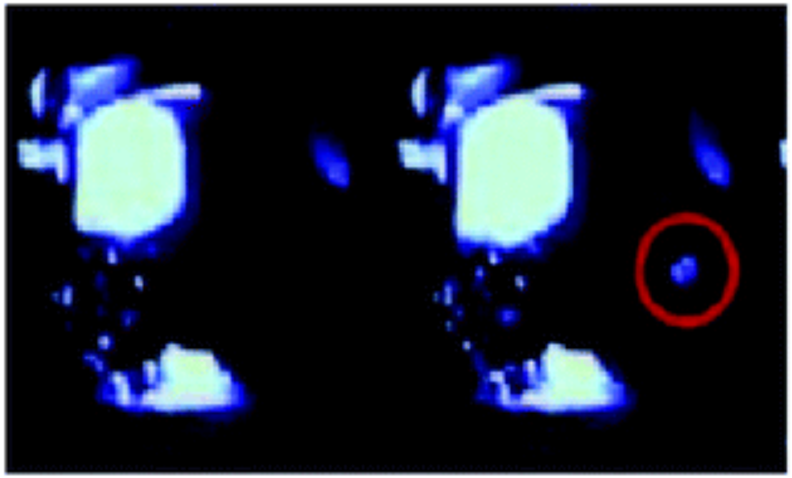
Metastable Water for Radiation Detection Applications: The Snowball Chamber

UNIVERSITY AT ALBANY
State University of New York



SUNY RF
The Research Foundation for
The State University of New York

Dr. Matthew Szydagis, Associate Professor, Department of Physics, University at Albany SUNY

The (Loose, Unfunded) Collaboration

- UCLA, BNL, RPI, Penn State, Duke/TUNL, all trying to start a large program with UAlbany

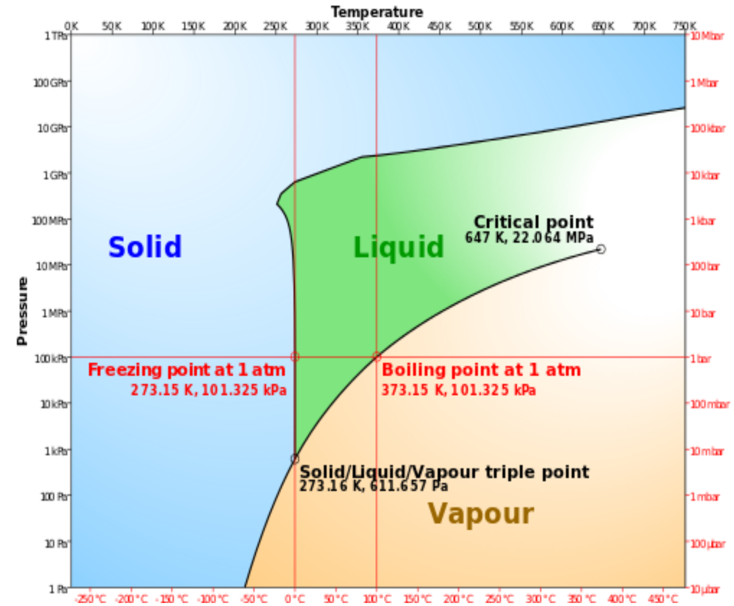
Faculty and lab staff : Alvine Kamaha, Milind Diwan, Aleksey Bolozdynya, Minfang Yeh, Ethan Brown, Carmen Carmona, Luiz de Viveiros, Phil Barbeau, + **Matthew Szydagis & Cecilia Levy**

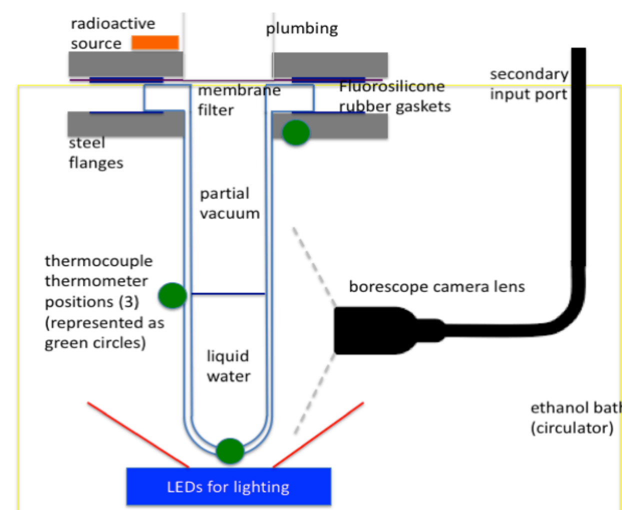
The Snowball Chamber

done before, but only with beta and gammas, most recently by Varshneya (*Nature*, 1971)

Physics Department, University of Roorkee, India

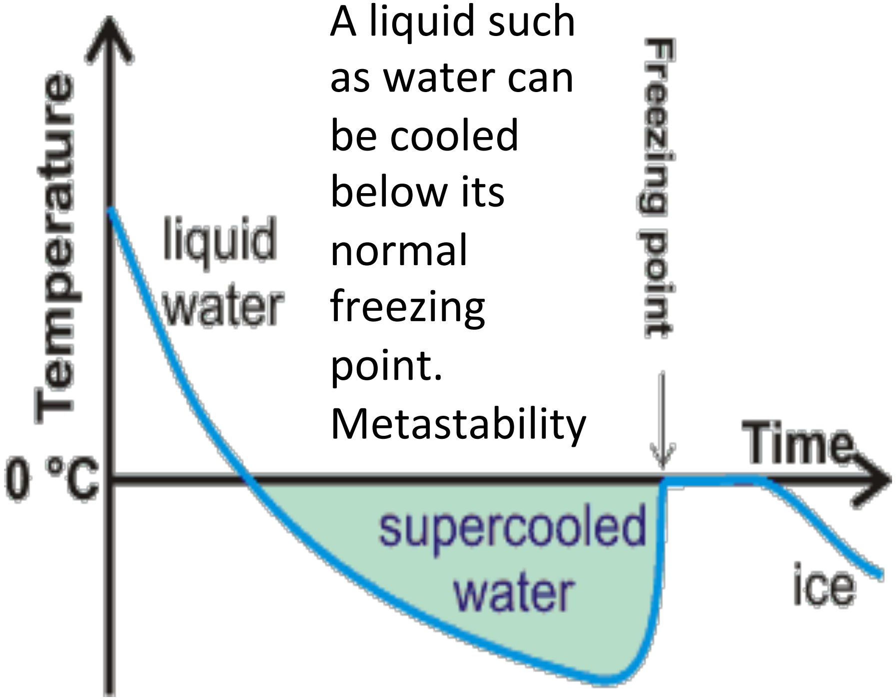
- The snowball chamber is analogous to the bubble & cloud chambers
  - It also relies on a phase transition
  - But it is a new instrument in nuclear & particle physics
- Relies on supercooling of high-purity water
  - Although, as with bubble chambers almost any other liquid should be usable





Supercooled Water

A liquid such as water can be cooled below its normal freezing point. Metastability

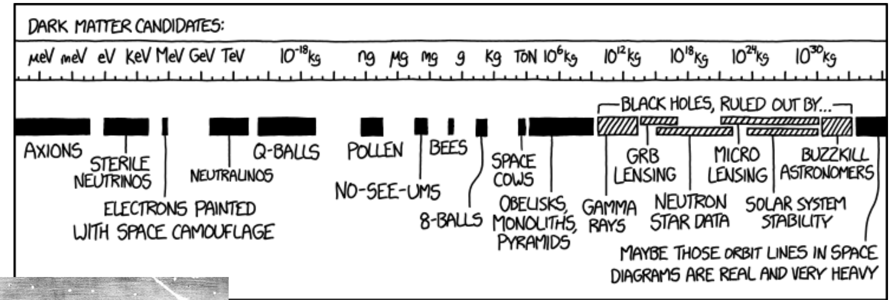


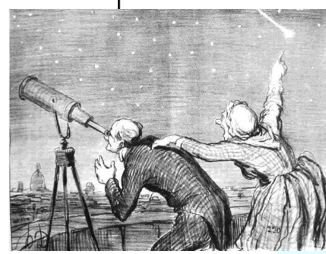
occurs naturally in organisms like the arctic ground squirrel, and in some Antarctic fish species. Also useful for human organ preservation

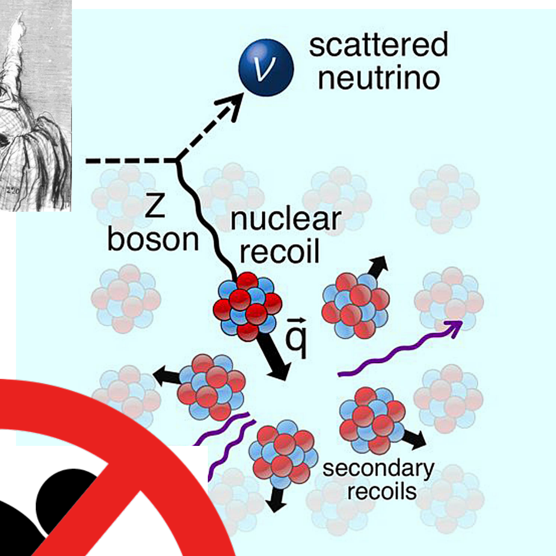
- Can remain metastable for long time periods
  - In a sufficiently clean and smooth container
  - Smoothness on the level of the critical radius of nucleation key
- Advantages
  - Scalable, given neutrino project examples
  - Water easy to purify
  - Possibly sub-keV energy for activating nucleation

Motivations

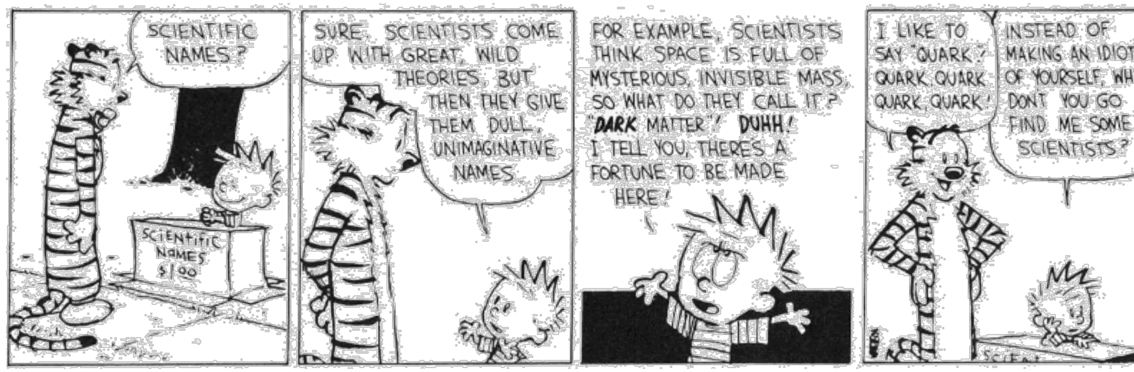
- ***Dark matter***
  - Low masses: low threshold coupled to low-mass target (H)
  - No cryogens or high voltage
- Neutrinos
  - Not just pure physics
  - Reactor monitoring for fuel rod theft
  - Channel: CEvNS
- Neutrons: similar to both above -- elastic scattering
  - Fissile materials
  - Calibration for above
- Atmospheric physics







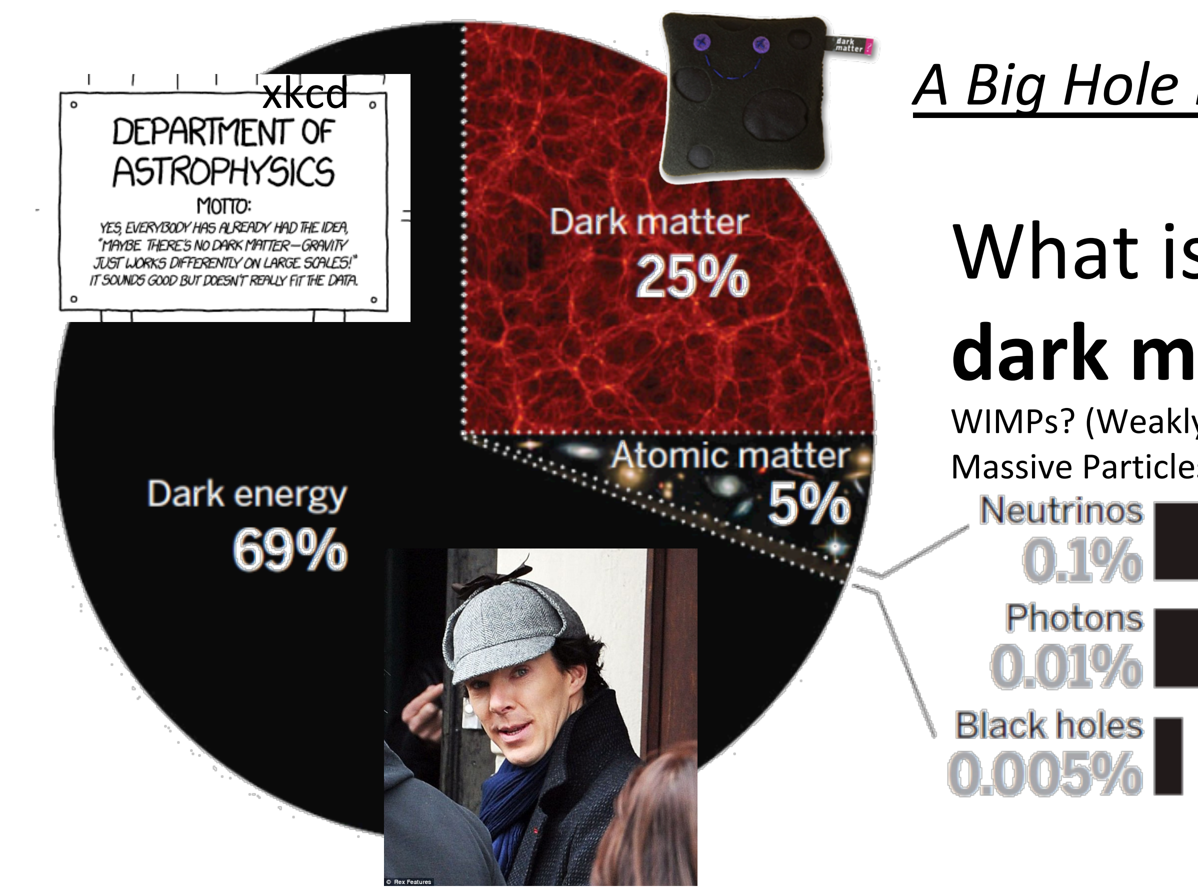
Dark Matter = ??????????



Calvin & Hobbes, by Bill Watterson

The multiple components that compose our universe

Current composition (as the fractions evolve with time)

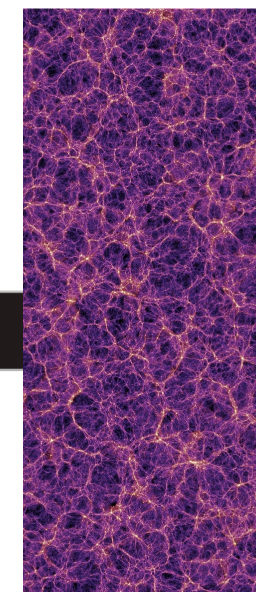


A Big Hole in Our Knowledge

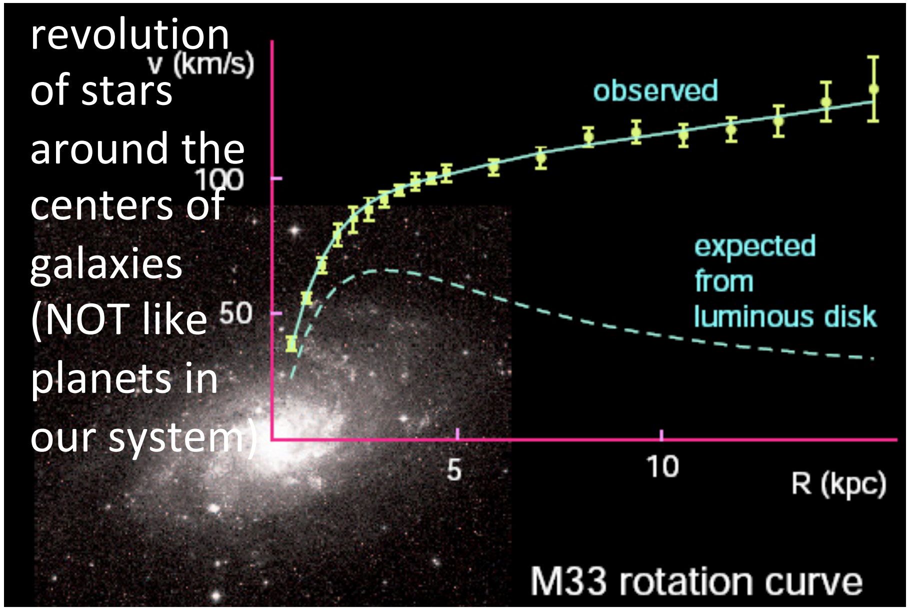
What is this **dark matter**?

WIMPs? (Weakly Interacting Massive Particles)

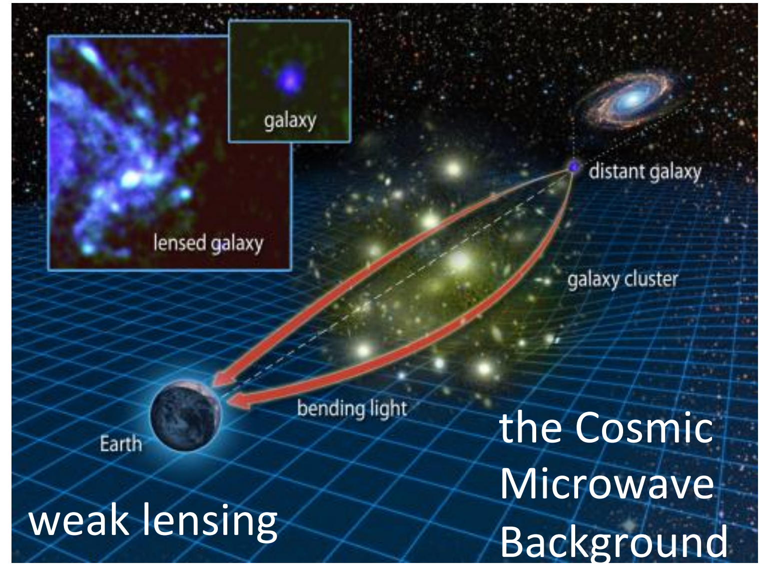
http://cdn.phys.org/newman/gfx/news/hires/2015/thedarksideo.png



The Observational Evidence

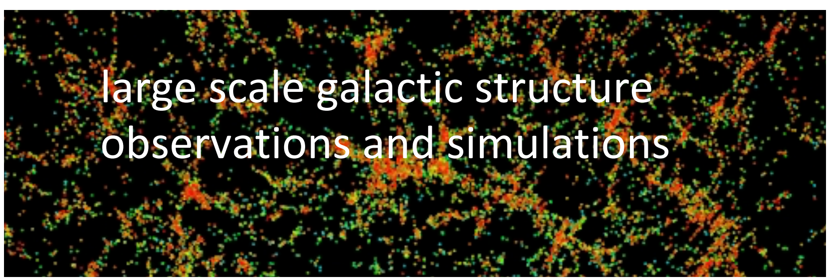


revolution of stars around the centers of galaxies (NOT like planets in our system)

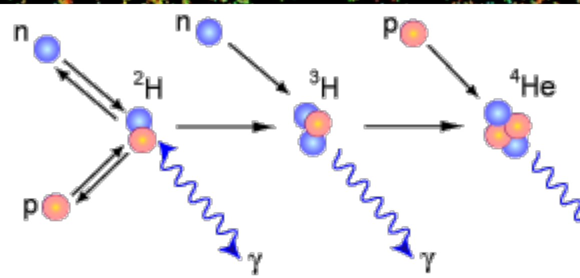


weak lensing

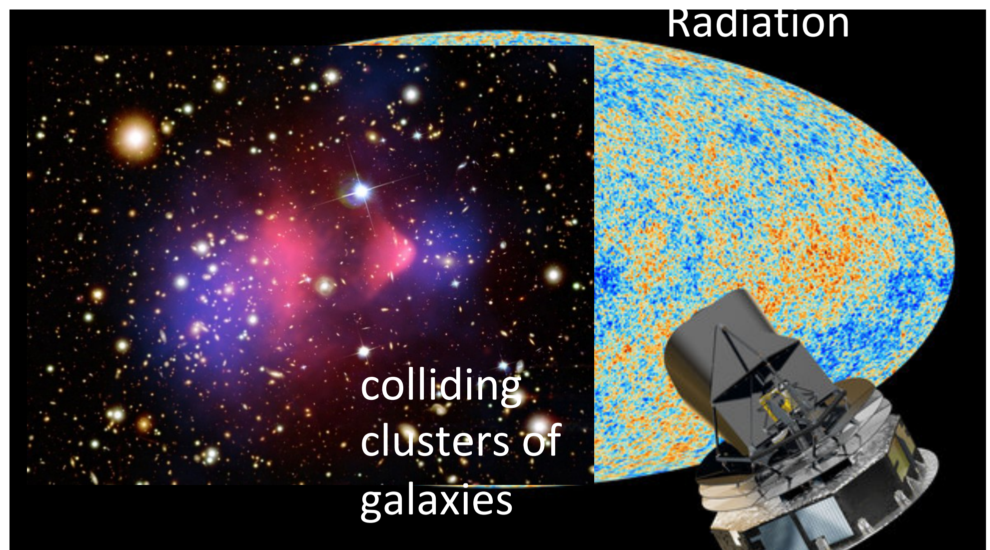
the Cosmic Microwave Background Radiation



large scale galactic structure observations and simulations

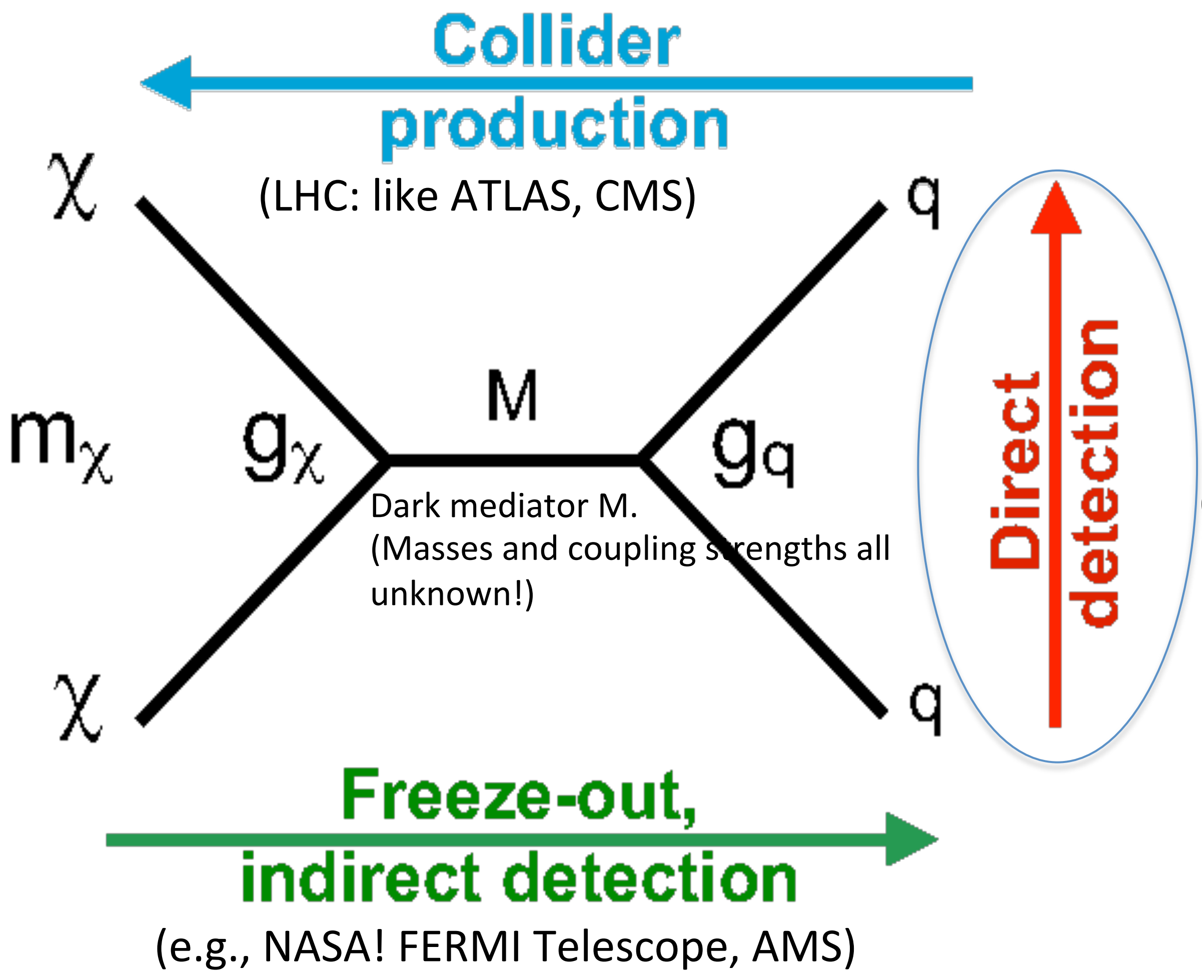


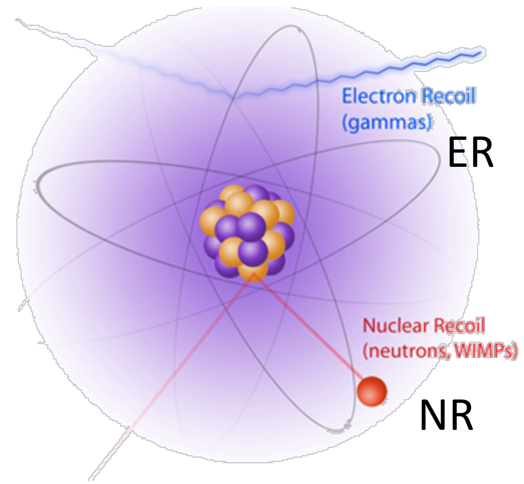
Big Bang Nucleo-synthesis



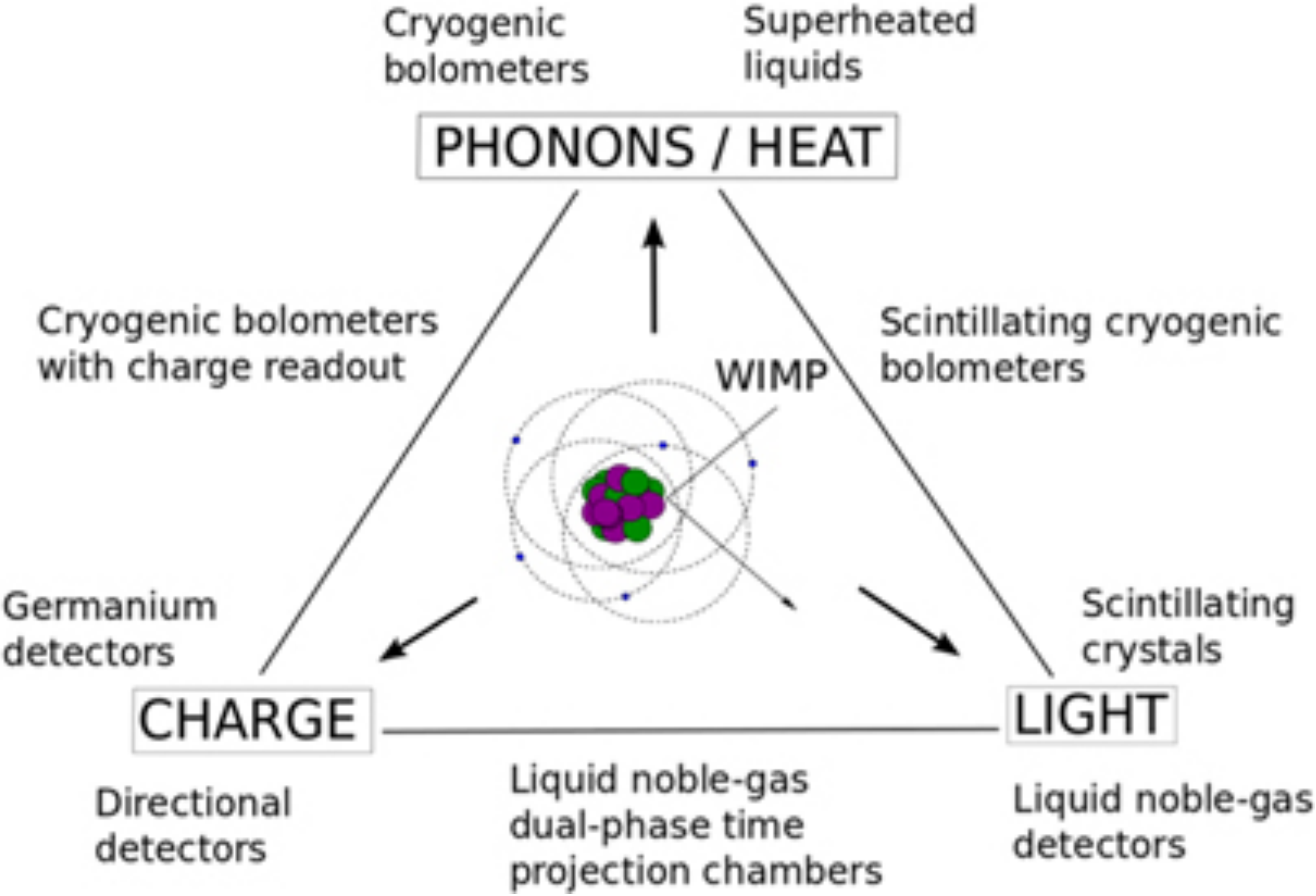
colliding clusters of galaxies

How to Look? Directly

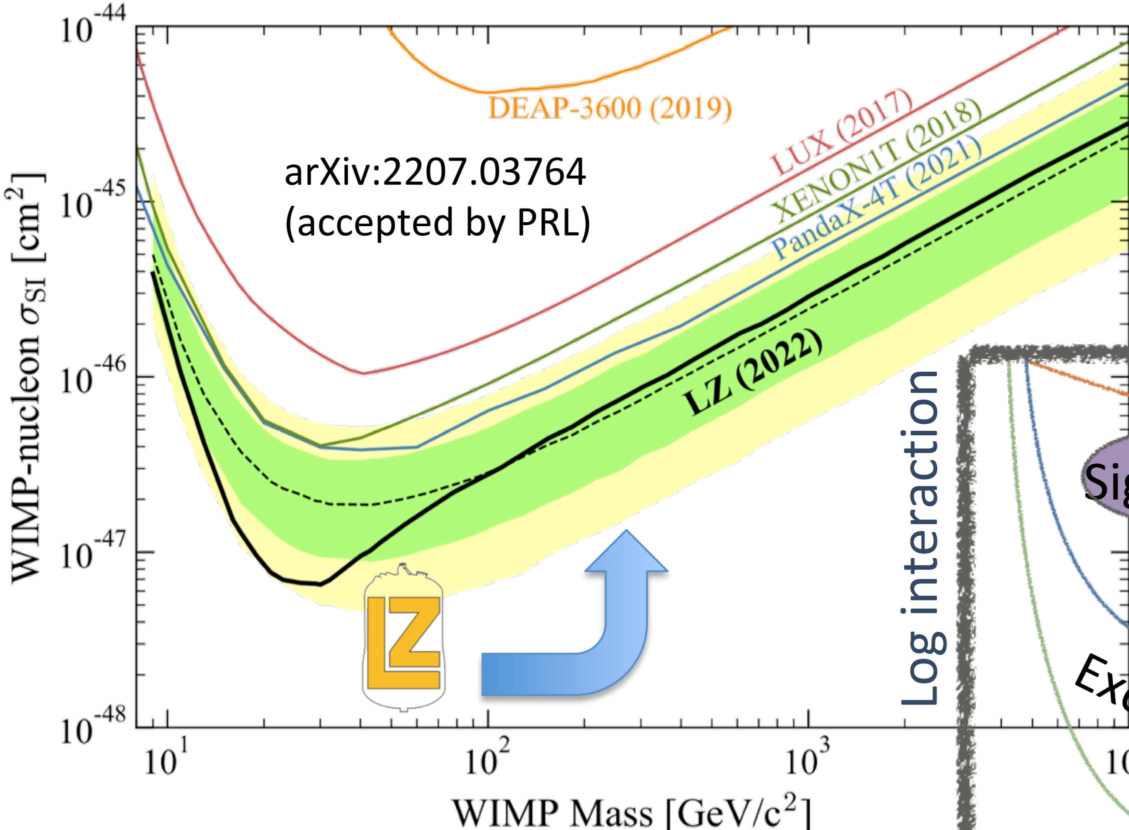




("billiard ball" collisions. Still need mediator. Higgs perhaps?)


Cryogenic bolometers
Superheated liquids
PHONONS / HEAT
Cryogenic bolometers with charge readout
Scintillating cryogenic bolometers
WIMP
Germanium detectors
Scintillating crystals
CHARGE
LIGHT
Directional detectors
Liquid noble-gas dual-phase time projection chambers
Liquid noble-gas detectors

The Parameter Space

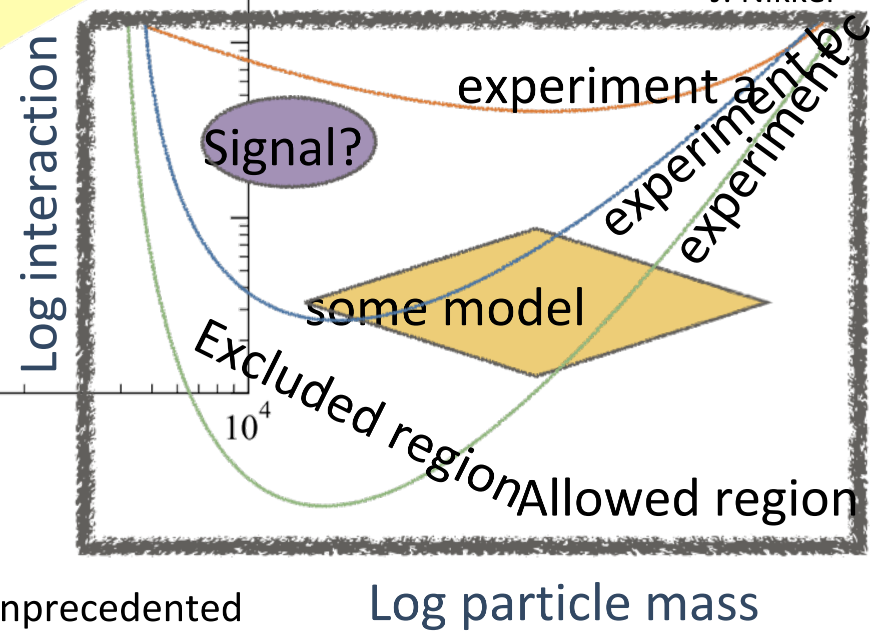


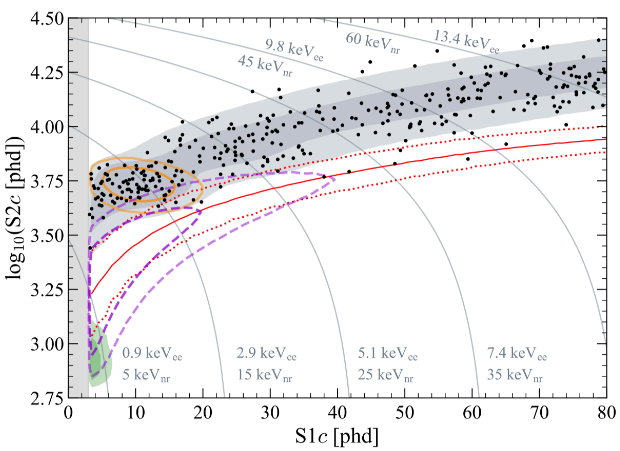
<= LZ is online and taking high-quality physics data

- All detectors performing well
- Backgrounds within expectation

A generic search plot explained

J. Nikkel



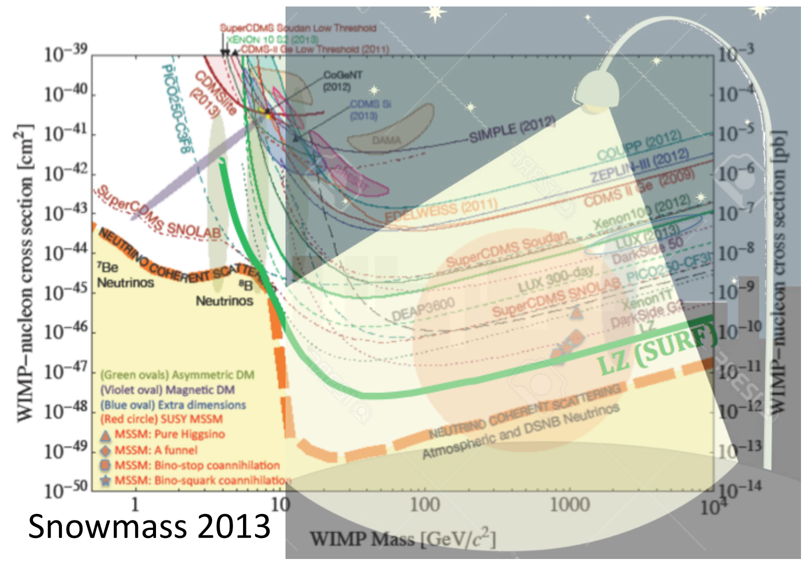


<= This was unprecedented agreement with simulation (from Greg Rischbieter, my former PhD graduate student, now a postdoc at the University of Michigan)

After 60 live days, LZ is the most sensitive dark matter detector in the world, for nuclear recoils from DM above 10 GeV in rest mass

Motivation for Snowball

- Continued lack of discovery of dark matter as a 10-1,000 GeV mass WIMP
  - Motivates looking elsewhere
- What is better target for lower-energy recoils, than the lightest possible target element, namely hydrogen?
  - A hydrogen bubble chamber might be great, but it's far less practical
  - Other ideas exist already (e.g. helium) so far from only game in town, even at sub-GeV
- Water is inexpensive, while great at moderating neutrons



Snowmass 2013

Our First Successful Publication

Issue 24, 2021

Previous Article | Next Article

made the journal cover!

From the journal:
Physical Chemistry Chemical Physics

(PRL and PRD were not interested!)

Also available on arXiv (open access) https://arxiv.org/pdf/1807.09253.pdf

Demonstration of neutron radiation-induced nucleation of supercooled water†

Check for updates

Matthew Szydagis, *[a] Cecilia Levy, *[a] Yujia Huang,[a] Alvine C. Kamaha,[a] Corwin C. Knight,[a] Gregory R. C. Rischbieter [a] and Peter W. Wilson *[bc]

Author affiliations

https://pubs.rsc.org/en/content/articlelanding/2021/cp/d1cp01083b

- The results from the first prototype setup (~20 g)

Decadal Survey LOI Submitted

Metastable Water: Breakthrough Technology for Dark Matter & Neutrinos

M. Szydagis[1], C. Levy[1], P. S. Barbeau[2], A. E. Bolotnikov[3], E. Brown[4], M. C. Carmona-Benitez[5], G. Cox[5], L. de Viveiros[5], M. Diwan[3], T. Guile[1], G. Homenides[1], Y. Huang[1], A. Kamaha[1], D. Kodroff[5], I. Magliocca[1], G.R.C. Rischbieter[1], D. Woodward[5], and M. Yeh[3]

[1] *The University at Albany, State University of New York (UAlbany)*
[2] *Duke University / Triangle Universities Nuclear Laboratory (TUNL)*
[3] *Brookhaven National Laboratory (BNL)*
[4] *Rensselaer Polytechnic Institute (RPI)*
[5] *Pennsylvania State University, University Park, PA*

August 2020

Cosmic Frontier Topical Groups:
- (CF1) Cosmic Frontier: Dark Matter: Particle-like

Neutrino Frontier Topical Groups:
- (NF04) Neutrino Physics Frontier: Neutrinos from Natural Sources
- (NF05) Neutrino Physics Frontier: Neutrino Properties
- (NF06) Neutrino Physics Frontier: Neutrino Interaction Cross-Sections
- (NF07) Neutrino Physics Frontier: Applications
- (NF10) Neutrino Physics Frontier: Neutrino Detectors

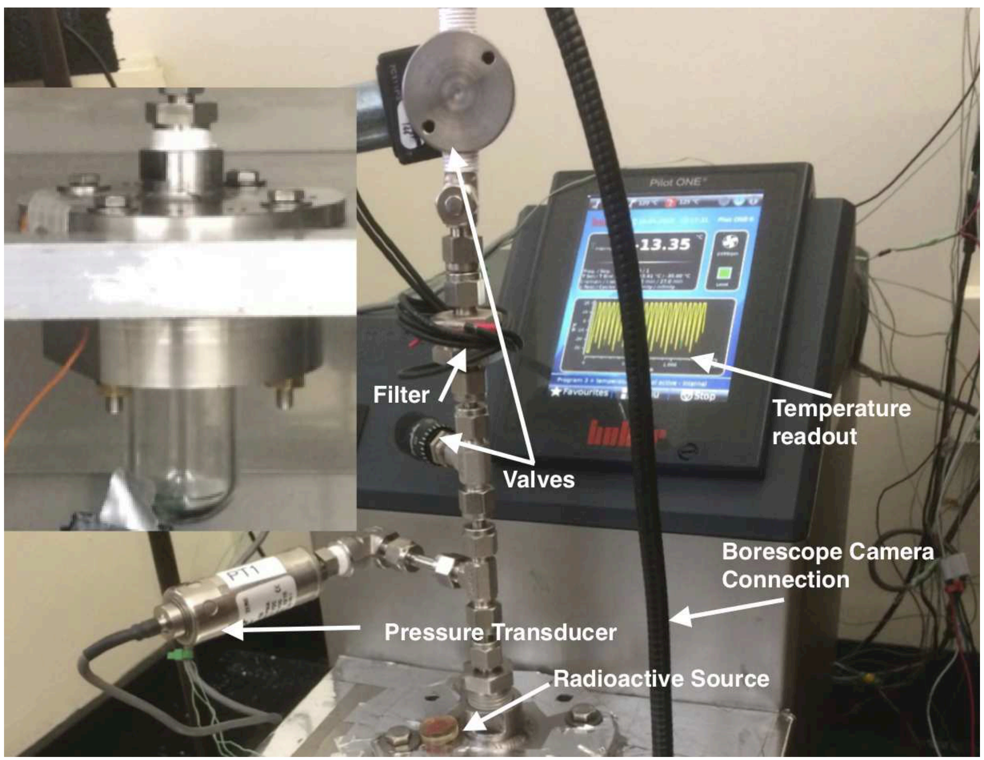
Intensity Frontier Topical Groups:
- (IF6) Instrumentation: Calorimetry
- (IF8) Instrumentation: Noble Elements

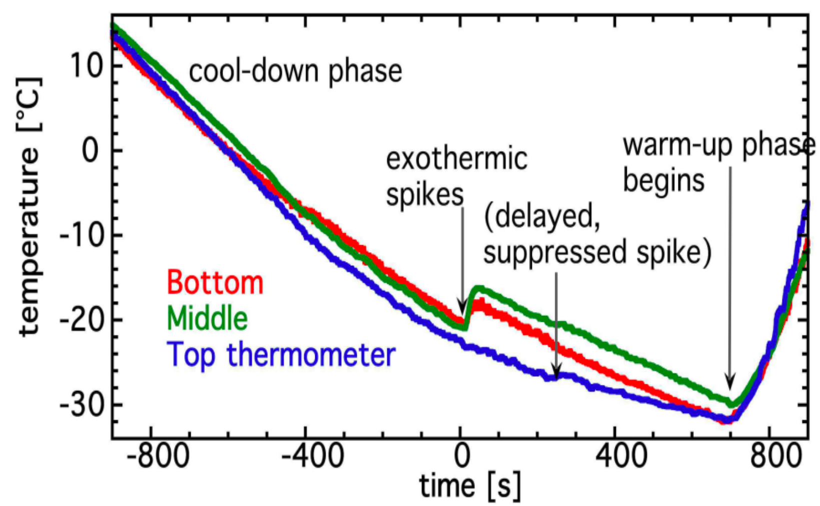
also gave a "Community Voices" talk (Snowmass)

Multiple disciplines were emphasized

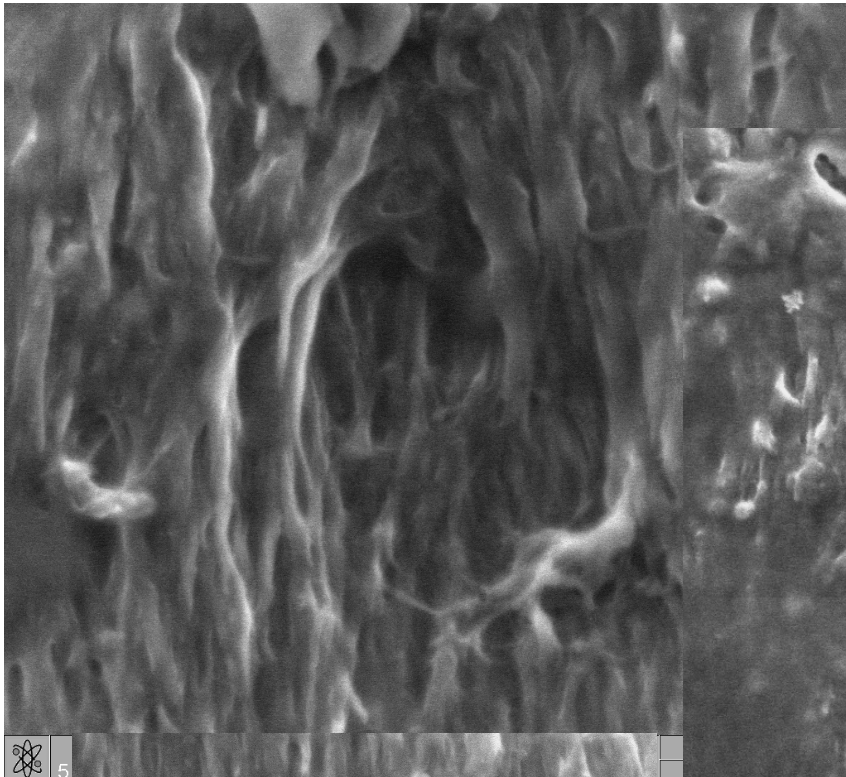
Photo of Setup & Example Event

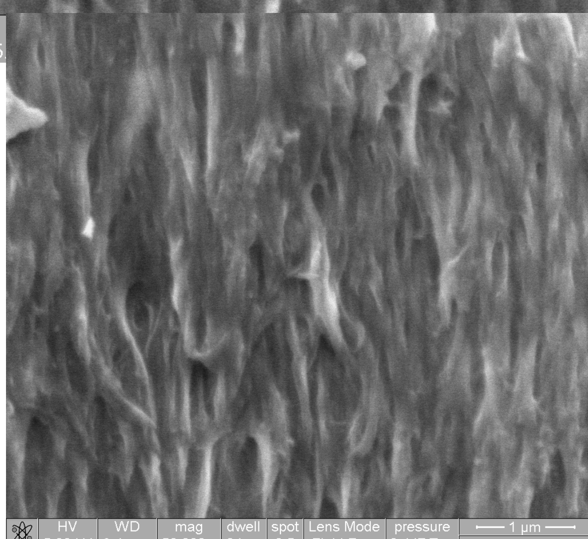
- 20 mL of purified water contained in a cleaned fused quartz jar
  - The water was processed through multiple filters, deionized, and ultimately distilled through a 20-nm flat-sheet non-linear membrane (only gas could pass through)
- Three thermocouple thermometers inside (plus 1 outside)
  - Top, middle, and bottom, for seeing the exothermic spike (plot)

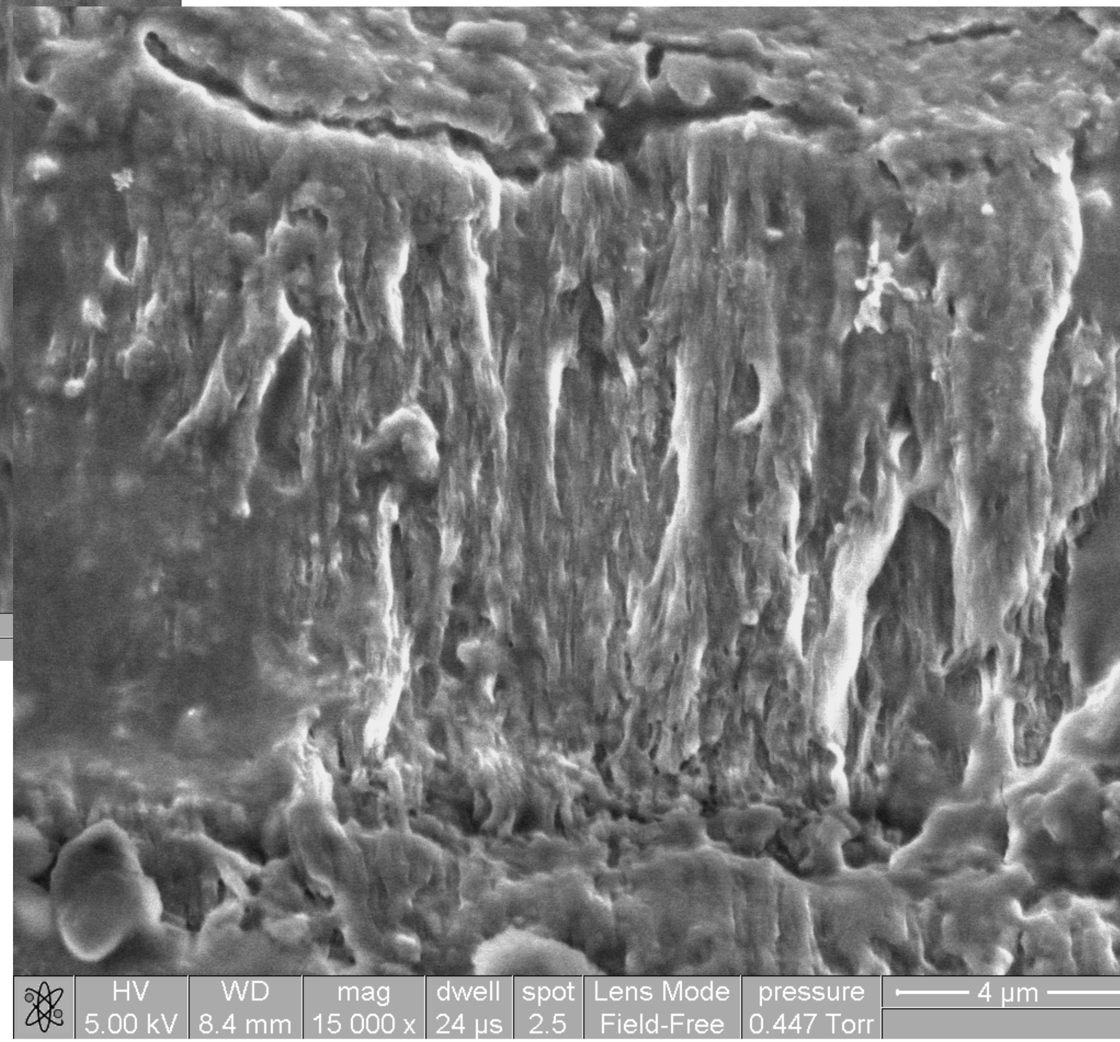




Key Filter for Purity

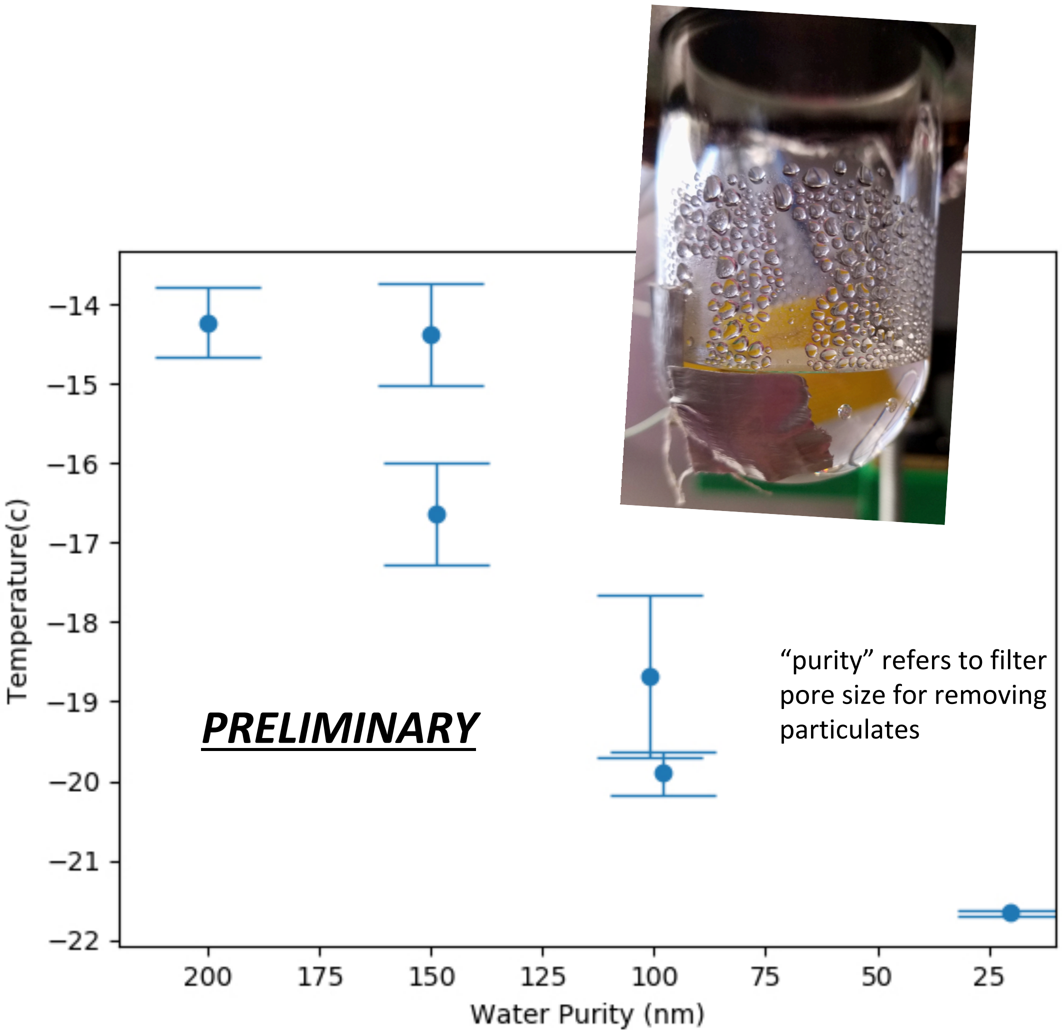






photos courtesy of Prof. Kathy Dunn, SUNY Poly CNSE

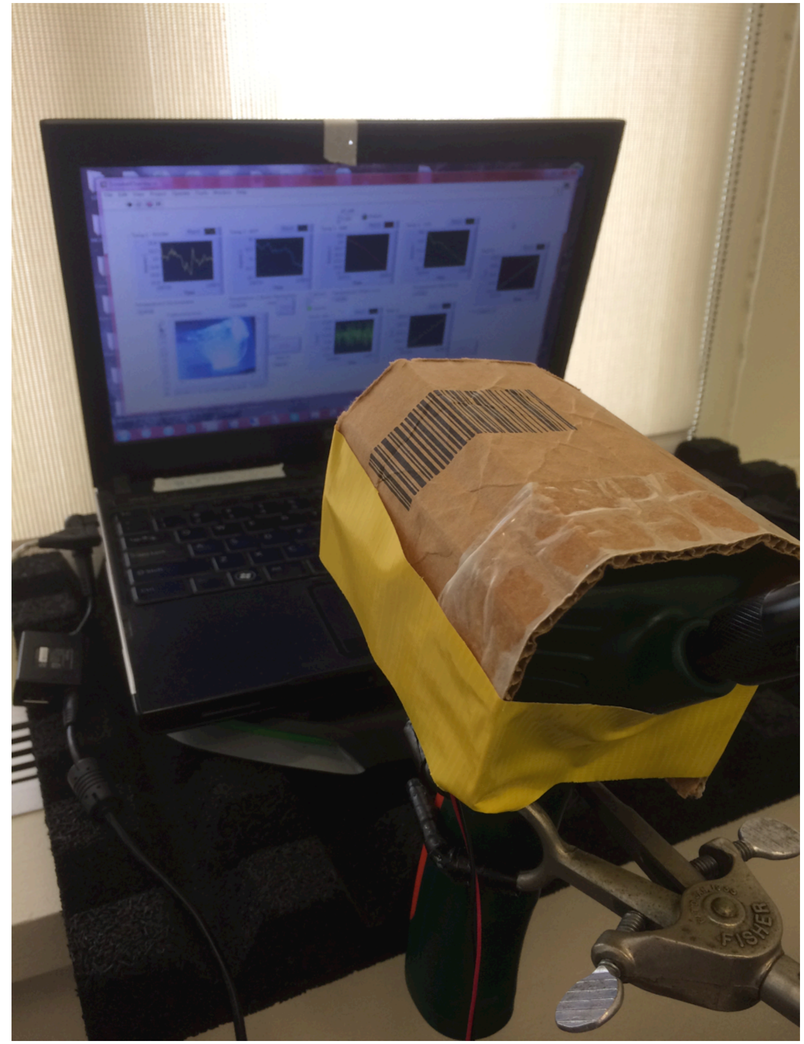
Measurement of Filtration Effect



- Min temperature achieved while supercooling before sample freezes
- Four 1-mL water samples tested 6 times: each point on plot is set of 24 measurements, complete with statistical and systematic errors bars
- Lowest point at right different: that is from the results published in PCCP

Operation and Data Acquisition

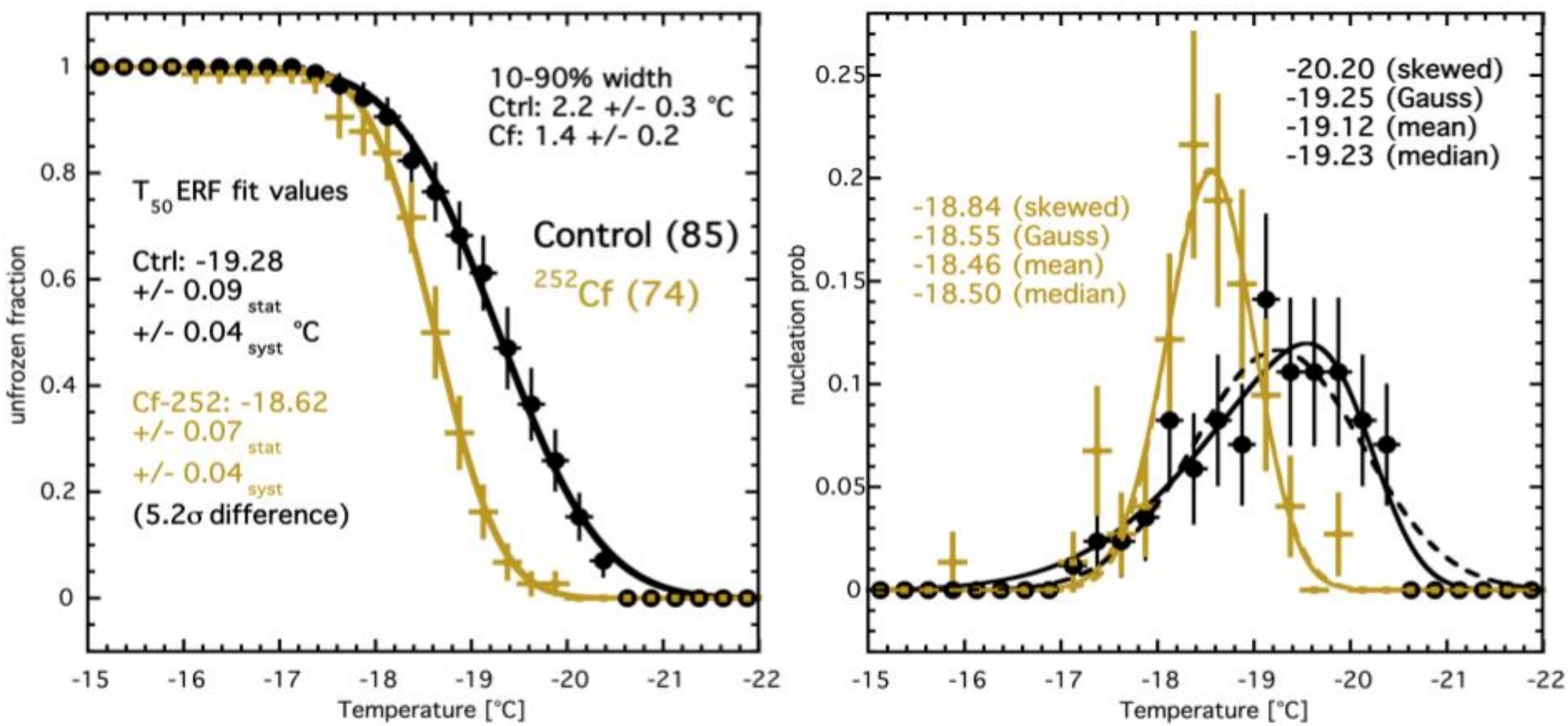
- About -20 °C and lower achieved, at a max cooling rate of -2°C / min.
  - Water may be able to go as cold as -40°C (world record: Goy, 2011)
- Partial vacuum of ~8-9 psia (water vapor, after earlier evacuation)
- 1h cooling & heating (melting) full cycle, with ~50% time spent < 0°C
- Multiple run conditions
  - Control (no radioactive source)
  - 200 n/s AmBe (with, w/o lead shielding)
  - 10 μCi ^{137}Cs gamma-ray source
  - 3,000 n/s ^{252}Cf (with Pb shielding)
- Shielding stopped gammas from interfering with the thermocouples
  - Also made more neutrons and altered their energy spectrum (slightly)



Operational Challenges

- Getting as cold as feasible, sans unwanted nucleation as a background
  - If like a bubble chamber except in reverse, colder should be **better**, because it should mean lower energy threshold
  - Must not just avoid particulates (heterogeneous nucleation) but the homogenous nucleation limit too if that exists (it would imply a low-energy-threshold asymptote)
- Finding the ideal rate of cooling
  - Too slow means low live-time and/or more opportunity for an unwanted nucleation (from vibration, background radiation, etc.)
  - But too fast means thermal lag/gradient, which encourages nucleation
- The scientific method in its purest form: “let’s try it and see” approach
  - Hypothesis: radiation, specifically neutrons, is/are able to freeze supercooled water

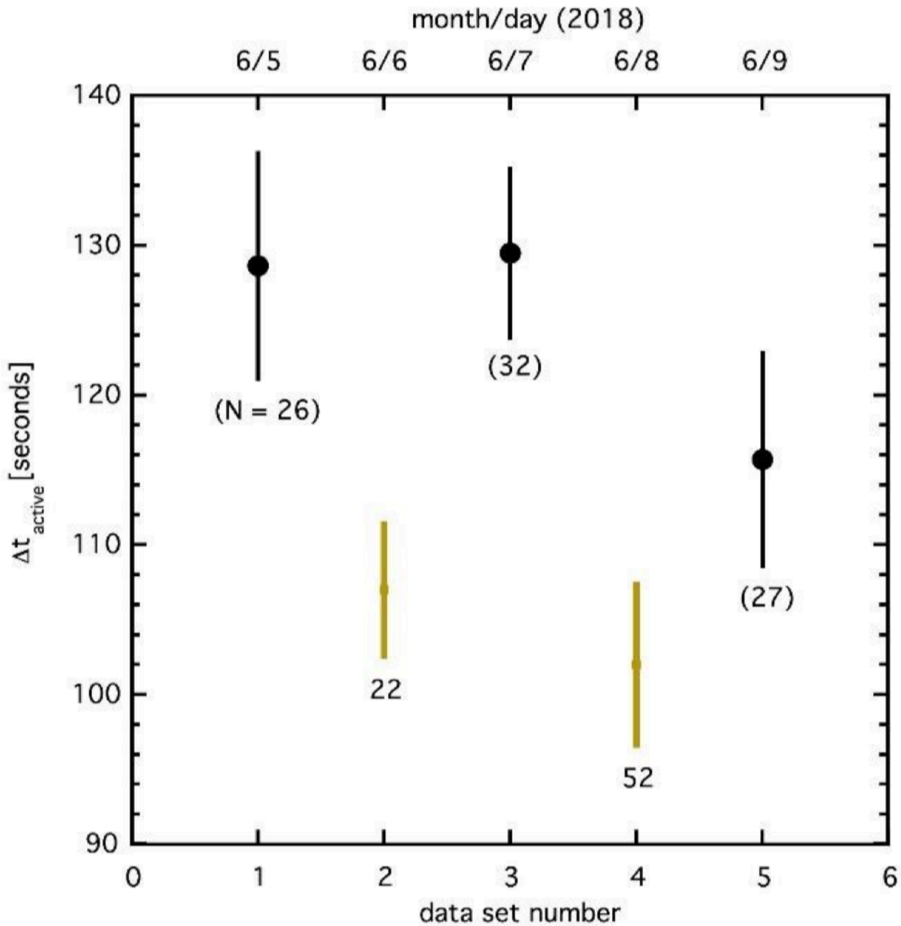
Cf-252 Source Deployment



KS test p-values: 6.64 x 10^-5 comparing times
Conservatively using only “local” control

p = 3.09 x 10^-8
for temperatures!

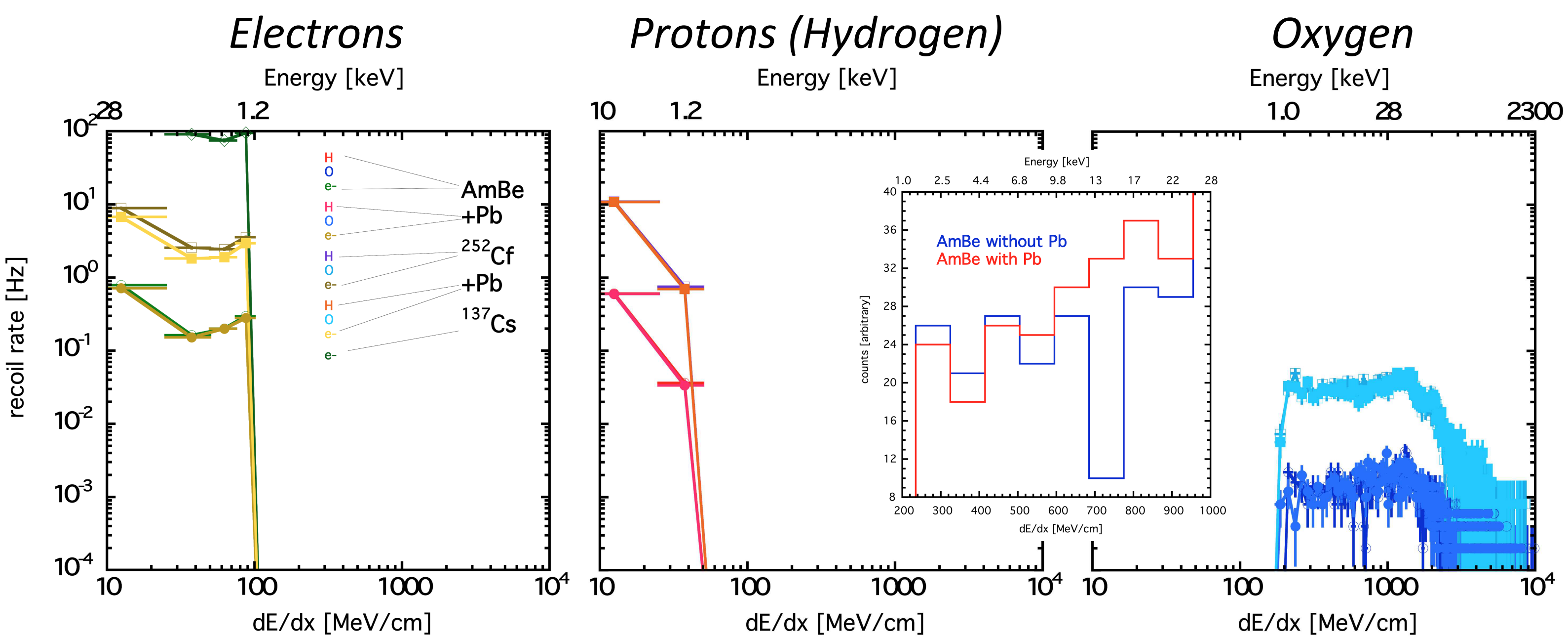
Systematics



- Alternated the source and BG runs
- Checked room temp as a systematic
  - No effect
- Source outside, could not “bump” the vessel

Simulation of Results: Geant4

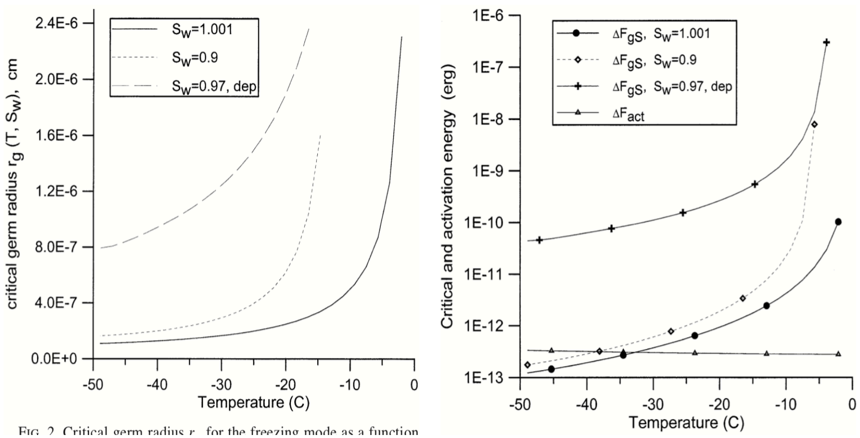
- Our initial data APPEAR to be following a “worst-case scenario” for threshold, but even then can extrapolate to O(10 eV) at ~ -30 °C. O(1 eV) across most of literature
- Our snowball chamber appears to have a pair of tunable thresholds, just like bubble chambers: one in energy and one in stopping power or *dE/dx* (aka linear *E* transfer)

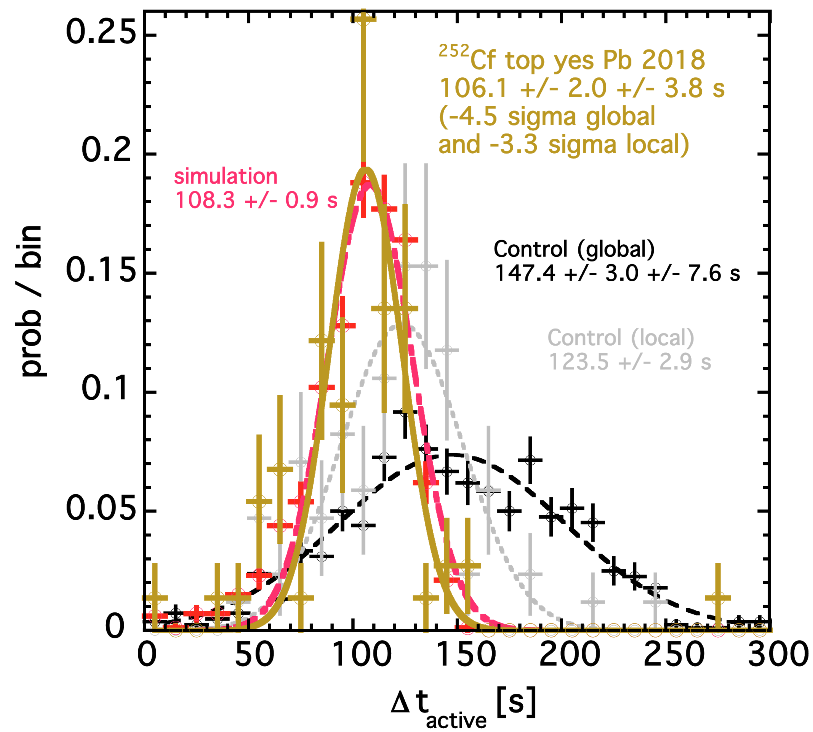


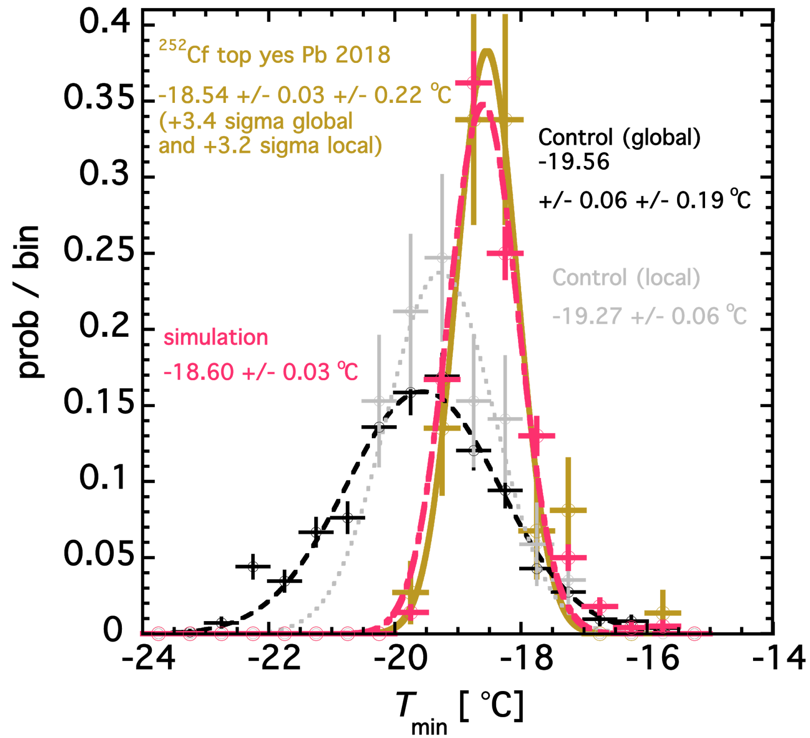
Post-G4 Sims

Open question: does n MFP match data?

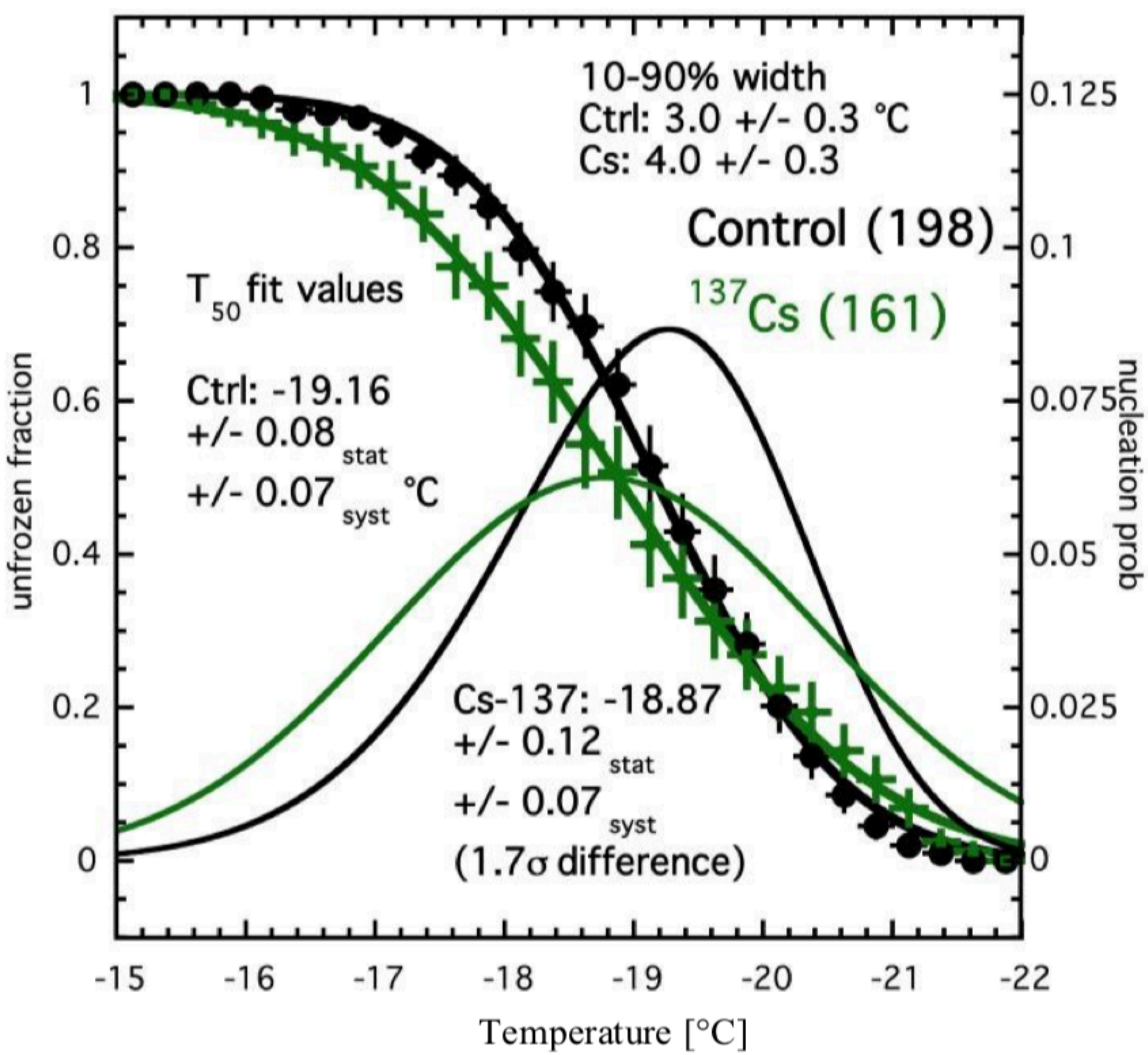
(1) $E > E_c = 0.2\ keV$ (post eqs. 2-3 E_c=1.2 effectively)
(2) $dE/dx > E_c/r_c = 10\ eV/nm = 100\ MeV/cm$
(3) $l > 2r_c = 40\ nm$
(4) $Efficiency = 1/(1 + (T/252.8 \pm 1.1\ K)^{540\pm150})$







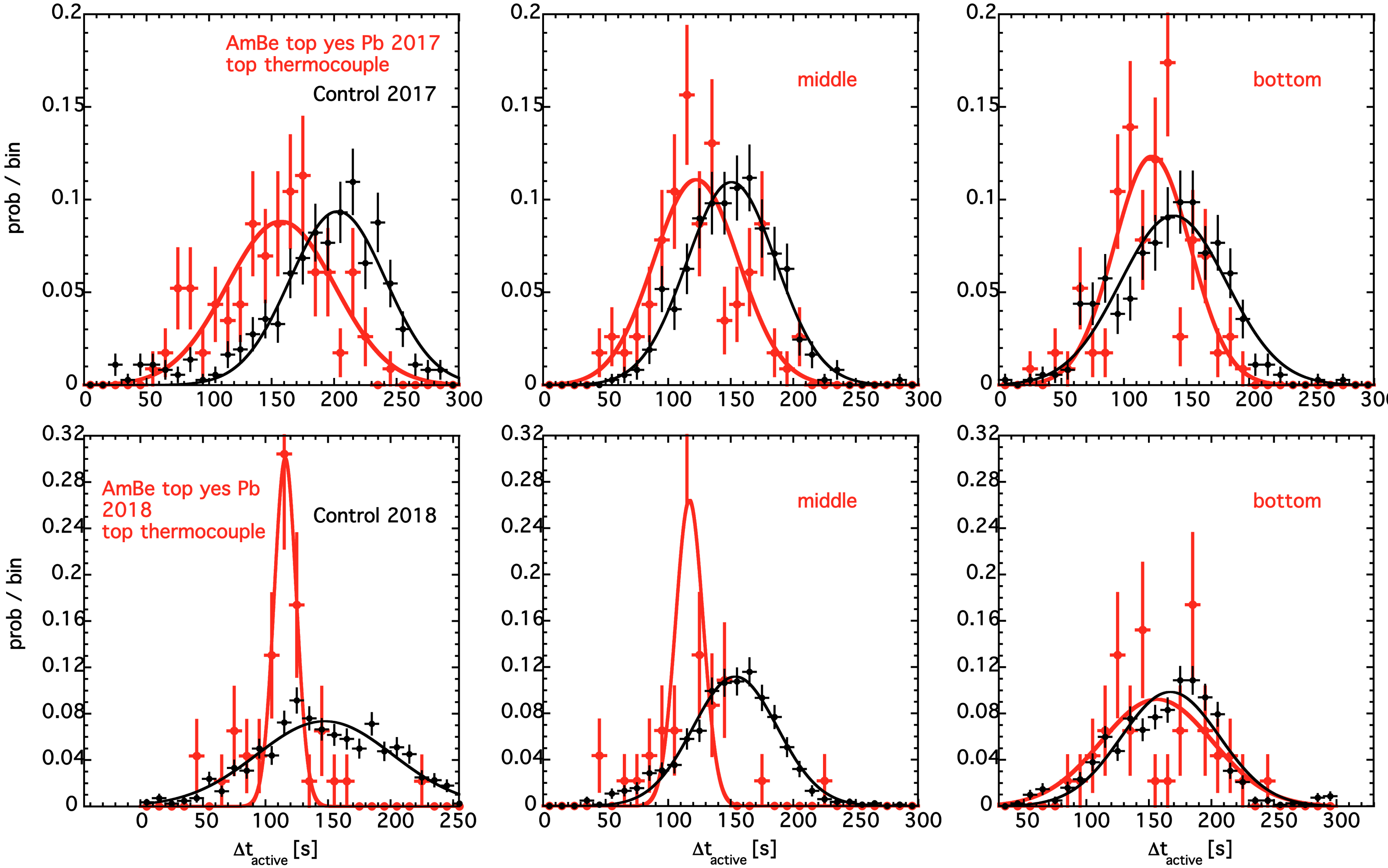
Cs-137 and Other Calibrations



- No statistically significant effect so far from gammas (0.662 MeV energy)
- May be a sign of SOME e- recoil rejection?

AmBe Neutrons (and Gammas)

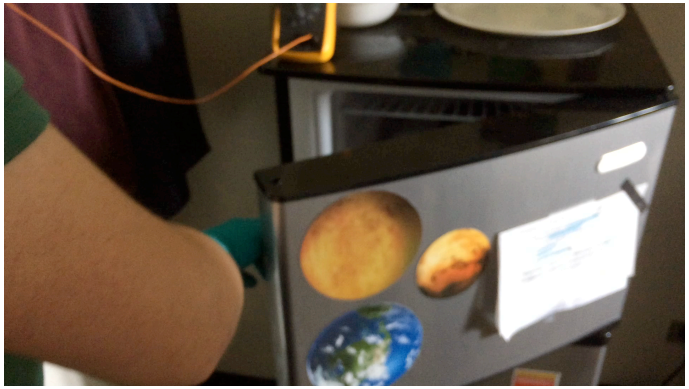
Across three different thermometers (Why not Cf? Similar study not possible for it)

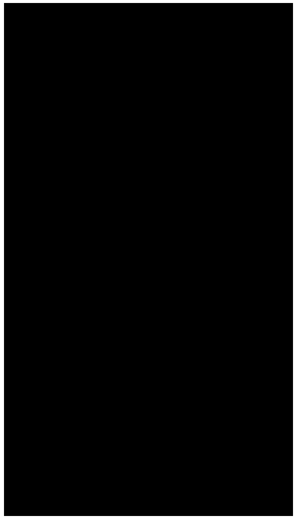


Sensitivity to Different Particles

- Efficient nucleation for different interaction types should be tunable
  - With temperature (and/or pressure?)
- This may explain several anomalies
  - Lack of alpha nucleation of supercooled water in the atmospheric chemistry literature
  - Gamma-ray sensitivity in Varshneya's work
- Imagine an array of optimized tubes
  - Multiple locations around world including UG

Video Examples





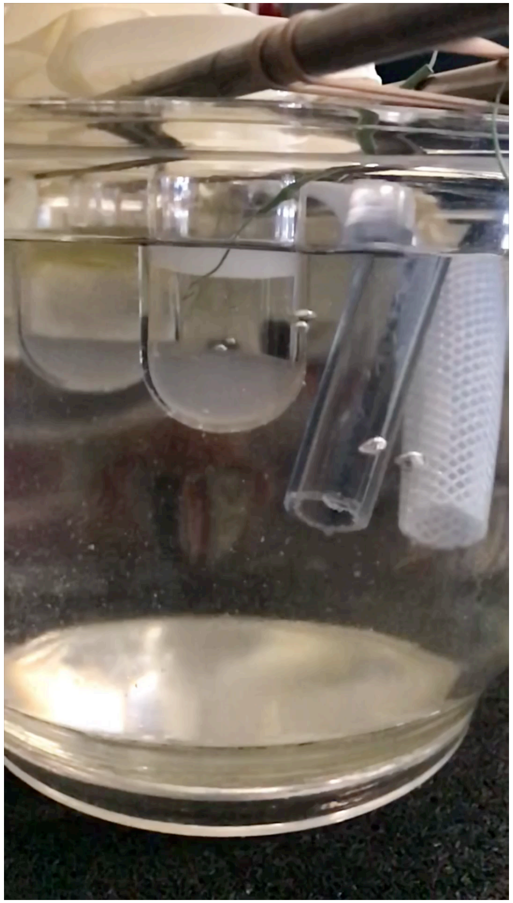
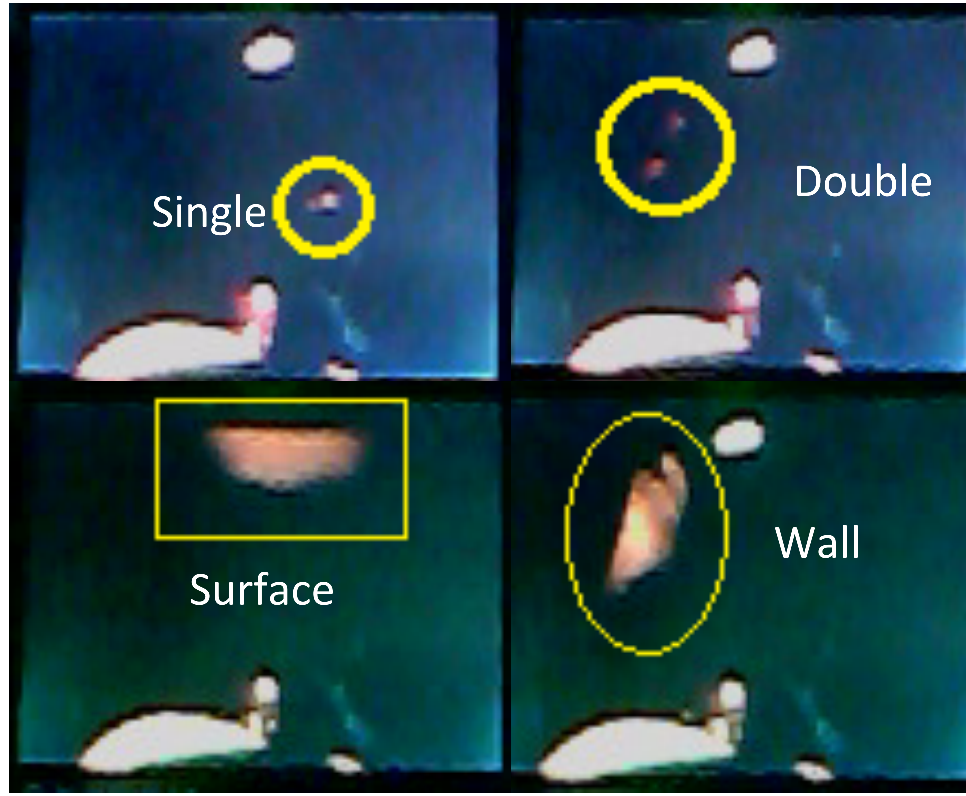
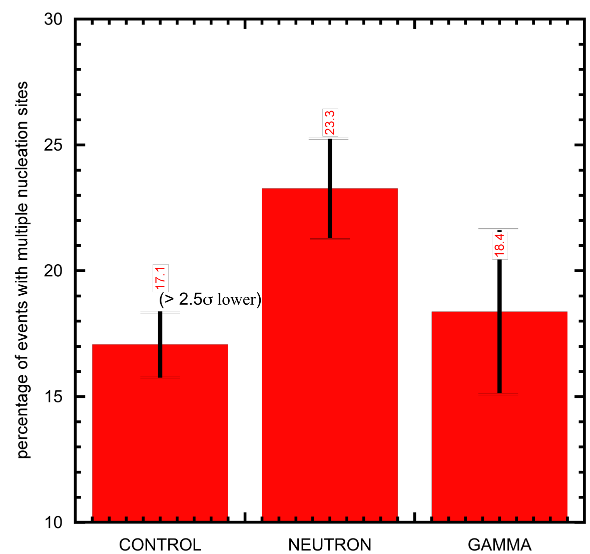


Image Analyses

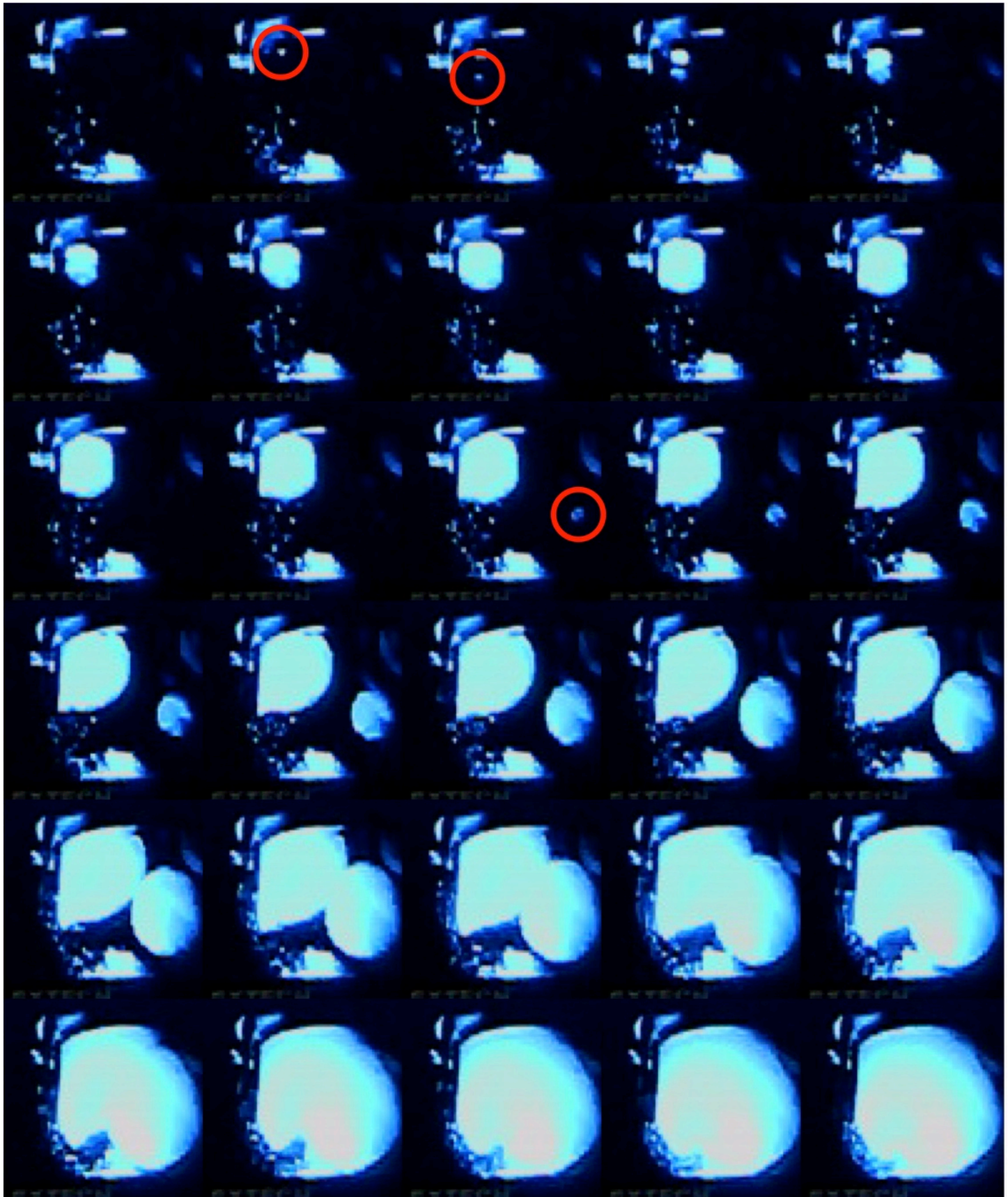
- Even without a second camera or mirror, can kind of tell wall and/or surface events
  - Most common, especially in control results
- Far from perfect by eye
  - So, focus was counting
- More multiple scatters in neutron data
  - Consistent with neutrons causing crystallization
- Future: more cameras, better cameras
  - High frame rate, high res

types of events

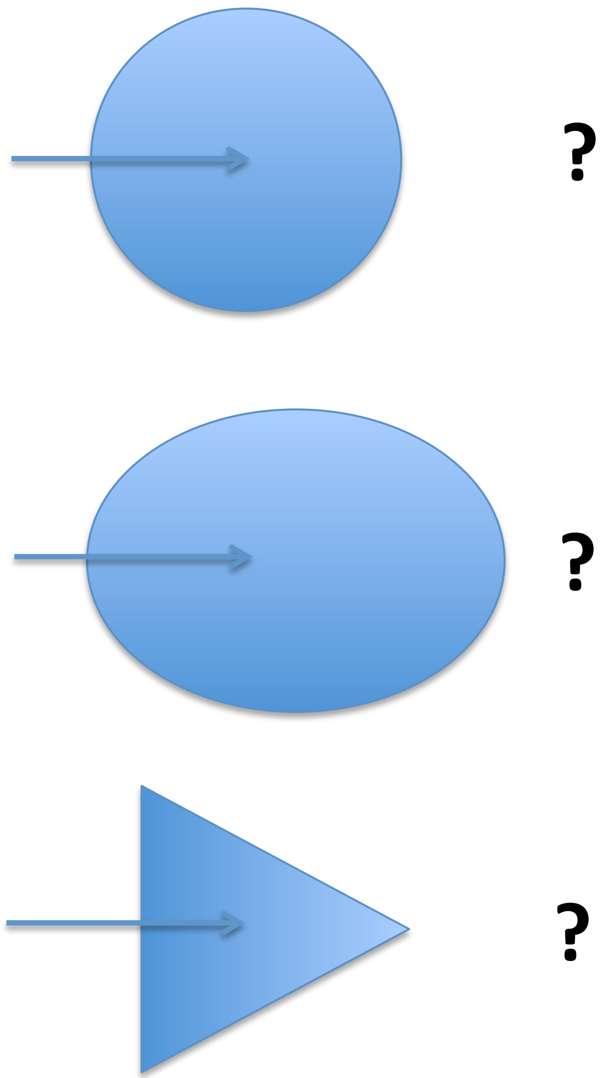




blind analysis performed, employing large team of undergraduate students scanning photographs



Potential for Particle Directionality

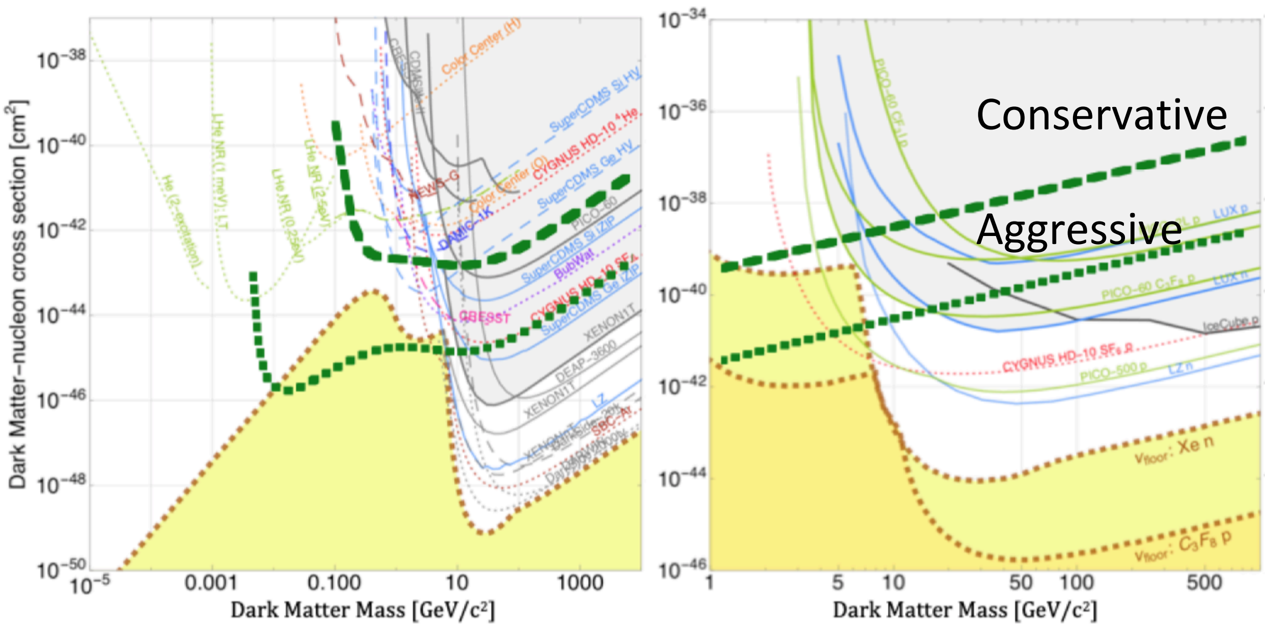


- Given at least 2 cameras can already have position reconstruction
  - You already saw neutron multiple scattering evidence (vertices in images)
  - Not what we mean here
- Asymmetry (slight?) in snowball formation
  - Including a possible head-tail effect, seen only in gases
  - Why possible potentially? Intense H-bonding in water
- Perfect for AI/ML? Similar computational problem to facial recognition

Sensitivity to Vanilla Default WIMPs

borrowed plot from DoE Cosmic Visions Report (arXiv:1707.04591) and overlaid our own curves. No directionality assumed

- Spin-independent (SI) and spin-dependent (SD)
  - Approaching the (lower for H) neutrino "floor"
- Dark photons and axions through e- scattering?



1 kg-year live exposure, at 12 eV energy threshold w/ low BG, underground
->e.g. only 1 kg for 1 yr!
100 kg-years, 16 meV is the lower curve

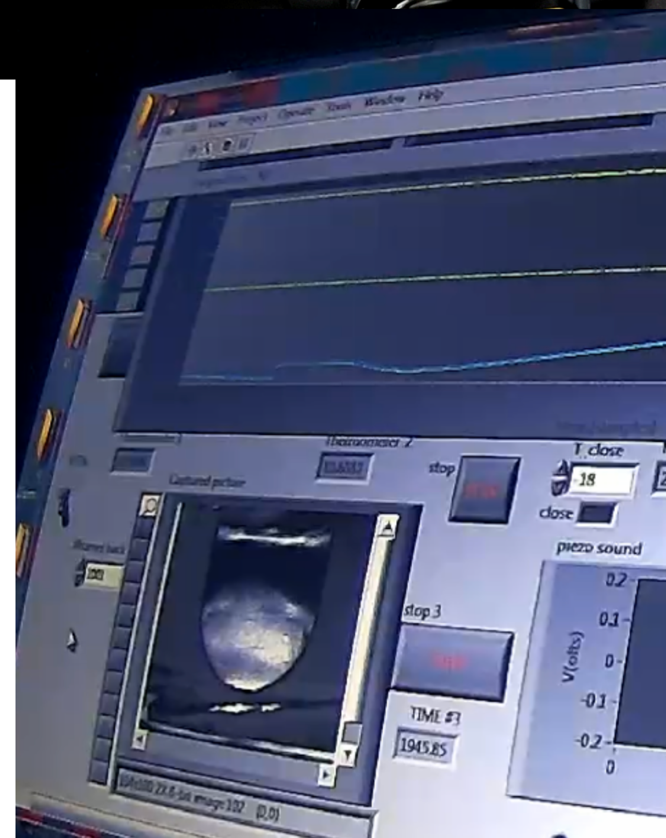
SI (left)
SD-proton (right)

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

Mid-Pandemic Setup: At Home

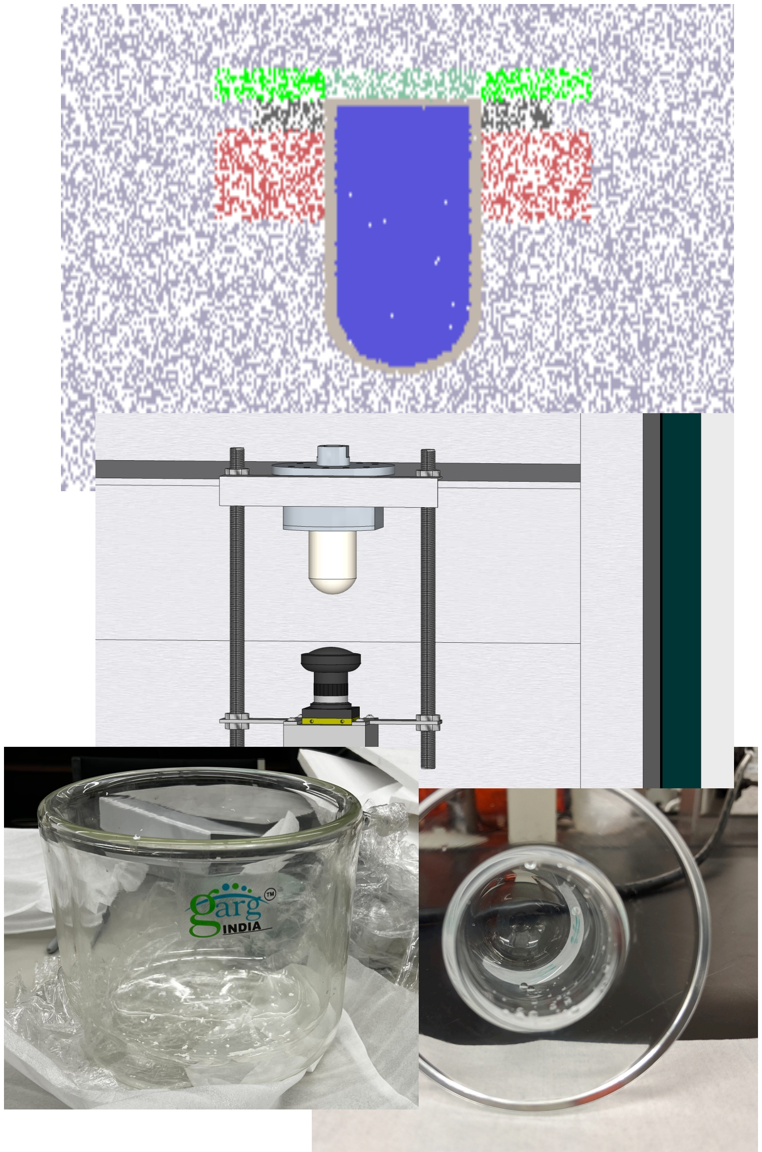
- Hundreds of test tubes tested, up to 4 at a time
- Different types of tubes, and oils on top (buffers)

New Setup: Snowball 1mL 2023 (to…?)



- Long time in coming
  - Pandemic
  - Lack of students
- Utilized my sabbatical to set up last semester
- Plan: long term runs
  - Greater variety of sources
- Much smaller volume
  - Upside: can get colder with less purity
  - Downside: less space for n scattering

Possible Future Enhancements



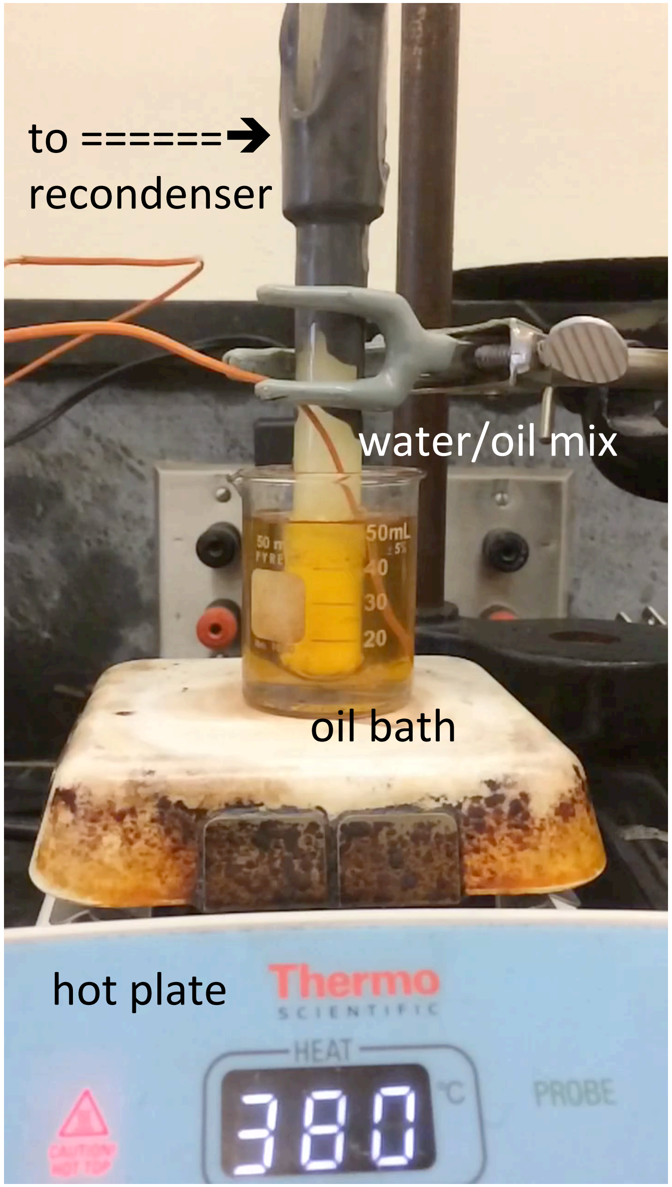
- Hydrophobic coating on walls
- Addition of energy reconstruction possible via scintillation and PMT/SiPMs
  - Similar to scintillating bubble chamber (Dahl)
  - Quantum dots?
  - WbLS (water-based liquid scintillator) from Minfang Yeh (chem division, BNL) *tour later!*
- Modularity
  - Monolithic detector better for ton-scale, or test tubes?
  - Supercooled droplet detector?
- Molecular dynamics sims

The Biggest Disadvantages

- Currently, livetime is poor (wait for reset!)
  - Can we stop nucleation quickly with lasers, microwaves, or sublimation? Something else? Unclear, as freezing process exothermic
  - Modularity may be the key to this problem
- No energy reconstruction: WbLS the fix? *tour later!*
  - Only if it can be supercooled: micelles smaller than the critical radius, so *should* work
- Directionality, if real, may not work at low *E*s
  - Gaseous detectors have the same problem
  - But this may only affect dark matter and neutrinos. For MeV neutrons could still work

SuperHEATED Water

- If supercooling fails to ever reset fast enough
  - OK for dark matter, not so much for nuclear security
- Superheat instead of supercool
  - Plus: 100% works, old tech
  - Minus: can be dangerous
- Combine with geyser and SDD concepts
  - Instrument primarily with piezos for fast DAQ



Conclusions

- Neutrons can make supercooled water freeze: a new discovery
- They can even multiply scatter, as they do in a bubble chamber!
- There is at least some degree of electron recoil (gamma) discrimination
- What are the actual backgrounds, from random nucleation, alphas,...?
- Energy threshold is not known, but likely sub-keV already at -20°C
- Need to calibrate it better. But looks good for low-mass DM & CEvNS
- Possible strong relationship to other fields (non-proliferation, clouds)
- All in all, this is a very promising start to a RE-discovered technology

Future Work

- Deployment of a larger (kg-scale) device underground for dark matter and neutrino physics
  – But also interdisciplinary applications in nuclear security and non-proliferation, through the detection of low-energy neutrons from nuclear (fissile) materials

- For you: any questions?
  – And, apply to UAlbany SUNY for grad school!