# *Monte Carlo simulations for bubble chambers*

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# Outline

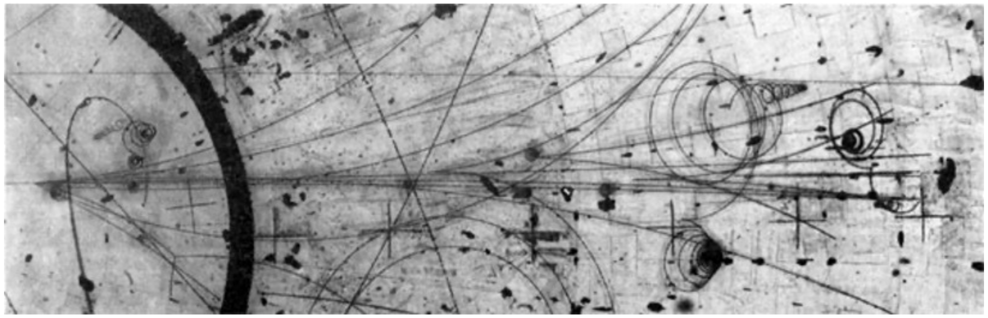
- **Experiment overview**
- **PICO bubble chambers at SNOLAB**
- **Monte Carlo simulations for PICO with GEANT4**
- **Final remarks**

# PICO: dark matter searches using bubble chambers

# Physics with bubble chambers

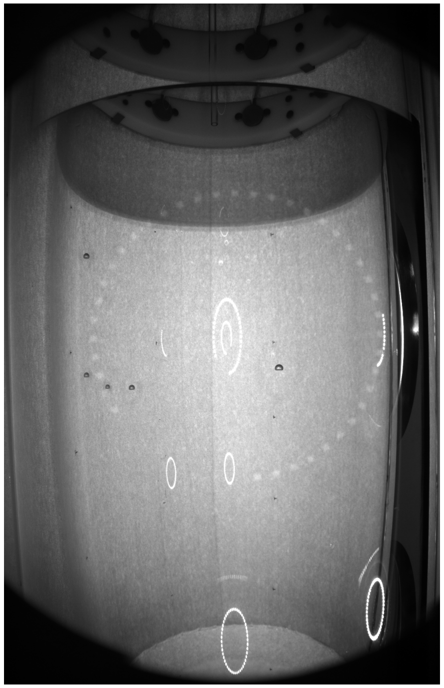
**1970s: Neutrino Beam Physics**

- **Sensitive to MIPs**
- **Particle tracks visible**
- **Threshold << 1 keV**
- **Multi-ton chambers, multiple fluids**



**2000-today: Nuclear Recoil Detectors**

- **Dark matter searches with fluorocarbon bubble chambers**
- **Electron recoil blind**
- **Nuclear recoil threshold $\sim$ 3keV**
- **Scalable at modest cost**



# PICO bubble chambers

- Target material: superheated $CF_3I$, $C_3F_8$, $C_4F_{10}$ spin-dependent/independent

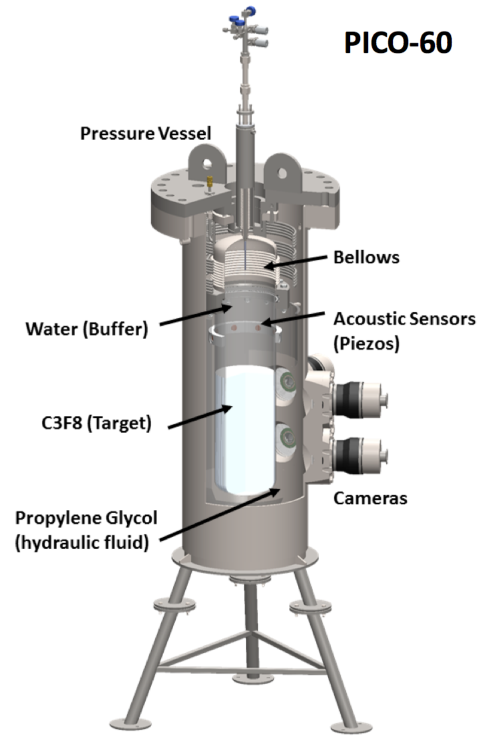
  Could make a dark matter bubble chamber with any liquid!

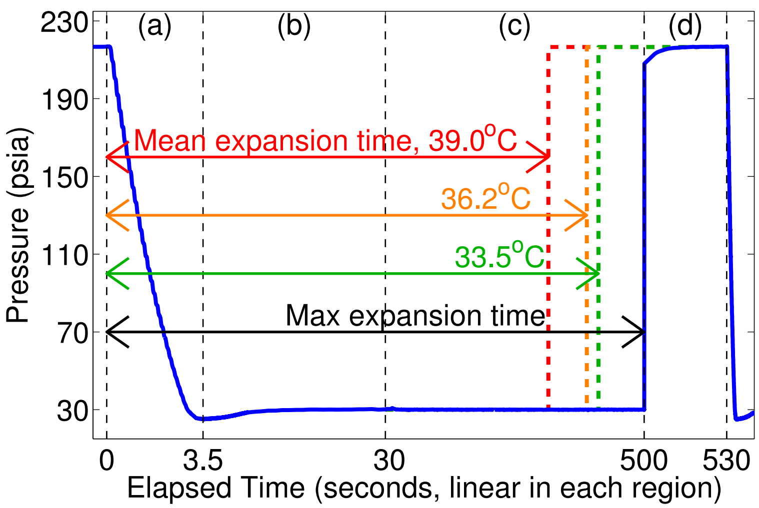
- Particles interacting evaporate a small amount of material: bubble nucleation

- Four Cameras record bubbles

- Eight piezo-electric acoustic sensors detect sound

- Recompression after each event



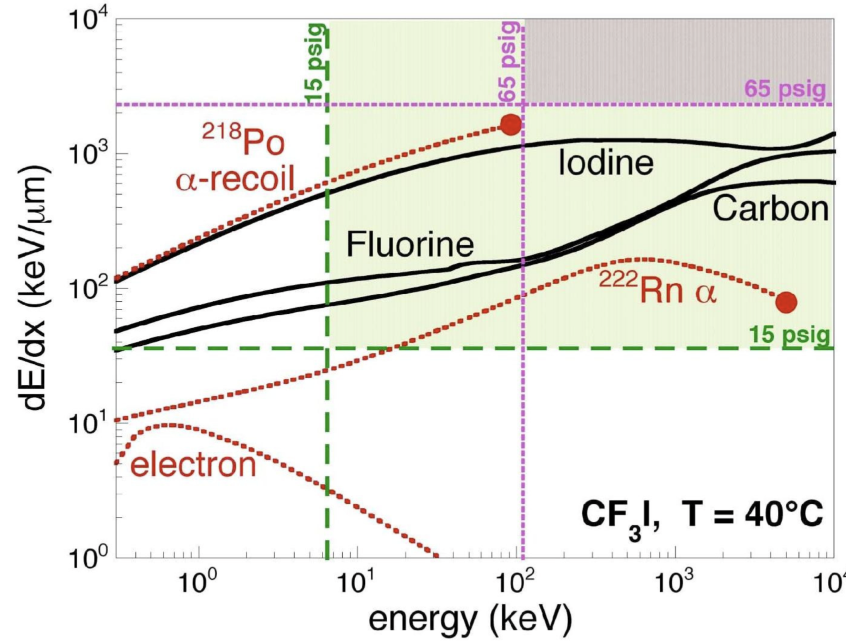



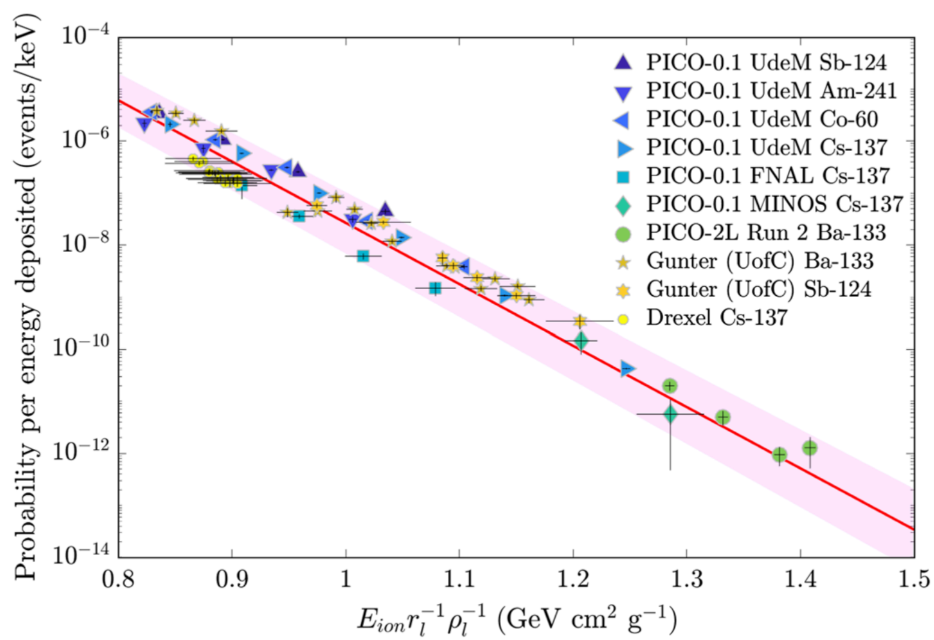
# Bubble nucleation

Dependence of bubble nucleation on the total deposited energy and dE/dx

- Region of bubble nucleation at 15 psig
- Backgrounds: electrons, $^{218}Po$, $^{222}Rn$
- Signal processes of Iodine, Fluorine and Carbon nuclear recoils

insensitive to electrons and gammas



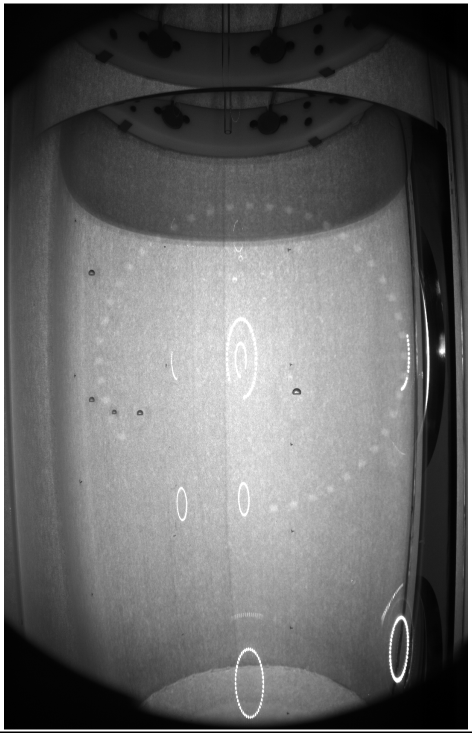



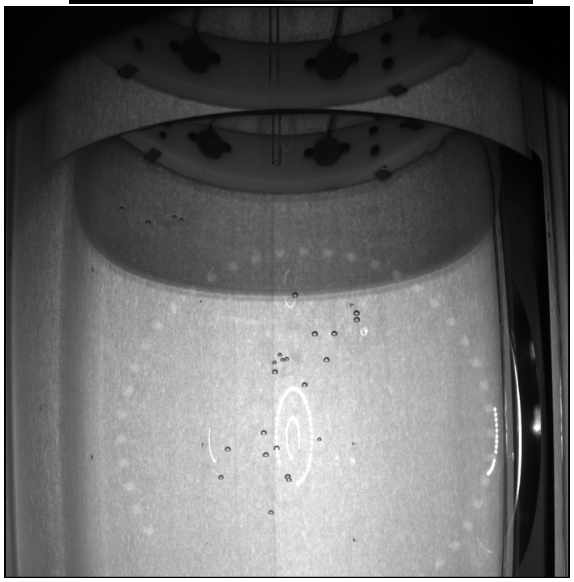
# Bubble chambers: signal

- **Alpha decays:**
  **Nuclear recoil and**
  **40 $\mu$m alpha track**
  **1 bubble**

- **Neutrons:**
  **Nuclear recoils**
  **mean free path $\sim$20 cm**
  **3:1 multiple-single ratio**
  **in PICO-60**

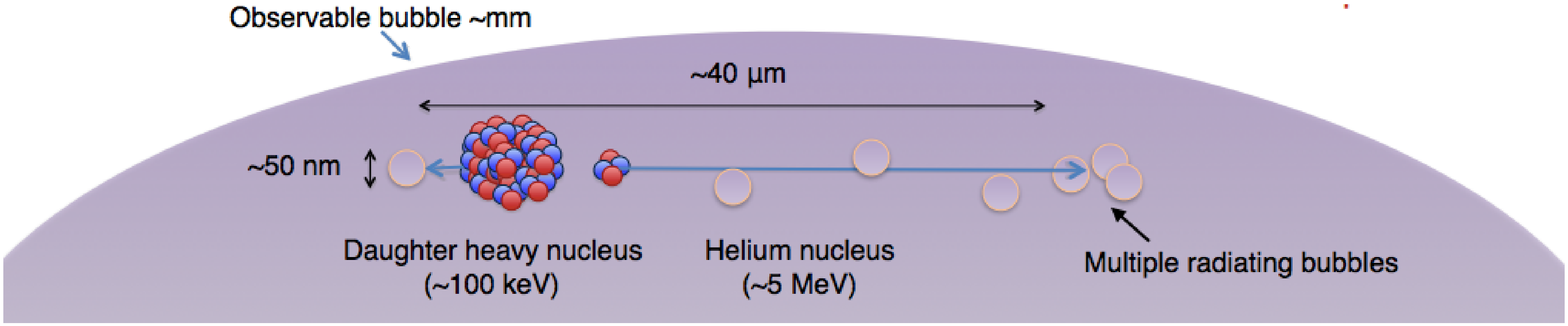
- **Neutrinos or WIMPs:**
  **Nuclear recoil**
  **mean free path $> 10^{10}$ cm**
  **1 bubble**



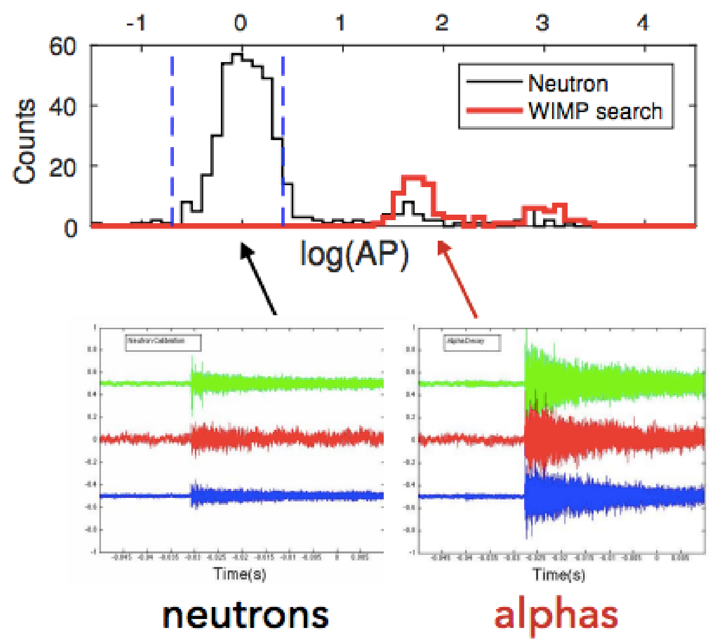


# Bubble chambers: Acoustics

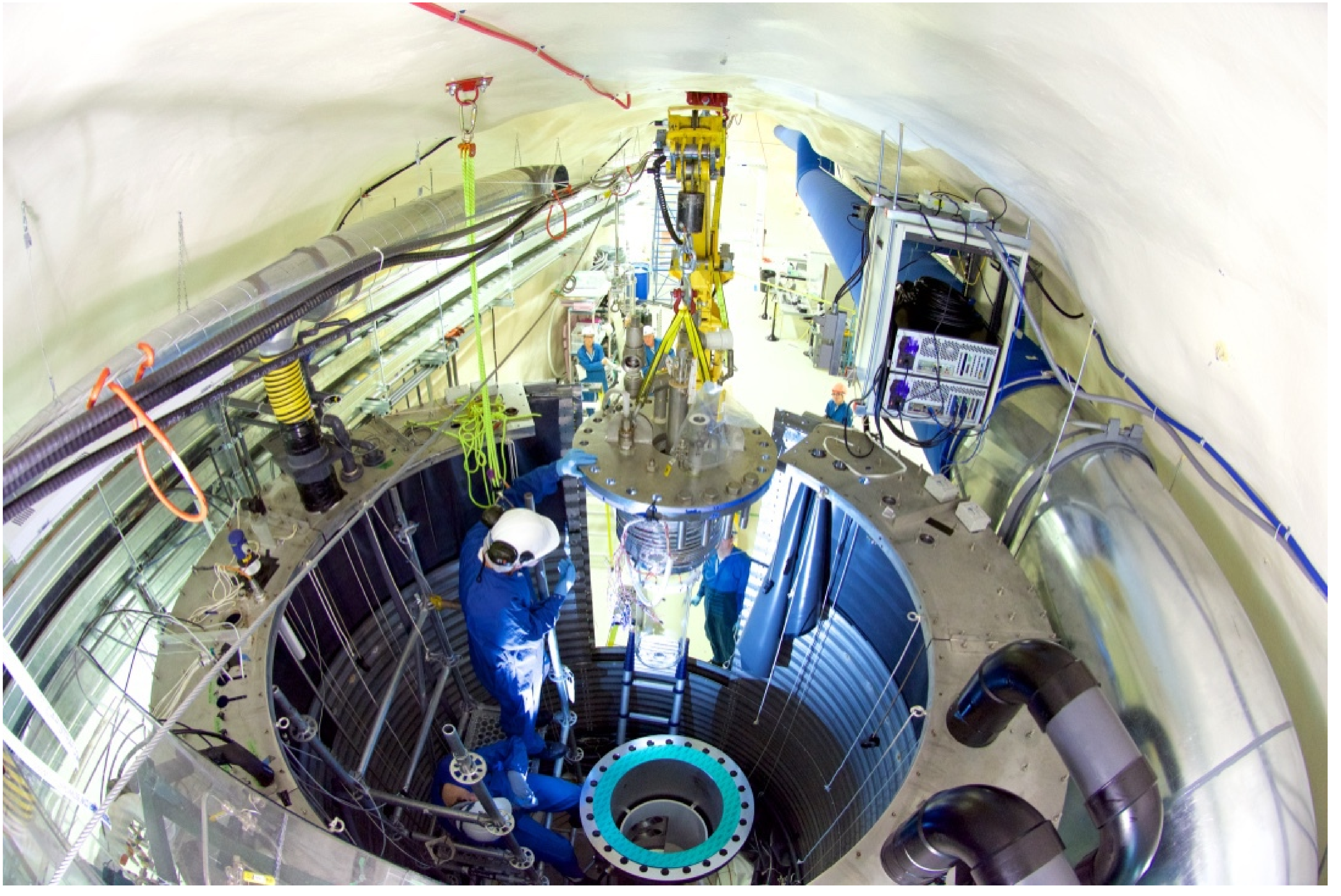
- Alphas are $\sim 4$ times louder than nuclear recoil bubbles




- $>99.4\%$ discrimination against alpha events demonstrated
- Discovered by the PICASSO collaboration



# PICO-60



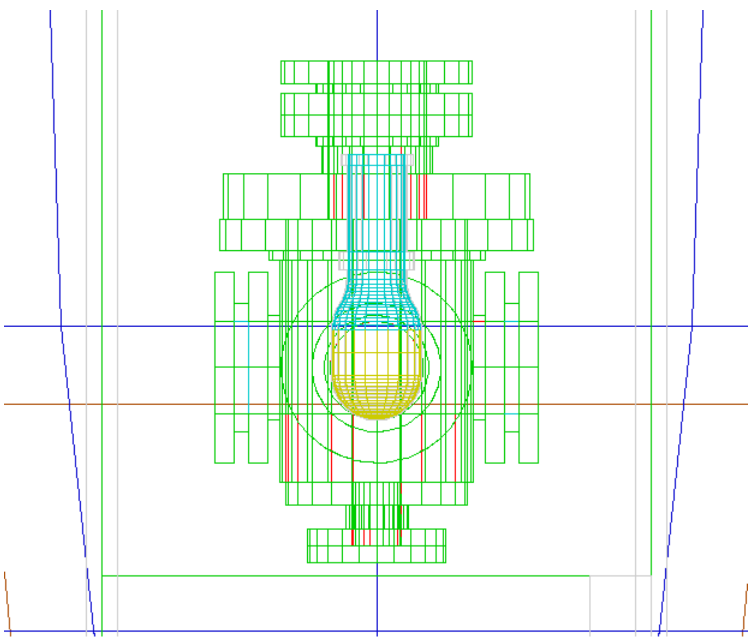
# PICO Collaboration

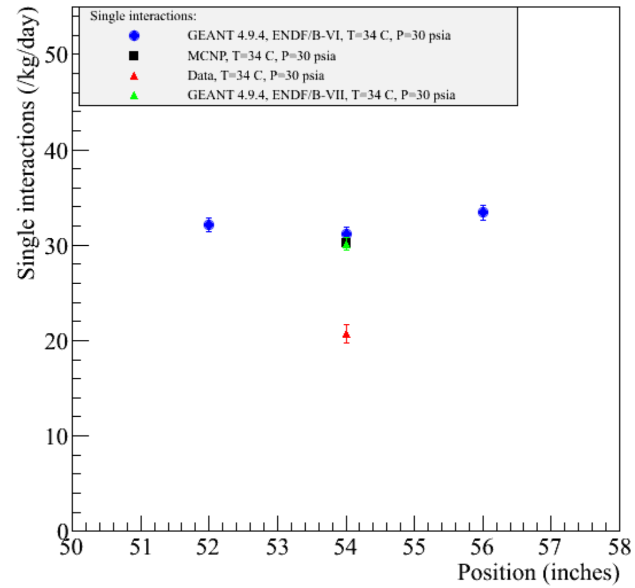
# Monte Carlo simulations for PICO with GEANT4

# Bubble chamber simulations and Seitz model

## GEANT and MCNP simulations: a bit of history

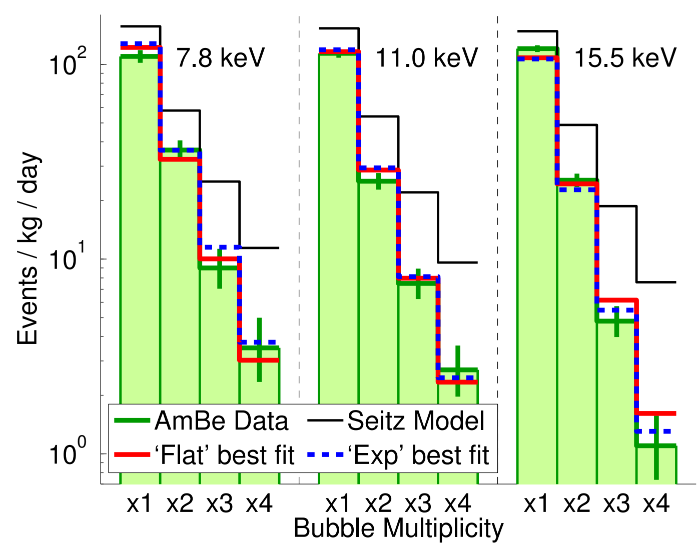
- Compare predicted rates of single and multiple bubble events with observation in COUPP-4kg






Data showed a shortfall of events compared to Seitz model simulation

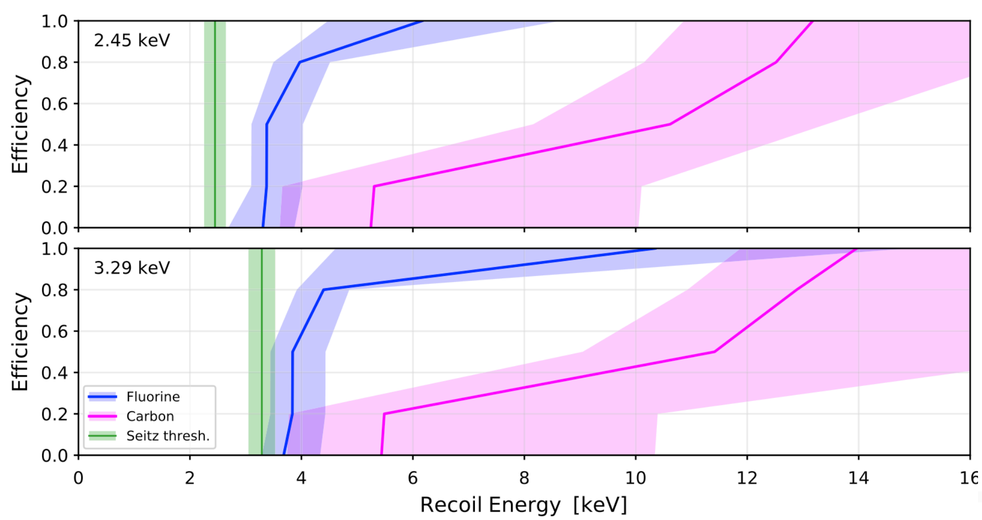
Threshold is determined using Seitz 'Hot Spike' Model Phys. Fluids 1, 2 (1958).

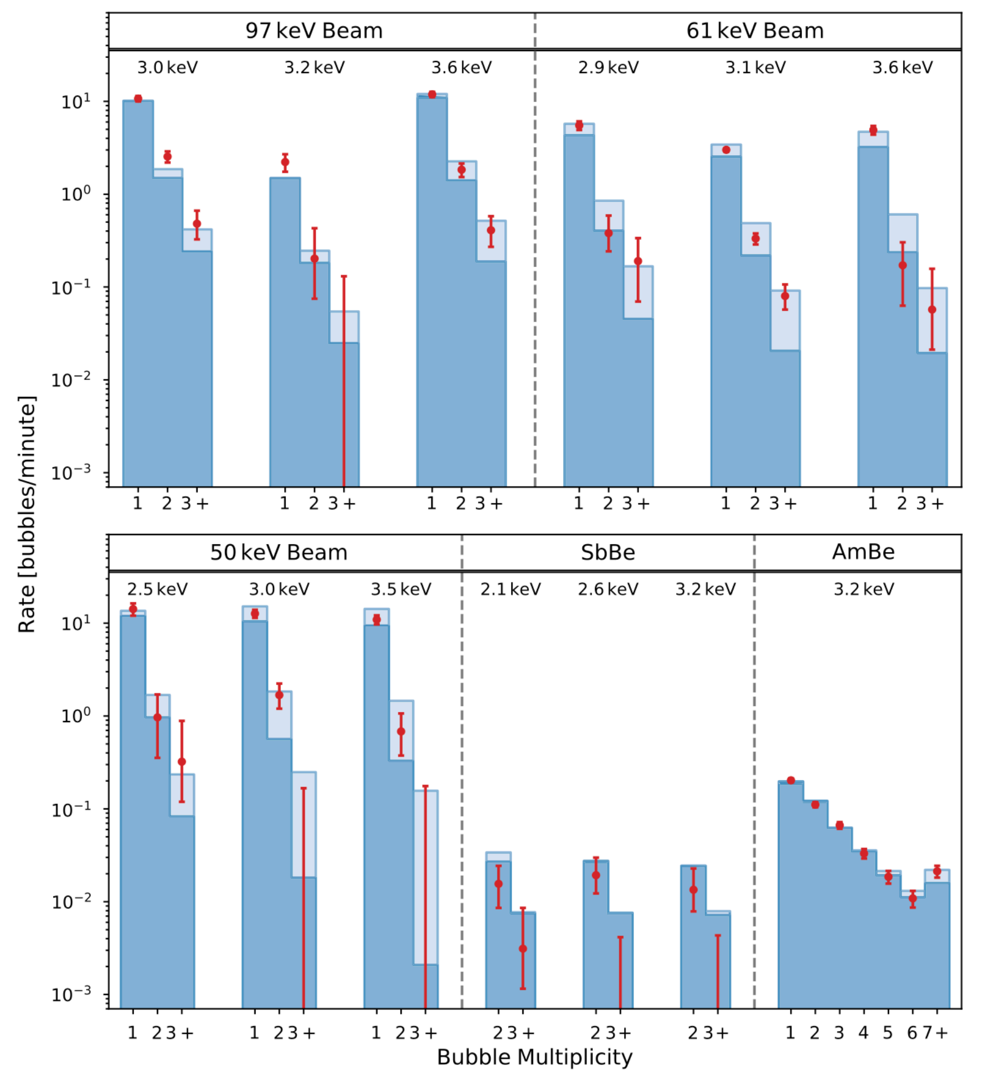


# Bubble nucleation efficiency

**Determining the bubble nucleation efficiency of low-energy nuclear recoils in superheated C3F8 dark matter detectors**
**PRD 106, 122003 (2022)**

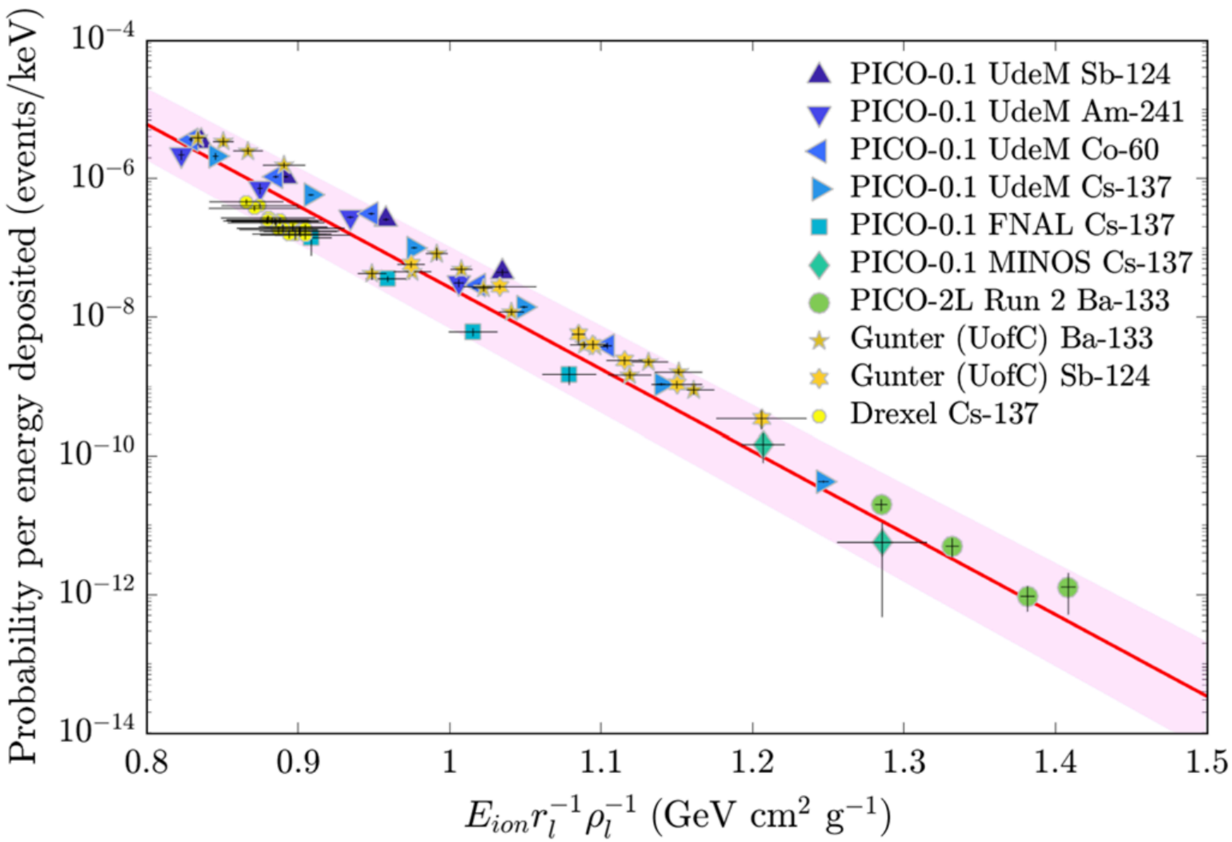
- Neutron beams: 97, 61 , and 50 keV
- SbBe and AmBe sources



## Electron recoil nucleation

- Nucleation model using calibration data
- Probability of nucleation (ER) given by exponential function
- Ionization nucleation model: probability per energy deposited
- Each $\delta$-electron acts as a nucleation trial rather than each photon scattering vertex



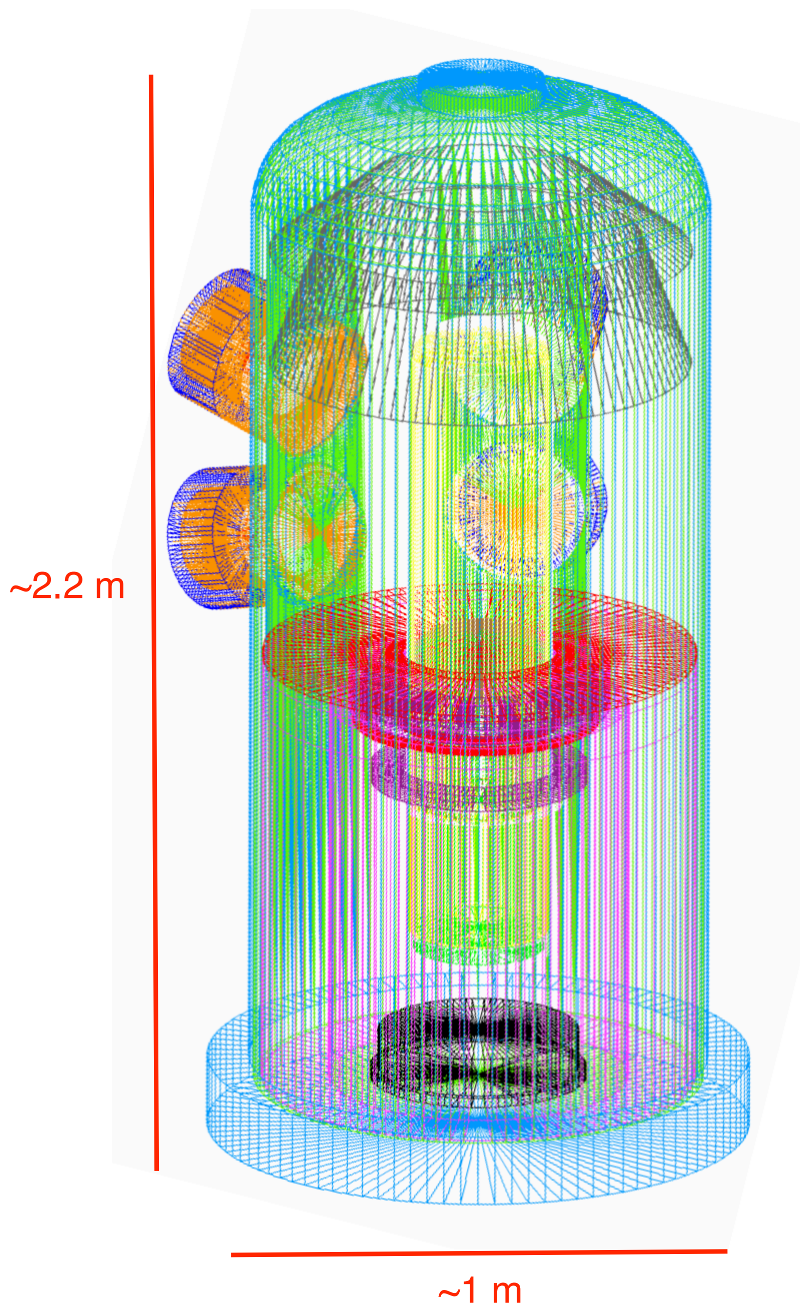

**Data-driven modeling of electron recoil nucleation in PICO $C_3F_8$ bubble chambers PRD 100, 082006 (2019)**

# PICO-40L and PICO-500 simulations

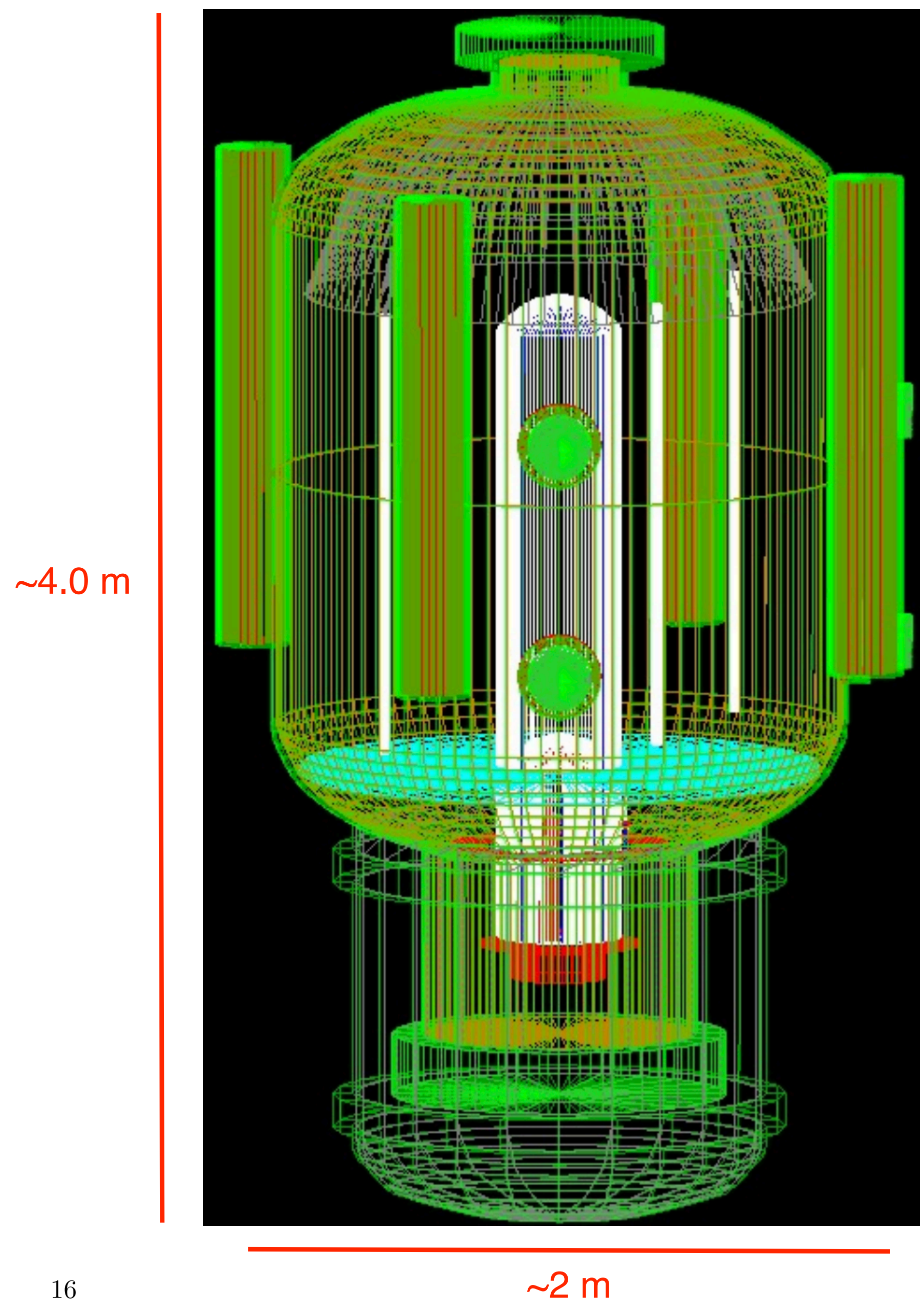
- **External backgrounds (SNOLAB):**
  - **Rock neutrons (SOURCES-4C, propagate through norite rock)**
  - **Muons and muon induced neutrons:**
    - **Muon-induced background study for underground laboratories (D.-M. Mei and A. Hime Phys. Rev. D 73, 053004)**
    - **MUTE: muon fluxes underground, convolution of the muon flux on surface with MCEq and the muon survival probability with the Monte Carlo code PROPOSAL**
  - **($\gamma$,n) reactions**
- **Internal backgrounds:**
  - **U and Th: fission and ($\alpha$,n) on light elements: SOURCES-4C and NeuCBOT (Neutron Calculator Based On TALYS)**
  - **$^{238}$U direct decay**
    - **Materials: stainless steel, quartz, cabling, piezos, cameras, sensors, HDPE, other innner components**
    - **Fluids: water, mineral oil, $CF_3I/C_3F_8$**
    - **Radon (deposition, emanation)**
    - **Mine dust, veto PMTs**

# Detectors in GEANT4 v11.1.3 using Shielding Physics List

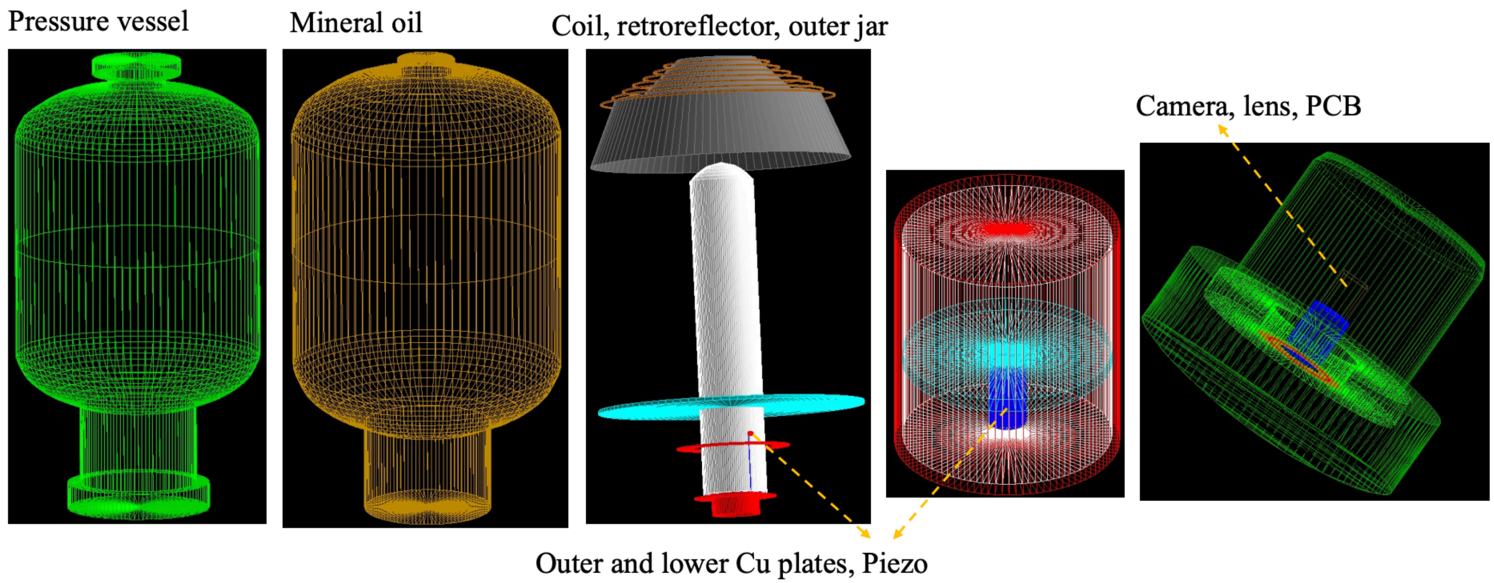
**PICO-40L: $\sim$ 45 kg (fiducial mass)**



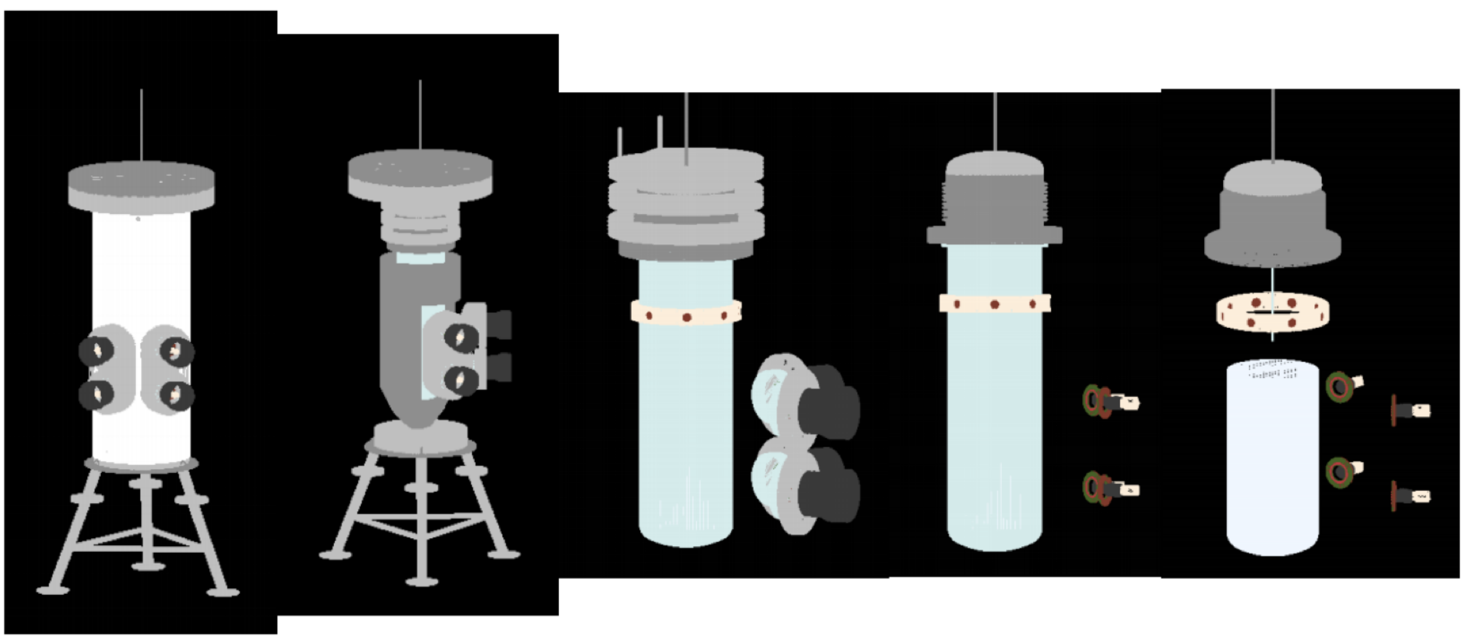

**PICO-500: $\sim$ 350 kg (fiducial mass)**



# Components and former detectors

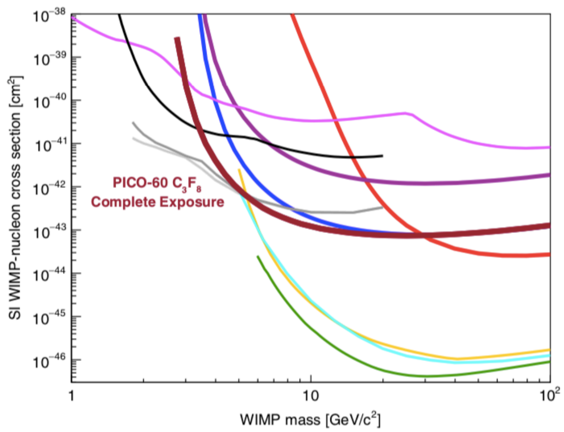



## PICO-60: completed experiment, 52 kg (fiducial mass), 59.9 live days



# Final remarks

- PICO bubble chambers are producing world leading direct detection limits using flourine targets:
  - Best limits for spin-dependent WIMP-proton couplings
  - Challenging nuclear and electron recoil nucleation efficiencies
  - Working GEANT4 framework for background simulations using external software




PICO-2L (thick purple), DarkSide-50 low-mass (gray), XENON1T (green), LUX (yellow), PandaX-II (cyan), CDMSlite (black), and CRESST-II (magenta)

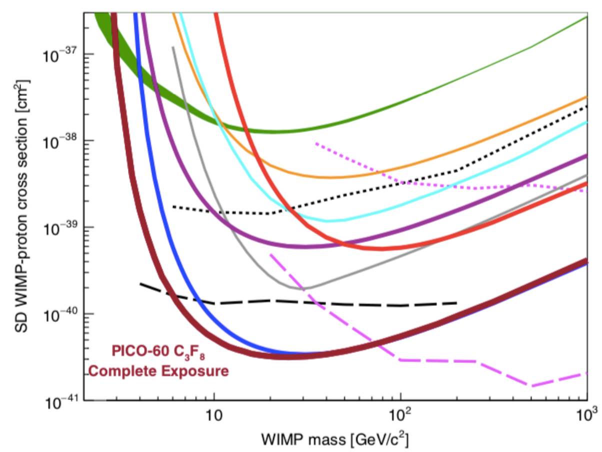
***Phys. Rev. Lett. 114, 231302 (2015)***

***Phys. Rev. D 93, 061101 (R) (2016) (Editor's choice)***

***Phys. Rev. D 93, 052014 (2016)***

***Phys. Rev. Lett. 118, 251301 (2017) (Editor's suggestion)***

***Phys. Rev. D 100, 022001 (2019)***




PICO-60 $CF_3I$ (thick red), PICO-2L (thick purple), PICASSO (green band), SIMPLE (orange), XENON1T (gray), PandaX-II (cyan), IceCube (dashed and dotted pink), and SuperK (dashed and dotted black)