Coherent Elastic Neutrino-Nucleus Scattering in Reactors Using a Liquid Argon Scintillating Bubble Chamber

Eric Vázquez Jáuregui

Instituto de Física, UNAM

Precision Tests with Neutral-Current Coherent Interactions with Nuclei
Mainz, Germany, May 27th, 2022

Outline

- **Bubble chambers**

- **SBC: A 10 kg LAr bubble chamber for dark matter and CEνNS**

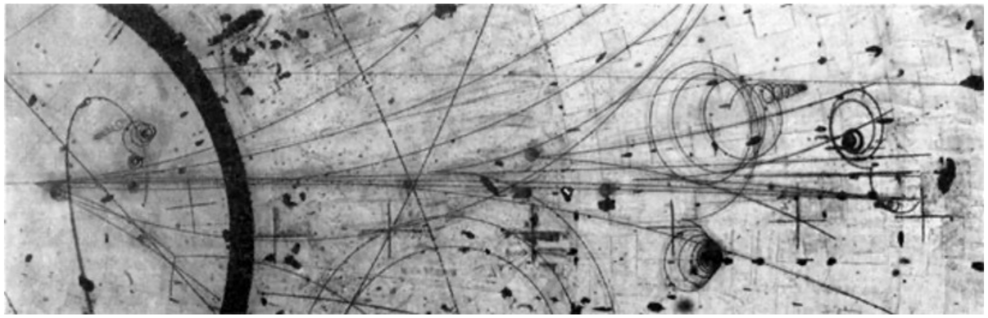
- **Physics reach for reactor neutrinos**

- **Final remarks**

Physics with bubble chambers

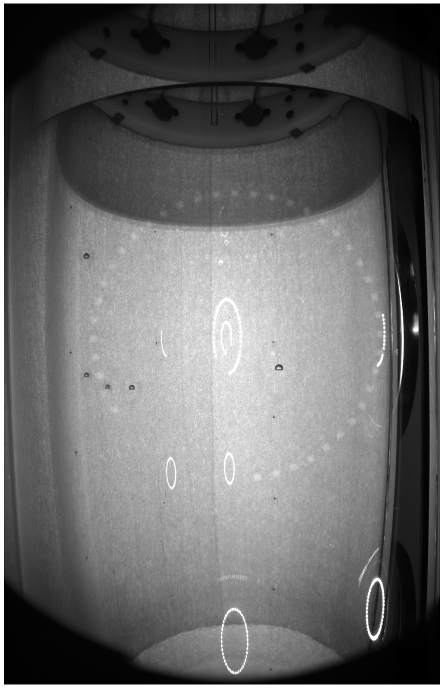
1970s: Neutrino Beam Physics

- 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

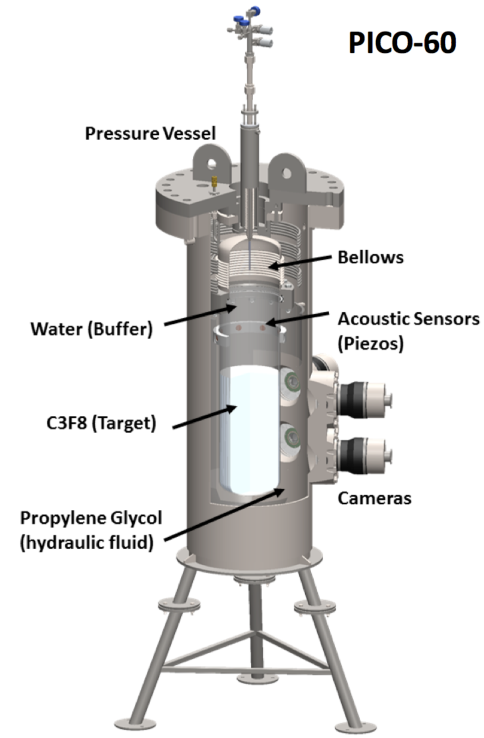


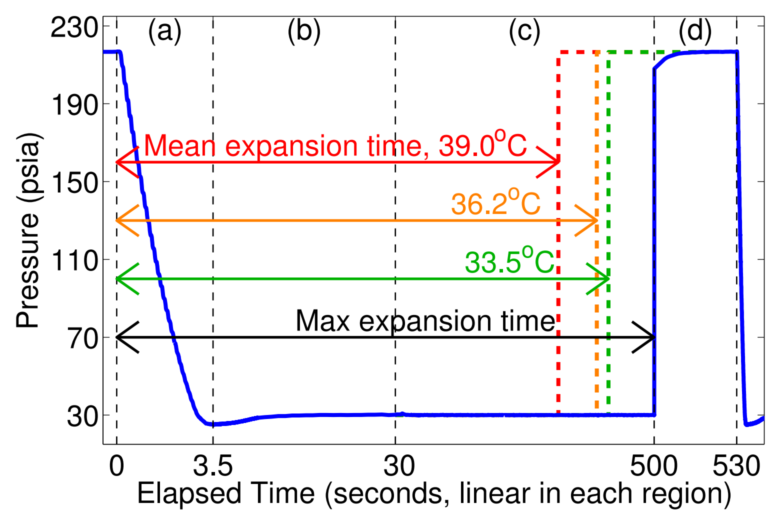
PICO bubble chambers

- 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



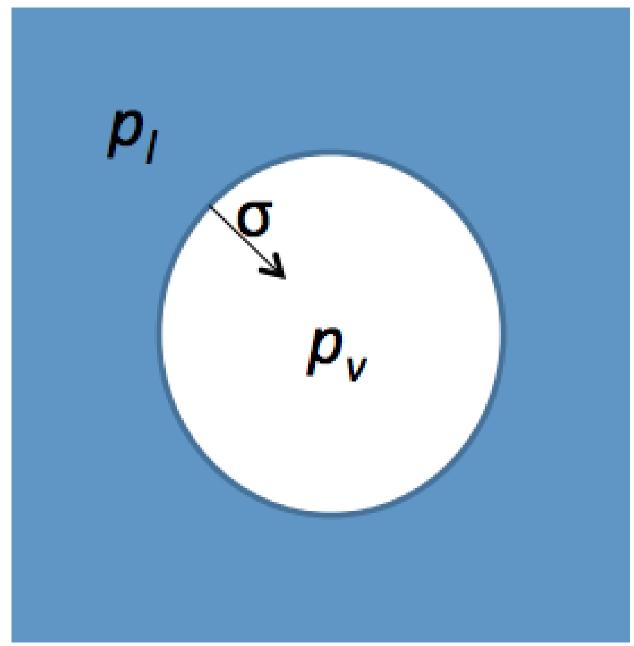


Bubble chambers: Physics

- **In a superheated fluid, energy deposition greater than E_{th} in a radius less than r_c will result in a bubble large enough to overcome surface tension (Seitz "Hot-Spike" Model)**
- **Low E or dE/dx result in smaller bubbles that immediately collapse**
- **Classical Thermodynamics:**

$$p_v - p_l = \frac{2\sigma}{r_c}$$

$$E_{th} = \underbrace{4\pi r_c^2 \left(\sigma - T\frac{\partial \sigma}{\partial T}\right)}_{\text{Surface energy}} + \underbrace{\frac{4}{3}\pi r_c^3 \rho_v h}_{\text{Latent heat}}$$

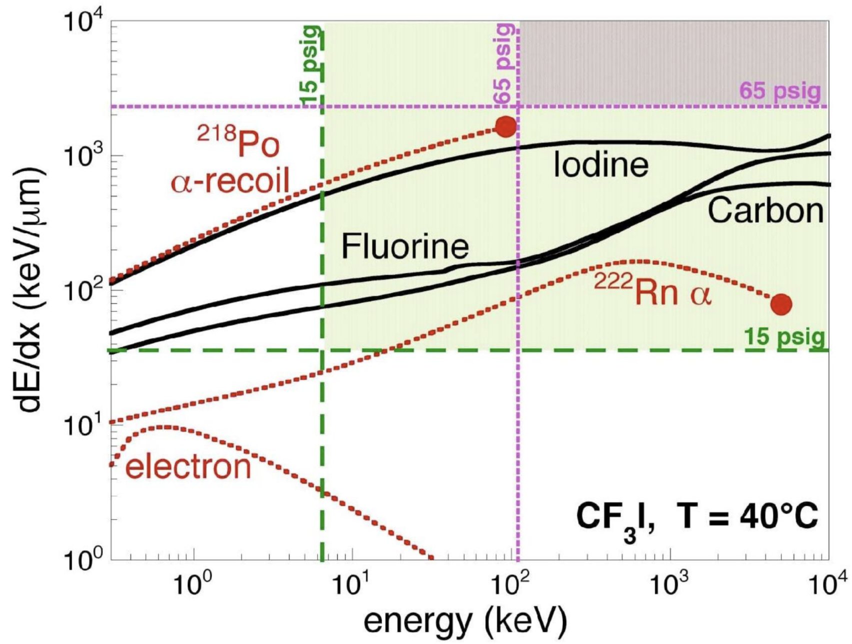


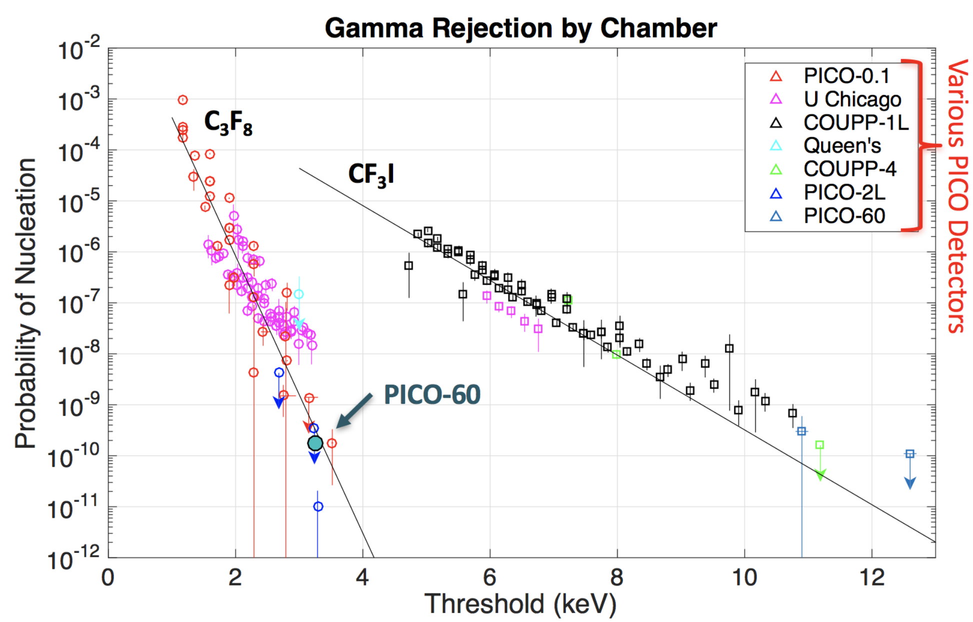
Bubble nucleation

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



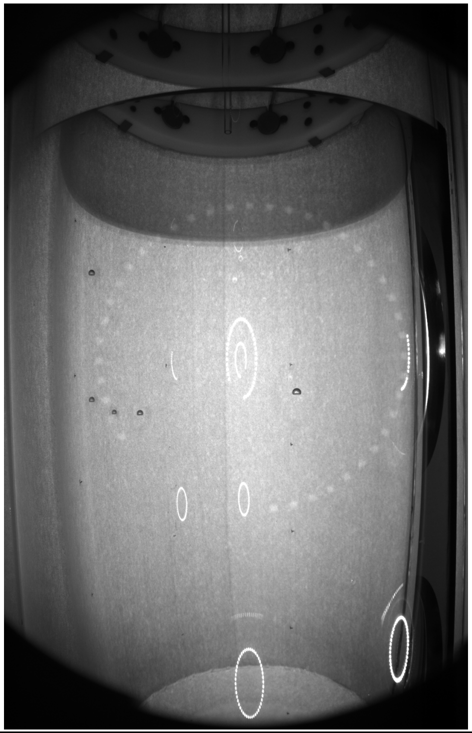


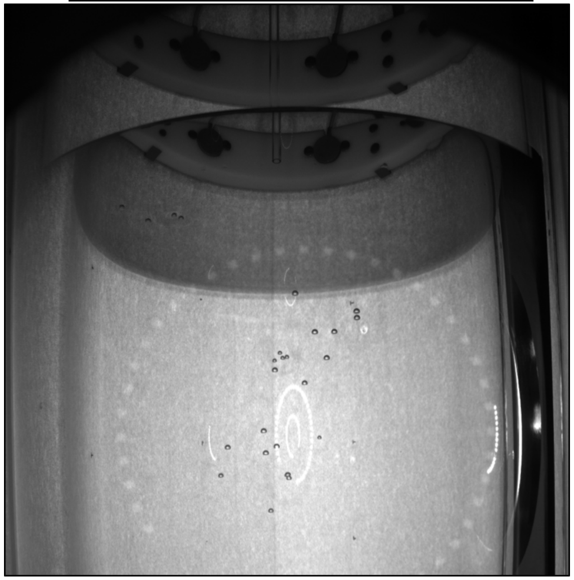
Bubble chambers: signal

- **Alpha decays:**
  Nuclear recoil and
  40 μm alpha track
  1 bubble

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

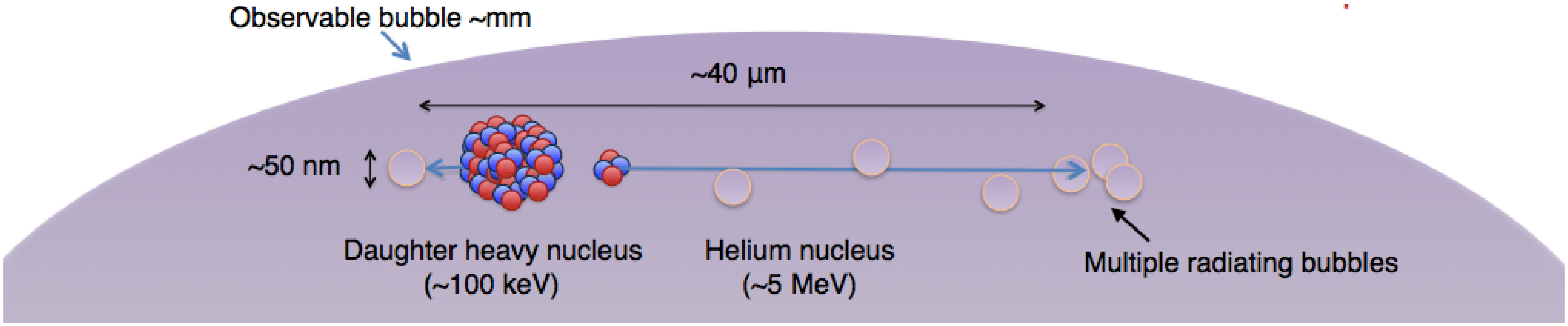
- **Neutrinos or WIMPs:**
  Nuclear recoil
  mean free path > 10^{10} cm
  1 bubble



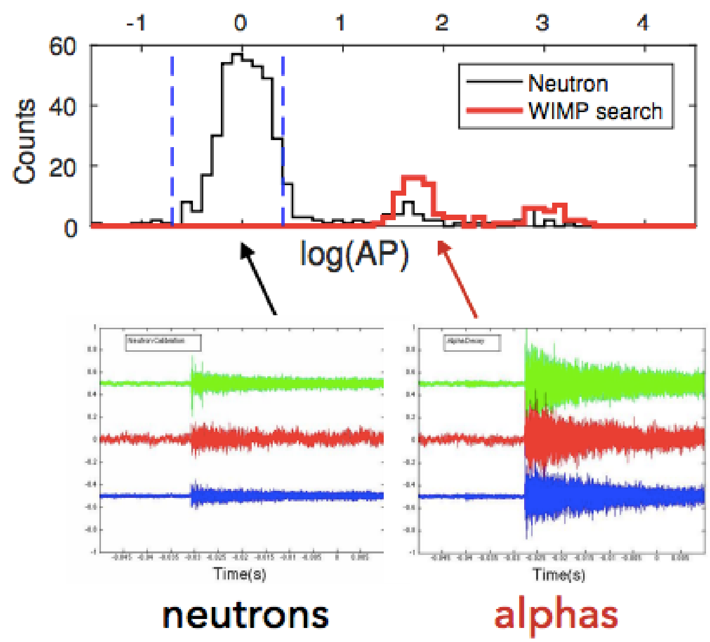


Bubble chambers: Acoustics

- Alphas are ~ 4 times louder than nuclear recoil bubbles



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

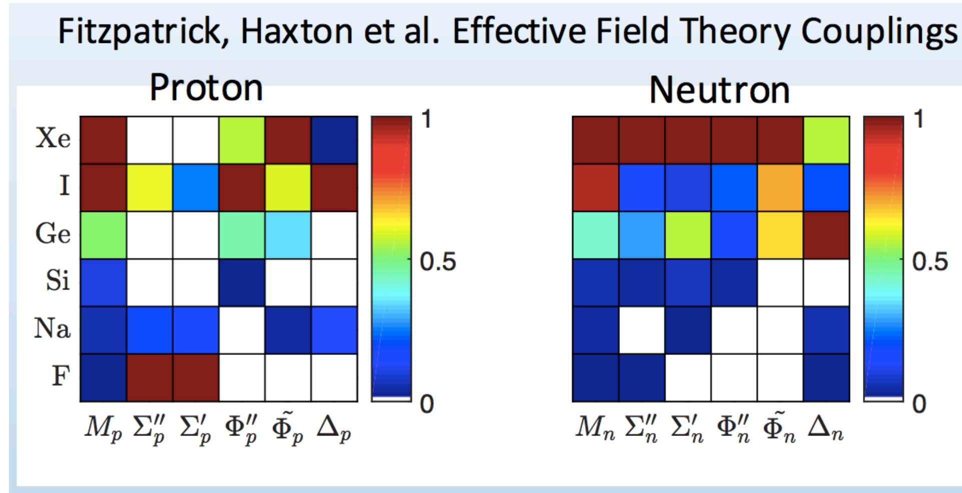


Why bubble chambers?

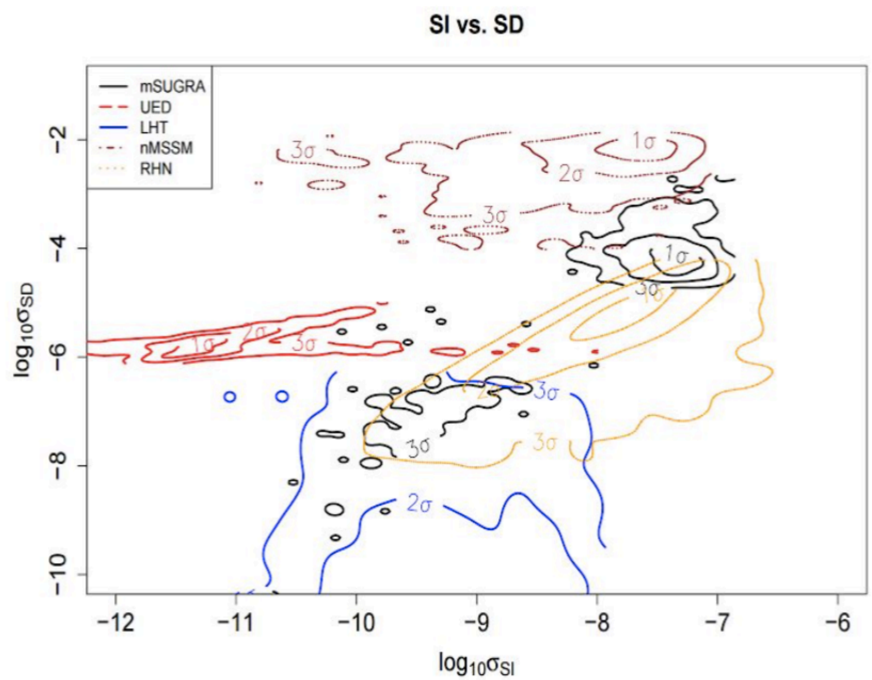
- **Zero background**
- **Large target mass**
- **Low energy threshold (a few keV, and down to eV for some fluids)**
- **Multiple target nuclei**
  test expected cross section dependences on
  atomic number and nuclear spin
  (Fluorine, Iodine, Chlorine, Xenon, Argon, Bromine, Hydrogen...)
- **Measure nuclear recoil energies (by varying threshold)**
- **No measure of nuclear recoil direction.**

EFT and SI vs SD

Capability to instrument a wide range of target nuclei with sensitivity to diverse WIMP-nucleon couplings. Unknown how WIMPs couple to matter



- Fluorine: Best sensitivity to spin dependent interactions.
- Iodine, Bromine, Xenon, Argon: High A targets to exploit A^2 dependence of spin-independent cross section.
- Hydrogen: Enhanced sensitivity to low mass particles.



V. Barger, W-Y Keung and G. Shaughnessy, Phys. Rev. D78 (2008) 056007

SBC Collaboration

Northwestern University

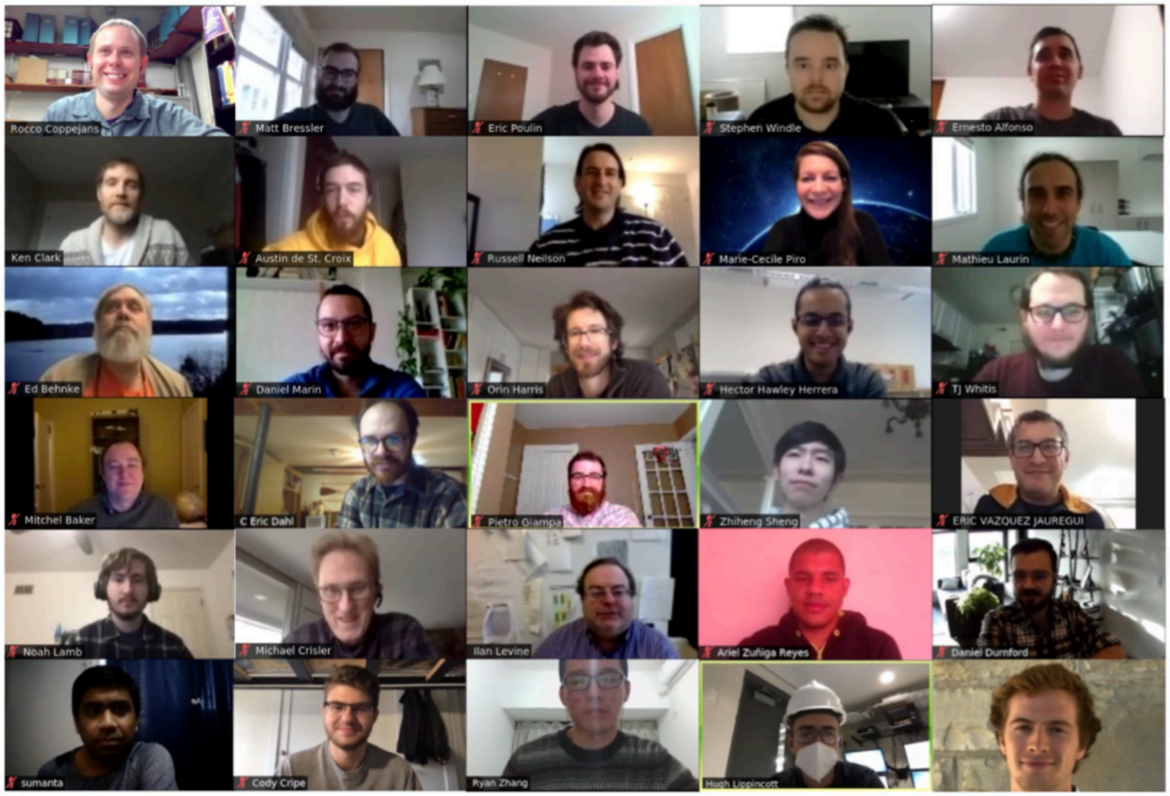
- **Eric Dahl**
- Rocco Coppejans
- Zhiheng Sheng
- Aaron Brandon
- David Velasco
- Ari Sloss
- Mahebub Khatri
- Dishen Wang
- Shishir Bandapalli

Queen's University

- **Ken Clark**
- Hector Hawley
- Patrick Hatch
- Austin De St Croix

University of Alberta

- Marie-Cécile Piro
- Carsten Krauss
- Daniel Durnford
- Sumanta Pal
- Youngtak Ko
- Mitchel Baker



Universidad Nacional Autónoma de México

- Eric Vázquez-Jáuregui
- Ernesto Alfonso-Pita
- Ariel Zuniga-Reyes
- Daniel Lámbarri

Drexel University

- Russell Neilson
- Matt Bressler
- Noah Lamb
- Stephen Windle

Indiana University South Bend

- Ilan Levine
- Ed Behnke
- Cody Cripe

UC Santa Barbara

- Hugh Lippincott
- TJ Whitis
- Runze Zhang

SNOLAB

- Pietro Giampa
- Eric Poulin

Université de Montréal

- Mathieu Laurin

Northeastern Illinois University

- Orin Harris

Pacific Northwest National Laboratory

- Chris Jackson

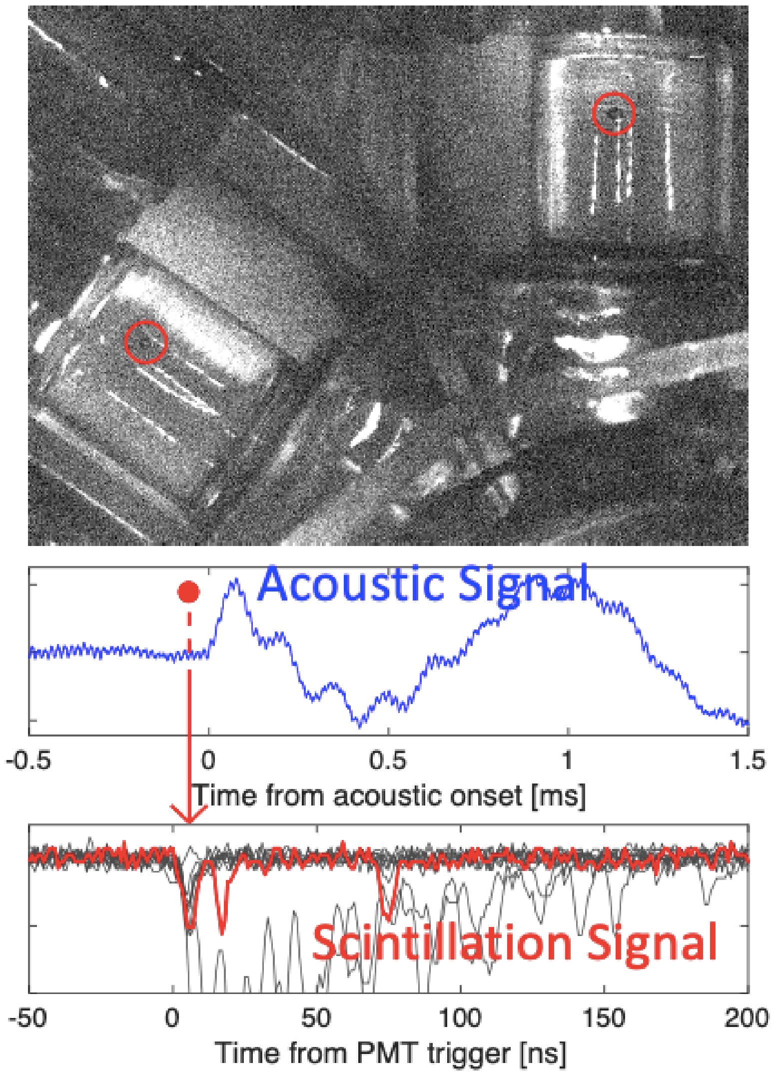
Fermilab

- Mike Crisler

First demonstration of SBC

Phys Rev Lett 118, 231301

A nuclear recoil:



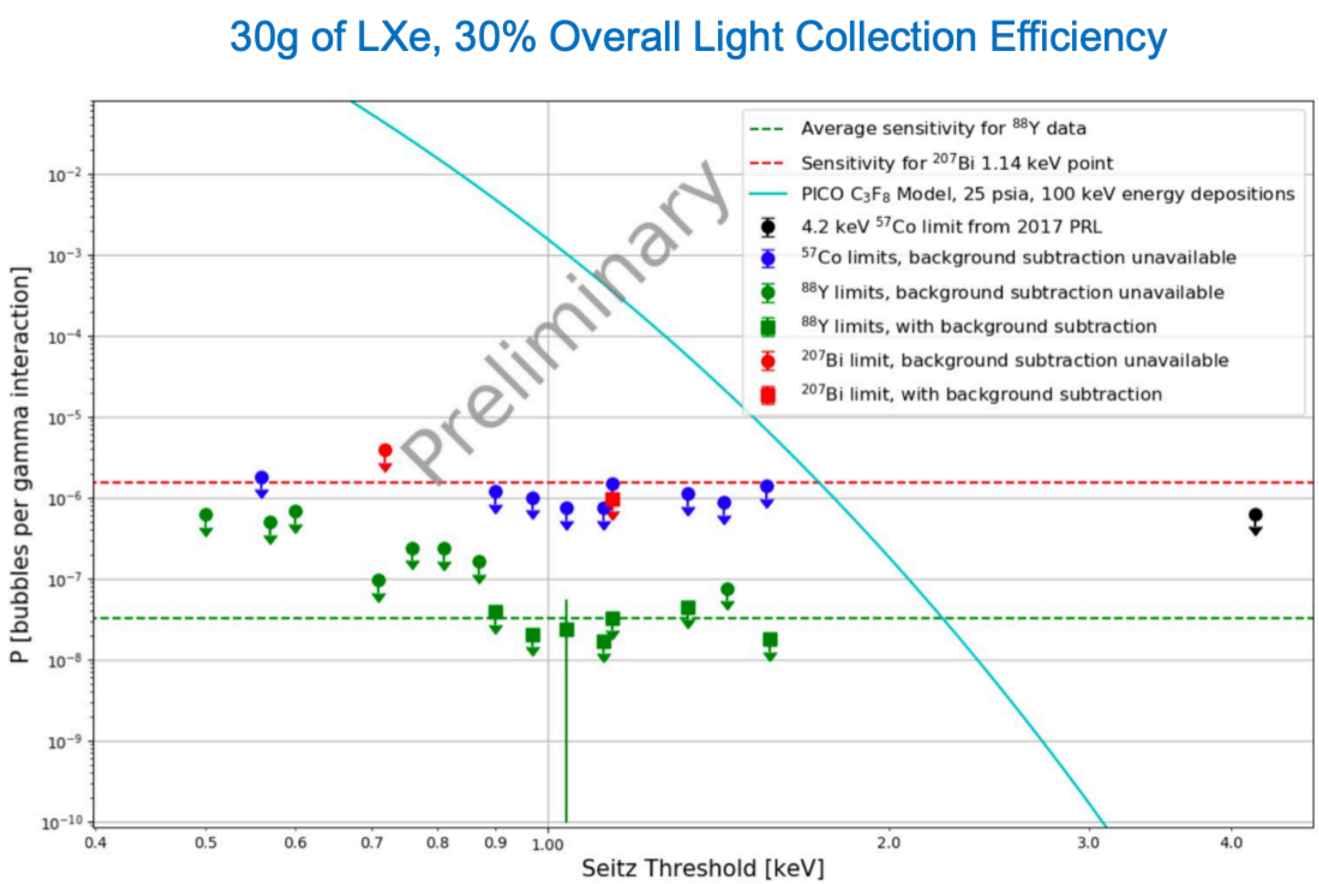
- Demonstrated (NU):
  - Xenon at 500 eV threshold
  - 30-gram target
  - 0.3% photon-detection efficiency

- Argon down to 40 eV threshold (1 bubble/ton-year from thermal fluctuations)
  - 10-kg target
  - 5% photon-detection efficiency (1 phd @ 2 keVr)

  Events with zero photons are signal

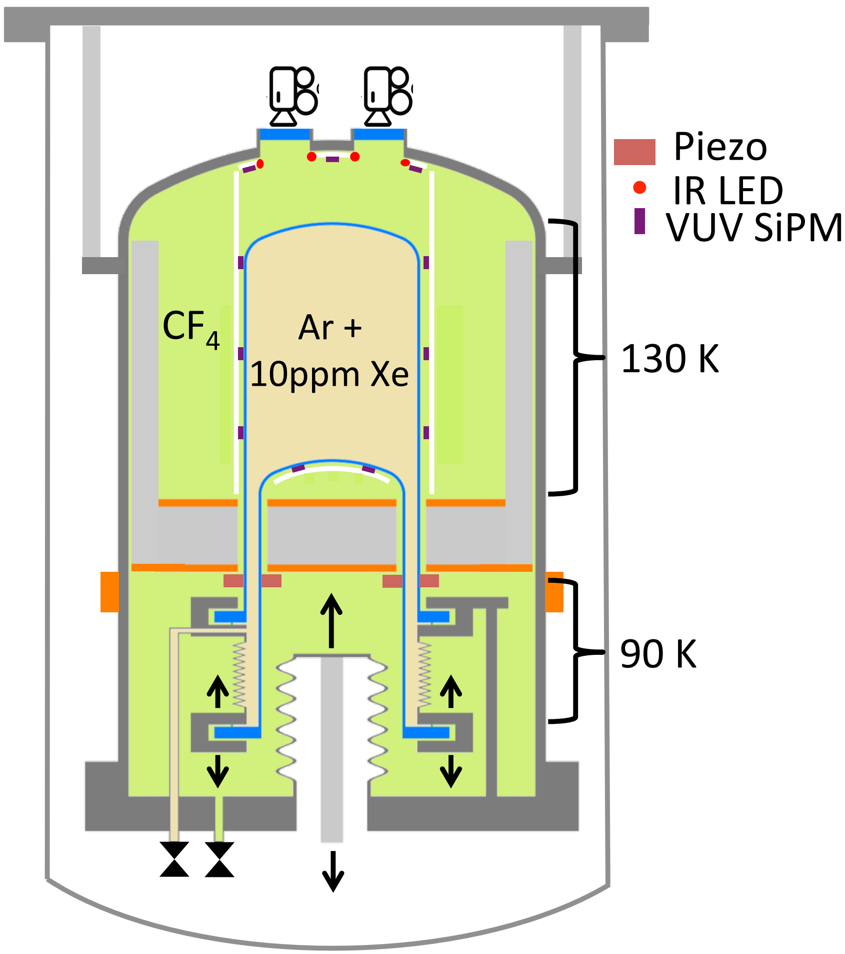
Xenon bubble chamber

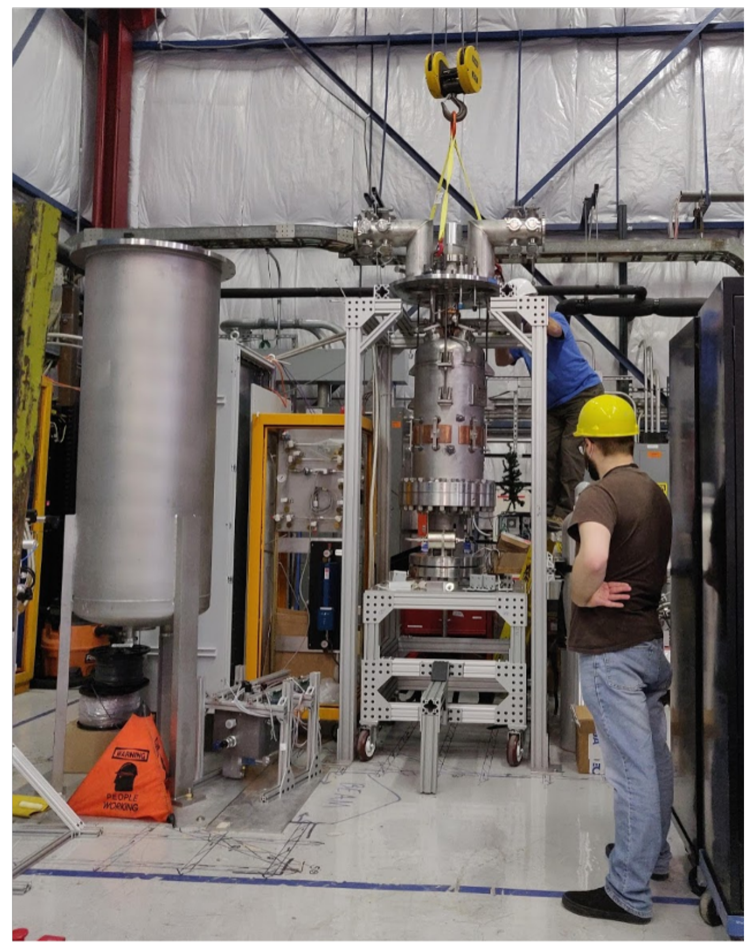
- Xenon measured to have outstanding ER discrimination
- Thresholds explored down to 500 eV
- No gamma induced ER observed
- Xe bubble chambers don't work for tracks (J.L. Brown, D.A. Glaser and M.L. Perl, Phys Rev 102, 1956), "solved" by adding 2% ethylene.



10 kg liquid Argon bubble chamber: 100 eV threshold

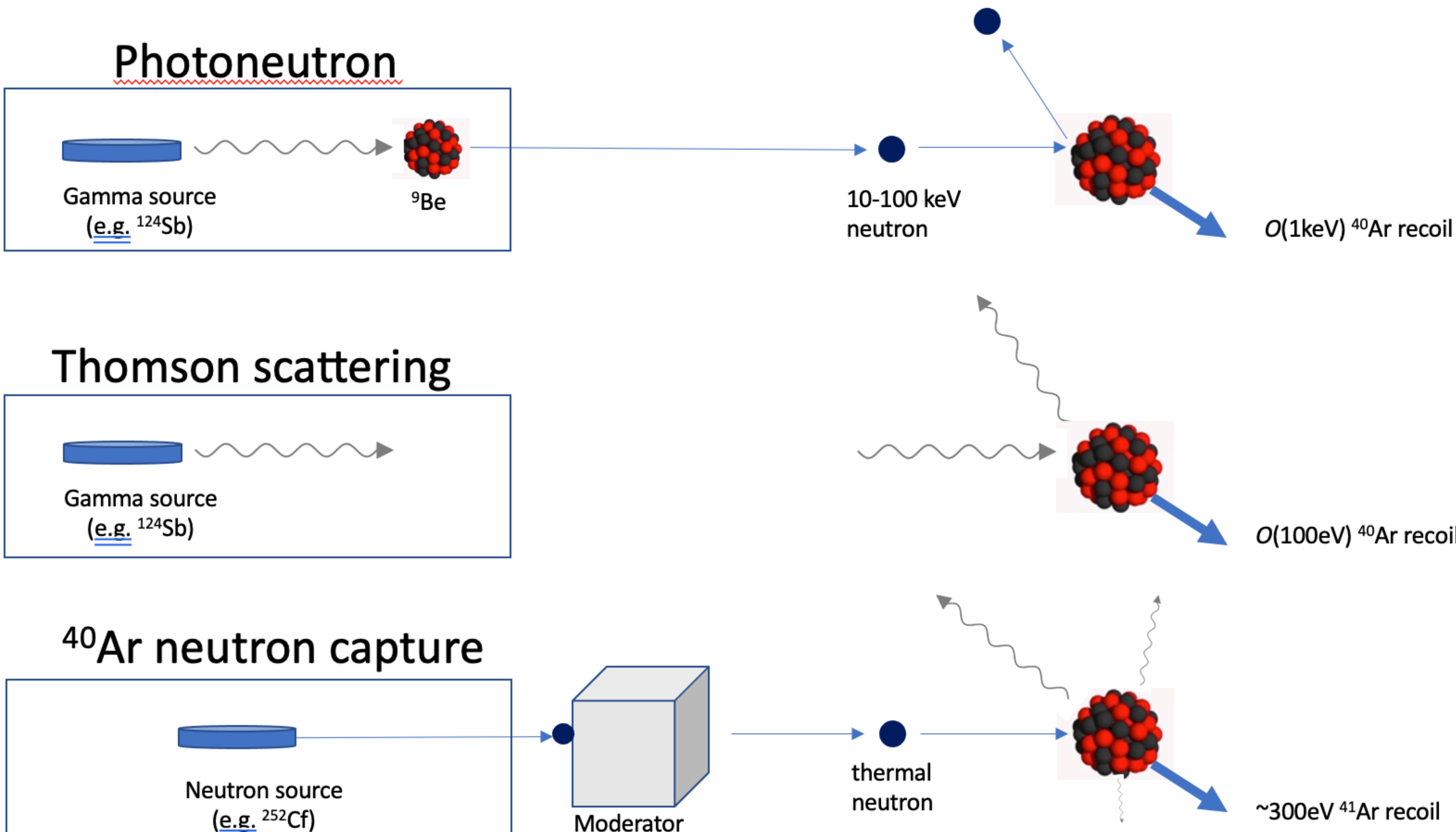
- Ar + 10-100 ppm Xe target, 178 nm scintillation
- SiPMs immersed in hydraulic fluid (CF4 at 130K)
- 20-360 psia (∼1-25 bar) cycles
- Single-fluid, "right-side-up" geometry used by PICO-40L





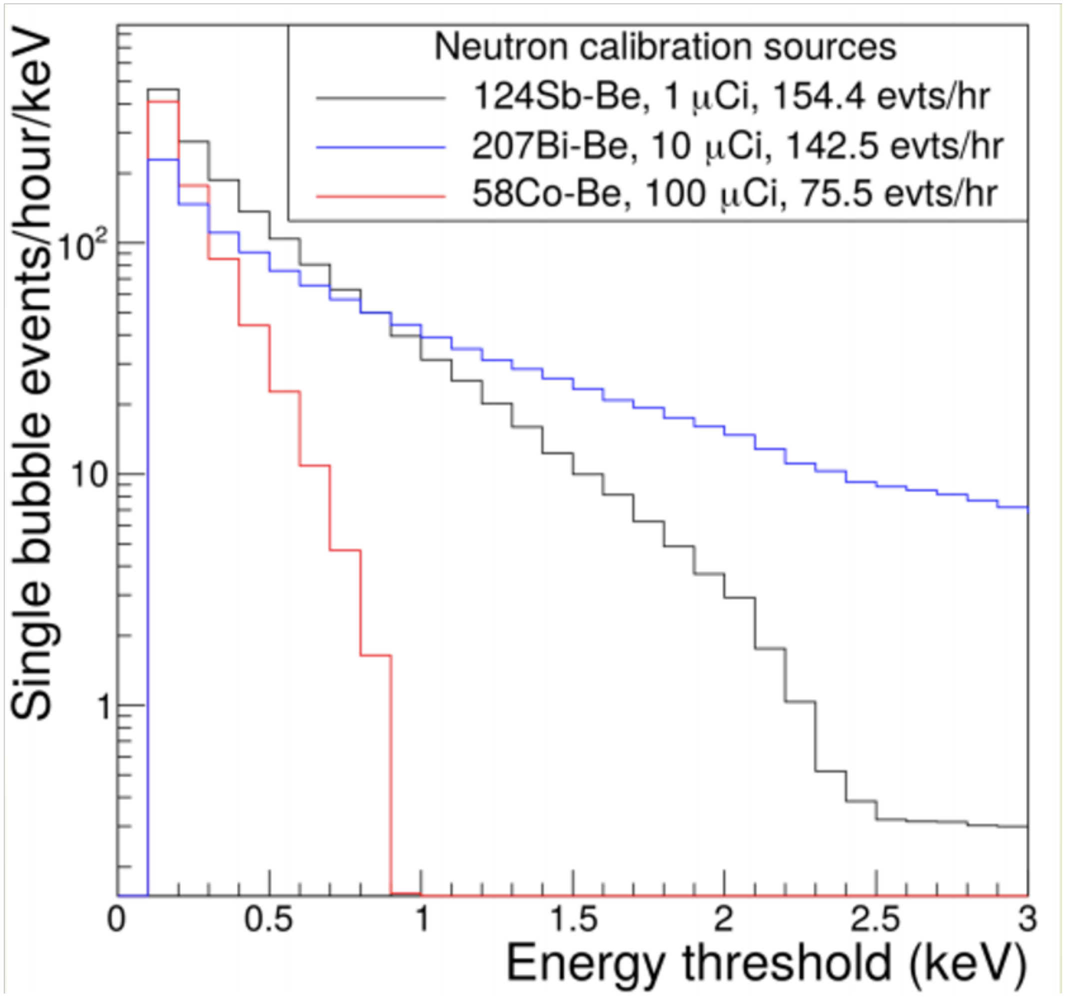
Calibration

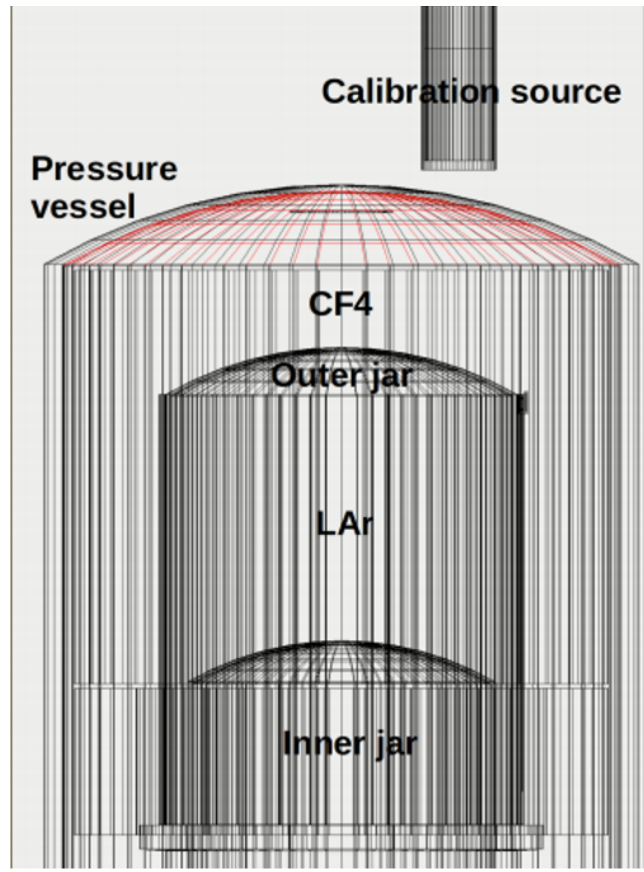
- Different nuclear recoil calibration techniques



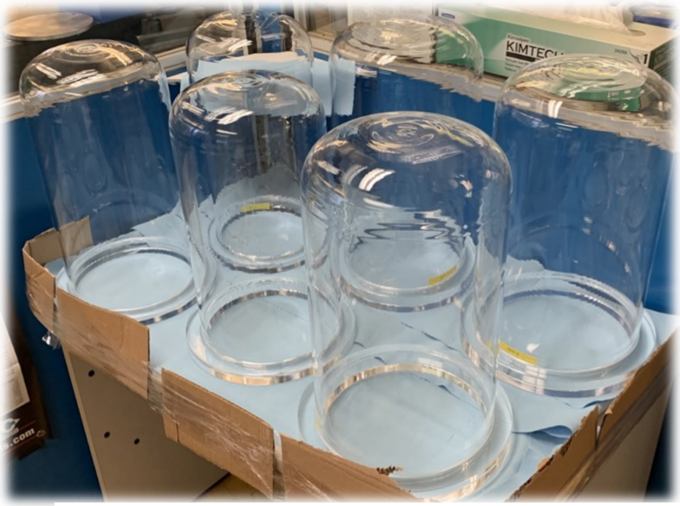
Calibration: photo-neutron sources

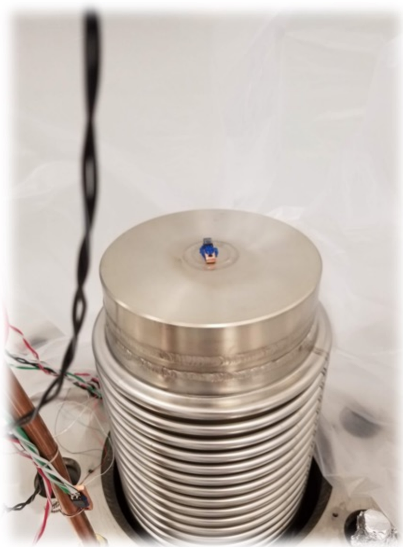
- 9Be(γ,n), $Q = 1664$, keV gives nearly monoenergetic neutrons. 207Bi: 90keV, 124Sb: 23keV, 58Co: 9keV





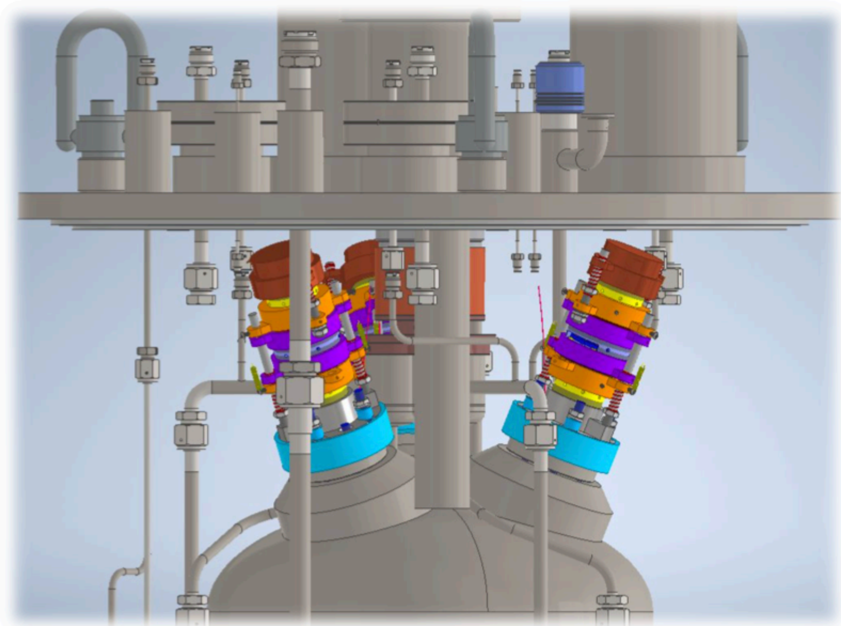
10 kg liquid Argon bubble chamber

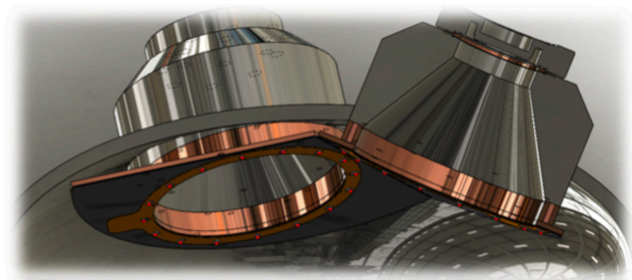


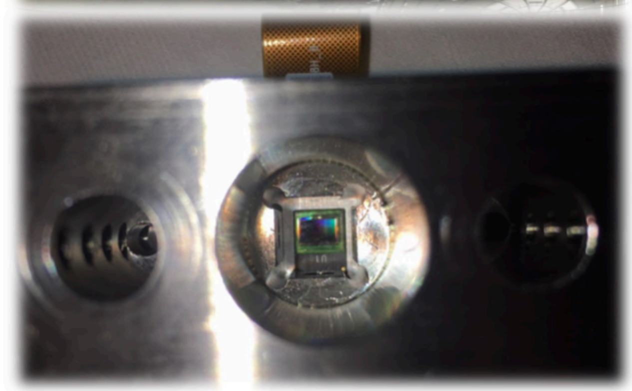


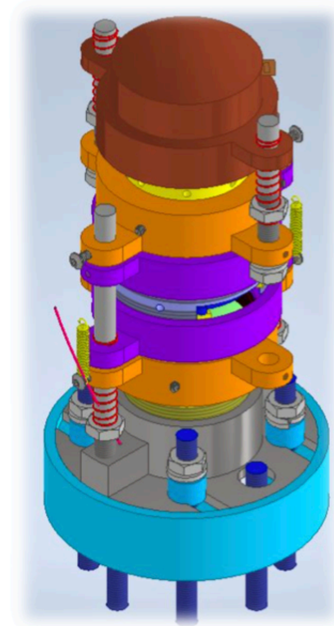
SBC-10kg: Readout systems

- **Three Raspberry-Pi Controlled Camera System**
- **Three LED Rings To Provide Illumination**



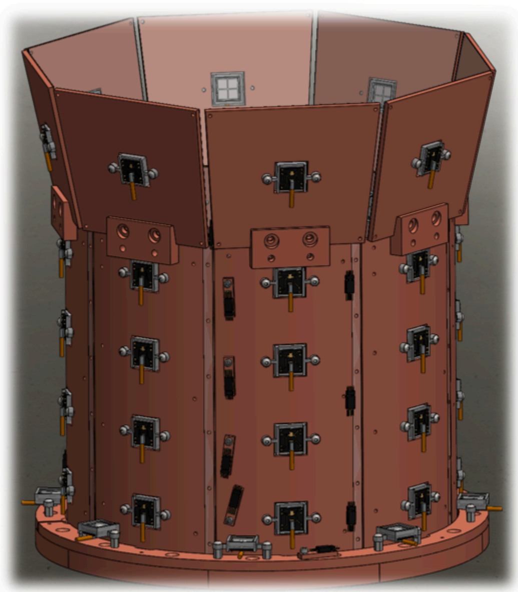


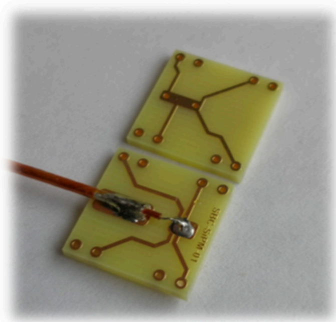
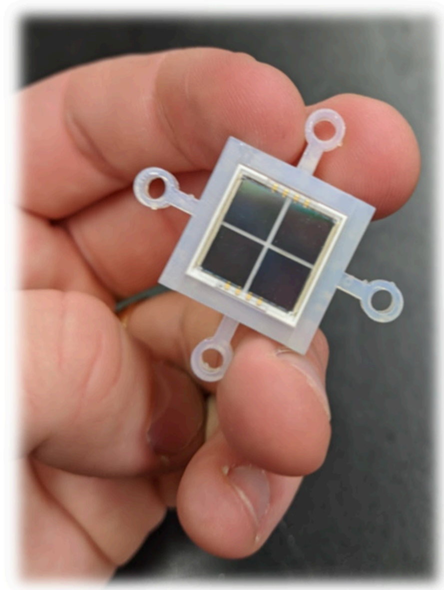
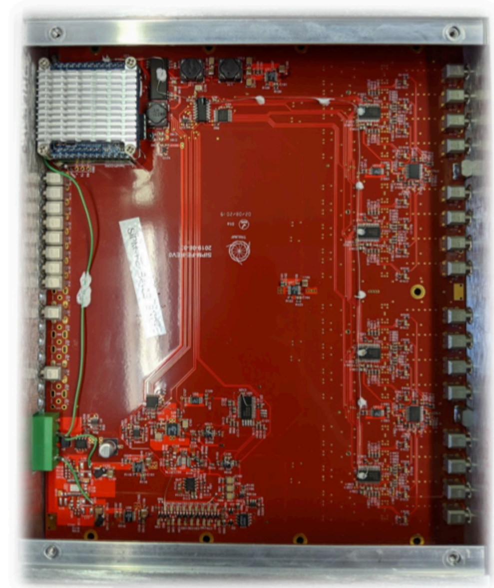




SBC-10kg: Readout systems

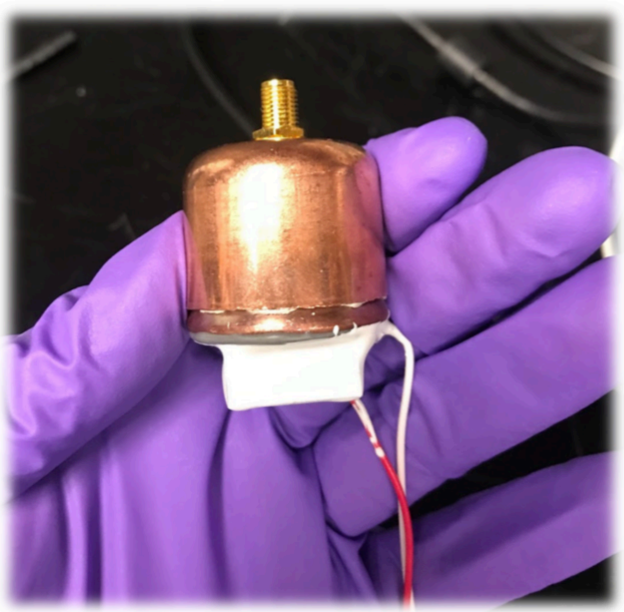
- **32 Hamamatsu VUV4 Quads**
- **Measure Scintillation Light In The Target Fluid.**

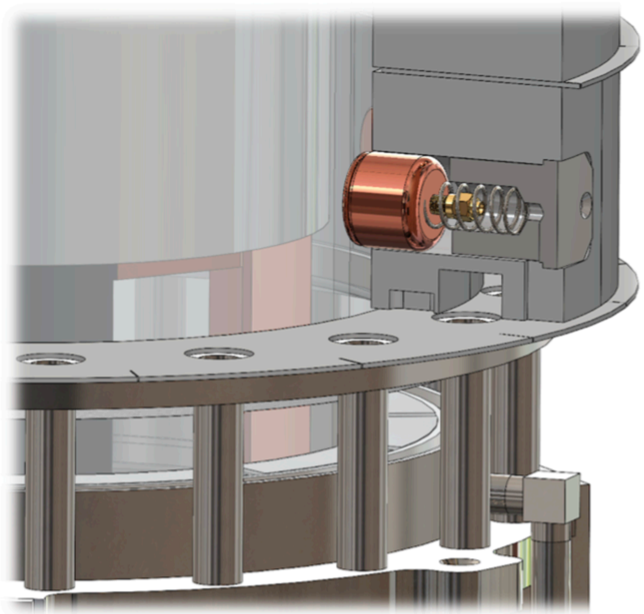


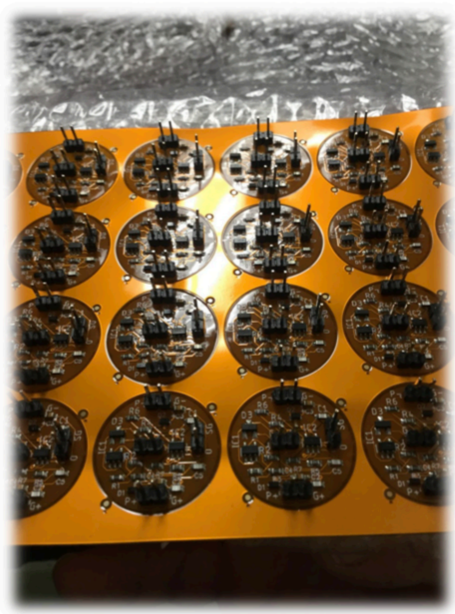




SBC-10kg: Readout systems

- Eight Piezo Acoustic Sensors
- Monitor The Nucleation Process







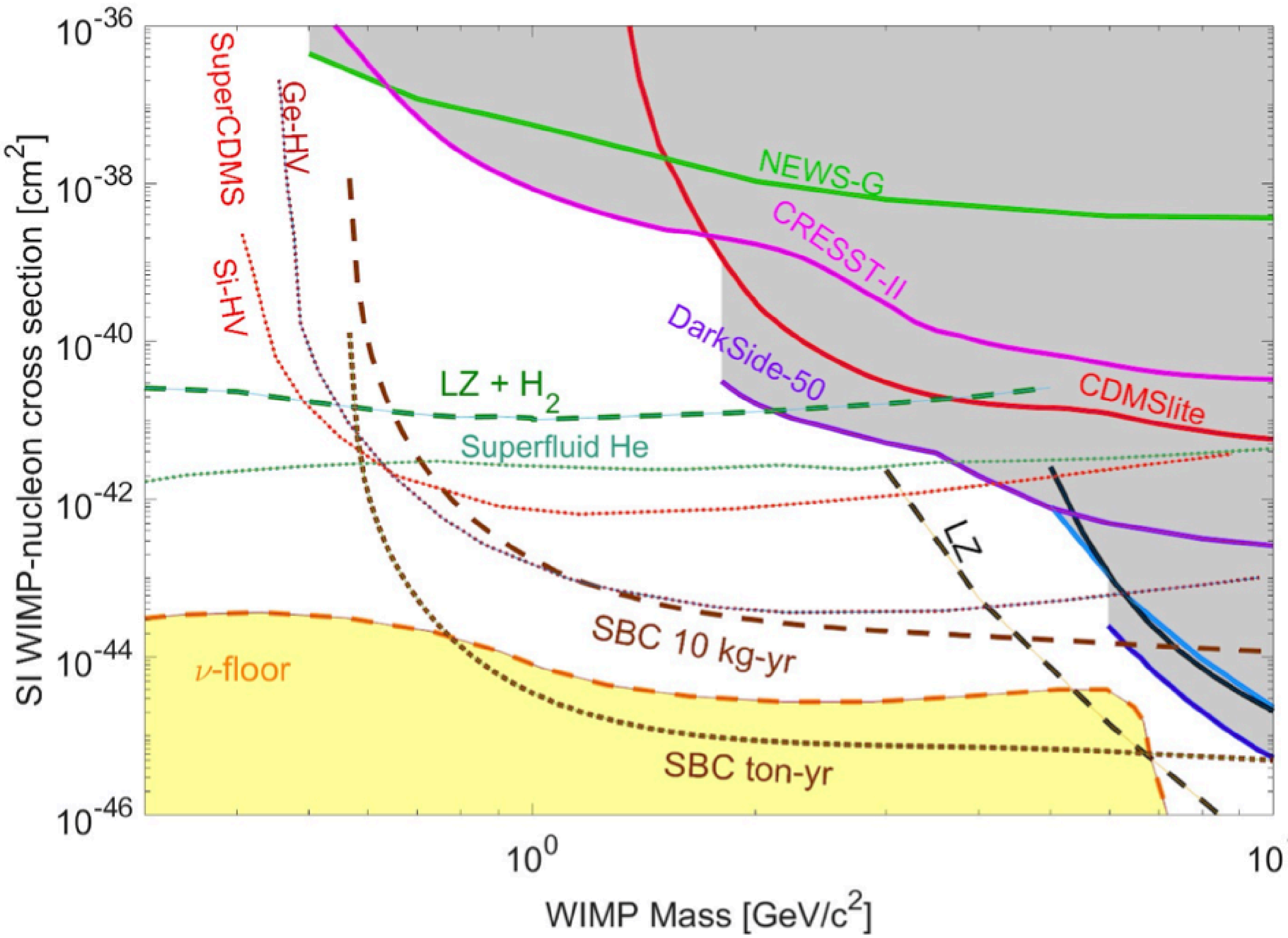
SBC: possible strategy

- **SBC-Fermilab:**
  Build and commission detector
  Calibrate NR and ER

- **SBC-SNOLAB:**
  Build and install 2nd detector
  Low mass dark matter searches

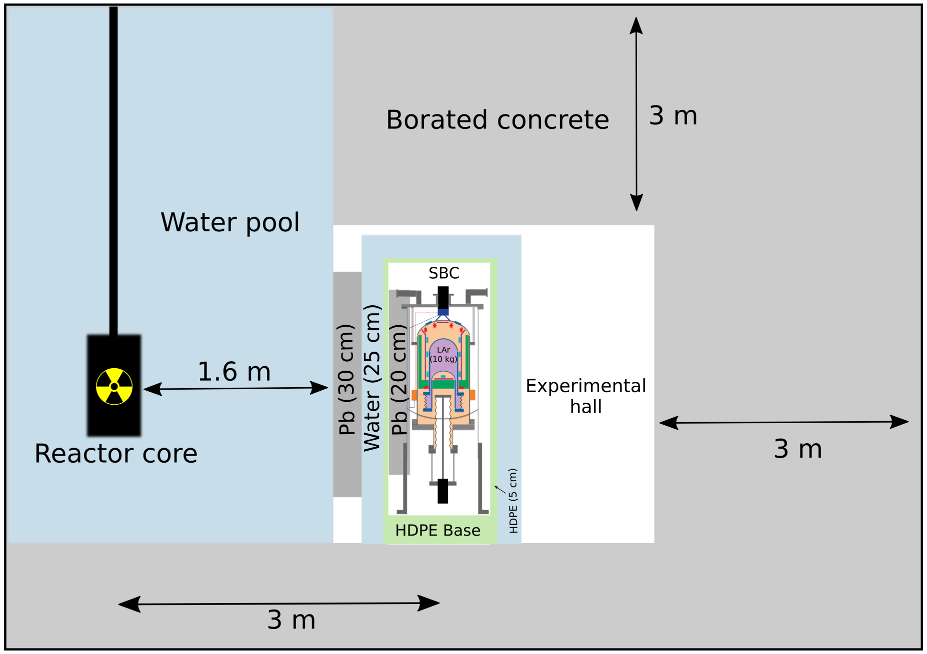
- **SBC-CEνNS:**
  Upgrade SBC-Fermilab detector
  Install at a reactor site for CEνNS

SBC Physics: Dark Matter

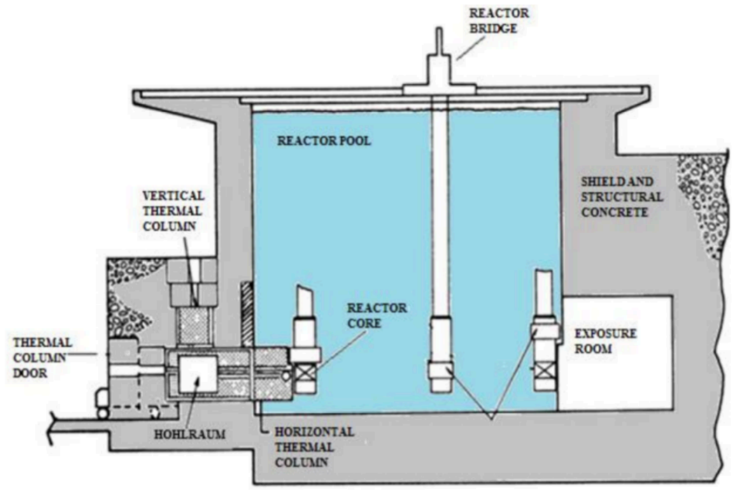


- **WIMP searches down to solar floor (0.7-7 GeV)**

SBC CEνNS: physics reach



ININ 1MW Triga Mark-III reactor in Mexico



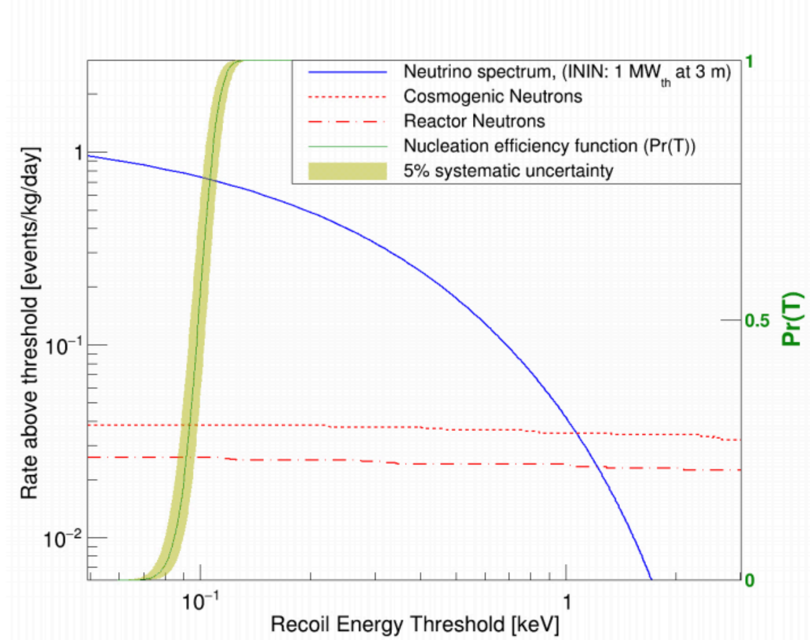
ININ exposure room

- **Two sites explored: ININ and Laguna Verde**

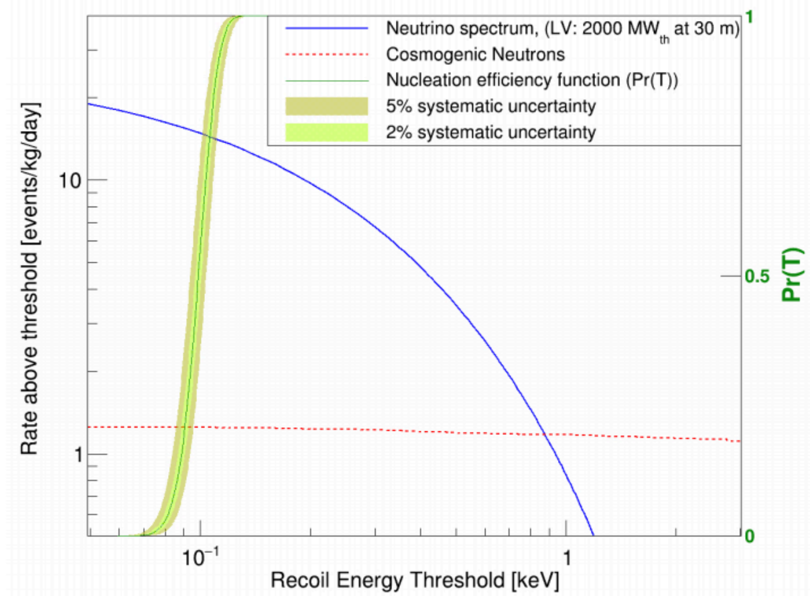
Setup	LAr mass (kg)	Power (MW_{th})	Distance (m)	Anti-ν flux uncertainty (%)	Threshold uncertainty (%)
A	10	1	3	2.4	5
B	100	2000	30	2.4	5
B(1.5)	100	2000	30	1.5	2

SBC Physics: CEνNS reach

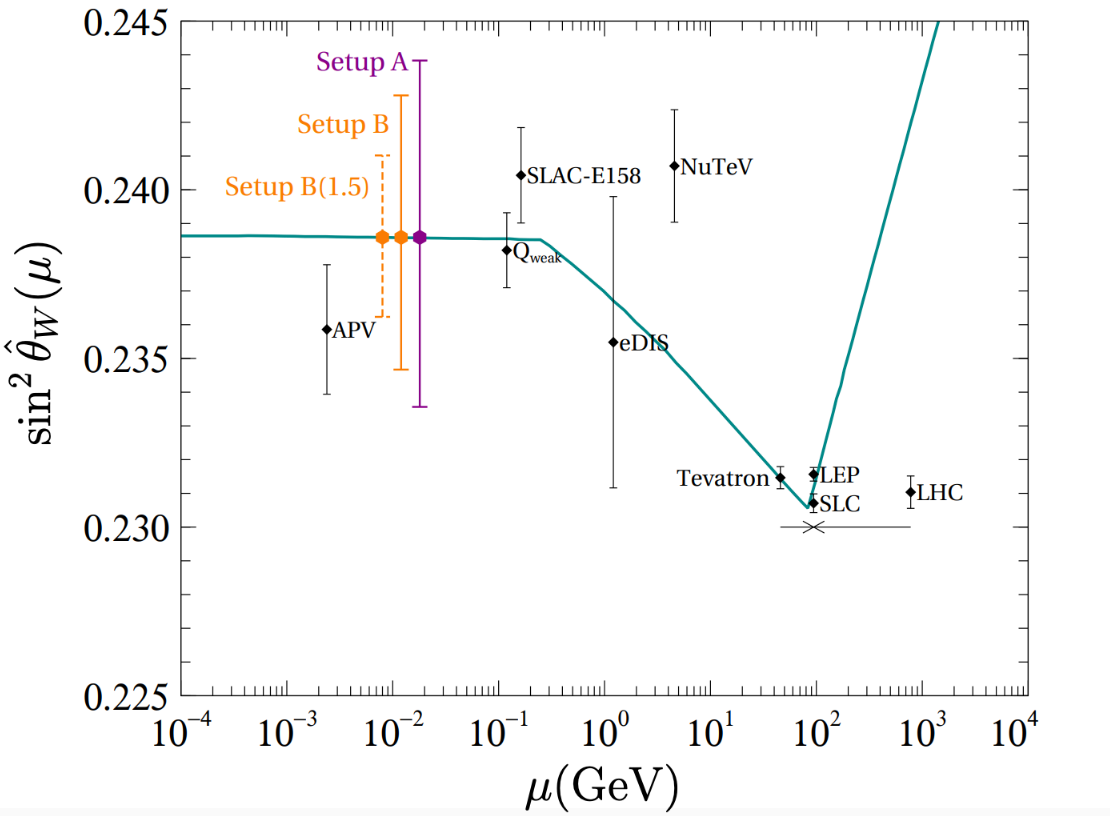
- **Setup A:**
  ~8 CEνNS/day at 100 eV
  0.25 evts/day - reactor backgrounds
  0.85 evts/day – cosmogenic
  Shielding = 0.3m Pb, 0.25m H_2O, 0.5m Polyethene, 0.2m Pb



- **Setup B:**
  ~1570 CEνNS/day at 100 eV
  negligible reactor backgrounds (30m + shielding)
  180 evts/day - cosmogenic
  Shielding = 3m H_2O, 0.5m Polyethen



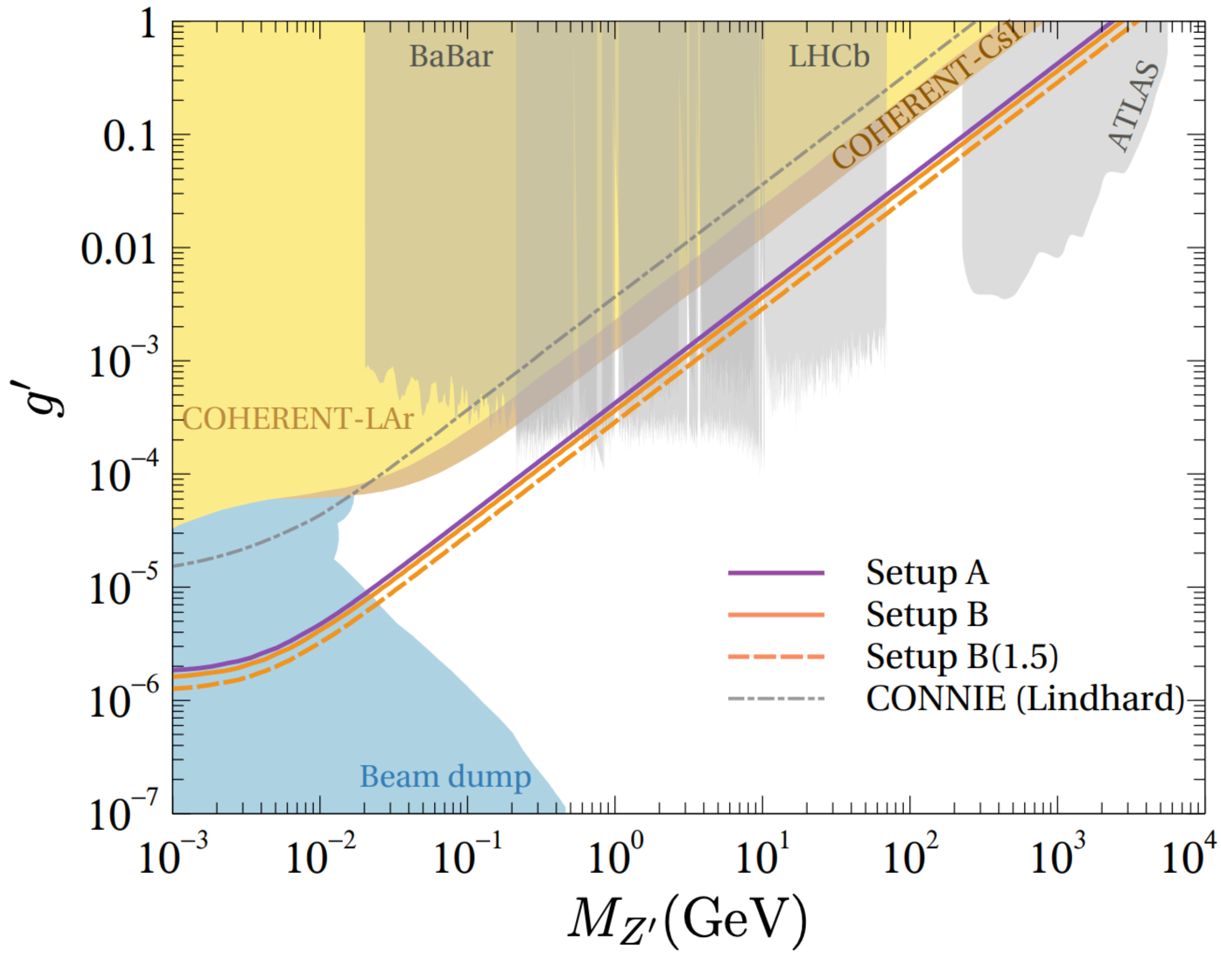
SBC CEνNS Physics: weak mixing angle



- **Precision as good as 1% in the weak mixing angle, similar to APV.**
- **Conservative: one year exposure, 2.4% flux uncertainty, 5% threshold uncertainty (A: ININ 10 kg, B: Laguna Verde 100 kg)**
- **Aggresive 1.5% flux, 2% threshold (B(1.5): Laguna Verde 100 kg)**

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right) F^2(q^2)$$

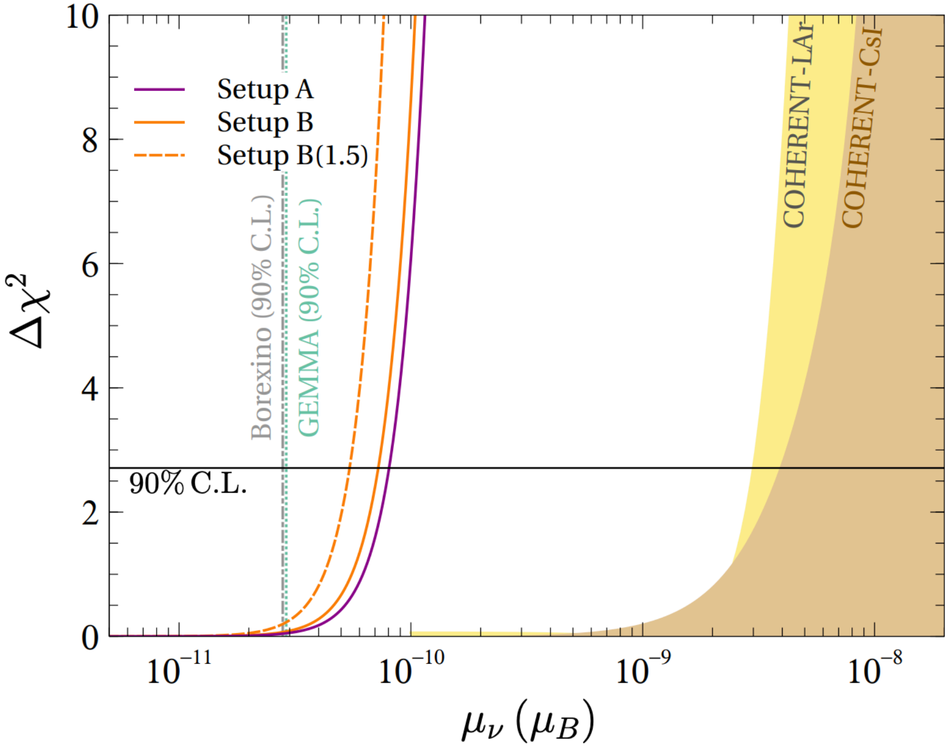
SBC CEνNS Physics: Z' boson



- **Most stringent bounds for new gauge vector bosons (20 MeV - 1 GeV and 70 - 230 GeV).**

$$\mathcal{L}_{\text{eff}} = -\frac{g'^2 Q_l Q_q}{q^2 + M_{Z'}^2}\left[\sum_{\alpha} \bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha\right]\left[\sum_q \bar{q}\,\gamma_\mu q\right]$$

SBC CEνNS Physics: ν magnetic moment



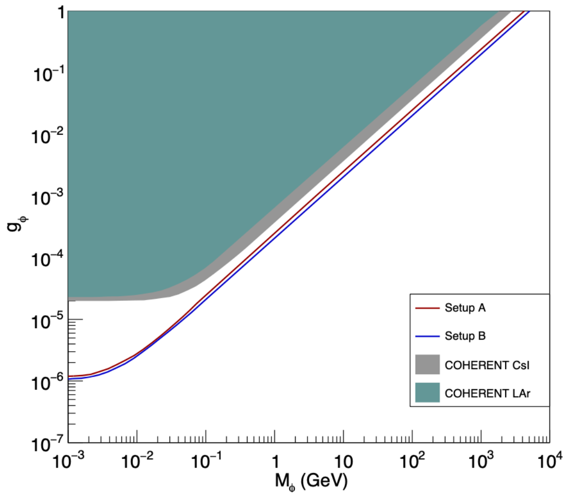
- **$\mu_\nu = 5.4 \times 10^{-11} \mu_B$ (90% C.L.), similar to GEMMA and Borexino.**

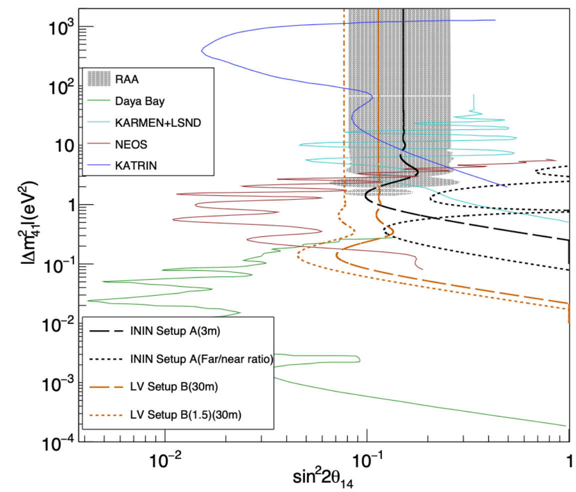
$$\frac{d\sigma}{dT} = \pi \frac{\alpha_{\rm EM}^2 Z^2 \mu_\nu^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_\nu} + \frac{T}{4E_\nu^2} \right) F^2(q^2).$$

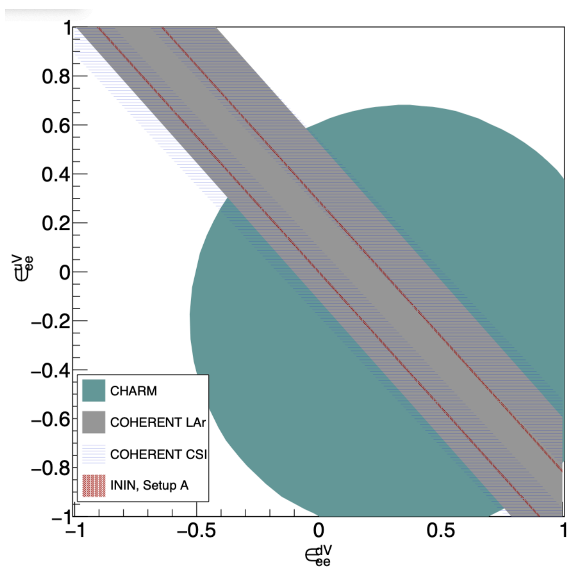
Physics reach of a low threshold scintillating argon bubble chamber in coherent elastic neutrino-nucleus scattering reactor experiments

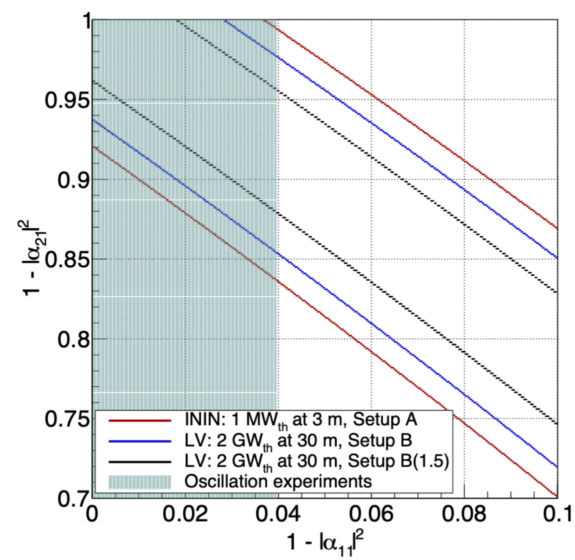
Phys. Rev. D 103, L091301 (2021)

SBC CEνNS: New Physics









New Physics searches in a low threshold scintillating argon bubble chamber measuring coherent elastic neutrino-nucleus scattering in reactors

https://arxiv.org/abs/2203.05982

Final remarks

- **SBC is a 10 kg LAr bubble chamber: unique potential for reactor CEνNS measurement with low backgrounds**
  - **100 eV nuclear recoil detection**
  - **Dark matter searches for masses 0.7-7 GeV**
  - **Rich CEνNS physics programme: weak mixing angle, Z' boson, neutrino magnetic moment, sterile neutrinos, NSI, unitarity violation**