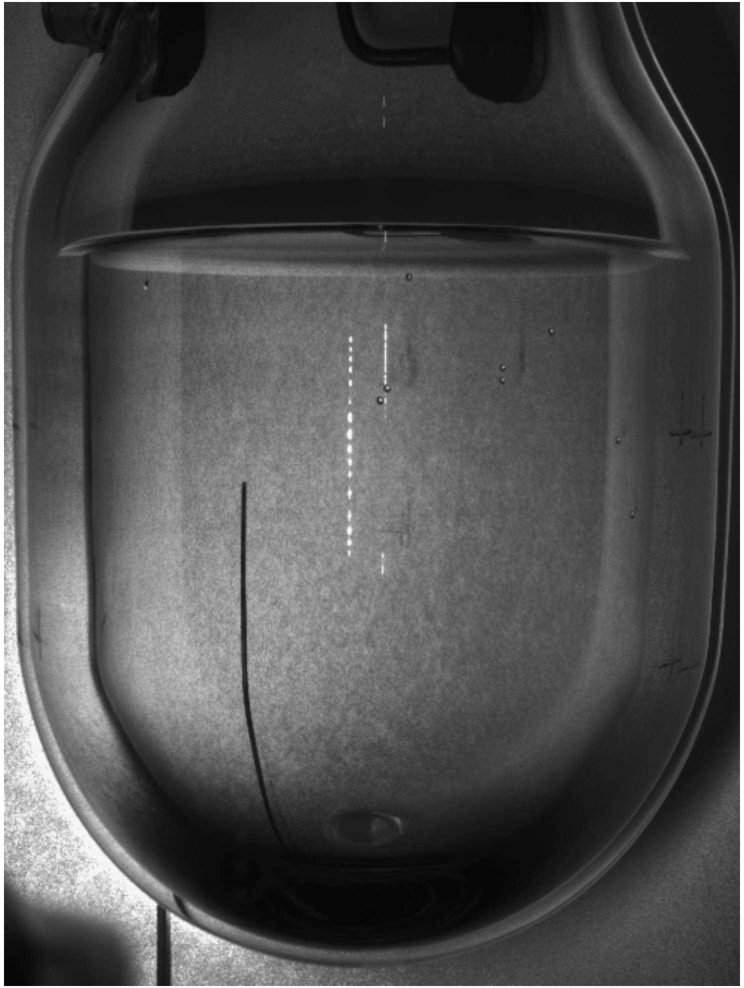

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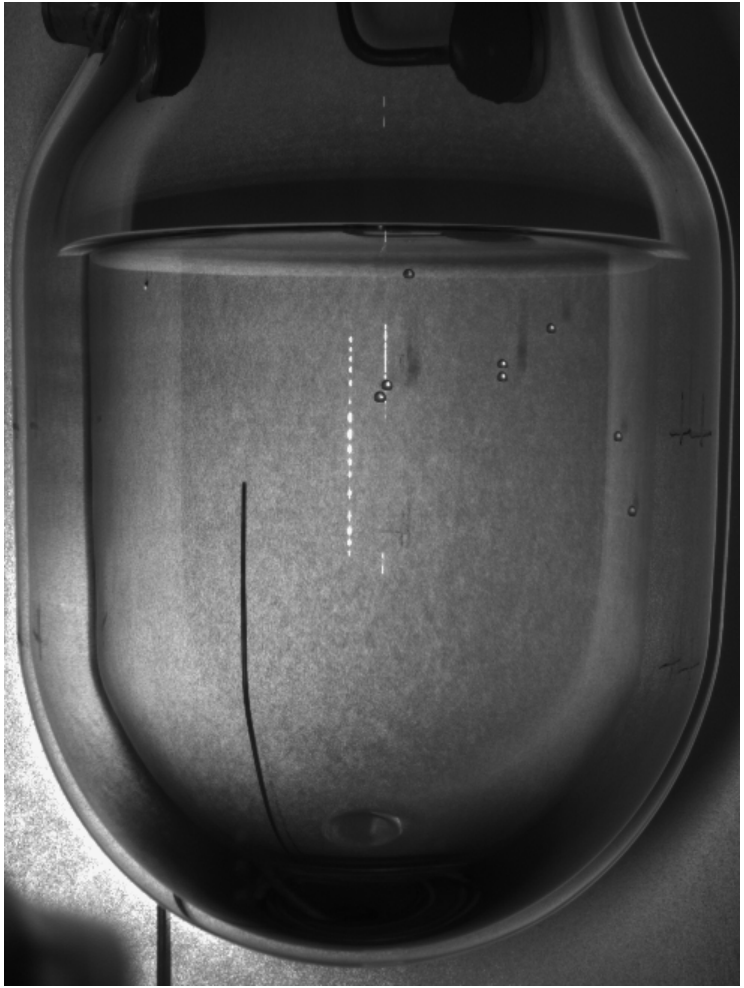

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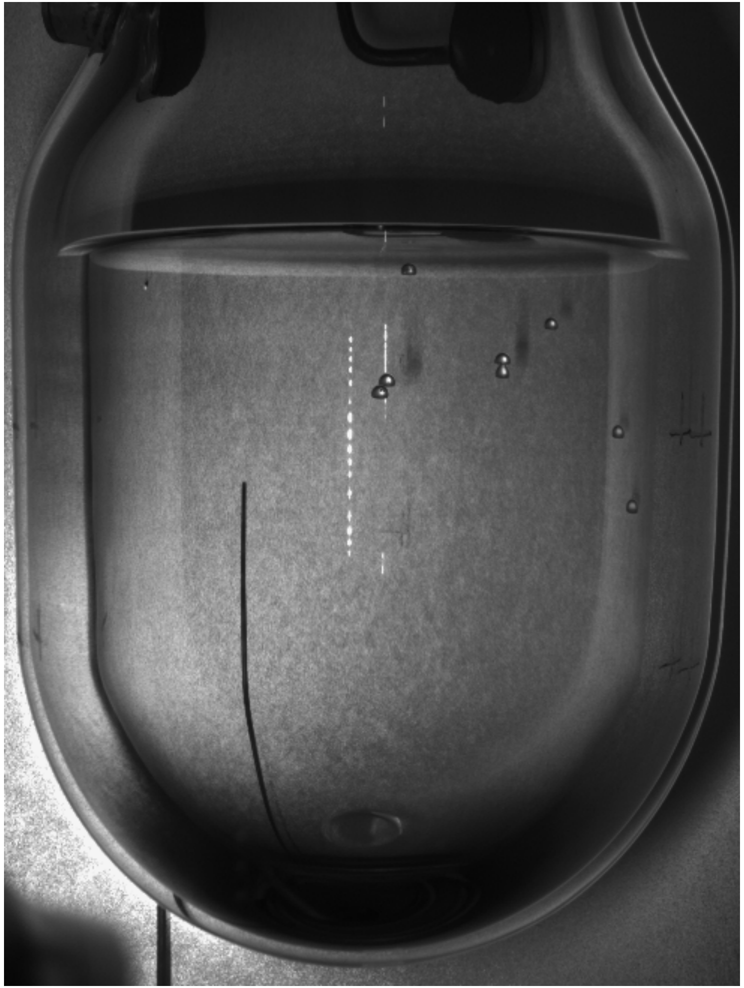

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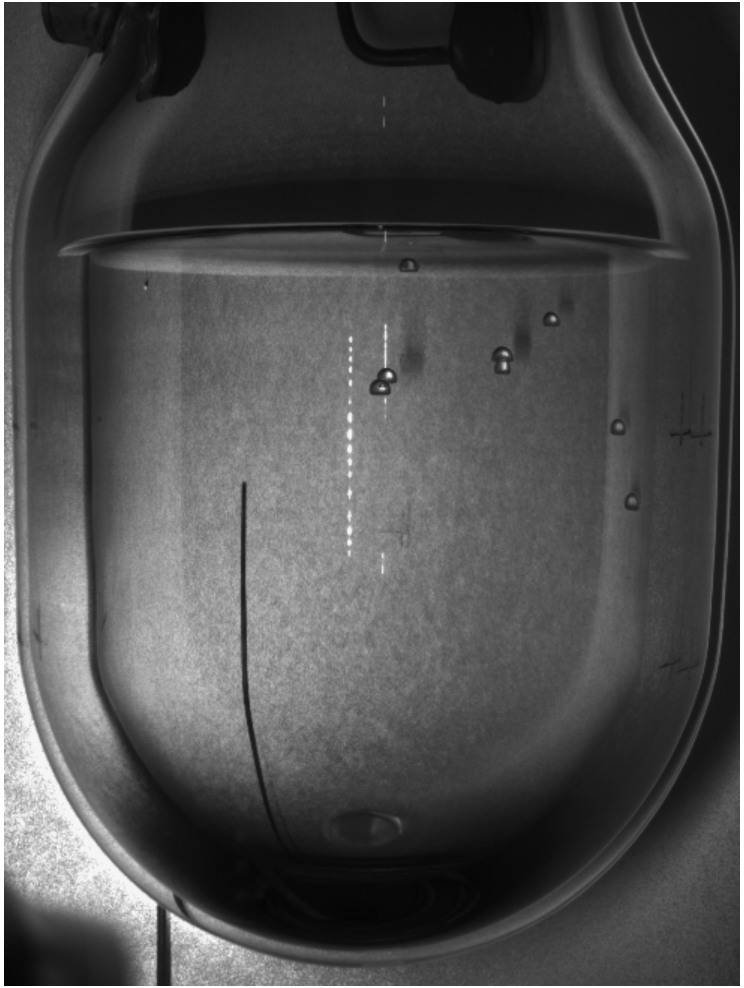

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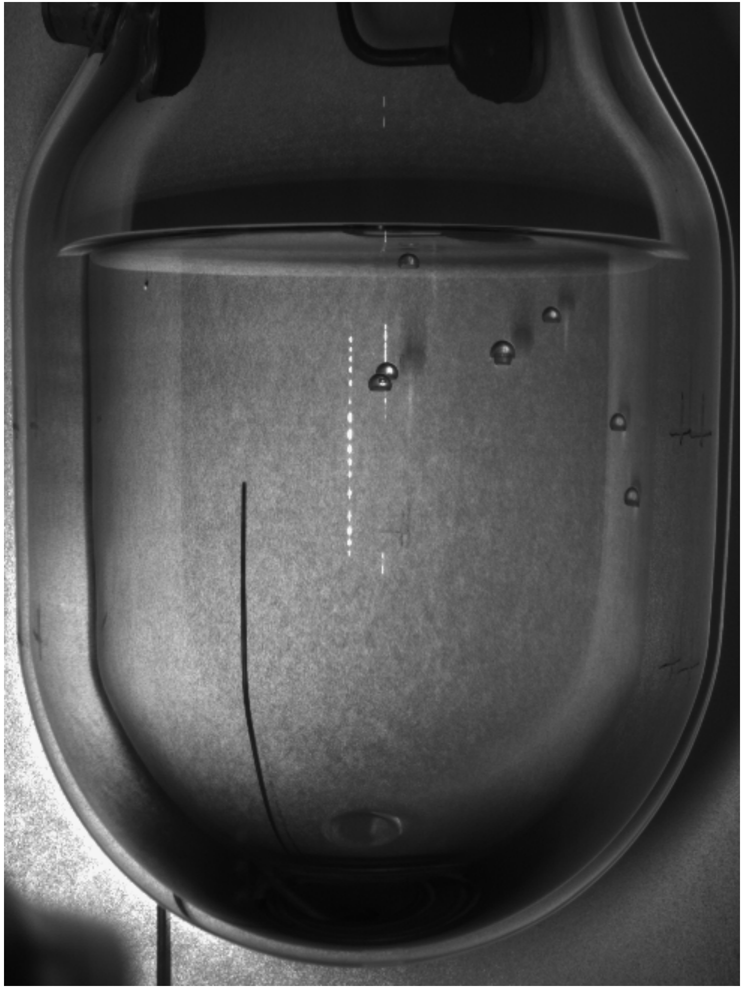

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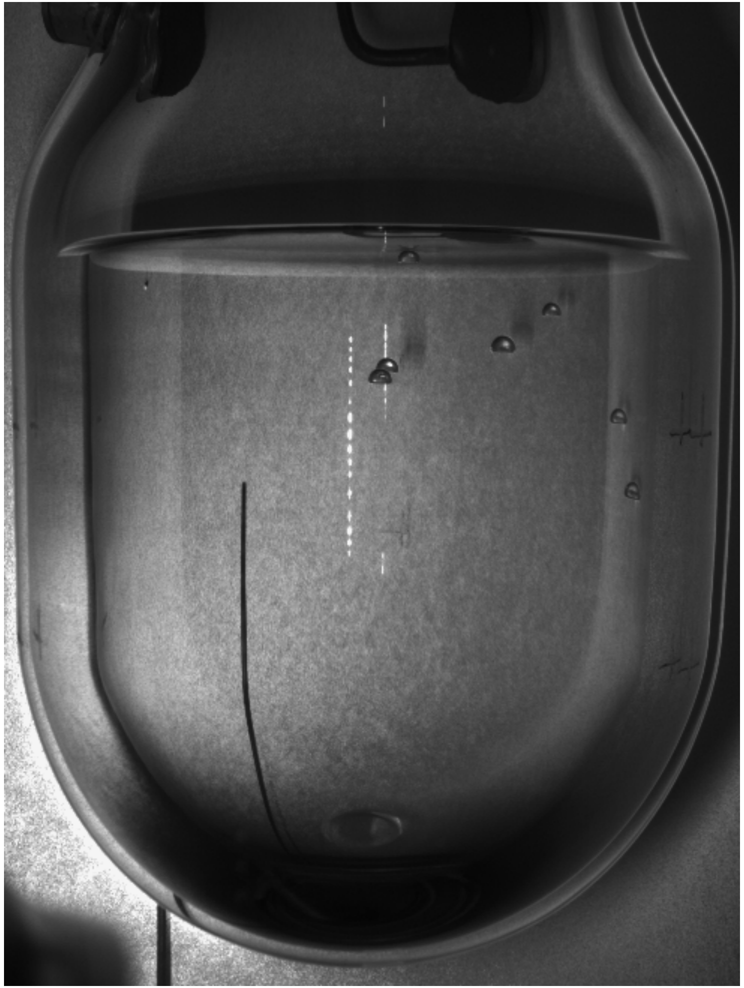

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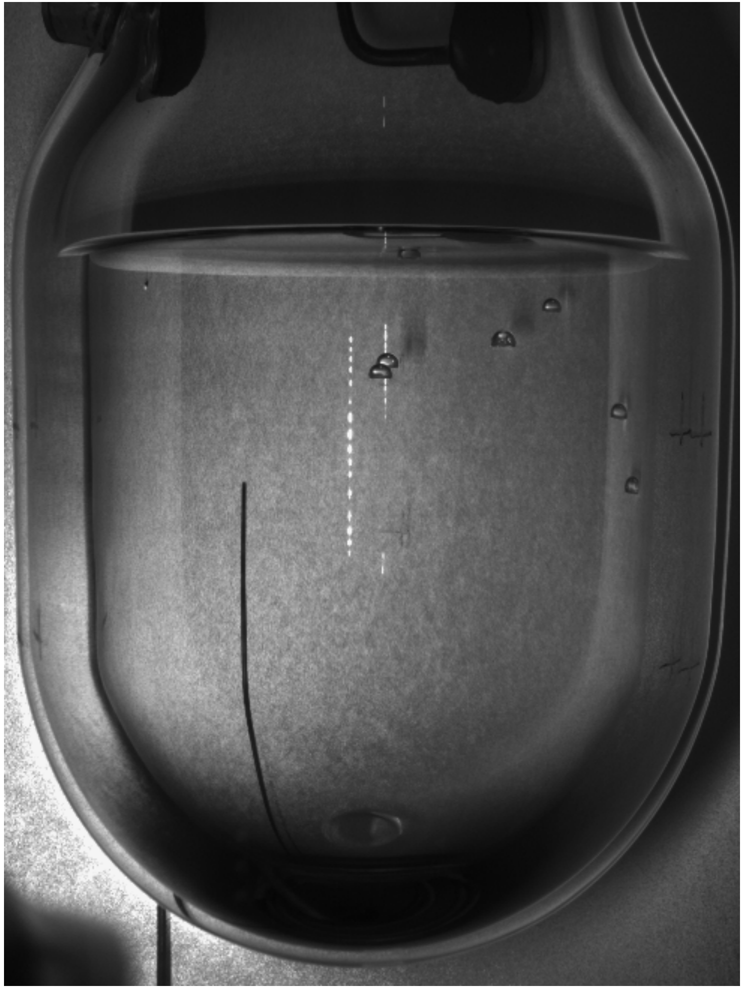

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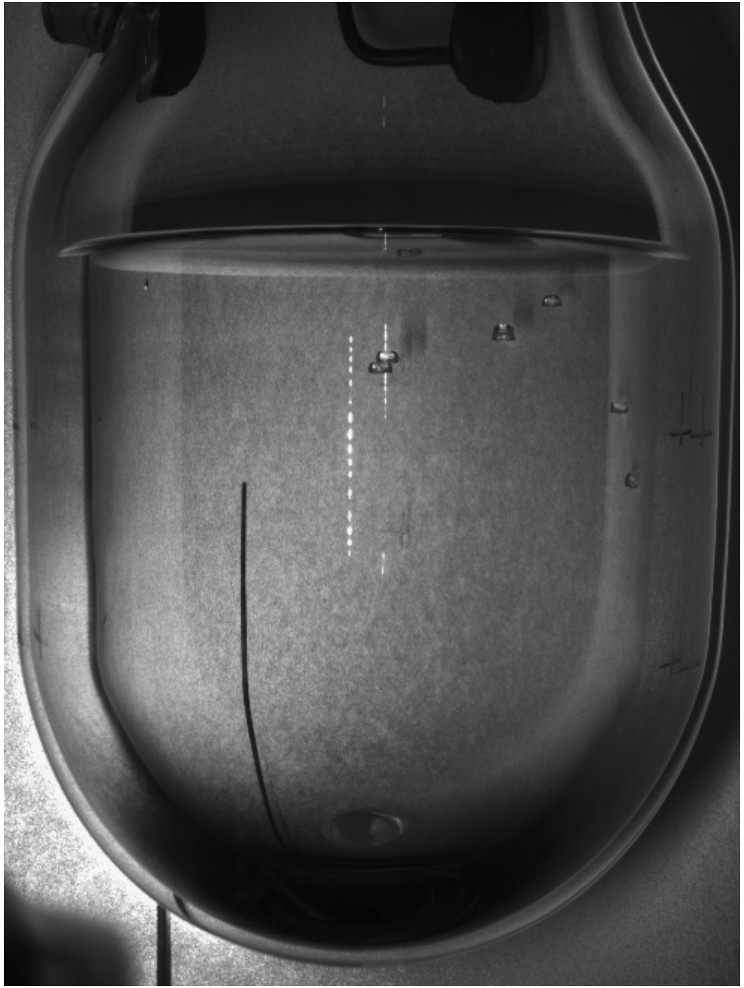

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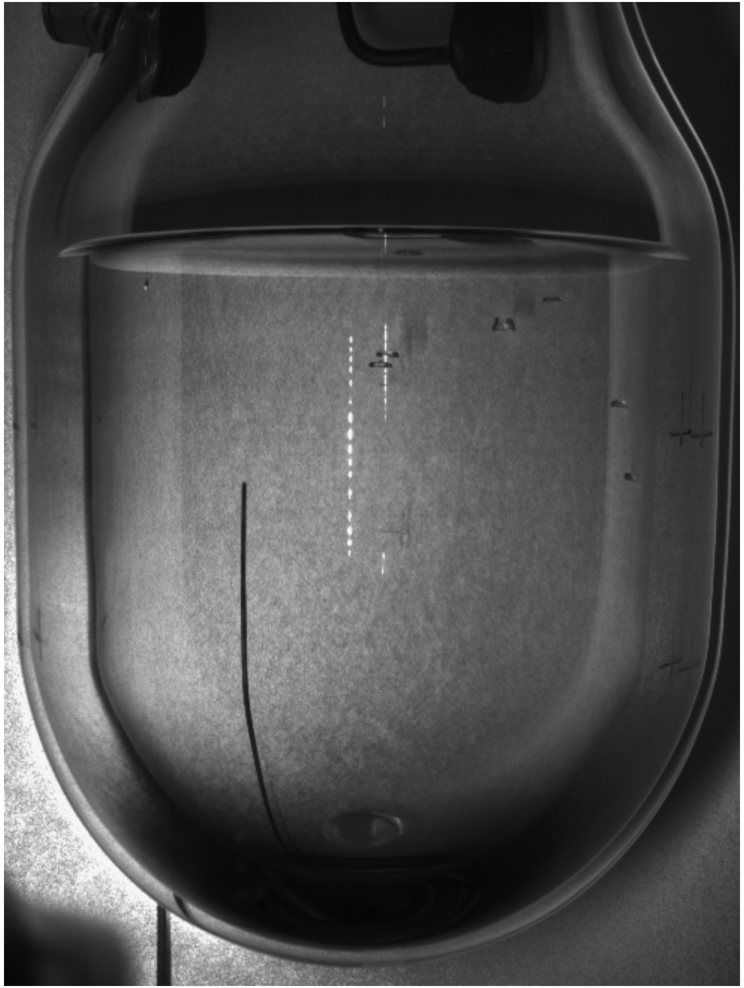

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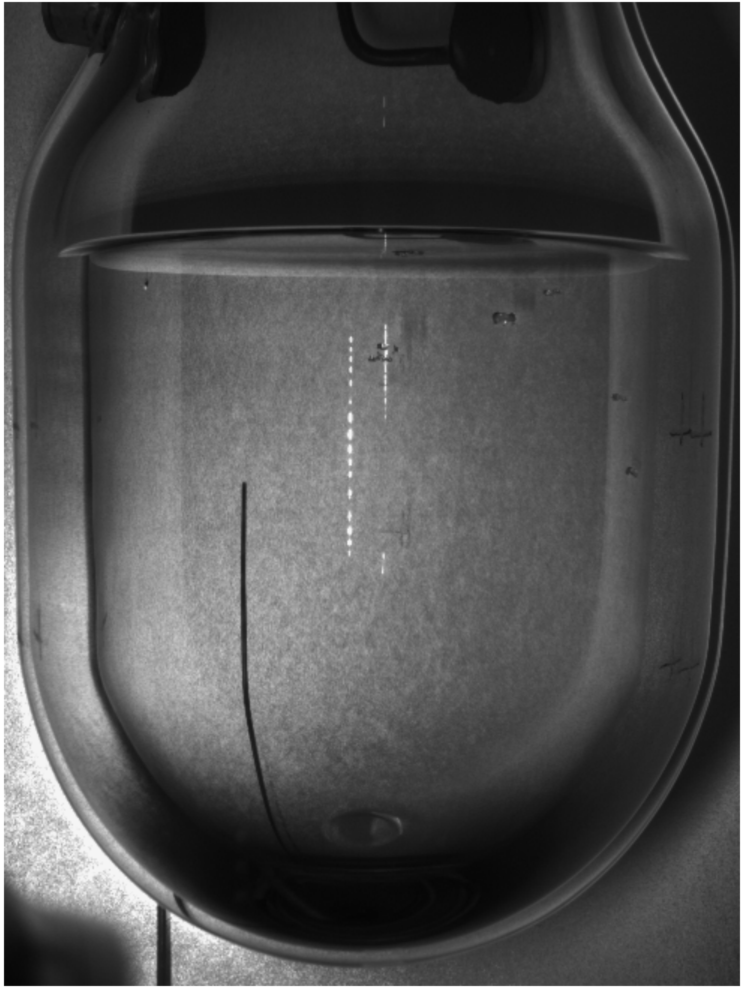

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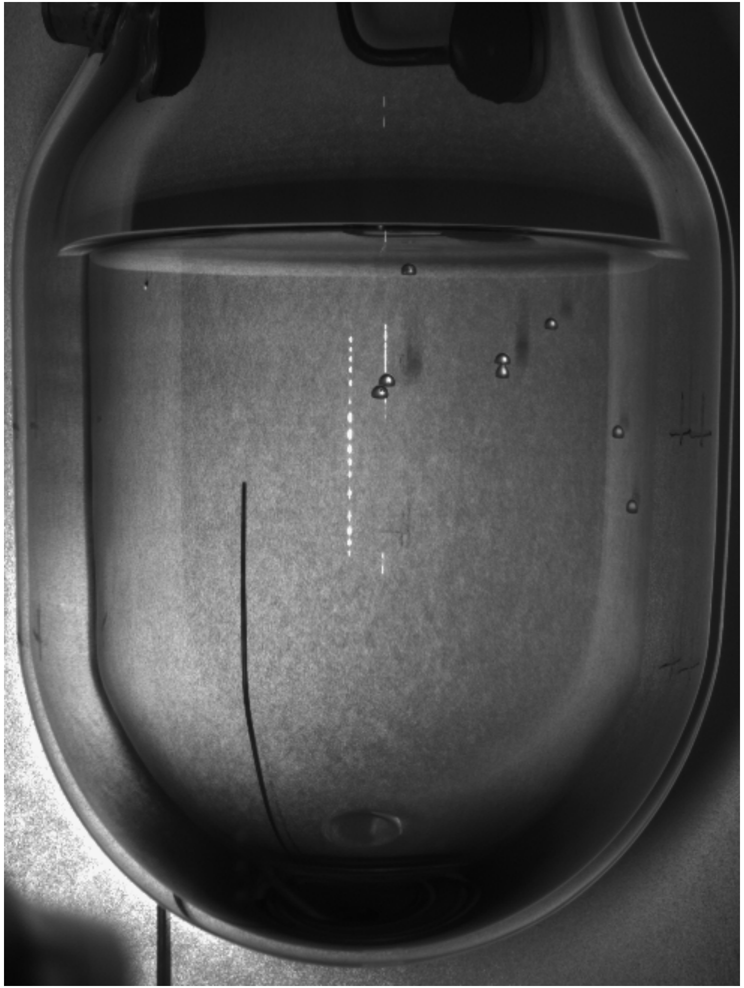
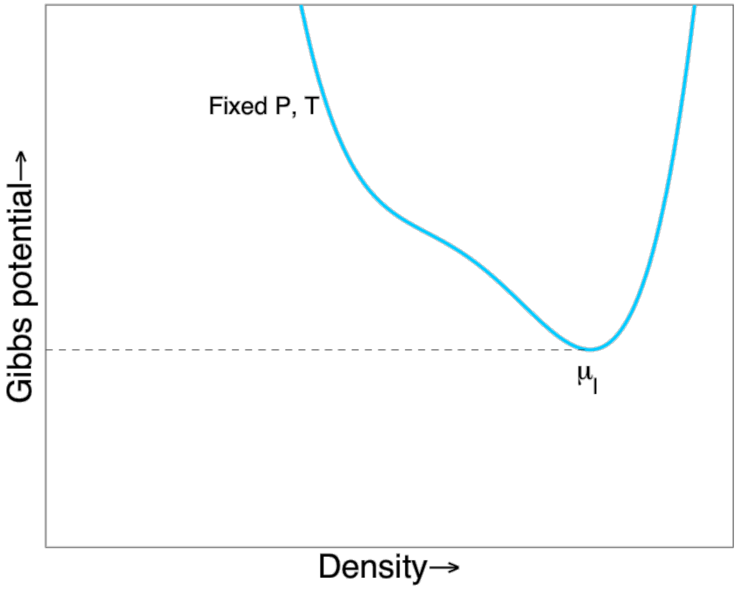
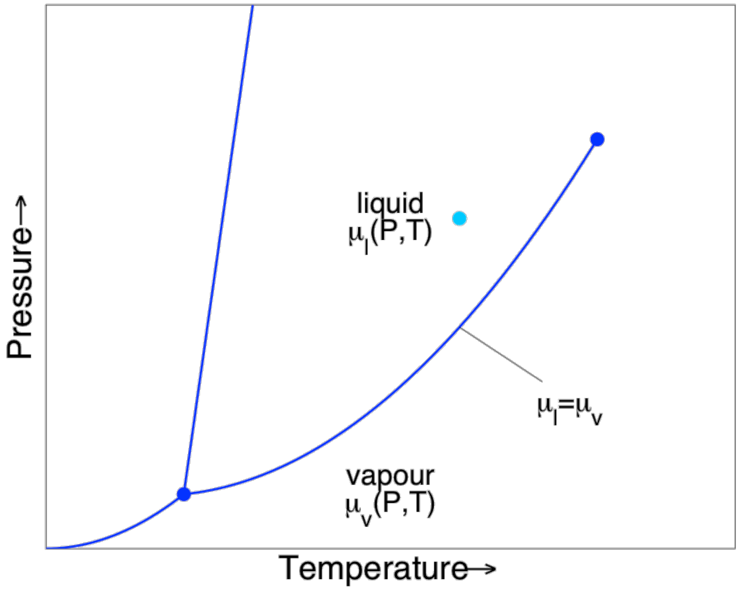


Bubble Chamber Thermodynamics

- What is a metastable state?





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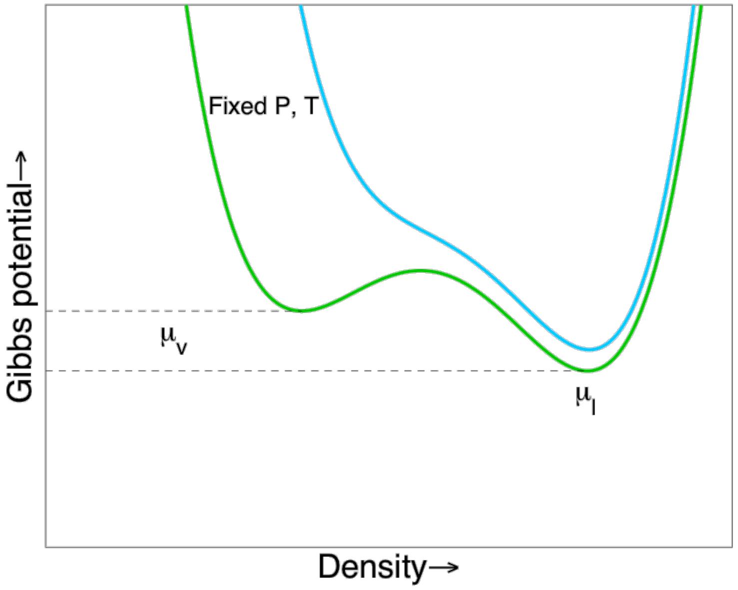

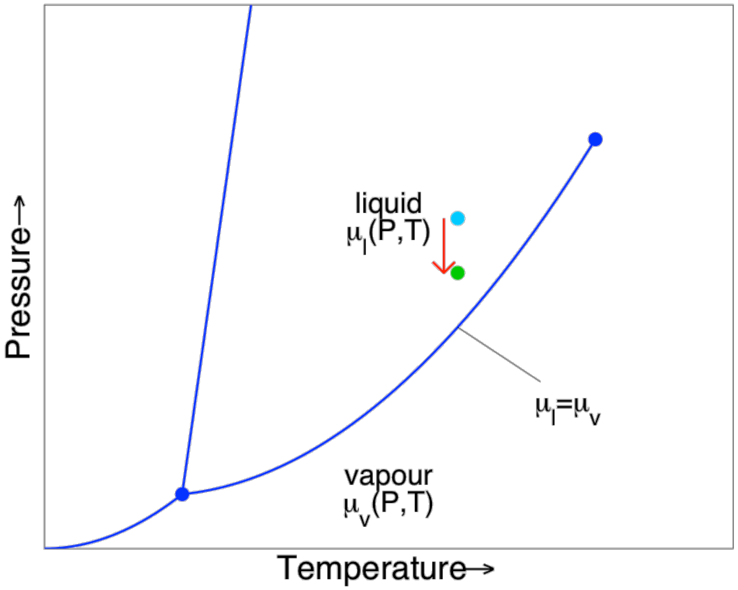

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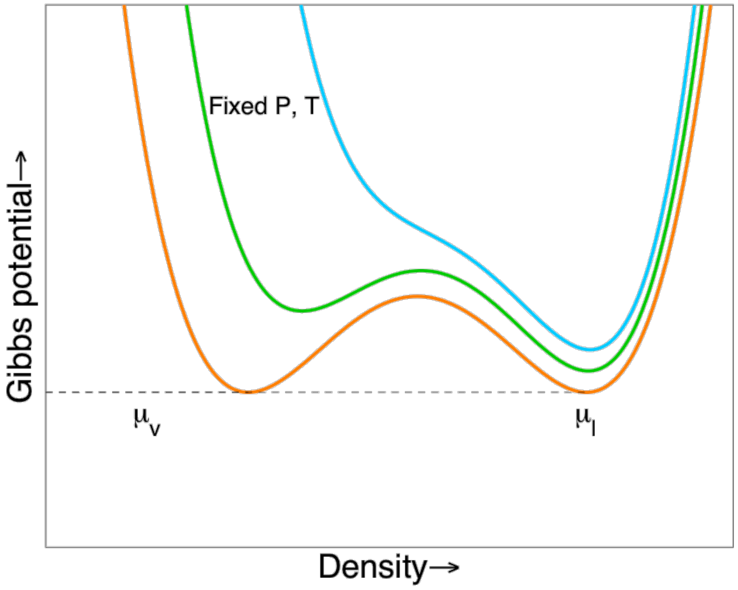

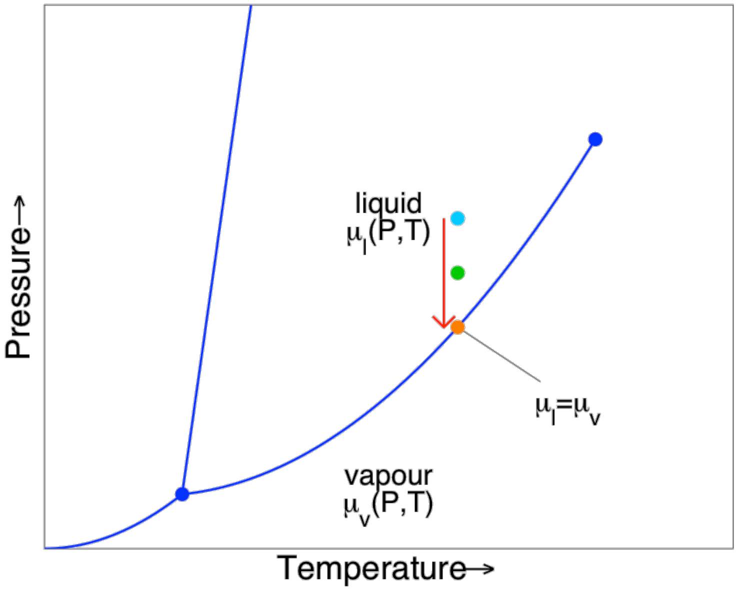

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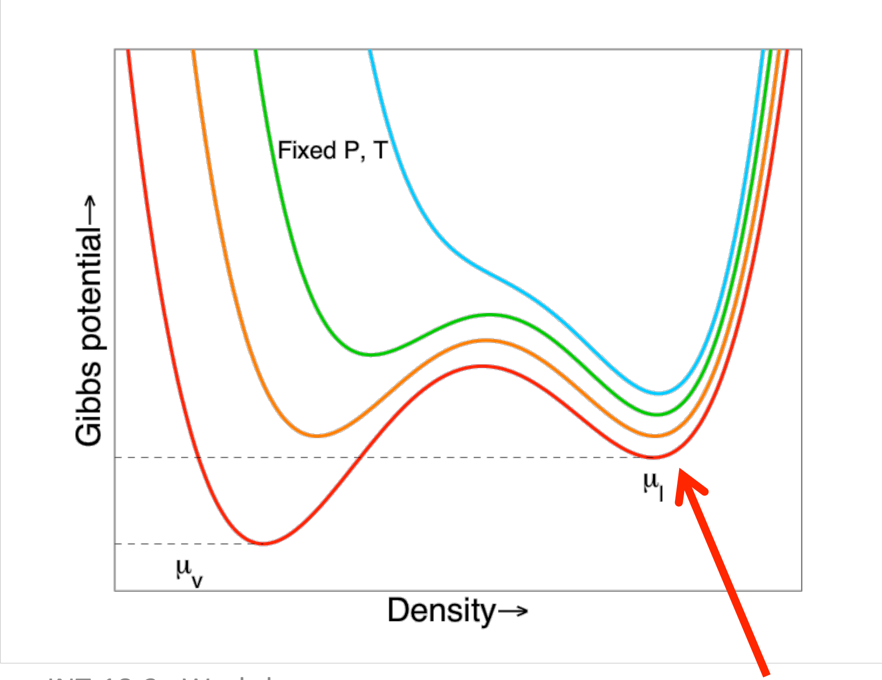
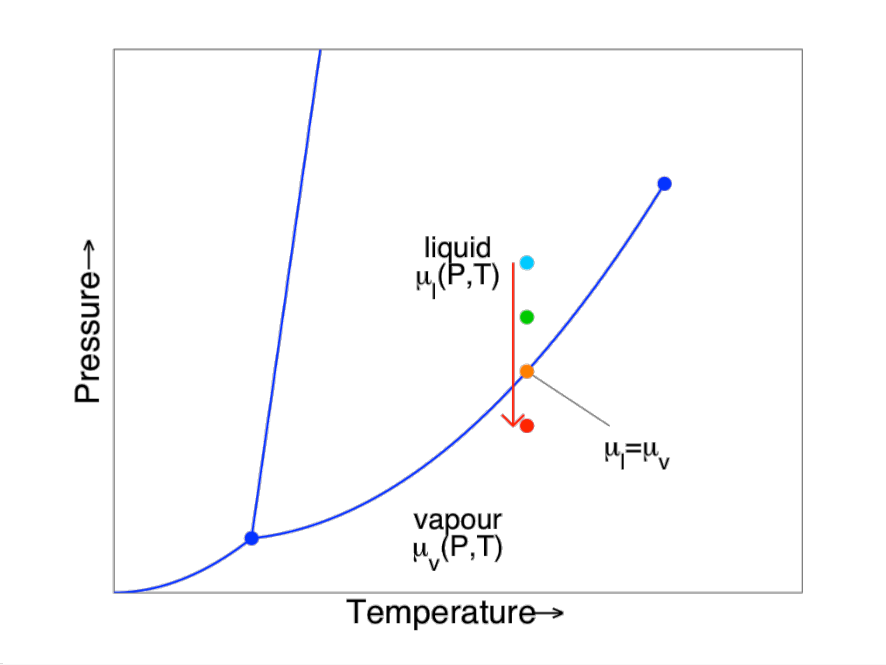
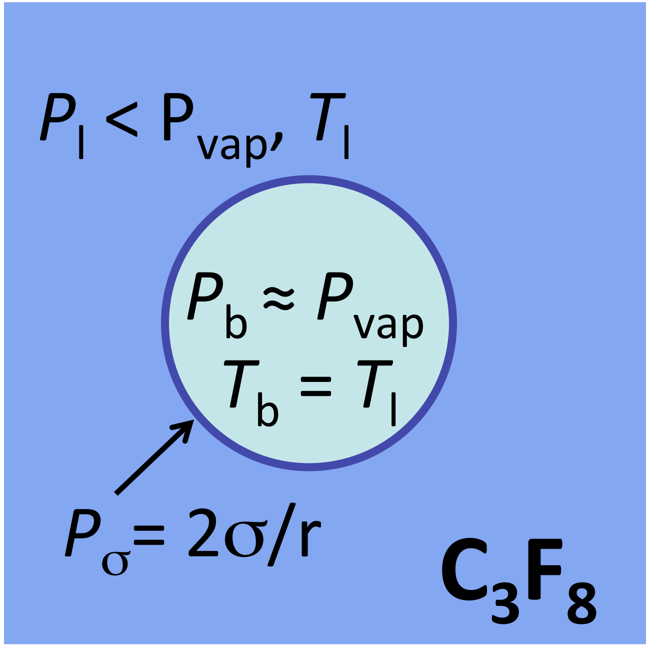




Superheated Liquid

Bubble Chamber Thermodynamics

- What does it take to nucleate a bubble?



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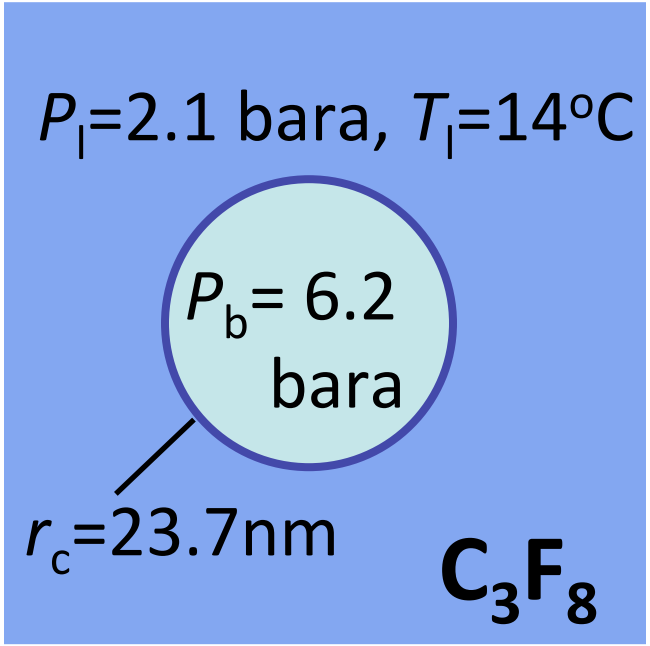


"Critical Radius"

Bubble Chamber Thermodynamics

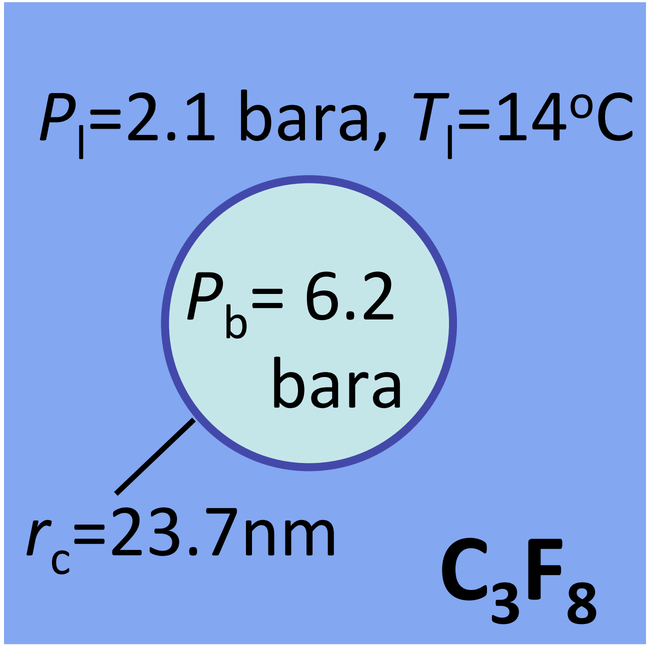
- What does it take to nucleate a bubble?

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

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

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

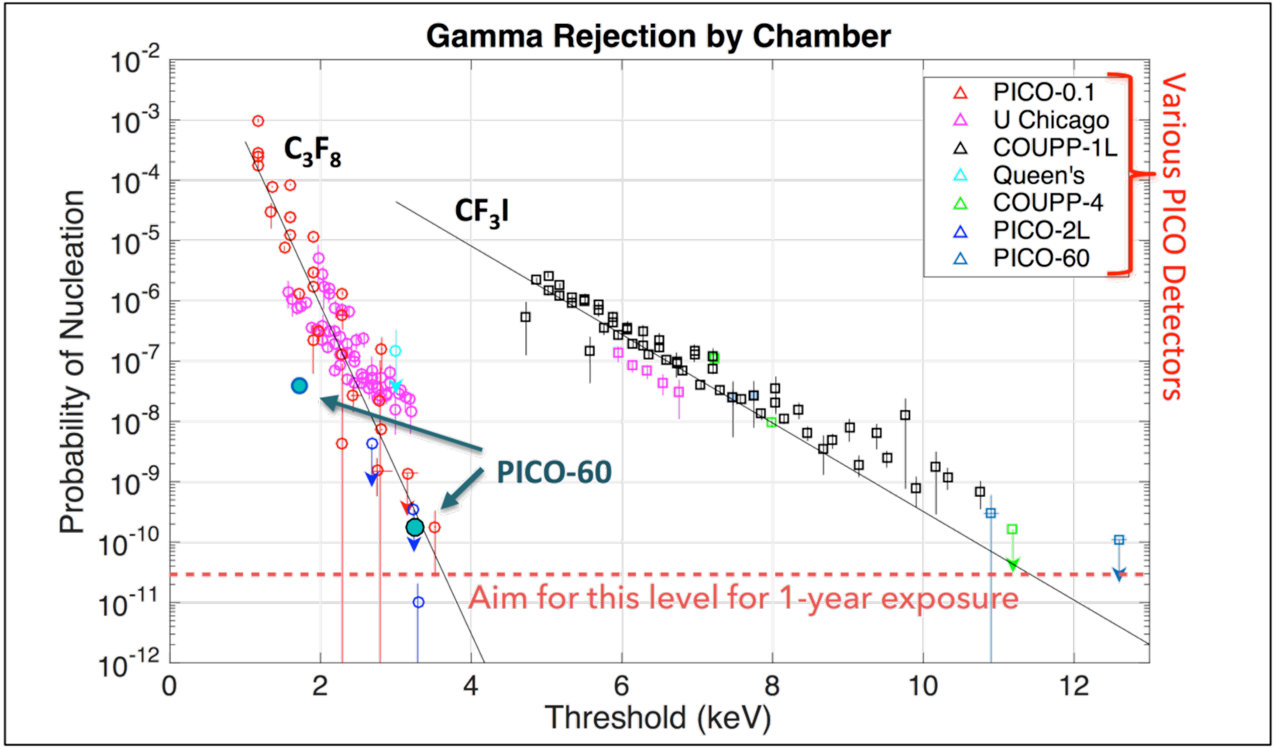
= 3.19 keV *"Thermodynamic Threshold"*



"Critical Radius"

Electron Recoil Discrimination

- Extreme discrimination against β, γ backgrounds
- β, γ sensitivity sets threshold for WIMP searches



(Dan Baxter, Conference on Science at SURF, May 14, 2017) 13

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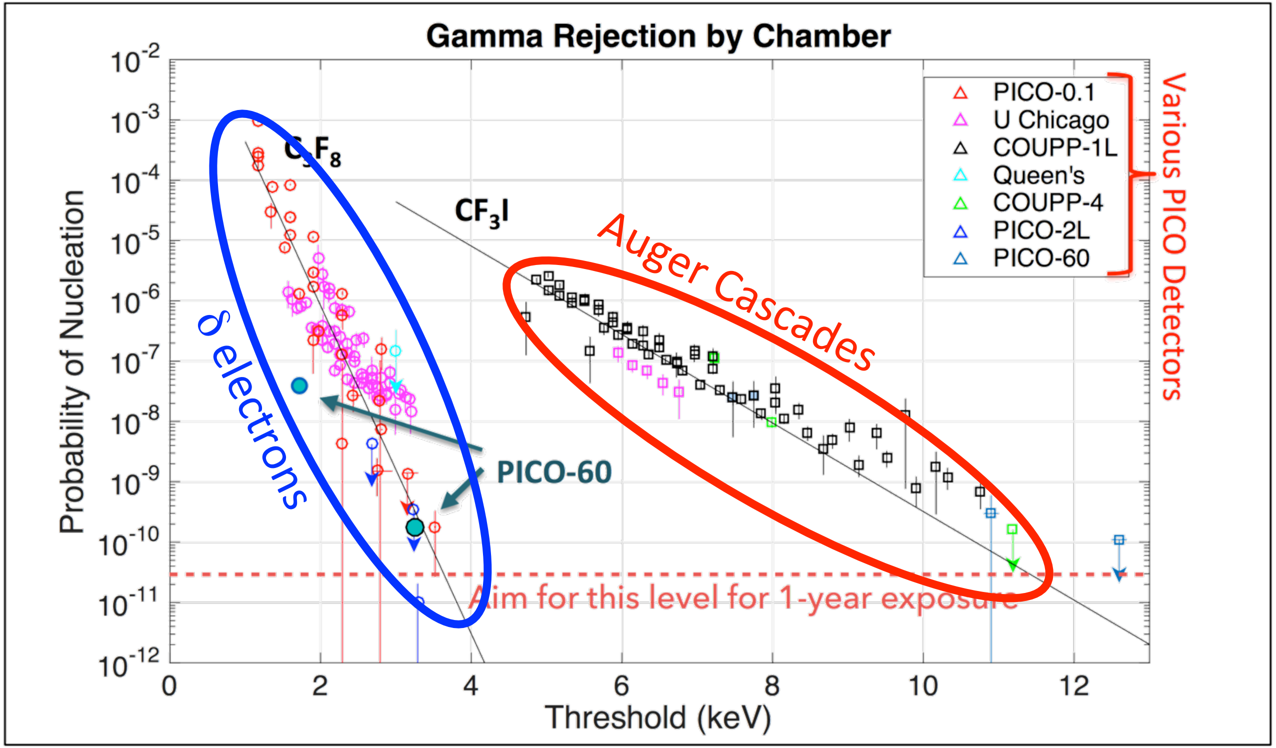

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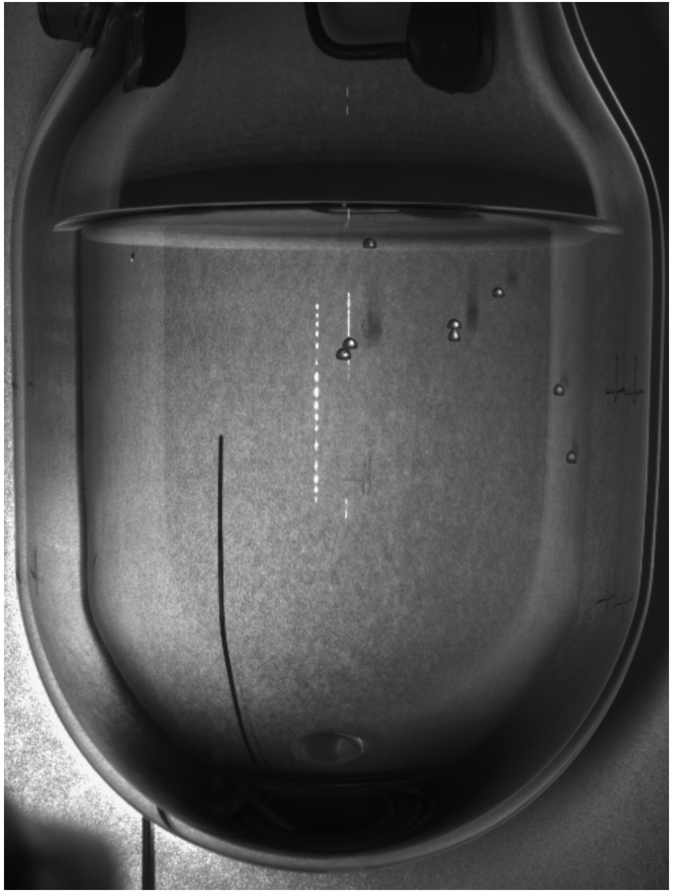
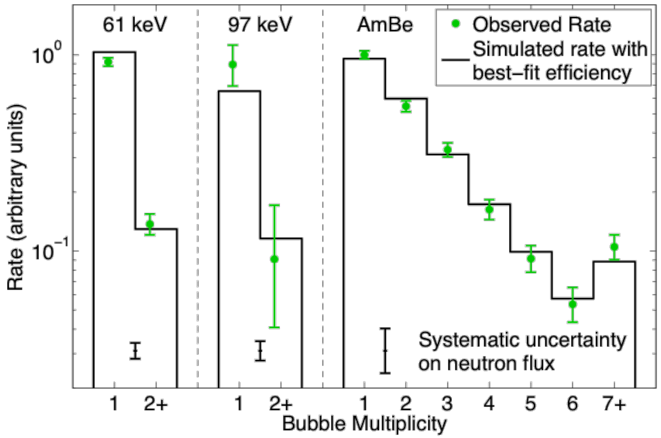
Nuclear Recoil Response

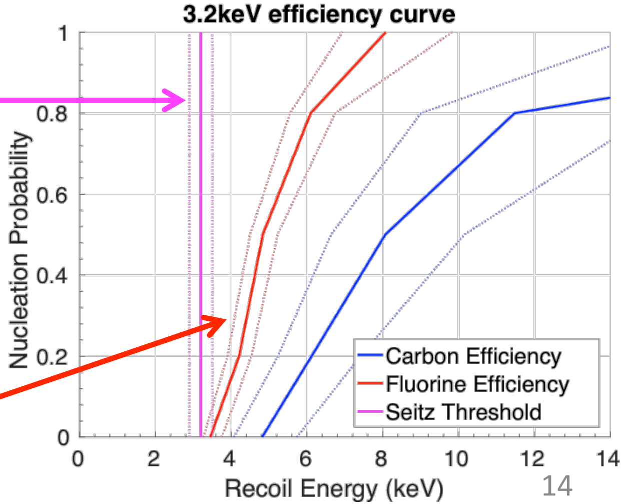


Multiple neutron sources used to constrain recoil detection efficiency

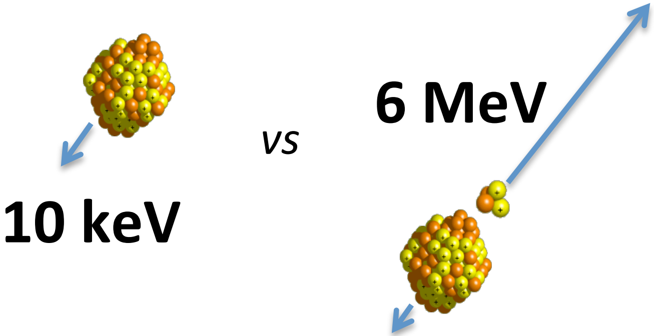


Thermodynamic threshold

Calibrated fluorine recoil detection efficiency



Alpha-Decay Discrimination



- All bubbles look the same!
  - 1-mm diameter bubble has drawn **10 PeV** from superheated fluid
  - Nuclear recoil *visually* indistinguishable from alpha-decay

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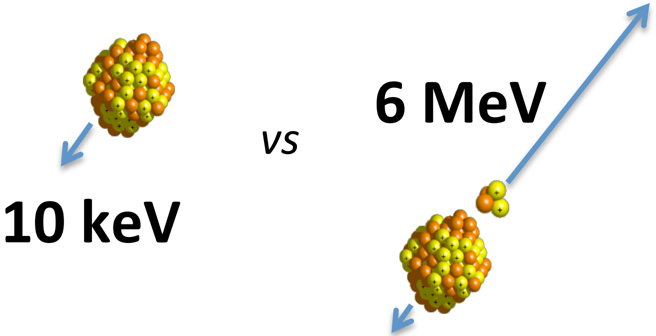

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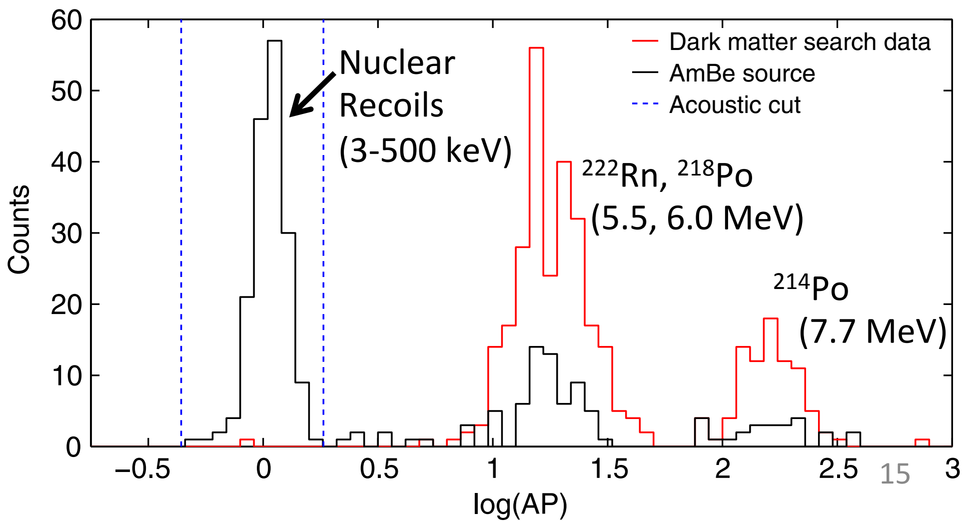
~1-MeV energy resolution in acoustic channel



C. Amole *et al.* Phys. Rev. D 93, 061101(R)

PICO-60, CF_3I

- SNOLAB Run 1 completed (June 2013 – May 2014)
- 35-kg CF_3I, upgradable to 80-kg
- >80% livetime (>90% by end of run)
- 3,415 kg-days exposure at 7—20 keV thresholds
- One multi-bubble event (consistent with expected neutron rate)

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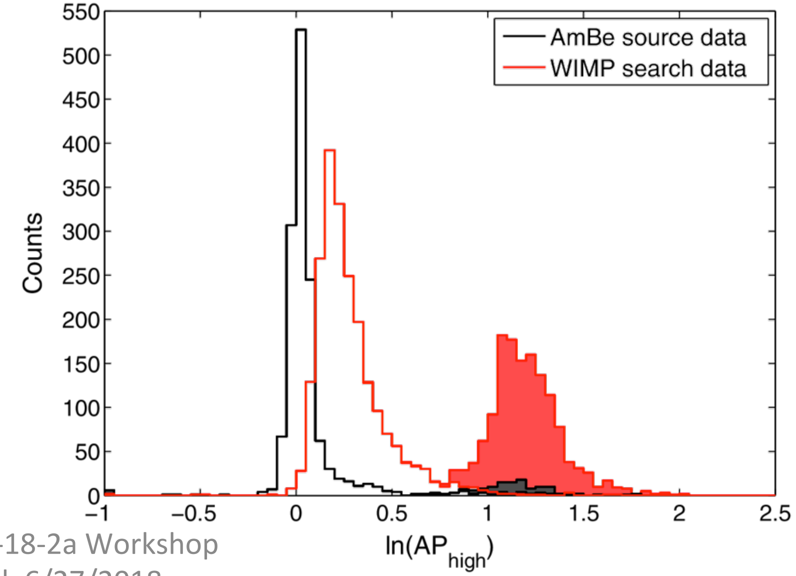
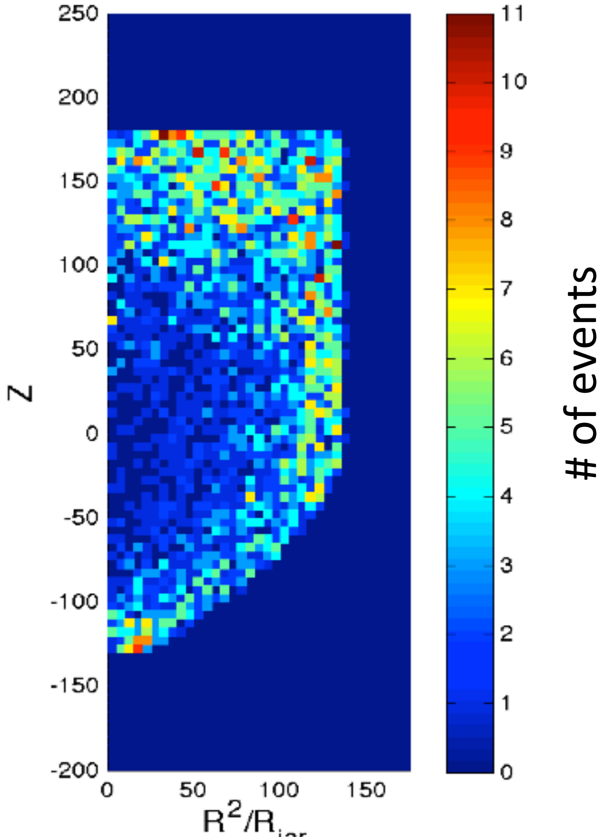
NOT WIMPS

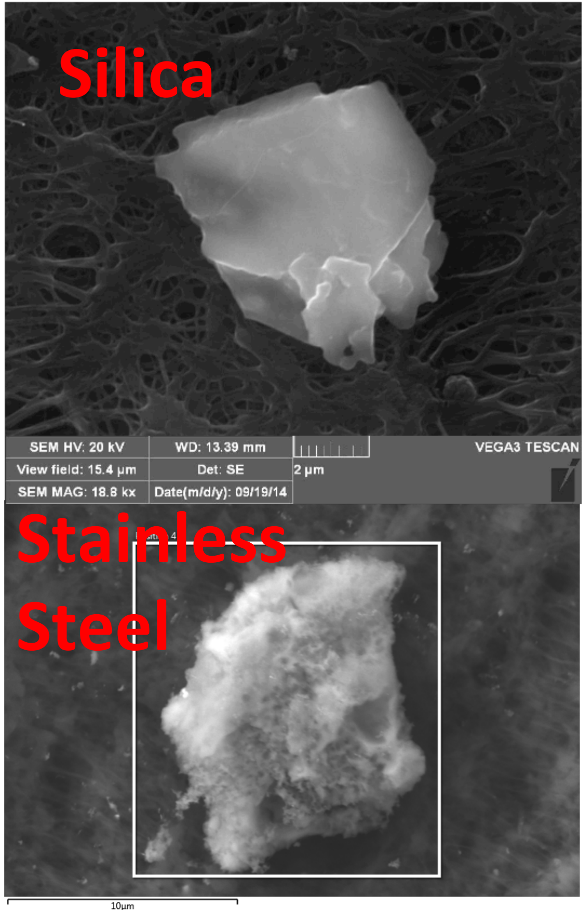
PICO-60 Anomalous Background

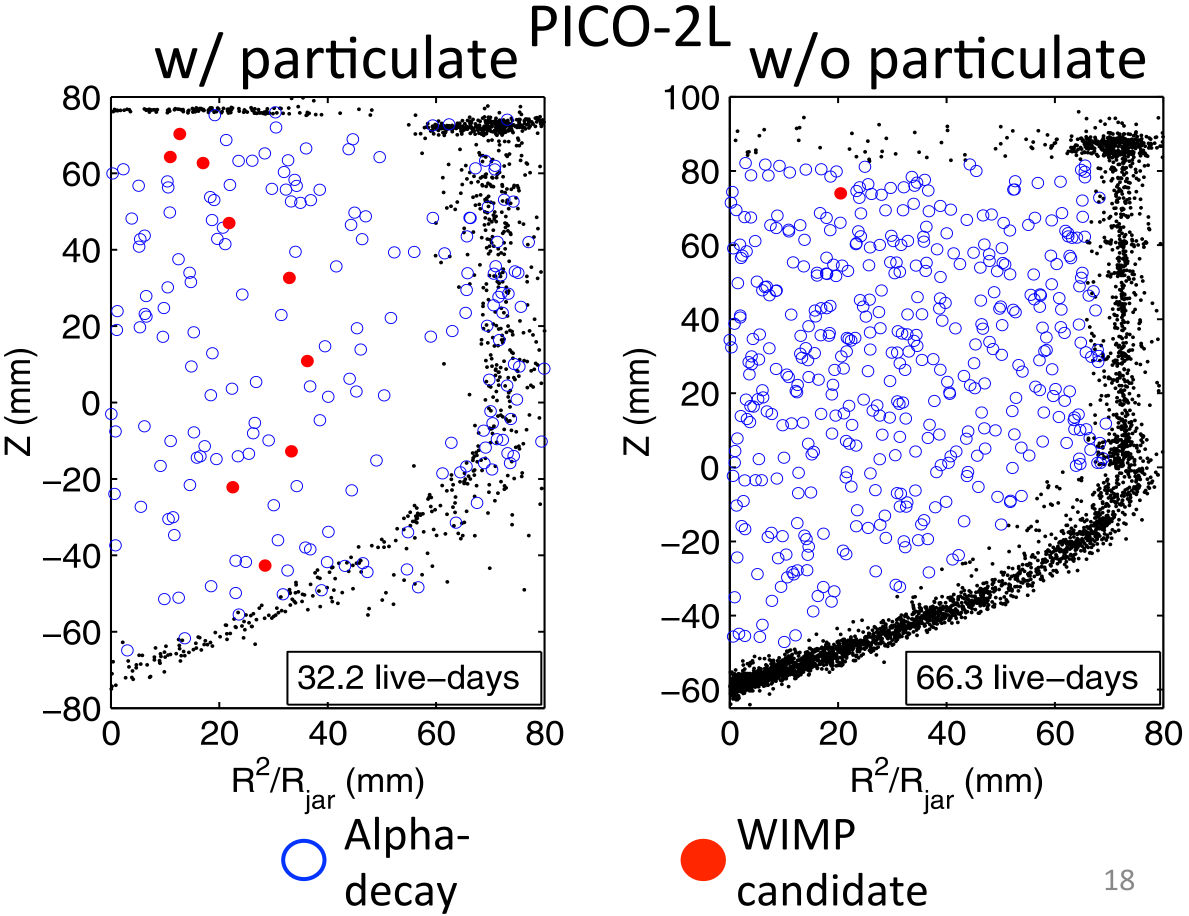
- Mostly at top, edges of detector
- Higher AP than nuclear recoils
- Not uniform in time





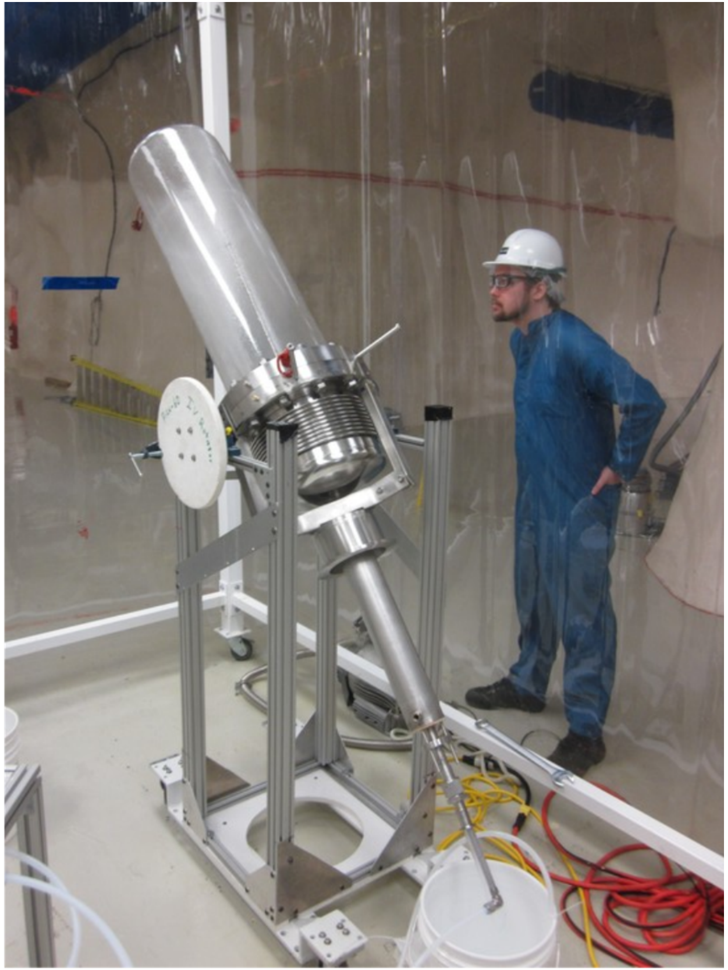
The Culprit: Particulate





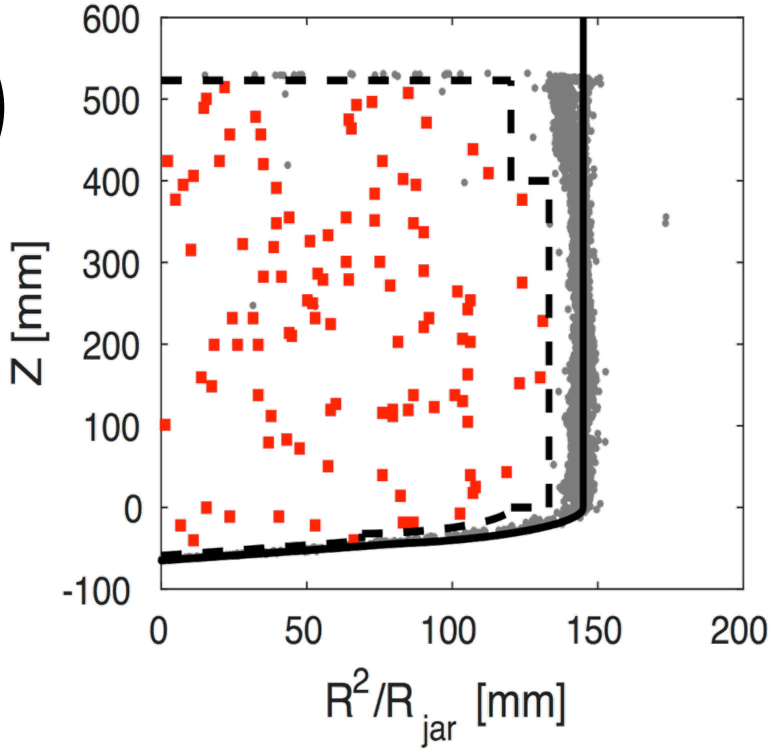
PICO-60 C_3F_8 (2017)

- Goal: Eliminate particulate backgrounds in 40-liters C_3F_8
  - Cleaning/assaying to MIL-STD1246C Level 50
  - Softer metal-quartz seal design
  - In-situ buffer filtration



PICO-60 C_3F_8 (2017)

- 1167 kg-day exposure
- 3.3 keV threshold
- 106 bulk single bubbles
  (3 multi-bubble events)
- "Deaf" Analysis (acoustics blinded)



C. Amole *et al.*, PRL 118, 251301 (2017)

0 – 3 neutron single-bubble events expected, based on multi-bubble event rate

PICO-60 C_3F_8 (2017)

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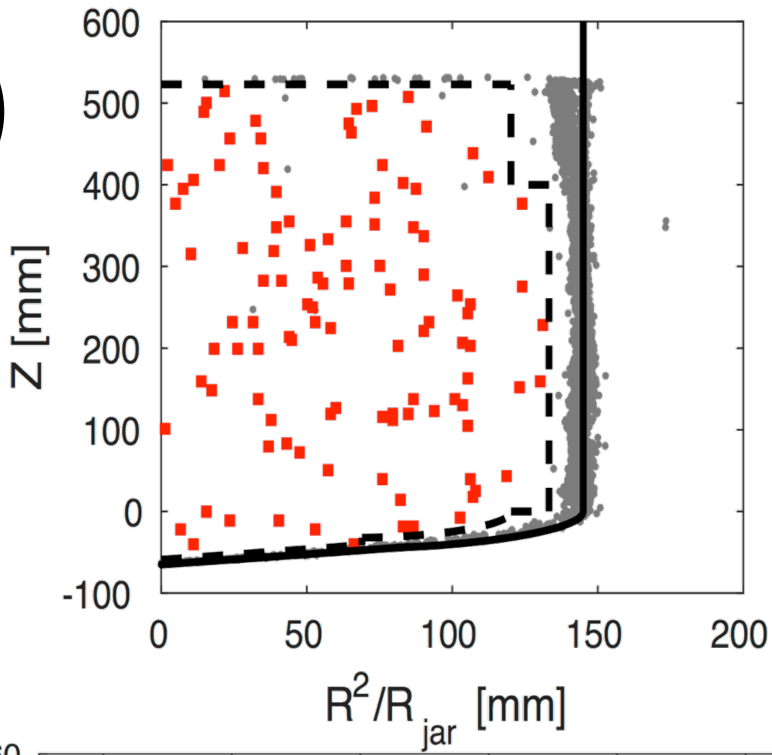
- 3.3 keV threshold
- 106 bulk single bubbles
  (3 multi-bubble events)

- **NO WIMP CANDIDATES**



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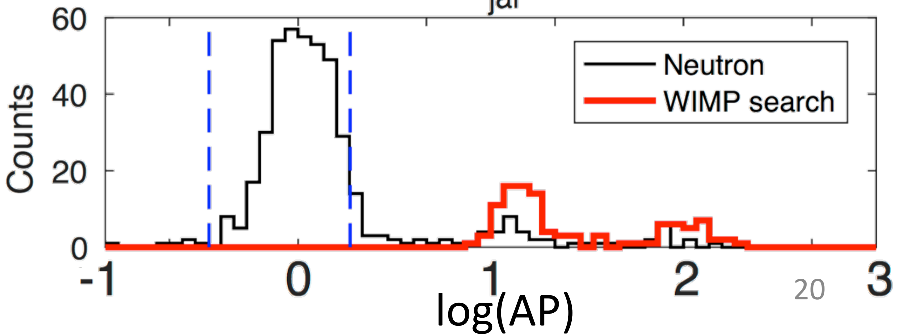
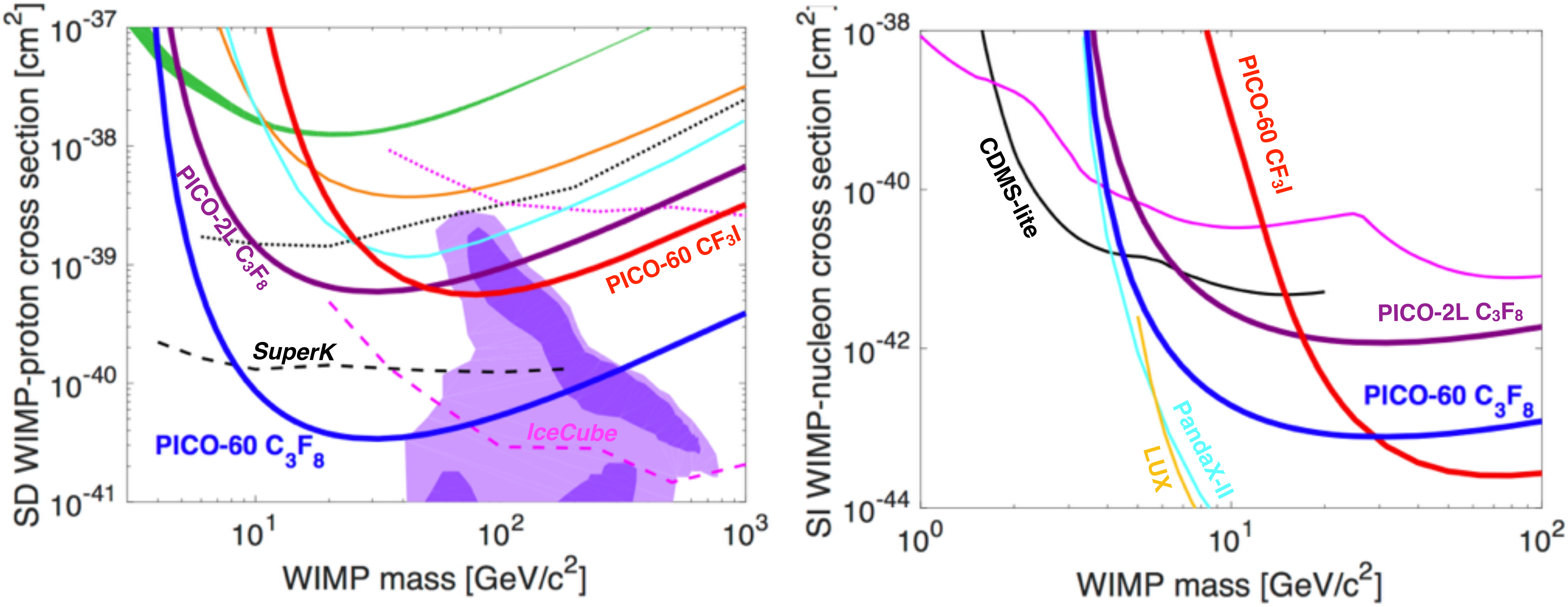
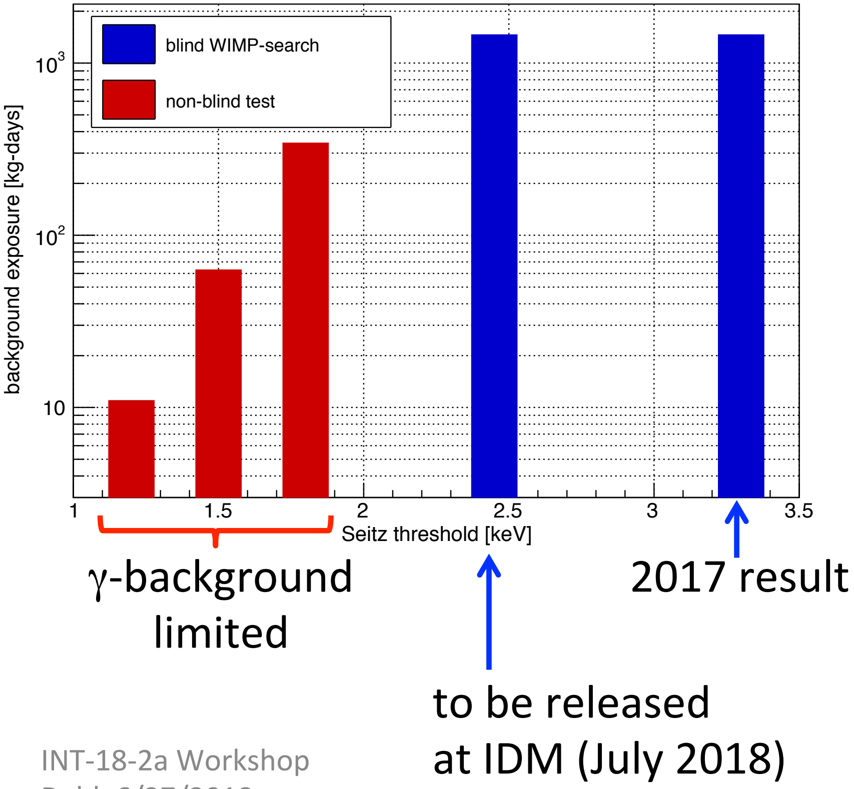


Results (2017)



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

PICO-60, Coming Results



- Since first result was already nearly neutron-limited, PICO-60 shifted to low-threshold (low-WIMP-mass) search
- Analysis of low-threshold calibrations ongoing
- PICO-60 decommissioned in 2017

The Future of PICO

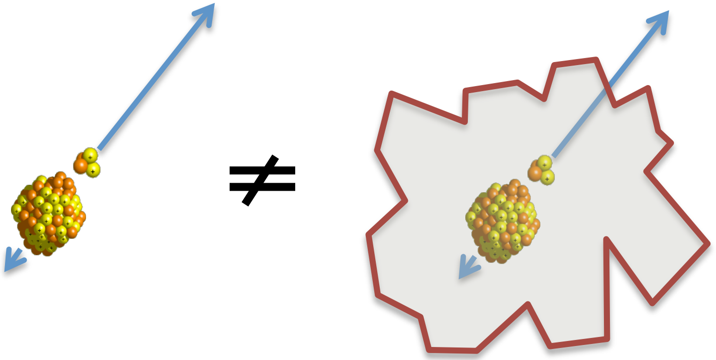
- We’ve shown we can mitigate our background and set new limits…

- But this is not *yet* a discovery machine

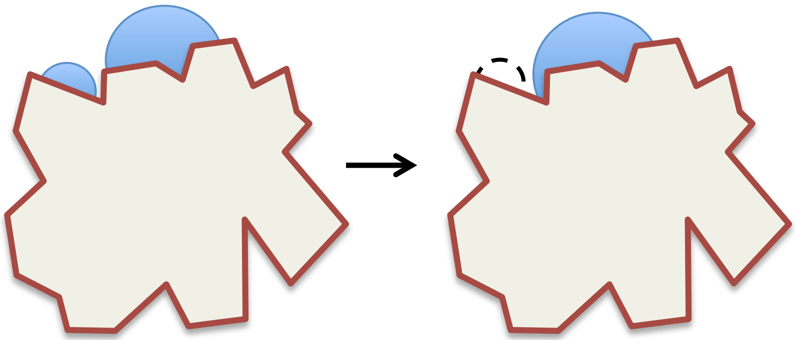
- We must either discriminate against this background, or prove that we have eliminated it entirely. (Or both…)

How to get Bubbles from Particulate

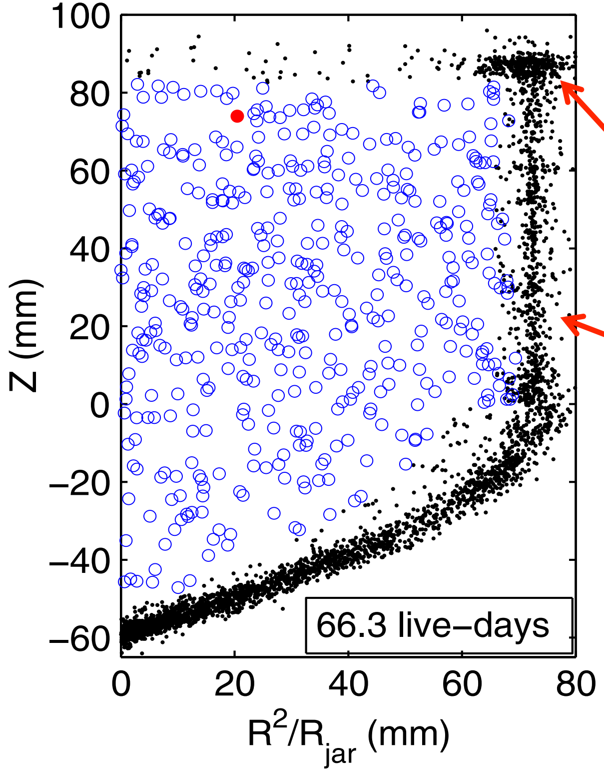
- Alpha decays from particulate, failed acoustics

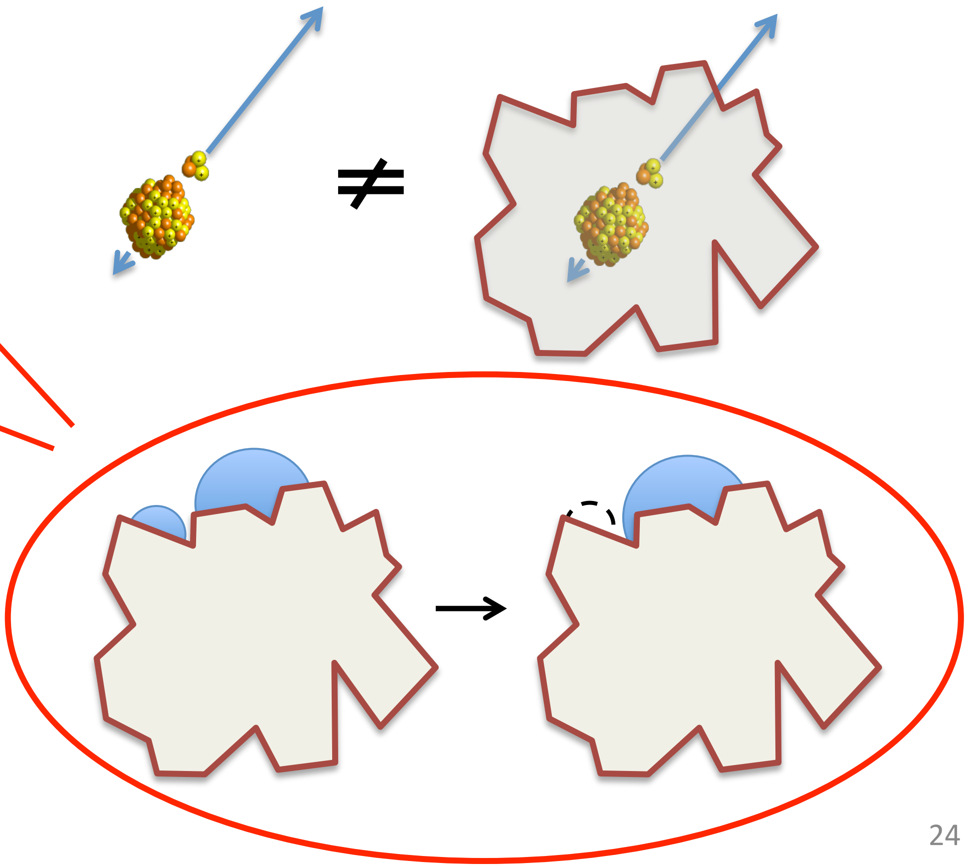


- Merging buffer fluid droplets, cavitation

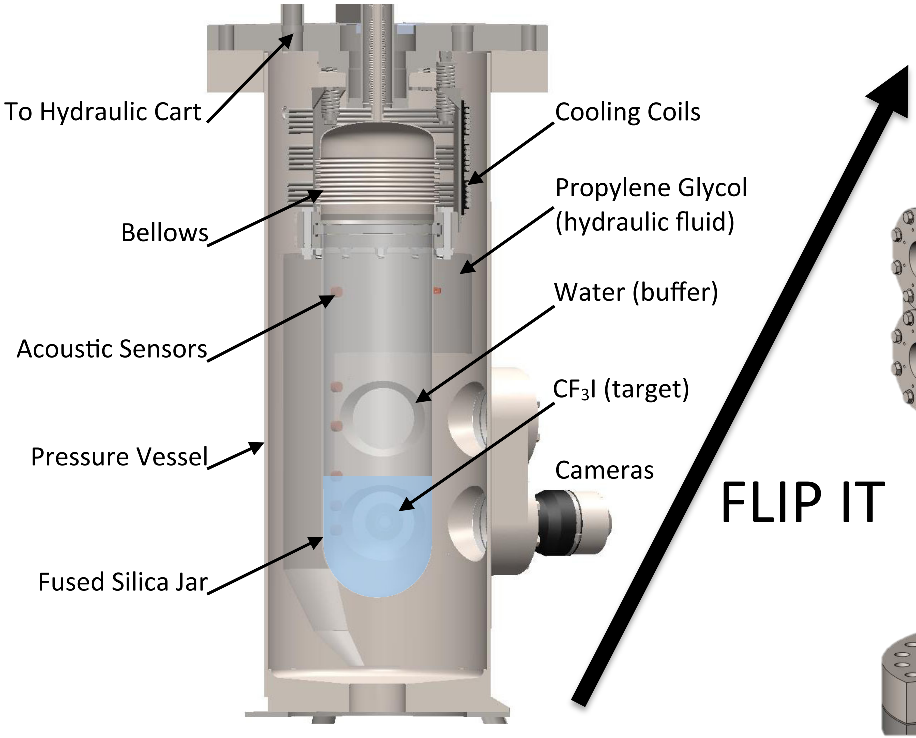


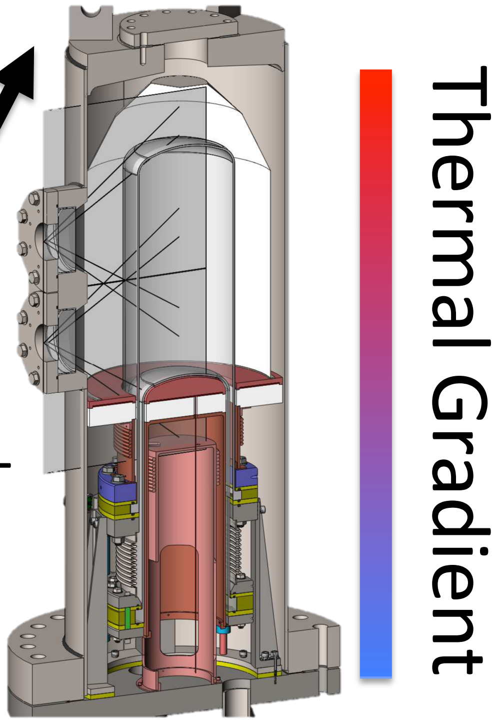
How to get Bubbles from Particulate





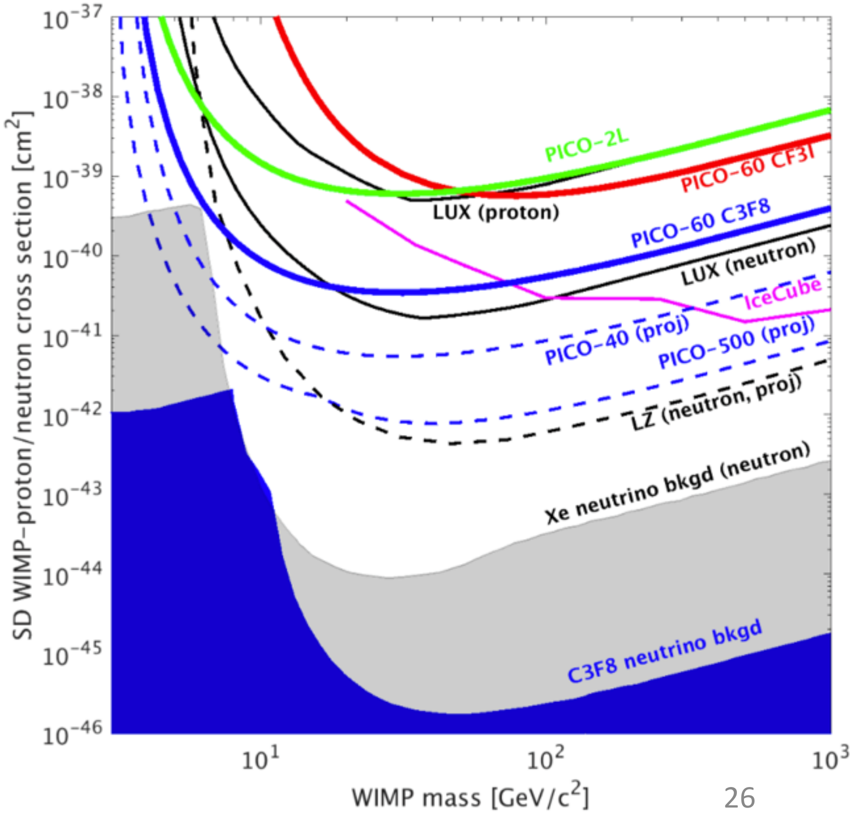
The no-buffer-fluid solution: PICO-40L





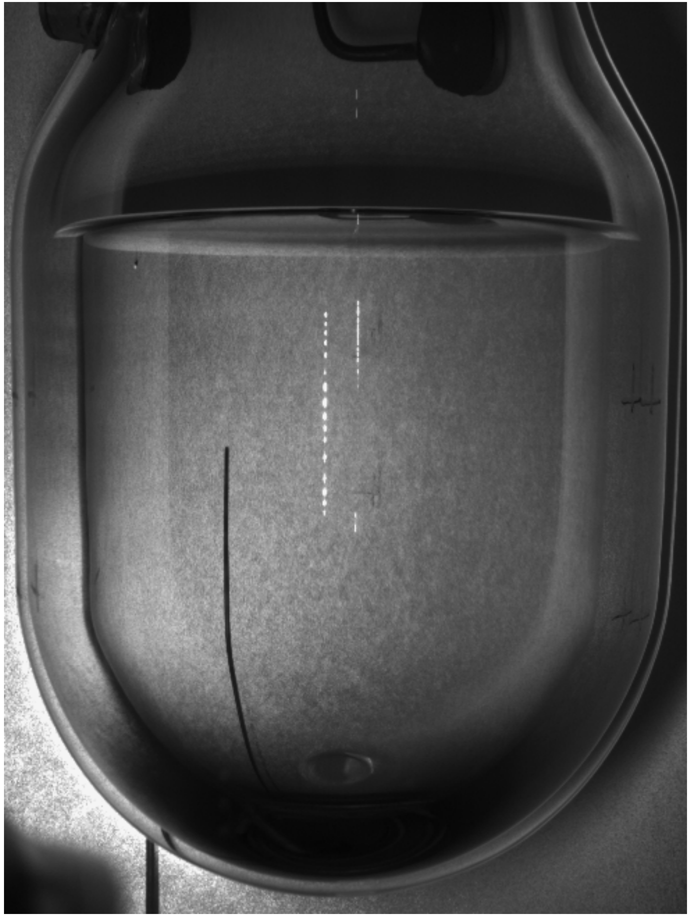
PICO-40L Mission:

- Demonstrate right-side-up geometry at large scale
- Address PICO-60 neutron background
  - 1-year physics exposure planned, beginning Fall 2018
- Dry-run for PICO-500*
  - *now funded by Canadian Foundation for Innovation



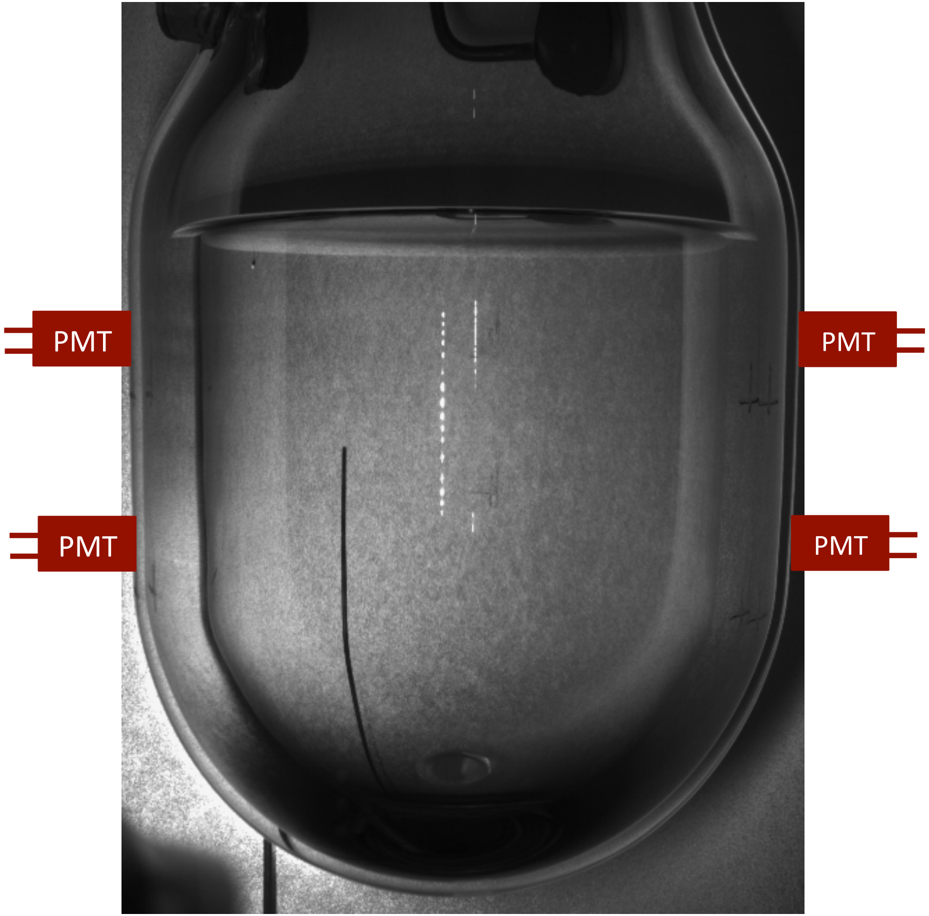
Bubble Chambers

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



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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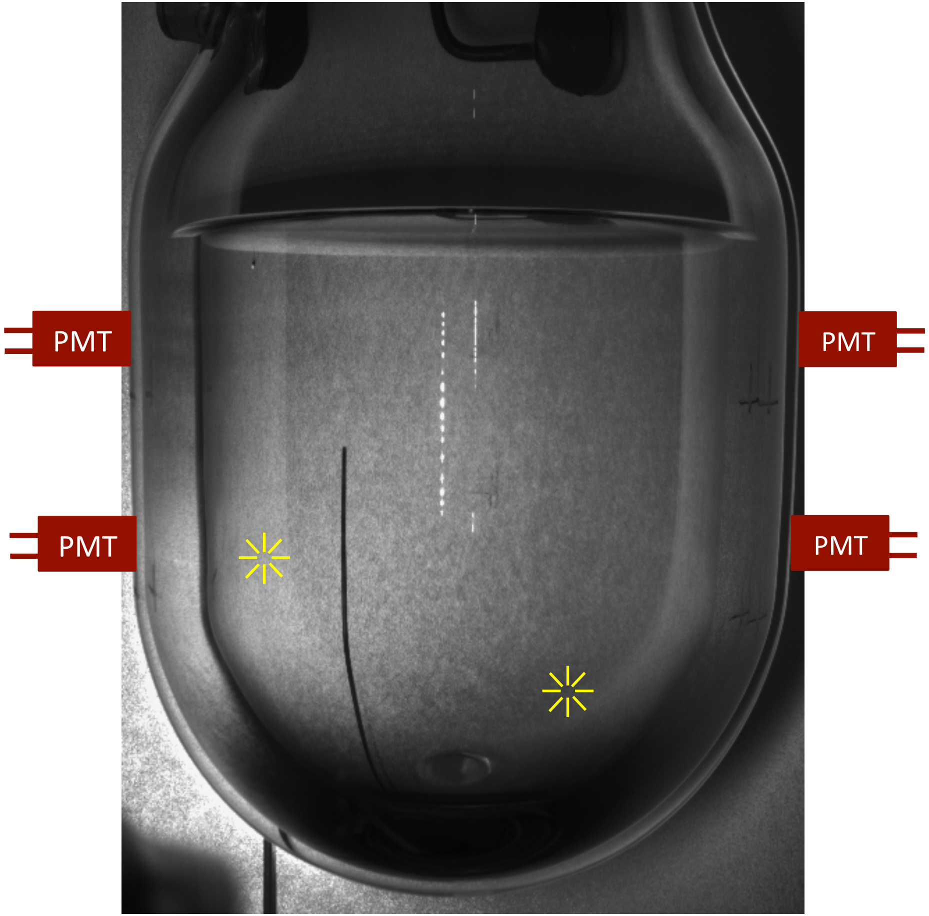

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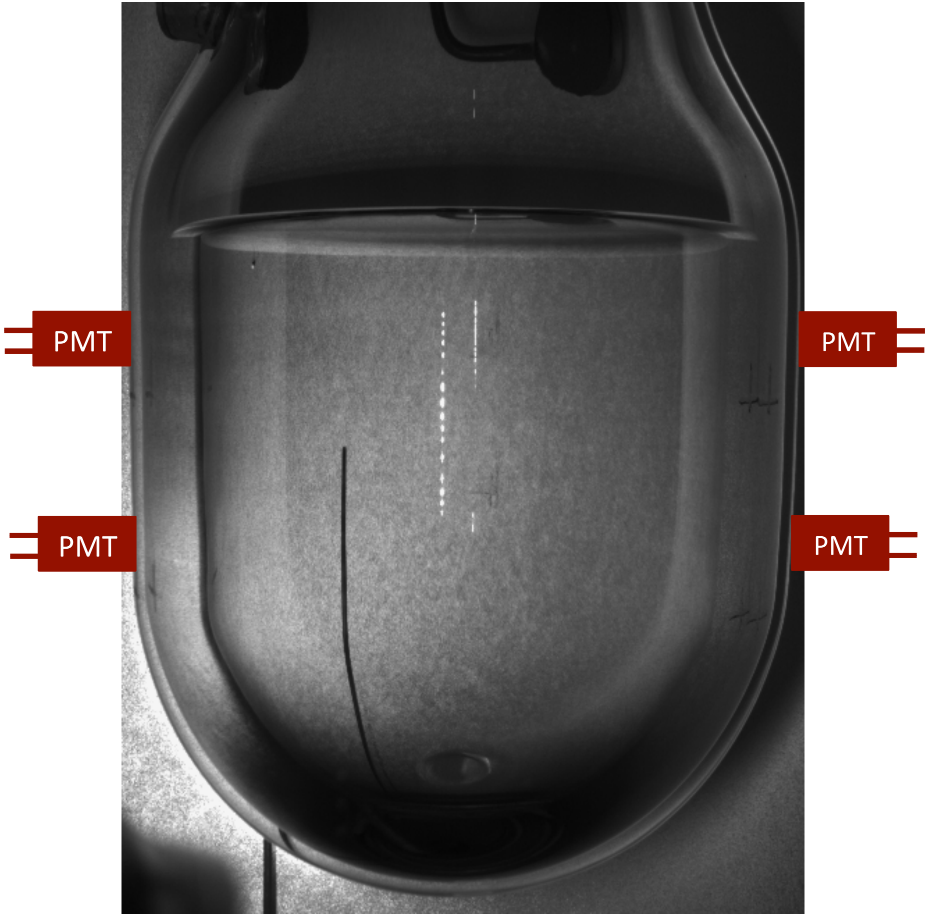

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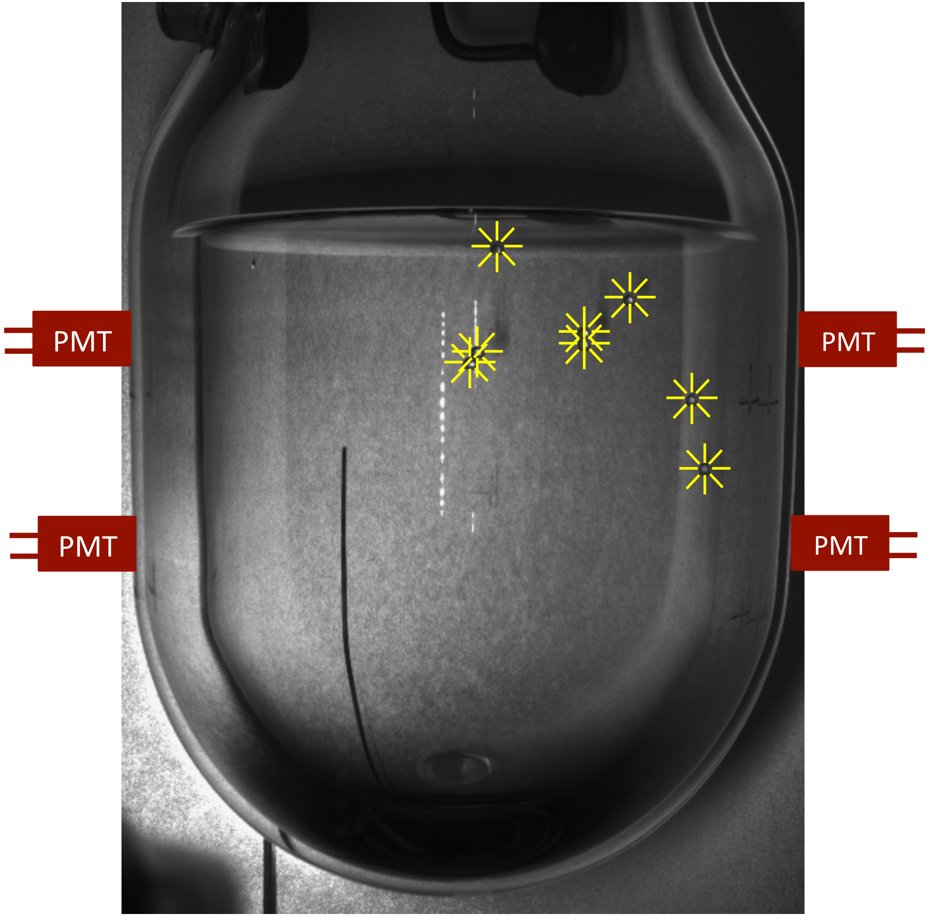

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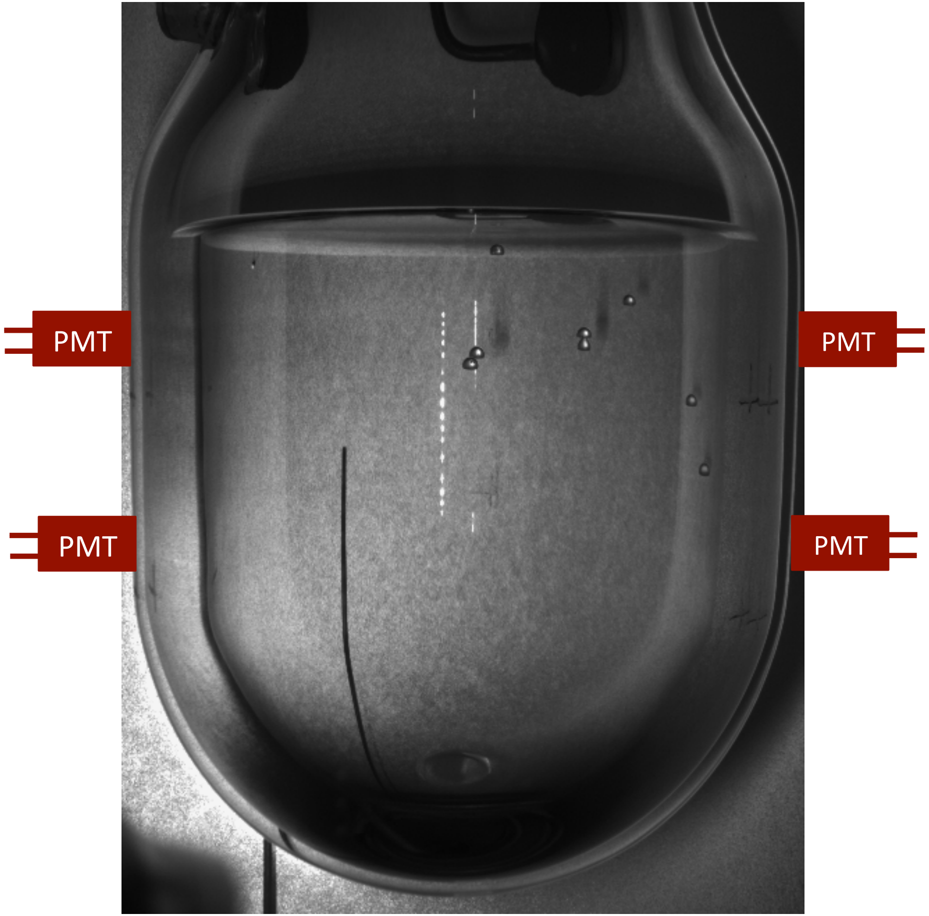
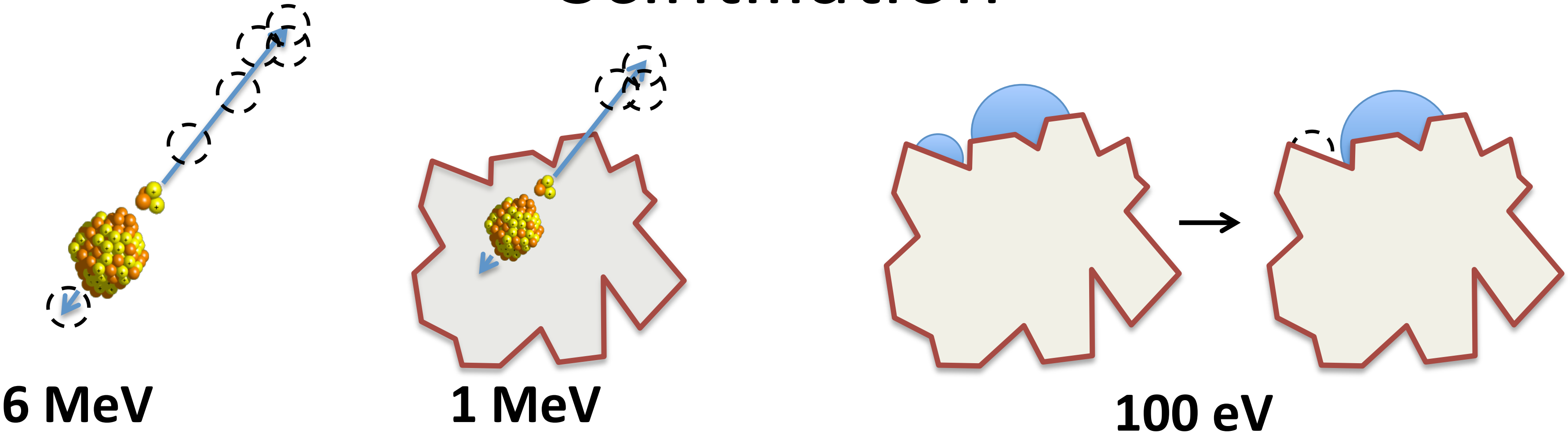
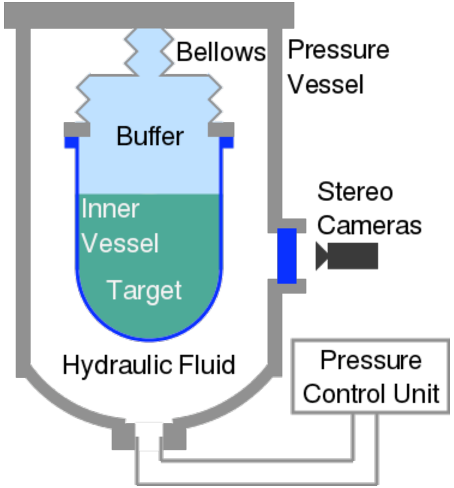


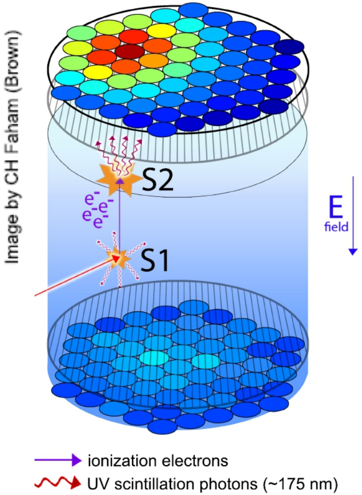
Eliminating Backgrounds via Scintillation

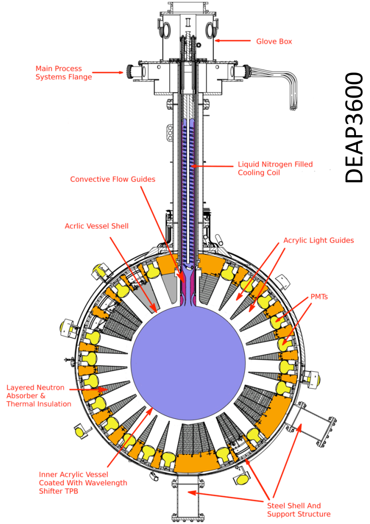


- ALL of these are trivially identified with scintillation signal
- More information *always* key to background discrimination

Why Liquid-noble Bubble Chambers

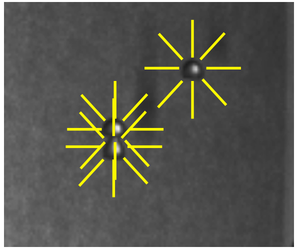






10^{-10} discrimination

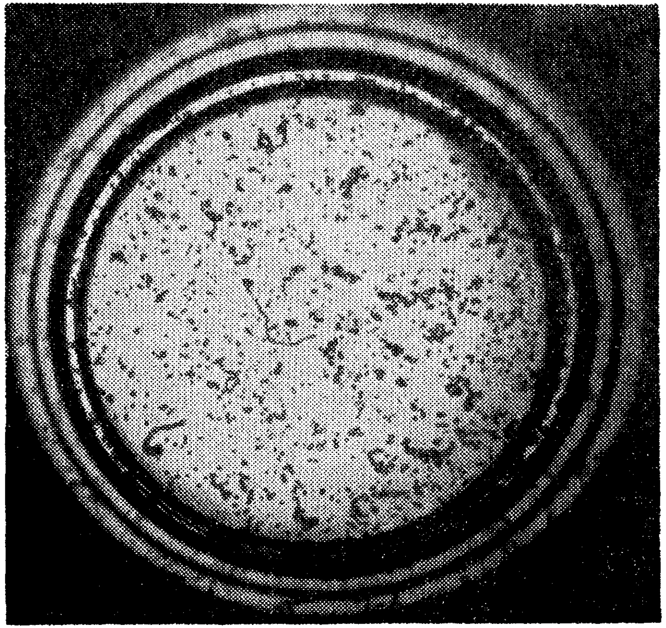
Event-by-event Energy



Low-threshold (< keV) ER discrimination

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

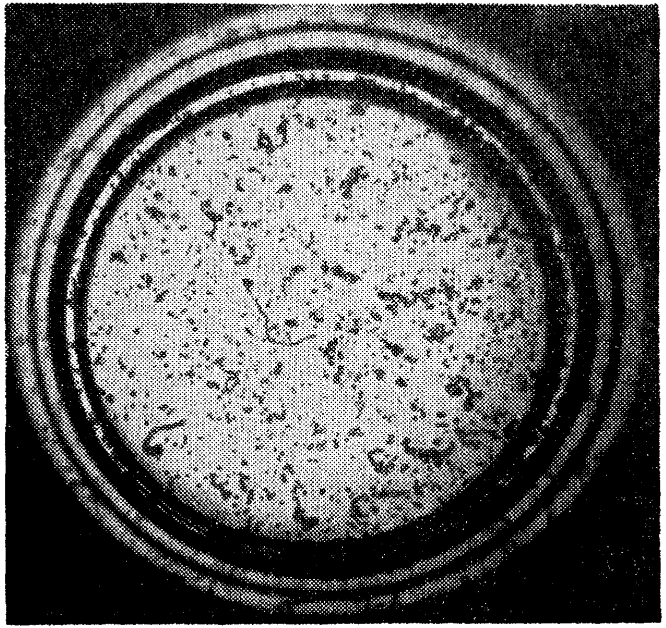
- Glaser built a xenon bubble chamber in 1956 and found:
  - **No bubbles** in pure xenon even at ~1 keV threshold (with gamma source)
  - Normal bubble nucleation in 98% xenon + 2% ethylene (scintillation completely quenched)



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

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

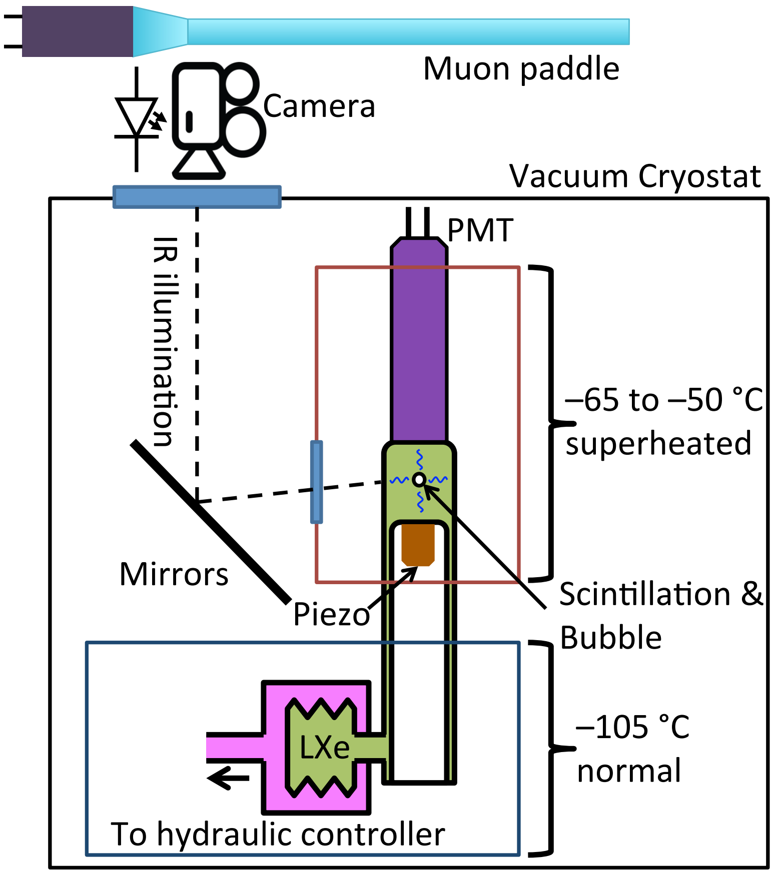
- Scintillation suppresses bubble nucleation?
  - **Electrons** should be even less likely to make bubbles than in freon chambers
  - Greater superheat (lower thresholds) possible
  - **Nuclear Recoils should be largely unaffected**, thanks to Lindhard Effect



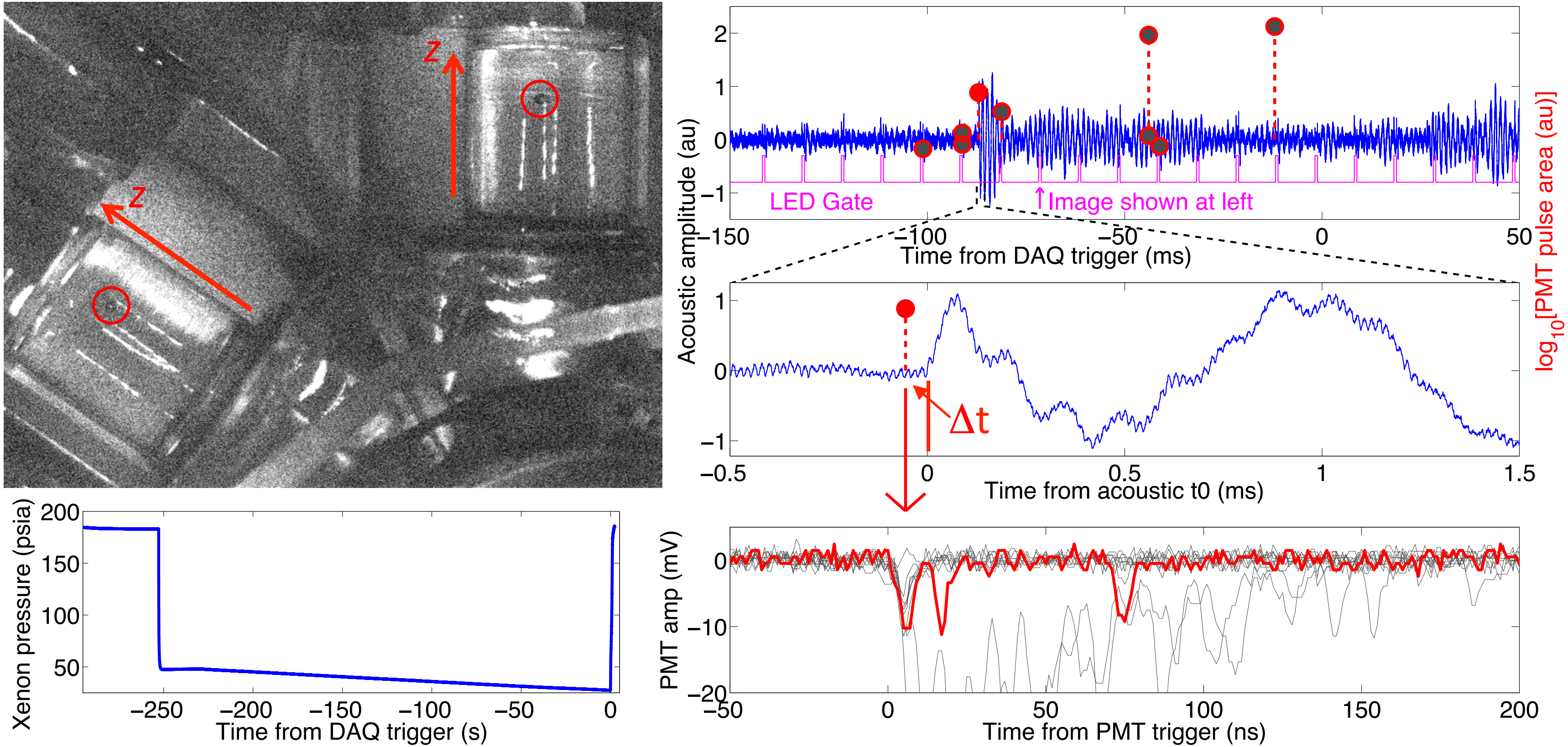
Phys.Rev. **102**, 586 (1956)

NU Xenon Bubble Chamber

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



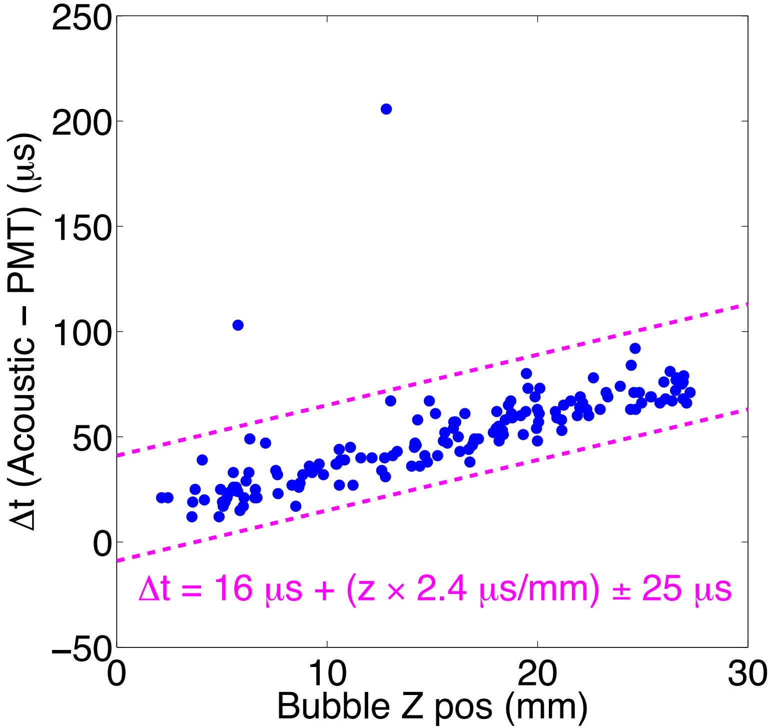
Nuclear Recoil Event



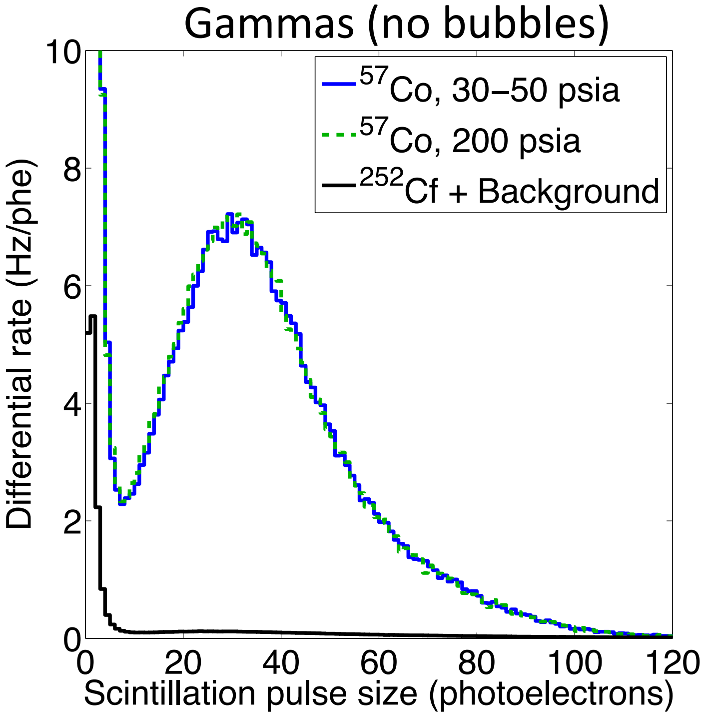
Acoustic – Scintillation Coincidence

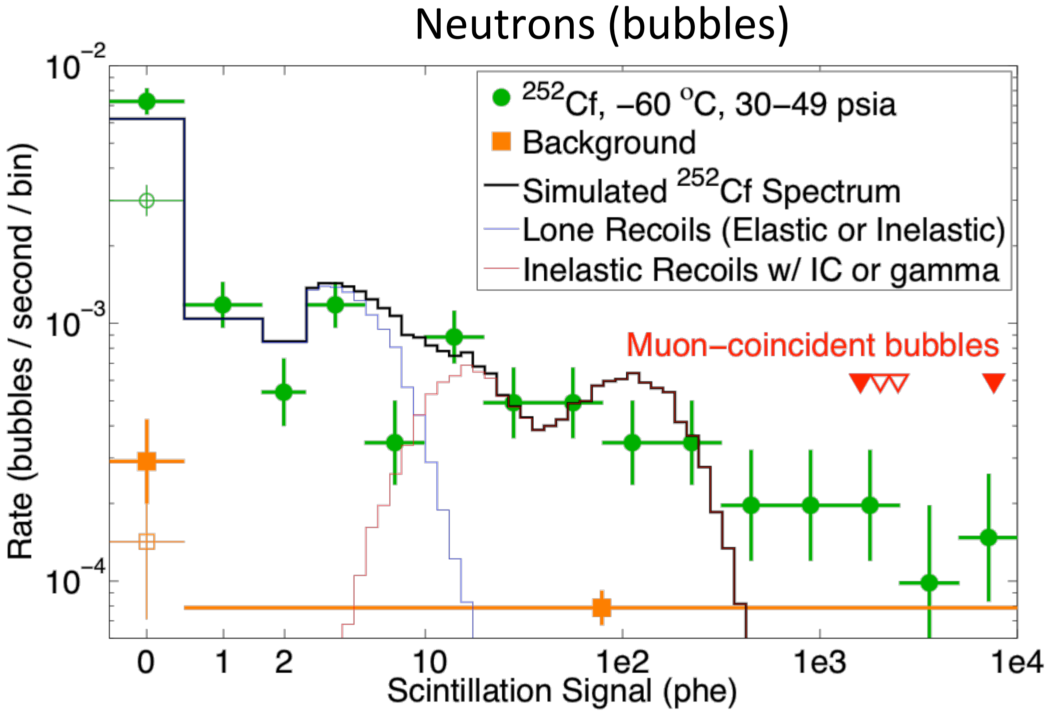
- $< 1\%$ accidental coincidence rate in calibration data

- Slope = speed of sound in xenon (to 20%)



Scintillation Spectra

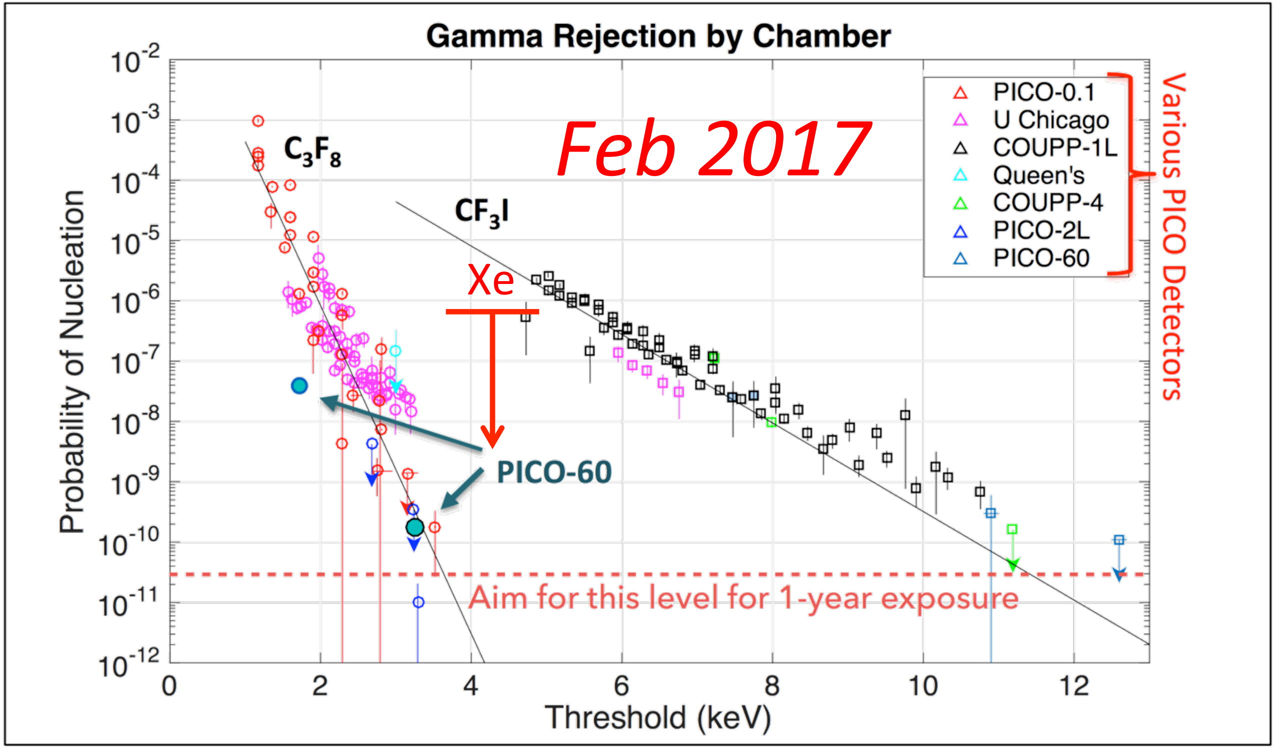




- Scintillation unaffected by superheated state

Electron Recoil Discrimination

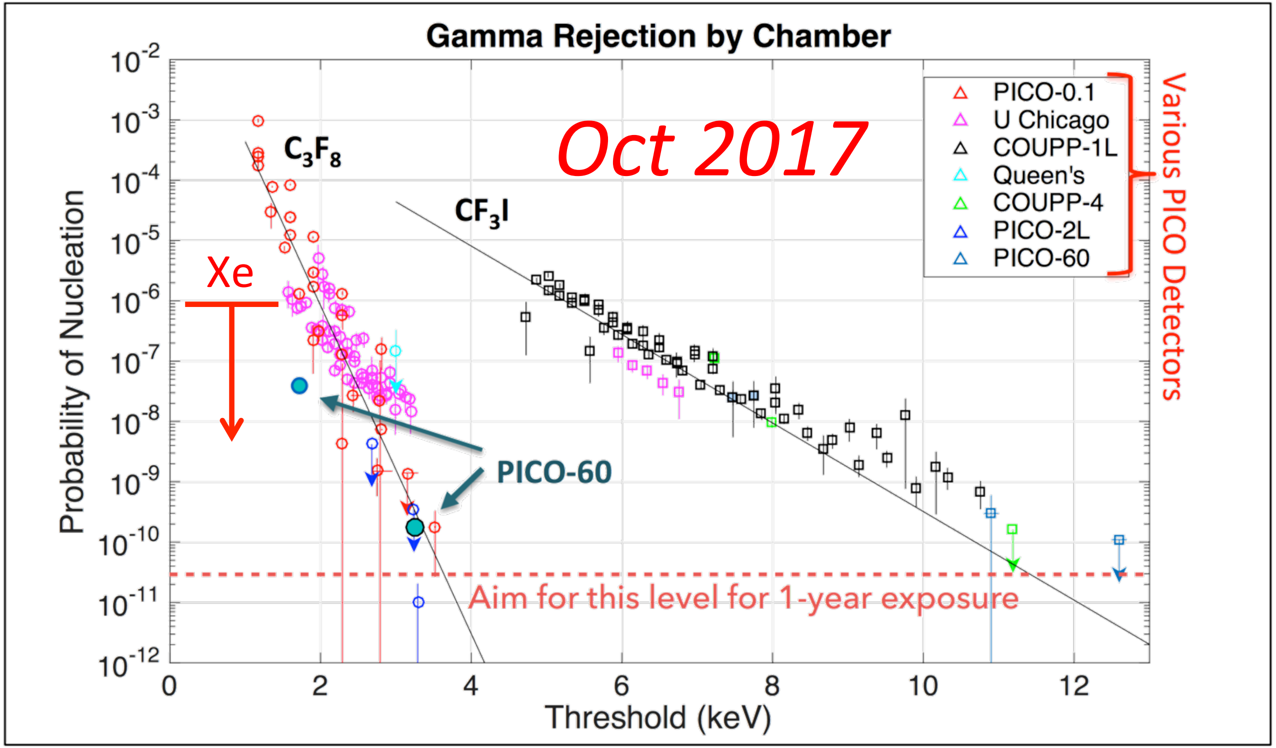
- No observation of bubbles nucleated by gamma-rays at any threshold!
- Rebuilding chamber to explore lower thresholds



(Dan Baxter, Conference on Science at SURF, May 14, 2017) 13

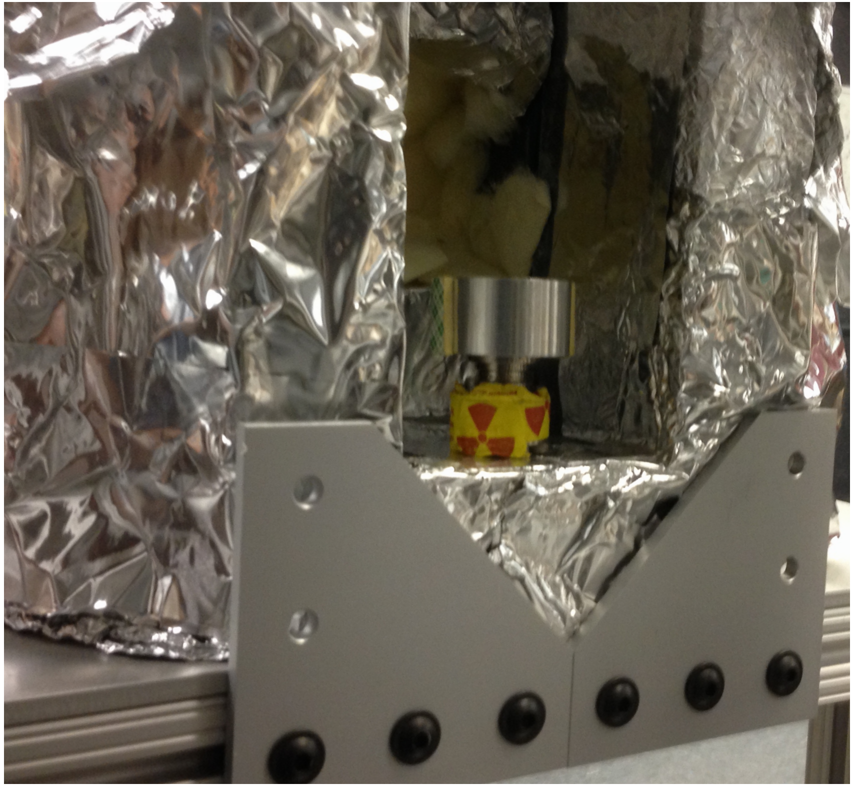
Electron Recoil Discrimination

- No observation of bubbles nucleated by gamma-rays at thresholds down to 900 eV!
- Rebuilding chamber to explore lower thresholds (higher superheat)



(Dan Baxter, Conference on Science at SURF, May 14, 2017) 13

Be(γ,n) Calibrations (ongoing)



- ^{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

How low can we go?

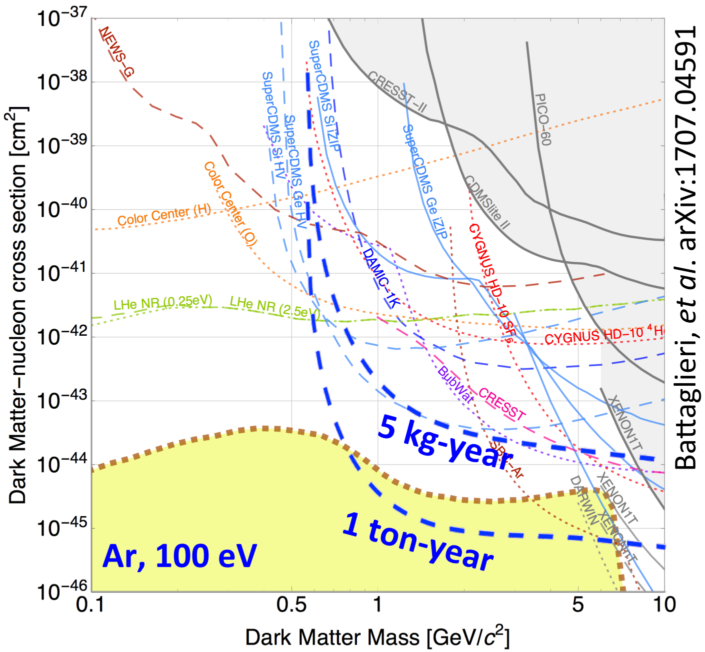
- Why aren't ER's making bubbles?
  - Local heat in a mono-atomic liquid means center-of-mass motion of atoms − No molecular bonds!
  - Very hard for electrons to shove atoms around

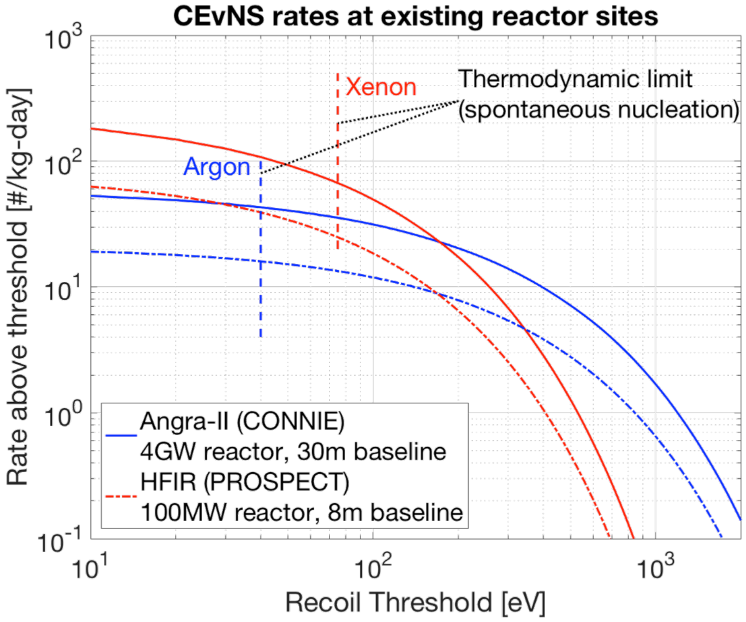
- If ER's don't make bubbles at all, what sets ultimate threshold?
  - Thermal fluctuations: 1 bubble / ton-year at
    E_T = 75 eV (xenon)
    E_T = 40 eV (argon)

  - Nuclear recoil threshold is still 2x-3x E_T

- Precision calibrations and higher superheat on the way…

Physics with an Argon Bubble Chamber

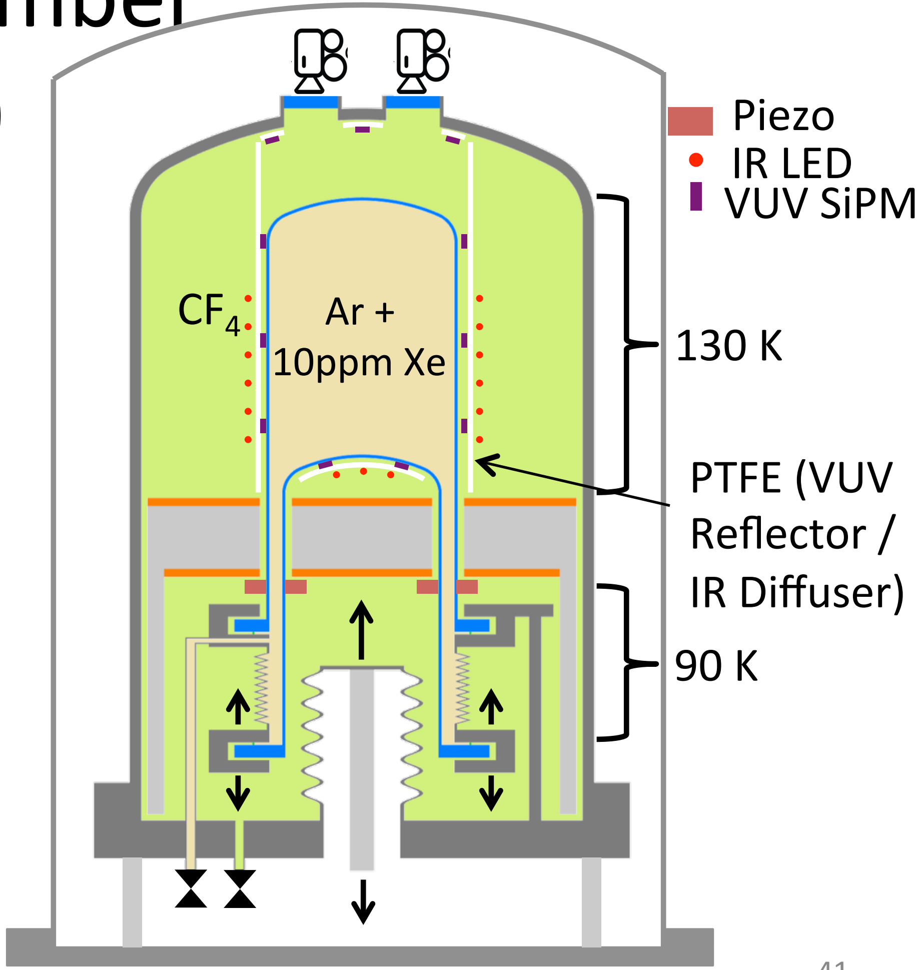




– Neutrino floor (1 – 7 GeV)
– $O(10^6)$ CEvNS events / ton-year @ reactor

Scintillating **B**ubble **C**hamber (Fermilab LDRD Project)

- 10-kg Argon bubble chamber
  - Technical design underway
  - Commissioning at Fermilab in FY19, FY20
  - Exploring potential physics sites at SNOLAB and ORNL (SNS, HFIR)



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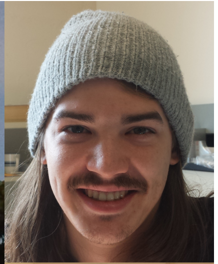

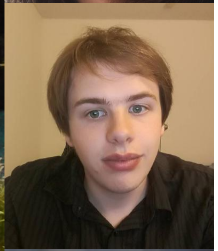

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Key Pubs:

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

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

Summary

- Bubble chamber capability still growing!
  - Anomalous background mitigated in PICO-60, annihilated in future chambers
  - New PICO-40L, PICO-500 detectors extend WIMP-SD sensitivity
  - Scintillating bubble chambers demonstrated
  - New opportunities at low-threshold with liquid-noble bubble chambers