The Snowball Chamber: An Alternative Detection Method for Dark Matter

Matthew Szydagis, UAlbany Physics APS DPF 2019 Conference, Northeastern University Boston

UNIVERSITY AT ALBANY
State University of New York

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arXiv:1807.09253

- Submitting for publication in near future
- Interdisciplinary implications (chemistry, meteorology, biology)
- Thanks for listening to me discuss my preliminary results today
- LZ/LUX + NEST is my "day job". Wearing my (G3) R&D hat today

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The Snowball Chamber: Neutron-Induced Nucleation in Supercooled Water

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(Dated: July 25, 2018)

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.

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 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.

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Presented at Many Conferences Now

And all over the popular press now too due to April 2019 APS Meeting (press conference!)

- CPAD Instrumentation Frontier Workshop, Brown
- Novel Instrumentation for Physics, Puerto Rico
  - Invited full-hour plenary
- Dark Interactions BNL, plus instrumentation seminar
- Brandeis University Dark Universe colloquium series
- International Dark Matter 2018, Brown University
  - Plenary announcing first conclusive results to world
- CIPANP 2018, Palm Springs (poster)
- MIT Workshop on Table Top Particle Physics
  - Invited plenary, on the earliest preliminary results

<u>people gave us new ideas to try at these</u>

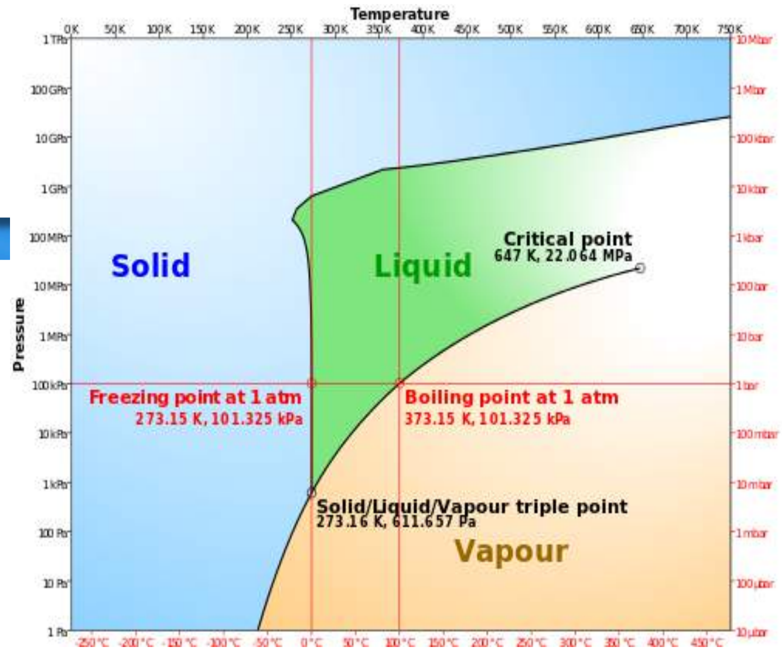
Google these to find my slides and see how our results have evolved with time

my UG students have also gone to conferences: Joshua Martin and Corwin Knight

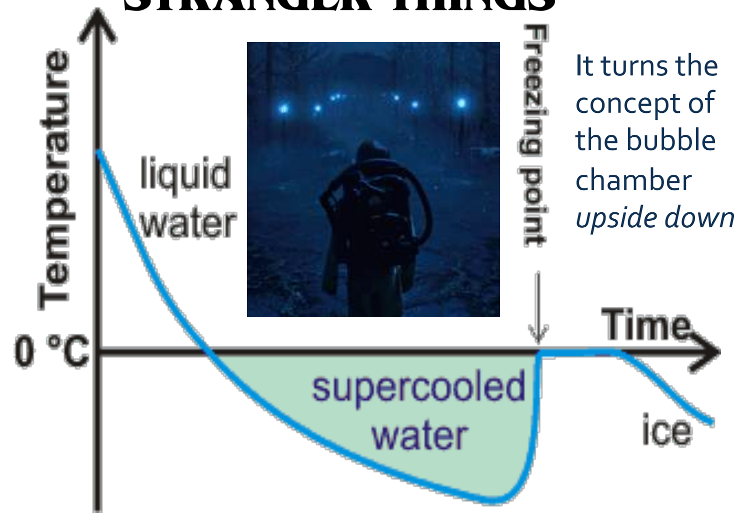
What is Supercooling?

- 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)

DM = Dark matter and PICO = PICASSO + COUPP



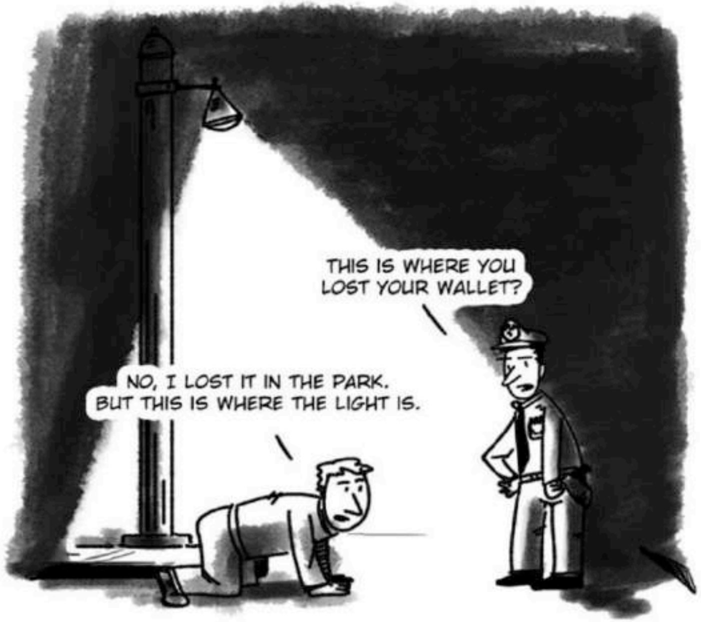
STRANGER THINGS



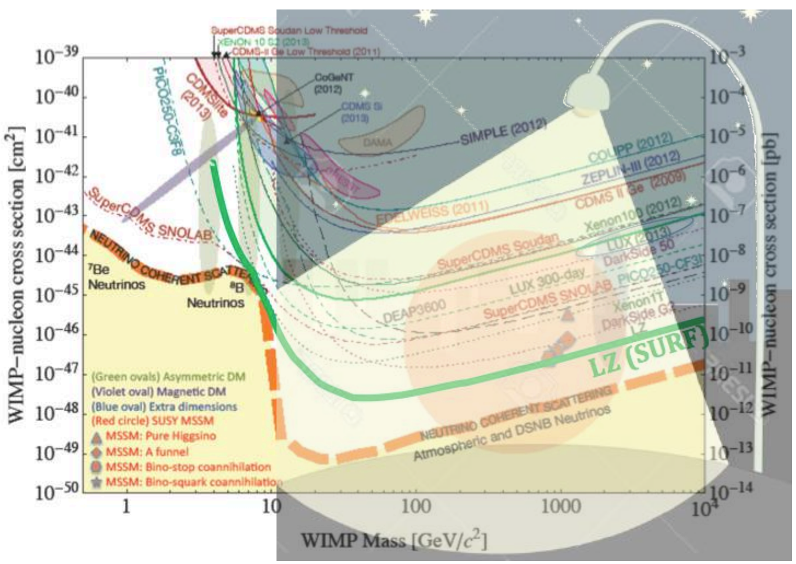
It turns the concept of the bubble chamber *upside down*

Motivation

Hopefully, we are all looking for dark matter in ALL possible places

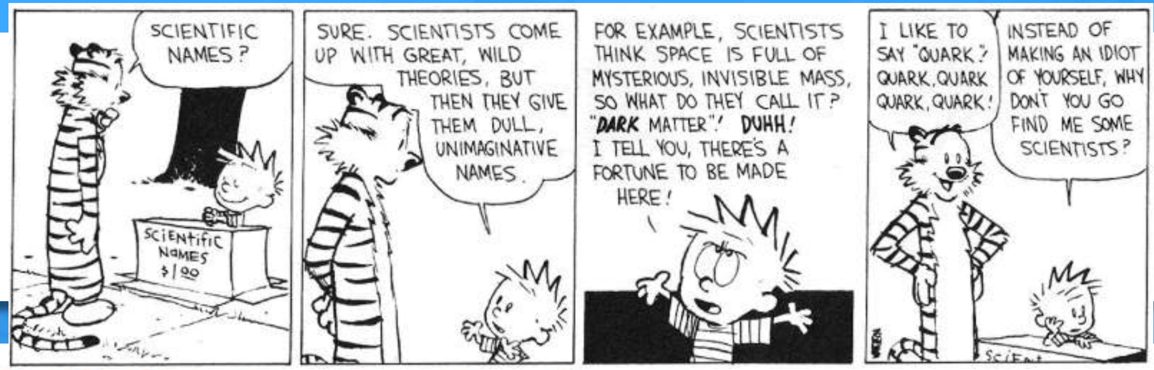


- Continued lack of discovery of dark matter as ~50-100 GeV/c^2 mass WIMP
  - Look elsewhere: dark sectors, freeze-in
- What better target for lower-energy recoils, than the lightest possible target element, hydrogen?
  - Hydrogen bubble chamber would be great, but the safety…
  - Other ideas exist already, 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



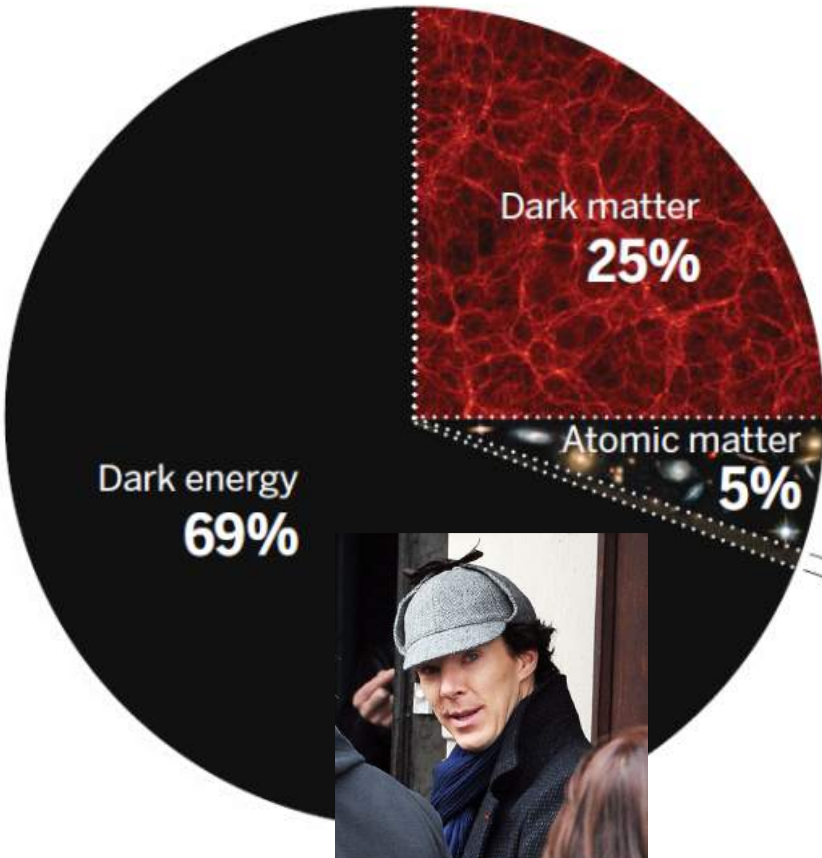
Snowmass (with LZ, my day job, highlighted :-)

Dark Matter = ??????????



The multiple components that compose our universe

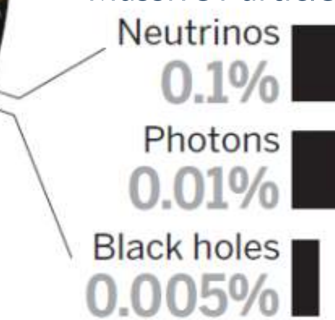
Current composition (as the fractions evolve with time)



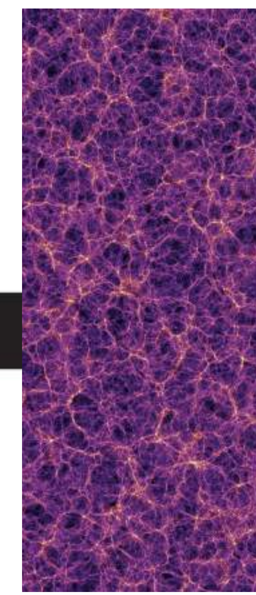
[A Big Hole in Our Knowledge]()

What is this **dark matter**?

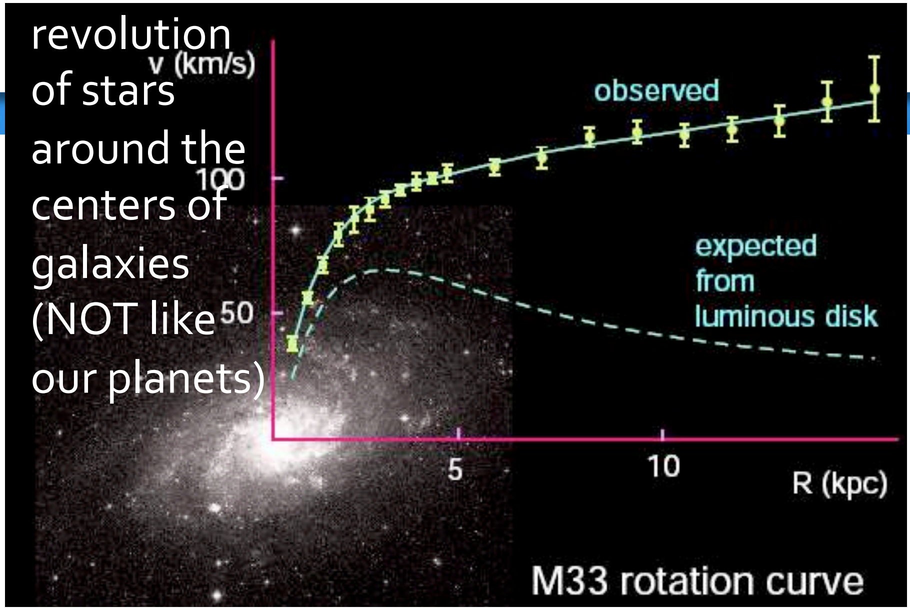
WIMPs? (Weakly Interacting Massive Particles)



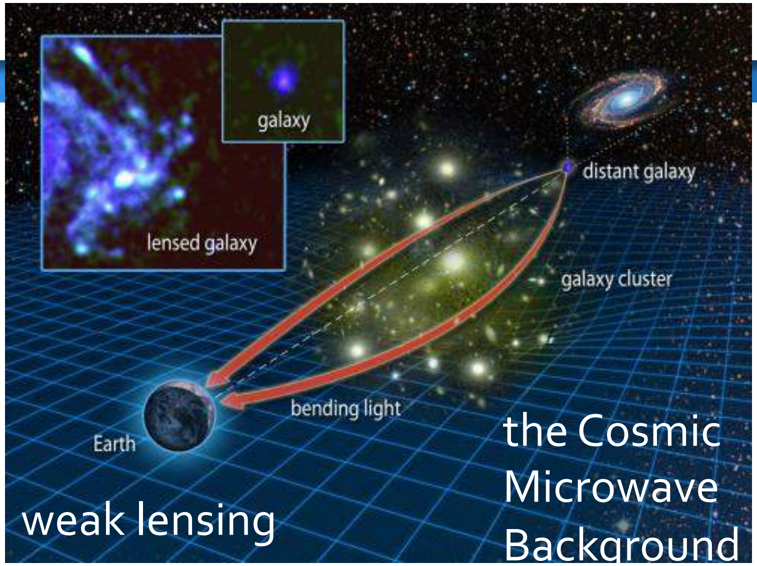
http://cdn.phys.org/newman/gfx/news/hires/2015/thedarksideo.png



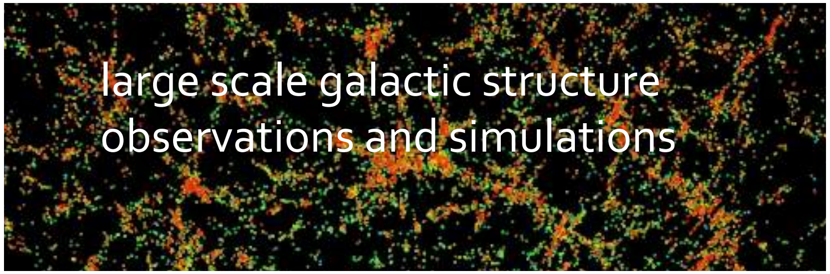
The Observational Evidence



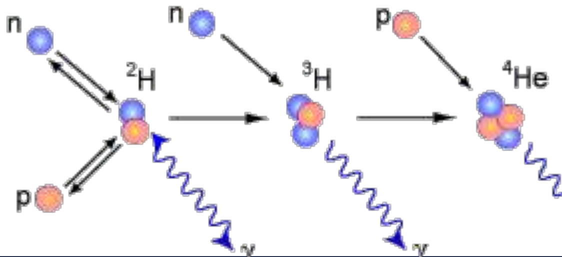
revolution of stars around the centers of galaxies (NOT like our planets)



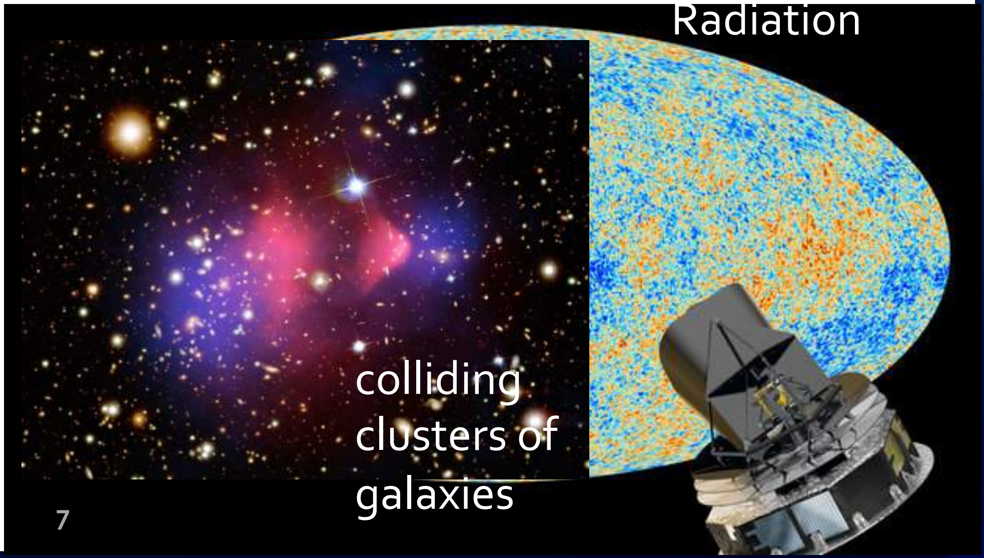
weak lensing



large scale galactic structure observations and simulations



Big Bang Nucleo-synthesis



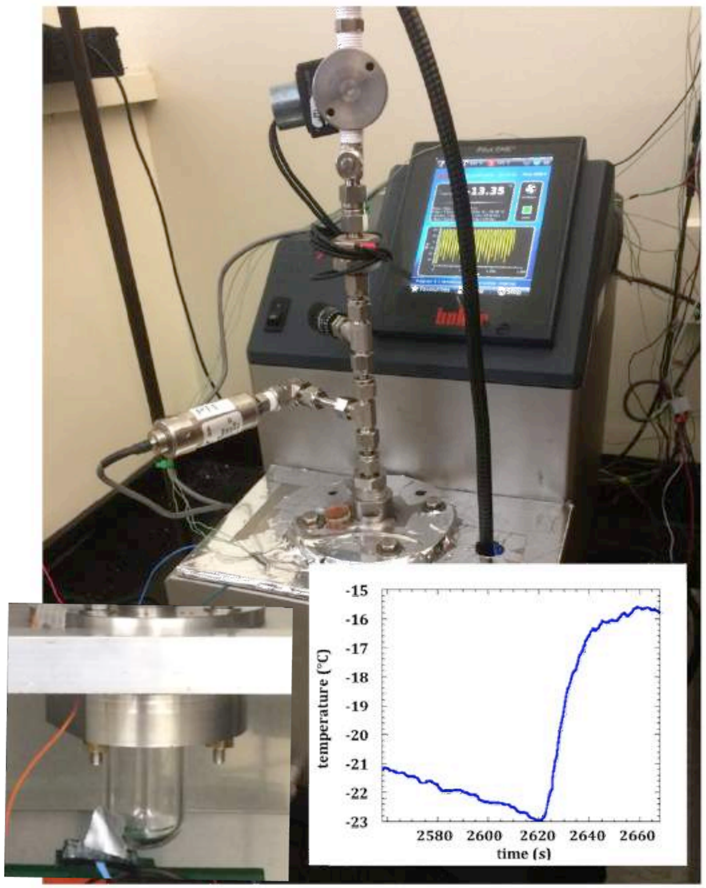
the Cosmic Microwave Background Radiation

colliding clusters of galaxies

The Challenges with Supercooled Water

- 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 (confirmed with lit search)
  - 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

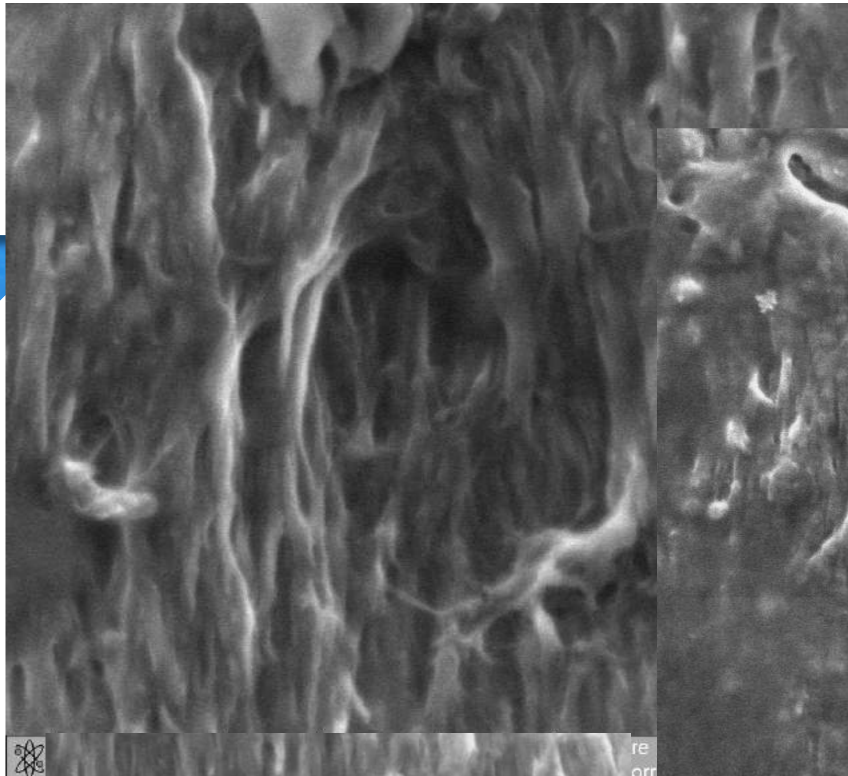
Prototype Detector Setup

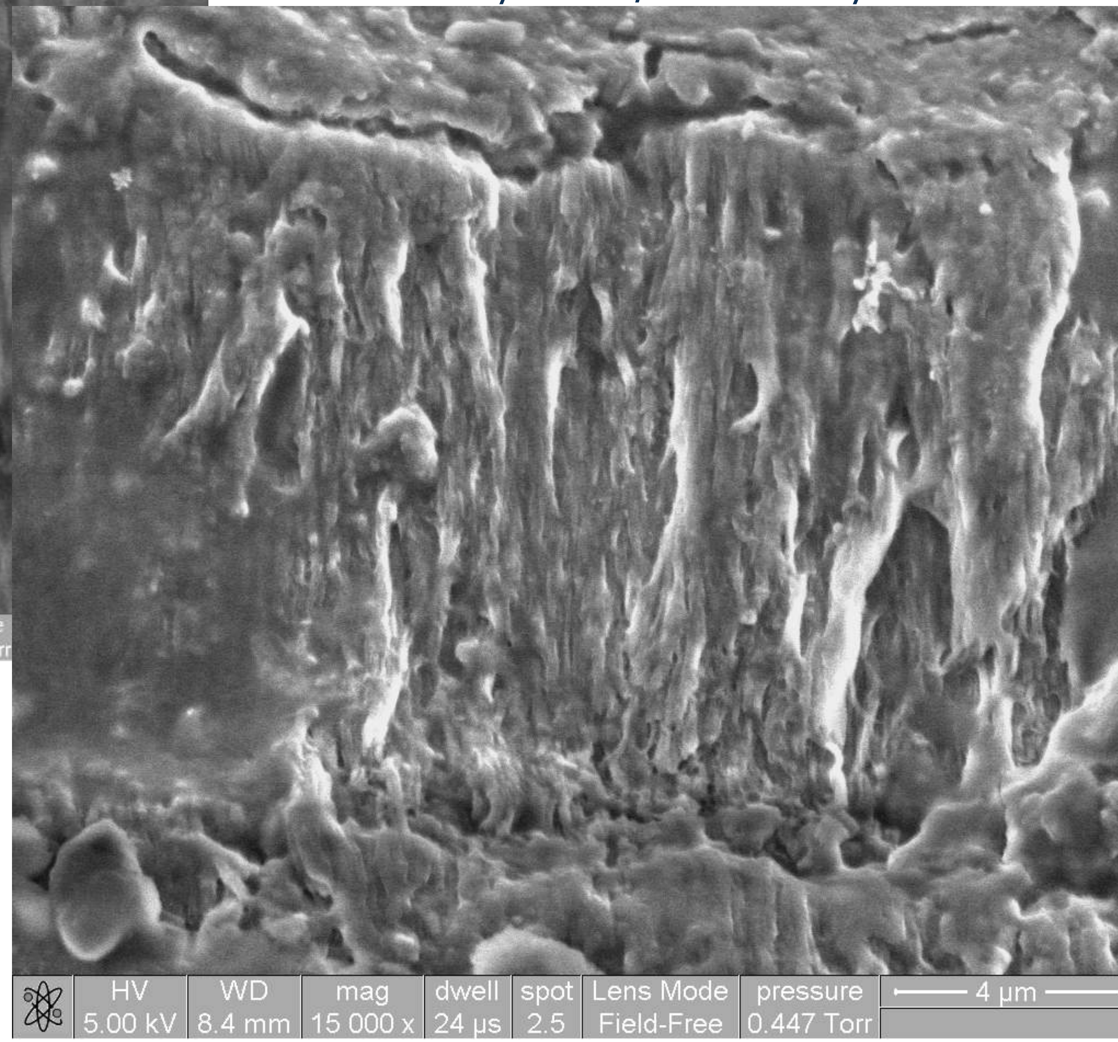


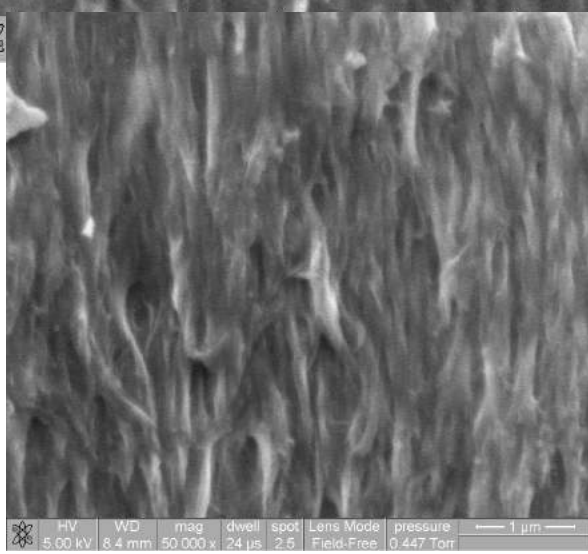
(constructed by Prof. Cecilia Levy
Operated mainly by Corwin Knight, undergraduate!)

- 20 g of pure water in a smooth, cleaned fused quartz vessel (TGP, PICO's supplier)
  - Water is filtered over and over, deionized, and ultimately distilled through 20-nm flat-sheet non-linear membrane (steam)
- 3 thermocouple thermometers deployed
  - 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

Prof. Kathy Dunn, SUNY Poly





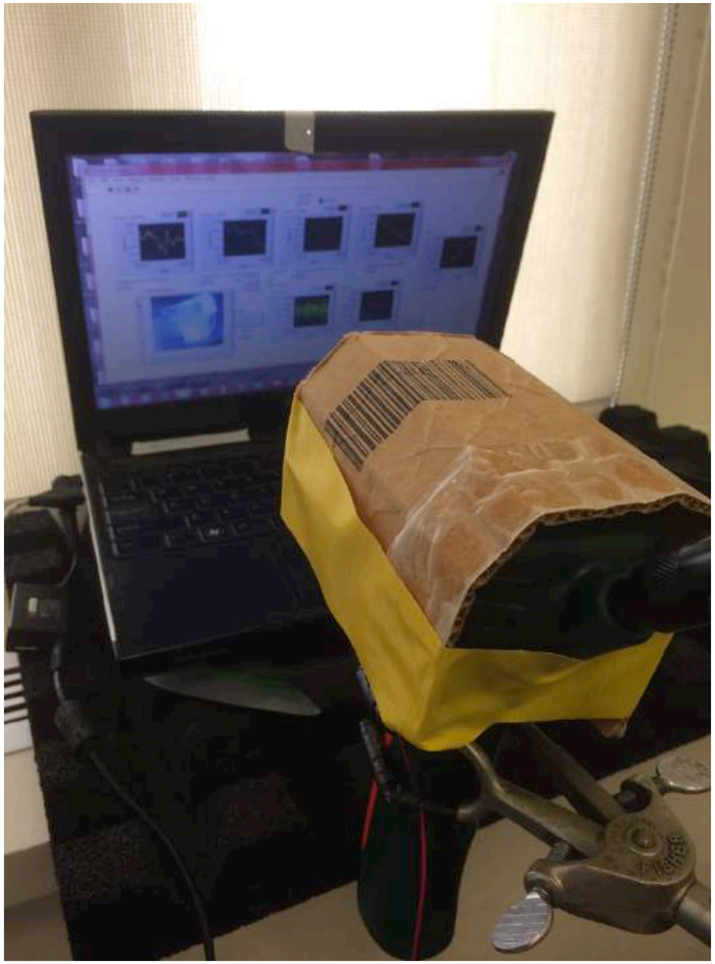


Operation

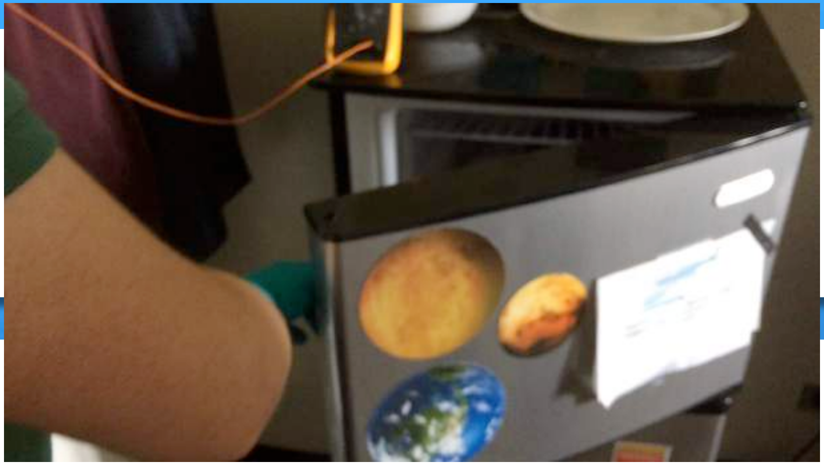
- About -20 °C and lower achieved, at a maximum cooling rate of -2°C per minute
  - Water may be able to go as cold as < -40°C
- Partial vacuum of ~8-9 psia (water vapor)
- 1-hour cooling and heating (melting) full cycle, with ~50% time spent < 0°C (“live”)
- Multiple run conditions / calibrations
  - 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)

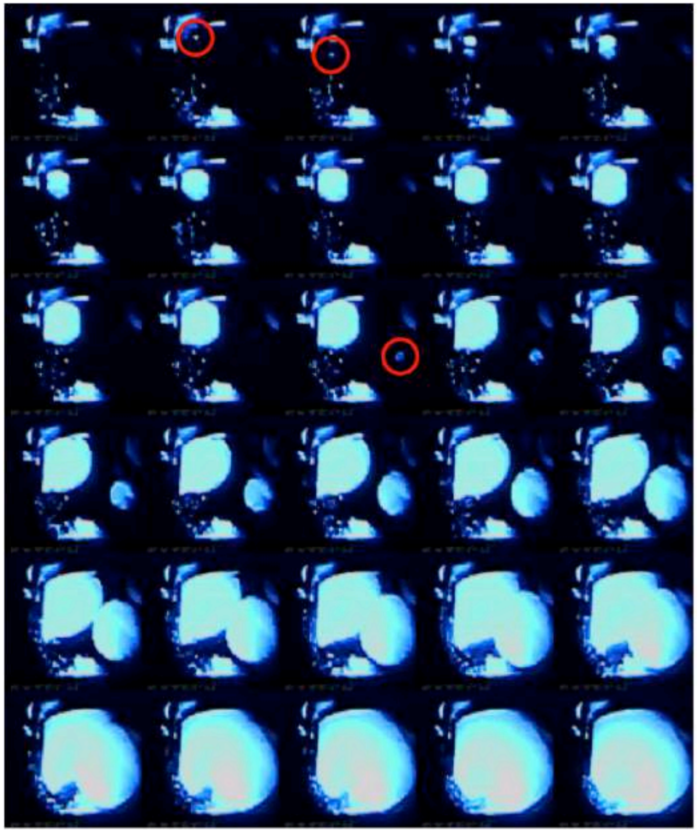


Corwin Knight



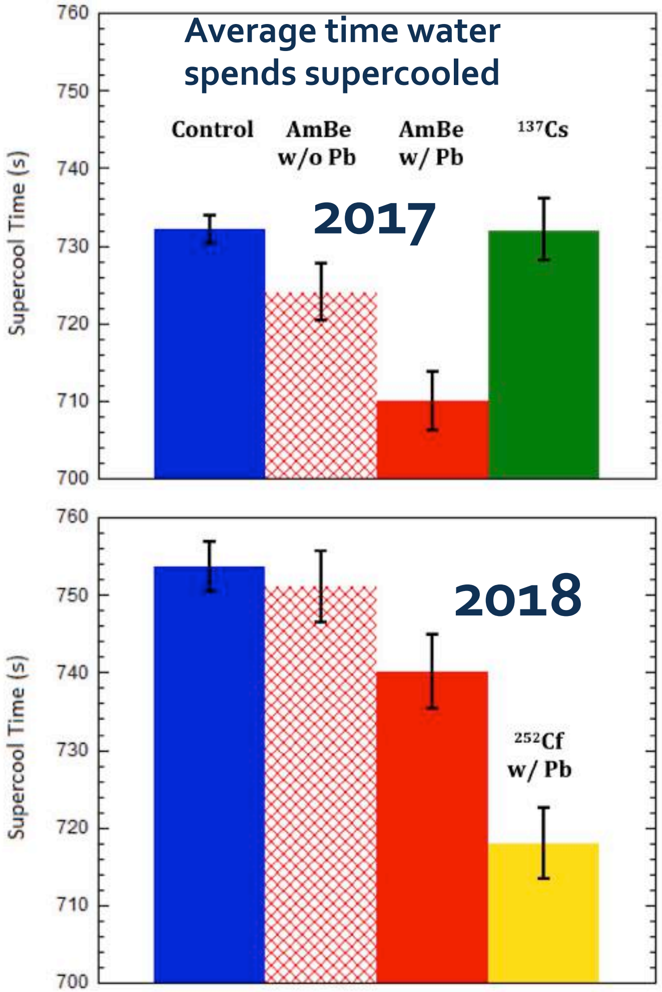
Example Events

https://www.eurekalert.org/pub_releases/2019-04/aps-ch041119.php



Joshua Martin

First Important Result



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

- 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 data sets all combined

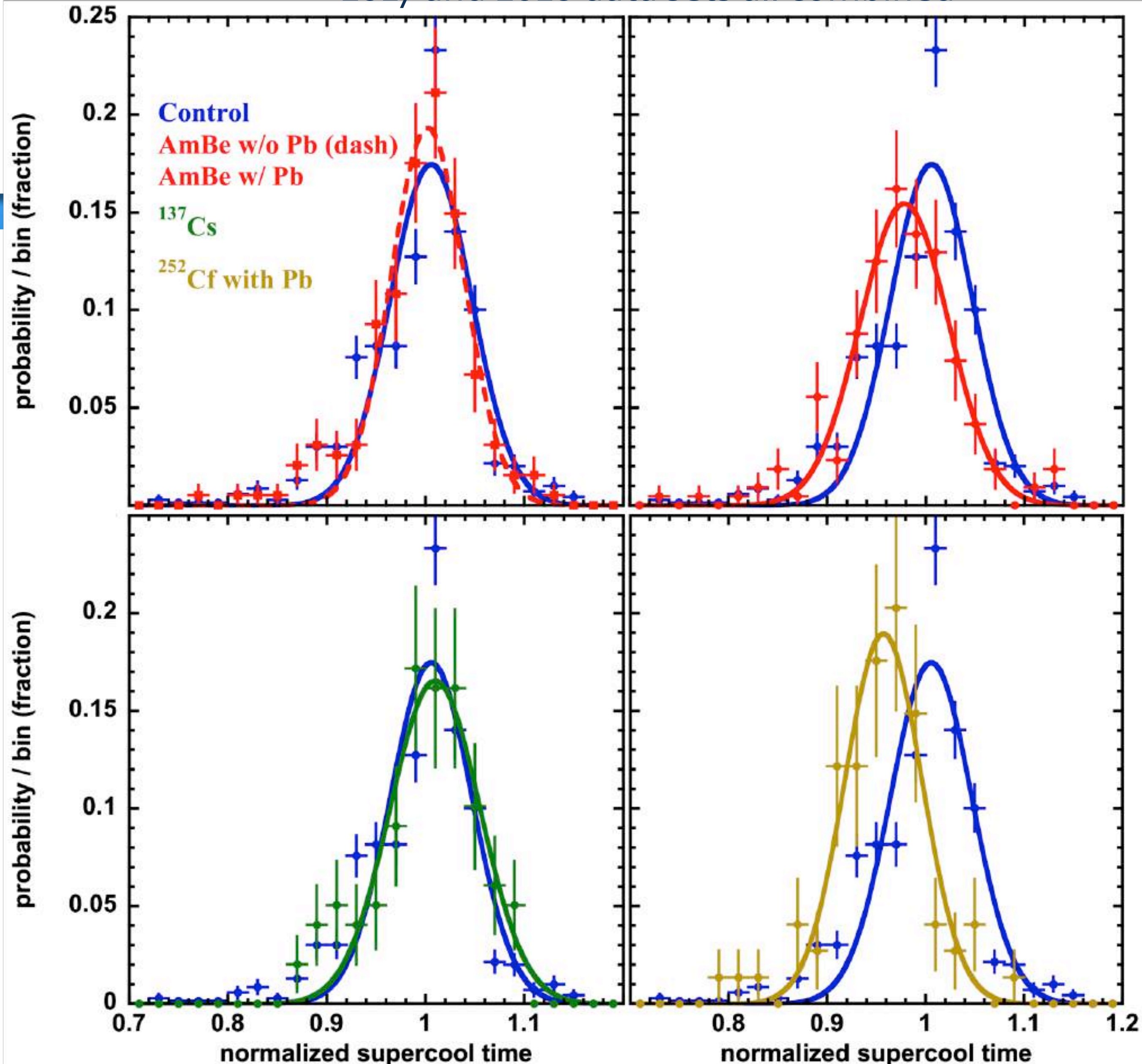
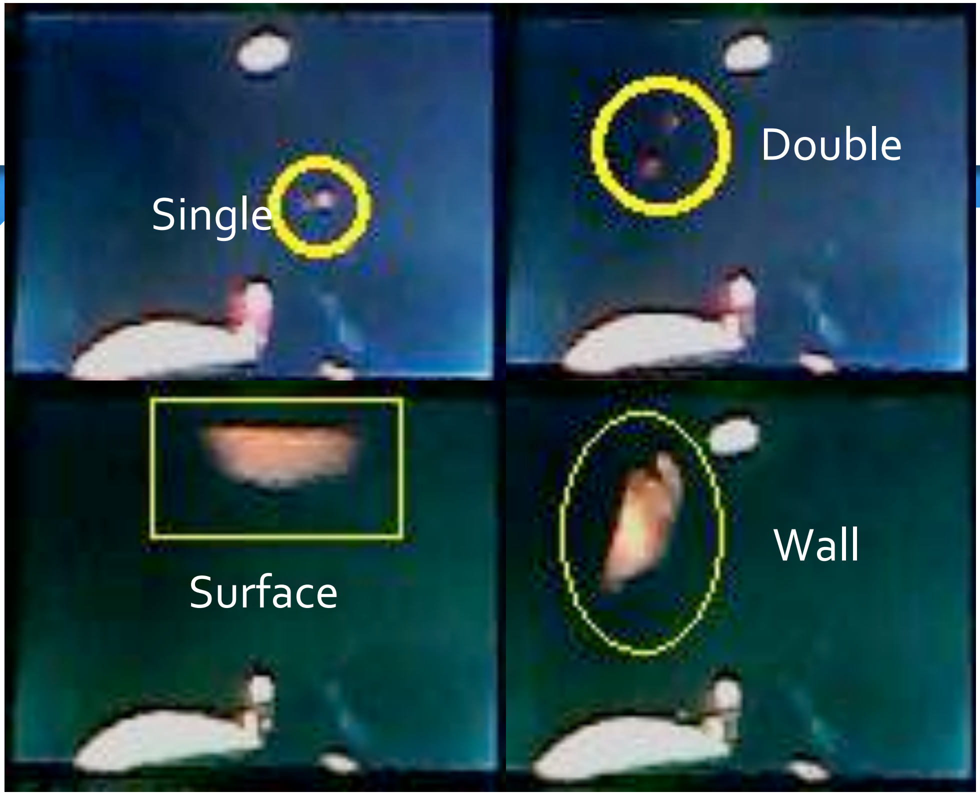


Image Analysis

types of events



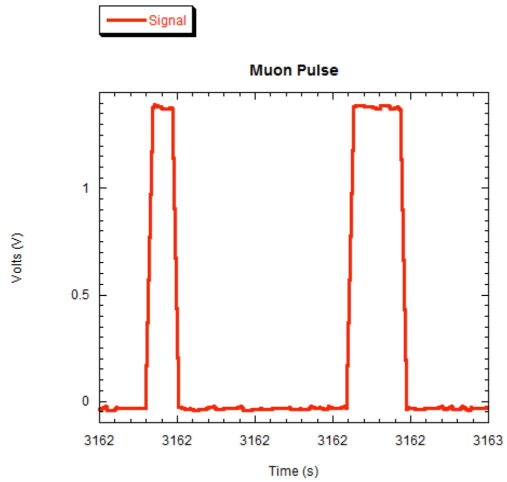
fractional probabilities

#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

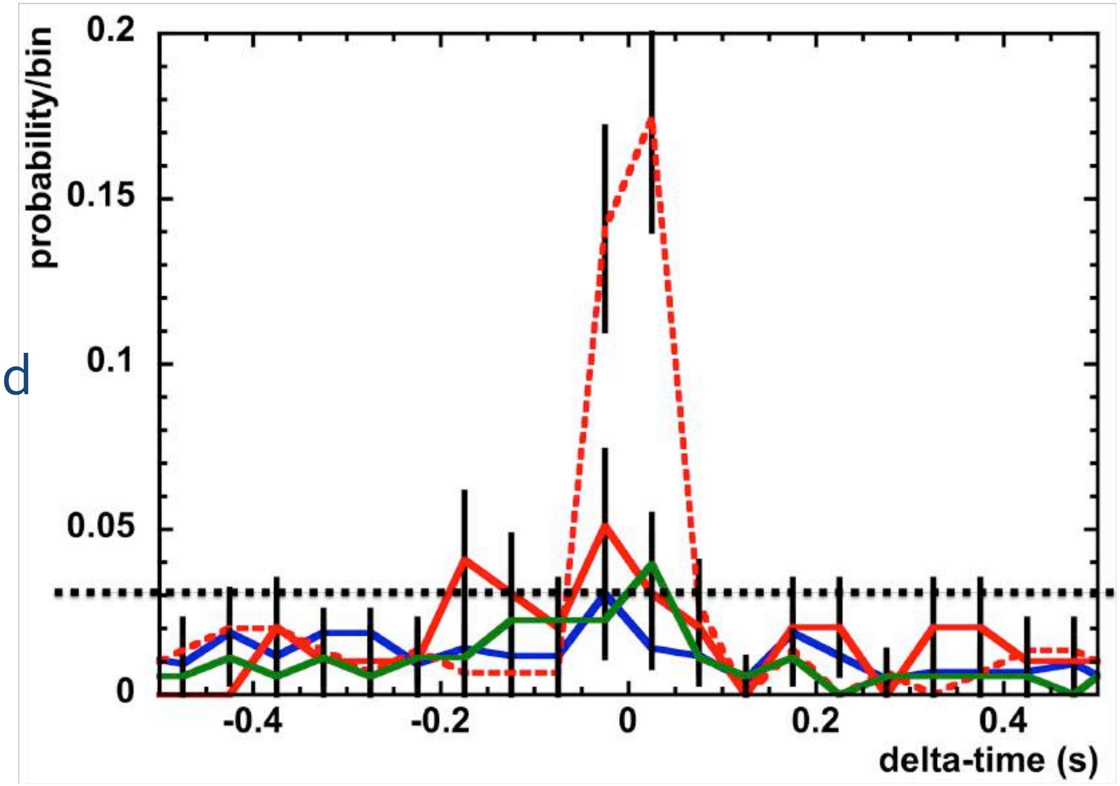
still need to double-check for reflections, but re-did blind and still saw differences

- 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

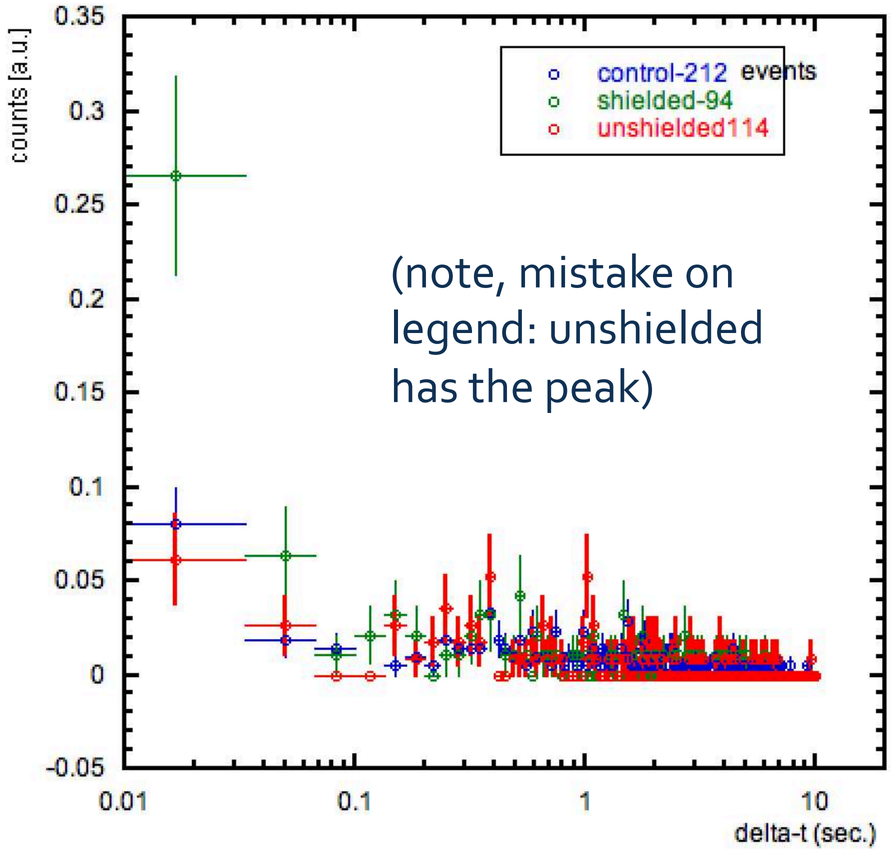
Muon Veto Analysis



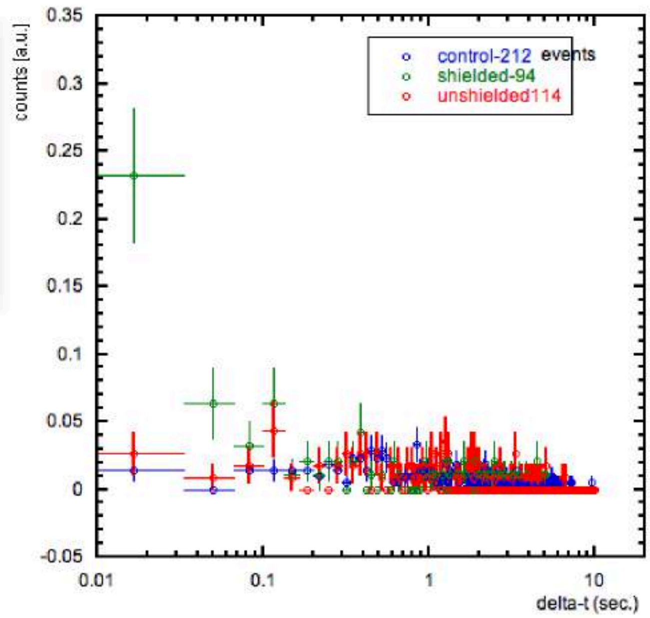
- A huge peak above accidental coincidence probability
  - Done with images
  - Checked with temperatures
- But only in UNshielded AmBe data
- Still puzzling
- Likely AmBe 4.4 MeV gammas or MeV n's

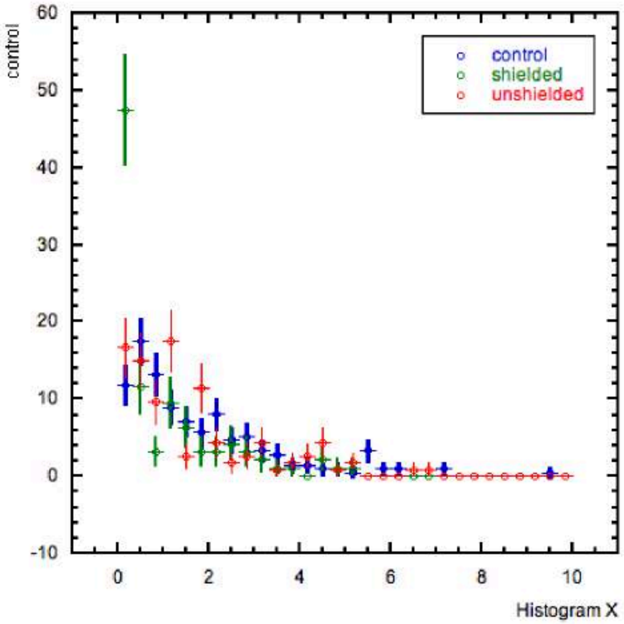


Checked with Temps!



(note, mistake on legend: unshielded has the peak)

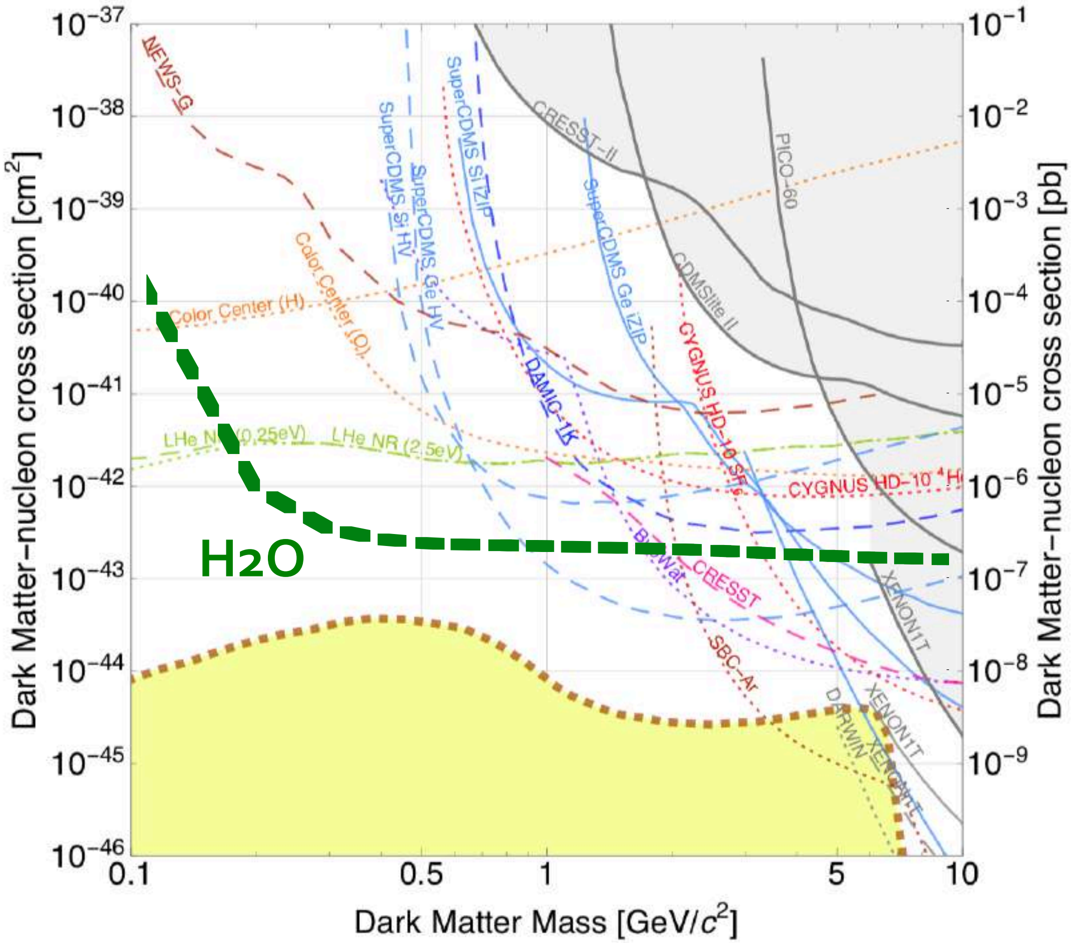




Sensitivity Projection

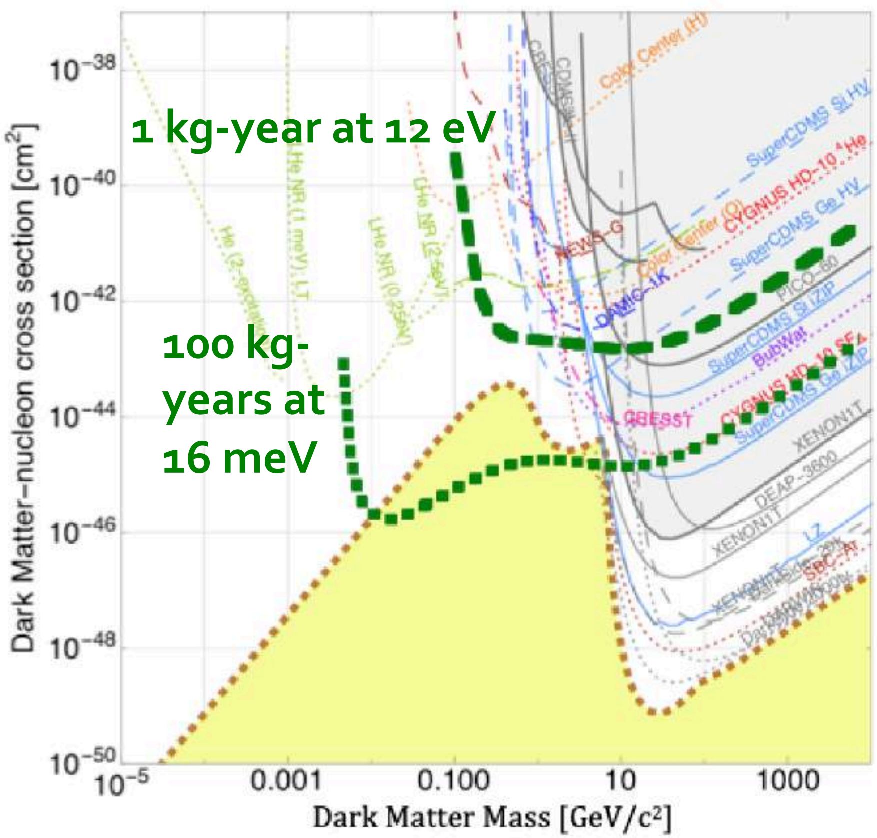
shamelessly copied plot from the DoE Cosmic Visions Report (arXiv:1707.04591) and overlaid our own curve

- This is conservative!
  - Assumes 10 eV energy threshold
  - Zero BG counts
  - Approaches ν floor
- 365 kg-days
  - So, only 1 kg UG for 1 year!!!
- Thresholds as low as O(10) meV should be possible, and way more than 1 kg-year

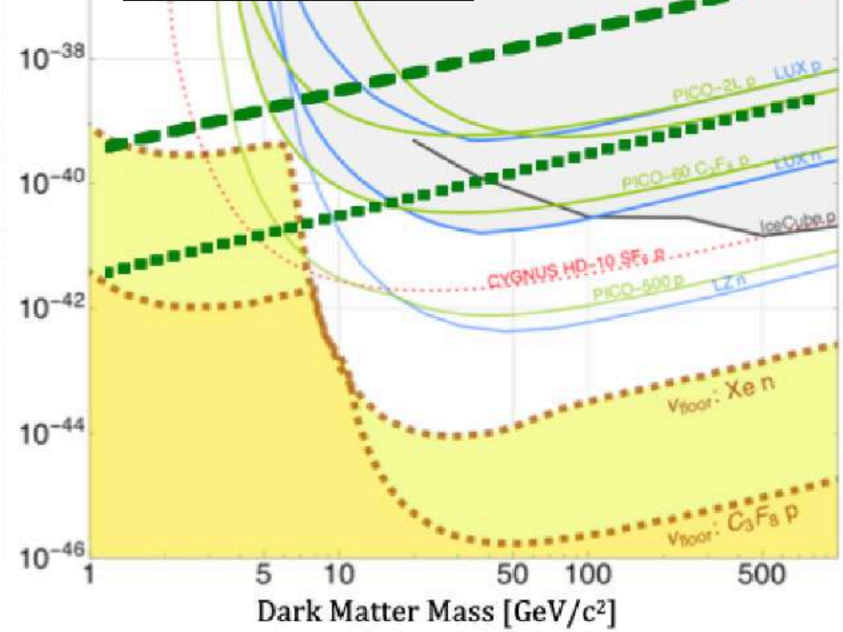


fraction of the cost (and complications) of competing experiments at 100 MeV to 10 GeV! Potentially self-confirming

Expanded View and Spin-Dependent Proton



Pinterest
quote from *Interstellar*

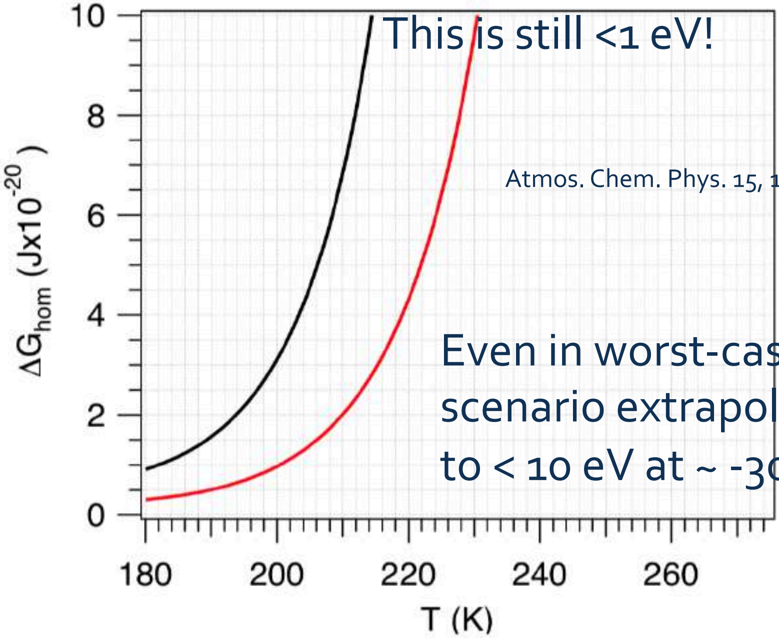


if we imagine a future HyperK-sized experiment, the largest water detector ever planned, run for 10 years, 10^-54 cm^2 is not out of the question -- well below our objective and most plots.

So Much More We Can Do

- Unparalleled spin-dependent proton sensitivity at sub-GeV
- Dark photons, mirror DM, LIPs, via electron scattering
  - ER sensitivity was already shown going back to 1969 and even earlier! (*Nature* **Vol. 223**, pages 826–827 and ref. therein) but just like with bubble chambers (c.f. PICO) temperature and pressure control allows one to make it "go away"
- The "floor" is ~160x lower for H than He and other elements

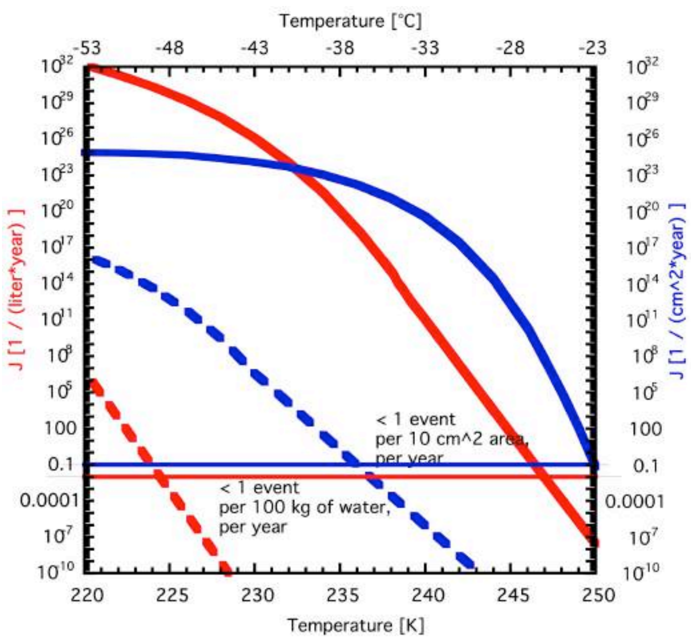
But, Is It Possible?



This is still <1 eV!

Atmos. Chem. Phys. 15, 13819-13831 (2015)

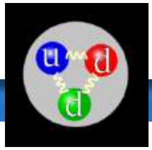
Even in worst-case scenario extrapolates to < 10 eV at ~ -30 °C



Based on ref. above and other works by D. Barahona

- Unclear whether to use homogeneous or heterogeneous nucleation energy thresholds
  - In either case, sub-keV threshold possible, even sub-eV
- Around ~240 K or -30 °C there appears to be a “sweet spot” of low threshold and 0 BG (from spontaneous nucleation)
  - The spontaneous rates drop precipitously with temperature
  - Considers both area & volume

Experimental Backgrounds



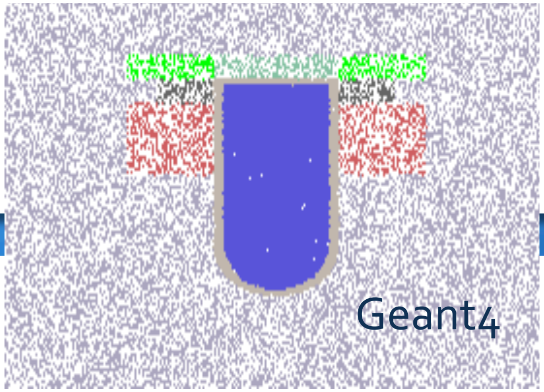
- Neutrons: Go bump in the night just like WIMPs. Can be remediated by cutting multiple scatter events and by aggressively fiducializing your detector volume, if it is self-shielding, and by simulating all of the neutrons sources you can think of. For a snowball chamber: multiple-scattering should be sufficient, b/c water

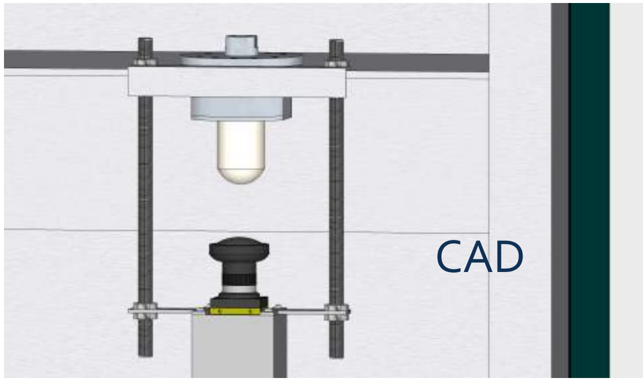
- Alphas: Can also produce nuclear recoil like WIMPs. Alpha events near detector walls can be removed from data by good fiducialization. However - (α,n) events remain a problem (above). For snowball chamber, α-n acoustic discrimination?

- Gammas and electrons: Not a problem if your detector is insensitive to electron recoil, or can discriminate between electron and nuclear recoils well (between 1 part in 10^3-10^{11} level discrimination i.e. acceptance achieved with current technologies). In snowball chamber, at least at temps achieved, looks like ~10^5
- Muons: Will induce neutrons in nearby material. Will also produce electron recoils. Can go deep underground to help avoid them. Can also tag them with a muon veto (water tank, plastic scintillator panels,…) All experiments solve

(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 LIVETIME (biggest current drawback)
  - Modular detector
  - Better circulation, microwaves, lasers, heat pads
  - 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





The SnowBall Consortium

UNIVERSITY AT ALBANY
State University of New York

In its infancy. Formed for DoE DM BRN proposal

BROOKHAVEN NATIONAL LABORATORY

THE PENNSYLVANIA STATE UNIVERSITY · 1855 ·

Duke UNIVERSITY

Rensselaer

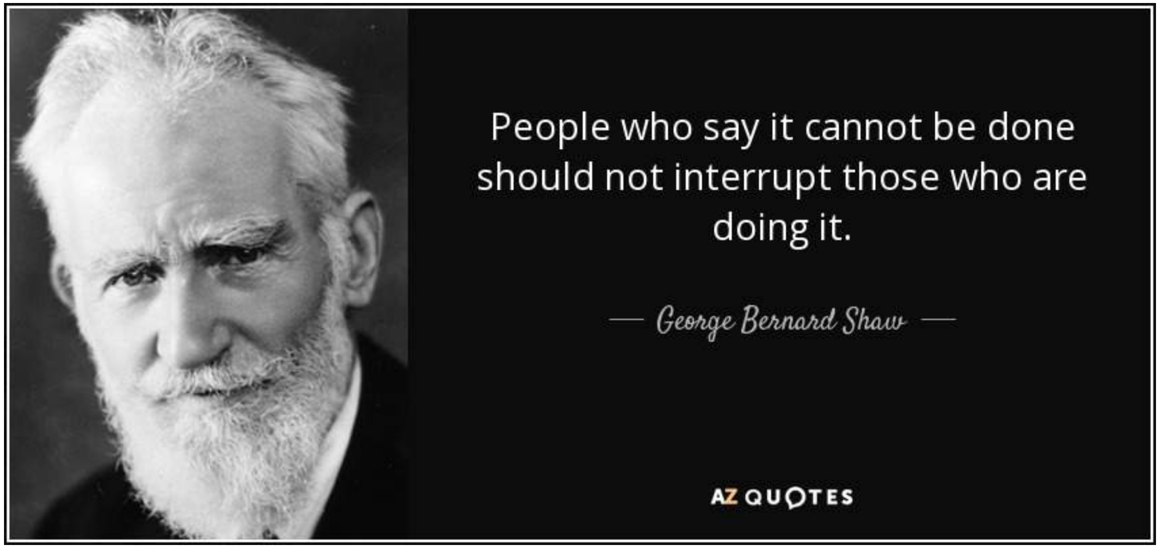
TUNL

CONCLUSIONs

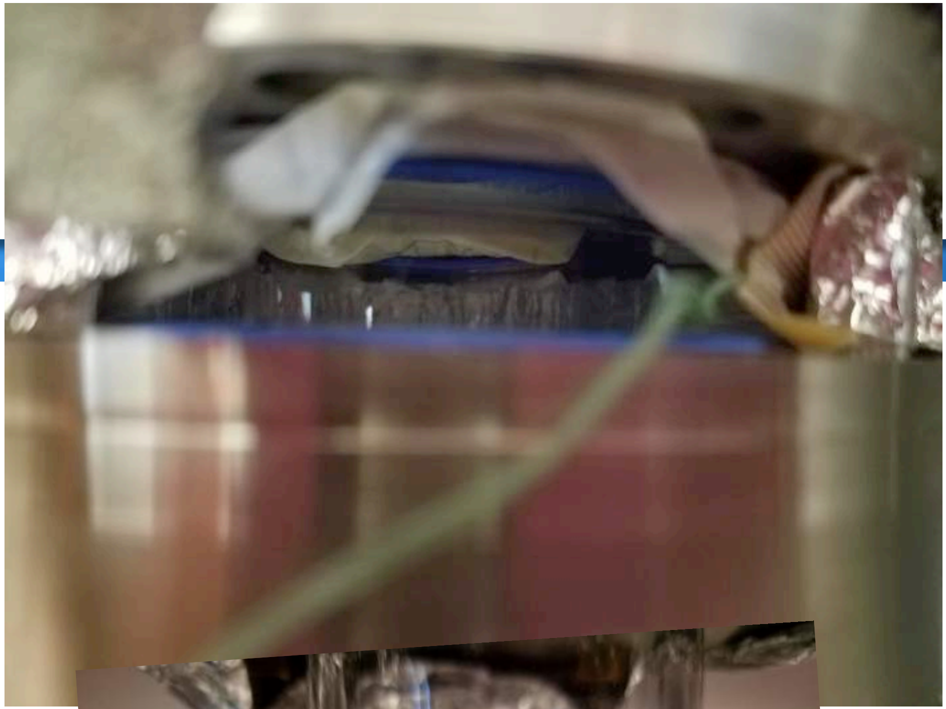
- Neutrons can make supercooled water freeze: a new discovery
- They can even multiply scatter, as they do in a bubble chamber!
- At least some types of events are coincident with a scintillator
- There is at least some degree of electron recoil discrimination
- Energy threshold is not known, but potentially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

Thank You!!

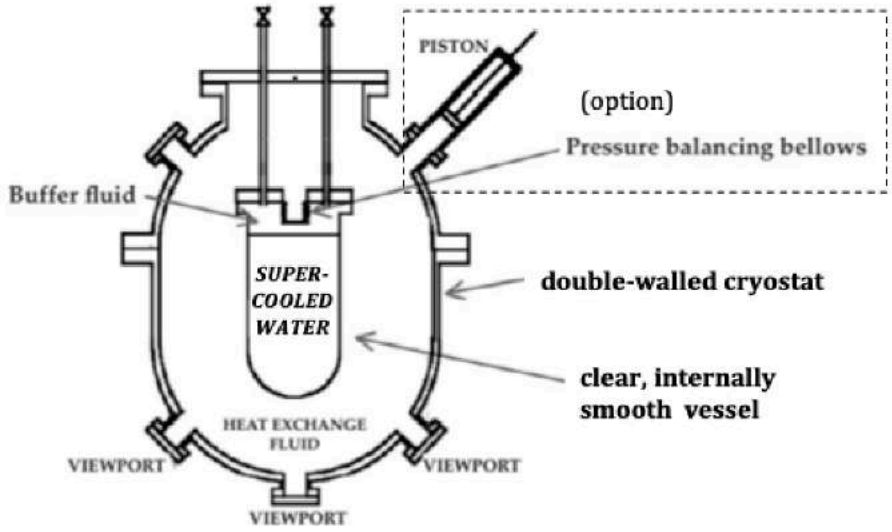
- Questions???
- Backup slides.....

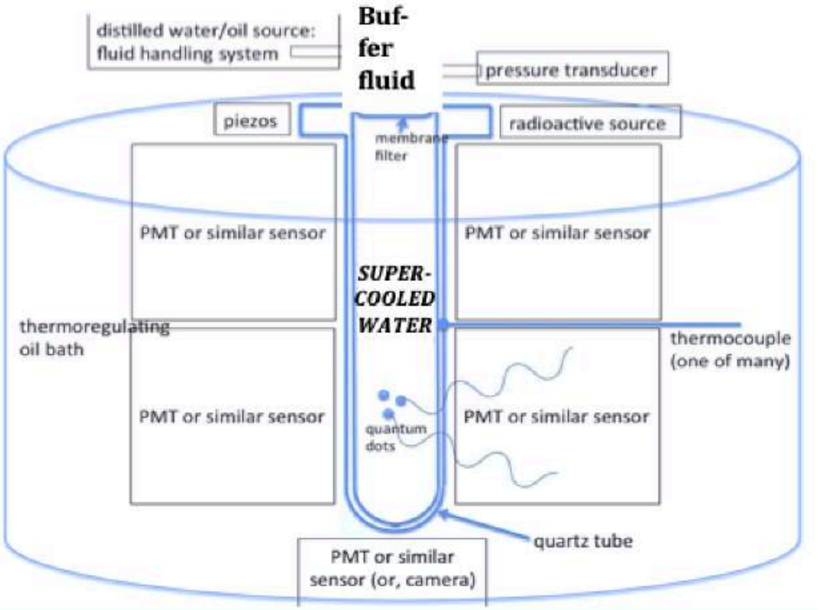


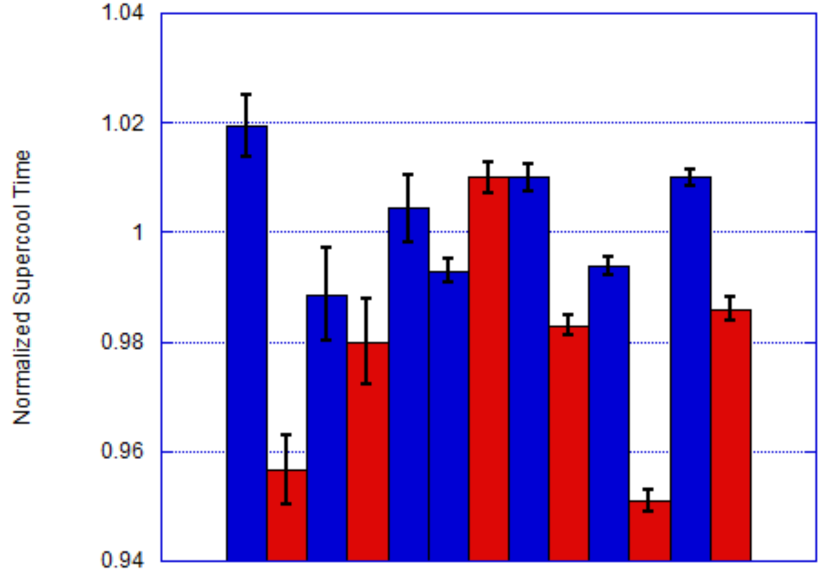
This research was funded by
UAlbany PIFRS and FRAP-A awards



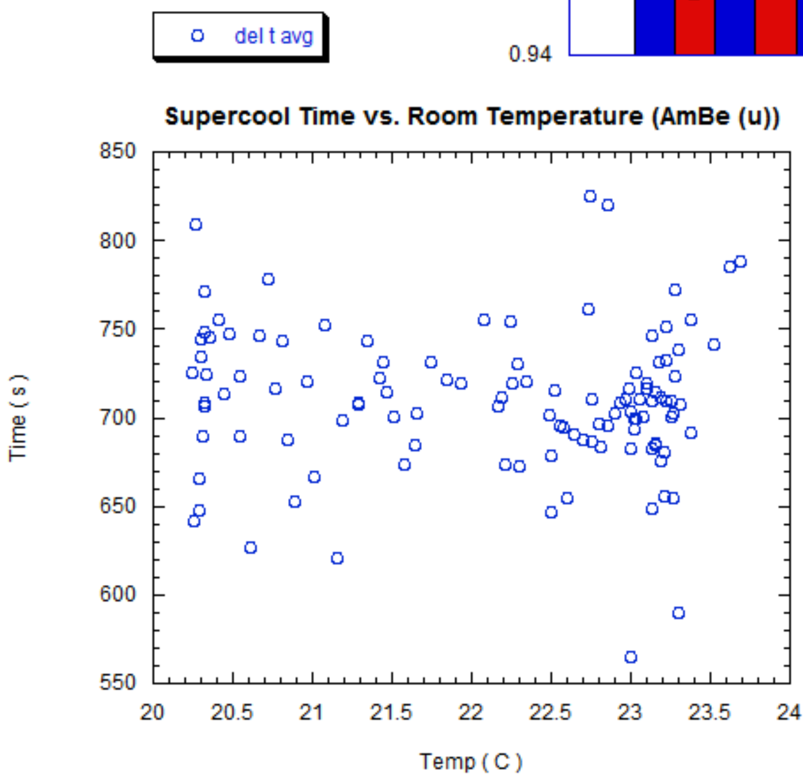
Detector Schematic



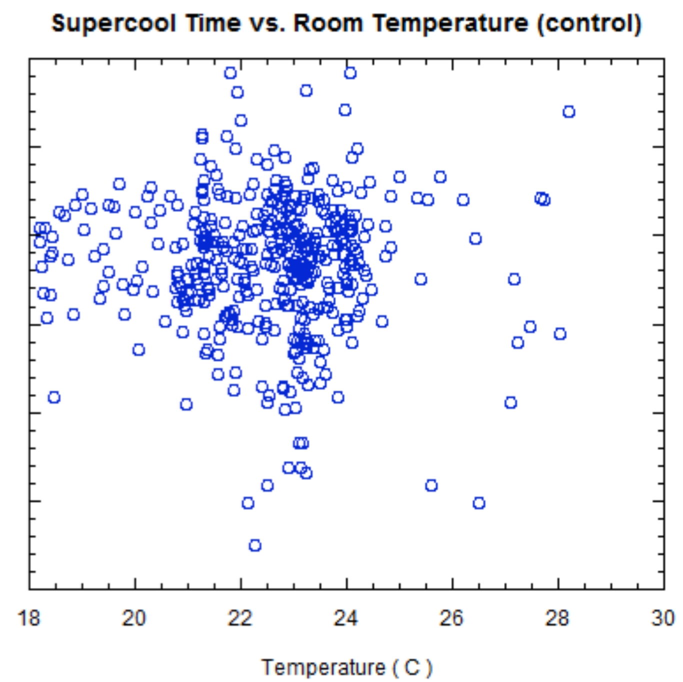




Normalized Supercool Time
1.04
1.02
1
0.98
0.96
0.94



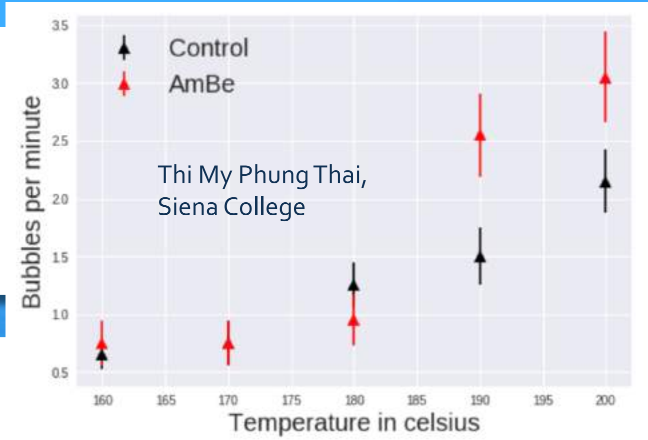
del t avg
Supercool Time vs. Room Temperature (AmBe (u))
Time (s)
850
800
750
700
650
600
550
20
20.5
21
21.5
22
22.5
23
23.5
24
Temp (C)



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

Double Crystal Slide Show

Plan B (or ~parallel) Superheated Water



- Superheated droplet geyser
  - Combine best ideas from the SDD, the bubble chamber, and the geyser, with recondenser

SDD = Superheated Droplet Detector

- 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?

Tony Ellis and Isabella Magliocca

~150 degree liquid water!

Going So Well May Have 2 Plans A's!

Biophysical Implications

- Remember this cute guy from my first slide?
- Well, it turns out that the arctic ground squirrel may supercool its blood during hibernation!
  - At one point at least not thought to be just freezing point depression
- Please see https://www.scientificamerican.com/article/arctic-ground-squirrel-brain/

DIRECTIONALITY, Varshneya (1969)