Title: Dark Matter Experiments: Requirements for Lower Thresholds and Improved Sensitivity

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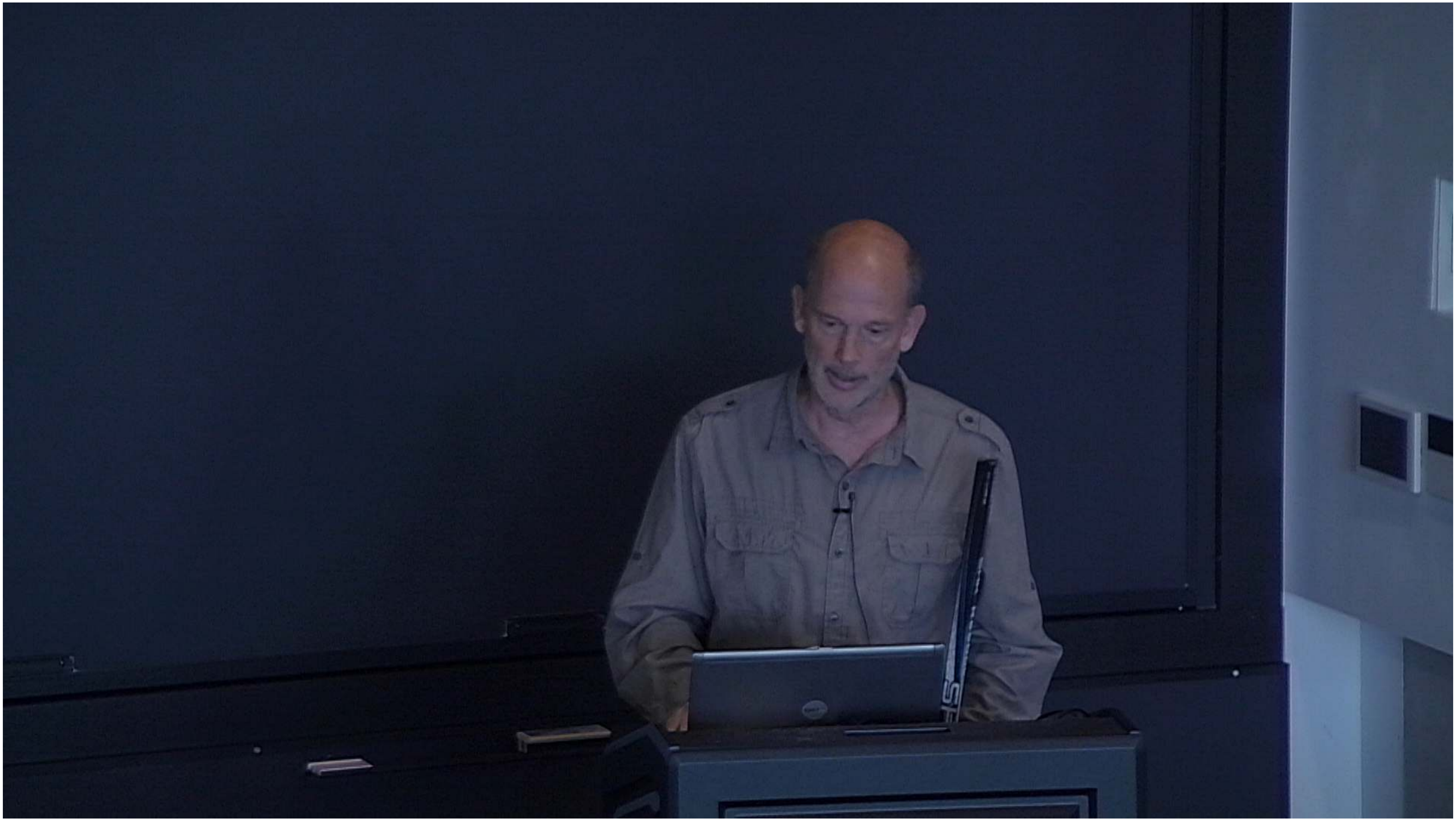
Abstract:

Addressing some of the Challenges in Dark Matter Searches

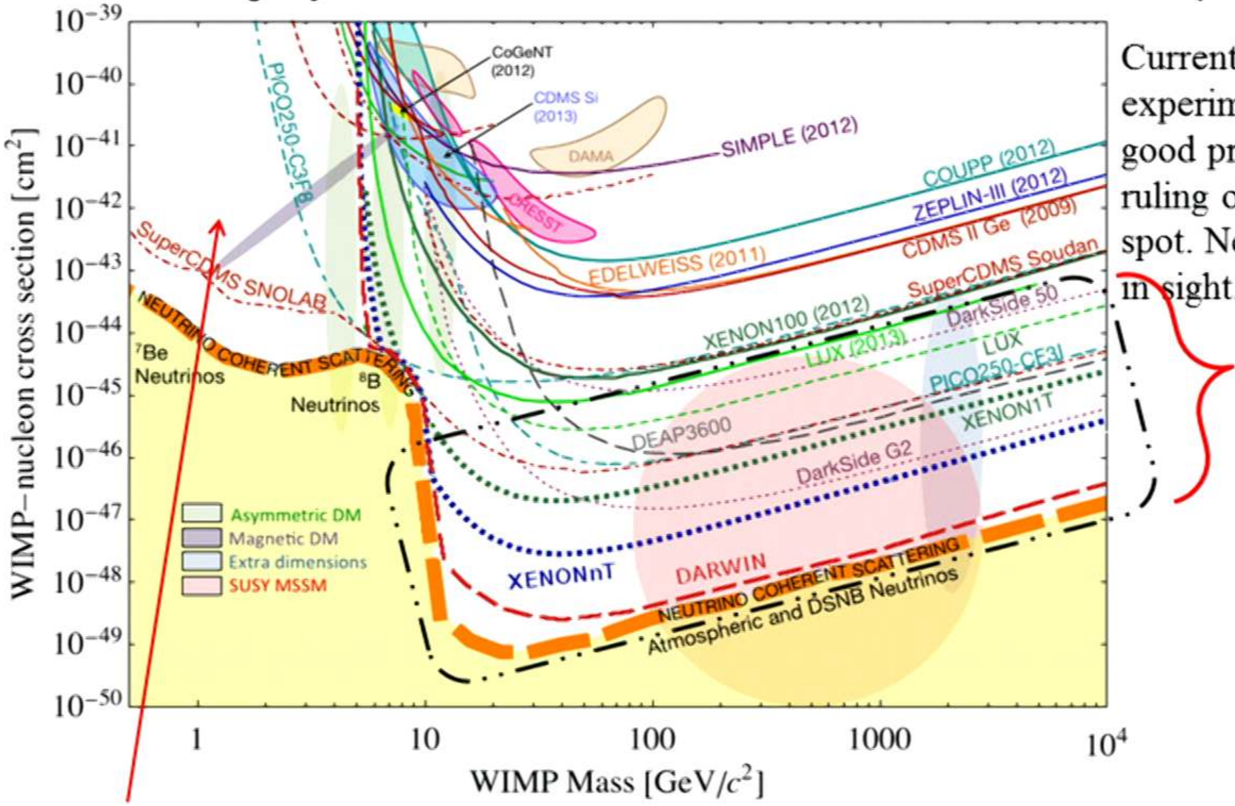
T. Noble. Queen's University

"Easy" bits of parameter space are disappearing … without a sighting.
The search gets harder now…

- Need guidance from theory → Workshops like this
- Too few people
- Not enough money
  } CPARC
- Need new technologies ….. → New detectors, like PICO



Slightly out of date … SI from Snowmass… but makes the point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

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Light Dark Matter: (< ~ 2 GeV/c^2)

Not your vanilla WIMP, because if light:
→ small annihilation cross-section
→ Overproduction of dark matter
→ Universe would be overclosed (could not have attained present age)

} In contrast with observations

Loopholes that allow us to avoid the Lee-Weinberg bound without the introduction of new forces are being ruled out …. Eg B decays.

Introduce new interactions: Annihilation proceeds through new force carrier. If coupling is sufficiently small, DM can be light: ~ 1 MeV – 1 GeV

Eg:

$\chi\chi \rightarrow e^+e^-$

Various possible Portals: Looking forward to hearing more about what theorists think are most likely:

- Direct detection of low energy recoils -- still some room for this technology
- Beam Dump Experiments looking at invisible decays
- Thin/Thick Targets with sensitivity to displaced vertices …

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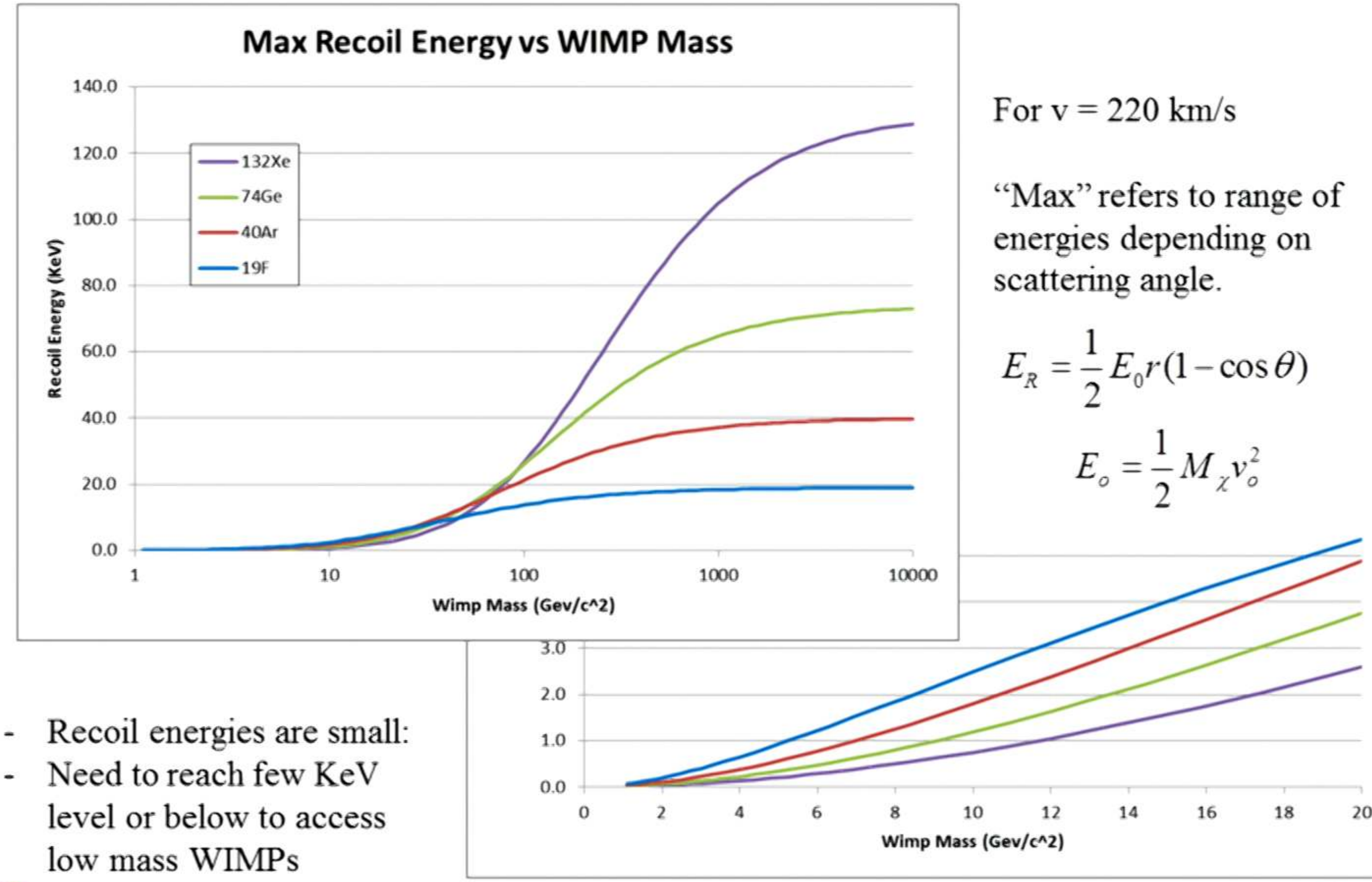
The challenge for Direct detection:



For v = 220 km/s

"Max" refers to range of energies depending on scattering angle.

$$E_R = \frac{1}{2} E_0 r (1 - \cos\theta)$$

$$E_o = \frac{1}{2} M_\chi v_o^2$$

- Recoil energies are small:
- Need to reach few KeV level or below to access low mass WIMPs

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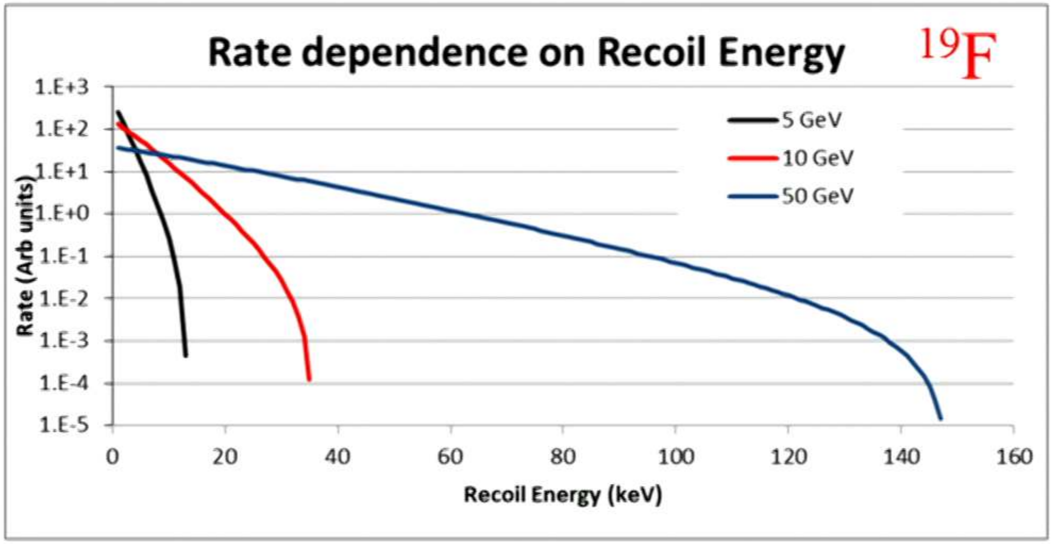
Realistic calculations treating the earth velocity and escape velocity cut-off exacerbate the situation.:



For $v_o = 220$ km/s
For $v_e = 230$ km/s
For $v_{esc} = 600$ km/s

There is a dramatic cut-off in rate when WIMP velocities exceed the escape velocity:

- Even more important to have low threshold capability for low mass WIMPs

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But…. Low thresholds are hard to achieve:

- Signal is weak. Not enough ions/scintillation photons/phonon signal to easily detect
- Electronic noise becomes a problem
- Radioactive backgrounds more plentiful
- Detectors are very large …. Full coverage → More channels/high cost ….

→ Current technologies are limited.

Example: A conventional 50 tonne scintillation based detector:

Assume $\rho \sim 1$ to get volume.

- Signal is typically of order 10,000 γ/MeV. So with a 2 keV threshold this implies ~20 γ
- PMT's will have a single PE at most
- With 25% QE → 5γ detected.
- For 50% cathode coverage need > 1000 8" pmt's
- If dark current is ~1000Hz, and digitized signal is 1000 μs, then ~60% chance of electronic noise pile up

Need better technology with lower noise, lower cost, better photon sensitivity, better coverage

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Also: Radioactive background rates increase at lower energies…

Example: ^{39}Ar …. $^{39}\text{Ar} \rightarrow {}^{39}K + \beta^{-} + \overline{\nu}_e$

- Radioactive isotope cosmogenically produced (from ^{40}Ar).
- Only exists at 8×10^{-16} g/g compared to normal Ar
- Half-life 269 years → 1 Bq/kg Argon
- ∴ for the DEAP-3600 detector →3600 decays/s →~1.1×10^{11} decays/year. To avoid backgrounds need particle identification discrimination accuracy at better that 10^{10} !
- Future Ar detectors will require depleted argon …. Orders of magnitude lower in activity. This can be achieved, with some effort, by finding deep underground reservoirs of Ar that is no longer cosmogenically active, and where any initial ^{39}Ar has decayed away. So far levels of better than 100 depletion have been demonstrated.

Background mitigation techniques:

Need **exquisite** particle id **discrimination**.
Better **counting techniques** to screen materials: HPGe, αβ counters, proportional counters, radon emanation, whole body, mass spectroscopy, neutron activation, chemical concentration techniques and manipulation at single atom level…
Better **materials production**: Largely underground, eg copper electroplating, industry compliance.

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How to make progress on new detector technologies?

Need ideas, funding, people….

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:

1. Expand on the scientific culture at Queen's University and its partner institutions by building a powerful and integrated team working on all aspects of particle astrophysics including the SNOLAB experimental program, astroparticle and astrophysics theory, related observational astrophysics, cosmology, detector development and low background techniques.

Build scientific and technical capacity and broaden the scope of scientific community within Canada

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CPARC will:

2. Create an integrated research team with the critical mass and skills required to prepare and lead the next generation of increasingly challenging experiments. This will attract international scientists and technology along with the capital and operational funding necessary to allow one or more global-scale next-generation detectors to be hosted at SNOLAB.

CPARC: Create scientific capacity and wherewithal to ensure we are positioned to lead in a next generation, truly global scale project.

SNOLAB: Create the environment where these 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.

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CPARC will:

3. Help obtain maximal scientific output from the suite of experiments that are currently operational or under development at SNOLAB by hiring key additional personnel, strengthening international collaborations, and engaging the broadened scientific community in the undertaking.

Apply some of the new resources strategically to help with the current program.

Help position ourselves for the future by delivering on the existing programs.

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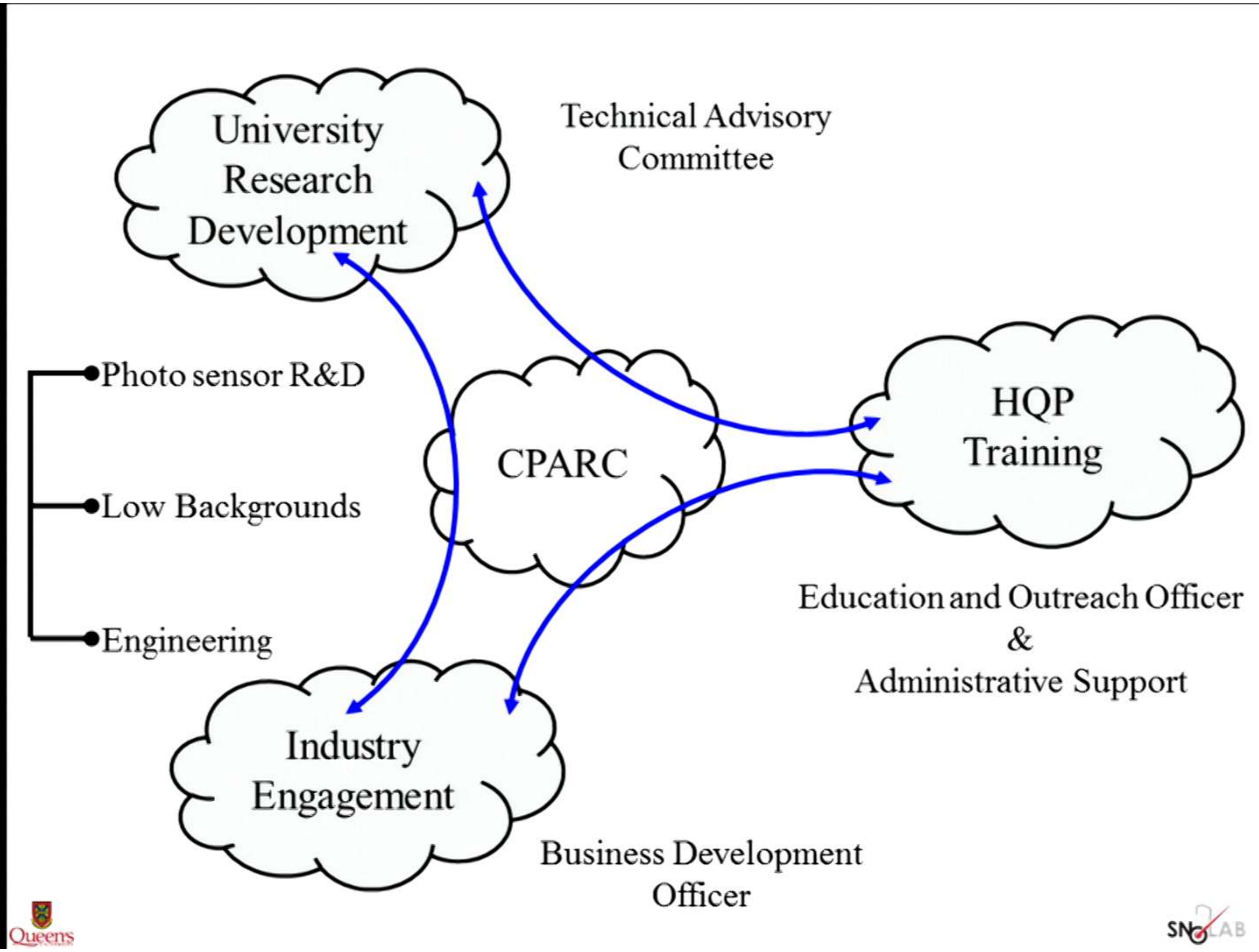
CPARC will:

4. Actively collaborate with industry to facilitate knowledge transfer and subsequent innovation.

Put dedicated resources onto this with the responsibility to make it happen.



University Research Development
Technical Advisory Committee
Photo sensor R&D
Low Backgrounds
Engineering
CPARC
HQP Training
Education and Outreach Officer & Administrative Support
Industry Engagement
Business Development Officer
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Research Partnerships

Lead Institution	Eligible Universities	Research Institutes
Queen's U.	U. Alberta	CIFAR
	U. British Columbia	IPP
	Carleton U.	PI
	U. Laurentian	SNOLAB
	McGill U.	TRIUMF
	U. Montreal	
	U. Toronto	

Main elements requested: The people. We will ramp up to:

- 7 new faculty members at Queen's in physics (theorist, experimentalist, engineering physicist, astro/astroparticle experimentalist), radio-chemist, geo-chemist/isotopic, nuclear materials engineering. To build on core group at Queen's with interdisciplinary expertise relevant to development of low background techniques, detector design, and broadening of the field.
- 7 new faculty members at universities across Canada (Alberta, Carleton, Laurentian, Montreal, Toronto). "SNOLAB experimentalists" and faculty equivalent RS at TRIUMF
- 3 Research Scientists and 3 project managers to support the SNOLAB scientific program.
- 4 Engineers, 1 designer, and 15 technical positions
- ~18 PDF and 31 graduate students supported annually.
- Scientific Director, Managing Director, Finance Officer, Business Development Officer, HR&Board Secretary, Education and Outreach Officer, 2 Admin @ QU
- Support for undergraduate summer research positions and internships in industry.

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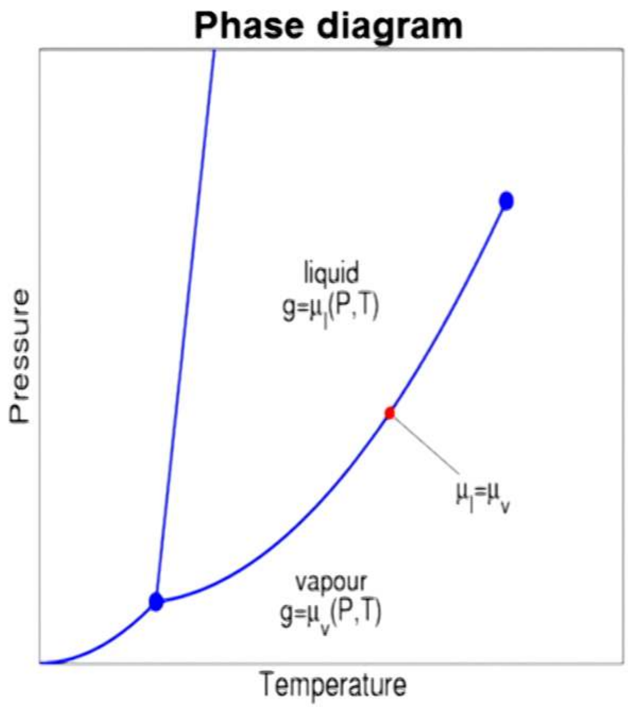
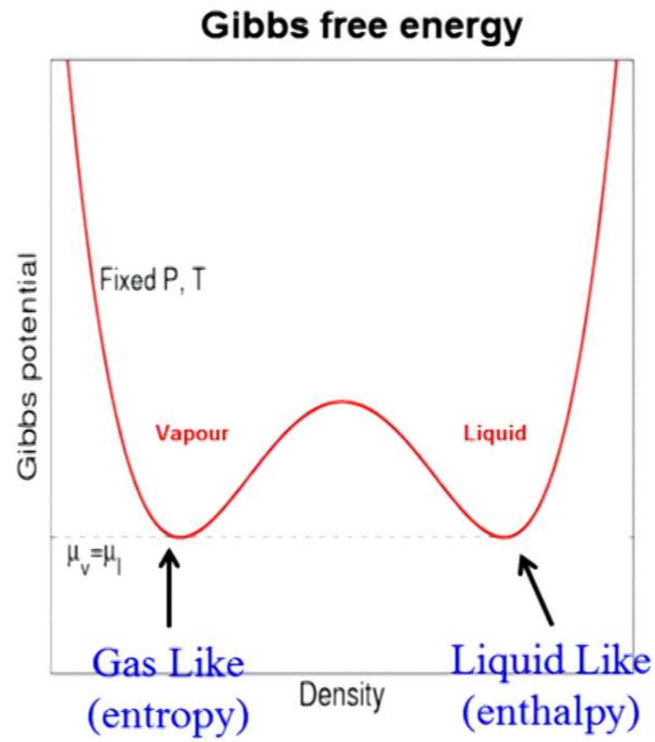
One example of a “novel” detector technology:
(actually a recycled idea)

- ~Low threshold sensitivity
- Good particle discrimination
- Funding for large scale detector. Lots of manpower…

PICO Bubble chamber

Bubble Chamber Operation

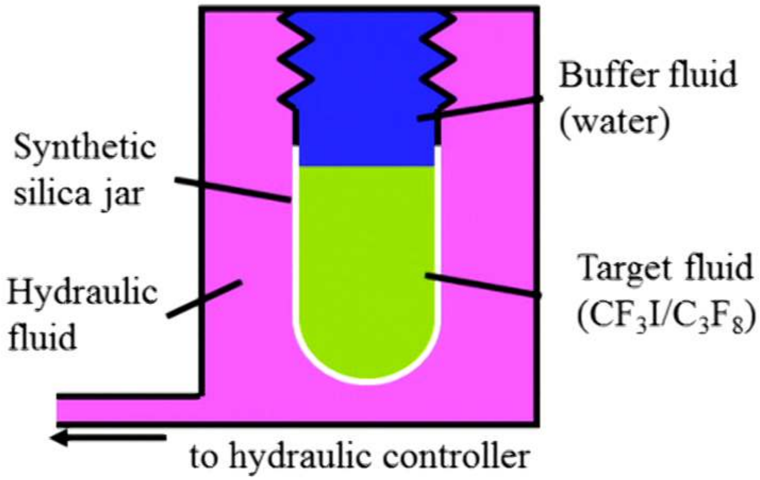


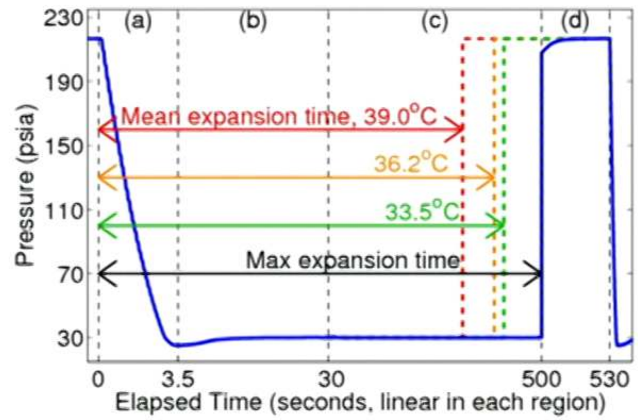


When on the saturation curve, liquid and gas are in equilibrium. (Same pressure, temperature and chemical potential).

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

Principle of Operation: Bubble Chamber





1. Lower the pressure to a superheated state.

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

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

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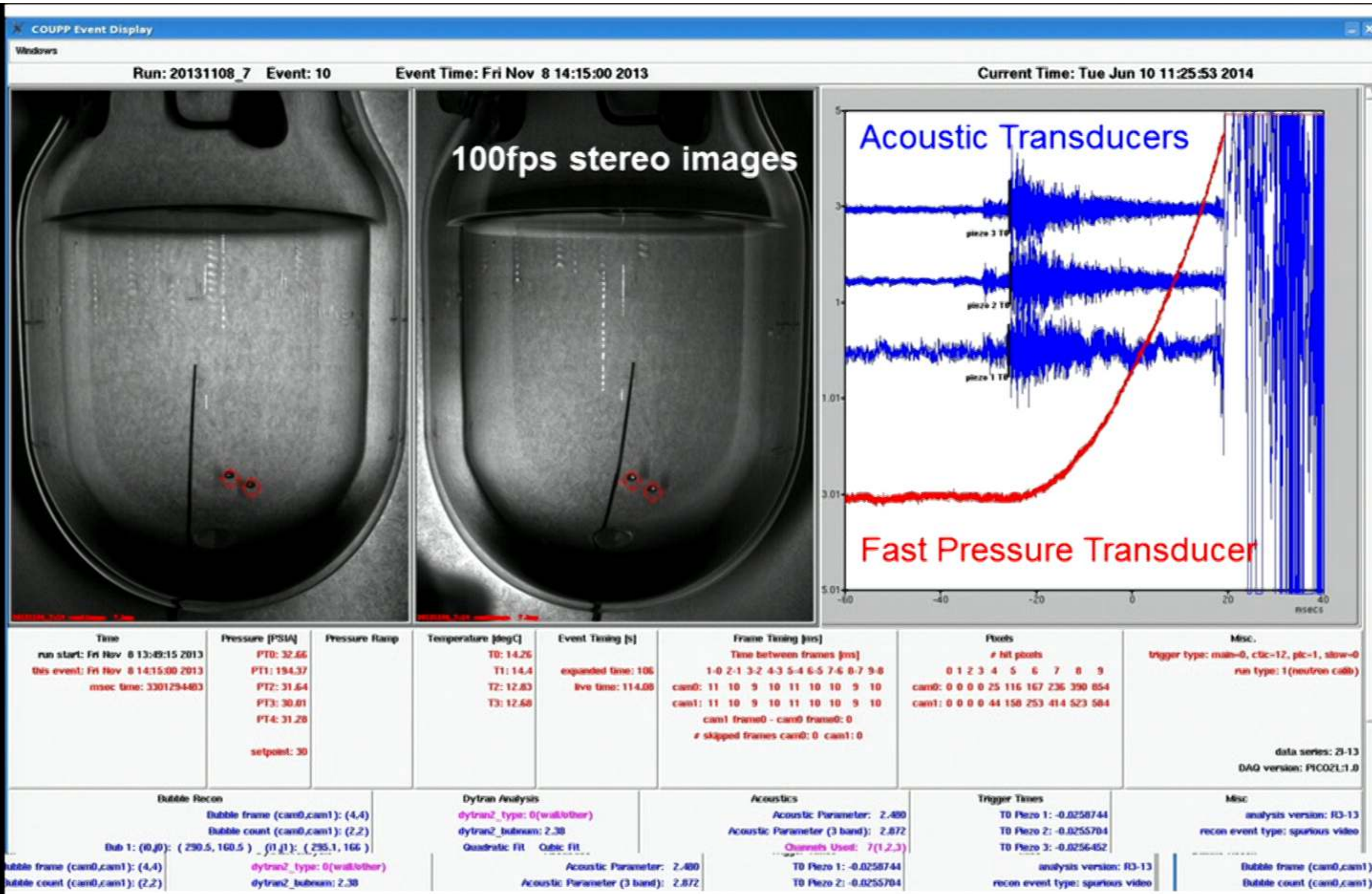
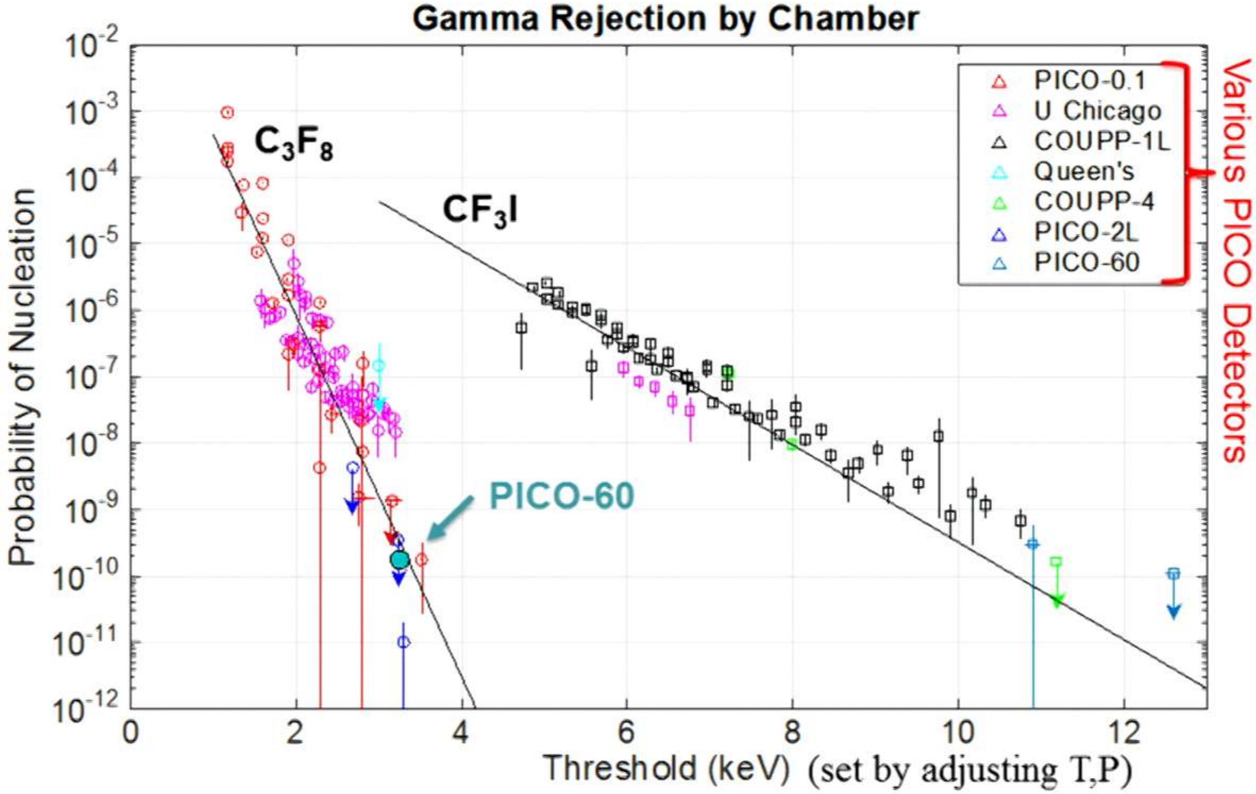


Screen Display during operations

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.

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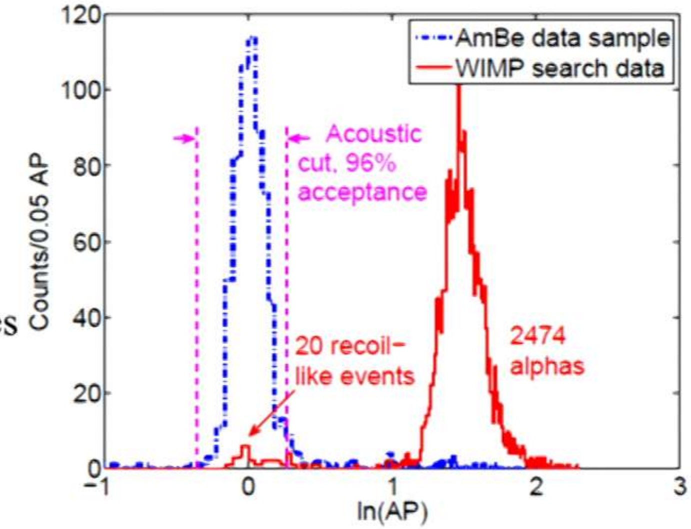
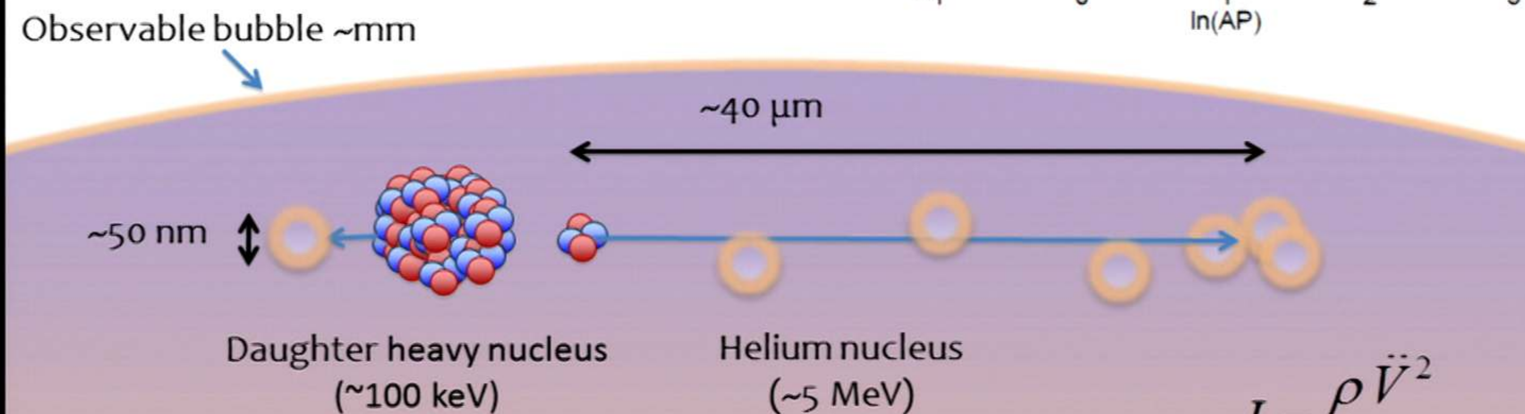
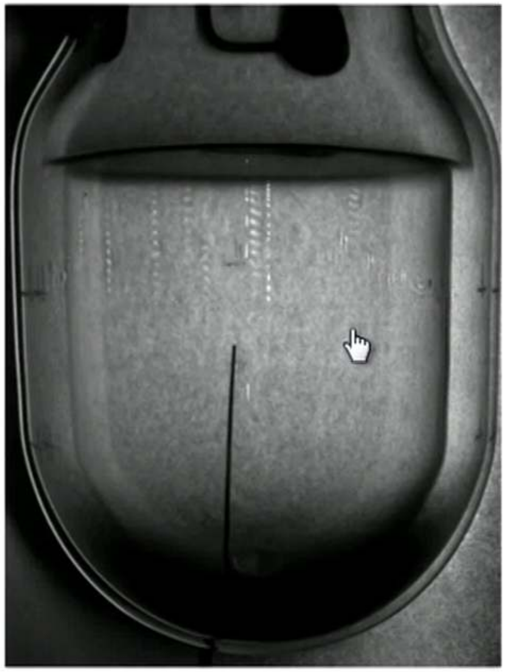
Alpha Acoustic Discrimination

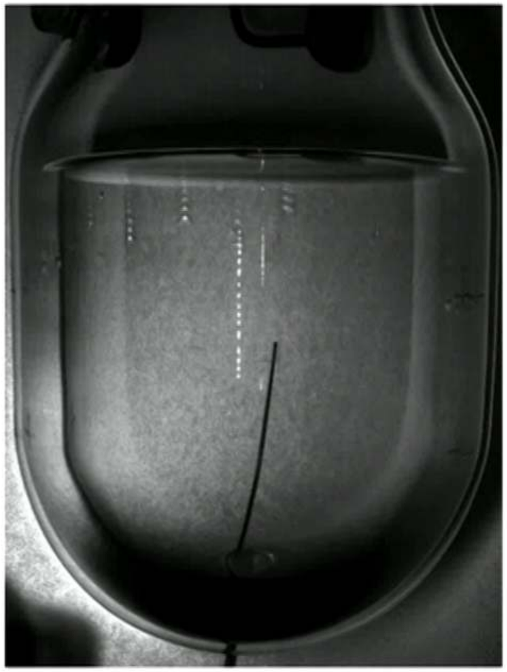
- Discovery by PICASSO of acoustic discrimination against alphas
  - **Nuclear recoils** deposit their energy over tens of nanometers.
  - **Alphas** deposit their energy over tens of microns.
- In bubble chambers alphas are several times louder due to the difference in the rate of expansion.





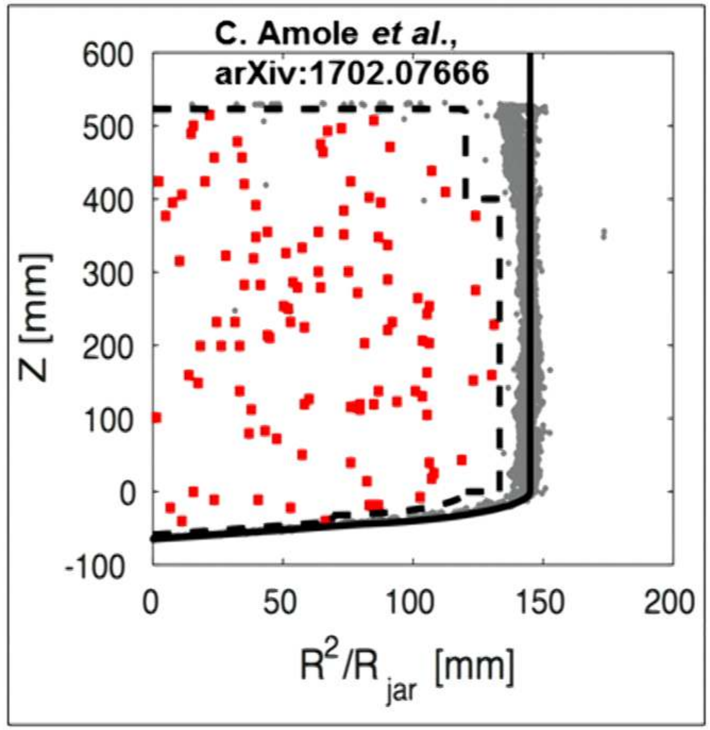
$$I = \frac{\rho \ddot{V}^2}{4\pi c}$$





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**



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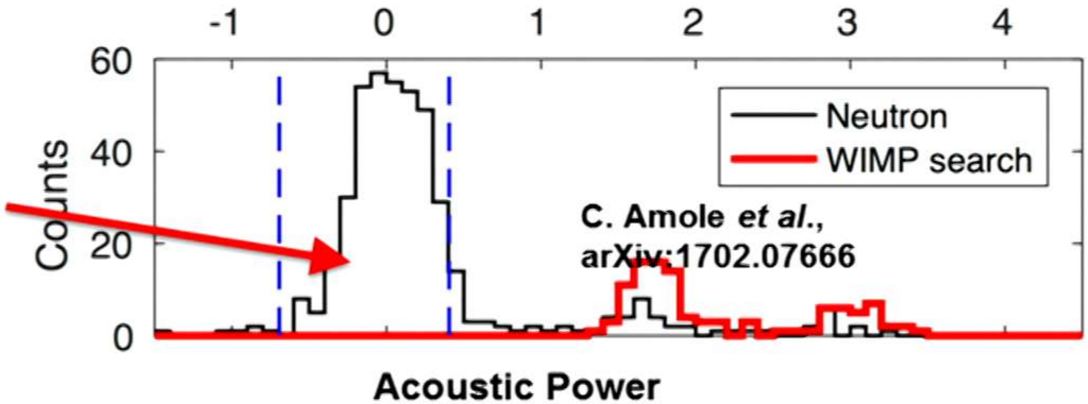
After Opening the Box

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

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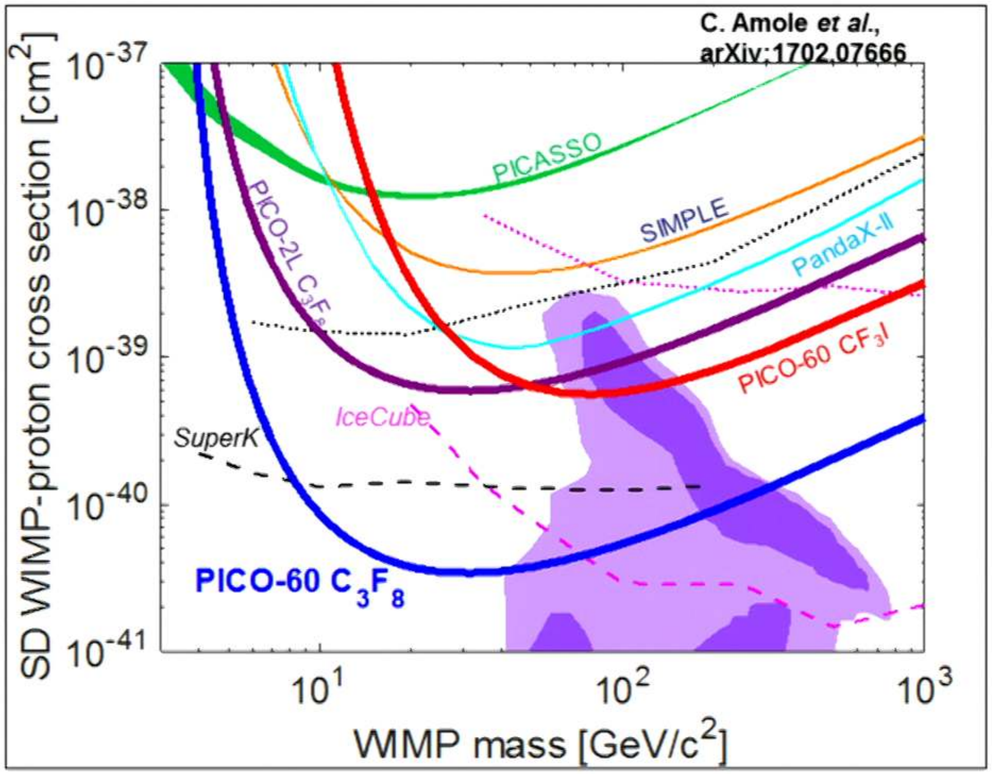
Spin-Dependent WIMP-Proton Coupling
Recent Limits from PICO-60



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

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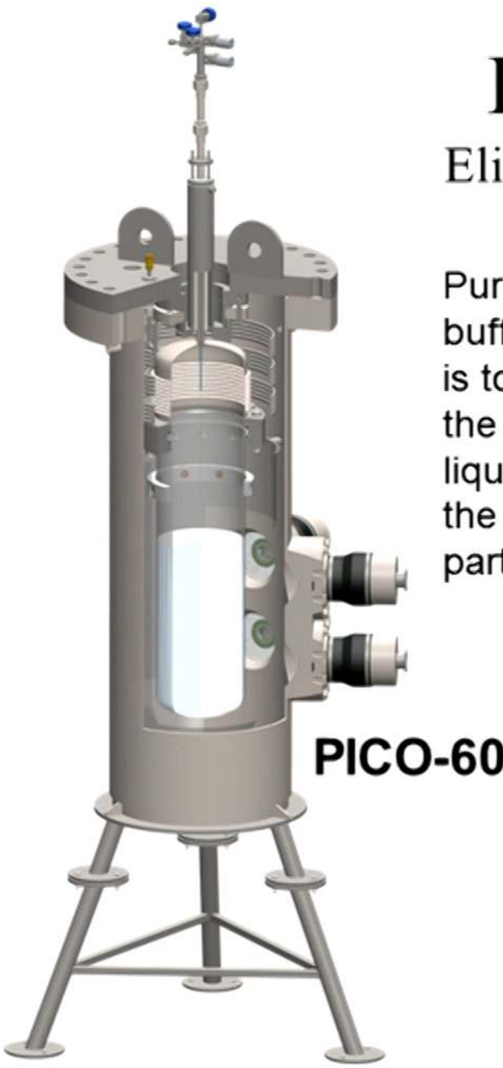
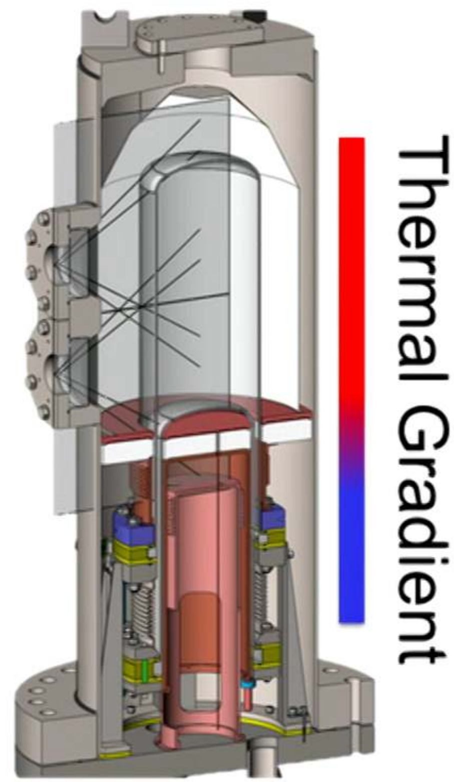
PICO-40L

Eliminate buffer fluid



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

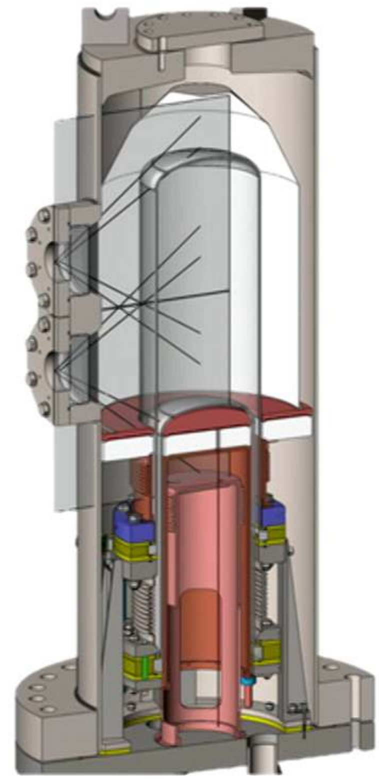
Thermal gradient can ensure that target fluid near stainless parts is not active



PICO-40L

Physics reach

- Added stability could allow us to push down in threshold (WIMP mass) until we hit electron-recoil backgrounds
- Ability to use new target fluids optimized for different WIMP masses
- Reduced neutron backgrounds, allowing us to push down in cross-section
- Tests technology for future tonne scale detector: PICO 500



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PICO-40L

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PICO-60

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PICO-40L

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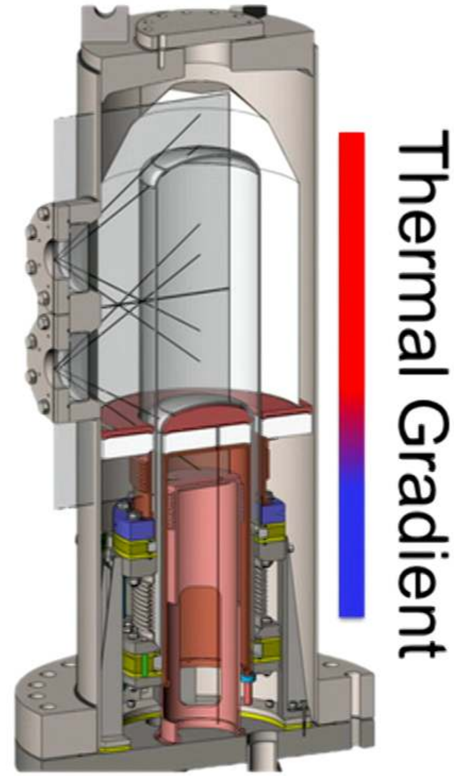

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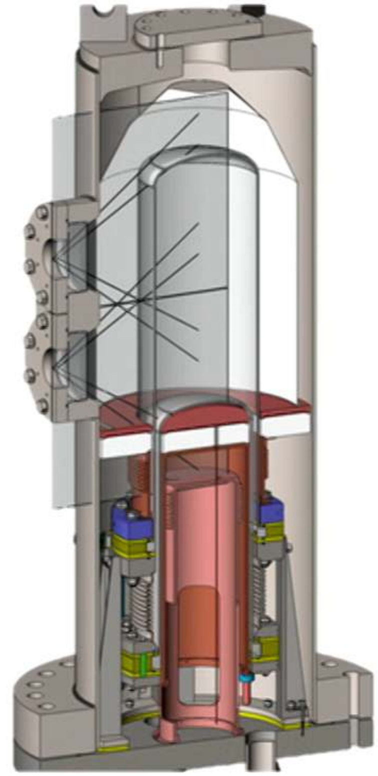
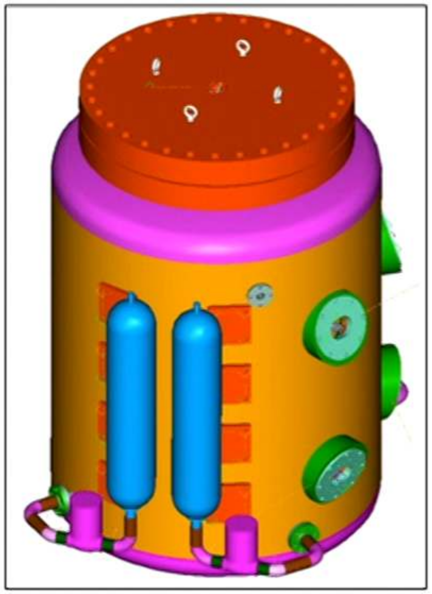
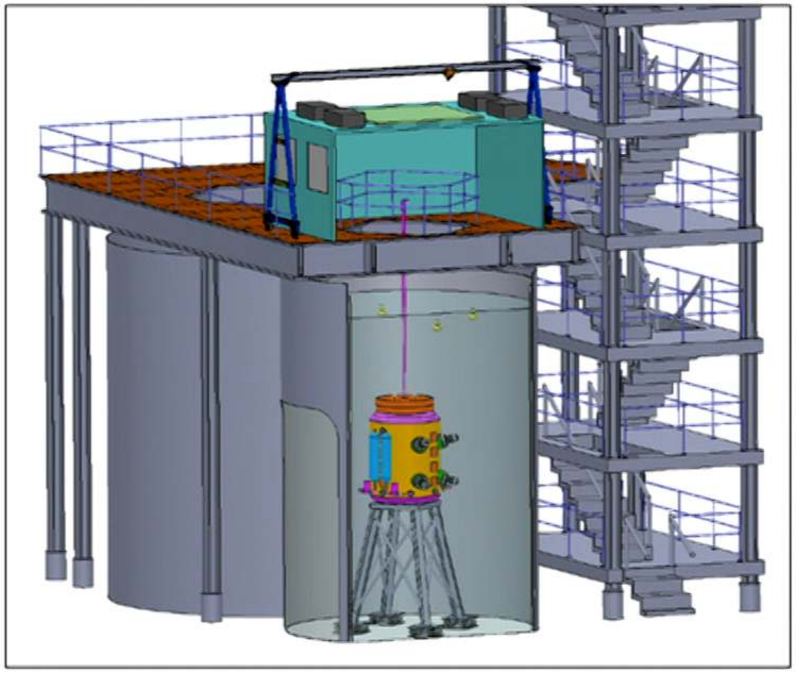


PICO-500

- Engineering work ongoing as part of R&D program
- Proposal for full detector (~$5M CAD) currently being adjudicated by CFI, decision expected June 2017
- Construction envisioned for early 2018





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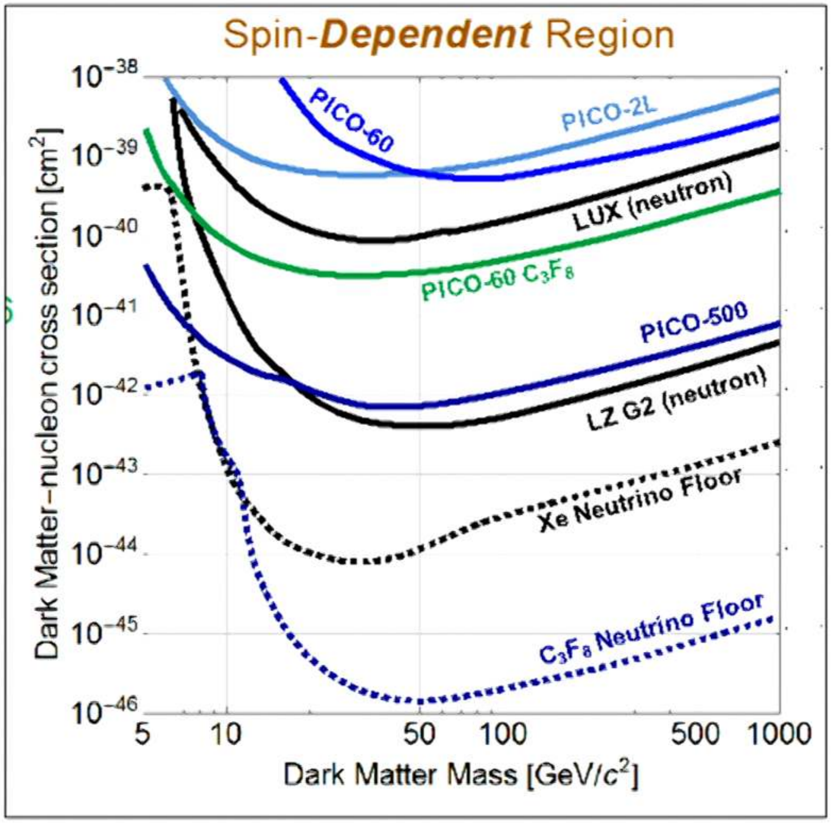
Spin-Dependent Future



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

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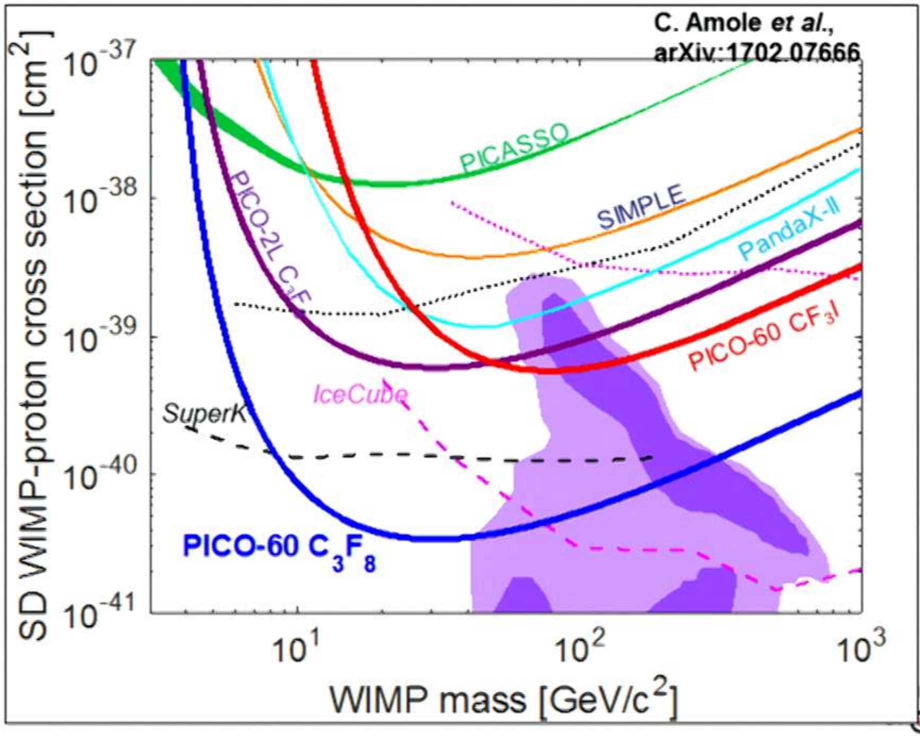
Summary

- PICO bubble chambers at the 40L scale can be built background-free
- PICO dominates the search for spin-dependent WIMP-proton couplings
- Construction of 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.



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