# *PICO: search for dark matter with bubble chambers*

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# PICO Collaboration

PICO

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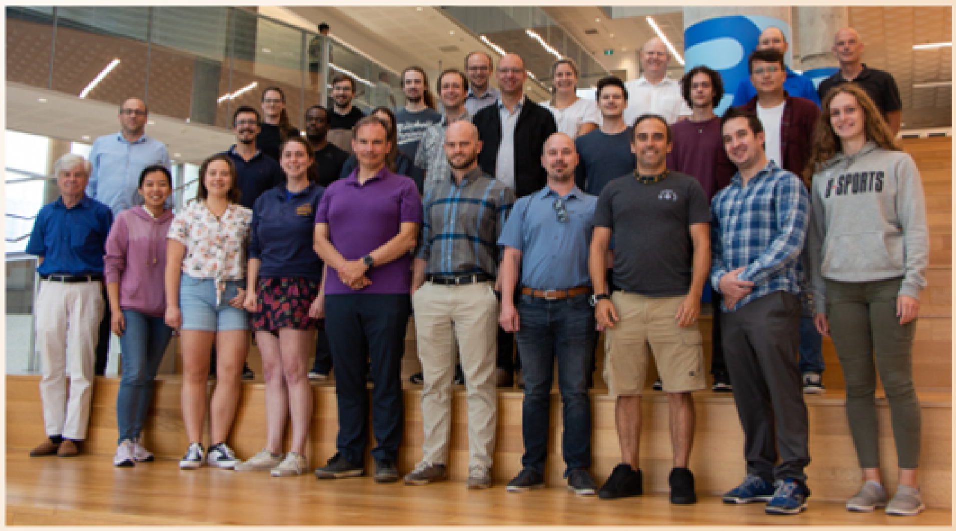

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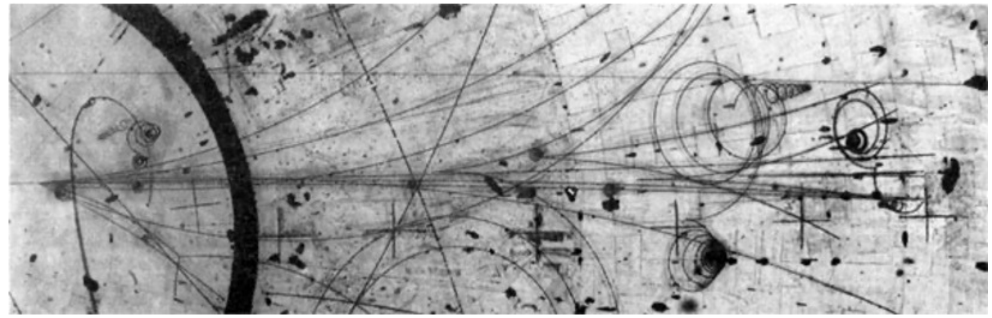
# Physics with bubble chambers

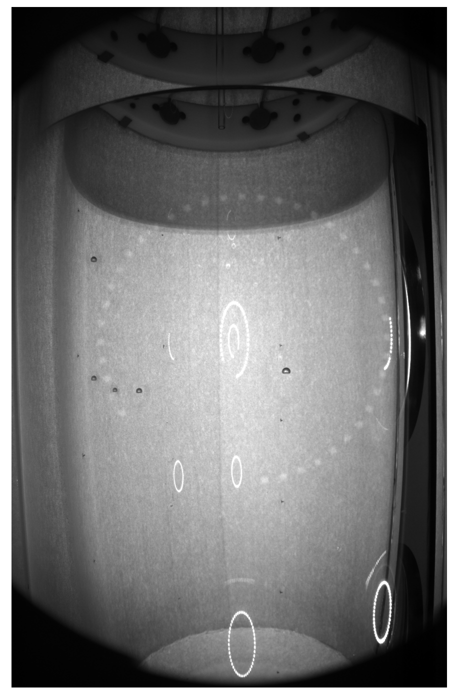
**1970s: Neutrino Beam Physics**

- 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

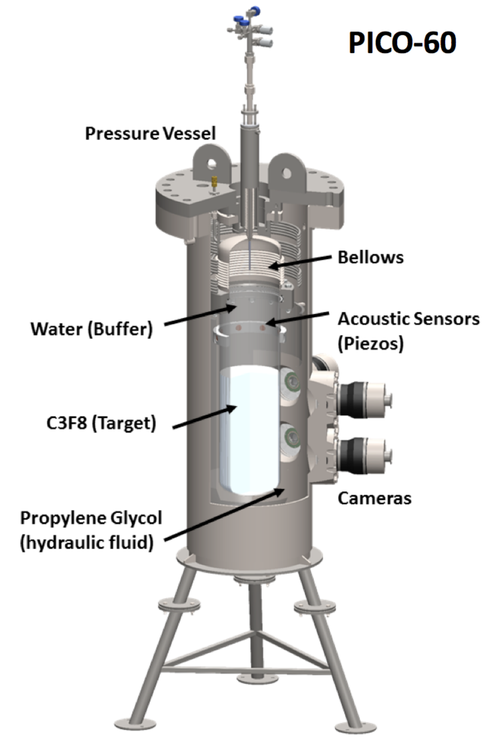
  Could make a dark matter bubble chamber with any liquid!

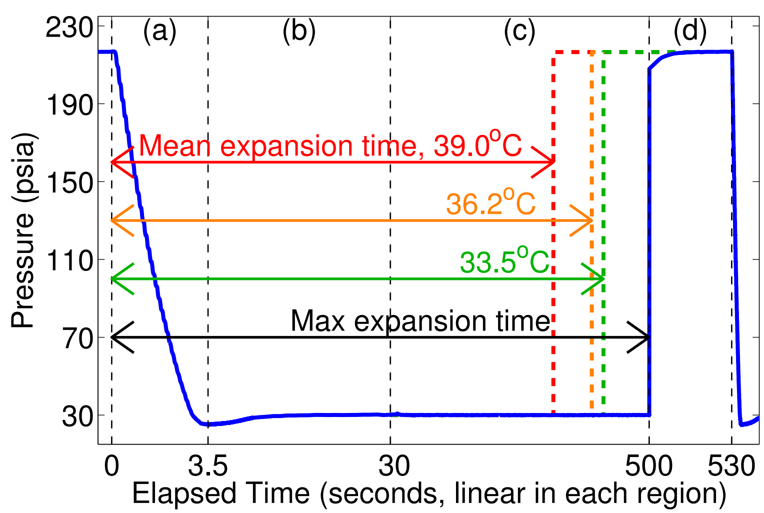
- Particles interacting evaporate a small amount of material: bubble nucleation

- Four Cameras record bubbles

- Eight piezo-electric acoustic sensors detect sound

- Recompression after each event



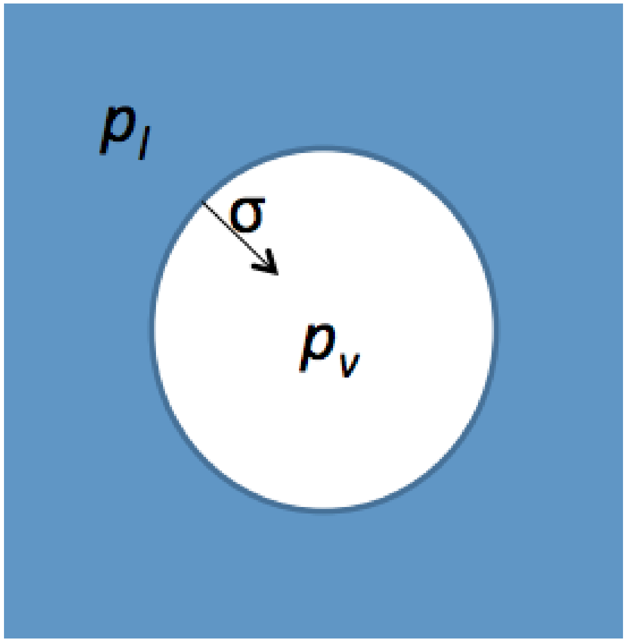



# Bubble chambers: Physics

- **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:**

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

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



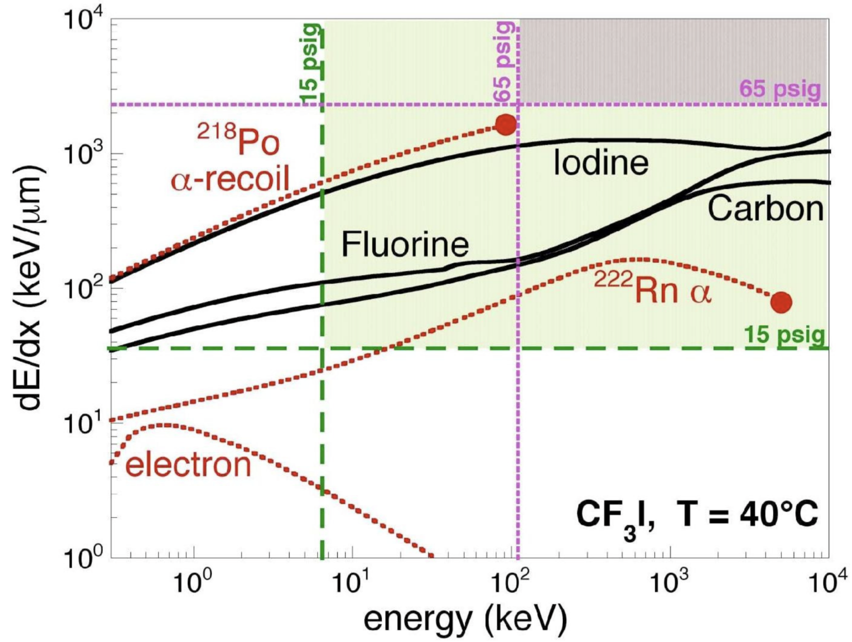
# Bubble nucleation

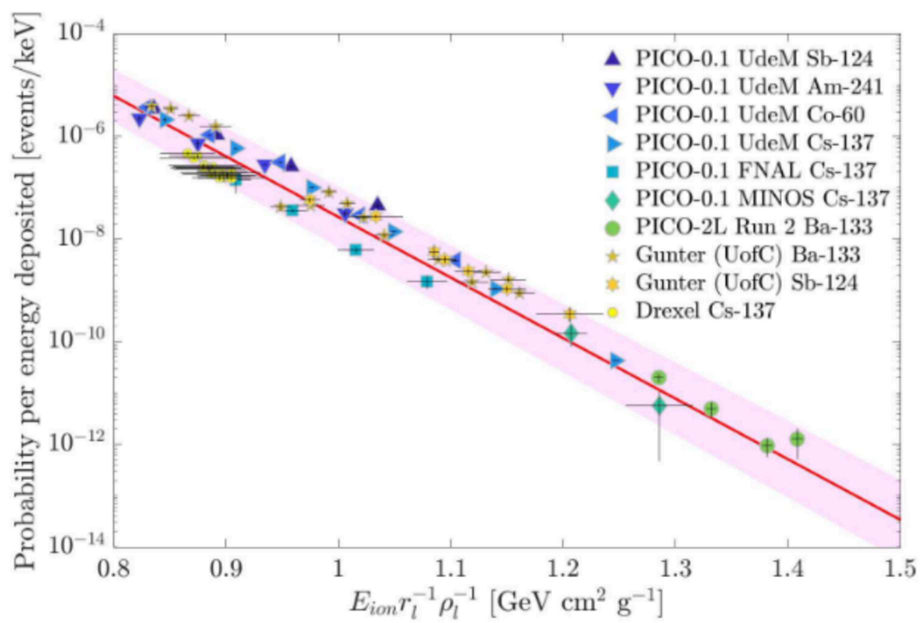
**Dependence of bubble nucleation on the total deposited energy and dE/dx**

- **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**

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



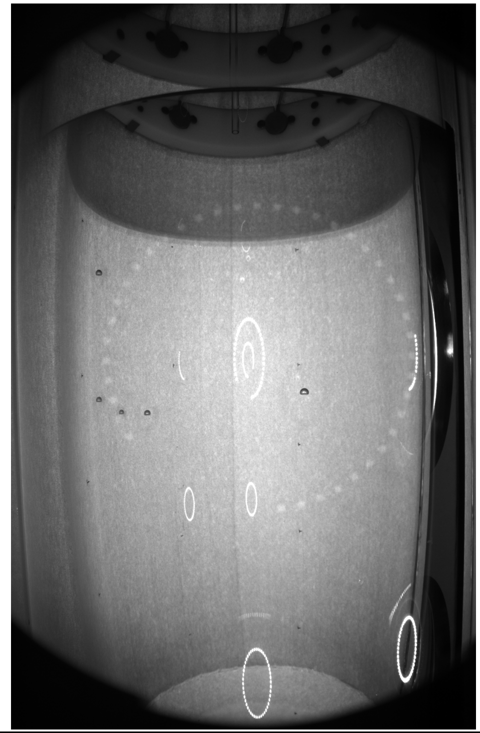



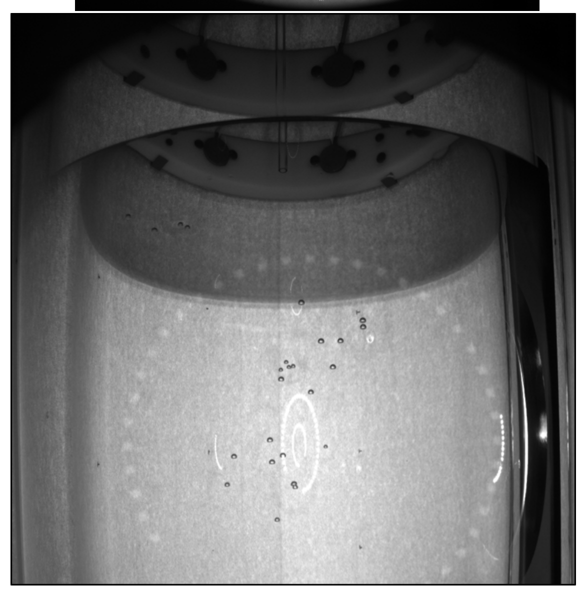
# Bubble chambers: signal

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

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

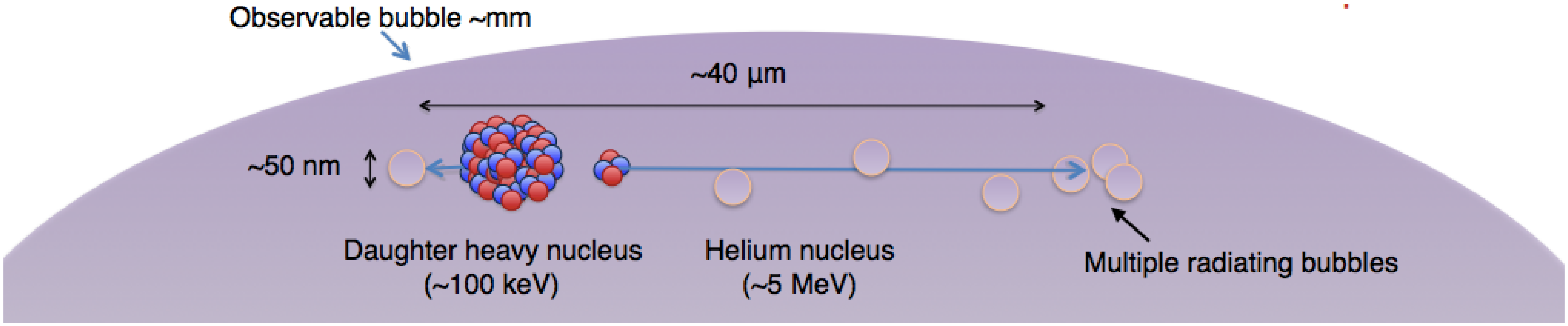
- **Neutrinos or WIMPs:**
  **Nuclear recoil**
  **mean free path $> 10^{10}$ cm**
  **1 bubble**



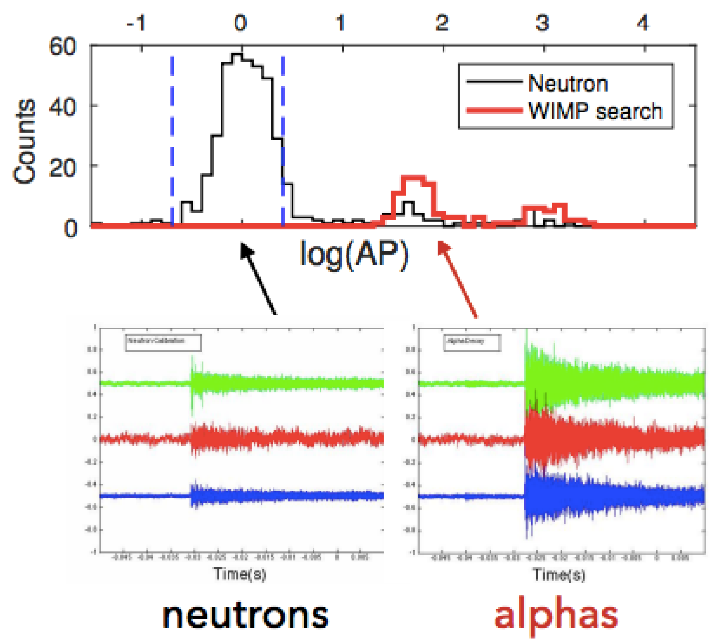


# Bubble chambers: Acoustics

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




- $>$ 99.9% discrimination against alpha events demonstrated
- Discovered by the PICASSO collaboration

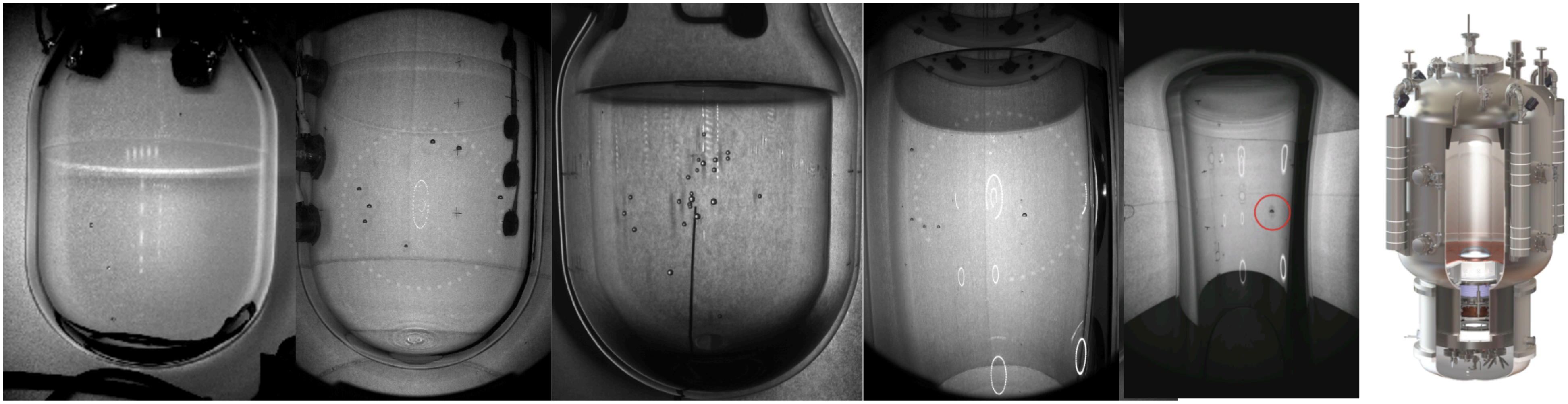


# Why bubble chambers?

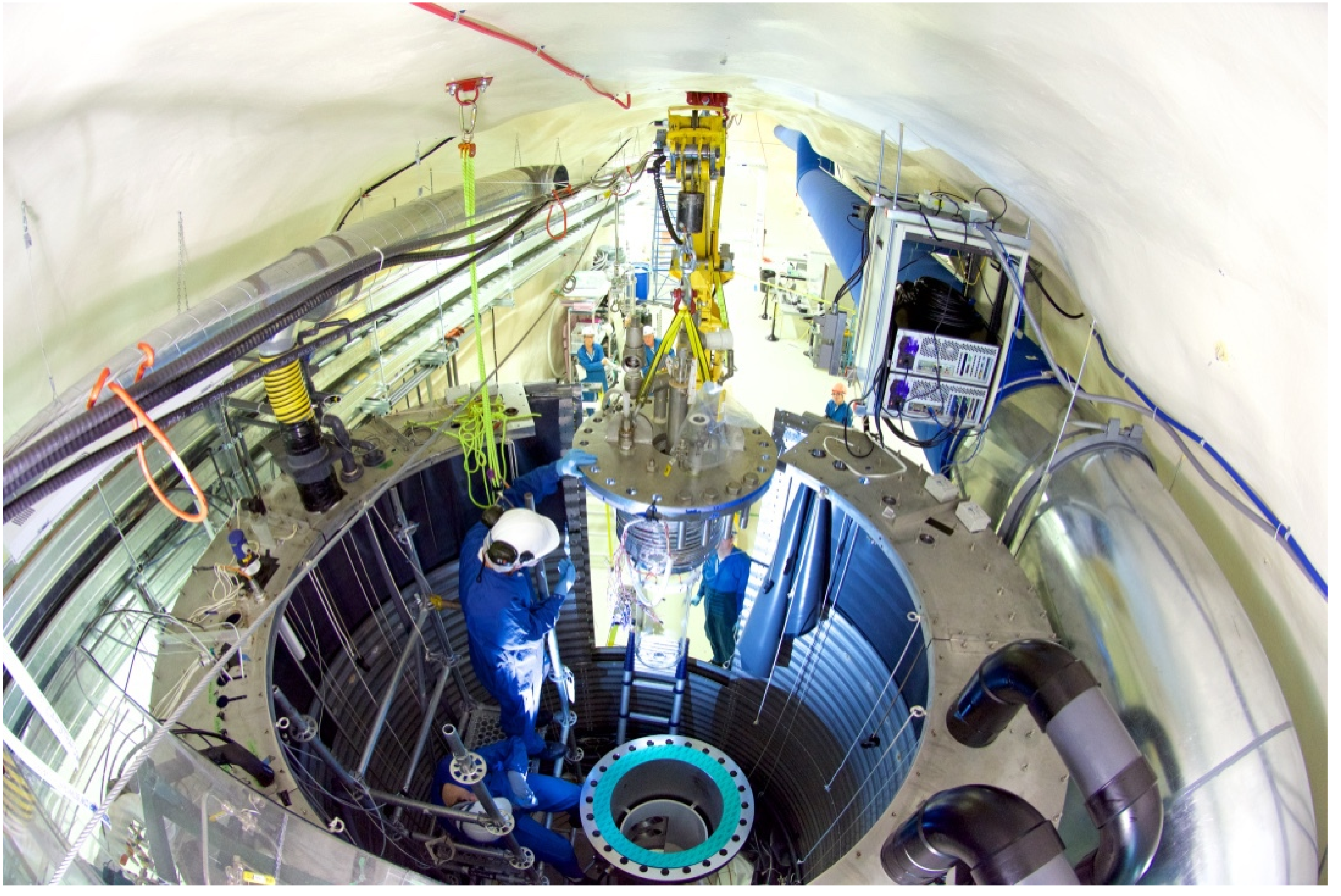
- **Zero background**
- **Large target mass**
- **Low energy threshold (a few keV, and down to eV for some fluids)**
- **Multiple target nuclei**
  **test expected cross section dependences on**
  **atomic number and nuclear spin**
  **(Fluorine, Iodine, Chlorine, Xenon, Argon, Bromine, Hydrogen...)**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

## Meet the family: PICO bubble chambers

- **COUPP4: a 2l $CF_3I$ chamber run at SNOLAB in 2010 and 2012**
- **COUPP60: up to 40l $CF_3I$ chamber run at SNOLAB 2013-14**
- **PICO-2L: a 2l $C_3F_8$ chamber run at SNOLAB 2013-14 and 2015-16**
- **PICO-60: up to 45l $C_3F_8$ chamber run at SNOLAB 2016-17**
- **PICO-40L: currently under commissioning and data taking**
- **PICO-500: future ton-scale experiment 2024-2026**

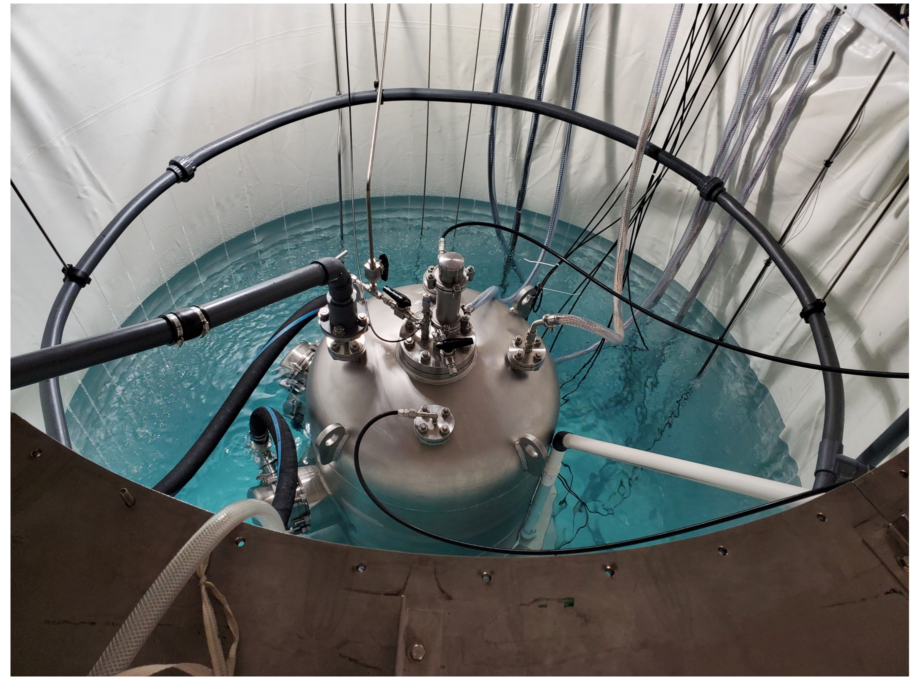


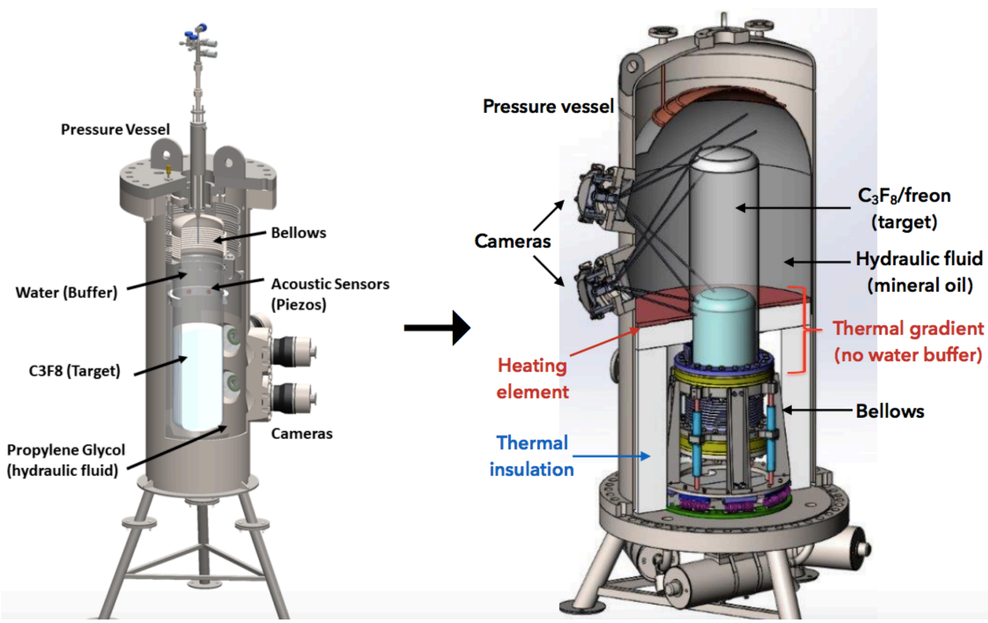
# PICO-60



# PICO-40L:"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



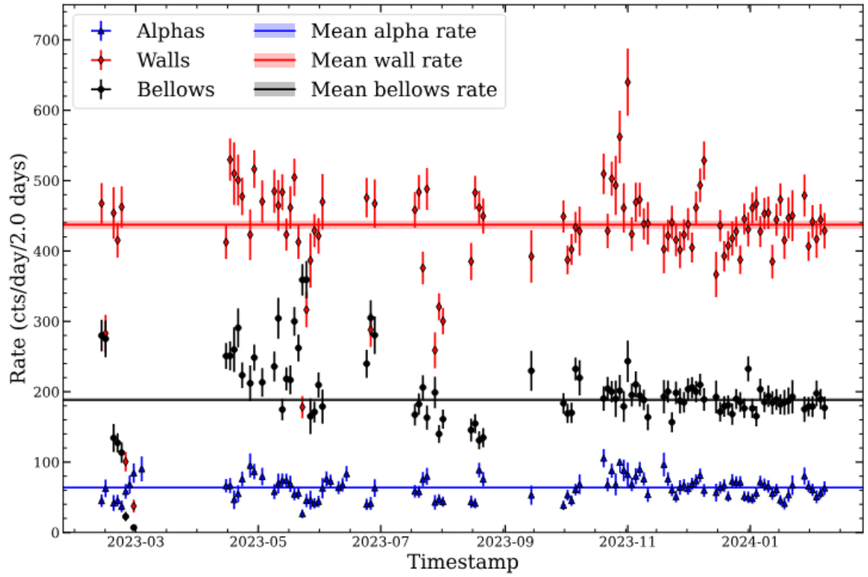



- **Science:**
  acquire one-year background-free exposure

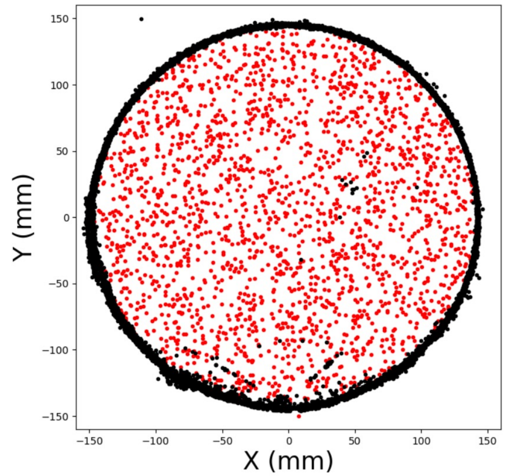
- Factor of 5 improved sensitivity on PICO-60 limits

# PICO-40L: current status

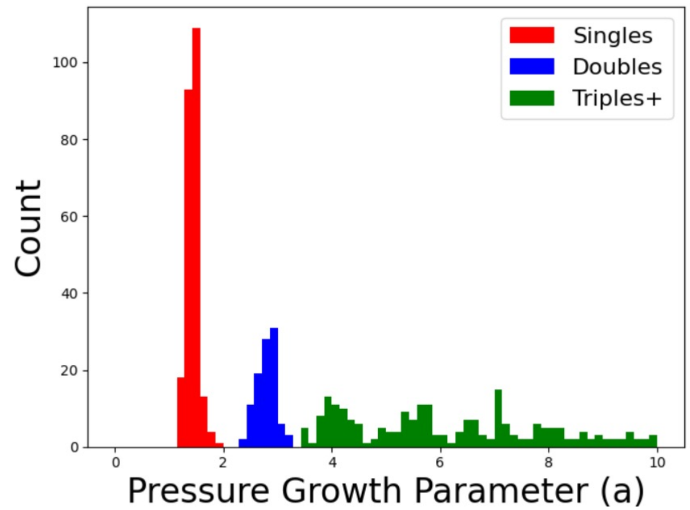
## Commissioning and data taking




- Detector fully assembled and operational with water shield
- Thermally stable
- Stable long term event rates

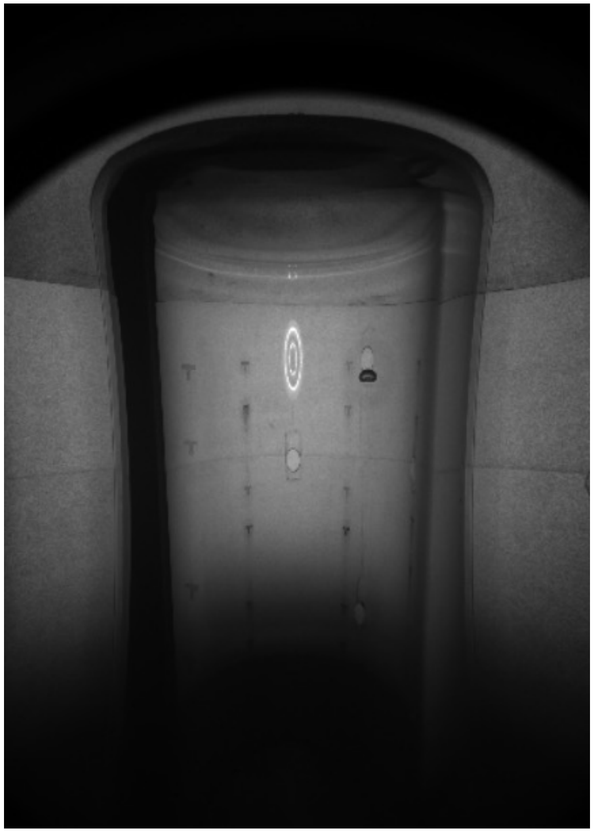



- Excellent position reconstruction, detailed ray-tracing simulation
- Single/multiple scattering ratio 1:3 sensed by pressure transducers

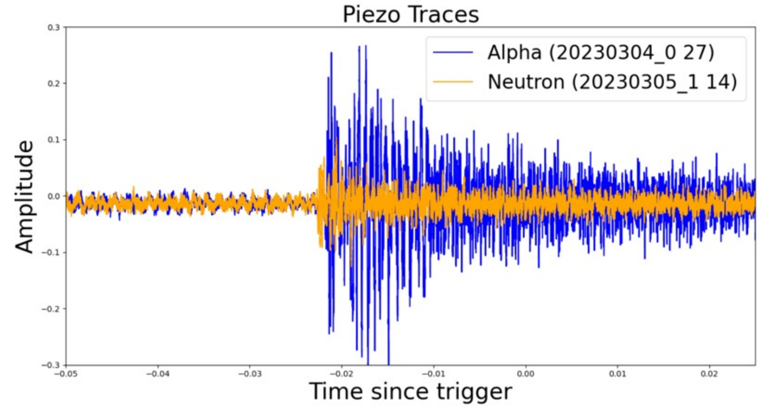


# PICO-40L: current status

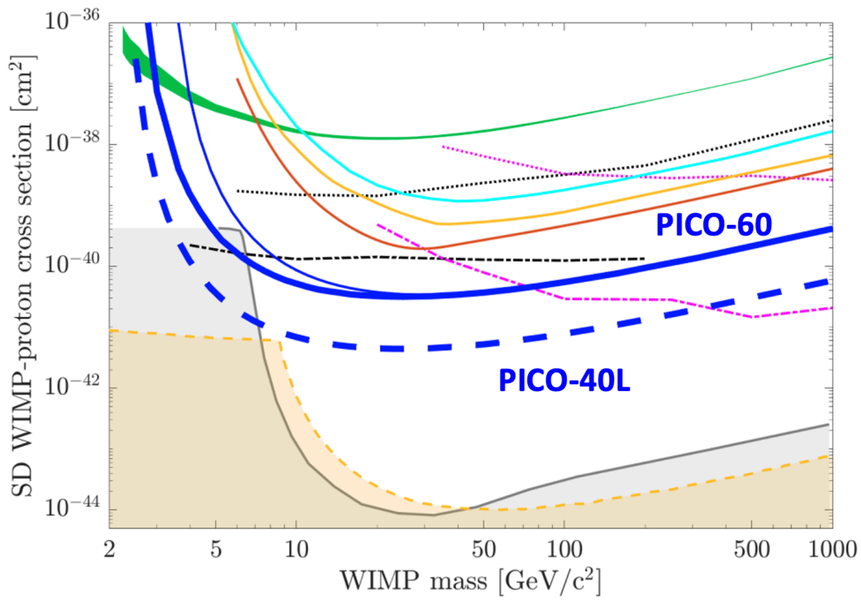
## Commissioning and data taking



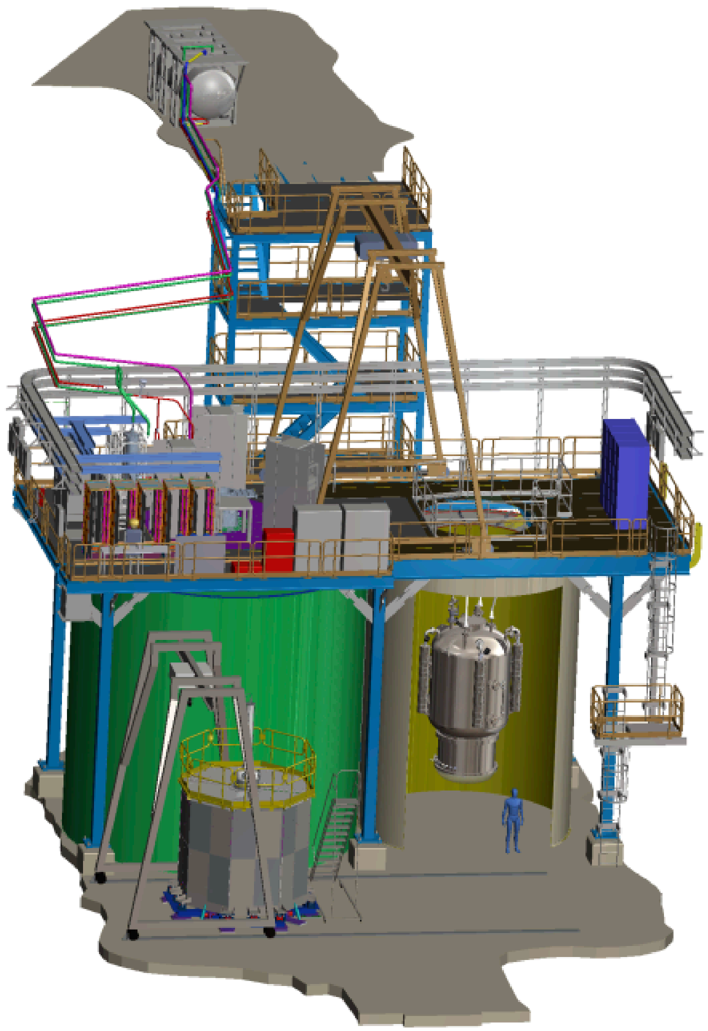
- **10 piezoelectric sensors, acoustic during bubble formation**
- **4 video cameras, images during bubble formation**




- *Dark matter search results from the complete exposure of the PICO-60 $C_3F_8$ bubble chamber PRD 100, 022001 (2019)*



# PICO-500: current status



**Tonne-scale bubble chamber located in the Cube Hall at SNOLAB**

**Under construction: parts arriving to SNOLAB!**

## Study of dark matter models in PICO: photon-mediated dark matter-nucleus interactions

# 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

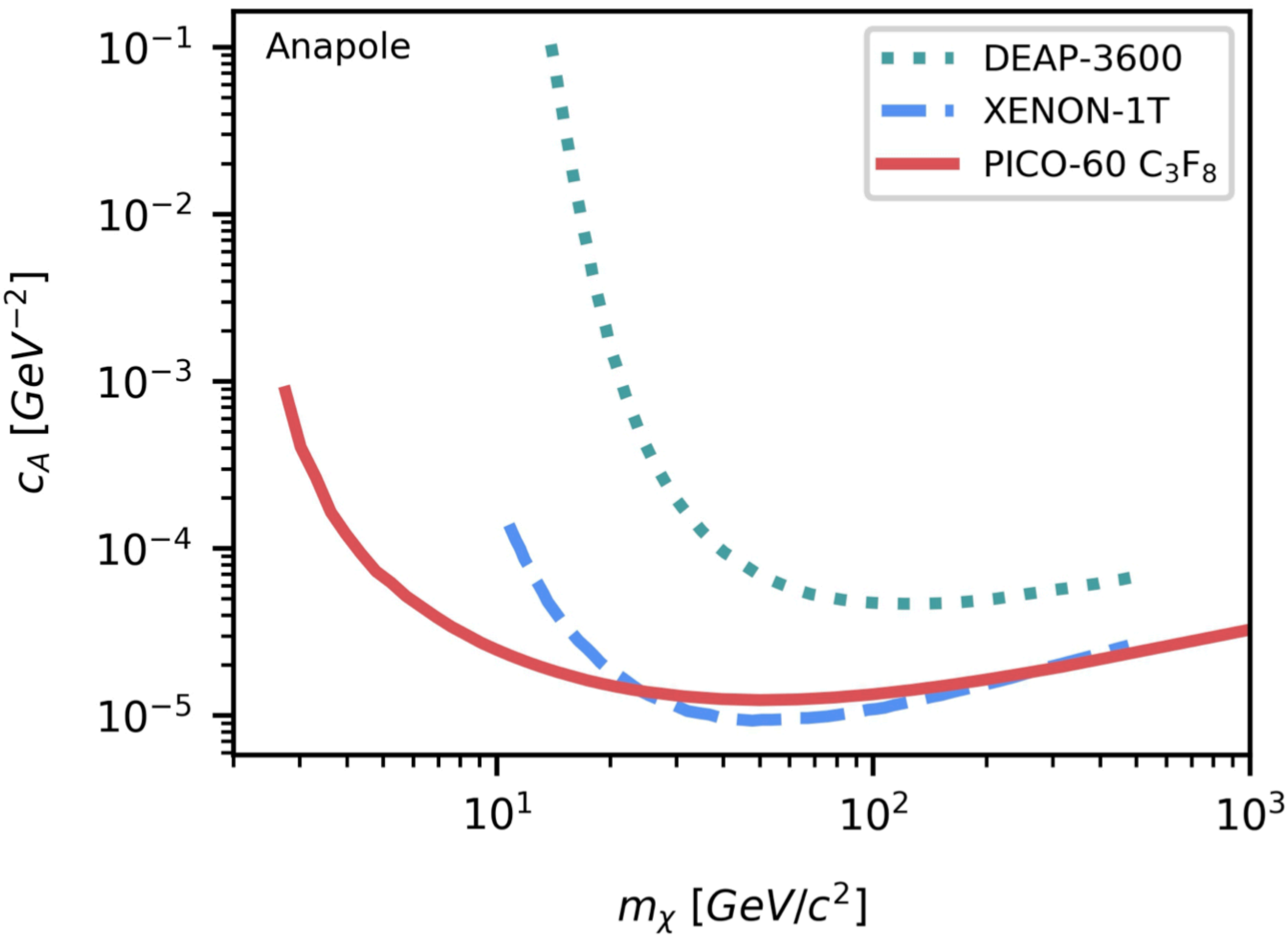
Nuclear physics: Nuclear response functions

- 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 in PICO: results

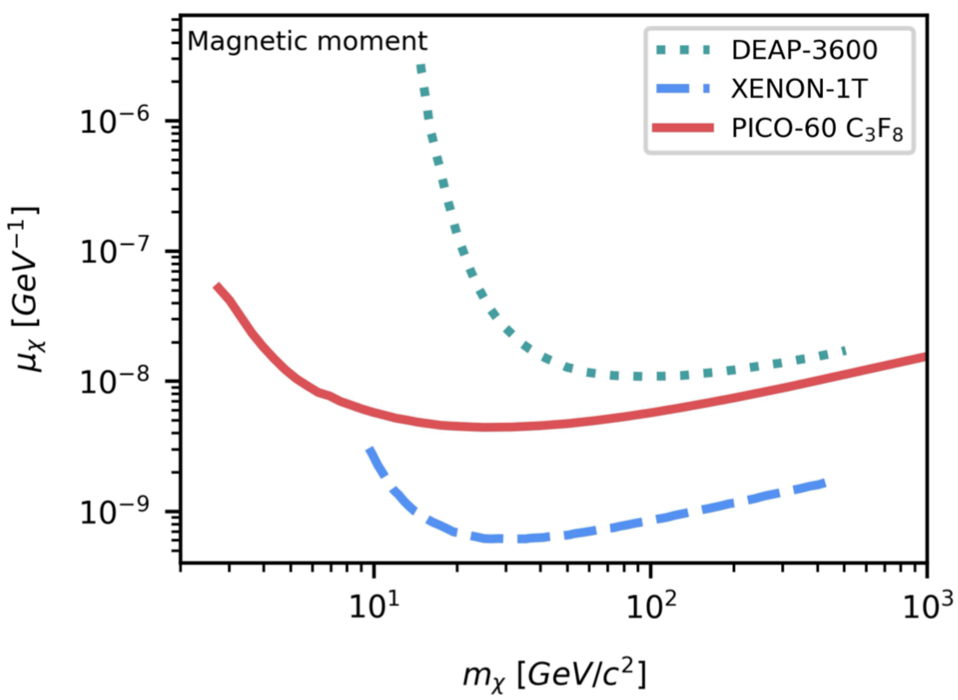
The only possible electromagnetic moment for a Majorana fermion is the anapole moment since the magnetic and electric dipole moments vanish



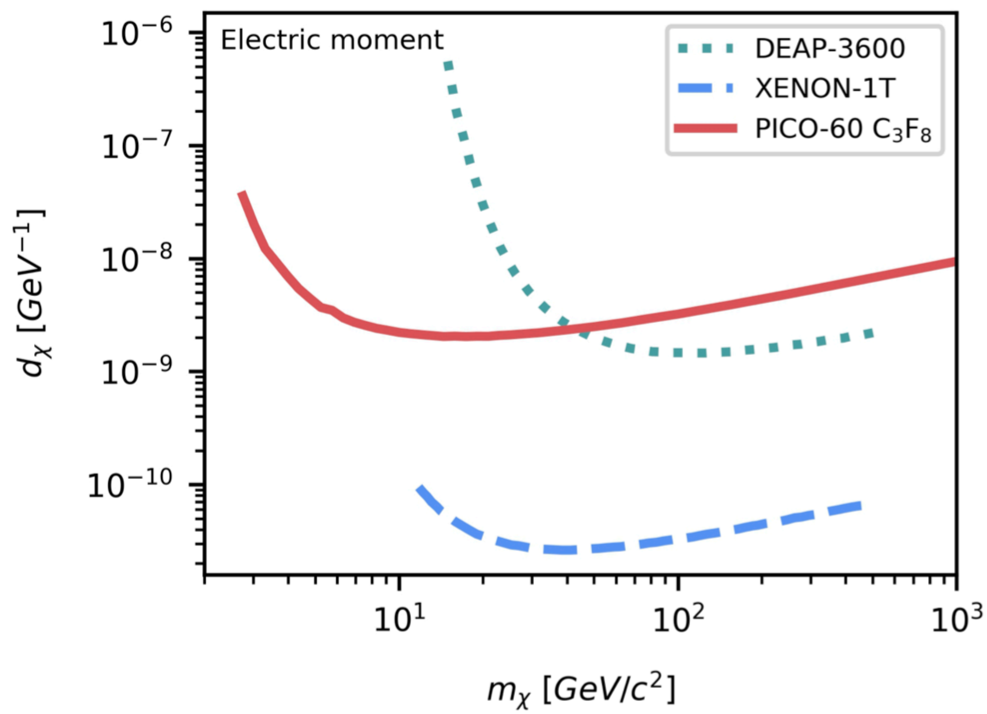
# Electric and magnetic moments in PICO: results

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

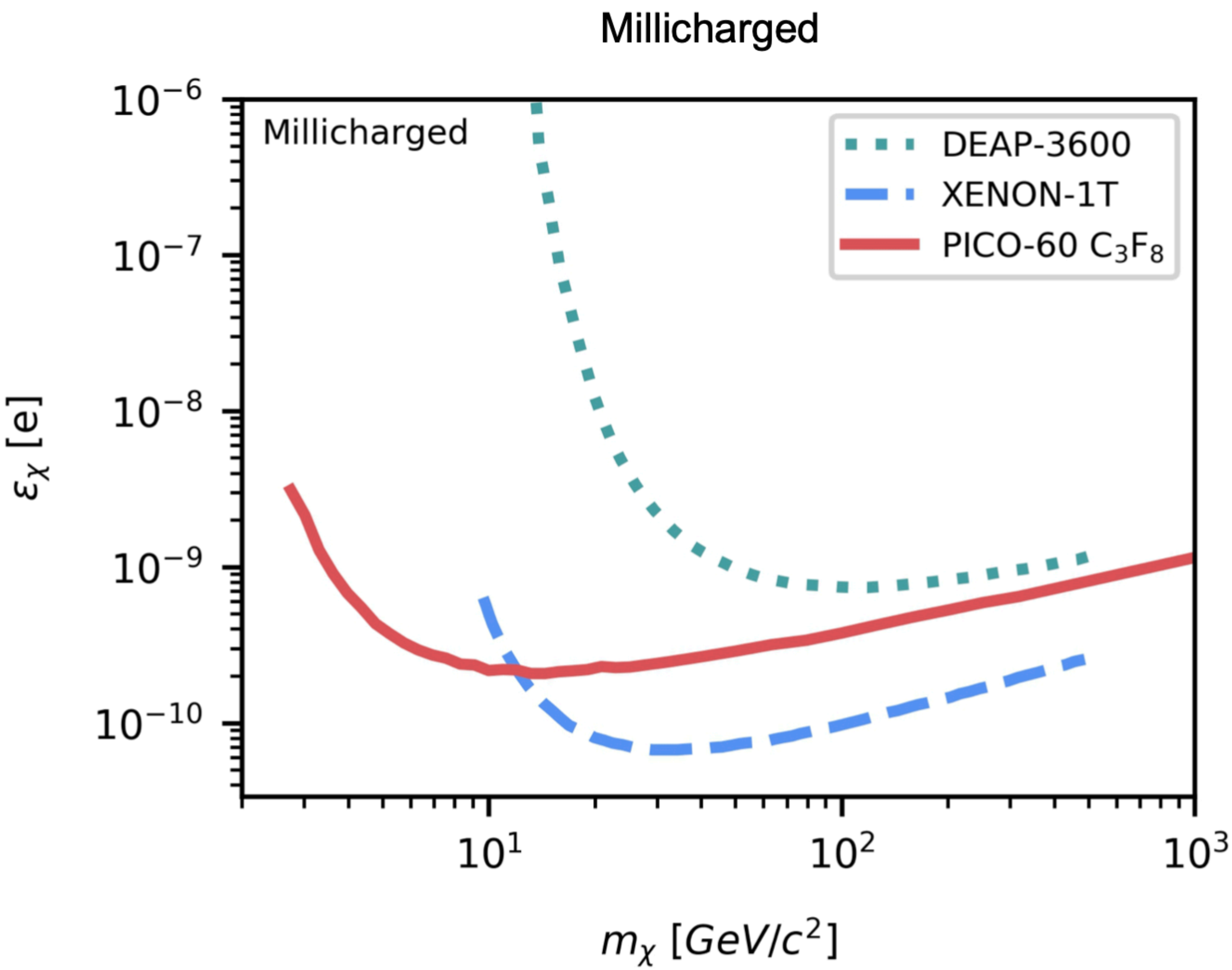
Magnetic dipole




Electric dipole



# Millicharged DM in PICO: results




*Results on photon-mediated dark-matter–nucleus interactions from the PICO-60 $C_3F_8$ bubble chamber*
*Phys. Rev. D 106, 042004 (2022)*

# Study of dark matter models in PICO: inelastic dark matter

# Inelastic dark matter

**If dark matter can't scatter elastically, kinematical effects distinguish experiments**

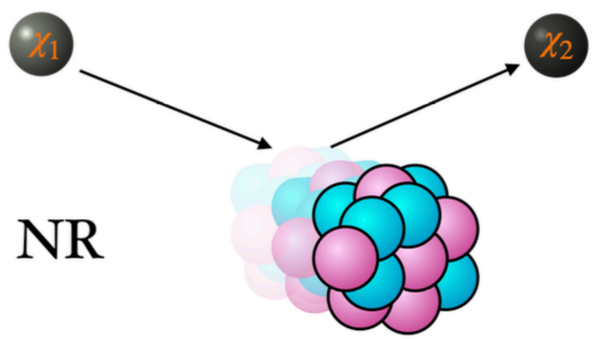
$$\delta_{\max} = \frac{1}{2}\mu_{\chi N}(v_e + v_{esc})^2$$

$$v_{\min}(E_R) = \frac{1}{\sqrt{2M_N E_R}}\left(\frac{M_N}{\mu_{\chi N}}E_R + \Delta\right)$$

- **Expected in varied dark matter models**
- **Possible explanation for 511 keV $\gamma$-ray excess in galactic center and DAMA-LIBRA annual modulation**

- **kinetic energy must overcome mass splitting**
- **only scatter with heavier nuclei**

NR

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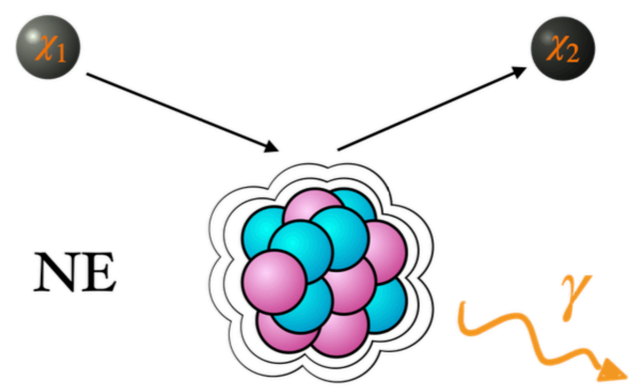
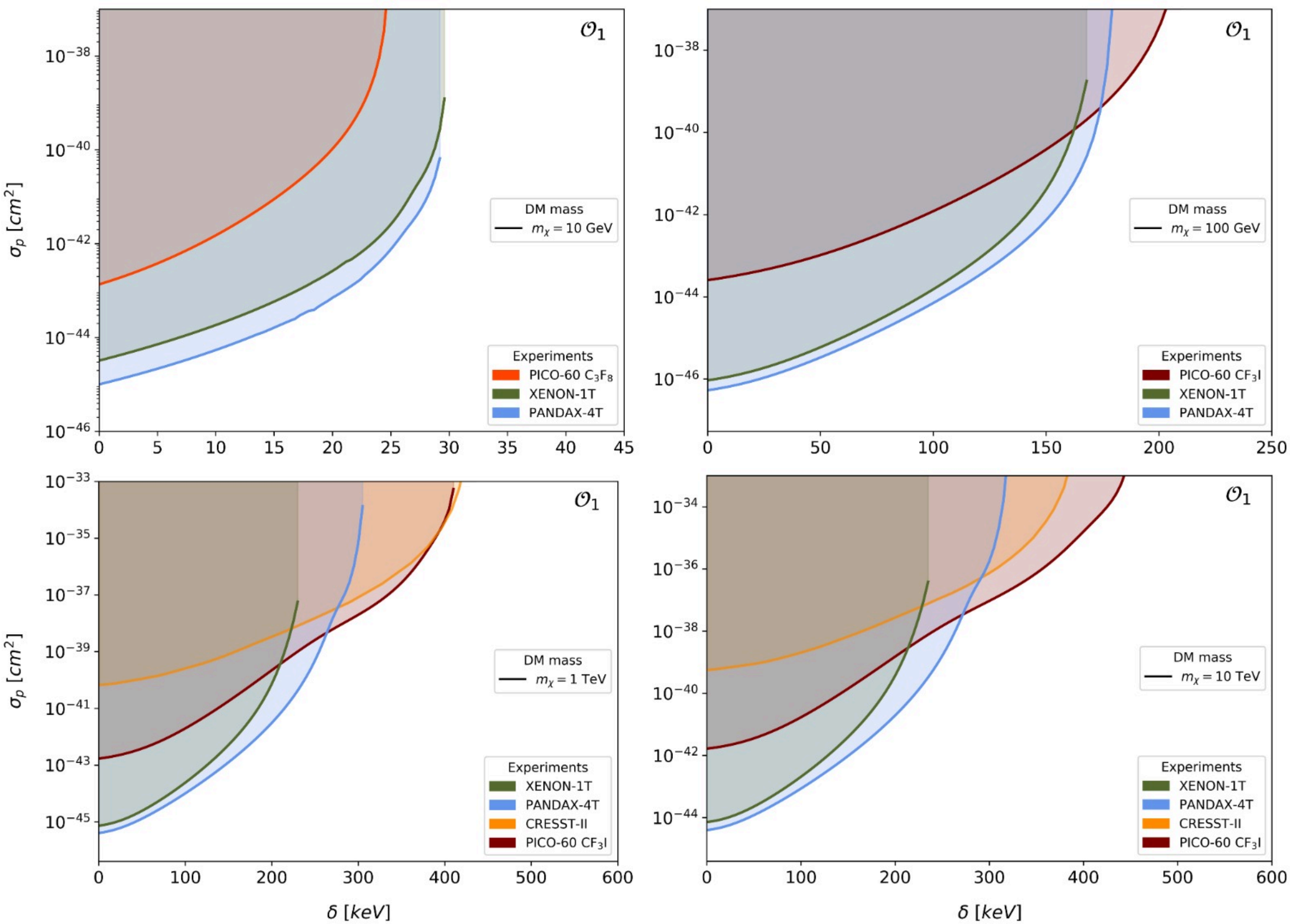


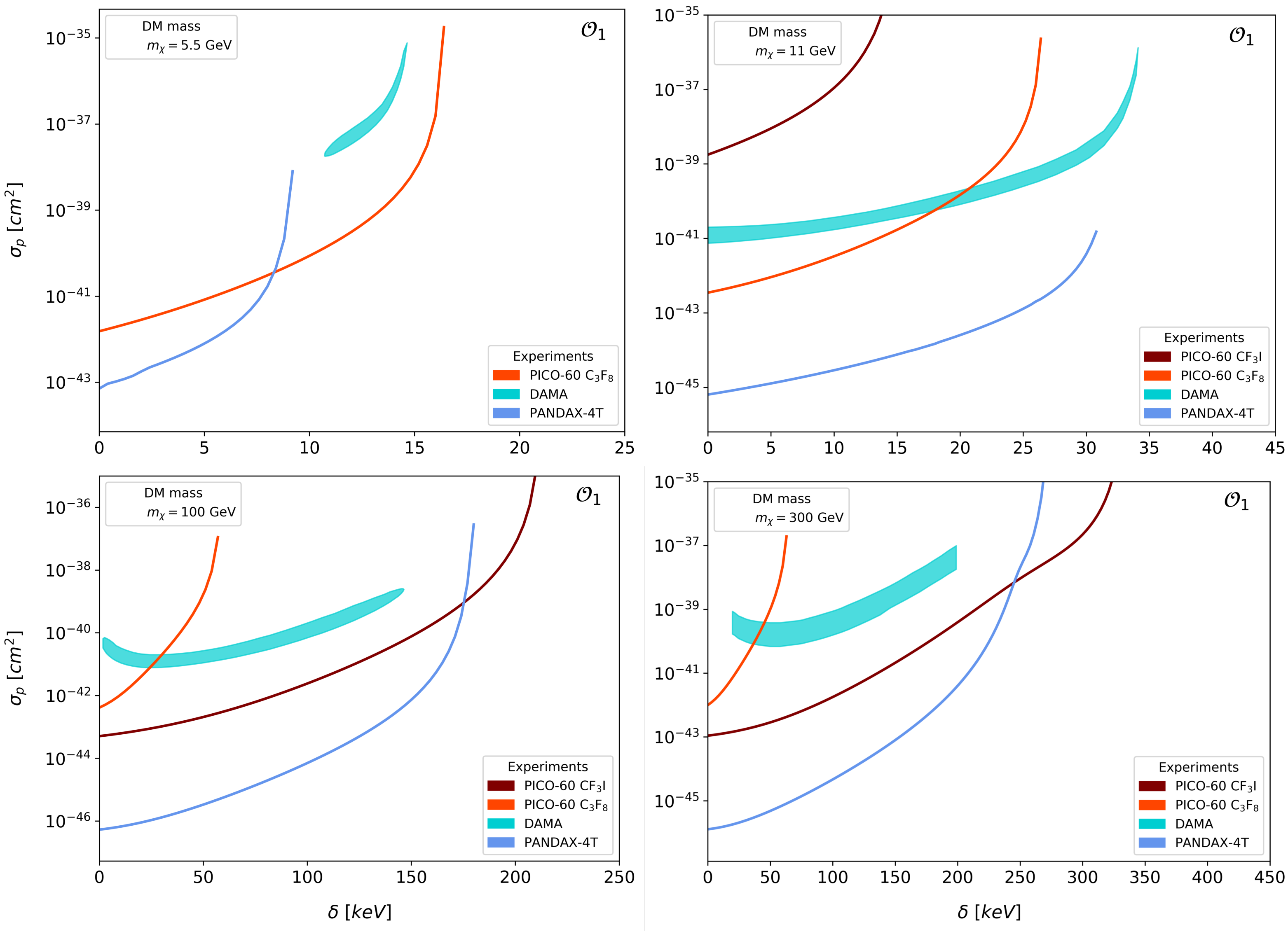

(https://doi.org/10.1103/PhysRevD.104.103032)

# Inelastic DM in PICO: results



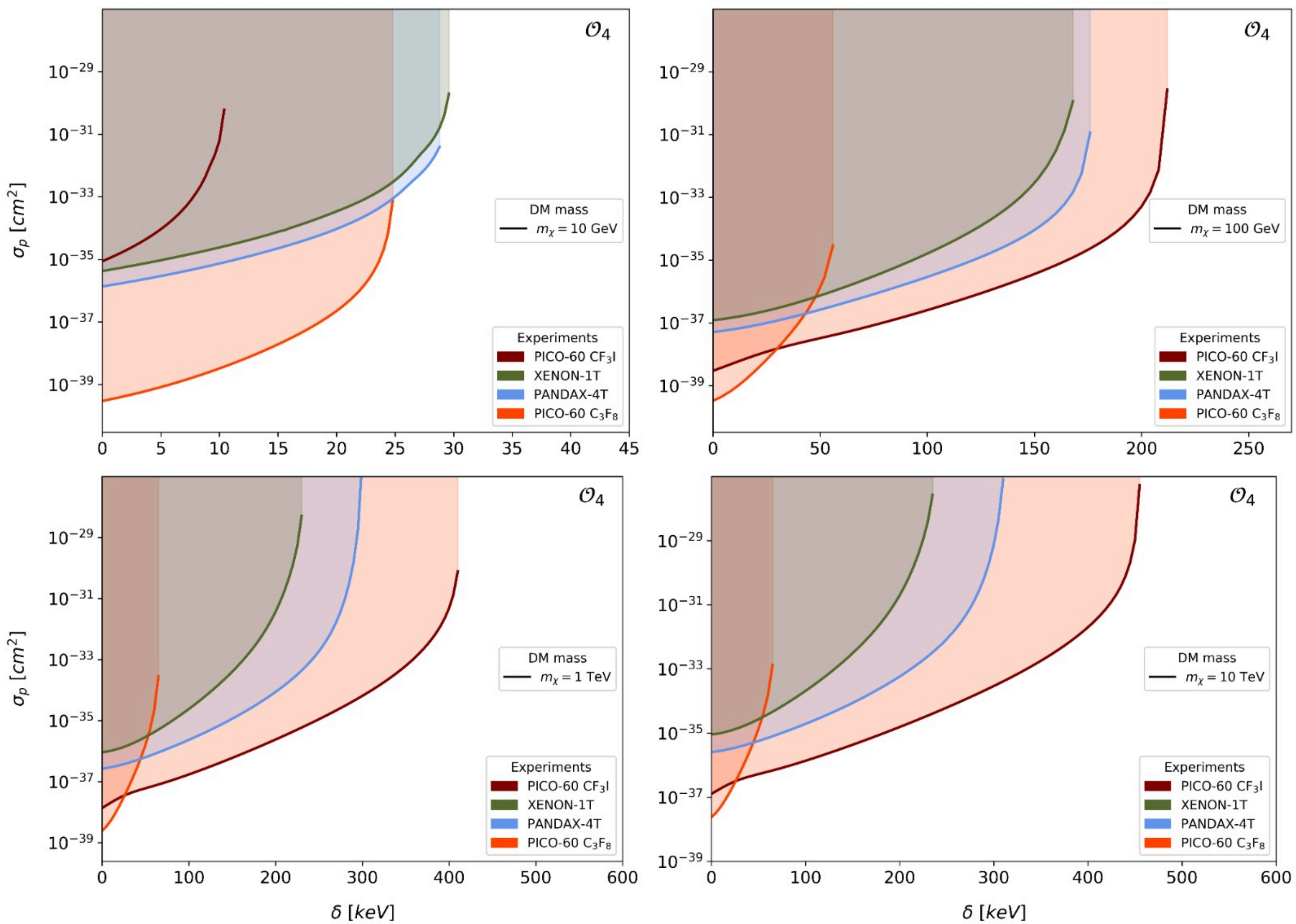

**Combined analysis with PICO-60 $C_3F_8$ and $CF_3I$ data**
**Leading limits on dark matter-nucleon scattering cross sections for inelastic dark matter interactions in a wide range of mass splittings and DM masses.**

# Inelastic DM in PICO: results




**Analysis disfavors various scenarios, in a wide region of parameter space, that provide a feasible explanation of the signal observed by DAMA, (PICO $CF_3I$ bubble chamber used iodine as the target material)**

# Inelastic DM in PICO: results




*Search for inelastic dark matter-nucleus scattering with the PICO-60 $CF_3I$ and $C_3F_8$ bubble chambers*

*Phys. Rev. D 108, 062003 (2023)*

## Final remarks

- **PICO bubble chambers are producing world-leading direct detection limits using fluorine targets**
  - **Best limits for spin-dependent WIMP-proton couplings**
  - **Leading results on photon-mediated DM–nucleus interactions and inelastic dark matter scenarios**
  - **PICO-40L is operational, running stable in a variety of operational modes, detailed analysis of the data is underway**
  - **PICO-500 is coming, construction during this year and in 2025**

**Stay tuned for news from PICO!**