Bubble Chamber Calibrations

E. Dahl, for PICO Collaboration

PICO

SNOLAB
Mining for knowledge
Creuser pour trouver... l'excellence

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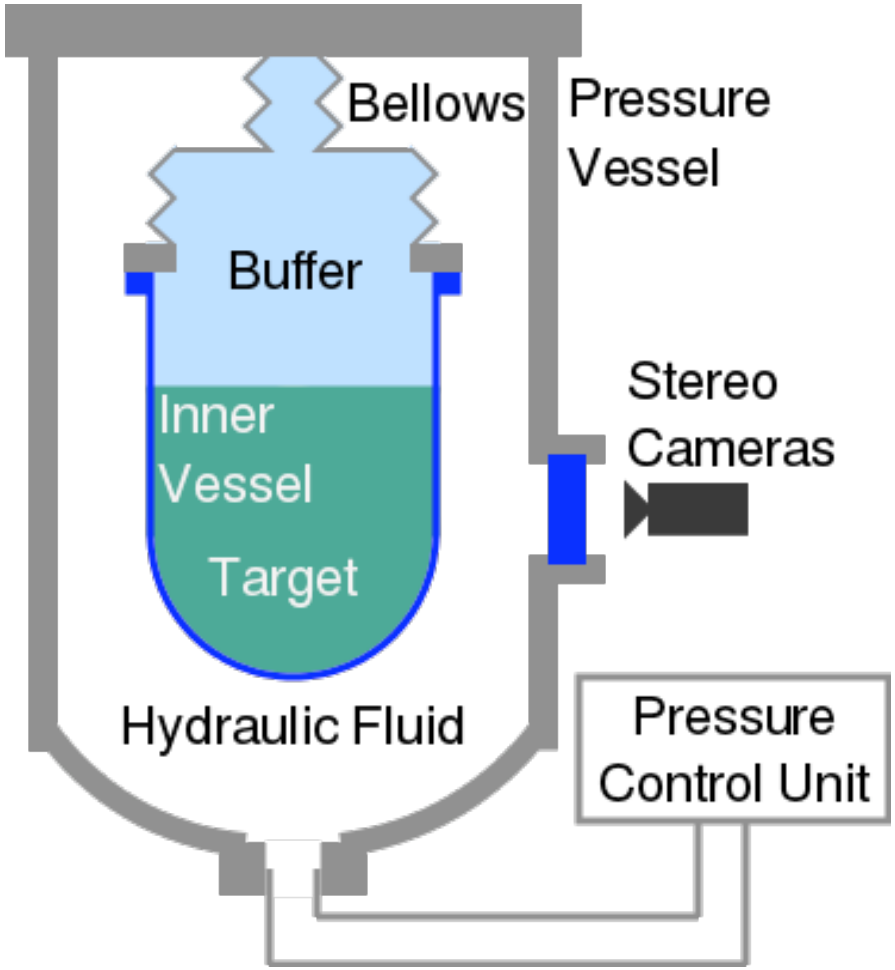
Outline

- Bubble Chamber Thermodynamics
- Nuclear Recoil Calibrations
  - Charged Pions
  - Low-energy neutrons
  - High-energy neutrons
- Electron Recoil Calibrations
  - When is an ER not just an ER?
- Scintillating bubbles…

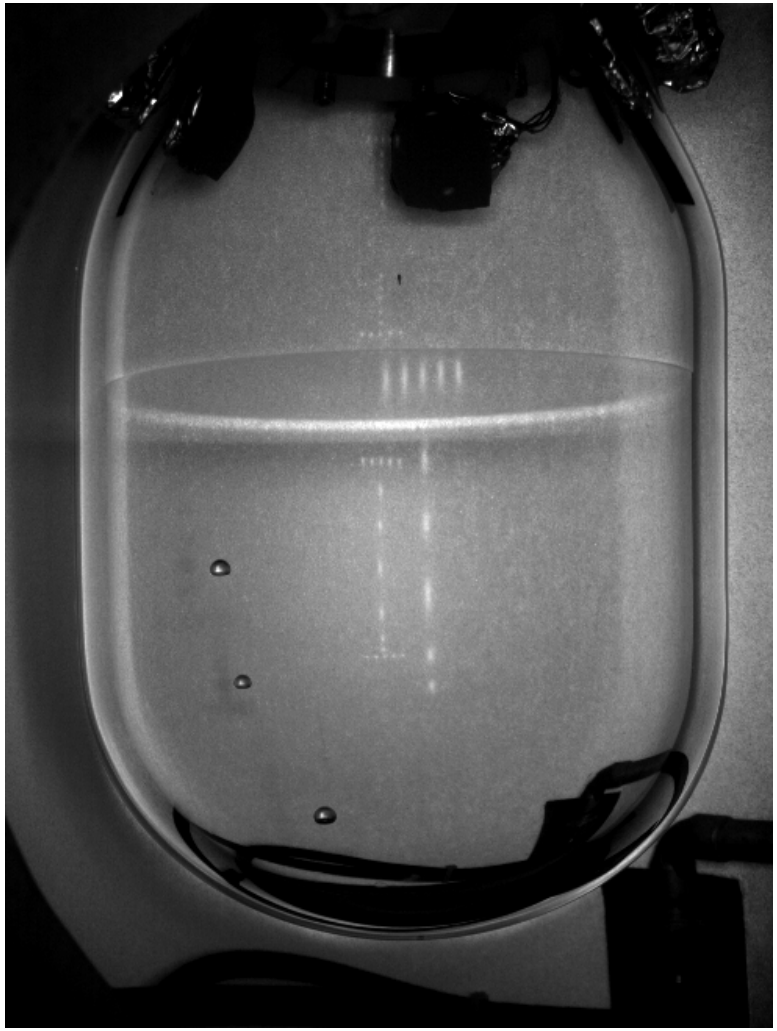
Bubble Chamber Basics

- Superheated Target
  - CF_3I, C_3F_8, …
- Particle interactions nucleate bubbles
- Cameras and acoustic sensors capture bubbles
- Chamber recompresses after each event



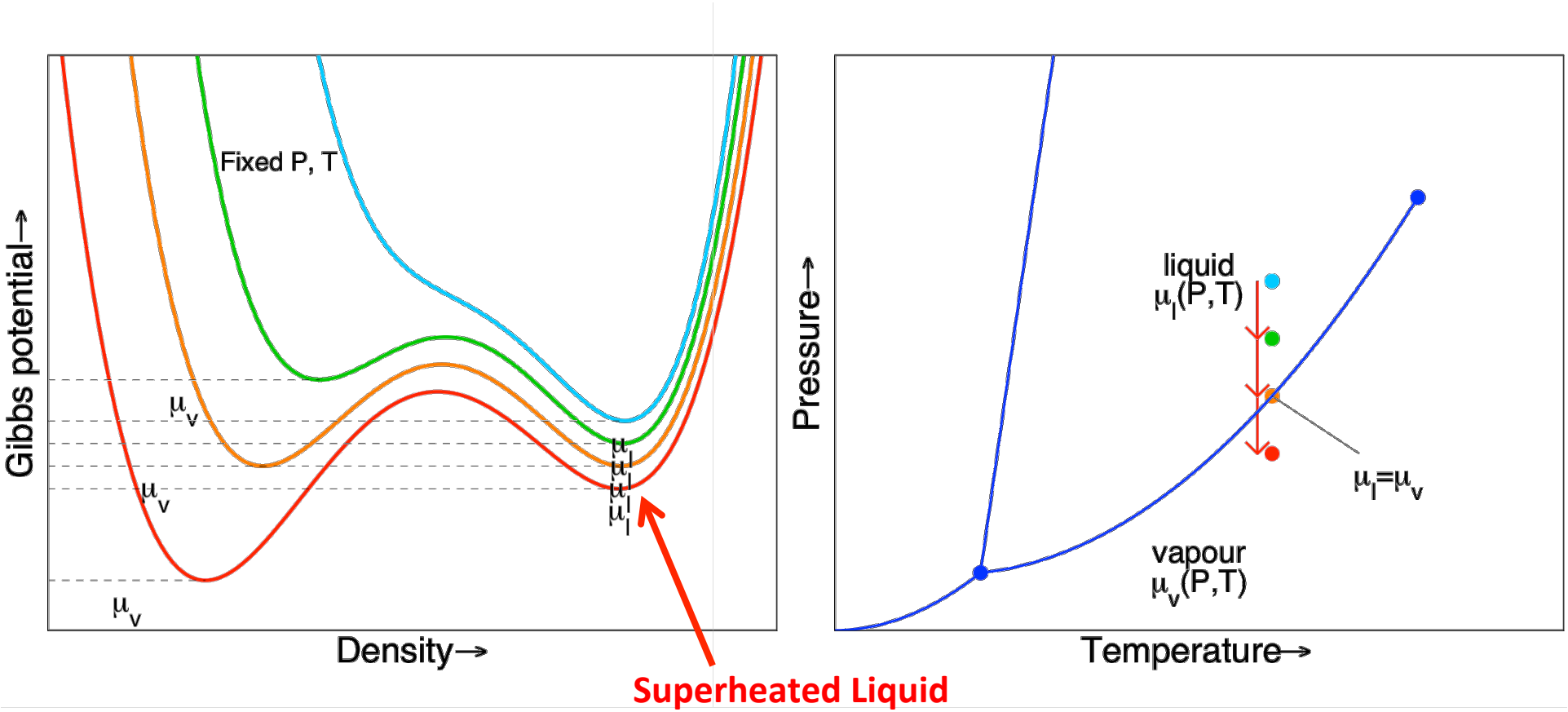
Bubble Chamber Basics

- For interactions in this talk, response is **BINARY** – bubble/no-bubble
  - By the time we *hear* a bubble, it's drawn 1 MeV from the fluid
  - By the time we *see* it, it's drawn 10 PeV



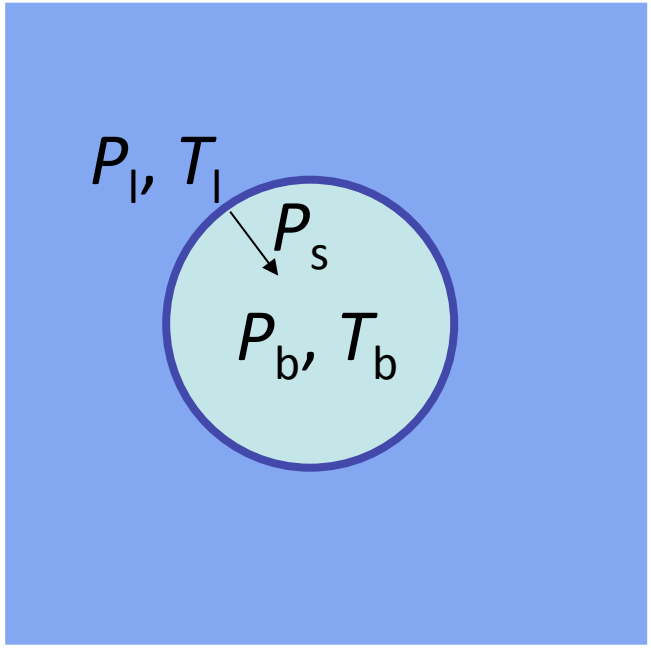
Bubble Chamber Thermodynamics

- Reaching the superheated state



Bubble Chamber Thermodynamics

- Consider the *equilibrium* state with a bubble:
  - $T_l = T_b$ (thermal equilibrium)
  - $\mu_l = \mu_b$ (chemical equilibrium) (so $P_b \approx P_{vap}$)
  - $P_b - P_l = P_s = 2\sigma / r_c$ (mechanical equilibrium)



Note, this is an *unstable* equilibrium

Bubble Chamber Thermodynamics

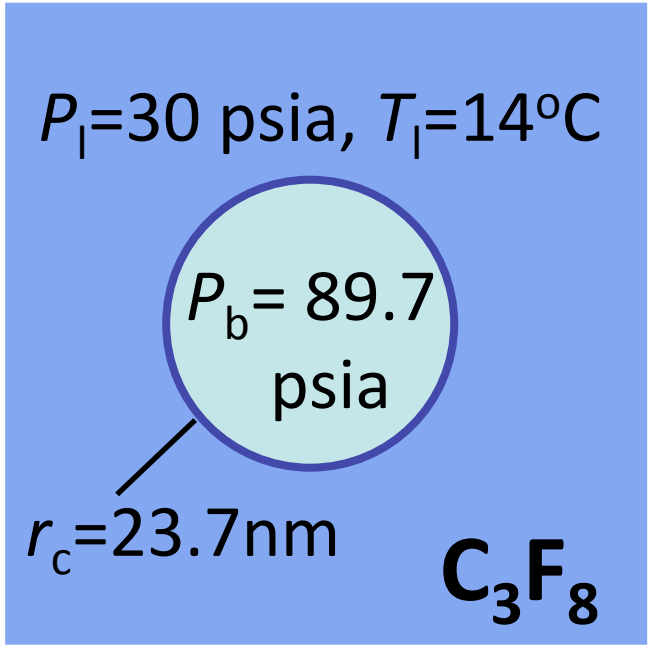
- What does it take to produce critical bubble?

$$E_T = 4\pi r_c^2 \left(\sigma - T \left(\frac{\partial \sigma}{\partial T} \right)_\mu \right)$$ 1.53 keV

$$+ \frac{4\pi}{3} r_c^3 \rho_b \left(h_b - h_l \right)$$ 1.81 keV

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

= 3.19 keV total



Surface energy, Bulk energy, Reversible Work

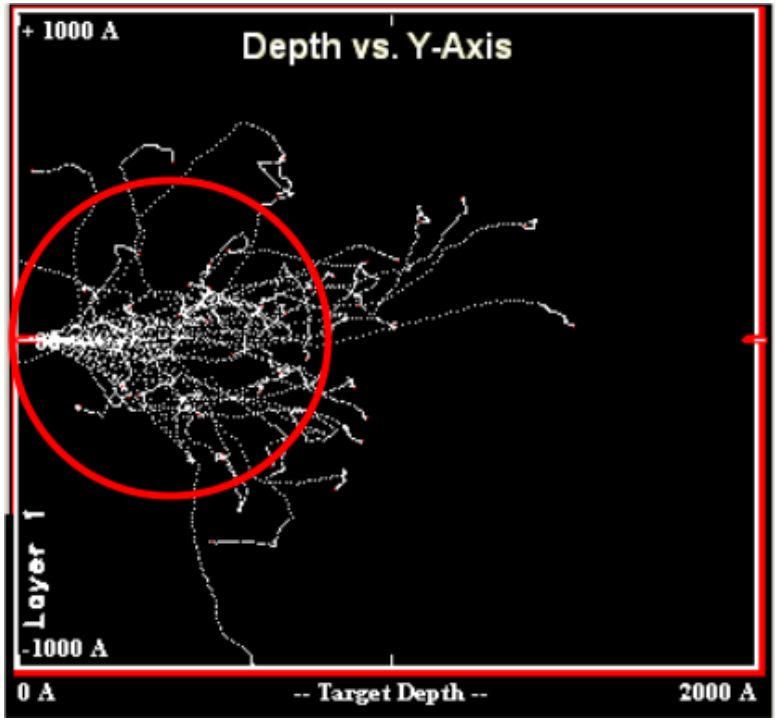
Bubble Chamber Thermodynamics

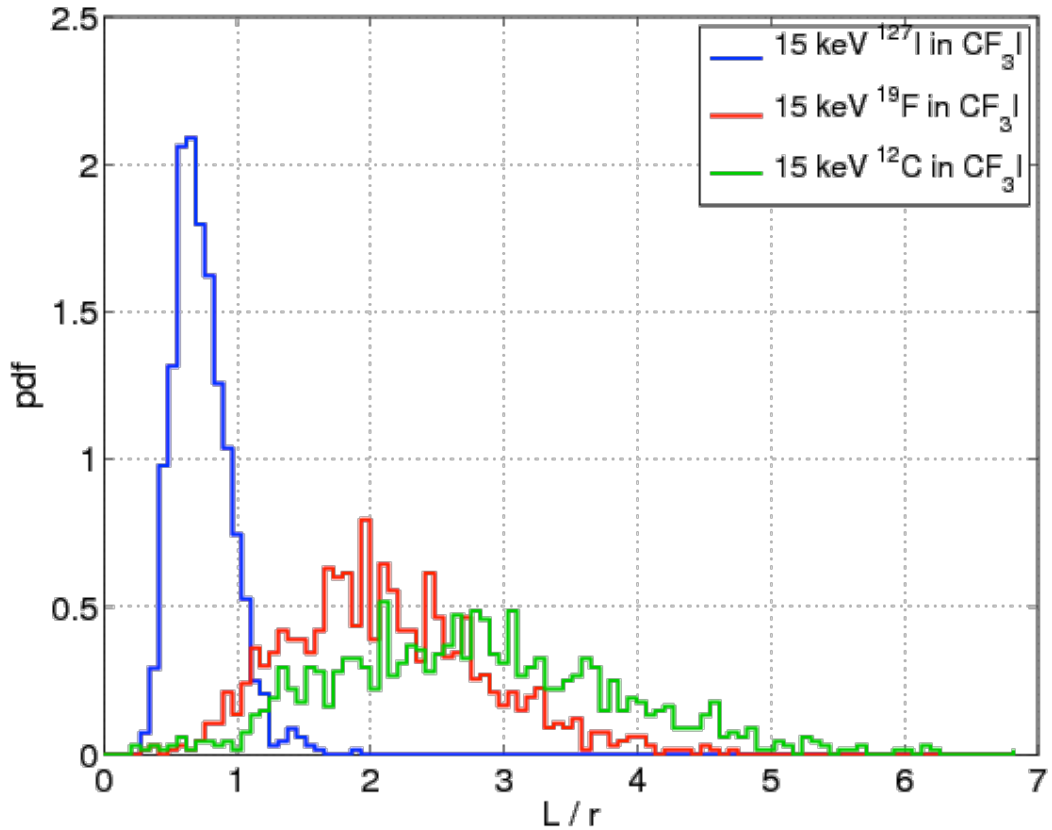
- What does it take to produce critical bubble?
  - Energy (heat) deposition > E_T
  - In a volume < r_c

- 0th order, dream scenario:
  - Nuclear recoils with $E_r > E_T$ make bubbles
  - Electron recoils don't make bubbles

Nuclear Recoils beyond 0th order

TRIM simulation (15 keV ^{19}F in CF_3I)





- Nuclear recoils not all < r_c, definitely not << r_c
- Not all electronic stopping converted to local heating (Inverse Lindhard effect)

Nuclear Recoil Efficiency – Definition

- For each target fluid, need to measure set of probabilities

$$P_X(E_r | E_T)$$

  that a recoil of energy E_r and species X makes a bubble in a chamber at *thermodynamic* threshold E_T

- Assumptions:
  - P_X monotonic in E_r, E_T
  - $P_X = 0$ for $E_r < E_T$
  - $P_{high\text{-}A} > P_{low\text{-}A}$ at fixed E_r, E_T

Nuclear Recoil Calibrations: Challenges

- Threshold detector!

$$\text{Bubble Rate} = \int dE_r \; \underbrace{P(E_r)}_{\text{Efficiency}} \times \underbrace{R(E_r)}_{\text{Spectrum}}$$

  – Cannot determine efficiency with single recoil spectrum
  – High-energy recoils wash out sensitivity near threshold

Nuclear Recoil Calibrations: Challenges

- Threshold detector!
- 1k bubbles / day max
  - Tagged scattering requires complete tagging (no wasted bubbles)
- Multiple nuclei with different kinematics

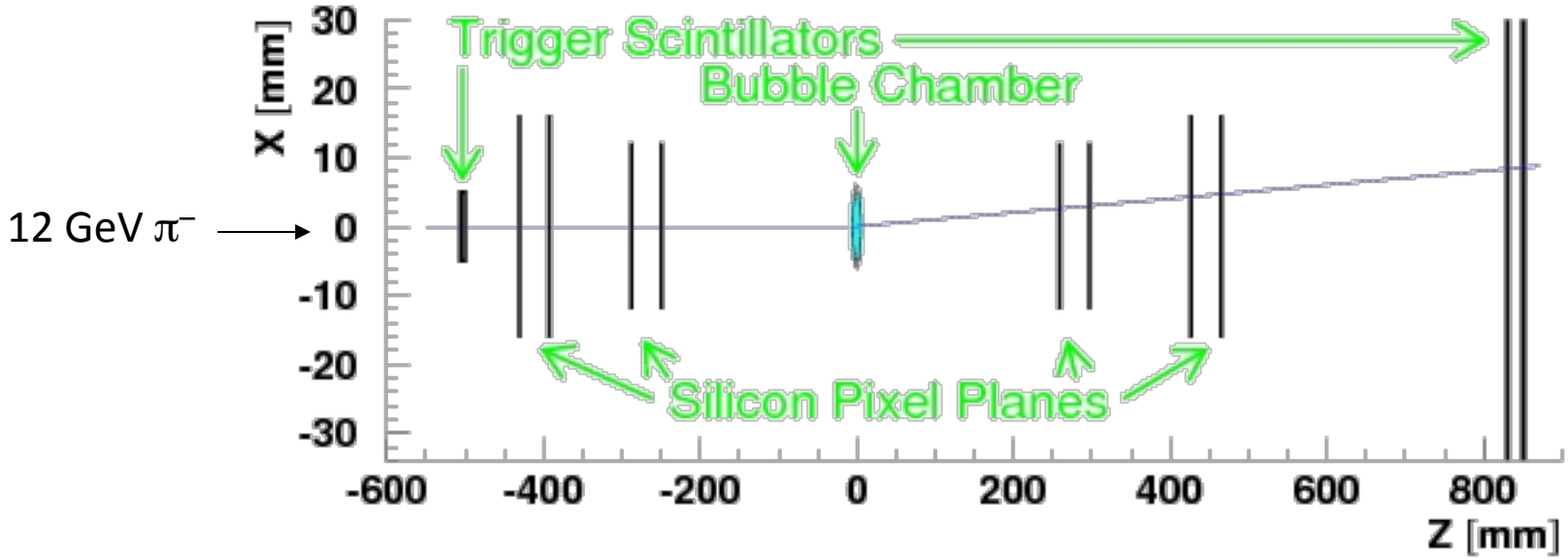
Nuclear Recoil Calibrations: Advantages!

- No electron sensitivity!
  - No shielding necessary with $^{9}Be(\gamma,n)$ sources
  - Can work with charged beams directly (e.g. π^- scattering)

- Excellent 3-D position reconstruction
  - Take advantage of multiple scattering

The CIRTE Experiment

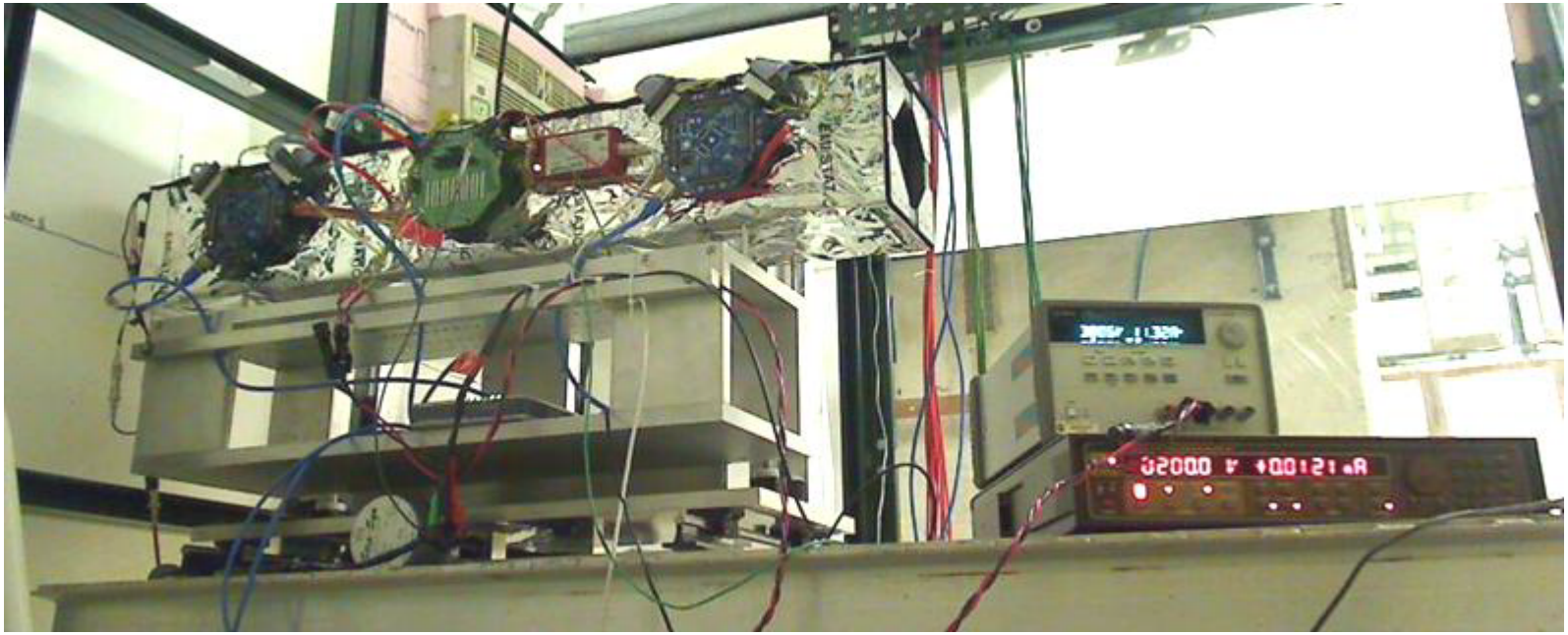
Phys. Rev. D 88, 021102 (2013)

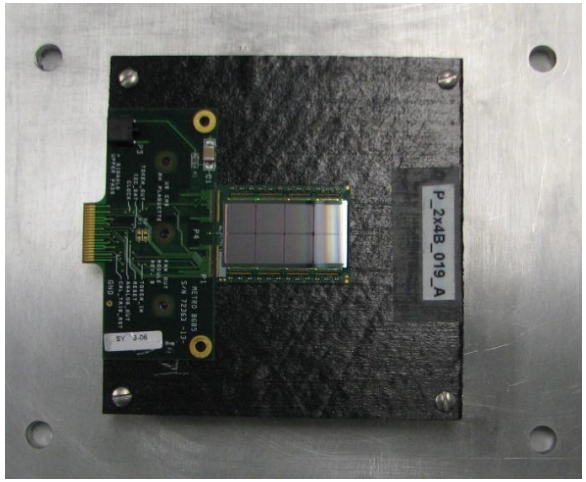


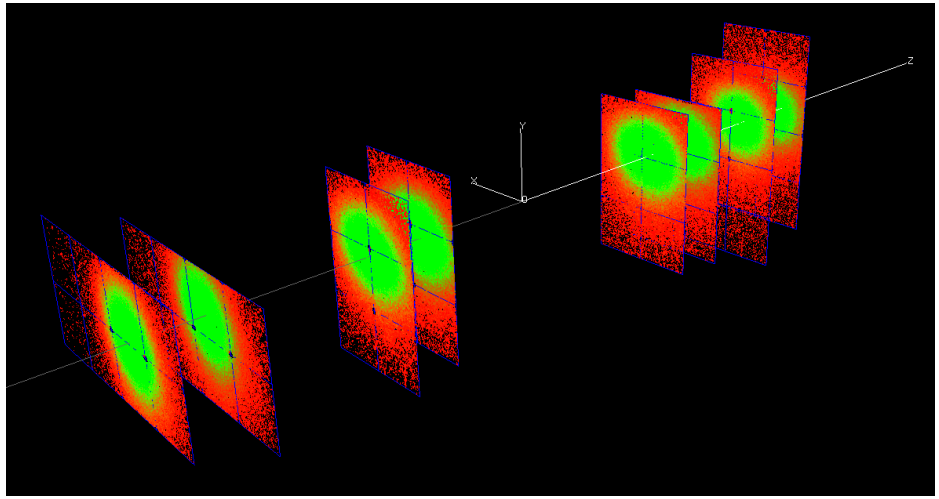
CF_3I

- $E_r = (p\theta)^2 / 2M_N$
- 13.5 keV ^{127}I recoil = 4.7 mrad scatter
- 0.7 mrad resolution (multiple Coulomb scattering and pixel size)

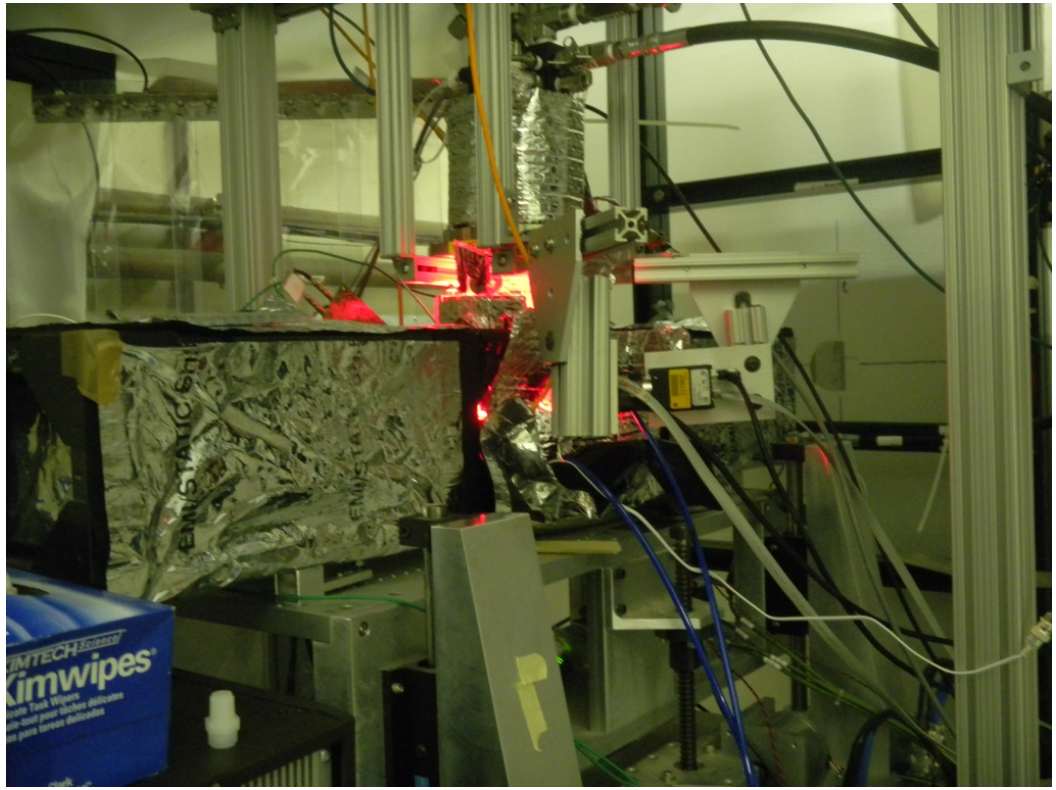
Silicon Pixel Telescope at the Fermilab Test Beam Facility



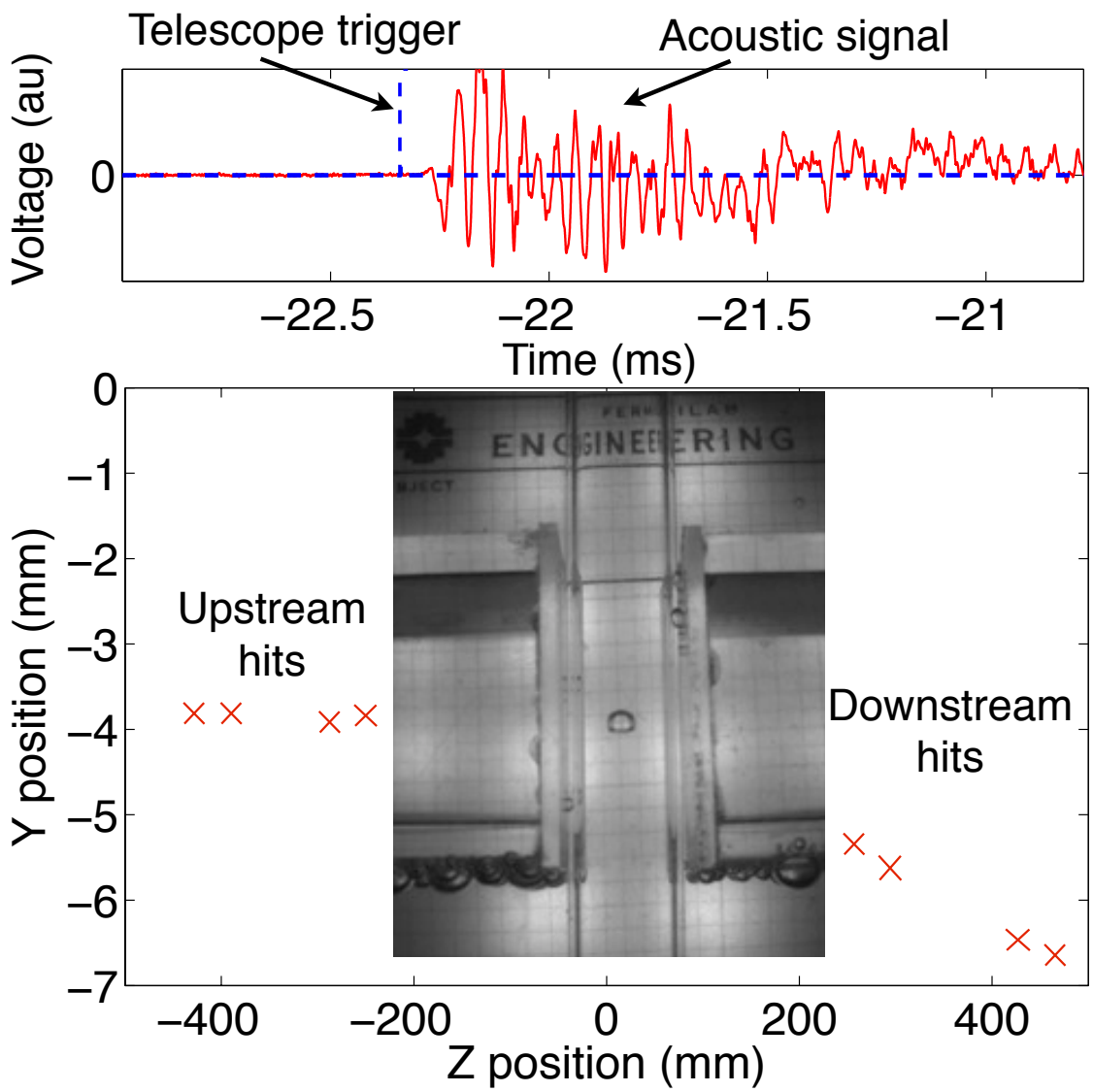




Silicon Pixel Telescope + Bubble Chamber

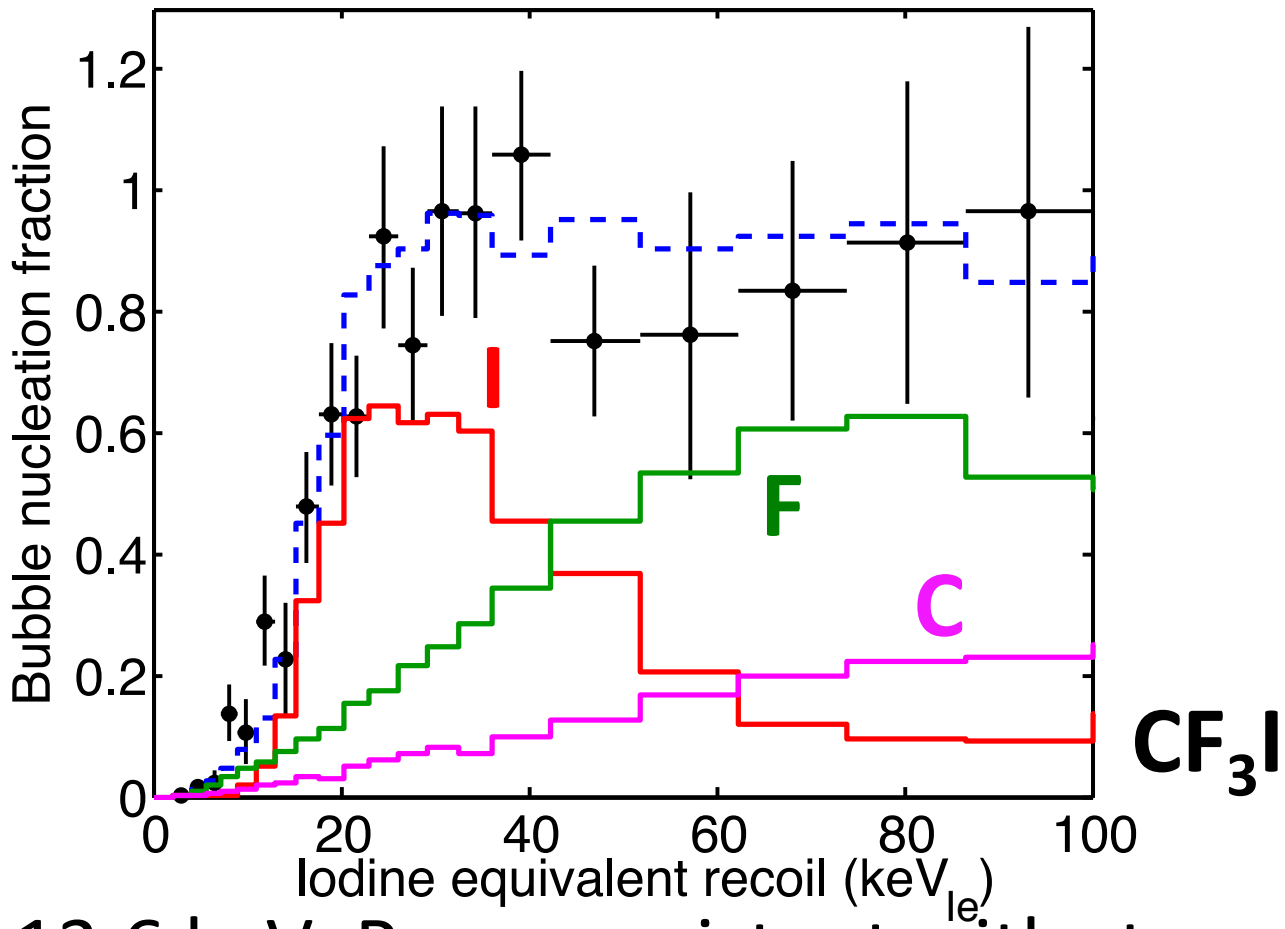


CIRTE Event



CF_3I

CIRTE Results

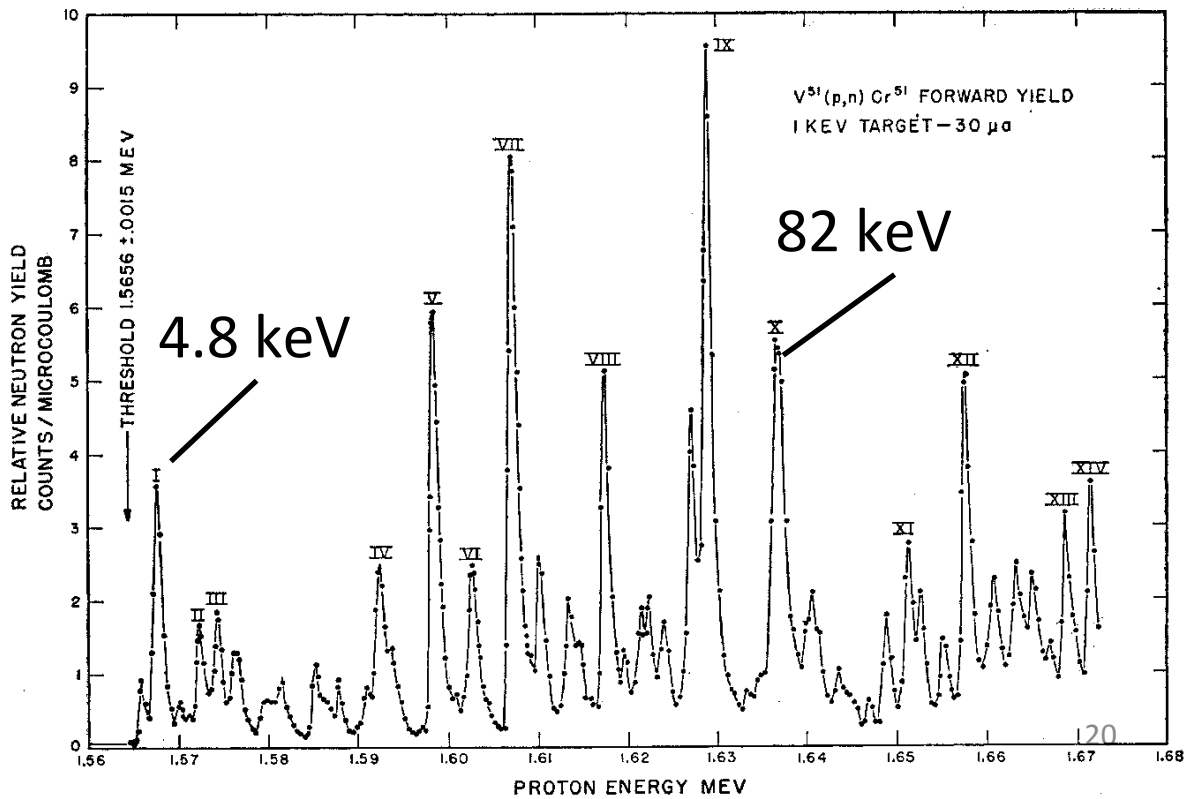


- At E_T=13.6 keV, $P_{I\text{-}127}$ consistent with step-function at E_r=16.8 keV

Neutron Calibrations

- Mono-energetic low-energy neutrons
  - $^{51}V(p,n)\ ^{51}Cr$
    - Many very sharp (~.25 keV) resonances
    - Neutrons from 4.8 to 119 keV
  - $^{9}Be(\gamma,n)$
    - ^{88}Y, ^{207}Bi, ^{124}Sb

Phys. Rev. **100**, 167 (1955)

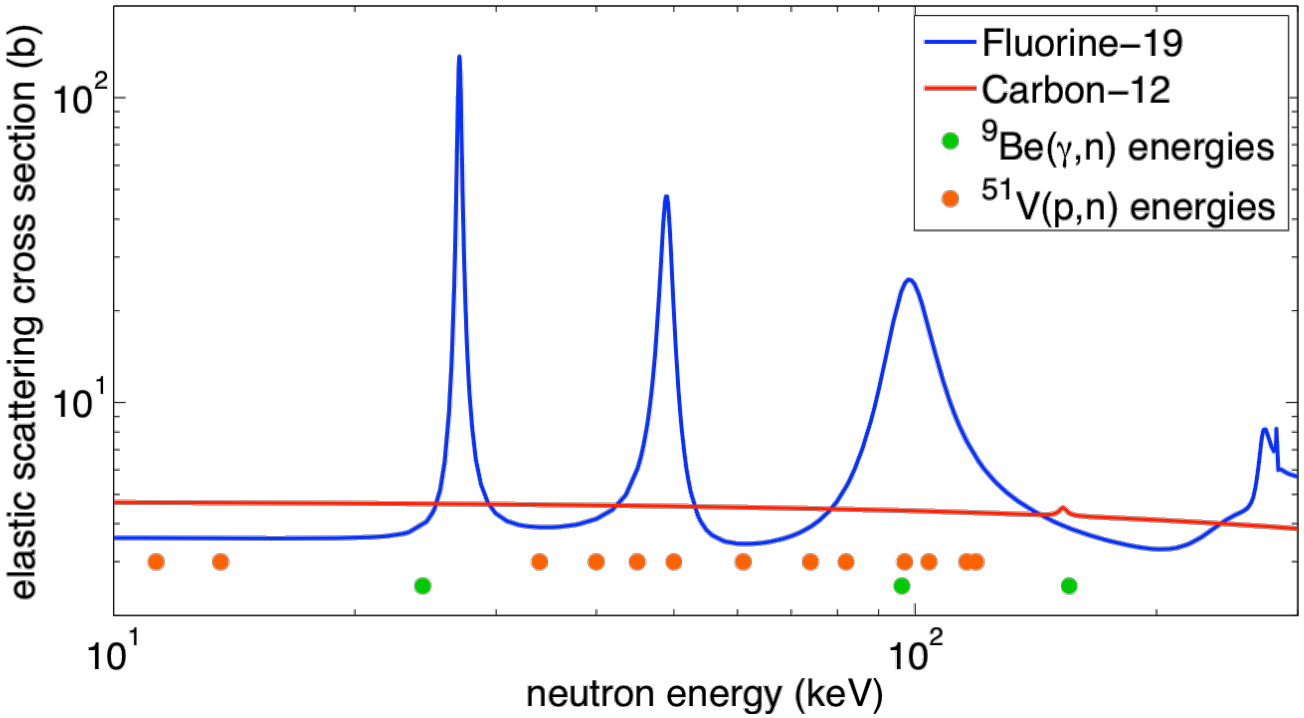


Neutron Calibrations

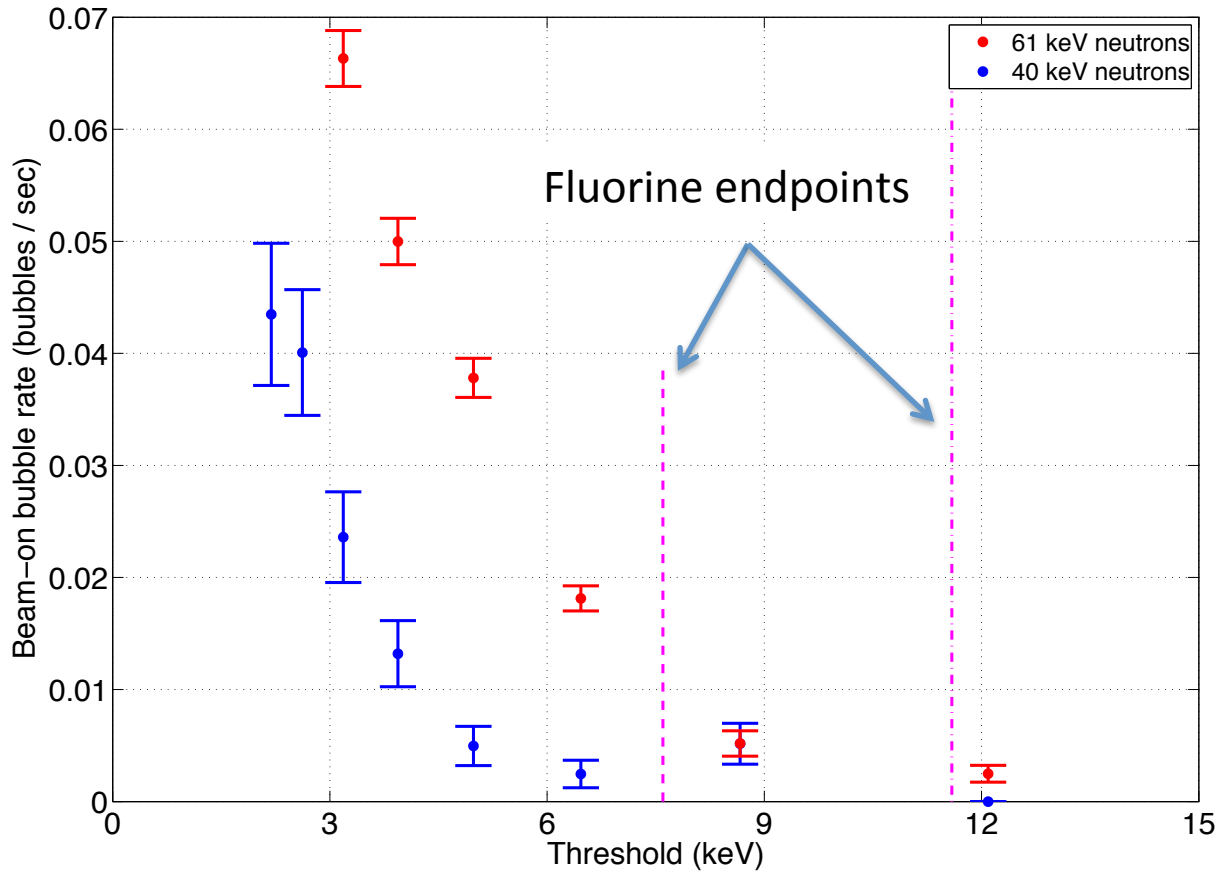
- Data on- and off- Fluorine resonances

ENDF (and thus Geant4, MCNP) gets these resonances *wrong* (has them as isotropic)

Fixed in:
A. Robinson
PRC 89, 032801 (2014)



Sample $^{51}V(p,n)$ data



C_3F_8

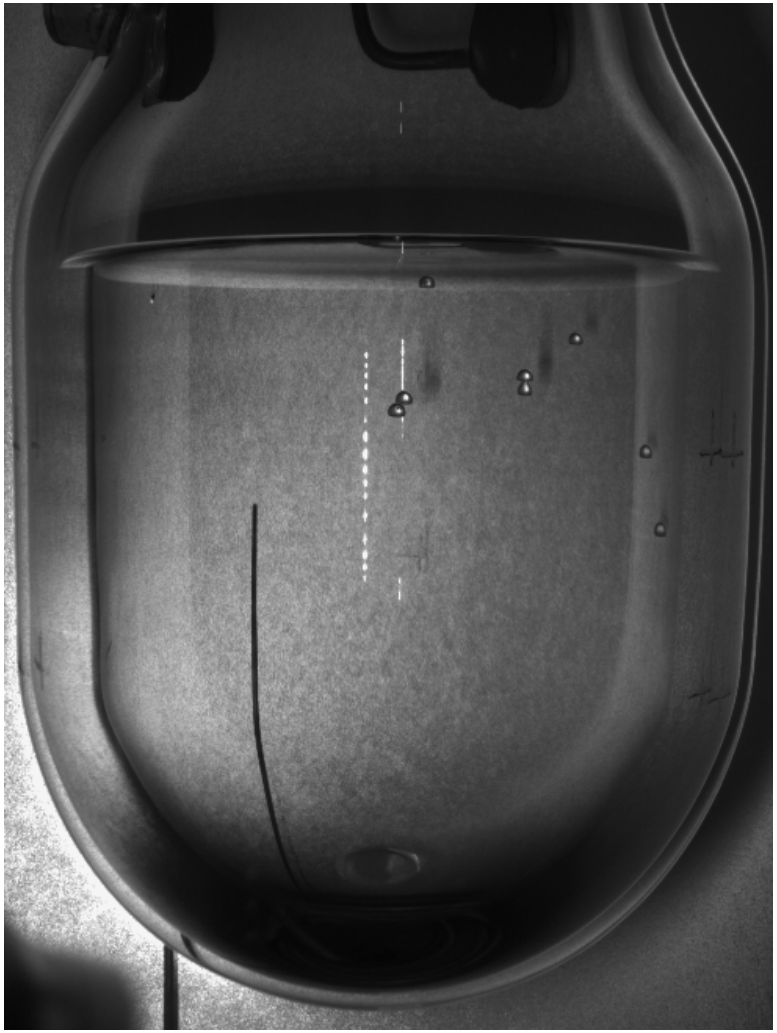
- No carbon turn-on, apparent fluorine turn-on…

Absolute Normalization of ^{51}V(p,n) Data

- Two ^{3}He counters recording neutron exposure in superheated state
  - 1 fixed position below ^{51}V target
  - 1 in various positions to measure angular distribution of emitted neutrons
  - Simulation must reproduce relative rates in 2 ^{3}He counters to include data
- Measure ^{51}Cr in target (27.7 day, 320-keV γ)
- Absolute neutron flux known to 7%-11%, depending on neutron energy

AmBe in PICO-2L

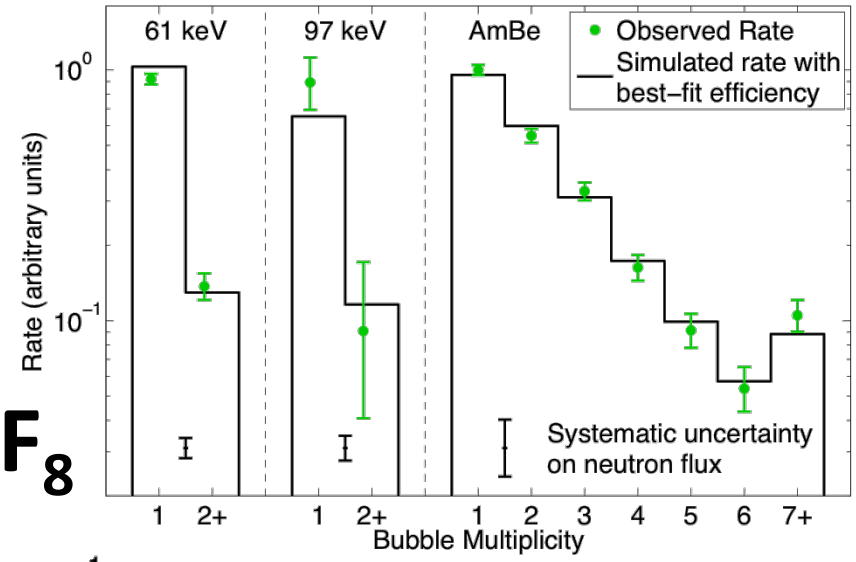
- High-multiplicity events measure sensitivity to low-energy recoils
  - e.g. neutron stays in fluorine resonance for many few-keV scatters

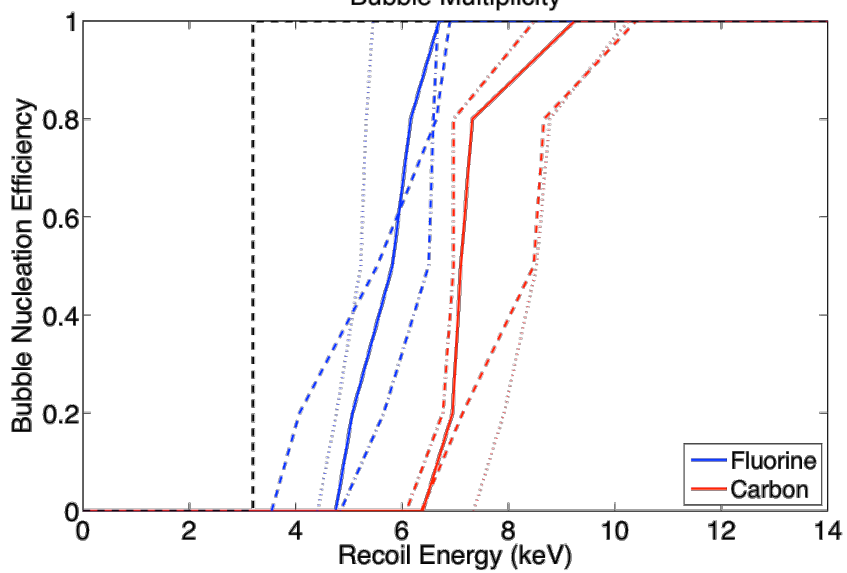


C_3F_8

Throw it all together

C_3F_8

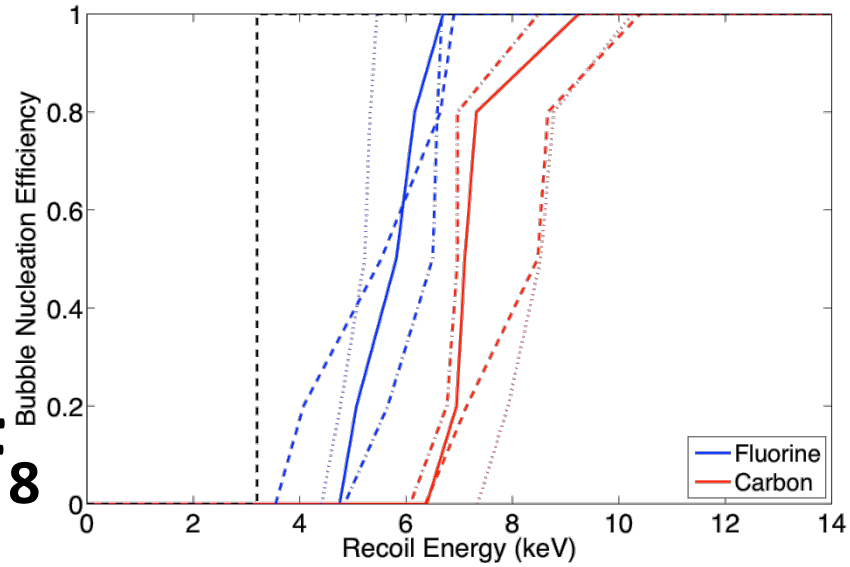




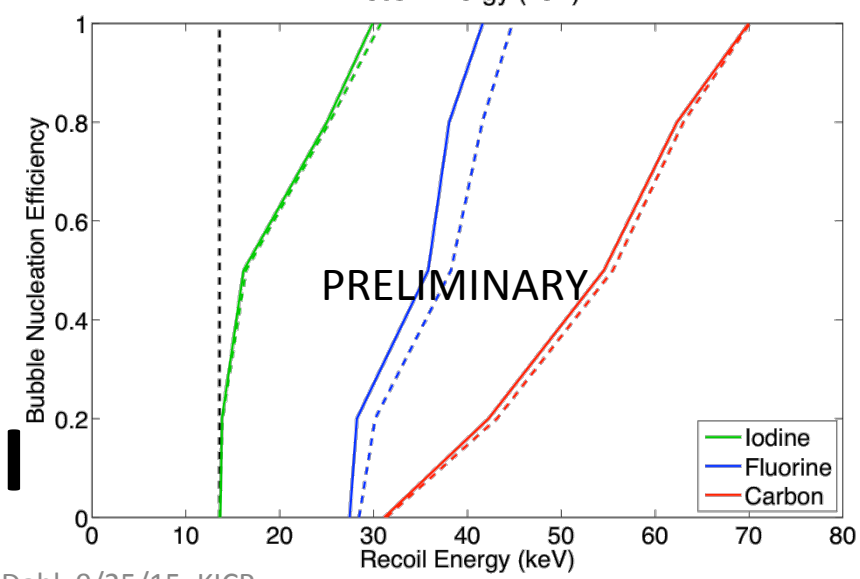
- Fit to piece-wise linear efficiency curves
  - `kinks' fixed at 0%, 20%, 50%, 80%, 100%
  - Energy of kinks floats (10 free parameters)
- For WIMP limit, use most pessimistic efficiency consistent with calibration data at 1-sigma
  - Depends on WIMP mass, interaction

Throw it all together

C_3F_8



CF_3I



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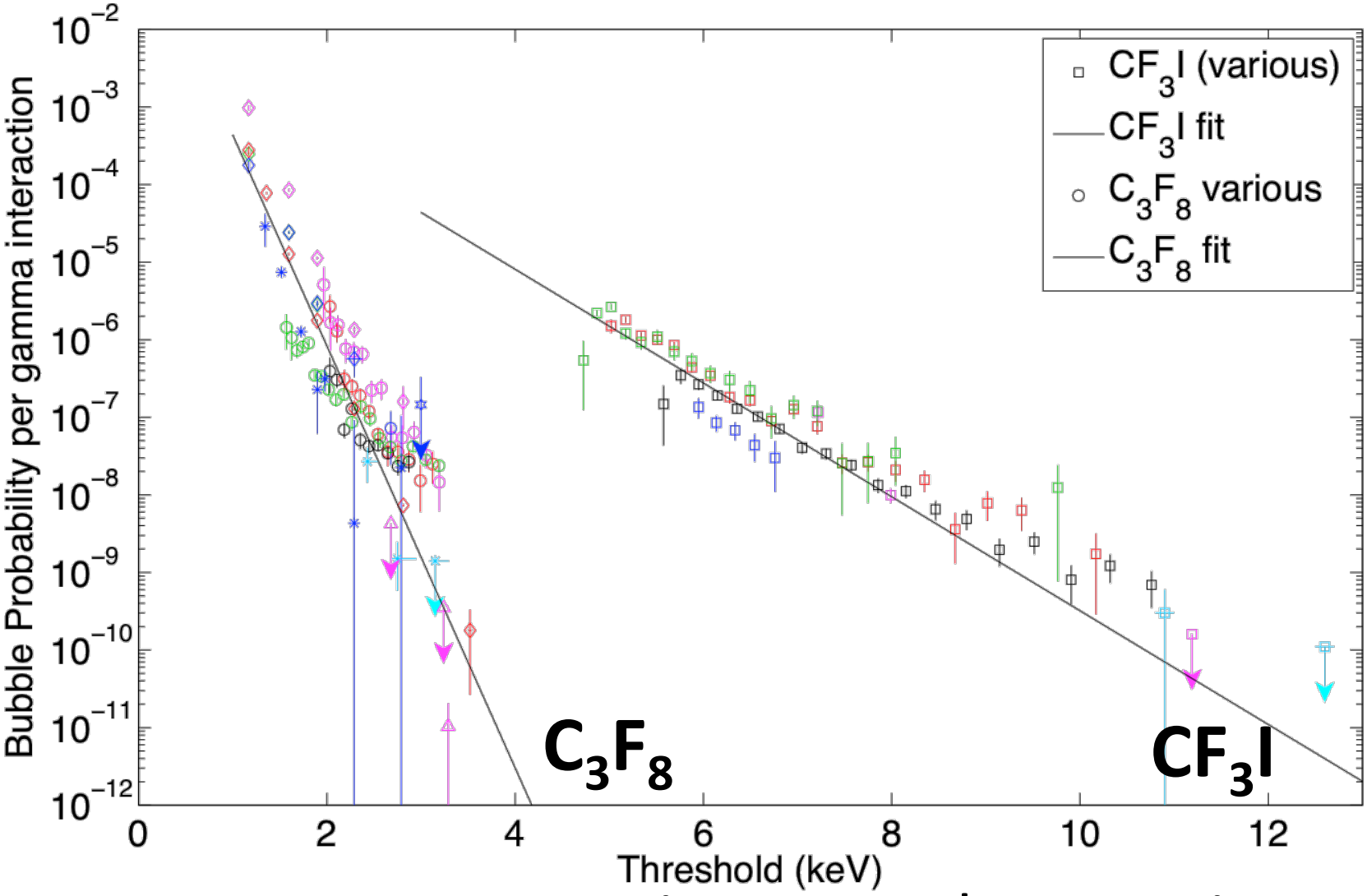
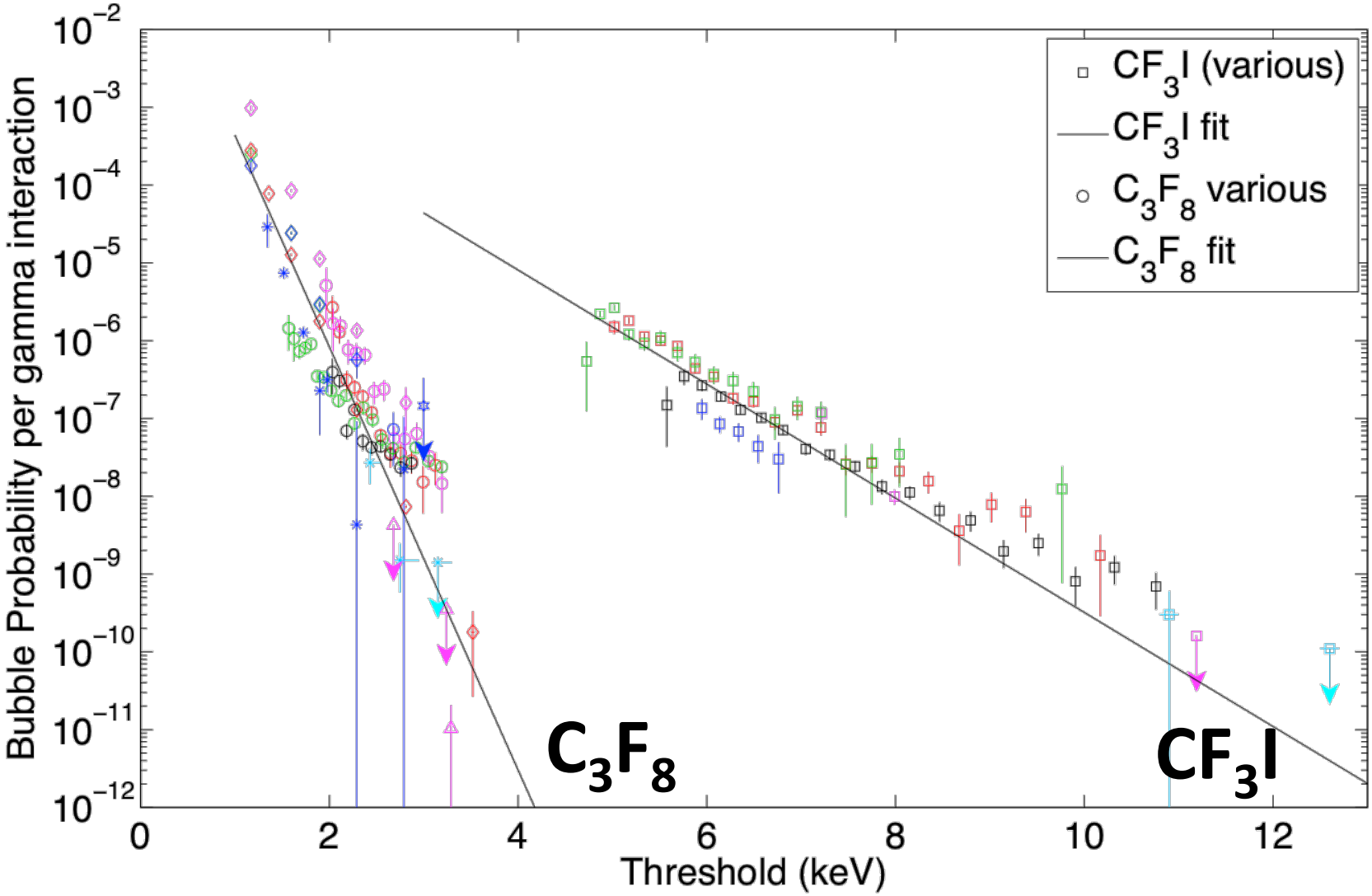
"Electron Recoils"



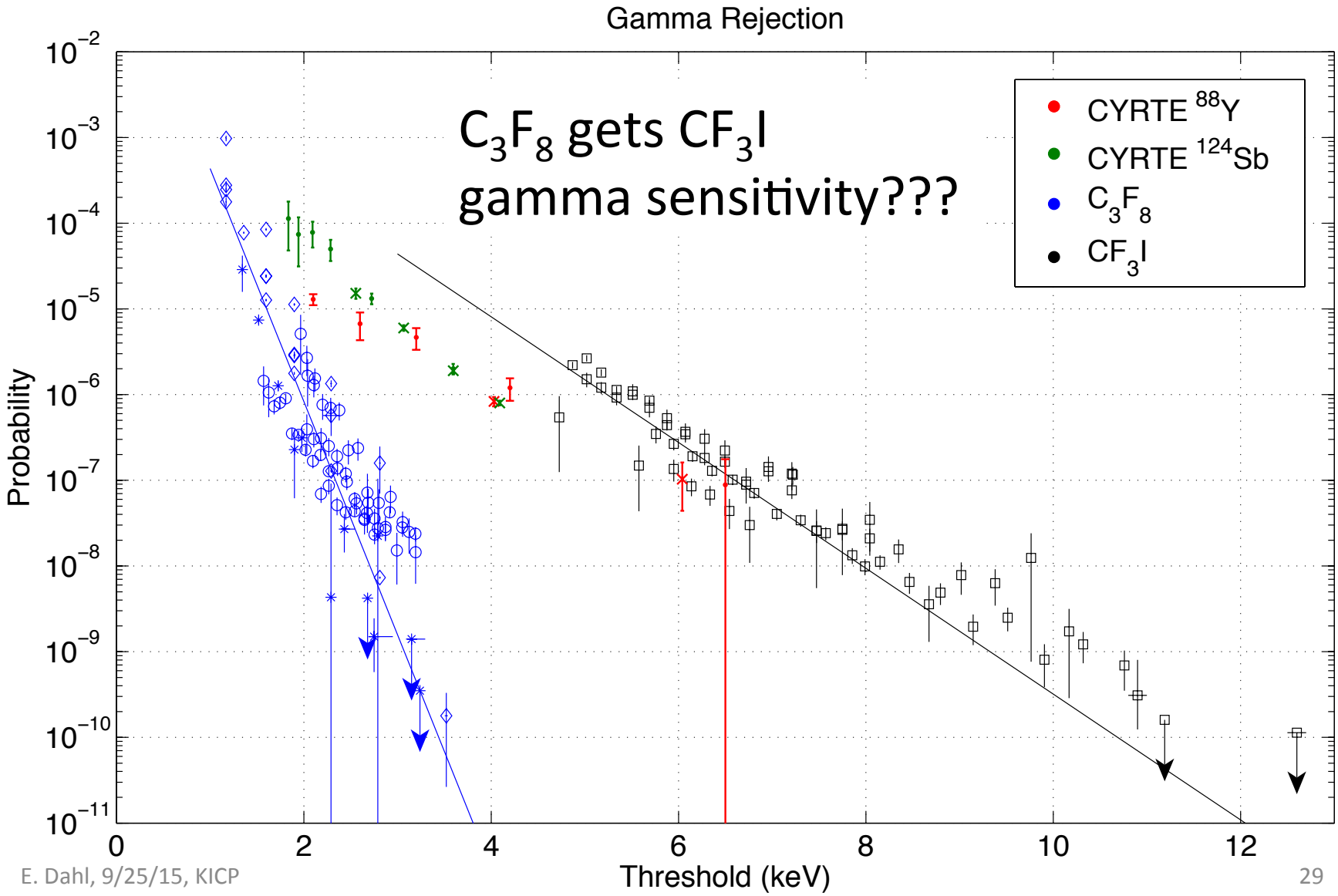
- Many gamma energies, several generations of detectors

"Electron Recoils"

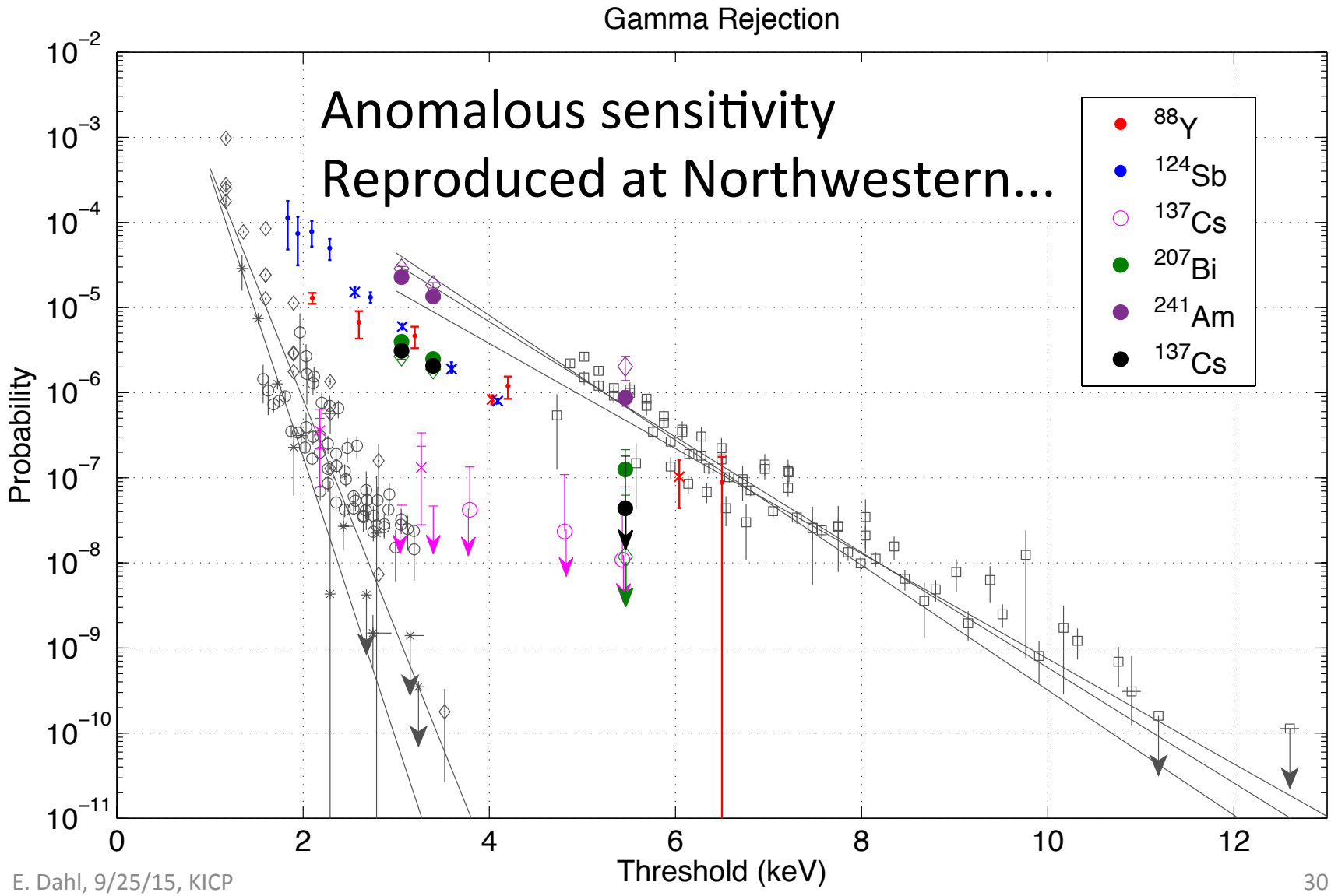


- But why are C_3F_8 and CF_3I so different?

Anomaly Discovered



Anomaly Verified



A common thread

- The C_3F_8 chambers with high gamma sensitivity all had potential for high-Z contaminants
  - Tungsten residue from a thoriated welding rod test in the Northwestern chamber…

- Are we seeing Auger cascades in high-Z nuclei?

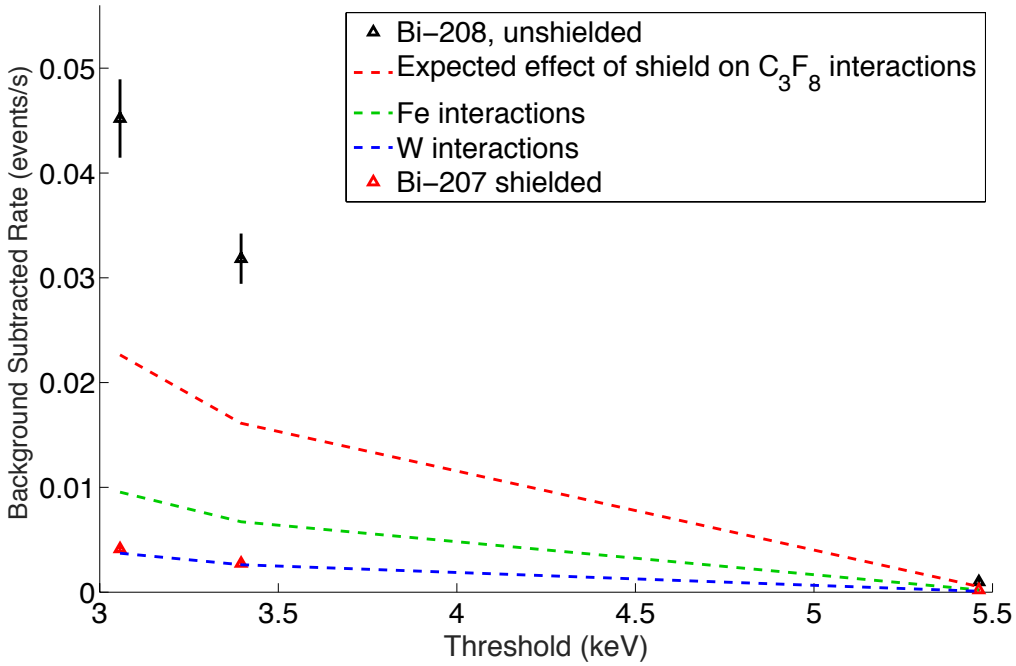
A test for Tungsten

- ^{207}Bi source
  - 73-85 keV: 74% BR <- Photoabsorption candidate
  - 570 keV: 98%
  - 1064 keV: 75%

- If W-photoabsorption is culprit, 2mm lead will cut rate by order of magnitude…

A test for Tungsten

- If W-photoabsorption is culprit, 2mm lead will cut rate by order of magnitude…



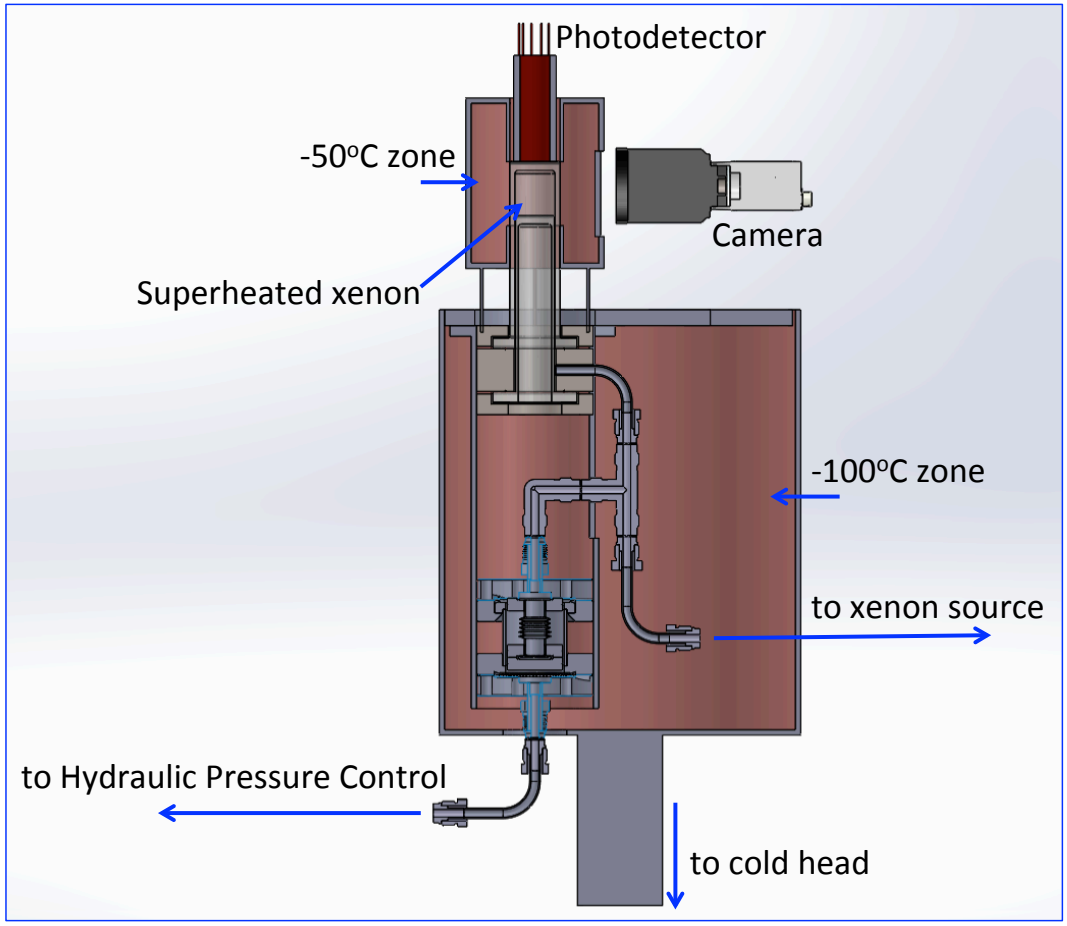
Bubble Nucleation by Auger Cascades

- Auger cascades can lead to 10+ sub-keV electrons from the parent atom
- Vastly different track topology than you get from single high-energy electron

- Compton Scatters and $\nu e \rightarrow \nu e$ *can* leave inner shell vacancies, unlike ^3H decays.
  - Thomas-Imel says this shouldn't matter in xenon below 10 keVee, but worth checking…

A Scintillating Xenon Bubble Chamber

- All the perks of a bubble chamber
  - ER insensitivity
  - Easy 3D recon (no E-field req'd)
- With scintillation light for energy scale



1 Year ago

A Scintillating Xenon Bubble Chamber

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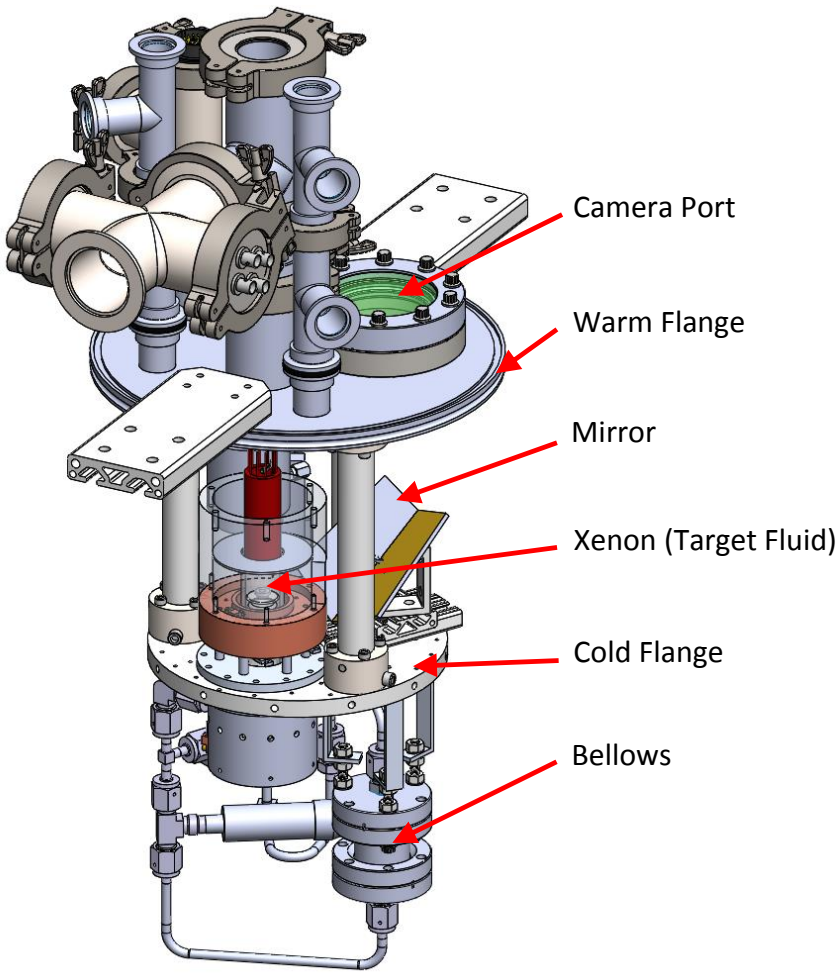
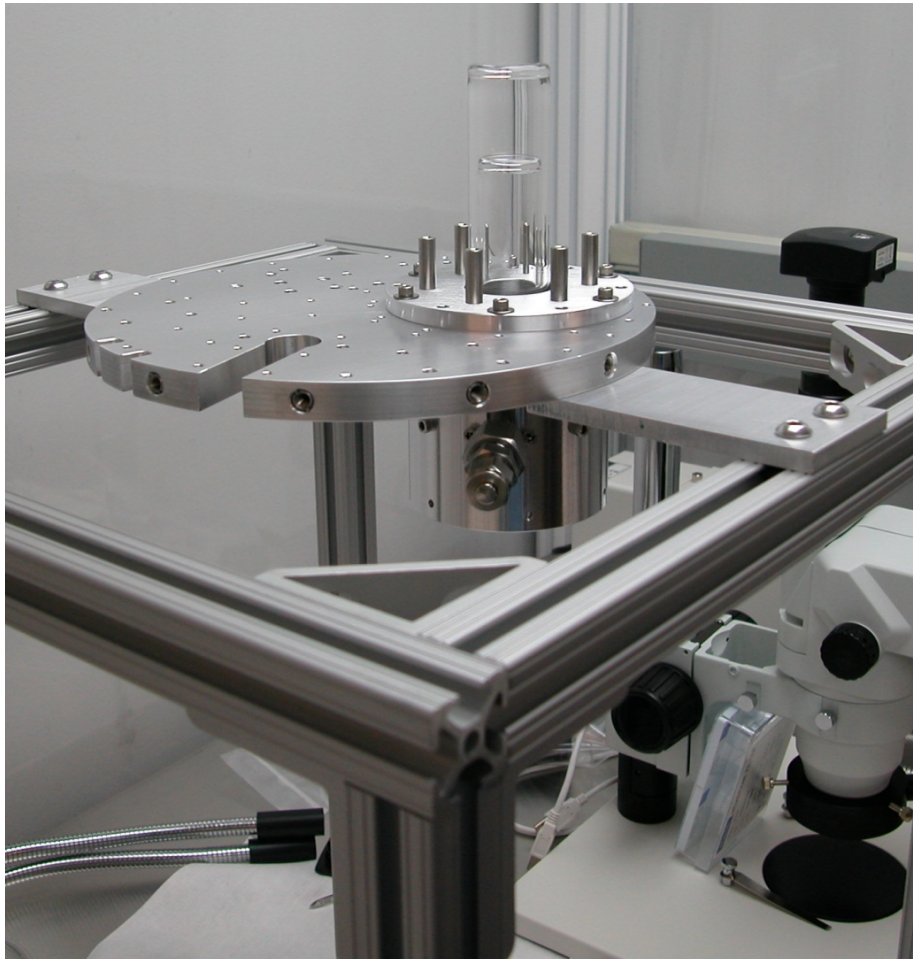


4 months ago

A Scintillating Xenon Bubble Chamber

- Possible new tool for calibrations
  - "Inverse Lindhard" measurement
  - Photoneutrons without shielding (S1 only)
  - Other ideas?



3 weeks ago

Summary

- Nuclear Recoils
  - Nucleation probability determined by
    - Pion scattering
    - Mono-energetic neutrons with absolute rate calibration
    - Bubble multiplicity
  - Close to thermodynamic limit when tracks are small
- Electron Recoils
  - Not all electron recoils are equal
  - Auger cascades give much higher bubble nucleation probability than beta's or valence Compton scatters