Search for Dark Matter with bubble chambers

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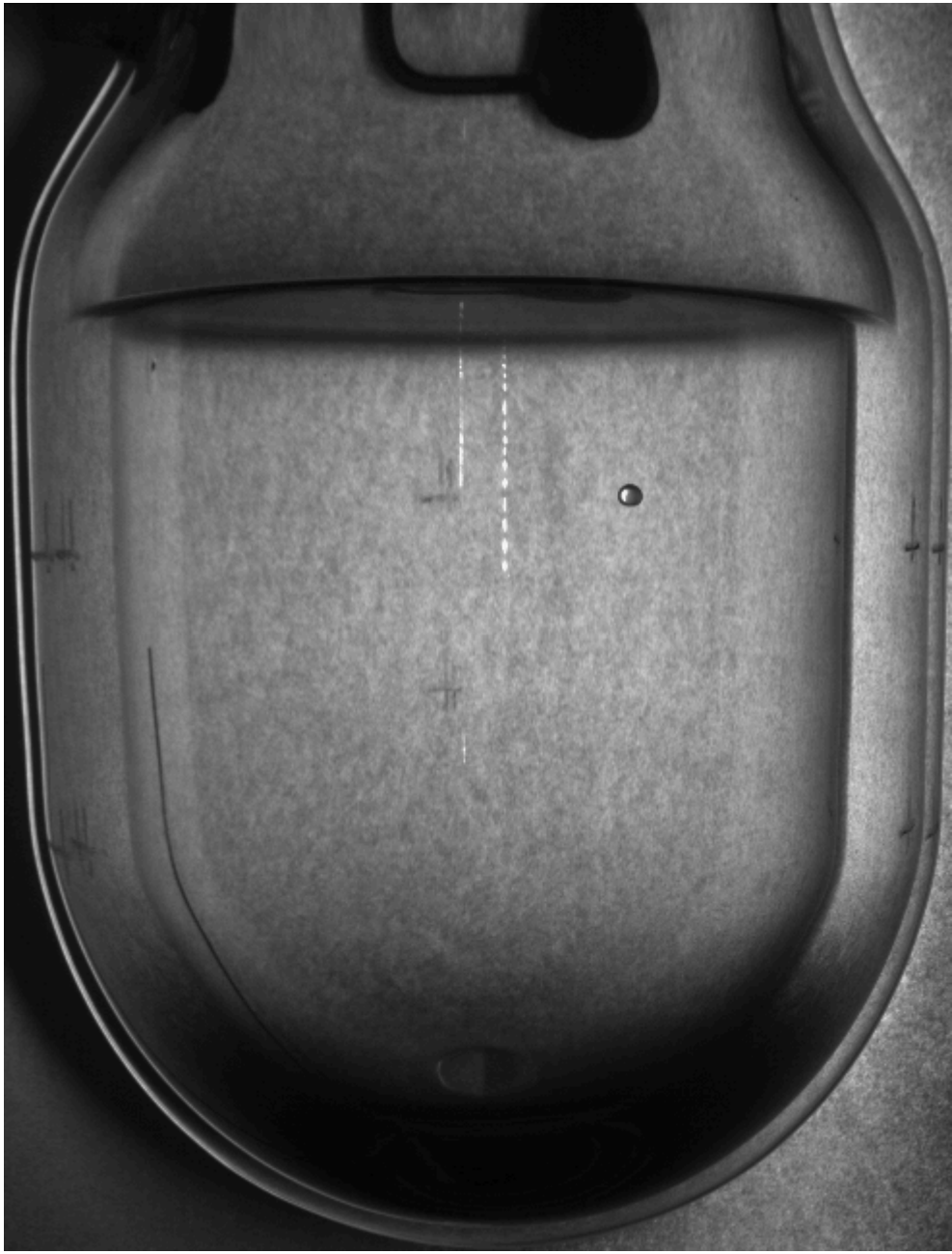
For the PICO Collaboration
at DPF 2015



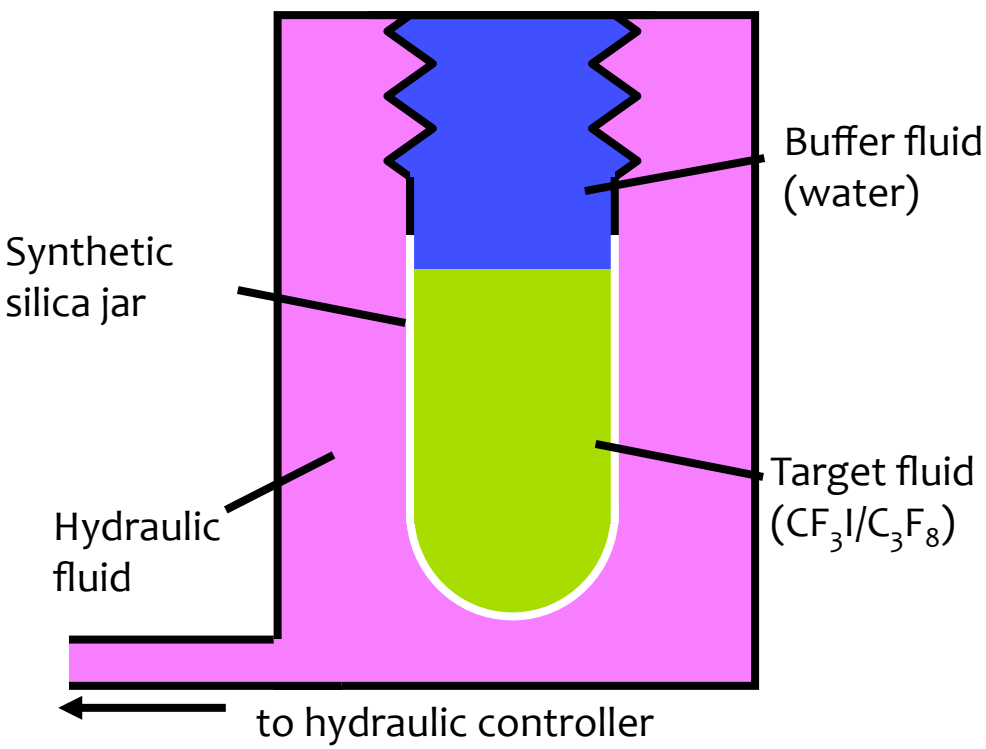
The PICO Dark Matter search

- PICO: merger of **PI**CASSO and **CO**UPP Collaborations
- In addition to various test and calibration chambers, PICO includes two main bubble chambers at SNOLAB
  - **PICO-2L**: a 2-liter bubble chamber currently operating with C_3F_8
  - **PICO-60**: a 60-liter bubble chamber undergoing a switch from CF_3I to C_3F_8

PICO fast compression bubble chambers

Pressure expansion puts fluid (**CF_3I** or **C_3F_8**) in superheated state

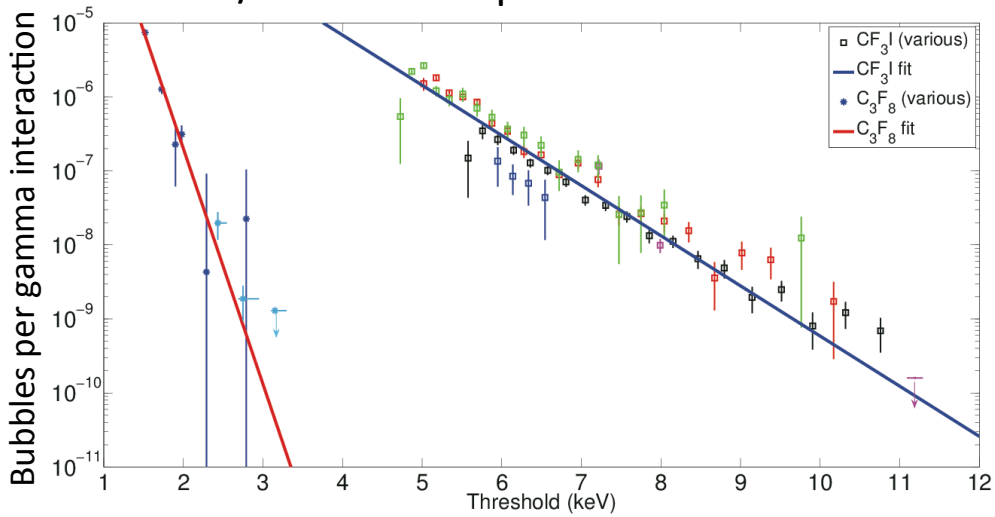
- **I** for spin-independent
- **F** for spin-dependent

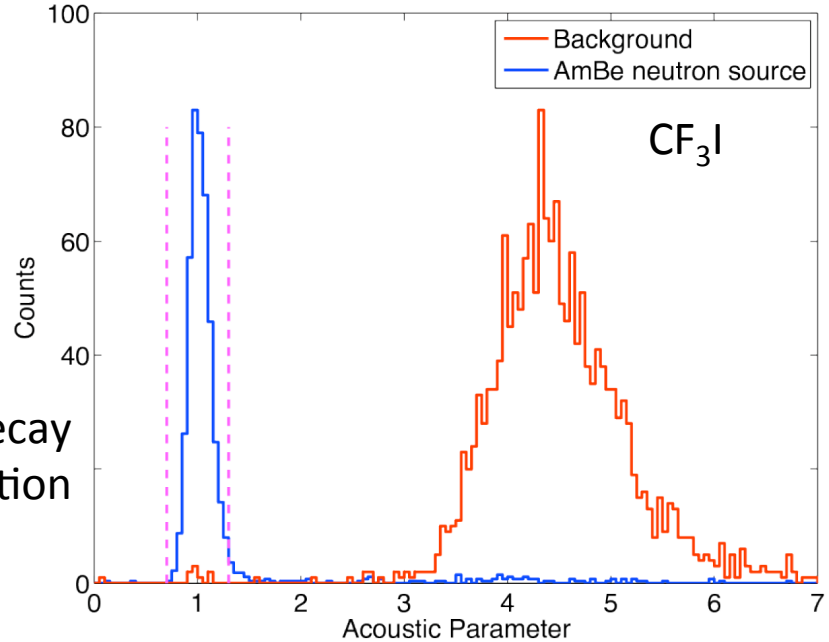


- Particle interactions nucleate bubbles
- Cameras capture stereoscopic bubble images
- Acoustic sensors capture bubble sound
- Chamber recompresses after each event
- Pressure & temperature define minimum energy, dE/dx threshold

Background Rejection

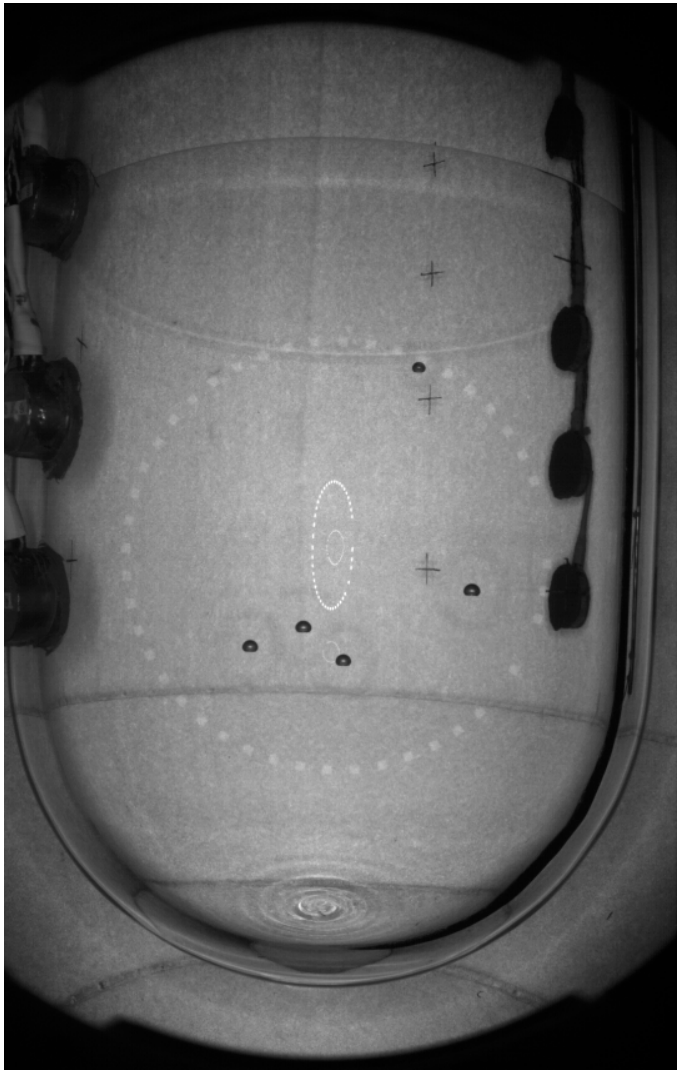
Gamma/Beta do not produce bubbles





Alpha-decay
>99.3% Rejection

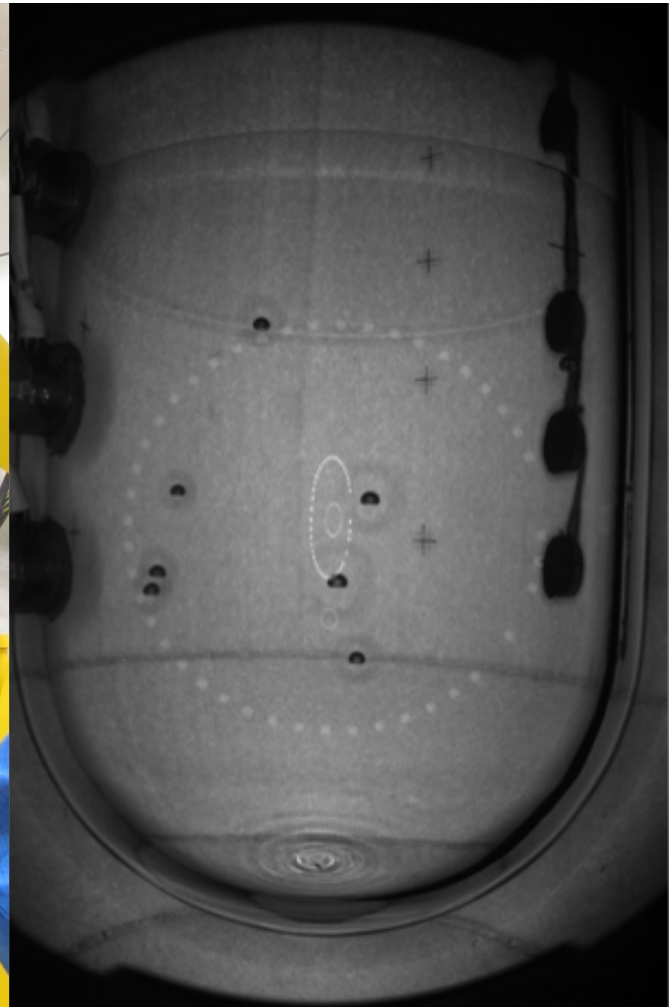
Neutron multiples



PICO-60

Scale-up of COUPP-4 chamber

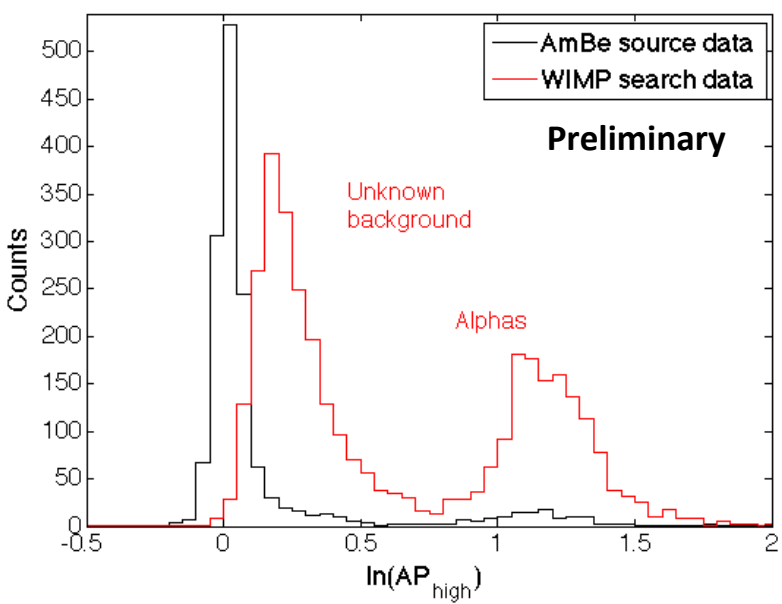
- 37-kg CF_3I target operated in SNOLAB from June 2013 to May 2014
- Collected >3000 kg-days of dark matter search data between 8 and 25 keV threshold



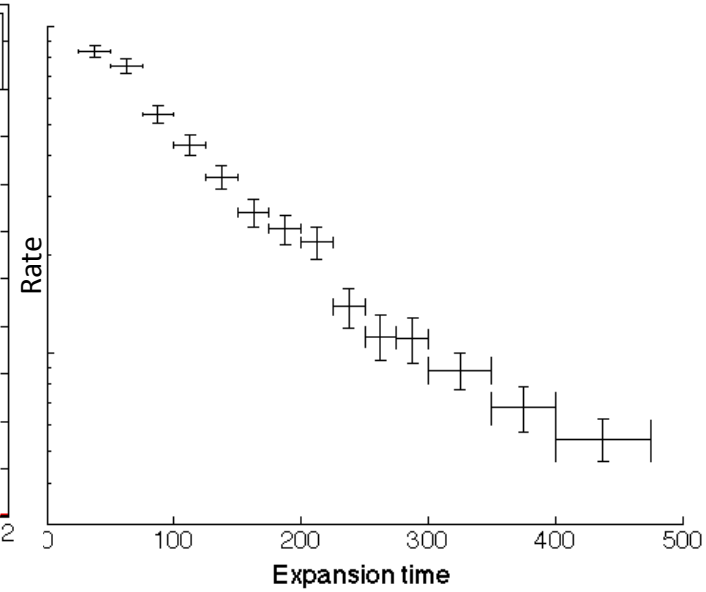
PICO-60

- Large background of unknown origin (>1000 events)
- Possible impurity/particle contamination
  - Addressible via cleaning/hardware/filtration/chamber-design
- Background can be discriminated against
  - Acoustics, timing, position

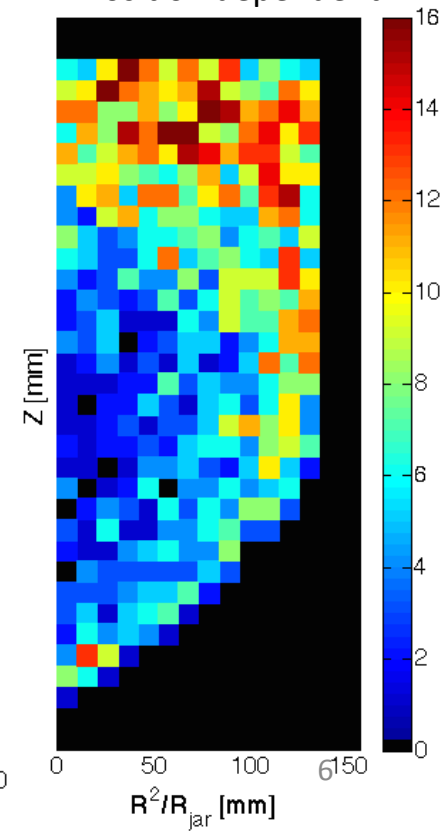
Louder than nuclear recoils



Time dependent

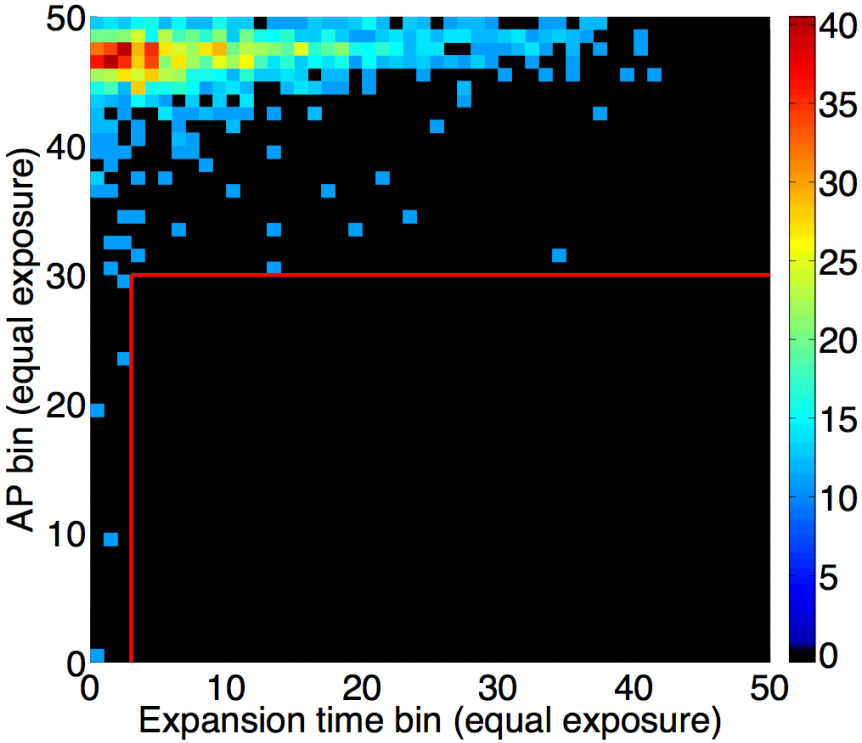


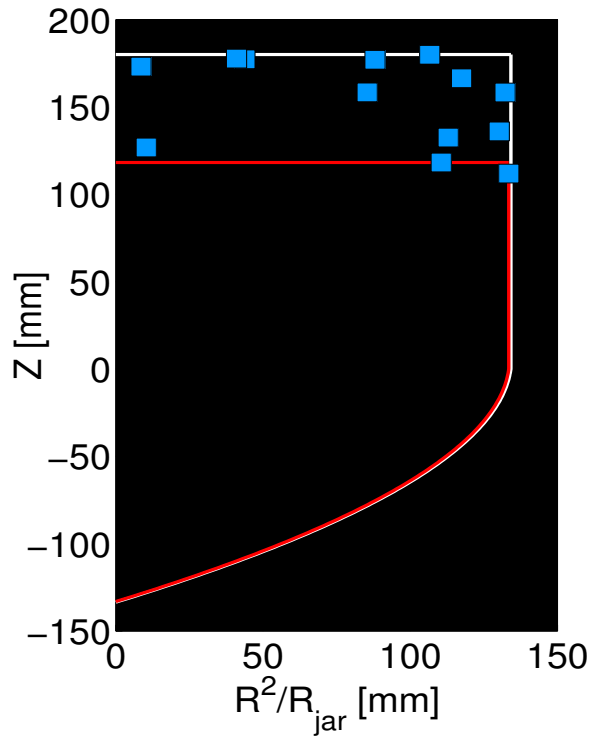
Position dependent



PICO-60 Final event selection

- Cut-setting method similar to the optimum interval method
  One-sided cuts on: AP, expansion time, bubble distance from wall/surface
  - Keeps 48% exposure, **0 candidates**
  - Cut choice results in a statistical penalty of 1.8



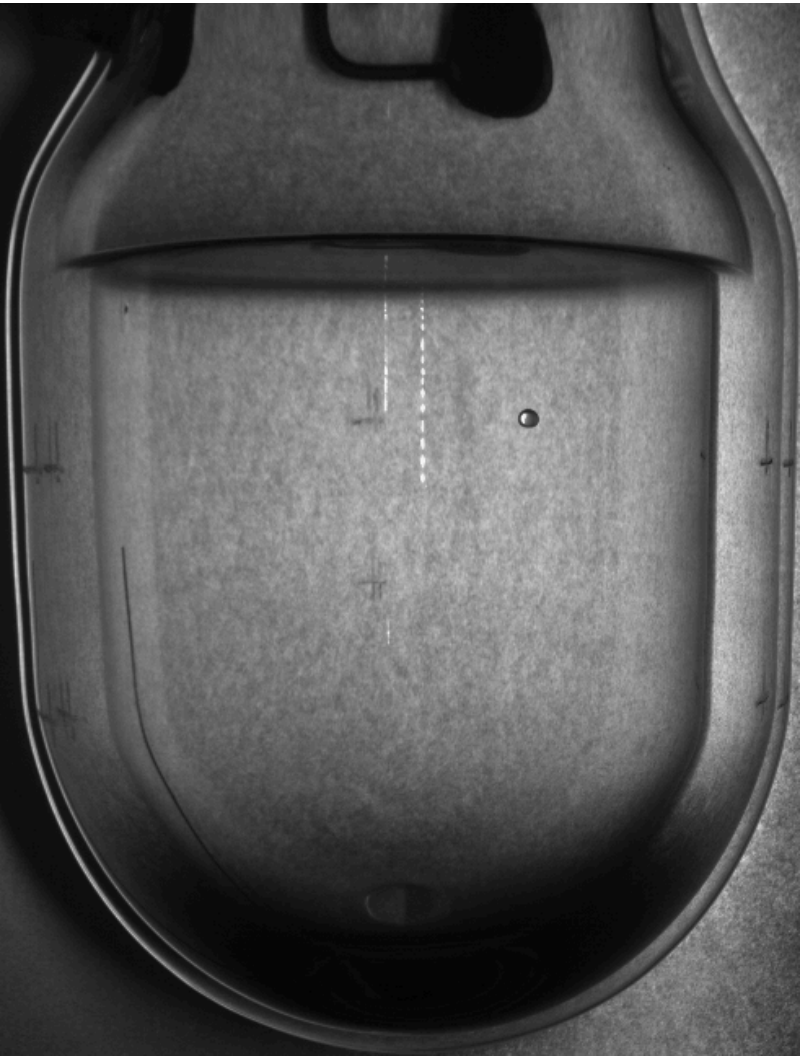


PICO-2L

A 2 liter C_3F_8 detector replacing COUPP-4 (CF_3I)

- Twice the F density
- Lower threshold
- Improved efficiency
- Lower background hardware

Oct 2013-May 2014:
>200 kg-day exposure with thresholds between 3-8 keV

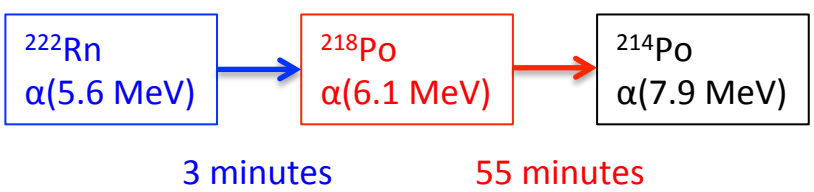


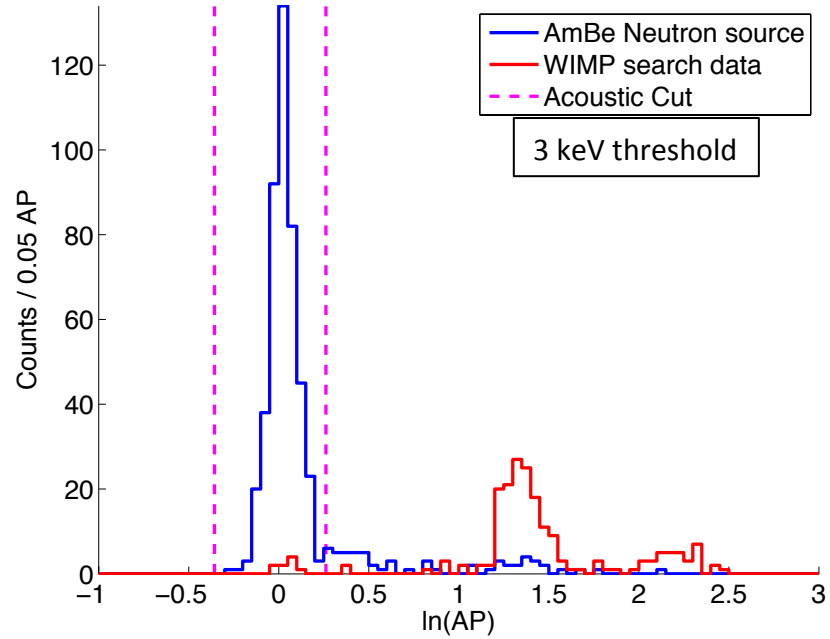
PICO-2L
Acoustic discrimination

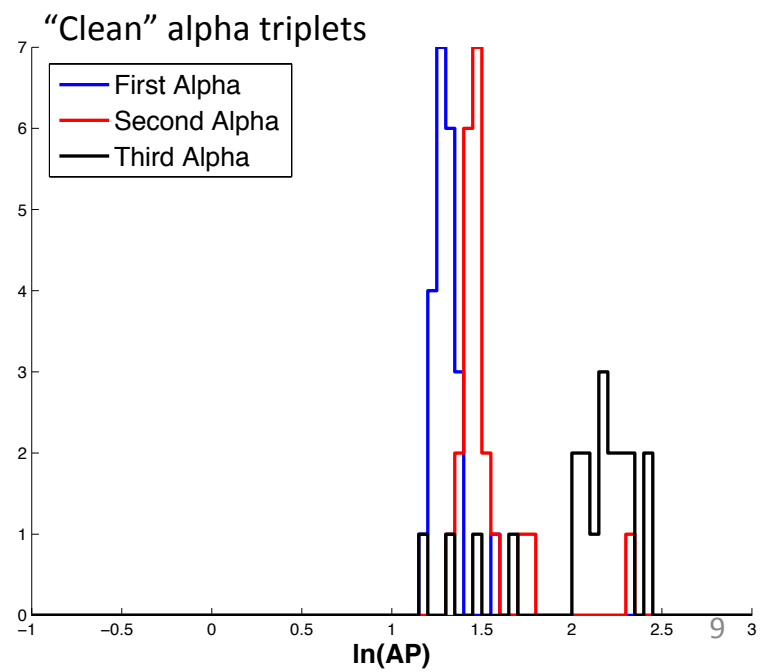
- Two distinct alpha peaks, clearly separated from nuclear recoils
- Timing of events in high AP peaks consistent with radon chain alphas, and indicate that the higher energy ^{214}Po alphas are significantly louder

→ **"Acoustic calorimetry"**

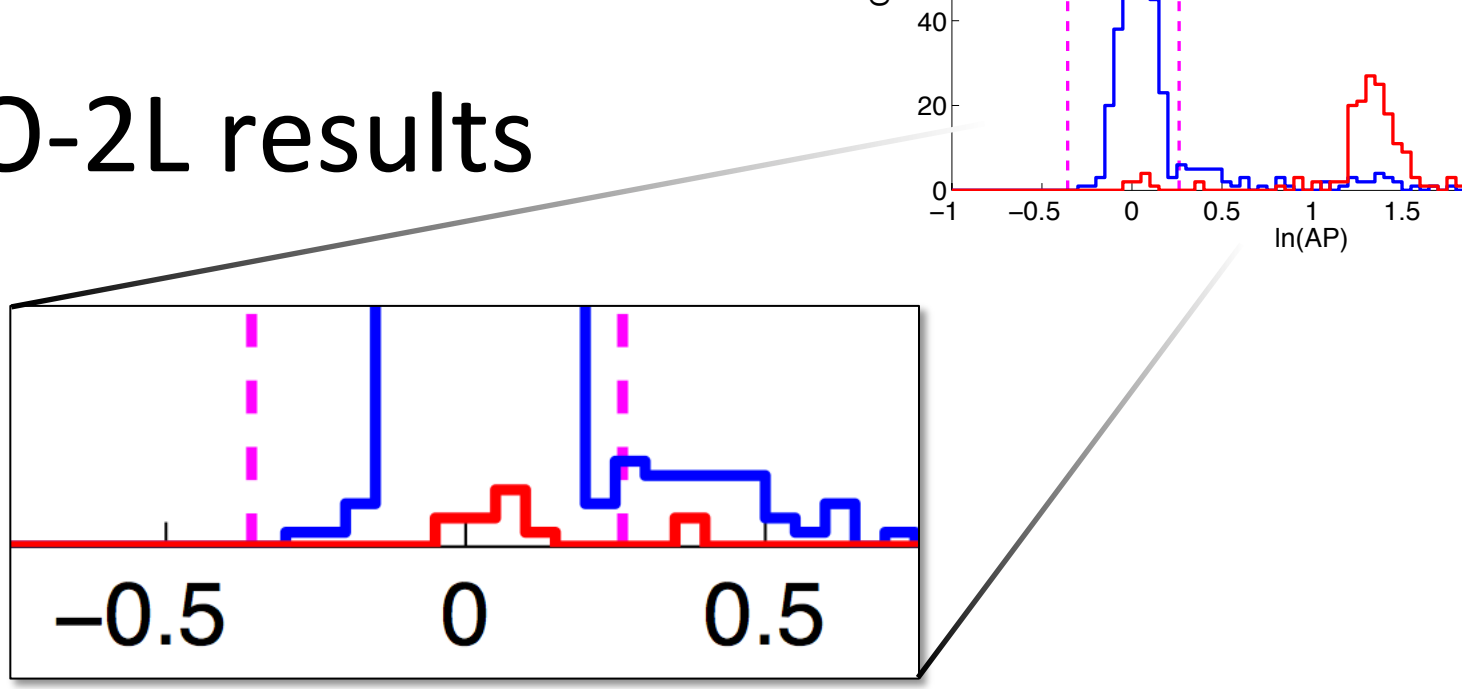
Radon chain alphas







PICO-2L results



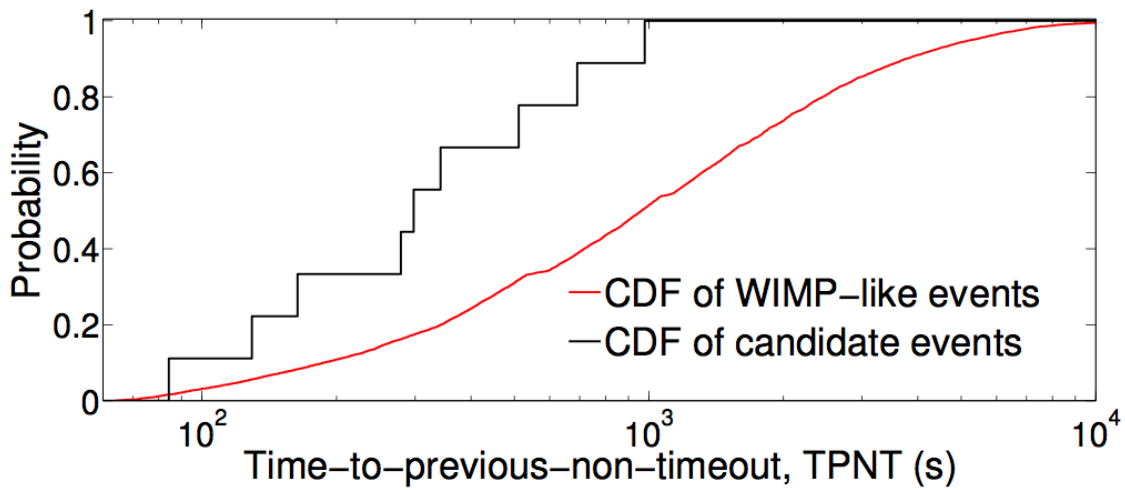
- 12 candidate events in 211.6 kg-days of exposure

Seitz threshold, E_T (keV)	Livetime (d)	WIMP exposure (kg-d)	Candidates
$3.2 \pm 0.2(\text{exp}) \pm 0.2(\text{th})$	32.2	74.8	9
$4.4 \pm 0.3(\text{exp}) \pm 0.3(\text{th})$	7.5	16.8	0
$6.1 \pm 0.3(\text{exp}) \pm 0.3(\text{th})$	39.7	82.2	3
$8.1 \pm 0.5(\text{exp}) \pm 0.4(\text{th})$	18.2	37.8	0

- Expected ~1 background event (neutrons)

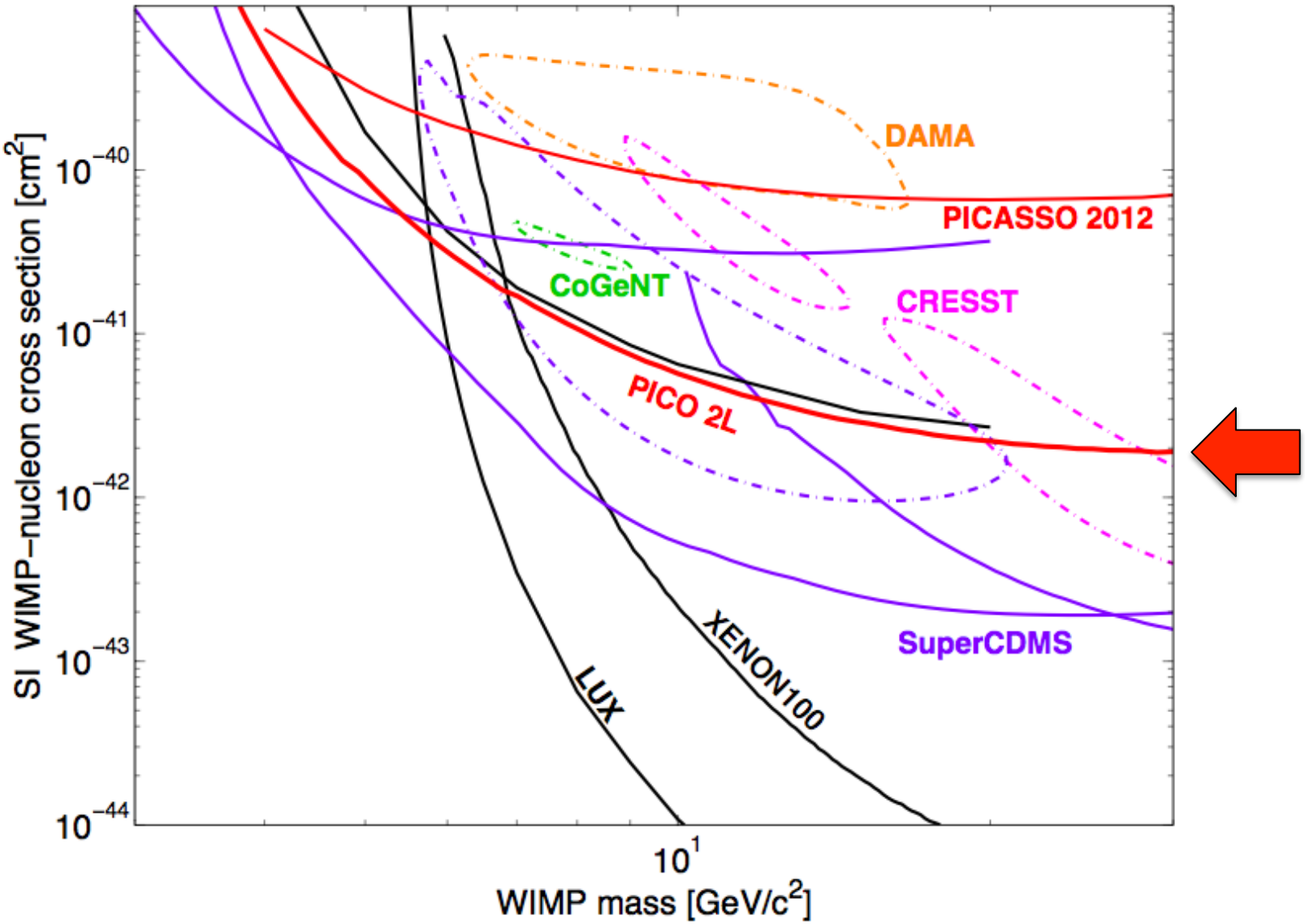
PICO-2L results

- However:
  - Post-run samples show evidence of particulate contamination
  - Candidate events have timing correlations inconsistent with WIMPs or neutrons

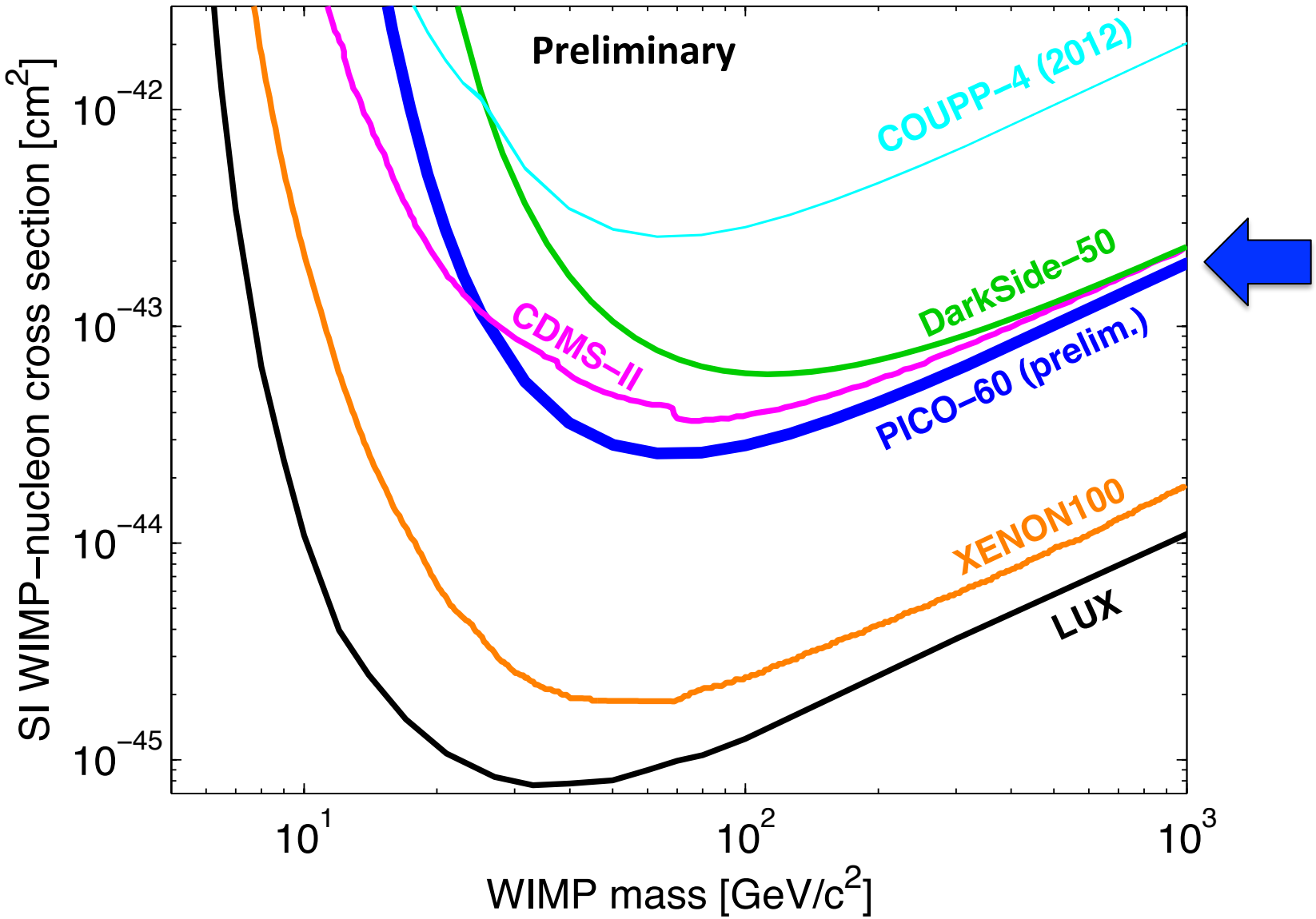


  - Timing becomes a cut variable, method similar to optimum interval of Yellin, PRD 66.032005 (2002)

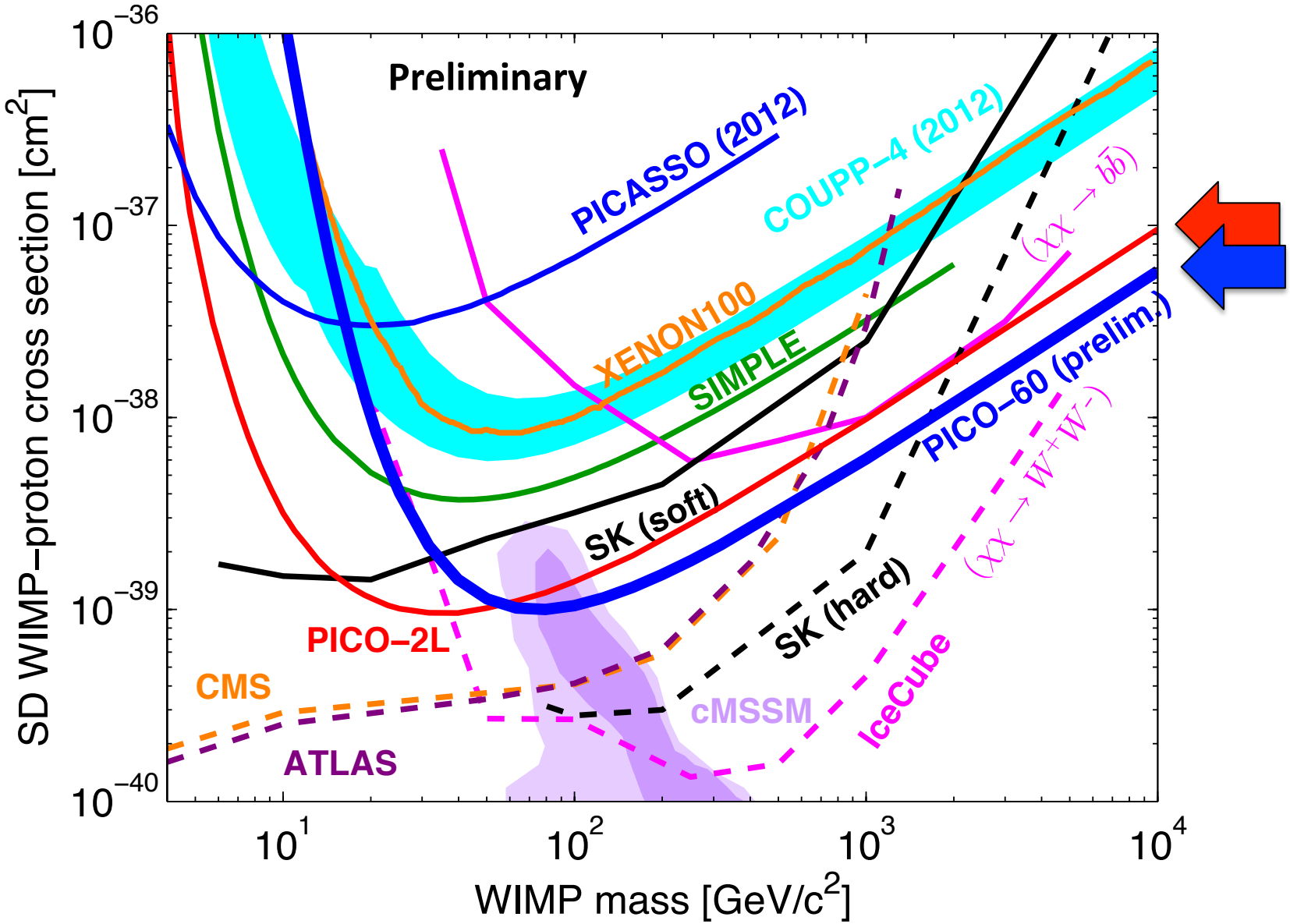
Spin-independent limits (low mass)



Spin-independent limits (high mass)



Spin-dependent limits



Summary

- PICO-60 is a 37 kg bubble chamber using CF_3I
  - Good acoustic rejection of alphas, as well as acoustic discrimination against unknown background
  - **PICO-60 has a new world-best SD WIMP-proton limit**
- With a brand new target fluid (C_3F_8) PICO-2L has demonstrated:
  - Successful operation at 3keV nuclear recoil threshold
  - No neutron background observed
  - Good acoustic rejection of alphas
  - Detailed Fuorine and Carbon-recoil efficiency calibrations (no time in this talk!)
  - **PICO-2L has a new world-best SD WIMP-proton limit**

PICO

SNOLAB — Mining for knowledge / Creuser pour trouver... l'excellence
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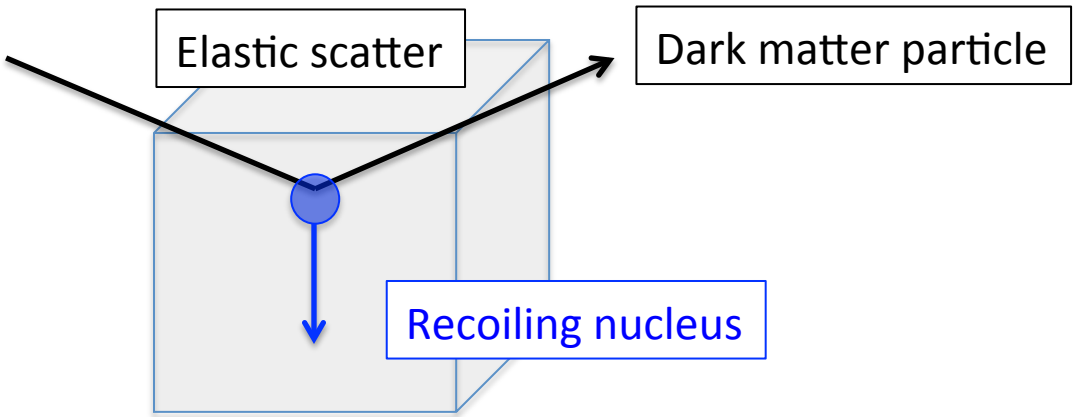
BACKUP

Dark matter direct detection



- Interaction rate depends on how the dark matter couples to quarks/gluons in target nuclei
  - Z, higgs, squark exchange, ...
- Model dependent
  - Eg SUSY: is lightest neutralino more bino-like, higgsino-like, what is the sparticle spectrum, etc

Dark matter direct detection

- WIMP-nucleus interaction could be
  - Spin-Independent (SI) (scalar/vector coupling)
    - Coherent scattering
      → enhancement for heavy nuclei: Ge, Xe, I, ...
      → higher sensitivity to WIMP-nucleon cross-section
    - Nonetheless depending on the model the SI cross-section could be small and another type of coupling could dominate...

Dark matter direct detection

- WIMP-nucleus interaction could be
  - Spin-Dependent (SD) (axial-vector coupling)
    - Couples to nuclear spin
      → requires unpaired nucleon, enhancement depends on nuclear shell structure

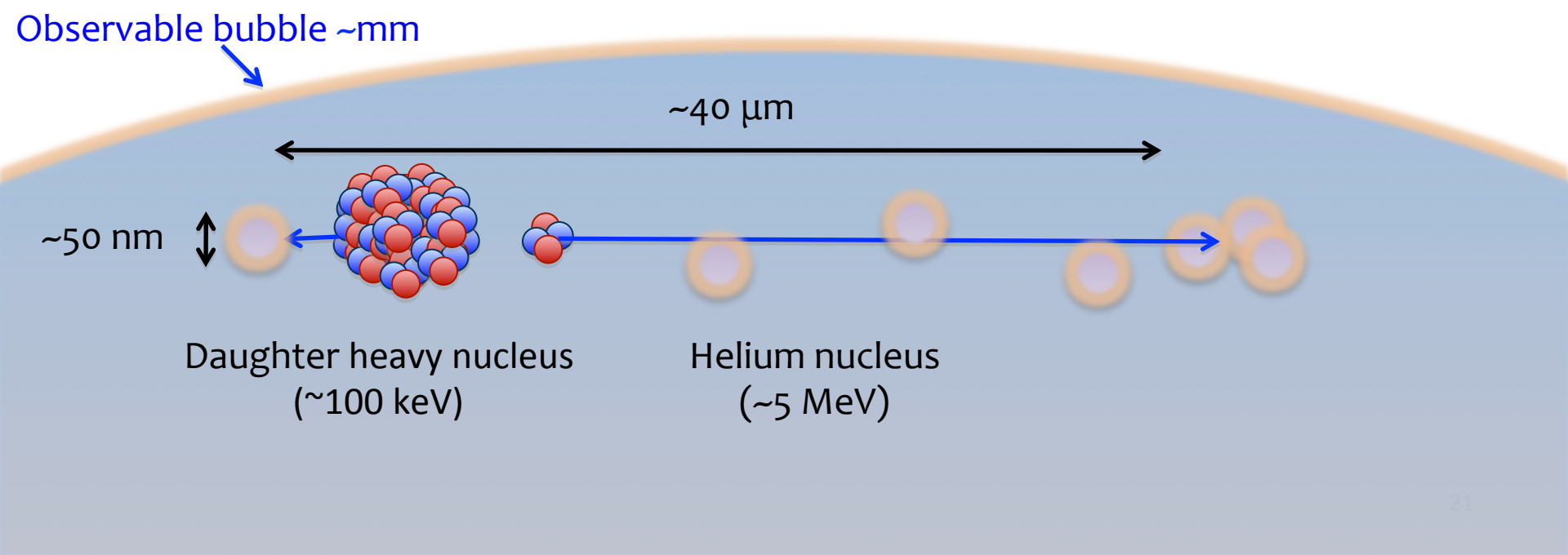
Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

← Fluorine is ideal

(Well, <u>multiple</u> targets is ideal!)

Acoustic discrimination

- Discovery of acoustic discrimination against alphas (Aubin et al., New J. Phys.10:103017, 2008)
  - Alphas deposit their energy over tens of microns.
  - Nuclear recoils deposit theirs over tens of nanometers.
- In PICO bubble chambers alphas are several times louder.

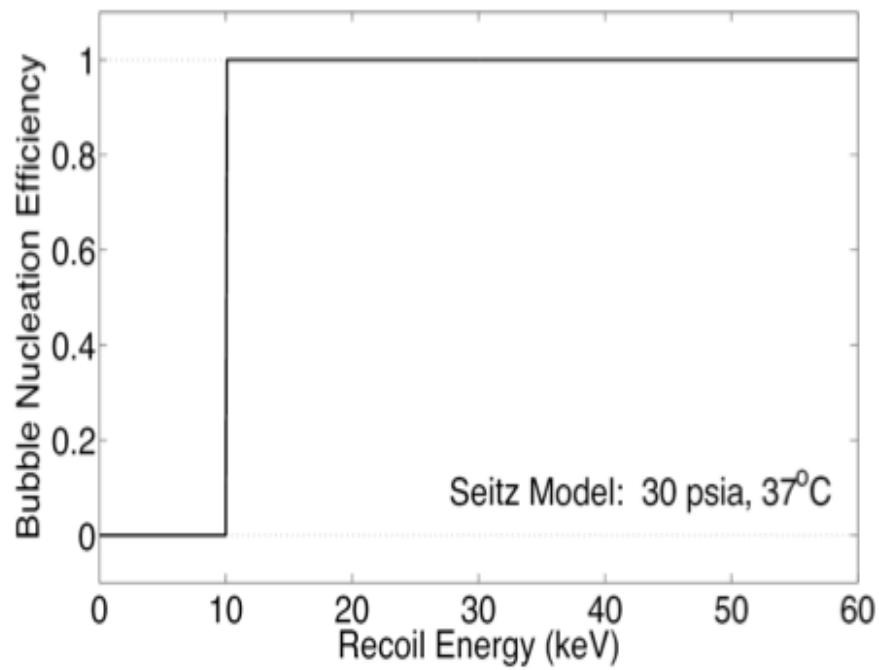


Threshold and efficiency

- Threshold based on theory of Seitz, Phys. of Fluids I, 2 (1958)
- Energy deposition E_{th} within length R_c will nucleate a bubble
- Seitz model assumes step function above threshold, but the track dependence is not fully specified

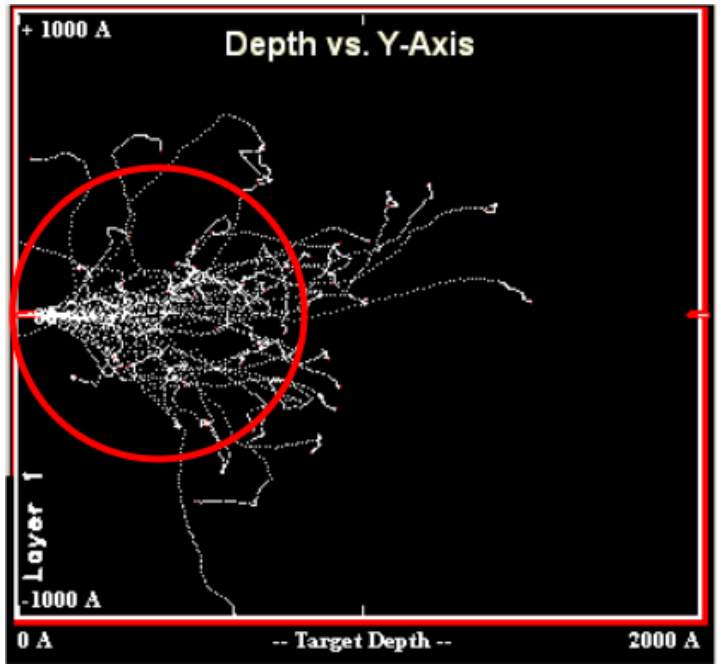
$$p_v - p_l = \frac{2\sigma}{r_c}$$

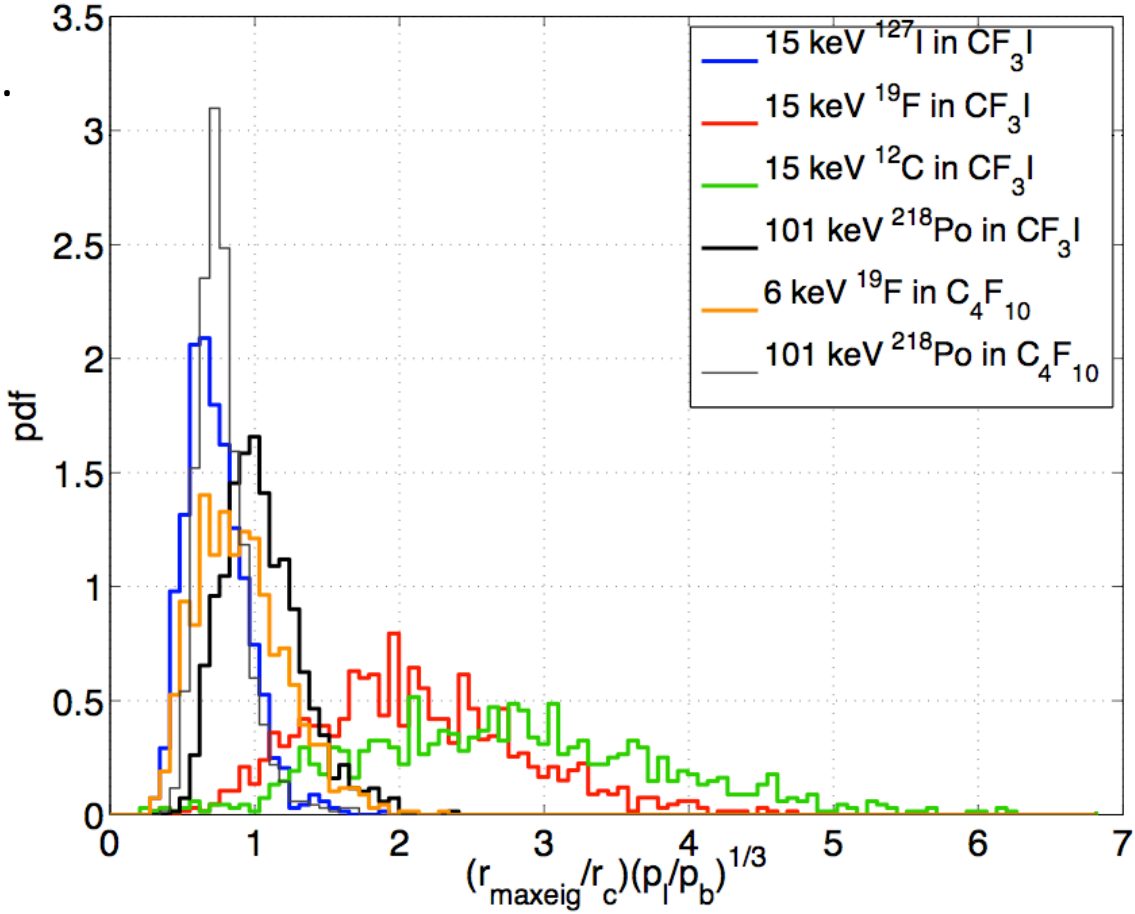
$$E_{th} = \underbrace{4\pi r_c^2 \left(\sigma - T\frac{\partial\sigma}{\partial T}\right)}_{\text{Surface energy}} + \underbrace{\frac{4}{3}\pi r_c^3 \rho_v h}_{\text{Latent heat}}$$



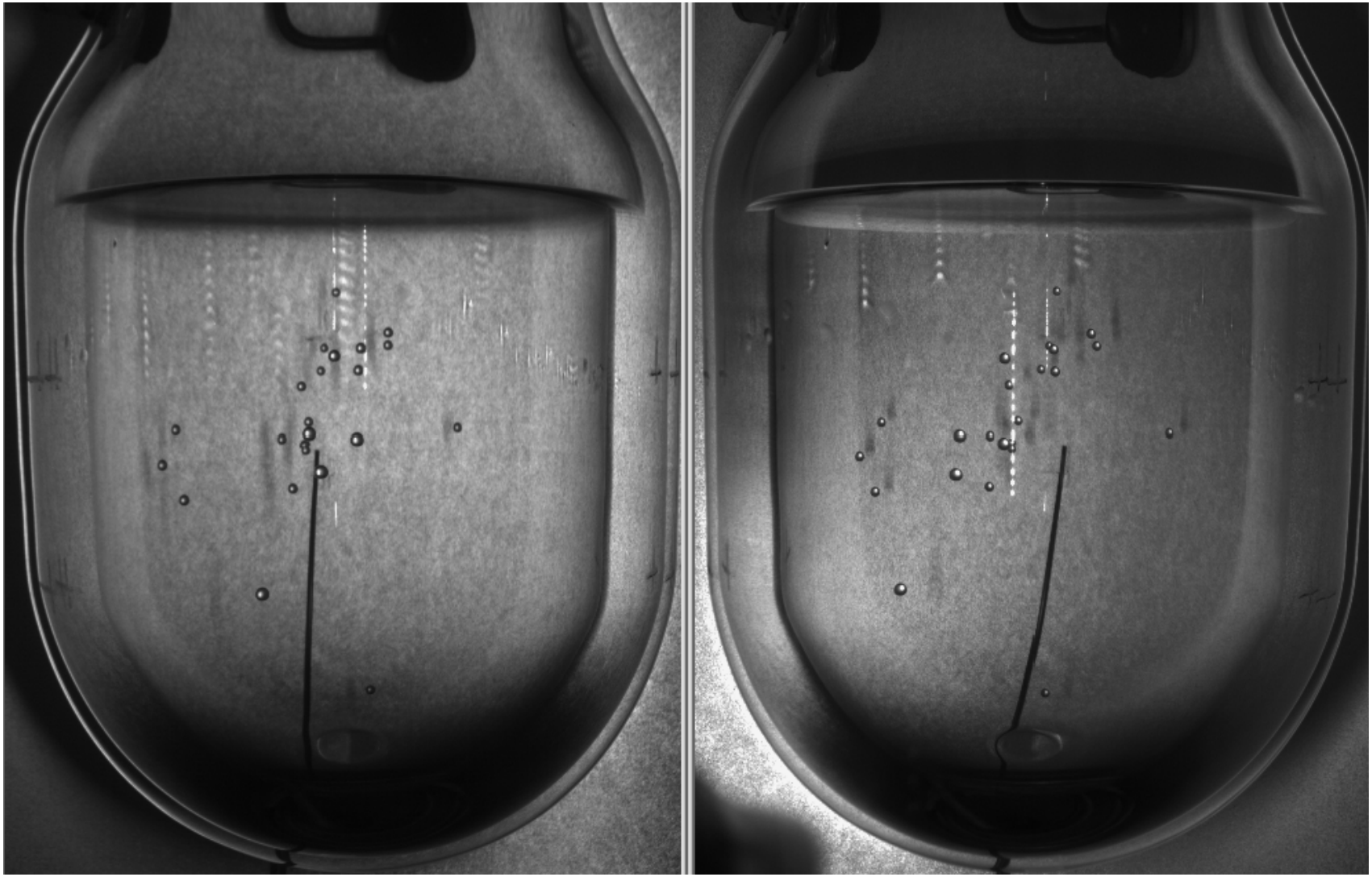
Understanding efficiency of F, C recoils

SRIM simulation of 15keV F recoils.





23 bubble AmBe neutron event

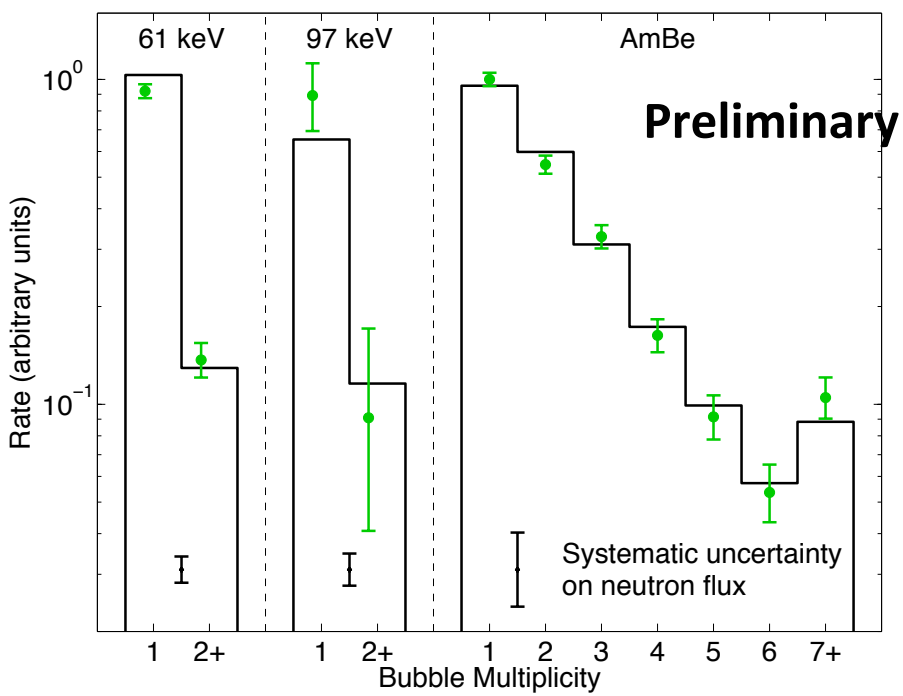


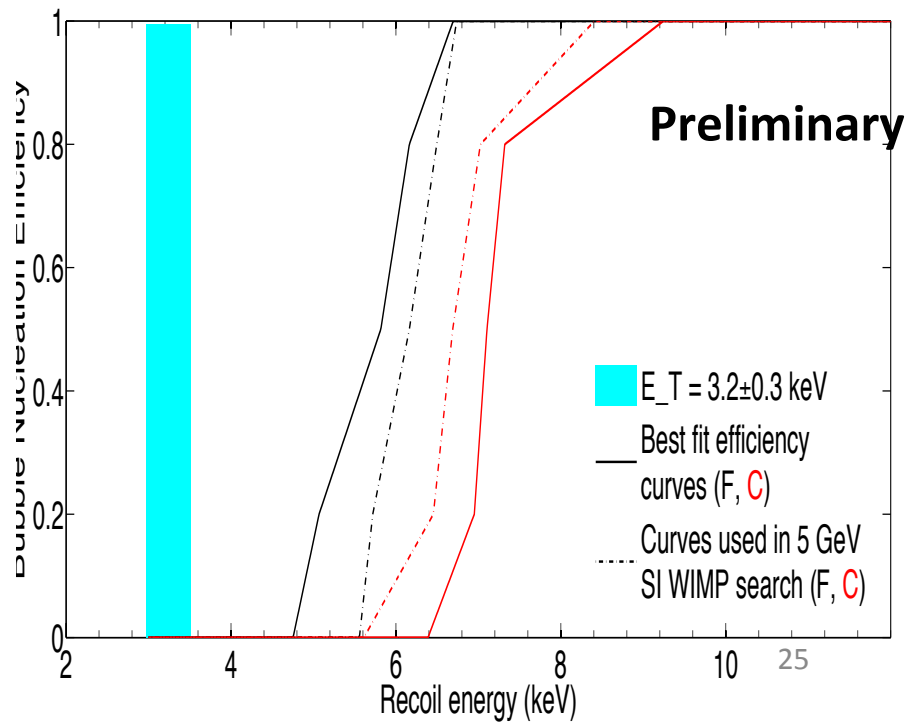
High multiplicity is a result of high bubble nucleation efficiency; 60% of neutron calibration events are multiples (compared to 25% in CF_3I).

C_3F_8 Sensitivity Calibrations

In addition to in-situ AmBe we calibrate the nuclear recoil response of C_3F_8 with 61 & 97 keV neutrons at U. of Montreal → probe very low energy recoils (12 & 20 keV max)

The shape of the efficiency curve is constrained at low energy, with agreement across calibrations. Conservative approach: choose least sensitive pair of eff curves 1σ consistent with calibrations

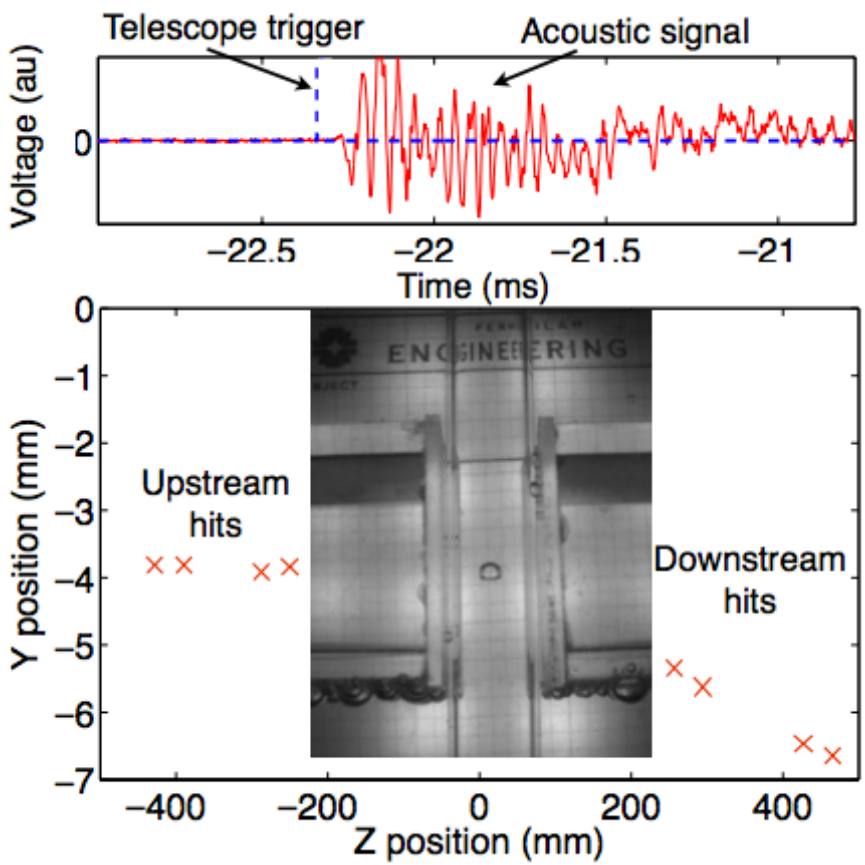


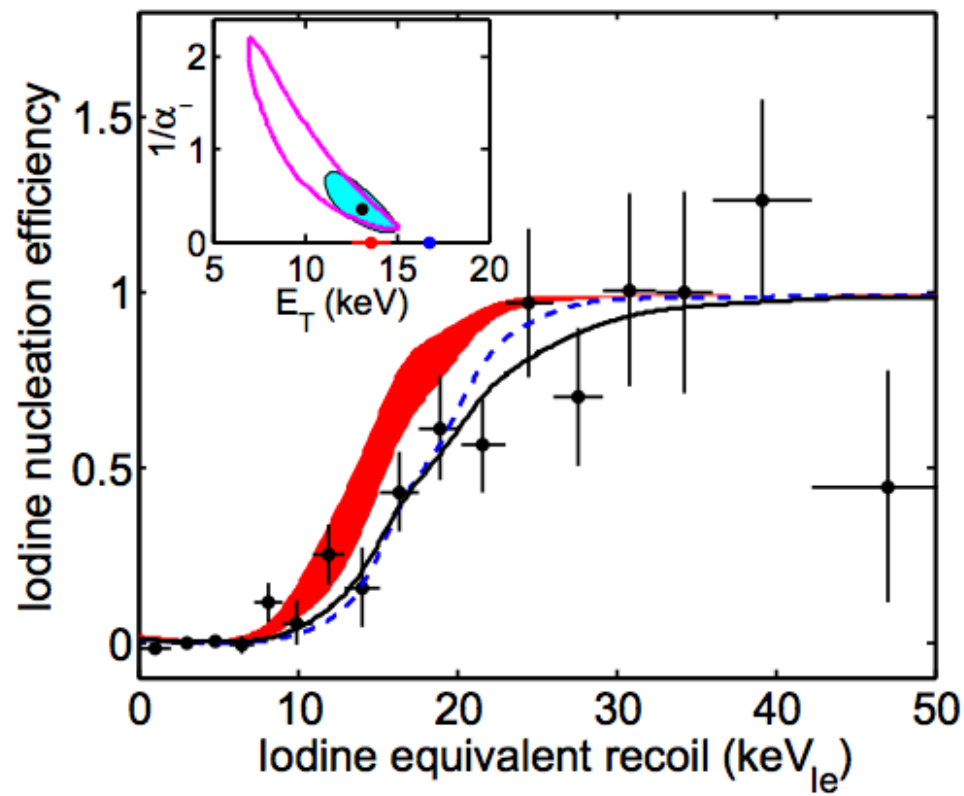


CF_3I Sensitivity Calibrations

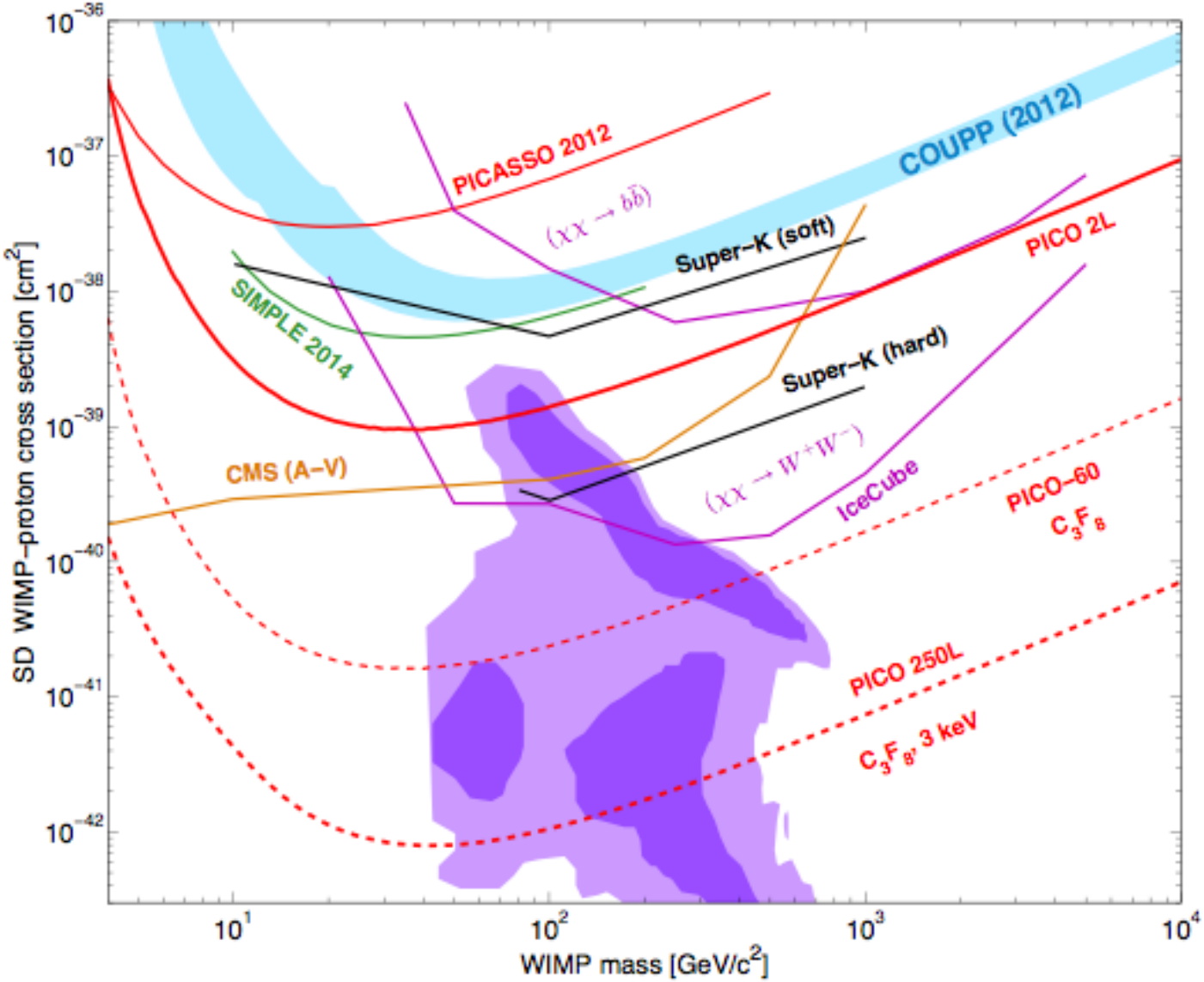
In addition to in-situ AmBe and test chamber calibrations, direct measurement through pion scattering

arXiv:1304.6001, PRD 88, 021102 (2013)





Projected limits



SI projections