UNIVERSITY OF ALBERTA

May 10th 2023

Summer AstroParticle Workshop

Scintillating Bubble Chamber

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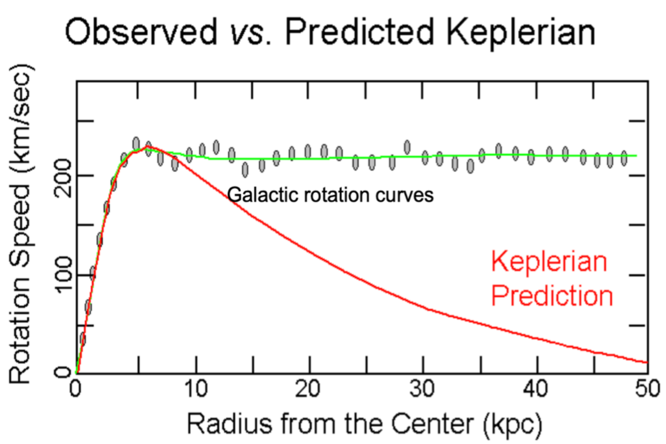
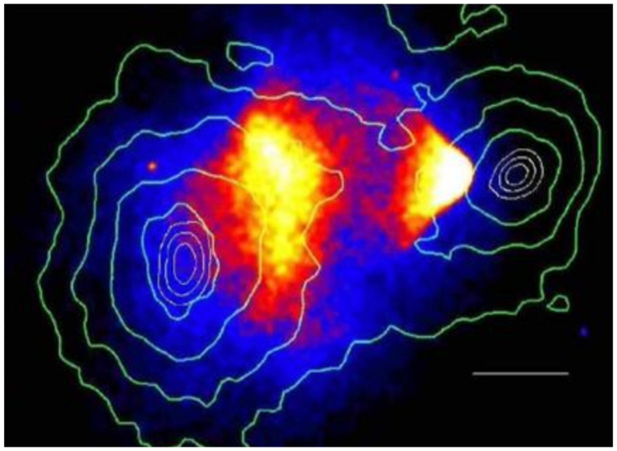
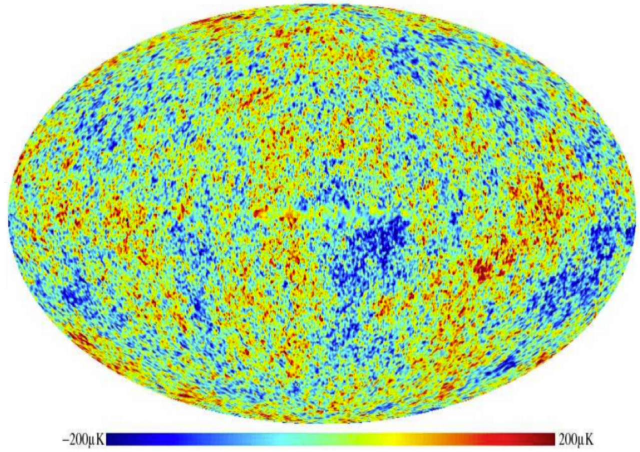
Dark matter evidence

- **There is lots of evidence for dark matter (DM)**
  - Early and late cosmology (CMB, LSS)
  - Clusters of galaxies
  - Galactic rotation curves







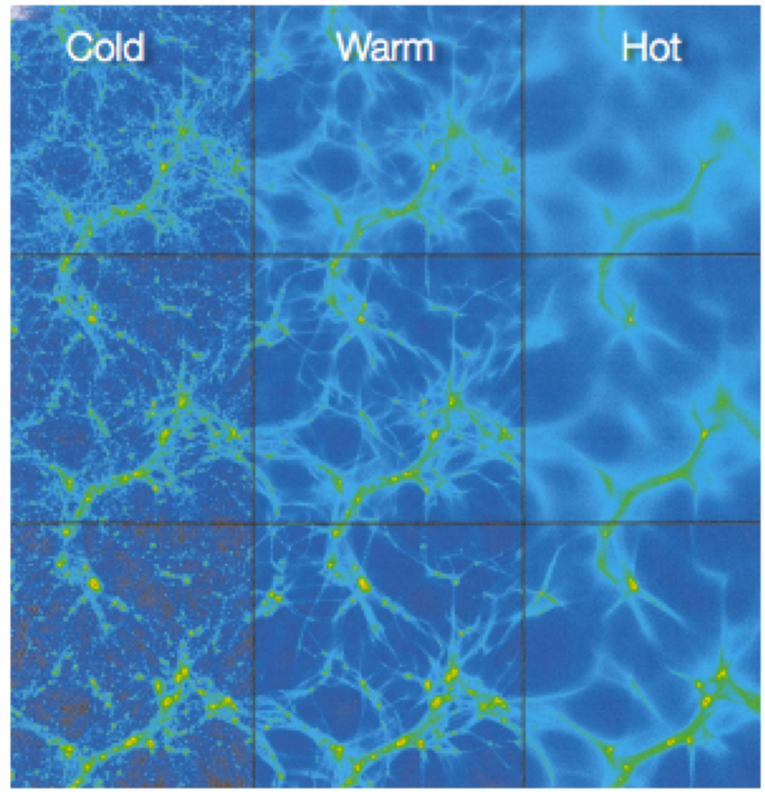
- No idea about its composition at the particle level

Dark matter : the famous candidate

• Constraints from astrophysics and searches for new particles:

- **CDM** (***C****old* ***D****ark* ***M****atter*) :
  → Not relativistic
- Non-baryonic
- Massive & stable particle
- Neutral particles
- Very weakly interacting
- Not Standard particle model

→ **New physics!**



Probing dark matter through gravity

Favorite candidate is *Weakly Interacting Massive Particles (WIMP)*.

Candidates for Dark Matter

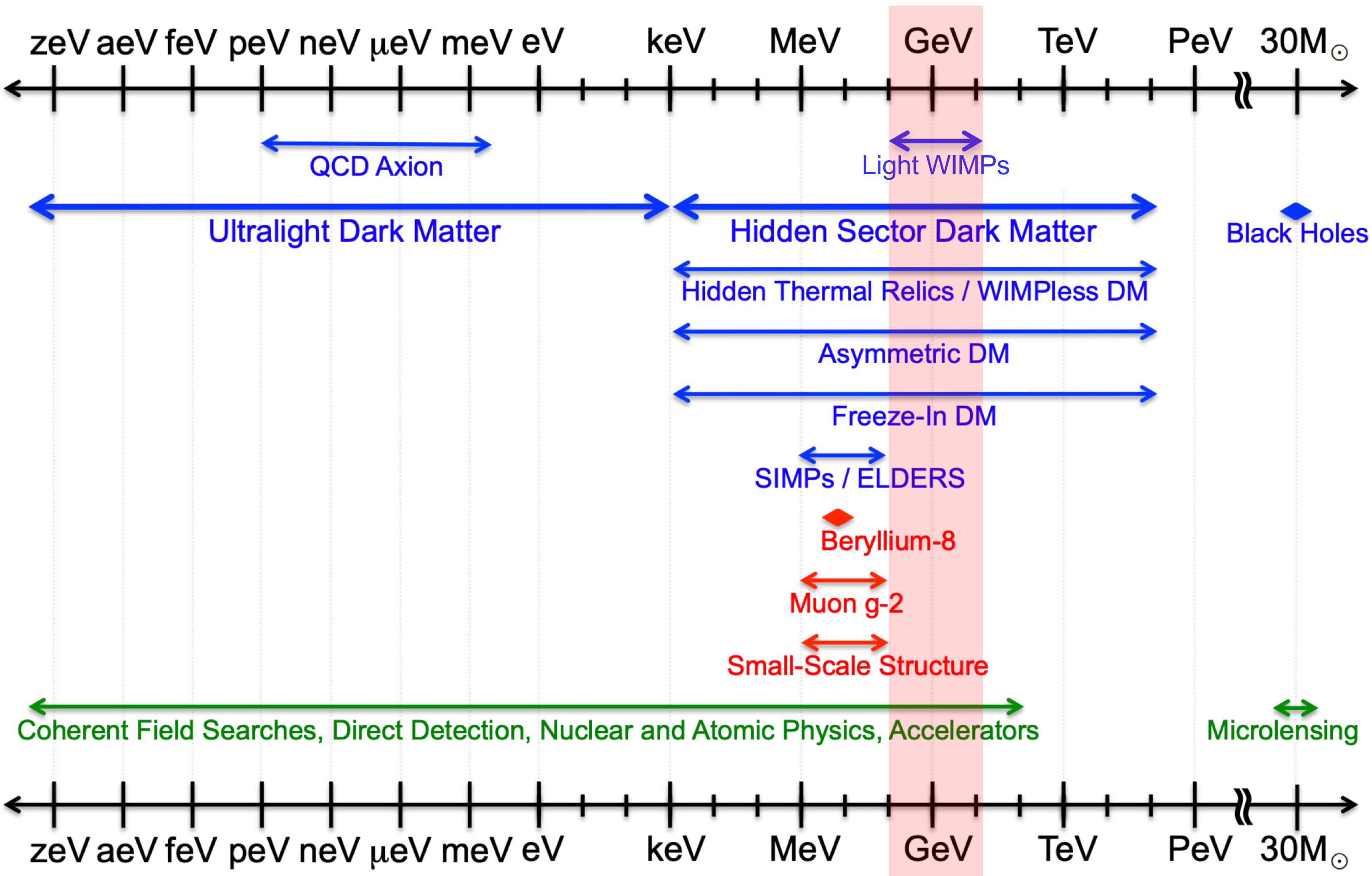


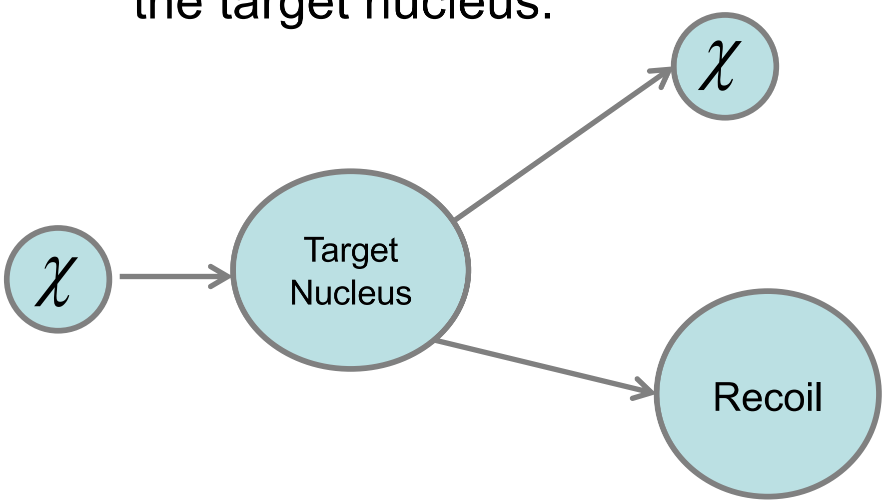
Figure adapted from arXiv:1707.04591

How to detect directly WIMP ?

Direct Detection :

Elastic scattering on nuclei

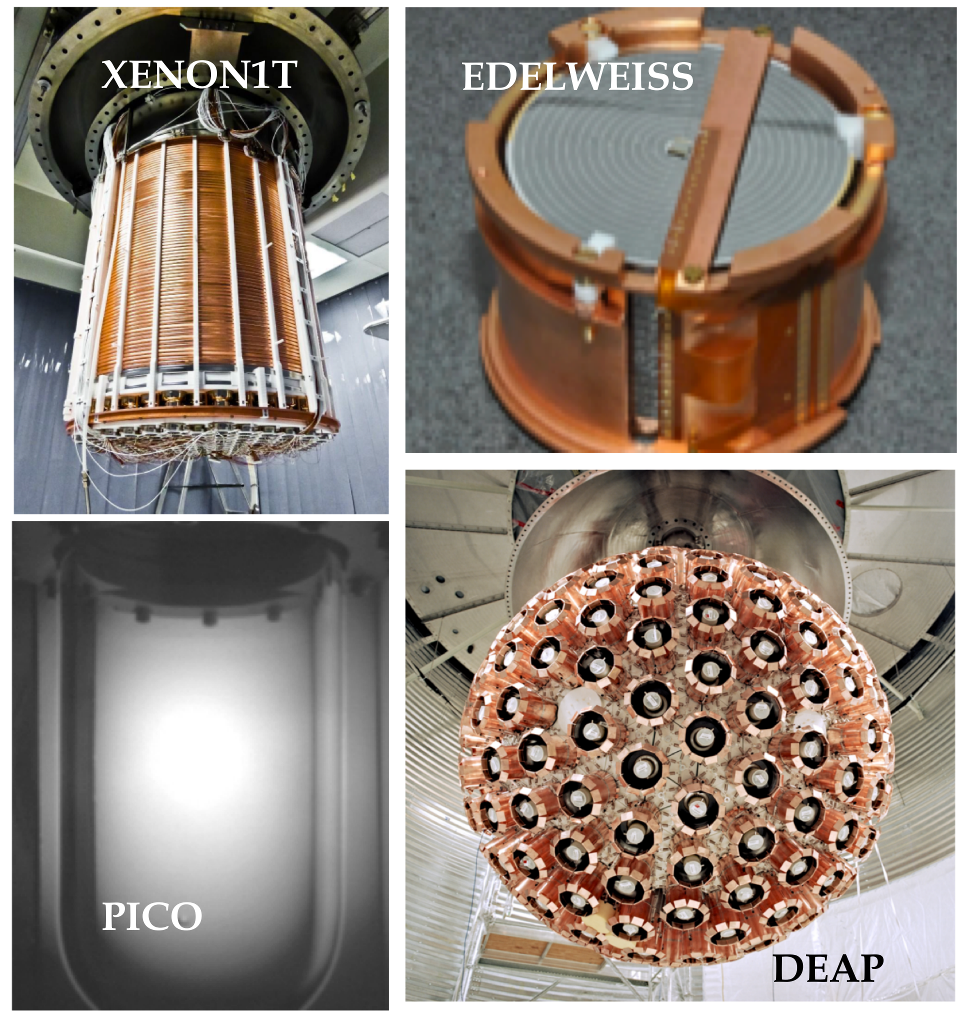
→ Look for the recoil of the target nucleus.



Energy E_R (1-100 keV)

- Very low recoil energy
- Wimp interacts with nucleus
  → **Nuclear Recoils**
  → Detectable via **different channels**

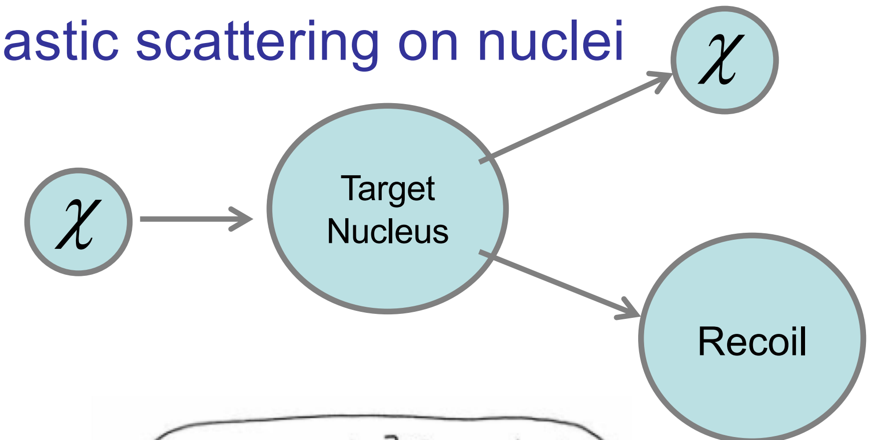
(XENON1T, LZ, PANDAX, DEAP-3600, PICO, EDELWEISS …)



Just to give you an idea !!

Direct Detection :

Elastic scattering on nuclei

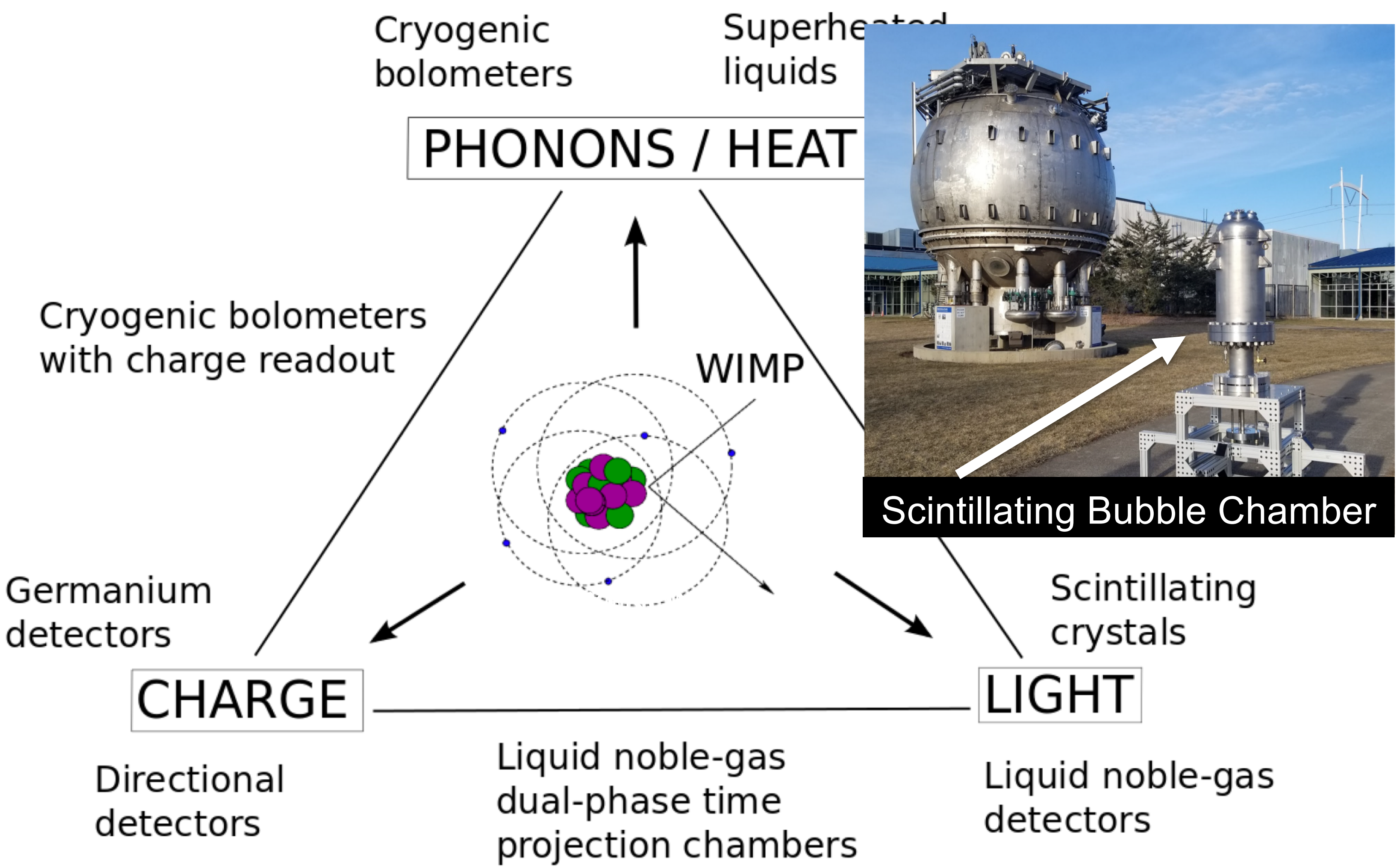


The recoil created by the WIMP is comparable to a grain of salt that touches the ground with a force divided by 100 billions.

Very low energy to detect !!

--> Hyper sensitive detectors !!

Direct Detection Experiment

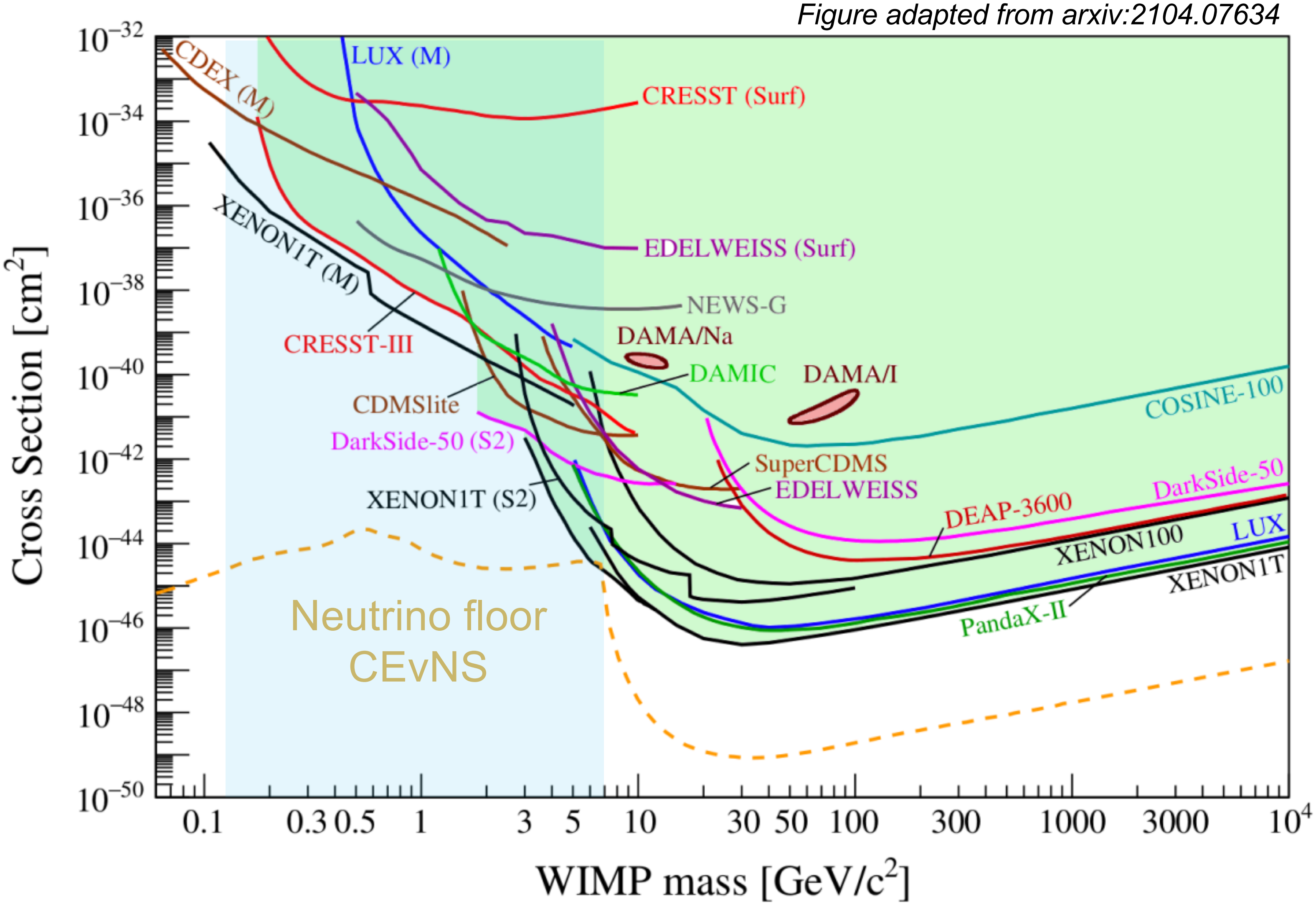


J. Phys. G: 43 (2016) 1, arXiv:1509.08767

Landscape of Dark Matter

Threshold & atomic mass

Figure adapted from arxiv:2104.07634



Detector size & exposure

Ultimate background

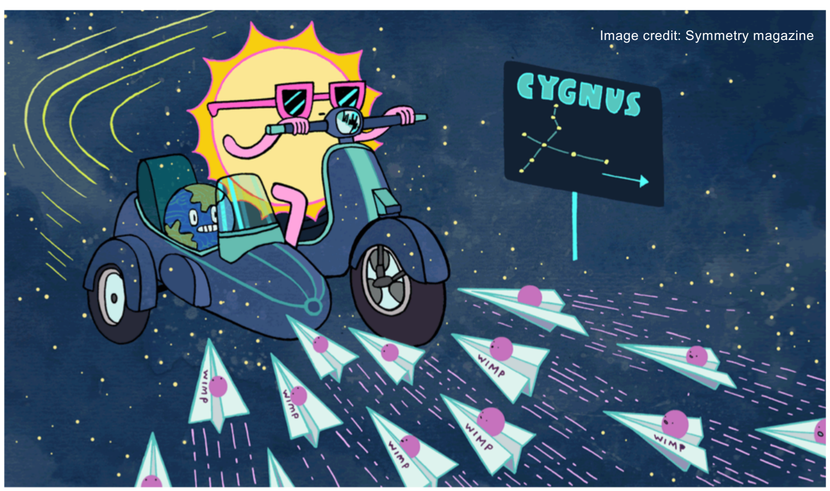
- **Ultimately: solar, atmospheric and supernovae neutrinos**

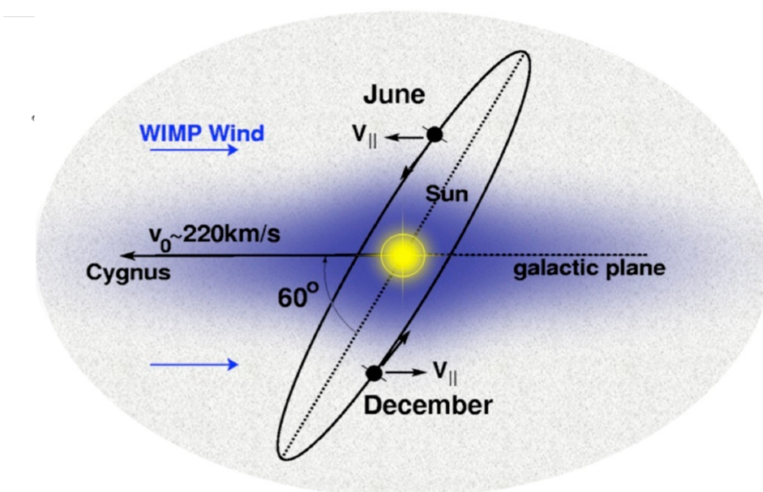
The coherent neutrinos scattering (CEνNS) will be the limiting irreducible background creating a "**neutrino floor**" for all DM experiments.

CEνNS can produce nuclear recoil and they cannot be shield

- Strategy :

→ Directionality channel or add it in current technology
→ Dedicated CEνNS calibration using nuclear reactor





What do we need for Direct Detection???

CHALLENGES FOR DIRECT DARK MATTER SEARCHES

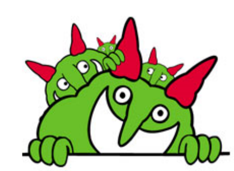
$Low\ Recoil\ Energy \leq 100\ keV$ → Low threshold detectors.

Very low Rate → Large volume detectors.

Background is the principal problem of all Dark Matter experiments!

→ High purity level is needed!

Enemies : muon-induced neutrons, gammas, neutrons, intrinsic betas decays, alpha background, neutrinos !



The SBC Collaboration

Northwestern University

Queen's University

Université de Montréal

SNOLAB

Fermilab

UC Davis University of California

University of Alberta

Drexel University

UC Santa Barbara

Indiana University South Bend

Pacific Northwest National Laboratory

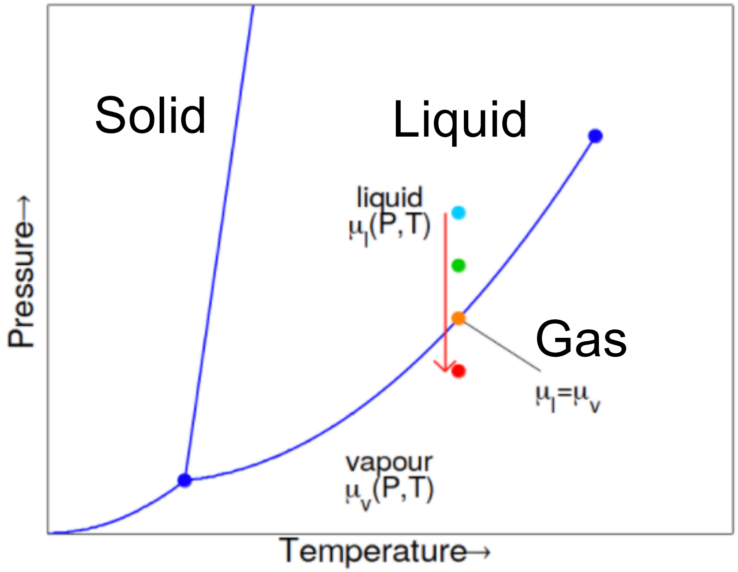
Universidad Nacional Autónoma de México

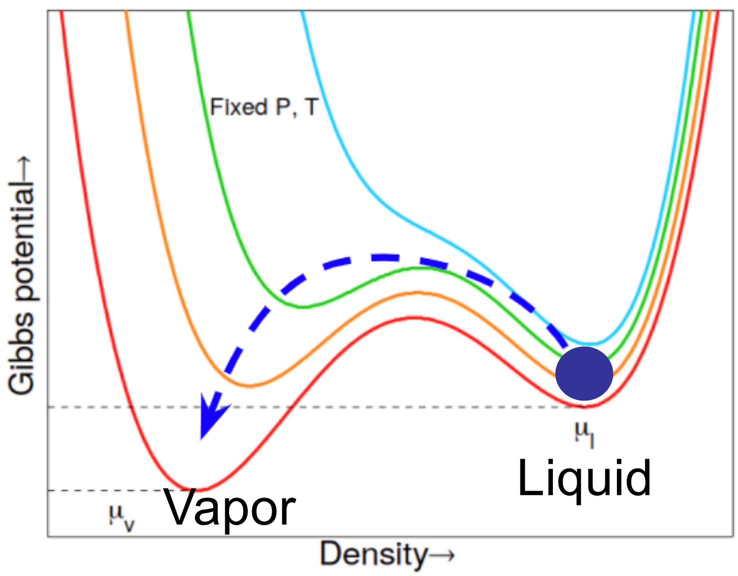
Bubble Chamber

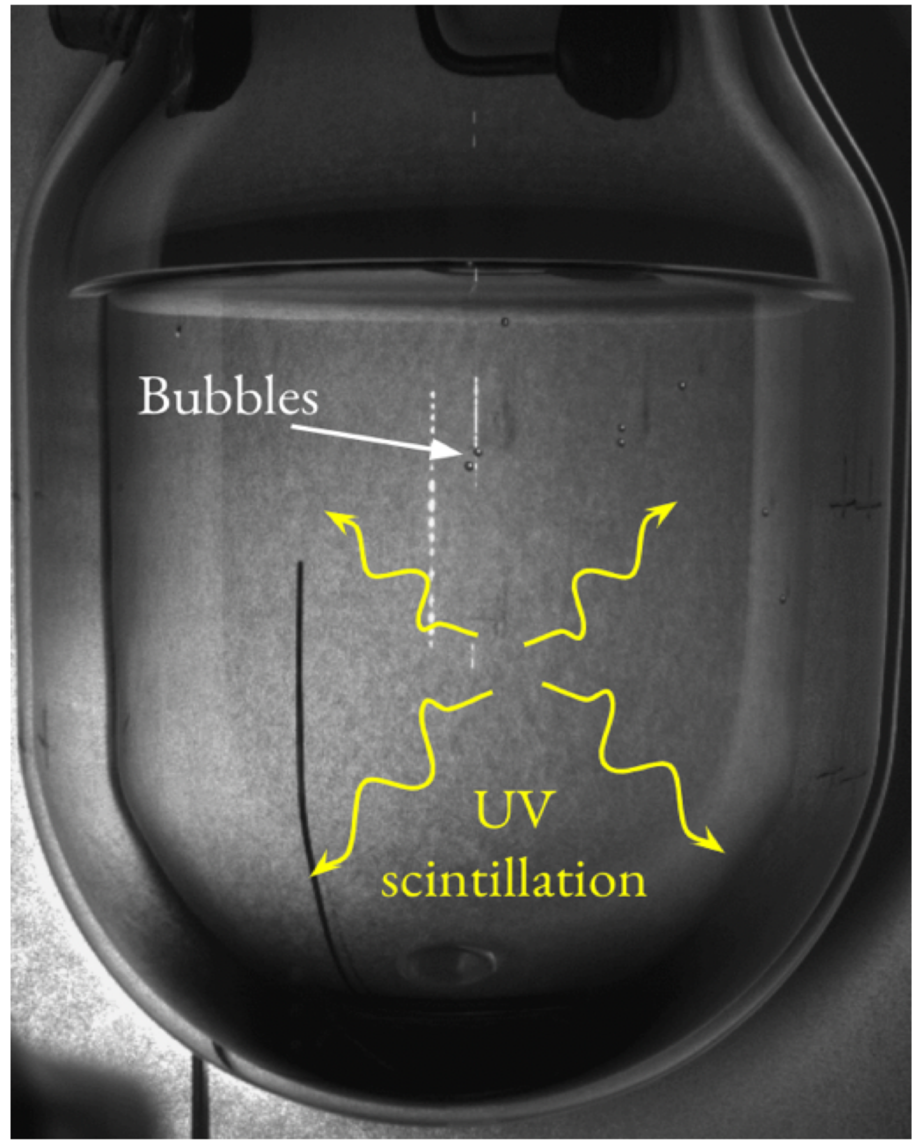
SBC: Scintillating Bubble Chamber

- Active liquid:
  - 10 kg total of Liquid Argon doped with Xenon
  - Xenon acts as a wavelength-shifter (178nm)
- Detector:
  - Superheated liquid within a pressure controlled vessel cooled at 130° Kelvin (-143.15ºC)
- Read-out:
  - Piezo-electric sensors/ pressure control unit.
  - Cameras → excellent position reconstruction.
  - Silicon Photomultipliers: SiPMs

Detector principle







Bubble chamber principle

• Bubble chambers are filled with superheated fluid:

→ Meta-stable state.

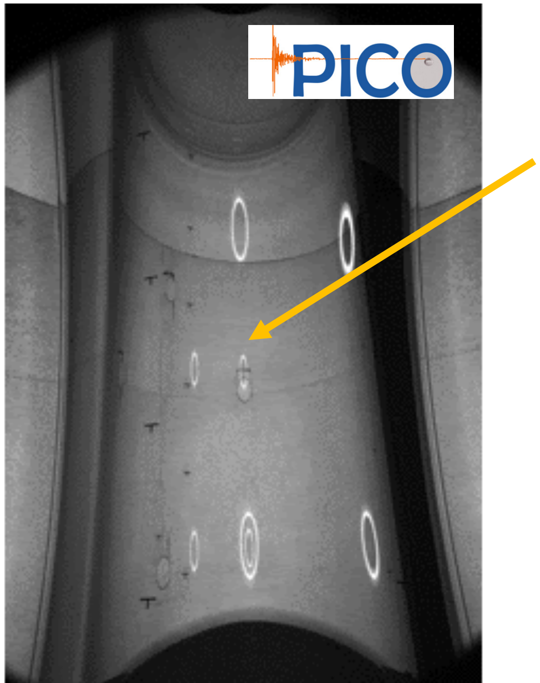
→ ***Should not be liquid at this pressure and temperature***

• Regulated by temperature and pressure:

→ Each condition of temperature and pressure correspond to an energy threshold.

→ This is the Seitz energy threshold

→ ***Heat spike model***



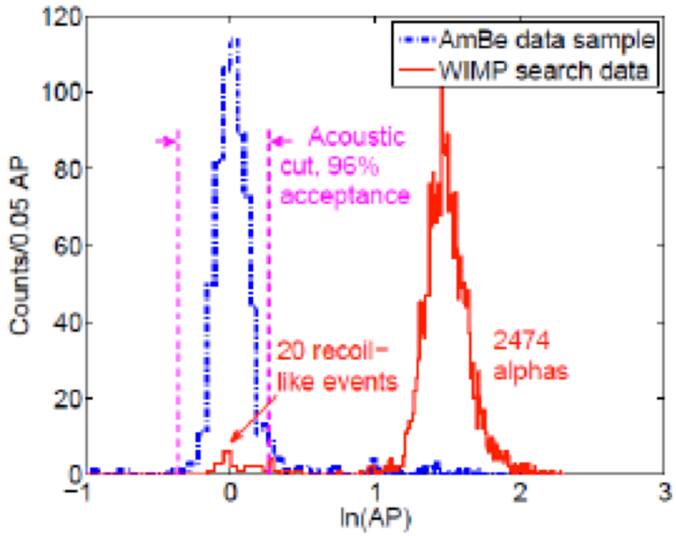
PICO 2L Detector

• Bubble chambers are threshold detectors

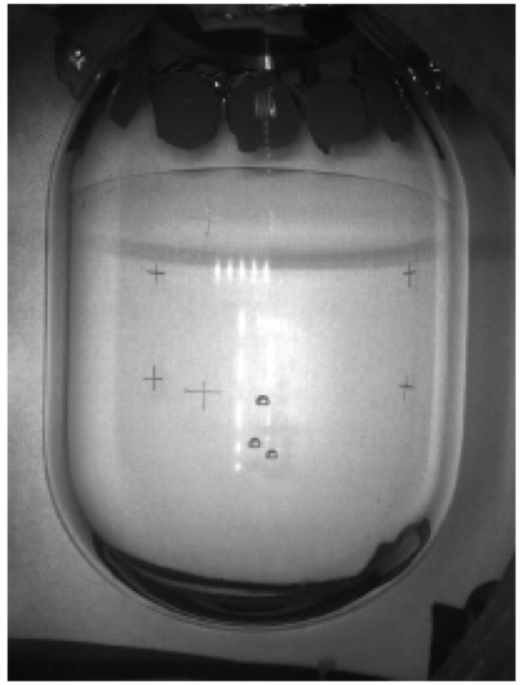
→ ***Energy deposited > Energy threshold***

Impressive Background Rejection

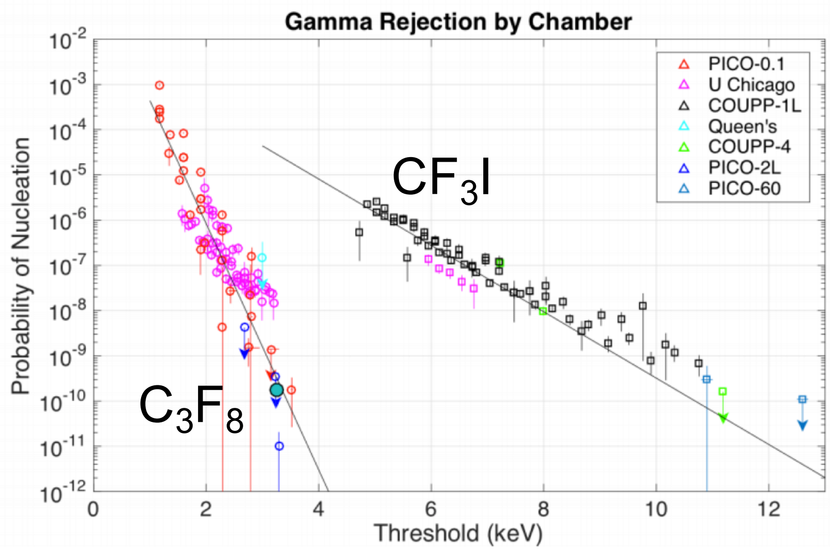
Acoustic Alpha Discrimination



Multiple Neutron Scattering



Gamma Interaction Insensitivity



But no energy information!!

PICO

Scintillating Bubble chamber

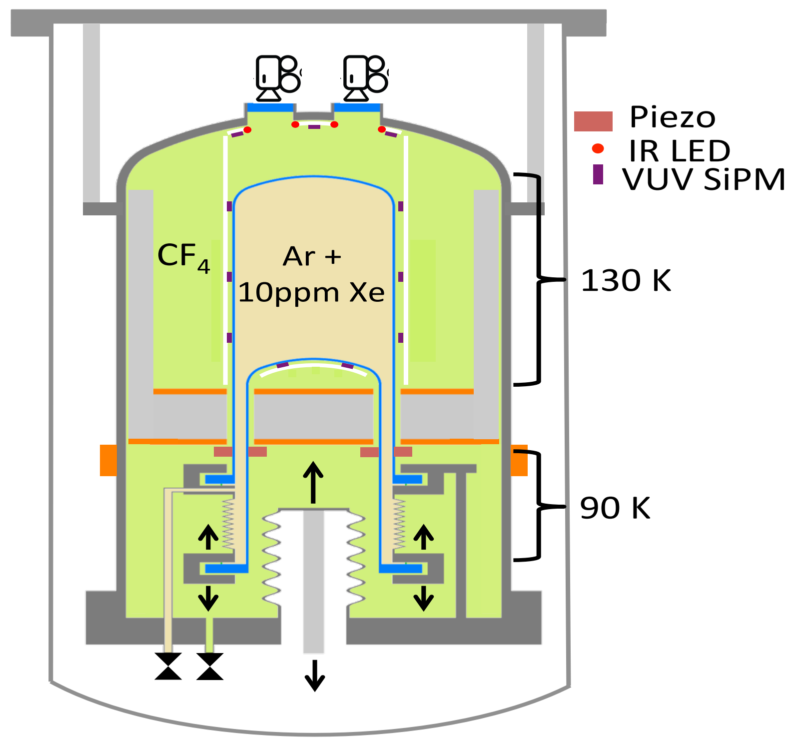
Mixing technologies:

Bubble chamber (PICO) + Scintillation (DEAP, DarkSide-20k)

→ *See talk C. Moore* → *See talk Friday by S. Manecki*

Combine the **Electron Recoil discrimination** of bubble chambers and the **event-by-event energy resolution.**

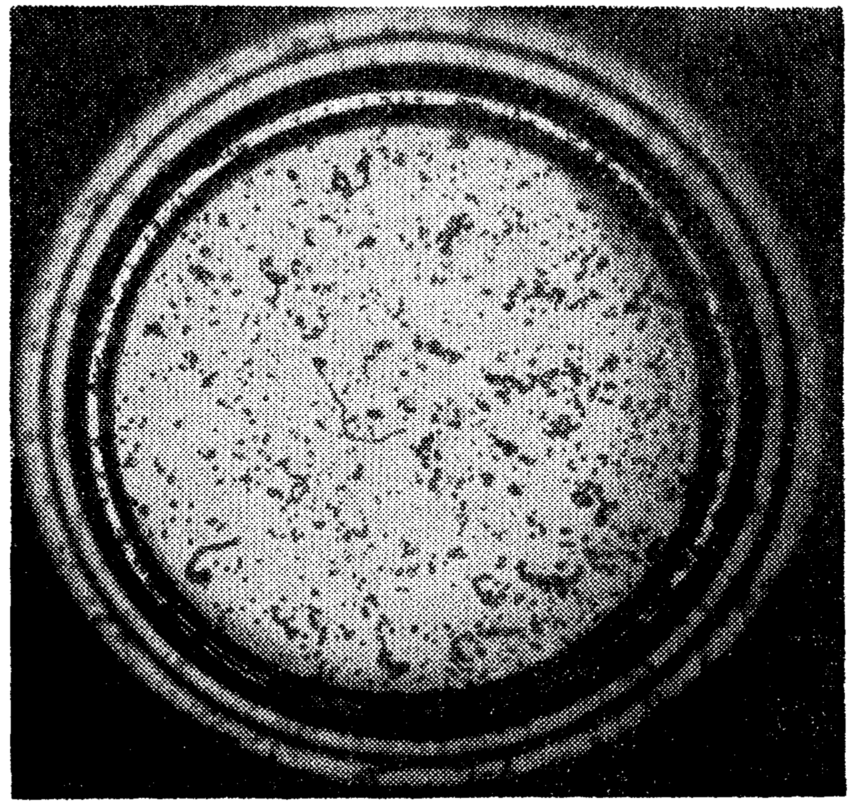

Scintillating Bubble Chamber SBC



Scintillating Bubble chamber history

Liquid-noble Bubble chambers didn't seem to work…

- **1956 – Glaser finds:**
  - **No bubbles** in pure xenon even at ~1 keV threshold (with gamma source)
  - Normal bubble nucleation in 98% xenon + 2% ethylene (scintillation completely quenched)
- **1962 (Stump, Pellett), 1981 (Harigel, Linser, Schenk)**
  - Tracks seen in pure argon, but only at extreme (*O* (10) eV) energy threshold.



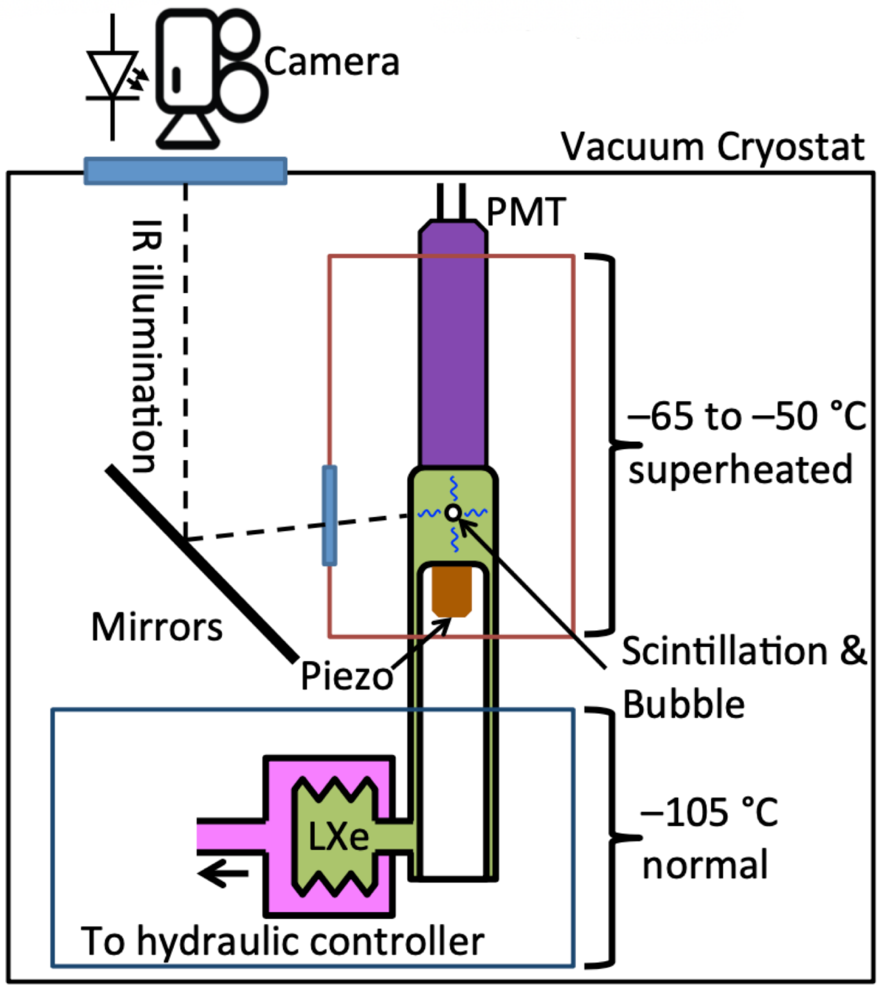
Phys.Rev. **102**, 586 (1956)

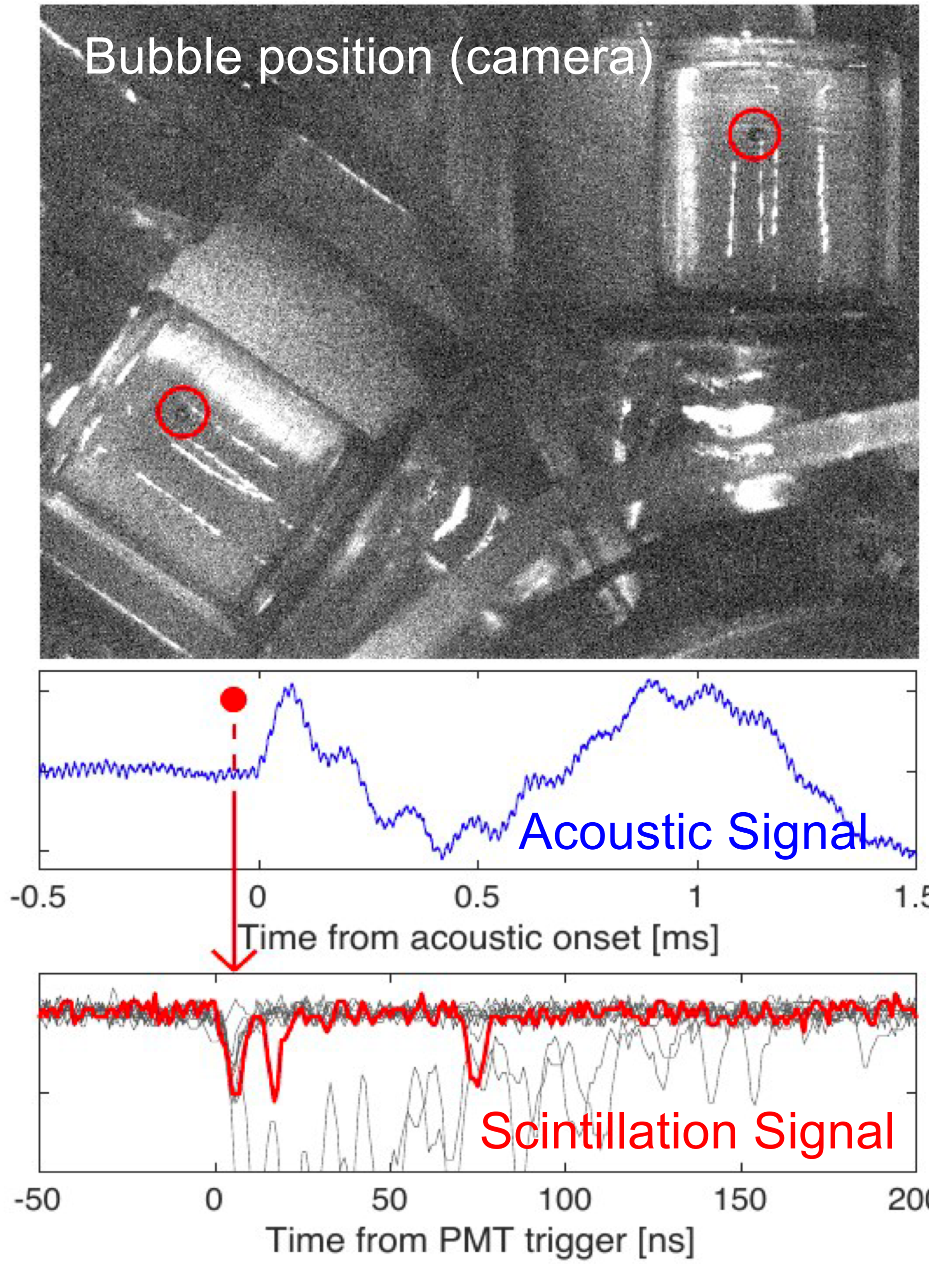
Scintillation suppresses Bubble nucleation!

Xenon Bubble Chamber

Proof of principle:

- 30g Xenon Bubble Chamber

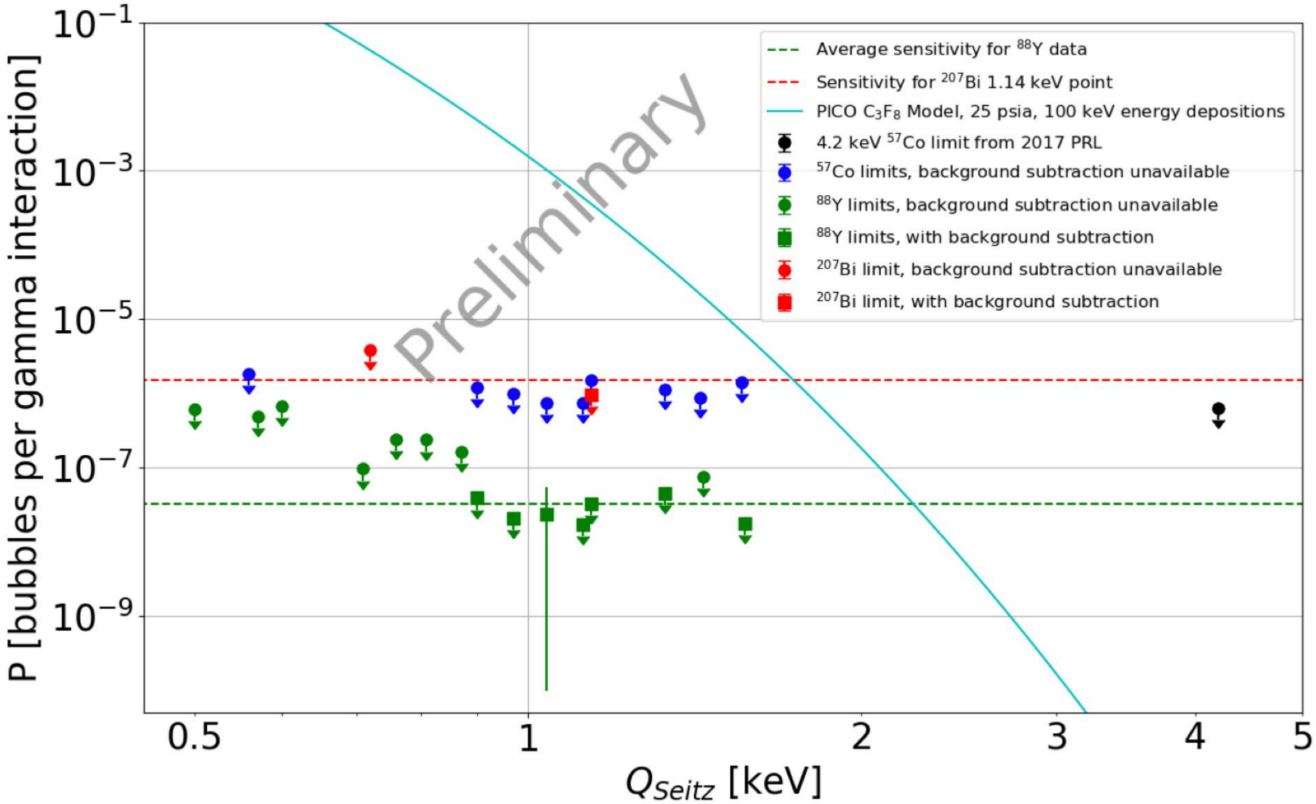




PRL 118, 231301 (2017), arXiv:1702.08861

Xenon Bubble Chamber

- Seitz thresholds as low as 0.5 keV
- Evidence of nucleation by Nuclear Recoils below 5 keV
- No sign of Electron Recoils nucleation at any threshold

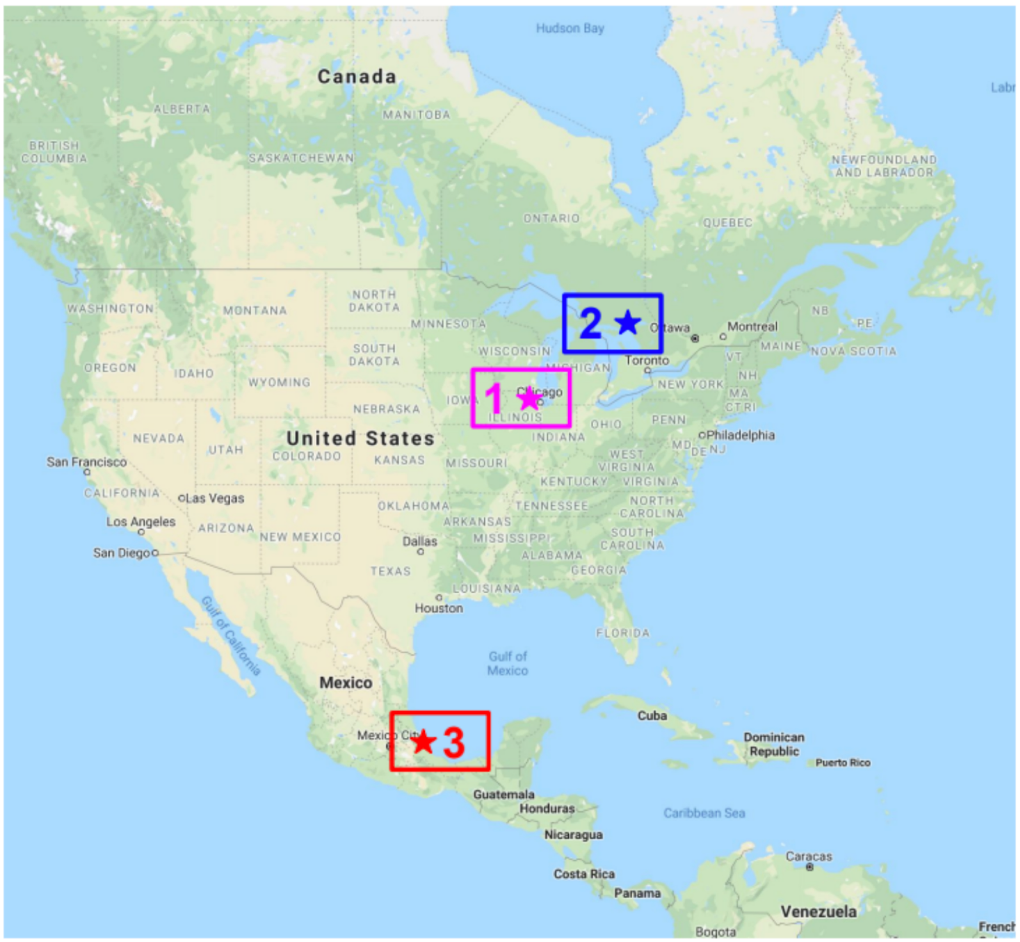


Scintillation suppresses Bubble nucleation!

New Detector: The SBC

The SBC Strategy

- Two detectors to be built for low-mass dark matter and CEvNS



SBC-Fermilab - Phase 1

Build and commission the first detector at Fermilab.

SBC-SNOLAB - Phase 2

Build and install a second detector at SNOLAB for low-mass dark matter searches.

SBC-CEvNS - Phase 3

Upgrade and install detector from (1) at a reactor site for CEvNS studies (currently considering Laguna Verde Mexico).

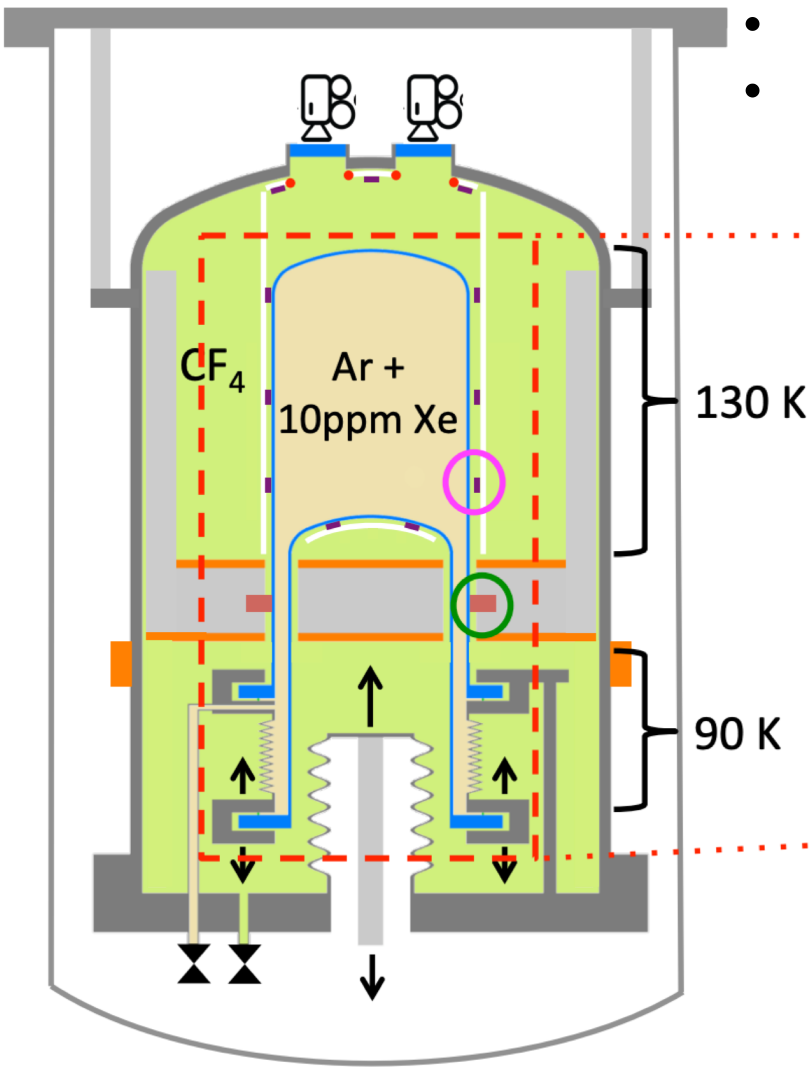
Status and Timeline

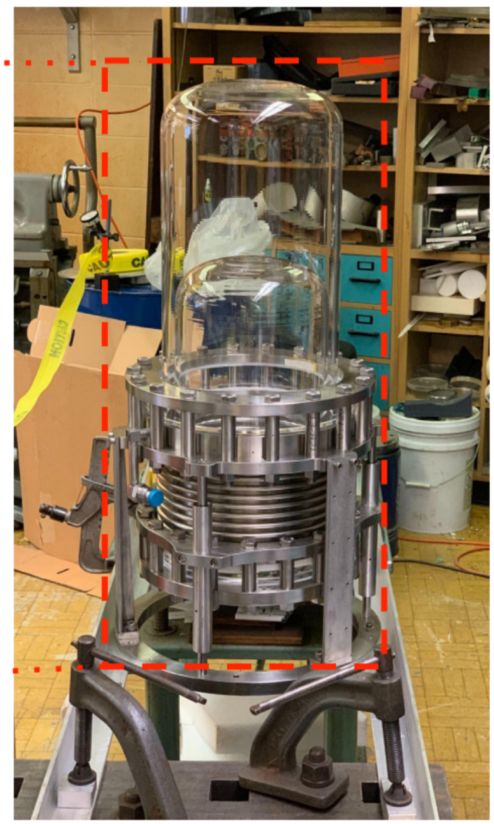
- SBC at Fermilab
  - Assembly and commissioning: Present → 2023
  - Science operation: 2023 → 2024
- SBC at SNOLAB
  - Construction = SBC-Fermilab + 1 year
  - DM search: 2024 & 2025
- SBC-CEvNS
  - Experimental program follows calibration at FNAL
  - Site investigations are underway → Laguna Verde

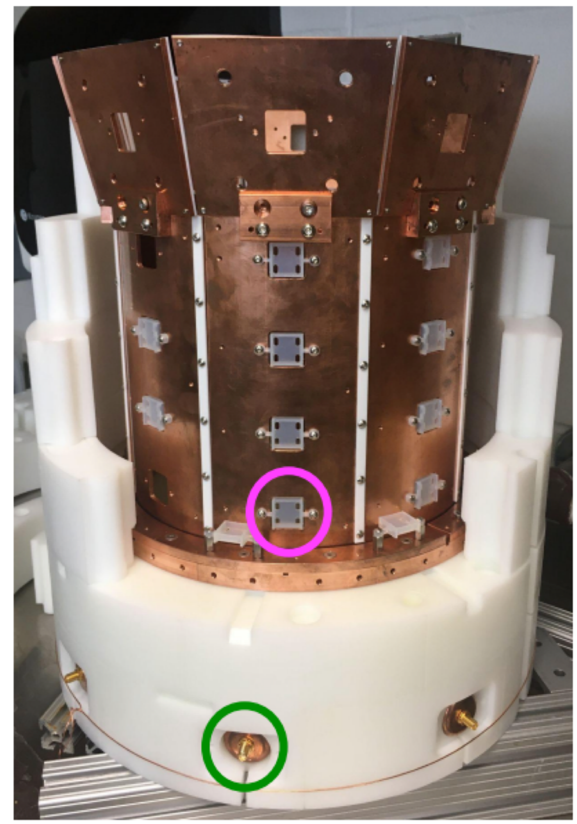
The detector

O(10 kg) LAr contained within two fused silica jars, inner and outer jars.

- Hydraulic piston controls the inner jar position
- Piezoelectric sensor and SiPM



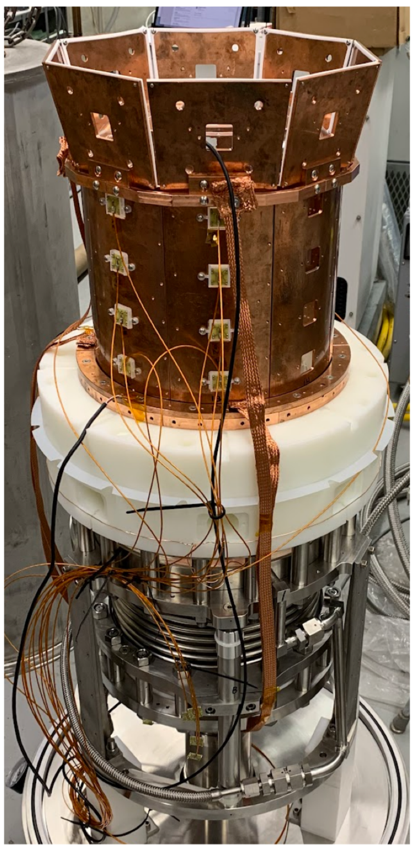


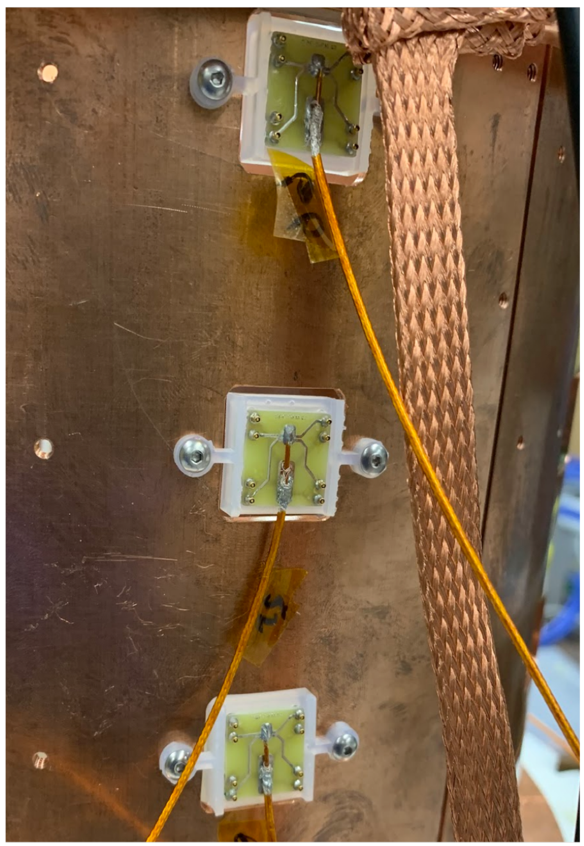


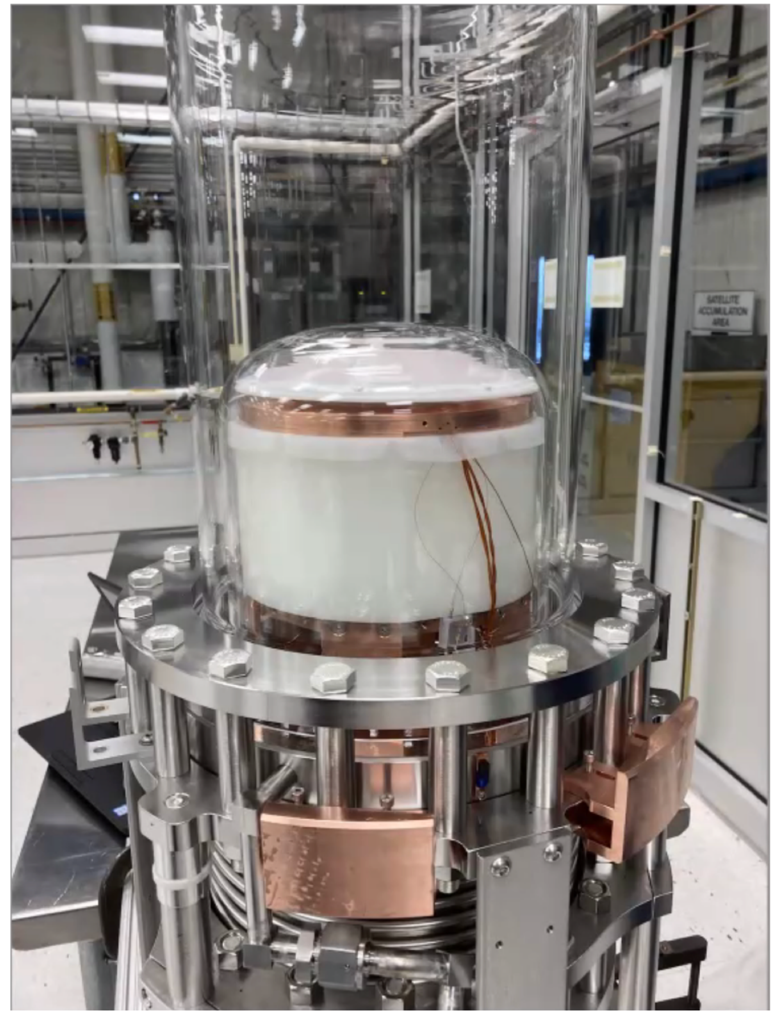
The detector

O(10 kg) LAr contained within two fused silica jars, inner and outer jars.

- It's happening now!

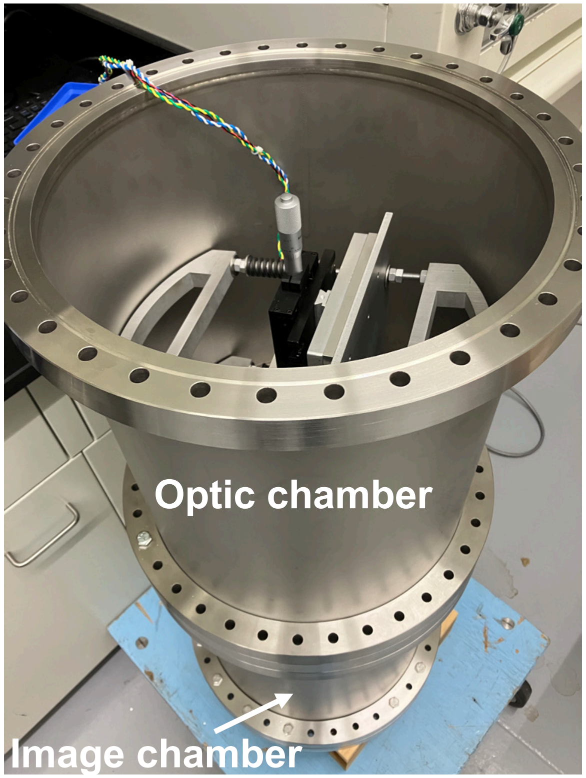


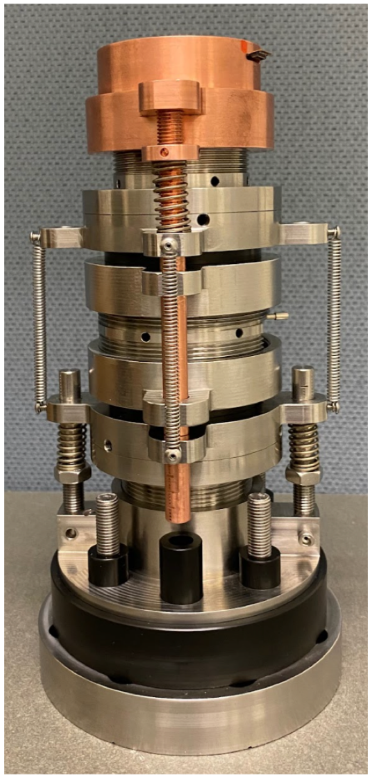


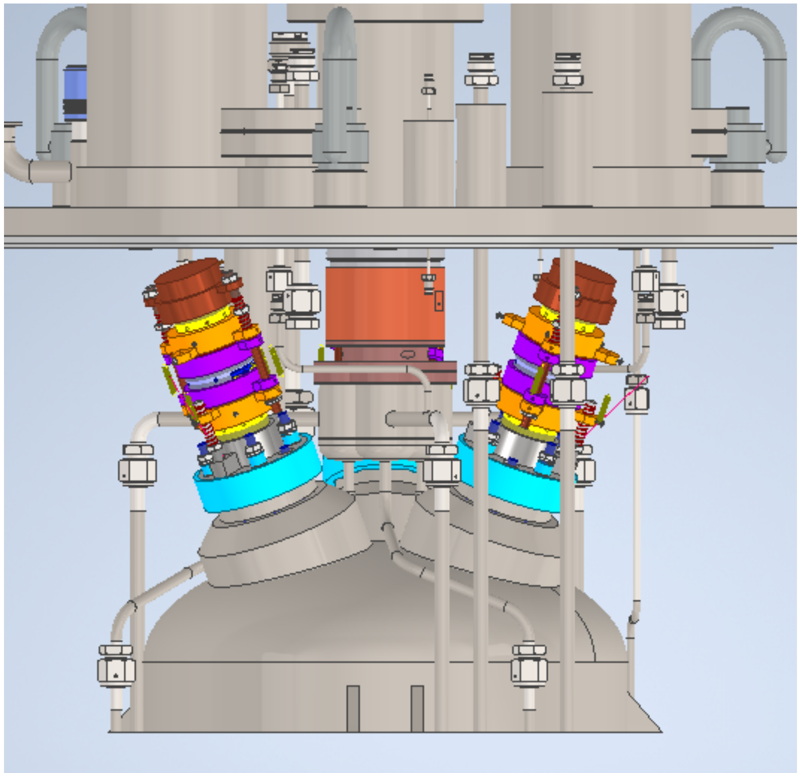


New camera system for SBC (UofA)

- The current camera produce too much radioactivity.
- Design of the relay lens system and a dedicated test bench has been built to test the optimal distance between lenses, the quality and resolution of the image in argon temperature.

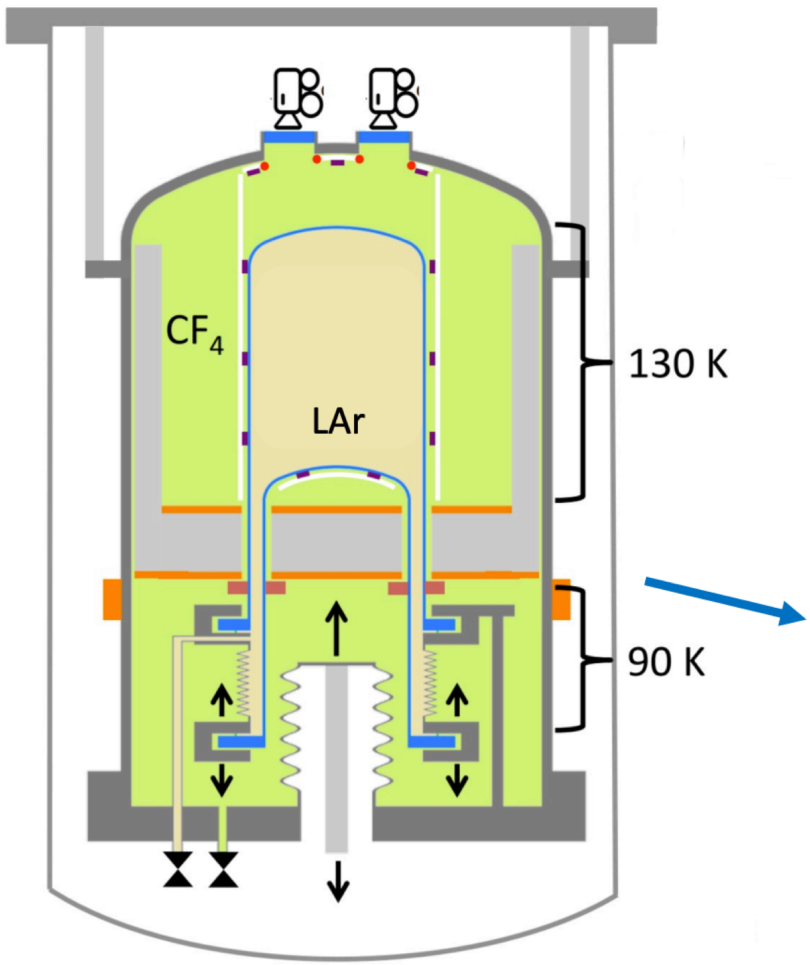






SBC Experimental Design

- The full inner assembly:
  placed inside a stainless-steel vacuum jacket vessel

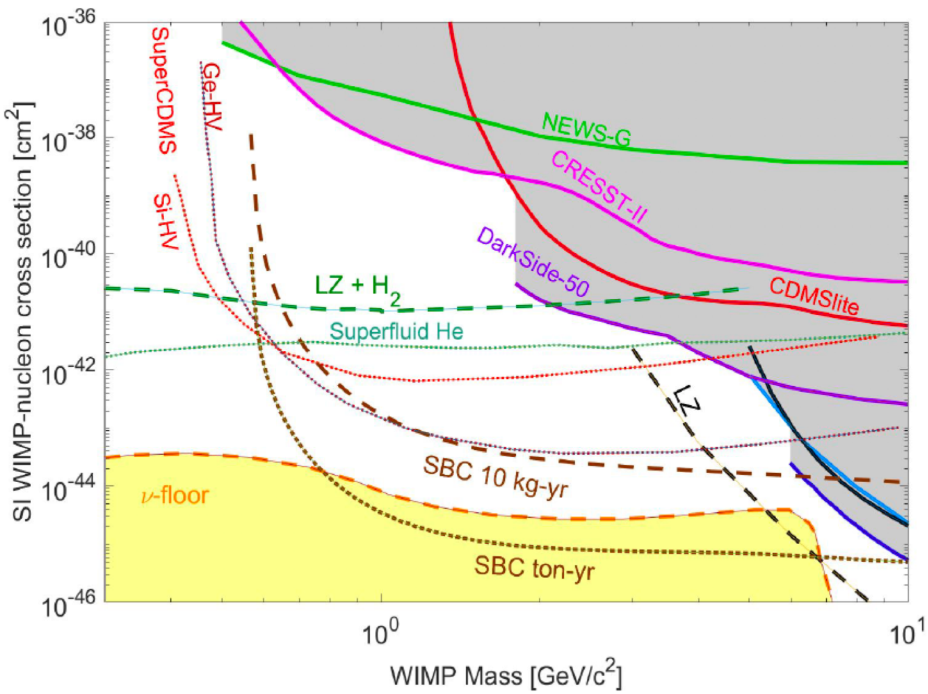


New Detector: The SBC

The Physics Reach

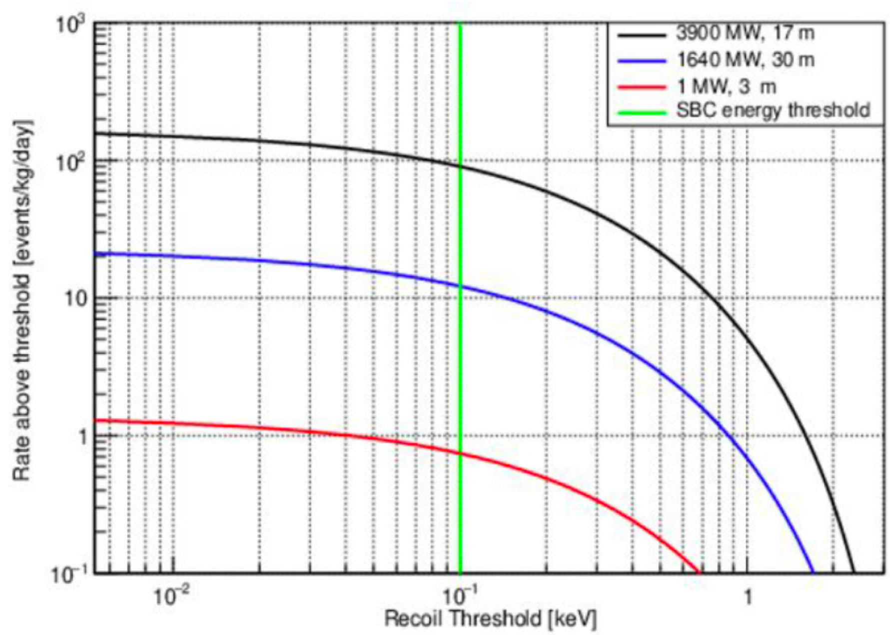
- Two detectors to be built for low-mass dark matter and CEvNS
- Energy threshold 100 eV

Perform competitive **Low-Mass WIMP** search (0.7-7 GeV/c2)



Location = SNOLAB

Precision study of **reactor CEvNS** interactions for Argon and Xenon

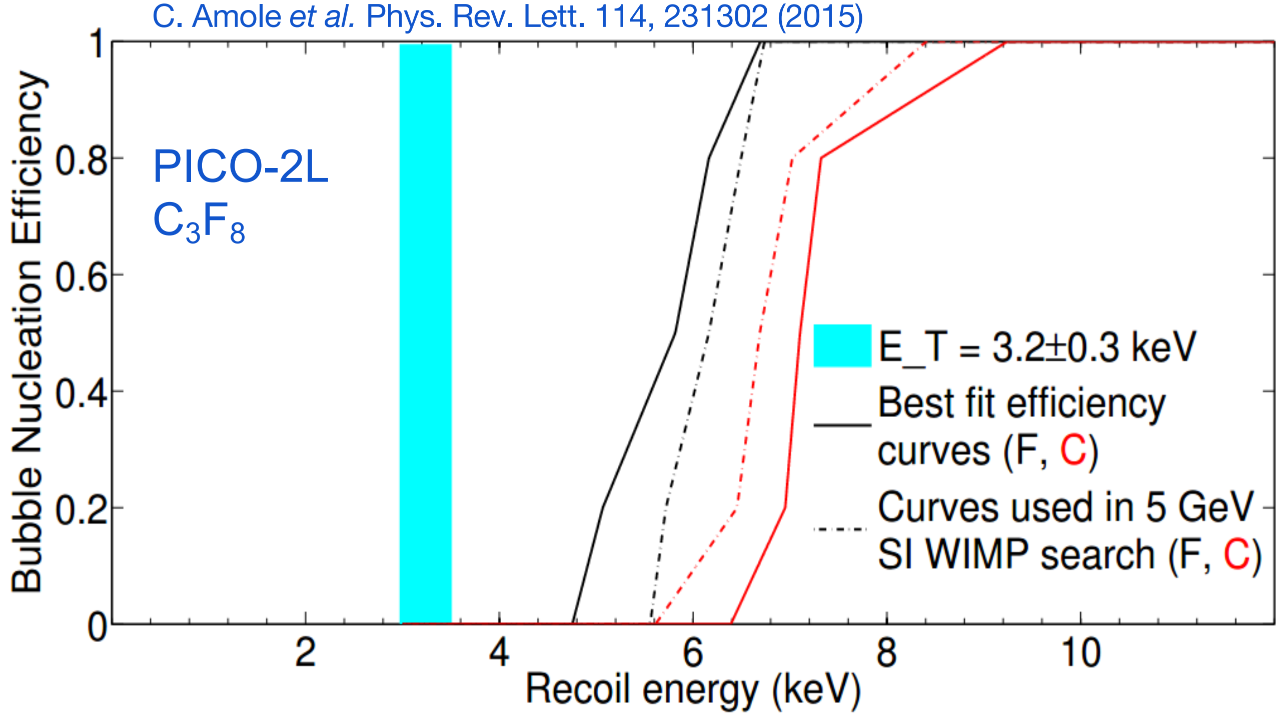


Collaborating with UNAM to identify reactor site

Nucleation efficiency studies

- Critical to know the response of bubble chambers to nuclear recoils to interpret the dark matter results.
- Known that the Seitz model underestimates the response threshold (PICASSO, COUPP, SIMPLE, PICO, SBC).

C. Amole *et al.* Phys. Rev. Lett. 114, 231302 (2015)



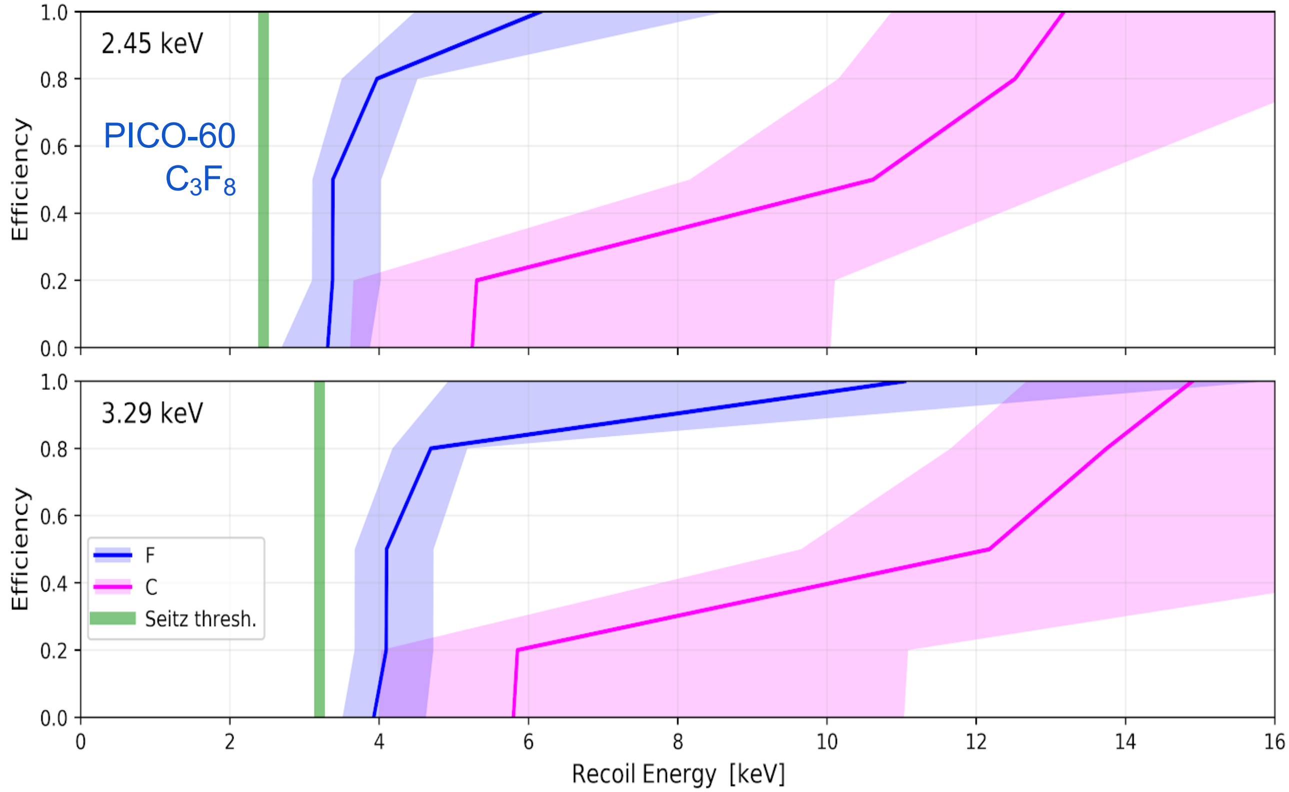
- Parametric fit is usually used on neutron calibration data

Nucleation efficiency studies at UofA

- New results obtained and published!
  Phys. Rev. D **106**, 122003, *arXiv: 2205.05771*

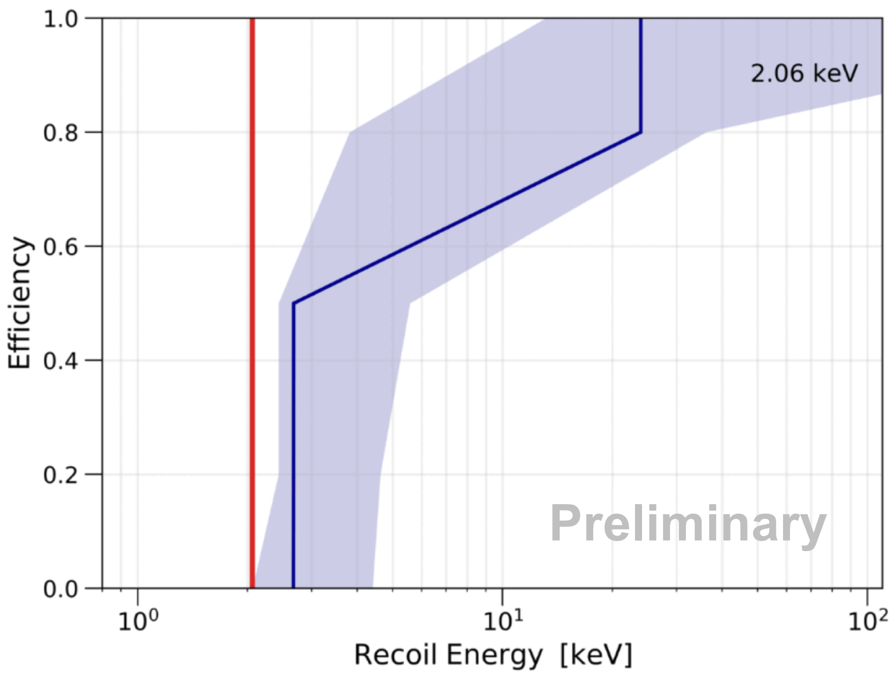
- A global fit of the simulations to the data performed to calculate the nuclear recoil bubble nucleation efficiency for PICO experiment

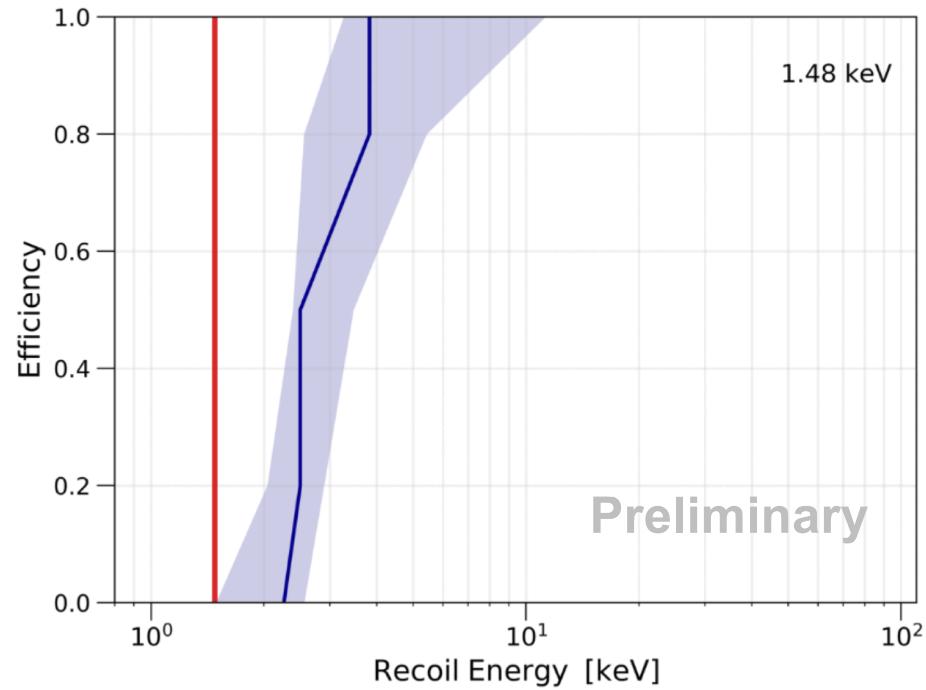
D. Durnford and M.-C. Piro, *JINST* 17 C01030 (2022)



Nucleation efficiency and Bubble growth

- Currently applying this method to the Xe SBC detector with Xenon
- Will be applied also for the SBC detector

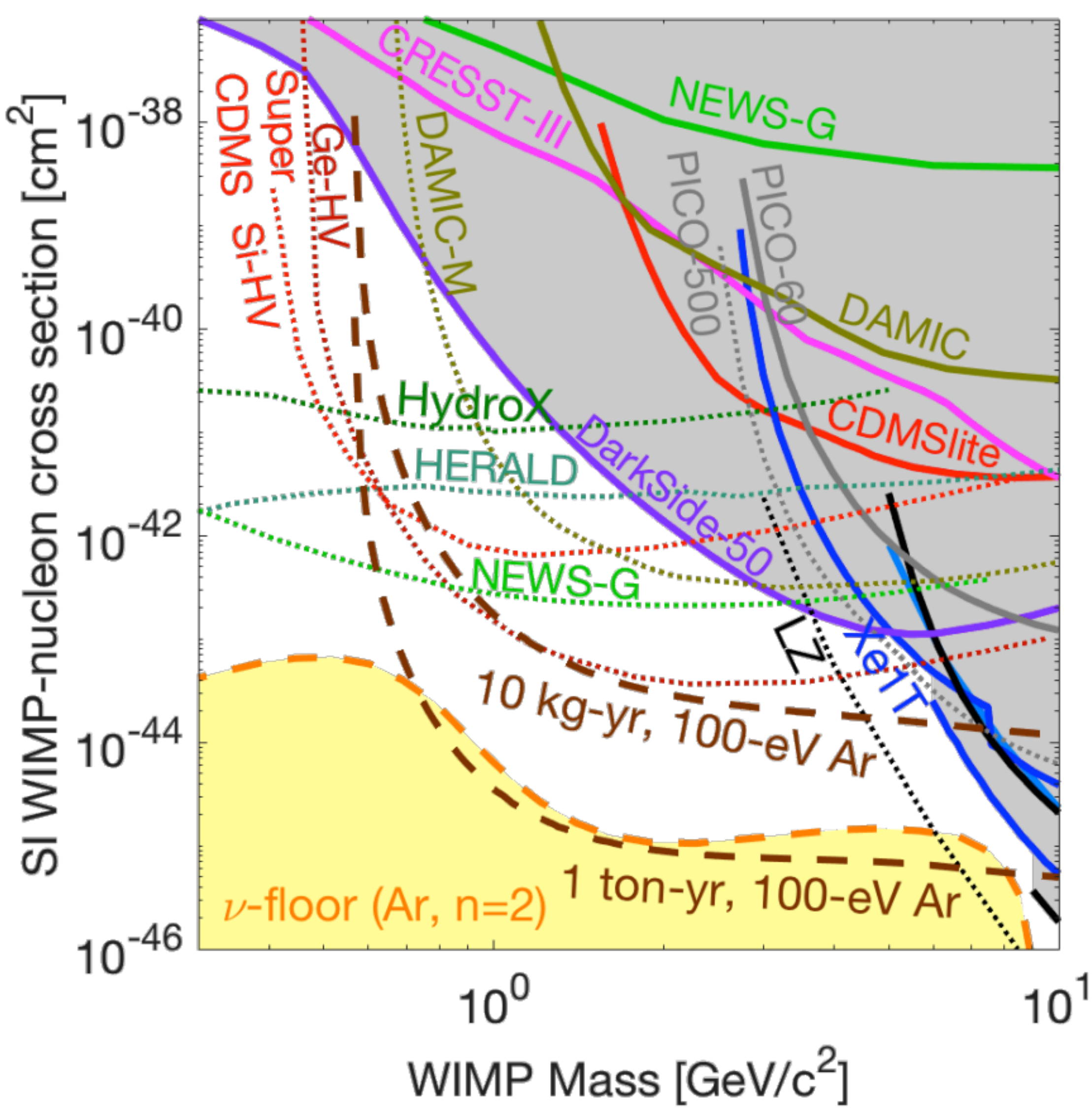




- However it is clear that there is a need to improve the theory of the bubble formation and growth in superheated liquids to understand the nucleation efficiency!

Summary

- **Liquid argon bubble chambers**
  - Scalable, electron recoil blind,
  - GeV-scale WIMP
  - Reactor CEvNS detection technique.
- 10kg LAr active mass is currently under **construction at Fermilab**.
- **Goal is 100 eVnr threshold.**
- A GeV-scale **WIMP search** will be conducted **at SNOLAB**.
- A future **1 ton-scale detector** will have sensitivity down to the **solar neutrino floor:** → SBC-CEvNS



Thank you!

What is essential is invisible to the eye …
for particle physicists is ***<u>Dark matter</u>****!*

@Le petit prince