The Scintillating Bubble Chamber

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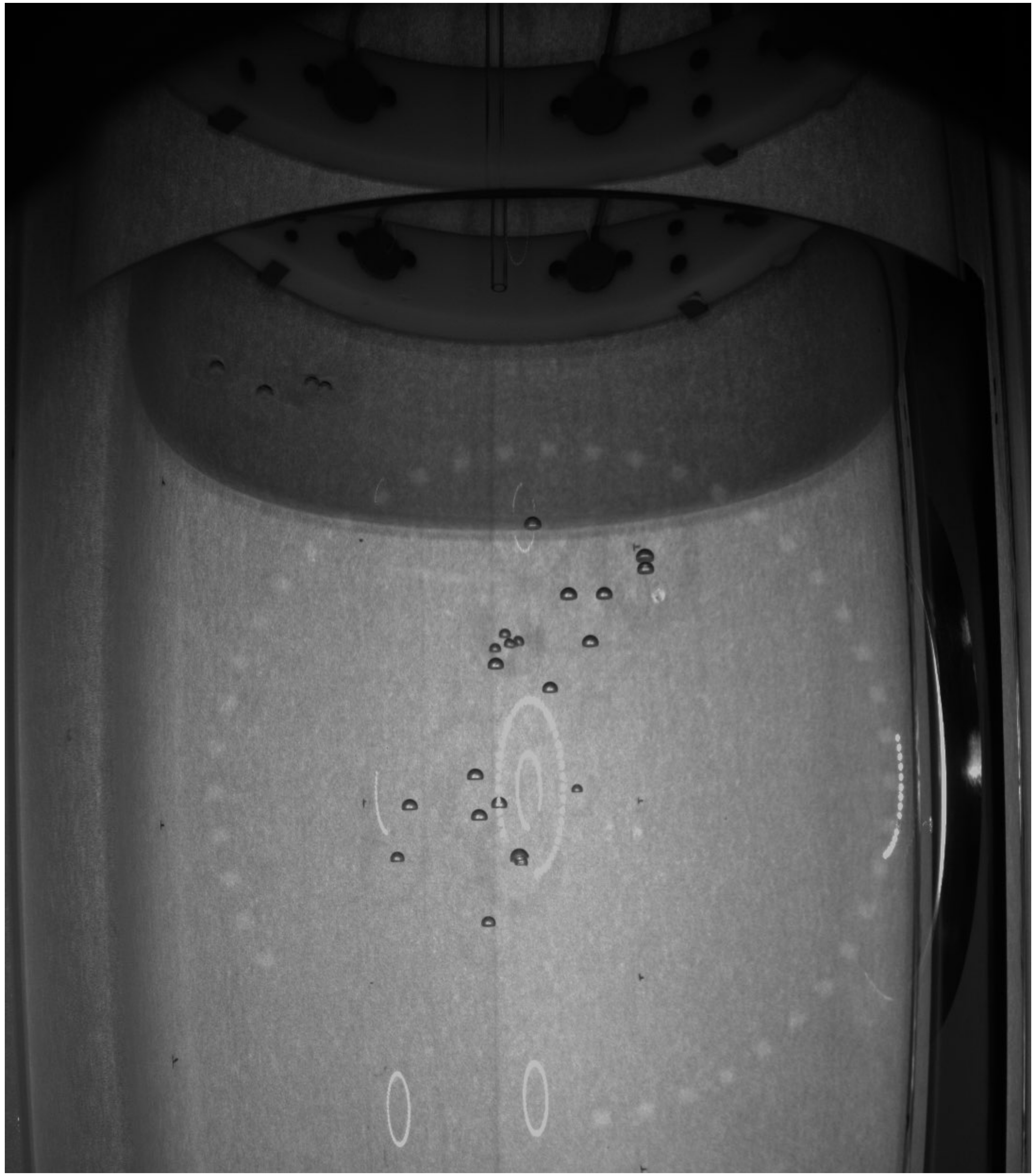
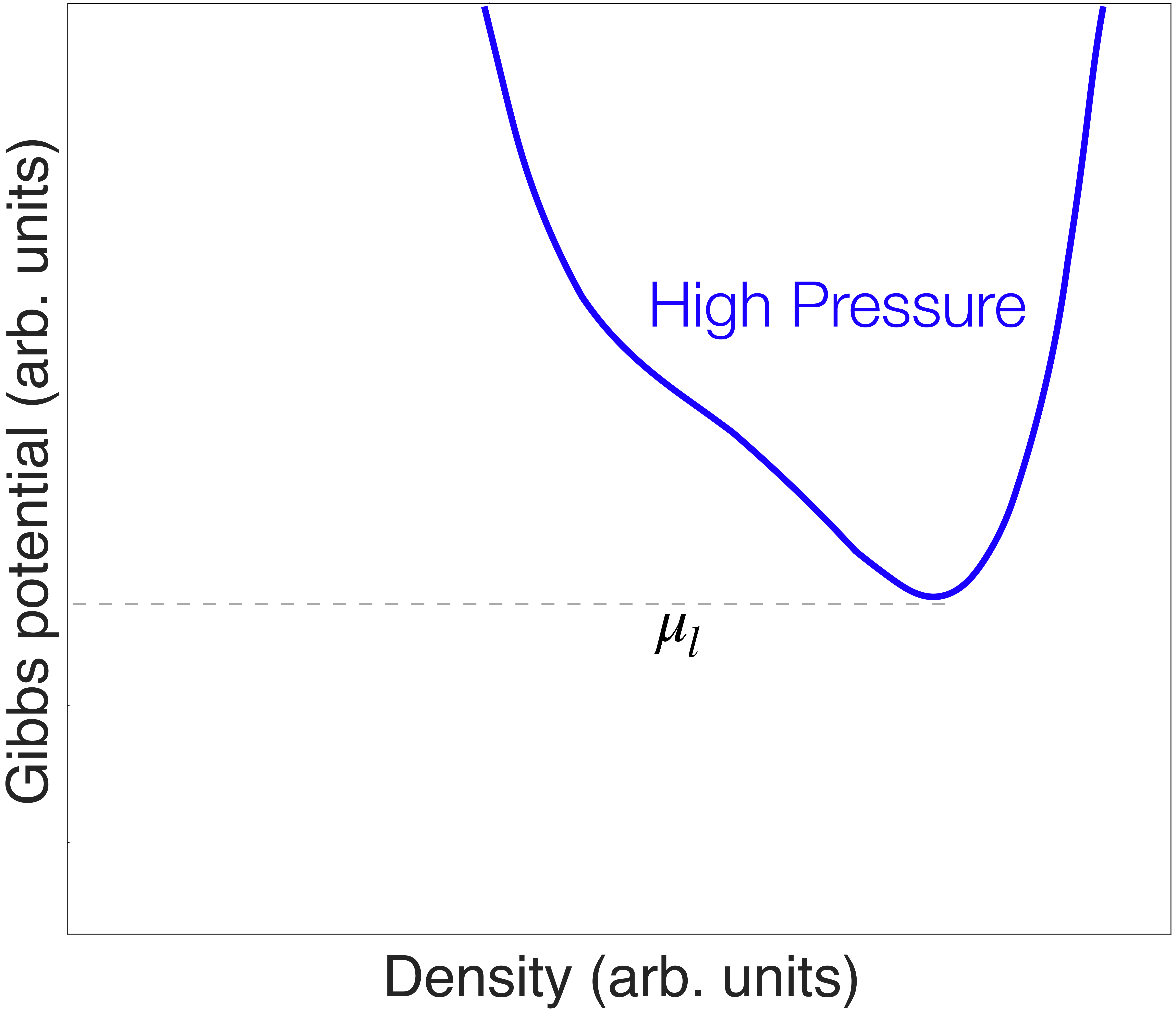
Bubble Chambers



- Long history with particle physics, and even with dark matter
- Particle interaction causes nucleation in superheated fluid
- This grows into a visible (and detectable) bubble
- Chamber can then be recompressed and ready for the next event

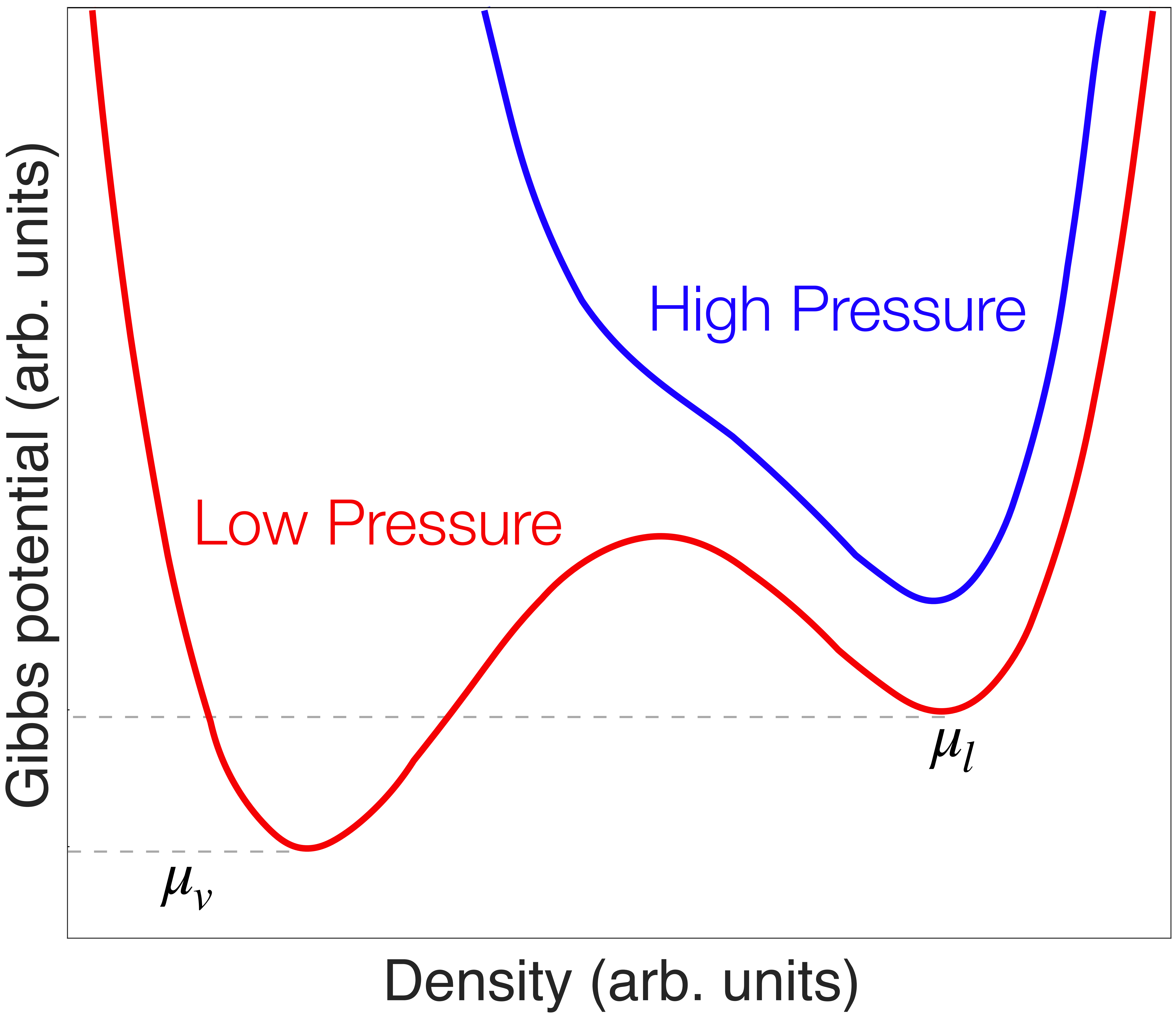
Theory, Graphically

- At high pressure the medium is stable in the liquid state



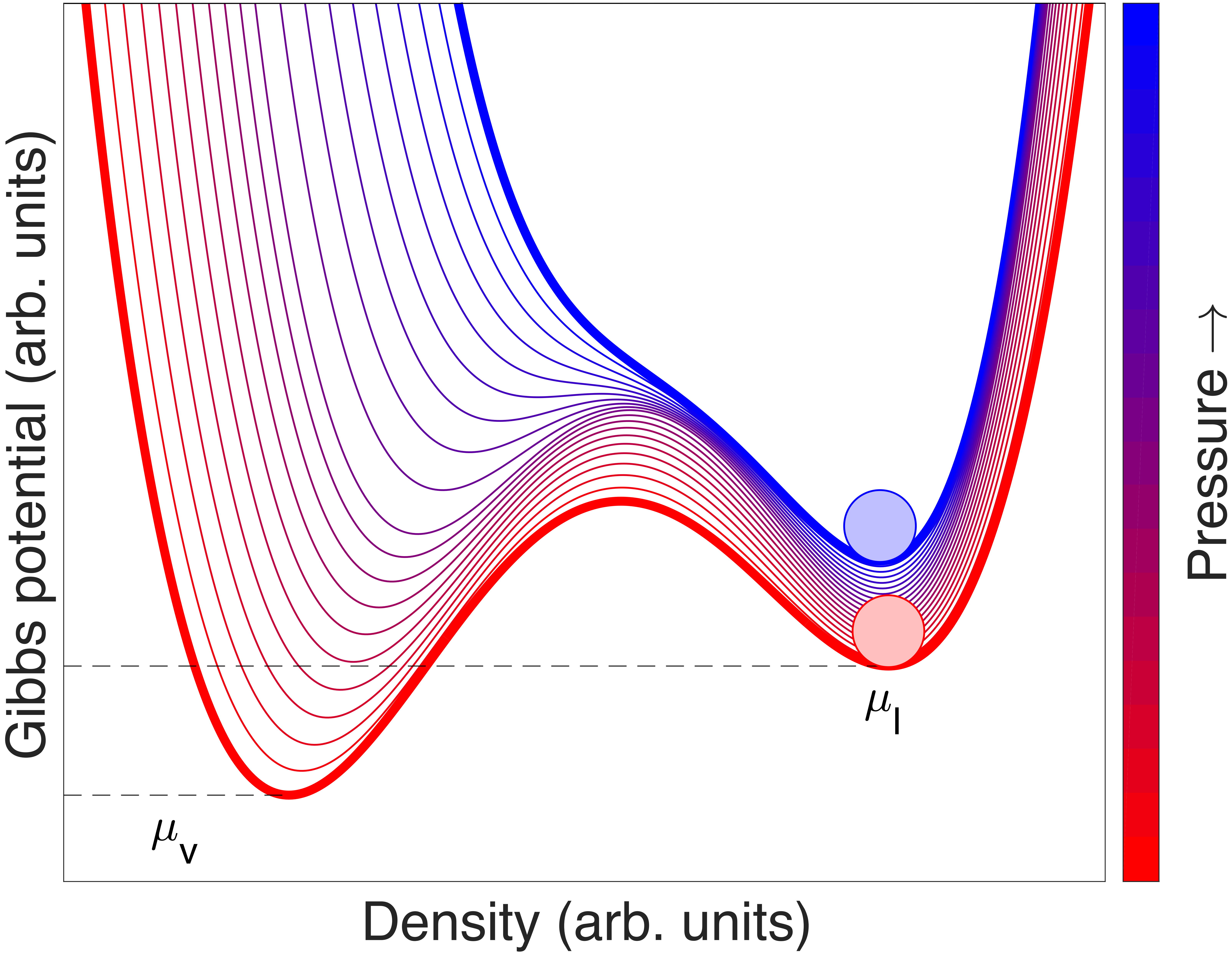
Theory, Graphically

- As the pressure is lowered, this becomes metastable, with a potential threshold to overcome before changing state

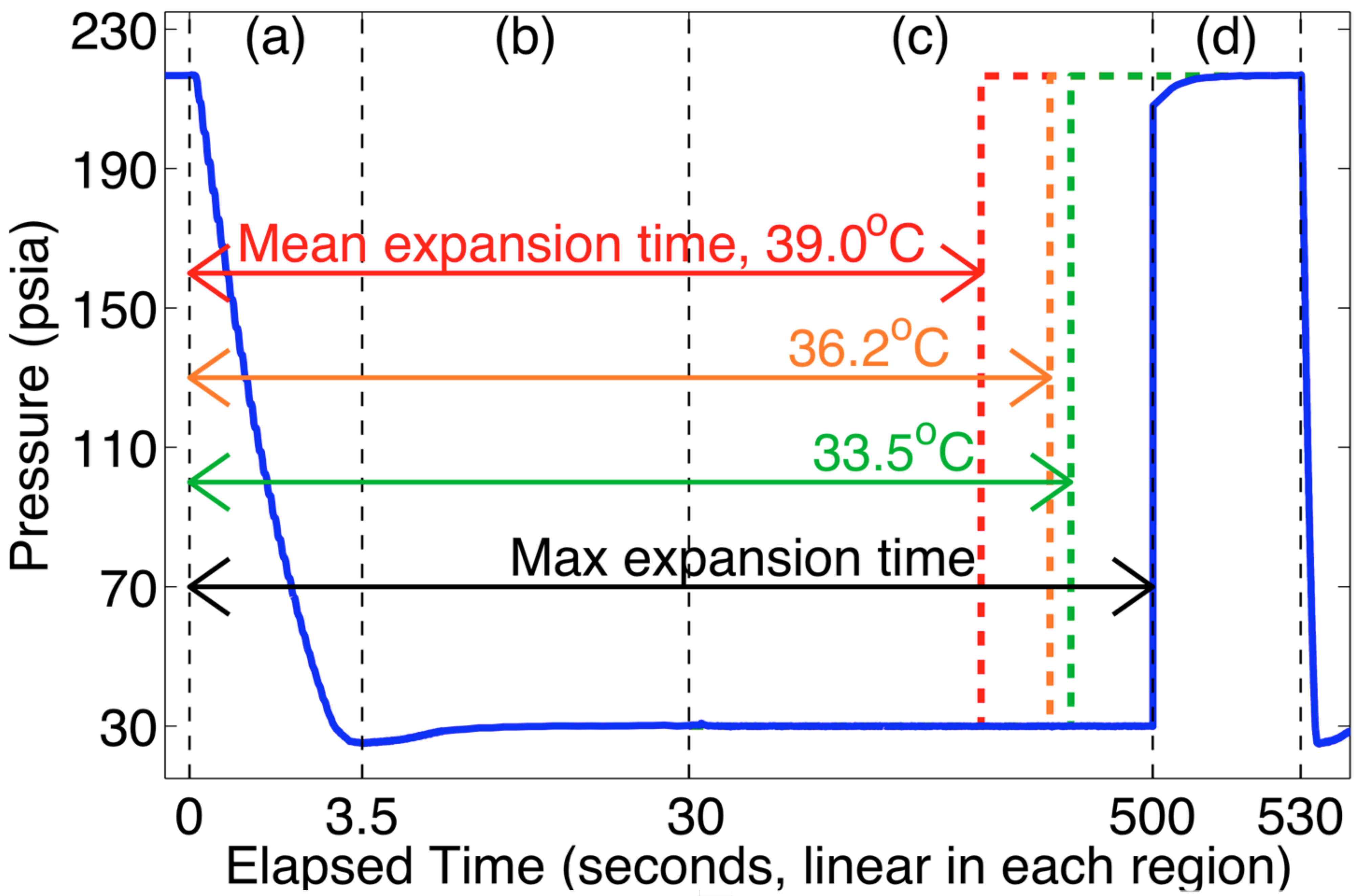


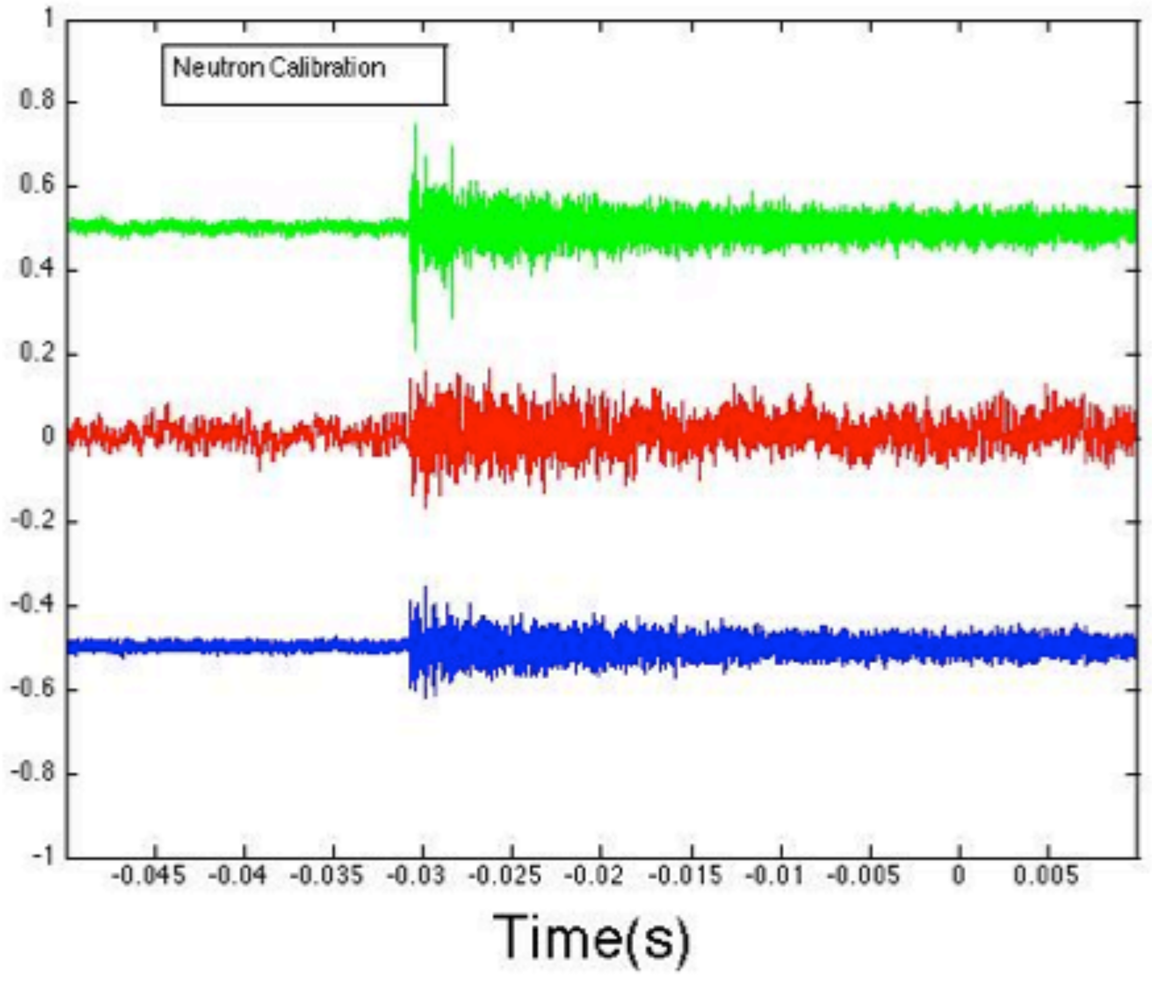
Theory, Graphically

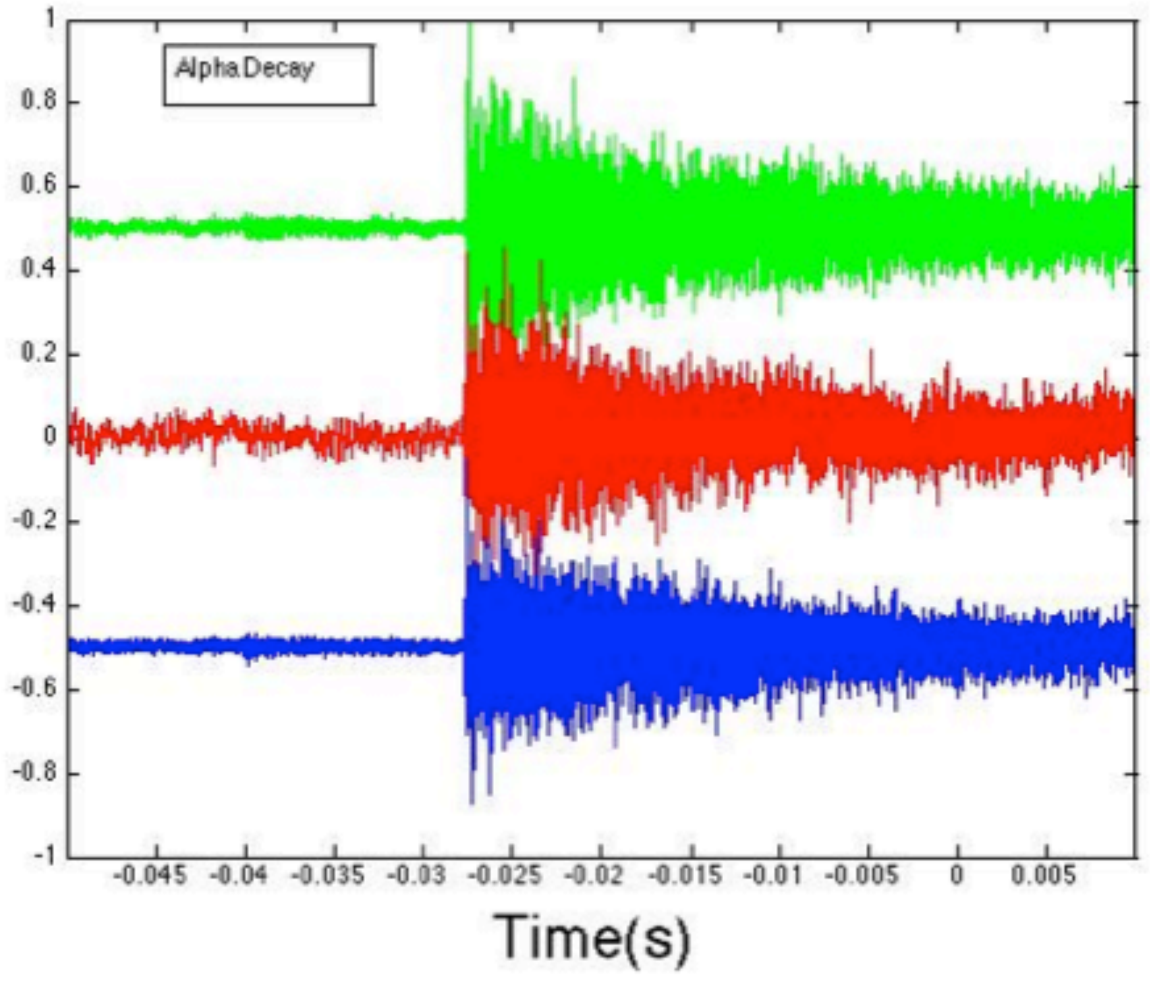
- The potential step is controllable with pressure (or temperature) providing a variable threshold



How Do Bubble Chambers Work?



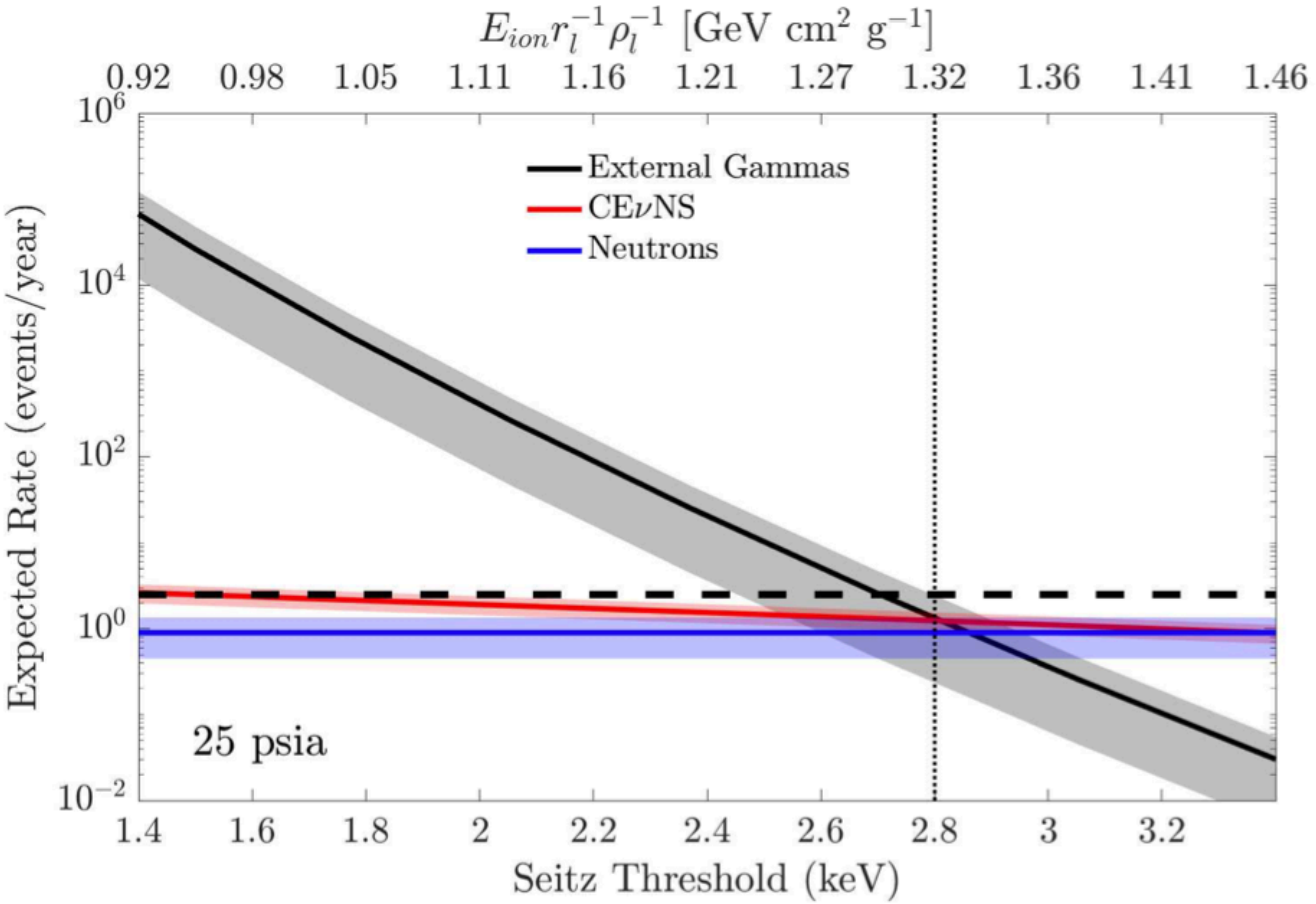




- Detector is made sensitive by depressurizing chamber
- Use video for trigger, acoustically monitor as well
- A trigger causes pressurization to force back into liquid state

Why Use Bubble Chambers for DM?

- The variable threshold has some advantages, and could be useful
- The real advantage is the gamma insensitivity

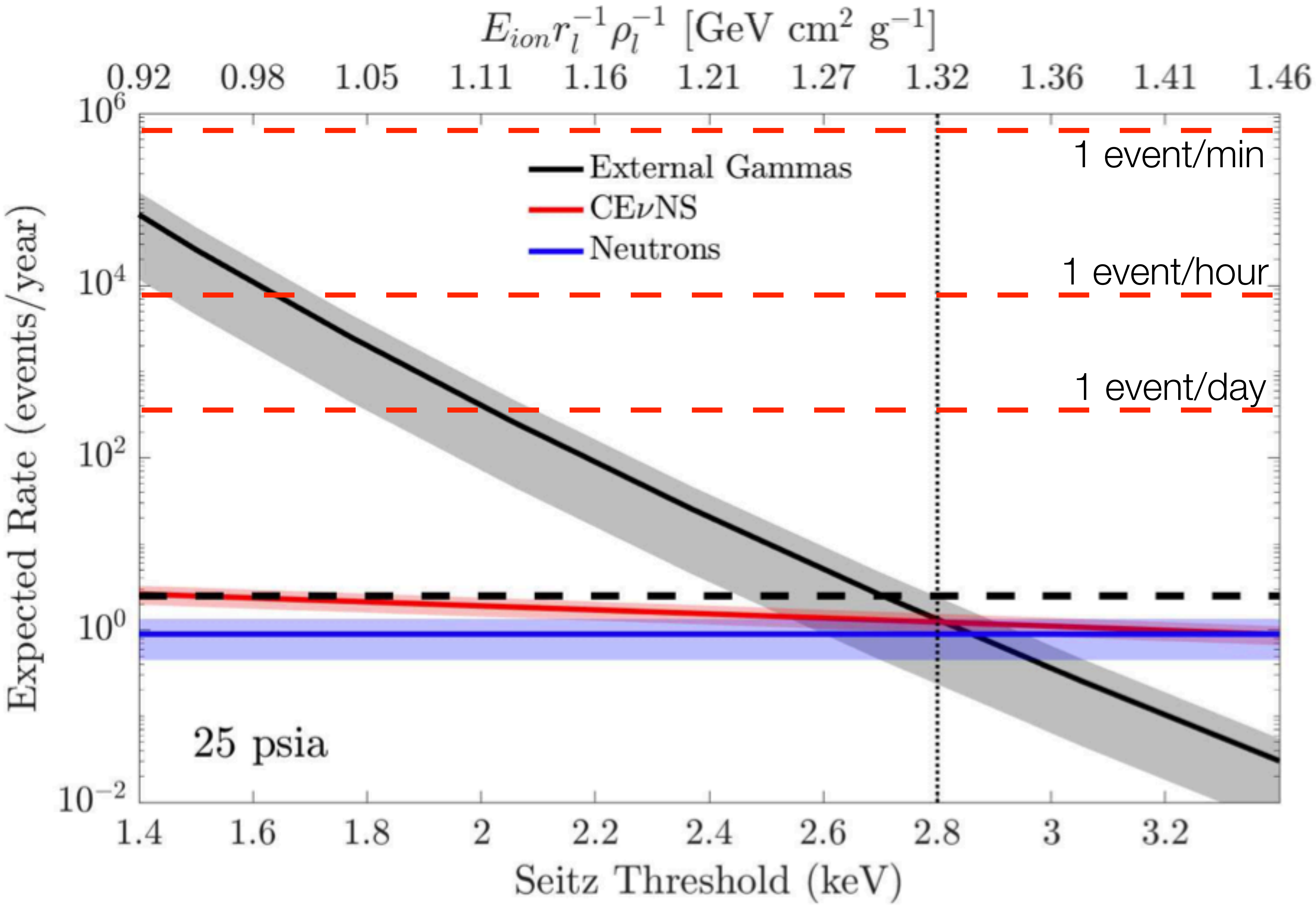


Note: Calculated for PICO 40L detector, horizontal black dashed line is target of 2 events/year

Phys. Rev. D 100, 082006 (2019)

Why Use Bubble Chambers for DM?

- The variable threshold has some advantages, and could be useful
- The real advantage is the gamma insensitivity… at “higher” thresholds



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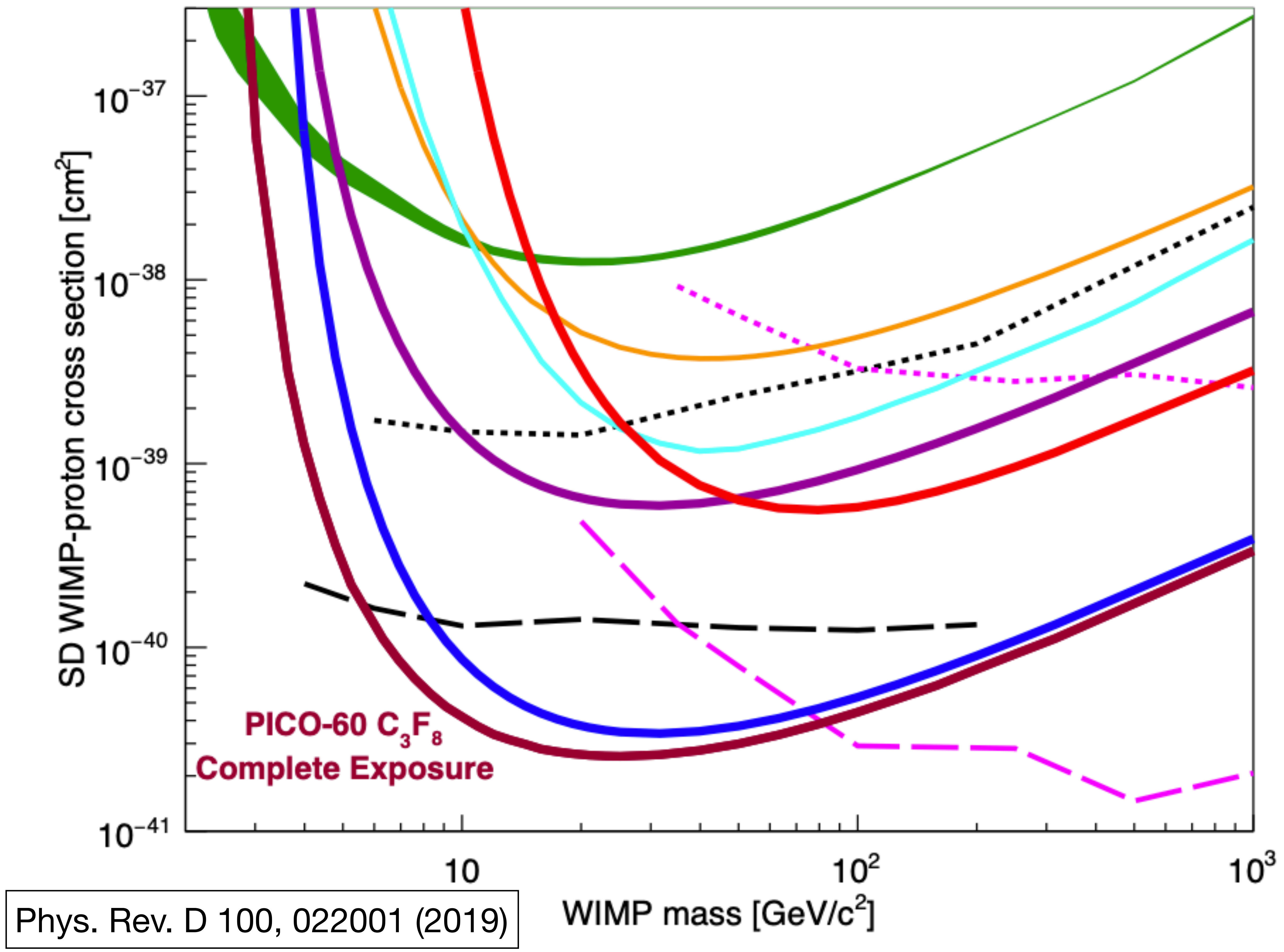
Phys. Rev. D 100, 082006 (2019)

So… how do we lower the threshold?



Phys. Rev. D 100, 022001 (2019)

FIG. 7. The 90% C.L. limit on the SD WIMP-proton cross section from the profile likelihood analysis of the PICO-60 C_3F_8 combined blind exposure plotted in thick maroon, along with limits from the first blind exposure of PICO-60 C_3F_8 (thick blue) [14], as well as limits from PICO-60 CF_3I (thick red) [11], PICO-2L (thick purple) [10], PICASSO (green band) [20], SIMPLE (orange) [21], PandaX-II (cyan) [46], IceCube (dashed and dotted pink) [47], and SuperK (dashed and dotted black) [48, 49]. The indirect limits from IceCube and SuperK assume annihilation to τ leptons (dashed) and b quarks (dotted). Additional limits, not shown for clarity, are set by LUX [51] and XENON1T [53] (comparable to PandaX-II) and by ANTARES [54, 55] (comparable to IceCube).

- In a PICO style bubble chamber there isn’t a good way to do this
- Obviously leads to the significant turn-up at lower WIMP masses
- Changing the target material can help…

Back to the past

- When Glaser was investigating bubble chambers, he made some interesting finds

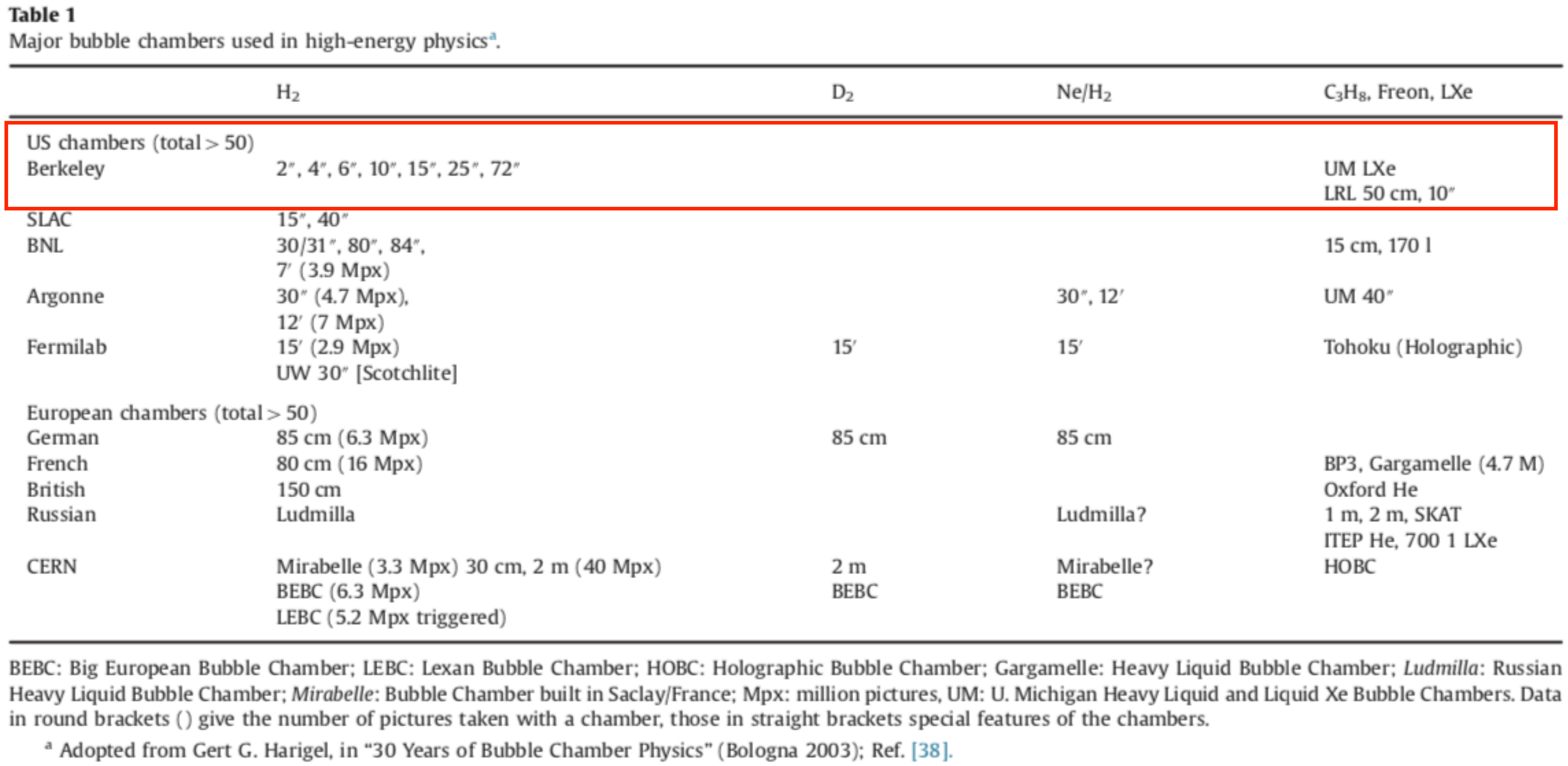


Table 1
Major bubble chambers used in high-energy physics[a].

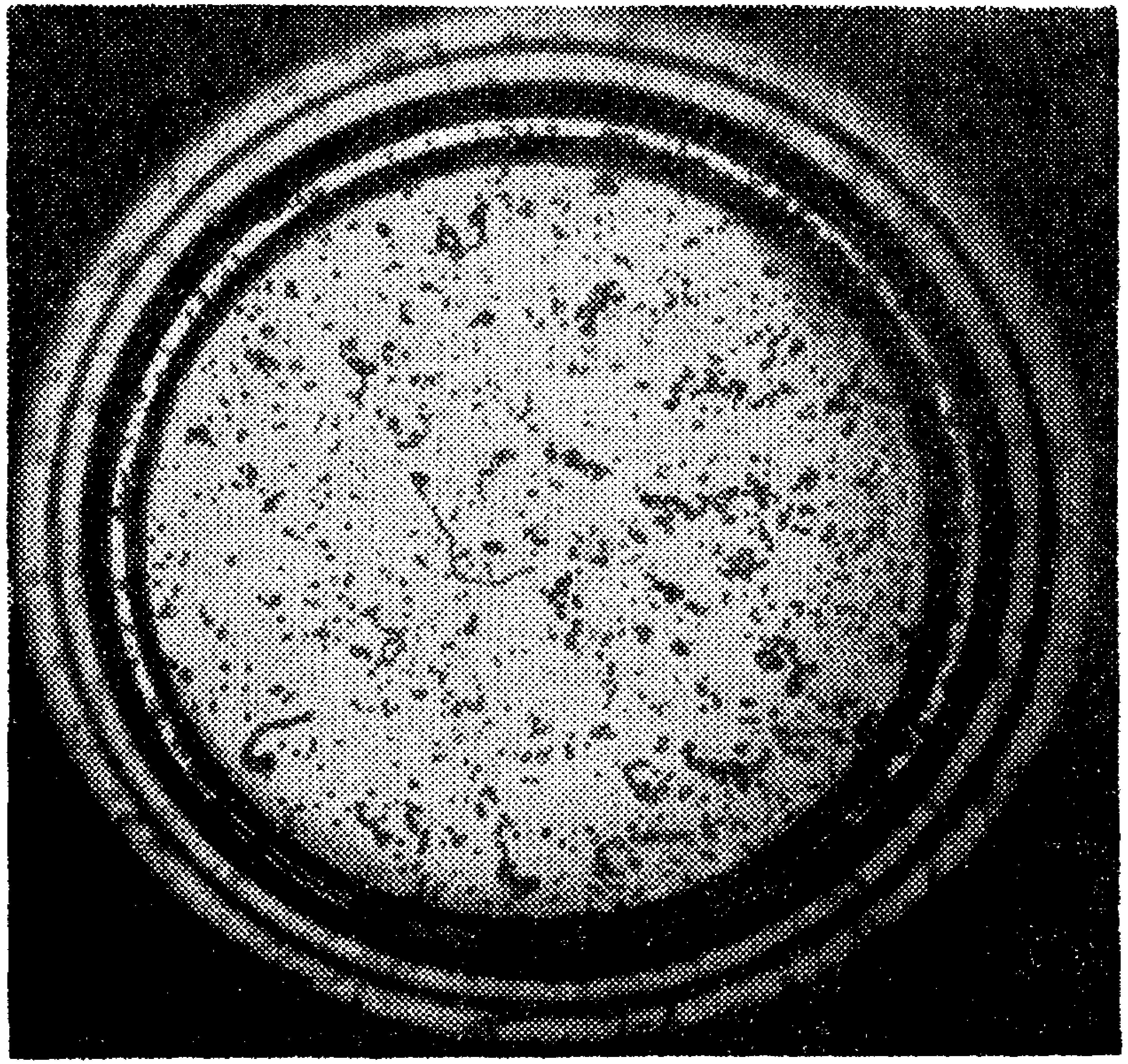
	H_2	D_2	Ne/H_2	C_3H_8, Freon, LXe
US chambers (total > 50)				
Berkeley	2″, 4″, 6″, 10″, 15″, 25″, 72″			UM LXe LRL 50 cm, 10″
SLAC	15″, 40″			
BNL	30/31″, 80″, 84″, 7′ (3.9 Mpx)			15 cm, 170 l
Argonne	30″ (4.7 Mpx), 12′ (7 Mpx)		30″, 12′	UM 40″
Fermilab	15′ (2.9 Mpx) UW 30″ [Scotchlite]	15′	15′	Tohoku (Holographic)
European chambers (total > 50)				
German	85 cm (6.3 Mpx)	85 cm	85 cm	
French	80 cm (16 Mpx)			BP3, Gargamelle (4.7 M)
British	150 cm			Oxford He
Russian	Ludmilla		Ludmilla?	1 m, 2 m, SKAT ITEP He, 700 1 LXe
CERN	Mirabelle (3.3 Mpx) 30 cm, 2 m (40 Mpx) BEBC (6.3 Mpx) LEBC (5.2 Mpx triggered)	2 m BEBC	Mirabelle? BEBC	HOBC

BEBC: Big European Bubble Chamber; LEBC: Lexan Bubble Chamber; HOBC: Holographic Bubble Chamber; Gargamelle: Heavy Liquid Bubble Chamber; *Ludmilla*: Russian Heavy Liquid Bubble Chamber; *Mirabelle*: Bubble Chamber built in Saclay/France; Mpx: million pictures, UM: U. Michigan Heavy Liquid and Liquid Xe Bubble Chambers. Data in round brackets () give the number of pictures taken with a chamber, those in straight brackets special features of the chambers.

[a] Adopted from Gert G. Harigel, in "30 Years of Bubble Chamber Physics" (Bologna 2003); Ref. [38].

History of the bubble chamber and related active- and internal-target nuclear tracking detectors, F.D. Becchetti, NIMA 784 (2015) 518-523

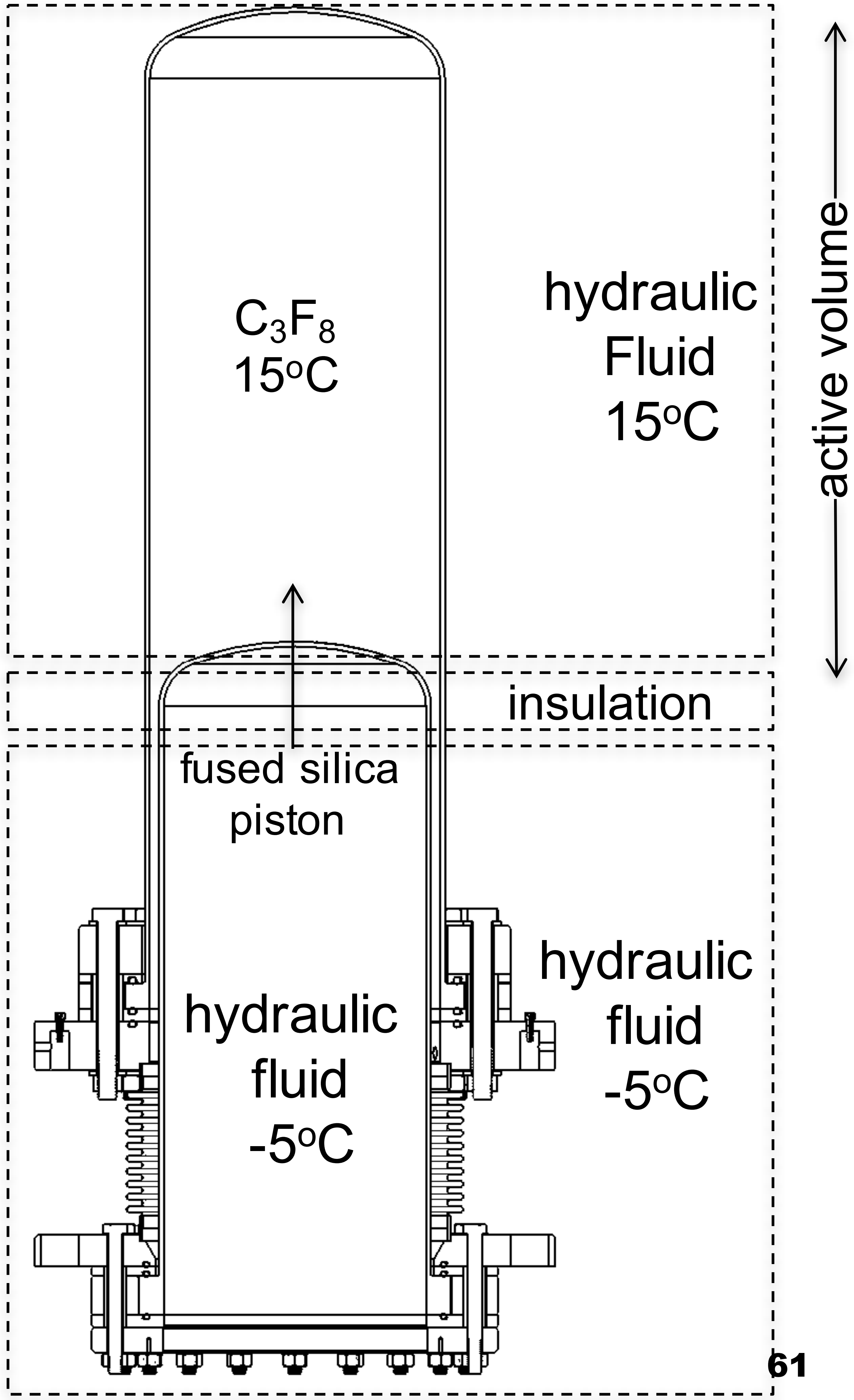
Back to the past



Phys. Rev. 102, 586 (1956)

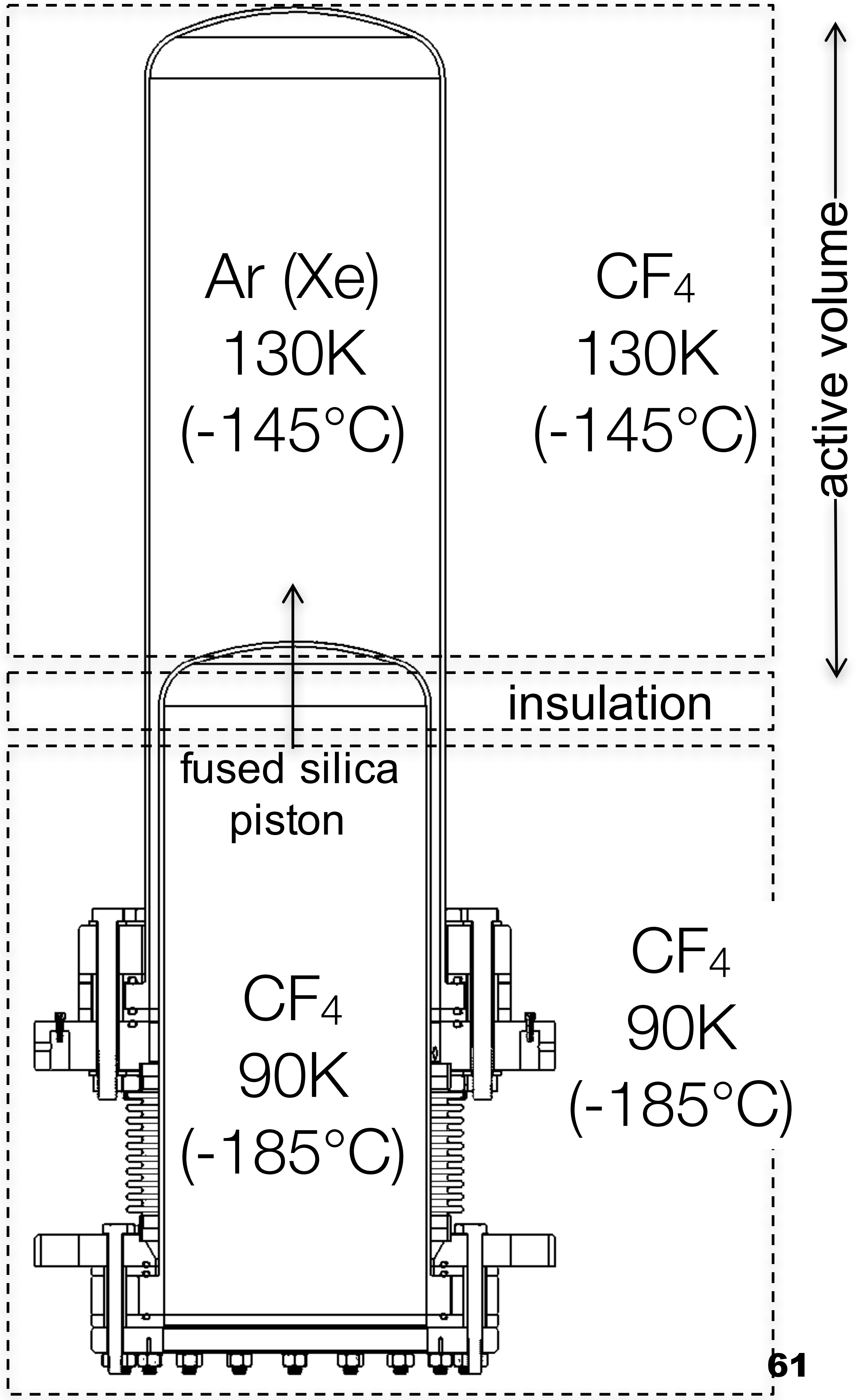
- In 1956, Glaser made a xenon bubble chamber
    - No bubbles in pure xenon even at 1keV threshold with gamma source
    - Normal production in 98% xenon + 2% ethylene (scintillation completely quenched)
- Scintillation suppresses bubble nucleation (?)

How will we do this?



PICO 40L

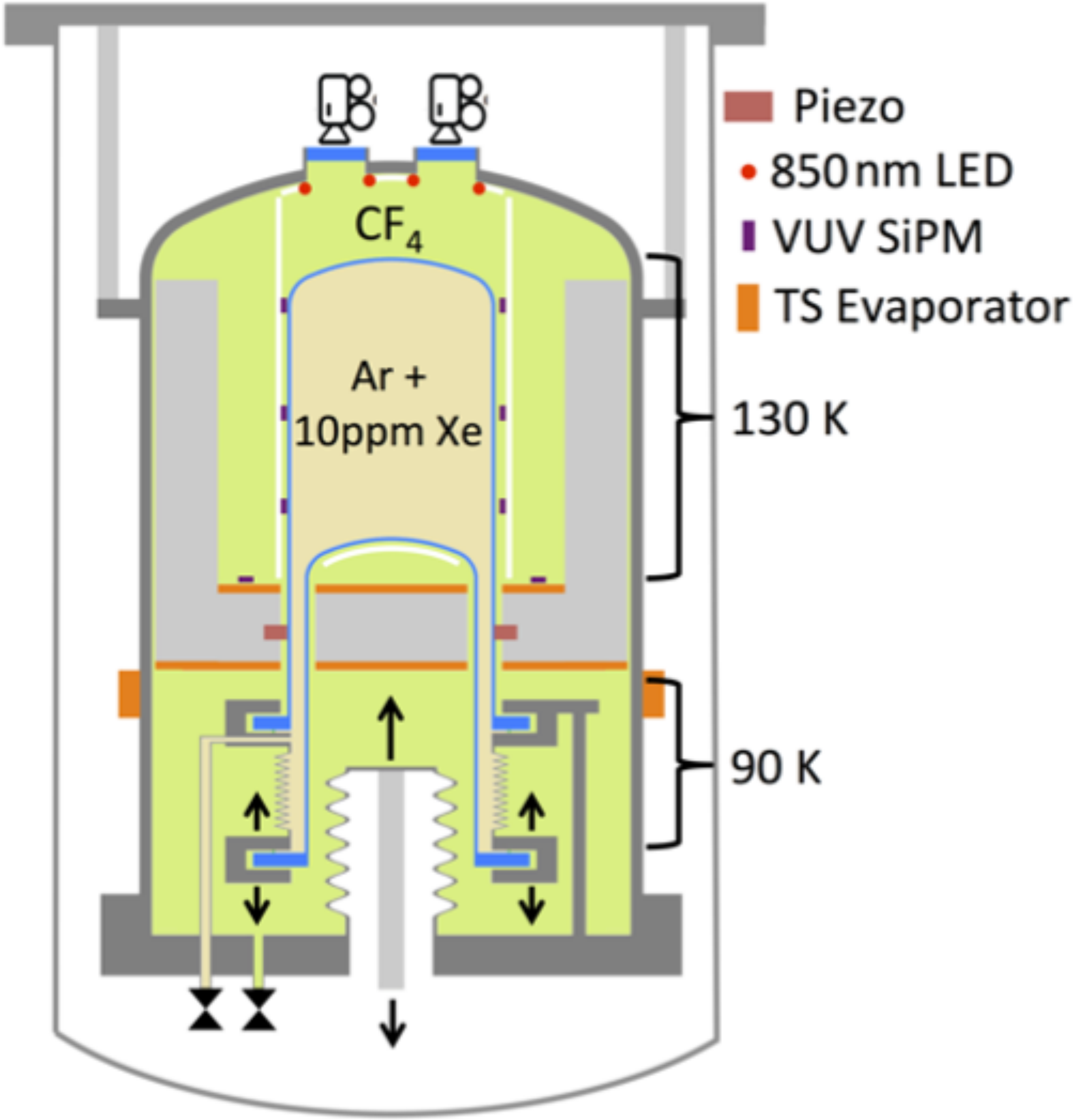
→



SBC

How will we do this?

- Roughly 10kg of argon
- SiPMs used for scintillation detection
- Much of the internal detail modelled on PICO 500
- “Only” added challenge is to keep it cold



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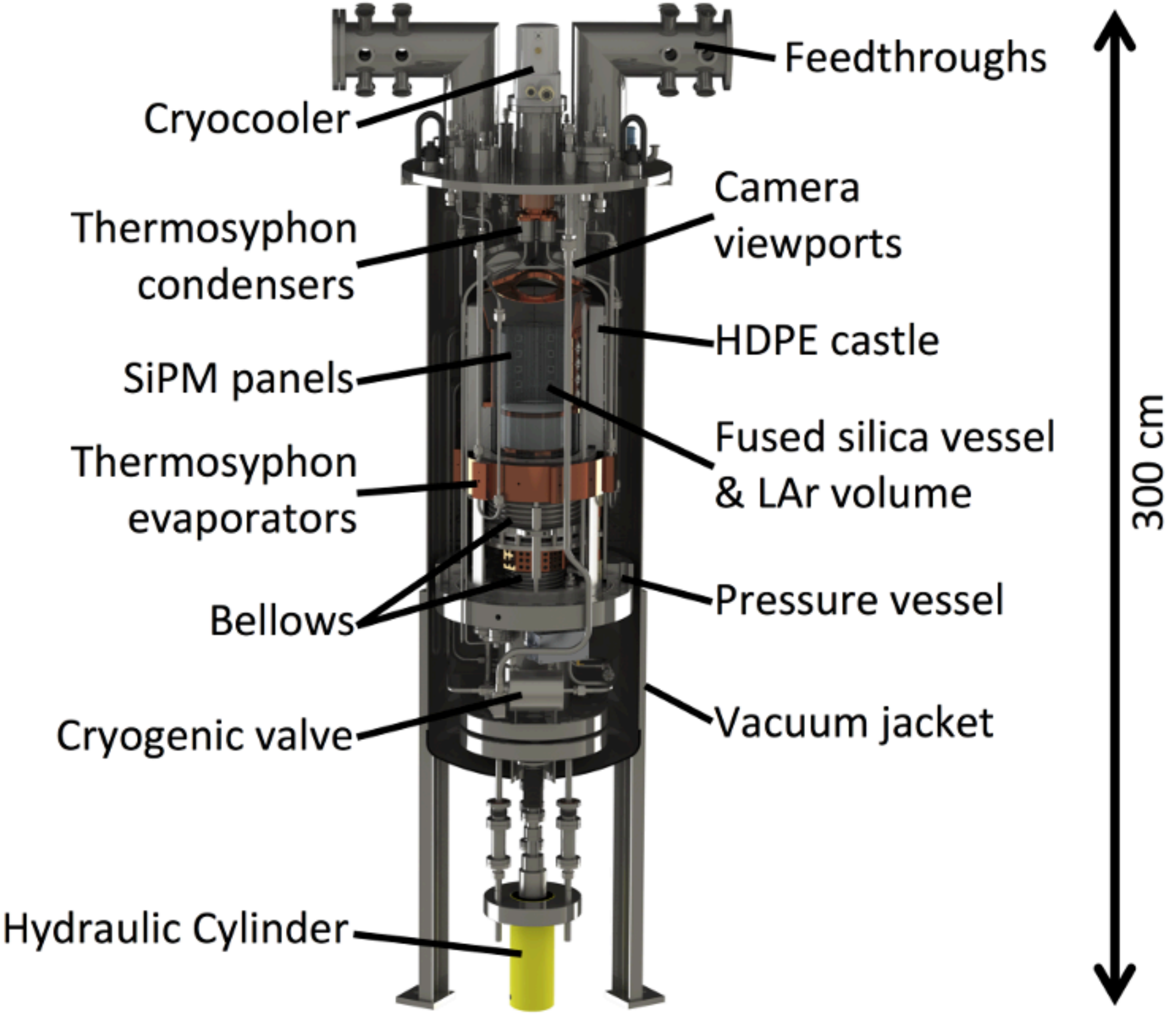
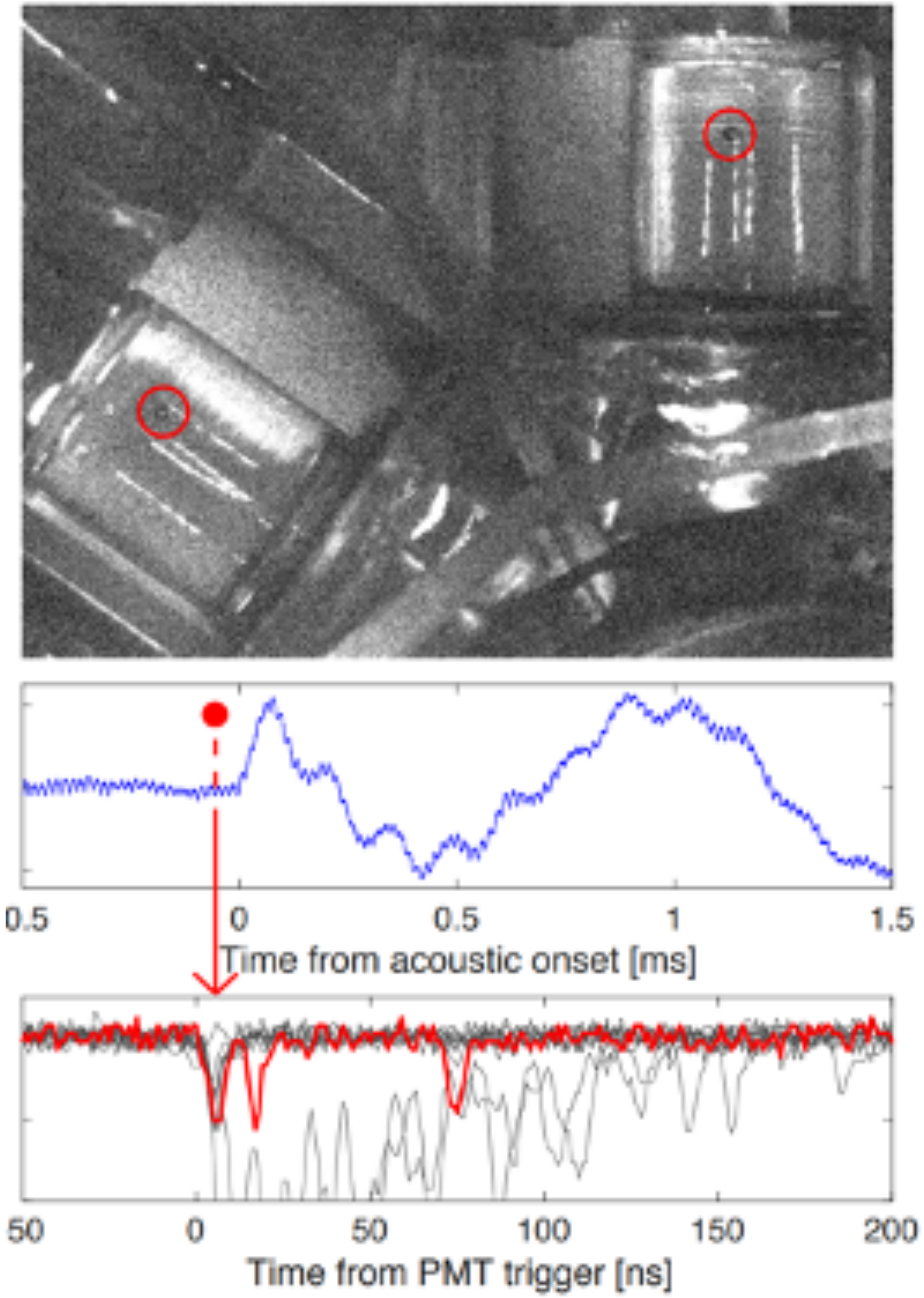
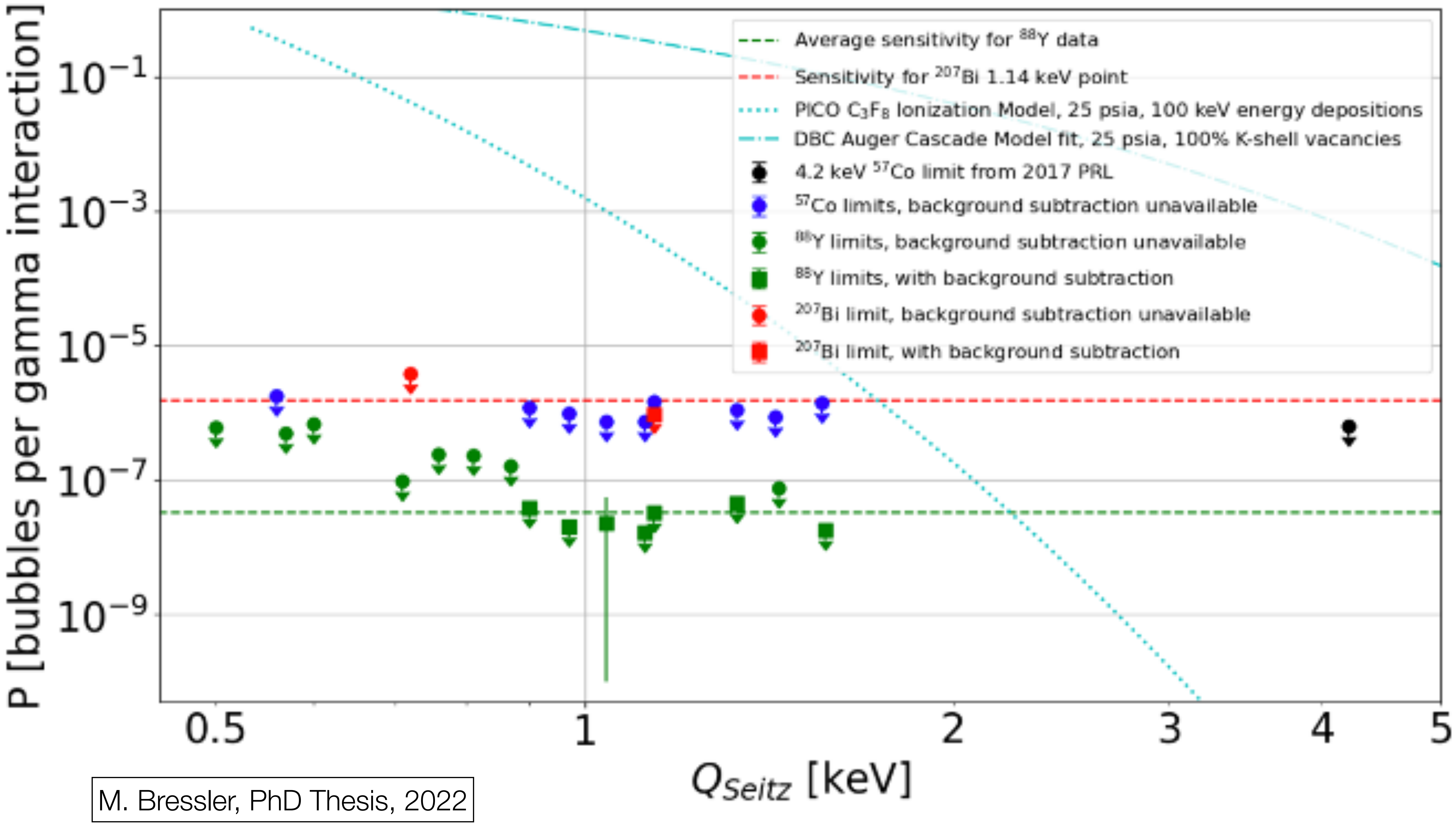


Why do we think this will work?



- This has been tried with a very small xenon bubble chamber at Northwestern
- Results were successful, and backed up what Glaser had suspected

Why do we think this will work?

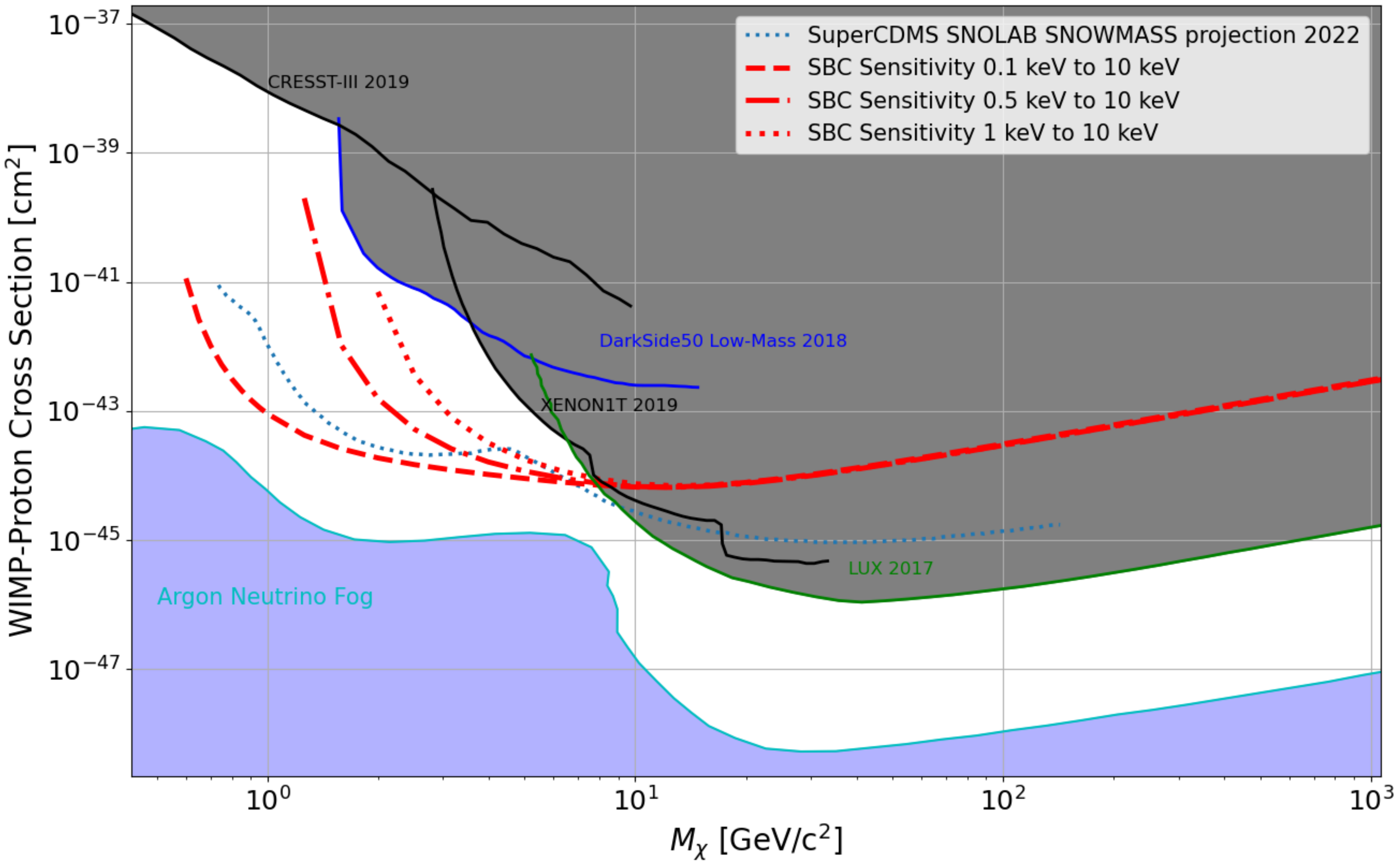


M. Bressler, PhD Thesis, 2022

- Actual data from the chamber filled with LXe
- Only found upper limits as far as threshold could be pushed

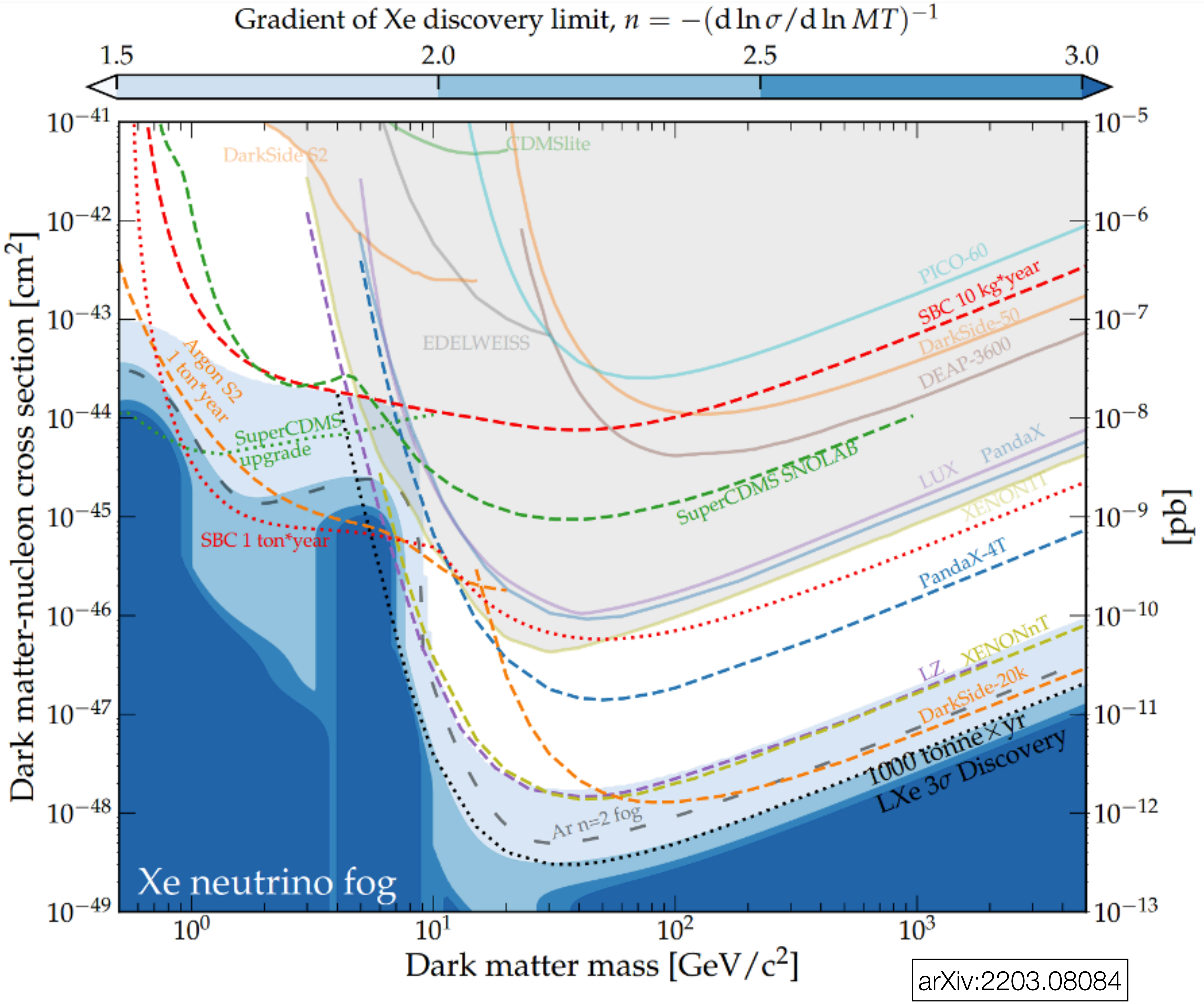
Threshold effects

- Lowering the threshold opens up significant area in the low mass search
- Note this assumes only CEvNS backgrounds and 10kg-year live time



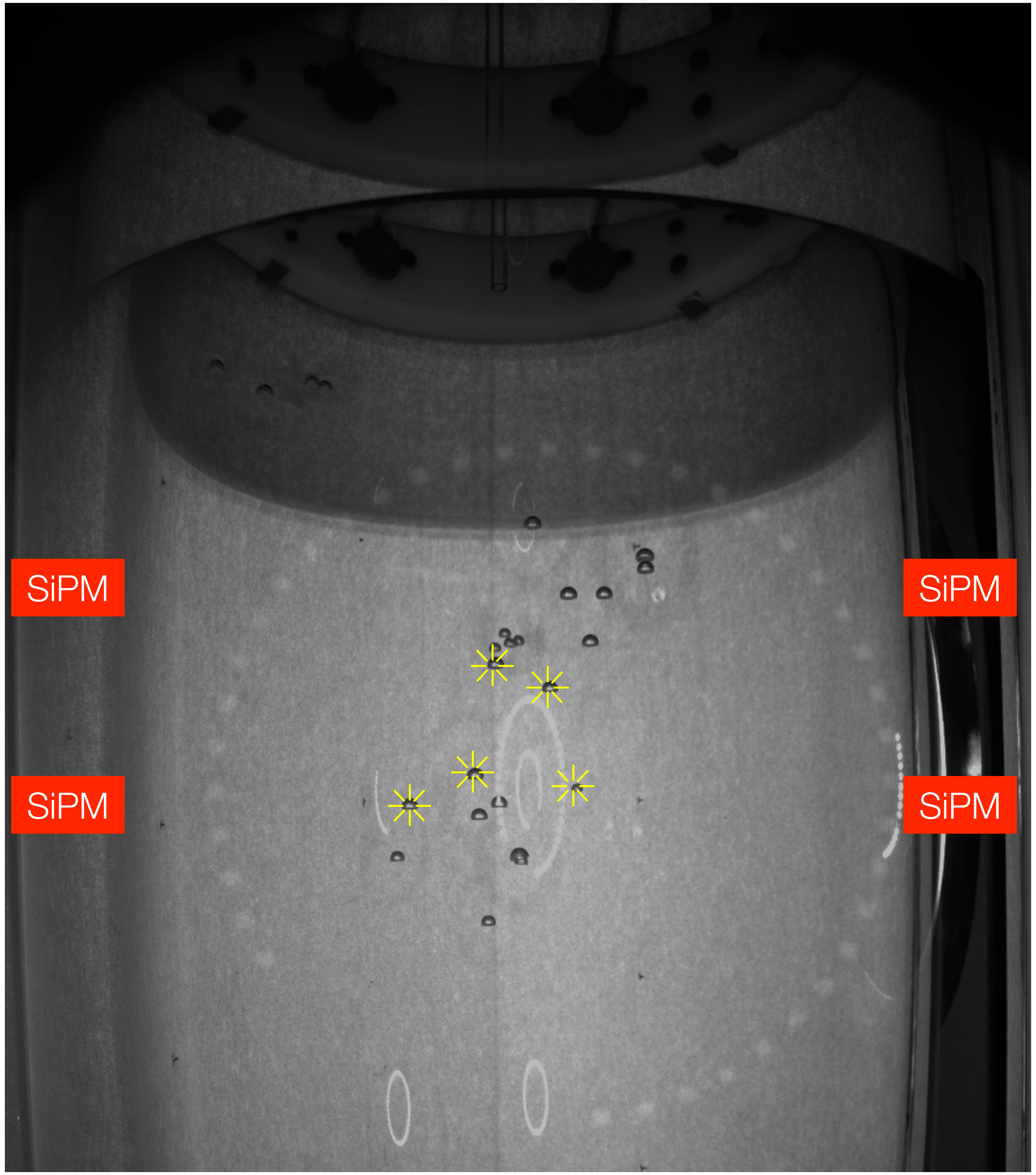
Limit Projections

- If you wanted a more complicated plot, we've got you covered there too
- Note the lower threshold (100eV) is assumed
- Also shown is a "potential" next step



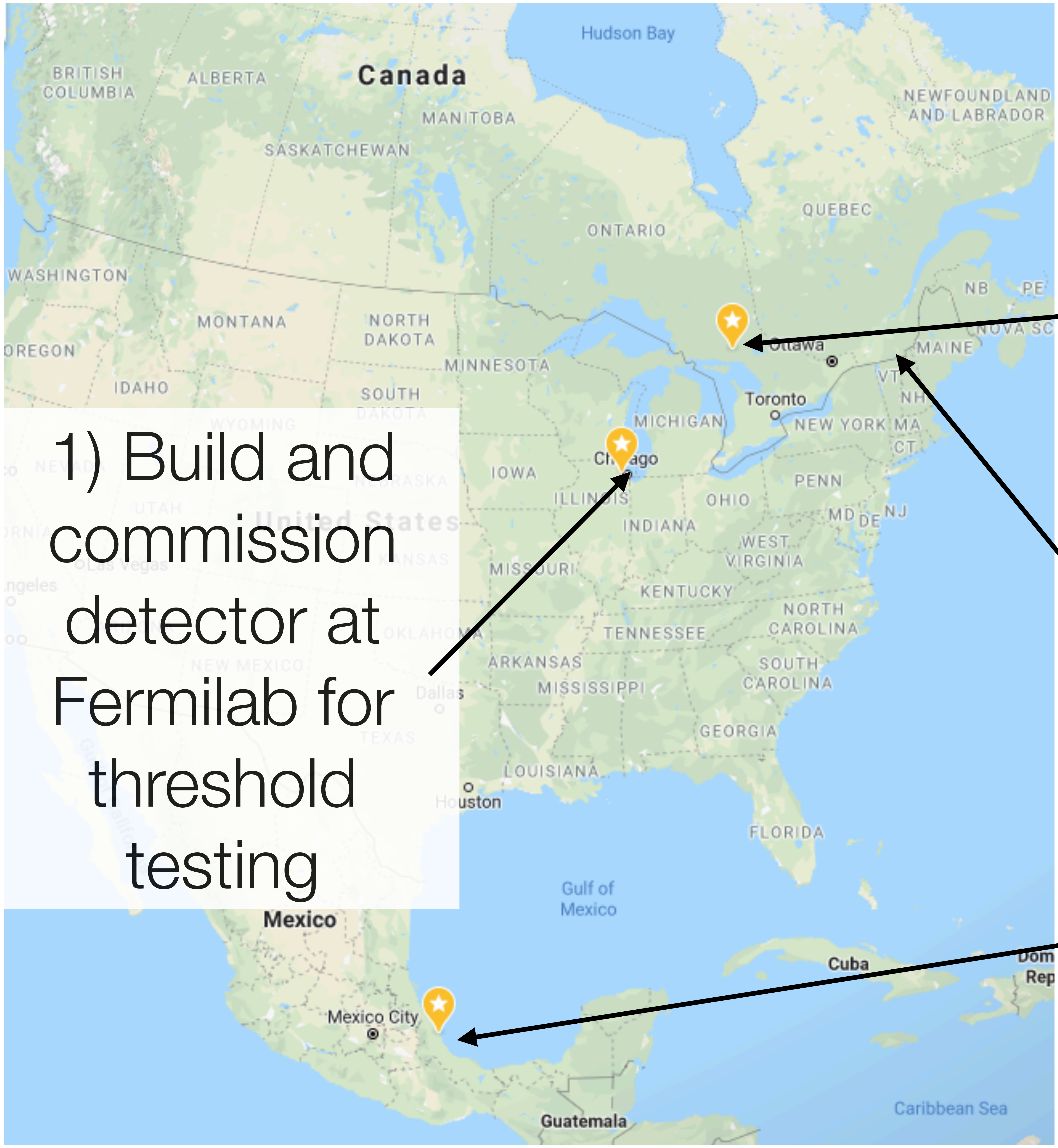
arXiv:2203.08084

Further Advantages



- NRs make bubbles with coincident scintillation
- Scintillation detection threshold above bubble threshold
    - (~1 phd / 5 keVr)
- Useful as veto of high-energy events
- We’ll come back to this a bit later…

Collaboration Plan



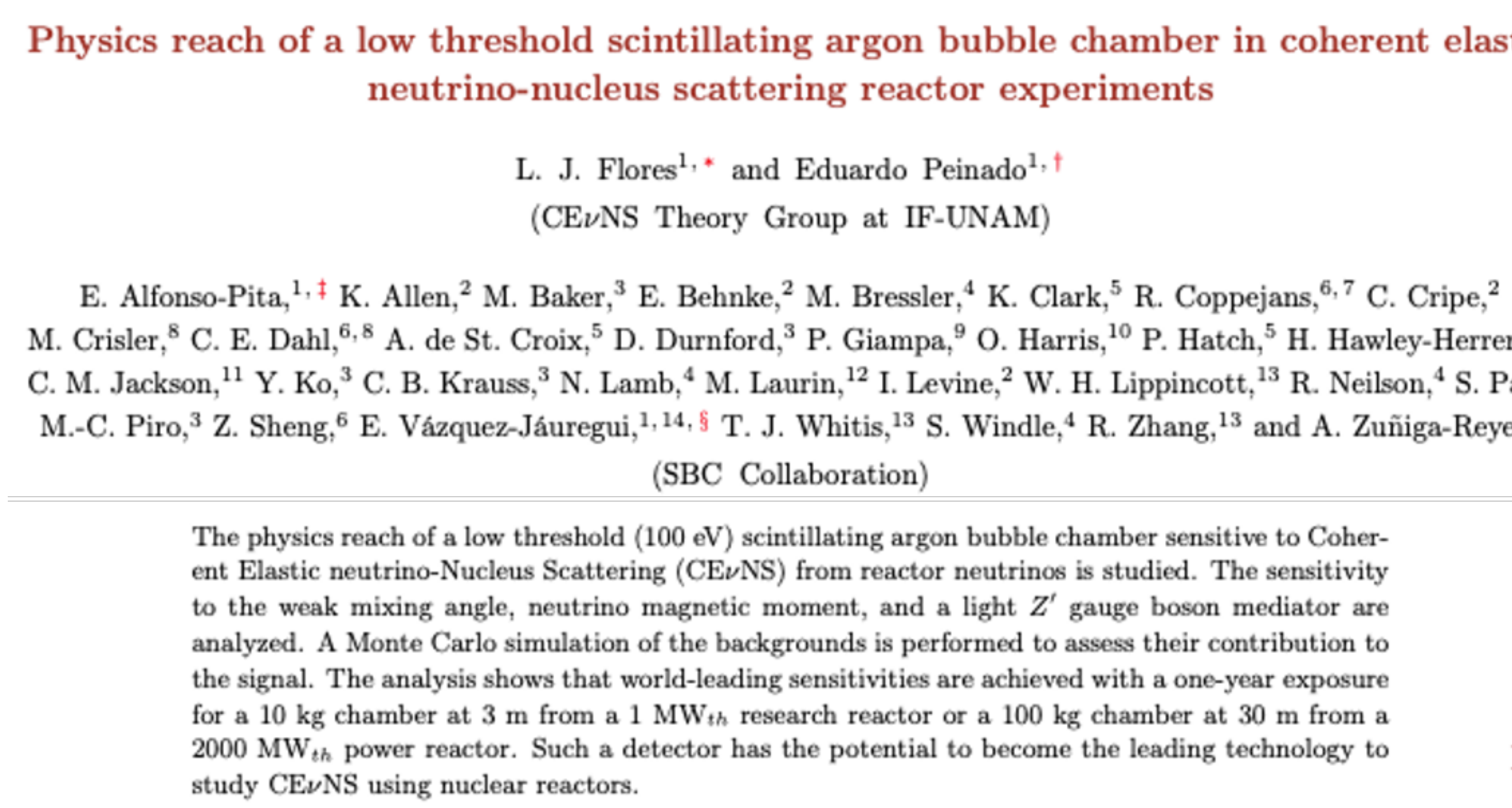
1) Build and commission detector at Fermilab for threshold testing

2) Build and install detector at SNOLAB for DM search

3) Upgrade and install detector from 1) at a reactor for neutrino studies

Wait… neutrino studies?

- The removal of backgrounds (and the lowered threshold) make this a good testbed for neutrino scattering studies



Physics reach of a low threshold scintillating argon bubble chamber in coherent elastic neutrino-nucleus scattering reactor experiments

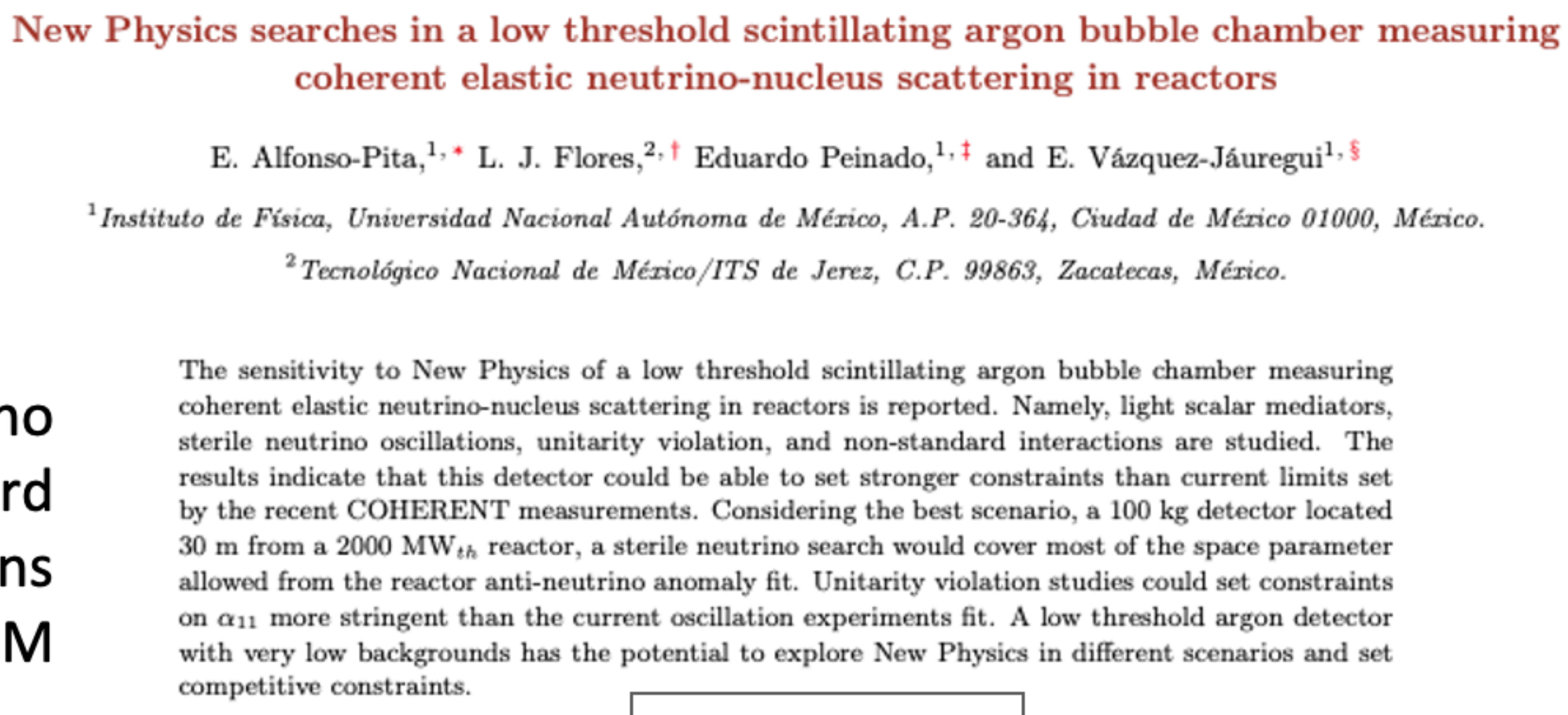
L. J. Flores[1,*] and Eduardo Peinado[1,†]
(CEνNS Theory Group at IF-UNAM)

E. Alfonso-Pita,[1,‡] K. Allen,[2] M. Baker,[3] E. Behnke,[2] M. Bressler,[4] K. Clark,[5] R. Coppejans,[6,7] C. Cripe,[2] M. Crisler,[8] C. E. Dahl,[6,8] A. de St. Croix,[5] D. Durnford,[3] P. Giampa,[9] O. Harris,[10] P. Hatch,[5] H. Hawley-Herrera,[5] C. M. Jackson,[11] Y. Ko,[3] C. B. Krauss,[3] N. Lamb,[4] M. Laurin,[12] I. Levine,[2] W. H. Lippincott,[13] R. Neilson,[4] S. Pal,[3] M.-C. Piro,[3] Z. Sheng,[6] E. Vázquez-Jáuregui,[1,14,§] T. J. Whitis,[13] S. Windle,[4] R. Zhang,[13] and A. Zuñiga-Reyes[1]
(SBC Collaboration)

The physics reach of a low threshold (100 eV) scintillating argon bubble chamber sensitive to Coherent Elastic neutrino-Nucleus Scattering (CEνNS) from reactor neutrinos is studied. The sensitivity to the weak mixing angle, neutrino magnetic moment, and a light Z' gauge boson mediator are analyzed. A Monte Carlo simulation of the backgrounds is performed to assess their contribution to the signal. The analysis shows that world-leading sensitivities are achieved with a one-year exposure for a 10 kg chamber at 3 m from a 1 MW$_{th}$ research reactor or a 100 kg chamber at 30 m from a 2000 MW$_{th}$ power reactor. Such a detector has the potential to become the leading technology to study CEνNS using nuclear reactors.

Phys. Rev. D 103, 091301 (2021)

- Covers the potential sensitivity of SBC to the weak mixing angle, neutrino magnetic moment, and a light Z' gauge boson mediator
- Collaboration paper led by theorists at UNAM



New Physics searches in a low threshold scintillating argon bubble chamber measuring coherent elastic neutrino-nucleus scattering in reactors

E. Alfonso-Pita,[1,*] L. J. Flores,[2,†] Eduardo Peinado,[1,‡] and E. Vázquez-Jáuregui[1,§]

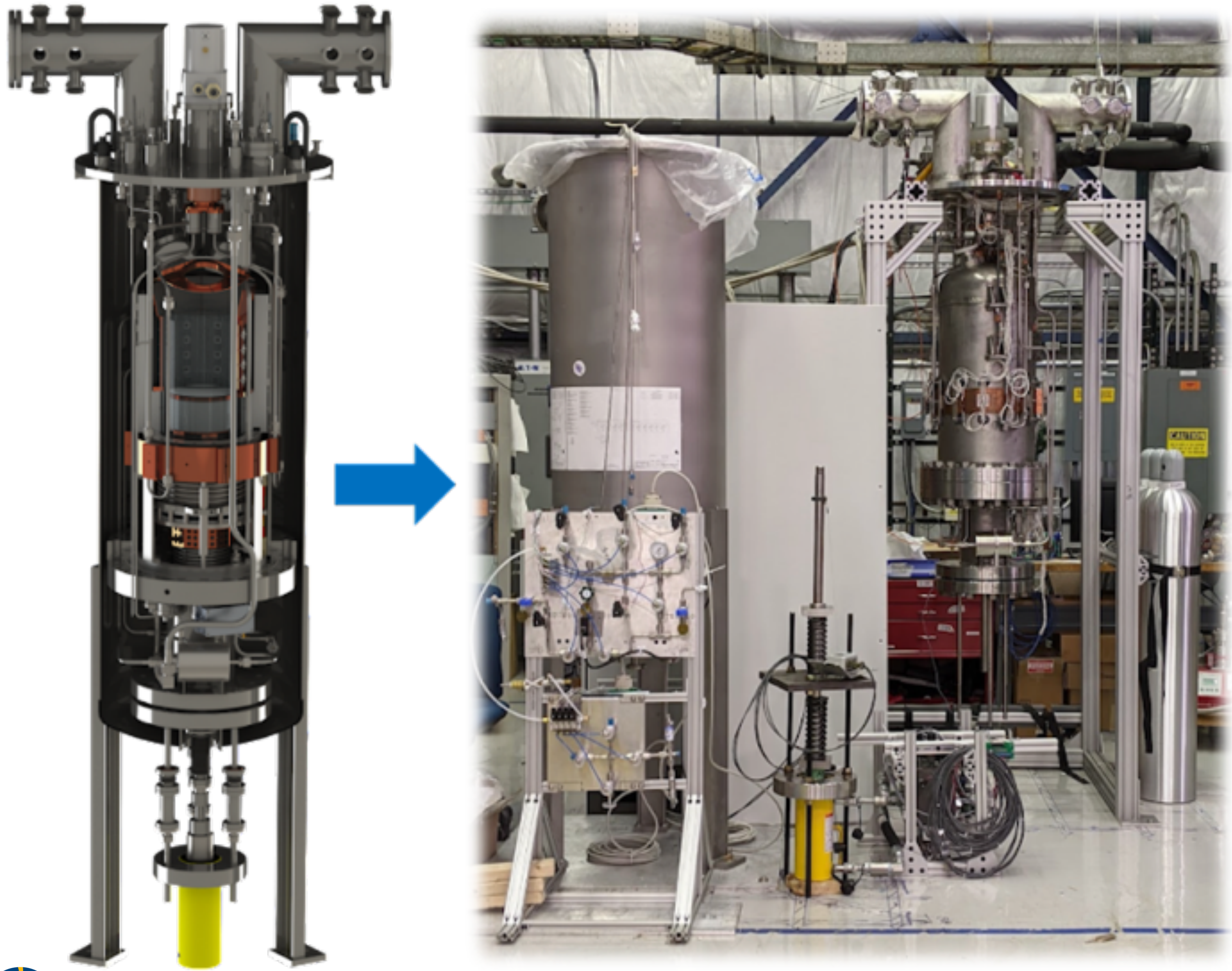
[1]*Instituto de Física, Universidad Nacional Autónoma de México, A.P. 20-364, Ciudad de México 01000, México.*
[2]*Tecnológico Nacional de México/ITS de Jerez, C.P. 99863, Zacatecas, México.*

The sensitivity to New Physics of a low threshold scintillating argon bubble chamber measuring coherent elastic neutrino-nucleus scattering in reactors is reported. Namely, light scalar mediators, sterile neutrino oscillations, unitarity violation, and non-standard interactions are studied. The results indicate that this detector could be able to set stronger constraints than current limits set by the recent COHERENT measurements. Considering the best scenario, a 100 kg detector located 30 m from a 2000 MW$_{th}$ reactor, a sterile neutrino search would cover most of the space parameter allowed from the reactor anti-neutrino anomaly fit. Unitarity violation studies could set constraints on α_{11} more stringent than the current oscillation experiments fit. A low threshold argon detector with very low backgrounds has the potential to explore New Physics in different scenarios and set competitive constraints.

- Study of CEvNS including sterile neutrino oscillations, unitarity violation, non-standard interactions
- Written by theorists at UNAM

arXiv:2203.05982

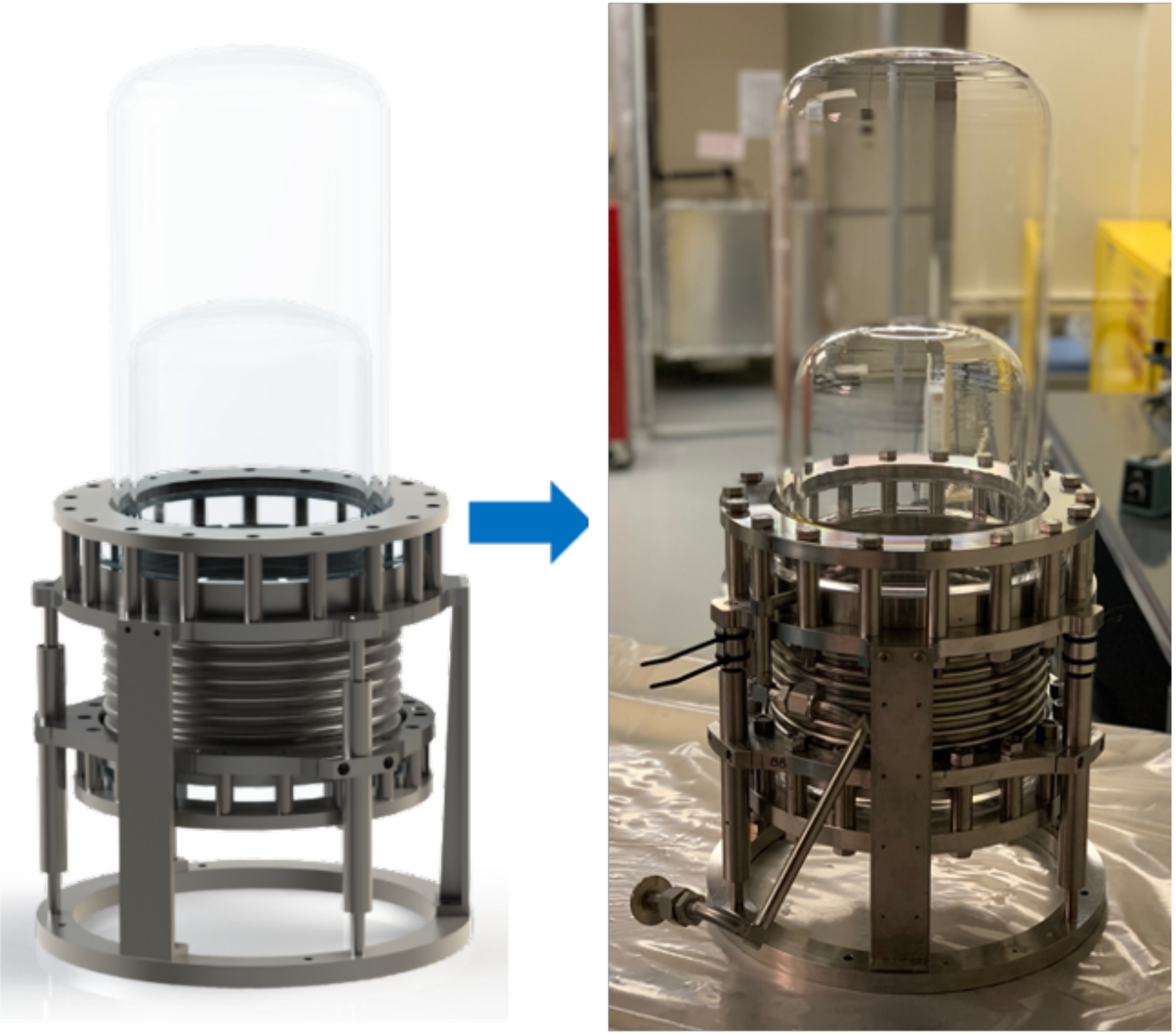
Experiment status



- 6/8 engineering notes have passed peer review
- 1/2 safety walkthroughs complete
- 11/11 pressure tests passed
- Mechanical and Cryogenic commissioning next

Experiment status

- Inner assembly construction complete
- Cryogenic seal tests currently happening
- Assembly to be sent to Fermilab at completion of FNAL mechanical and cryogenic commissioning



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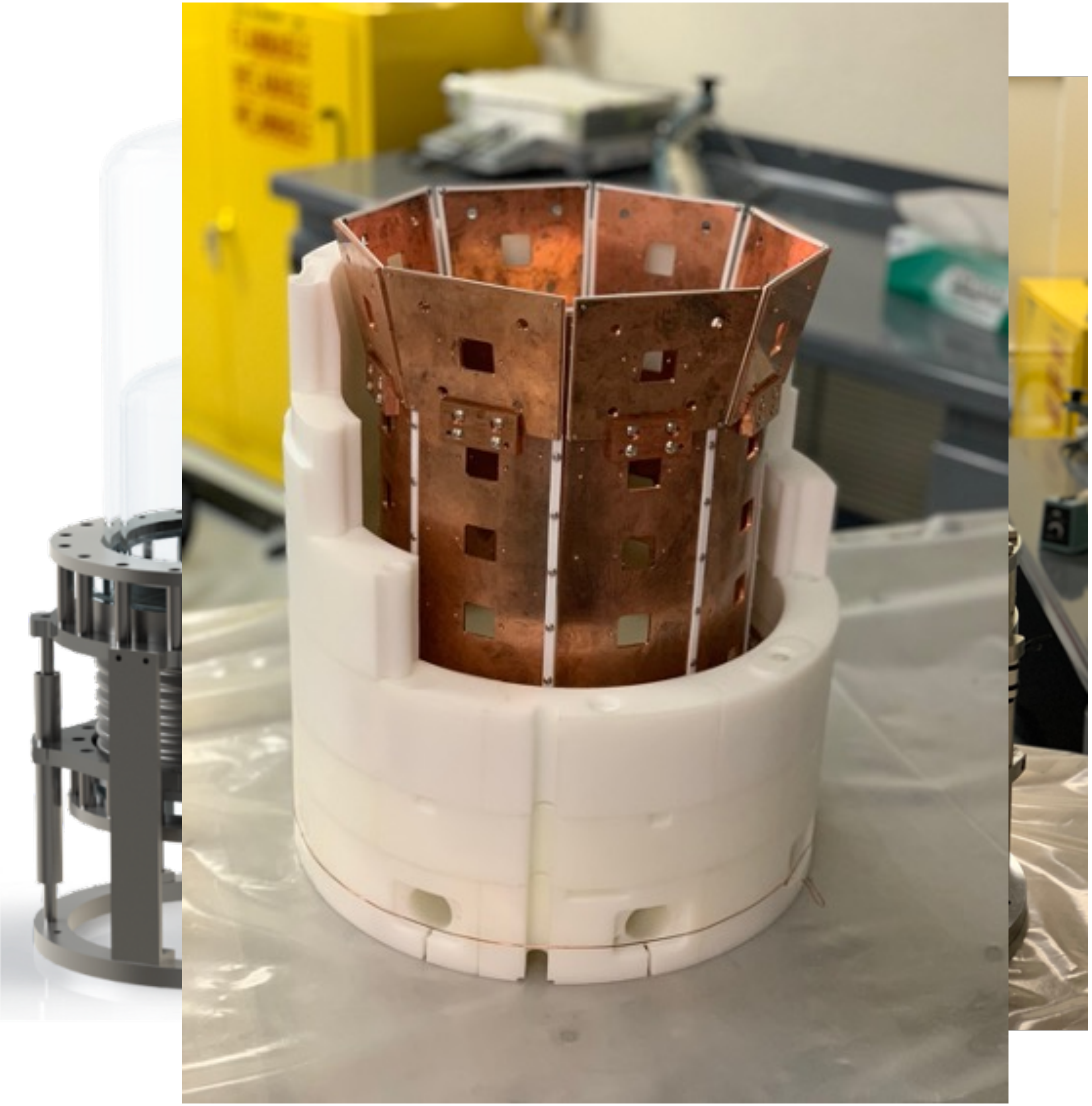

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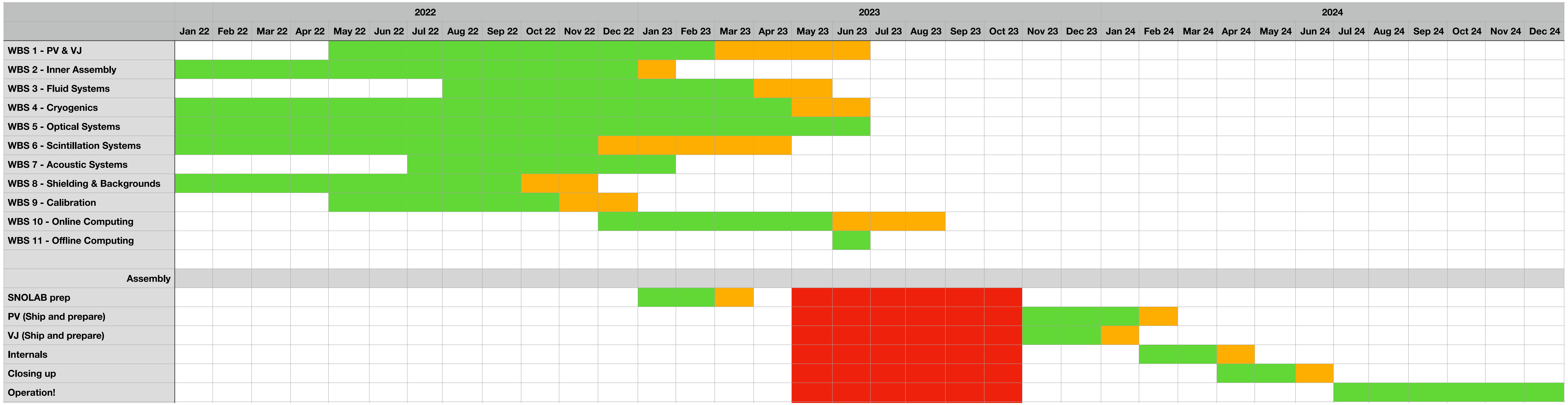
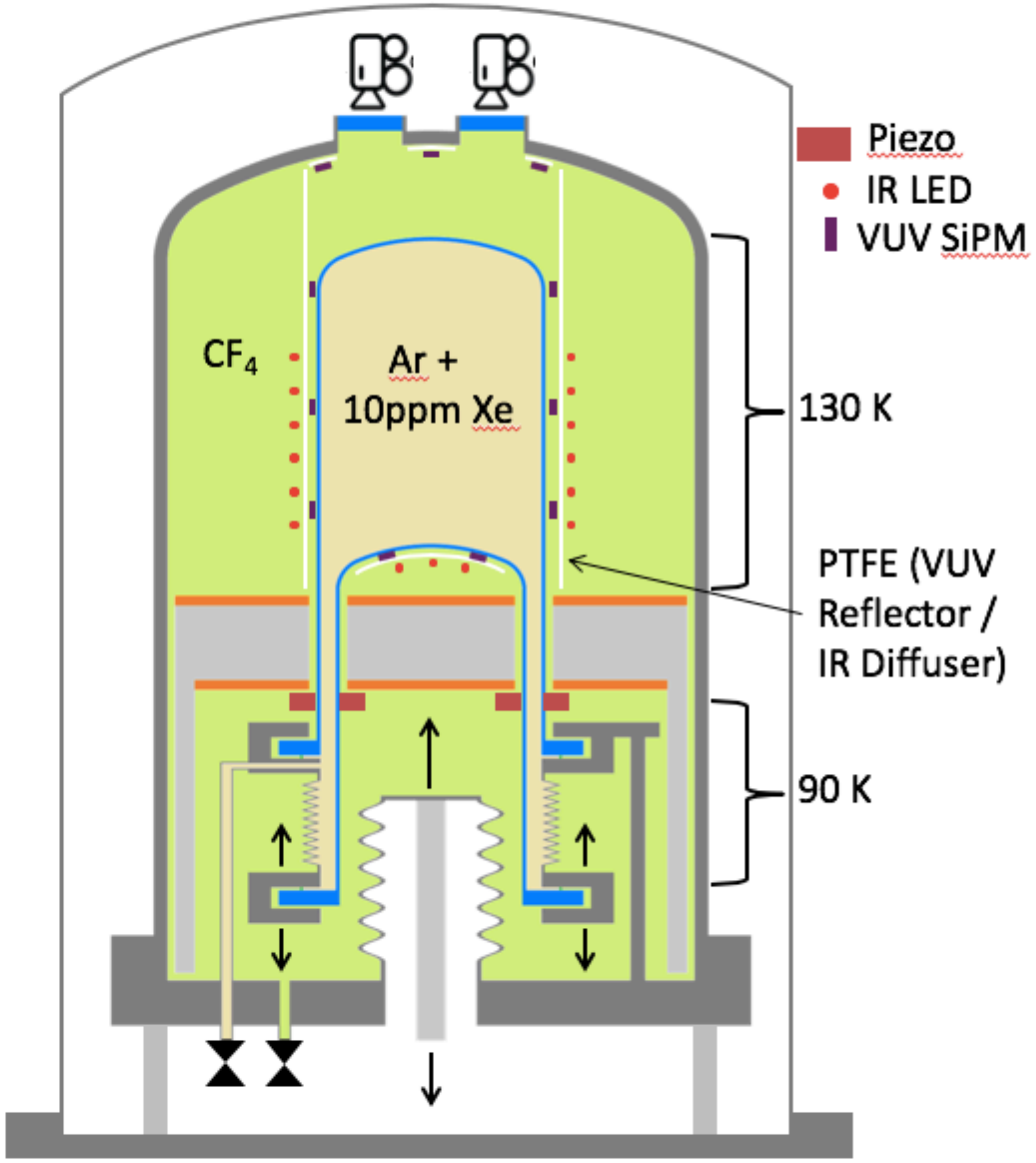
Projected timeline



	2022												2023												2024											
	Jan 22	Feb 22	Mar 22	Apr 22	May 22	Jun 22	Jul 22	Aug 22	Sep 22	Oct 22	Nov 22	Dec 22	Jan 23	Feb 23	Mar 23	Apr 23	May 23	Jun 23	Jul 23	Aug 23	Sep 23	Oct 23	Nov 23	Dec 23	Jan 24	Feb 24	Mar 24	Apr 24	May 24	Jun 24	Jul 24	Aug 24	Sep 24	Oct 24	Nov 24	Dec 24
WBS 1 - PV & VJ					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧																		
WBS 2 - Inner Assembly	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧																							
WBS 3 - Fluid Systems								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧																			
WBS 4 - Cryogenics	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧																		
WBS 5 - Optical Systems	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																		
WBS 6 - Scintillation Systems	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧																				
WBS 7 - Acoustic Systems							🟩	🟩	🟩	🟩	🟩	🟩	🟩																							
WBS 8 - Shielding & Backgrounds	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧																									
WBS 9 - Calibration					🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧																								
WBS 10 - Online Computing												🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧																
WBS 11 - Offline Computing																		🟩																		
Assembly																																				
SNOLAB prep													🟩	🟩	🟧		🟥	🟥	🟥	🟥	🟥	🟥														
PV (Ship and prepare)																	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟧										
VJ (Ship and prepare)																	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟧											
Internals																	🟥	🟥	🟥	🟥	🟥	🟥				🟩	🟩	🟧								
Closing up																	🟥	🟥	🟥	🟥	🟥	🟥						🟩	🟩	🟧						
Operation!																	🟥	🟥	🟥	🟥	🟥	🟥									🟩	🟩	🟩	🟩	🟩	🟩

- Green shown is projected schedule, orange represents contingency (obviously estimated)
- Primary point is that by May 23 should be ready to install
- SNOLAB inaccessibility shown in red

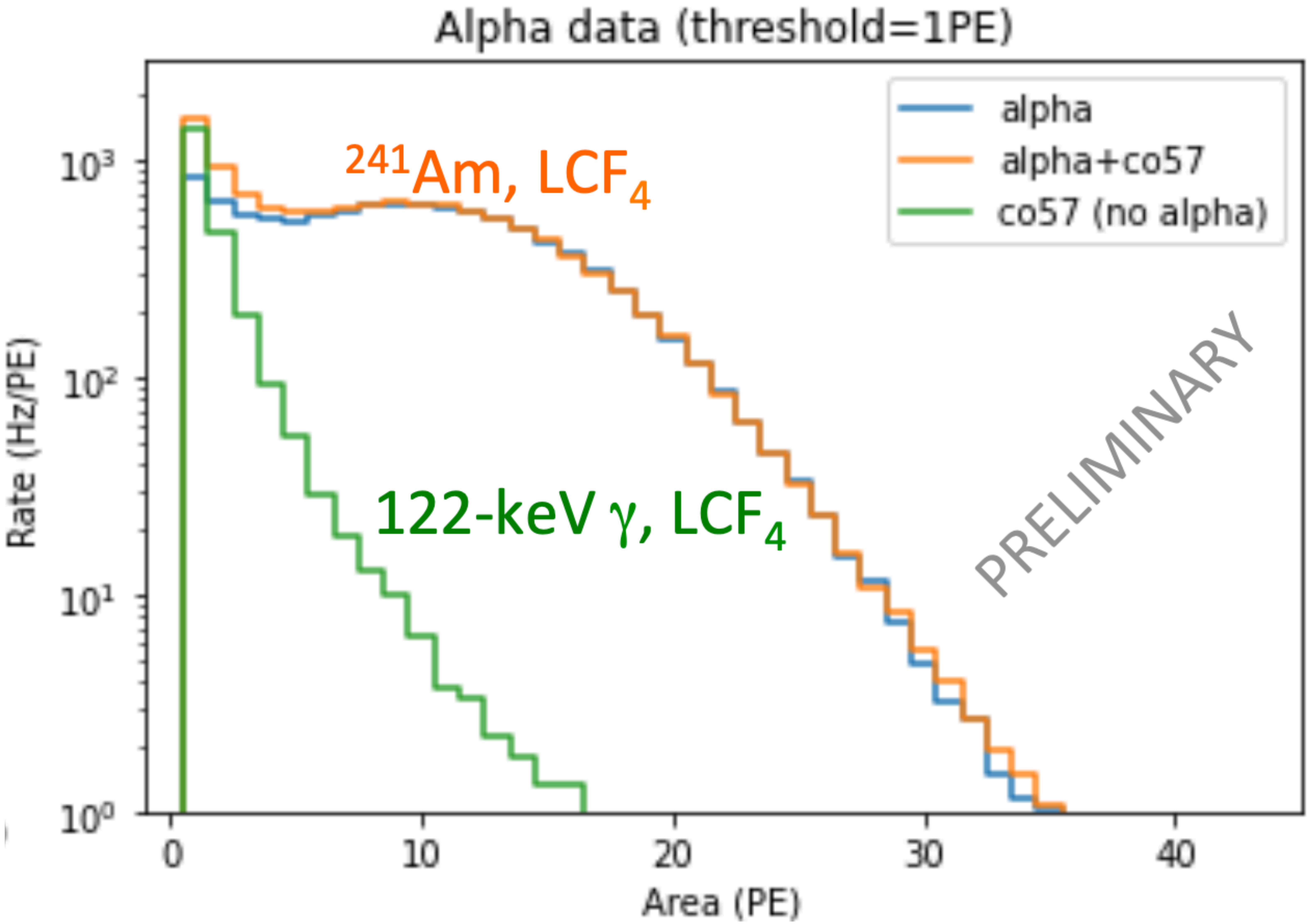
“Bonus” physics!



- SBC uses CF_4 as a hydraulic fluid
- Testing has progressed with validating components in liquid CF_4, including SiPMs
- At this point, there was a bit of a surprise

“Bonus” physics!

- Evidence that alphas can be seen in the hydraulic fluid
- Redesigned the SiPMs to have a few looking outward
- Potential for veto information from the surrounding fluid

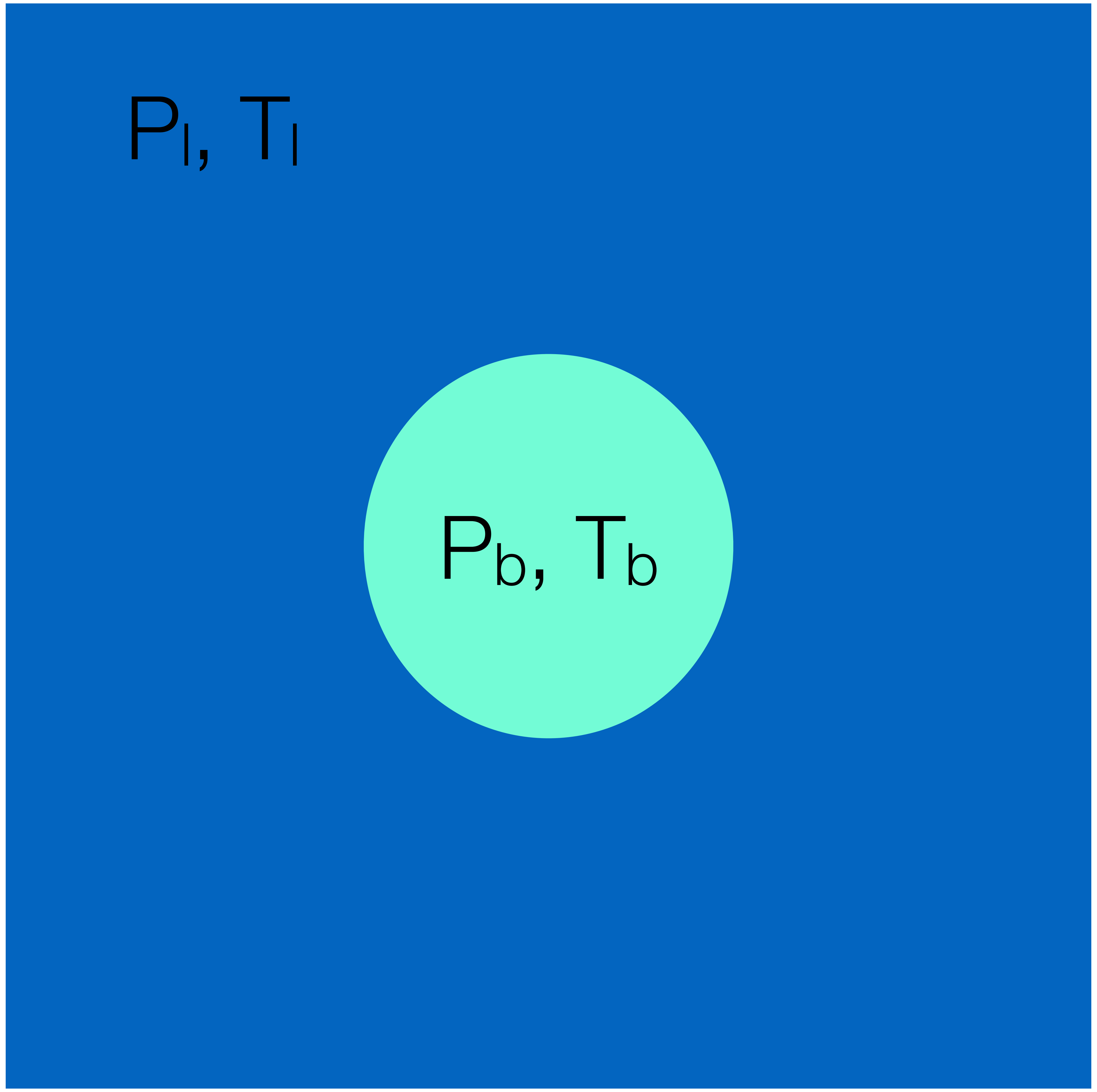


Conclusion

- Very cool physics can be done with our detectors
- Always looking for interested parties!

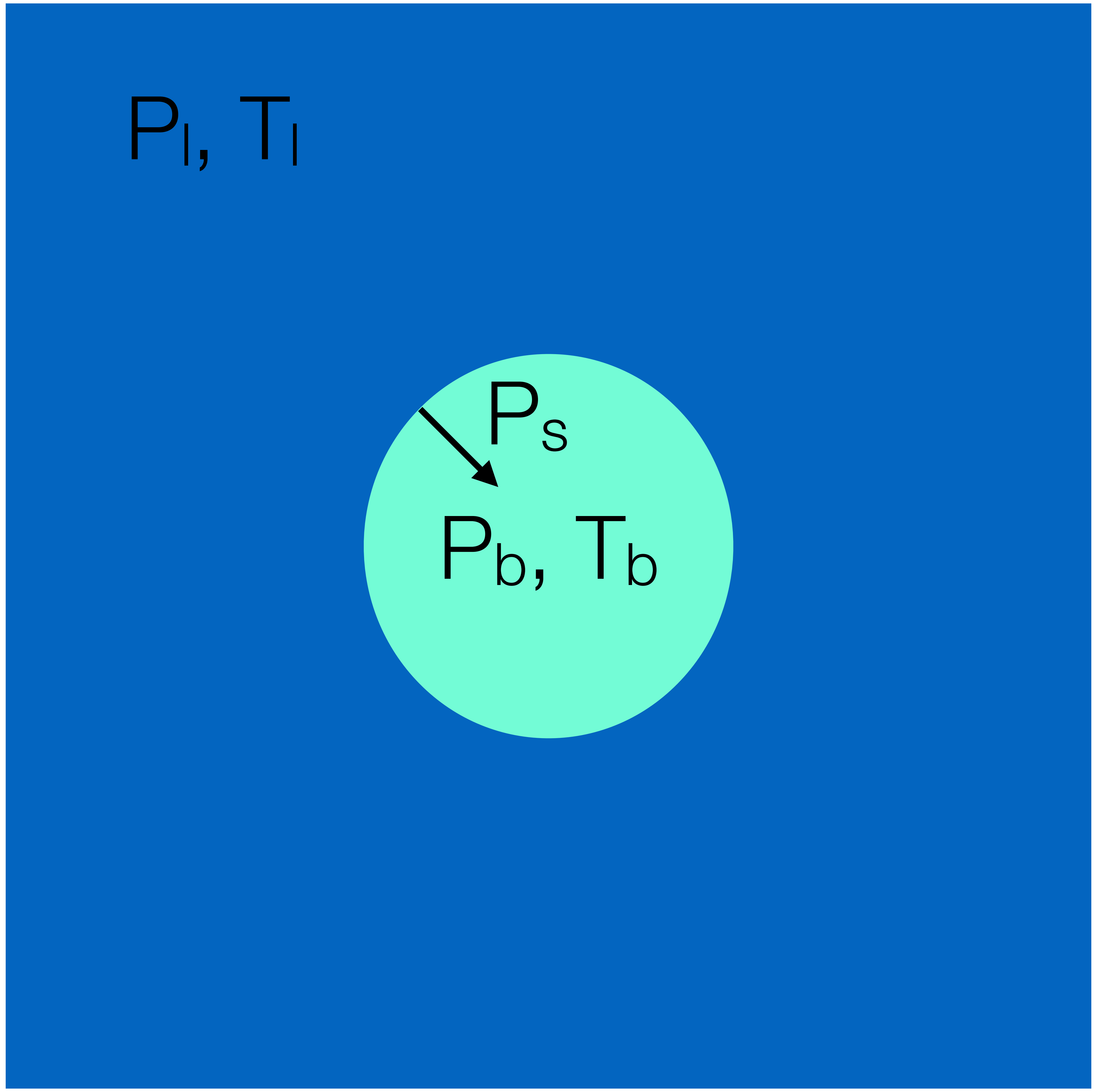
How Do Bubble Chambers Work?

- Start with a bubble in a liquid
- In thermal equilibrium, so $T_l = T_b$
- P_b is then roughly the vapour pressure at temperature T, and $P_b > P_l$, so the bubble should expand



How Do Bubble Chambers Work?

- Start with a bubble in a liquid
- In thermal equilibrium, so $T_l = T_b$
- P_b is then roughly the vapour pressure at temperature T, and $P_b > P_l$, so the bubble should expand… if there were no surface tension



How Do Bubble Chambers Work?

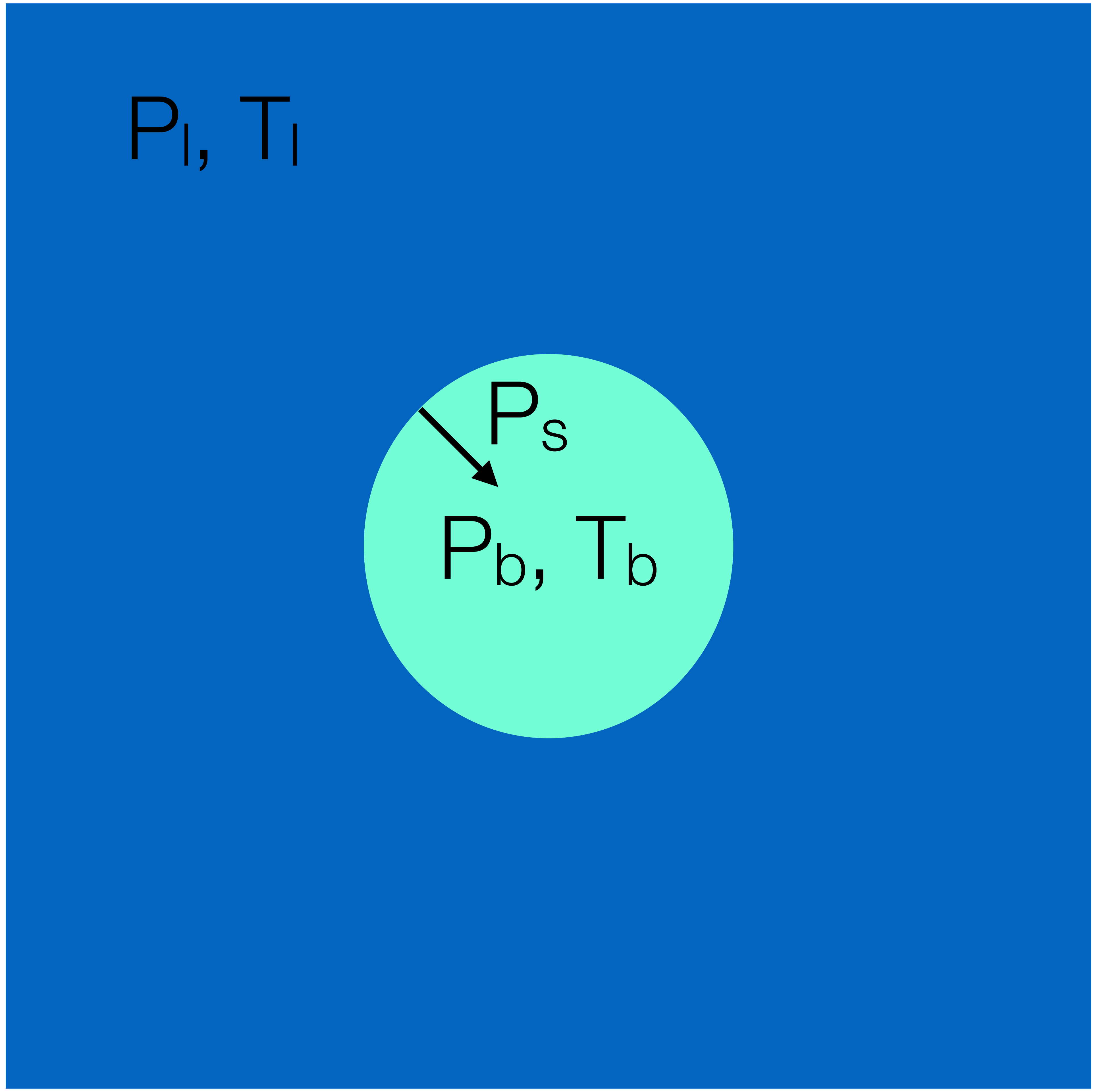
- Include pressure from surface tension $P_s = 2\sigma/r$
- This means the bubble will grow only if:

$$P_b > P_l + P_s$$

and

$$r > \frac{2\sigma}{P_b - P_l}$$

- Which we call the critical radius r_c



Calculation of Threshold

- So how is the threshold energy calculated?

$$E_T = 4\pi r_c^2 \left(\sigma - T \left[\frac{d\sigma}{dT} \right]_\mu \right)$$

Surface energy

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

Bulk energy

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

Reversible work

- Where ρ is the density and h the specific enthalpy

Calculation of Threshold

- So how is the threshold energy calculated?

$E_T = 4\pi r_c^2 \left(\sigma - T \left[\frac{d\sigma}{dT} \right]_\mu \right)$	Surface energy	1.53 keV
$+\frac{4\pi}{3} r_c^3 \rho_b (h_b - h_l)$	Bulk energy	1.81 keV
$-\frac{4\pi}{3} r_c^3 (P_b - P_l)$	Reversible work	0.15 keV
		3.19 keV

- Where ρ is the density and h the specific enthalpy