Current Status and Future Plans for Dark Matter Searches with PICO Bubble Chambers

Tony Noble
Queen's University

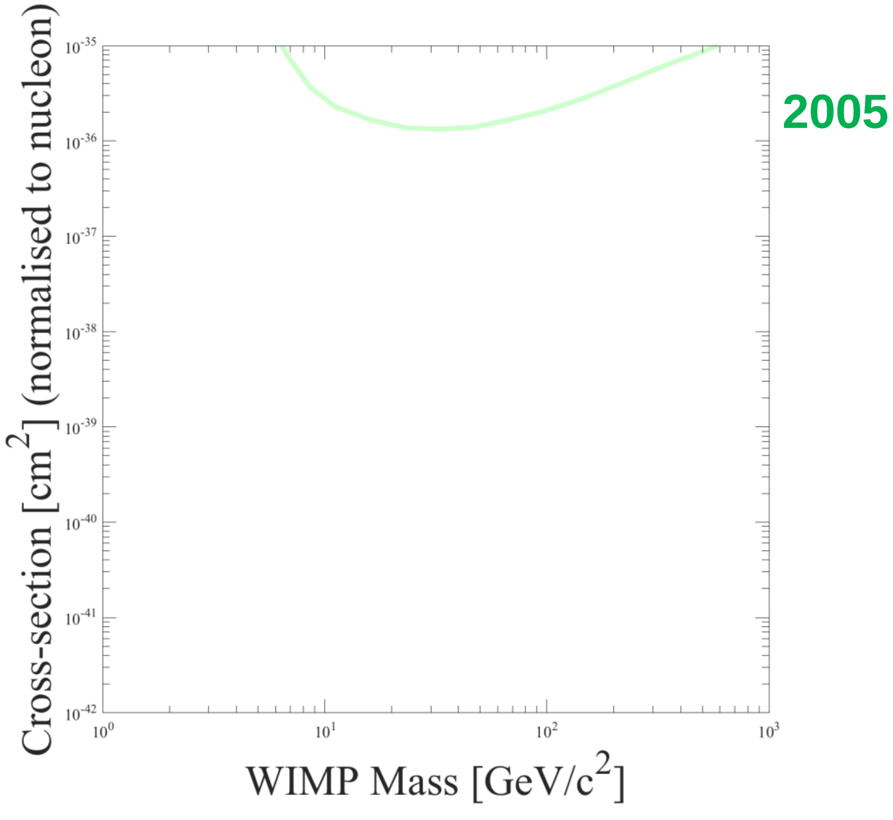
Outline

- Collaboration is Good !
- A Unique Technology. See our bubble
  Hear our bubble
  Feel our bubble
- Current Status: World Leading Results
- Future Plans … Near and Far

A brief History of the PICO collaboration

PICO

In the beginning,
there was **PICASSO** in Canada



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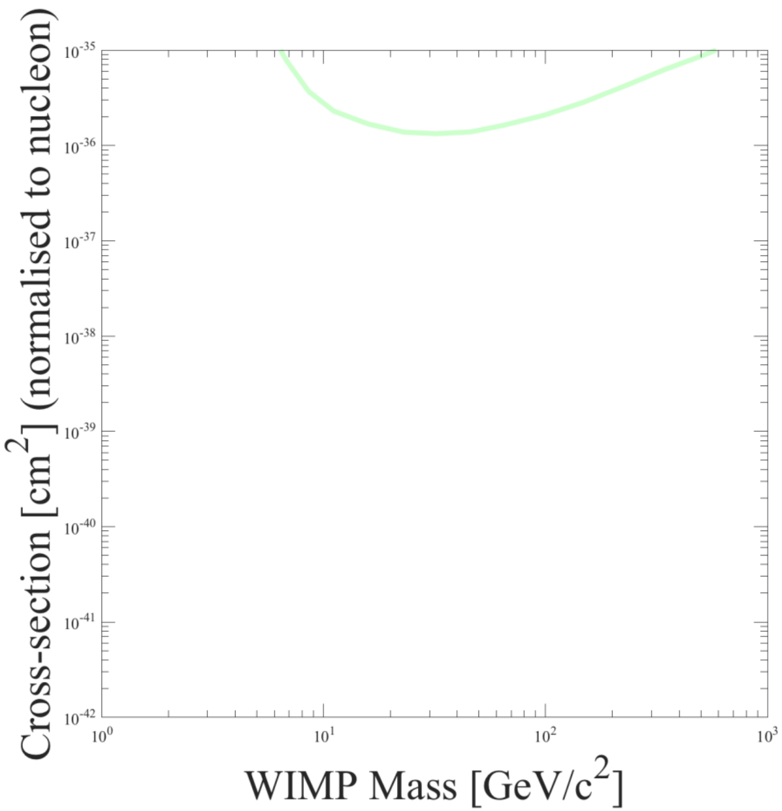
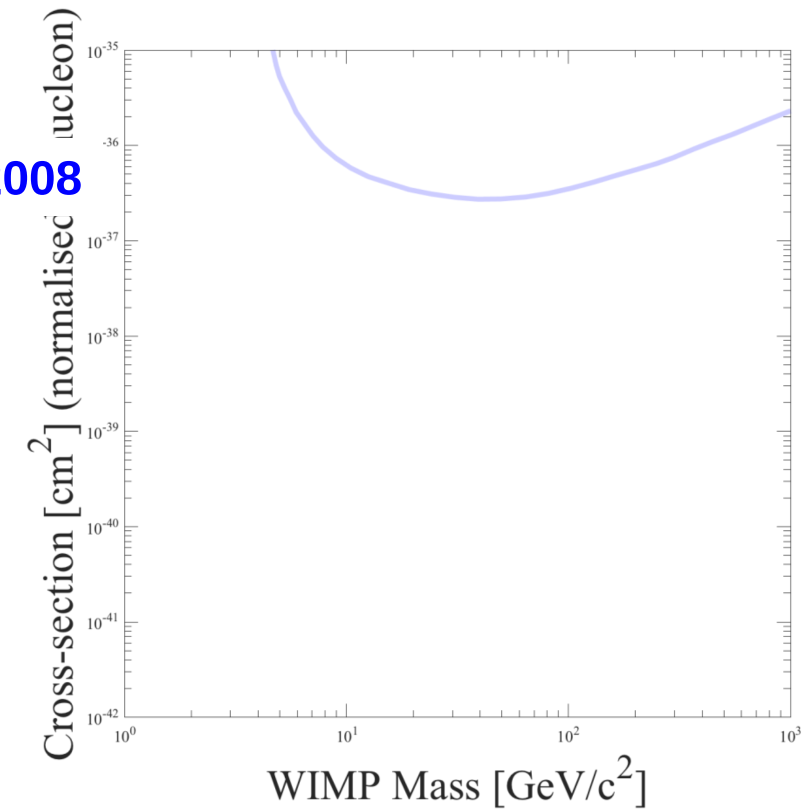


2005

2008



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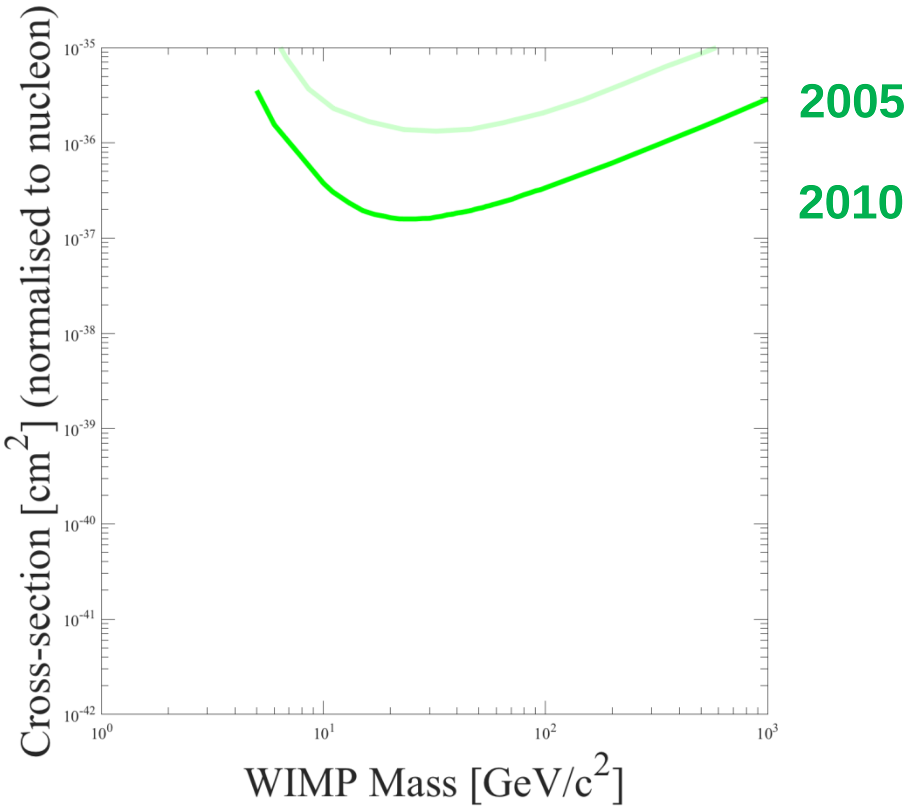

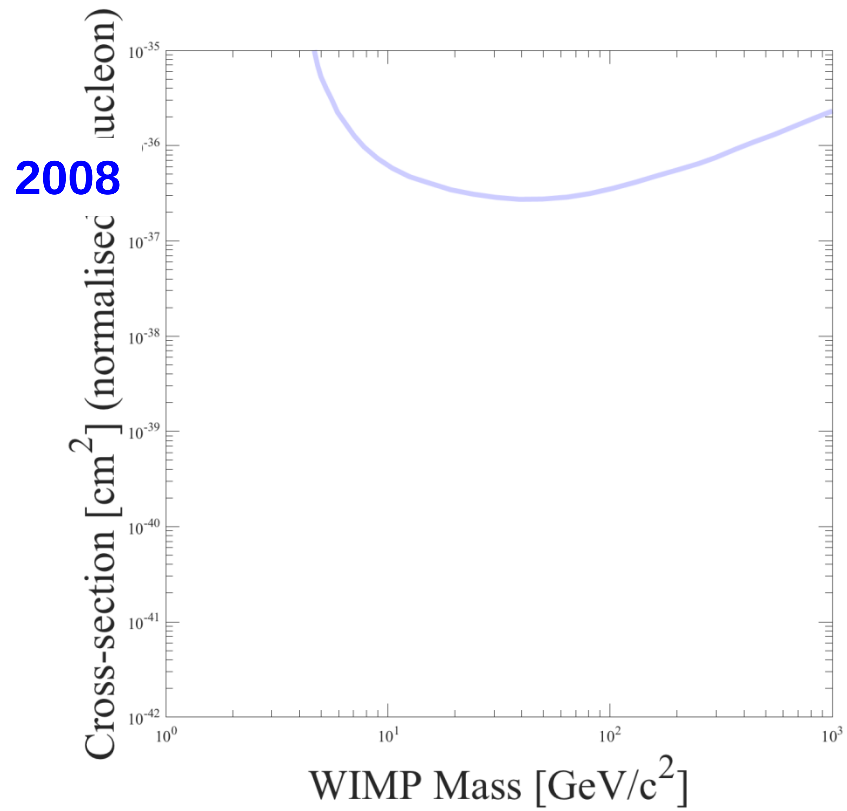

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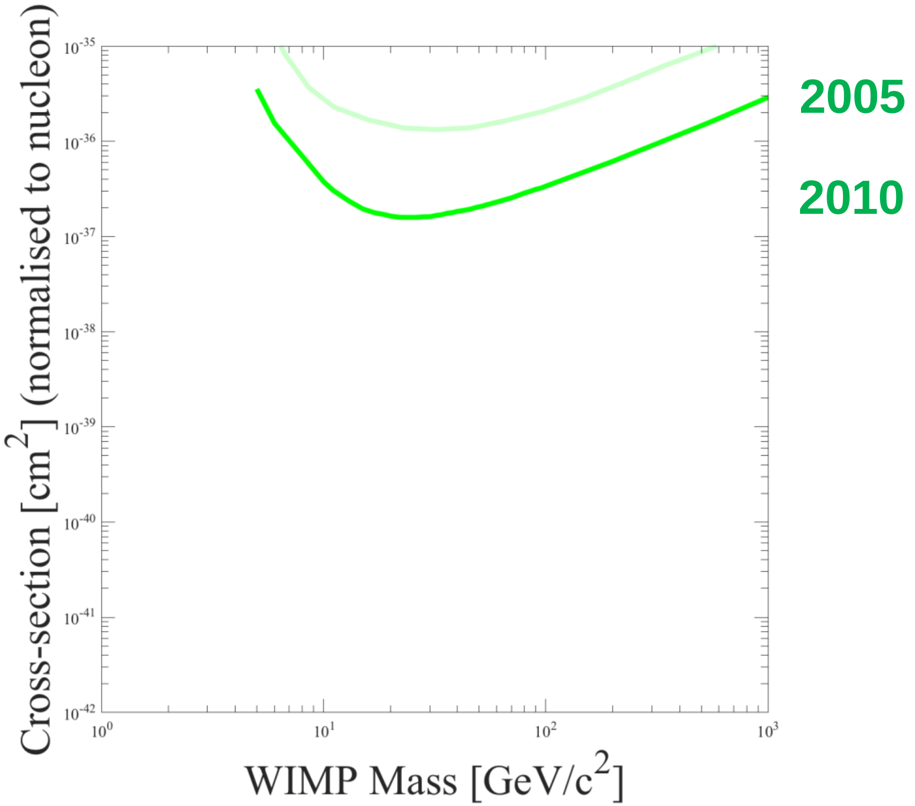

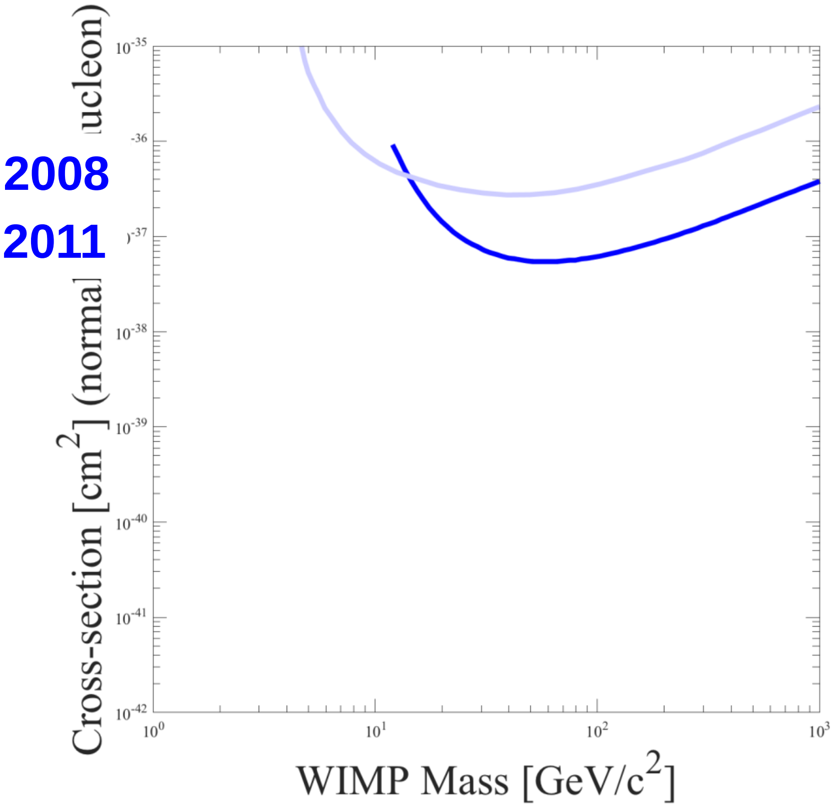

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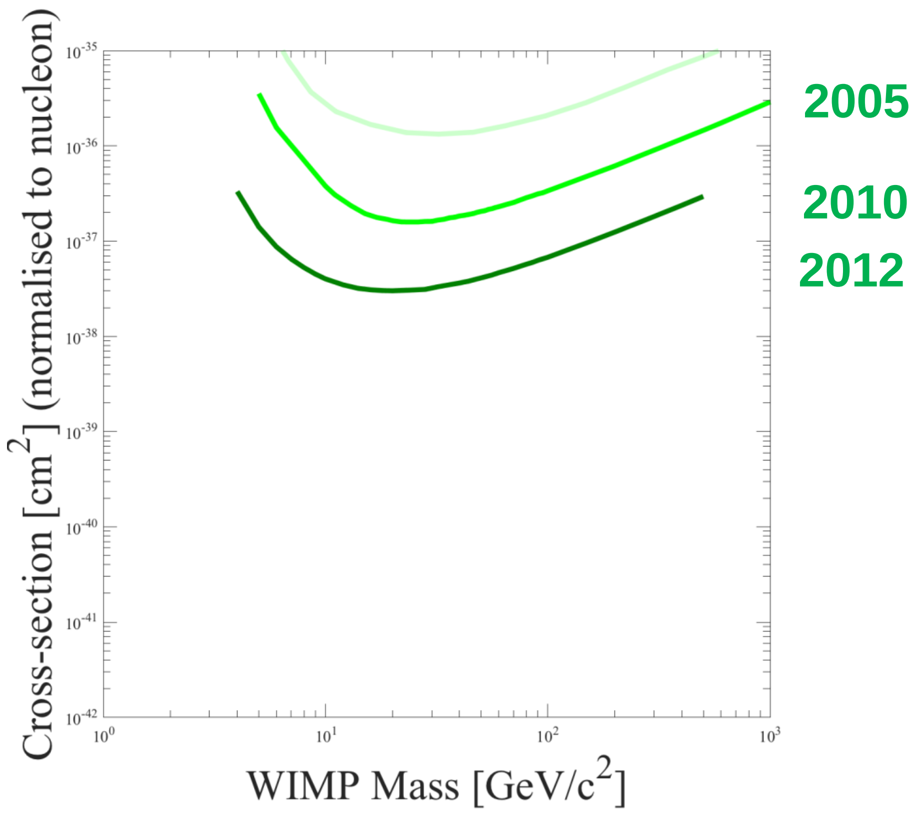

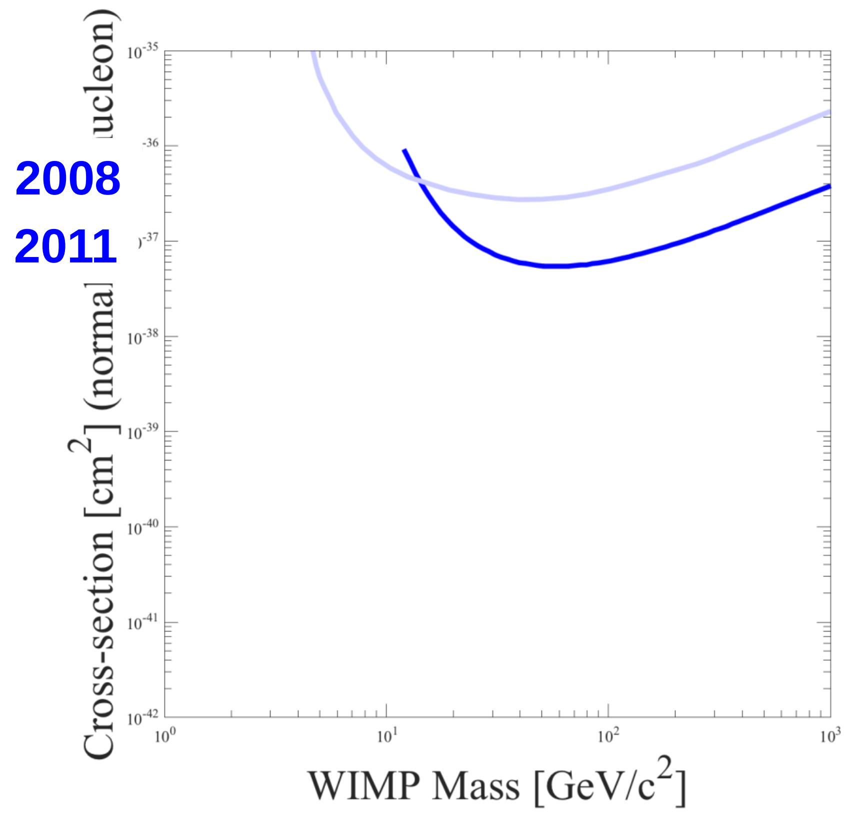

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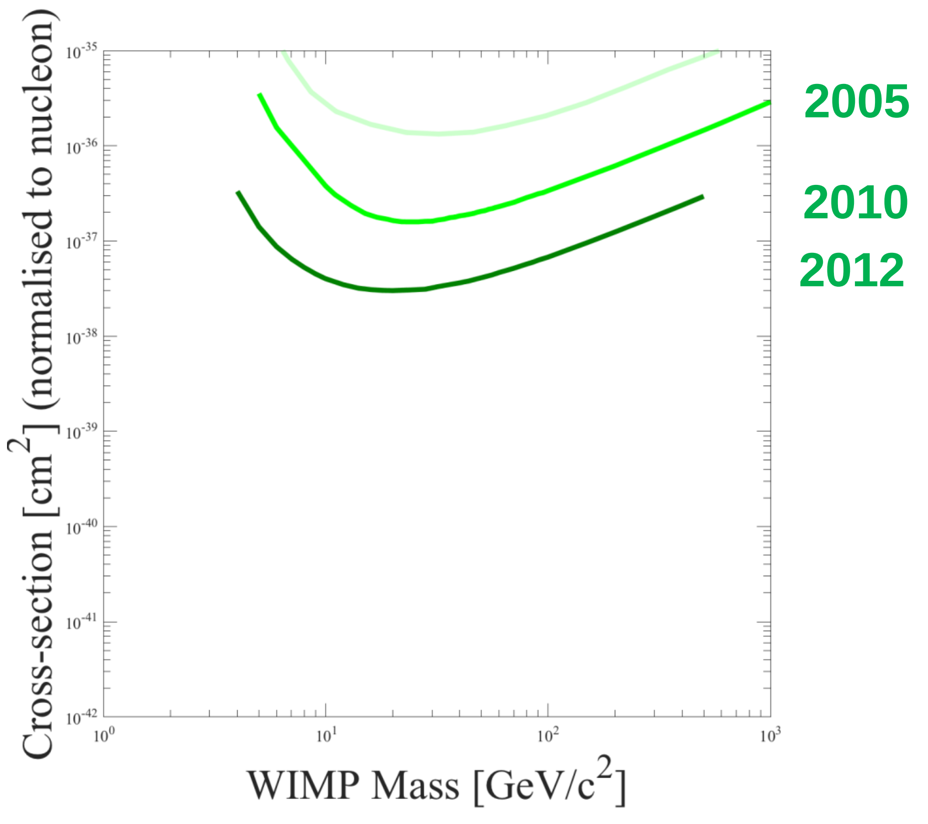
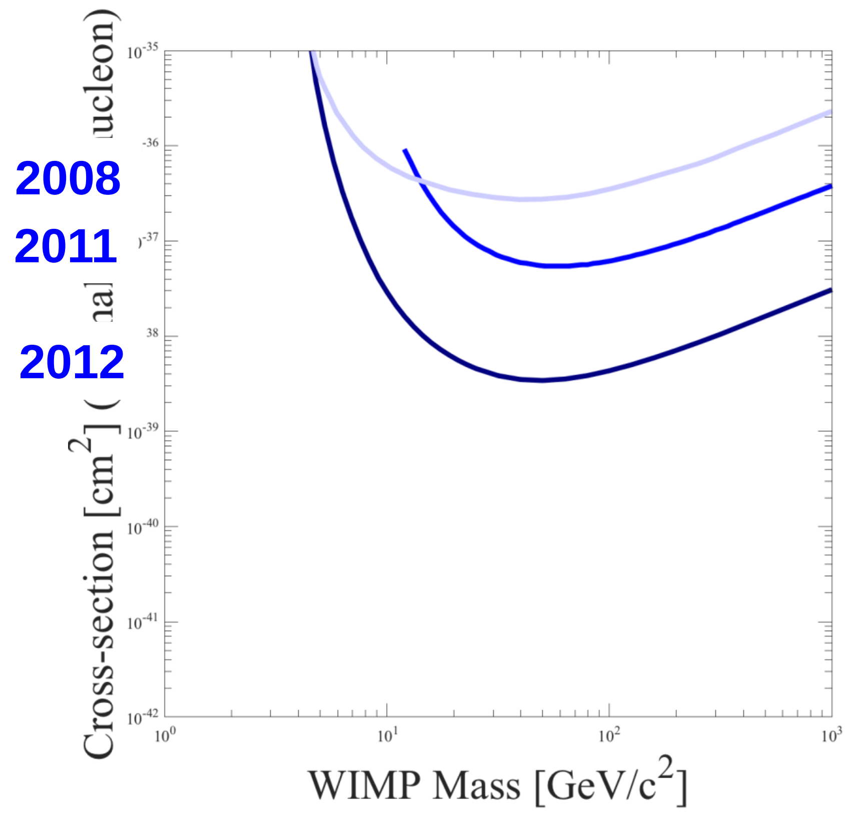
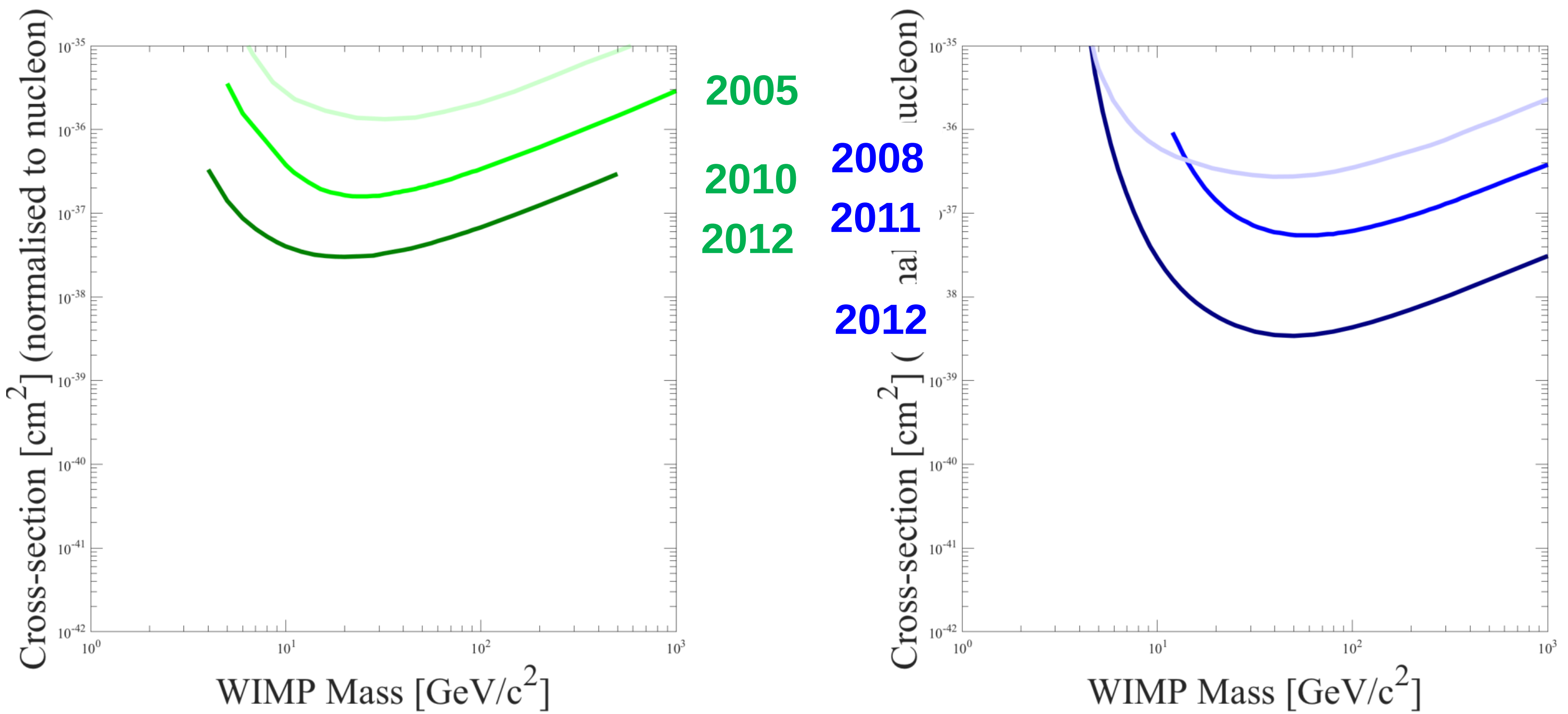
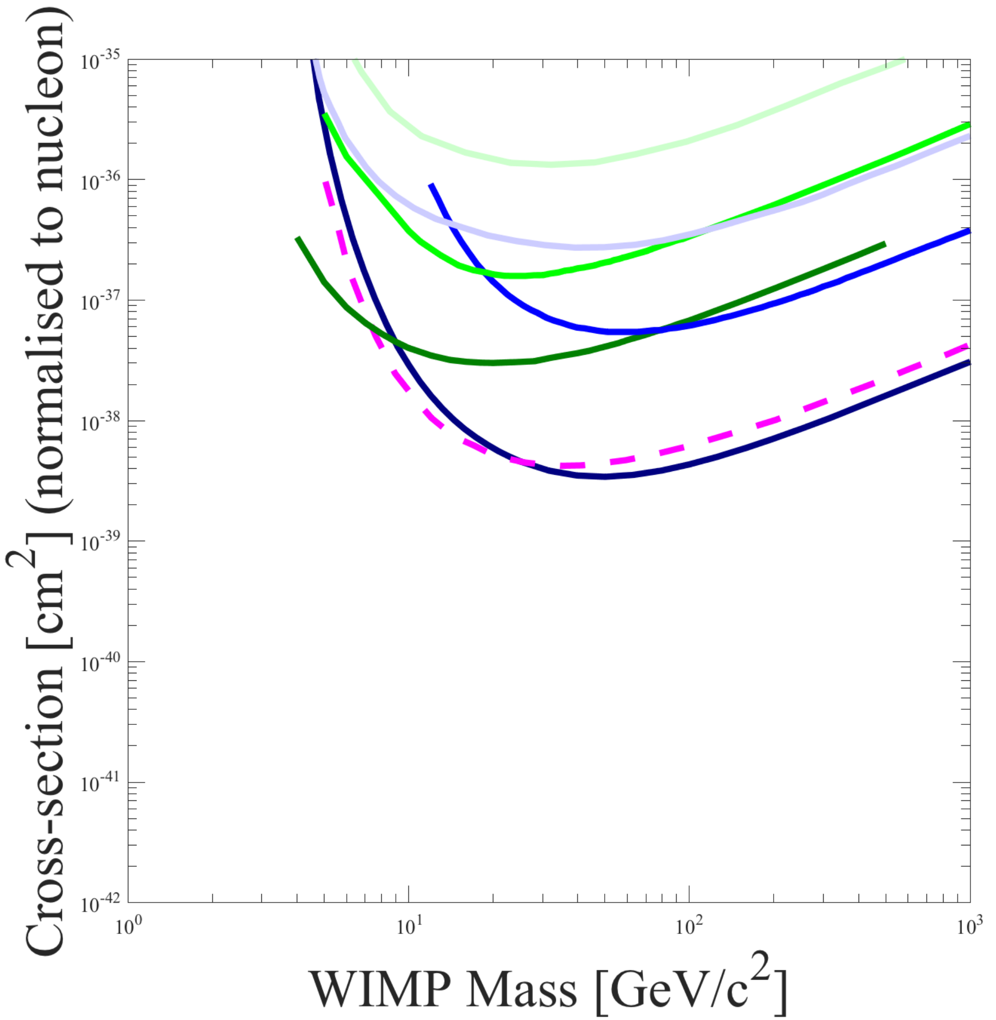




In 2012: Decide to form International Collaboration of PIcasso and COupp with a goal of working together to eventually produce a tonne scale bubble detector

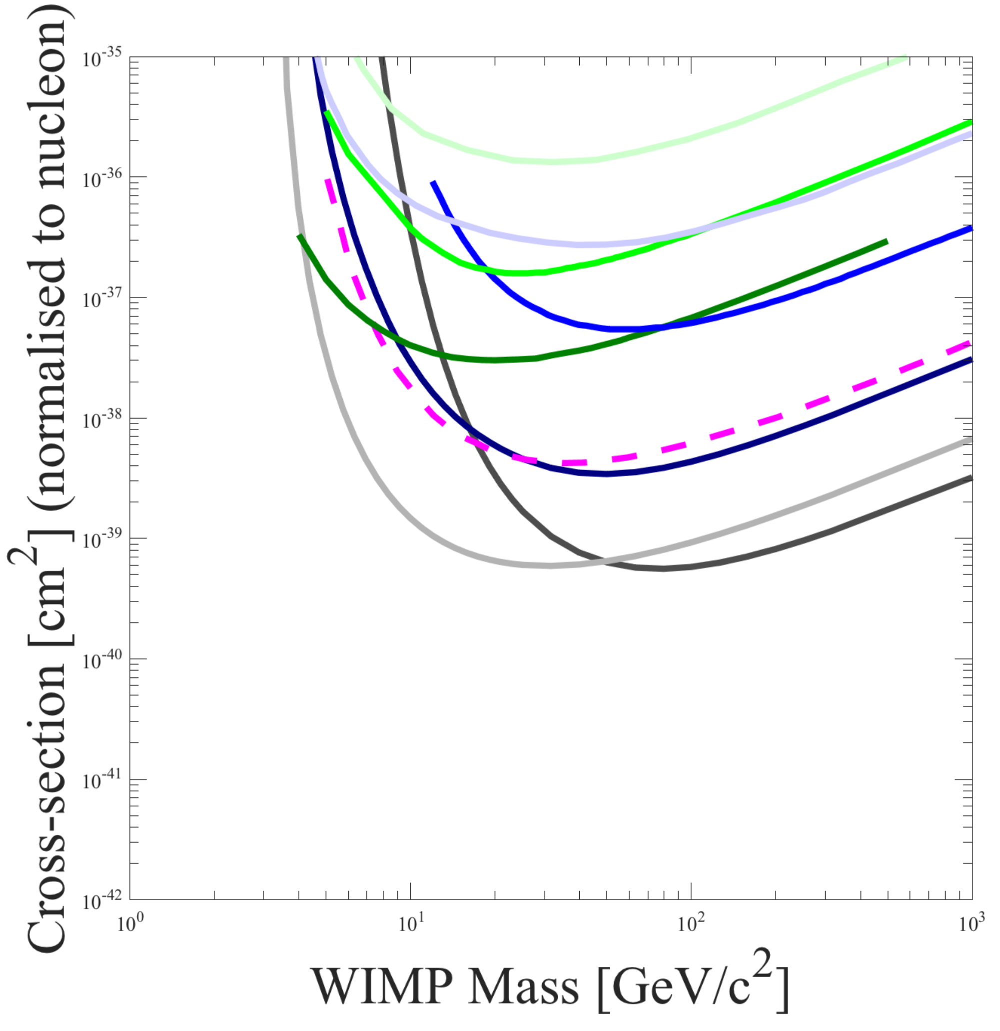
PICO





There was also competition from a European Group. **Simple**

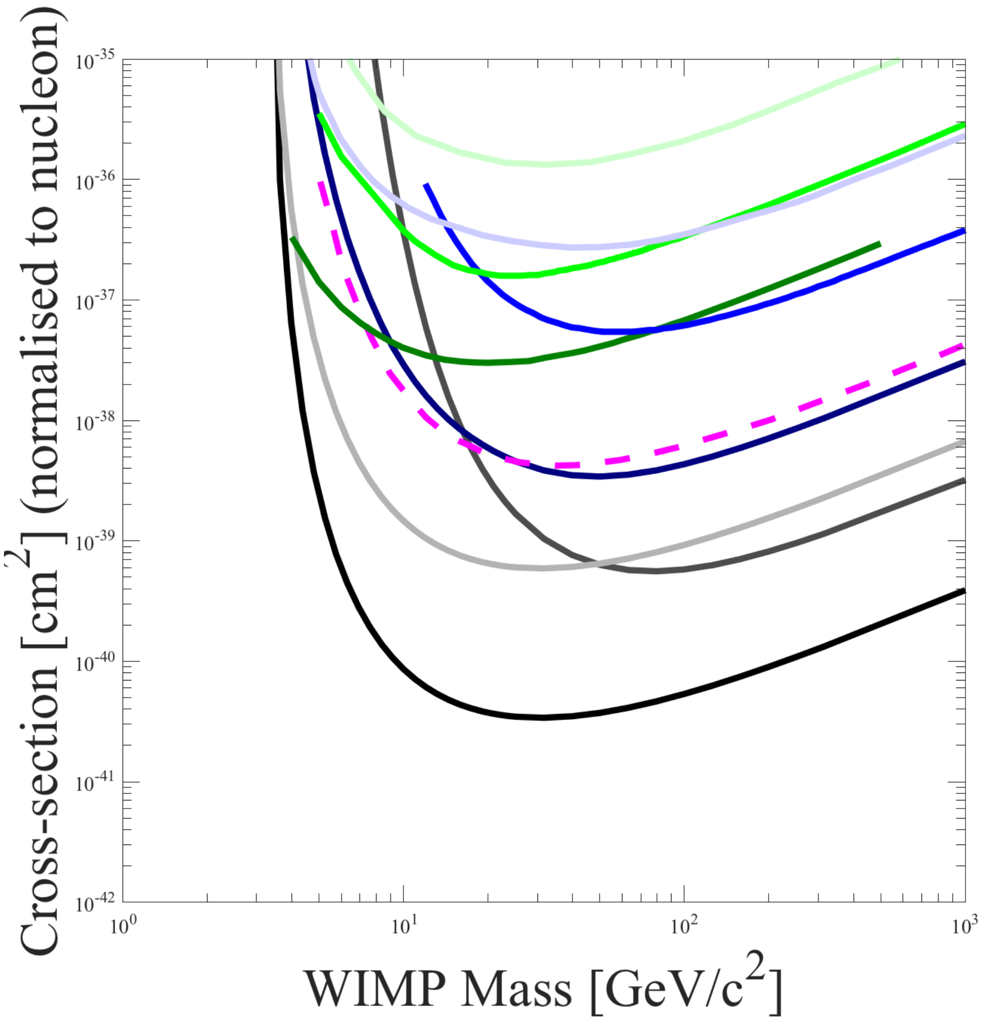
PICO



Early Results from PICO

With 2 different targets:
C_3F_8 in PICO 2L and, CF_3I in PICO 60

PICO



Early Results from PICO

With 2 different targets:
C_3F_8 in PICO 2L and, CF_3I in PICO 60

2017: PICO 60 with C_3F_8

~ 100,000 times improvement since 2005 combining best of two technologies.

The Collaboration

The Collaboration

- 5 Canadian Institutions: (Alberta, Laurentian, Montreal, Queen's, SNOLAB)
- 8 USA Institutions: (Chicago, Drexel, Fermilab, Indiana SB, Northeastern Il, Northwest, PNNL, Virginia Tech)

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Group leaders

SINP: Mala Das

CTU: Ivan Stekl

Valencia: Miquel Ardid

UNAM: Eric Vazquez Jauregui

PICO

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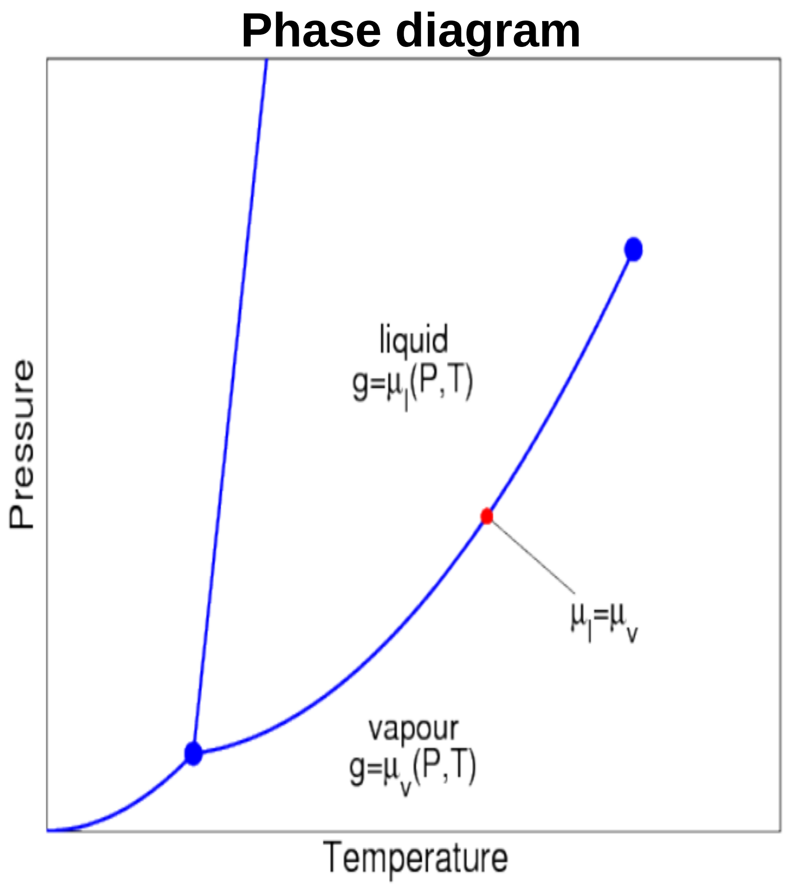
Canadian Leadership, on large **international experiment**, at **SNOLAB**, building on the goals of **CPARC**. Has proven track record.

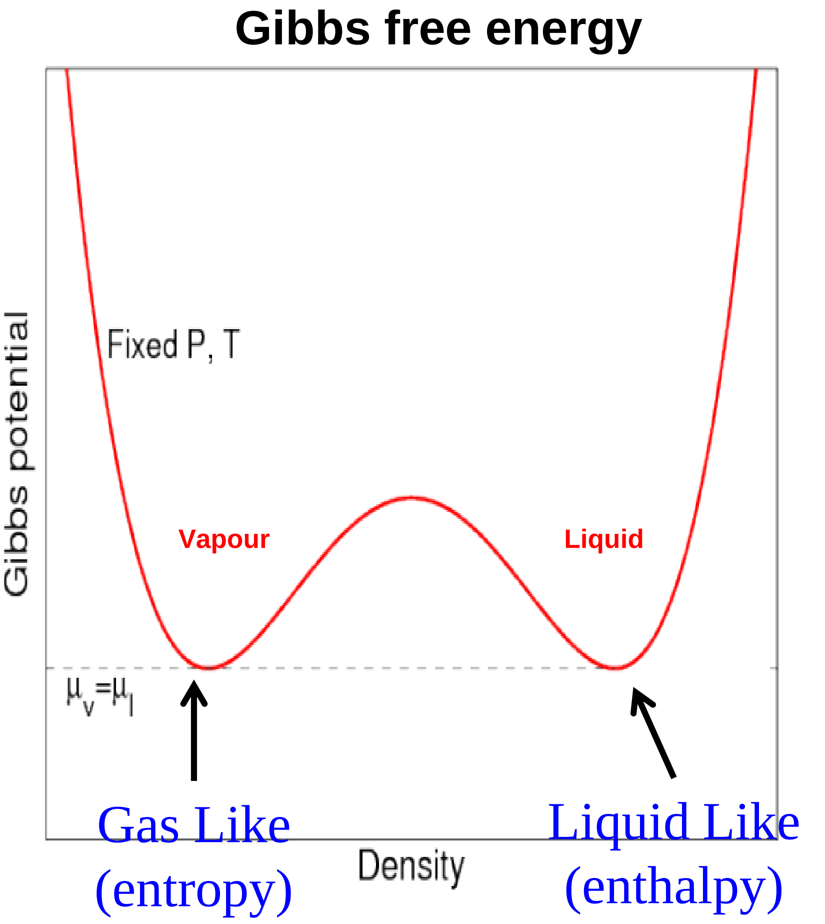
How does the PICO Detector Work?

The Bubble Chamber Technology

- At the right temperature and pressure, the fluid can become superheated in a metastable state
- WIMP interactions in the fluid should create recoiling nuclei
- The kinetic energy from the recoiling nuclei triggers the rapid phase transition and the fluid begins to boil.

Bubble Chamber Operation



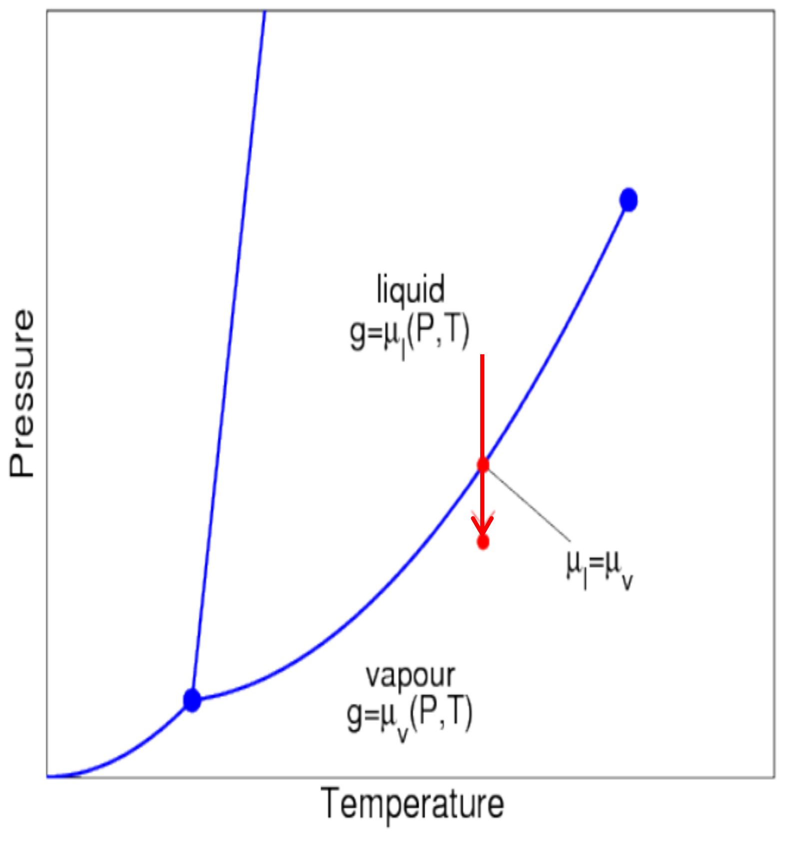


When on the saturation curve, liquid and gas are in equilibrium. (Same pressure, temperature and chemical potential).

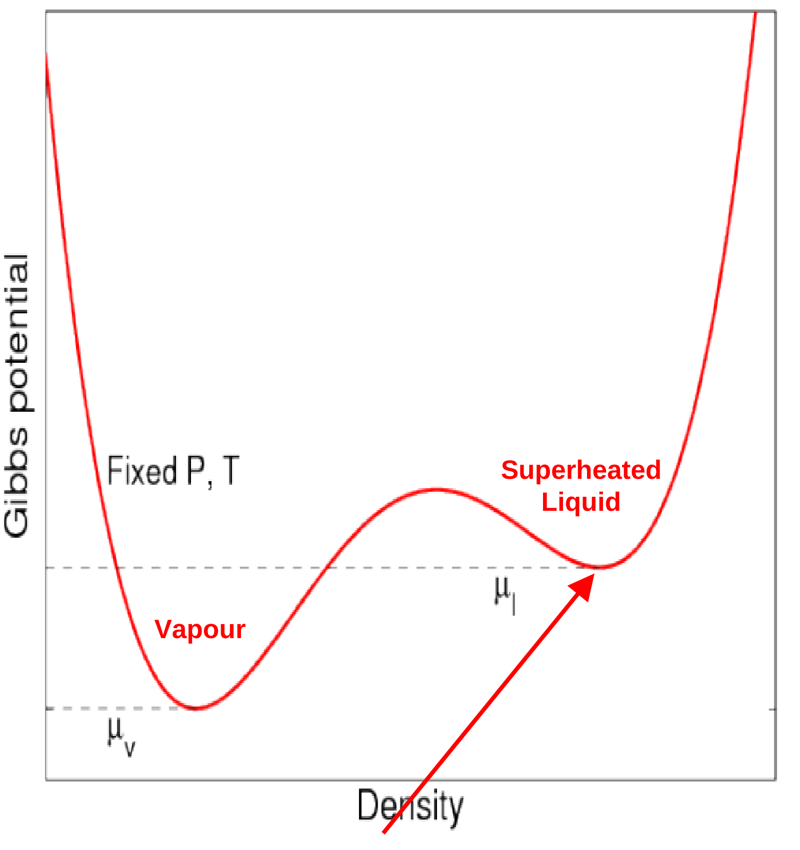
At equilibrium, the potential has two minima (one dominantly gas like and one liquid dominated)

Bubble Chamber Operation

Phase diagram



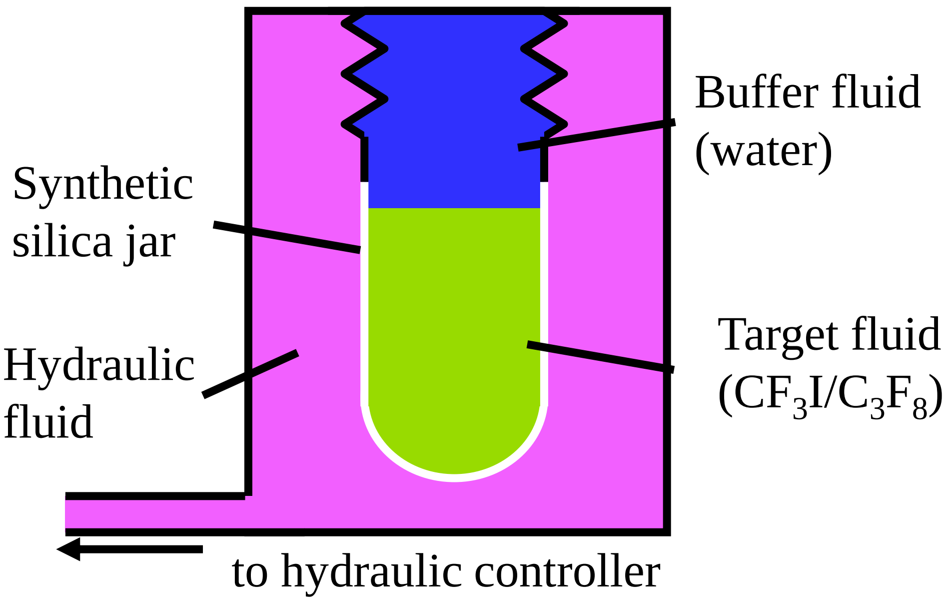
Gibbs free energy

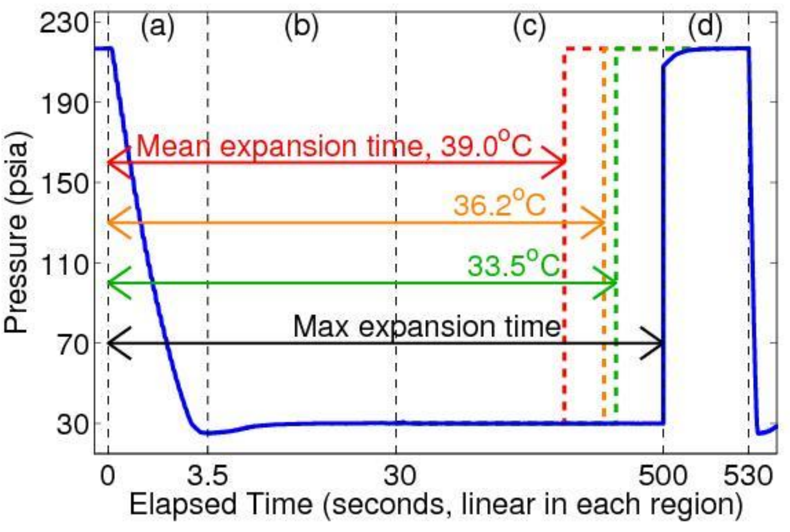


We now lower the pressure of the chamber carefully….starting from the pure liquid phase.

This distorts the potential, leading to a **meta-stable** superheated liquid state. Unless sufficient energy is added, it will stay in meta-stable state.

Principle of Operation: Bubble Chamber

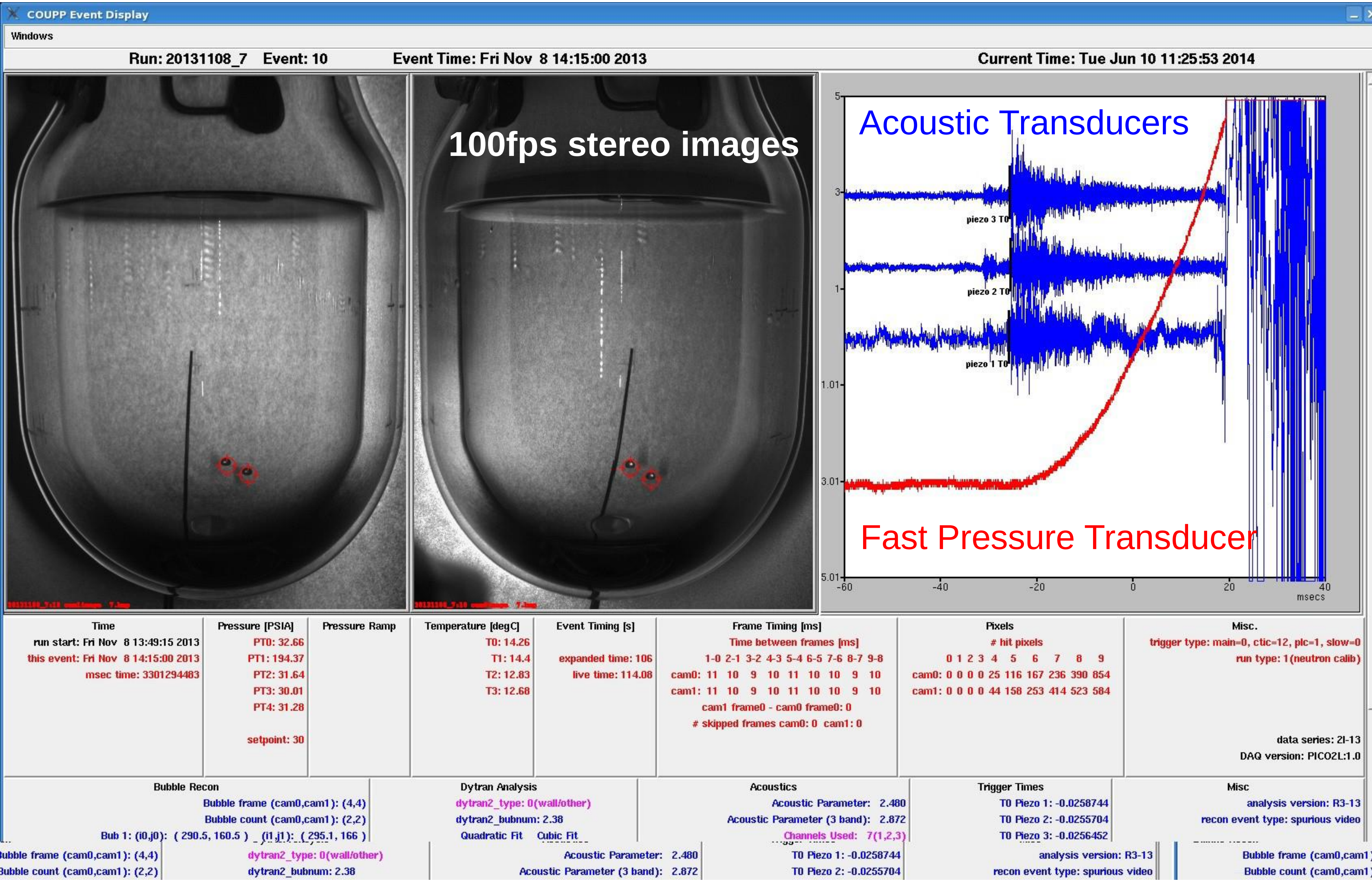




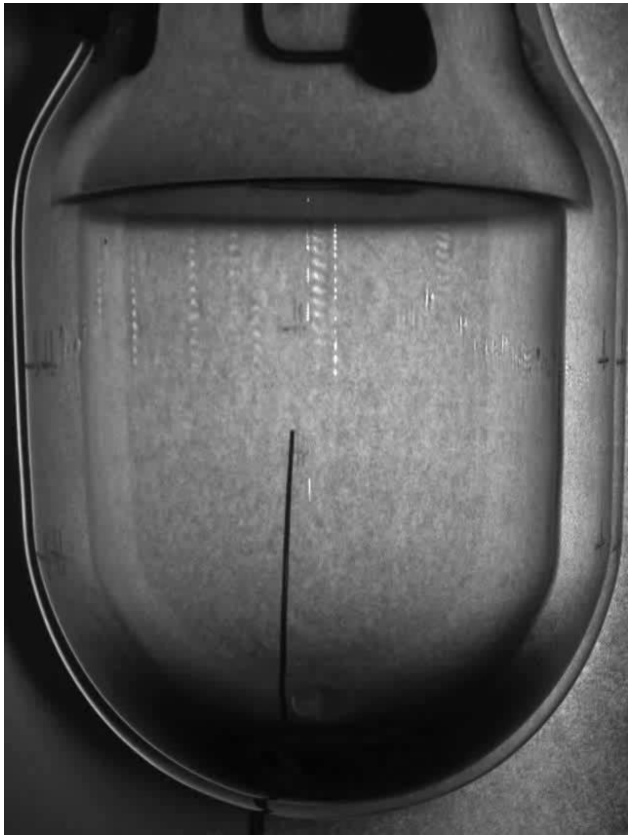
1. Lower the pressure to a superheated state.

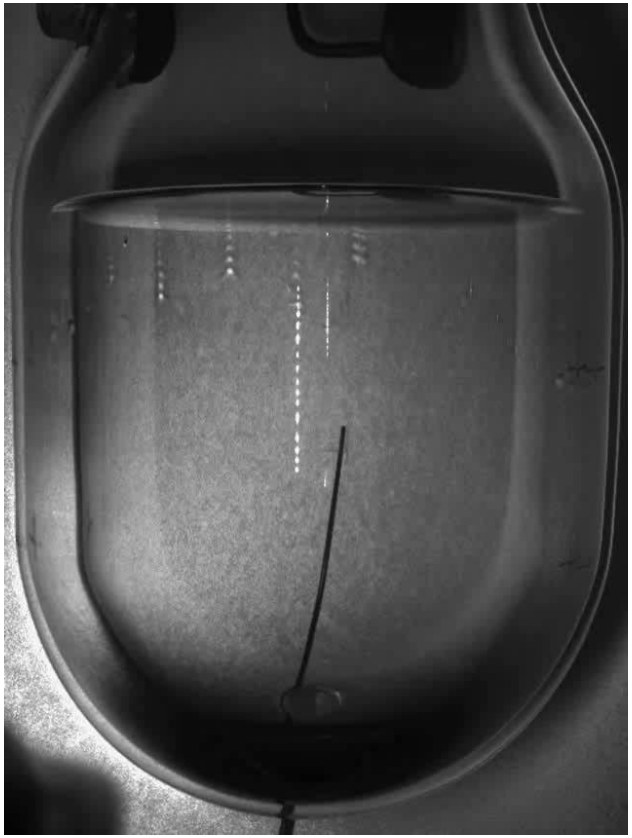
2. See the bubble:
   - Cameras trigger. record position, multiplicity: **See**
   - Microphones record acoustic trace. **Hear**
   - Fast pressure transducer recording. **Feel**

3. Raise pressure to stop bubble growth (100ms), reset chamber (30sec)



Screen Display during operations





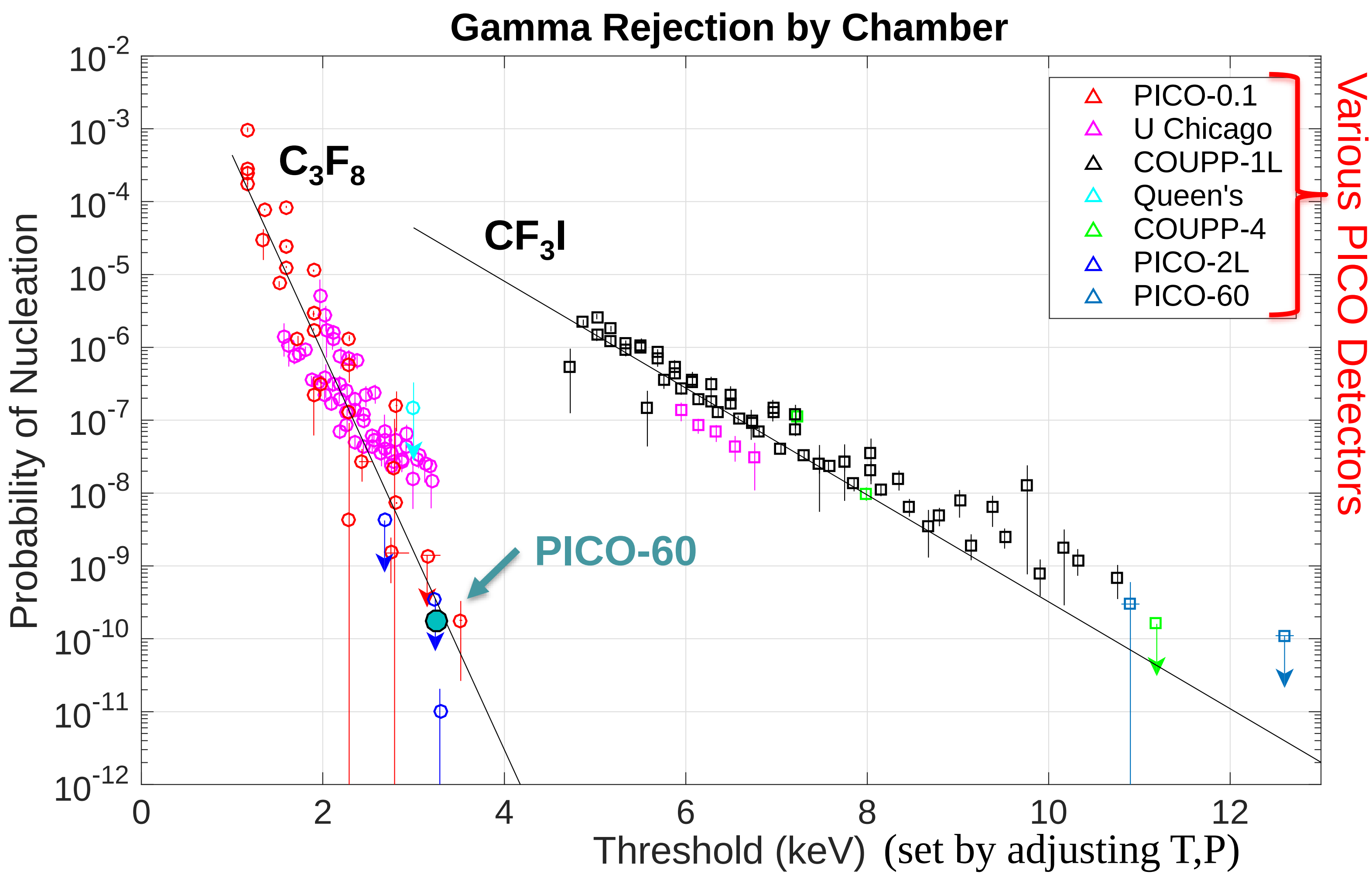
PICO

How well do we control Backgrounds?

Queen's UNIVERSITY

SNOLAB

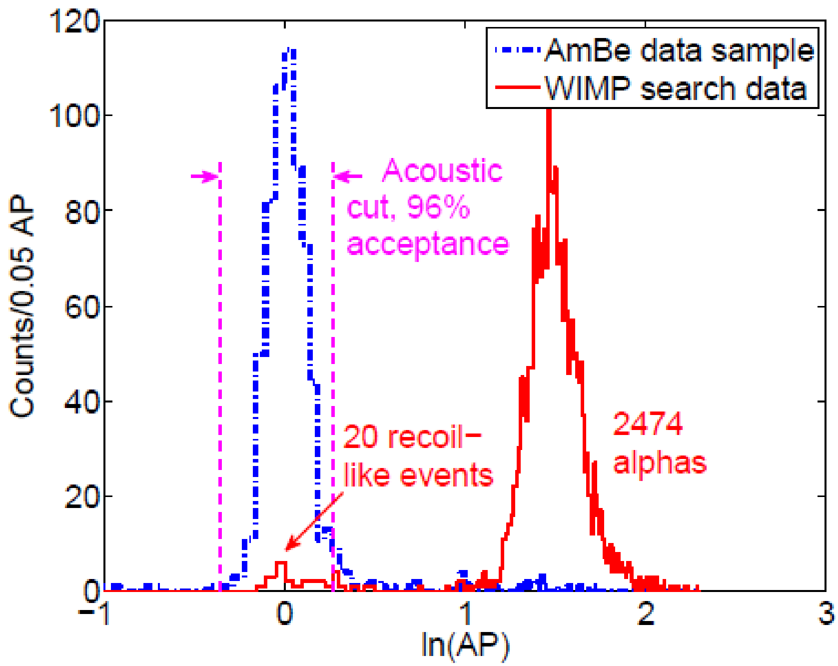
Gamma/Beta Background Rejection

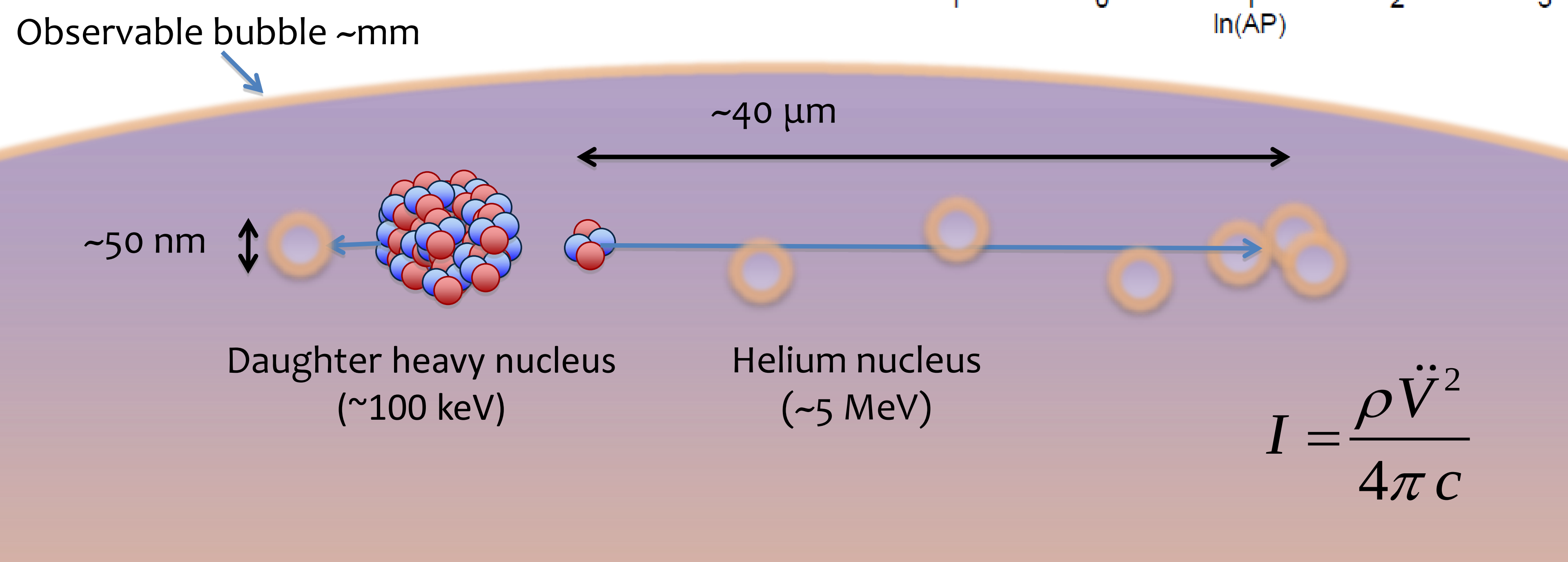


- Excellent electron/gamma rejection has been demonstrated.
- C_3F_8 can reach lower thresholds than CF_3I for same rejection.
- A lower threshold extends the sensitivity to lower mass WIMPs.

Alpha Acoustic Discrimination

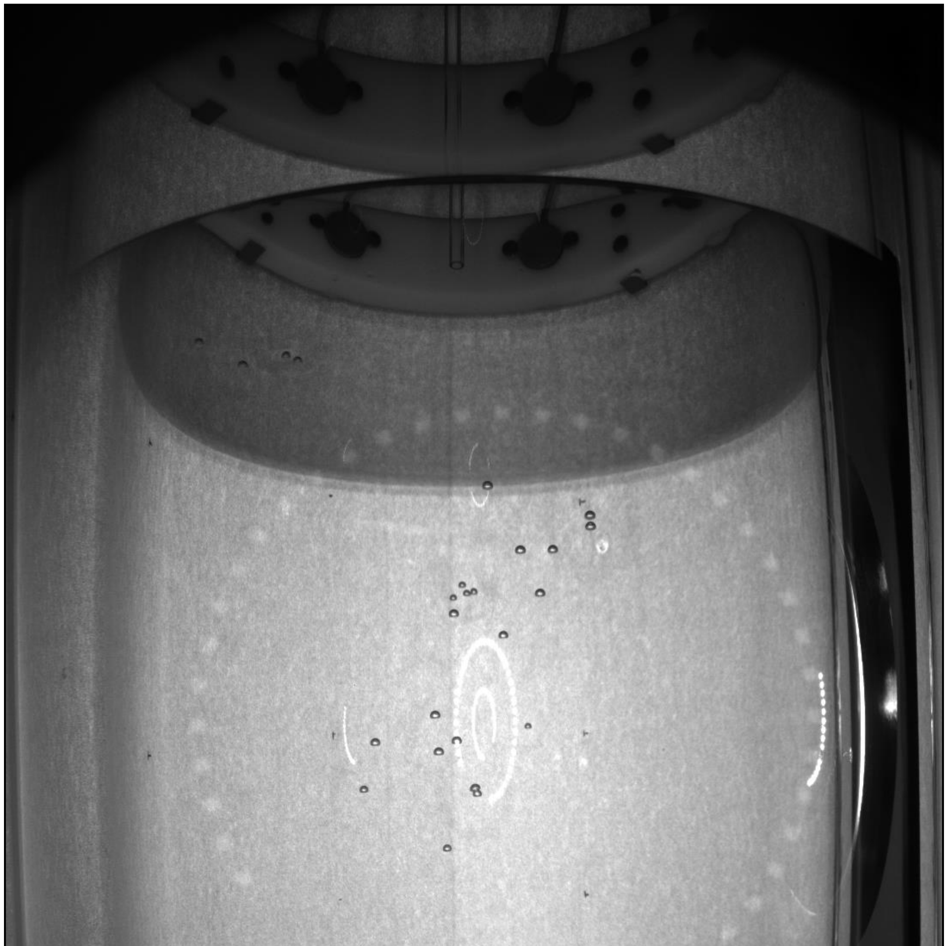
- Discovery by PICASSO of acoustic discrimination against alphas
  - **Nuclear recoils** deposit their energy over tens of nanometers.
  - **Alphas** deposit their energy over tens of microns.
- In bubble chambers alphas are several times louder due to the number of nucleation sites and the difference in the expansion of the bubble.





$$I = \frac{\rho \ddot{V}^2}{4\pi c}$$

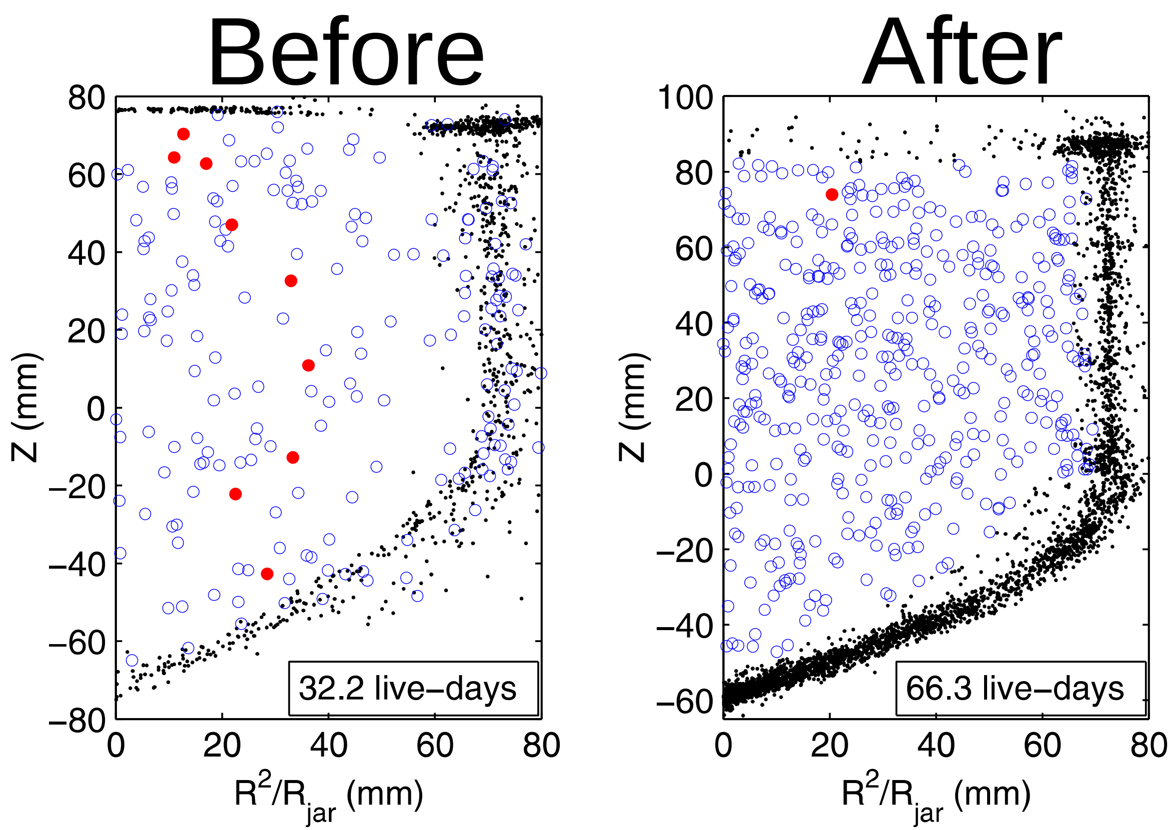
Neutron Backgrounds



- Preferentially Multiple-scatter
  - Allows us to measure background rate directly
- Simulation tells us to expect 3:1 multiples to singles ratio in PICO 60
- With water tank to shield external sources, residual background dominated by detector materials

Anomalous Particulate Background Suppression

- PICO-2L Run1
  - 9 candidate events in 32 live-days at 3.2keV
  - **Inconsistent with known radioactive backgrounds AND dark matter**
- PICO-2L Run2
  - 1 candidate event in 66 live-days at 3.2keV
  - **Consistent with neutron expectations**
- Between runs, the detector was cleaned of particulate contamination



C. Amole *et al*. Phys. Rev. D 93, 061101(R) (2016)

Hypothesis: combination of particulate matter and water leads to anomalous nucleation mechanism

The most recent PICO 60 result

What did we measure?

- Camera images (primary trigger)
  - How many bubbles were there? **Neutron Rejection**
  - What was the bubble's position? **Surface Rejection**
- Temperature
- Pressure (secondary trigger)

  } **Threshold Determination**
- Acoustic signal **Alpha Rejection**

What did we measure?

- Camera images (primary trigger)
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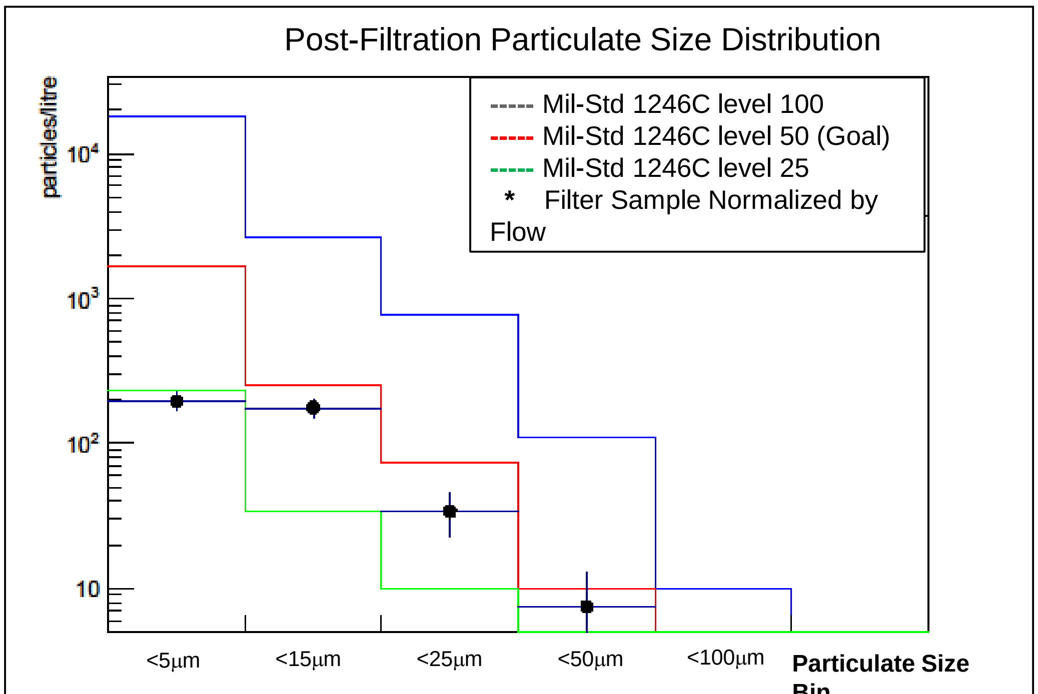
Threshold Determination (Temperature, Pressure)

- Acoustic signal **Alpha Rejection**

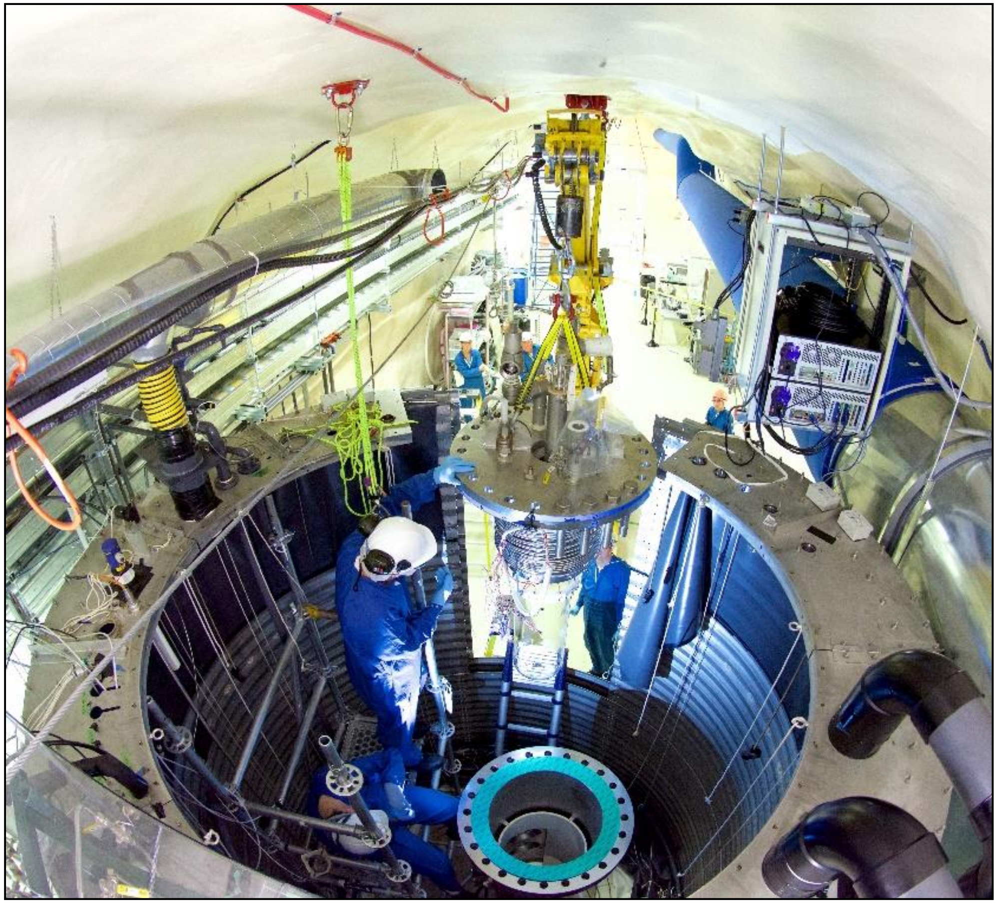
Blind this information

PICO-60 Cleaning

- Every component touching the inner volume was cleaned against MIL-STD-1246C level 50



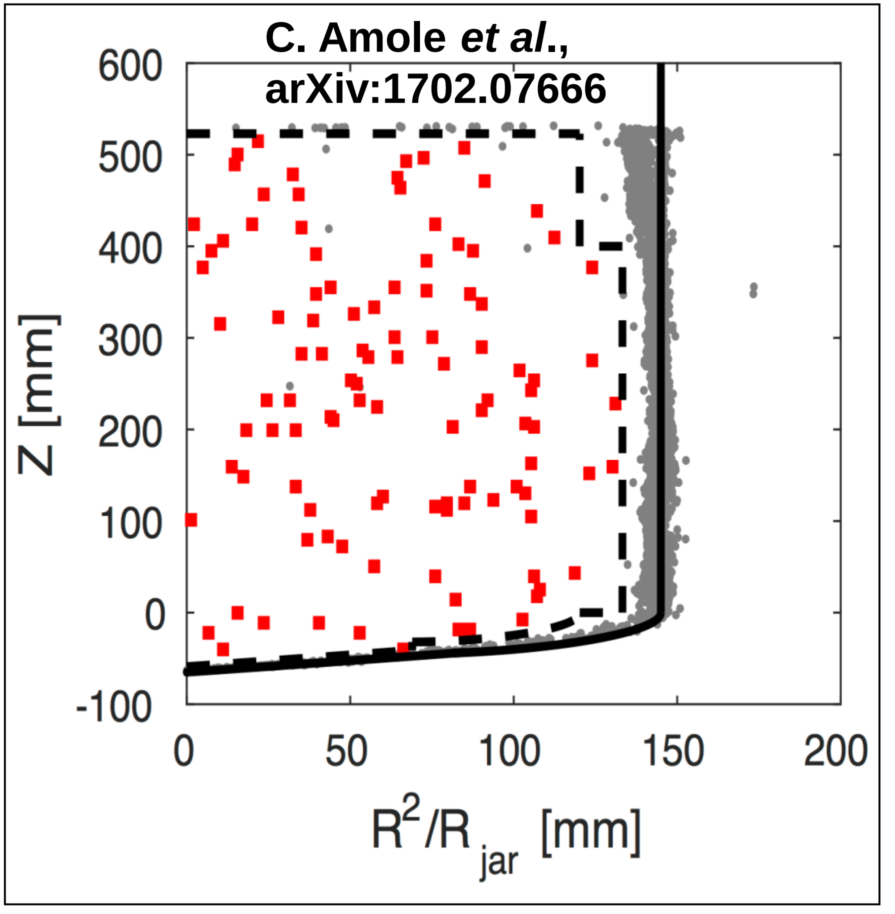
Commissioning



- Filled with 40L C_3F_8 on June 30, 2016
- First physics run Nov. 2016 – Jan. 2017

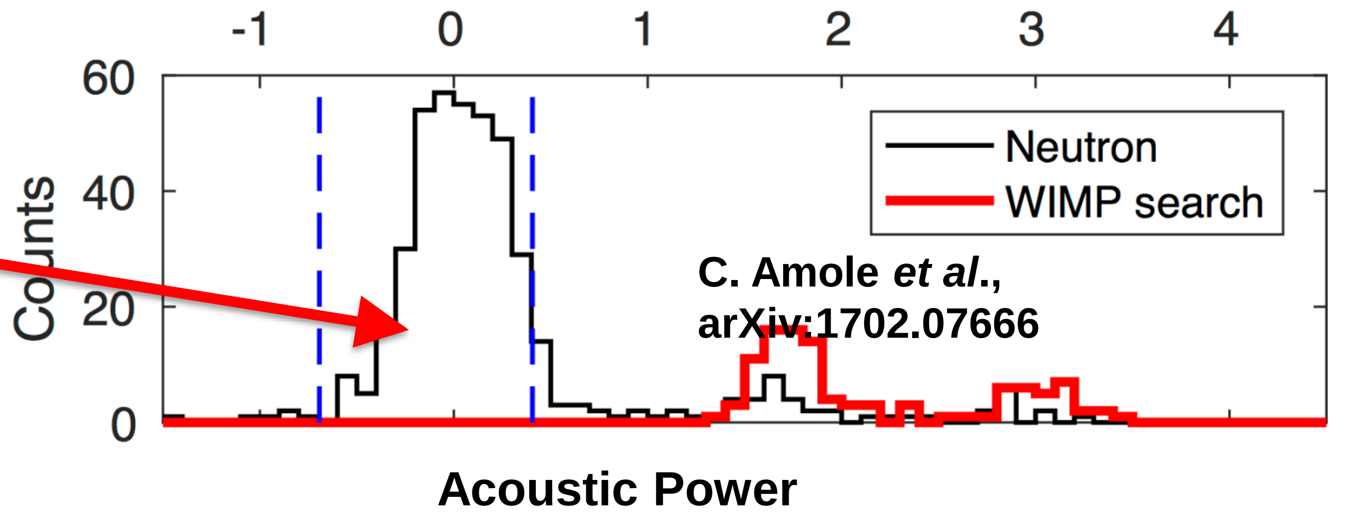
PICO 60 Before Opening the Box

- 106 bulk singles in WIMP search dataset
  - *Acoustics Blind*
  - Consistent with Rn decay rate in pre-WIMP search unblinded data
- Neutron Background
  - Not blinded to multiplicity
  - 3 multiple bubble events in the physics data
  - Multiples to singles ratio is approximately 3:1 from calibration and simulation
- **Conclusion: 0-3 bulk singles would be consistent with neutrons and no anomalous background**



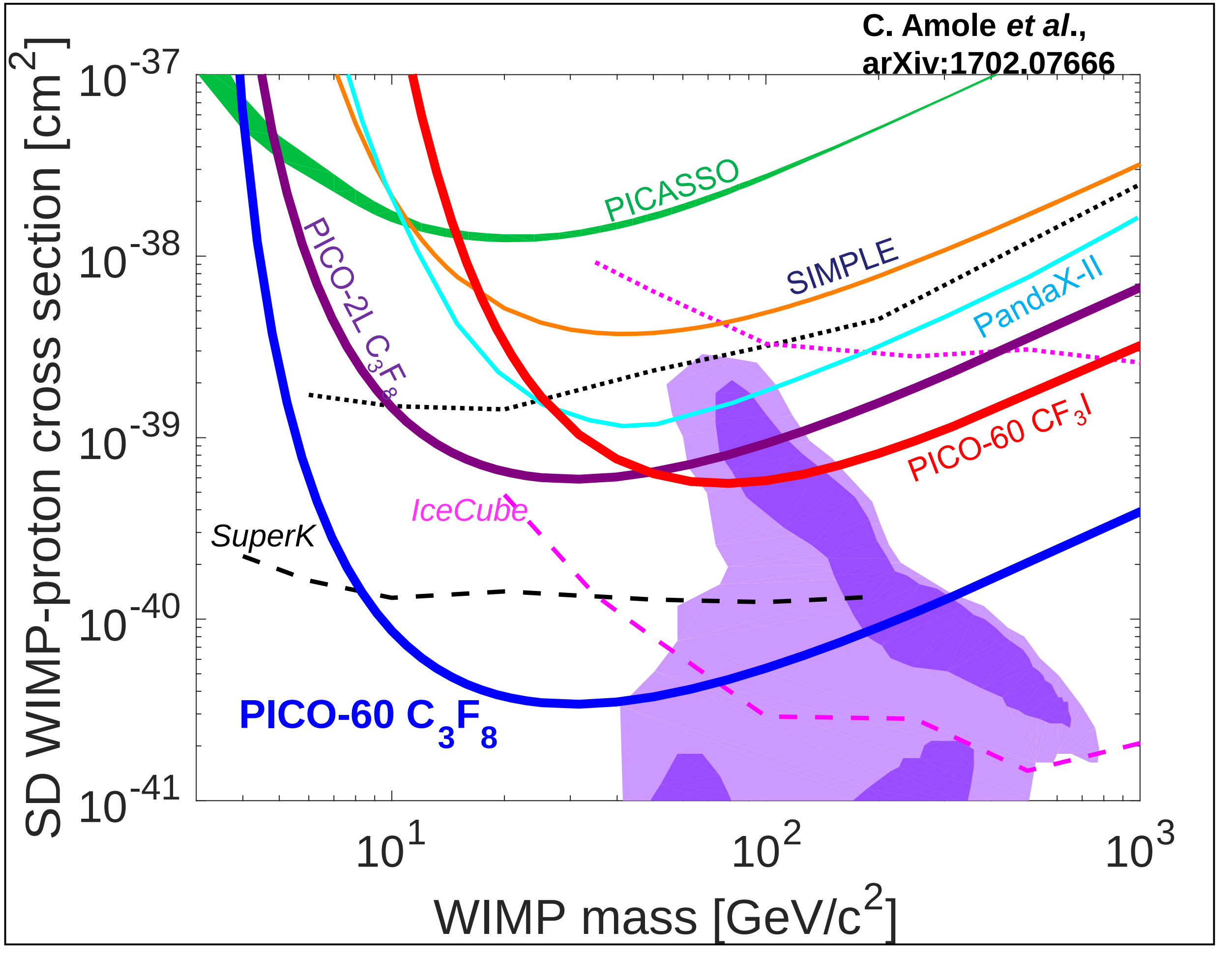
After Opening the Box

No events in signal region!



- Of the 106 fiducial-bulk singles, **none** are consistent with nuclear recoil hypothesis (all are consistent with radon chain alphas)
- No background events observed !
- Blind analysis

Spin-Dependent WIMP-Proton Coupling
Recent Limits from PICO-60



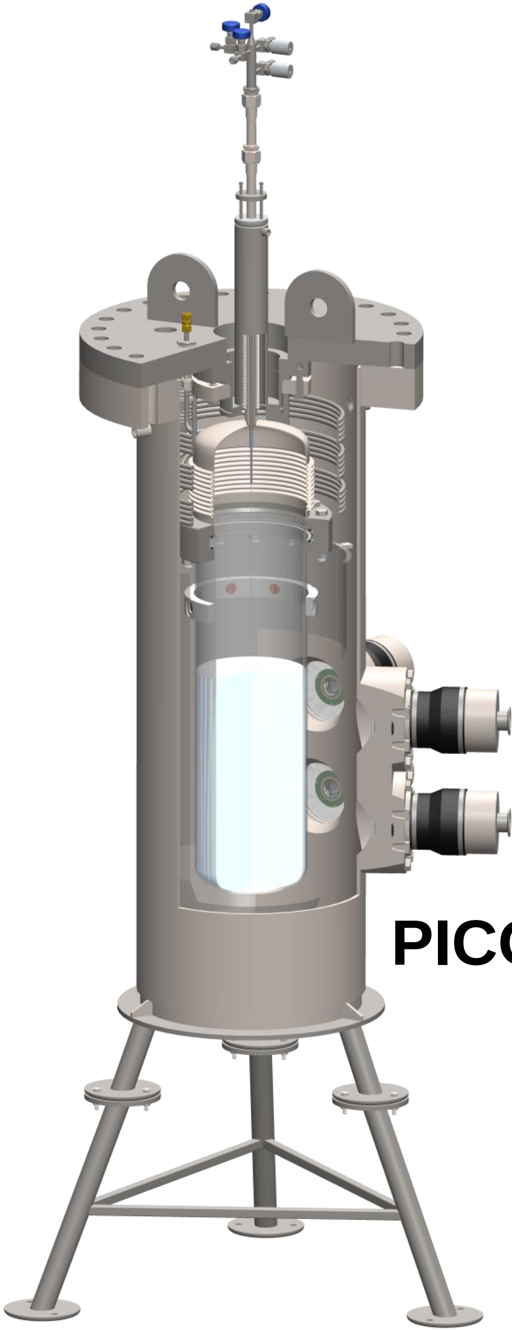
- PICO-60 – Blind analysis, 0 events observed, x17 improvement to set world best limit on spin dependent proton coupling

Whither Next?

- **PICO 40 – "Right side up" – Now**
- PICO 500 – with C3F8 – over next few years
- Extended PICO 500 Program – longer term program

PICO-40L

Eliminate buffer fluid

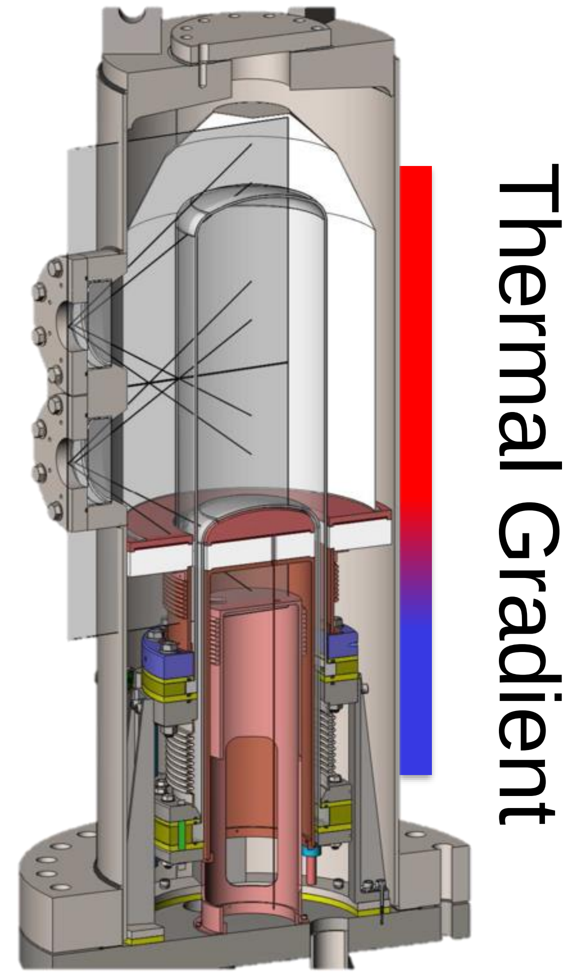


Purpose of buffer liquid is to isolate the active liquid from the stainless parts

PICO-60

PICO-40L

Thermal gradient can ensure that target fluid near stainless parts is not active



PICO 40 Physics reach

- Added stability could allow us to push down in threshold (**lower WIMP mass sensitivity**) until we hit electron-recoil backgrounds
- **Reduced neutron backgrounds**, allowing us to push down in cross-section and improve on current limits
- **Informs design** of future tonne scale detector: PICO 500
- Ability to **explore new target fluids** optimized for different WIMP masses

PICO 40 is on track to begin operations in early 2018

PICO-40L

Pressure Vessel at SNOLAB

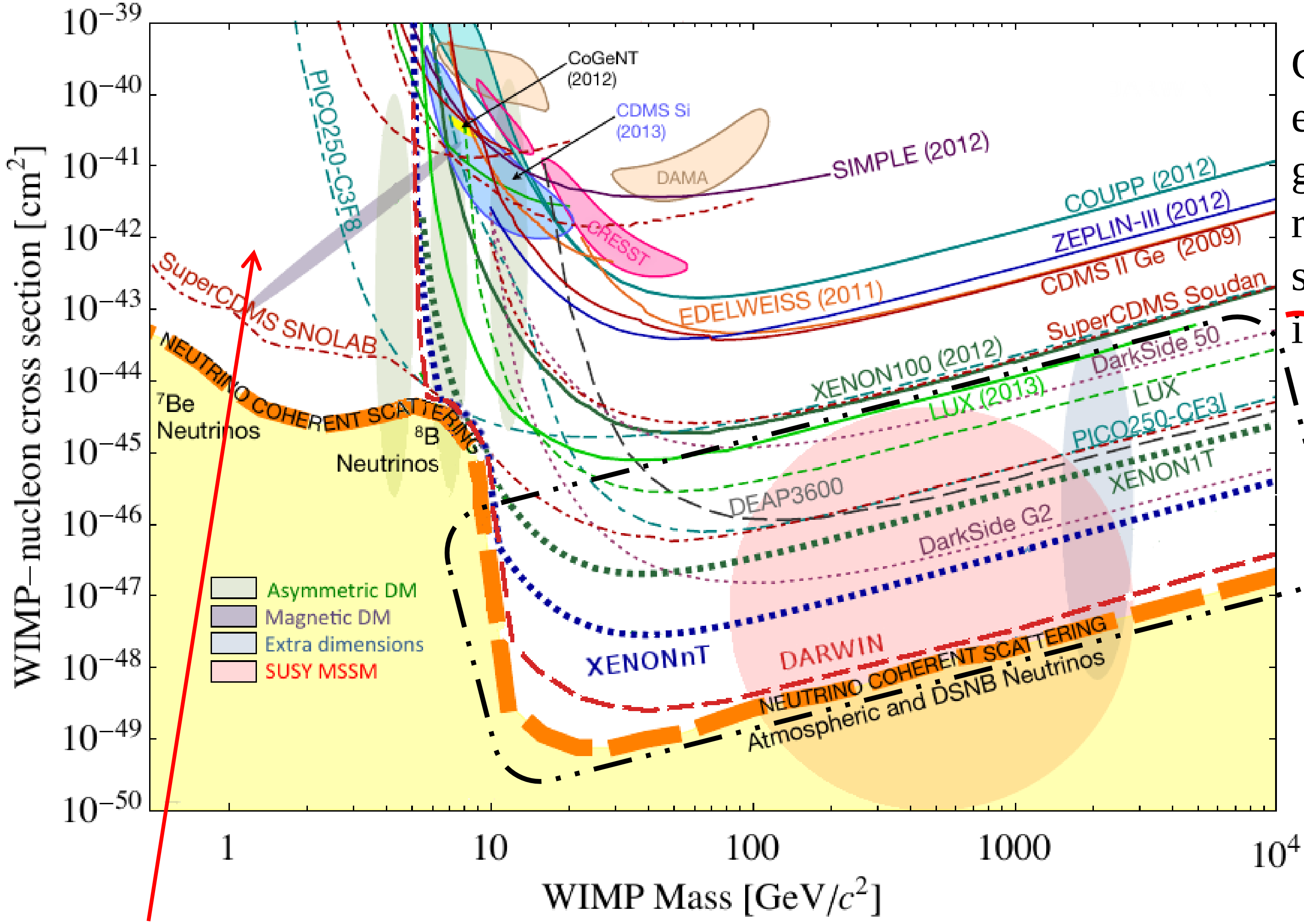
Trial Assembly

Clean Bellows
at SNOLAB

Whither Next?

- PICO 40 – “Right side up” – Now
- **PICO 500 – with C_3F_8 – over next few years**
- Extended PICO 500 Program – longer term program

Slightly out of date … SI from Snowmass… but makes the point



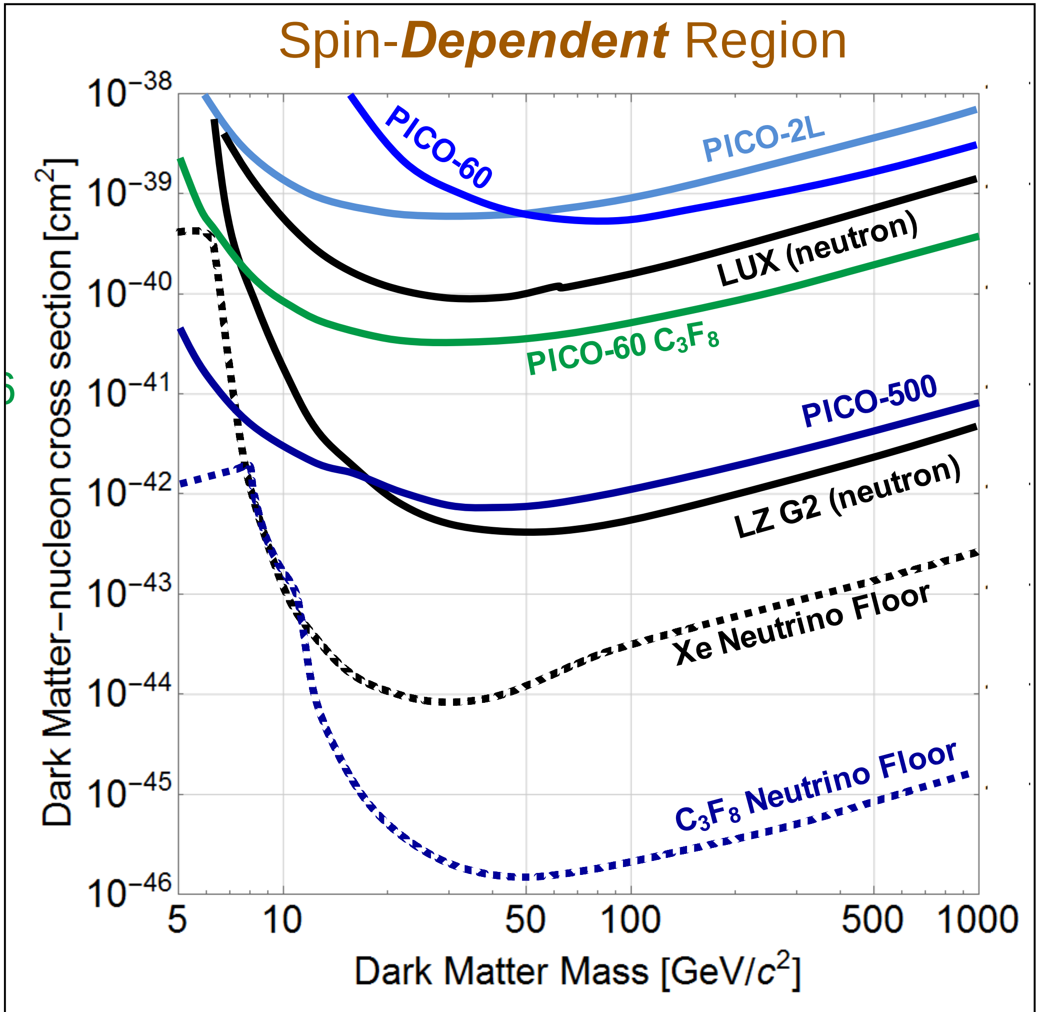
Current suite of experiments making good progress towards ruling out initial sweet spot. Neutrino floor is in sight.

Terra incognito

Expectation from "WIMP miracle"

Lee-Weinberg Window: GeV < m_χ < TeV

Spin-Dependent Future

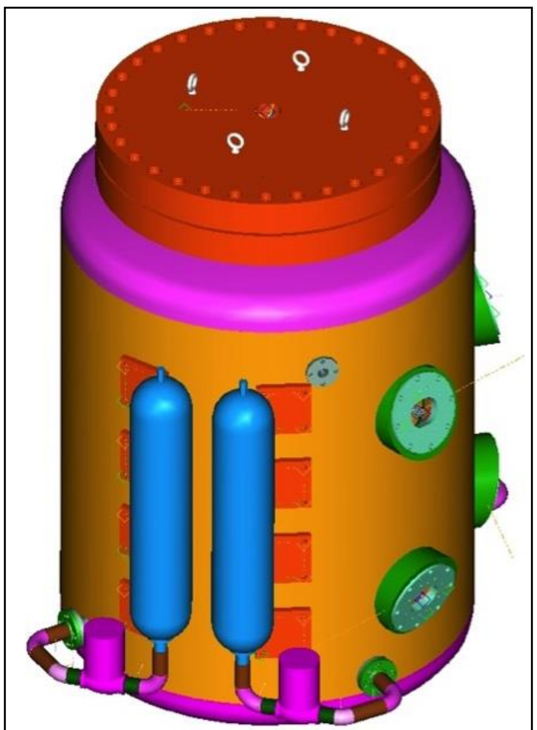


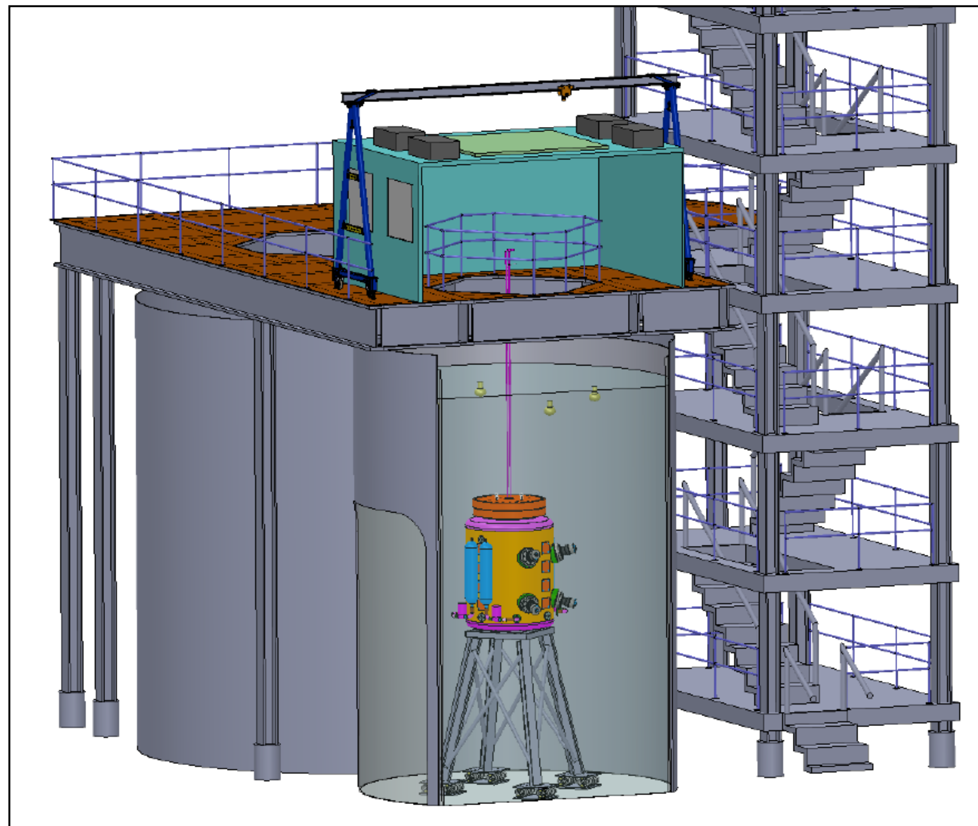
- PICO program has significant reach in parallel to G2 experiments
- Lower neutrino floor opens unique phase to PICO

Factor O(30) improvement anticipated for PICO 500. Assuming 1 year at a threshold of 10 keV, 6 months at 3 keV, and a neutron background of 0.75 per year.

PICO-500

- Engineering work ongoing as part of R&D program
- Proposal for full detector (~$5M CAD) recently adjudicated by CFI, decision June 2017. Official announcements soon.
- Construction envisioned for mid 2018. Sequencing of PICO 40 and 500 being established.





Whither Next?

- PICO 40 – “Right side up” – Now
- PICO 500 – with C3F8 – over next few years
- **Extended PICO 500 Program – longer term program**

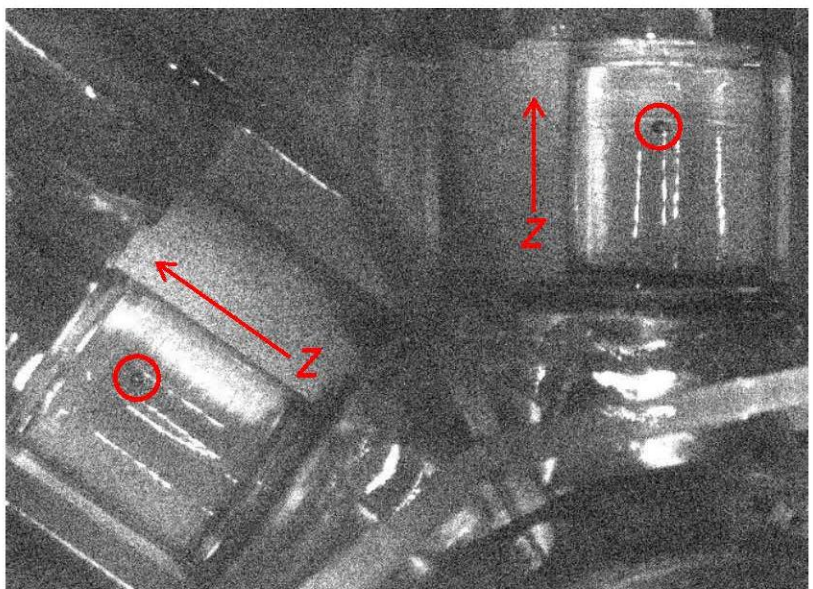
We envision PICO 500 serving as a detector facility that will explore DM in a variety of ways:

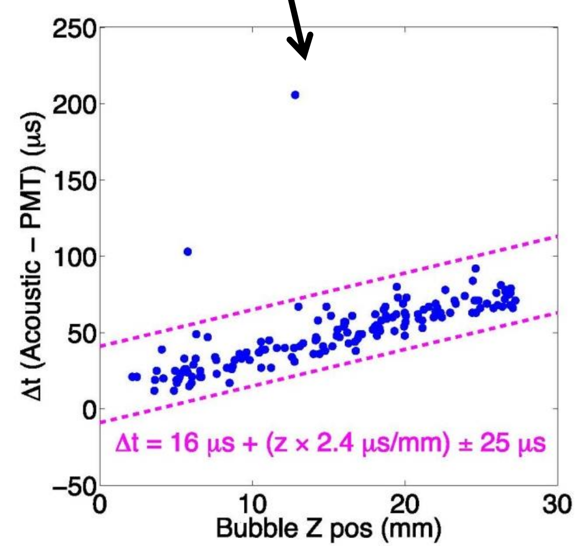
- With background free operations, the experiment will continue to probe the **canonical WIMP** to even lower cross-sections, not limited by the neutrino floor for the foreseeable future.
- Our current limitation to even lower thresholds is being explored. We are designing cleaner detectors to knock down gamma/beta background sources (this has not been the primary focus so far), we are looking into electron recoil discrimination.
- We can also more easily swap fluids to explore lower mass DM scenarios, or Spin-Independent interactions.

We envision PICO 500 serving as a detector facility that will explore DM in a variety of ways:

For example: We have running prototypes of right-side-up chambers ….

- Including a Liquid Xenon bubble chamber with scintillation light as well….. Exciting





We envision PICO 500 serving as a detector facility that will explore DM in a variety of ways:

For example: We have running prototypes of right-side-up chambers ….

- Now being prepared for running of liquid Argon.
- Also testing hydrogen rich fluids, eg. $C_2H_2F_4$ at the University of Montreal ….. Excellent for sub keV thresholds.

What is required to get there?

- A strong international collaboration and investment from our funding agencies. ✓
- Demonstrated technology and background free capability. ✓
- Strong engagement with SNOLAB to provide the location and operational support ✓
- Increasing support from the community. This is being accomplished through CPARC ✓

Canadian Particle Astrophysics Research Centre (CPARC)

A Canada First Research Excellence Fund (CFREF)
Award of $64 M$

Hosted at Queen's University with support to the Canadian community

Director: Tony Noble,
Queen's University

Canadian Particle Astrophysics Research Centre

CPARC

To ensure the highest level of international excellence,
CPARC will:

- Build scientific and technical capacity and broaden the scope of scientific community within Canada
- Create scientific capacity and wherewithal to ensure we are positioned to lead in a next generation, truly global scale project.
- Help position ourselves for the future by delivering on the existing programs.

SNOLAB will:

Create the environment where international collaborations see SNOLAB as the place to go to enable the science. Not just in depth and cleanliness, but in demonstrated ability to engage with experiments to enable science delivery safely and expeditiously

Canadian Particle Astrophysics Research Centre

CPARC

As an example. Through CPARC, 15 new faculty level positions are being created across Canada. Eleven of these have already been filled, and four of the Candidates have indicated a research program that will include PICO

Ken Clark:	Queen’s University
Guillaume Giroux:	Queen’s University
Marie Cecil Piro:	University of Alberta
Alan Robinson:	Université de Montréal

CPARC will also provide research funds, postdoctoral and graduate student support to these individuals, helping to enable PICO (and other Canadian programs in Particle Astrophysics)

Summary

- PICO bubble chambers at the 40L scale can be built background-free
- PICO dominates the search for spin-dependent WIMP-proton couplings with world leading results
- PICO 40 is well underway
- The design of PICO 500 is very advanced. Final technology choice for inner vessel to be made based on PICO 40 experience.
- The PICO 500 program looks to have lots of potential as a platform for ongoing research into the nature of Dark Matter
- This is made possible by the support and synergies developed through the international collaborations, funding agencies, SNOLAB, and CPARC

Latest PhD recipient
Chanpreet Amole
August 16, 2017