Final WIMP-search results from PICO-60

Scott Fallows *for the* PICO Collaboration

Lake Louise Winter Institute – 2019 February 12 – 17:45 MST

OVERVIEW

- The PICO bubble chamber programme:
  dark matter direct detection with superheated fluids

- PICO-60 C_3F_8 — final WIMP-search results, enabled by:

  - Stable low-event-rate operation at high degrees of superheat

  - Low-energy nuclear recoil calibrations to characterize details of threshold for bubble nucleation

- Successor chambers:
  PICO-40L — commissioning now, data in May; demonstrator for—
  PICO-500 — fully funded tonne-scale detector

PICO PROGRAMME OVERVIEW

- **PICO** (not an acronym) — 2012 merger of the **PICASSO** and **COUPP** collaborations

- Small surface test chambers at Université de Montréal, Queen's University, Northwestern, Drexel, NEIU (for threshold calibration, etc.)

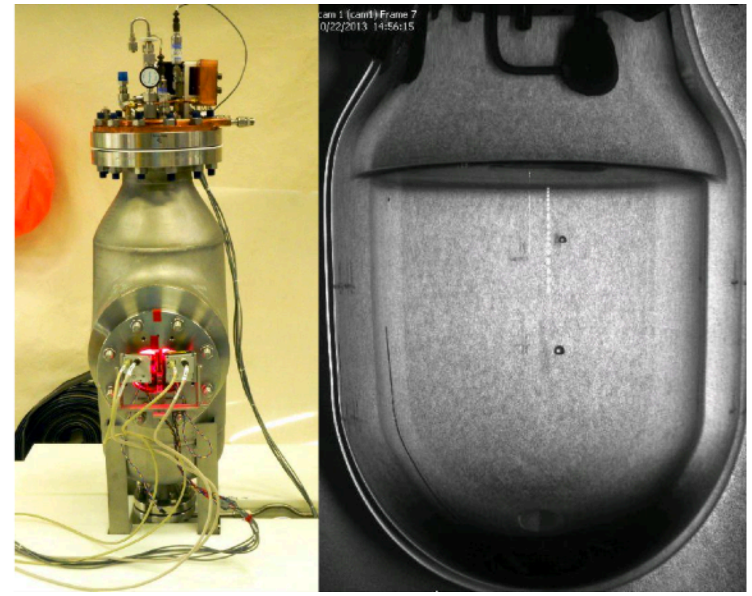
- PICO-2L C_3F_8 (2014–17)
  C. Amole *et al.*, PRL **114**, 231302 **(2015)**
  C. Amole *et al.*, PRD **93**, 061101 **(2016)**

- PICO-60 CF_3I (2013)
  C. Amole *et al.*, PRD **93**, 061101 **(2016)**

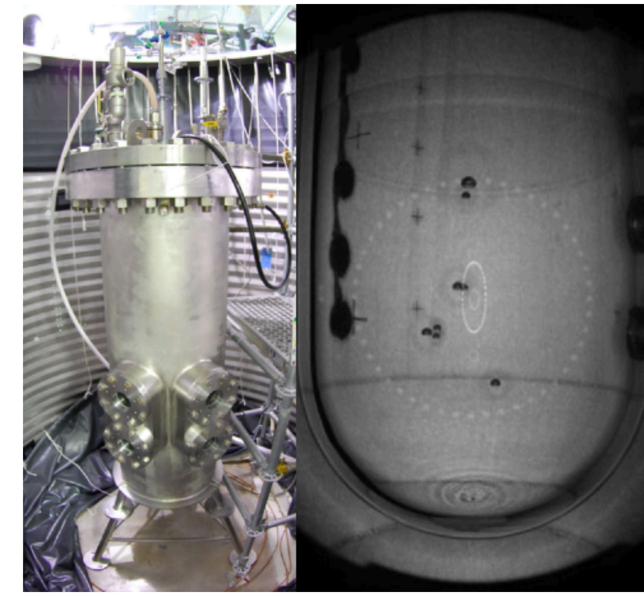
  PICO-60 C_3F_8 (2016–17)
  C. Amole *et al.*, PRL **118**, 251301 **(2017)**
  C. Amole *et al.*, arXiv:1902.04031 **(2019)**
  (this result)

- PICO-40L (2018–20)

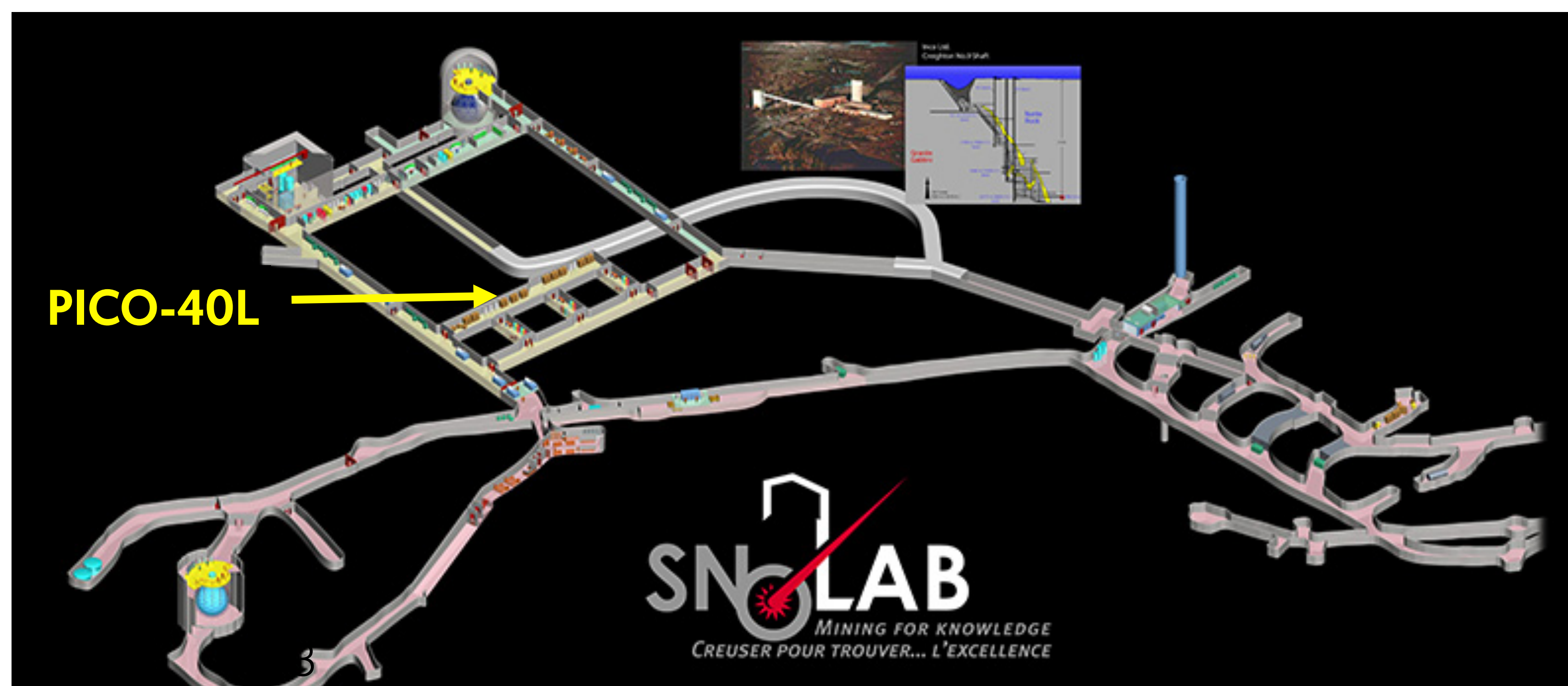
- PICO-500 (~2019+)



PICO-2L
C_3F_8



PICO-60
CF_3I, C_3F_8



PICO

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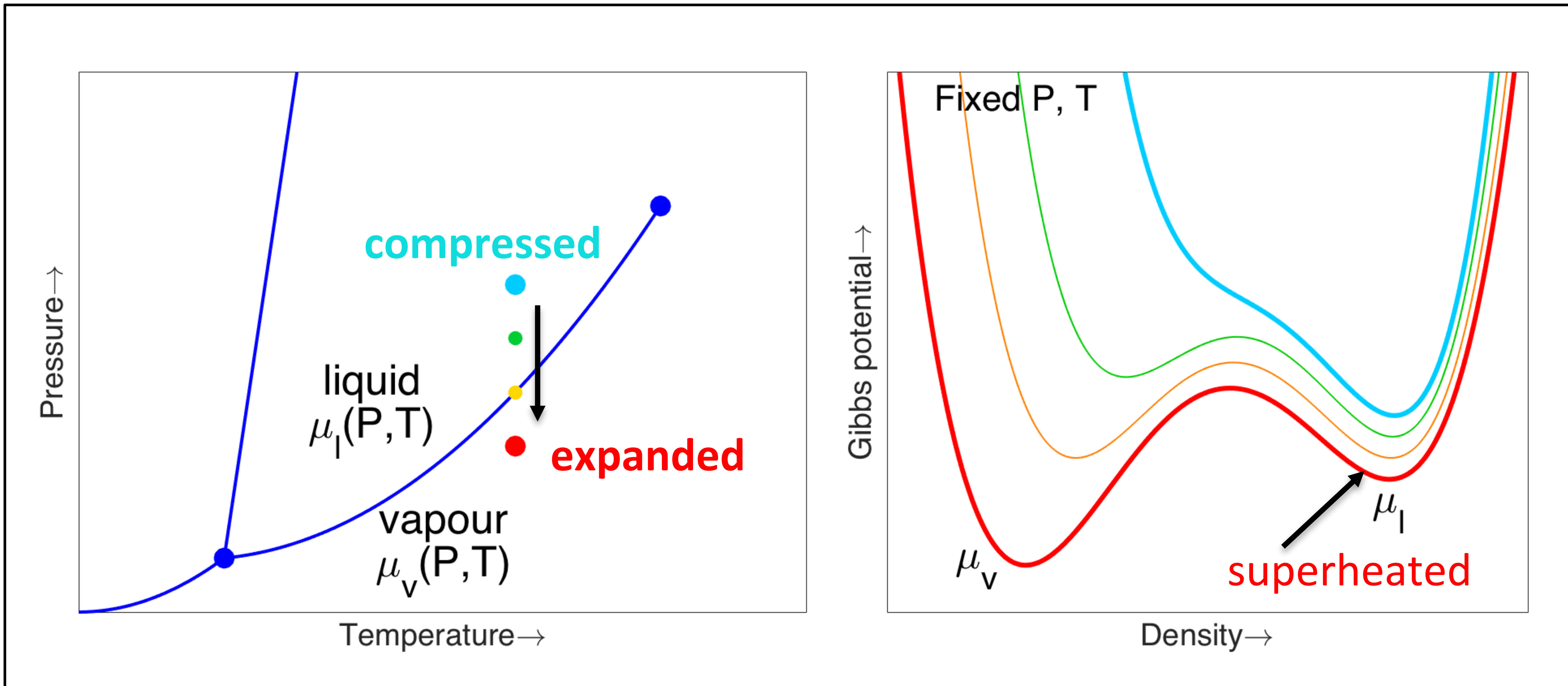
TARGET: SUPERHEATED FLUID

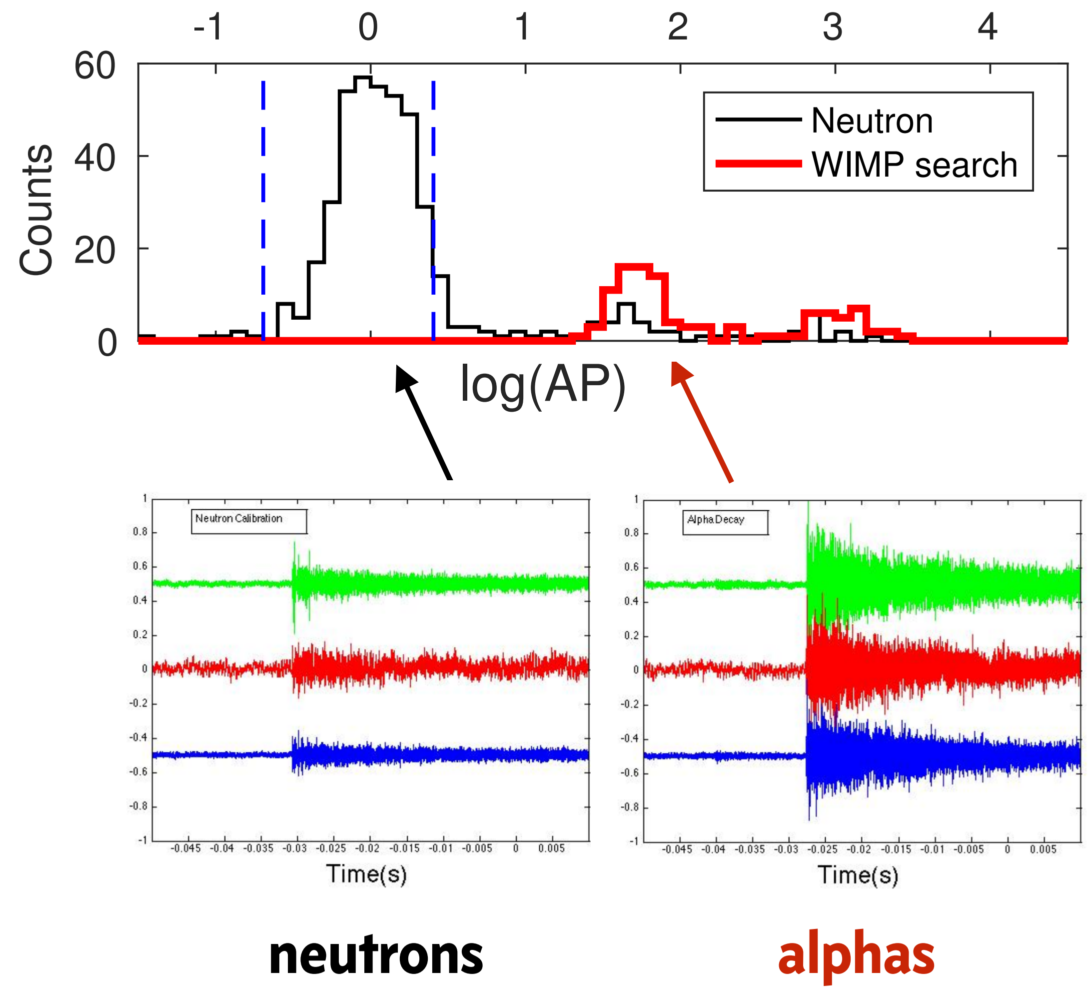
1. Lower pressure in target liquid until it is in *metastable superheated* state
2. *Sufficiently dense* energy deposition *nucleates* small bubble that grows to visible size
3. *Cameras* watch for visible bubble(s) and issue the *primary trigger*, begin recompression

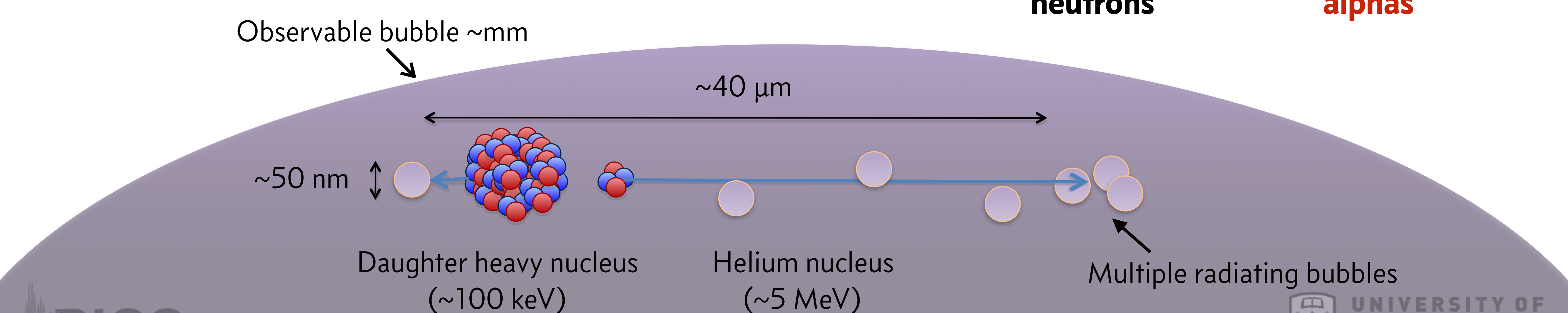


(plot credit: Eric Dahl)

ACOUSTIC DISCRIMINATION

- Acoustic discrimination against alpha decays discovered by PICASSO
  (Aubin *et al.*, New J. Phys.10:103017, **2008**)
  - Alphas deposit their energy over **tens of μm**
  - Nuclear recoils deposit energy over **tens of nm**
- In PICO, **alphas** are several times **louder** than recoils
- For a WIMP-search run, the acoustic signals are blinded in order to set an unbiased cut on this "acoustic parameter" ("AP")

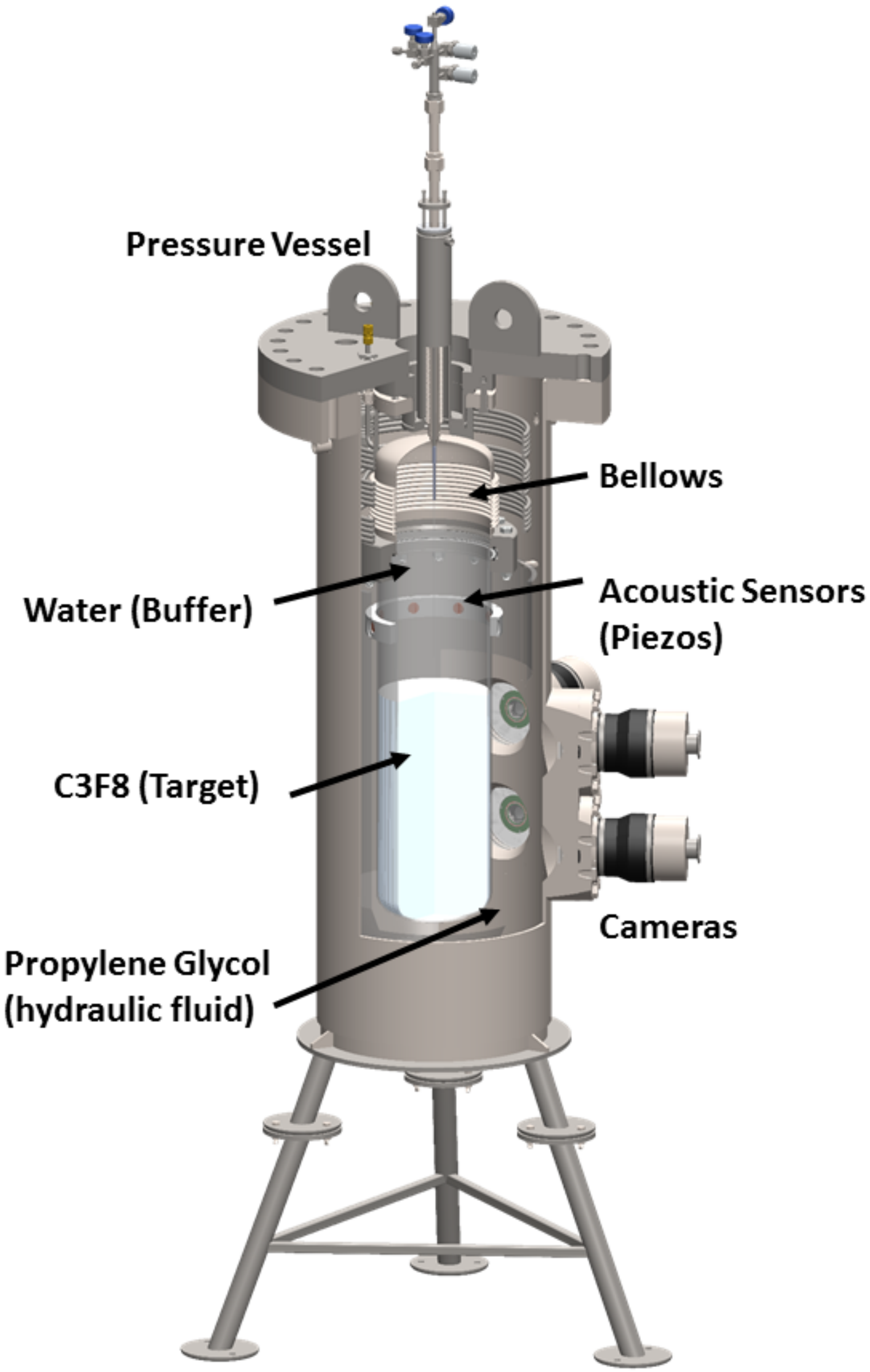




BACKGROUNDS SUMMARY

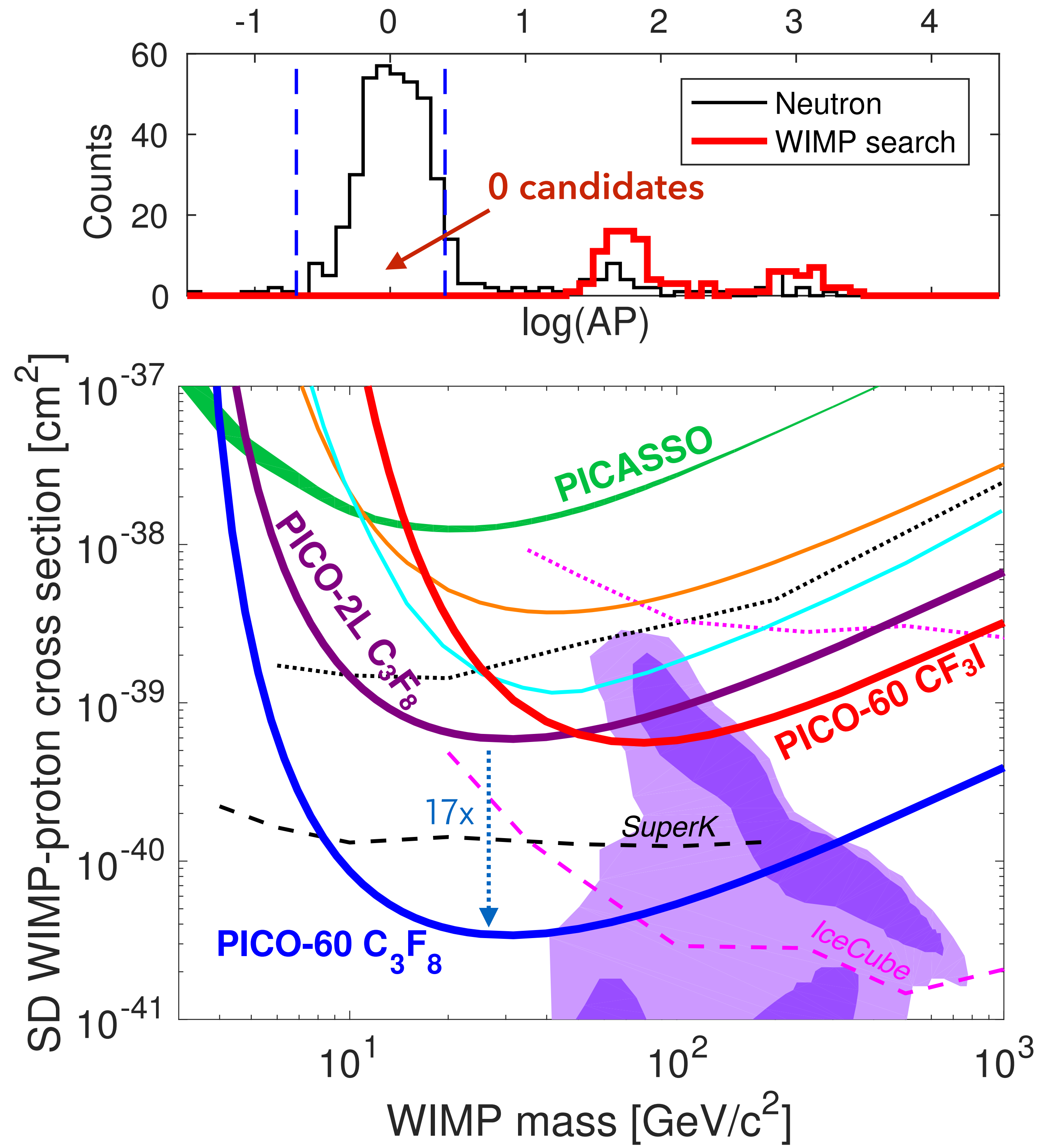
- **Gammas/betas:**
  - d*E*/dx threshold in superheated detectors affords "intrinsic" rejection ~10^{-10} for typical PICO energy thresholds in C_3F_8
- **Alpha decays (U/Th chain):**
  - large acoustic signals enable discrimination at >99.4% (stats. limited)
- **Neutrons:**
  - reject multiple scatters visually, veto detector-adjacent cosmogenics, minimize other sources (extensive material screening, shielding)

PICO-60 APPARATUS



PICO-60 INITIAL PHYSICS DATA

- **30 live-day run at 3.3 keV:** *background-free* **1167 kg-day** blind WIMP-search exposure
- Factor of 17 improvement in upper limit on spin-dependent WIMP-proton cross-section
- Saw 3 multi-bubble events: signature of neutron background
- Further exposure at 3.3 keV expected to be background limited, but before decommissioning for PICO-40L, reduce threshold…



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

PICO-60 LOW-THRESHOLD

Non-WIMP-search

never blinded; used to study sensitivity to gamma-induced events*

T (°C)	P (psia)	Seitz threshold, E_T (keV)	Livetime (d)	Exposure (kg-d)
19.9	25.5	$1.20 \pm 0.1(\text{exp}) \pm 0.1(\text{th})$	0.21	8.2
19.9	34.3	$1.58 \pm 0.1(\text{exp}) \pm 0.1(\text{th})$	1.29	50.3
15.9	21.7	$1.81 \pm 0.1(\text{exp}) \pm 0.2(\text{th})$	7.04	311
15.9	30.5	$2.45 \pm 0.1(\text{exp}) \pm 0.2(\text{th})$	29.95	1404 *(new)*
13.9	30.2	$3.29 \pm 0.1(\text{exp}) \pm 0.2(\text{th})$	29.96	1167 (PRL 2017)

Combined blinded WIMP-search

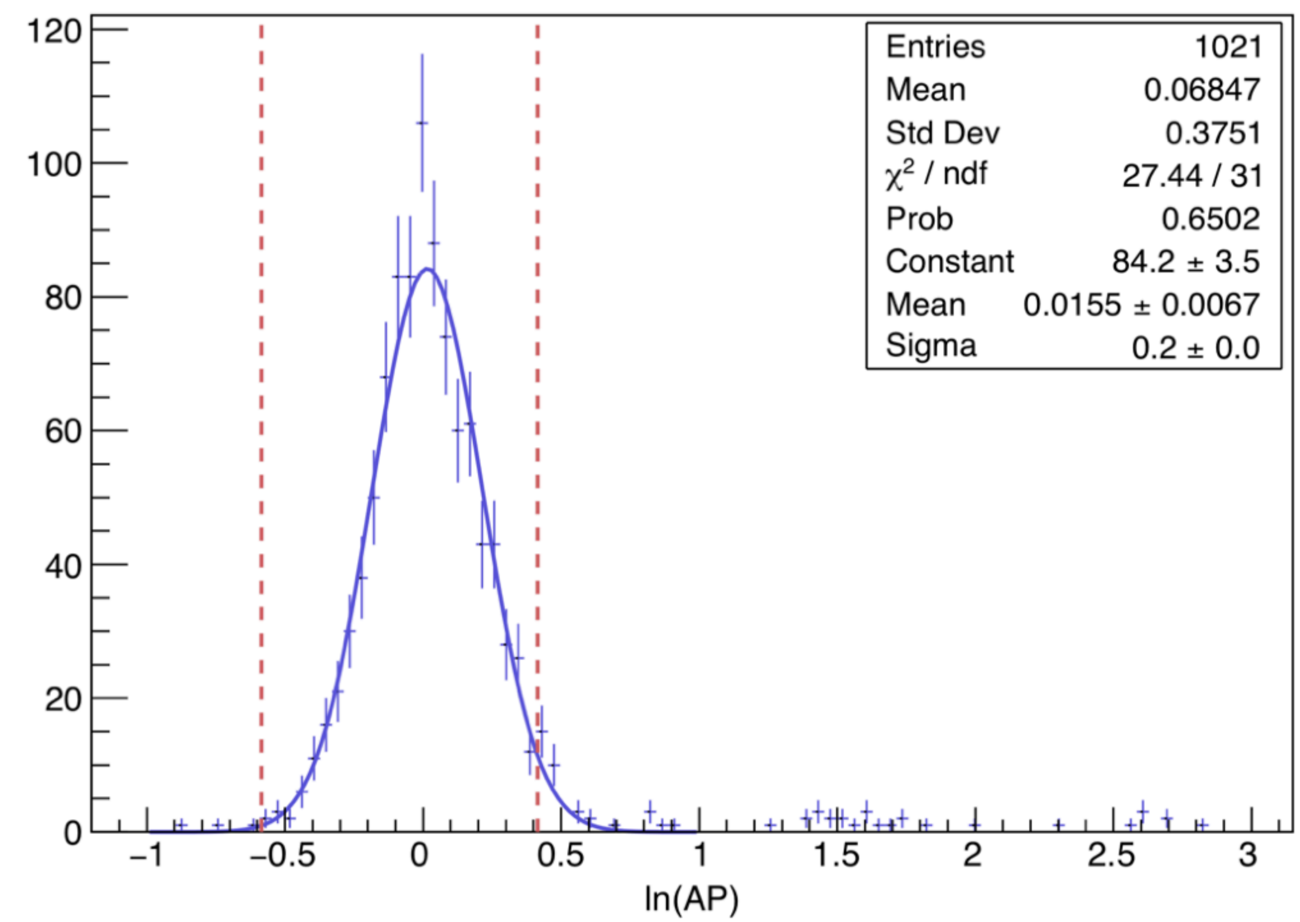
second blind run at 2.45 keV initiated when low background rate observed

*see D. Baxter, **IDM 2018**

PRE-UNBLINDING EVENT SELECTION

- Data quality cuts: 99.9% efficient
- Single-bubble selection: 98.7% efficient
- AP cut: 97.4% efficient on bulk single-bubble γ/nuclear recoil calibration events
- No neural network acoustic cut used here (unlike PRL 2017), but methods in development* for future detectors
- Increase in acoustic selection acceptance contributes **12% exposure increase**

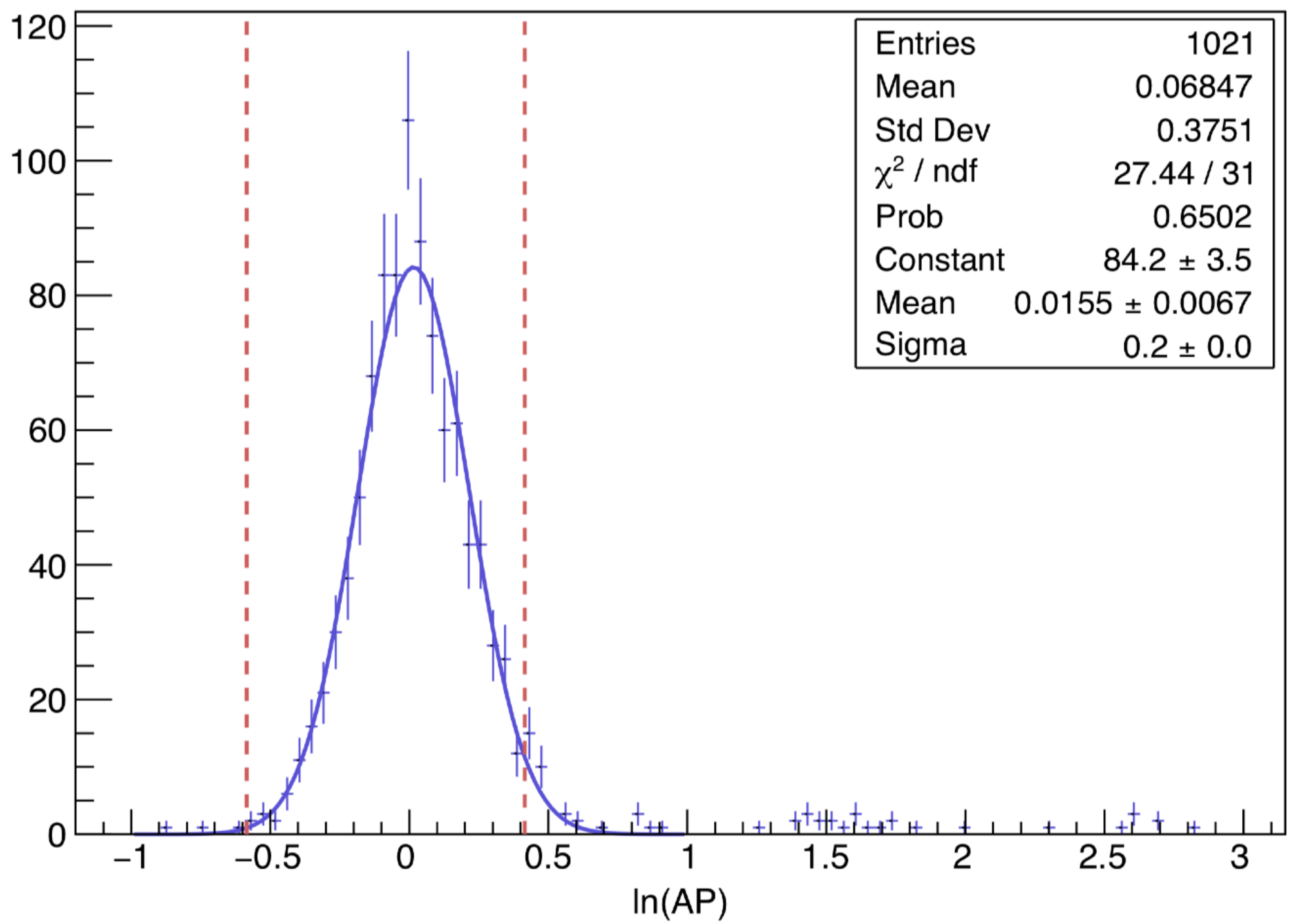
Neutron and γ calibration data at 2.45 keV



*B. Matusch et al., arXiv:1811.11308

BLIND ACOUSTICS

Neutron and γ calibration data at 2.45 keV



defined AP acceptance window: (μ - 3σ, μ + 2σ)

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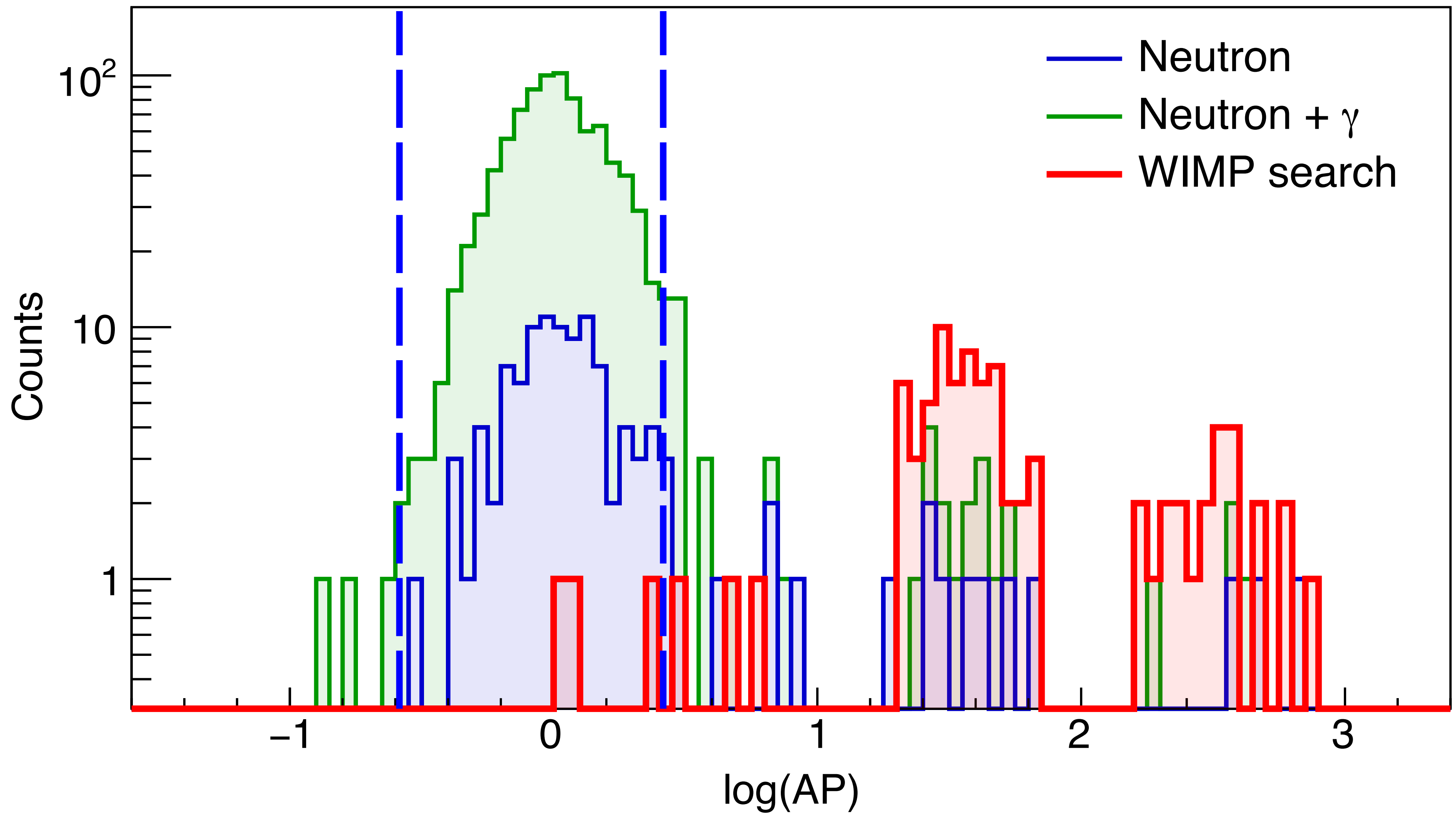
POST-UNBLINDING ACOUSTICS



three WIMP candidate events in AP acceptance window

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FIDUCIAL VOLUME INCREASE

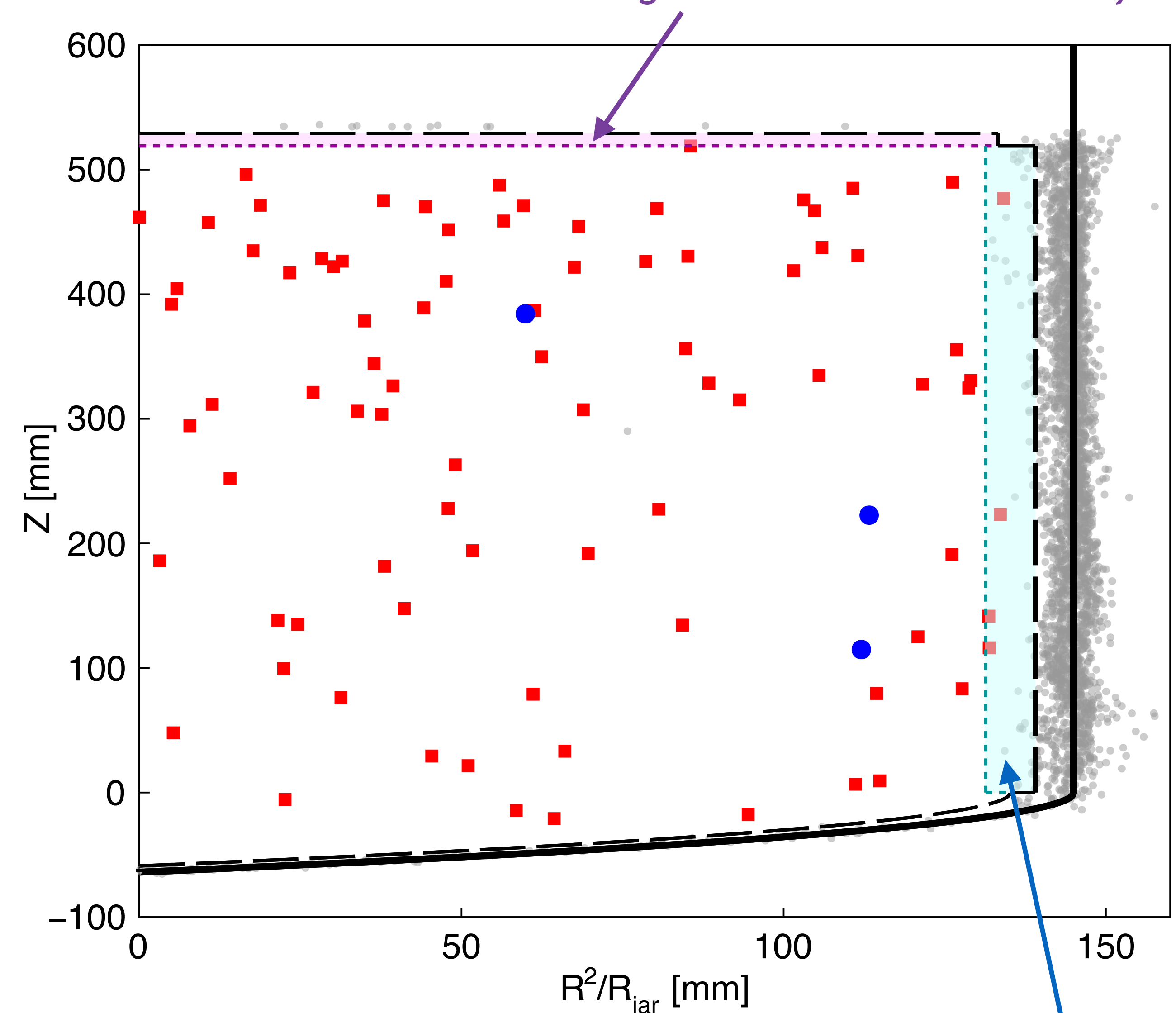
(fixed while still blinded)

More advanced optical reconstruction:

- Bubble tracking for up to 30 ms after appearance allows accurate wall-event tagging by track zenith angle
- Finer sub-pixel resolution in lookup table from ray-tracing
- Automatic inner vessel motion correction added

Enables a ~7% increase in fiducial mass from 45.7 kg to 48.8 kg (88 to 94%)

camera timing agreement cut in region of reduced visibility



Grey: wall/surface
Red: fiducial alphas
Blue: WIMP candidates

tracking identifies wall events by zenith angle

EFFICIENCY-CORRECTED EXPOSURE

3.3 keV: 1167 kg-days [C. Amole *et al.*, PRL **118**, 251301 **(2017)**]

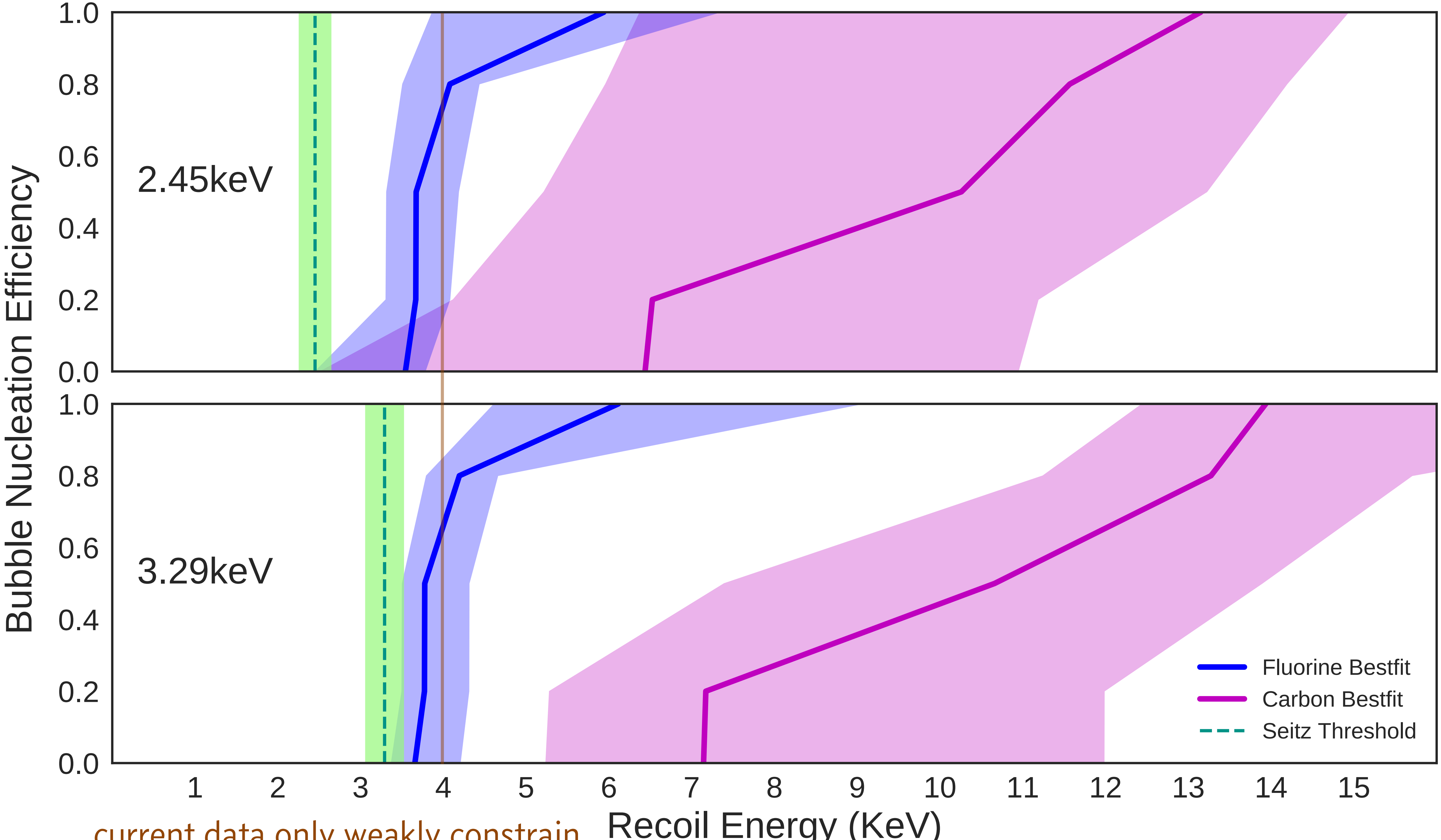
Dataset	Efficiency (%)	Fiducial Mass (kg)	Exposure (kg-days)	# events
Singles	85.1 ± 1.8	45.7 ± 0.5	1167 ± 28	0
Multiples	99.4 ± 0.1	52.2 ± 0.5	1555 ± 15	3

2.45 keV: 1404 kg-days [*+20%, this result,* arXiv:1902.04031]

Dataset	Efficiency (%)	Fiducial Mass (kg)	Exposure (kg-days)	# events
Singles	95.9 ± 2.6	48.8 ± 0.8	1404 ± 62	3
Multiples	99.9 ± 0.1	52.0 ± 0.1	1556 ± 4	2

BUBBLE NUCLEATION EFFICIENCY

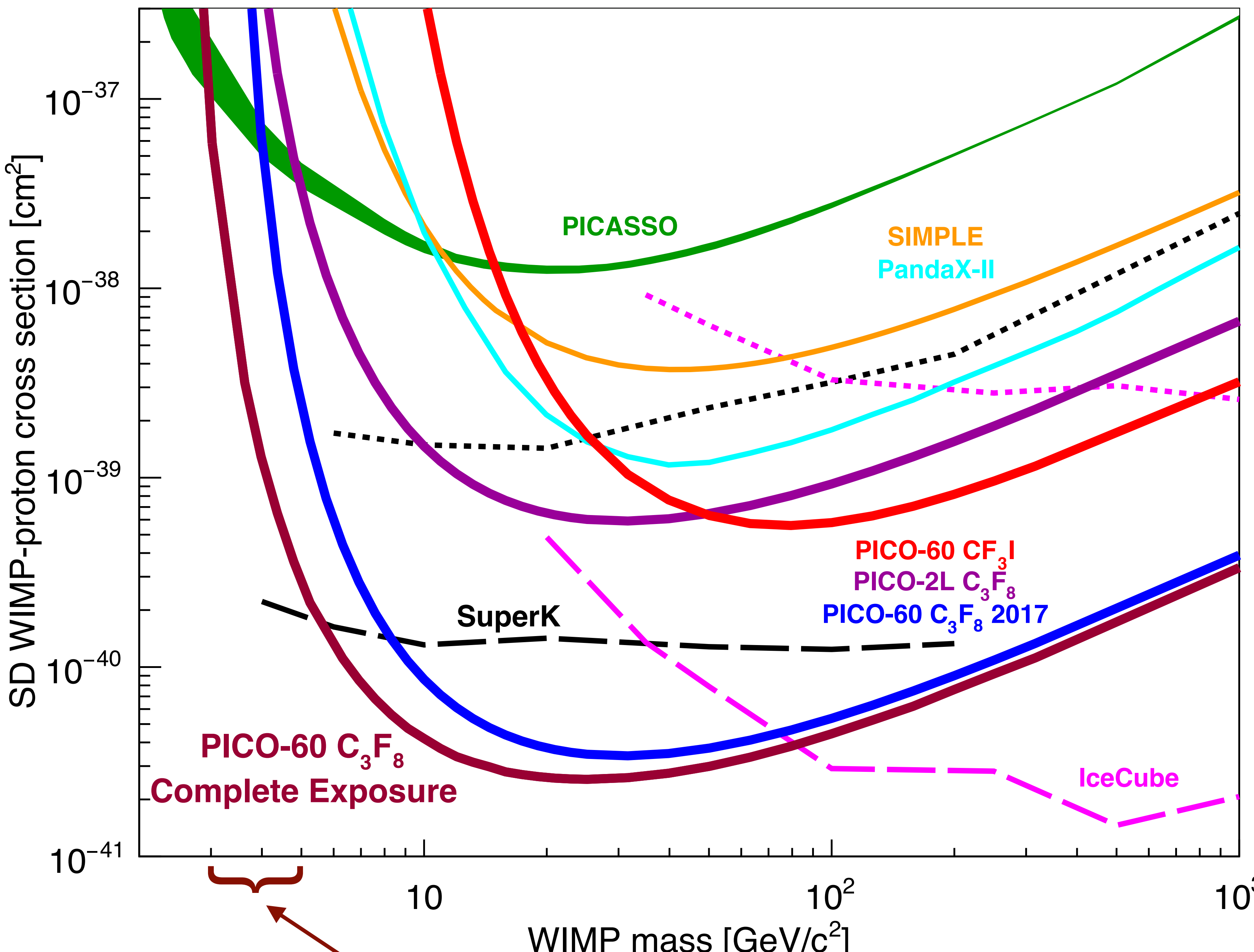
MCMC fit using multiplicity in surface (UdeM) mono-energetic neutron calibration data



current data only weakly constrain sensitivity below ~4 keV

EXCLUSION LIMIT: SD WIMP-PROTON

arXiv:1902.04031



improved mainly in 3–5 GeV range
(order of magnitude more stringent)

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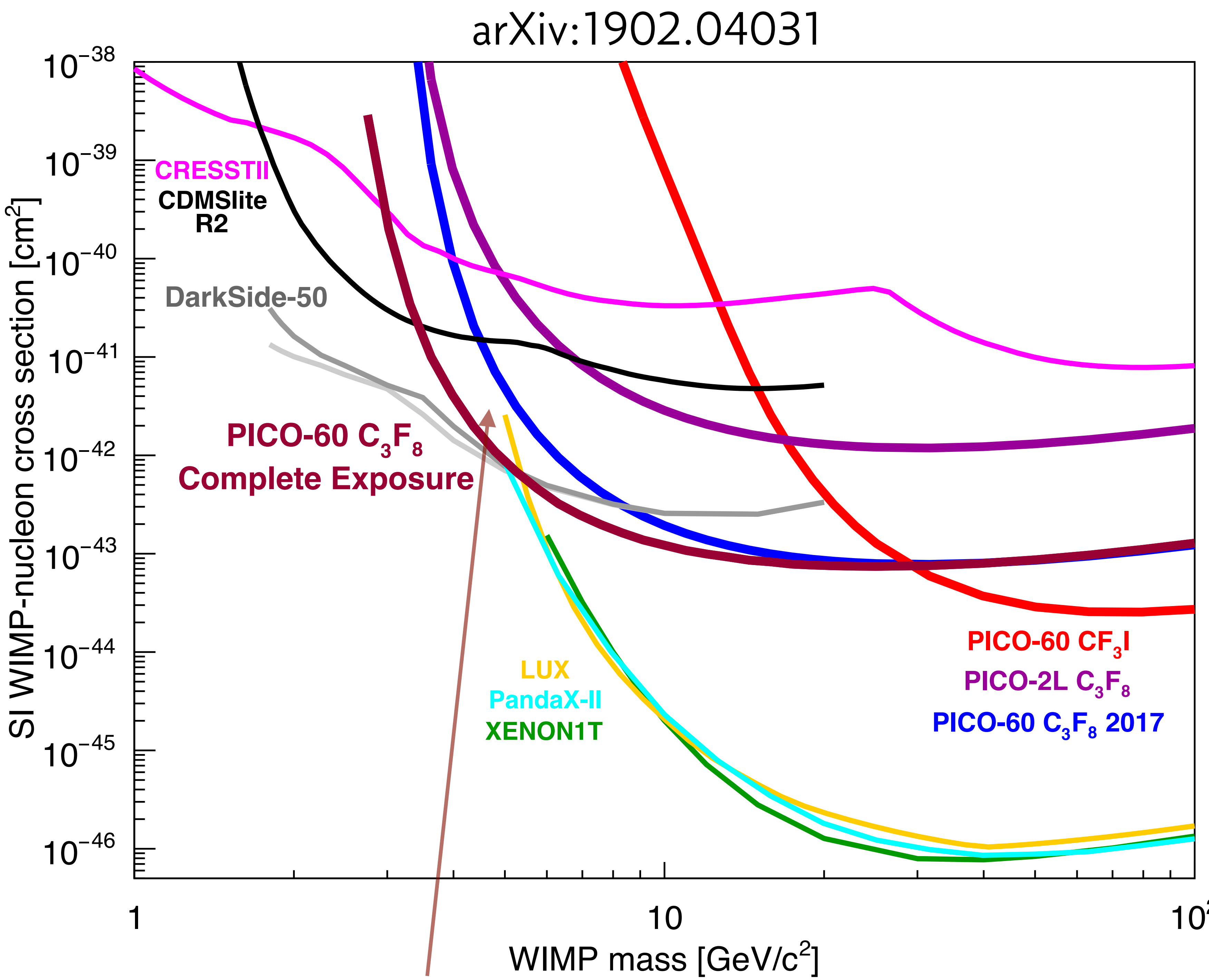
EXCLUSION LIMIT: SI WIMP-NUCLEON



small region previously excluded
only by DarkSide-50 low-mass

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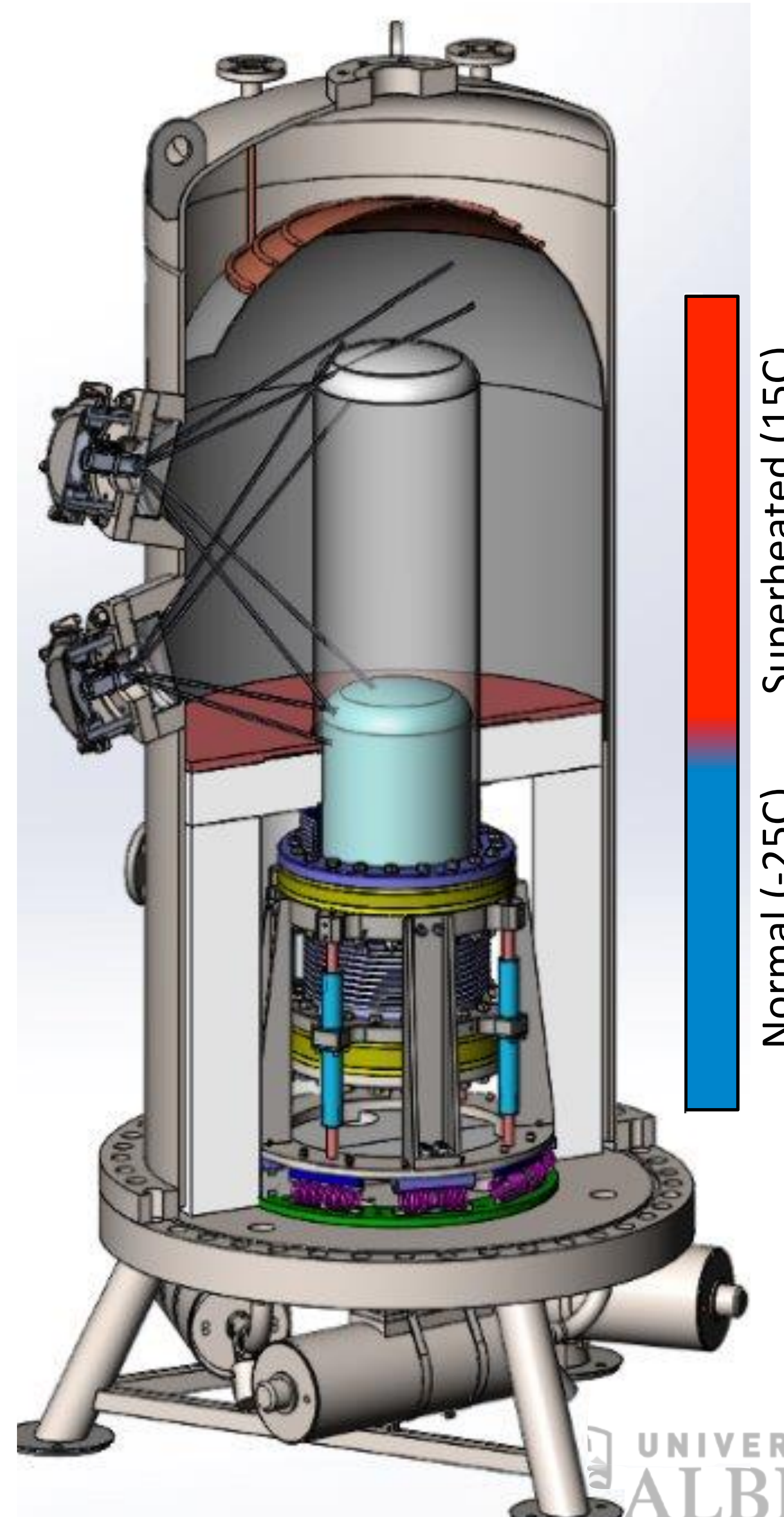
CURRENT CHAMBER: PICO-40L

- Similar to PICO-60, but inverted orientation
- Larger pressure vessel – reduced neutron backgrounds
- No water buffer – two quartz jars attached to bellows to control pressure
- Thermal gradient maintained with heaters, cooling coils, and HDPE insulation
- Active recirculation/purification of the C_3F_8 target
- Designed to allow for one year of background-free running: order of mag. improvement on PICO-60
- Commissioning now; data-taking summer 2019



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NEXT CHAMBER: PICO-500

- Fully funded tonne-scale chamber — with funding now accessible
- Currently in design and early procurement phases
- Work underground at SNOLAB is scheduled to start at the end of 2019
- WIMP sensitivity at another order of magnitude beyond PICO-40L
- Big enough to see 10 kpc SN neutrinos*

SNOLAB Cube Hall, next to DEAP-3600

*T. Kozynets *et al.*, Astroparticle Phys. 105 (2019) 25–30

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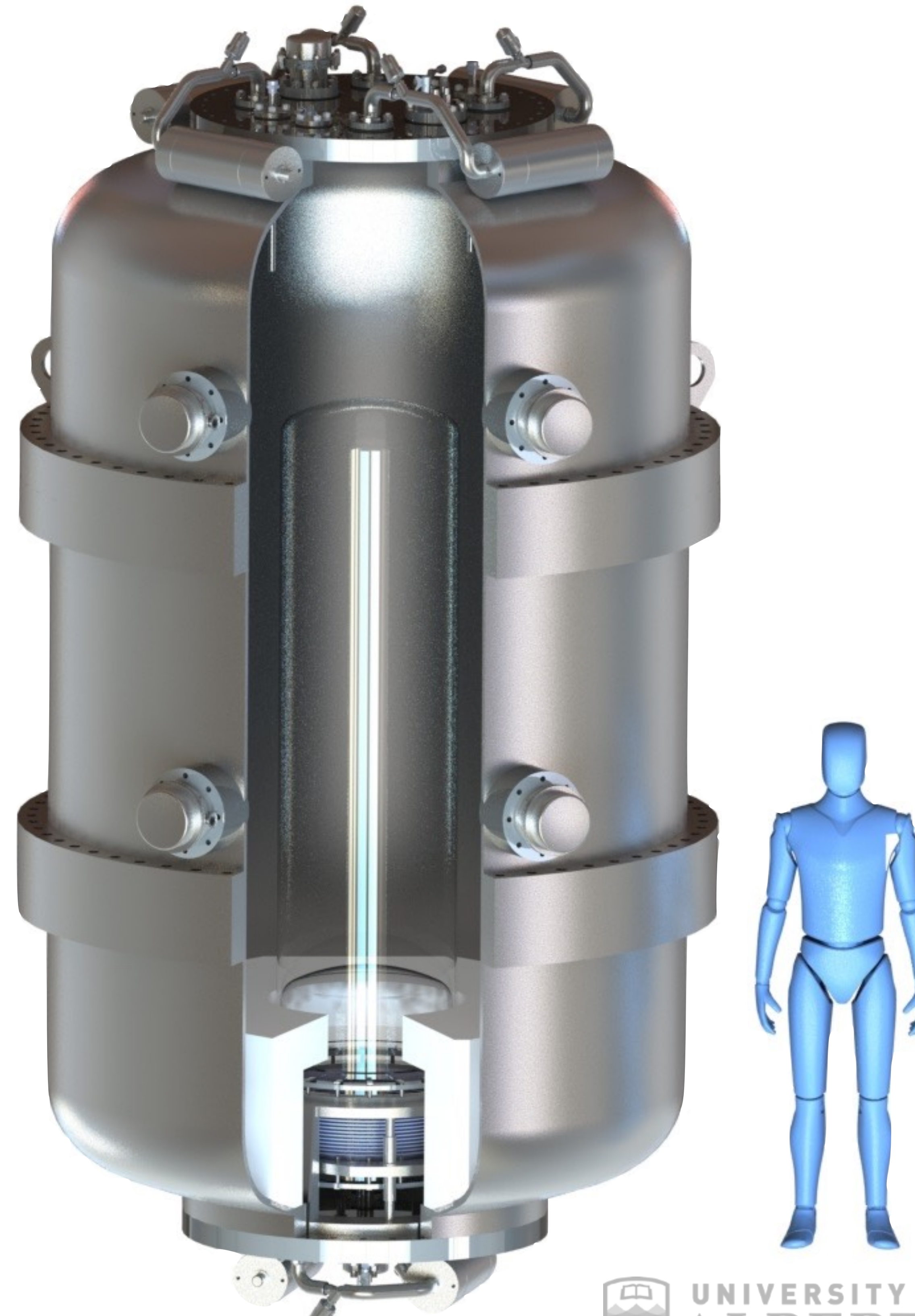

*T. Kozynets et al., Astroparticle Phys. 105 (2019) 25–30

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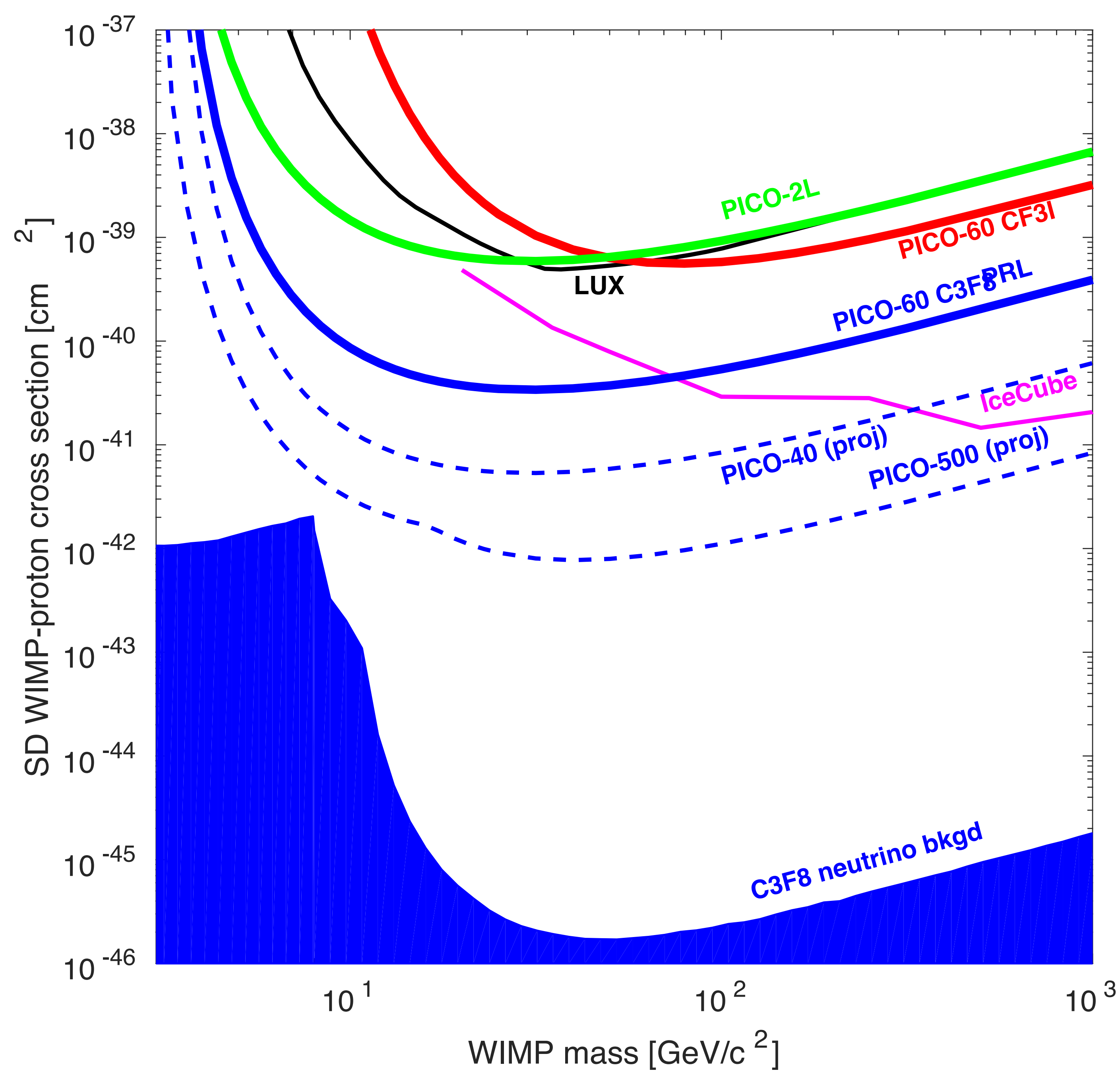
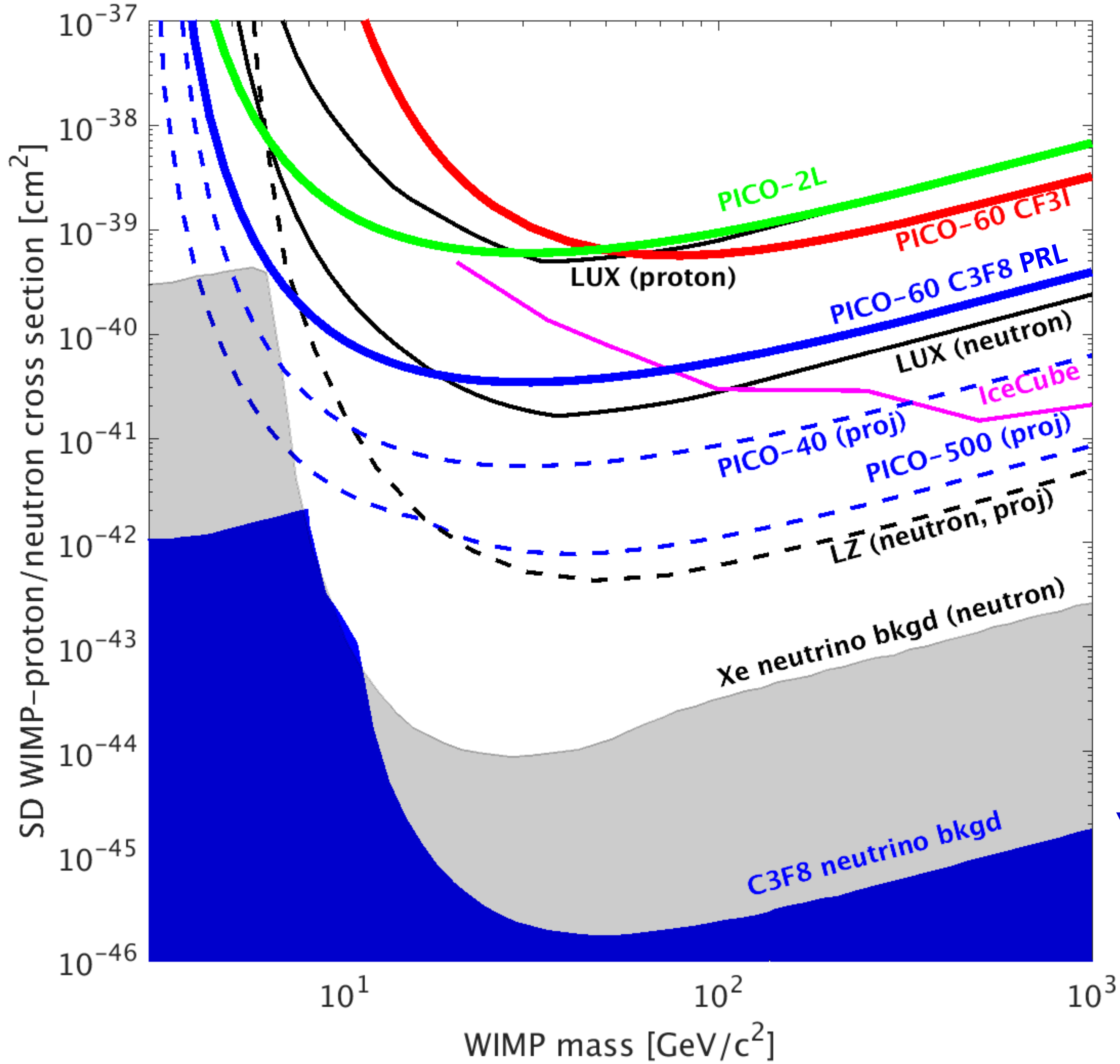
PICO-500 WIMP-SEARCH REACH

- Designed for at least an additional order of magnitude sensitivity beyond PICO-40L
- Initially planned/budgeted to run C_3F_8 – but can maintain flexibility to future target changes (i.e. CF_3I or hydrocarbons like $C_2H_2F_4$) to probe higher/lower mass or reduce a WIMP signal in a predictable way
- Begin to see a possible path from setting limits toward discovery



PICO-500 REACH IN CONTEXT

SD WIMP-proton/-neutron **combined** projections



complementarity with xenon

lots of room left above the C_3F_8 neutrino floor

CONCLUSIONS AND OUTLOOK

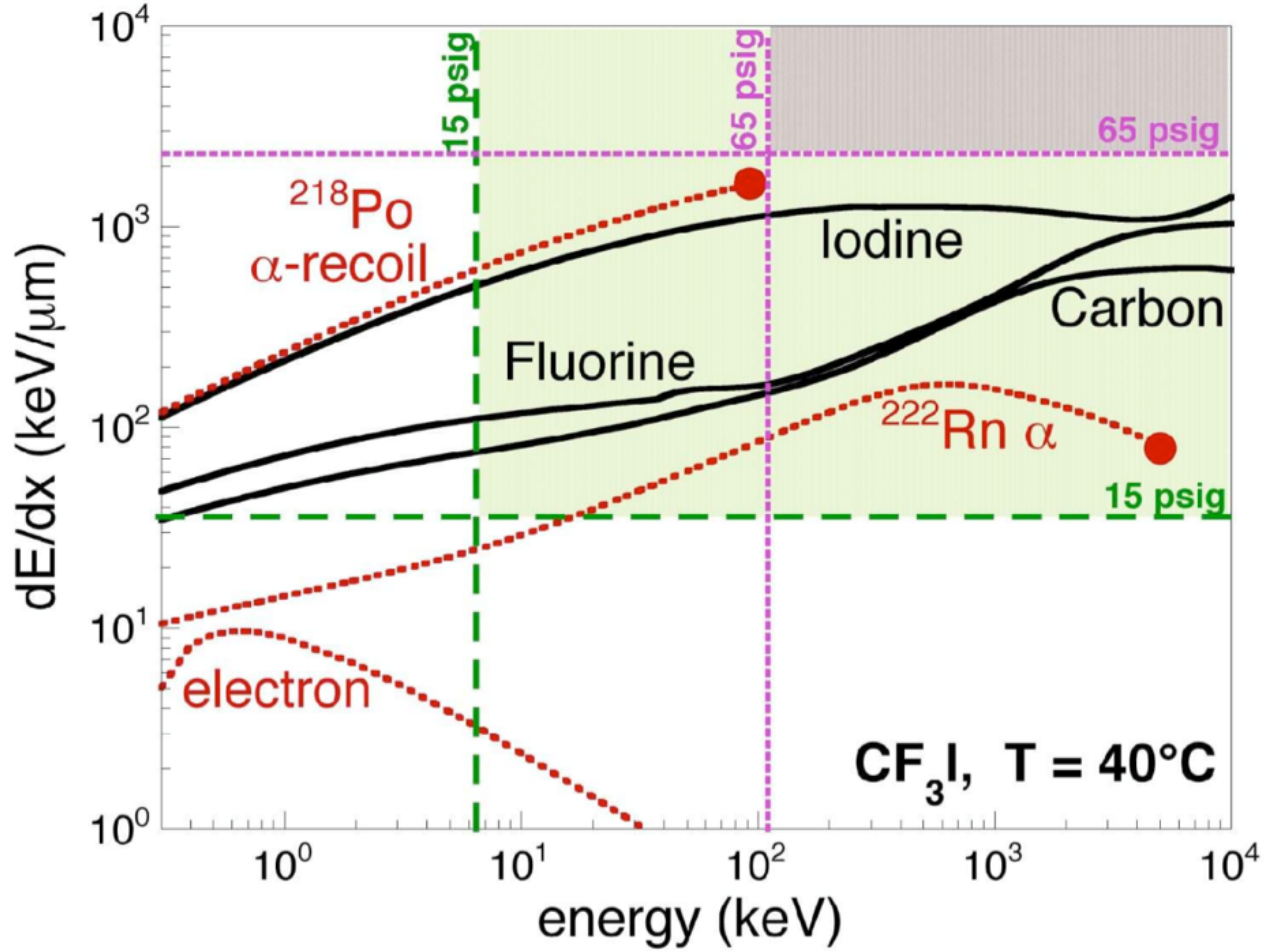
- PICO-60's complete exposure, while just background-limited, sets the best SD WIMP-proton limit from direct detection to date
  - Low-threshold stability demonstrates potential for future chambers to run at lower thresholds, probe lower WIMP masses
  - New calibration data at lower thresholds/nuclear recoil energies are required to fully exploit this sensitivity
- PICO-40L to begin taking data this summer
- PICO-500 installation to begin end of 2019

Extra slides

BACKGROUND ESTIMATES

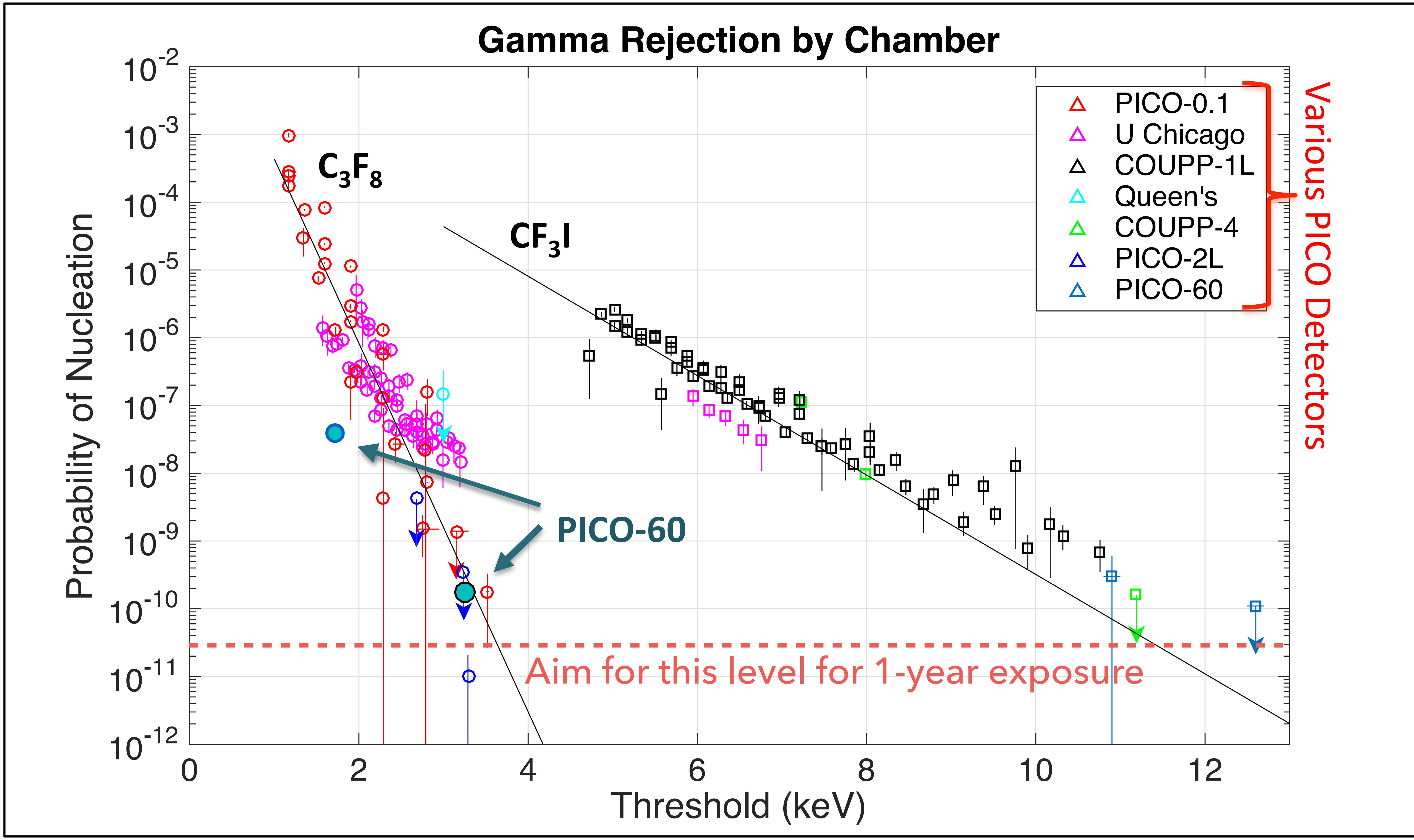
Seitz threshold	Neutron	Gamma	CEνNS	Total
2.45 keV	(0.8 ± 0.4)	(0.12 ± 0.02)	(0.10 ± 0.02)	(1.0 ± 0.4)

GAMMA REJECTION



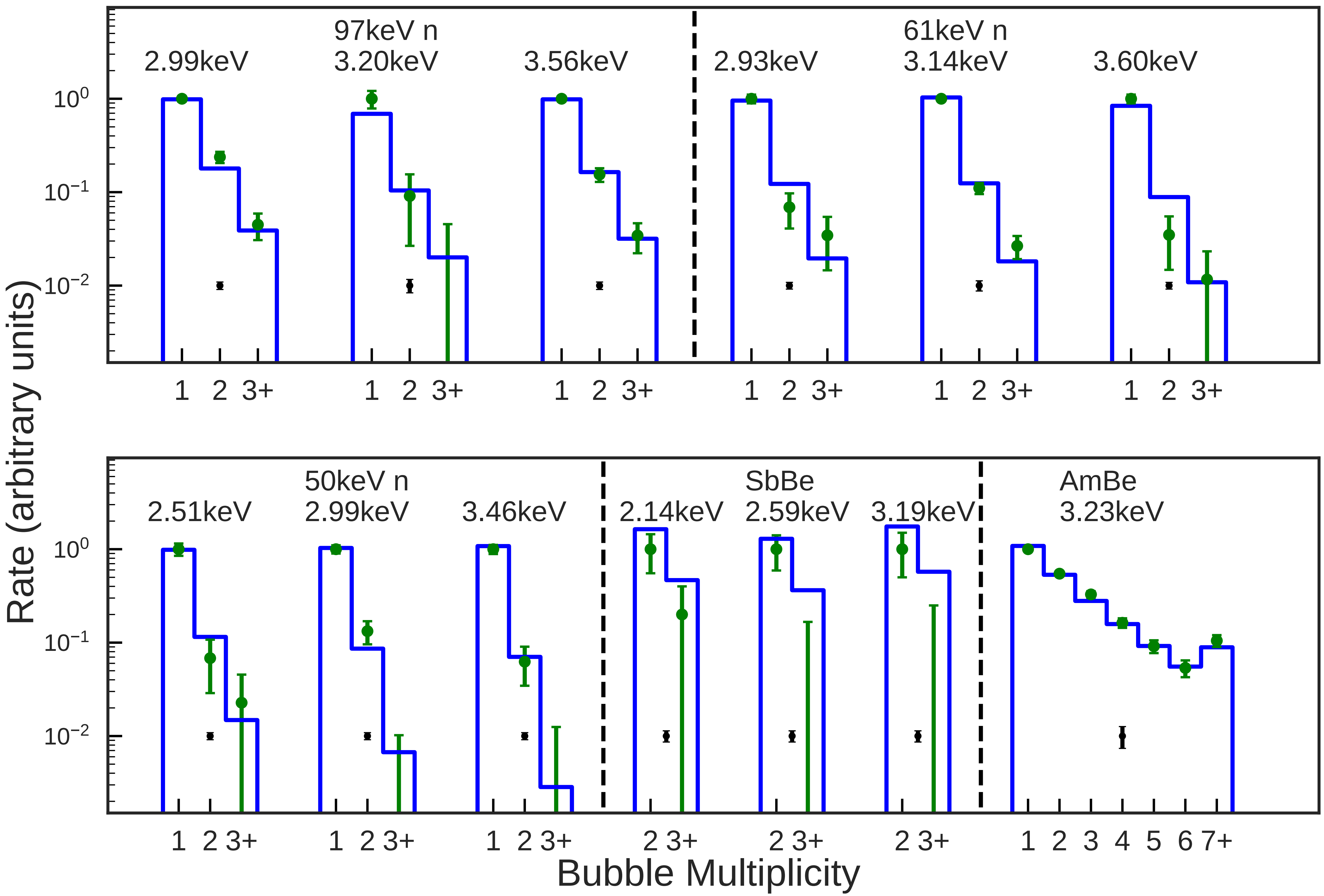
Choose thermodynamic parameters for sensitivity to nuclear recoils, but **not** electron recoils

GAMMA REJECTION (OLD MODEL)



(Dan Baxter, Conference on Science at SURF, May 14, 2017)

MCMC: GOODNESS OF FIT



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