UNIVERSITY OF ALBERTA

cap

May 4th 2022

Summer AstroParticle Workshop

Scintillating Bubble Chamber

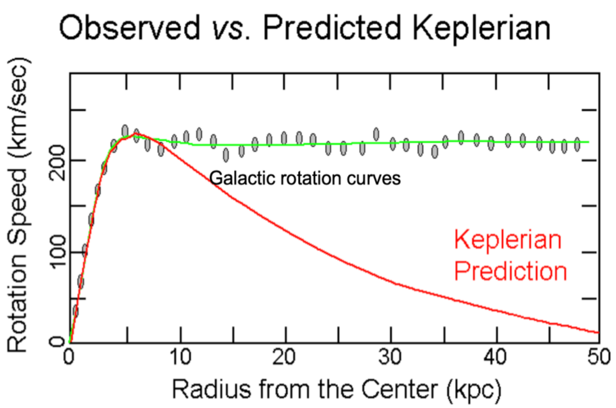
SBC

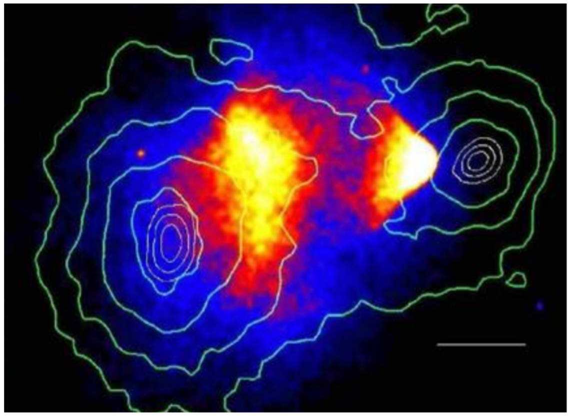
Marie-Cécile Piro

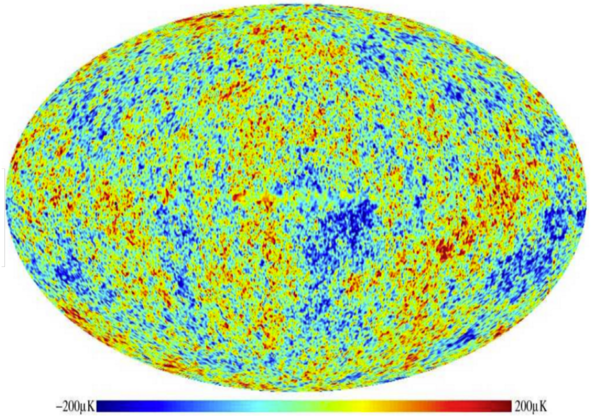
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

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

→ ***See talk Friday by G. Mohlabeng***

Dark matter : the famous candidate

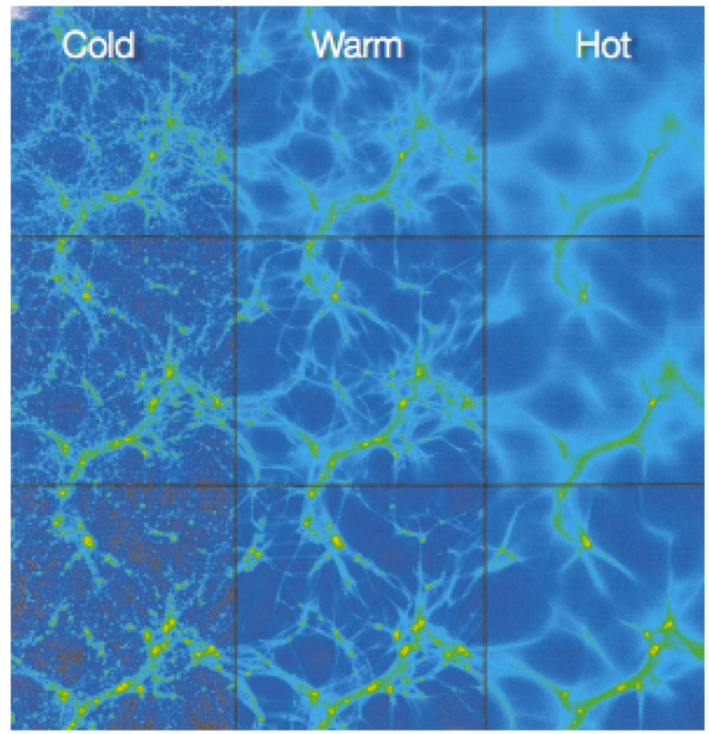
- Constraints from astrophysics and searches for new particles:

- 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)*.

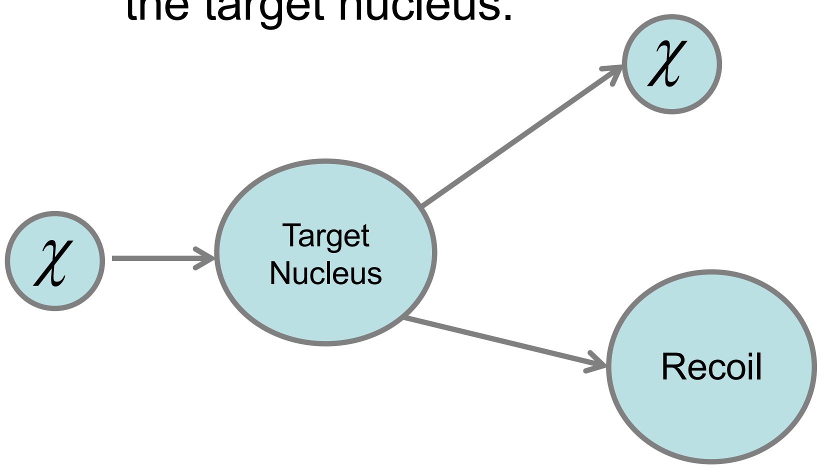
→ See talk Friday by G. Mohlabeng

How to detect directly WIMP ?

Direct Detection :

Elastic scattering on nuclei

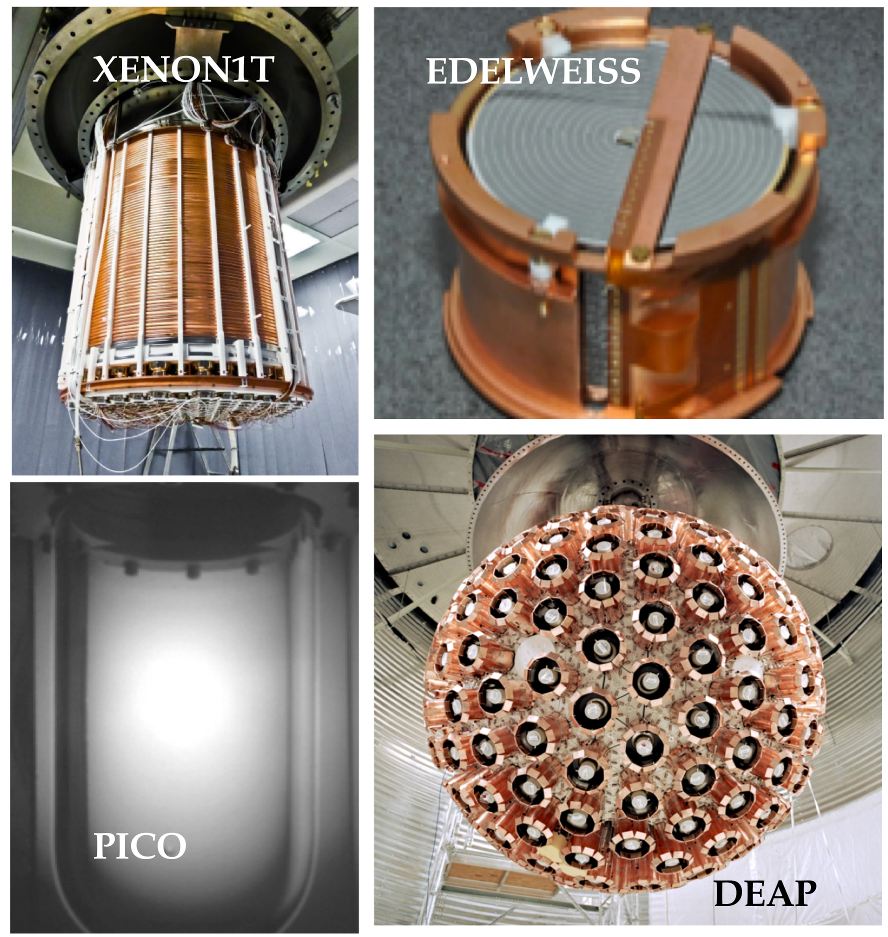
→ Look for the recoil of the target nucleus.



Energy E_R (1-100 keV)

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

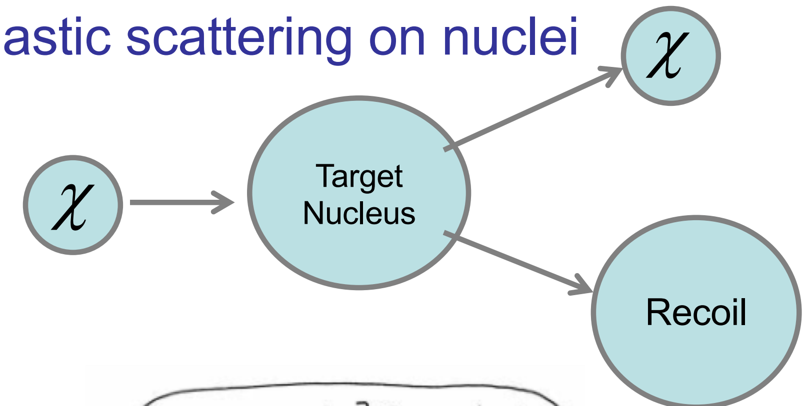
(XENON1T, LZ, PANDAX, DEAP-3600, PICO, EDELWEISS …)



Just to give you an idea !!

Direct Detection :

Elastic scattering on nuclei

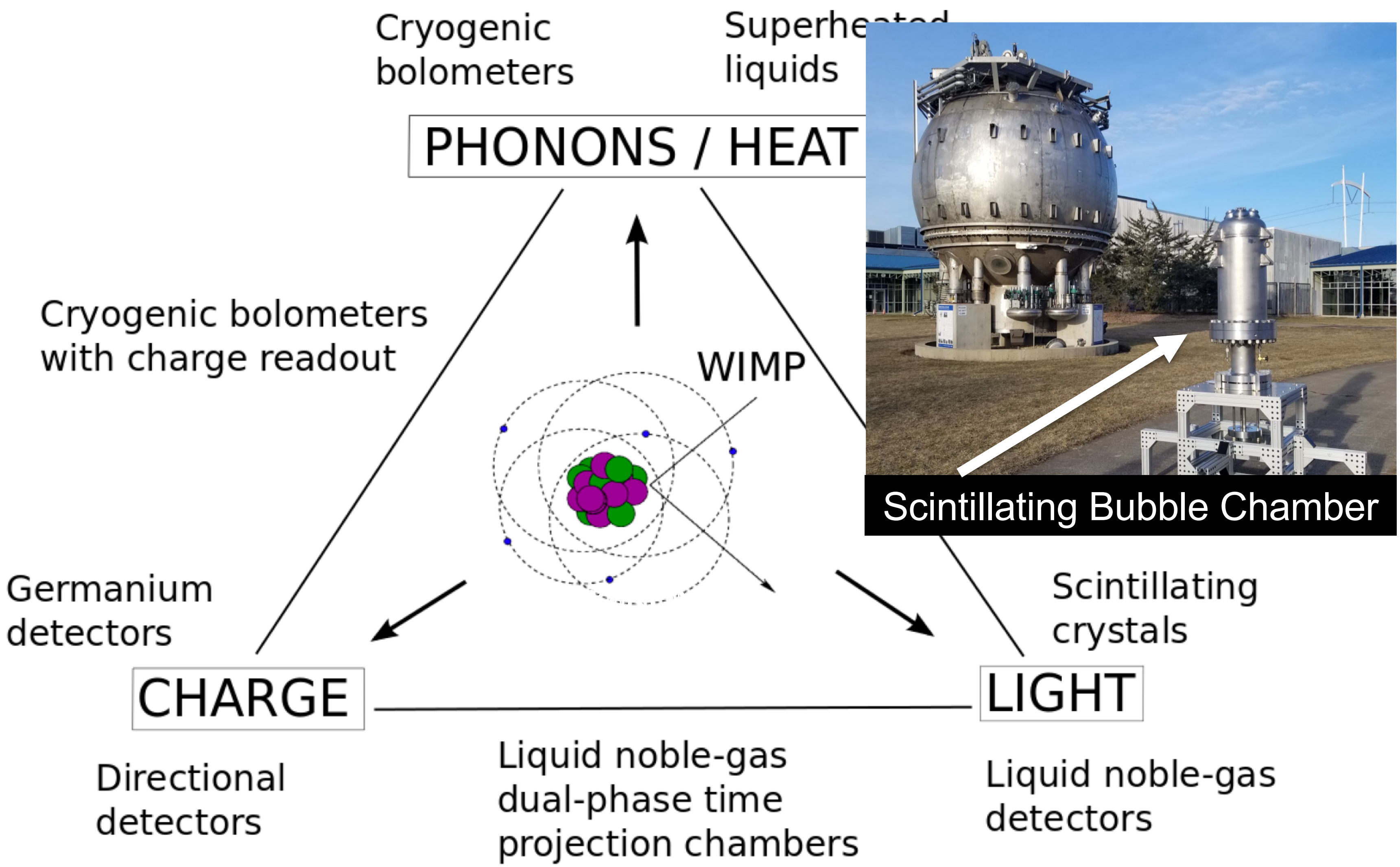


The recoil created by the WIMP is comparable to a grain of salt that touches the ground with a force divided by 100 billion.

Very low energy to detect !!

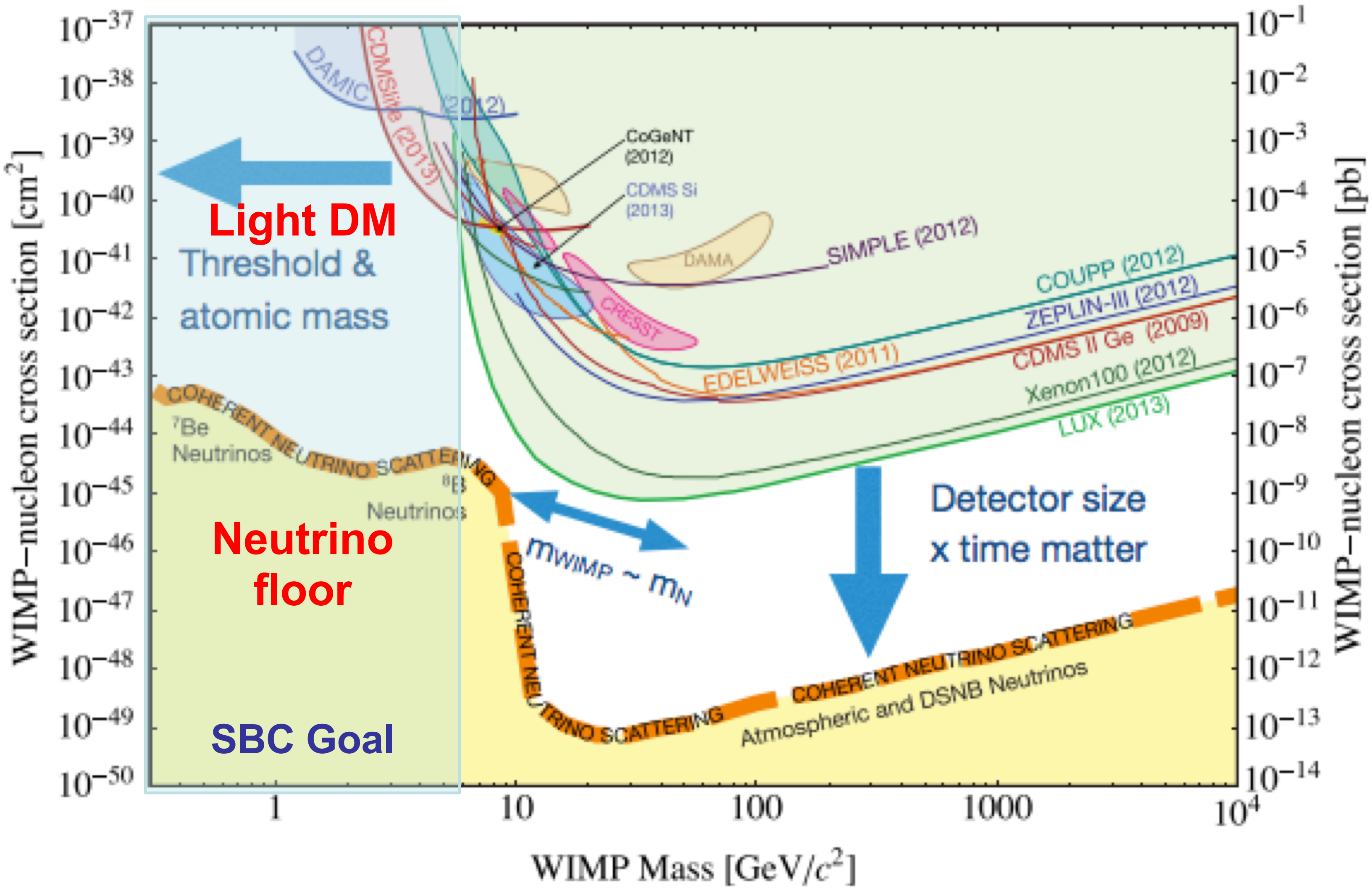
--> Hyper sensitive detectors !!

Direct Detection Experiment



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

Direct Detection Landscape



The neutrino floor

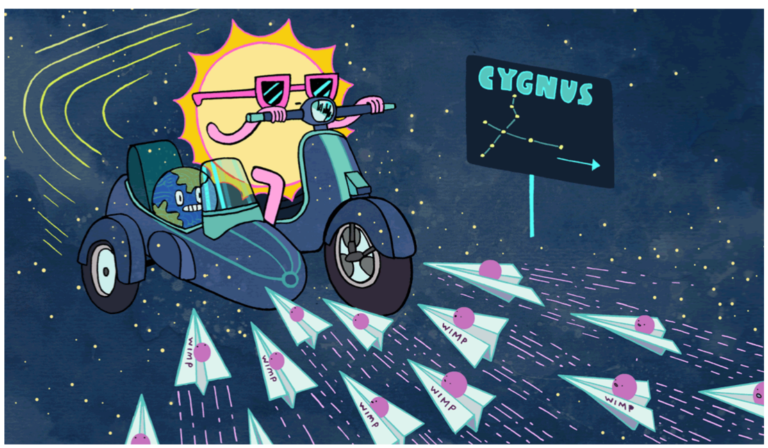
- Ultimately: solar, atmospheric and supernovae neutrinos

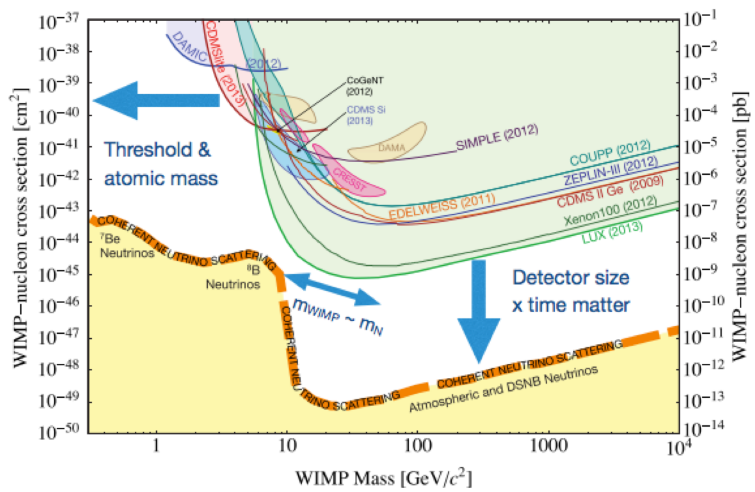
The coherent scattering of solar neutrinos (CEvNS) will be the limiting irreducible background creating a "**neutrino floor**" for all DM experiments.

Currently there is no way to distinguish between DM and CEvNS

- Strategy :

→ Add the directionality channel in current technology
→ Dedicated CEvNS calibration using nuclear reactor





→ ***See talk Friday by R. Martin***

What do we need for Direct Detection???

CHALLENGES FOR DIRECT DARK MATTER SEARCHES

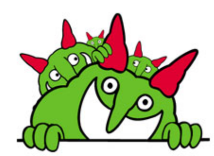
$Low\ Recoil\ Energy \leq 100\ keV$ → Low threshold detectors.

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

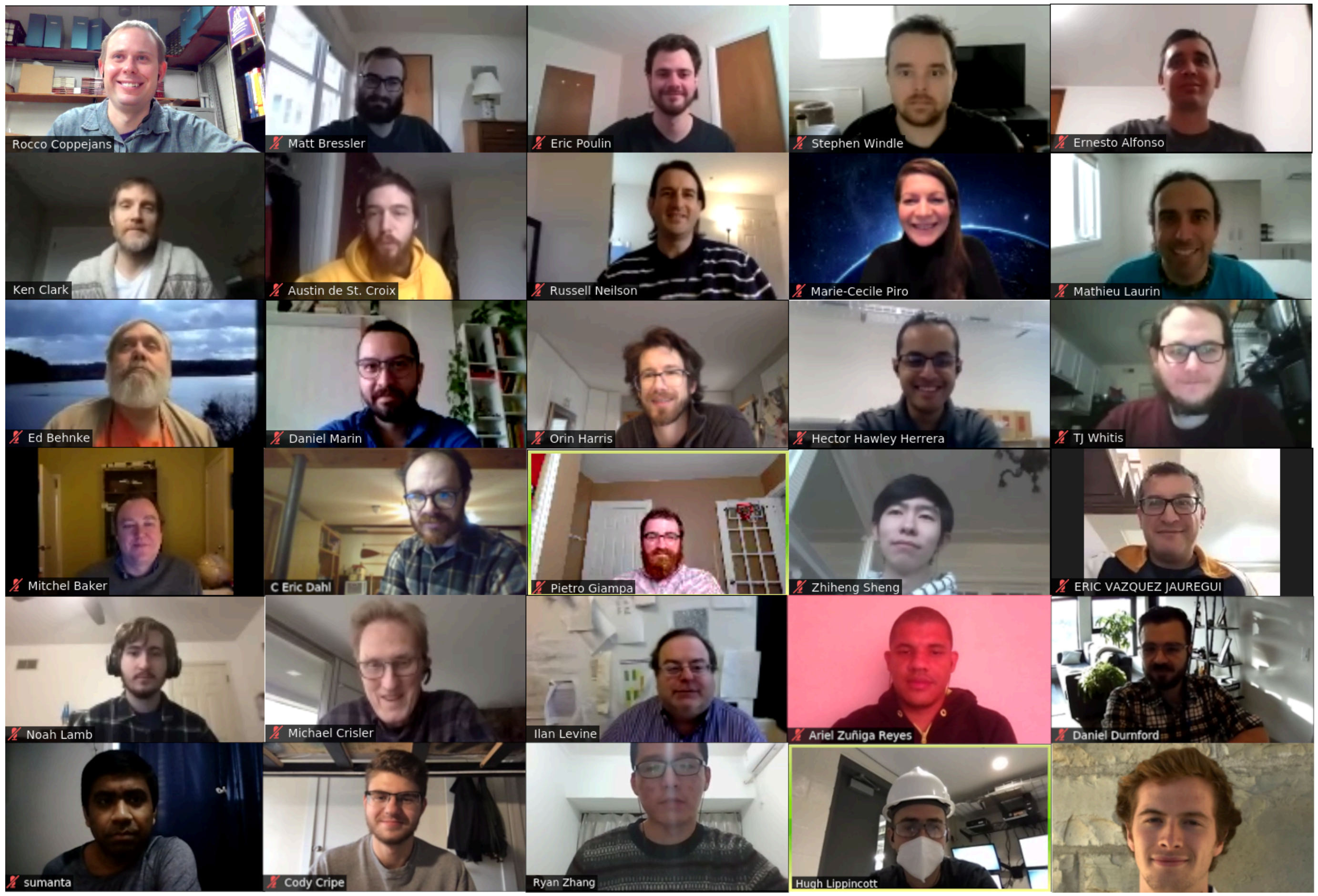
University of Alberta

Université de Montréal

SNOLAB

Fermilab

Pacific Northwest National Laboratory



Northeastern Illinois University

UC Santa Barbara

Indiana University South Bend

Drexel University

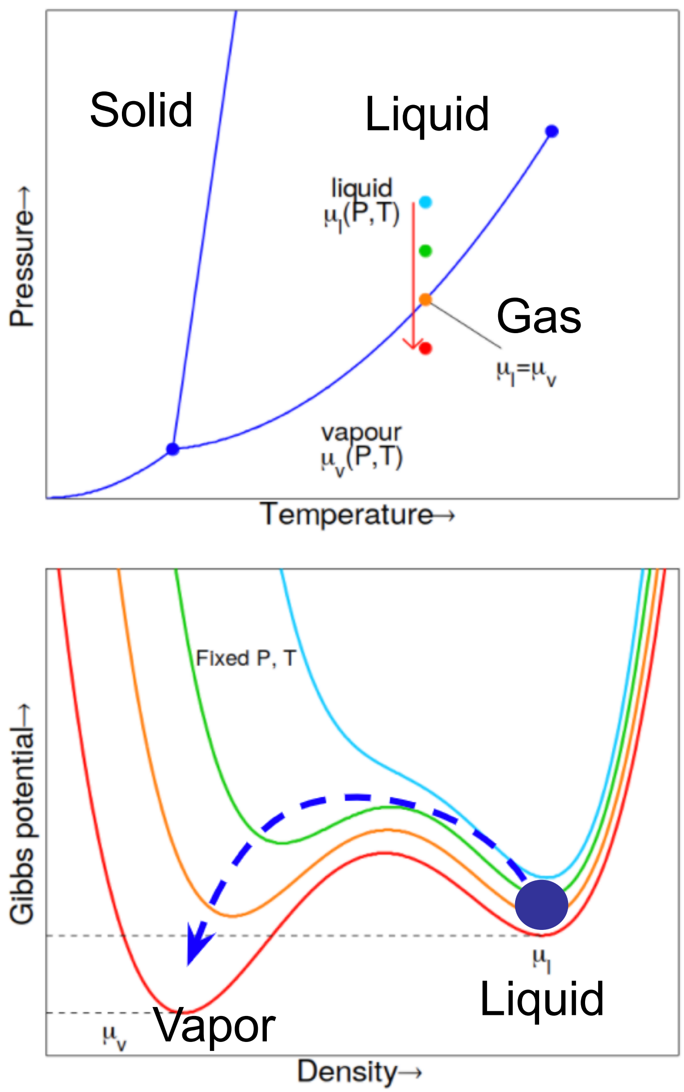
Universidad Nacional Autónoma de México

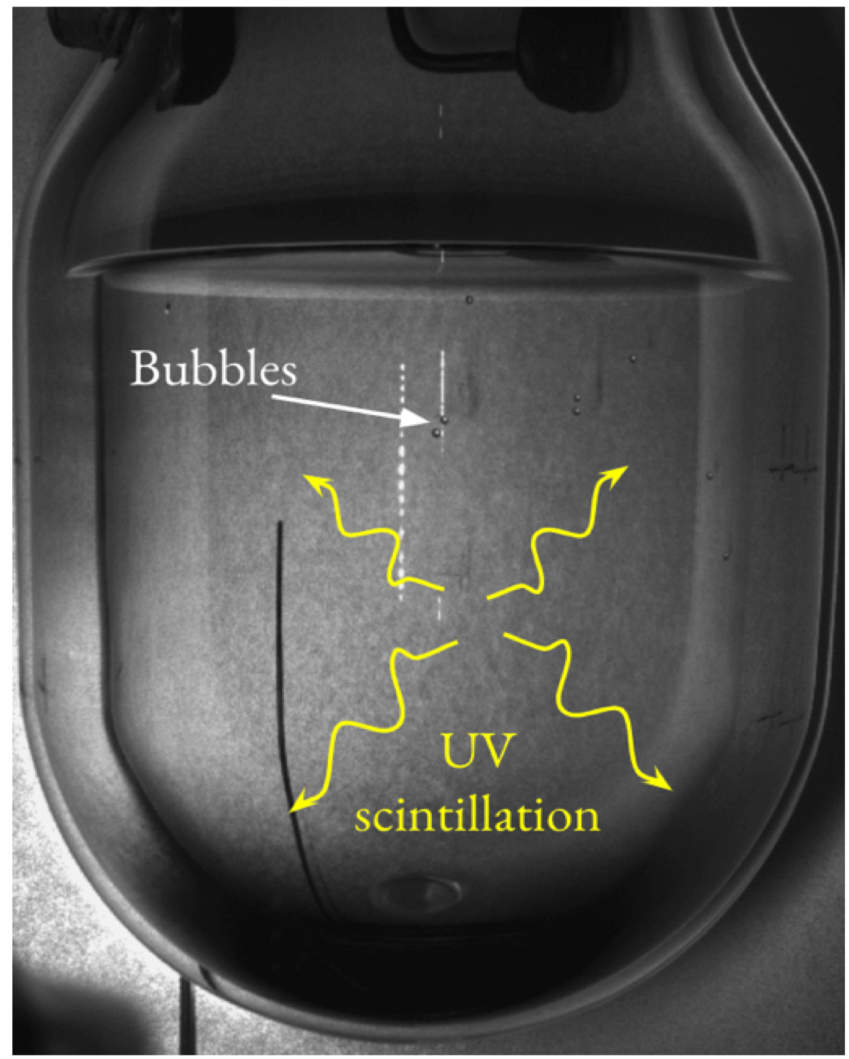
Bubble Chamber

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 (-143.15℃)
- 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.

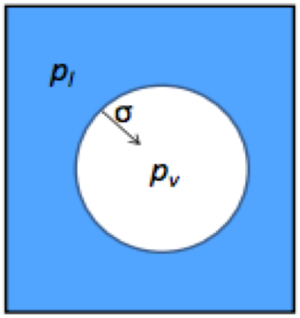
→ ***Should not be liquid at this pressure and temperature***

- Regulated by temperature and pressure:

→ Each condition correspond to an energy threshold (Seitz model).

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

Surface energy — Latent heat



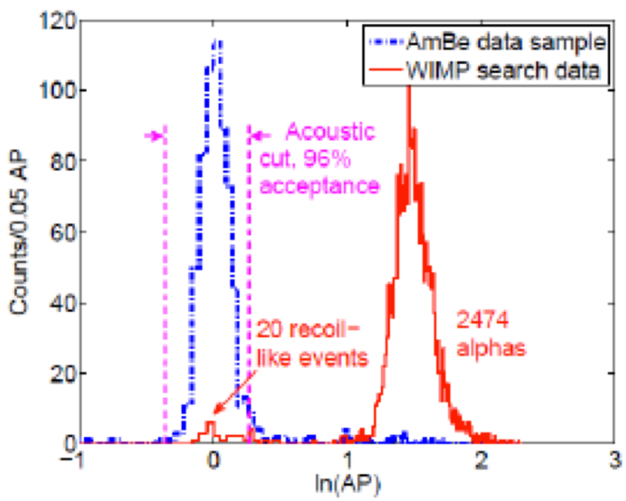
$$p_v - p_l = \frac{2\sigma}{r_c}$$

- Bubble chambers are threshold detectors

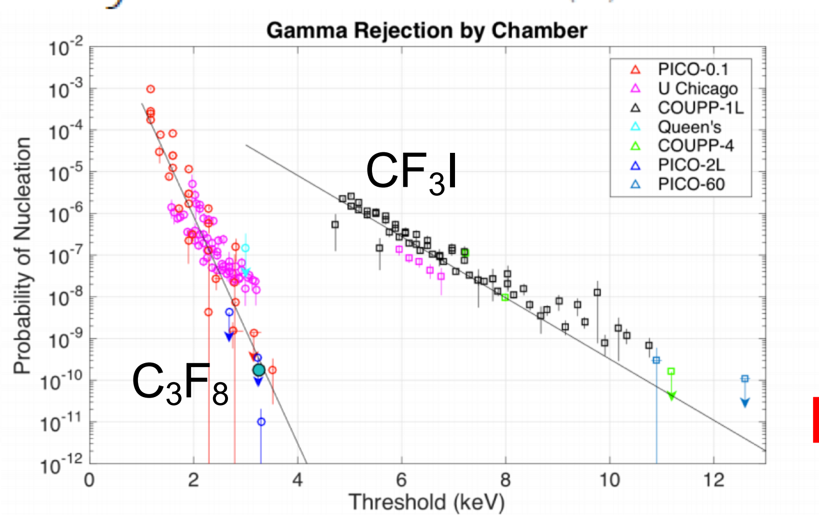
Why Bubble Chamber very good?

Impressive Background Rejection

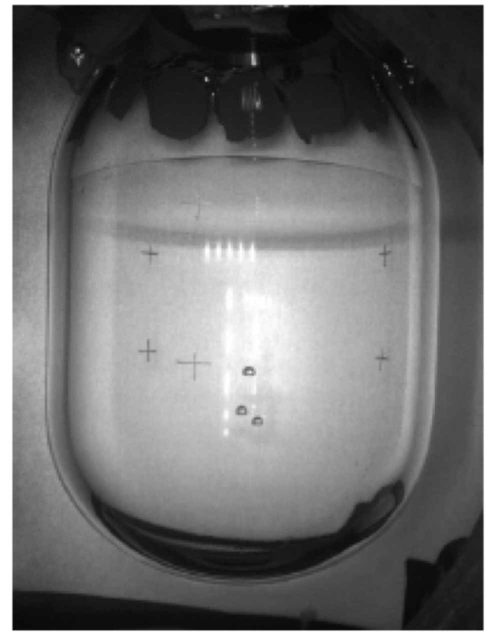
Acoustic Alpha Discrimination



Gamma Interaction Insensitivity



Multiple Neutron Scattering



But no energy information!!

New Detector: The SBC

Mixing technologies:

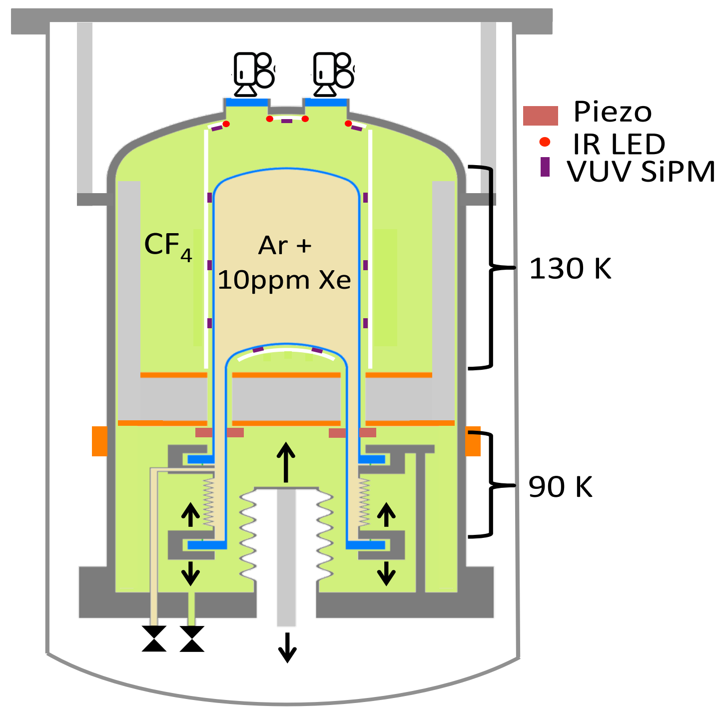
Bubble chamber (PICO) + Scintillation (DEAP, DarkSide)

→ See talk Friday by C. Moore

→ See talk Monday by S. Manecki

Combine the **background rejection** of bubble chambers and the **event-by-event energy resolution.**

Scintillating Bubble Chamber SBC

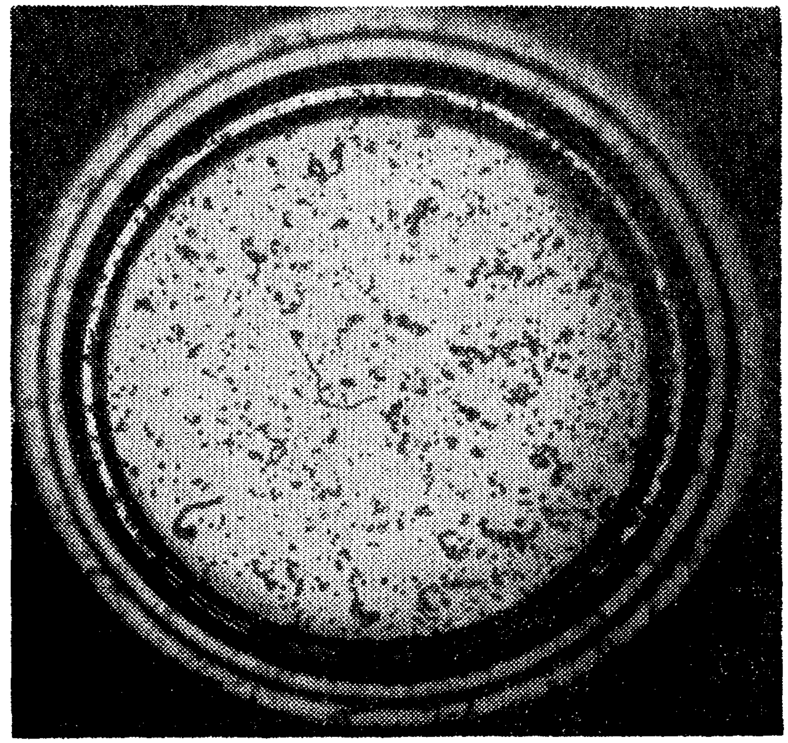


Scintillating Bubble chamber history

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) superheat



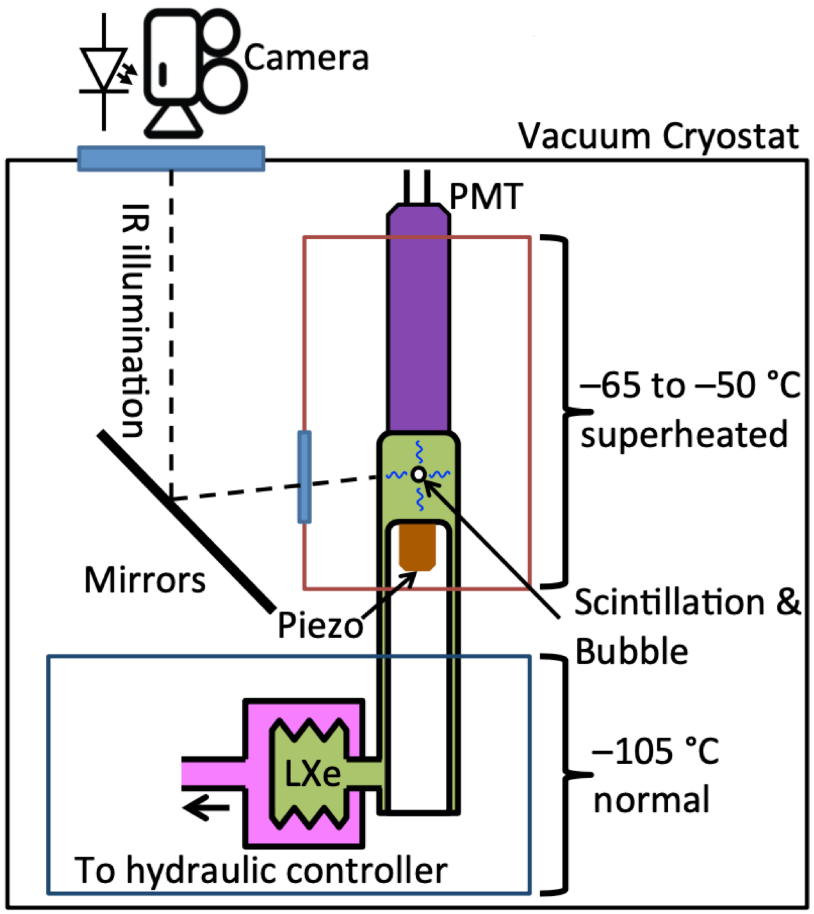
Phys.Rev. **102**, 586 (1956)

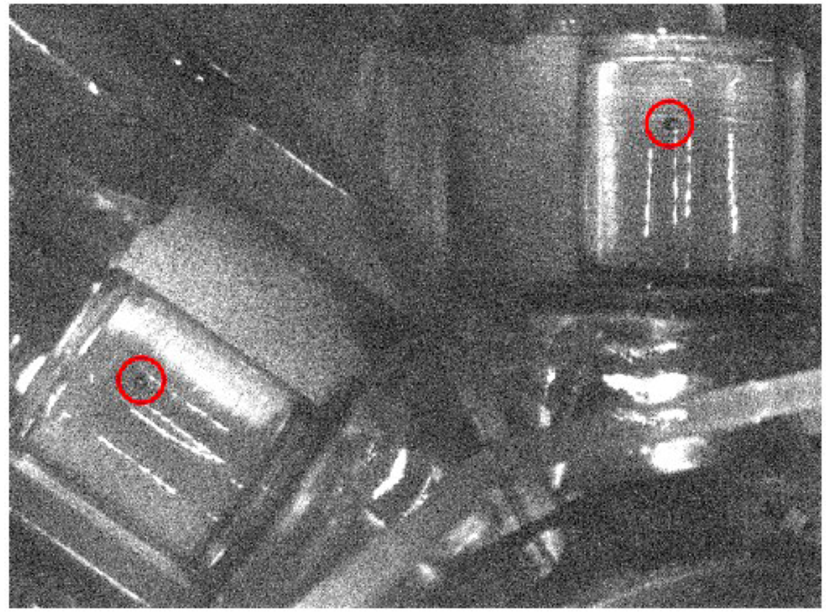
Scintillation suppresses Bubble nucleation!

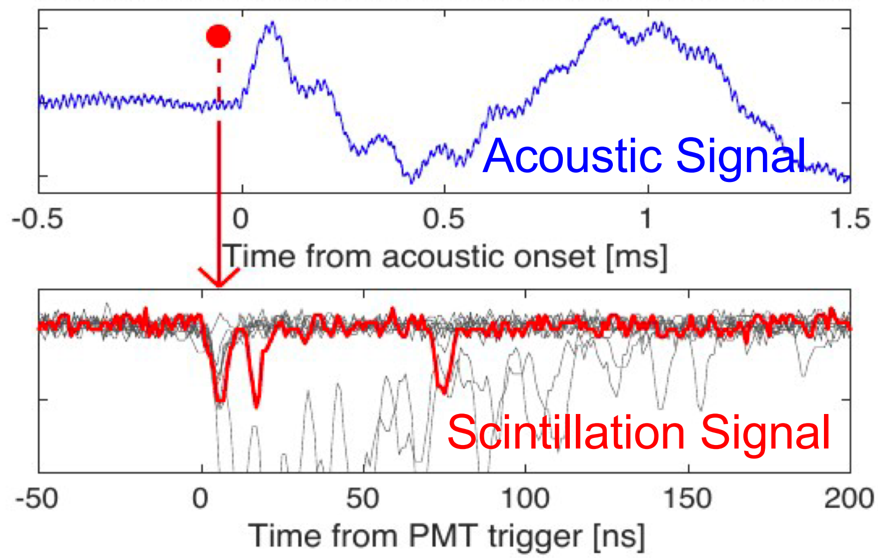
Bubble Chamber

Proof of principle:

- 30g Xenon Bubble Chamber



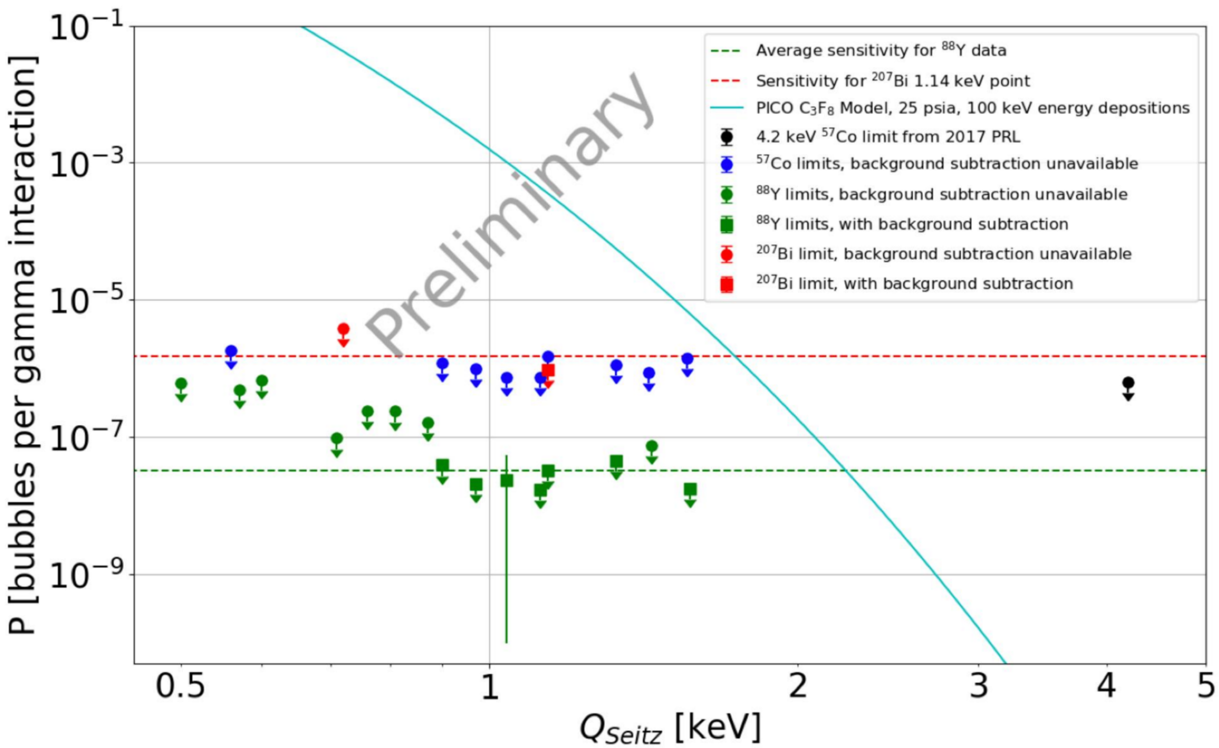




PRL 118, 231301 (2017), arXiv:1702.08861

Xenon Bubble Chamber

- Seitz thresholds as low as 0.5 keV
- No sign of gamma interaction nucleation at any threshold!!!
- Nucleation by Nuclear Recoils below 5 keV

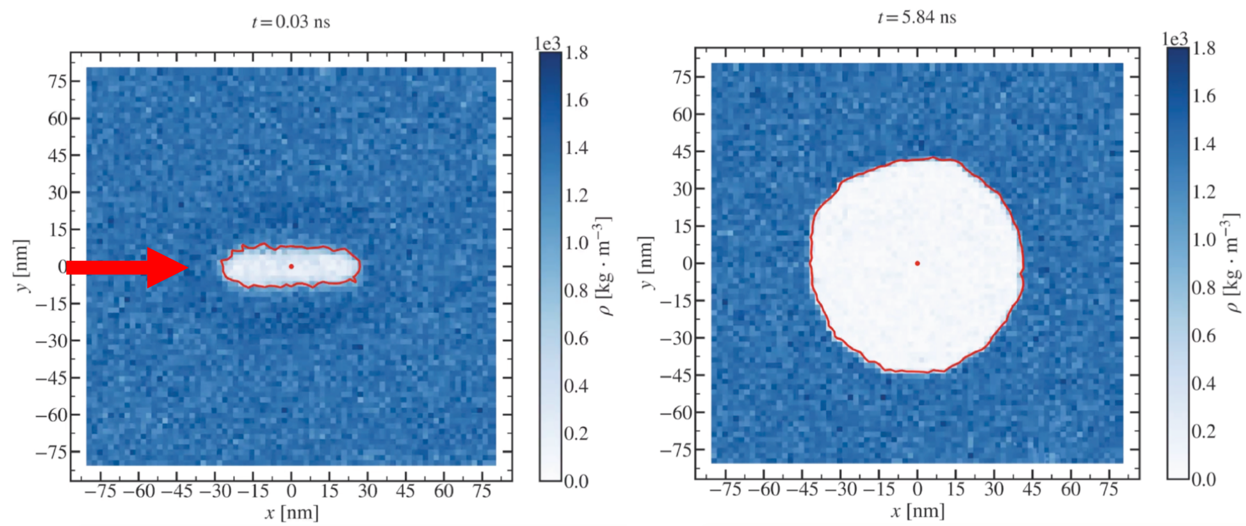


Scintillation suppresses Bubble nucleation!

Directionality channel in detectors

- Hint in bubble growth formation in superheated liquids

→ **Dependence of particle direction at ns time scale!**



Currently working with my group (R&D program CFI secured)

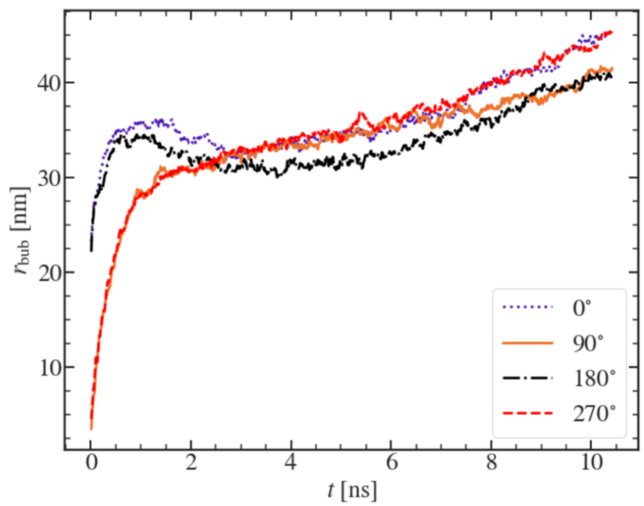
→ **New idea:** fast camera, new acoustic sensors, E field etc.

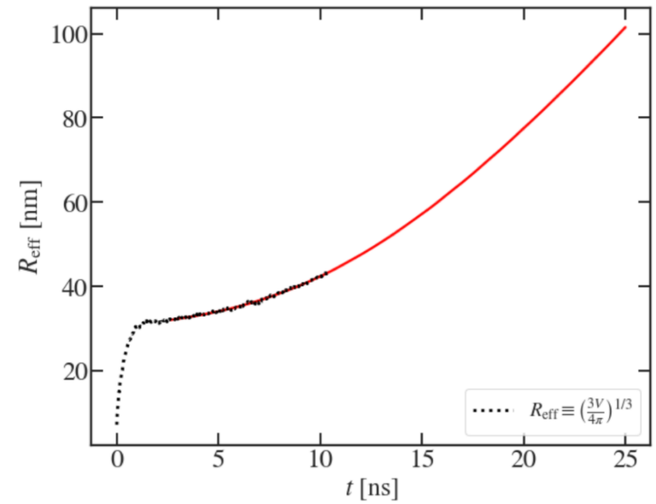
- Molecular Dynamic (MD) simulation to understand the bubble growth → **New theory is needed!**

Directionality channel in detectors

- Hint in bubble growth formation in superheated liquids

→ **Dependence of particle direction at ns time scale!**





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→ **New idea:** fast camera, new acoustic sensors, E field etc.

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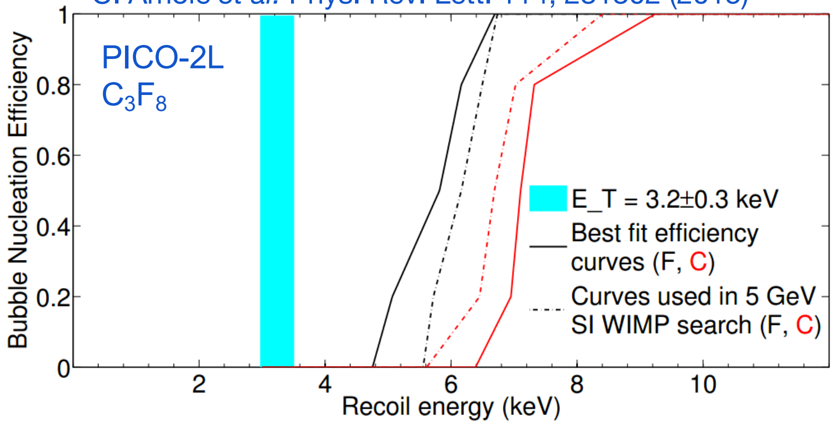
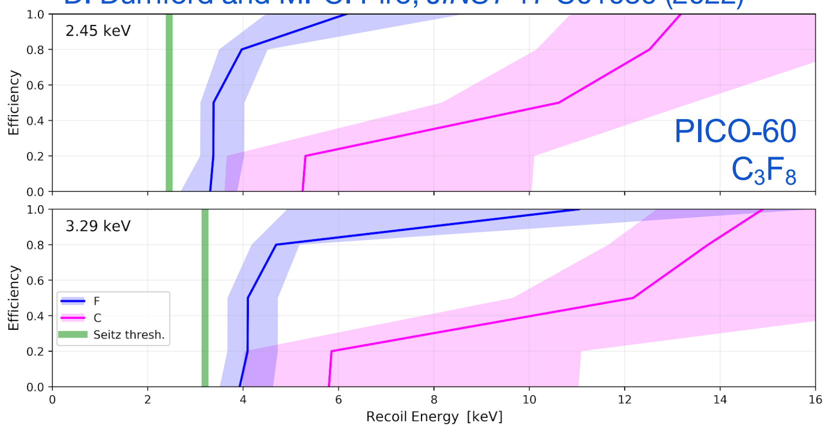
Bubble growth studies

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

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



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



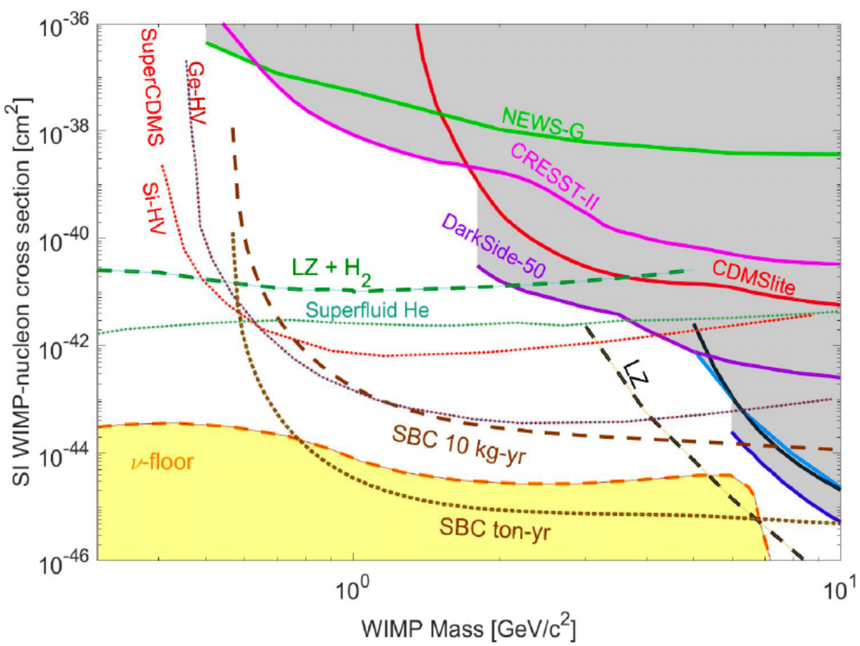
- Parametric fit is used on neutron calibration data
- Leading efforts to improve the theory of the bubble formation and growth in superheated liquids using molecular dynamics simulations

New Detector: The SBC

The Physics Reach

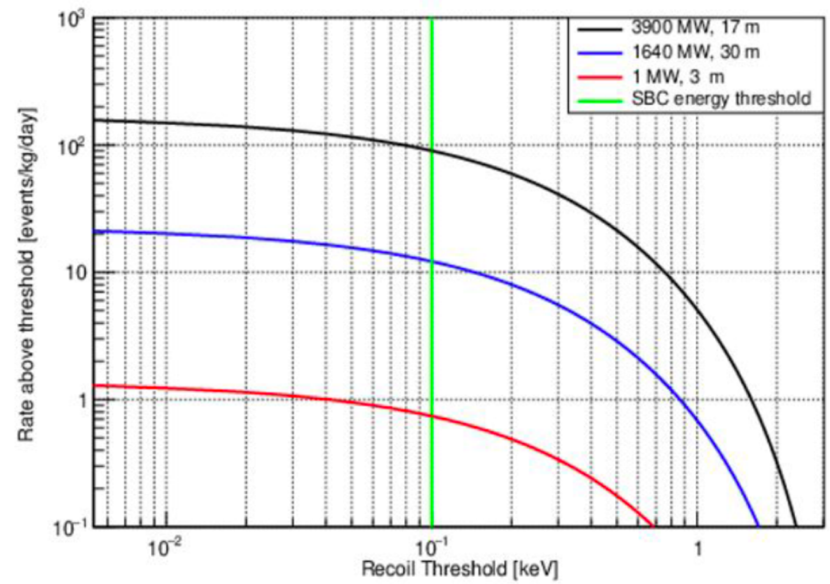
- Two detectors to be built for low-mass dark matter and CEvNS

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



Location = SNOLAB

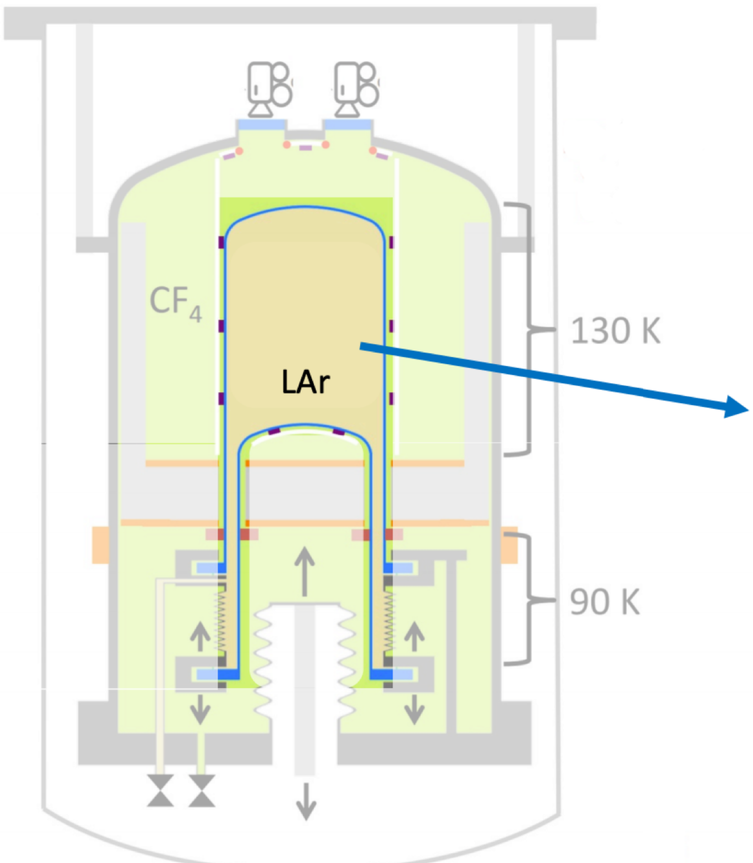
Precision study of **reactor CEvNS** interactions for Argon and Xenon

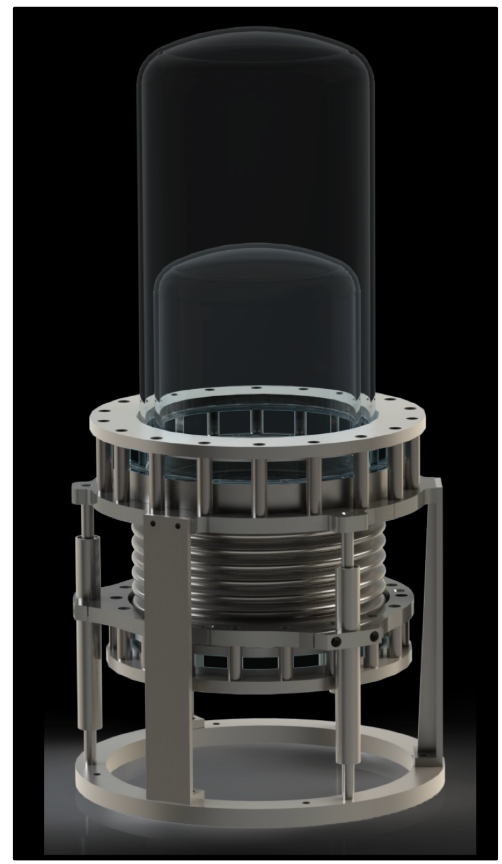


Collaborating with UNAM to identify reactor site

SBC Experimental Design

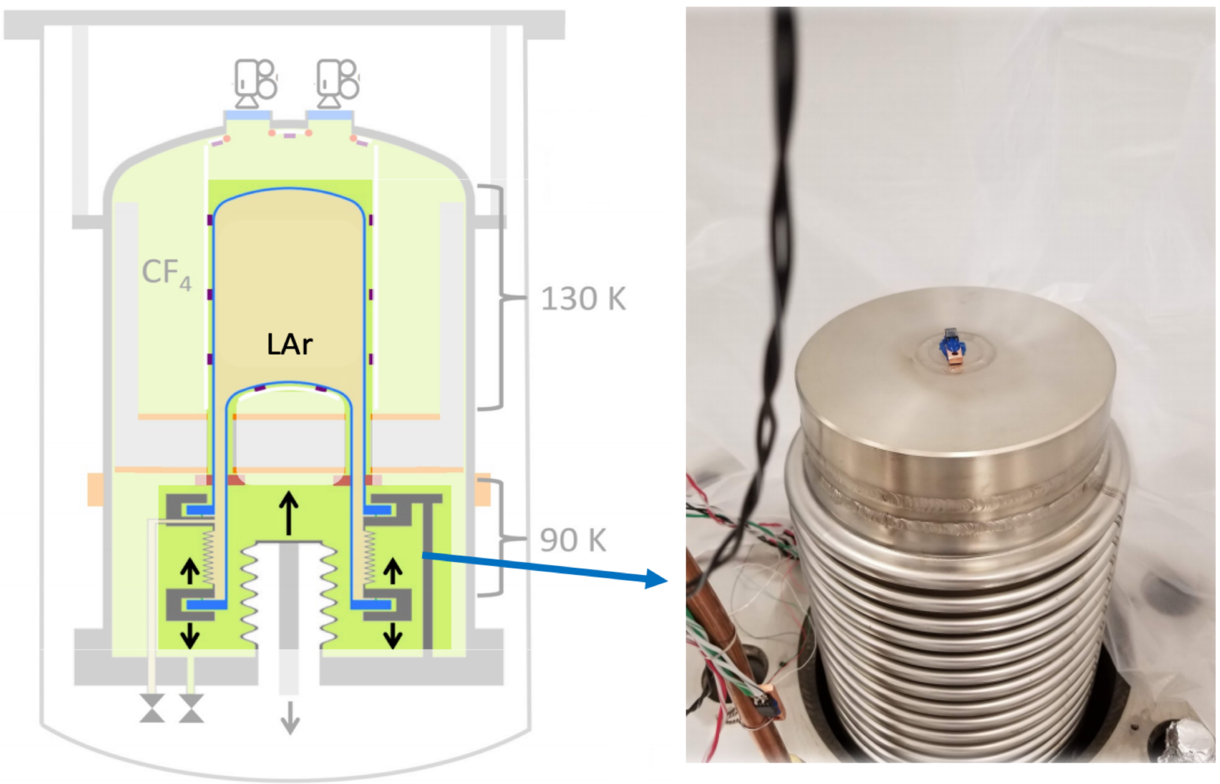
- O(10 kg) LAr contained within two fused silica jars, inner and outer jars.

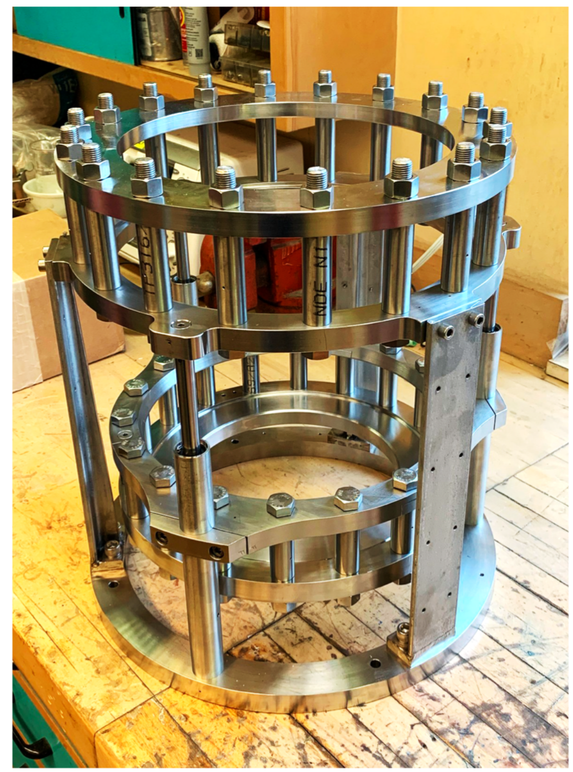




SBC Experimental Design

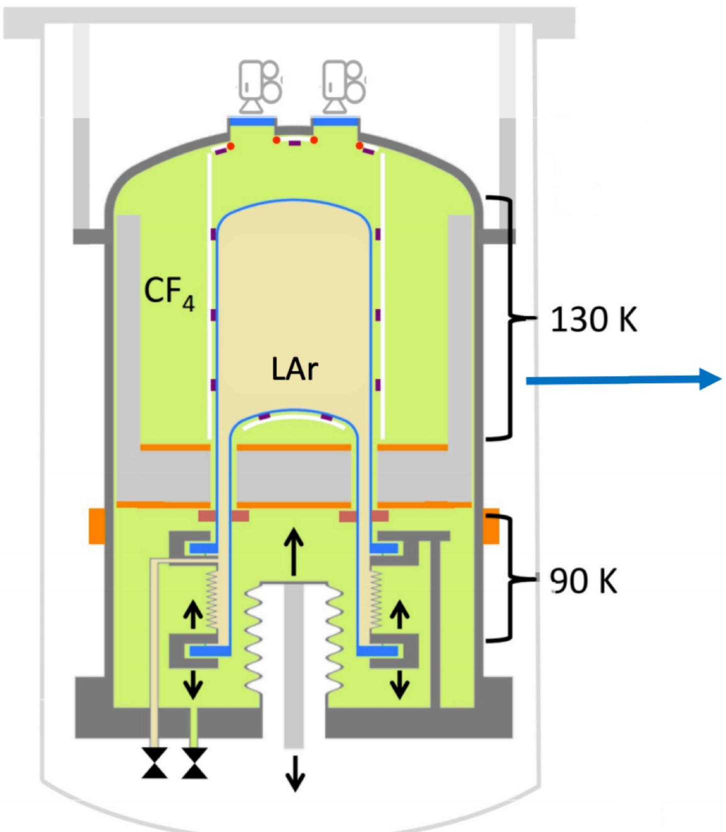
- Hydraulic piston controls the inner jar position
- Compressing/Decompressing the target fluid





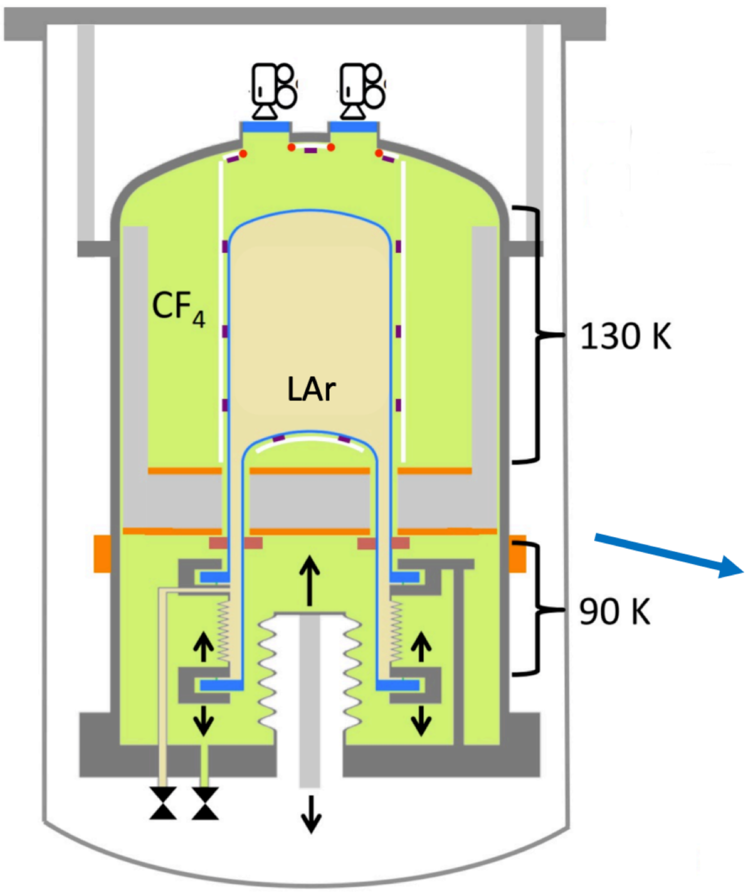
SBC Experimental Design

- Cryogenic hydraulic fluid: Liquid CF_4 contained within a stainless-steel pressure vessel



SBC Experimental Design

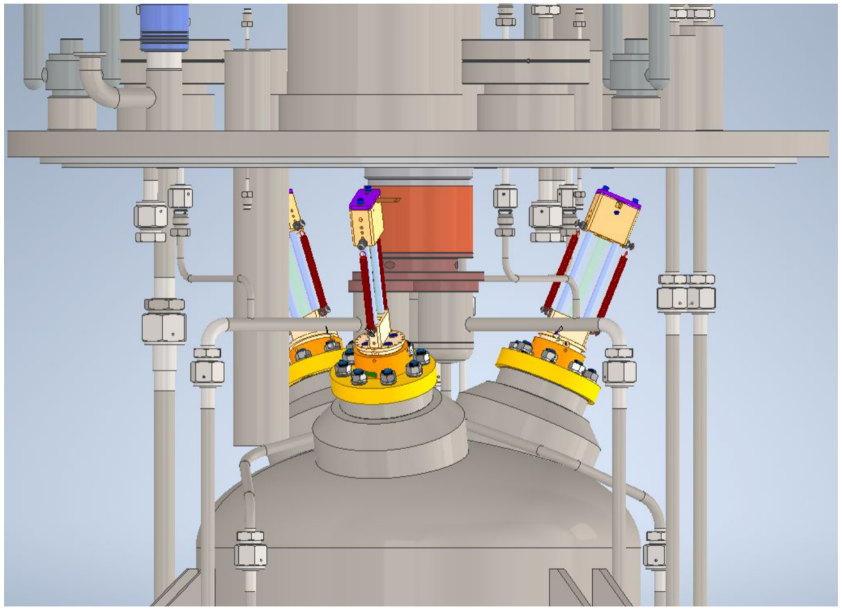
- The full inner assembly
  placed inside a stainless-steel vacuum jacket vessel

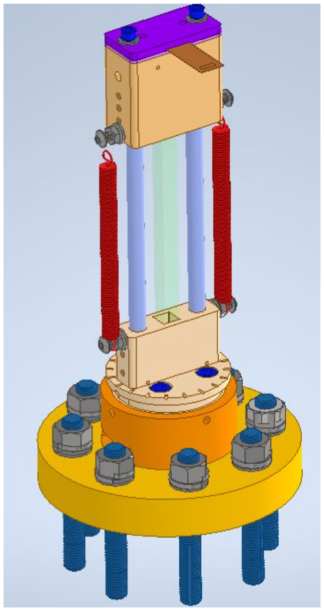


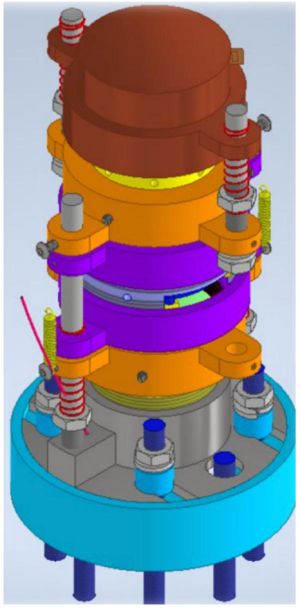
Camera new design at UofA

Camera activity too high for the SBC detector:

- New design to keep them away of the active liquid!
- Nanoguide system and relay lens system

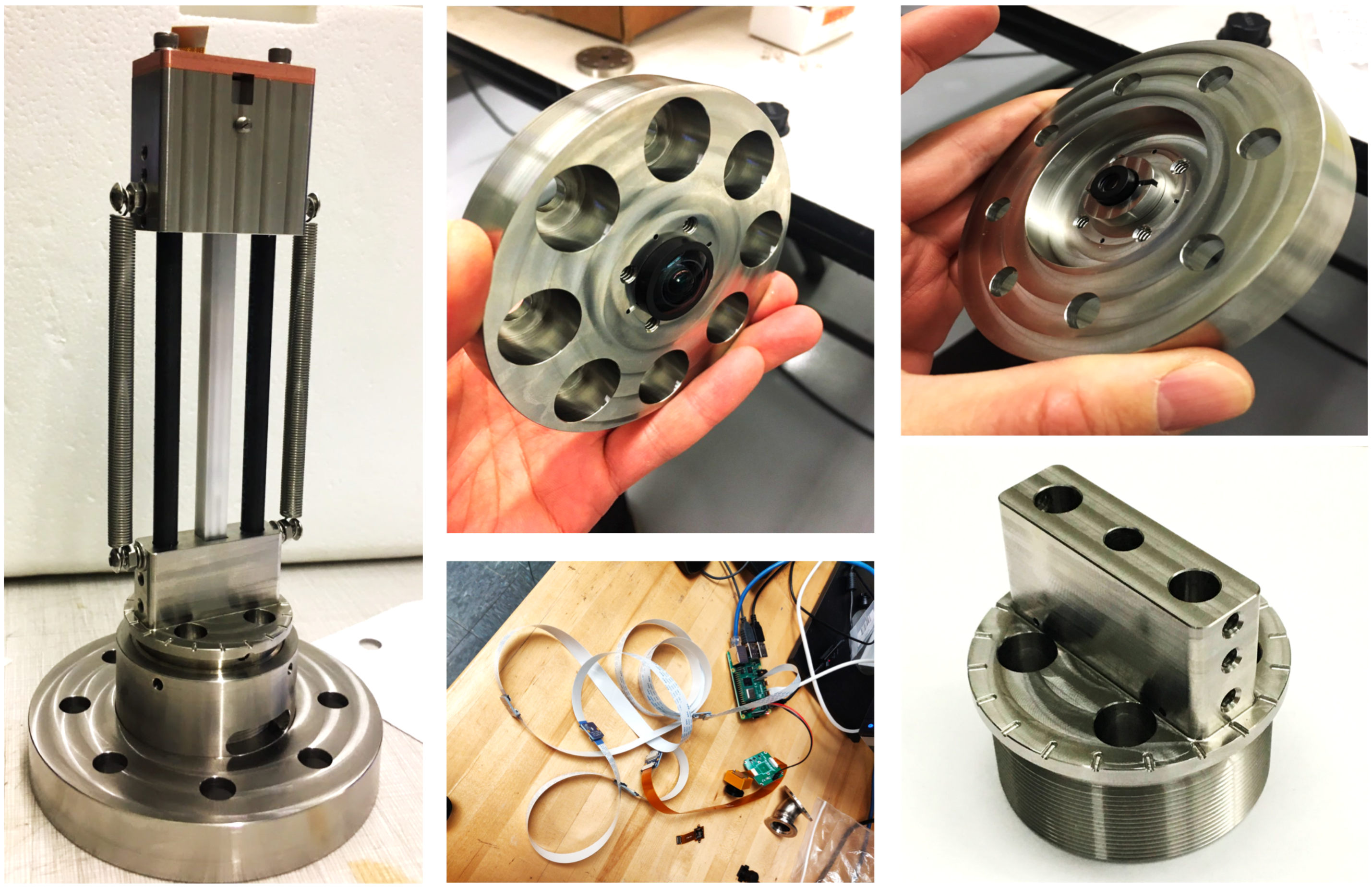






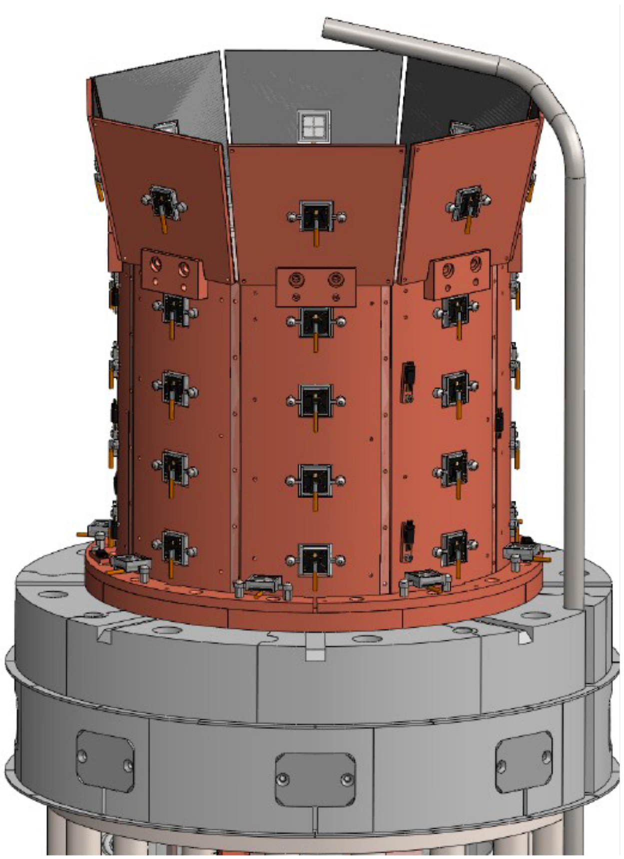
SBC: Bubble Imaging

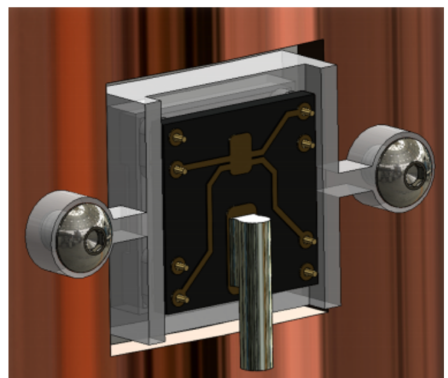
- Three raspberry-pi controlled camera system
- Three LED rings to provide illumination

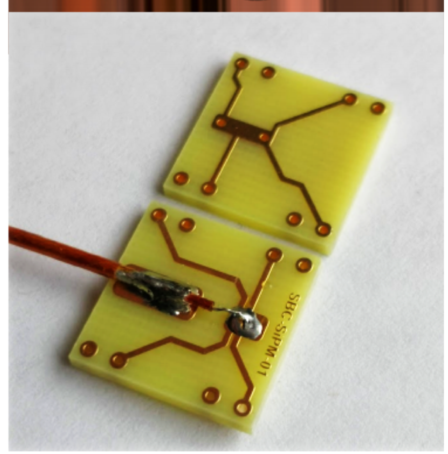


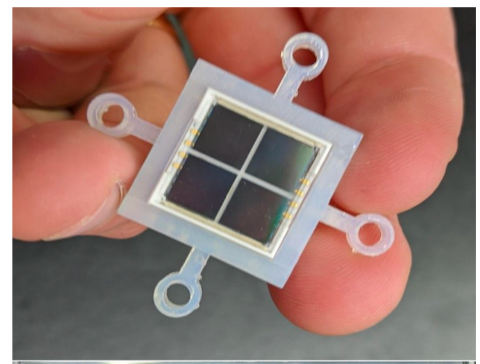
SBC: Scintillation

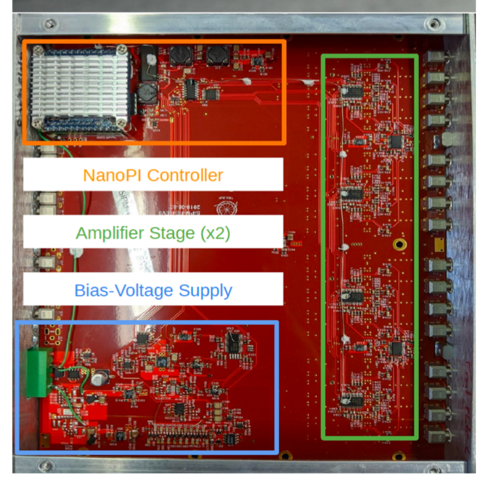
- 32 Hamamatsu VUV4 Quads
  to measure scintillation light in the target fluid.





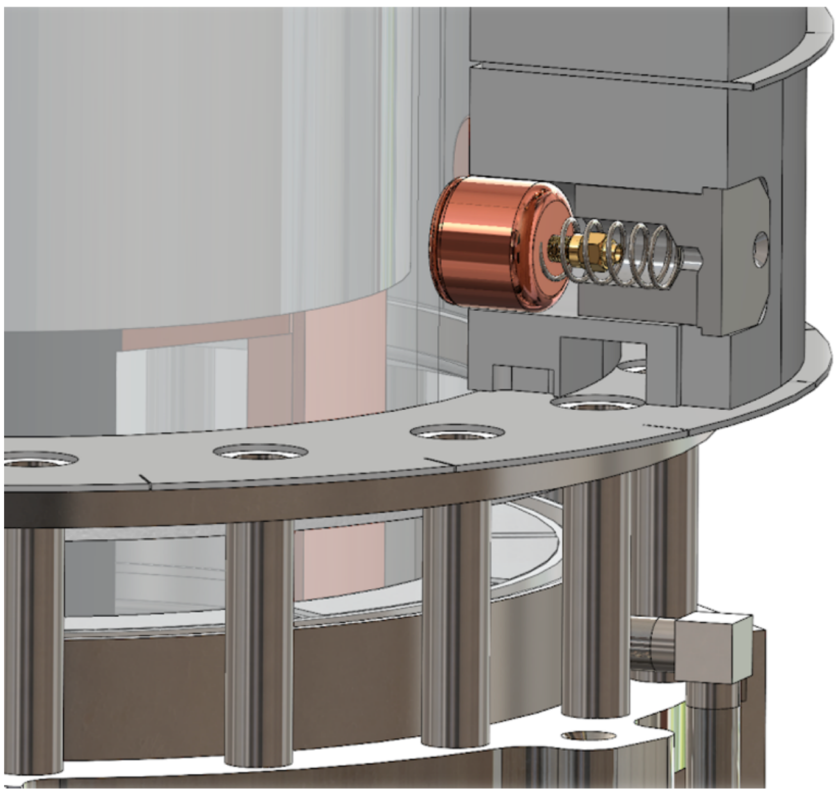


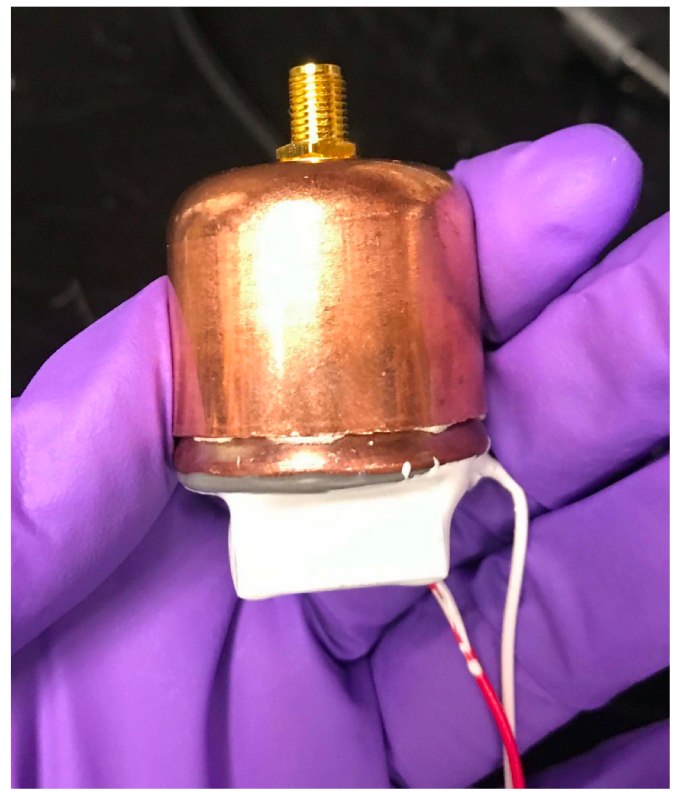




SBC: Acoustic

- Eight piezo acoustic sensors
  to monitor the nucleation process

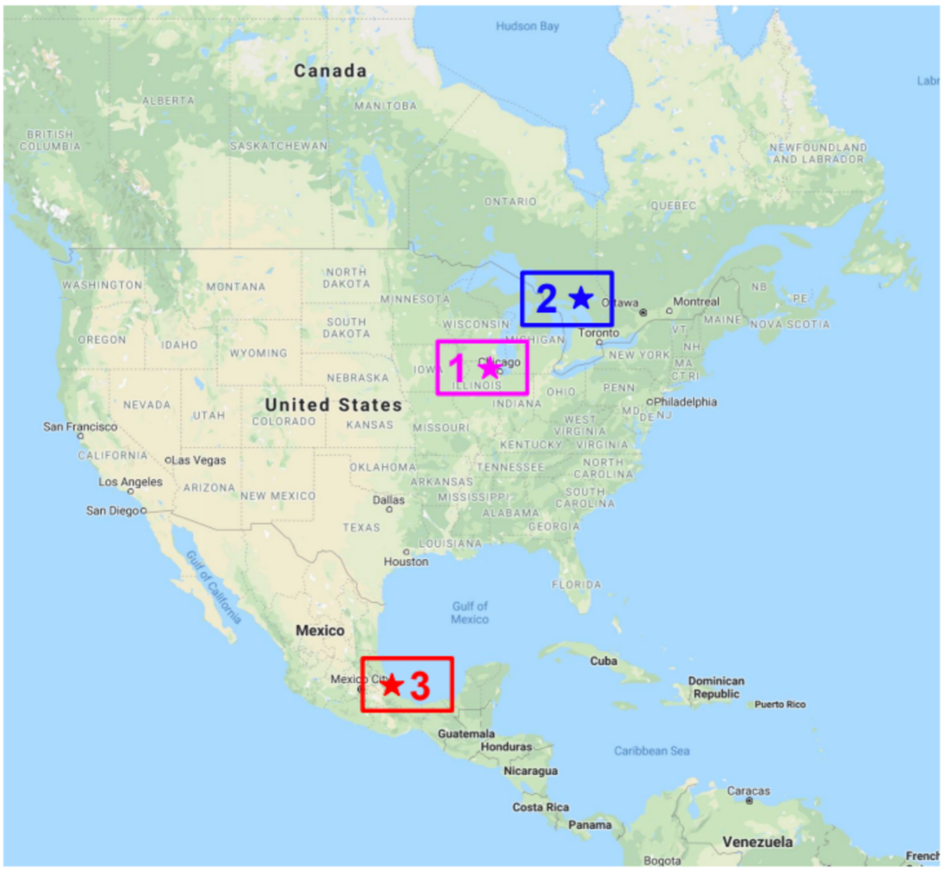




New Detector: The SBC

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).

We are at the beginning of a new era for particle physics!

Take away!

Very exciting era in particle physics for discoveries and new challenges!!!

→ **Potential discovery can be achieved soon!**

→ **Future for DM detectors is: ton scale + Very low threshold!**

New challenges for future direct detection :

→ **Expected backgrounds need to be known very well**

  → **High purification needed and background understanding**

→ **Neutrino floor: the ultimate background**

  → **R&D to add the directionality channel**

  → **Dedicated calibration with neutrino reactor!**

Thank you!

What is essential is invisible to the eye …

*for particle physicists is **Dark matter**!*

@Le petit prince