The COUPP Dark Matter Experiment

(Chicagoland Observatory for Underground Particle Physics)

Ilan Levine, IU South Bend (on behalf of the COUPP Collaboration)

2009 Meeting of the Division of Particles and Fields of the American Physical Society Wayne State University, Detroit, MI

University of Chicago

Principle Investigator:
Juan Collar
(Spokesperson)

Kavli Fellow:
C. Eric Dahl

Gradate Students:
Drew Fustin
Nathan Riley
Matthew Szydagis

Undergraduates:
Luke Goetzke
Hannes Schimmelpfennig

Fermilab

Scientists:
Steve Brice
Daniel R Broemmelsiek
Peter Cooper
Mike Crisler
Lauren Hsu
Martin Hu
Erik Ramberg
Andrew Sonnenschein
Bob Tschirhart

Indiana University South Bend

Principle Investigator:
Ilan Levine

Physicist/Engineer
Edward Behnke

Undergraduates:
Henry Hinnefeld
Andrea Palenchar
Tina Shepherd
Brendan Sweeney

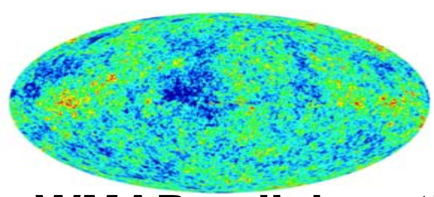
Funding:
National Science Foundation
Kavli Institute for Cosmological Physics
Department of Energy

A Large Amount of Dark Matter Exists ….

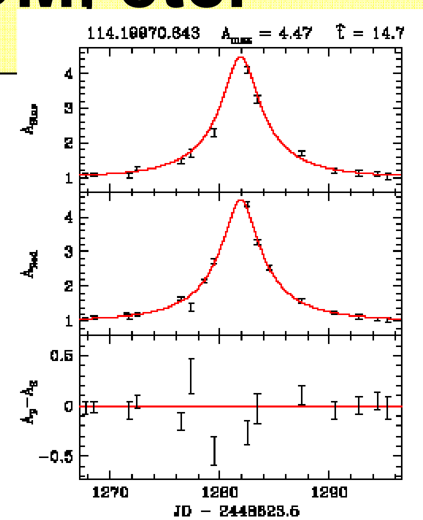
- **Dynamical**
- **Gravitational Lensing**
- **BBN**
- **Structural**
- **Cosmic microwave background**
- **X-ray emitting gas from clusters**
- **Galaxy cluster collisions**

Photo Credits: NASA

…..And it is not dominantly MaCHOs, νs, HDM, etc.



WMAP collaboration



MACHO collaboration

Excellent Candidates From… **SUSY**

UED?

…Or, **Axions?**

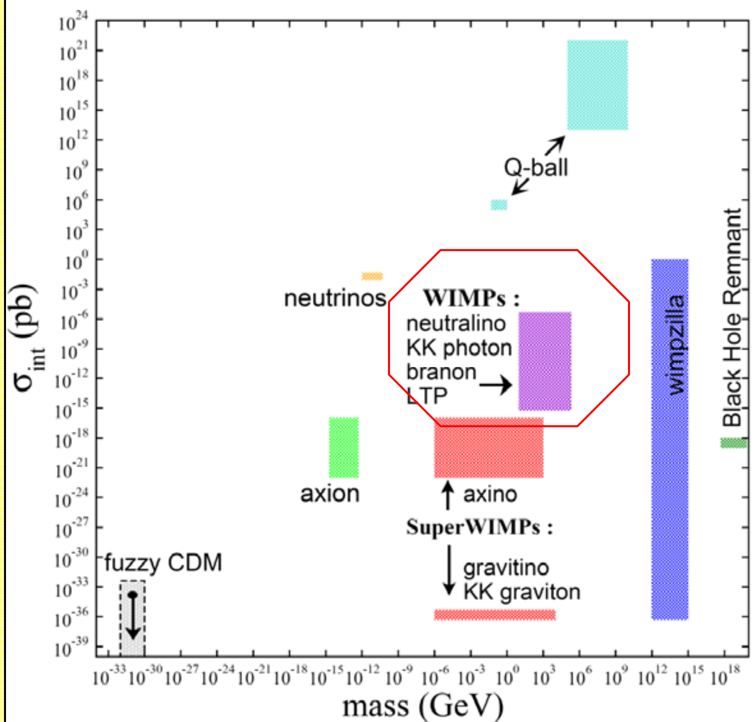
…Or,

…Or, techni-baryons, gravitinos, axinos, WIMPZILLAS, Sterile neutrinos, Little Higgs, Q-balls CHArged massive particles (CHAMPS), Self-interacting, D-matter, Cryptons, Superweakly interacting dark matter (SWIMPS), Brane-world dark matter, Heavy 4th generation neutrinos, Mirror particles,

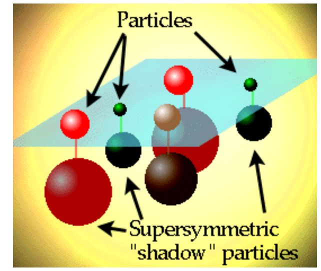
…etc.

Patient compilation by C. Hailey (Columbia)

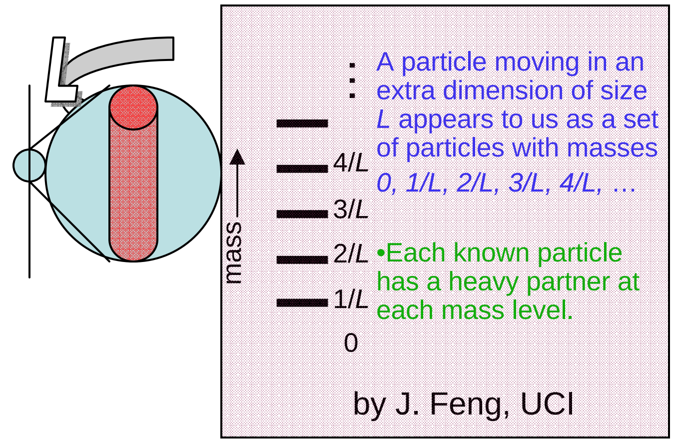
The nature of Dark Matter?



HEPAP/AAAC DMSAG Subpanel (2007)



LSP stable assuming R-parity conservation.



Suppose Stable Weakly Interacting Massive Particles

In self gravitating halo

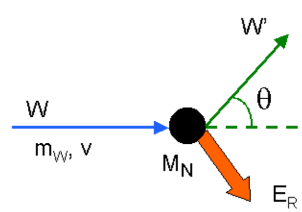
Maxwellian velocity distribution

(< v > ~230km/s)

Local density: ρ_{Sun} ~ 0.3 GeV / cm^3.

(J.D. Lewin and P. Smith, Astrop. Phys.6 (1996) 87)

Direct detection



E_{recoil} ~ 1-100 keV

Rates ~ 1/kg/day -1/Ton/year

Which atoms to use as target?

Selection of nuclear target

Neutralino Interaction with matter:

$$\sigma_A = 4G_F^2 \left(\frac{M_\chi M_A}{M_\chi + M_A} \right)^2 C_A$$

Spin independent interaction ($C_A \propto A^2$)
(but small or vanishing cross sections possible)

$$C^{SI}_A = (1/4\pi)(Zf_p+(A-Z)f_n)^2$$

Spin dependent interaction
(small, but stable and can dominate for some candidates)

$$C^{SD}_A = (8/\pi)\underbrace{(a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2}_{\lambda}(J+1)/J$$

(Spin of nucleus ~ spin of unpaired proton or neutron)

Cf: JD. Lewin and P Smith Astrop. Phys. 6 (1996) 87 and J. Engel et al., Int J. Mod Phys. E1 (1991) 1

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

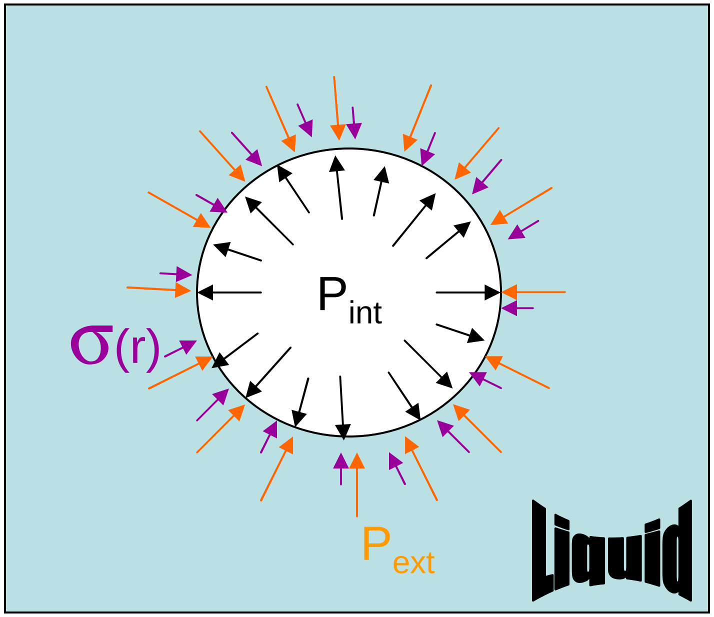
^{19}F ideal for SD(p)
^{127}I excellent for SI

Best of both worlds: CF_3I

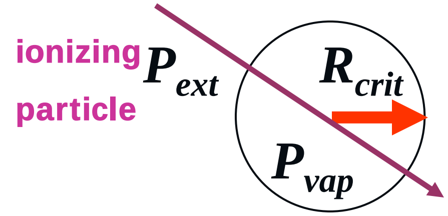
J. Ellis and R. Flores, PLB **263**, no. 2, pg 259, 1991

How to amplify ~1-100 keV?

Superheated Liquid Detection Technique



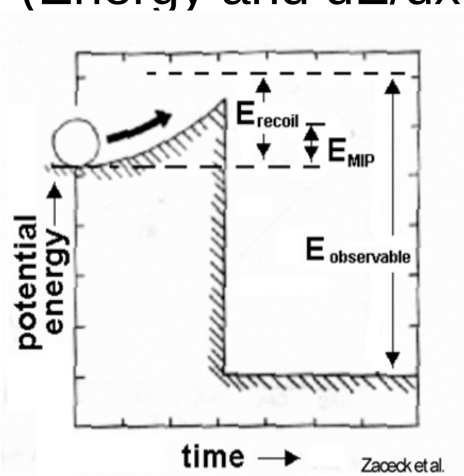
$$\frac{dE}{dx} > \frac{E_c}{ar_c}$$



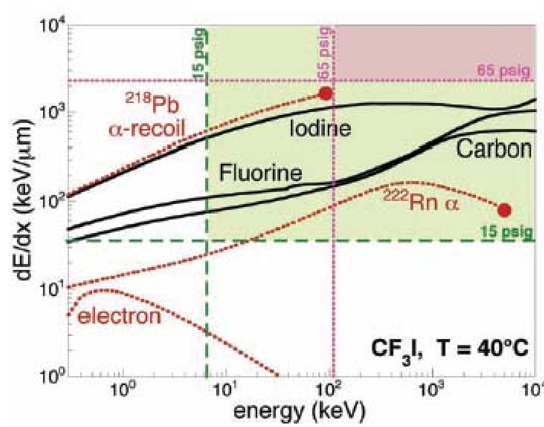
$$E > E_c = 4\pi r_c^2\left(\gamma - t\frac{\partial\gamma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v \frac{h_{fg}}{M} + \frac{4}{3}\pi r_c^3 P, \quad r_c = \frac{2\gamma}{\Delta P}$$

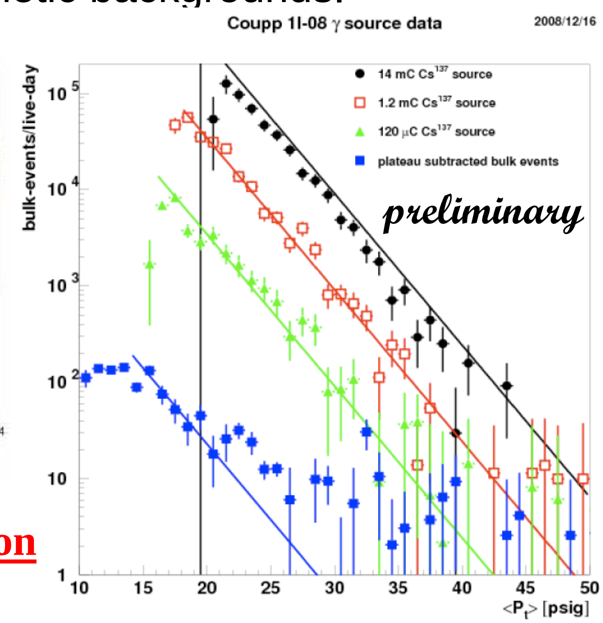
Can adjust operating parameters to be fully sensitive to recoiling nuclei while completely insensitive to electromagnetic backgrounds.

A Double Threshold (Energy and dE/dx)



Heat spike theory of phase transition (Seitz):Seitz, F. "On the Theory of the Bubble Chamber." Phys. Fluids 1(1), 2-13 (1958).

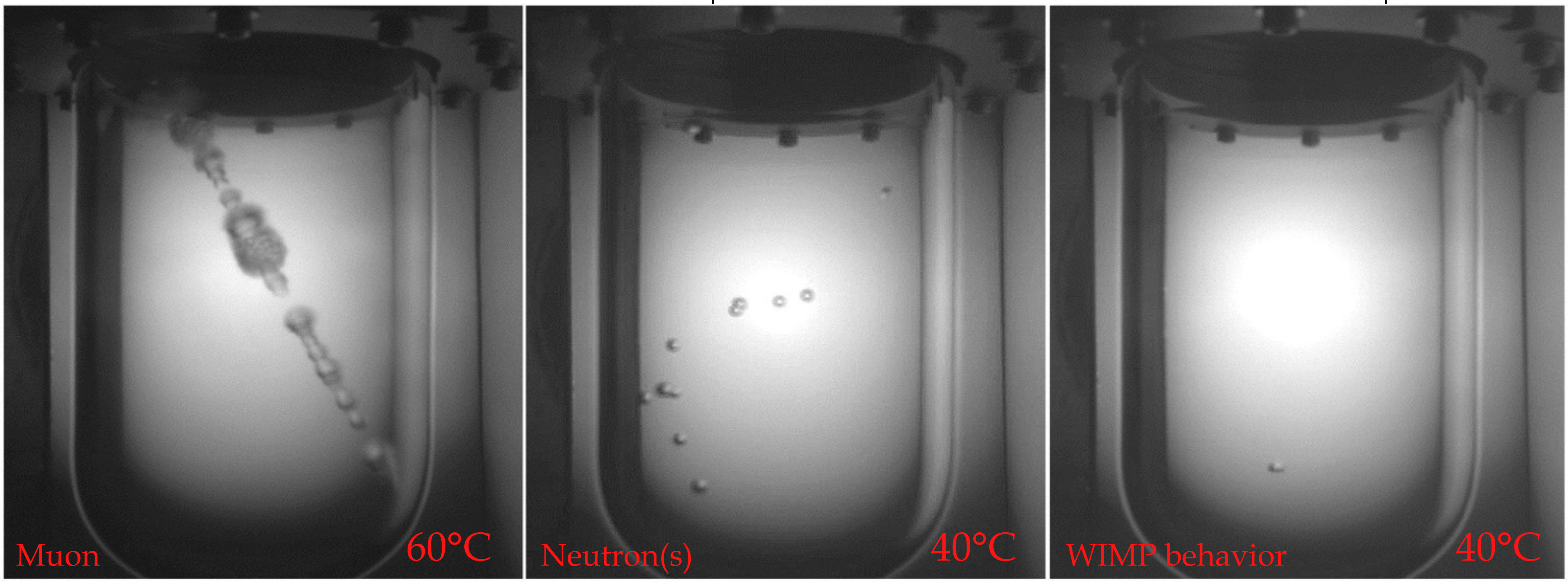




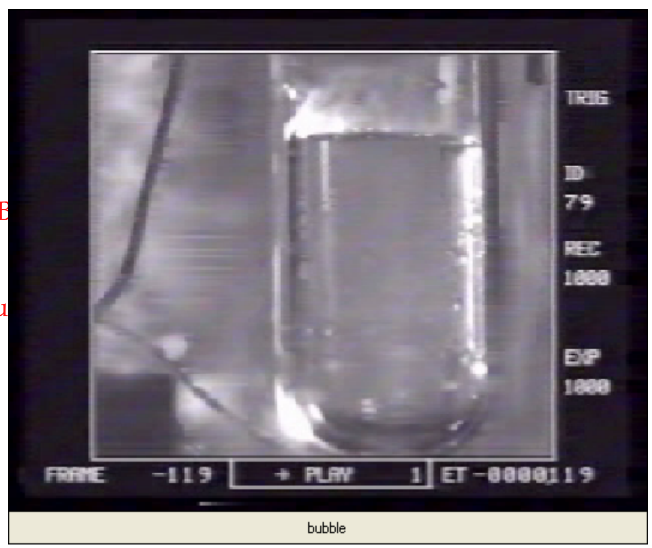
Intrinsic electromagnetic rejection ~10^{-11} at threshold of 10 keV (preliminary)

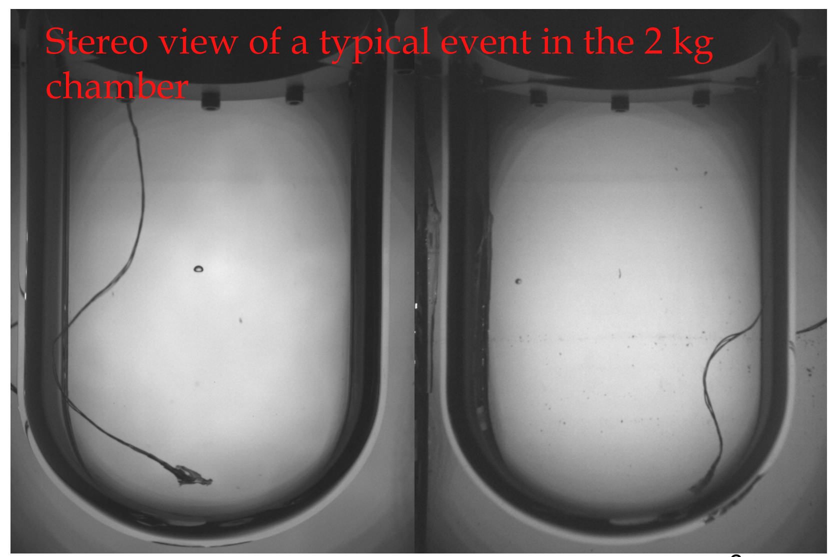
Conventional BC operation
(high superheat, MIP sensitive)

Low degree of superheat, sensitive to nuclear recoils only



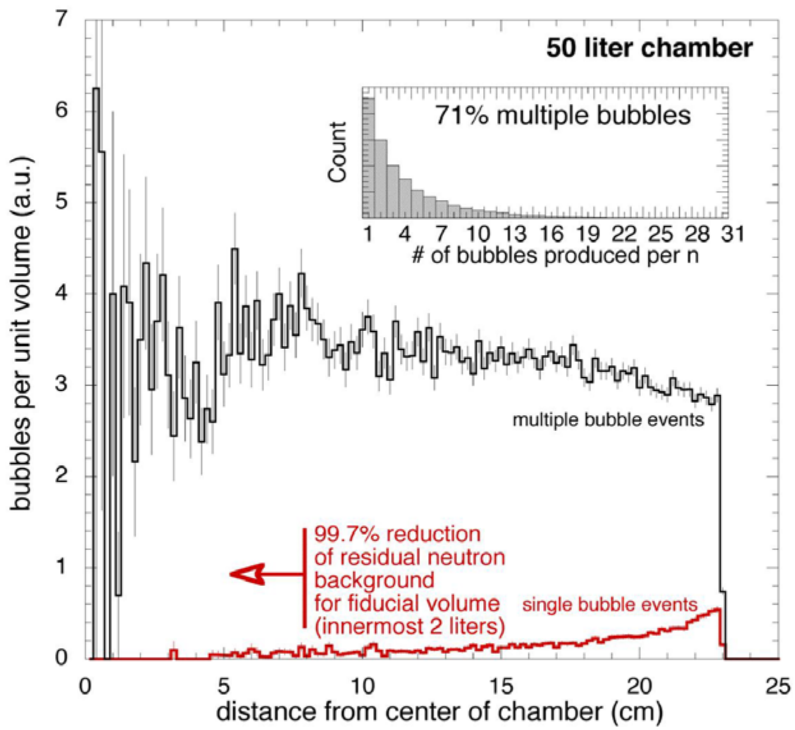
neutron-induced
nucleation in 20 cm^3 CF_3B
(0.1 s real-time span)
Movie available from
http://cfcp.uchicago.edu
~collar/bubble.mov





Backgrounds

- γ,β and other mips don't contribute.(Intrinsic rejection ~10^{-11}.)
- Neutrons: spallation, (α,n), NuMI (for now.)
- α from U/Th in detector materials/ Rn diffusion.



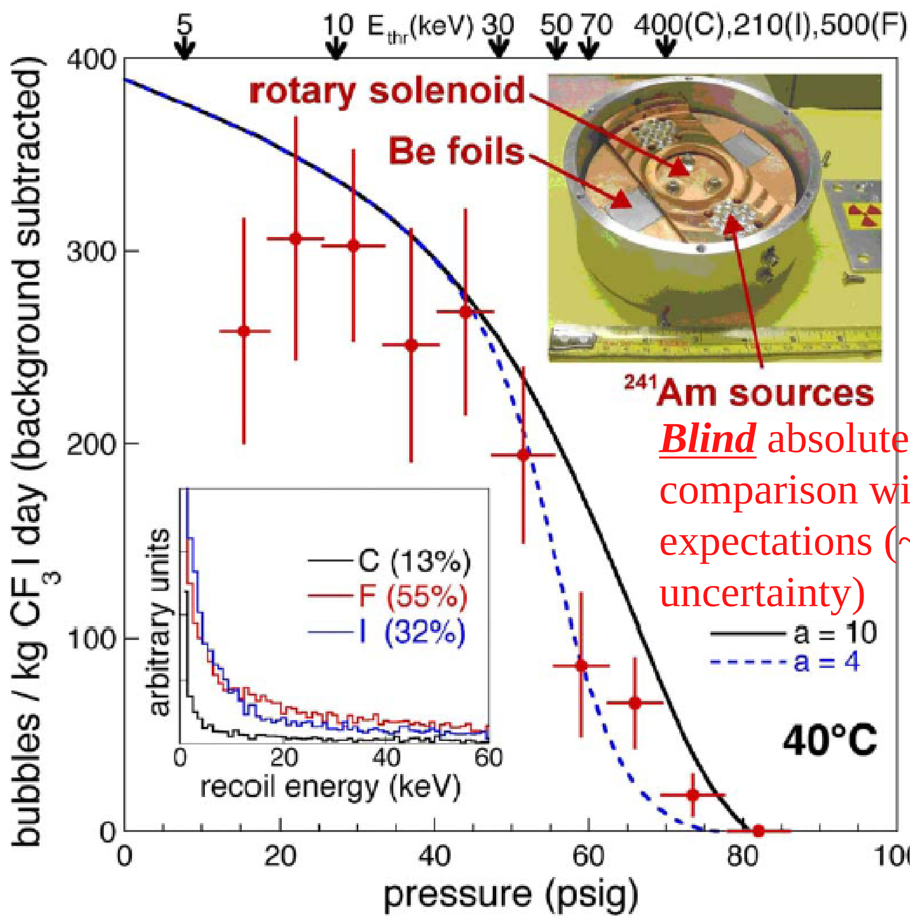
Neutron contribution:
Muon veto, go deep, volumetric analysis, multiplicity ratios, and exciting recent discovery by PICASSO. (Even more useful for COUPP)

α contamination is sole concentration for radiopurification.

COUPP Engineering Run and First Results

(Reported in *E Behnke et al., Science* ***319****, 933 (2008)* Feb 15

- First run meant to demonstrate engineering details of small scale device. Daq, recompression, vessel, bellows, pressure transducers, ccd cameras etc.
- Develop experimental tools: Calibration techniques, test CF3I properties, thresholds, etc.
- 2kg of CF3I.
- 52 kg d analyzed
- (almost) No measures against α background.
- No measures against cosmic or NuMI beam background
- Experiment in NuMI tunnel at Fermilab.

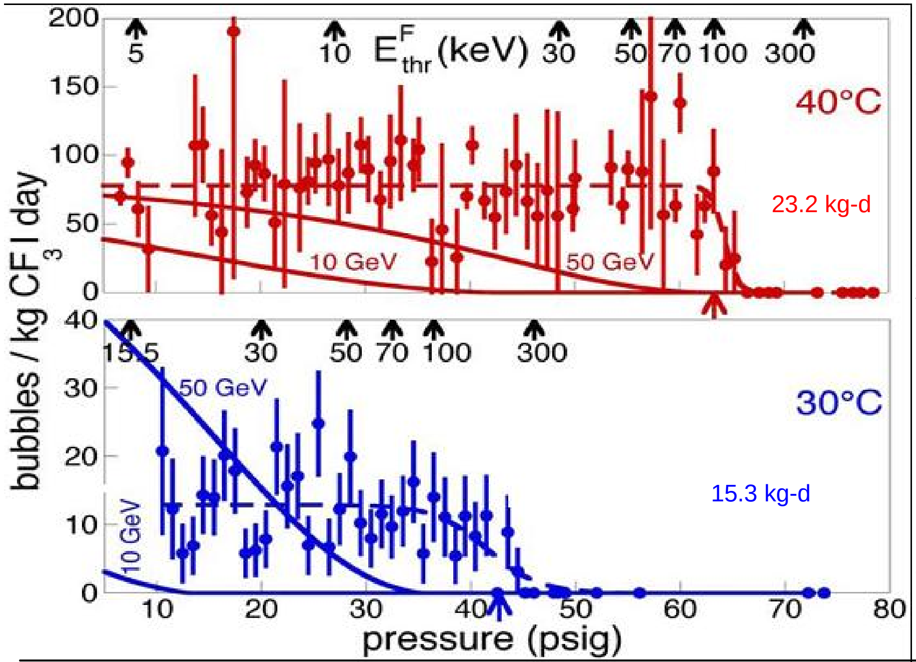


5n/s

Blind absolute comparison with expectations (~30% uncertainty)

WIMP response studies (Neutrons)
Lines –'blind' M.C.(theory folded with detector details).

COUPP Engineering Run and First Results

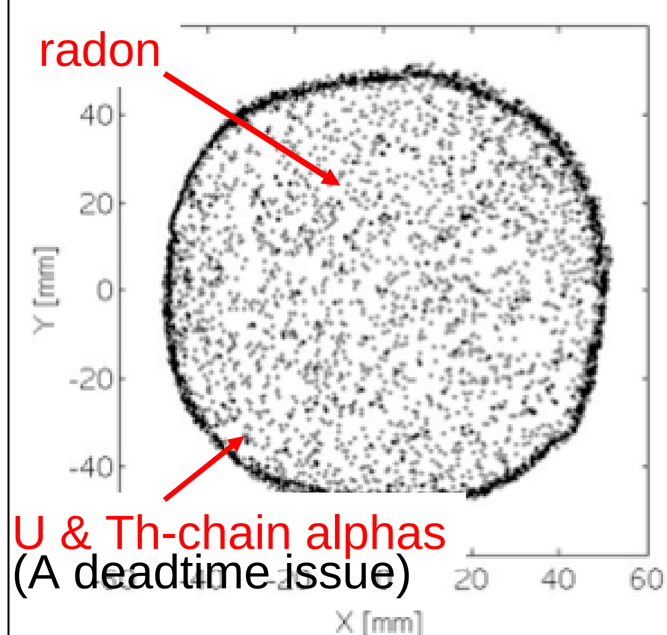


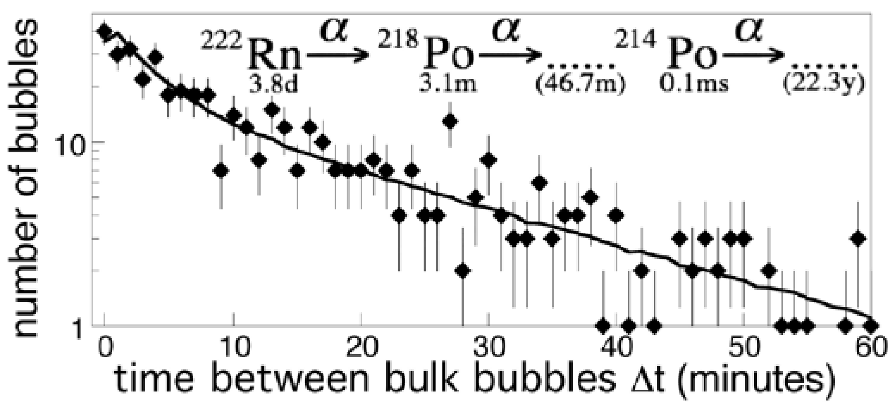
Dotted lines: expected response to monoenergetic alphas from Rn.

Solid lines: expected response to different mass WIMPs (@3pb.)

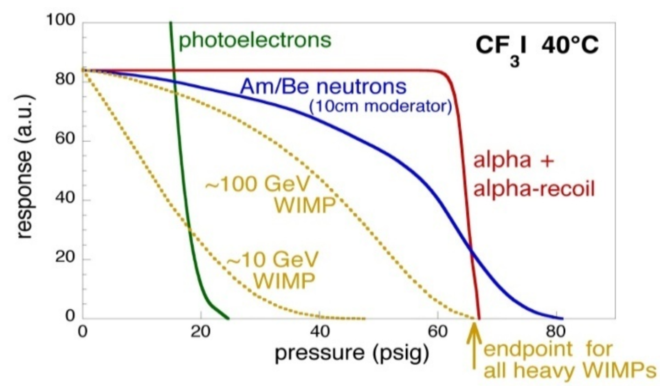
Colored arrows: expected onset to Rn decays.

Top axes: Calc thresholds for ^{19}F recoils.

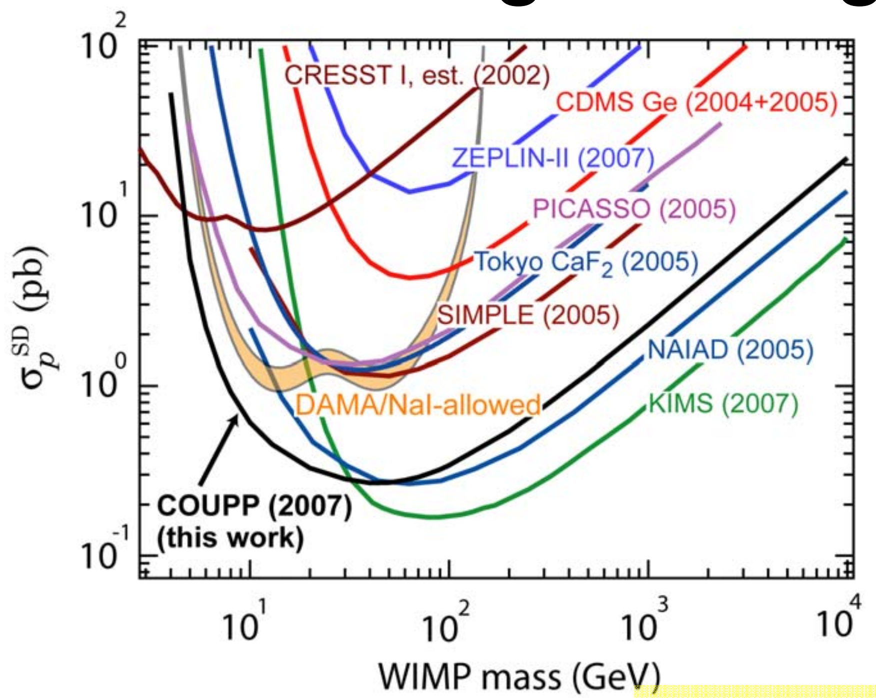


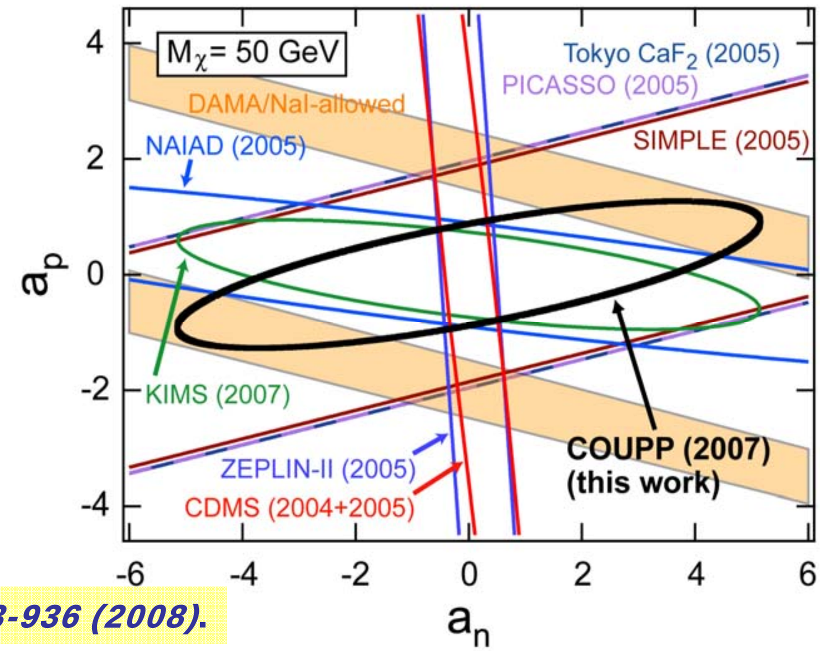


Time~100% Rn.

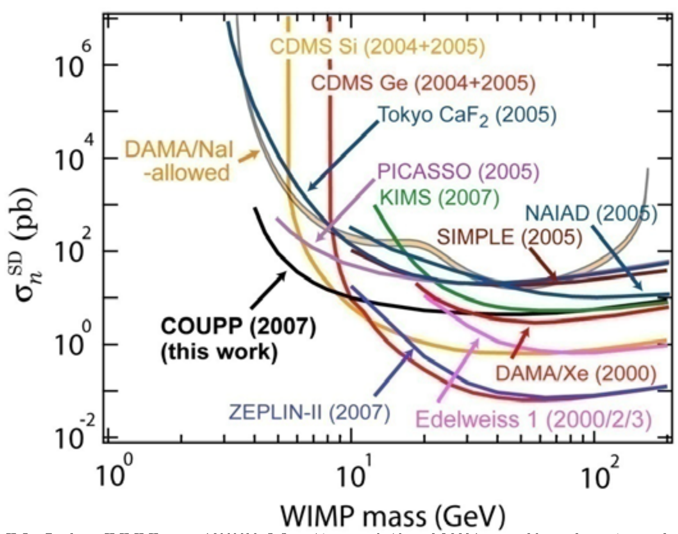


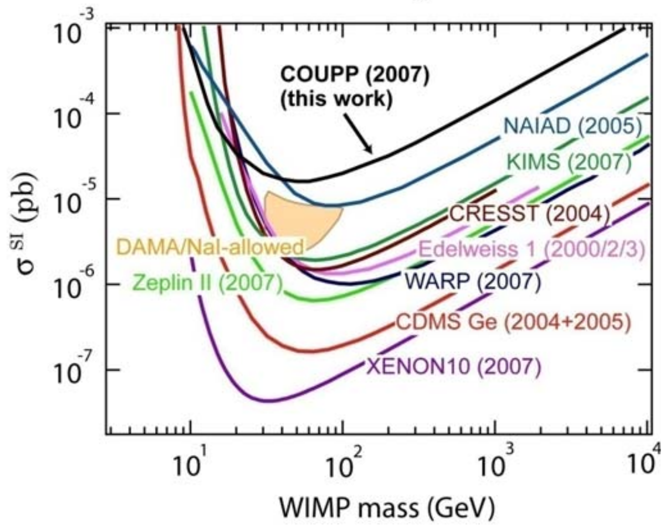
COUPP Engineering Run and First Results





Science, 319: 933-936 (2008).





Moving Forward

- Cosmic induced Background
- α-Background – step I
- Live Fraction
- Energy Thresholds

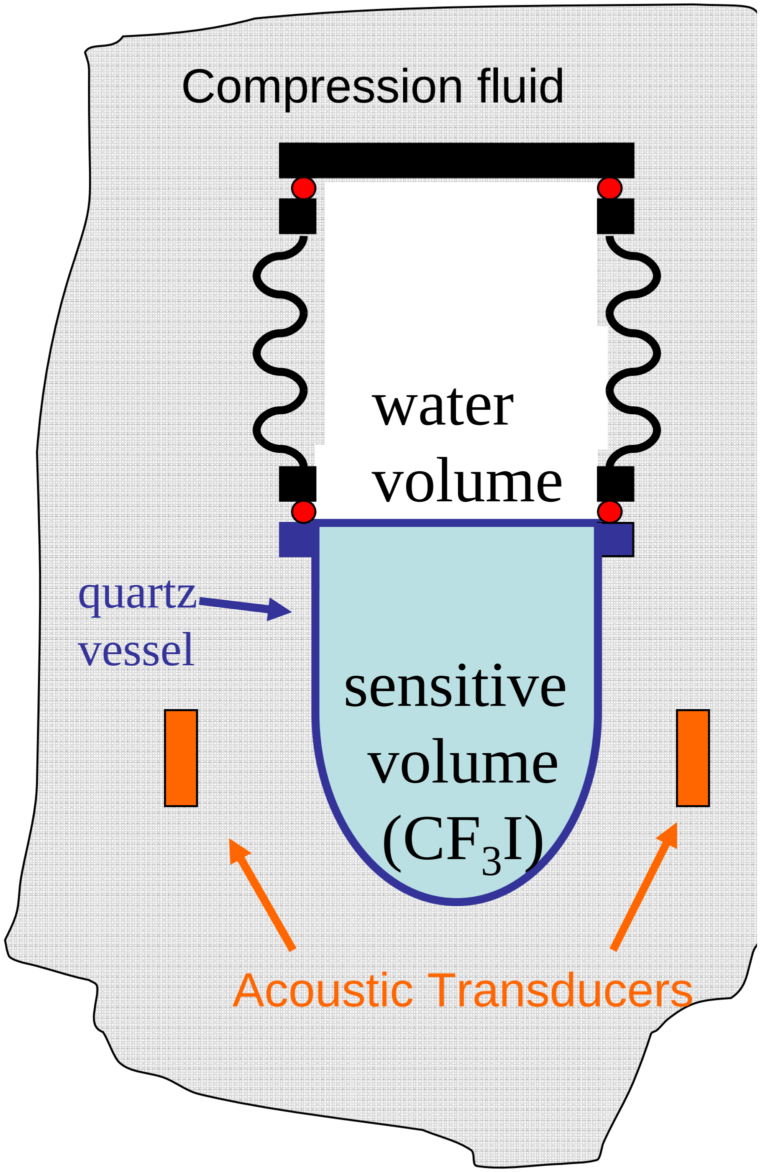
Run II and beyond

- α-Background – step II
- Acoustic Particle ID
- Larger target masses
- Schedule

Run III and beyond

COUPP Run II: (July '07- June '08) Cosmics:

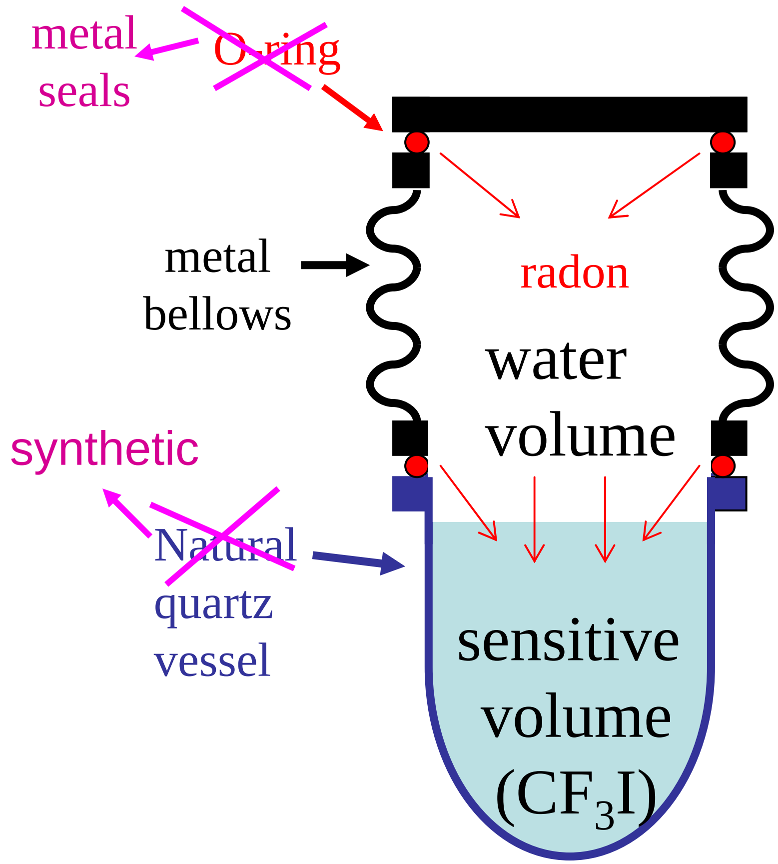
- **Muon veto system**
  - Counters surplus from KTeV
  - Acoustic Transducers for T_0



COUPP Run II: (July '07- June '08)
Reduce Bulk Rn, Increase Live Fraction

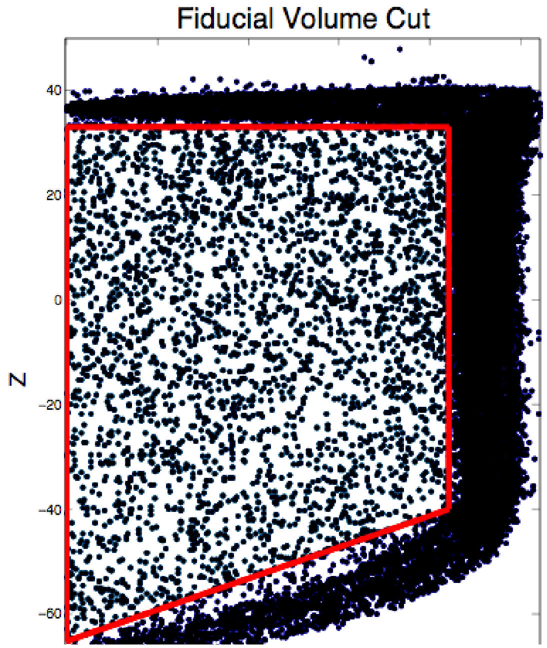
- **•Improved quartz-to-metal seals**
  - – Viton rubber -> Teflon- coated Inconel
  - – Low radon emanation

    <1.6 atoms per day per O-ring
- • Improved cleaning procedures
- **•Ultra high purity water from SNO**
- • New bellows assembly with non-thoriated welding
- • Improved photography
- • Improved operations procedures

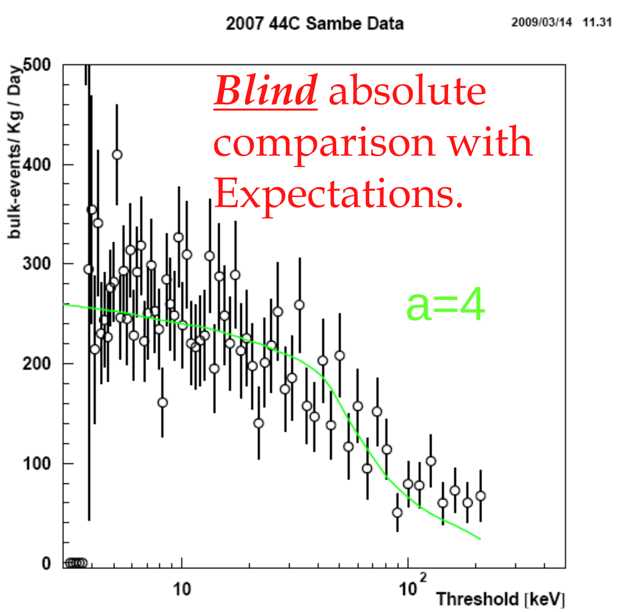


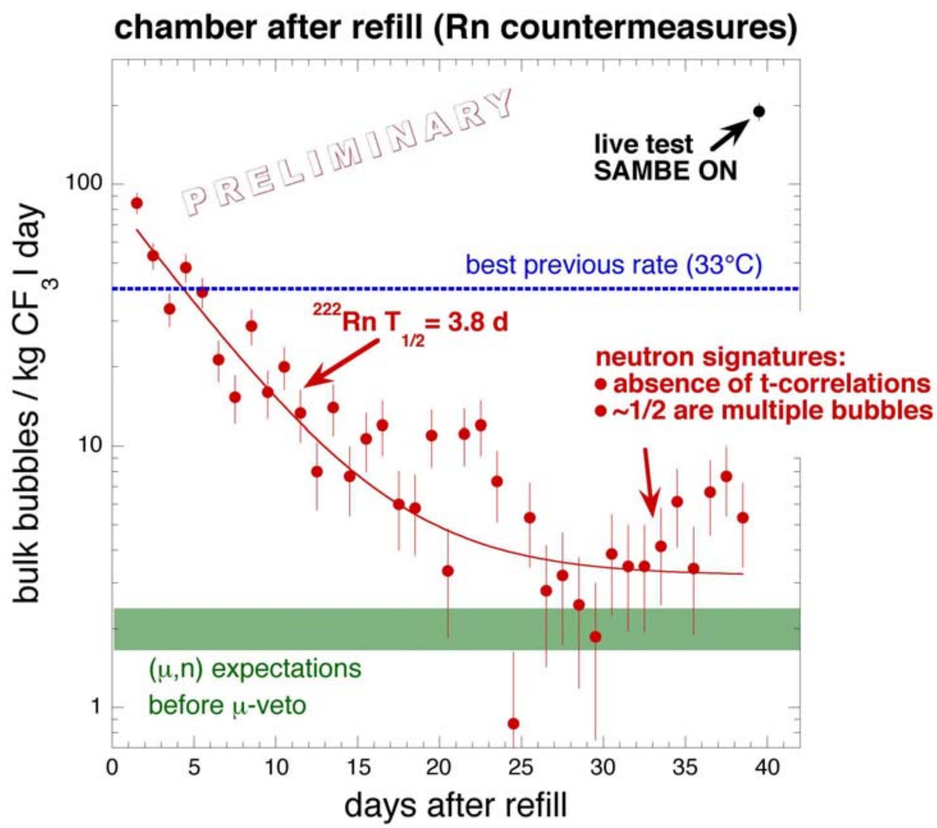
- **• New quartz Inner Vessel**
  - – Lower exposure to atmospheric radon, but still natural quartz
  - – Etching of quartz to remove shallow implanted Rn daughters

Data From COUPP Run II: July '07-June '08



- Wall events unaffected ☹
- **Radon reduced ! ☺**
- **Numi induced ~5ev/d, 4% livetime loss**
- **Improved calibrations ☺**
- **Ambiguity of veto at low superheat. ☹ Can fix with improved transducers/coupling!**





Run III: Improved Radiopurification

Water: Start with distilled, deionized lab water.

UV biocide, organic breakdown, ultra-filtration.

degassing (liquicel.)

CF_3I pressure vessels

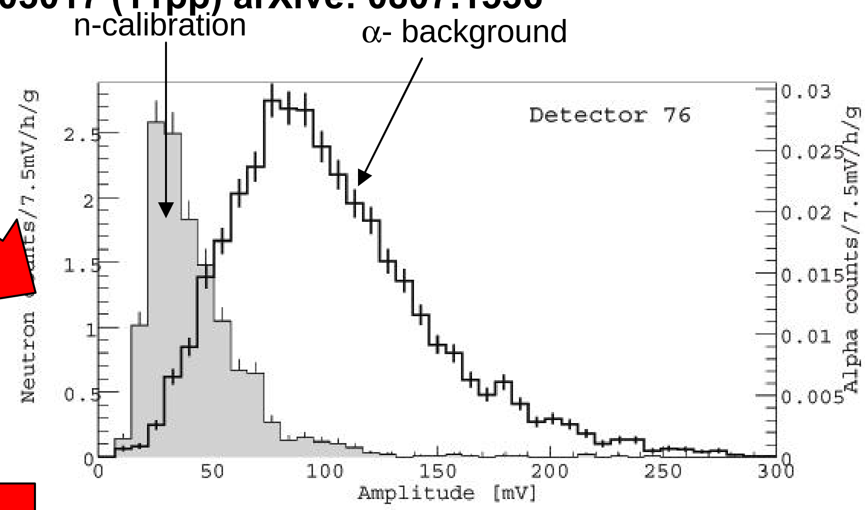
High purity distillation

Bubble chamber.

Run III R&D: Acoustic Discrimination of Nuclear Recoils from α Particles

PICASSO discovered a significant difference between amplitudes of neutron and α- particle induced events ! New J. Phys. 10 No 10 (October 2008) 103017 (11pp) arXive: 0807.1536

Average of peak amplitudes of nine transducers / detector. High pass filter with cut-off at 15 KHz



Signals carry information about first moment of bubble formation

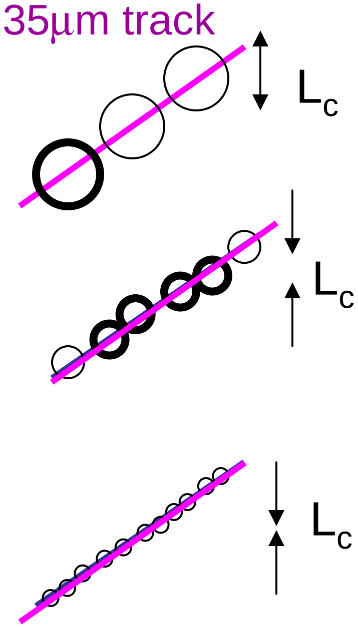
Nuclear recoil:point like, dense ionisation

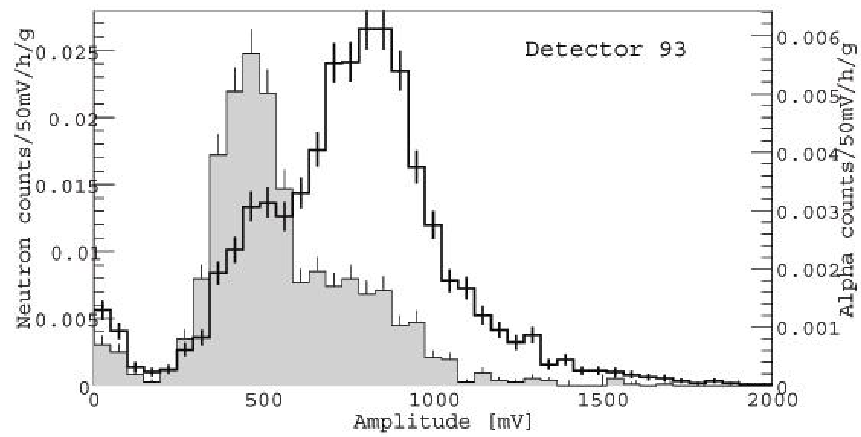
α-particles: ionization on 35μm track

T = 30^{0}C

T = 40^{0}C

T = 50^{0}C





α-WIMP discrimination: independent of α–emitter purity requirements.

COUPP Run III 60 kg chamber

Traditional design – 60 kg Vessel now being assembled about 90% finished.

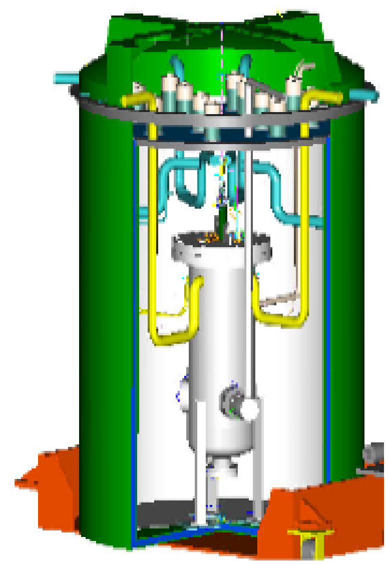
Complete fabrication and testing at D0 Summer 2009

Install in NuMI tunnel FY2010

(NuMI run:unattended operation, α backgrounds ~ 1ev/kg/d (or better!) (2007 run ~10ev/kg/d). Estimate untagged cosmics ~0.1 ev/kg/d. Significant new limits

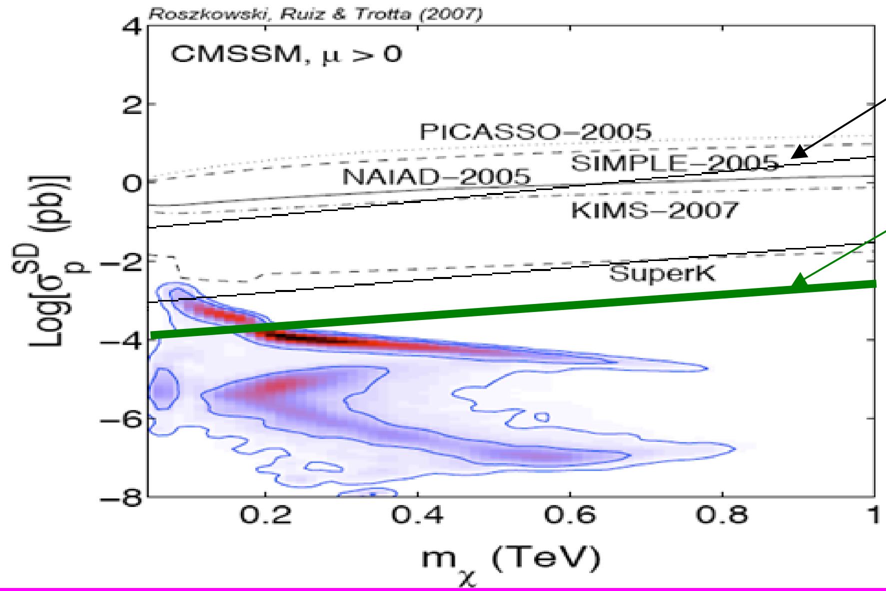
(Run IV)Installation in deep site and operate ~FY 2011

‘Traditional’ 60 Kg Vessel:



E-961 Physics Reach (Runs III & IV)

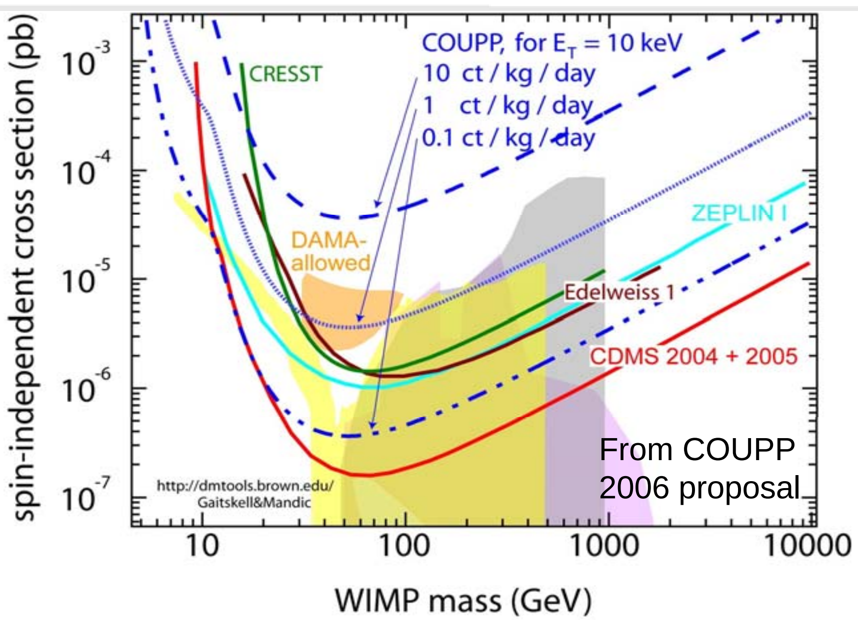
Background goal for E-961: <1 bulk event per kg per day



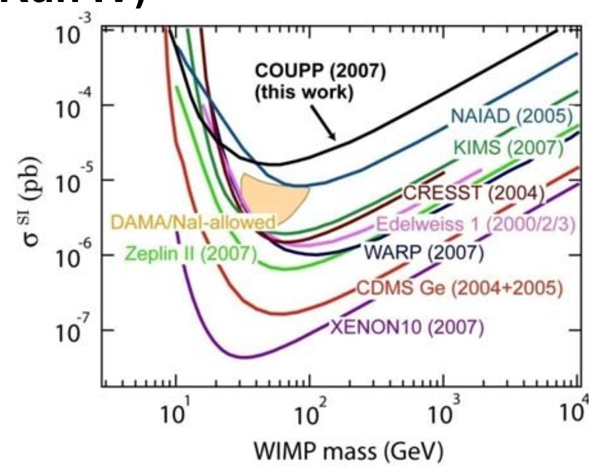
COUPP (2kg, 2007)

COUPP 2009 expected sensitivity {muon veto running, 300 mwe, ~1ct/kg/d} **Exploring SD favored region for the first time.**

300 mwe (Run III)



SI limits for various bulk event rates assuming all signal candidates→limits below shown- 0.01 ct/kg/d background conceivable deep (Run IV)



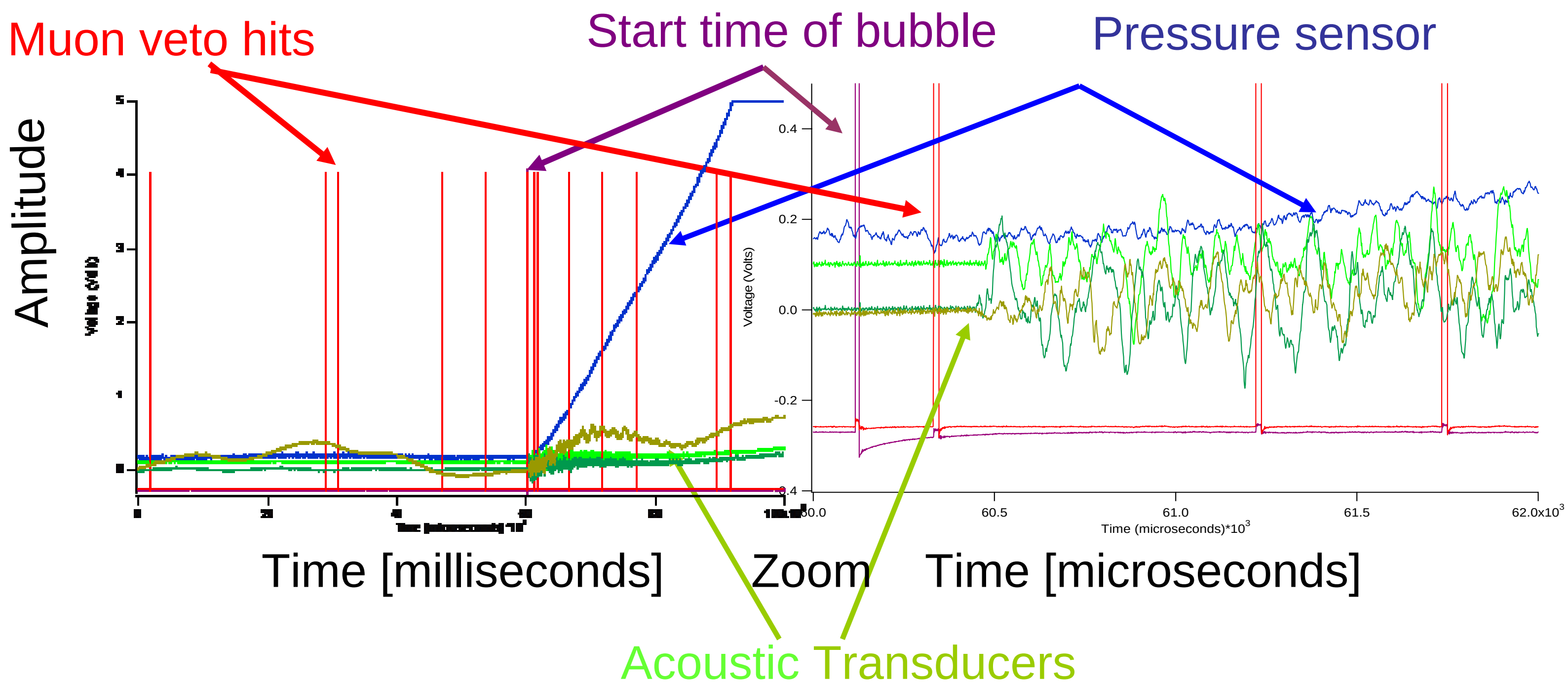
Conclusions

- Moderately superheated BC: inexpensive technology for DM search
- Easy to switch to a number of room temp superheated fluid targets.
- Entering ~100kg regime now.
- Intrinsically insensitive to β,γ and mip. (rejection O 10^{-11})
- Increased effort on radiopurification now under way.
- Exciting possibility of event-by-event alpha/WIMP discrimination.
- Deep in FY2010.
- Entering SD favored region and approaching SI forefront soon.
- Considering larger scale experiment (500kg units?, Traditional? Windowless?)
- PICASSO-COUPP MOU. Joint R&D under way, Eventual collaboration.

QUESTIONS?

Extra slides

COUPP Run II: Timing Bubbles With Acoustic Pulses



- Fast rise time (~5μs) of acoustic sensors leads to small veto-induced dead time.
- High efficiency when pulses are relatively large (low operating pressure, low energy threshold)
- Becomes challenging as energy threshold is increased (noise level, low gain, inadequate acoustic coupling.)

Run III R&D Acoustic Sensor Designs

Don't know the frequency content of the phase transition.

PICASSO experiment has found rich information in acoustic signal

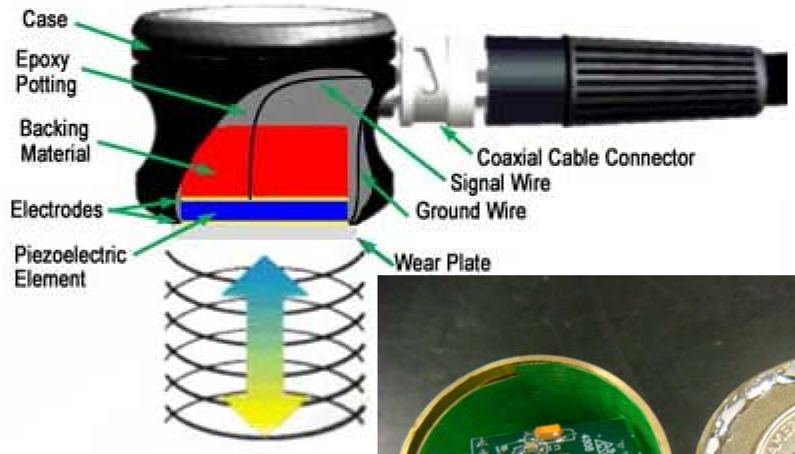
Mixture of Resonant/Non-resonant transducers.

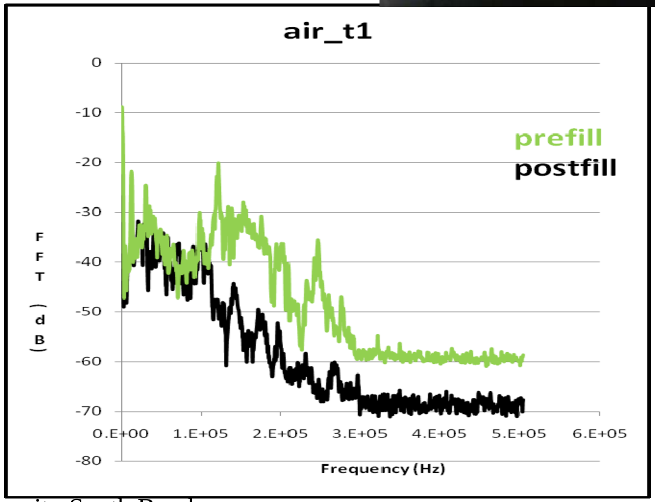
Backing design: (kill resonances)
  Epoxy/tungsten
  Epoxy/tungsten/liquid rubber

Higher gain, wider bandwidth preamp to get to ~O(10MHz) regime.

Go from 2 sided boards to 4 sided for decreased noise.

Thin brass Faraday cage.



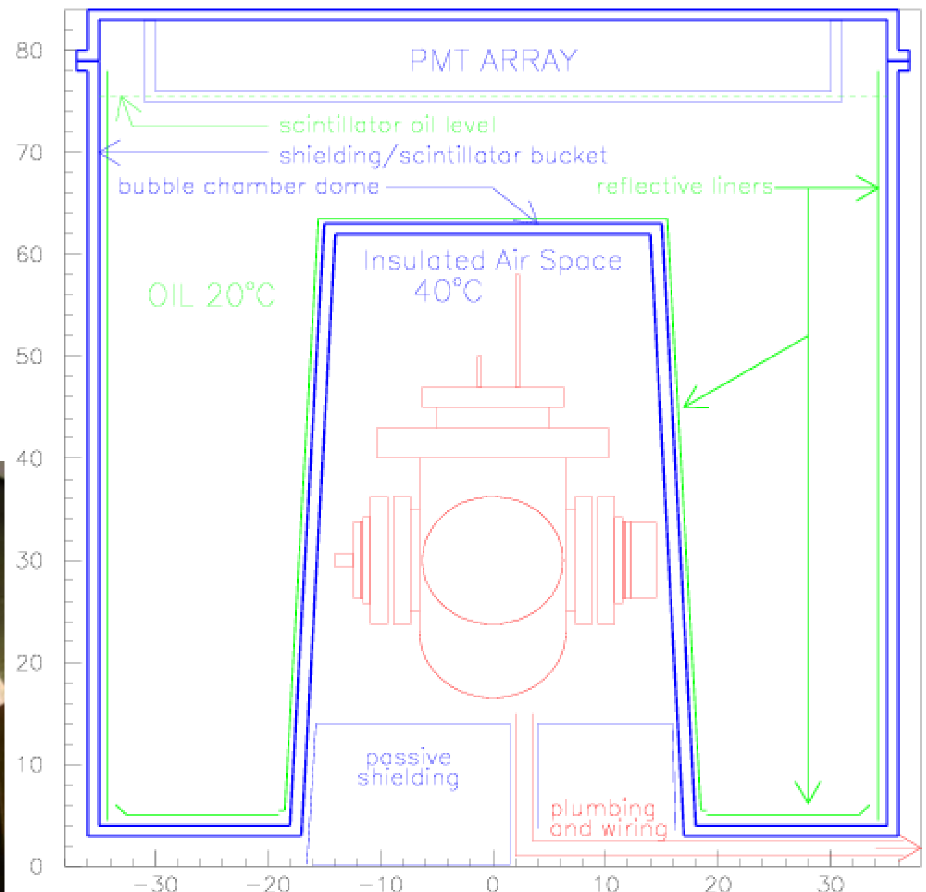


Run III COUPP 4kg Chamber

- 1 liter natural quartz vessel (42 ppb Uranium)
  –-> 2 liter Synthetic quartz (21 ppt Uranium)
- Improved Pressure controller

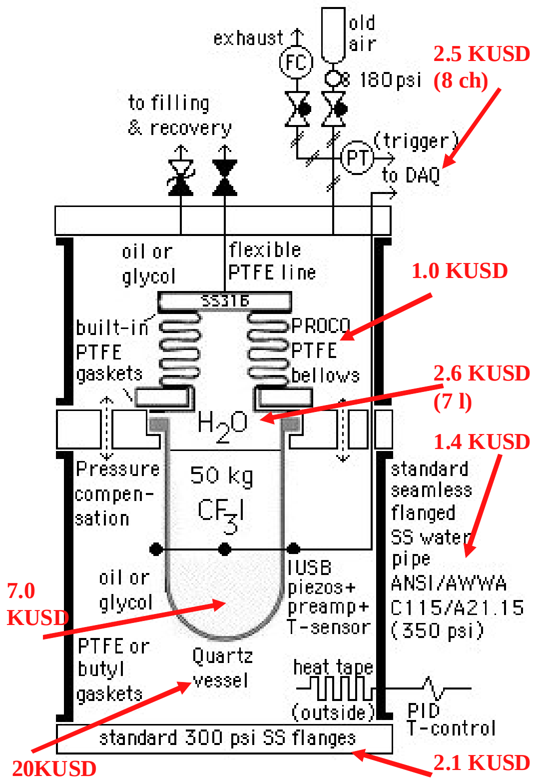
To address cosmic veto weakness

- Liquid scintillator veto tank for better muon identification.
- Improved acoustic sensors.
- Better location of acoustic sensors.



COUPP Run III:Windowless Design

- Windowless concept (much cheaper) test device.
- Suprasil vessel now (21ppt U/Th measured by EXO)



Potentially much less expensive.

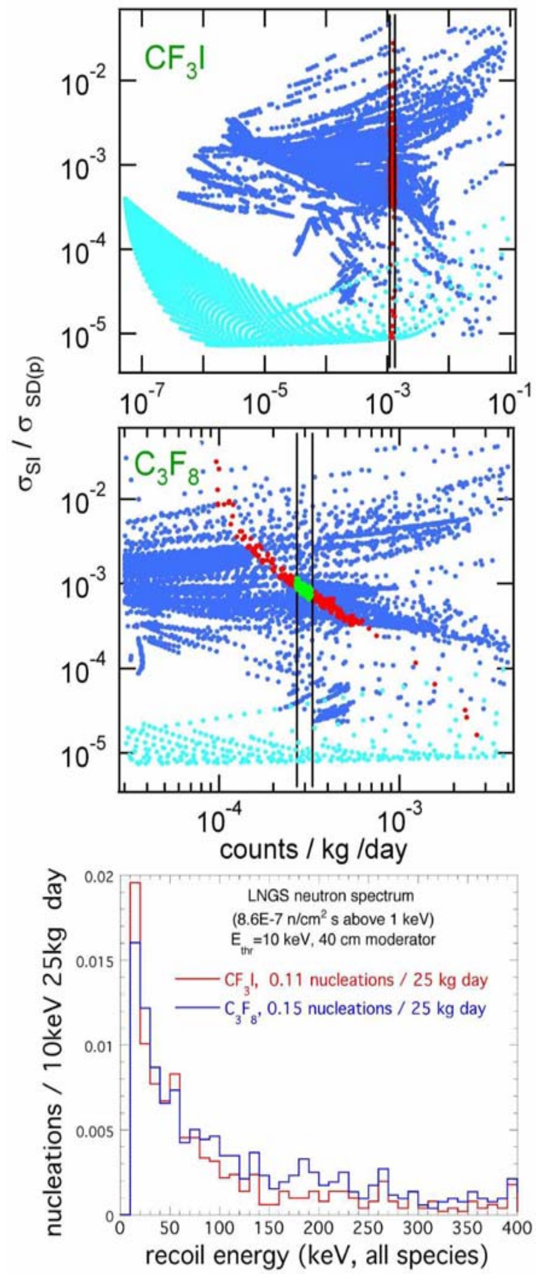
20 kg vessel tested at U. Chicago. Now taking data in the sewers of Chicago at TARP facility (300 mwe.) Wall event rates look low!

Some Other Advantages of Moderately Superheated Technique

1) Once double threshold crossed, growth irreversible (no signal degradation with growth in detector size.)

2) Detector costs much lower than other techniques. No cryogenics or isotopic enrichment. Inexpensive channels and purification.

3) Easy to switch to other fluids ("No liquid that has been tested seriously has failed to work as a bubble chamber liquid" {Glaser, 1960.}) - WIMP/neutron discrimination, study detailed properties of WIMP candidate.



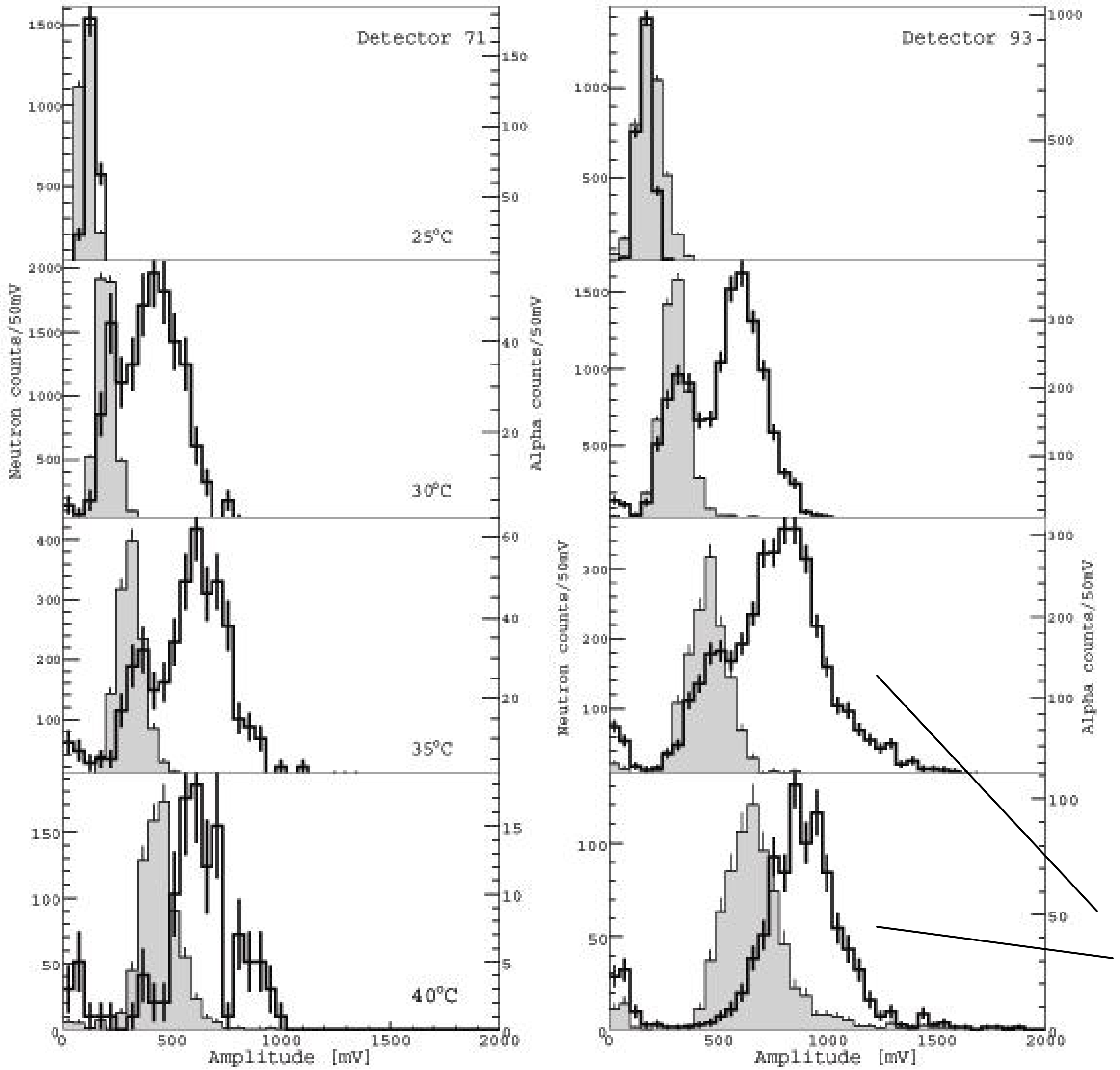
G. Bertone, D.G. Cerdeño, J.I. Collar and B. Odom PRL **99** 151301 (2007)

Rates measured in CF_3I and C_3F_8 (vertical bands) tightly constrain responsible SUSY parameter space and type of WIMP (LSP vs. LKKP)

Neutrons on the other hand produce essentially the same rates in both (σ_n for F and I are very similar)

Can take one's pick of a fluid – they all superheat!

α - n Discrimination: Temperature Dependence



Strong saturation of raw signals above 30^{0}C!