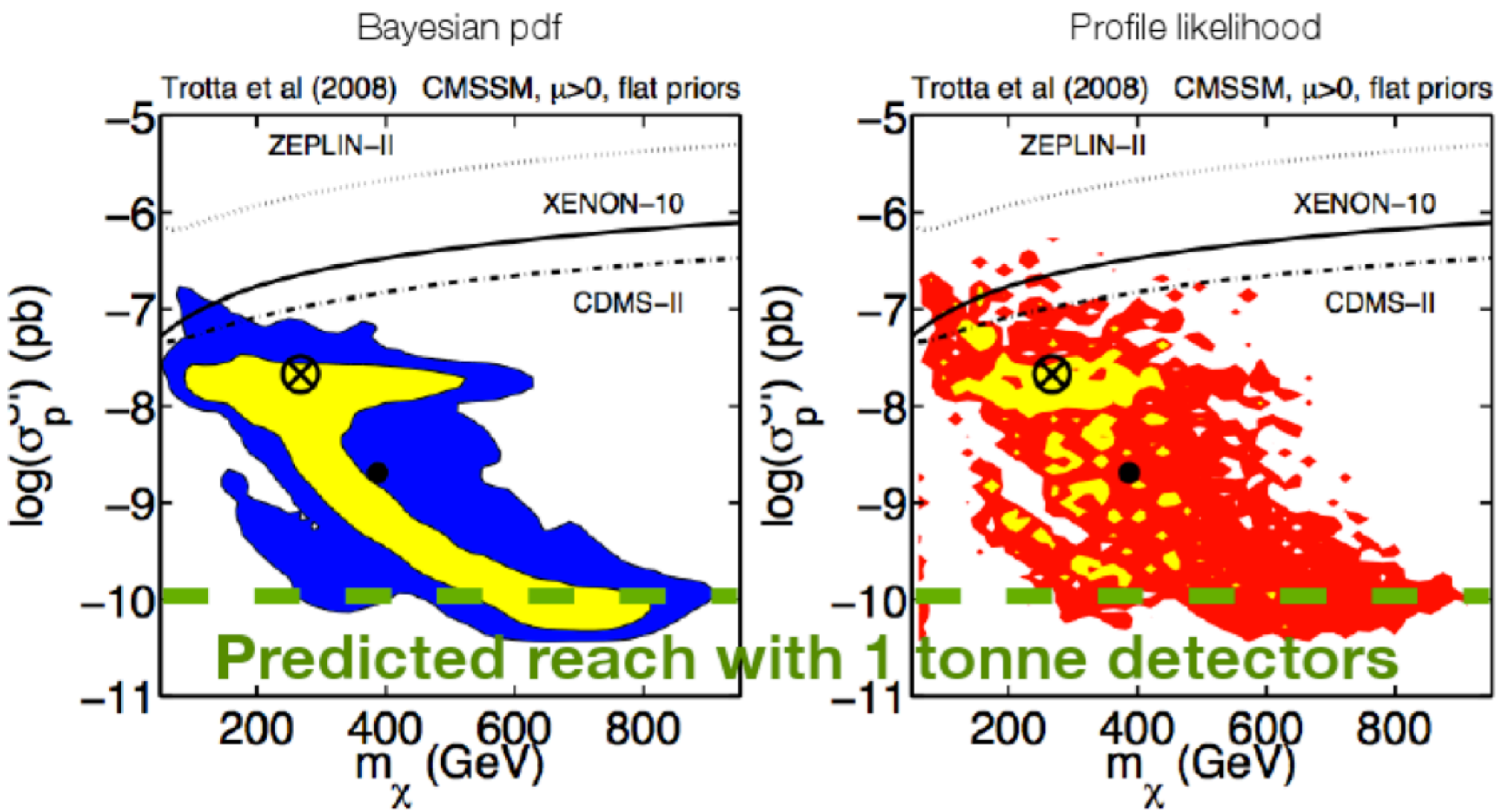

Towards COUPP-500

Direct detection prospects

R. Trotta, F. Feroz, M.P. Hobson, R. Ruiz de Austri and L. Roszkowski, 0809.3792

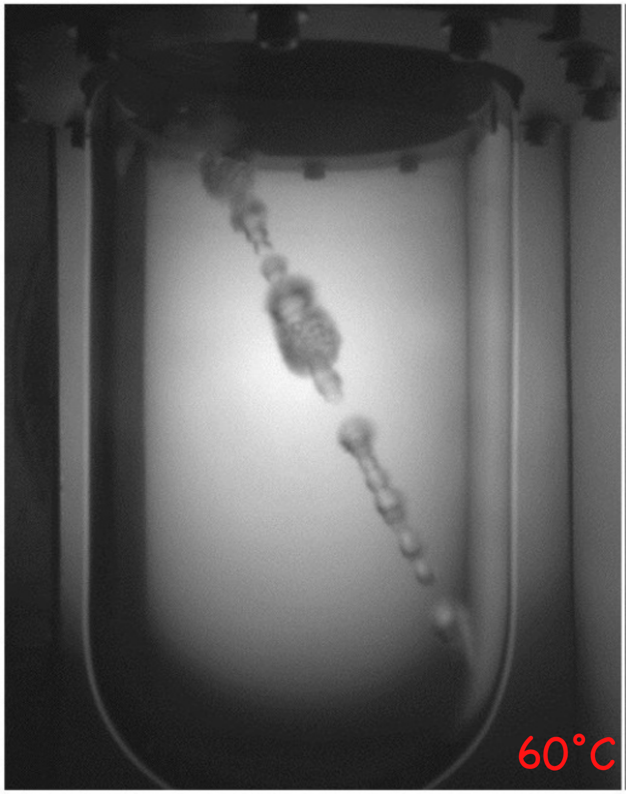


IMHO, COUPP-500 (or its equivalent) is the "ultimate" DM detector

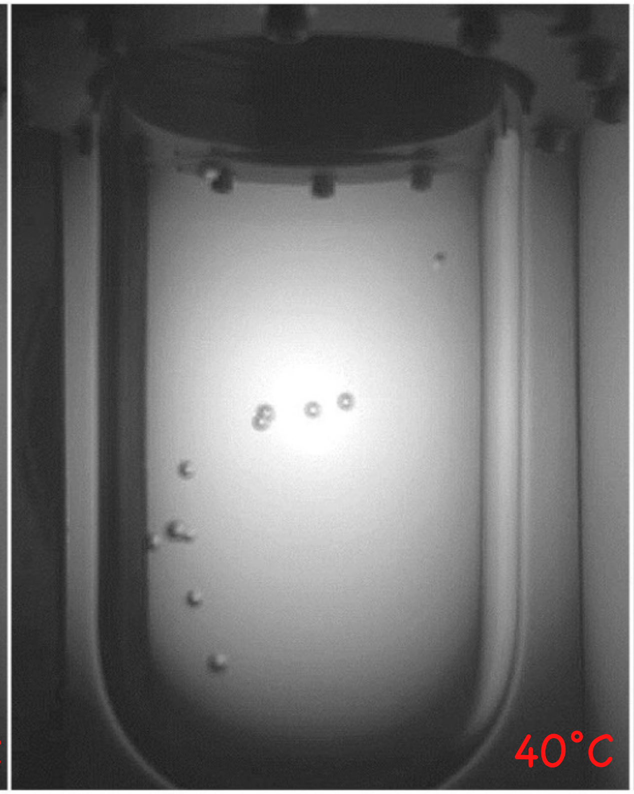
COUPP: not your daddy's bubble chamber:

Conventional BC operation
(high superheat, MIP sensitive)

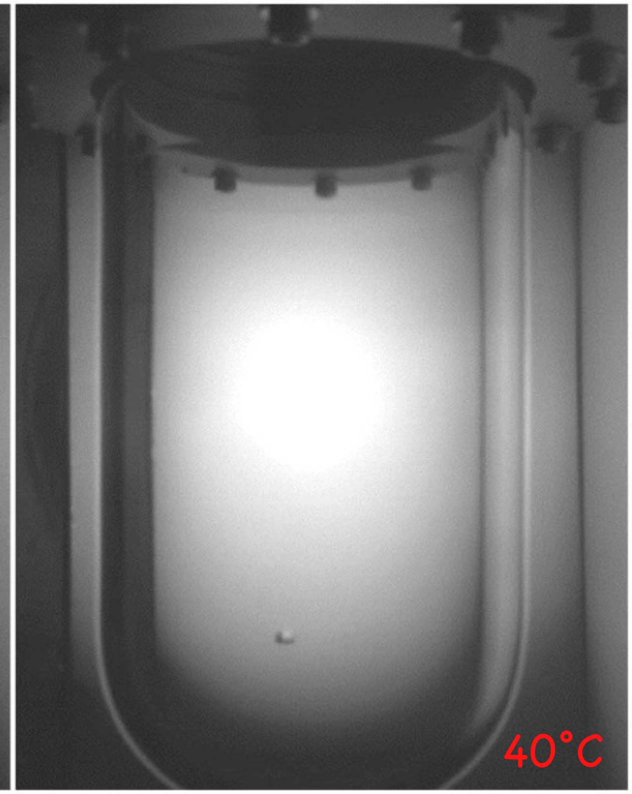
Low degree of superheat, <u>sensitive to nuclear recoils only</u>



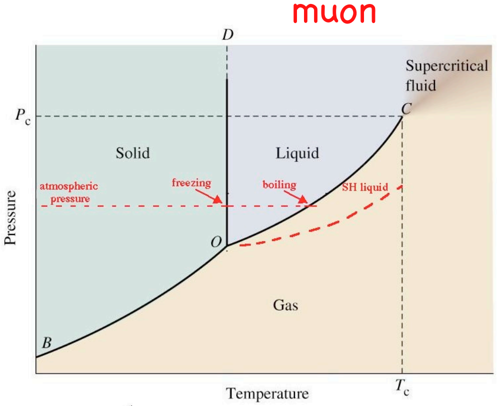
muon



Neutron



WIMP (yeah, right)



ultra-clean BC: Bolte *et al.*, NIM A577 (2007) 569

Science 319 (2008) 933, Phys. Rev. Lett. 106 (2011) 021303

COUPP approach to WIMP detection:

- Detection of single bubbles induced by high-dE/dx nuclear recoils in heavy liquid bubble chambers

- $<10^{-10}$ rejection factor for MIPs. *INTRINSIC* (no data cuts)

- Scalability: large masses easily monitored (built-in "amplification"). Choice of three triggers: pressure, acoustic, motion (video))

- Revisit an old detector technology with improvements leading to extended (unlimited?) stability (*ultra-clean* BC)

- Excellent sensitivity to both SD and SI couplings (CF_3I)

- Target fluid can be replaced (e.g., C_3F_8, C_4F_{10}, CF_3Br). Useful for separation between n- and WIMP-recoils and pinpointing WIMP in SUSY parameter space.

- High spatial granularity = additional n rejection mechanism

- Low cost, room temperature operation, safe chemistry (fire-extinguishing industrial refrigerants), moderate pressures (<200 psig)

- Single concentration: reducing or rejecting α-emitters in fluids to levels already achieved elsewhere (~10^{-17}) will lead to complete probing of SUSY models

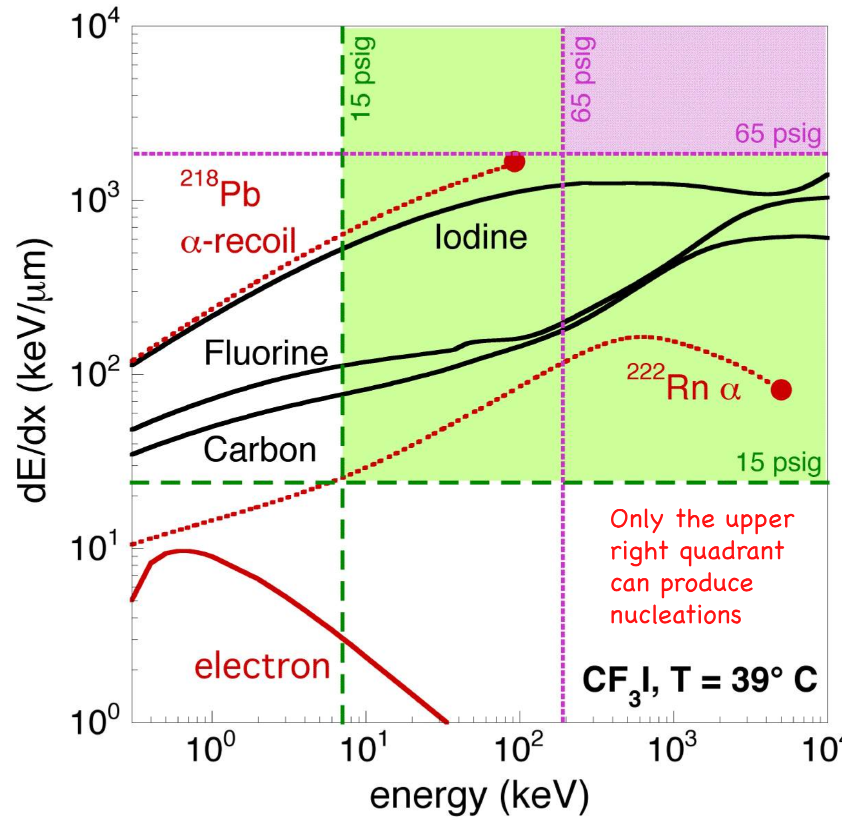
Seitz model of bubble nucleation (classical BC theory):

Threshold in deposited energy

$$E > E_c = 4\pi r_c^2 \left(\gamma - T\frac{\partial \gamma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v \frac{h_{fg}}{M} + \frac{4}{3}\pi r_c^3 P \quad , \quad r_c = 2\gamma/\Delta P$$

$$\mathrm{d}E/\mathrm{d}x > E_c/(a r_c)$$

Threshold also in stopping power, allows for efficient INTRINSIC MIP background rejection



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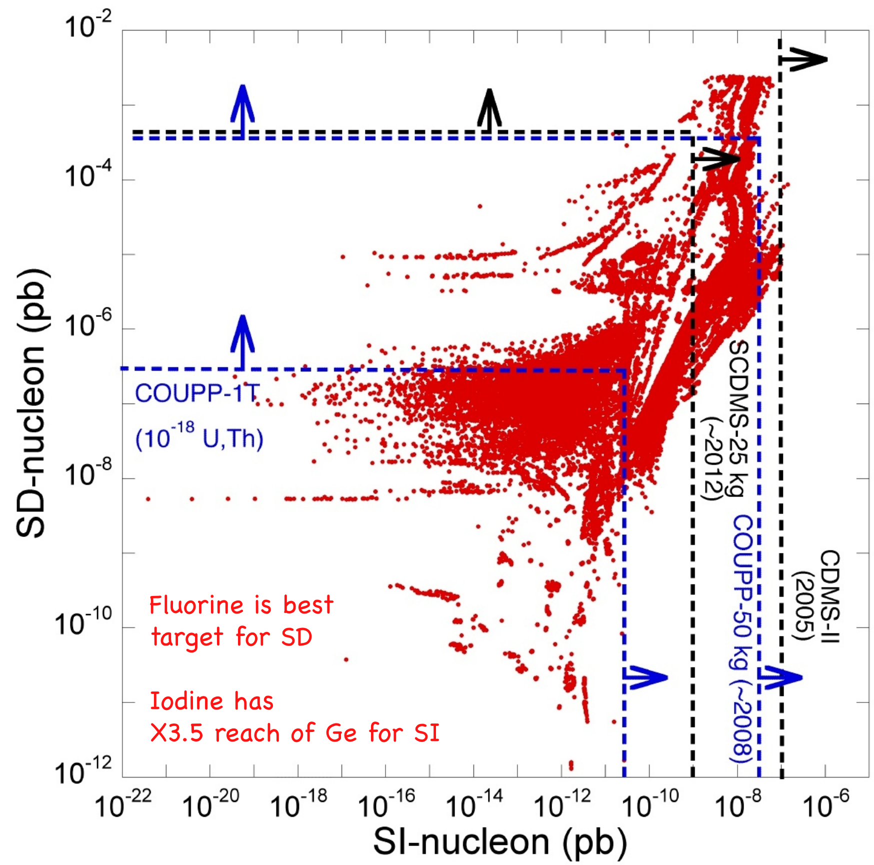
An old precept: attack on both fronts

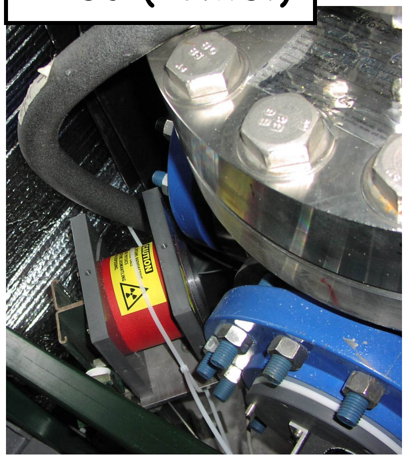


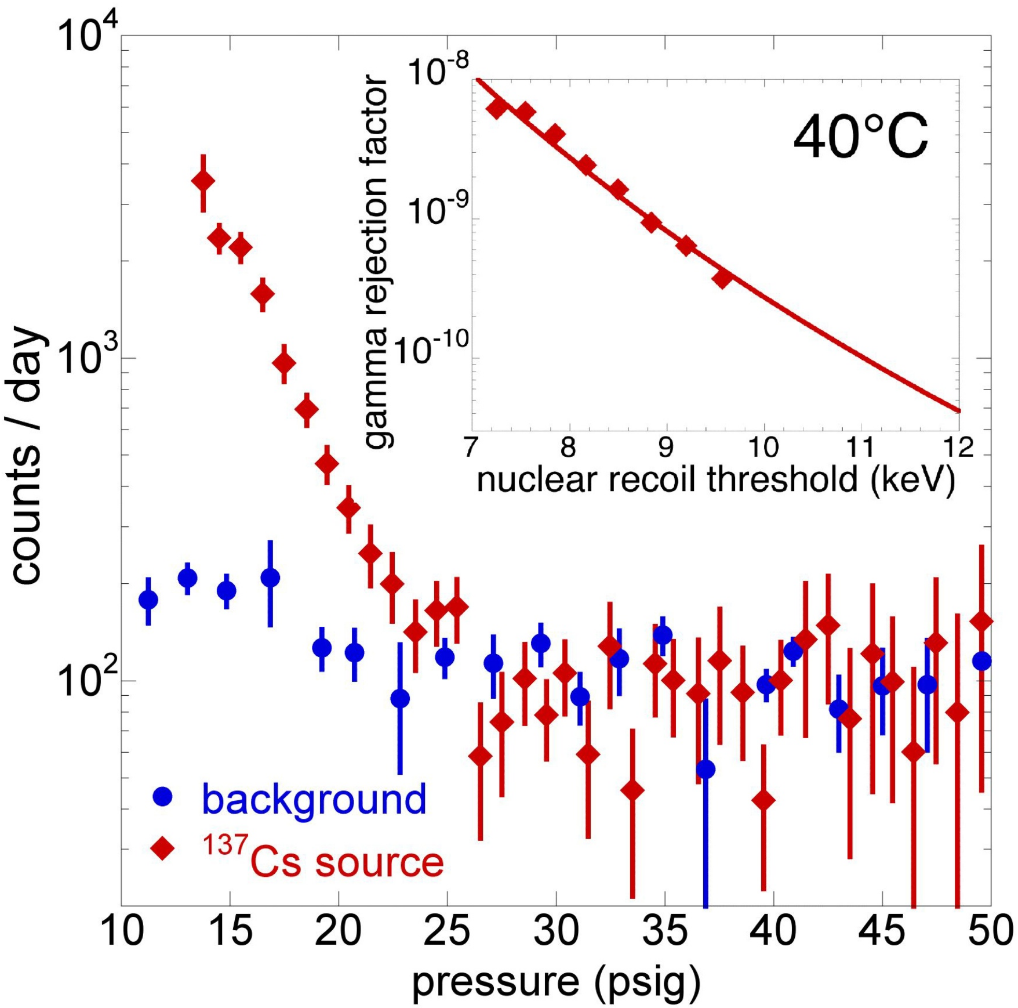
Baltz & Gondolo, JHEP 0410:052,2004. (WMAP-II update)

SD SUSY space harder to get to, but predictions are more robust and phase-space more compact. Worth the effort. (astro-ph/0001511, 0509269, and refs. therein)

E-961 progress: gamma and neutron calibrations

^{137}Cs (13mCi)





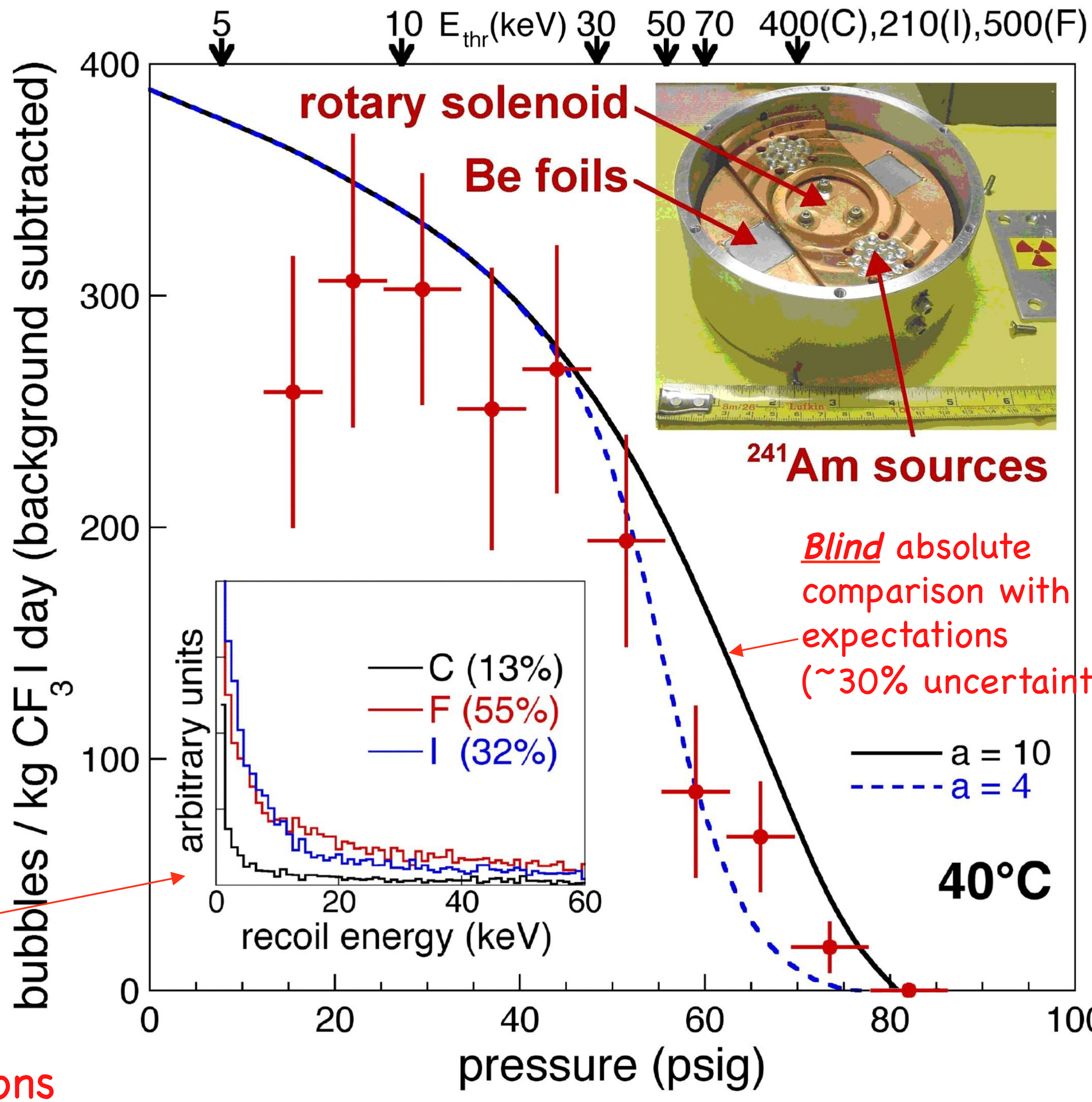
Best MIP rejection factor measured anywhere ($<10^{-10}$ INTRINSIC, no data cuts)

Other experiments as a reference:
XENON ~10^{-2}-10^{-3}
CDMS 10^{-4}–10^{-5}
WARP ~10^{-7}-10^{-8}

^{14}C betas not an issue for COUPP (typical O(100)/kg-day)
<u>No need for high-Z shield, nor exaggerated attention to chamber material selection</u>

E-961 progress: gamma and neutron calibrations

Switchable
Am/Be (5 n/s)



Blind absolute comparison with expectations (~30% uncertainty in those)

Low-energy WIMP-like recoil energy signal used in these calibrations

Listening to particles (yes, listening)

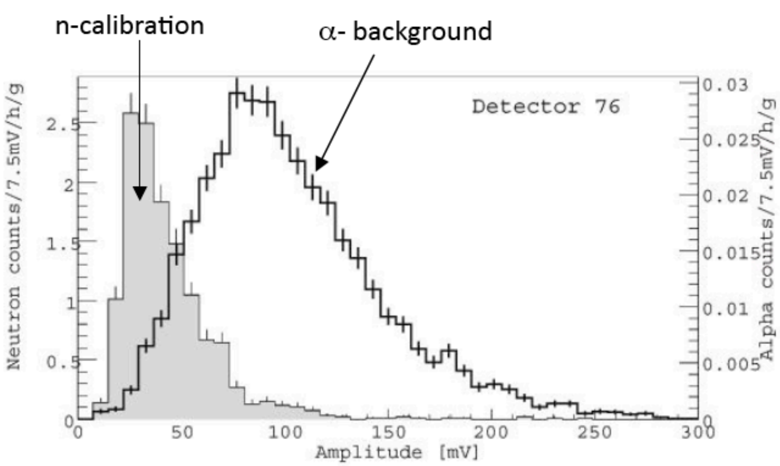
Glaser (1955)

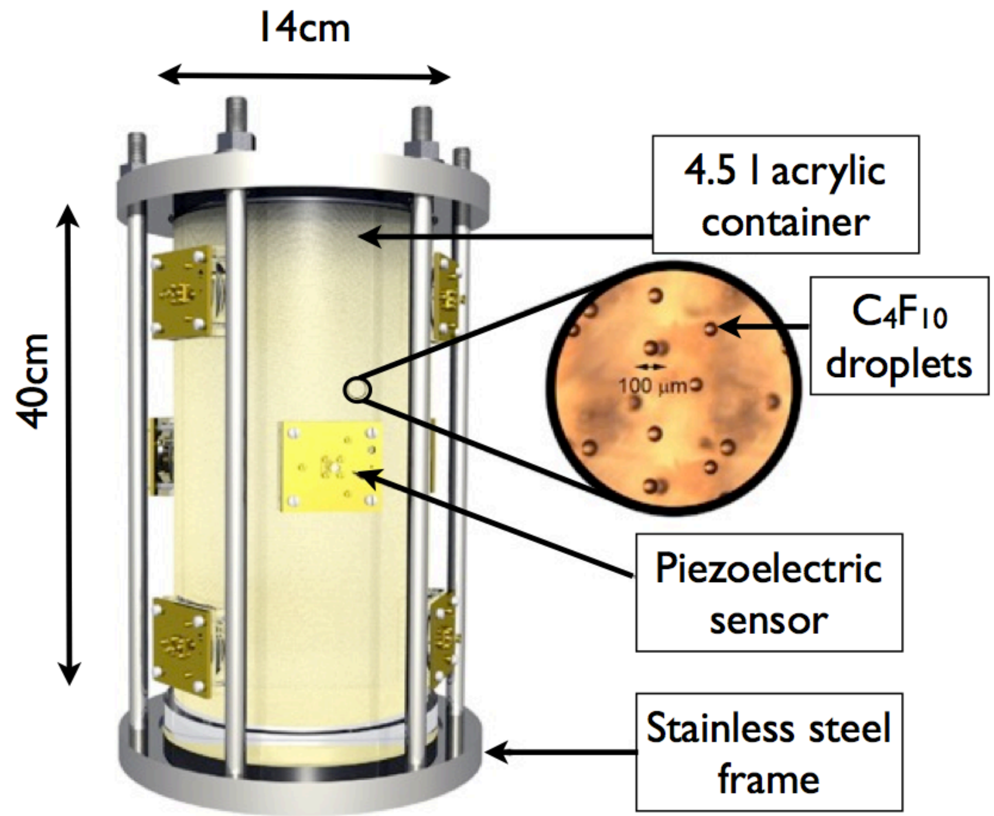
In order to see events more interesting than muons passing straight through the chamber, we took advantage of the violence of the eruption which produces an audible "plink" at each event. A General Electric variable-reluctance phonograph pickup was mounted with its stylus pressing against the wall of the chamber. Vibration signals occurring during the quiescent period after the expansion were allowed to trigger the lights and take pictures. In this way we saw tracks of particles passing through the chamber in various directions,

Martynyuk & Smirnova (1991)

The initial pressure in the volume *V* depends on the energy transmitted by the particle to that volume. Consequently, the characteristics of the acoustic pulse depend on the parameters of the particle responsible for formation of the bubble….
The parameters of these pulses must depend strongly on the characteristics of the particle.

PICASSO collab. (2009)

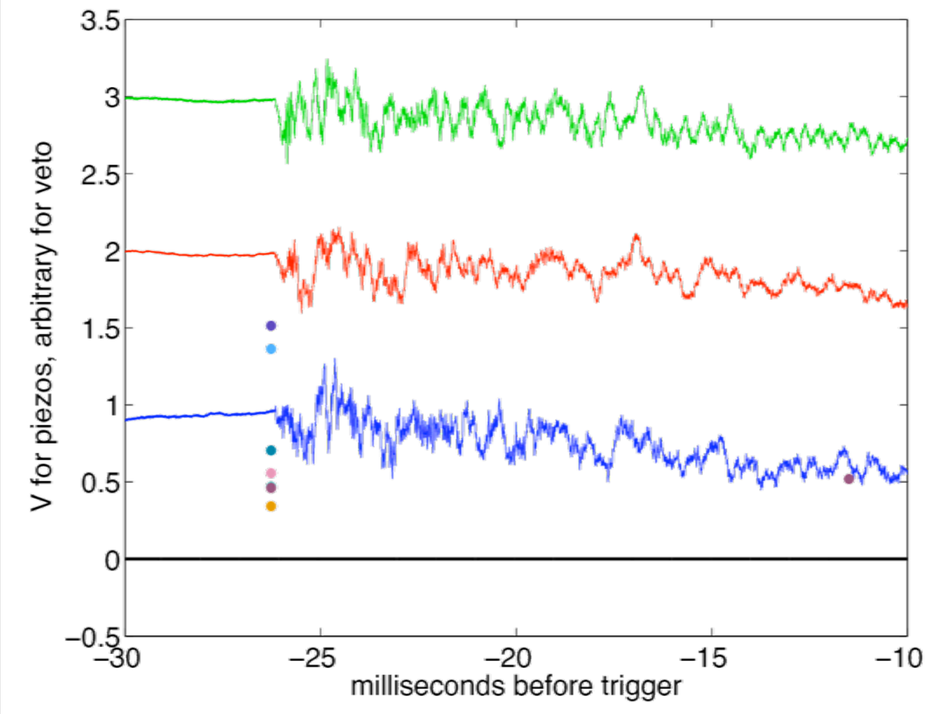




PICASSO demonstrates α – nuc. recoil acoustic discrimination in Superheated Droplet Detectors (SDDs)
F. Aubin *et al.*, New J. Phys 10 (2008) 103017

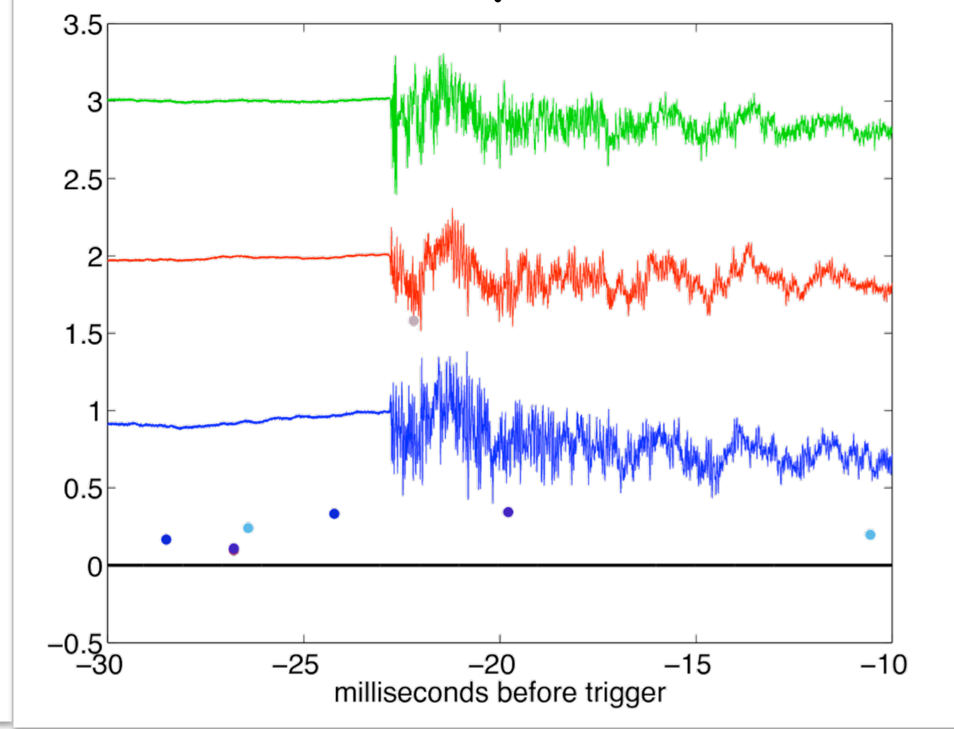
E-961 progress: acoustic alpha - nuclear recoil discrimination

Neutron



Phys. Rev. Lett. 106 (2011) 021303

Alpha



We observe two distinct families of single bubble bulk events in a 4 kg chamber:

- Discrimination increases with frequency, as expected.
- We have a handle on which is which (Rn time-correlated pairs following injection, S-AmBe calibrations, NUMI-beam events).
- Polishing off the method, but potential for high discrimination against α's is clear.
- Challenge in obtaining same discrimination in the 60kg device: increasing sensors to 24, also their bandwidth (IUSB group)

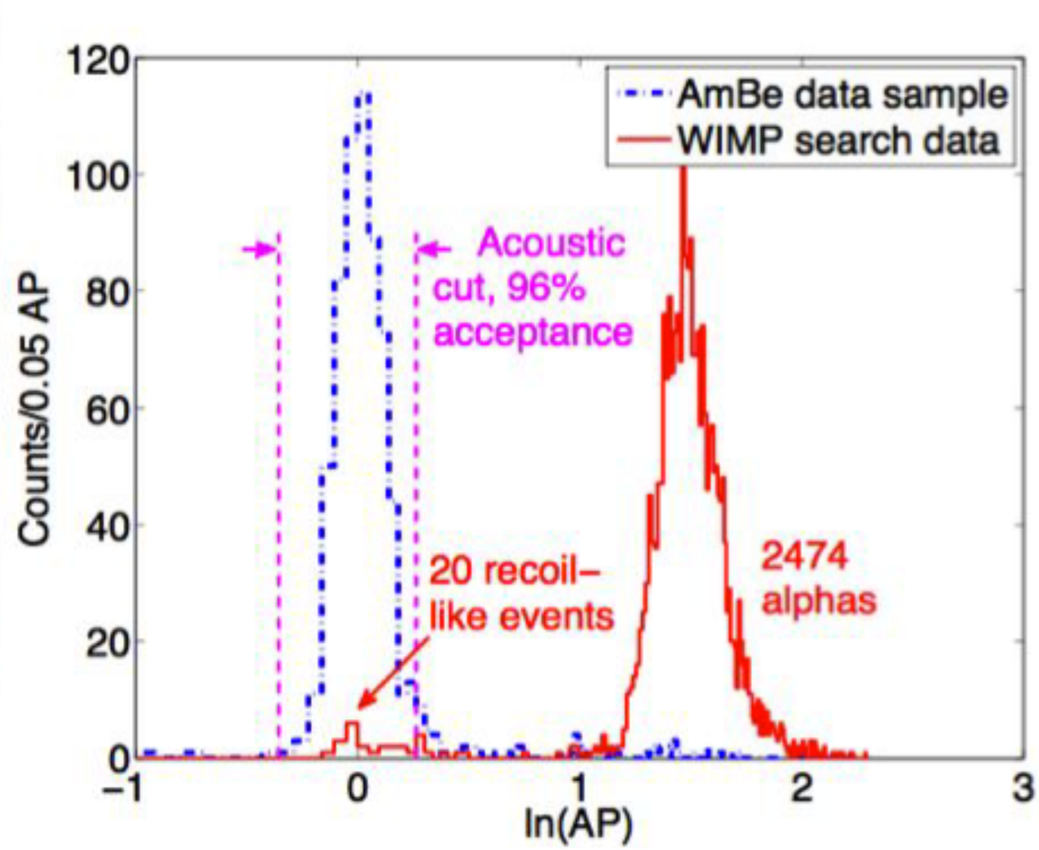
A zero-background experiment soon?

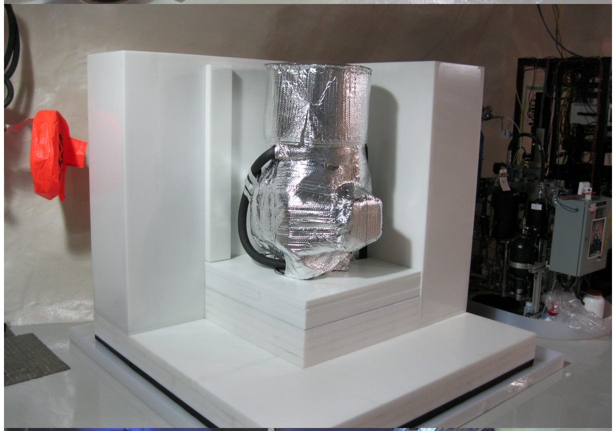
COUPP progress: acoustic alpha - nuclear recoil discrimination

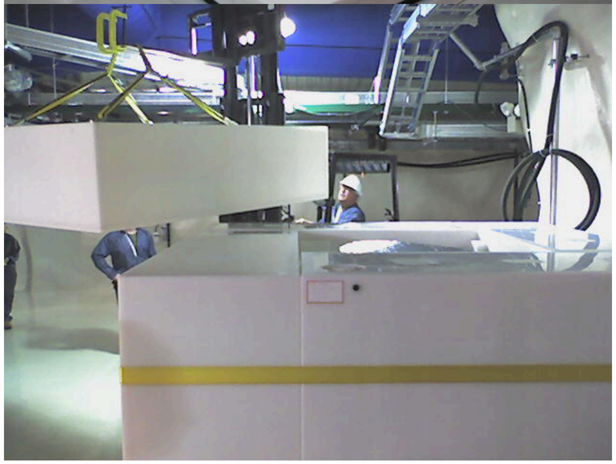
SNOlab COUPP-4kg data

Gamma rejection >1E+10
(best in the field)

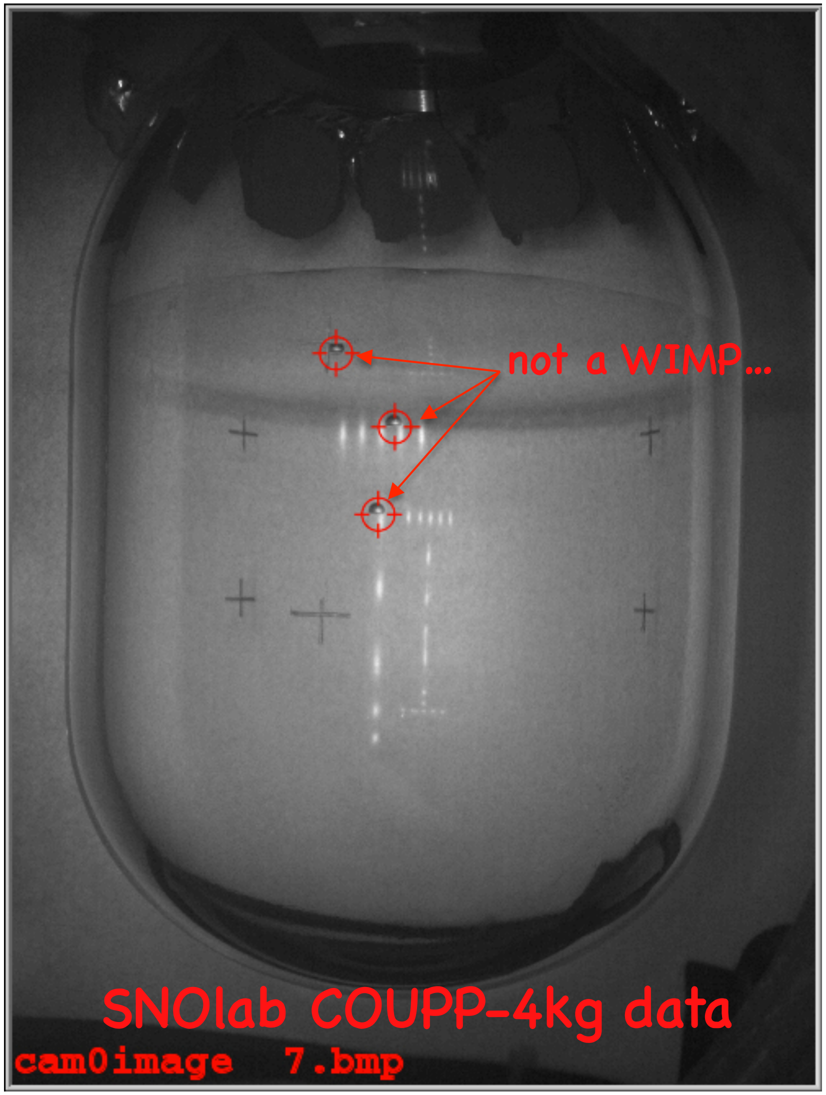
acoustic α rejection >>99.9%
(don't know where it will stop yet)







2011 COUPP-4 runs at SNOLAB



We have crossed the Rubicon: Dark Matter experiments from now on to produce their own "WIMPs"

WIMP searches: a quixotic fight against backgrounds

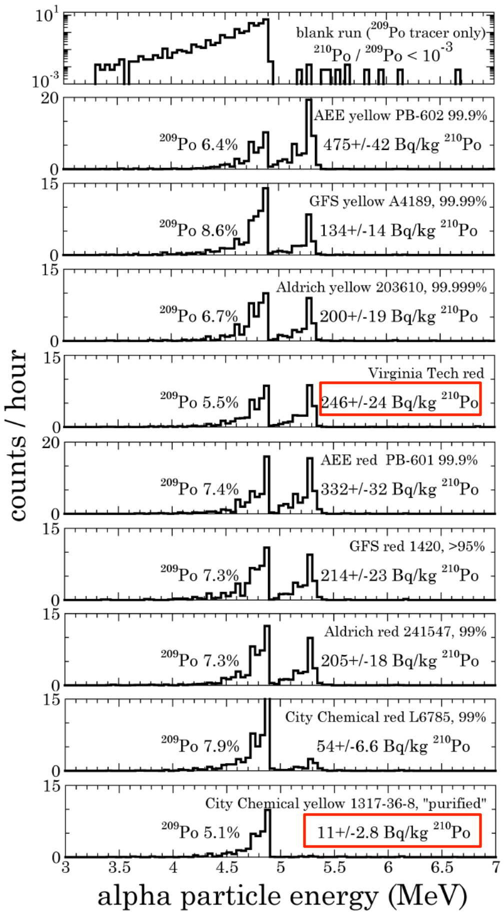
Dominant sources:
Po-210 and U, Th in PZT transducers and inspection windows. Replacement accomplished.

COUPP's dubious distinction:
first DM experiment to see (α,n) neutrons

Six-month screening & simulation campaign

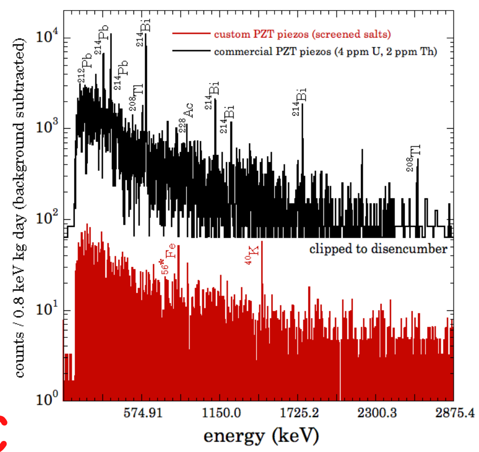
(leading to factor >200 improvement to present (α,n) activity)

Present limiting factor is Pb-210 in lead oxide (PZT)

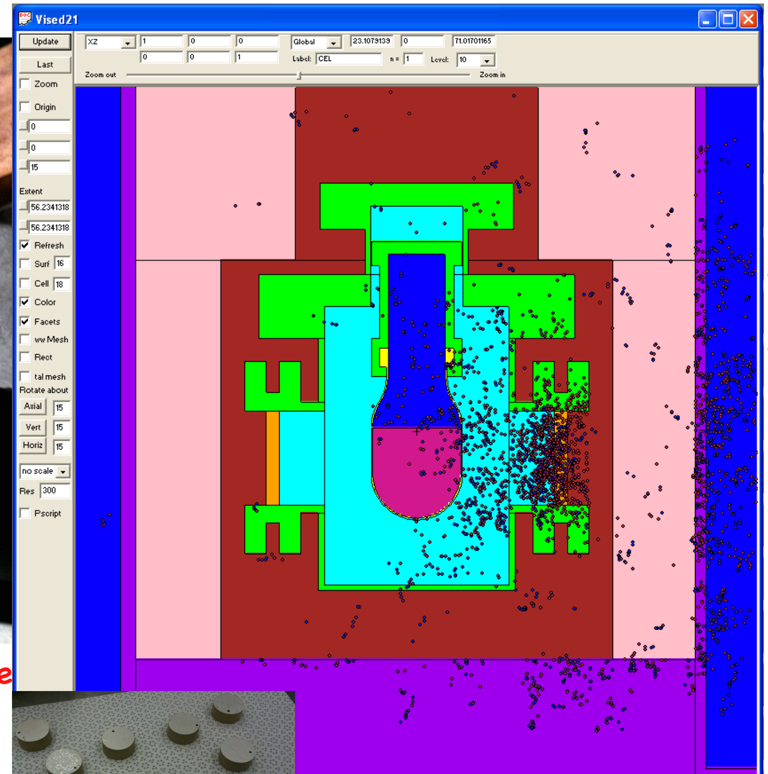


<u>**<1 event/yr expected in 60kg BC from latest PZT batch**</u>

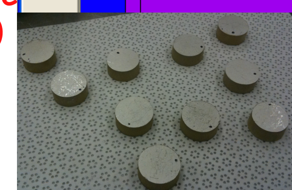
Pb-210 screening in PZT Pb oxide (low-bckg HPGe "well" detector)



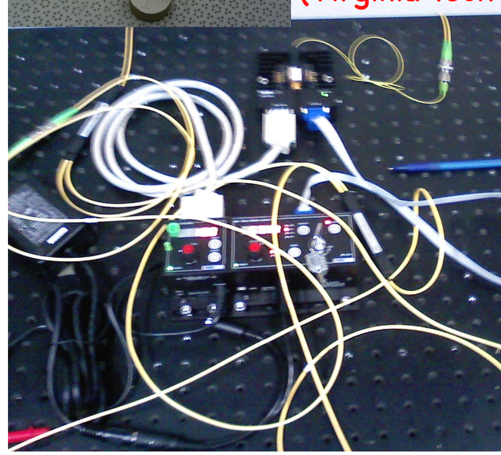
U, Th, Pb-210 screening (UC+SNOlab)



SOURCES + MCNP-Polimi (α,n) + fission simulations using screened activities



Radioclean PZT piezos (Virginia Tech + IUSB)



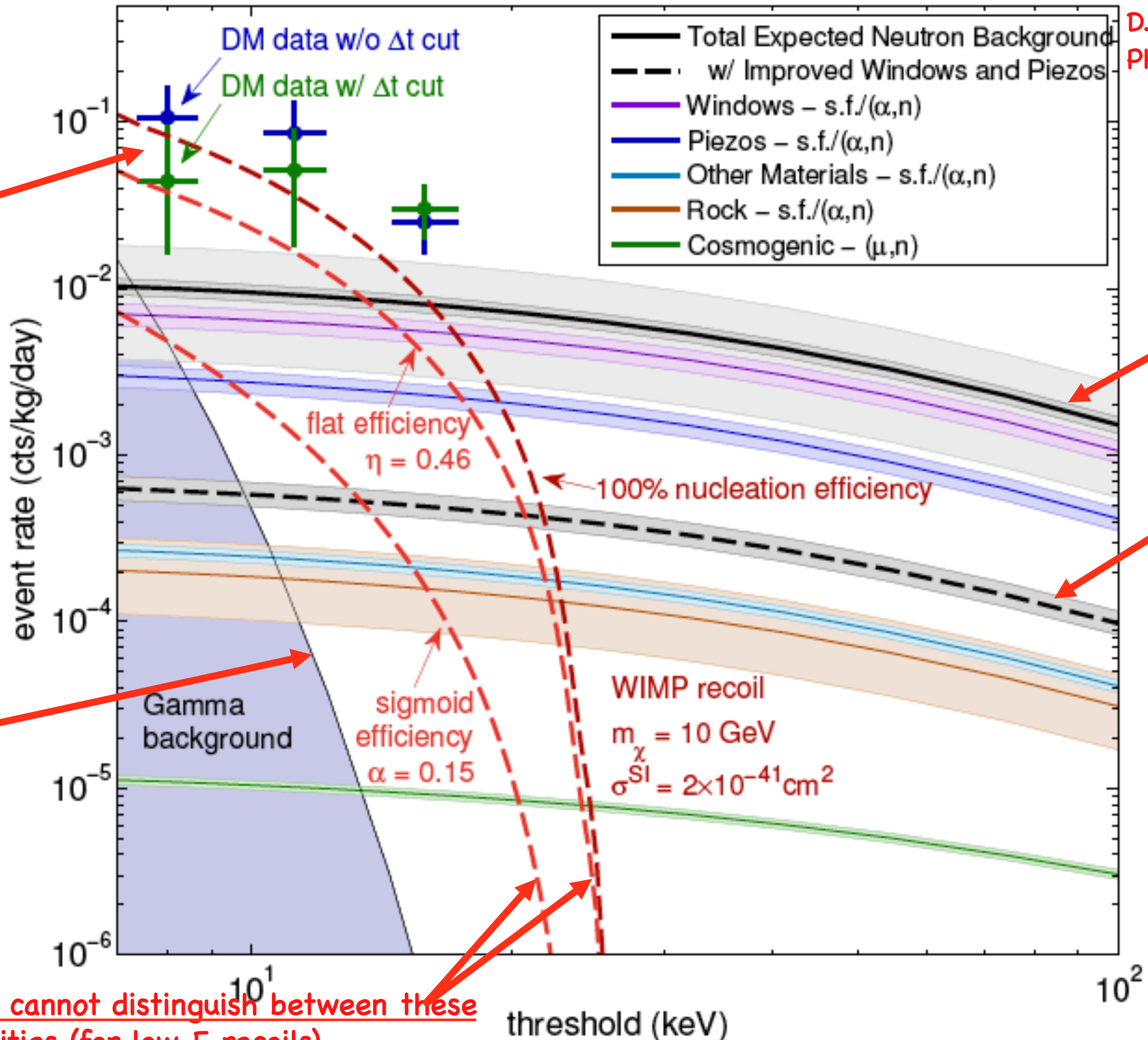
Remote acoustic sensing via Mach-Zender interferometry (FNAL)

Calibrations: the importance of accounting for uncertainty.

D. Fustin PhD Thesis

Δt cut removes events anomalously clumped in time (no clumping observed at 15keV threshold. No good present hypothesis –nor tremendous significance-)

Not a simulation: based on measurement of environmental gamma flux at position of CF3I, and of gamma rejection factor.



Present neutron background (two methods of estimation agreeing)

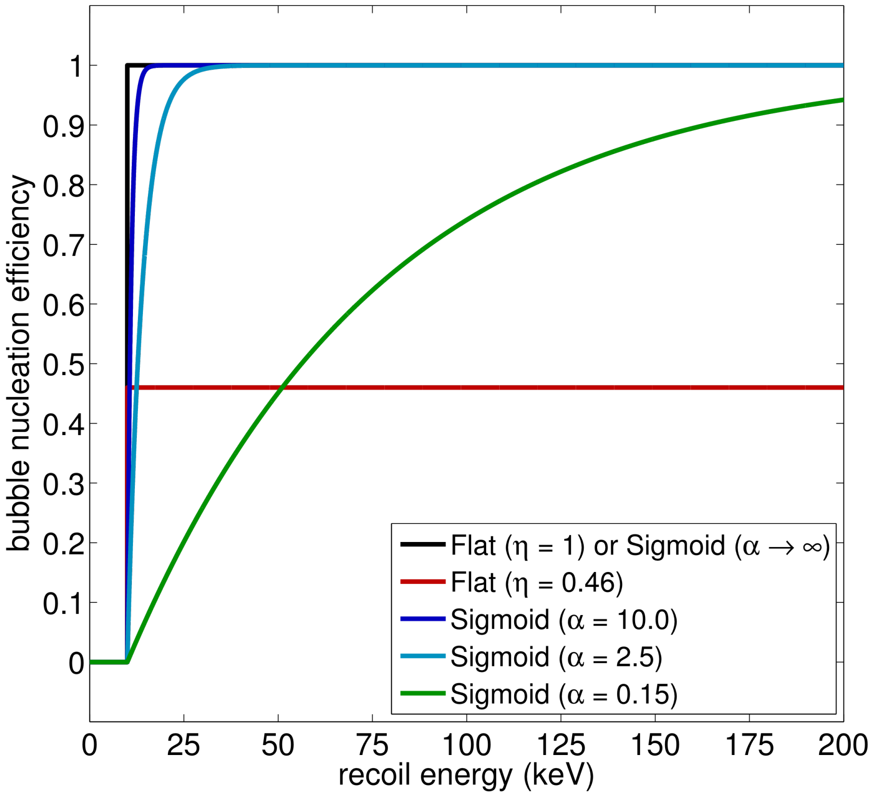
Next 4 kg run expectation

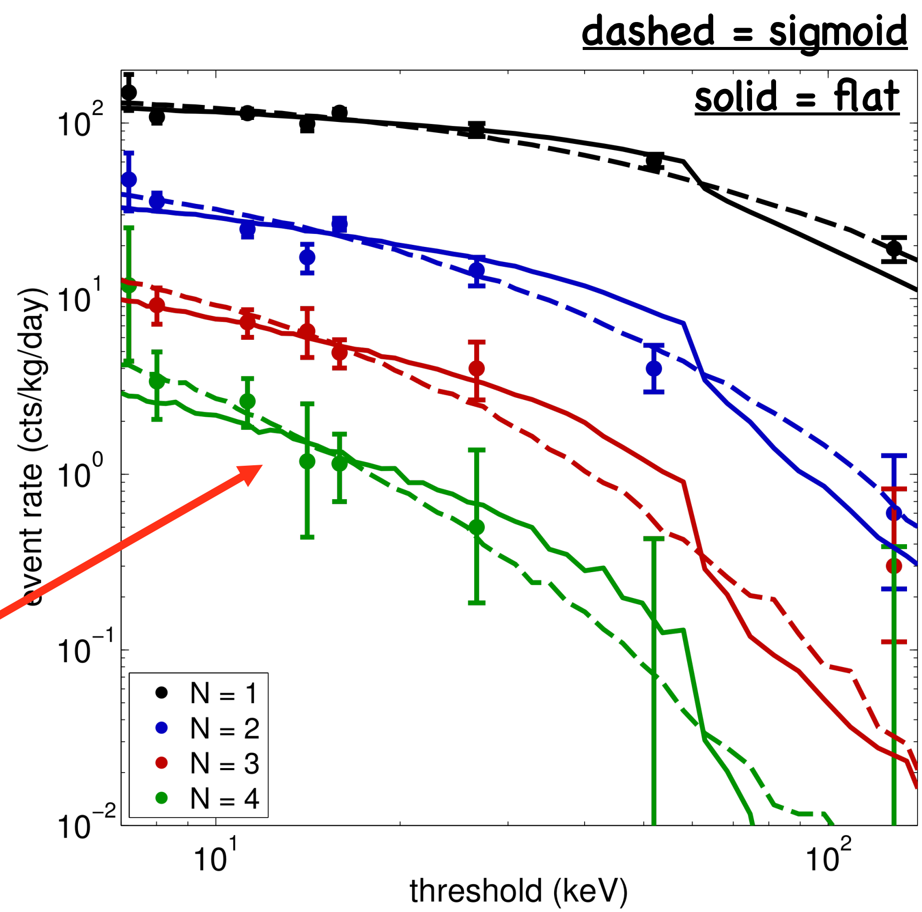
(further piezo purification in progress, expected additional x25 reduction for 60kg chamber)

<u>We presently cannot distinguish between these three possibilities (for low-E recoils).</u>

Rational solution: design a relevant calibration. In the mean time, account for uncertainty.

Calibrations: the importance of accounting for uncertainty.

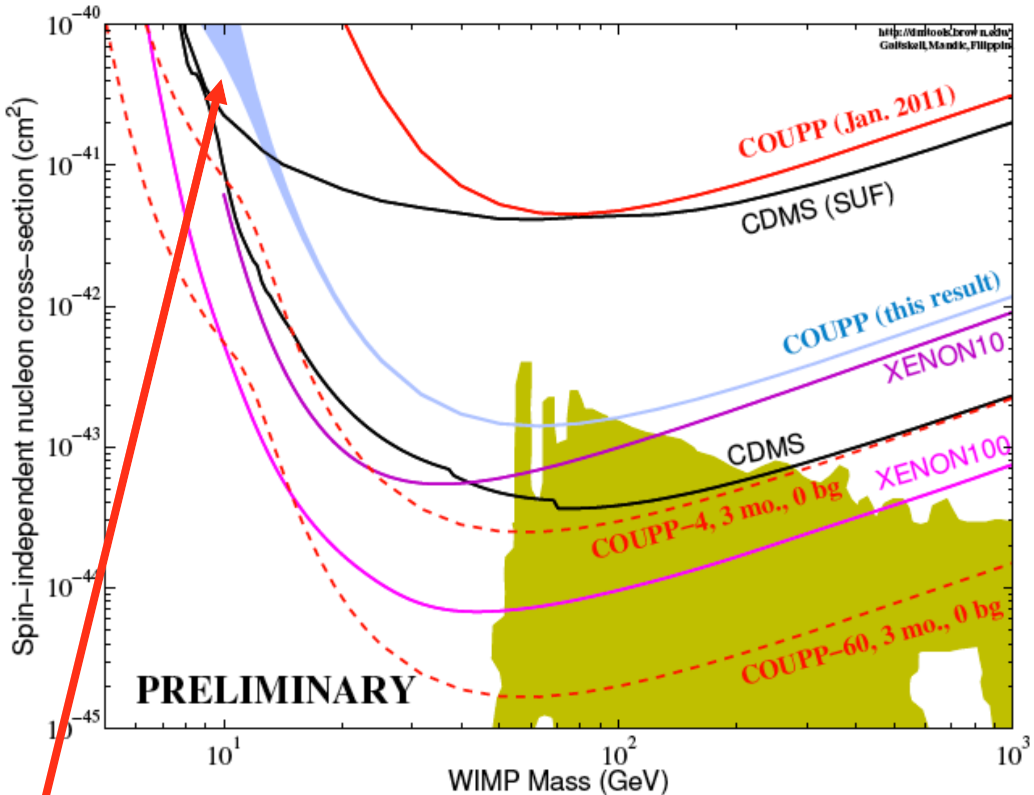




Must understand response to low-E recoils before making a statement about light WIMPS.

Threshold models that work for Am/Be and Cf recoils predict large uncertainty for low-E recoils: dedicated Y-88/Be calibrations in progress (monochromatic low energy 152 keV neutrons)

Calibrations: the importance of accounting for uncertainty.



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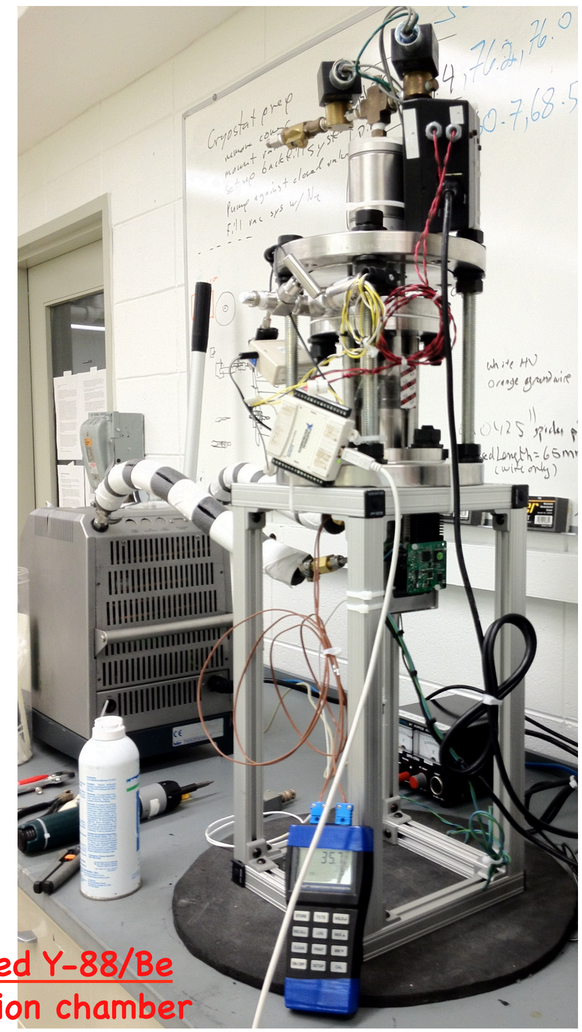
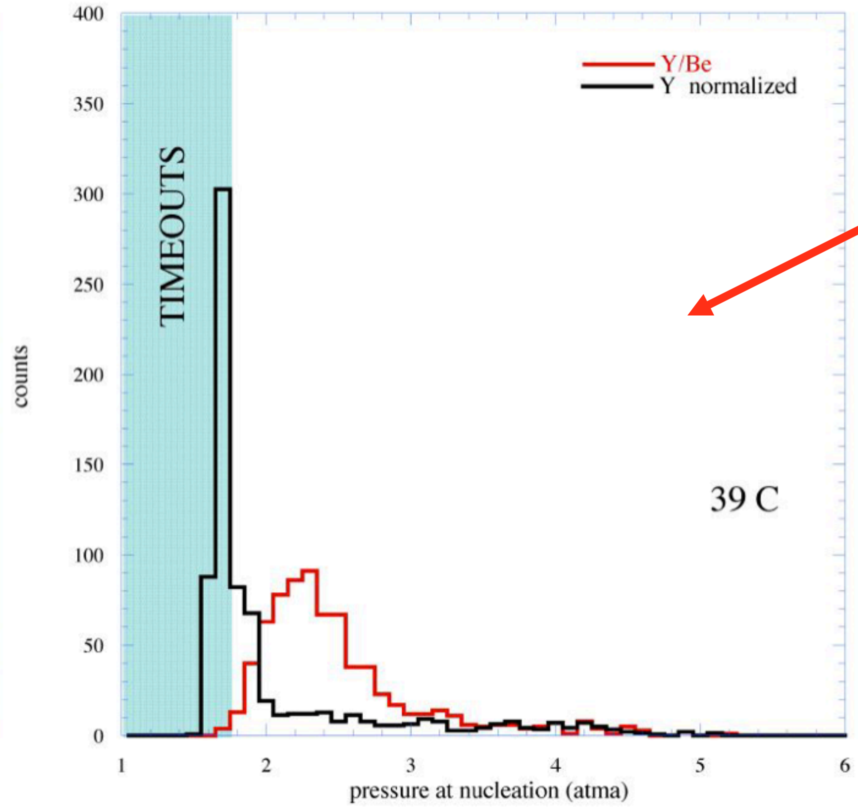


Dedicated Y-88/Be calibration chamber

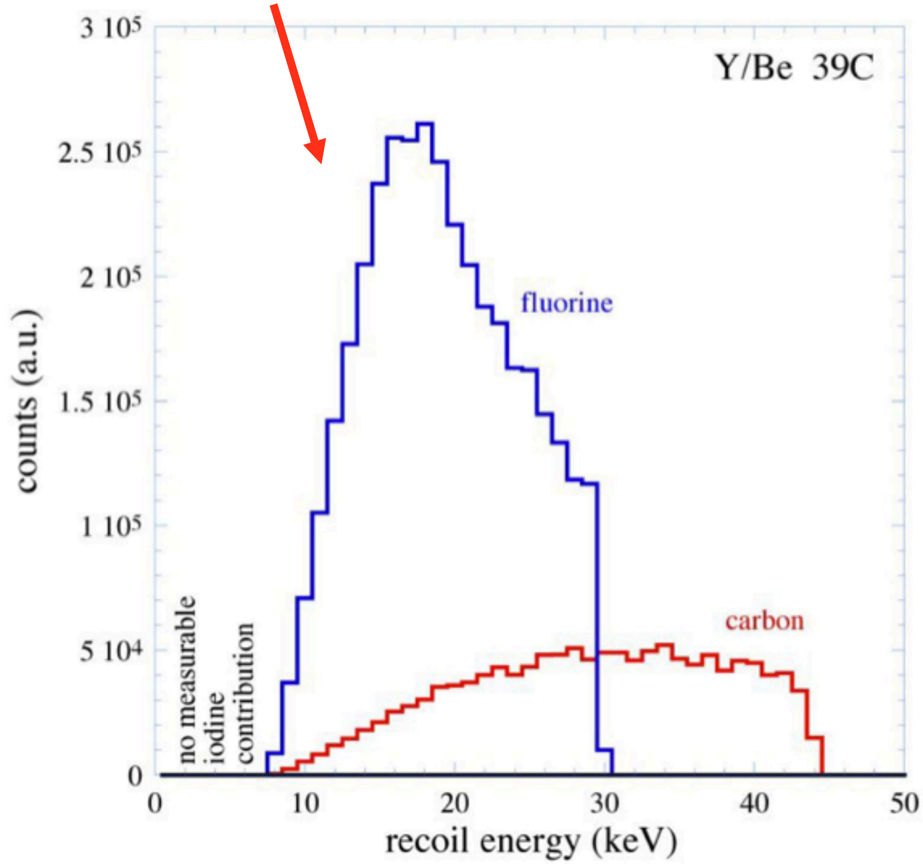
Calibrations: the importance of accounting for uncertainty.



Preliminary data showing

good separation between Y-88/Be neutrons and Y-88 gammas.

Recoil energies investigated (iodine recoils cannot be reached in this calibration mode)



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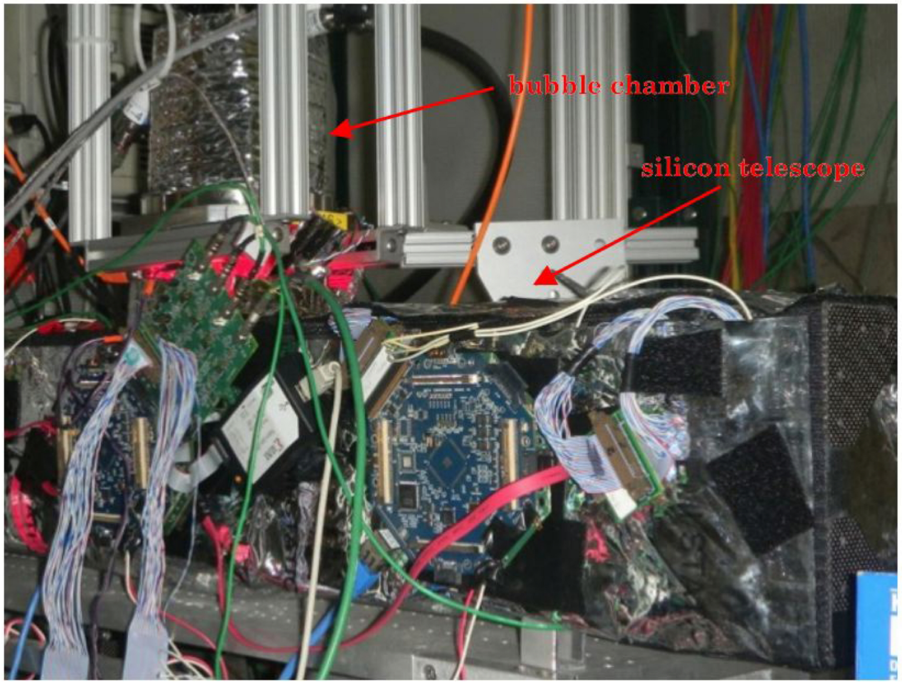
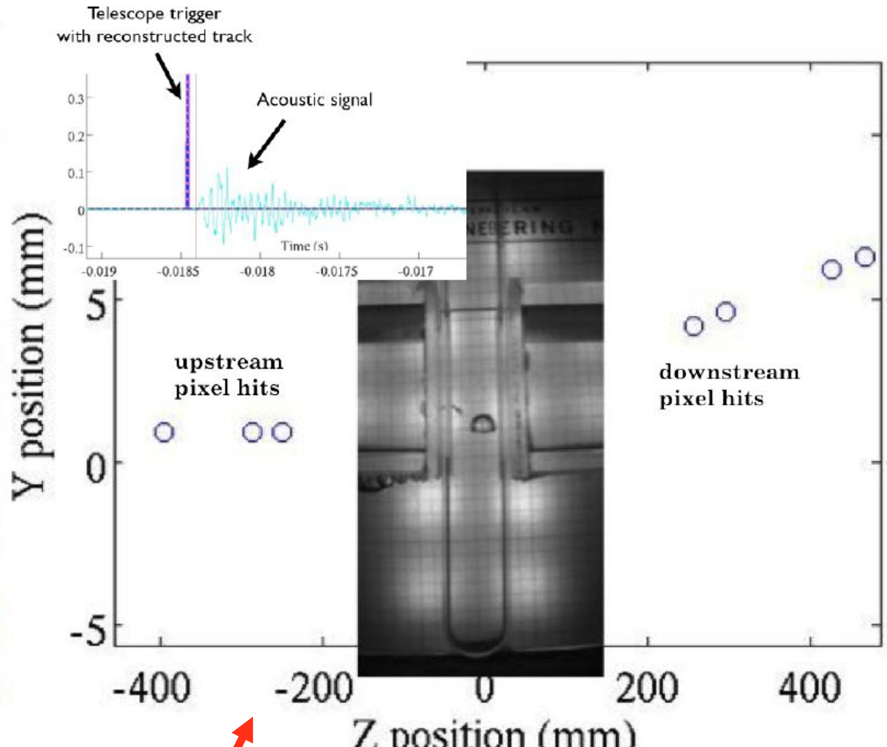




CIRTE @ FNAL
(COUPP Iodine Recoil Threshold Experiment)

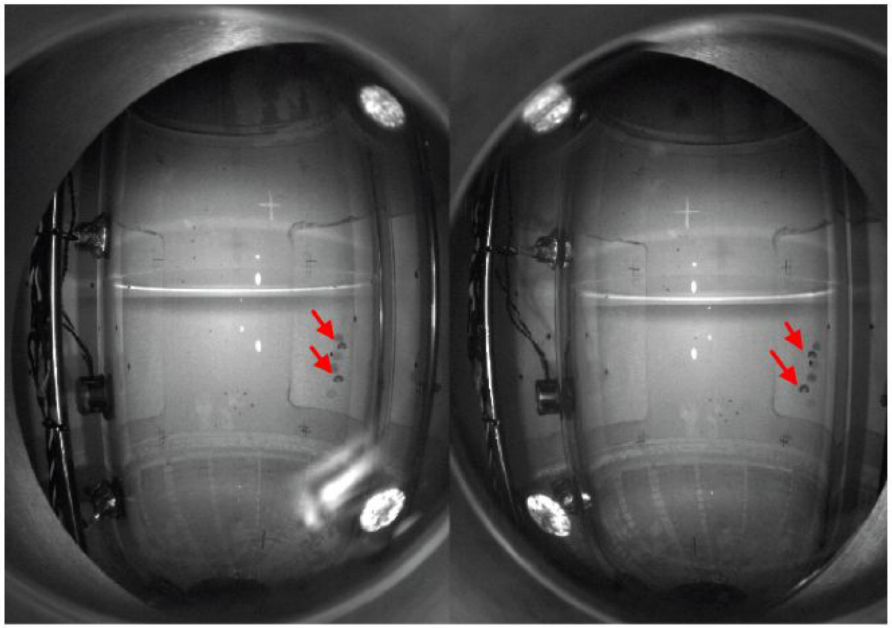
Goal: isolate response to low-energy (~20 keV) iodine recoils using a pion beam and silicon trackers.

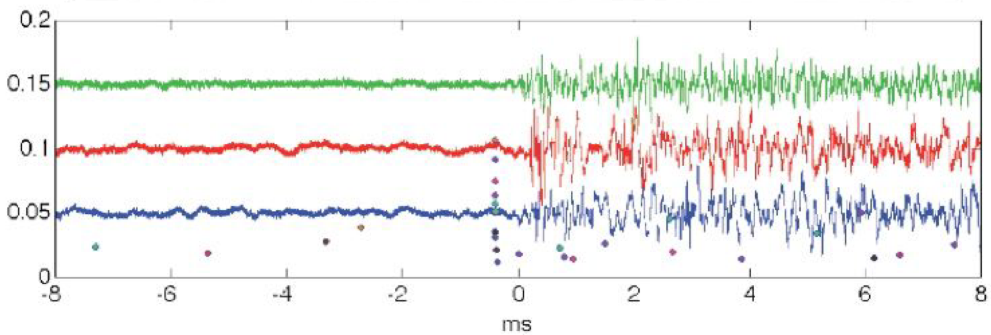
While theory predicts an optimal response to I recoils due to their large dE/dx, this is an important test before claiming best spin-independent sensitivity.

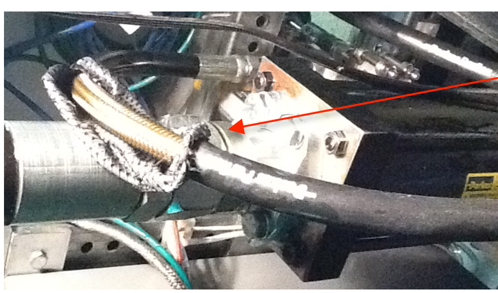
Example CIRTE event (10 mrad pion scattering, 56 keV iodine recoil energy)

COUPP-60 milestones

COUPP-60 @ NUMI gallery (300 mwe)





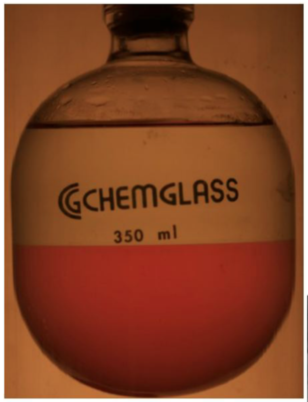


Not done with occasional surprises...

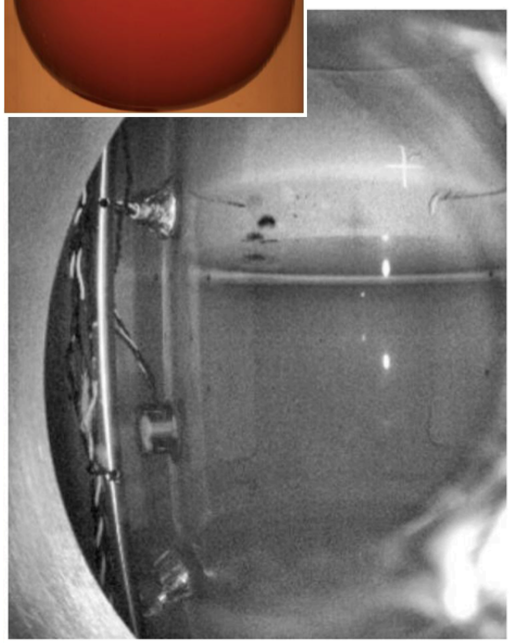
(FNAL provides excellent safety investigation/prevention of incidents)

- Successful commissioning of new pressure control hardware, PLC, DAQ and purification/fluid handling systems.
- Demonstration of acoustic discrimination against alphas in large chamber.
- HOWEVER: CF_3I initially reacted with impurities and (uncontrolled or excessive) illumination during fill -> photolysis. High bubble nucleation rate at CF_3I/H_2O interface was also observed.
- Neither effect observed previously nor in one year of 4kg operation at SNOlab.
- Other minor glitches identified (illumination uniformity & intensity, frame-rate, image resolution)
- After improved chemical purification and illumination: 2 months of successful data-taking at MINOS in the absence of observable darkening + factor 10 reduction in interface nucleation rate.
- COUP-60 is ready for SNOLAB (installation summer 2012)

COUPP-60 milestones



(intentional) photolysis of CF_3I



Initial darkening after 20d

Absence of measurable darkening after 50d

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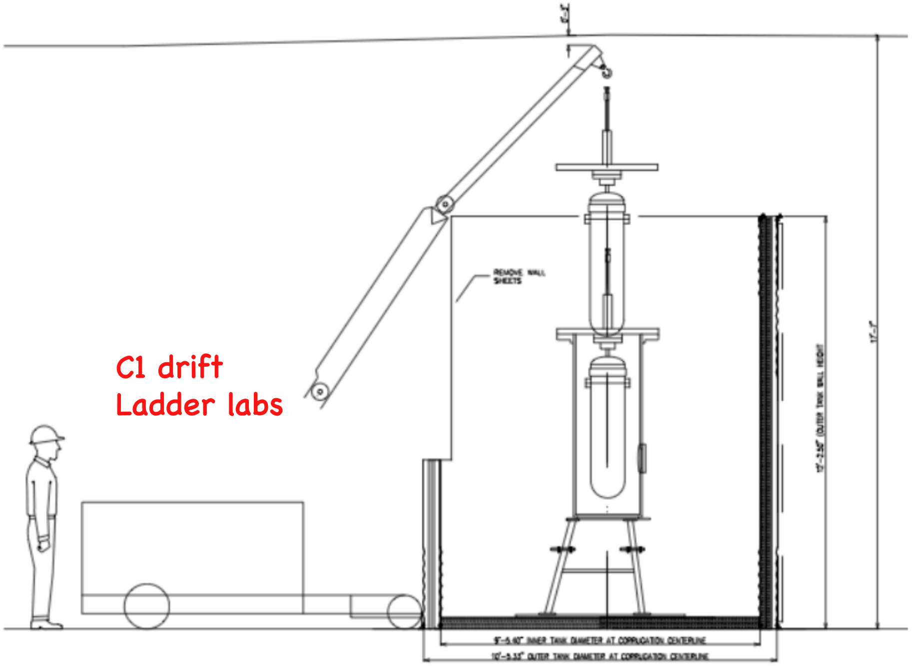

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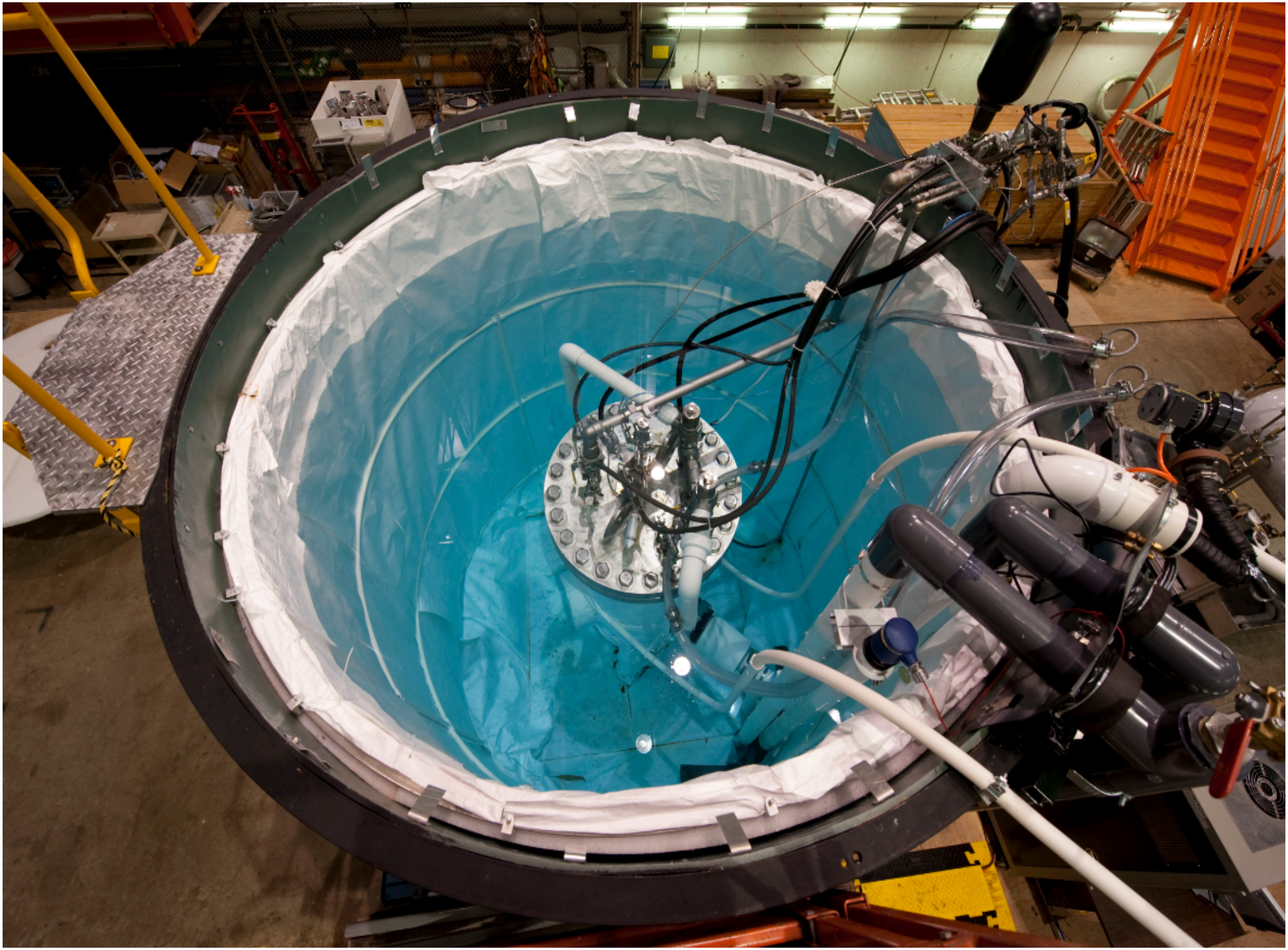
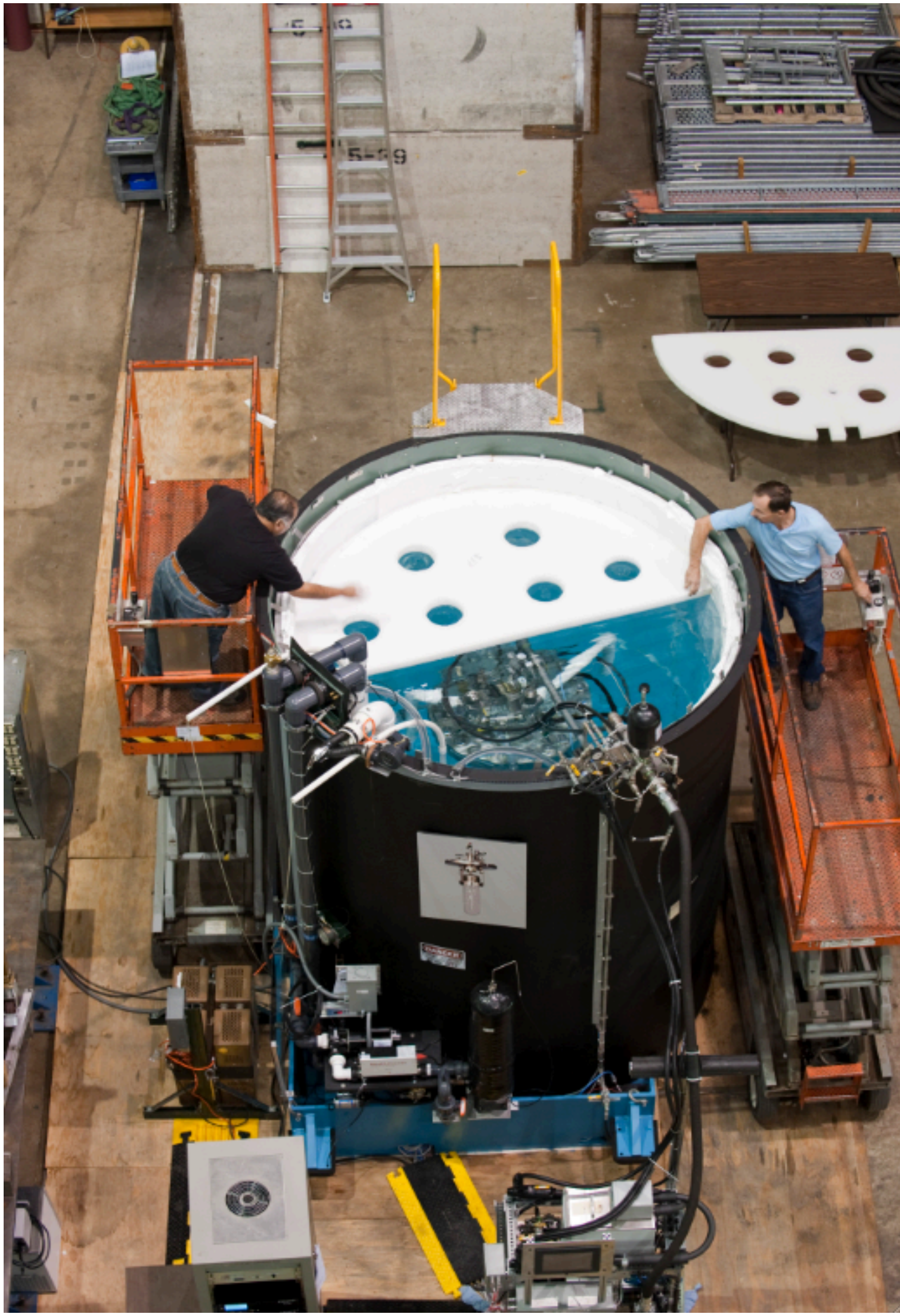
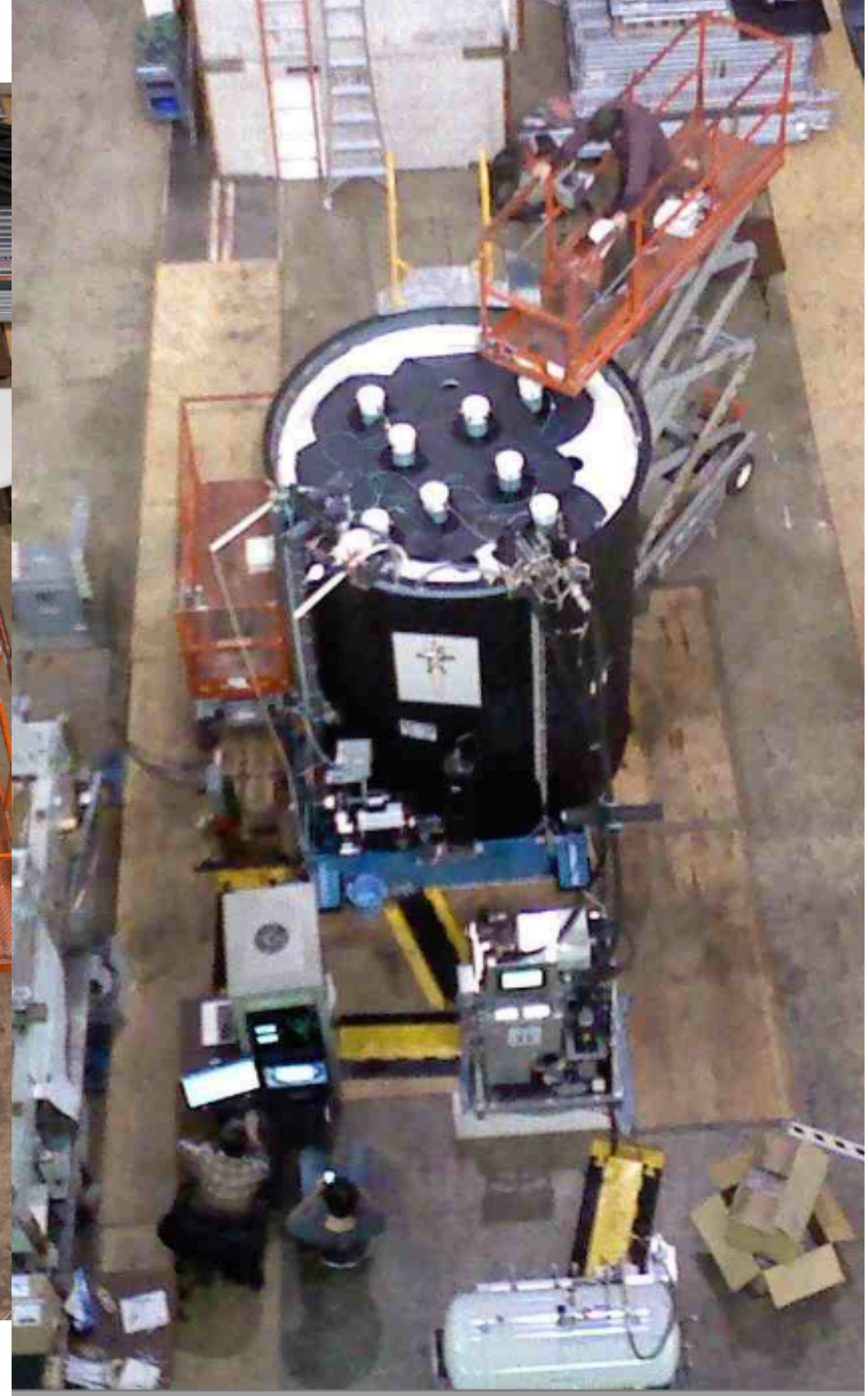
60kg chamber construction & testing


NOTICE
EXIT

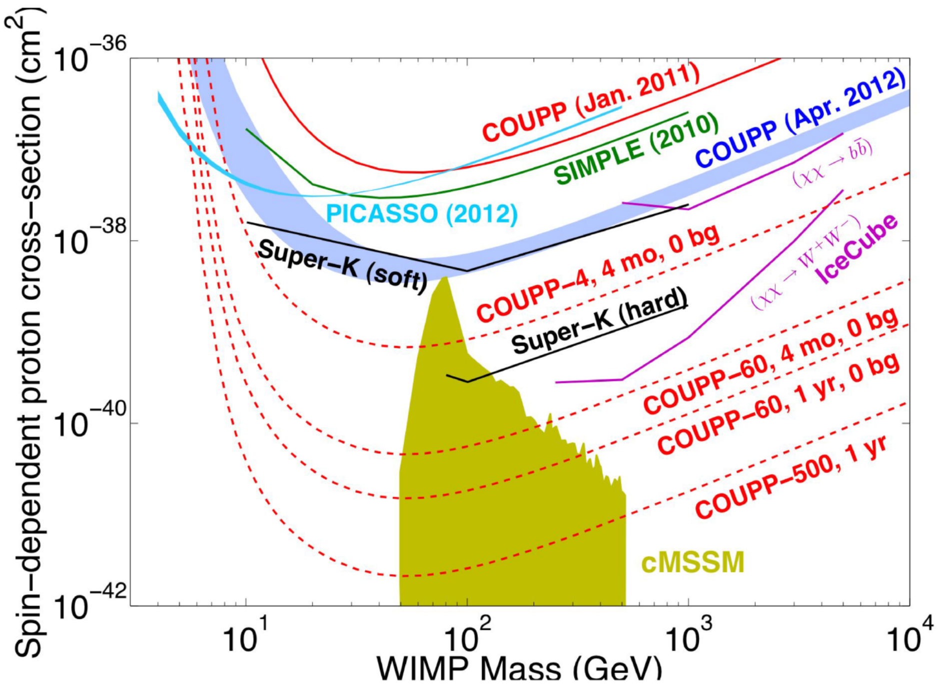


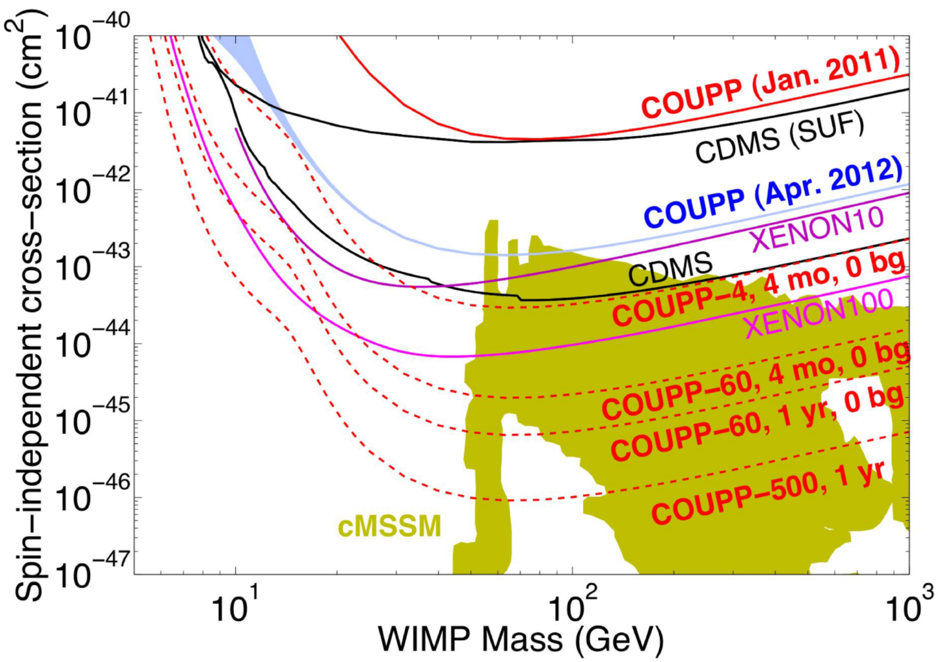



Next physics goals:

Following piezo replacement our modest next physics goal (World Domination) seems within grasp

(Plus we should be able to explore the light-WIMP hypothesis with confidence)

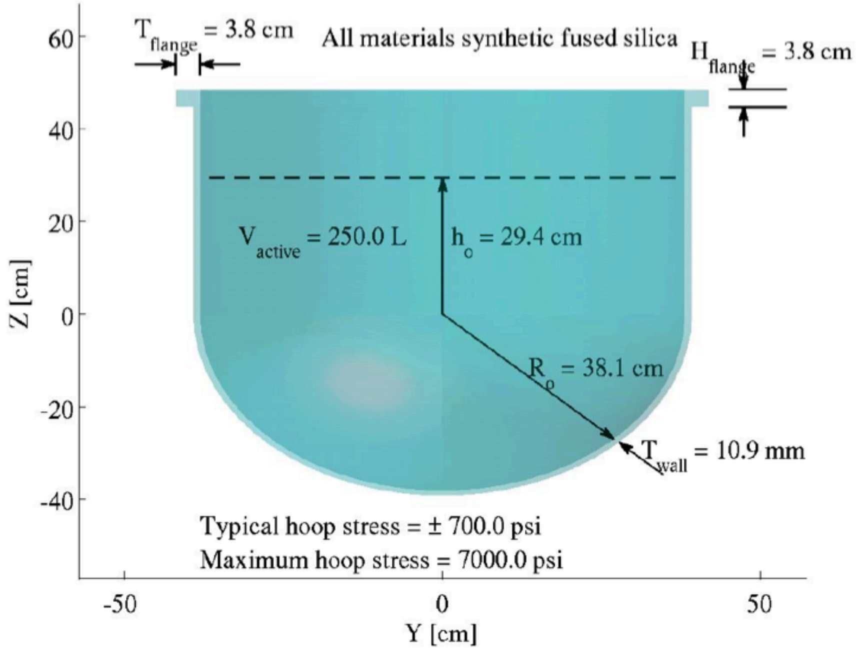


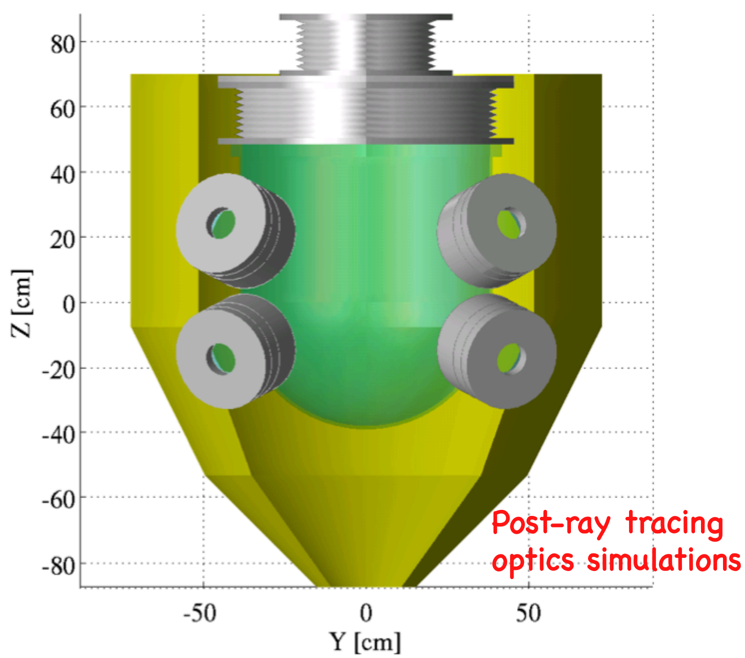


We expect COUPP to be at the forefront of *both* SD and SI WIMP searches starting 2012.

COUPP has produced a x10 improvement in sensitivity every other year, starting in 2008: we are about to accelerate this rate of progress.

The next step: COUPP-500





- Programmatic "one step at a time": we are ready for this. Dimensions defined by SNOLAB shaft (60" maximum diameter for outer vessel)
- Most systems to be minimal extensions of COUPP-60: engineering effort has started.
- Physics reach clearly beyond G-2, however within DOE "small experiment" category (<5 MUSD DOE, similar from NSF, after costing and contingency).
- Extensive bckg simulation effort completed (includes 2nd order sources such as (γ,n), photonuclear, fission fragments, ^{14}C, etc.). <1 event / 500kg-yr expected. Slightly larger water tank than for C-60 required.
- Must guarantee acoustic rejection capability in a large chamber: simulation campaign ongoing (new UPV collaborators).
- Use of alternative fluids (e.g., C_4F_{10}) contemplated (see PRL 99 (2007) 151301). Surface event dead-time expected is ~6%.
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The next step: COUPP-500

TABLE I: Abridged COUPP-500kg background estimates for all considered neutron production processes. Muon induced neutrons within the water shield/muon veto and (α,n) reactions occurring in the CF_3I are considered vetoable (Figs. 6 and 7).

Neutron source	Rate	Single evts/yr	Multiple evts/yr
Rock	4000 ± 1000 n/m^2/d	$O(10^{-11})$	$O(10^{-11})$
Muon induced from rock	5.4×10^{-11} n/cm^2/s	0.0904 ± 0.0131	0.2544 ± 0.0219
Muon induced from shield or detector	$67.11 \pm 1.85\,\mu$/d	0.493 ± 0.014	1.050 ± 0.030
U and Th in detector materials		0.0504 ± 0.0030	0.1242 ± 0.0068
↳ steel only	1ppb ^{238}U and ^{232}Th	0.0360 ± 0.0026	0.0922 ± 0.0062
↳ quartz only	10^{-2}ppb ^{238}U and ^{232}Th	0.0131 ± 0.0012	0.0290 ± 0.0026
Radon deposition onto and diffusion into outer surface of quartz jar	Dep. Rate= 10^{-3}/m/y 100 Bq^{222}Rn/m^3 in air S=10, d_e=1.0 mm	0.0198 ± 0.0015	0.0415 ± 0.0030
Radon in water tank	S=0.25, 100 Bq/m^3 Rn inner 18500L	$(1.83 \pm 0.28) \times 10^{-3}$	$(5.17 \pm 0.60) \times 10^{-3}$
Radon in heat exchange pipes	S=0.25 100 Bq/m^3 Rn, 10L	0.0230 ± 0.0021	0.0572 ± 0.0052
Radon emanation from quartz and steel	A=34.81m^2 100 μBq/m^2 Rn	$(1.39 \pm 0.13) \times 10^{-3}$	$(2.93 \pm 0.26) \times 10^{-3}$
Mine dust on top surfaces	0.01 g/m^2, 2.21 m^2 1.11 ppm ^{238}U 5.56 ppm ^{232}Th	0.0127 ± 0.0011	0.0286 ± 0.0026
^{127}I$(\gamma$,n$)^{126}$I	4.0 γ/cm^2/yr $>$ 9MeV	< 0.0069	
^{2}H$(\gamma$,n$)^1$H	0.057γ/m^2/s at 2615keV	0.0040 ± 0.0004	0.0044 ± 0.0004
other photonuclear		$< 1.1 \times 10^{-4}$	
Piezoelectric acoustic transducers	10 ppb ^{238}U 10 ppb ^{232}Th	0.0577 ± 0.0031	0.142 ± 0.008
↳ side only	0.1 ppb ^{235}U	0.0036 ± 0.0002	0.0072 ± 0.0004
↳ bottom only	10 Bq/kg ^{210}Pb	0.0541 ± 0.0031	0.134 ± 0.008
CF_3I U and Th $(\alpha$,n$)$	0.0159 ppt ^{238}U 0.0488 ppt ^{232}Th 0.0025 ppt ^{235}U 25 μBq/kg ^{222}Rn 25 μBq/kg ^{210}Pb	1.078 ± 0.061	4.37 ± 0.25
Other radon induced backgrounds	6mo. deposition on steel 92.6μBq/m^3 in IV	$(8.0 \pm 0.5) \times 10^{-6}$	$(2.00 \pm 0.12) \times 10^{-5}$
Total		1.84 ± 0.06	6.08 ± 0.25
Total unvetoable		0.268 ± 0.014	0.667 ± 0.025

- Programmatic "one step at a time": we are ready for this. Dimensions defined by SNOLAB shaft (60" maximum diameter for outer vessel)
- Most systems to be minimal extensions of COUPP-60: engineering effort has started.
- Physics reach clearly beyond G-2, however within DOE "small experiment" category (<5 MUSD DOE, similar from NSF, after costing and contingency).
- Extensive bckg simulation effort completed (includes 2nd order sources such as $(\gamma$,n$)$, photonuclear, fission fragments, ^{14}C, etc.). <1 event / 500kg-yr expected. Slightly larger water tank than for C-60 required.
- Must guarantee acoustic rejection capability in a large chamber: simulation campaign ongoing (new UPV collaborators).
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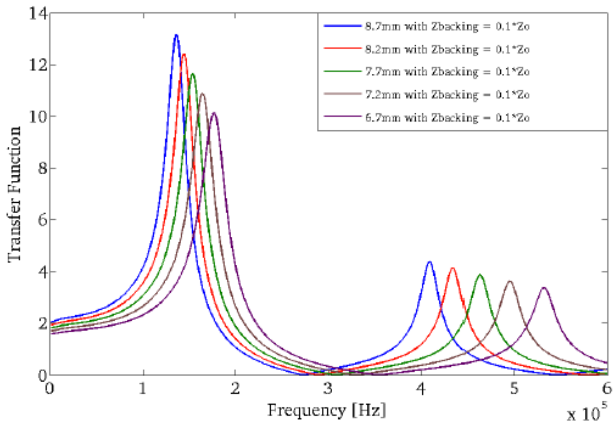
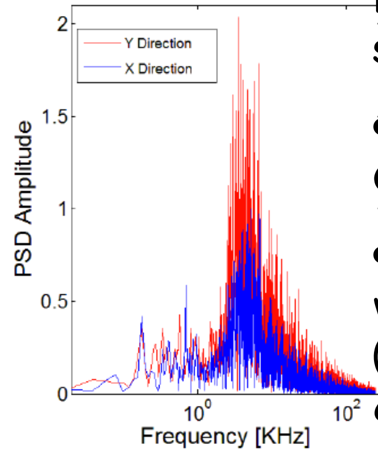
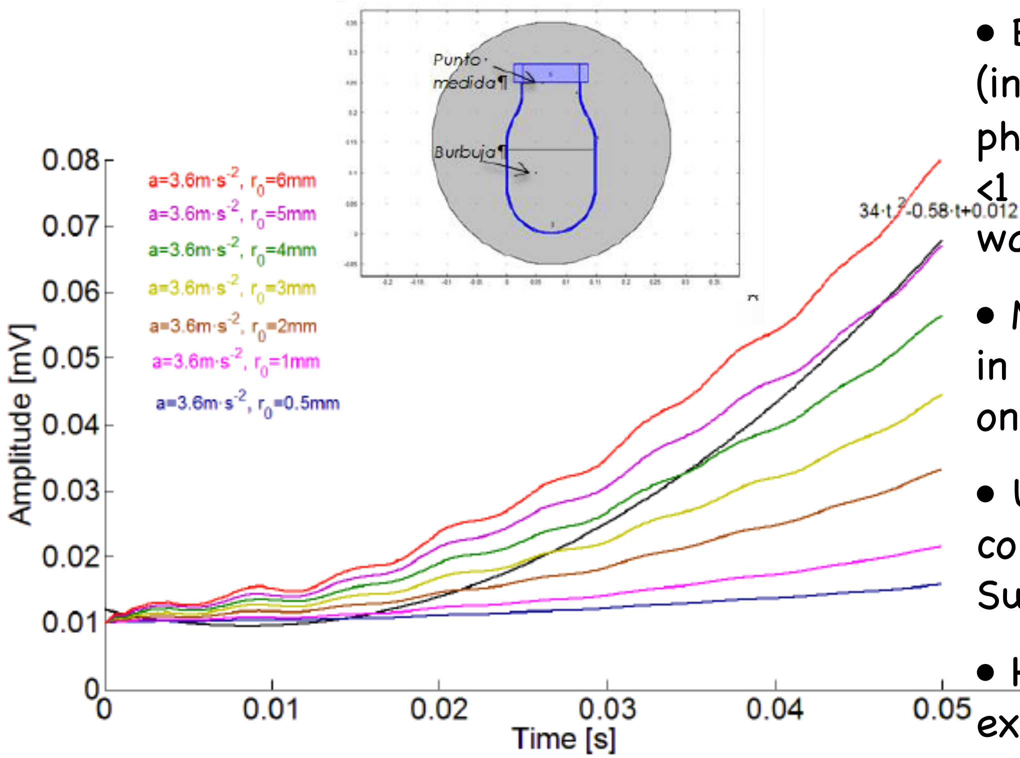
The next step: COUPP-500

COMSOL acoustic simulations (generation, transport, detection)







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The next step: COUPP-500

FY13	• Finish mechanical design, all major components • Order outer vessel • Prototype hydraulic system • Test pressure control at full scale • First tests of 3rd generation acoustic sensors • Select SNOLAB installation location
FY14	• Water tank construction at SNOLAB • Inner vessel prototype testing at Fermilab • High purity fluid system construction • Control system, DAQ testing
FY15	• Construction of final inner vessel • Installation of all equipment at SNOLAB • Commissioning

Table 4: Milestones towards the completion of COUPP-500.

- Programmatic "one step at a time": we are ready for this. Dimensions defined by SNOLAB shaft (60" maximum diameter for outer vessel)
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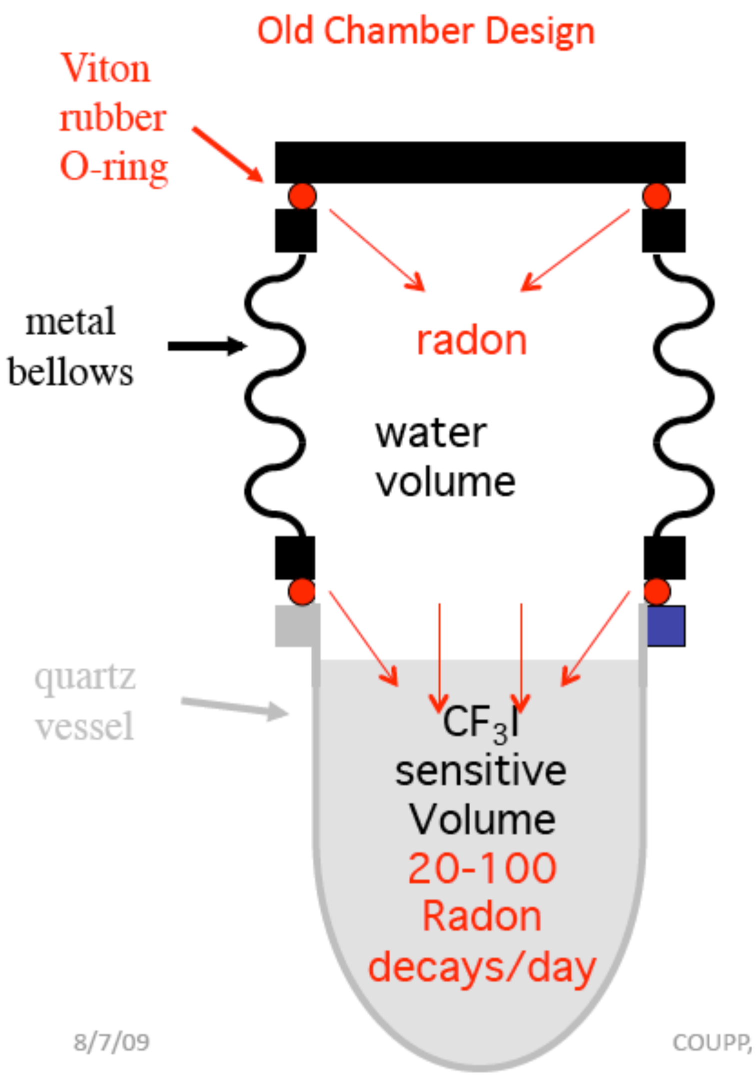
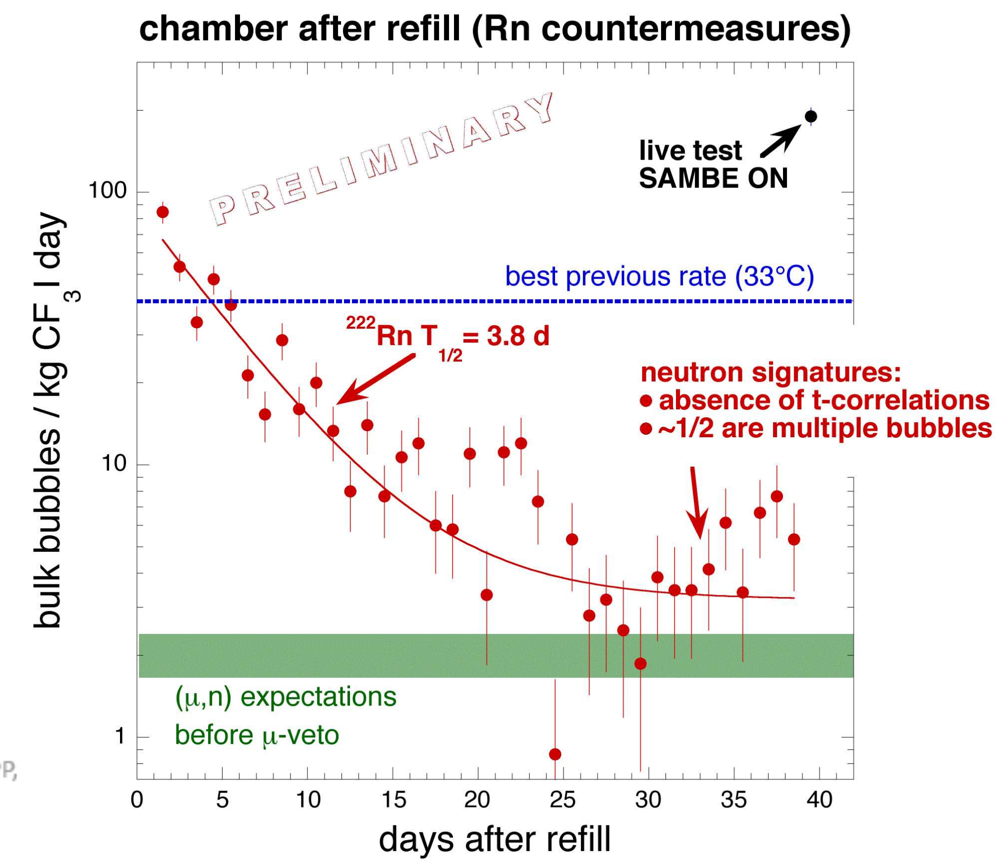
reserve

E-961 progress: Rn control

2-kg Chamber 2008 Data



- Radon greatly reduced by replacement of Viton O-rings with metal seals.
- We begin to see backgrounds from cosmic-ray coincident neutrons

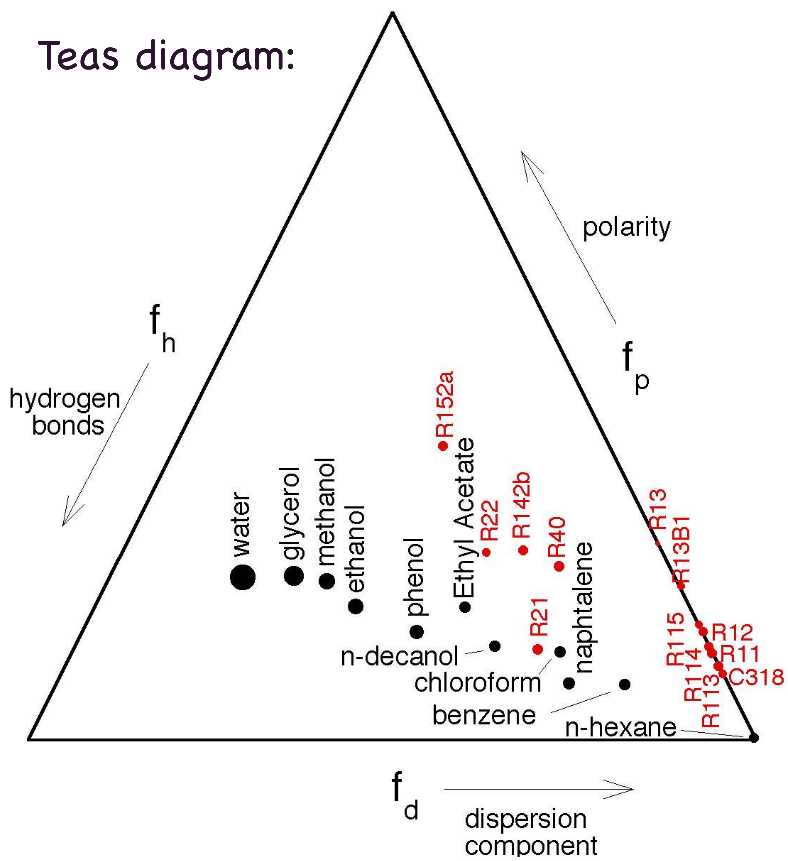


E-961 progress: fluid purification & handling

"like dissolves like"

U & Th salts readily dissolve in H_2O, refrigerants do not. **Solubility of U,Th in CF_3I expected to be very small** (a situation similar to mineral oil-based ν dets.)

Teas diagram:



Fractional cohesion parameters for refrigerants and common solvants (size of marker ~ δ_t)

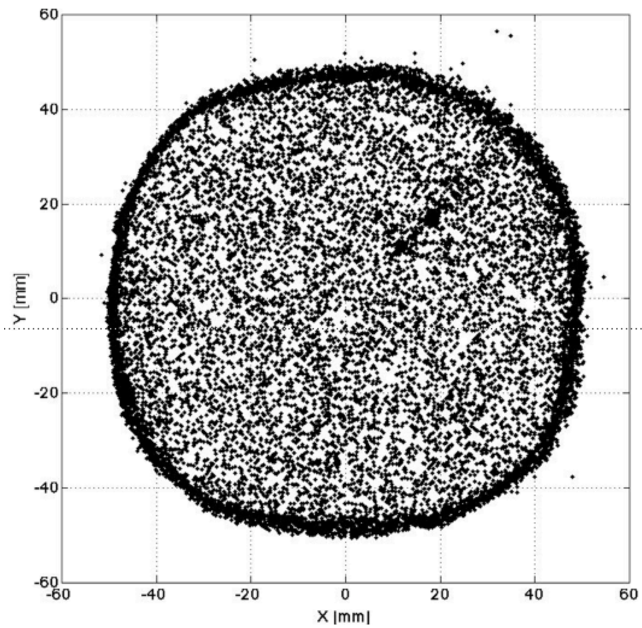
First serious attempt at fluid handling/purification, commissioned during NUMI 60-kg fill.

So far we have only profited from SNOlab water availability (to reach already <5 α-like ev/kg-day)

We foresee most future effort on H_2O purification.

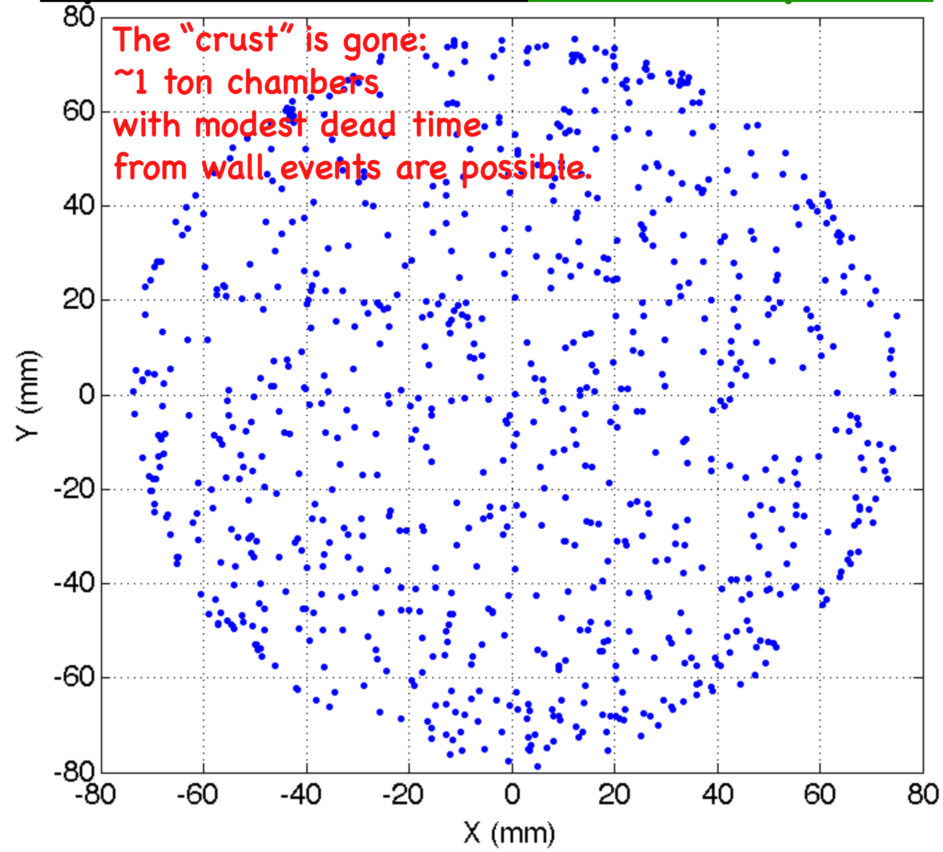
E-961 progress: wall events a thing of the past

Natural Quartz: 0.8/day/cm^2



~40 live-days (2007-08)

Synthetic Silica: ≤1e-2/day/cm^2



88 live-days (2009)

- We detected a ~50 ppb U,Th contamination in regular quartz used in early chambers.
- Alpha emission from surface was independently confirmed, at the same rate as wall evts.
- New chambers now featuring synthetic silica (~3 orders of magnitude lower U,Th content)
- New rate will allow us to reach 1 ton without any live-time penalty.
- Synthetic silica vessels available up to 250kg CF3I: extrapolation to ~500kg part of our DUSEL S4 charge. UPDATE: vessels up to >1 m^3 may be readily available.