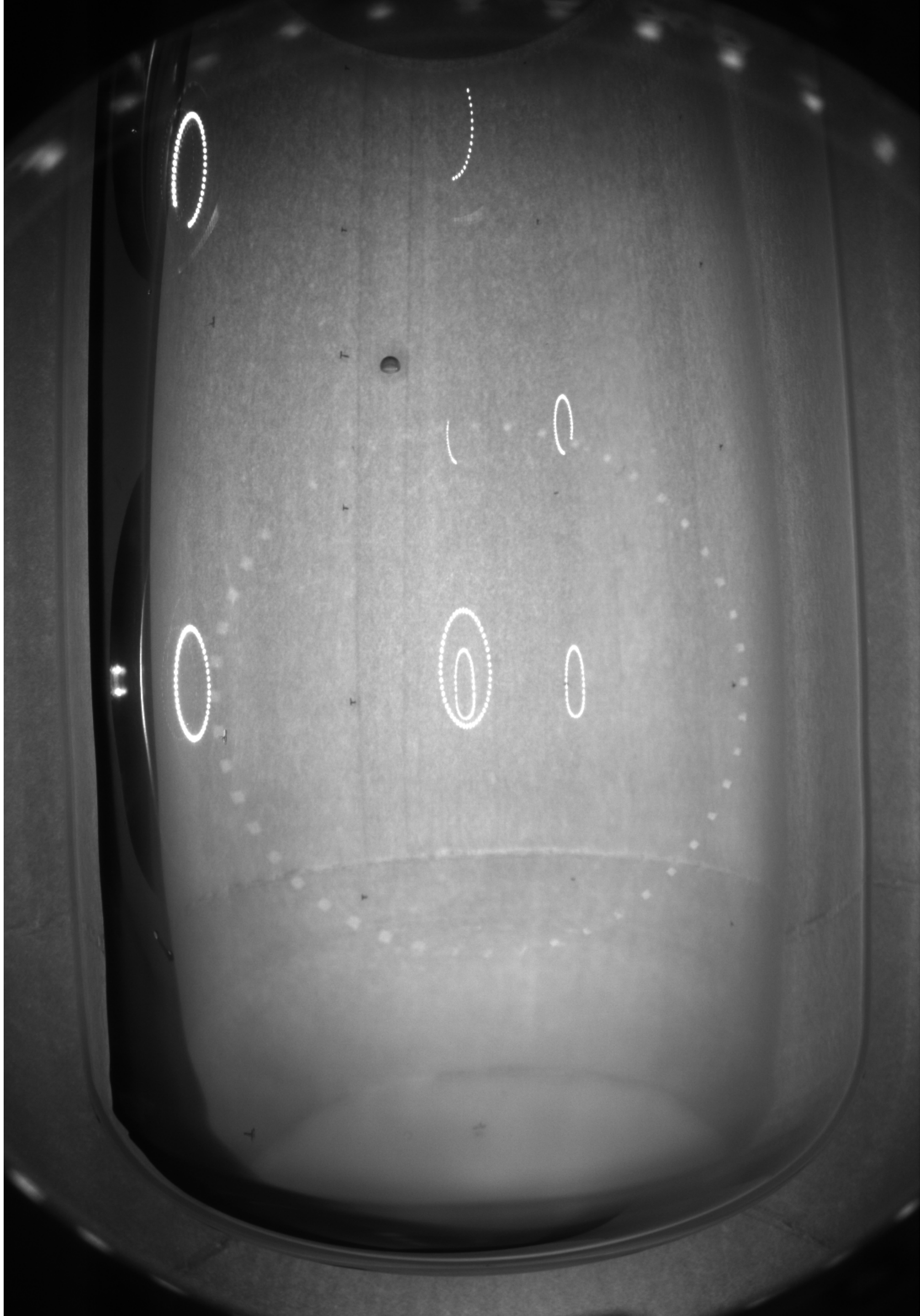
# Updated Dark Matter Search Results from the PICO-60 Bubble Chamber



Orin Harris
Northeastern Illinois University

Oct 22 at DBD18

# PICO

Northeastern Illinois University
O. Harris

České vysoké učení technické v Praze
R. Filgas, I. Stekl

KICP – Kavli Institute for Cosmological Physics at The University of Chicago
J.I. Collar

Université de Montréal
S. Chen, M. Laurin, J.-P. Martin, A. Plante, A.E. Robinson, N. Starinski, F. Tardif, D. Tiwari, V. Zacek, C. Wen Chao,

SNOLAB
I. Lawson

Indiana University South Bend
E. Behnke, I. Levine, T. Nania

Universitat Politècnica de València
M. Ardid, M. Bou-Cabo, I. Felis

Saha Institute of Nuclear Physics, Calcutta
M. Das, S. Sahoo, S. Seth

Drexel University
M. Bressler, R. Neilson

PennState
D. Maurya, S. Priya, Y. Yan

Fermilab
P.S. Cooper, M. Crisler, W.H. Lippincott, A. Sonnenschein

University of Alberta
C. Coutu, S. Fallows, C. Krauss, M.-C. Piro

Northwestern University
D. Baxter, C.E. Dahl, M. Jin, J. Zhang

IF
E. Vázquez-Jáuregui

Queen's University
B. Broerman, G. Cao, K. Clark, G. Giroux, C. Hardy, C. Moore, A. Noble

Pacific Northwest National Laboratory
I. Arnquist , C. Cowles, C.M. Jackson, B. Loer, K. Wierman

Laurentian University / Université Laurentienne
J. Farine, A. Le Blanc, C. Licciardi, O. Scallon, U. Wichoski

# PICO: merger of **PI**CASSO and **CO**UPP Collaborations

main bubble chambers at SNOLAB + various test and calibration chambers

-2012 | 2013-2017 | 2018- | 2019-

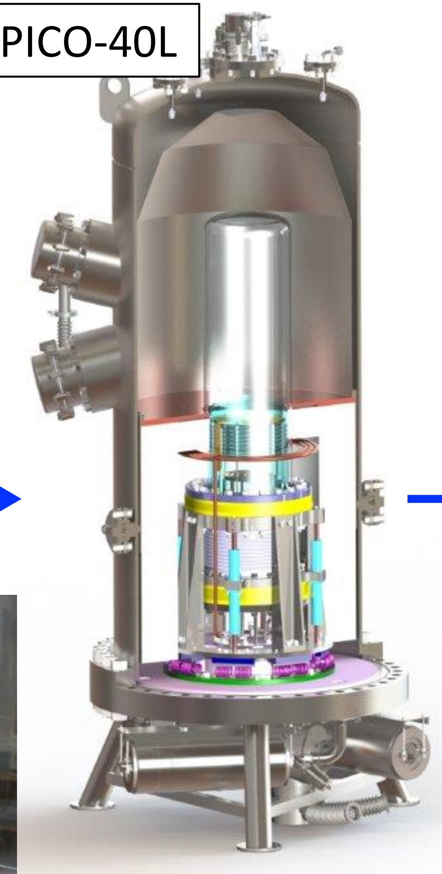
COUPP

PICASSO

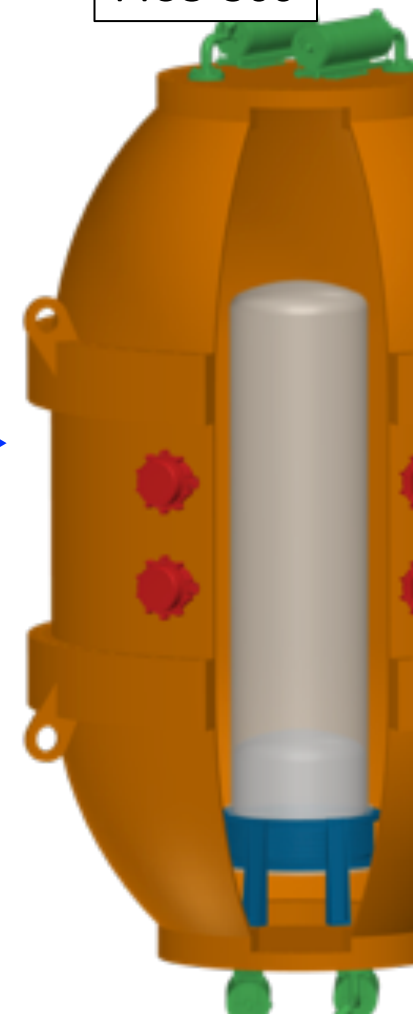
PICO-2L

PICO-60

PICO-40L



PICO-500



# Superheated fluid: Pressure & Temp → E, dE/dx threshold

- In a superheated fluid, bubbles will collapse unless they are large enough to overcome surface tension: must deposit $E_{th}$ in a radius less than $r_c$ → $E_{th}$, dE/dx threshold
- Threshold based on theory of Seitz (Phys. of Fluids I, 2 (1958))
  Classical Thermodynamics gives $E_{th}$, $r_c$ in terms of P, T (for a given fluid)

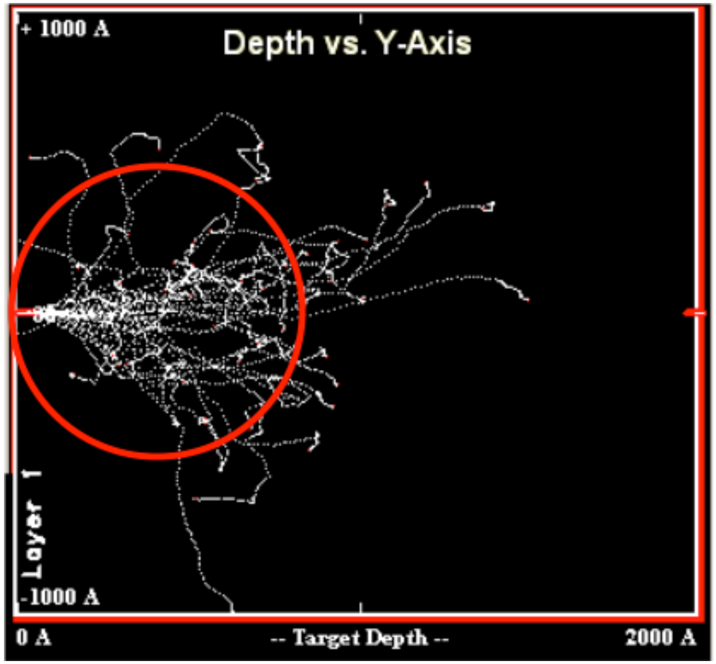
$$p_v - p_l = \frac{2\sigma}{r_c}$$

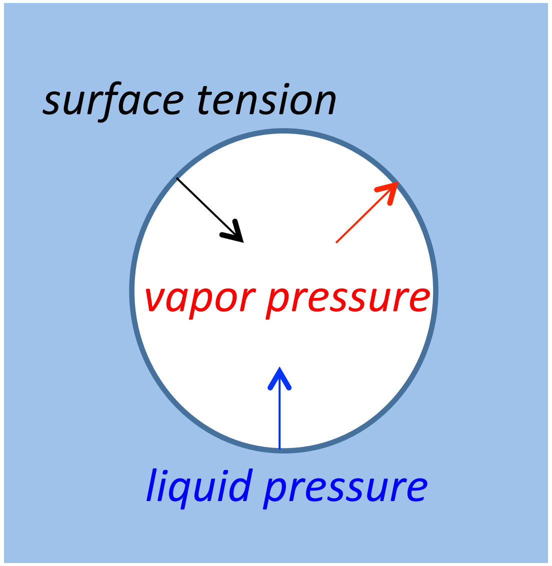
$$E_{th} = 4\pi r_c^2 \left(\sigma - T\frac{\partial \sigma}{\partial T}\right)$$

(surface energy)

$$+ \frac{4}{3}\pi r_c^3 \rho_v h$$

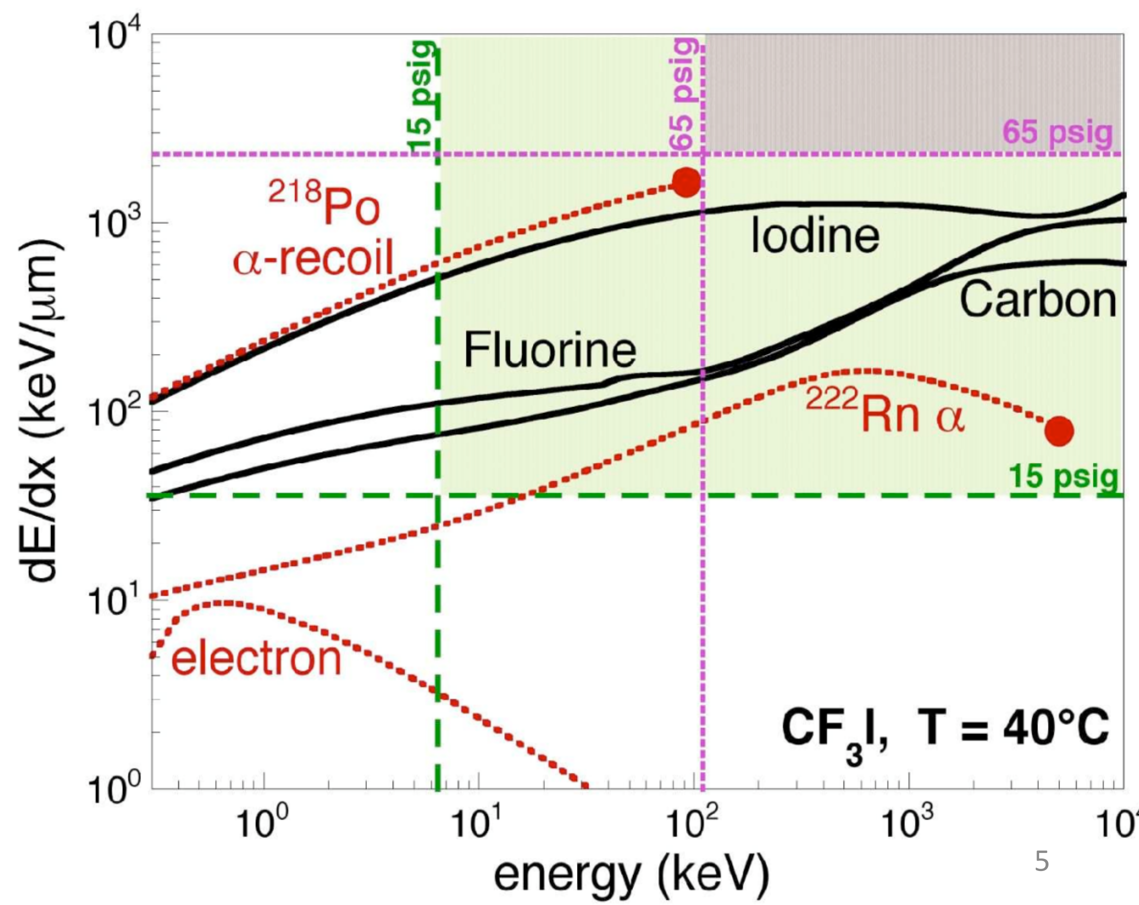
(latent heat)



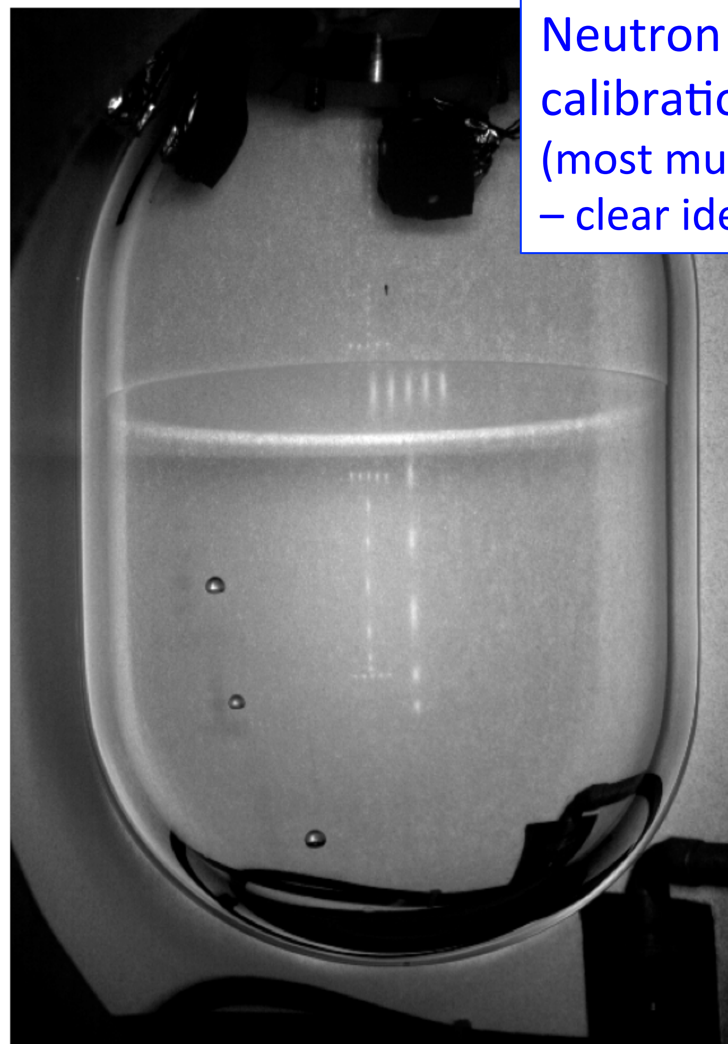
# Pressure & temperature define minimum energy, dE/dx threshold

By choice of thermodynamic parameters, sensitive to nuclear recoils but not electron recoils



# Pressure & temperature define minimum energy, dE/dx threshold

No analysis cuts
Simply don't see electron recoils

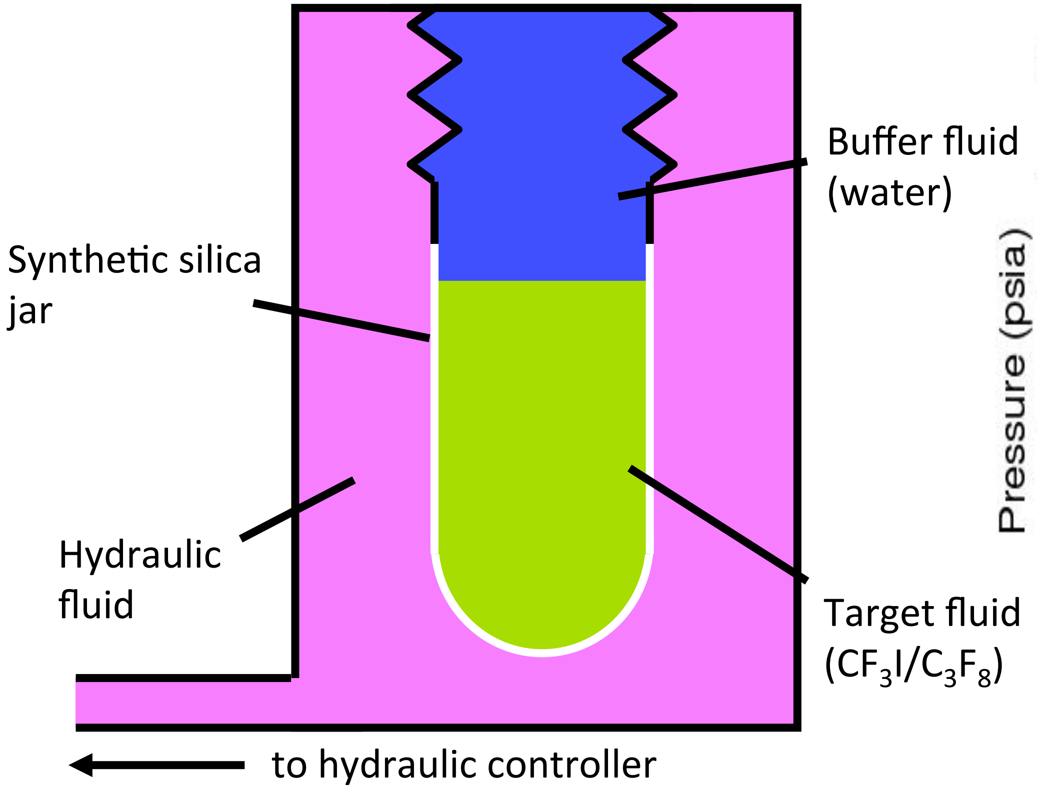


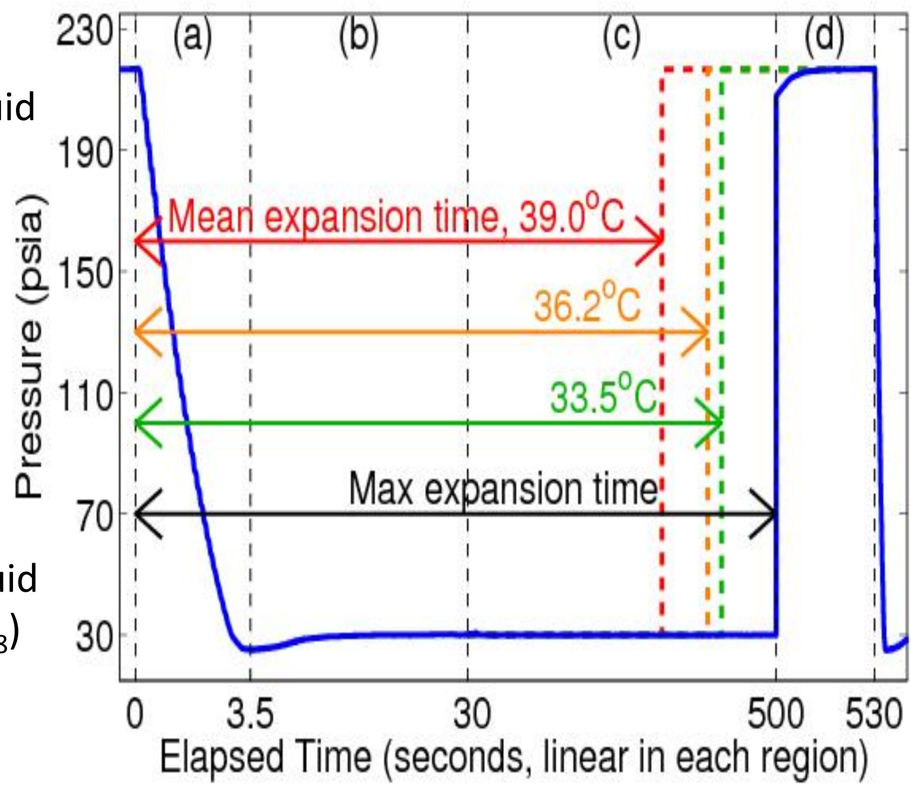
Neutron calibration event (most multiply scatter – clear identification)

# PICO bubble chambers

Pressure expansion puts target fluid in superheated state

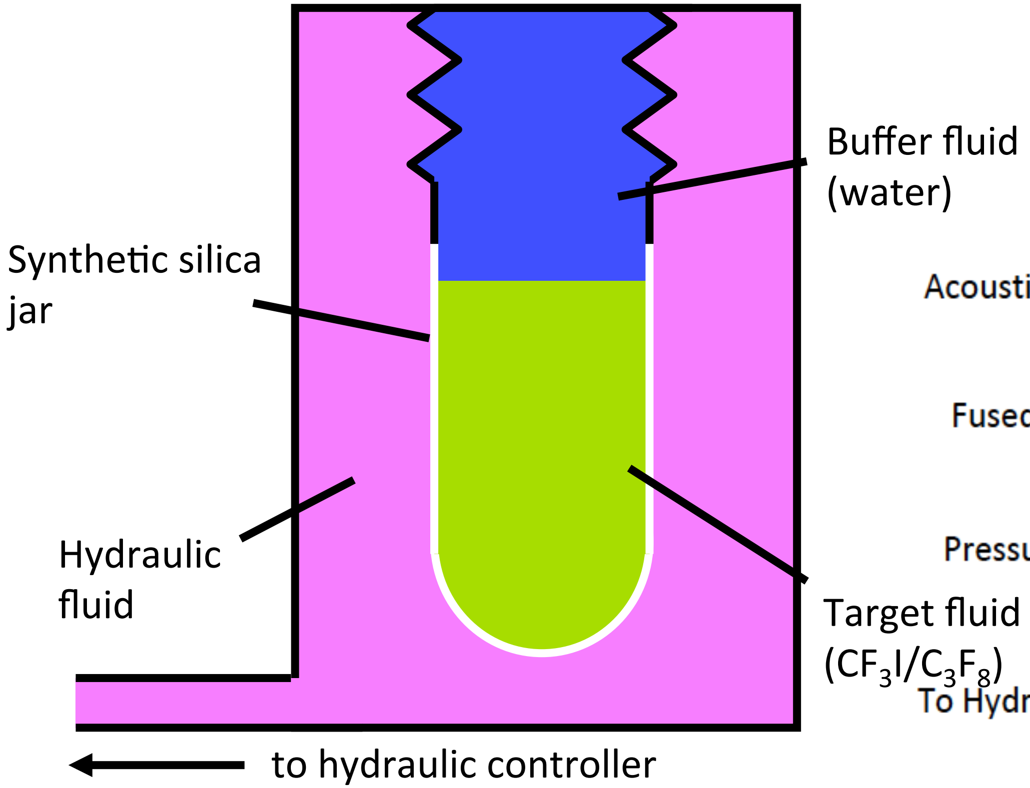
Wait for particle interaction to nucleate a bubble, recompress



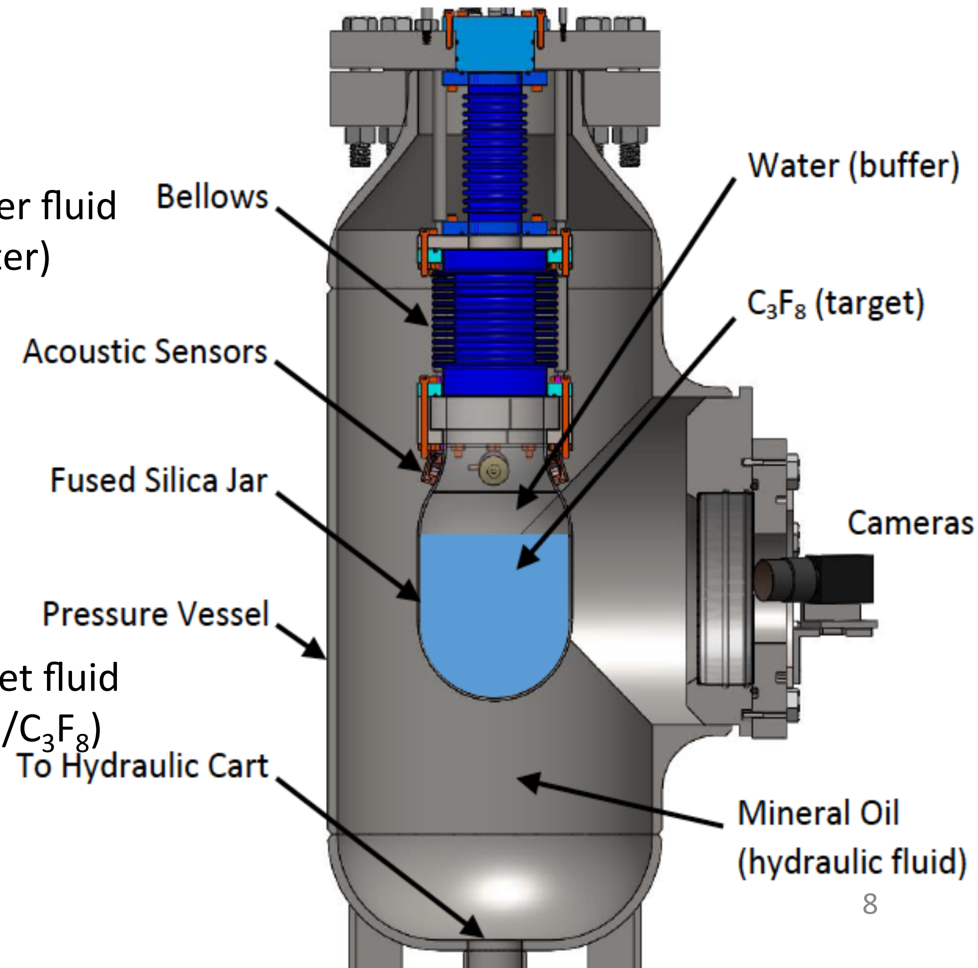



# PICO bubble chambers

Pressure expansion puts target fluid in superheated state

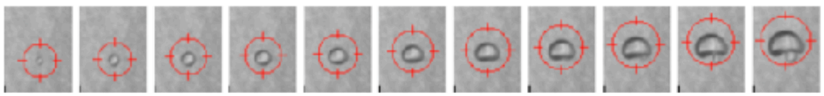


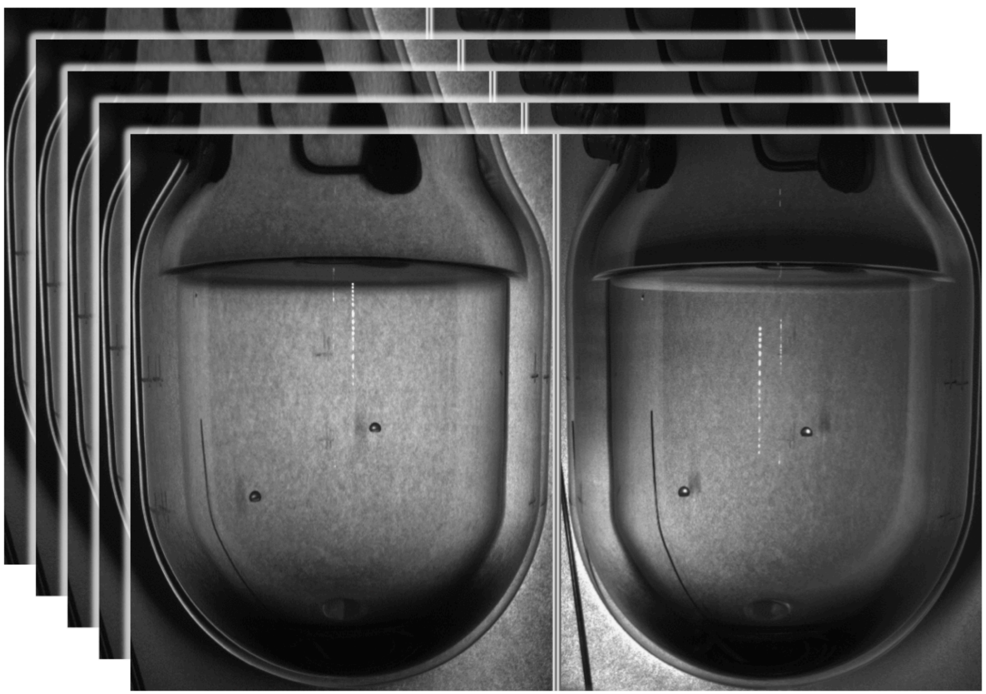

Example design: PICO-2L



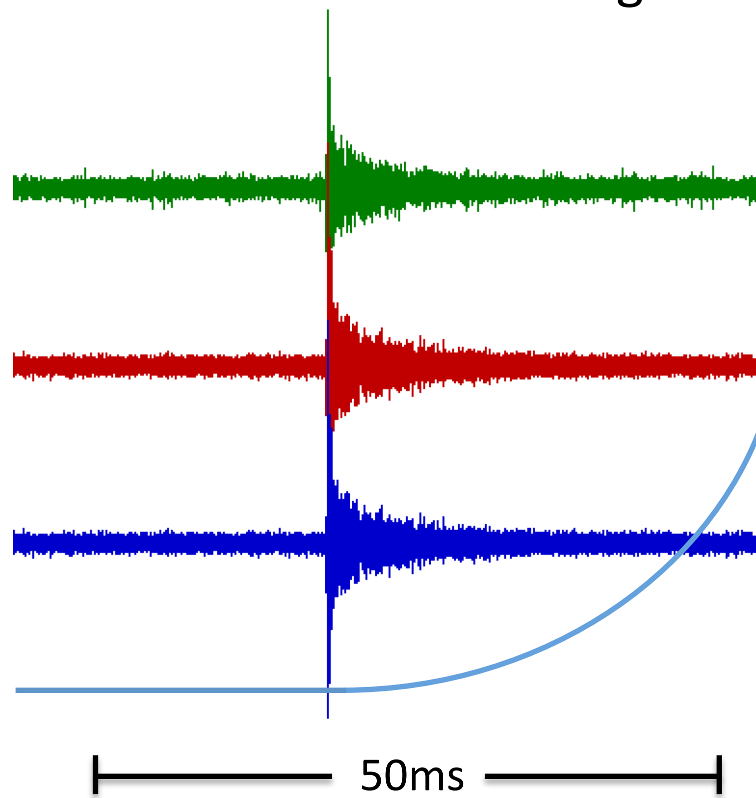
# PICO bubble chambers

Cameras capture stereoscopic bubble images @ 300 fps





Acoustic sensors & fast pressure transducer capture sound & pressure rise from bubble growth

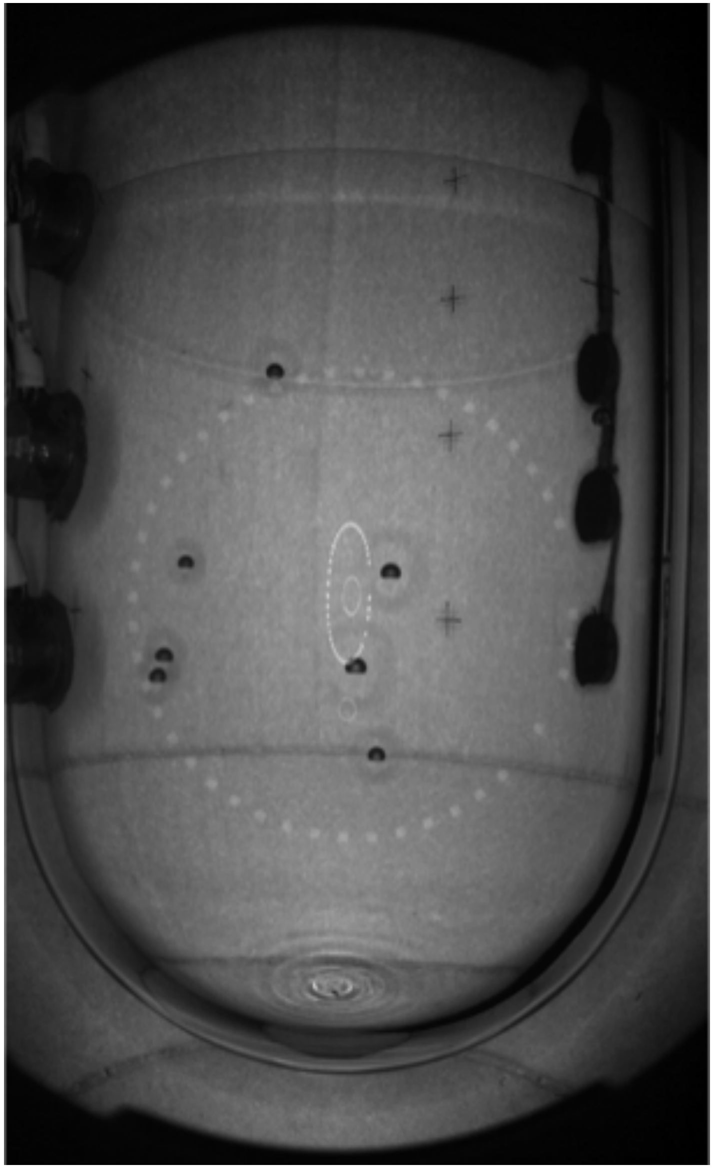


# Same basic design scales

Test tube
(2005, FNAL)

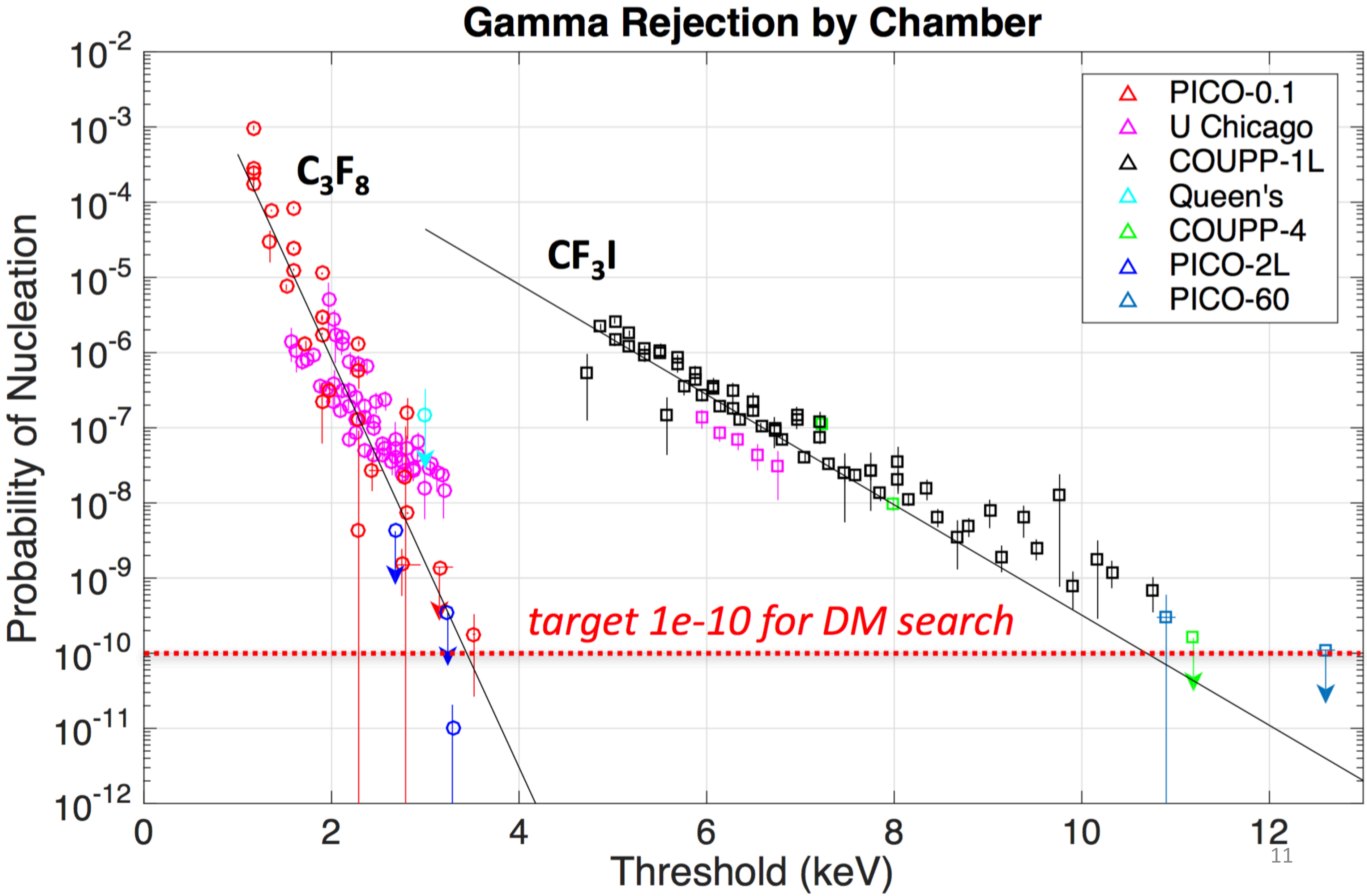
2 kg
(2007, FNAL)

4 kg
(2010, SNOLAB)



60 kg
(2013, SNOLAB)

# Electron recoil calibrations



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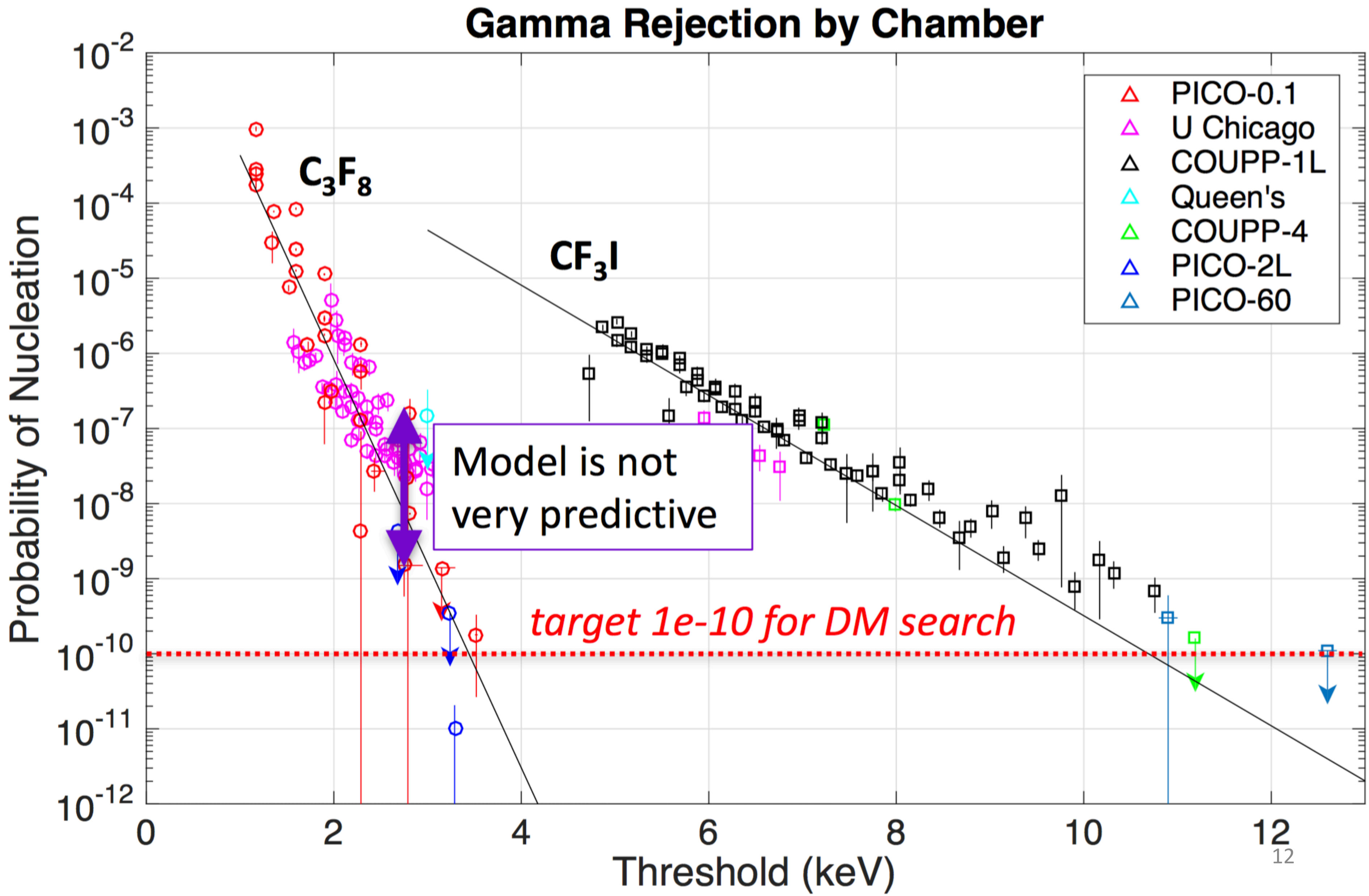
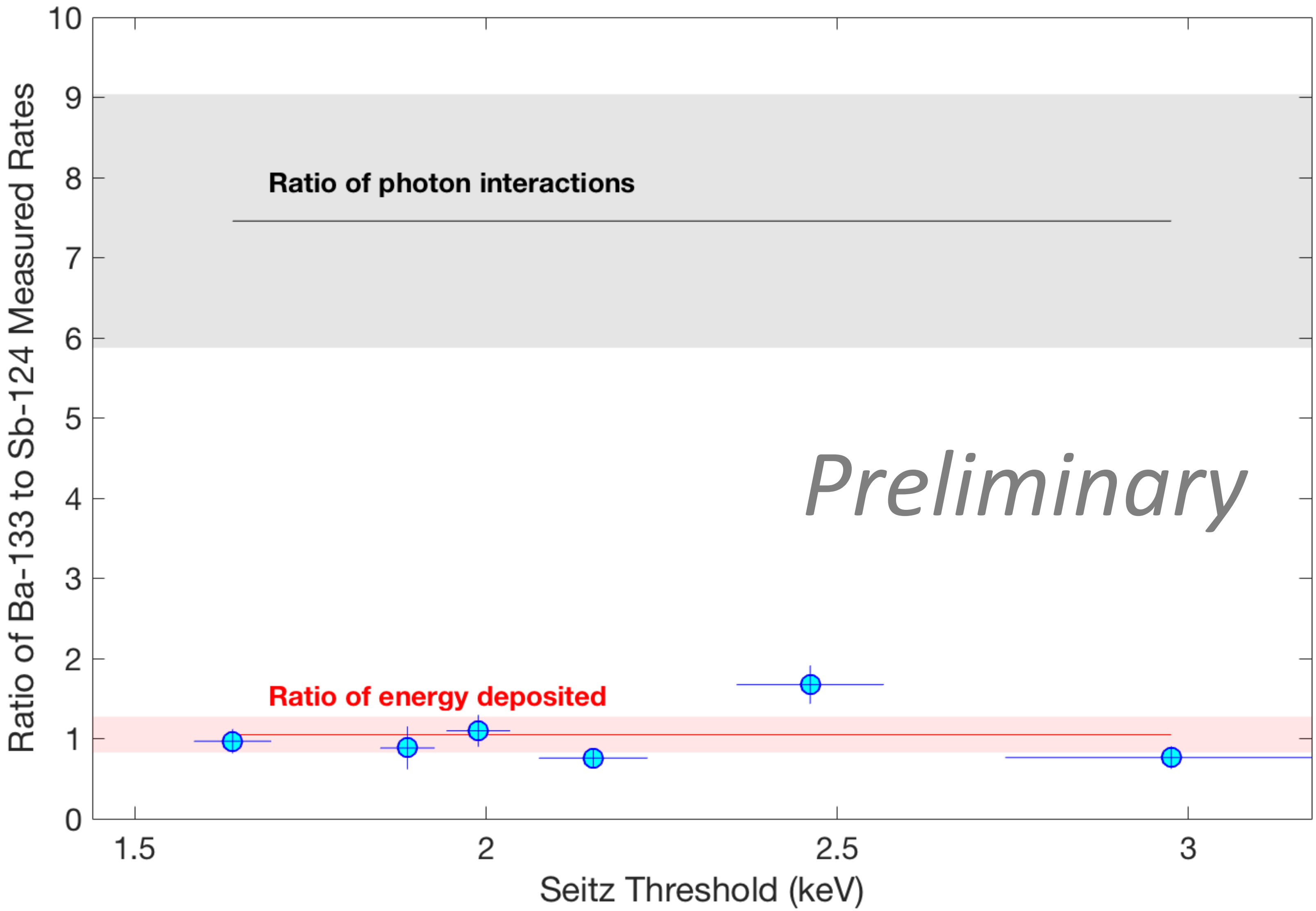


# Probability of nucleation (ER)

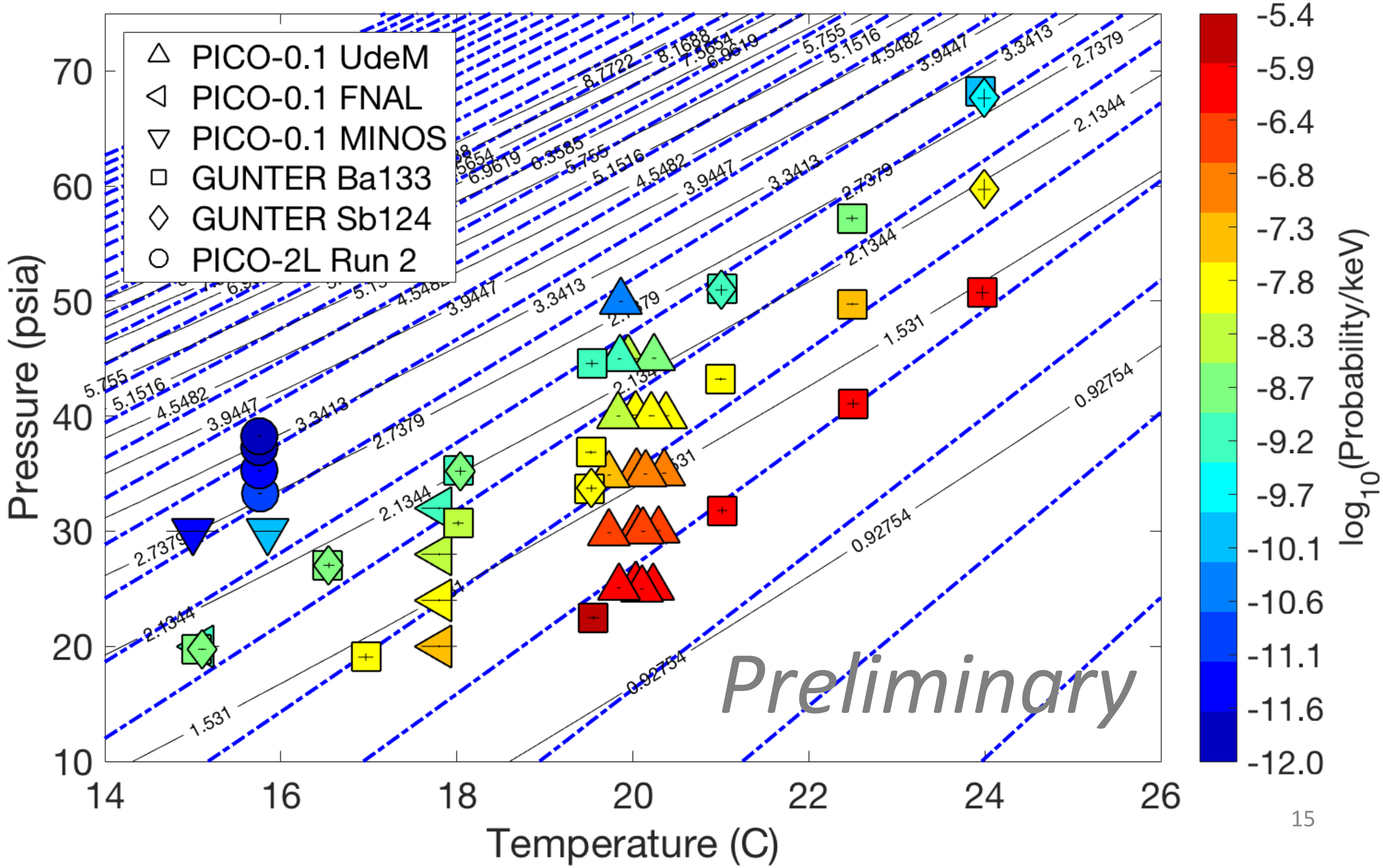
- Historically modeled as:
  - Each photon interaction has some probability to nucleate bubble
  - Caused by local heat deposition
  
  → nucleation rate scales with Seitz threshold (~keV)
- Work is in progress on a much more predictive model:
  - Each δ electron has probability to nucleate bubble (scales with energy deposited, not # photons)
  - Caused by cavitation (no vaporization required)
  
  → nucleation rate scales with minimum work (<100 eV)

# Electron recoil calibrations and new threshold model

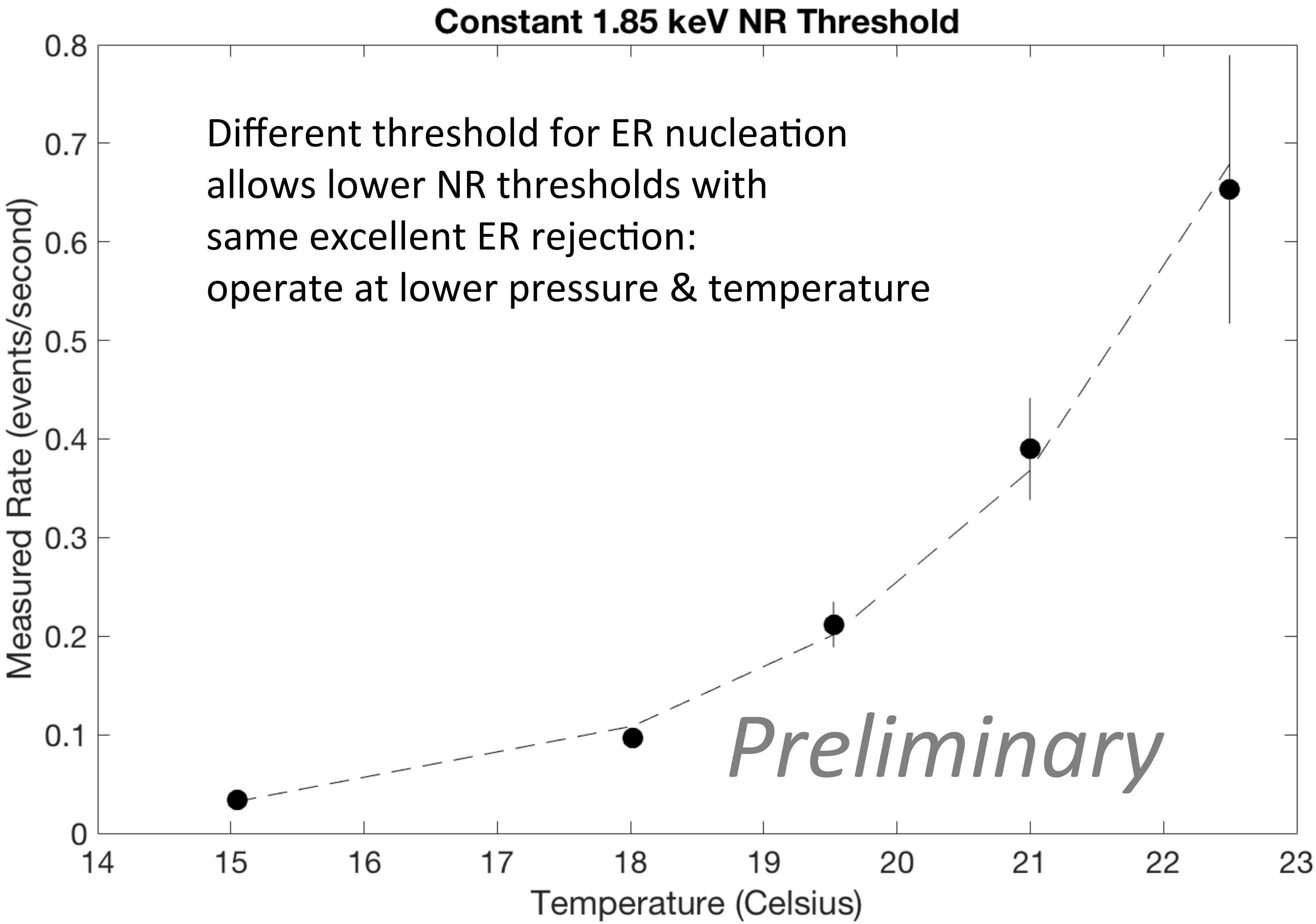


# Electron recoil calibrations and new threshold model

NR (heat) threshold ER (cavitation) threshold



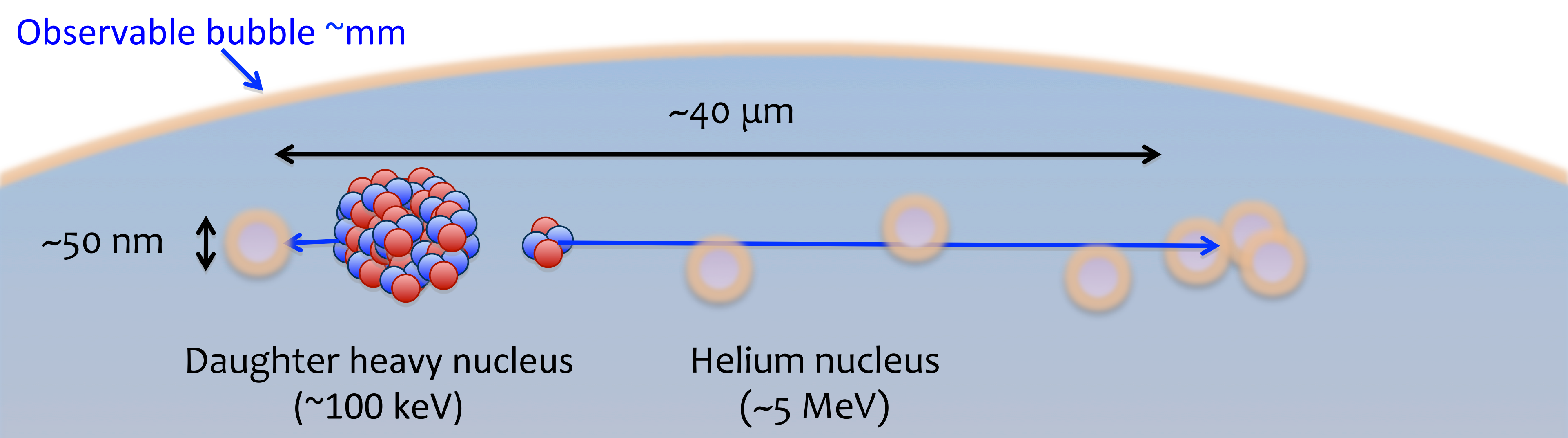
# Electron recoil calibrations and new threshold model



# What about backgrounds that nucleate bubbles? Acoustic discrimination

- Sound emission peaks at $r_{bubble} \approx 10\ \mu m$
- Clear acoustic signature of single nuclear recoil (< µm)
- Length scale of α track much larger (~40 µm)

  → separate nucleation sites → **α's several times louder**



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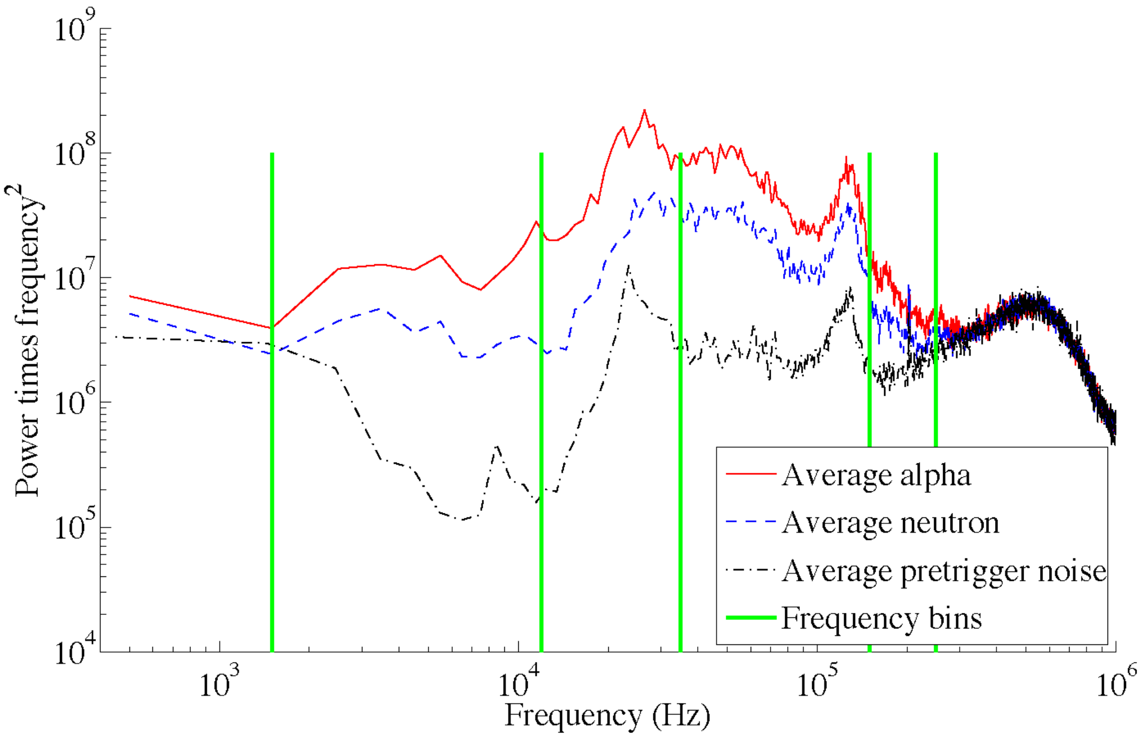
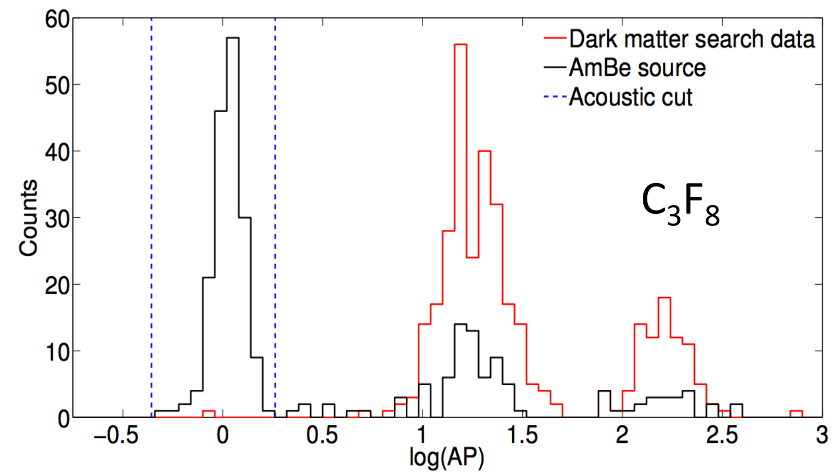
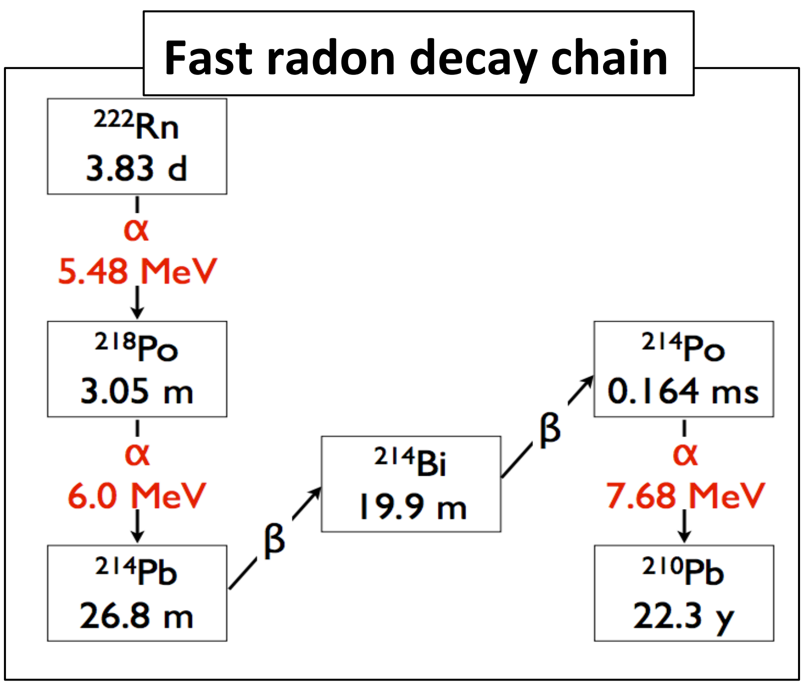


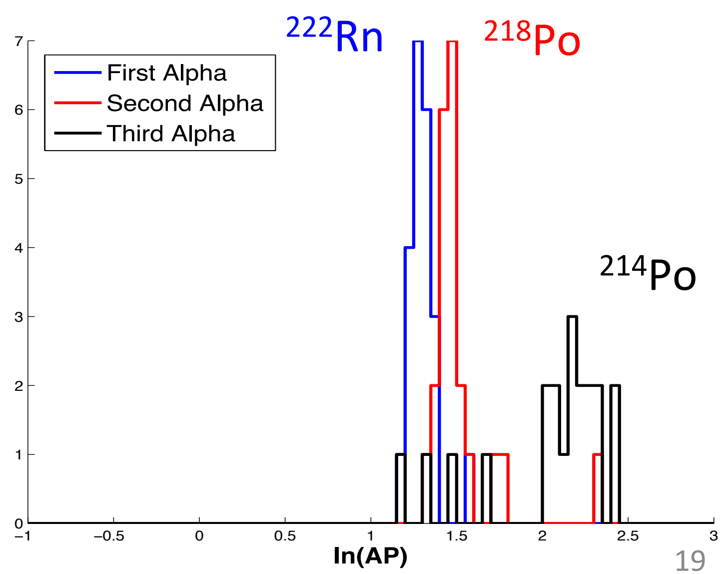
# Acoustic "Calorimetry"

- Multiple distinct alpha peaks, clearly separated from nuclear recoils
- Timing of events in high AP peaks consistent with radon chain alphas, and indicate that the higher energy $^{214}Po$ alphas are significantly louder




Radon α triplets selected by timing:



# Choice of nuclear target

- Interaction rate depends on how the dark matter couples to quarks/gluons in target nuclei
  - Z, higgs, squark exchange, **model dependent**
- Broadly: spin-independent vs spin-dependent

$$C_A^{SI} \propto A^2 \qquad\qquad C_A^{SD} \propto (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2$$

But can go deeper – see previous talk (Haxton)
WIMP-nucleon EFT: prefer diversity of nuclear targets

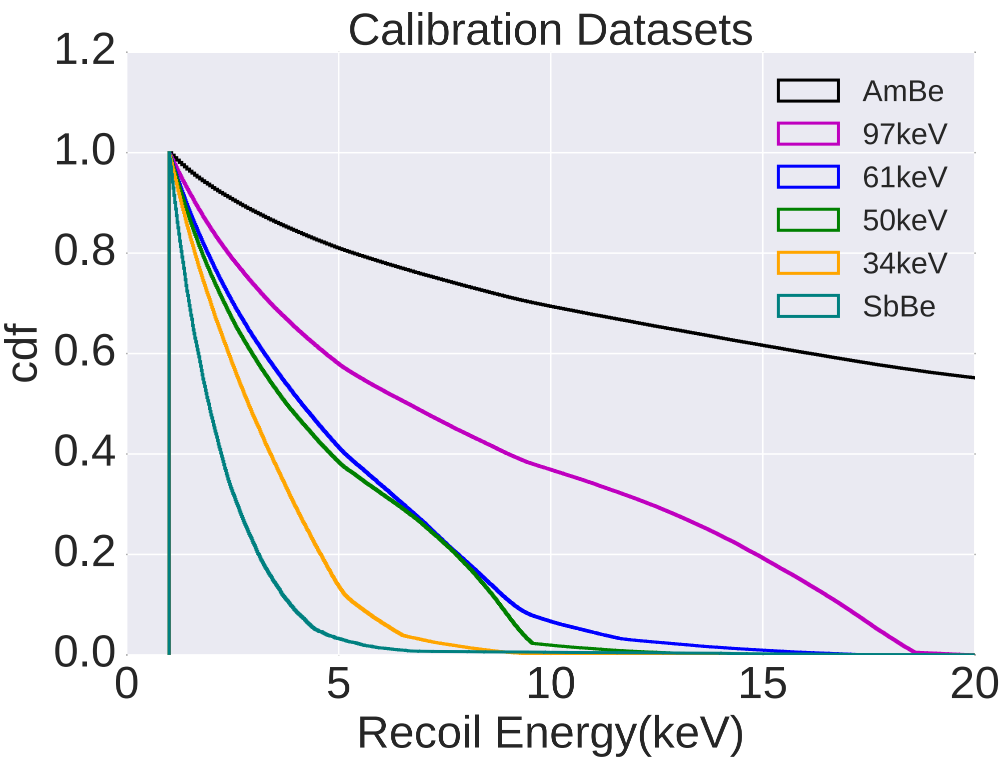
- PICO's heavily flourinated targets ($CF_3I$, $C_3F_8$) give excellent spin-dependent sensitivity
  - Unpaired proton; *More* rather than *heavier* nuclear targets
- Ability to change target in same detector
(refridgerants don't require cryogenics, but nearly any nuclear target possible)

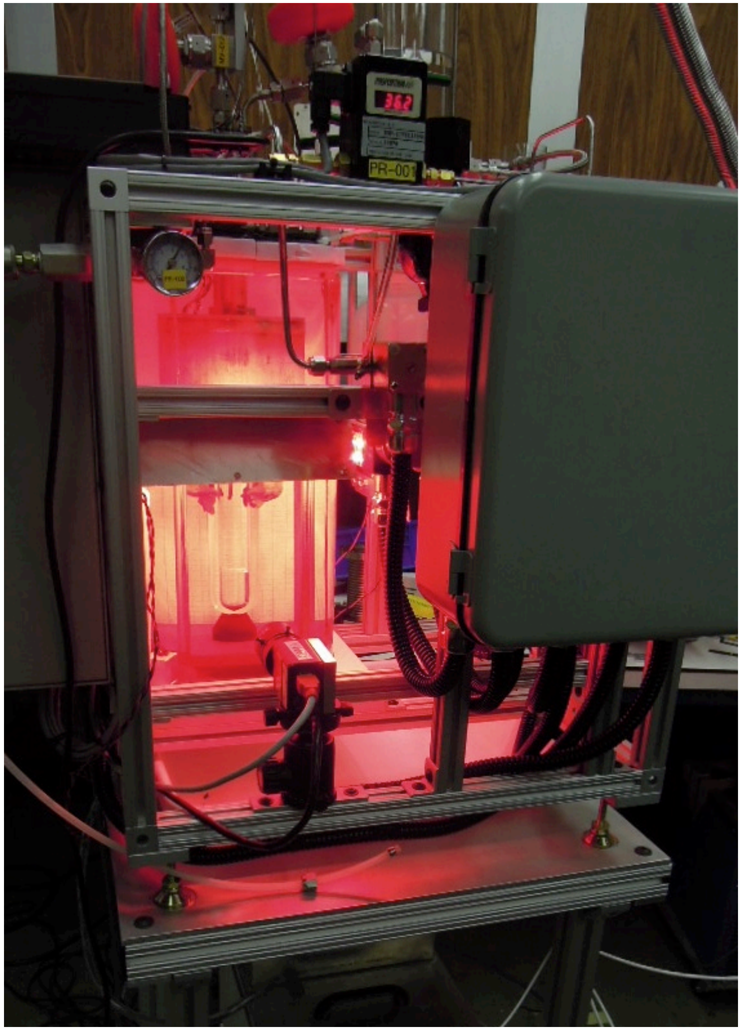
# Low energy neutron calibrations

Monoenergetic neutrons

Tandem Van der Graaff at U. de Montréal: Resonances in $^{51}V(p,n)^{51}Cr$

$^{124}SbBe$ photoneutron source
1,691 keV $\gamma$ → 24keV neutrons

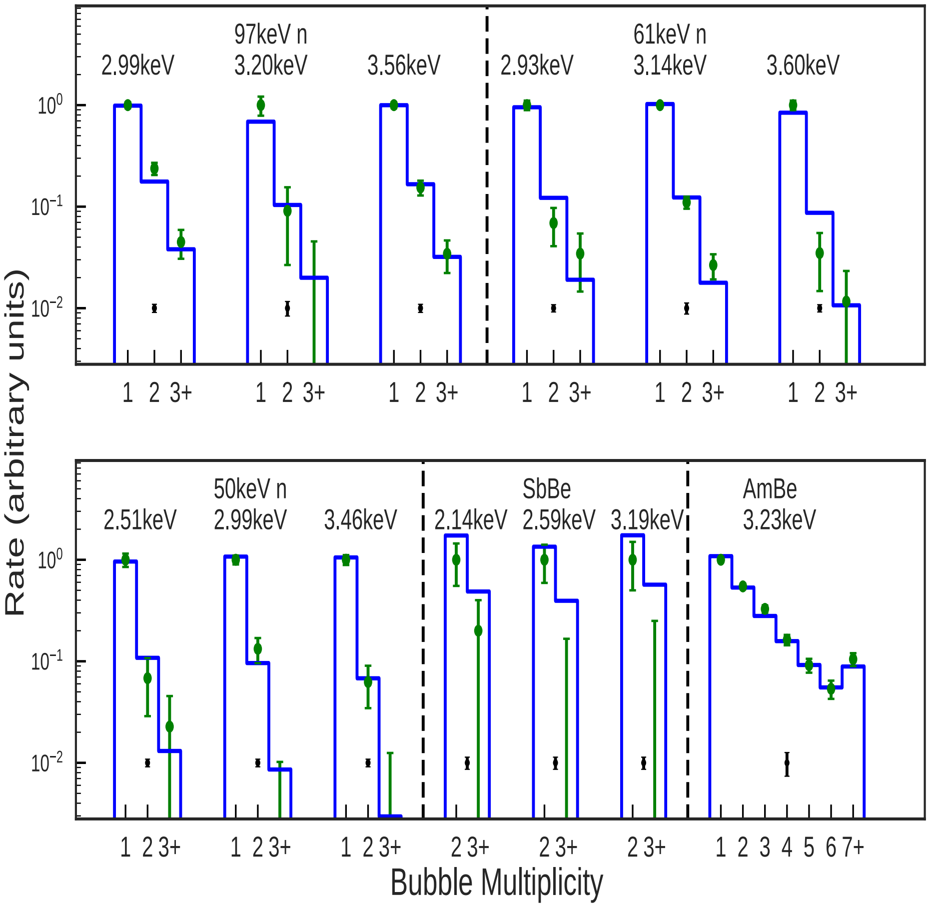


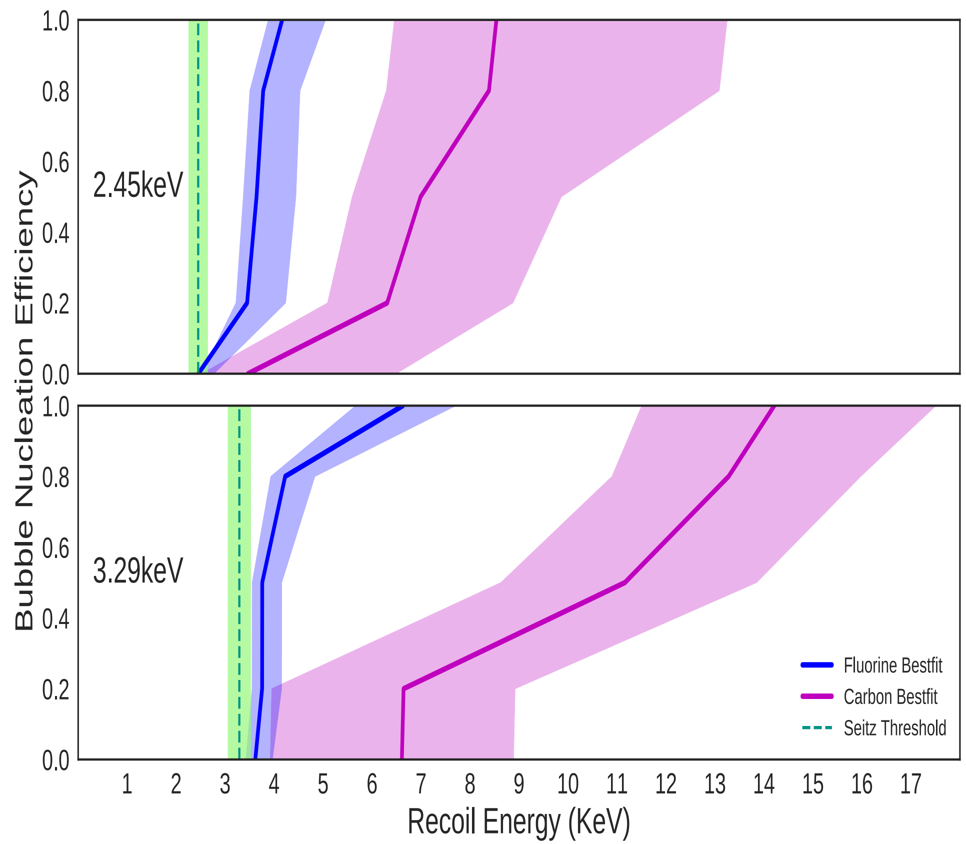



PICO-0.1

# Nucleation efficiency fits and curves

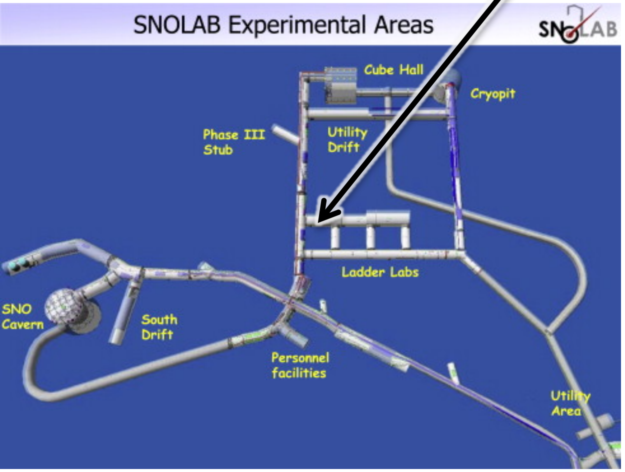
Thermodynamic Seitz threshold only used as guide
Calibrations constrain sensitivity to Flourine recoils below 3 keV



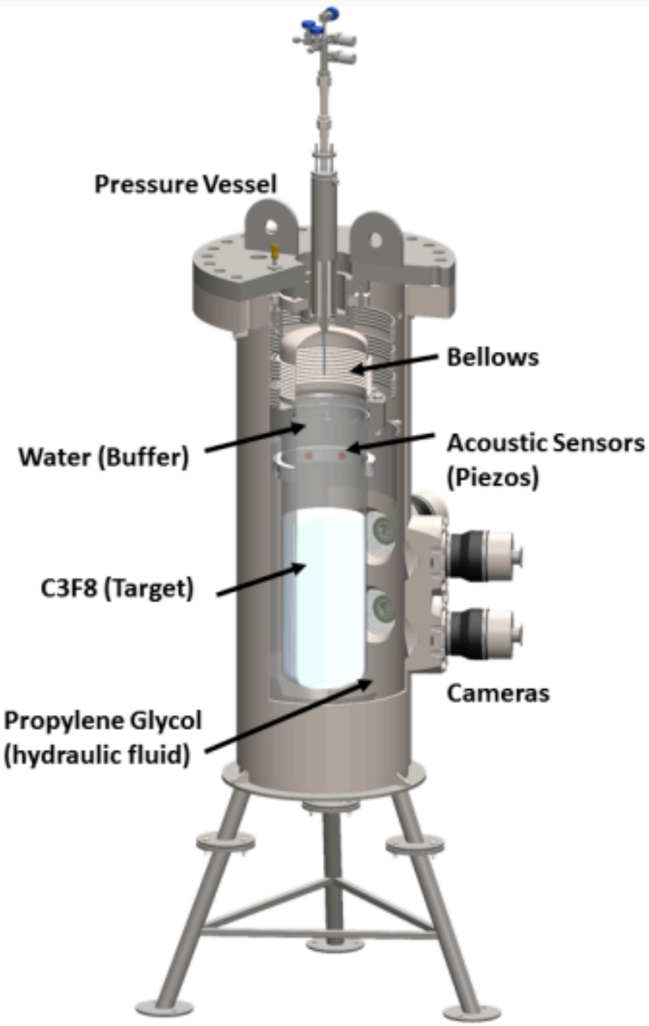



# PICO-60

at SNOLAB




# PICO-60



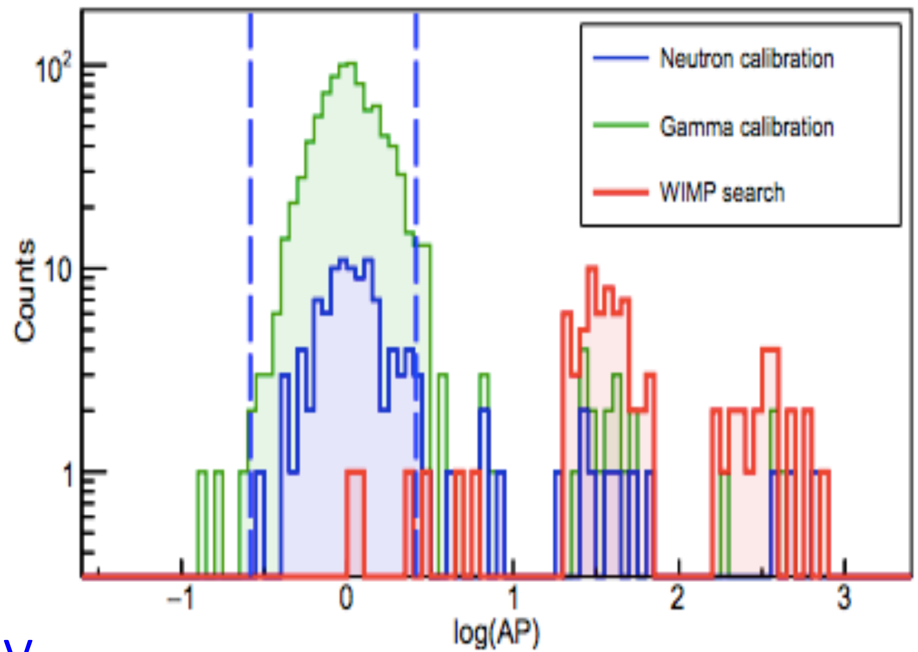
Pressure Vessel
Bellows
Water (Buffer)
Acoustic Sensors
(Piezos)
C3F8 (Target)
Cameras
Propylene Glycol
(hydraulic fluid)


# PICO-60 low-threshold

Decommission to make space for PICO-40L, but first dial down the threshold and see what happens...

Smooth running down to 1.20 keV

New blinded physics run at 2.45 keV



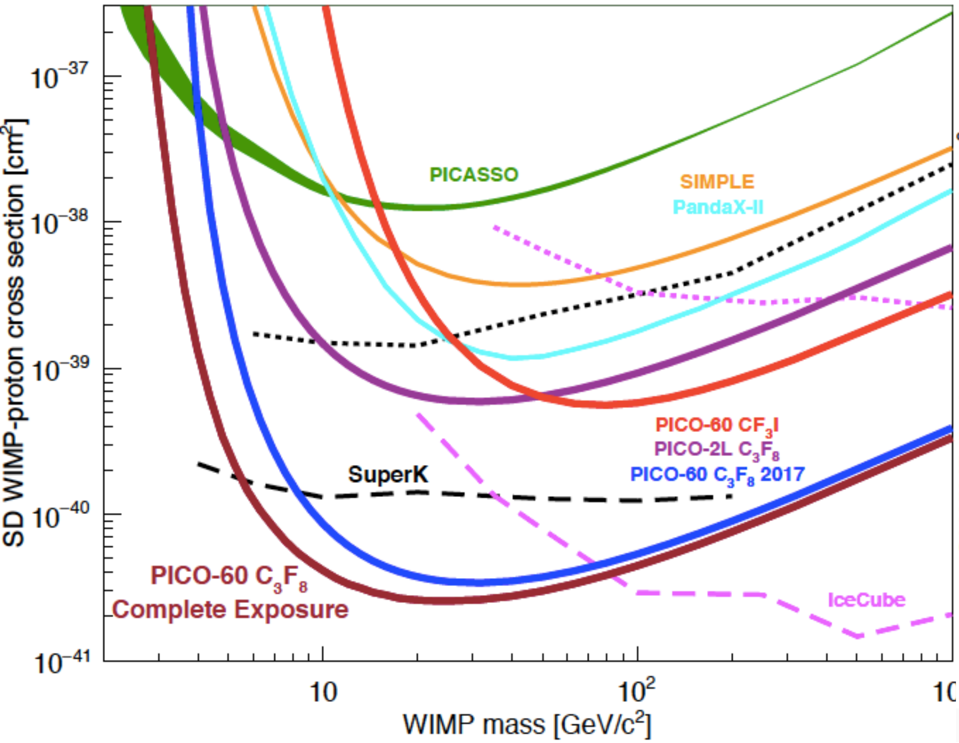

Old ER model: no WIMP search below 2keV

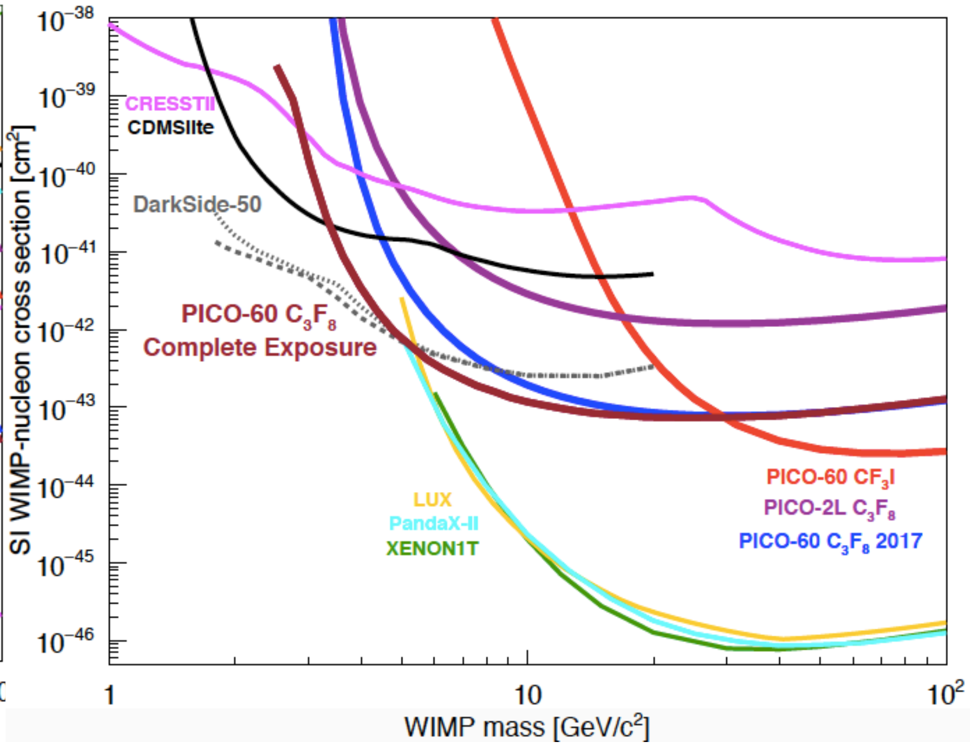
| T (°C) | P (psia) | Seitz threshold, $E_T$ (keV) | Livetime (d) | Exposure (kg-d) |
|---|---|---|---|---|
| 19.9 | 25.5 | $1.20 \pm 0.1(\mathrm{exp}) \pm 0.1(\mathrm{th})$ | 0.21 | 8.2 |
| 19.9 | 34.3 | $1.58 \pm 0.1(\mathrm{exp}) \pm 0.1(\mathrm{th})$ | 1.29 | 50.3 |
| 15.9 | 21.7 | $1.81 \pm 0.1(\mathrm{exp}) \pm 0.2(\mathrm{th})$ | 7.04 | 310.81 |
| 15.9 | 30.5 | $2.45 \pm 0.1(\mathrm{exp}) \pm 0.2(\mathrm{th})$ | 29.95 | 1404.22 |
| 13.9 | 30.2 | $3.29 \pm 0.1(\mathrm{exp}) \pm 0.2(\mathrm{th})$ | 29.96 | 1167 |

| WIMP candidates | neutron bkd prediction from multiples |
|---|---|
| 3 | 0.8 |
| 0 | 0.5 |

Combined WIMP-search dataset

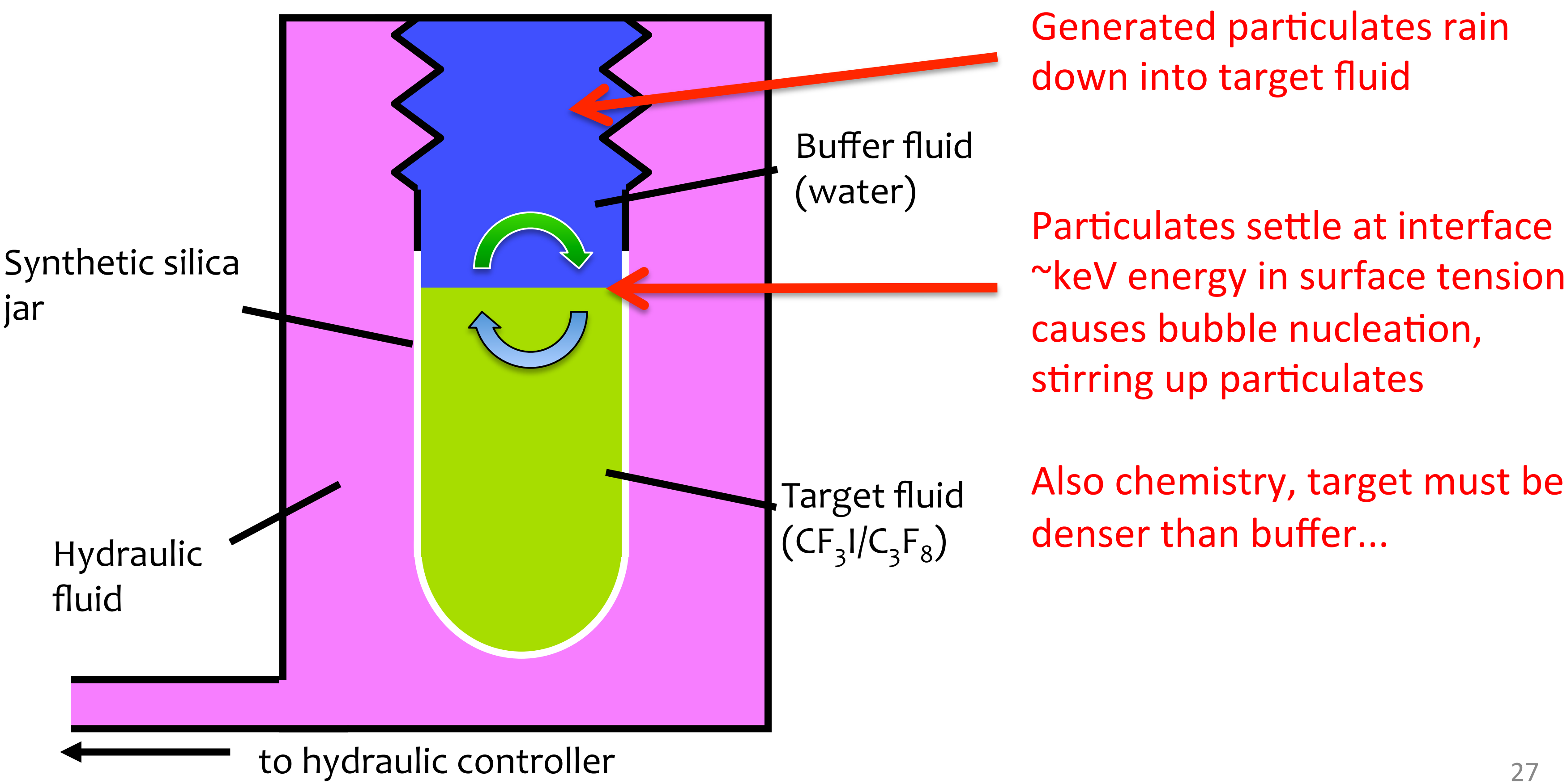
# PICO-60 combined exposure limits

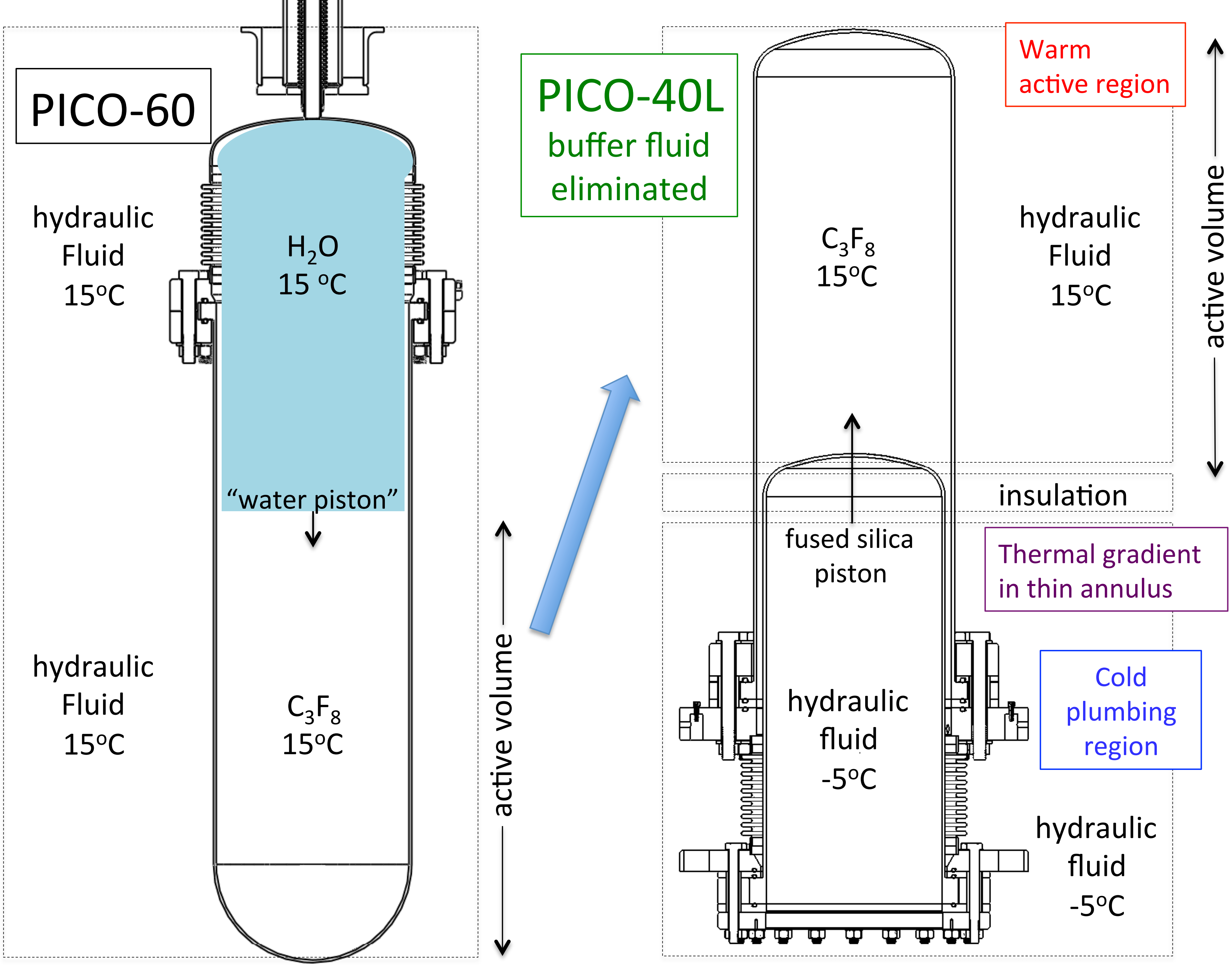


# Moving forward

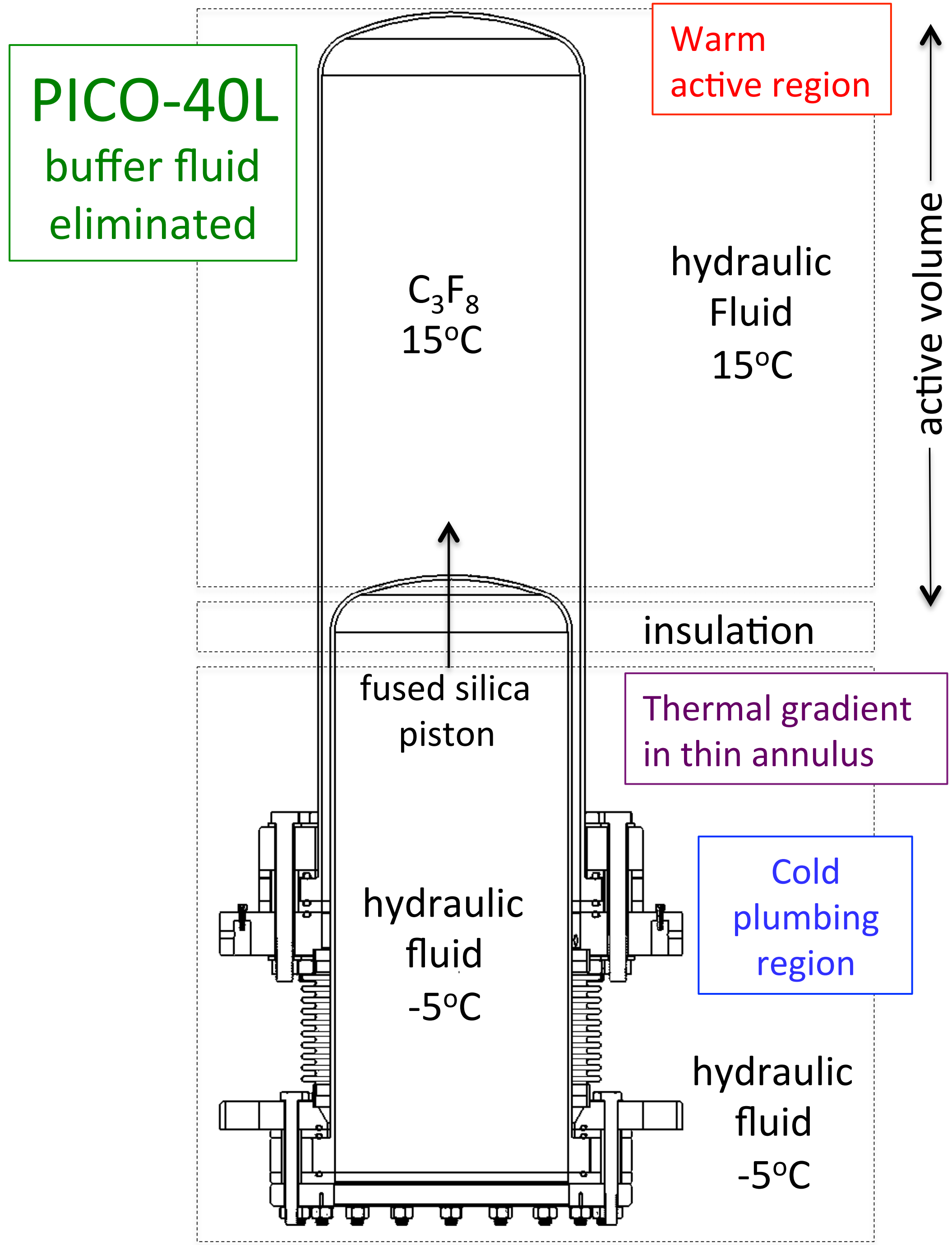
- Historical chamber design is susceptible to particulate contamination





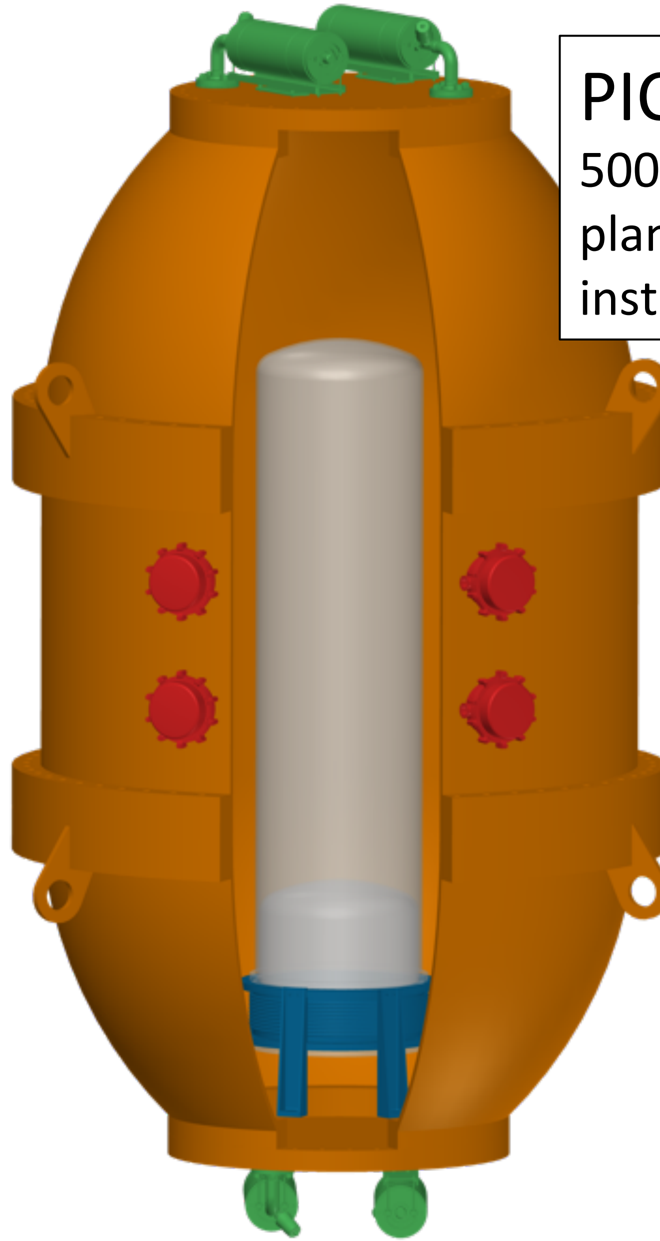
PICO-60
hydraulic Fluid 15°C
$H_2O$ 15 °C
"water piston"
hydraulic Fluid 15°C
$C_3F_8$ 15°C
active volume
PICO-40L
buffer fluid eliminated
$C_3F_8$ 15°C
Warm active region
hydraulic Fluid 15°C
active volume
insulation
fused silica piston
Thermal gradient in thin annulus
hydraulic fluid -5°C
Cold plumbing region
hydraulic fluid -5°C

# Assembly in progress



## PICO-40L

New design – no buffer fluid
Lower thresholds expected
First data expected early 2019



## PICO-500

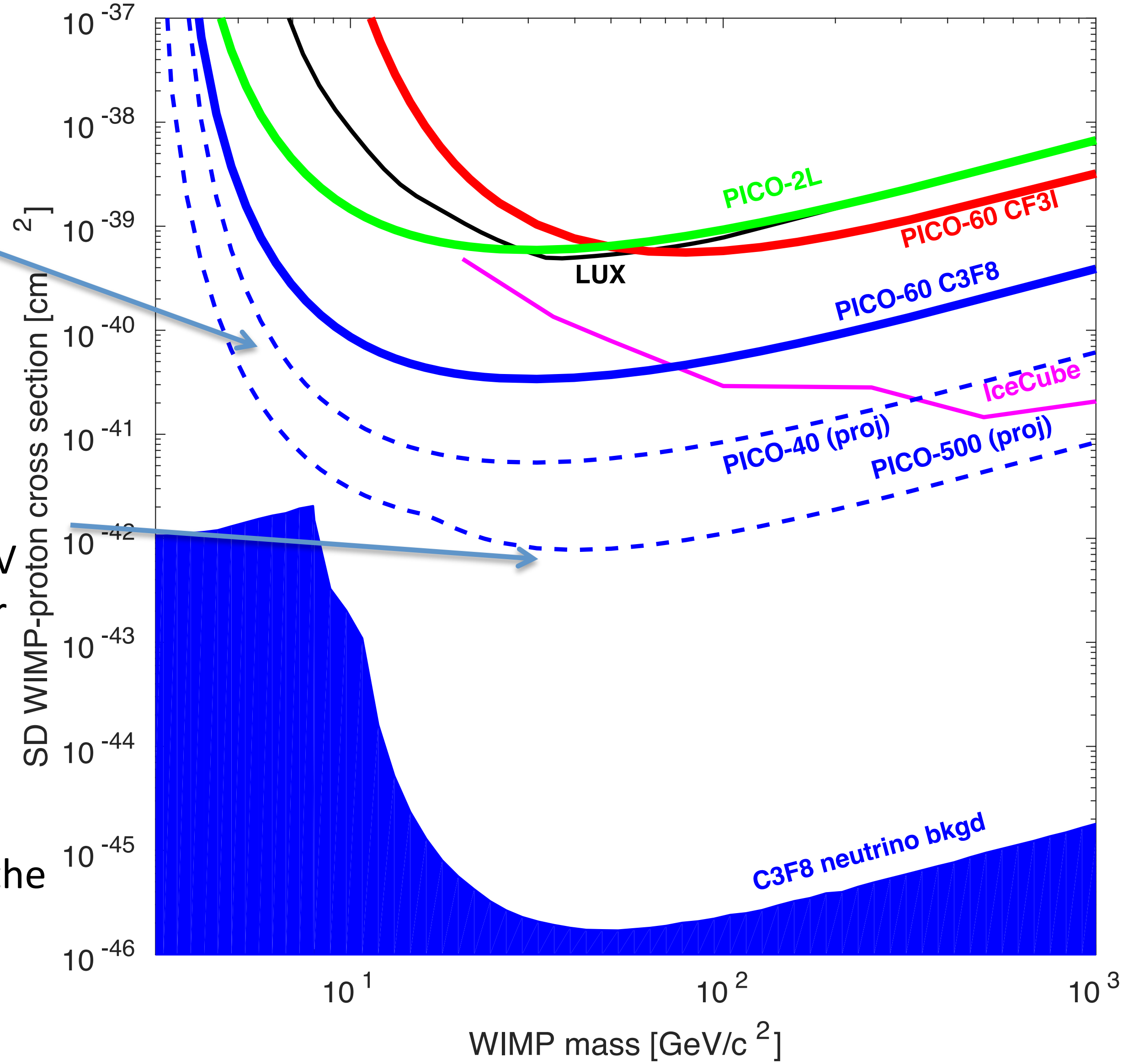
500 liter chamber planned to begin installation in 2019

# Projections

PICO 40L
One year of running
at 3 keV

PICO-500
1/4 year of running at 3 keV
+1/2 year of running at 10 keV
Expect <1 neutron event/year

Will be updated once
PICO 40L has established the
low threshold capabilities of the
PICO $C_3F_8$ bubble chamber



# Summary

- PICO bubble chambers are currently neutron background limited, with stable operation down to ~1 keV nuclear recoil sensitivity
- PICO-60 completed operations in June 2017 and is now decommissioned to make room for PICO-40L, an improved chamber design to be operational in 2019
- Expect gains in sensitivity from studying gamma rejection as a function of pressure and temperature
- Ton-scale PICO-500 detector procurement and first installation planned for 2019

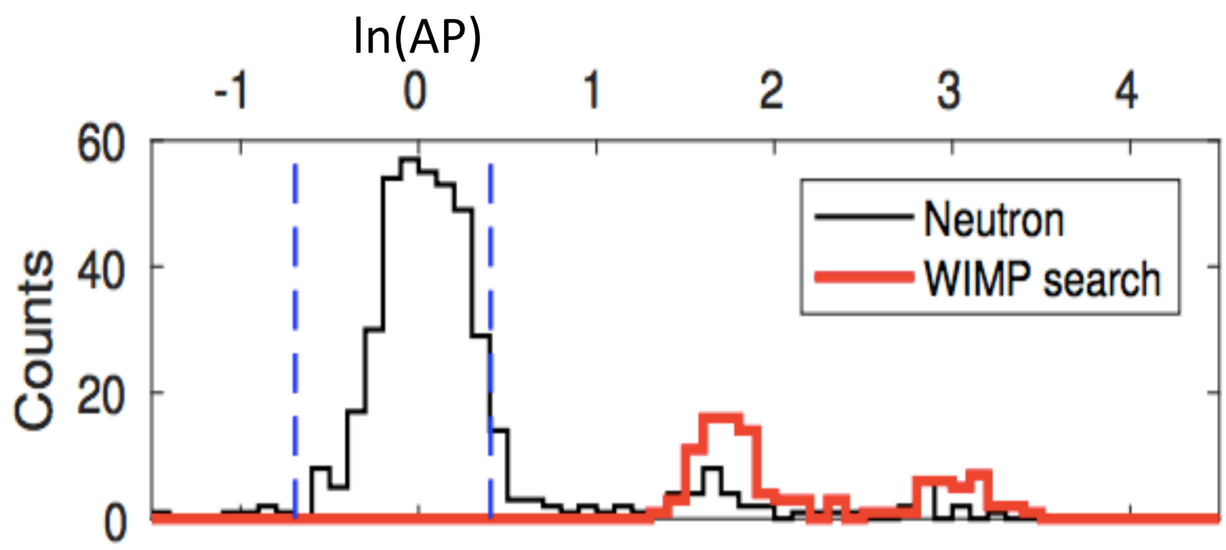
# BACKUP

# PICO-60 $C_3F_8$ 3.29keV run (2016)

Particule mitigation steps produced neutron-limited run in PICO-2L

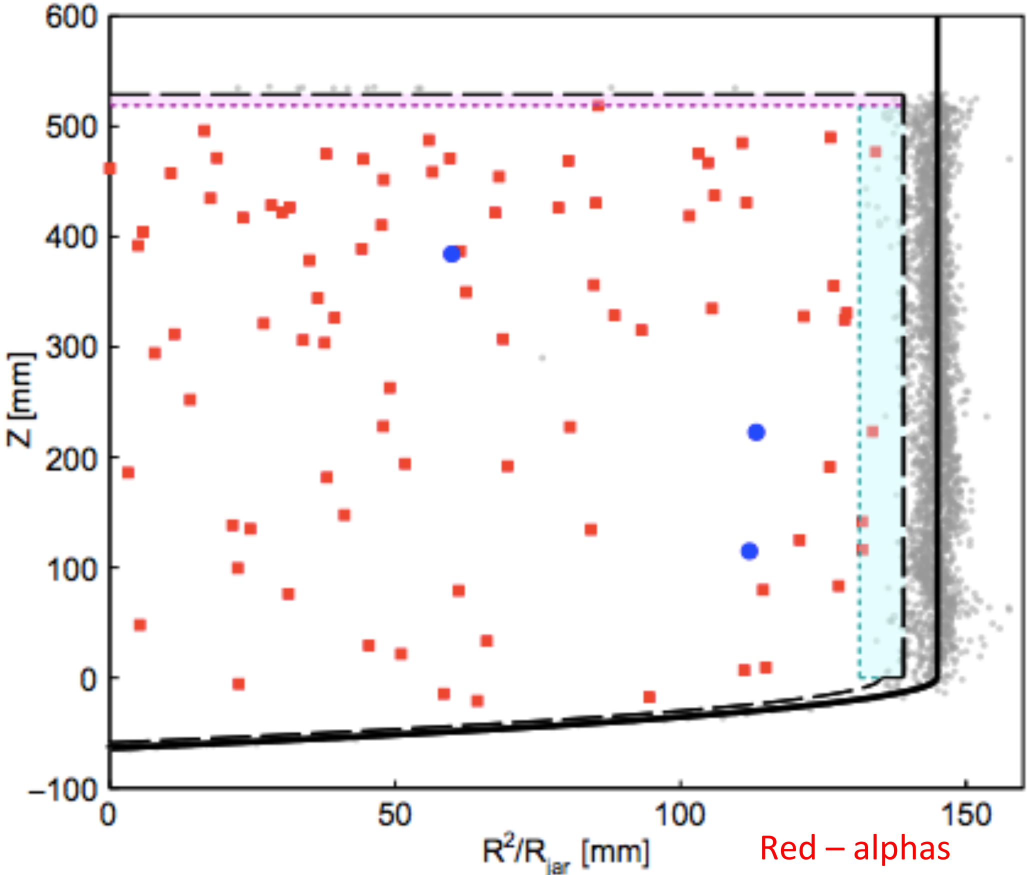
- Lower stress seal on fused silica flange
- Fluid recirculation/filtration
- Improved cleaning with baseline particulate measurements

- 52 kg $C_3F_8$, 30 live-days Nov 2016 – Jan 2017.
- 1167 kg-days blind exposure.
- Zero WIMP candidates.
- Three multiple bubble events observed, signature of neutron background.




C. Amole et al., Phys. Rev. Lett. 118, 251301 (2017)

# Spatial distribution 2.45keV run




Red – alphas
Blue – WIMP candidates
Grey – Wall/surface

Fiducial mass increased from to 45.7 to 48.8kg (from 88 to 94% of active mass).

- Improved optical reconstruction.
- Fiducial cut moved closer to walls with additional data quality cuts added.
  - Bubble track angle cut in cyan region.
  - Camera timing agreement cut in magenta region.

# Combined PICO-60 $C_3F_8$ results

| | 2.45keV | 3.29keV | Total |
|---|---|---|---|
| Exposure (kg-d) | 1404.2 | 1167.0 | 2571.2 |
| **WIMP candidates** | **3** | **0** | **3** |
| Multiple bubble events* | 2 | 3 | 5 |

| **Background prediction** | | | |
|---|---|---|---|
| Neutron background from multiples** | 0.8 | 0.5 | 1.3 |
| Neutron background from simulation | 0.38 | 0.25 | 0.63 |
| Gamma background | 0.13 | 0.03 | 0.16 |
| $^{8}$B CEVNS background | 0.10 | 0.06 | 0.16 |

Rough (2-sigma) agreement between observation and background simulation, but we choose not to make use of the background prediction in setting exclusion limits.

*Multiples exposure is larger than WIMP search exposure due to fewer cuts.
**Expect 3.8 multiples per single bubble from neutron backgrounds.

# History

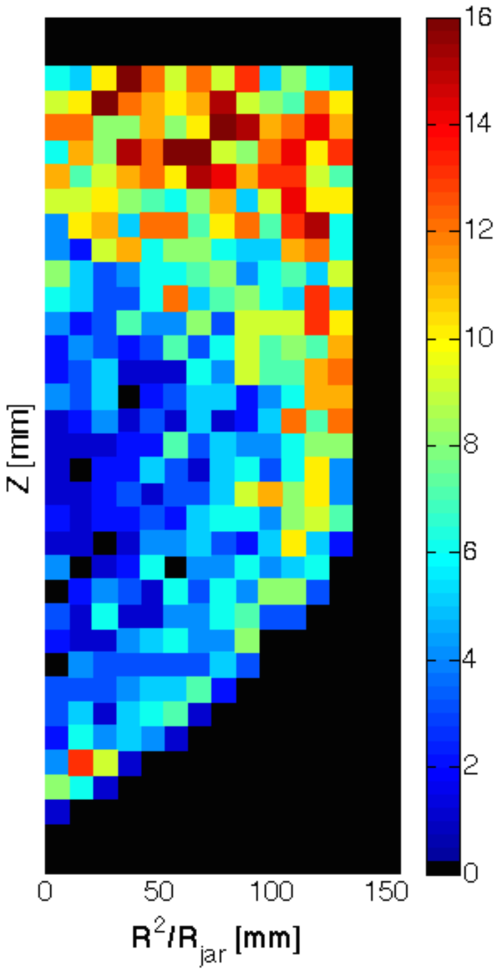
- **COUPP-4 (2010-2011) -- $CF_3I$ with $E_{nr}$ sensitivity down to 8 keV**
  20 time-clustered candidate events in 553 kg-days
  ~5 expected from neutrons
- **PICO-2L (2013-2014) -- $C_3F_8$ with $E_{nr}$ sensitivity down to 4 keV**
  12 time-clustered candidate events in 211 kg-days
  ~1 expected from neutrons
- **PICO-60 (2013-2014) -- $CF_3I$ with $E_{nr}$ sensitivity down to 8 keV**
  ~2000 anomalous events in 3415 kg-days
  ~1 expected from neutrons
- **PICO-2L (2015) – $C_3F_8$ with $E_{nr}$ sensitivity down to 4 keV**
  1 event in 191 kg-days
  ~1 expected from neutrons
- **PICO-60 (2016-2017) -- $C_3F_8$ with $E_{nr}$ sensitivity down to 4 keV**
  0 events in 1167 kg-days of blinded data
  ~1 expected from neutrons

Neutron-limited background after particulate mitigation

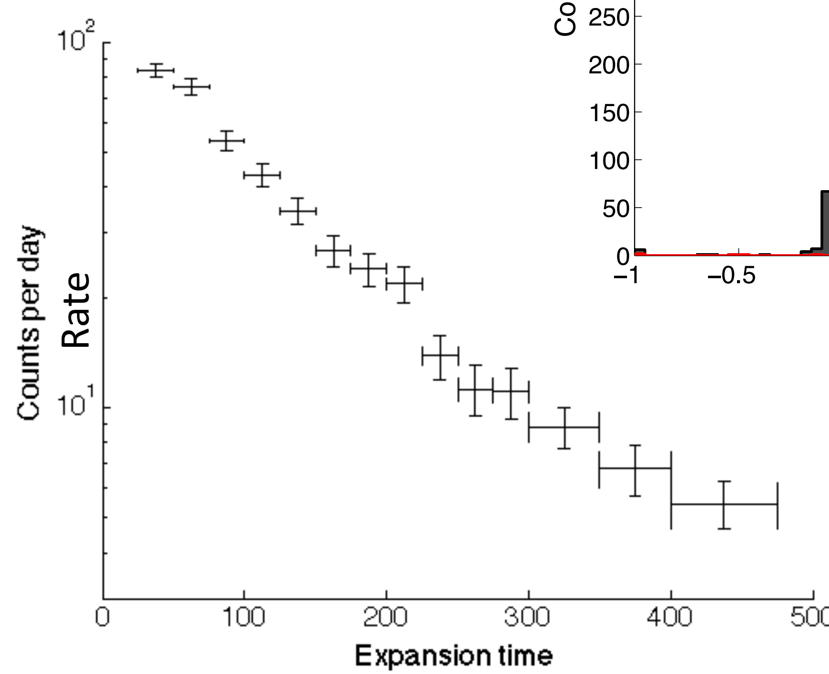
Low stress seal ,
Quartz flange → fused silica,
Fluid recirculation/filtration,
improved cleaning,
baseline particulate measurements

# PICO-60 $CF_3I$ background (2013)

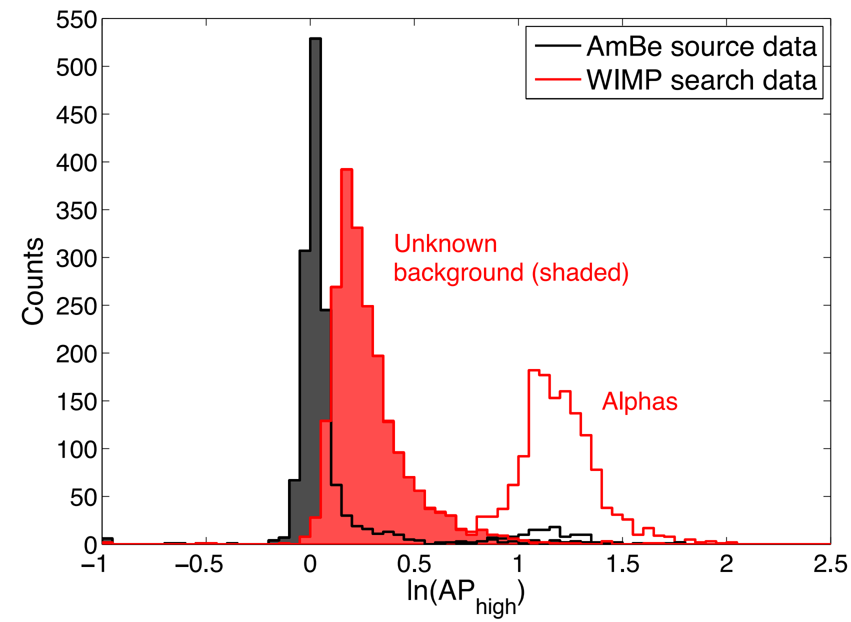
<u>Position dependent</u>
Events cluster near walls & surface, and move upward with time



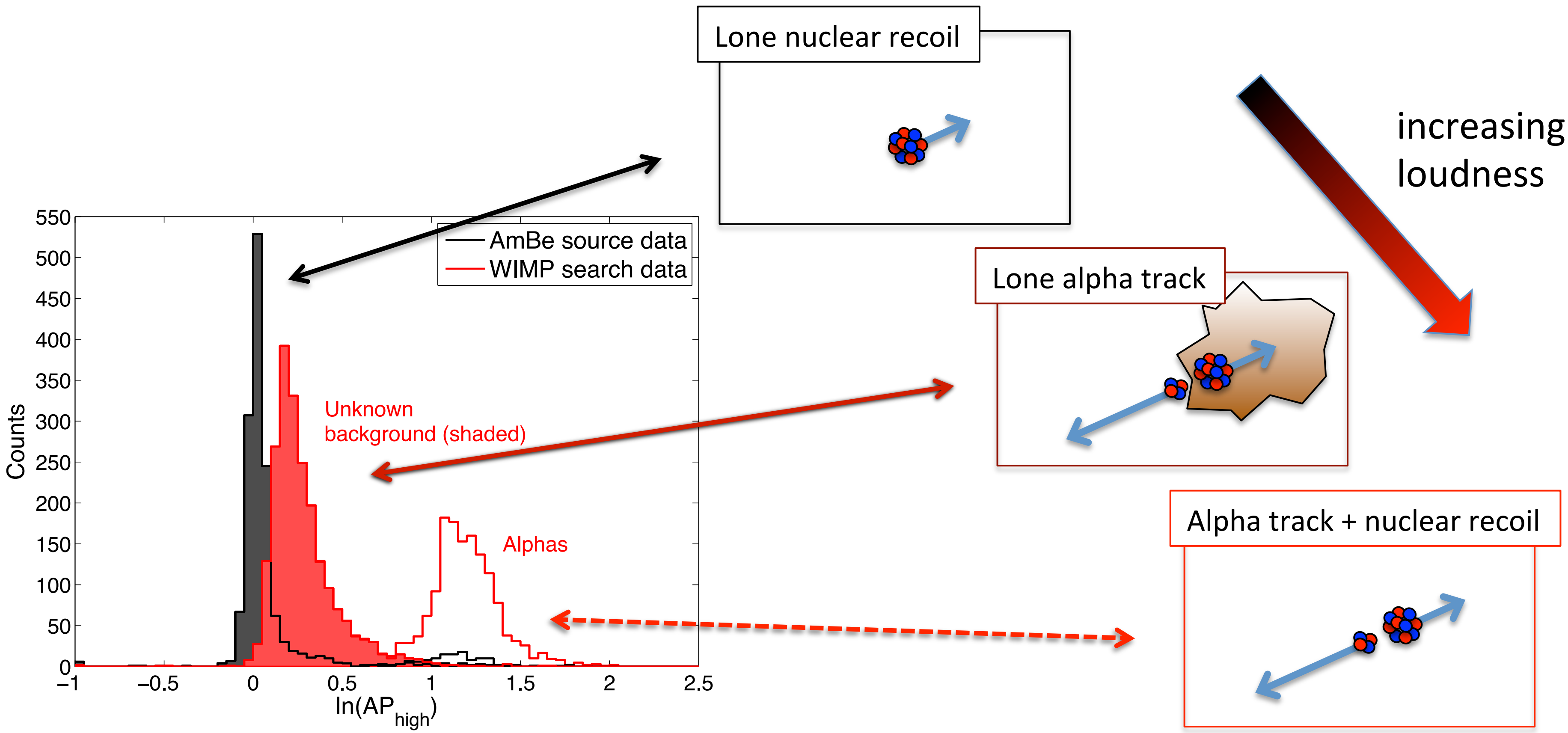

<u>Time dependent</u>
Events occur soon after expansion




<u>Acoustically anomalous</u>
Events are systematically louder than nuclear recoils



# Trace U/Th embedded in particulates



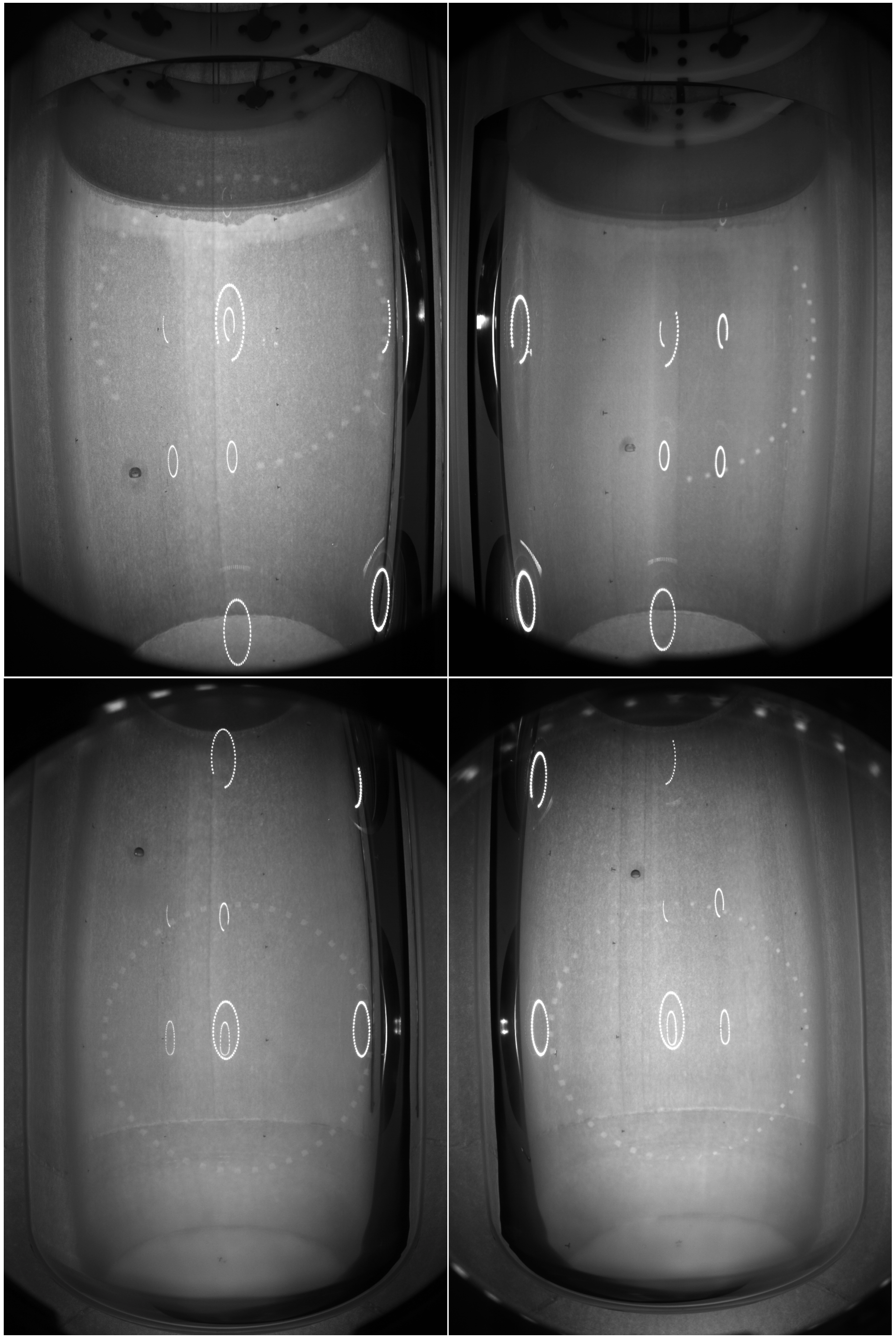
# Post-run assays: steel/silica particulate contamination

- Particulate mitigation steps lead to neutron-limited PICO-2L and PICO-60 runs, BUT

- Particulates injected into test chamber settle on walls/interface
  → Radioactivity in active volume cannot be responsible for anomalous background,
  & particulate can only enter the $C_3F_8$ in a water droplet

- Leading suspect: stored energy in surface tension of 50 nm water droplet is ~3.5 keV. Non-spherical water droplet stretched over particulate is metastable and can nucleate bubbles!

→ The **buffer fluid** is the problem



Larger PICO-60 chamber uses 2 sets of cameras for full chamber coverage

# Combined PICO-60 analysis

Use a 1D Profile Likelihood Ratio to calculate combined WIMP cross-section upper limits.

No constraint is placed on the background at each threshold (flat likelihood function).

Nucleation efficiency uncertainty is converted into a 2D likelihood surface in WIMP detection efficiency Φ in events per kg-day-pb.