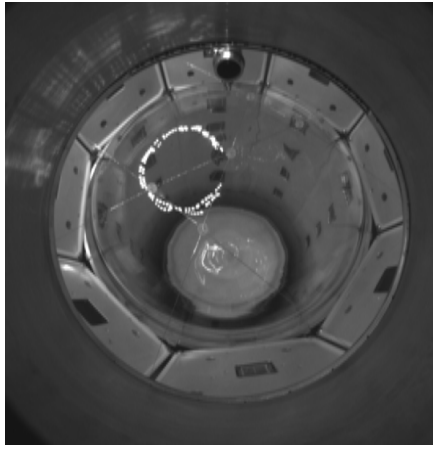
Liquid Noble (Scintillating) Bubble Chambers

Eric Dahl
Northwestern / Fermilab

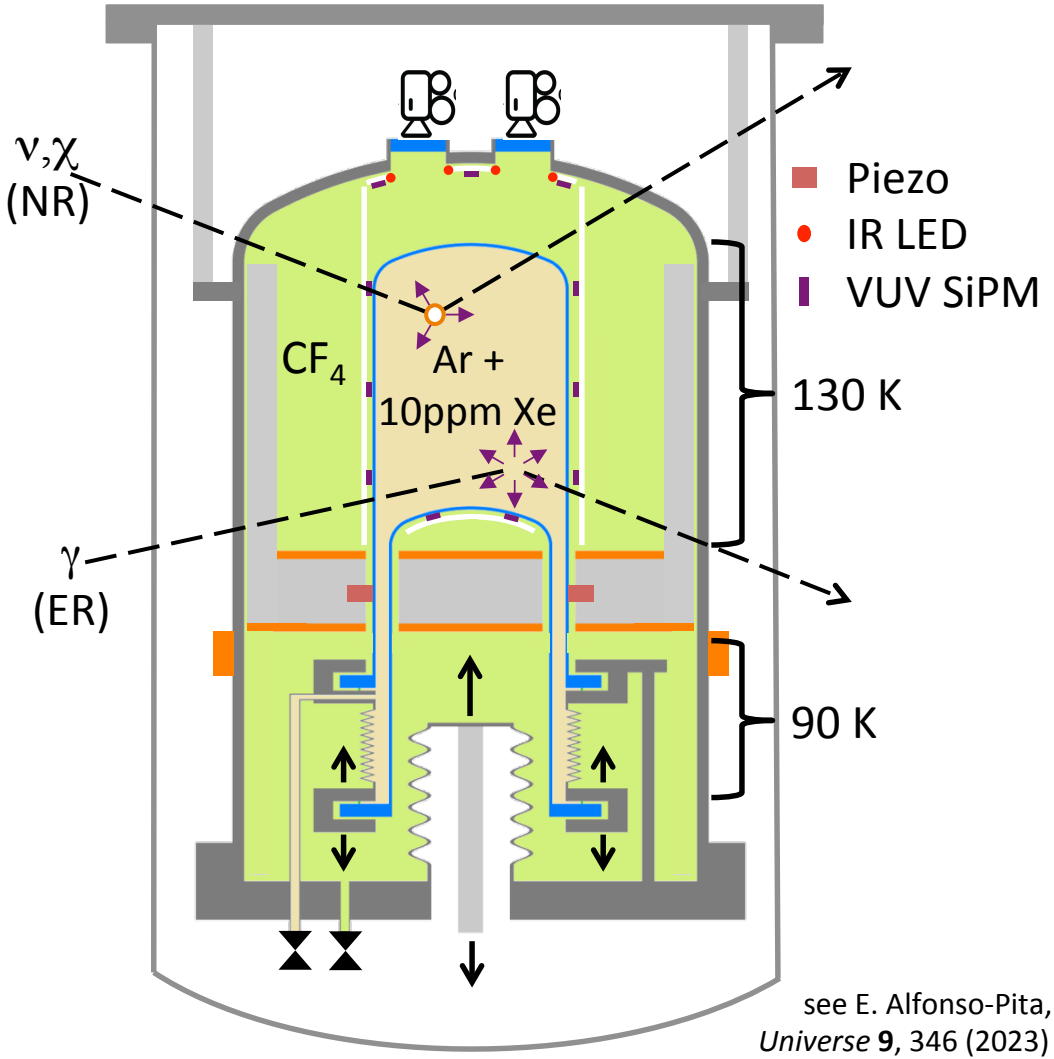
KICP 20th Celebration

June 6, 2024



Roadmap

- Yes, I'm still looking for (particle) dark matter
  - Why we need a scalable low-threshold option
- Yes, I still love bubble chambers
  - The allure of superheated noble liquids…
- Yes, we've finally built SBC-LAr10
  - Expecting first bubbles this fall



see E. Alfonso-Pita, *Universe* **9**, 346 (2023)

Northwestern University

- **Eric Dahl**
- Zhiheng Sheng
- Baisakhi Mitra
- Jianyu Long

Queen's University

- **Ken Clark**
- Ben Broerman
- Jonathan Corbett
- Austin De St Croix
- Koby Dering
- Hector Hawley
- Gary Sweeny
- Ezri Wyman

University of Alberta

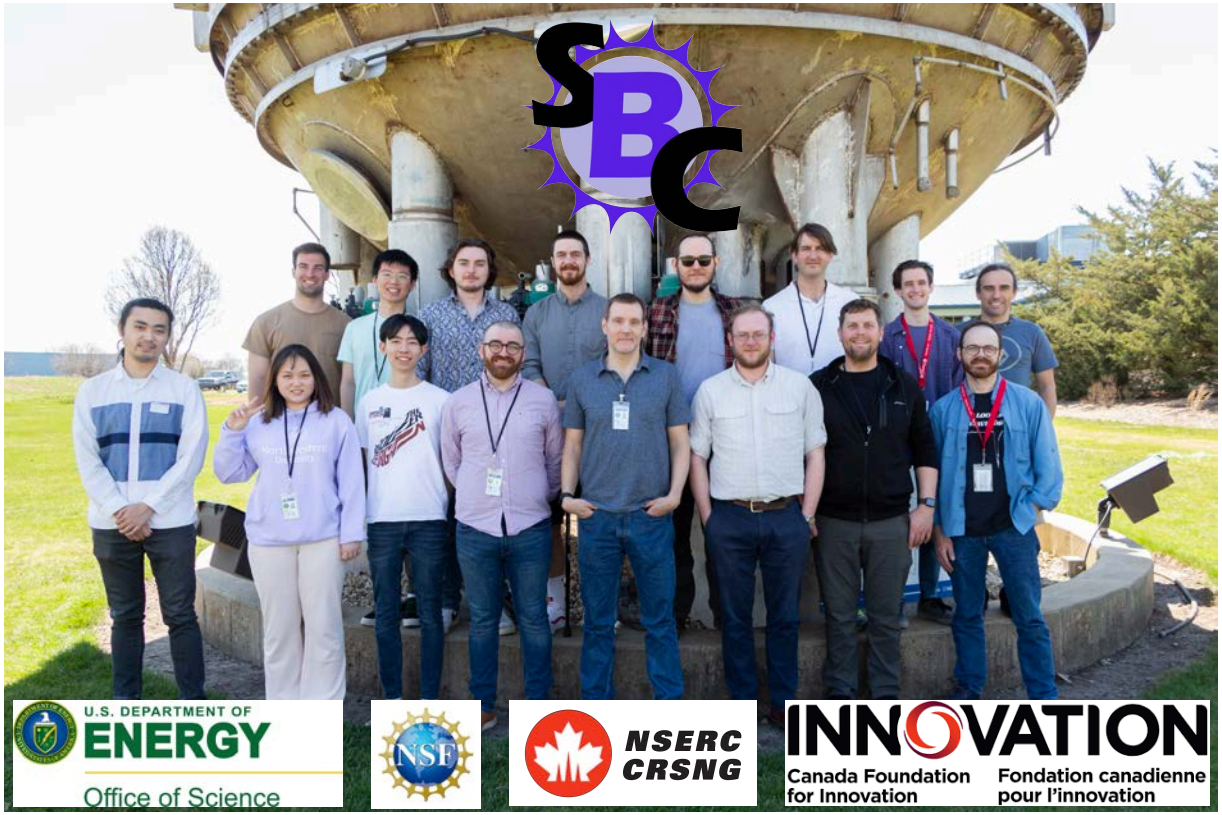
- Marie-Cécile Piro
- Carsten Krauss
- Mitchel Baker
- Daniel Durnford
- Youngtak Ko

SNOLAB

- Jeter Hall
- Alex Claveau

TRIUMF

- Pietro Giampa



Université de Montréal

- Mathieu Laurin
- Pierre Frédérick

Northeastern University

- Orin Harris

UC Riverside

- Shawn Westerdale

Universidad Nacional Autónoma de México

- Eric Vázquez-Jáuregui
- Ernesto Alfonso-Pita

Drexel University

- Russell Neilson
- Julian Fritz-Littman
- Noah Lamb
- Daniel Pyda

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- Ilan Levine
- Ed Behnke
- Cody Cripe

UC Santa Barbara

- Hugh Lippincott
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- TJ Whitis
- Runze Zhang

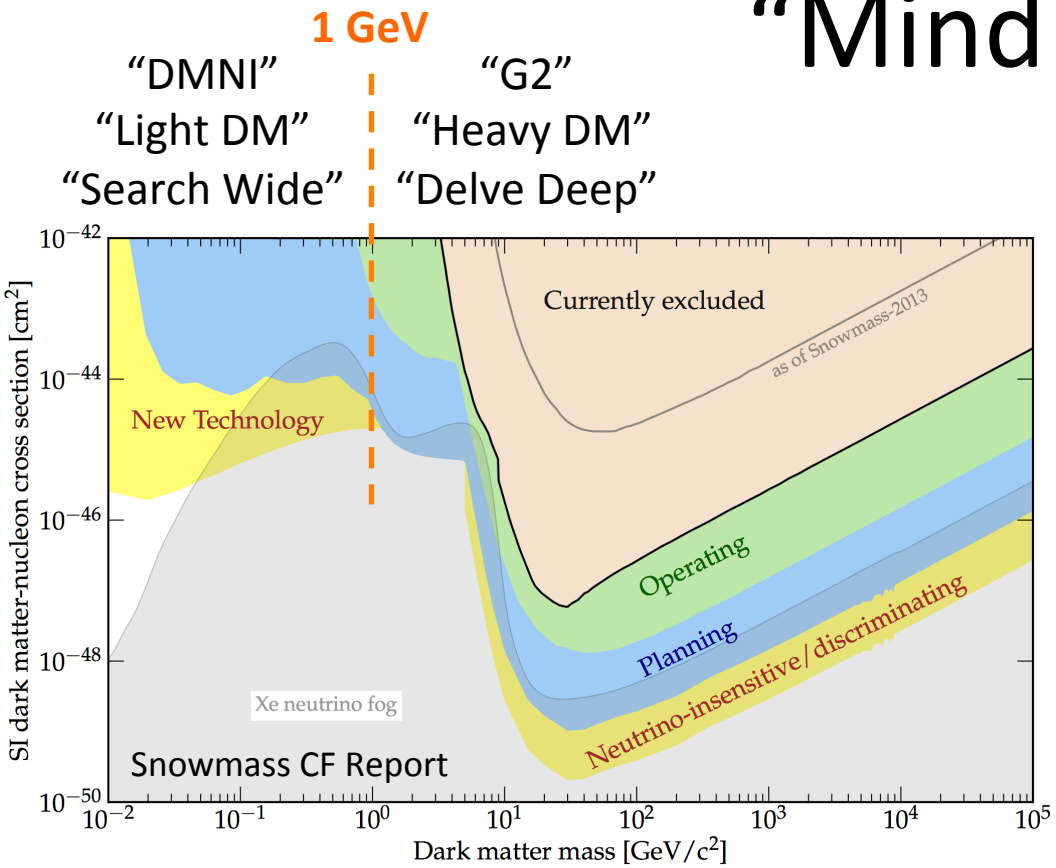
Fermilab

- Gray Putnam
- Vrushank Patel

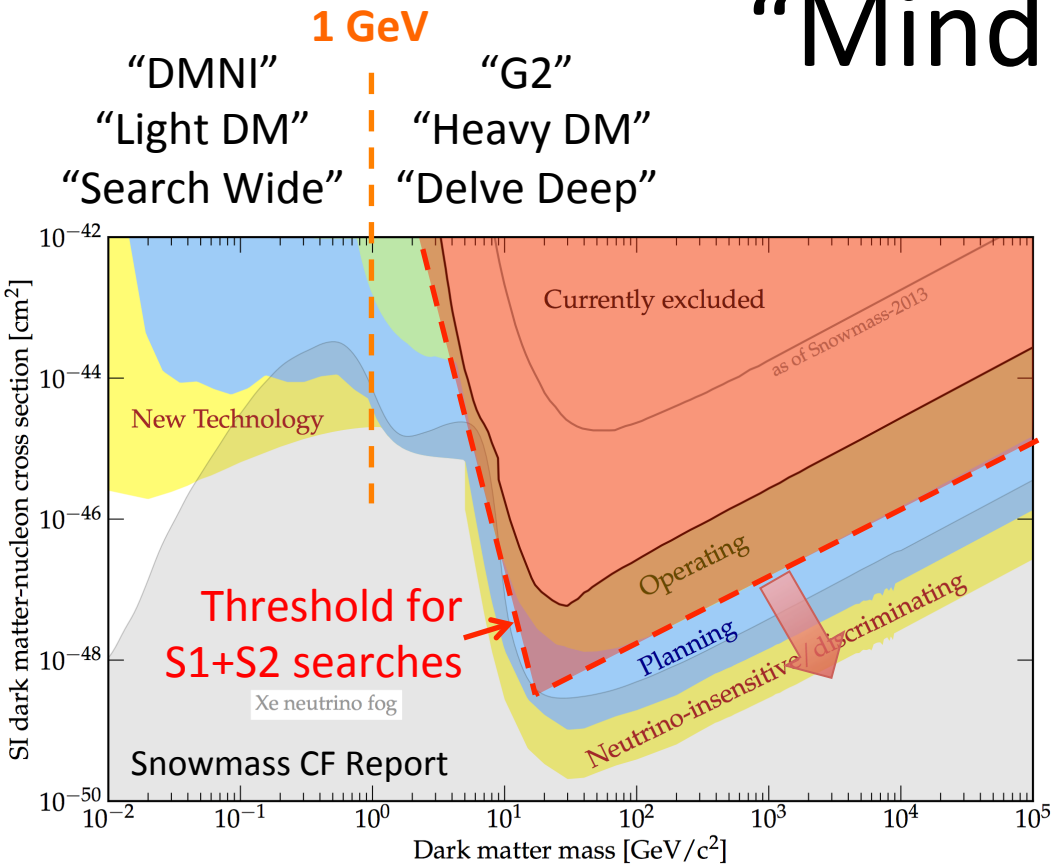
PennState

- Shashank Priya

“Mind the gap”


1 GeV
“DMNI”
“Light DM”
“Search Wide”
“G2”
“Heavy DM”
“Delve Deep”
Currently excluded
as of Snowmass-2013
New Technology
Operating
Planning
Neutrino-insensitive/discriminating
Xe neutrino fog
Snowmass CF Report
SI dark matter-nucleon cross section [cm^2]
Dark matter mass [GeV/c^2]
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

“Mind the gap”



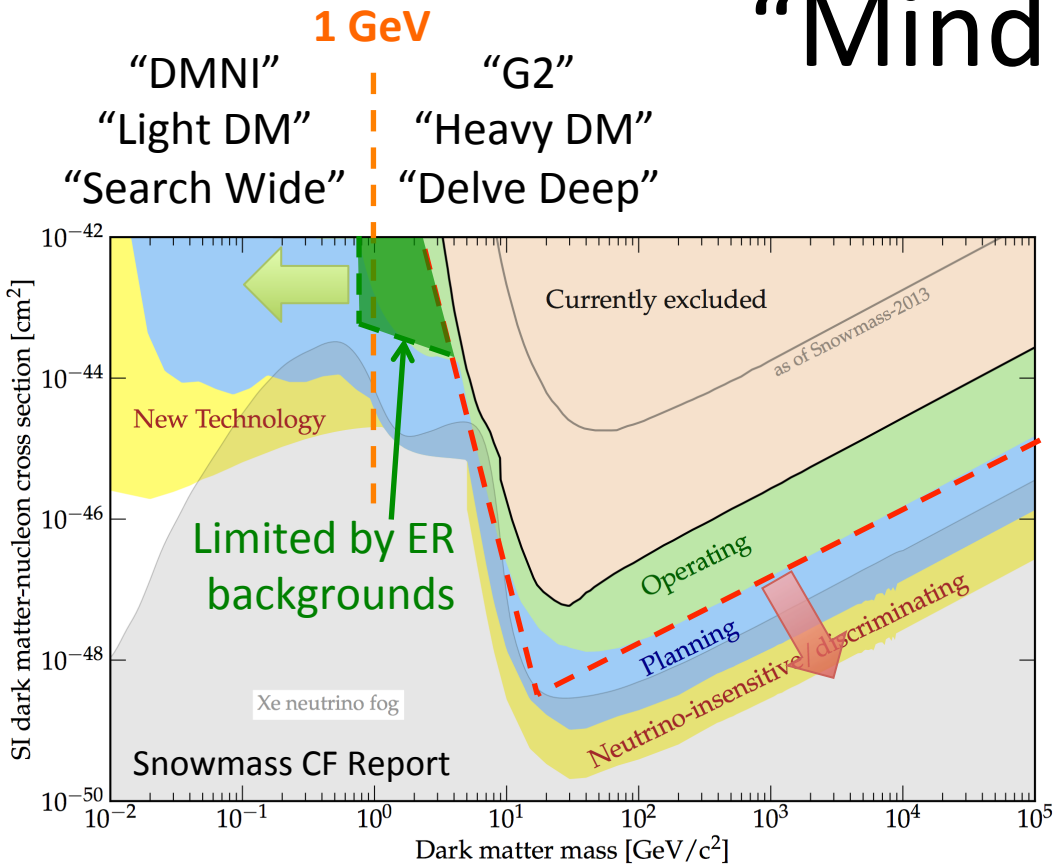
Quasi-background-free Nuclear Recoil (NR) searches in multi-ton targets

- Detector features:
  - Scalability
  - Background discrimination

“Mind the gap”

Background-limited Nuclear- and Electron-Recoil (ER) searches in kg-scale targets

- Detector features:
  - Low threhsold (eV to meV)



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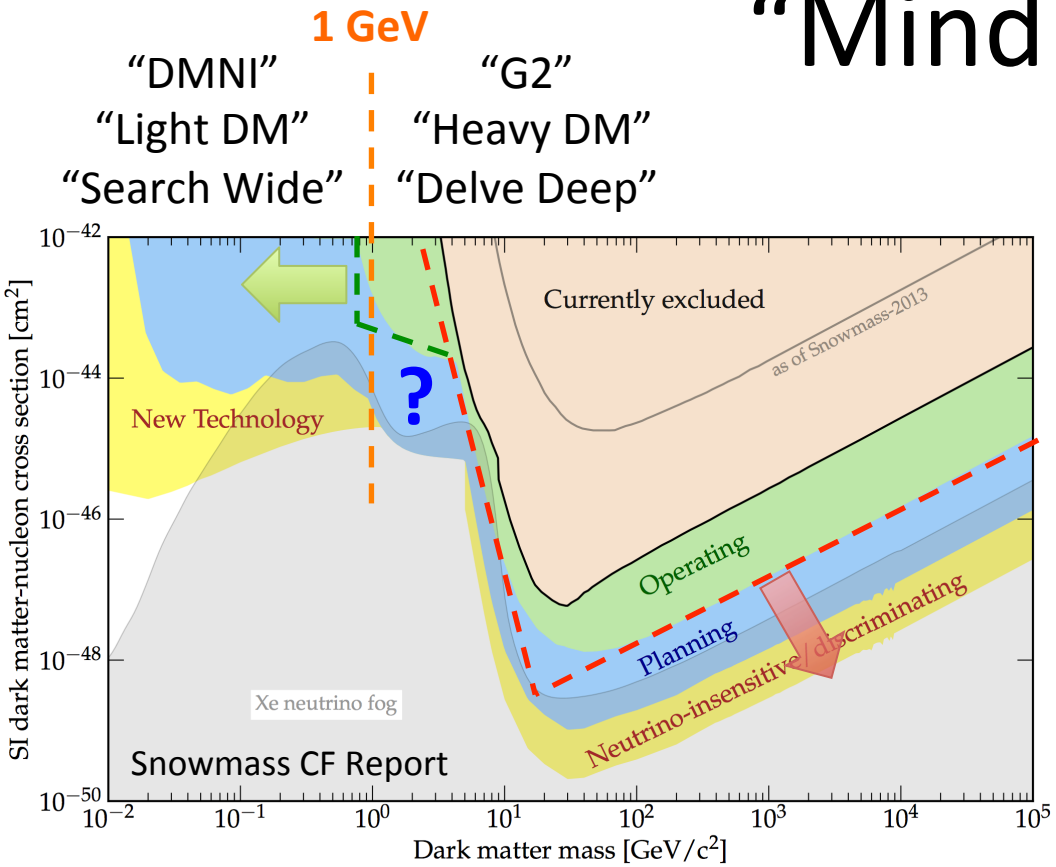


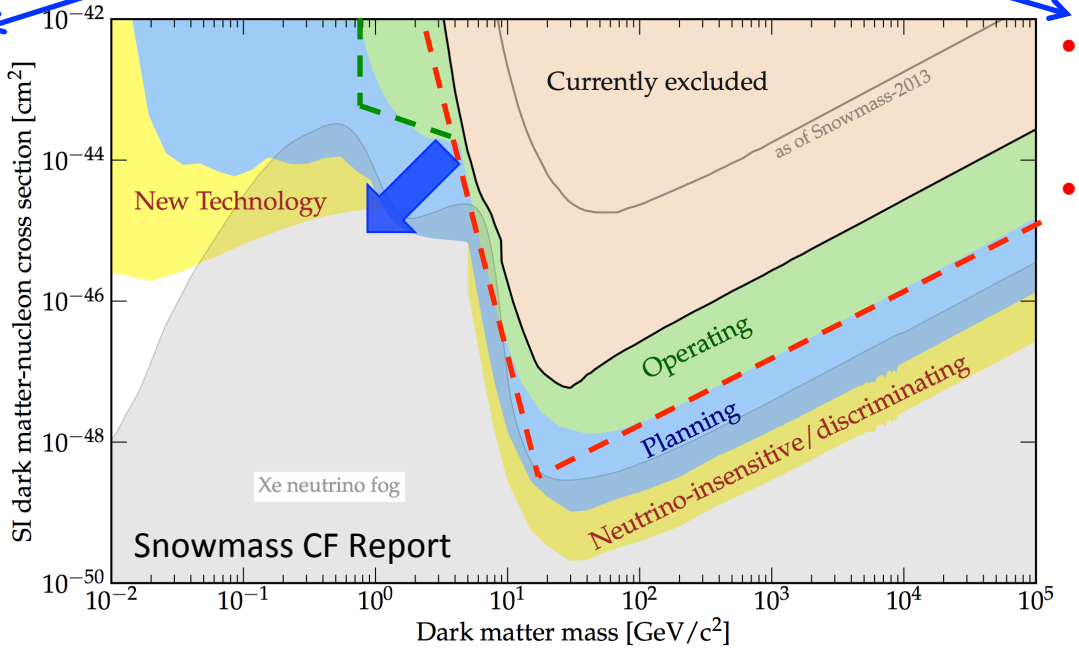
Quasi-background-free Nuclear-Recoil (NR) searches in multi-ton targets

- Detector features:
  - Scalability
  - Background discrimination

“Exploring the ^{8}B CEvNS fog”

Detector Requirements

- Low Threshold
  - ~3 MeV/c momentum
  - e.g.: O(100) eV argon recoils



- Scalability
  - O(1) ton-year exposure
- Low background
  - ER discrimination
  - Fiducialization

No existing technique meets these requirements

Liquid Noble Bubble Chambers

Objective:

Quasi-background-free detection of sub-keV Nuclear Recoils

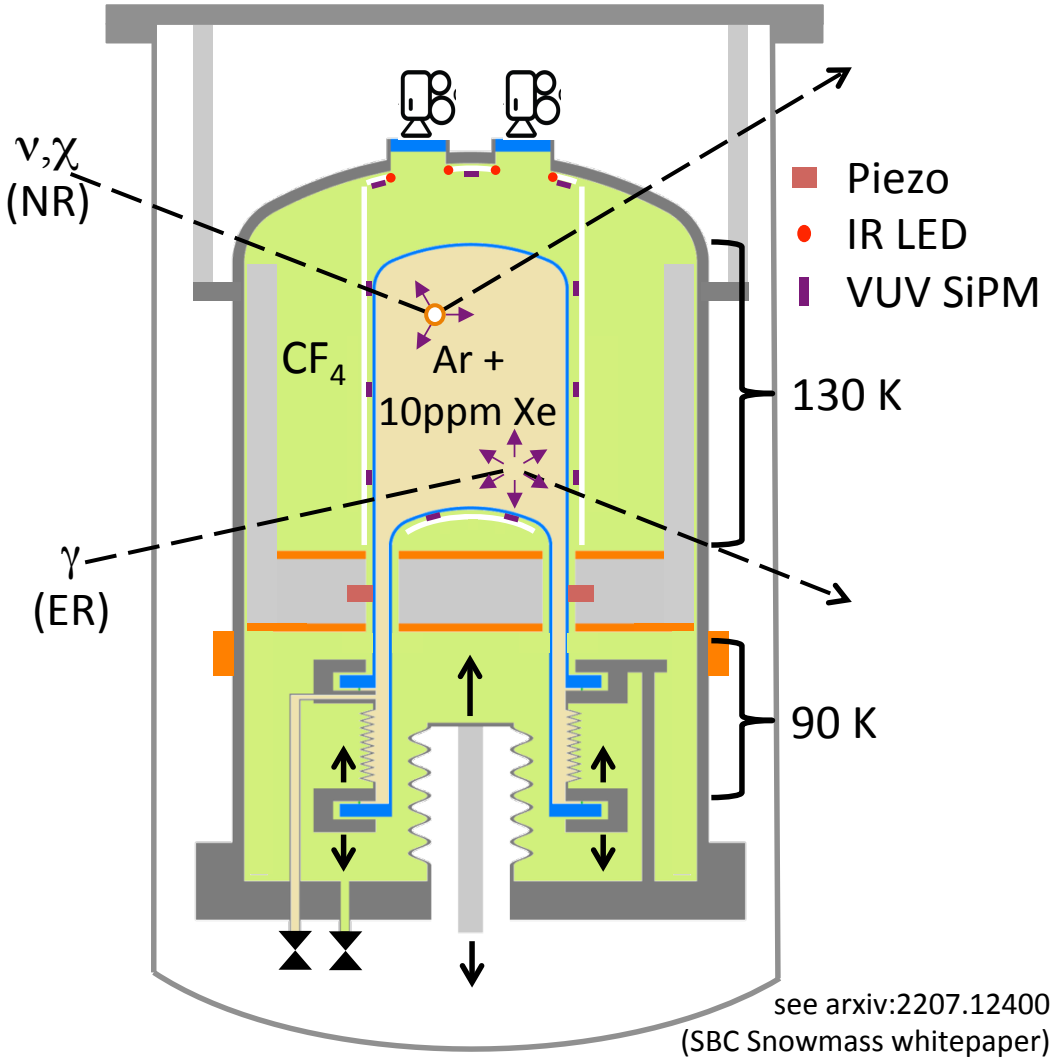
Signal:

Single bubble with little or no coincident scintillation

Backgrounds:

ER's (beta, gamma):
No bubbles

NR's (fast neutron):
Multiple bubbles
Strong coincident scintillation



see arxiv:2207.12400
(SBC Snowmass whitepaper)

Liquid N
Bubble

Objective:

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coincident scintillat

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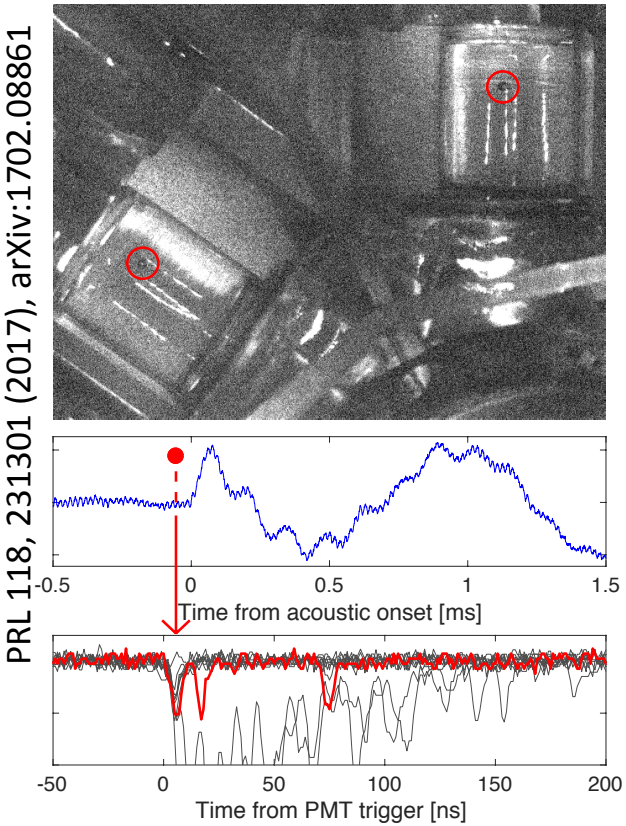
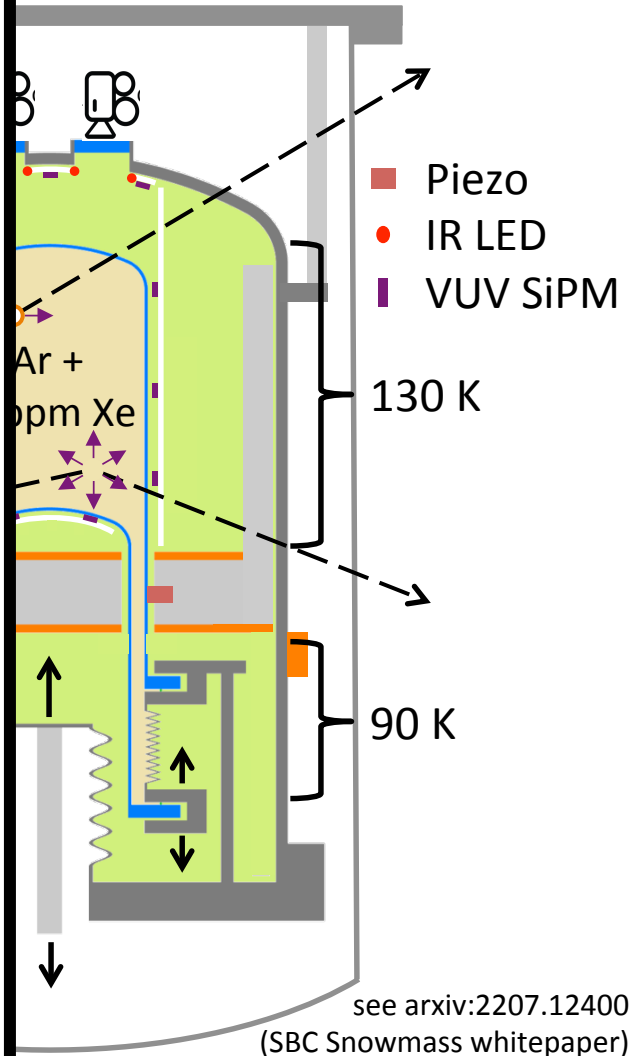
Multiple bubbles
Strong coincident

2017

30-gram xenon prototype





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Liquid Noble Bubble Chambers

Objective:

Quasi-background-free detection of sub-keV Nuclear Recoils

Signal:

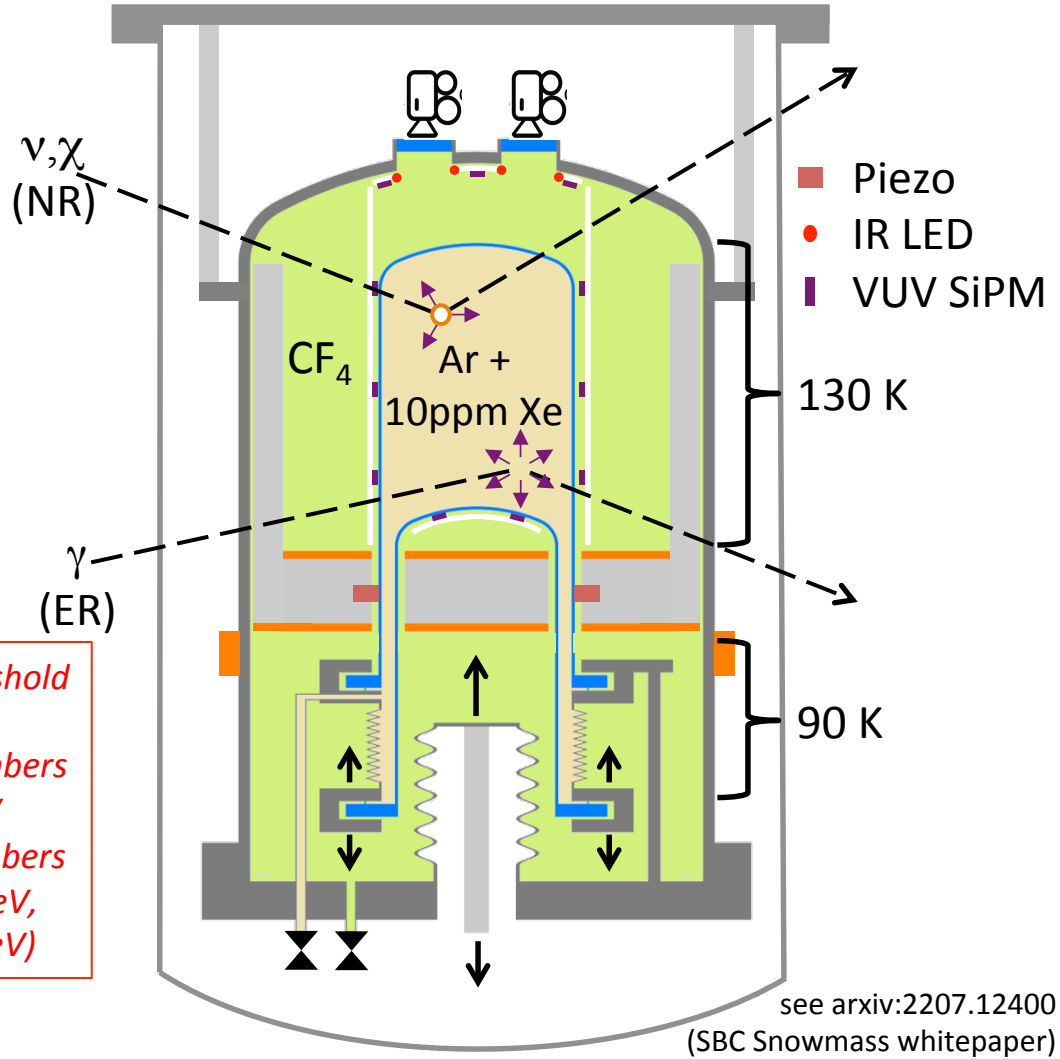
Single bubble with little or no coincident scintillation

Backgrounds:

ER's (beta, gamma):
No bubbles

Depends on NR threshold and target fluid:
- *Freon-based chambers ER-blind @ ~3 keV*
- *Liquid-noble chambers ER-blind @ < 500 eV, (target 100 eV)*

NR's (fast neutron):
Multiple bubbles
Strong coincident scintillation



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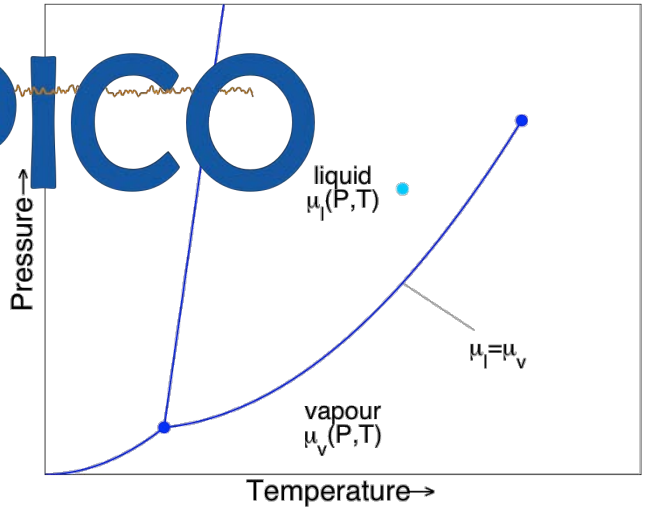
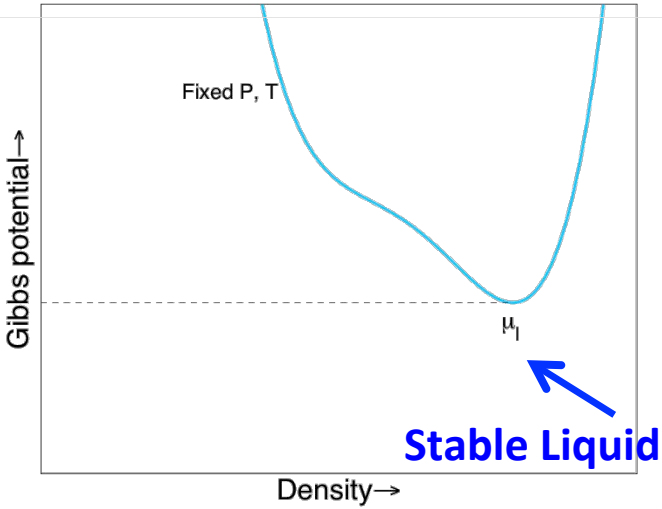
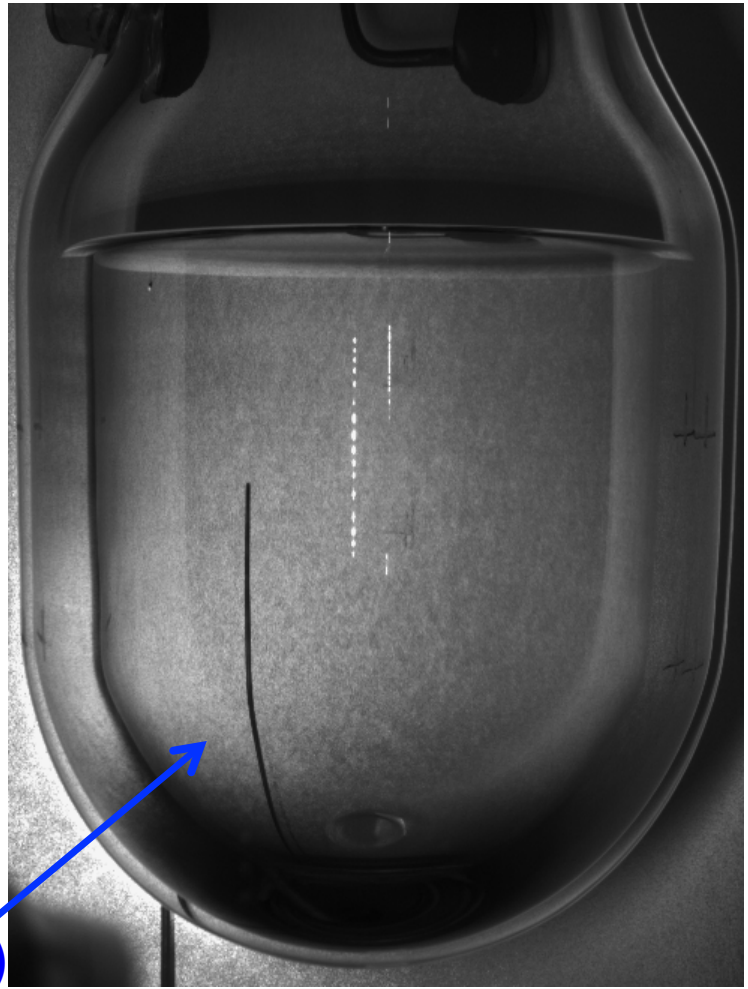
Bubble Chamber

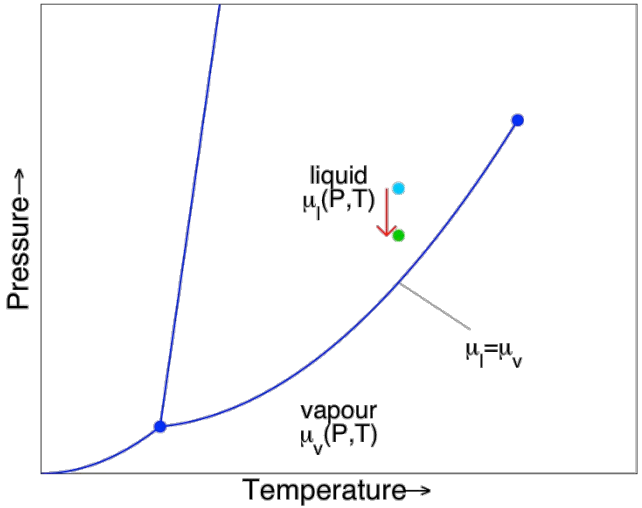


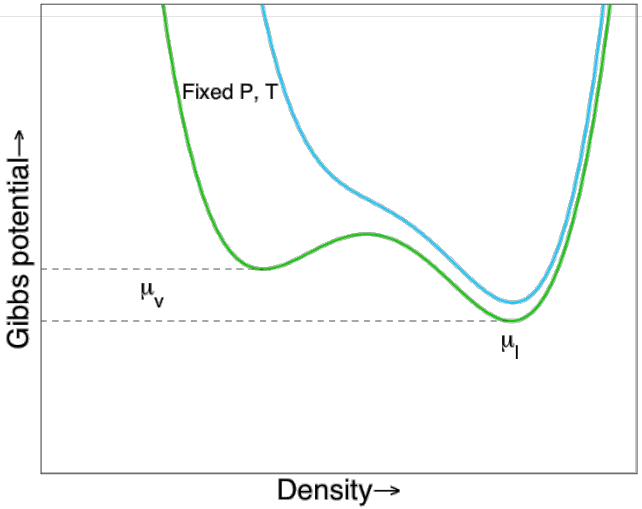


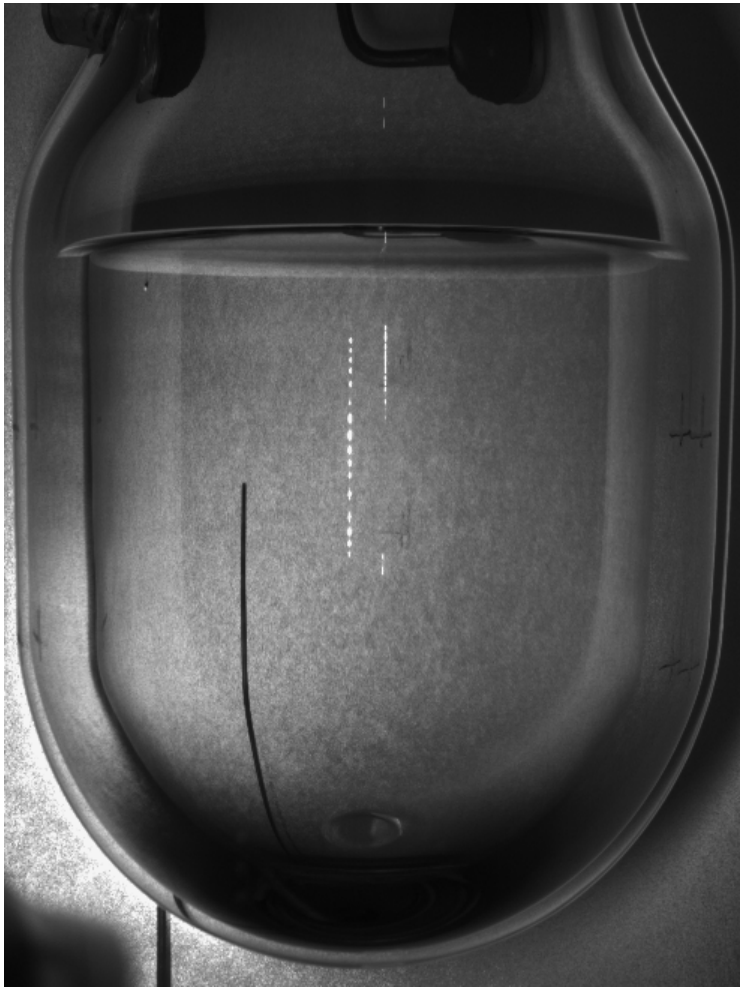


Stable Liquid (C_3F_8)

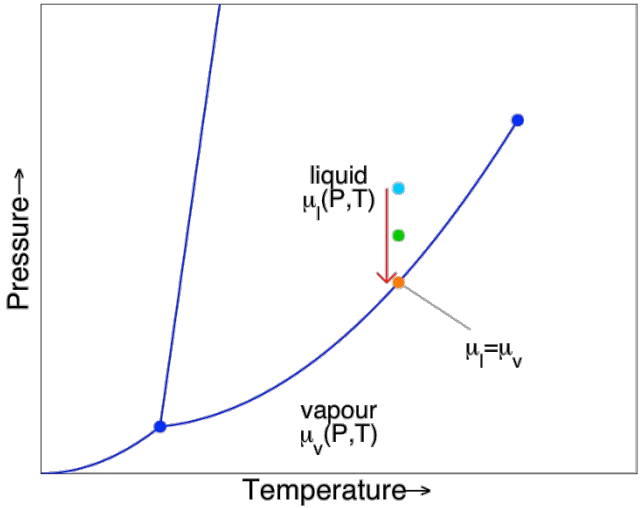
Bubble Chamber

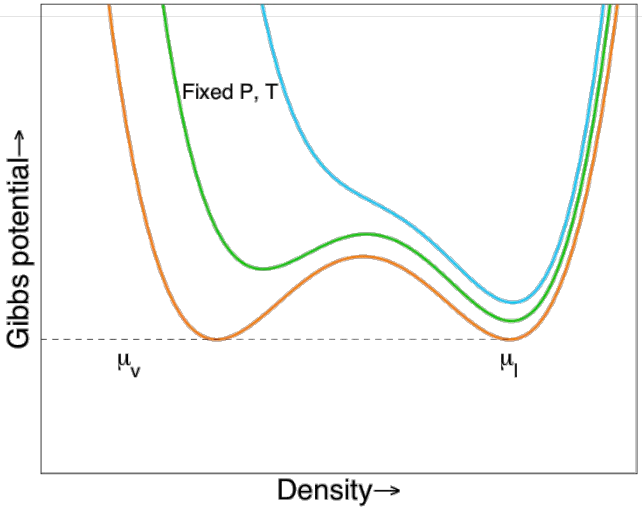


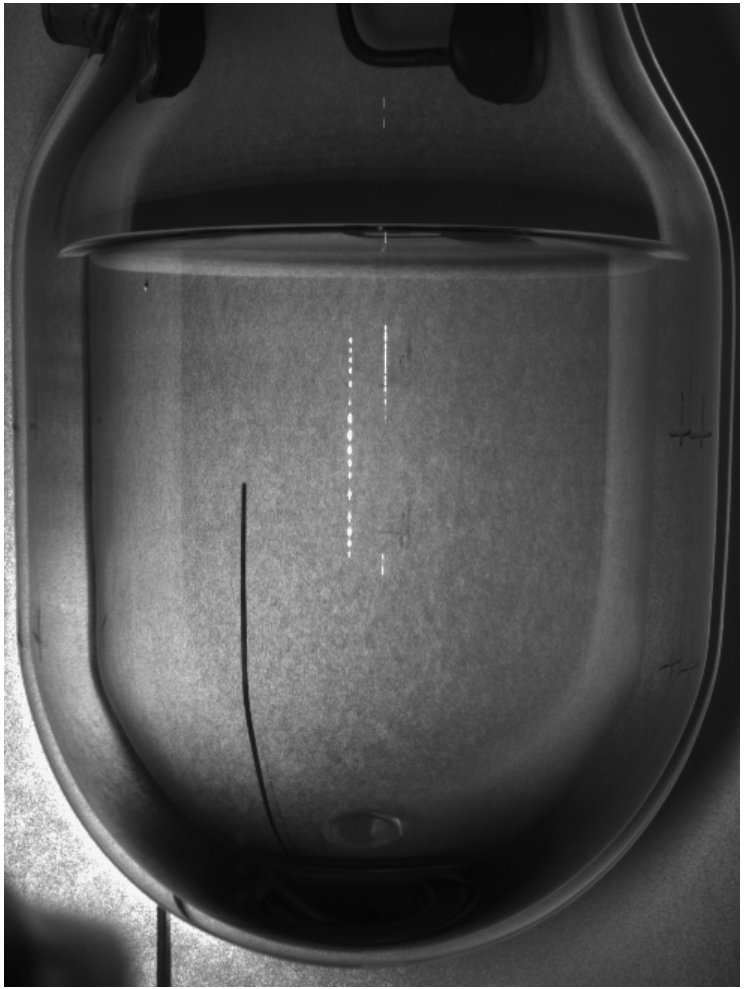




Bubble Chamber







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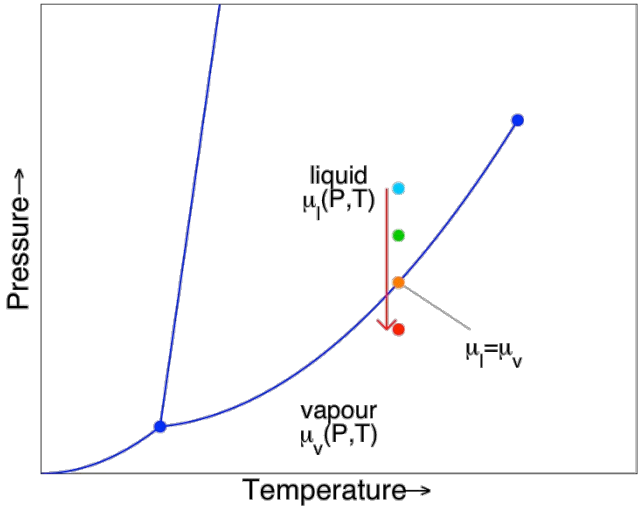

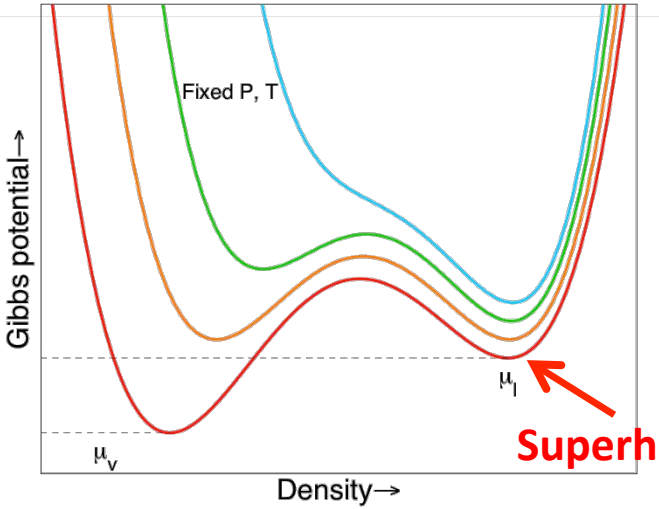

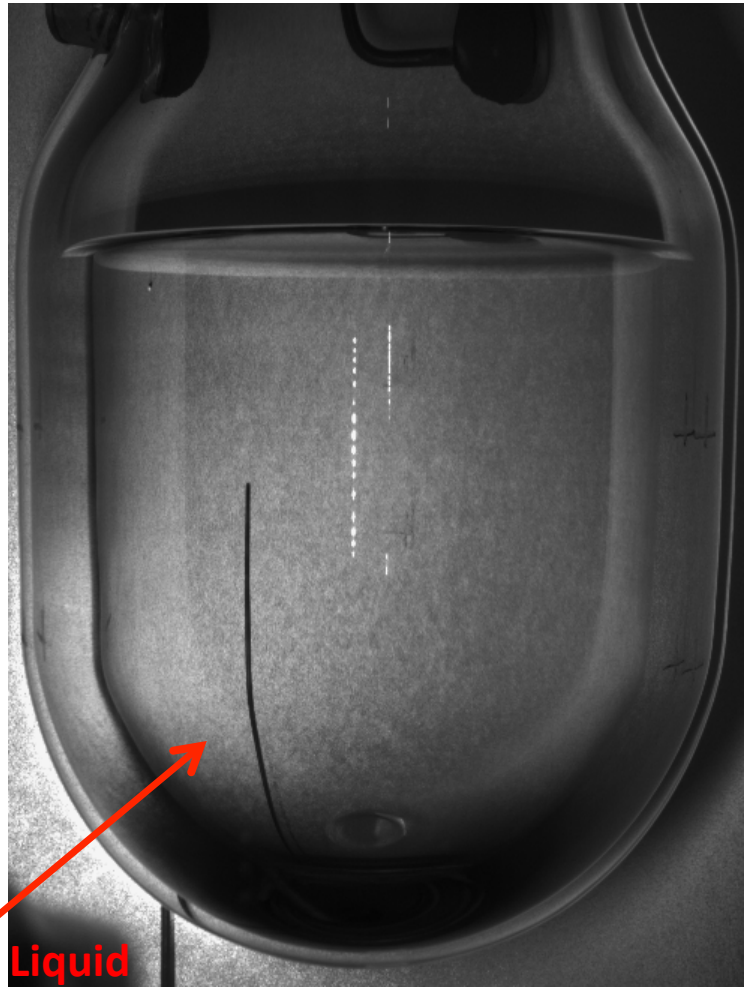

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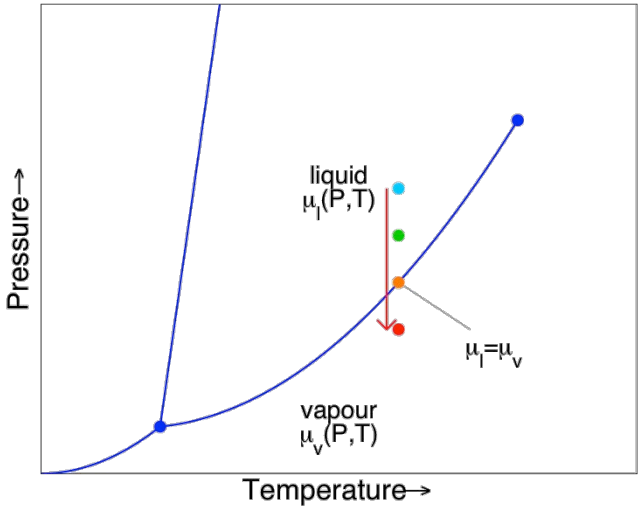

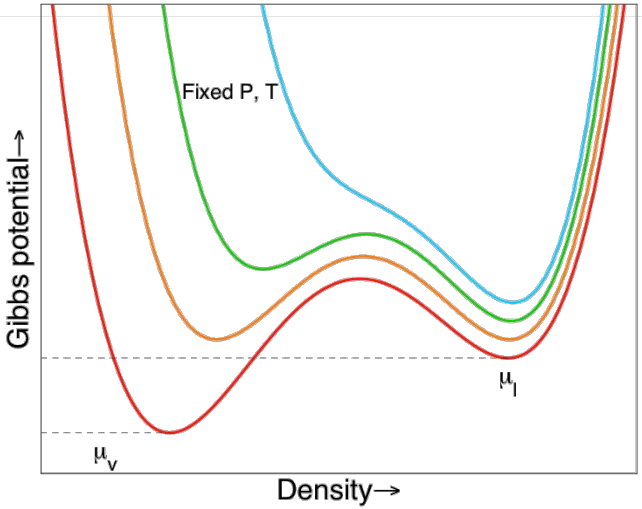

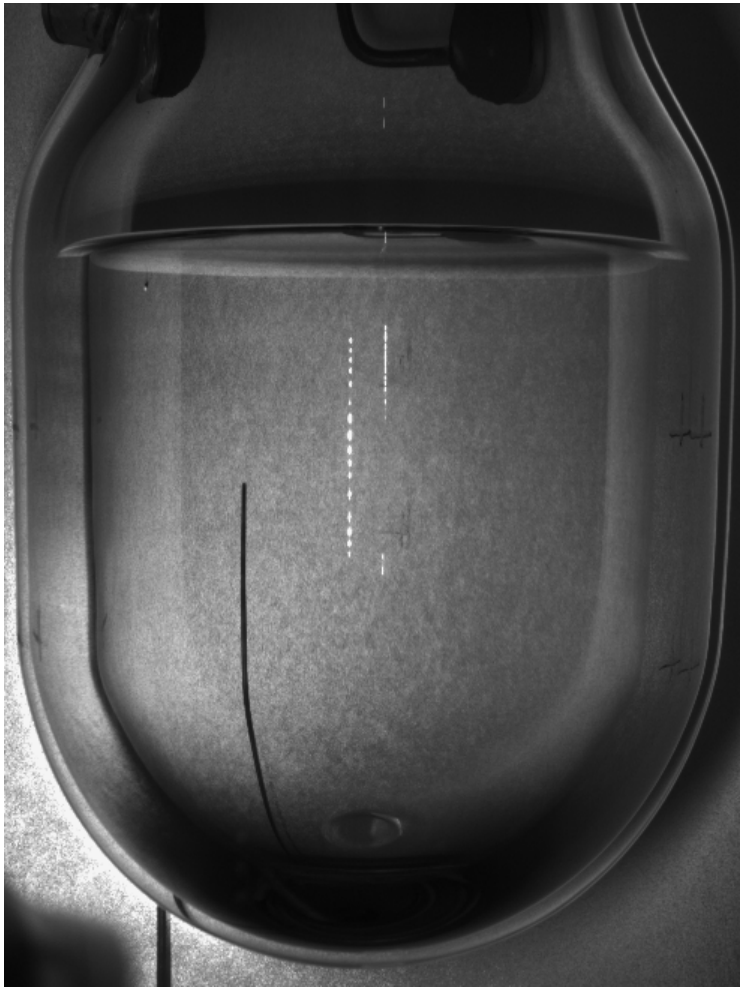

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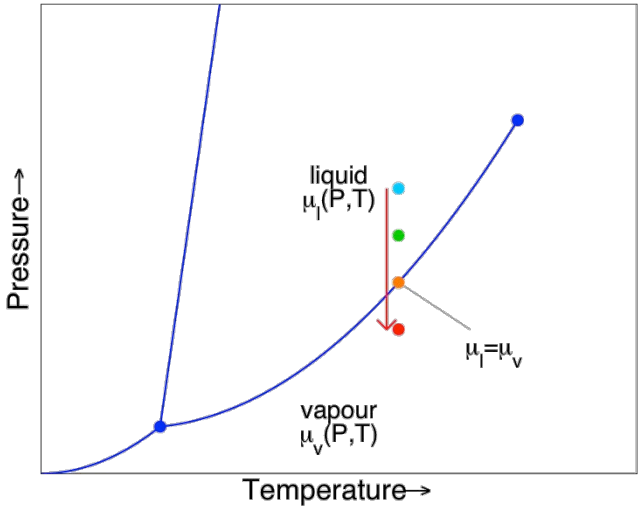

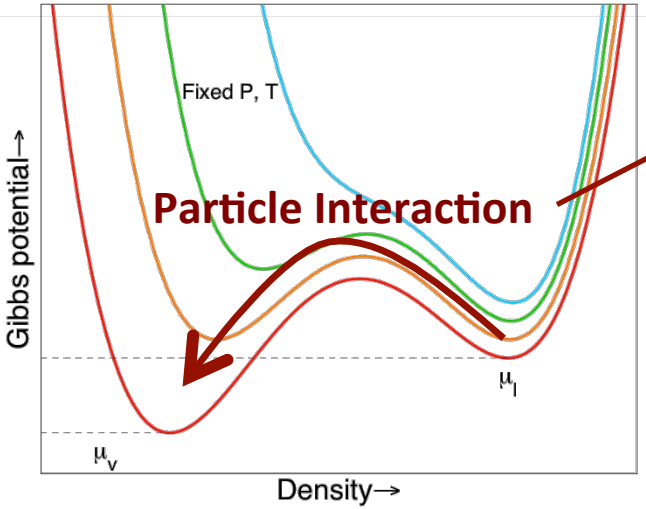

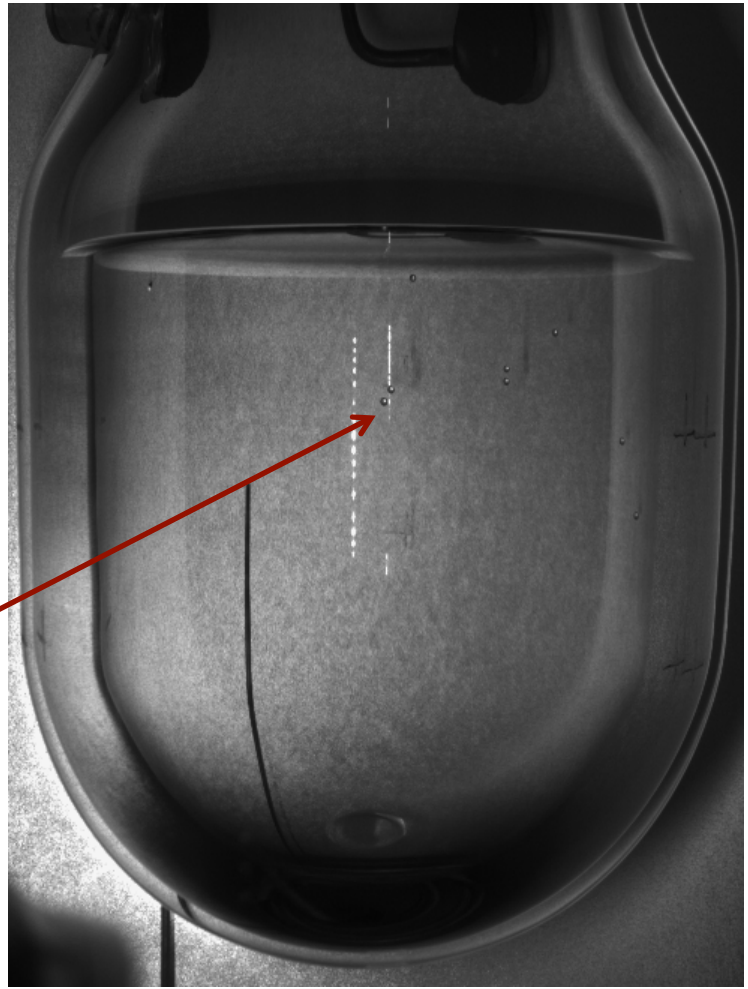

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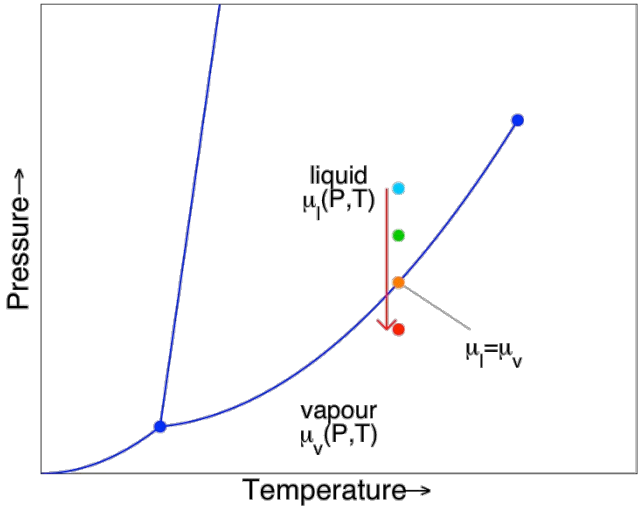

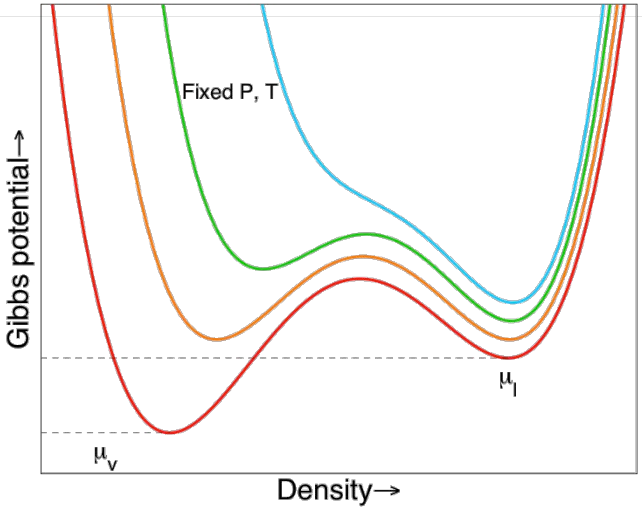

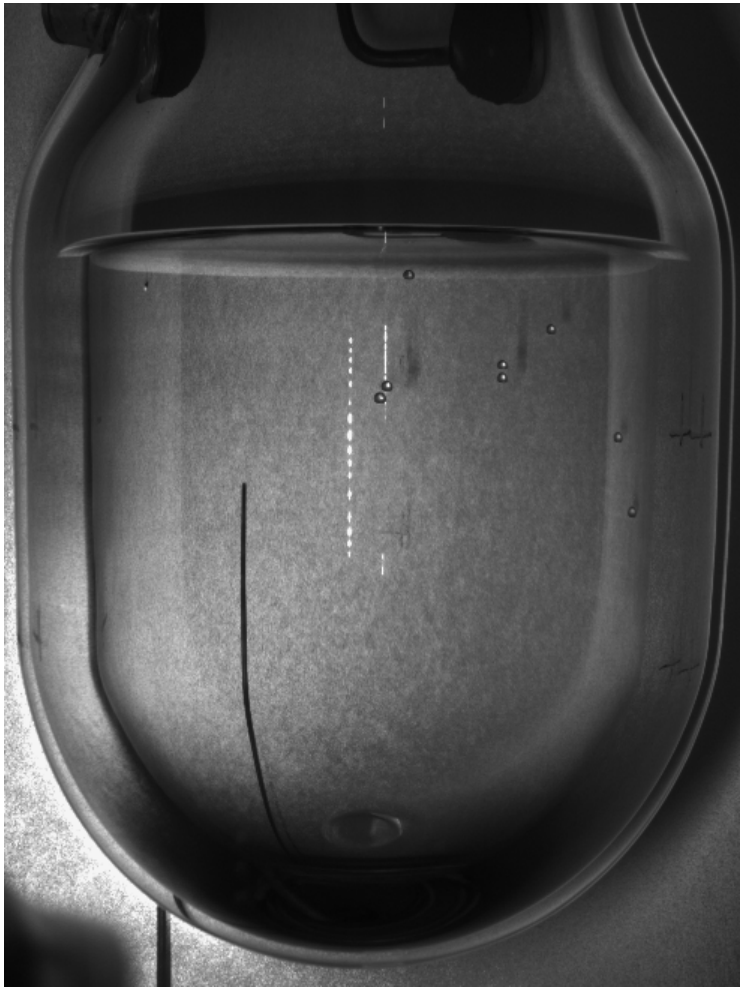

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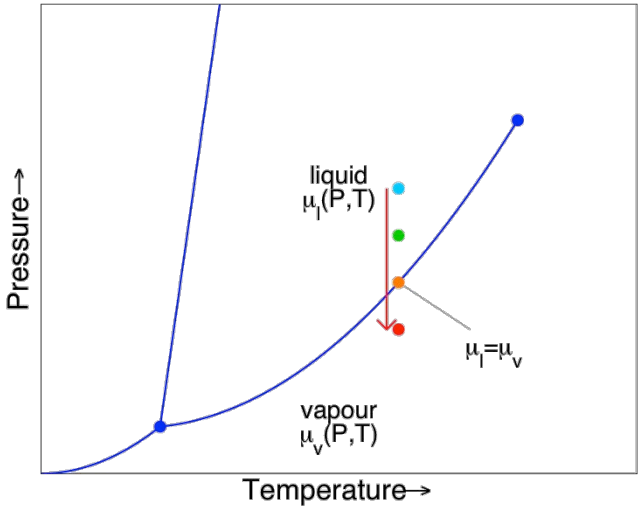

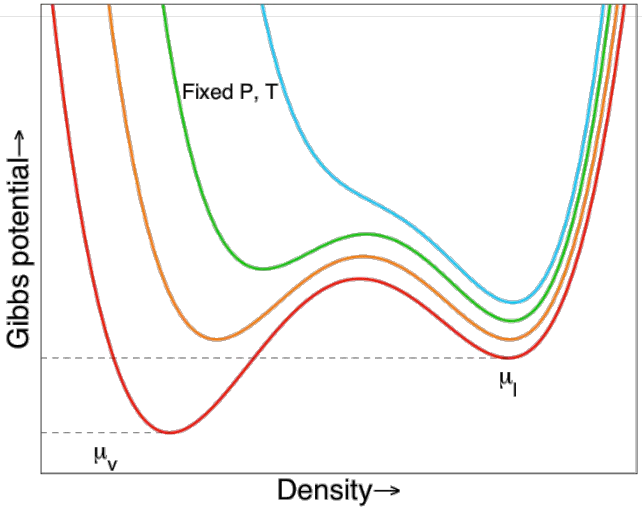

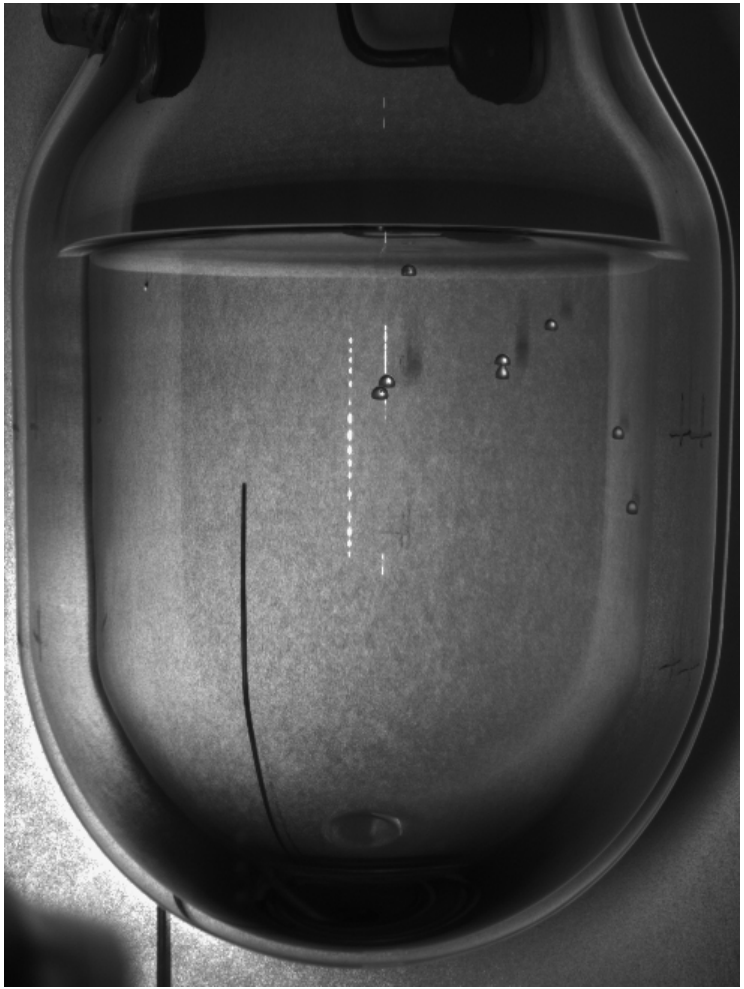

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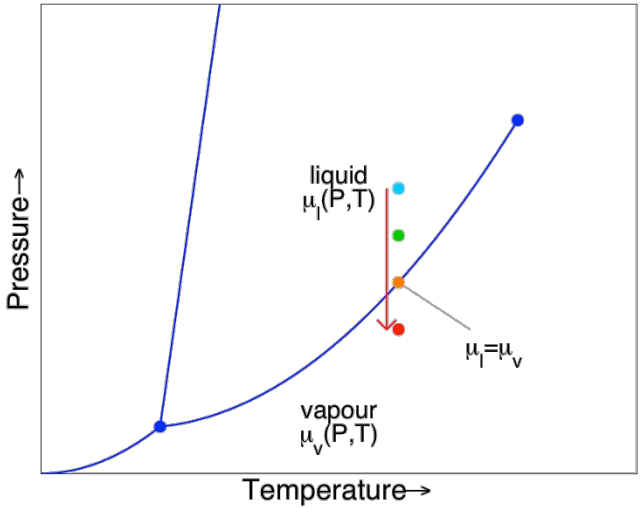

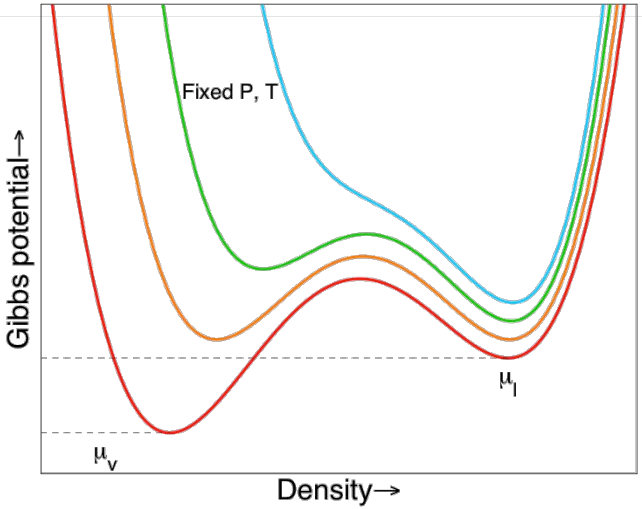

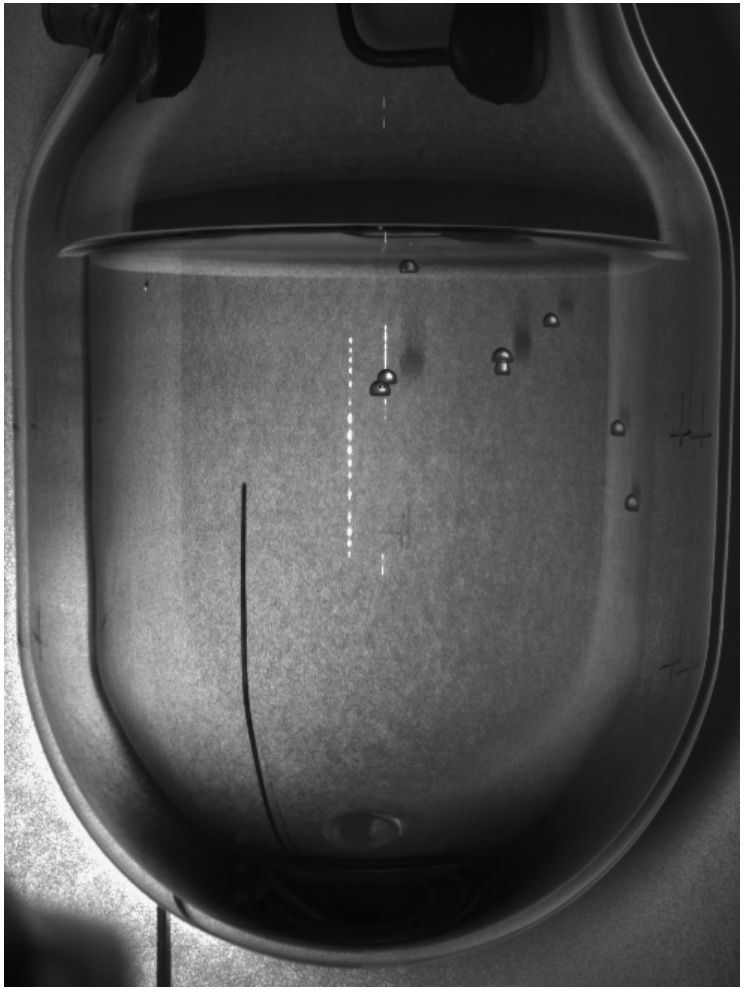

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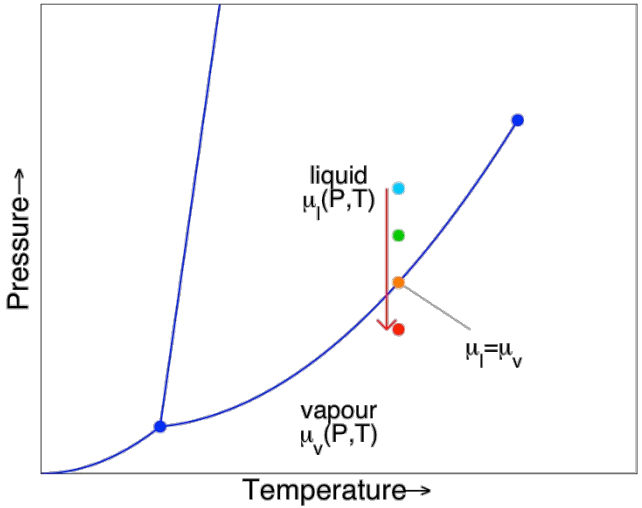

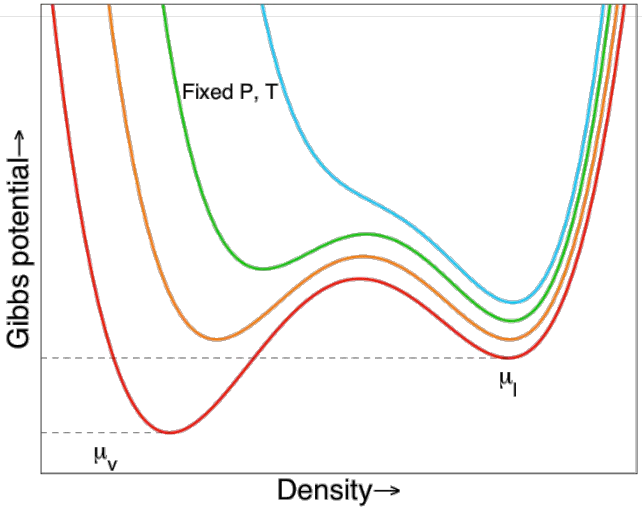

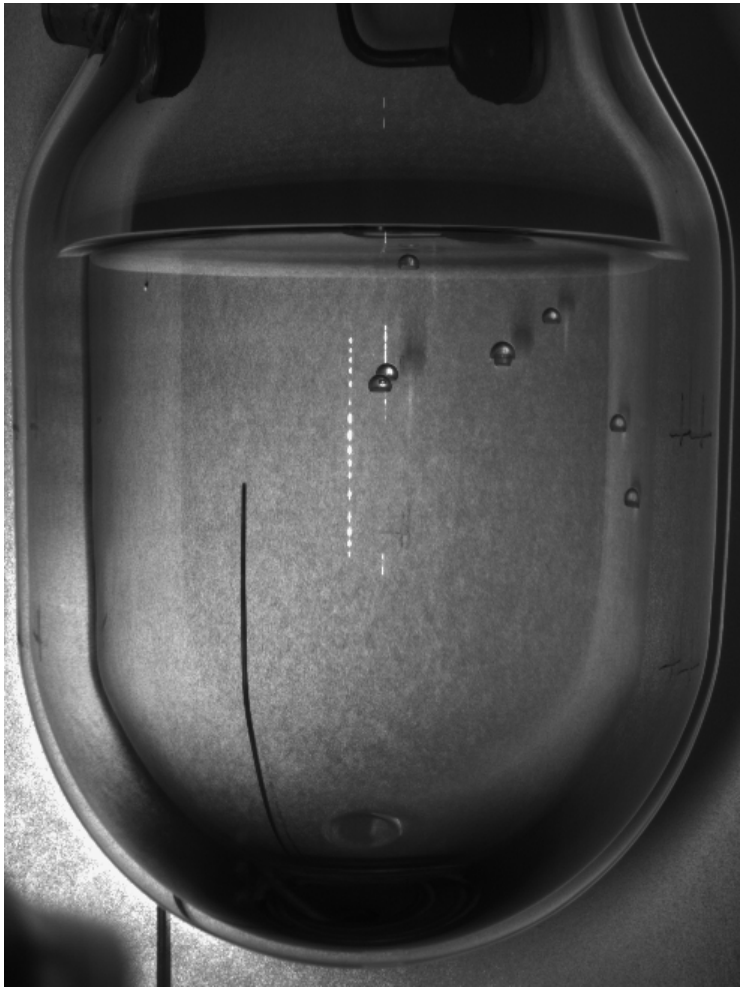

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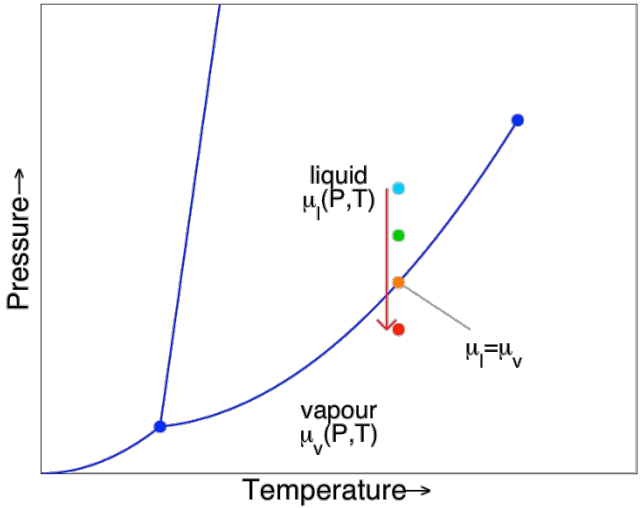

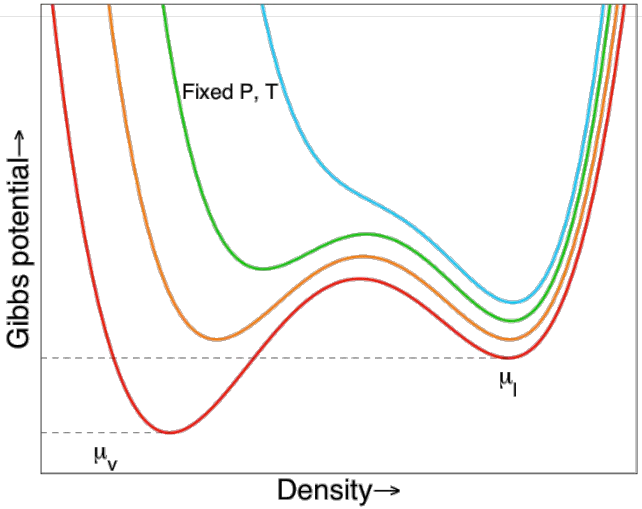

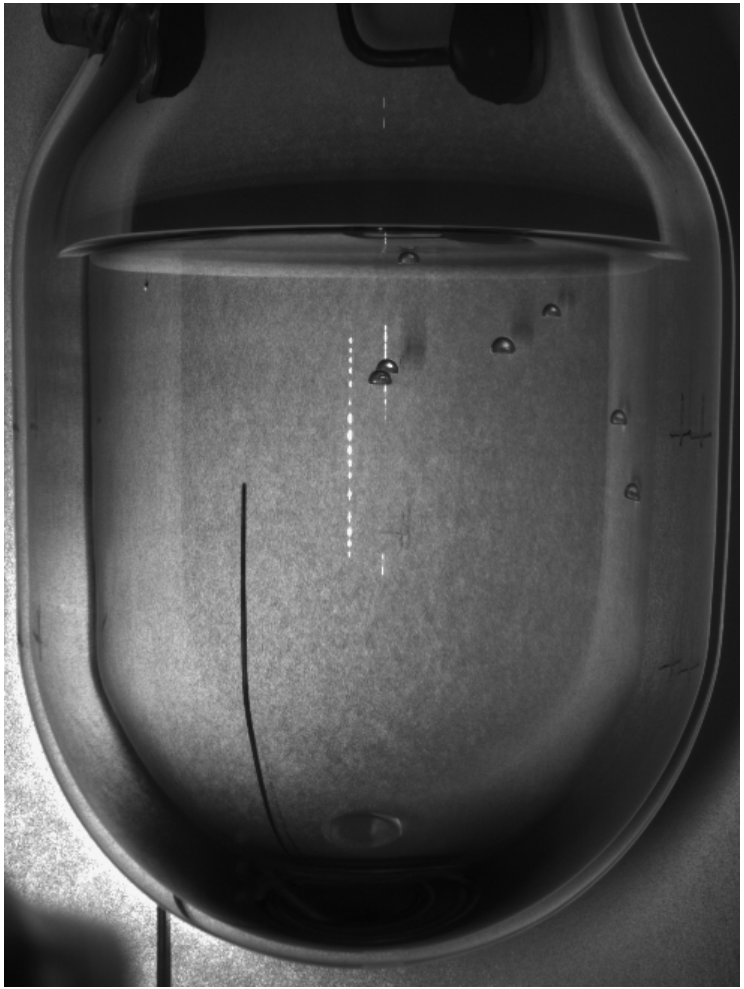

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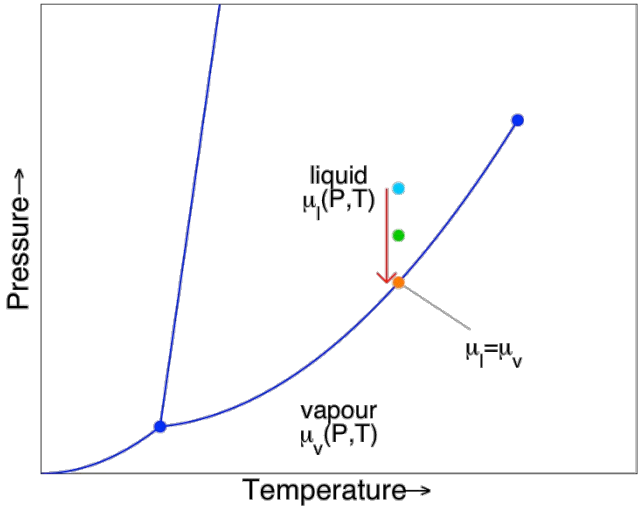

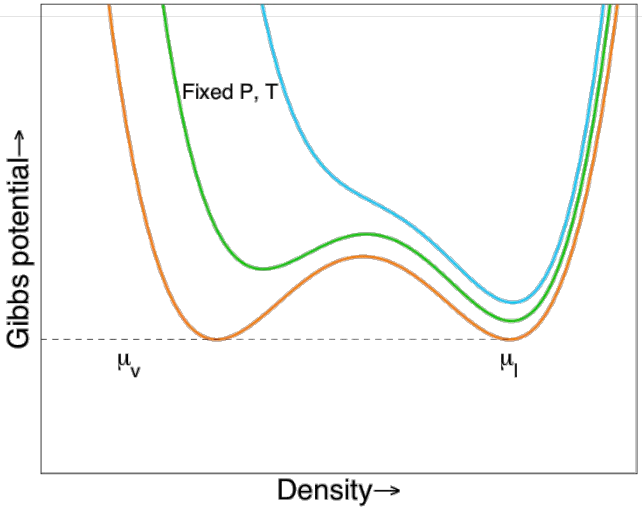

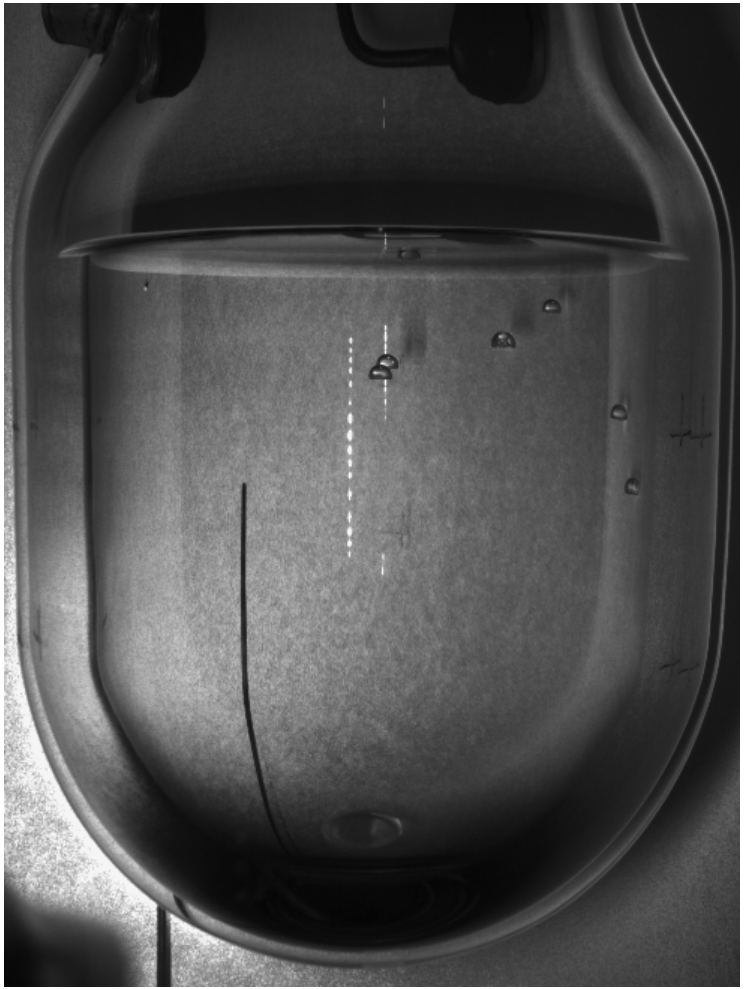

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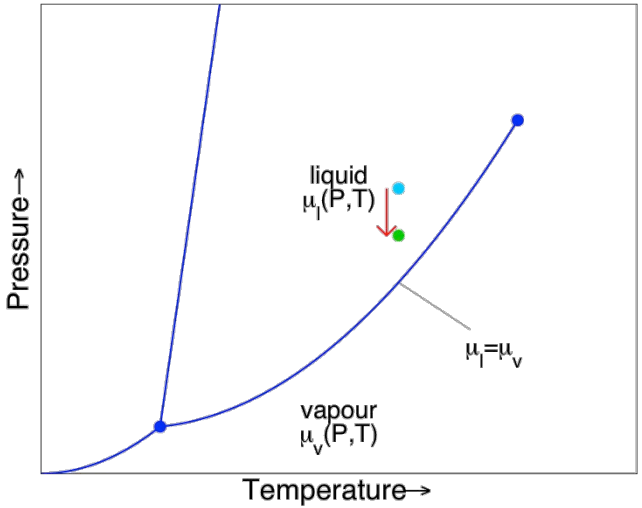
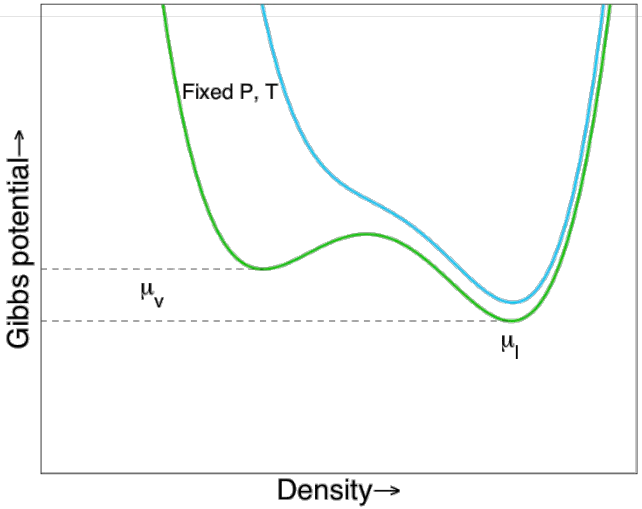
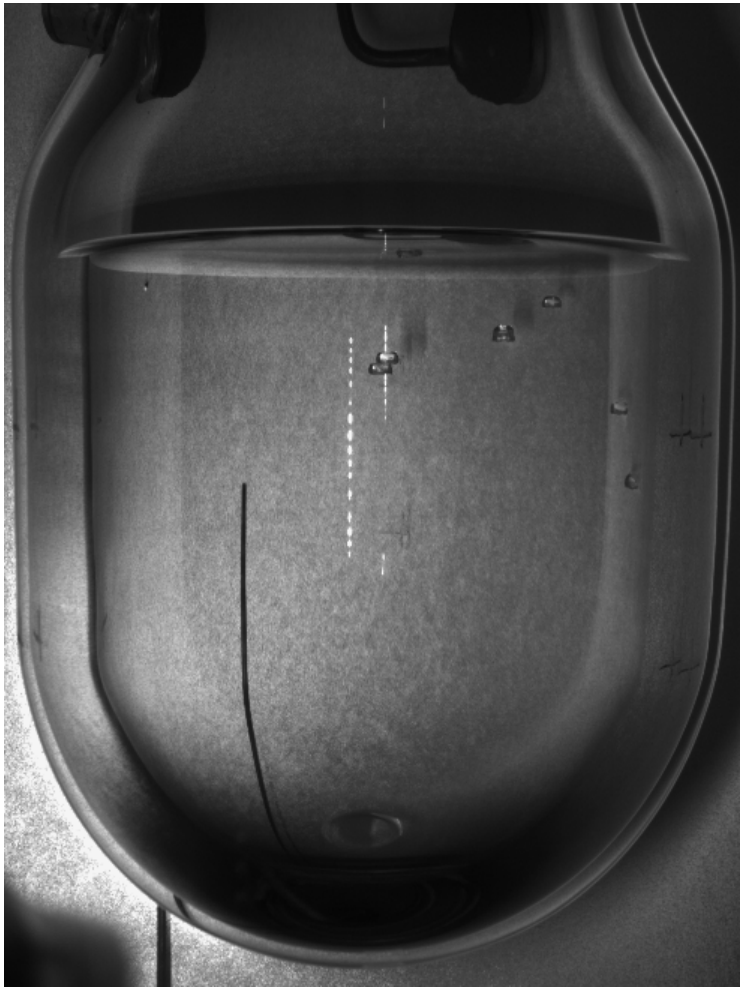
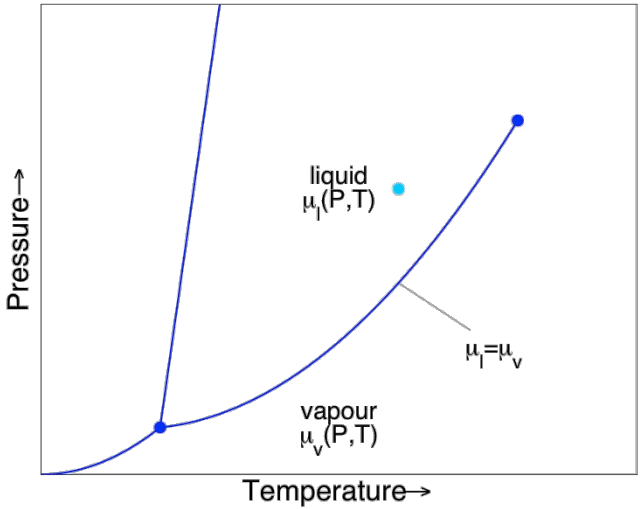
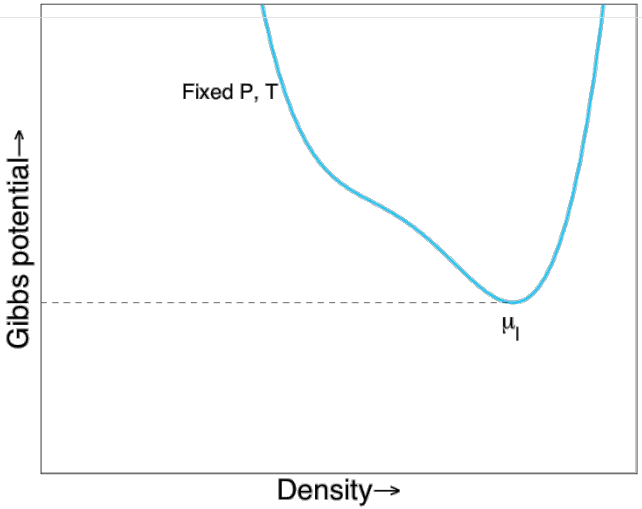


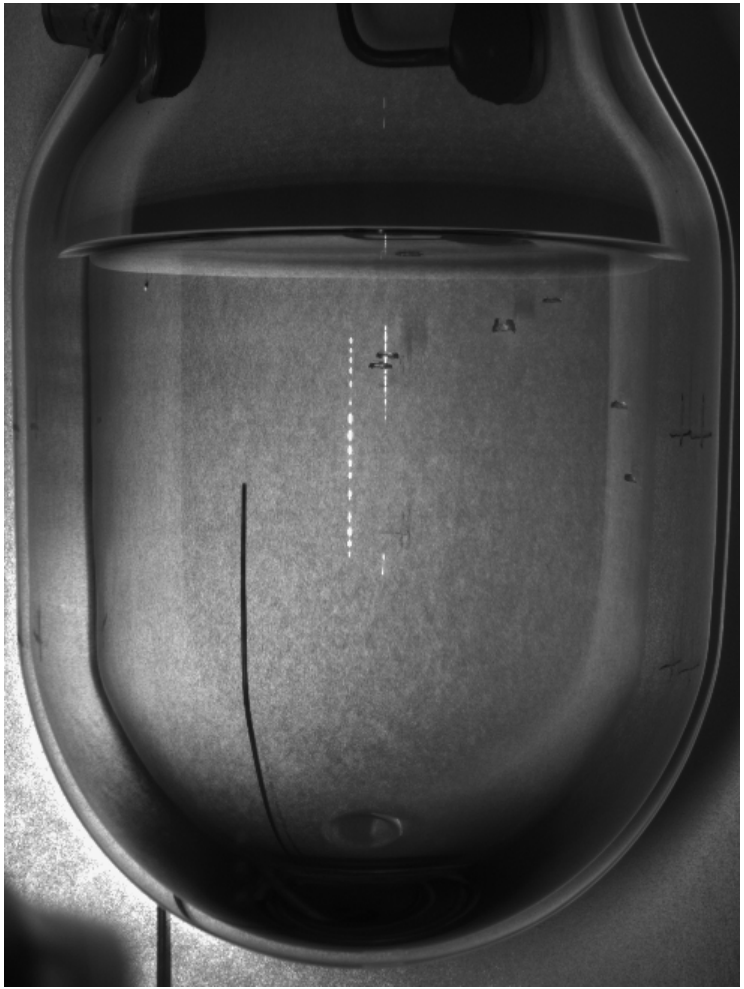




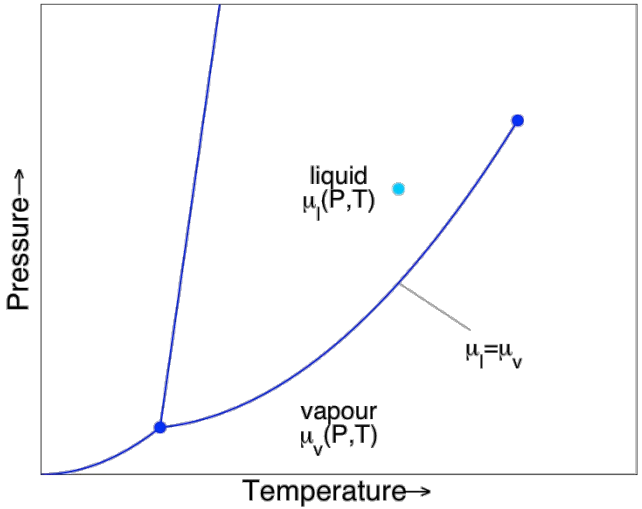
Bubble Chamber

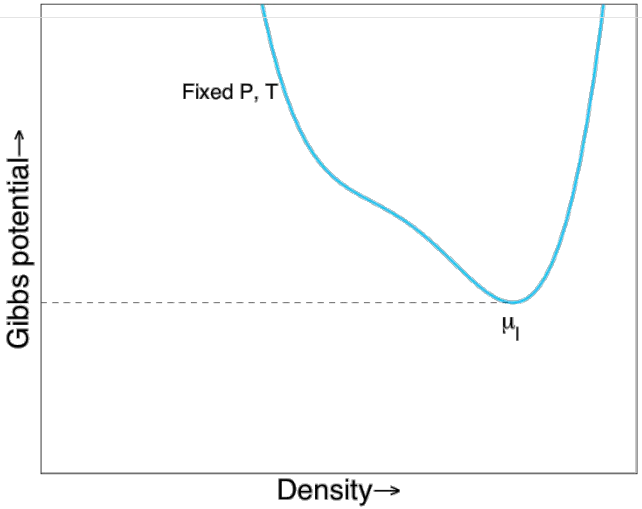


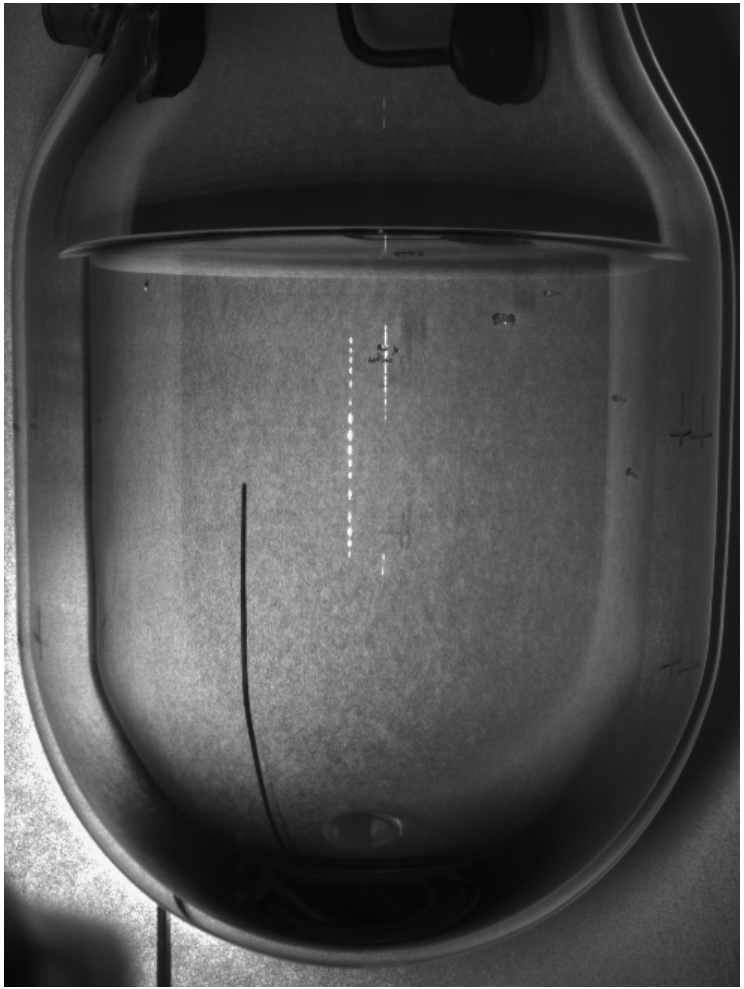




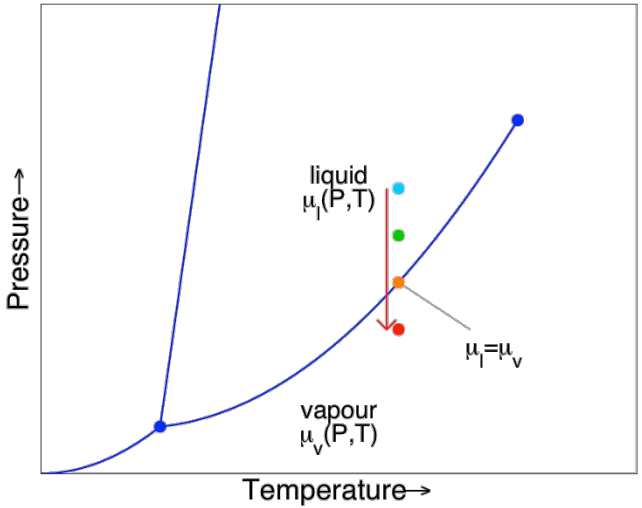
Bubble Chamber

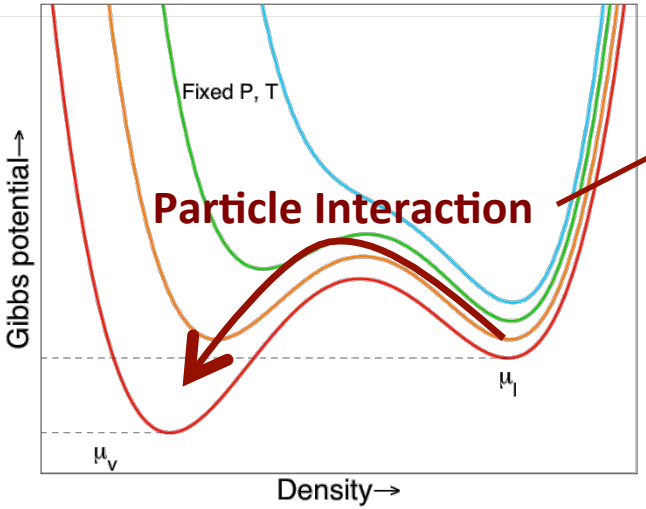


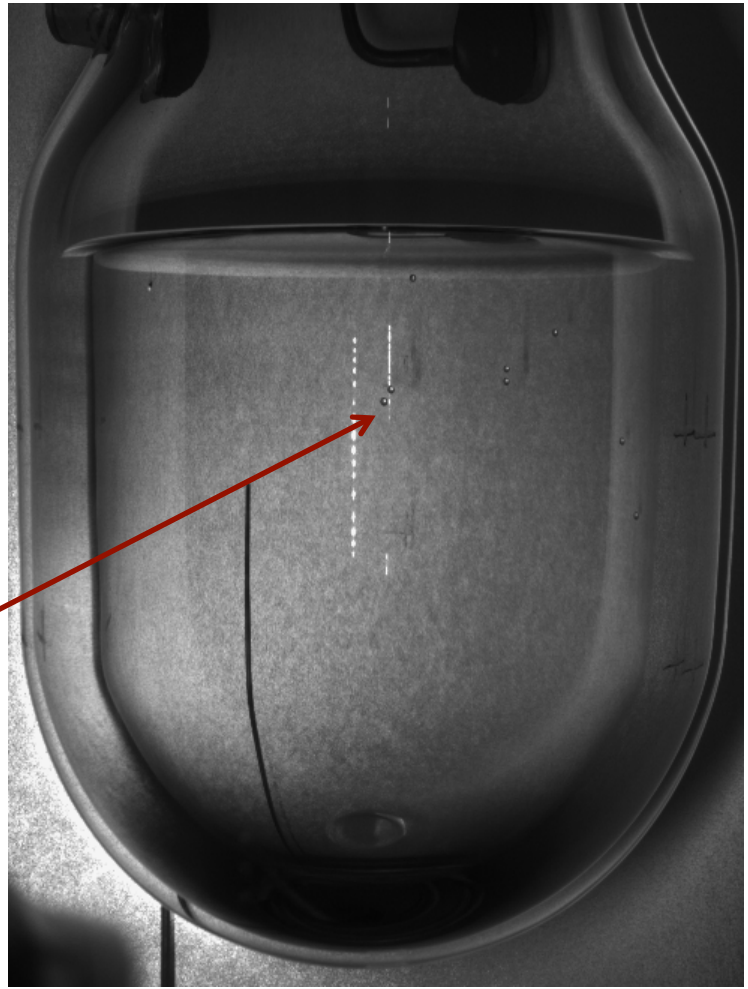




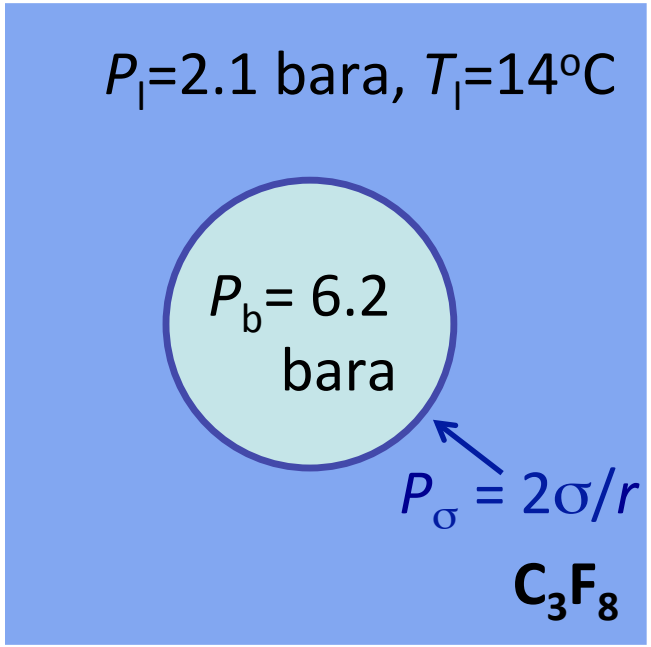
Bubble Chamber



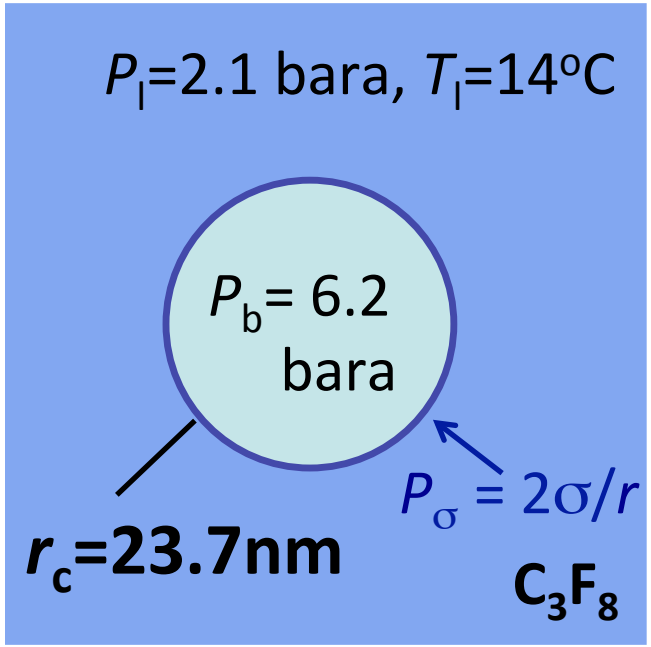




Bubble Nucleation Thermodynamics

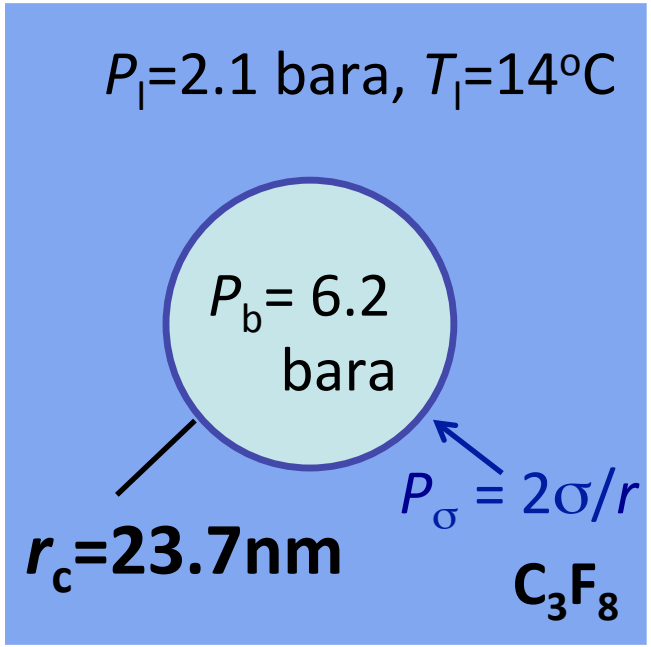


Bubble Nucleation Thermodynamics



"Critical Radius"

Bubble Nucleation Thermodynamics



"Critical Radius"

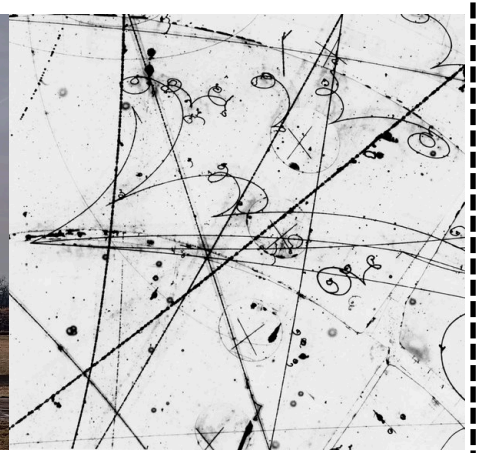
$$E_T = 4\pi r_c^2 \left(\sigma - T \left(\frac{\partial \sigma}{\partial T} \right)_\mu \right)$$ 1.53 keV

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

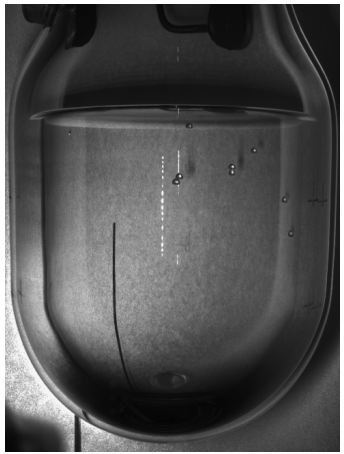
$$- \frac{4\pi}{3} r_c^3 \left(P_b - P_l \right)$$ -0.15 keV

= 3.19 keV *"Thermodynamic Threshold"*

Tracking Chambers vs NR Detectors



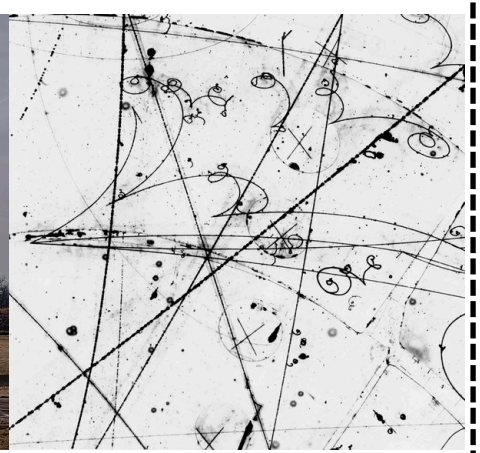
Bubbles in tracks nucleated by δ-electrons



No bubbles (< 1 in 10^9) nucleated by ER's at the P, T selected for dark matter search

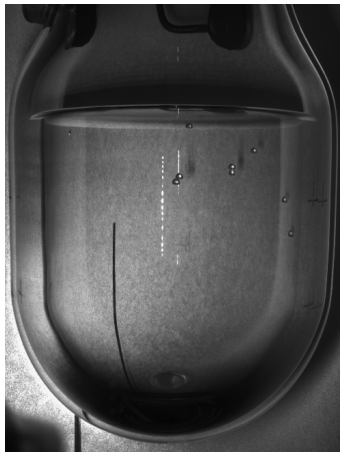
(insufficient dE/dx for nucleation)

Tracking Chambers vs NR Detectors



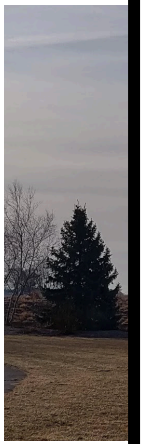
Bubbles in tracks nucleated by δ-electrons

Pure noble liquids never worked
(no heat loss by electrons)



No bubbles (< 1 in 10^9) nucleated by ER's

Pure noble liquids are ideal
(no bubbles from ER's even at high superheat)



Bu

R's

heat)

"Xenon, being predominantly a monatomic medium, has no rotational or vibration atomic oscillation modes, and as a result, it is effectively converting the energy of δ-electrons into light (scintillation). To convert the energy of scintillation into localised heat and enhance the formation of bubbles, molecular admixtures of ethylene or propane have been used in LXe bubble chambers."

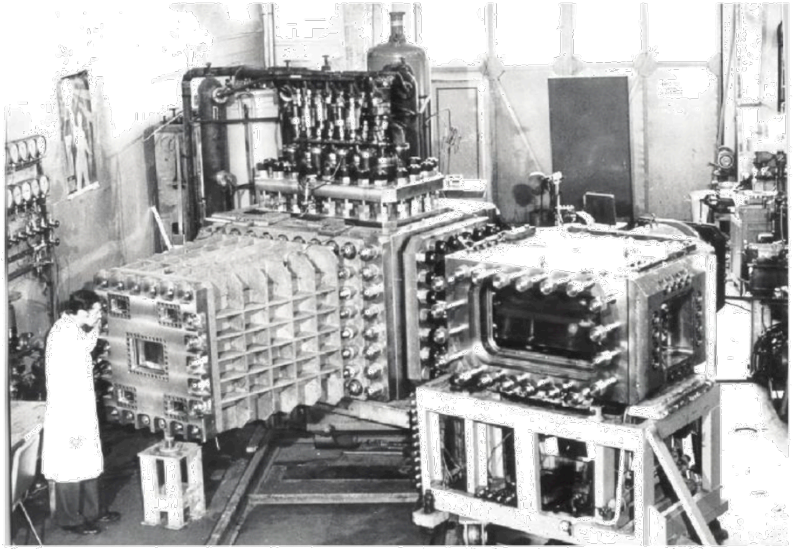


Figure 1.1 Liquid xenon bubble chamber DIANA with 1.5x0.7x 0.7 m^3 active volume constructed at ITEP in the 1970s. Courtesy of A.G. Dolgolenko.

Bolozdynya, Alexander I. Emission Detectors. Singapore: World Scientific, 2010.

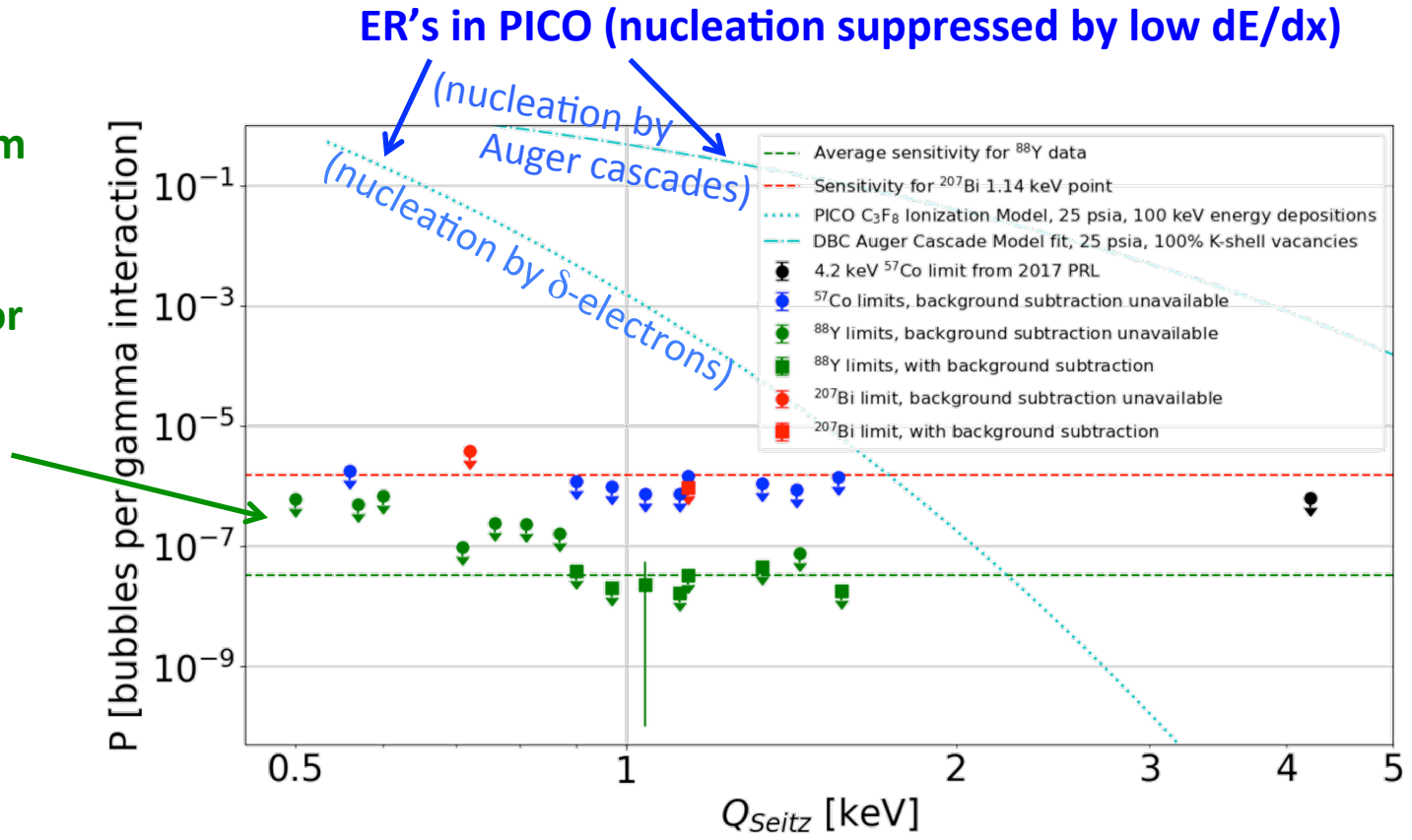
No molecular degrees of freedom

↓

No mechanisms for local heating by electrons

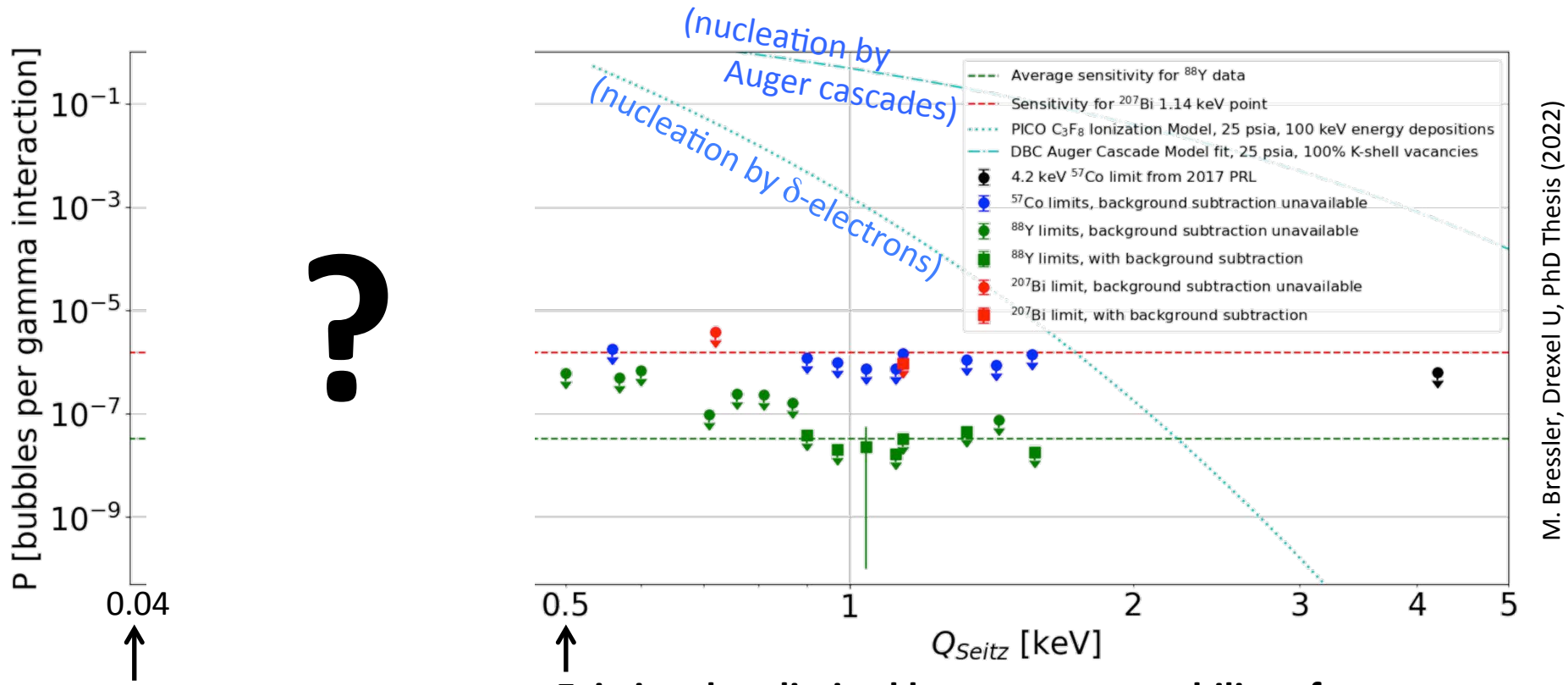
↓

No bubbles from ERs



M. Bressler, Drexel U, PhD Thesis (2022)

Performance at Low Threshold – ER's



Homogeneous nucleation (1 bubble / ton-yr in LAr)

Existing data limited by pressure capability of prototype

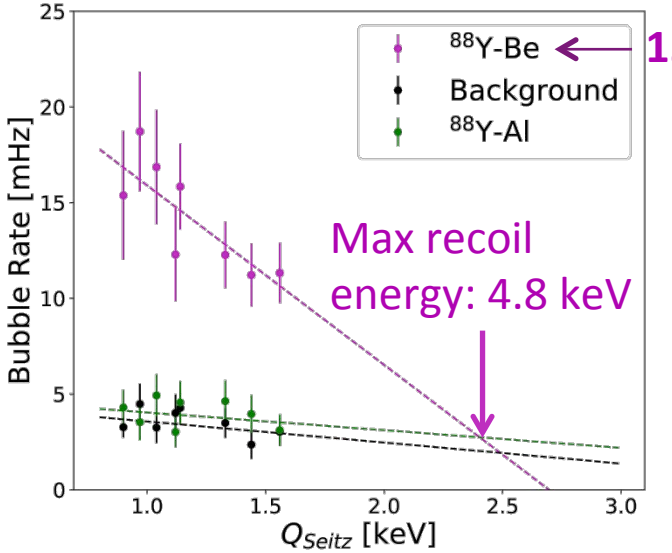
M. Bressler, Drexel U, PhD Thesis (2022)

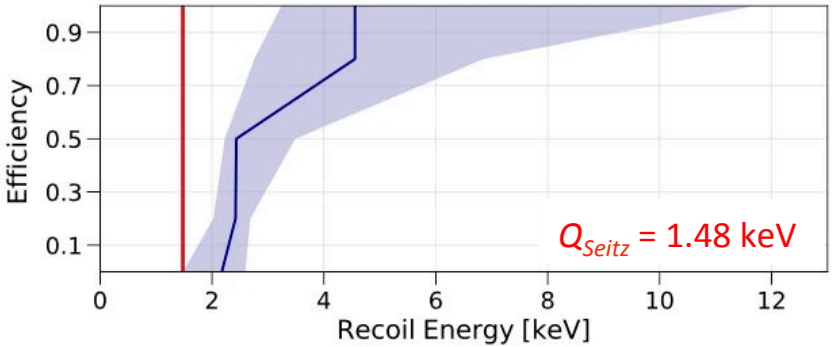
Performance at Low Threshold – NR's

- Neutron Scattering
  - C_3F_8 @ 3 keV:
    $E_{NRthreshold} \approx 1.5 \times Q_{seitz}$

    [Ali *et al*. Phys Rev **D 106**, 122003, (2022)]
  - Xe @ 1.5 keV:
    $E_{NRthreshold} \approx 1.5 \times Q_{seitz}$ →
- MD Simulations
  - L-J Fluid @ 3,000 ε (Ar @ 40 eV):
    $E_{NRthreshold} \approx 1.5 \times Q_{seitz}$

    [Denzel, Diemand, Angélil. Phys Rev **E 93**, 013301 (2016)]



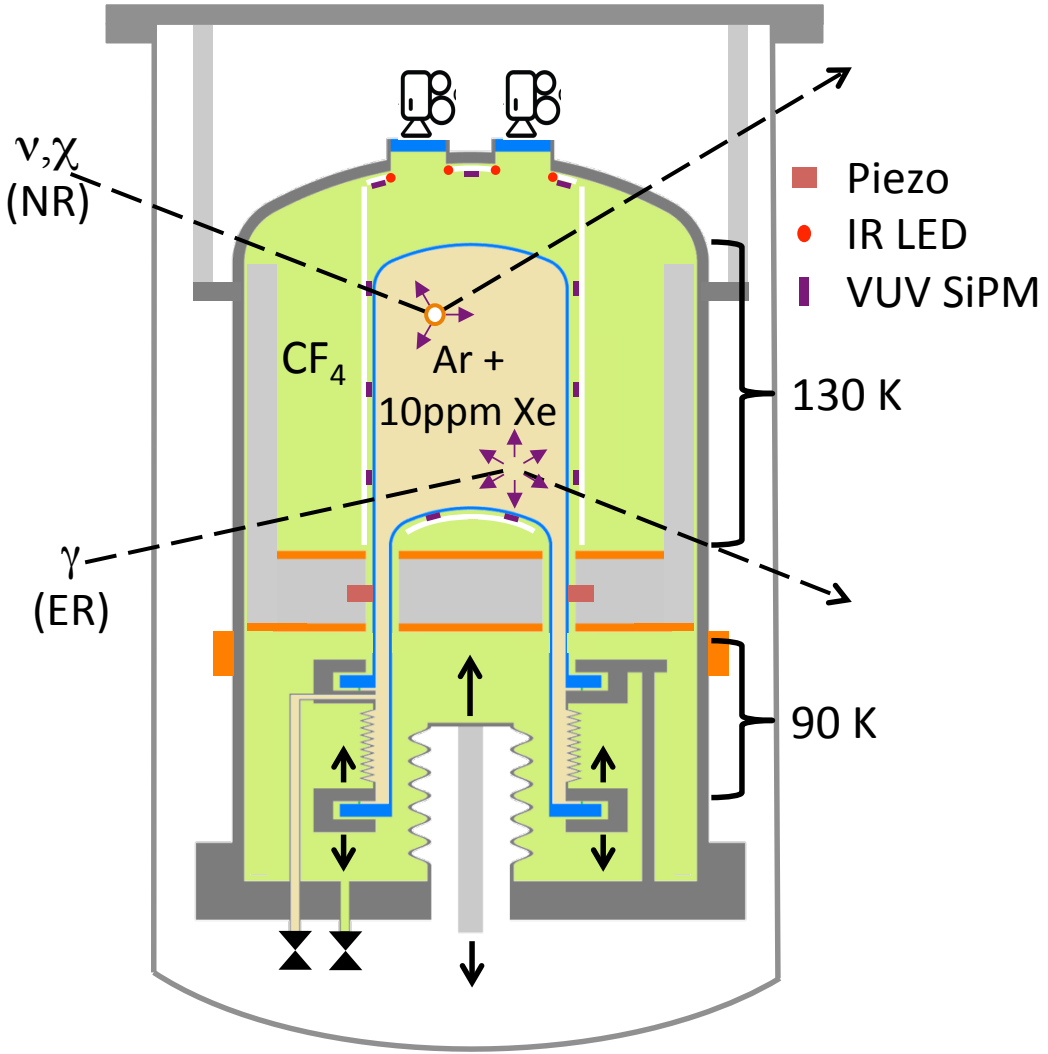


(Xe NR analysis by D. Durnford)

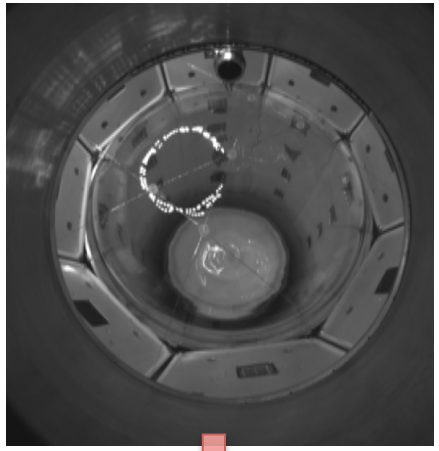
SBC-LAr10

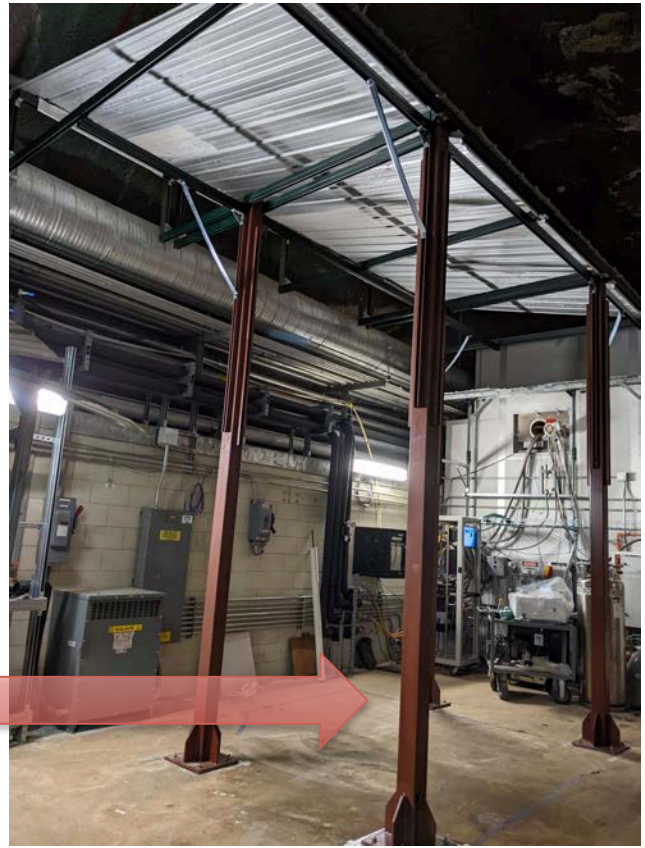
(Fermilab LDRD 2018-003,
with support from
DOE-HEP Det R&D,
NSF Particle-Astro, and CFI)

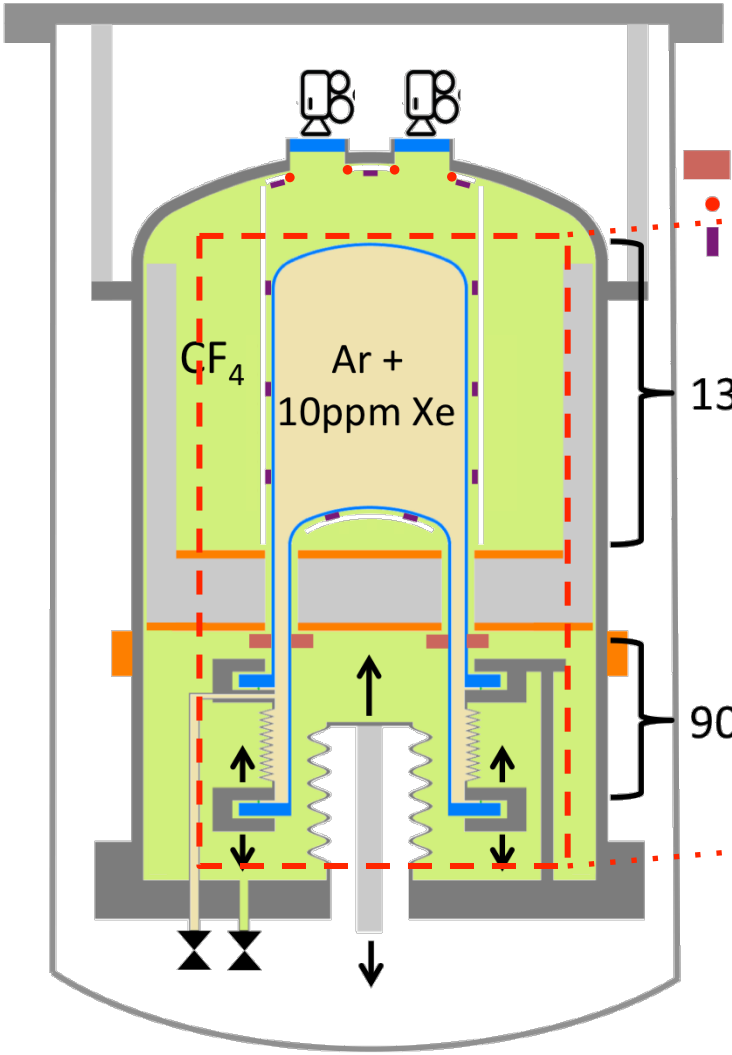
- Designed for 40 eV operation
  (stat mech stability limit)
- Primary target: LAr
  (Xe, CF_4, N_2 also possible)
- Design scalable to 1-ton
  (can do physics at 10-kg)
- To be calibrated at
  O(10)-eV resolution



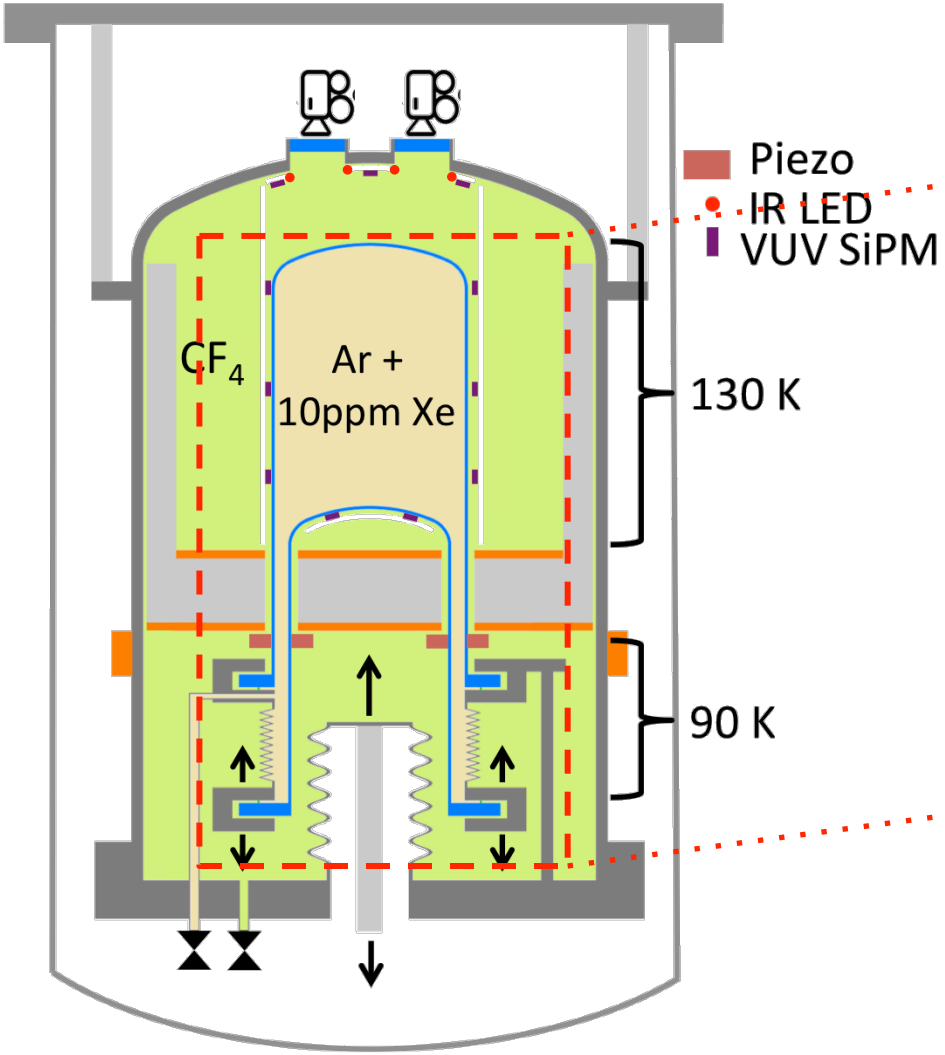
SBC-LAr10



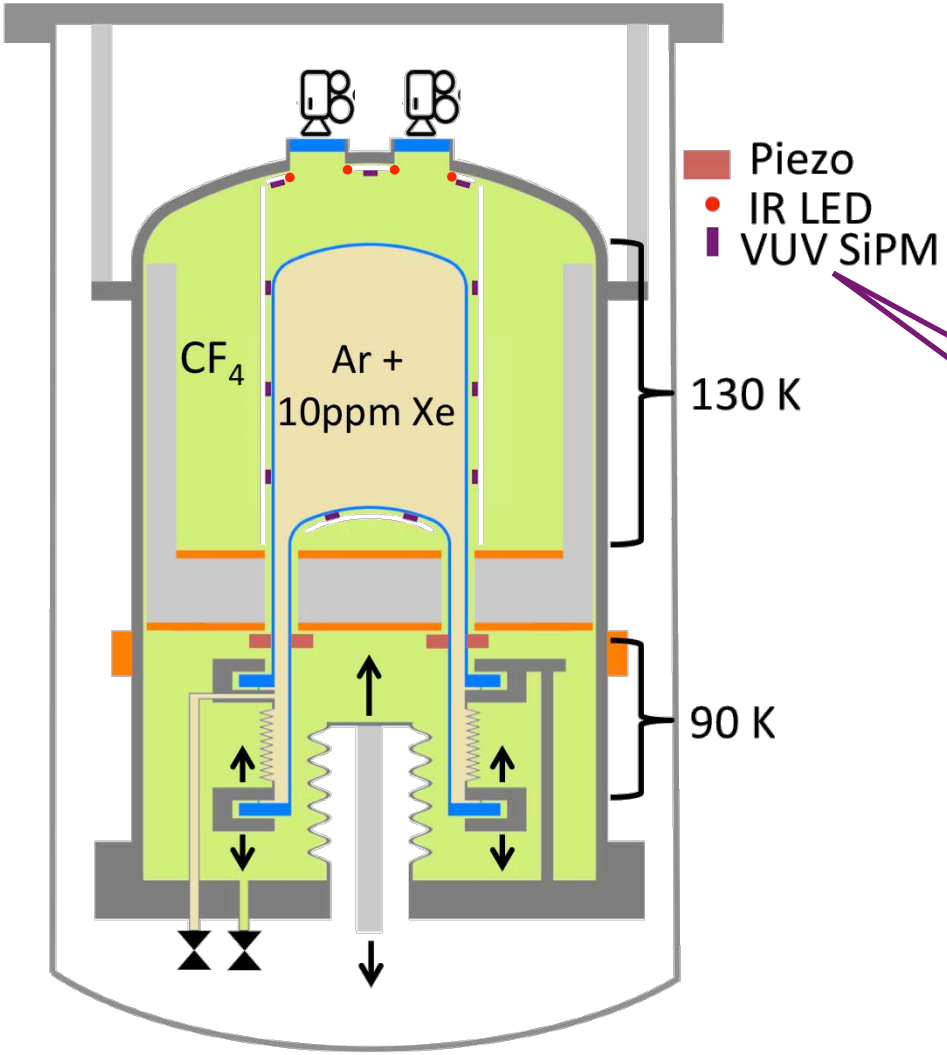




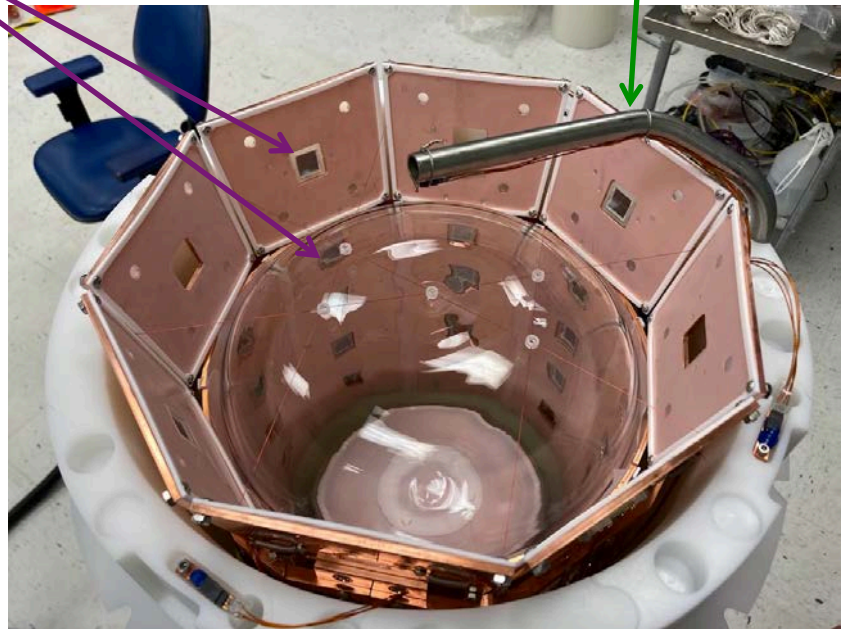
Hector Hawley-Herrera
Queen's Ph.D. Student



Ryan Zhang (UCSB PhD student)
and Ben Broerman (Queen's postdoc)

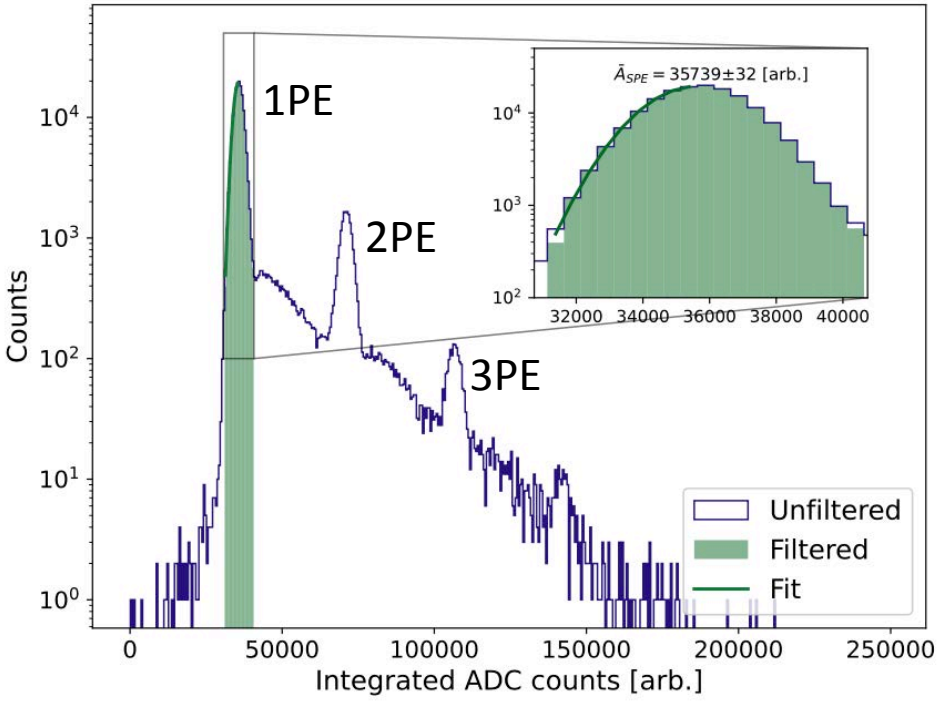


CF_4 Fill/Drain Standpipe

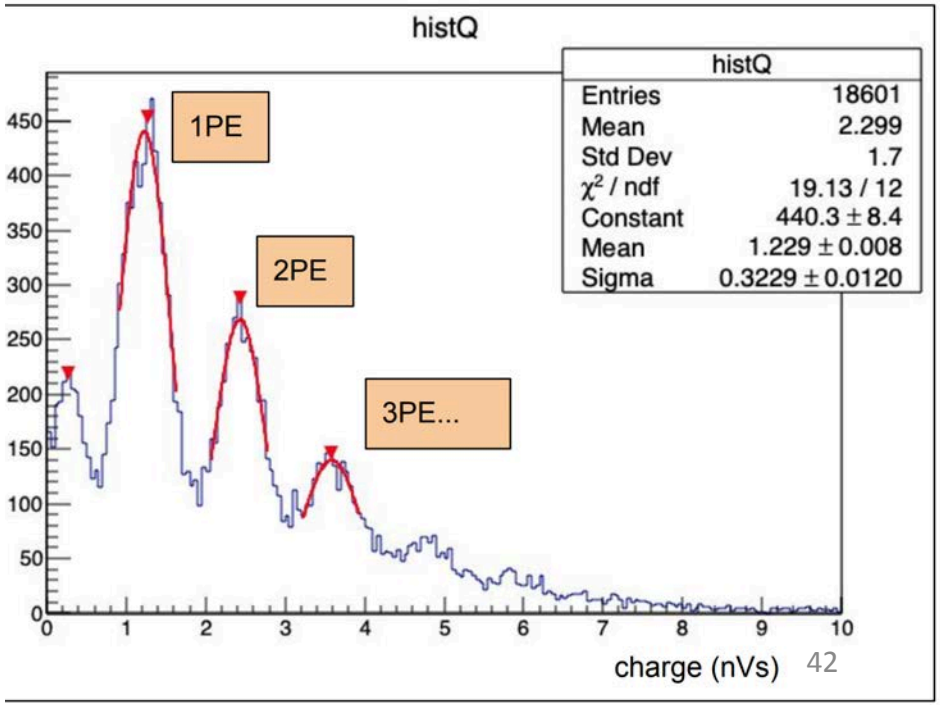


SiPM (Hamamatsu VUV4) Performance

SiPM Characterization @ Queen's
(Hawley-Herrera et al, arXiv:2405.18403)

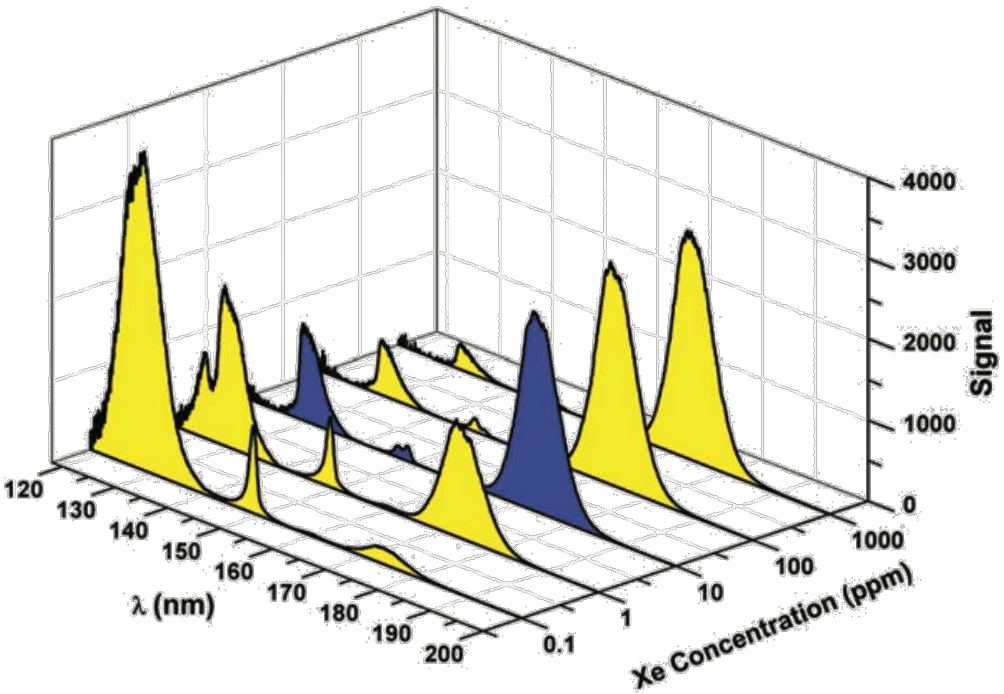


In high-pressure, cryogenic LCF_4 @ NU
(Sheng + de SaintCroix)

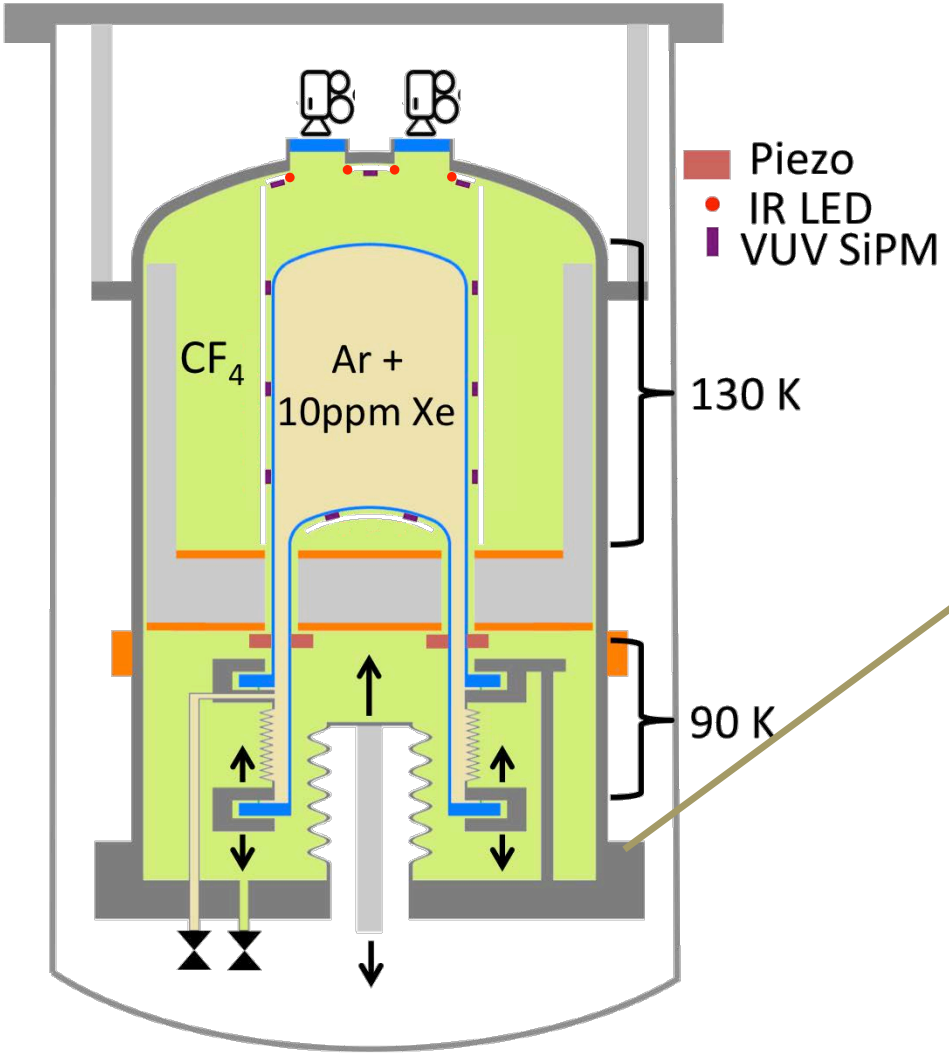


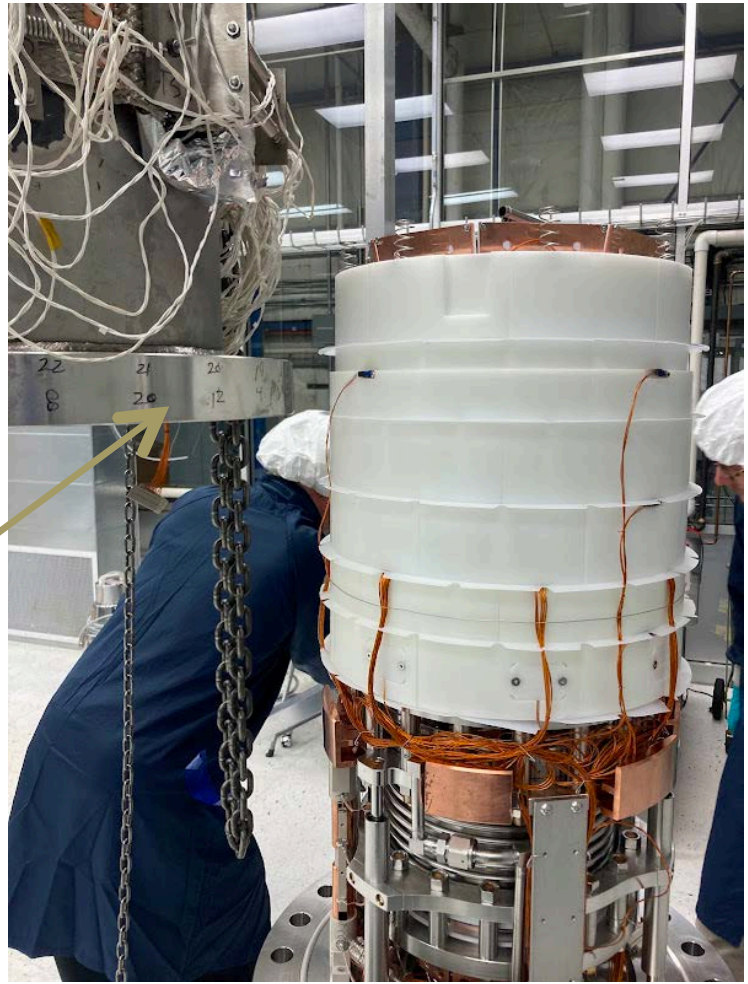
Scintillation: Doping

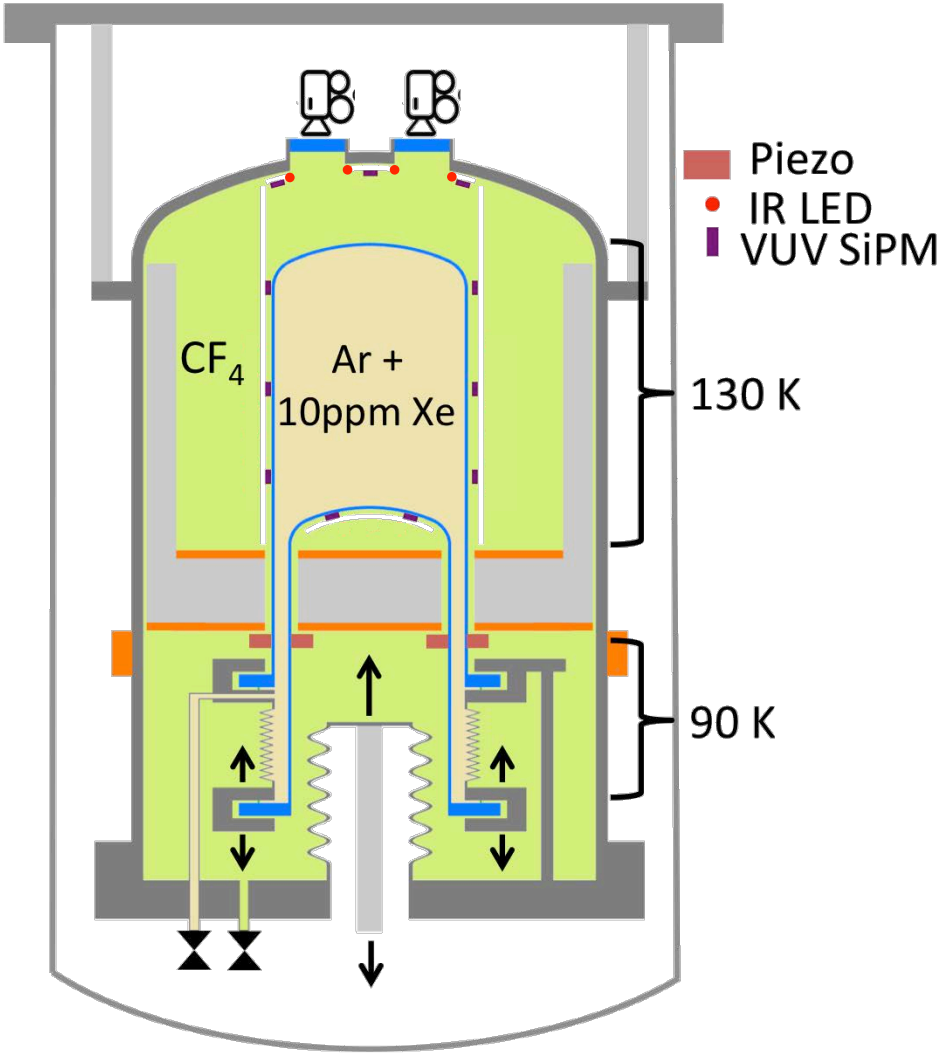
- Silica jars opaque to 128nm Ar scintillation
- 10ppm Xe sufficient to exchange Ar_2* for Xe_2*
  - 175nm, jars transparent
  - Expect 1 photon detected for ~5-keV NR

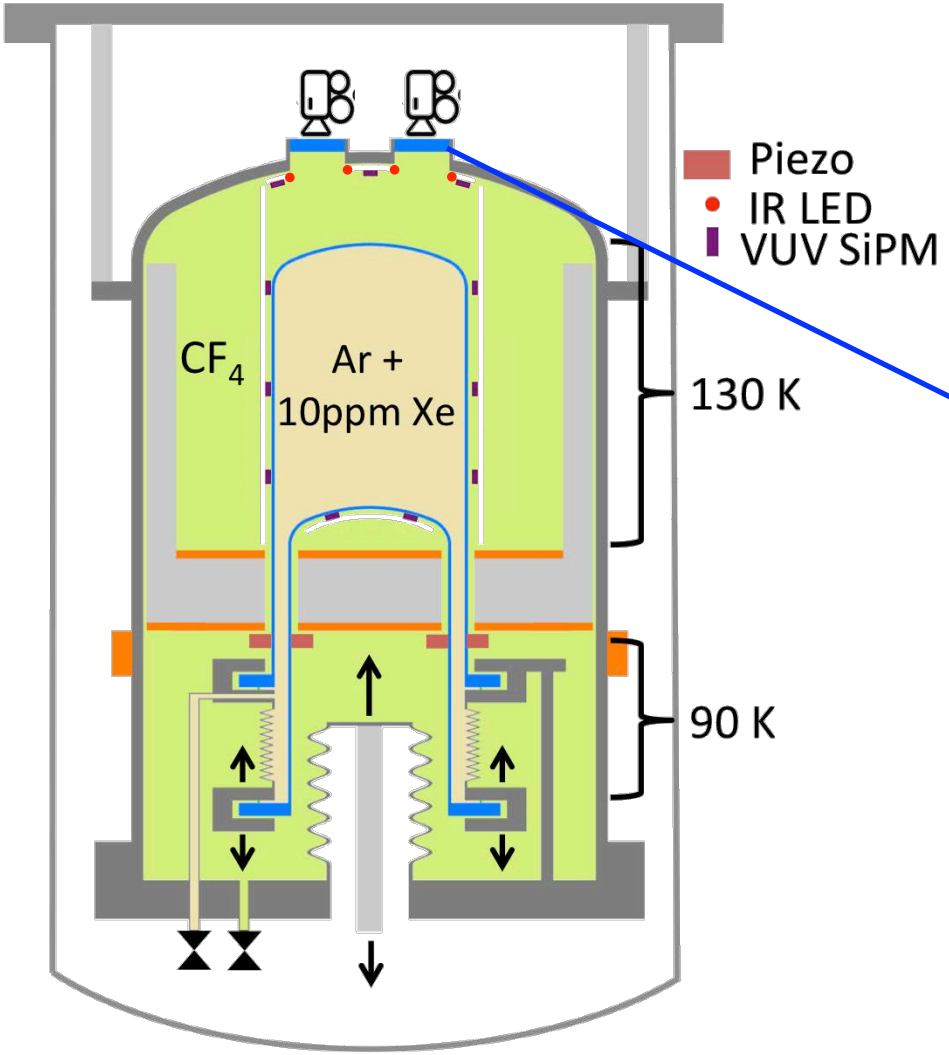


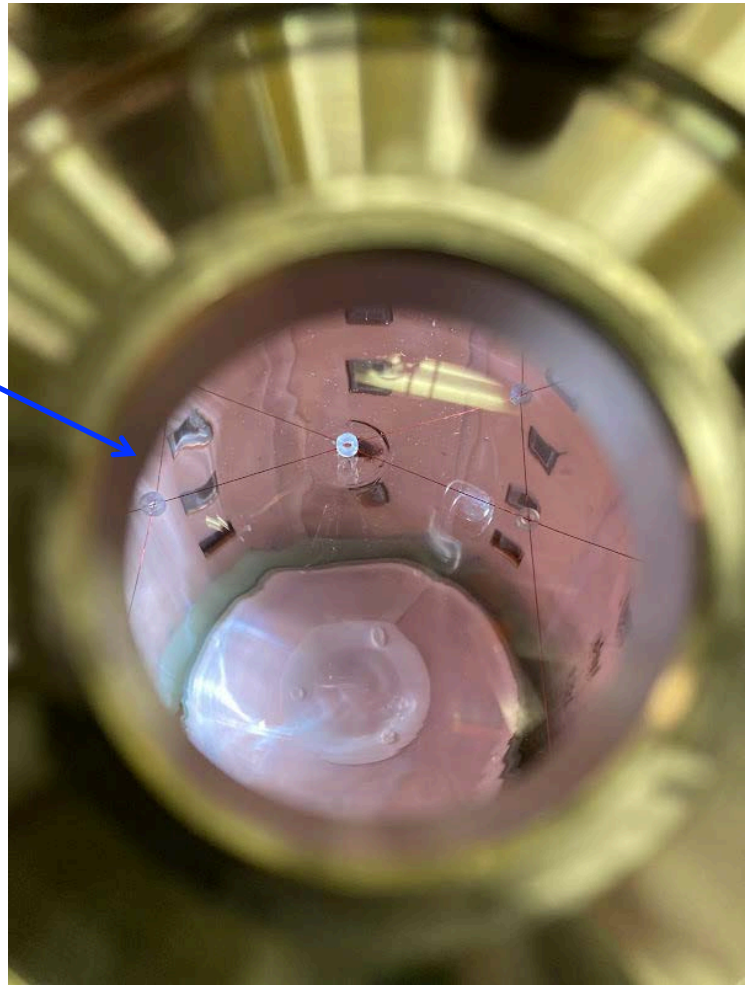
A. Neumeier *et al* 2015 *EPL* **109** 12001

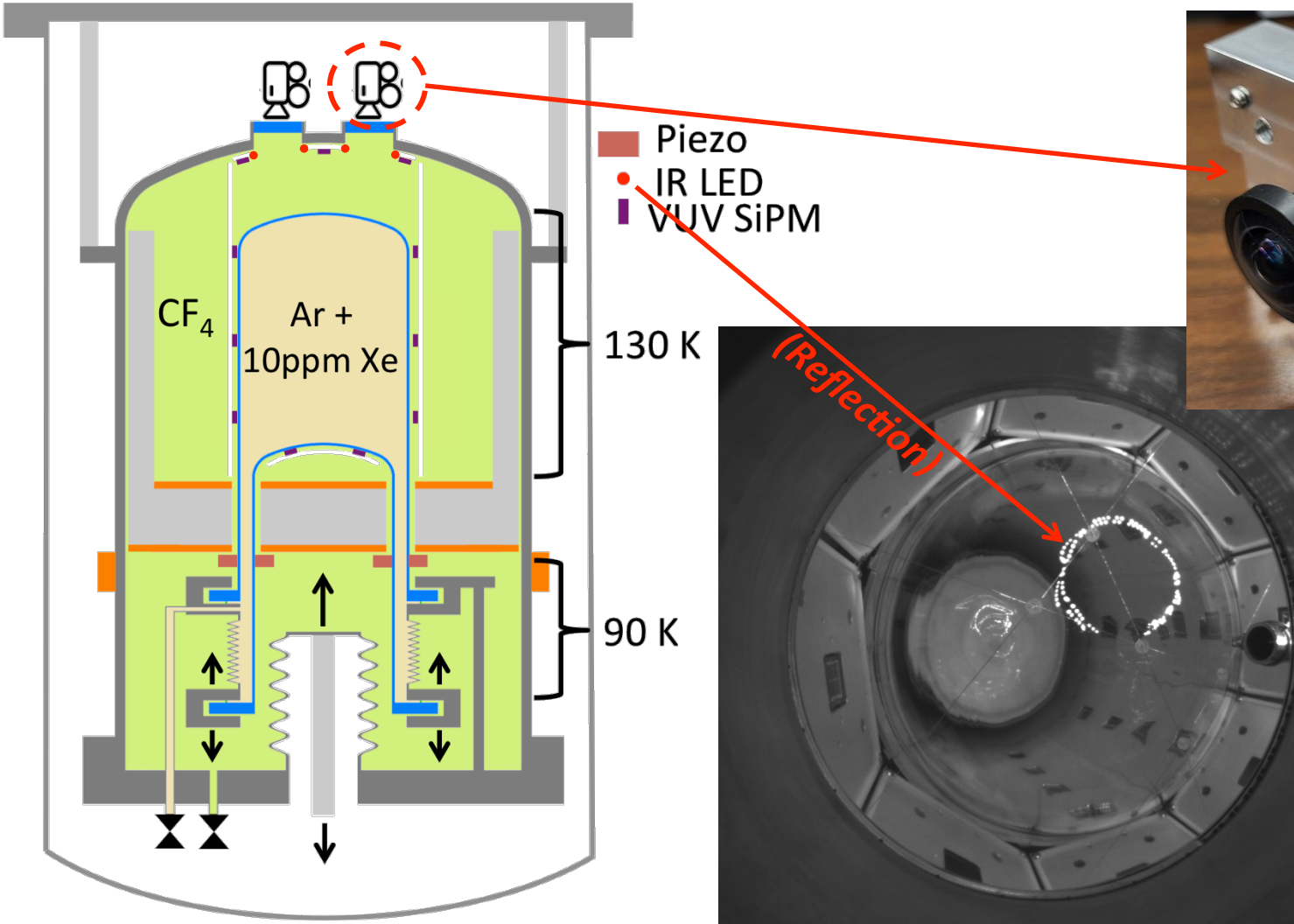

Piezo
IR LED
VUV SiPM
CF_4
Ar +
10ppm Xe
130 K
90 K

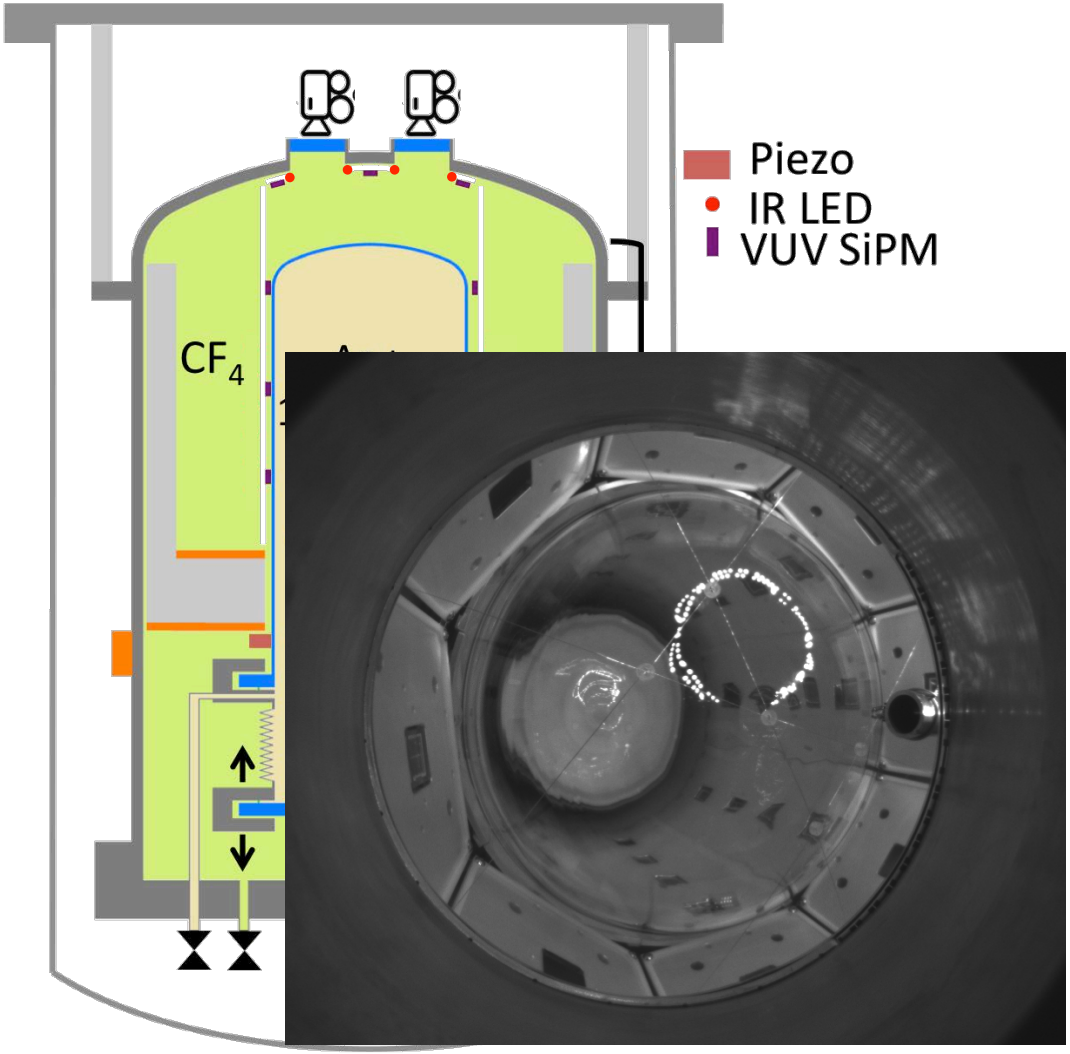


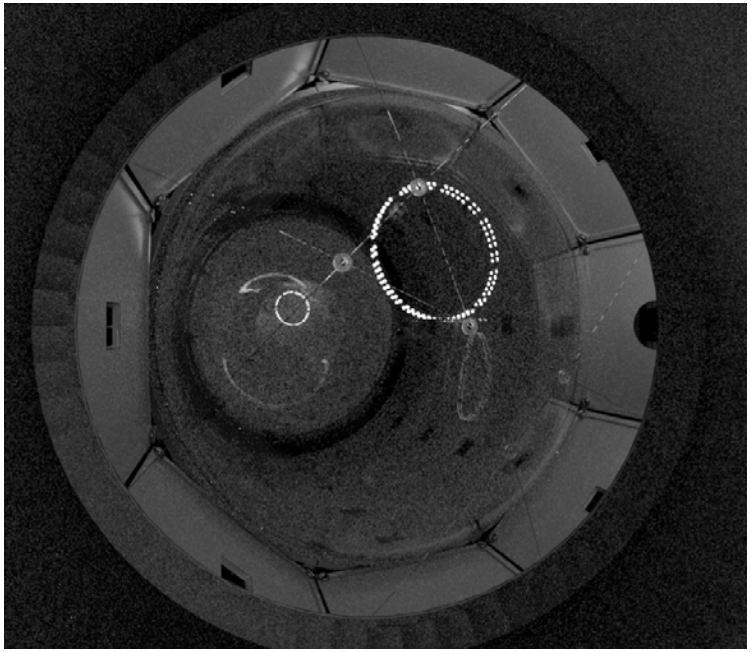

Piezo
IR LED
VUV SiPM
CF_4
Ar +
10ppm Xe
130 K
90 K


Piezo
IR LED
VUV SiPM
CF_4
Ar +
10ppm Xe
130 K
90 K



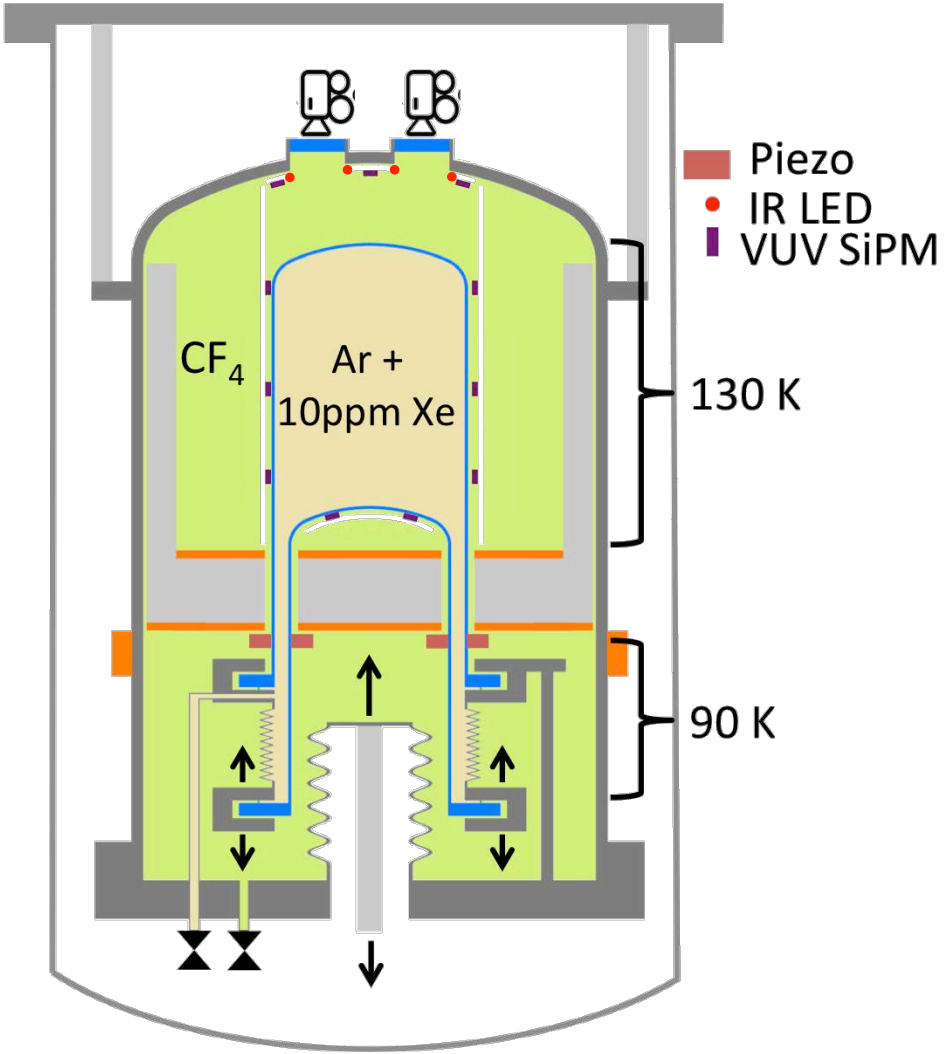

Piezo
IR LED
VUV SiPM
CF_4
Ar +
10ppm Xe
130 K
90 K
(Reflection)



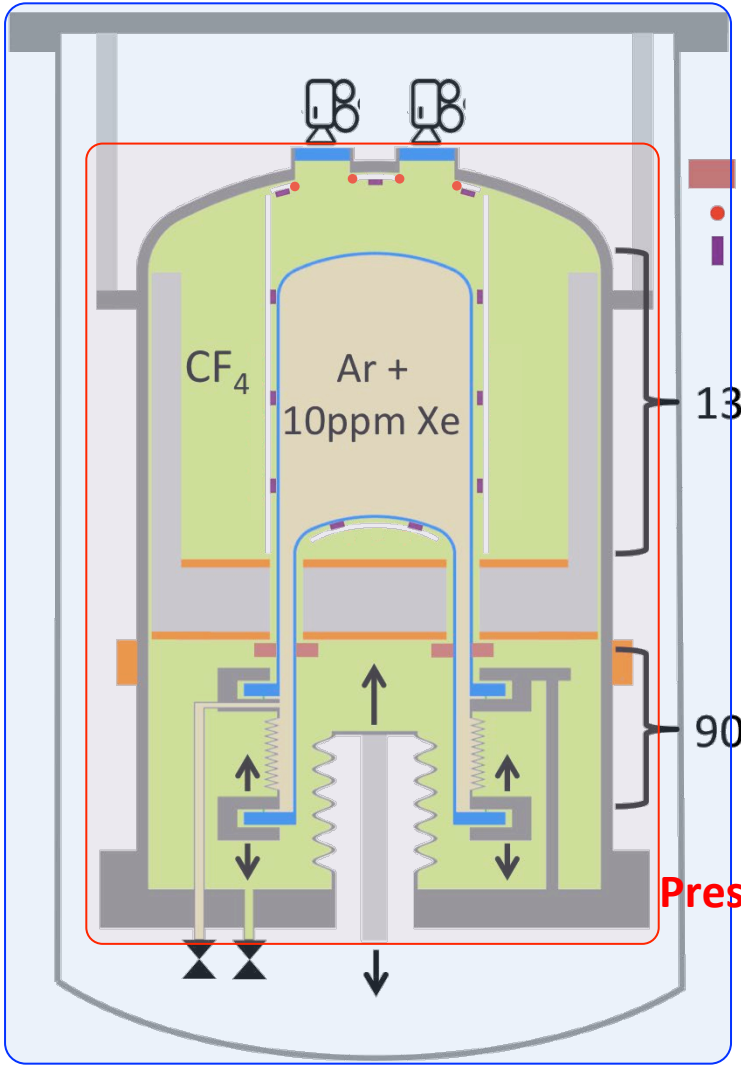


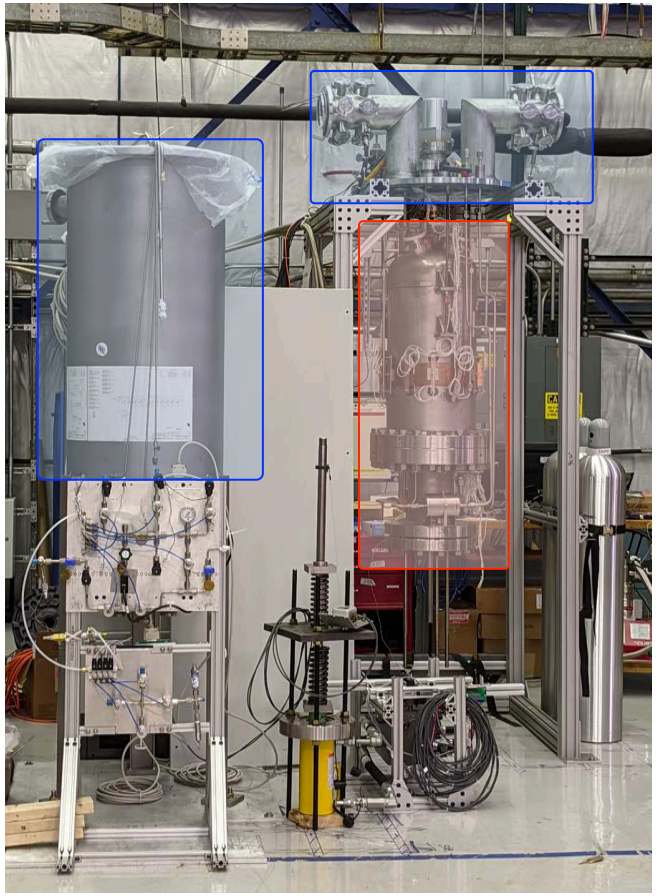
^ Simulated Image
(MA Khatri, Northwestern)

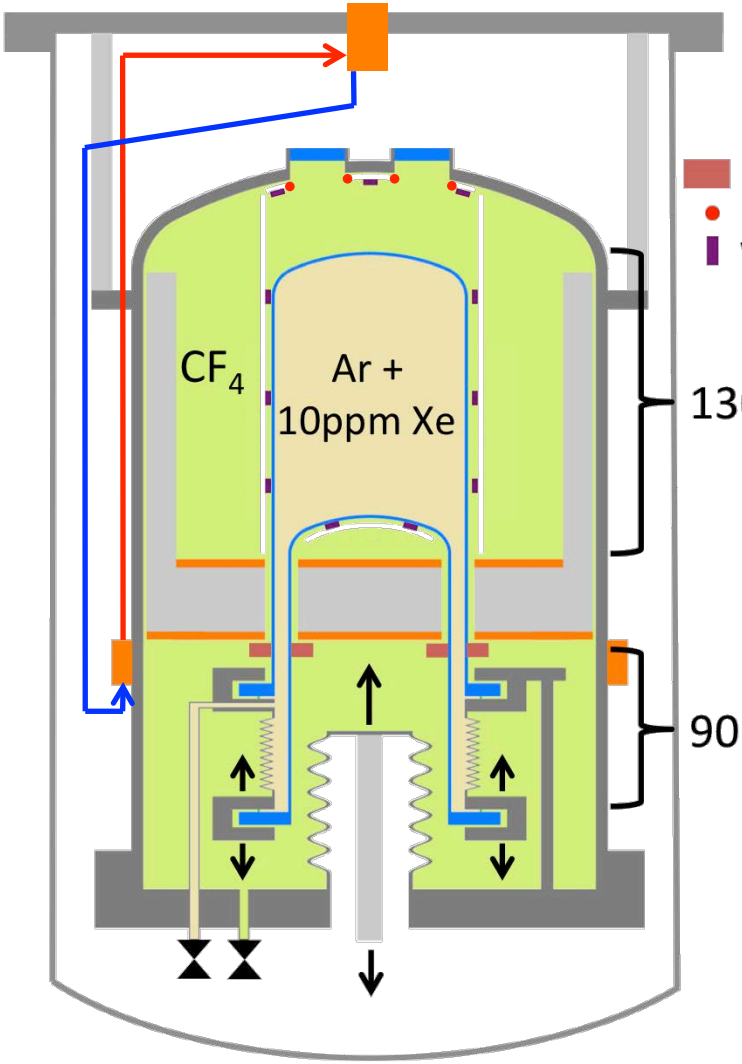
<- Real Image



Lab B, Fermilab Silicon Detector Facility

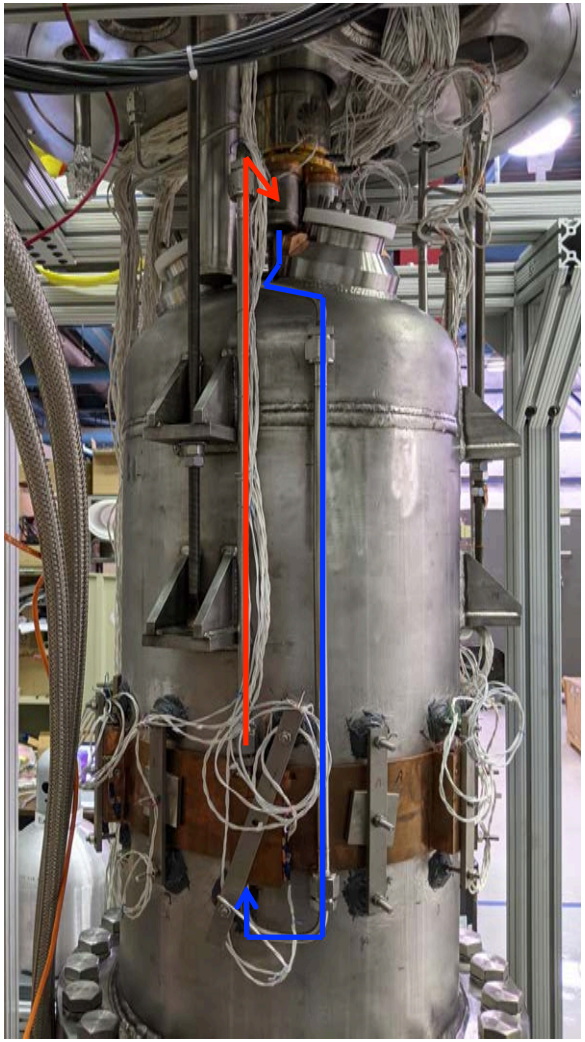

Piezo
IR LED
VUV SiPM
CF_4
Ar +
10ppm Xe
130 K
90 K
Pressure Vessel
Vacuum Jacket

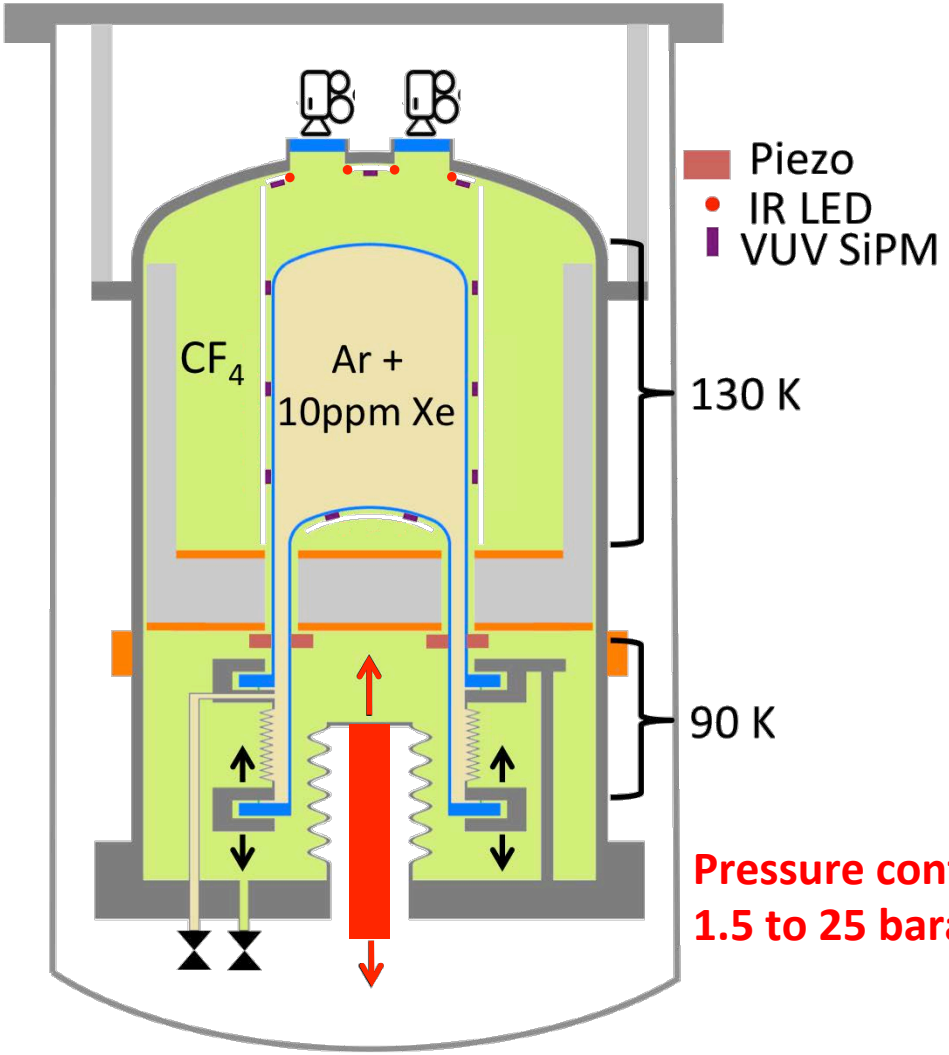




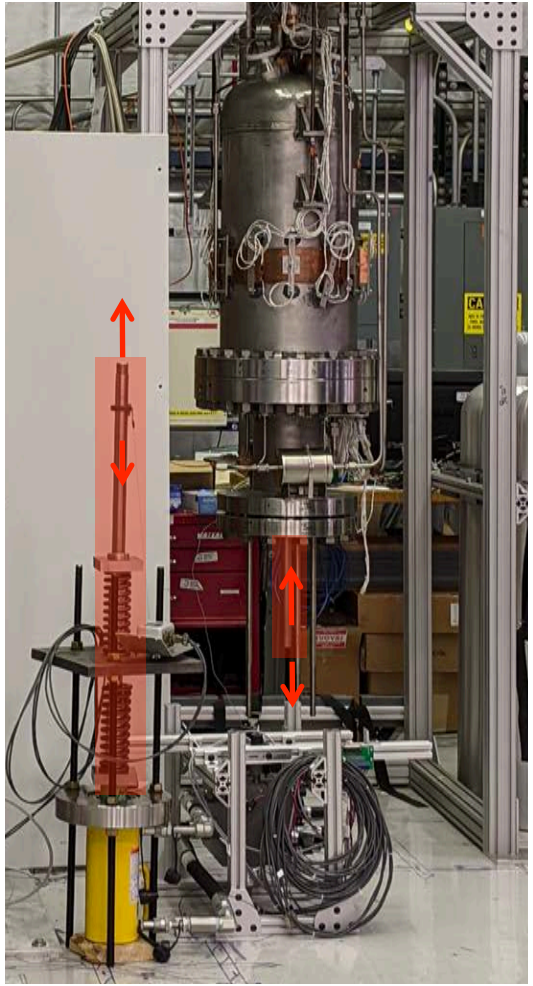
Closed-loop LN_2 Thermosiphons deliver cooling where we need it

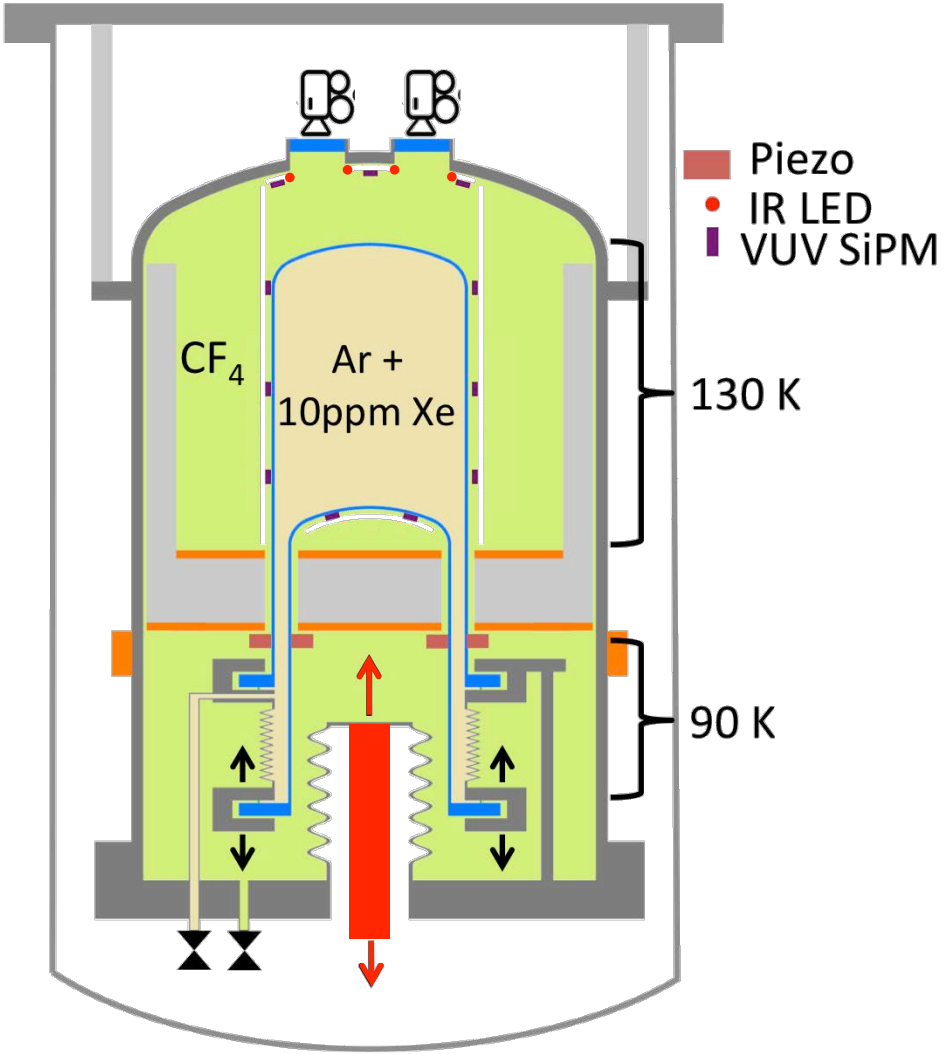
Design/ Inspiration Credit: LUX, LZ





Pressure control from 1.5 to 25 bara



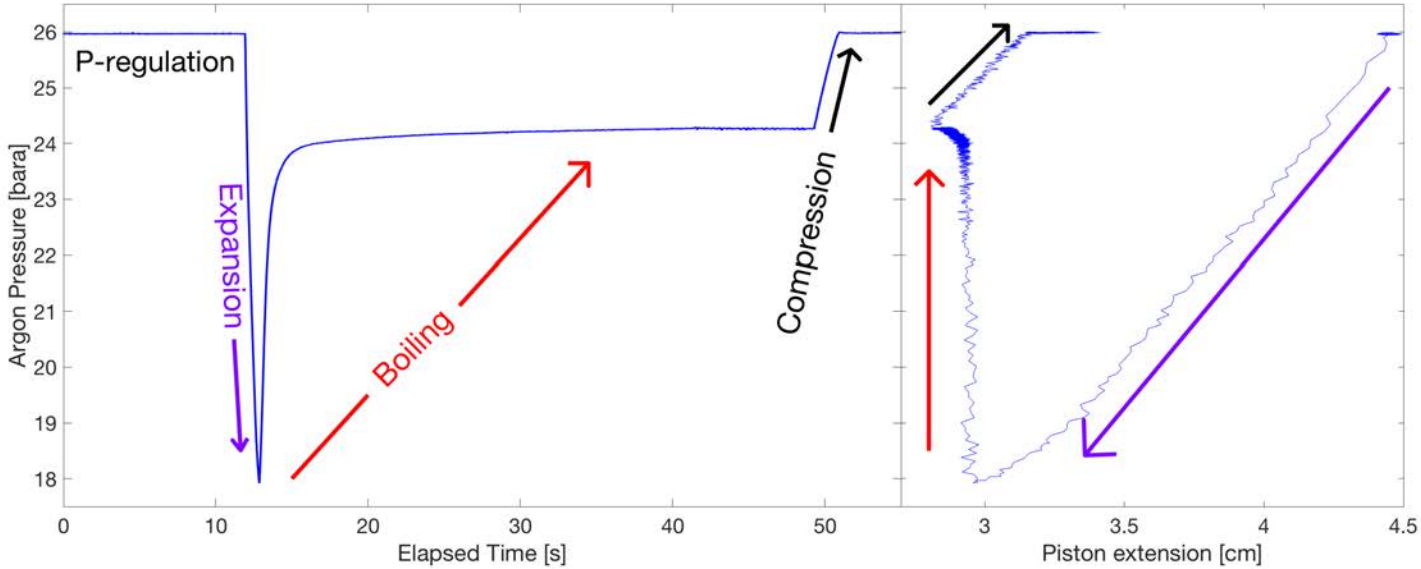


Pictured left-to-right: TJ Whitis, M Bresler, R Coppejans, ED
March 2020

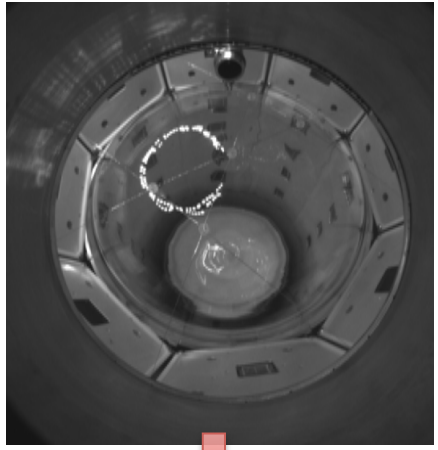
SBC-LAr10 – Engineering Run

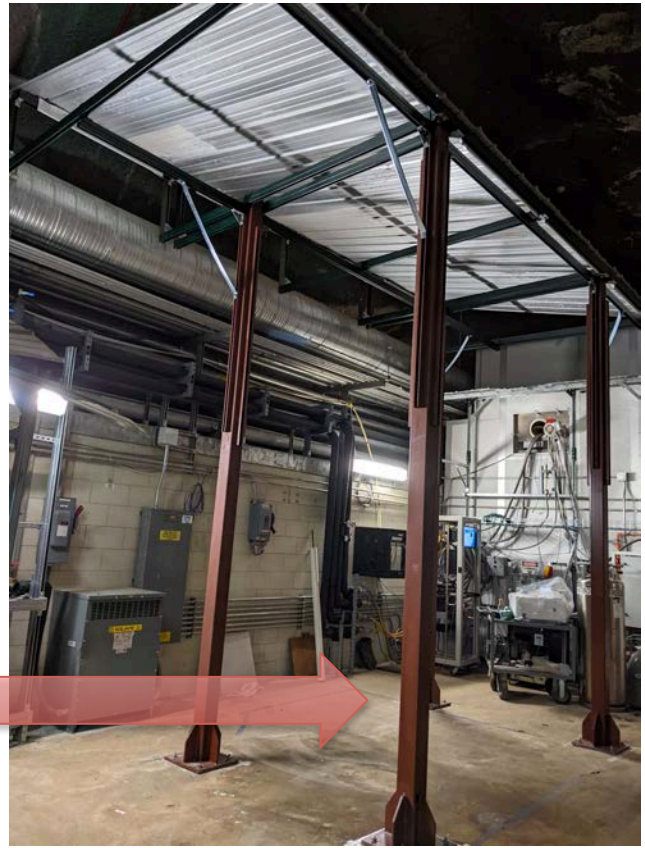
Dec 2022 – March 2023, @ SiDet (Fermilab)

- 100kg LAr condensed in pressure vessel ; no inner assembly
- Demonstrated:
  - Thermal performance: cooling power, base temperature, thermal gradient
  - Pressure control: 0.01 bara precision in single-phase (liquid) state
  - Slow Controls and automation – pressure cycling!



SBC-LAr10





Move Resumed! – May 15

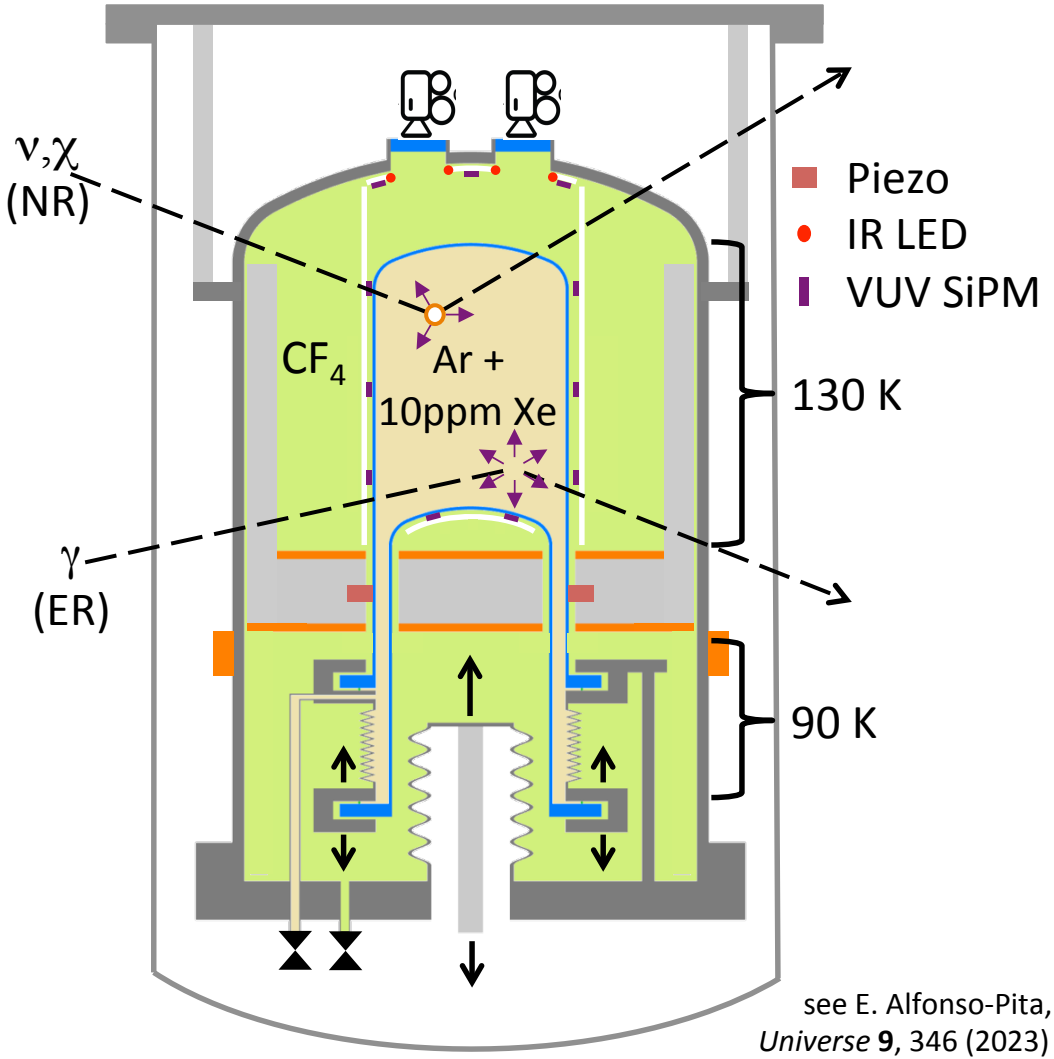
300 feet down


SBC-LAr10: June 4, 2024

Liquid Noble Bubble Chambers

Objectives for SBC-LAr10 in MINOS:

- **Demonstrate operation** of physics-scale liquid-noble bubble chamber
- **Determine maximum superheat** for ER-blind operation
- **Calibrate Threshold** for NR detection, @ 100 eV, with 10 eV resolution



see E. Alfonso-Pita, *Universe* **9**, 346 (2023)

Calibration Strategies
(for the ER-blind)

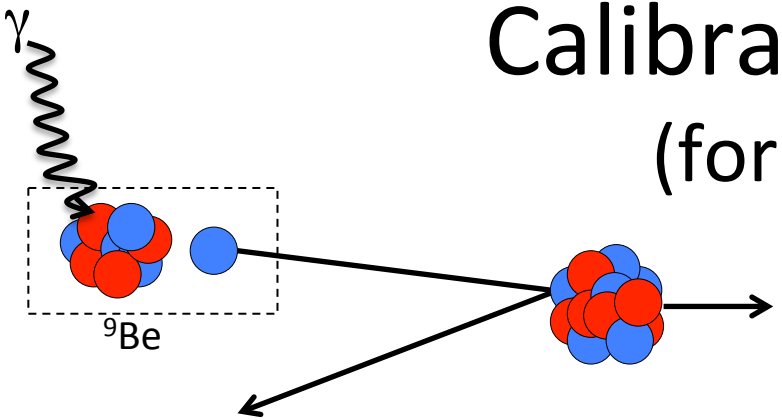
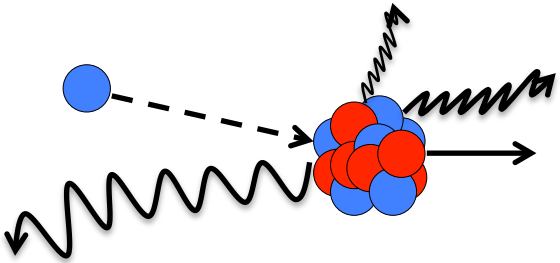
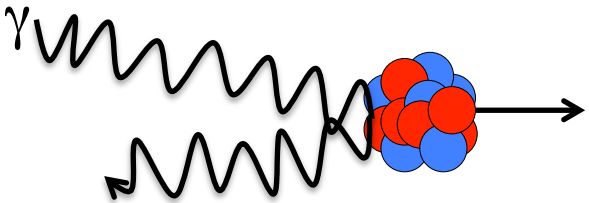


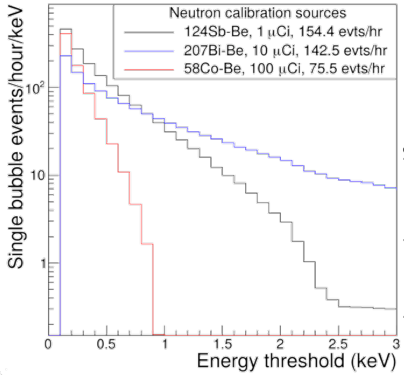
Photo-neutron Sources
(> 500 eV recoils)



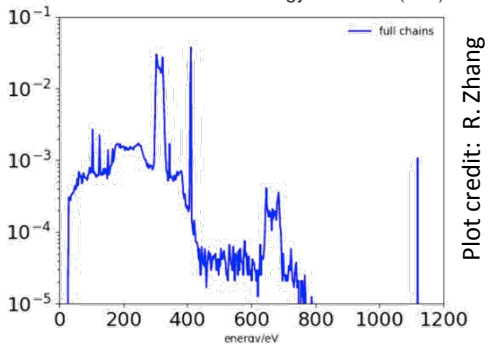
Thermal neutron Capture
(200 – 500 eV recoils)



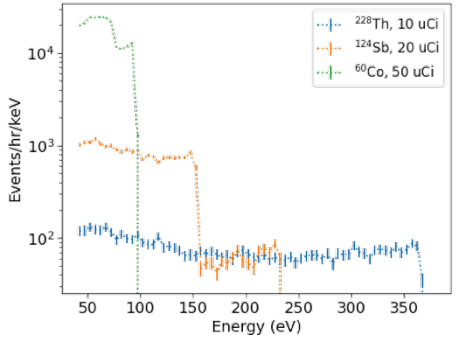
Photon-nucleus Scattering
(< 300 eV recoils)



Plot credit: E. Alfonso



Plot credit: R. Zhang



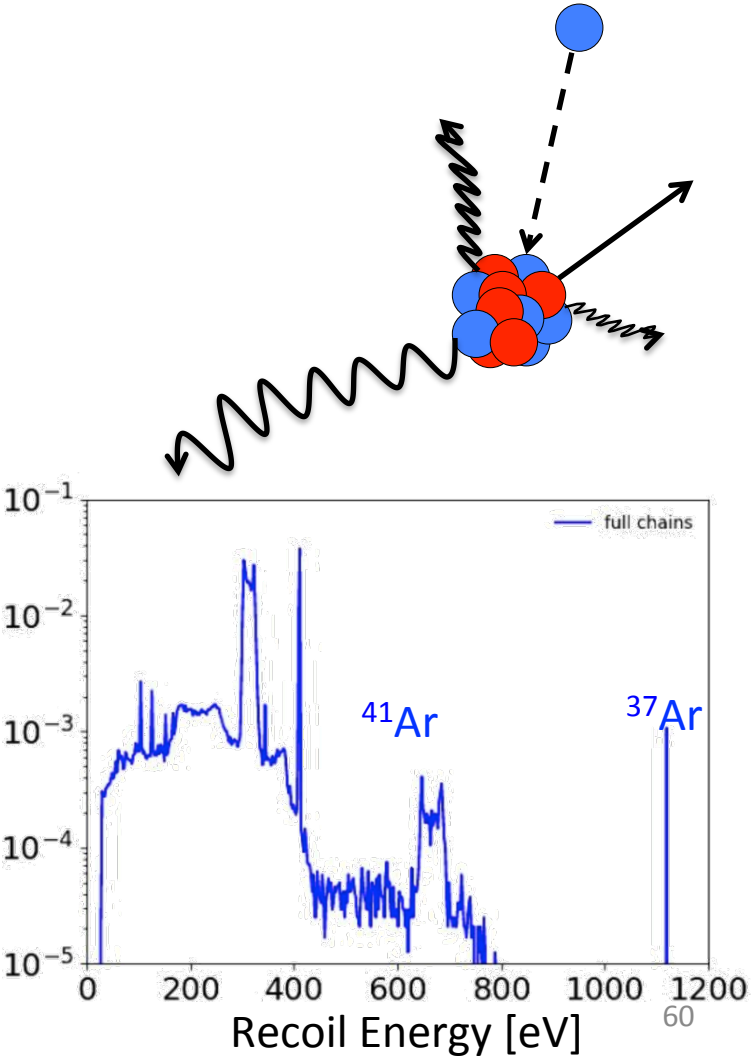
Plot credit: N. Lamb

Calibration Strategies

Thermal neutron capture

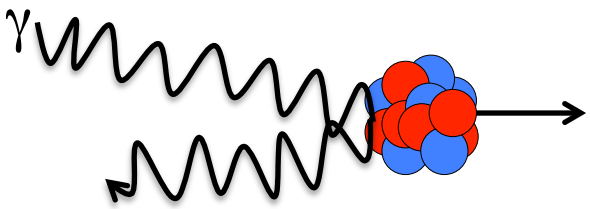
$^{40}Ar(n,\gamma) \rightarrow {}^{41}Ar$

- 6 MeV gamma cascade
  - Visible in SBC-LAr10 via ***scintillation***
  - Also useful for DUNE!
- ^{41}Ar nuclear recoil (~300 eV)
  - Visible in SBC-LAr10 via ***bubble nucleation***

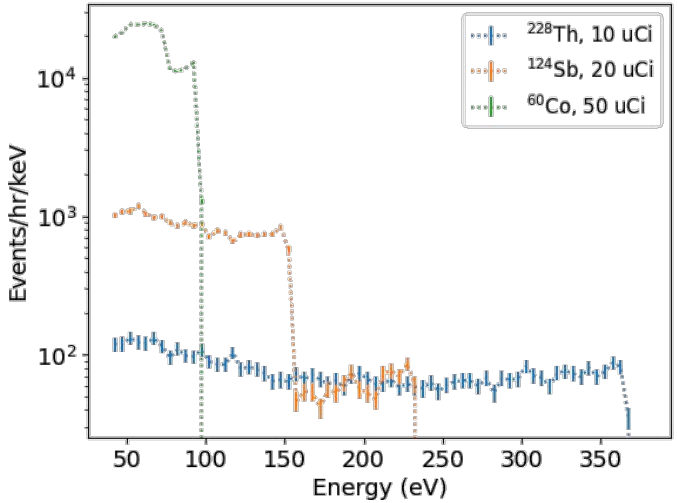


Plot credit: R. Zhang

Calibration Strategies

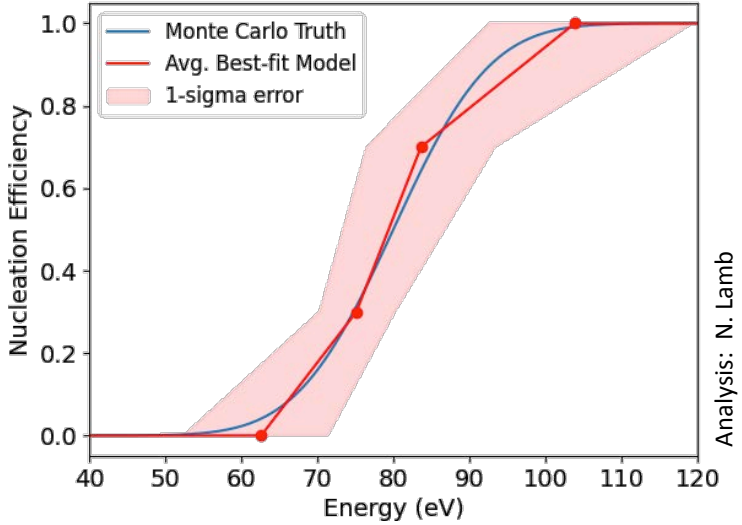


Photon-nucleus Scattering



Mock analysis based on simulated bubble rates with a suite of three gamma sources

(assumes no nucleation by ER's)

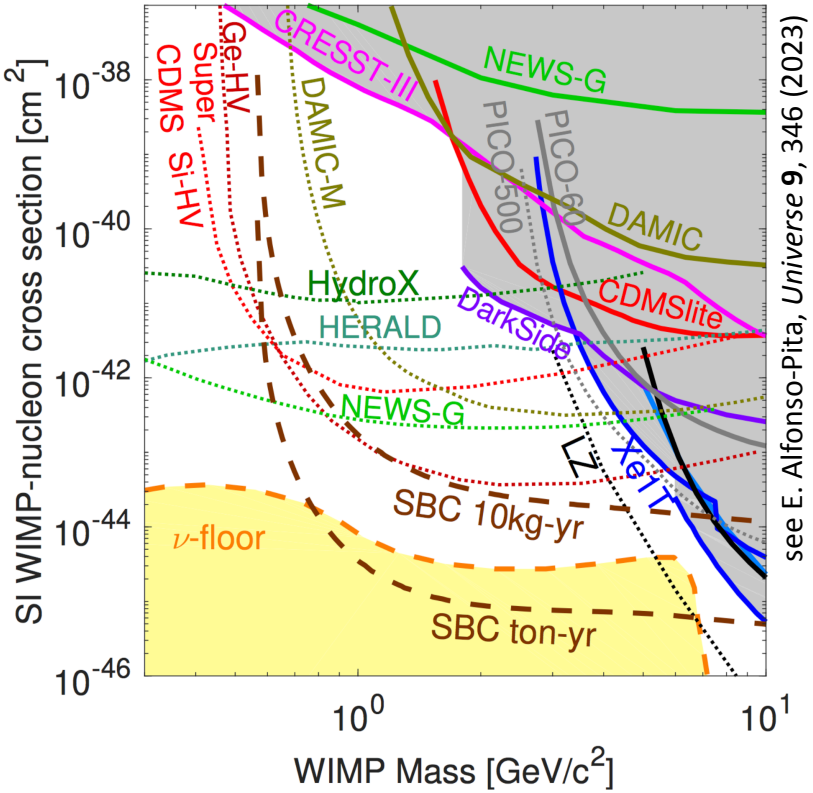


SBC Strategy: Build two detectors

@Fermilab (2018 – 2026)

- What superheat can be achieved in LAr while keeping ER discrimination?
- What is the *calibrated* NR threshold at that superheat?

@SNOLAB (2019 – 2028)

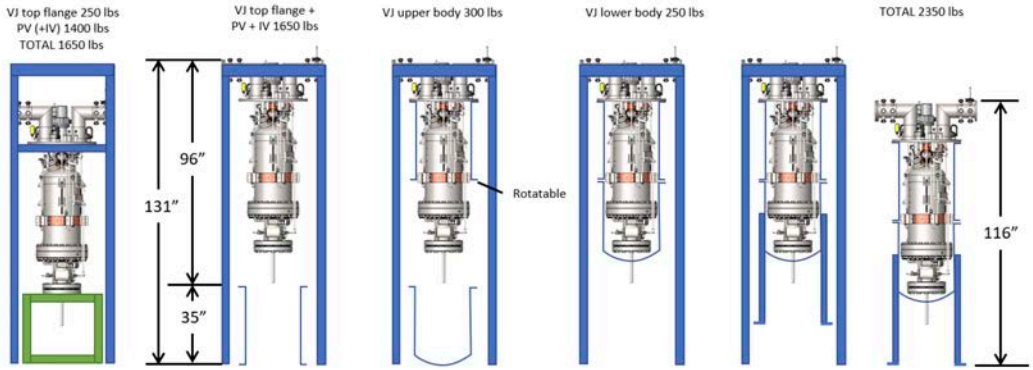


On to Dark Matter

SBC-LAr10: SNOLAB

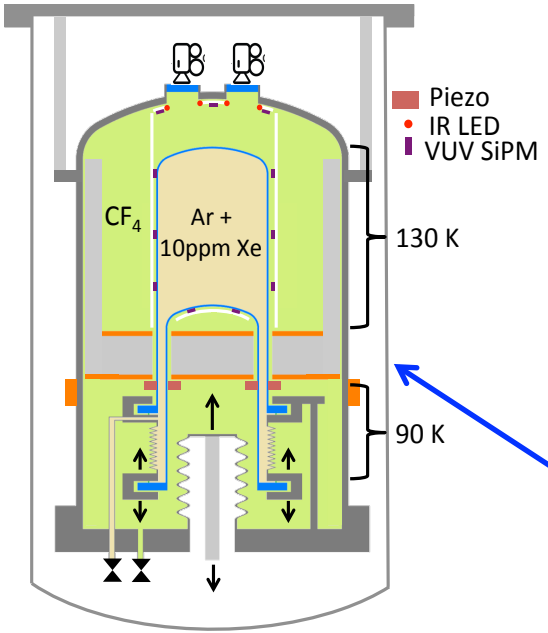
CFI-supported, radiopure clone of SBC-LAr10

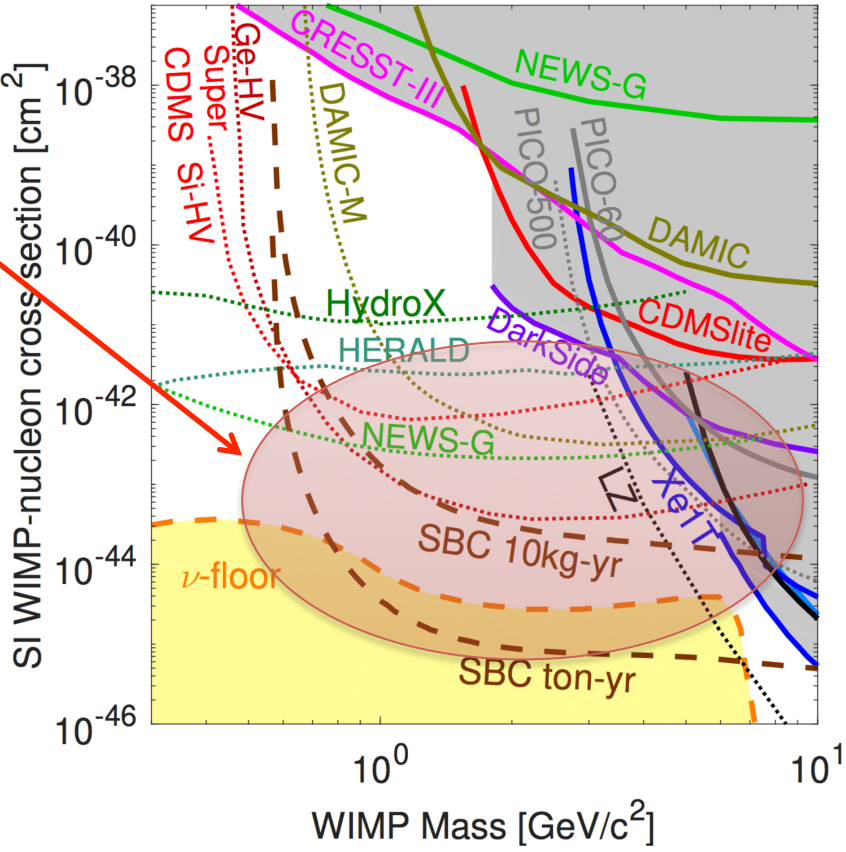
- PV Fabrication underway
  - With lessons learned from FNAL engineering run
- SNOLAB TDR planned for Fall 2024
  - Rapid progress towards critical TSSA approvals



Summary

Dark matter might live here
and if it does…





…this will be the tool to find it.