Searching For Dark Matter with COUPP

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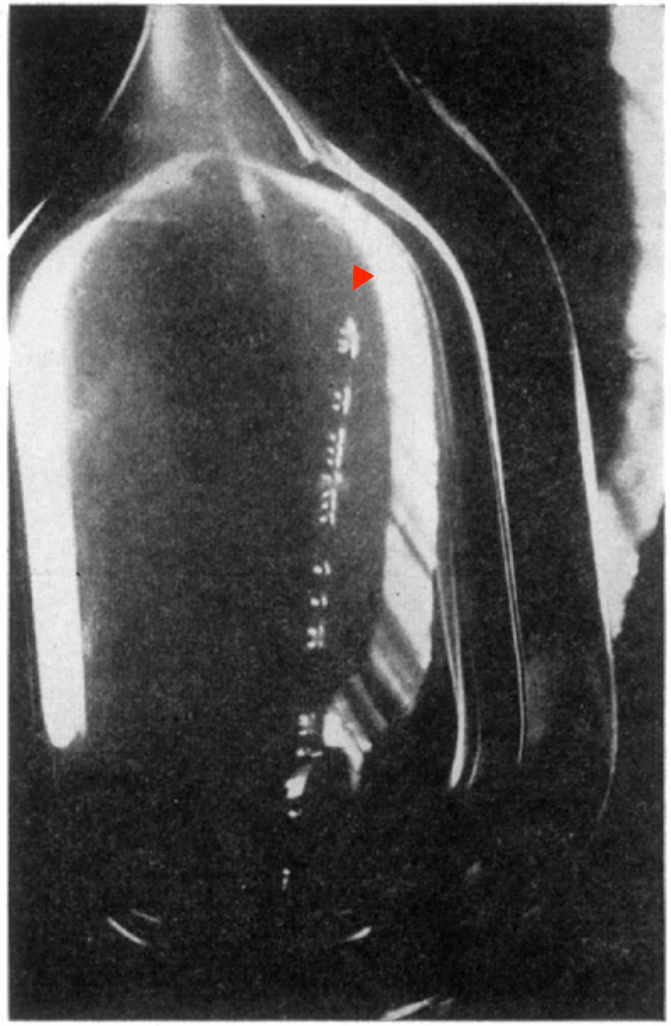
Fermilab Dark Matter Involvements

- CDMS– Cryogenic detectors
- DarkSide- Liquid Argon TPC
- **COUPP- Bubble Chambers**
- DAMIC- CCDs

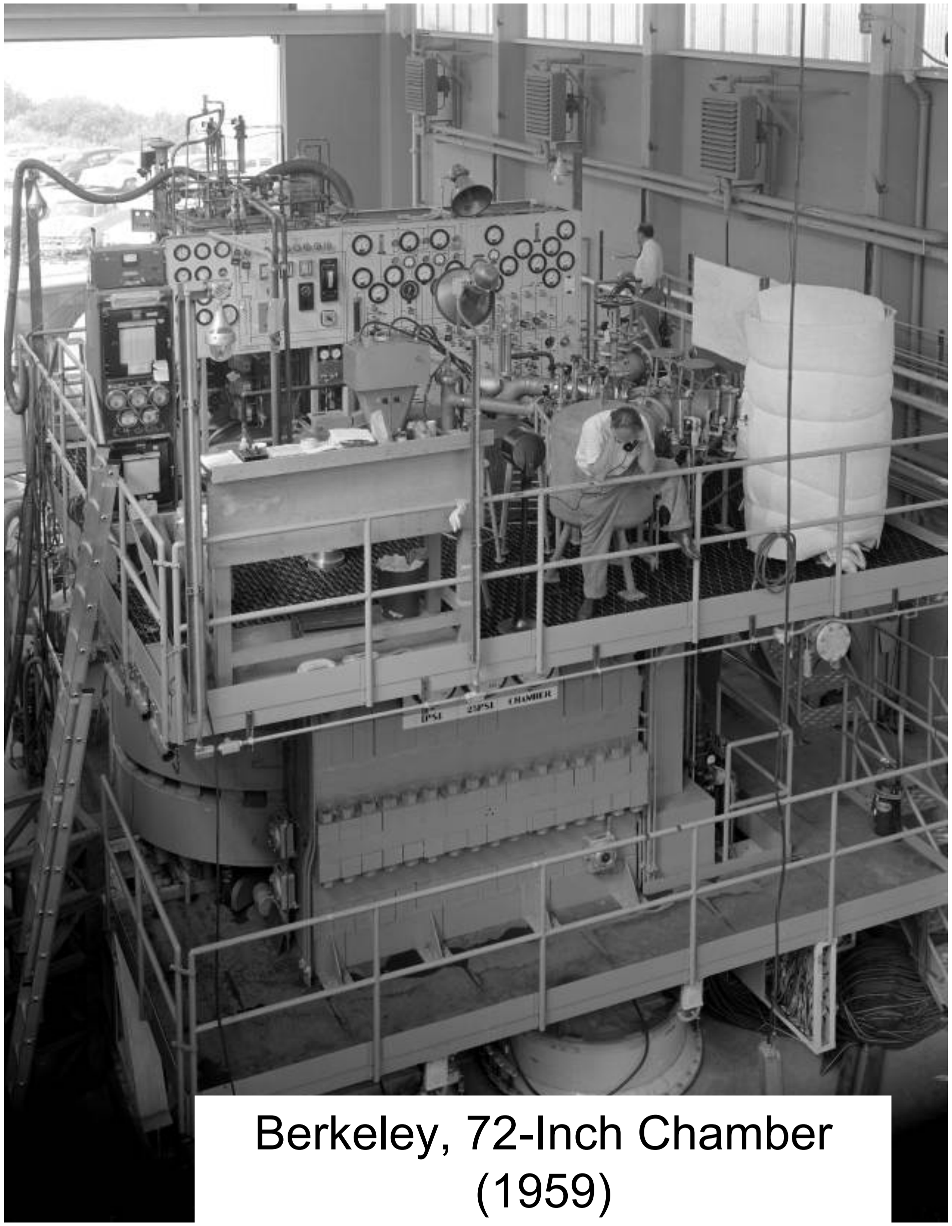
First Bubble Chamber (Glaser, 1952)

Cosmic ray



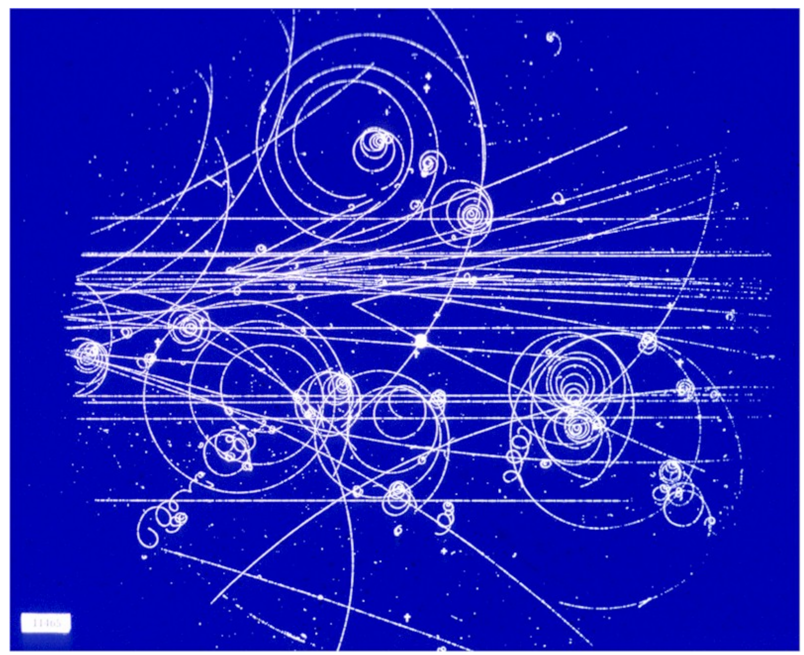
1-cm diameter glass tube, filled with ether

The Bubble Chamber Age: 1952-1987



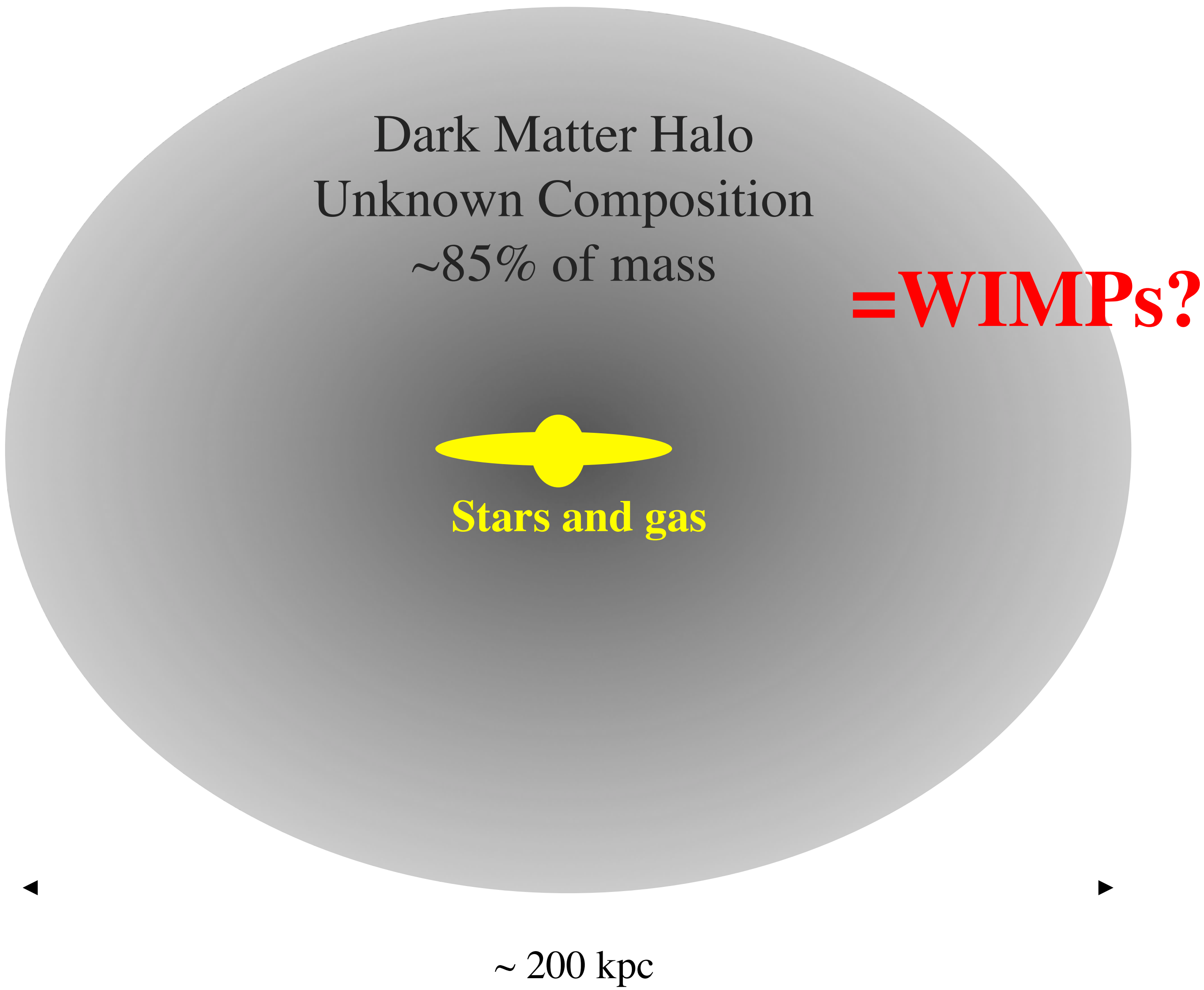
Berkeley, 72-Inch Chamber (1959)

- Astonishing growth in size and sophistication driven by national accelerator labs.
- Many discoveries in 60’s-70’s.
- Bubble chamber images still define particle physics in popular culture.
- Bubble formation process too slow to keep up with interaction rates in modern experiments.



New Role: Lawn Ornaments (1987- present)

Cartoon of a Galaxy



The Experimental Challenge

- Energy transferred by WIMP to a target nucleus is low.
  - ~10 keV, similar to an X-ray
  - Recoil track has a length of only ~100 nm in a solid material

- Event rate is low.
  - Cross sections for nuclear scattering $<10^{-43}$ cm^2
  - Implies < 0.01 events per kg of target per day

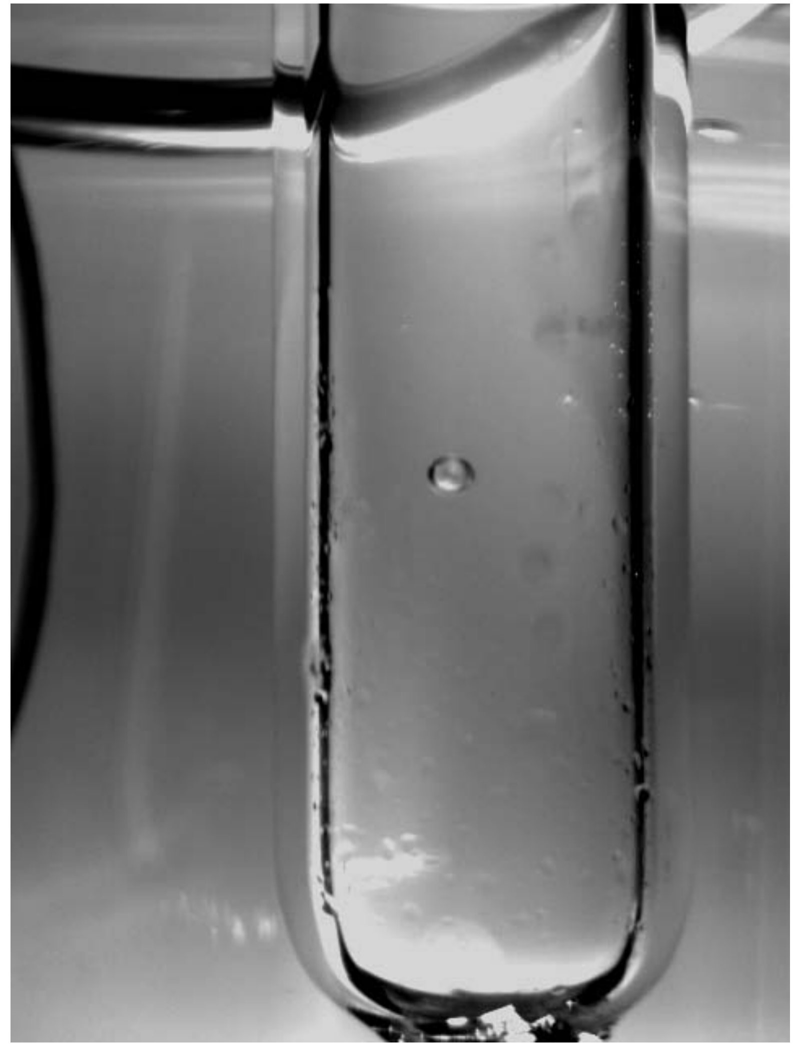
- Backgrounds from environmental radioactivity are high.
  - Trace levels of radioactive isotopes in environment and detector construction materials.
  - ~10^2/kg-day with state-of-the-art shielding
  - _Most of these events are due to scattering on electrons (Compton, photoelectric scattering), while the signal is a nuclear recoil.

We need a technology which is <u>scalable</u> to large target mass and has <u>good background rejection for electron-like events.</u>

Basic idea:

• Look for single bubbles produced by WIMP-nucleus recoils.

• Theory of bubble chamber operation (Seitz, 1957) shows that low energy thresholds can be reached for single bubble production.



Why Bubble Chambers?

1. **Large target masses would be possible at relatively low cost.**
   - Multi ton chambers were built in the 50's- 80's.
2. **An exciting menu of available target nuclei.**

   ***No liquid that has been tested seriously has failed to work as a bubble chamber liquid* (Glaser, 1960).**

   - Most common: Hydrogen, Propane, but also "Heavy Liquids": Xe, Ne, CF_3Br, CH_3I, and CCl_2F_2.
   - Good targets for both spin- dependent and spin-independent scattering.
   - Possible to "swap" liquids to check suspicious signals.
3. **Backgrounds due to environmental gamma and beta activity can be suppressed by running at low pressure.**
4. **Backgrounds due to neutrons can be tagged by observation of multiple scattering.**
5. **Backgrounds due to alpha activity can be rejected with acoustic measurements.** **New!**

Technology Choices for Dark Matter Detection

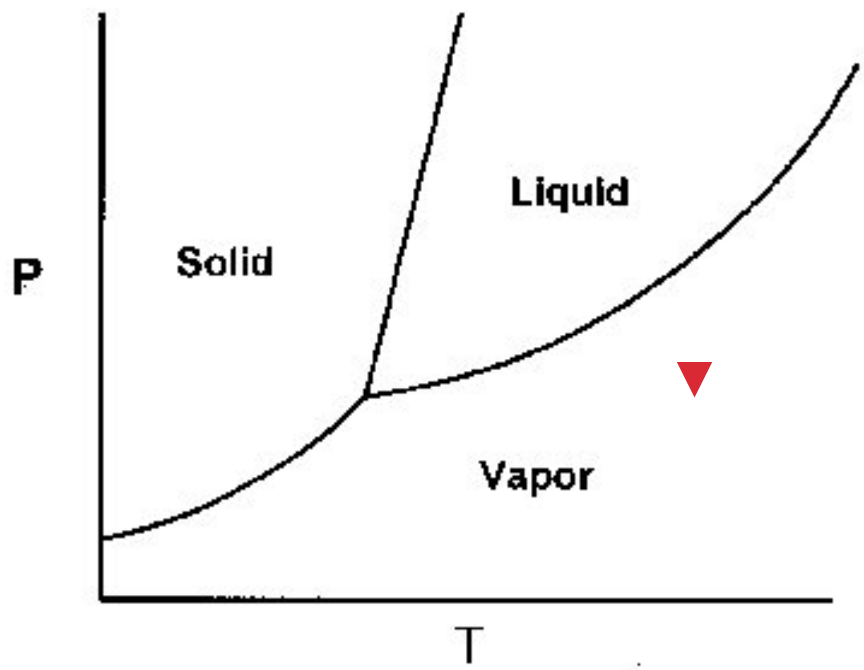
Technique	Good features	Bad features
Cryogenic detectors *CDMS, Edelweiss*	Excellent to good (>99.9%) discrimination for alpha, beta, gamma	High cost, difficult to manufacture, scale up
Xenon TPC + Scintillation *Xenon, Lux*	Scalability, Easy cryogenics, high Z, good position resolution	Modest discrimination for beta, gamma (99%), expensive
Argon, scintillation only *DEAP*	Excellent discrimination for alpha, beta, gamma	Radioactivity of Ar-39
Argon TPC + Scintillation *WARP, ARDM*	Best discrimination	Radioactivity of Ar-39?
Bubble chamber *COUPP* *PICASSO*	Low cost, easy to scale best spin target (F) gamma discrimination, alpha discrimination, neutron tagging	? To be determined
Drift chambers *DRIFT*	Directionality!	Small target mass

Why Do Liquids Not Always Boil When They Pass into the "Vapor" Part of the Phase Diagram?

- In the "vapor" region, the equilibrium state is a vapor.
- But liquids have **surface tension**, so there is an energy cost to create a bubble.
- This energy barrier may be greater than *kt*.

➡ **a metastable ("superheated") liquid state may continue to exist for some time.**

- The liquid will boil violently once the energy barrier to the vapor phase is overcome.



Bubble Nucleation by Radiation

(Seitz, "Thermal Spike Model", 1957)

particle

$P_{external}$

P_{vapor}

R_c

- 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, while smaller bubbles will shrink to zero.
- Boiling occurs when energy loss of throughgoing particle is enough to produce a bubble with radius > R_c

Surface tension σ

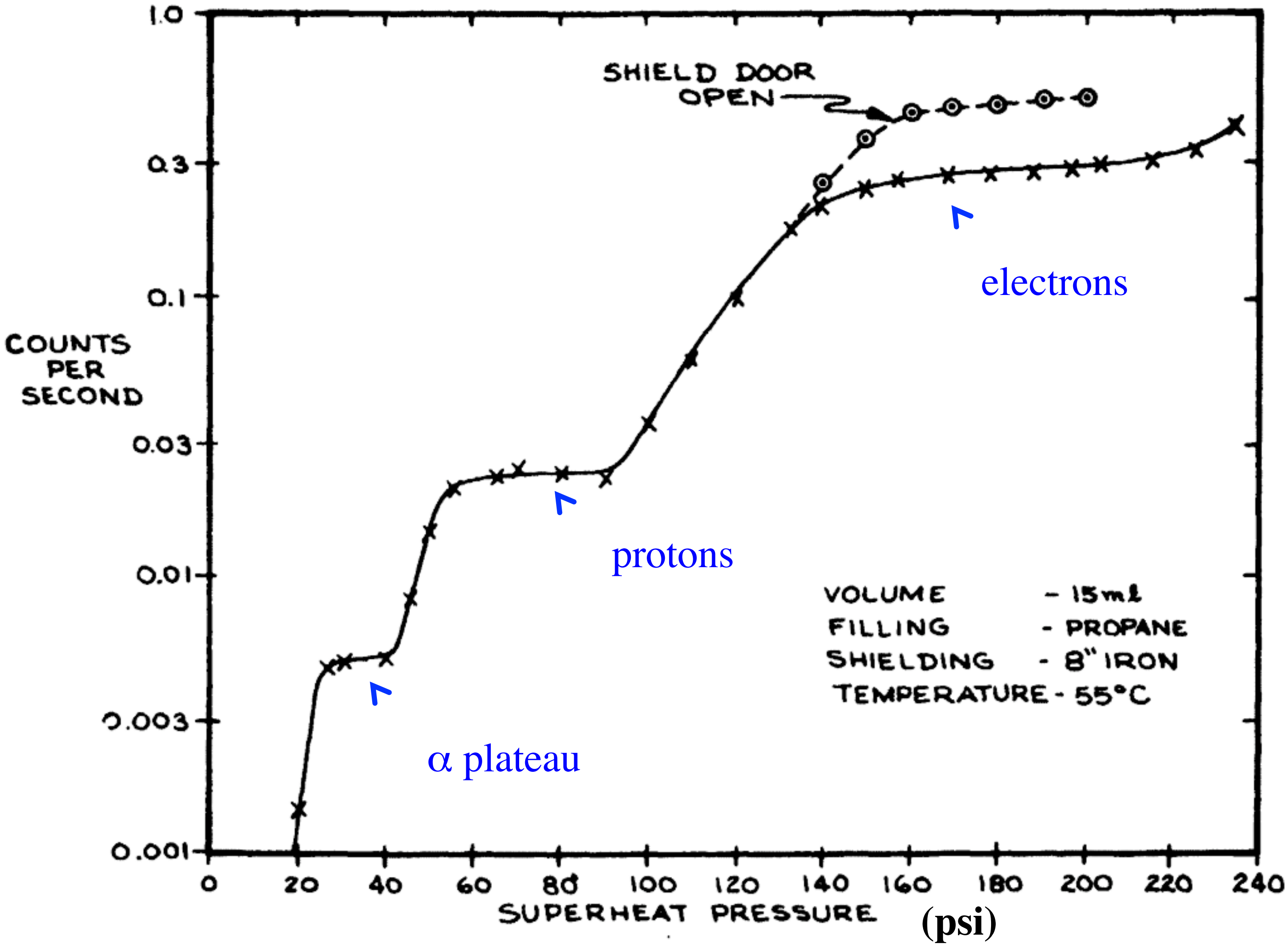
E_c

Work

R_c

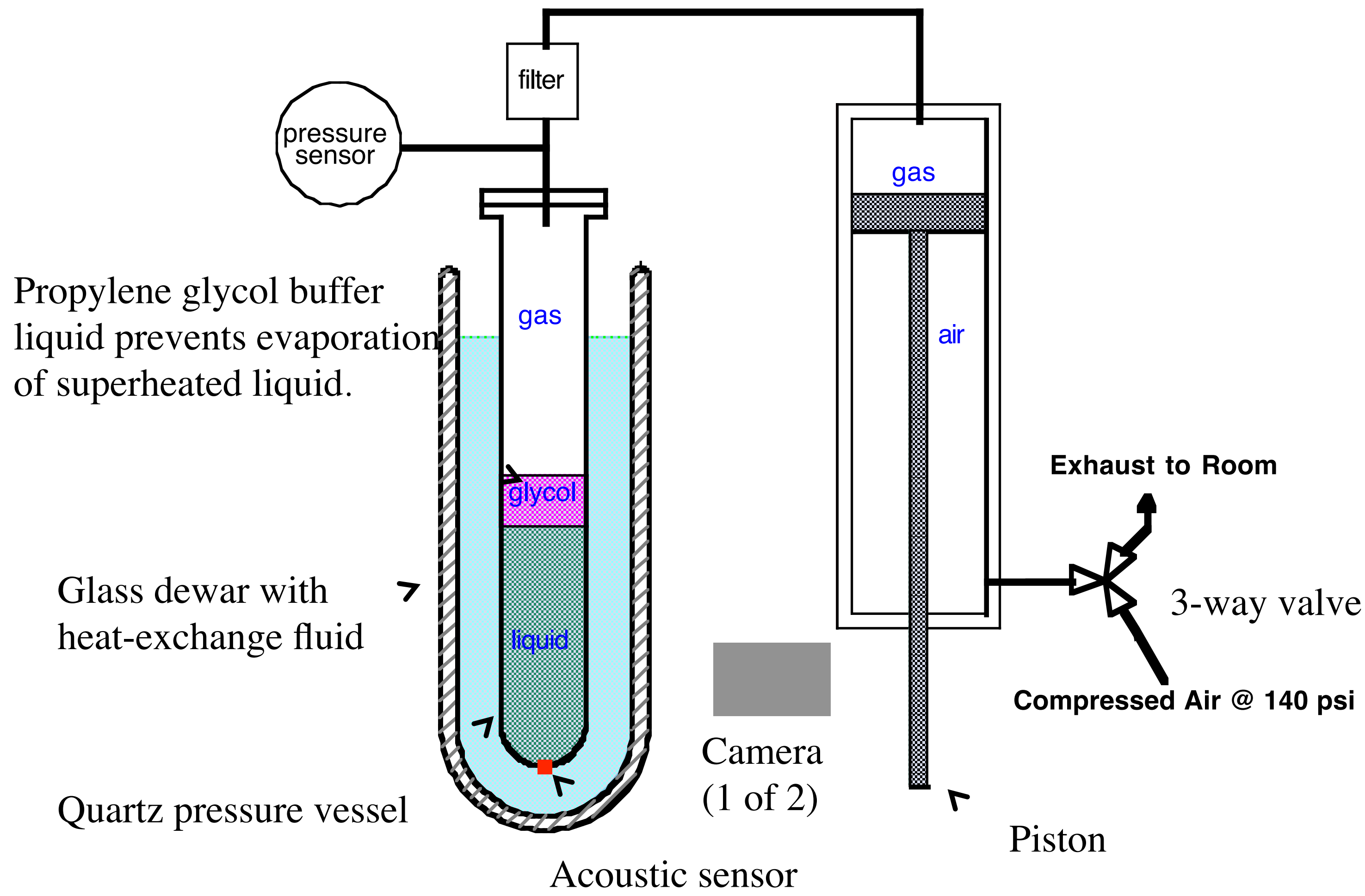
Radius

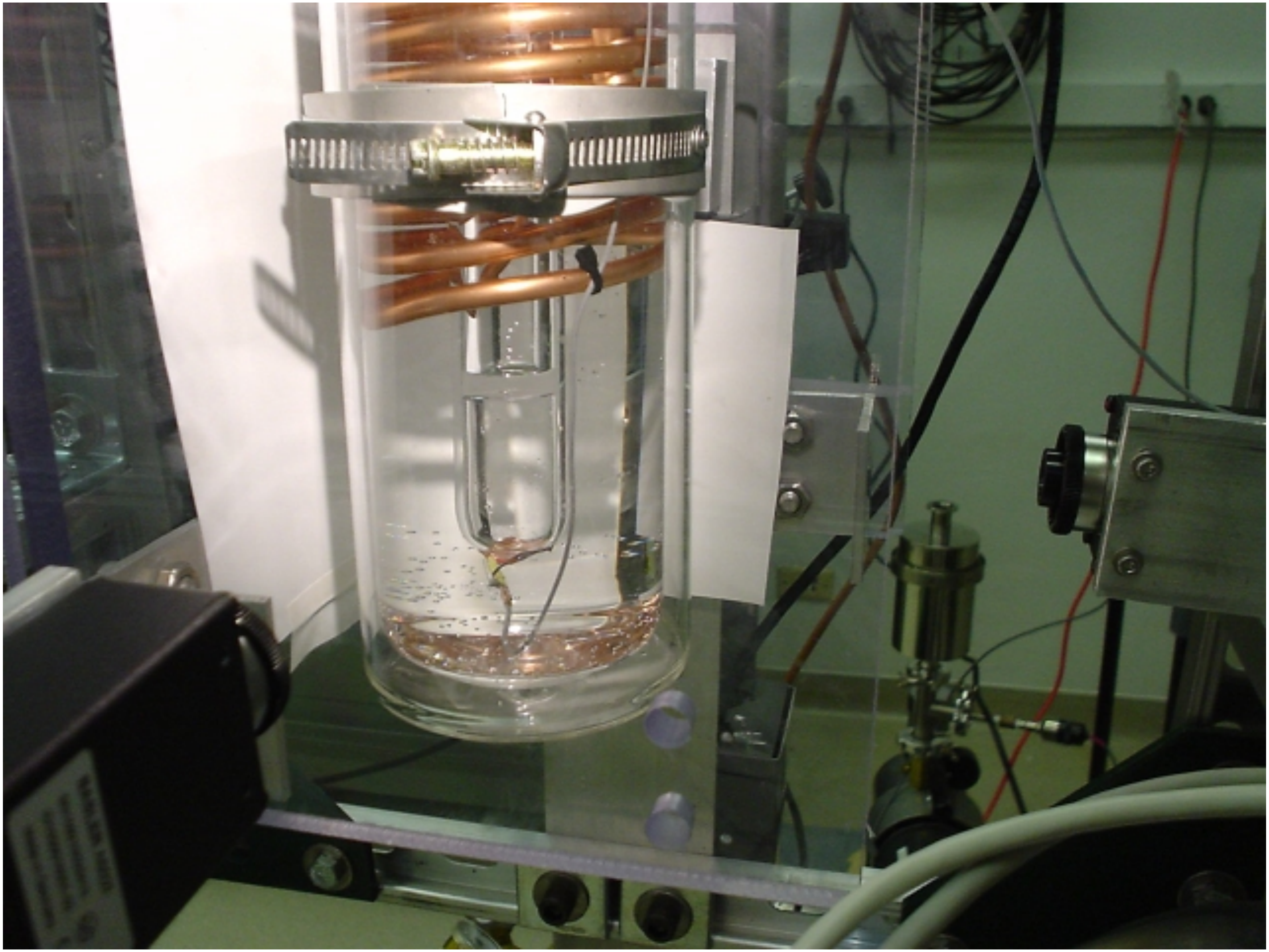
Background Discrimination in Bubble Chambers



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

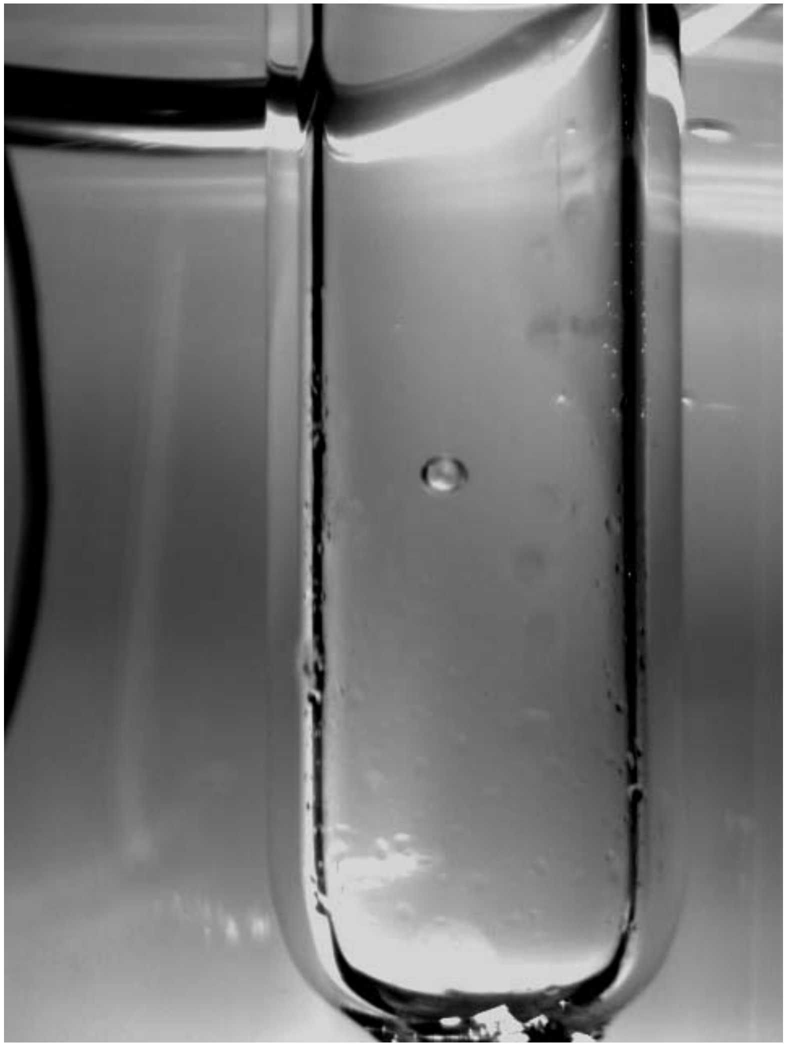
Prototype Dark Matter Detector (2003)





Bad surface

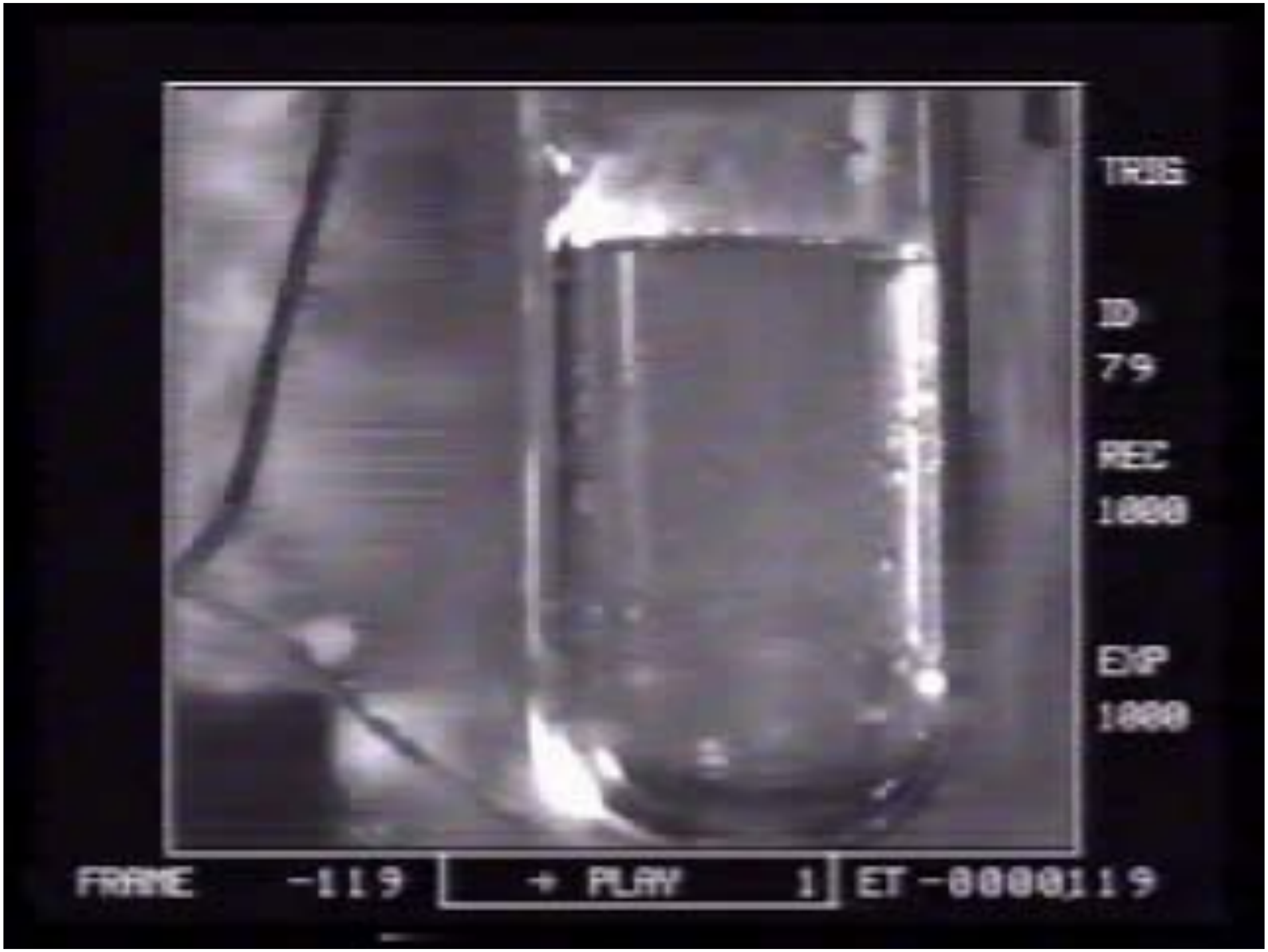
Good surface



High Speed Bubble Chamber Movie

1000 frames/ second

^{241}Am-Be neutron source

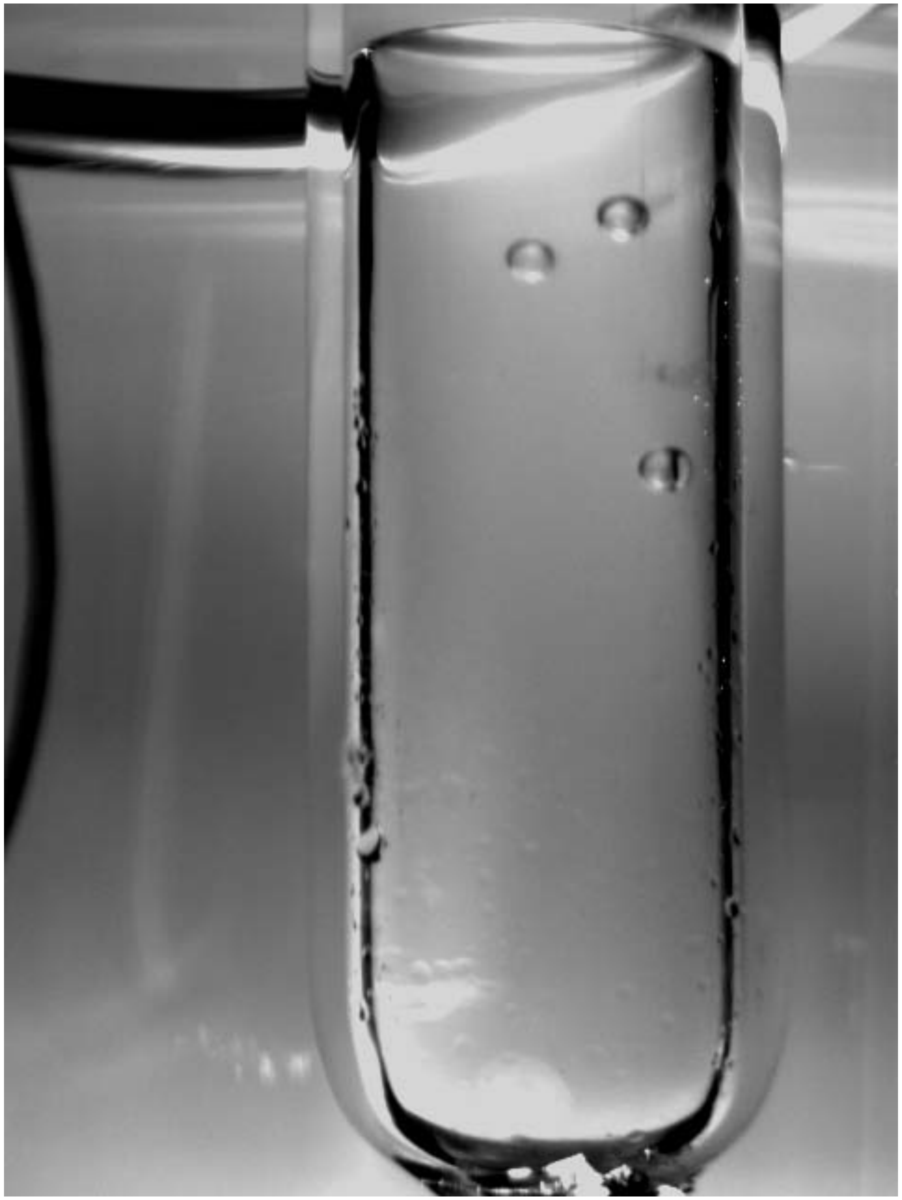


Neutron Multiple Scattering

- A fraction of events have more than 1 bubble.

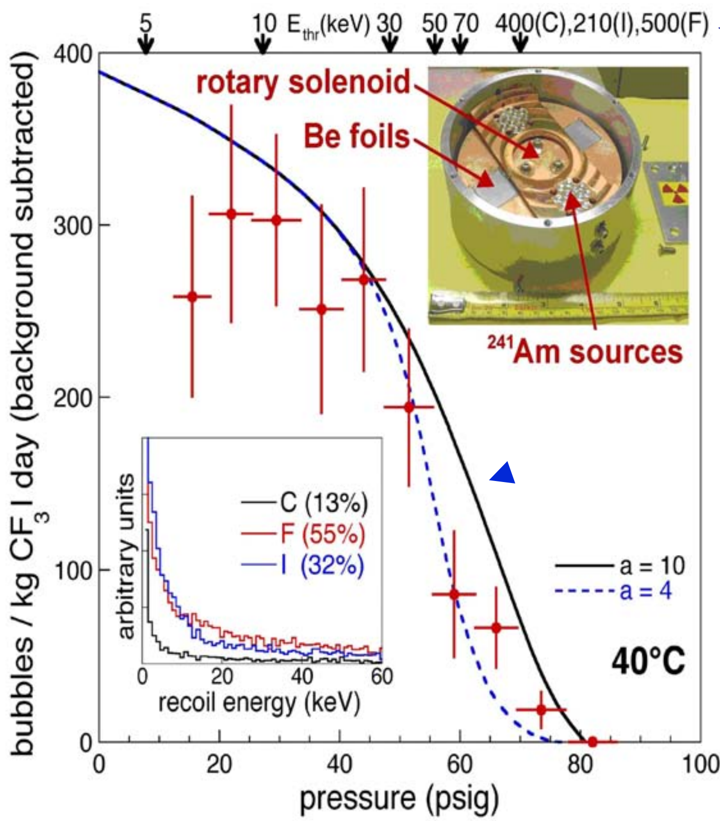
- These events can only be caused by multiple neutron scattering, since uniform size of bubbles implies simultaneous nucleation at multiple sites.

- Events such as this can be used to measure neutron backgrounds *in-situ* while searching for recoils due to WIMPs.



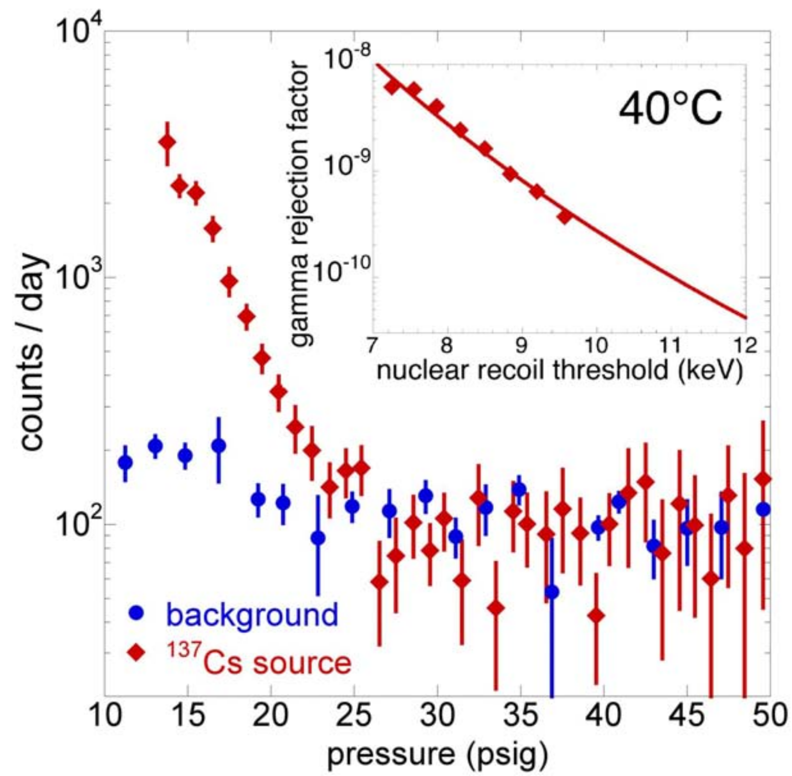
Neutron and Gamma Calibrations

- Neutron scattering data (^{241}Am-Be) is well-described by standard Seitz bubble nucleation theory with the assumption of a sharp energy threshold.
- Exposure to high-intensity gamma sources demonstrates insensitivity to beta and gamma backgrounds.



Threshold

Seitz bubble nucleation model



The COUPP Collaboration

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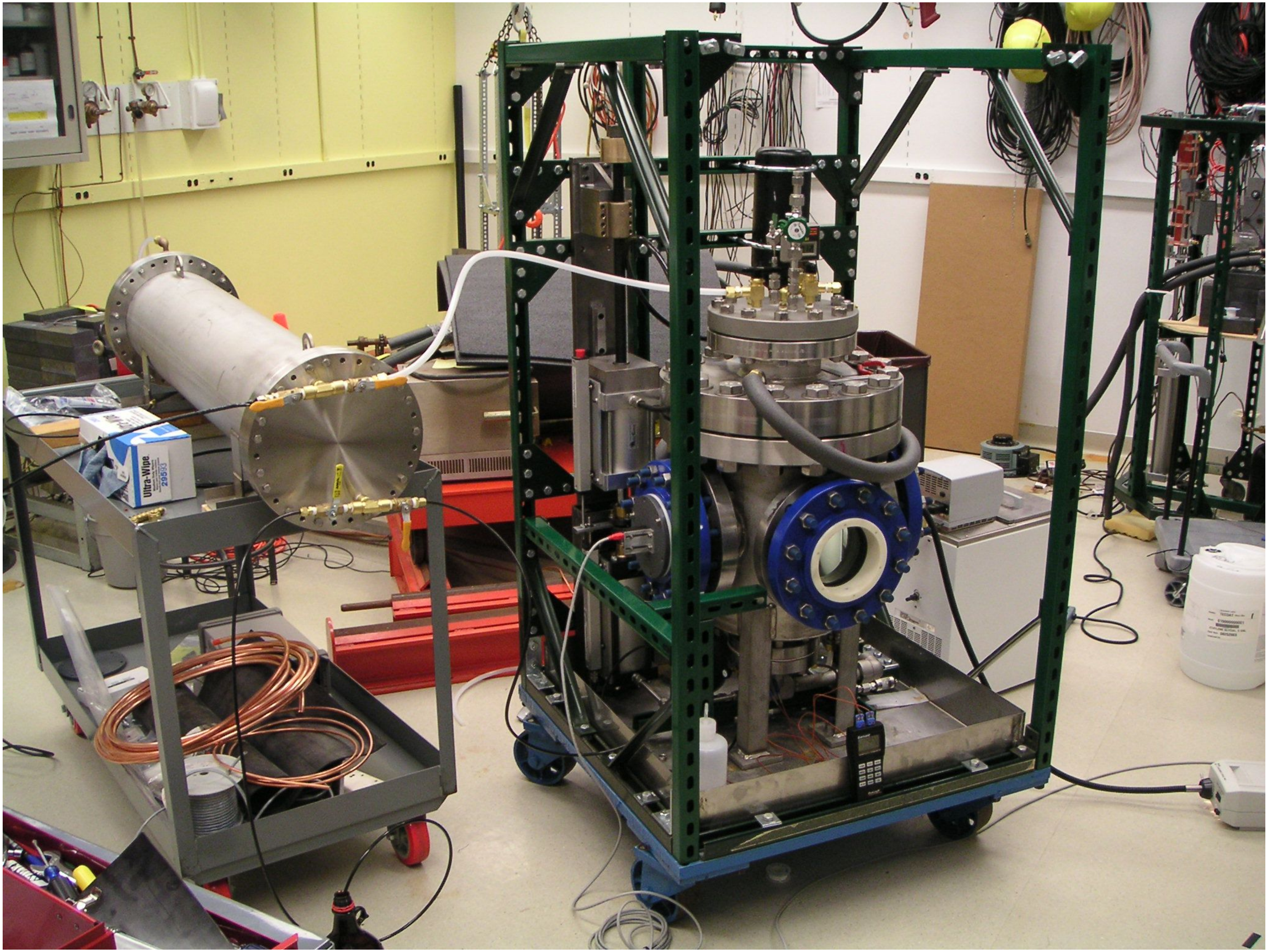
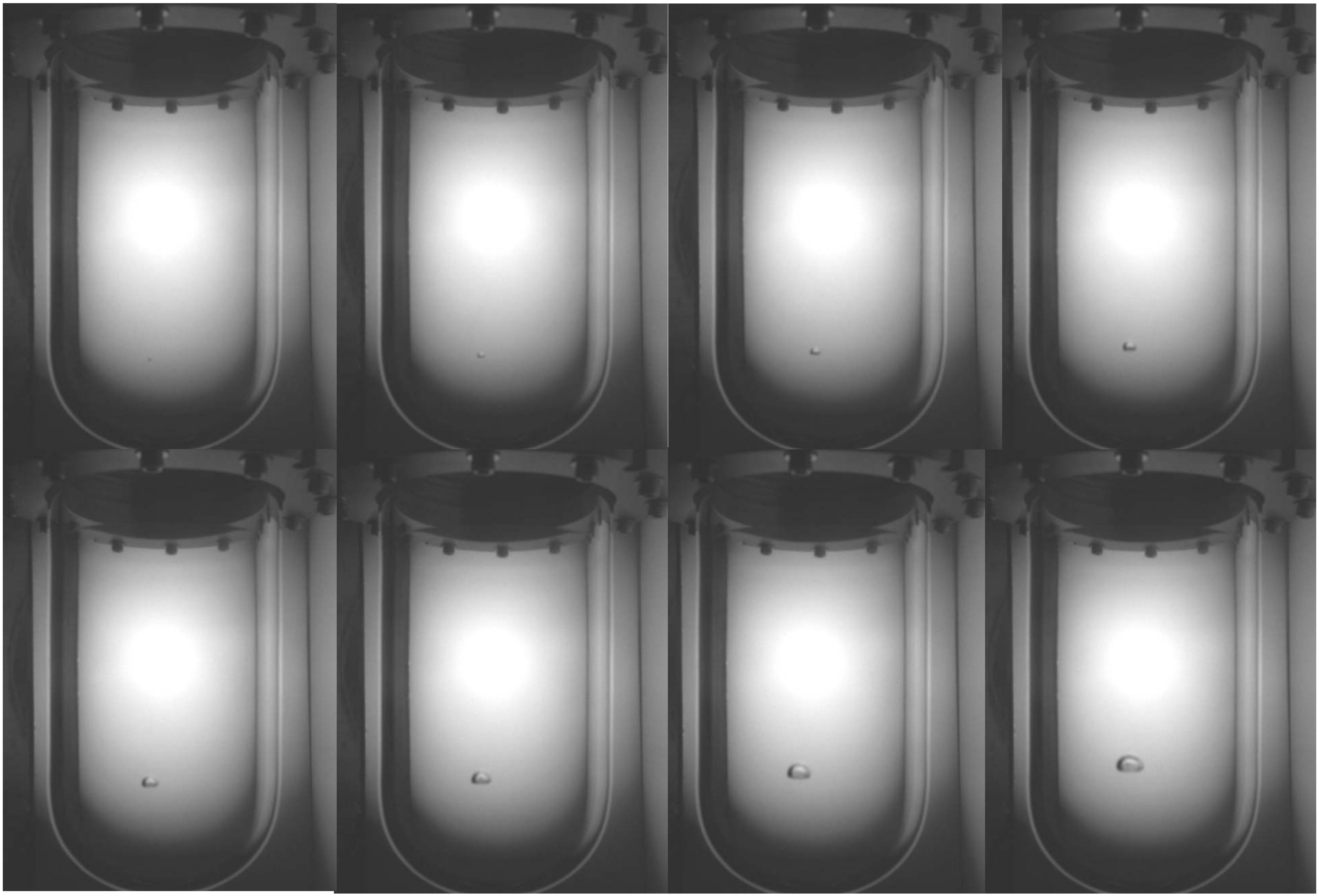
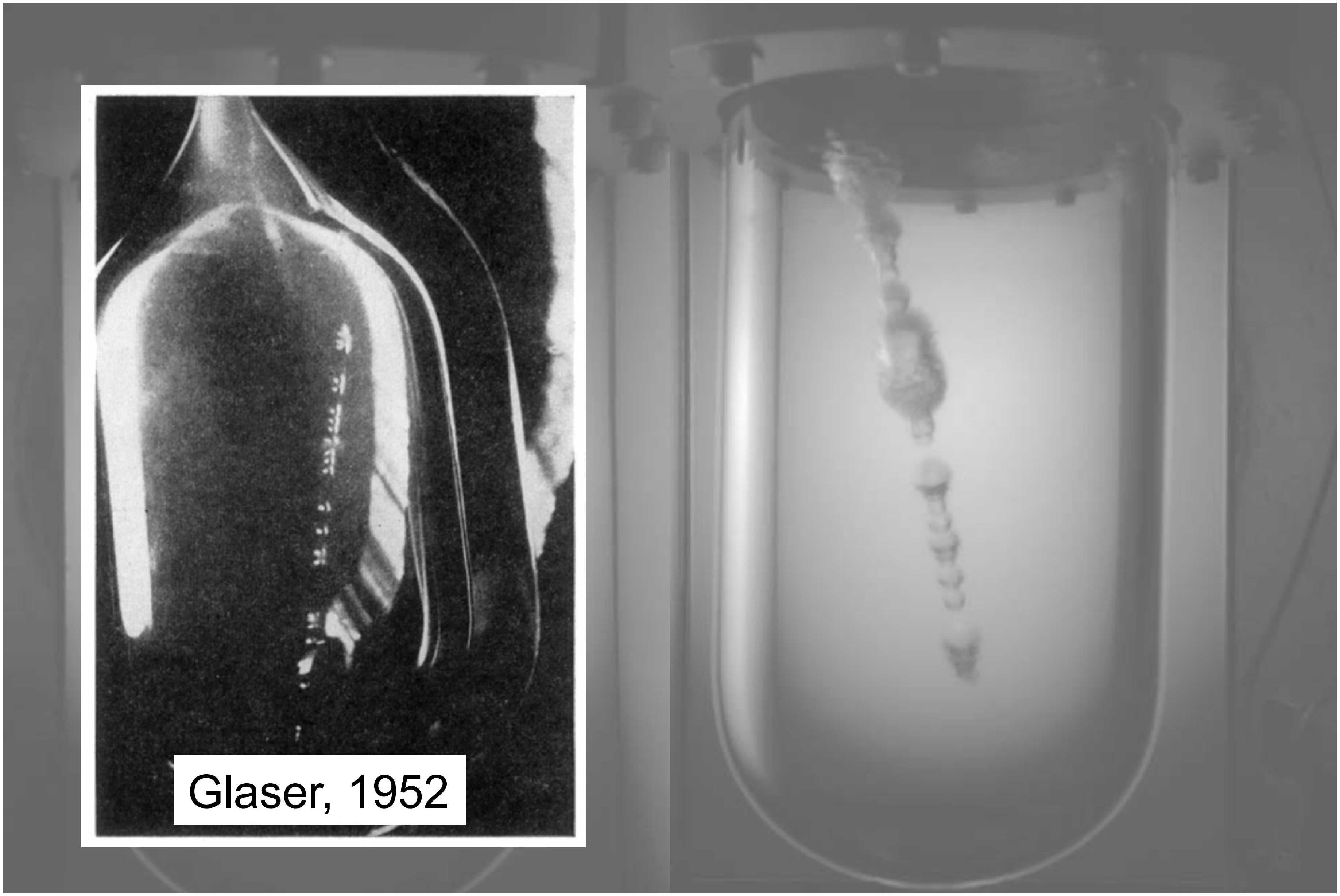
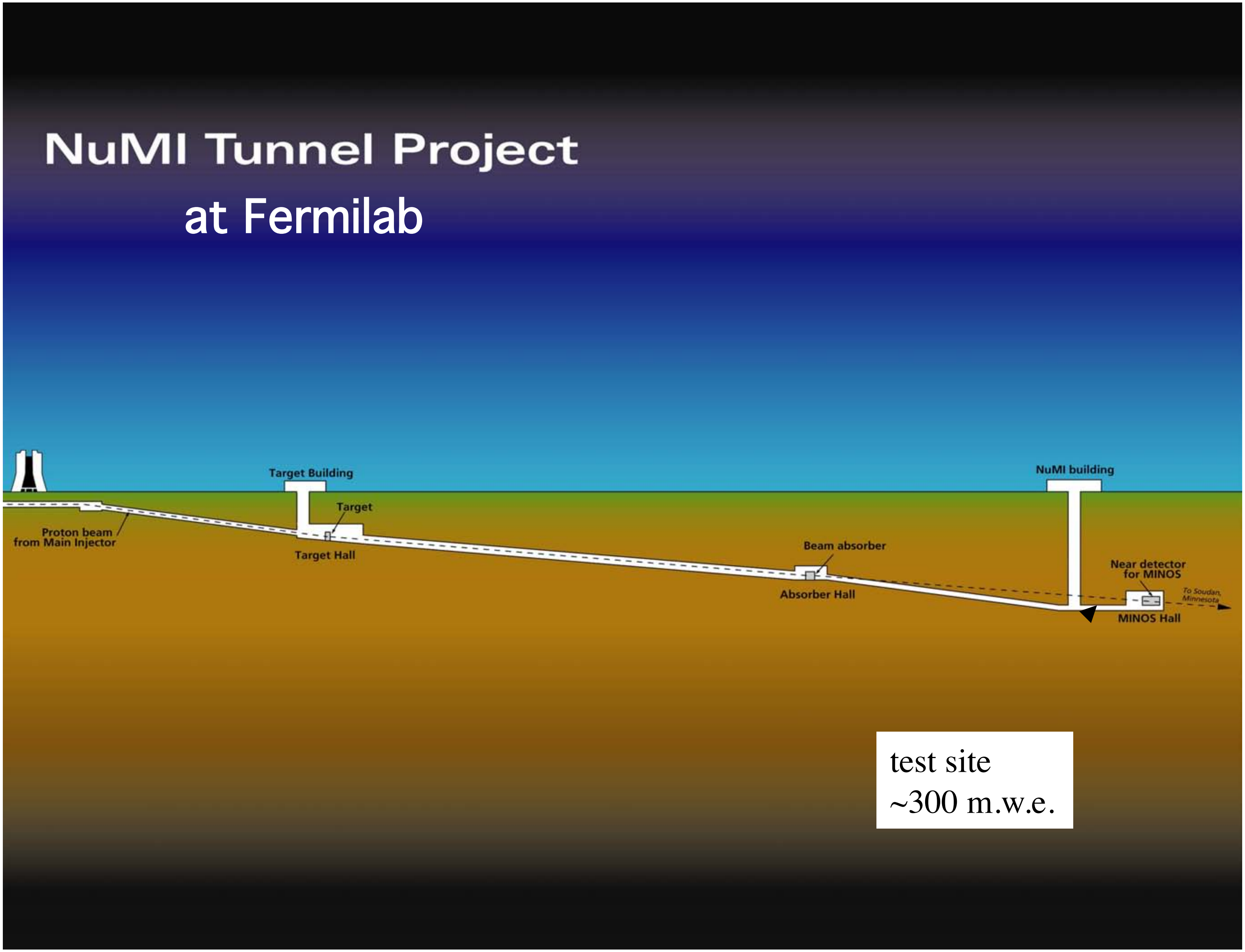

Ultra-Wipe
29593

160 msec of Video Buffer (20 msec/frame)



Muon Track @ 160 psi Superheat Pressure




NuMI Tunnel Project
at Fermilab
Target Building
Target
Proton beam
from Main Injector
Target Hall
Beam absorber
Absorber Hall
NuMI building
Near detector
for MINOS
To Soudan,
Minnesota
MINOS Hall
test site
~300 m.w.e.

Small Chamber Runs at Fermilab 2005-2010

- Small chamber initially installed at Fermilab NuMI tunnel in 2005.

- Served as R&D platform and proof-of-principle.

- Rebuilt several times to incorporate new features-
  - Higher purity materials
  - External muon tagger
  - Acoustic sensors
  - Pressure and temperature control upgrades

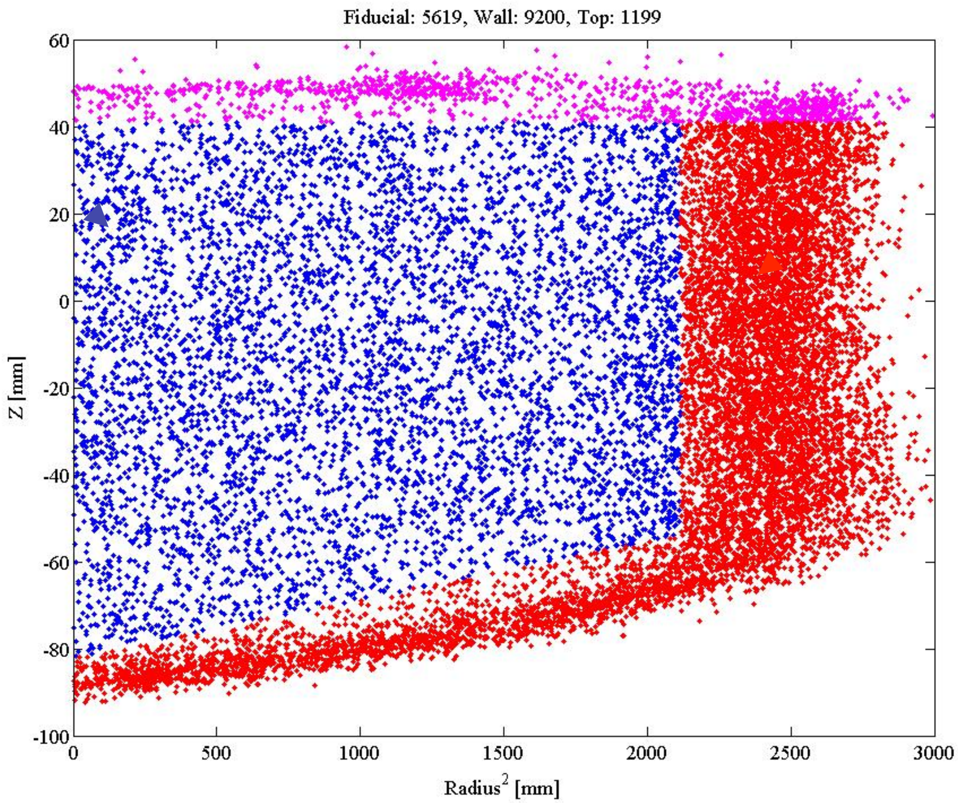
- Also did some physics…

Science 319:5865, 2008
Phys Rev Lett 106:021303, 2011

Spatial Distribution of Single Bubbles

Bulk events: indistinguishable from WIMP interactions on an event-by-event basis.

~ 20- 100 events/day



Wall Events: not a background, but they reduce our live time due to the need to decompress afterwards, prohibitive for larger chambers.

~ 300/day

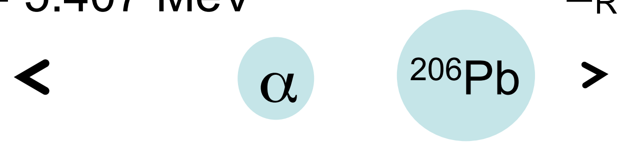
Alpha Particle Backgrounds

- Alpha decay produces monoenergetic, low energy nuclear recoils.

For example, consider $^{210}Po \rightarrow ^{206}Pb$:

E_α = 5.407 MeV

E_R= 101 keV



• The recoiling nucleus will nucleate a bubble in any chamber that is sensitive to the lower energy (~10 keV) recoils expected from WIMP scattering.

Radium Decay Chain: Dominant Source of Environmental α's

O-rings

^{226}Radium
$T_{1/2}$=1600 y

Present at significant levels in most natural and man-made materials

^{222}Radon
$T_{1/2}$=3.8 d

Noble gas- highly diffusive, universally present in air, water

BULK

^{218}Polonium
$T_{1/2}$=3.1 m

^{214}Lead
$T_{1/2}$= 27 m

^{214}Bismouth
$T_{1/2}$= 20 m

^{214}Polonium
$T_{1/2}$=0.2 ms

BULK

^{210}Lead
$T_{1/2}$= 22 y

^{210}Bismouth
$T_{1/2}$= 5 d

^{210}Polonium
$T_{1/2}$= 138 d

WALL?

^{206}Lead
Stable

Red: alpha decay

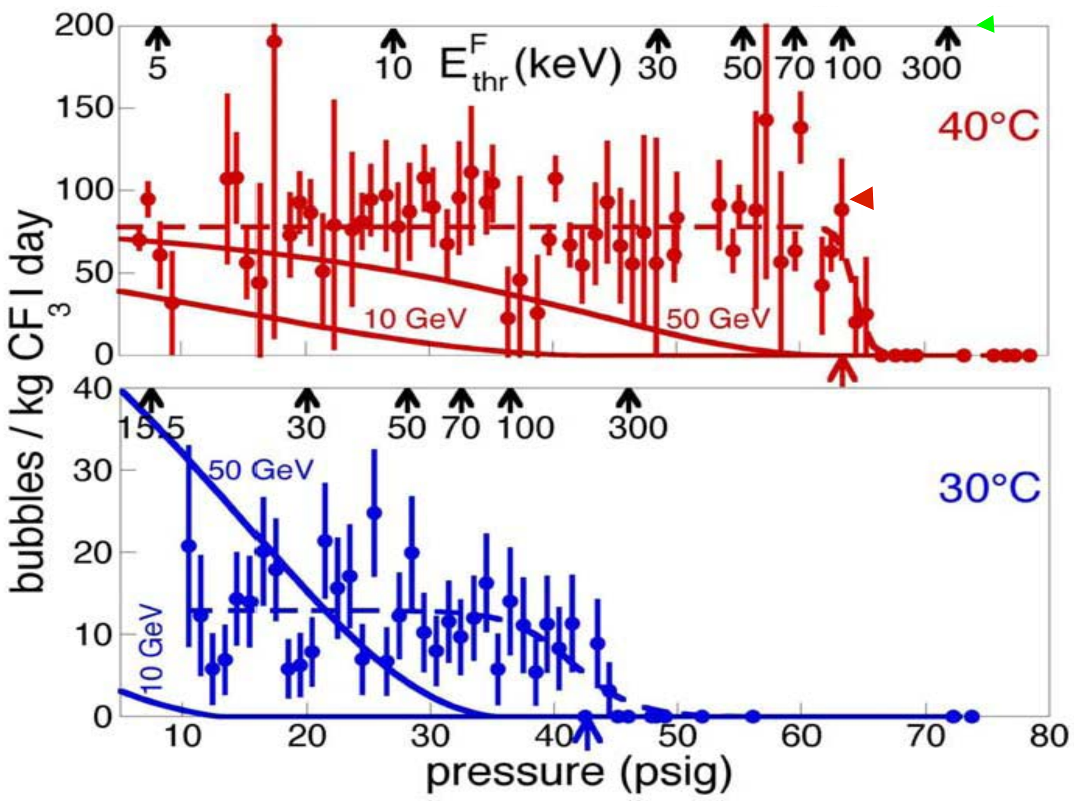
Blue: beta decay

Long half-life, implanted in surfaces by 100 keV recoil from decay of parent

<u>Hard to clean off!</u>

Data from 2006 Run

- Data from pressure scan at two temperatures.
- Fit to alphas + WIMPs



Energy Threshold In KeV

Radon background

<u>Solid lines:</u>
Expected WIMP

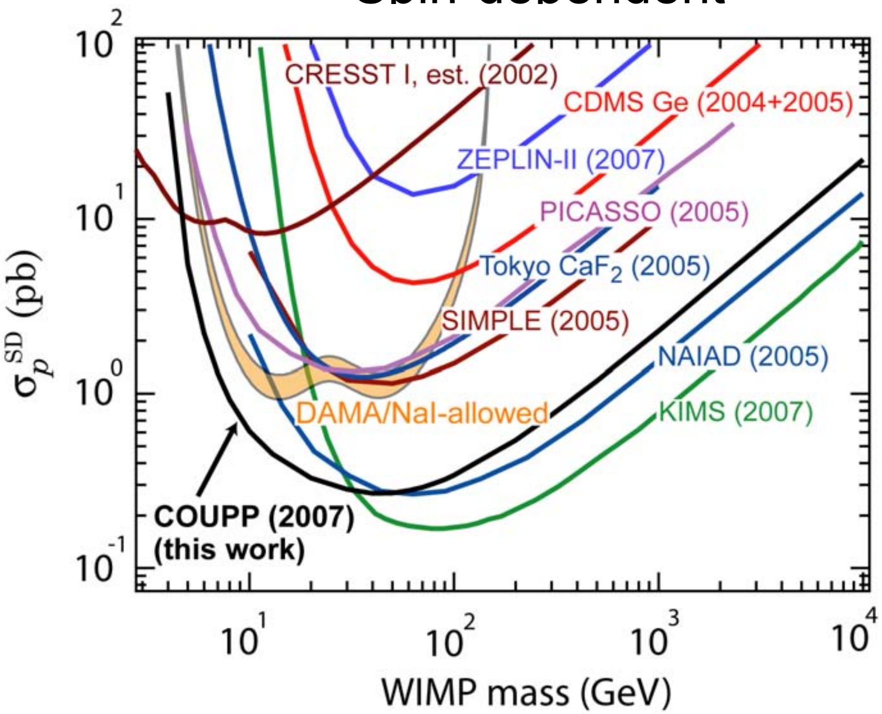
response for

$\sigma^{SD(p)}$=3 pb

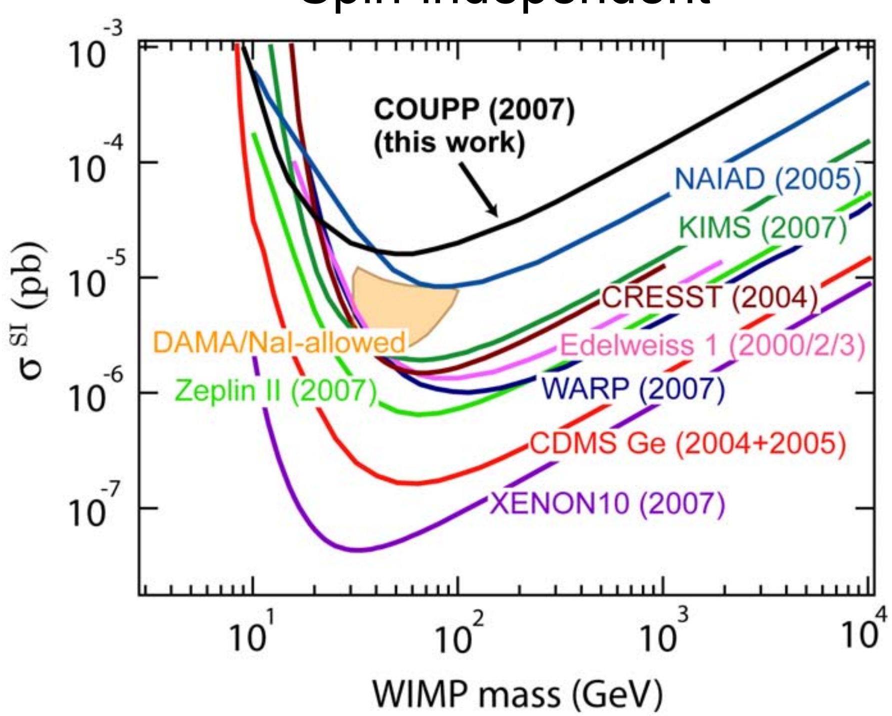
Results from 2006 Run

- Competitive result was obtained for spin-dependent cross section despite high alpha background.
- Poor spin-independent sensitivity.

Spin-dependent



Spin-independent



Science, 319: 933-936 (2008).

Quartz Purity

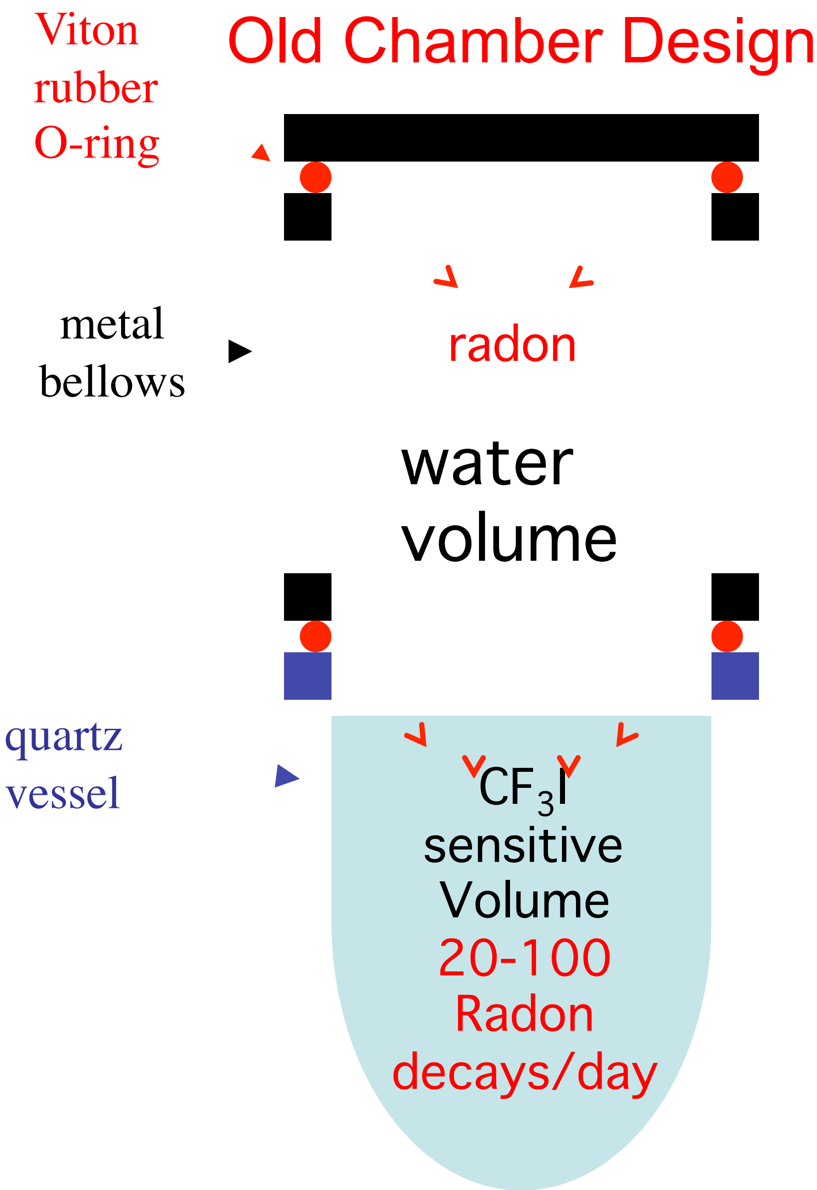
• Rate of wall events (0.8/cm^2-day) in early runs of 2 kg chamber was explained by 42 ppm contamination of quartz with Uranium + daughters (natural GE-214 quartz).

• Our newer small detectors and the 60-kg chamber use lower-activity synthetic quartz. No discernable excess of events at chamber wall.

Material	Uranium [ppt]	
Natural (GE-214)	42,000 (0.8 /cm^2-day)	2-kg chamber 2006
Heraeus Suprasil synthetic (20 kg chamber)	21*	4 kg, 20 kg chamber
Covalent T-6040 synthetic (60 kg chamber)	< 100	60-kg chamber inner vessel procured. Available in sizes up to 500 kg
Corning synthetic	260*	
Dynasil synthetic	226*	
Kvartzsteklo synthetic	17*	
St. Gobain Spectrosil	< 4.6*	

* EXO compilation of quartz activity measurements [Arxiv 0709.4524.v1]

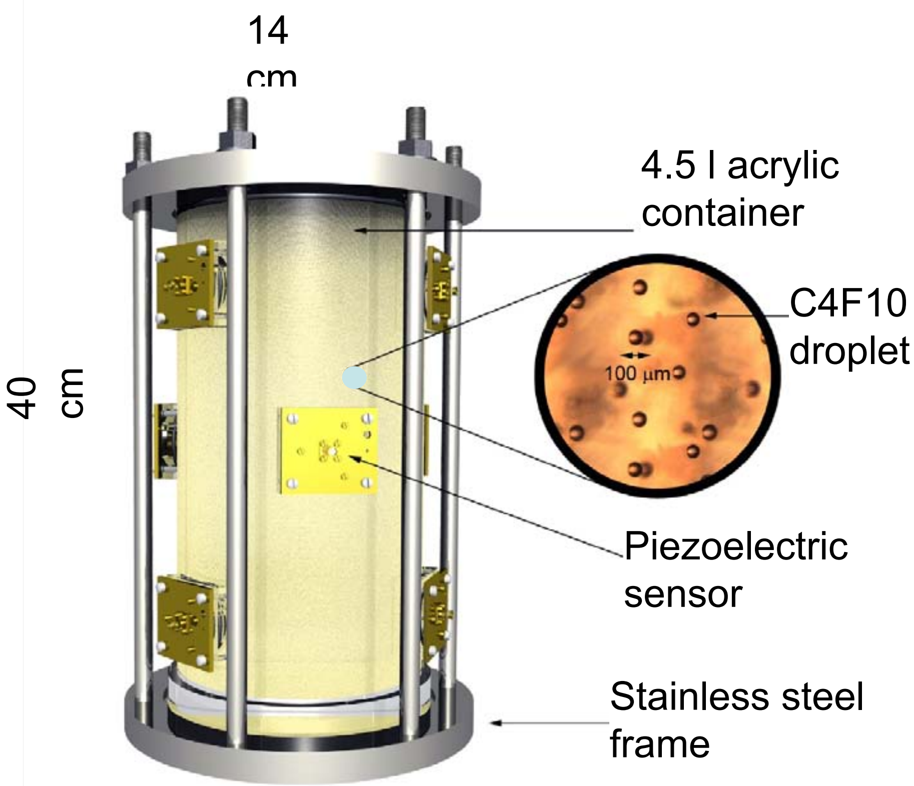
Alpha Events from Radon Dissolved in Chamber

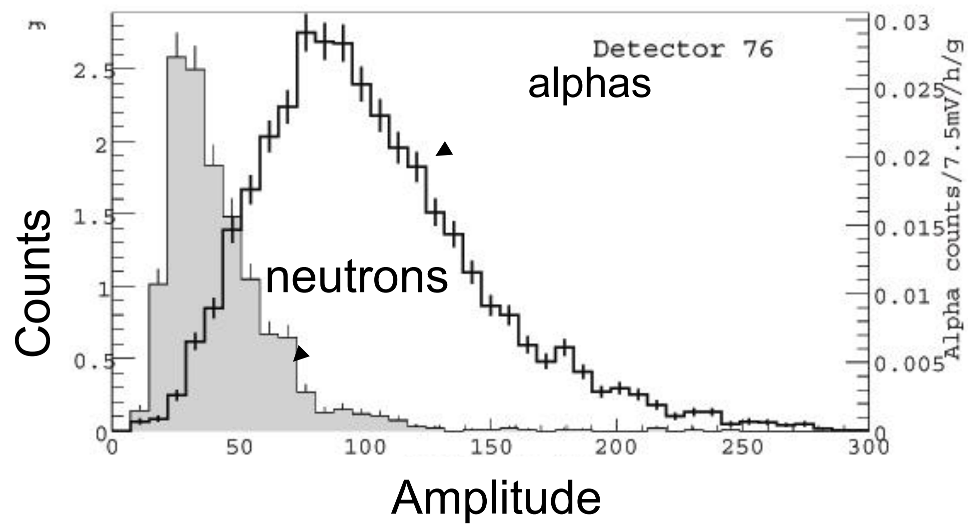


- **Time correlation studies show that all alpha activity in bulk comes from ^{222}Rn decay chain.**
- **Elimination of Viton O-rings in favor of metallic seals reduced rate by an order of magnitude: current rate in 4-kg detector at SNOLAB is 6 counts per kg-day, down from 77 cts/kg-day in 2006.**
- **Still far from SNO/Borexino levels, corresponding to ~0.01 cts/Kg-day.**
- **Radon emanation from surfaces?**

PICASSO Discovery of Acoustic Alpha Discrimination (2008)

- First seen in superheated emulsion detectors operated by the Picasso collaboration: small droplets (~10 micron) of superheated liquids suspended in a viscous gel.
- Larger amplitude acoustic signals reported for bubbles nucleated by alpha particles compared to nuclear recoils.
- Distributions overlap at the ~10% level.

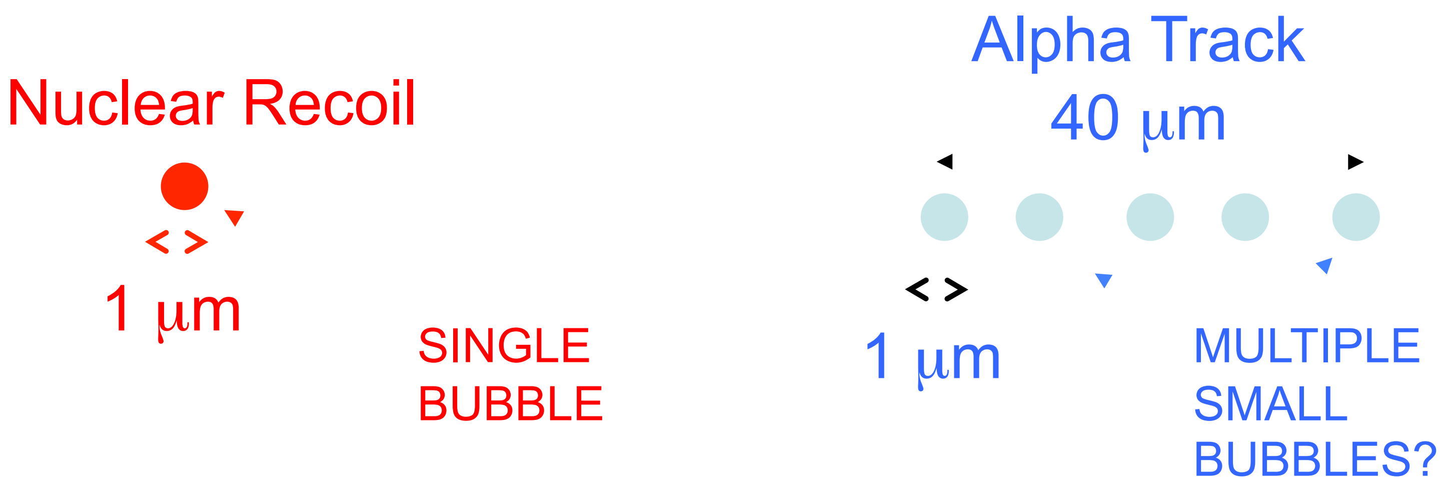




New Journal of Physics arXiv:0807.1536

Discrimination Between Alpha Decay Bubbles and Nuclear Recoils?

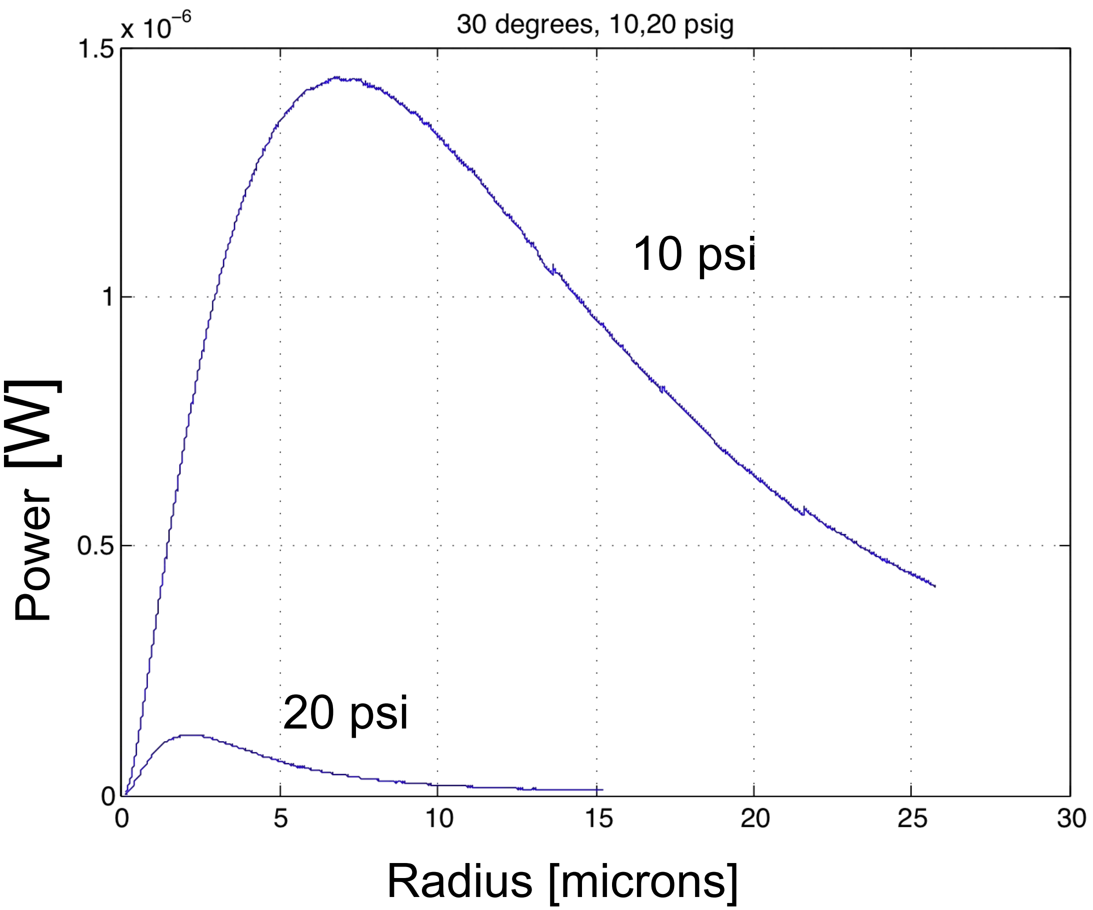
Imagine that we could photograph the bubble track with micron resolution a few microseconds after nucleation occurs, while bubbles are still just ~ 1 micron in diameter.



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

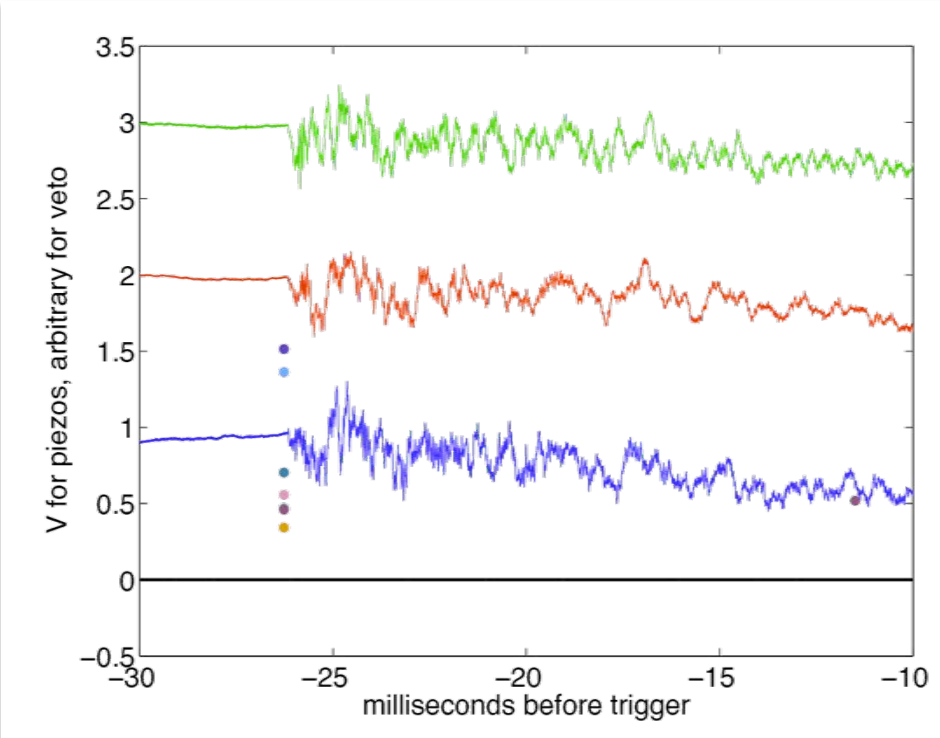
The Acoustic Microscope

• Numerical simulations of bubble growth indicate that the maximum acoustic power output occurs when bubbles are ~10 microns diameter for typical pressure and temperature conditions.
• Measured acoustic pulse contains information about early phase of bubble growth.

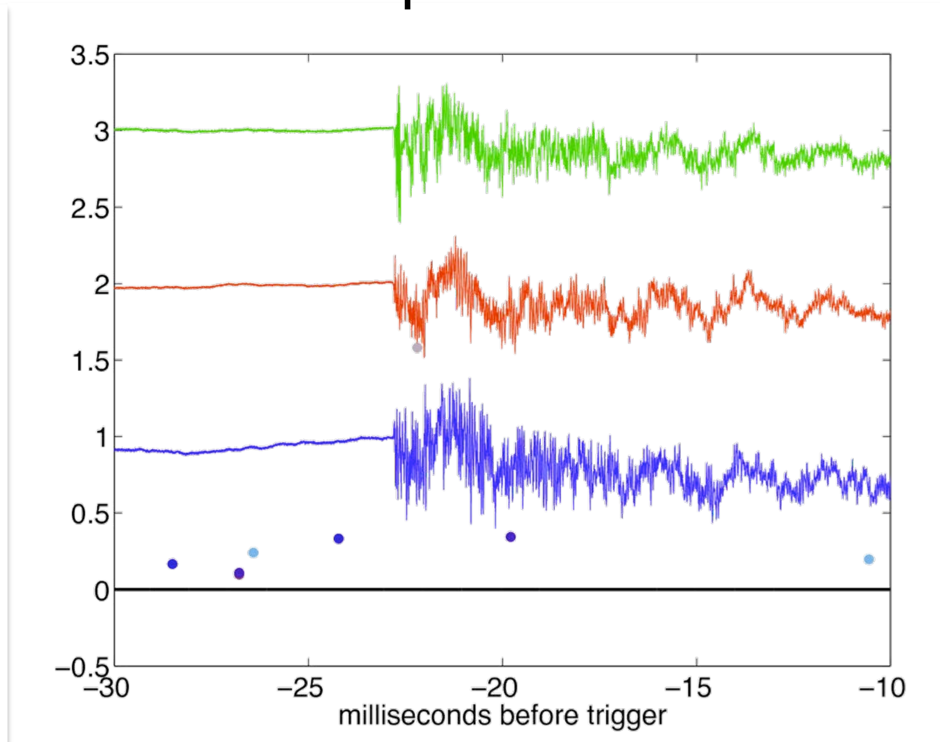


Acoustic Waveforms in COUPP 4-Kg Chamber

Neutron

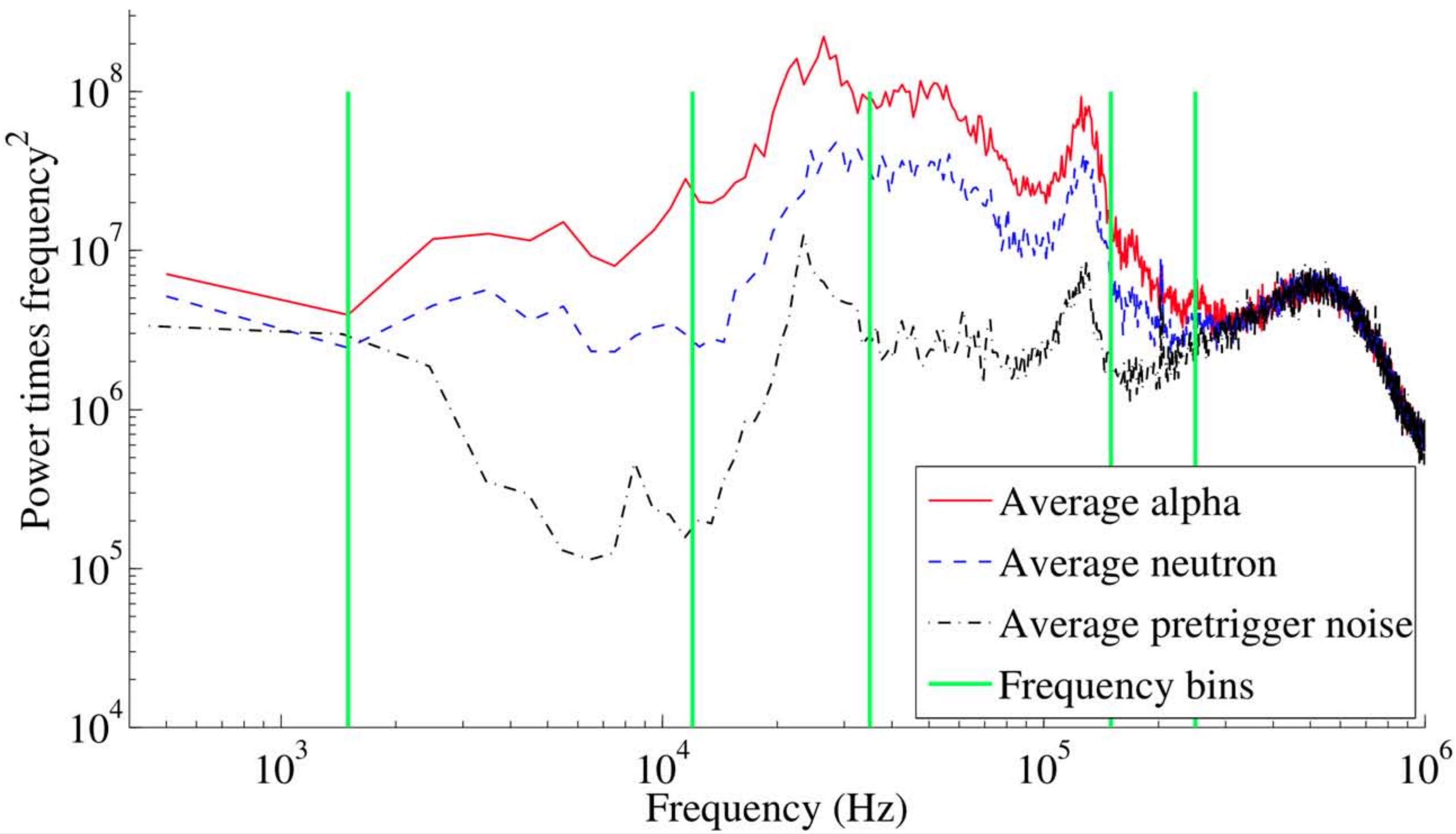


Alpha



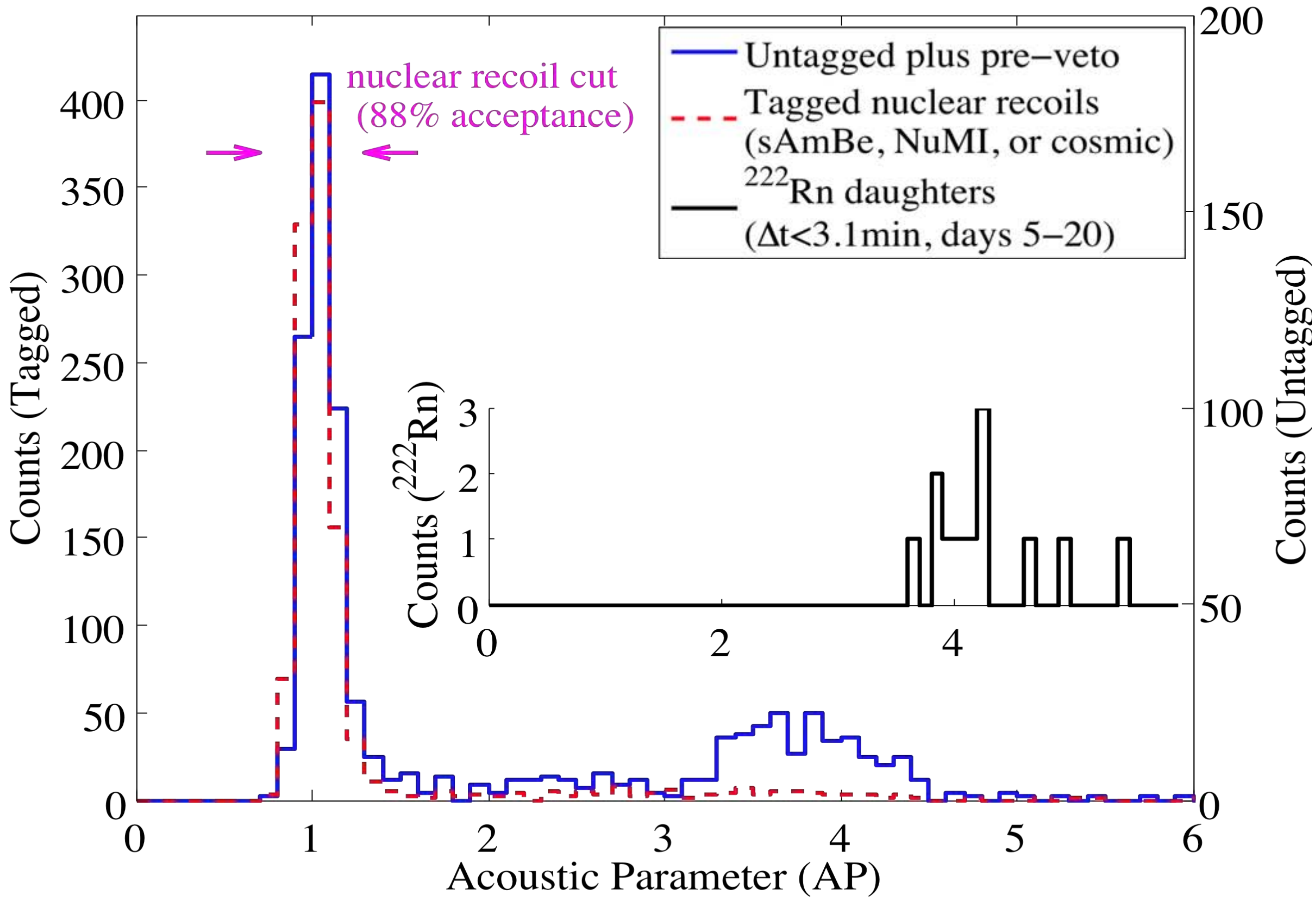
Acoustic Power Spectrum

- Alphas are louder than neutrons, especially at higher frequencies.
- Amplitude depends on position of bubble in the chamber as well as the type (alpha or neutron) of each bubble.
- We form a “acoustic alpha/neutron discrimination parameter” by a weighted average of power in 5 frequency bins, corrected to remove position dependence.

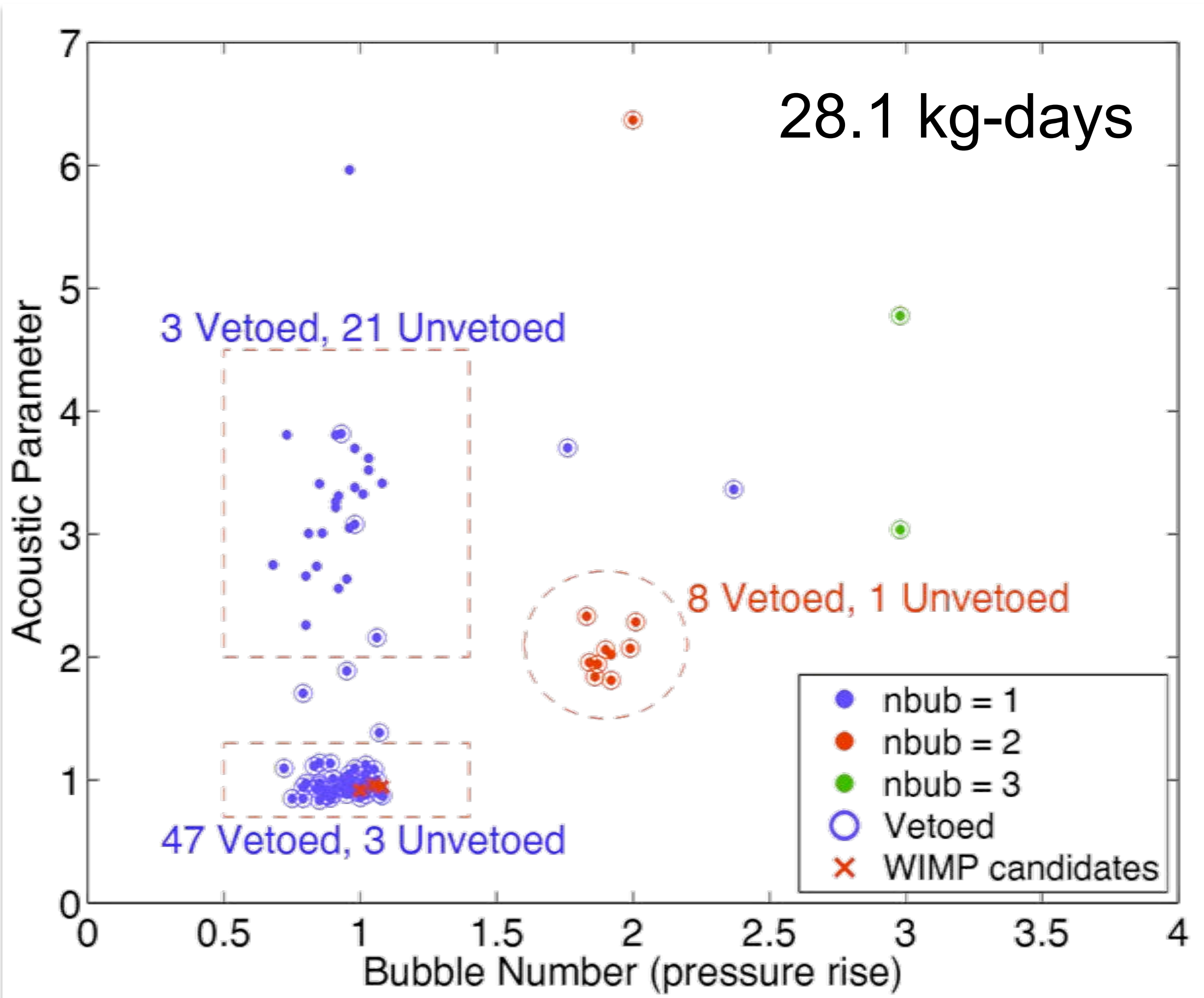


COUPP Alpha Discrimination 2009

- Effect appears to be much cleaner than seen in superheated droplet detectors.
  - In droplet detectors, alpha path length not fully contained in superheated liquid.
  - Sound dispersion in liquid?



COUPP Dark Matter Search Results (2010 PRL)



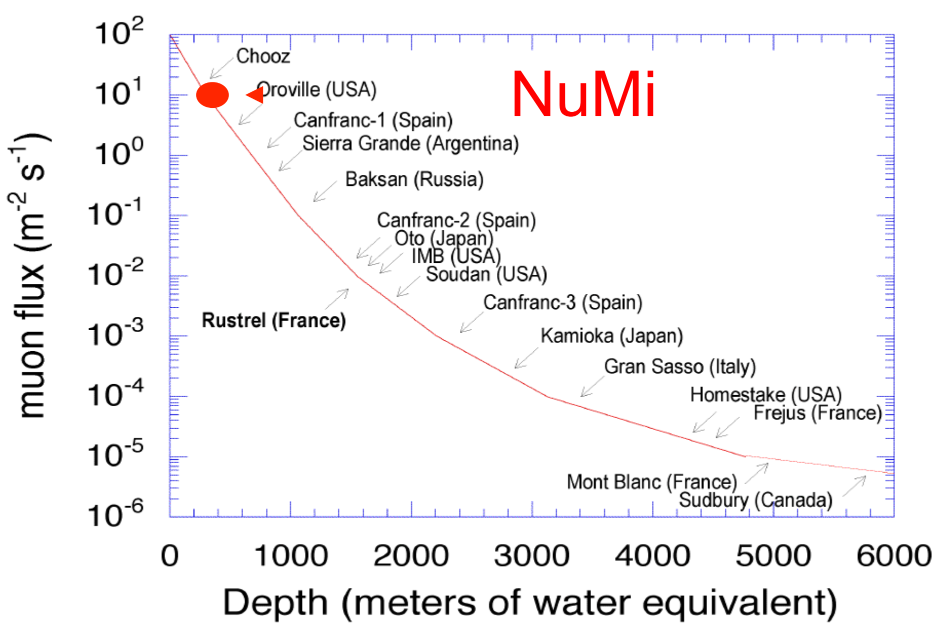
- Three single bubble events pass cuts on acoustic amplitude (rejecting alphas) and external muon tagging (rejecting neutrons from cosmic rays)
- One double bubble event indicates the presence of neutrons that were not cosmic-ray coincident.
- 3:1 ratio of single to multiple bubble events is consistent with interpreting all to neutrons.

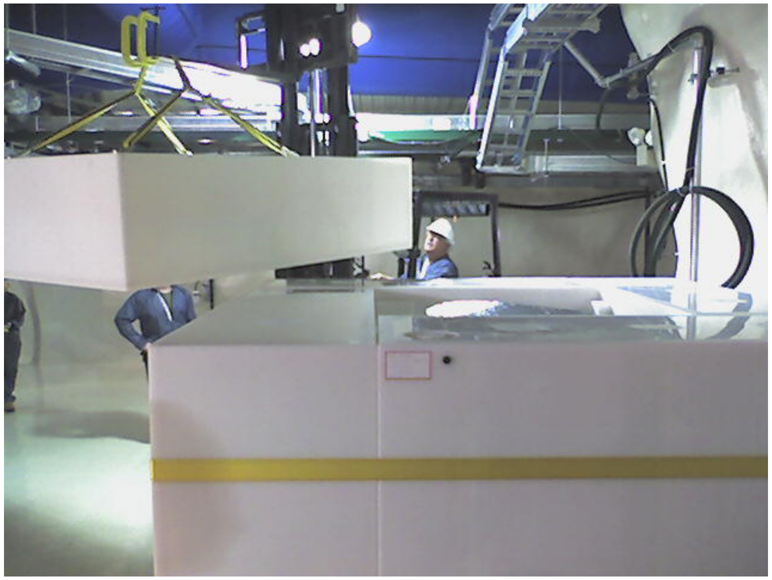
COUPP-4 At SNOLAB

• 4-kg Detector transferred to SNOLAB in Summer 2010 after runs at Fermilab indicated that neutrons from cosmic rays had become limiting background.

• At SNOLAB, detector is shielded from local neutrons with polyethylene water tanks.

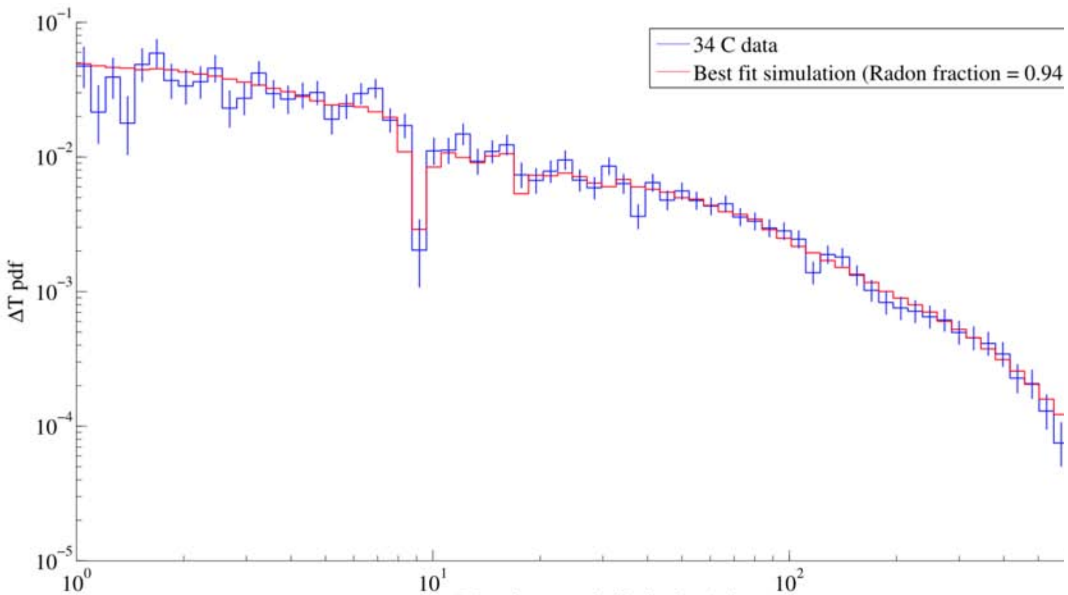
• First physics run ended June 2011 with 500 kg-days exposure.



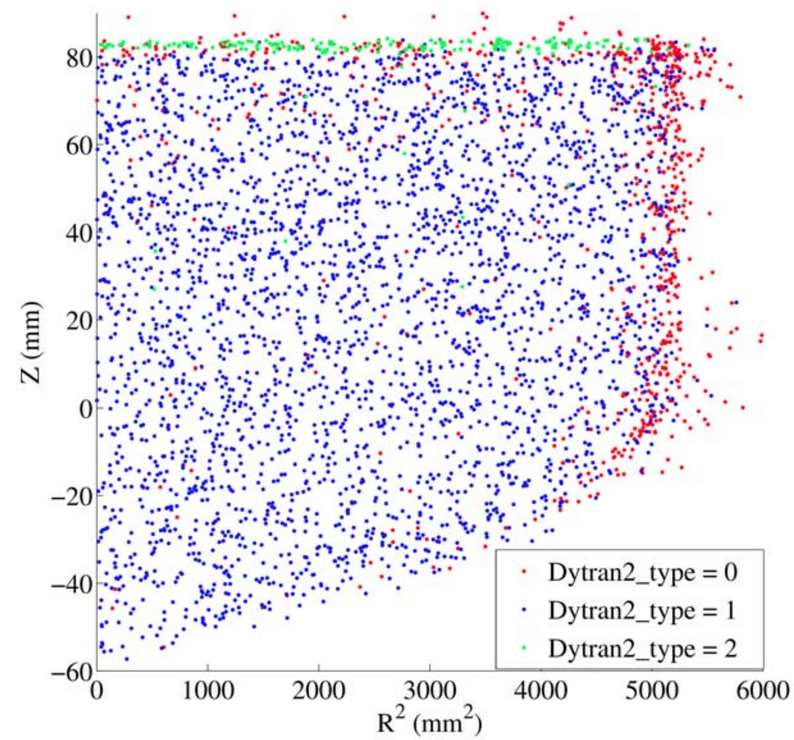


Radon Background

- Alpha decay produces low energy nuclear recoil of the daughter nucleus with energy ~100 keV. The recoiling nucleus will nucleate a bubble in any chamber that is sensitive to the lower energy (~10 keV) recoils expected from WIMP scattering.
- In early COUPP runs, alphas produced ~ 100 events/kg-day
- Currently 6/kg-day. Observed time correlations indicate this is due to dissolved ^{222}Rn plus its daughters ^{218}Po ($T_{1/2}$=3.1 m) and ^{214}Po.

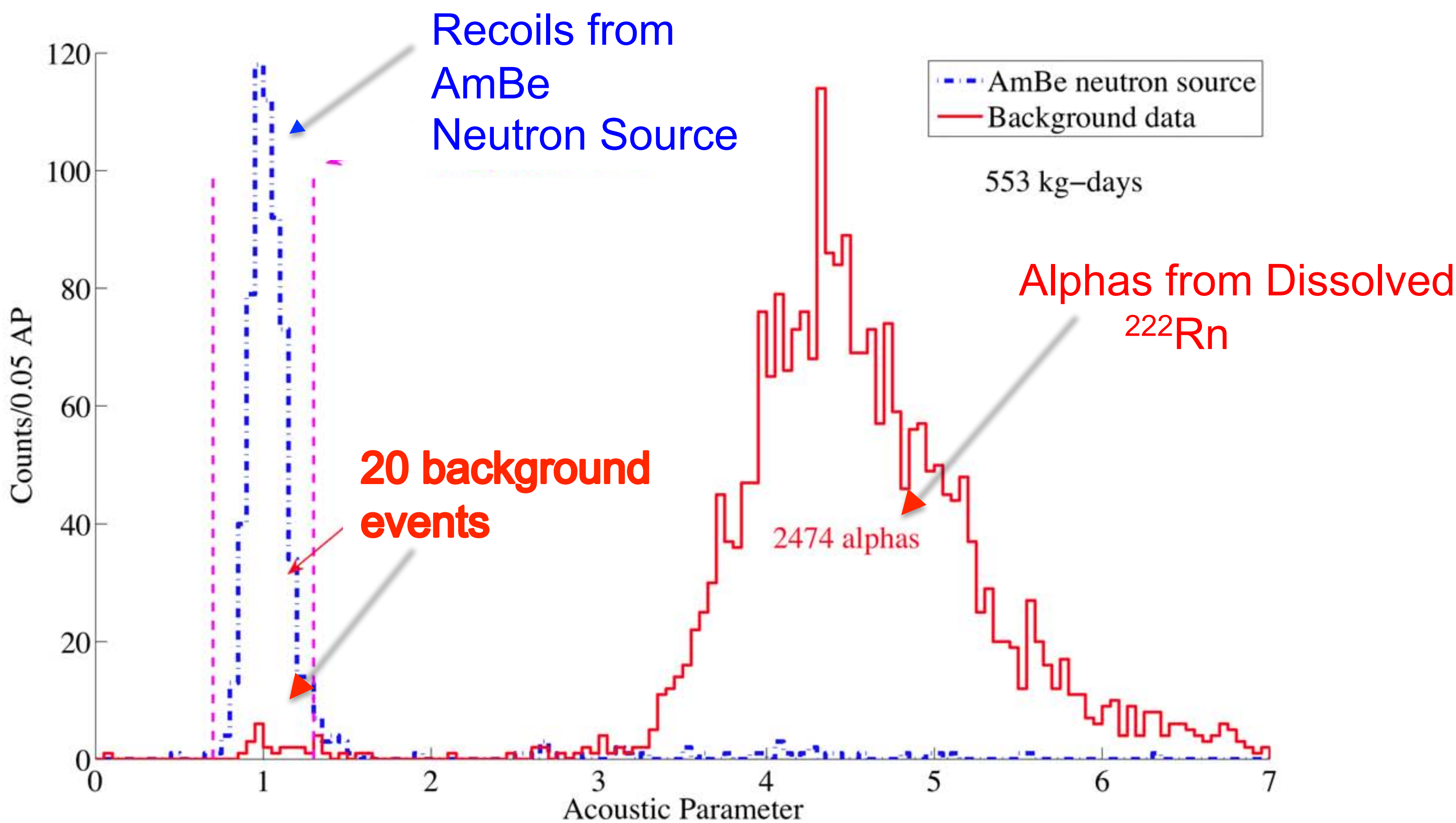


Time Since Previous Event [minutes]



First COUPP Results at SNOLAB

• >99% of alpha events rejected with 96% acceptance for signal. Time correlations indicate that all alphas are from ^{222}Rn decay chain.
• 20 remaining single bubble events in 553 kg-days exposure at three temperatures (34, 37, 40 deg C, corresponding to 8, 11, 16 keV thresholds)
• Three multiple bubble events indicate the presence of neutrons.



Origin of Neutron Backgrounds

• Neutron fluxes have been simulated with using measured activity of construction materials. In simulations, neutrons from PZT acoustic sensors and glass observation windows make a significant contribution to rate– the sum is consistent with the observed nuclear recoil rate to within a factor of ~2.

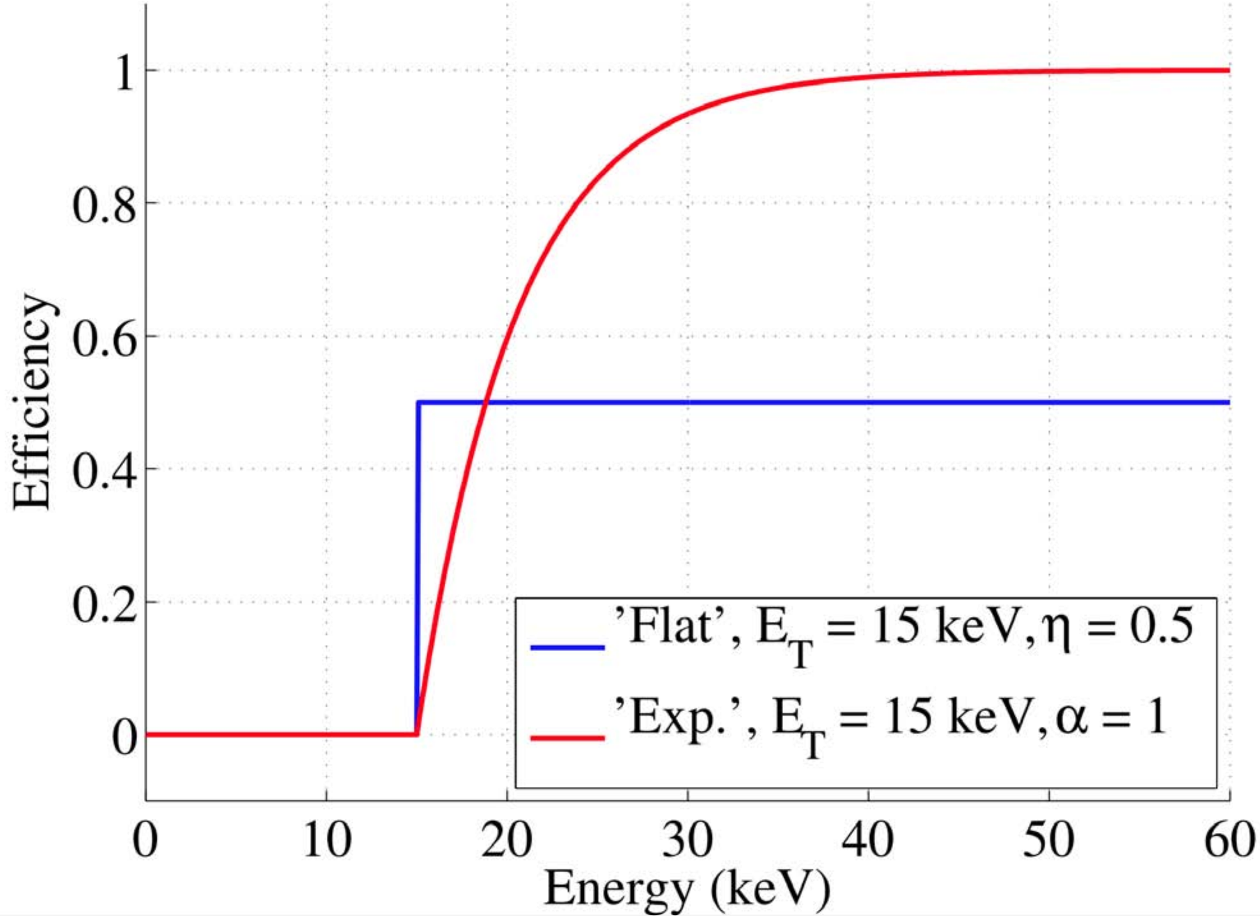
• Work is underway to replace the hot materials. High purity chemical reagents for PZT ceramic production have been identified with <1% of current activity. New COUPP collaborators at Virginia Tech are preparing new PZT.

• Observation windows will be replaced with high purity fused silica, negligible activity.

• Other materials (glycol, quartz, steel) make negligible contribution to the rate in COUPP4 and should also be negligible in COUPP60 with modest attention to radiopurity.

Efficiency Systematic Uncertainty

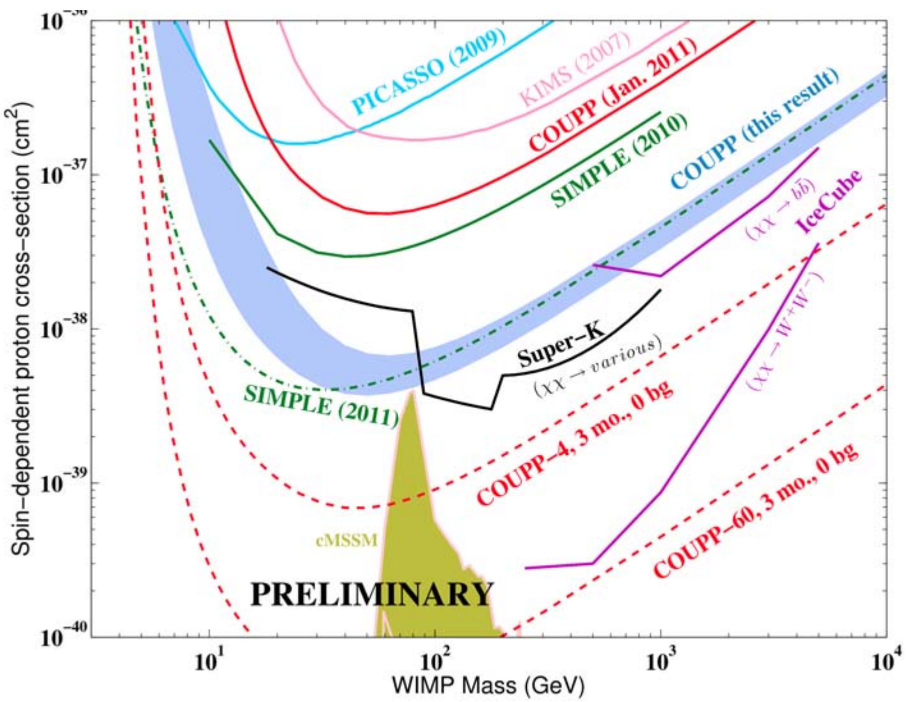
- Current calibration data with ^{241}Am-Be neutron sources does not strongly constrain efficiency near threshold.
- Need more data with lower energy neutron sources– in progress.
- Currently we show range of possible results with two efficiency models that fit existing calibration data.



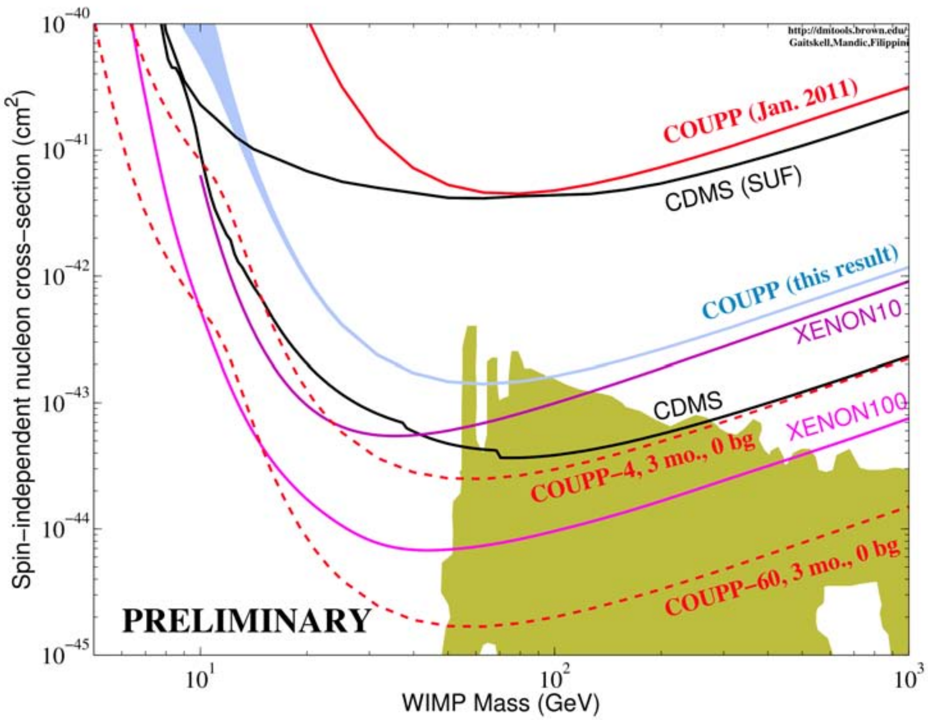
COUPP-4 2011 Sensitivity

- 553 kg days, 20 events.
- Three data sets with 8, 11, 16 keV thresholds.
- Uncertainty in sensitivity due to threshold modeling issues (blue band) – needs more calibration data to resolve.

Spin-dependent



Spin-Independent



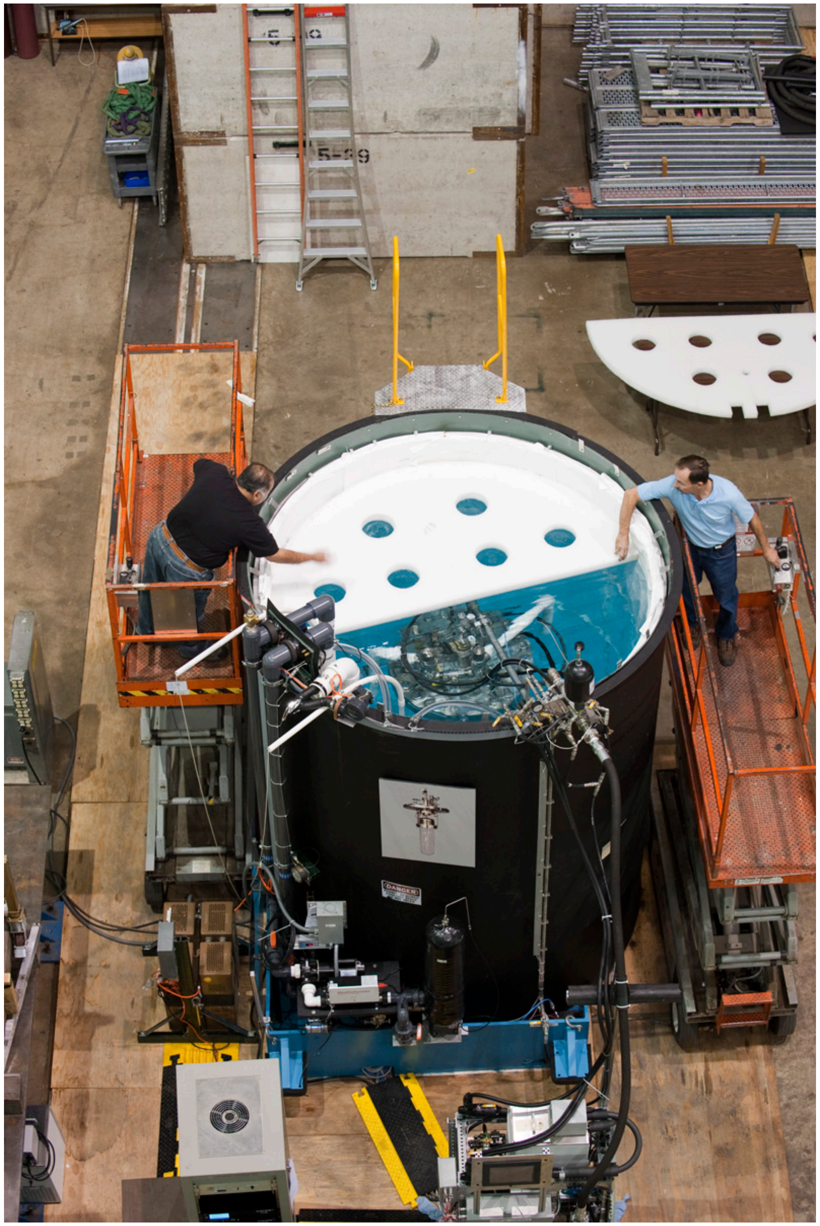
COUPP-60

- COUPP-60 is currently installed in NuMI tunnel at Fermilab. A first test run was completed in 2010.

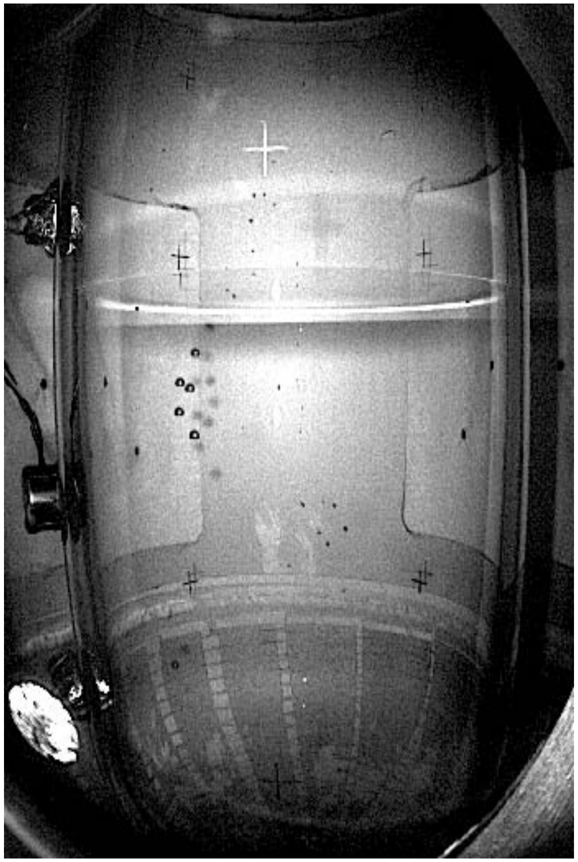

Outer Vessel

Inner Vessel


60-Kg Chamber Testing At Fermilab 2010-2011



Sample Neutron Event



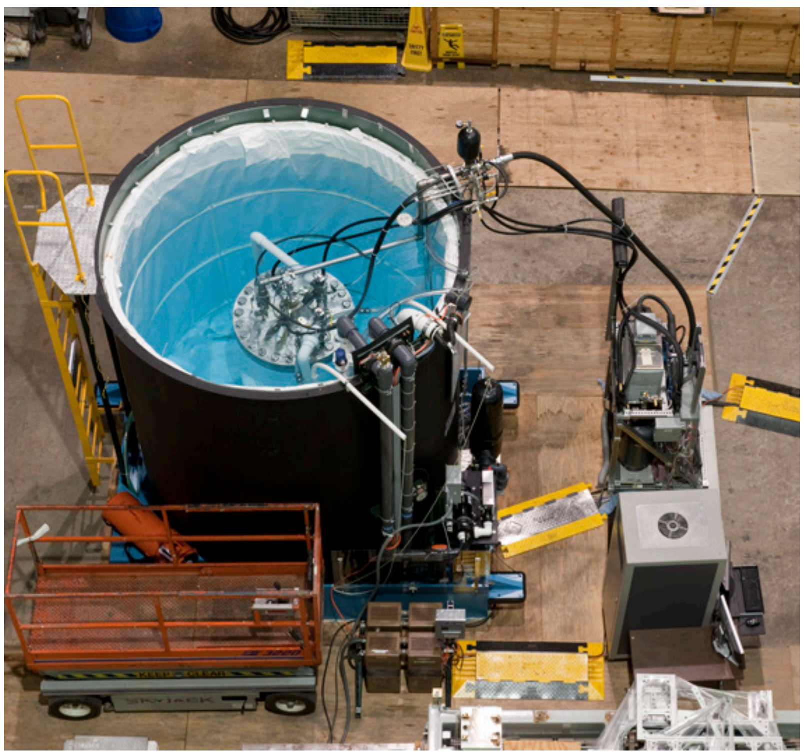
COUPP-60 SNOLAB Plans

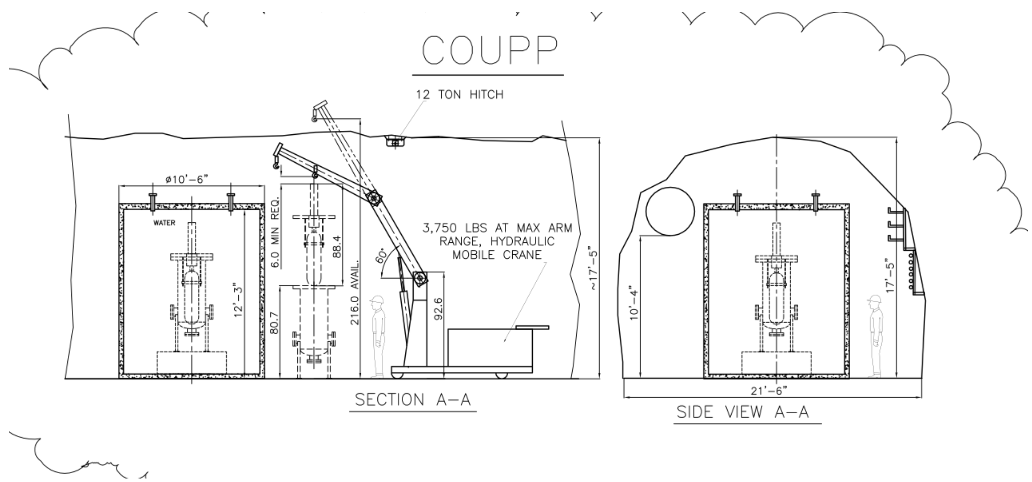
- Beautiful space, ready for move in.

- Safety issues, water shielding tank design are under study.

Future SNOLAB Site

Equipment layout at Fermilab





COUPP-60 SNOLAB Installation Status

- Equipment used at Fermilab has been dismantled. Will ship to SNOLAB in March-April.
- New pressure vessel, optical system under construction.
- Safety engineering continuing– CF3I exposure, seismic activity from rock bursts.
- Water tank and utility construction should start soon.

COUPP Timeline

	2003	2005	2007	2009	2011
Mass	18 g	2-Kg	4-Kg		60-kg
Site	U. Chicago	Fermilab/ NuMI			SNOLAB
Depth	10 m.w.e.	300 m.w.e.			6000 m.w.e.
Backgrounds	7000 events/kg-day	77 events/kg-day	0.7 events/kg-day		0.04 events/kg-day
Physics		Best spin-dependent (W-p)			Best spin-independent?
		10^{-10} gamma rejection			
Technical Developments	Continuously sensitive bubble chamber	Pressure balancing of inner/outer vessel			>99% accoustic alpha rejection
			Radon reduced	Fused silica inner vessel wall events eliminated	
				Retroreflective illumination	

- Active mass increased by 4 orders of magnitude 2003-2011
- Backgrounds decreased by 5 orders of magnitude

Conclusions

- Exploitation of acoustic information for alpha background rejection had a huge impact in last two years. Alpha/ recoil discrimination >99%

- New results from COUPP-4 at SNOLAB:
  - Leading sensitivity for spin-dependent mode

  - For spin-independent mode, sensitivity still lags Xenon-100 and CDMS due to residual neutron background. Simulations indicate that this background can be eliminated with higher purity materials.

- Efficiency uncertainty requires more emphasis on calibration at low recoil energies. Measurements in progress with 171 keV neutrons from ^{88}Y-Be source and other techniques.

- 60 Kg chamber to be installed at SNOLAB in 2012.