The Snowball Chamber:
Using Supercooled Water for Discovering Sub-GeV Dark Matter

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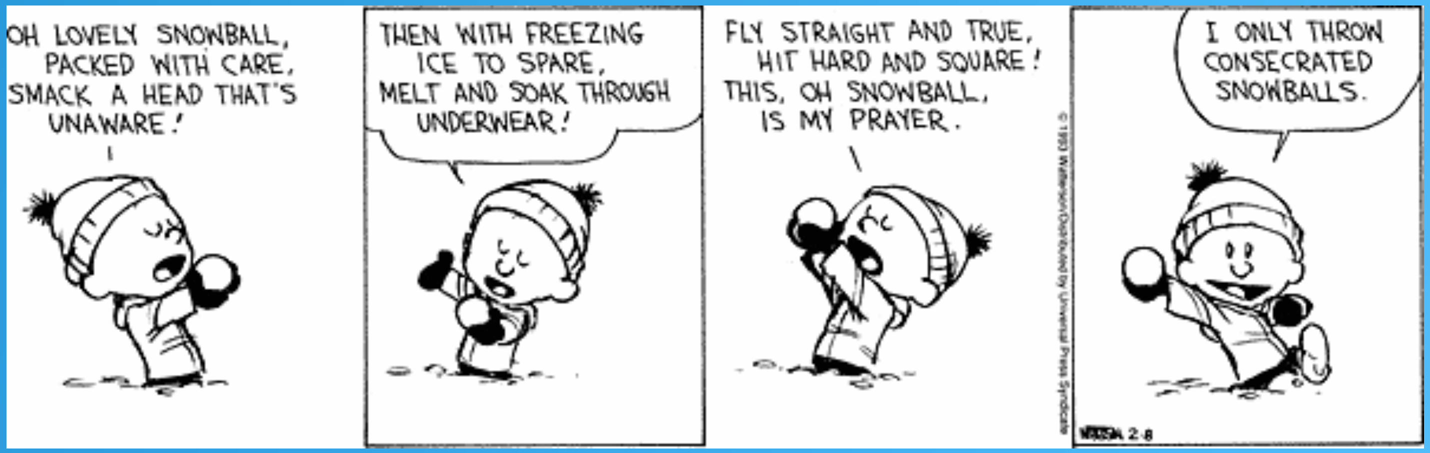
on behalf of the SnowBall Collaboration



CPAD INSTRUMENTATION FRONTIER WORKSHOP 2019
December 8, Madison Wisconsin

SnowBall Collaboration

University at Albany, State University of New York

PennState

Brookhaven National Laboratory

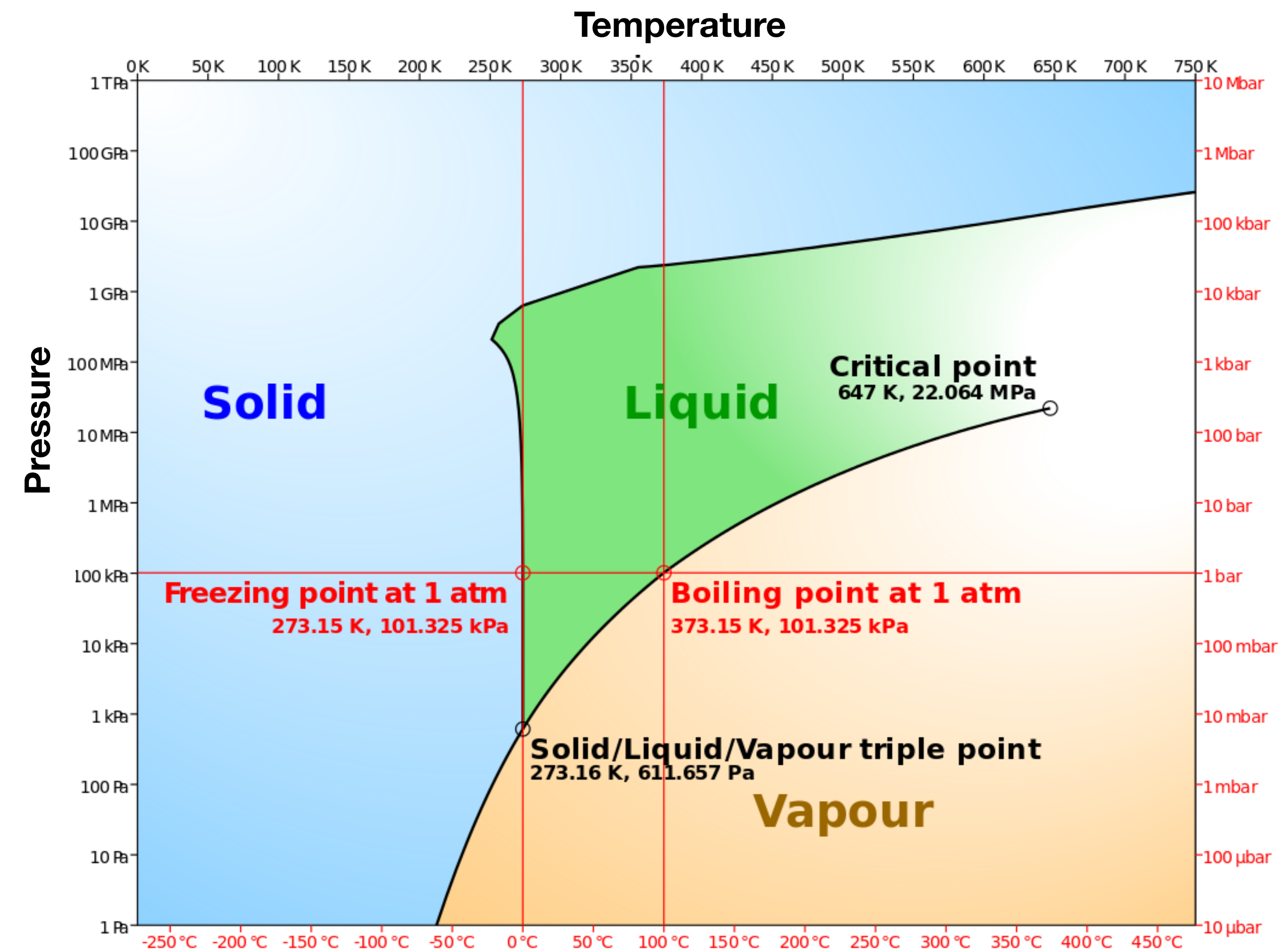
Duke University

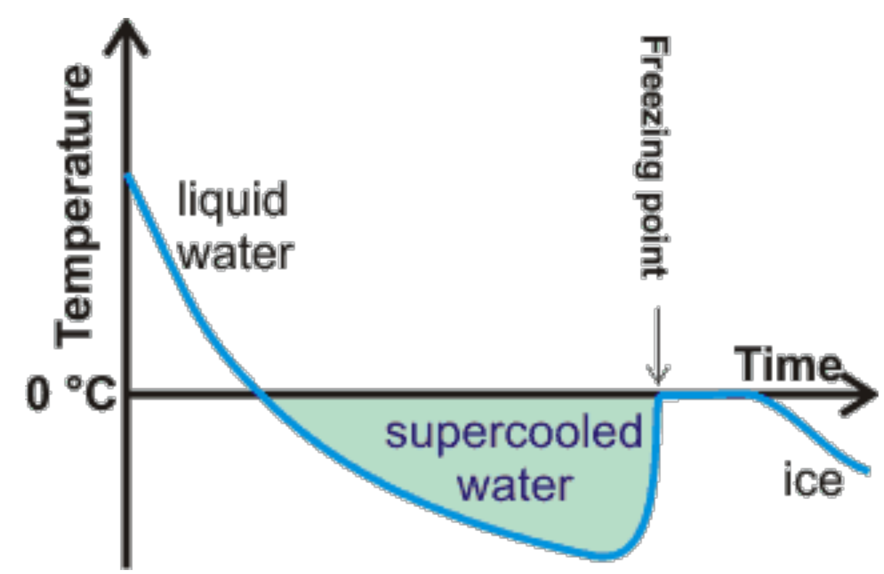
Rensselaer

TUNL

What is supercooling?

- Liquid is cooled below its normal freezing point
  - Metastable
  - High purity and clean, smooth container
- Freezing: when liquid finds a nucleation site, or is"disturbed"
  - Cannot stop nucleation: it snowballs
  - Highly exothermic!
- Smaller samples are easier to cool
  - Minimum T depends on radius of sample
- Unexplored phase transition in physics!
  - Cloud & bubble chambers both done
- New technology!
  - Multiple applications, although in this talk I will focus on the search for low-mass dark matter





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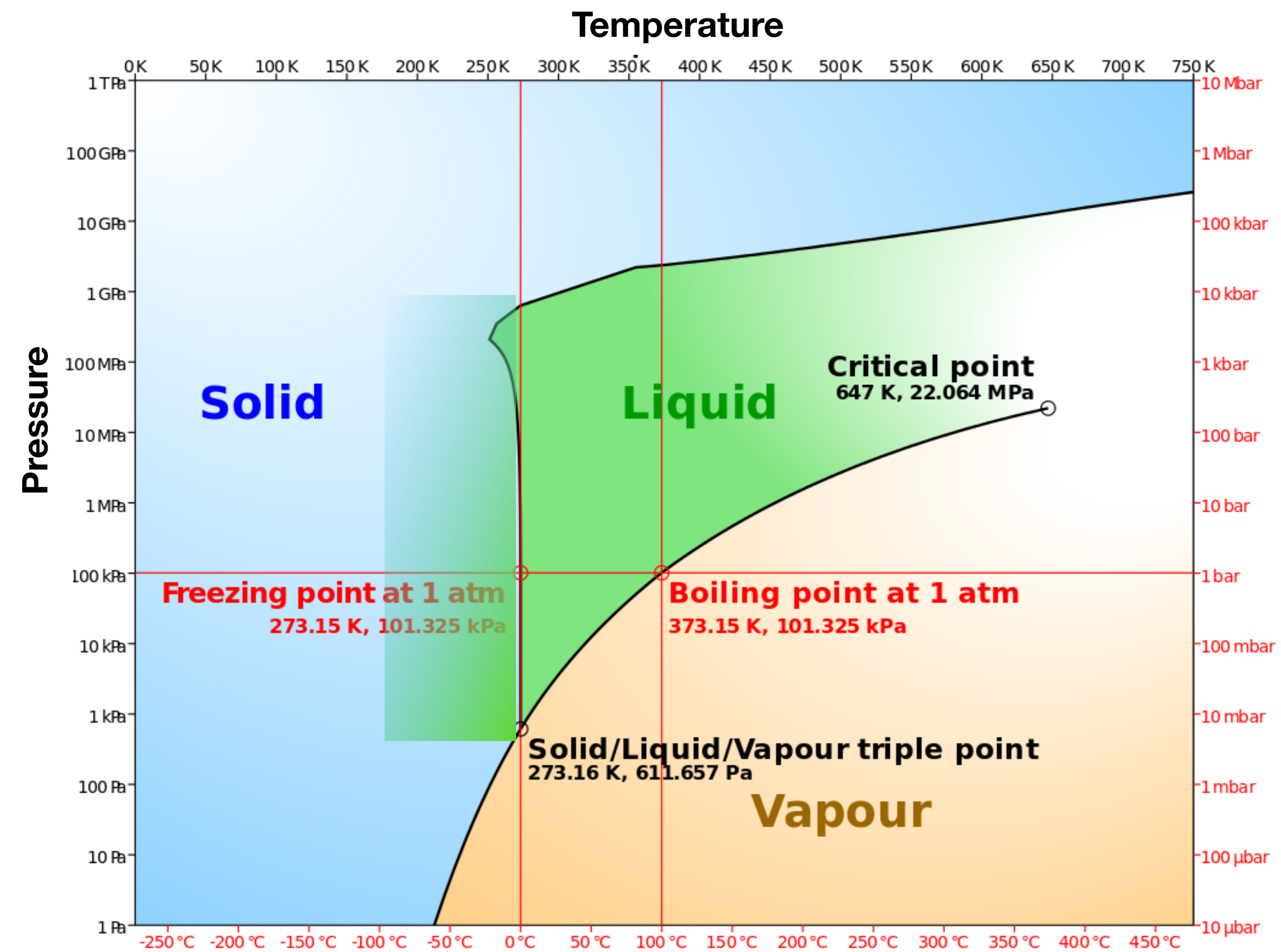
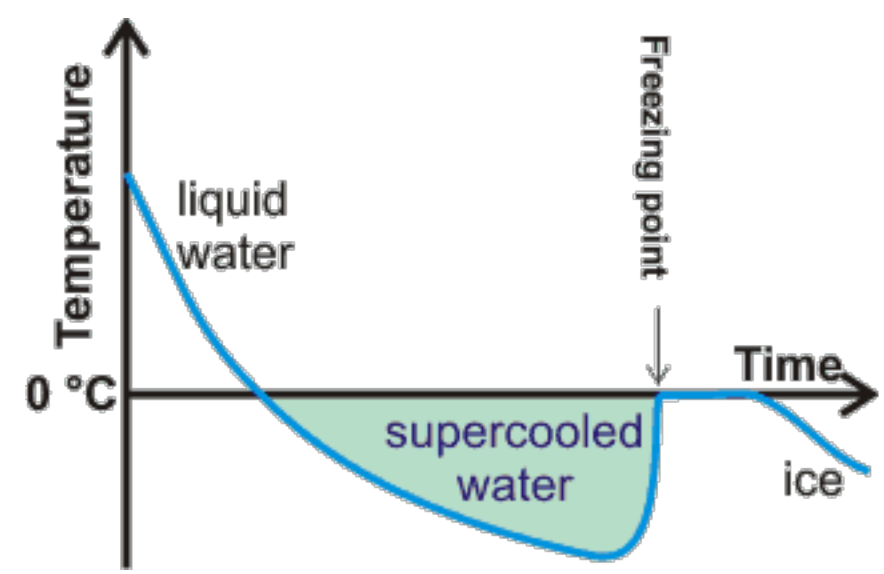
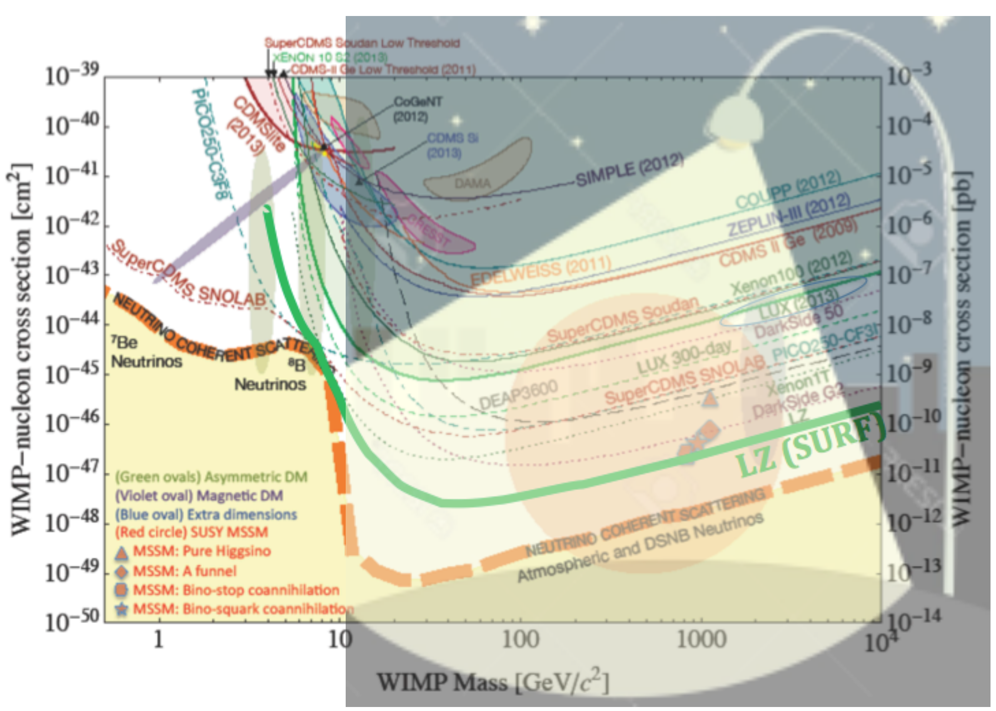




Motivation

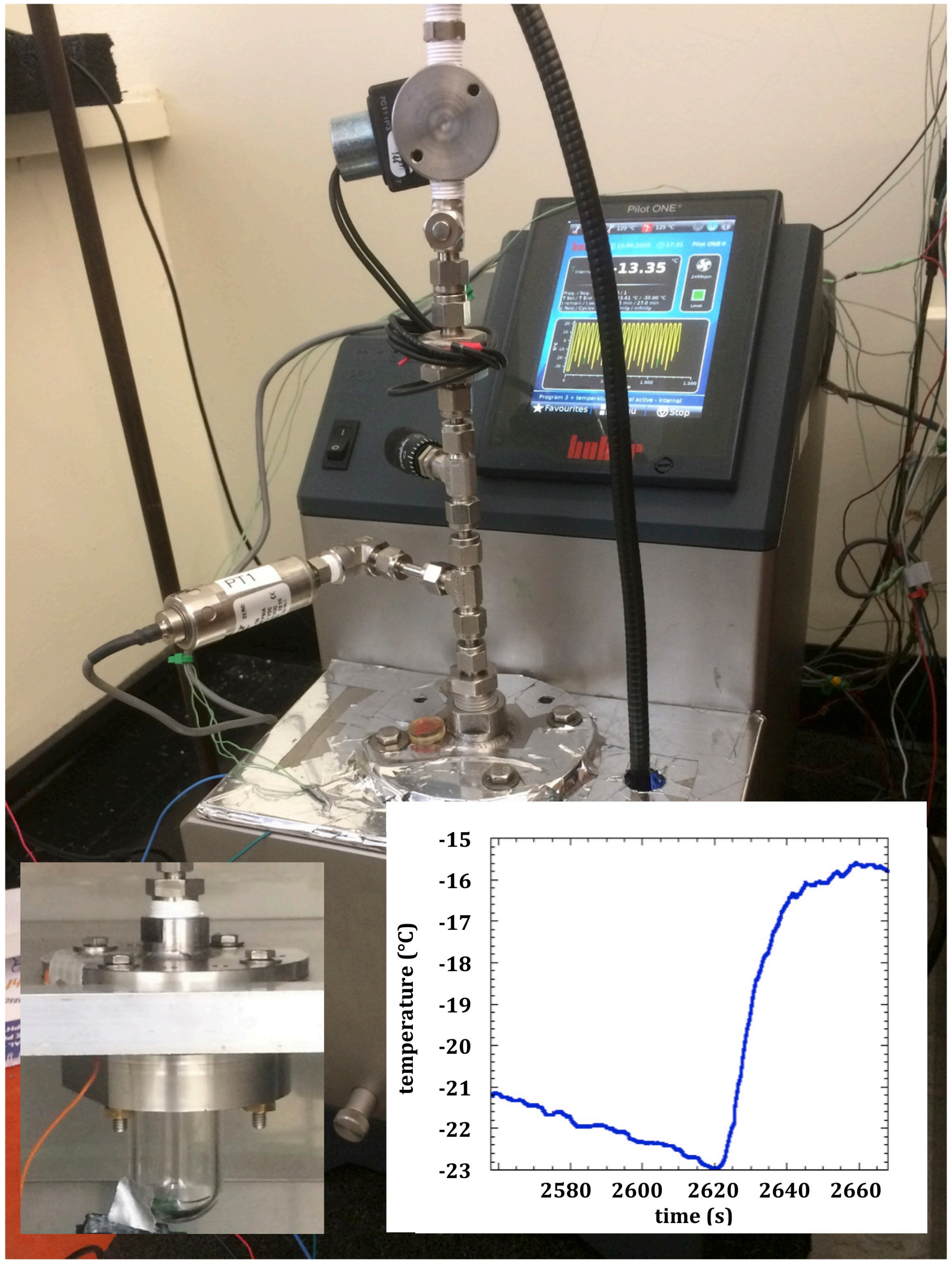


- Lack of discovery of dark matter in the range ~10-1000 GeV/c^2 mass
  - Motivates looking elsewhere
- What better target for lower-energy recoils, than the lightest possible target element, hydrogen?
  - Hydrogen bubble chamber would be great, but the safety...
  - Other ideas exist already, so far 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

Challenges Using Supercooled Water

- Getting as cold as feasible, without unwanted nucleation as a background
  - It's like a bubble chamber except in reverse: colder should be better → lower energy threshold
  - Must avoid both particulates (heterogeneous nucleation) and homogenous nucleation
- 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 scientific method in its purest form: "let's try it and see" approach
  - Testability, reproducibility, control, bias mitigation, and statistical significance all involved.
  - Hypothesis: radiation, specifically neutrons, freezes supercooled water

Prototype Detector



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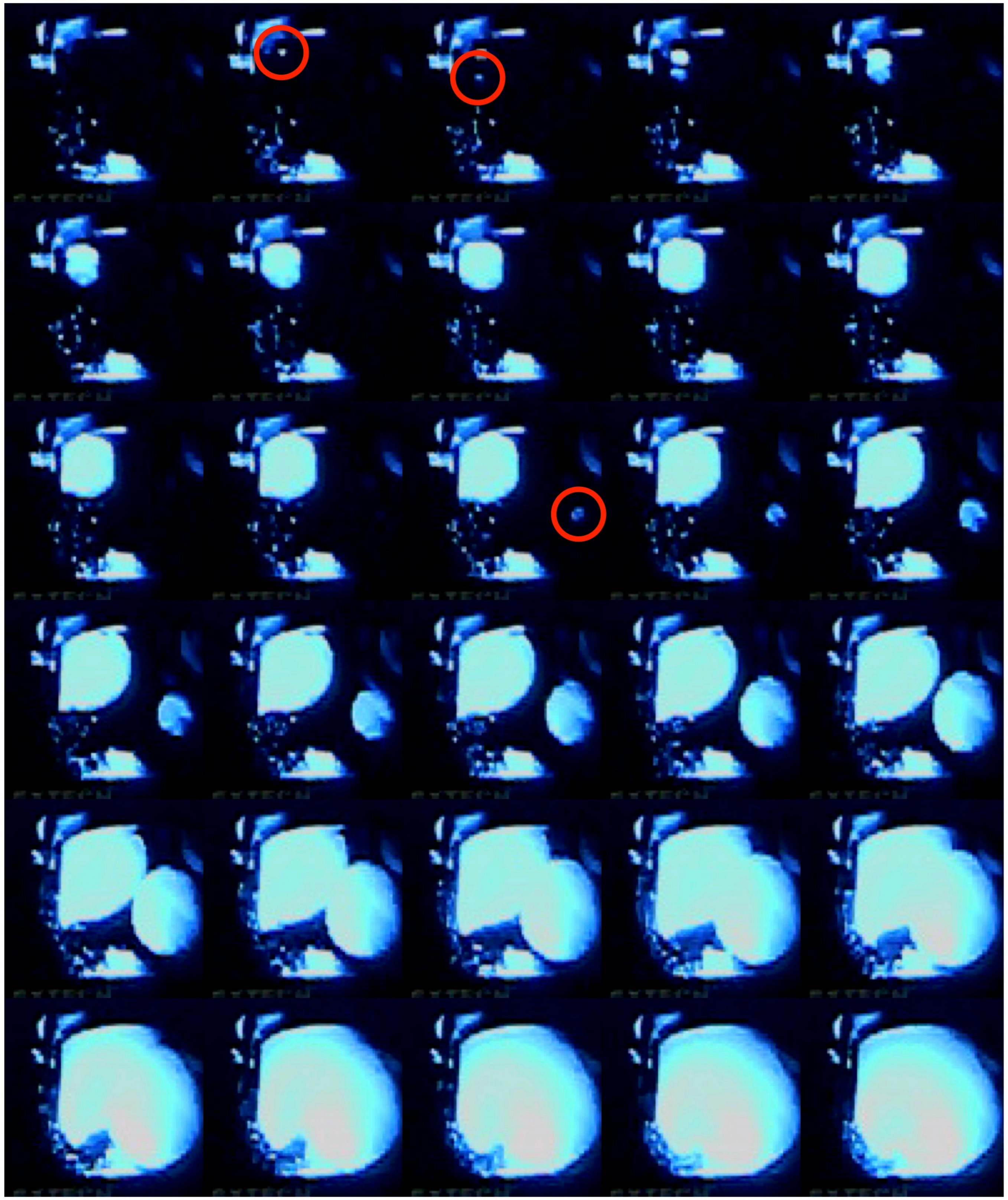
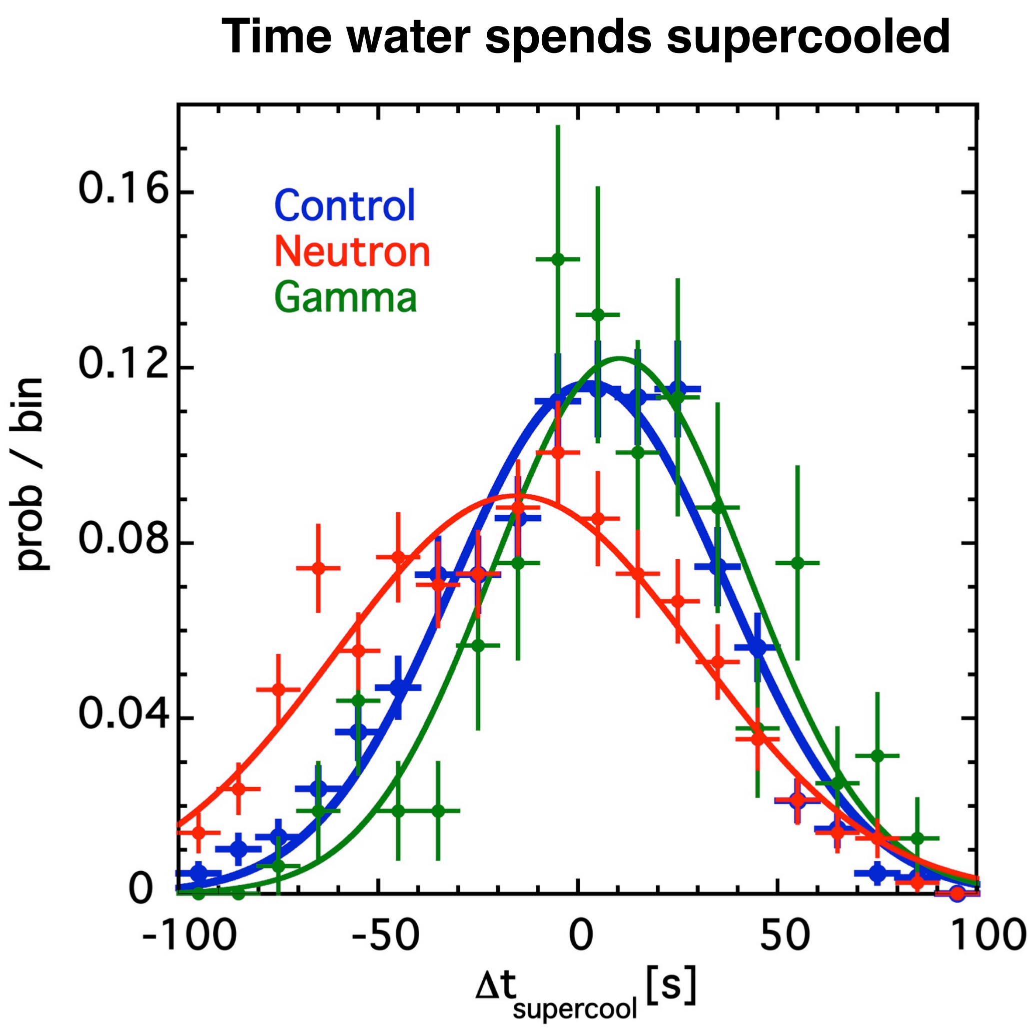
- 20 g (20 mL) of purified water contained in a smooth, cleaned fused quartz vessel
  - ✦ Water processed through multiple filters, deionized, and ultimately distilled through a 20-nm flat-sheet non-linear membrane
- Thermocouple thermometers (averaged)
- Borescope camera for image acquisition
- Coincident counter under vessel
- -20 °C achieved (maximum cooling rate of -2°C per minute)
- Multiple run conditions / calibrations
  - ✦ Control (no radioactive source)
  - ✦ 200 n/s AmBe (with, w/o lead shielding)
  - ✦ 10 μCi 137Cs gamma-ray source
  - ✦ 3,000 n/s 252Cf (with Pb shielding)

Example Events



First Quantitative Results



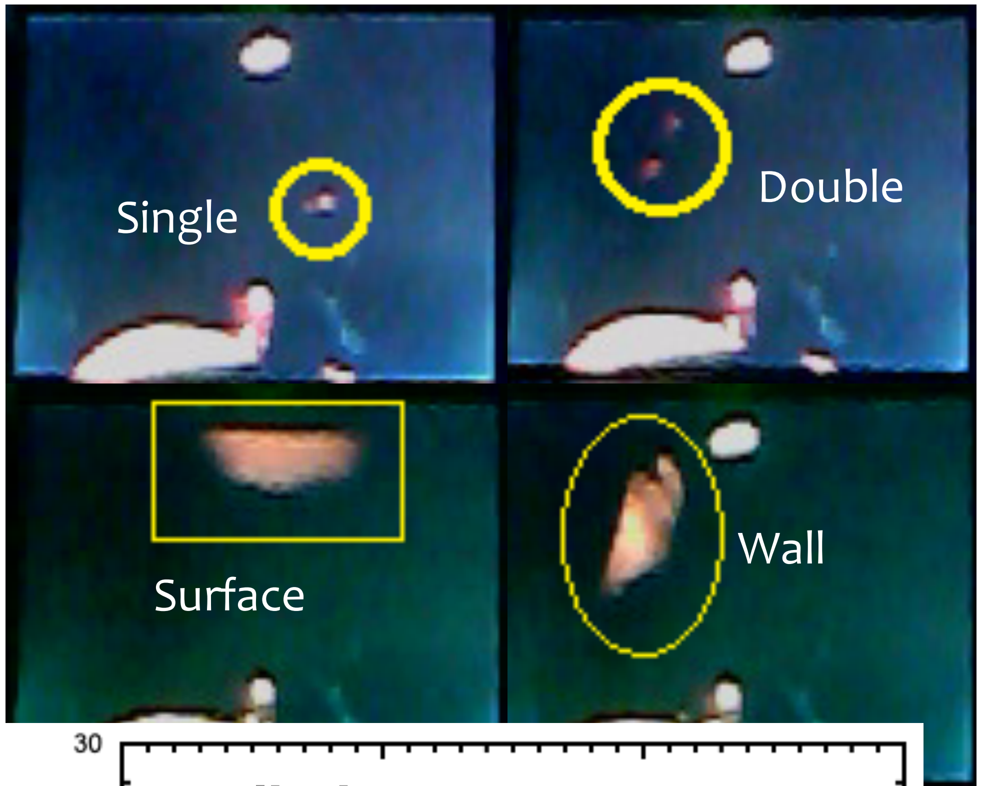
Calibration Type	$< \Delta t_{superc} >$ [s]	$< T_{min} >$ [°C]
Control (no source)	0.00±1.0	-19.16±0.03
AmBe Top	-0.71±2.4 (-0.05)	-19.40±0.05
AmBe w/ Pb (Top)	-35.4±2.7 (-2.5)	-18.87±0.07
AmBe side	-3.94±2.8 (-0.3)	-19.28±0.06
^{137}Cs gamma	9.83±2.7 (0.7)	-19.41±0.07
FWBe (Fiestaware)	-17.8±5.6 (-1.2)	-19.19±0.13
^{252}Cf (2018 only)	-58.4±3.6 (-4.σ)	-18.48±0.07

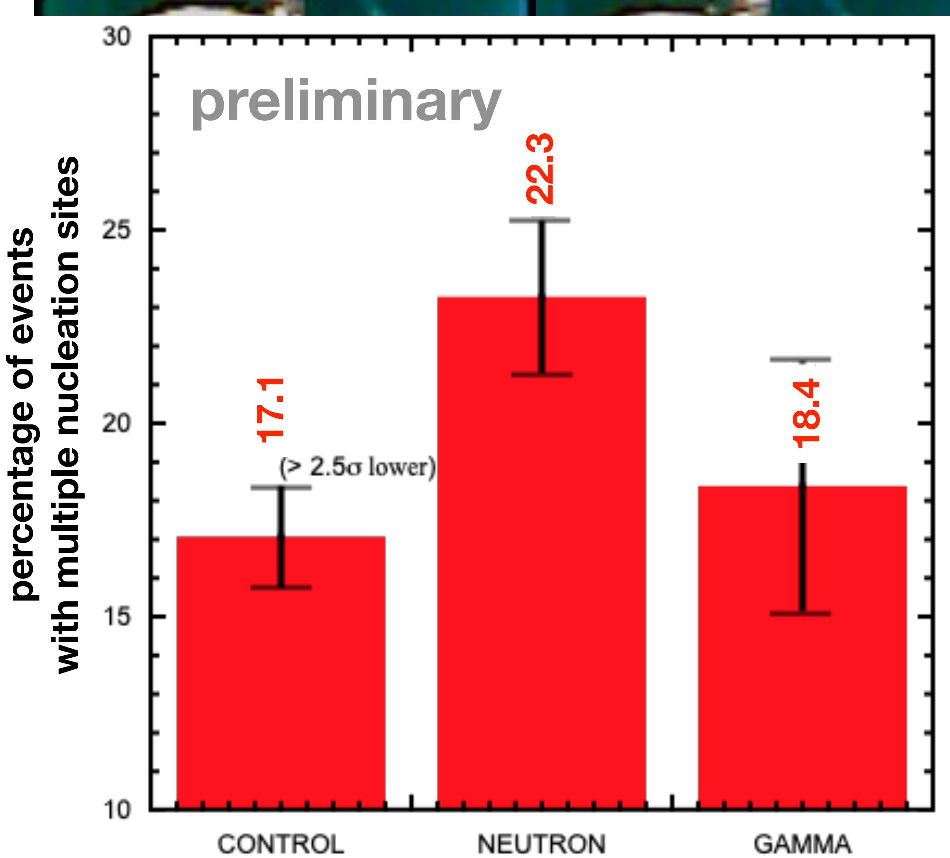
- Reduction in supercooled time in presence of neutron sources
  - ✦ Effect enhanced with lead shielding
  - ✦ Bigger effect with stronger source
- No statistically significant effect so far from gammas (662 keV energy)
  - ✦ May be a sign of e- recoil rejection
- We conclude that neutrons can freeze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

M. Szydagis et al. arXiv:1807.09253

Preliminary Image Analysis

Types of events



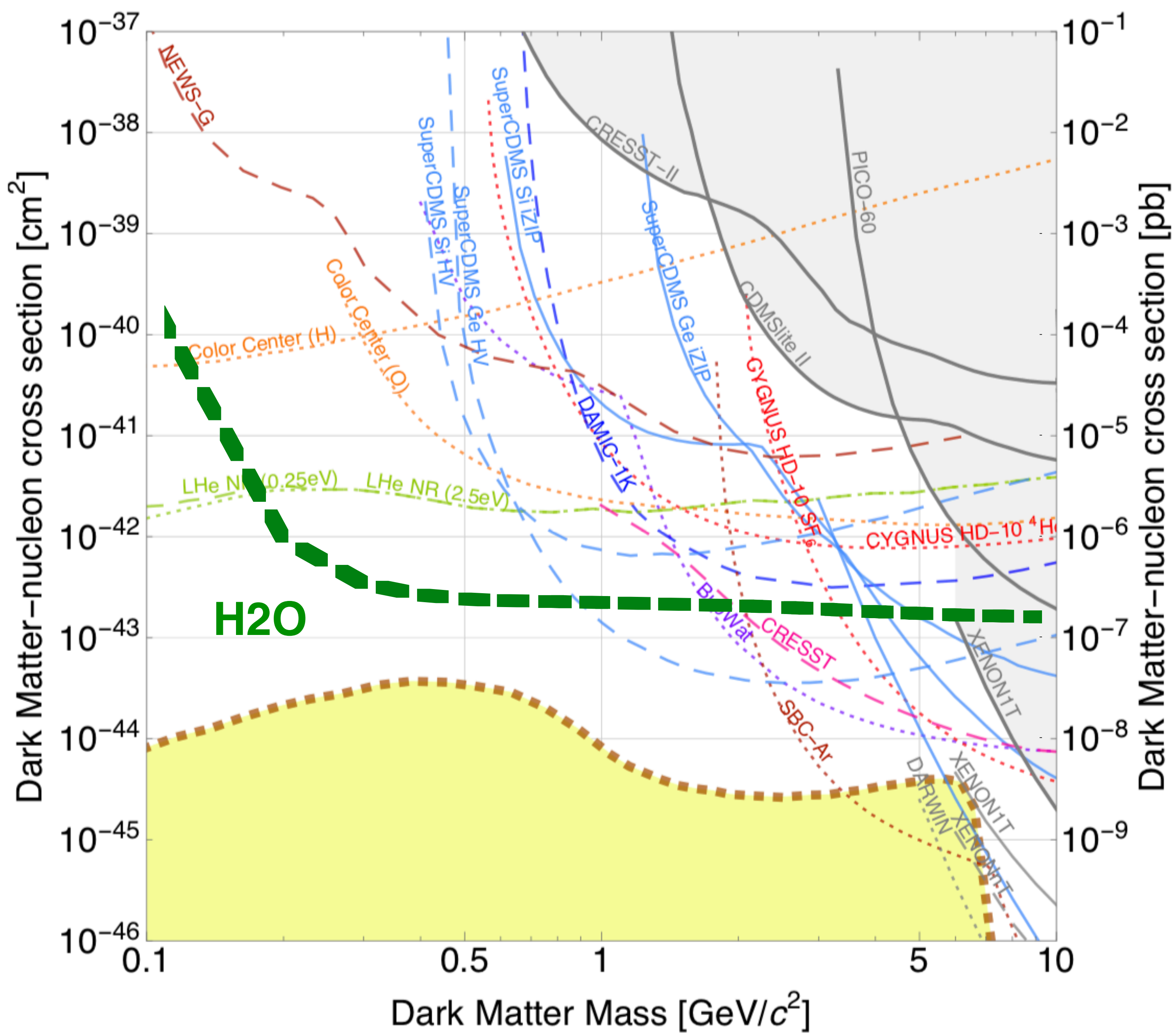


blind analysis performed, employing large team of undergraduate students scanning photographs

- Even without a second camera or mirror, can differentiate 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
  - ✦ Even triples, quad seen!

Sensitivity

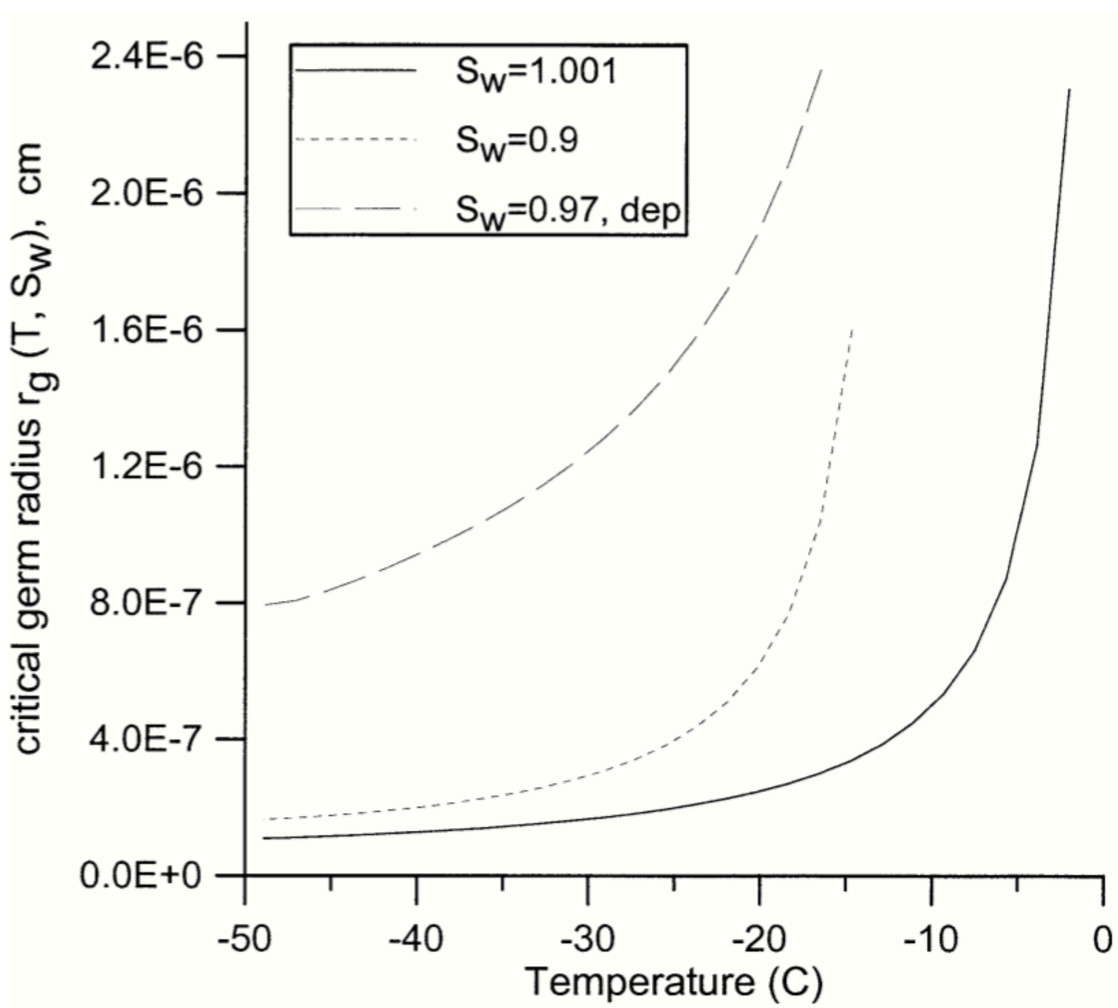
- This is optimistic case:
  - ✦ Assumes 10 eV energy threshold
  - ✦ Zero BG counts
  - ✦ Approaches ν floor
- 365 kg-d exposure
  - ✦ So, only 1 kg UG for 1 year!!!
- Thresholds as low as ~30 meV should be possible, and way more than 1 kg-year

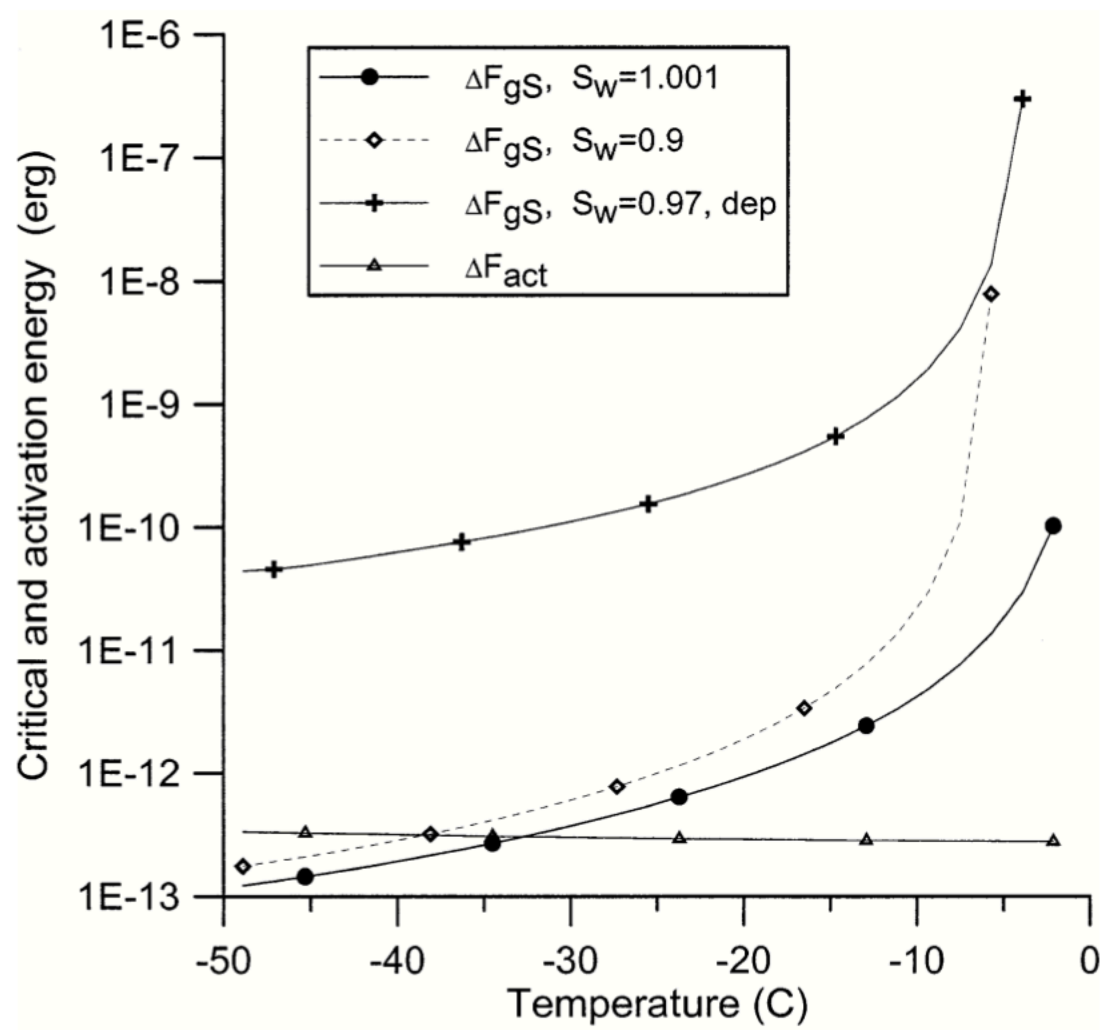


Fraction of the cost (and complications) of competing experiments at 100 MeV to 10 GeV! Potentially self-confirming

How to make that all possible

- Sub-keV threshold possible, even sub-eV
- Around ~240 K or -30 °C there appears to be a "sweet spot" of low threshold, to be sensitive to proton recoil but not too sensitive to gammas and spontaneous nucleation.

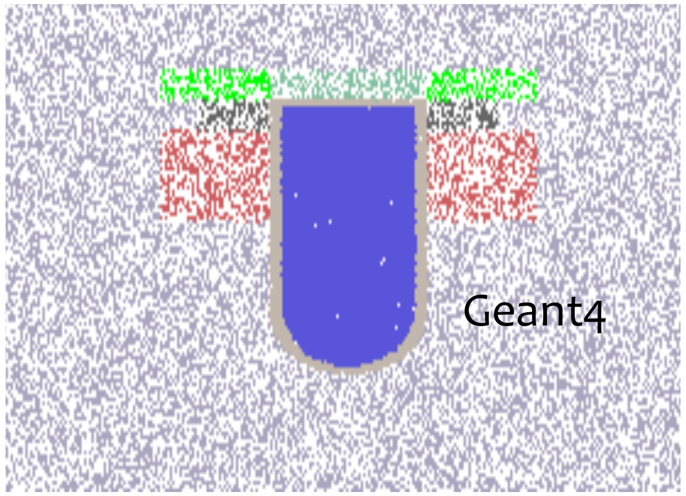


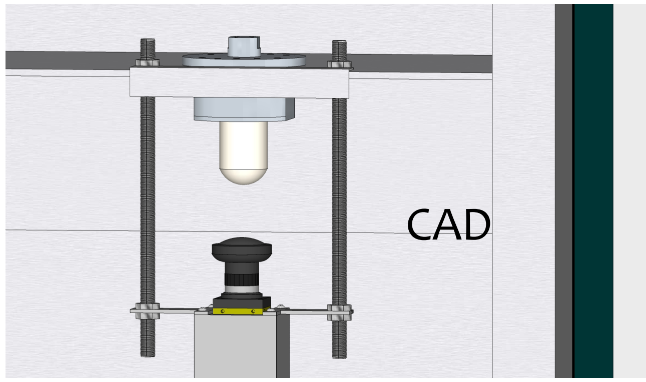


V.I. Khvorostyanov, J. A. Curry, Journal of Atmospheric Sciences 61, 2676 (2004)

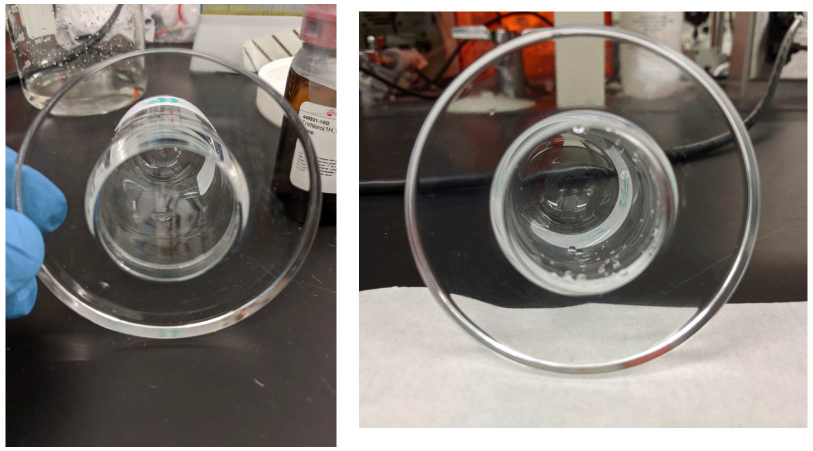
Future Work

- More cameras (higher FPS)/mirror for 3-D reconstruction
  - ✦ Including event type; show directionality?
- Lower threshold with lower T, hydrophobicity
  - ✦ Volume optimization, of water, and environment
- 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





hydrophobic coat (CNSE)



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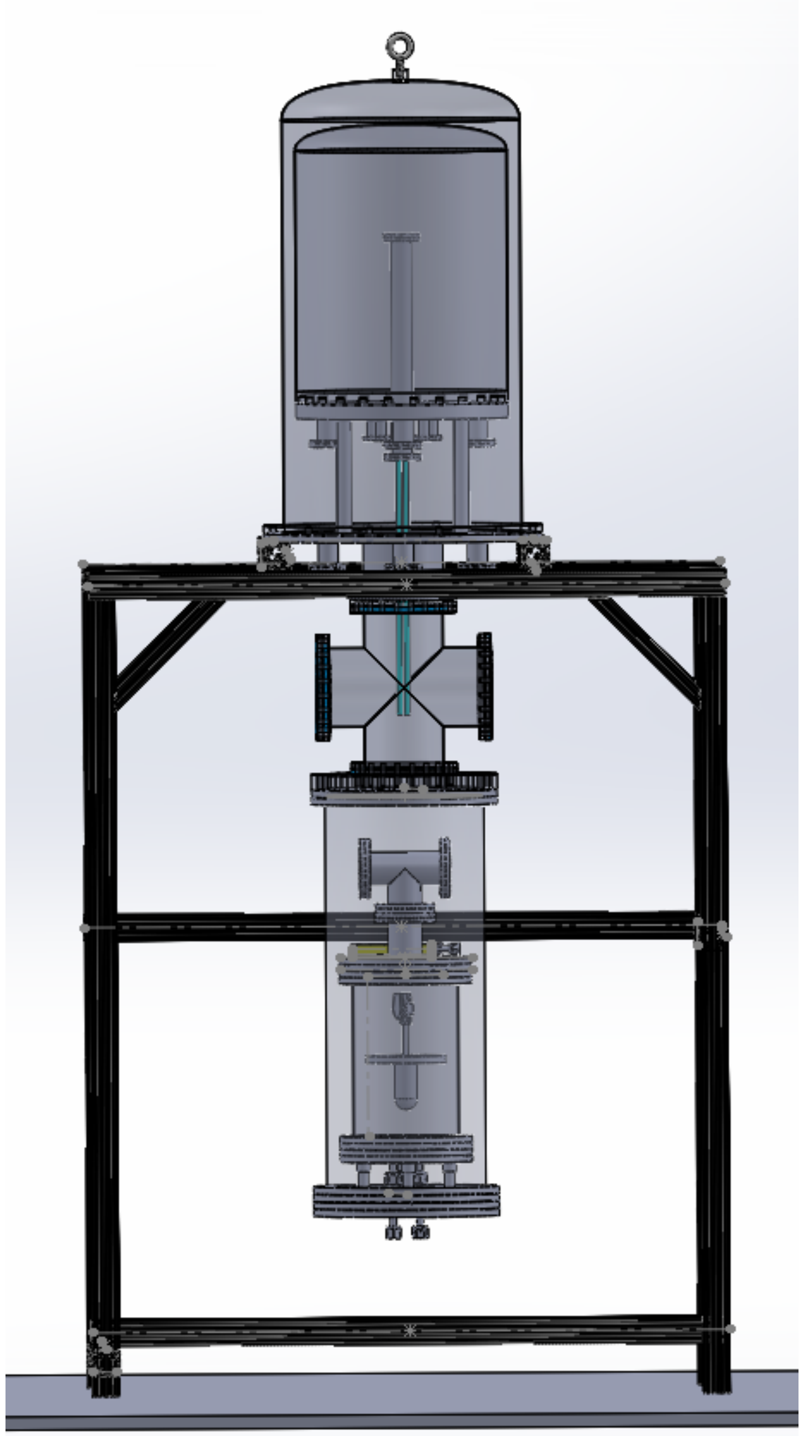
Future Work

- Increase the live-time (the main current drawback, as it is too low)
  - Modular detector
  - Supercooled droplet detector (ScDD)
  - Extreme heat, lasers, microwaves, agitation
- Cryogenic system and snowball detector being built at Penn State, with a focus on heating and cooling R&D
  - Establishing a stable operational temperature at a set point
  - Rapid heating of snow after a trigger
  - Rapid re-cooling of the water after a complete melting
- Studies of detector sensitivity, and discovery potentials for different dark matter models

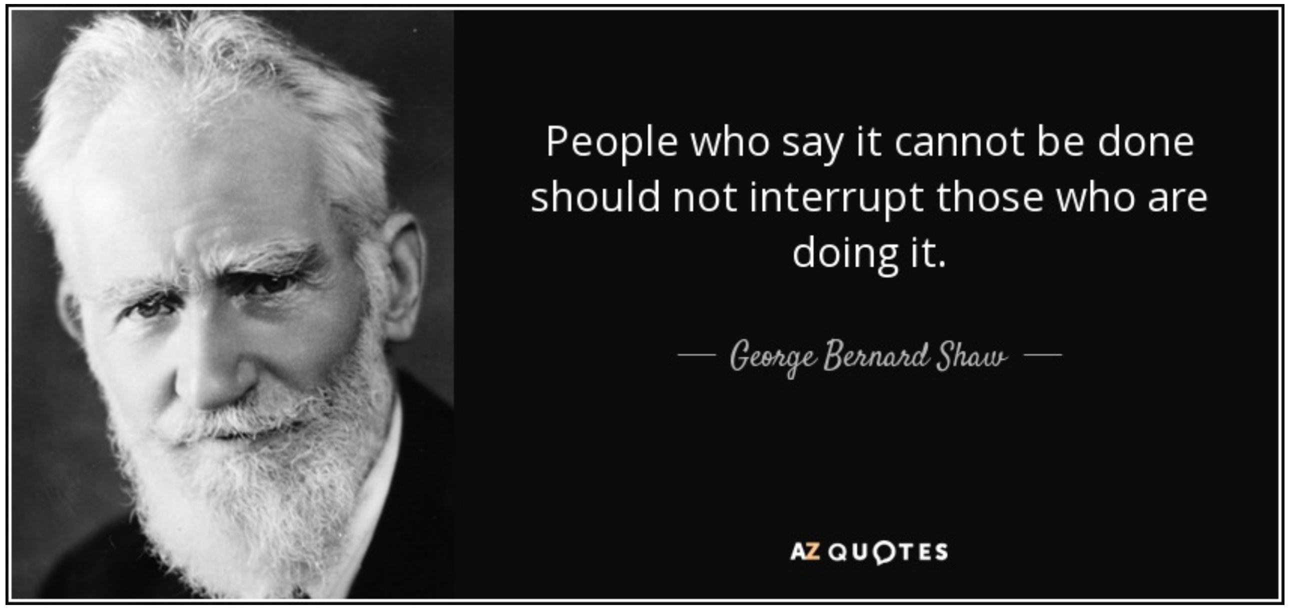


Design of setup at Penn State

Conclusions

- SnowBall Chamber: New technology!
  - Among other things, it can be used to search for low-mass Dark Matter!
- Neutrons can make supercooled water freeze: a new discovery!
  - They can do multiple scatters, as they do in a bubble chamber
- There is at least some degree of electron recoil discrimination
- Energy threshold is not known, but likely sub-keV already at -20°C

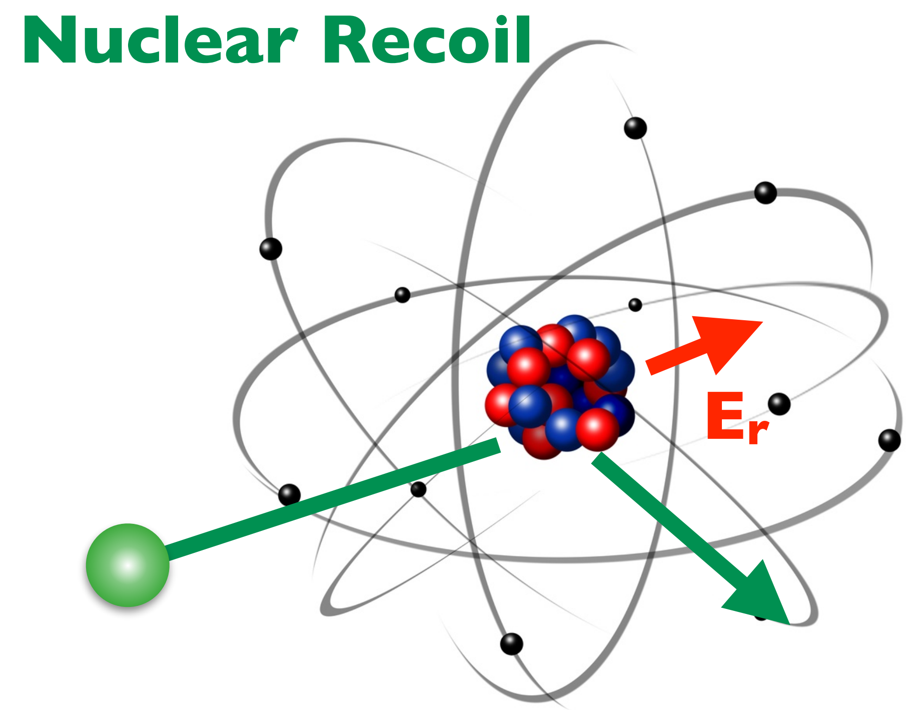
Thank you!

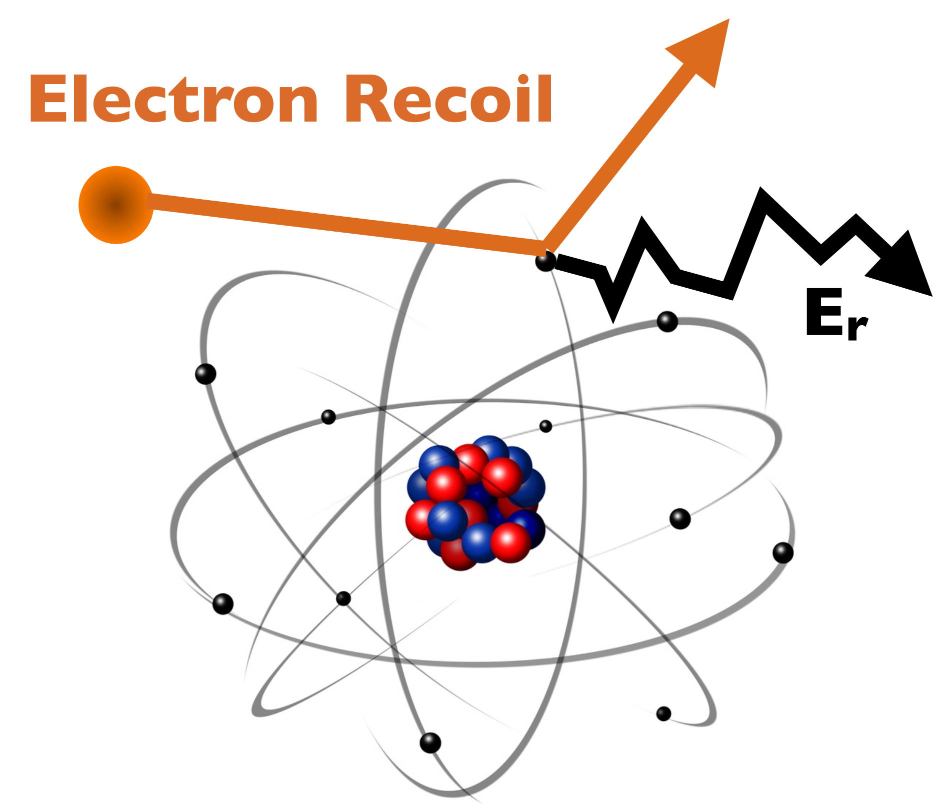

People who say it cannot be done should not interrupt those who are doing it.
— George Bernard Shaw —
AZ QUOTES

Backup Slides

Experimental backgrounds

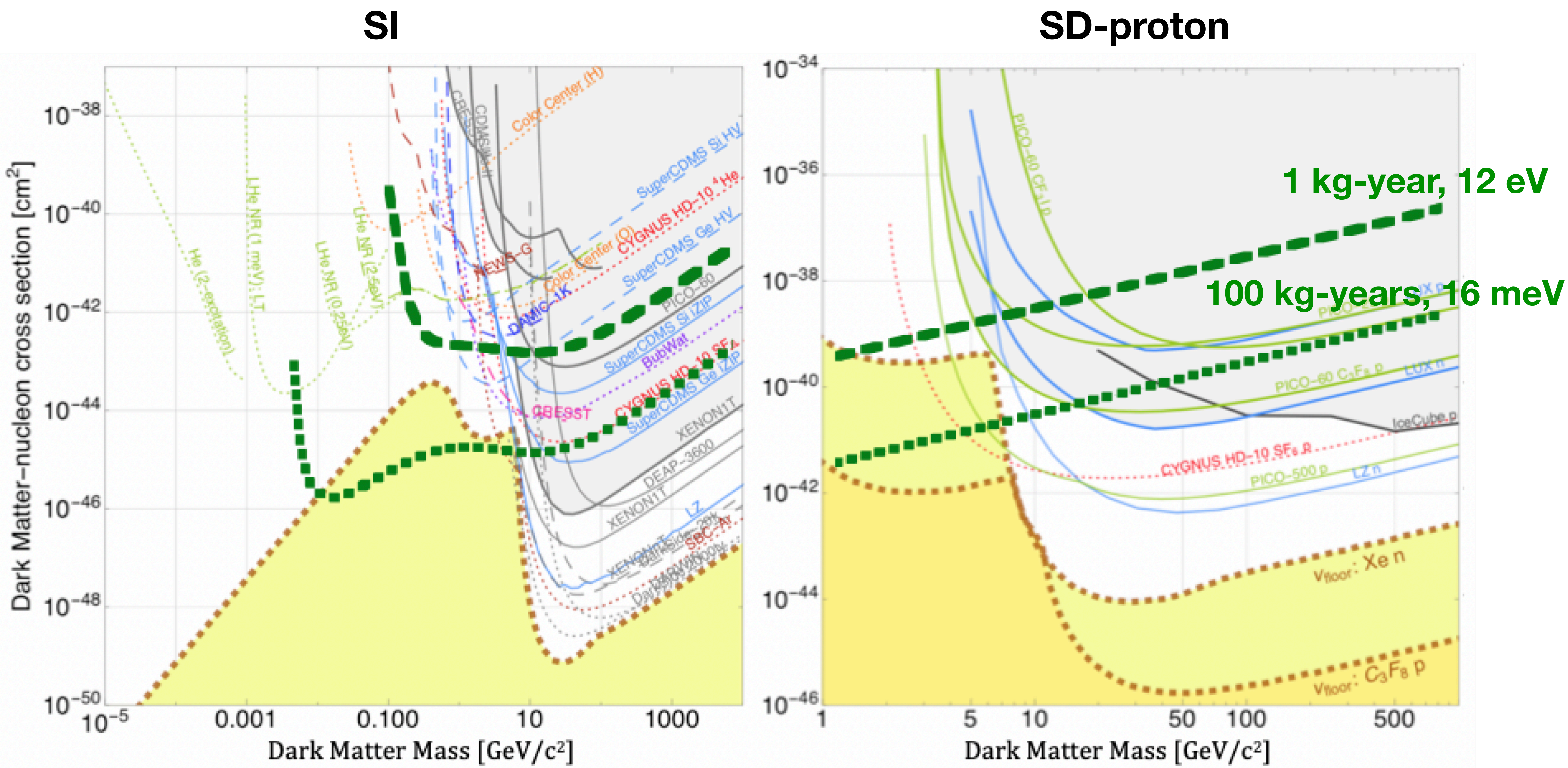
- Neutrons
  - ✦ Removed cutting multiple scatters
- Alphas:
  - ✦ Near walls: removed by good fiducialization.
  - ✦ α-n acoustic discrimination?
- Gammas and electrons:
  - ✦ Not a problem in SnowBall chamber!
- Muons:
  - ✦ Go deep underground
  - ✦ Tag them with a muon veto





But wait, there is more!

- Spin-dependent proton sensitivity
- Dark photons and axions through electron scattering



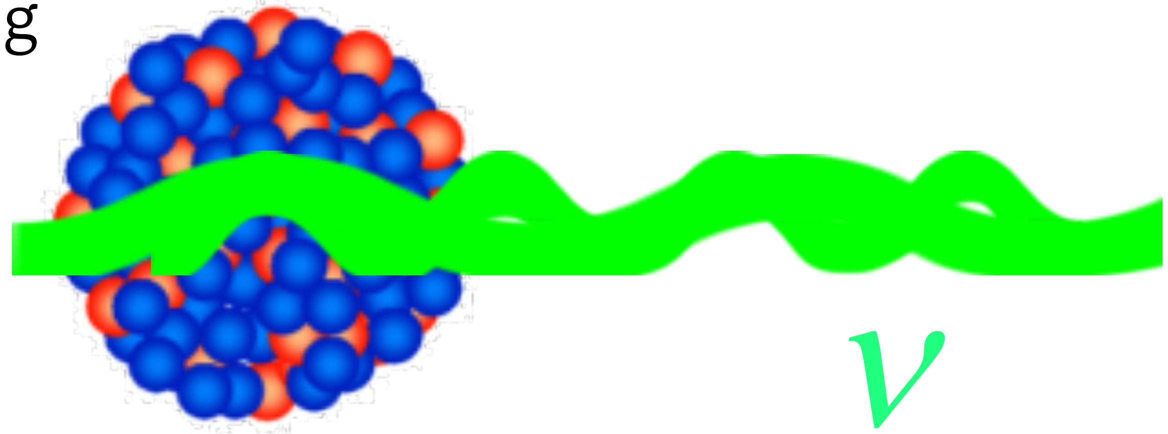
Besides Dark Matter, There is:

nuclear
security

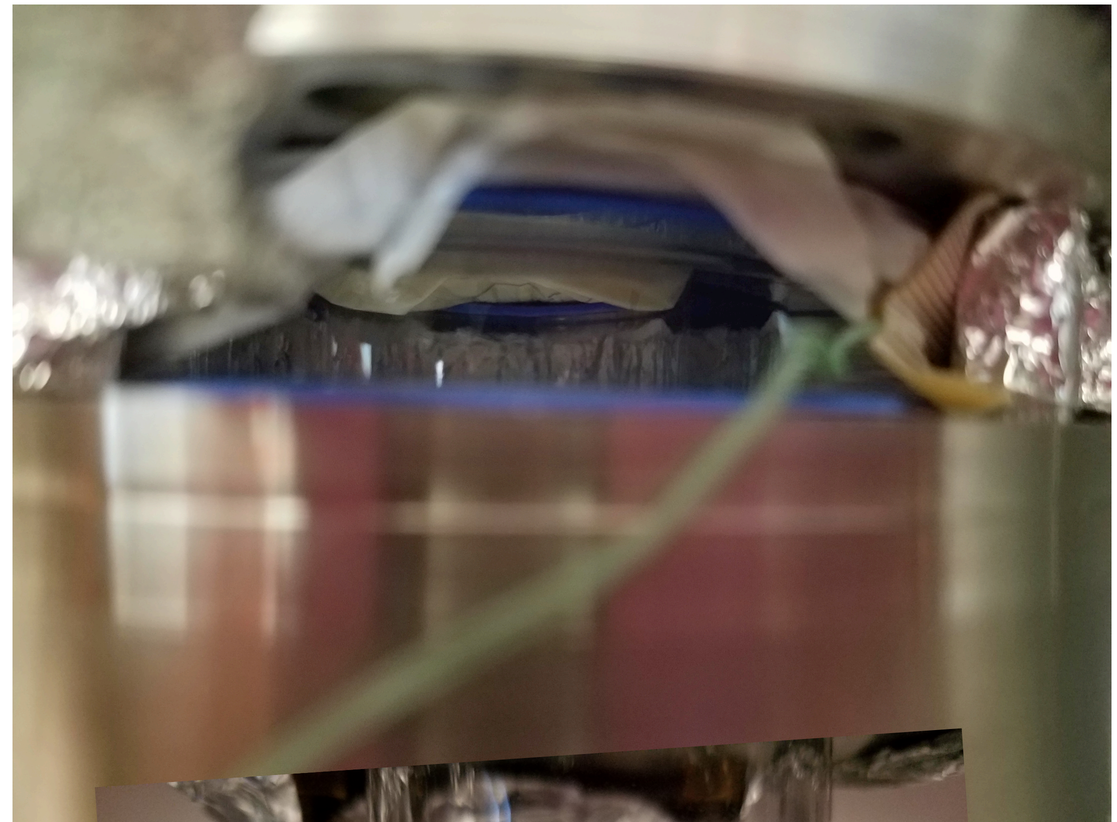
nuclear
astrophysics

cloud formation
and climate modeling

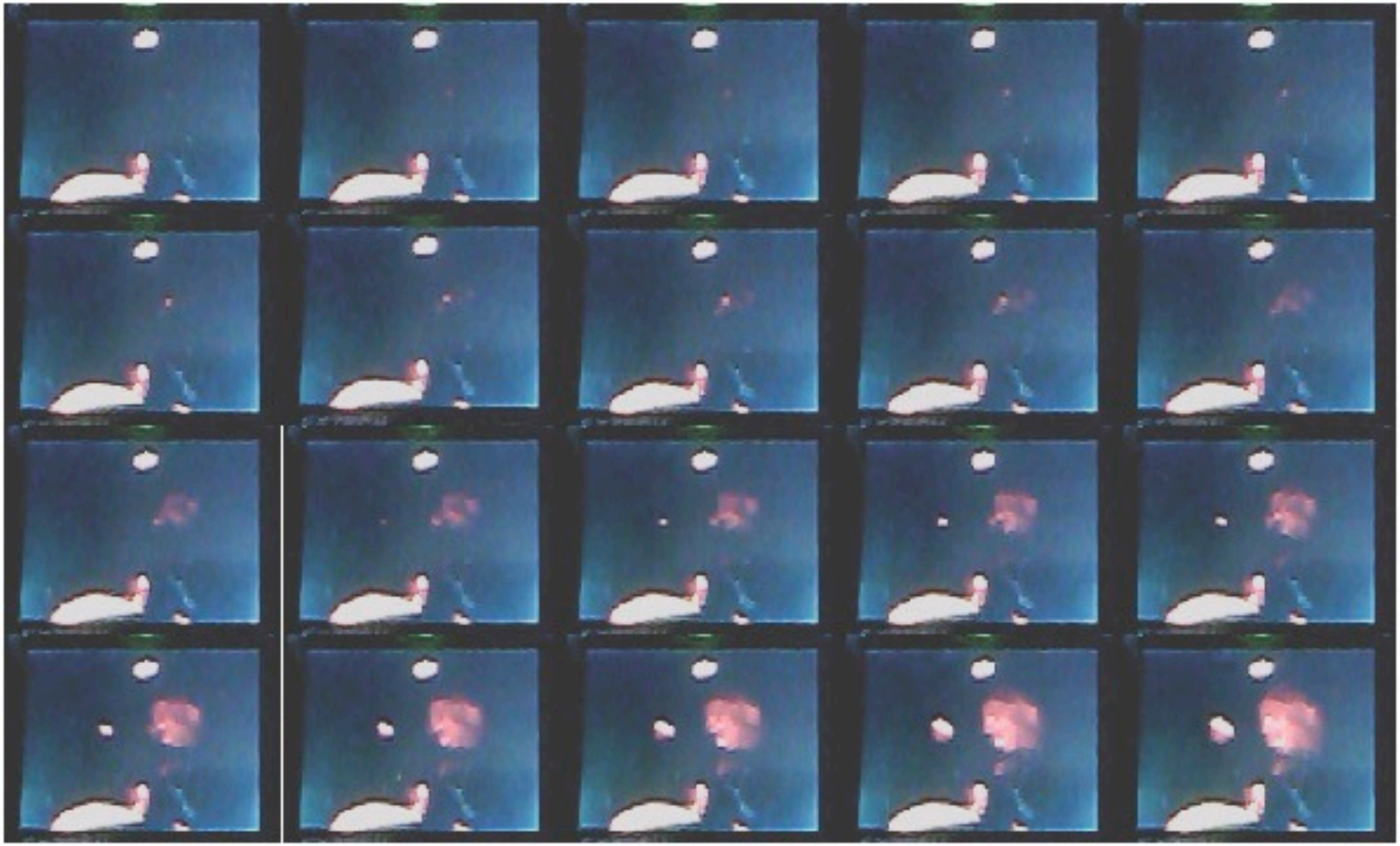
coherent neutrino scattering?



More pics

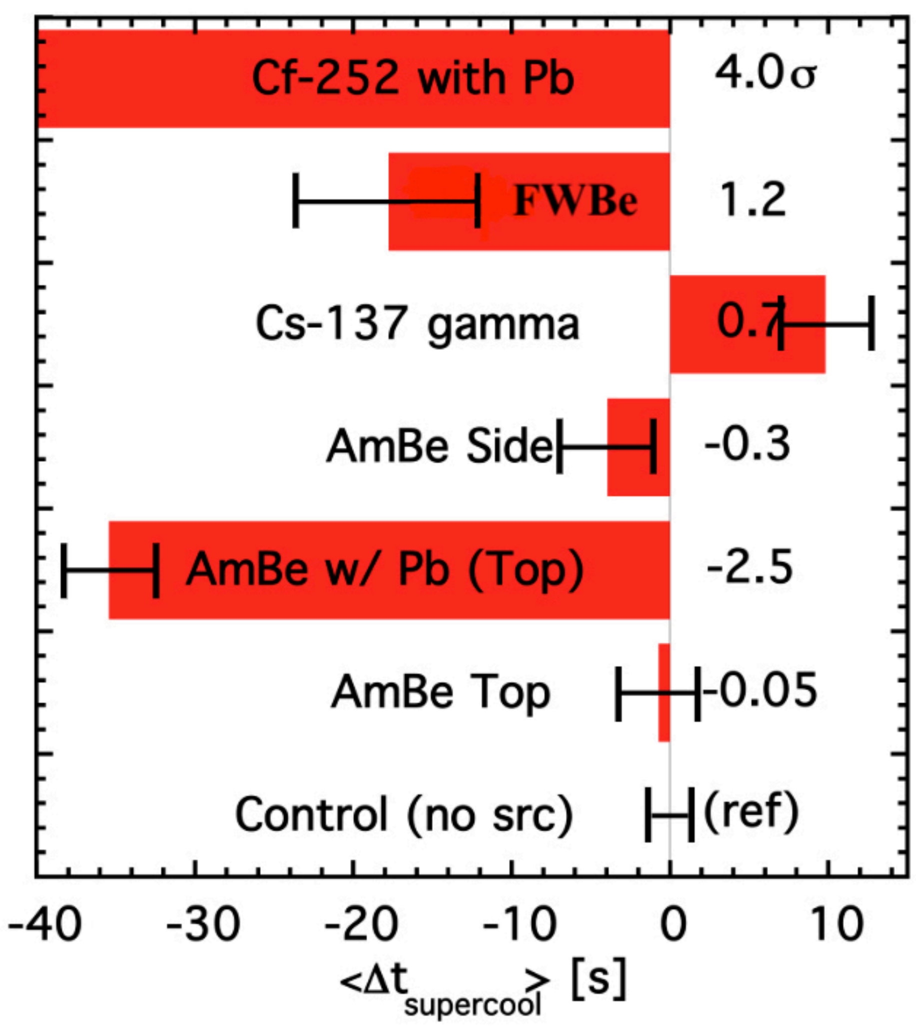


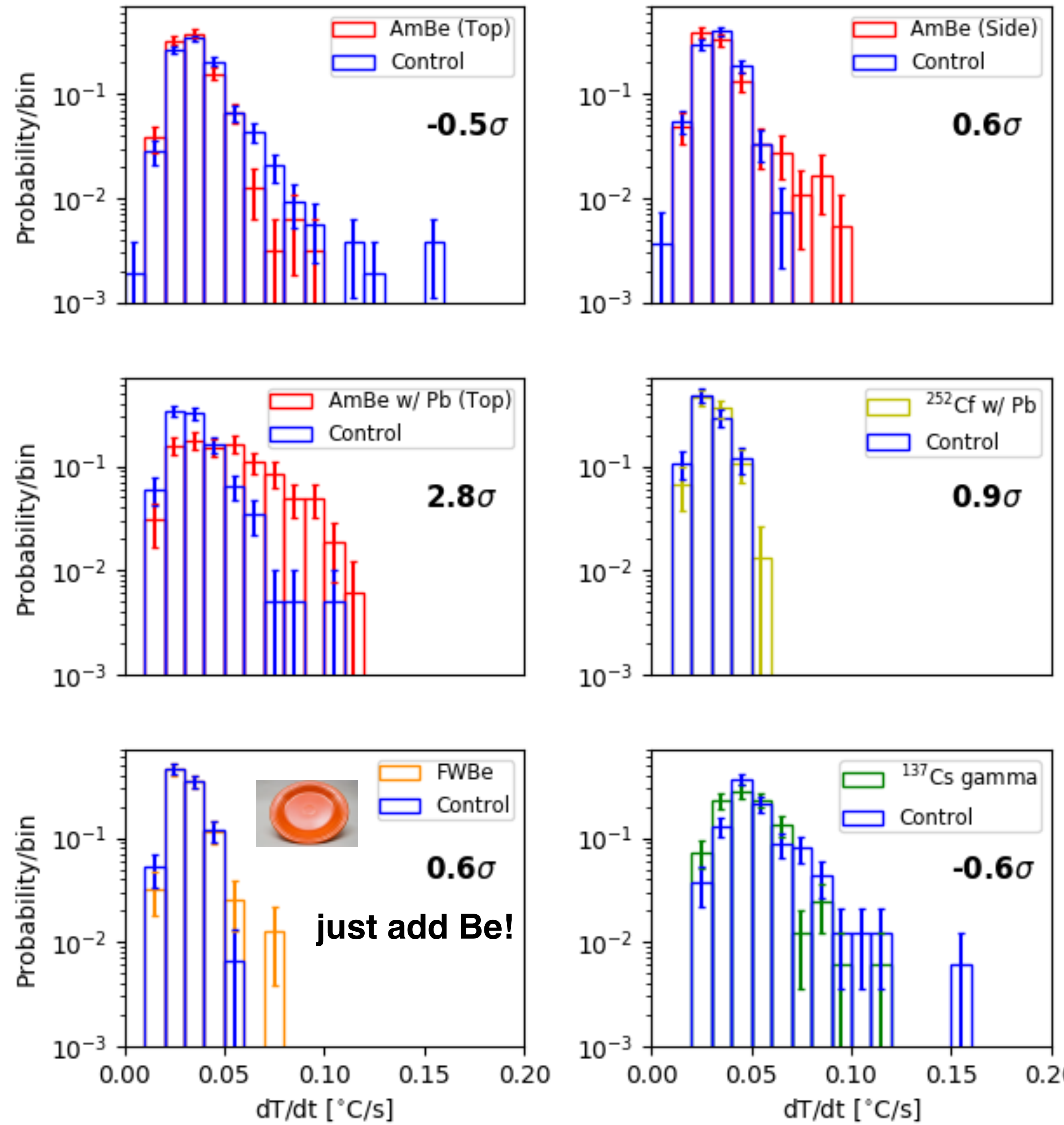
Double Crystal Slide Show



It gets better

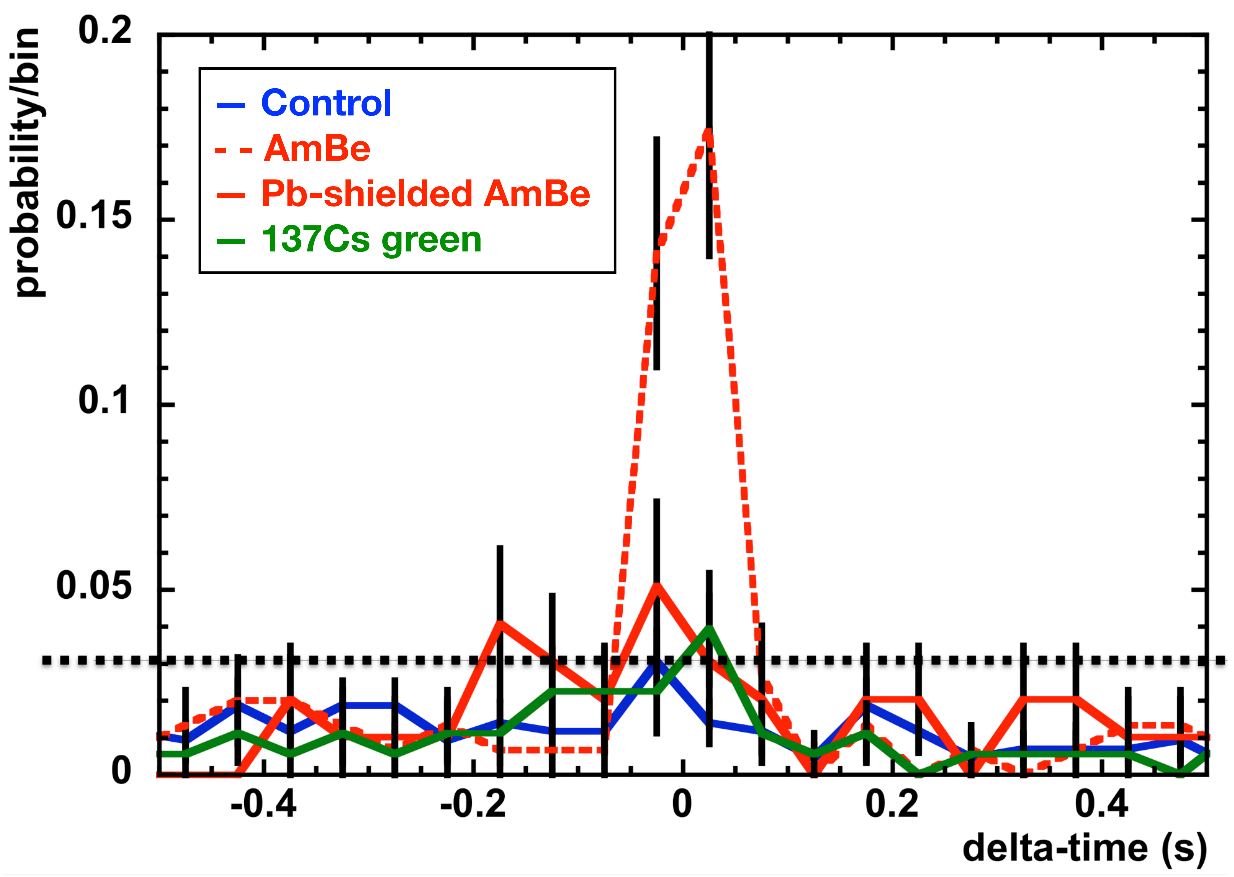
Break downs by source type



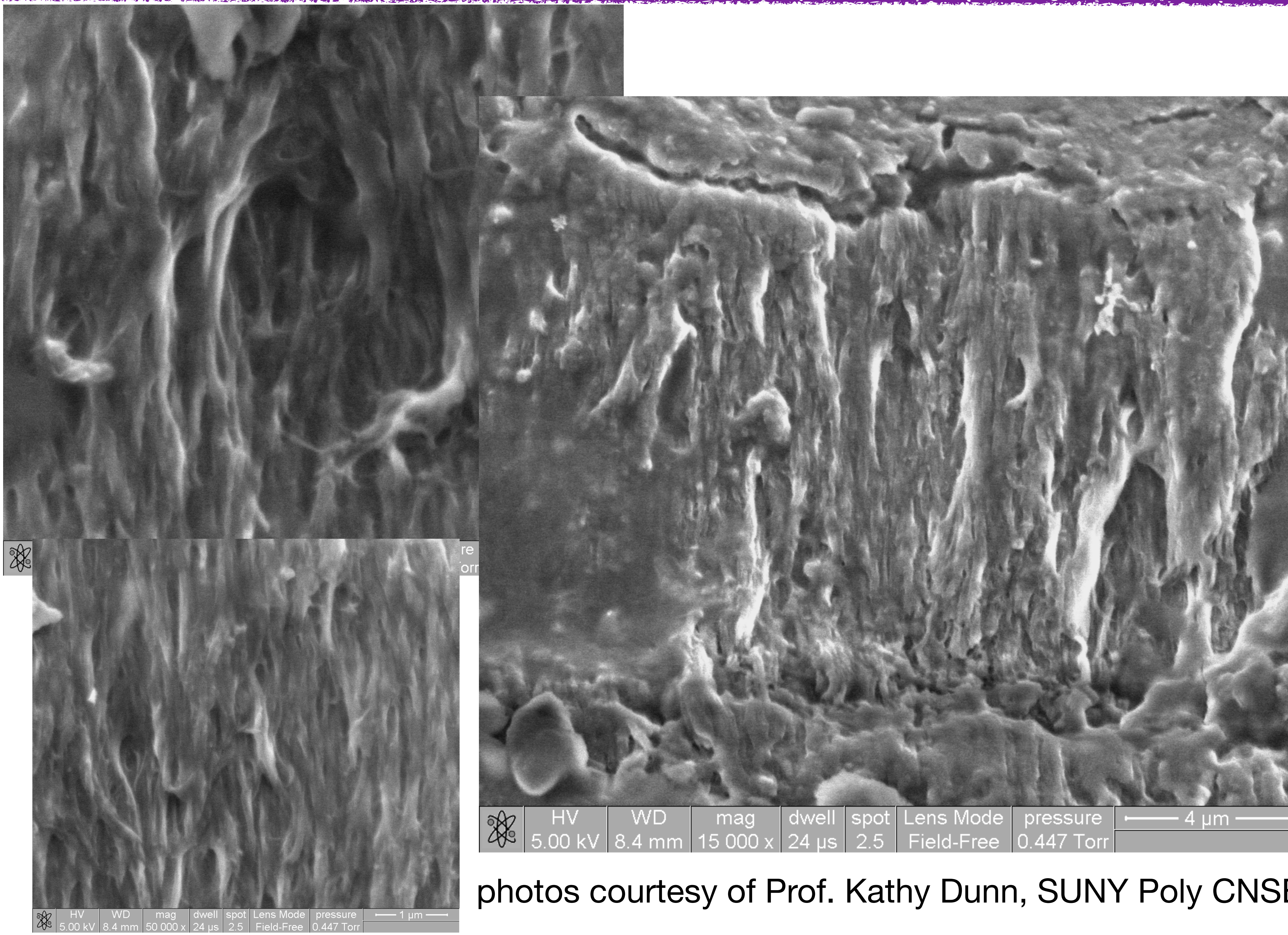


Coincidence Counter Analysis

- 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



Electron Microscope Images of a Membrane Filter (Novamen)



photos courtesy of Prof. Kathy Dunn, SUNY Poly CNSE