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The *Snowball* Chamber: Supercooled Water for Low-Mass Dark Matter!

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UNIVERSITY AT ALBANY
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FIRST MAJOR CONFERENCE TALK ANNOUNCING NEW RESULTS AFTER ARXIV POSTING!

arXiv:1807.09253

- Submitting to *Nature* or *Science* magazine shortly
- Why? Interdisciplinary implications (chemistry, meteorology, bio)
- Thanks to organizers for allowing me to come and announce the result!
- LZ/LUX + NEST is my "day job". Wearing my (G3) R&D hat today

The Snowball Chamber: Neutron-Induced Nucleation in Supercooled Water

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The cloud and bubble chambers have been used historically for particle detection, capitalizing on supersaturation and superheating respectively. Here we present the snowball chamber, which utilizes supercooled liquid. In our prototype, an incoming particle triggers crystallization of purified water. We demonstrate water is supercooled for a significantly shorter time with respect to control data in the presence of AmBe and ^{252}Cf neutron sources. A greater number of multiple nucleation sites are observed as well in neutron calibration data, as in a PICO-style bubble chamber. Similarly, gamma calibration data indicate a high degree of insensitivity to electron recoils inducing the phase transition, making this detector potentially ideal for dark matter searches seeking nuclear recoil alone, while muon veto coincidence with crystallization indicates that at least the hadronic component of cosmic-ray showers triggers nucleation. We explore the possibility of using this new technology for WIMP and low-mass dark matter searches, and conclude with a discussion of the interdisciplinary implications of radiation-induced freezing of water for chemistry, biology, and atmospheric sciences.

PACS numbers: 95.35.+d,29.40.V,29.40.-n,25.40.Dn

Keywords: dark matter, direct detection, sub-GeV, water, supercooling, low-mass WIMPs

I. INTRODUCTION

The nature of dark matter has remained an enduring enigma for over eight decades now, for both cosmology and astroparticle physics. Continued lack of unambiguous evidence from direct detection experiments of the traditional Weakly Interacting Massive Particle (WIMP) has led to an impetus to consider particle masses both higher and lower than before, driven by many hypotheses/models [1]. The goal of this work is inexpensive, scalable detectors for low masses, but also multi-purpose.

Water has the advantages of hydrogen content, ideal for considering dark matter candidates $O(1)$ GeV/c^2 in mass due to the recoil kinematics, and the possibility of a high degree of purification, even *en masse* [2]. Threshold detectors for dark matter, such as bubbles chambers employed by COUPP [3] then PICO [4], while possessing no energy reconstruction, do have the advantage of a high degree of insensitivity to electron recoil backgrounds, in a search for nuclear recoil. The recoil energy threshold can remain low while the dE/dx threshold is high, both set simply by temperature and pressure of operation.

Instead of using superheated water in a bubble chamber, implemented successfully in the past [5] (though at higher energy threshold, not for a dark matter search) we consider here supercooled water, oft-studied [6]. The reason is that freezing is exothermic not endothermic like boiling. This should naïvely imply near-0 energy threshold, as the phase transition will be entropically favorable in this case. The frontier of lower-mass dark matter becomes within reach with lower-energy recoil threshold.

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II. EXPERIMENTAL SETUP

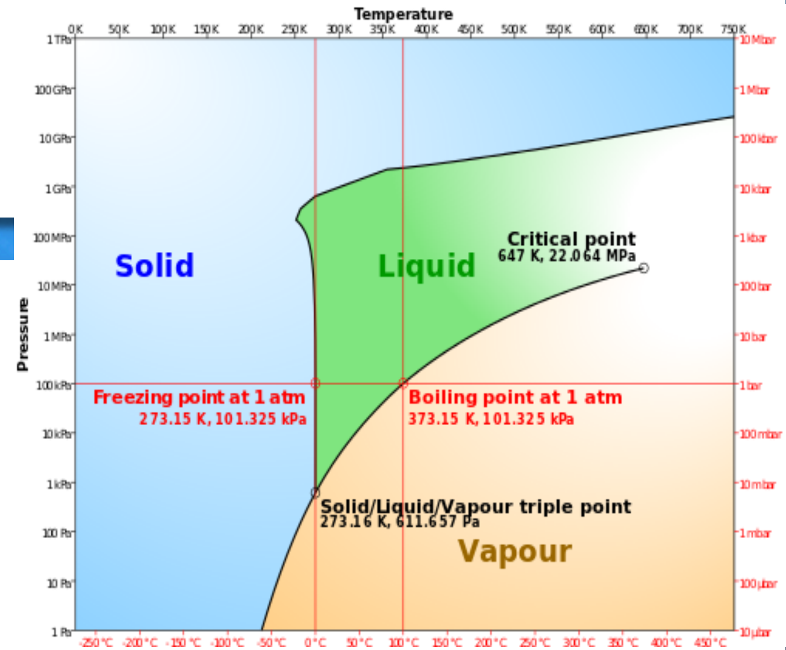
A cylindrical fused quartz vessel from Technical Glass Products with hemispherical bottom and quartz flange at top for sealing was prepared with 22±1 g of water and a partial vacuum on top, 8.5±0.5 psia of water vapor at room temperature. The overall volume of water as active detector was limited by the low throughput of the final filter used, described below, likely caused by particulate build-up. The quartz vial was fully submerged in a Huber ministat circulator from Chemglass Life Sciences for thermal regulation, instrumented with three thermocouples for recording the temperatures, including the exothermic increase [7]. These were located near the top (below the flange), middle (water line), and bottom (hemispherical tip). A piece of plastic scintillator with an attached silicon photomultiplier (SiPM) served as the muon veto, situated below the thermo-regulating circulator, but aligned with the central vertical axis of the quartz.

A. Water Purification

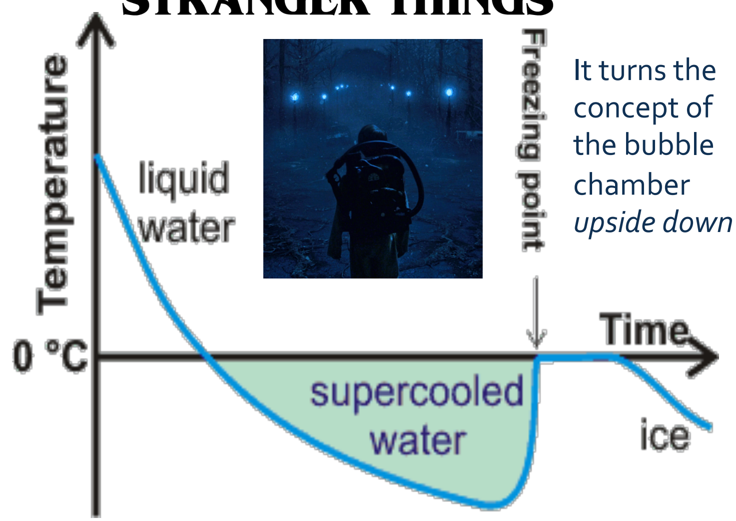
Ordinary tap water was passed through a commercial deionizer and a 0.150-μm filter first, then boiled. Steam passed through multiple μm-scale filters and a final 20-nm NovaMem PVDF thin-film membrane filter similar to that used by [8], which remained in place above the quartz jar during operation. The quartz vessel was prepared by ultrasonic cleaning with an Alconox solution for 15 minutes at 50°C and 25 kHz, rinsed with deionized and pre-filtered (150-nm) water above, then dried before sealed in its flange assembly, in a Class-1000 cleanroom. A low-power vacuum pump reached ~1 psia before steam flow.

What is Supercooling?

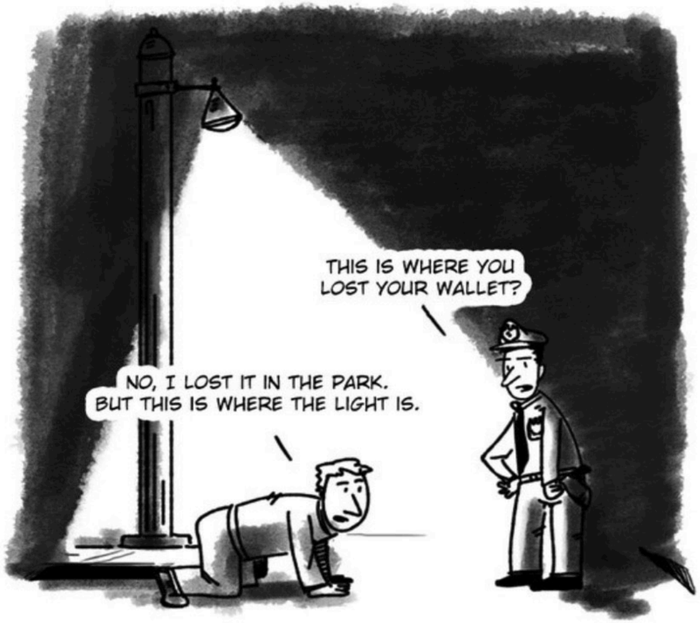
- A liquid is cooled below its normal freezing point, not using freezing point depression
  - Metastable
  - Requires high purity and a clean, smooth container, just like with superheating liquid
- Freezing will occur when the liquid finds a nucleation site, or it is otherwise disturbed
  - One cannot stop nucleation: it snowballs
  - This process is highly exothermic: at the right
- Smaller samples are easier to cool
  - Min temperature depends on radius of sample (Bigg 1953, Mossop 1955)
- Unexplored phase transition in high-energy particle physics!
  - Cloud and bubble chambers already done
  - Latter case: at big scale, even for DM (PICO)

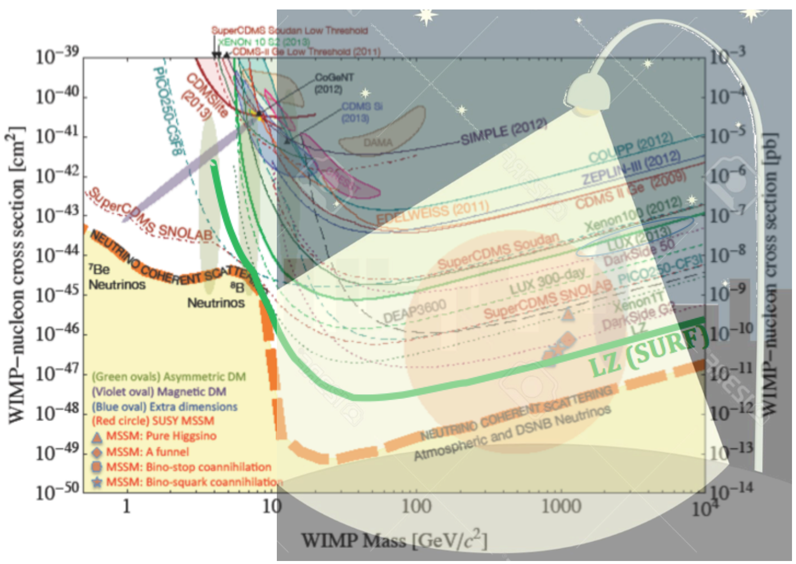


STRANGER THINGS



It turns the concept of the bubble chamber *upside down*





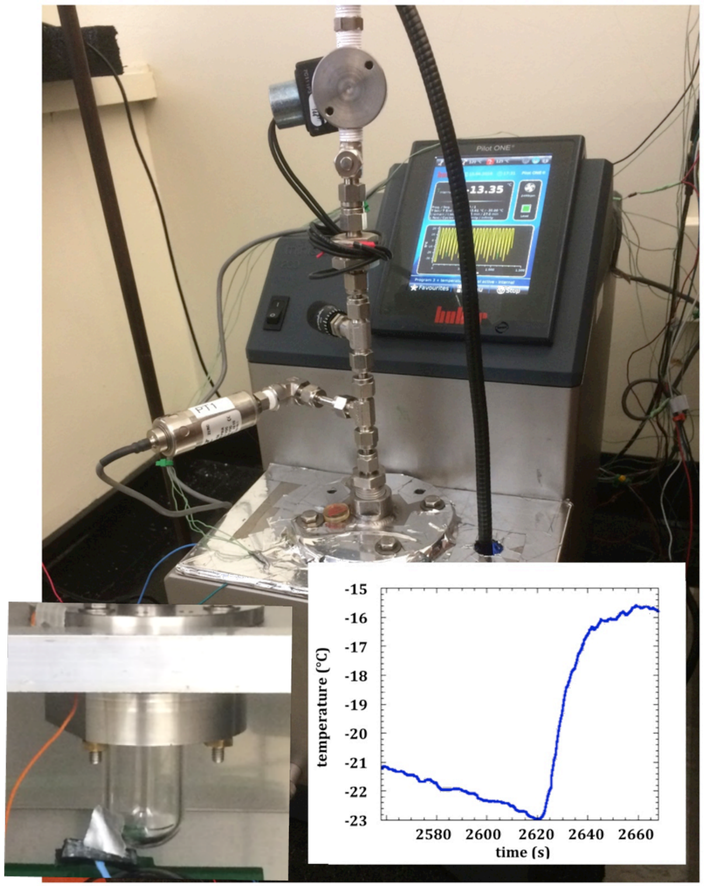
Motivation

- Continued lack of discovery of dark matter as ~50-100 GeV/c^2 mass WIMP
  - Motivates looking elsewhere
- What better target for lower-energy recoils, than the lightest possible target element, hydrogen?
  - Hydrogen bubble chamber would be great, but the safety…
  - Other ideas exist already, so far from only game in town, even at ~1 GeV
- Water is inexpensive and relatively easy to purify even on large scales (SNO, SuperK) while great at moderating n's
  - Cheap and scalable particle detection technology in the past already

The Challenges

- Getting as cold as feasible, sans unwanted nucleation as a background
  - If like bubble chamber except in reverse, colder would be better, because it would probably mean lower energy threshold
  - Must not just avoid particulates (heterogeneous nucleation) but also the homogenous nucleation limit (which may imply a 0-threshold asymptote)
- Finding the ideal rate of cooling
  - Too slow means low live-time and/or more opportunity for an unwanted nucleation
  - But too fast means thermal lag/gradient, which encourages nucleation
- The most common neutron sources (AmBe, Cf) also produce gammas
  - Crucial for nuclear recoil calibration, but want to study electron recoil too
  - Can add Pb as shielding for gamma-rays but changes NR energy spectrum

Prototype Detector Setup



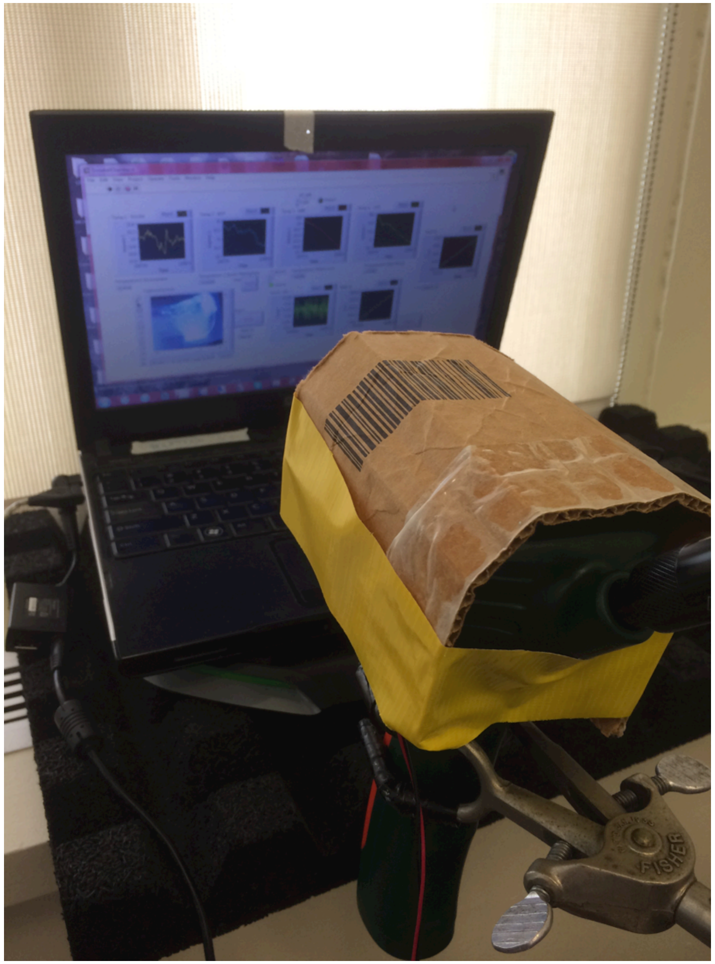
- 20 g of pure water in a smooth, cleaned fused quartz vessel (TGP, PICO's supplier)
  - Water is multi-filtered, deionized, and ultimately distilled through 20-nm flat-sheet non-linear membrane (gas only)
- Thermocouple thermometers (averaged)
  - 3: top, mid, bot -- to see exothermic spike
- Borescope camera for image acquisition
  - Only 1, so no 3D info, but counted scatters
- Muon veto underneath quartz, lined up
  - Plastic scintillator with an attached SiPM

Operation

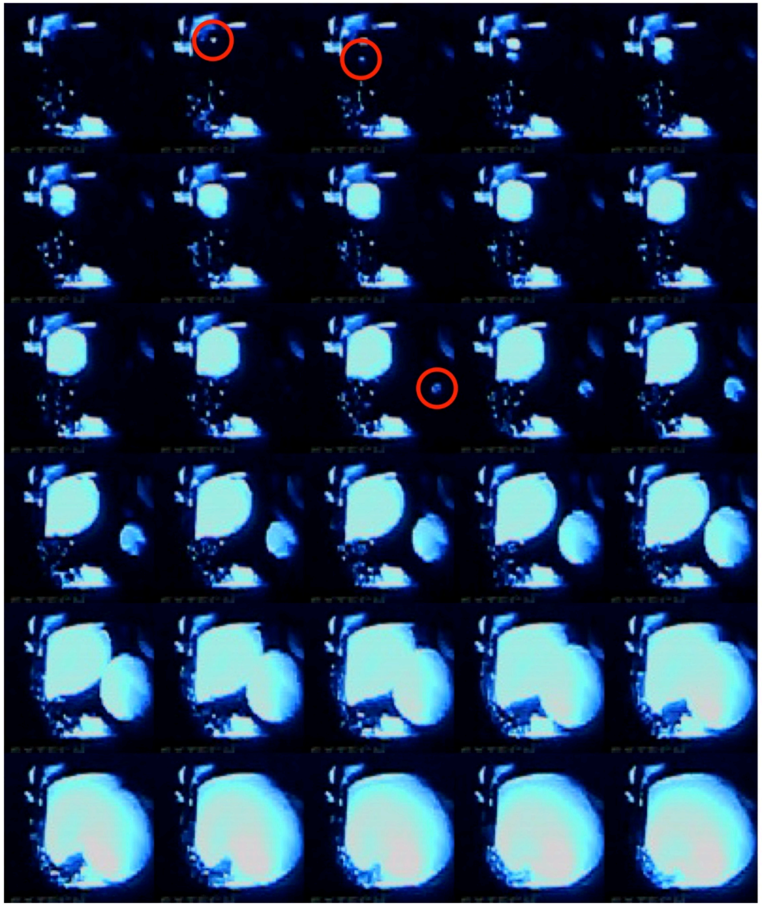
- About -20 °C and lower achieved, at a maximum cooling rate of -2°C per minute
  - Water may be able to go as cold as < -40°C
- Partial vacuum of ~8-9 psia (water vapor)
- 1-hour cooling and heating (melting) full cycle, with ~50% time spent < 0°C ("live")
- Multiple run conditions / calibrations
  - Control (no radioactive source)
  - 200 n/s AmBe (with, w/o Pb shielding)
  - 10 uCi Cs-137 gamma-ray source
  - 3,000 n/s Cf-252 (with Pb shielding)

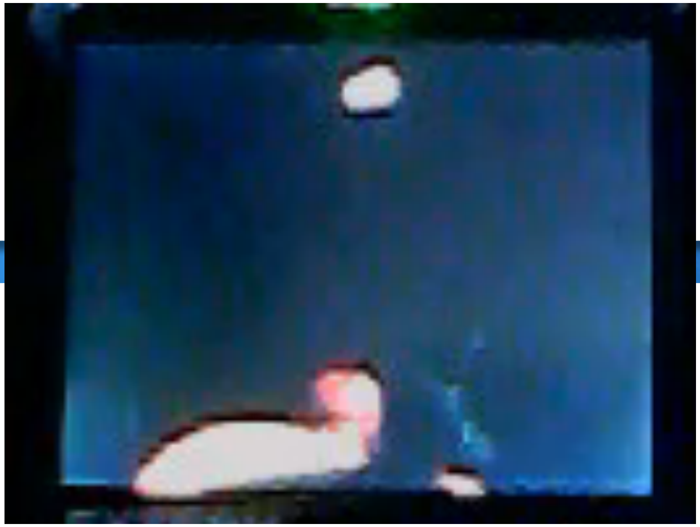
neutrons as WIMP-like stand-in as typical <== *here*

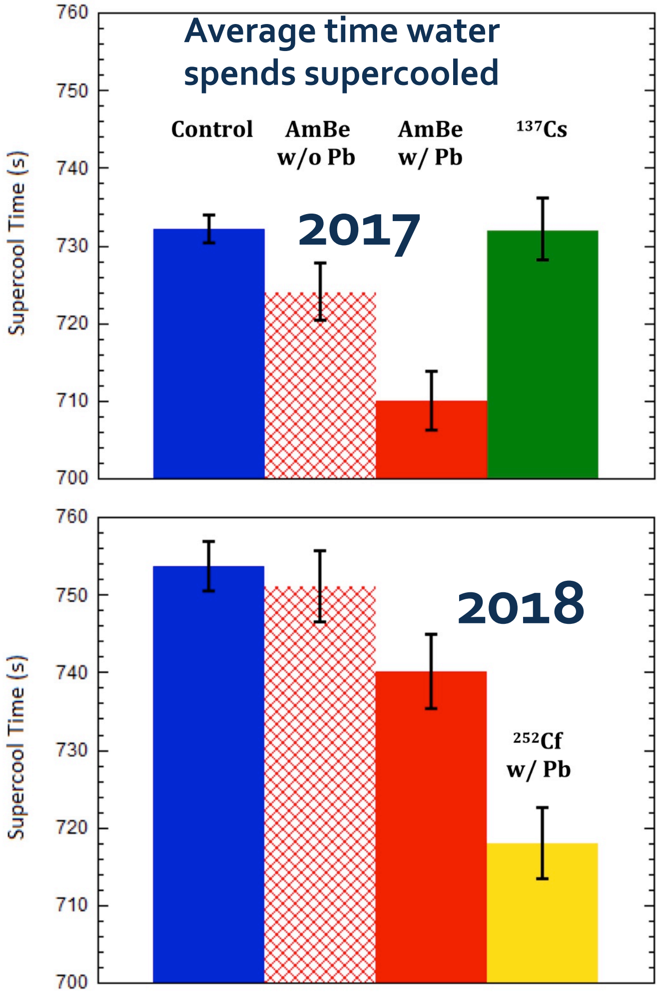
- Shielding stops gammas from interfering with the thermocouples' operation
  - Also makes more n's (secondaries)



Example Events





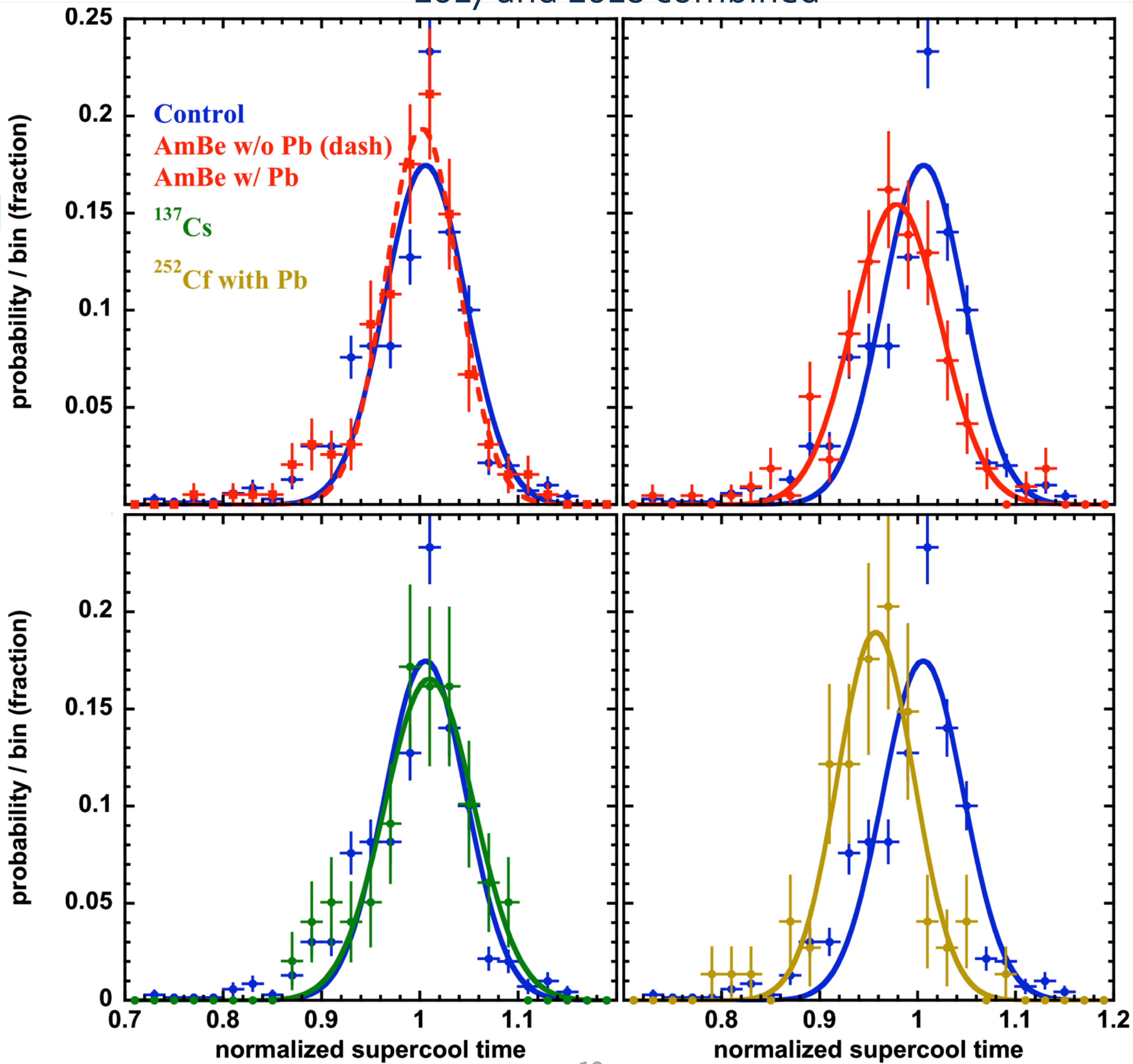


Calibration Type	T_{min} (°C) 2017	T_{min} (°C) 2018
Control (no source)	-20.31 ±0.05	-20.07 ±0.07
AmBe w/o Pb	-20.70 ±0.10	-20.53 ±0.11
AmBe w/ Pb	-20.00 ±0.11	-19.69 ±0.14
^{137}Cs OR ^{252}Cf	-20.40 ±0.12	-19.30 ±0.09

First Important Result

- Reduction in supercooled time in presence of neutron sources
  - Effect enhanced with lead shielding
  - Bigger effect with stronger source
- No statistically significant effect so far from gammas (662 keV)
  - May be a sign of good ER rejection?
- We conclude that neutrons can freeze water (first observation)
  - Alternated the source and BG runs
  - Checked room temp as systematic

2017 and 2018 combined



types of events

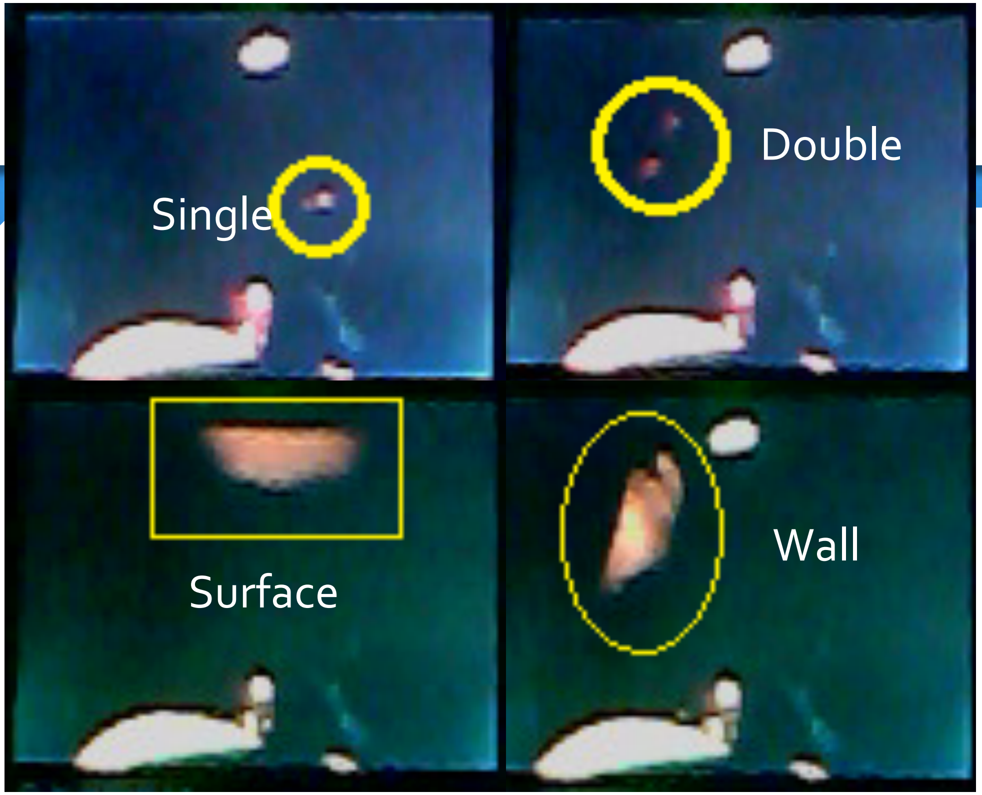


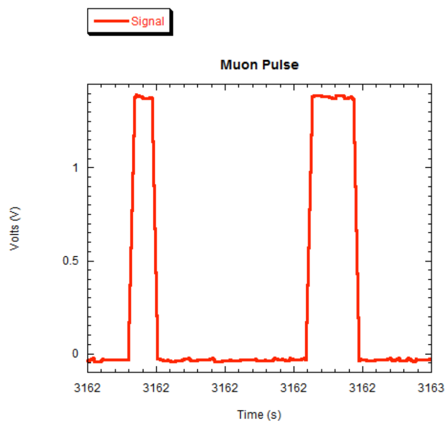
Image Analysis

- Even without a second camera or mirror, can kind of tell wall/surface events
  - Most common, especially in control results
- Still far from perfect by eye
  - So, focus only on counting
- More multiple scatters by A LOT in neutron data
  - Confirmation neutrons can cause crystallization
  - Triples, quad seen even

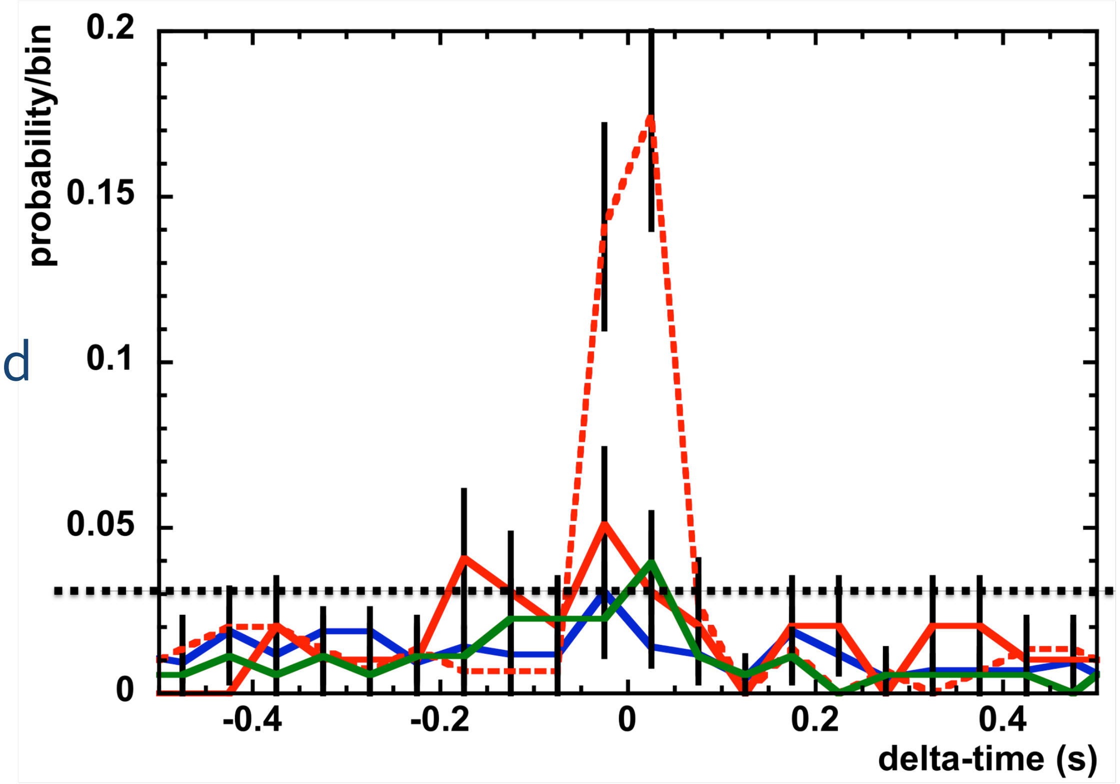
fractional probabilities

#Vertices	Control	AmBe	w/ Pb	^{137}Cs γ
1	0.9532	0.8539	0.8000	0.9474
2	0.0468	0.1348	0.1846	0.0526
3	0.0000	0.0000	0.0154	0.0000
4	0.0000	0.0112	0.0000	0.0000
(uncertainty)	3×10^{-5}	5×10^{-4}	9×10^{-4}	2×10^{-4}

Muon Veto Analysis



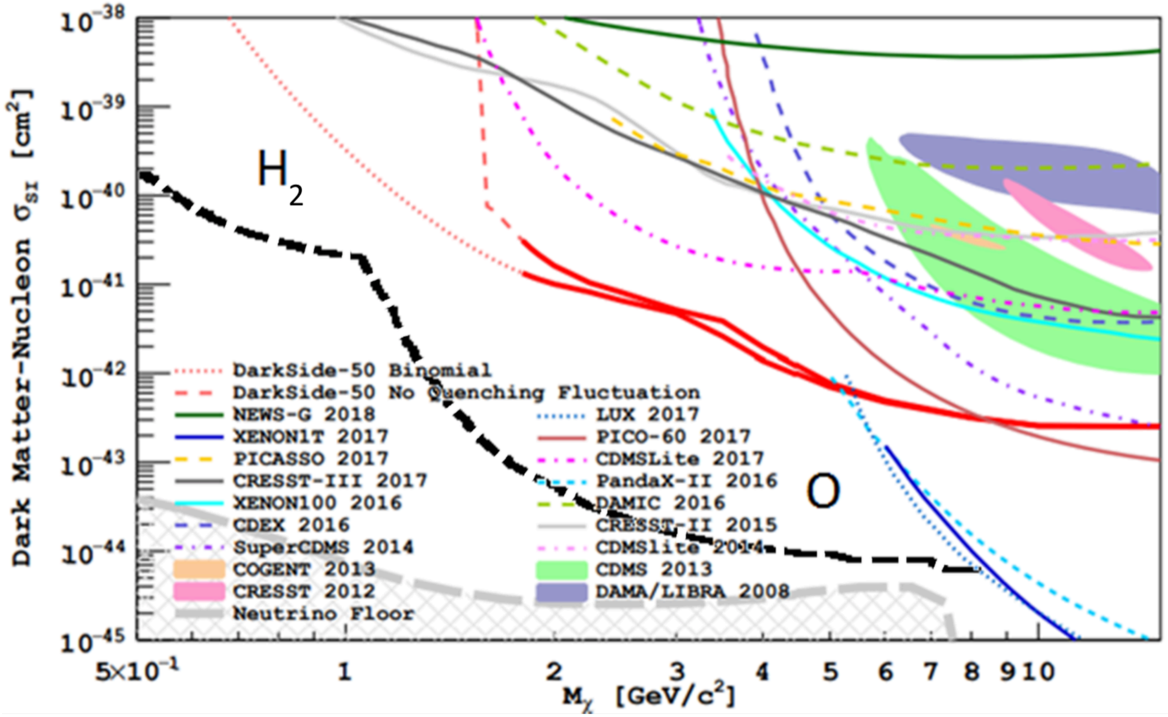
- A huge peak above accidental coincidence probability
  - Done with images
  - Checked with temperatures
- But only in UNshielded AmBe data
- Still puzzling
- May be gammas (higher energy than Cs) or MeV n's



Sensitivity Projection

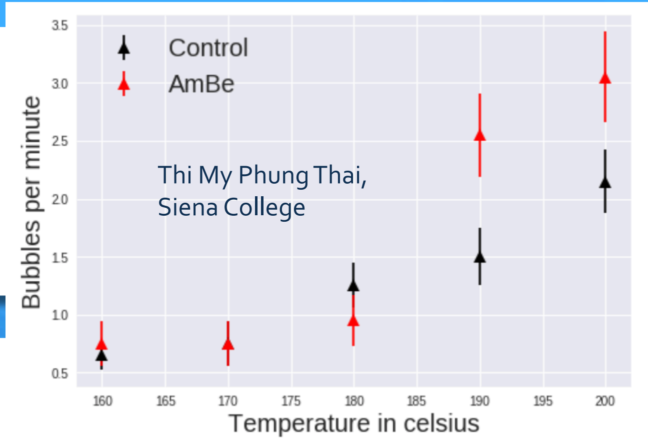
- This is ~aggressive
  - Assumes 1 keVnr energy threshold
  - Zero BG counts
  - Kisses ν shoulder
- 10,000 kg-days
  - So, only 10 kg UG for 3 years, or 100 for 3 months!!!
- If supercooling can't achieve such a low threshold, ready with another idea…

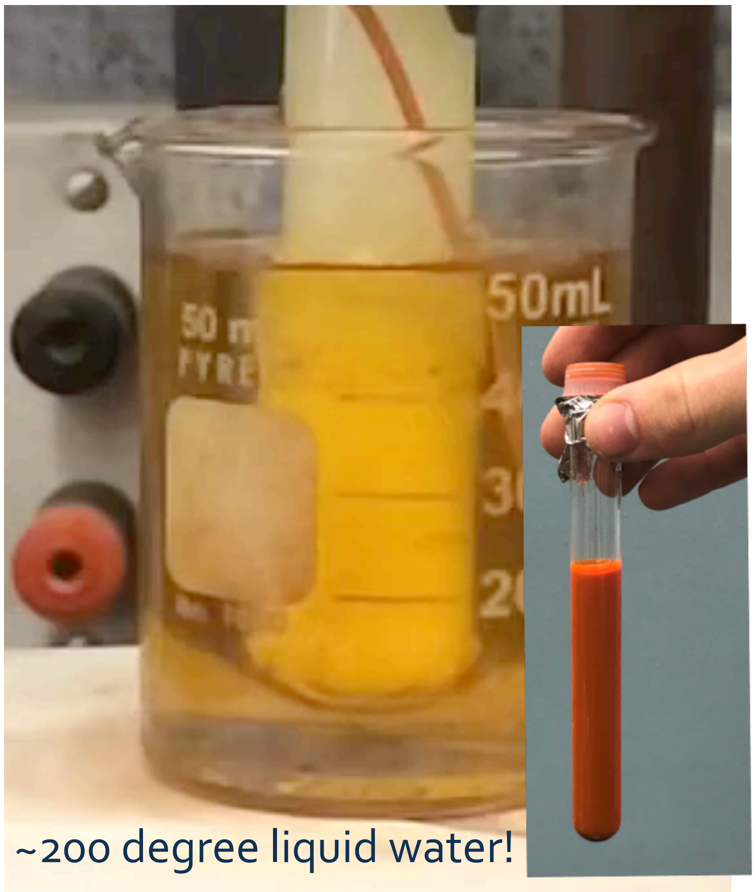
shamelessly copied plot from current best in this mass range, DarkSide (arXiv:1802.06994) and overlaid our own curve



fraction of the cost (and complications) of competing experiments at 500 MeV to 5 GeV! Potentially self-confirming

Plan B (or ~parallel) Superheated Water



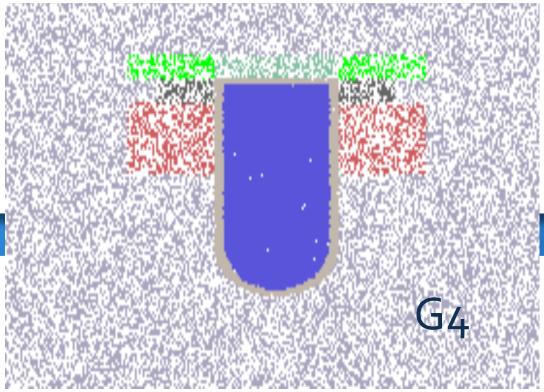


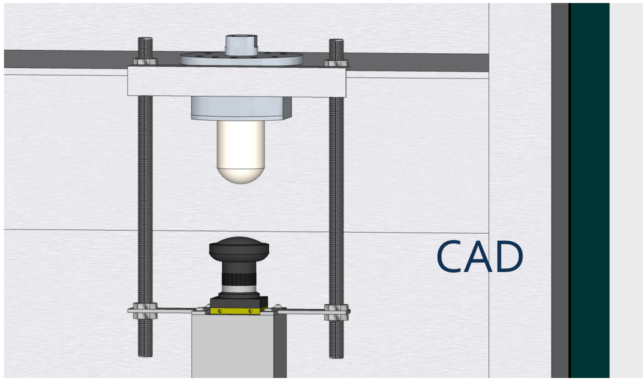
~200 degree liquid water!

- Superheated droplet geyser
  - Combine best ideas from the SDD, the bubble chamber, and the geyser, with recondenser
- Water droplets emulsified in high-temperature oil
  - Self-resets post explosion
- Quantum dots for energy reconstruction (scintillate?)
  - Can be made too small to trigger nucleation
  - Useful for snowball too?

(Near-) Future Work

- More cameras (higher FPS)/mirror for 3-D recon
  - Auto, including event type; snow directionality?
- Lower threshold with lower T, hydrophobicity
  - Volume optimization, of water, and environment
- Increase the livetime (biggest current drawback)
  - Modular detector
  - Extreme heat
  - Supercooled droplet detector (ScDD)
- Full Geant4 sim, for n and γ rates and #vertices
  - Molecular dynamics in more distant future
- Exhaustive characterization of energy threshold
  - Possibly P too not just T, and more source types
- Hardest: secure some $$, start global program





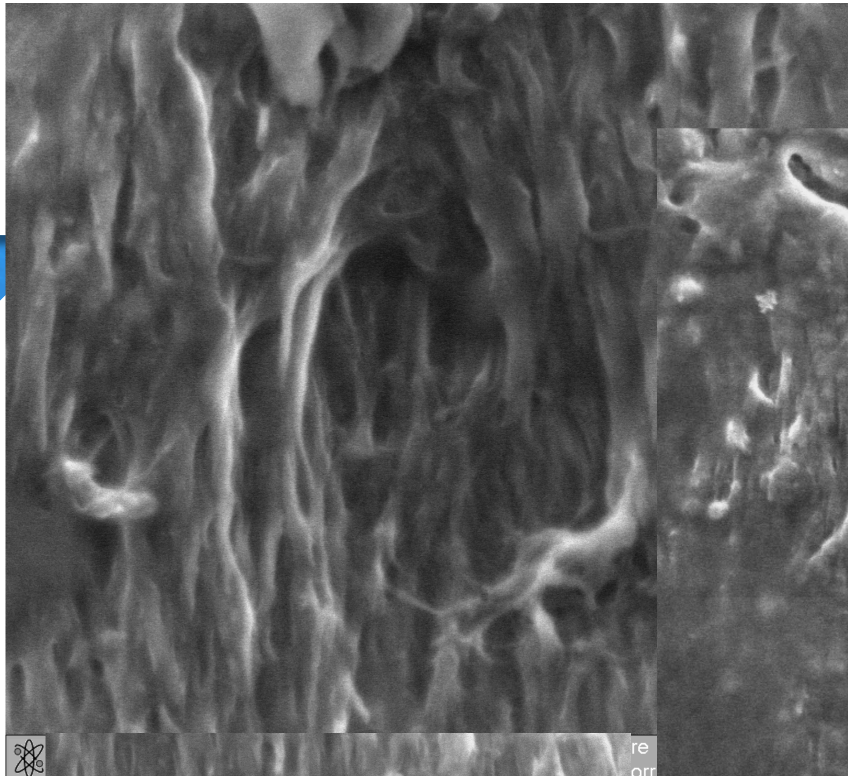
Conclusion

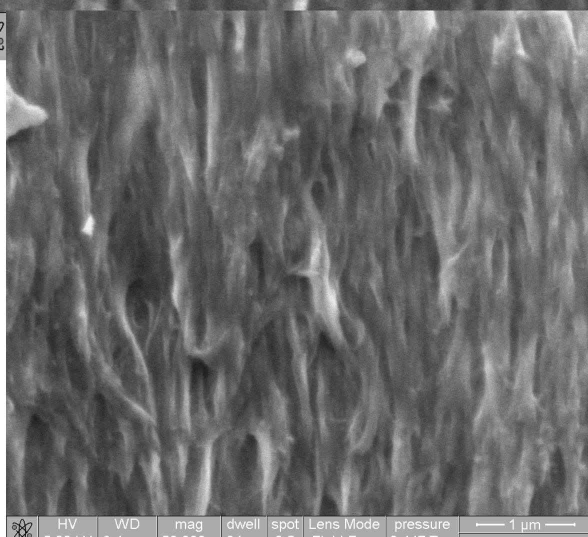
+ Neutrons can make supercooled water freeze: a new discovery
+ They can even multiply scatter, as they do in a bubble chamber!
+ At least some types of events are coincident with a scintillator
+ There is at least some degree of electron recoil discrimination
+ Energy threshold is not known, but high right now still probably
+ Possible tangential relationship to other fields (think CLOUD @CERN)
+ All in all, this is a promising start to a completely new technology

Thank You!!

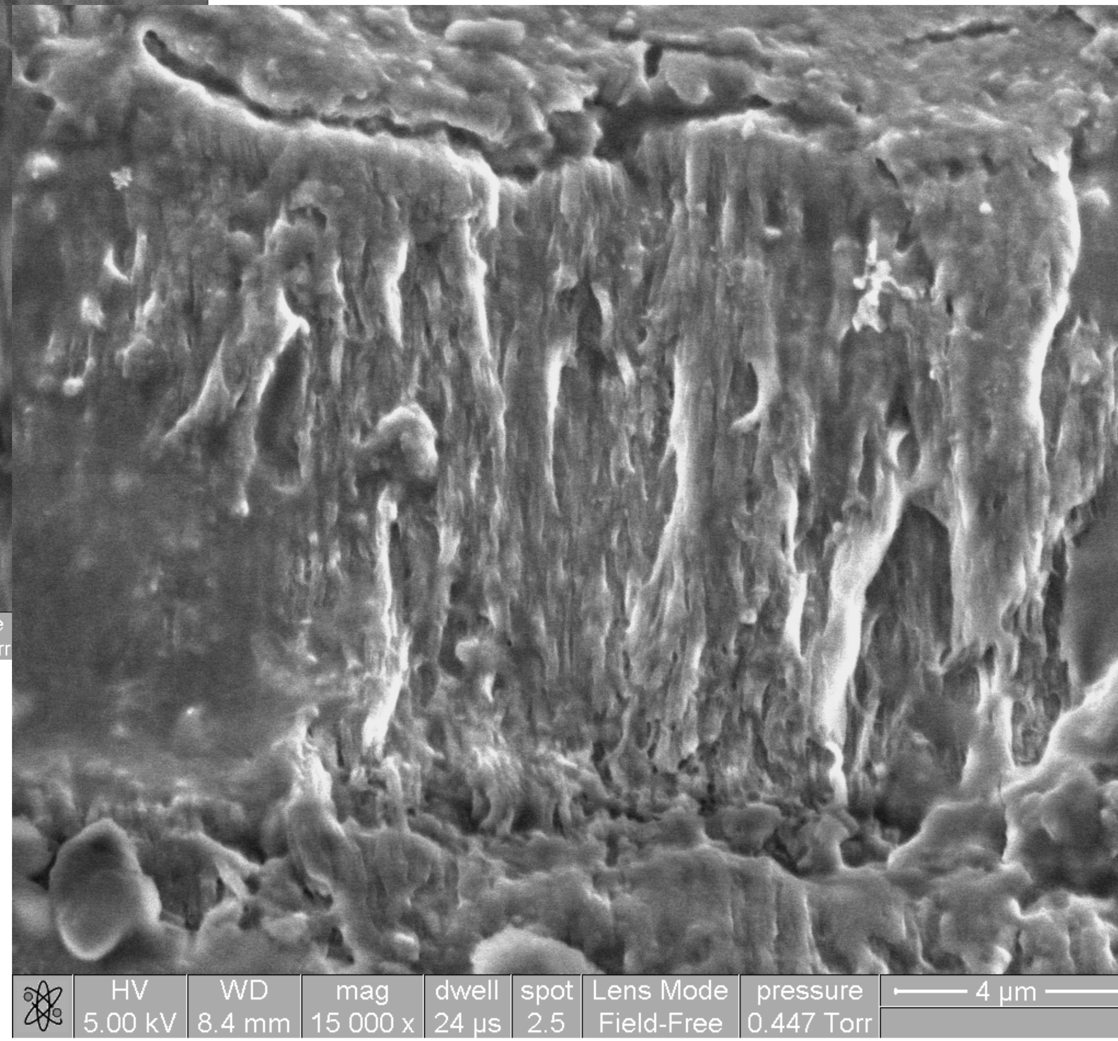
- Questions???
- Backup slides.....

This research was funded by a UAlbany PIFRS award





HV
5.00 kV
WD
8.4 mm
mag
50 000 x
dwell
24 µs
spot
2.5
Lens Mode
Field-Free
pressure
0.447 Torr
1 µm



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Lens Mode
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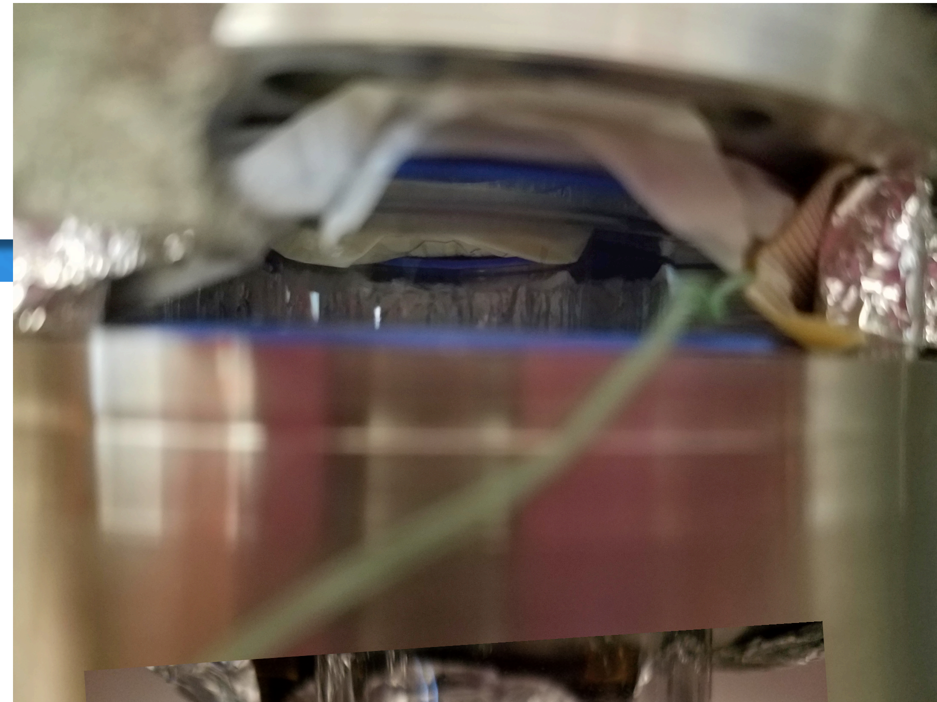
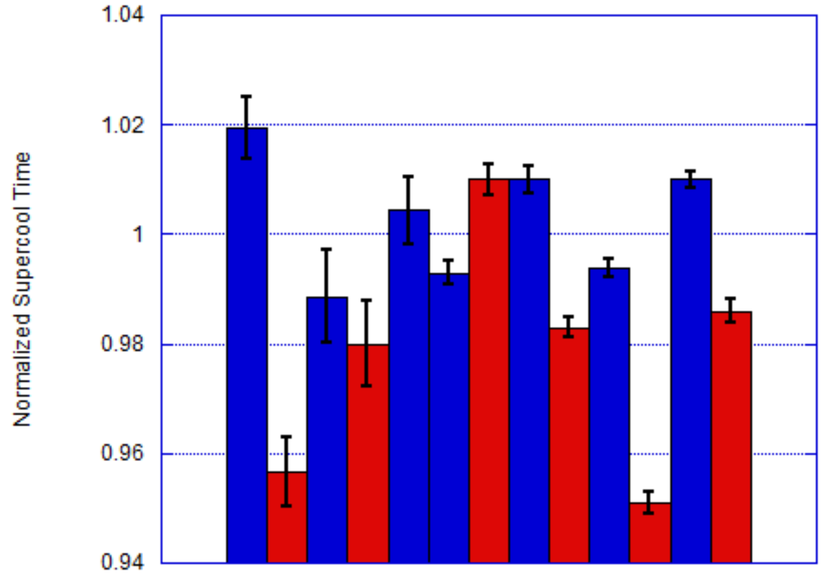
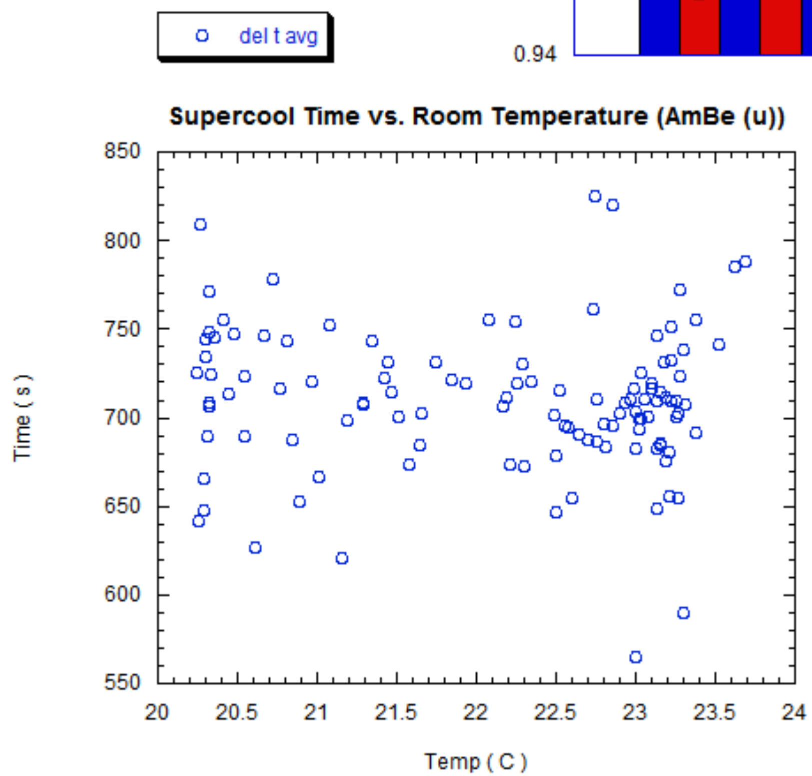
4 µm

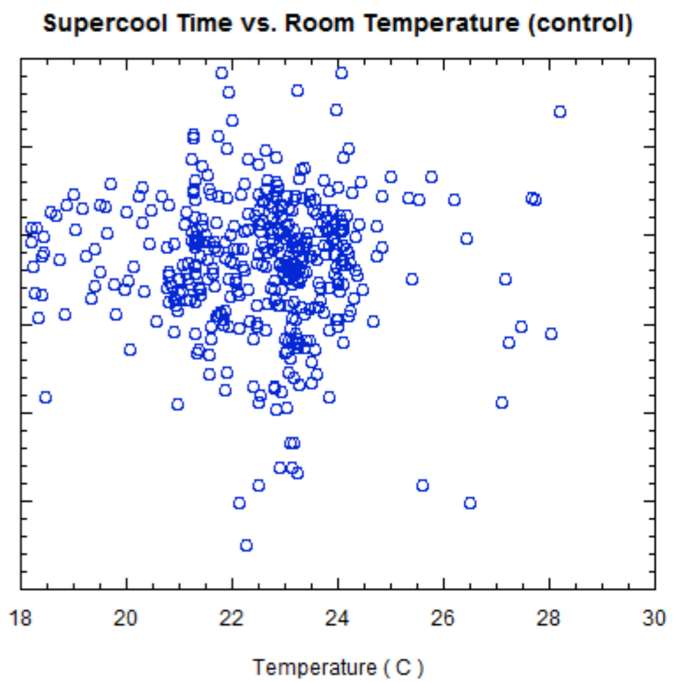




1.04
1.02
1
0.98
0.96
0.94
Normalized Supercool Time



del t avg
Supercool Time vs. Room Temperature (AmBe (u))
850
800
750
700
650
600
550
20
20.5
21
21.5
22
22.5
23
23.5
24
Time (s)
Temp (C)



Supercool Time vs. Room Temperature (control)
18
20
22
24
26
28
30
Temperature (C)

Double Crystal Slide Show