Searching for Dark Matter With Bubble Chambers

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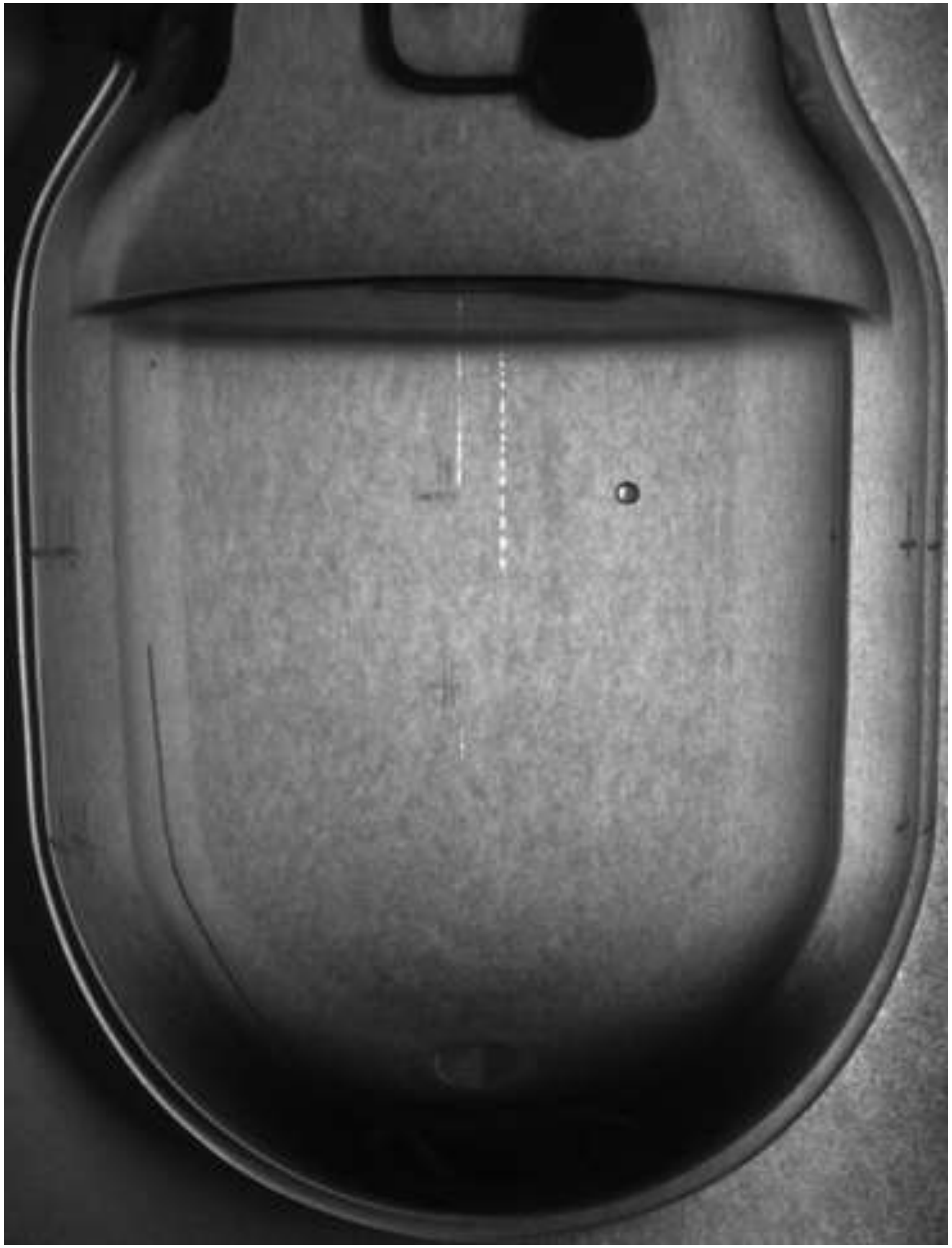
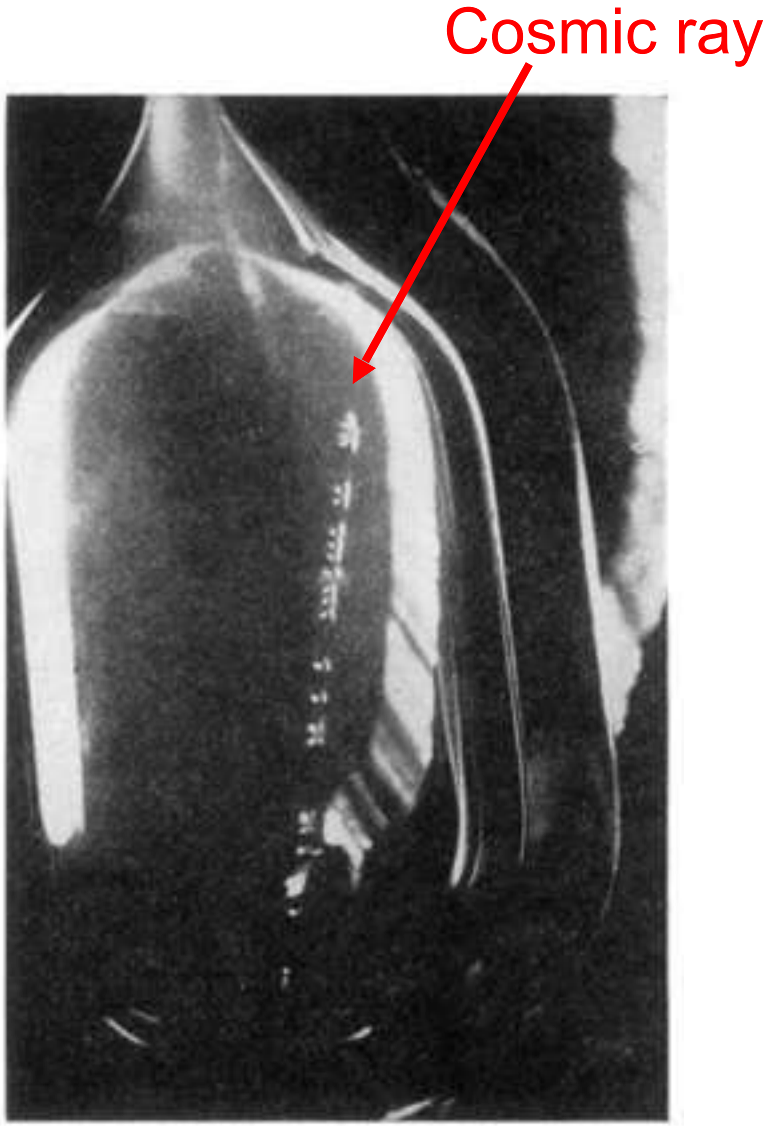
Fermilab

ICTP- SAIFR
August 1st, 2018

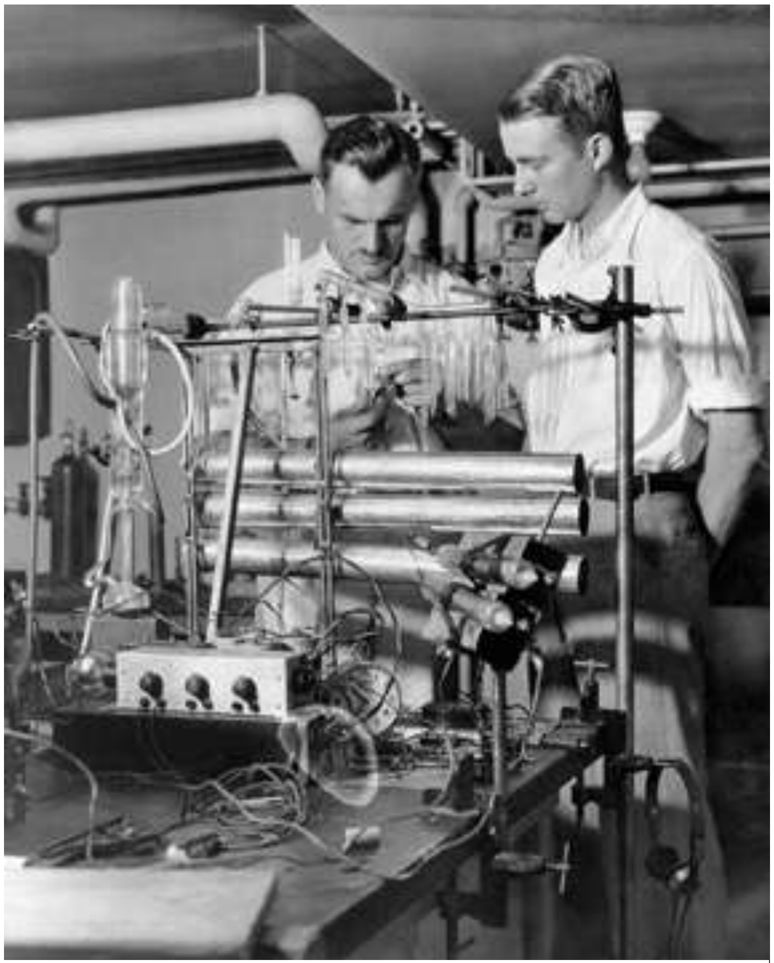


First Bubble Chamber (Glaser, 1952)

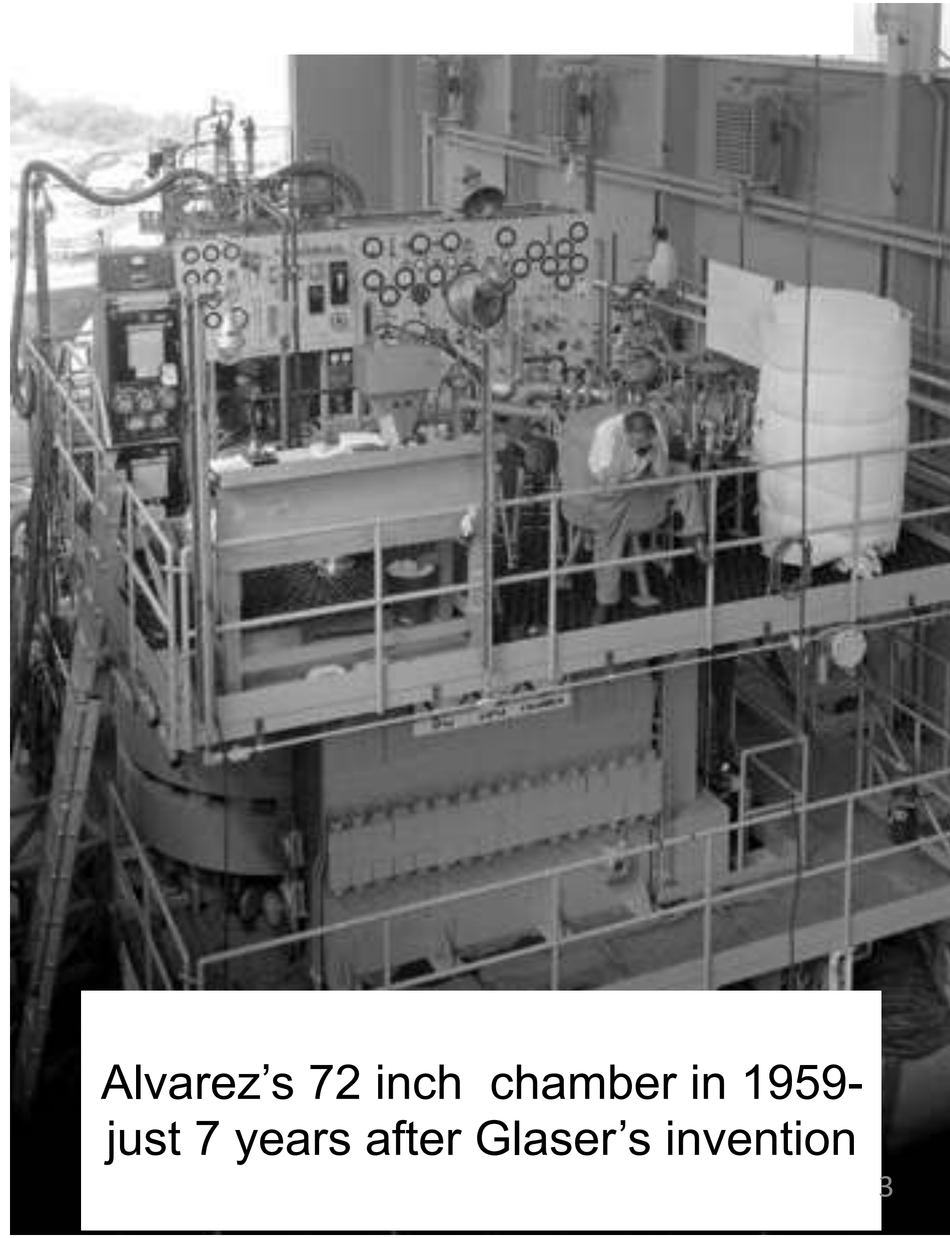


1-cm diameter glass tube, filled with ether

In those days, if anybody had an idea, and people thought it was a good idea, then you could start working on it. You didn't write proposals and that sort of stuff. Luis Alvarez



Luis Alvarez as U. Chicago Grad Student w/ Arthur Compton, 1933



Alvarez's 72 inch chamber in 1959- just 7 years after Glaser's invention

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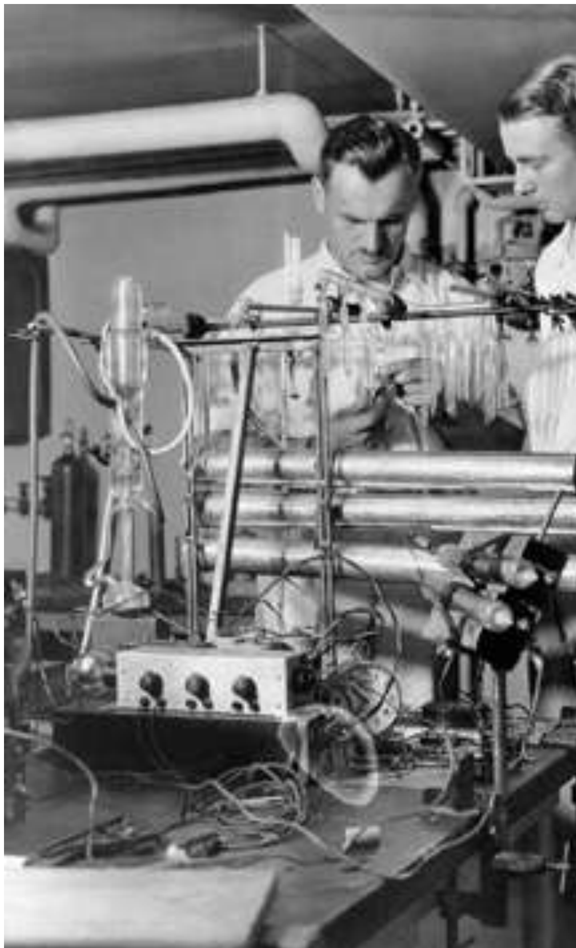
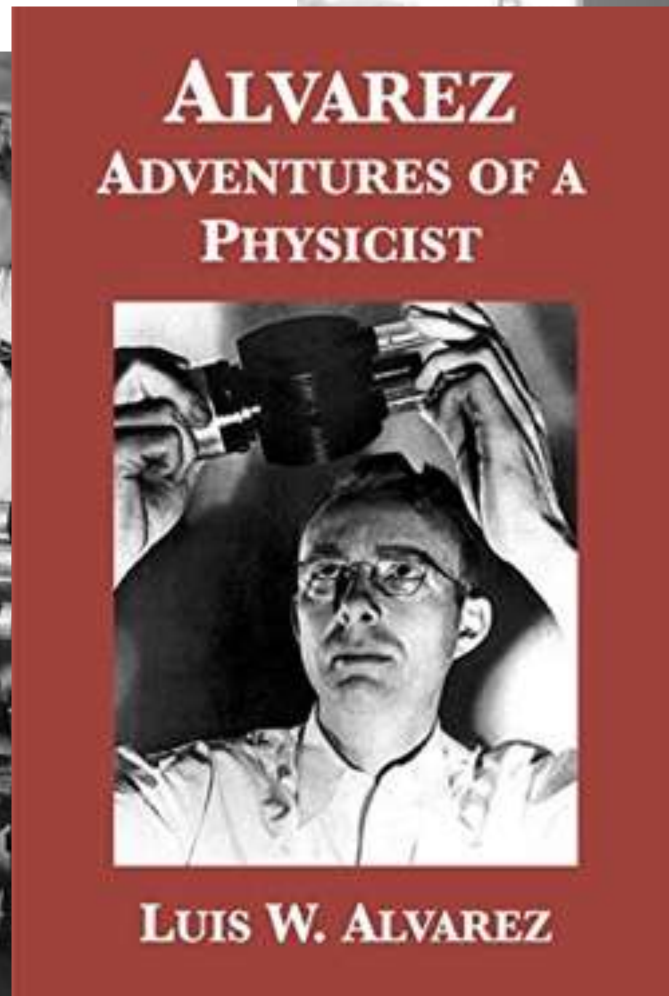
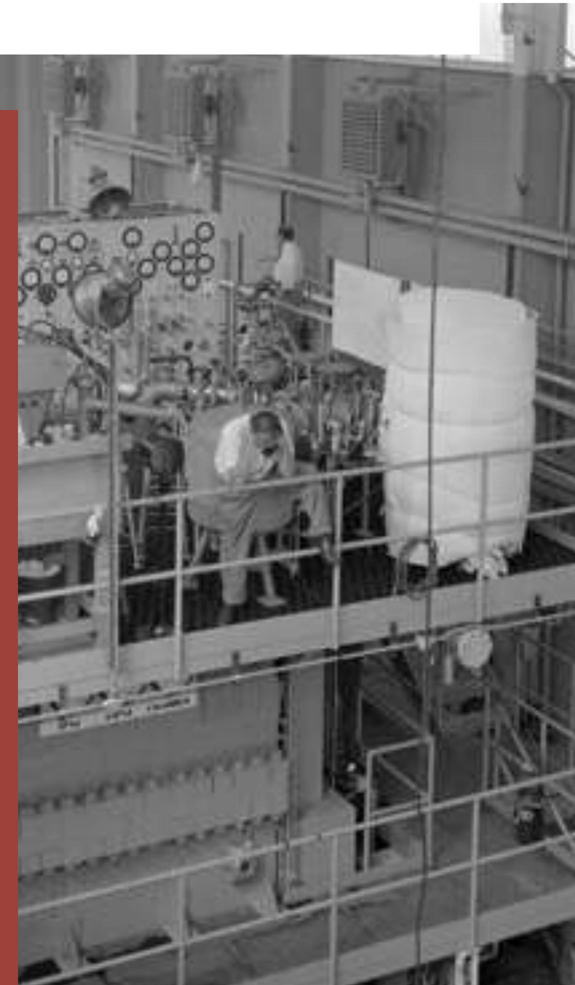
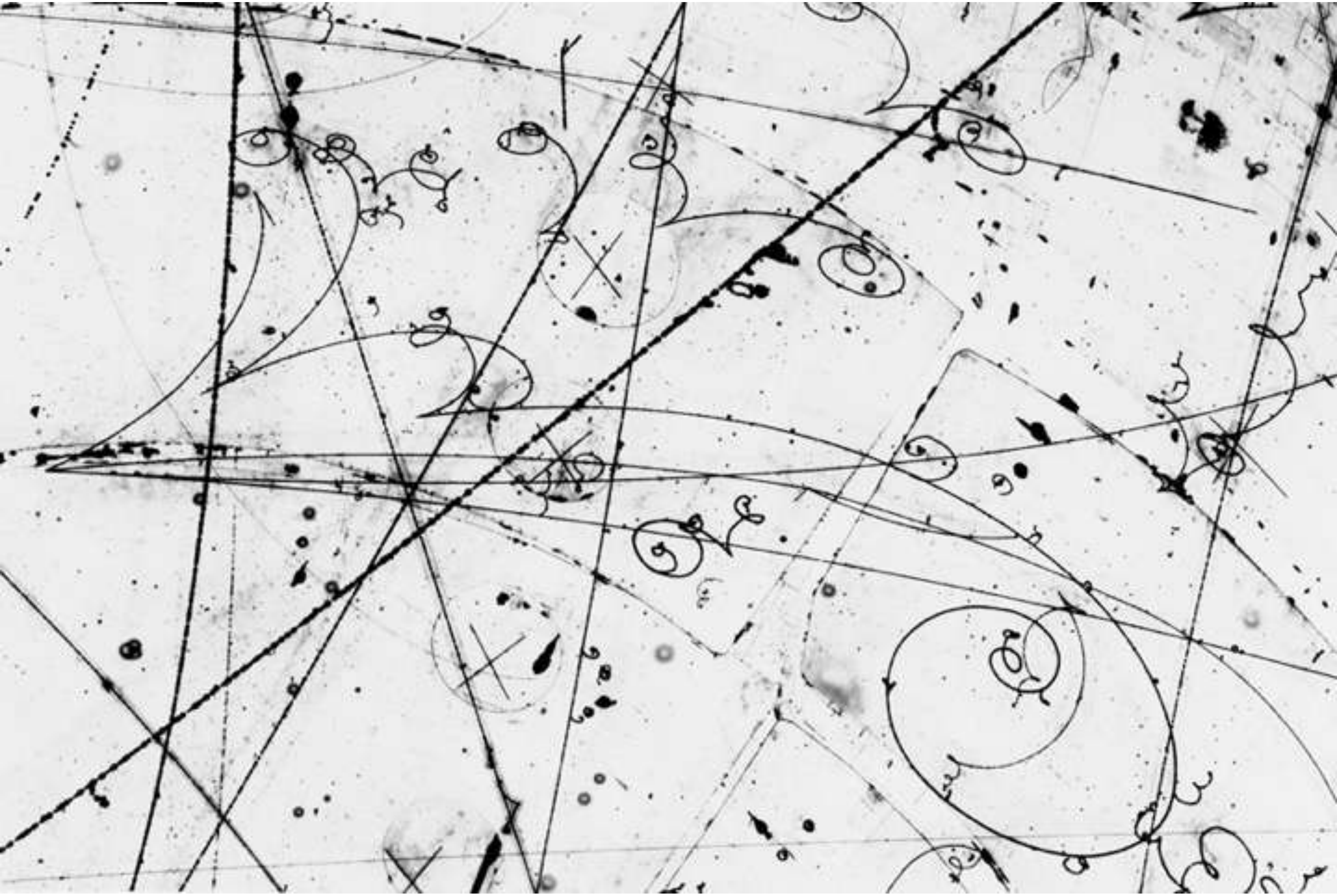


Luis Alvarez as U. Chicago Grad Student w/ Arthur Compton, 1933



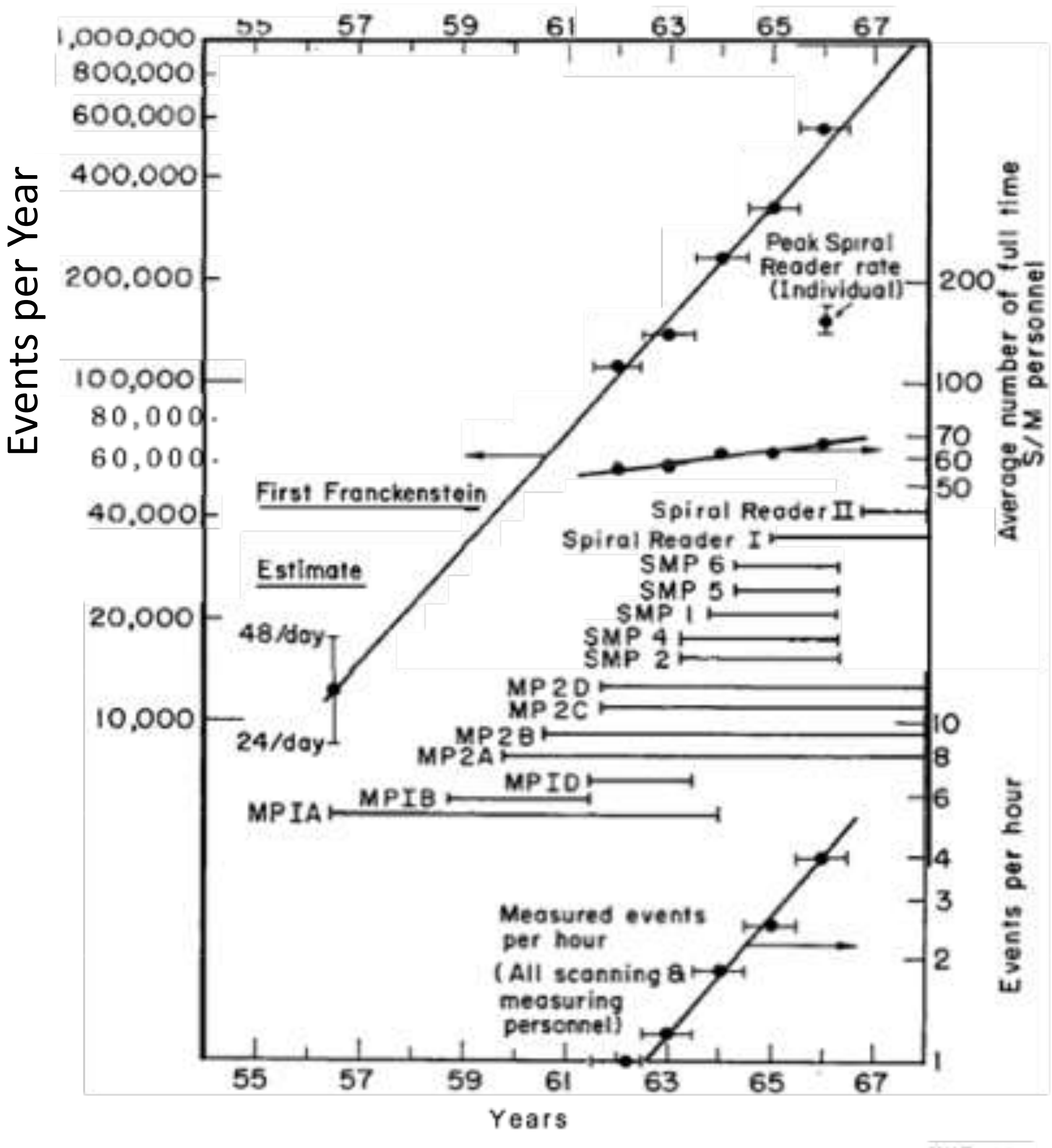


nch chamber in 1959- just 7 years after Glaser's invention



From Fermilab 15-ft hydrogen chamber, 1980 (Fermilab Visual Media Services)

Why Bubble Chambers Didn't Last



- Bubble chamber image analysis throughput: ~ 1 million events per year by end of the 1960s.
- Bubbles take about 100 microseconds to grow to visible size.
- For comparison: LHC beams cross at a rate of 40 MHz, with ~ 10 interactions per crossing.

Figure: Alvarez Nobel Prize Lecture, 1968.

New Role: Lawn Ornaments?

WIMP Dark Matter Detector Wish List

- Large target mass (>1 ton for next generation)
- Low energy threshold. (~ 10 keV for standard WIMPs, lower for light WIMP models)
- Multiple target nuclei- test expected cross section dependences on atomic number and nuclear spin.
- Zero backgrounds from environmental radioactivity.
- Measure nuclear recoil energies.
- Measure nuclear recoil direction.

Bubble Chambers?

- Large target mass (>1 ton for next generation) ✔
- Low energy threshold. ✔
- Multiple target nuclei- test expected cross section dependences on atomic number and nuclear spin. ✔
- Zero backgrounds from environmental radioactivity. TBD.
- Measure nuclear recoil energies. By varying threshold
- Measure nuclear recoil direction. No

Coherence and Couplings

- WIMP interactions are coherent over target nucleus due to long wavelength

$$\lambda = \frac{h}{m_\chi v_\chi} \simeq 0.9 \text{ fm} \cdot \left(\frac{m_\chi}{100 \text{ GeV}}\right)^{-1} \left(\frac{v_\chi}{220 \text{ km}/s}\right)^{-1}$$

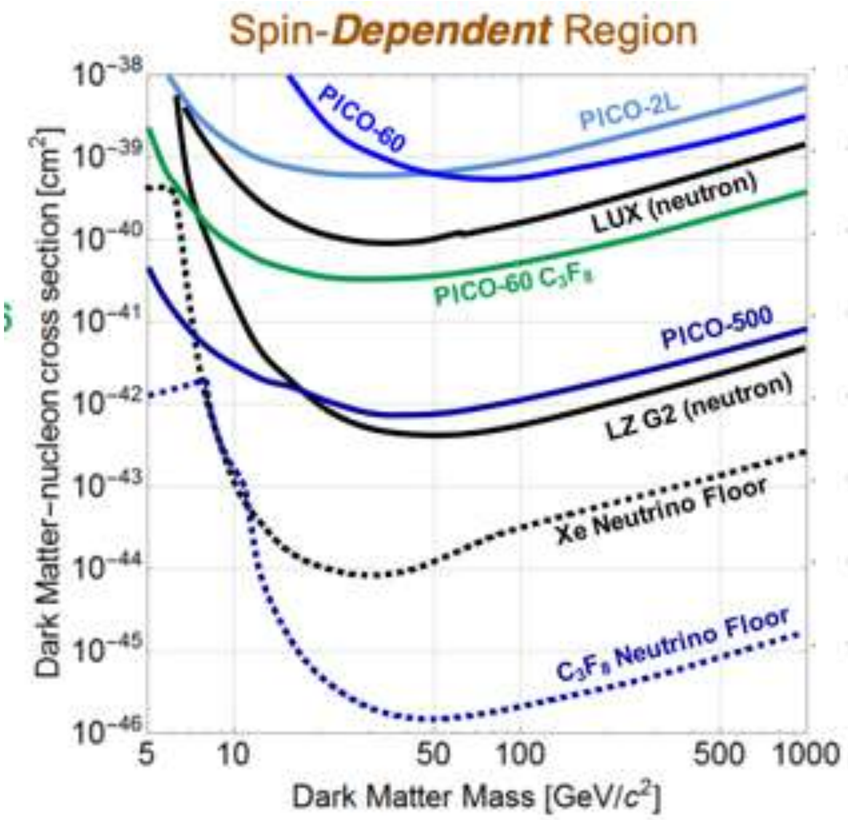
- For "spin-independent" couplings, this typically causes enhancement of cross section by A^2 (A= atomic number) due to summing over nucleons. Strongly favors detection on high-A targets (Germanium, Xenon,…).

- For "Spin-dependent" couplings, opposite spin pairs interfere with net coupling only to any remaining unpaired nucleon– either proton or neutron.

- We would like to have targets of varying A and spin (and form factors) to explore these dependences.

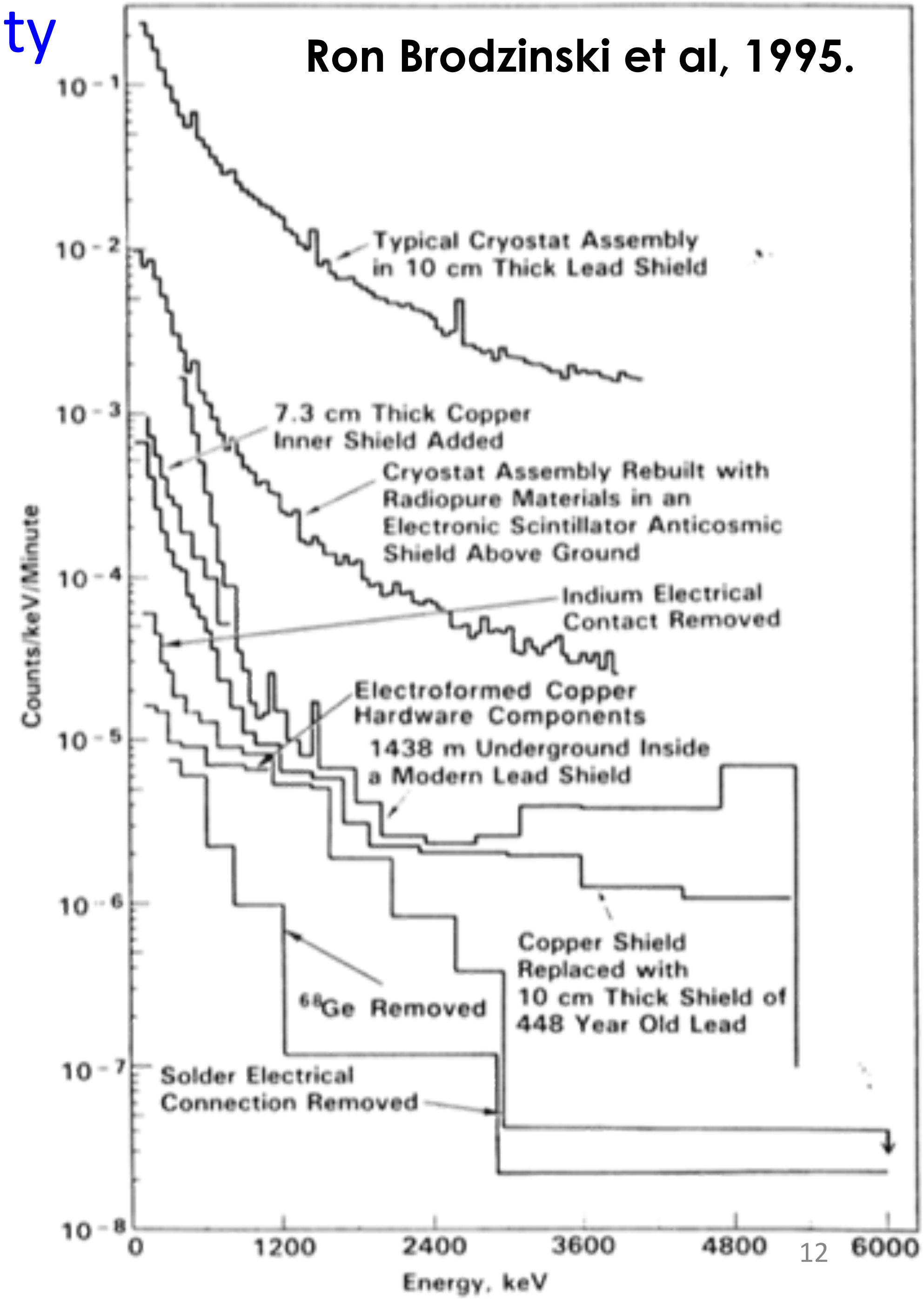
Unique contribution of bubble chambers to WIMP searches

- Capability to instrument a wide range of target nuclei with sensitivity to diverse WIMP-nucleon couplings. For example,
  - **^{19}Fluorine:** Best sensitivity to spin-dependent interactions.
  - **Iodine, Bromine, Xenon, Argon:** High-A targets to exploit A^2 dependence of spin-independent cross section.
  - **Hydrogen:** Enhanced sensitivity to low-mass particles.
- Very low backgrounds, due to unique discrimination mechanisms.
- Thresholds below 3 keV nuclear recoil energy.
- Lowest cost per ton of target mass.

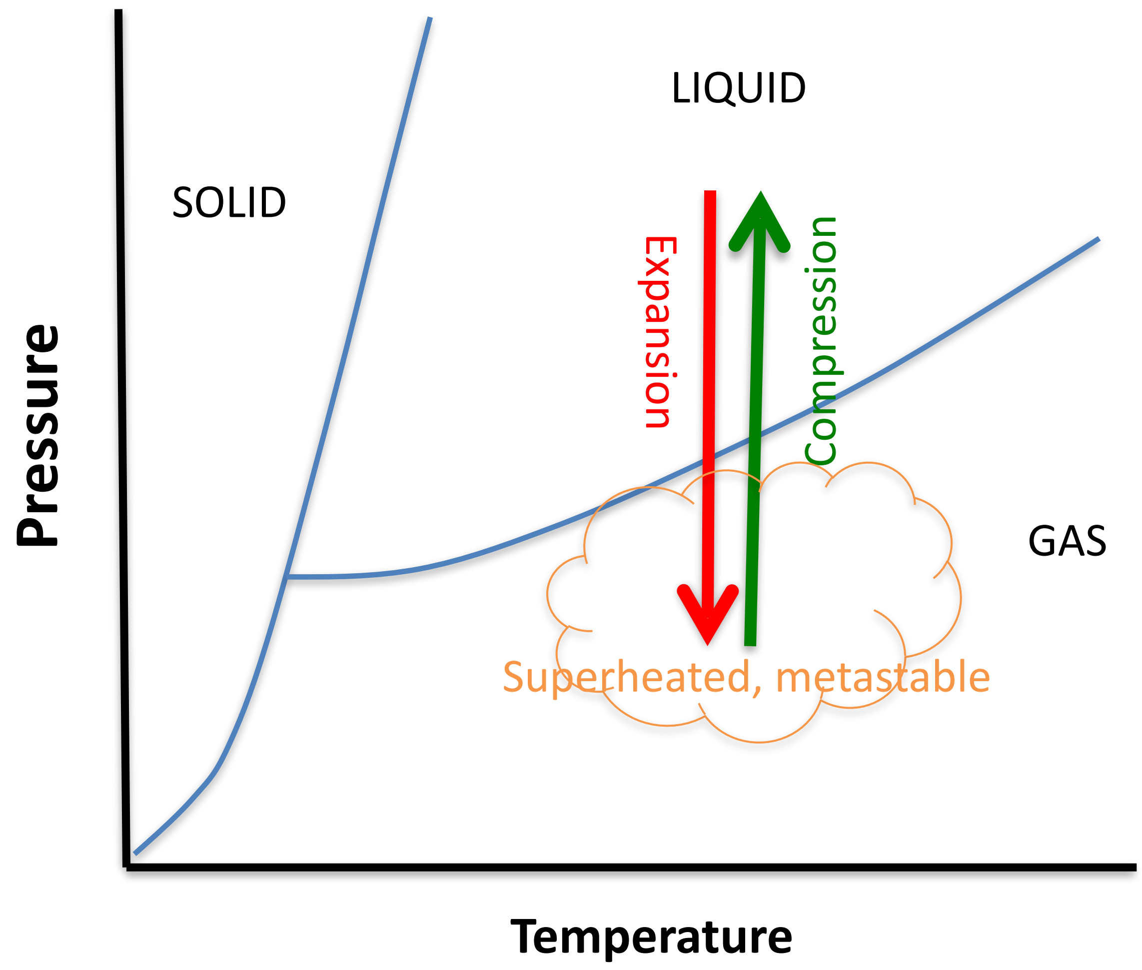


Backgrounds from Radioactivity

- Detector materials contain trace radioisotopes from environment.
- "Primordial" Uranium and thorium at levels of 10^{-6} - 10^{-9} atoms/atom in most materials. Typically >10^5 ionizing events per day per kg of material.
- Cosmic rays muons and secondary neutrons. Reduced by going underground.
- Unstable isotopes produced in detector by cosmics rays.

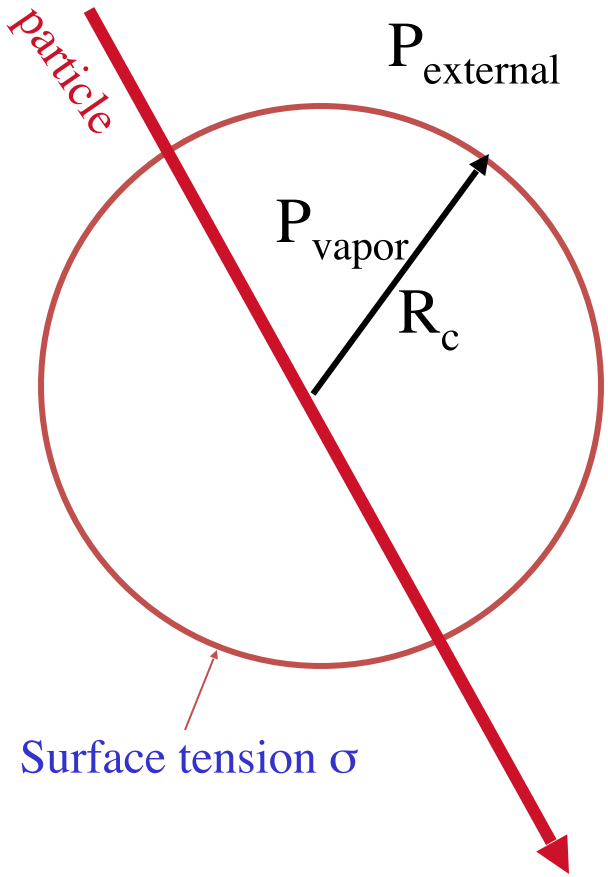


Bubble Chamber Expansion/ Compression Cycle



Bubble Nucleation by Radiation

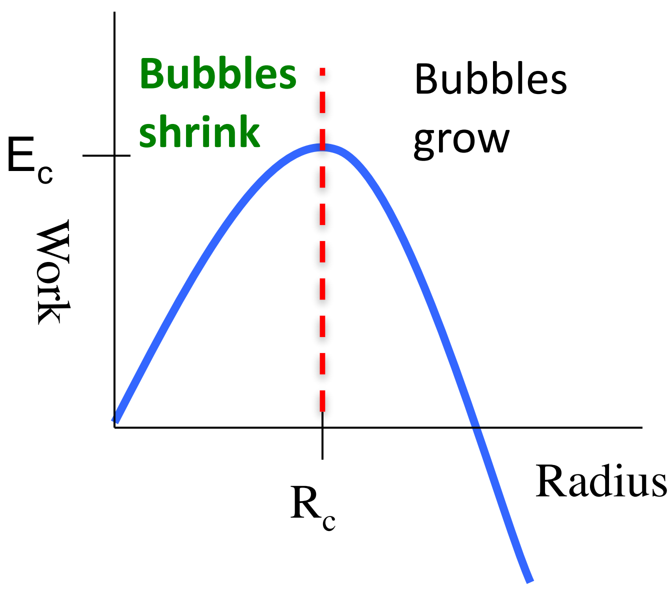
(Seitz, "Thermal Spike Model", 1957)



- Pressure inside bubble is equilibrium vapor pressure.
- At critical radius R_c surface tension balances pressure.

$$R_C = \frac{2\sigma}{P_{vapor} - P_{external}}$$

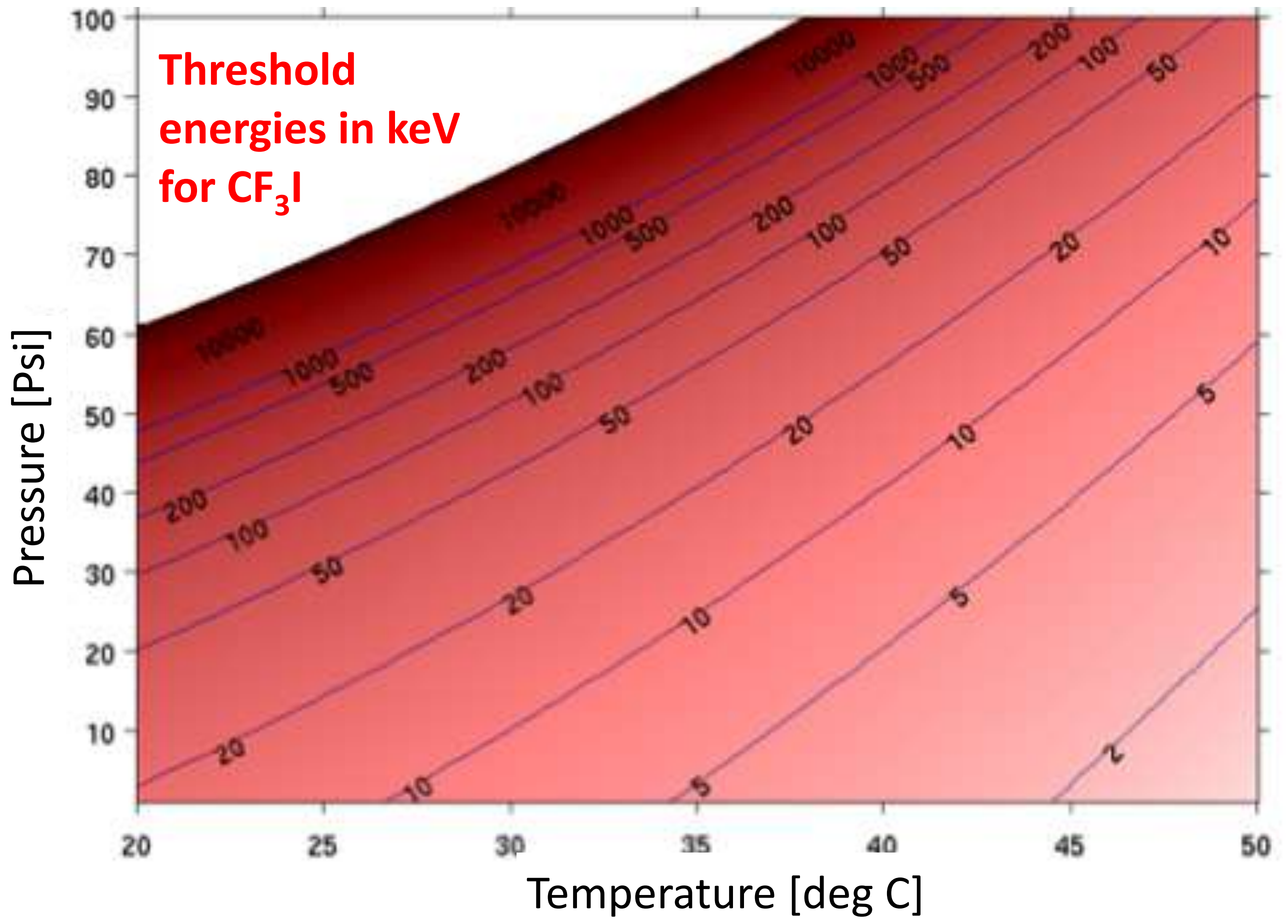
- Bubbles bigger than the critical radius R_c will grow; smaller bubbles will shrink to zero.



Energy Barrier to Bubble Nucleation

$$E_{th} = 4\pi r_c^2 \left(\sigma - T \frac{\partial \sigma}{\partial T} \right) + \frac{4}{3} \pi r_c^3 \rho_v h$$

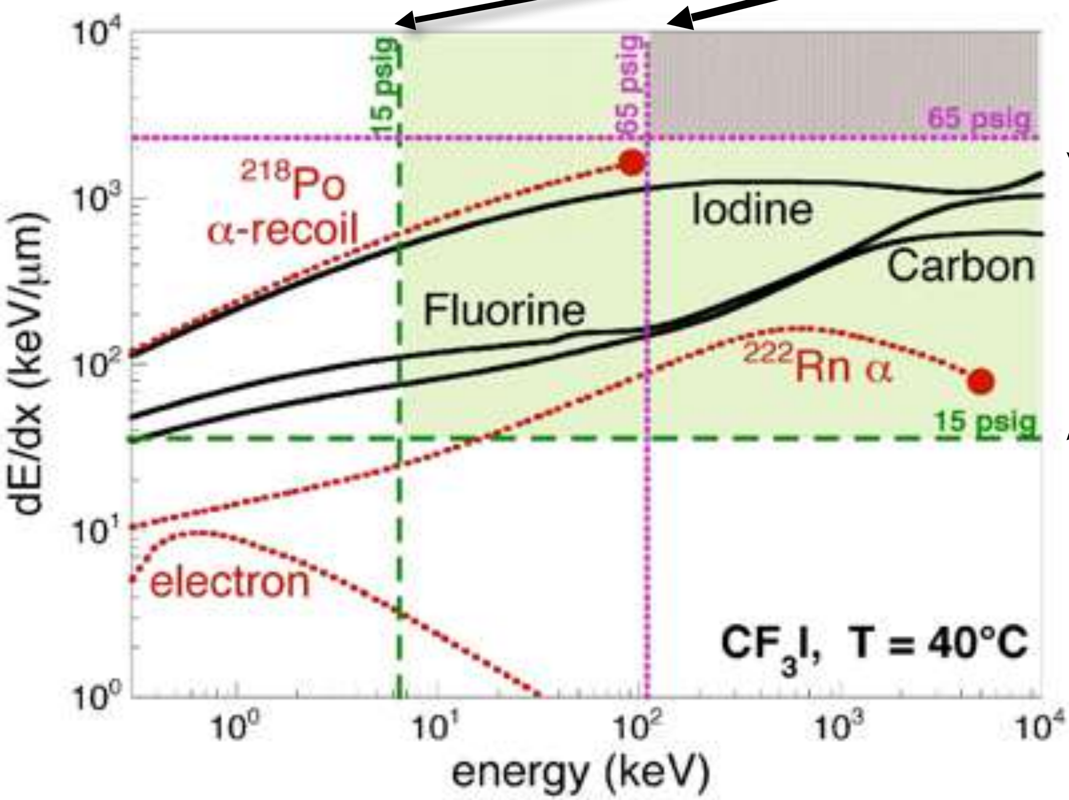
Surface energy | Latent heat



Tuning the dE/dX Threshold for Bubble Nucleation

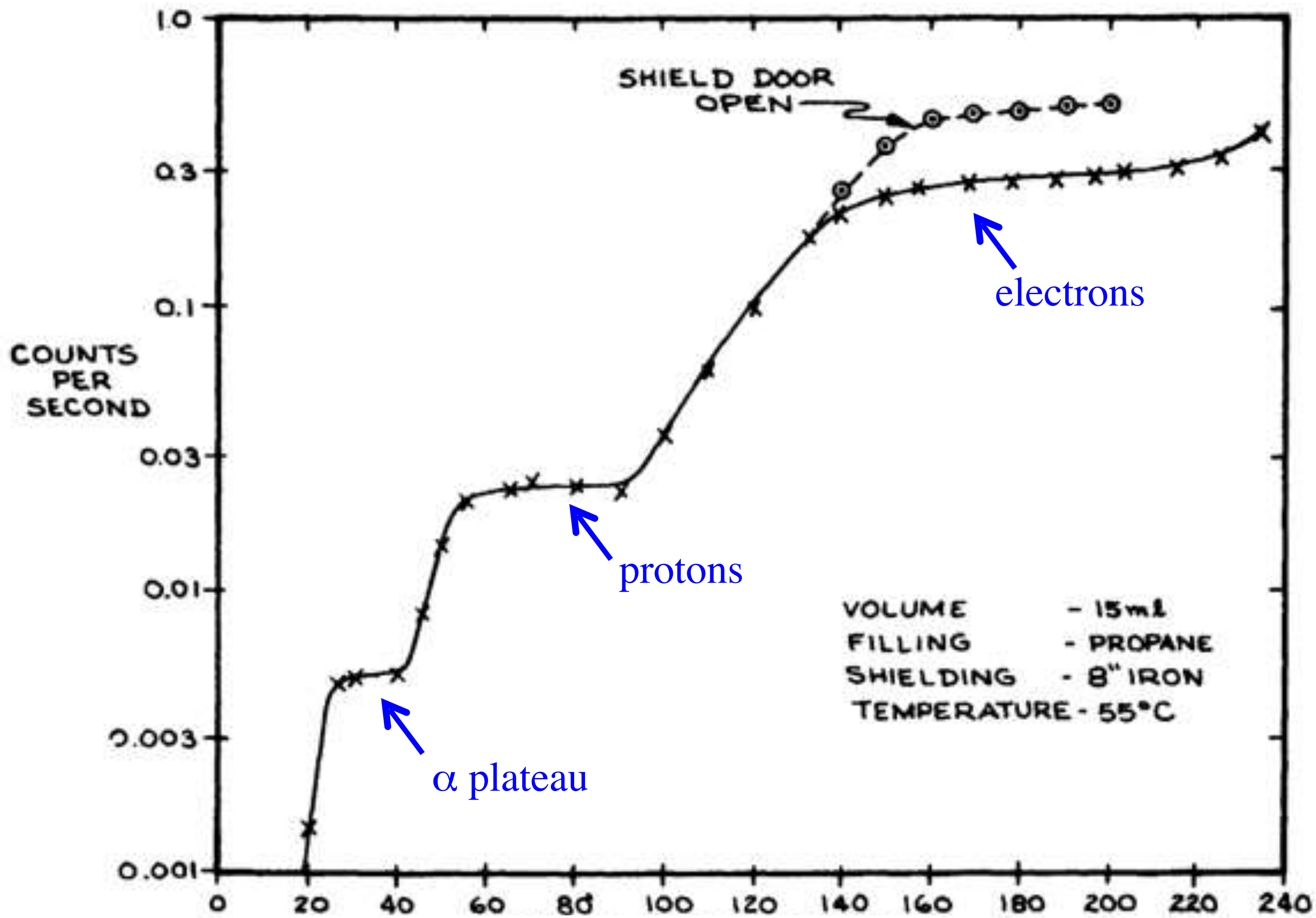
- The bubble chamber operator chooses a pressure and temperature, fixing the minimum size of bubbles that are allowed to grow against surface tension.
- This simultaneously determines minimum deposited energy and energy loss density (dE/dX) that will nucleate bubbles.
- Example below: superheated CF_3I at fixed temperature, two operating pressures.

Energy Thresholds



dE/dX threshold at 15 psi and 65 psi

dE/dX Discrimination in 1960's Bubble Chambers

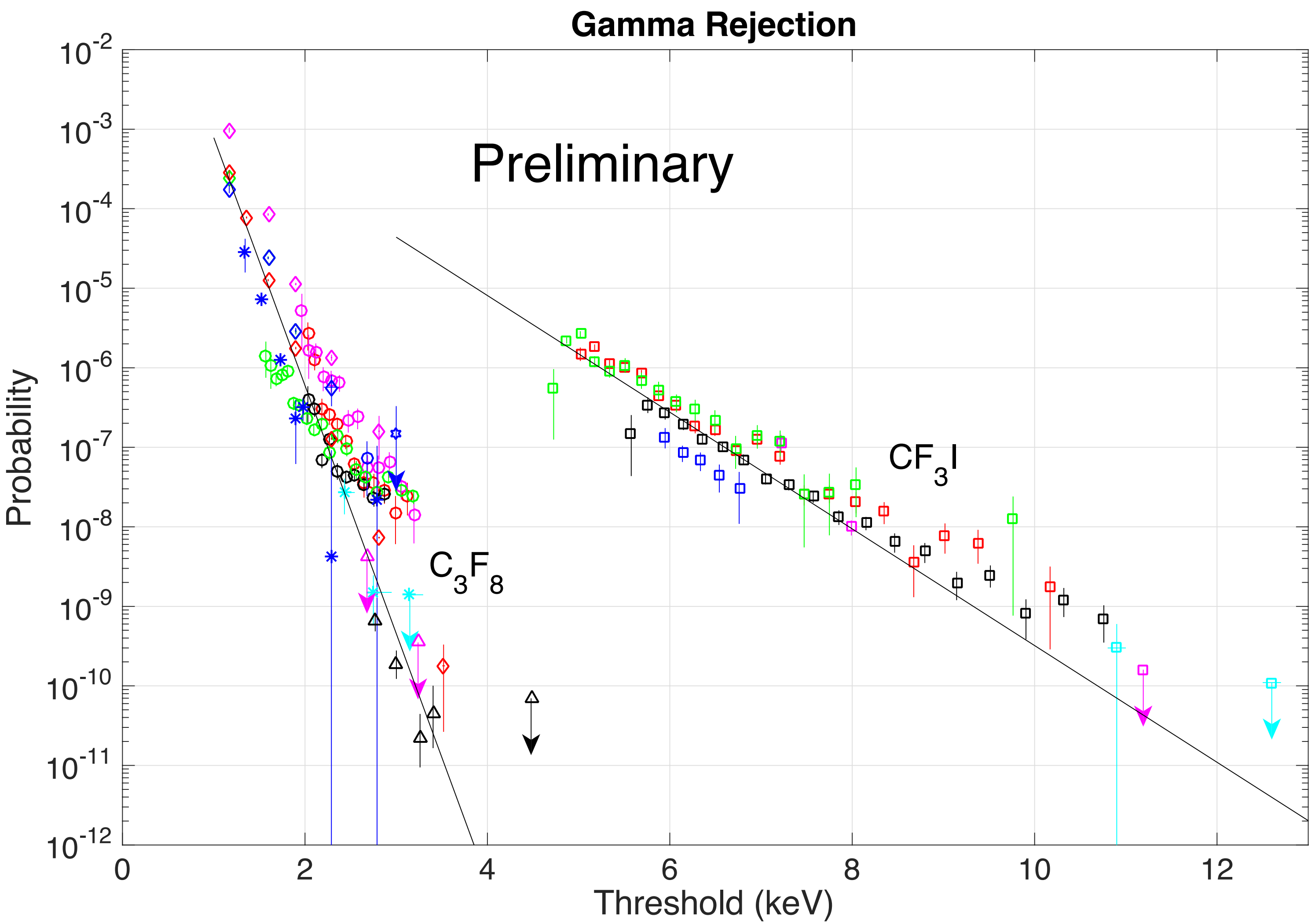


Vapor Pressure – Operating Pressure (psi)

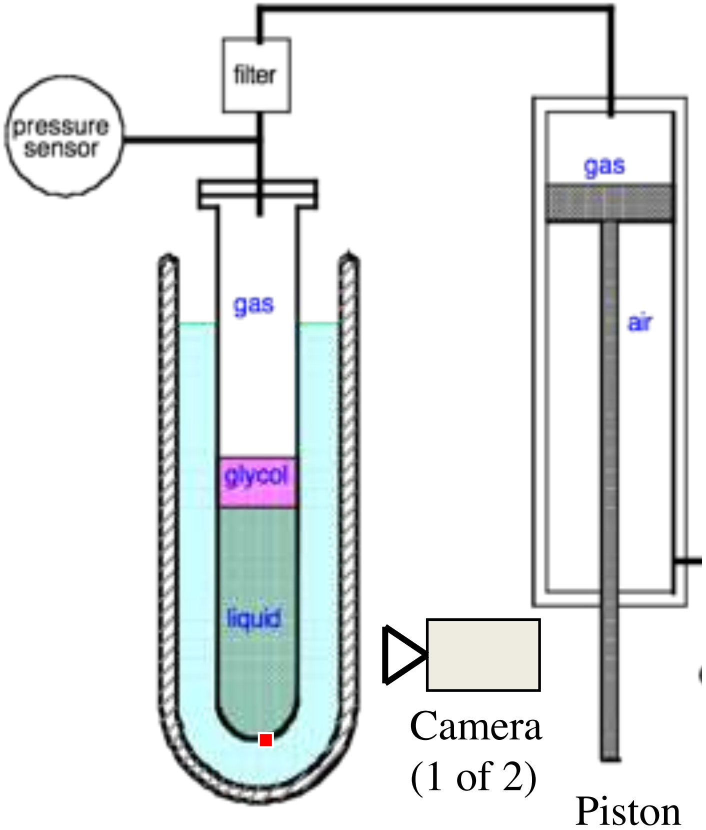
Waters, Petroff, and Koski, IEEE Trans. Nuc. Sci. 16(1) 398-401 (1969)

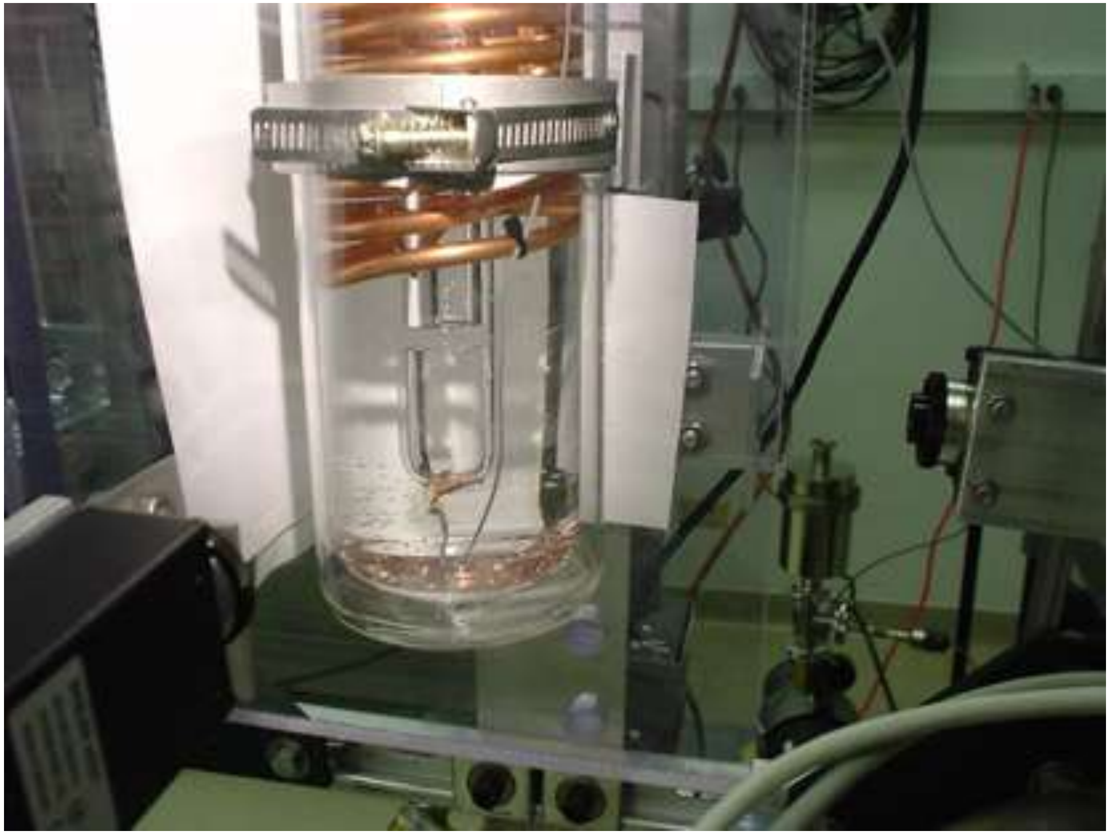
Gamma Insensitivity

Bubble nucleation probability for a gamma interaction in C_3F_8 or CF_3I



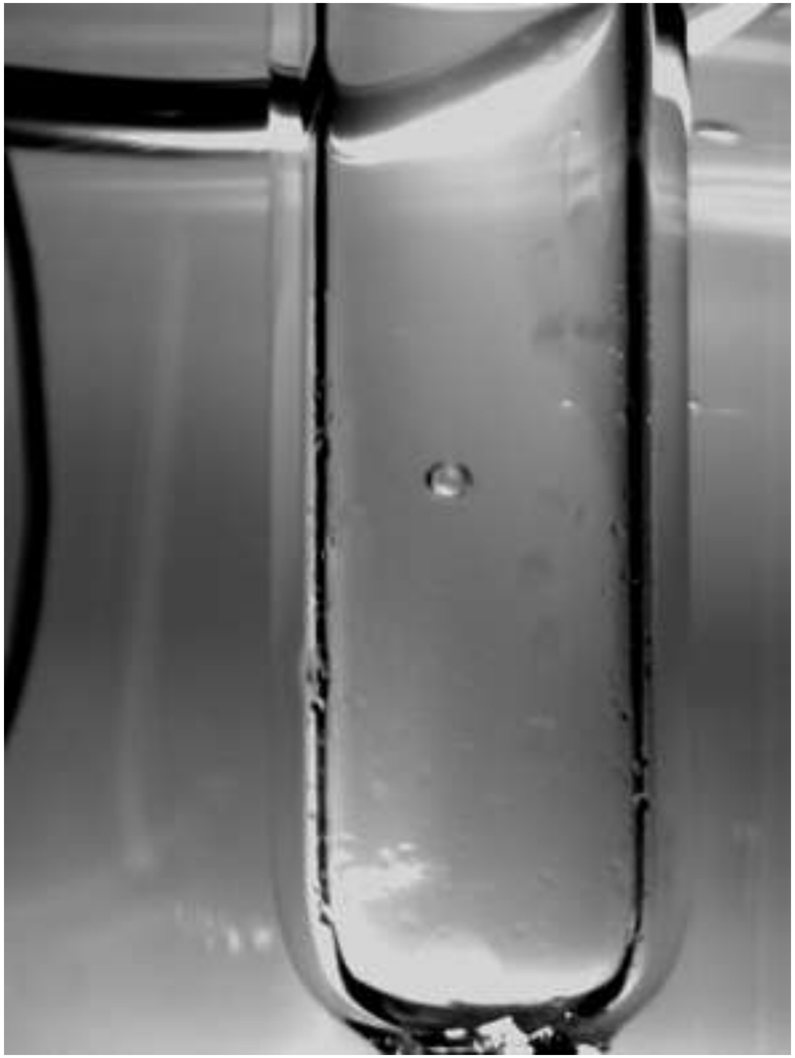
Prototype Dark Matter Detector at KICP, 2003





Dirty Surfaces

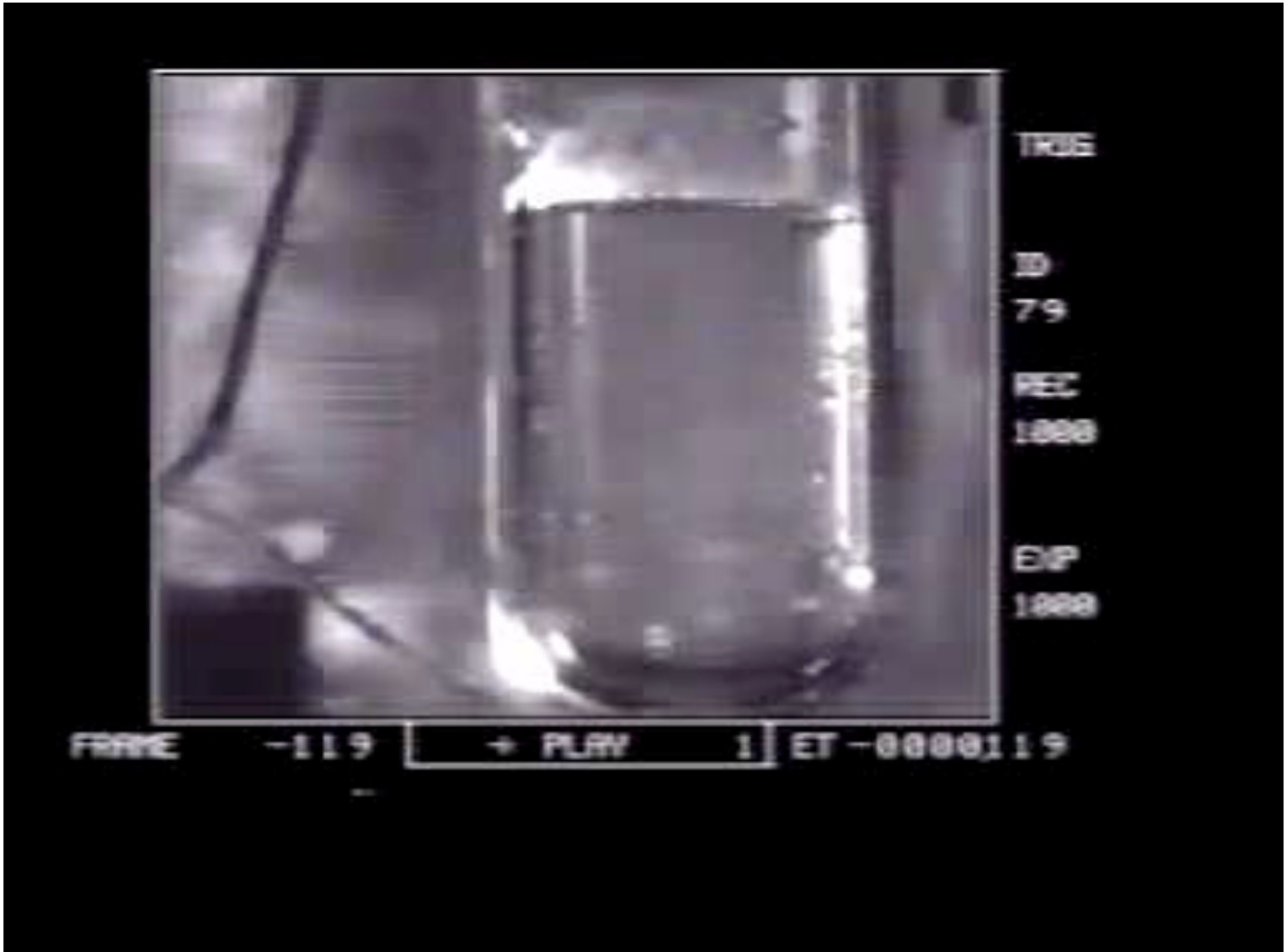
Clean Surfaces



High Speed Bubble Chamber Movie

1000 frames/ second

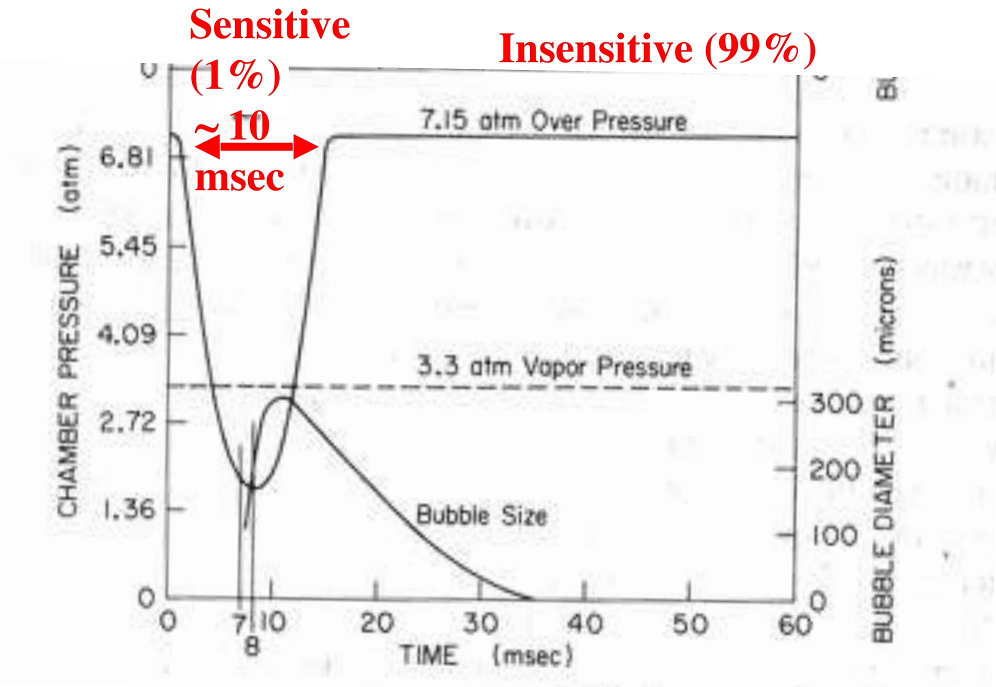
^{241}Am-Be neutron source



Demonstration of Continuously Sensitive Bubble Chamber

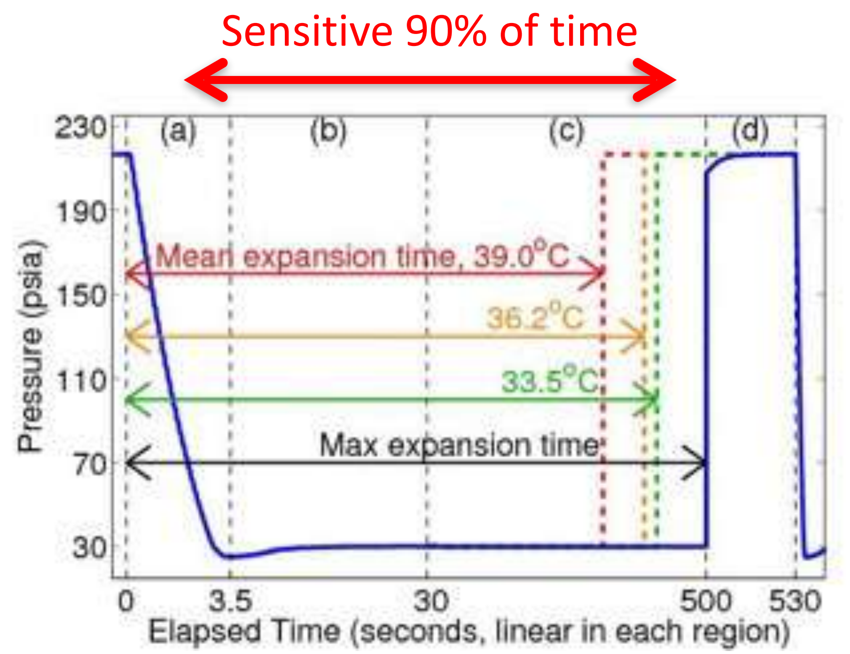
- Reinventing history-Glaser's original "clean", glass bubble chamber would remain sensitive for 10's of seconds.
- Alvarez pioneered "dirty chambers" with metal surfaces: easy to build, but only sensitive for a few milliseconds.

Conventional Bubble Chamber



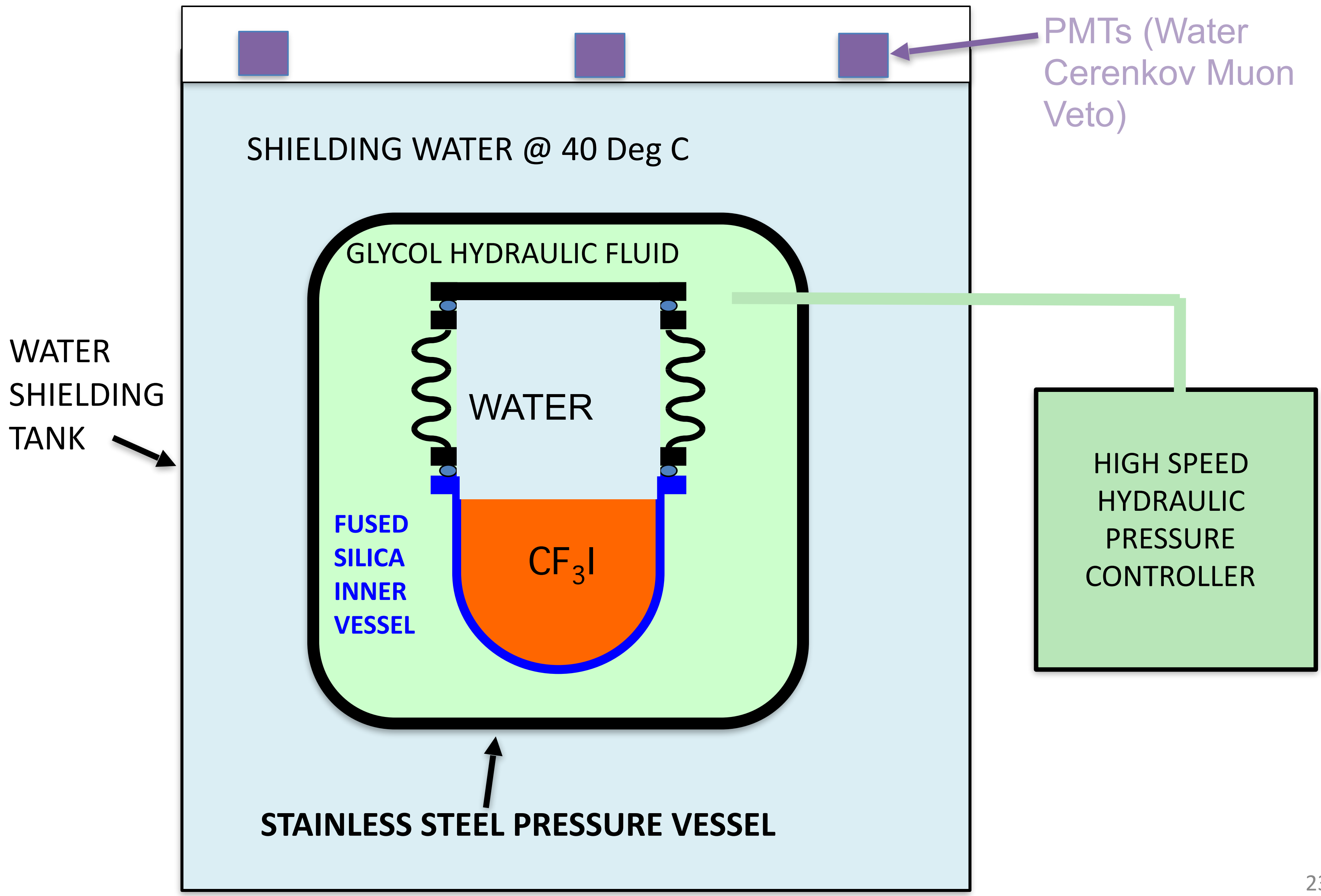
SLAC 1- meter hydrogen chamber

"Continuously Sensitive" Chamber

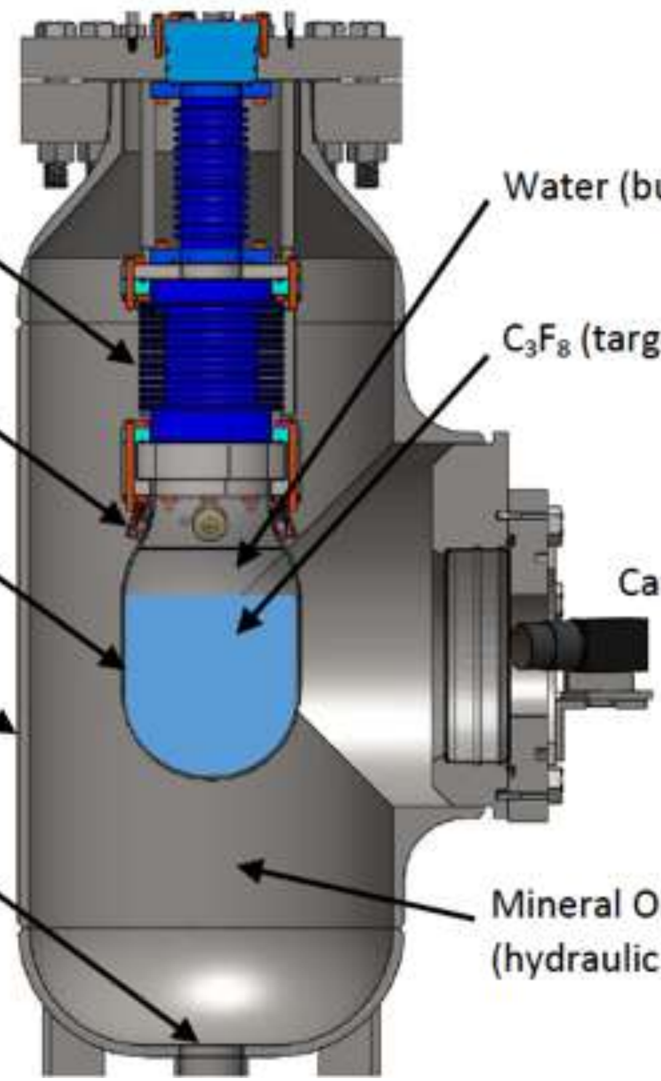


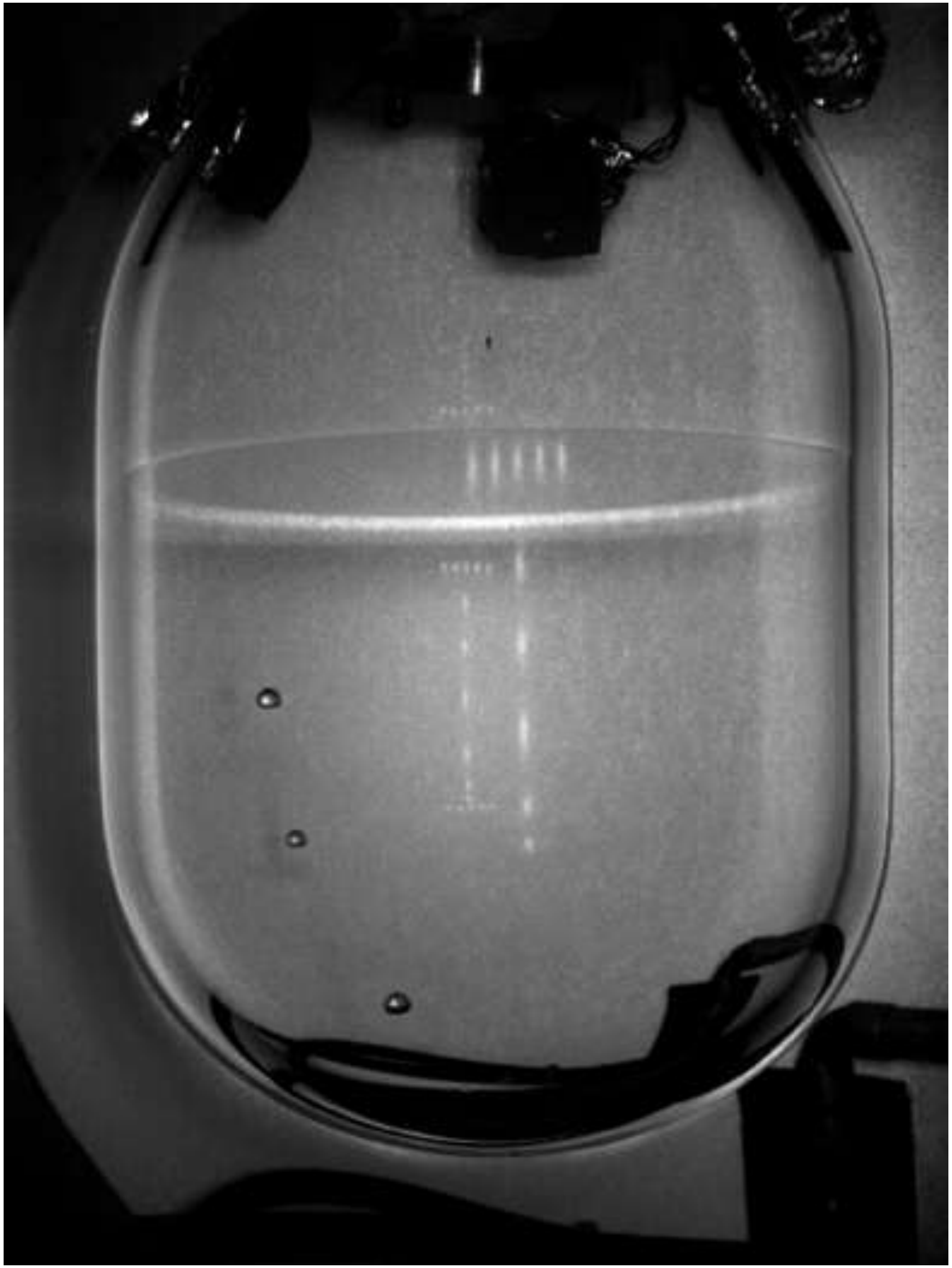
PICO-2L Chamber with CF_3I

Large Bubble Chamber WIMP Detector Cartoon



2-Liter Chamber : PICO-2L





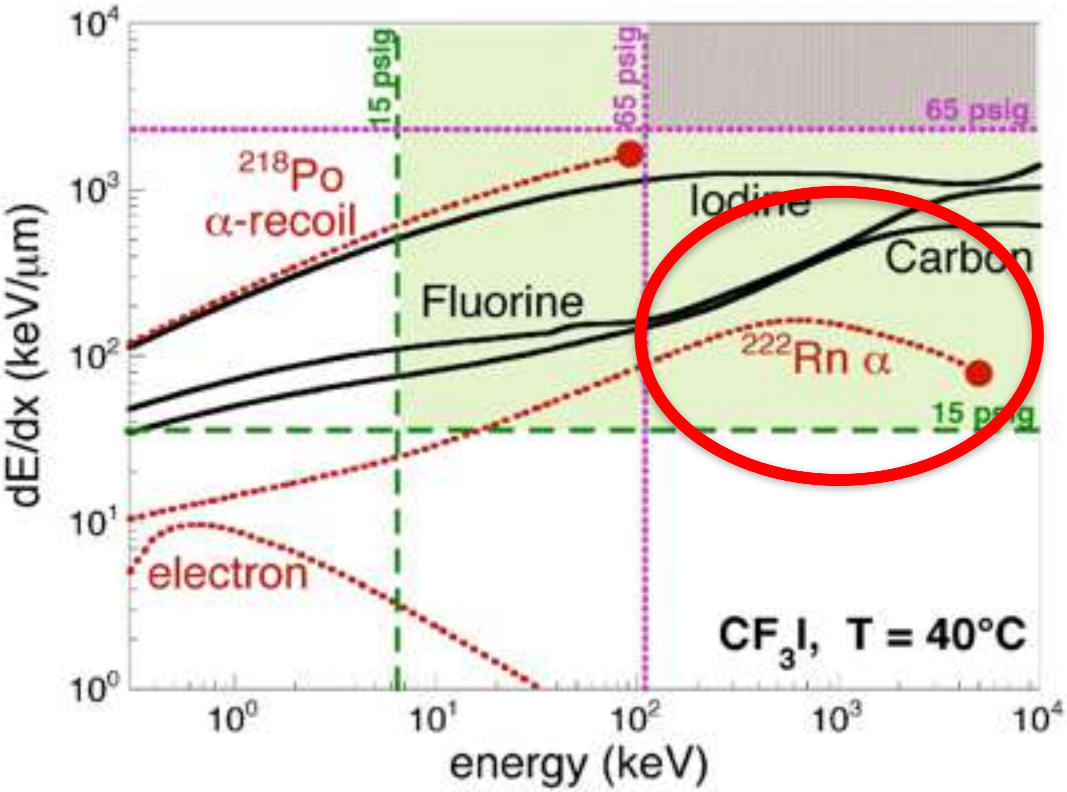
Large Chamber: PICO-60

STEEL PRESSURE VESSEL

INNER VESSEL ASSEMBLY

PICO-60 Chamber Testing at Fermilab

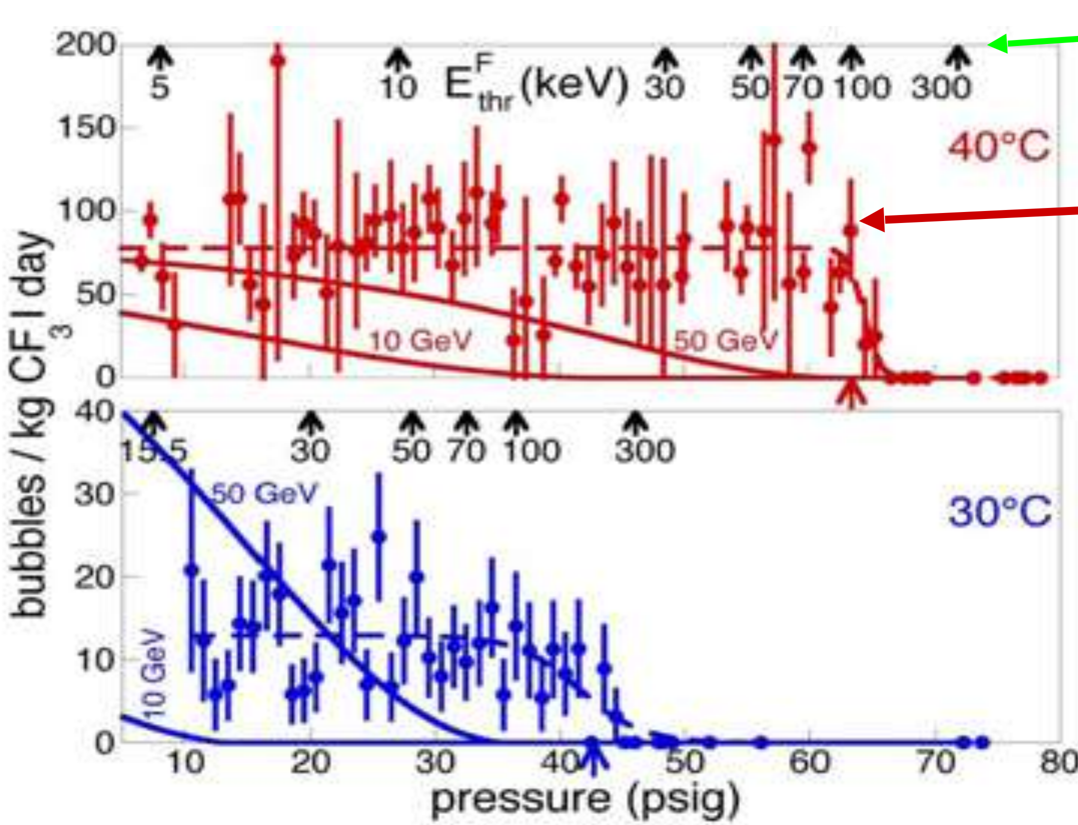
Alpha Decay Backgrounds



- Alpha particles and recoiling daughter nuclei can nucleate bubbles.
- The ^{238}U and ^{232}Th decay series include many alpha emitters, including radon (^{222}Rn) and its daughters, which are ubiquitous in the environment.

Alpha Backgrounds in 2006 COUPP Run at Fermilab

- High alpha background rate from radon dissolved in target fluid.
- Used pressure scanning to separate WIMPs/ Alphas on basis of energy spectrum.



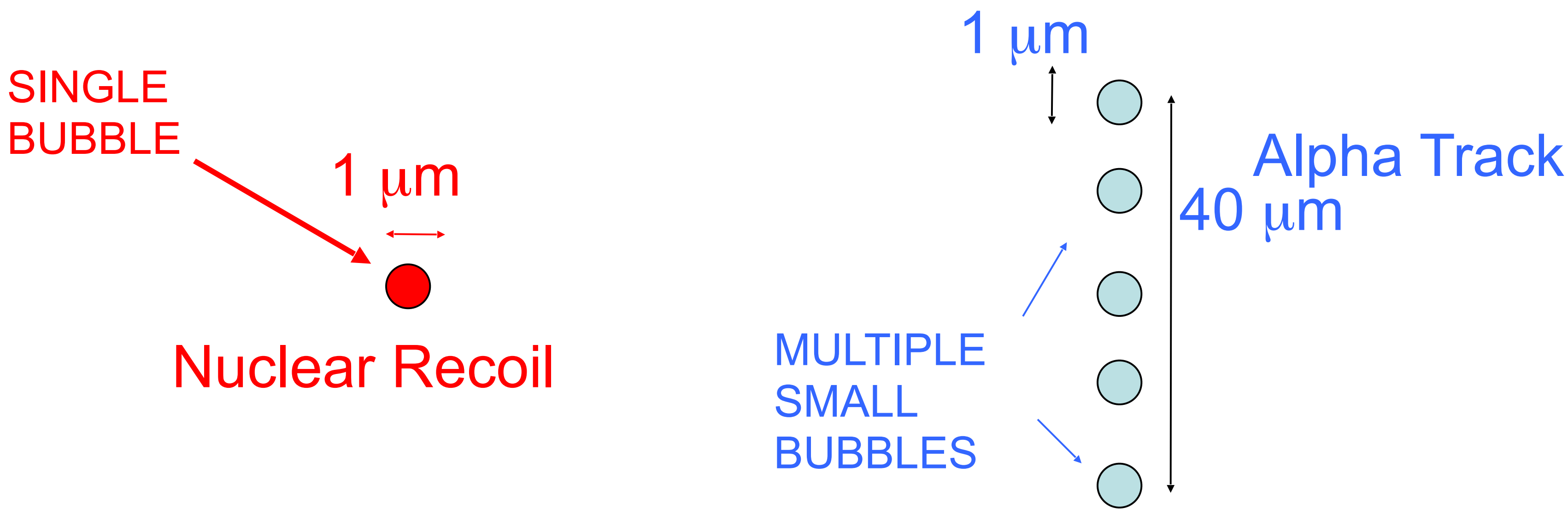
Energy Threshold In KeV

Radon background

Solid lines: Expected WIMP response for $\sigma^{SD(p)}$=3 pb

Discrimination Between Alpha Decay Bubbles and Nuclear Recoils?

Imagine that we could photograph the bubble track with micron resolution a few microseconds after nucleation occurs, while bubbles are still just ~ 1 micron in diameter.



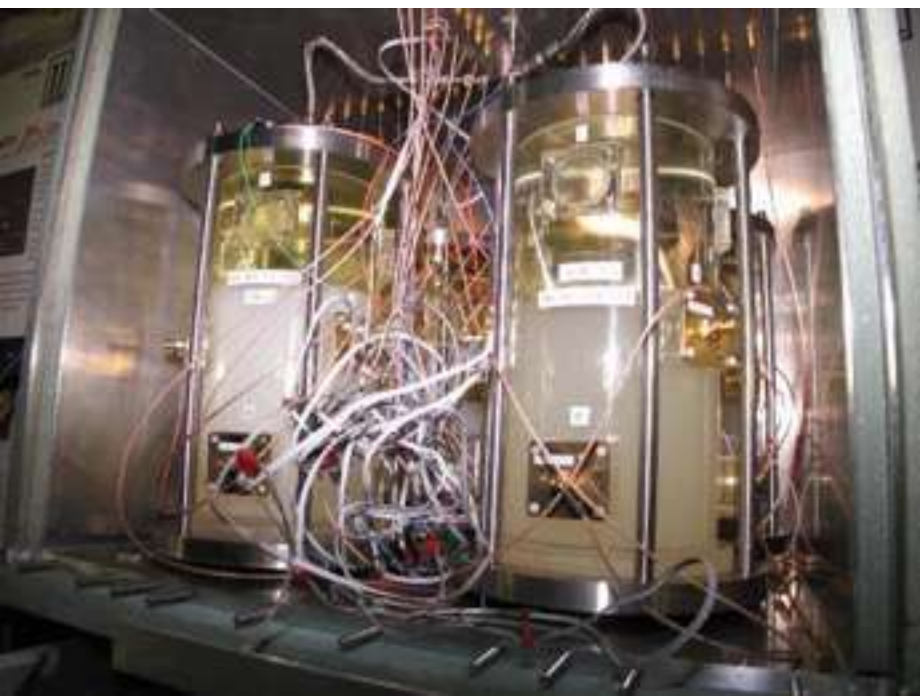
Video imaging of events on these time and distance scales impossible over the large required field of view: e.g. ~ 1 m^3 of volume with ~1 micron resolution at a video rate of ~1 MHz.

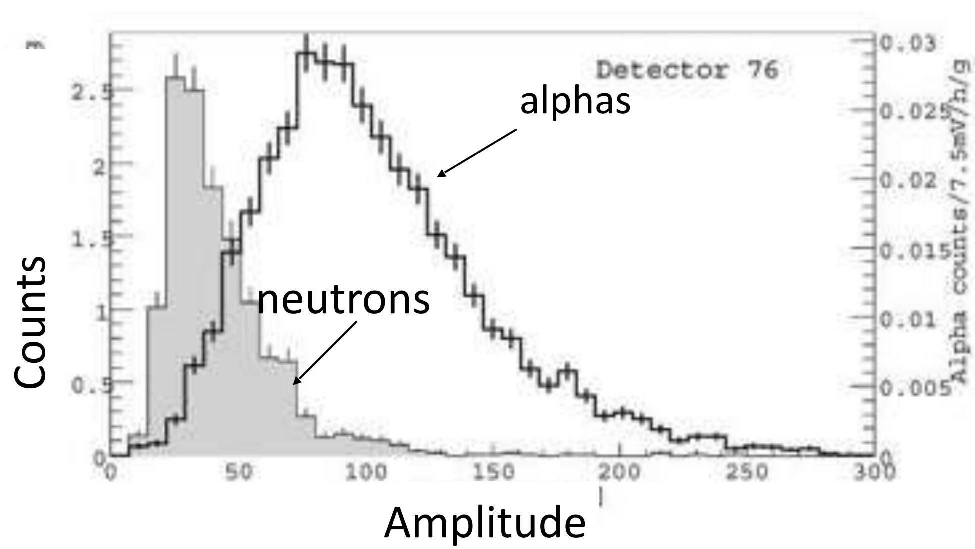
<u>but</u>

Acoustic signal from alpha track is several times louder than recoil signal at high frequencies due to presence of multiple radiating bubbles.

PICASSO Discovery of Alpha Discrimination Using Sound Waves (2008)

- Bubble nucleation detected acoustically using piezoelectric microphones.
- Amplitude of acoustic signal differs for Alphas vs. Nuclear recoils.
- Distributions overlap at the ~10% level.

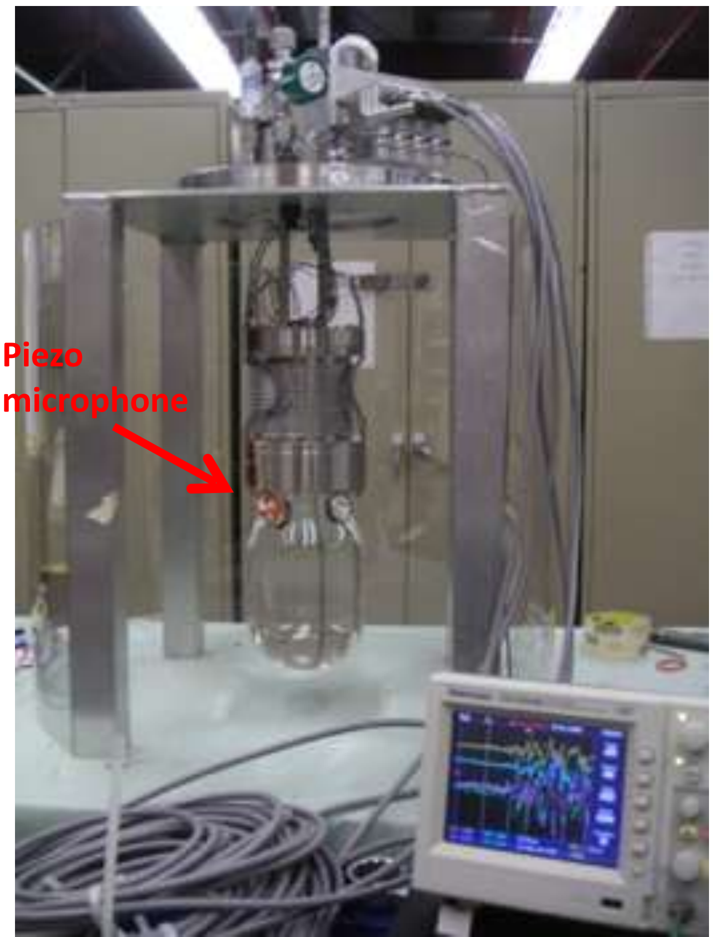


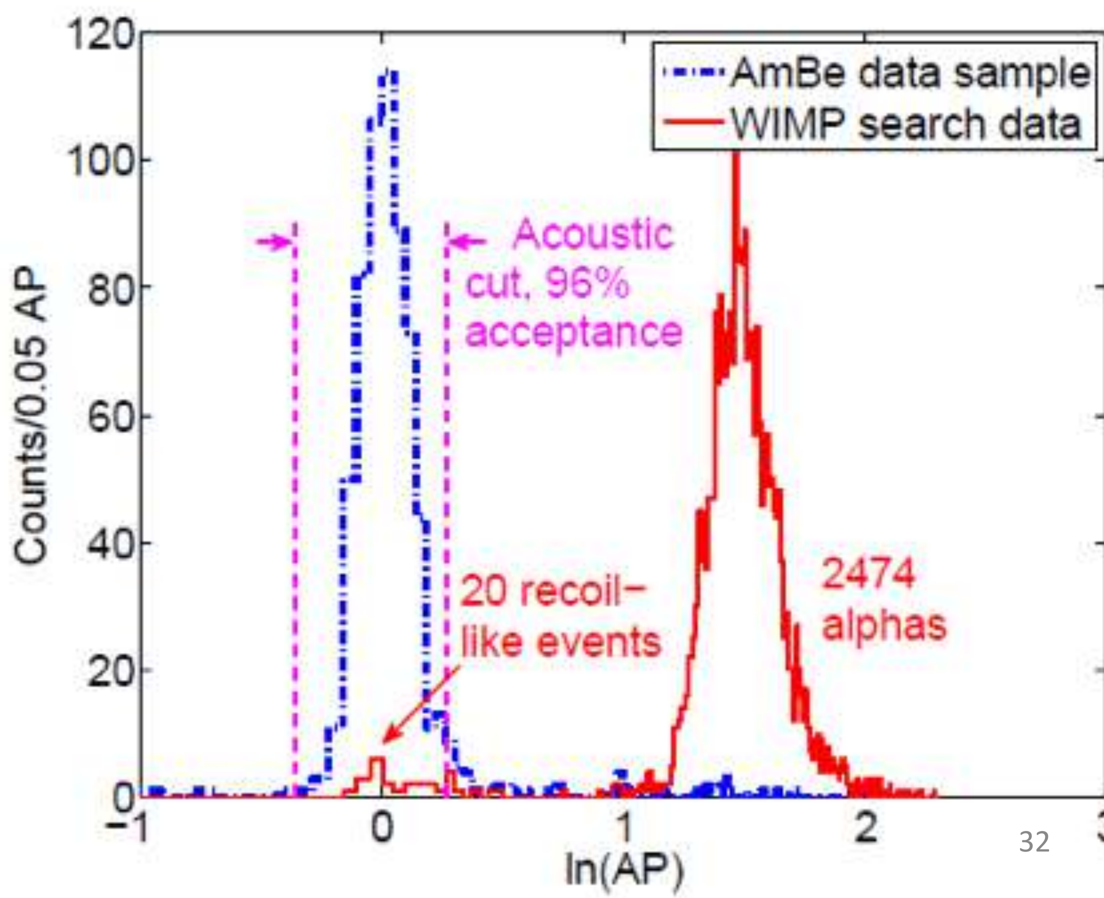


New Journal of Physics arXiv:0807.1536

Acoustic Particle ID in Bubble Chambers

• Works much better in bubble chambers than in droplet detectors.
• >99.3% of alpha background rejected with 96% signal acceptance.





PICO

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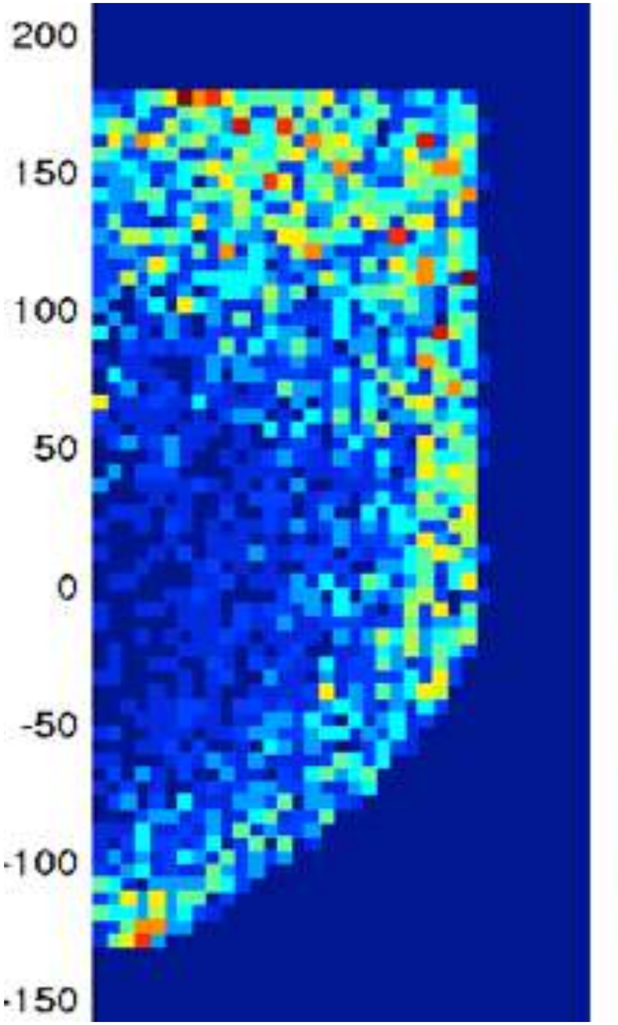
PICO-60 at SNOLAB, 2012

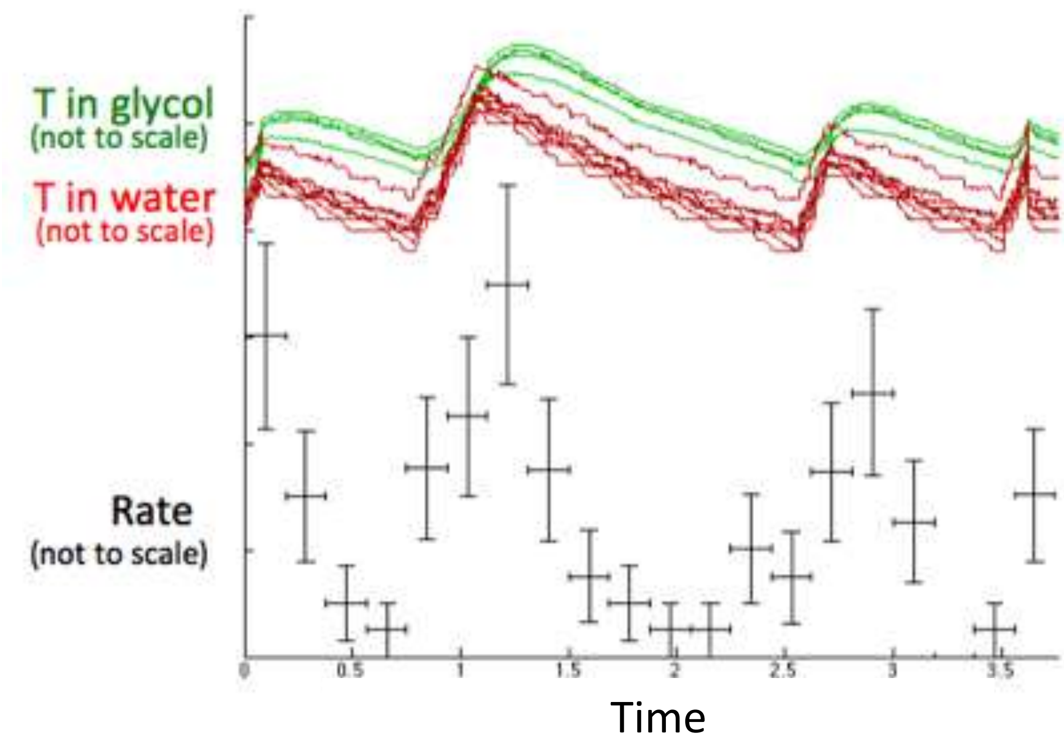
Anomalous Background Events

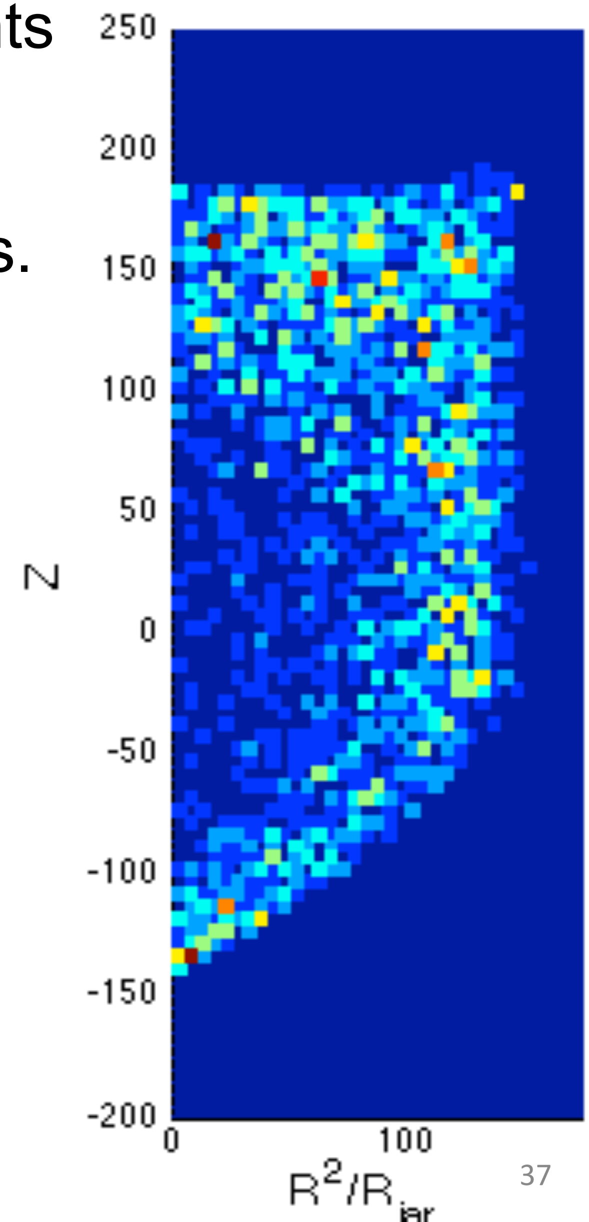
- Fluctuating rate of background events, from ~10-100 counts per day.
- Non-uniform spatial distribution, with highest rates near top and walls of chamber.
- Highest rates during periods of temperature instability.
- Highest rates at beginning of bubble chamber expansion cycle.
- Anomalous acoustic amplitude distribution.



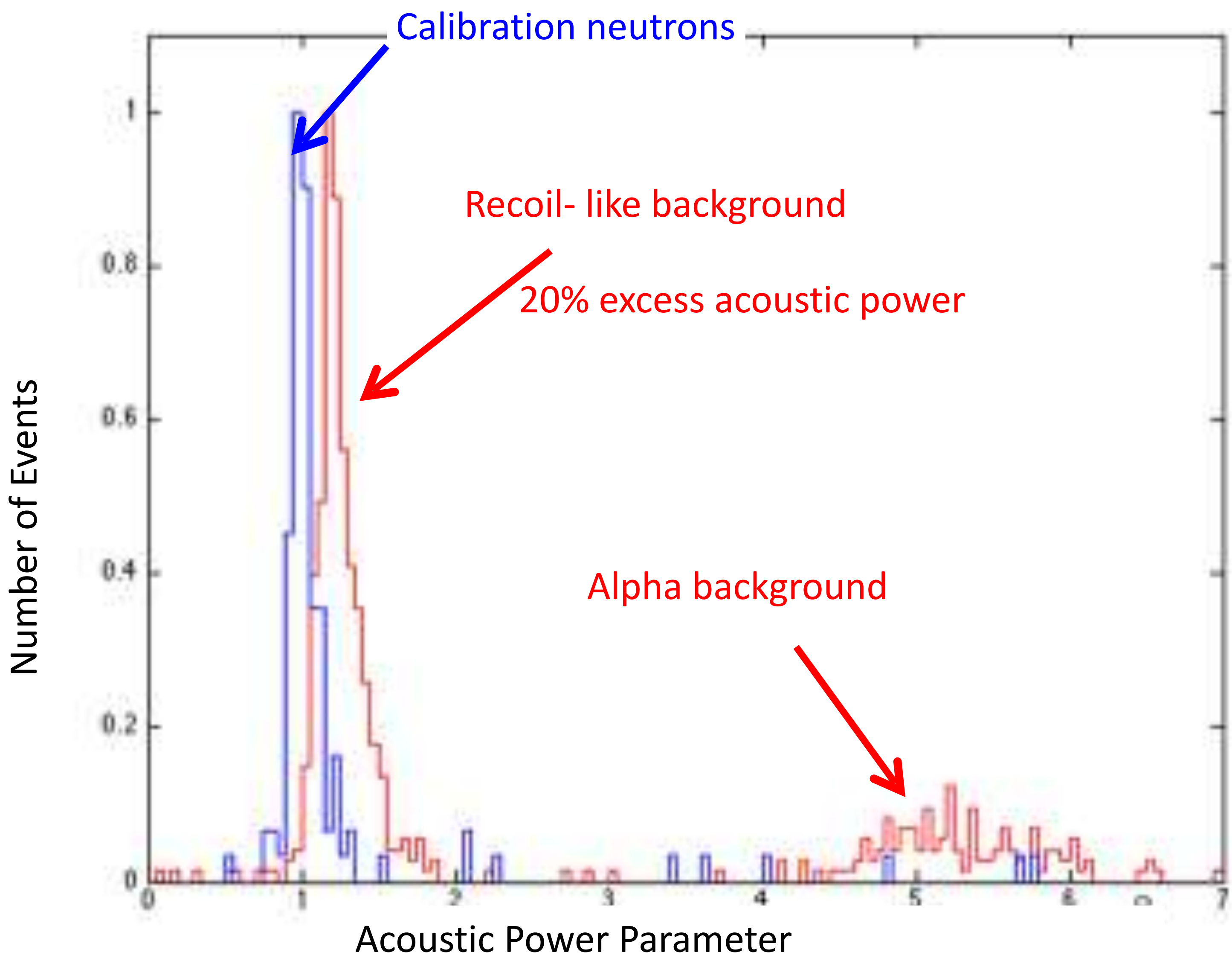
Space and Time Distribution of Recoil-Like Events

- Acoustically identified recoil-like events have anomalous spatial and time distributions.
- Correlation with temperature changes.
- This cannot be dark matter.





Acoustic Distribution



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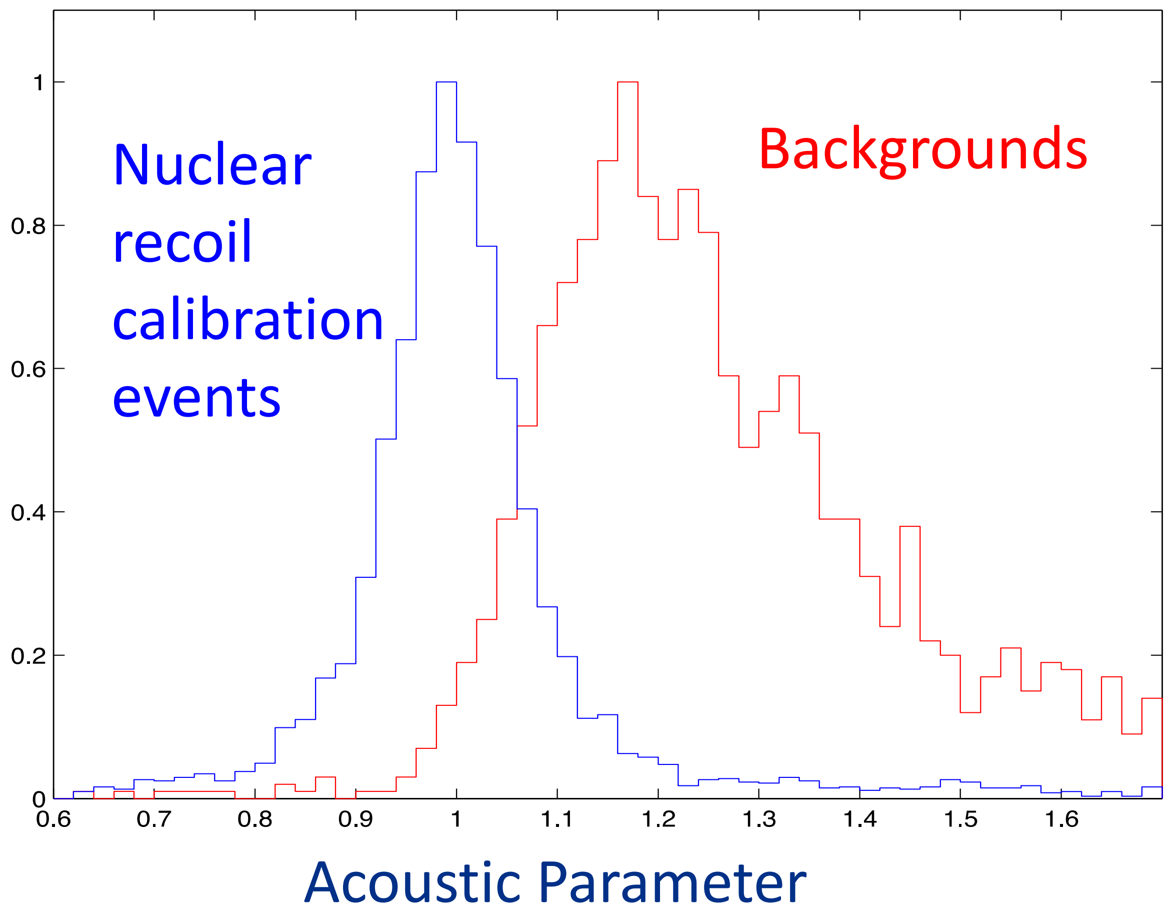
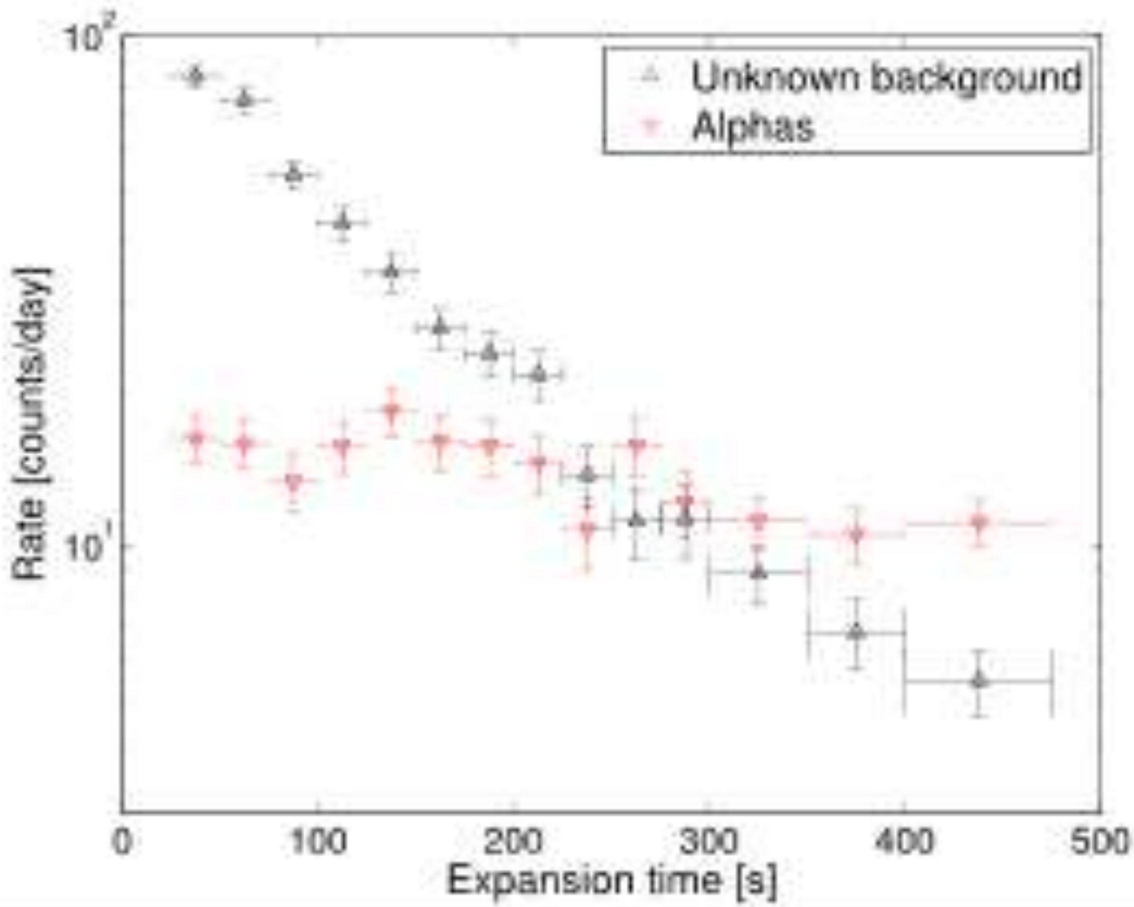
Anomalous acoustic amplitude distribution of background



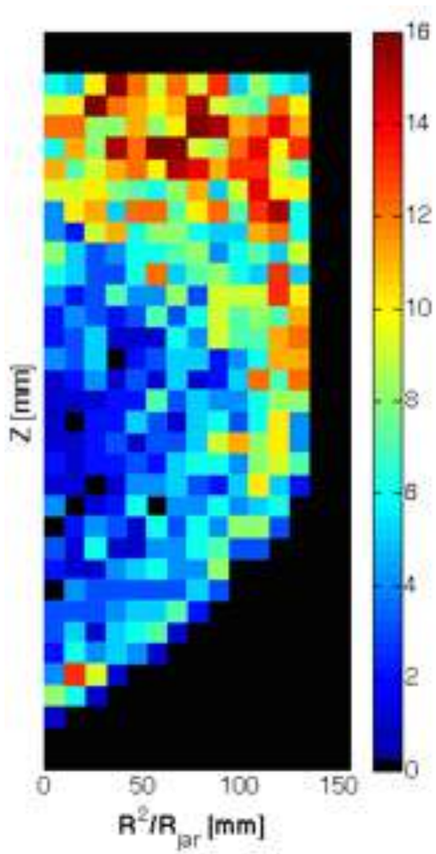
Expansion Time Dependence

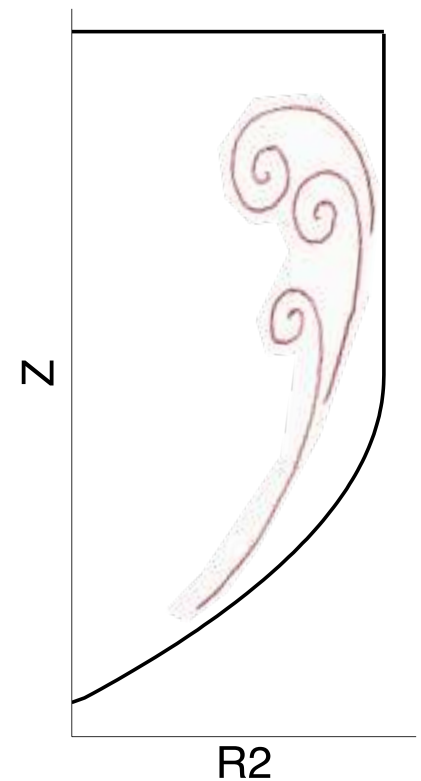
- Probability of seeing a background event decreases the longer the chamber is expanded.



Something Floating in the Detector?

- PICO bubbles chambers contain repeatedly stressed mechanical parts (steel and quartz) in contact with fluids → generation and transportation of particulates?



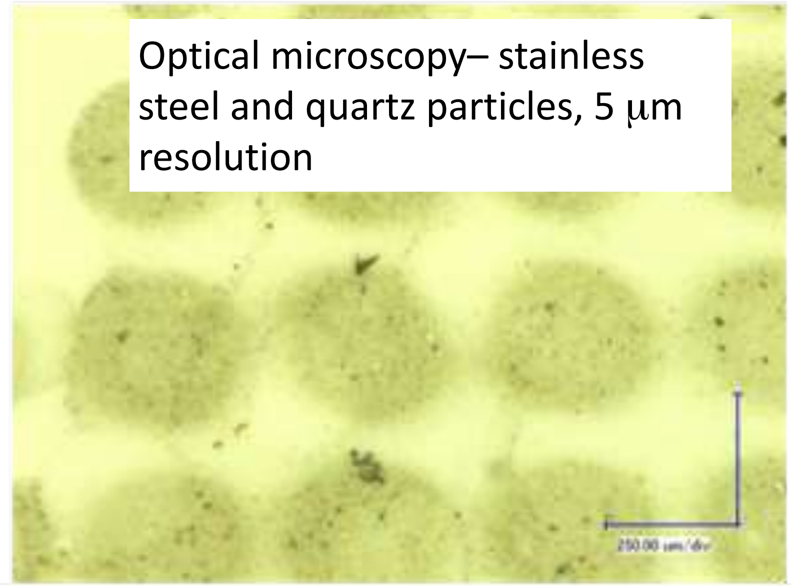


Convection stirring up particulates?

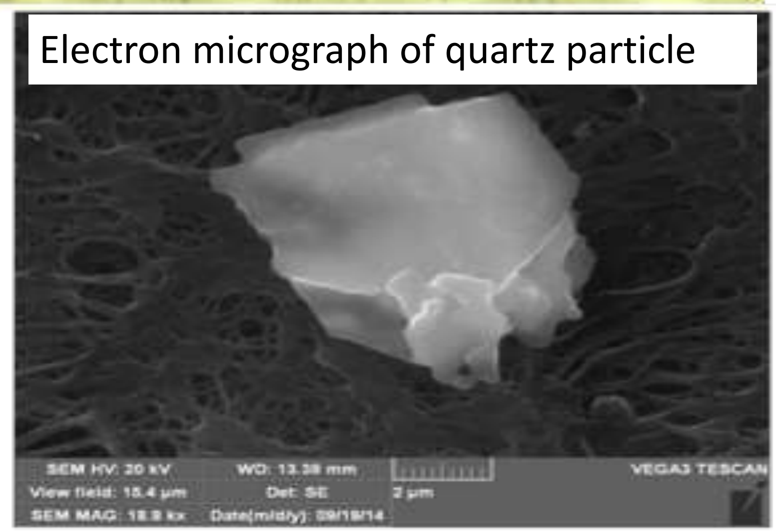
Looking for Dust with Microscopes

- Liquids passed through teflon filters with 200 nm pore size.
- Studied using optical and electron microscopy, X-ray fluorescence, Alpha spectroscopy, mass spectroscopy at PNNL and University of Alberta.
- Result: majority of contamination from quartz and stainless steel materials used in chamber construction.

- PICO-60 sample:
  - 7 μg quartz particles
  - 240 μg stainless steel and iron oxide

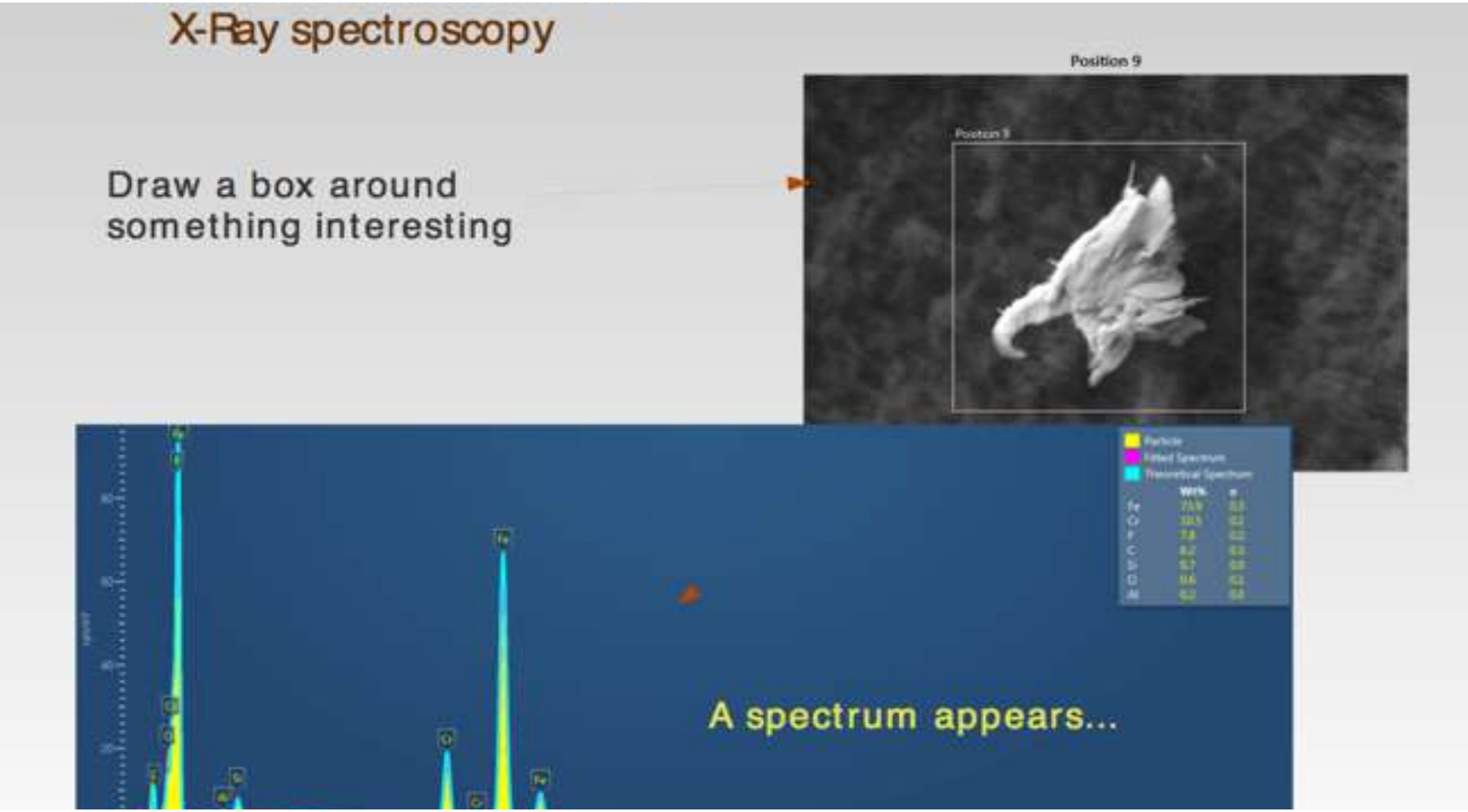


Optical microscopy– stainless steel and quartz particles, 5 μm resolution



Electron micrograph of quartz particle

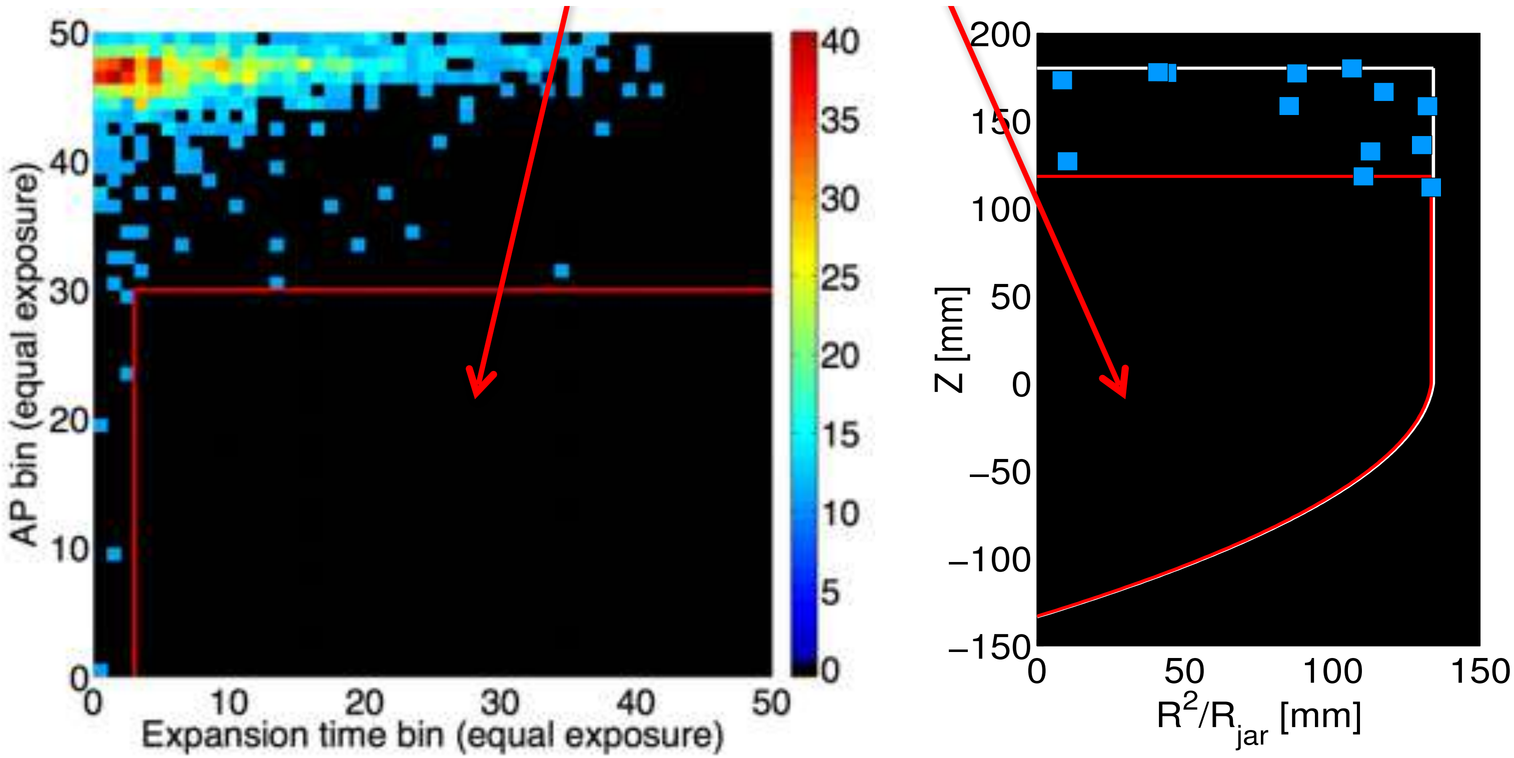
X-Ray Fluorescence Under the Microscope



Optimization of Cuts

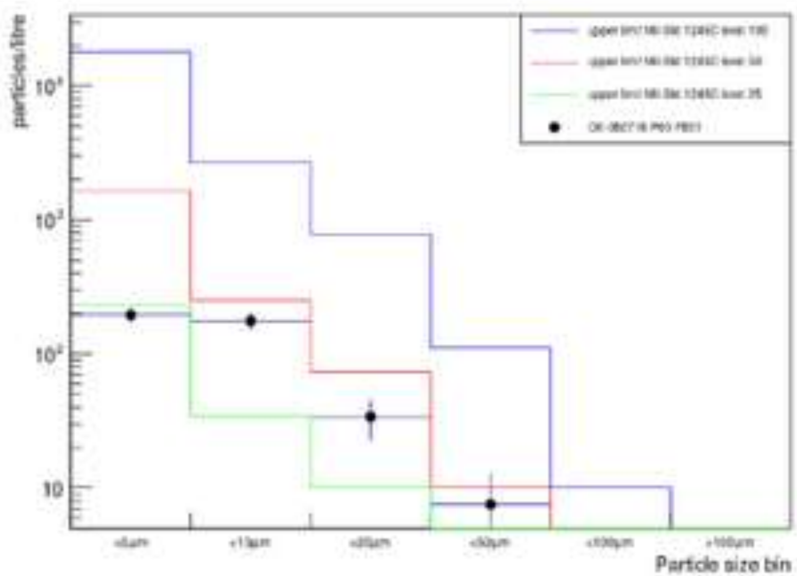
- Combined cuts on position, expansion time and acoustic amplitude yield background free region.
- Monte Carlo methods used to estimate sensitivity.

A background free region (~50% of exposure) by cutting on AP, expansion time, and Z



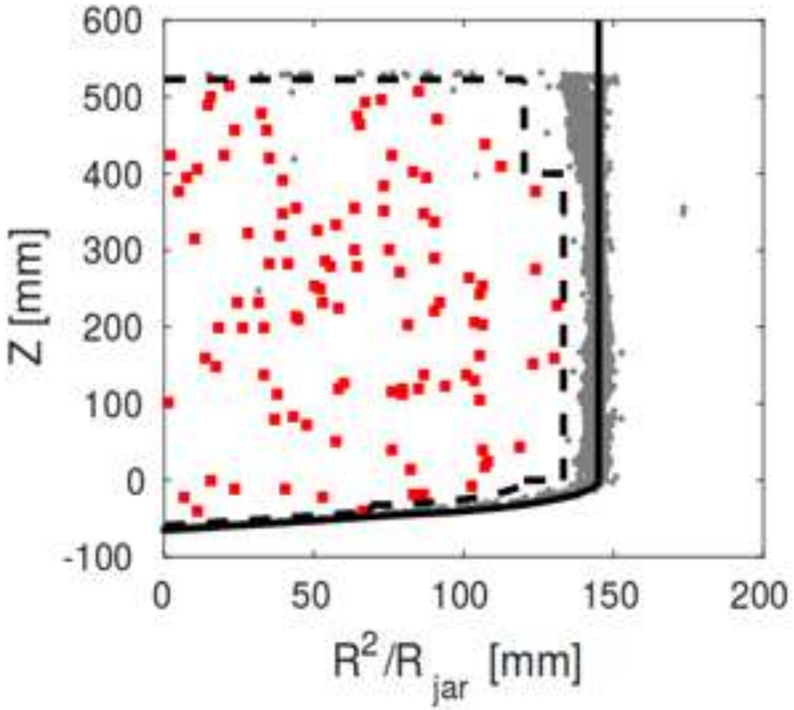
Improved Cleaning Procedures for 2016-2017 Run

- Spray jet cleaning with high purity, hot detergent system.
- Measurements of fluid particle counts for quality control.



Most Recent PICO Result: PICO-60 2017 Run

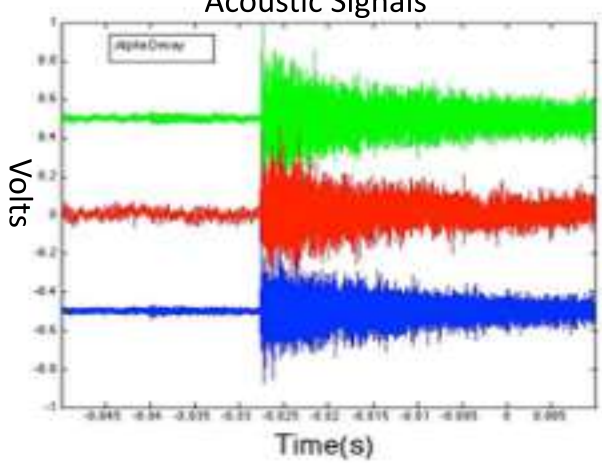
- Data taken November 2016- January 2017.
- Aggressive cleaning to remove Inner Vessel particulate contamination.
- 52 kg of C_3F_8 target liquid (46 kg fiducial)
- 1167 kg-day efficiency-corrected exposure.
- 3.3 keV threshold (14 degrees C, 30 psi)
- 106 single bubble events passing basic data quality and optical fiducial volume cuts.
- Phys. Rev. Lett. 118, 251301 (2017)

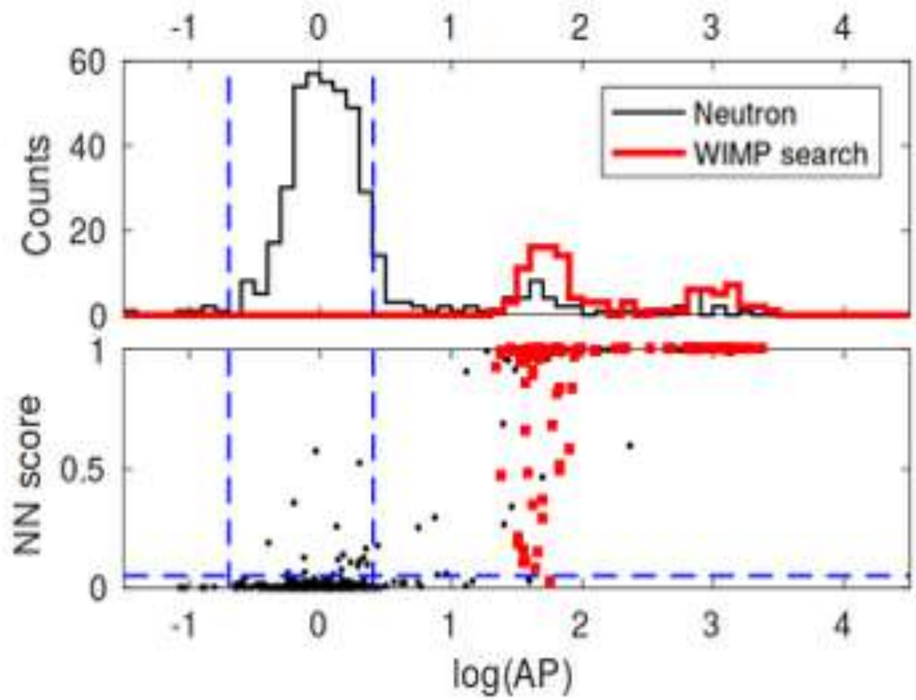


PICO-60 2017 Acoustic Analysis

- Two parameter acoustic analysis:
  - Acoustic Power (AP)
  - Neutral Network score
- Blind analysis- first time for PICO.
- Zero WIMP candidates passing acoustic cuts!

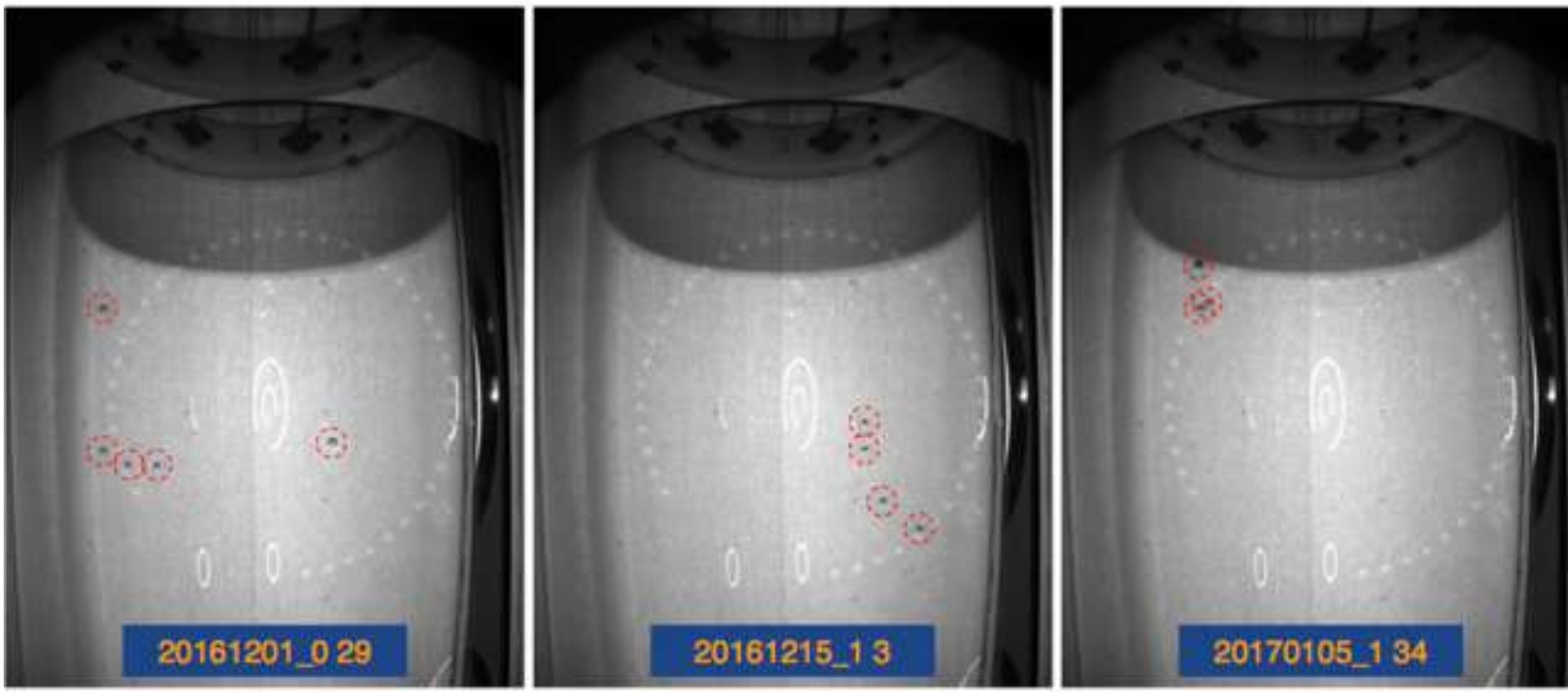
Acoustic Signals



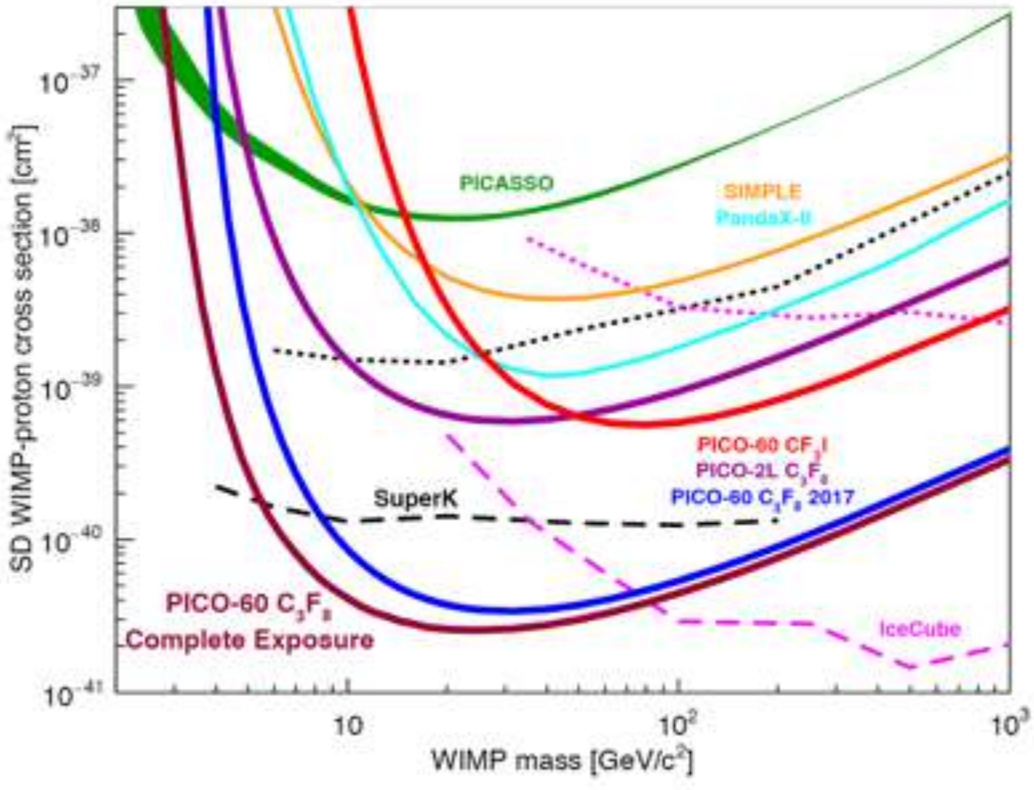


PICO-60 Incipient Neutron Background

- Three multiple scatters observed, no singles.
- Marginally compatible with background model expectation (0.96 multiple, 0.25 single)



PICO 60 WIMP - Proton Exclusion

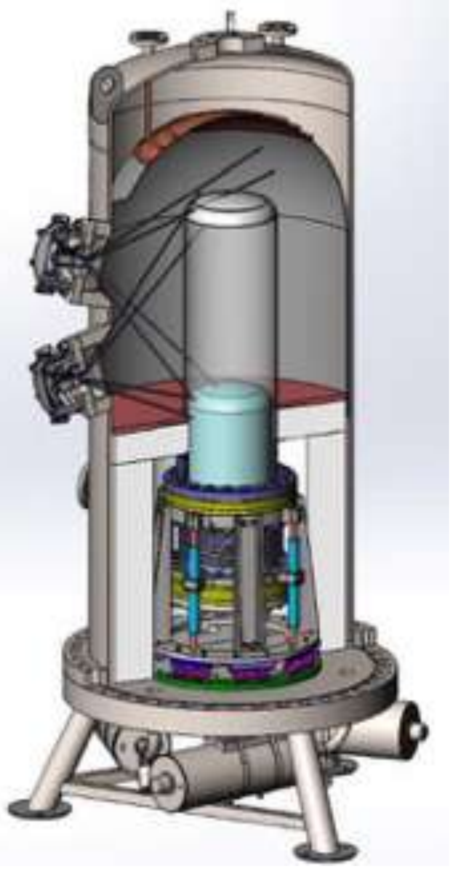


The 90% C.L. limit on the SD WIMP-proton cross section from PICO-60 C_3F_8 blue, along with limits from PICO-60 CF3I (red), PICO-2L (purple), PICASSO (green), SIMPLE (orange), PandaX-II (cyan), IceCube (dashed and dotted pink), and SuperK (dashed and dotted black)

C. Amole *et al.*, Phys. Rev. Lett. 118, 251301 - new paper on archive soon (R. Neilson's talk)

PICO-40L: A ”Right Side Up” Bubble Chamber without Water

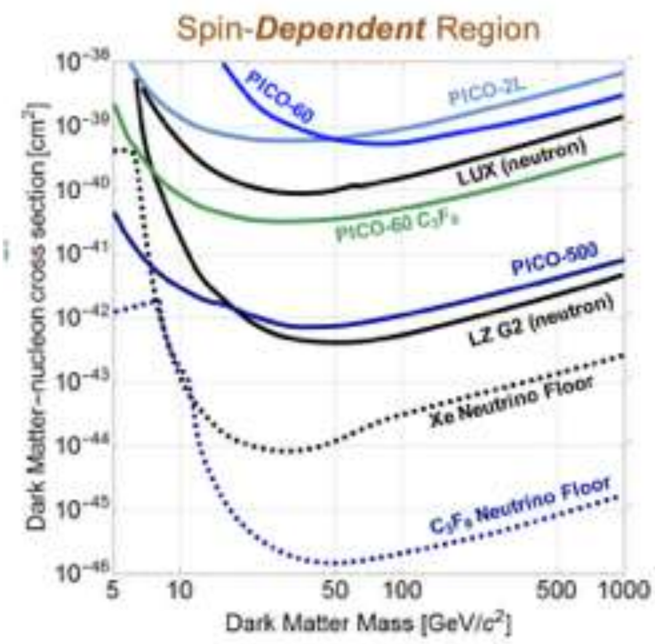
- New design concept eliminates water buffer layer from chambers.
  - Water/ target liquid interface traps contamination.
  - Water coating of particulates suspected to play a role in bubble nucleation mechanism.
- Larger pressure vessel increases separation between radioactive construction materials and fiducial voluum.
- Goal: background-free 15 ton-day physics run.
- To be commissioned in Summer 2018.

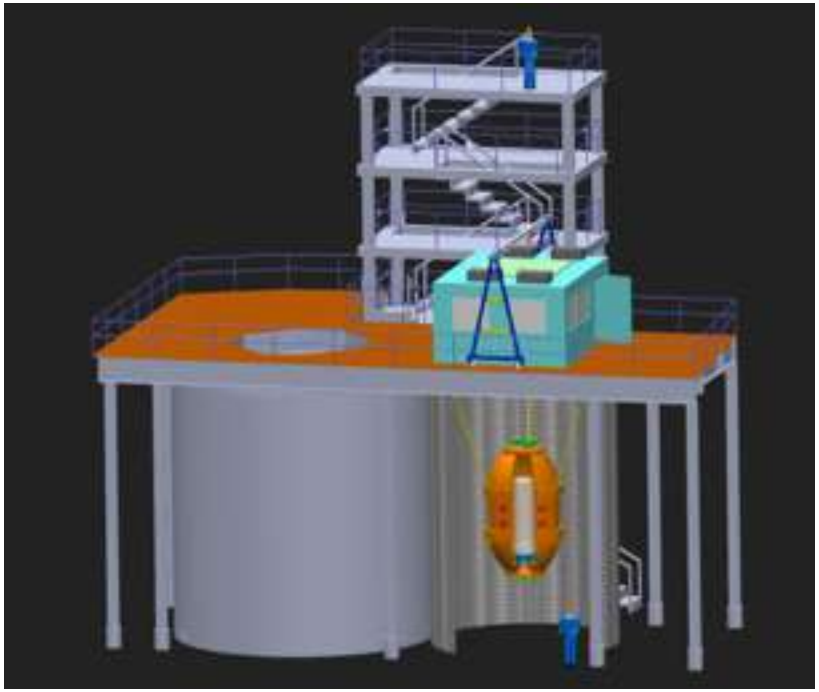


PICO-40L Under Construction

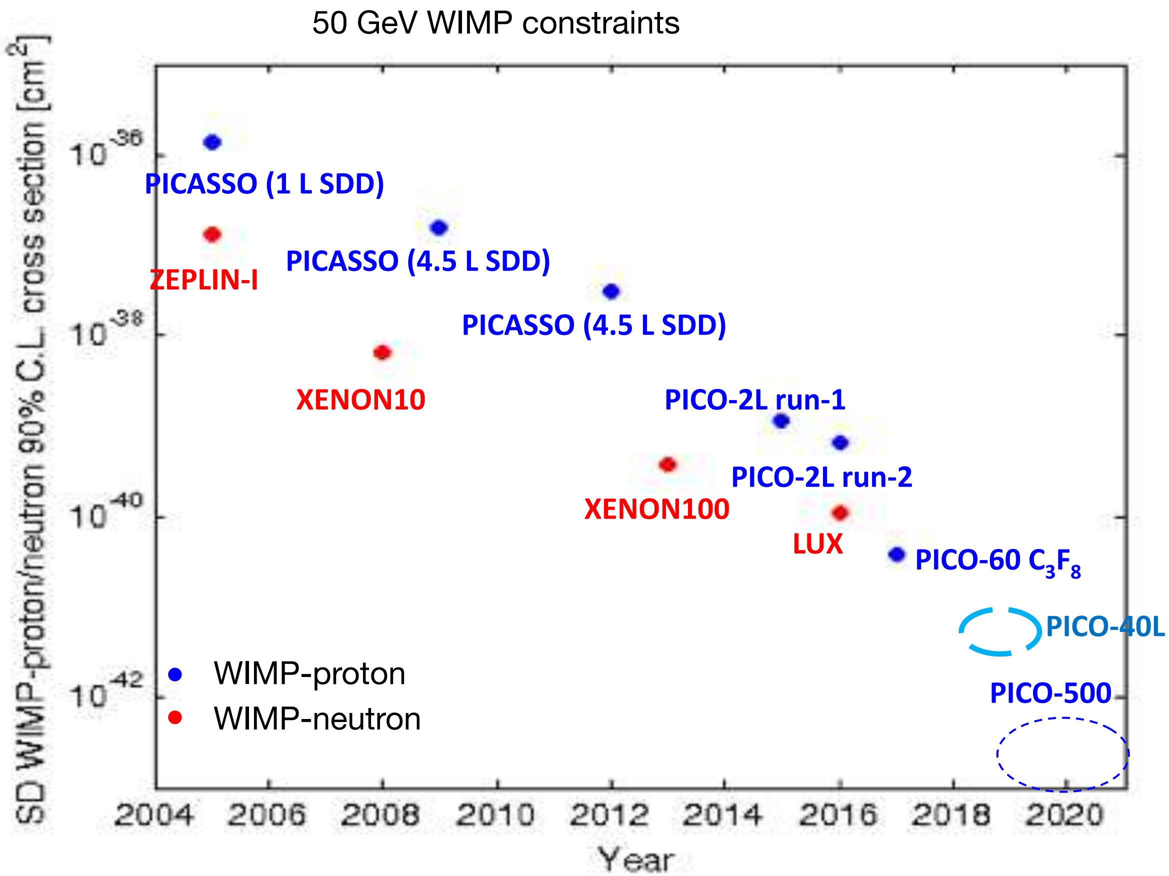
PICO-500

- PICO-500 proposal approved in 2017 by Canada Foundation for Innovation (CFI).
- Detector final design is underway, with many concepts tested in PICO-40L





Progress of PICASSO/COUPP/ PICO Program



PICO

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D. Maurya, S. Priya, Y. Yan

Northeastern Illinois University
O. Harris

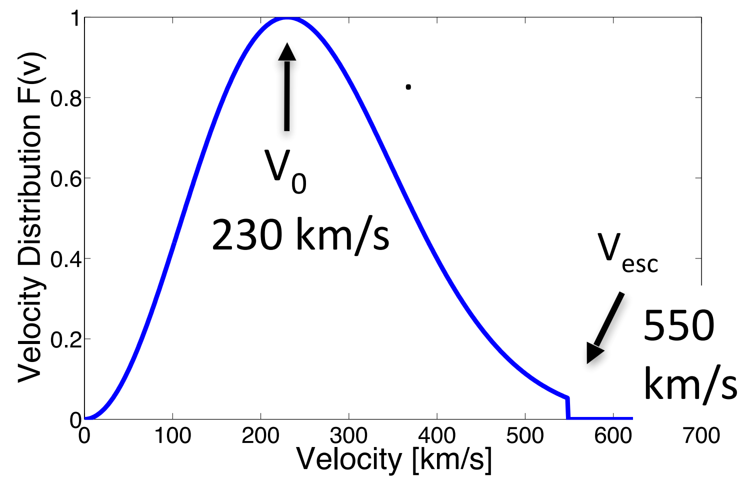
IF Instituto de Física
E. Vázquez-Jáuregui

Backup slides

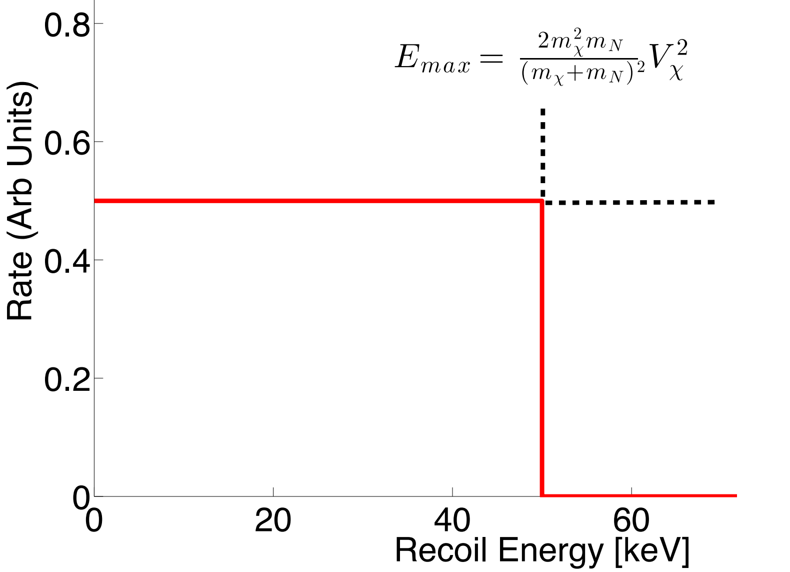
Nuclear Recoil Signal from WIMPs-Ingredients

- WIMP spectrum in a detector is obtained by convolution of monoenergetic detector response with modeled dark matter velocity distribution.
- Standard dark matter density is 0.3 GeV/cm^3

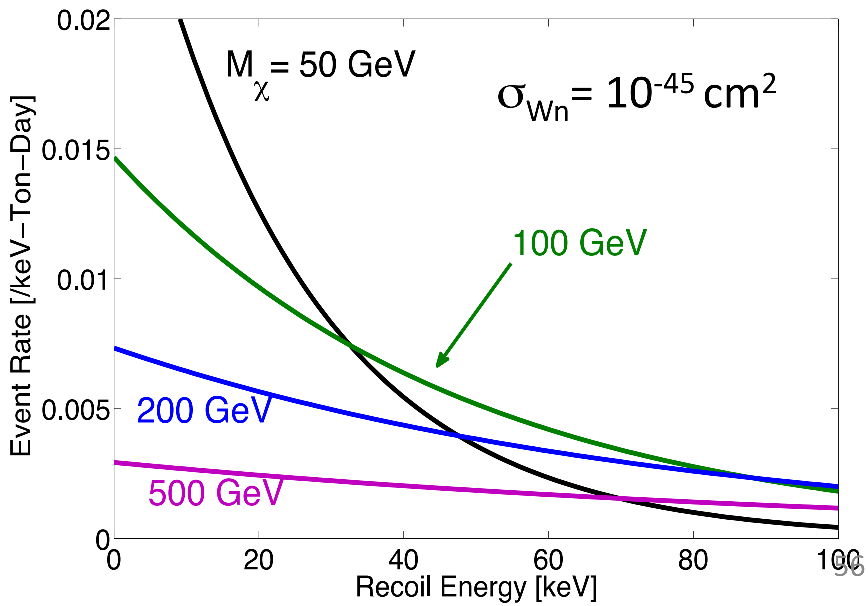
Standard Halo Model WIMP Velocity Distribution



Response to single velocity component

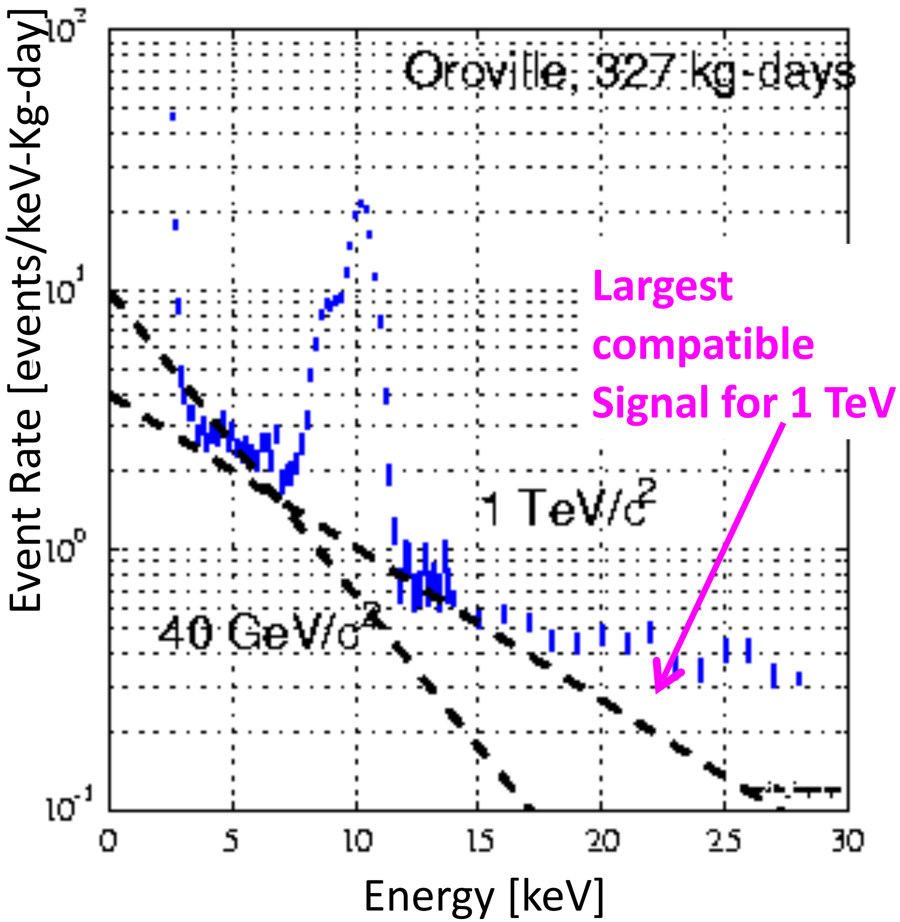


Energy Spectrum for WIMP recoils on Germanium

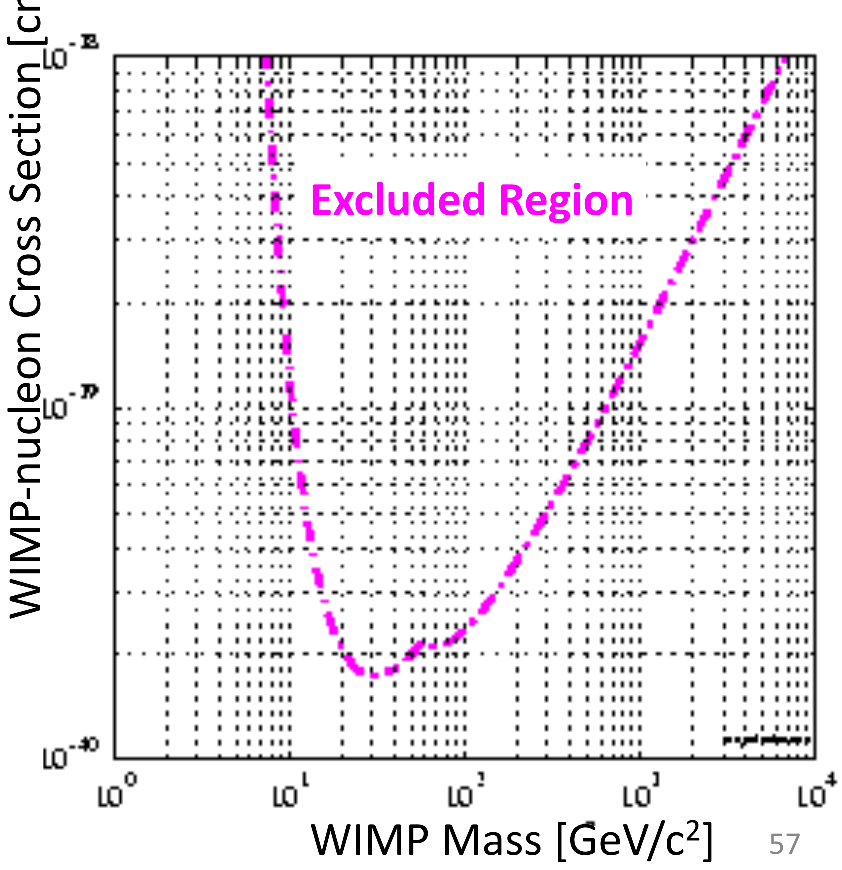


Construction of Sensitivity Plots

- Often in this field backgrounds cannot be accurately modeled and subtracted.
- For any possible WIMP mass, the data allow a maximum possible signal amplitude,
- Excluded region in Mass * Cross Section plane is the envelope of these amplitudes.
- Figures below illustrate trivial case where spectrum is known with high statistical accuracy.
  Other techniques have been developed for the case of a sparse spectrum.



Assume local WIMP density 0.3 GeV/cm³



Background Discrimination: Possible Observables

- Pulse shape differences in scintillation light in noble liquids or crystals. DarkSide, DEAP, KIMS, DAMA.

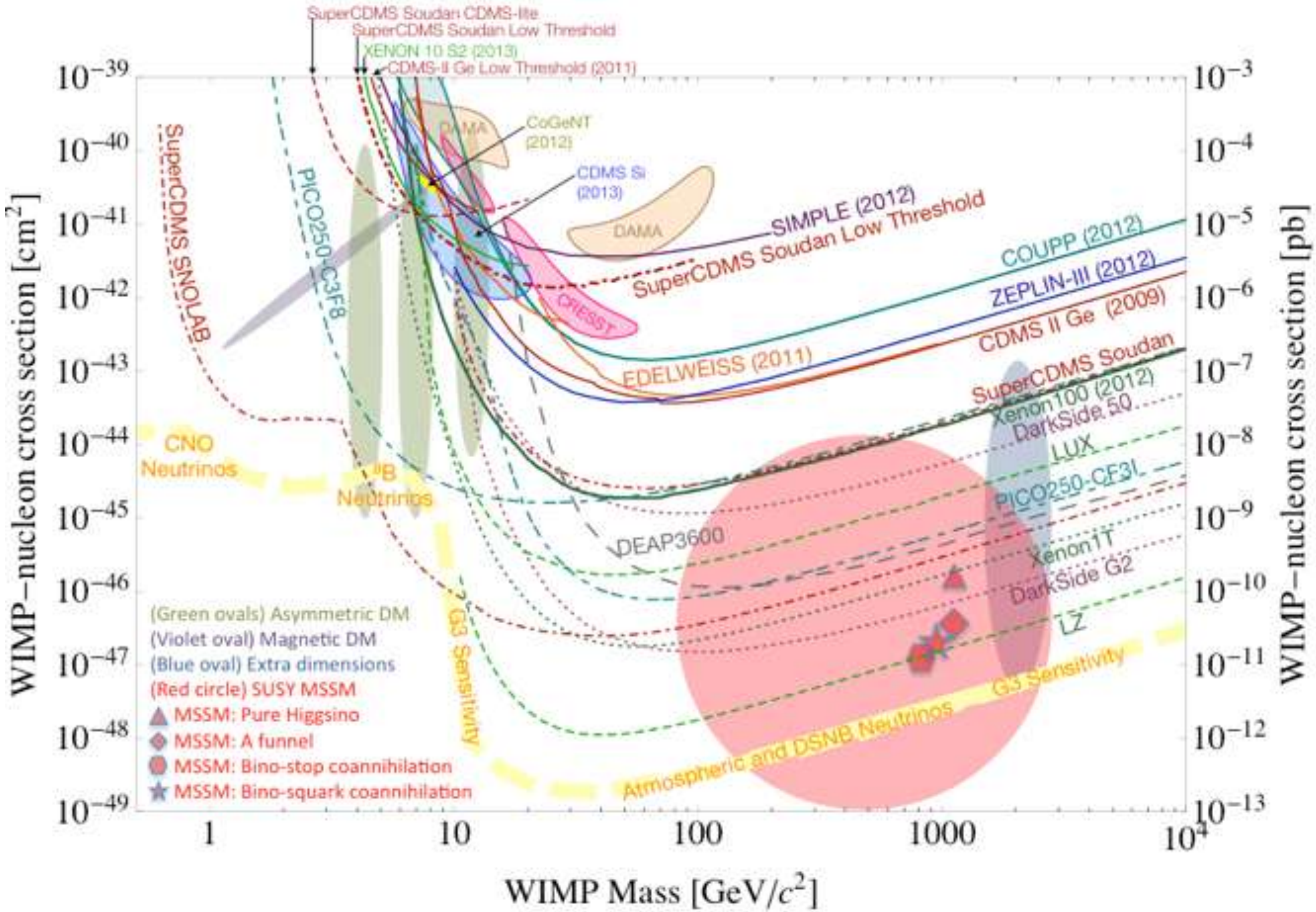
- Ratio of ionization to scintillation in liquid noble gases. LUX, LZ, Xenon, PANDA-X

- Ratio of ionization or scintillation to total deposited heat energy in cryogenic calorimeter. CDMS, EDELWEISS, CRESST.

- Efficiency for bubble formation in superheated liquids. COUPP, PICO, PICASSO, SIMPLE.

- Annual modulation in spectrum due to motion of Earth around the Sun. DAMA

- Track ion charge density in gas drift chamber. Daily modulation in direction of ion tracks. DMTPC, DRIFT



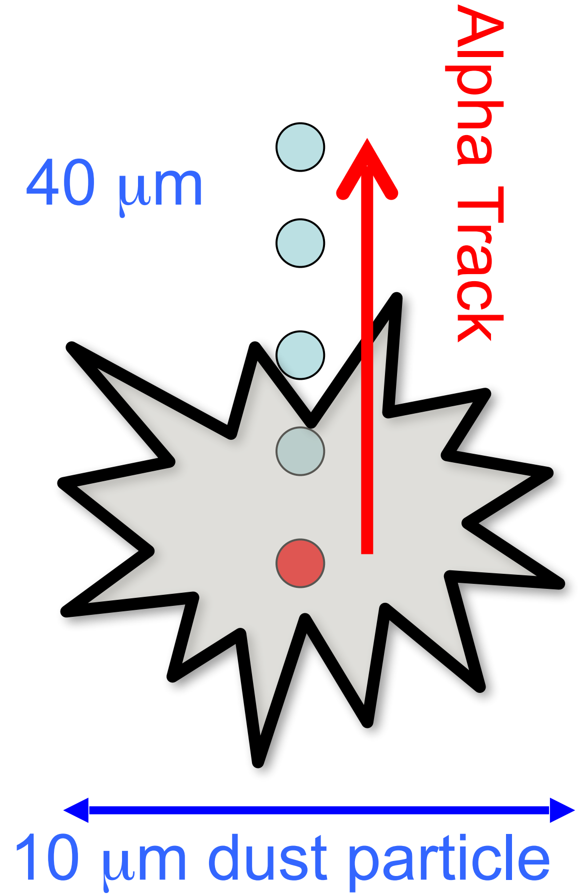
SNOWMASS 2013 Cosmic Frontier Working Group

Possible Mechanism for Generating Events-Embedded Alpha Emitters

- When an alpha decay occurs in liquid, alpha particle and daughter nucleus recoil contribute about equally to amplitude of acoustic signal → alpha decay acoustic amplitude approximately 2 x nuclear recoil from a neutron or WIMP.

- If the alpha-emitting isotope is embedded in solid material <10 microns thick, alpha particle can escape to make a bubble, but nuclear recoil is hidden in the solid. Acoustic amplitude similar to nuclear recoil.

- Ongoing R&D: We are attempting to demonstrate suppressed acoustic signal from alpha activity in particulates with test chambers at Northwestern, Queen's University.

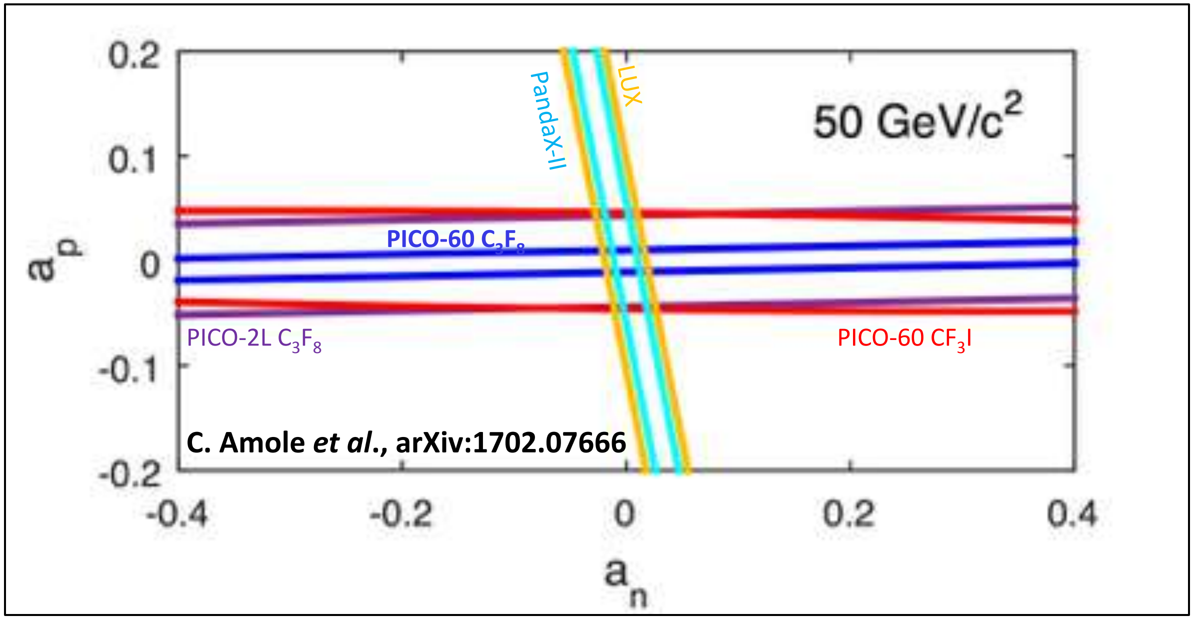


PICO-60 2013-2014 Physics Run

- Detector began operating in April ‘13. First physics data in June.
- Target: 37 kg CF_3I. Optimal for sensitivity to spin-independent WIMP-nucleon couplings.
- High live time fraction, growing to >90% by end of run.
- 5000 kg-days “WIMP exposure” from June ‘13 to May ’14.
- Several different operating modes explored: fixed threshold points (temperature, pressure), threshold scans from 7 keV to 30 keV.
- Extensive neutron calibration data.
- Run was ended in May ’14 to allow inspection of detector and fluids for particulate contamination.

Nucleon Coupling Limits

Consider spin-dependent coupling to proton and neutron

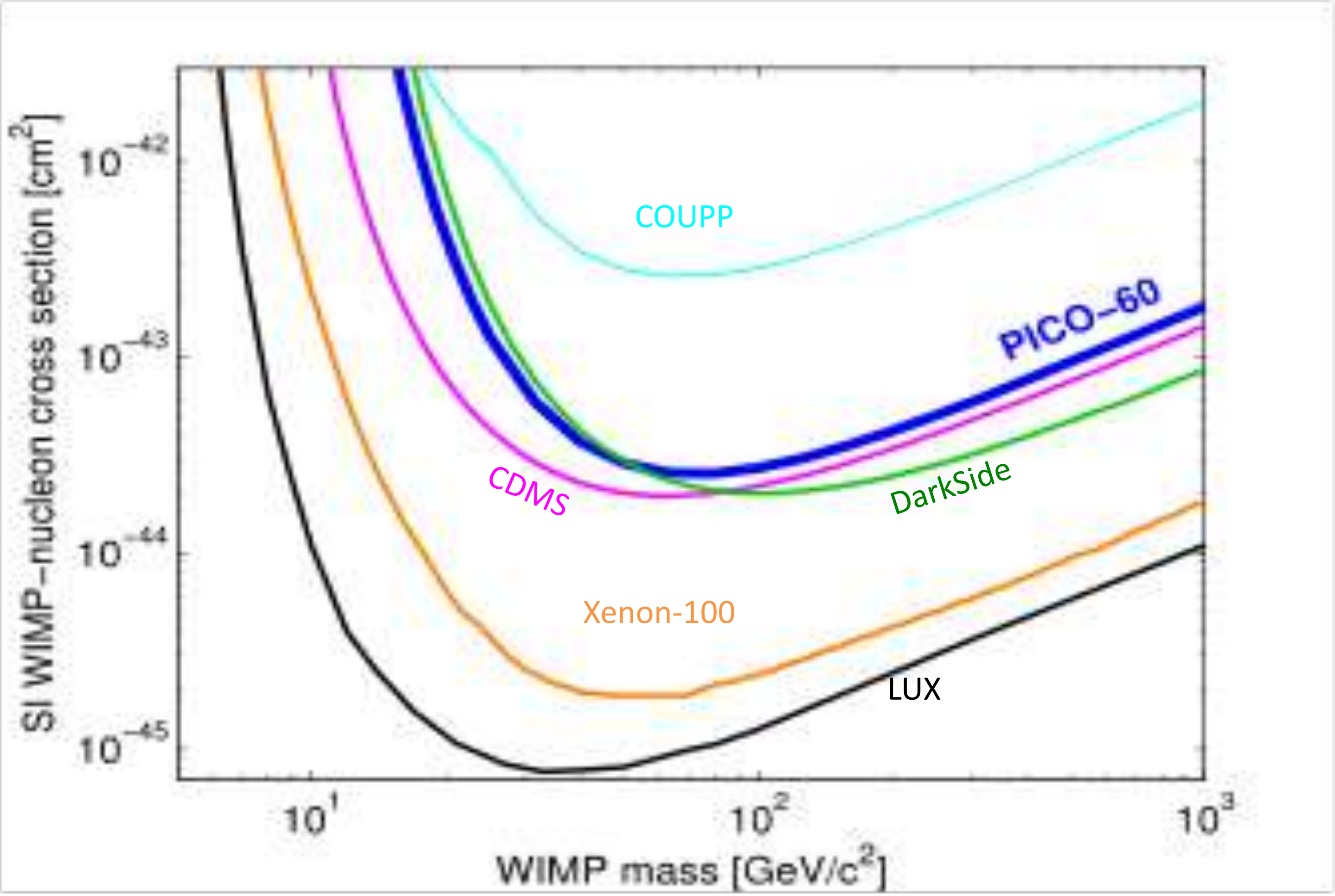


See Tovey for details:

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

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

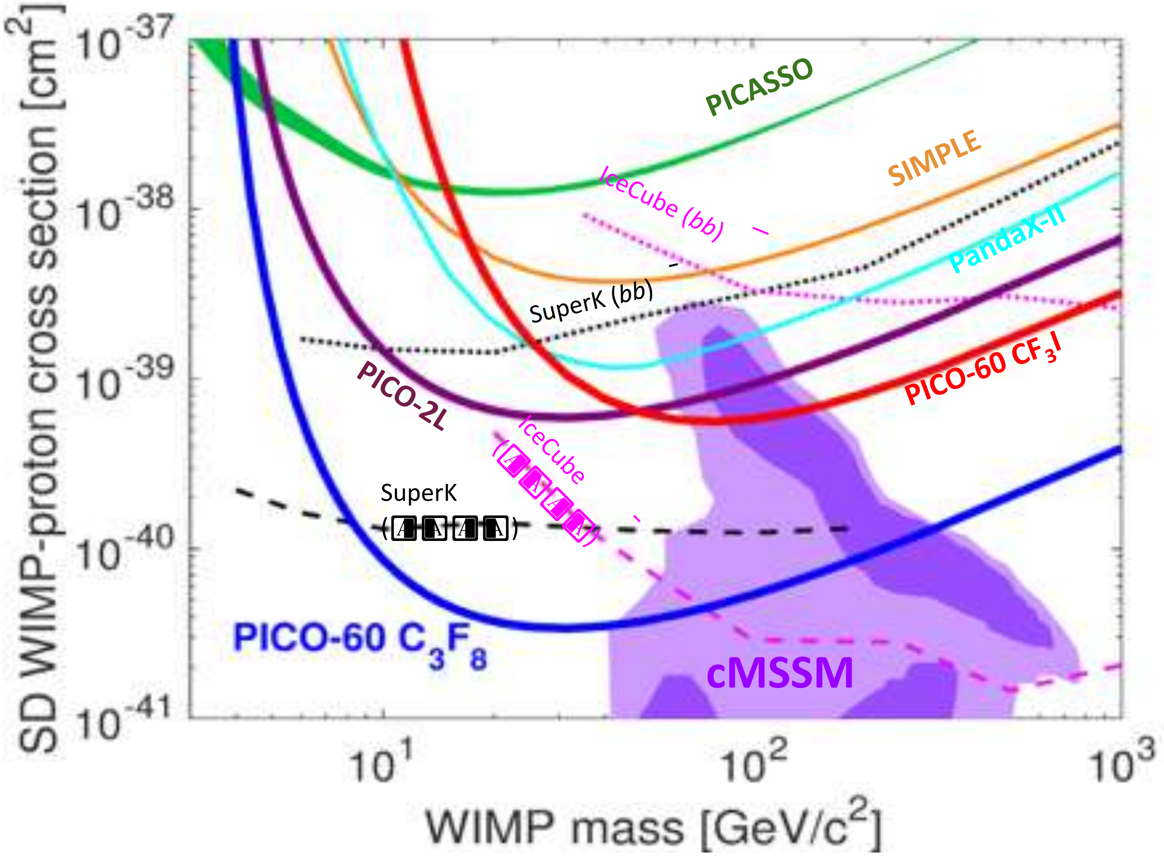
Spin-Independent WIMP Scattering Limits from PICO-60 2013-2014 Run



The Future

- PICO-60 2016-2017 Run
  - Switch from CF_3I to C_3F_8 target to enhance spin-dependent sensitivity.
  - New techniques to reduce particulate load, including semi-continuous filtration of liquids during the run.
  - Potential for 2 orders of magnitude improvement in sensitivity, depending on resulting backgrounds.
- R&D: Development of single-fluid bubble chamber design.
  - Eliminate the water/ target liquid interface where “dirt” accumulates.
  - Could be the basis for future experiment with ton- scale target mass- our long term goal.

2017 PICO Result: Factor of 17 Improvement in Spin-Dependent Sensitivity



Spin-independent Limits

- Iodine (high Z) is good for heavy WIMPs.
- Fluorine target gives better sensitivity to lighter WIMPs.
- 3.3 keV nuclear recoil threshold– still high compared to what has been achieved with cryogenic detectors, CCDs and liquid xenon/ argon.