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Instituto de Física Teórica UAM-CSIC
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UNIVERSITAT POLITÈCNICA DE VALÈNCIA

PICO:

Dark Matter Search Results from the PICO-60 C_3F_8 Bubble Chamber

Ivan Felis, Miguel Ardid

(Slides adapted from Dan Baxter talk at the Conference on Science at SURF, May 2017)

PICO

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J.I. Collar, A. Ortega

M. Laurin, A. Plante, N. Starinski, F. Tardif, V. Zacek

R. Figas, F. Mamedov, I. Stekl

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D. Maurya, S. Priya, Y. Yan

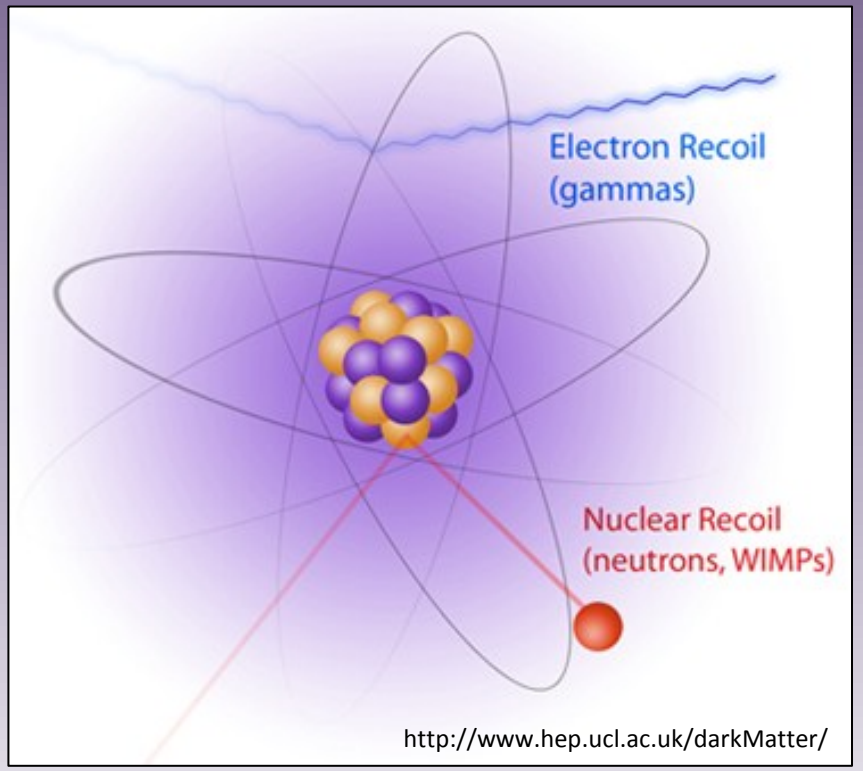
O. Harris

S. Fallows, C. Krauss, P. Mitra

E. Vázquez-Jáuregui

Dark Matter Detection

- Galactic dark matter may scatter with ordinary nucleii
- Interaction is rare
  - $\sigma < 10^{-40}$ cm^2
- Energy transfer is small
  - 1-100 keV
- Exact interaction is unknown
  - Does it depend on nucleon spin?
- Need to reject radioactive backgrounds



Bubble Chambers

located in SNOLAB

PICO-2L

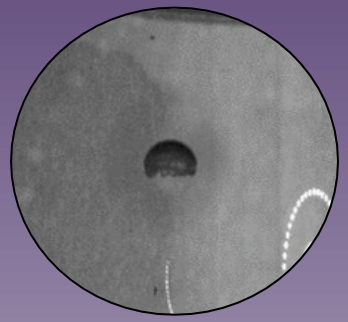
100 kg-day exposures

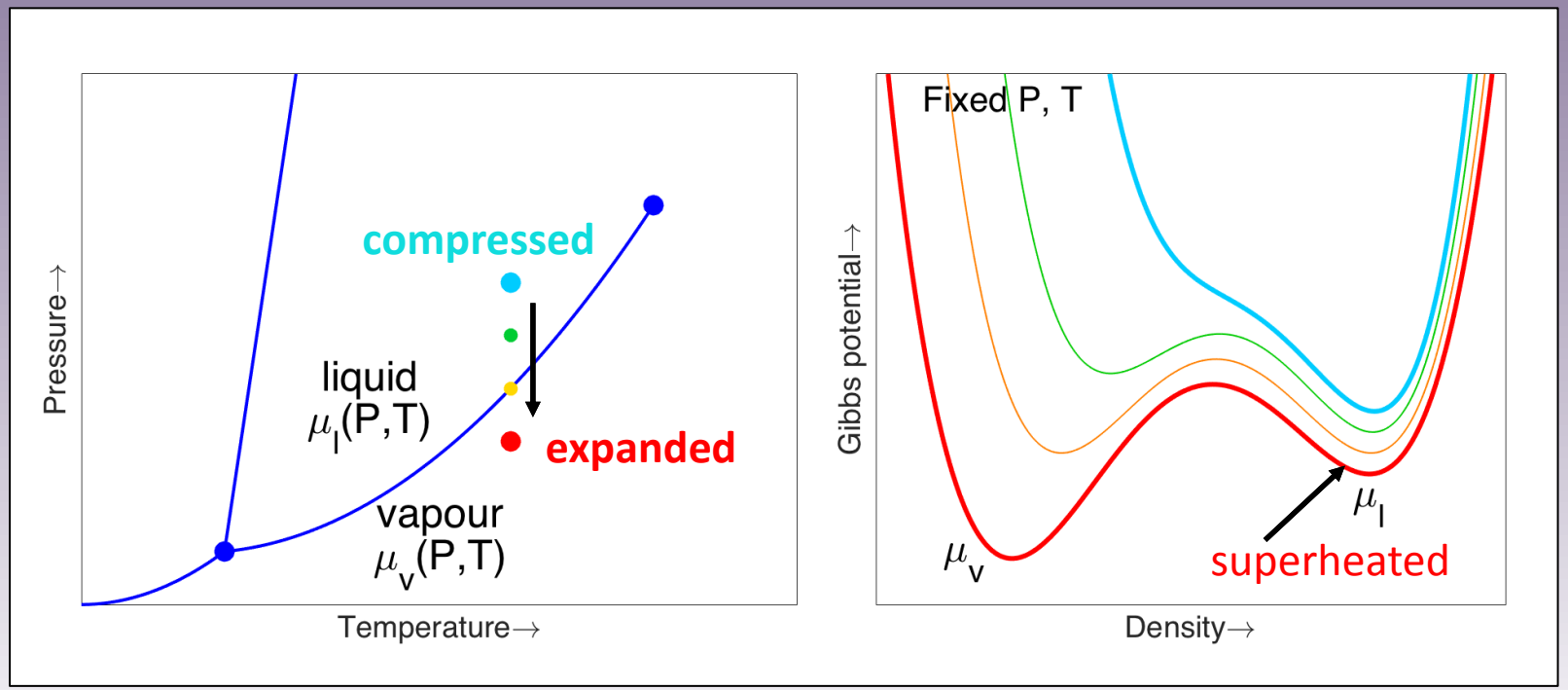
PICO-60

ton-day exposures

Basic Principles

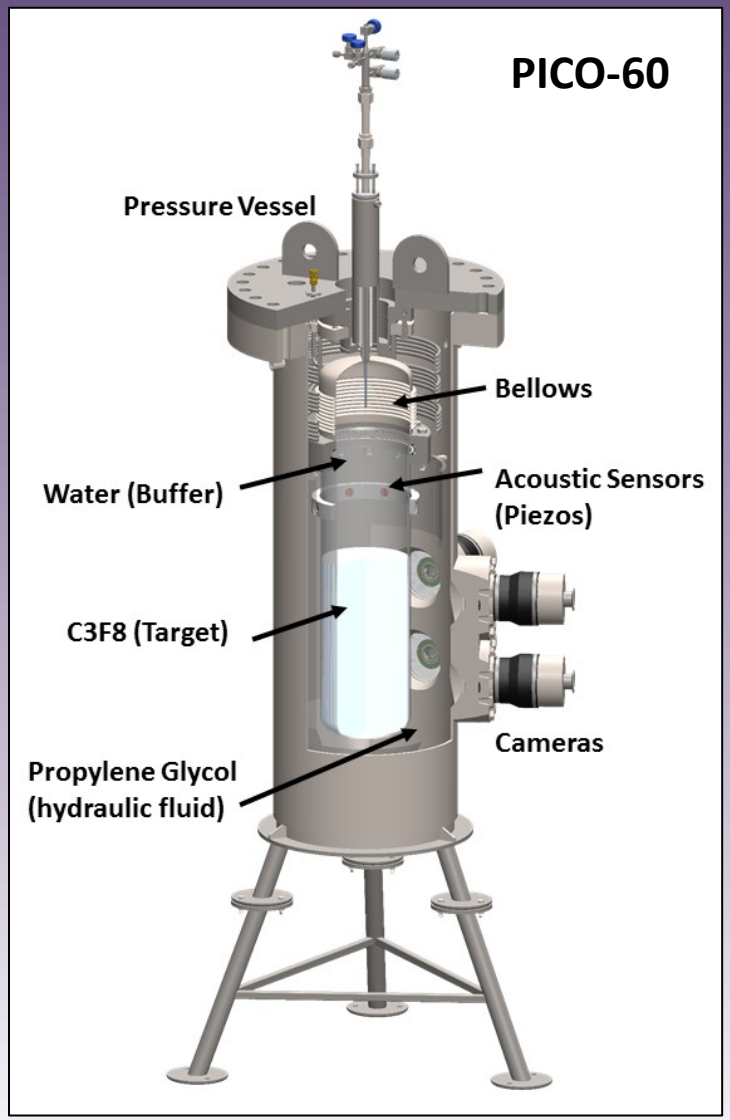
- Superheat a fluid by lowering pressure
- Wait for energy deposition in metastable state
- Interaction nucleates small gas pocket that grows
- Trigger on bubble with cameras



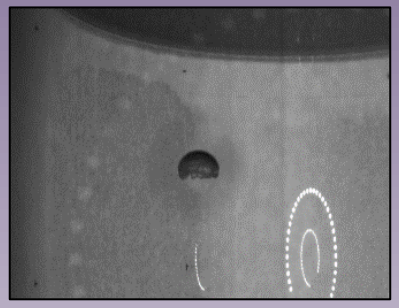


plots courtesy of Eric Dahl

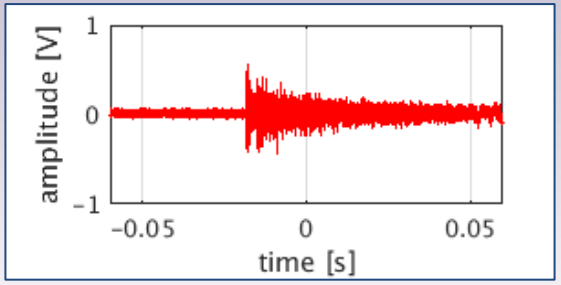
Bubble Chamber Design



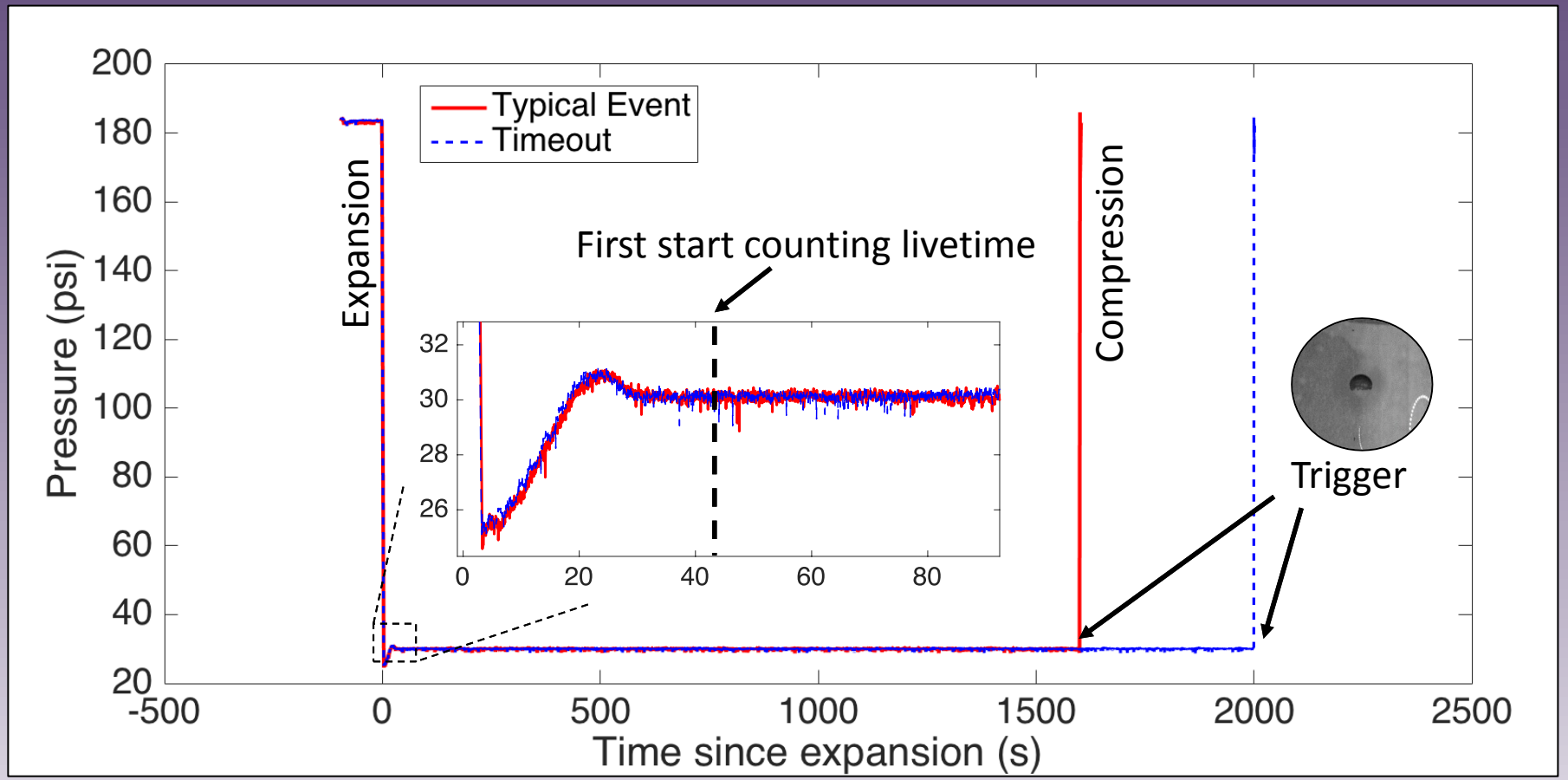
- Four cameras monitor for bubble nucleation in active liquid using LED illumination



- Eight piezoelectric acoustic sensors listen for the bubble



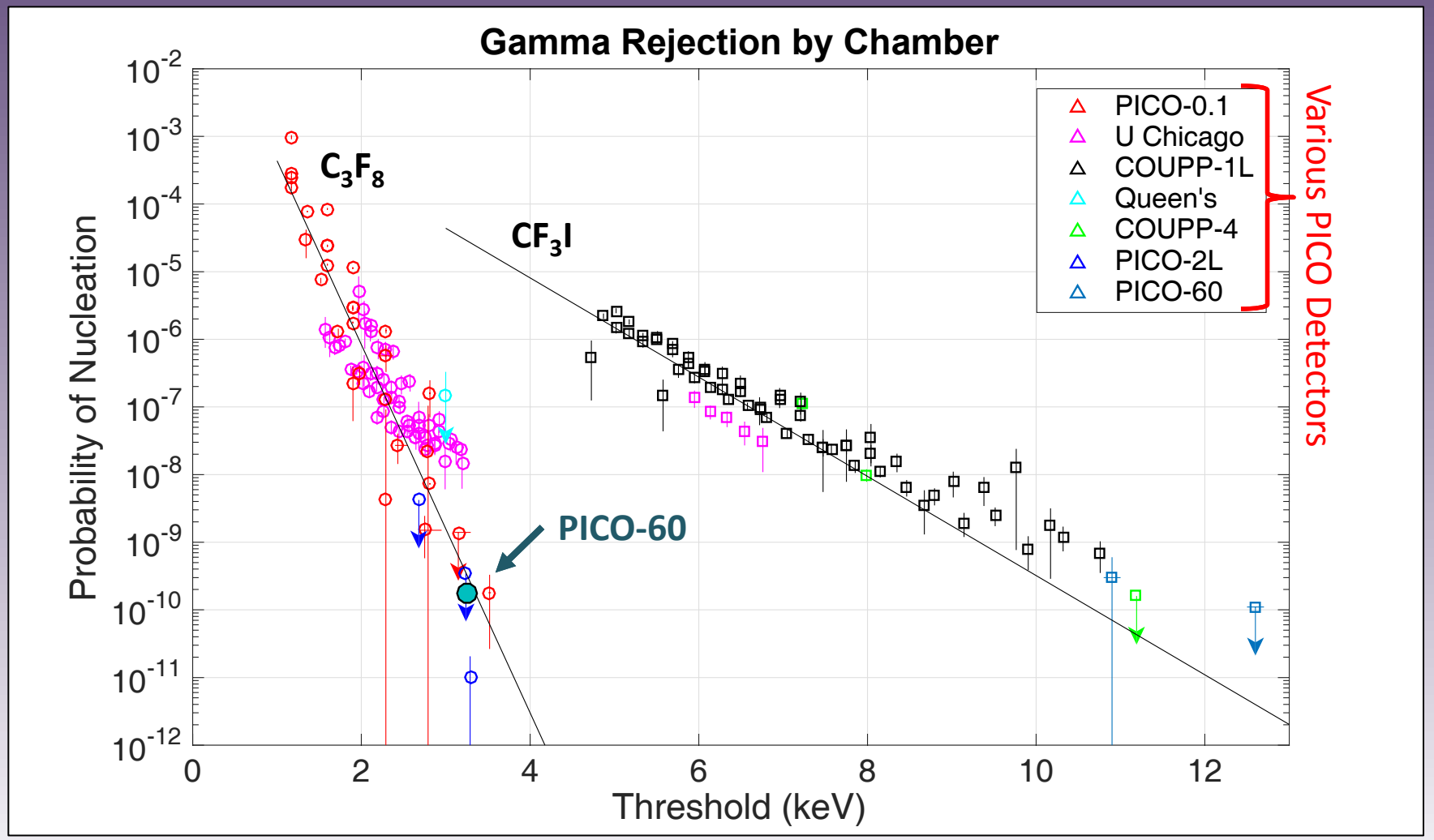
Detector Event Cycle



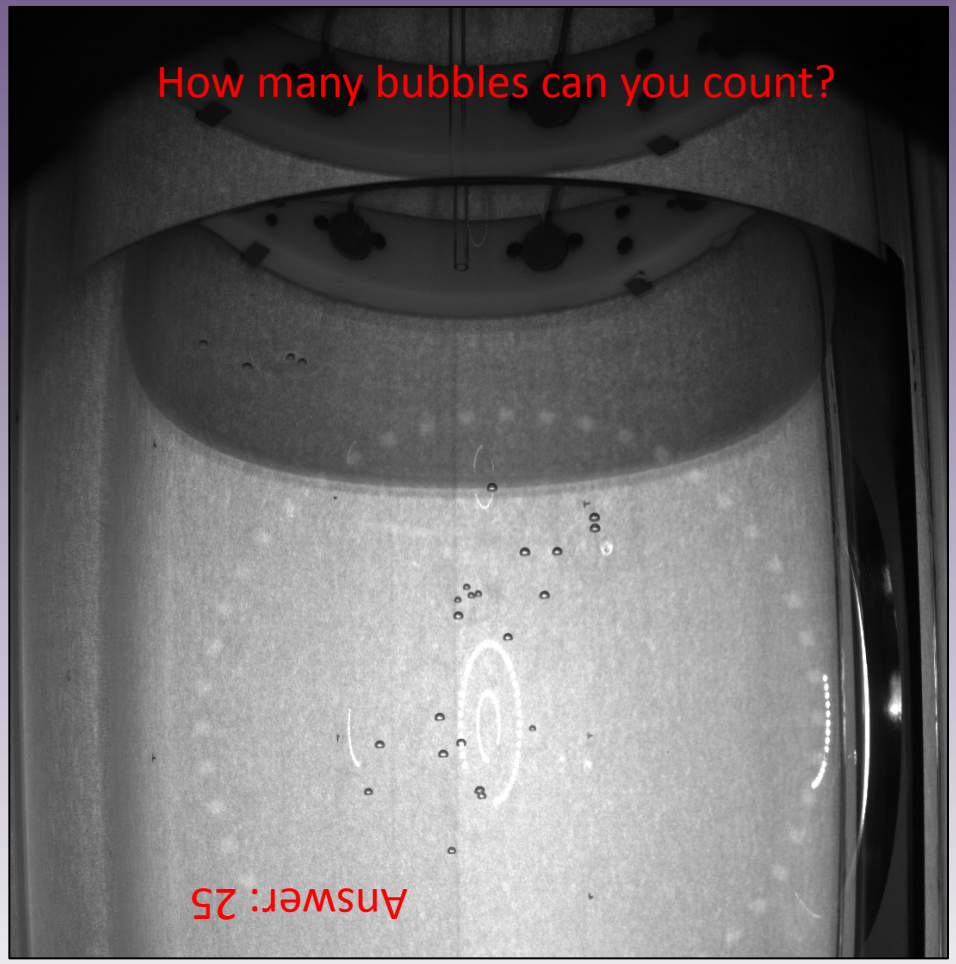
- Primary optical trigger (look for change in images)
- Timeout trigger at 2000s (improves stability)

Gamma/Beta Backgrounds

Our detectors have a dE/dx threshold (E_T/r_c) that we get to set



Neutron Backgrounds

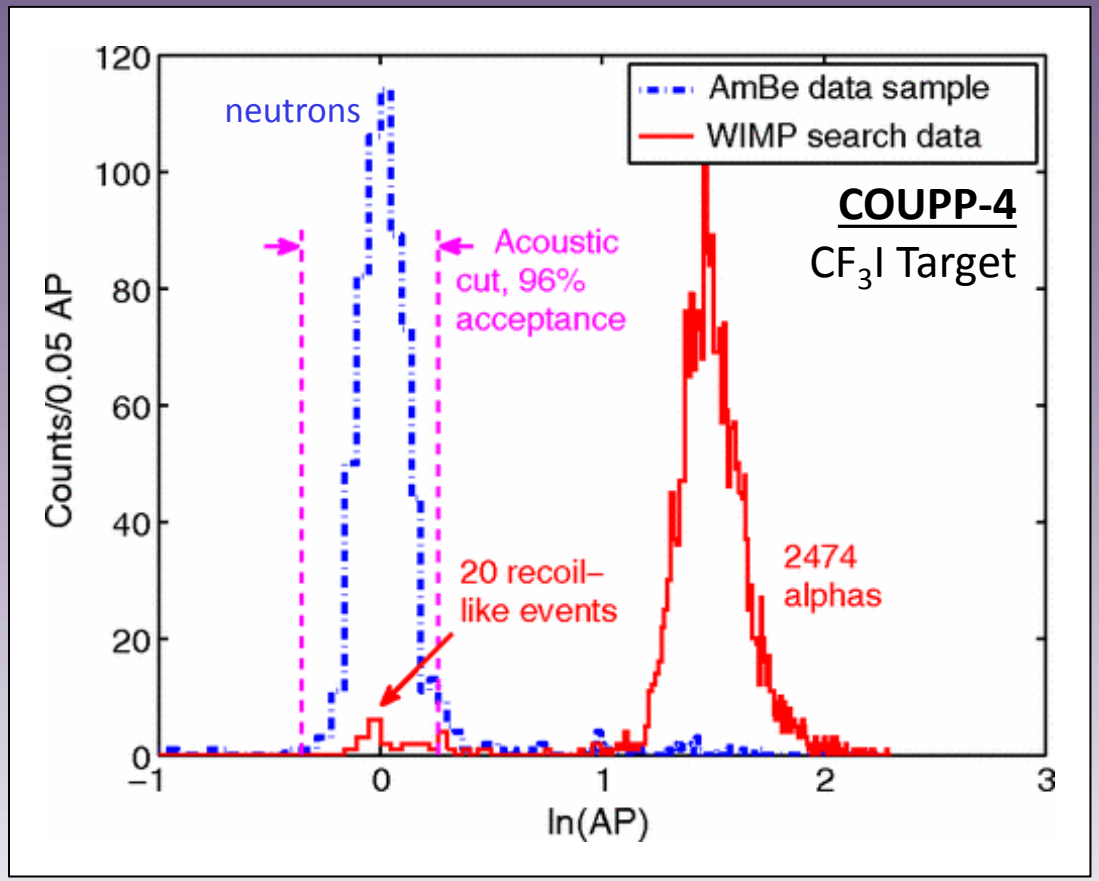


- Preferentially Multiple-scatter
  - Allows us to measure background rate directly
- Simulation tells us to expect 3:1 multiples to singles ratio
- Dominated by detector materials

Alpha Decay Backgrounds

- Measure the acoustic power of an event to construct AP (acoustic parameter)

- Three populations:
  1. Neutrons *(Normalize AP to nuclear recoil signature)*
  2. Alphas are louder!
  3. Recoil-like background…

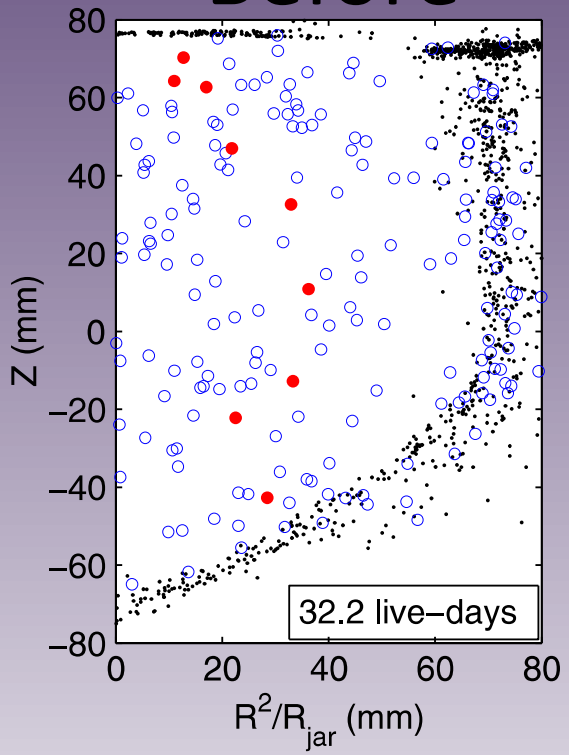


E. Behnke *et al*. Phys. Rev. D 86, 052001 (2012)

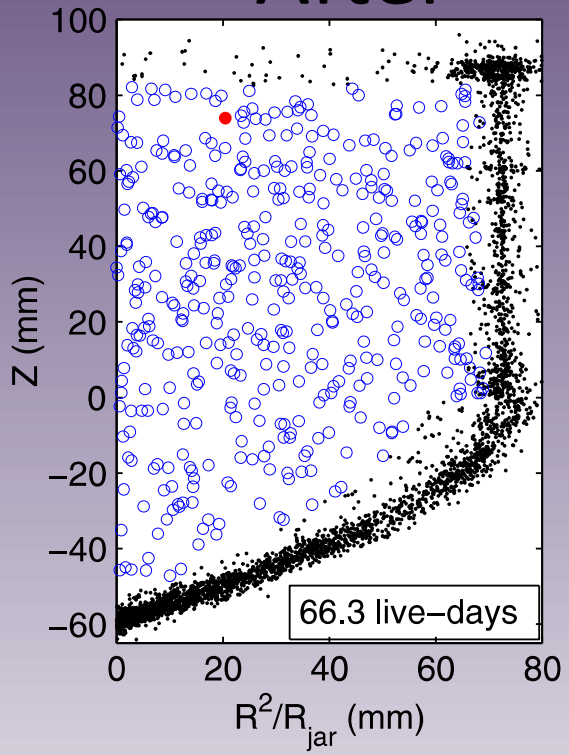
Anomalous Background

- PICO-2L Run1
  - 9 candidate events in 32 live-days at 3.2keV
  - **Inconsistent with known radioactive backgrounds AND dark matter**
- PICO-2L Run2
  - 1 candidate event in 66 live-days at 3.2keV
  - **Consistent with neutron expectations**
- Between runs, the detector was cleaned of particulate contamination

Before



After

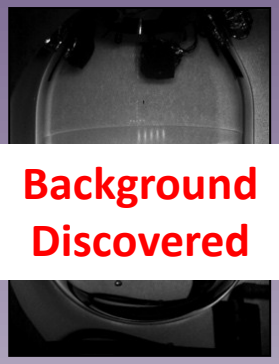


C. Amole *et al*. Phys. Rev. D 93, 061101(R) (2016)

Hypothesis: combination of particulate matter and water leads to anomalous nucleation mechanism

PICO Timeline

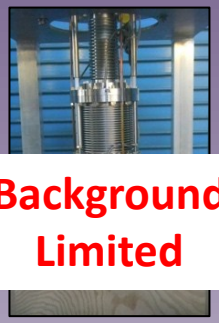
COUPP-4 (2011)
CF_3I Target



Background Discovered

Try switching target fluids

PICO-2L (2014)
C_3F_8 Target

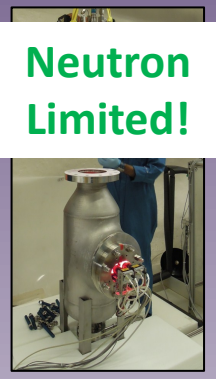


Background Limited

Try removing particulate

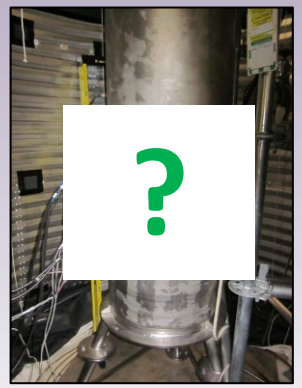
PICO-2L (2016)
C_3F_8 Target

Neutron Limited!



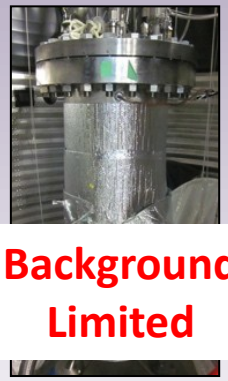
Try scaling

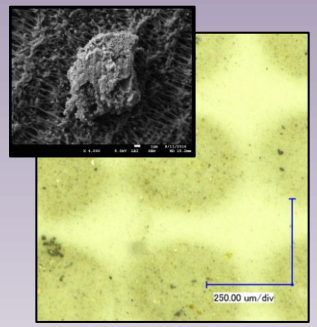
PICO-60 (2017)
C_3F_8 Target



Try scaling to increase statistics

PICO-60 (2014)
CF_3I Target

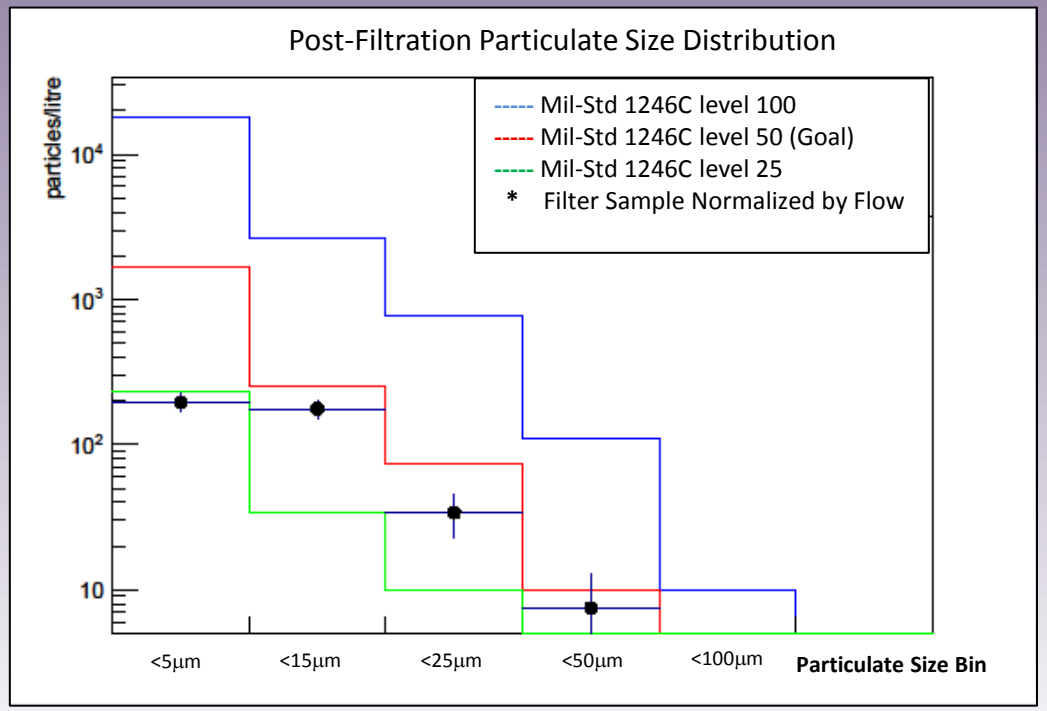




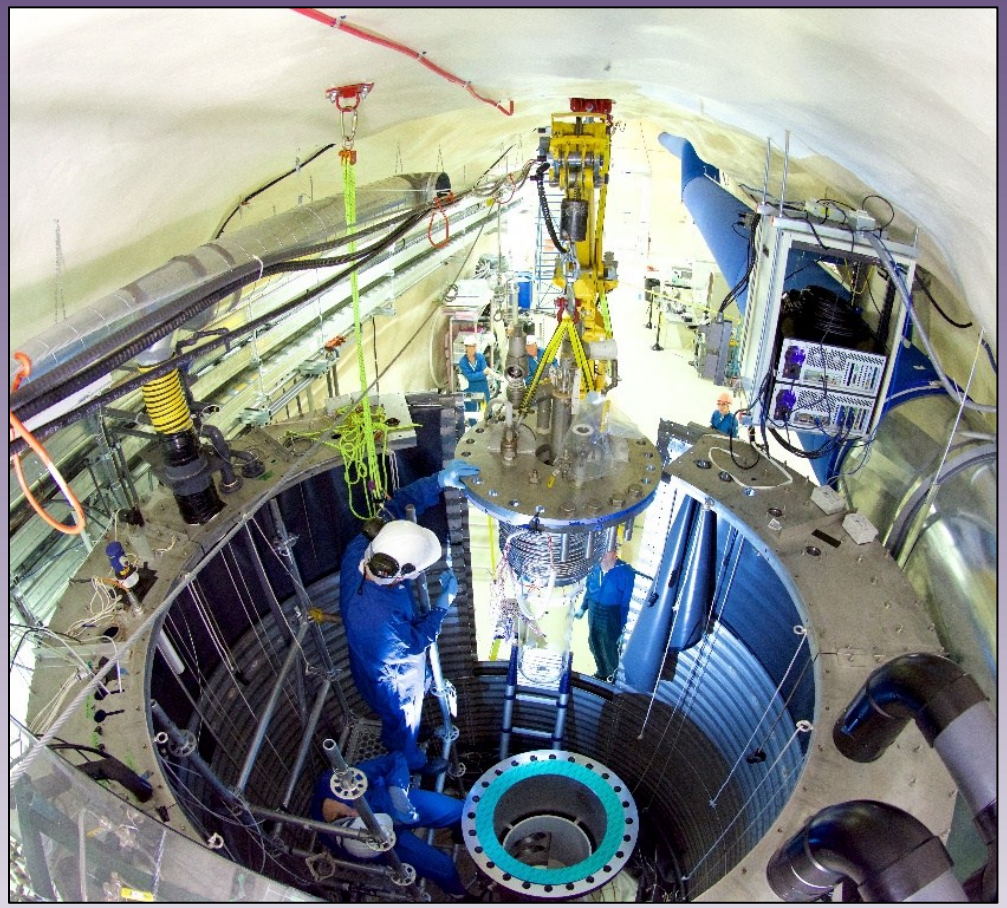
Background Limited

PICO-60 Cleaning

- Every component touching the inner volume was cleaned against MIL-STD-1246C level 50



Commissioning



- Filled with 40L C_3F_8 on June 30, 2016
- First physics run Nov. 2016 – Jan. 2017

What do we measure?

- Camera images (primary trigger)
  - Was there a bubble (Y or N)? **Electron Recoil Rejection**
  - How many bubbles were there? **Neutron Rejection**
  - What were the bubble positions? **Surface Rejection**
- Temperature
- Pressure (secondary trigger)

Threshold Determination

- Acoustic signal **Alpha (radon) Rejection**

What do we measure?

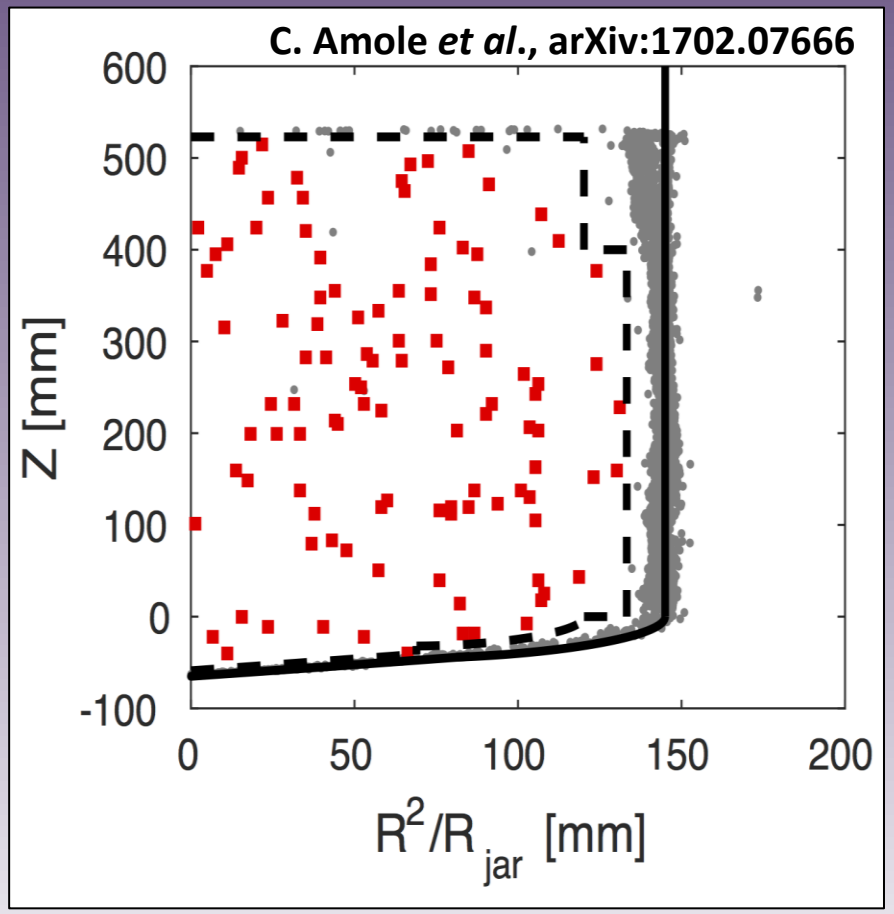
- Camera images (primary trigger)
  - Was there a bubble (Y or N)? **Electron Recoil Rejection**
  - How many bubbles were there? **Neutron Rejection**
  - What were the bubble positions? **Surface Rejection**
- Temperature
- Pressure (secondary trigger)

Threshold Determination

Blind this information

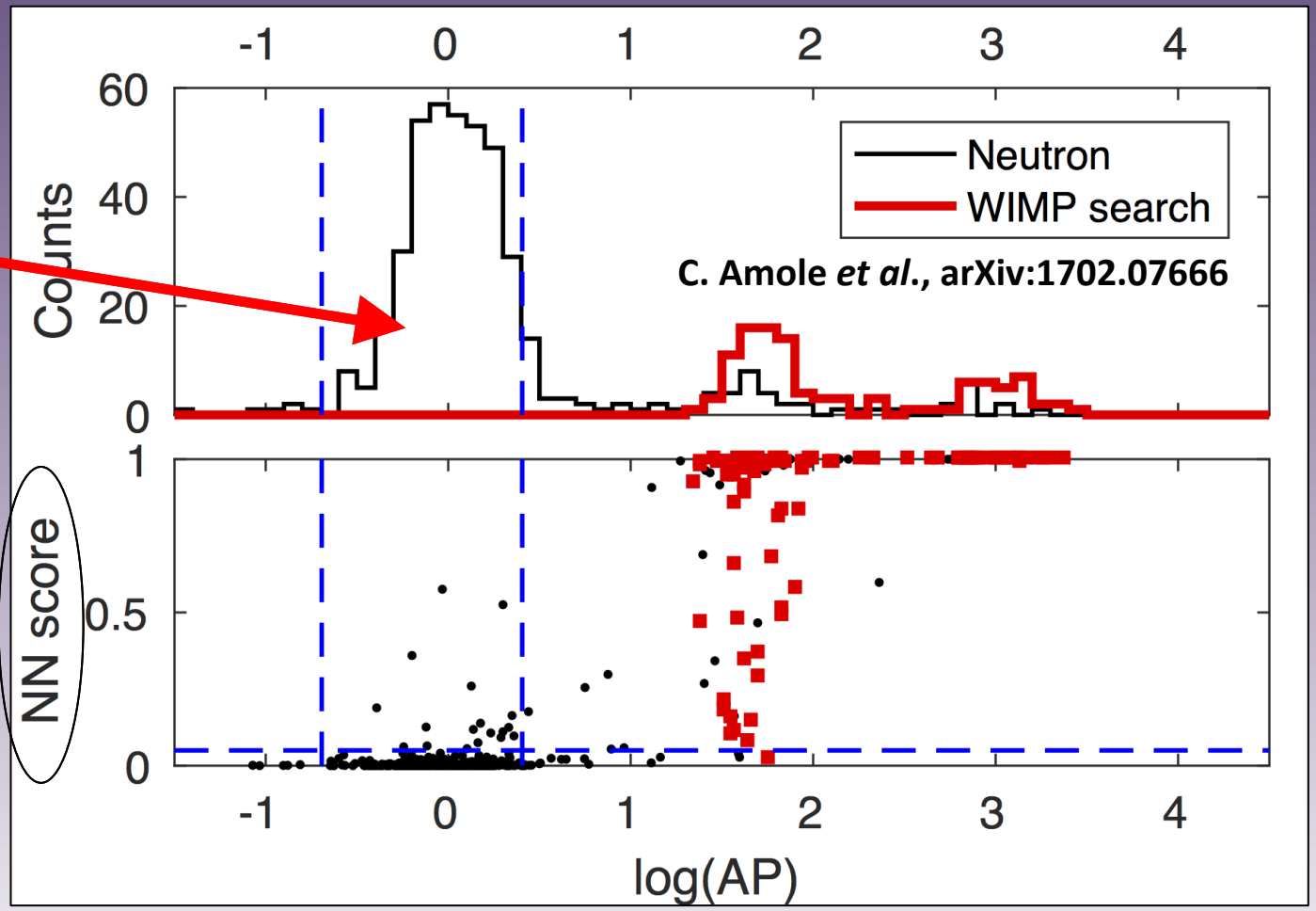
Before Opening the Box

- 106 bulk singles in WIMP search dataset
  - *Acoustics Still Blind*
  - Consistent with Rn decay rate in pre-WIMP search unblinded data
- Neutron Background
  - Not blinded to multiplicity
  - 3 multiple bubbles in the physics data
  - Multiples to singles ratio is approximately 3:1 from calibration and simulation
- **Conclusion: 0-3 bulk singles would be consistent with neutrons and no anomalous background**



After Opening the Box

No events in signal region!



(~ Acoustic Power)

Neural Network Acoustic Analysis

- Not as good as AP, ***yet…***

PICO-60 Results

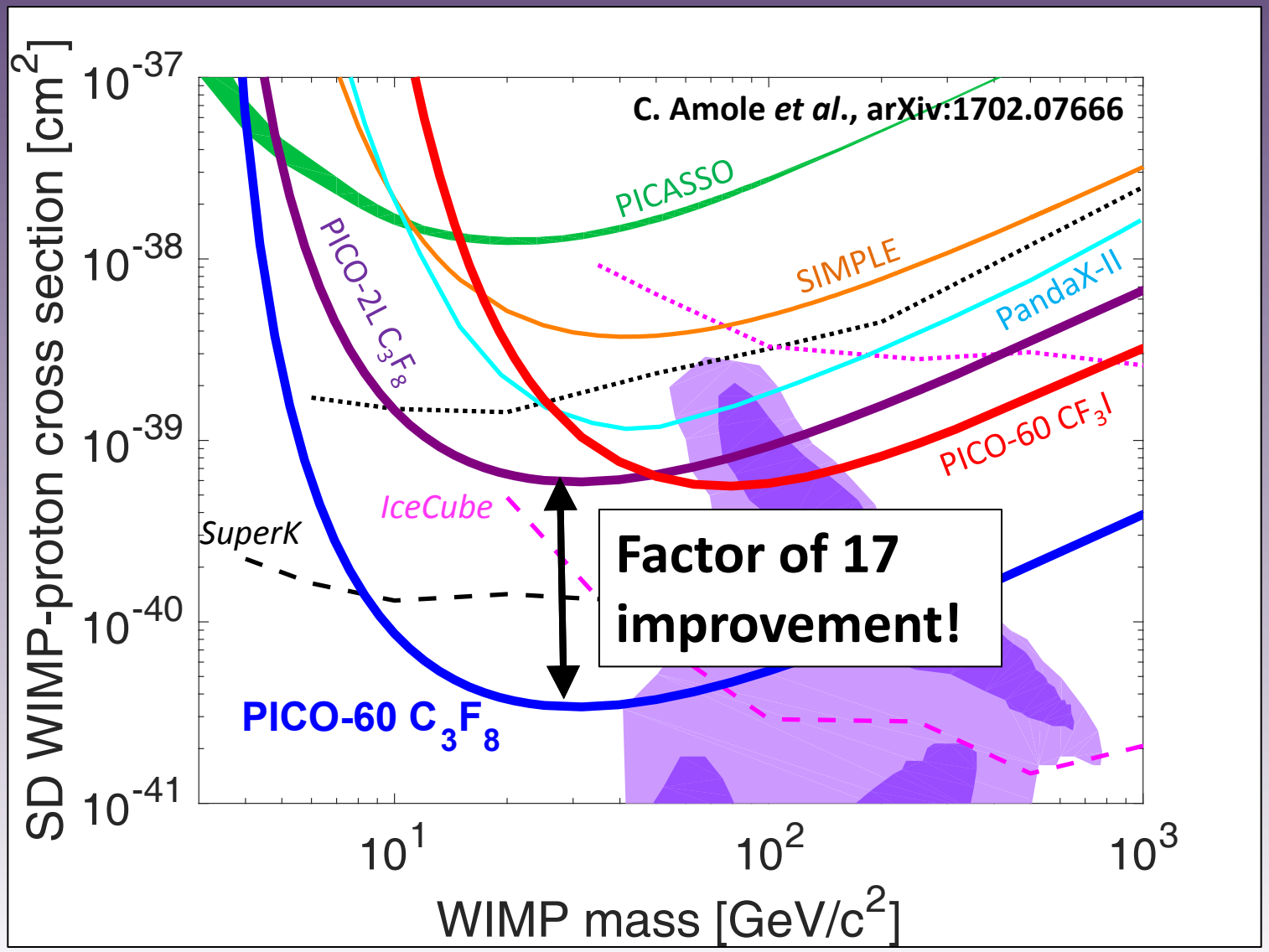
Dataset	Efficiency (%)	Fiducial Mass (kg)	Exposure (kg-days)	No. of events
Singles	85.1 ± 1.8	45.7 ± 0.5	1167 ± 28	0
Multiples	99.4 ± 0.1	52.2 ± 0.5	1555 ± 15	3

TABLE I. Summary of the final number of events and exposure determination for singles and multiples in the 30.0 live-day WIMP search dataset of PICO-60 C_3F_8 at 3.3 keV thermodynamic threshold.

C. Amole *et al.*, arXiv:1702.07666

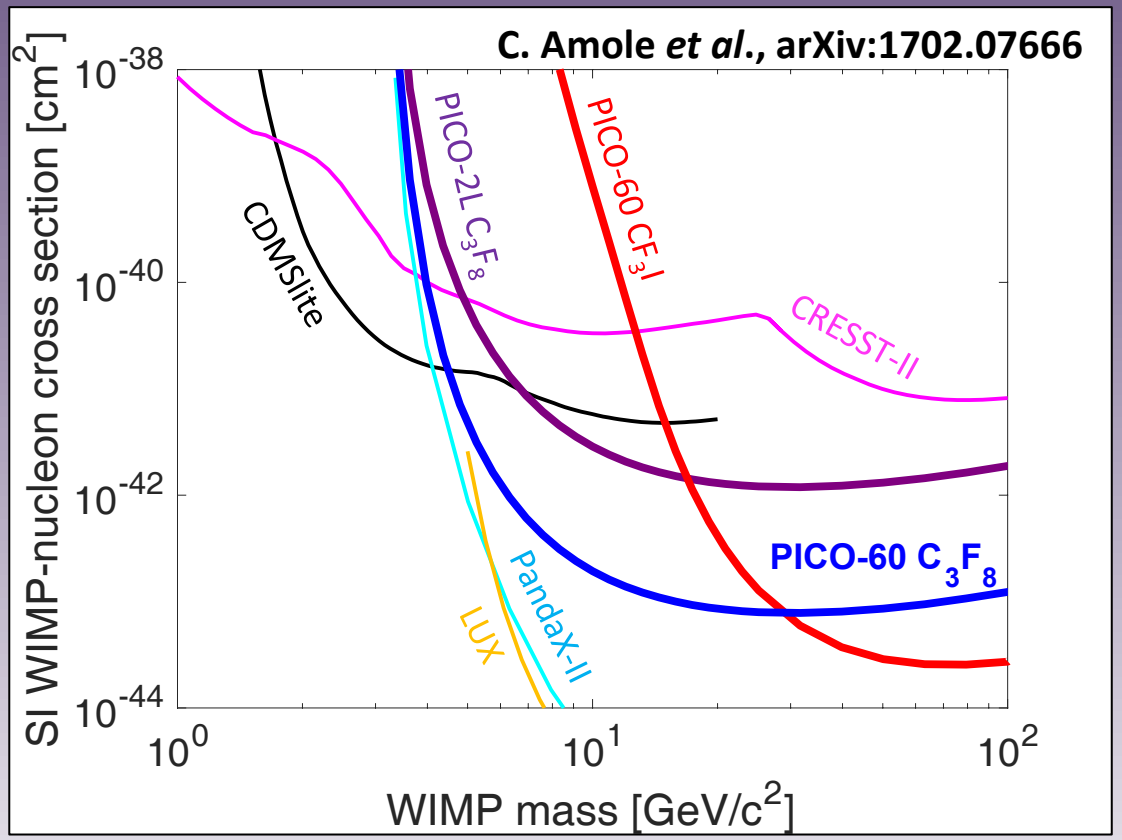
- Multiples efficiency is higher because no fiducial, acoustic cuts
- We simulate and measure a 3:1 ratio of multiples to singles for neutron calibration data
- **Of the 106 fiducial-bulk singles, none are consistent with nuclear recoil hypothesis (all are consistent with radon chain alphas)**

Spin-dependent Limits



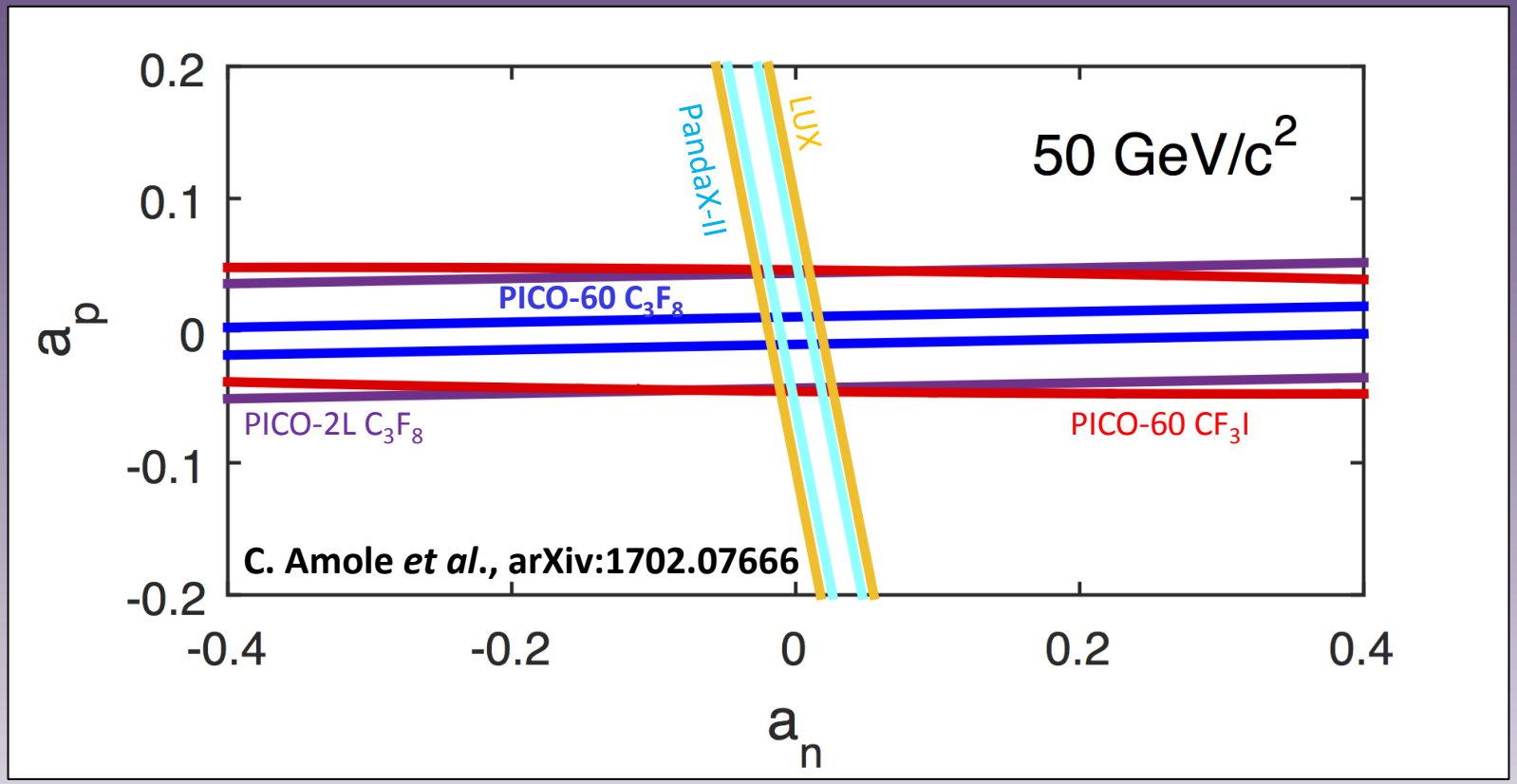
Spin-independent Limits

- Light nuclear targets give sensitivity to low-mass WIMPs
- Unexplored phase space would be accessible with slightly reduced threshold
- short runs with reduced threshold ongoing to explore low WIMP masses.



Nucleon Coupling Limits

Consider spin-dependent coupling to proton and neutron

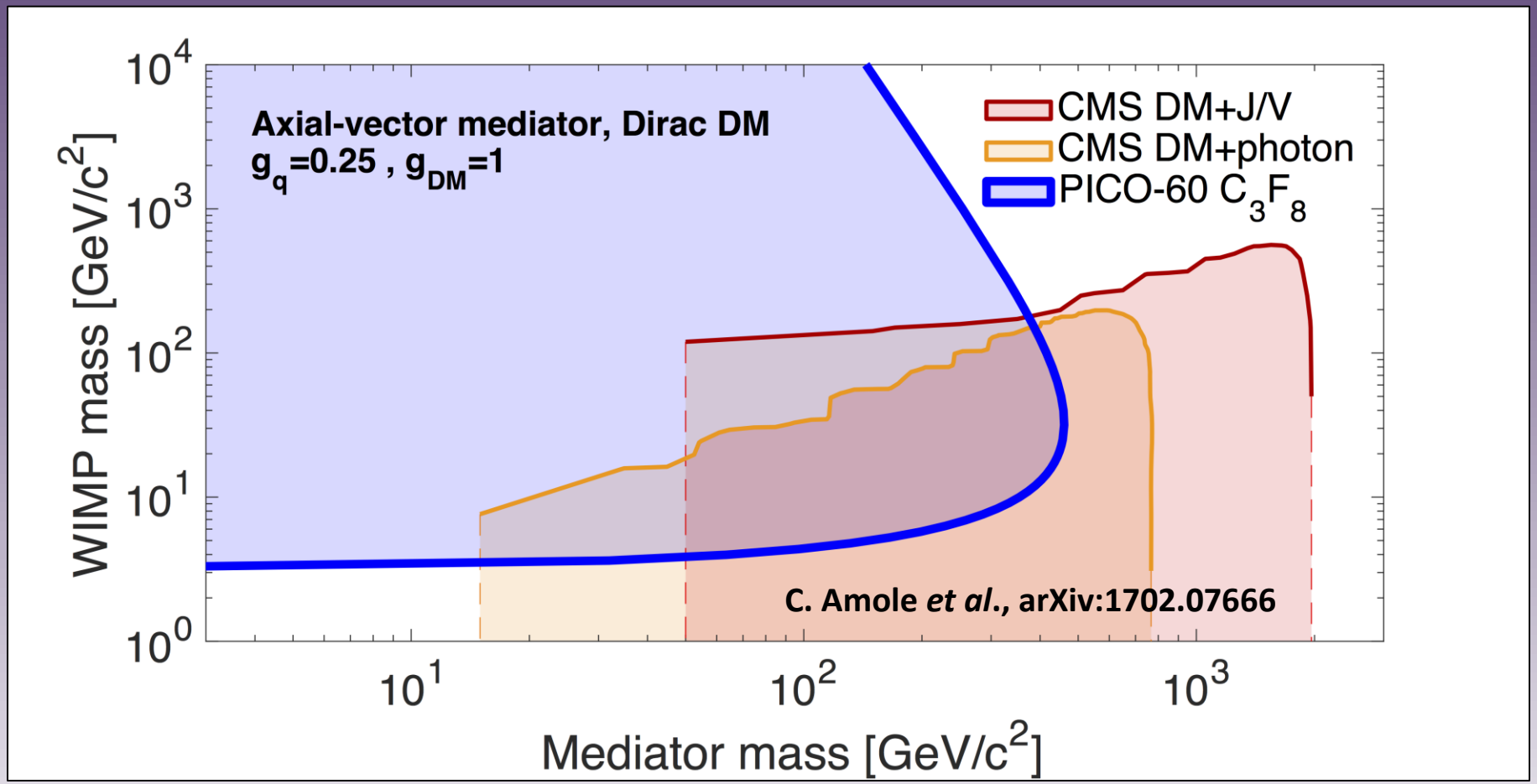


See Tovey for details:

D.R. Tovey, *et al.*, Phys. Lett. B 488, 17 (2000)

$$\sigma_A^p = \frac{32 G_F^2 \mu_A^2}{\pi} \left(a_p \langle S_p \rangle\right)^2 \frac{J+1}{J}$$

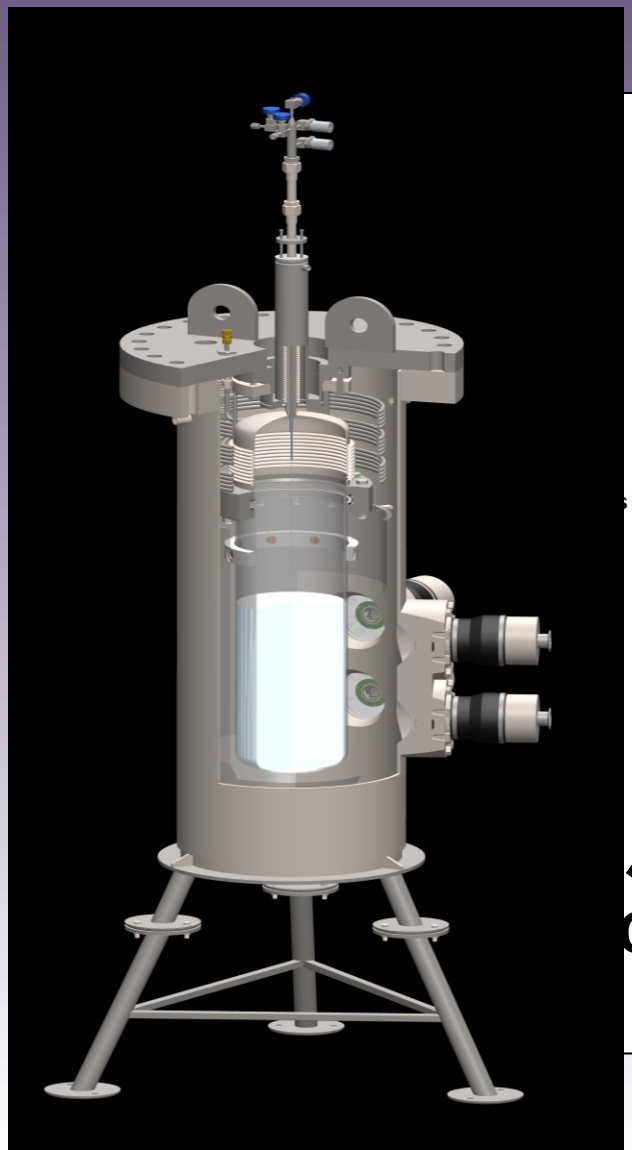
Comparison to Collider



Idea: rather than try to plot model-dependent collider limits in our space, let's plot our limits on their model

PICO-40L

Eliminate buffer fluid

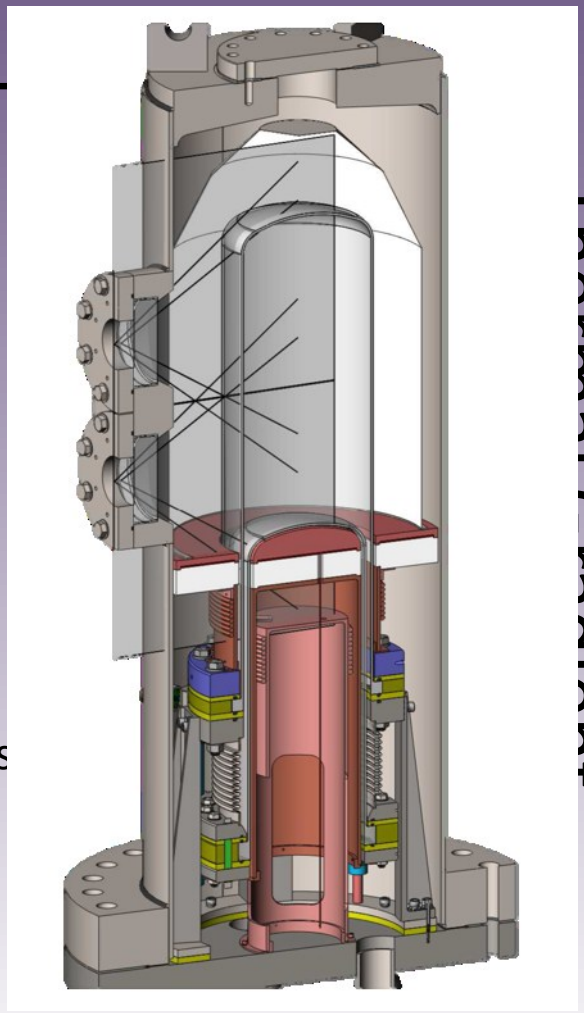


Purpose of buffer liquid is to isolate the active liquid from the stainless parts

PICO-

O-60

Thermal gradient can ensure that target fluid near stainless parts is not active



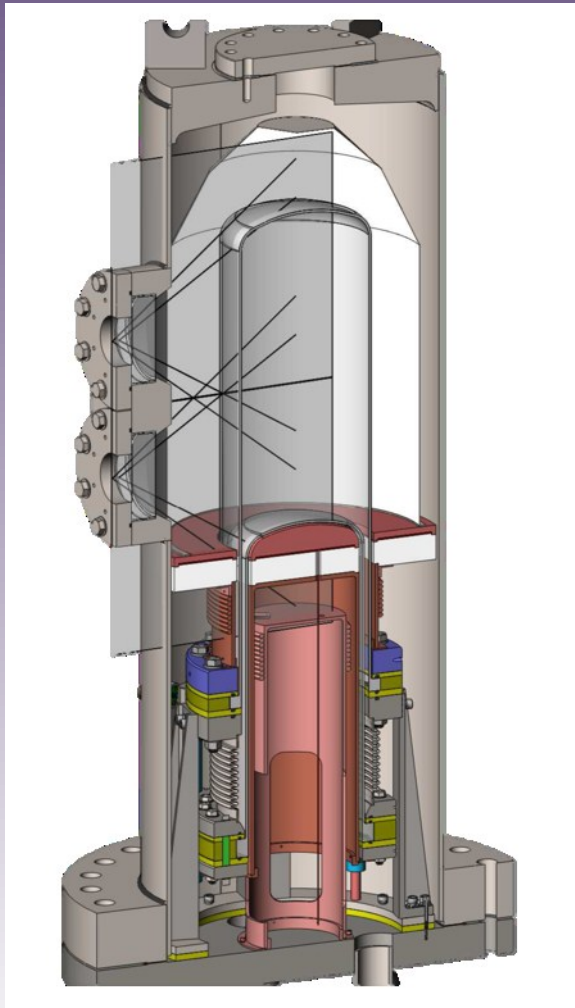
Thermal Gradient

(Installation, this summer)

PICO-40L

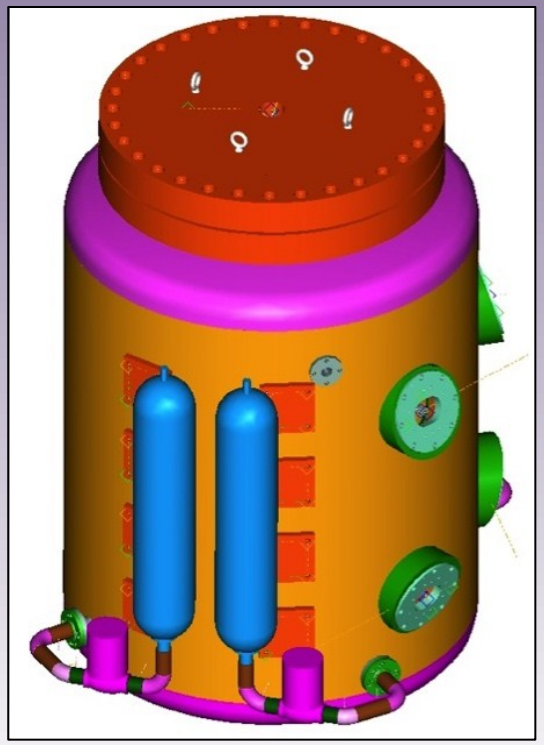
Physics reach

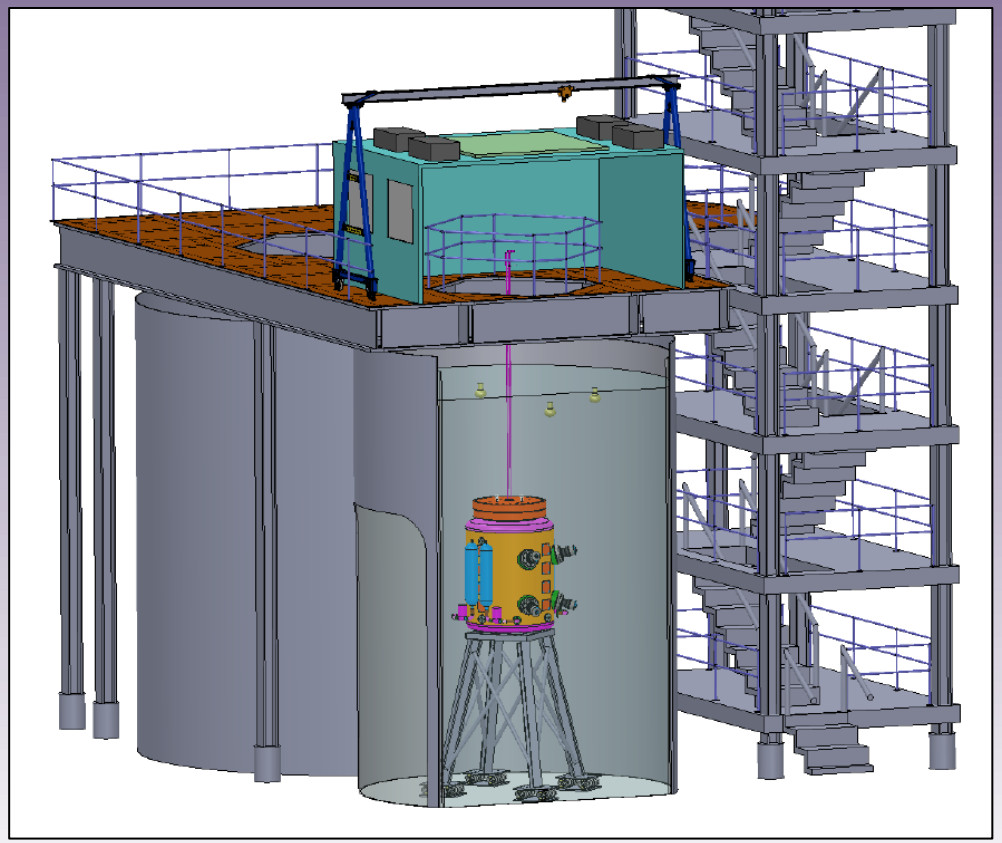
1. Added stability could allow us to push down in threshold (WIMP mass) until we hit ER backgrounds
2. Ability to use new target fluids optimized for different WIMP masses
3. Reduced neutron backgrounds, allowing us to push down in cross-section



PICO-500

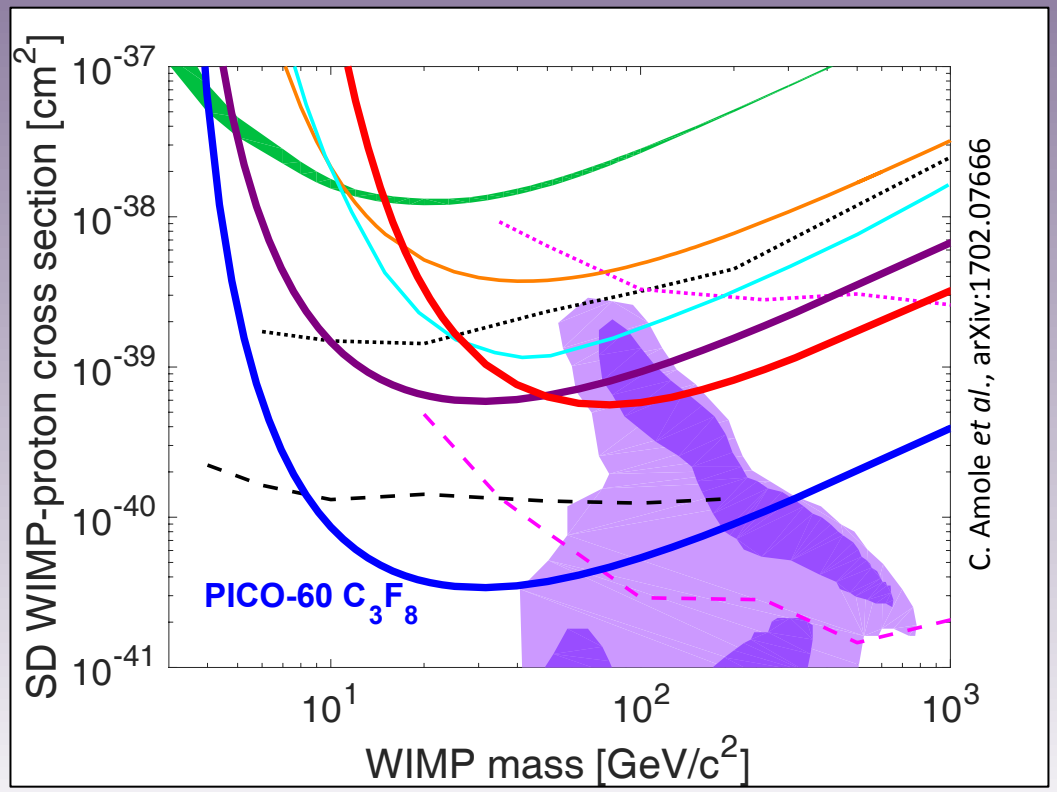
- Engineering work ongoing as part of R&D program
- Proposal for full detector ($3M CAD) currently submitted to CFI, decision expected this summer





PICO-60 Summary

- PICO bubble chambers at the 40L scale are background-free
- PICO dominates the search for spin-dependent WIMP-proton coupling



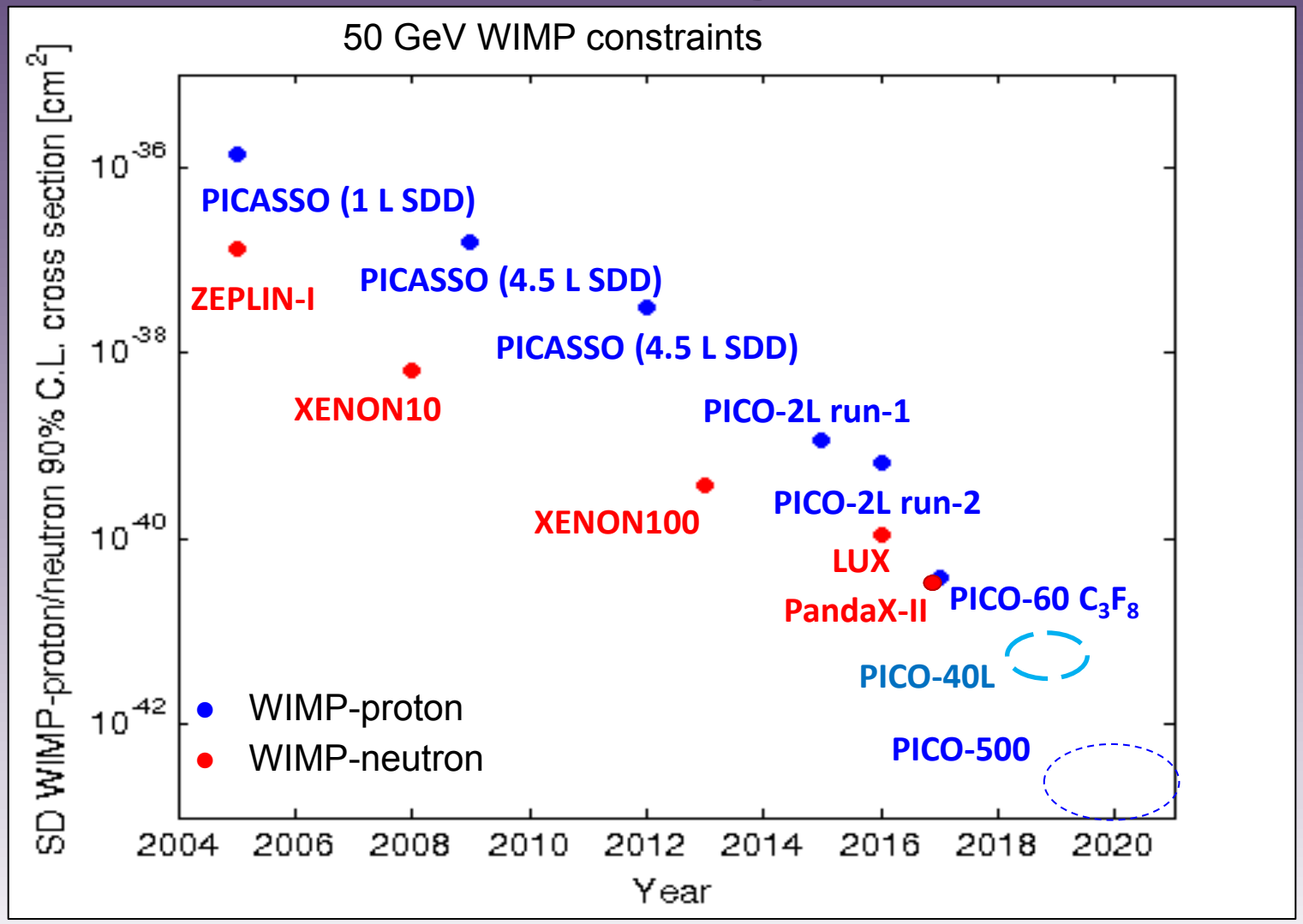
Acknowledgements

- Support:
  - SNOLAB, the National Sciences and Engineering Research Council of Canada (NSERC), the Canada Foundation for Innovation (CFI), the National Science Foundation (NSF) (Grant 1506337, 1242637 and 1205987), U.S. Department of Energy (DOE) Office of Science, Office of High Energy Physics (under award DE-SC-0012161), the Department of Atomic Energy (DAE), DGAPA-UNAM through grant PAPIIT No. IA100316, CONACyT (Mexico) through grant No. 252167, the Government of India, under the Center of AstroParticle Physics II project (CAPP-II) at SAHA Institute of nuclear Physics (SINP), the Czech Ministry of Education, Youth and Sports (Grant LM2015072) and **the Spanish Ministerio de Economía y Competitividad, Consolider MultiDark (Grant CSD2009-00064)**, Fermi National Accelerator Laboratory (Contract No. De-AC02-07CH11359), and Pacific Northwest National Laboratory, which is operated by Battelle for the U.S. Department of Energy under Contract No. DE-AC05-76RL01830.

- Papers:
  - **C. Amole *et al*. (PICO Collaboration), *Dark Matter Search Results from the PICO-60 C_3F_8 Bubble Chamber*. [arXiv:1702.07666] (Accepted in PRL)**
  - C. Amole *et al*. (PICO Collaboration), *Dark Matter Search Results from the PICO-60 CF_3I Bubble Chamber*, Phys. Rev. D **93**, 052014, Published: 28 March 2016, [arXiv:1510.07754].
  - C. Amole *et al*. (PICO Collaboration), Improved Dark Matter Search Results from PICO-2L Run-2, Phys. Rev. D **93**, 061101(R), Published: 21 March 2016, [arXiv:1601.03729].
  - C. Amole *et al*. (PICO Collaboration), Dark Matter Search Results from the PICO-2L C_3F_8 Bubble Chamber, Phys. Rev. Lett. **114**, 231302, Published: 11 June 2015 [arXiv:1503.00008].

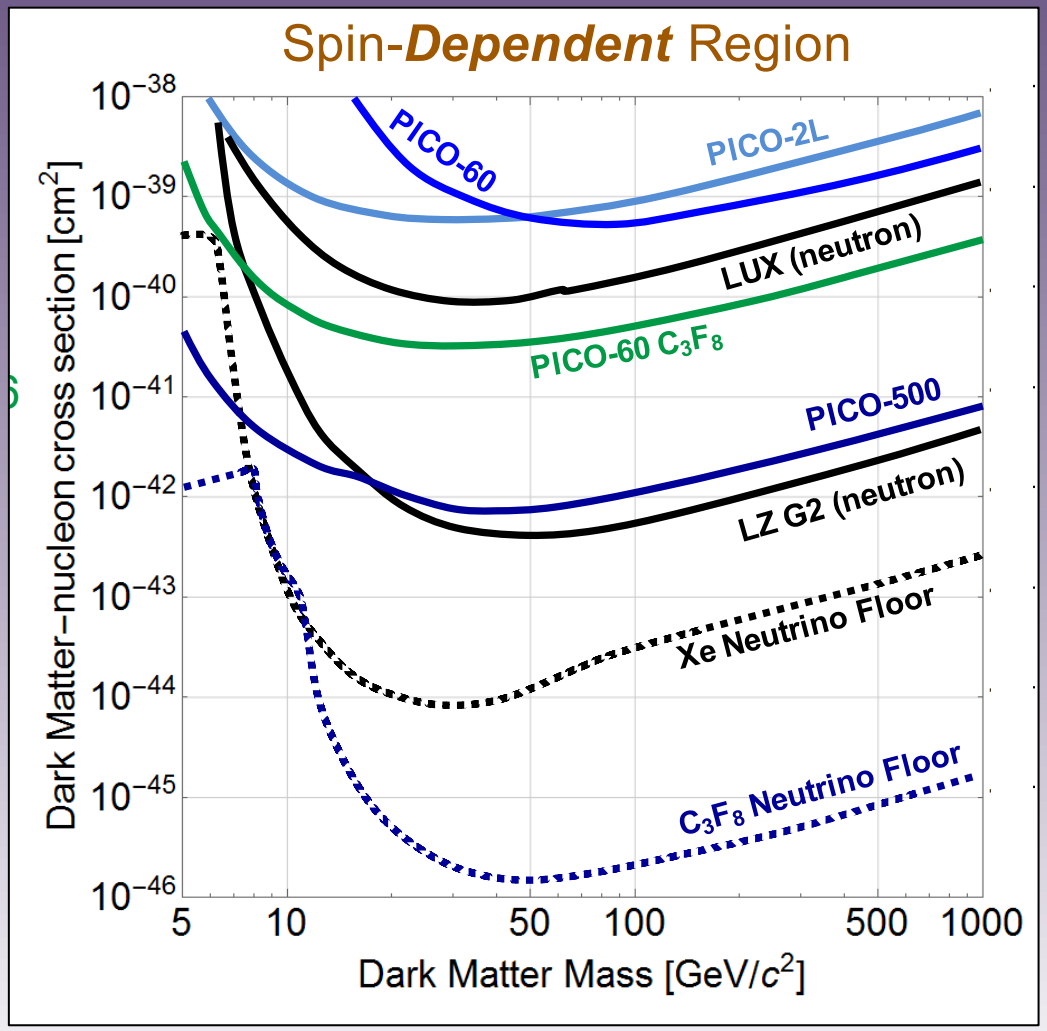
Extra Slides

PICO Program



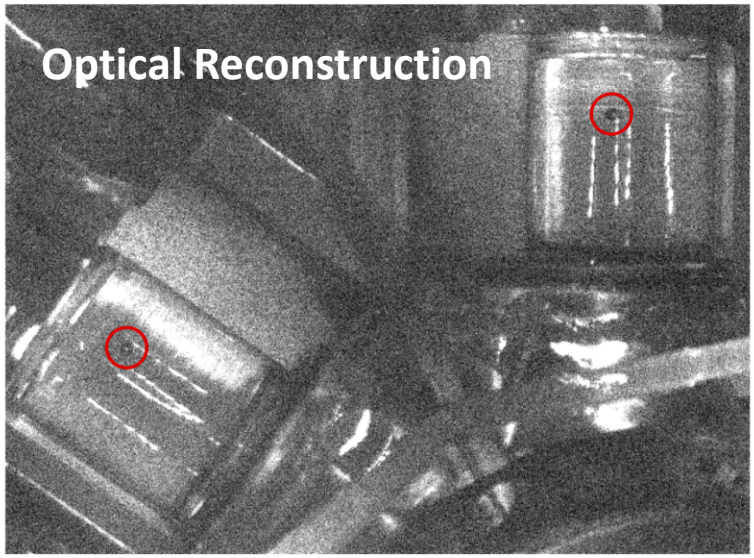
plot courtesy of Guillaume Giroux

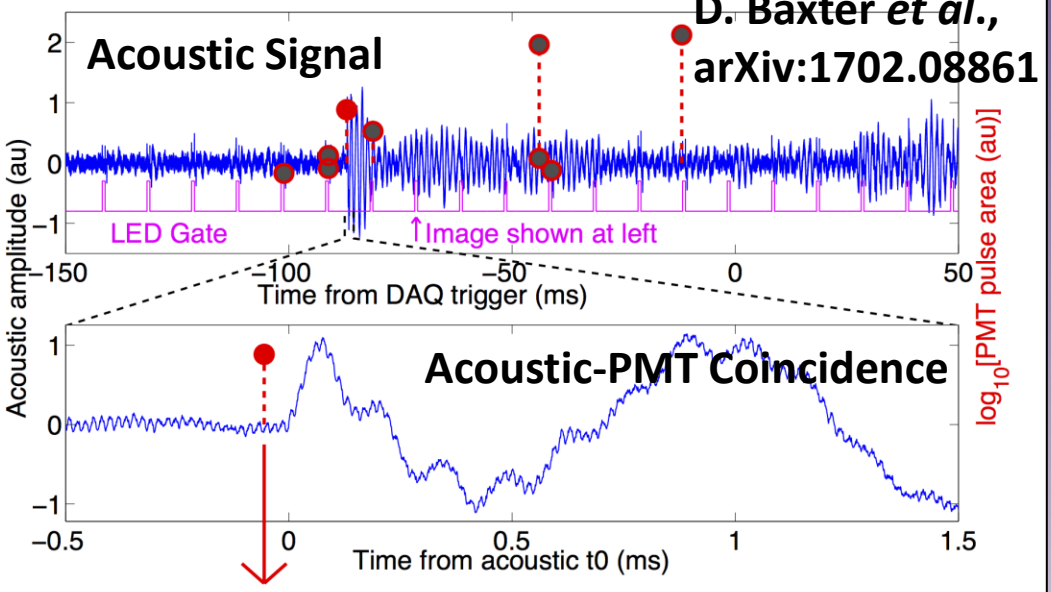
Spin-Dependent Future

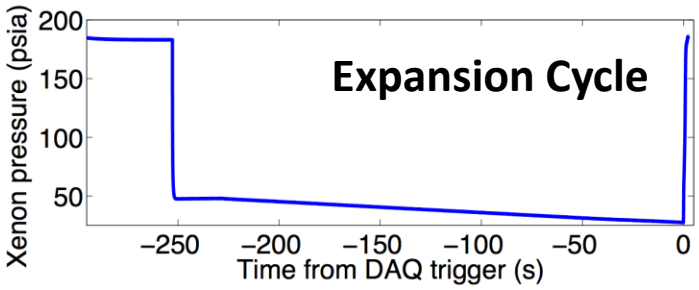


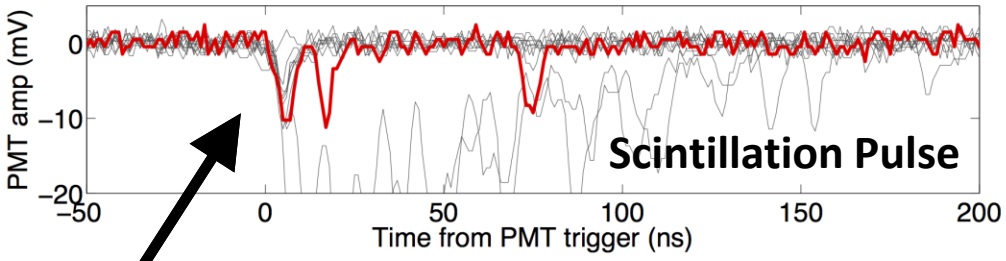
- PICO program has significant reach in parallel to G2 experiments
- Lower neutrino floor opens unique phase to PICO

Scintillating Bubble Chambers





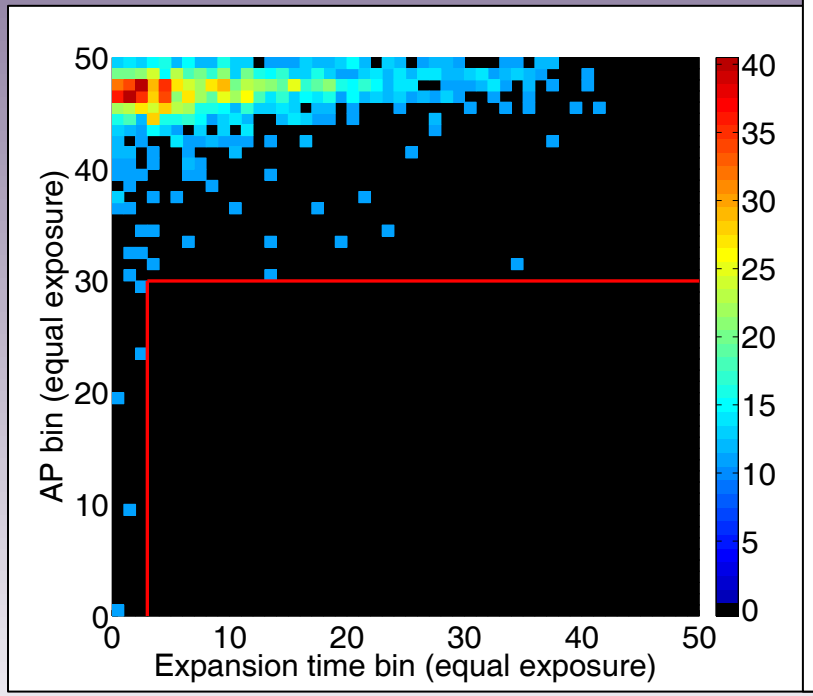


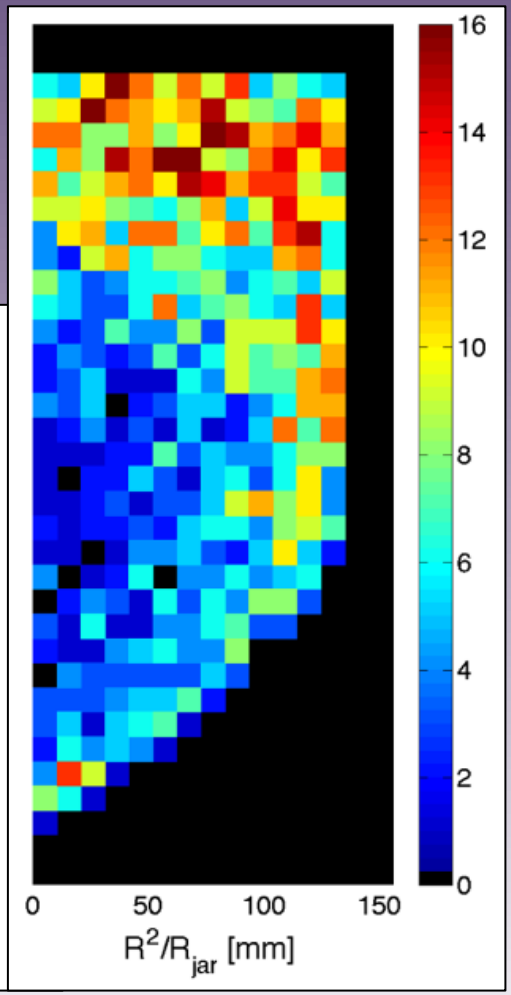


Energy Resolution!

Particulate Hypothesis

Clues from timing and spatial profiles





Assay reveals significant contamination

C. Amole *et al*. Phys. Rev. D 93, 052014 (2016) [arXiv:1510.07754]

Threshold Calculation

Surface energy, Bulk energy, Reversible Work

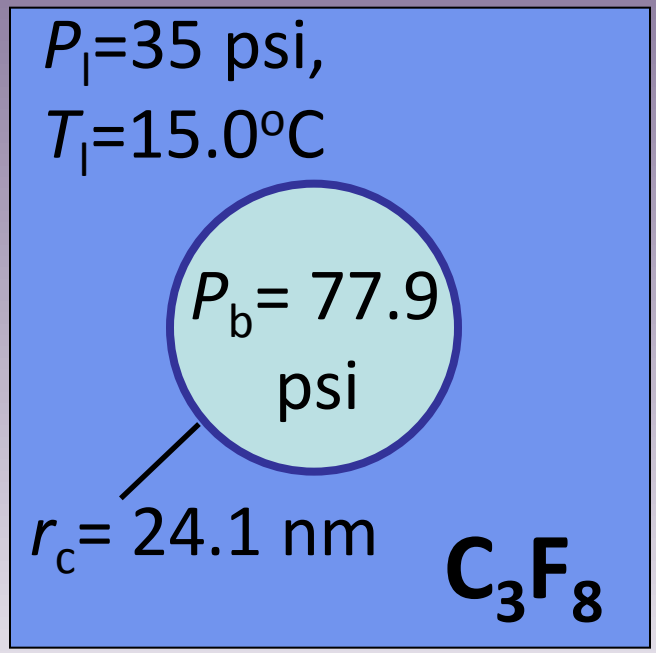
$$E_T = 4\pi r_c^2 \left(\sigma - T \left(\frac{\partial \sigma}{\partial T} \right)_\mu \right) + \frac{4\pi}{3} r_c^3 \rho_b \left(h_b - h_l \right) - \frac{4\pi}{3} r_c^3 \left(P_b - P_l \right)$$

1.57 keV

1.95 keV

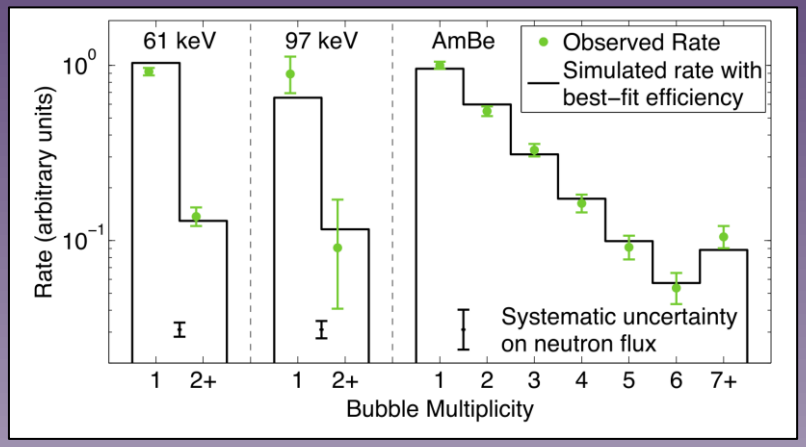
-0.15 keV

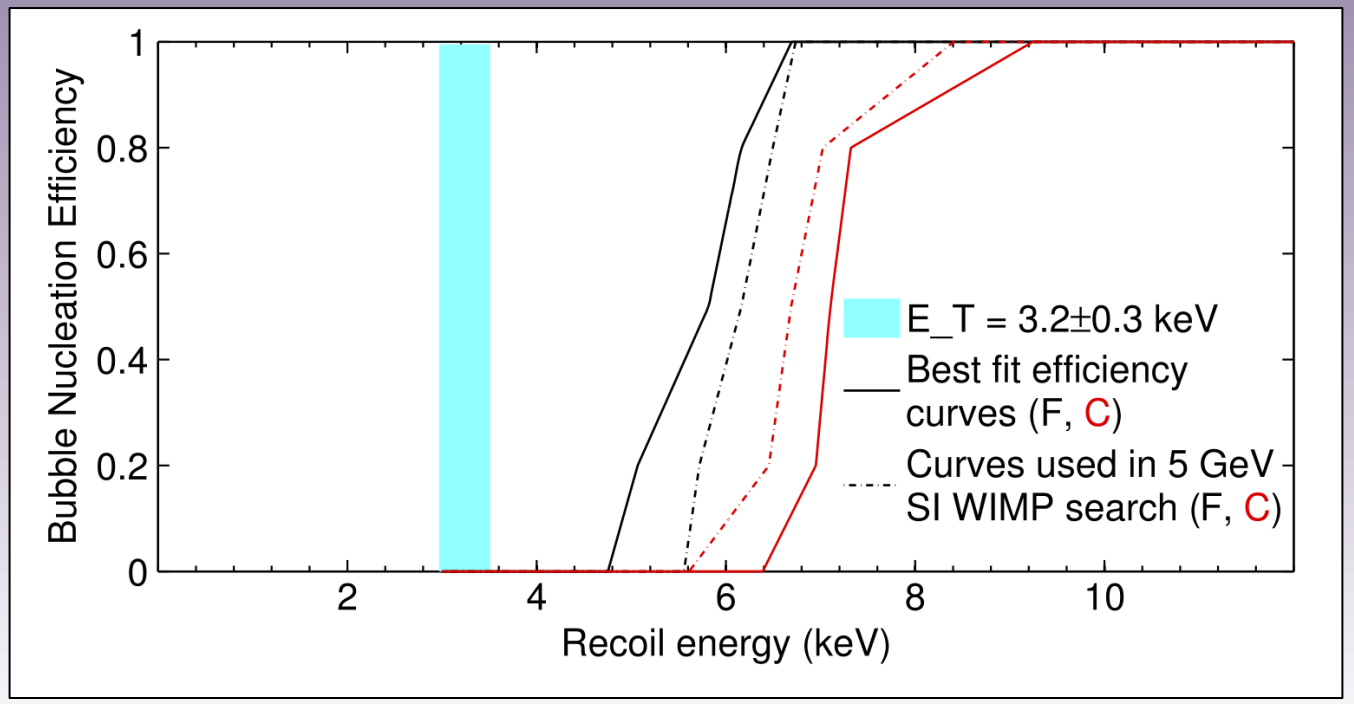
= 3.37 keV



Nuclear Recoil Efficiency

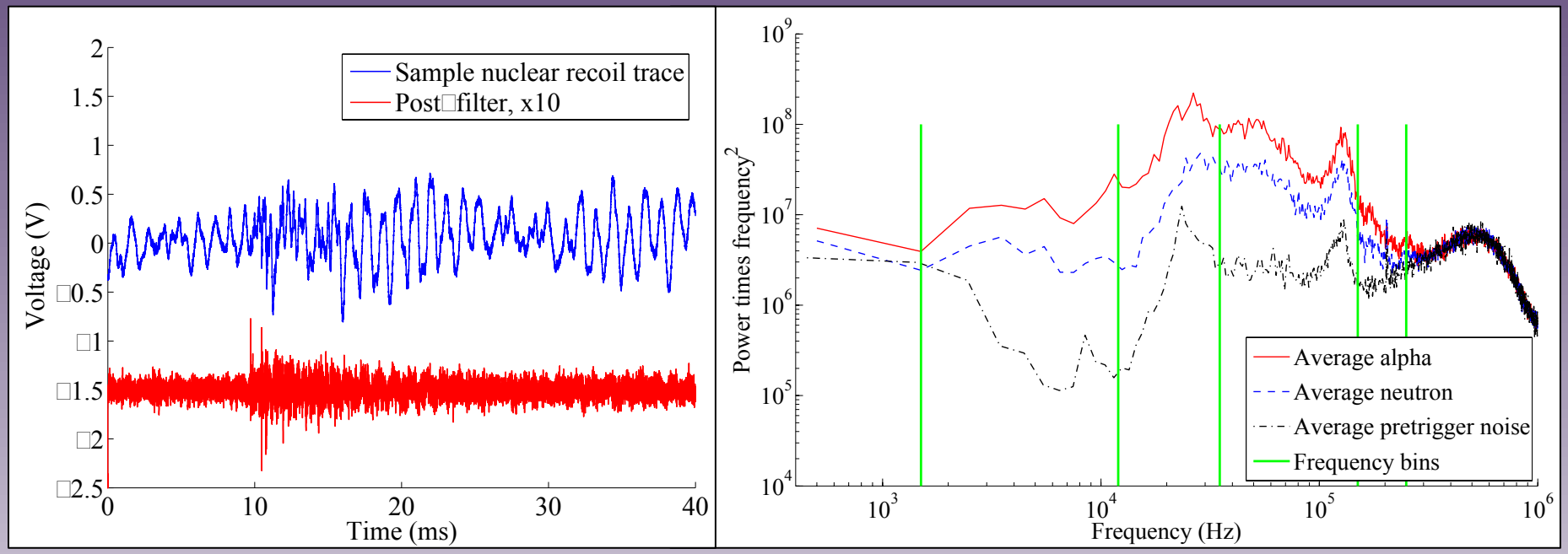
- Use neutrons to determine nucleation efficiency from nuclear recoils
- Full paper is in preparation





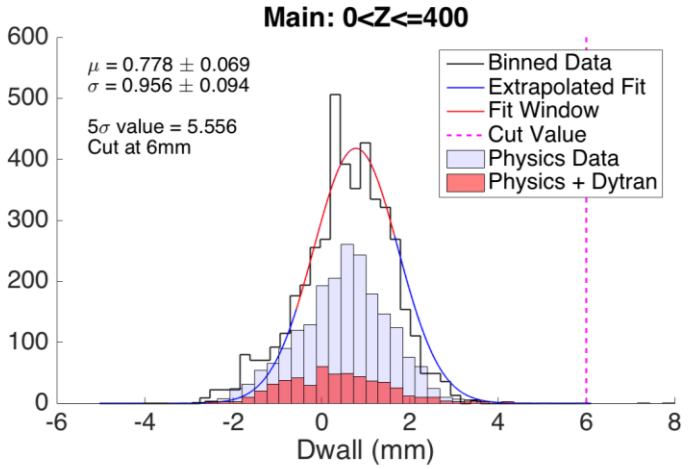
Amole, C. et al. Phys. Rev. Lett. 114, 231302 (2015)

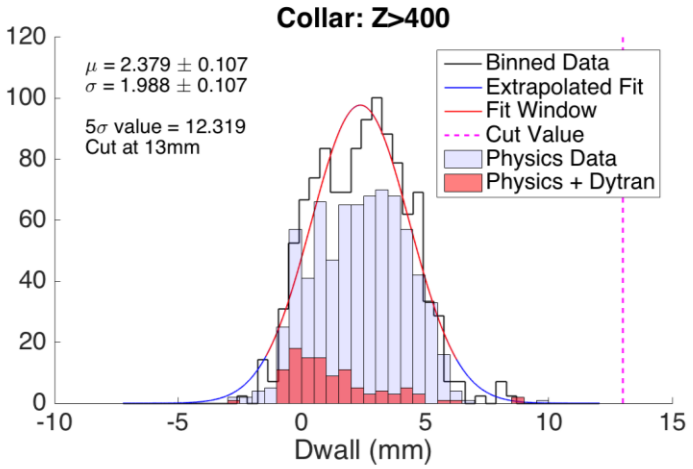
Acoustic Parameter (AP)

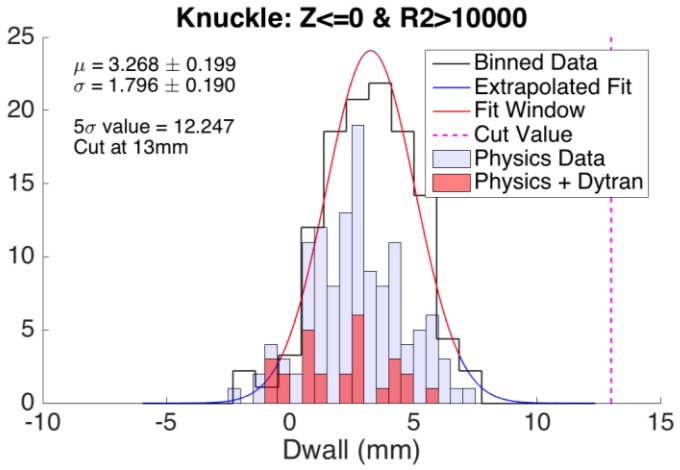


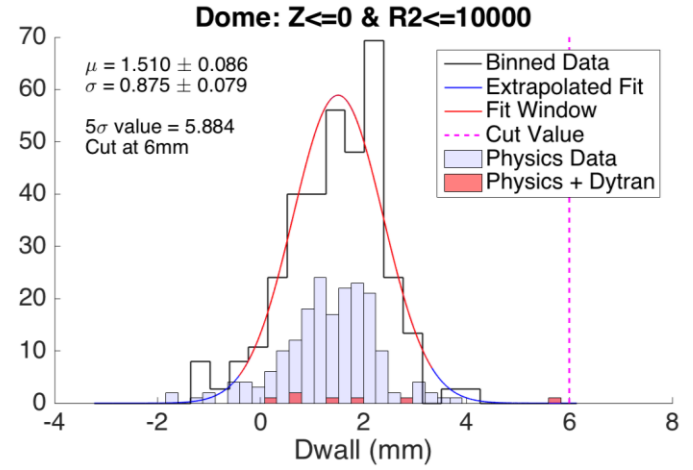
- Filter the raw trace and divide it up into frequency bands
- Correct each band for position (normalize to emitted power)
- Combine the bands that show separation between alpha and neutron data

Fiducialization

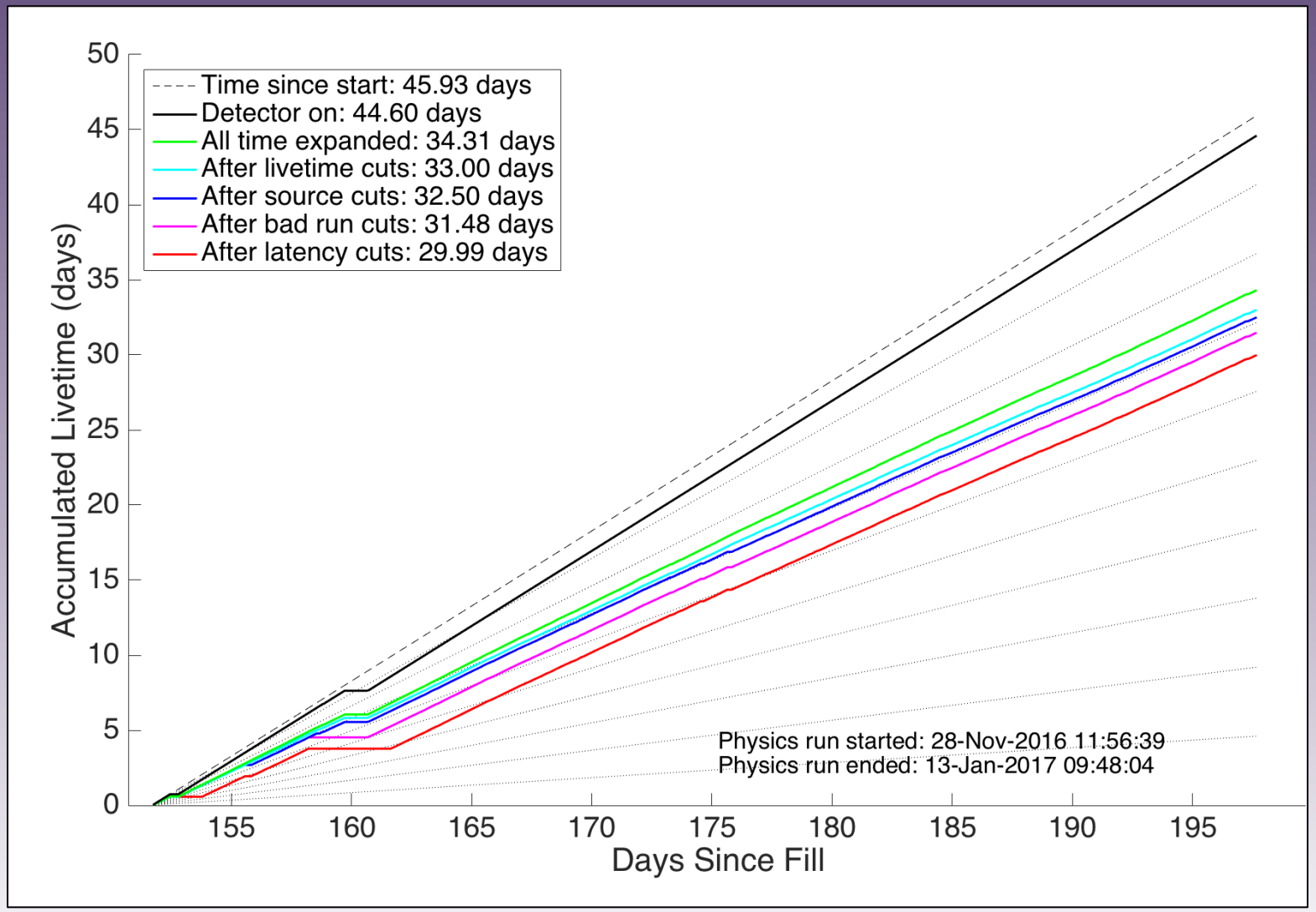






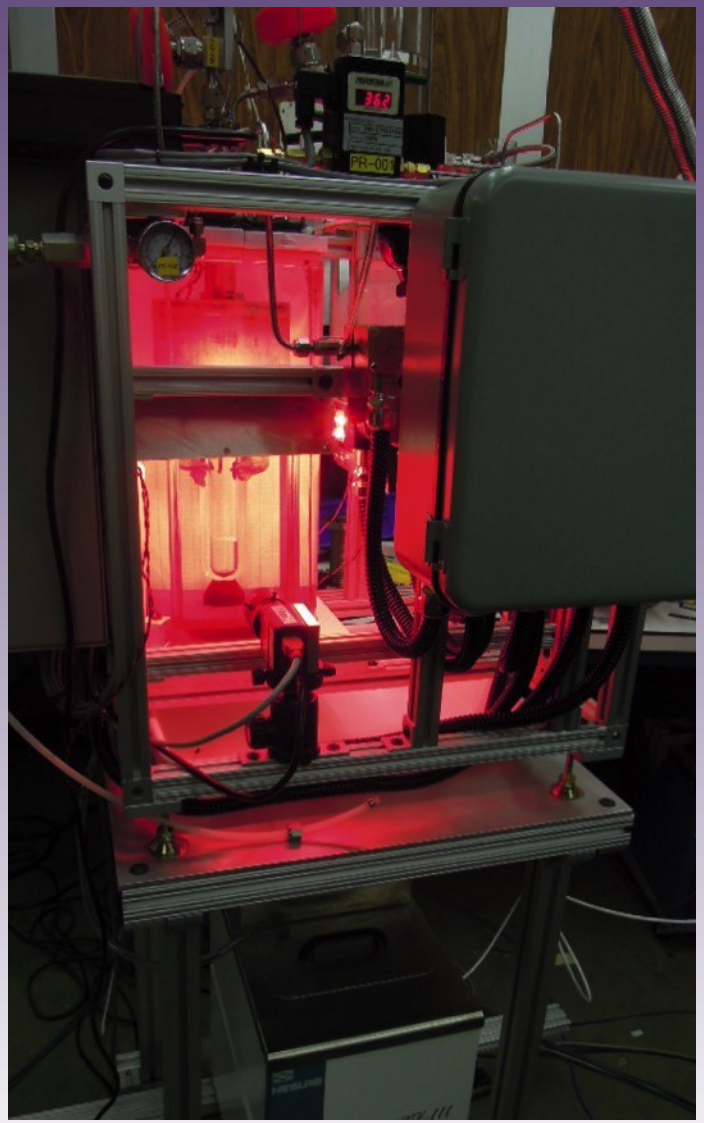
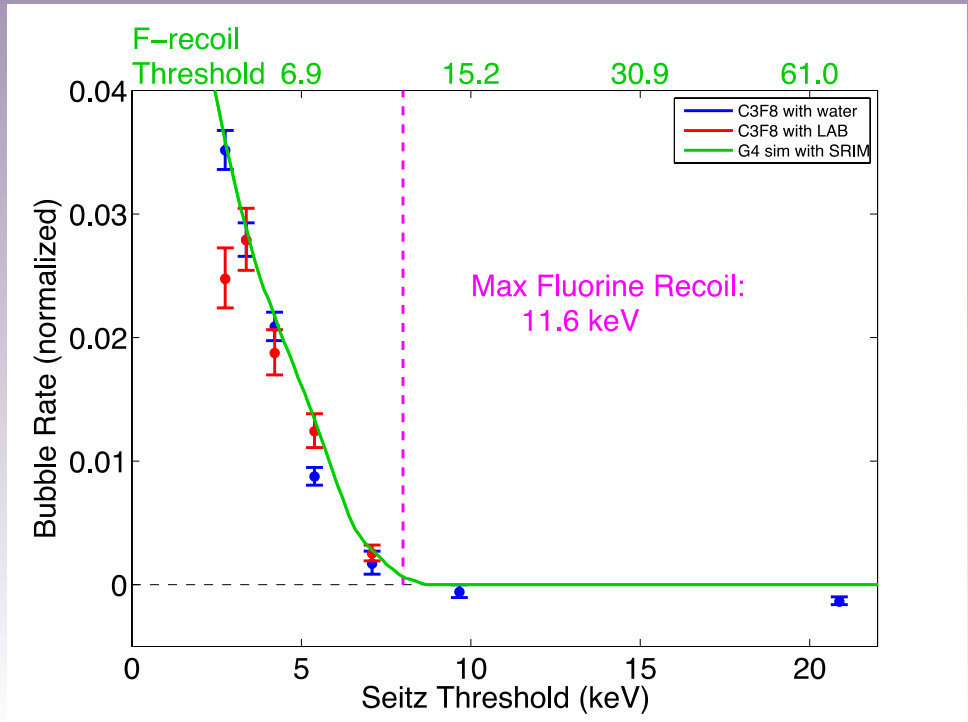


Livetime Selection



Event Selection

Acoustic information (cuts in red) were blinded for WIMP search

Cut	Description
Data Write	No errors writing to disk
Camera Trigger	Event was triggered by cameras
Pressure	Within 1psi of target
Single Bubble	Optical reconstruction algorithms found one bubble
Acoustic Noise	Pre-trigger noise was within specified range
Acoustic Timing	Acoustic signal within window of camera trigger
Fiducial	Optical reconstruction places bubble in bulk
Secondary Fiducial	Pressure rise consistent with bulk event
Acoustic Parameter (AP)	Consistent with neutron calibration
NN Score	Neural net thinks acoustics are from a neutron
Manual Scan	All events passing the above are checked

Mono-energetic neutron beam