The Scintillating Bubble Chamber

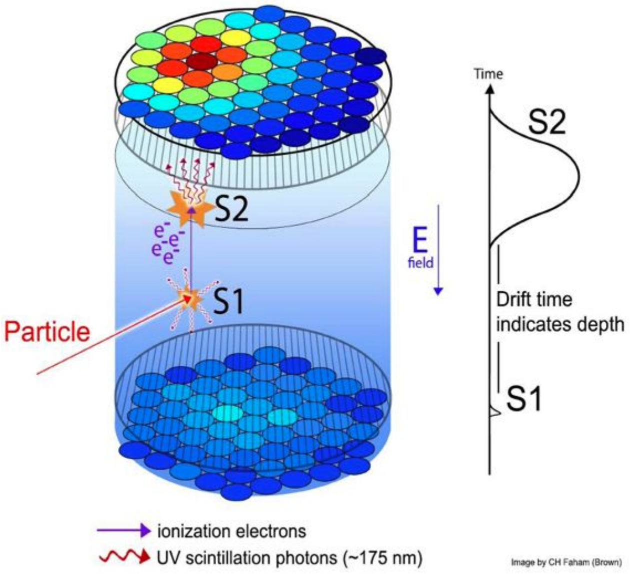
LAr-10: Overview and progress

LIDINE 2023 - Madrid

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

Talk Roadmap

1. **SBC overview**
2. **Bubble Chamber Basics**
    a. physics motivation (low E NRs)
    b. superheat and nucleation
    c. a bubble event
3. **Current status** (SBC-LAr 10)
    a. the detector
    b. progress at Fermilab
    c. future plans & SNOLAB chamber
4. **Nucleation thresholds**
    a. in molecular fluids
    b. why use argon
    c. proof of concept (Xenon)
5. **Expected Physics Reach**



we are **NOT a TPC**

Scintillating Bubble Chamber

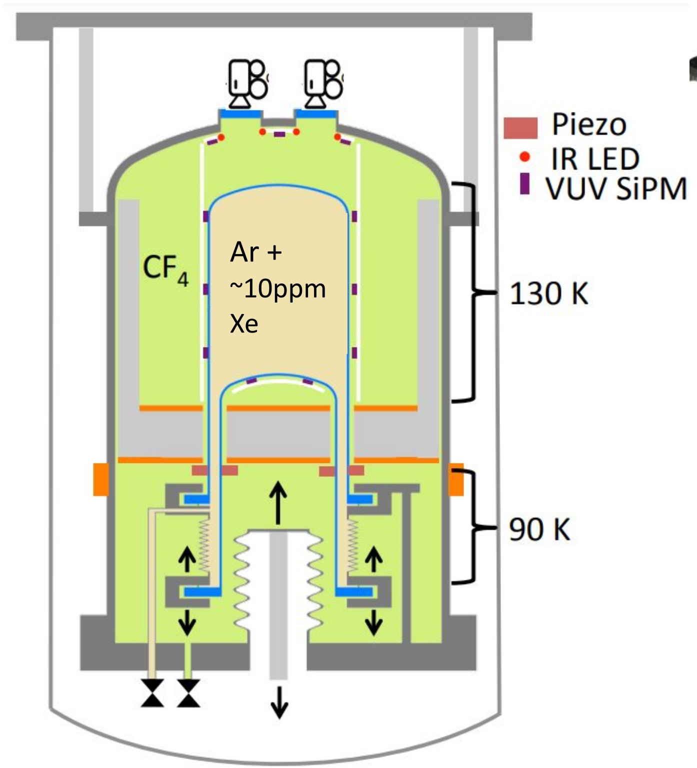
SBC-LAr10: physics scale chamber

- 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
  (XYZ position)

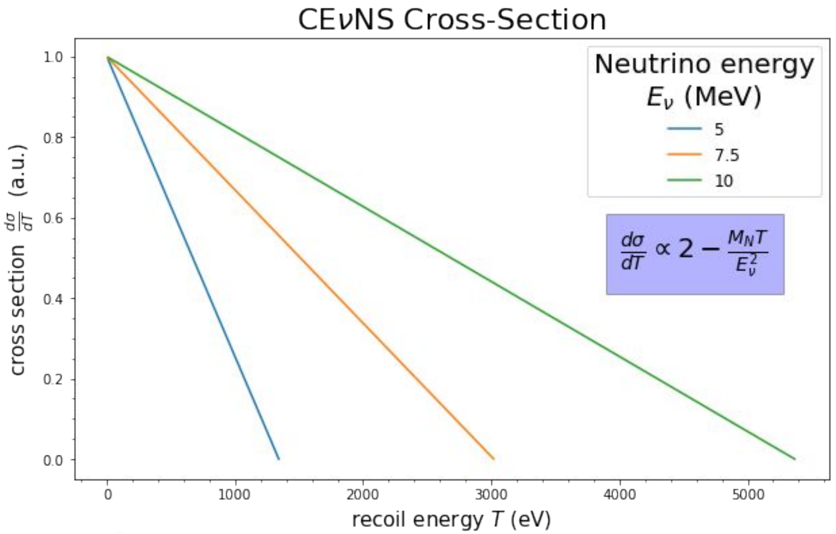
Inspiration from others:
bubble chamber design: **PICO 40L/500**
scintillation system: **LoLX** (see LIDINE 2020-22)
cryo-cooling: **LUX/LZ**



Why low energy nuclear recoils?

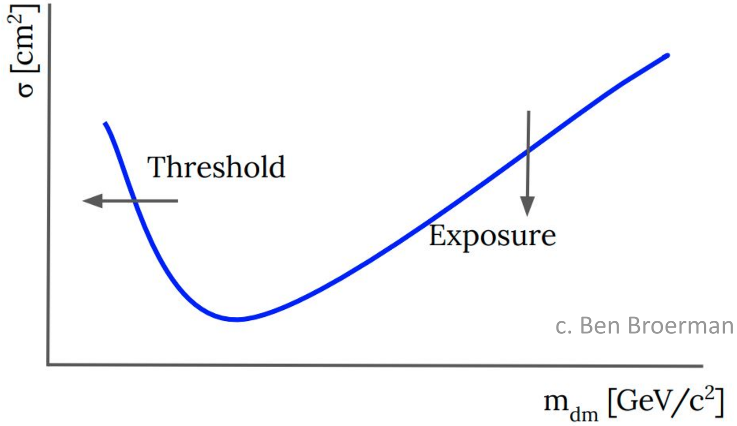
search for **WIMP** dark matter
test SM via **CEvNS**

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



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

*with discrimination against electron recoils (ERs)



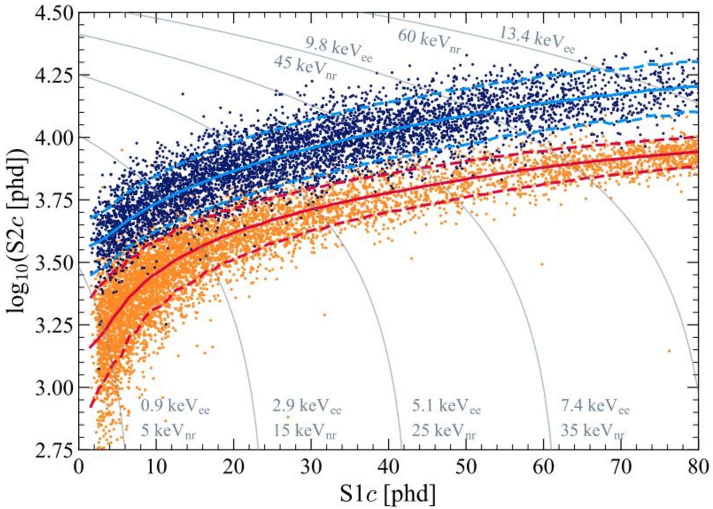
c. Ben Broerman

Why a Bubble Chamber?

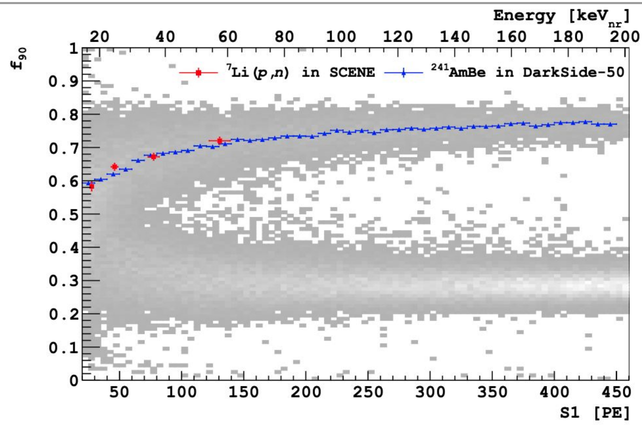
Conventional Ar/Xe experiments: scintillation & charge.

high energy → discrimination is excellent

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



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



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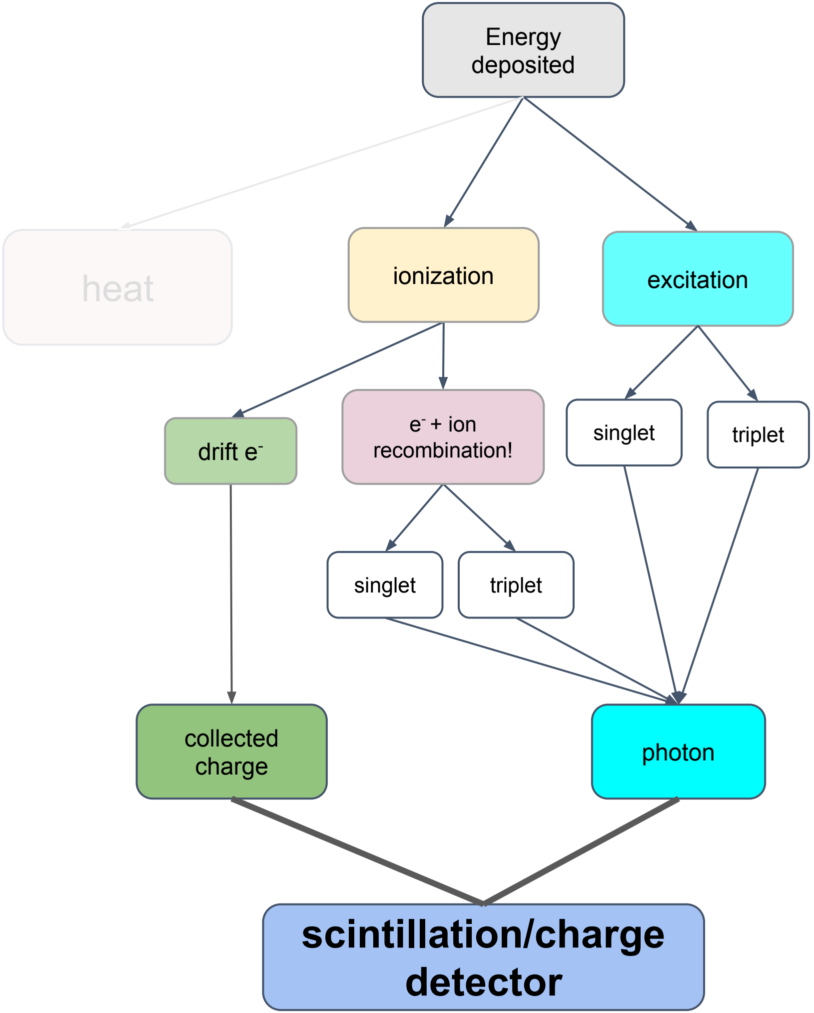

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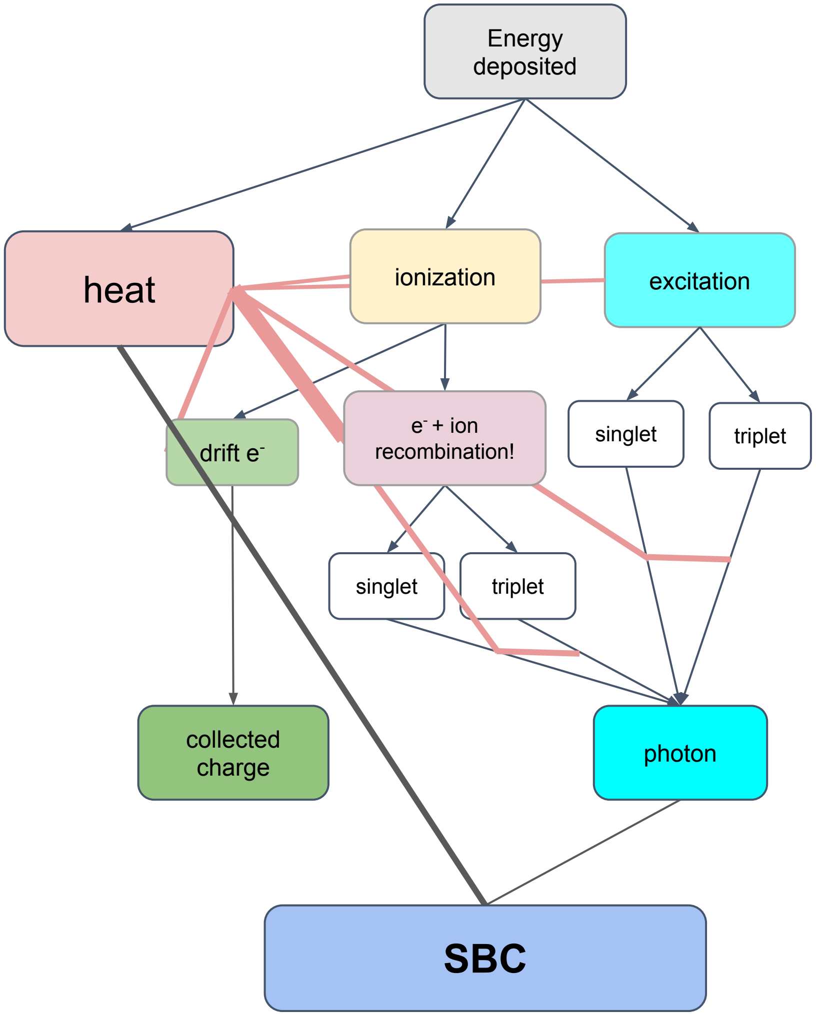
Solution

measure heat more directly

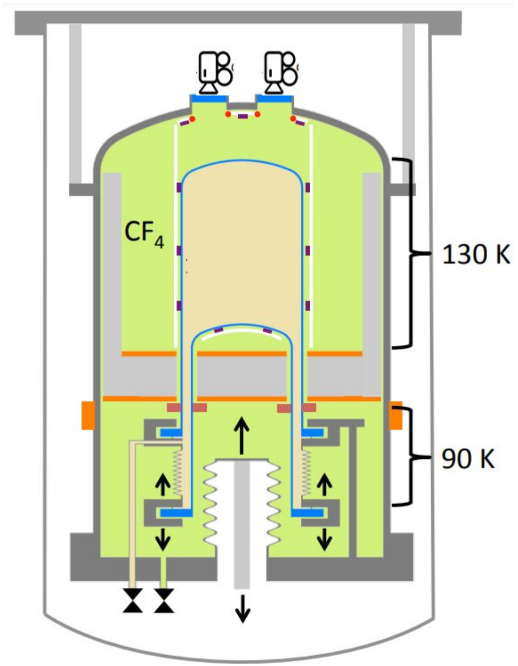
(threshold detector)



Bubble Chamber - Superheat

Filling SBC (like normal chamber)

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



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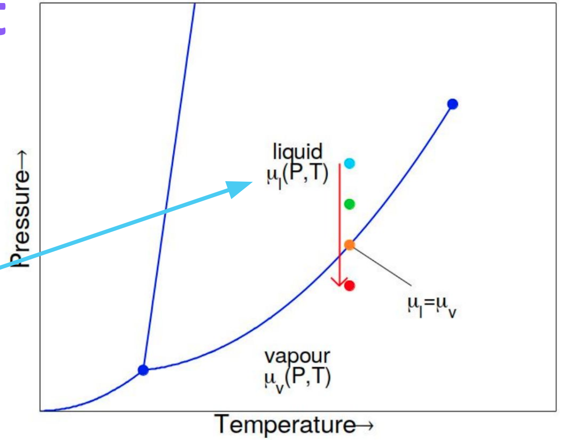
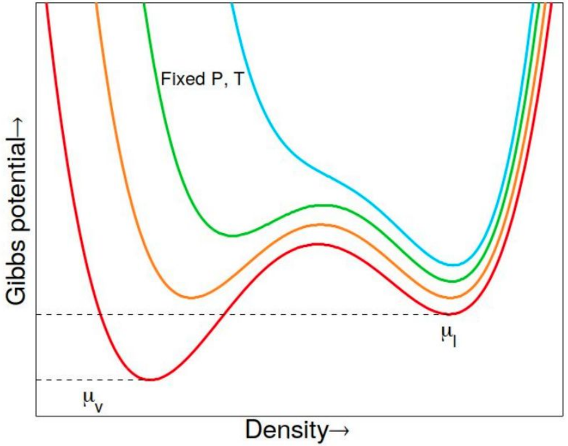
Superheated or 'bubble-ready'

1. chamber compressed (stable)



diagrams from K. Clark



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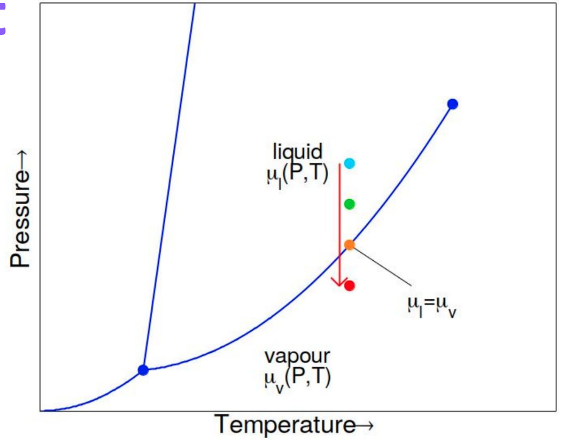
Superheated or 'bubble-ready'

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



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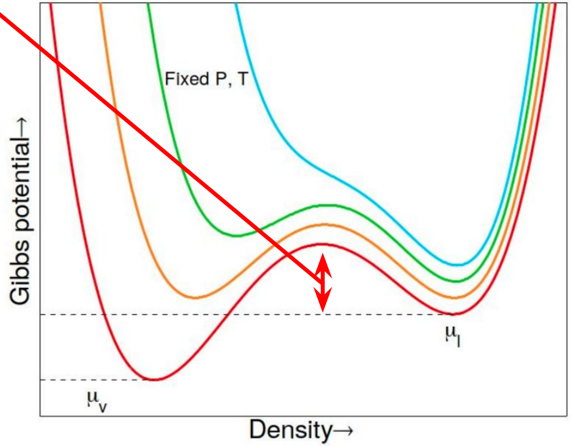

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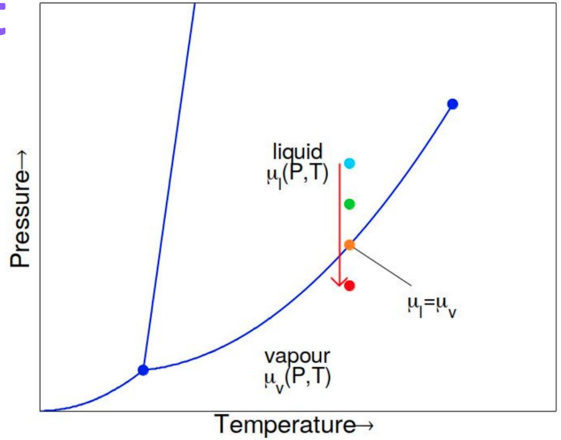
3. particle deposits *enough heat in small volume*
   - **nucleation/bubble formation!**



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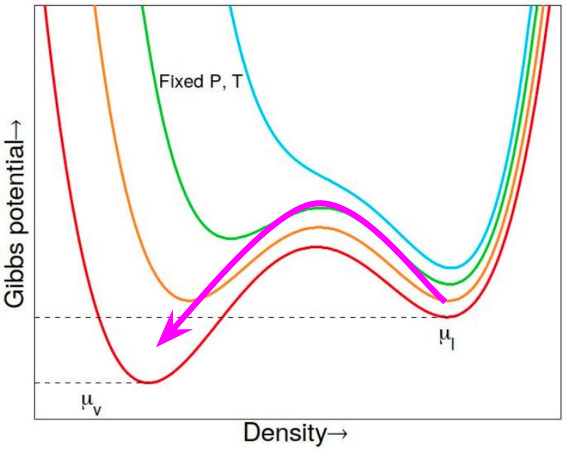

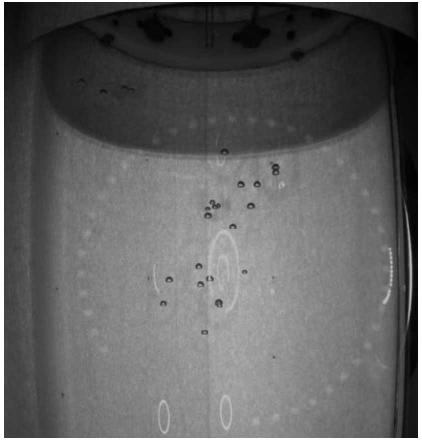

Neutron multi-scatter in PICO chamber,
Ken Clark - https://indi.to/pXh9y

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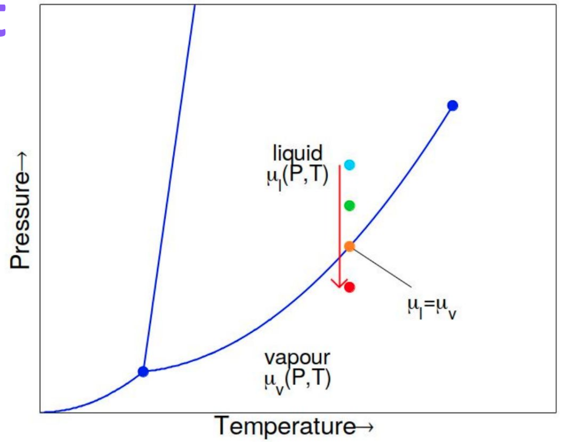
useful heat threshold model: *Seitz hot spike*

tune Seitz threshold via Temp, Pressure

Seitz threshold relates to NR threshold



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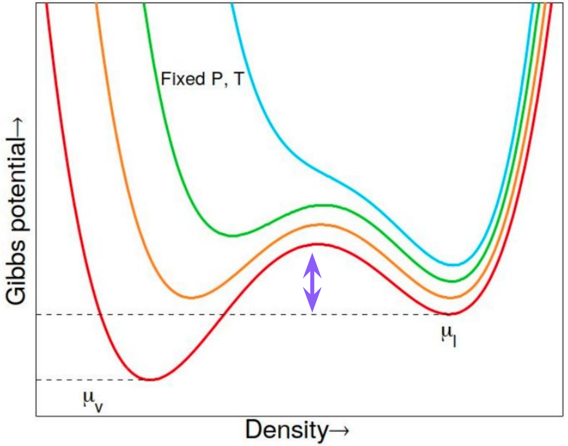

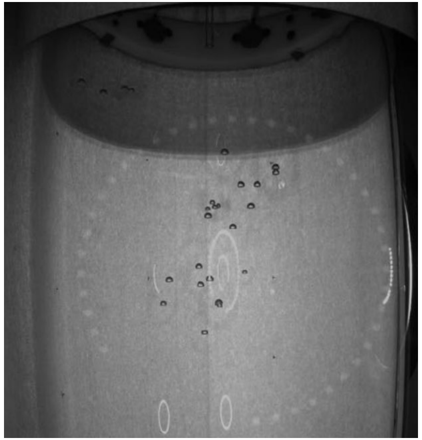

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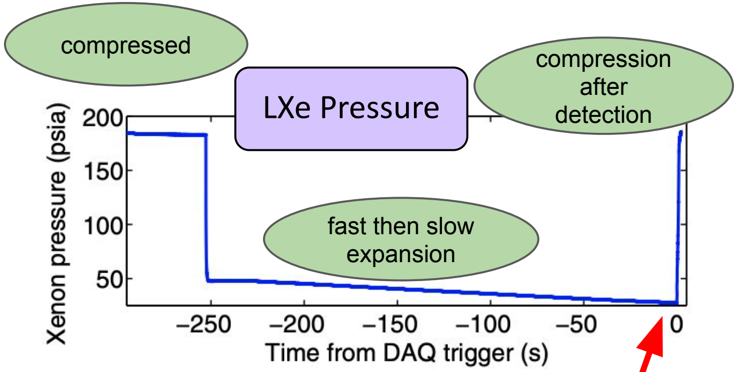
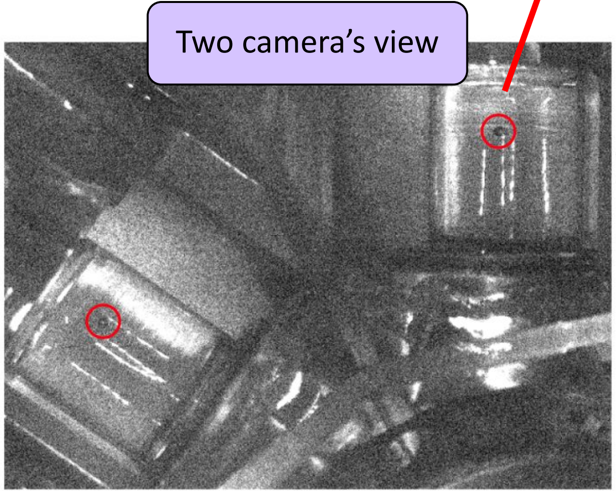
A bubble event (in 30g LXe chamber)





Chamber Operation

1. expansion **(many seconds)**

wait…

high dE/dx interaction

2. scintillation **(ns)**

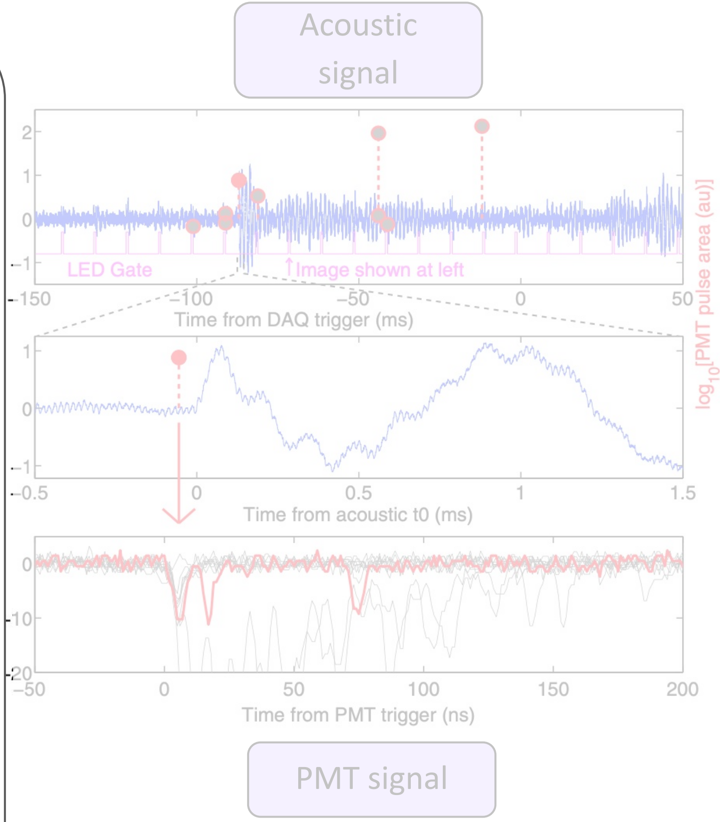
bubble forms

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)

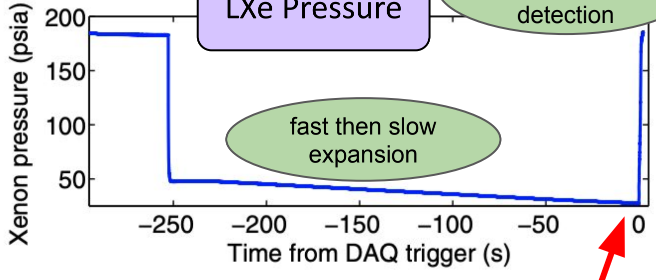
A bubble event (in 30g LXe chamber)

LXe Pressure

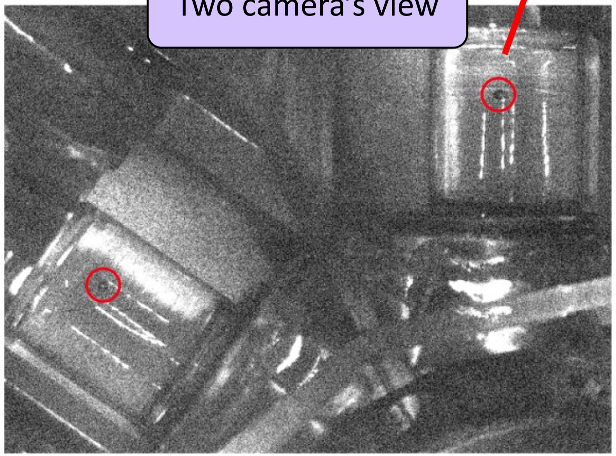
compressed

compression after detection

fast then slow expansion



Two camera's view



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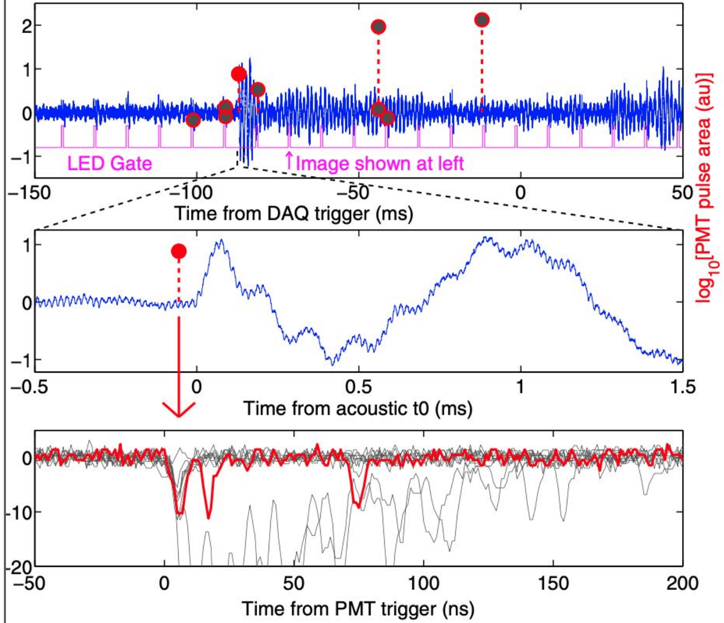
Acoustic signal



PMT signal

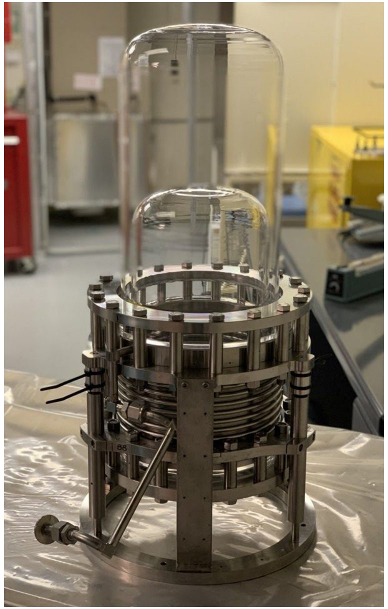
figures from Xe bubble chamber (arXiv:1702.08861)

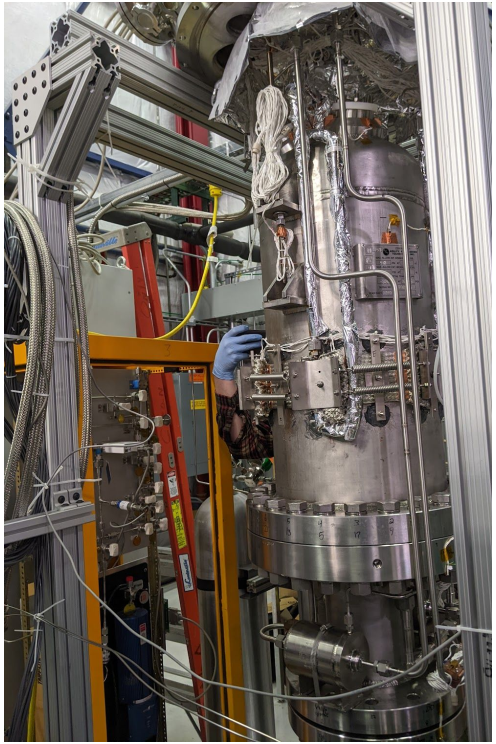
SBC: Status and Progress

SBC LAr10 Plan

Revisiting plan from LIDINE 2022 - **items in progress**

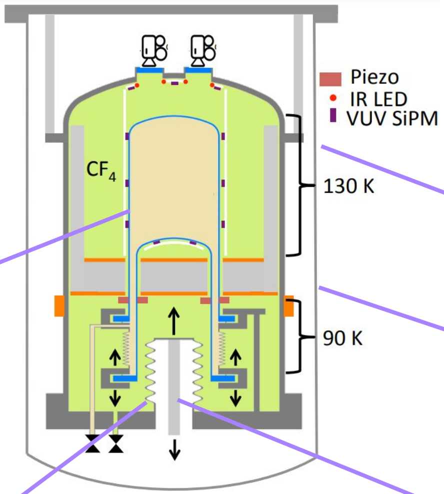
1. **instrument Inner Vessel, install in PV (Fermilab)**
    a. commissioning & calibration (2023-2025)
2. **build second cleaner chamber (DM search)**
    a. improve cleanliness/backgrounds
    b. operate at SNOLAB (2024 - ?)
3. install Fermilab chamber at nuclear reactor (future)
    a. study reactor CEvNS (in Mexico?)

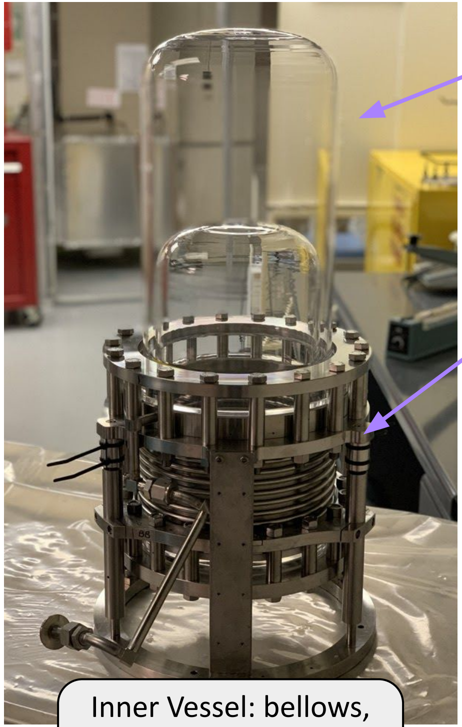




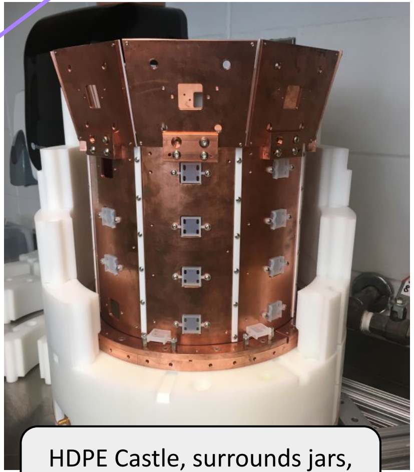
SBC LAr10 - 2022

2023 has been about *combining systems*

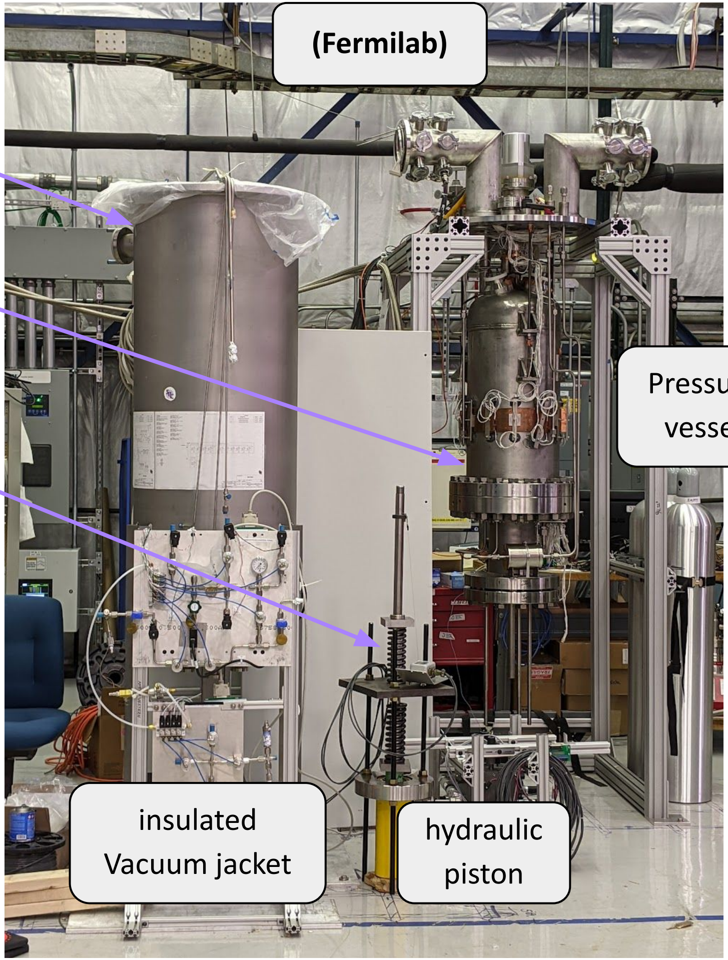




Inner Vessel: bellows, fused silica jars **(Queen's)**



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



(Fermilab)

Pressure vessel

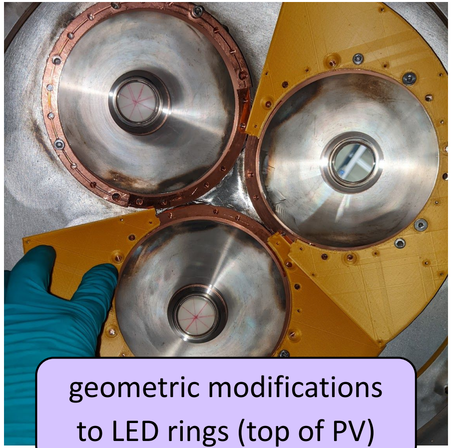
insulated Vacuum jacket

hydraulic piston

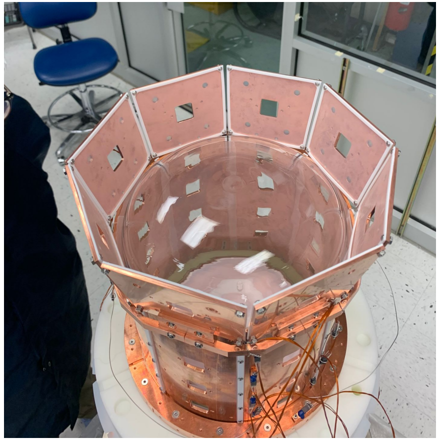
SBC LAr10 at Fermilab

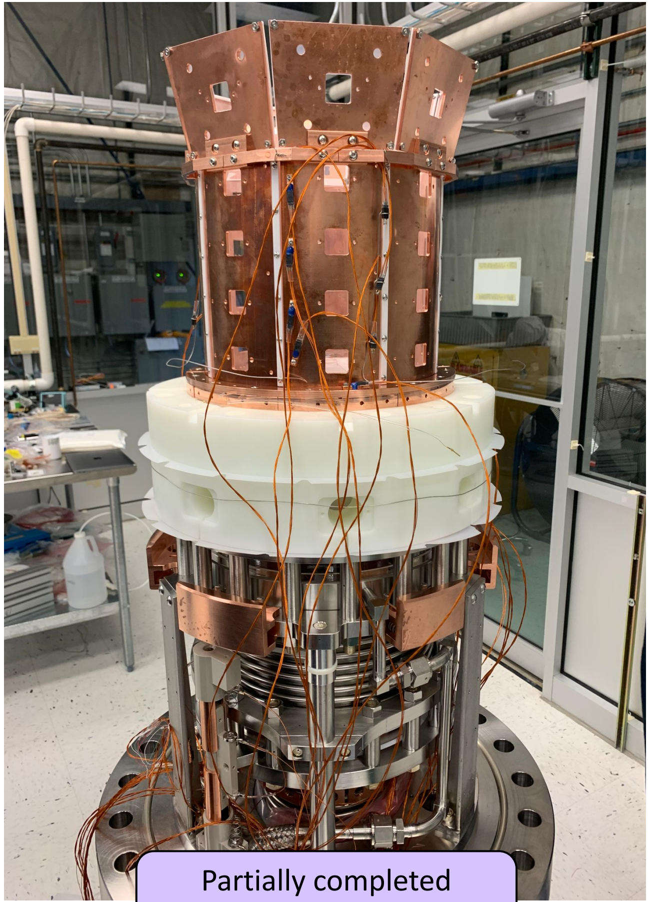
Since 2022… **chamber construction**

- improved/replaced majority of plumbing and wiring
- studied SiPM grounding and signal integrity
- installing **inner assembly** instrumentation
  - RTDs
  - acoustic sensors (installed, tested cold)
- cameras tested (temperature gradient)
- **goal:** PV and IV combined, closed **october 2023**



geometric modifications to LED rings (top of PV)





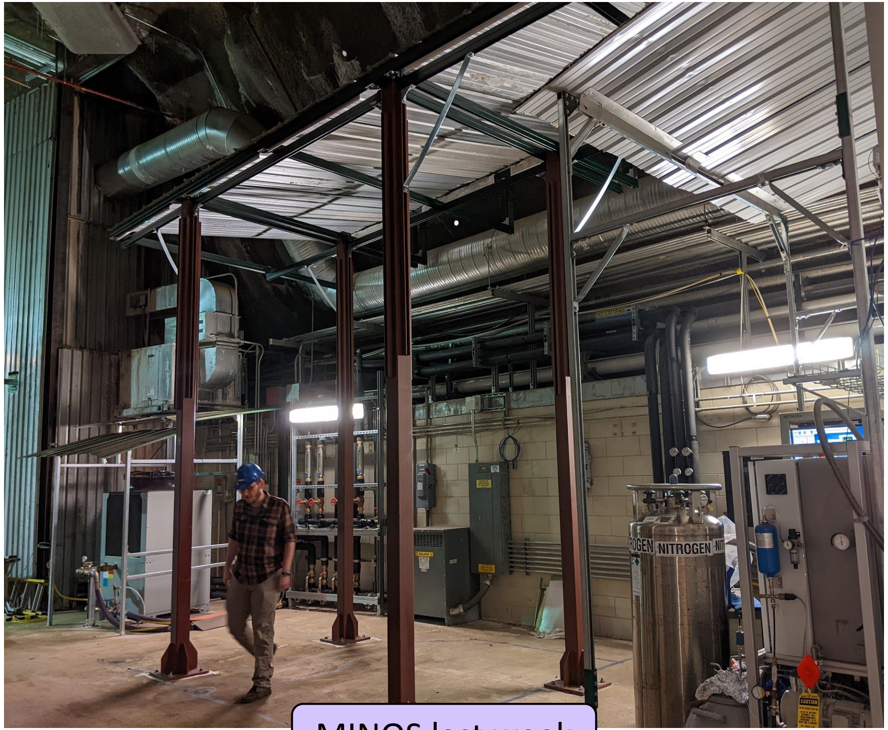
Partially completed assembly (July 2023)

SBC LAr10 at Fermilab

Since 2022… **MINOS site** for commissioning, calibration

- underground location with neutron source
- construction completed (roof!), prep for install
- **goal: bubbles in Jan 2024**
  - **do low thresholds work in Ar?**

MINOS in 2022



MINOS last week

SBC LAr10 cryosystem

Cooling system and Pressure Vessel

- closed-loop LN_2 thermosiphons
- control cooling power via N_2 pressure

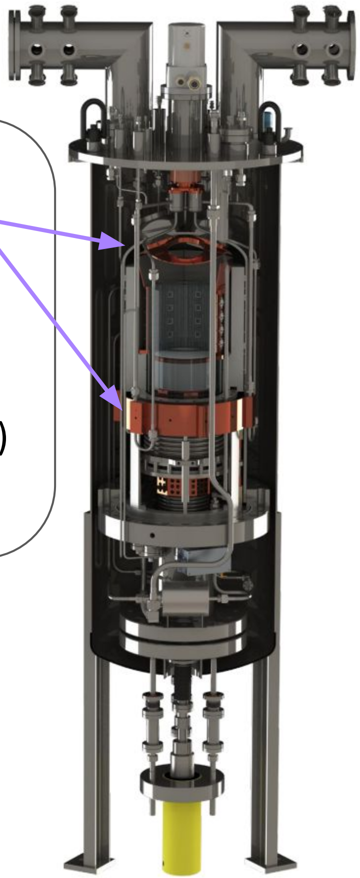
can reach argon thermodynamic limit:

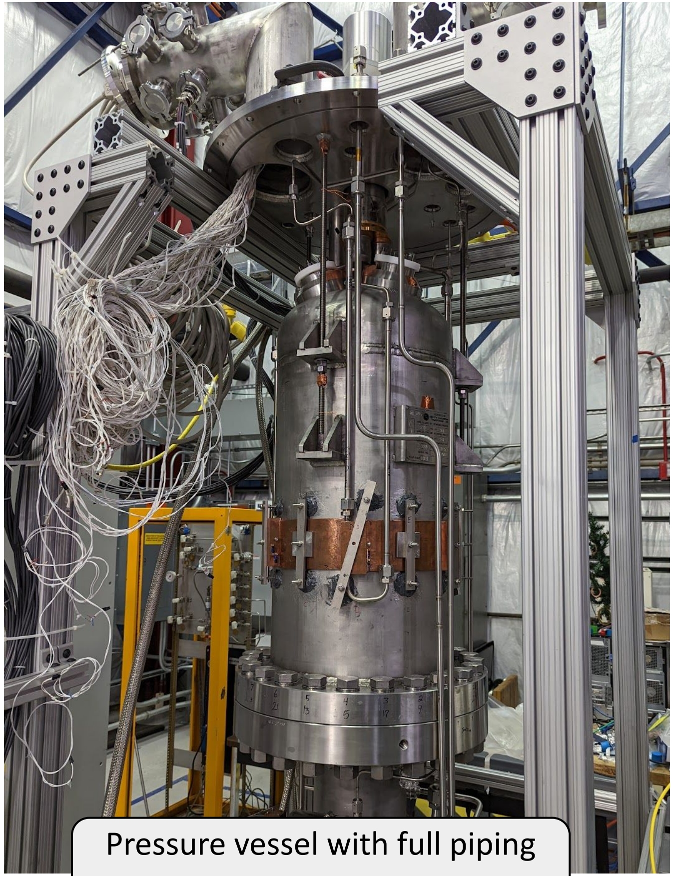
- 40 eV heat threshold (1.4 bar @ 130K)

max pressure ~20 bar

Cooling works: PV filled with LAr!

Can operate with Xe, N_2 or CF_4

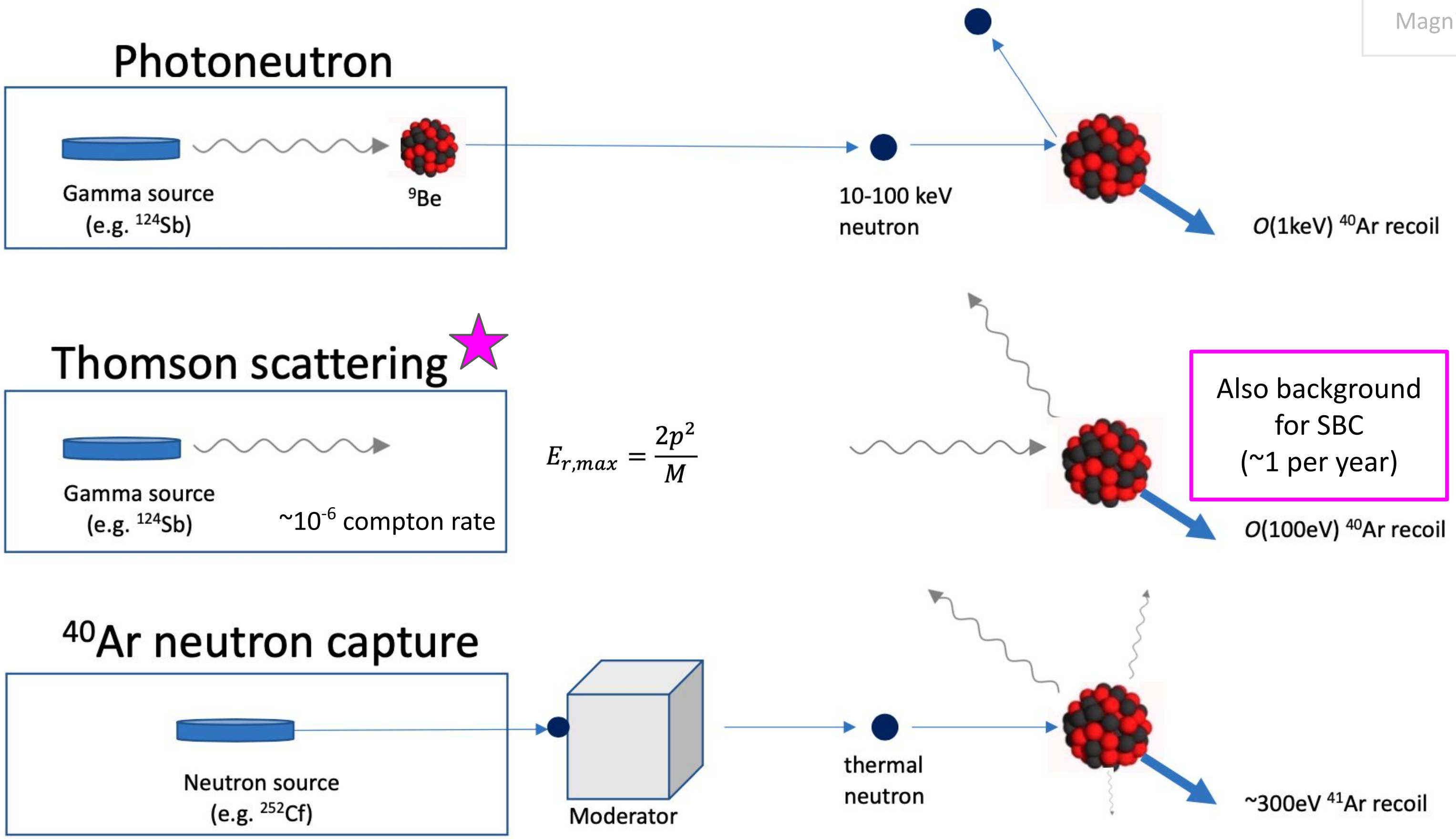




Pressure vessel with full piping and wiring (Fermilab, 2022)

Calibration Schemes

Figures from Russell Neilson's talk, Magnificent CEvNS 2021

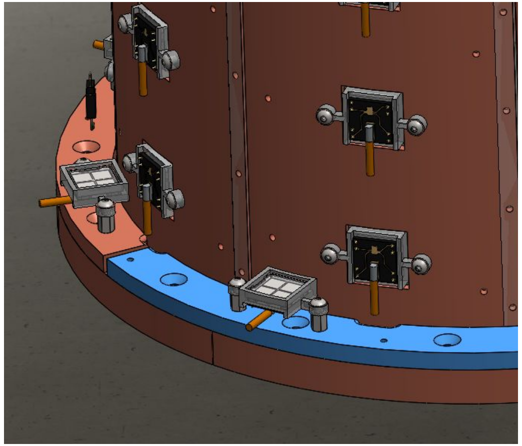


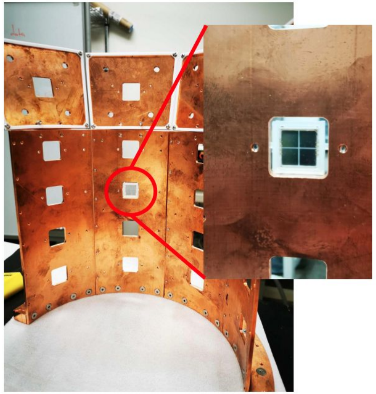
data-taking: measure comptons & NRs simultaneously?

Scintillation System - 2022

Silicon Photo-Multiplier (SiPM) for light detection

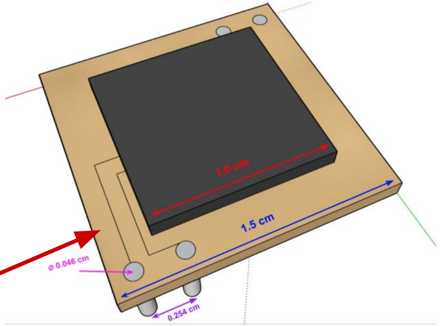
- 32 SiPMs: 24 facing LAr, 8 in LCF_4 (veto)
- high speed analog electronics (LoLX)
  coupled to 16 ns digitizer (62.5 MHz)
- 10-1000 ppm Xe doping
  (at 128 nm jars absorb, lowers SiPM PDE)

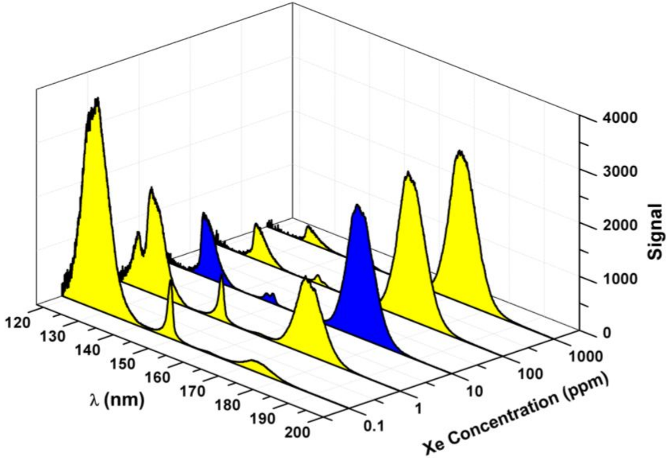




Fermilab Chamber
Hamamatsu VUV4 devices
quadrants summed in-situ via PCB

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





arXiv:1511.07723

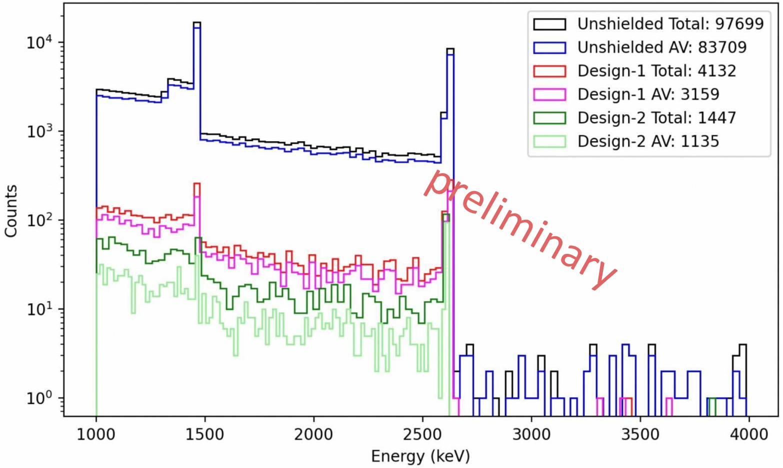
LAr10 SNOLAB/DM chamber

second chamber for DM search at SNOLAB

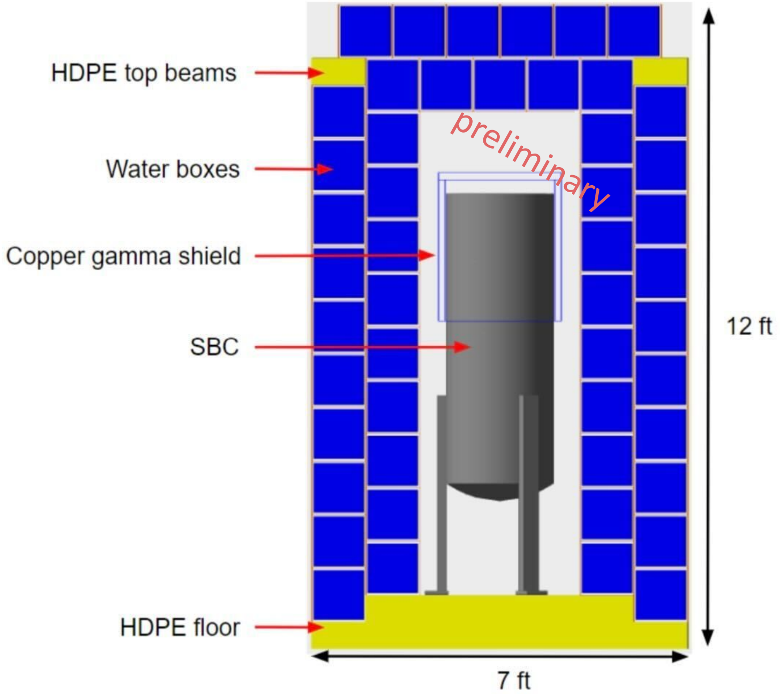
- different SiPMs, camera strategy (cleanliness)
- optimizing external shielding

  dominant bkg is gamma induced NRs

timeline: begin assembly summer 2024

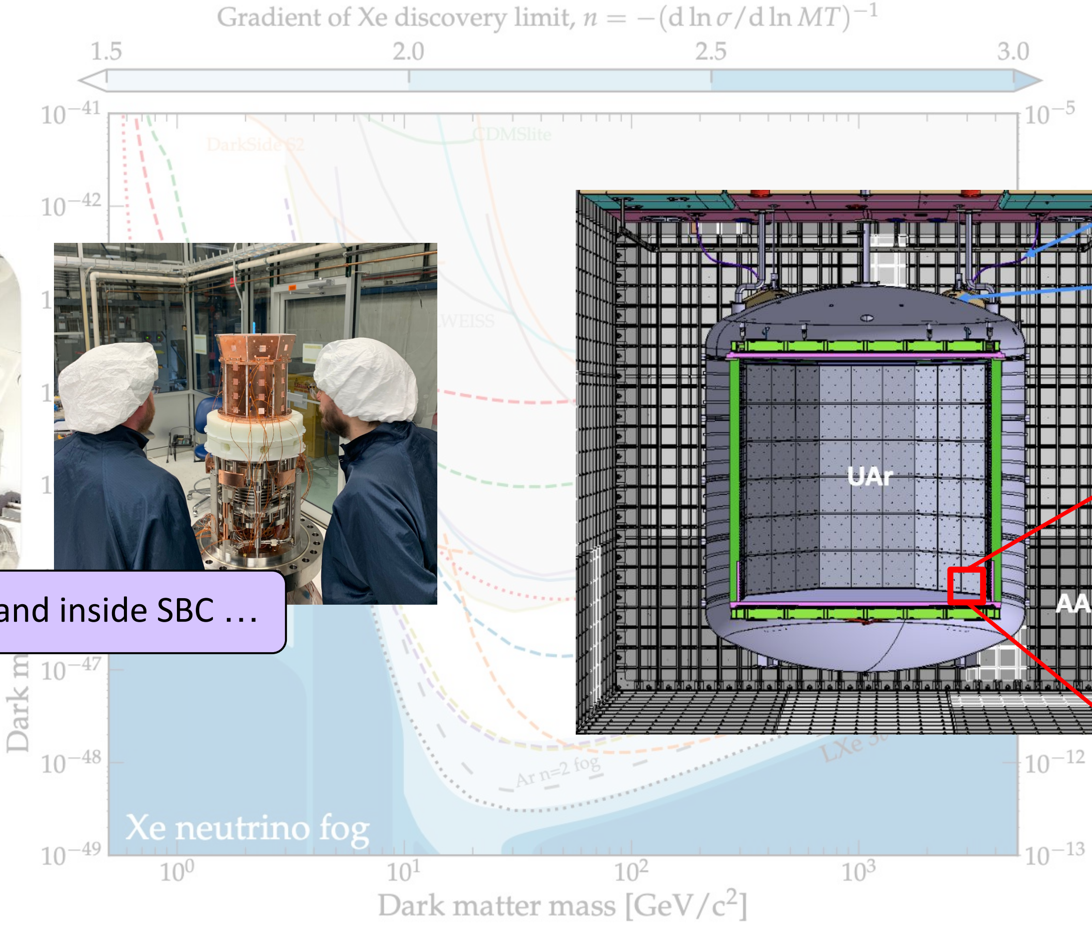


gamma spectra from shielding (G. Sweeney)

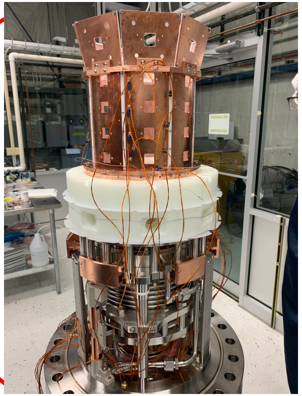


'Design 1' shielding configuration (Gary Sweeney)

Searching for DM with 10 kg of Argon…



you can't stand inside SBC …



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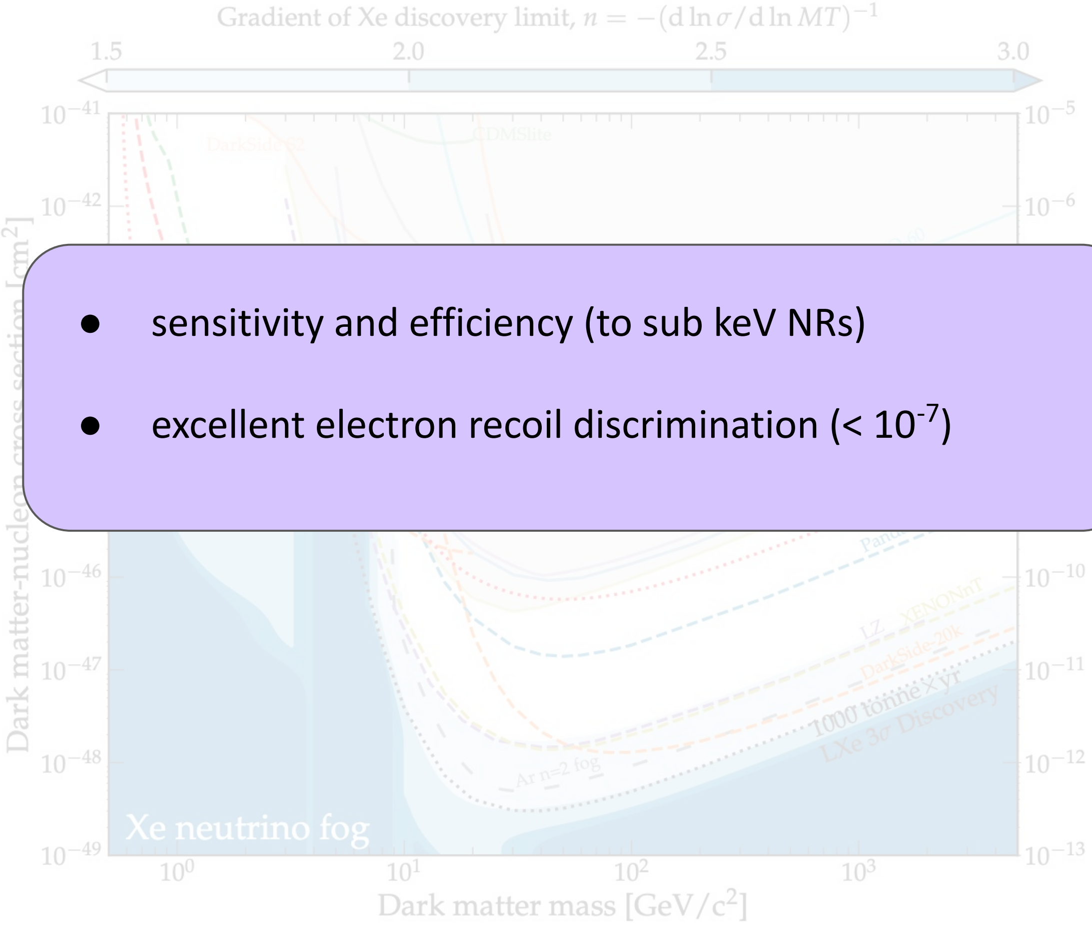


- sensitivity and efficiency (to sub keV NRs)
- excellent electron recoil discrimination (< 10^{-7})

Nucleation requirements - Seitz Model

Seitz 'hot spike' model

- require energy $\mathbf{E_T}$ to produce bubble of size $\mathbf{R_c}$
  - overcome enthalpy, external pressure
- bubble smaller than critical radius $\mathbf{R_c}$ will collapse
  - must overcome surface tension $\boldsymbol{\sigma}$

    see https://arxiv.org/abs/1905.12522 for derivation

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

vapour/liquid pressure difference

$$E_T = 4\pi R_c^2 \left(\sigma - T \left(\frac{\partial \sigma}{\partial T} \right)_\mu \right) + \frac{4\pi}{3} R_c^3 \rho_b (h_b - h_l) - \frac{4\pi}{3} R_c^3 (P_b - P_l)$$

total energy of surface

gas density

enthalpies

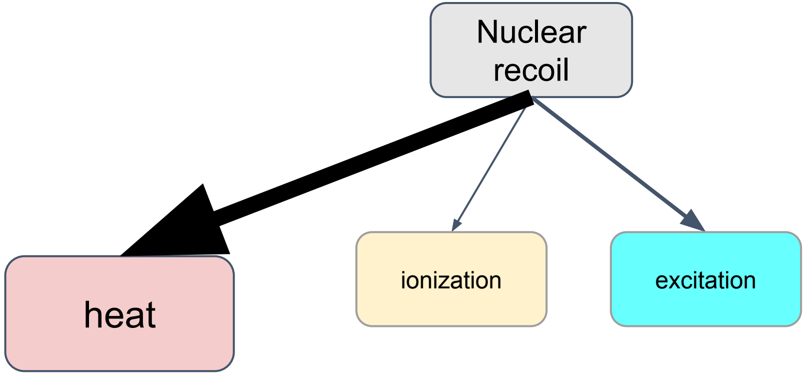
'like' PΔV work

require dE/dx (or dE/dV) over some threshold

Bubble Chamber Discrimination (why use argon)

NRs create heat

- lindhard and quenching



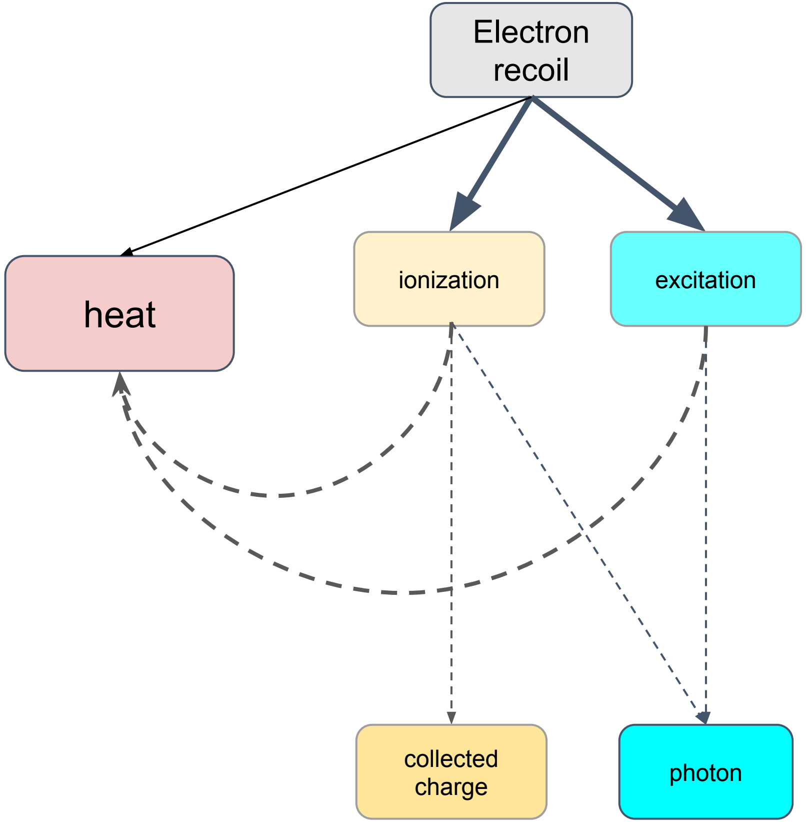
Bubble Chamber Discrimination (why use argon)

NRs create heat

- lindhard and quenching

Electronic Recoil creating heat:

require electronic energy transfer to atomic motion

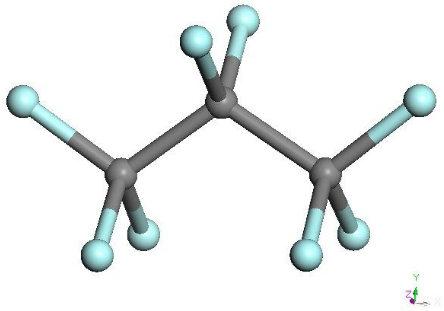


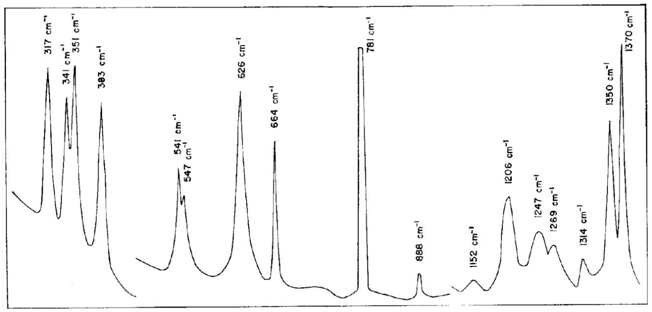
Bubble Chamber Discrimination (why use argon)

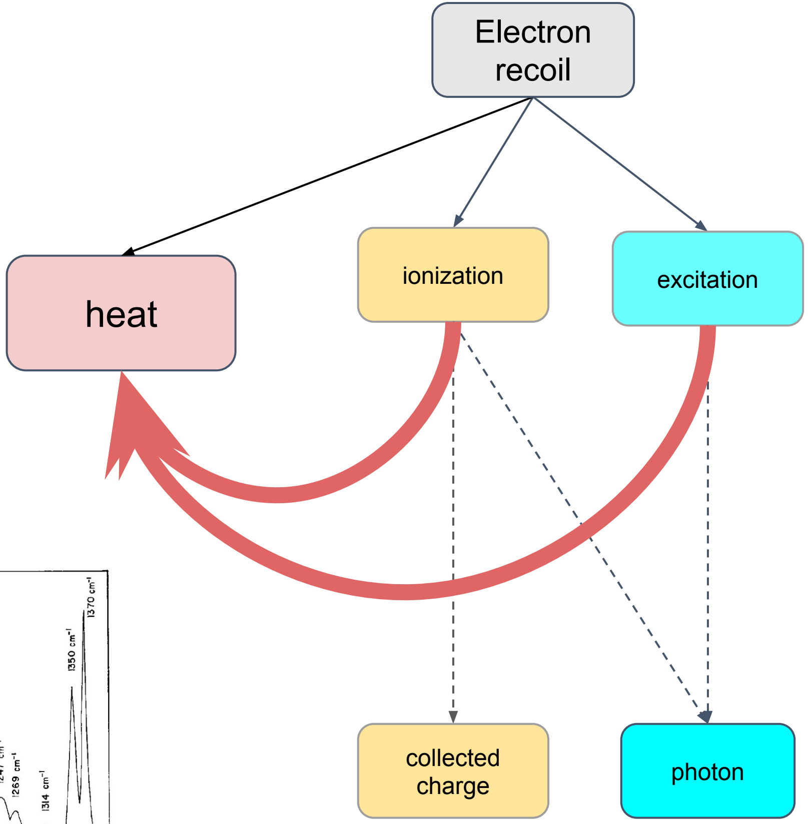
NRs create heat
- lindhard and quenching

ERs creating heat:
require electronic energy transfer to atomic motion

molecular fluids (complex molecules): effective transfer due to overlapping vibrational/rotational modes





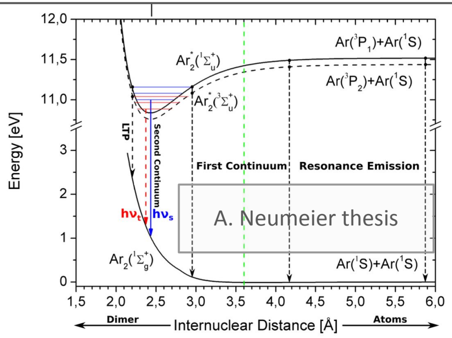


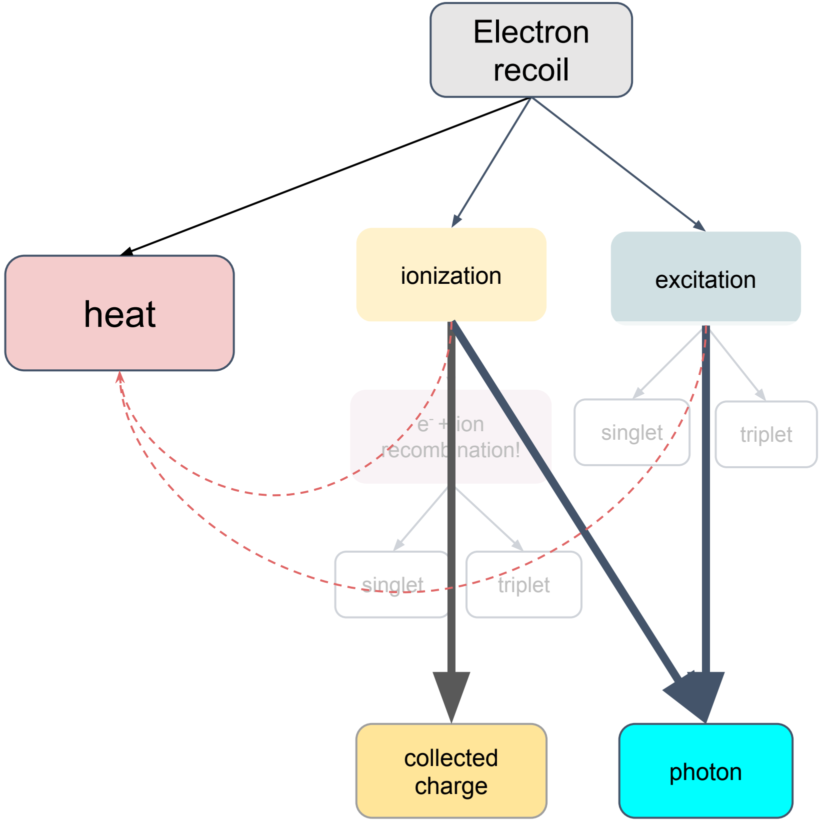
Bubble Chamber Discrimination (why use argon)

NRs create heat
- lindhard and quenching

ERs creating heat:
require electronic energy transfer to atomic motion

Noble Gases: inefficient transfer
Minimal vib/rotational modes → 'stuck'
(same fundamental reason for high LY and ER insensitivity)

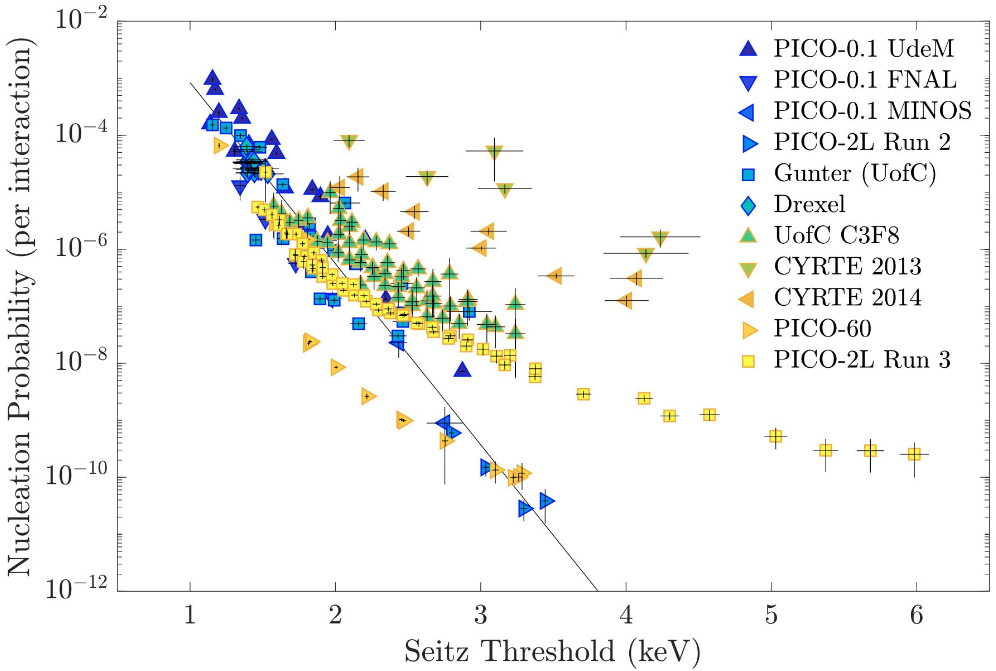




Molecular Fluids (not) discriminating

Successful DM searches with molecular fluids

- COUPP, PICASSO, **PICO** (40 active)
  CF_3I C_4F_{10} $\mathbf{C_3F_8}$
- Gammas nucleate at few keV via …
  - delta rays
  - Auger cascades (if possible)
    Iodine or Xe contamination
    (arXiv:2110.13984)

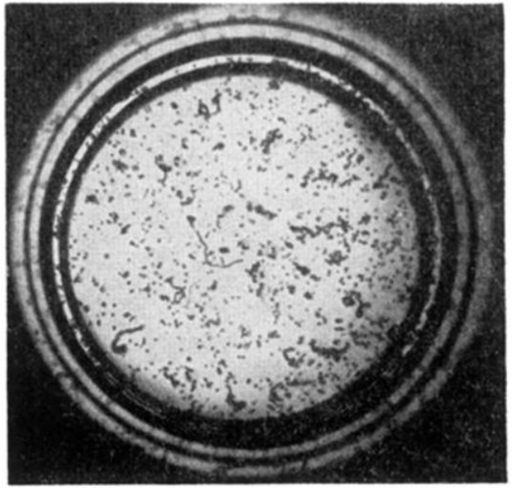


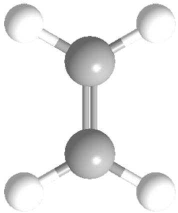
nucleation probability by ERs in $\mathbf{C_3F_8}$
(from arXiv:1905.12522)

Argon and Xenon ER discrimination

Historical evidence of ER insensitivity in noble liquids
(bubbles at sub 100eV thresholds) (see Matt Bressler thesis)

- Stump/Pellet, Ar, 1960s ~ 10-30 eV
- Harigel, Ar, 1980s ~ 50-75 eV
- Glaser, Xe - 1985 2% ethylene





nucleation in xenon requires 2% ethylene doping (quenching)
from (1985) https://doi.org/10.1103/PhysRev.102.586

Xenon ER discrimination

Historical evidence of ER insensitivity in noble liqu
(bubbles at sub 100eV thresholds) (see Matt Bressler th

- Stump/Pellet, Ar, 1960s ~ 10-30 eV
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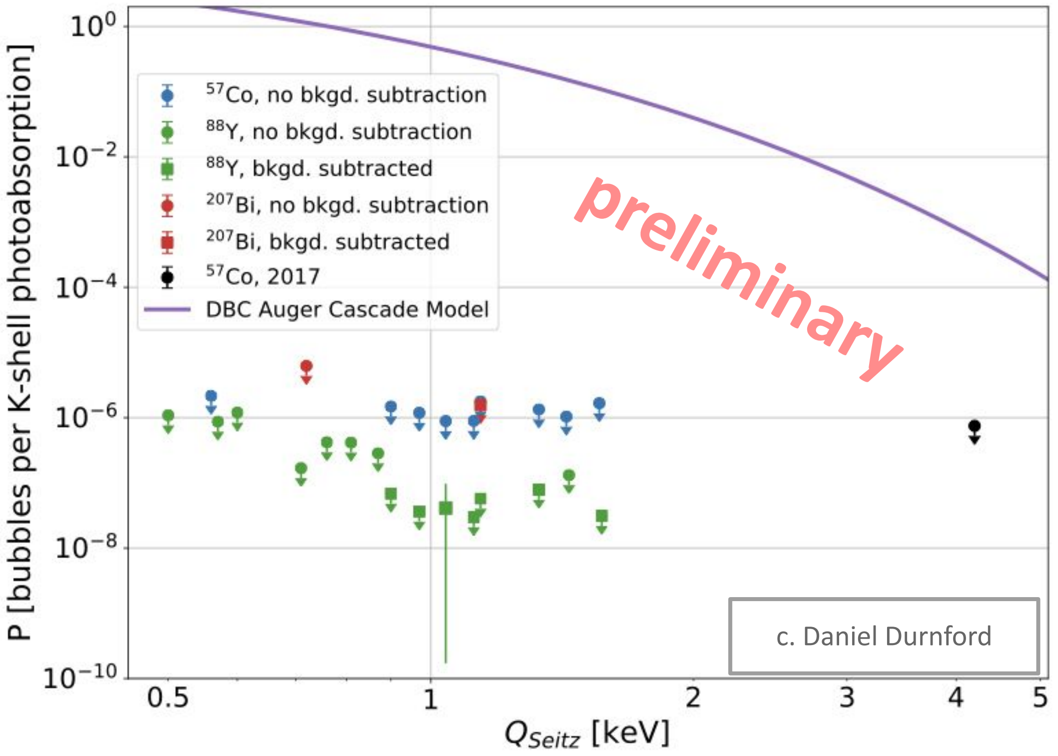
- Glaser, Xe - 1985 2% ethylene

- **D. Durnford & SBC, Xe - 2023** - upper limit

ER Nucleation in Xenon



Upper limits on ER induced nucleation in Xe, paper in progress
(or see D. Durnford CPAD 2022 talk)
purple - Xe contamination in C_3F_8, black point from 2017 Xe paper (arXiv:1702.08861)

Xenon ER discrimination

Historical evidence of ER insensitivity in noble liqu
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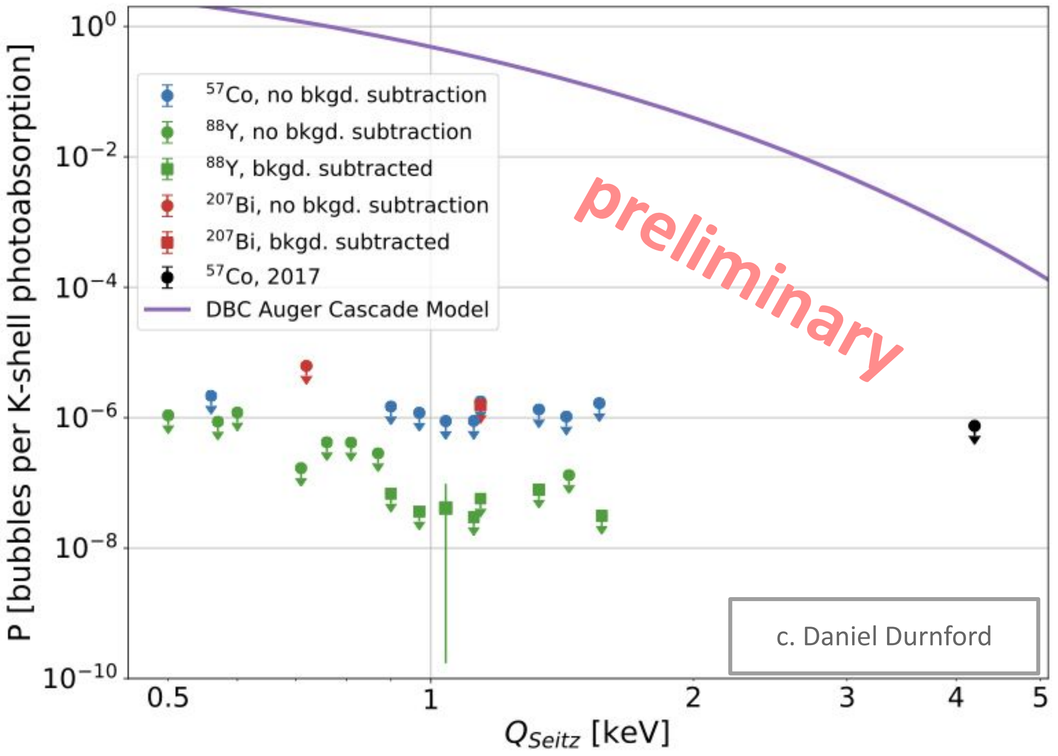
- Stump/Pellet, Ar, 1960s ~ 10-30 eV
- Harigel, Ar, 1980s ~ 50-75 eV
- Glaser, Xe - 1985 2% ethylene
- **D. Durnford & SBC, Xe - 2023** - upper limit

the hypothesis: LAr behaves similarly
(gammas don't nucleate!)
SBC @ 100 eV heat threshold
what is NR energy equivalent?



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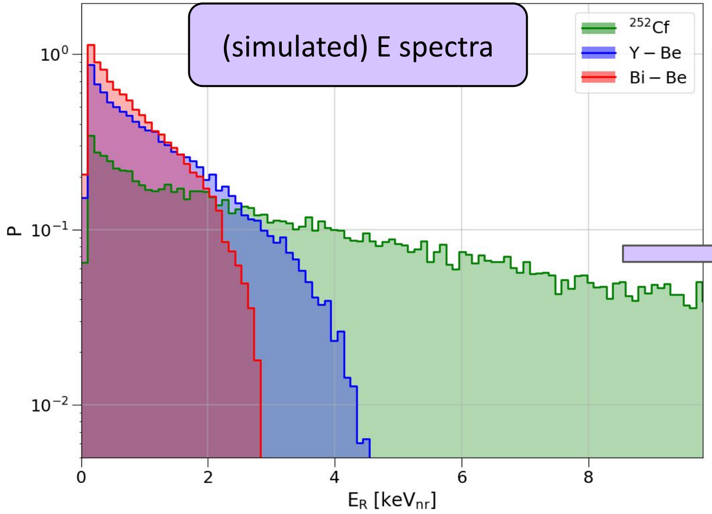
Bubble Chamber - NR sensitivity (Xenon)

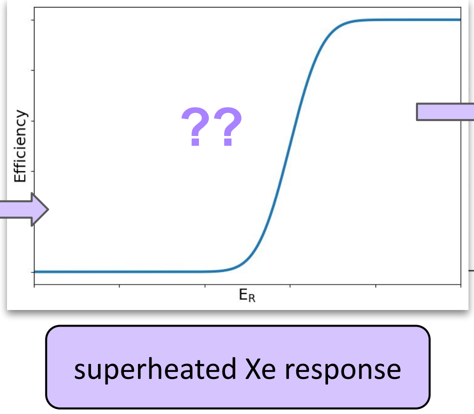
heat threshold ≠ NR threshold

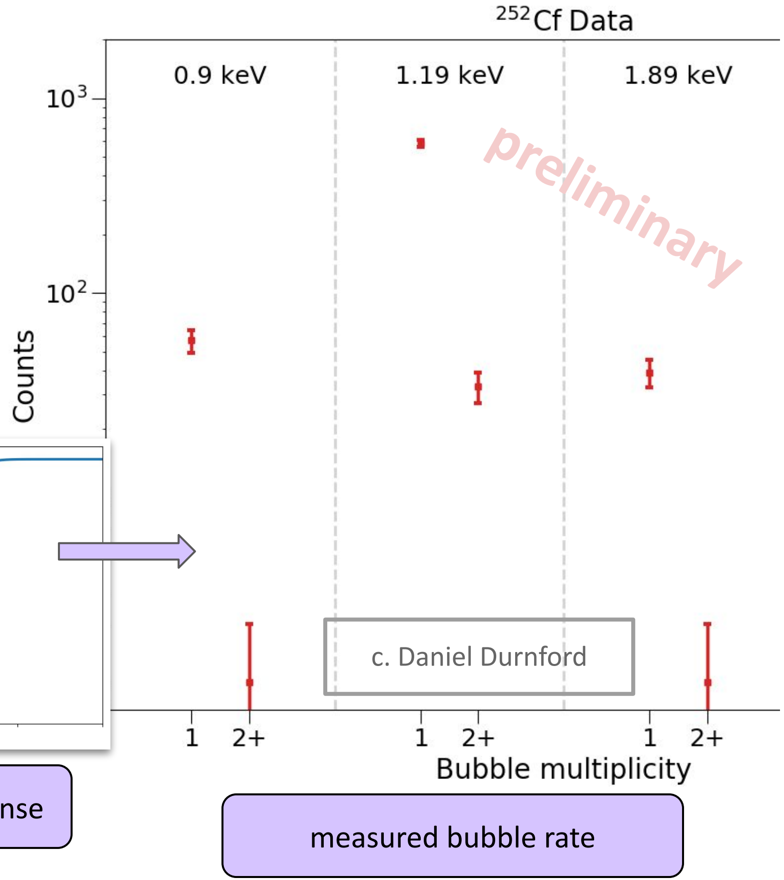
energy escapes critical radius via:

track length, scintillation, electron thermalization or drift, phonons, etc…

Efficiency: NR's probability to create bubble







Bubble Chamber - NR sensitivity (Xenon)

heat threshold ≠ NR threshold

energy escapes critical radius via:

track length, scintillation, electron thermalization or drift, phonons, etc…

Efficiency: NR's probability to create bubble

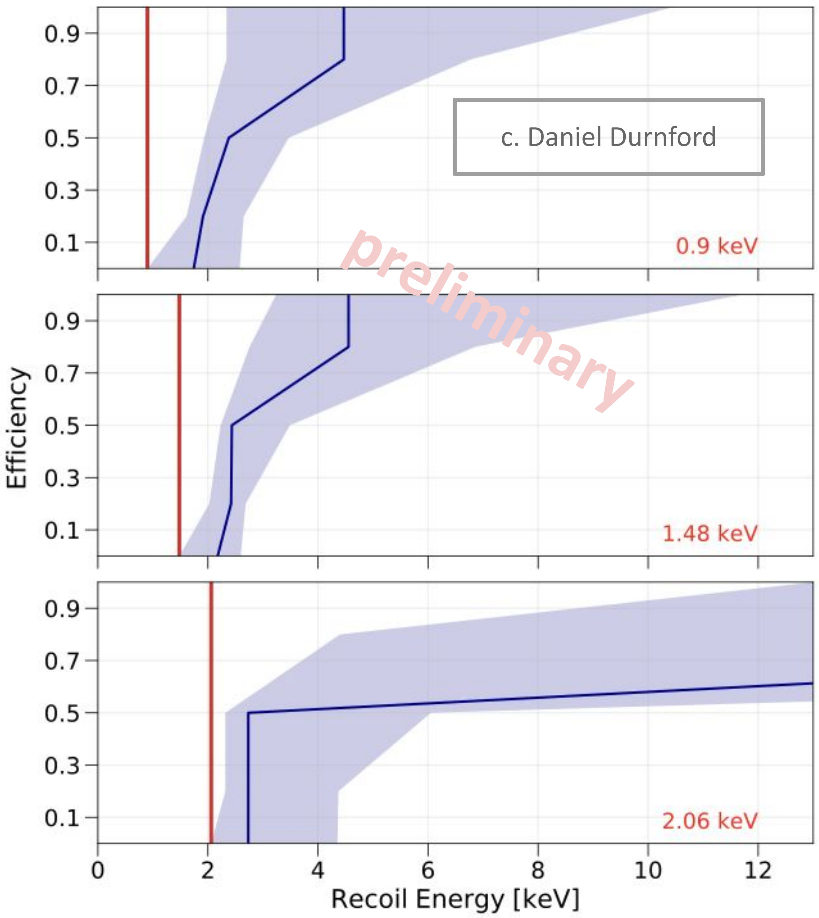
Xenon nucleation efficiencies!

relate closely to E_{NR}

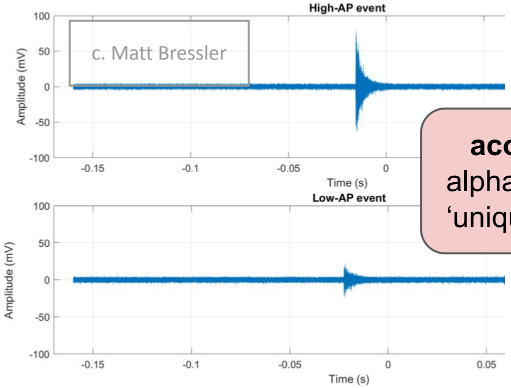
three different Seitz thresholds

(credit to Daniel Durnford. paper coming soon)

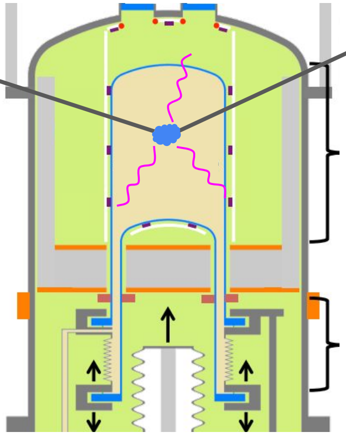
must repeat for Argon using SBC LAr10



Physics Reach - Discrimination and Veto



acoustics
alphas sound 'unique'



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

ER vs NR
discrimination is binary
bubble or no bubble!

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

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

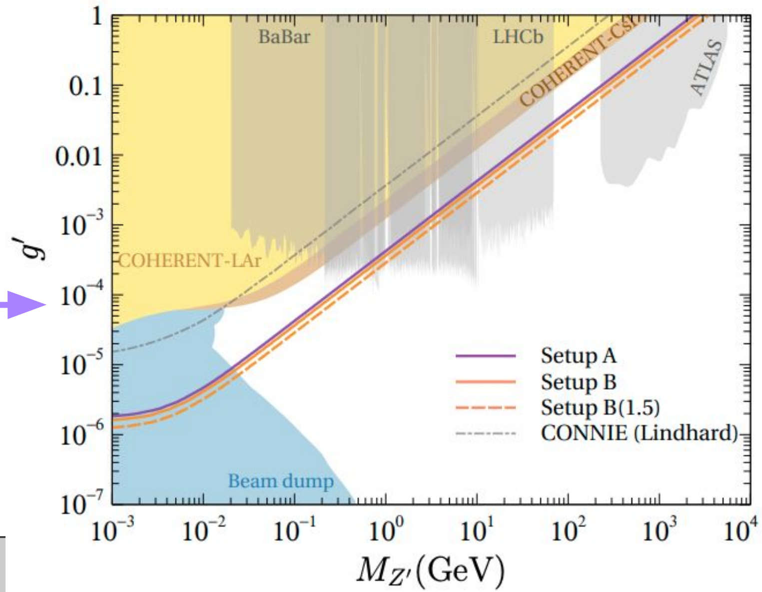
Physics signal (or bkg)
bubble and no light

Physics Reach - Reactor CEvNS

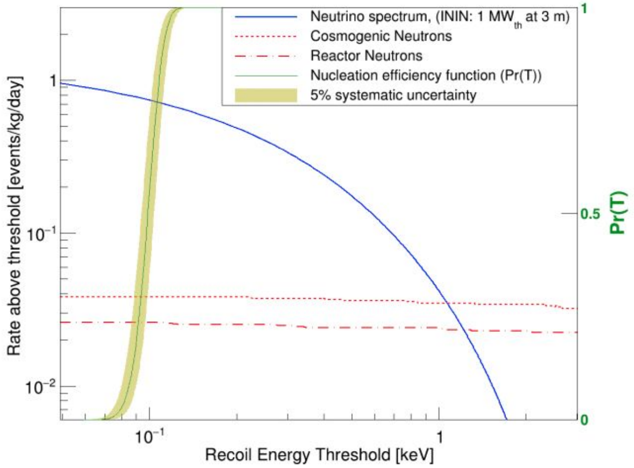
Test SM via CEvNS cross-section

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

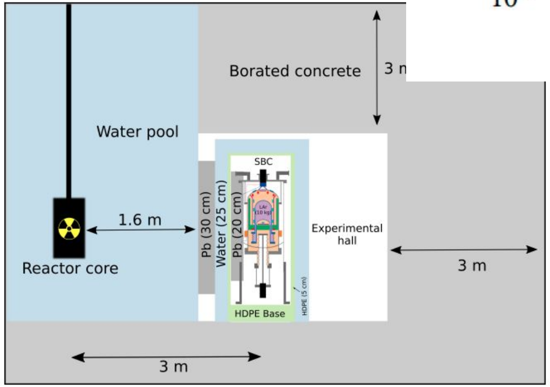
see more arXiv:2101.08785



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, 100 eV threshold

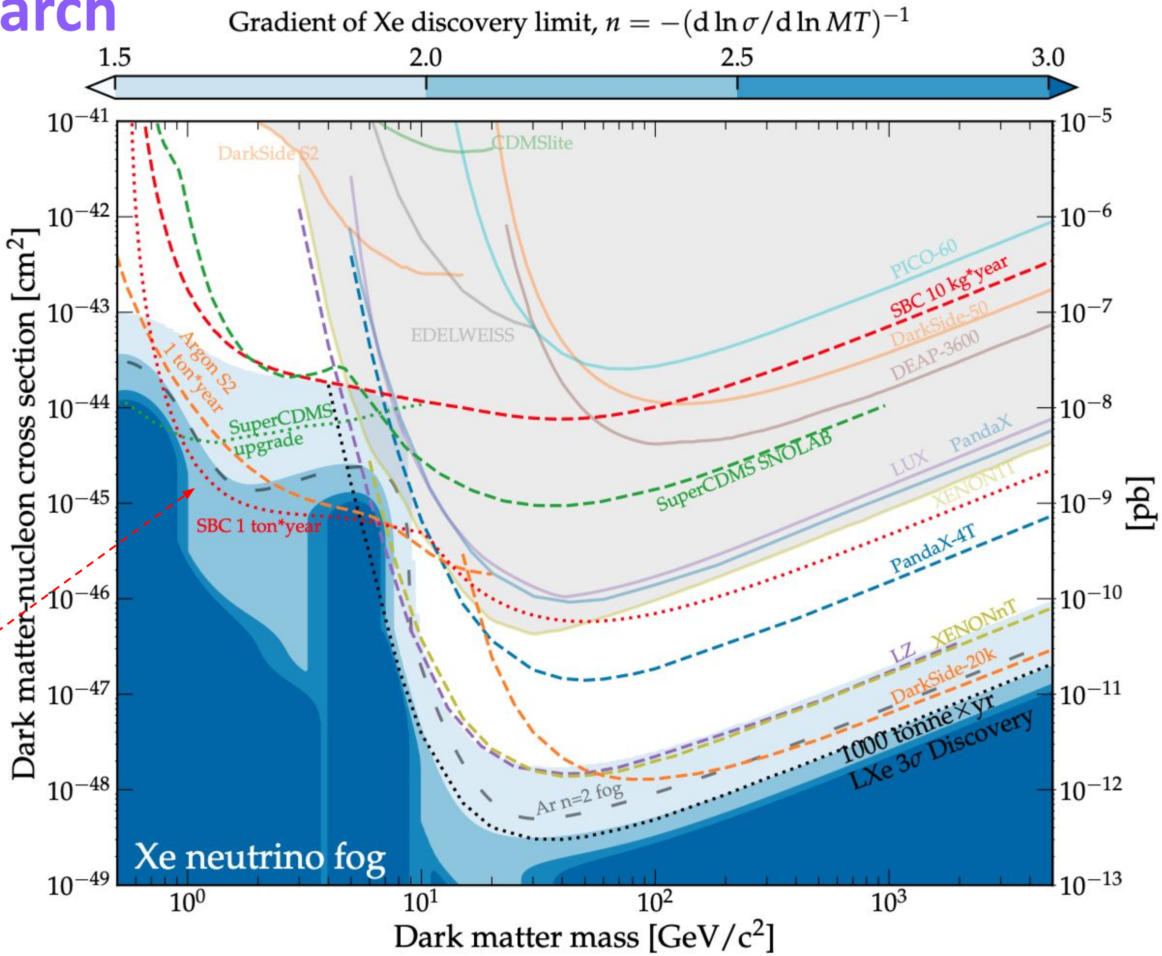
'Standard' halo parameters - arXiv:2105.00599

2.5 background CEvNS events

10 keV scintillation veto

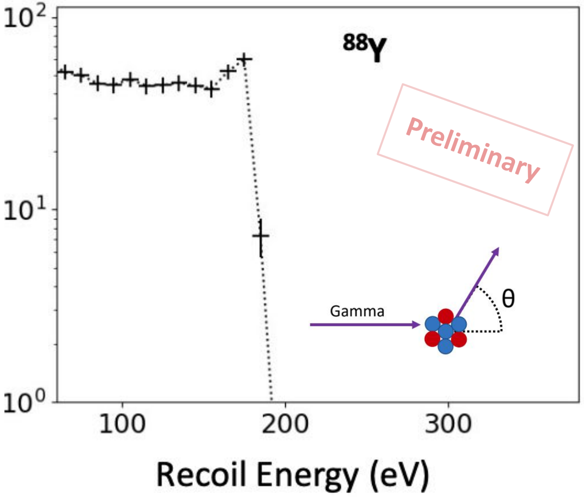
very scalable technology! (see PICO 500)

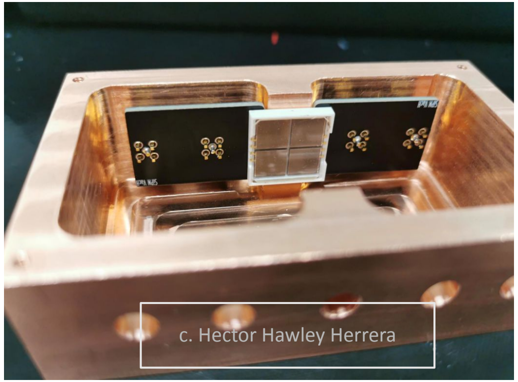
1 ton year reaches neutrino fog (1-10 GeV)

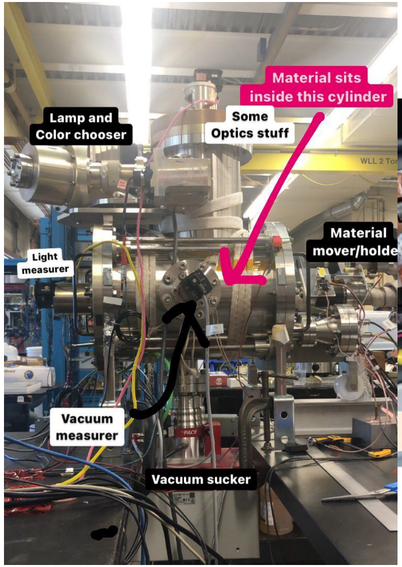


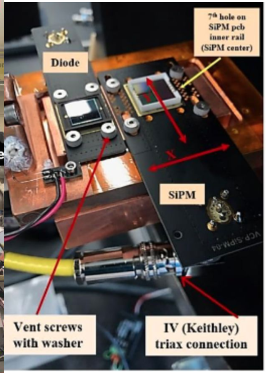
(from SNOMASS cosmic frontier white paper, arXiv:2203.08084)

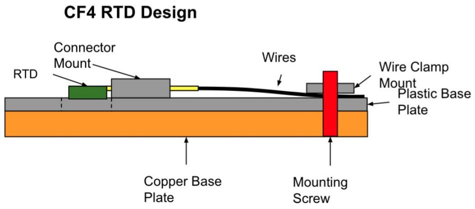
and much more!



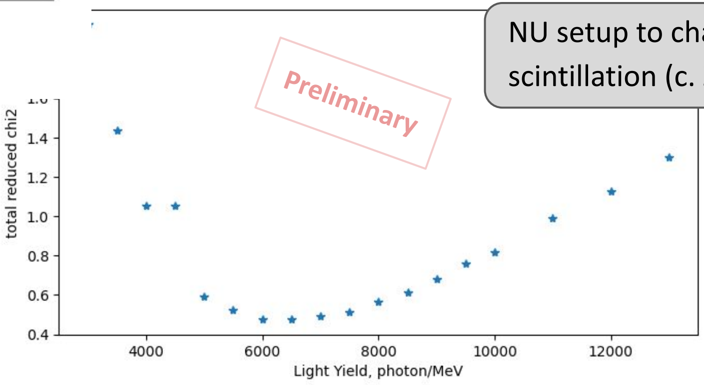




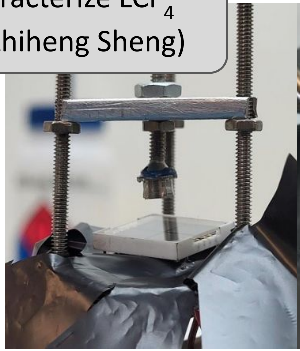


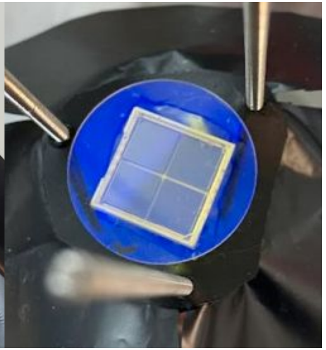


c. Gary Sweeney



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





Exciting two years on horizon!

In Summary:

- Full detector nearing completion!
- Calibration to begin this winter (Fermilab)
- exciting and broad research potential:

  from signal production to DM search

SBC white paper: arXiv:2207.12400v1

Interesting questions and challenges:

- (when) do ERs start nucleating? (Electric field, doping)
- xenon doping homogeneity and photo efficiency
- pressure trigger and DAQ challenges (LEDs vs SiPMs)
- scintillation (CF_4) veto
- accuracy of background model, etc…

SBC Collaboration


SBC collaborators
(Fermilab, April 2023)

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

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

Measuring Low E Light Yields in Argon

Typical LY experiment: excellent photo-collection efficiency, *uncertainty in NR rate*

In SBC:
lower photo efficiency, but know NR rate ~100%
'how often do we see excess photon proceed a bubble'

takeaway: with realistic numbers and careful tuning, can measure NR LY at 300 eV in Ar

Calibrate NR response with gamma source

T_{Bubble} ~ 60s (one bubble a minute)
P_{NR} ~ 1e-6 (gamma induced NR prob)
P_{ER} ~ 0.30 (gamma competition prob)

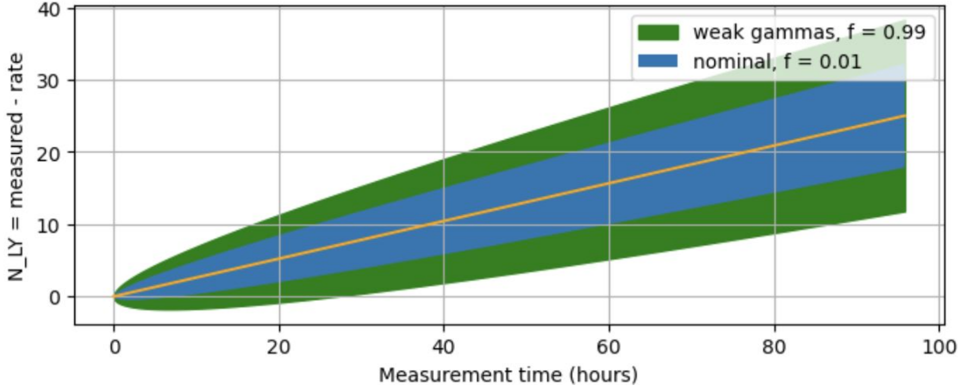
$R_{gamma} = 1/T_{bubble}\ 1/P_{NR}$ ~ 16.6 kHz

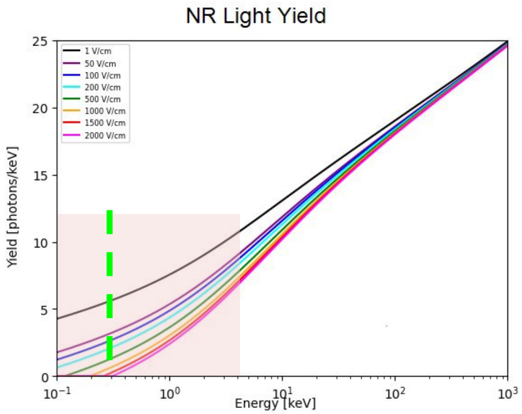
(Gamma ER rate ~ 5kHz)**

$R_{ambient1PE}$ ~ 1kHz (background 1PE events)
f ~ 0.01 (fraction ERs giving 1PE)

T_{ac} ~ 10us (time resolution of bubble)
PDE ~ 0.01 (photo detection efficiency)

$\langle LY \times E_{NR} \rangle$ ~ {2, 0} (physics we care about!)





Physics Reach - DM Search

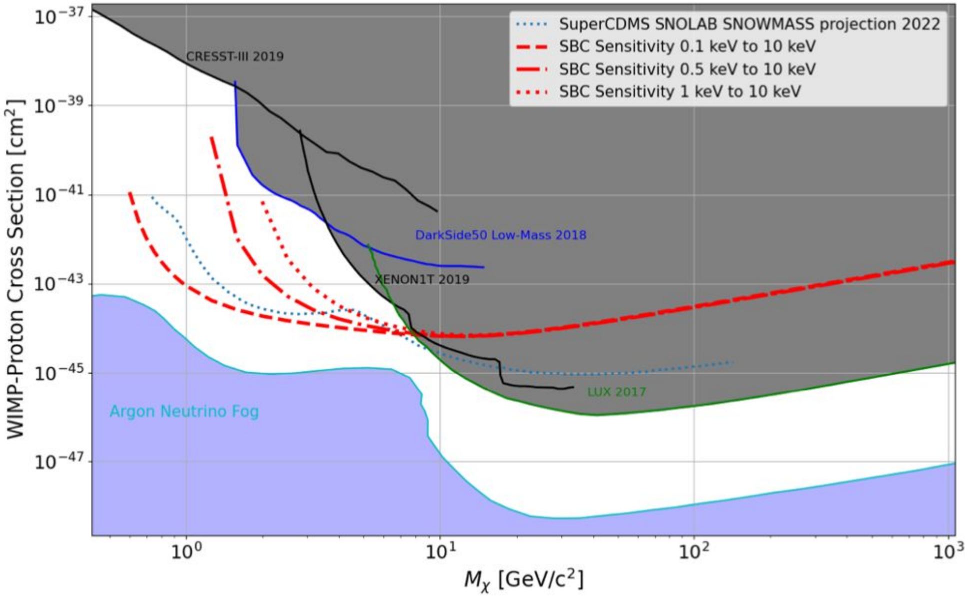
parameters

10 kg-year exposure

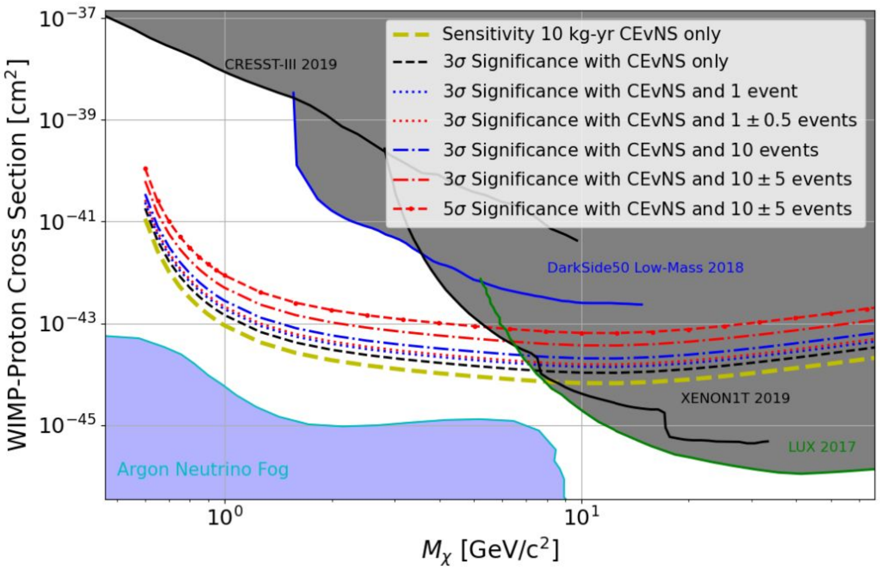
'Standard' halo parameters - [arXiv:2105.00599]

2.5 bkg neutrino CEvNS events

10 keV scintillation veto



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



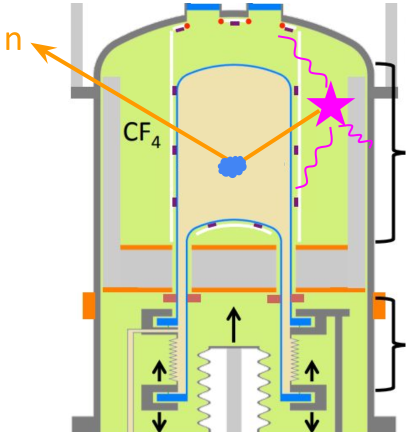
Sensitivity for 0.1 keV threshold, various material backgrounds scenarios

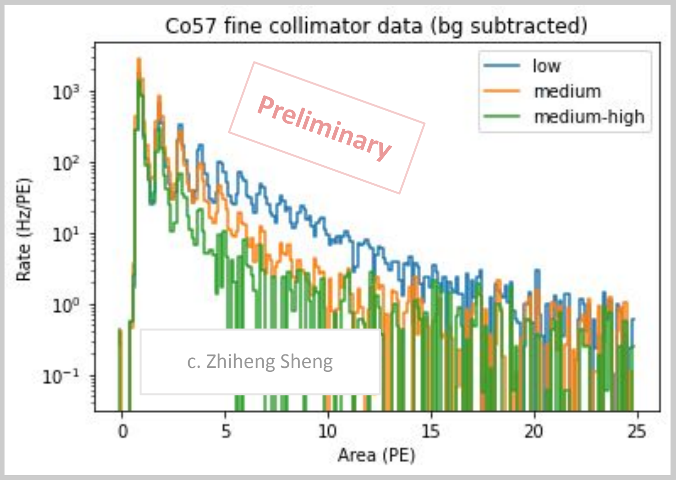
all from Matt Bressler's thesis

Backgrounds and CF_4

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

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

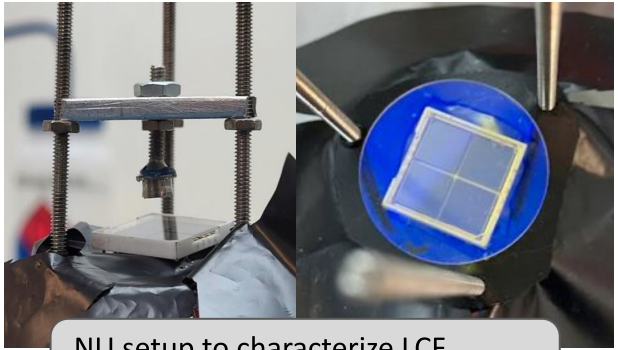




$^{19}F(\alpha, n)^{22}Na$ — ^{19}F(alpha, n)^{22}Na cross-section is large!

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!

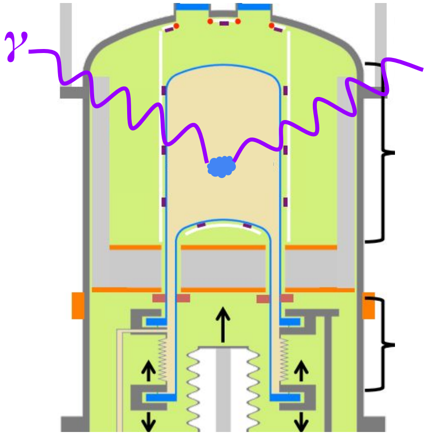


NU setup to characterize LCF_4 scintillation (c. Zhiheng Sheng)

Uncommon background - Gamma induced NR

Bkgs within 'Physics signal' region:

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



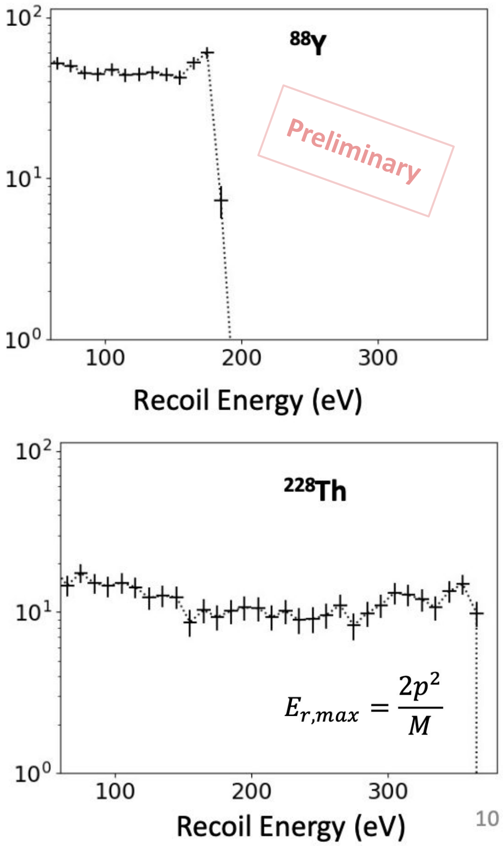
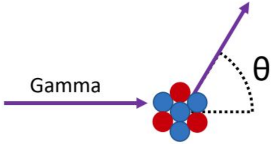


Photo-Nuclear elastic scattering

- 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 ∝ 1 + $\cos^2\theta$

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)

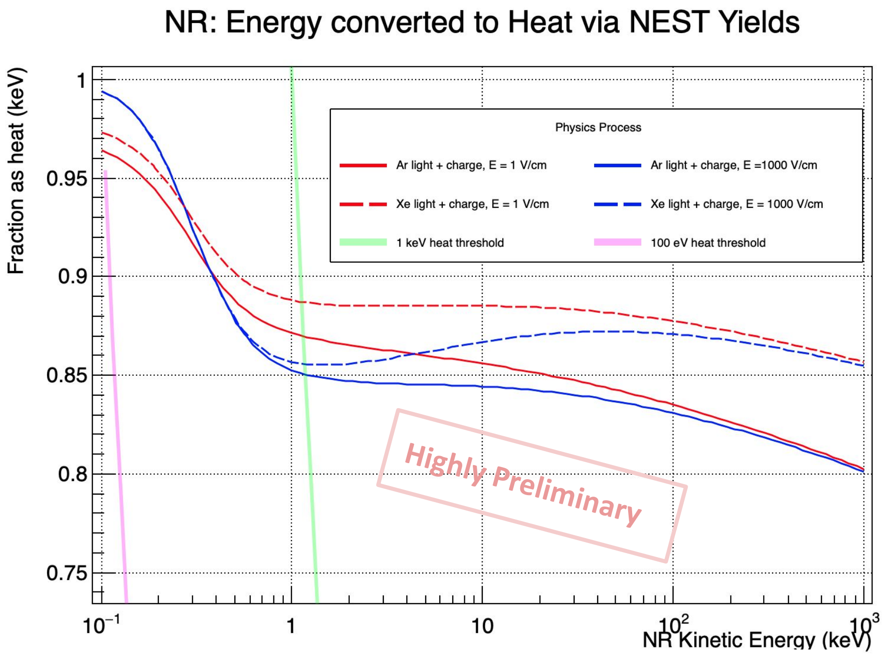
$$E_{heat} = K - N_{PE} \times E_{photon} - N_{e-} \times (E_{gap} + E_{ion})$$

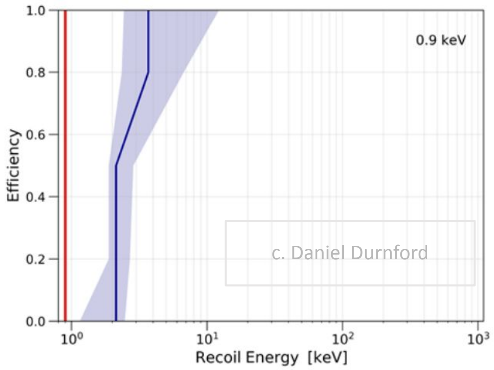
Assumptions in toy model calculation

- 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)





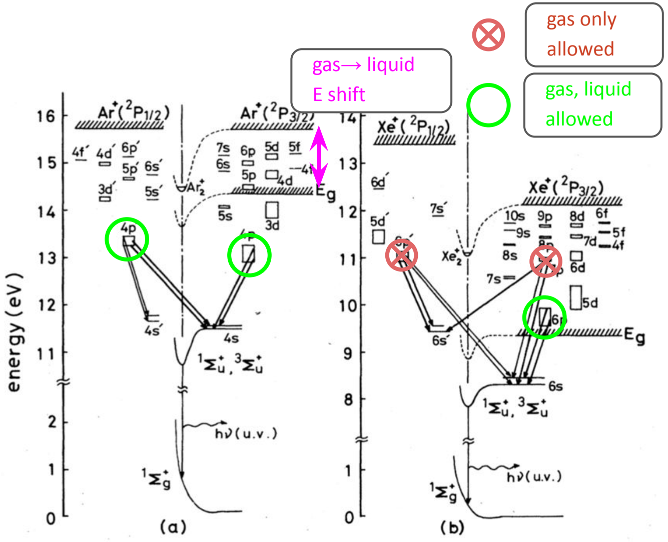
Note on signal production

Recombination is different between Ar/Xe

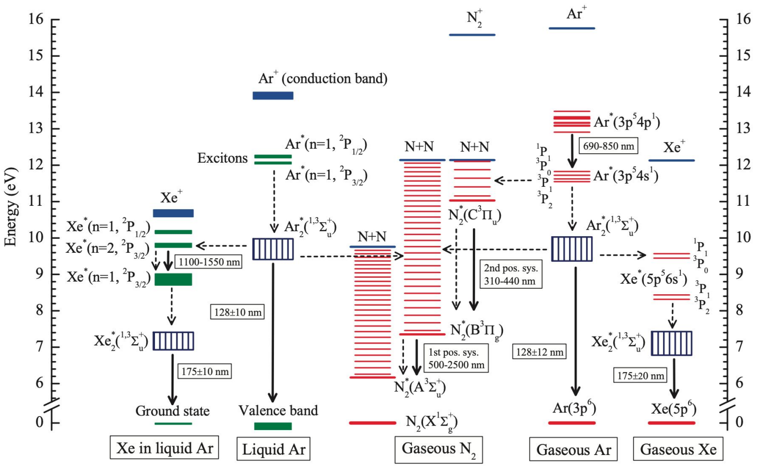
- faster/easier in Ar
- produces additional local heat (via dissociation)
- **test ER nucleation with few 100V/cm field**

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