NORTHWESTERN UNIVERSITY

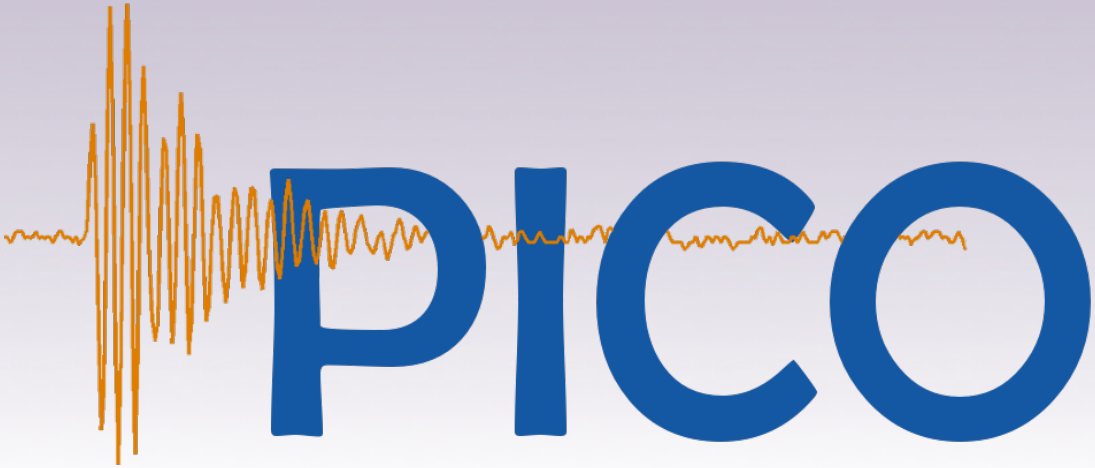
Fermilab

Electron Recoil Bubble Nucleation in PICO Bubble Chambers

Dan Baxter

July 23, 2018

Identification of Dark Matter 2018



PICO

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Northwestern University
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I. Arnquist , C. Cowles, C.M. Jackson, B. Loer, K. Wierman

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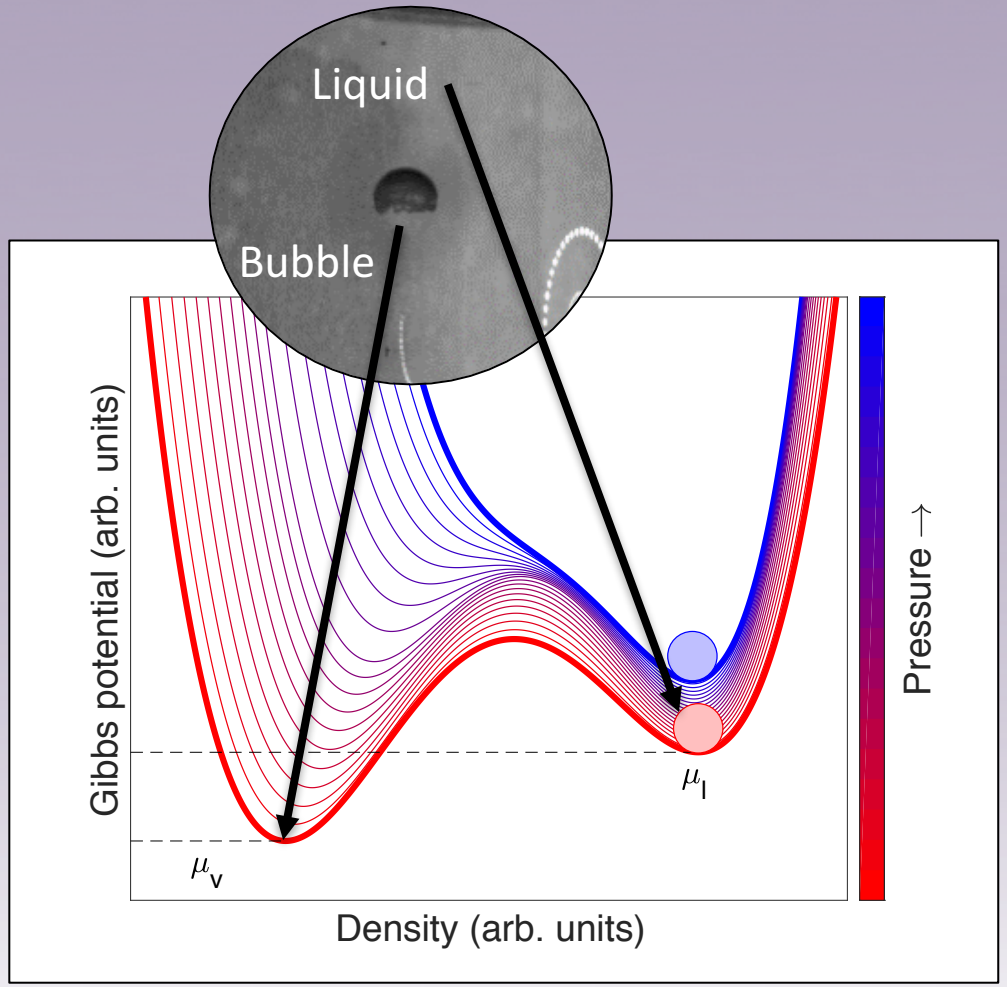
Bubble Chambers

- Superheat a fluid by lowering pressure under constant temperature
- Metastable state awaits energy deposition
- Interaction nucleates small gas pocket that grows
- Trigger on bubble with cameras



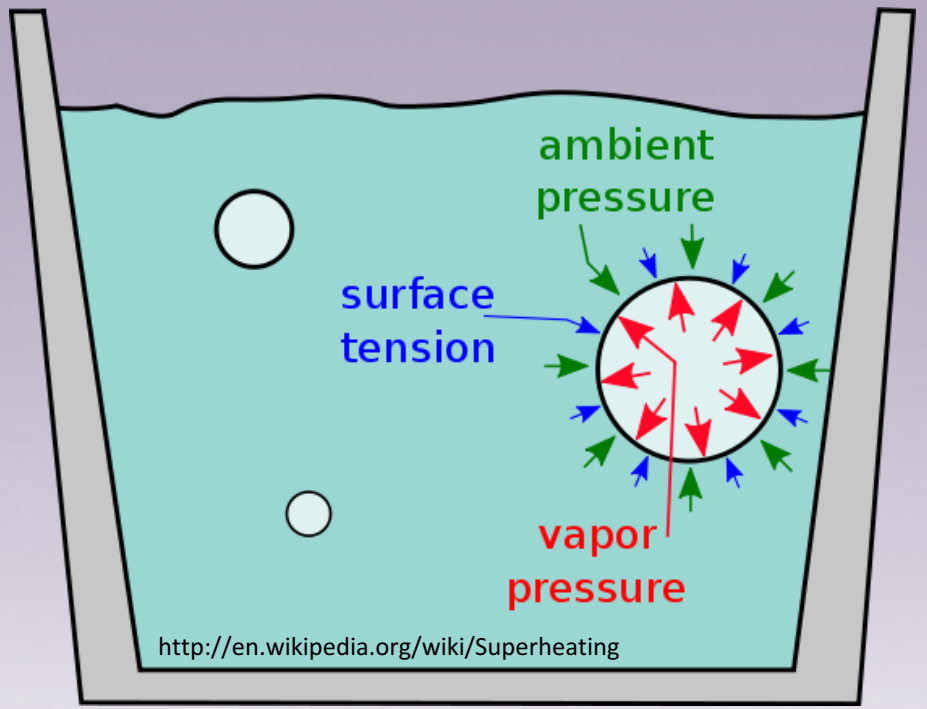
Threshold Determination

- Critical radius set by fluid properties and run conditions

$$P_v - P_l \geq \frac{2\sigma}{r_c}$$

- Critical radius determines energy threshold

$$E_T = E(T, P, fluid)$$



Threshold Calculation

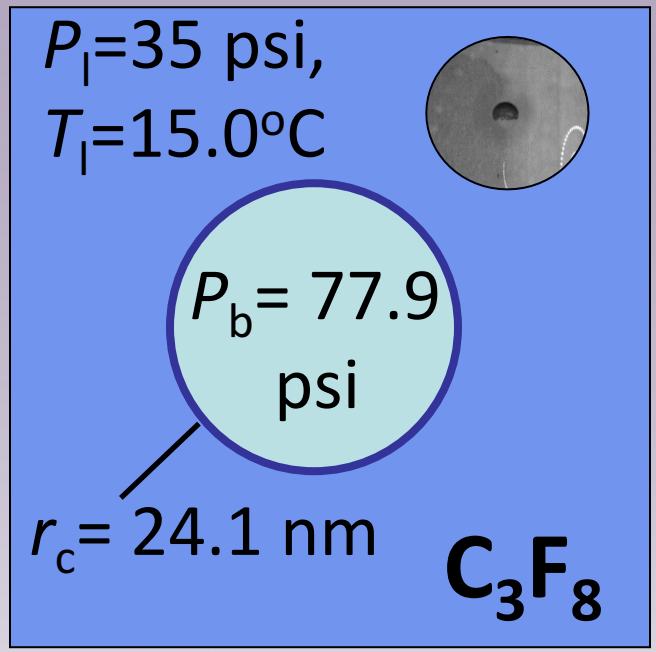
Surface energy, Bulk energy, Reversible Work

$$E_T = 4\pi r_c^2 \left(\sigma - T \left(\frac{\partial \sigma}{\partial T} \right)_\mu \right)$$ 1.57 keV

$$+ \frac{4\pi}{3} r_c^3 \rho_b \left(h_b - h_l \right)$$ 1.95 keV

$$- \frac{4\pi}{3} r_c^3 \left(P_b - P_l \right)$$ -0.15 keV

Heat threshold = 3.37 keV



Threshold Calculation

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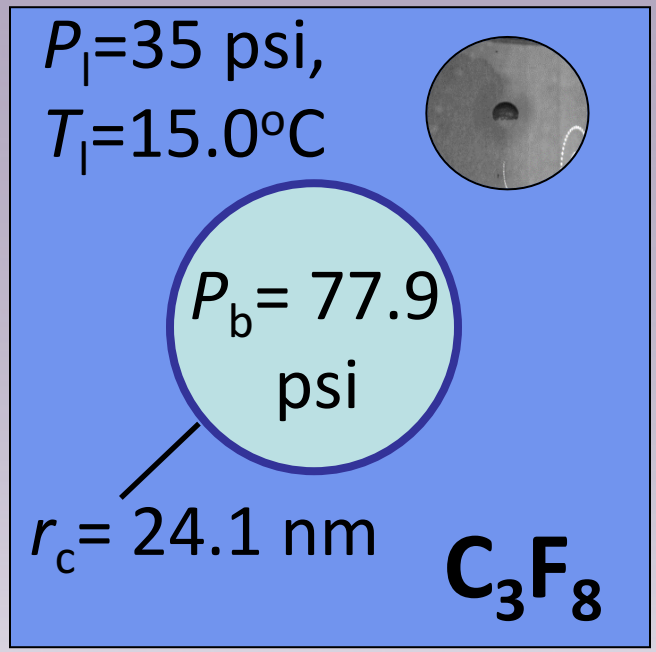
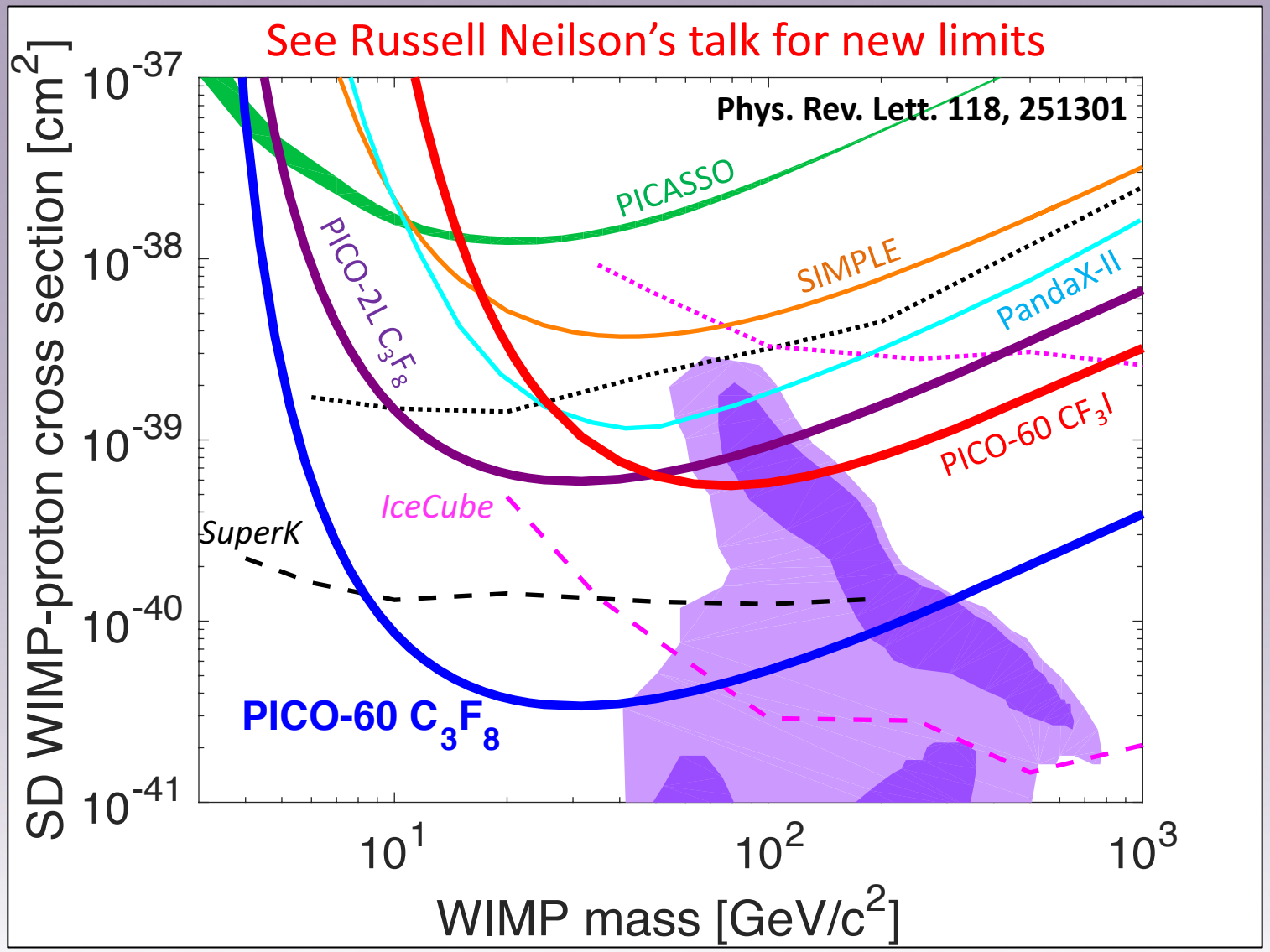


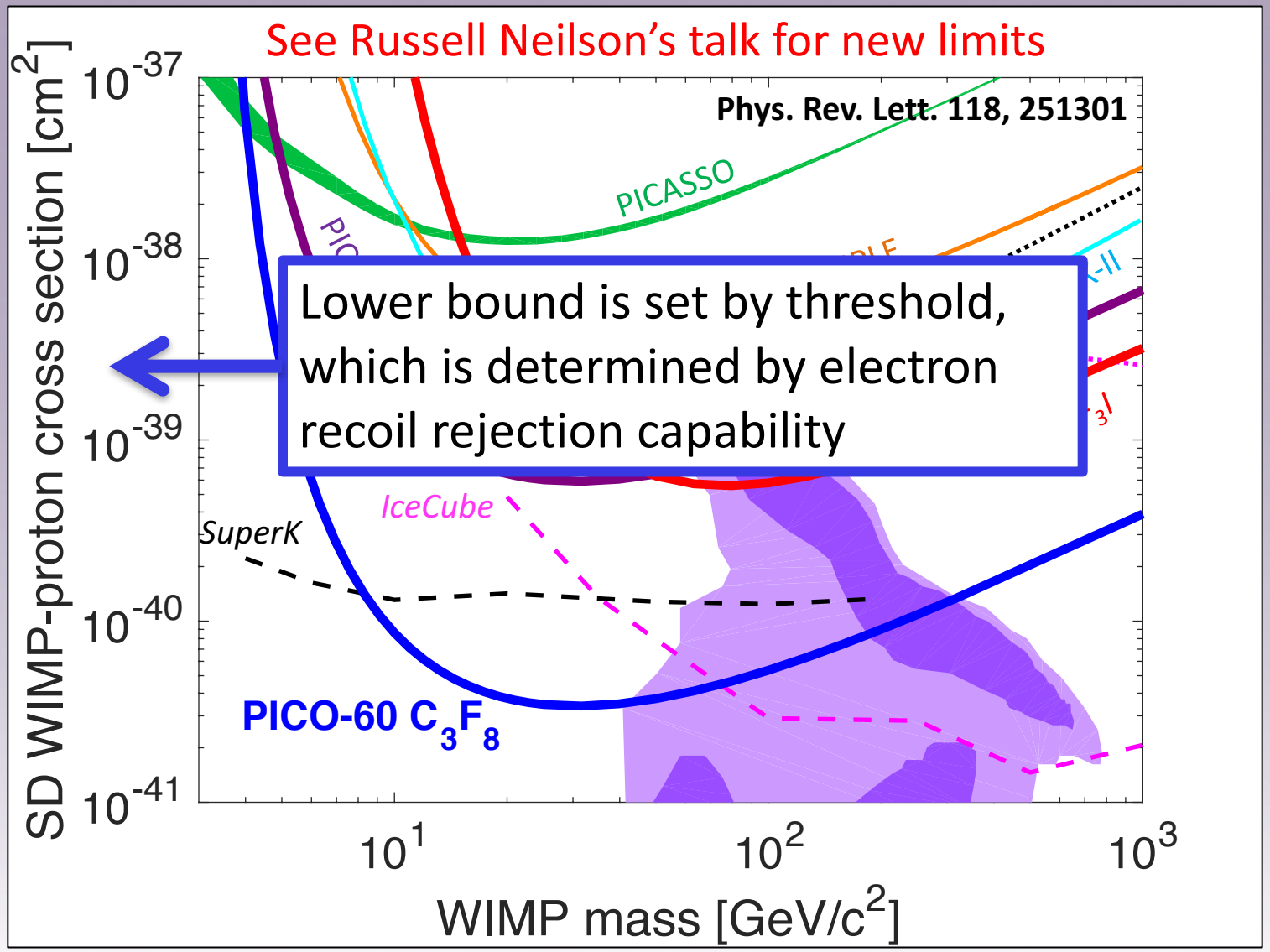
Minimum Work:

$$W = \int_0^{r_c} 4\pi r^2 dr \left(\frac{2\sigma}{r} - (P_b - P_l)\right) = \frac{4}{3}\pi\sigma r_c^2 \approx 50 - 75 \text{ eV}$$

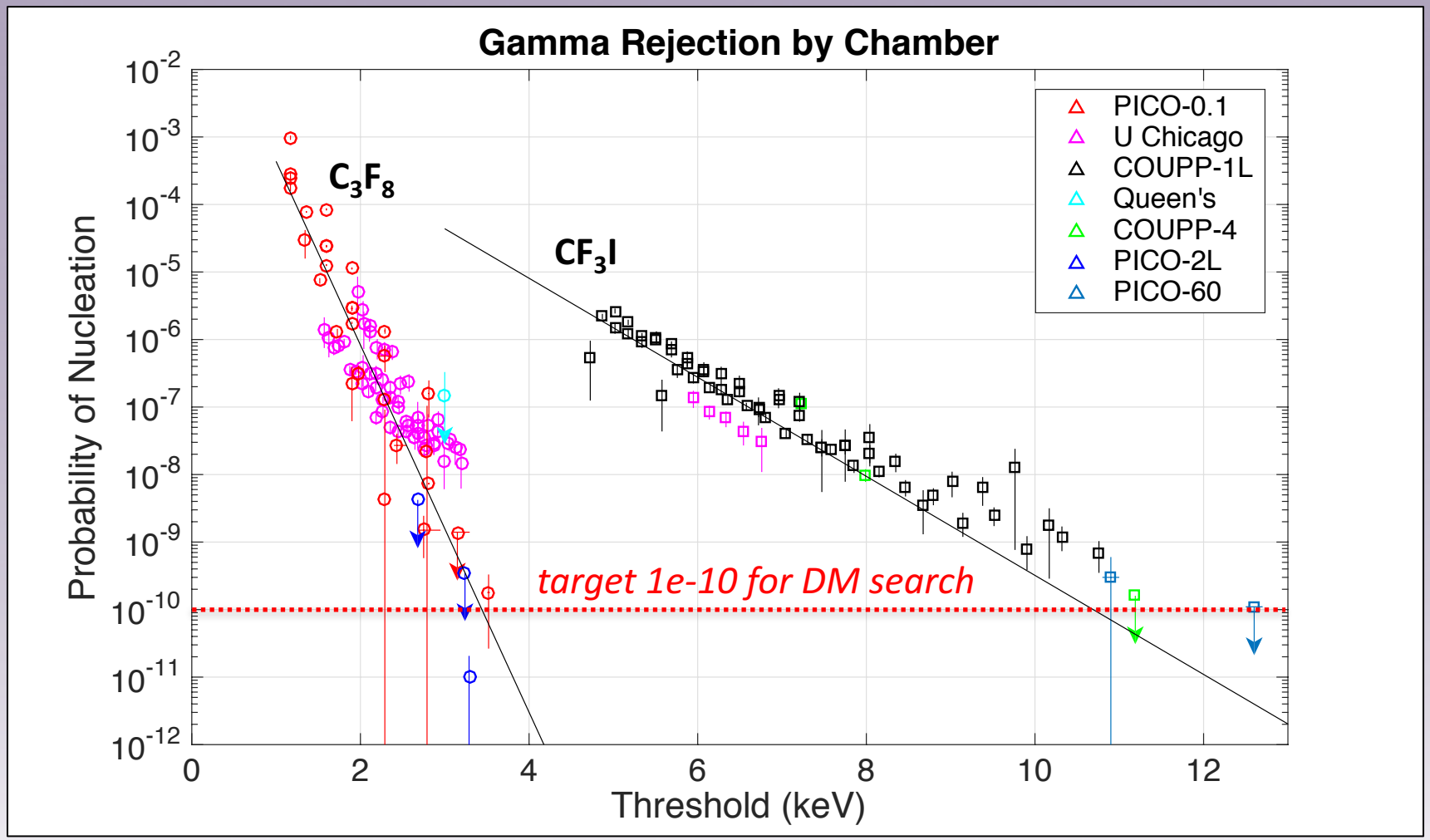
Existing Limits



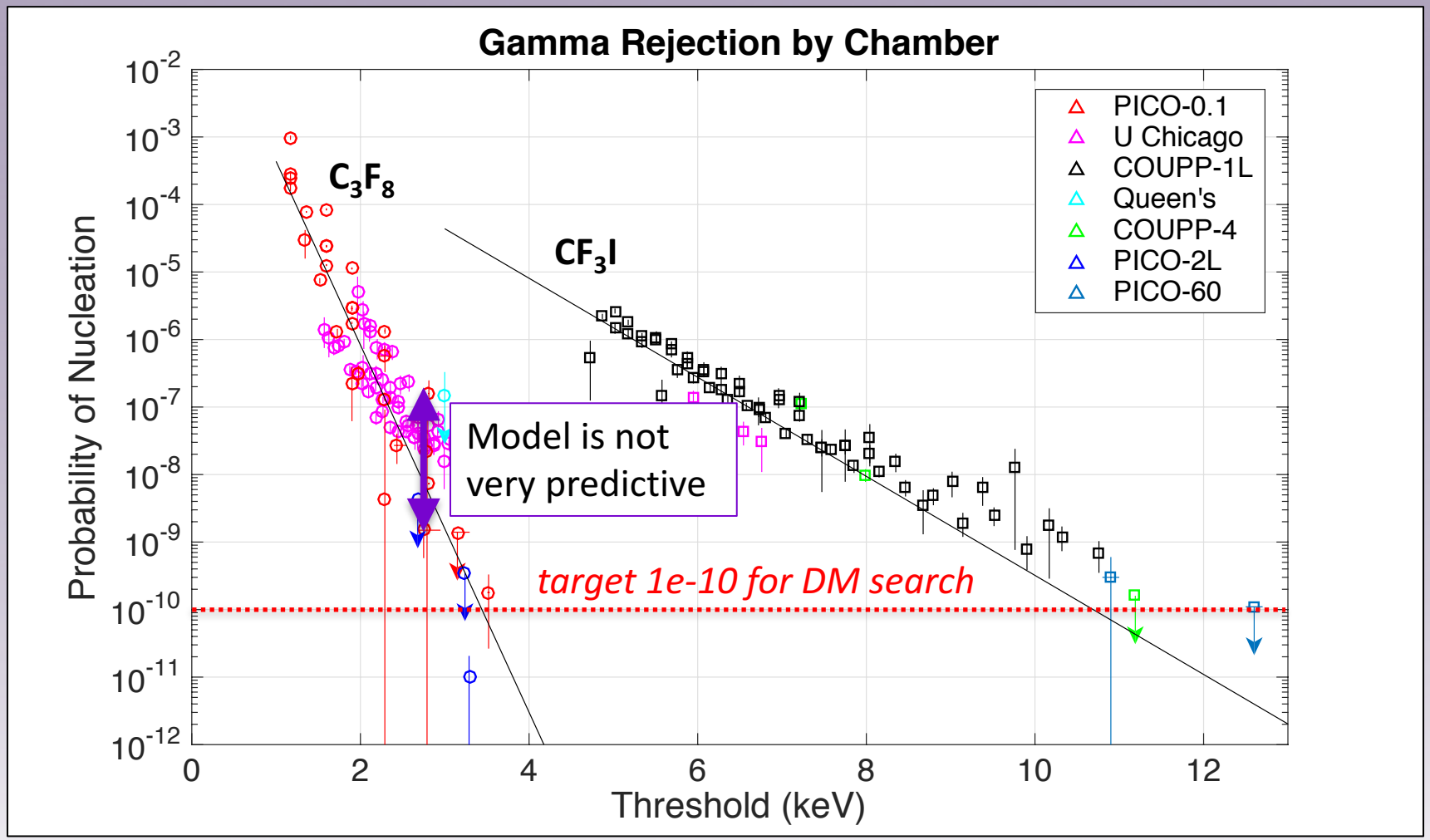
Existing Limits



Traditional ER Plot



Traditional ER Plot



Probability of Nucleation

(Historically)

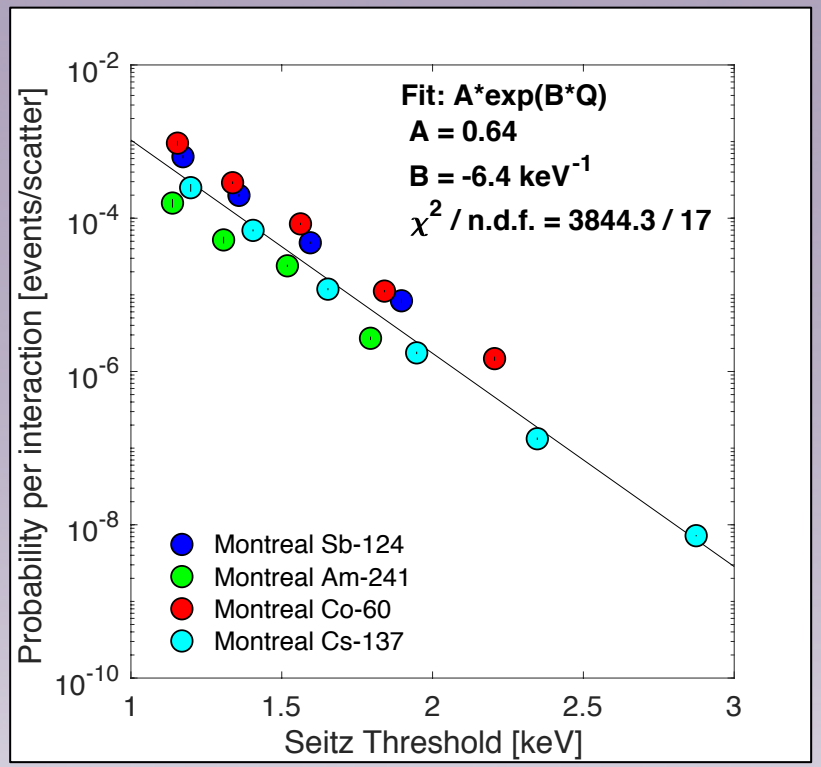
- Per what… **y-axis**
  - **Photon Interaction**: *each photon interaction has some probability to nucleate a bubble*

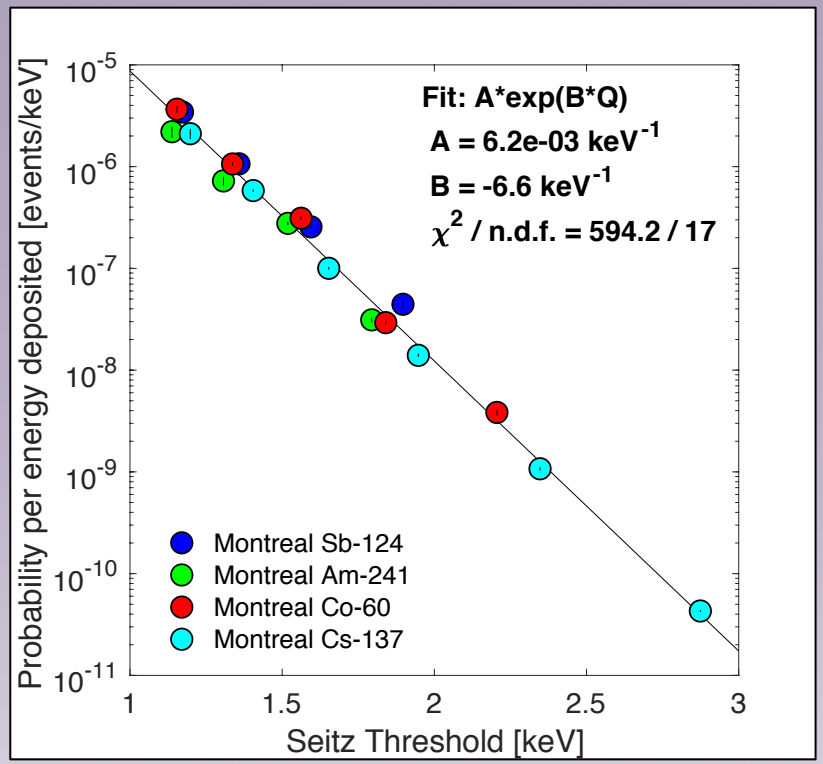
- Nucleation by… (scales with) **x-axis**
  - **Heat**: *Seitz Model describes threshold (few keV)*

Probability of Nucleation

- Per what…
  - **Photon Interaction**: *each photon interaction has some probability to nucleate a bubble*
  - **Track length**: *each delta electron has some probability to nucleate a bubble*
    - (Scales with energy deposited)
- Nucleation by… (scales with)
  - **Heat**: *Seitz Model describes threshold (few keV)*
  - **Cavitation**: *Only minimum work to create bubble is required (less than 100 eV)*

Nucleation by delta electrons

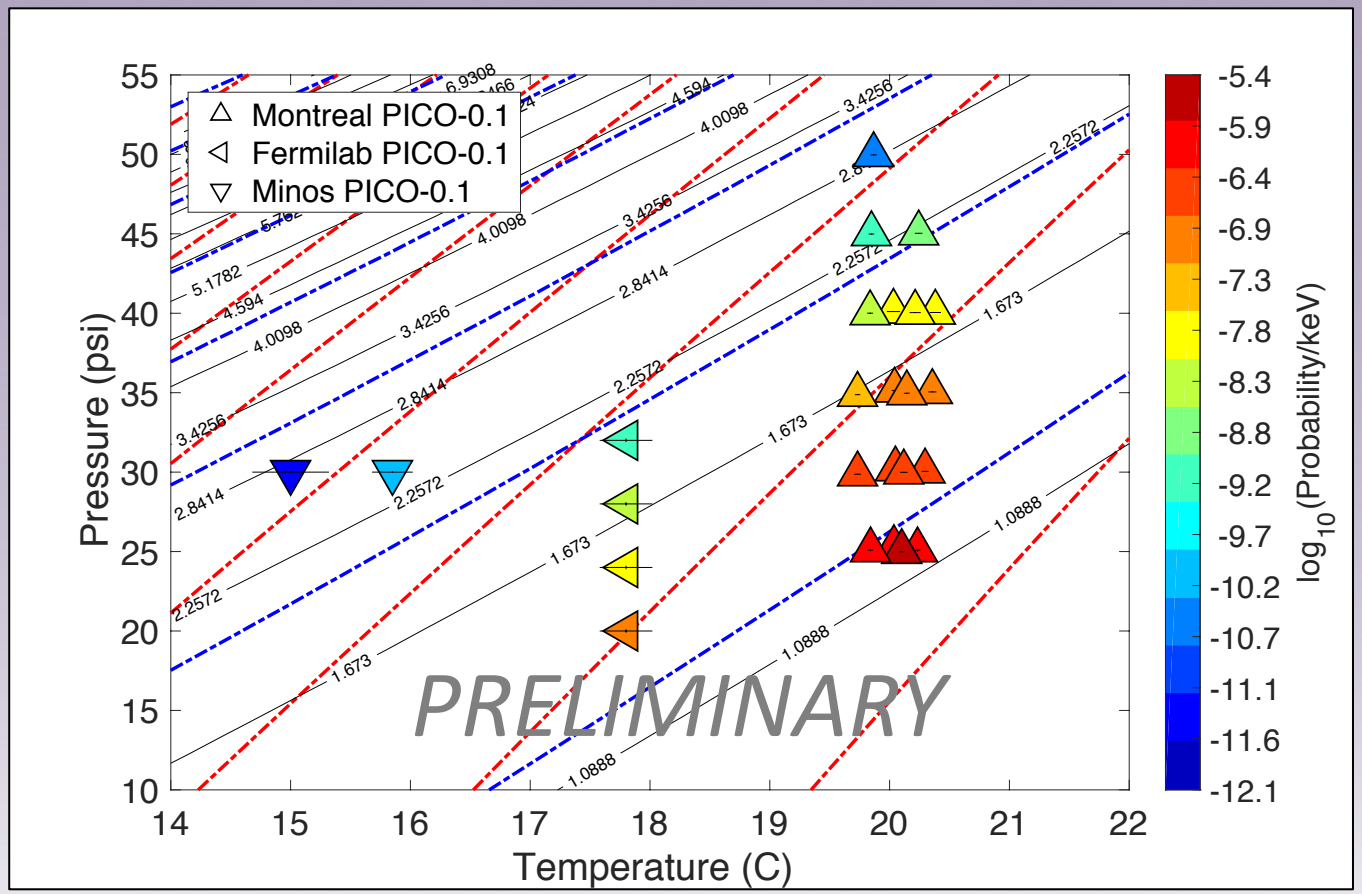




- Only statistical error bars are shown, but there are almost no systematic errors between these data
- Nucleation by delta electrons (~total energy deposited) was actually put forward to describe classical bubble chamber nucleation (Tenner 1963)

Nucleation by delta electrons

Q = Seitz Threshold W = Minimum Work r_I = Critical Length Scale

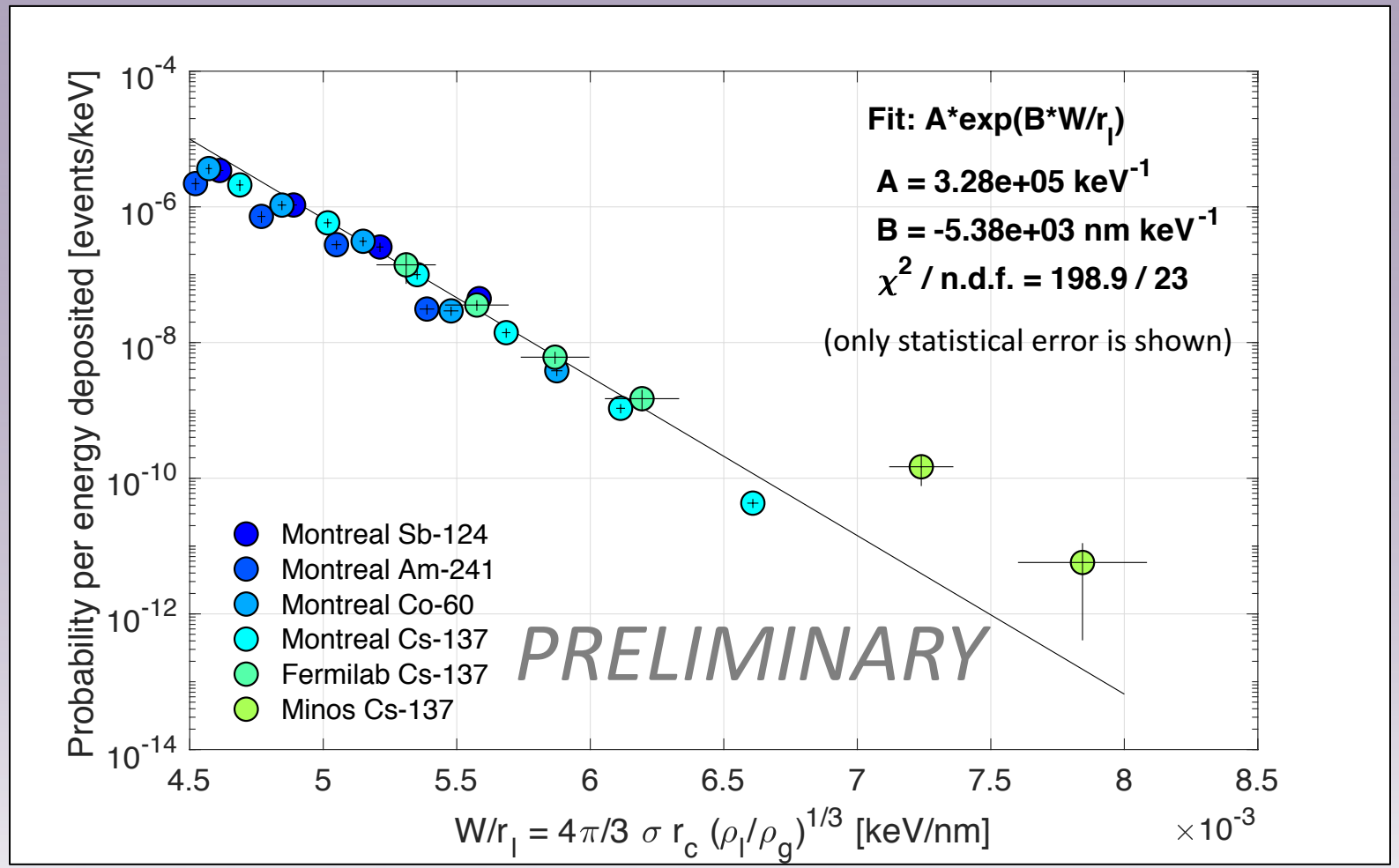


Contours of Constant

- Black: Q
- Blue: Q/r_I
- Red: W/r_I
- *something else?*

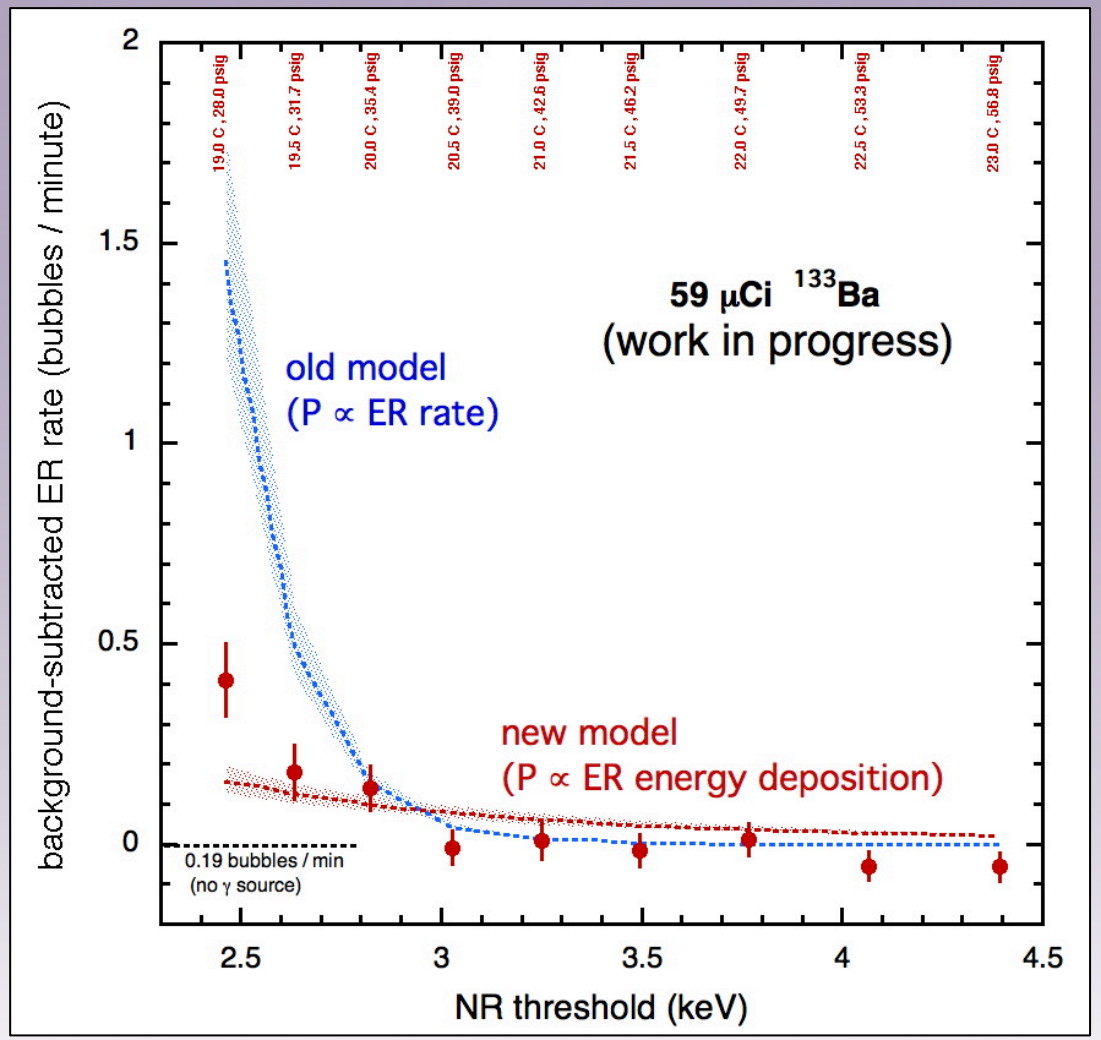
- Constant minimum work per radius is best fit

Nucleation by cavitation



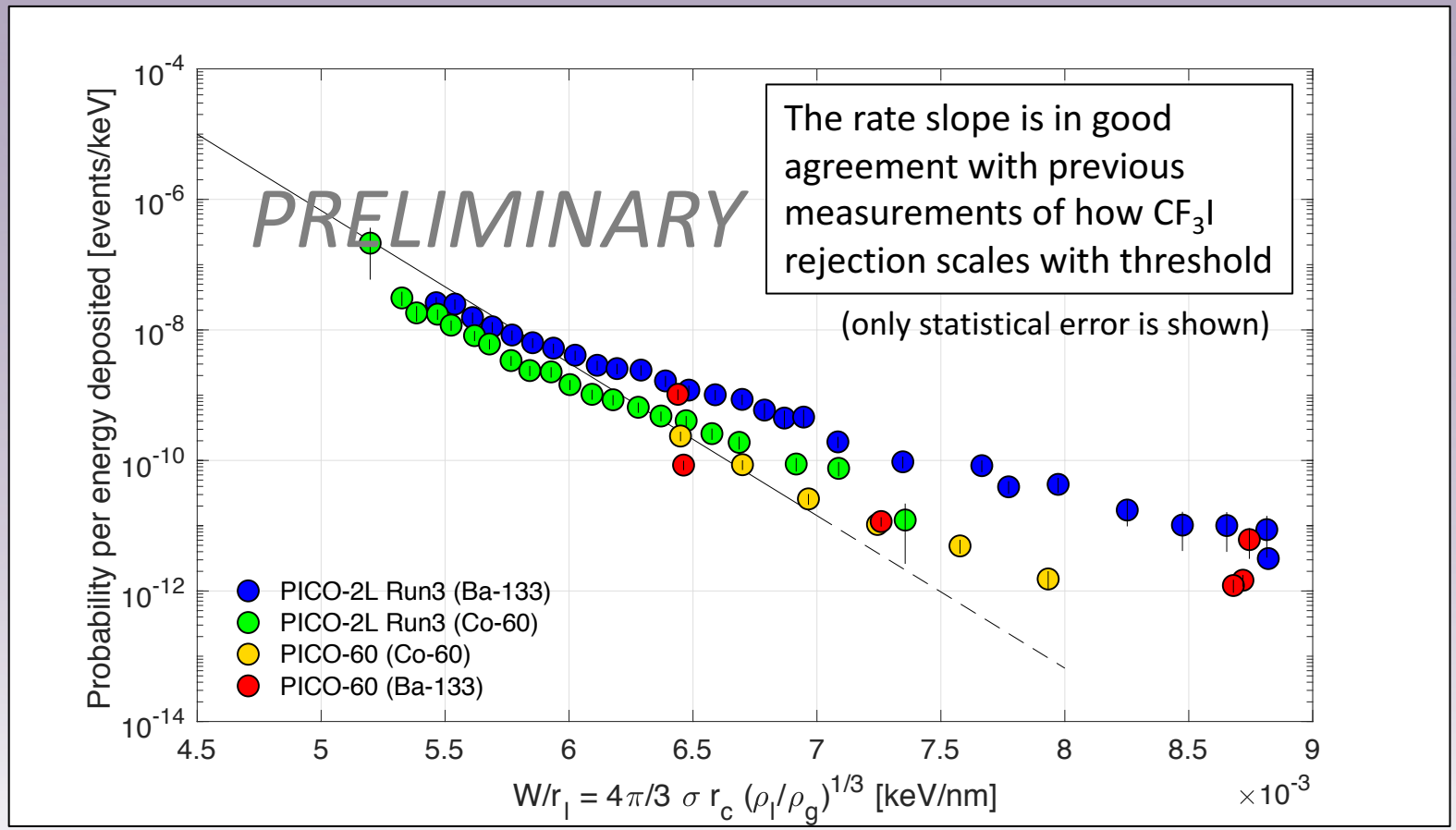
Nucleation by cavitation

- Beginning to test at UofChicago with the GUNTER chamber (first results)
- Initial results favor cavitation threshold by delta electrons



Anomalous Behavior

- In the C_3F_8 runs of both PICO-60 and PICO-2L Run 3, we expect some residual iodine



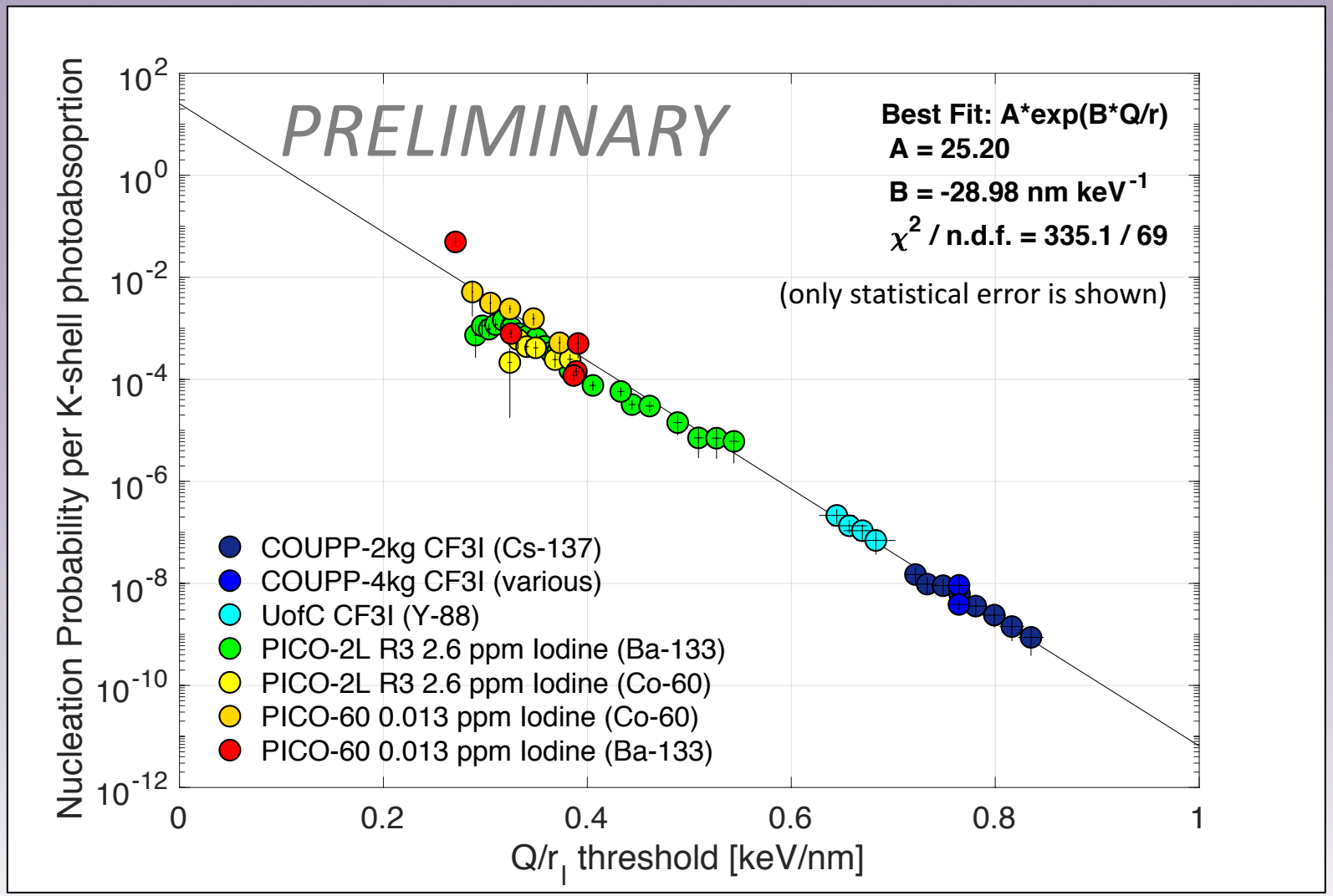
Auger Cascades

- An Auger cascade occurs when an inner shell vacancy results in the emission of many low-energy x-rays and electrons originating from the same atom
- In the presence of heavy contamination, binding energy release through an Auger cascade is:
  1. Over the heat threshold (for K-shell iodine, 30keV)
  2. Local on the scale of the critical radius

Auger Cascades

- For our existing dark matter results, only contamination at <ppmv levels
  - In situ calibrations still account for this
- Could be present in any chamber which previously saw iodine (CF_3I)
  - PICO-60: first run was with CF_3I -> expect residual cross-contamination
  - PICO-2L: third run filled with C_3F_8 from an old, empty CF_3I bottle -> expect cross-contamination
- Should also be the dominant nucleation mechanism in CF_3I -> constrains normalization

Nucleation by Auger Cascade



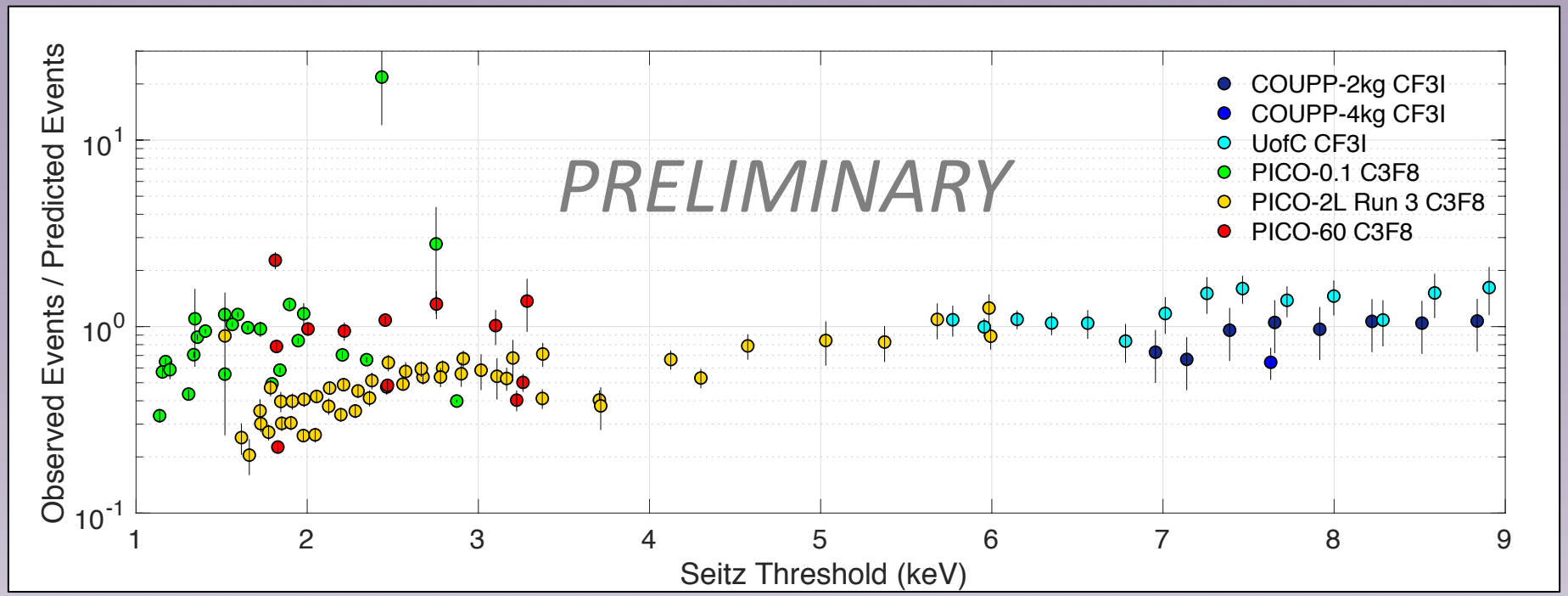
Assay Results

- Assays are in order-of-magnitude agreement with the best fit values
- We are still working on correctly determining the error in each of these measurements

Sample	Source	ICP-MS (PNNL)	GC-MS (PNNL)	Best Fit
PICO-2L Run 3*	Old CF3I storage	0.64 ppmv	0.96 ppmv	2.6 ppmv
PICO-60 Run 2	Run 1 w/ CF3I	0.020 ppmv	0.09 ppmv	0.013 ppmv

*Note: The PICO-2L sample sat in a plastic collection back for months before being analyzed. Thus these assays should be treated as lower bounds on the concentration in the detector itself.

Putting it together



- We now have a model that is reasonably predictive to an order of magnitude
- In C_3F_8, data points towards nucleation by cavitation through delta electrons
- Heavy contamination (like iodine) allows for more efficient nucleation through Auger cascades
  - Even in PICO-60, iodine contamination is under control and understood
  - Future chambers from PICO-40L and beyond will **NOT** have previous exposure to CF_3I

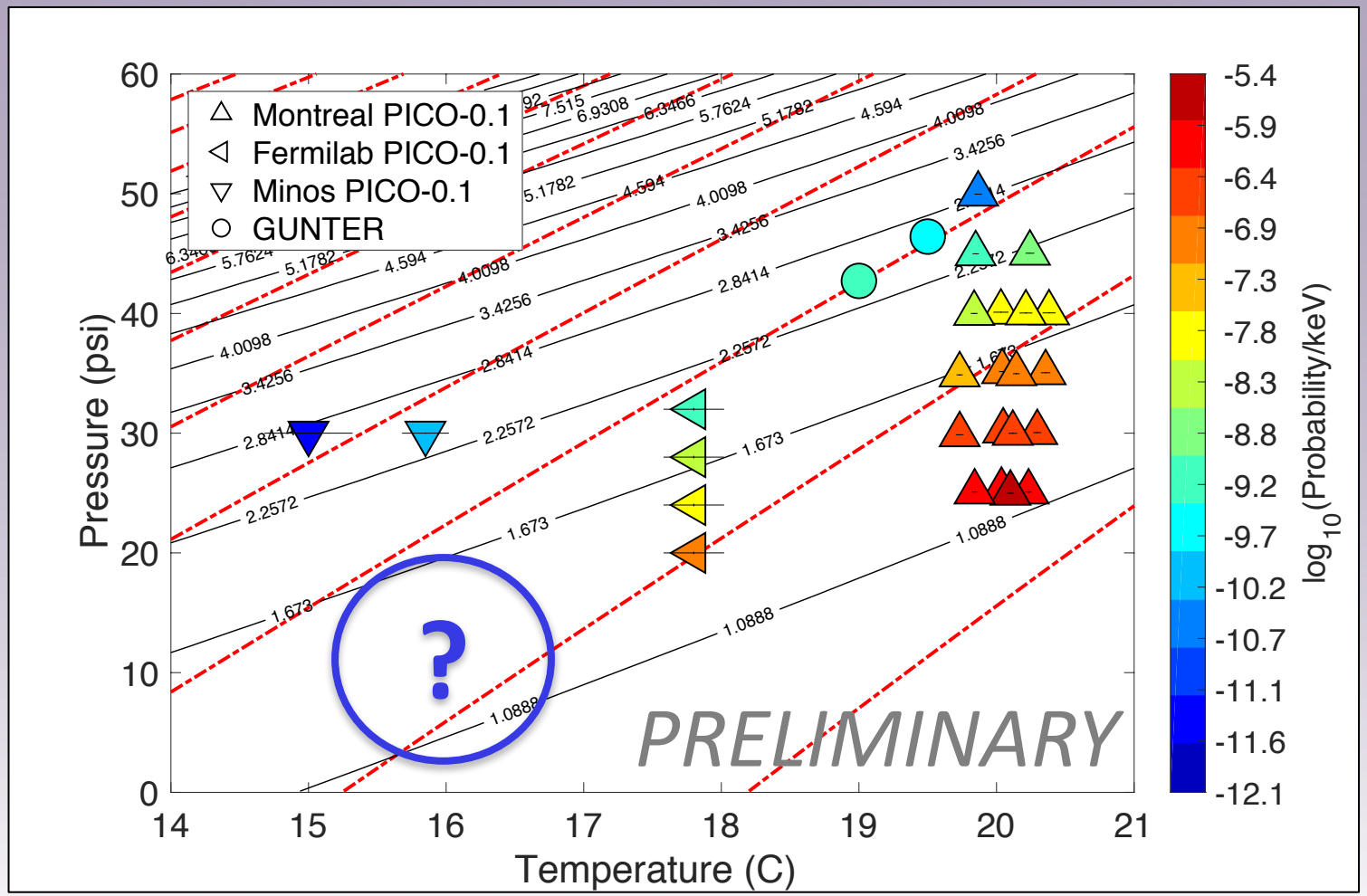
Probability of Nucleation

In pure C_3F_8

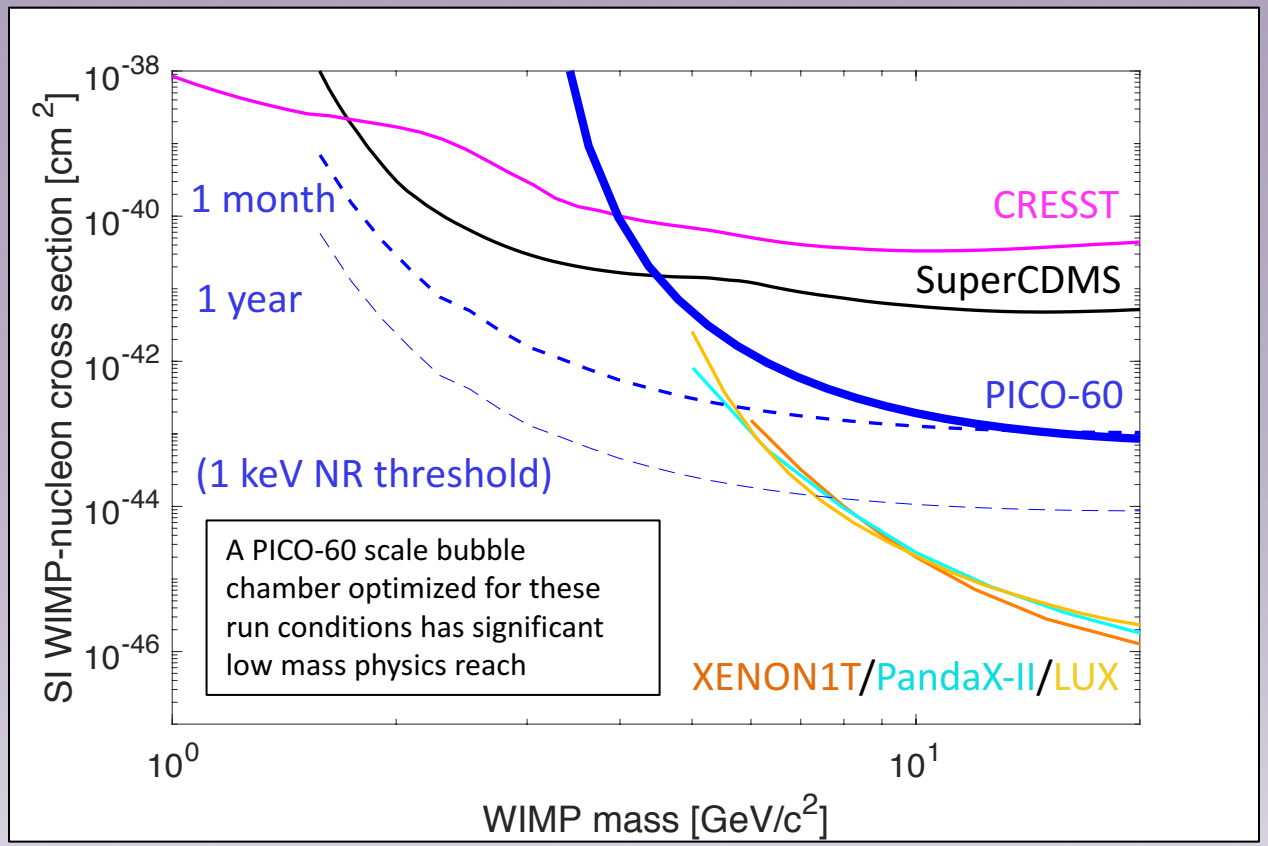
- Per what…
  - ~~Photon Interaction: each photon interaction has some probability to nucleate a bubble~~
  - **Track length**: *each delta electron has some probability to nucleate a bubble*
    - (Scales with energy deposited)
- Nucleation by… (scales with)
  - ~~Heat: Seitz Model describes threshold (few keV)~~
  - **Cavitation**: *Only minimum work to create bubble is required (less than 100 eV)*

What does this mean?

Black: NR (heat) Threshold Red: ER (cavitation) Threshold



What does this mean?



Different threshold for ER nucleation allows **lower NR thresholds** with same ER rejection

- Prefer operation at lower pressure & temperature

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PICO

Paper coming soon* to an arXiv near you…