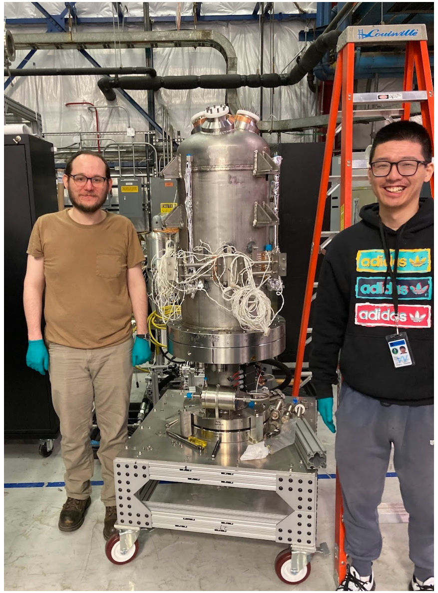
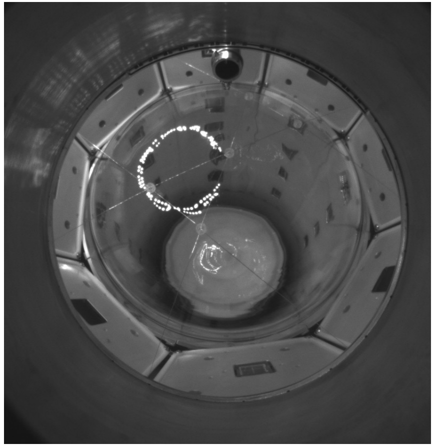
Liquid Noble (Scintillating) Bubble Chambers

Hugh Lippincott
UCSB

ICHEP 2024





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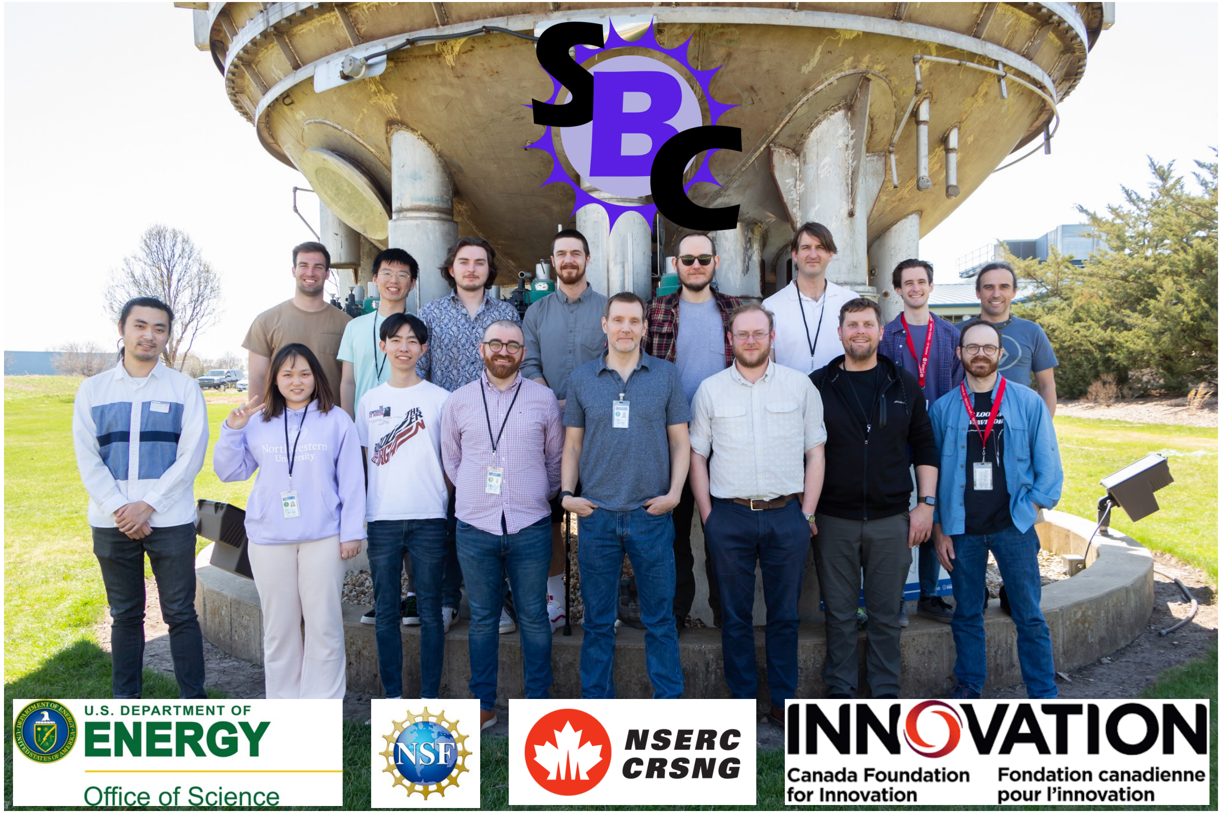

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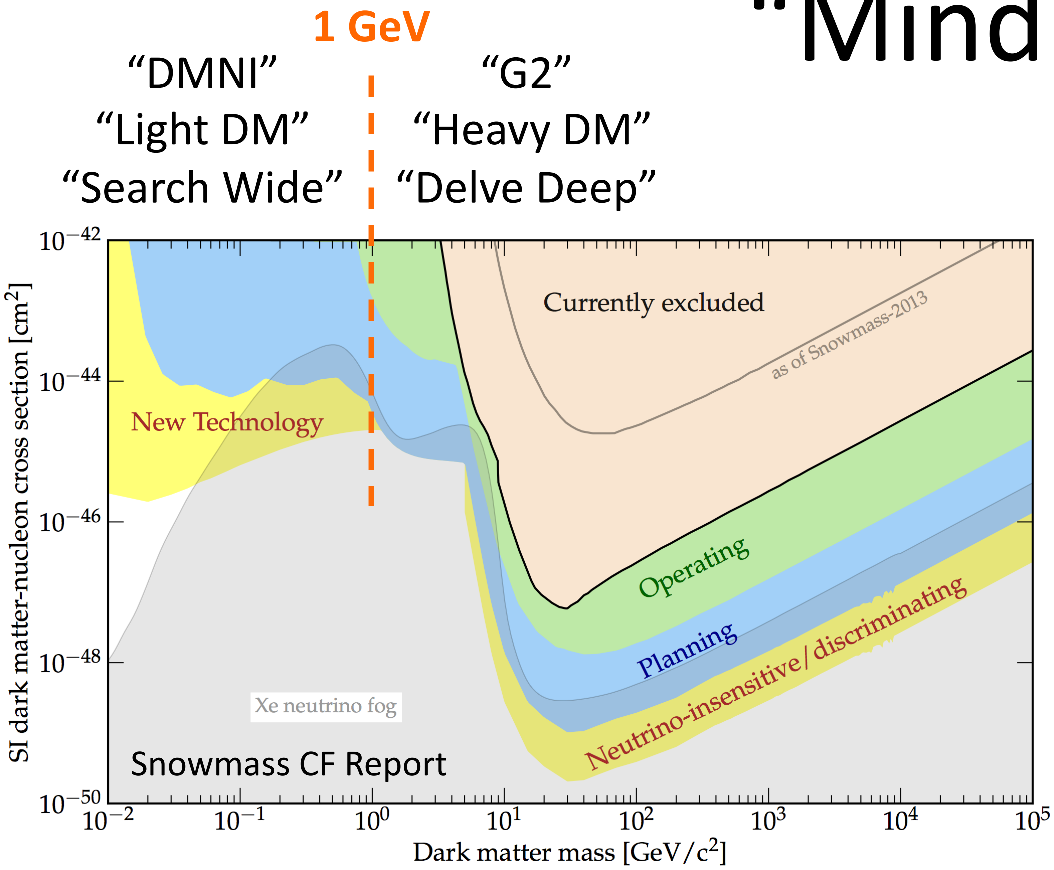
“Mind the gap”


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}
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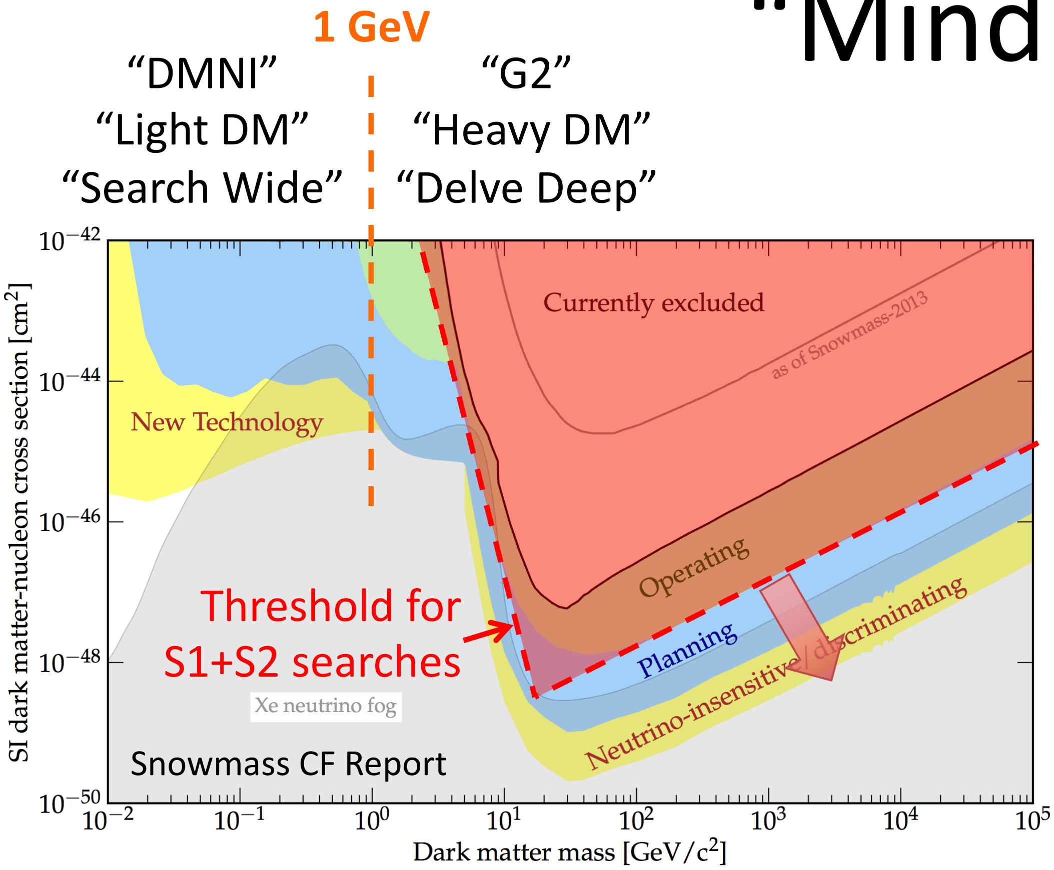
“Mind the gap”



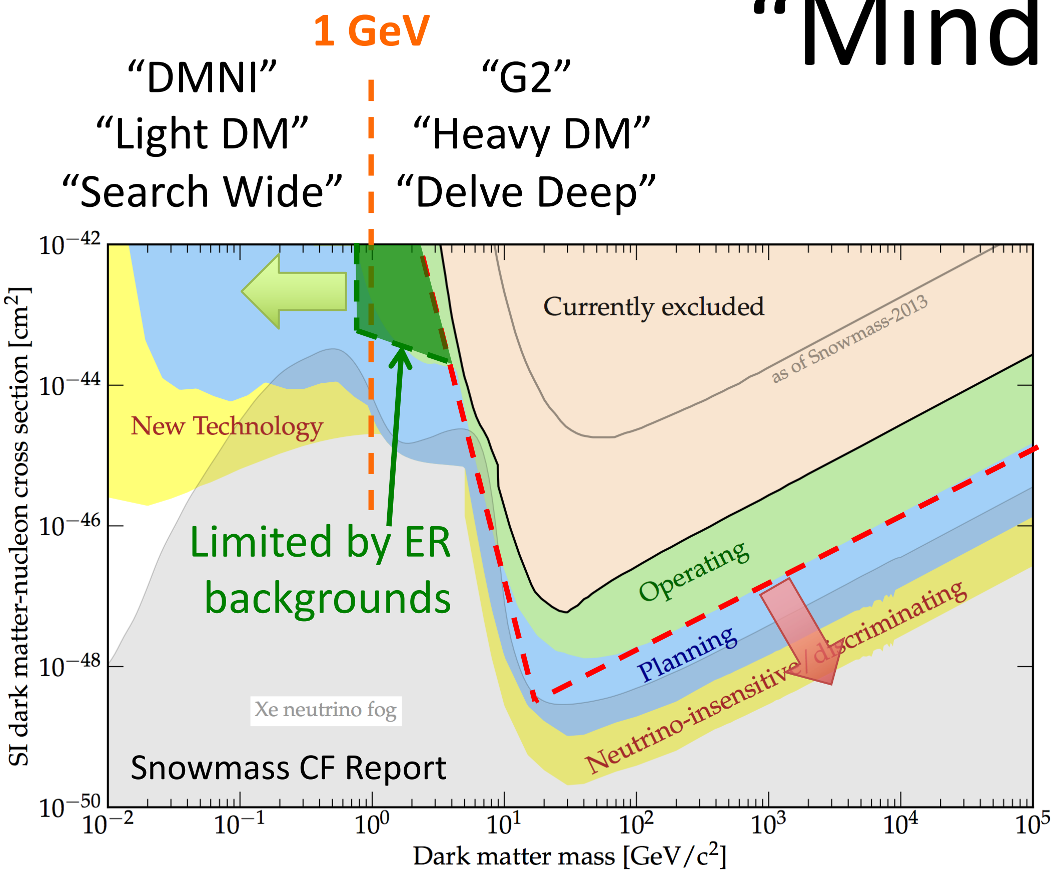
Quasi-background-free Nuclear Recoil (NR) searches in multi-ton targets

- Detector features:
  - Scalability
  - Background discrimination

"Mind the gap"

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

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



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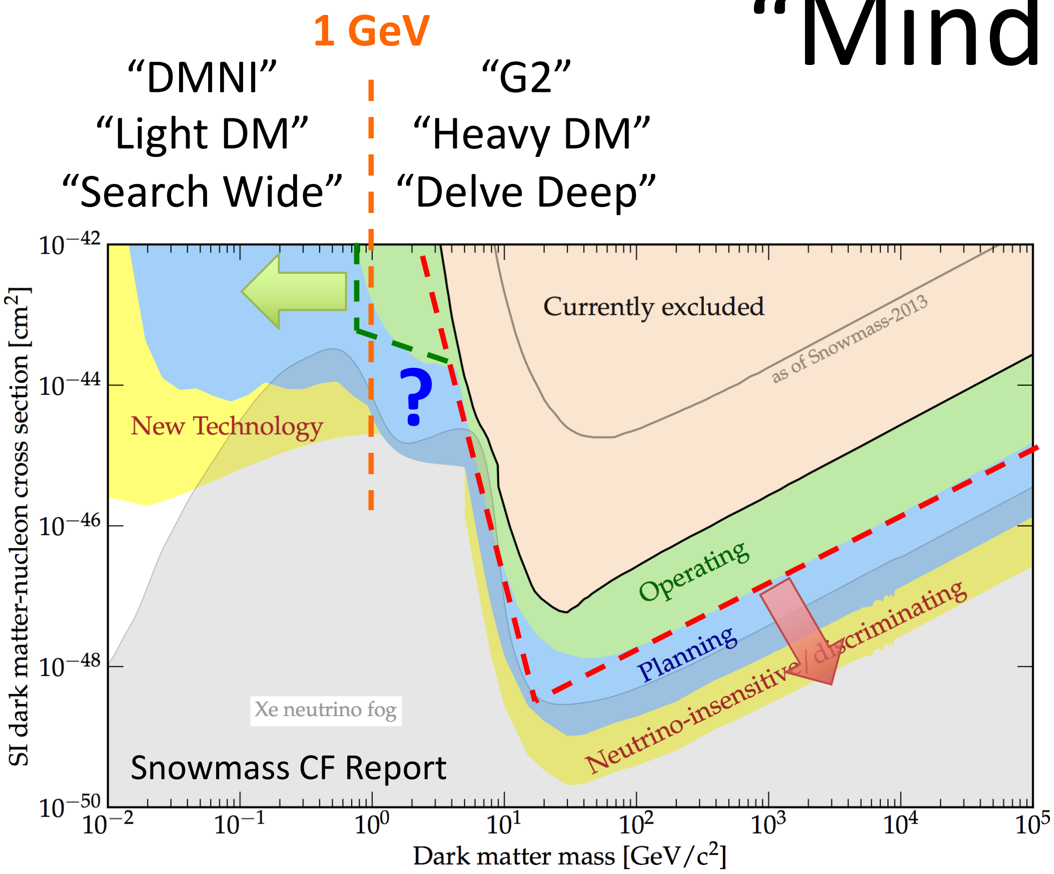


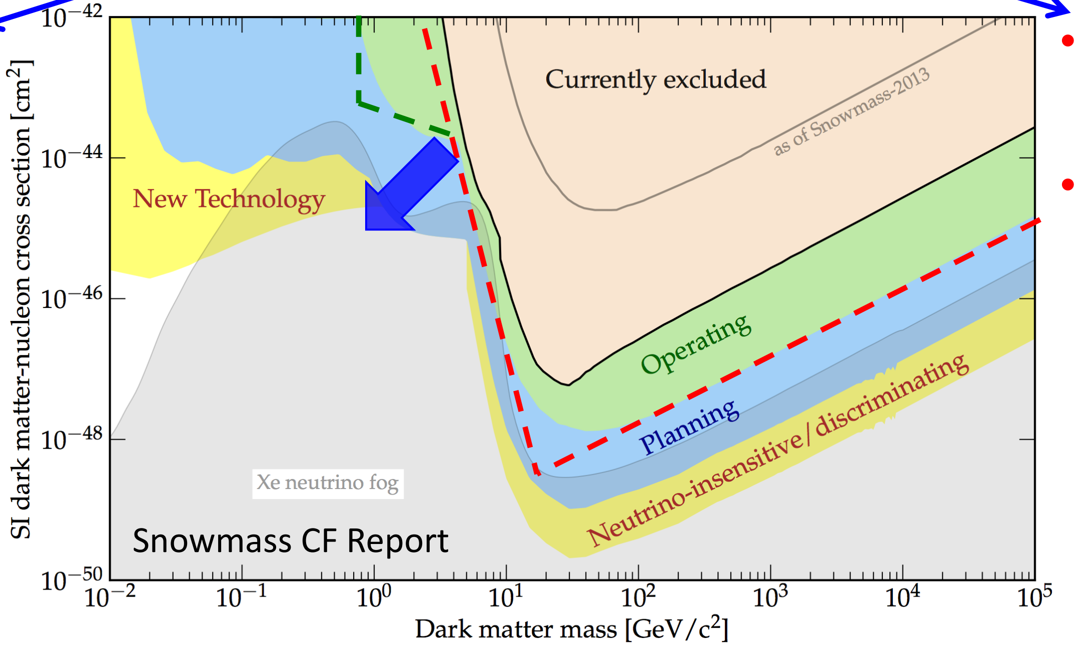
Quasi-background-free Nuclear-Recoil (NR) searches in multi-ton targets

- 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:

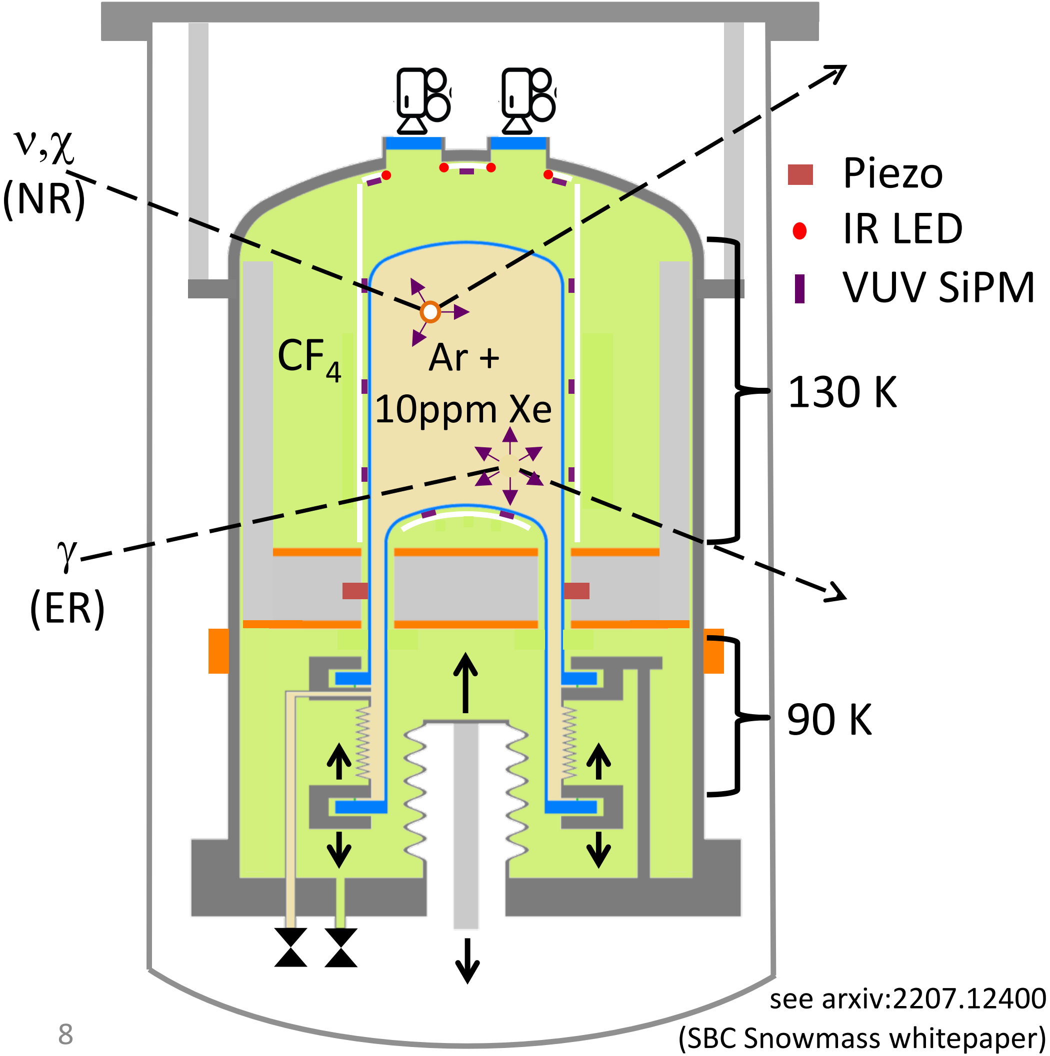
ER's (beta, gamma):

No bubbles

NR's (fast neutron):

Multiple bubbles

Strong coincident scintillation



see arxiv:2207.12400
(SBC Snowmass whitepaper)

Liquid N
Bubble C

Objective:

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of sub-keV Nuclear

Signal:

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coincident scintillat

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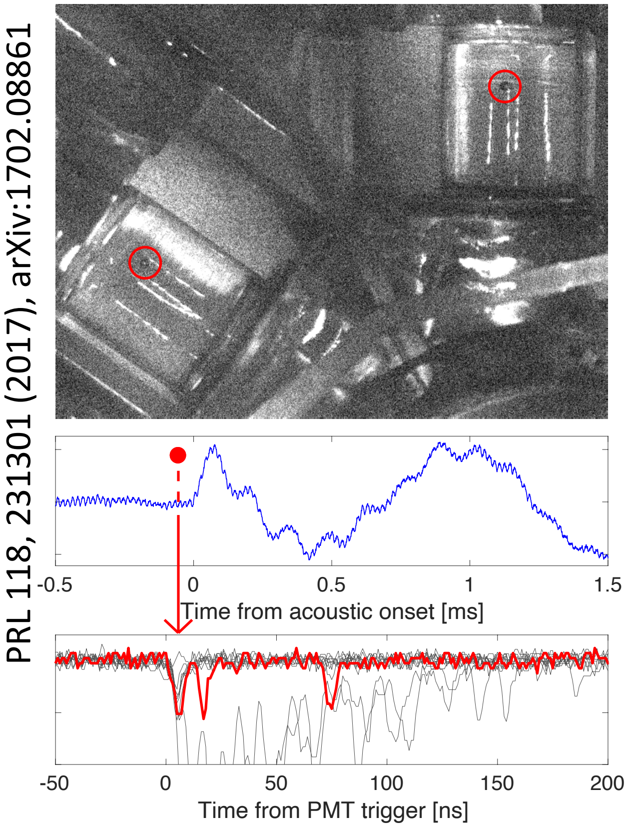
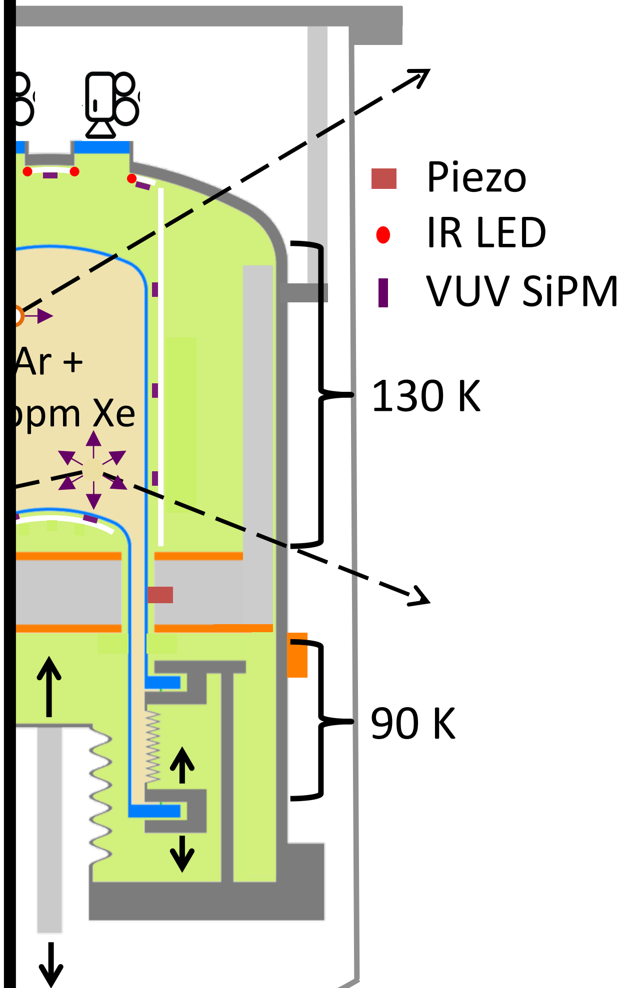
ER's (beta, gamma)
No bubbles

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

2017

30-gram xenon prototype





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(SBC Snowmass whitepaper)

Liquid Noble Bubble Chambers

Objective:

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

Signal:

Single bubble with little or no coincident scintillation

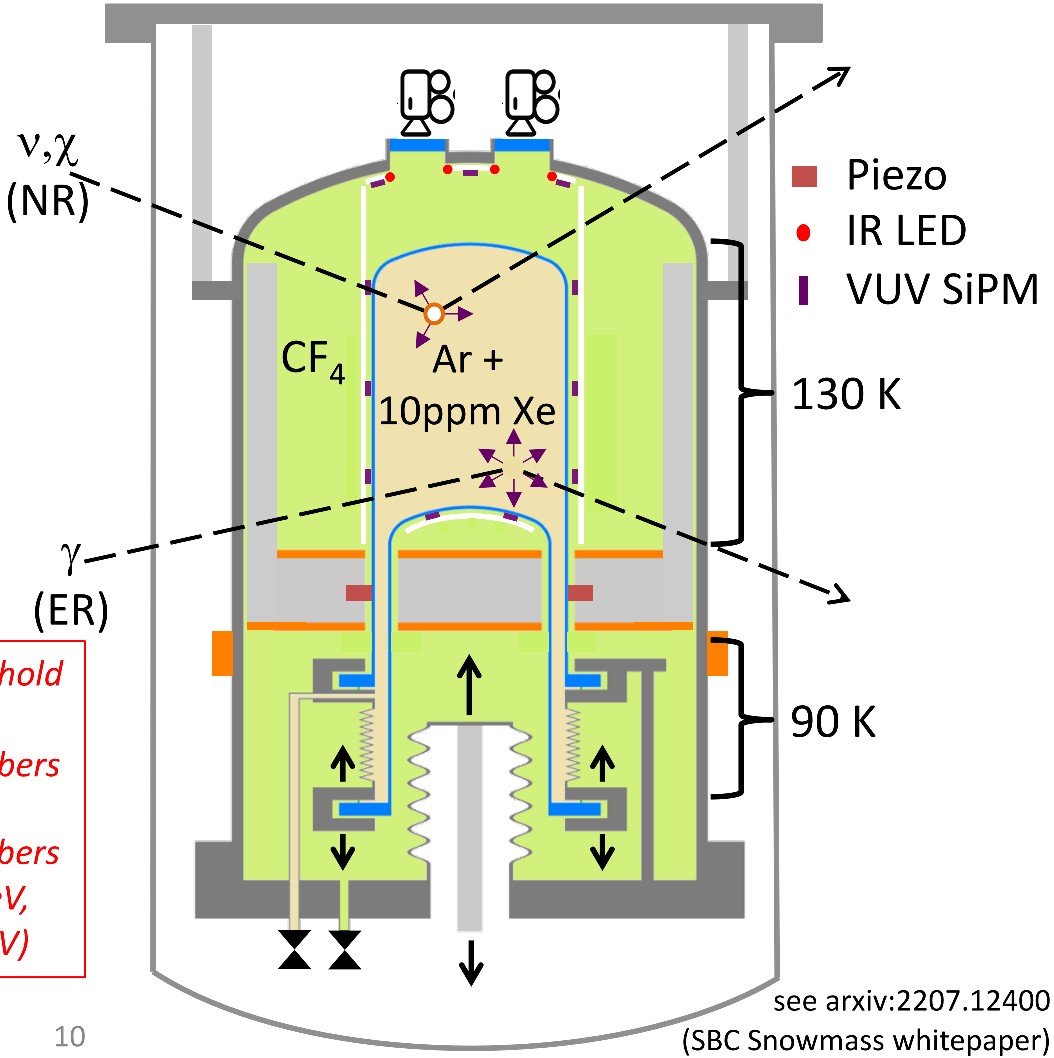
Backgrounds:

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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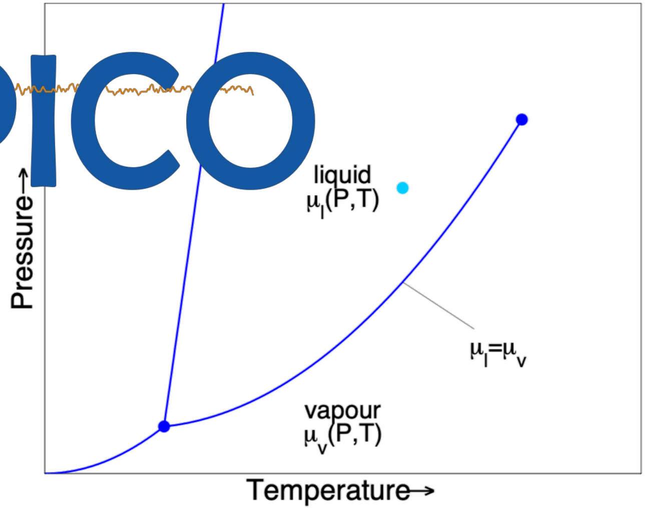
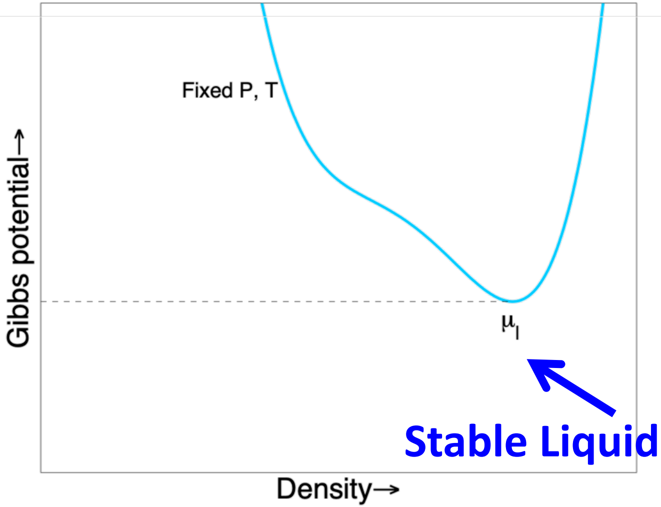
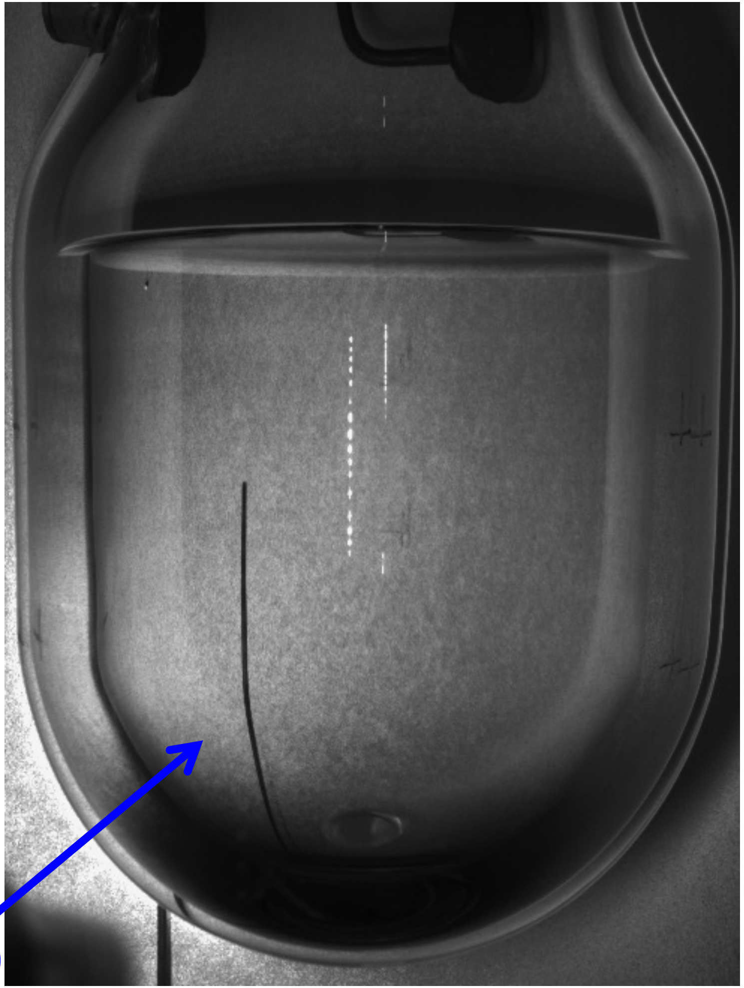
Bubble Chamber

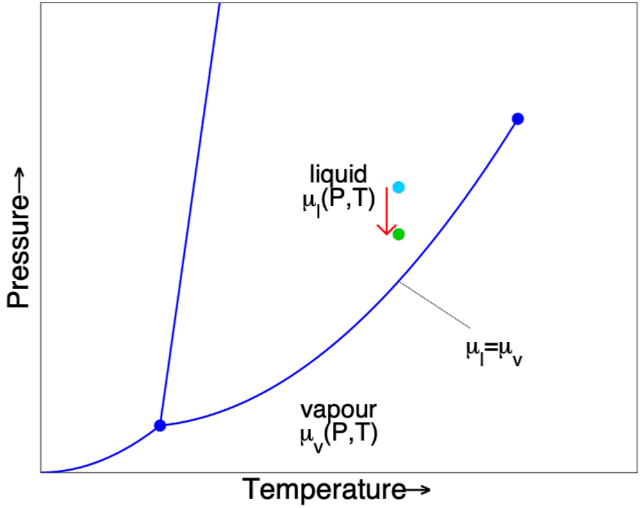


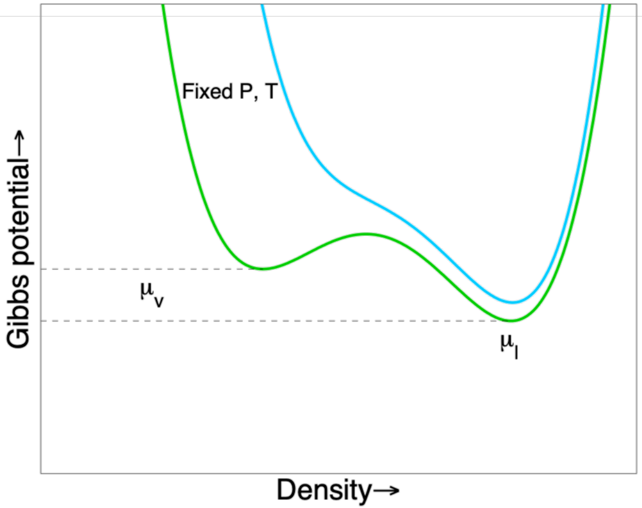


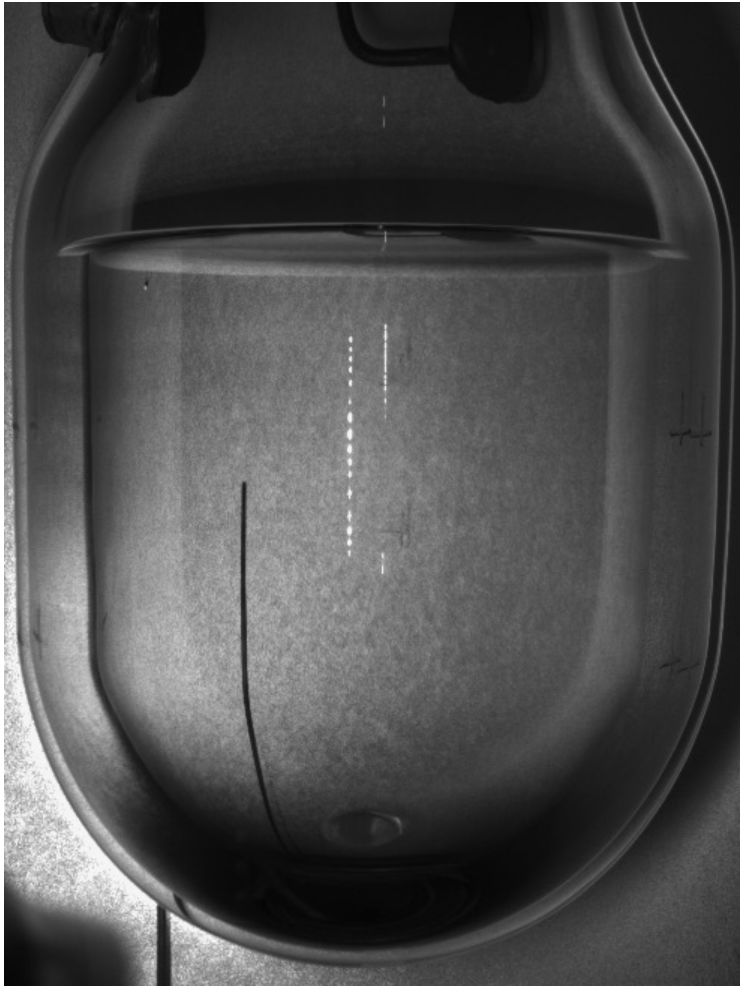


Stable Liquid (C_3F_8)

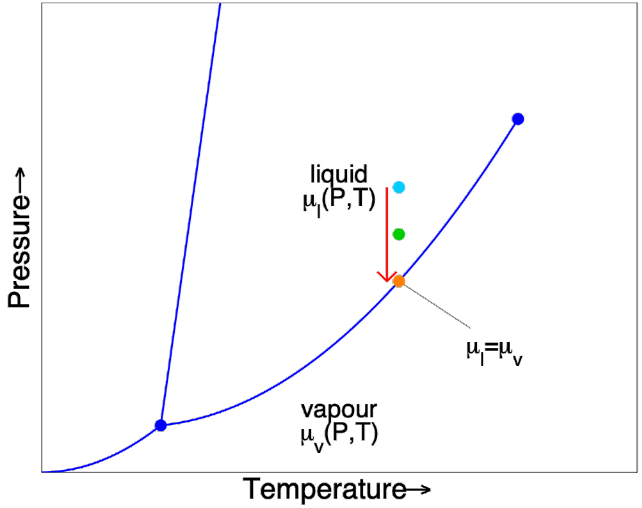
Bubble Chamber

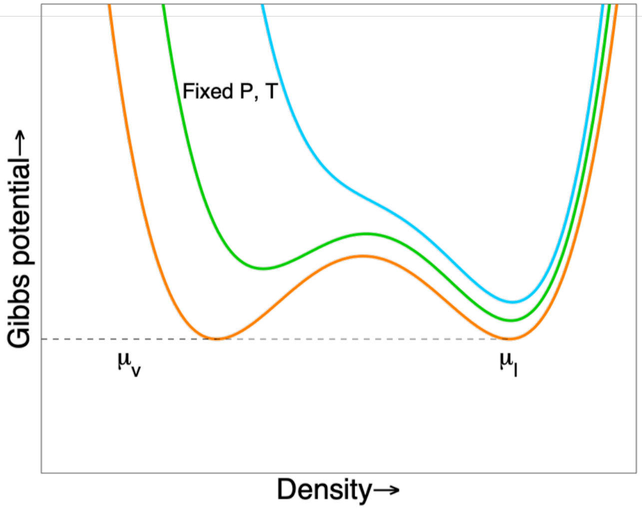


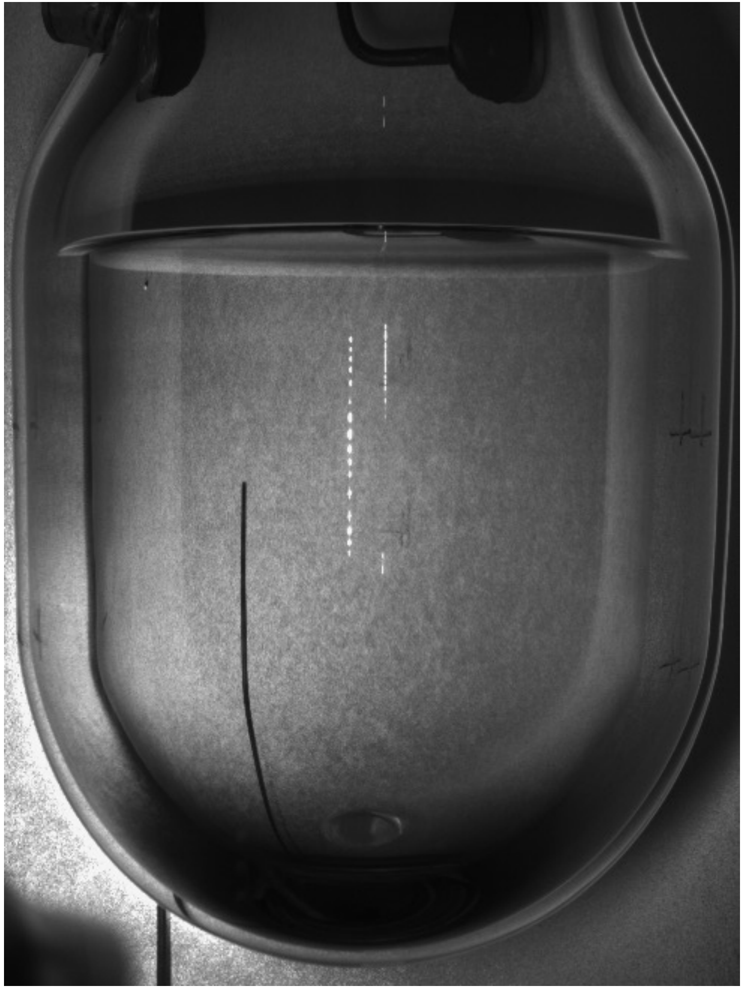




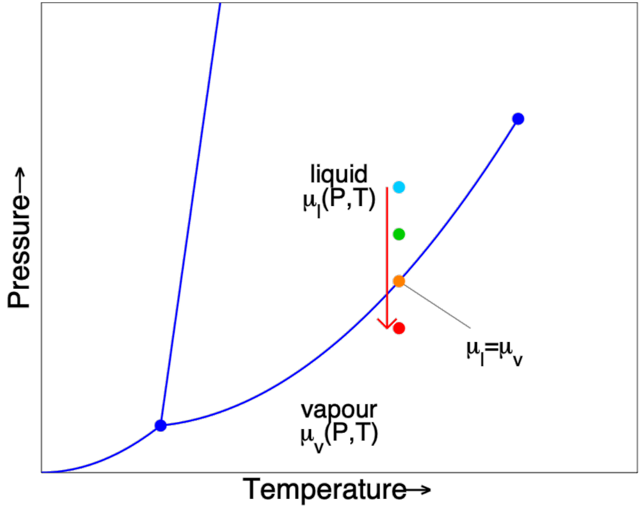
Bubble Chamber

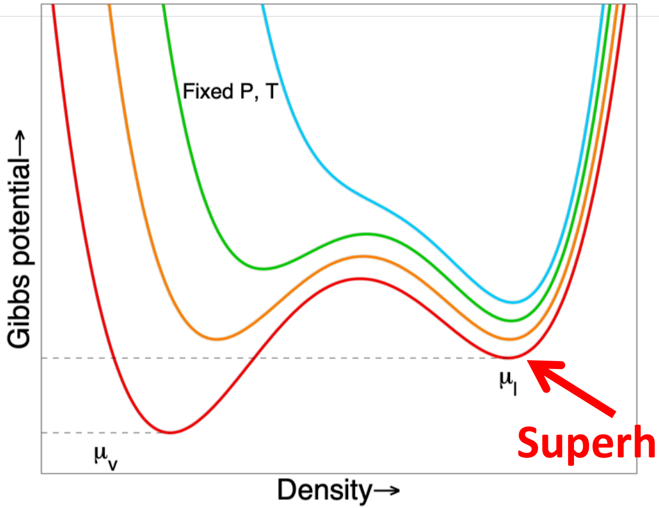


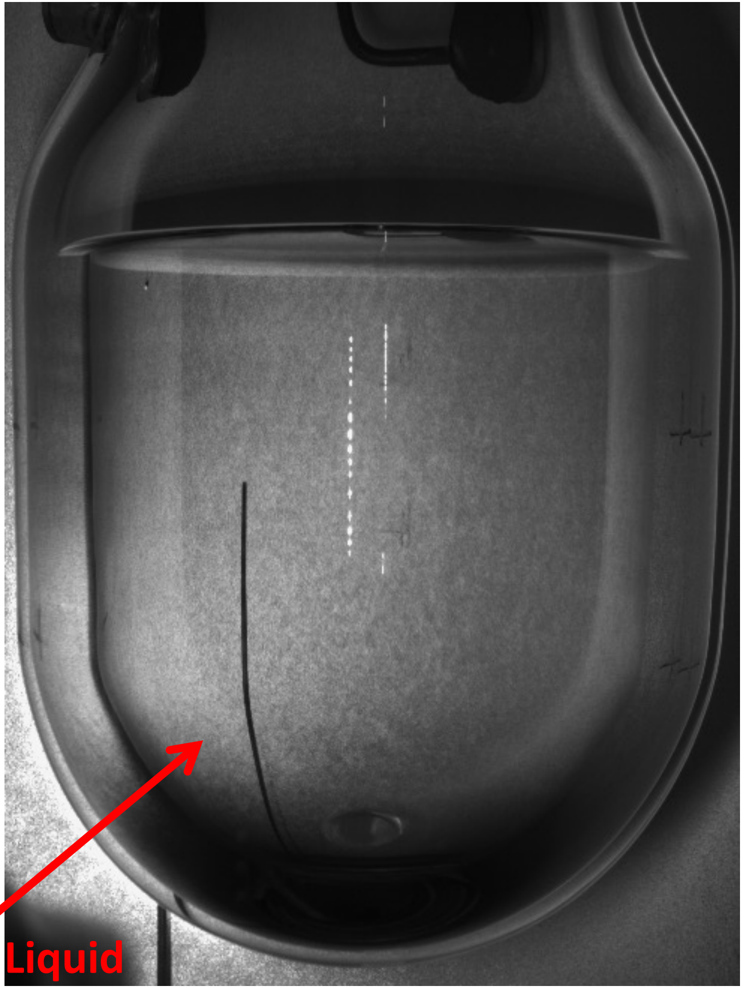




Bubble Chamber

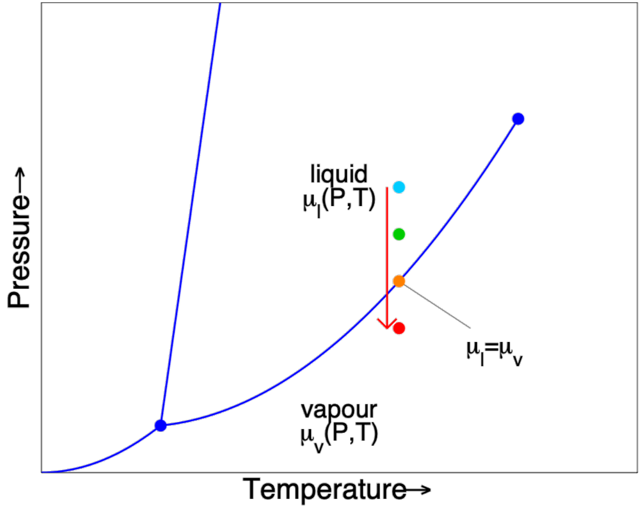


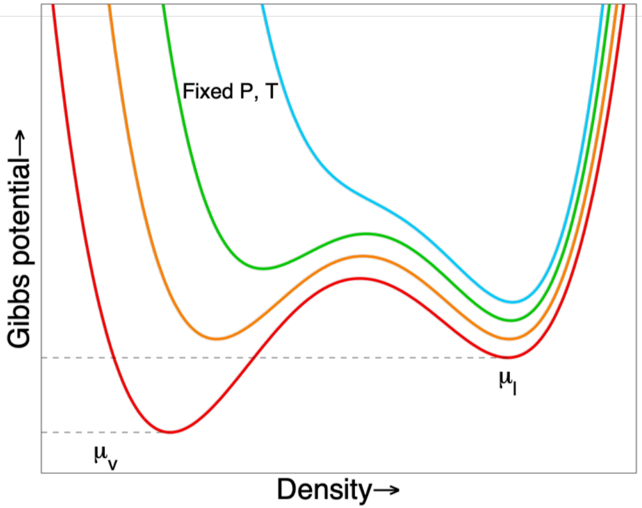


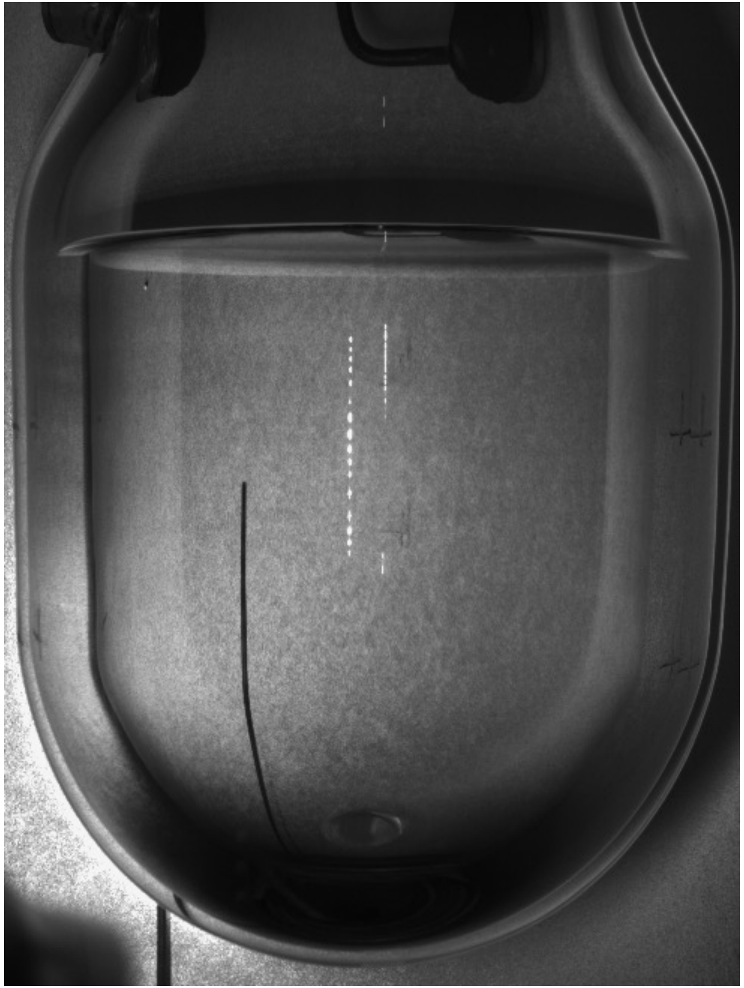


Superheated Liquid

Bubble Chamber







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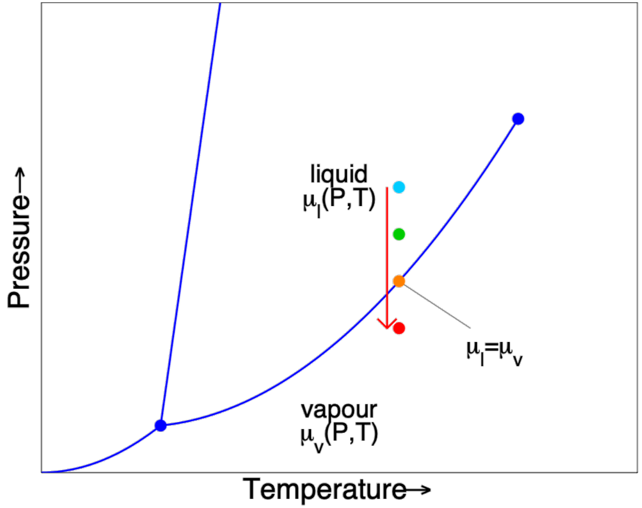

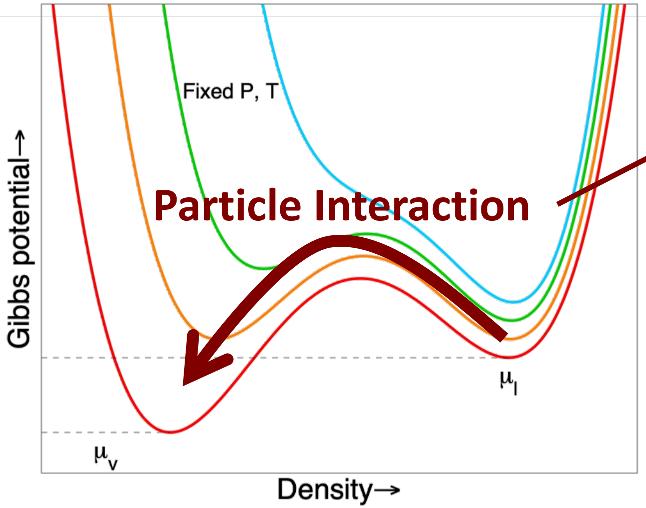

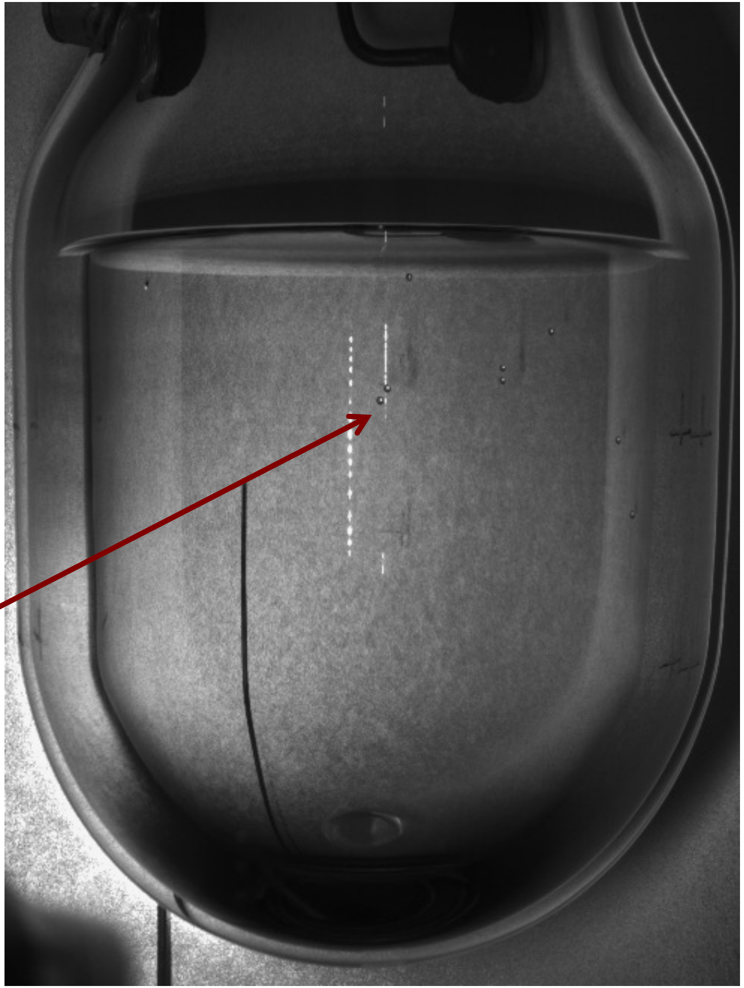

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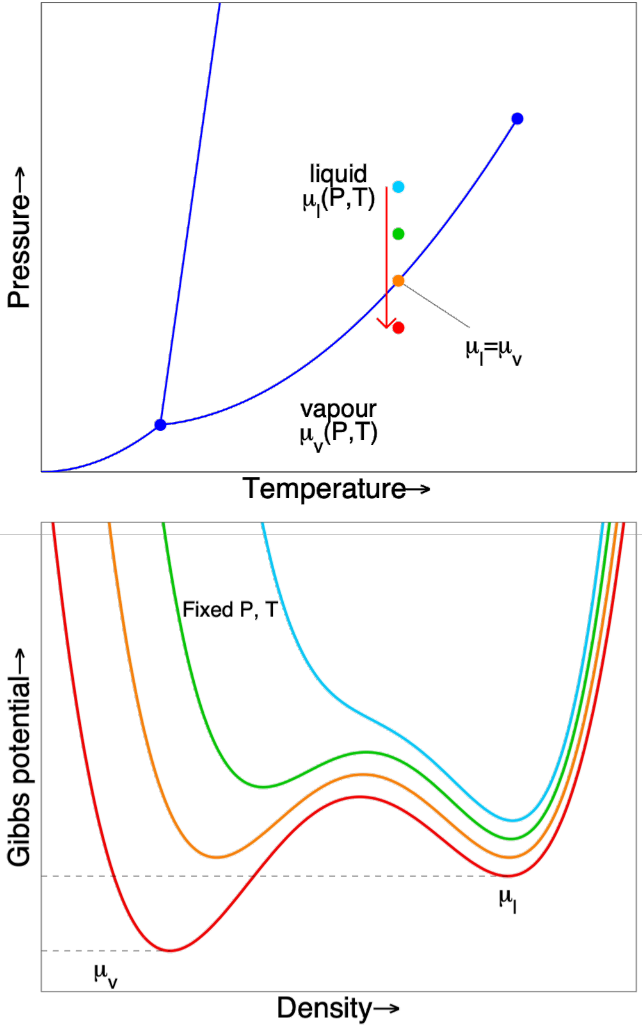

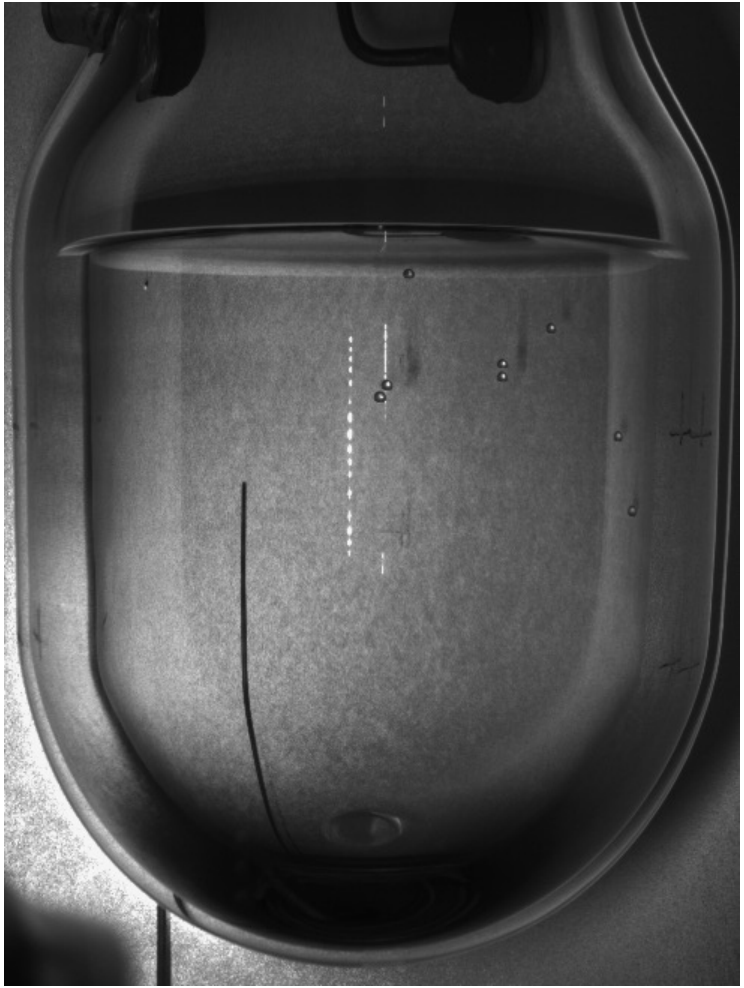

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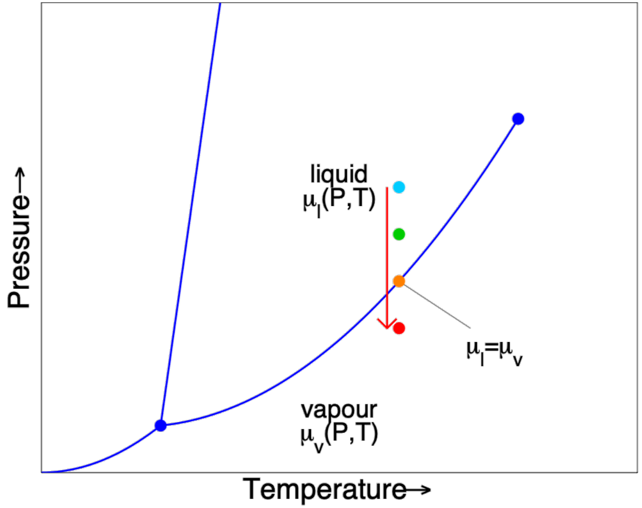

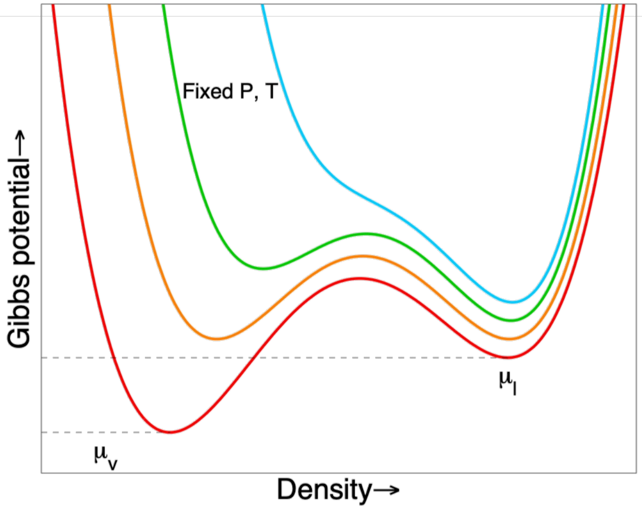

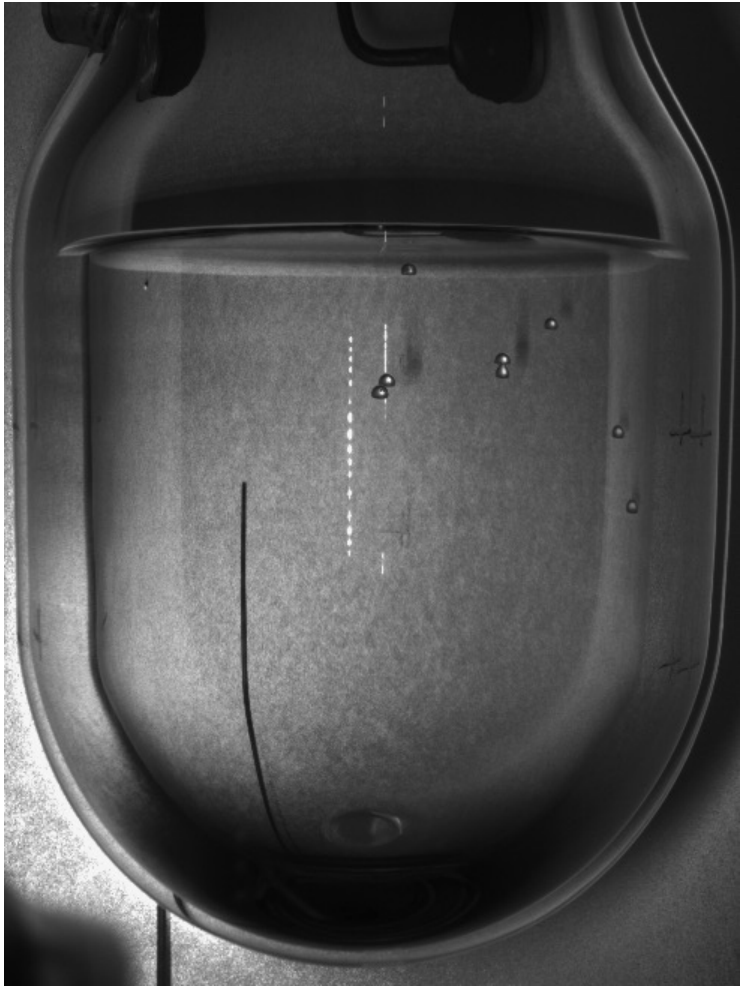

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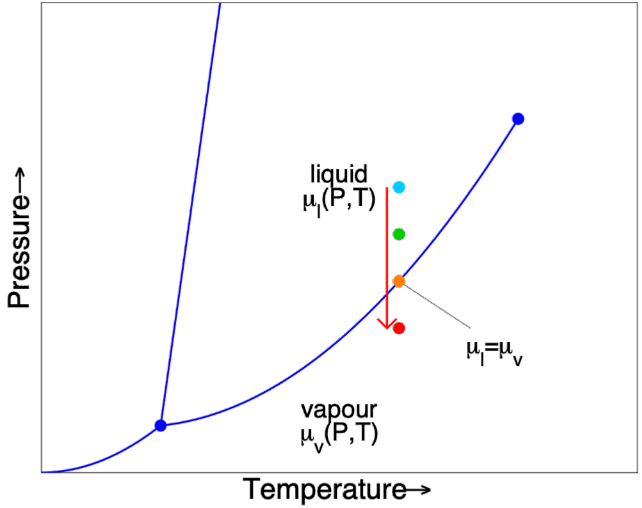

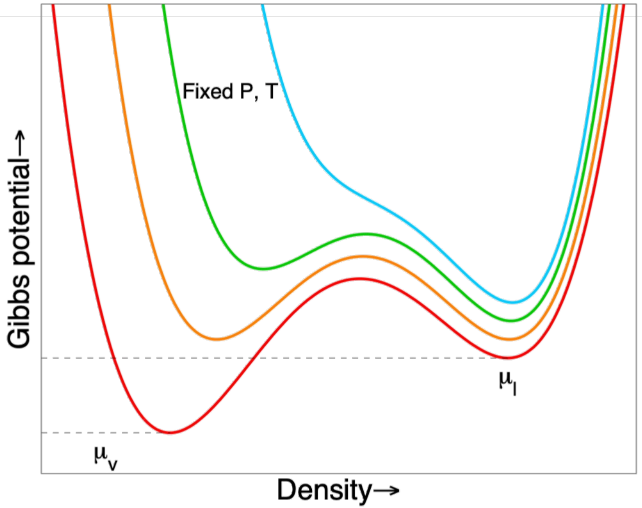

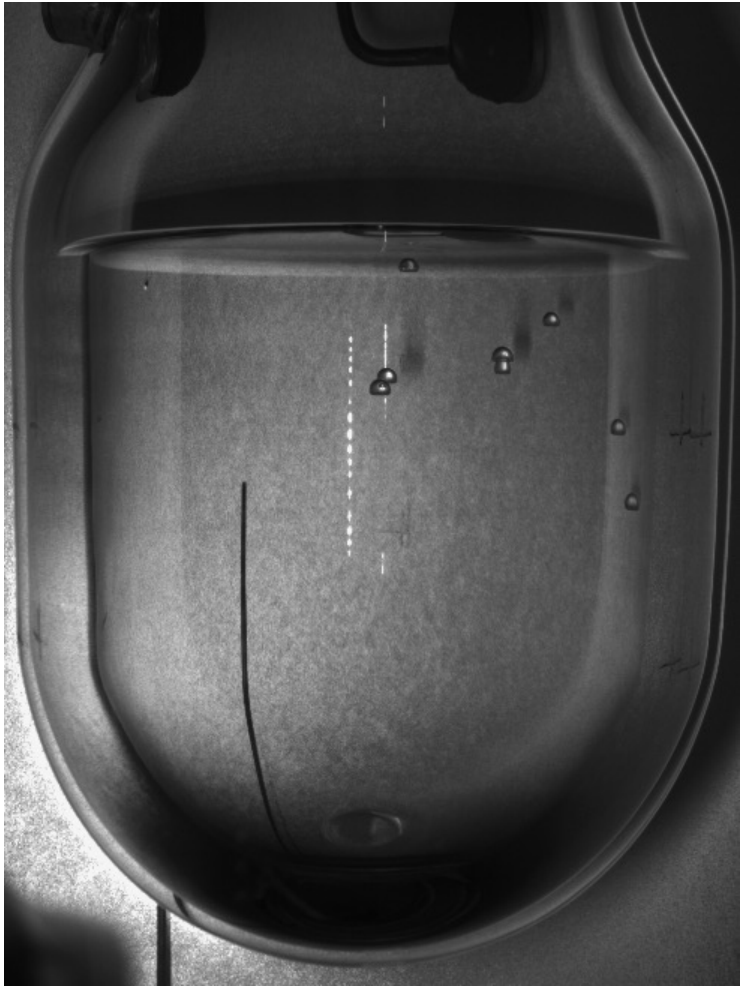

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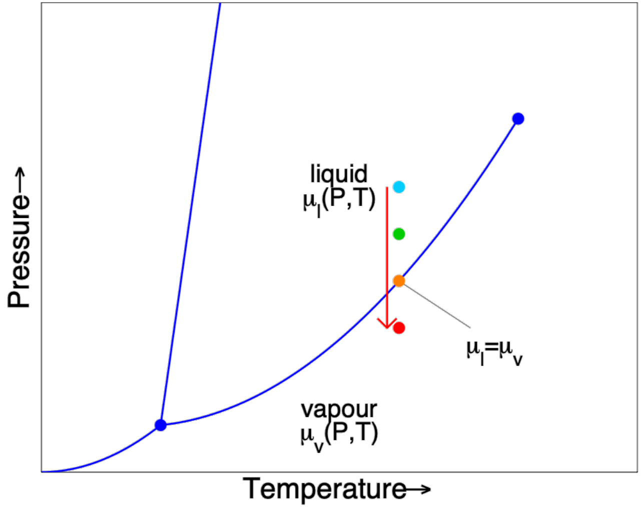

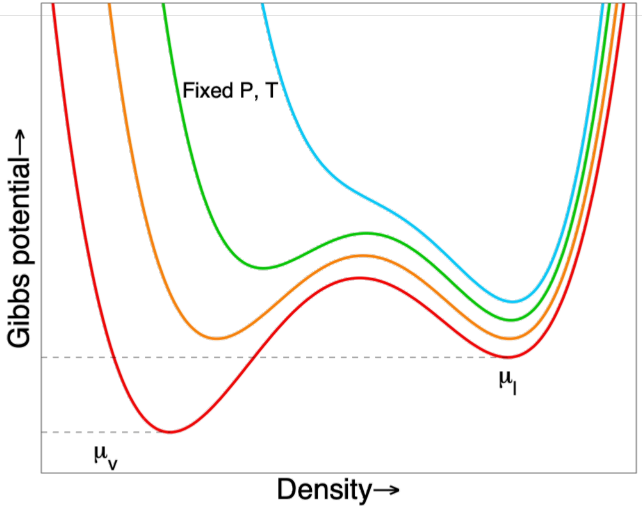

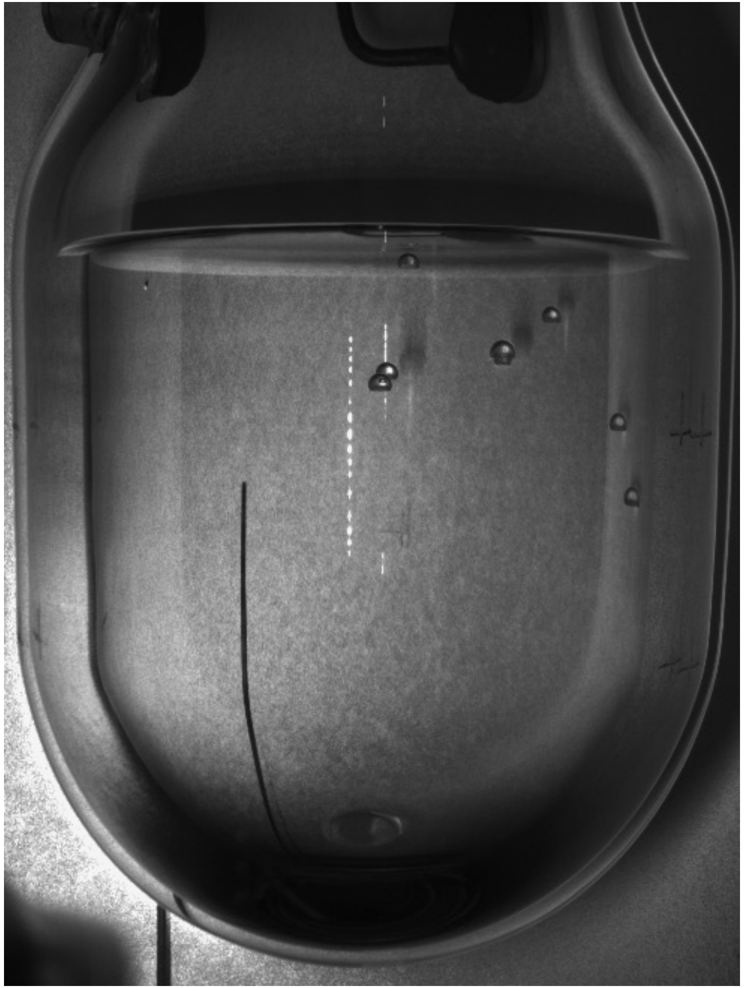

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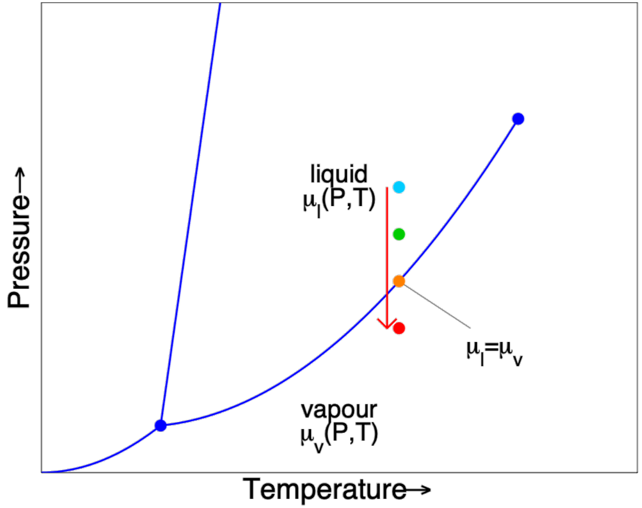

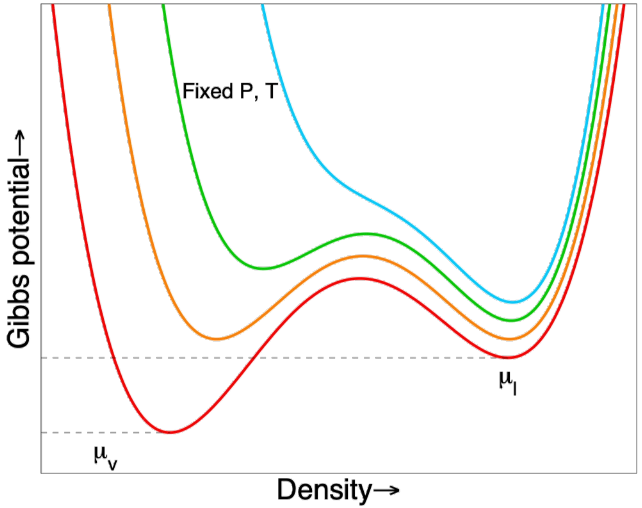

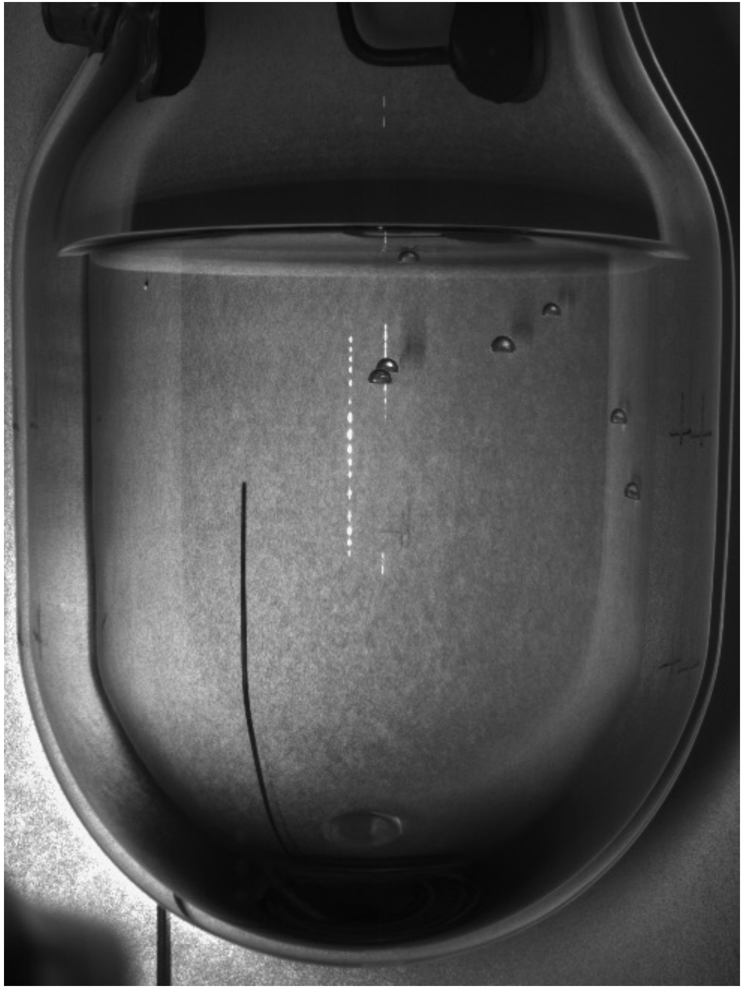

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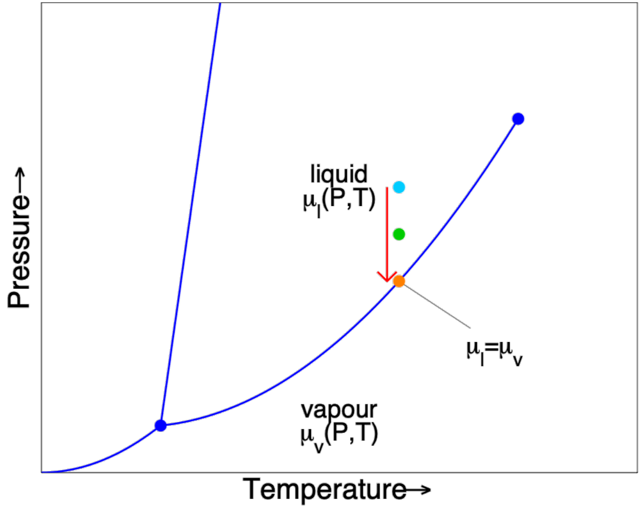

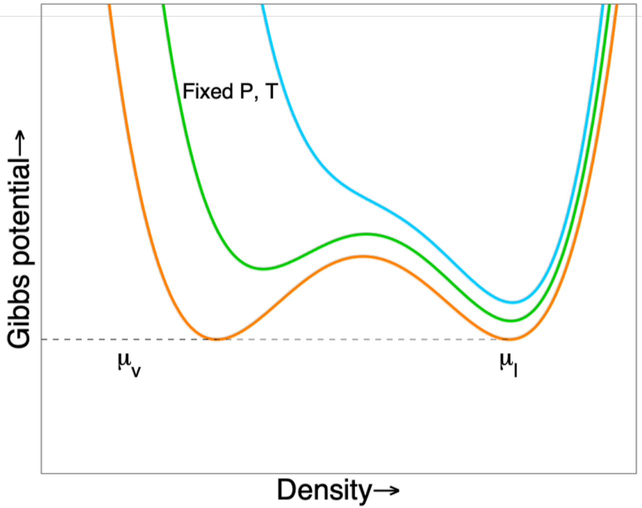

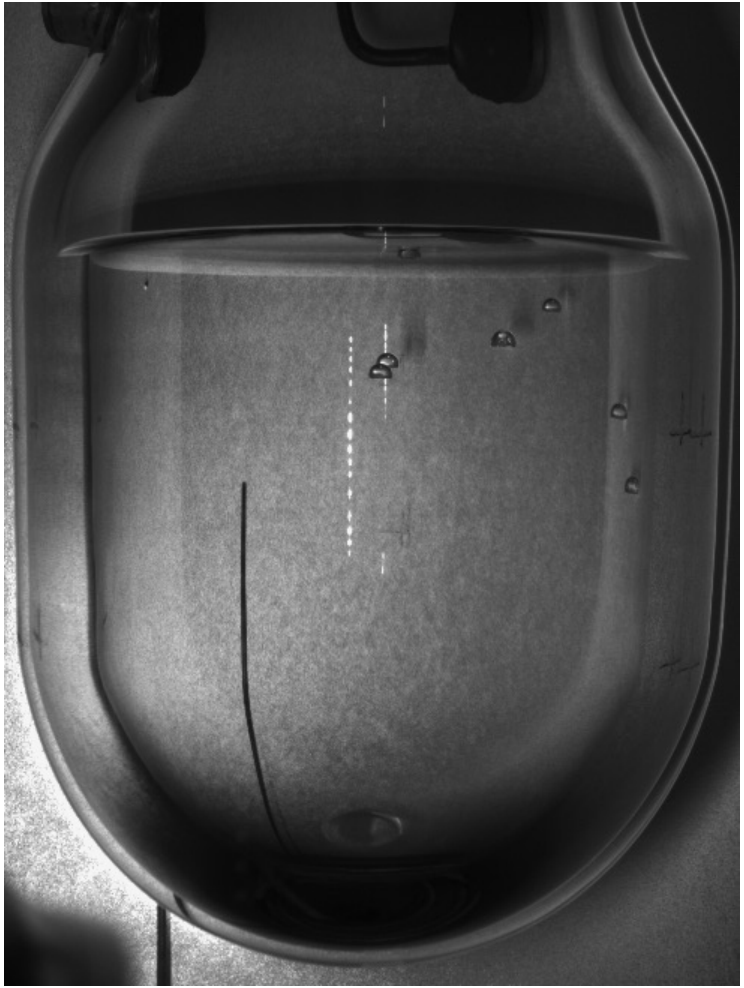

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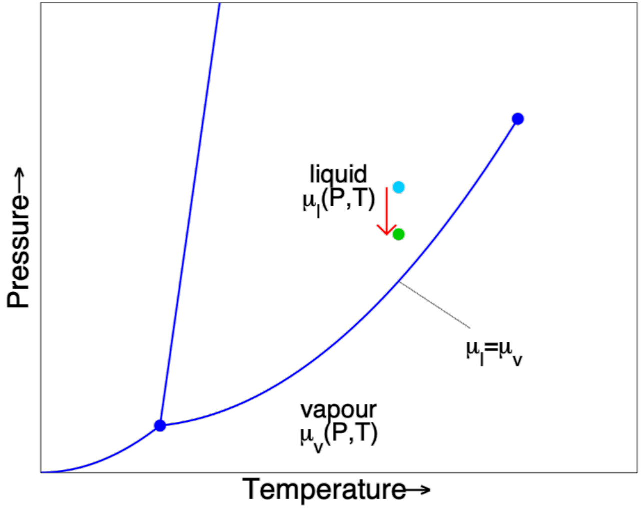

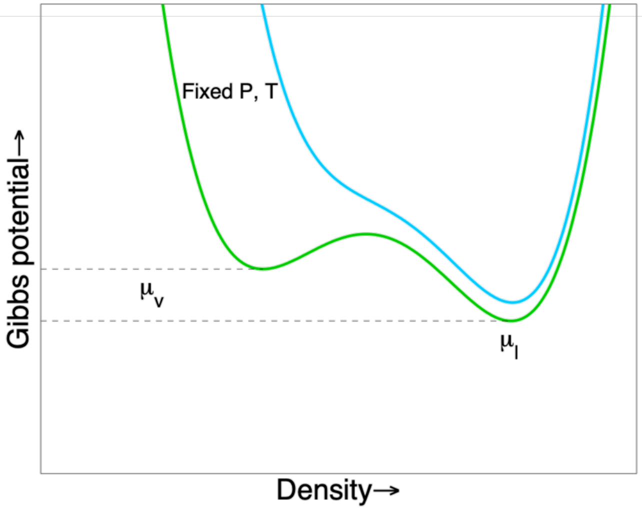

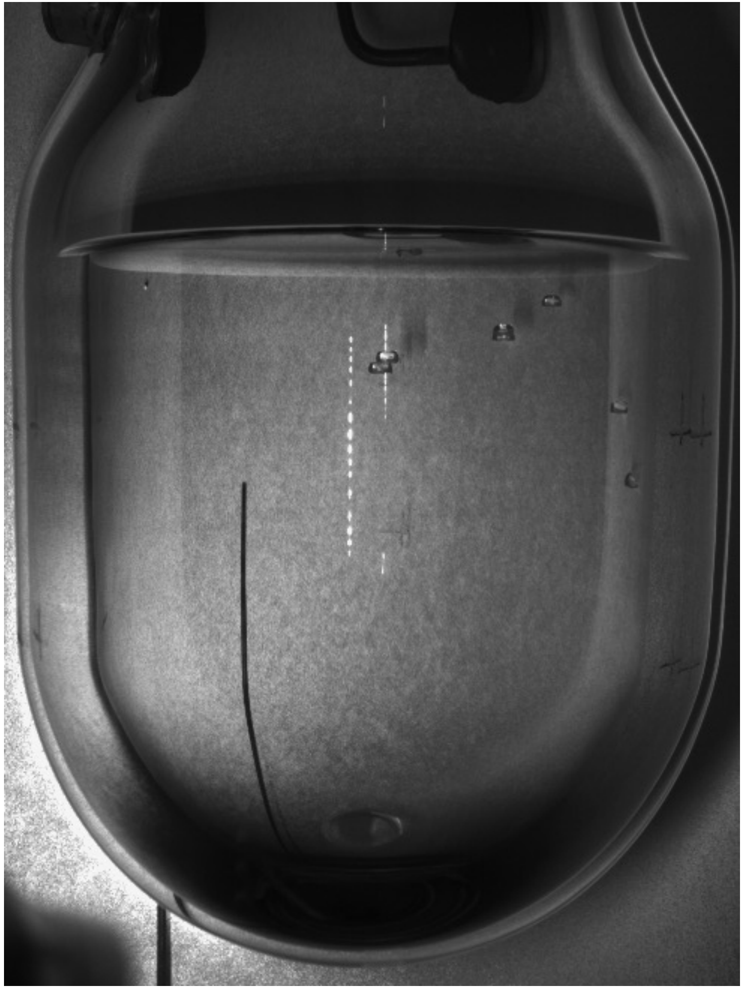

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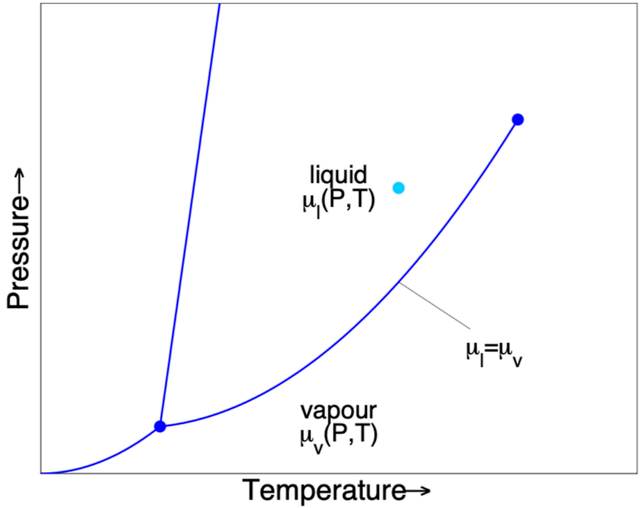

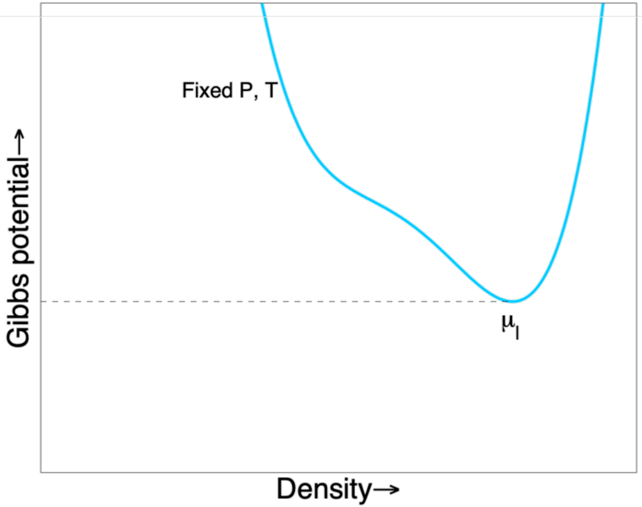

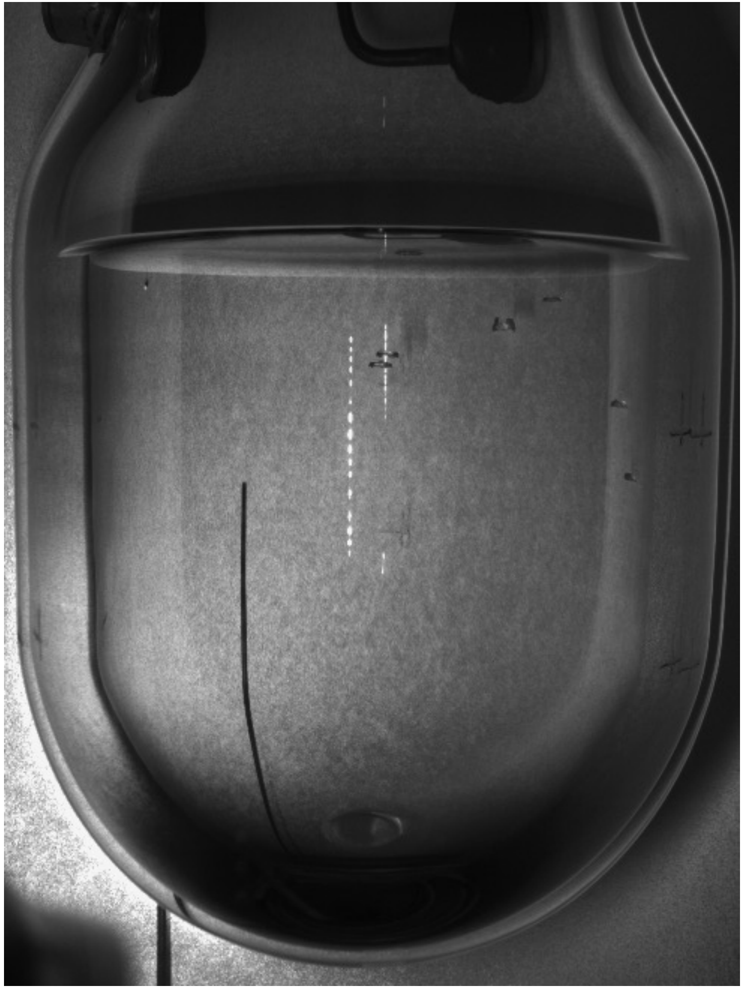

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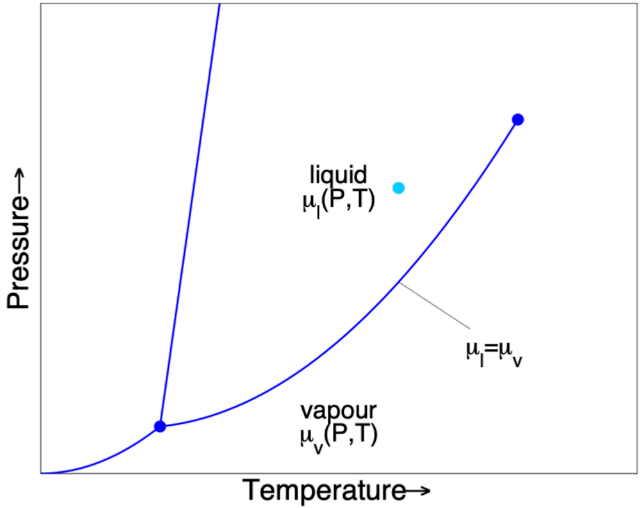

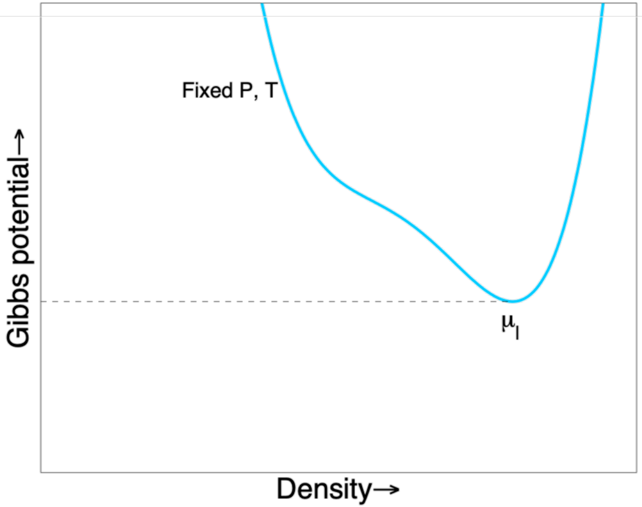

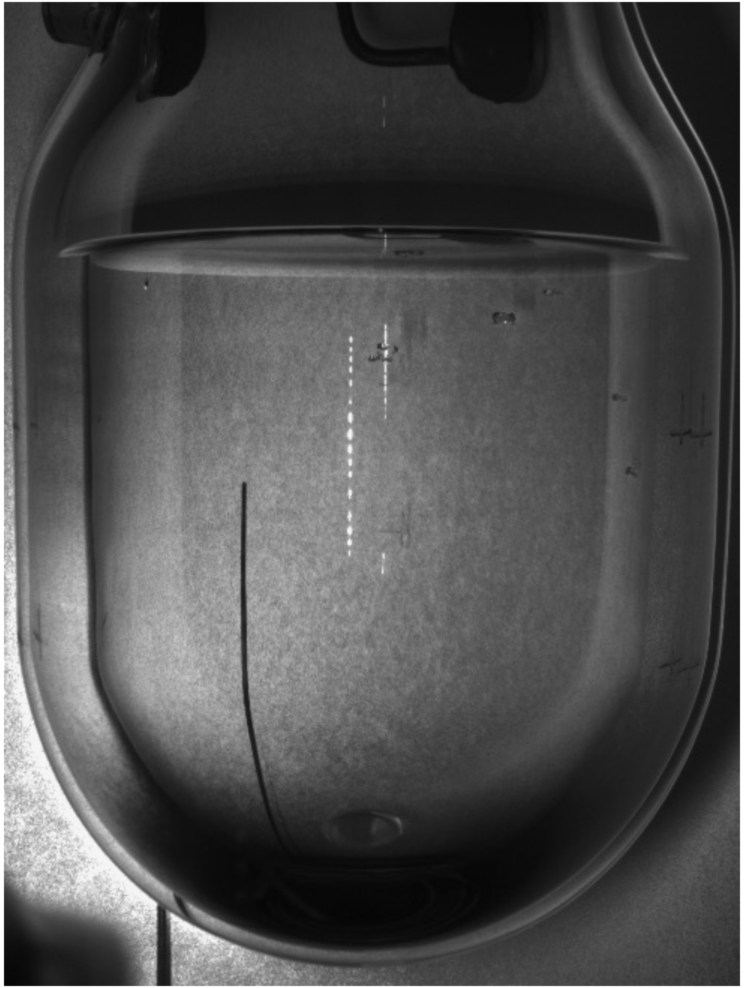

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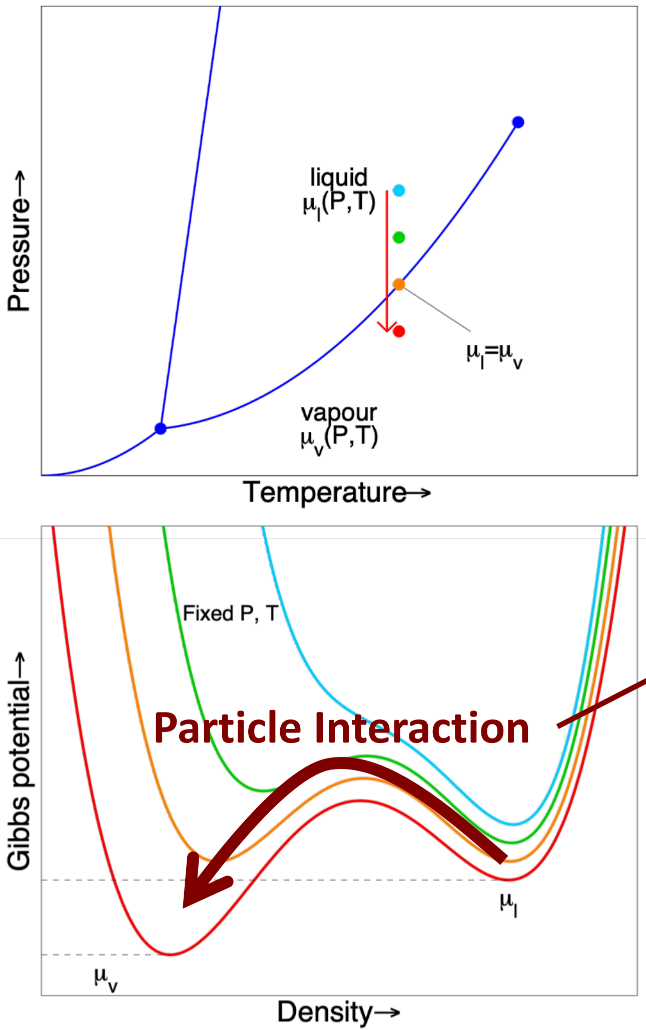
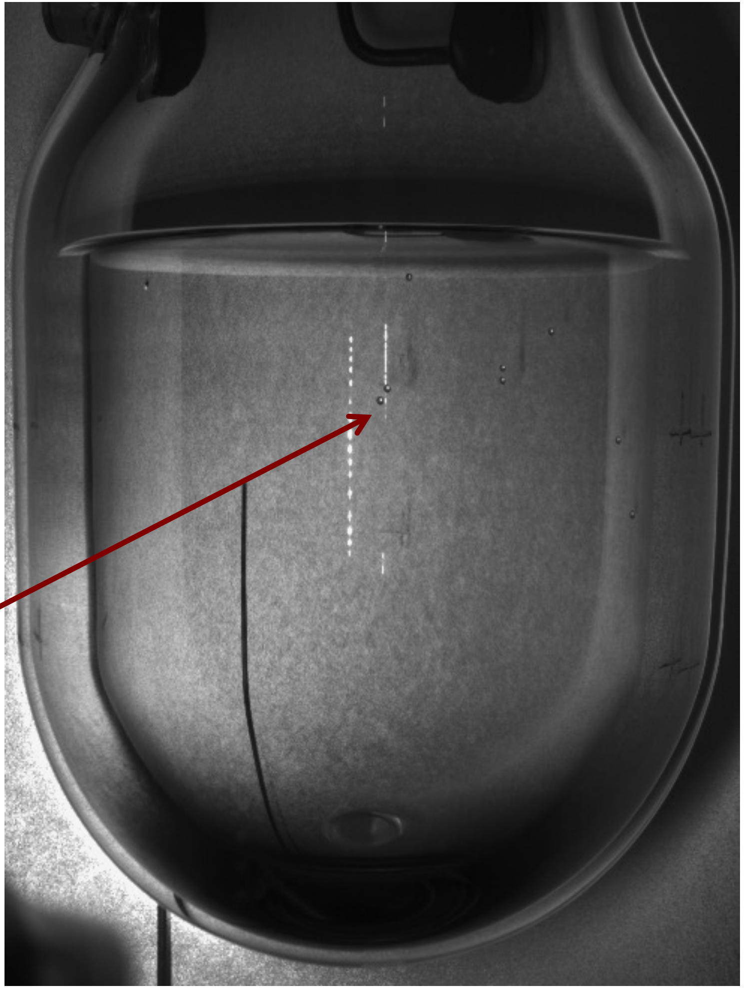
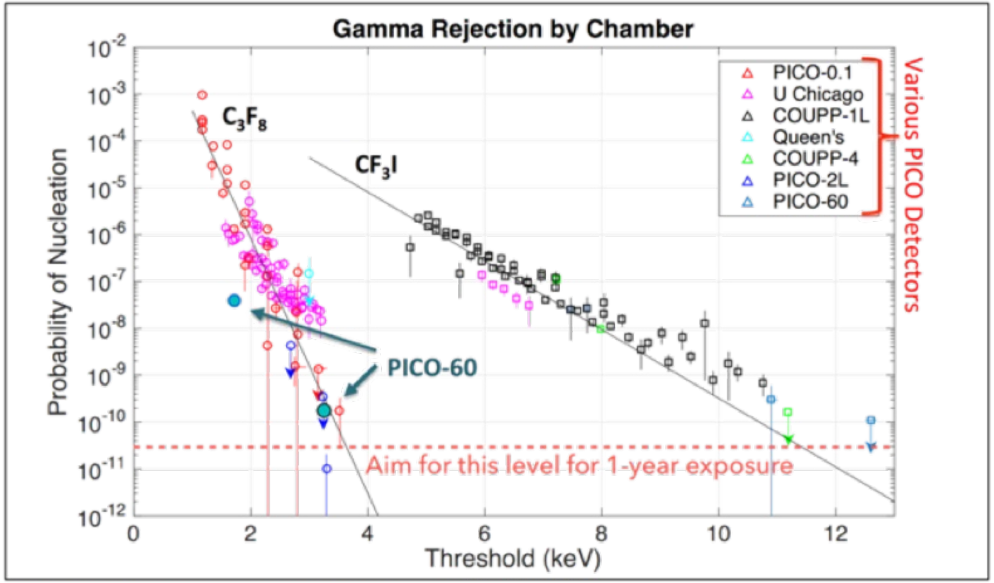




Why Bubble Chambers?

- By choosing superheat parameters appropriately (temperature and pressure), bubble chambers are blind to electronic recoils (10^{-10} or better)
  - The probability for a gamma to make a bubble:



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

Why Bubble Chambers?

- By choosing superheat parameters appropriately (temperature and pressure), bubble chambers are blind to electronic recoils (10^{-10} or better)
  - The probability for a gamma to make a bubble:

- Bubble formation requires two things:
  - Enough energy
  - Enough energy density – length scale must be comparable to critical bubble size

Electron recoil deposition is too diffuse!

Why Liquid Noble Bubble Chambers?

"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."

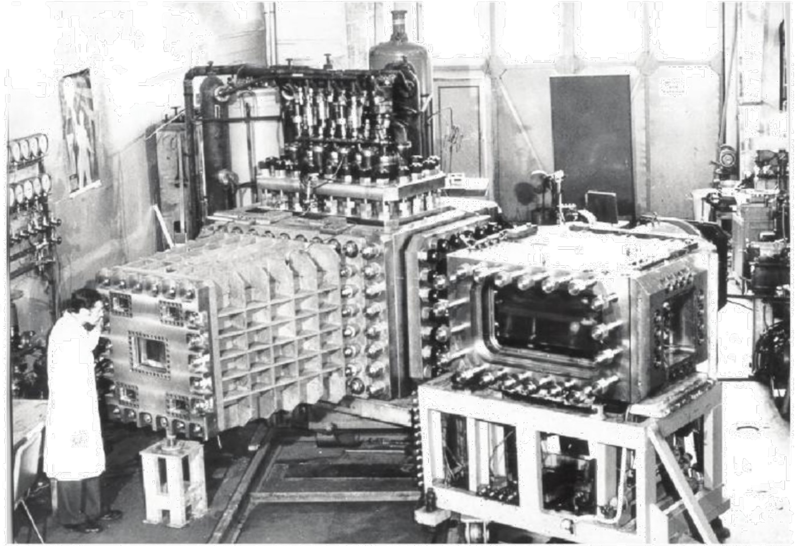


Figure 1.1 Liquid xenon bubble chamber DIANA with 1.5x0.7x 0.7 m^3 active volume constructed at ITEP in the 1970s. Courtesy of A.G. Dolgolenko.

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

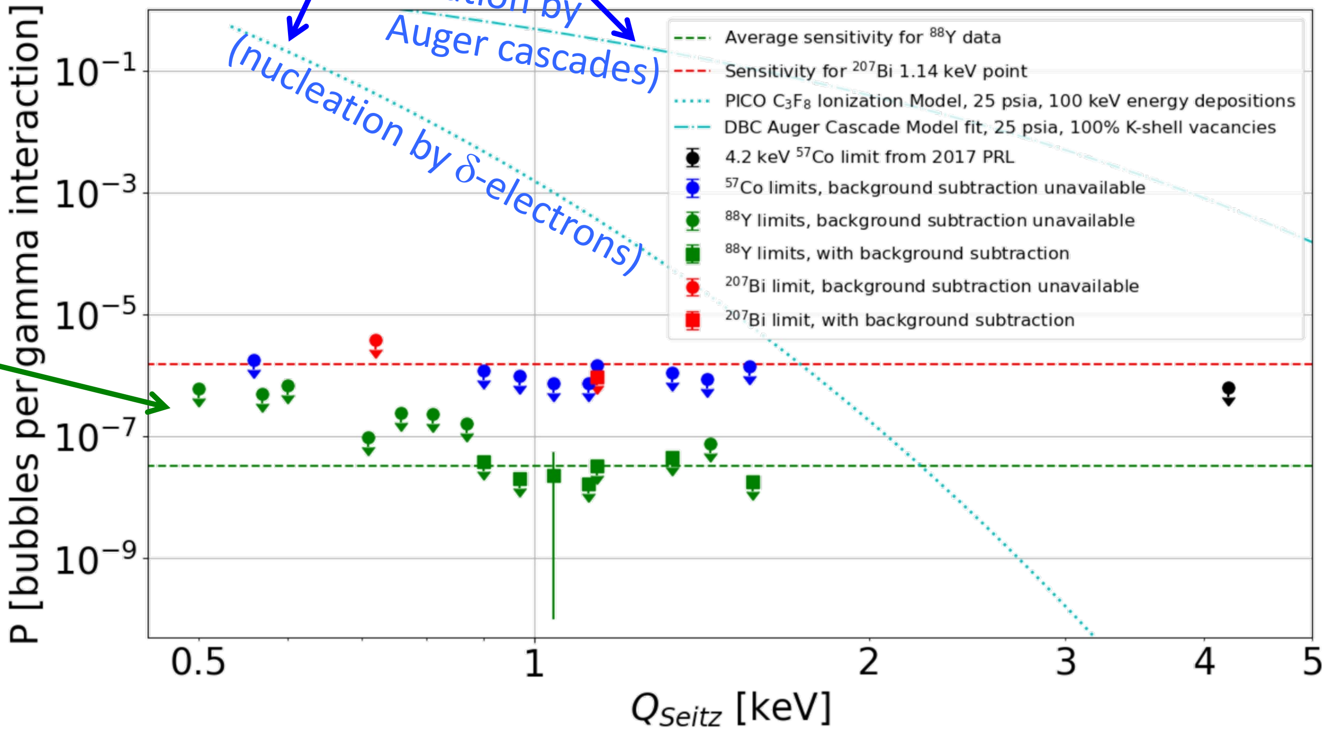
Why Liquid Noble Bubble Chambers?

No molecular degrees of freedom

No mechanisms for local heating by electrons

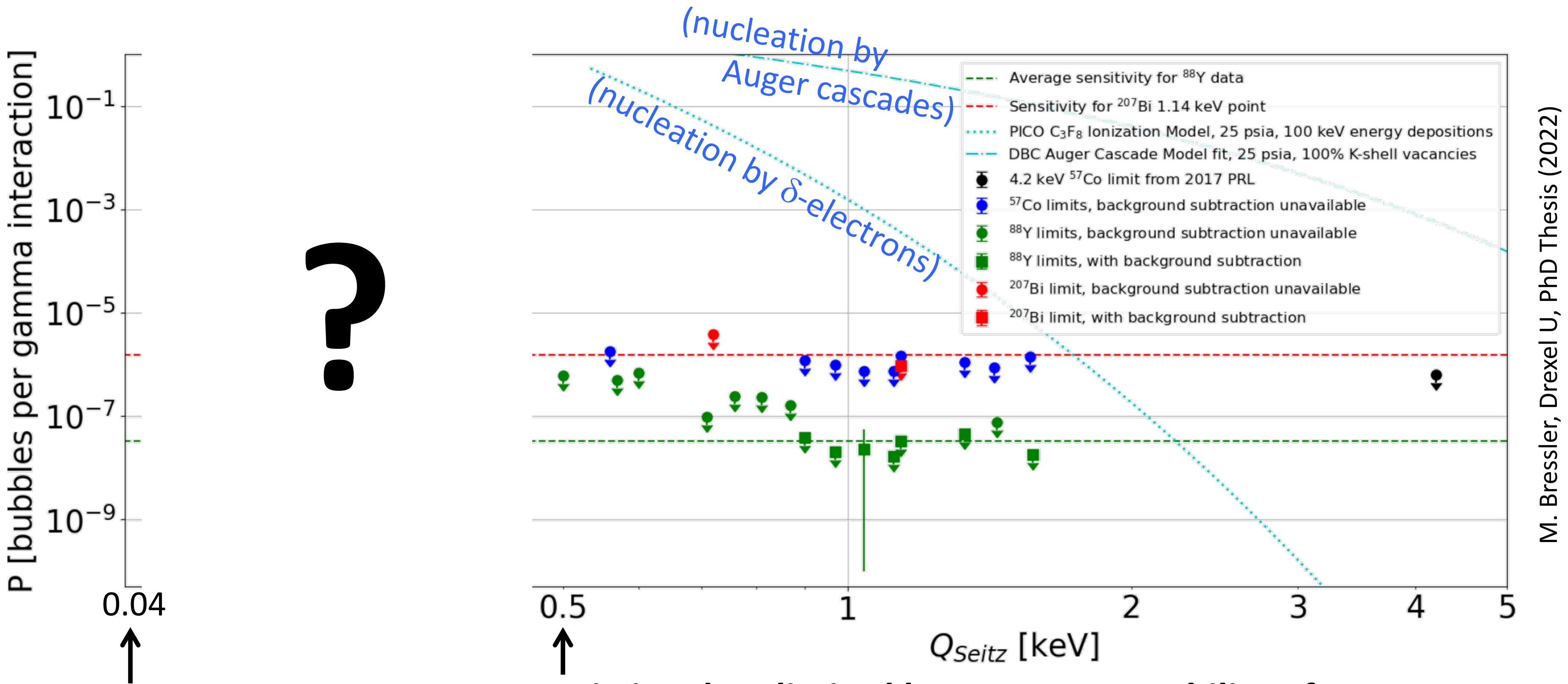
No bubbles from ERs

ER's in PICO (nucleation suppressed by low dE/dx)



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

Performance at Low Threshold – NR's

- Bubble chambers are threshold detectors
  - We know we saw a bubble, but not the energy that created it
  - Sensitivity to dark matter depends crucially on the threshold
- Threshold calculation from Seitz, Phys of Fluids 1, 2 (1958)

$$p_v - p_l = \frac{2\sigma}{r_c}$$

$$E_{th} = 4\pi r_c^2 \left(\sigma - T\frac{\partial \sigma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v h$$

Surface energy

Latent heat

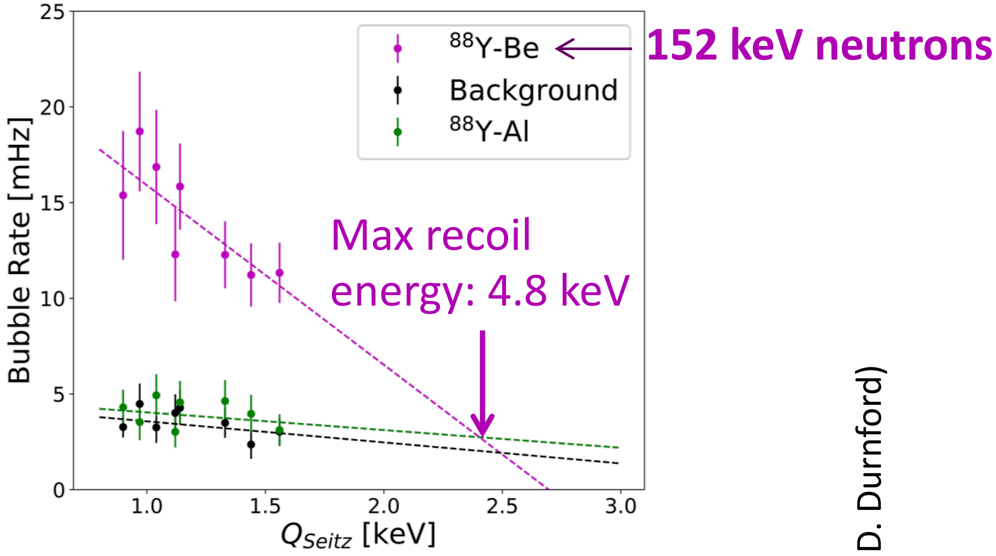
- Assumes step function above threshold
  - Calibration required!

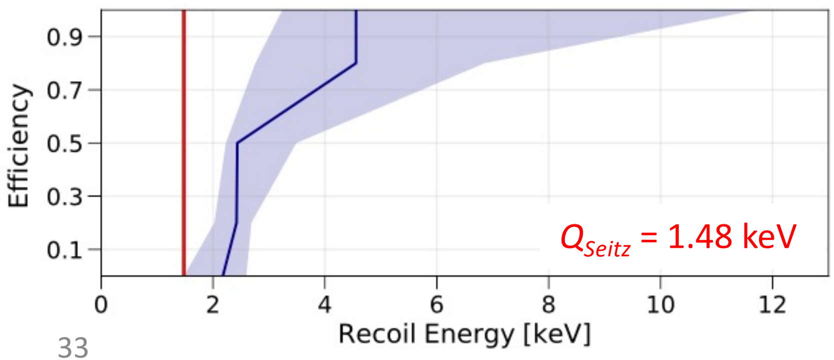
Performance at Low Threshold – NR's

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

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

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



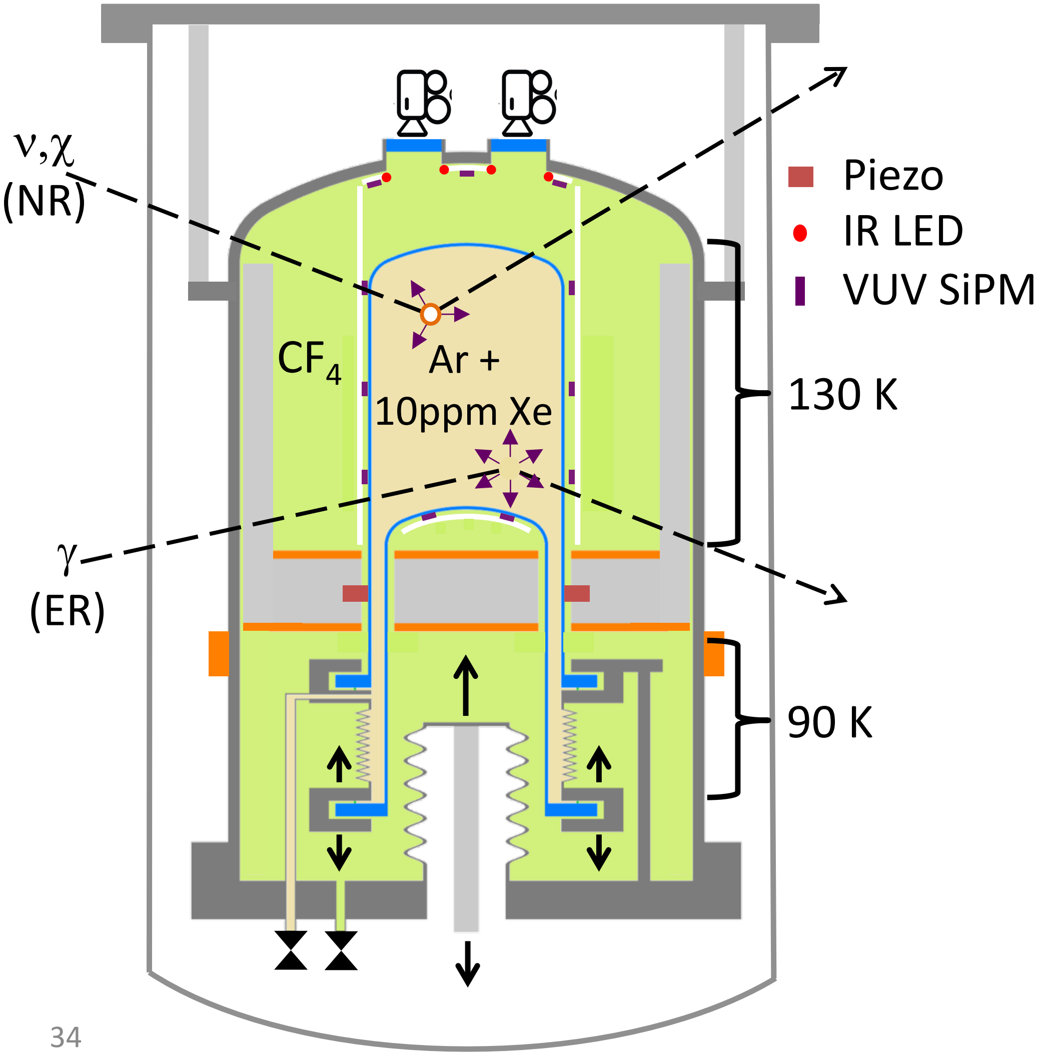


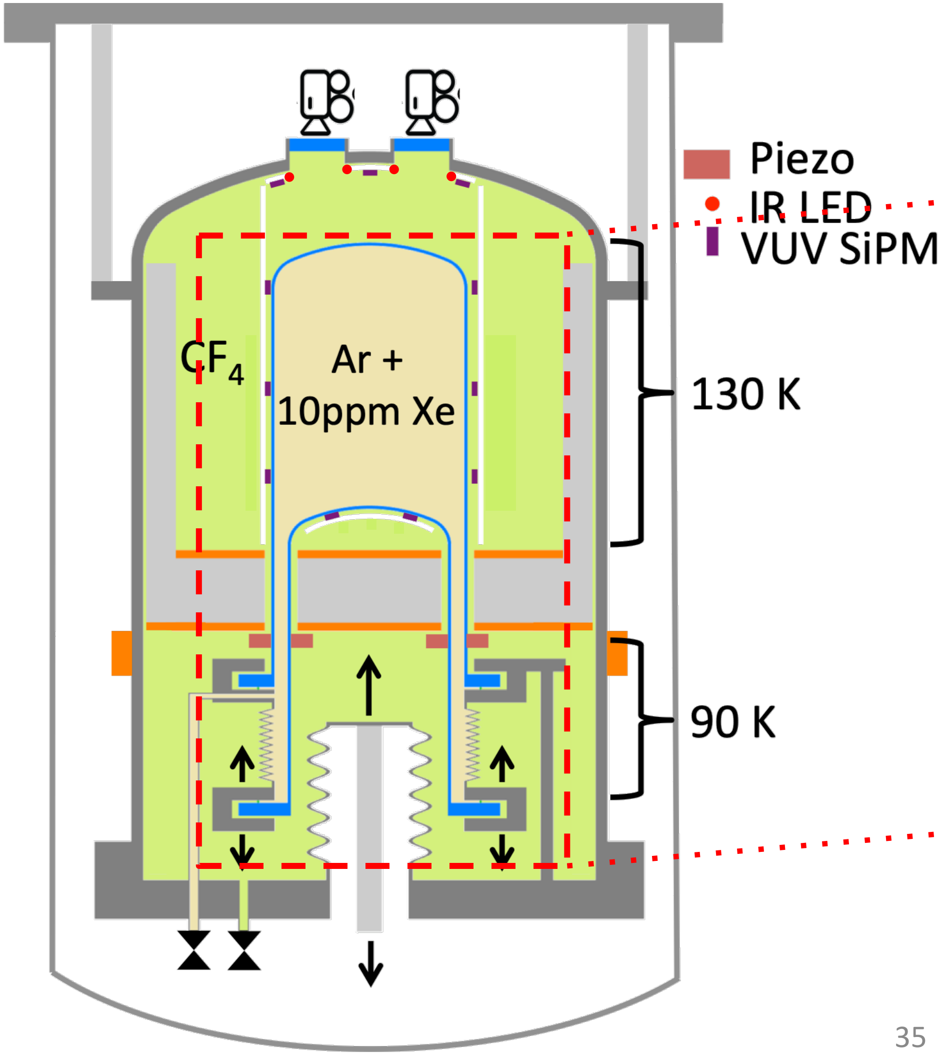
(Xe NR analysis by D. Durnford)

SBC-LAr10

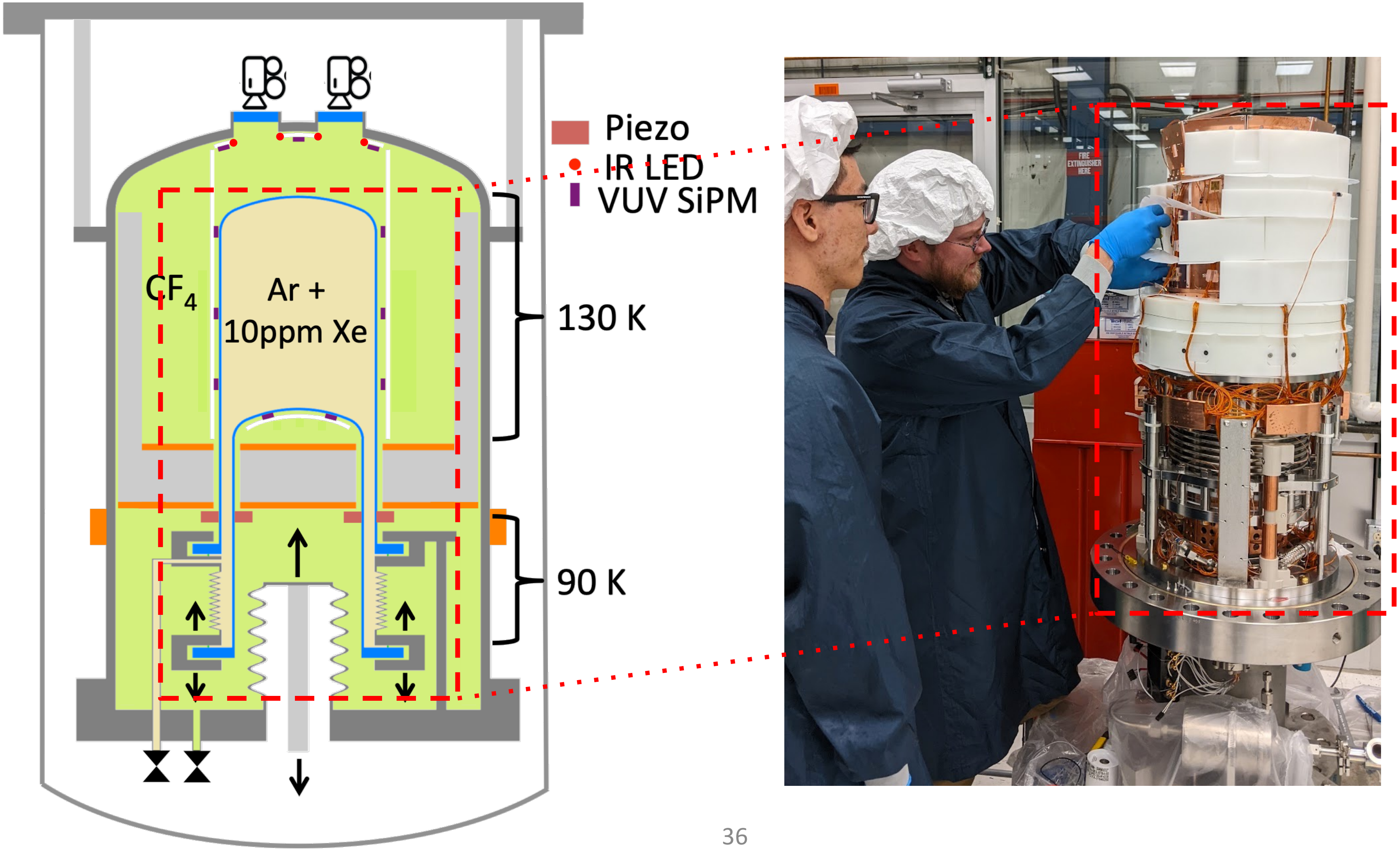
(Fermilab LDRD 2018-003,
with support from
DOE-HEP Det R&D,
NSF Particle-Astro, and CFI)

- 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

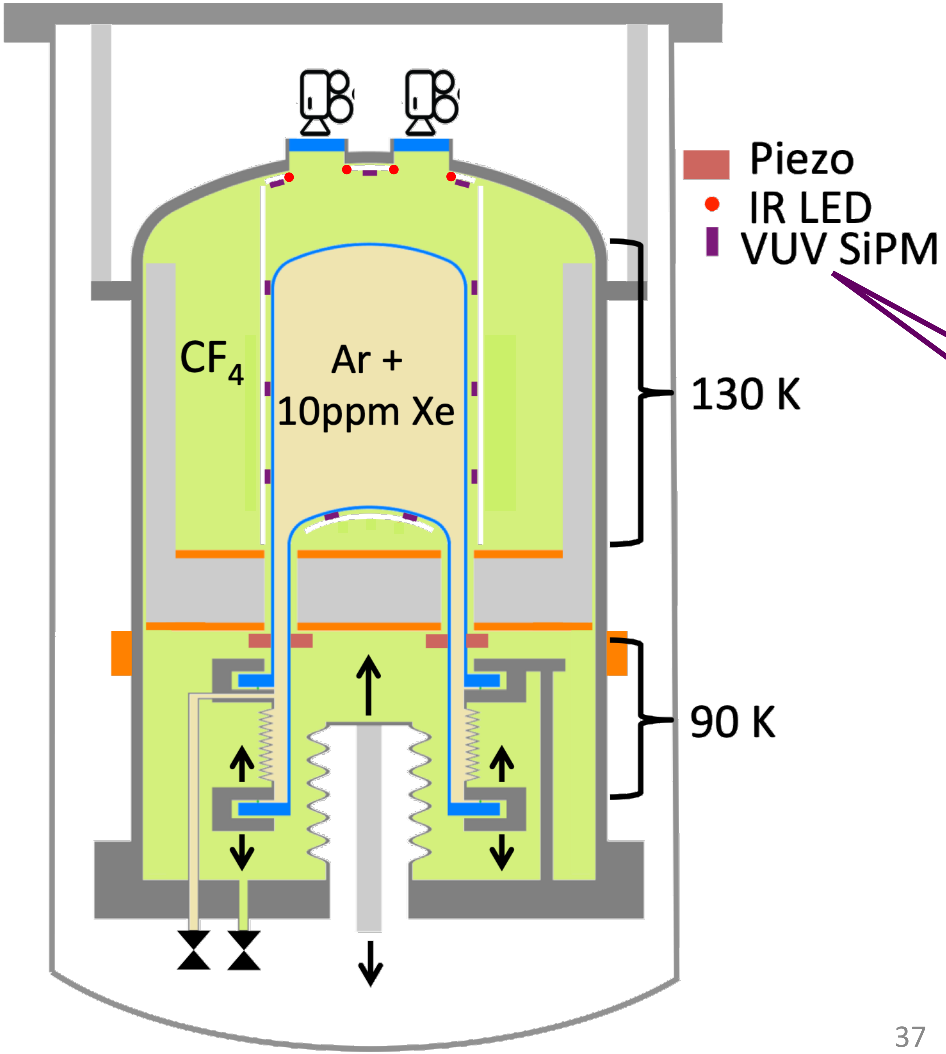




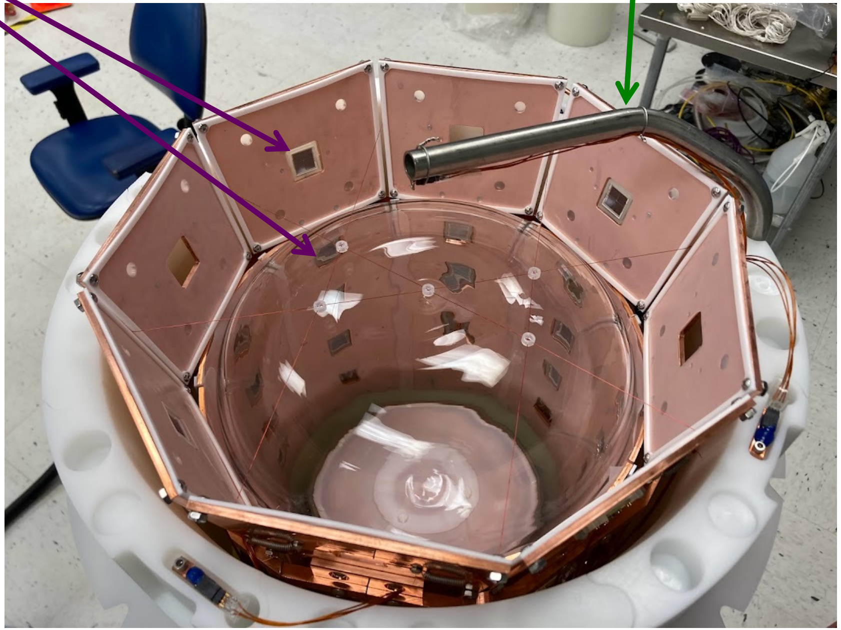
Hector Hawley-Herrera
Queen's Ph.D. Student



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



CF$_4$
Ar +
10ppm Xe
Piezo
IR LED
VUV SiPM
130 K
90 K

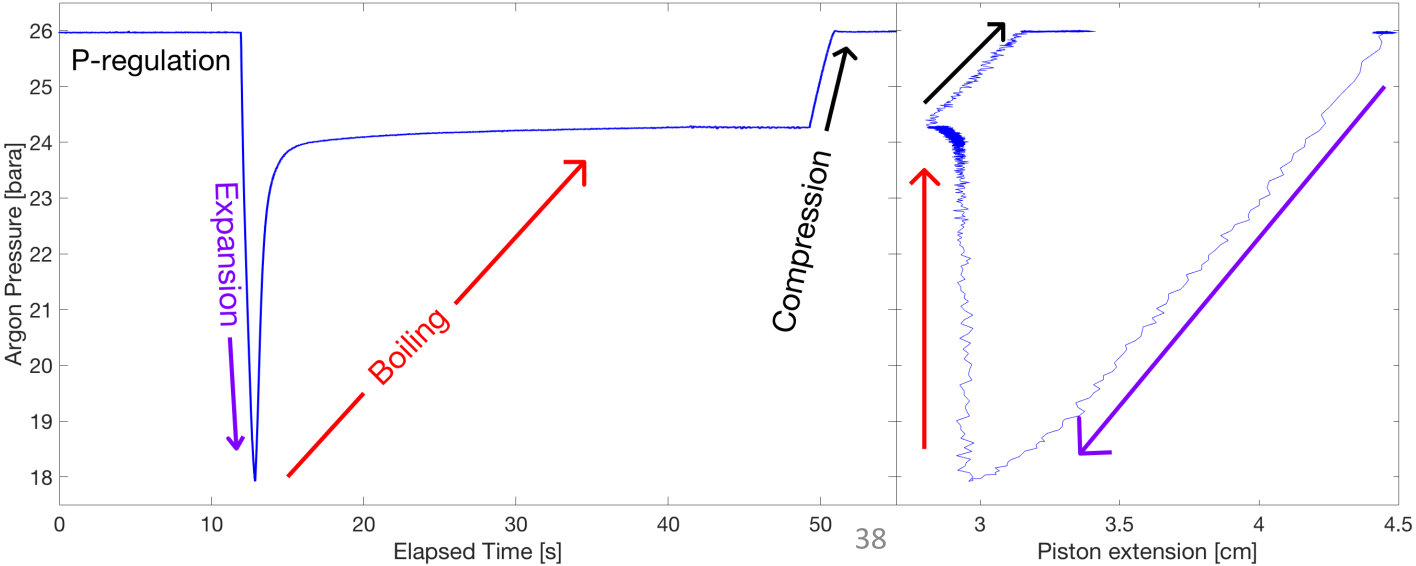


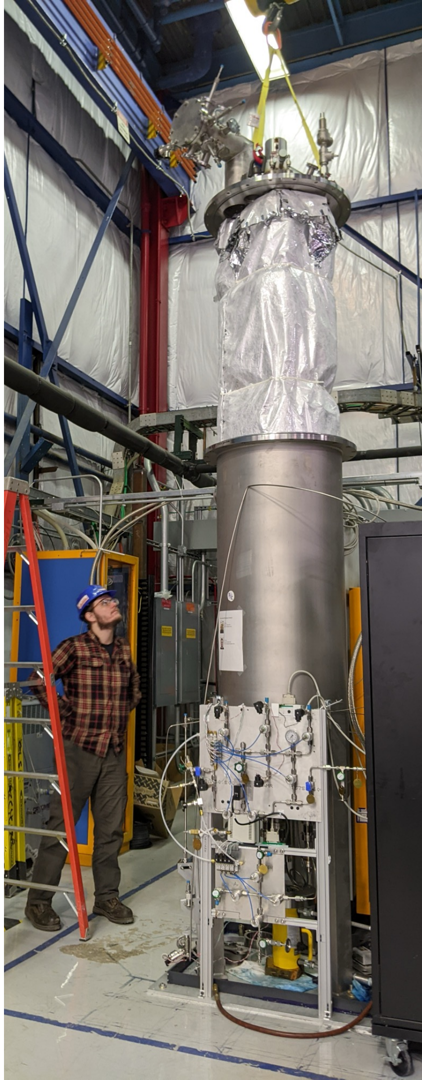
CF$_4$ Fill/Drain Standpipe

SBC-LAr10 – Engineering Run

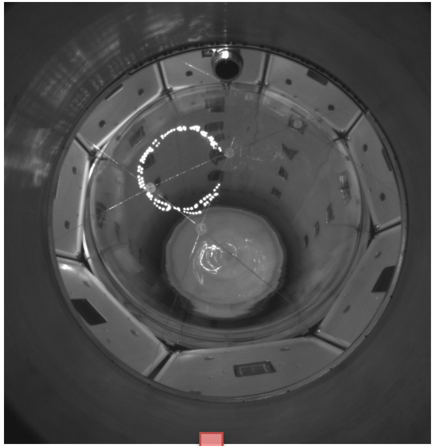
Dec 2022 – March 2023, @ SiDet (Fermilab)

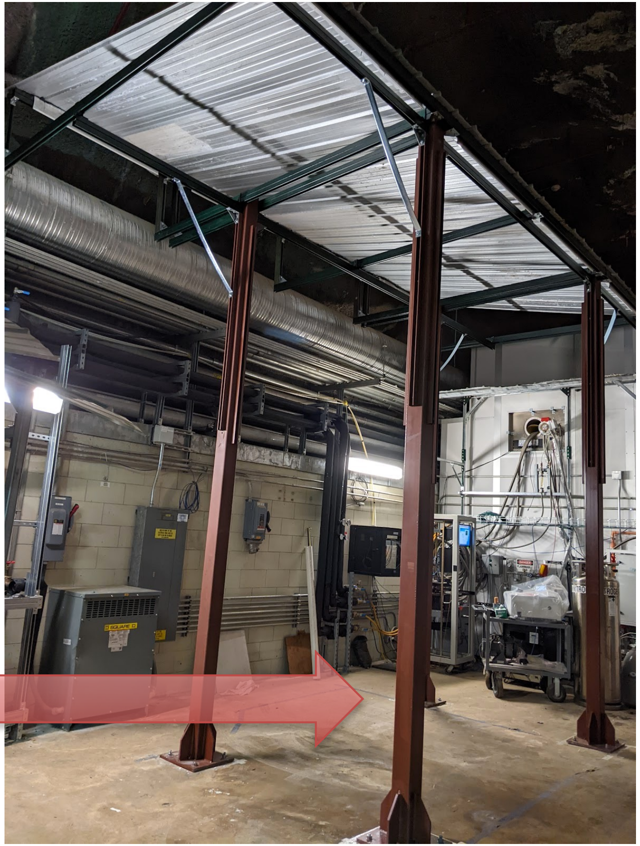
- 100kg LAr condensed in pressure vessel ; no inner assembly
- Demonstrated:
  - Thermal performance: cooling power, base temperature, thermal gradient
  - Pressure control: 0.01 bara precision in single-phase (liquid) state
  - Slow Controls and automation – pressure cycling!





SBC-LAr10





Move Resumed! – May 15

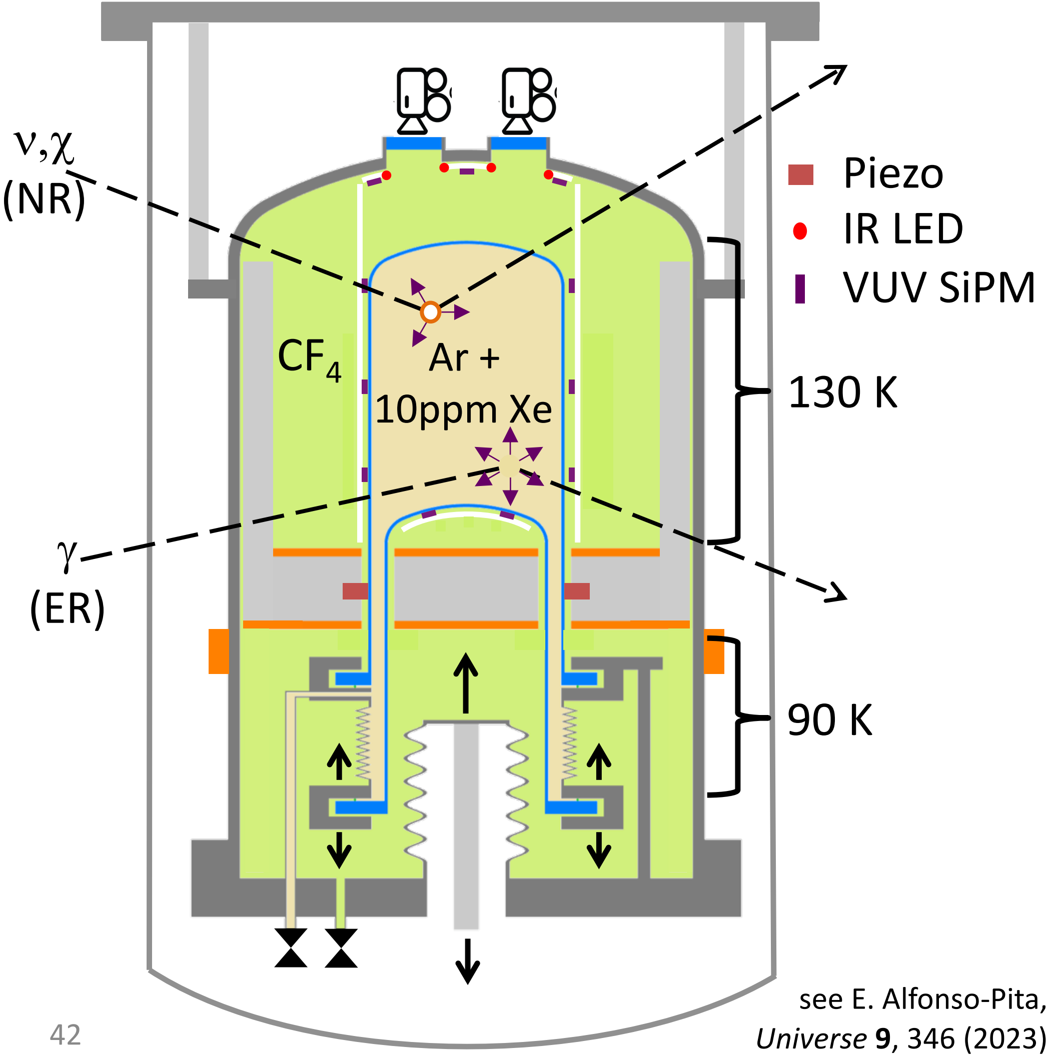
300 feet down

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)

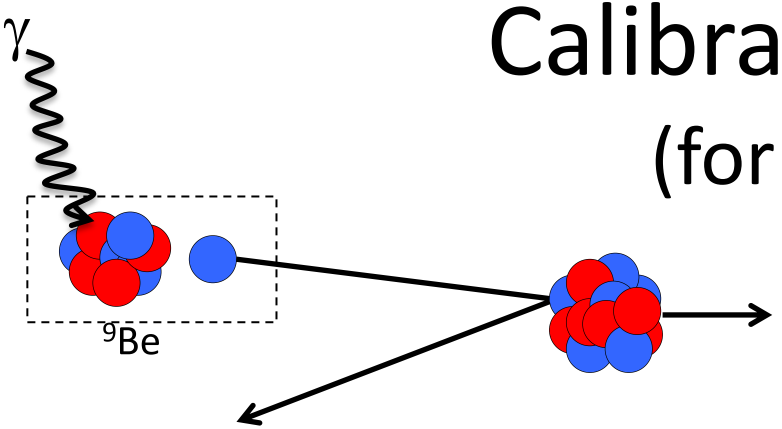
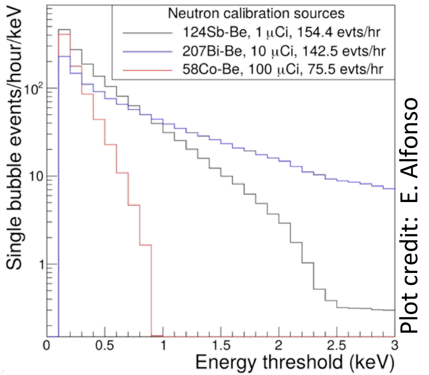
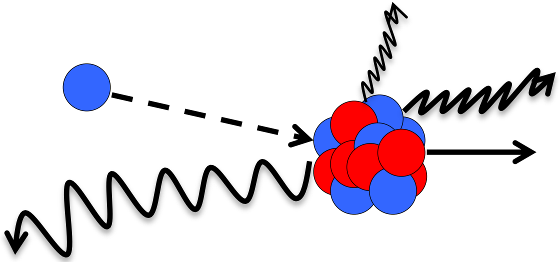
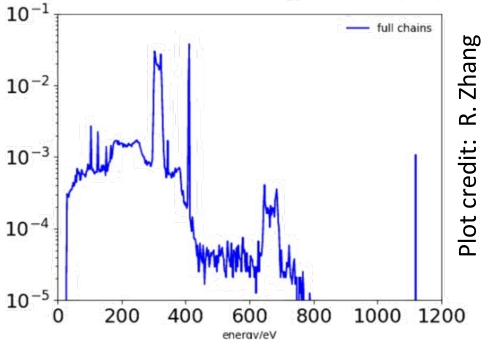


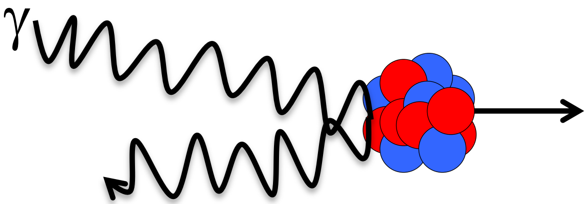
Photo-neutron Sources
(> 500 eV recoils)



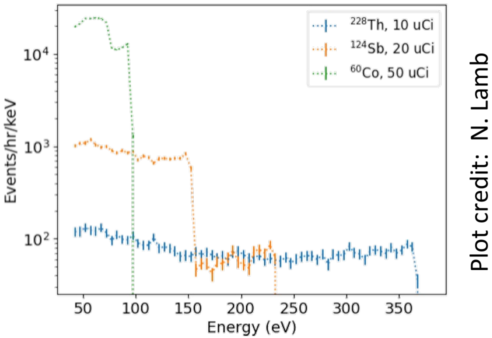


Thermal neutron Capture
(200 – 500 eV recoils)

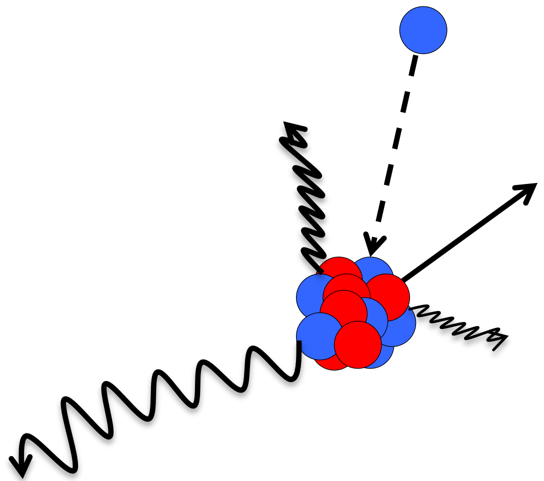




Photon-nucleus Scattering
(< 300 eV recoils)



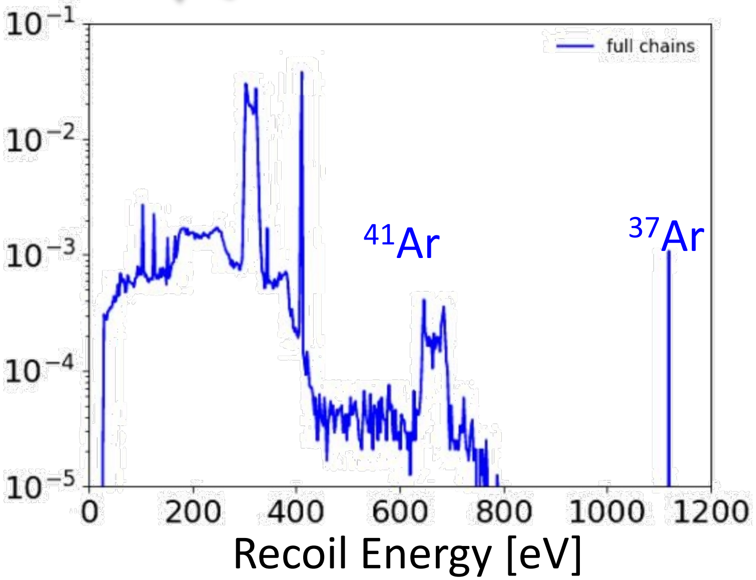
Calibration Strategies



Thermal neutron capture

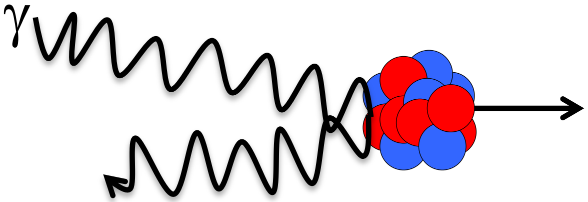
$^{40}Ar(n,\gamma) \rightarrow {}^{41}Ar$

- 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***

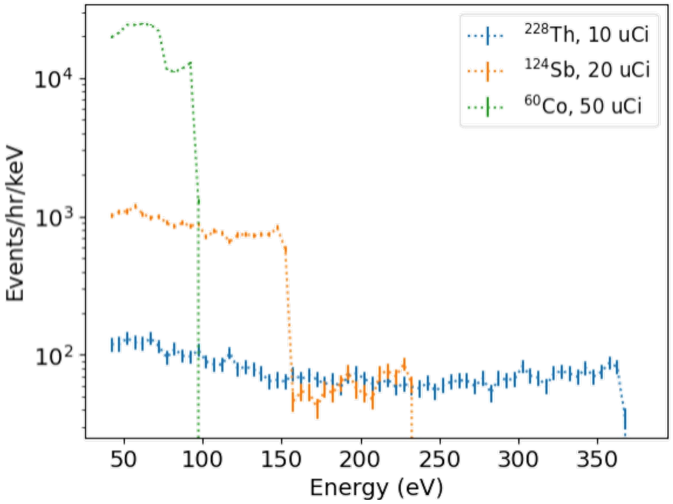


Plot credit: R. Zhang

Calibration Strategies

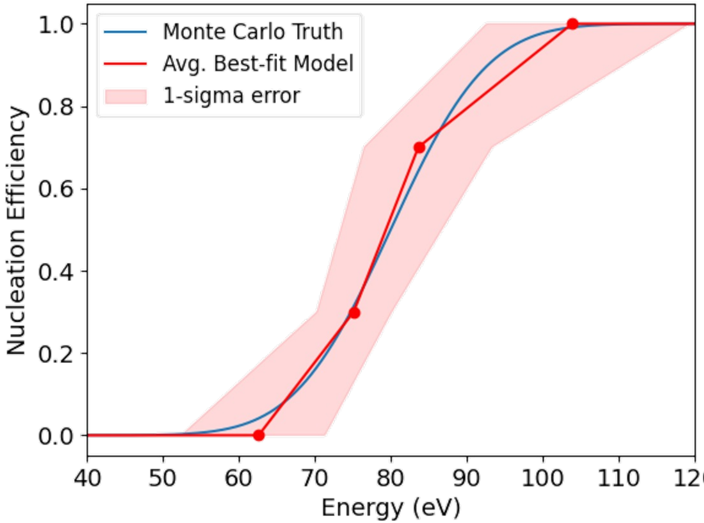


Photon-nucleus Scattering



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

(assumes no nucleation by ER's)



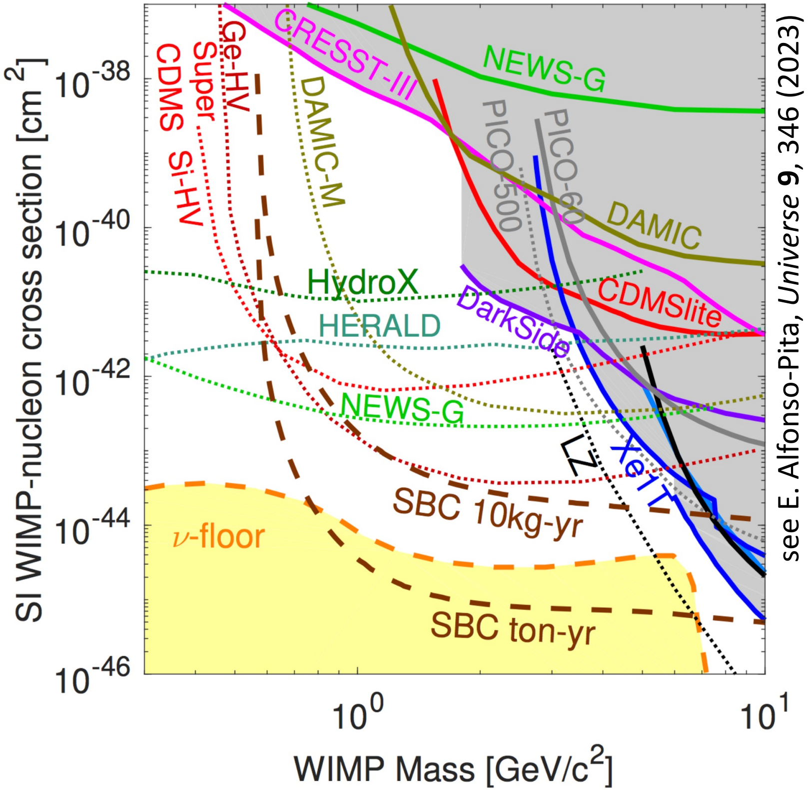
Analysis: N. Lamb

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)



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

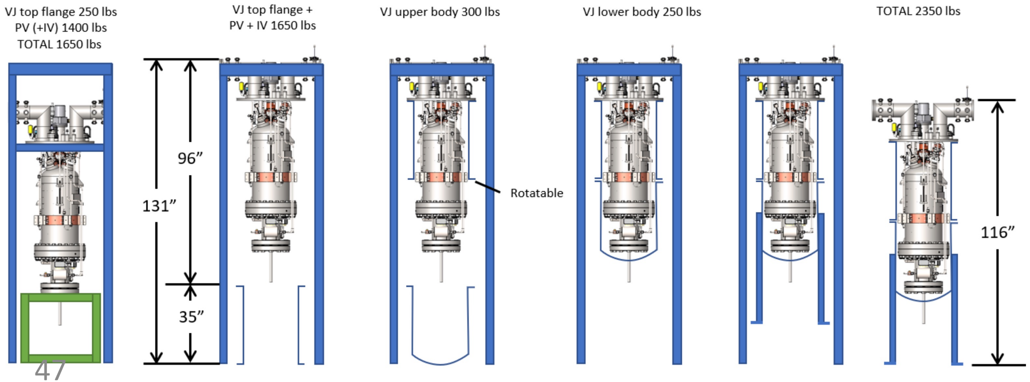
On to Dark Matter

SBC-LAr10: SNOLAB

CFI-supported, radiopure clone of SBC-LAr10

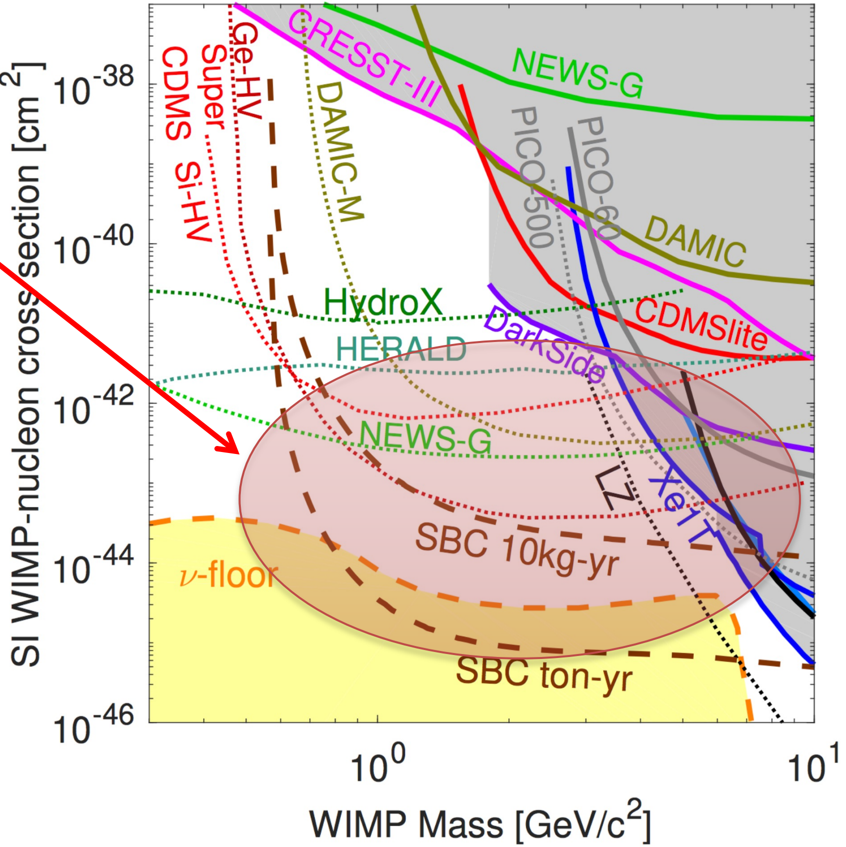
- PV Fabrication underway
  - With lessons learned from FNAL engineering run

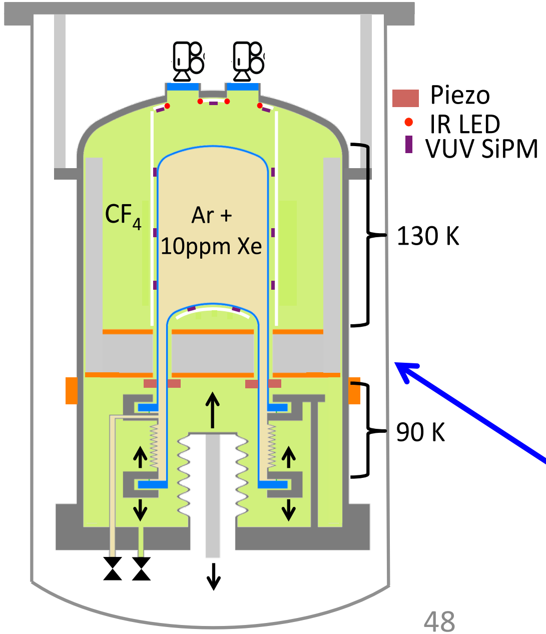
- SNOLAB TDR planned for Fall 2024
  - Rapid progress towards critical TSSA approvals



Summary

Dark matter might live here
and if it does…



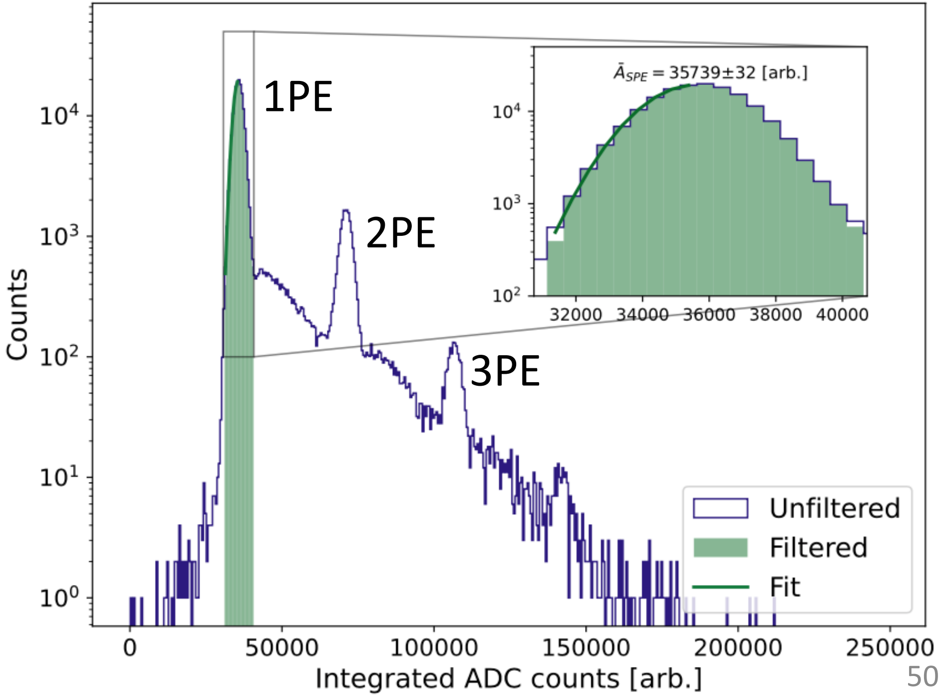


…this will be the tool to find it.

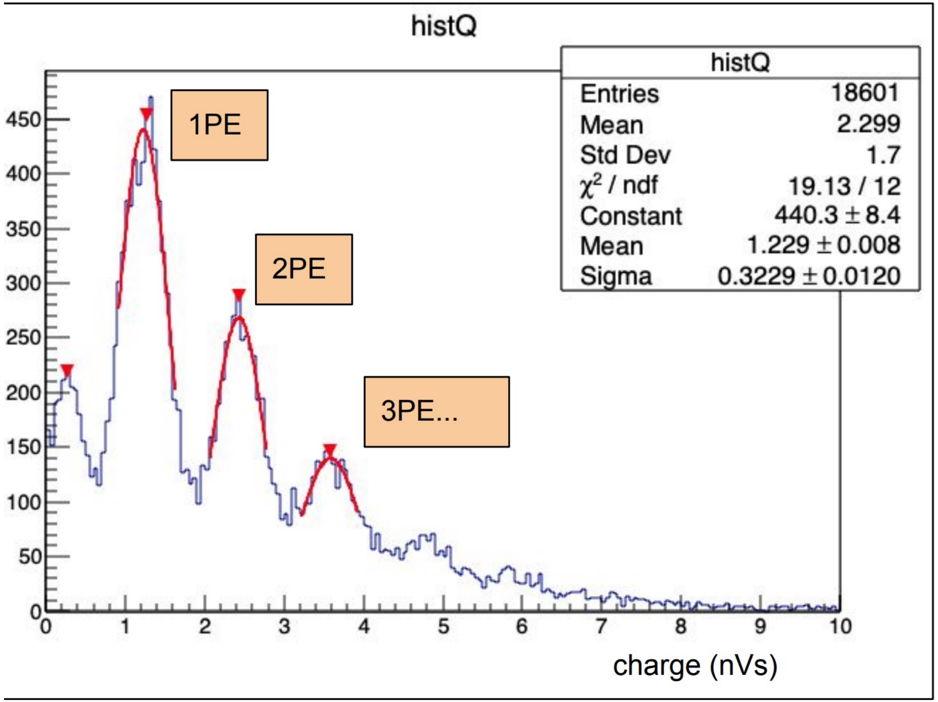
Backup

SiPM (Hamamatsu VUV4) Performance

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



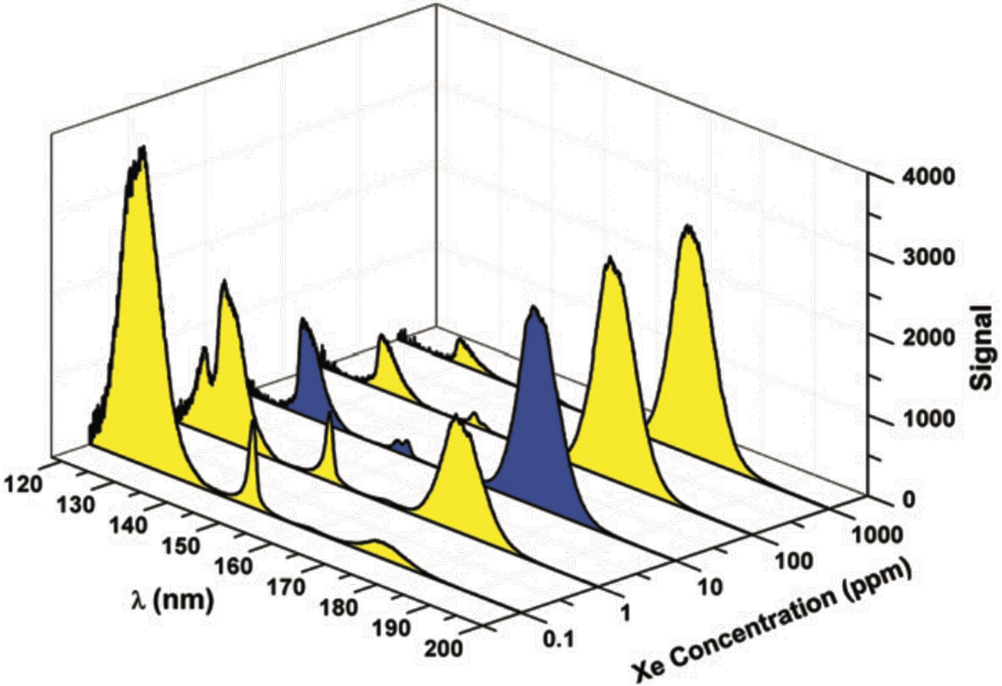
In high-pressure, cryogenic LCF_4 @ NU
(Sheng + de SaintCroix)



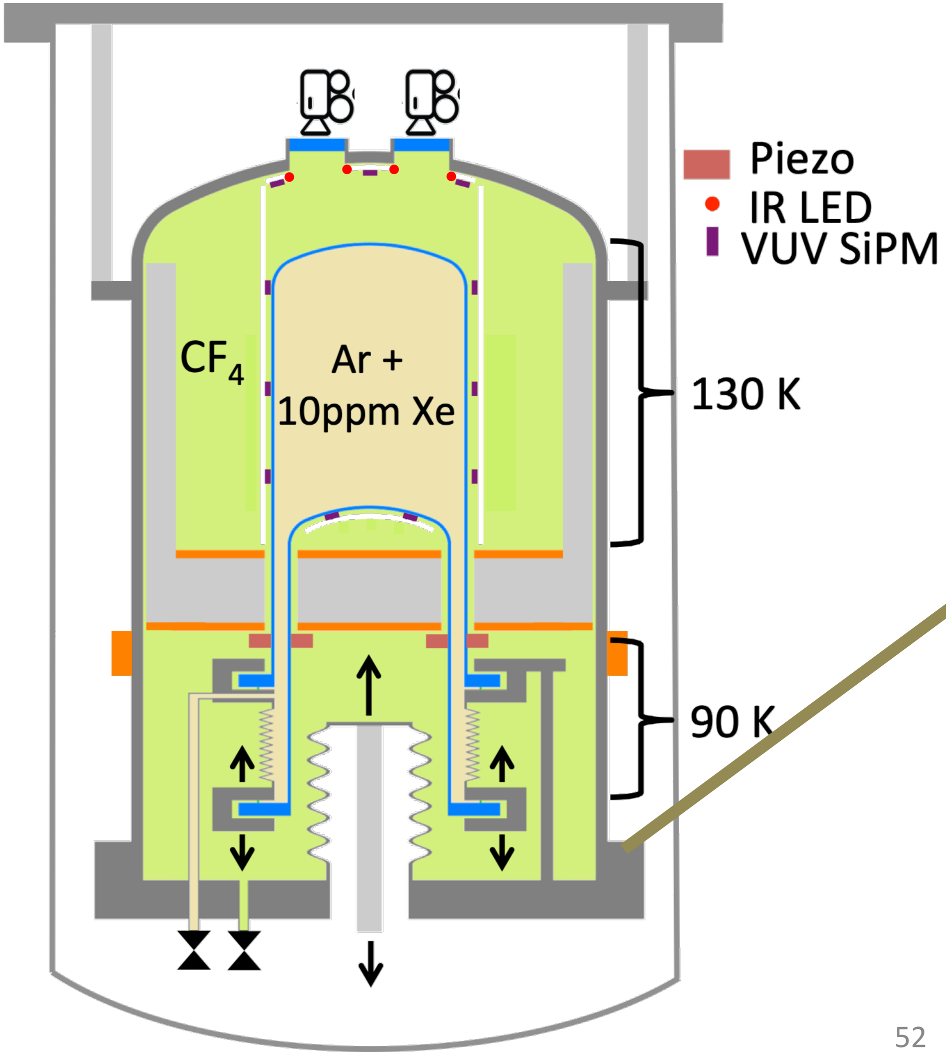
Scintillation: Doping

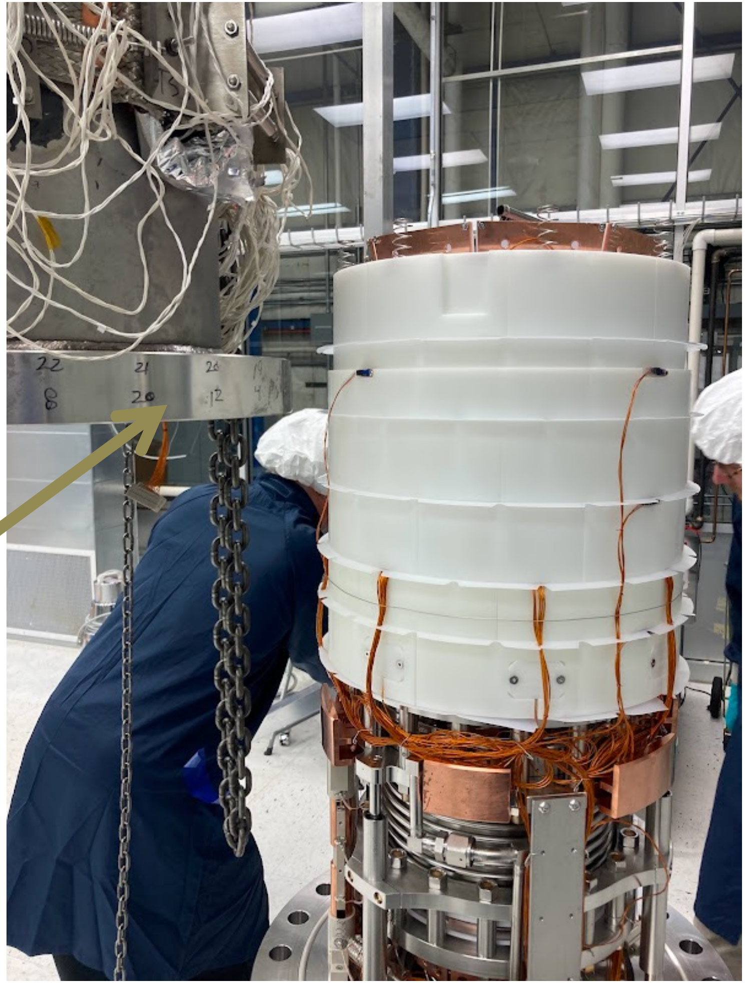
- Silica jars opaque to 128nm Ar scintillation

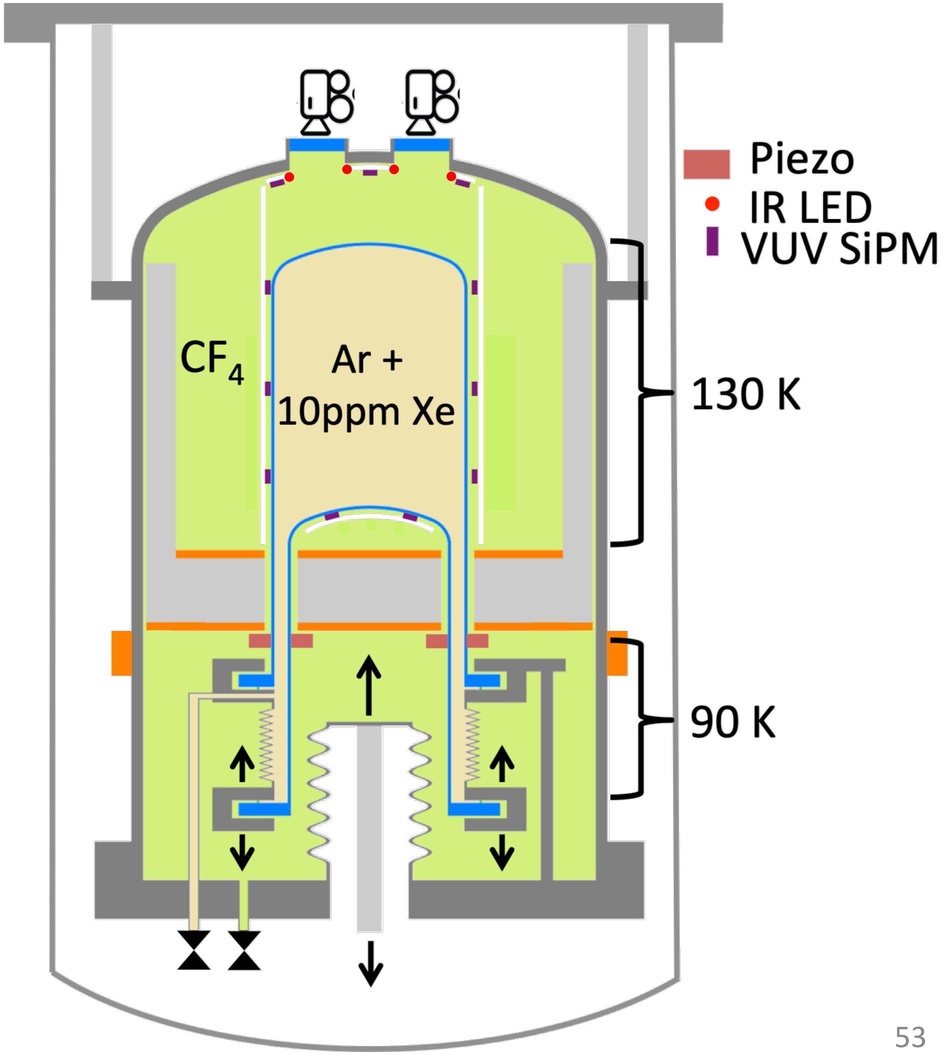
- 10ppm Xe sufficient to exchange Ar_2^* for Xe_2^*
  - 175nm, jars transparent
  - Expect 1 photon detected for ~5-keV NR

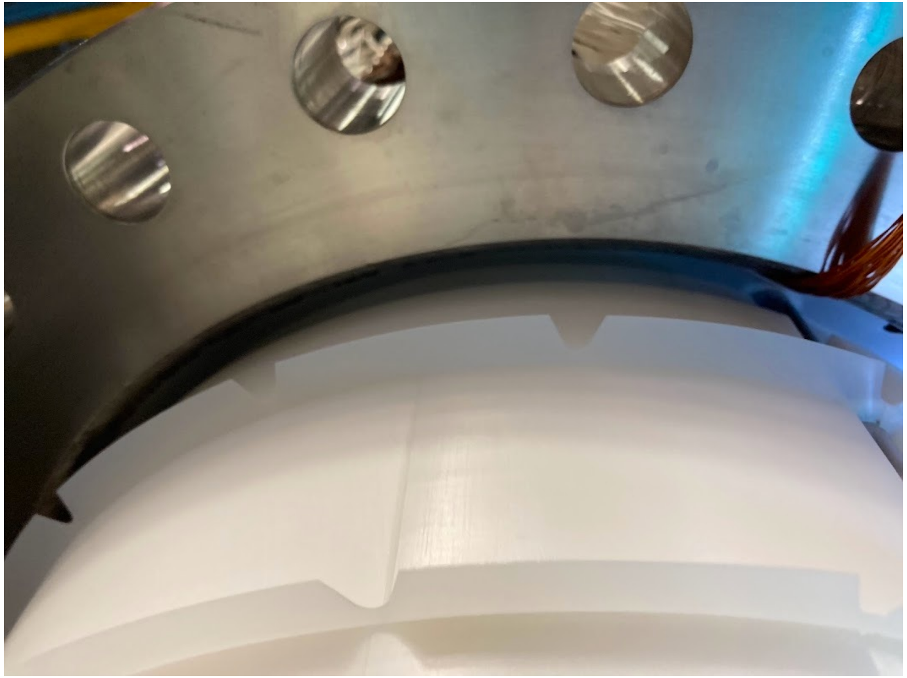


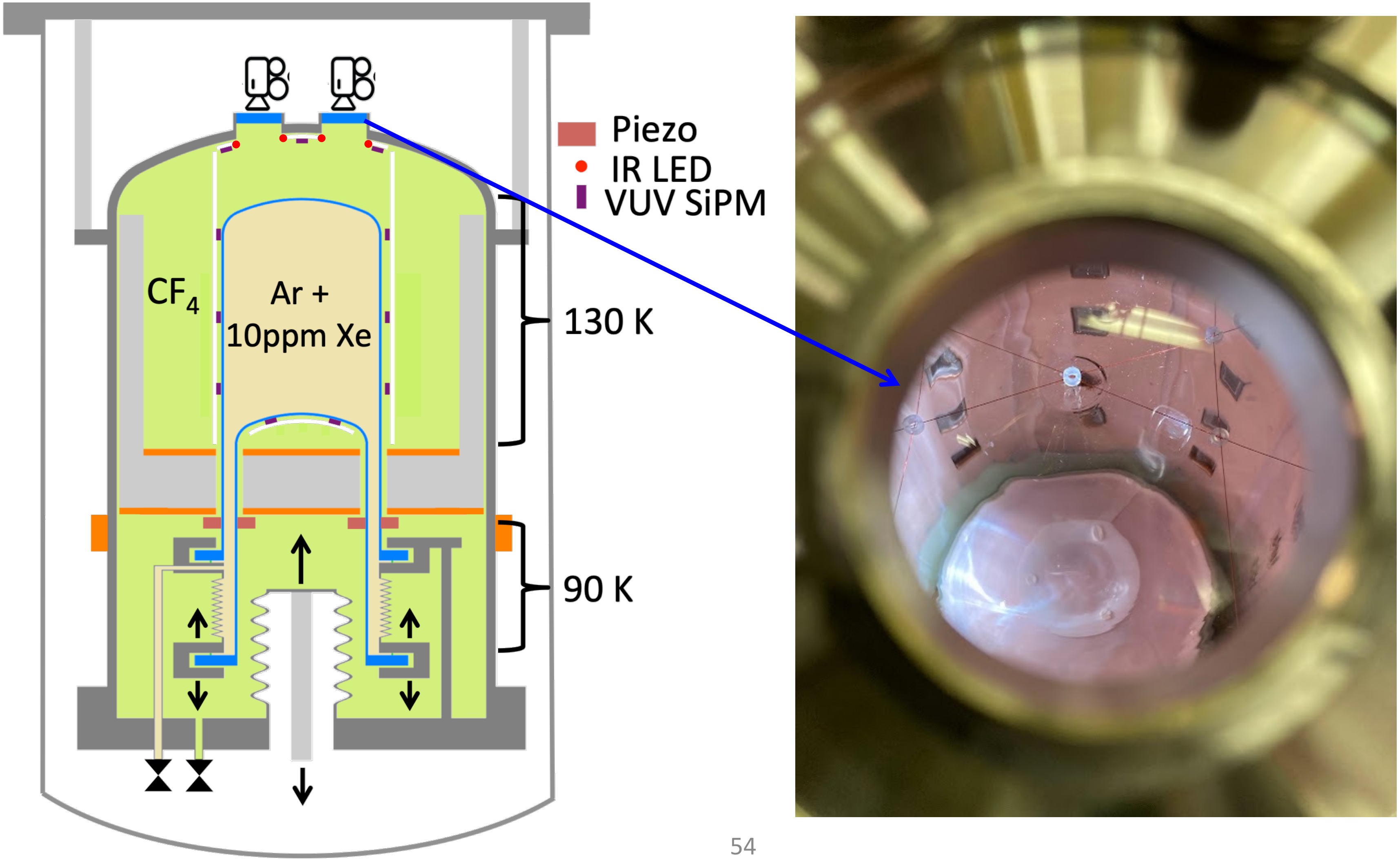
A. Neumeier *et al* 2015 *EPL* **109** 12001

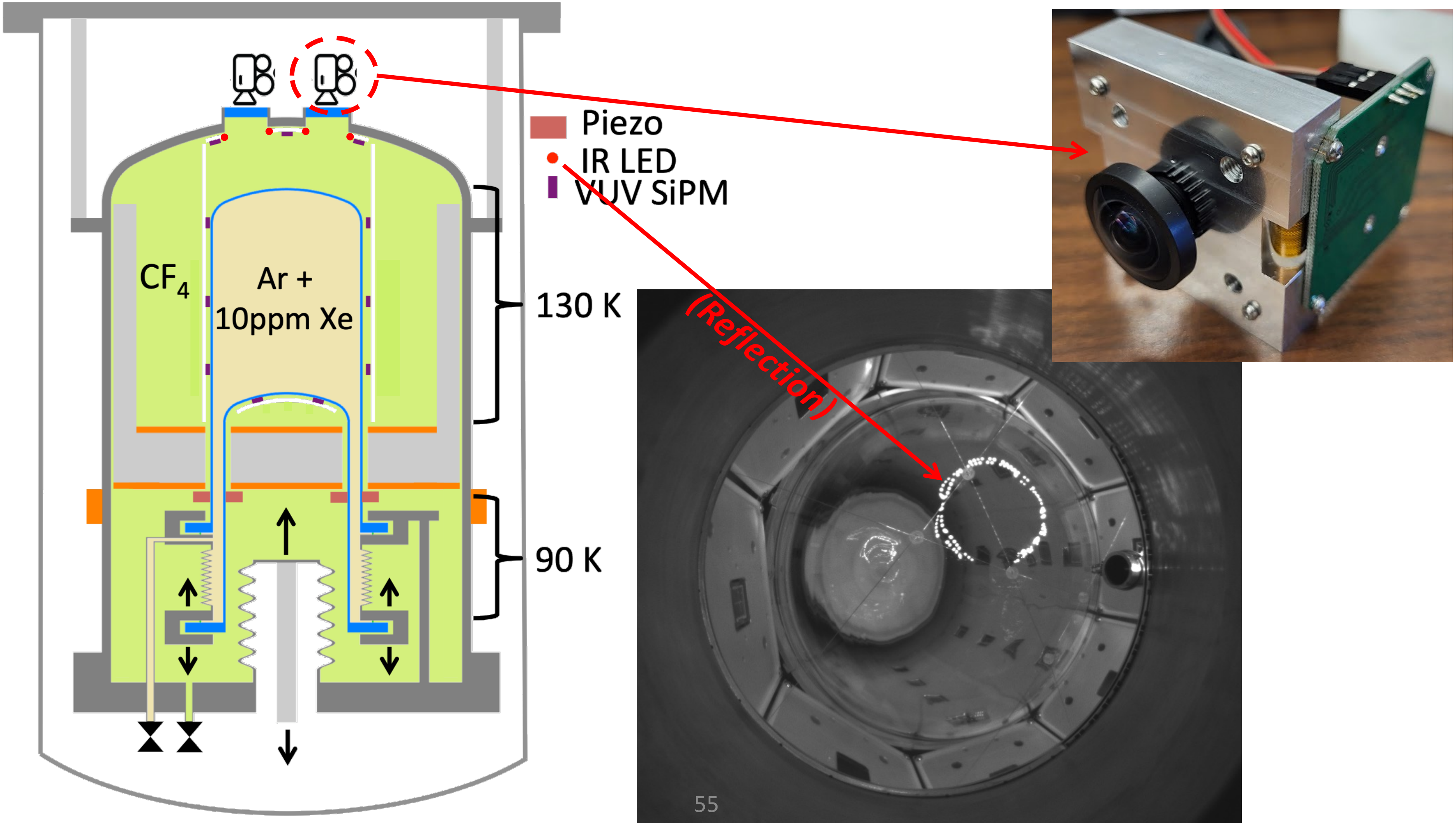

Piezo
IR LED
VUV SiPM
CF_4
Ar +
10ppm Xe
130 K
90 K



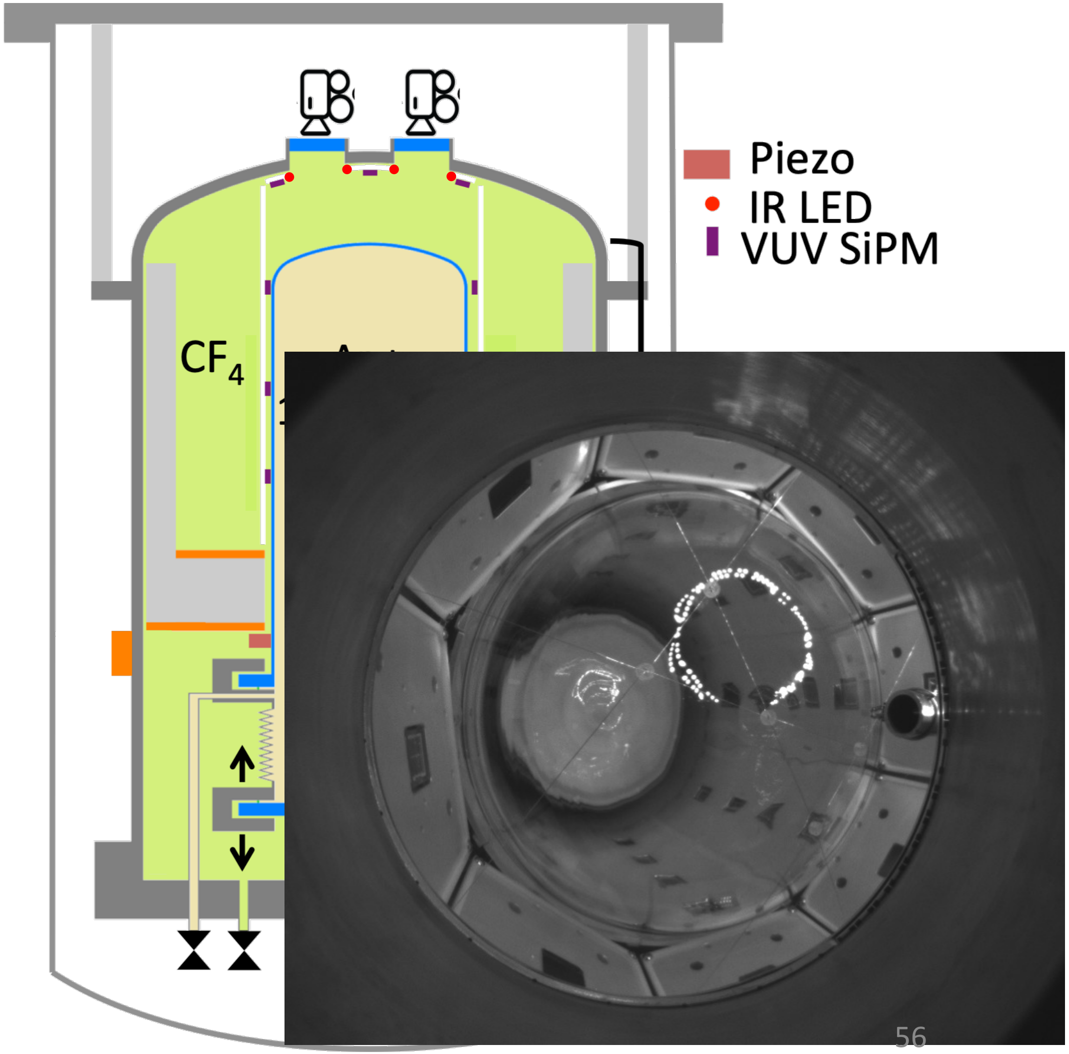

Piezo
IR LED
VUV SiPM
CF_4
Ar +
10ppm Xe
130 K
90 K



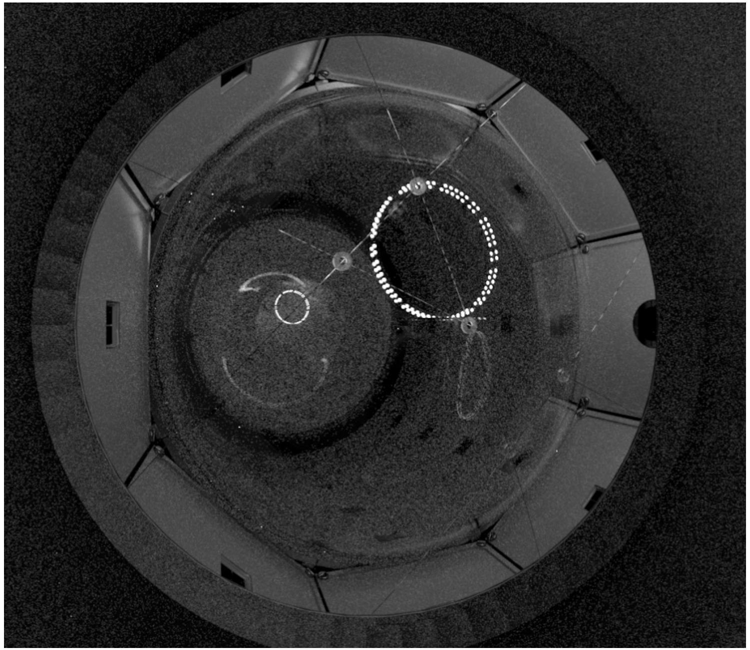

Piezo
IR LED
VUV SiPM
CF4
Ar +
10ppm Xe
130 K
90 K



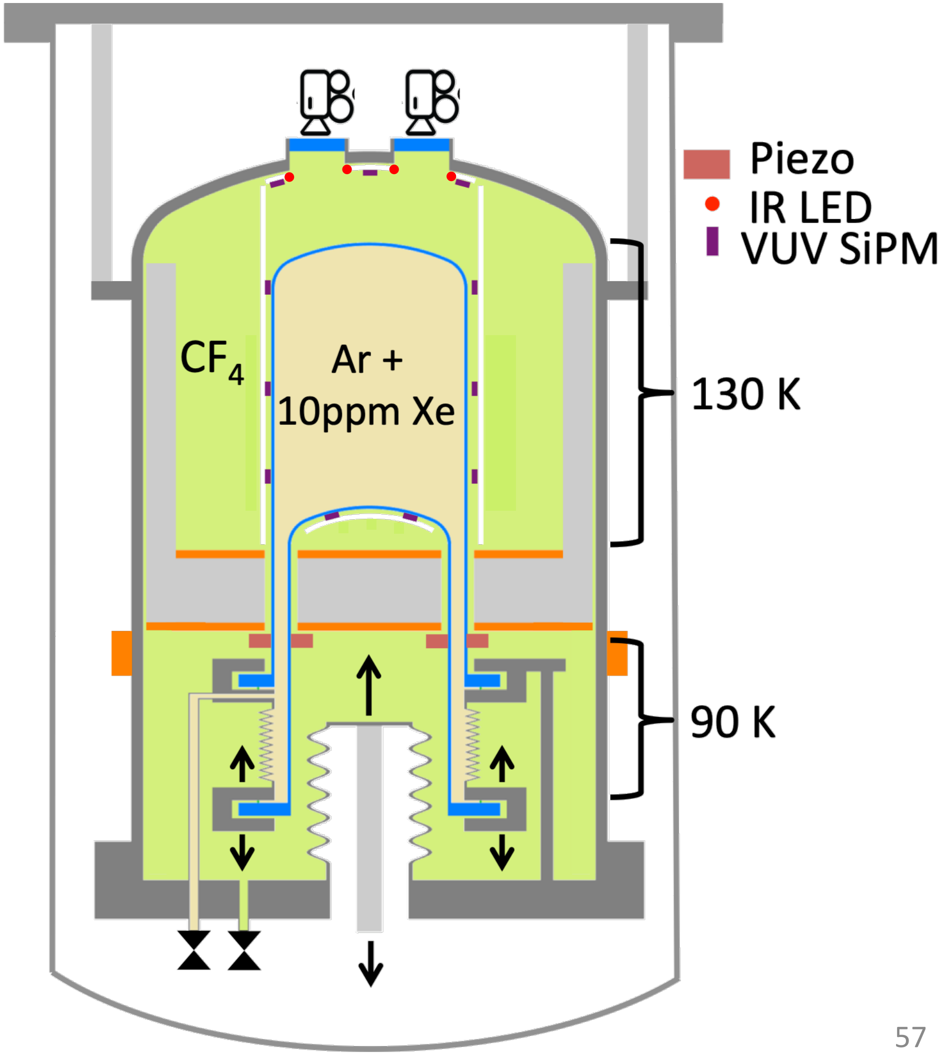
Piezo
IR LED
VUV SiPM
CF4
Ar +
10ppm Xe
130 K
90 K
(Reflection)



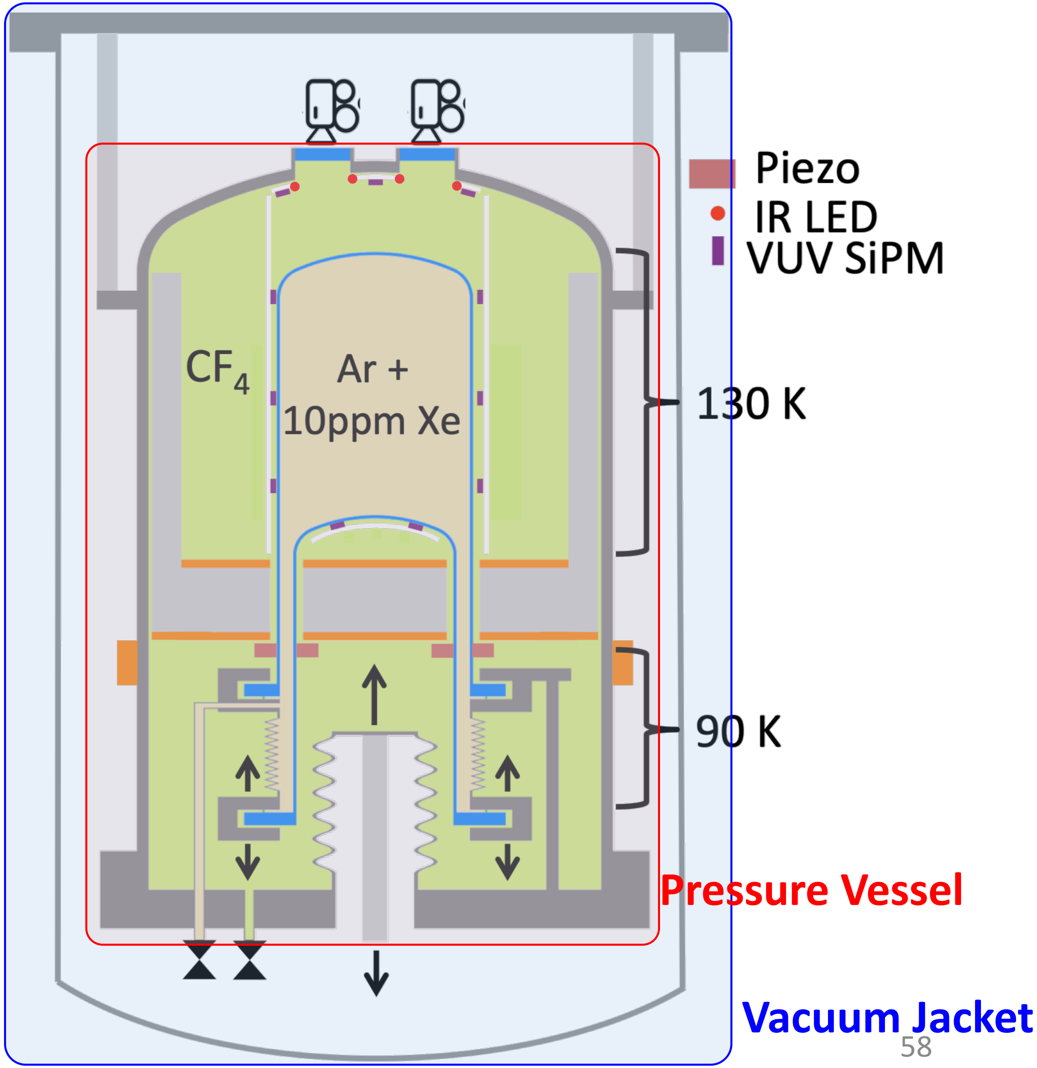
<- Real Image

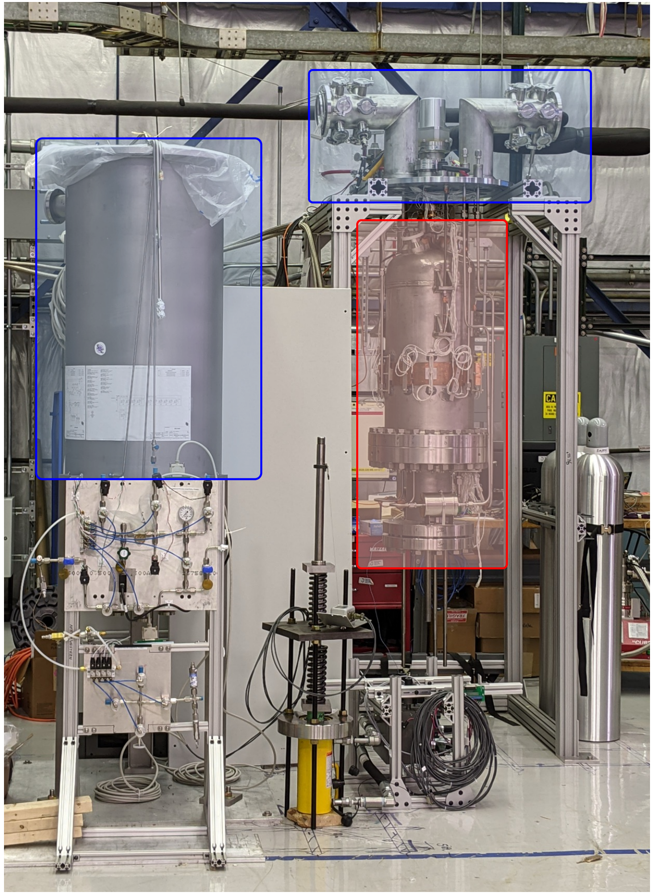


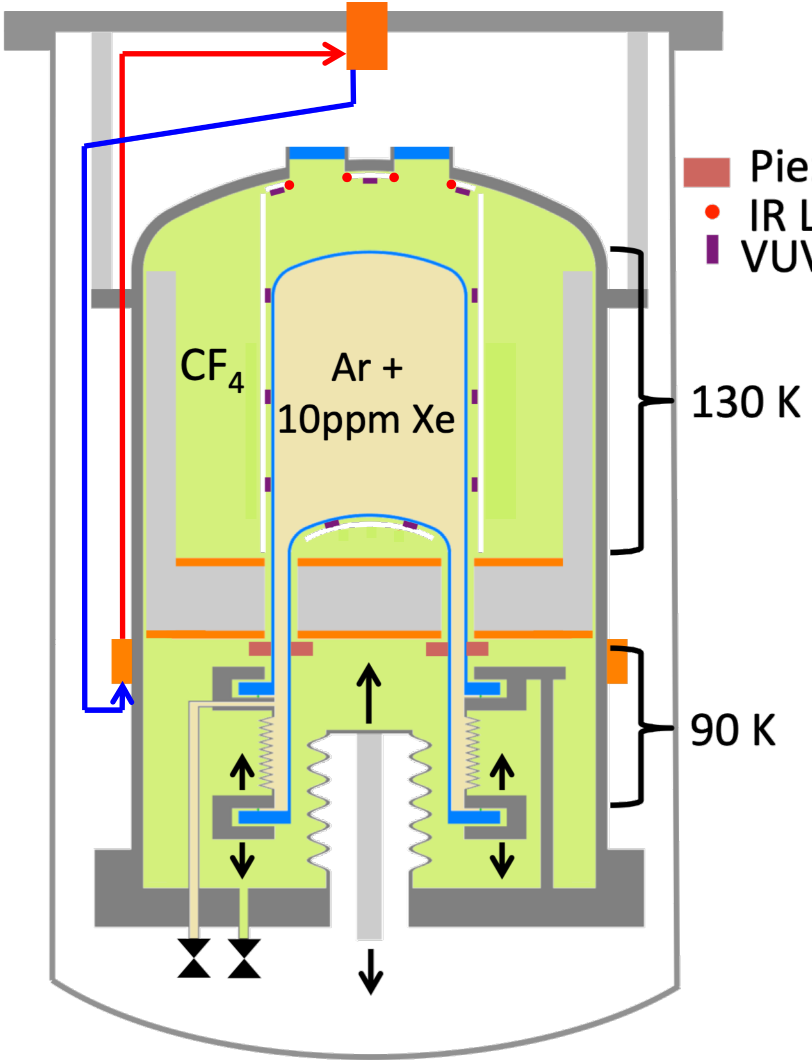
^ Simulated Image
(MA Khatri, Northwestern)



Lab B, Fermilab Silicon Detector Facility

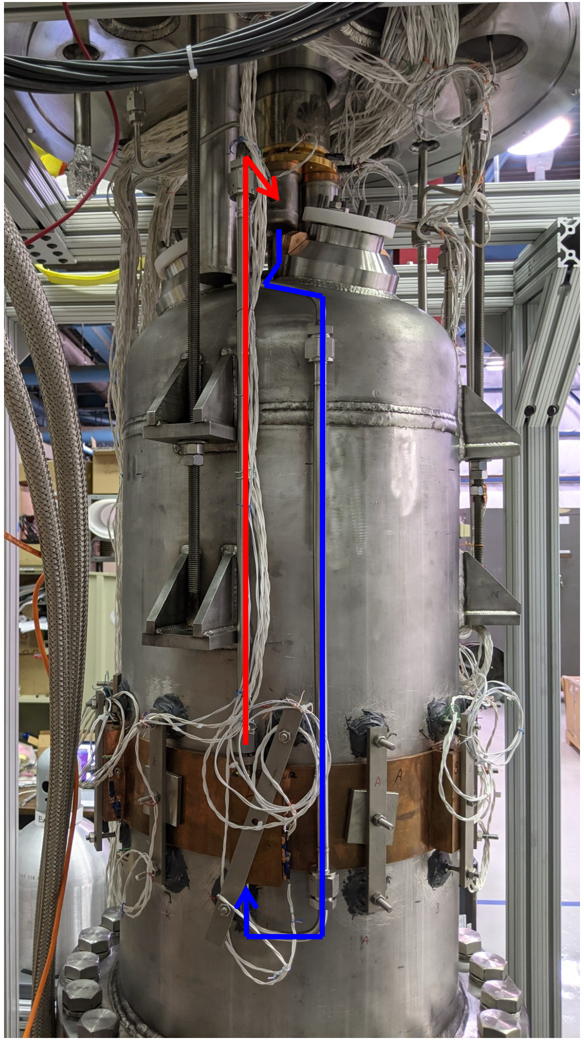

Piezo
IR LED
VUV SiPM
CF_4
Ar +
10ppm Xe
130 K
90 K
Pressure Vessel
Vacuum Jacket

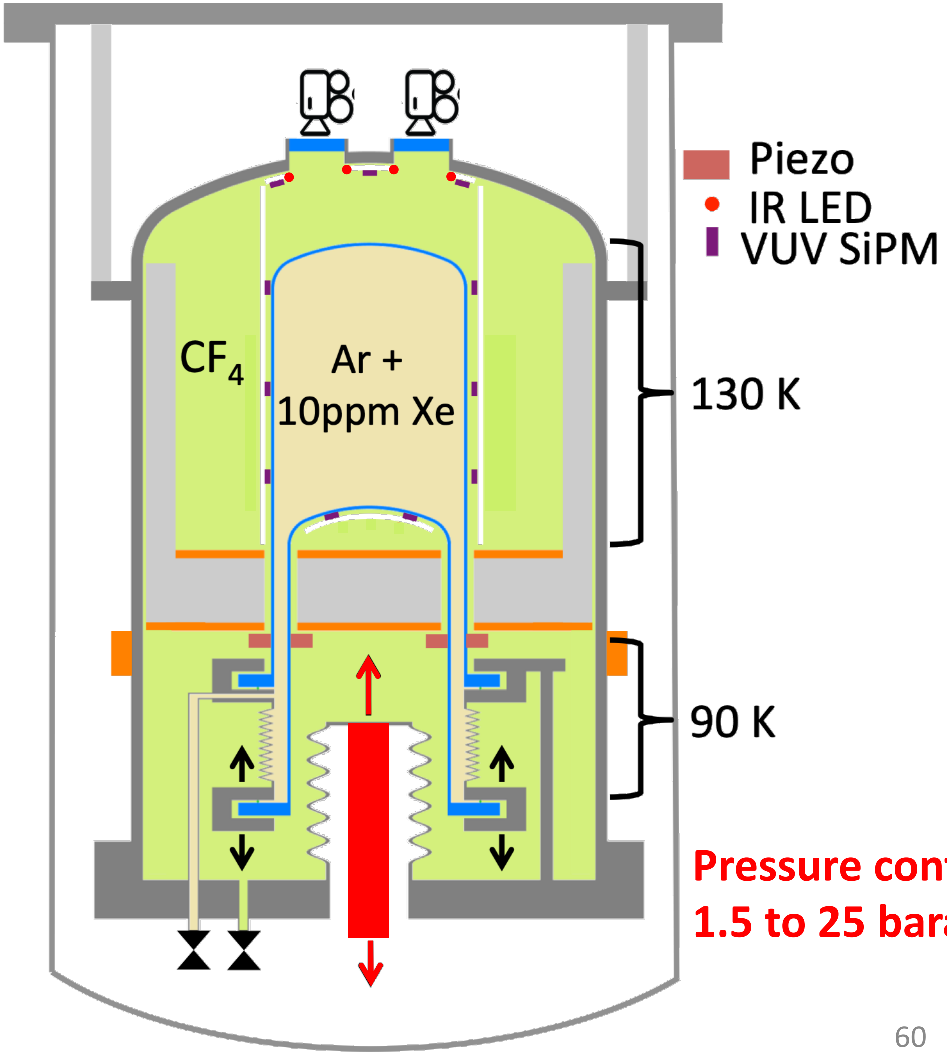




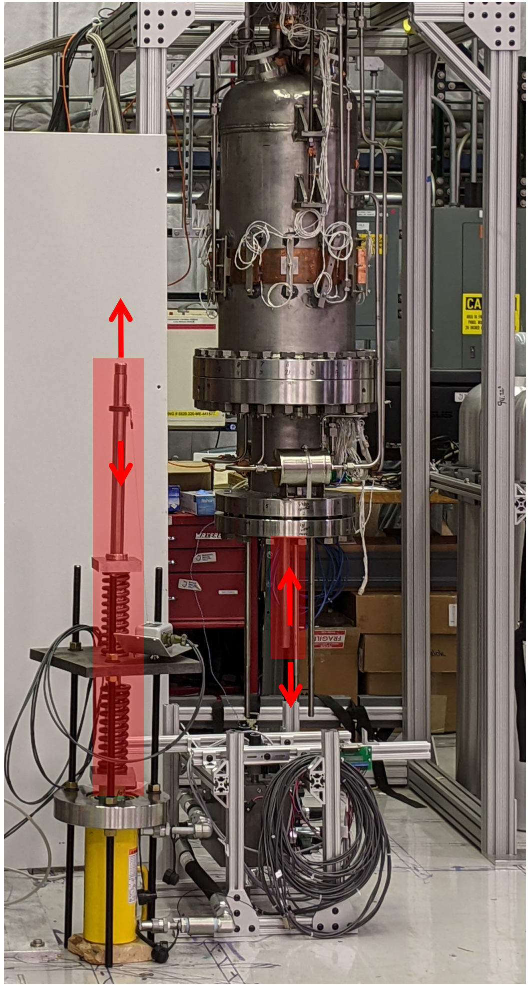
Closed-loop LN_2
Thermosiphons
deliver cooling
where we need it

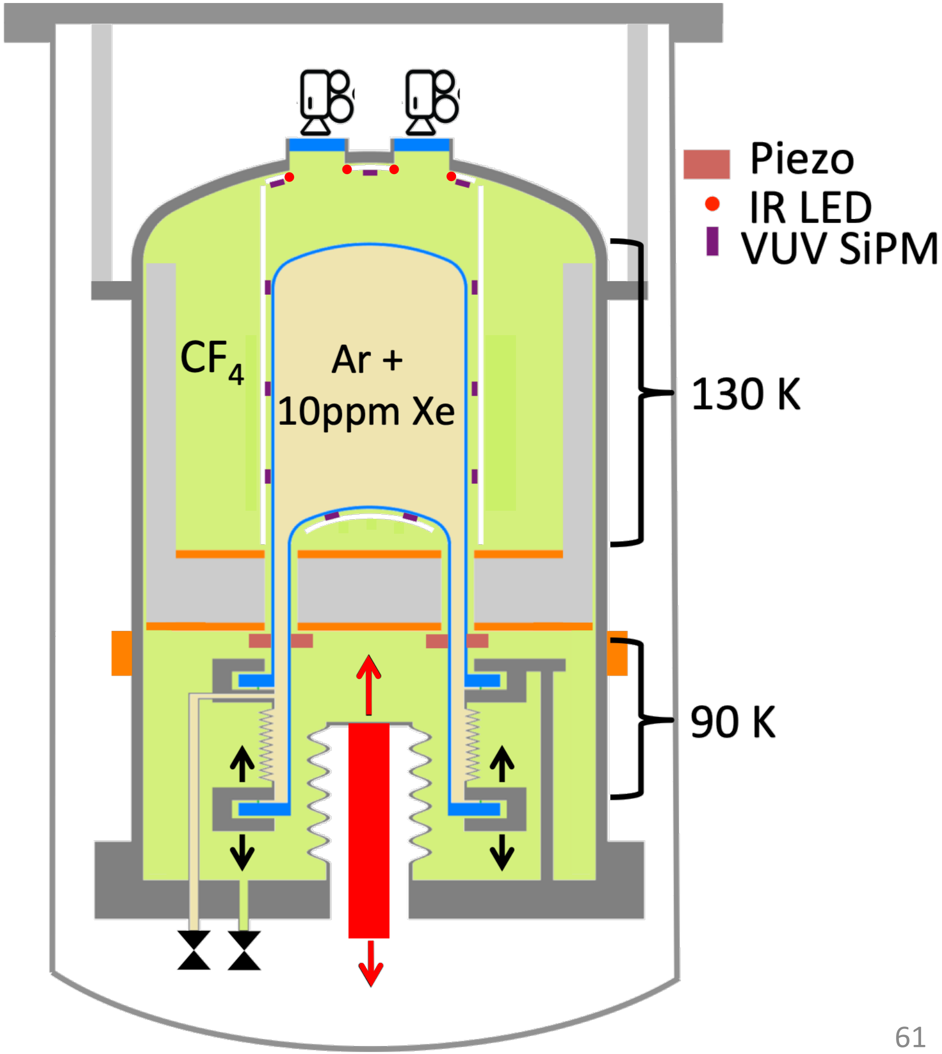
Design/Inspiratio
n Credit: LUX, LZ





Pressure control from 1.5 to 25 bara





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