

Monte Carlo simulations for bubble chambers



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Outline

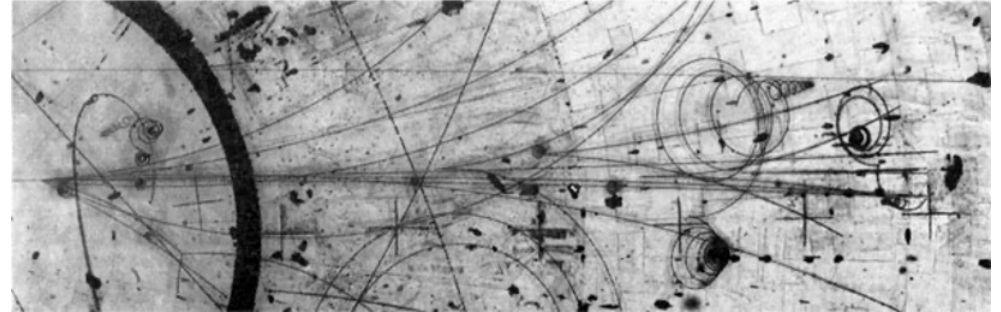
- Experiment overview
- PICO bubble chambers at SNOLAB
- Monte Carlo simulations for PICO with GEANT4
- Final remarks

PICO: dark matter searches using bubble chambers

Physics with bubble chambers

1970s: Neutrino Beam Physics

- Sensitive to MIPs
- Particle tracks visible
- Threshold $\ll 1$ keV
- Multi-ton chambers, multiple fluids



2000-today: Nuclear Recoil Detectors

- Dark matter searches with fluorocarbon bubble chambers
- Electron recoil blind
- Nuclear recoil threshold ~ 3 keV
- Scalable at modest cost

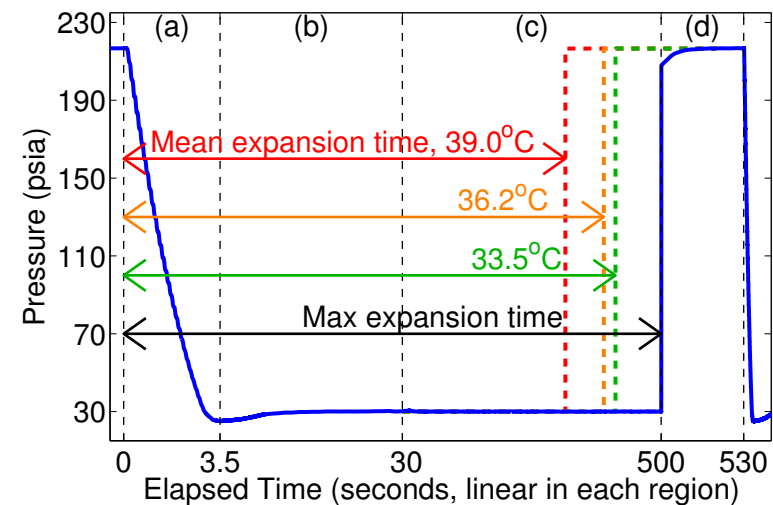
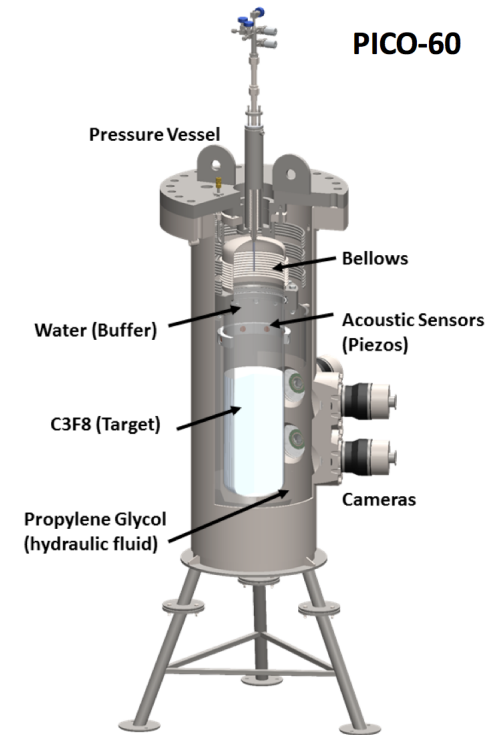


PICO bubble chambers

- 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

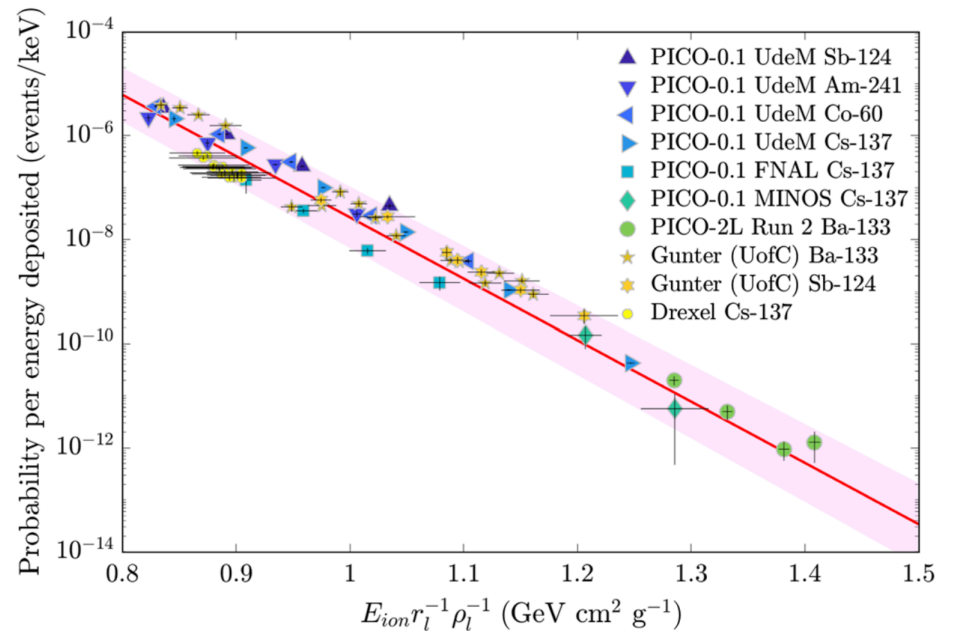
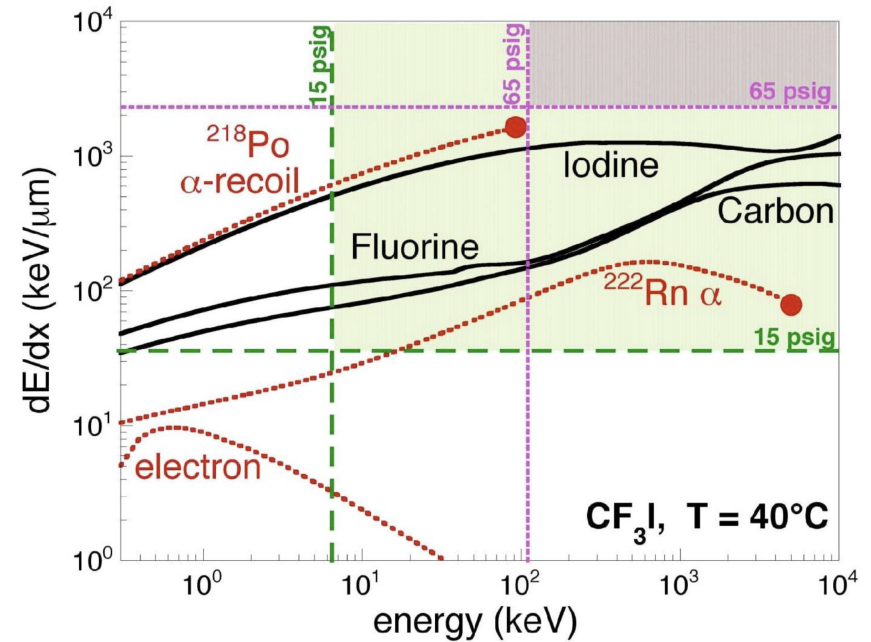


Bubble nucleation

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

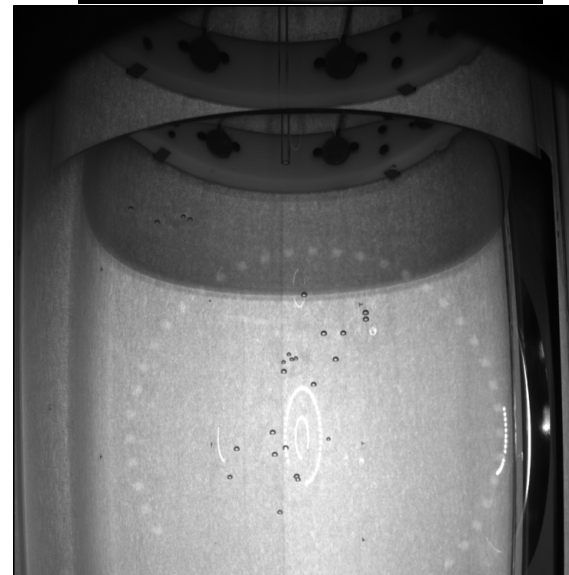
- Region of bubble nucleation at 15 psig
- Backgrounds: electrons, ^{218}Po , ^{222}Rn
- Signal processes of Iodine, Fluorine and Carbon nuclear recoils

insensitive to electrons and gammas



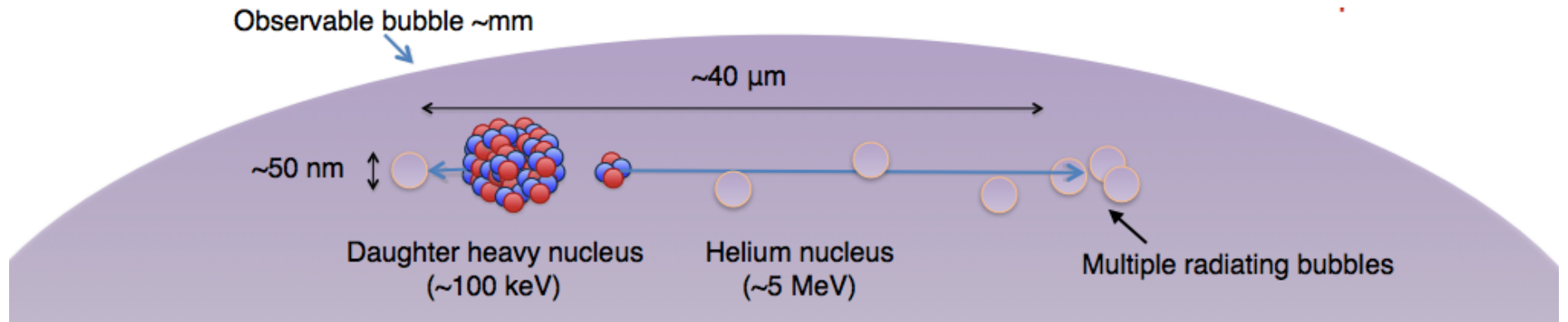
Bubble chambers: signal

- Alpha decays:
Nuclear recoil and
 $40 \mu\text{m}$ alpha track
1 bubble
- Neutrons:
Nuclear recoils
mean free path $\sim 20 \text{ cm}$
3:1 multiple-single ratio
in PICO-60
- Neutrinos or WIMPs:
Nuclear recoil
mean free path $> 10^{10} \text{ cm}$
1 bubble

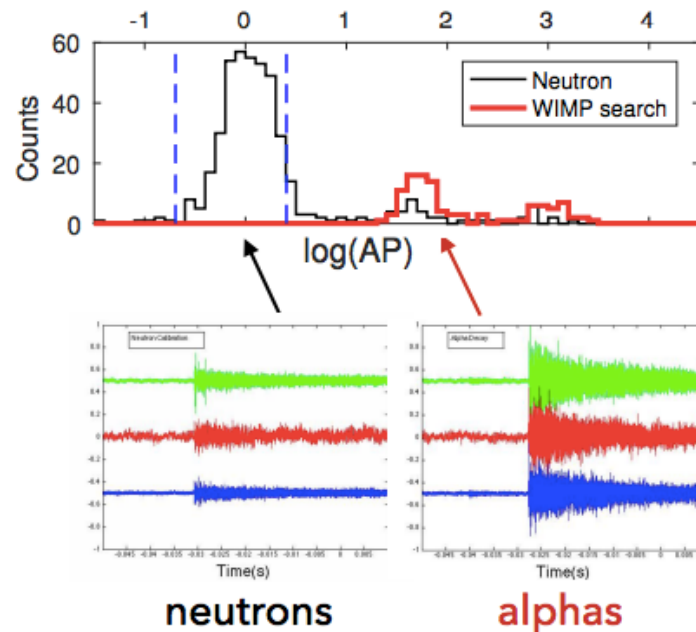


Bubble chambers: Acoustics

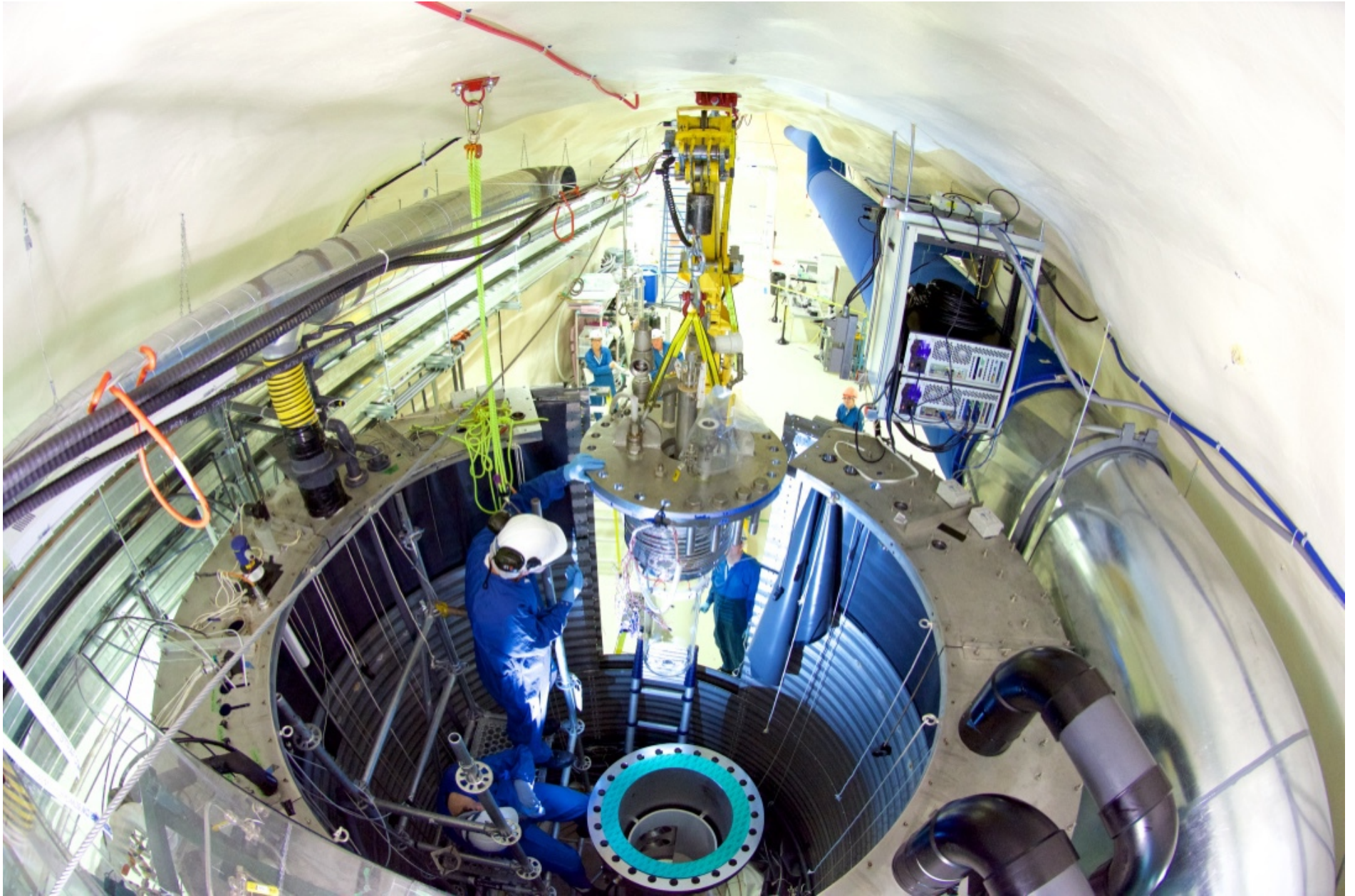
- Alphas are ~ 4 times louder than nuclear recoil bubbles



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



PICO-60



PICO Collaboration



 **NORTHWESTERN UNIVERSITY**
C.E. Dahl, M. Jin, J. Zhang

 **PennState**
S. Priya, Y. Yan

 **ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE**
R. Filgas, I. Stekl

 **UNIVERSITAT POLITÈCNICA DE VALÈNCIA**
M. Ardid, M. Bou-Cabo, I. Felis


 **Drexel UNIVERSITY**
M. Bressler, R. Neilson

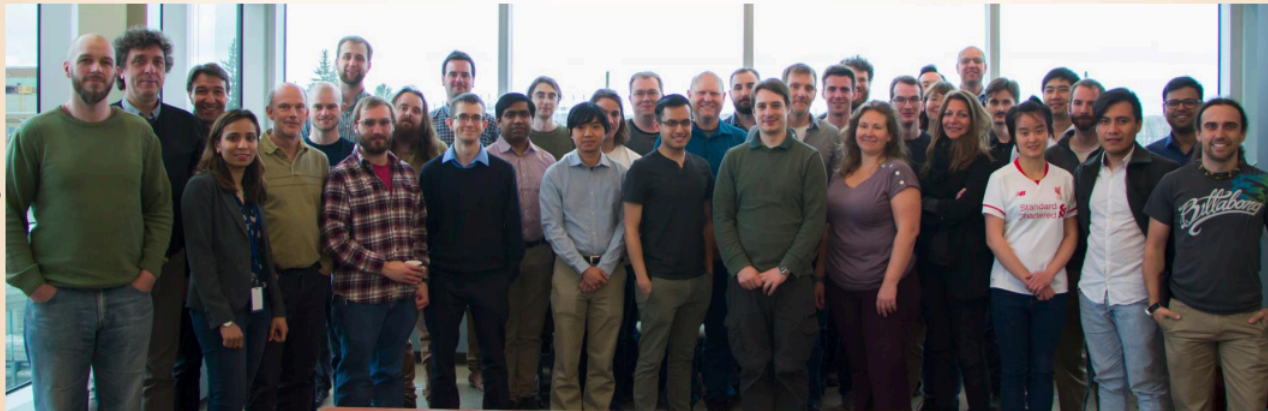
 **IF**
F. Flores, A. Gonzalez, E. Noriega-Benítez, E. Vázquez-Jáuregui


 **SNO+ LAB**
I. Lawson

 **Fermilab**
P.S. Cooper, M. Crisler, W.H. Lippincott, A. Sonnenschein


 **Northeastern UNIVERSITY**
O. Harris

 **Queen's UNIVERSITY**
B. Broerman, G. Cao, K. Clark, G. Giroux, C. Hardy, H. Herrera, C. Moore, A. Noble, T. Sullivan



 **Saha Institute of Nuclear Physics**
S. Ali, M. Das, S. Sahoo

 **KICP**
Kavli Institute for Cosmological Physics at The University of Chicago
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 **UNIVERSITY OF ALBERTA**
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 **INDIANA UNIVERSITY SOUTH BEND**
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 **Université de Montréal**
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 **Pacific Northwest NATIONAL LABORATORY**
I. Arnquist, T. Grimes, B. Hackett, A. Hagen, C.M. Jackson, K. Kadooka, B. Loer

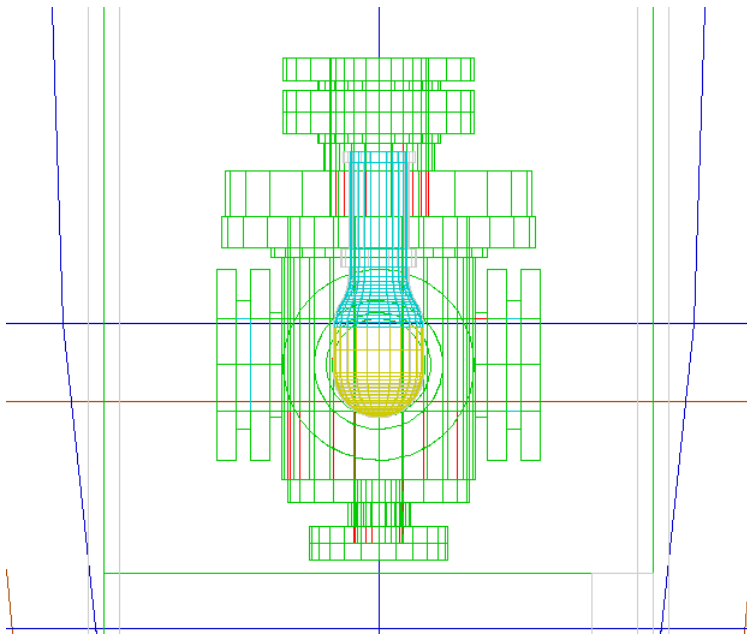
 **Laurentian University Université Laurentienne**
J. Farine, A. Le Blanc, T. Hillier, C. Licciardi, O. Scallon, U. Wichoski

Monte Carlo simulations for PICO with GEANT4

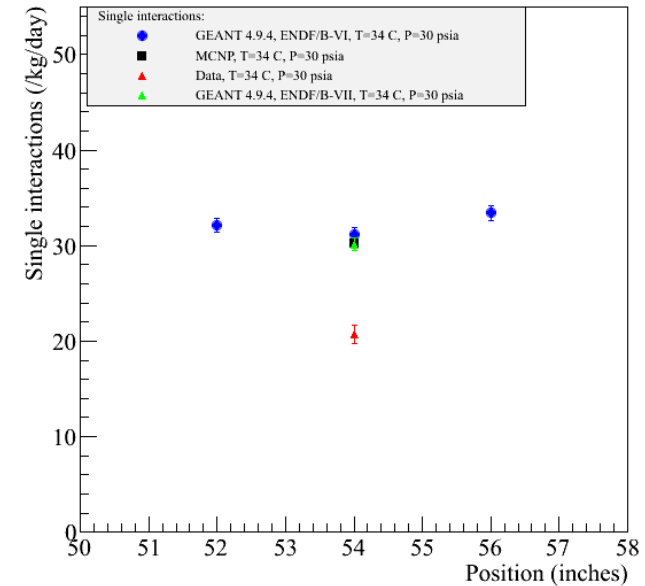
Bubble chamber simulations and Seitz model

GEANT and MCNP simulations: a bit of history

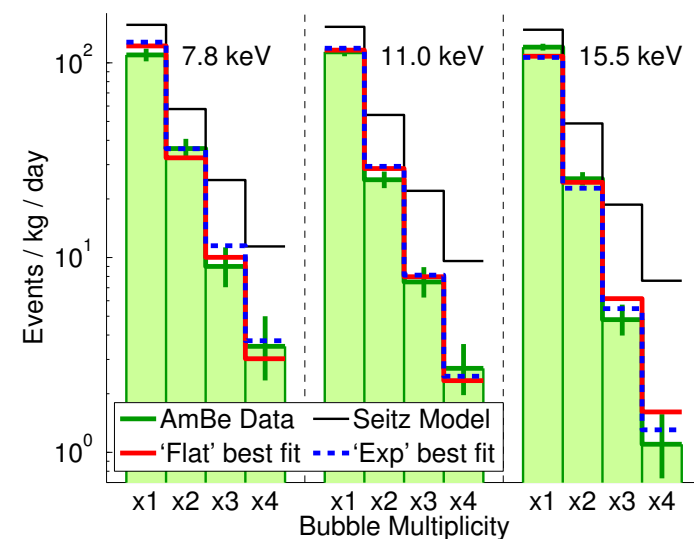
- Compare predicted rates of single and multiple bubble events with observation in COUPP-4kg



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



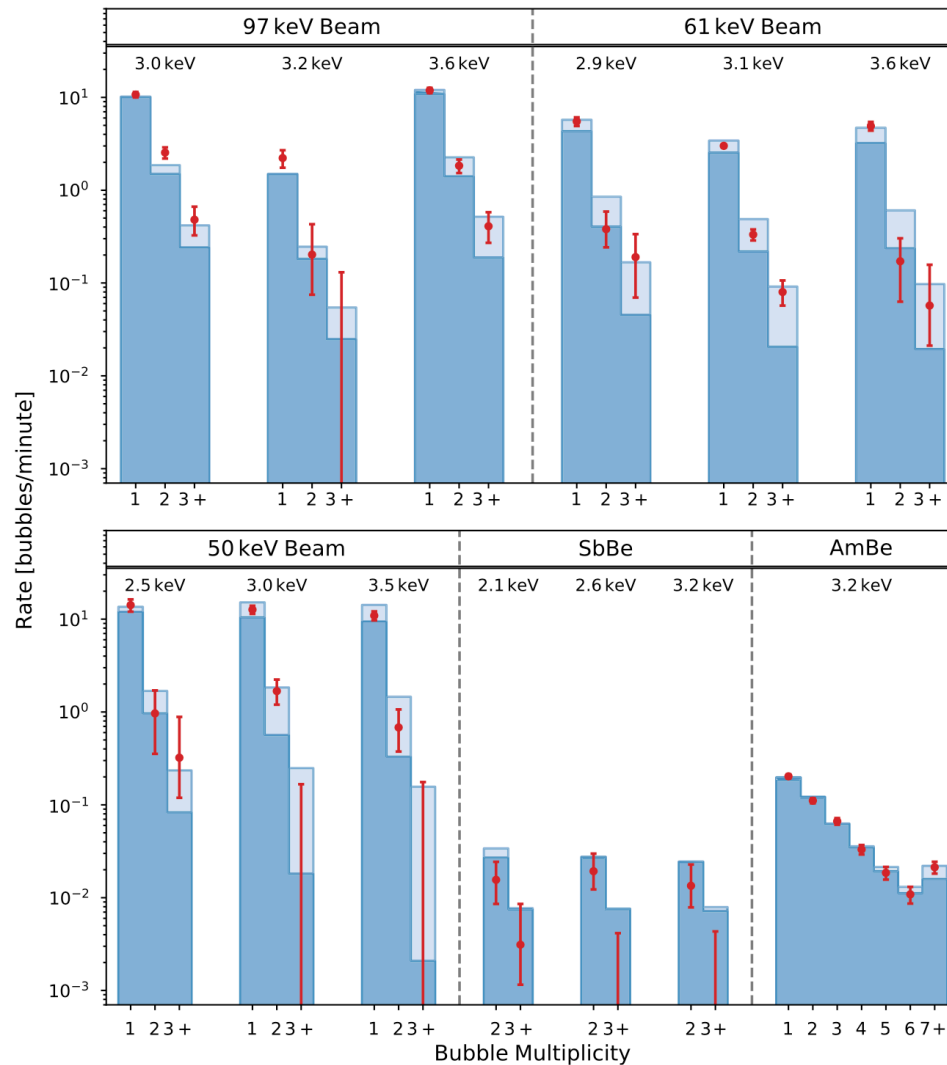
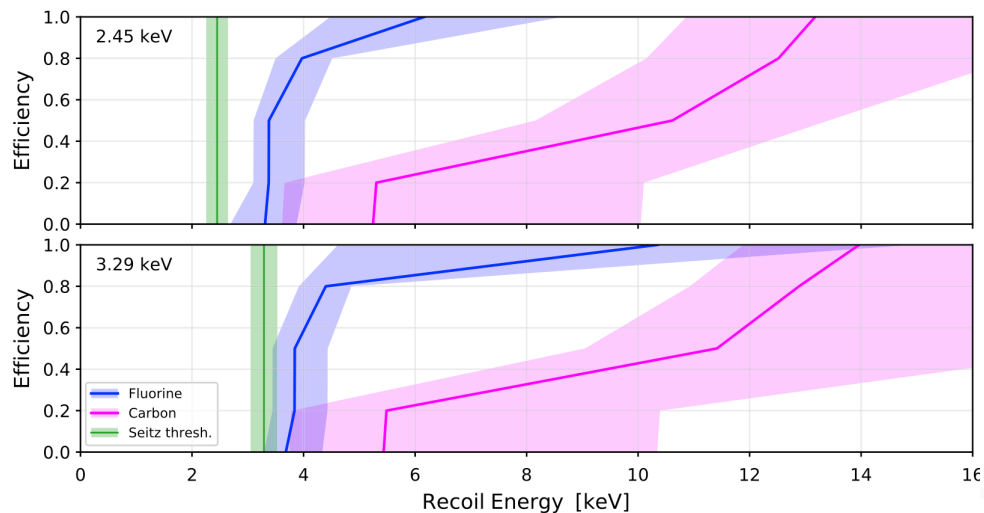
Data showed a shortfall of events compared to Seitz model simulation



Bubble nucleation efficiency

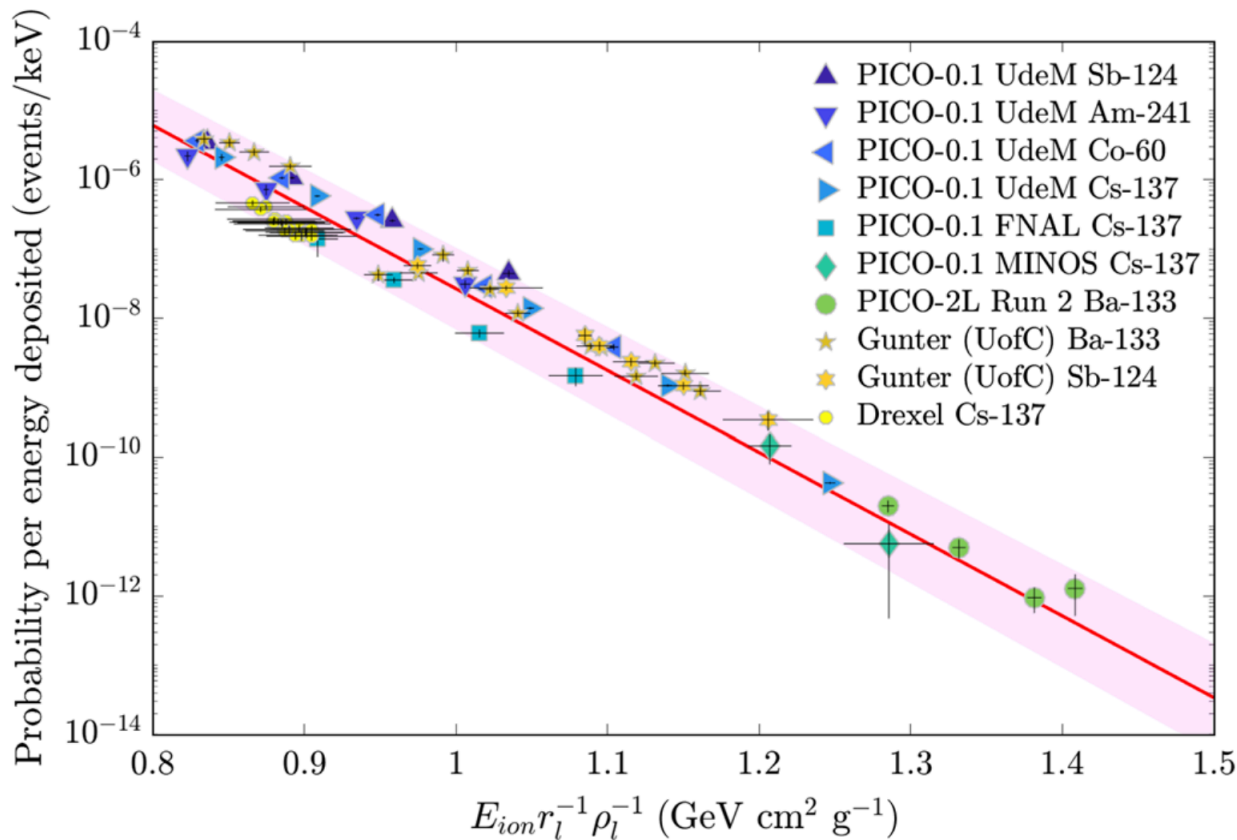
Determining the bubble nucleation efficiency of low-energy nuclear recoils in superheated C3F8 dark matter detectors
 PRD 106, 122003 (2022)

- 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 δ -electron acts as a nucleation trial rather than each photon scattering vertex



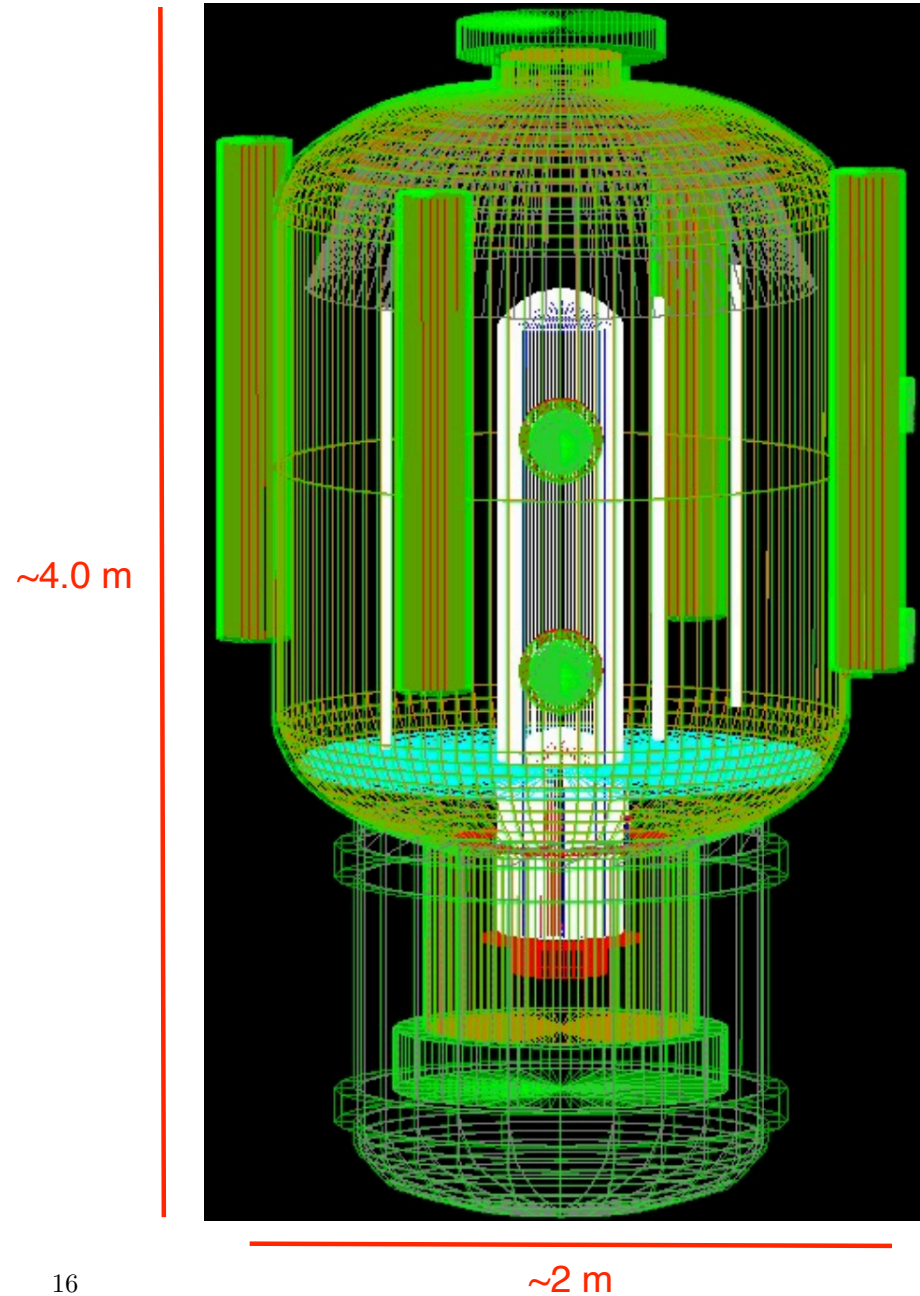
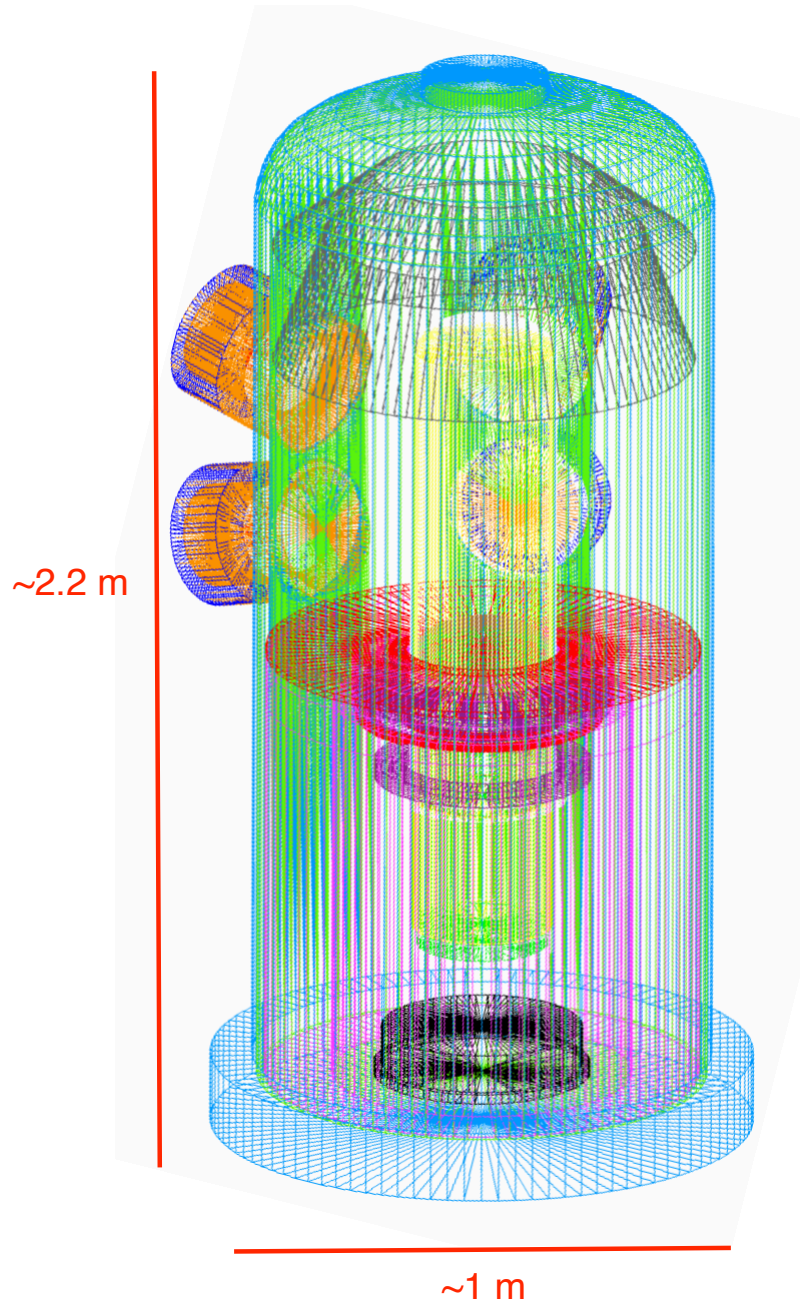
Data-driven modeling
of electron recoil
nucleation in PICO
 C_3F_8 bubble chambers
PRD 100, 082006 (2019)

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
 - (γ, n) reactions
- Internal backgrounds:
 - U and Th: fission and (α, 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 inner components
 - * Fluids: water, mineral oil, $\text{CF}_3\text{I}/\text{C}_3\text{F}_8$
 - * Radon (deposition, emanation)
 - * Mine dust, veto PMTs

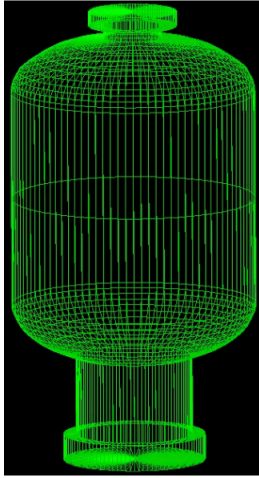
Detectors in GEANT4 v11.1.3 using Shielding Physics List

PICO-40L: ~ 45 kg (fiducial mass) PICO-500: ~ 350 kg (fiducial mass)

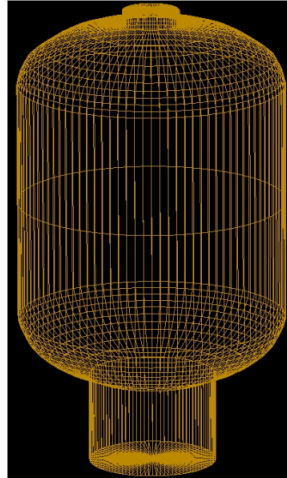


Components and former detectors

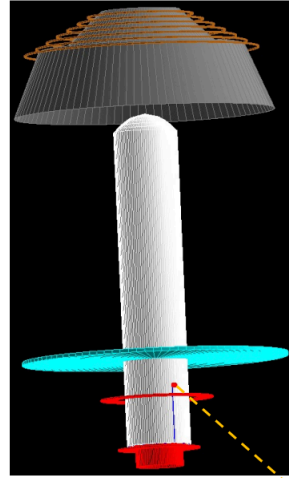
Pressure vessel



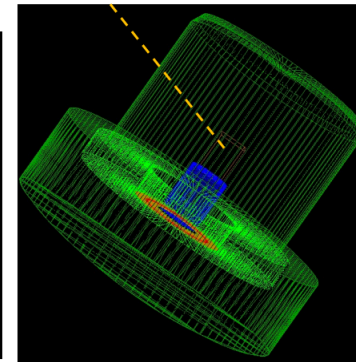
Mineral oil



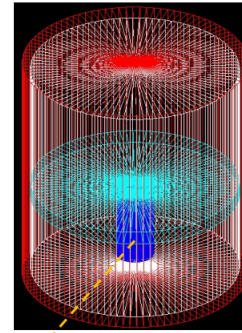
Coil, retroreflector, outer jar



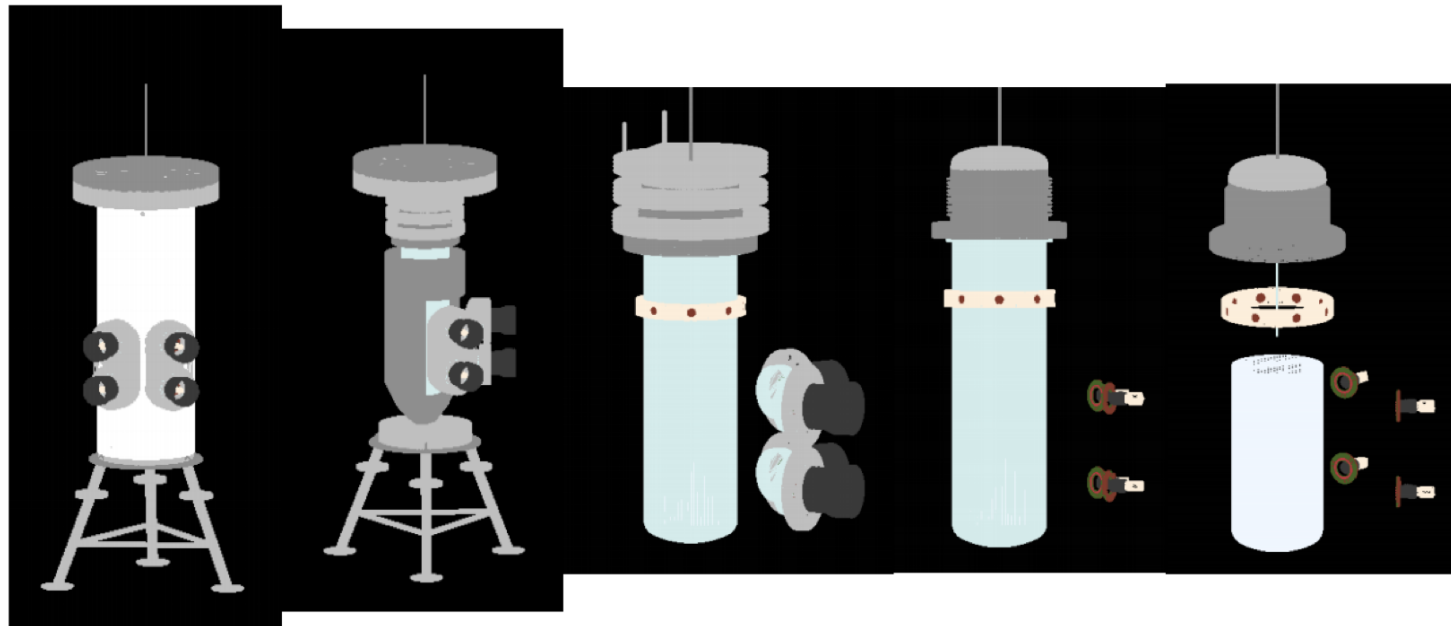
Camera, lens, PCB



Outer and lower Cu plates, Piezo

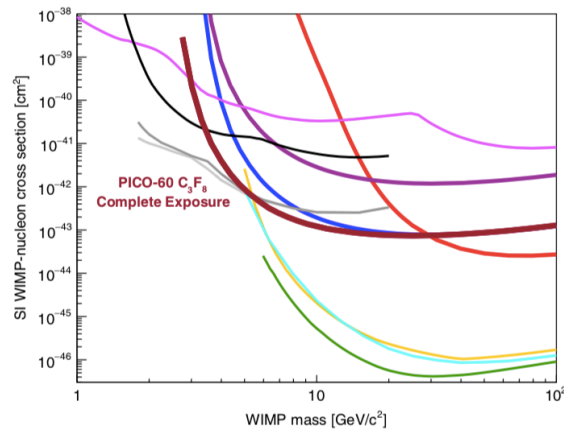


PICO-60: completed experiment, 52 kg (fiducial mass), 59.9 live days



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)

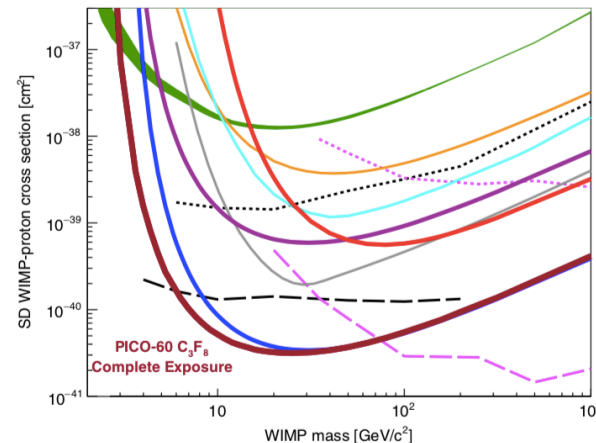
Phys. Rev. Lett. **114**, 231302 (2015)

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 CF₃I (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)