Tiny Bubbles in the Mine:
Results from PICO-60

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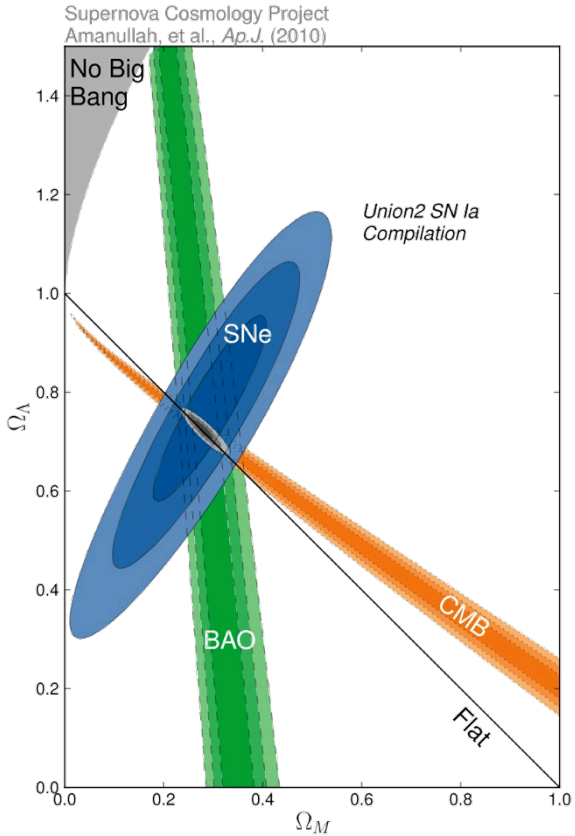
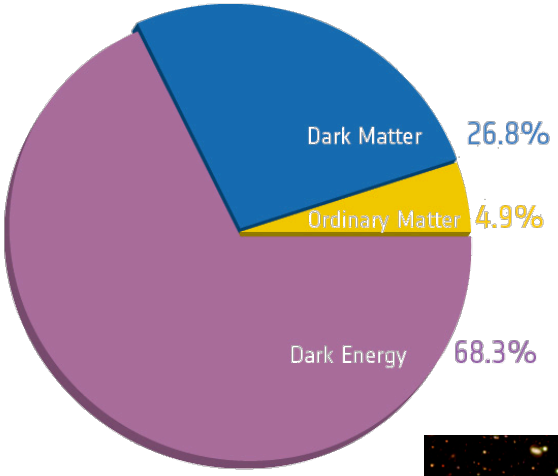
SLAC Summer Institute

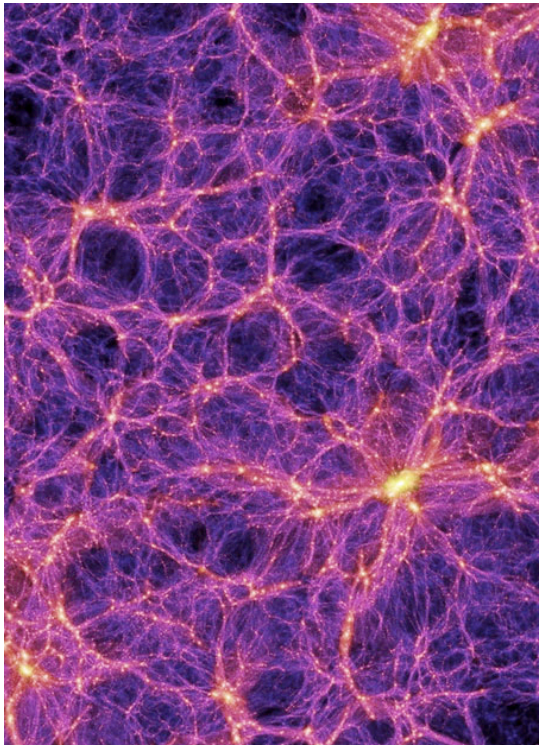
Roadmap

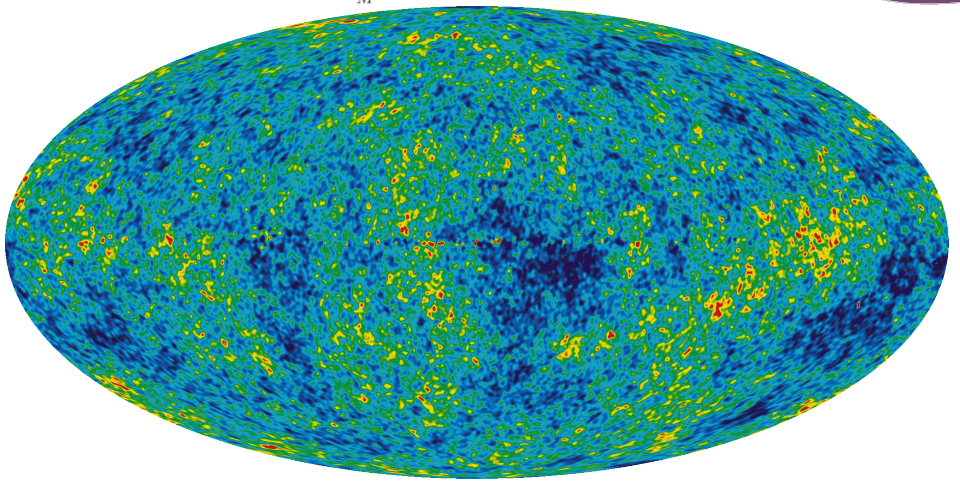
- Motivation – Why Bubble Chambers?
  - Spin-Independent vs Spin-Dependent WIMP interactions
  - Backgrounds and Discovery
- Bubble Chamber Overview
- The PICO-60 Experiment
  arXiv:1702.07666 [PRL 118, 251301 (2017)]
- The road forward
  - Right-side-up Bubble Chambers
  - Scintillating Bubble Chambers

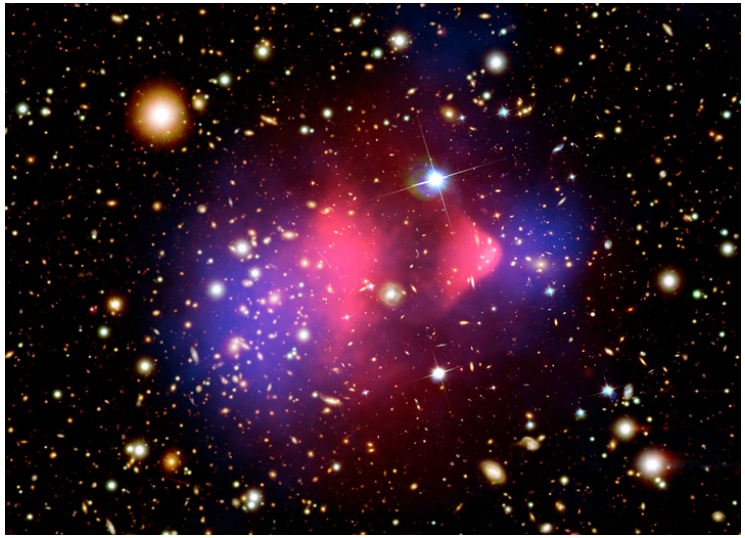
Evidence for Dark Matter







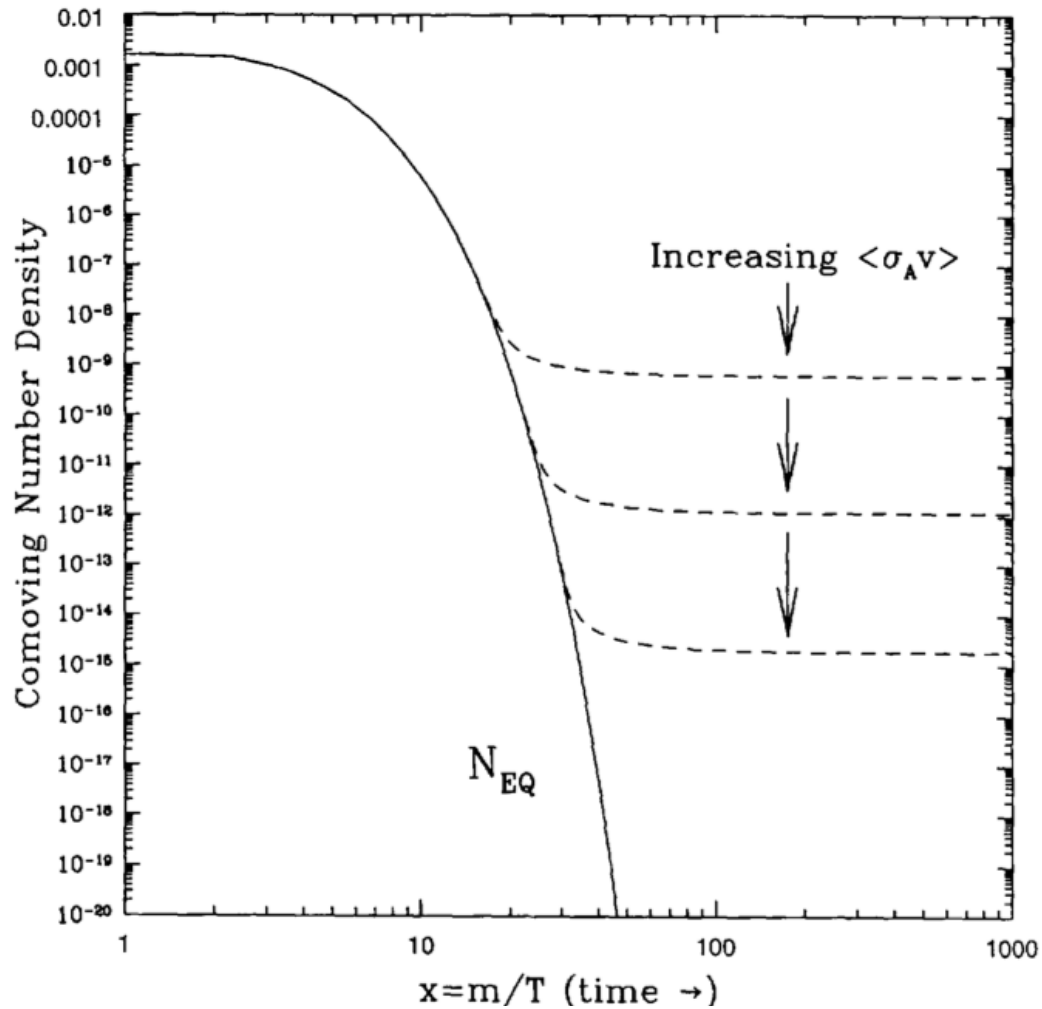




Relics and Miracles

$$\frac{dn_\chi}{dt} = -\langle \sigma_a v \rangle \left[(n_\chi)^2 - \left(n_\chi^{eq}\right)^2 \right] - 3Hn_\chi$$

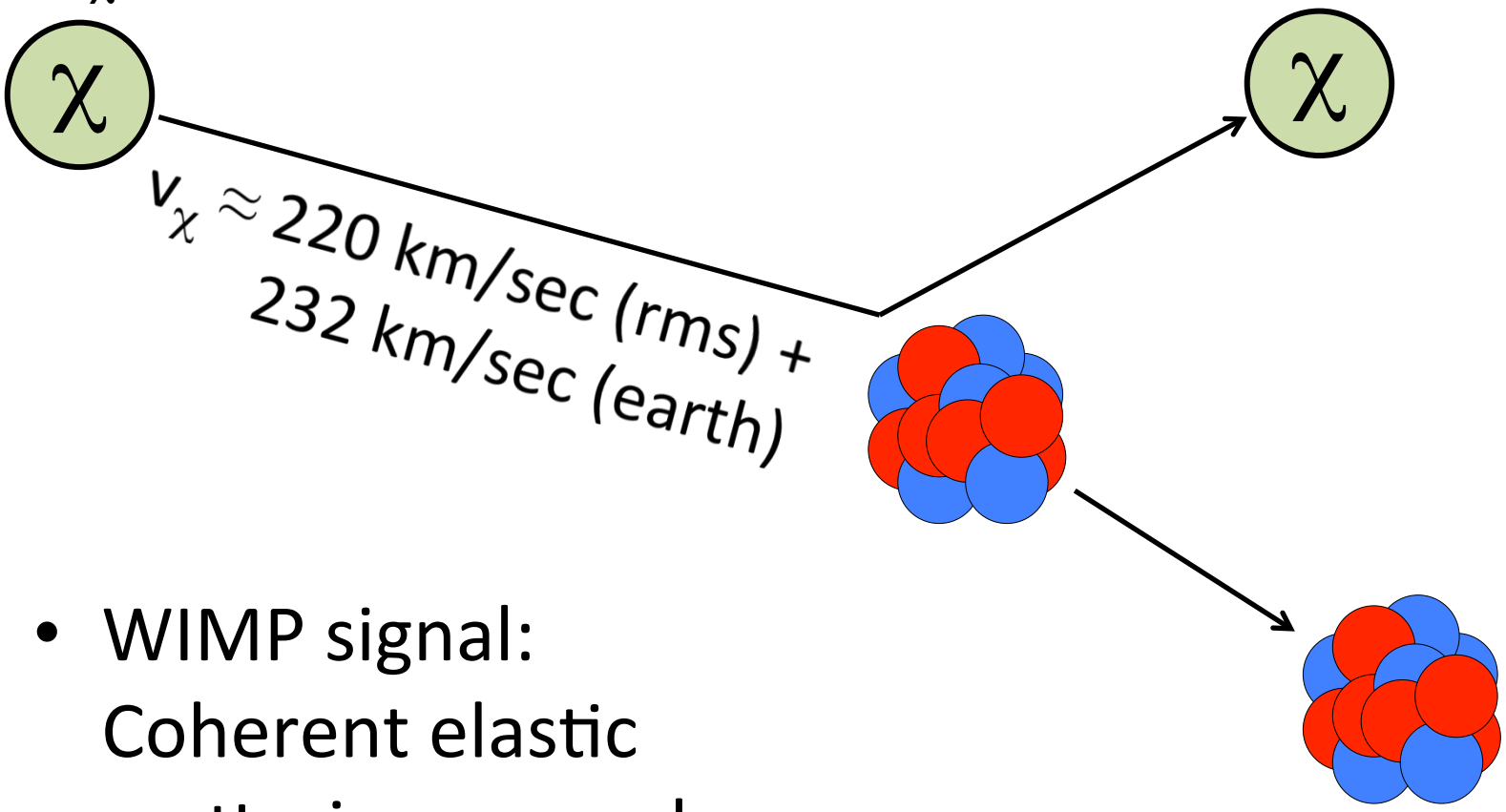
- Suppose Dark Matter is:
  - Stable Particle (LSP…)
  - Thermal Relic of Big Bang
- Weak-scale interaction gives required density for dark matter



E. Kolb and M. Turner, The Early Universe. Redwood City: Addison-Wesley, 1989.

WIMP Direct Detection

$M_\chi \approx$ GeV – TeV

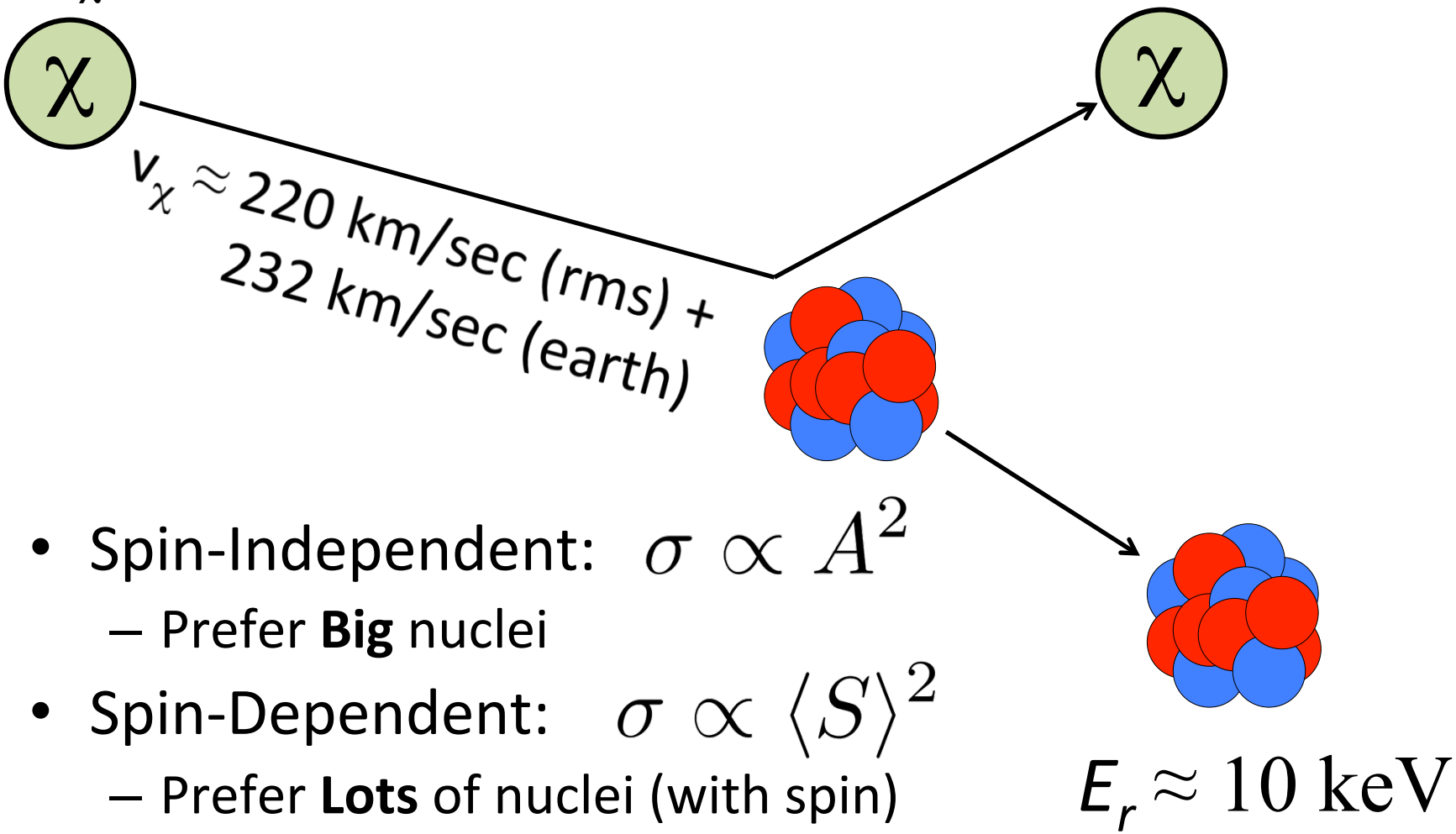


- WIMP signal: Coherent elastic scattering on nucleus

$E_r \approx 10$ keV

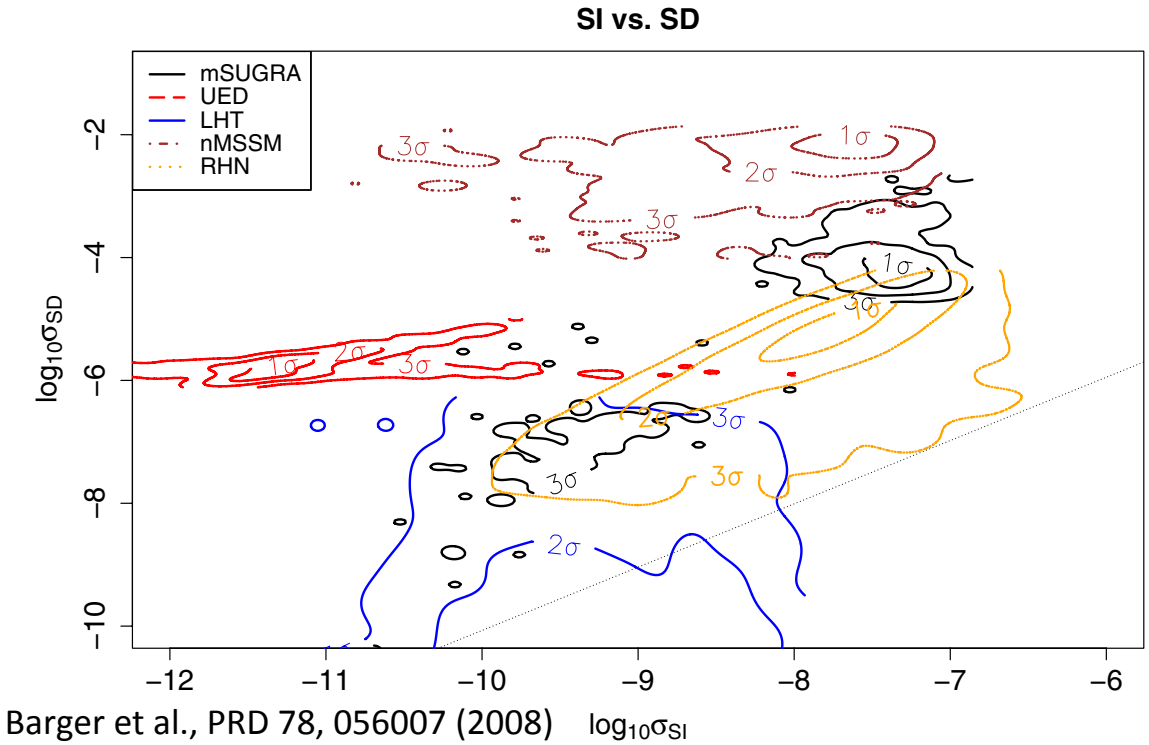
WIMP Direct Detection

$M_\chi \approx$ GeV – TeV



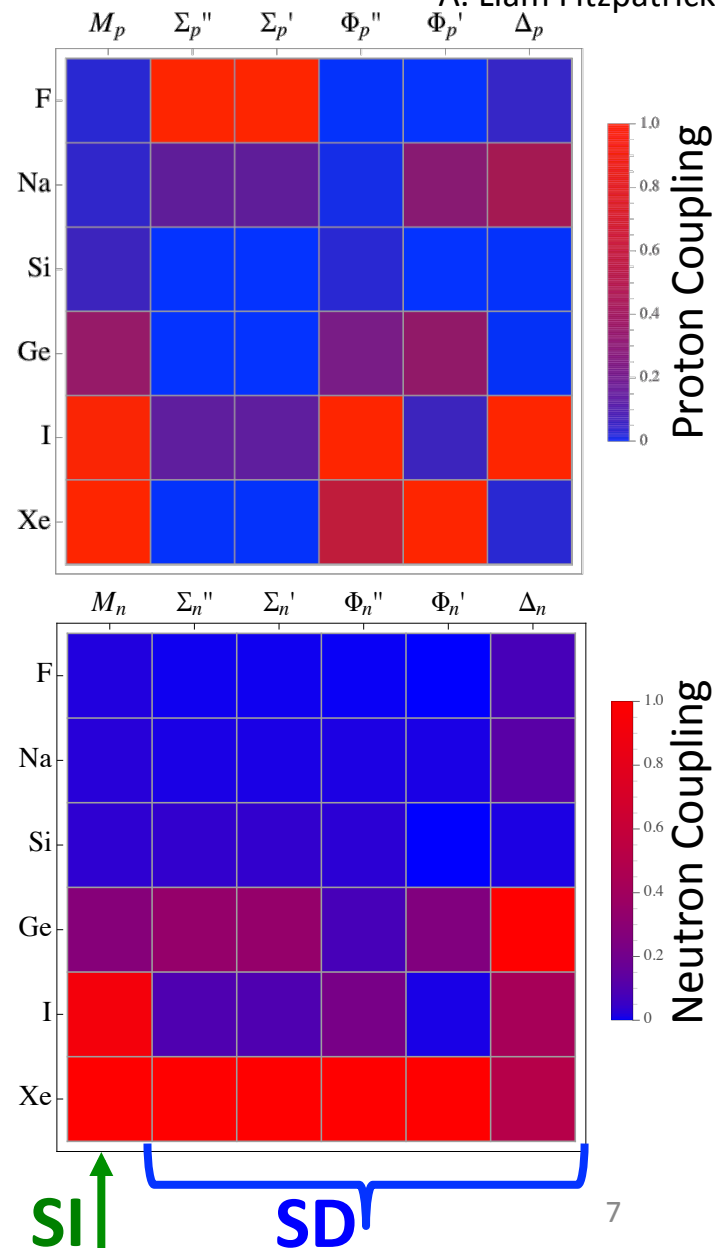
- Spin-Independent: $\sigma \propto A^2$
  - Prefer **Big** nuclei
- Spin-Dependent: $\sigma \propto \langle S \rangle^2$
  - Prefer **Lots** of nuclei (with spin)

WIMP Detection – Interactions



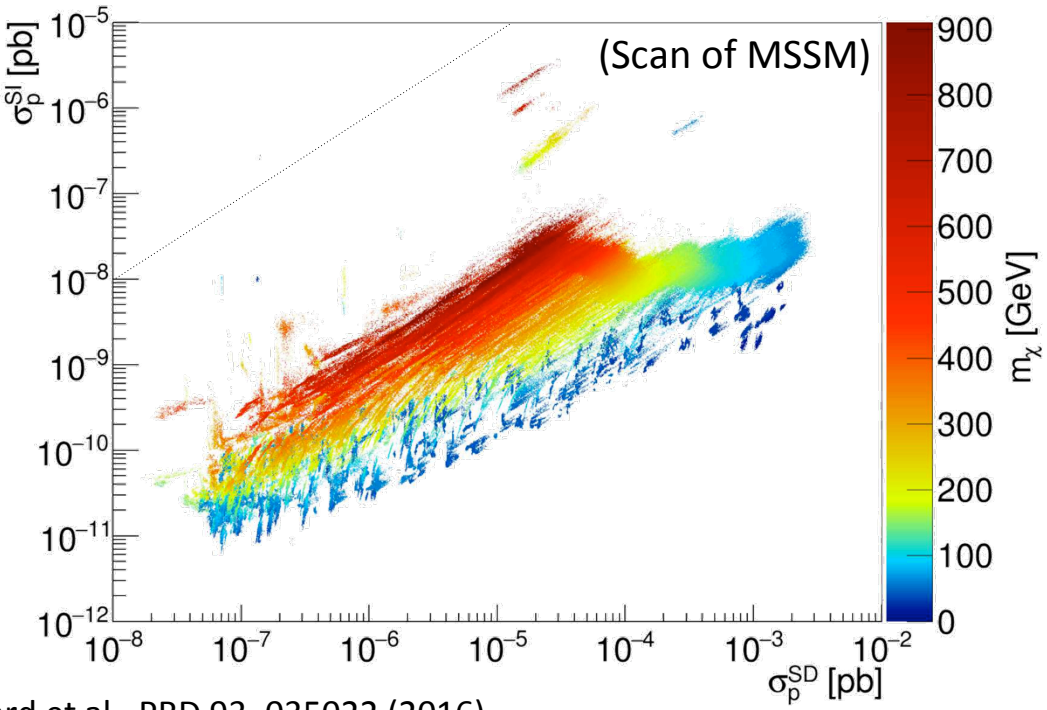
Barger et al., PRD 78, 056007 (2008)

A. Liam Fitzpatrick



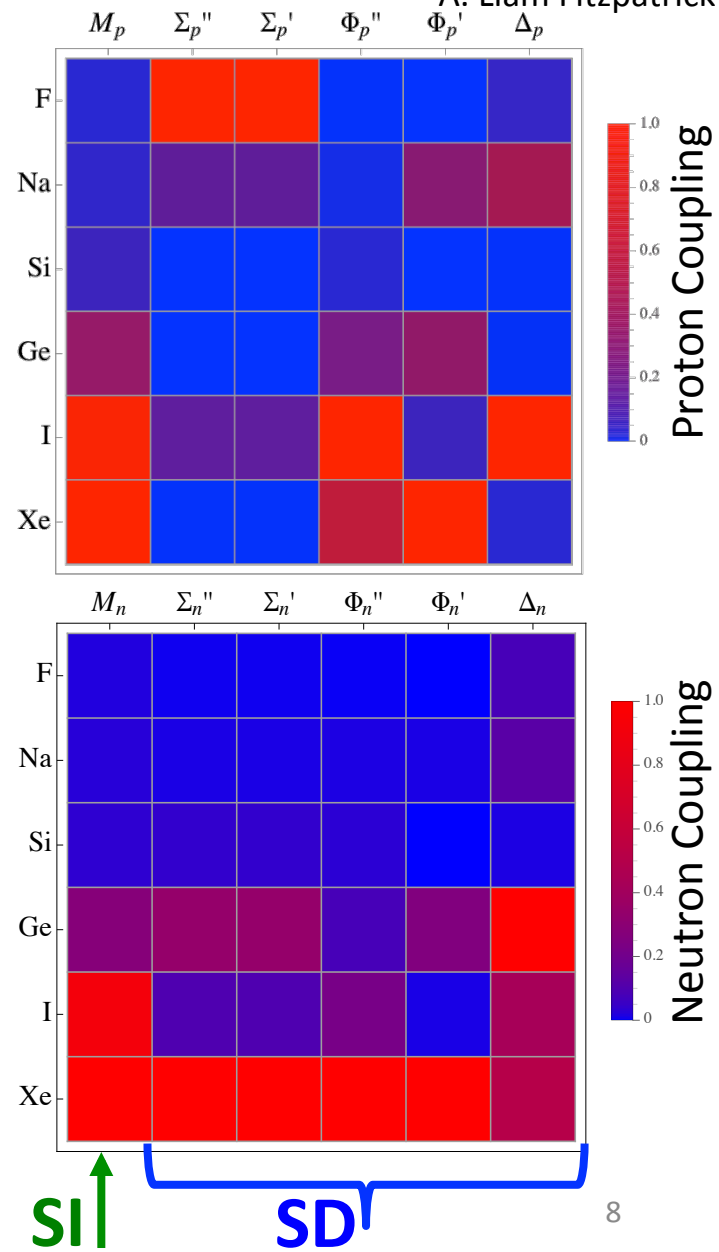
- Even for xenon (A=128−136), detection may come via SD interaction
- Xenon alone cannot distinguish SD from SI

WIMP Detection – Interactions



Riffard et al., PRD 93, 035022 (2016)

A. Liam Fitzpatrick



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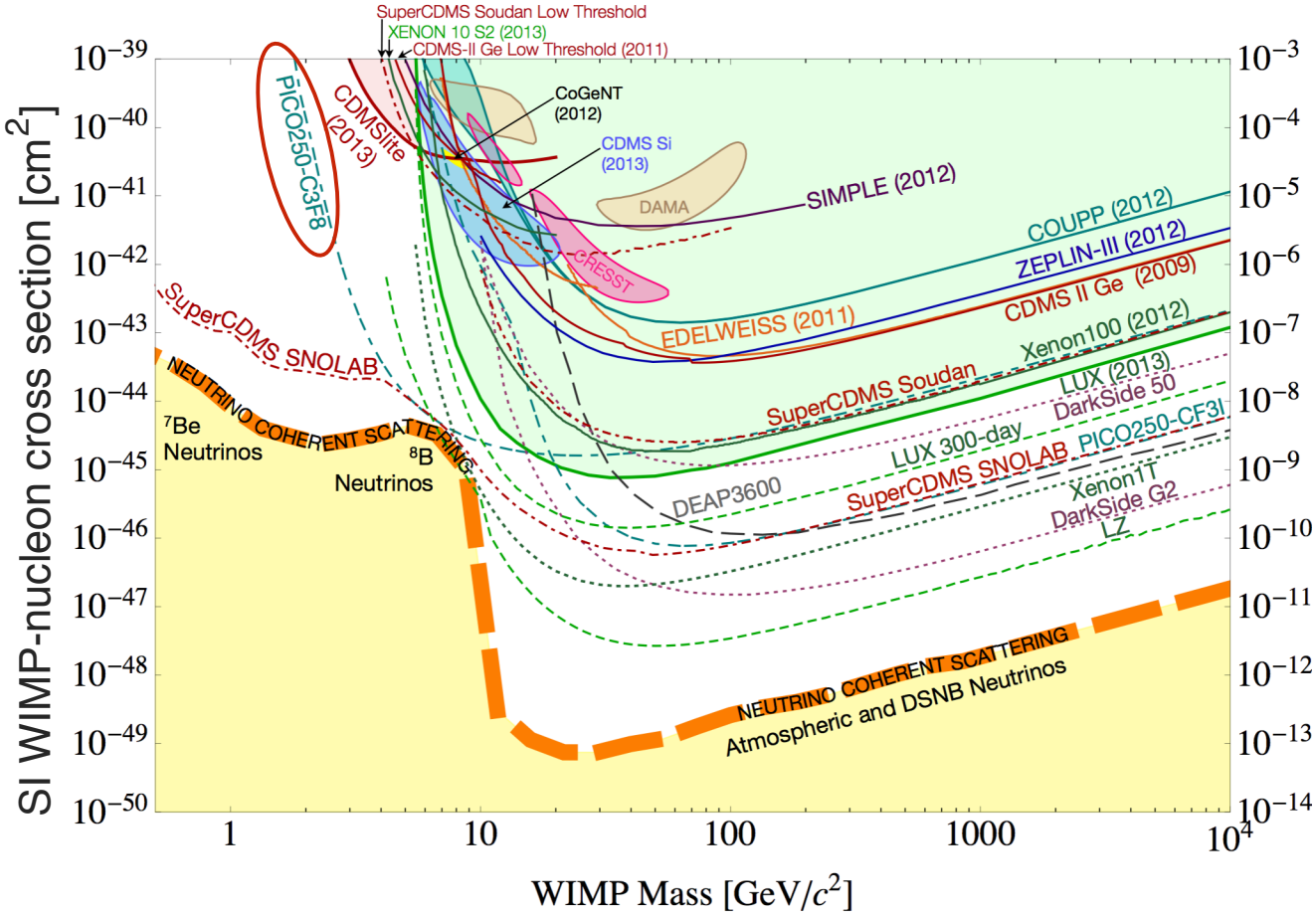
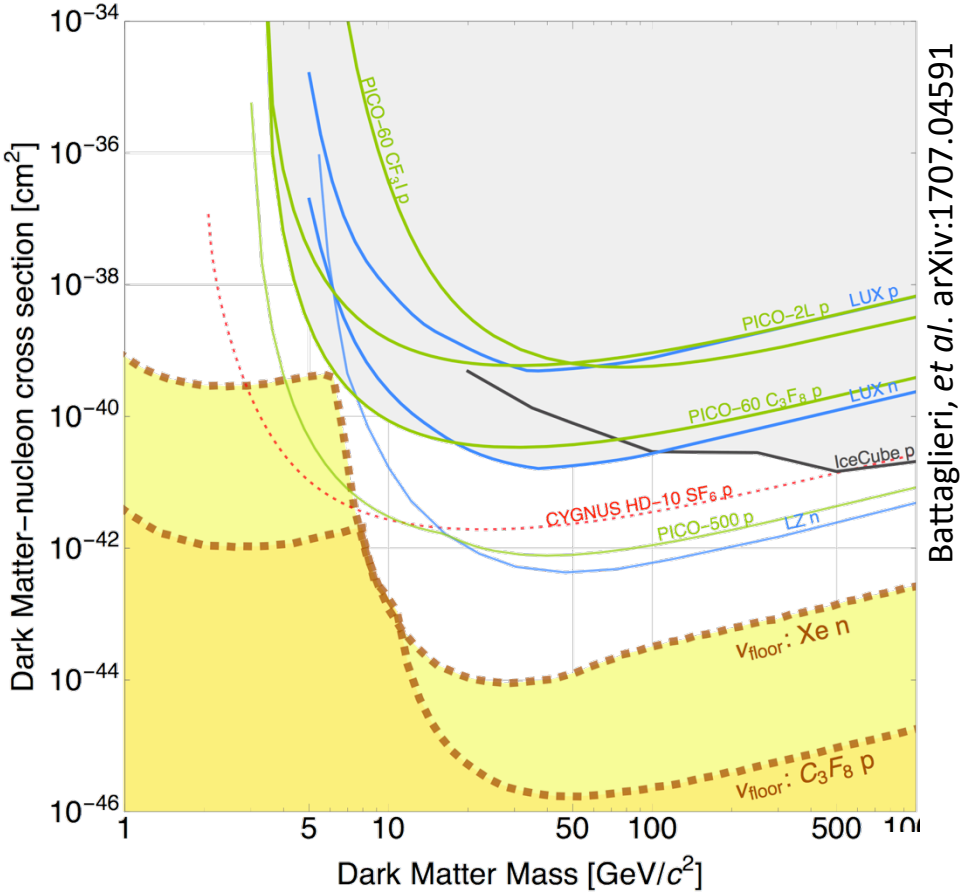
WIMP Detection – Neutrino Floor

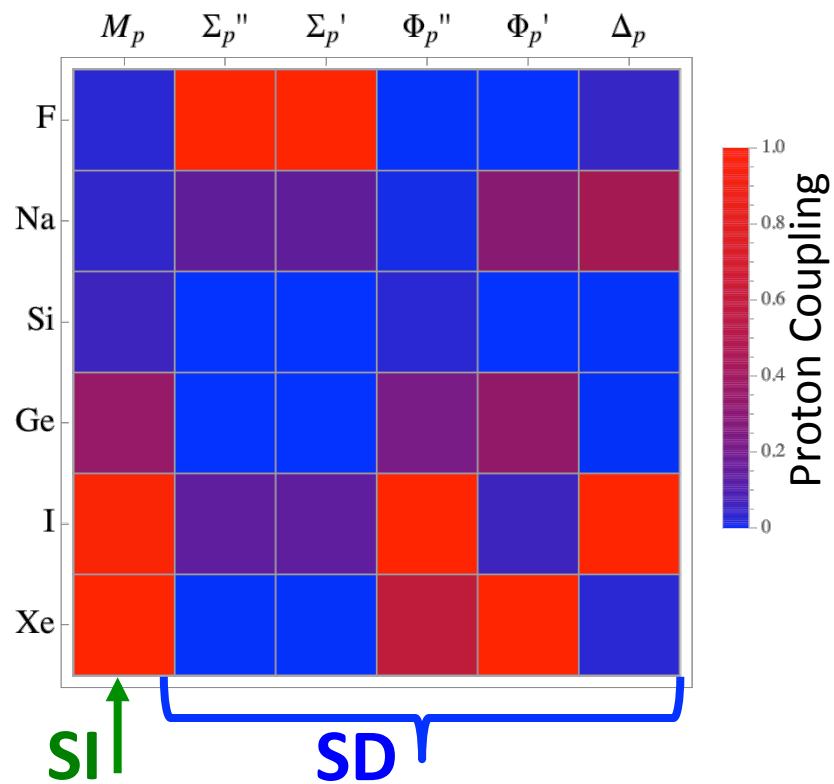


- Elastic neutrino-nucleus scattering is an SI process
- Can suppress neutrino floor using targets with *low* SI sensitivity

WIMP Detection – Neutrino Floor



Battaglieri, *et al.* arXiv:1707.04591



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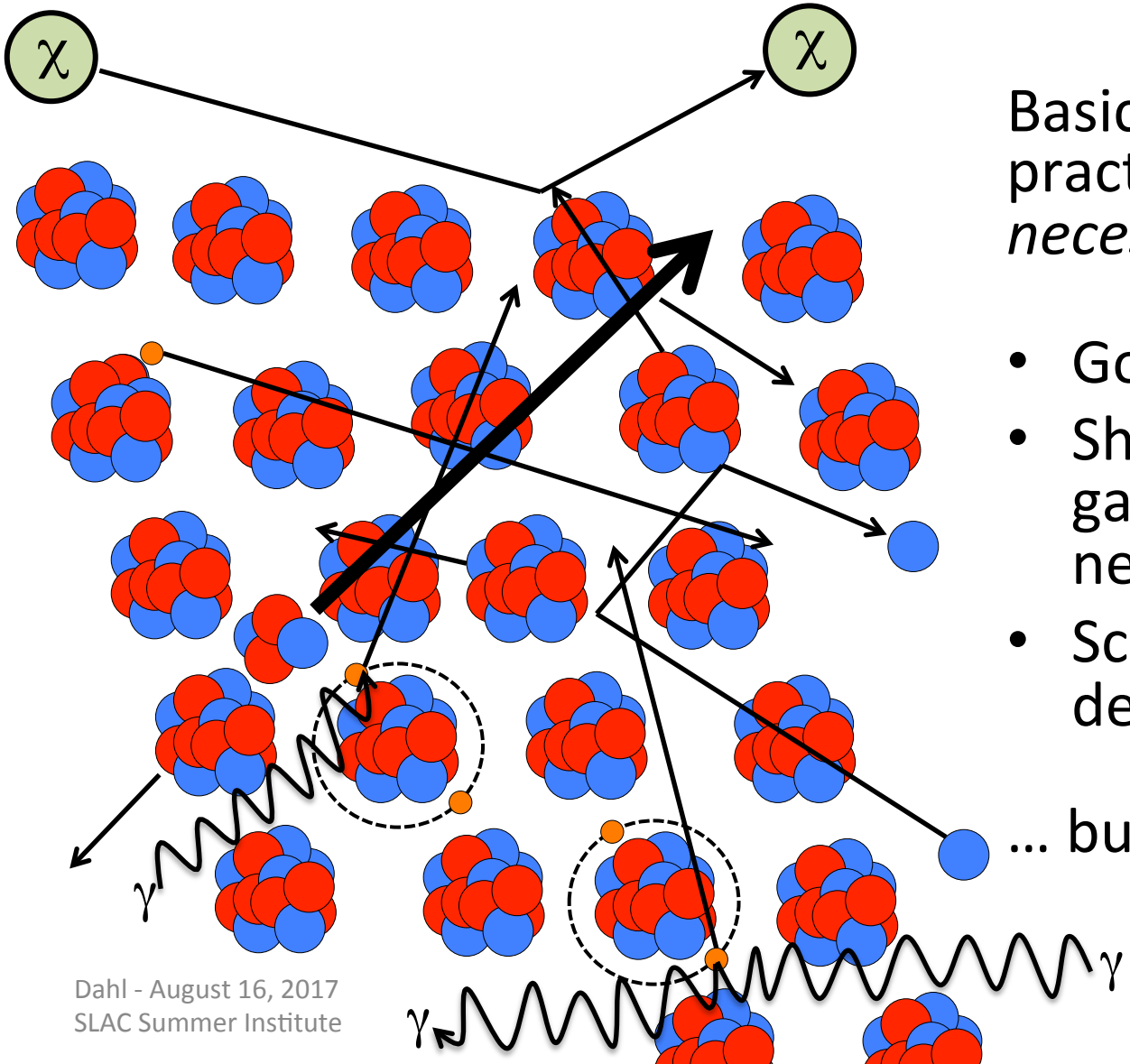
WIMP Detection – Backgrounds

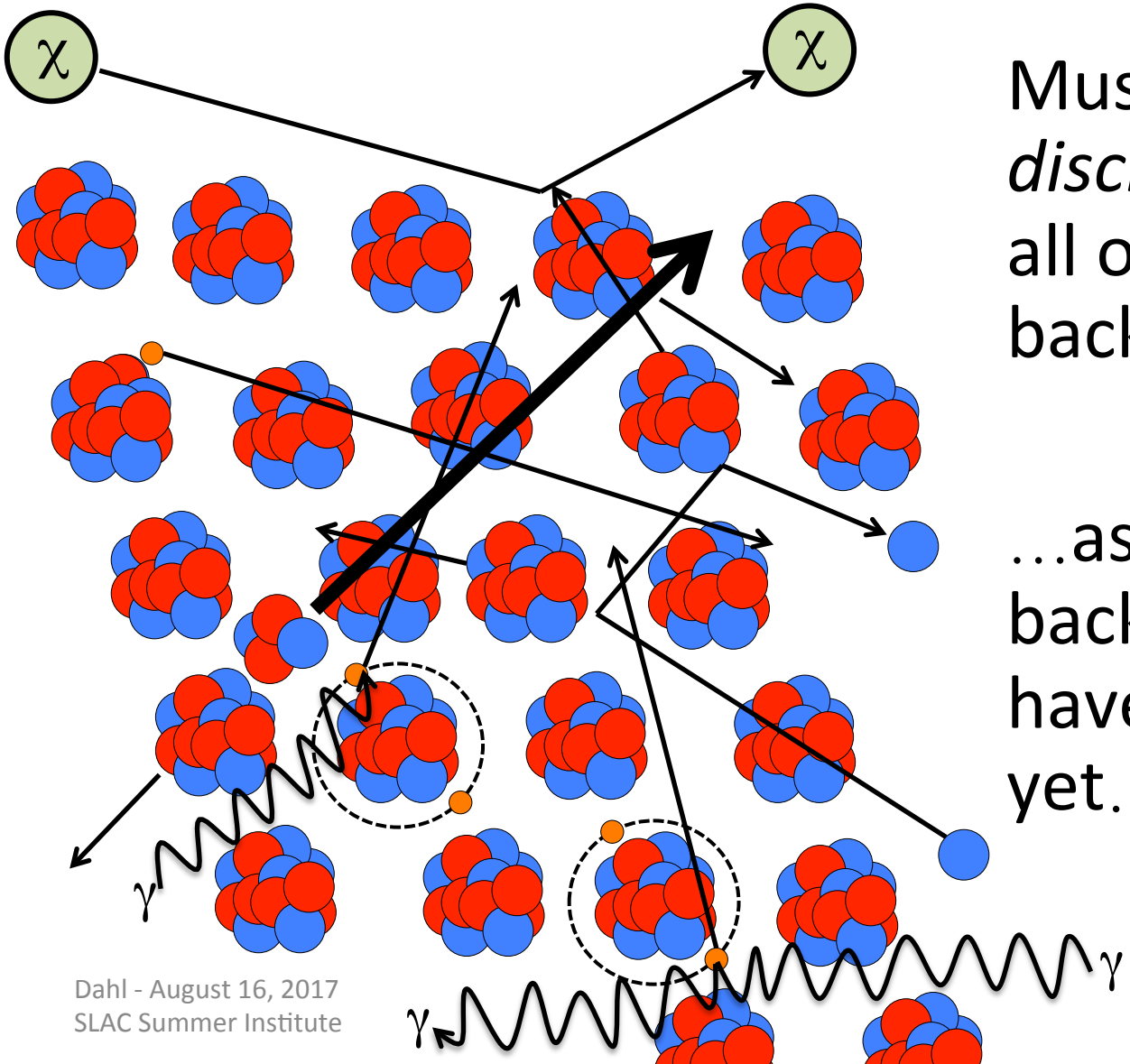


Basic low-background practices are *necessary* …

- Go underground
- Shield external gammas and neutrons
- Screen and purify detector elements

… but not *sufficient*

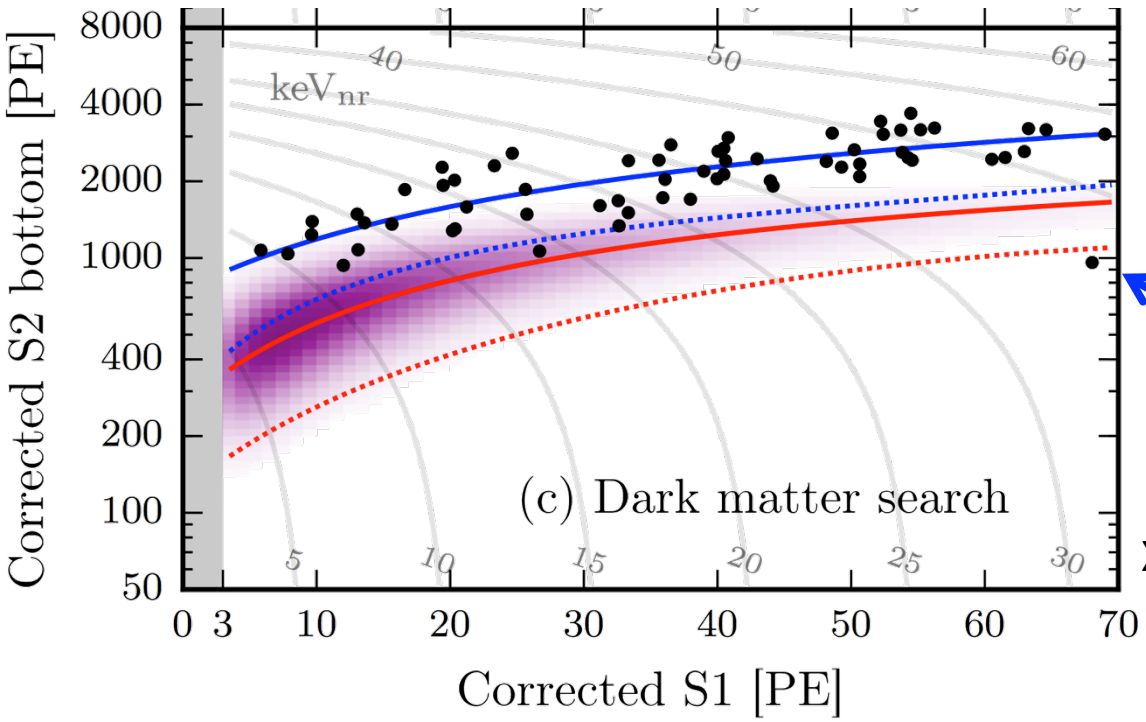
WIMP Detection – Backgrounds



Must be able to *discriminate* against all of these backgrounds…

…as well as against backgrounds we haven't run into yet…

Background? Or Signal?



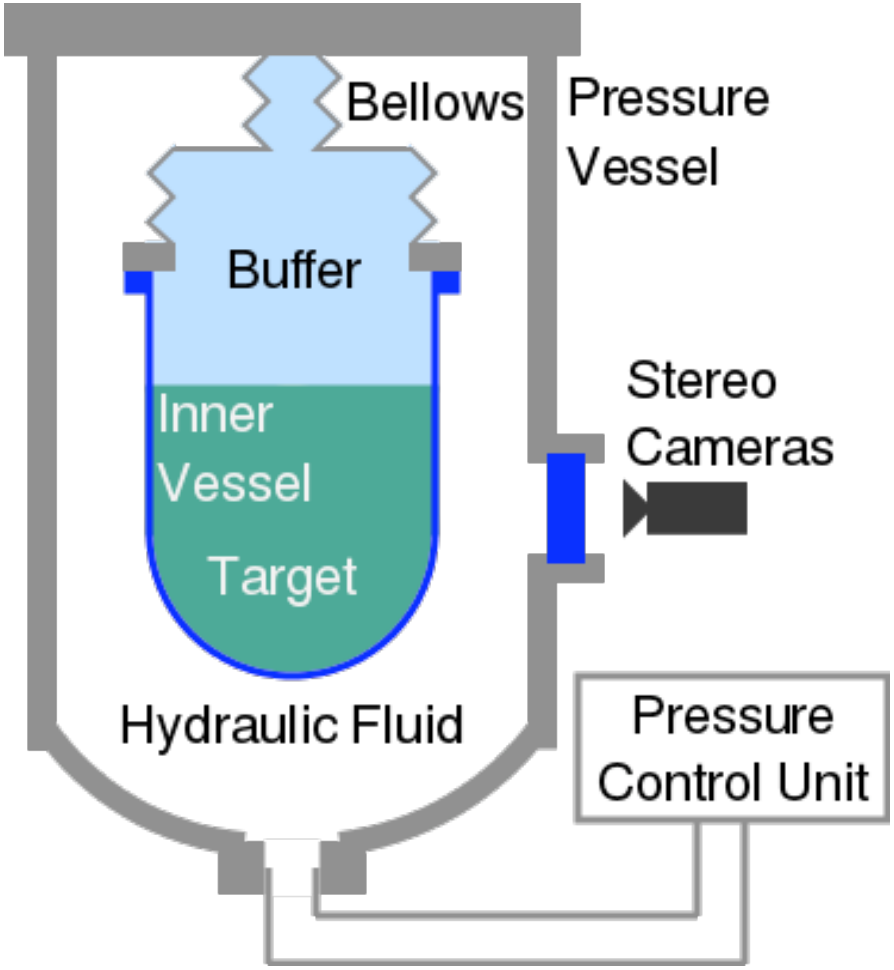
Electron recoil?
Dust?
Inelastic dark matter?
Something else?

XENON1T, arXiv:1705.06655

- Every detection technique has the potential for anomalous backgrounds:
  - Ways discrimination may be systematically fooled
  - Backgrounds we weren't creative enough to think of *a priori*…
- The dark matter signal might not be what we expect!
- Confirmation from a different technology, with different anomalous backgrounds, will be crucial

Bubble Chambers

- Superheated Target
  - CF_3I, C_3F_8, …
- Particle interactions nucleate bubbles
- Cameras and acoustic sensors capture bubbles
- Chamber recompresses after each event



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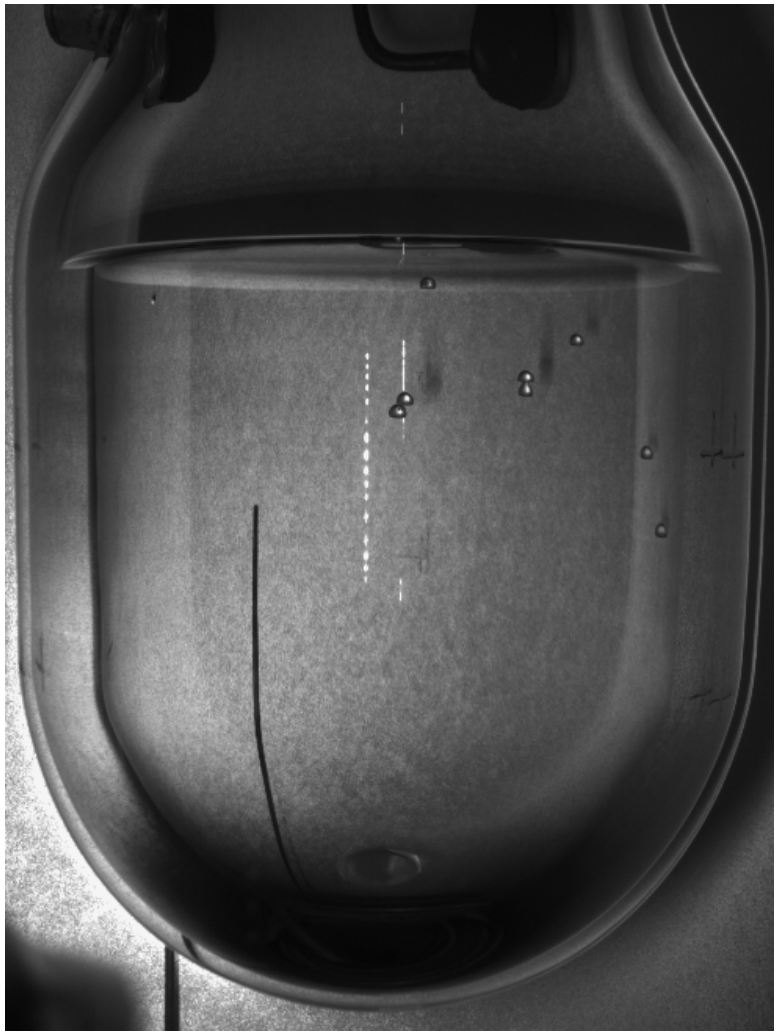
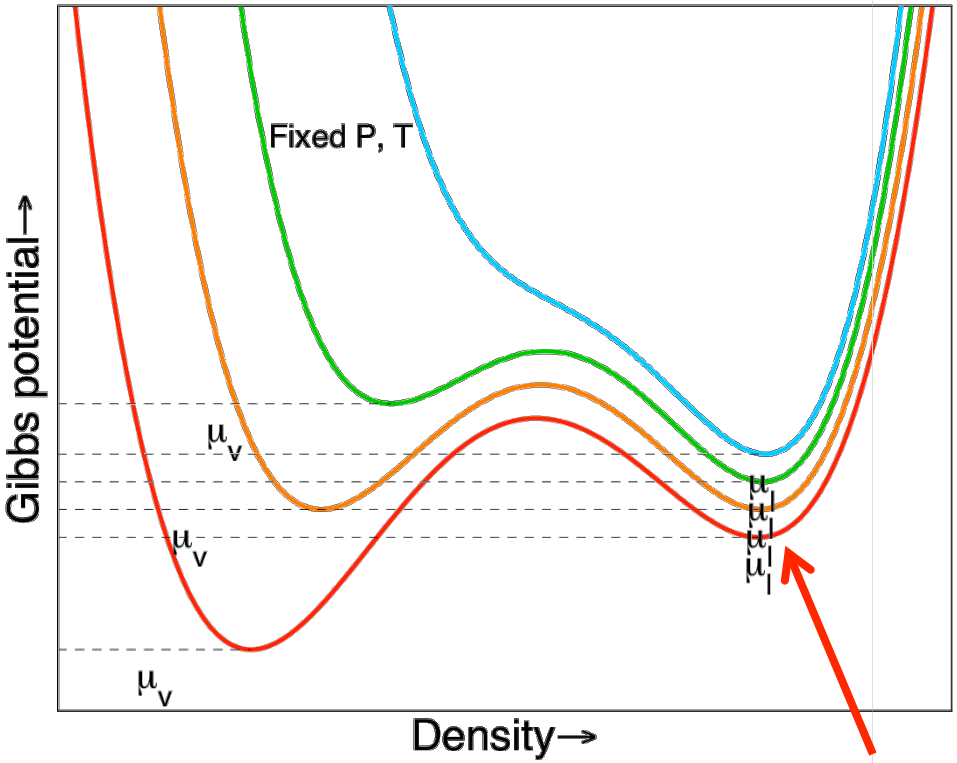
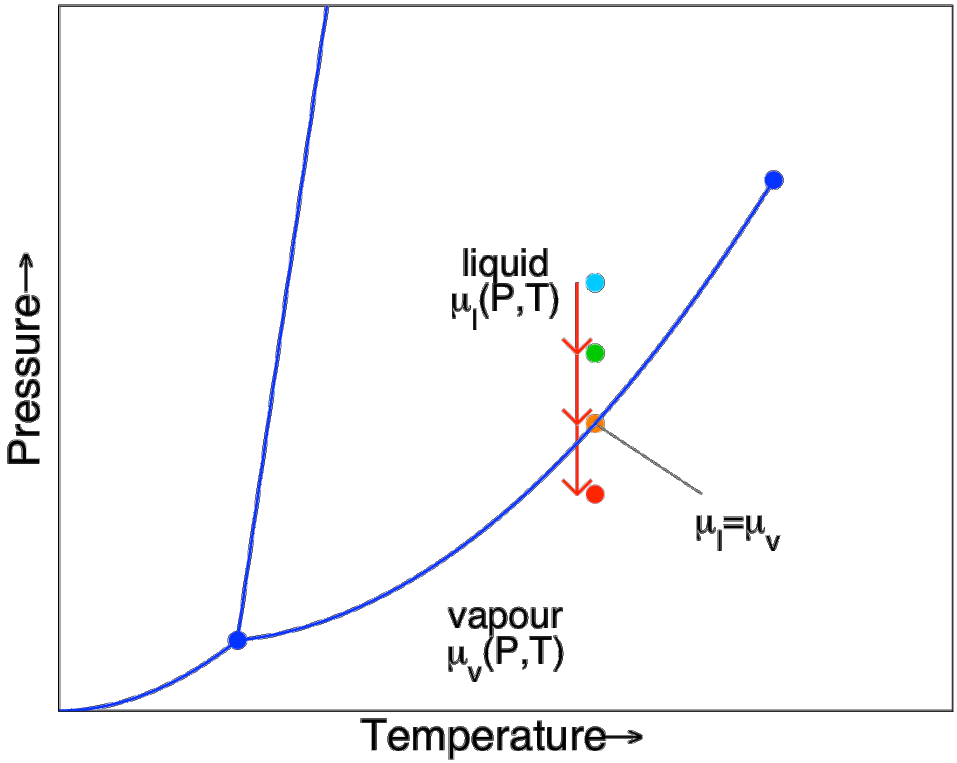


Bubble Chamber Thermodynamics

- What is a meta-stable state?

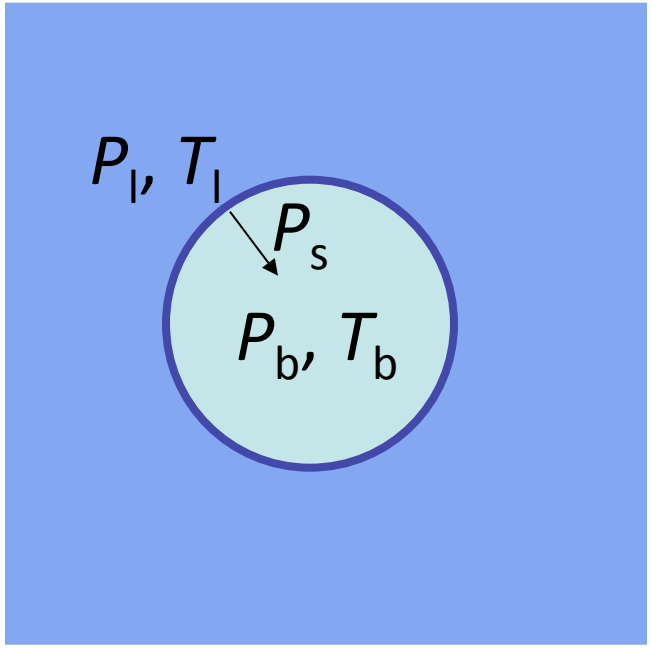




Superheated Liquid

Bubble Chamber Thermodynamics

- Consider a bubble with
  - $T_l = T_b$ (thermal equilibrium)
  - $\mu_l = \mu_b$ (chemical equilibrium)



- Then P_b is (approx) the vapor pressure at temperature T

- $P_b > P_l$, so bubble should grow… *until we consider surface tension*

Bubble Chamber Thermodynamics

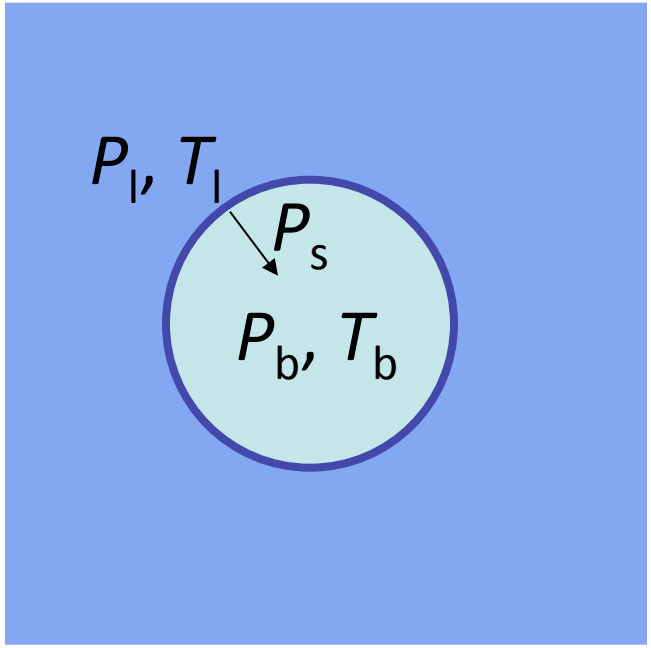
- Inward pressure from surface tension!
  - $P_s = 2\sigma/r$

- Bubble will *grow* if

$$P_b > P_l + P_s$$

$$r > r_c = 2\sigma / (P_b - P_l)$$

- Bubbles with $r < r_c$ collapse and re-condense



Bubble Chamber Thermodynamics

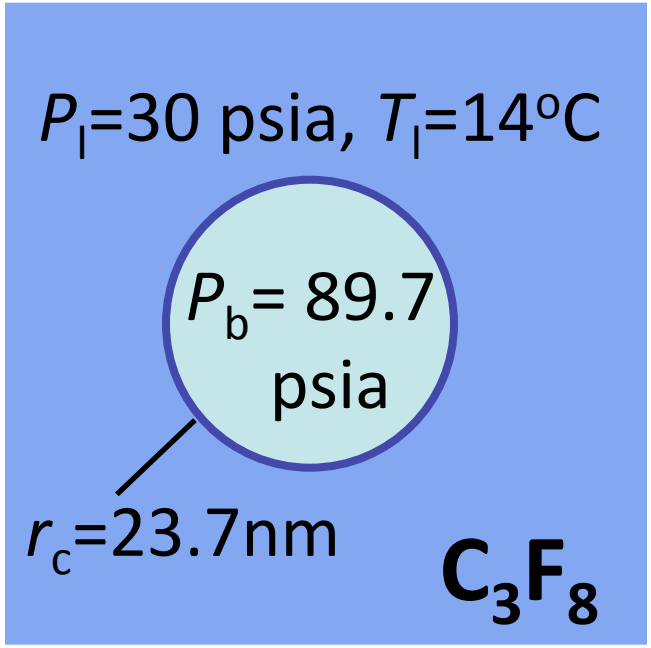
- What does it take to produce critical bubble?

$$E_T = \boxed{4\pi r_c^2 \left(\sigma - T \left(\frac{\partial \sigma}{\partial T} \right)_\mu \right)} \quad \text{1.53 keV}$$

$$\boxed{+ \frac{4\pi}{3} r_c^3 \rho_b \left(h_b - h_l \right)} \quad \text{1.81 keV}$$

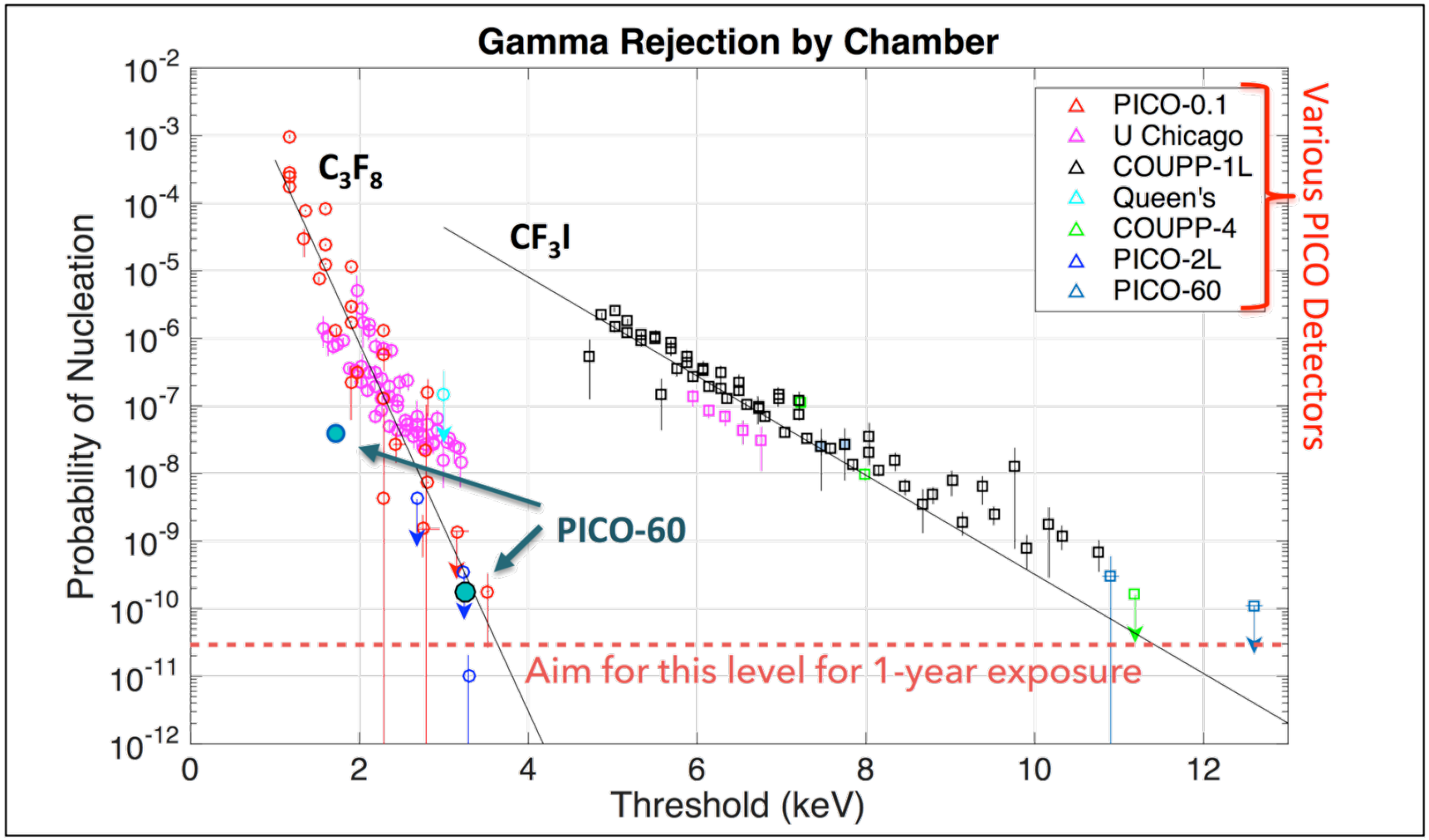
$$\boxed{- \frac{4\pi}{3} r_c^3 \left(P_b - P_l \right)} \quad \text{-0.15 keV}$$

= 3.19 keV total



Surface energy, Bulk energy, Reversible Work

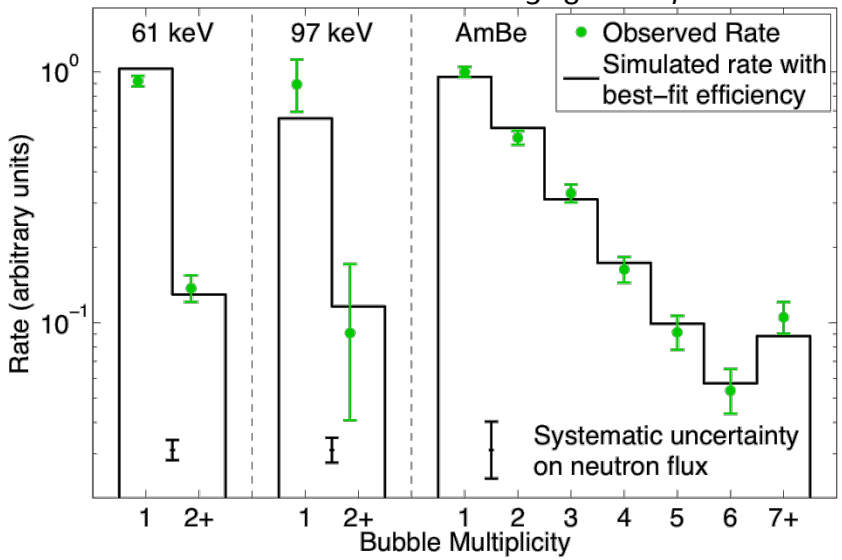
Bubble Chamber Discrimination

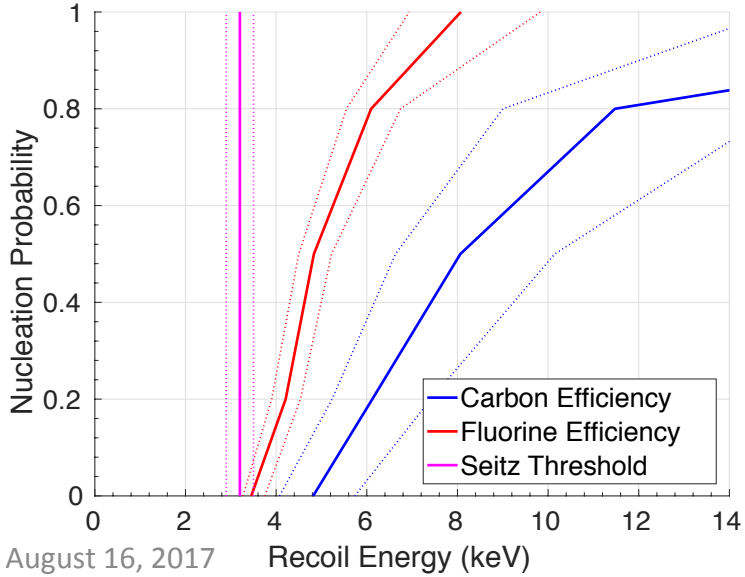


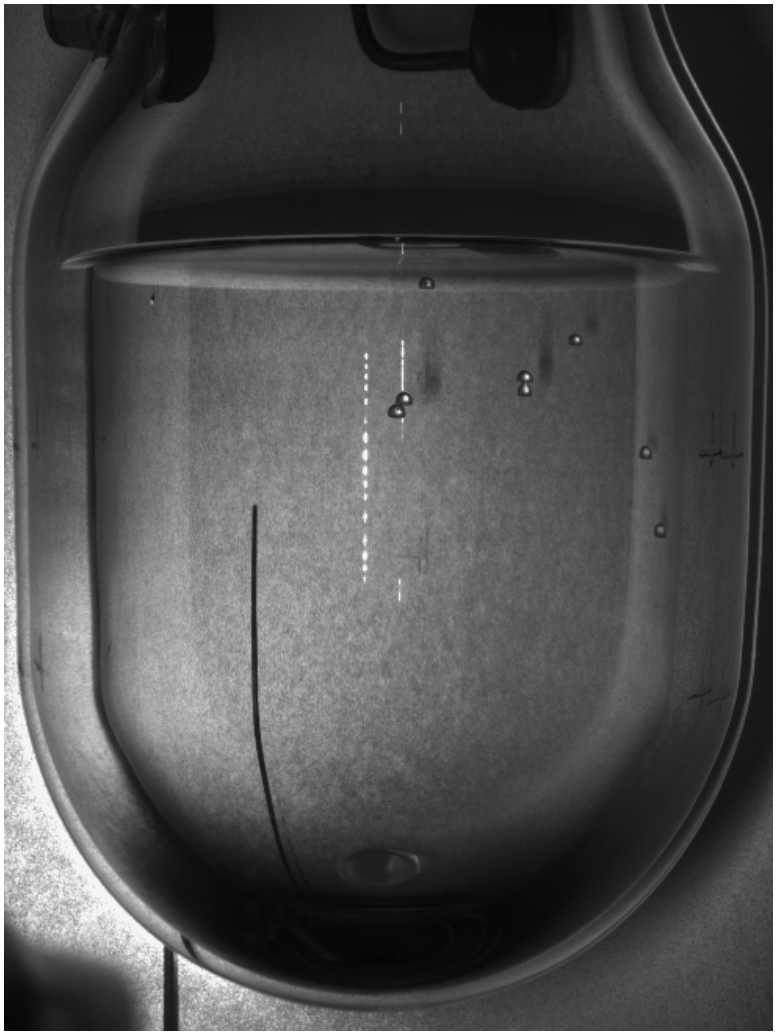
(Dan Baxter, Conference on Science at SURF, May 14, 2017)

Nuclear Recoil Threshold

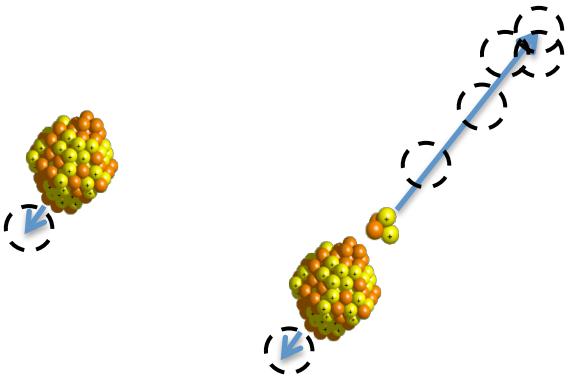
Neutron Calibrations in C_3F_8 @ E_T = 3.2 keV







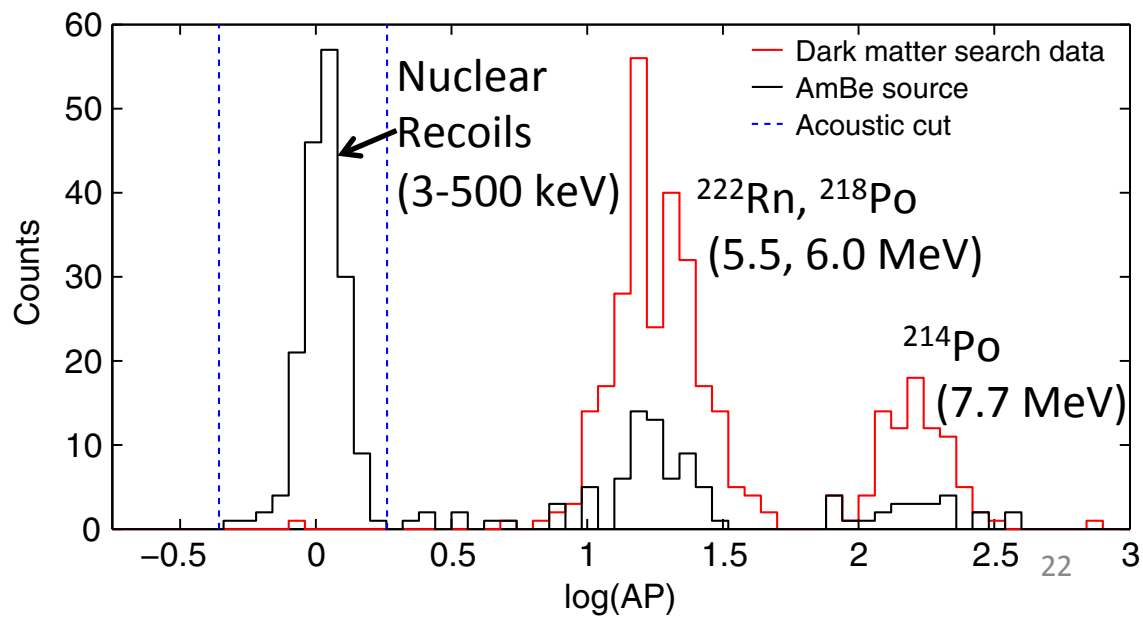
Alpha-Decay Discrimination



10 keV **6 MeV**

- All bubbles look the same!
  - 1-mm diameter bubble has drawn **10 PeV** from superheated fluid
  - Nuclear recoil visually indistinguishable from alpha-decay

- ~1-MeV energy resolution in acoustic channel



C. Amole *et al.* Phys. Rev. D 93, 061101(R) (2016) [arXiv:1601.03729]

Sudbury, Ontario

6800 Feet Down

SNOLAB

PICO-60

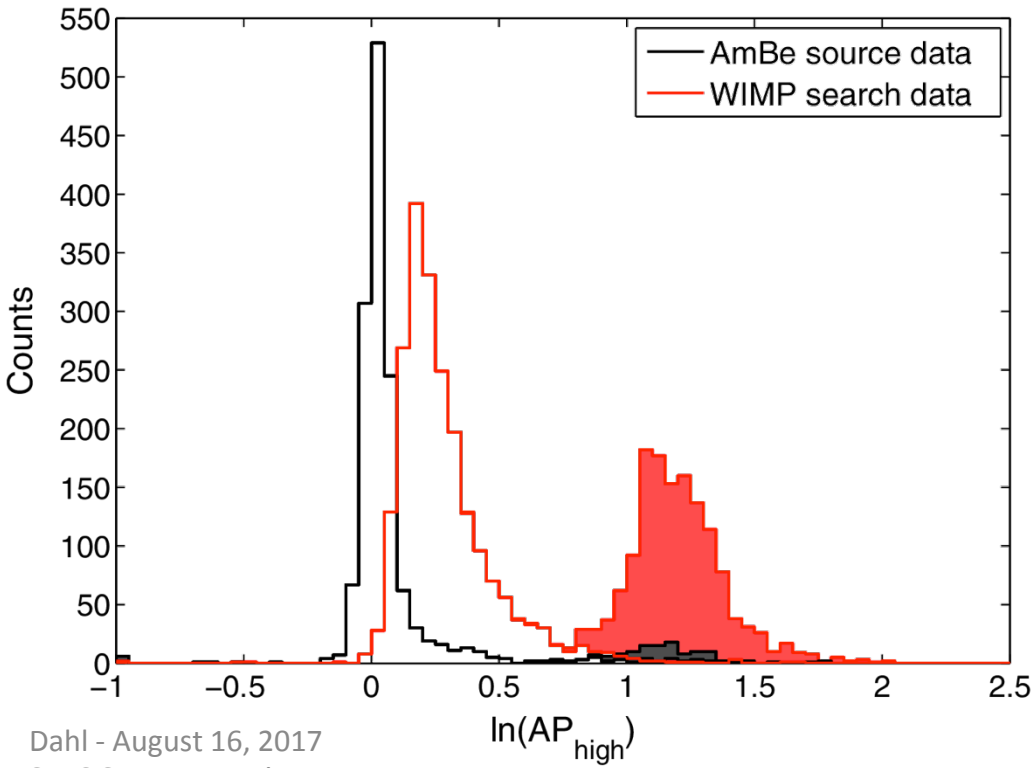
- SNOLAB Run 1 completed (June 2013 – May 2014)
- 35-kg CF_3I, upgradable to 80-kg
- >80% livetime (>90% by end of run)
- 3,415 kg-days exposure at 7—20 keV thresholds

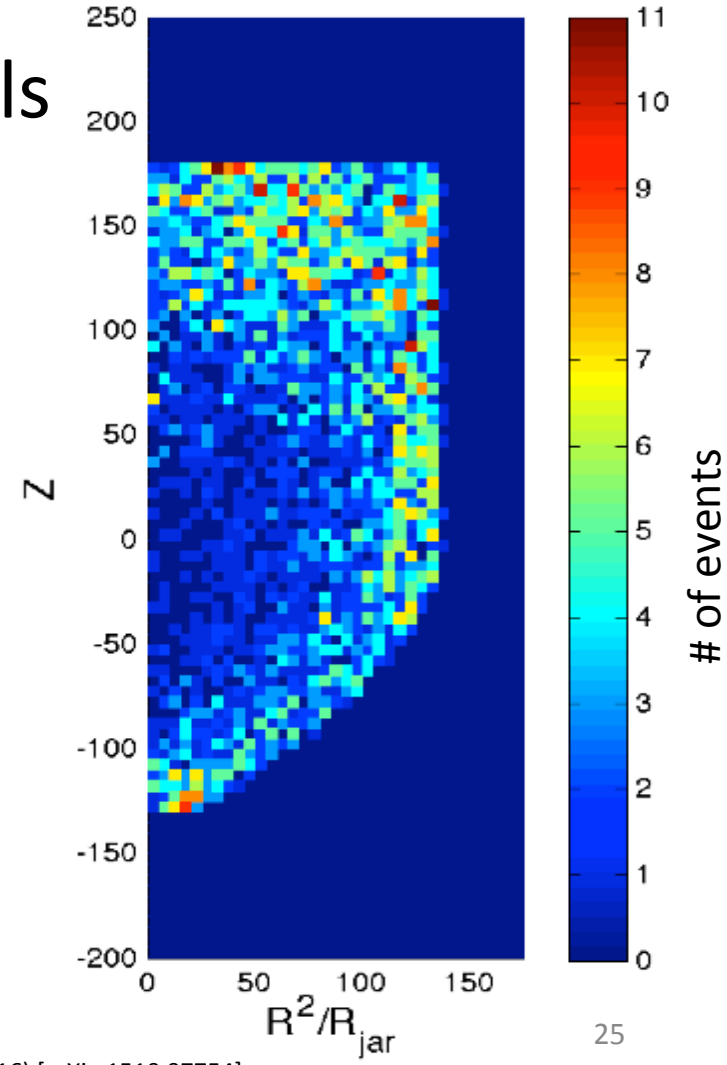
2,111 WIMP-like events

NOT WIMPS

PICO-60 Background Characteristics

- Mostly at top, edges of detector
- Higher AP than nuclear recoils
- Not uniform in time





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

PICO-2L

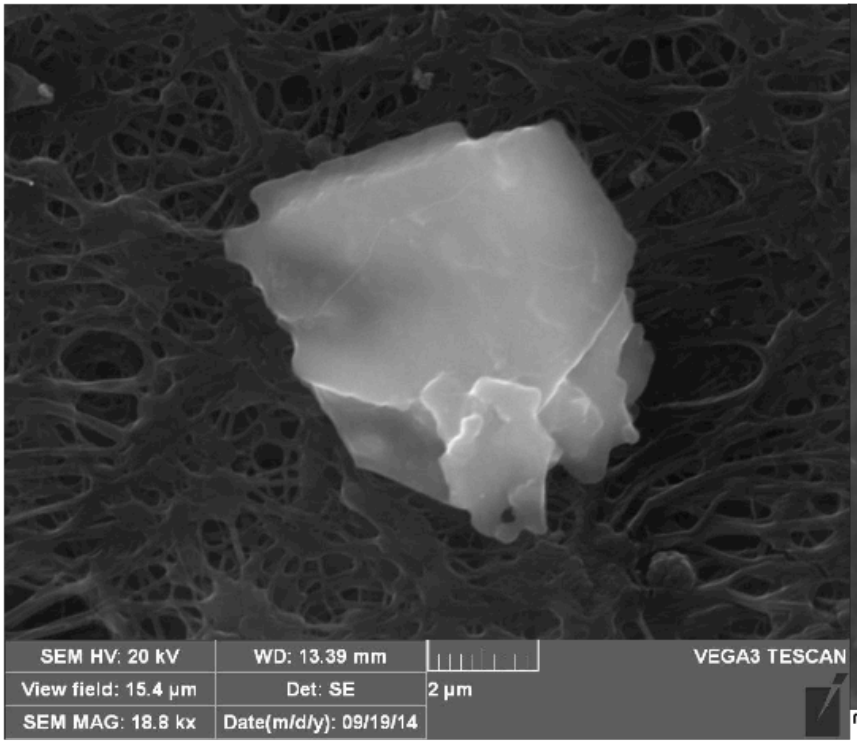
- Run 1 complete:
  Sept 2013 – May 2014

12 WIMP-like events

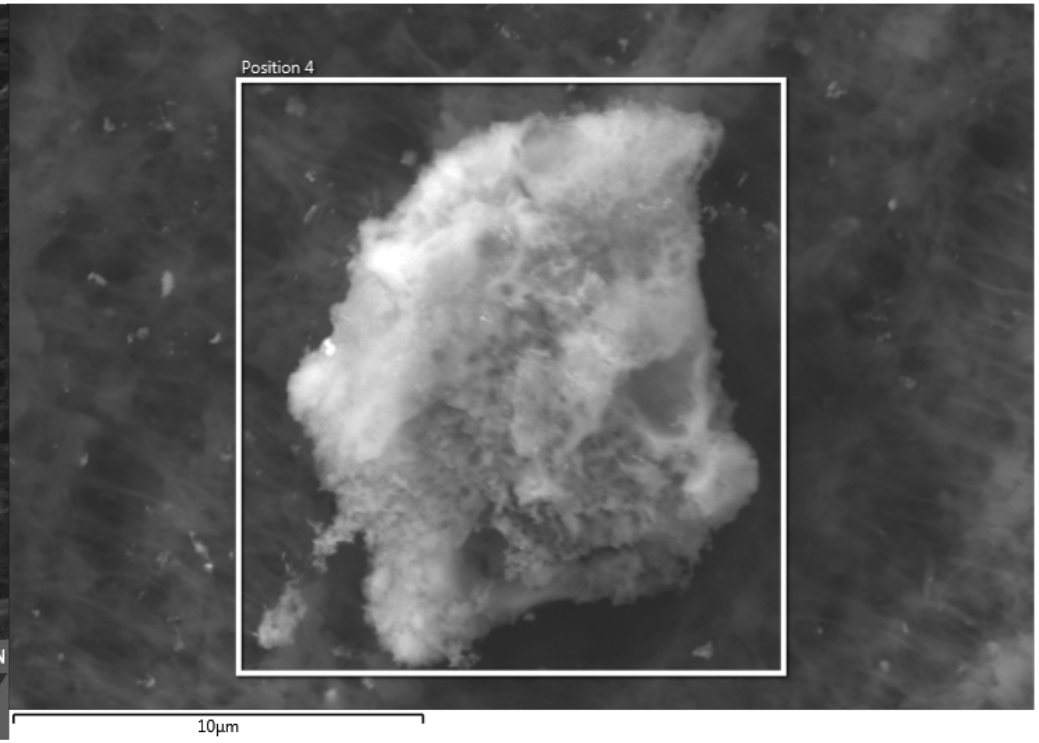
ALSO NOT WIMPS

The Culprit: Particulate

Silica

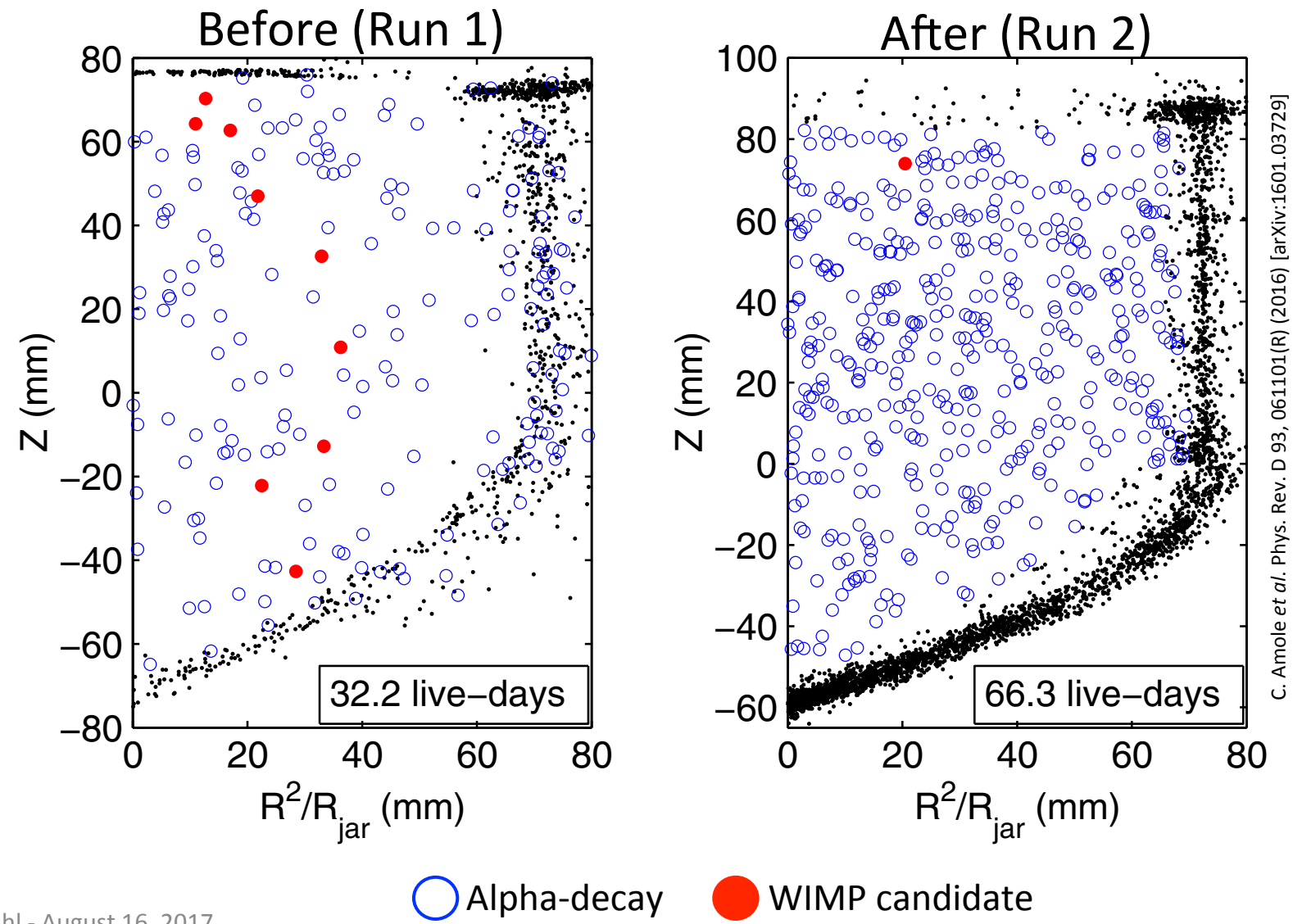


Stainless Steel



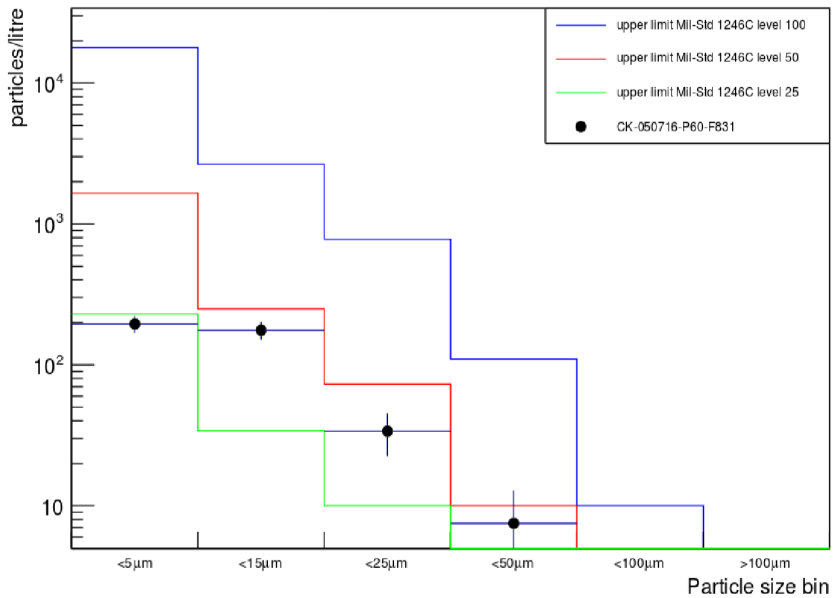
- Particulate mostly from wetted materials
- Rebuilt PICO-2L in 2015 with new cleanliness, assembly, and operating procedures designed to minimize particulate production

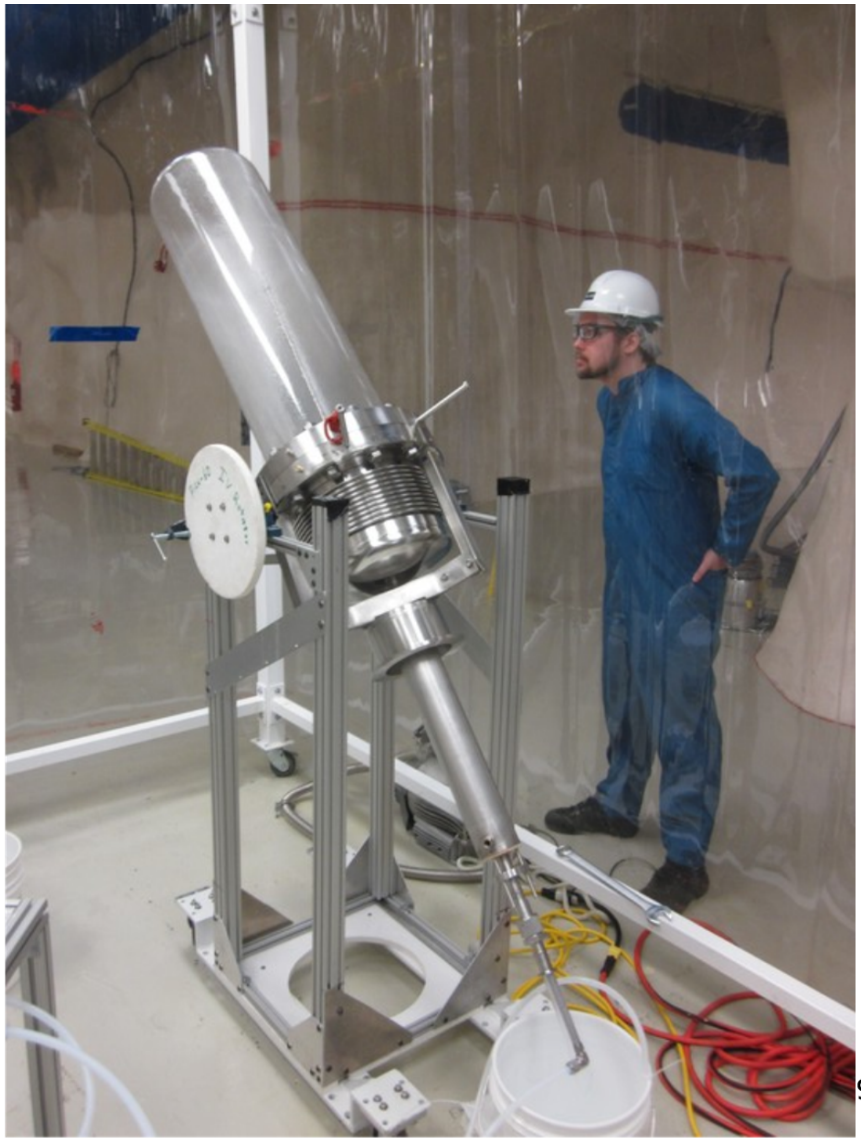
Particulate Mitigation in PICO-2L



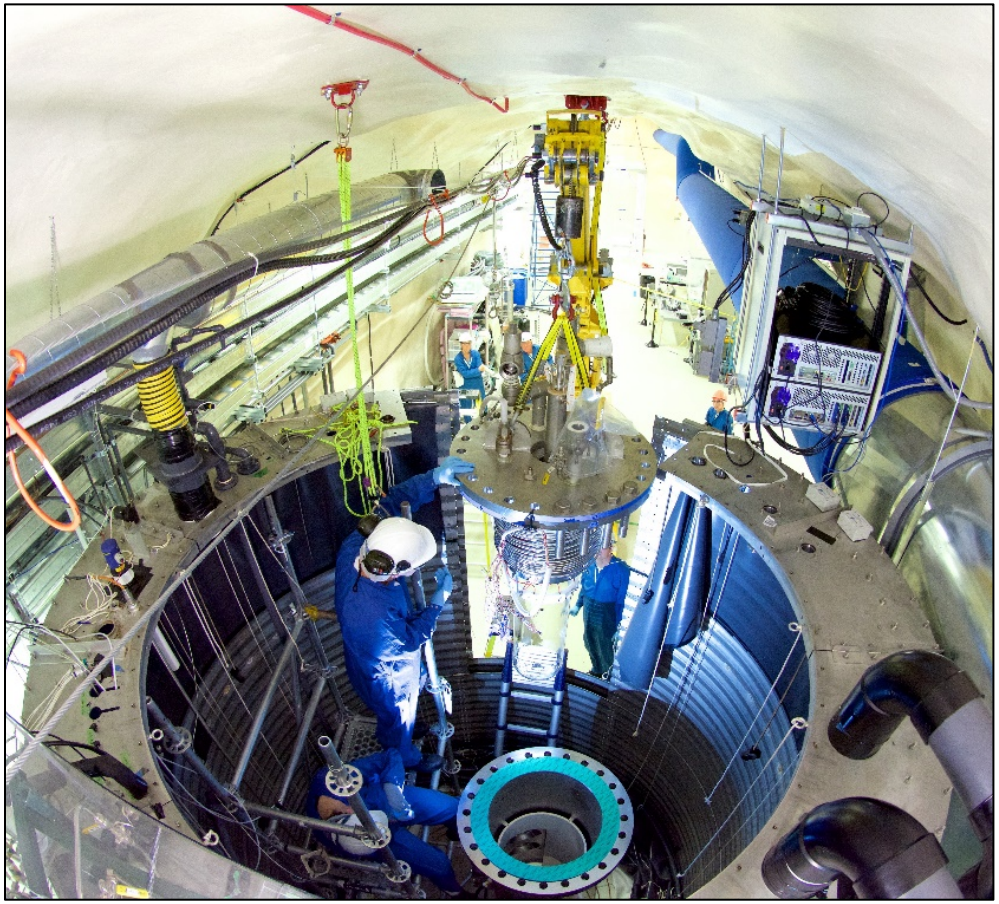
PICO-60 C_3F_8

- Goal: Eliminate particulate backgrounds in 40-liters C_3F_8





Commissioning

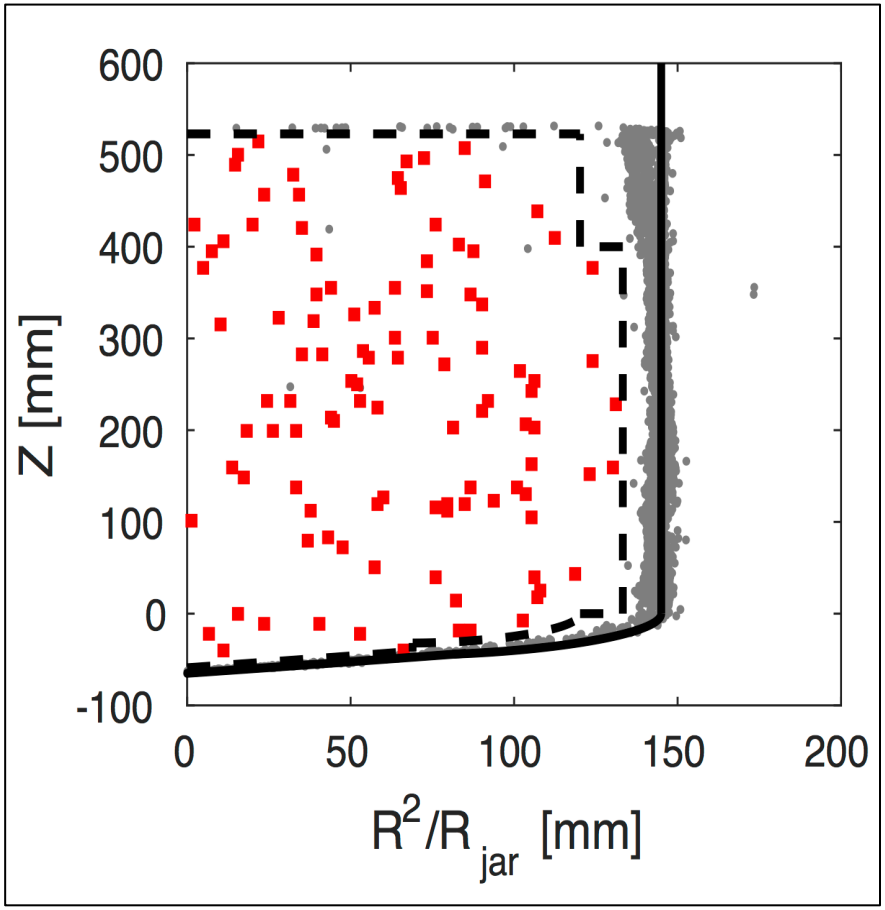


- Filled with 40L C_3F_8 on June 30, 2016
- First physics run began Nov 28, 2016

Before Opening the Box

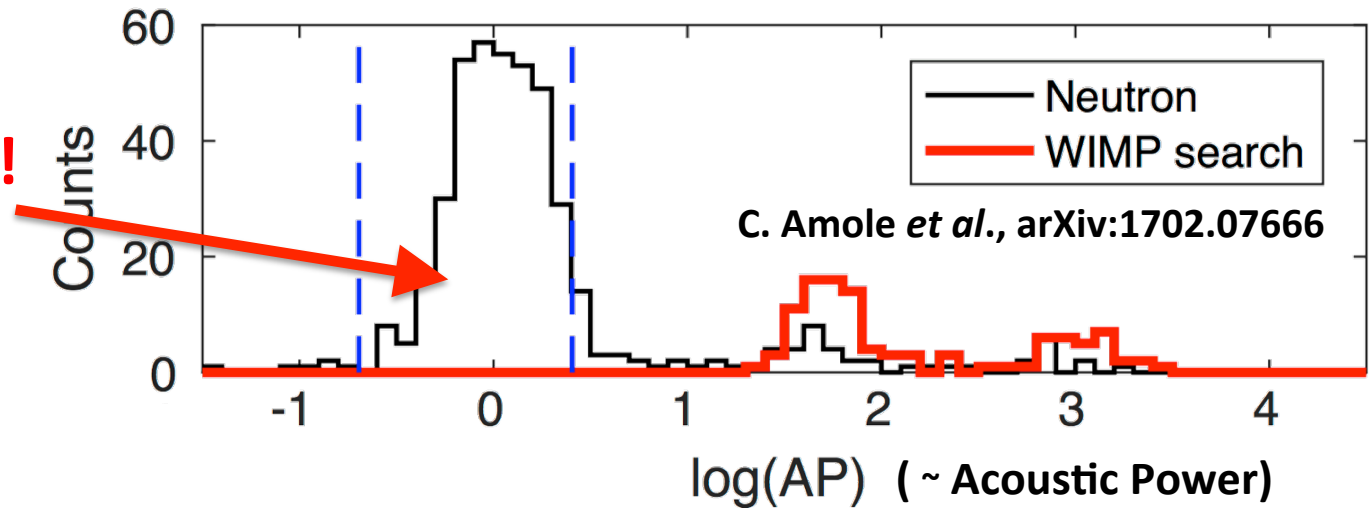
- 30.0 live-day Blinded Dataset
  - "Blind" for PICO means deaf, *i.e.* no acoustic information
  - Effectively salts data with 3 bulk singles per day (alpha-decays)
  - 106 bulk-single bubbles observed
- Neutron Background
  - ***Not*** blinded to images
  - 3 multiple-bubble events in the physics data
  - 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**

C. Amole *et al.*, PRL 118, 251301 (2017)



After Opening the Box

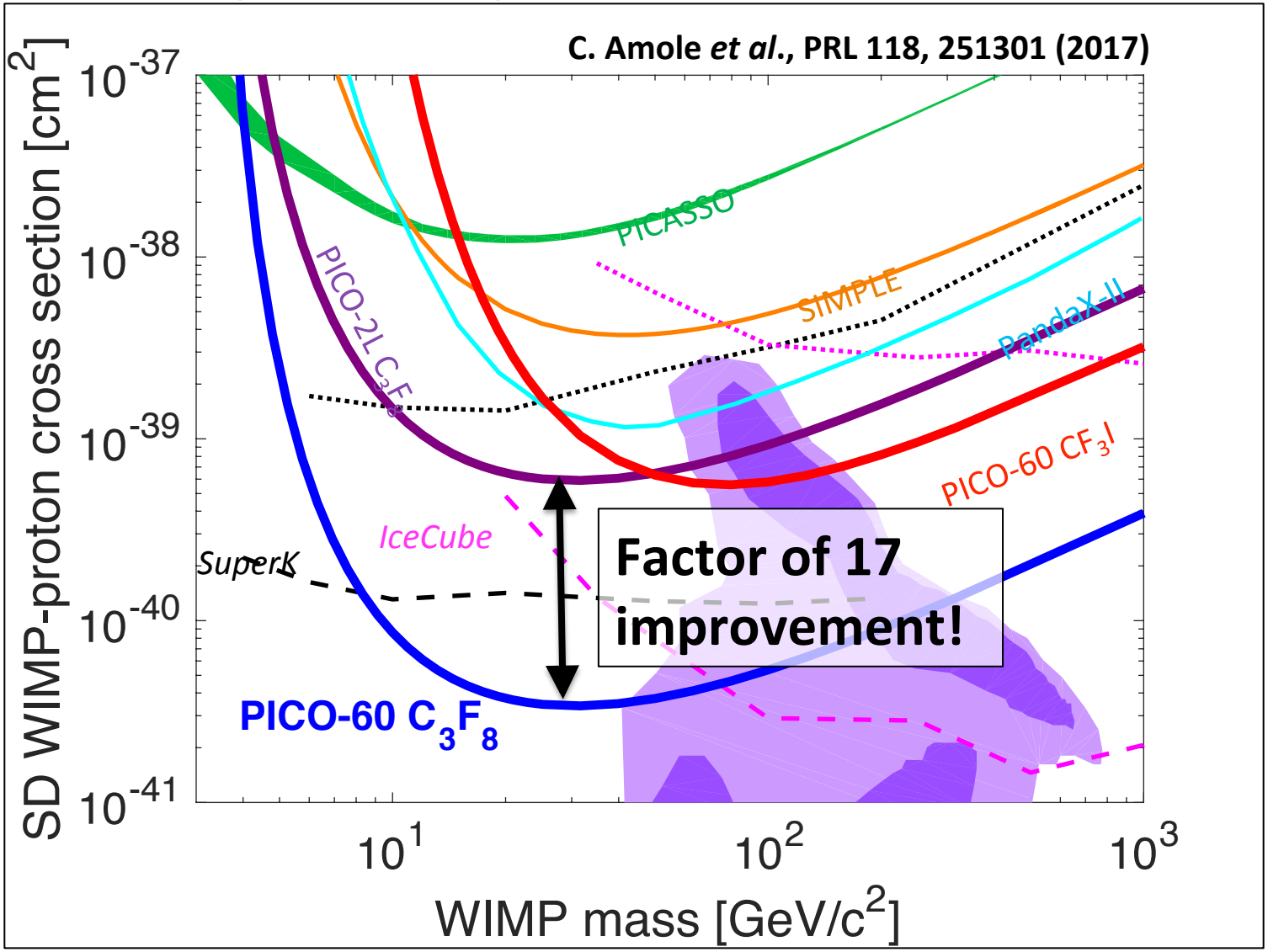
No events in signal region!



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

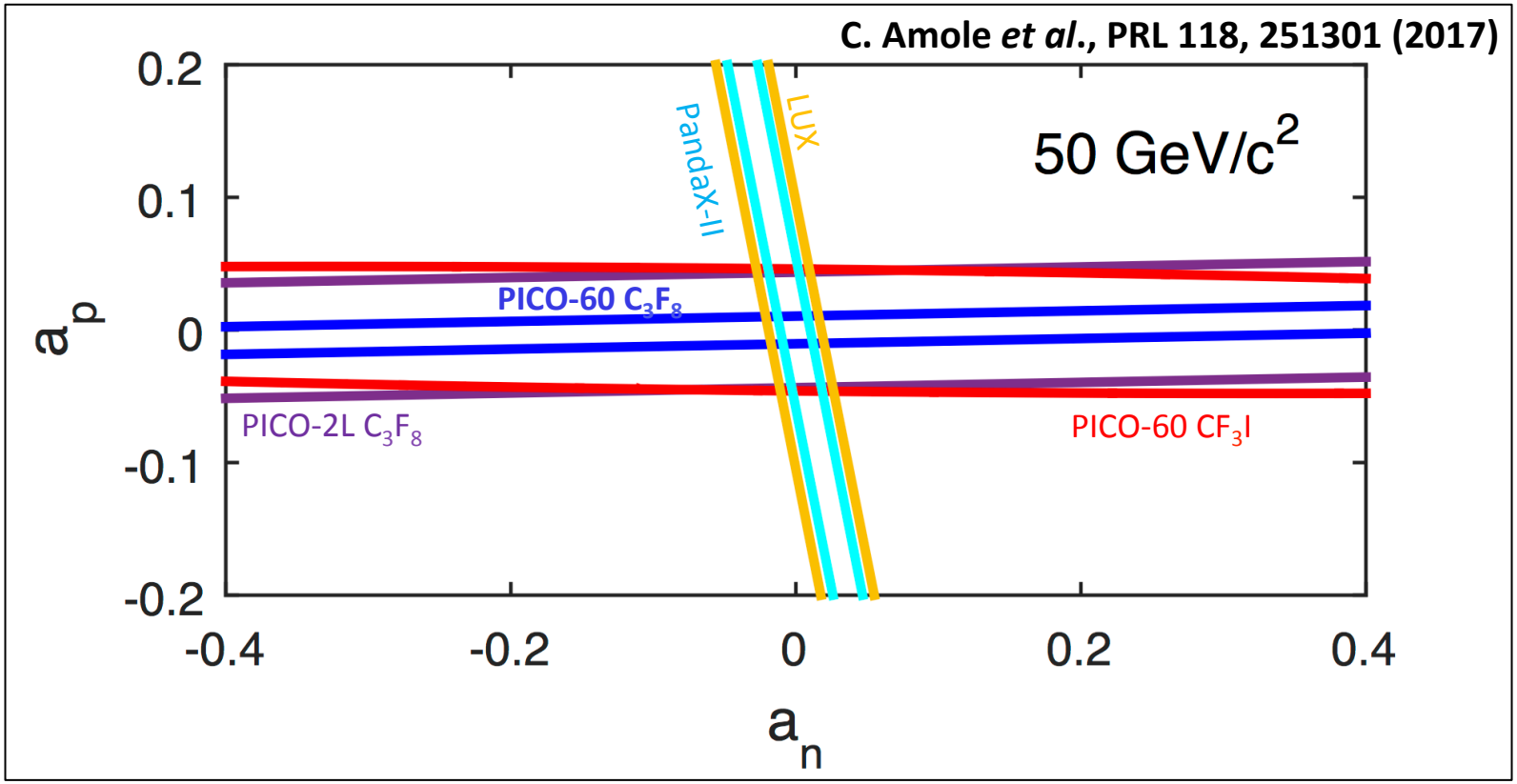
TABLE I. Summary of the final number of events and exposure determination for singles and multiples in the 30.0 live-day WIMP search dataset of PICO-60 C_3F_8 at 3.3 keV thermodynamic threshold.

Spin-dependent Limits



Nucleon Coupling Limits

Consider spin-dependent coupling to proton and neutron



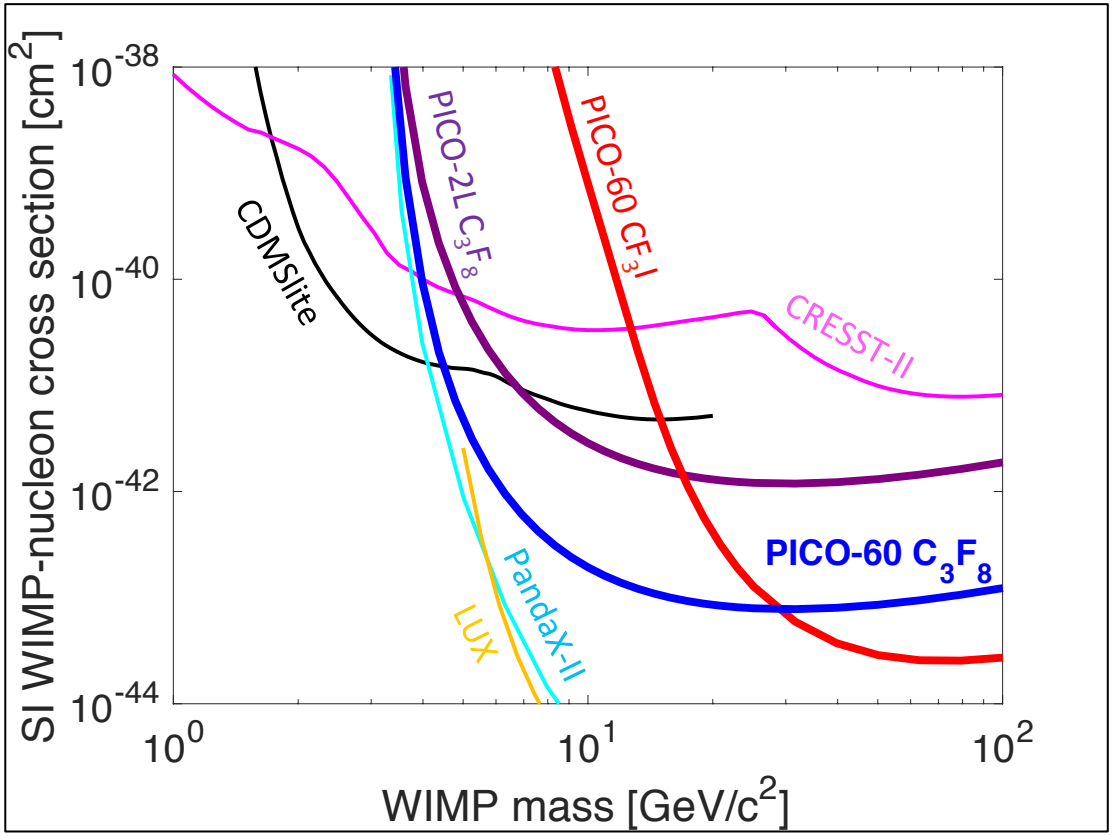
See Tovey for details:

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

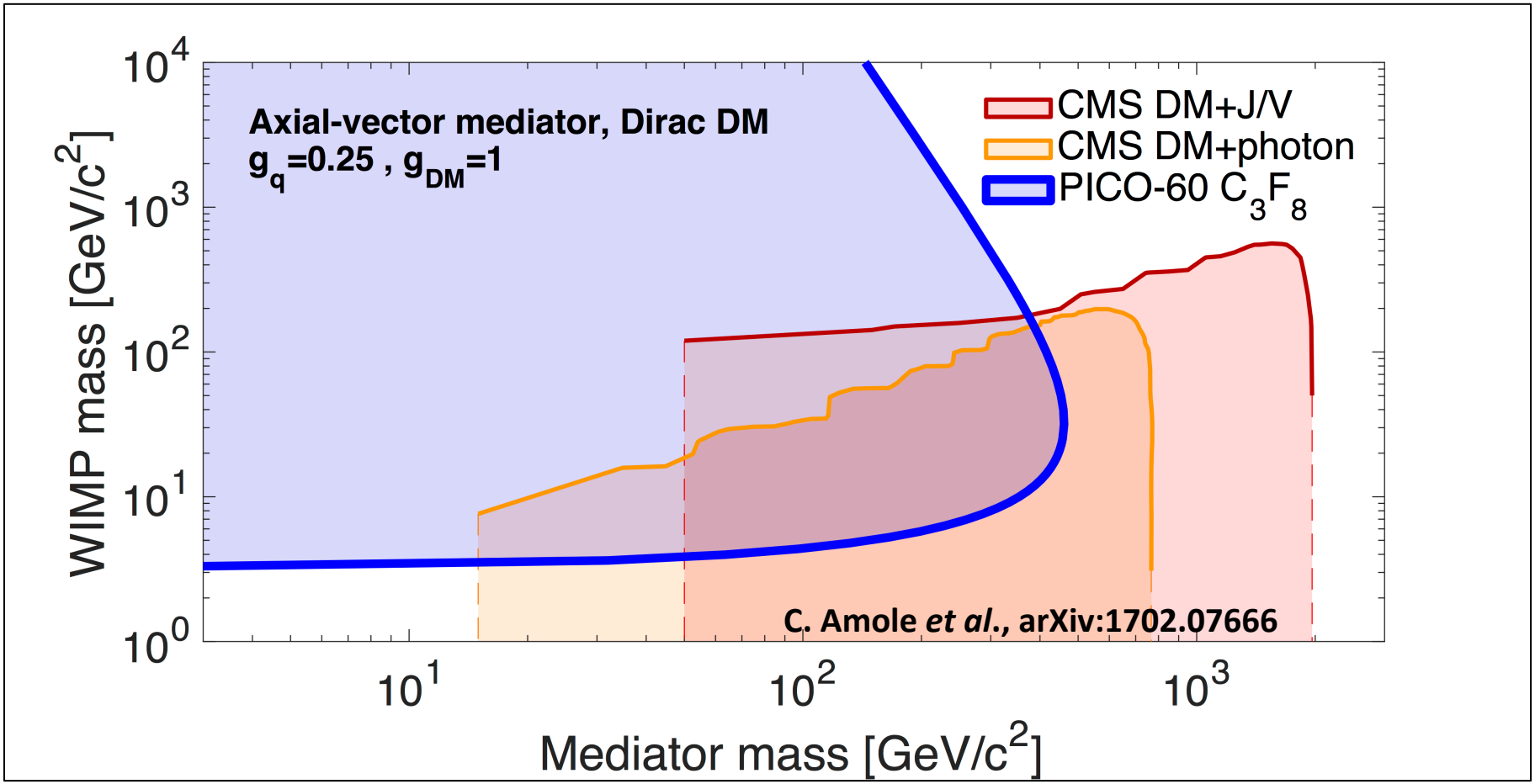
Spin-independent Limits

- Light nuclear targets give sensitivity to low-mass WIMPs
- A second live-month exposure at 2.4 keV in hand (still blinded) aiming at ~GeV WIMPs

C. Amole *et al.*, PRL 118, 251301 (2017)



Comparison to Collider



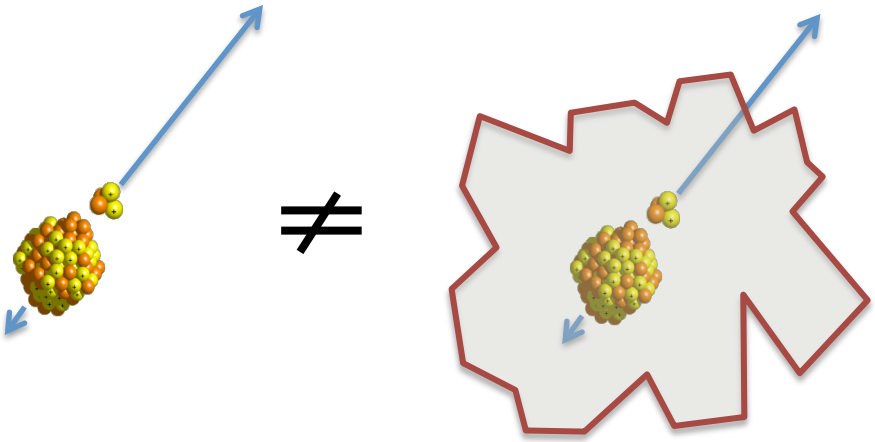
For direct detection, this simplified model boils down to EFT at all mediator masses (trivial scaling with g's)

The Future of PICO

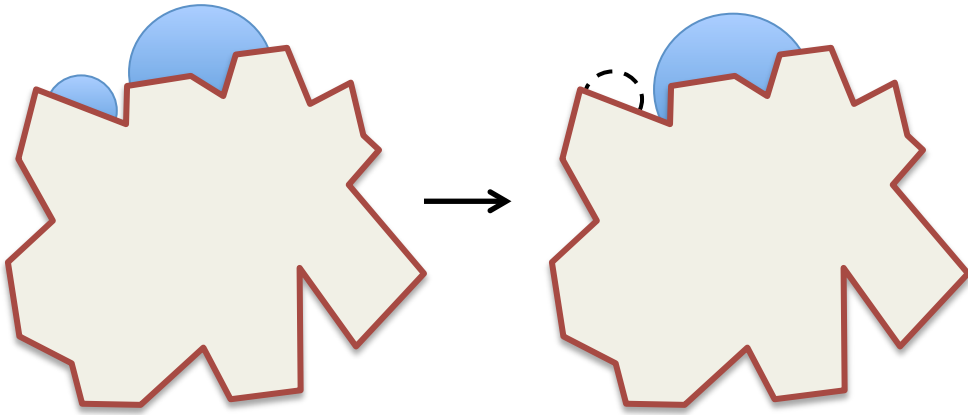
- We've shown we can mitigate our background and set new limits…
- But this is not *yet* a discovery machine
- We must either discriminate against this background, or prove that we have eliminated it entirely. (Or both…)

How to get Bubbles from Particulate

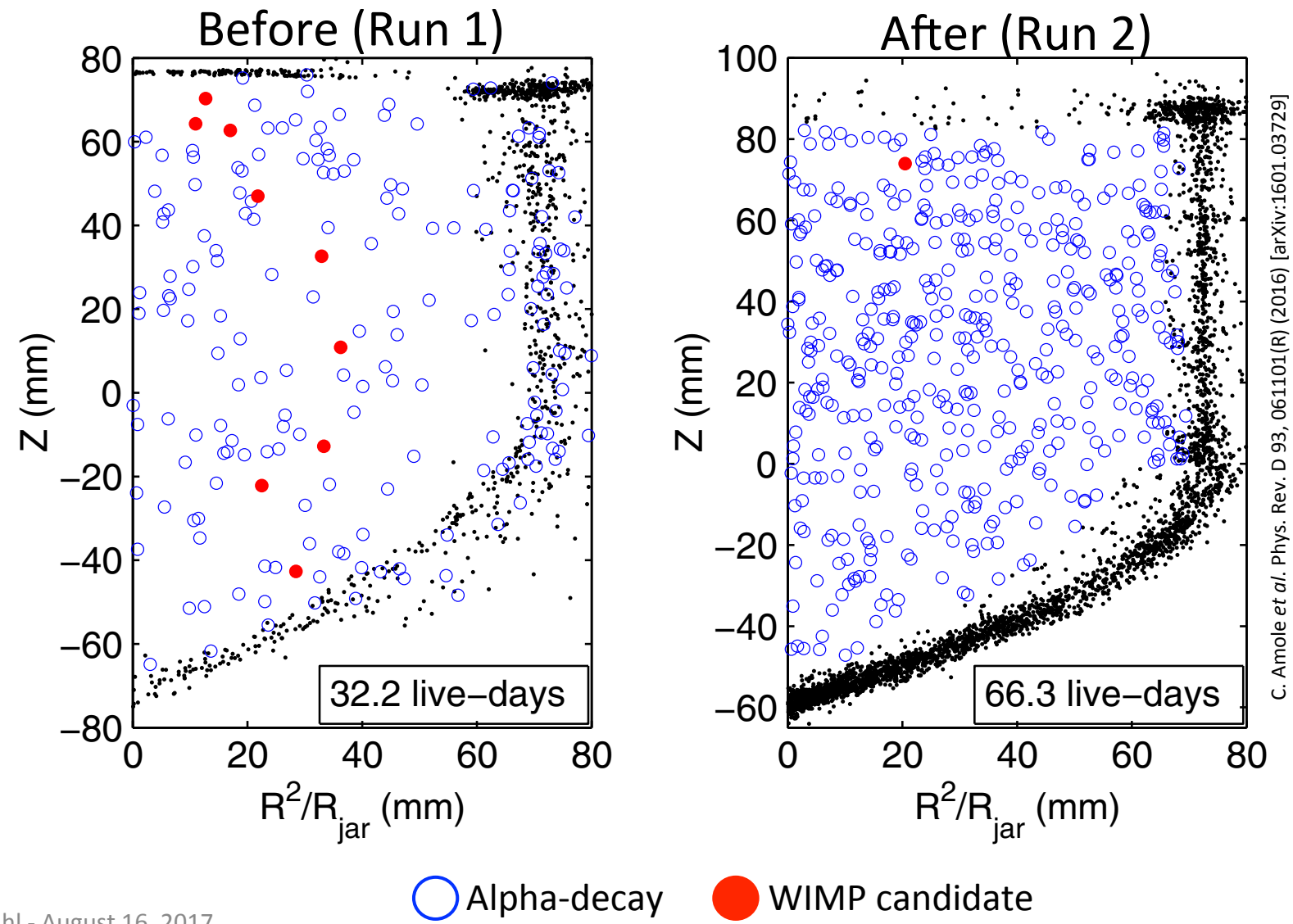
- Alpha decays from particulate, failed acoustics



- Merging buffer fluid droplets, cavitation

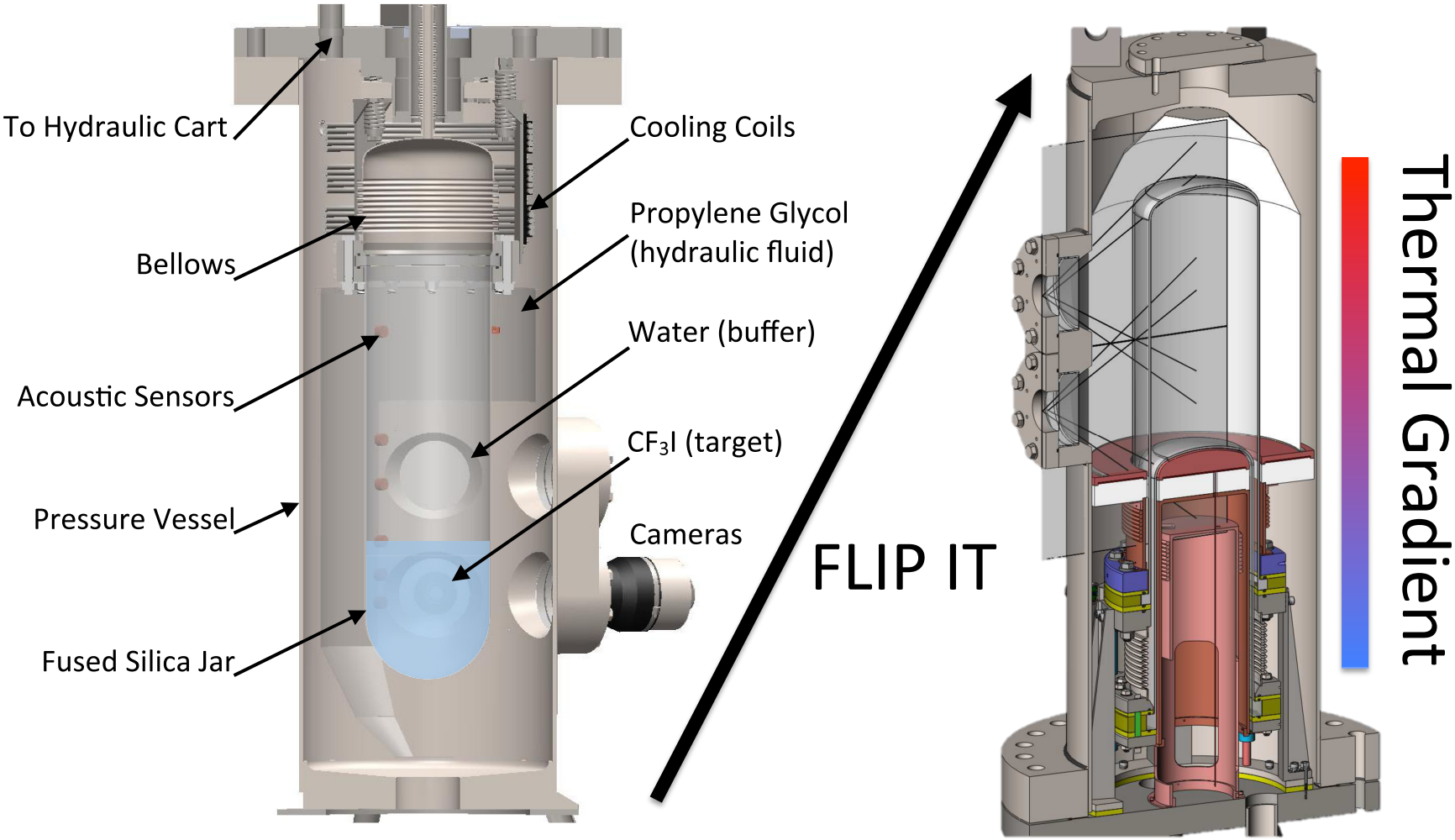


Particulate Mitigation in PICO-2L



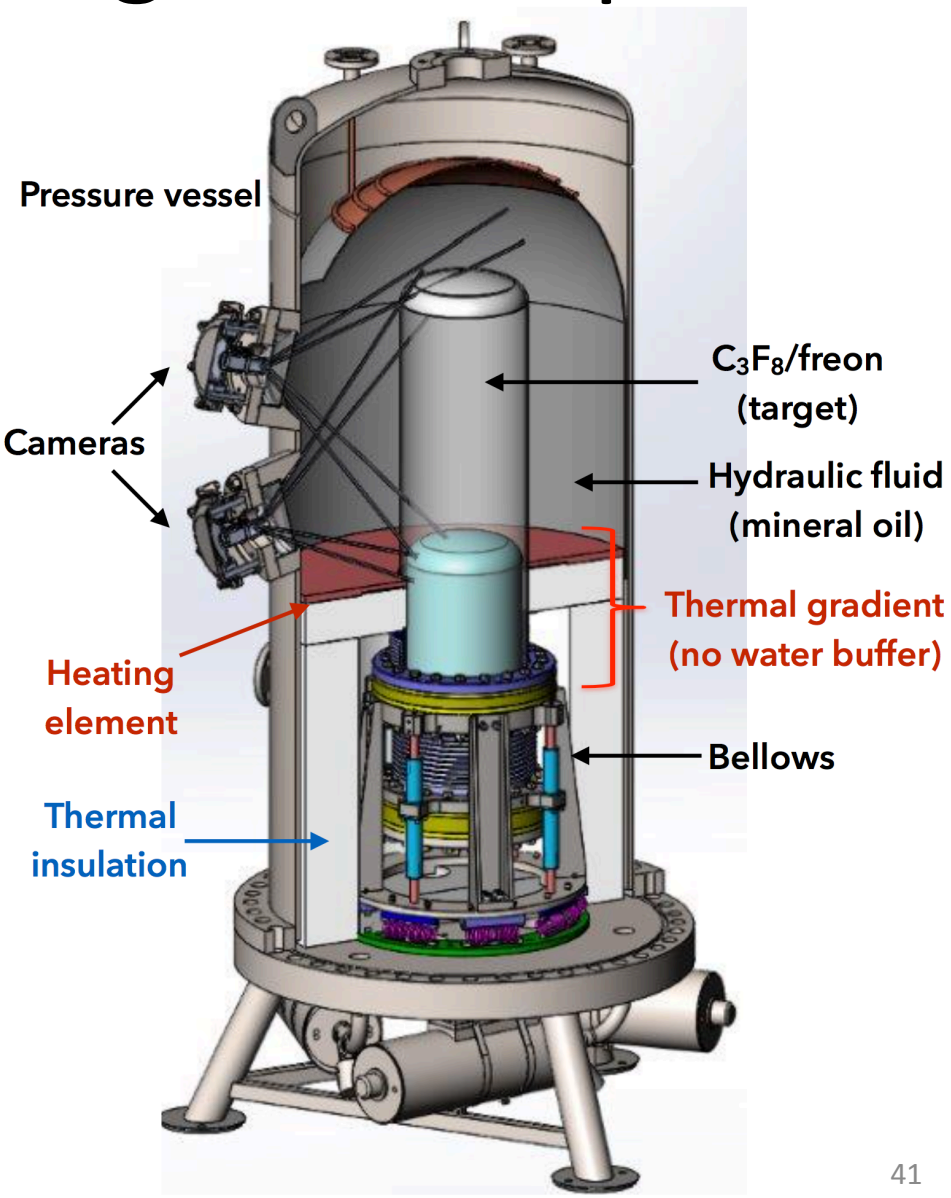
C. Amole *et al.* Phys. Rev. D 93, 061101(R) (2016) [arXiv:1601.03729]

Solution: PICO-40L no-buffer-fluid bubble chamber



PICO-40L: "Right-side-up"

- Replace buffer fluid with thermal gradient
- Larger diameter pressure vessel to reduce neutron background
- Parts now arriving at SNOLAB, physics in 2018



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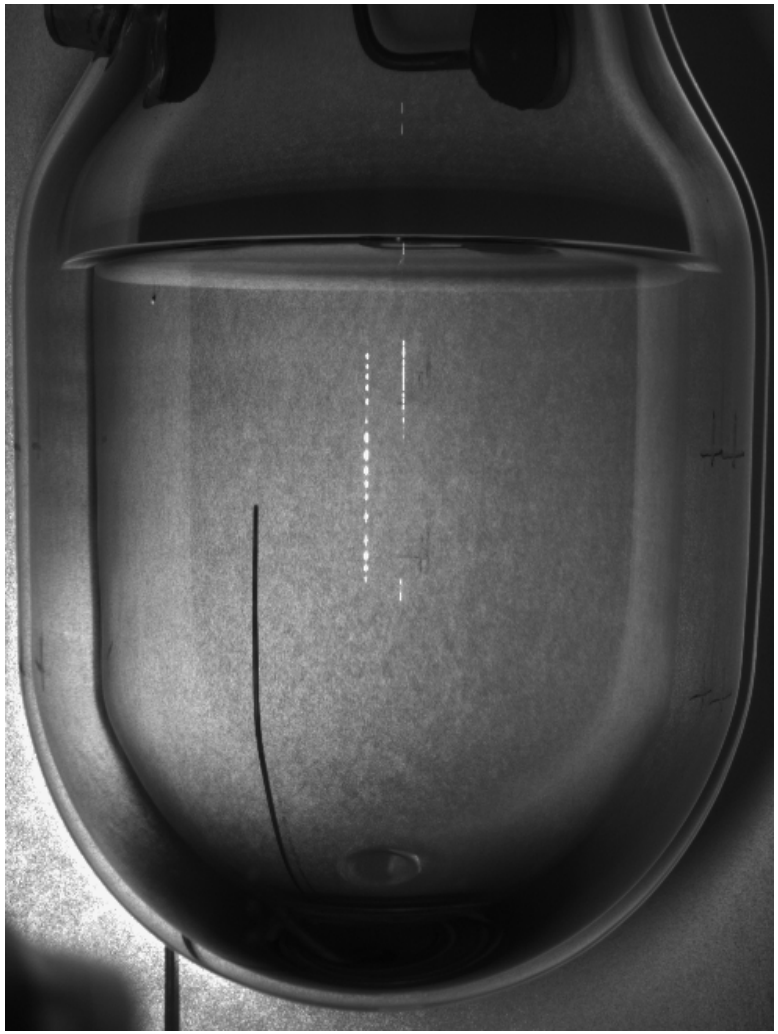
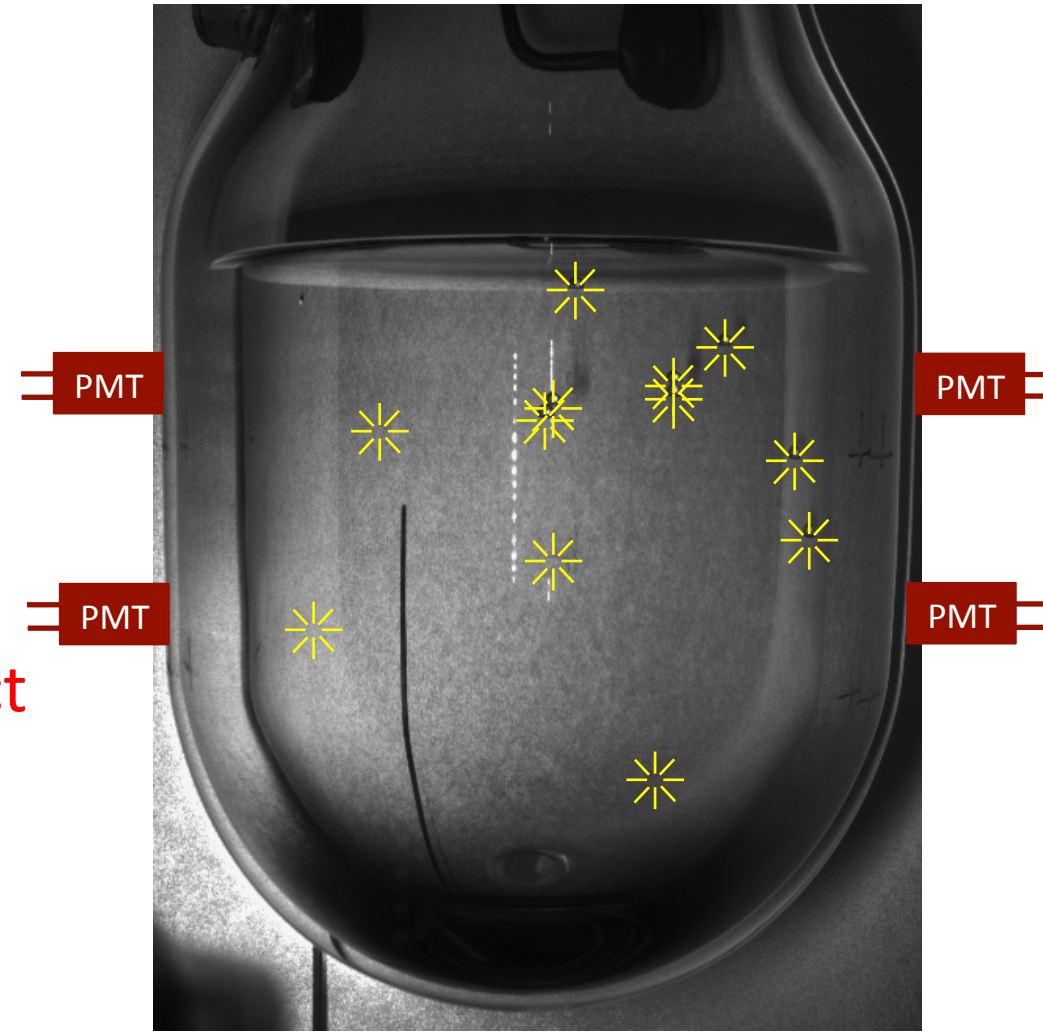
Bubble Chambers

- Superheated Target
  - CF_3I, C_3F_8, …
- Particle interactions nucleate bubbles
- Cameras and acoustic sensors capture bubbles
- Chamber recompresses after each event

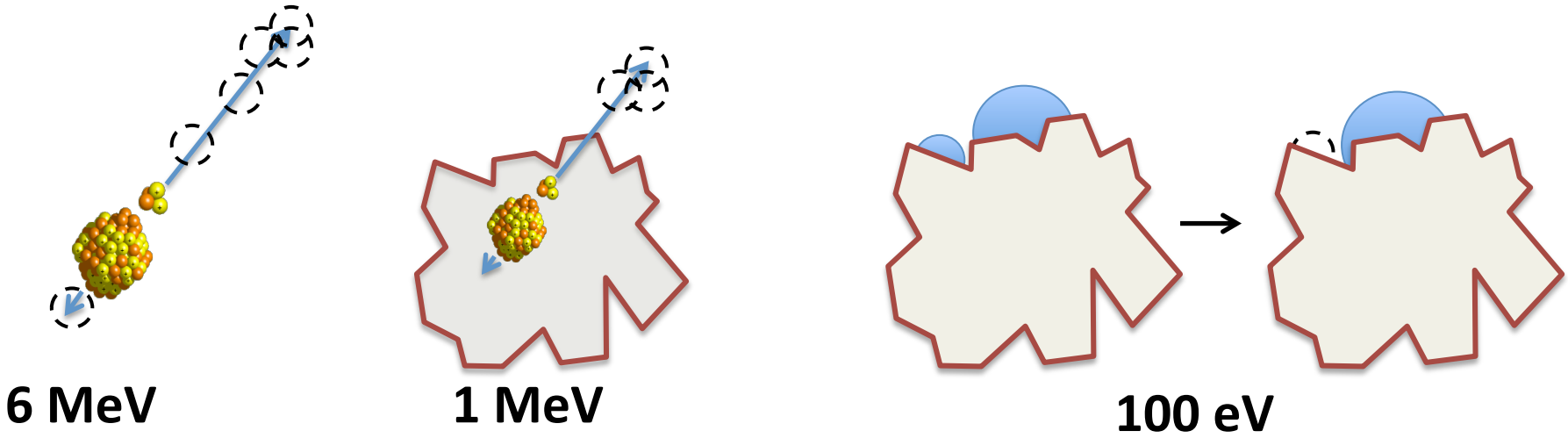


Scintillating Bubble Chambers

- Superheated Scintillator
  - Xe, Ar, CF_4, …
- Particle interactions nucleate bubbles and produce scintillation
- Cameras and acoustic sensors capture bubbles and photodetectors collect scintillation light
- Chamber recompresses after each event



Bubble Chamber Backgrounds

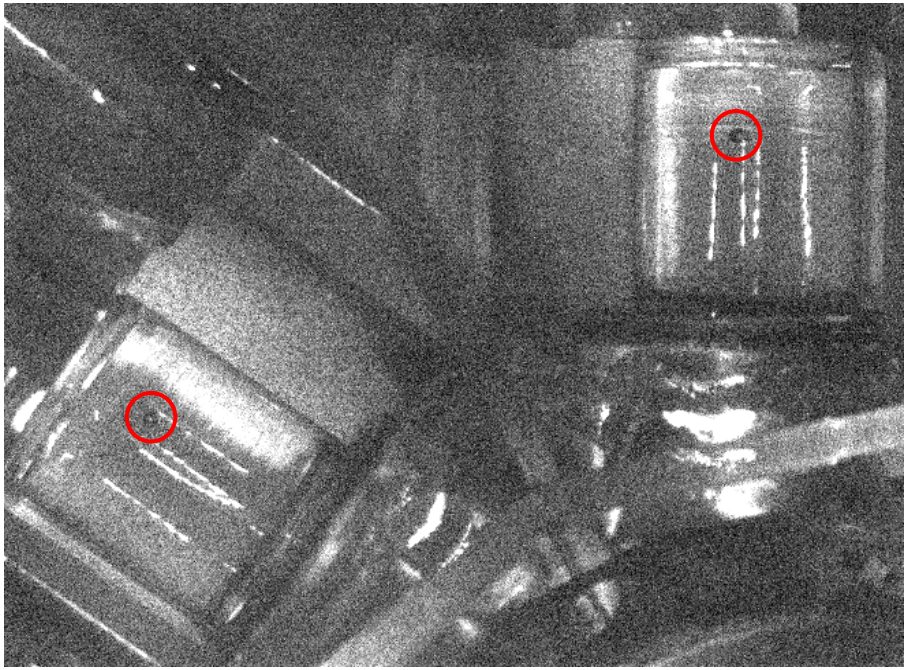


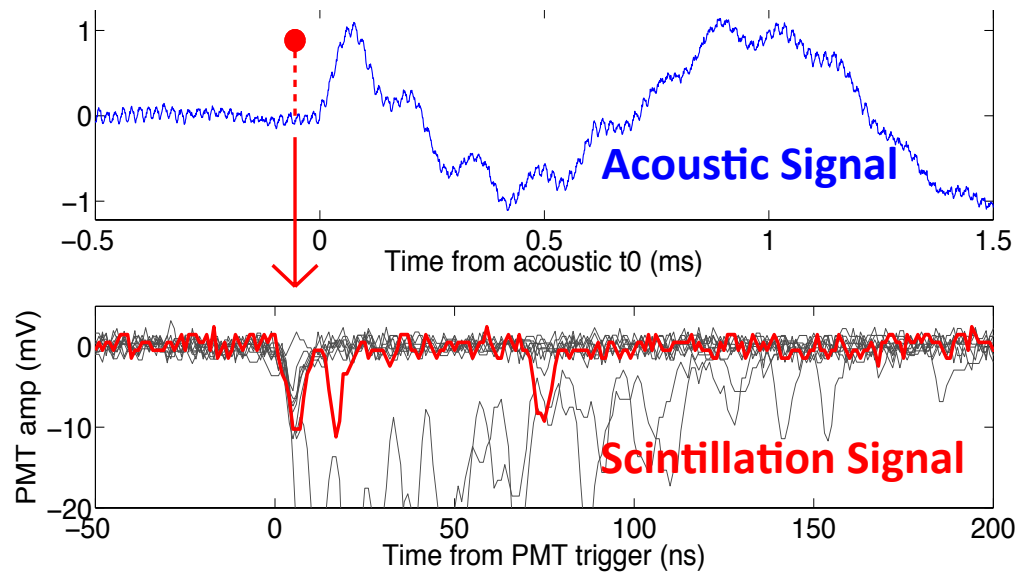
- ALL of these are trivially identified with scintillation signal
- More information *always* key to background discrimination

Scintillating Bubble Chamber

- Now demonstrated in superheated xenon
  - 30-gram right-side-up prototype at Northwestern arXiv:1702.08861 [PRL **118**, 231301]

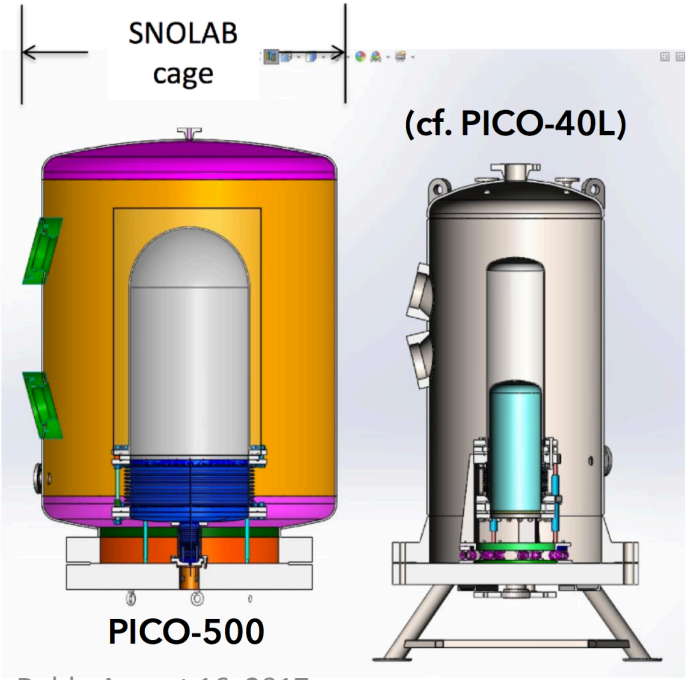
- Potential for sub-keV thresholds and multiple targets (Xe, Ar, CF_4, …)
  - Better low-threshold electron discrimination than freon chambers
  - Low-energy NR calibrations underway

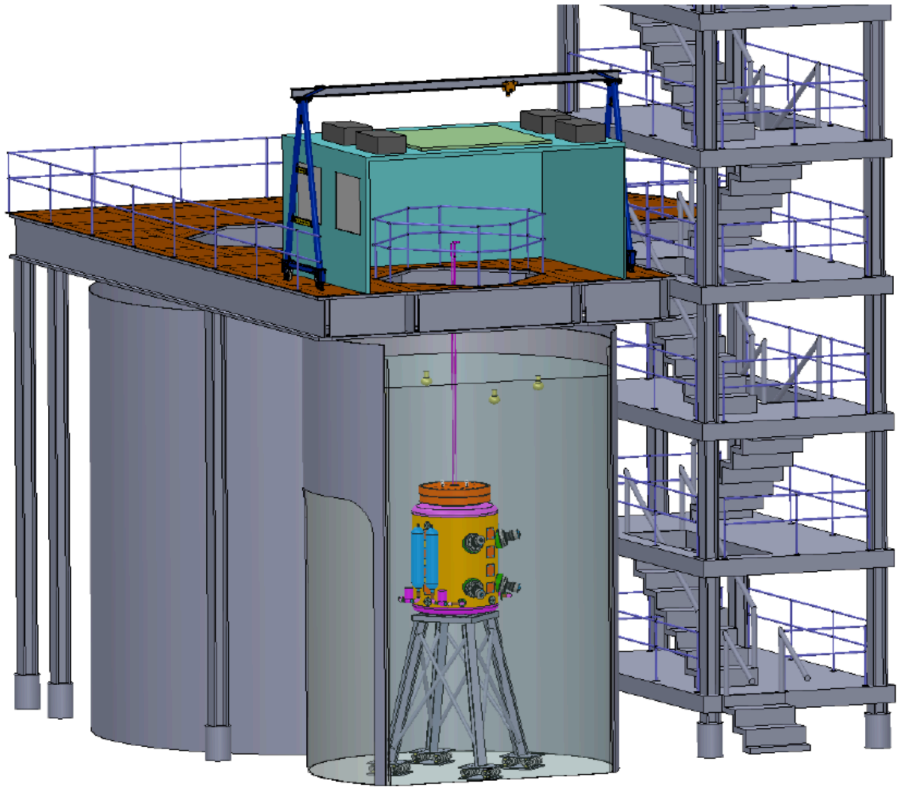




PICO-500

- Ton-scale detector, $3M proposal to CFI (Canadian Foundation for Innovation)
- Right-side-up design, straight-forward scale-up of PICO-40L
- On track to turn on in 2019





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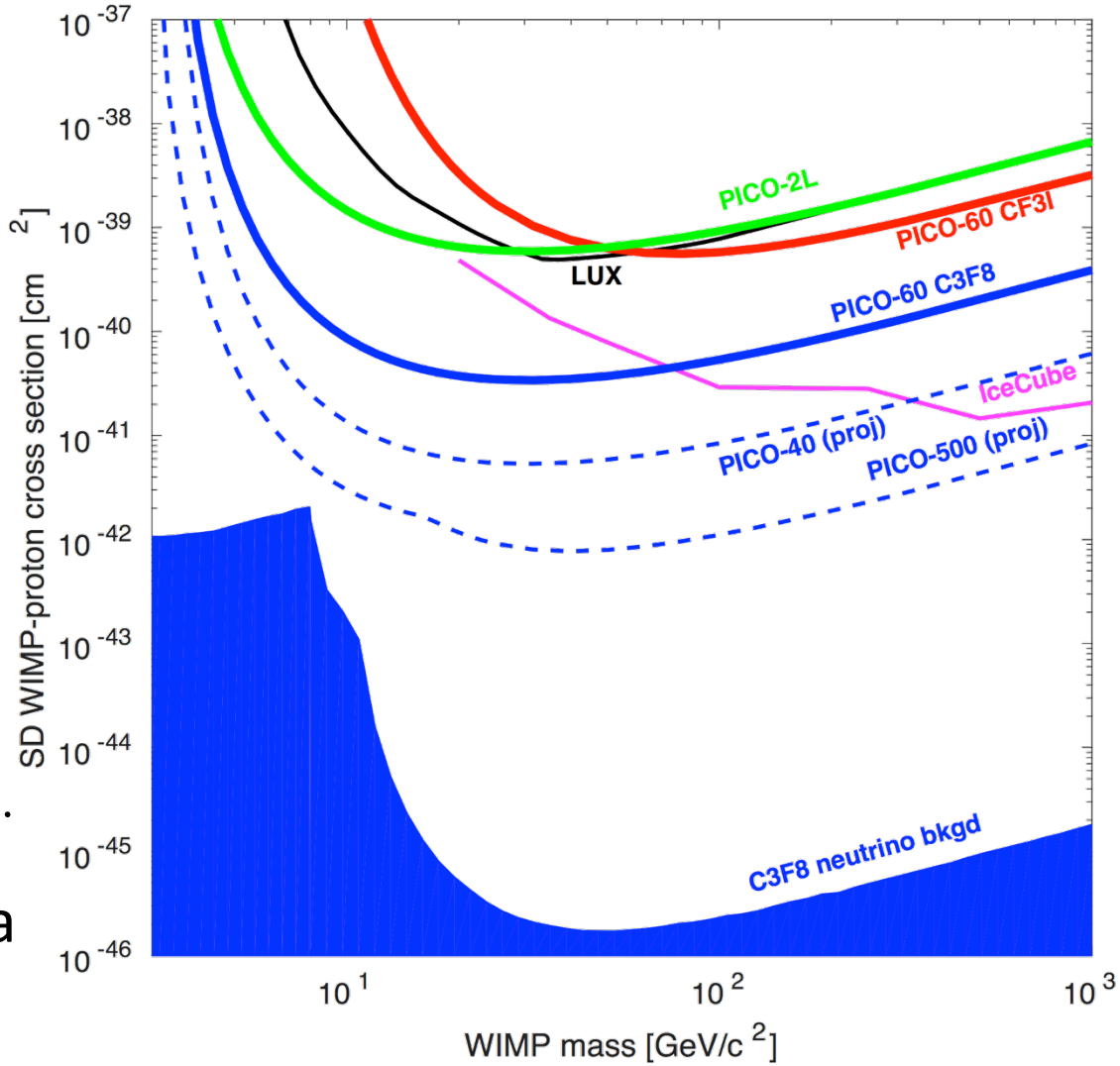
Summary

- **PICO-60 result: Background-free**
- PICO technology still getting better
  - PICO-40L (right-side-up)
  - Scintillating Bubble Chambers
- PICO-500 underway, could make WIMP discovery
- Bubble chambers are key exploring SD space…

  …and to characterizing a future WIMP signal!



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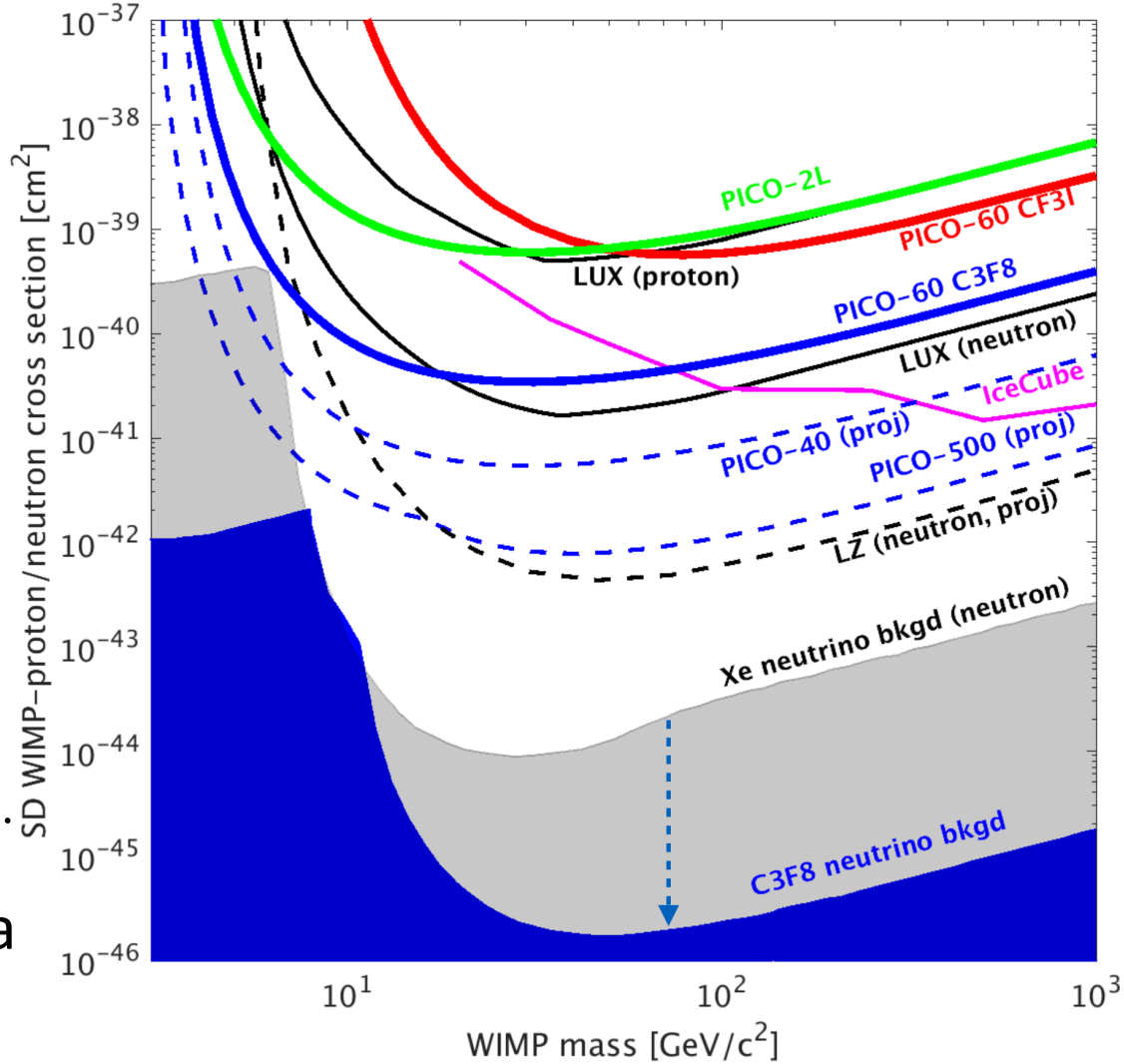


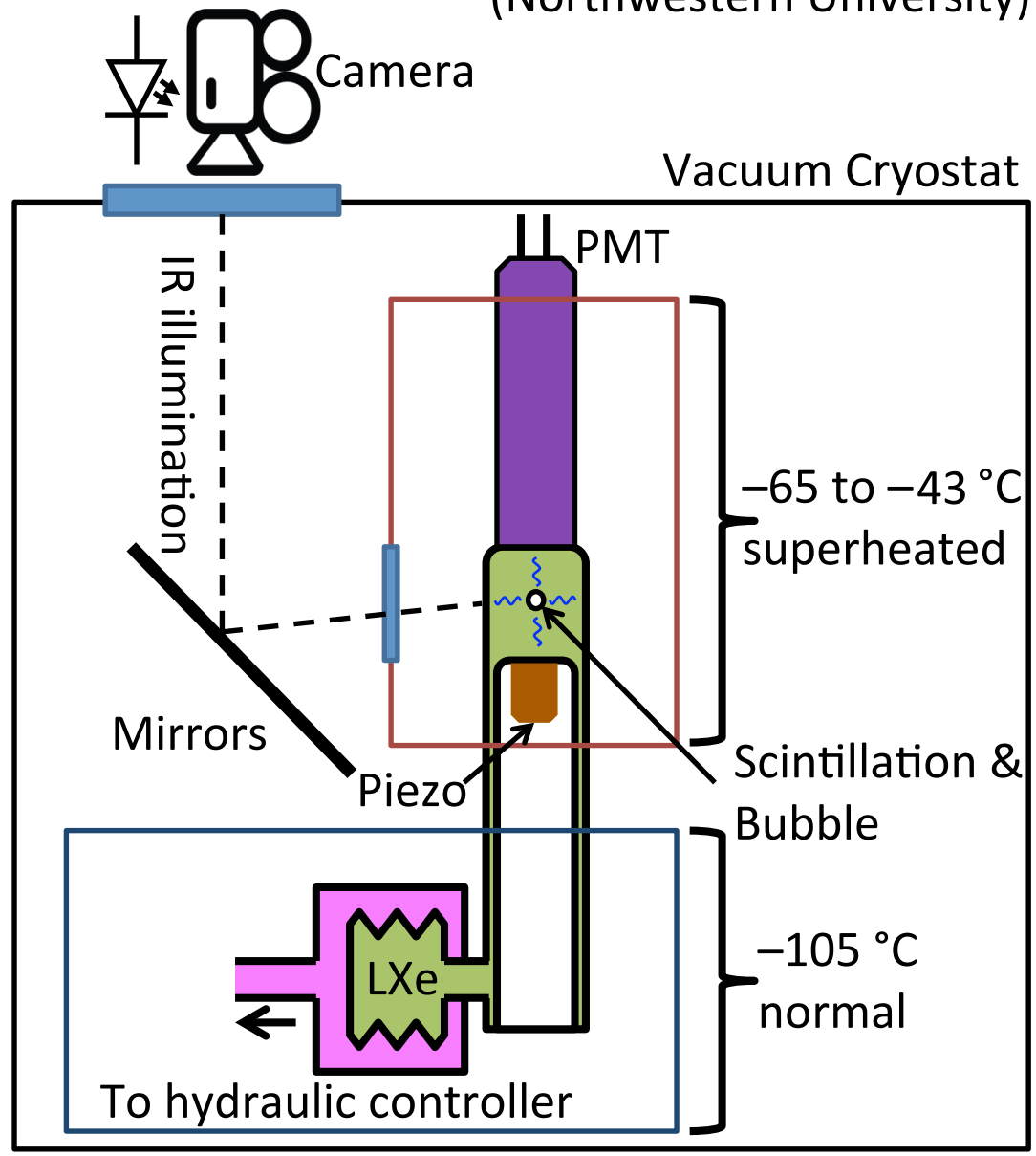
Backup

Scintillating Bubble Chamber

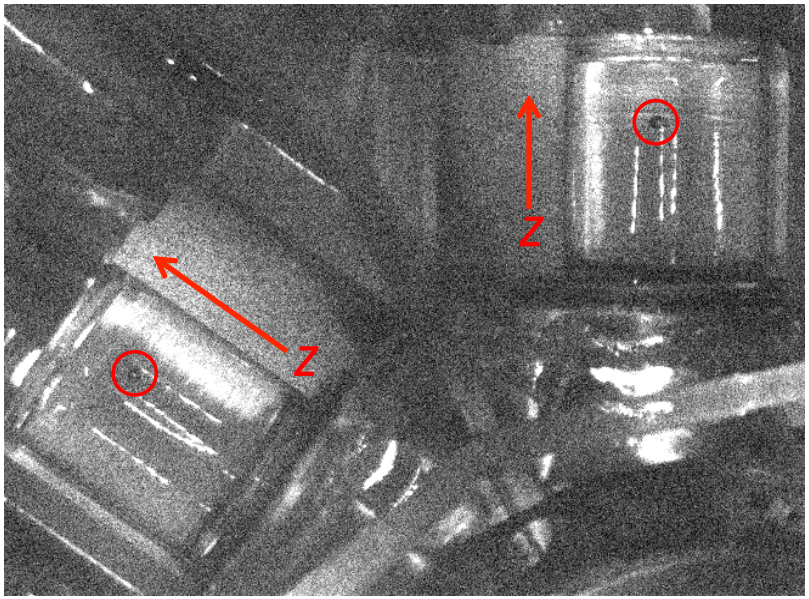
- **Concept:**
  Coincident scintillation and bubble nucleation by nuclear recoils
  - Extreme electron recoil discrimination as in freon bubble chambers
  - Event-by-event energy from scintillation signal
  - Now demonstrated in liquid xenon

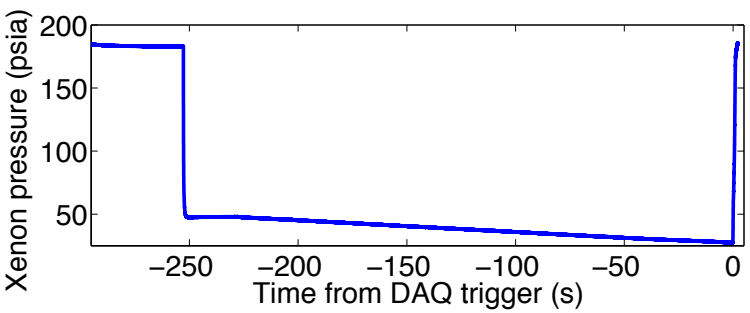
    arXiv:1702.08861
    [PRL **118**, 231301]

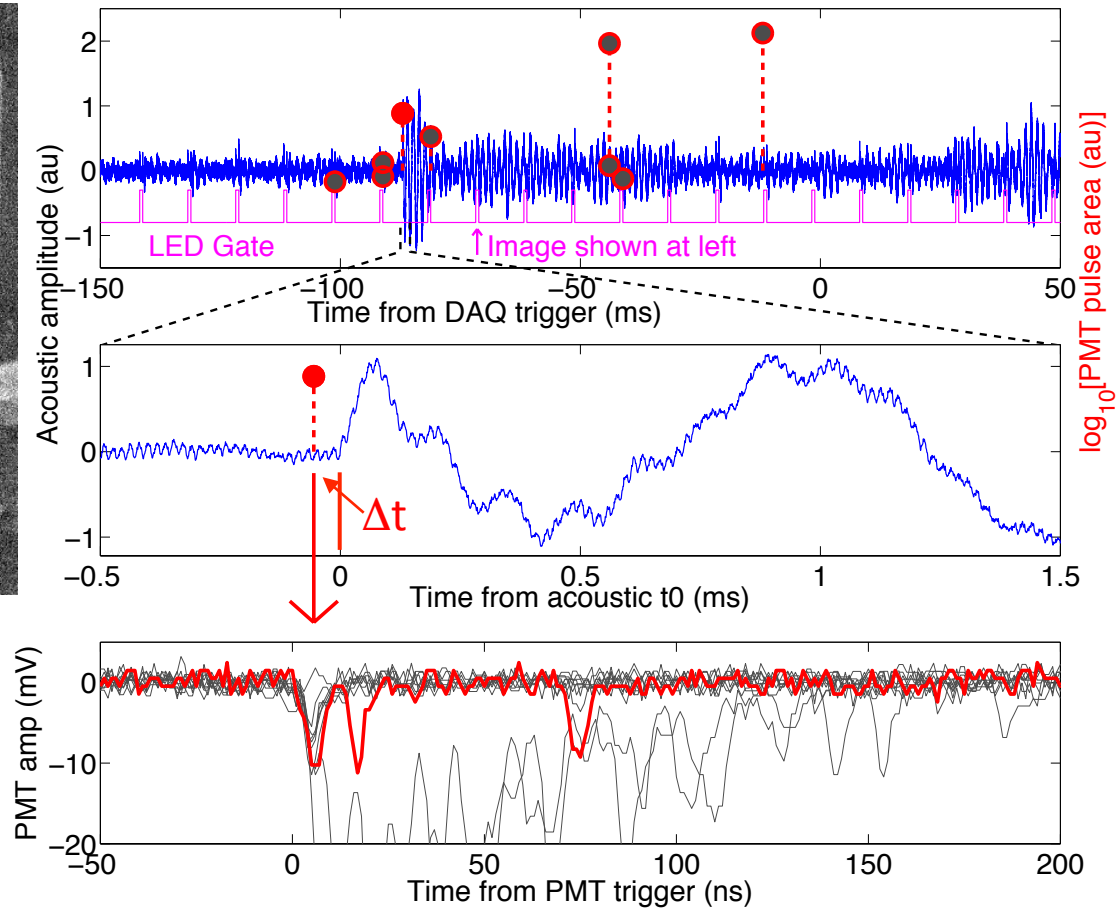
Xenon Bubble Chamber Prototype
(Northwestern University)



Sample Nuclear Recoil Event

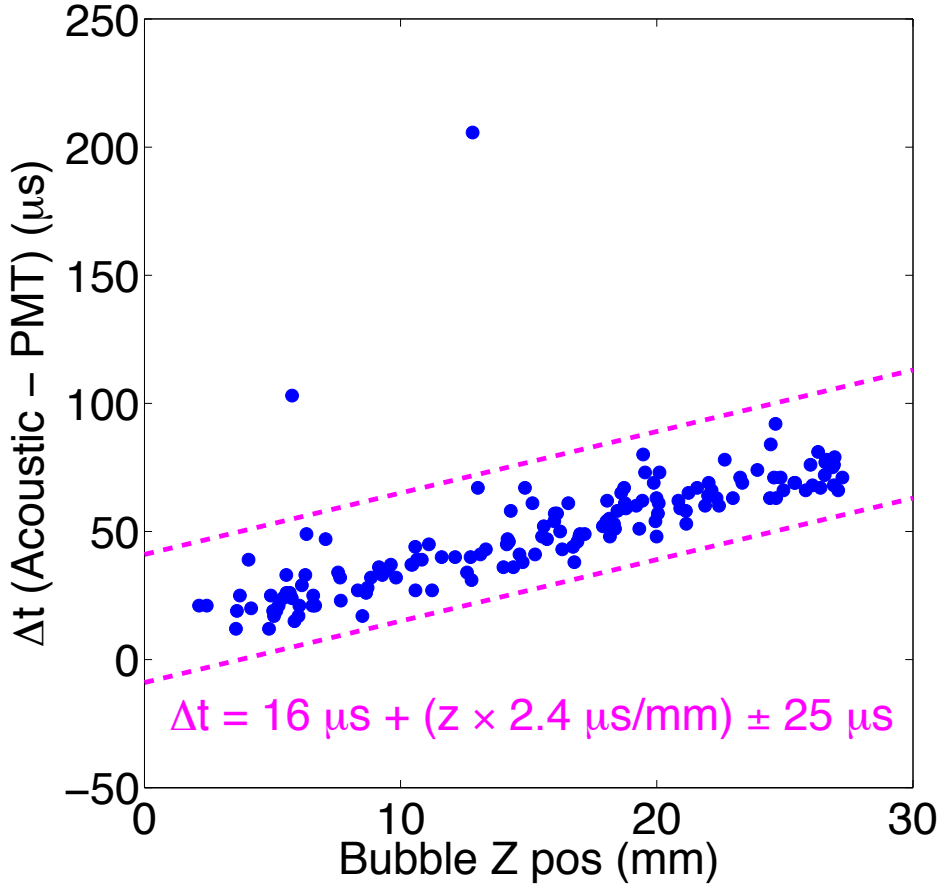




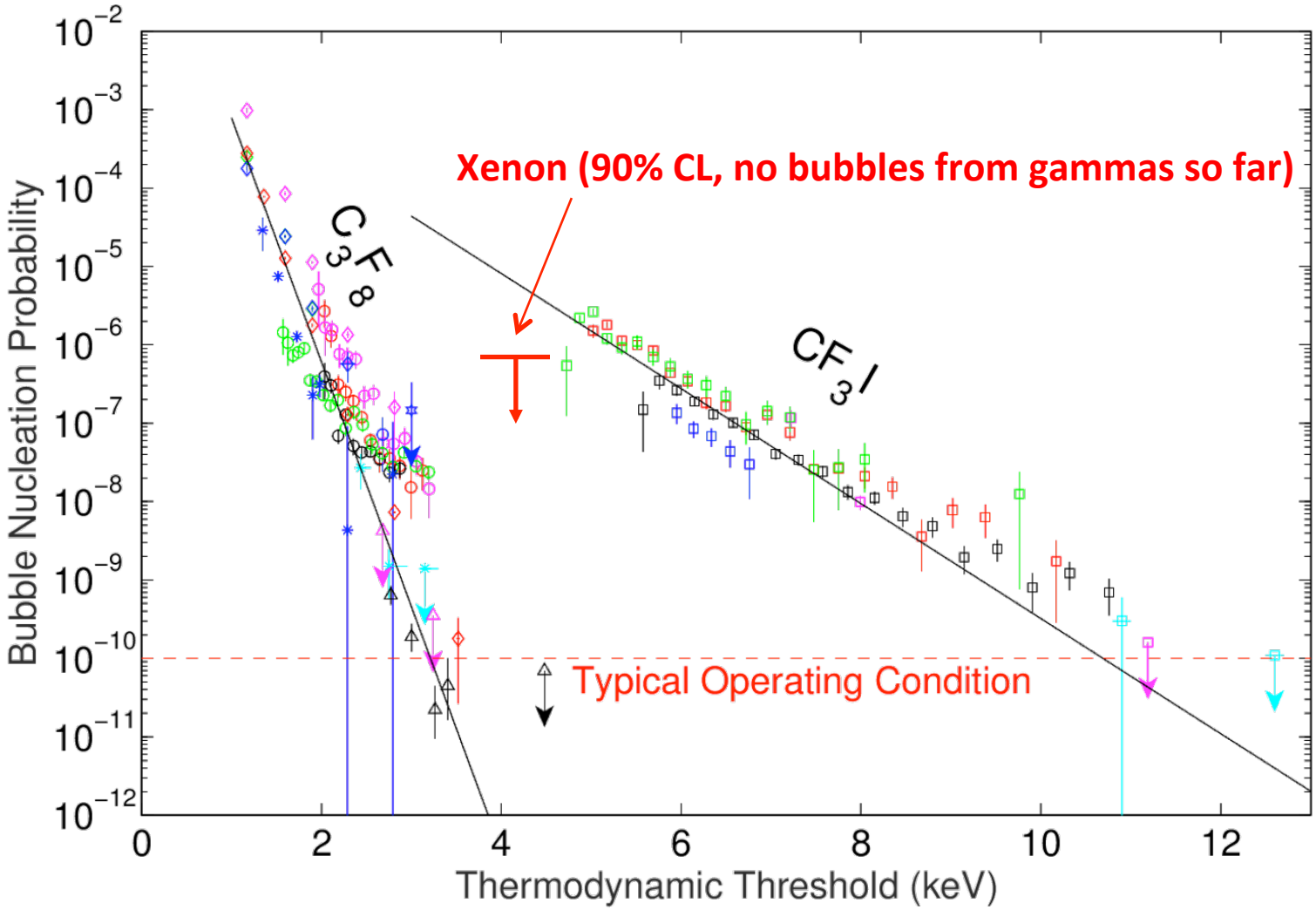


Acoustic – Scintillation Coincidence

- $< 1\%$ accidental coincidence rate in calibration data
- Slope = speed of sound in xenon (to 20%)



Gamma Discrimination

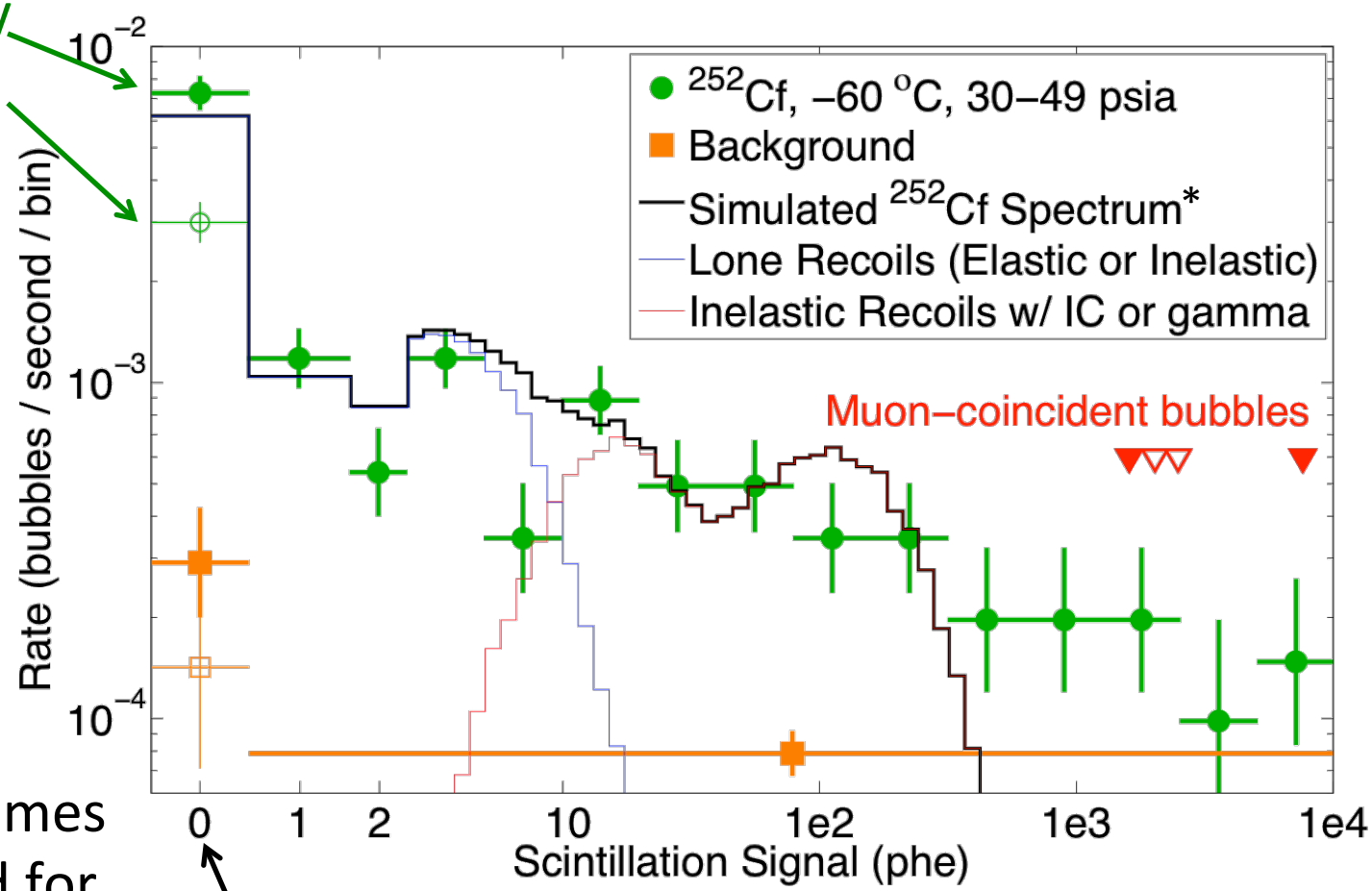


- Without scintillation, we would expect poorer discrimination in xenon than CF_3I

Scintillation Spectrum for Bubble Events

E_T = 8.2 – 8.6 keV
E_T = 8.6 – 15 keV

No E_T dependence observed in other bins



*Simulation assumes 15-keV threshold for bubble nucleation

Bubbles with no PMT Trigger