Search for dark matter with bubble chambers

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IFUNAM

Dark Matter Days
CIFFU, Puebla; November 6, 2017

PICO: search for dark matter with superheated liquids

PICO Collaboration

PICO

SNOLAB – Mining for knowledge – Creuser pour trouver... l'excellence

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Saha Institute of Nuclear Physics, Calcutta

P. Bhattacharjee. M. Das, S. Seth

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KICP – Kavli Institute for Cosmological Physics at the University of Chicago

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Indiana University South Bend

E. Behnke, H. Borsodi, O. Harris, A. LeClair, I. Levine, E. Mann, J. Wells

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Fermilab

S.J. Brice, D. Broemmelsiek, P.S. Cooper, M. Crisler, W.H. Lippincott, E. Ramberg, M.K. Ruschman, A. Sonnenschein

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J. Farine, F. Girard, A. Le Blanc, R. Podviyanuk, O. Scallon, U. Wichoski

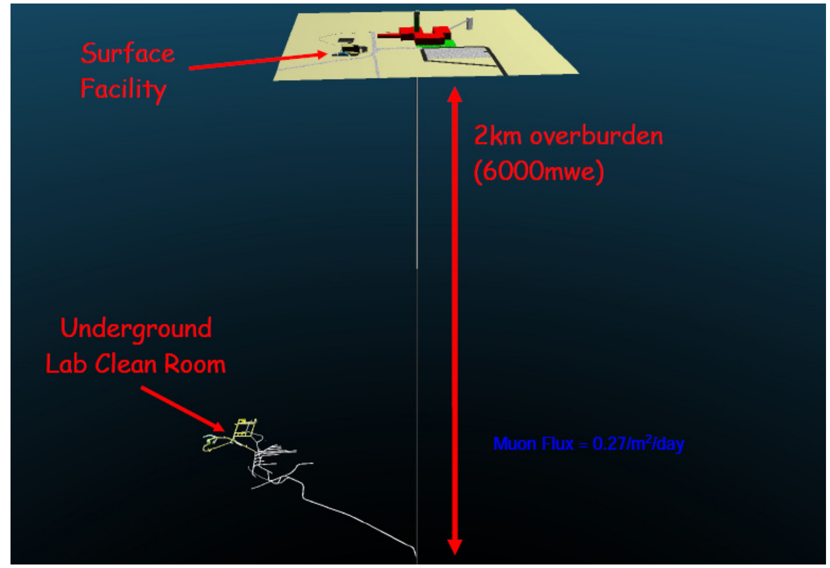
Sudbury Neutrino Observatory Laboratory

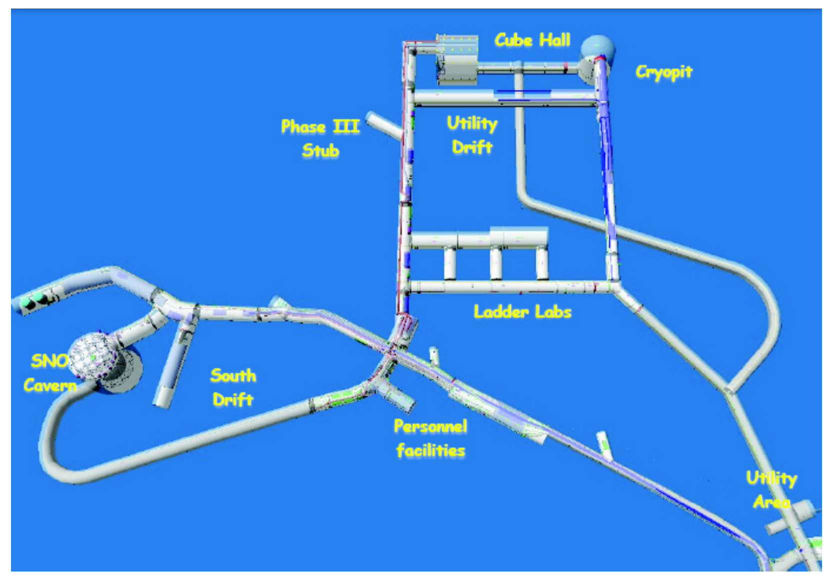
SNOLAB

deepest and cleanest large-space international facility in the world

- 2 km underground near Sudbury, Ontario
- ultra-low radioactivity background environment Class 2000
- Physics programme focused on neutrino physics and direct dark matter searches

Home of the SNO experiment
2015 Nobel prize in Physics





PICO bubble chambers

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

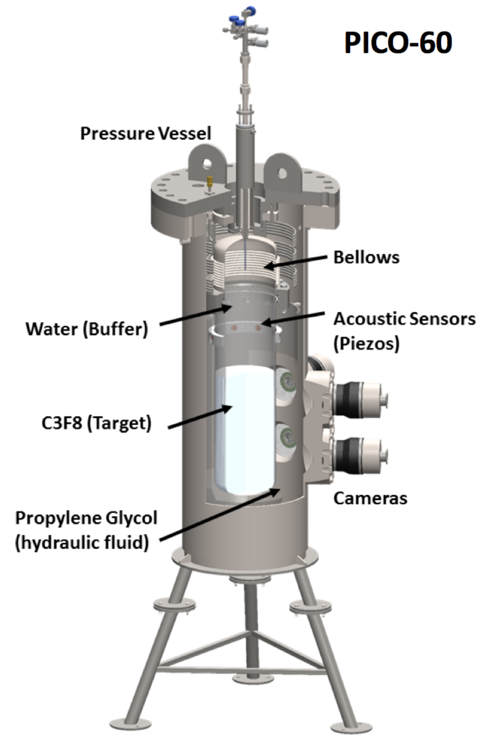
  Could make a dark matter bubble chamber with any liquid!

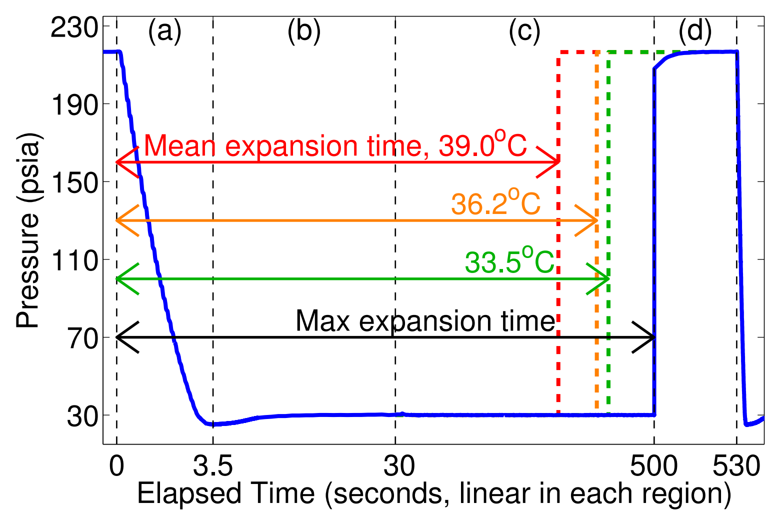
- Particles interacting evaporate a small amount of material: bubble nucleation

- Four Cameras record bubbles

- Eight piezo-electric acoustic sensors detect sound

- Recompression after each event

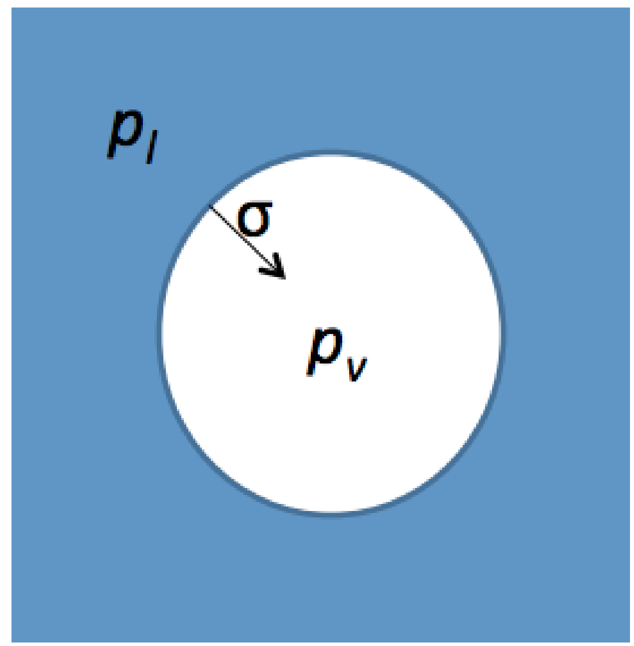




- **In a superheated fluid, energy deposition greater than E_{th} in a radius less than r_c will result in a bubble large enough to overcome surface tension (Seitz "Hot-Spike" Model)**
- **Low E or dE/dx result in smaller bubbles that immediately collapse**
- **Classical Thermodynamics:**

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

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

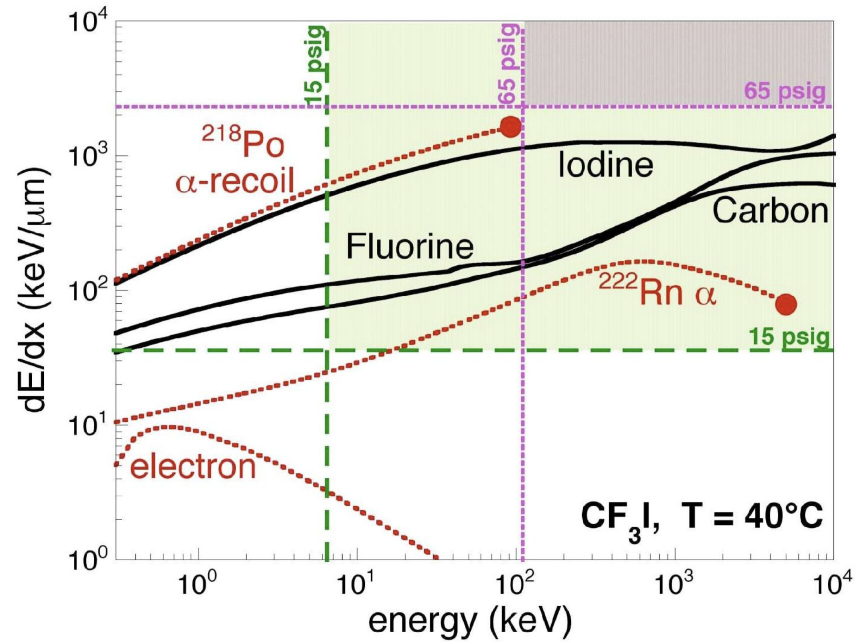


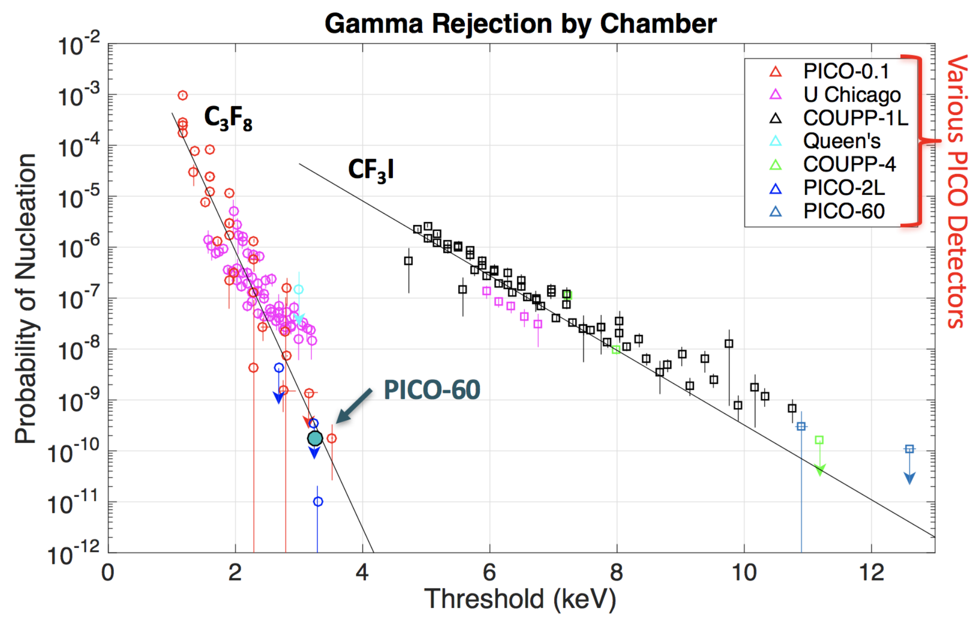
Bubble nucleation

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



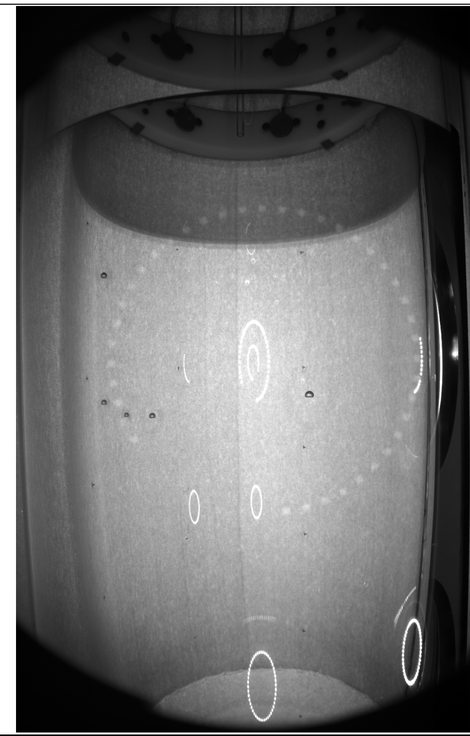


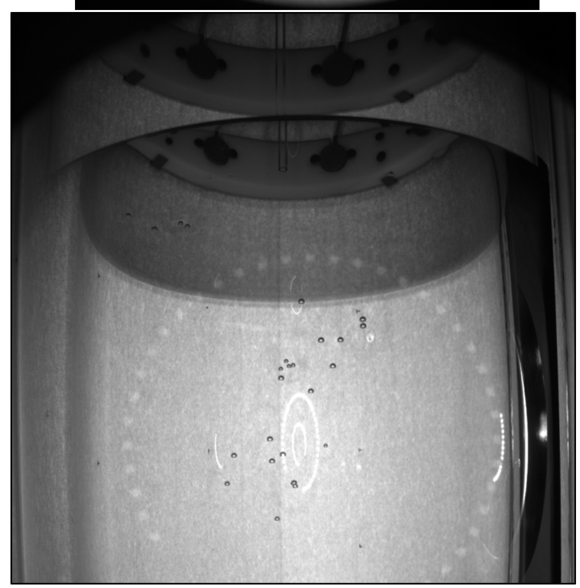
PICO bubble chambers

- **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

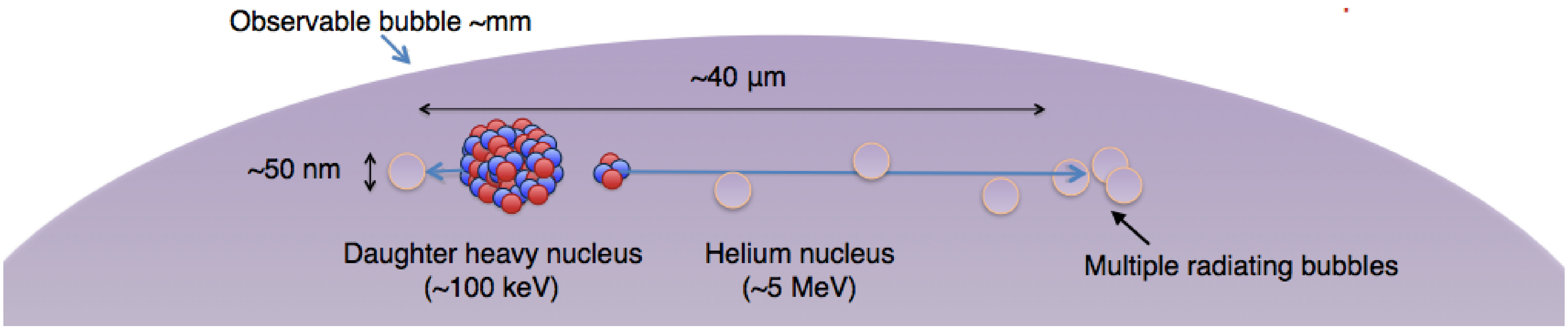
- **WIMPs:**
  Nuclear recoil
  mean free path $> 10^{12}$ cm
  1 bubble



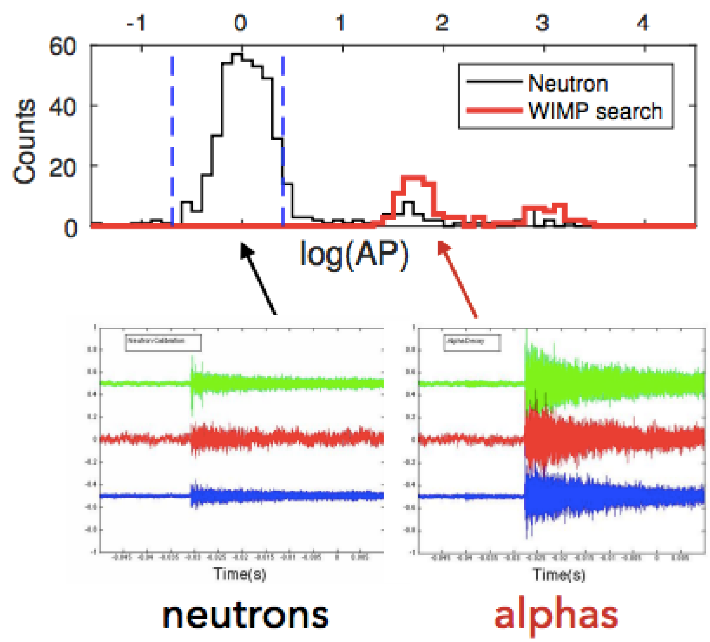


PICO bubble chambers

- Alphas are ~ 4 times louder than nuclear recoil bubbles

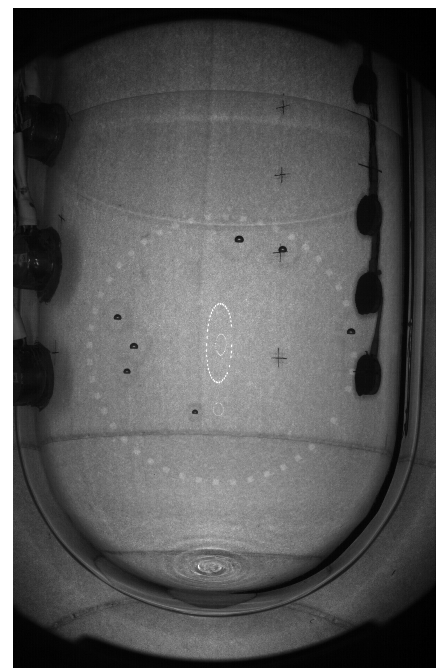


- $> 99.4\%$ discrimination against alpha events demonstrated
- Discovered by the PICASSO collaboration



PICO detectors features

- Energy: threshold detector
- Background suppression:
  - UG at SNOLAB
  - Water shielding
  - Clean materials
- Background discrimination:
  - Neutrons:
    multiples bubbles
    Nuclear recoil, $l \sim 20$ cm
  - α: acoustic parameter
    Nuclear recoil, 40 μm track
- Large target mass:
  COUPP4 to COUPP60
  PICO-2L to PICO-60
  PICO40L-RSU, PICO-500

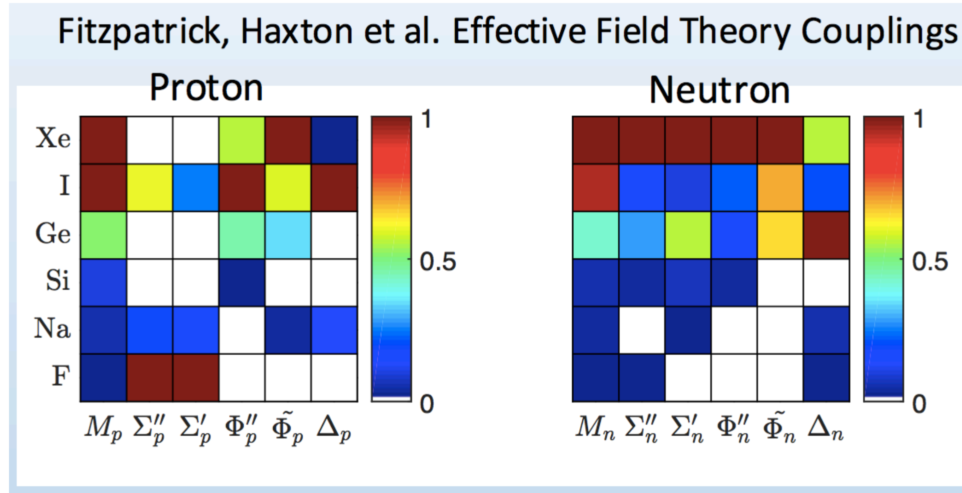


Why bubble chambers?

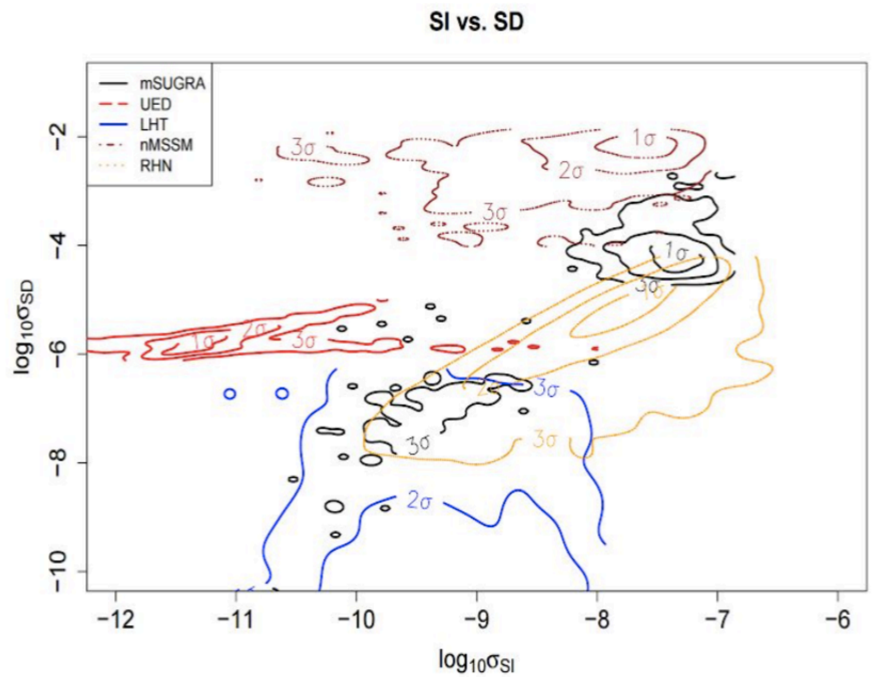
- **Zero background (now under control)**
- **Large target mass (PICO-500: ton-scale for next generation)**
- **Low energy threshold (a few keV, and down to eV for some fluids)**
- **Multiple target nuclei**
  test expected cross section dependences on
  atomic number and nuclear spin
  (Fluorine, Iodine, 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



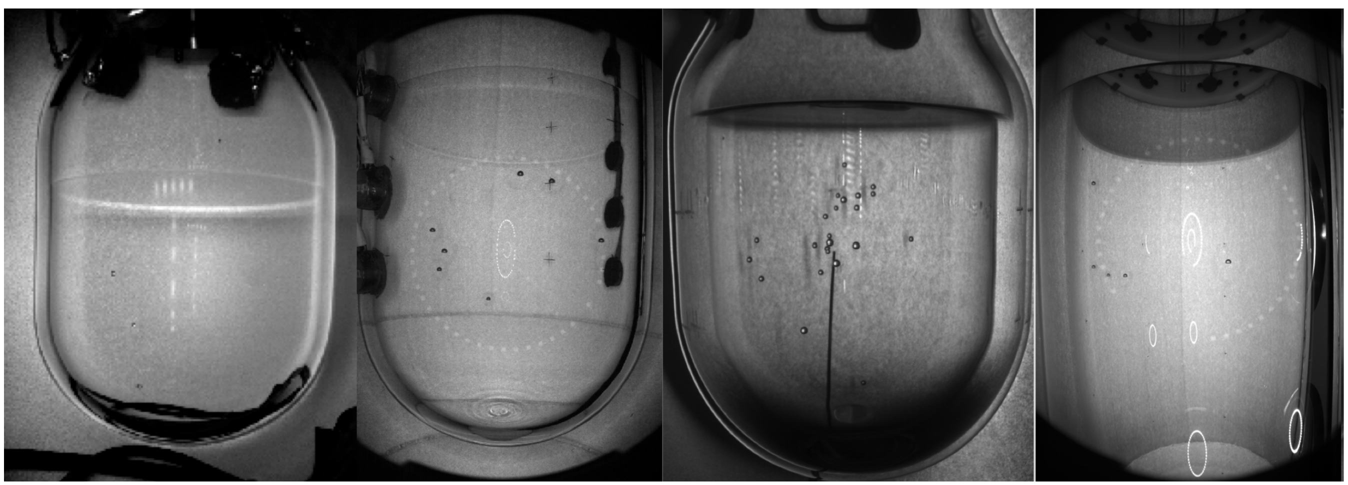
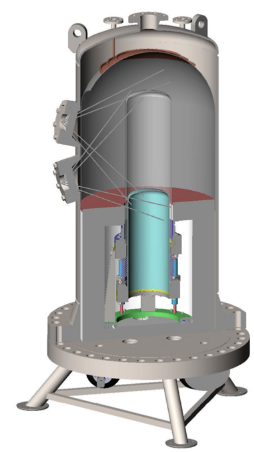
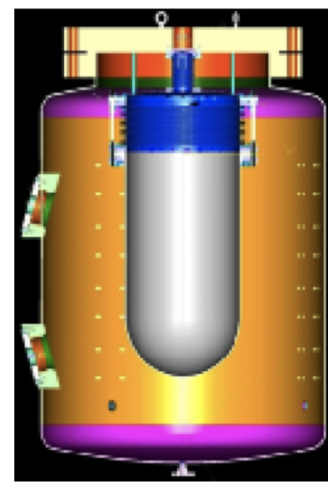
- **Fluorine: Best sensitivity to spin dependent interactions.**
- **Iodine, Bromine, Xenon, Argon: High A targets to exploit A^2 dependence of spin-independent cross section.**
- **Hydrogen: Enhanced sensitivity to low mass particles.**



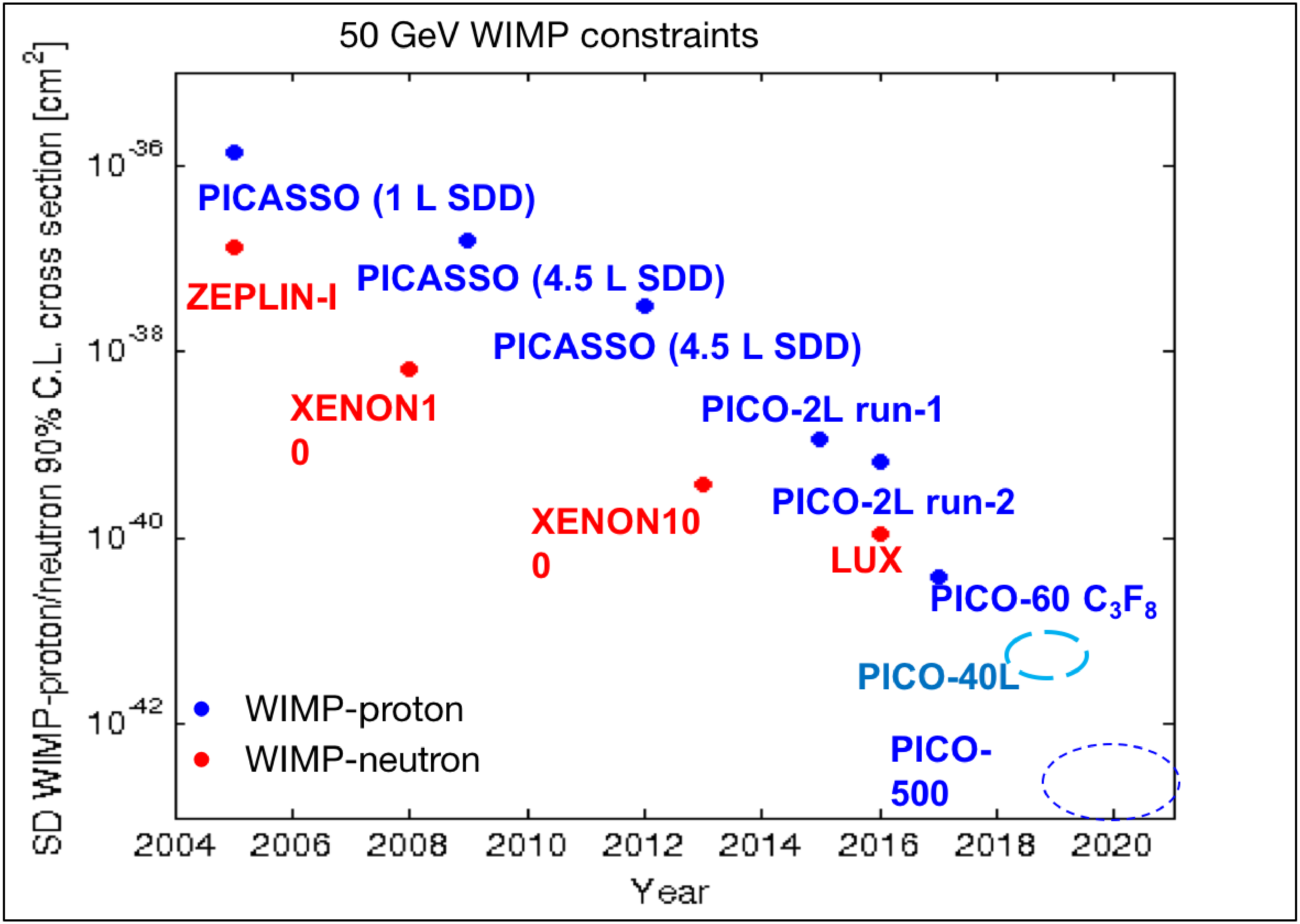
V. Barger, W-Y Keung and G. Shaughnessy, Phys. Rev. D78 (2008) 056007

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 being deployed (early 2018)**
- **PICO-500: future ton-scale experiment 2019**

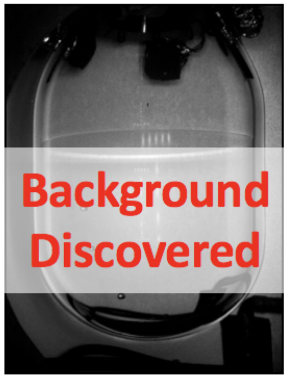
Spin-Dependent



COUPP and PICO timeline

COUPP-4 (2011)

CF_3I Target



Try switching target fluids

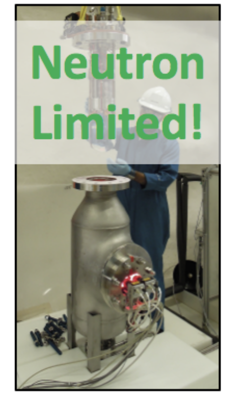
PICO-2L (2014)

C_3F_8 Target

Try removing particulate

PICO-2L (2016)

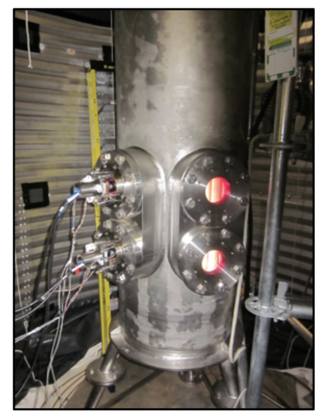
C_3F_8 Target

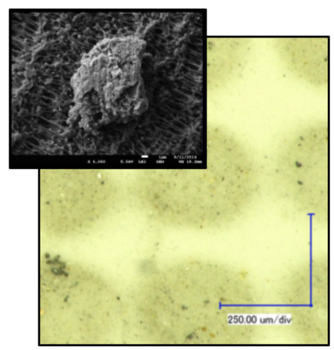


Try scaling

PICO-60 (2017)

C_3F_8 Target

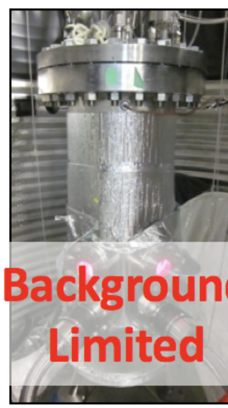




Try scaling to increase statistics

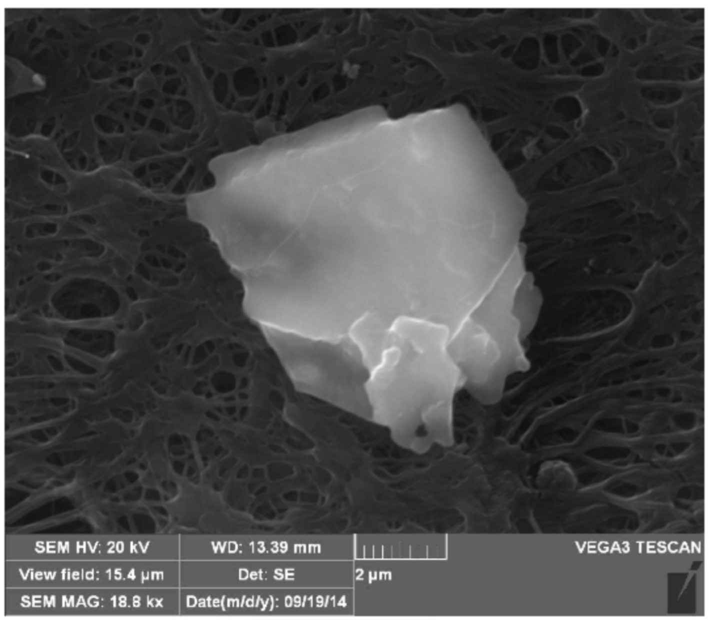
PICO-60 (2014)

CF_3I Target

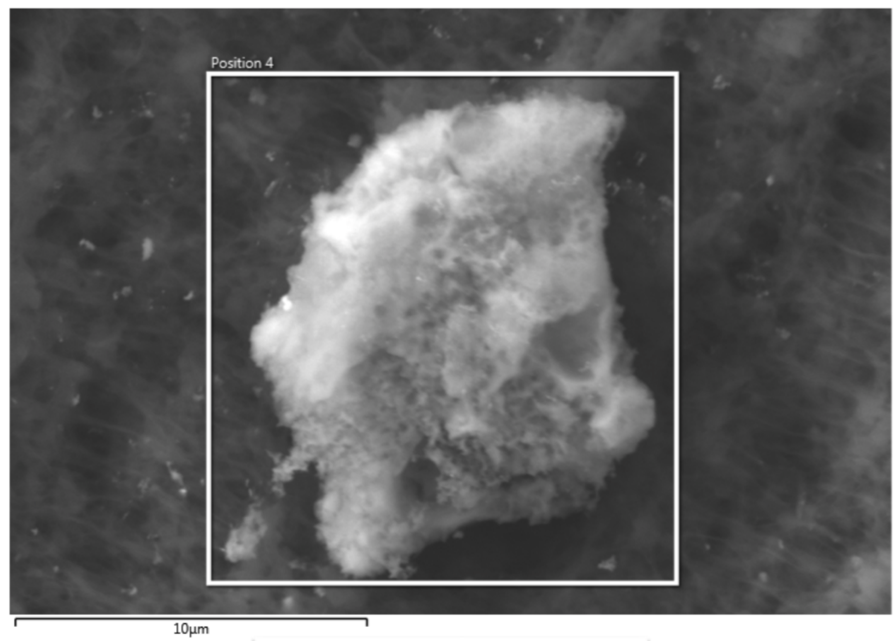


Radioactive particulates suspected to be part of the problem.
Careful assays of the liquids after the end of fill revealed contamination (radioactivity not enough to account for backgrounds observed)

- Merging of two water droplets releases O(1 keV) of surface tension energy
- The water lowers the bubble nucleation threshold, released energy can nucleate bubbles at PICO operating thresholds of a few keV
- The merging water droplets could be attached to solid particulate

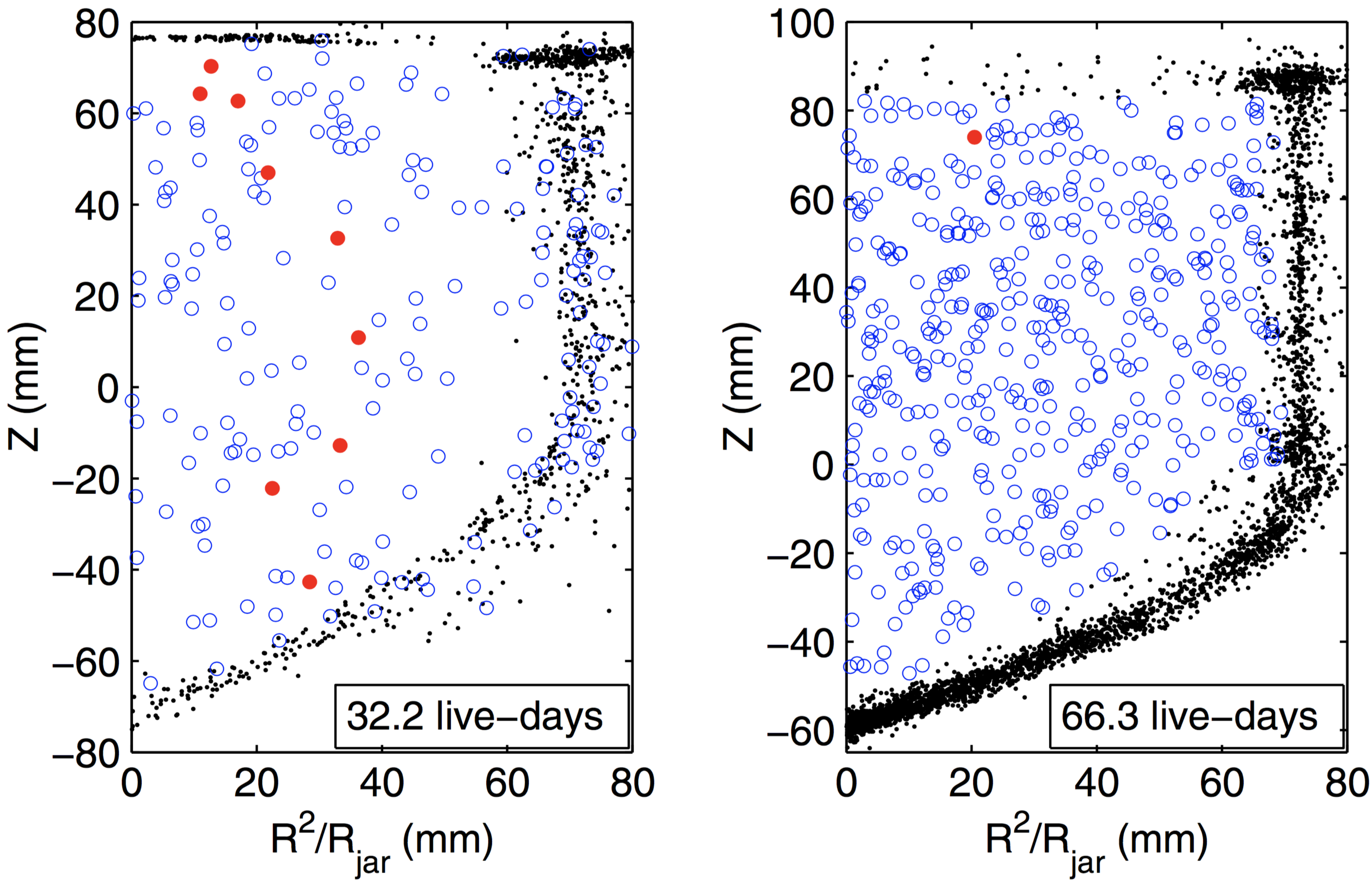


Quartz

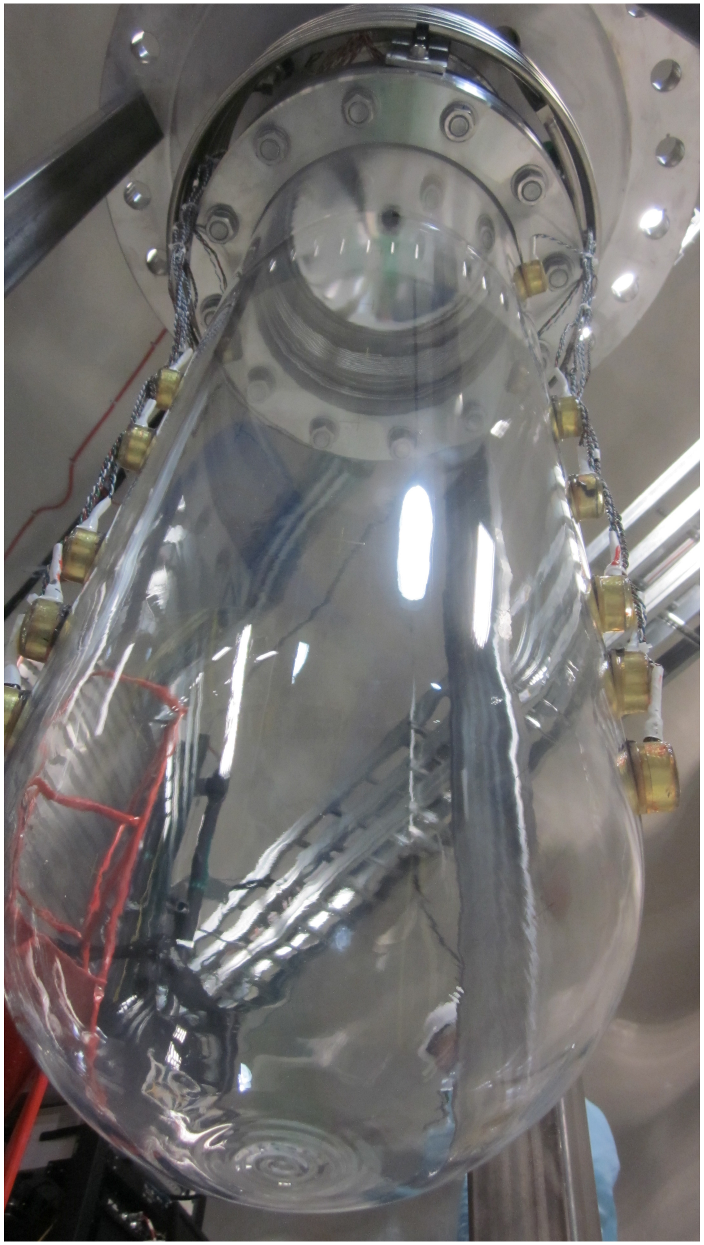


Stainless steel

This is what happened in PICO-2L



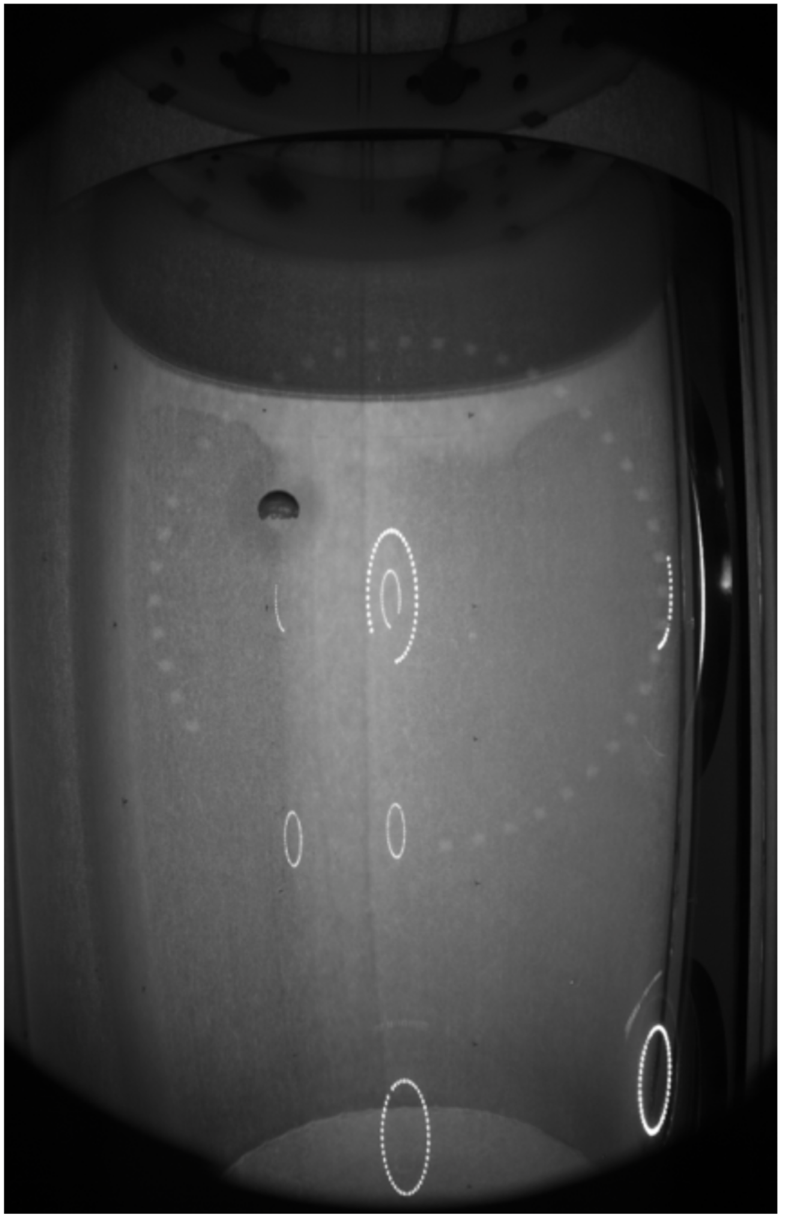
COUPP60 and PICO-60



COUPP60 and PICO-60

This is what happened in PICO-60

- **First bubble on August 1st 2016**
- **Water shield filled on Aug 3-4**
- **Data taking started on Nov. 2016**



(PICO60 run1)

PICO-60 physics run

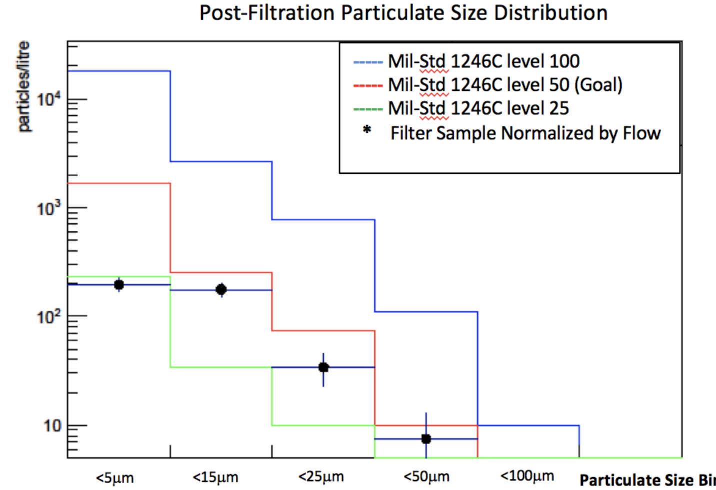
Physics run: Nov 2016-Jan 2017
(30 days live-time)

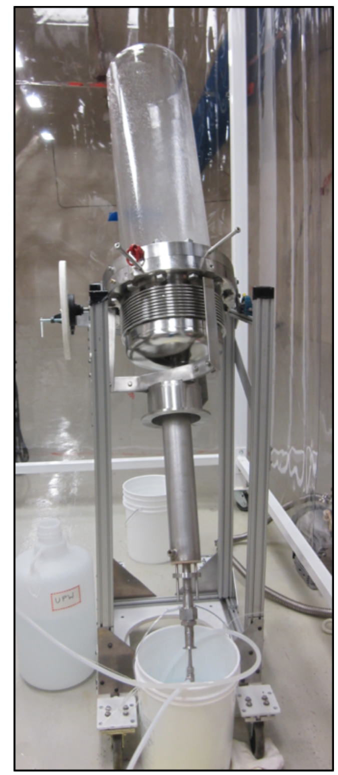
- Filled with 52kg of C_3F_8 on June 30, 2016
- Collected 1167 kg-days of dark matter search data
- 3.3 keV threshold

- Inner volume components cleaned to MIL-STD-1246C level 50 and active filtration

Blind(deaf) analysis

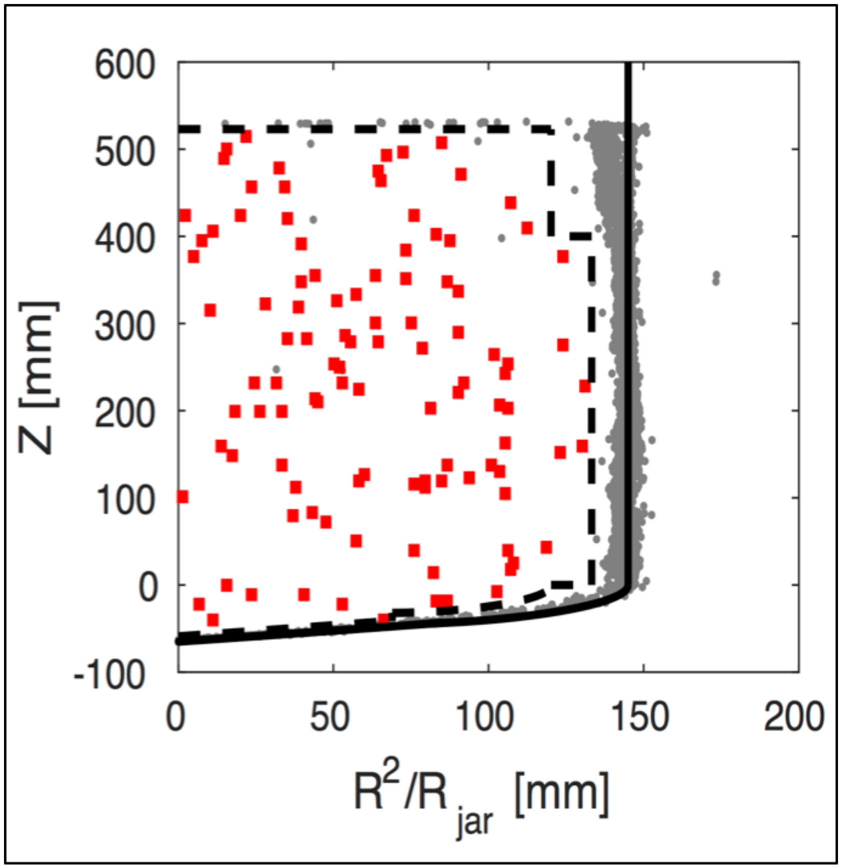
Three multiple bubbles observed

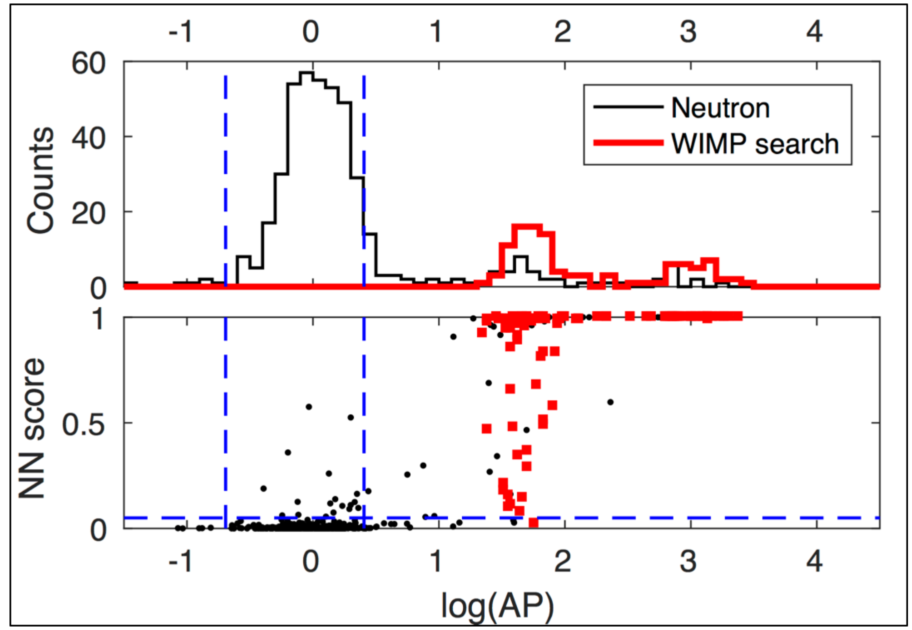




PICO60 physics run

- 45.7 kg fiducial mass
- 85.% WIMP slection efficiency
- 106 events considered after cuts

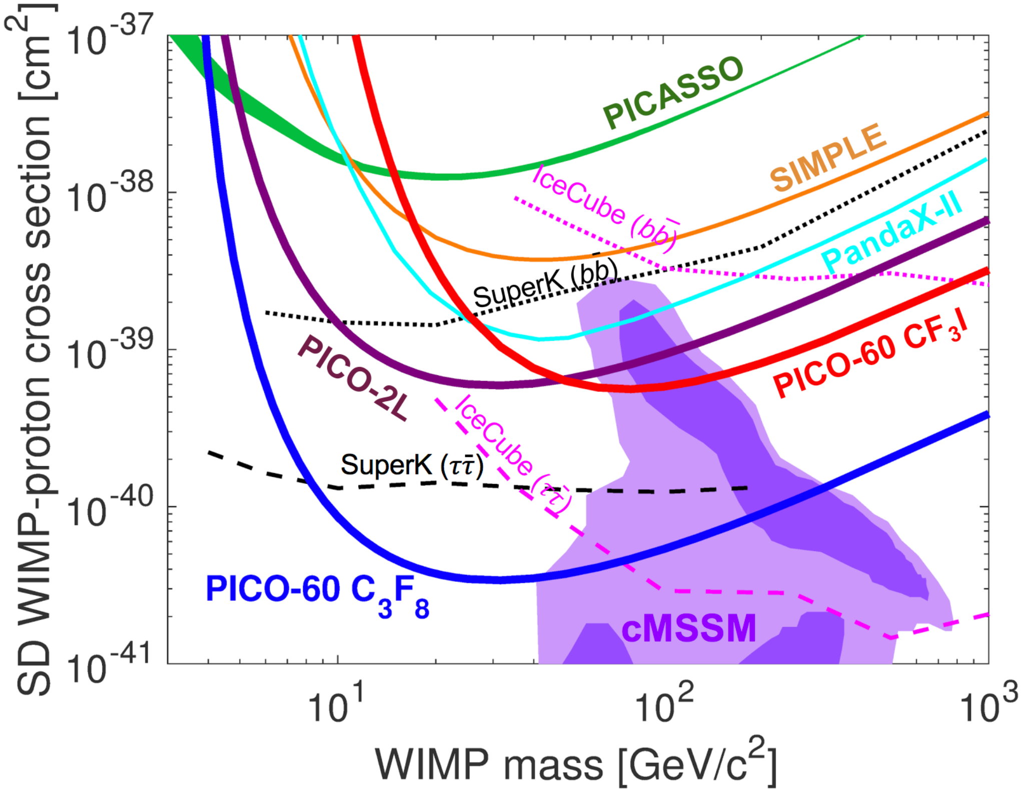




Blinded acoustics analysis:
alpha decays indistinguishable
from nuclear recoils

Unmasking revealed
no nuclear recoil candidates

PICO limits

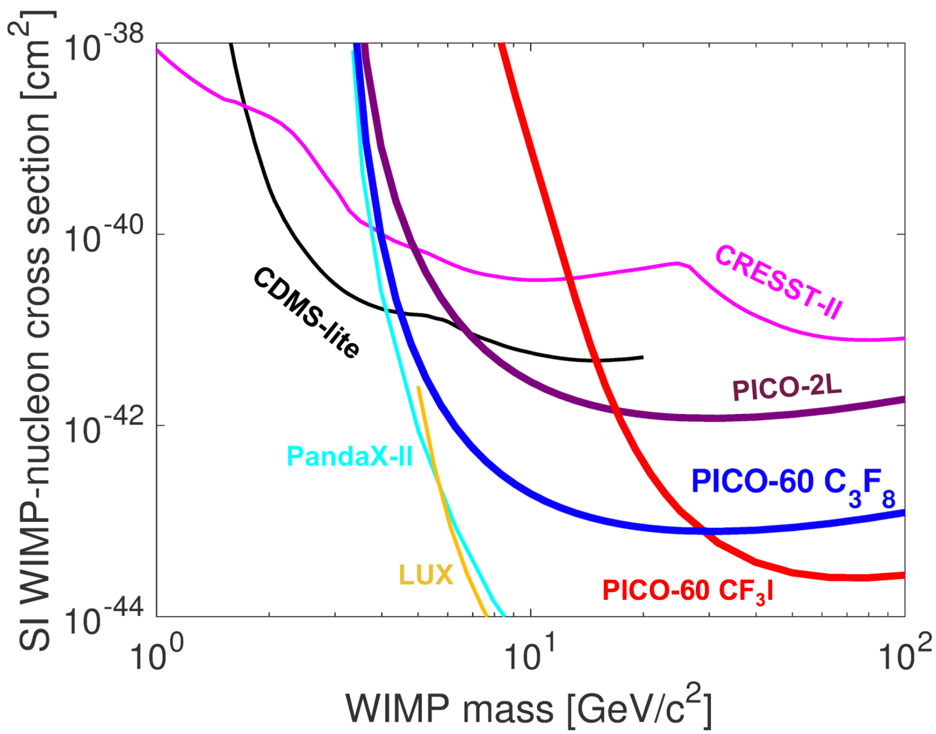


Phys. Rev. D 93, 052014 (2016)

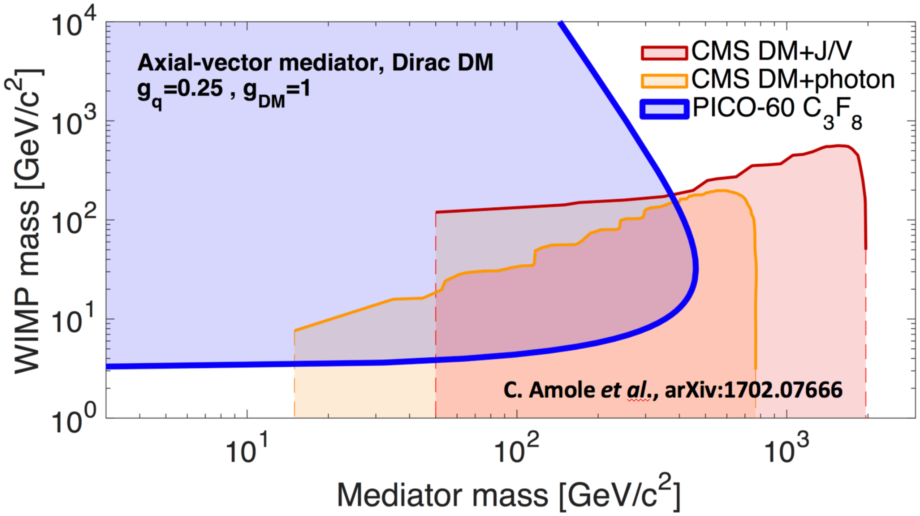
Phys. Rev. Lett. 118, 251301 (2017)
(Editor's suggestion)

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

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



PICO limits



$$\sigma_A^p = \frac{32 G_F^2 \mu_A^2}{\pi} \left(a_p \langle S_p \rangle\right)^2 \frac{J+1}{J}$$

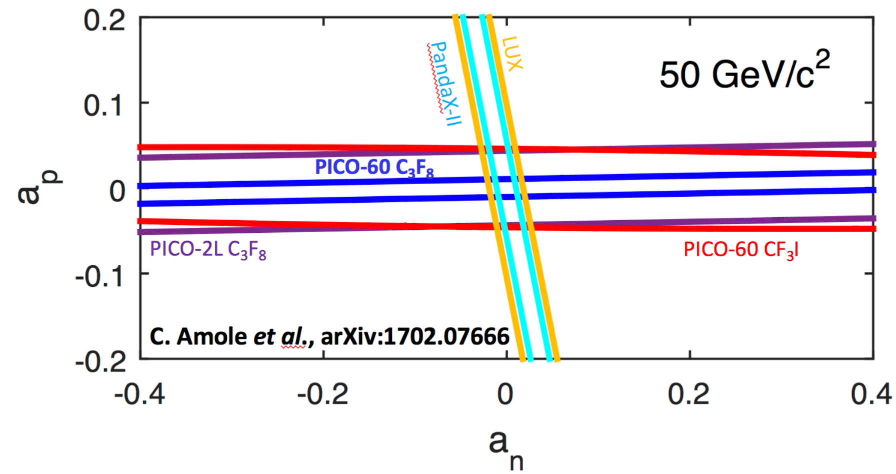
See Tovey for details:
D.R. Tovey, *et al.*, Phys. Lett. B 488, 17 (2000)

LHC Dark Matter Working Group (LHCDMWG) recommendations on simplified models:

For a mediator exchanged in the s-channel, 4 free parameters:

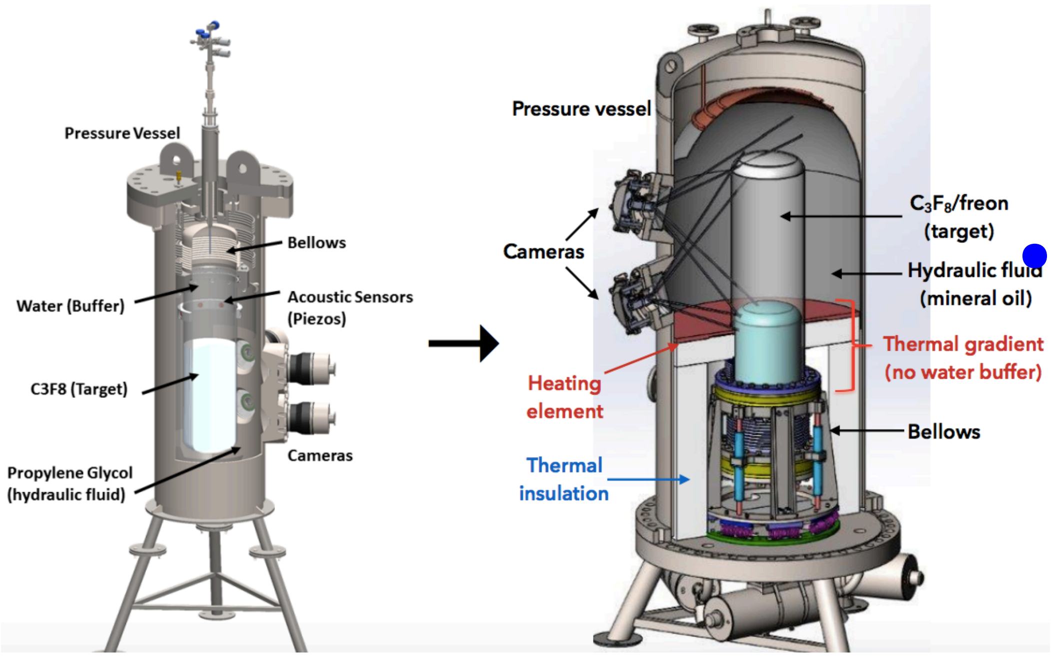
- Dark matter mass: $\boldsymbol{m_{DM}}$
- Mediator mass: $\boldsymbol{m_{med}}$
- Universal mediator coupling to quarks: $\boldsymbol{g_q}$
- Mediator coupling to dark matter: $\boldsymbol{g_{DM}}$

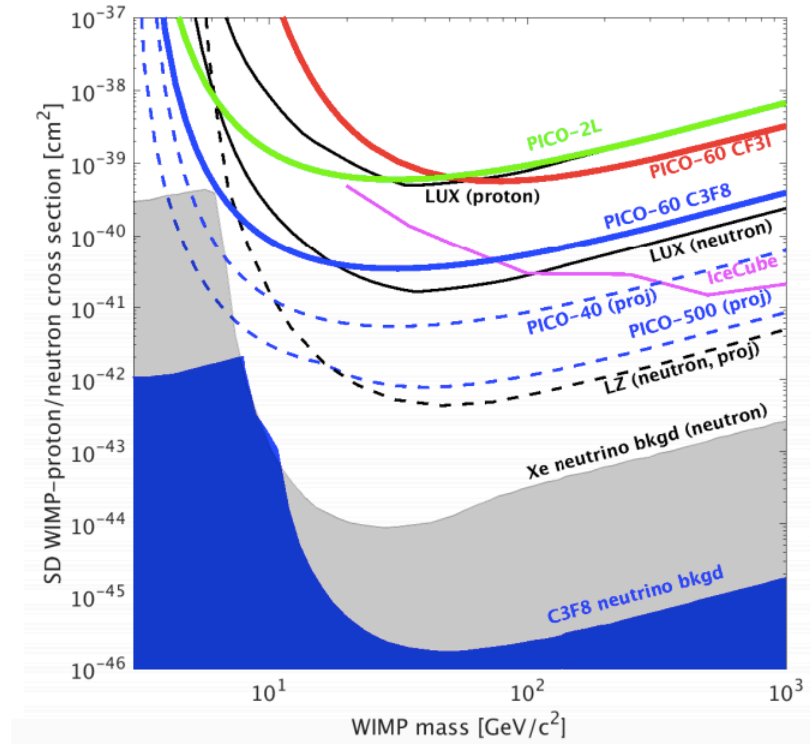
(constraints presented on m_{DM} and m_{med} for g_q = **0.25** and g_{DM} = **1** for an axial-vector mediator exchanged in the **s-channel)**



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



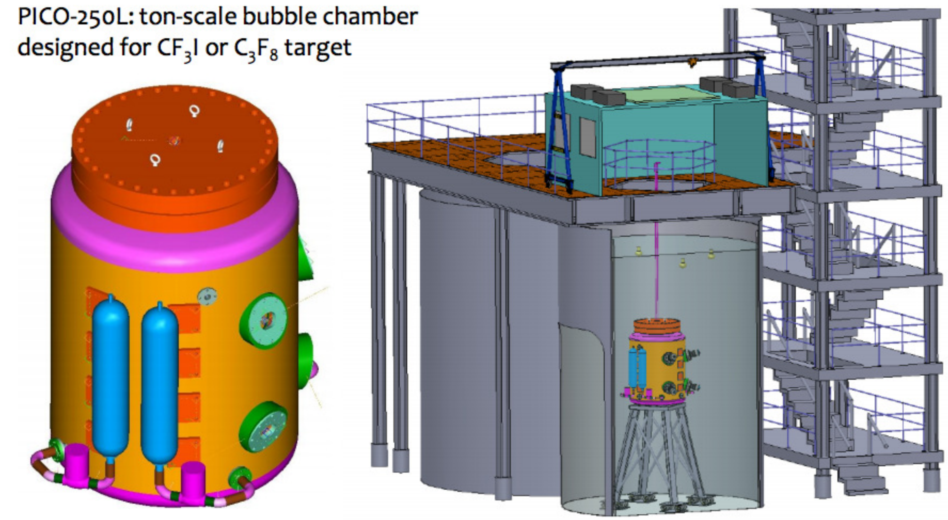


- **Science:**
  acquire one-year background-free exposure
  - Order of magnitude improvement on PICO-60 limits

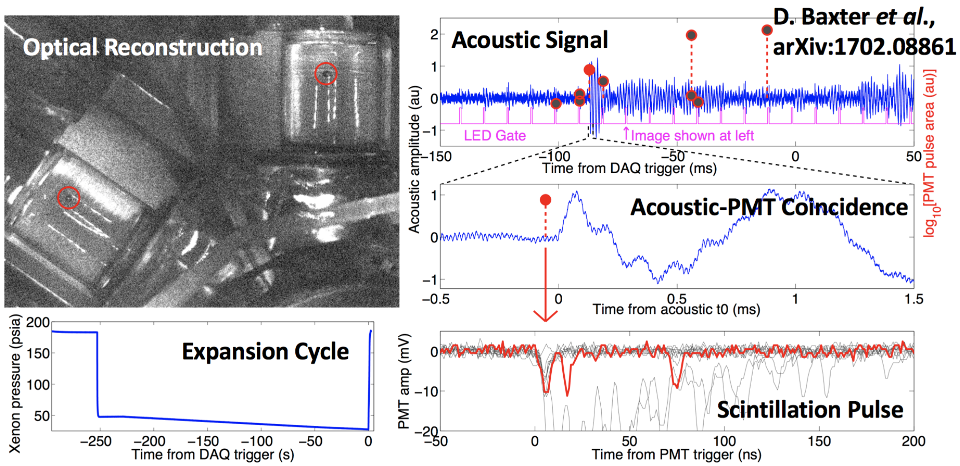
PICO40L-RSU, PICO-500, et al.

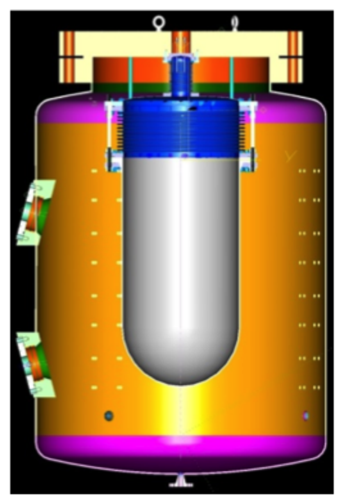
Deploying new detector (2018) PICO40L: Right Side Up

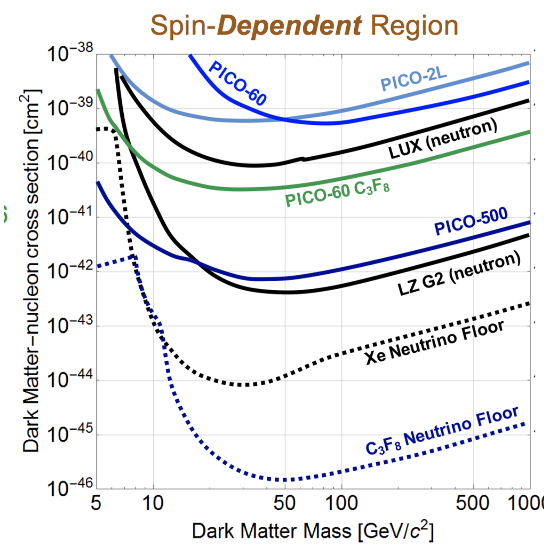
PICO-500 on 2019



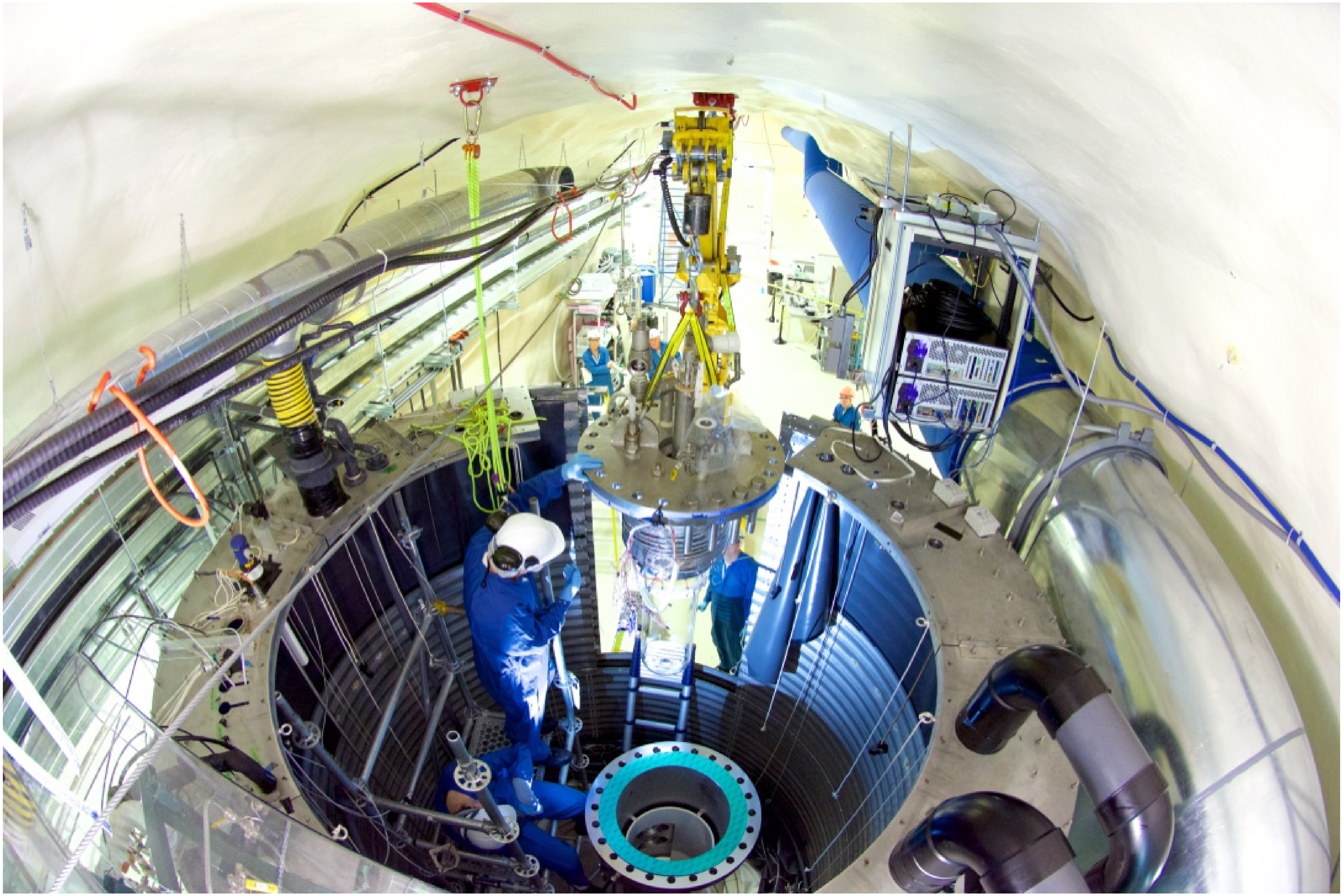
Xenon/Argon bubble chambers







This is PICO...



Conclusions

- **PICO bubble chambers are producing world leading direct detection limits using flourine targets**
- **No WIMP-candidates in latest PICO-60 run**
- **PICO-60 C_3F_8: a factor 17 improvement on SD WIMP-proton constraints**
- **Lower threshold physics run in 2017, soon to publish**
- **Backgrounds under control: bubble chamber technology is ready to be scaled-up to ton-scale**

A bright future for amazing science!

Conclusions

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A ~~bright~~ (dark) future for amazing science!