PICO
Dark Matter Searches with Bubble Detectors

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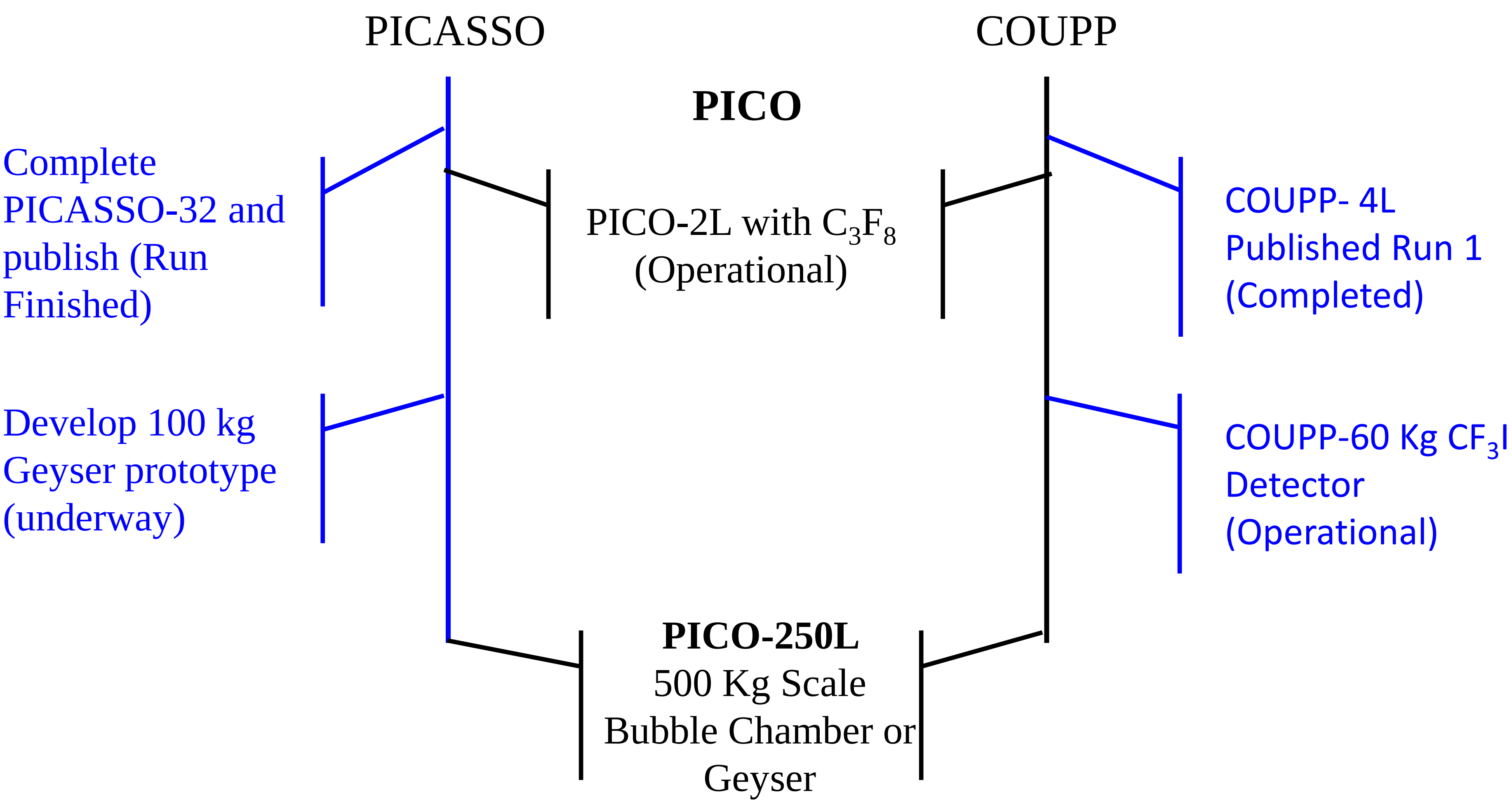
Moriond
Mar 18, 2014

PICO:
The marriage of PICASSO and COUPP



PICO

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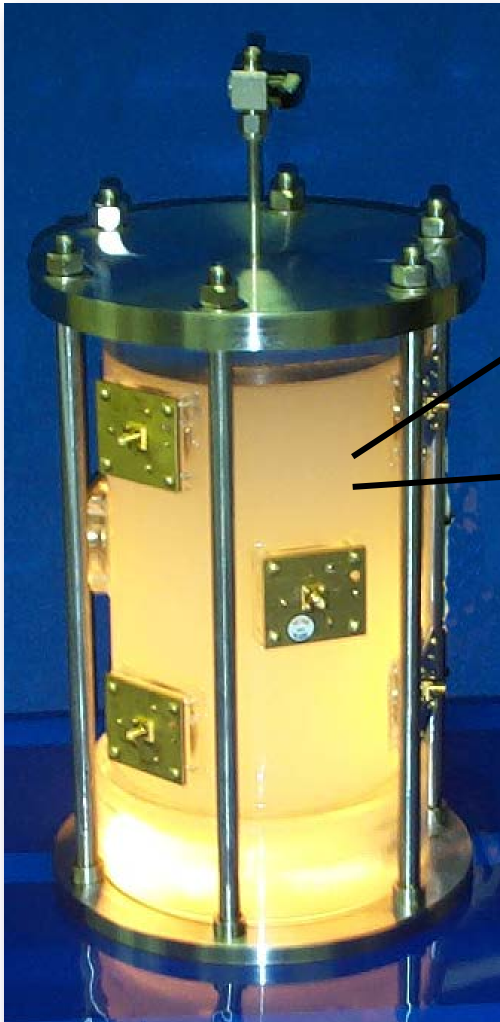
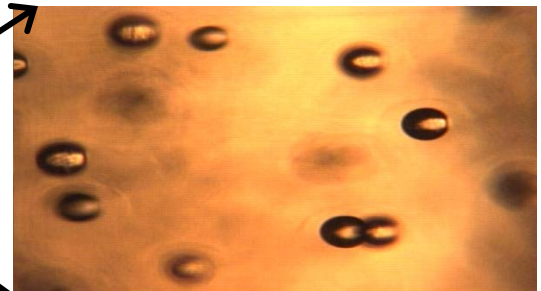
Principle of Operation: Droplet Detector

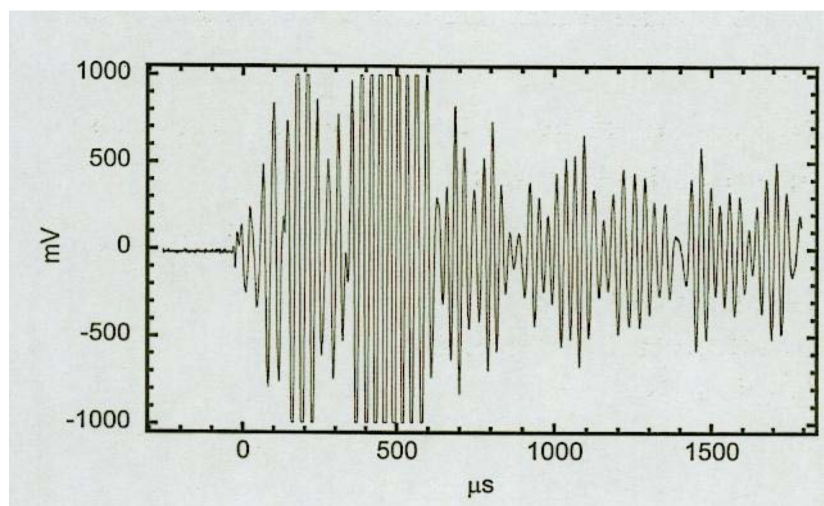
PICASSO Droplet Detector



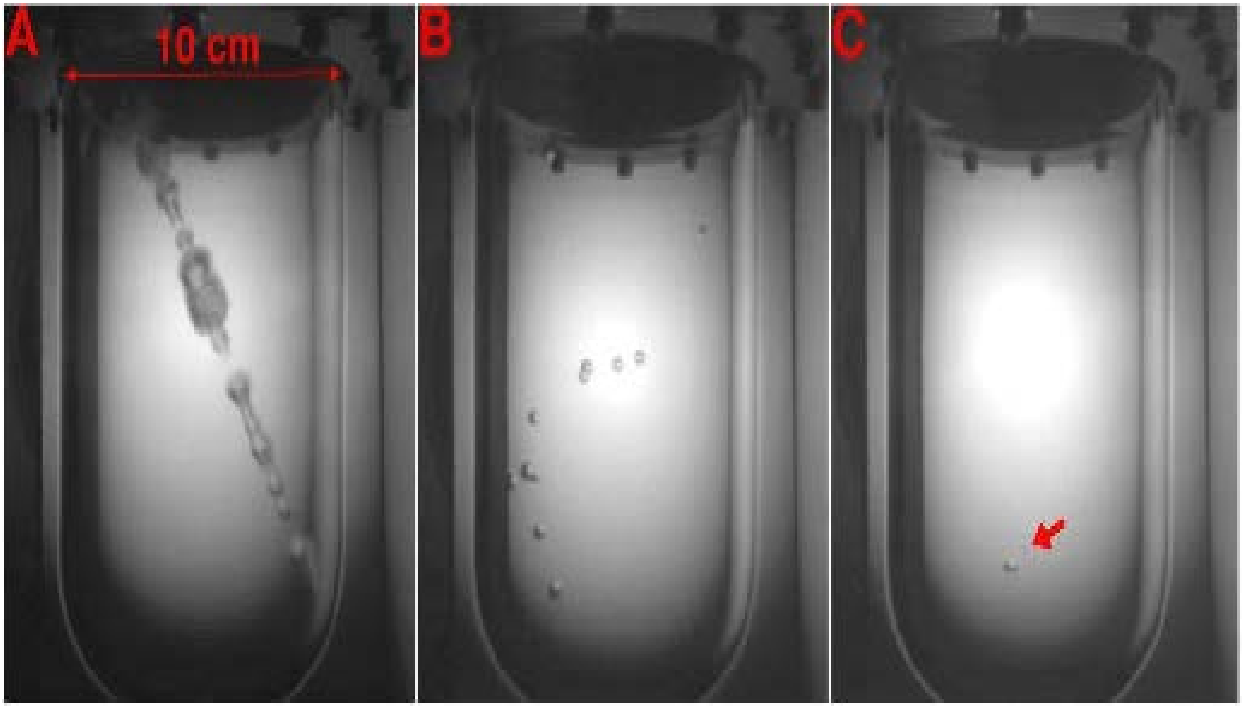
Detectors consist of millions of tiny (~100 µm) halocarbon liquid droplets (C_4F_{10}) embedded in a gel. Each behaves like a little bubble chamber.



- If a nuclear recoil deposits a spike of heat into droplet, it rapidly changes phase.
- The expanding bubble creates an acoustic shock wave which is be recorded by piezo-electric transducers



Bubble Chamber Data

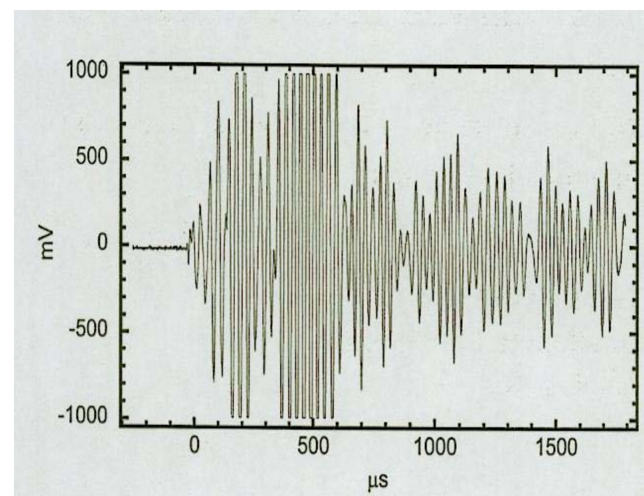


- See Event with Stereo Cameras
- Record Pressure Rise
- Hear Acoustic Signal

A cosmic ray passing through chamber

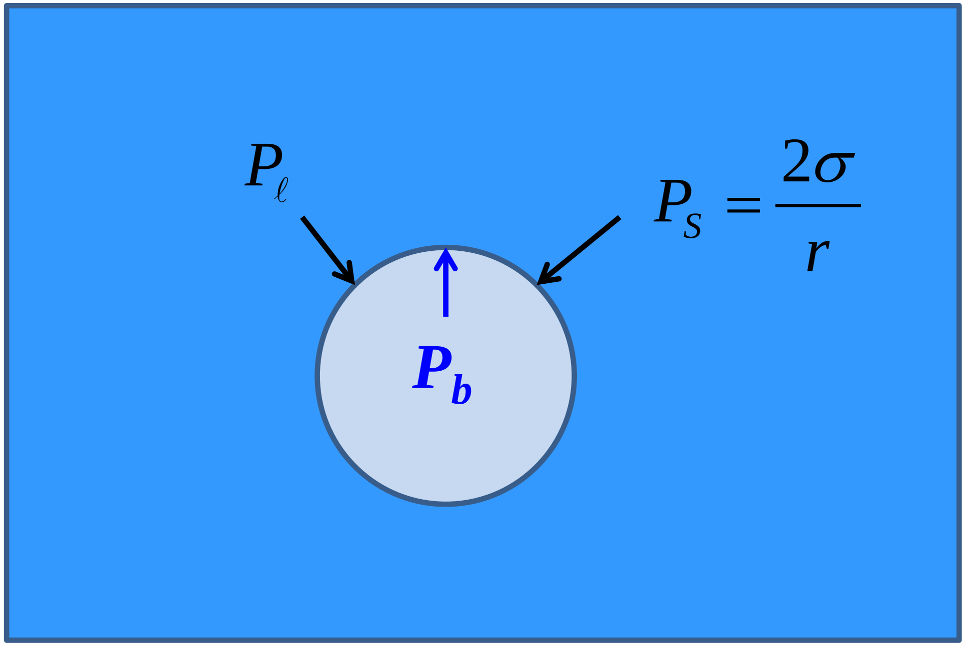
A neutron bouncing around in chamber

A single bubble candidate



Bubble Nucleation Dynamics. What Controls Bubble Growth?

1. A small proto-bubble is produced.
2. The bubble begins to expand as the vapour is produced. Outward pressure P_b
3. This is opposed by the external pressure of the liquid P_ℓ, and …
4. It is opposed by the surface tension at the interface.



At equilibrium: $P_\ell + P_S = P_b$

Critical radius for (unstable) equilibrium: $P_\ell - P_b = \frac{2\sigma}{r_c}$

At larger radii, diff pressure is small, bubble grows easily …. Rapid boiling

At smaller radii, diff pressure is large, bubble can’t grow …. Collapse

Particle detection with bubble chambers

- A bubble chamber is filled a superheated fluid in meta-stable state.

- Energy deposition greater than E_{th} in radius less than r_c from particle interaction will result in expanding bubble *(Seitz "Hot-Spike" Model).*

$$E_{th} = 4\pi r_c^2 \left(\sigma - T \frac{\partial \sigma}{\partial T} \right) + \frac{4}{3} \pi r_c^3 \rho_v h$$

Surface energy Latent heat

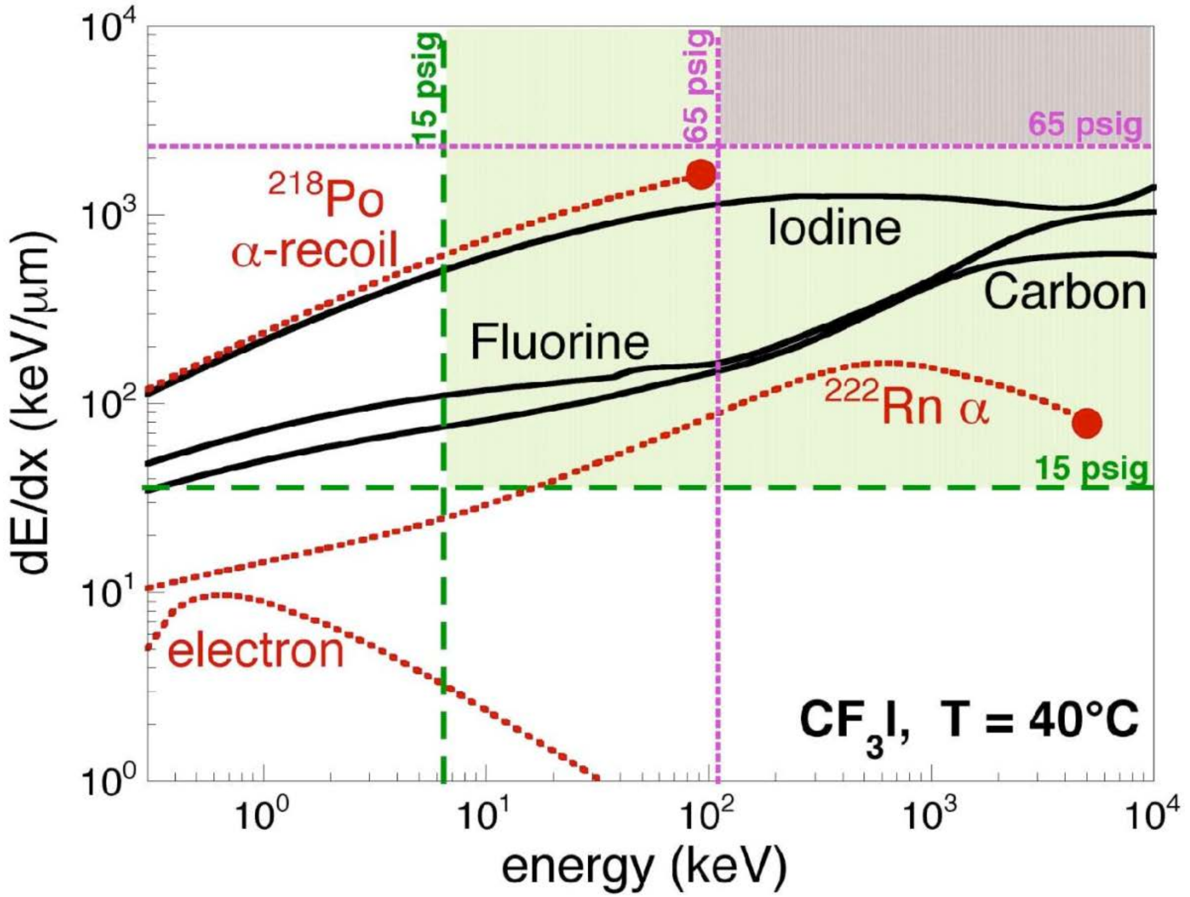
- A smaller or more diffuse energy deposit will create a bubble that immediately collapses.

<u>Take away message:</u>

- To be sensitive, particle must deposit enough energy within a critical radius.

Bubble chambers as nuclear recoil detectors

- Thermodynamic parameters are chosen for sensitivity to nuclear recoils but not electron recoils.
- Better than 10^{-10} rejection of electron recoils (betas, gammas).
- Alphas are (were) a concern because bubble chambers are threshold detectors.



Take away message:

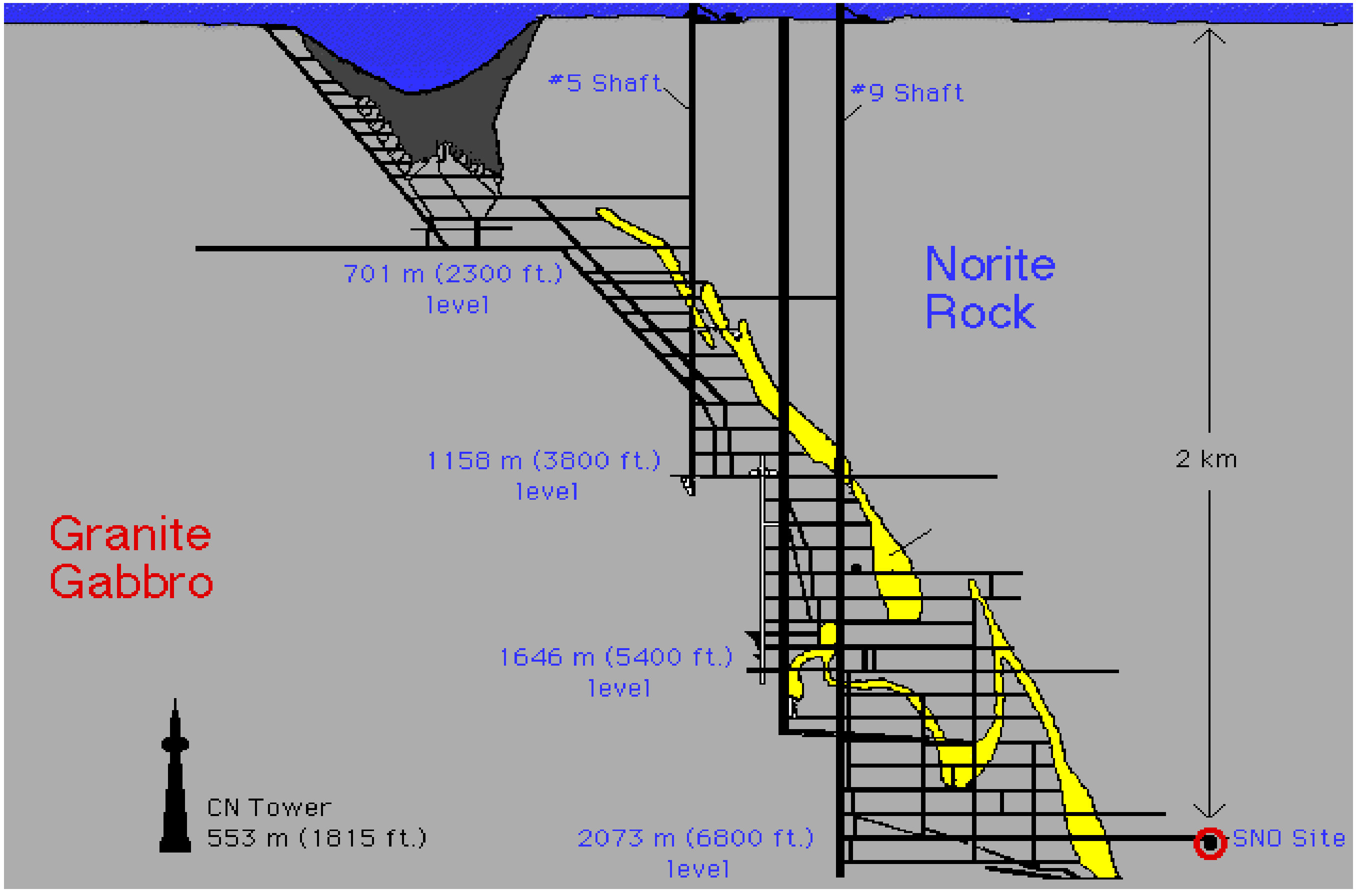
- Energy deposition depends on particle type. So can tune detector to be sensitive to certain types only. → Particle discrimination

Backgrounds: Generic Comments

Require very low background environment to see rare events ….

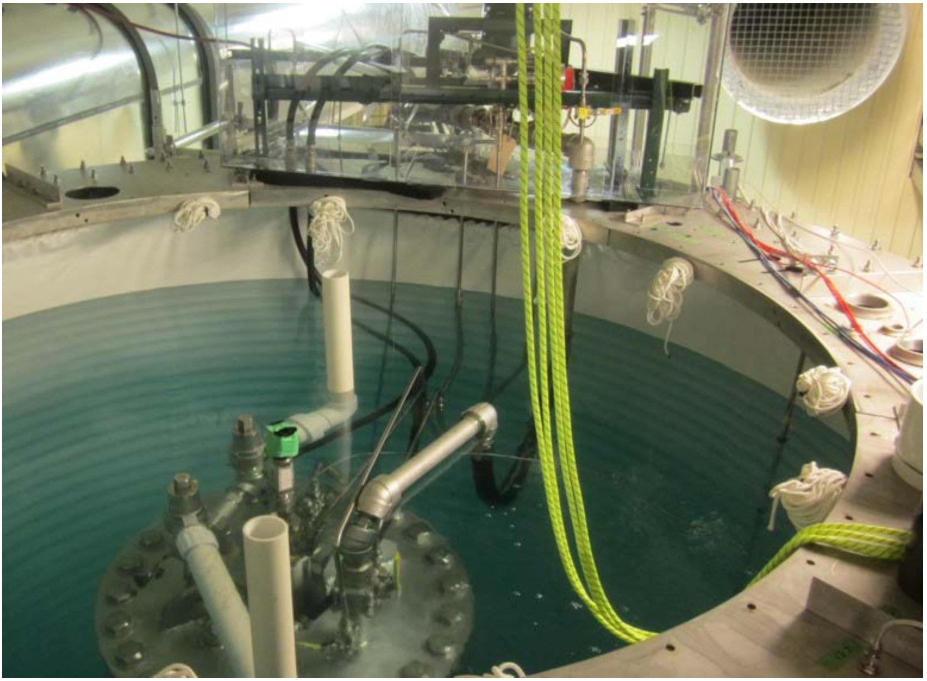
- Go deep underground to escape cosmic rays.
- Provide local shielding
- Use materials with ultra-low levels of radioactivity
- **Develop particle discrimination techniques….**

SNOLAB, CANADA

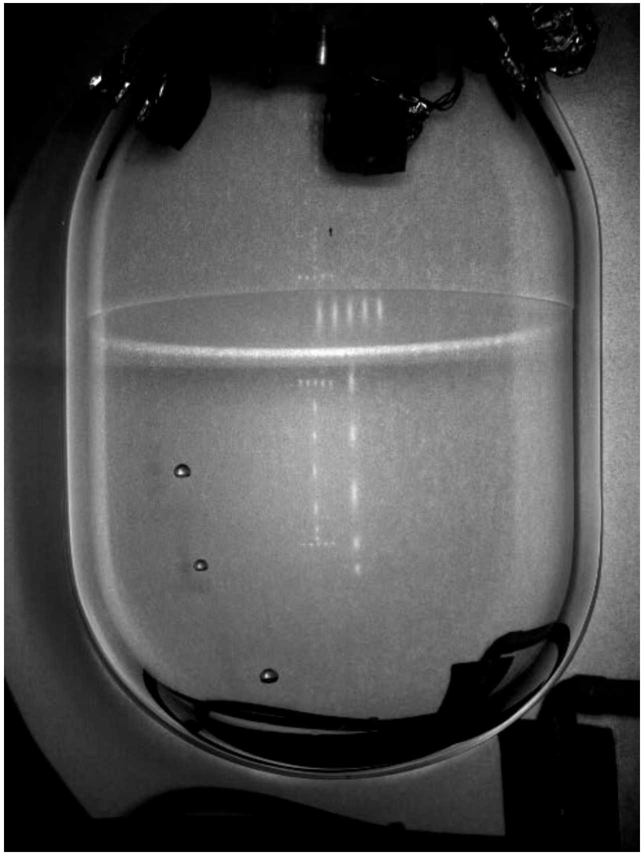


Neutrons

- Go deep underground to escape cosmic rays.
- Provide local shielding



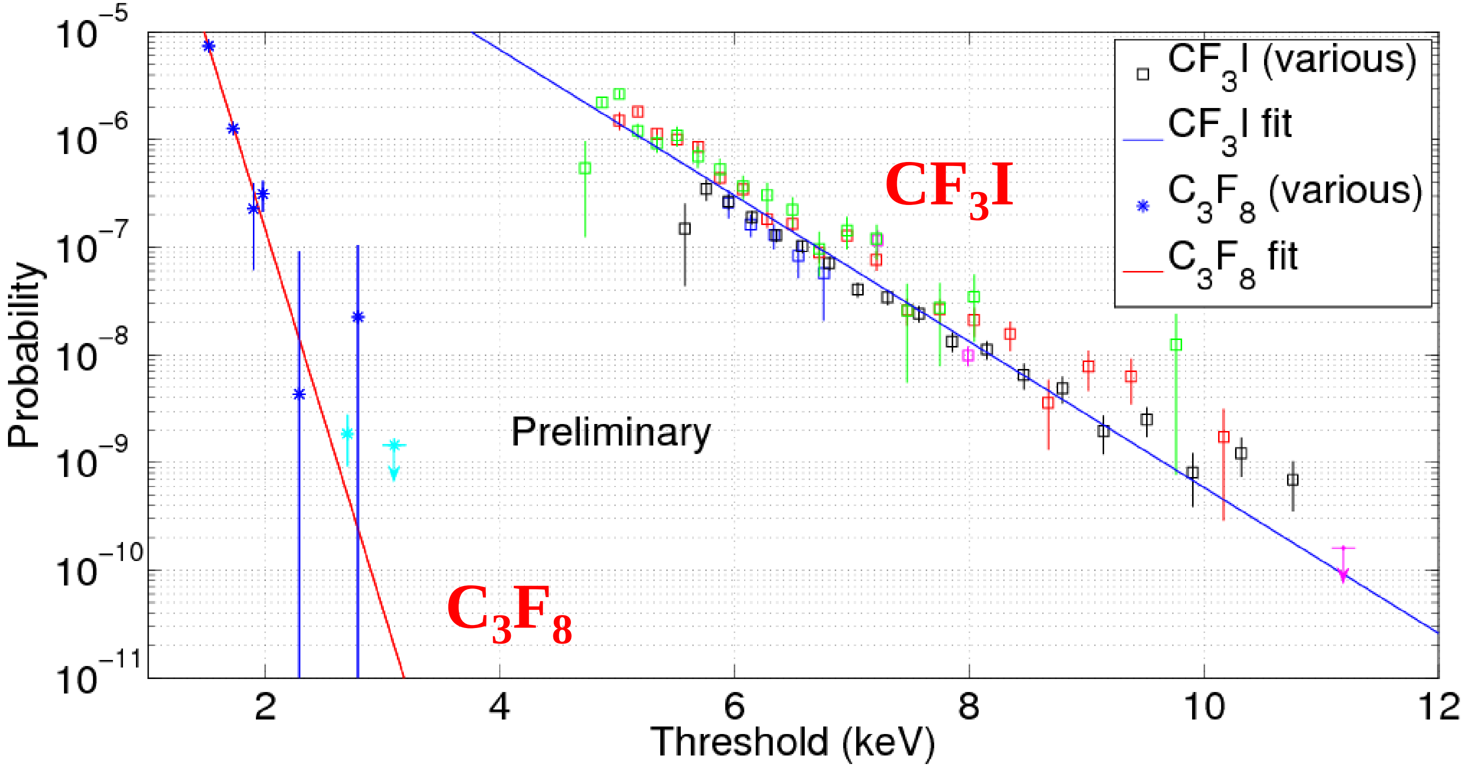
COUPP-60 in neutron shielding tank.



Confirm neutron rate with multiples.

Electron recoil rejection

Bubble nucleation probability from gamma interactions in C_3F_8 and CF_3I

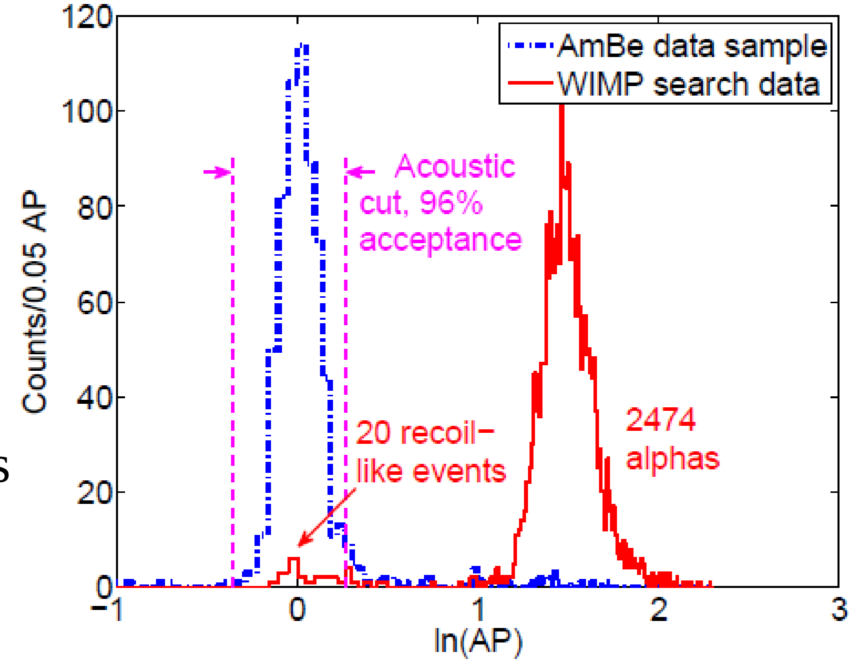


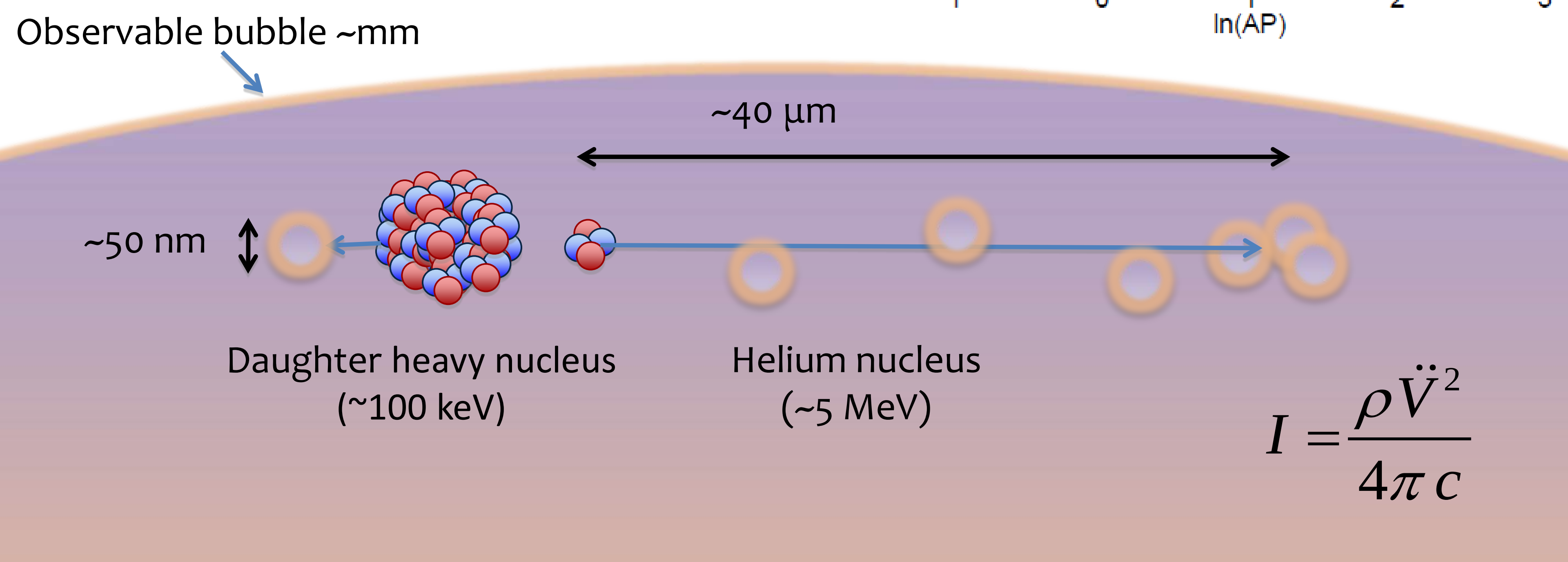
Key Points:

- 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 (Aubin et al., New J. Phys.10:103017, 2008)
  - **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 expansion rate difference.





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

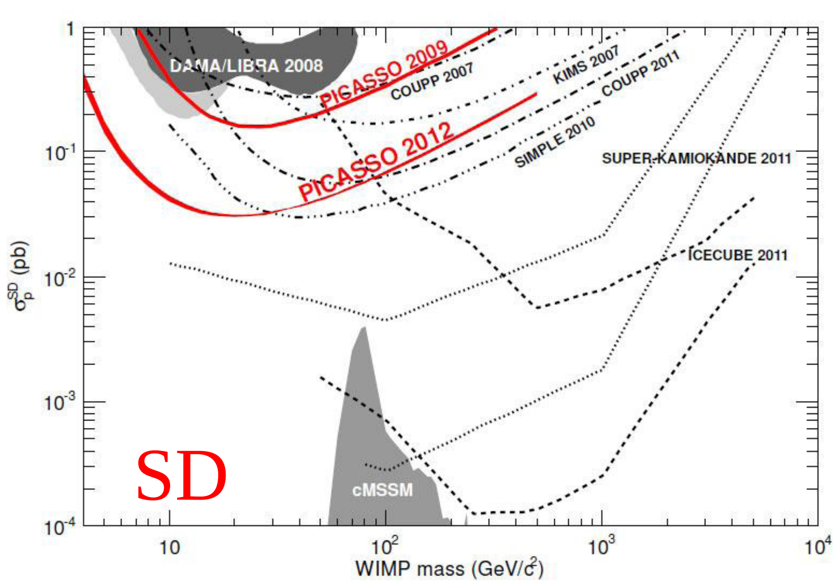
The PICASSO Experiment

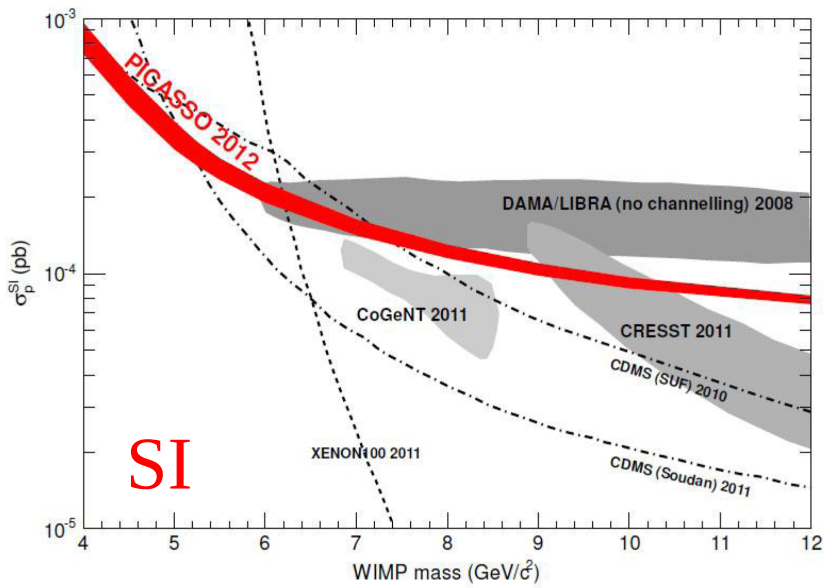
Spin-Dependent dark matter search with C_4F_{10}

- 32 Droplet Detectors in operation since 2010.
- First Results Published in 2012. Worlds best at that time.
- Discovered alpha discrimination technique …
  but it is of no help for PICASSO. Irony.
- Final run now complete. Analysis of data is nearly complete.
- Good results … but scale up of this technology not practical. Need alpha disc.. Gel is background limitation.
- Excellent threshold capability… ~ 1 keV demonstrated.

Reminder: PICASSO Published Limit

Results from data prior to upgrades published in 2012





Run Completed. Final Publication "soon"

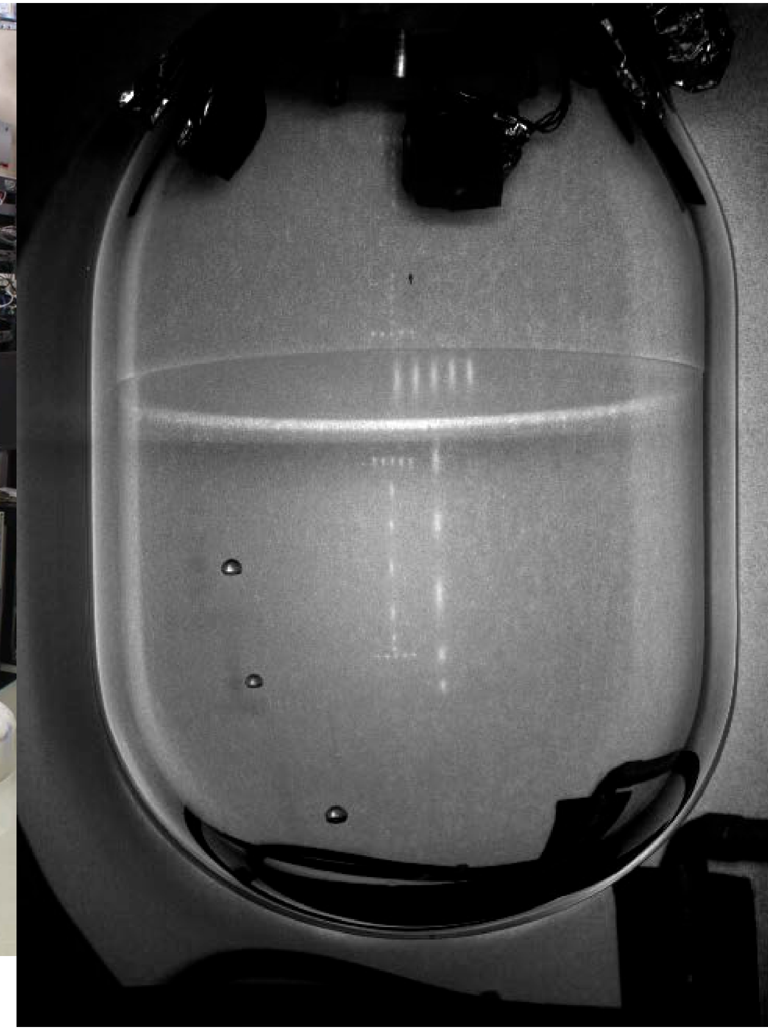
New results of current run with improved background rejection and factor or >4 in exposure will push limits much further....

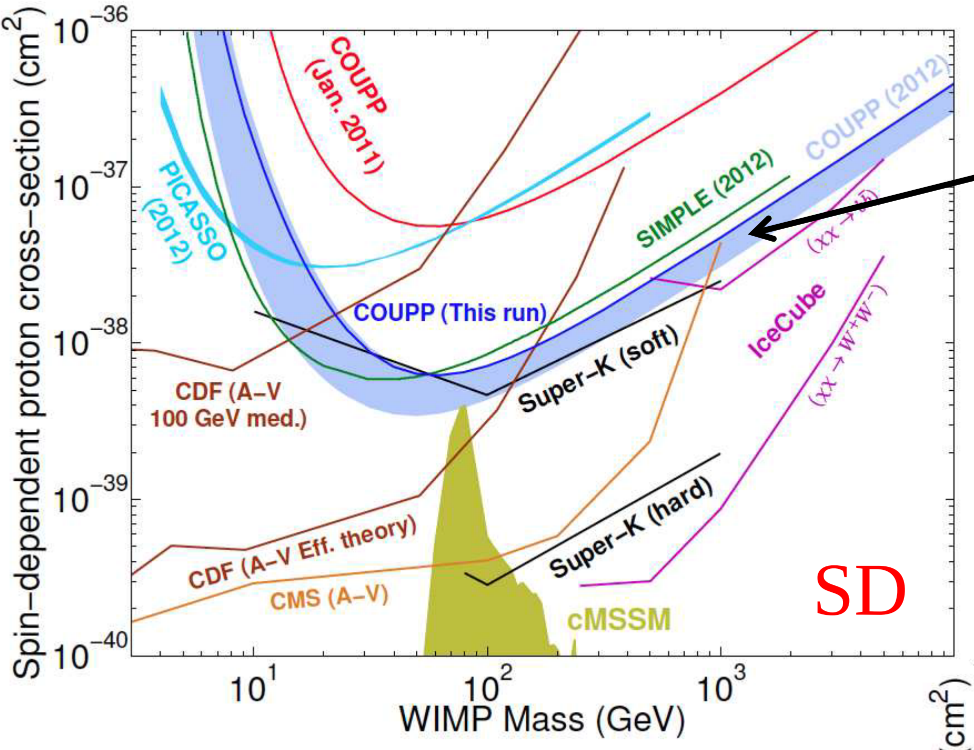
COUPP 4

Dark matter search with CF_3I

- Ideally has sensitivity to both spin-dependent (F) and spin-independent (I).
- First Results Also Published in 2012. Became Worlds best at that time.
- Had issues with backgrounds. Had 20 anomalous recoil-like events in first run, but limits still good. Similar results in second run even after removing identifiable neutron sources.
- Some events clearly correlated with surface activity and not dark matter. But rate too small to study. Could be chemistry of CF_3I ?

COUPP-4

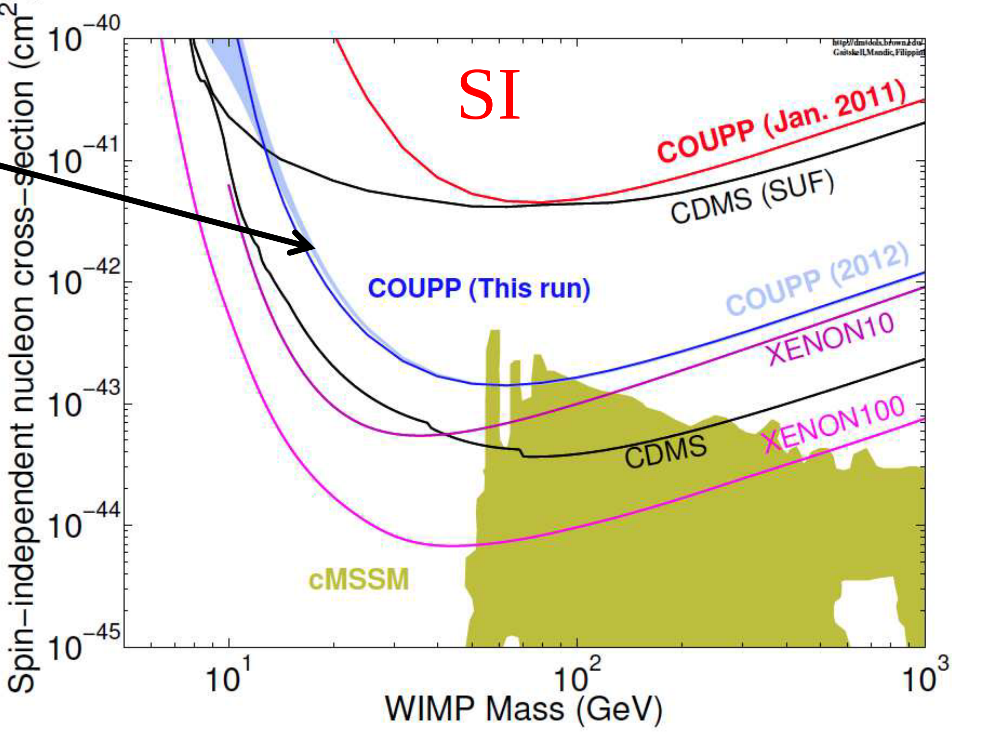




Spin-dependent results. Best results at that time.

Turns out that in CF_3I the F has low efficiency to trigger bubble … less sensitivity…more uncertainty.

Spin-independent results. (I)



- Need to understand anomalous events
- Need detector large enough to study these while making good physics measurement.

    → COUPP 60 with CF_3I

COUPP 60

Dark matter search with CF_3I

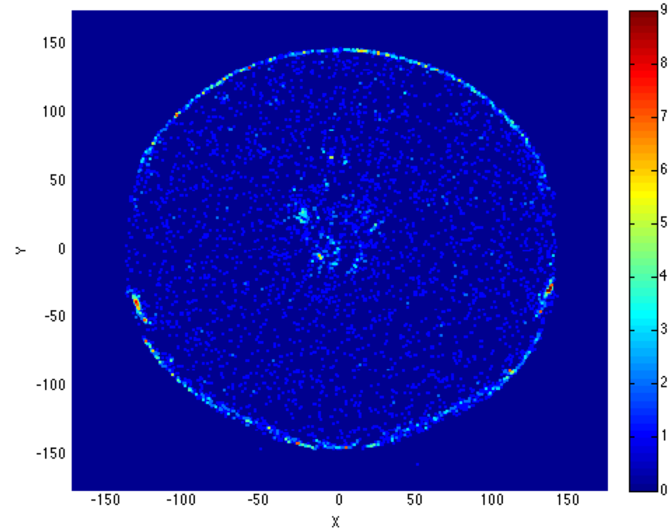
- 2 main objectives…. a quality physics run and if they still persist, study the mystery events with larger sample.
- Still running, so not everything is public. > 4500 Kg-days collected.
- Good news: No multiple events have been seen, so source of neutrons has been removed. Large data set. Despite backgrounds a good limit will be set.
- Bad news: There are still some events that look/sound like recoils, but clearly are not dark matter.
    - Silver lining: Detector is large enough we can collect enough statistics to study them

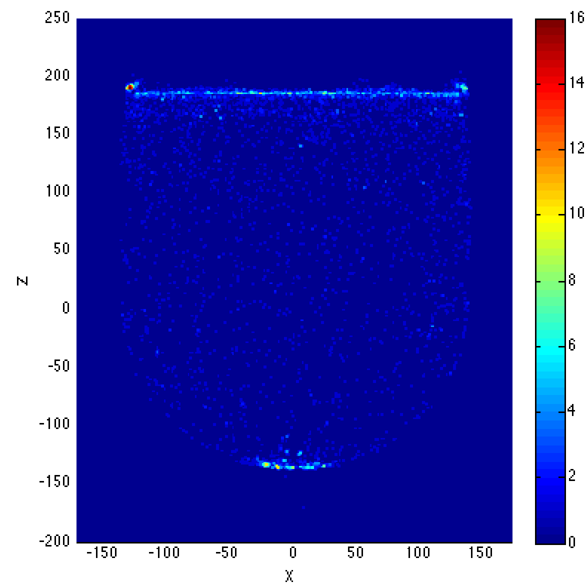
COUPP-60

COUPP-60 data

- Zero multiple bubbles
  - No neutron background.

- But , a population of events that sound similar to nuclear recoils but are clearly not WIMPs.
  - Non-istropic distribution.
  - Time dependence.
  - Appear louder on average than nuclear recoils.
  - This population is being studied in detail.



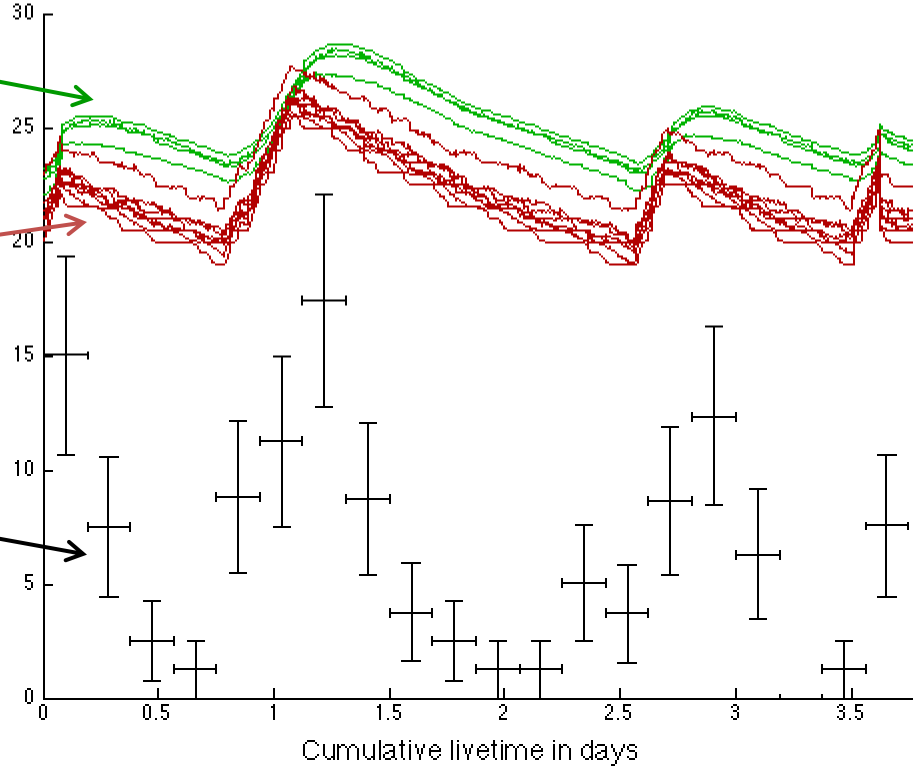


Also, some classes of events clearly correlated with the temperature of the water and glycol …. Correlation with pump, heaters, electrical noise, vibrations, convection…?

Temperature in Glycol (not to scale)

Temperature in Water (not to scale)

Event rate (not to scale)



PICO 2L

Dark matter search with C_3F_8

- Objective 1…. a quality physics run (if background free and CDMS-Si had seen WIMPs, should get an event per day)

- Objective 2…. See how well C_3F_8 works in bubble chamber. Can such a low threshold as was seen in PICASSO be achieved? → low mass sensitivity. It has potential to be a much better fluid.

- Still running, so not everything is public.

- Good news: Low thresholds can be achieved. Running at ~3 keV. Acoustic discrimination works well. Chamber looks to be working very well over all.

- Bad news: There was a mishap during the fill which appears to have contaminated the vessel. Will need to exchange flask.

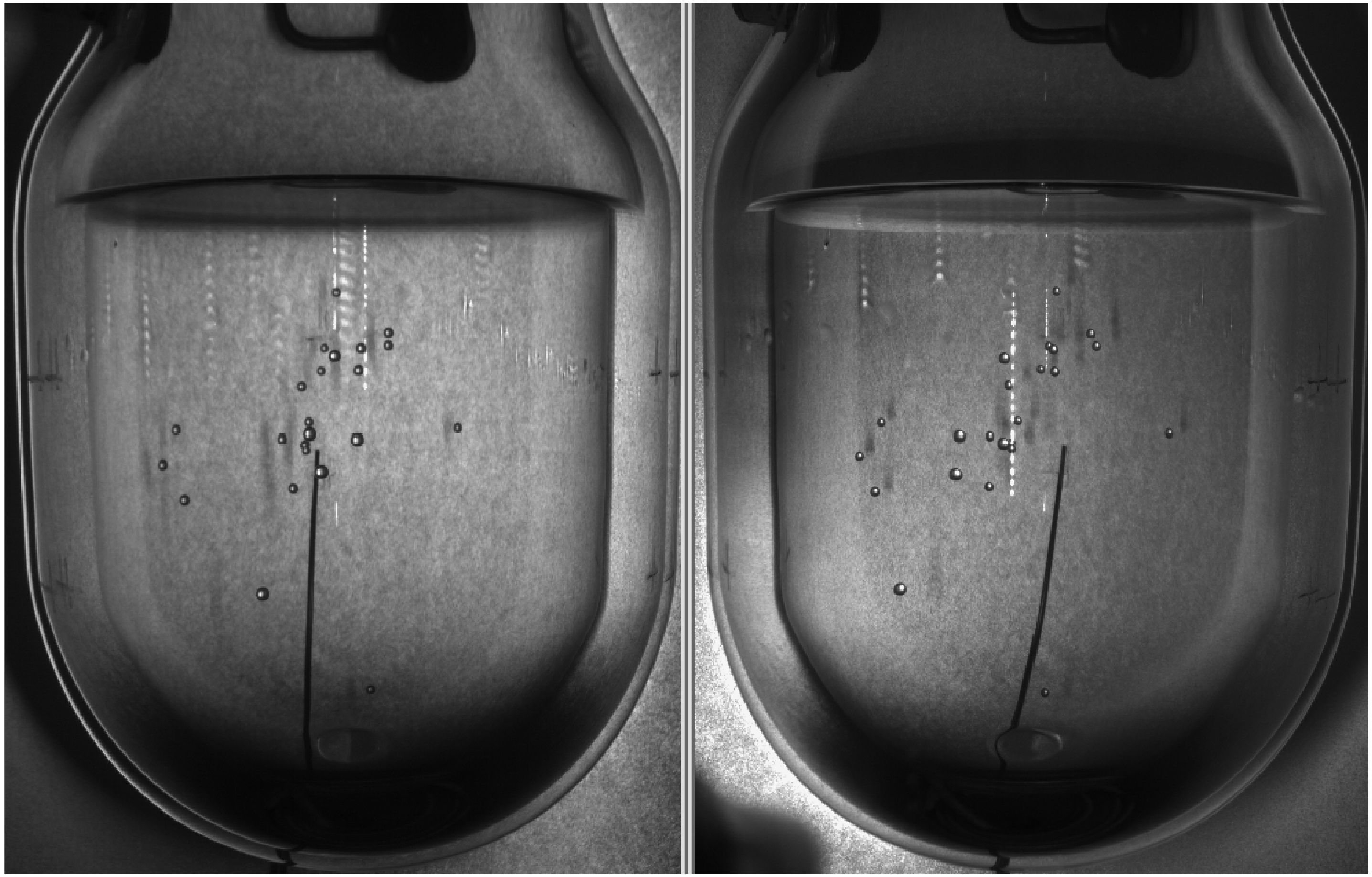
PICO-2L

- Two liter active mass (same as COUPP-4):
  - Re-uses COUPP-4 location, neutron shield, other infrastructure.
- New active fluid
  - C_3F_8 instead of CF_3I.
  - Better fluorine sensitivity:
    - Twice the F density.
    - Lower threshold.
    - Improved efficiency.
    - More stable chemistry.
- New hardware:
  - Lower background.
  - Simpler controls.
  - Prototyping for ton-scale experiment.

New two-bellows design inner vessel assembly. Silica jar is an exact replica of COUPP-4 jar.

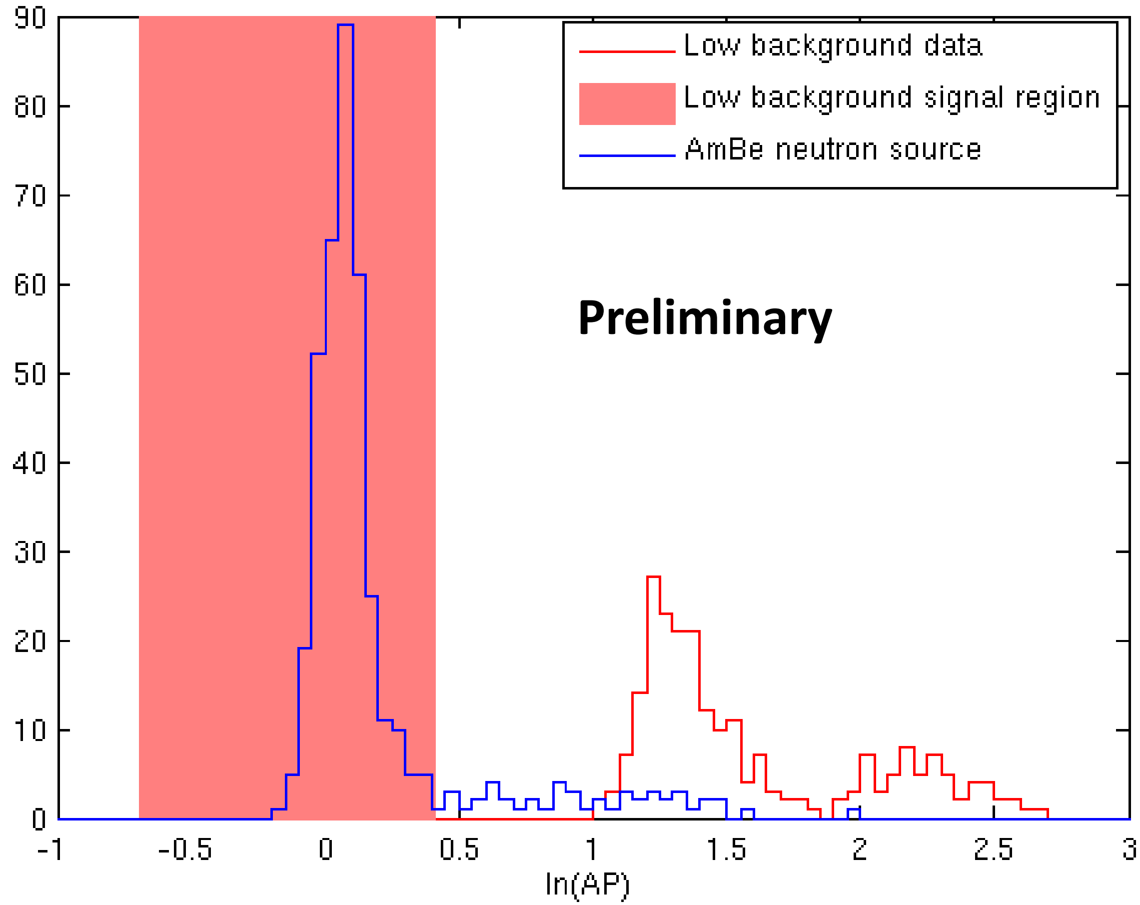
Simplified pressure vessel – ¼ the mass of steel as COUPP-4.

23 Bubble AmBe neutron event



High neutron multiplicity implies high efficiency and means better rejection and measurement of neutron backgrounds.

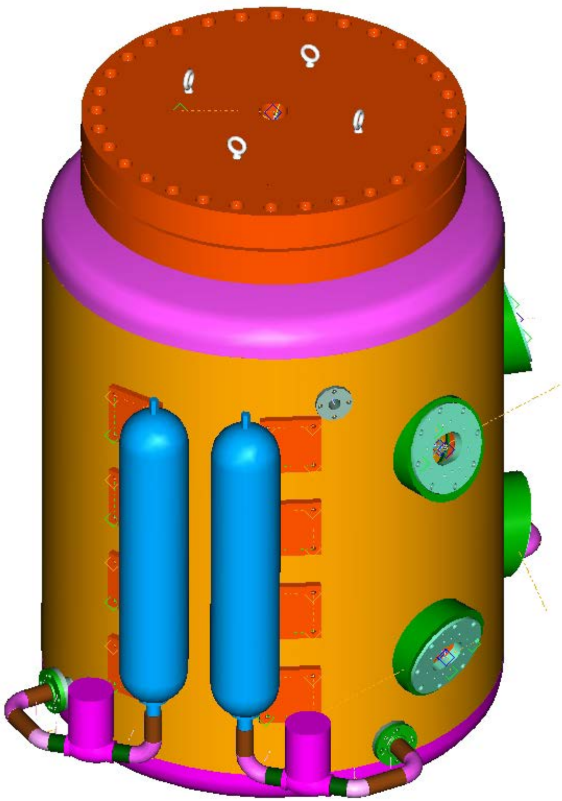
Acoustic discrimination

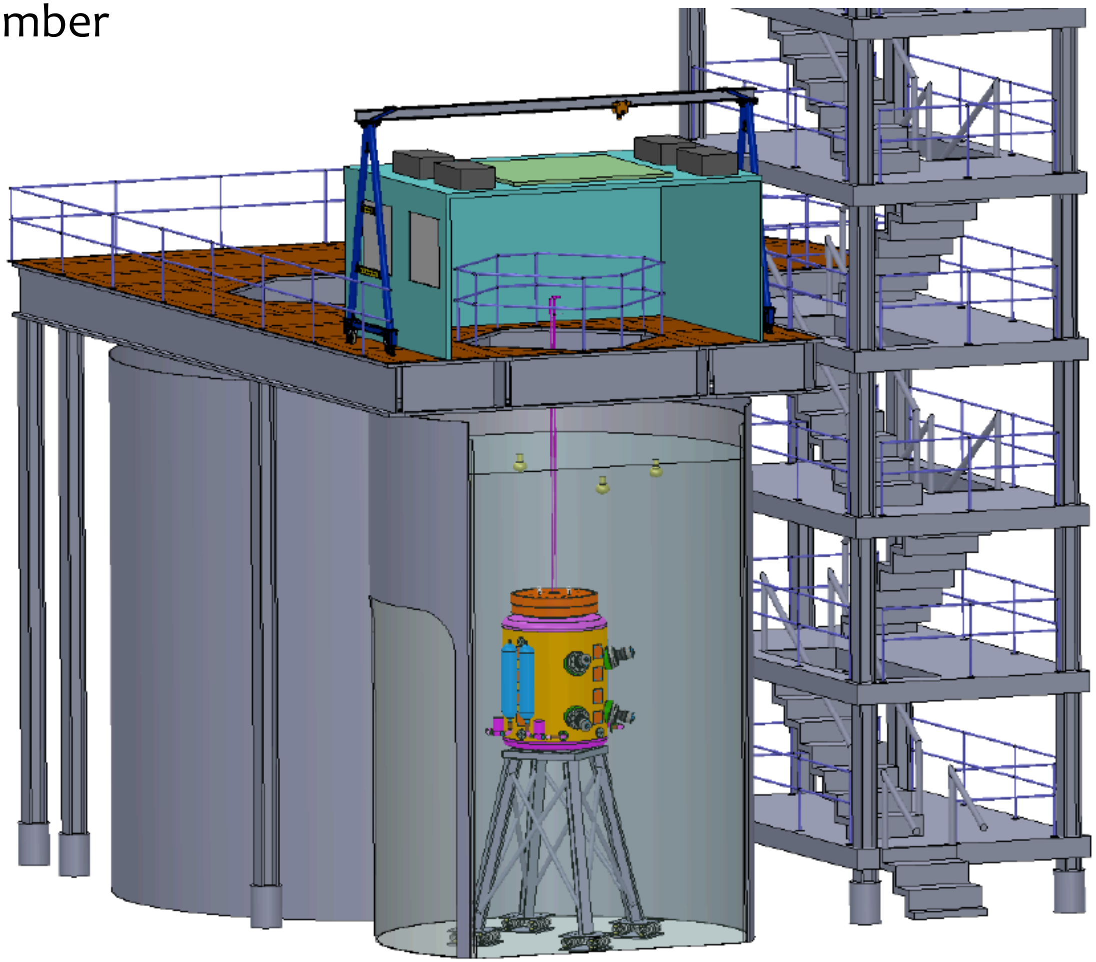


- Alpha events are significantly louder than nuclear recoils (similar to CF_3I).
- Two distinct alpha peaks, and a valley with zero events between the alpha peaks and the signal region.
- No multiple bubble events in the low background data (would expect ~3 multiples so far if we had the neutron background observed in COUPP-4).

PICO-250L

PICO-250L: ton-scale bubble chamber designed for CF_3I or C_3F_8 target

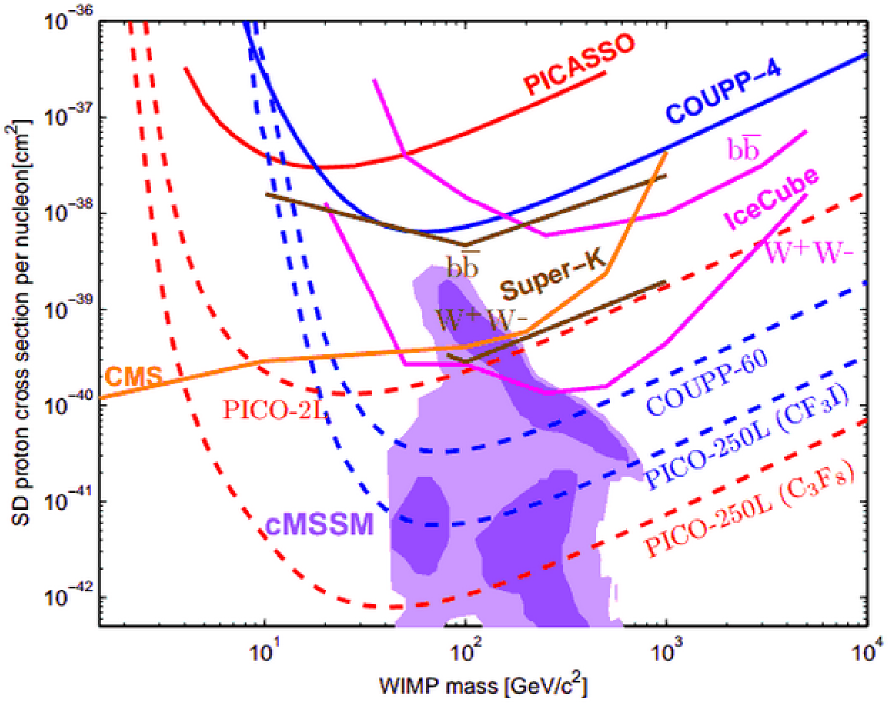


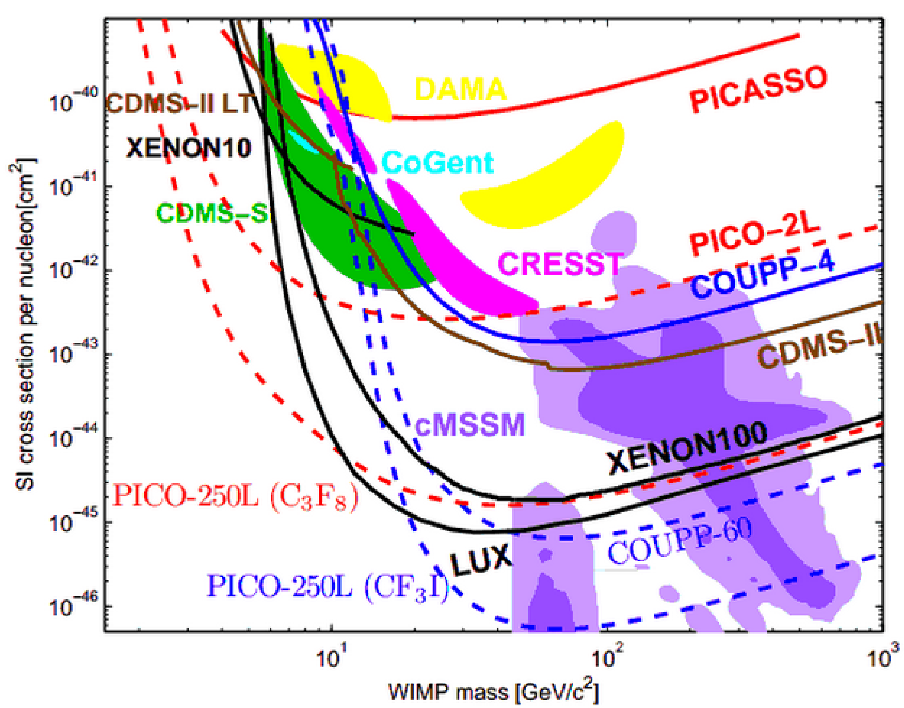


Sensitivity projections

Spin-Dependent

Spin-Independent





cMSSM model space from Roszkowski et. al., JHEP 0707:075 (2007).

PICO-2L projection based on 100 live-days of background free data.

Conclusions:

- Bubble Chambers for Dark Matter are coming of age.
- Background free potential.
- Should "own" the Spin-Dependent Sector with C_3F_8
- Should have world leading results for low mass WIMPS in SD and SI with C_3F_8
- With change to CF_3I, could be competitive in SI sector as well.
- Inexpensive, engineering understood, …

Stay tuned!

Bubble chamber fluids

- Could make a dark matter bubble chamber with any liquid.
- Fluorocarbons are ideal:
  - Superheated fluid at room temperature and pressure.
  - Not flammable.
  - Low toxicity.
  - Fluorine is ideal spin-dependent target.
  - Fluorine can be replaced with high-mass halogen (Cl, Br, I) for improved A^2 enhancement.
- COUPP/PICO bubble chambers have until now used CF_3I as active fluid. Now also C_3F_8.
- PICASSO used similar C_4F_{10}

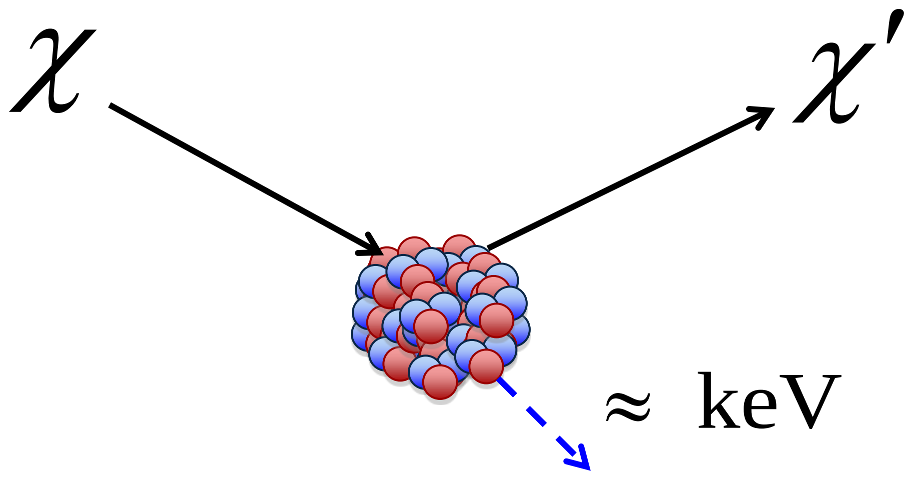
Spin-independent   Spin-dependent

$$\sigma_0 = \frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2 + \frac{32 G_F^2 \mu^2}{\pi}\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

$\sim A^2$ λ^2

Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

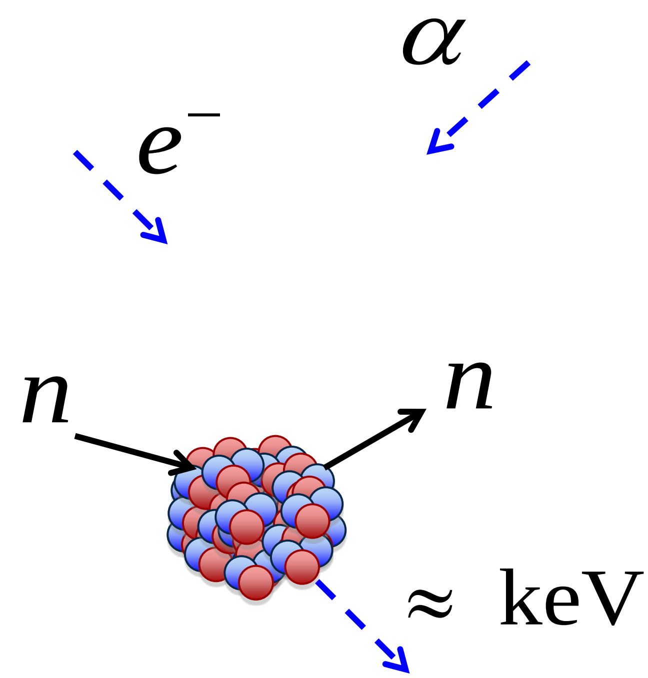
Direct Dark Matter Detection…The challenges:



Must detect kinetic energy of recoiling nucleus in WIMP interaction. ~(1-100 keV).

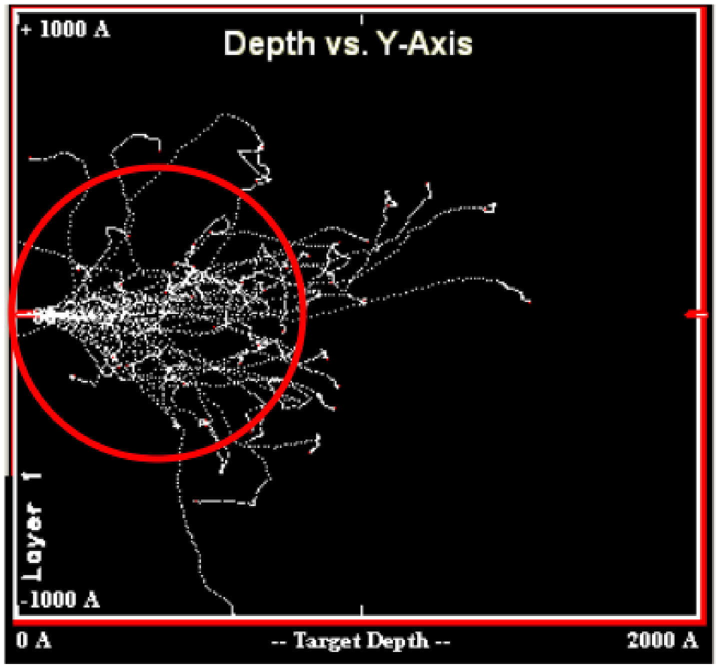
Very low event rate expected ~(1 event per tonne/year)

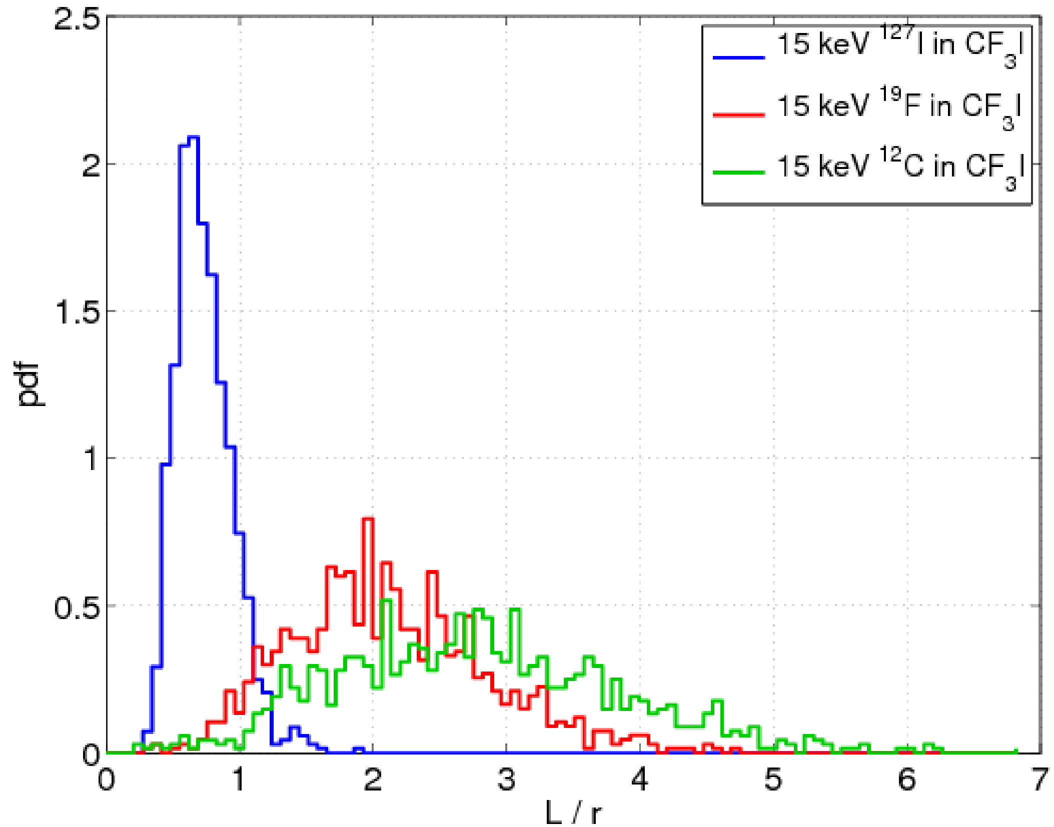
Need to remove ~all sources of backgrounds.



Nuclear Recoil Profiles

TRIM simulation (15 keV ^{19}F in CF_3I)





- ^{127}I recoils usually smaller than critical bubble
- ^{19}F and ^{12}C recoils more spread out

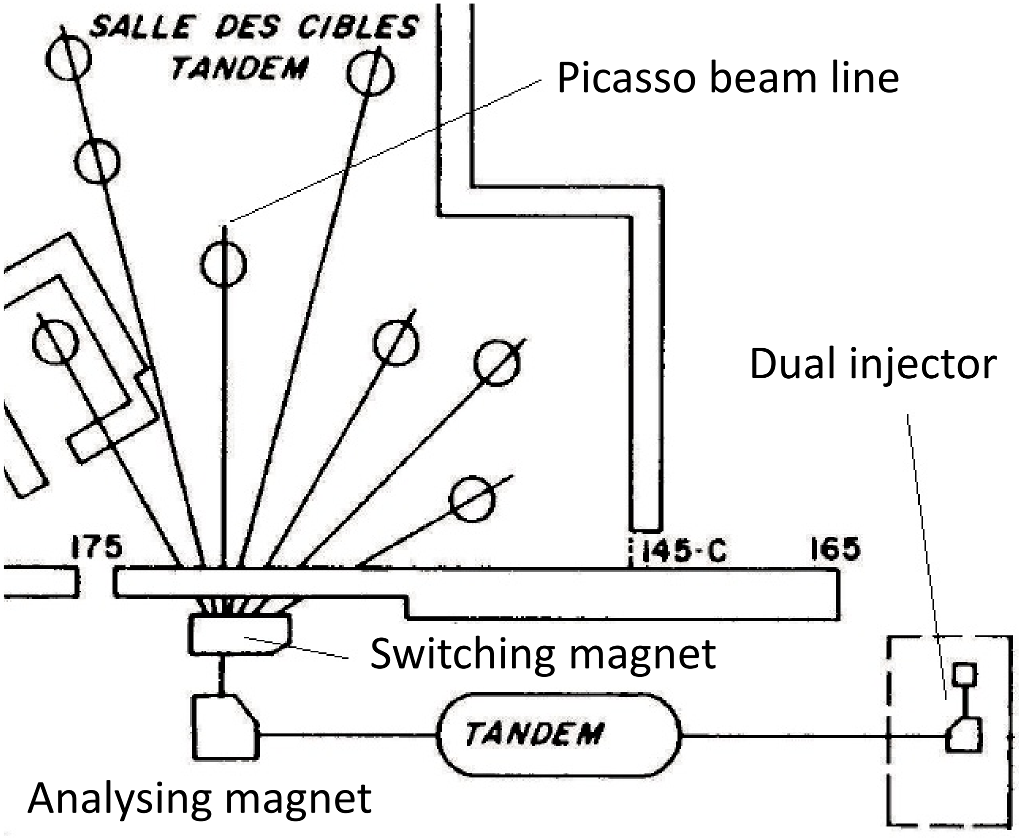
Understanding the Threshold

As a threshold detector, knowing the threshold is critical…But it is not easy:

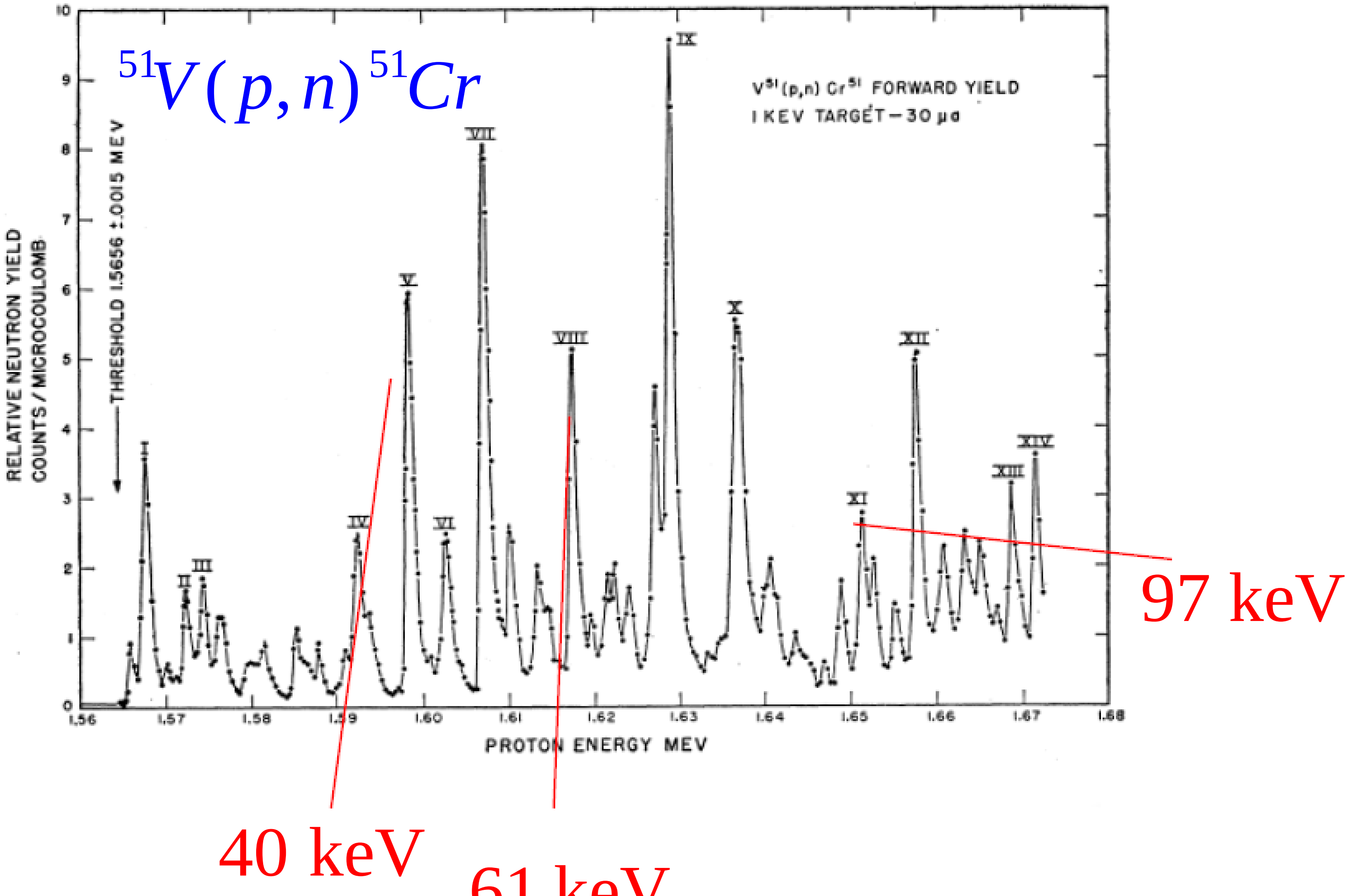
- The threshold is not abrupt, but can be quite soft depending on the nucleus
- There are several nuclei (C, F, I) each with their own threshold.
- We use a variety of techniques for calibration:

➢ ^{241}Am-Be Source.	^{9}Be(α,n)C	Broad spectrum source
➢ ^{88}Y- Be Source	^{9}Be(γ,n)^{8}Be	Monoenergetic n, 152keV
➢ Pion beam scattering	$\pi^{-} + I \rightarrow \pi^{-\prime} + I'$	Scattering angle → I recoil energy
➢ Montreal Tandem	^{51}V(p,n)^{51}Cr	Quasi-monoenergetic. Selectable

Montréal Tandem Van de Graaff

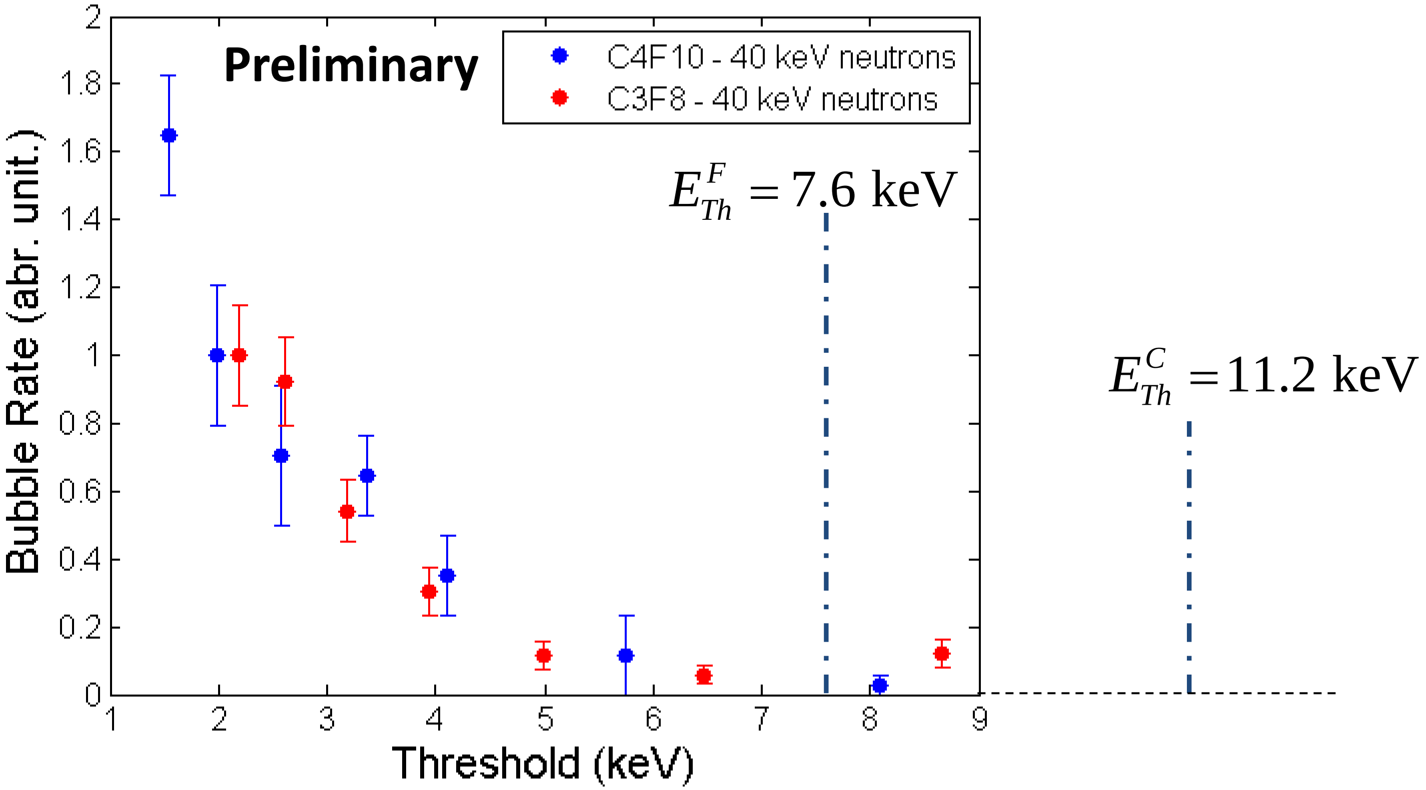


By choosing the beam energy and scattering angle, one can generate a beam of quasi-mono-energetic neutrons.



Recent example… preliminary. 40 keV neutrons, scan temperature

- Obtain shape of threshold.
- Good agreement with Seitz theory.



Good agreement between experimental results and theoretical predictions.