PICO-500L: Simulations for a 500L Bubble Chamber for Dark Matter Search

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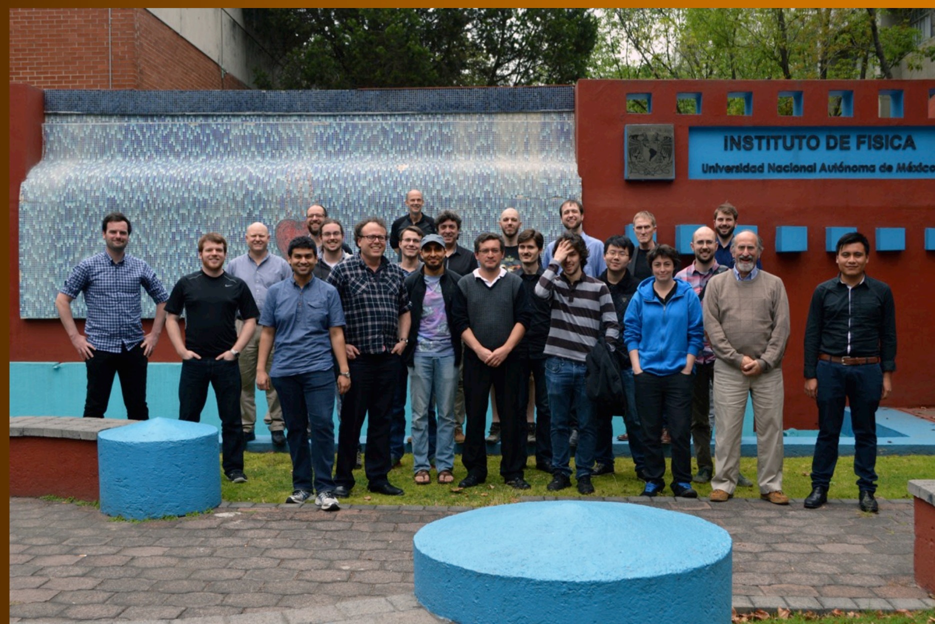
for the PICO collaboration

TAUP2017
Sudbury ON, Canada; July 25, 2017

PICO Collaboration

PICO



SNOLAB — Mining for Knowledge — Creuser pour trouver... l'excellence
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K. Clark

Laurentian University / Université Laurentienne
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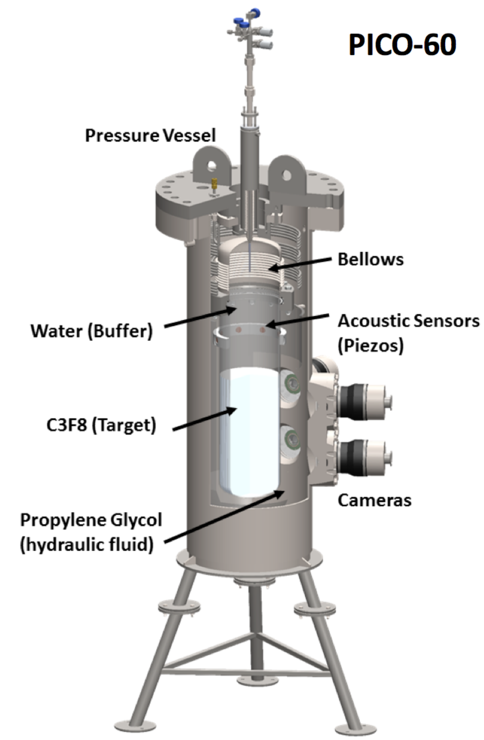
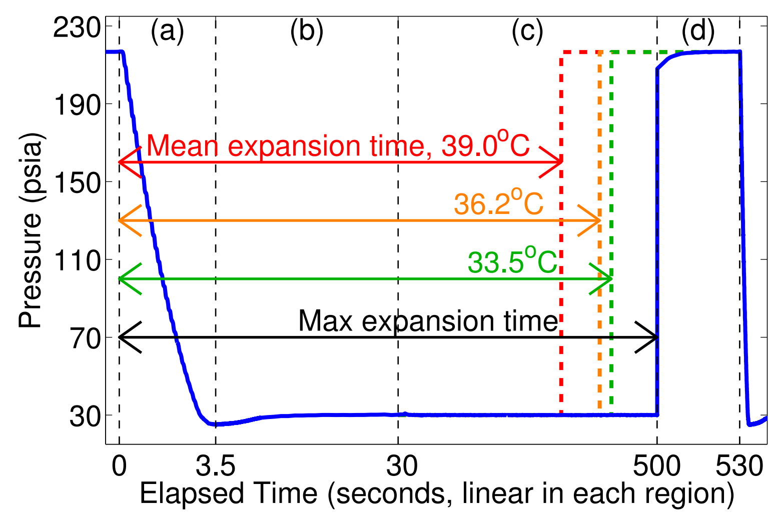
PICO bubble chambers

- Target material: superheated C_3F_8, CF_3I spin-dependent/independent

  Could make a dark matter bubble chamber with any liquid!

- Particles interacting evaporate a small amount of material: bubble nucleation
- Cameras record bubbles
- Piezo-electric acoustic sensors detect sound
- Recompression after each event

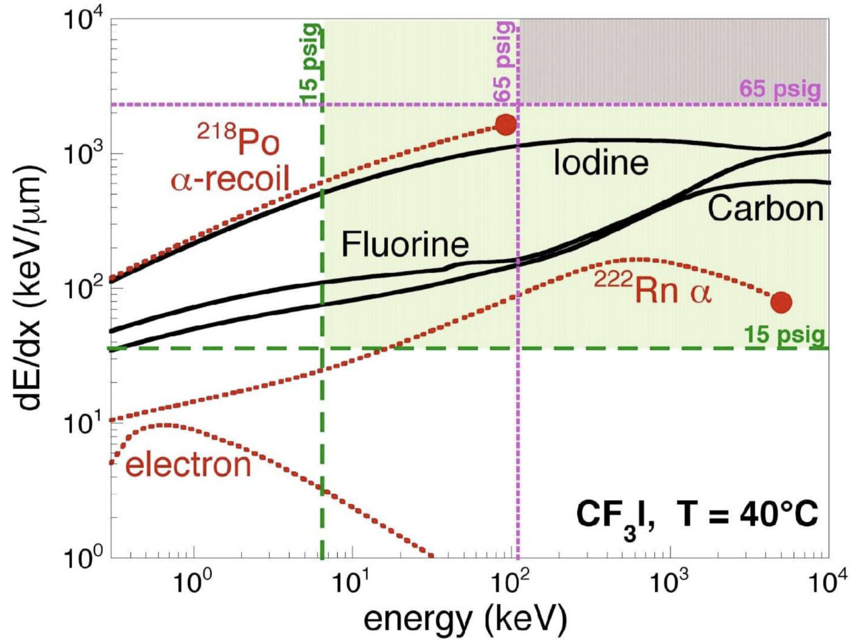


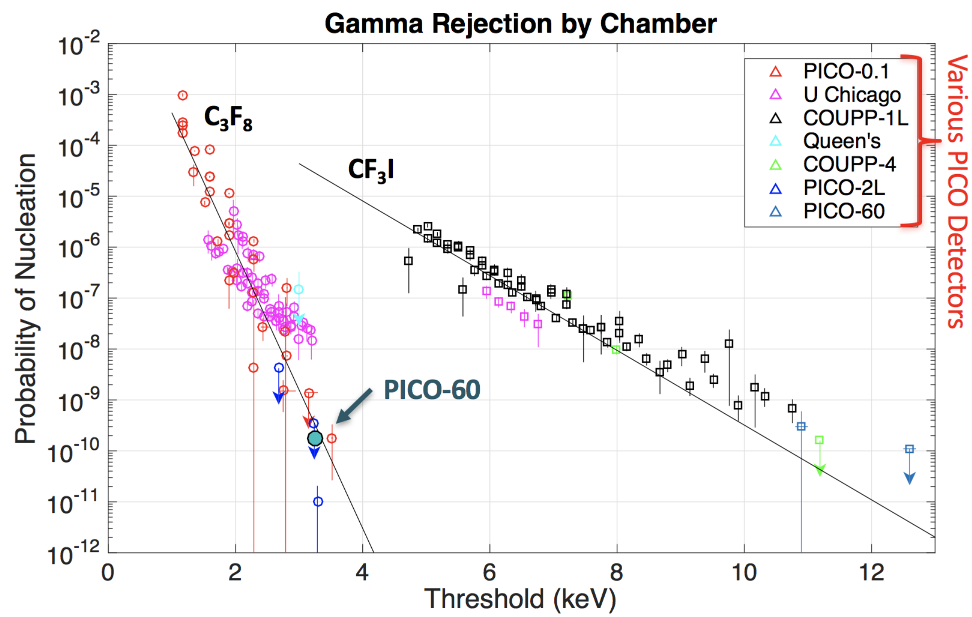


Dependence of bubble nucleation on the total deposited energy and dE/dx

- 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

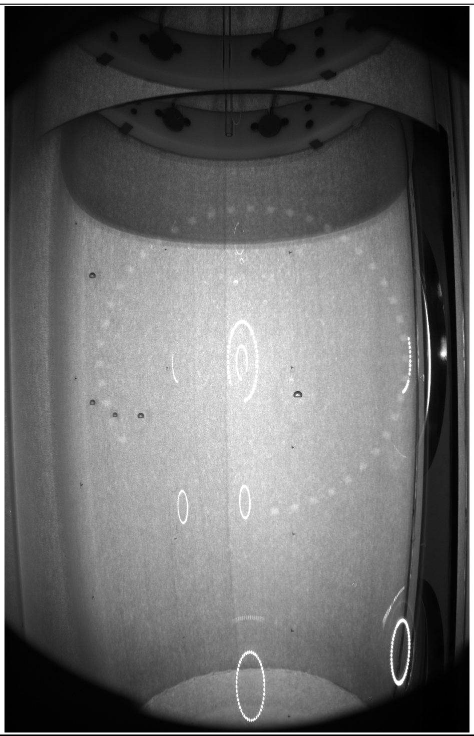


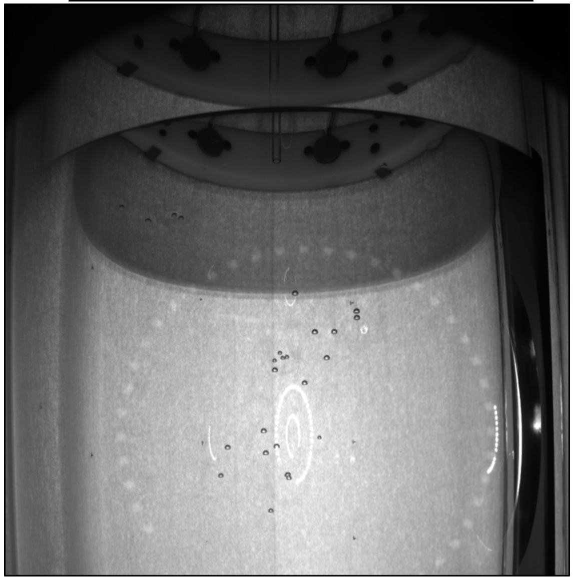


- **Alpha decays:**
  Nuclear recoil and
  40 μm alpha track
  1 bubble

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

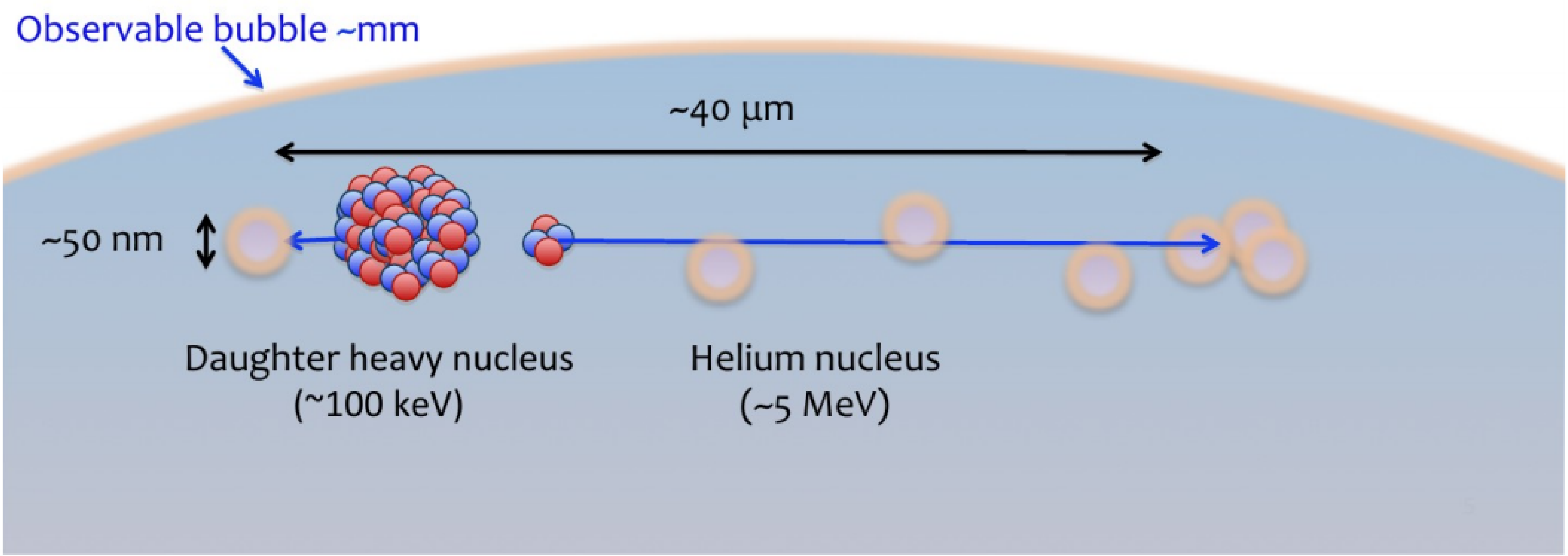
- **WIMPs:**
  Nuclear recoil
  mean free path $> 10^{12}$ cm
  1 bubble





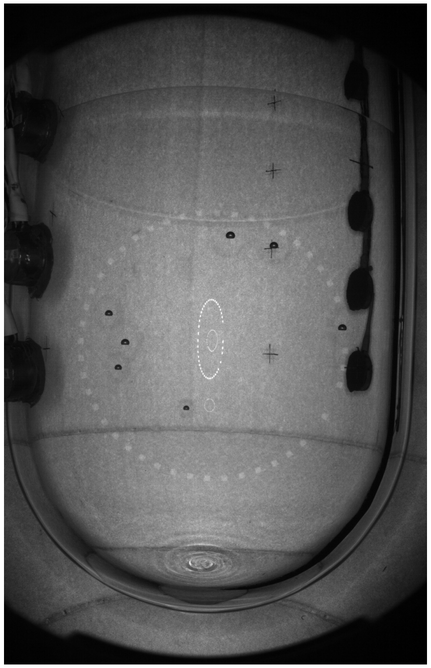
Alpha backgrounds

- Alphas are $\sim$ 4 times louder than nuclear recoil bubbles
- $>$ 99.4% discrimination against alpha events demonstrated
- Discovered by the PICASSO collaboration



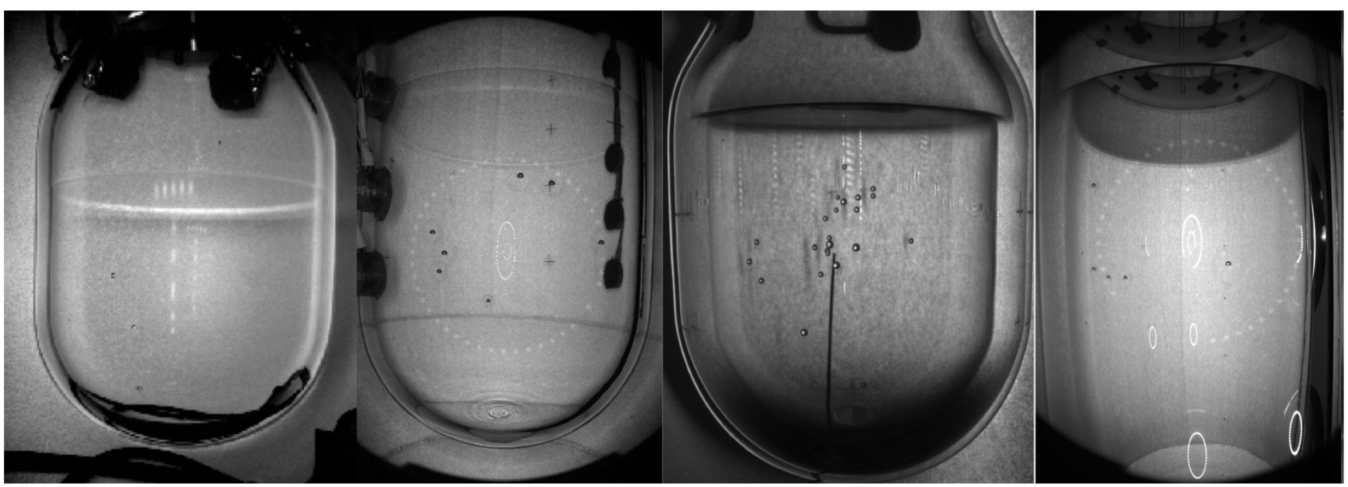
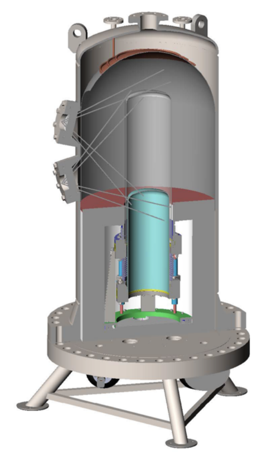
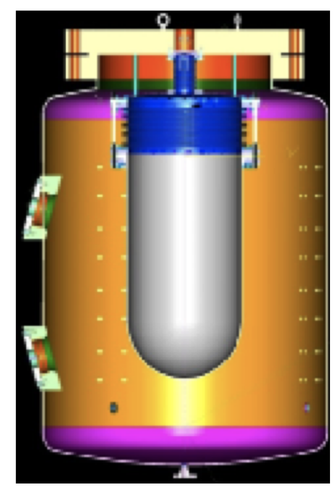
PICO detectors features

- 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
  - γ: rejection to
    electron recoils ($\sim 10^{-10}$)
- Large target mass:
  COUPP4 to COUPP60
  PICO-2L to PICO-60
  PICO-40L, PICO-500L



Meet the family

- 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 (summer 2017)
- PICO-500L: future ton-scale experiment 2018

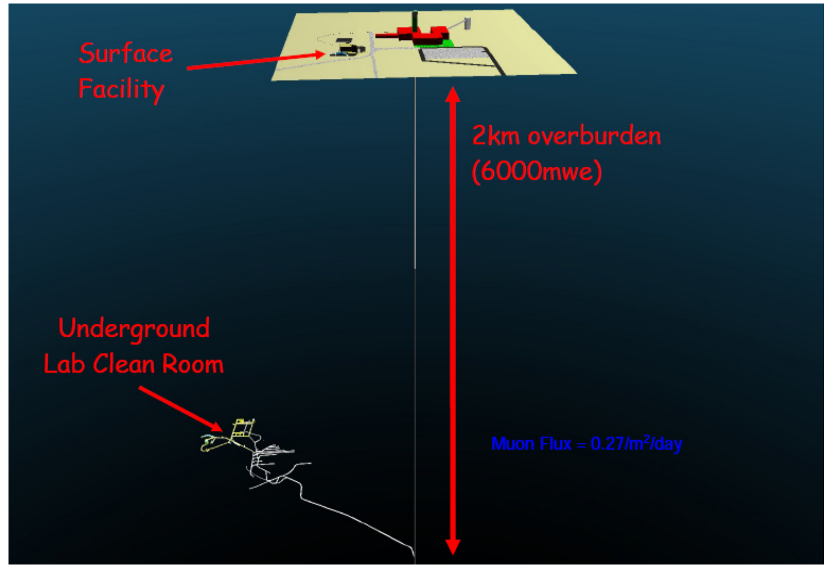




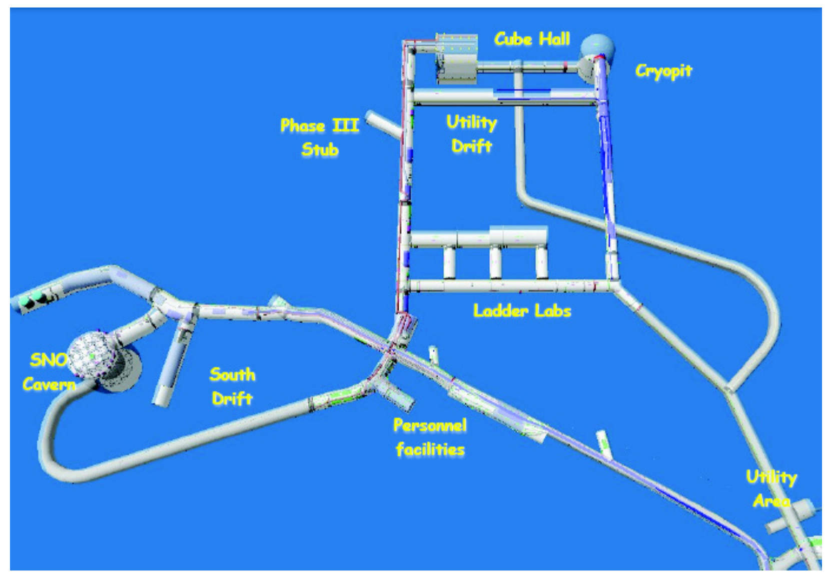
PICO at SNOLAB

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

- **The ability to reject electron and gamma backgrounds by arranging the chamber thermodynamics such that these particles do not even trigger the detector**

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- **The ability to increase the size of the chambers without changing the size or complexity of the data acquisition**
- **Sensitivity to spin-dependent and spin-independent WIMP couplings**

PICO and PICO related talks here at TAUP...

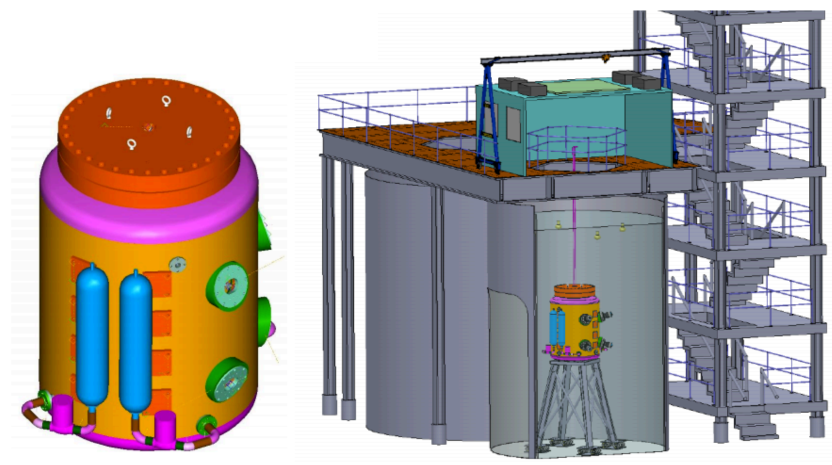
- **C. Krauss, "PICO Results and Outlook", plenary on Tuesday 9:50am**

- **S. Fallows, "Toward a next-generation dark matter search with the PICO-40L bubble chamber", Monday 4:45pm**
- **J. Zhang, "First Demonstration of a Scintillating Xenon Bubble Chamber for Dark Matter and CEνNS Detection", Monday 1:15pm**
- **P. Mitra, "Threshold verification in the PICO-60 detector and study of the growth and motion of nucleation bubbles", Monday 2:45pm**

- **Miaotianzi Jin, "Nuclear recoil calibration for PICO bubble chambers", poster session**
- **U. Chowdhury, "PICO-60: World's largest bubble chamber for dark matter detection", poster session**
- **B. Loer, "The PICO-40L Detector Design", poster session**

PICO-500L

- $> 10^{10}$ γ/β insensitivity
- $> 99.3\%$ acoustic α discrimination
- Multi-target capability
  SD- and SI-coupling
  High- and low-mass WIMPs
- Easily scalable,
  inexpensive to replicate
- Probed technology:
  PICO-2L, PICO-60
- Two possible detector configurations: PICO-60 style vs PICO-40L(RSU)

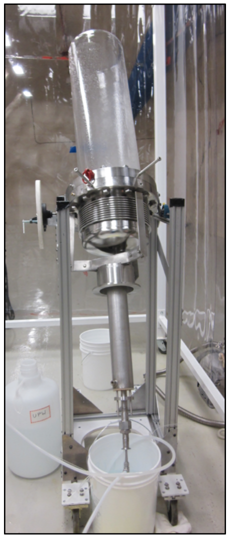


Installation begins 2018

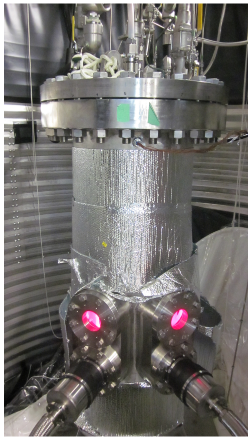
Data taking by 2019

PICO-500L design

- Target fluid: C_3F_8
- Inner vessel assembly: ultra-high-purity synthetic fused silica jar



- Outer vessel: Stainless steel (ϕ= 60 inches) with mineral oil as hydraulic fluid

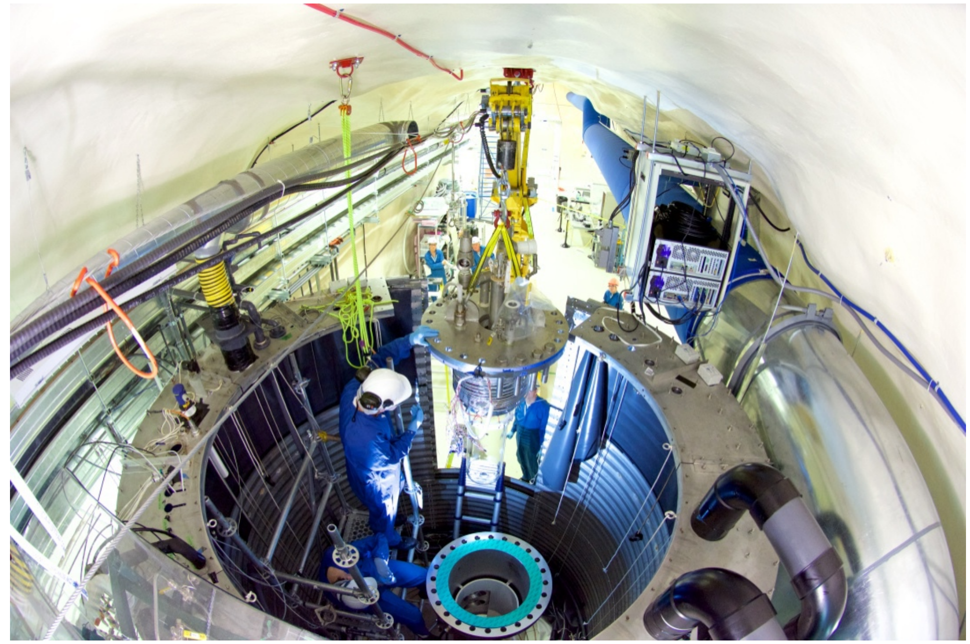


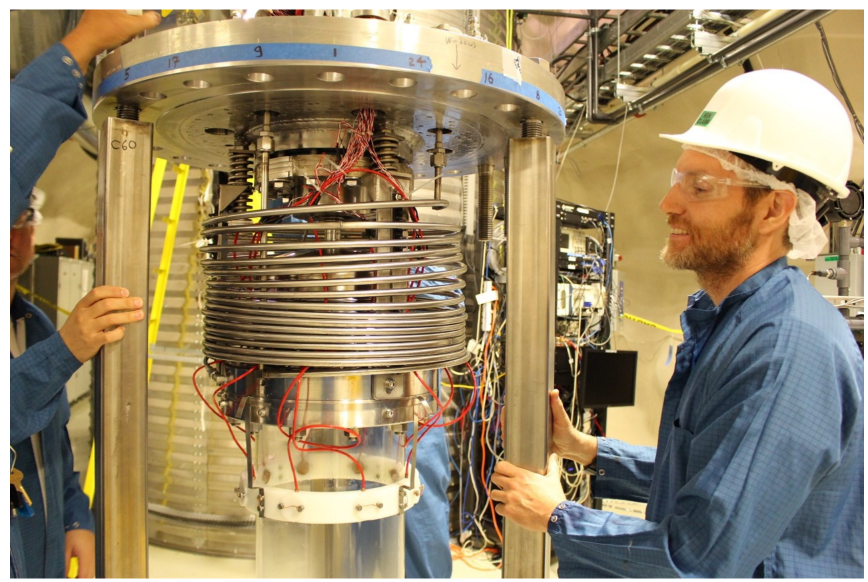
PICO-500L design

- **Outer neutron shielding:**
  - neutron moderator
  - muon veto
  - temperature control

- **Pressure control unit:**
  - expand and recompress the chamber
  - regulate chamber pressure

- **Data acquisition:**
  - T and P sensors
  - machine vision cameras
  - acoustic transducers





Backgrounds in PICO

Goal is to limit the rate from the combined set of backgrounds to less than one per year

- **Each part (or set of similar parts) contributes at most 10% of the total background budget (0.05 single-site events per live-year)**
- **Require fewer than 0.1 total events, including multi-site events, per live-year for each part**

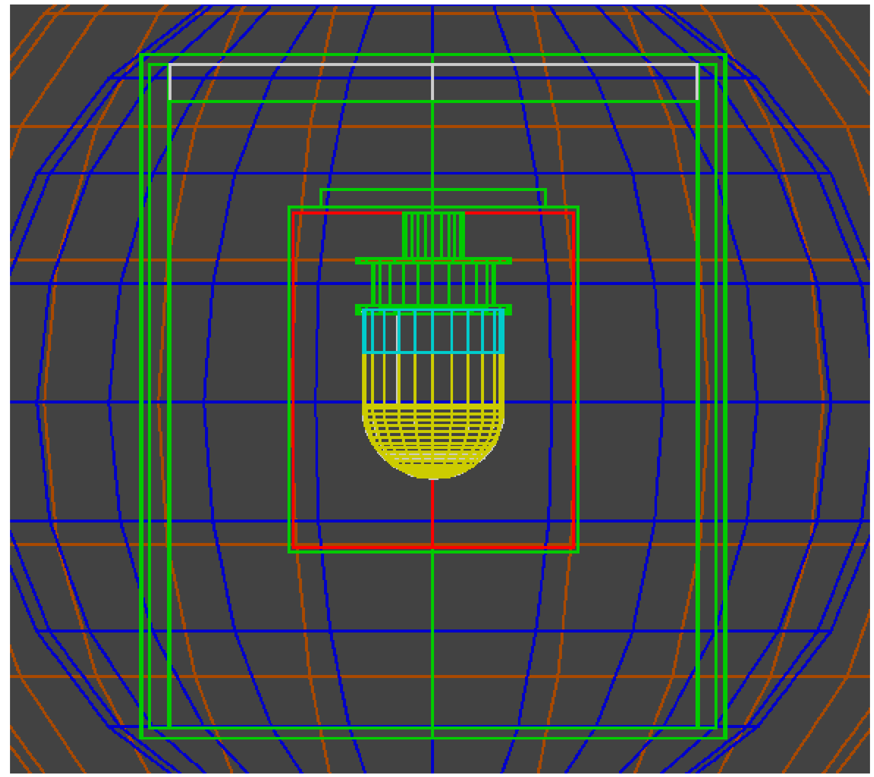
Couting facilities:

- **University of Chicago germanium counter**
- **SNOLAB germanium counters**
- **ICPMS counting at PNNL**
- **Radon emanations at SNOLAB**

PICO-500L simulations

- **External backgrounds:**
  - Rock neutrons
  - Muon induced neutrons
  - Photo-nuclear reactions

- **Internal backgrounds:**
  - U and Th: fission and (α,n) on light elements
  - ^{238}U direct decay
    - Materials: SS, quartz,...
    - Fluids: water, mineral oil, C_3F_8
    - Radon: emanation, deposition
    - Mine dust
    - veto PMTs
    - Acoustic transducers
    - Cameras, lenses, PCB, cables



Toy MC
GEANT4 model

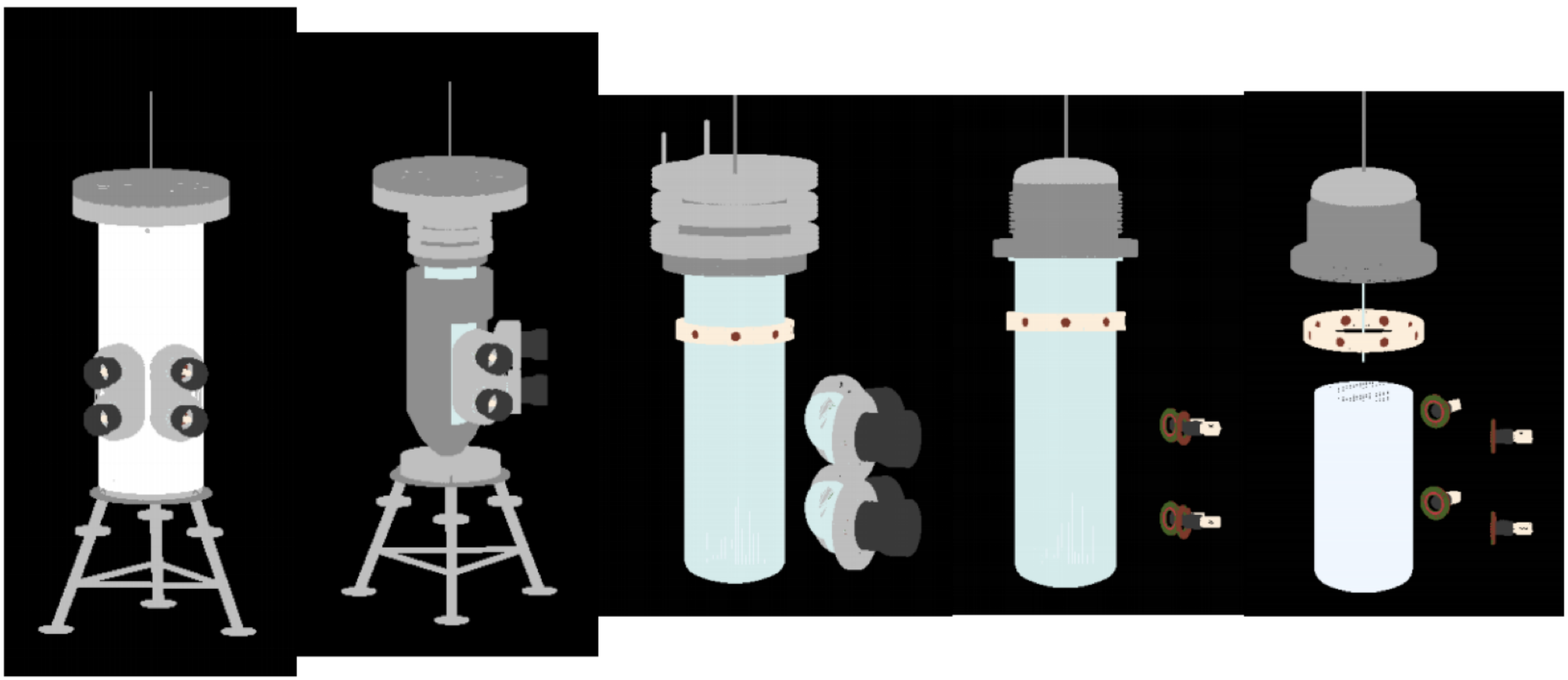
3D model implemented in GEANT4

PICO-60 simulations:

- Successful implementation of 3D bubble chamber models (Computer-Aided Design) into GEANT4
- Use of commercial software: freeCAD, CAD-Mesh, MC-Cad

In PICO-500L:

Use Monte Carlo to design CAD models based on background budget
Import CAD model into GEANT4



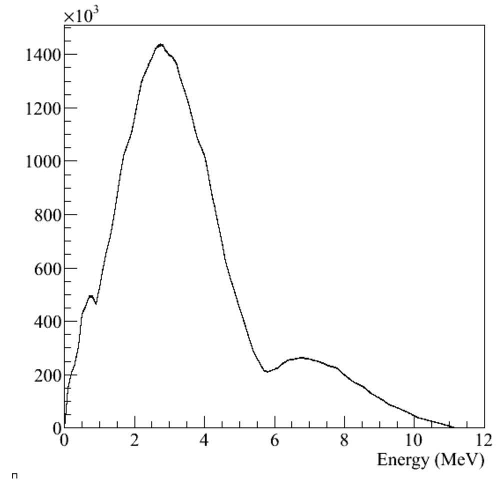
PICO-500L: external neutrons

SNOLAB: 6000 m.w.e.
Rate is less than 0.27 $\mu/m^2/day$

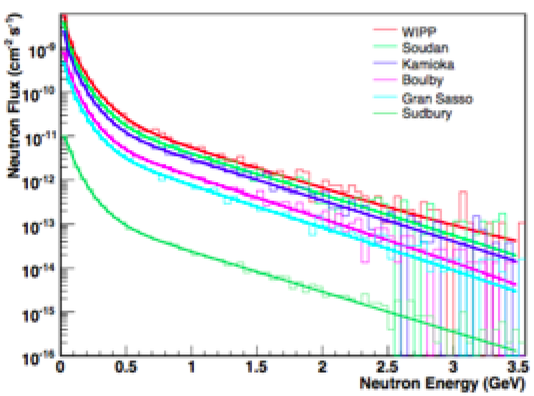
Fast neutrons from norite:
Rate is $\sim$4000 $n/m^2/day$

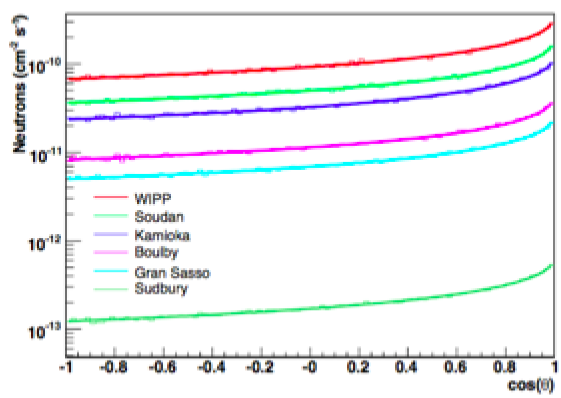
Water tank dimensions:

- $\phi = 5.6$ m and L $= 7.9$ m



Neutron energy spectrum for (α,n) and SF in norite

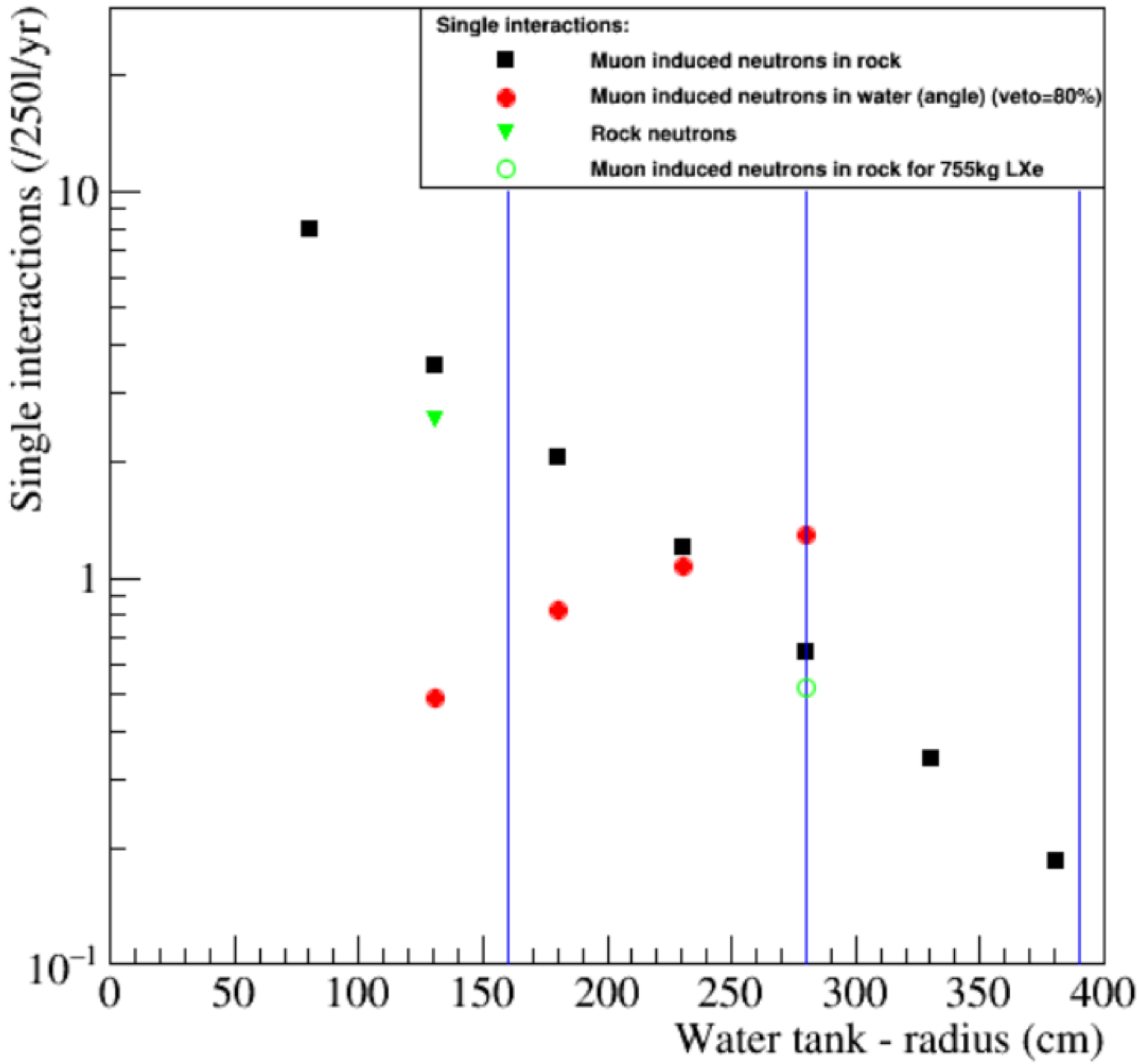




Muon induced neutron energy and angular spectra at SNOLAB (Phys. Rev. D 73, 053004)

Muon induced neutrons in rock, water, mineral oil and stainless steel driving the water shield specifications

Water tank shielding and muon veto

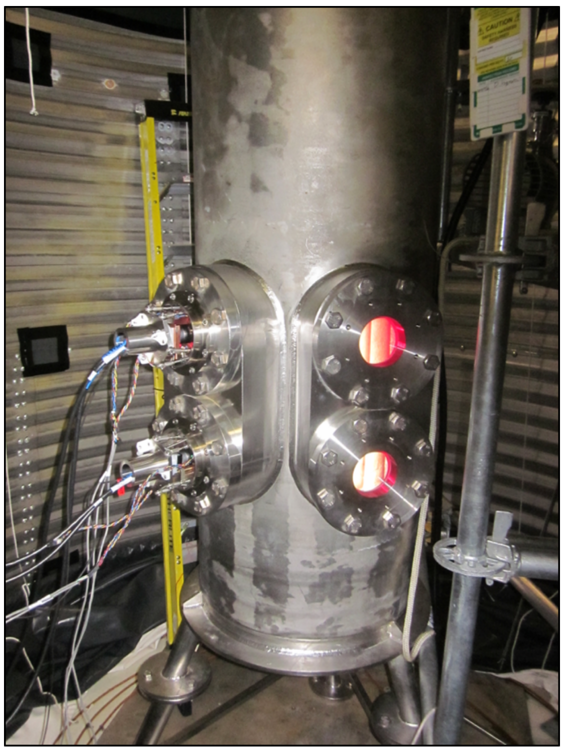


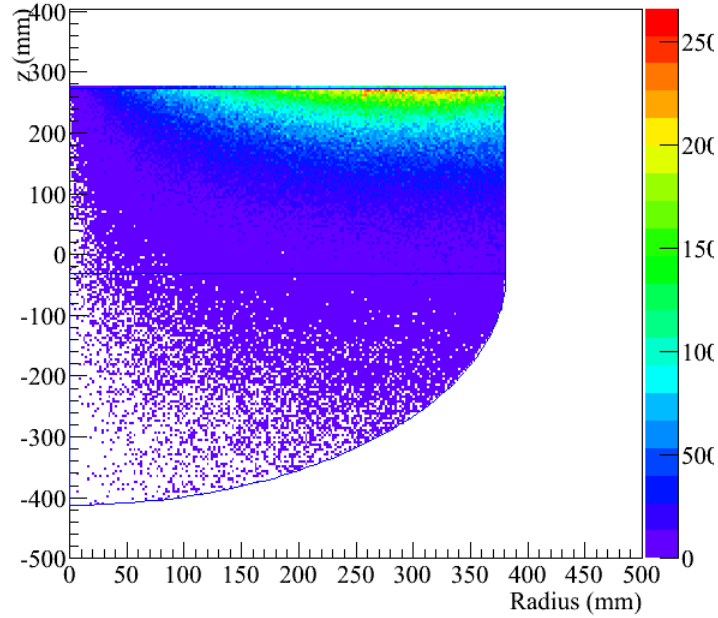
PICO-500L: internal neutrons

Estimated purity limits:

Stainless steel: a few ppb
Quartz: a few ppt

Mineral oil: ∼ 10 ppt
C_3F_8: ppt level, alpha-n tagging





Other backgrounds
(ppb to ppt purity):

- Acoustic sensors
  (simulation shown above)
- Cameras, lenses
- Radon:
  emanation, deposition, diffusion
- Mine dust, veto PMTs

PICO-500L: gammas, betas and neutrinos

Gamma and beta decays:

Interact by Compton scattering, photoelectric absorption, and pair production

Rejection factor: $\sim 10^{-10} - 10^{-12}$

gamma rate expected to be less than $< 4 \times 10^{6}$ interactions/litre-year

PICO-500L expected:
$< 3 \times 10^{-4}$ events/year at 3 keV

Photo-nuclear reactions:

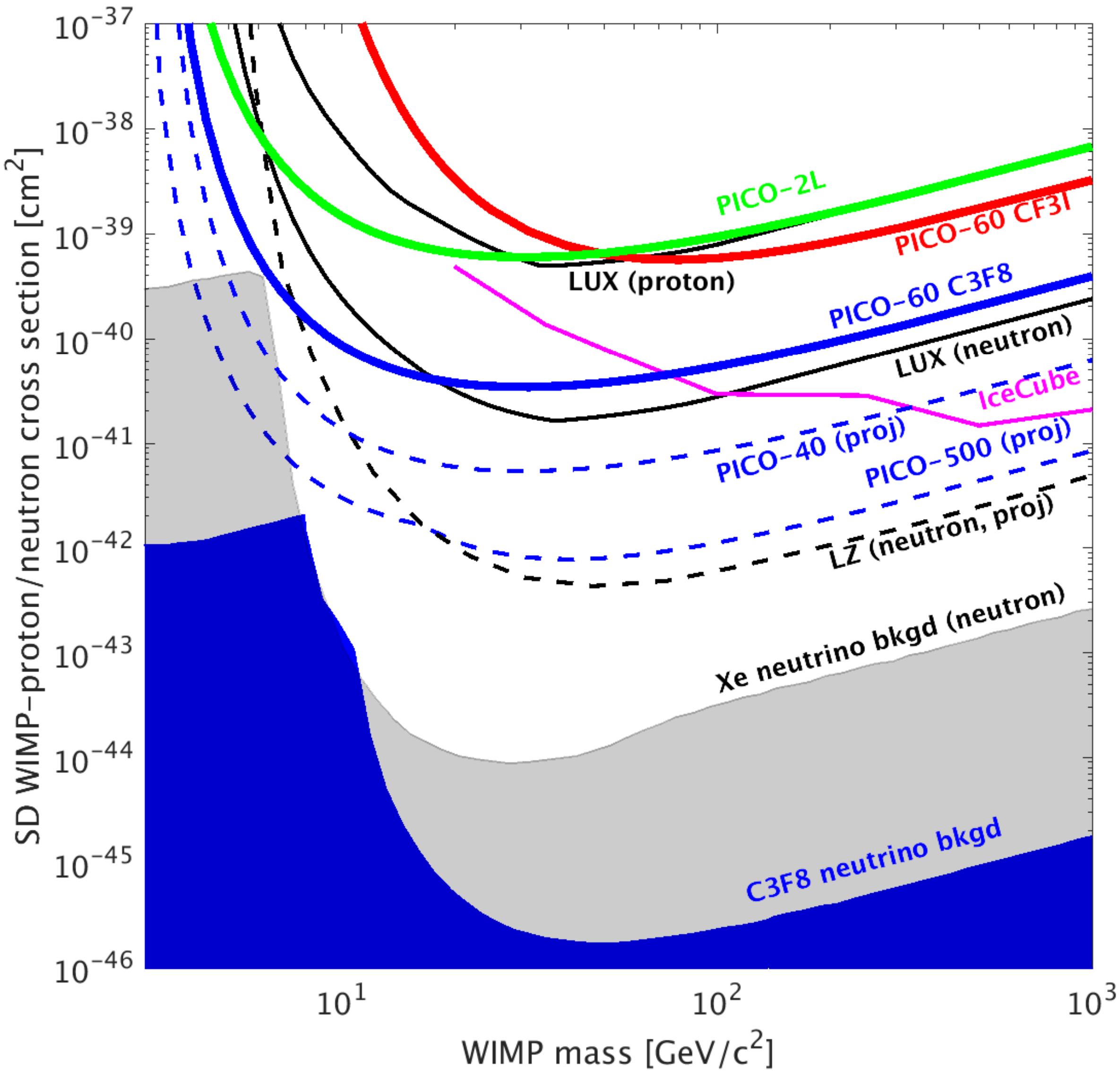
- **d(γ,n)p:Carbon and fluorine have negligible cross sections for 1-50 MeV**
- **^{2}H(2615 γ, n)^{1}H produces 145 to 252 keV neutrons**

  $< 1 \times 10^{-7}$ events/kg-day

  SNOLAB: 4 γ/cm^{2}/yr $>$ 9MeV

- **Neutrinos:**
  1 event per 40 live-days at 3 keV, raise threshold to 10 keV once observed

PICO-500L expected sensitivity at SNOLAB



One year at a threshold of 10 keV, 6 months at 3 keV, and a neutron background of 0.75 per year

Schedule

- **2017:**
  - **Operations completed for PICO-60**
  - **Deployment of PICO-40L**
  - **PICO-500L design: pressure vessel, internal components**
- **2018:**
  - **PICO-40L Physics data taking**
  - **Decision on detector configuration for PICO-500L**
  - **PICO-500L selection of SNOLAB location and installation**
- **2019:**
  - **PICO-500L commissioning**
  - **PICO-500L Physics data taking**

Ready for Physics data taking in 2019!

Conclusions

PICO bubble chambers are producing world leading direct detection limits using flourine targets

- **PICO-60 C_3F_8: a factor 17 improvement on SD WIMP-proton constraints; PICO-40L currently being deployed**
- **Backgrounds under control:**
  bubble chamber technology is ready to be scaled-up to tonne-scale

PICO-500L is a tonne scale detector:

- **spin-dependent sensitivity $\sim 10^{-42} cm^2$, spin-independent sensitive at low WIMP masses**
- **inexpensive, versatile and ready for physics in 2019**

Backgrounds in PICO-500L:

- **PICO-500L programme to keep backgrounds under control:**
  - **Material screening, in-situ measurements**
  - **Simulations: GEANT and MCNP (CAD implementation)**

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Stay tuned for the rise of PICO!