Búsqueda de materia oscura y física de neutrinos con cámaras de burbujas

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Outline

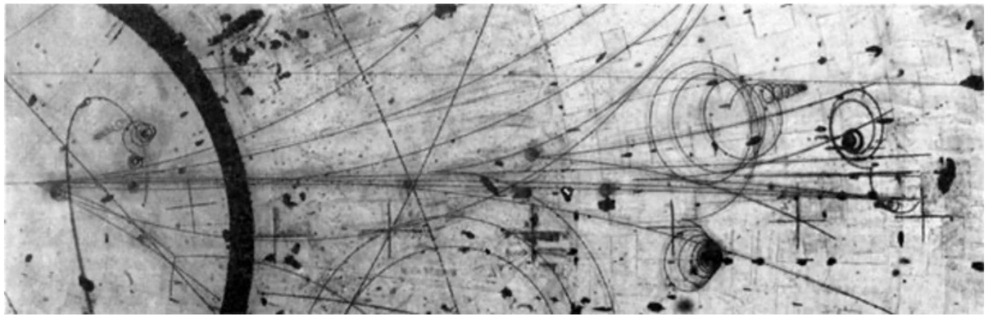
- **Dark matter search with bubble chambers using octofluoropropane**
- **Reactor neutrinos with a liquid argon scintillating bubble chamber**
- **Lab DM-ν: instrumentation and spectroscopy at IFUNAM**
- **Final remarks**

PICO: dark matter searches using bubble chambers

Physics with bubble chambers

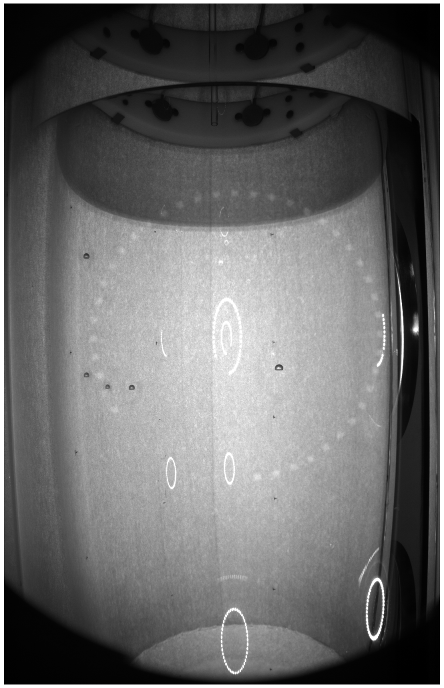
1970s: Neutrino Beam Physics

- **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

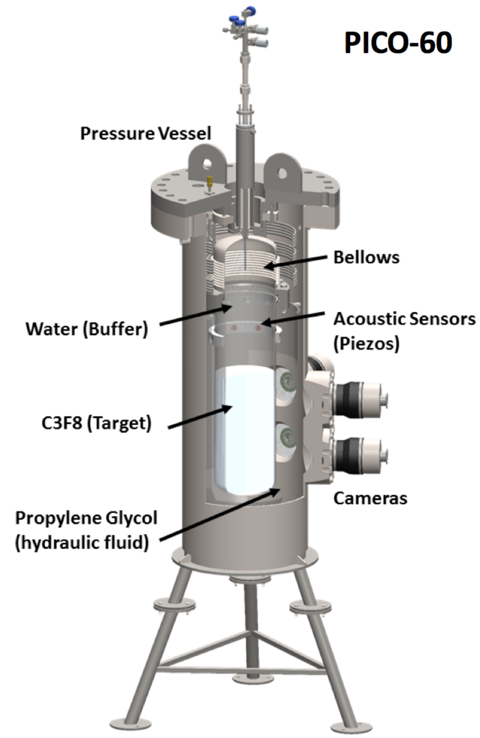
  Could make a dark matter bubble chamber with any liquid!

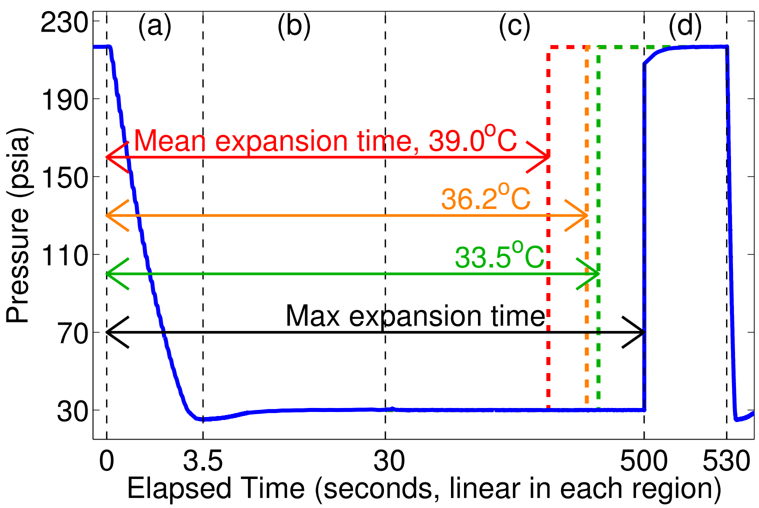
- Particles interacting evaporate a small amount of material: bubble nucleation

- Four Cameras record bubbles

- Eight piezo-electric acoustic sensors detect sound

- Recompression after each event



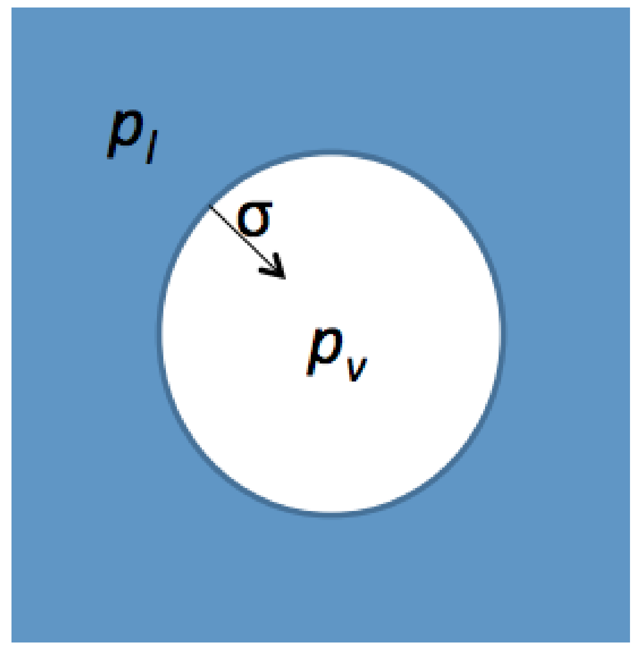


Bubble chambers: Physics

- **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:**

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

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

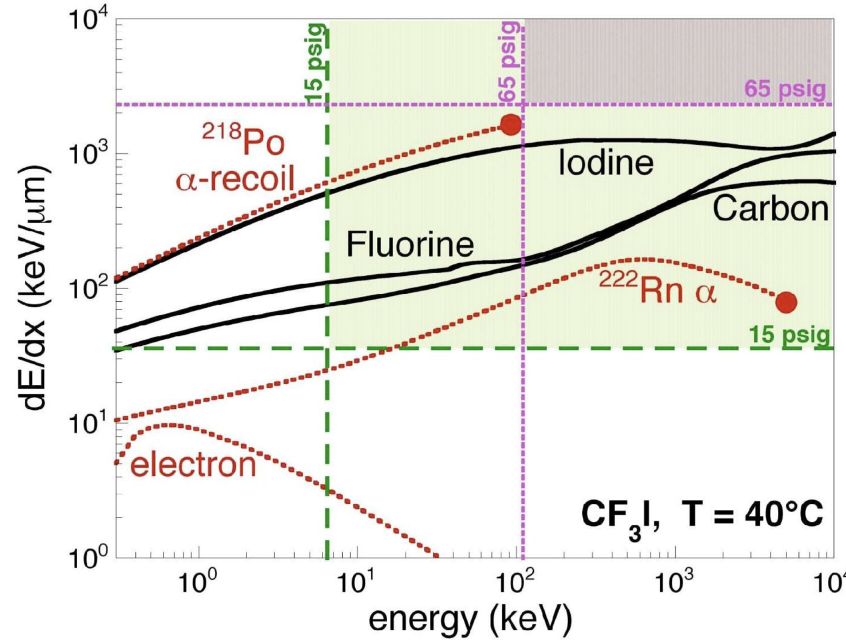


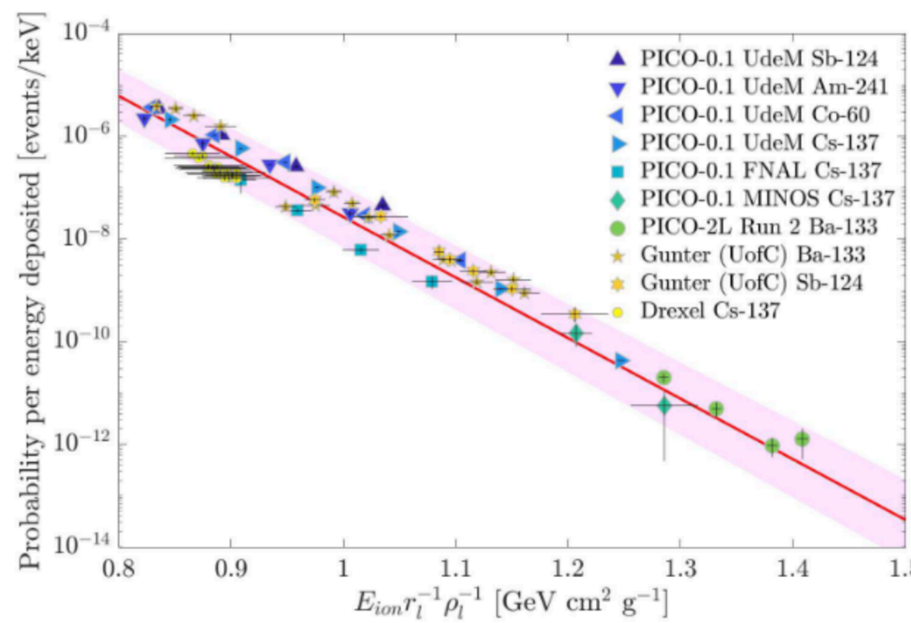
Bubble nucleation

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



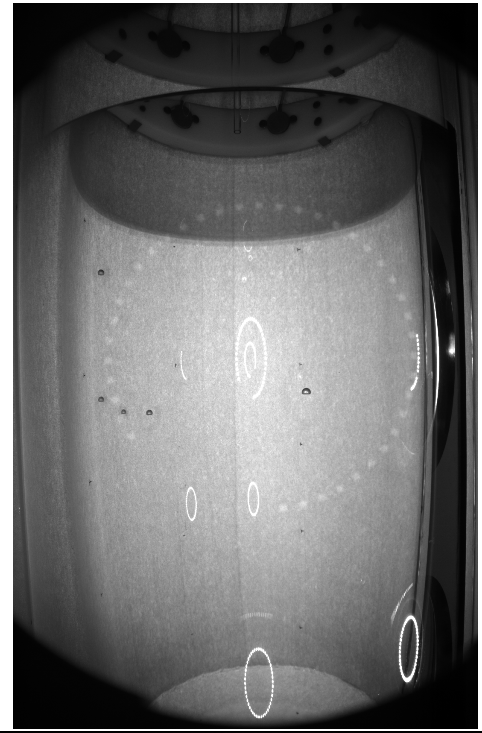


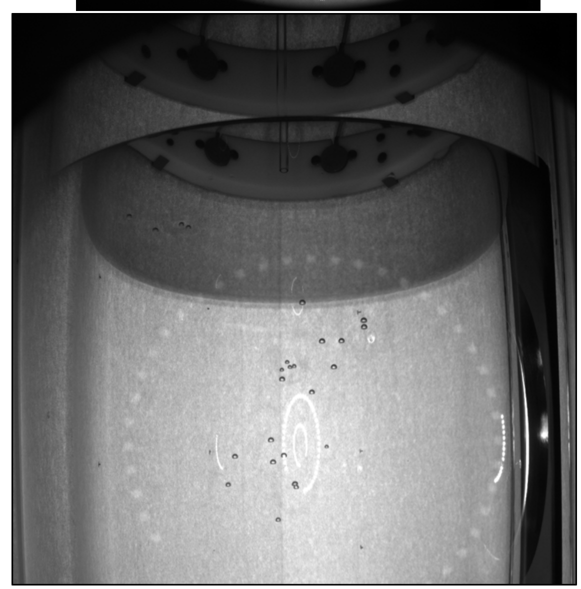
Bubble chambers: signal

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

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

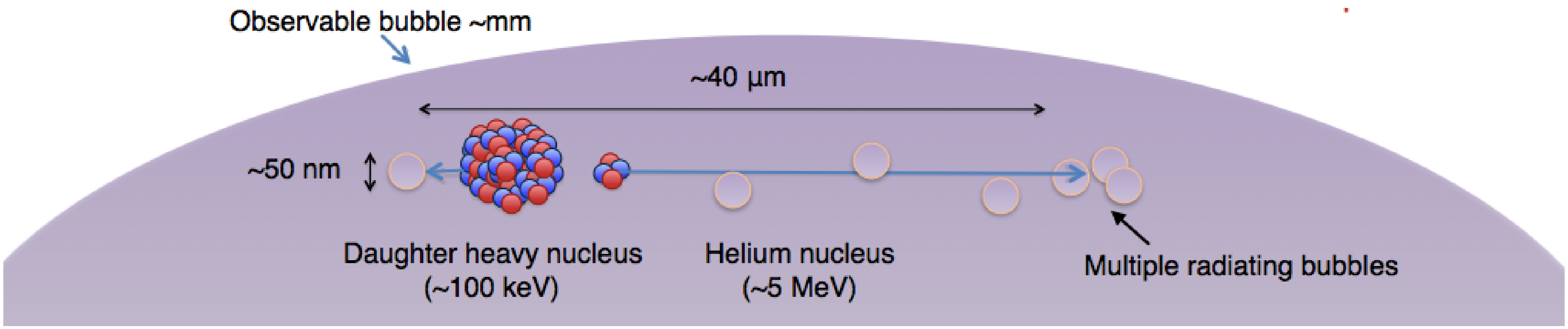
- **Neutrinos or WIMPs:**
  Nuclear recoil
  mean free path $> 10^{10}$ cm
  1 bubble



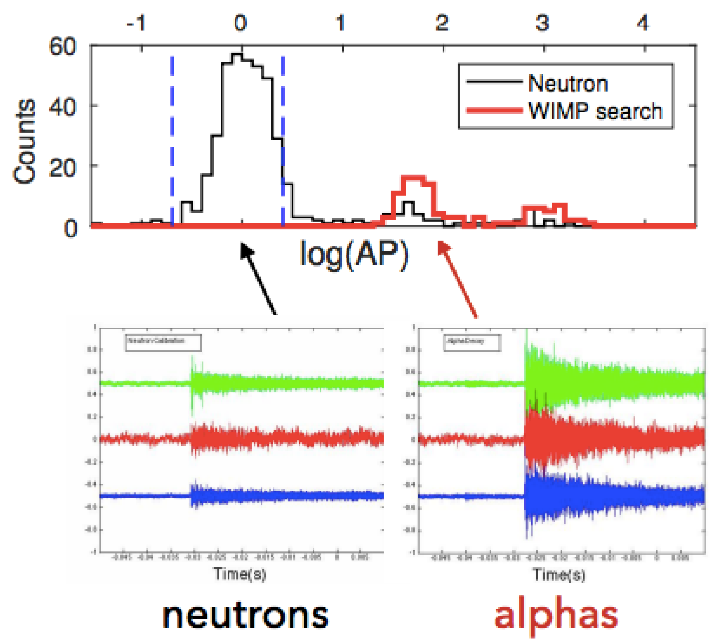


Bubble chambers: Acoustics

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



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

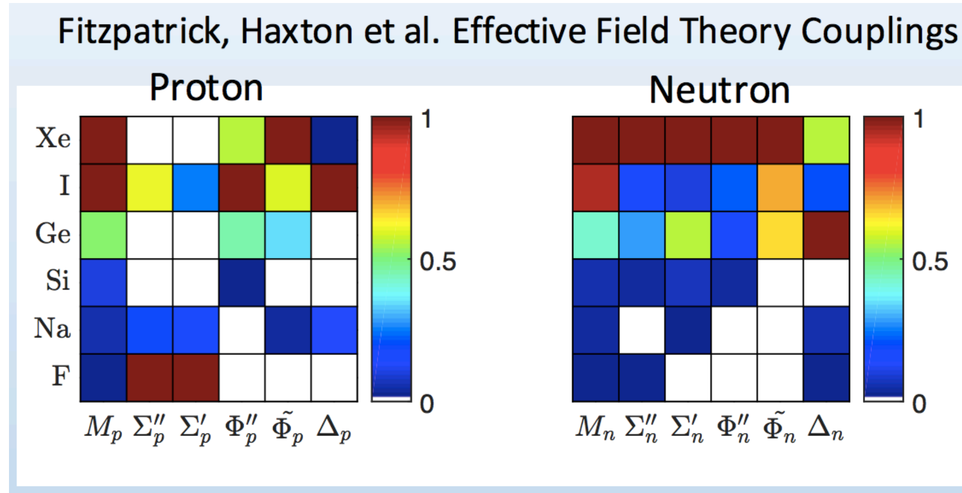


Why bubble chambers?

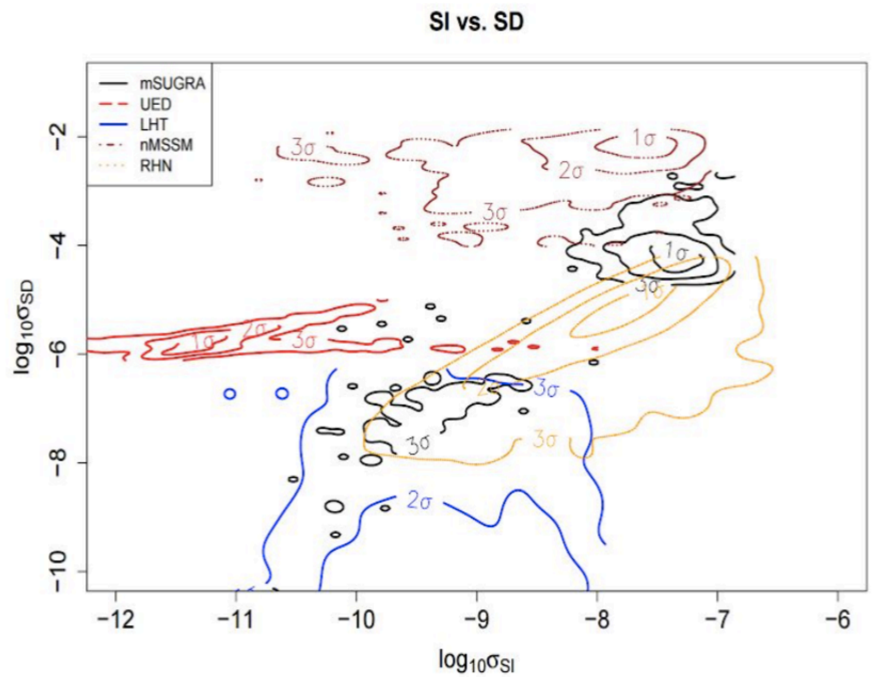
- **Zero background**
- **Large target mass**
- **Low energy threshold (a few keV, and down to eV for some fluids)**
- **Multiple target nuclei**
  test expected cross section dependences on
  atomic number and nuclear spin
  (Fluorine, Iodine, Chlorine, Xenon, Argon, Bromine, Hydrogen...)
- **Measure 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



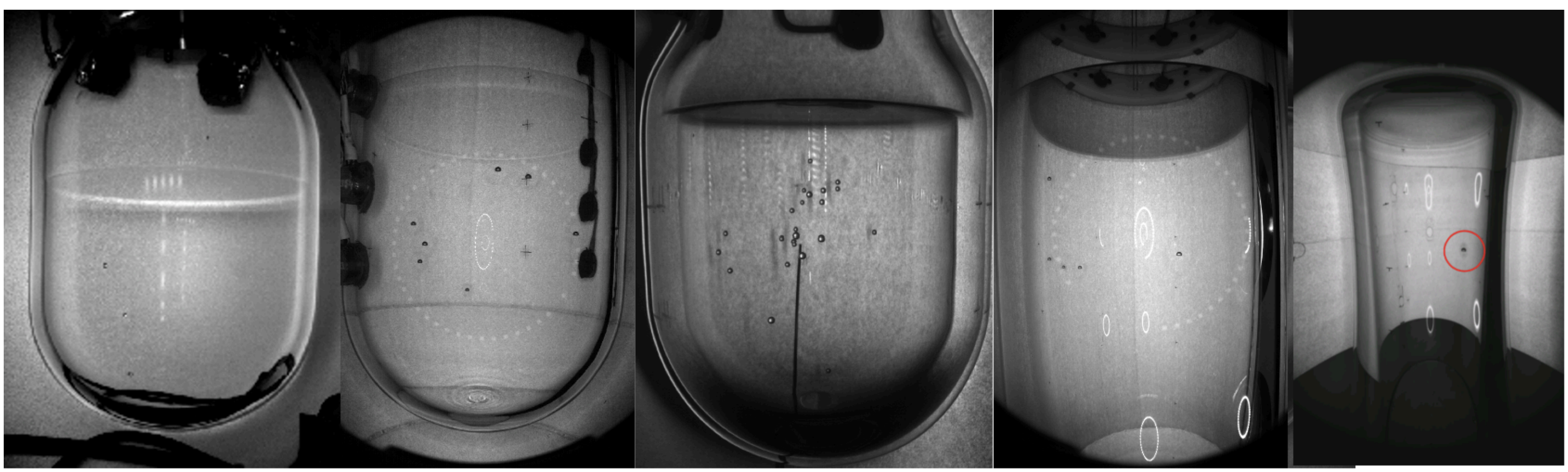
- Fluorine: Best sensitivity to spin dependent interactions.
- Iodine, Bromine, Xenon, Argon: High A targets to exploit A^2 dependence of spin-independent cross section.
- Hydrogen: Enhanced sensitivity to low mass particles.



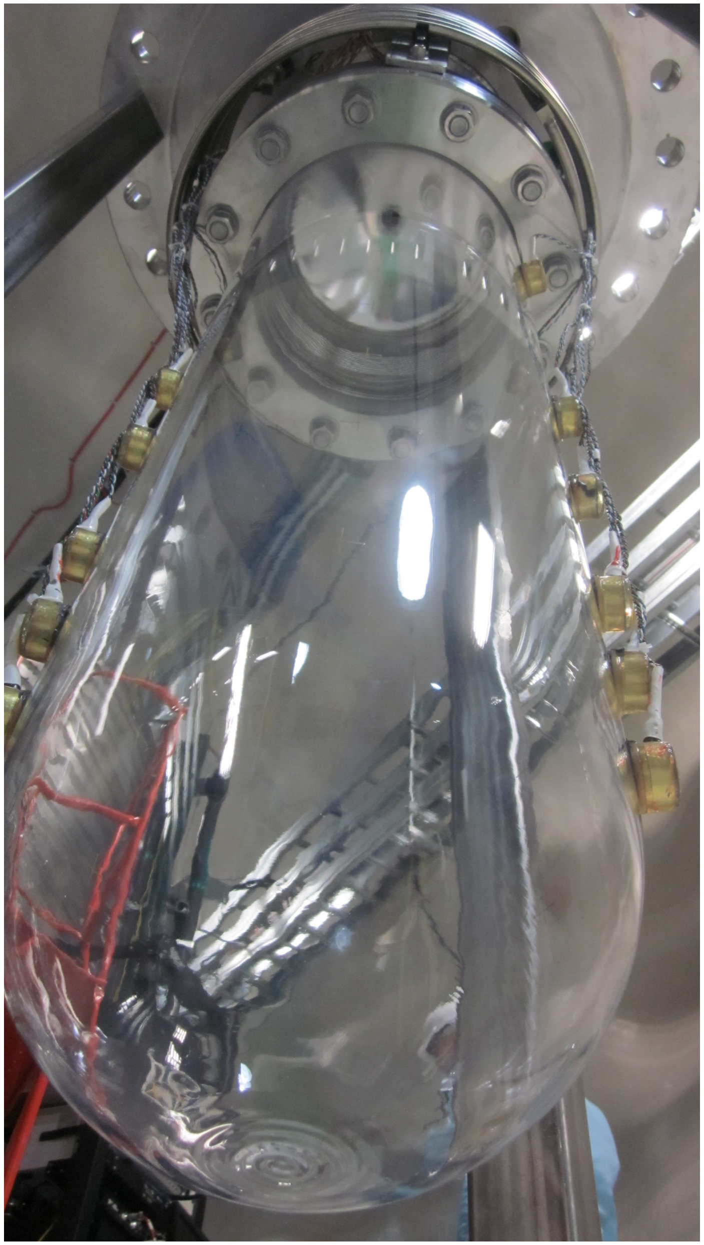
V. Barger, W-Y Keung and G. Shaughnessy, Phys. Rev. D78 (2008) 056007

Meet the family: PICO bubble chambers

- COUPP4: a 2l CF3I chamber run at SNOLAB in 2010 and 2012
- COUPP60: up to 40l CF3I chamber run at SNOLAB 2013-14
- PICO-2L: a 2l C3F8 chamber run at SNOLAB 2013-14 and 2015-16
- PICO-60: up to 45l C3F8 chamber run at SNOLAB 2016-17
- PICO40L: currently under commissioning (fall 2022)
- PICO-500: future ton-scale experiment 2023-2024

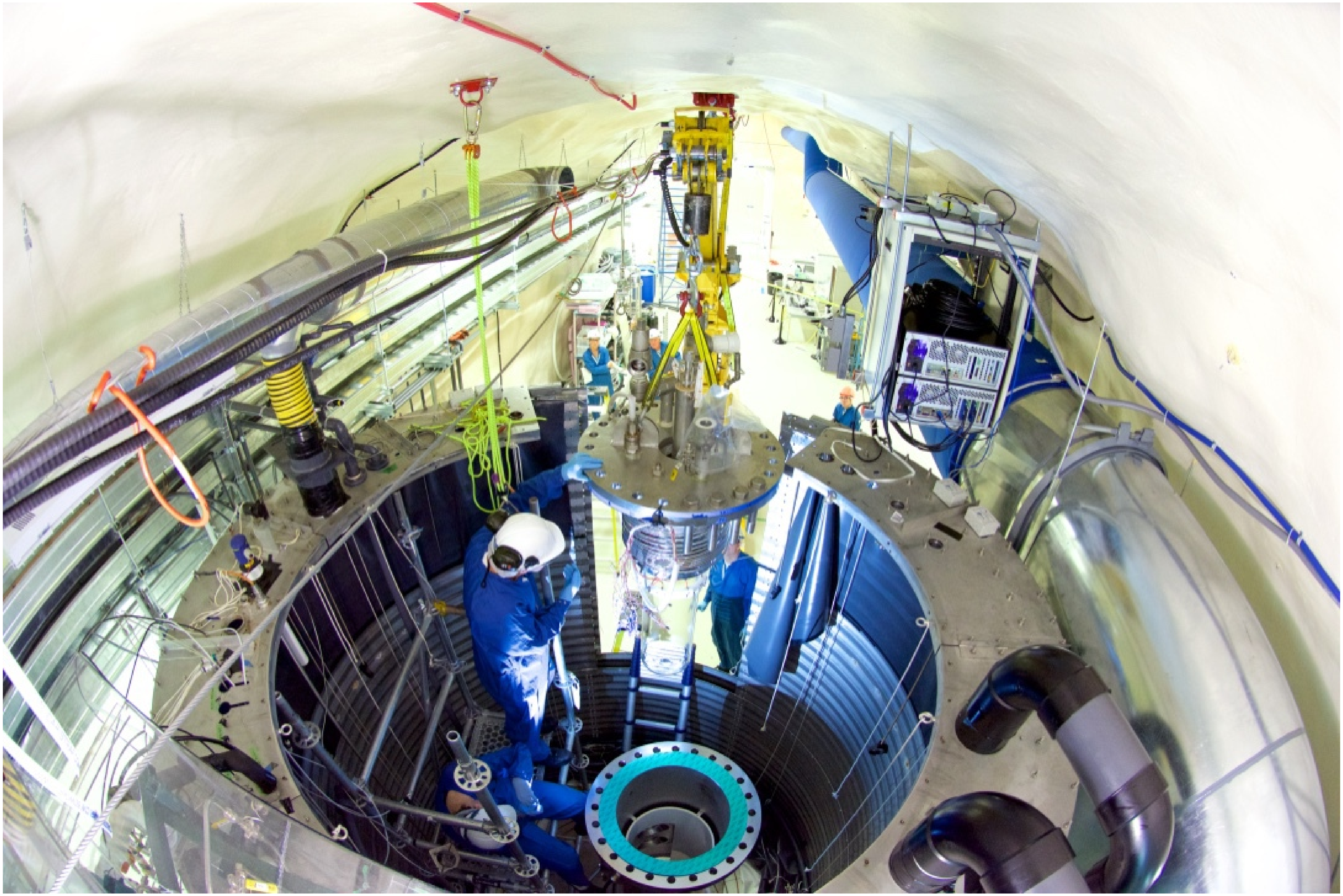


COUPP60 and PICO-60

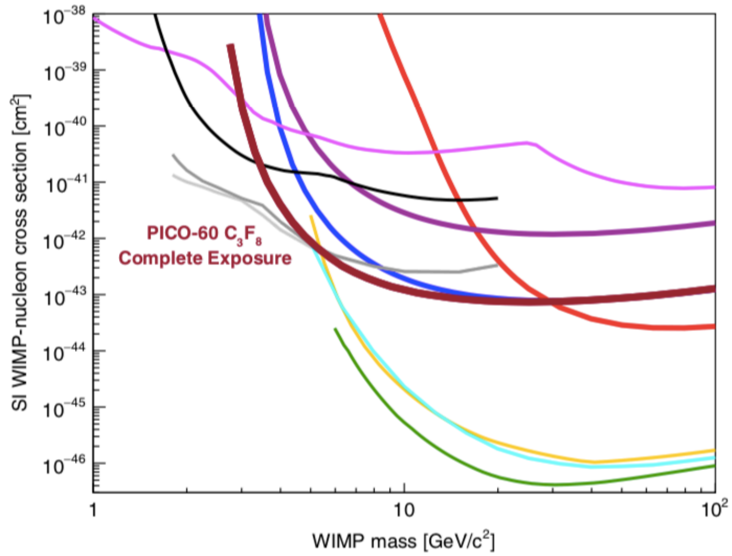



COUPP60 and PICO-60

PICO-60



PICO latest WIMP SD and SI limits



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

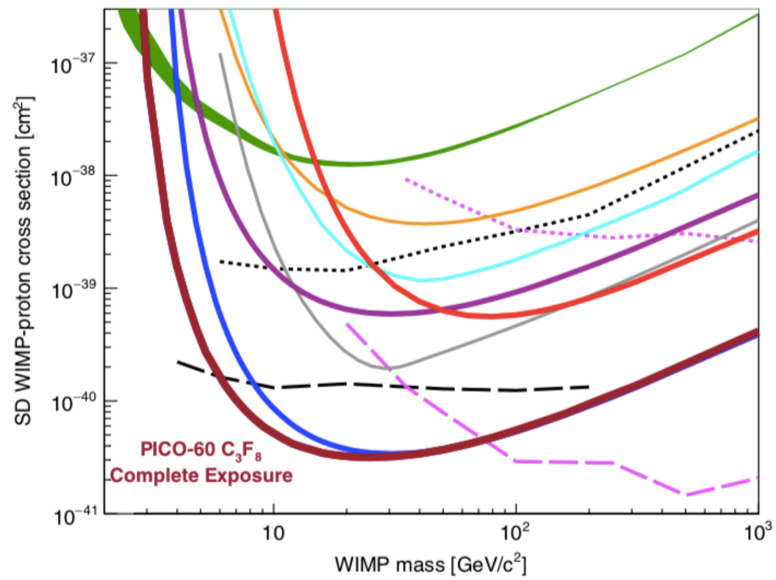
Phys. Rev. Lett. 114, 231302 (2015)

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)

PICO Collaboration

PICO

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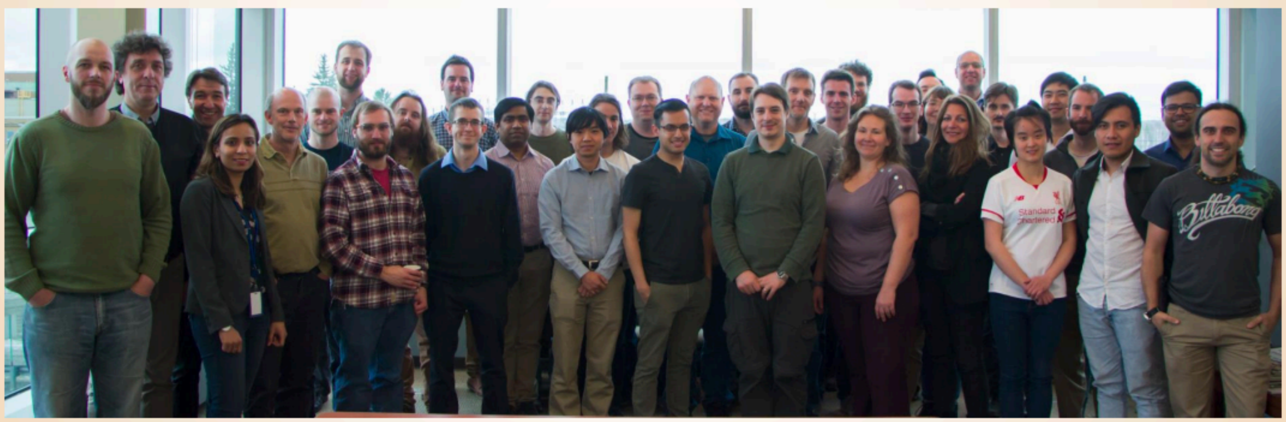

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PICO Collaboration 2022

NREFT approach in PICO

- In the NREFT, the differential cross section is presented as the product of the WIMP response function and the Nuclear response function.

$$\frac{d\sigma_T(v, E_r)}{dE_r} = \frac{2m_T}{4\pi v^2}\left[\frac{1}{(2j_\chi+1)}\frac{1}{(2J+1)}|\mathcal{M}_T|^2\right]$$

- In NREFT, the nucleus is not treated as a point particle, but its composite nature is reflected

probability of dispersion

$$\frac{1}{(2j_\chi+1)}\frac{1}{(2J+1)}\sum_{spins}|\mathcal{M}_T|^2 \equiv \sum_k \sum_{\tau=0,1}\sum_{\tau'=0,1} R_k\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}, \{c_i^\tau c_j^{\tau'}\}\right) W_k^{\tau\tau'}(\vec{q}^2 b^2)$$

$$k = M, \Sigma'', \Sigma', \Phi'', \Phi'' M, \Delta, \Delta\Sigma'$$

- With this theory, 6 new nuclear response functions have been identified in addition to the classical SI/SD

Particle physics — WIMP response functions

Nuclear physics — Nuclear response functions

- In this theory we have 11 operatos

$$\mathcal{L}_{\rm int} = \sum_{N=n,p}\sum_i c_i^{(N)}\mathcal{O}_i\chi^+\chi^-N^+N^-$$

Anapole moment

- The anapole moment is the lowest electromagnetic moment allowed for a Majorana particle

$$\mathcal{L}_{\mathcal{A}} = c_{\mathcal{A}} \bar{\chi} \gamma^{\mu} \chi \partial^{\nu} F_{\mu\nu} \qquad \mathcal{O}_{\mathcal{A}} \rightarrow c_{\mathcal{A}} \sum_{N=n,p} (Q_N \mathcal{O}_8 + g_N \mathcal{O}_9)$$

$c_{\mathcal{A}}$: anapole coupling constant $[GeV^{-2}]$

$\mathcal{O}_8 = \vec{S}_{\chi} \bullet \vec{v}^{\perp}$ momentum independent

Q_N: is the nucleon charge ($Q_p = 1,\ Q_n = 0$)

g_N: is the nucleon g-factor ($g_p = 5.59,\ g_n = -3.83$)

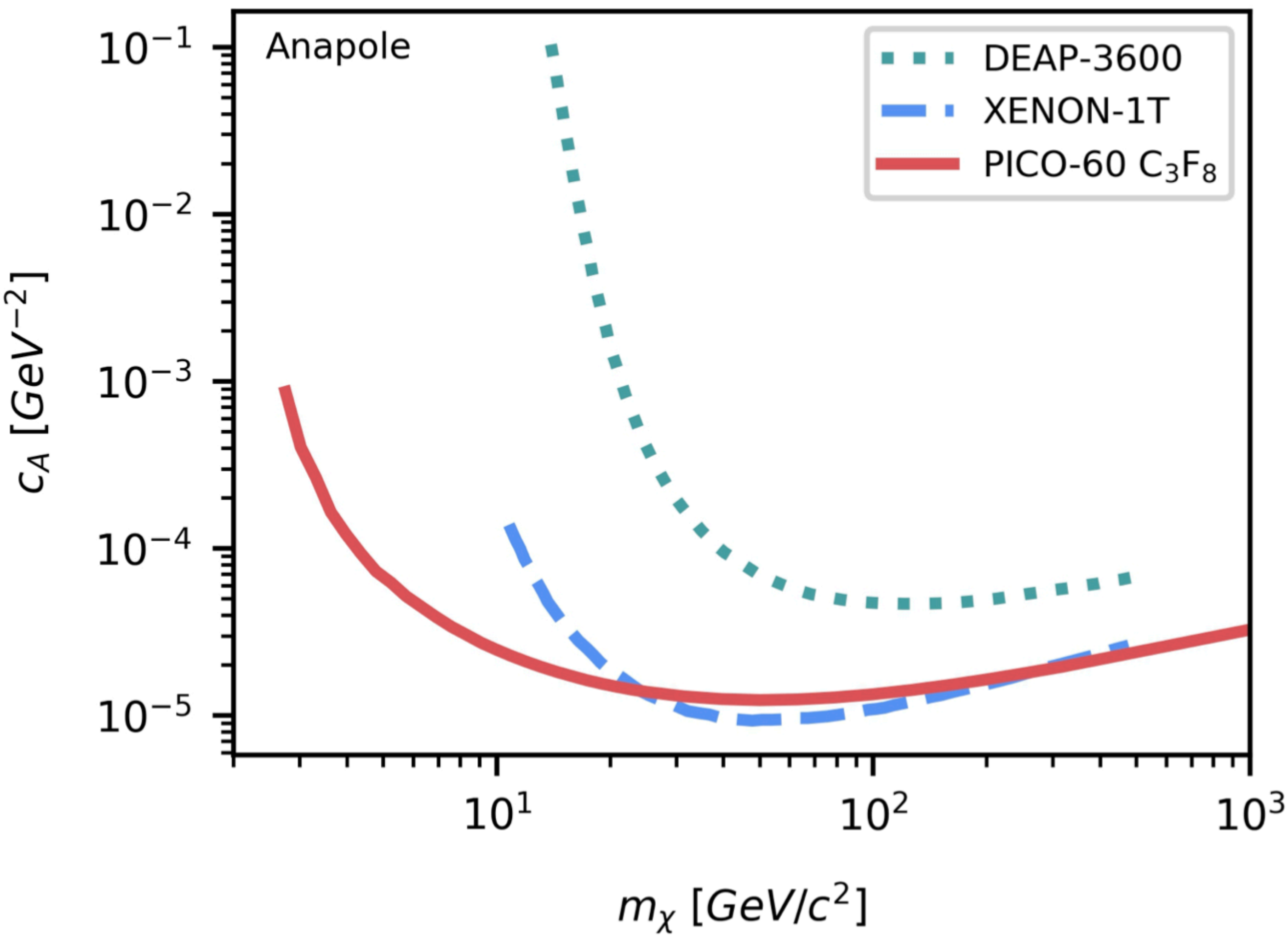
$\mathcal{O}_9 = i\vec{S}_{\chi} \bullet (\vec{S}_N \times \frac{\vec{q}}{m_N})$ momentum dependent

$$\sigma_{\mathcal{A}} = \frac{c^2{}_{\mathcal{A}} \mu^2{}_N}{\pi}$$

- Due to the interesting nature of this coupling, limits using the PICO-60 data were studied

Anapole moment in PICO: results

The only possible electromagnetic moment for a Majorana fermion is the anapole moment since the magnetic and electric dipole moments vanish



Electric and magnetic moments

- Long-range interactions ($|\vec{q}| \gg m_\phi$), where m_ϕ is the mass of the mediator, are enhanced at small momentum transfer
- Examples of long-range interactions are DM with magnetic/electric dipole moments and millicharged DM

$$\mathcal{L}_{\mathcal{MD}} = \frac{\mu_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} \qquad \mathcal{O}_{\mathcal{MD}} = 2e\mu_\chi \sum_{N=n,p}\left[Q_N m_N \mathcal{O}_1 + 4Q_N \frac{m_\chi m_N}{q^2}\mathcal{O}_5 + 2g_N m_\chi \left(\mathcal{O}_4 - \frac{1}{q^2}\mathcal{O}_6\right)\right]$$

$$\mathcal{L}_{\mathcal{ED}} = \frac{d_\chi}{2} i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu} \qquad \mathcal{O}_{\mathcal{ED}} = 2ed_\chi \frac{1}{q^2}\mathcal{O}_{11}$$

μ_χ: is the magnetic moment coupling in units of μ_B

$$\boxed{\sigma_{\mathcal{MD}(\mathcal{ED})} = \frac{\mu^2{}_\chi}{\pi}}$$

d_χ: is the electric dipole moment coupling in units of $e \cdot cm$

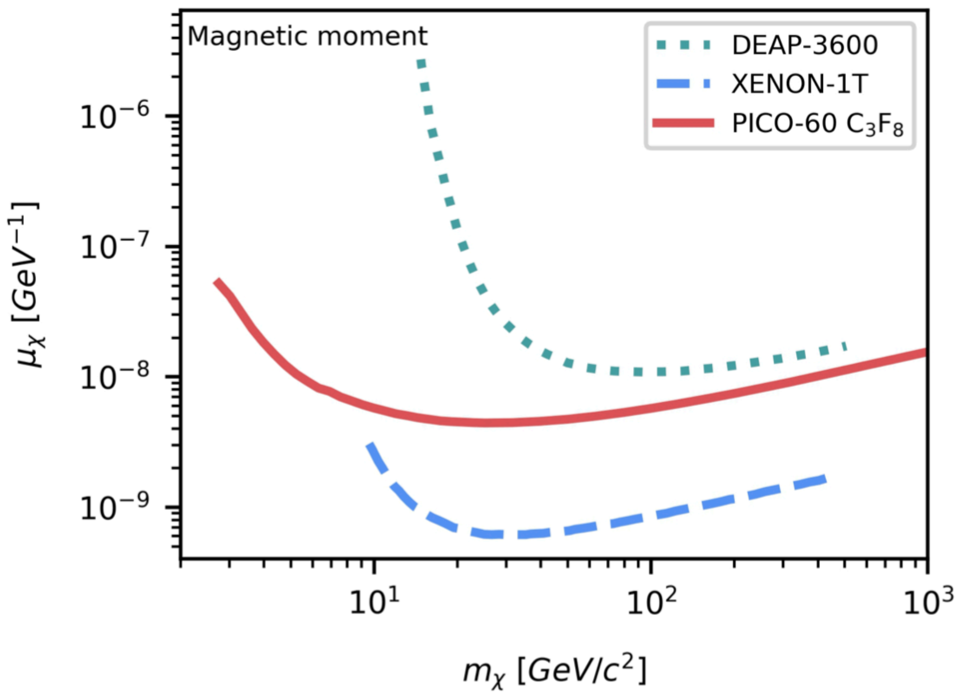
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N \qquad \mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \qquad \mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

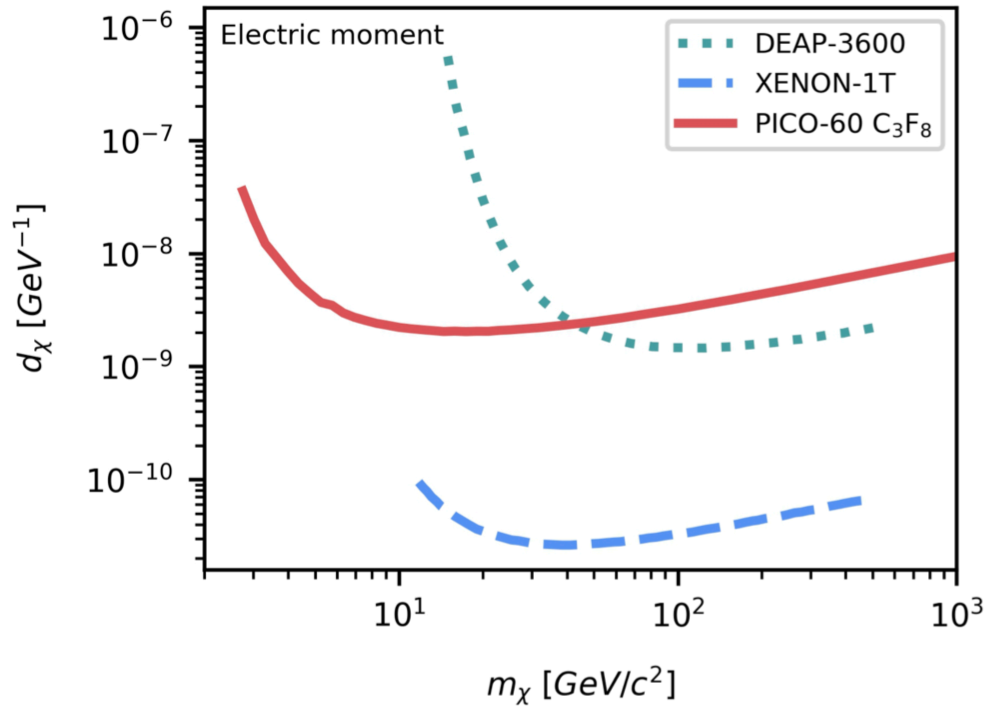
Electric and magnetic moments in PICO: results

Assuming DM is a fermion with electromagnetic moments, the lowest order electromagnetic interaction is through the magnetic or electric dipole moments

Magnetic dipole



Electric dipole



Millicharged DM

- Millicharged particles have attracted interest since they represent elegant extensions to the SM

$$\mathcal{L}_{\mathcal{M}} = e\epsilon_{\chi} A_{\mu} \bar{\chi} \gamma^{\mu} \chi \qquad \mathcal{O}_{\mathcal{M}} = e^2 \epsilon_{\chi} \frac{1}{q^2} \mathcal{O}_1$$

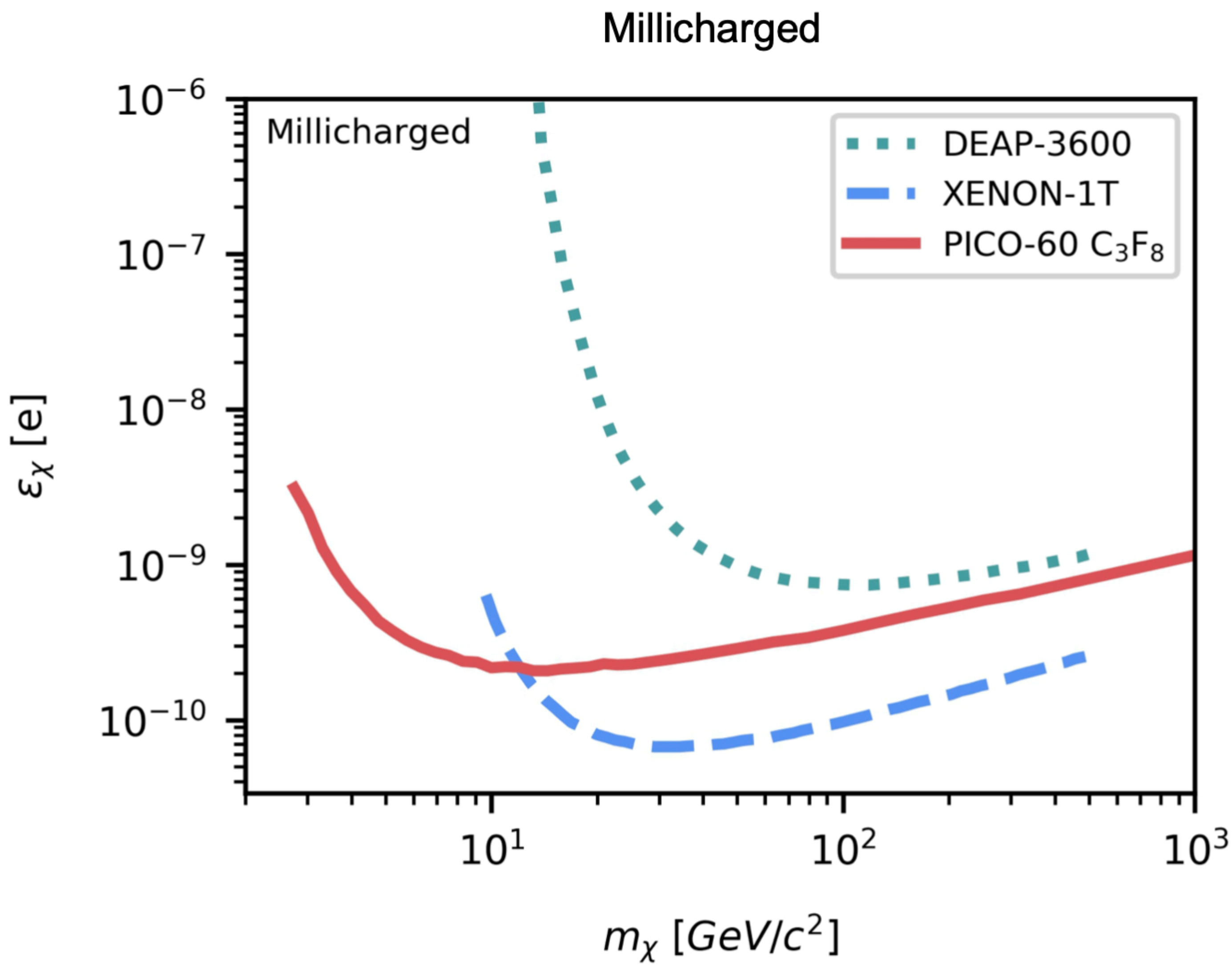
ϵ_{χ}: is the millicharge fraction of the electron charge

$$\mathcal{O}_1 = 1_{\chi} 1_N$$

$$\sigma_{\mathcal{M}} = \frac{\epsilon^2{}_{\chi}}{\mu^2{}_N \pi}$$

eps $= \epsilon_{\chi}$

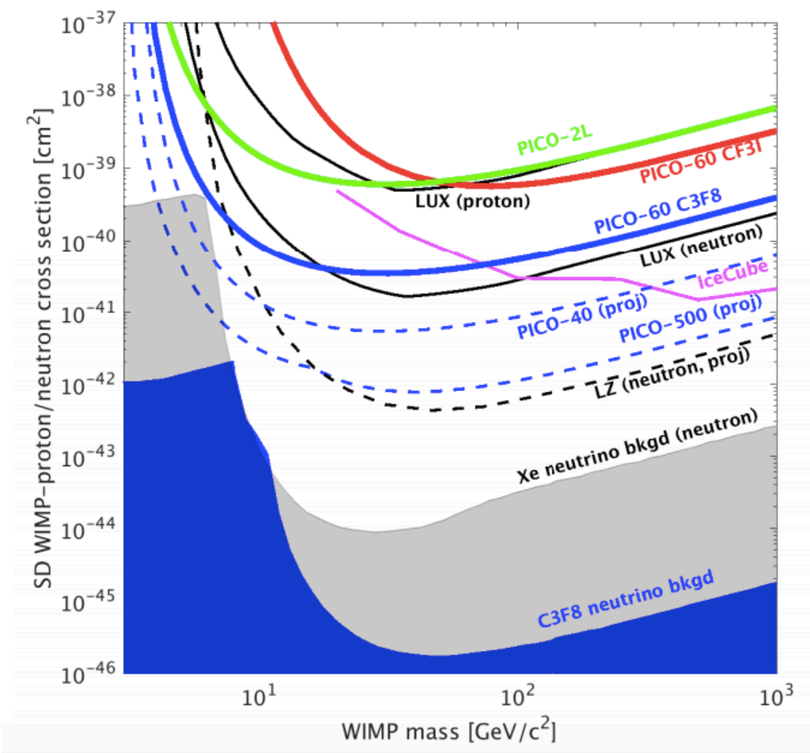
Millicharged DM in PICO: results

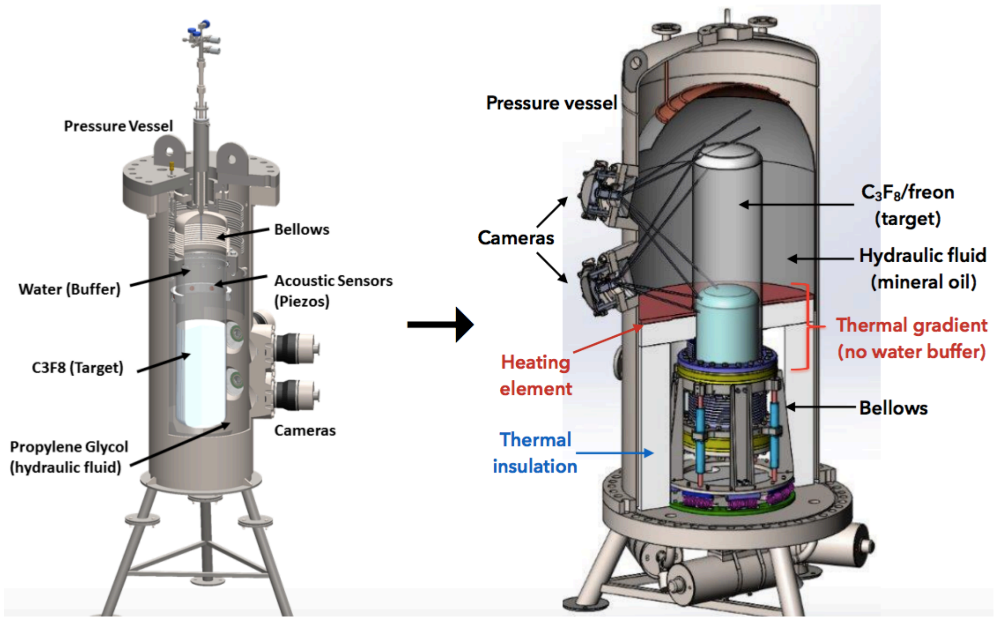


Results on photon-mediated dark-matter–nucleus interactions from the PICO-60 C3F8 bubble chamber
Phys. Rev. D 106, 042004 (2022)

PICO40L:"Right side up" (RSU)

- Engineering:
  demonstrate background reduction and technology improvements for PICO-500
  - Focus on (neutron) background reduction
  - Confirm "RSU" design used in prototype chambers

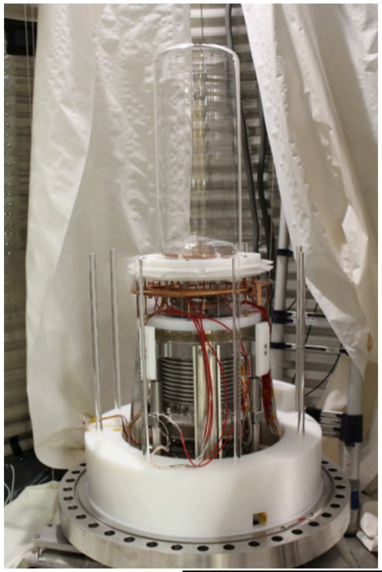


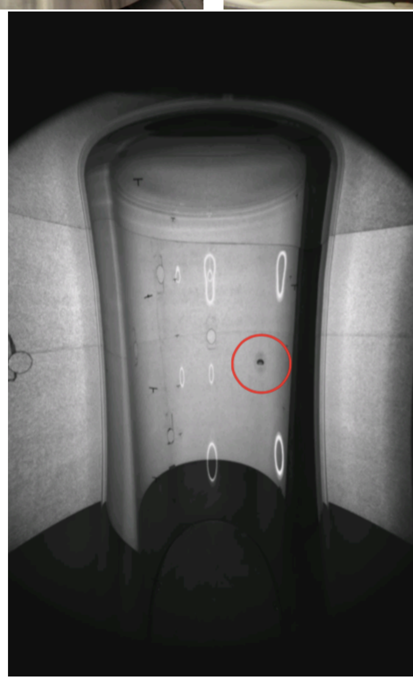


- Science:
  acquire one-year background-free exposure
  - Order of magnitude improvement on PICO-60 limits

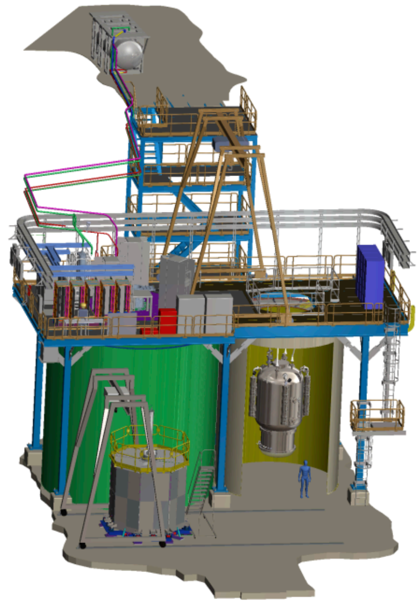
PICO-40L and PICO-500

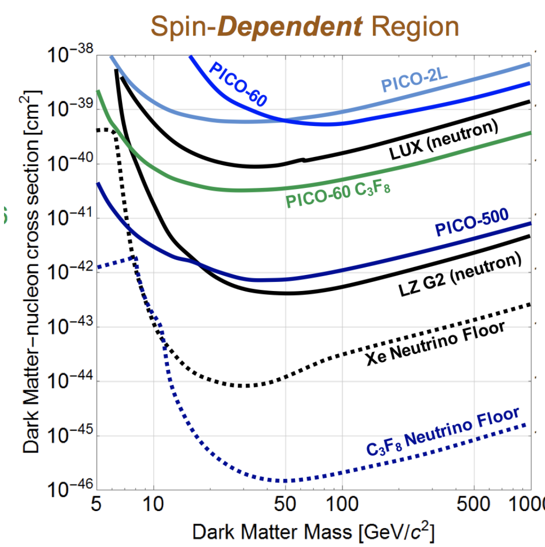
Commissioning new detector



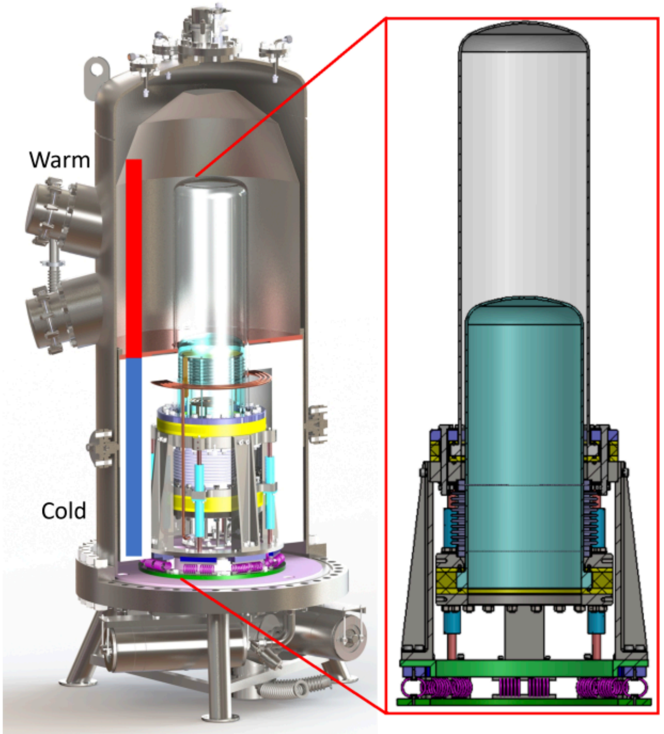


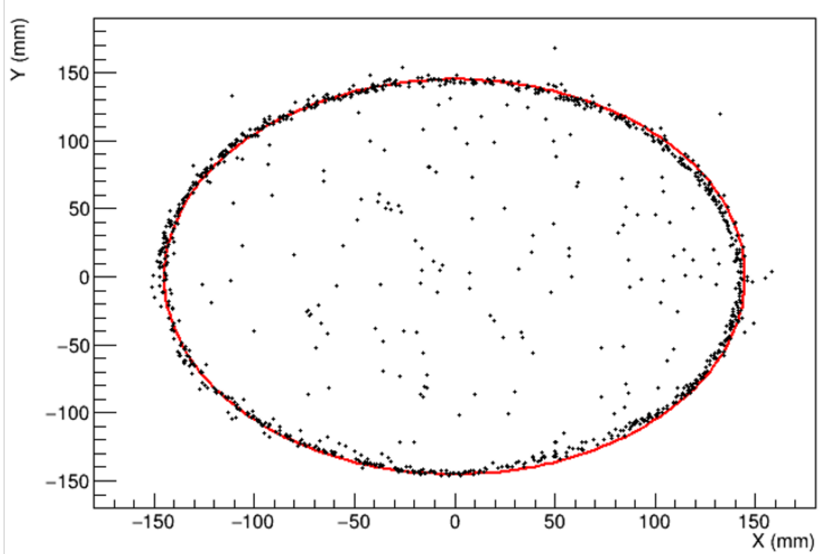
PICO-500 coming soon



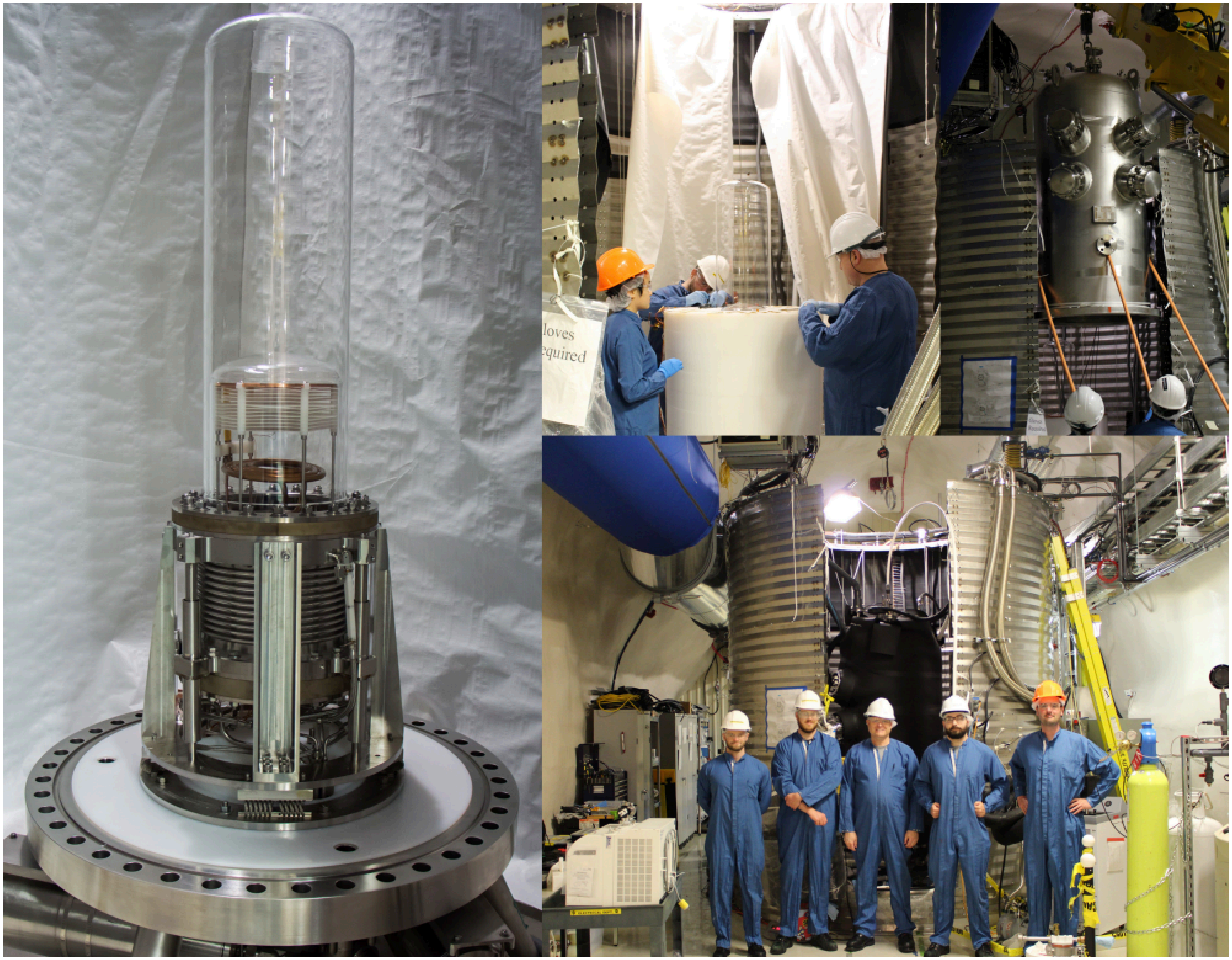


PICO-40L





PICO-40L

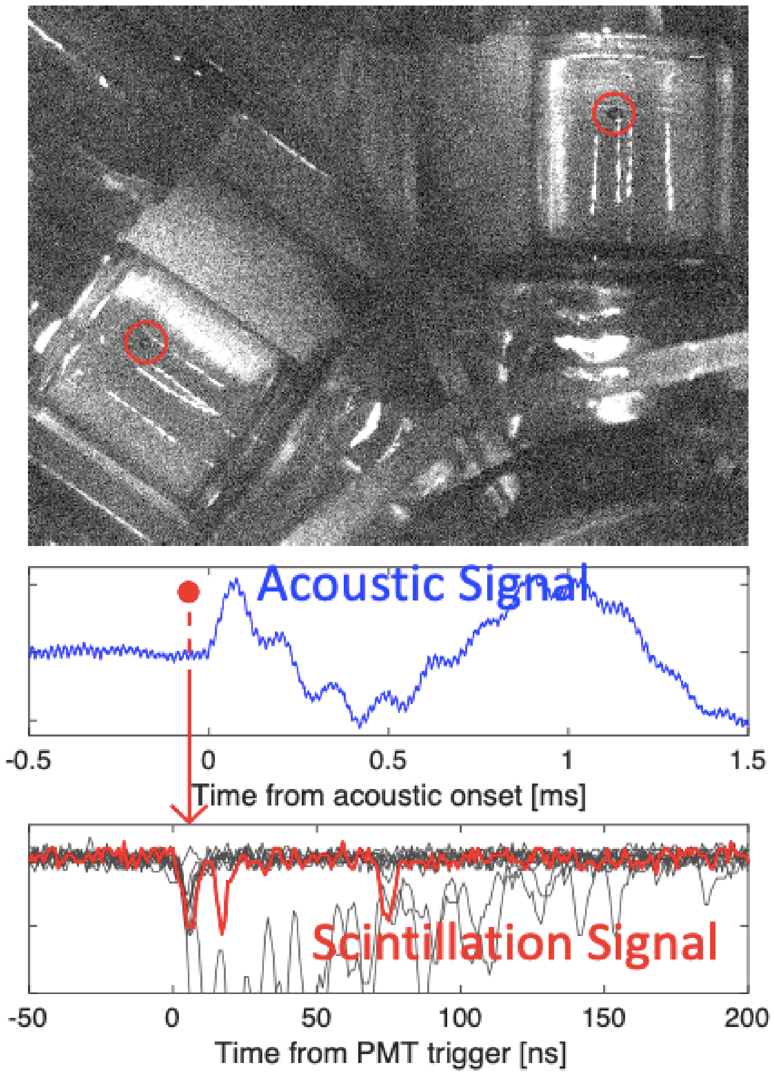


SBC: a 10 kg LAr bubble chamber for dark matter and CEνNS

First demonstration of SBC

Phys Rev Lett 118, 231301

A nuclear recoil:



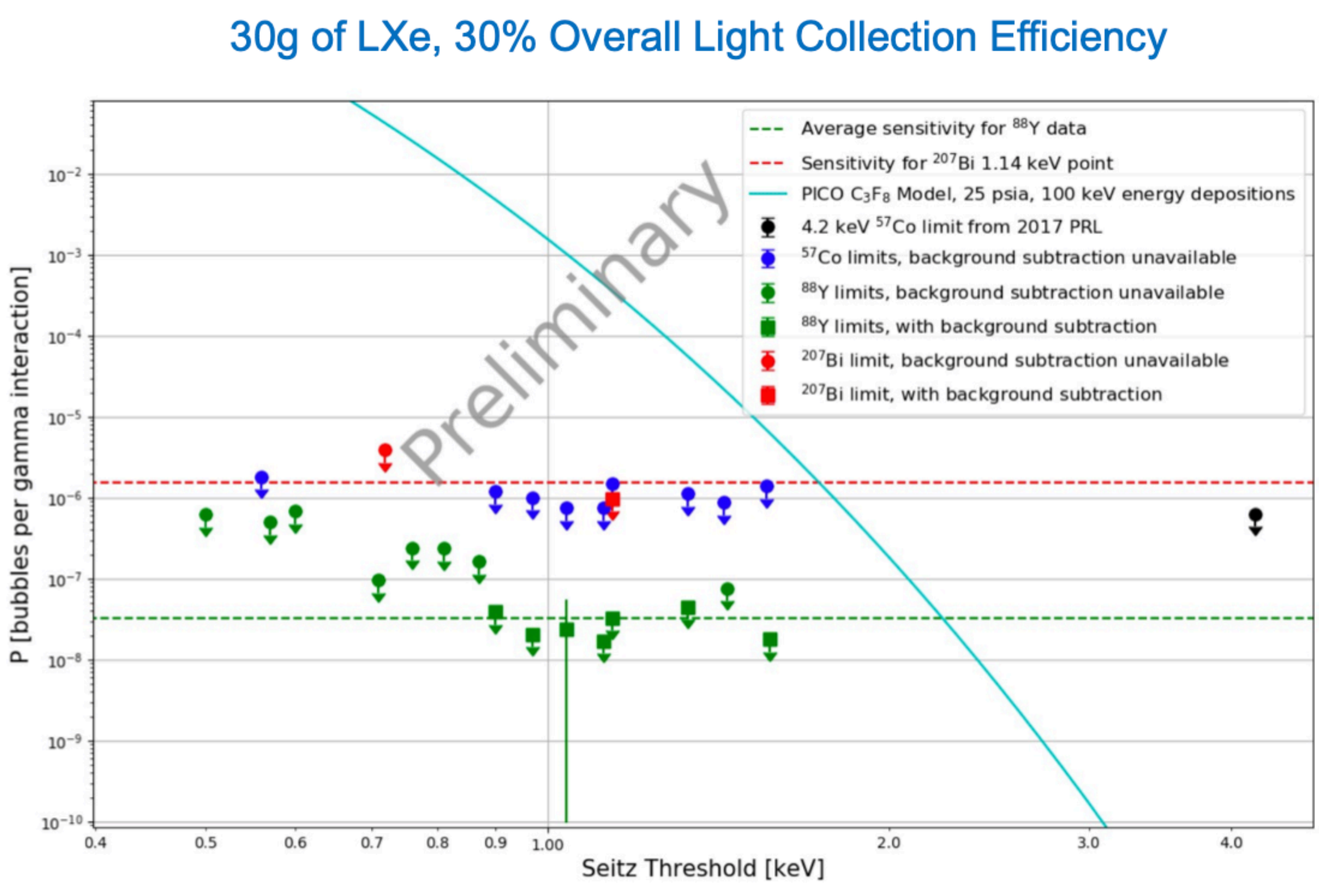
- Demonstrated (NU):
  - Xenon at 500 eV threshold
  - 30-gram target
  - 0.3% photon-detection efficiency

- 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

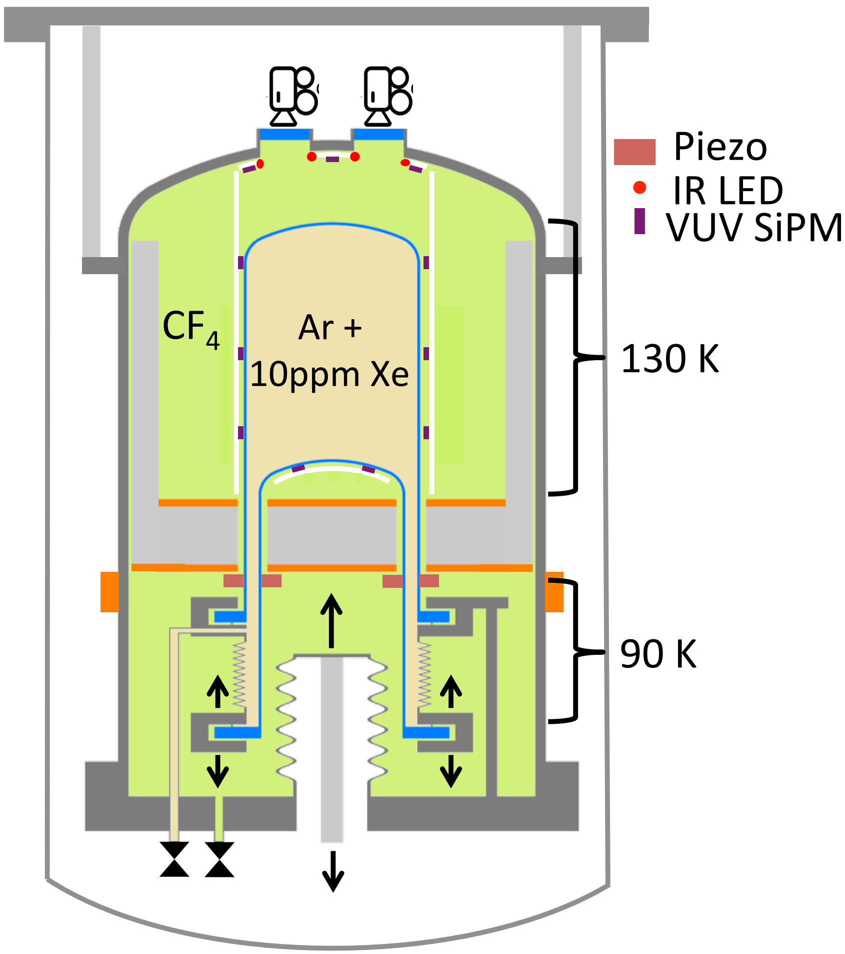
Xenon bubble chamber

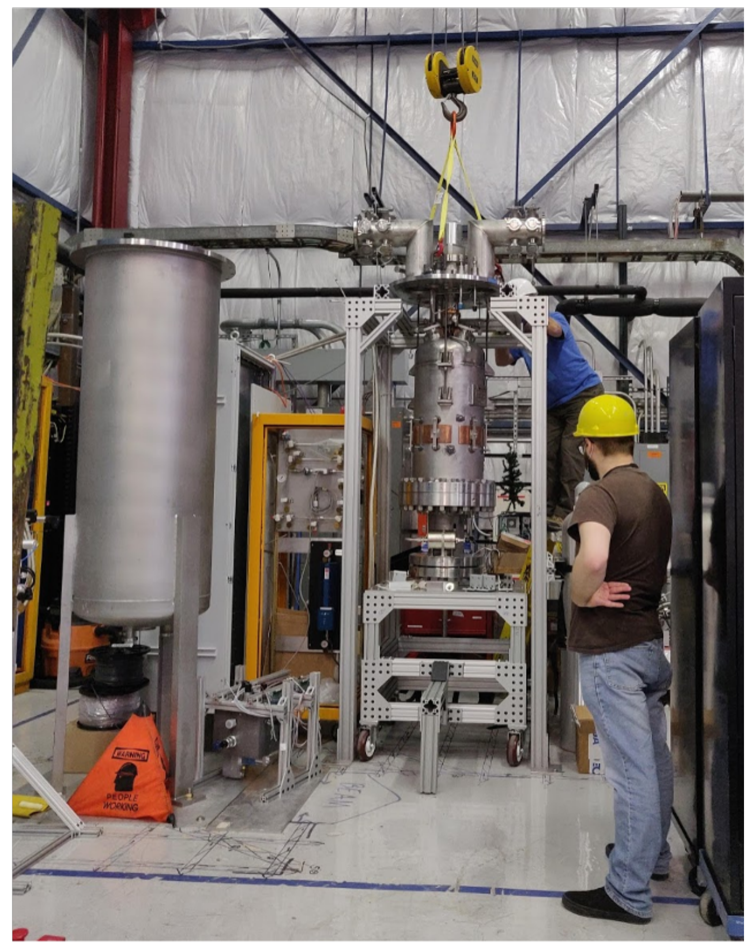
- **Xenon measured to have outstanding ER discrimination**
- **Thresholds explored down to 500 eV**
- **No gamma induced ER observed**
- **Xe bubble chambers don't work for tracks (J.L. Brown, D.A. Glaser and M.L. Perl, Phys Rev 102, 1956), "solved" by adding 2% ethylene.**



10 kg liquid Argon bubble chamber: 100 eV threshold

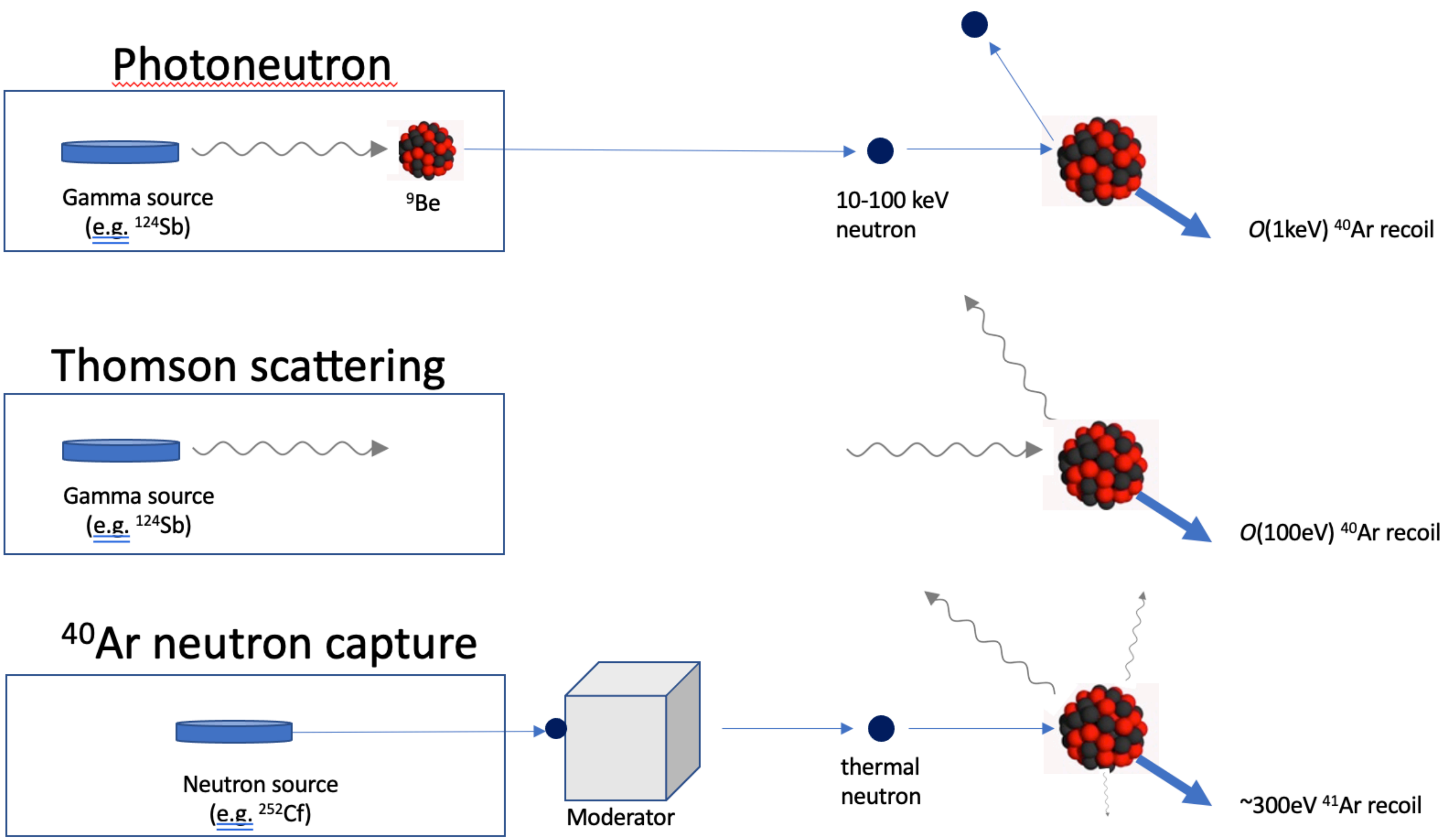
- Ar + 10-100 ppm Xe target, 178 nm scintillation
- SiPMs immersed in hydraulic fluid (CF4 at 130K)
- 20-360 psia (∼1-25 bar) cycles
- Single-fluid, "right-side-up" geometry used by PICO-40L



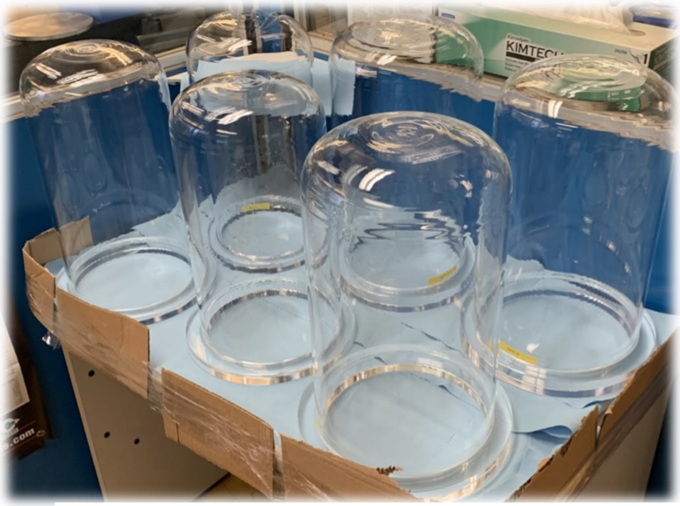


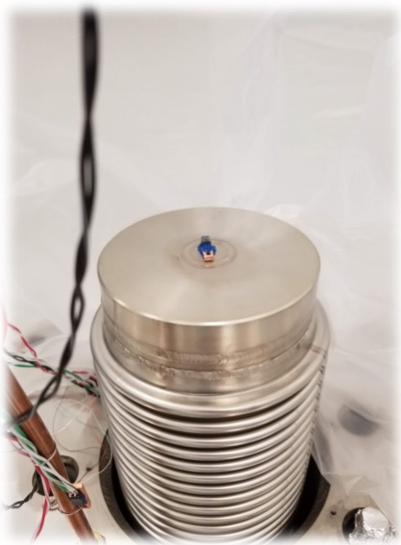
Calibration

- Different nuclear recoil calibration techniques



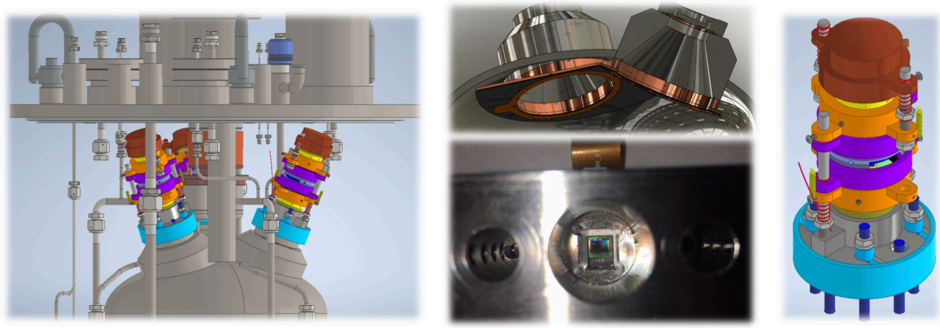
10 kg liquid Argon bubble chamber



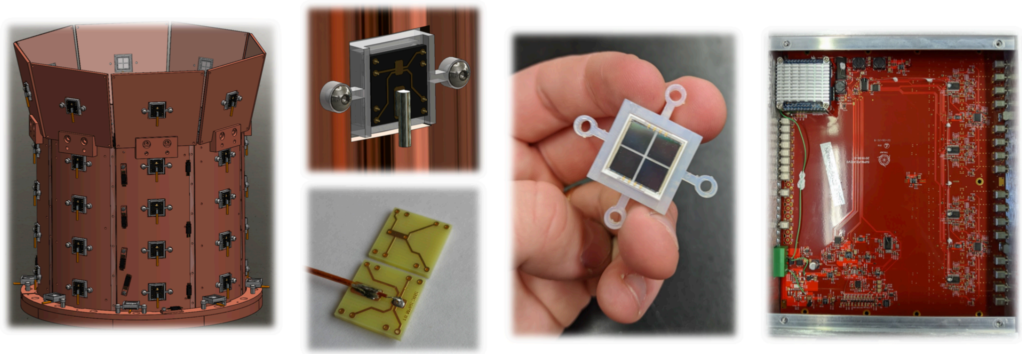


SBC-10kg: Readout systems

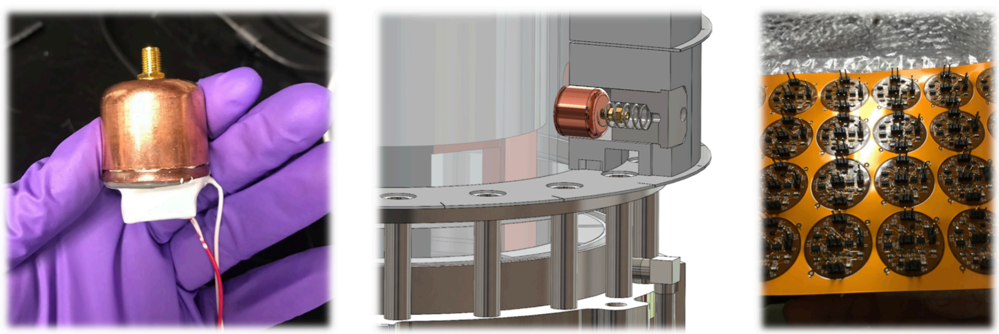
- **3 Raspberry-Pi controlled cameras and LED rings for illumination:**



- **32 Hamamatsu VUV4 Quads to measure scintillation light:**



- **8 piezo acoustic sensors to 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 Collaboration

Northwestern University

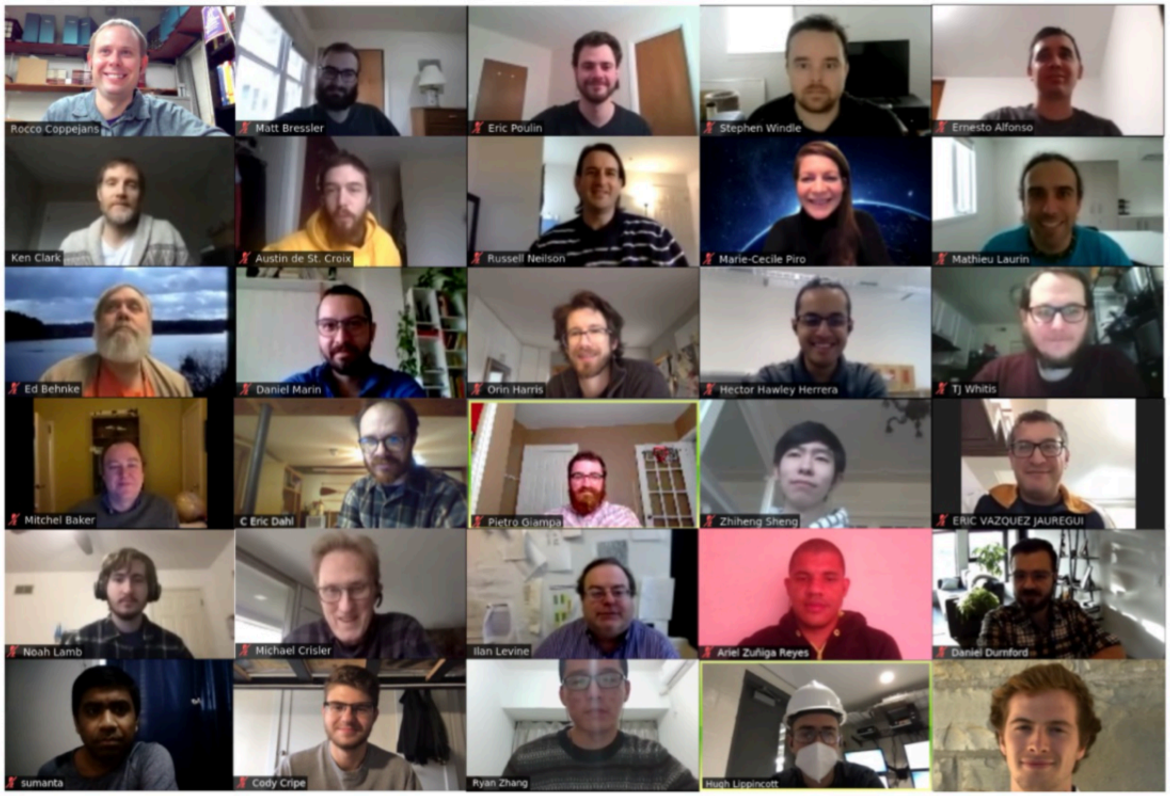
- **Eric Dahl**
- Rocco Coppejans
- Zhiheng Sheng
- Aaron Brandon
- David Velasco
- Ari Sloss
- Mahebub Khatri
- Dishen Wang
- Shishir Bandapalli

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

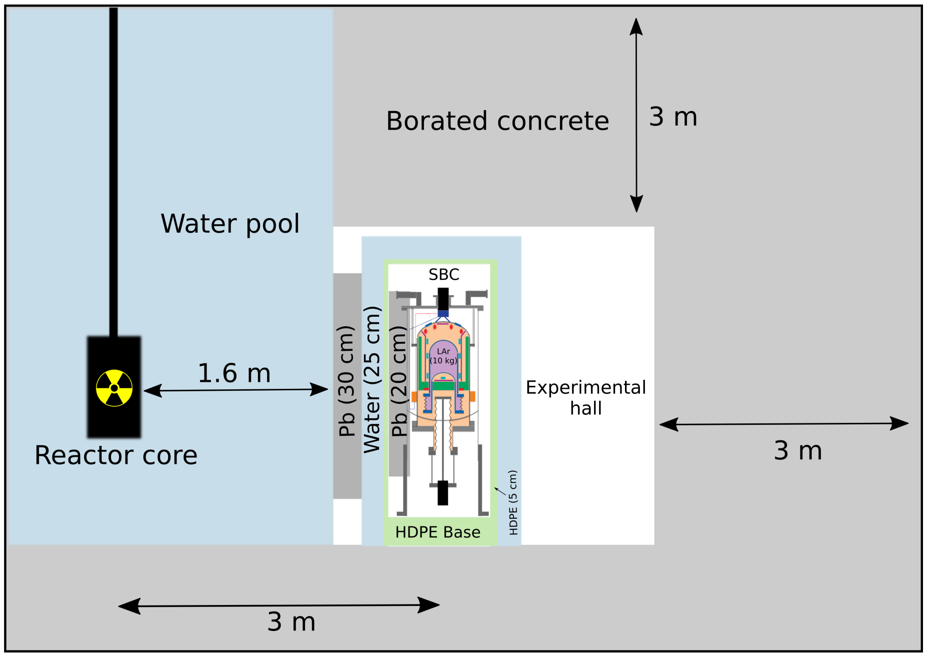
- Chris Jackson

Fermilab

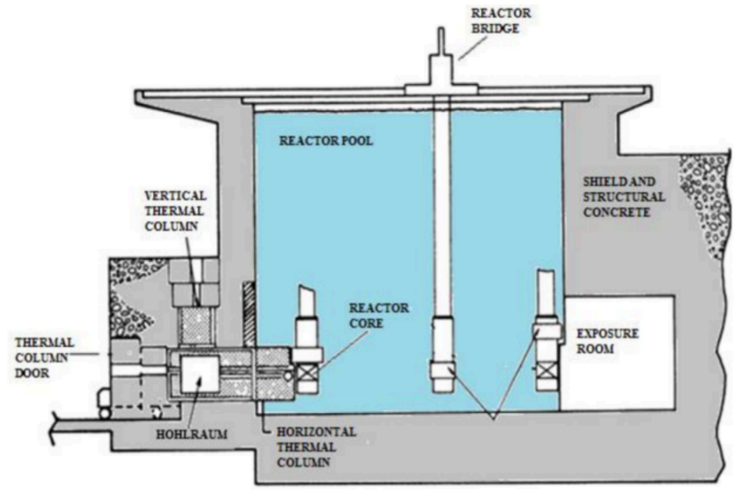
- Mike Crisler

SBC Collaboration 2022

SBC CEνNS: physics reach



ININ 1MW Triga Mark-III reactor in Mexico



ININ exposure room

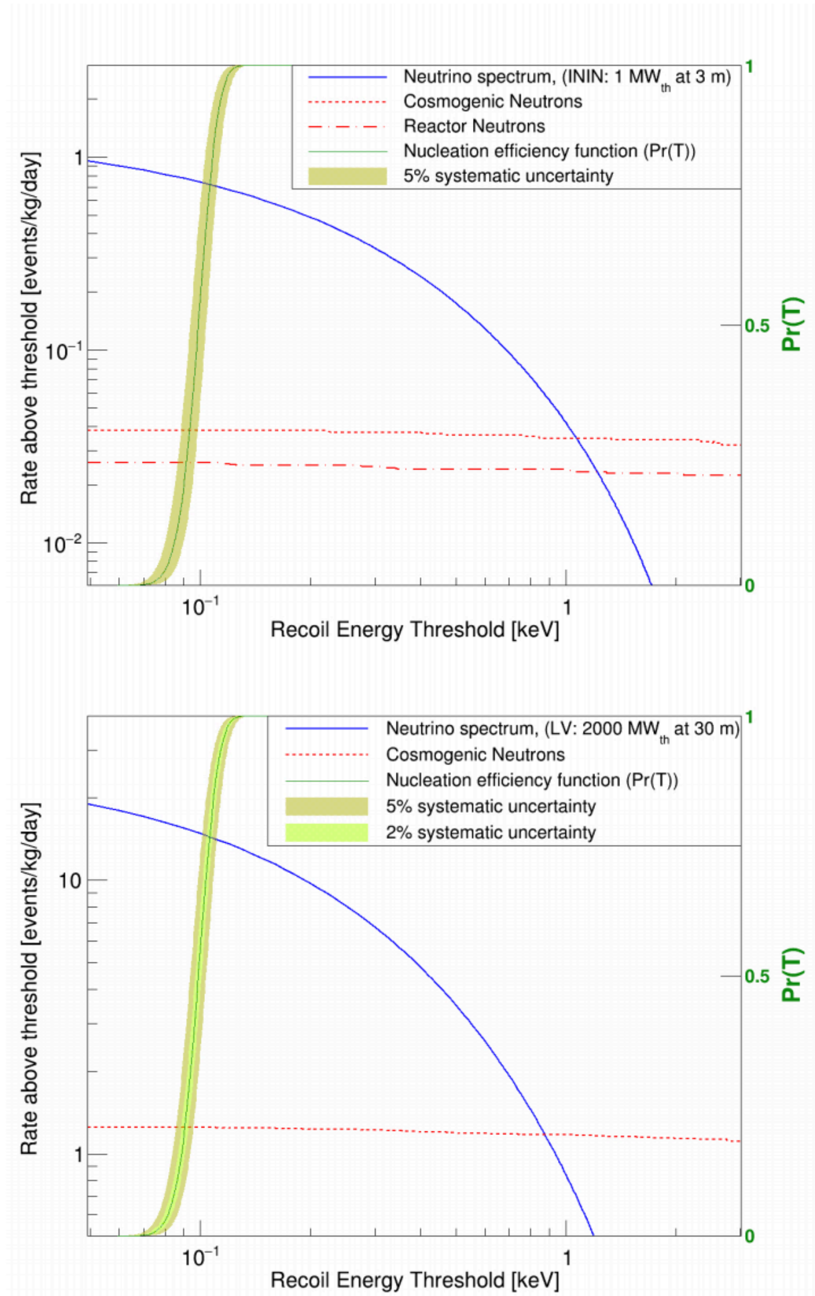
- **Two sites explored: ININ and Laguna Verde**

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

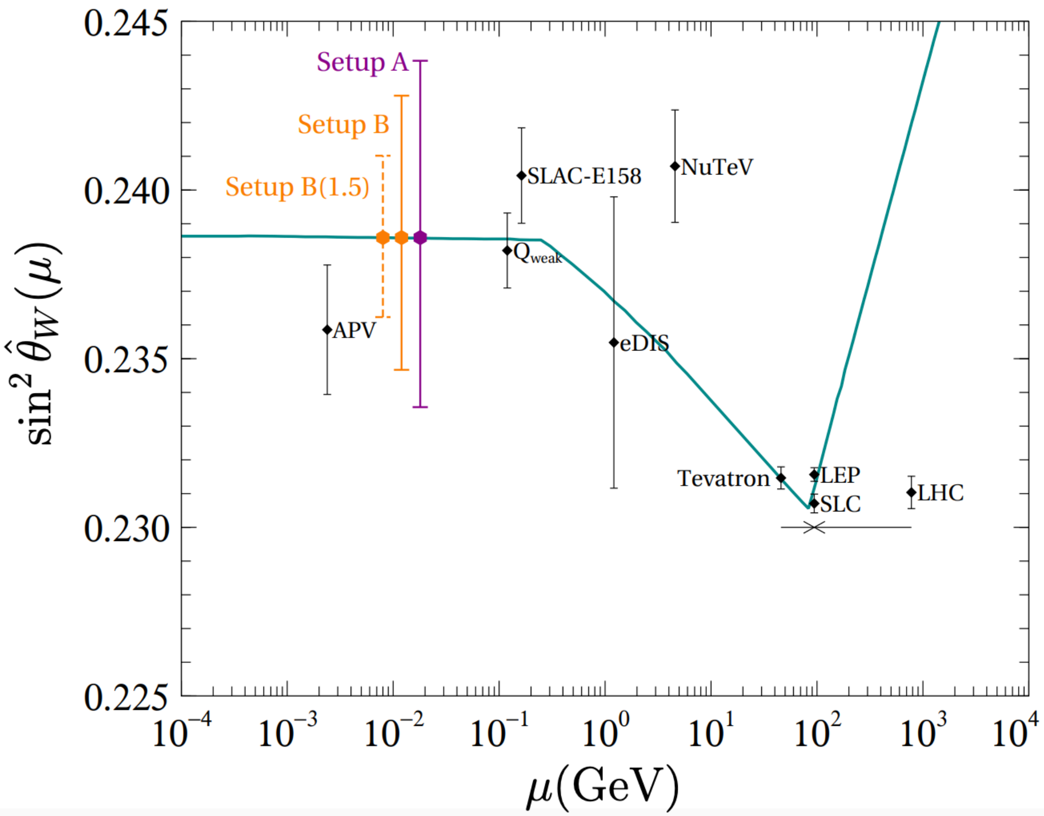
SBC Physics: CEνNS reach

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



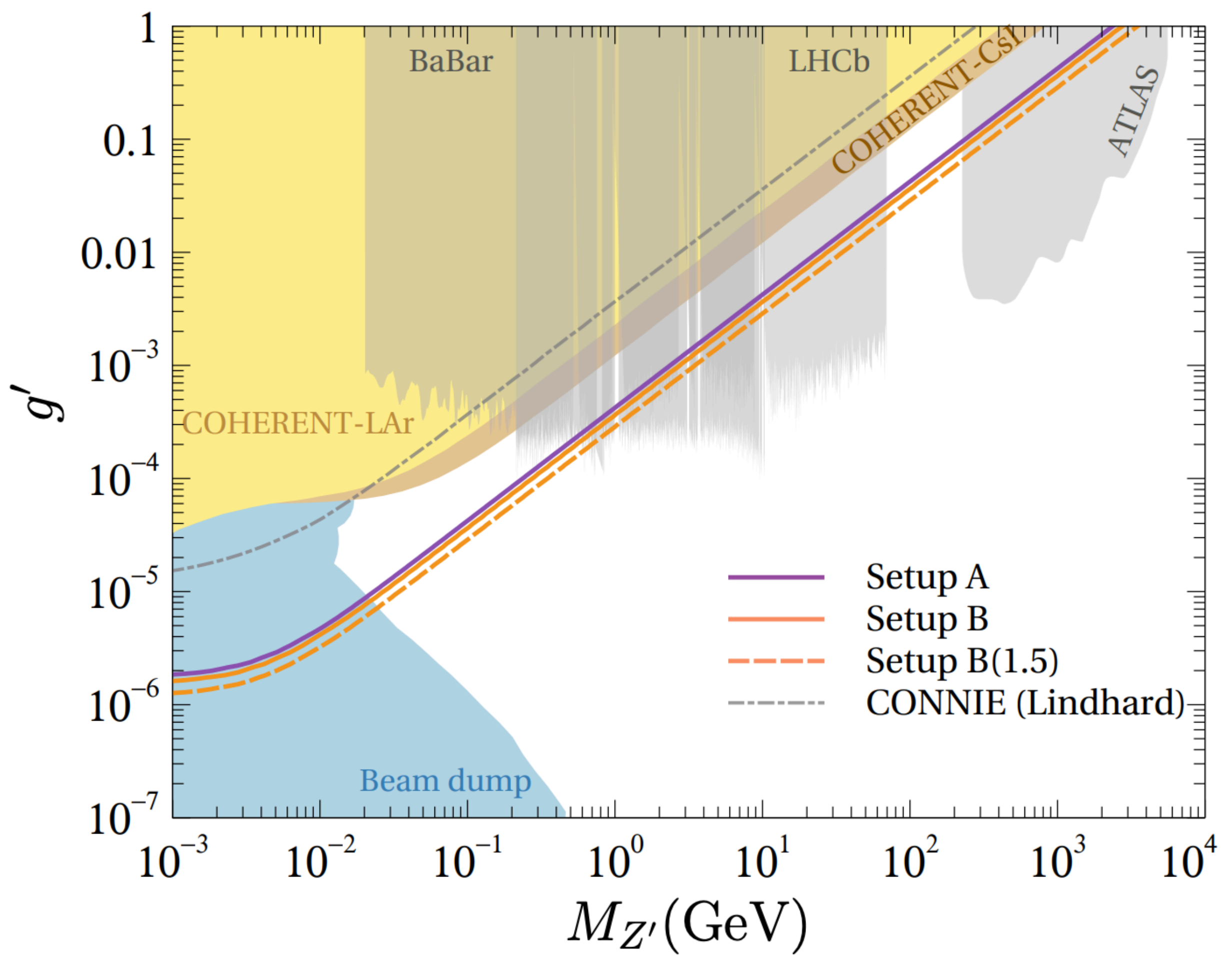
SBC CEνNS Physics: weak mixing angle



- **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)**

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

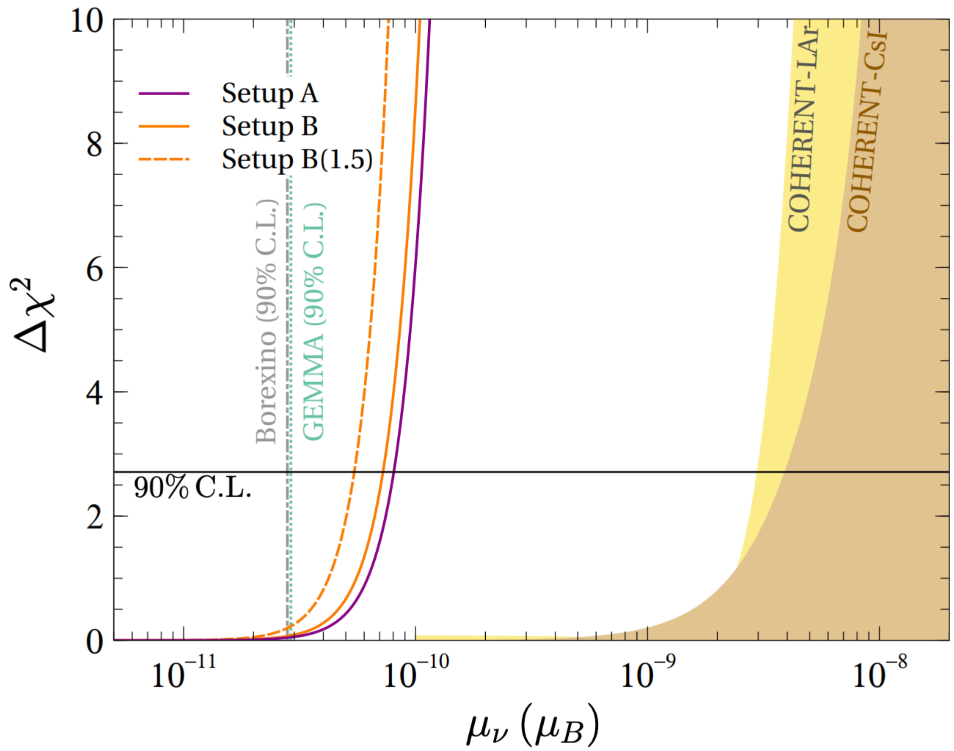
SBC CEνNS Physics: Z' boson



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

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

SBC CEνNS Physics: ν magnetic moment

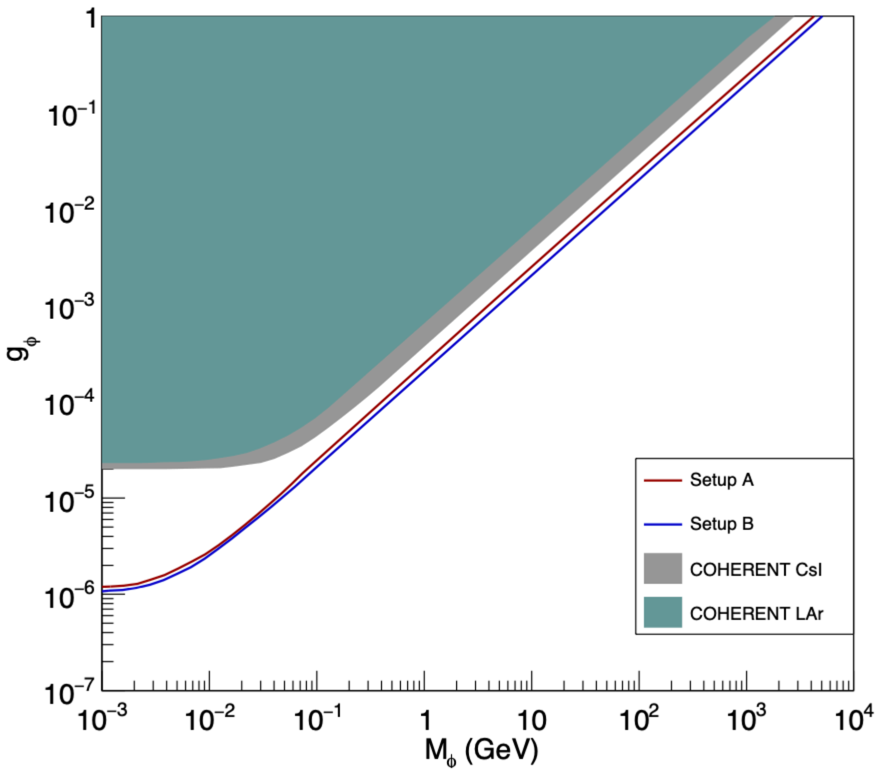


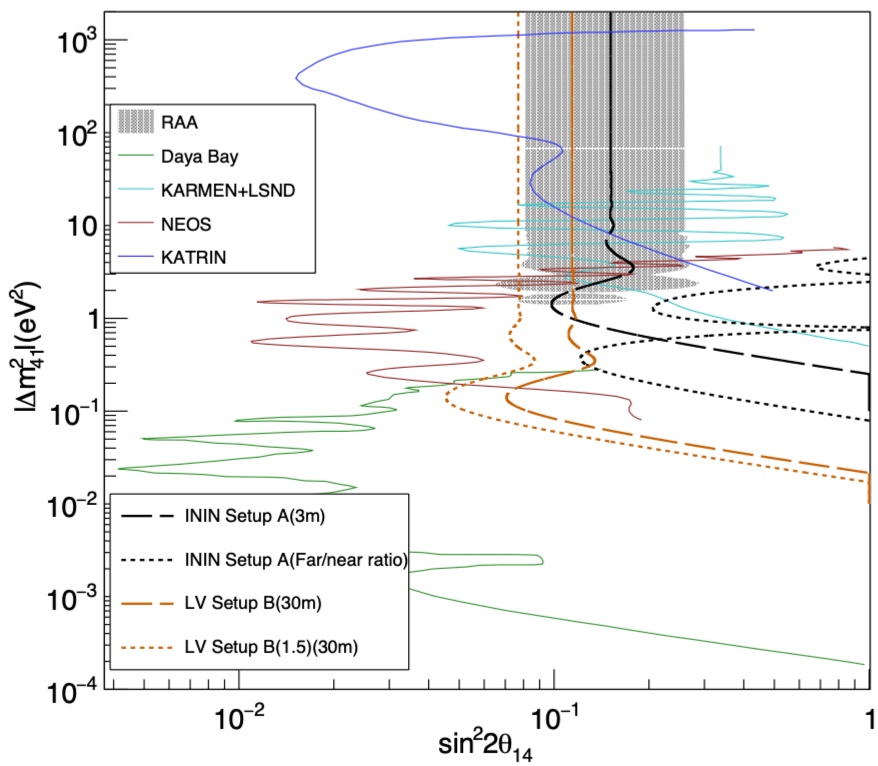
- $\mu_\nu = 5.4 \times 10^{-11} \mu_B$ **(90% C.L.), similar to GEMMA and Borexino.**

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

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

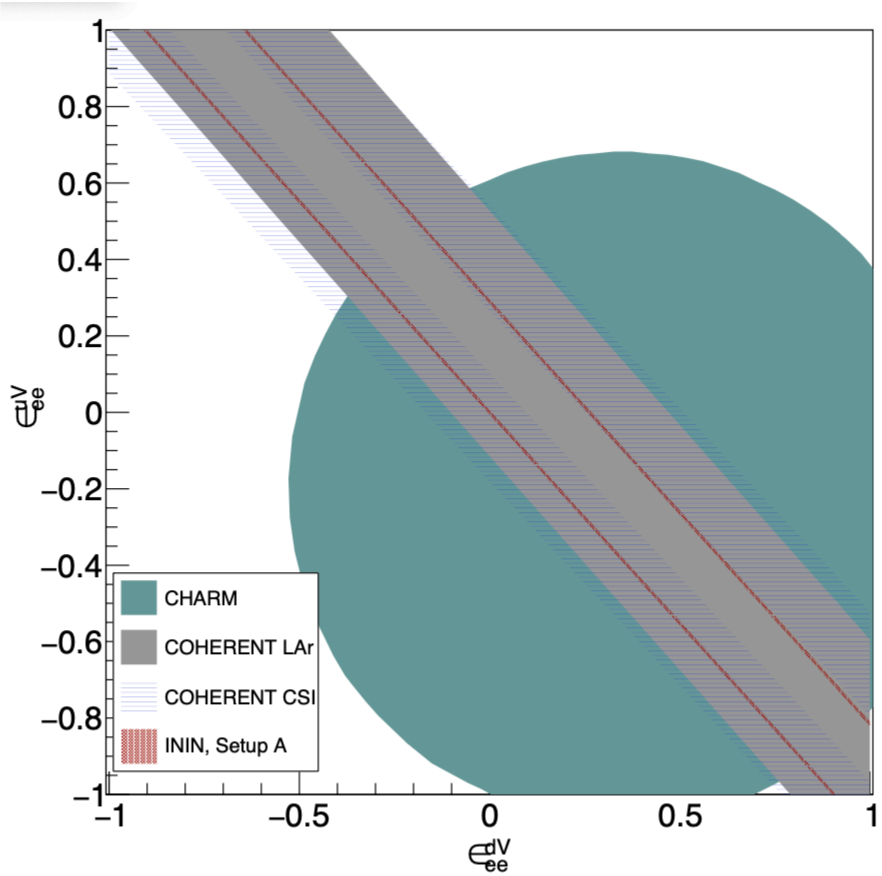


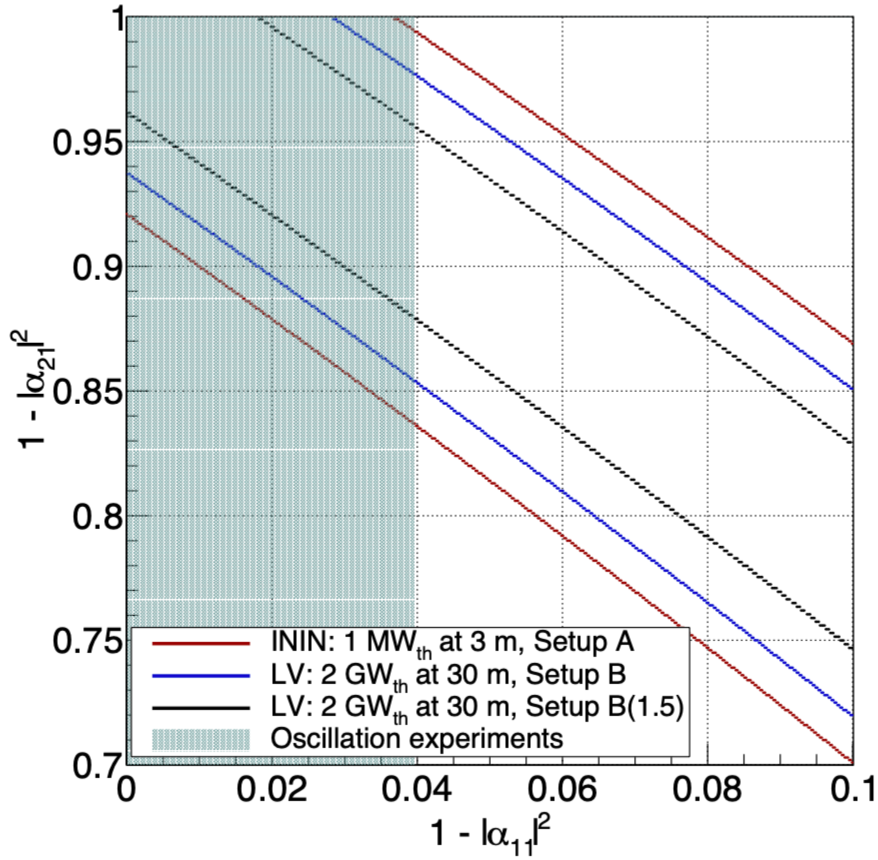


Light scalar mediators

Sterile neutrino oscillations

SBC CEνNS: New Physics





Non-standard interactions

Unitarity violation

New Physics searches in a low threshold scintillating argon bubble chamber measuring coherent elastic neutrino-nucleus scattering in reactors
Phys. Rev. D 105, 113005 (2022)

Lab DM-ν and spectroscopy at IFUNAM

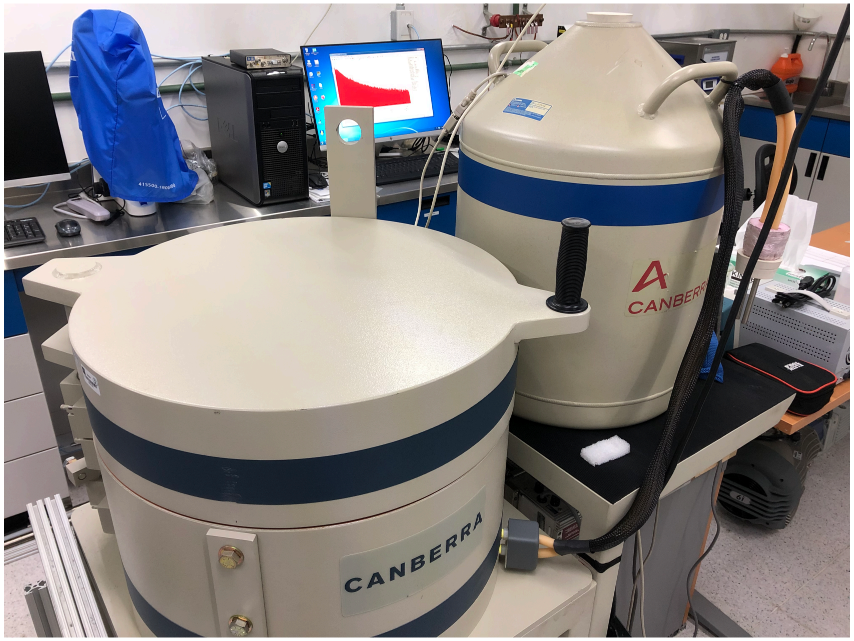
Spectroscopy and low background counting at IFUNAM

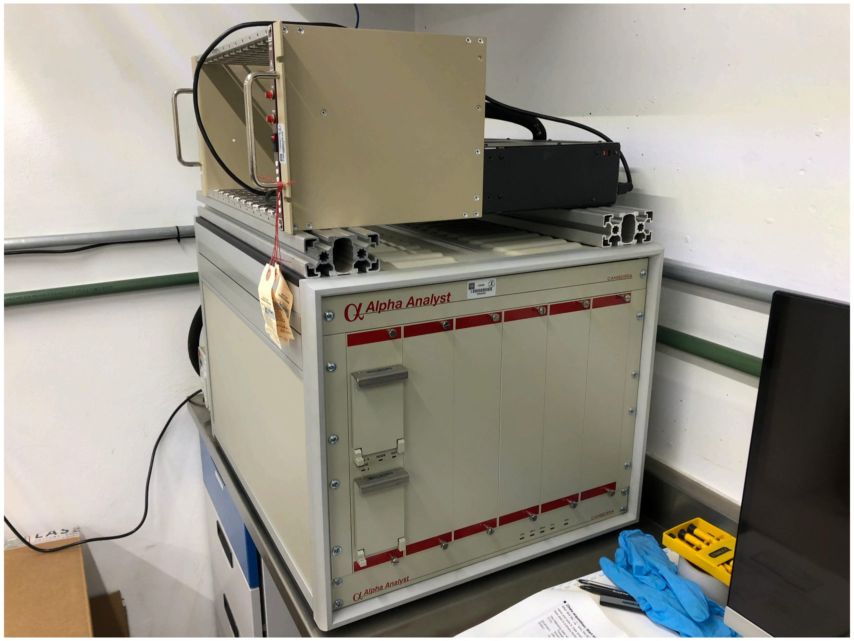
- **Germanium detectors:**
  Gamma assay

- **Alpha counters:**
  alpha spectroscopy

- **Assay programme at IFUNAM**

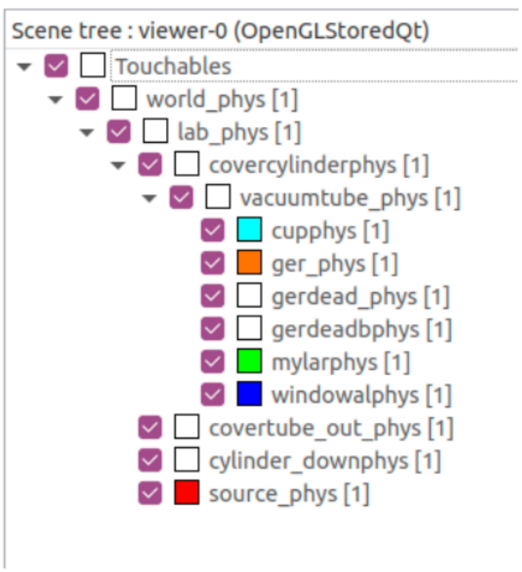
- **Applications to**
  environmental radioactivity

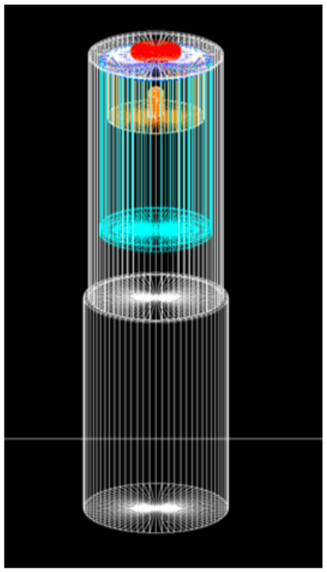


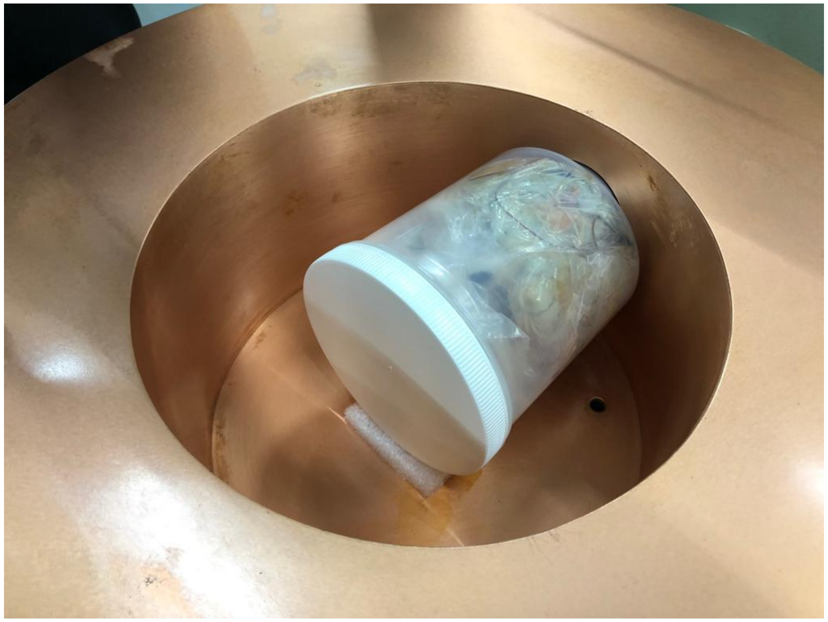


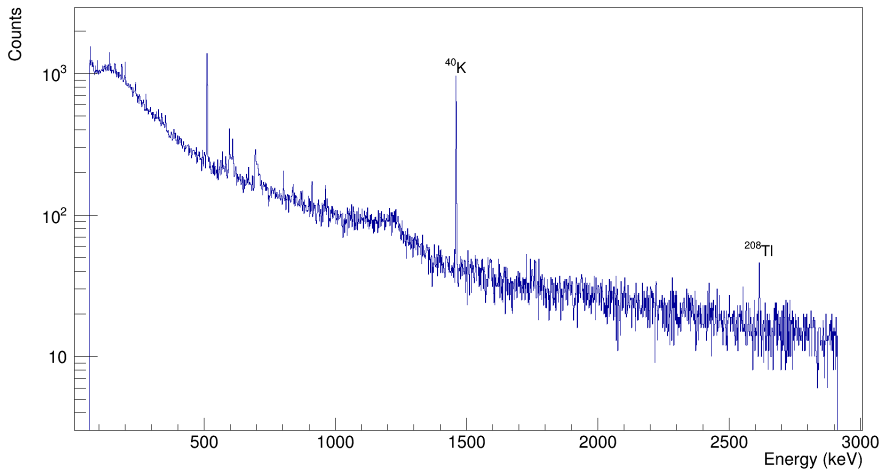
Detector characterization and Monte Carlo simulations

- **Four Germanium detectors: two undergrad thesis**
- **Three laboratory courses: environmental radioactivity**
- **Several projects: prototype bubble chamber scintillator detector**



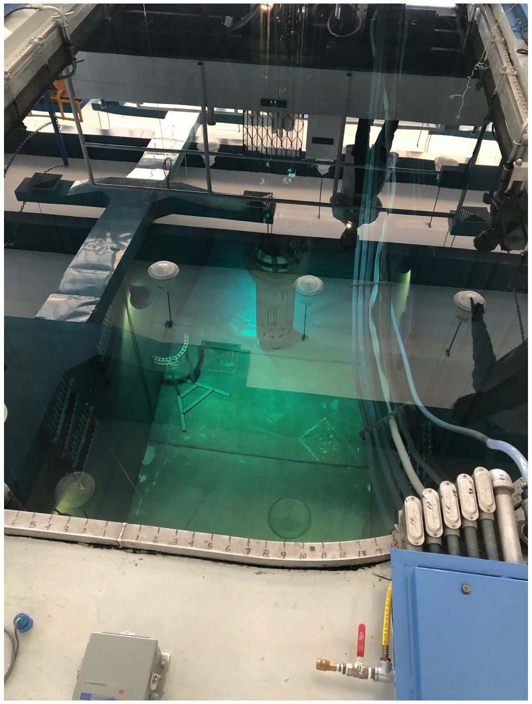






Scintillator detector at ININ

- Liquid scintillator detector:
  Two modules,
  60cm x 60cm x 30cm,
  100 lts per module,
  0.25% Gd loaded scintillator

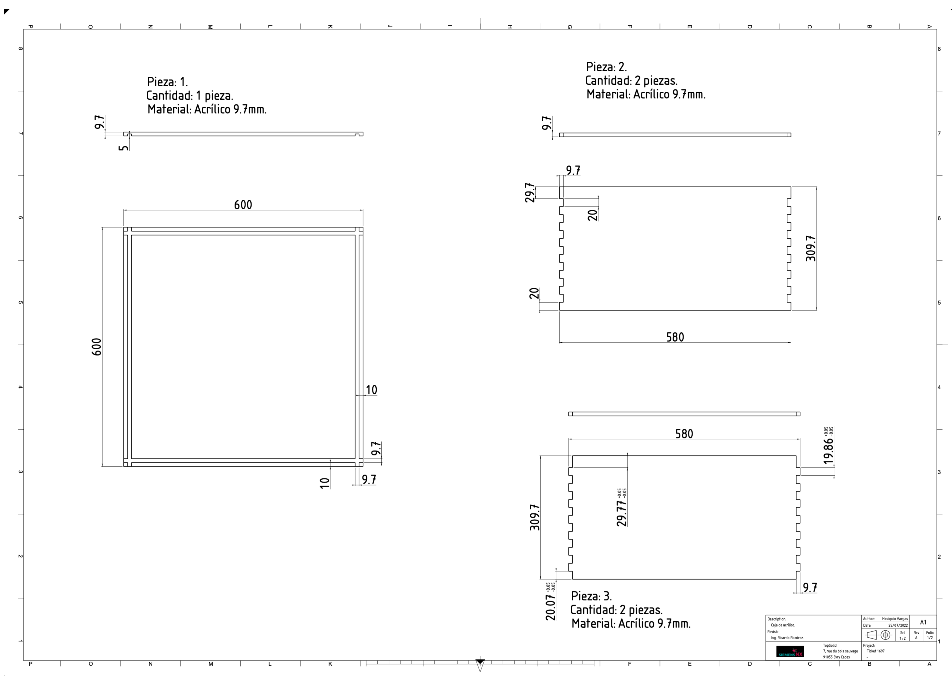


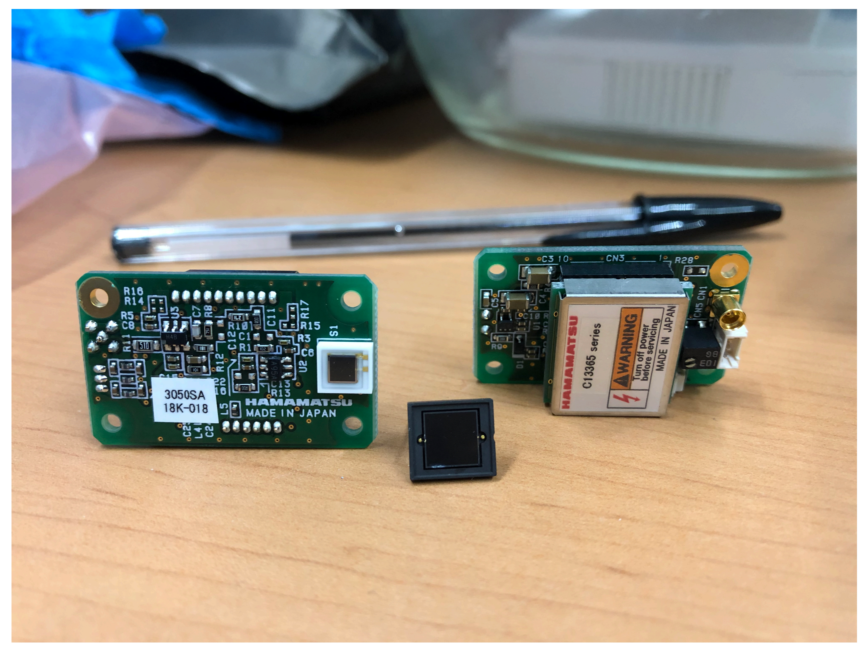
- Measure IBD:
  Tagging coincidence,
  $\boldsymbol{\nu + p \rightarrow n + e^{+}}$

- Background characterization:
  Cosmic: neutrons, muons, γ's
  Reactor: neutrons and γ's

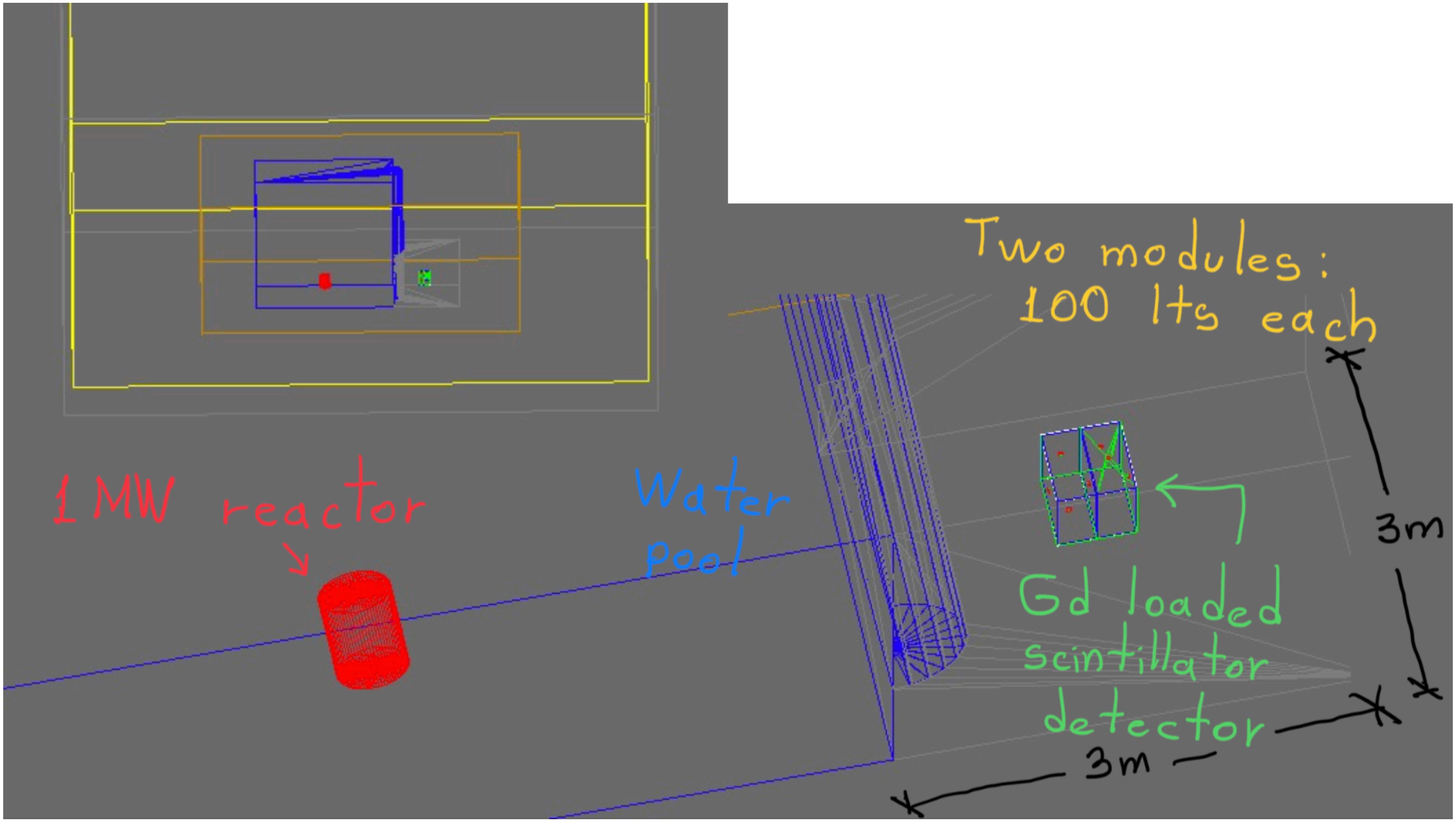
Scintillator detector at ININ

- Cast acrylic:
  Gamma and alpha assay
- Light detection:
  8 SiPMs, CAEN digitizer, MIDAS
  Considering to install 8 extra SiPMs
  Gamma and alpha assay



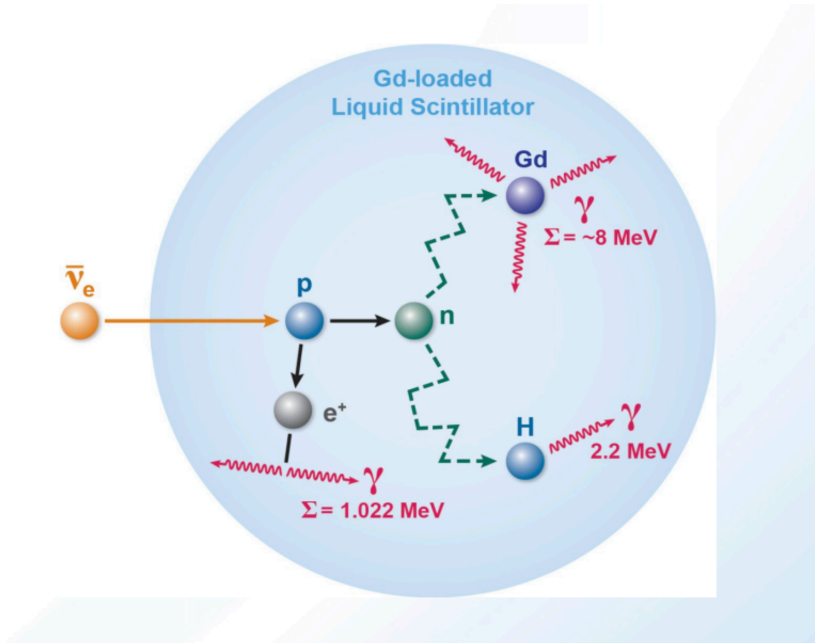


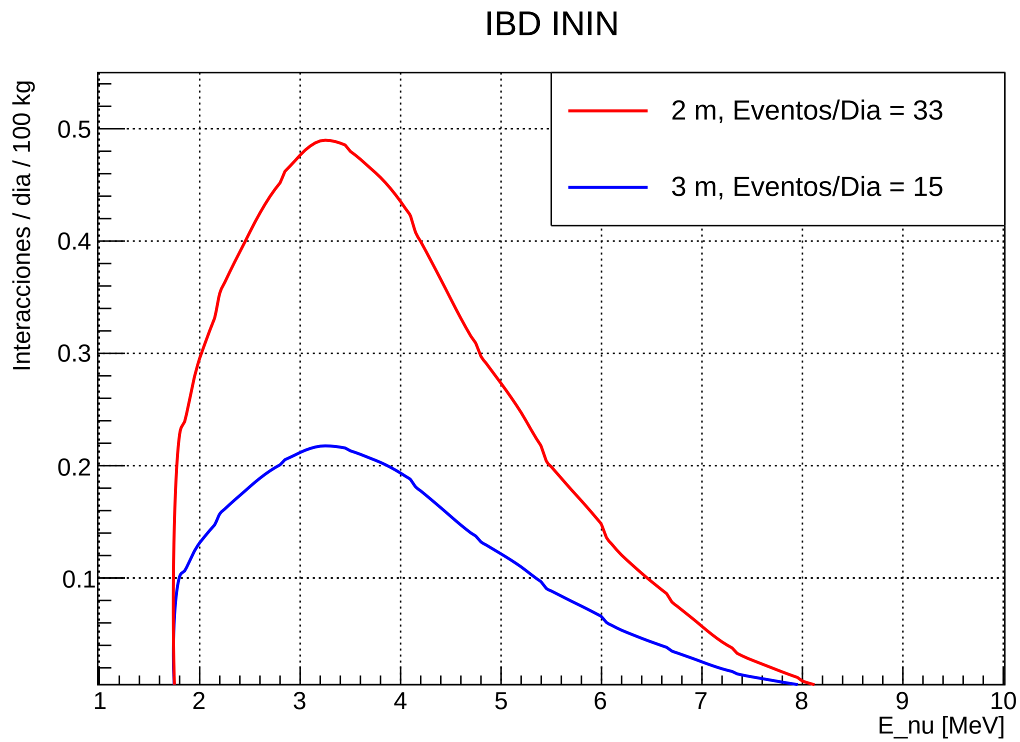
Detector design and modelling



GEANT4 simulations underway to estimate backgrounds from cosmogenics and reactor

Expected signal





Still like Cowan and Reines, but 66 years later!
This could represent the first observation of neutrinos in Mexico
Background assessment in the vicinity of the reactor for SBC

Final remarks

- **PICO bubble chambers are producing world leading direct detection limits using flourine targets:**
  - **Best limits for spin-dependent WIMP-proton constraints**
  - **Leading results on photon-mediated DM–nucleus interactions**

- **SBC is a 10 kg LAr bubble chamber: potential for background-free DM and reactor CEνNS measurements**
  - **Rich CEνNS physics programme: weak mixing angle, Z' boson, neutrino magnetic moment, oscillations, Unitarity violation, NSI**

- **Infrastructure and instrumentation in Mexico:**
  - **Lab DM-ν: spectroscopy and applications to environmental radiation**
  - **A liquid scintillator detector in Mexico**
  - **Detector prototypes**