The Scintillating Bubble Chamber

LAr-10: Overview and outlook

LIDINE 2022 - AstroCeNT

Austin de St Croix, PhD student
on behalf of the SBC collaboration

Scintillating Bubble Chamber

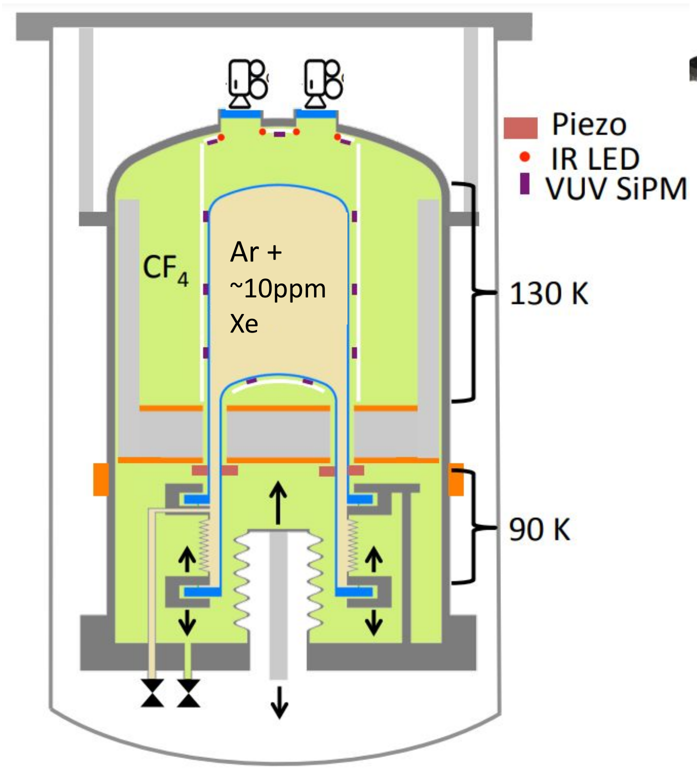
SBC-LAr10: physics scale chamber

- 10kg Ar target, xenon-doping
  sub keV NR sensitivity (100 eV heat)
- gamma *insensitivity*
- fused silica jars (contains Argon)
  submerged in CF_4 (hydraulic fluid)

Readout

- scintillation: SiPMs
- bubble acoustics: piezos
- bubble imaging: LEDs and cameras

Inspiration from others:
bubble chamber design: **PICO 40L/500**
scintillation system: **LoLX** (see D Gallacher's talk thursday)
cryo-cooling: **LUX/LZ**



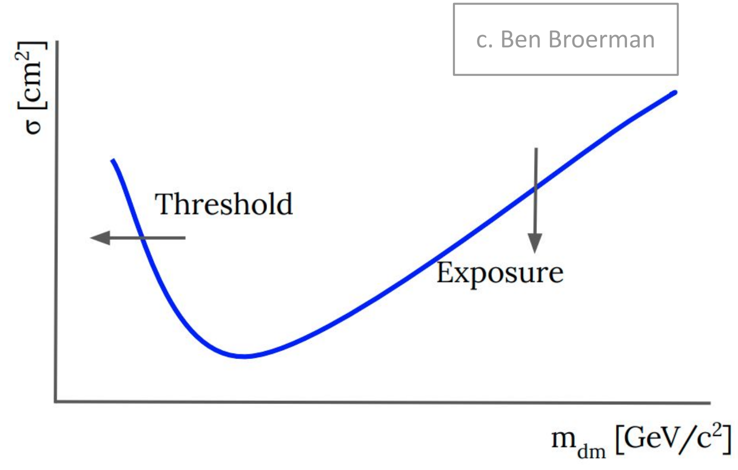
Why low energy nuclear recoils?

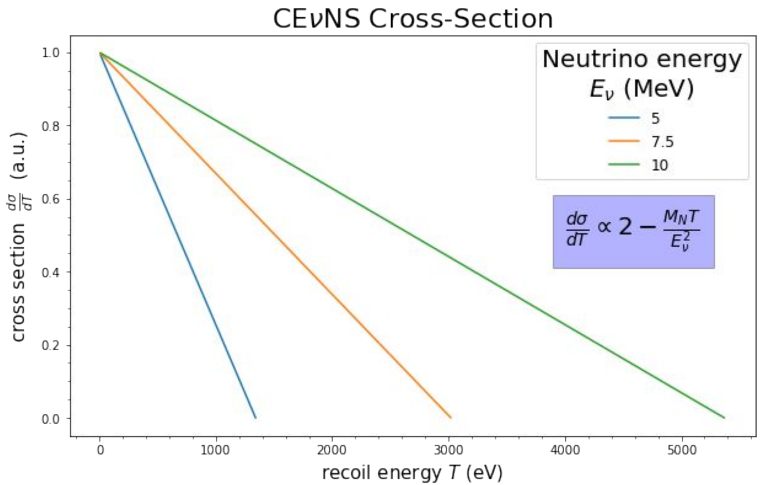
search for **WIMP** dark matter
test SM via **CEvNS**

experimental signature is **nuclear recoil** (NR)

lower energy NRs → lower mass WIMPs
→ more CEvNS events
→ **more physics***

*with discrimination against electron recoils (ERs)





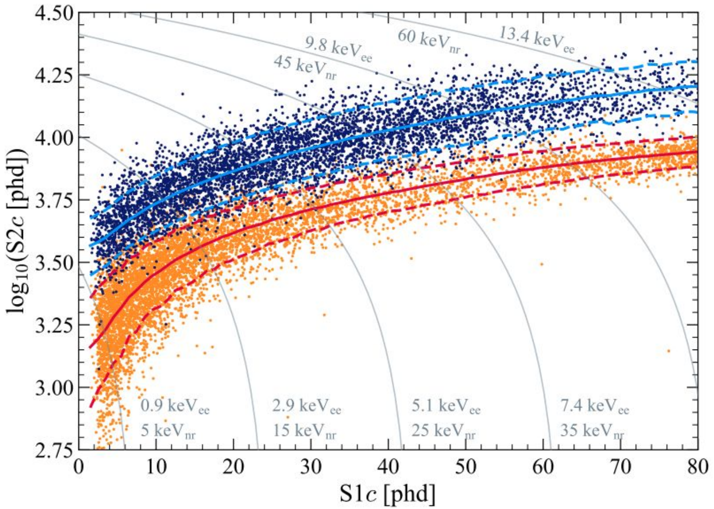
Why a Bubble Chamber?

Conventional noble experiments: scintillation & charge.

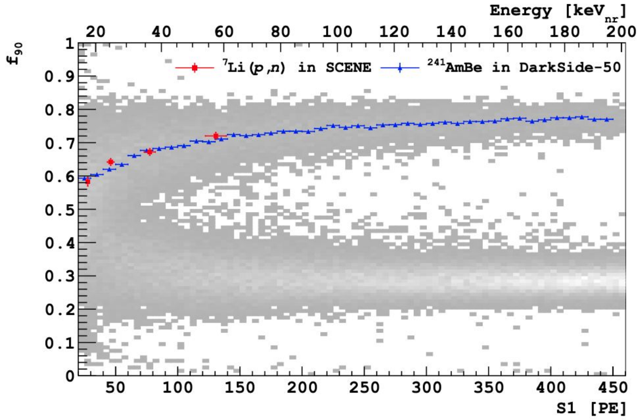
high energy → discrimination is excellent

at low energy **(∽keV NR)** → **discrimination gets harder**

(**ER** & **NR** look similar)



ER/NR bands merging at lower energy. (top) xenon - LZ, from arXiv:2207.03764, (bottom) argon - DS50, from arXiv:1510.00702



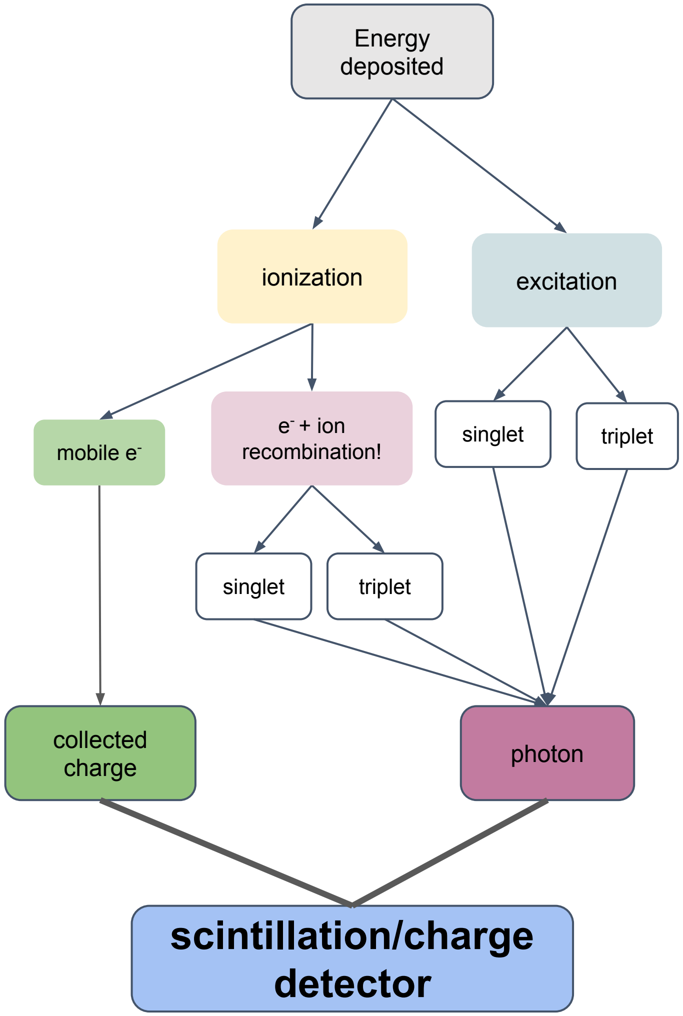
Why a Bubble Chamber?

Conventional noble experiments: scintillation & charge.

high energy → discrimination is excellent

at low energy **(∽keV NR)** → **discrimination gets harder**

(**ER** & **NR** look similar)



Why a Bubble Chamber?

Conventional noble experiments: **scintillation** & **charge**.

high energy → discrimination is excellent

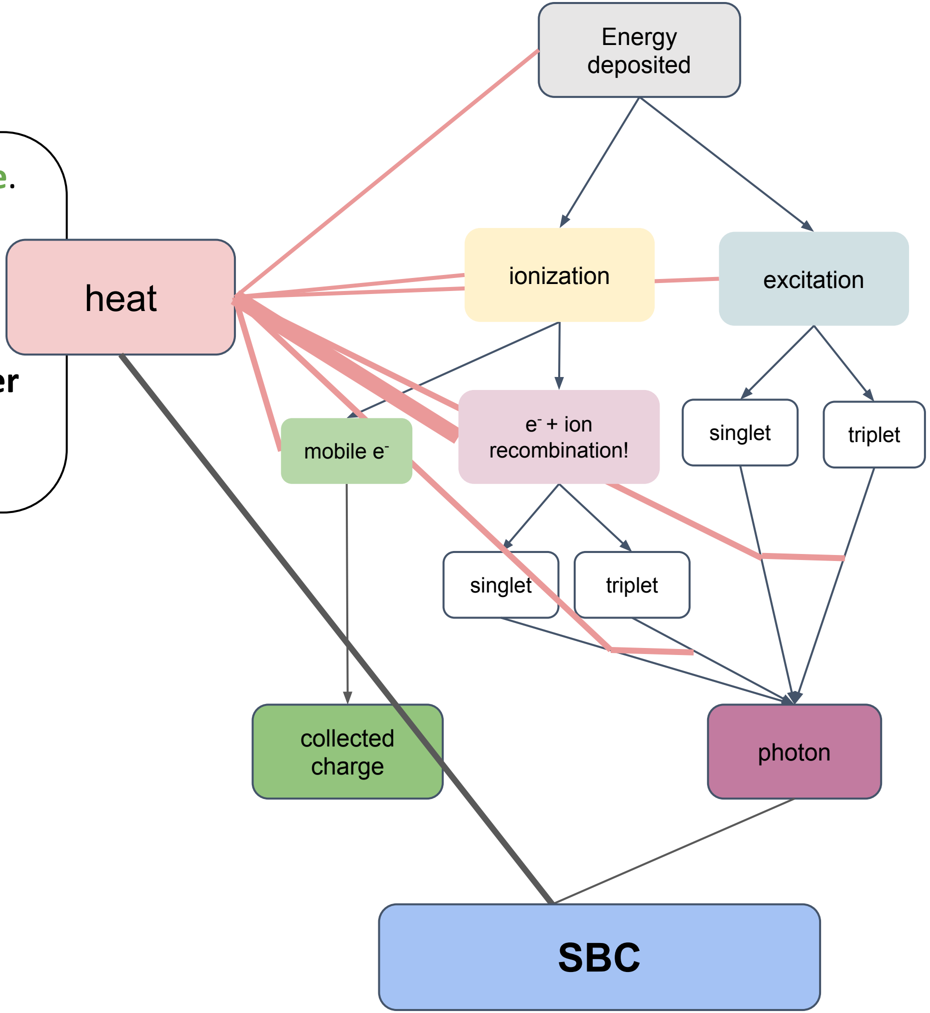
at low energy **(~keV NR) → discrimination gets harder**

(**ER** & **NR** look similar)

Solution

measure heat more directly

(threshold detector)



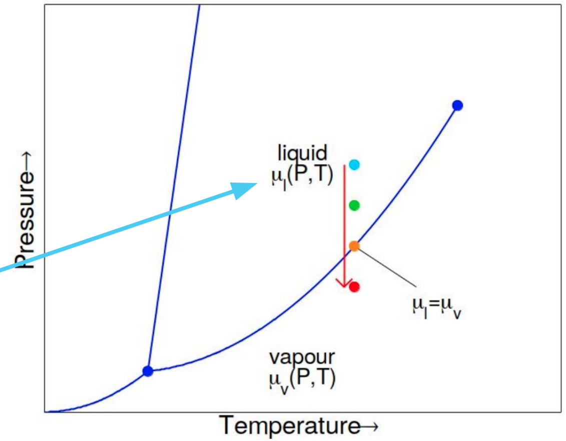
Bubble Chamber Basics

Filling SBC (like normal chamber)

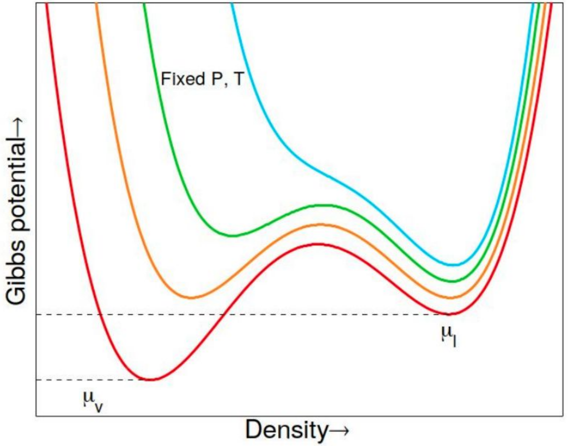
- fill with argon at 1.5 bar, ∽90K
- slowly warm active region to 120-130K

Superheated or 'bubble-ready'

1. chamber compressed (stable)



diagrams from K. Clark



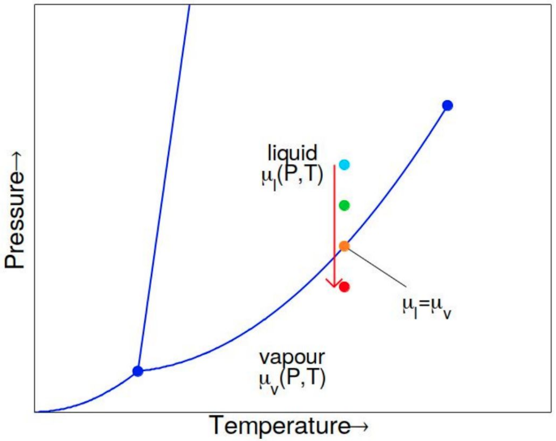
Bubble Chamber Basics

Filling SBC (like normal chamber)

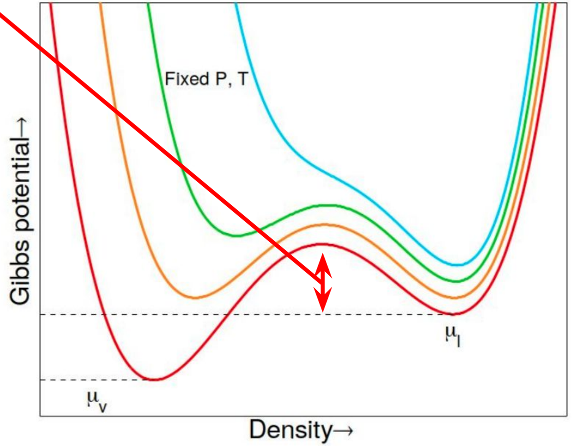
- fill with argon at 1.5 bar, ∽90K
- slowly warm active region to 120-130K

Superheated or 'bubble-ready'

1. chamber compressed (stable)
2. expand chamber (to **superheated** liquid)
    - metastable state, energy barrier prevents boiling!



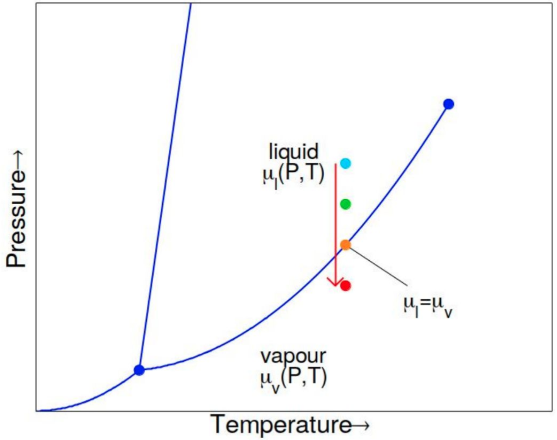
diagrams from K. Clark



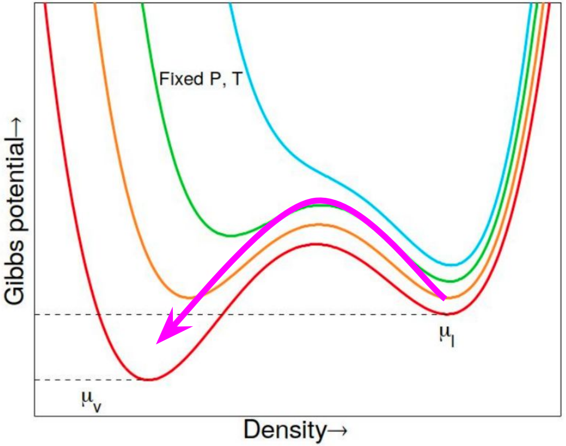
Bubble Chamber Basics

Filling SBC (like normal chamber)
- fill with argon at 1.5 bar, ~90K
- slowly warm active region to 120-130K

Superheated or 'bubble-ready'
1. chamber compressed (stable)
2. expand chamber (to superheated liquid)
   - metastable state, energy barrier prevents boiling!
3. particle deposits *enough heat in small volume*
   - **nucleation/bubble formation!**



diagrams from K. Clark



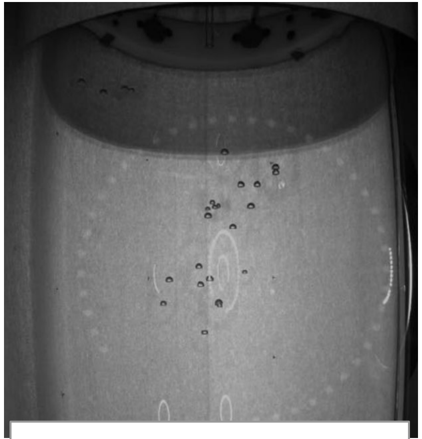


image from PICO chamber,
c. Ken Clark - https://indi.to/pXh9y

Bubble Chamber Basics

Filling SBC (like normal chamber)

- fill with argon at 1.5 bar, ~90K
- slowly warm active region to 120-130K

Superheated or 'bubble-ready'

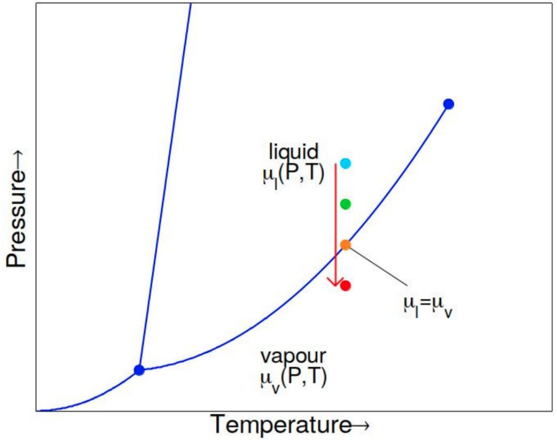
1. chamber compressed (stable)
2. expand chamber (to superheated liquid)
    - metastable state, energy barrier prevents boiling!
3. particle deposits *enough heat in small volume*
    - nucleation/bubble formation!

useful threshold model: *Seitz hot spike*

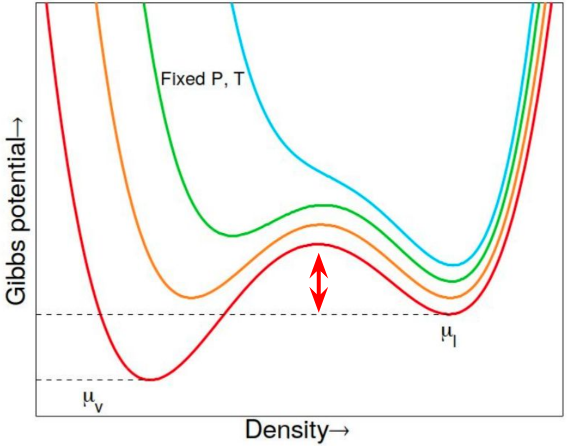
tune Seitz threshold via **Pressure, Temperature**

Seitz heat threshold relates to NR threshold

(Daniel Durnford's LIDINE talk on NR thresholds)



diagrams from K. Clark



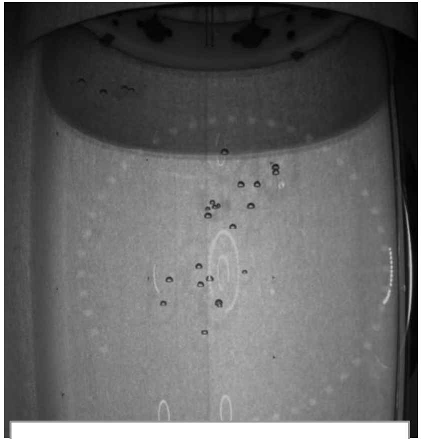
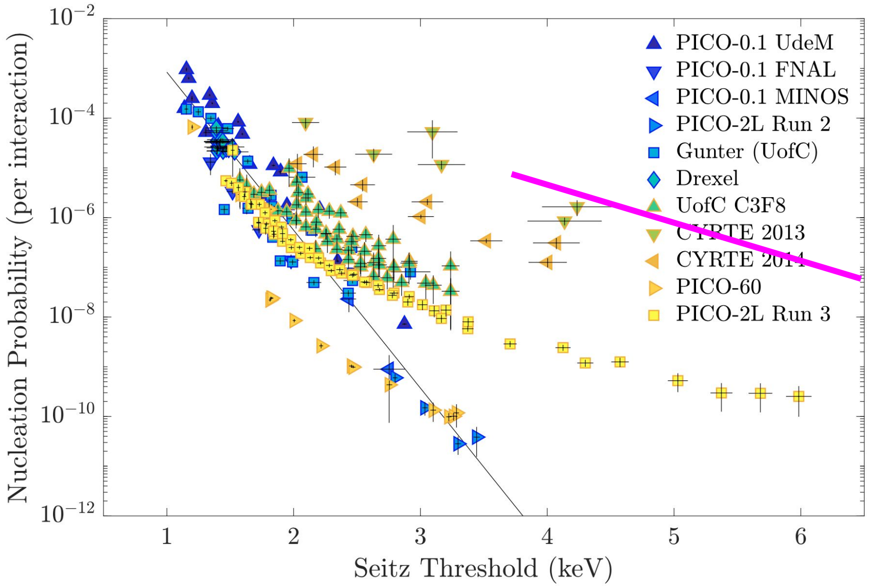


image from PICO chamber,
c. Ken Clark - https://indi.to/pXh9y

Bubble Chamber Discrimination (why use argon)

Successful DM searches with molecular fluid BCs …

- COUPP, PICASSO, **PICO** (40 active, 500 in future)
  CF_3I C_4F_{10} **C_3F_8**
- Gammas nucleate bubbles at few keV threshold…
  - delta rays
  - Auger cascades (if possible)
    Iodine or Xe contamination (arXiv:2110.13984)



nucleation probability by ERs in **C_3F_8** (from arXiv:1905.12522)
approximate CF_3I line

Bubble Chamber Discrimination (why use argon)

Successful DM searches with molecular fluid BCs …

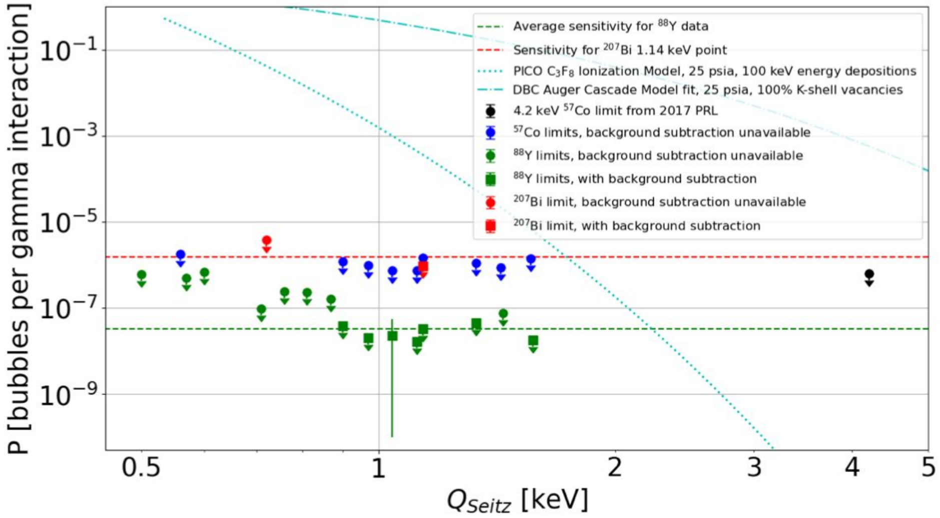
- COUPP, PICASSO, **PICO** (40 active, 500 in future)
  CF_3I C_4F_{10} $\mathbf{C_3F_8}$
- Gammas nucleate bubbles at few keV threshold…
  - delta rays
  - Auger cascades (if possible)

  Iodine or Xe contamination (arXiv:2110.13984)

No evidence of ER induced nucleation in atomic fluids (Ar, Xe chambers operated in 50s, 60s, 80s, present)

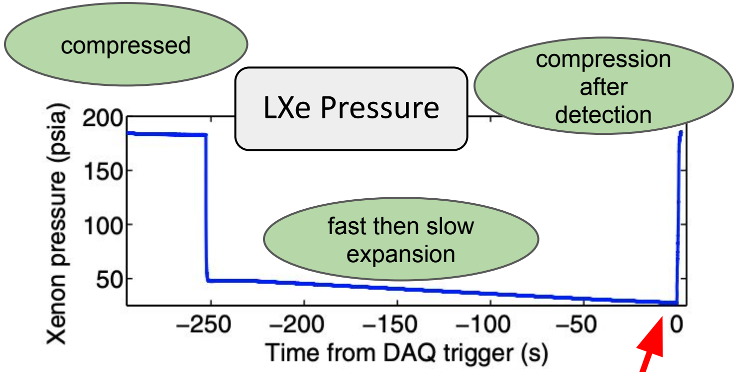
- no molecular structure/degrees of freedom: inefficient transfer of electronic energy to heat

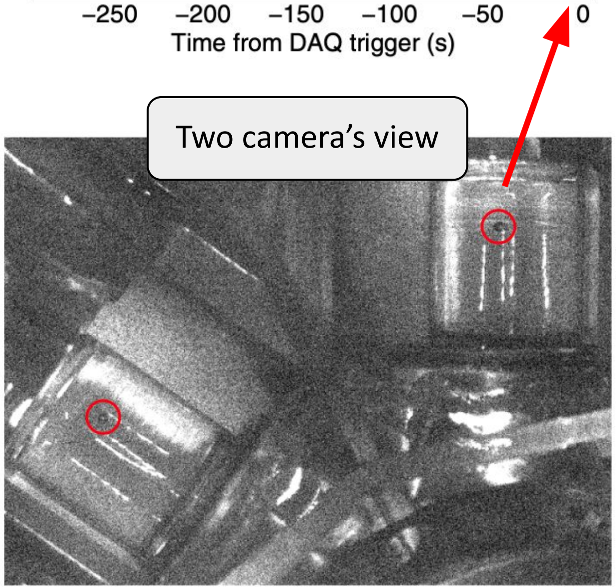
SBC operation = 100 eV heat (Seitz) threshold!



Upper limits on ER nucleation in pure **xenon**.
blue lines: pure $\mathbf{C_3F_8}$ or with Xe contamination
(from Matt Bressler's thesis, 2022)

A bubble event (in 30g LXe chamber)





Chamber Operation

1. expansion **(many seconds)**

wait…

high dE/dx interaction

2. scintillation **(ns)**

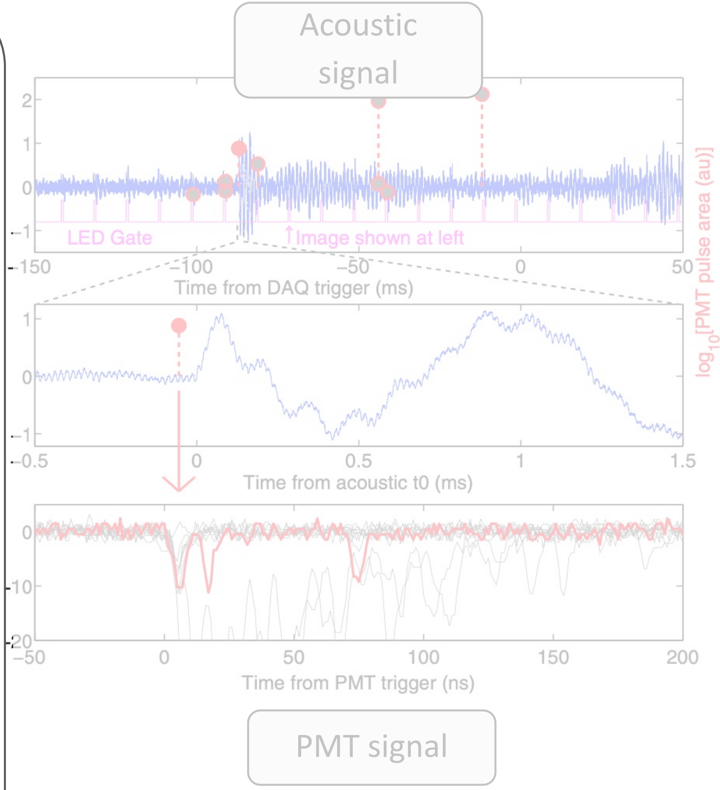
bubble forms

3. acoustic **(us)**

4. pressure increase, LEDs turn on (if not continuous)

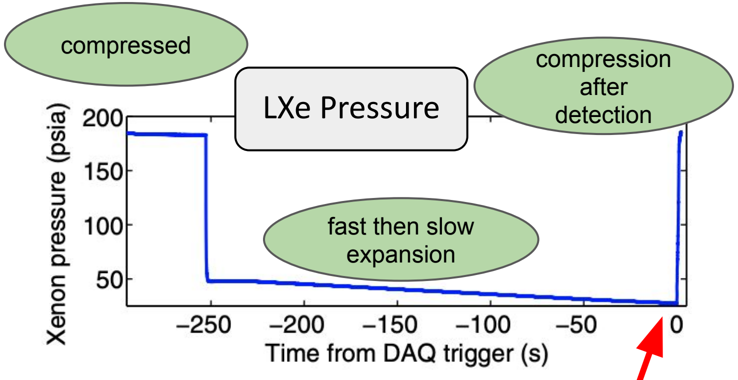
5. camera imaging **(ms)** (sends BC trigger)

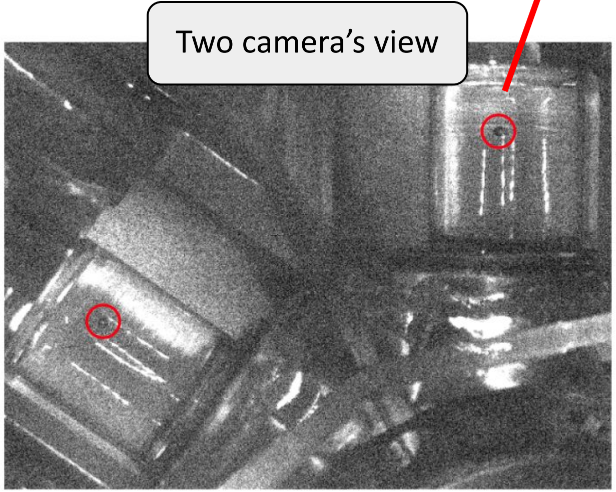
6. recompress **(seconds)**



figures from Xe bubble chamber (arXiv:1702.08861)

A bubble event (in 30g LXe chamber)





Chamber Operation

1. expansion **(many seconds)**

wait…

high dE/dx interaction

2. scintillation **(ns)**

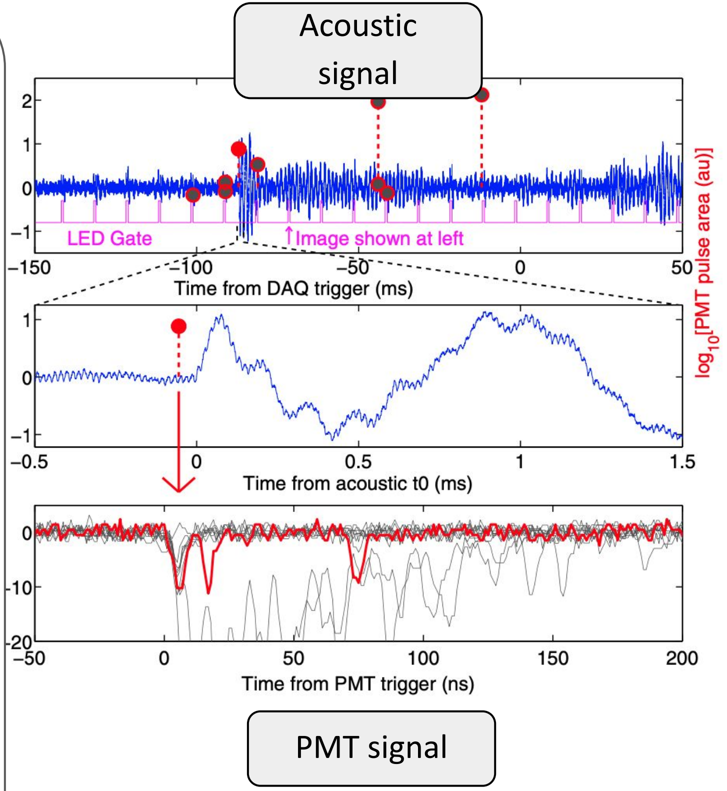
bubble forms

3. acoustic **(us)**

4. pressure increase, LEDs turn on (if not continuous)

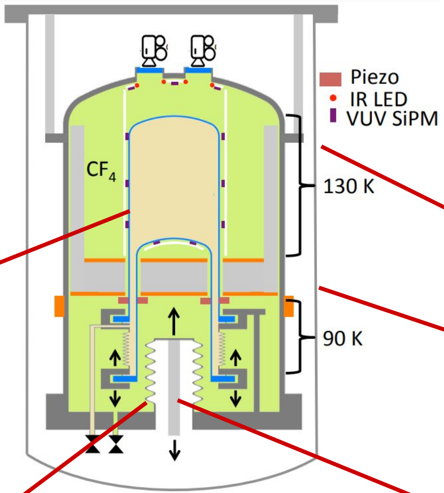
5. camera imaging **(ms)** (sends BC trigger)

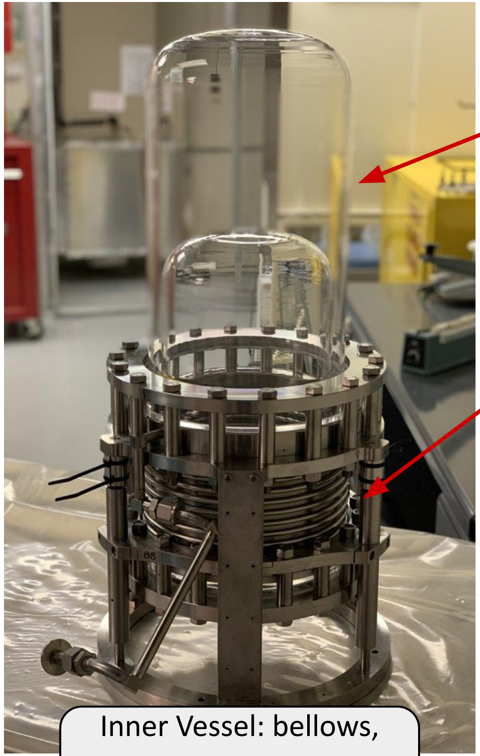
6. recompress **(seconds)**



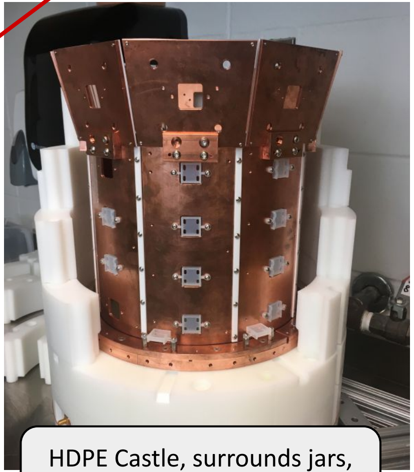
figures from Xe bubble chamber (arXiv:1702.08861)

SBC-LAr10 Status

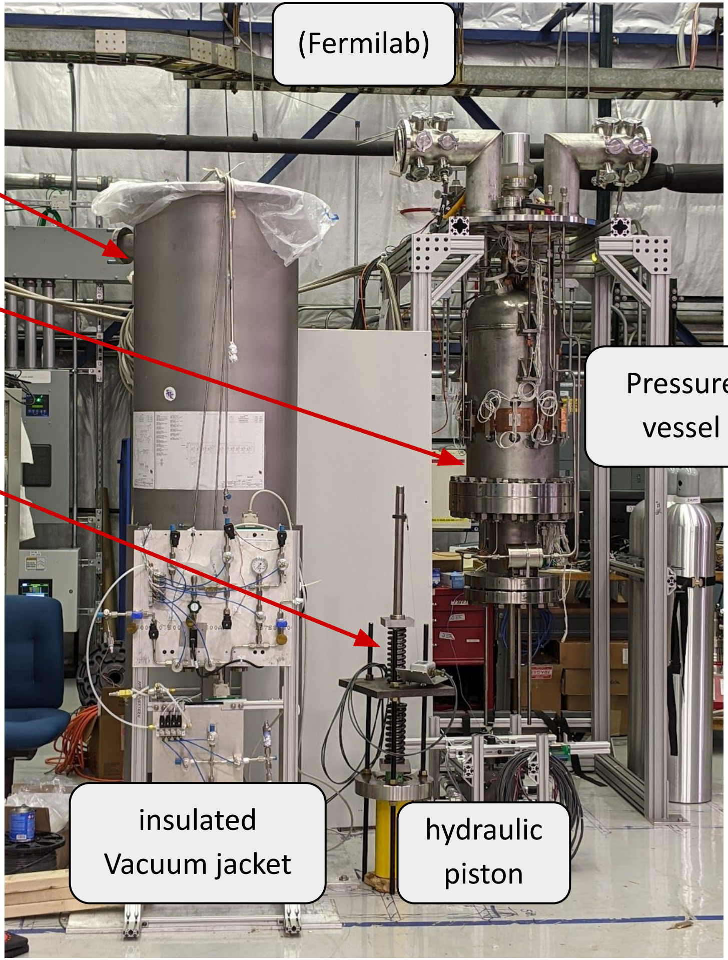




Inner Vessel: bellows, fused silica jars (Queen's)



HDPE Castle, surrounds jars, holds SiPMs (Queen's)



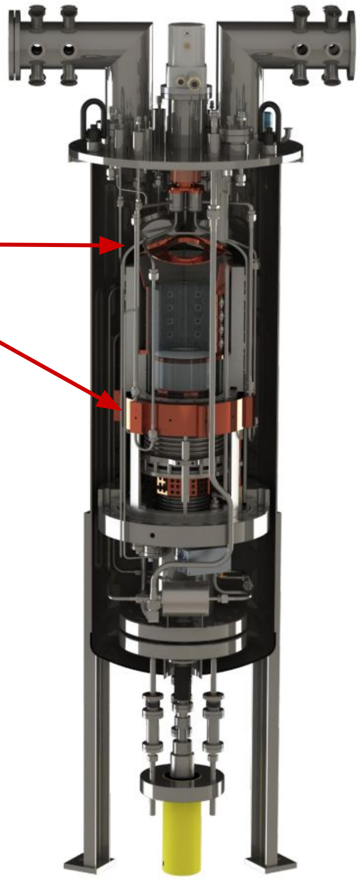
SBC-LAr10 Status

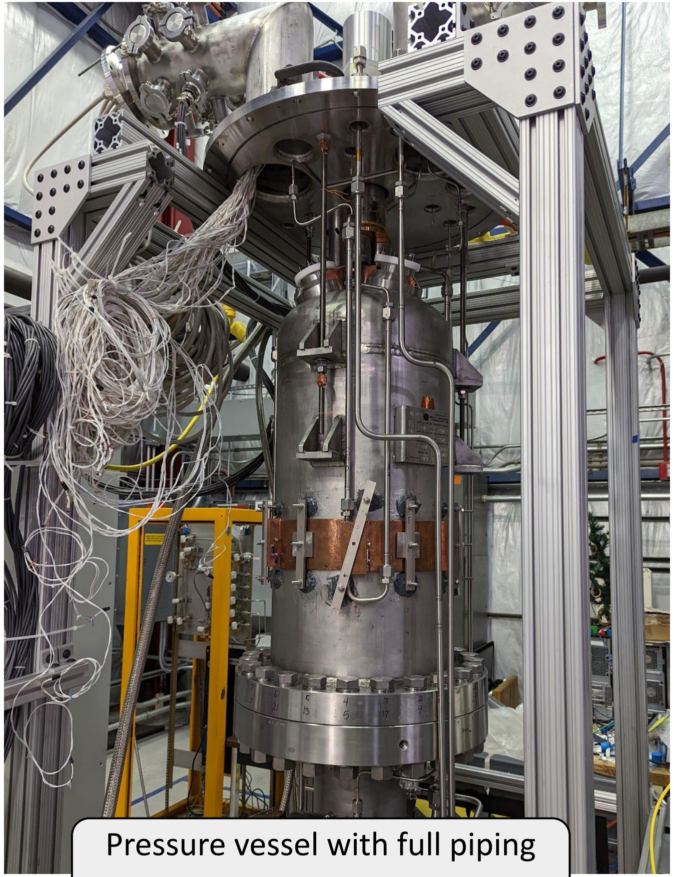
Cooling system and Pressure Vessel
- closed-loop LN_2 thermosiphons

Designed for argon thermodynamic limit:
- **40 eV** heat threshold (1.4 bar @ 130K)

max pressure ~20 bar

Can also operate with Xe, N_2 or CF_4





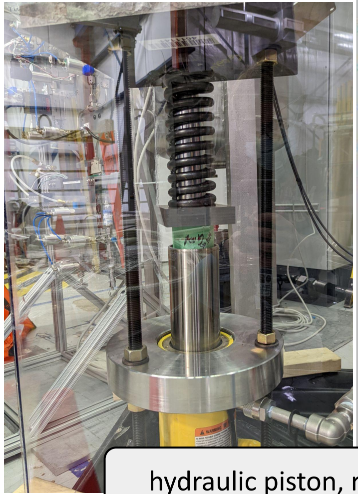
Pressure vessel with full piping and wiring (Fermilab)

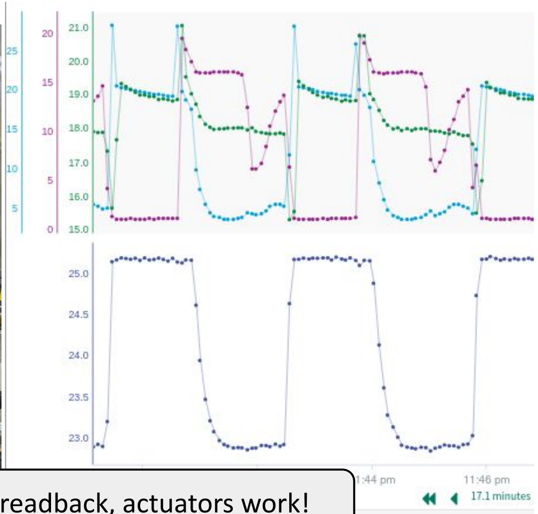
SBC-LAr10 Status

Construction complete (separately)!

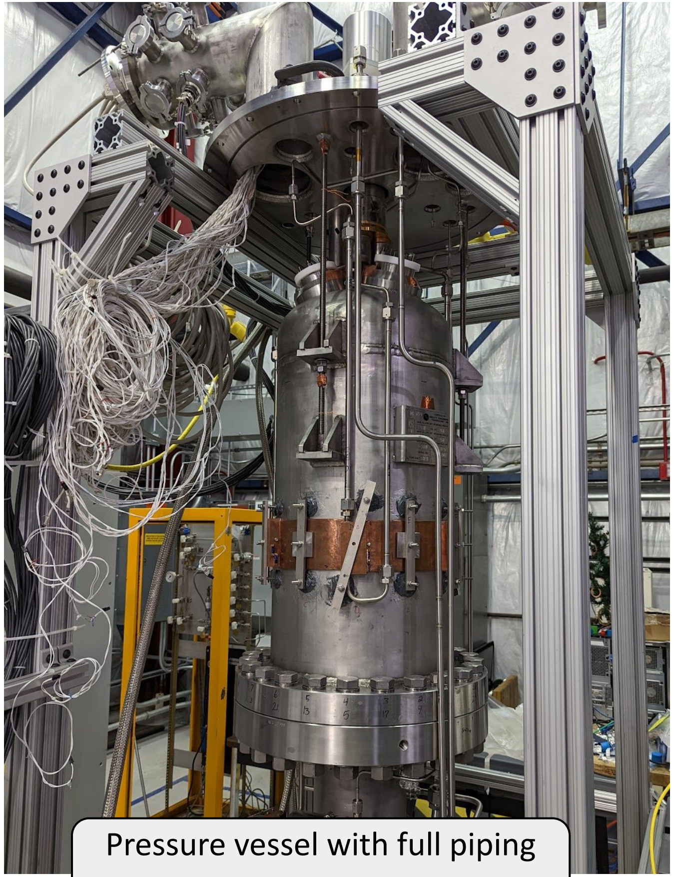
Fermilab

- must test BC slow control and DAQ
    - hydraulic piston works!
- pressure vessel and cryosystems





hydraulic piston, readback, actuators work!



Pressure vessel with full piping and wiring (Fermilab)

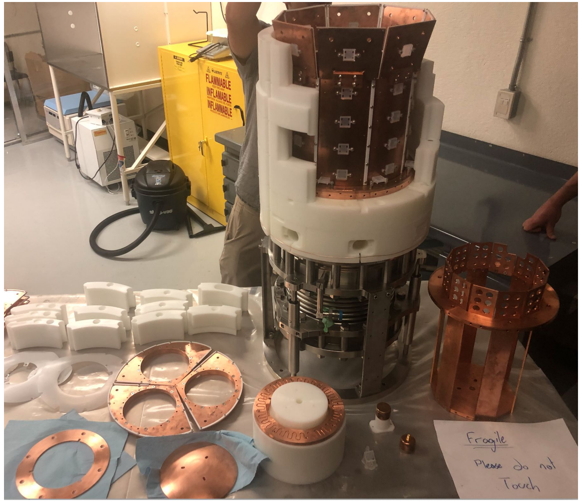
work of Matt Bressler, TJ Whitis, others

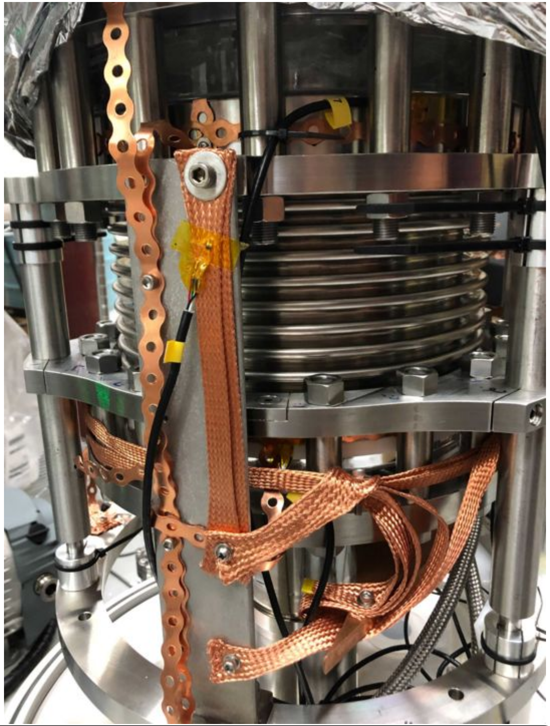
SBC-LAr10 Status

Construction complete (separately)!

Queen's

- scintillation DAQ - testing soon
- cool inner vessel, test seal on jars





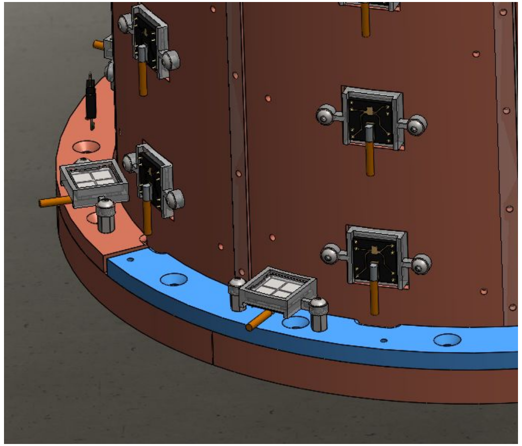
thermal coupling for cooling IV alone, to test seals on quartz (Queen's)

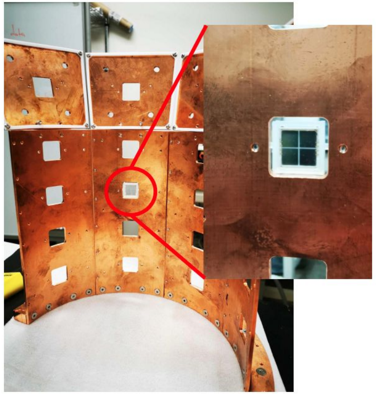
J Corbett, Ben Broerman, Hector HH, more (Queens)

Scintillation System

Silicon Photo-Multiplier (SiPM) for light detection

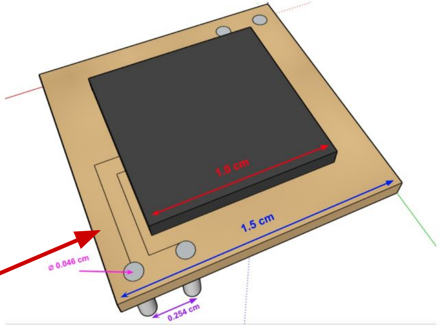
- 32 SiPMs facing LAr, 8-16 facing LCF_4 (Veto)
- high speed analog electronics (LoLX) coupled to 16 ns digitizer (62.5 MHz)
- 10-1000 ppm Xe doping (at 128 nm jars absorb, lower SiPM PDE)

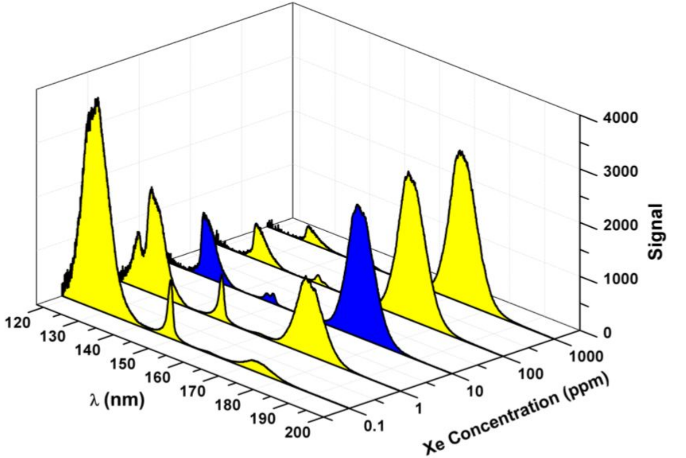




Fermilab Chamber
Hamamatsu VUV4 devices
quadrants summed in-situ via PCB

SNOLAB/DM Chamber
switch to FBK-LF devices (less radioactive)
wirebond to custom PCB (TRIUMF)



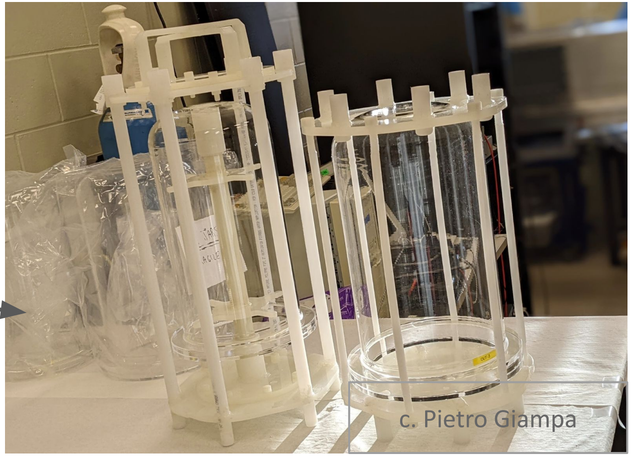


arXiv:1511.07723

SBC-LAr10 Plan

Future plan

1. combine systems at Fermilab
    a. fresh jars acid leached at SNOLAB
    b. commissioning & calibration **(2023-2025)**
2. build second DM chamber
    a. more stringent materials selection
    b. operate at SNOLAB **(2024 -)**
3. install Fermilab chamber at nuclear reactor
    a. study reactor CEvNS (in Mexico?)

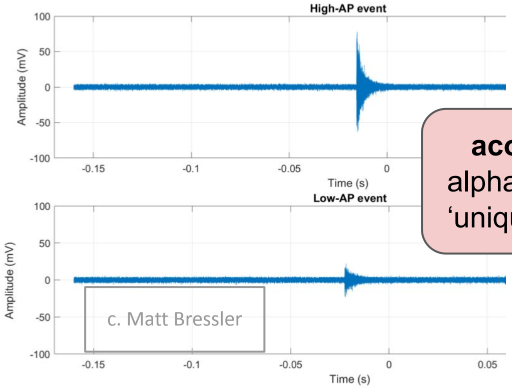


UG site at Fermilab (MINOS)

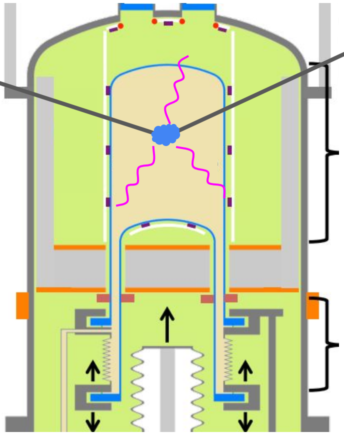
Physics Reach - Discrimination and Veto

ER vs NR
discrimination is binary
bubble or no bubble!

Scintillation veto: no SiPM signal = low energy
expected threshold: ~10-20 keV_{ee}



acoustics
alphas sound 'unique'



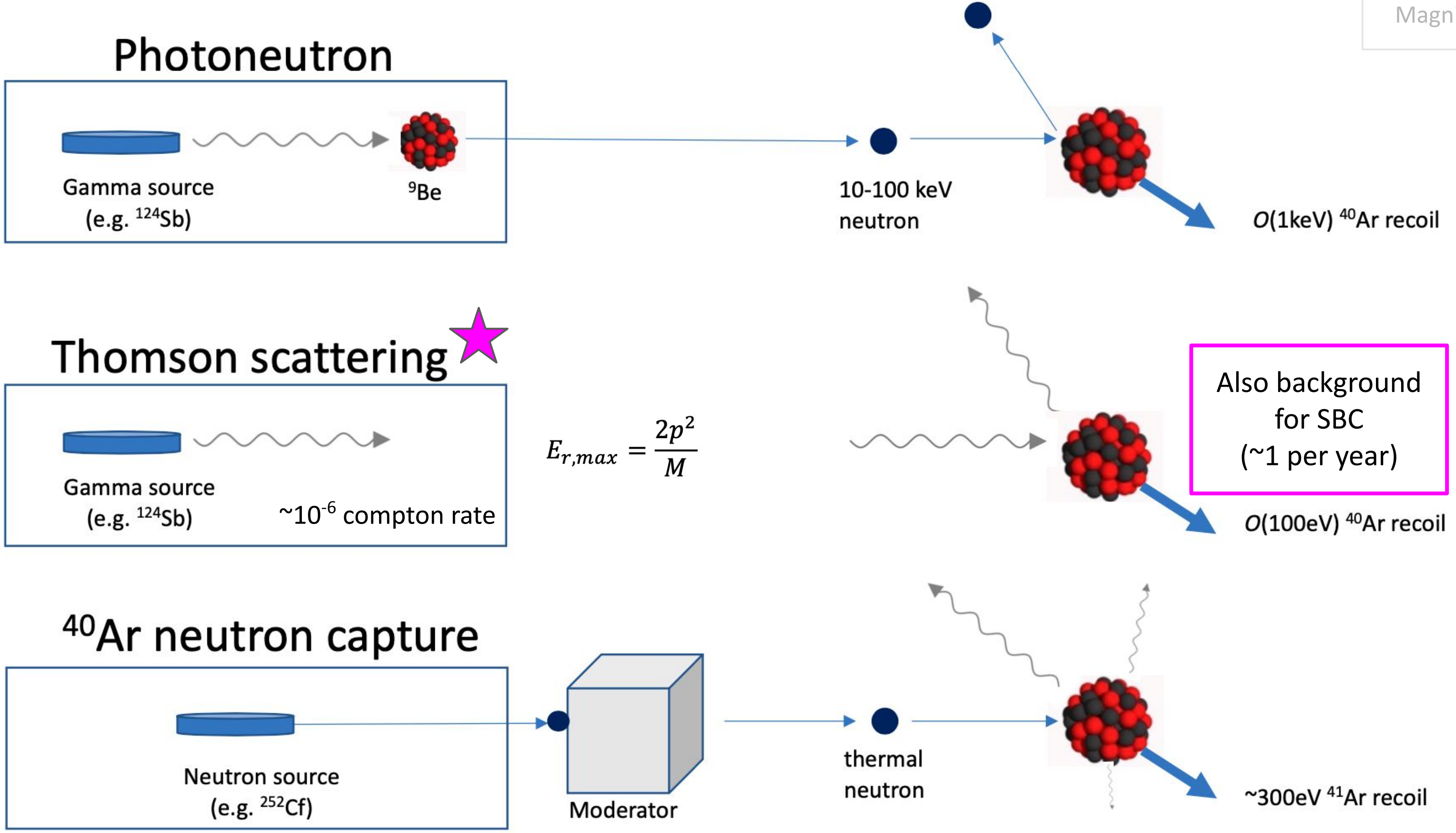
Camera Images
- fiducialization
- multi-scatter neutrons (multiple bubbles)

Interaction	scintillation	bubble
alpha	yes	yes
ER	energy dependent	no ($<10^{-7}$ @ 1 keV)
energetic NR (above 10-20 keV_{ee})	likely	yes (multi-bubble)
low energy NR (below threshold)	none	yes

Physics signal (or bkg)
bubble and no light

Calibration Schemes

Figures from Russell Neilson's talk, Magnificent CEvNS 2021



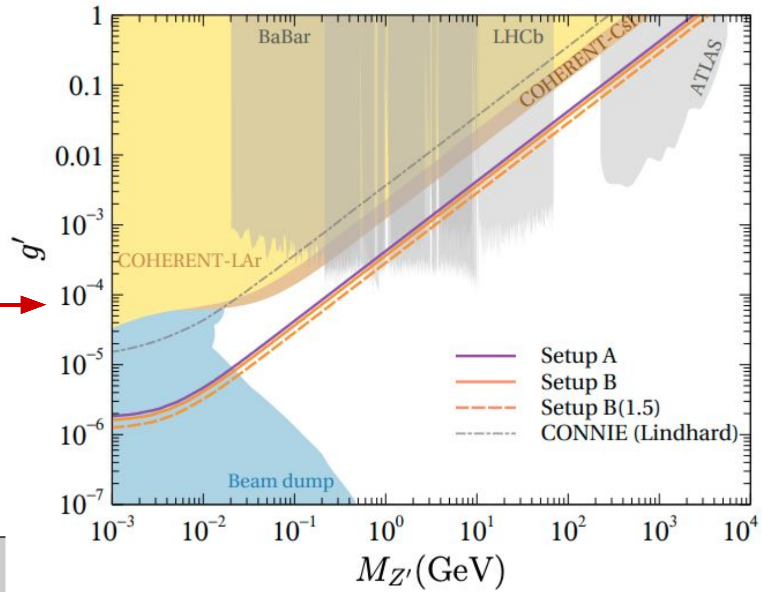
data-taking: measure comptons & NRs simultaneously?

Physics Reach - Reactor CEvNS

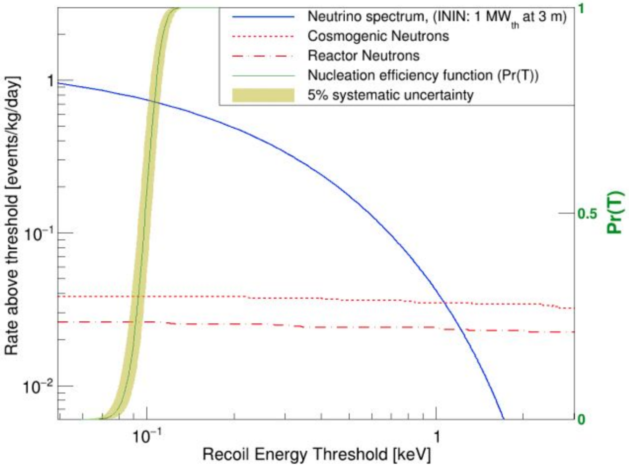
Test SM via CEvNS cross-section

- weak mixing angle
- neutrino magnetic moment
- **light gauge boson mediator**

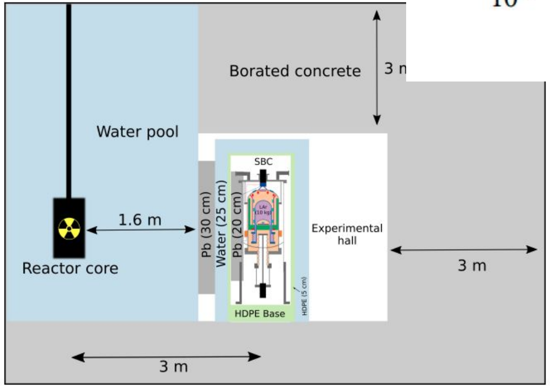
see more arXiv:2101.08785



sensitivity for 10 kg, 100 eV threshold detector (or better, setup B)



Setutp A - 10kg chamber 3m from 1 MW reactor (ININ)



Physics Reach - DM Search

Parameters

10 kg-year exposure

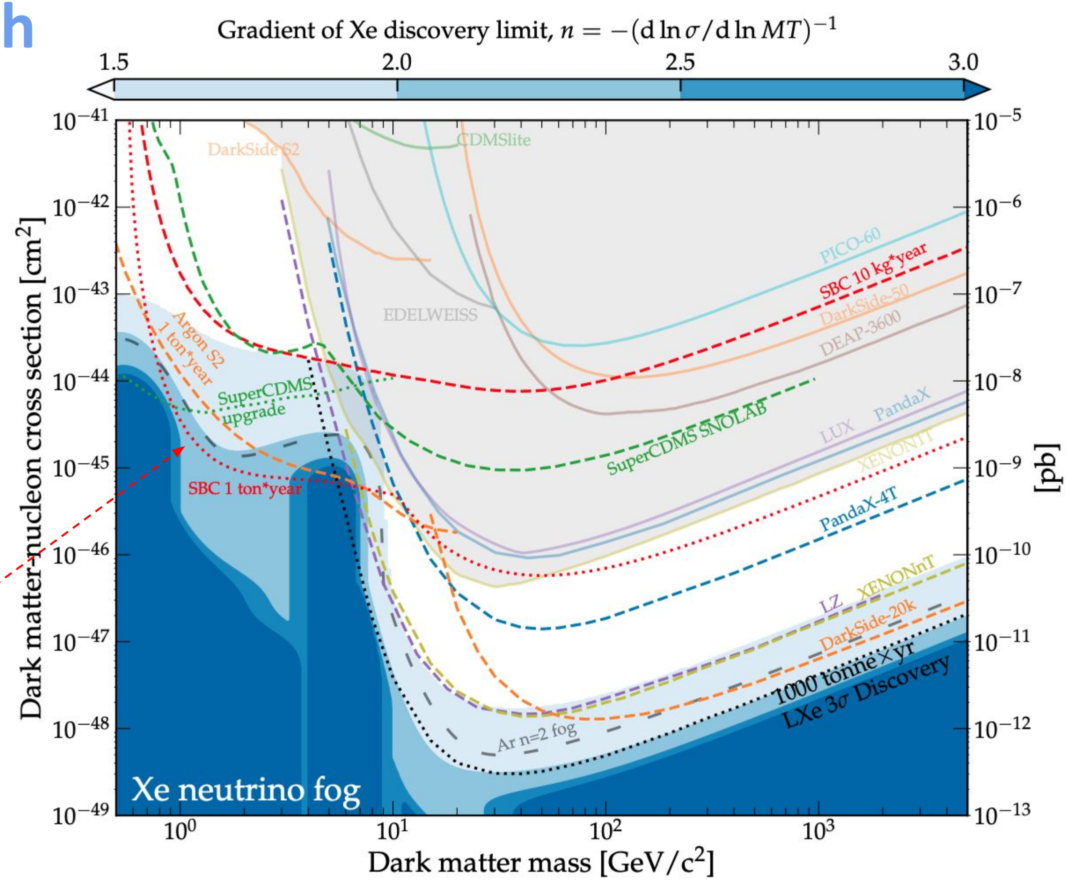
'Standard' halo parameters - arXiv:2105.00599

2.5 background CEvNS events

10 keV scintillation veto

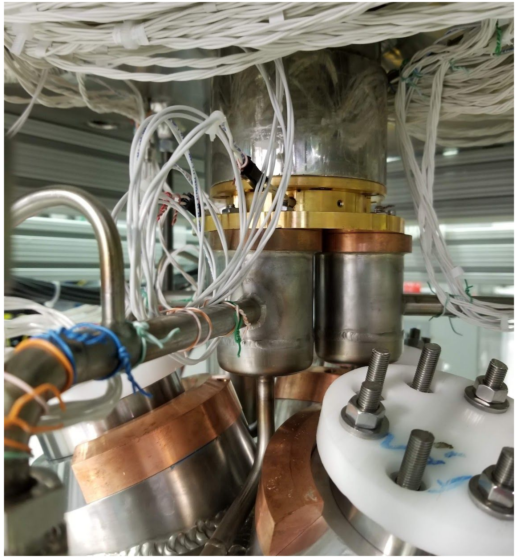
very scalable technology! (see PICO 500)

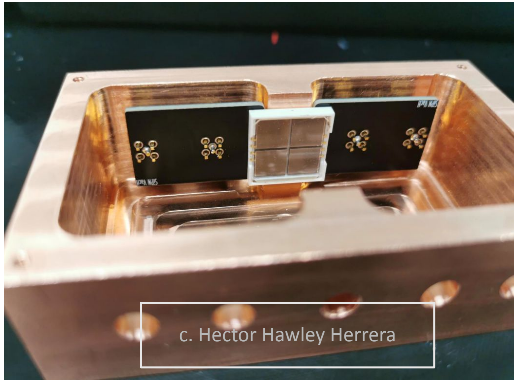
1 ton year reaches neutrino fog (1-10 GeV)



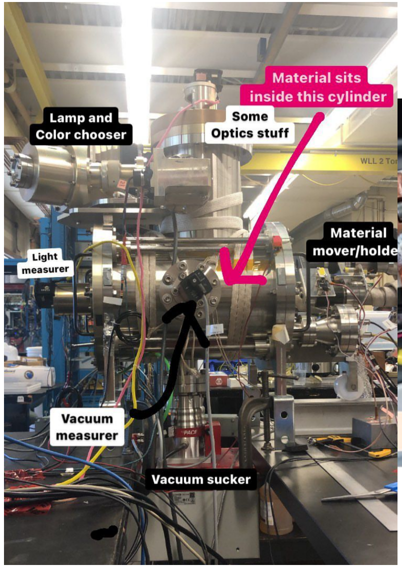
(from SNOMASS cosmic frontier white paper, arXiv:2203.08084)

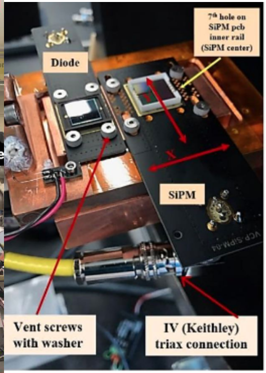
and much more happening!



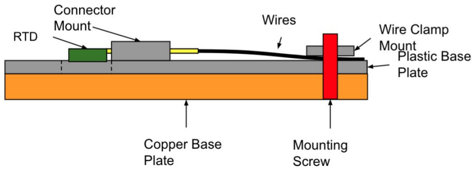


c. Hector Hawley Herrera

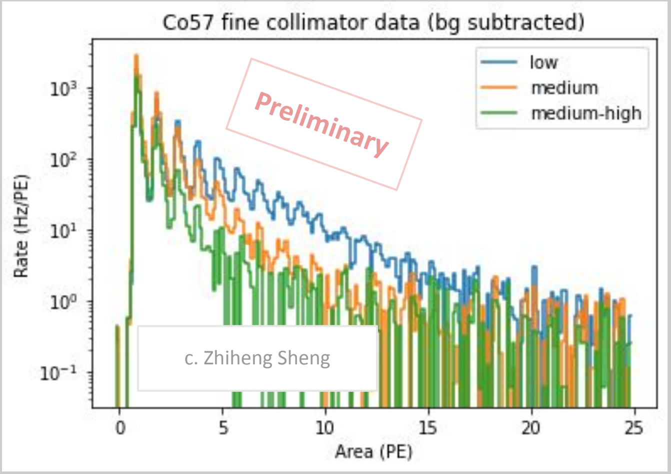




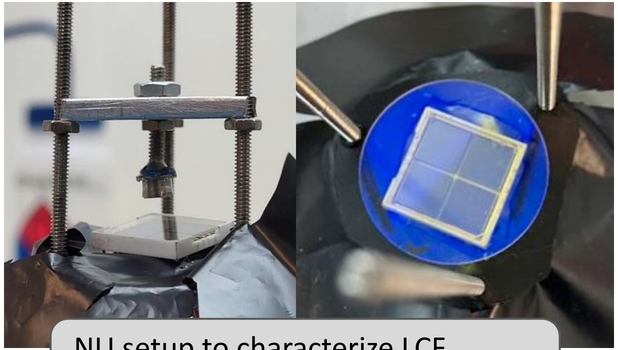
CF4 RTD Design



c. Gary Sweeney



c. Zhiheng Sheng



NU setup to characterize LCF_4 scintillation (c. Zhiheng Sheng)

Bright future ahead

- Detector systems built and being tested!
- Calibration to begin in 2023 (Fermilab)
- exciting physics programs on horizon!

SBC white paper: arXiv:2207.12400v1

Open detector questions:

- (when) do ERs start nucleating?
  - Electric field, xenon doping…
- pressure trigger (keep LEDs off before bubble)
- scintillation veto threshold?
- accuracy of background model, etc…

SBC Collaboration

Queen's University

K. Clark, A. de St Croix, H. Hawley-Herrera, J. Corbett, B. Broerman, K. Dering, K. Foy

University of Alberta

M.-C. Piro, M. Baker, D. Durnford

Université de Montréal

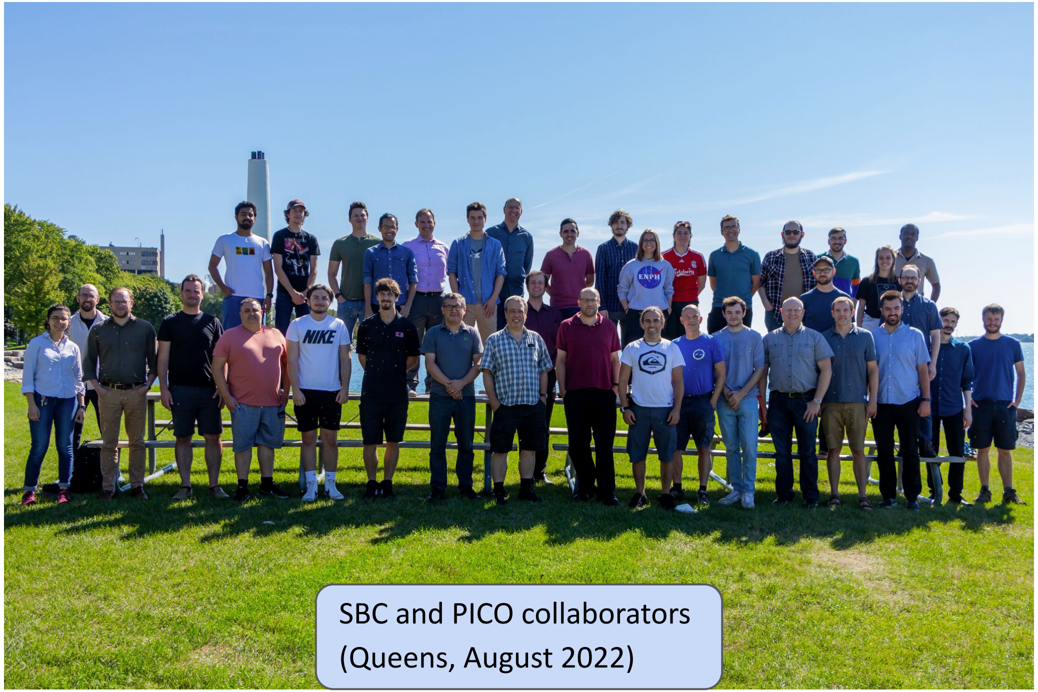
M. Laurin

SNOLAB

P. Giampa, J. Hall

Fermilab

M. Crisler



SBC and PICO collaborators (Queens, August 2022)

Pacific Northwest National Laboratory

C.M. Jackson

PennState

S. Priya

UC Riverside

S. Westerdale

Northwestern University

C.E. Dahl, X. Liu, Z. Sheng, W. Zha

Drexel University

R. Neilson, M. Bressler, N. Lamb

Universidad Nacional Autónoma de México

E. Vázquez-Jàuregu, E. Alfonso-Pita

Indiana University South Bend

E. Behnke

UC Santa Barbara

W.H. Lippincott, R. Zhang

Backup slides

Physics Reach - DM Search

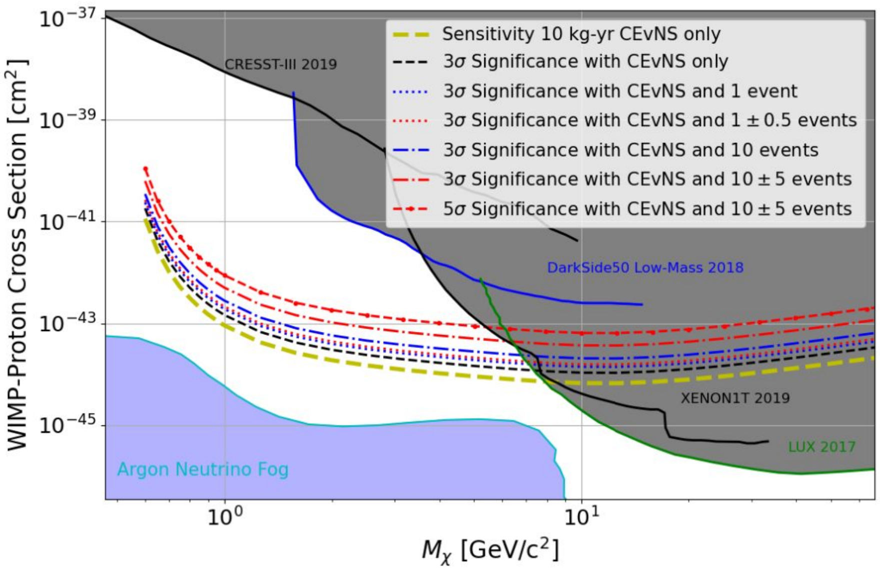
parameters

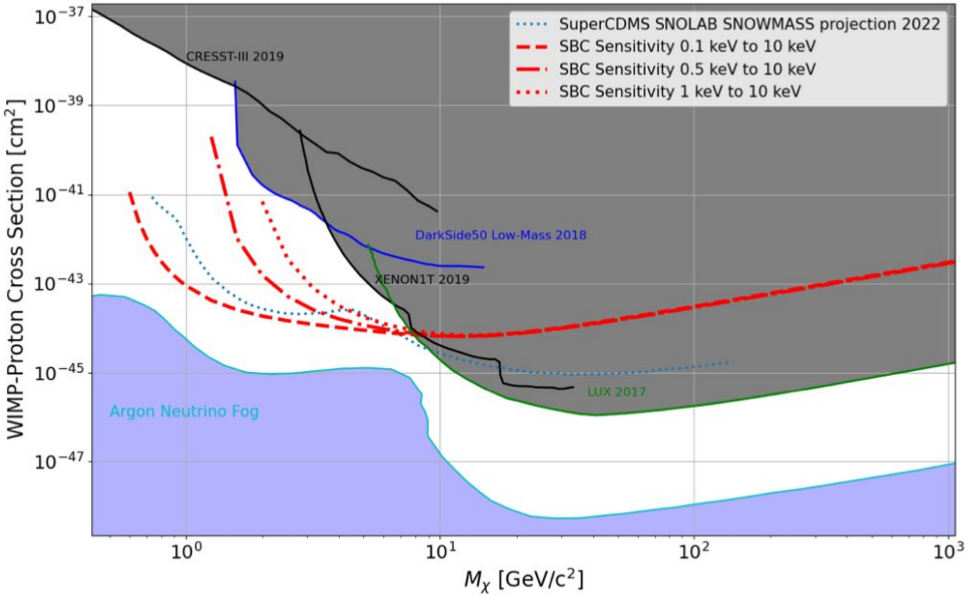
10 kg-year exposure

'Standard' halo parameters - arXiv:2105.00599

2.5 bkg neutrino CEvNS events

10 keV scintillation veto





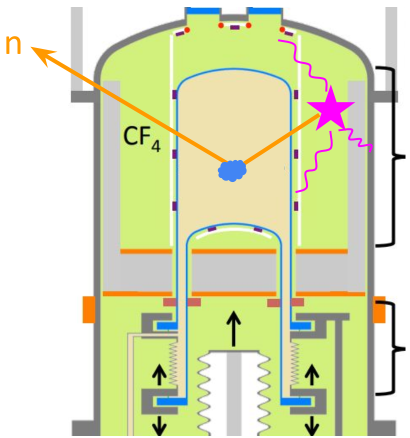
Sensitivity vs different NR thresholds (0.1, 0.5, 1keV)
(step function efficiency)

Sensitivity for 0.1 keV threshold,
various material backgrounds scenarios

all from Matt Bressler's thesis

Backgrounds and CF_4

Bkgs within ‘Physics signal’ region:
- single bubble far from walls
- non-distinguishable acoustics
- below scintillation veto threshold

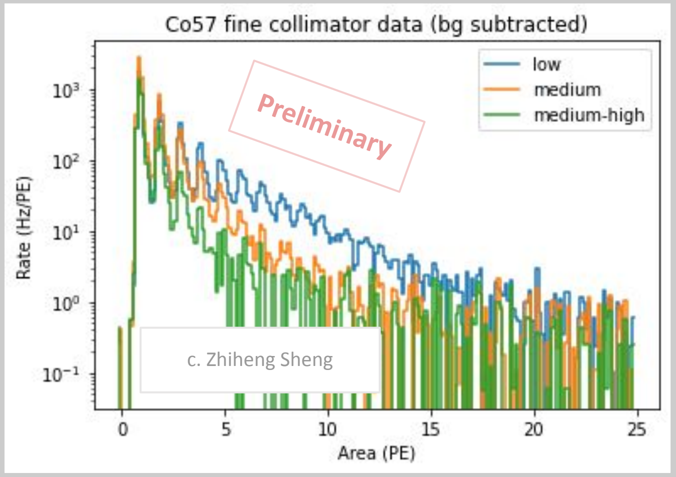


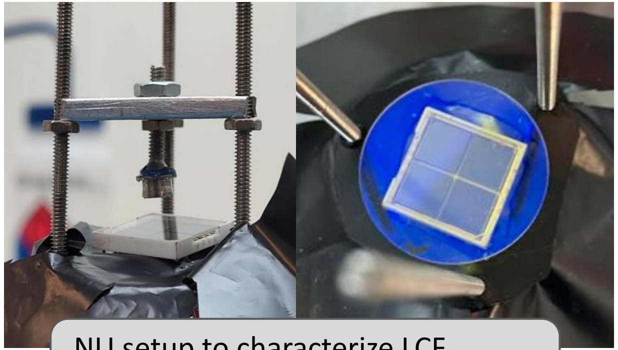
$^{19}F(\text{alpha}, n)^{22}Na$
cross-section is large!

but liquid CF_4 scintillates!
(~10 PE/keV - gamma)
(<5 PE/keV - alpha)

Liquid CF_4 veto:
- Instrument CF_4 space w/ SiPMs
- tag neutron producing events!

- single site neutrons (various sources)
  neutrons from CF_4
- solar CEvNS (irreducible)
- wall nucleation…





NU setup to characterize LCF_4 scintillation (c. Zhiheng Sheng)

Uncommon background - Gamma induced NR

Bkgs within 'Physics signal' region:

- single bubble far from walls
- non-distinguishable acoustics
- below scintillation veto threshold

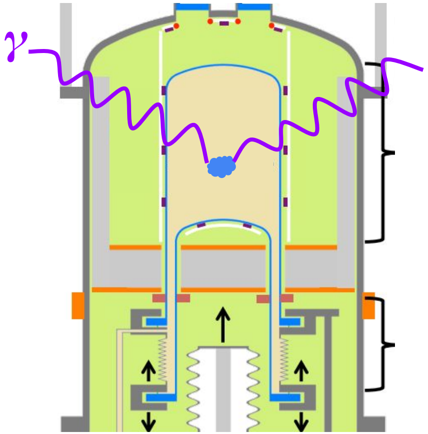
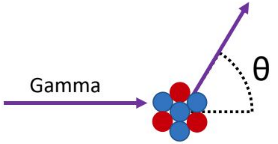


Photo-Nuclear elastic scattering

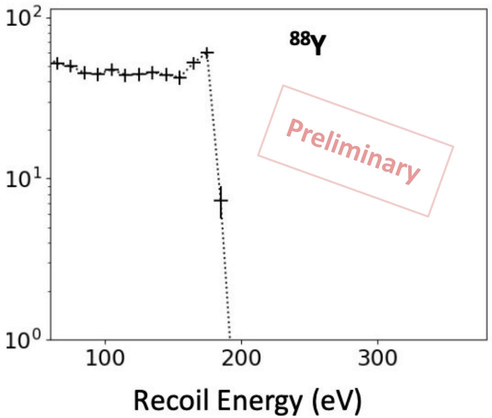
- Delbrück, Thomson scattering
- a gamma induced NR!
- ~10^{-6} probability (1-3 MeV gamma)

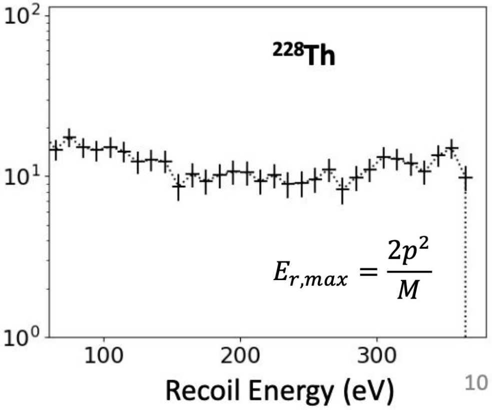
current simulation: ~1 event per year (shielding dependent)



2 MeV gamma
max Ar recoil ~ 200 eV

cross-section $\propto$ 1 + $\cos^2\theta$





10

work of Noah Lamb, PhD student (Drexel)

Heat vs NR recoil - first order

Has been said *"scintillation quenches nucleation"*
in reality - **scintillation removes energy**
charge as well (e^- in bandgap, ion in liquid)

$$E_{heat} = K - N_{PE} \times E_{photon} - N_{e-} \times (E_{gap} + E_{ion})$$

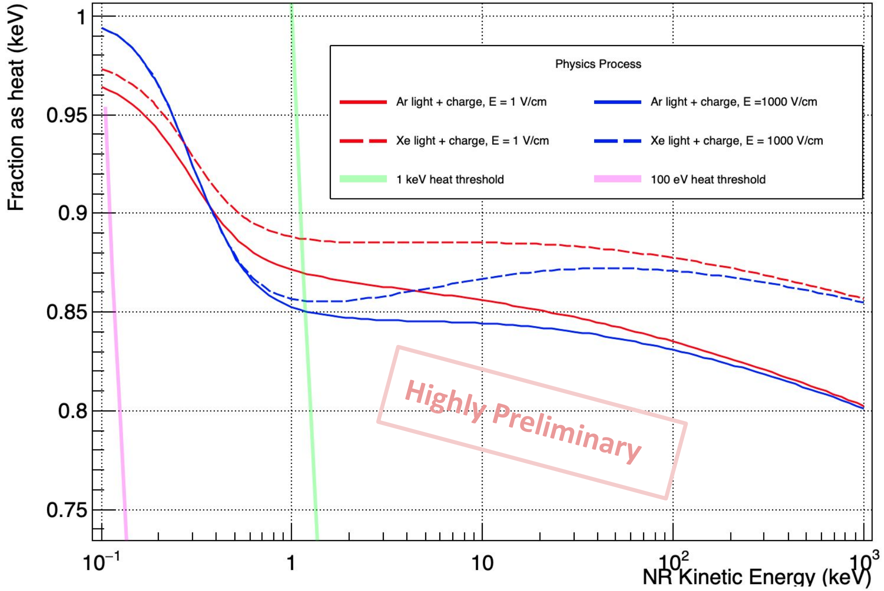
Assumptions in toy model calculation

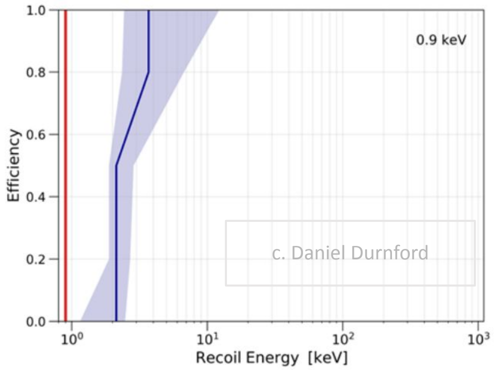
- NR range < Seitz critical radius
- electron thermalization < Seitz critical radius
- ignore other processes
- NEST yields to calculate non-heat energy

* yields below 1 keV are extrapolated

full calibration campaign to characterize response
(calculations are for guidance)

NR: Energy converted to Heat via NEST Yields





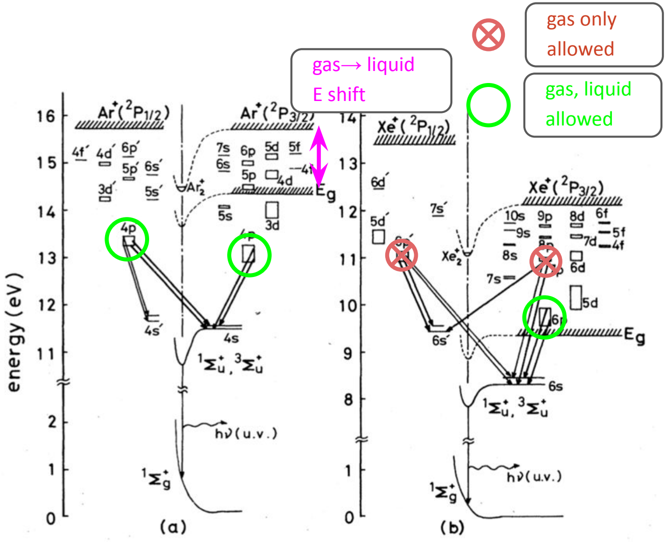
Note on signal production

Recombination is different between Ar/Xe

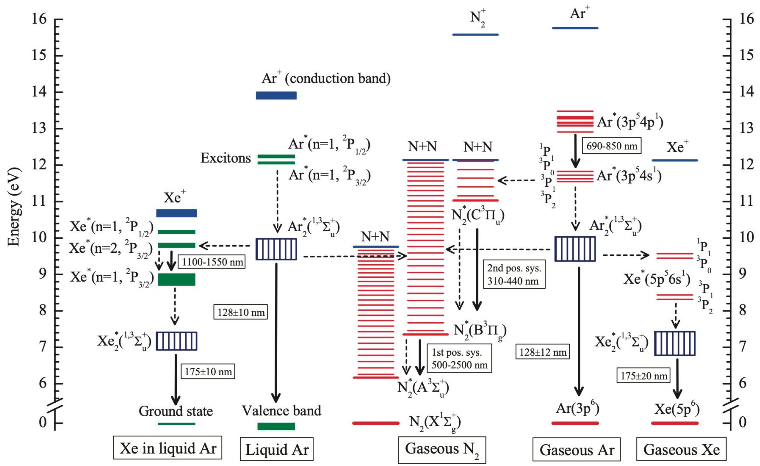
- faster/easier in Ar
- produces additional local heat (via dissociation)
- **test ER nucleation with few 100V/cm field**

Xe doping: 178 nm removes 2.7 eV less energy compared to 128 nm

- **does ER induced nucleation depend on doping?**



from PhysRevB.20.3486



from arXiv:1702.03612v1