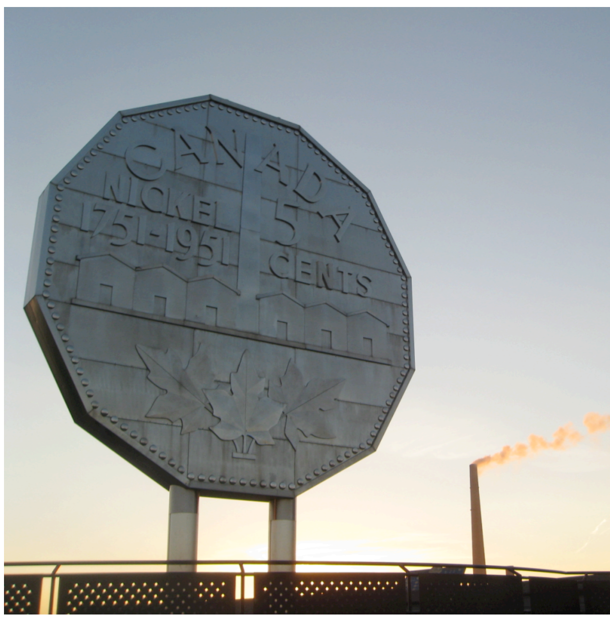
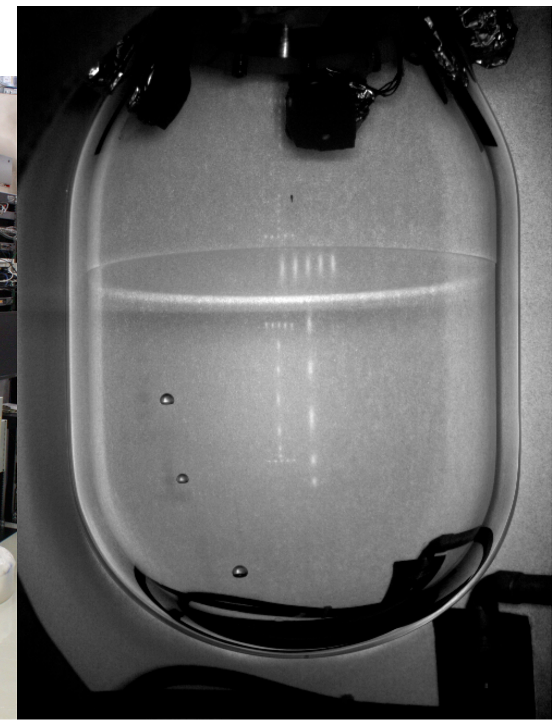
The COUPP Dark Matter Search

Results from the first year of deep-underground running at SNOLAB





The COUPP Collaboration

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Fermilab

Steve Brice, Dan Broemmelsiek, Peter Cooper, Mike Crisler, Jeter Hall, Hugh Lippincott, Erik Ramberg, Andrew Sonnenschein, Fermilab Engineers and Technicians

SNOLAB

Eric Vazquez Jauregui

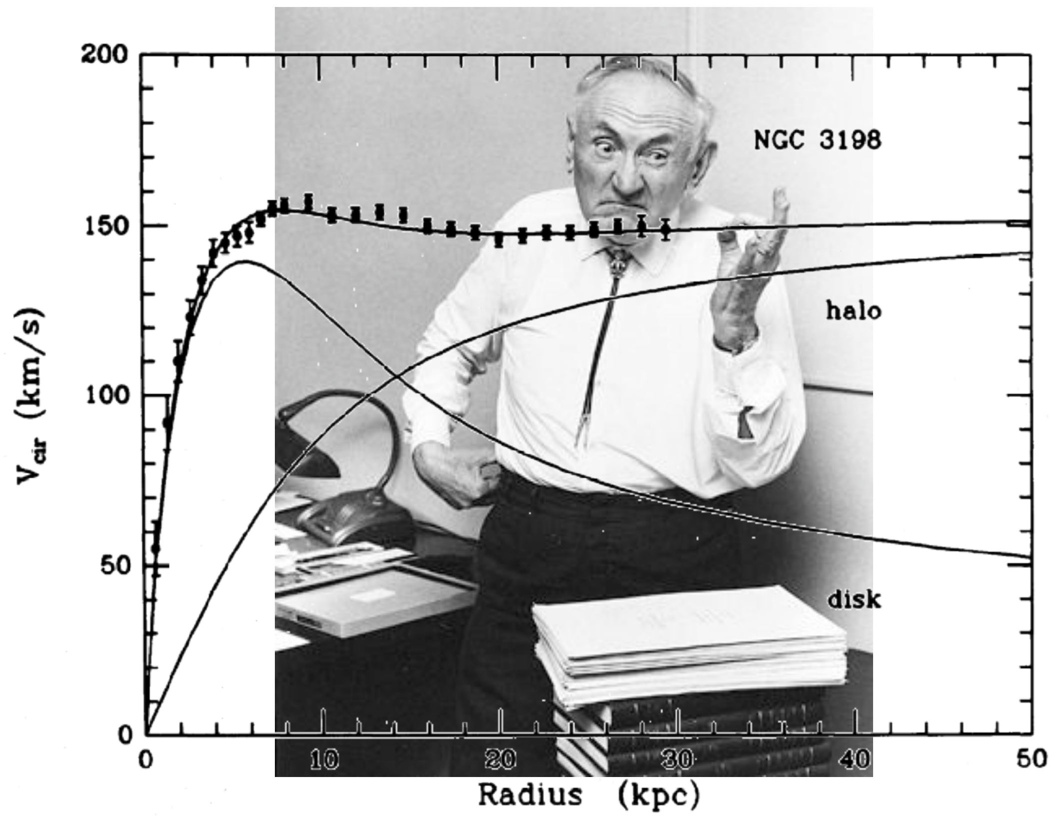
SNOLAB Mining for knowledge Creuser pour trouver... l'excellence

Outline

- The Hunt for Dark Matter
  - Brief History of Dark Matter
  - The WIMP Miracle
  - How to Catch a WIMP
- Bubble Chamber Basics
  - Bubble Chambers as Dark Matter Detectors
- COUPP 4kg @ SNOLAB Results
  - Acoustic Discrimination
  - Limits on WIMP scattering cross sections
  - The road onward…

Early Evidence for Dark Matter

- Fritz Zwicky, 1933
  - Motion of galaxies in Coma Cluster
- Vera Rubin et. al., 1960's
  - Motion of stars, satellites around galaxies



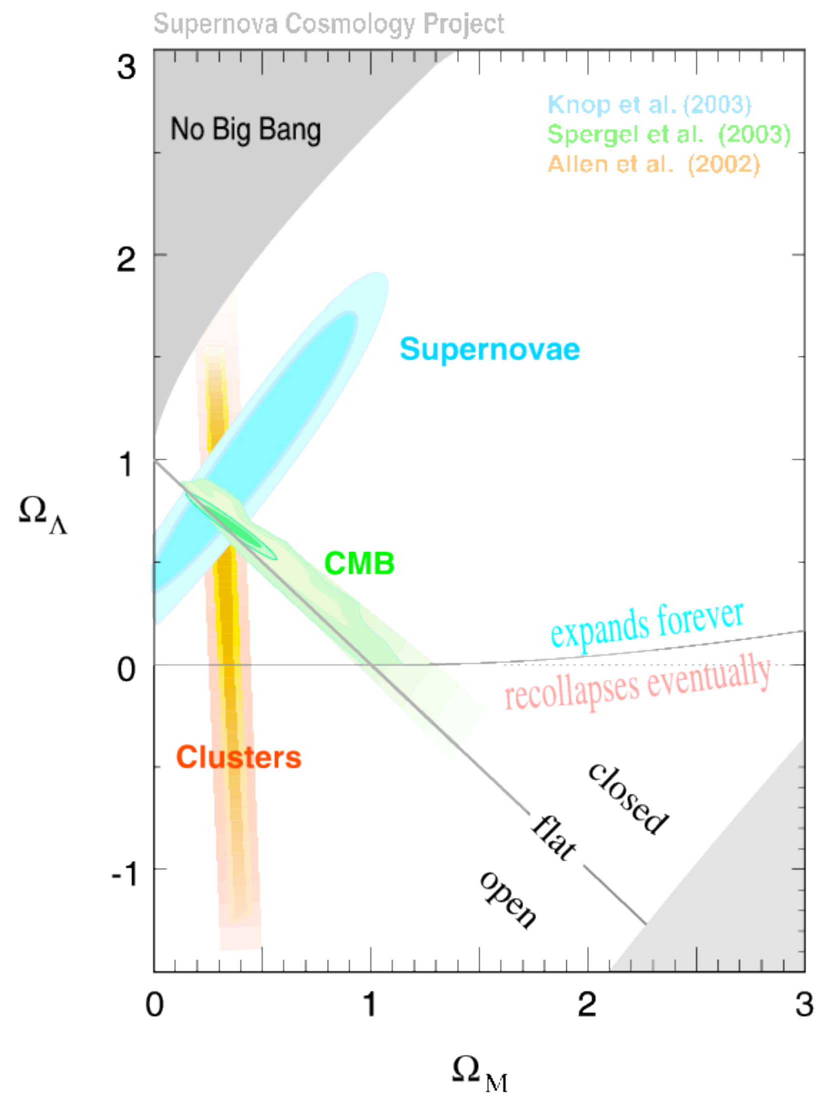
Precision Cosmology: Ω_M

- Mass in clusters
  - Velocity dispersion
  - Gravitational lensing

  measure Ω_M
- CMB anisotropy

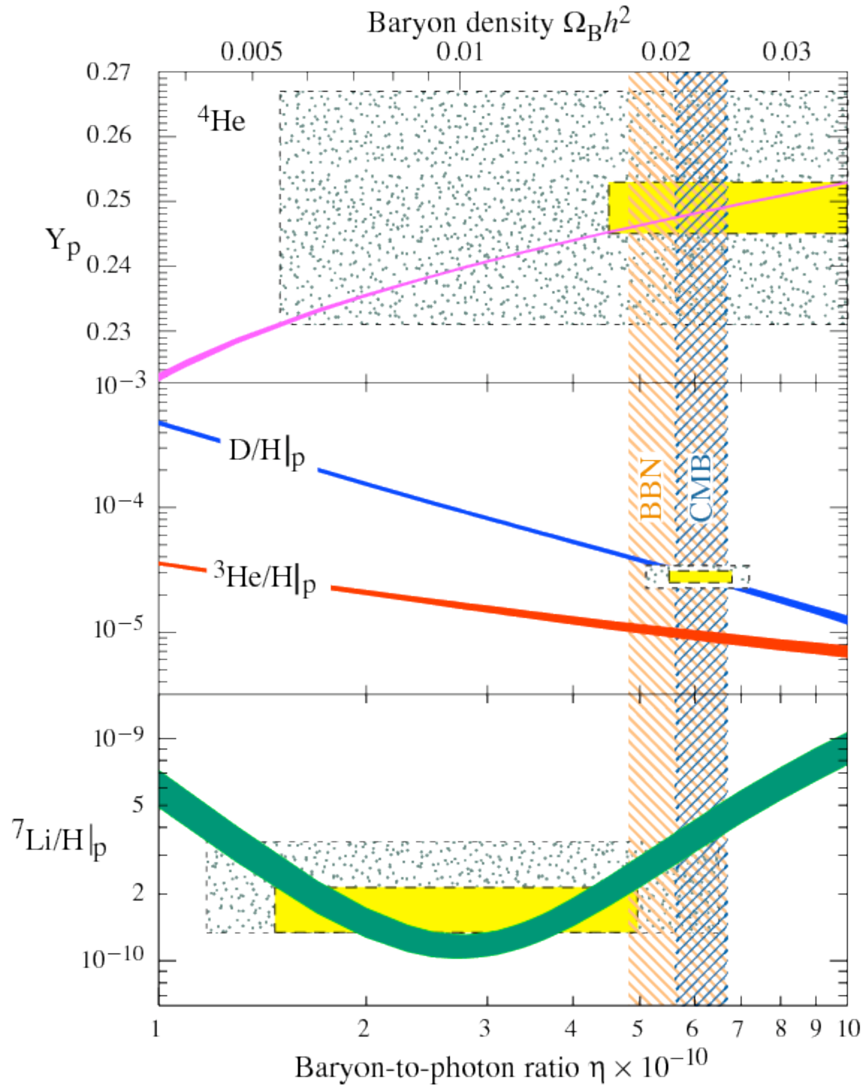
  $$\Omega_\Lambda + \Omega_M = 1$$
- Expansion history of Universe

  $$\frac{1}{H_0^2}\frac{\ddot{a}}{a} = -\frac{1}{2}\Omega_m \left(\frac{a_0}{a}\right)^3 + \Omega_\Lambda$$



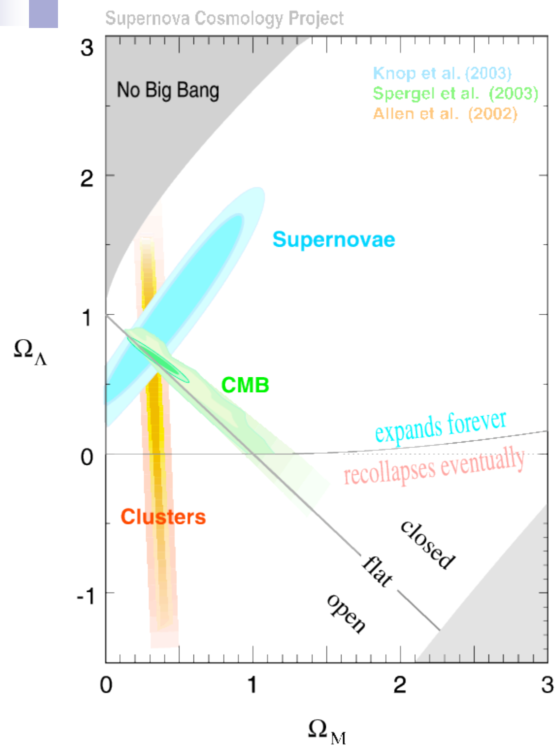
Precision Cosmology: Ω_B

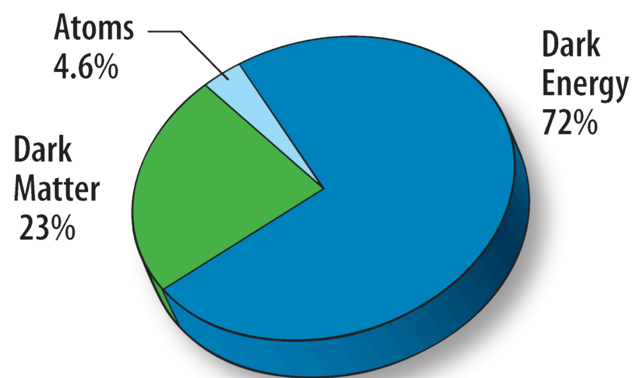
- Big Bang Nucleosynthesis
  - Baryon density determines primordial abundance of light nuclei

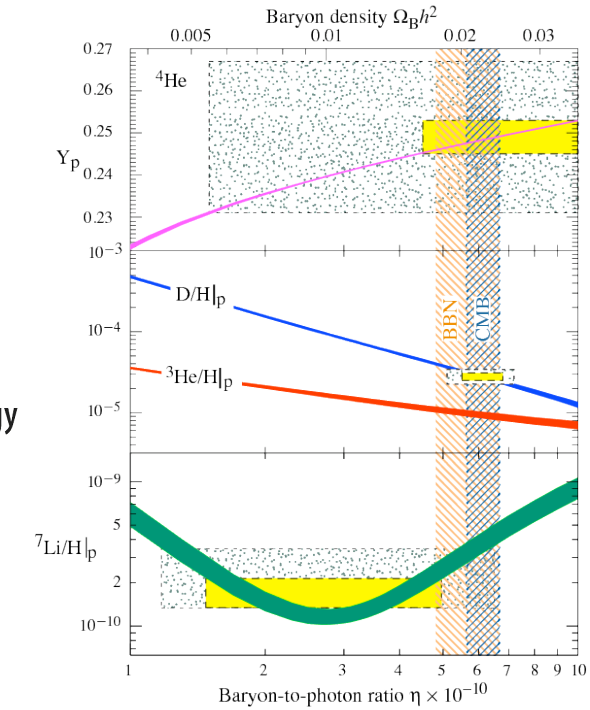


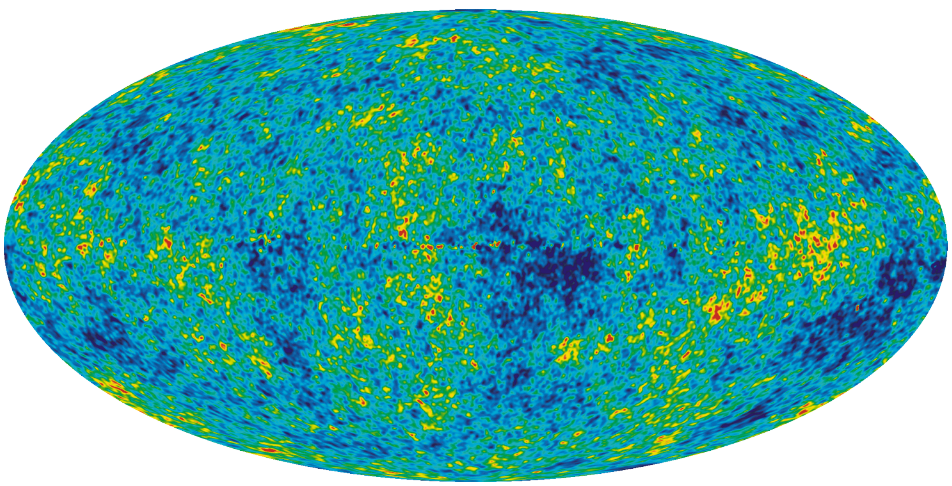
- CMB Anisotropy
- X-ray emmision from intracluster gas

Evidence for Dark Matter



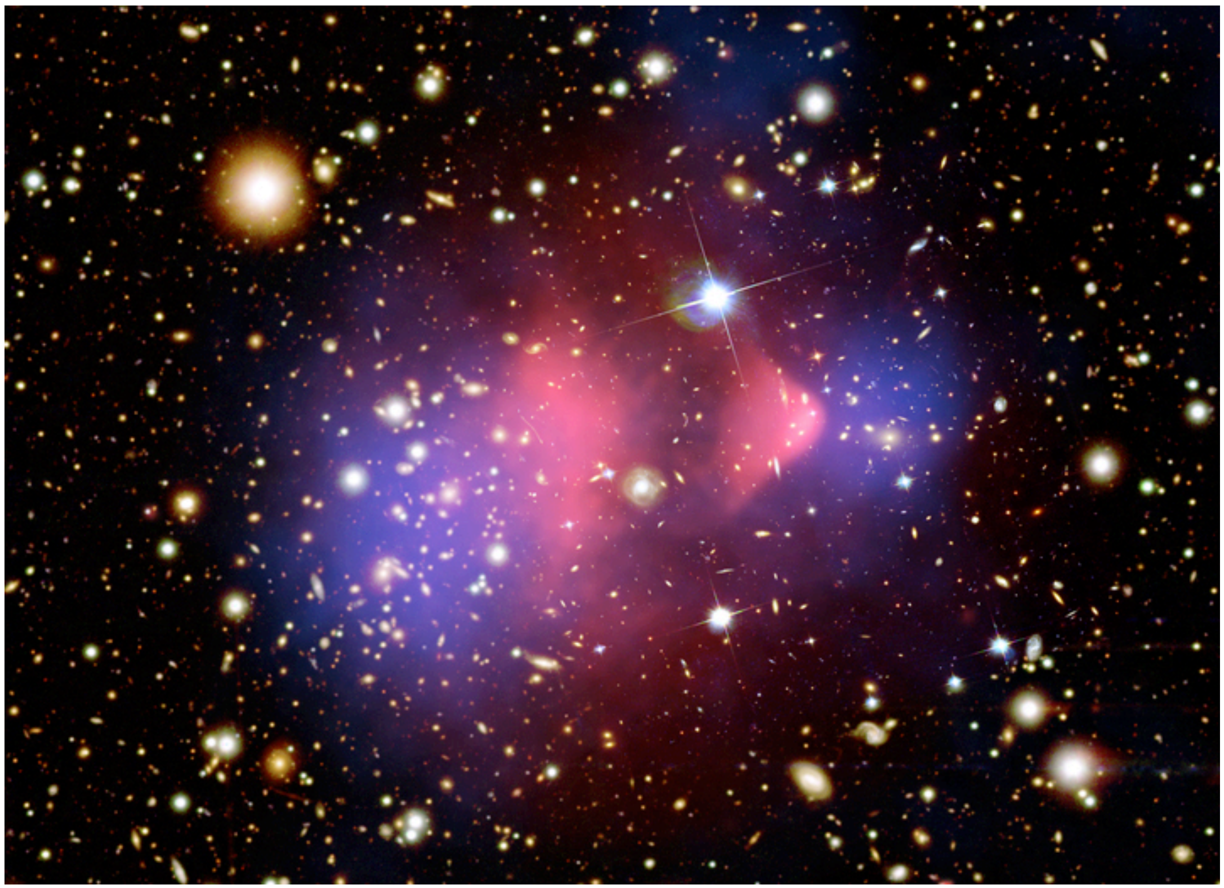






Two more things…

- Structure Formation requires non-relativistic dark matter
- Bullet Cluster shows non- or weakly-interacting dark matter



Dark Matter …

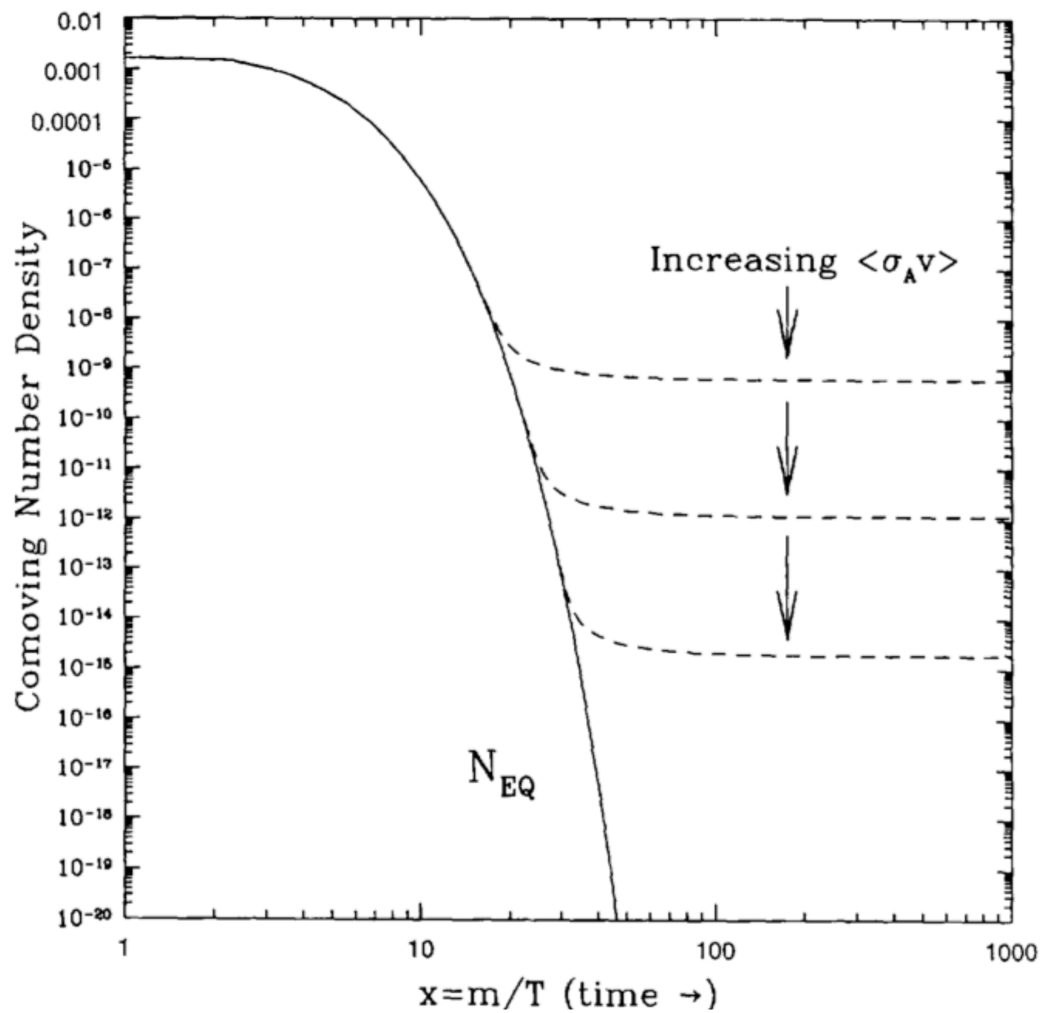
- doesn't emit, absorb, or scatter photons,
  Its dark!
- doesn't decay,
  Its made in the BB & still here
- isn't baryonic,
  or BBN doesn't work
- isn't relativistic,
  bound to (is) the galaxy
- doesn't have any strong interactions…
  The sun isn't 6x heavy

No candidates in the Standard Model!

Relics and Miracles

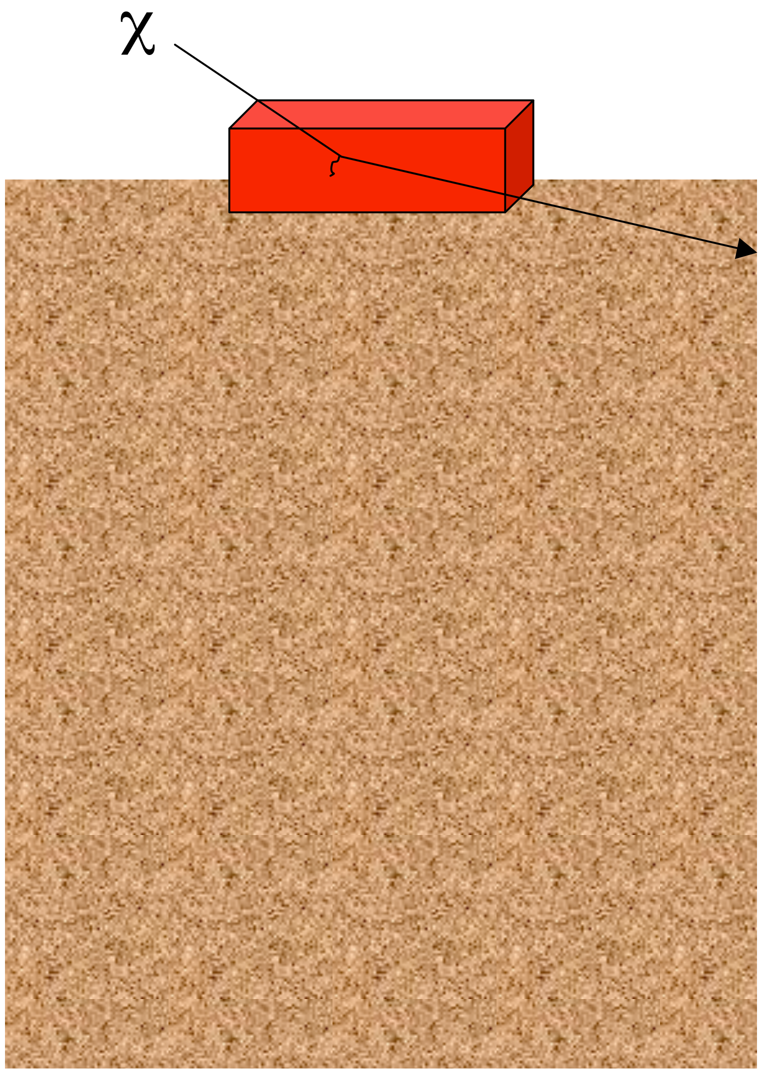
$$\frac{dn_\chi}{dt} = -\langle\sigma_a v\rangle\left[(n_\chi)^2 - (n_\chi^{eq})^2\right] - 3Hn_\chi$$

- Suppose Dark Matter is:
  - Stable Particle (LSP…)
  - Thermal Relic of Big Bang
- Weak-scale interaction gives required density for dark matter



WIMP Detection

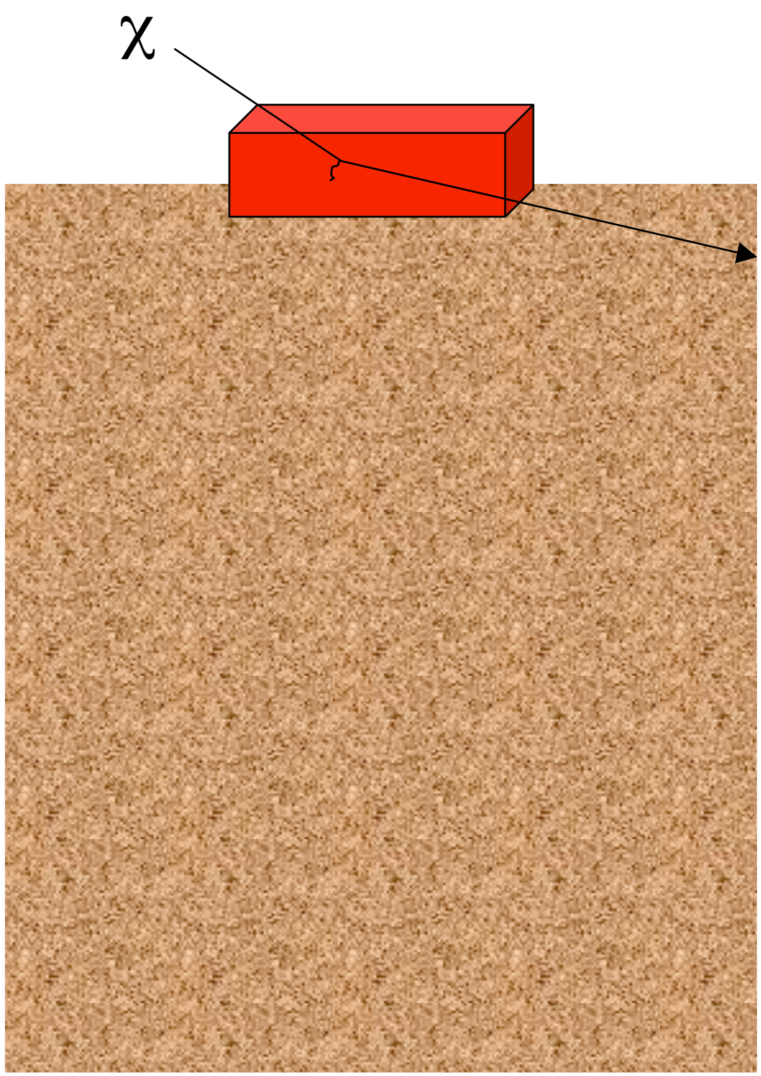
- We live in a Dark Matter halo!
  - Local density ~0.4 GeV/cm^3
  - rms velocity 230 km/s
- Look for coherent elastic scattering off of nuclei
- Two generic interactions
  - Spin-Independent (*e.g.*, scalar coupling, …) Coherent Scattering ($\sigma \propto A^2$)
  - Spin-Dependent (*e.g.*, vector coupling, …) Couples to odd-nucleon



WIMP Detection

- We live in a Dark Matter halo!
  - Local density ~0.4 GeV/cm^3
  - rms velocity 230 km/s
- Look for coherent elastic scattering off of nuclei
  - Recoil energies *O*(10) keV
  - Rates ≤ *O*(1) event / kg-year

  XENON100, 3 events in 4 kg-years,
  (consistent with expected background)
  Phys. Rev. Lett. **107**, 131302 (2011)



WIMP Detection

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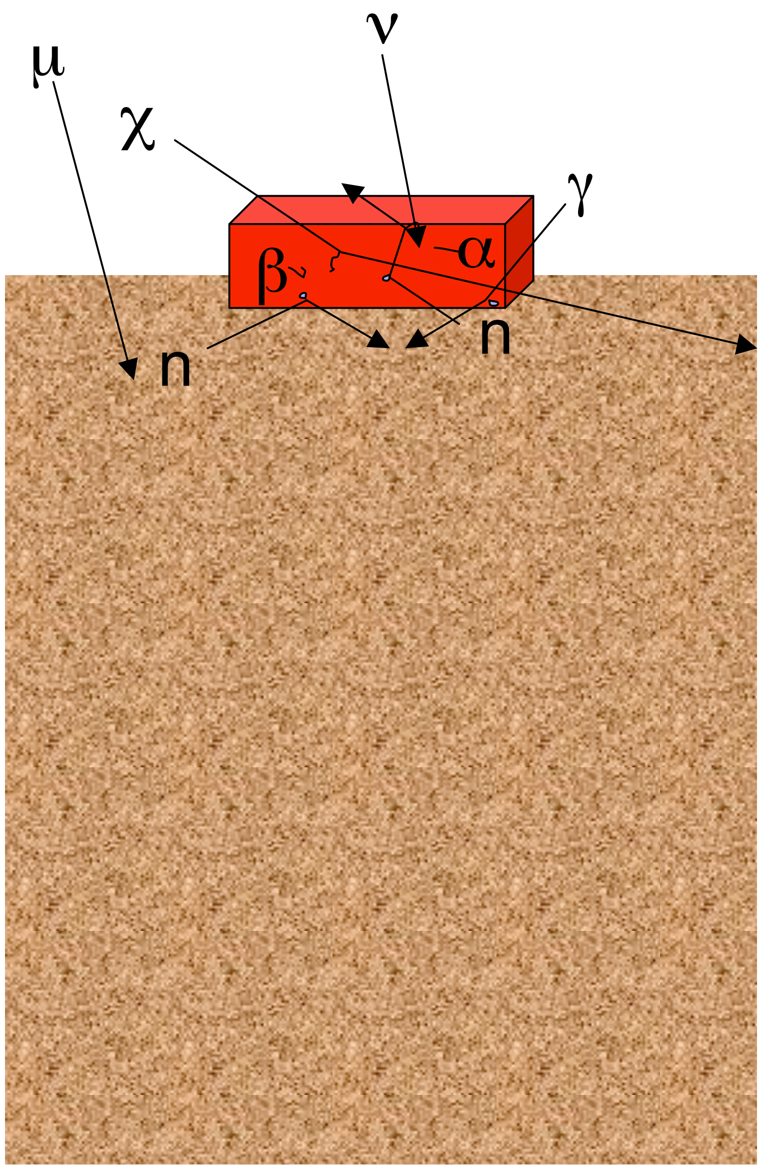
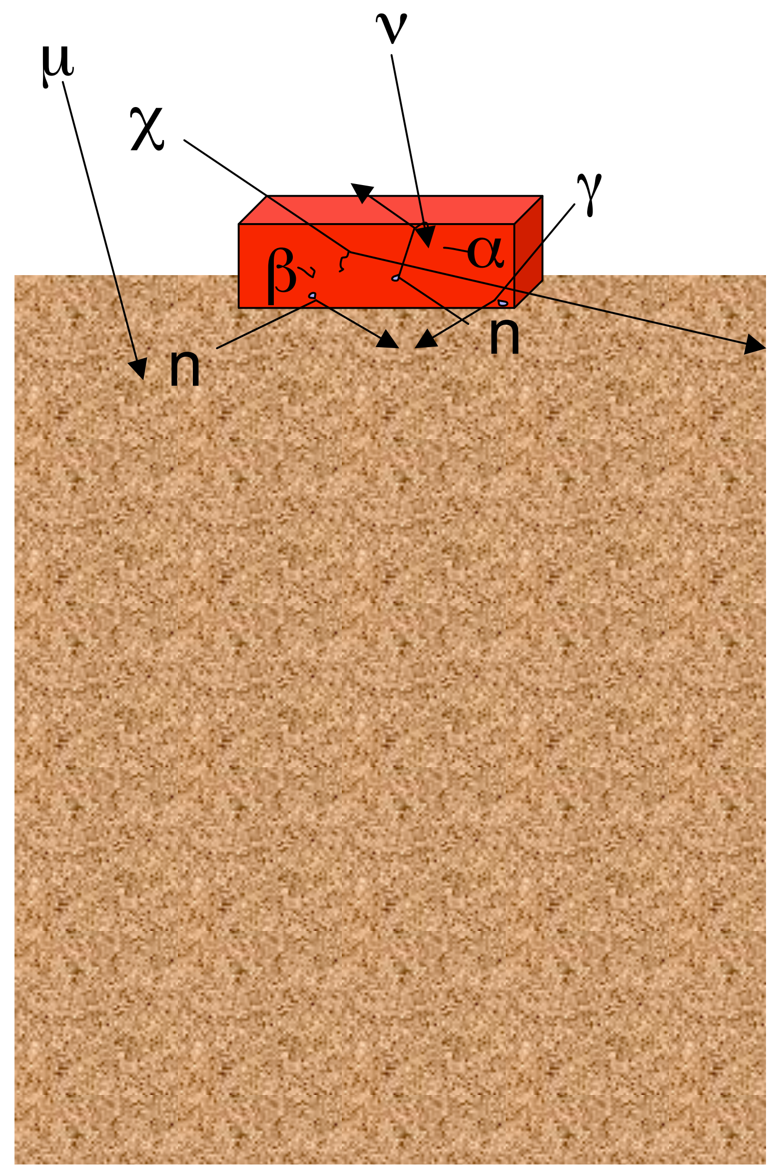
  - Local density ~0.4 GeV/cm^3
  - rms velocity 230 km/s
- Look for coherent elastic scattering off of nuclei
  - Recoil energies *O*(10) keV
  - Rates ≤ *O*(1) event / kg-year
  - Many backgrounds from natural radioactivity



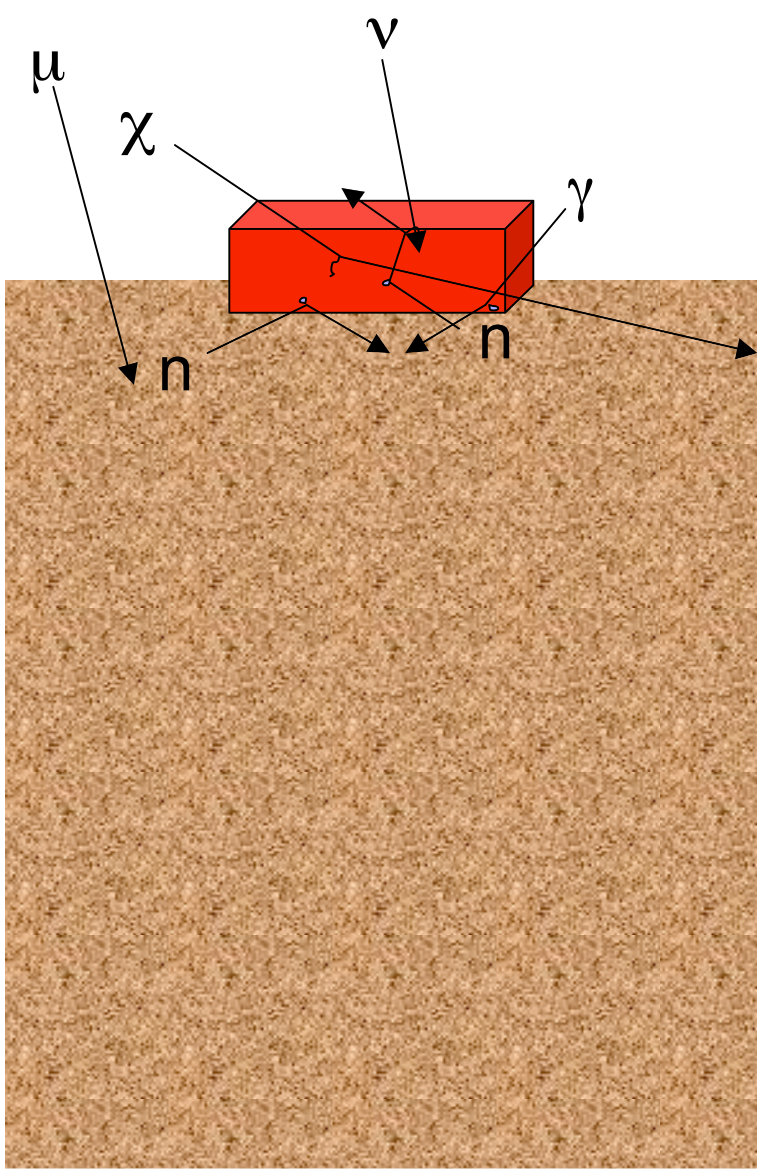
Internal Backgrounds



- β-decays
  - Screen and purify detector materials
  - Discriminate between electron tracks and nuclear recoils
- α-decays
  - Screen and purify detector materials
  - Discriminate between *O*(10) keV WIMP events and 5 MeV α-decays

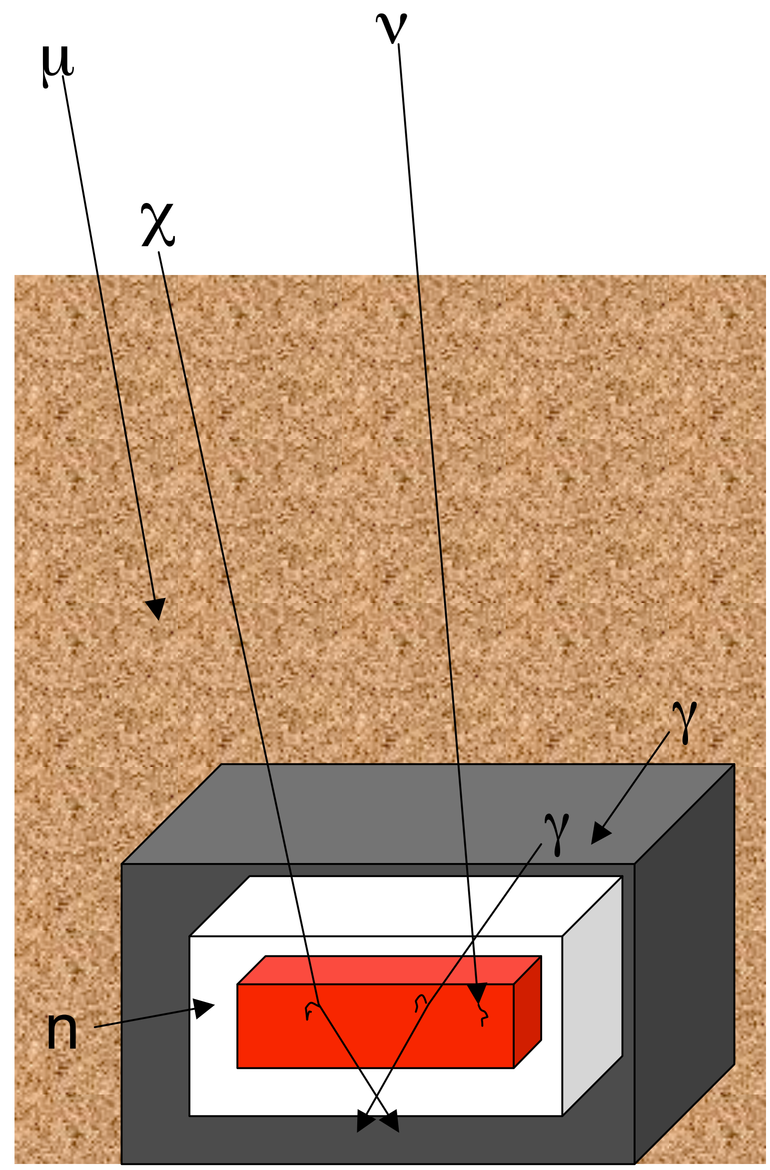
External Backgrounds

- neutrons
  - Produced by fission, (α,n) reactions, cosmic rays
  - Give elastic scatters off nuclei, same as WIMP signal
  - Shield detector with low-z moderator, screen materials, go underground
  - Reject multiple-scatters



External Backgrounds

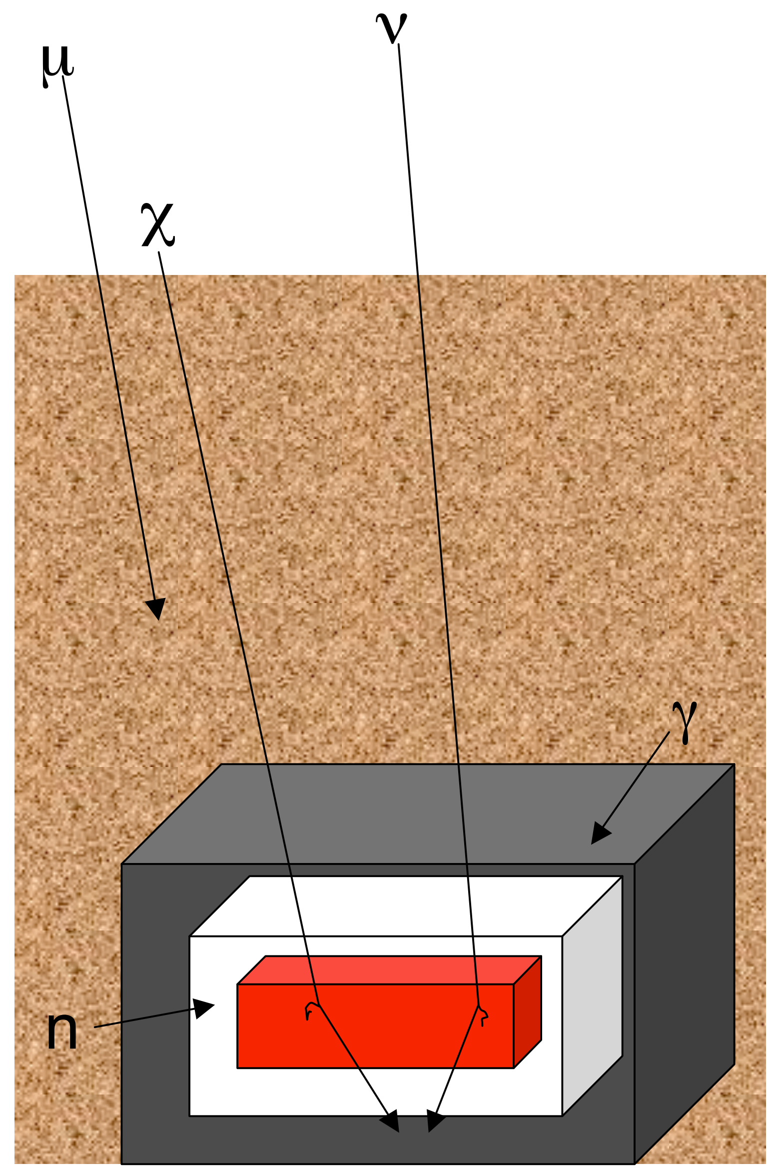
- neutrons
  - Produced by fission, (α,n) reactions, cosmic rays
  - Give elastic scatters off nuclei, same as WIMP signal
  - Shield detector with low-z moderator, screen materials, go underground
  - Reject multiple-scatters
- gammas
  - Compton Scatter in detector
  - Discriminate between electron tracks and nuclear recoils
  - Shield detector with high-z materials, screen components
  - Reject multiple-scatters



External Backgrounds

- neutrinos
  - Discriminate against charged-current interactions
  - No defense against high-energy neutrino neutral-current elastic scatters off nuclei

Irreducible neutrino background at $O(1)$ event / 10 ton-years



Detector Requirements

- Sensitivity to *O*(10) keV nuclear recoils
- Scalability to ton-scale targets
- Discrimination against backgrounds

Present Detection Schemes

- Cryogenic
  - CDMS, EDELWEISS — Ge, phonon + charge
  - $ $ $ CRESST — $CaWO_4$, phonon + scintillation
- Liquid Noble
  - XENON, LUX, ZEPLIN — Xe, TPC (charge + scintillation)
  - XMASS — Xe, scintillation only
  - $ $ WARP, ArDM, Darkside — Ar, TPC (charge + scintillation)
  - DEAP/CLEAN — Ar, Ne, scintillation only
- Solid Scintillator
  - Dama/Libra, KIMS — NaI / CsI, scintillation only

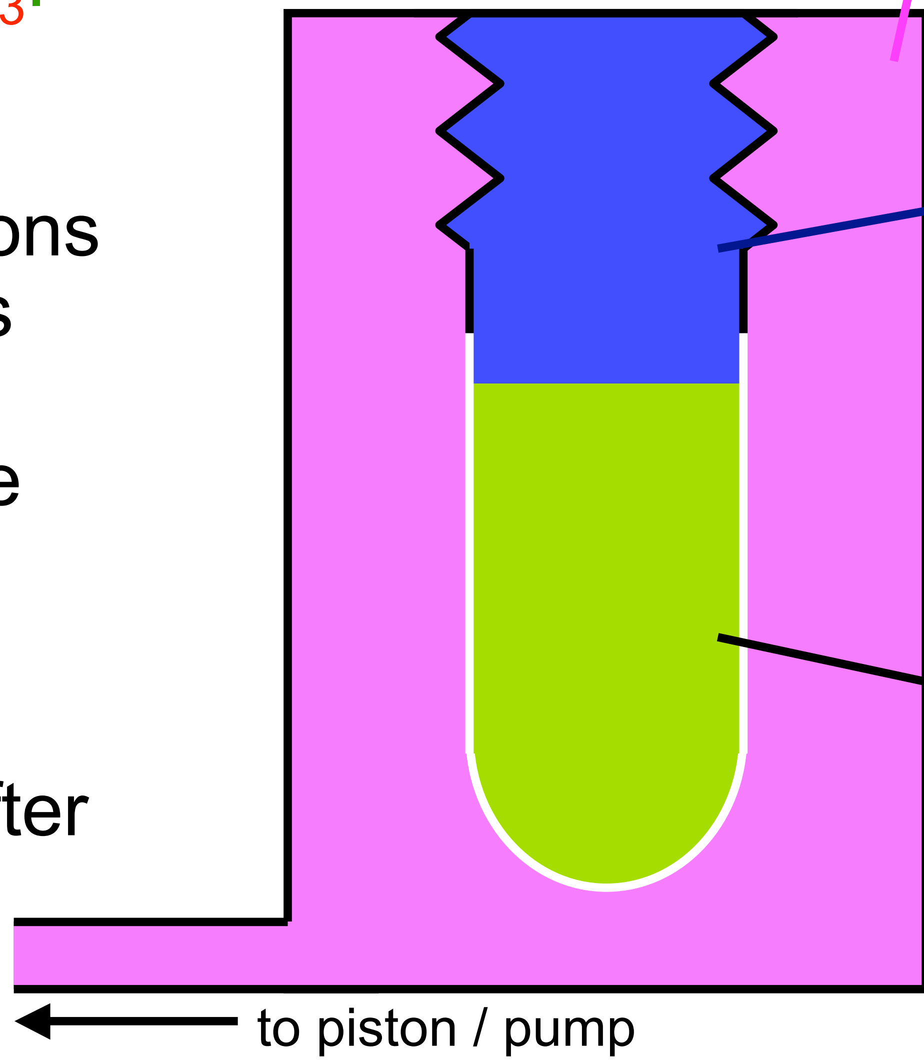
  $ $
- Superheated Fluid
  - COUPP — CF_3I, bubble chamber
  - $ PICASSO, SIMPLE — C_4F_{10}, superheated droplets

Why So Many Experiments & Techniques?

- Signal is small
  - Handful of events with limited information in 1-1000 Kg-year
    - Energy deposited
    - Time of event
    - Prompt signal / delayed signal
    - Maybe just a bubble if above threshold
- Backgrounds are not well quantified
  - Radio-assay in very clean real materials is hard
  - Simulation is hard (neutron transport, …)
  - What about the background(s) we don't know about yet?
  - Its all about the backgrounds - not the tonnage!
- Impact of a real discovery is huge (think Sweden)
  - The same signal in different detectors / nuclei is required
  - It going to "take a village"
- I'll not be convinced by one experiment's discovery claim - even if we're the ones making it!

Bubble Chamber

- Superheated CF_3I target (Spin-dep: F; Spin-indep: I)
- Particle interactions nucleate bubbles
- Cameras capture bubbles
- Chamber recompresses after each event



Bubble Chamber

- Superheated CF_3I target
  - Spin-indep
  - Spin-dep
- Particle interactions nucleate bubbles
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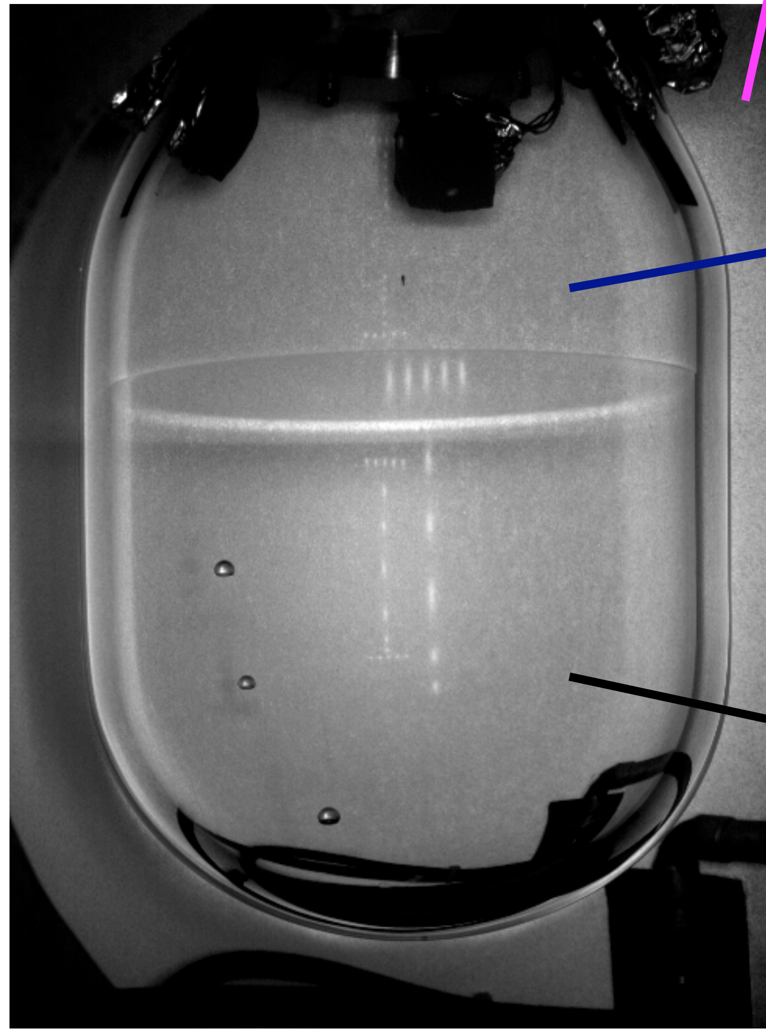
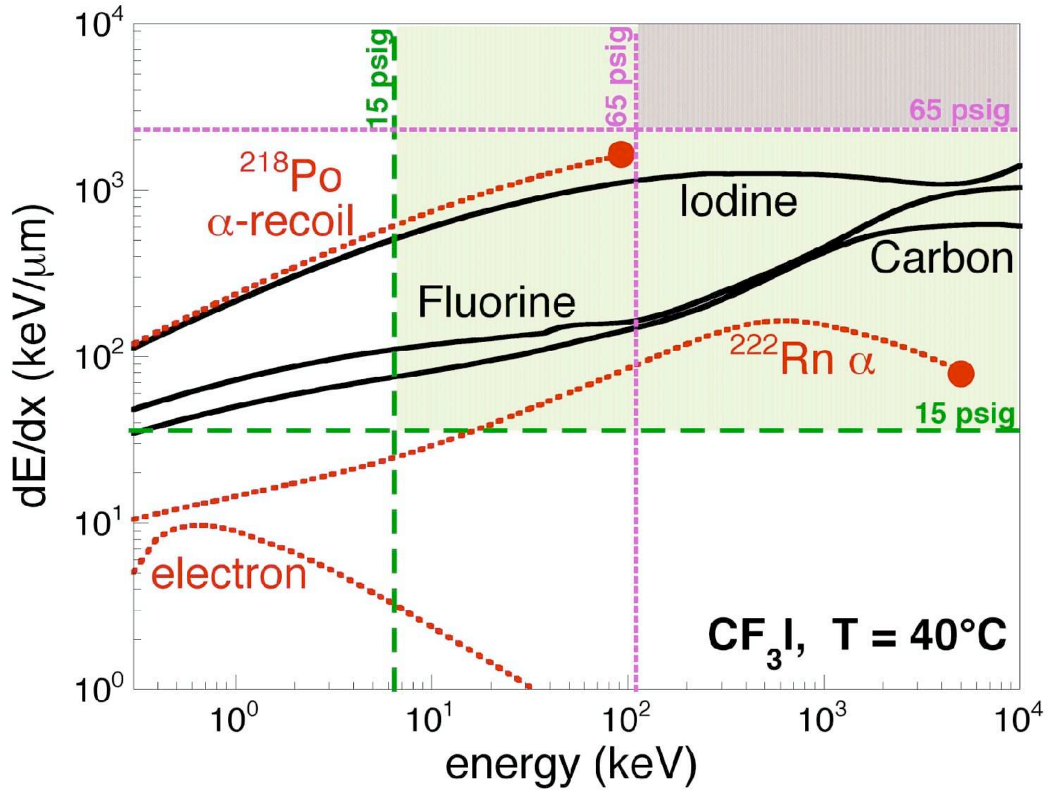


What does it take to nucleate a Bubble?

- Only proto-bubbles with $r > r_{crit}$ grow to be macroscopic
- Critical proto-bubble requires minimum dE within minimum volume
- Recoil must be over thresholds in both E and dE/dx

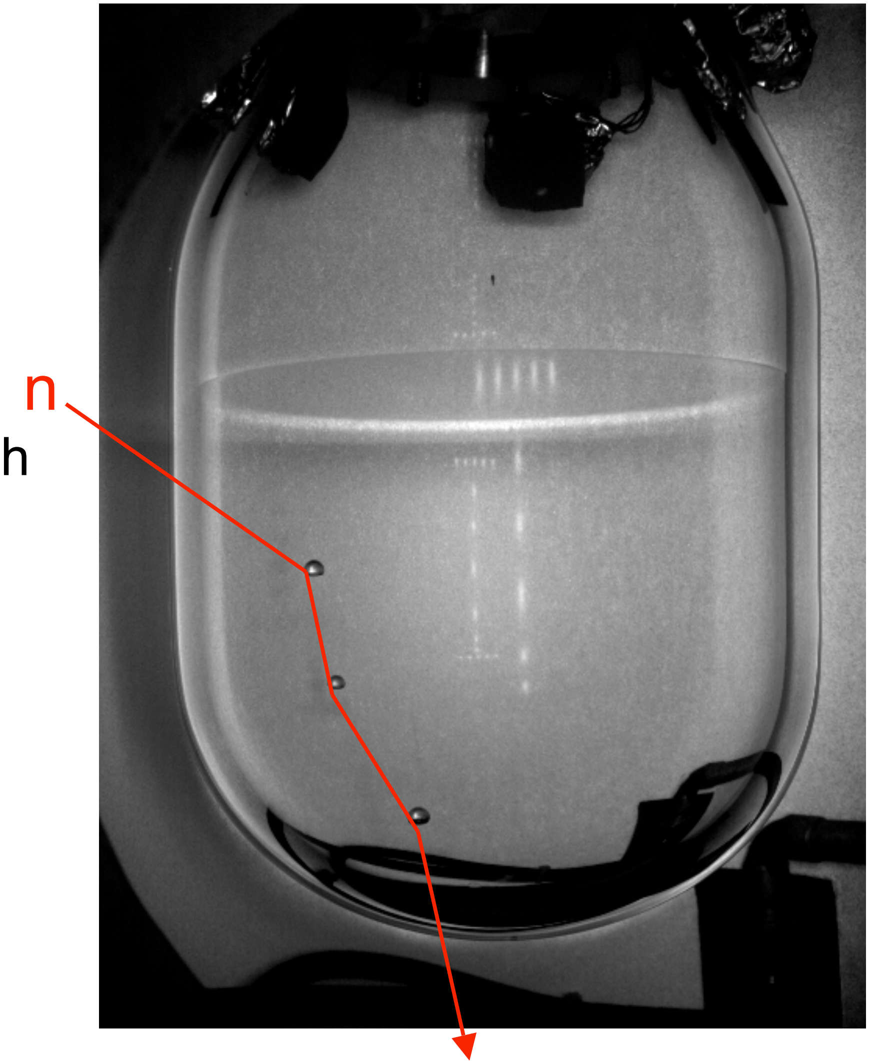


No sensitivity to γ's or β's,

but α's do make bubbles

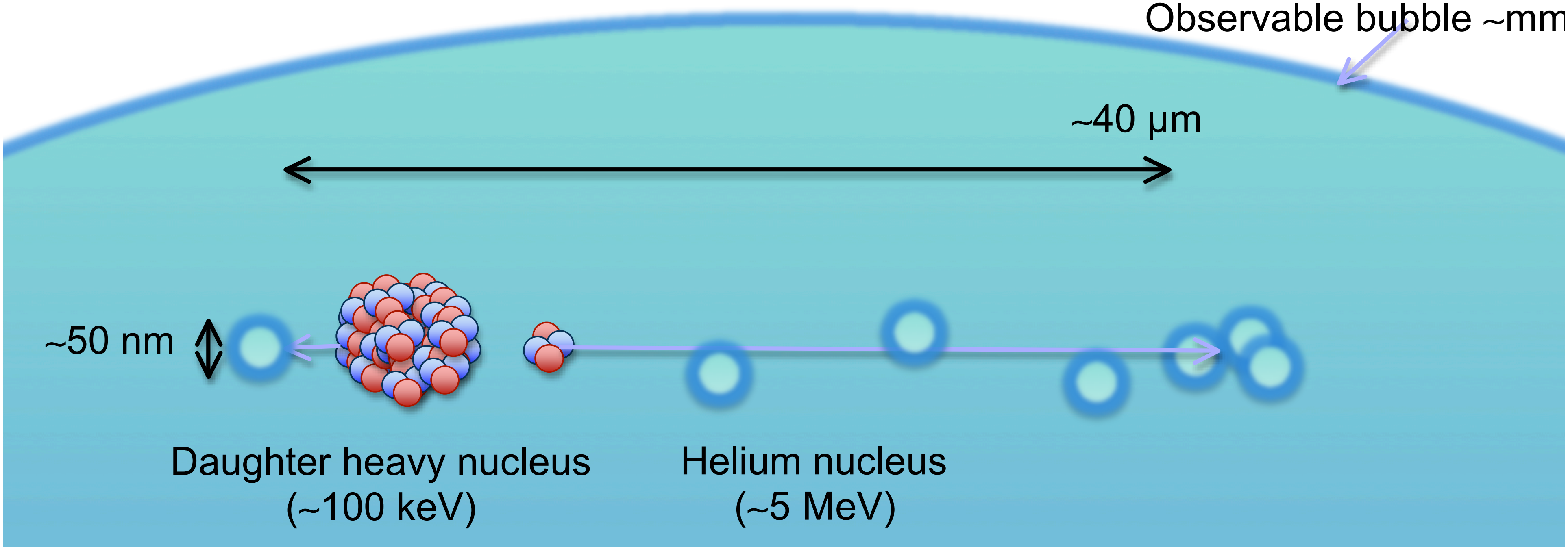
3 basic event types

- alpha-decays
  - Nuclear recoil + 40 μm alpha track
  - 1 bubble
- neutrons
  - Nuclear recoils, mean free path ~20 cm
  - 3:1 single-multiple ratio in COUPP 4kg
- WIMPs
  - Nuclear recoil, mean free path > 10^{12} cm
  - 1 bubble

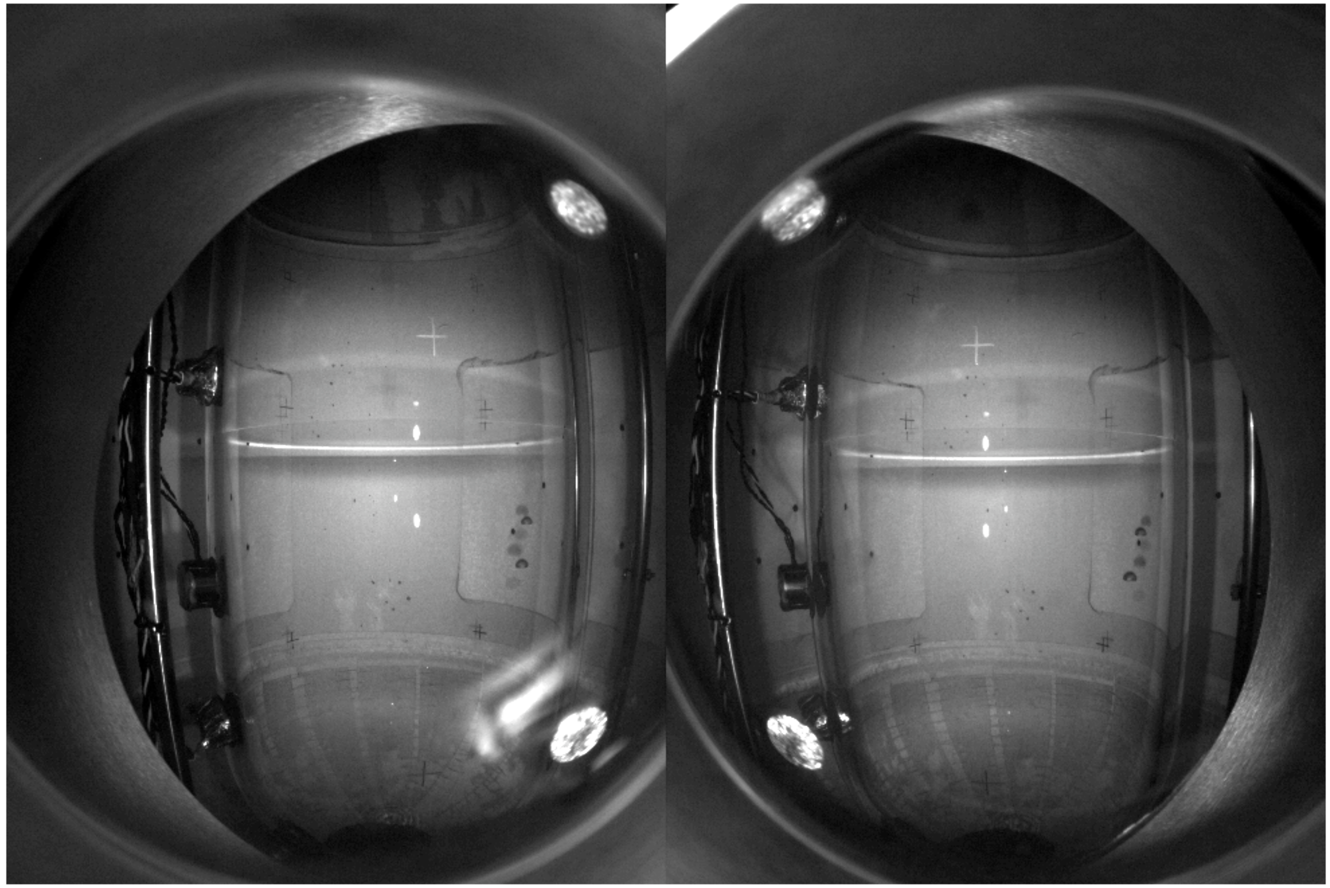


Acoustic Discrimination

- Alpha louder when probing length scales <40 μm
- Acoustic emission peaks at ~10 μm

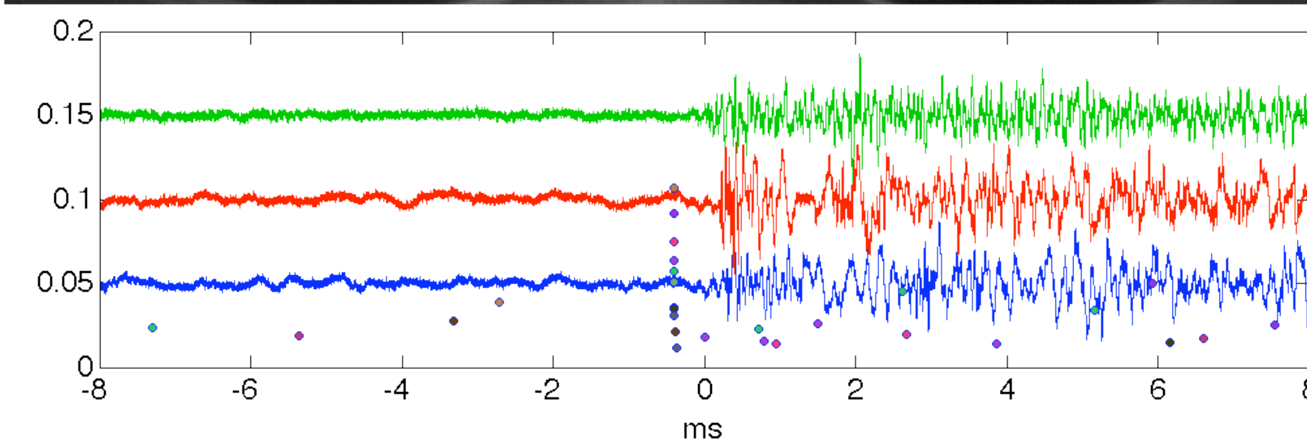


COUPP 60 @ MINOS



SNOLAB installation in 2012…

- Cosmic-induced neutron (2 bubbles)



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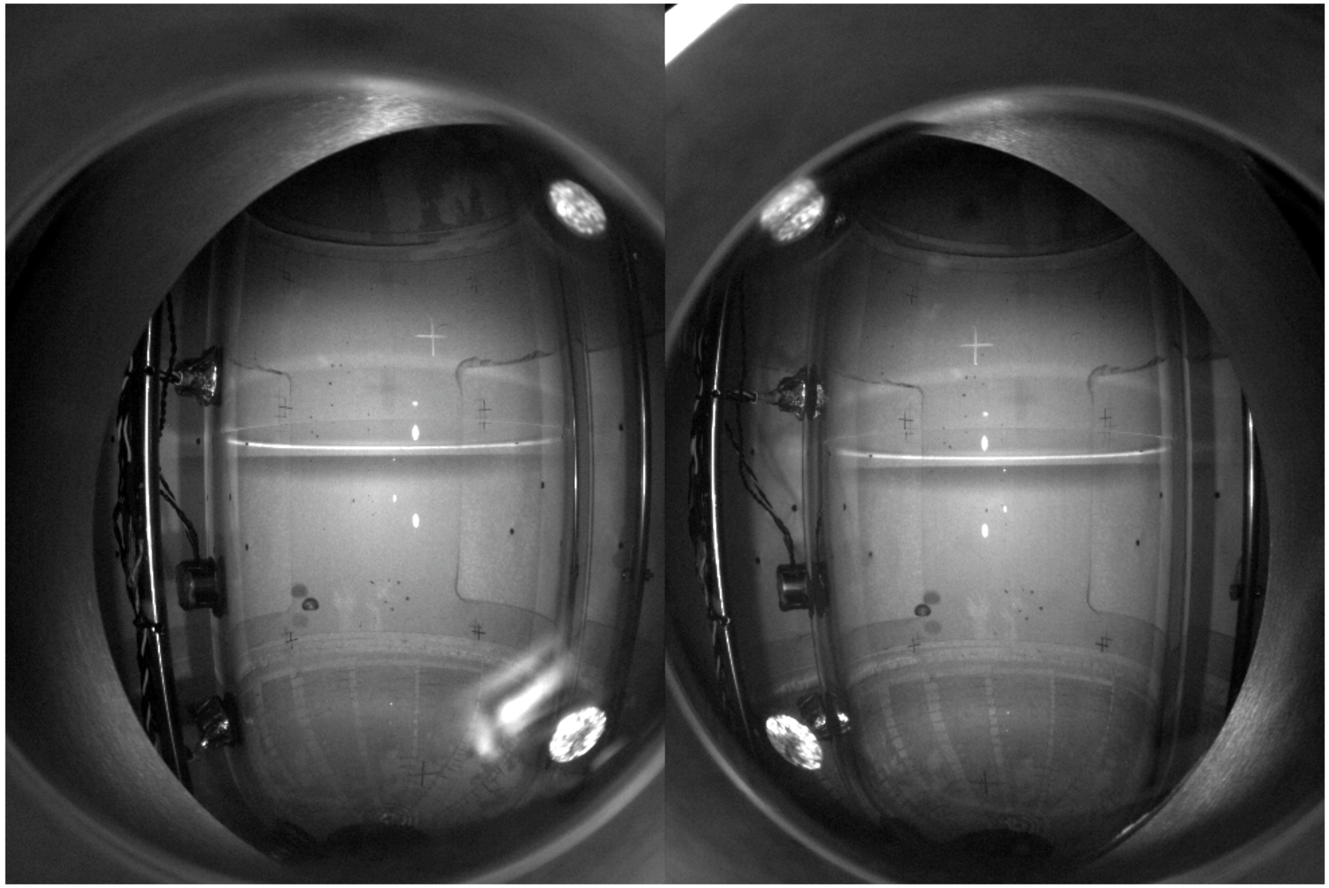
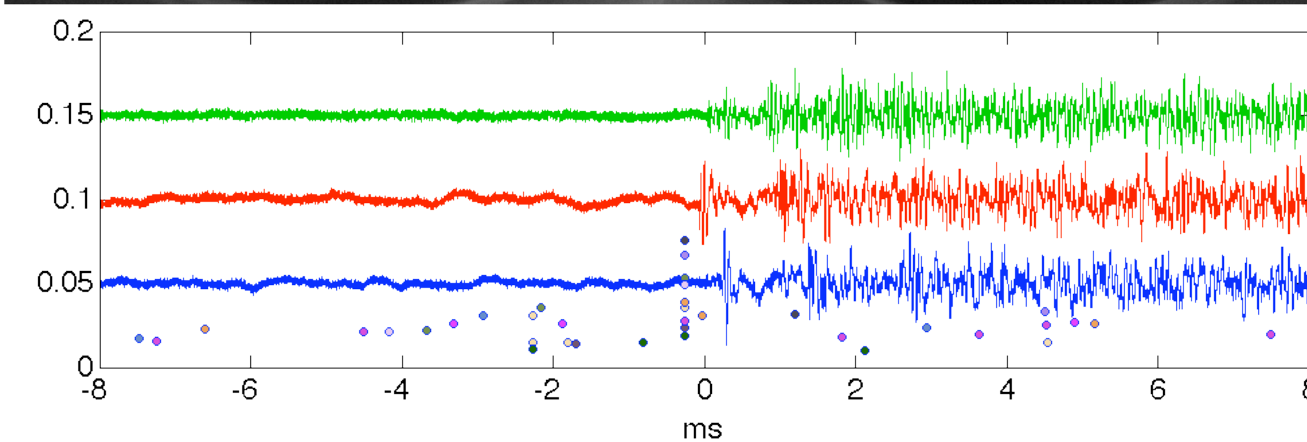
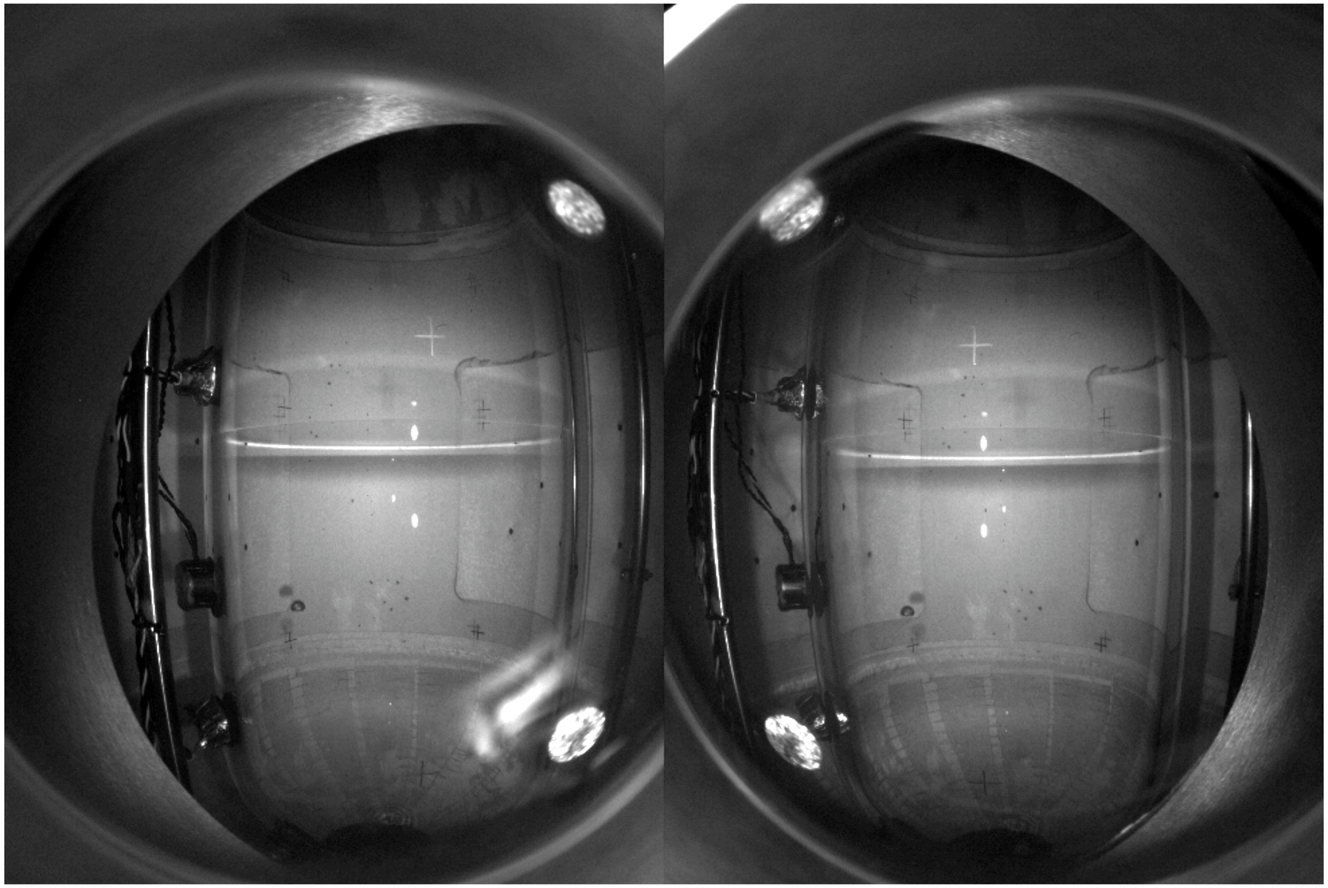


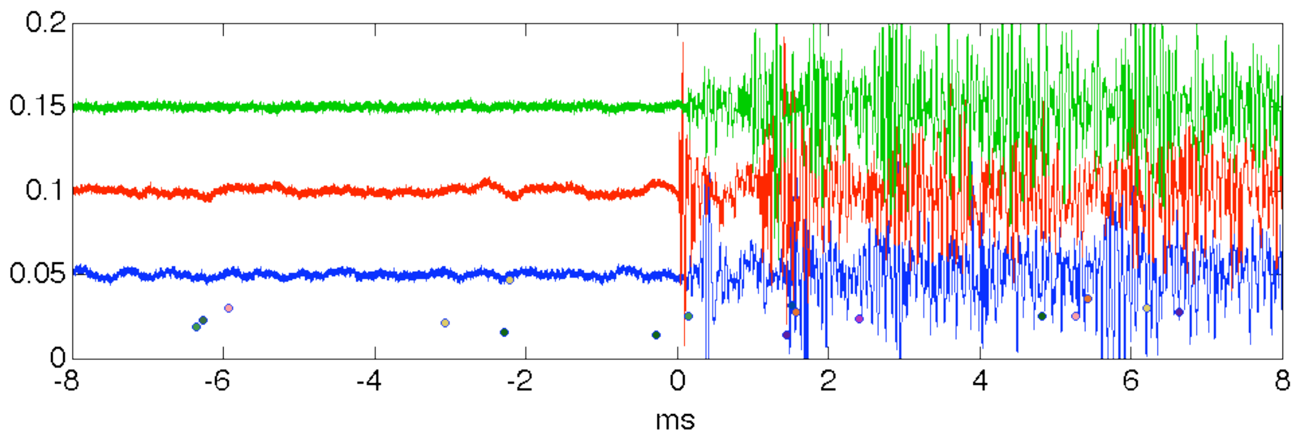


COUPP 60 @ MINOS

SNOLAB installation in 2012…

- Alpha-decay (1 bubble)





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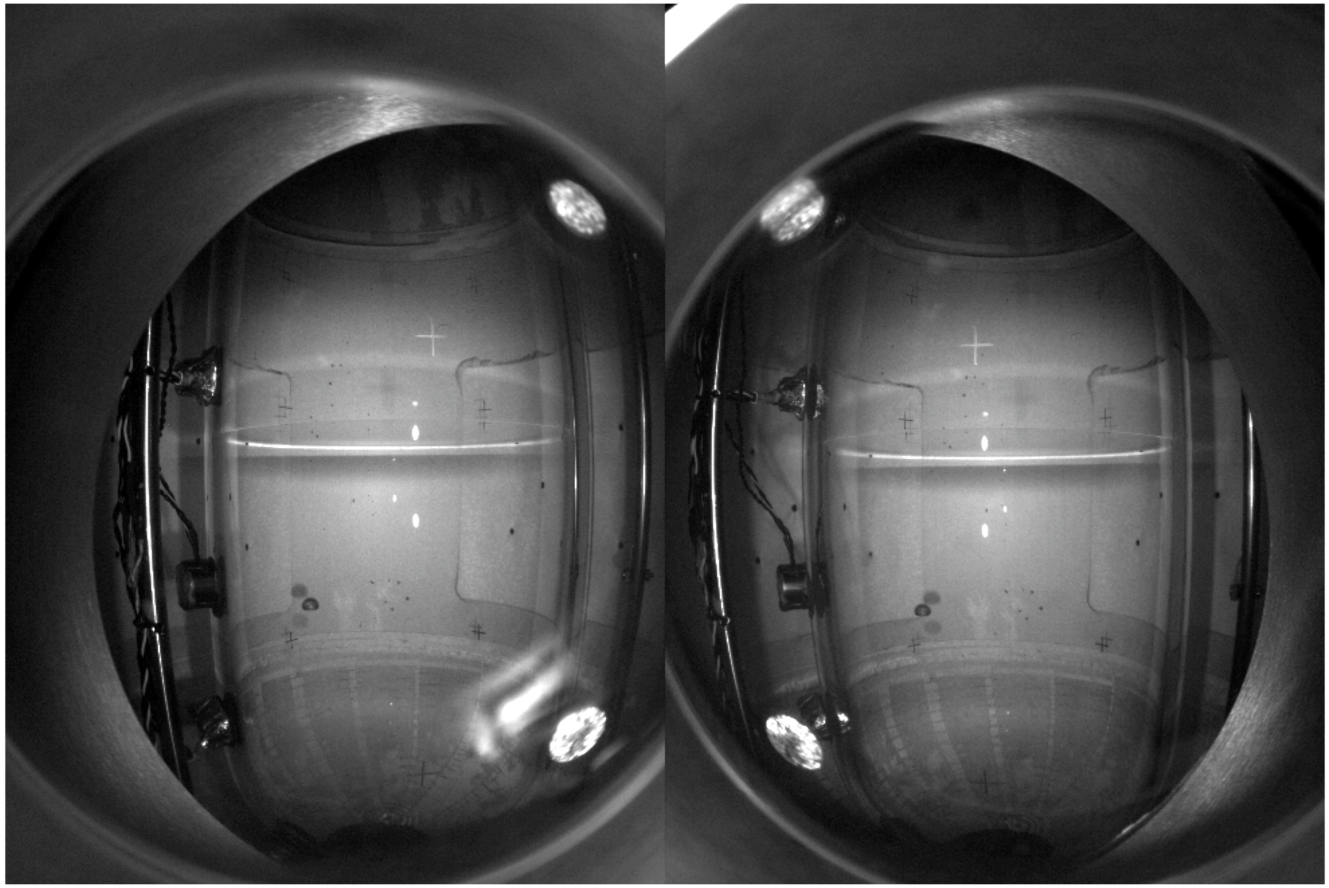
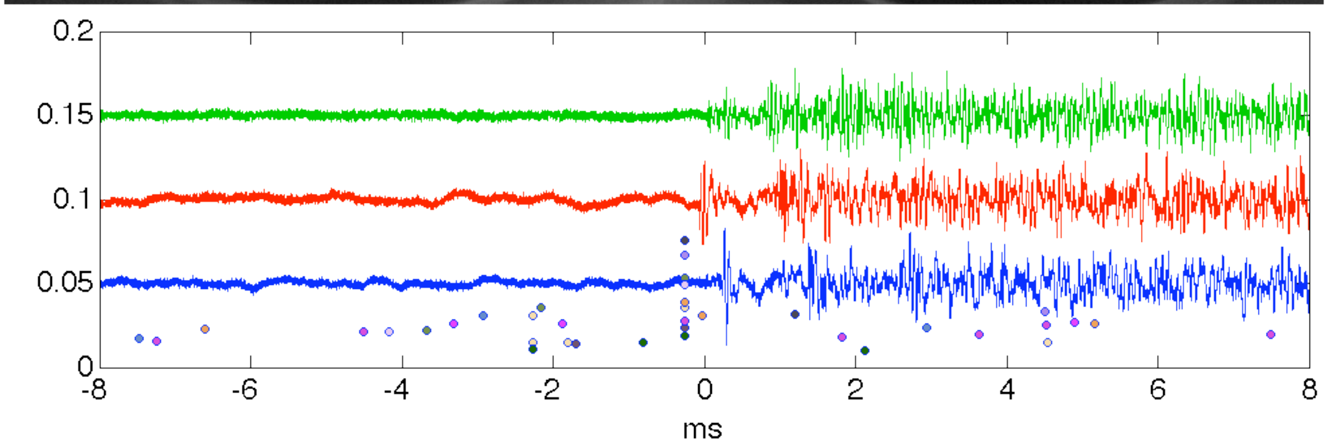


First data, July 28, 2010

- Cosmic-induced neutron (1 bubble)



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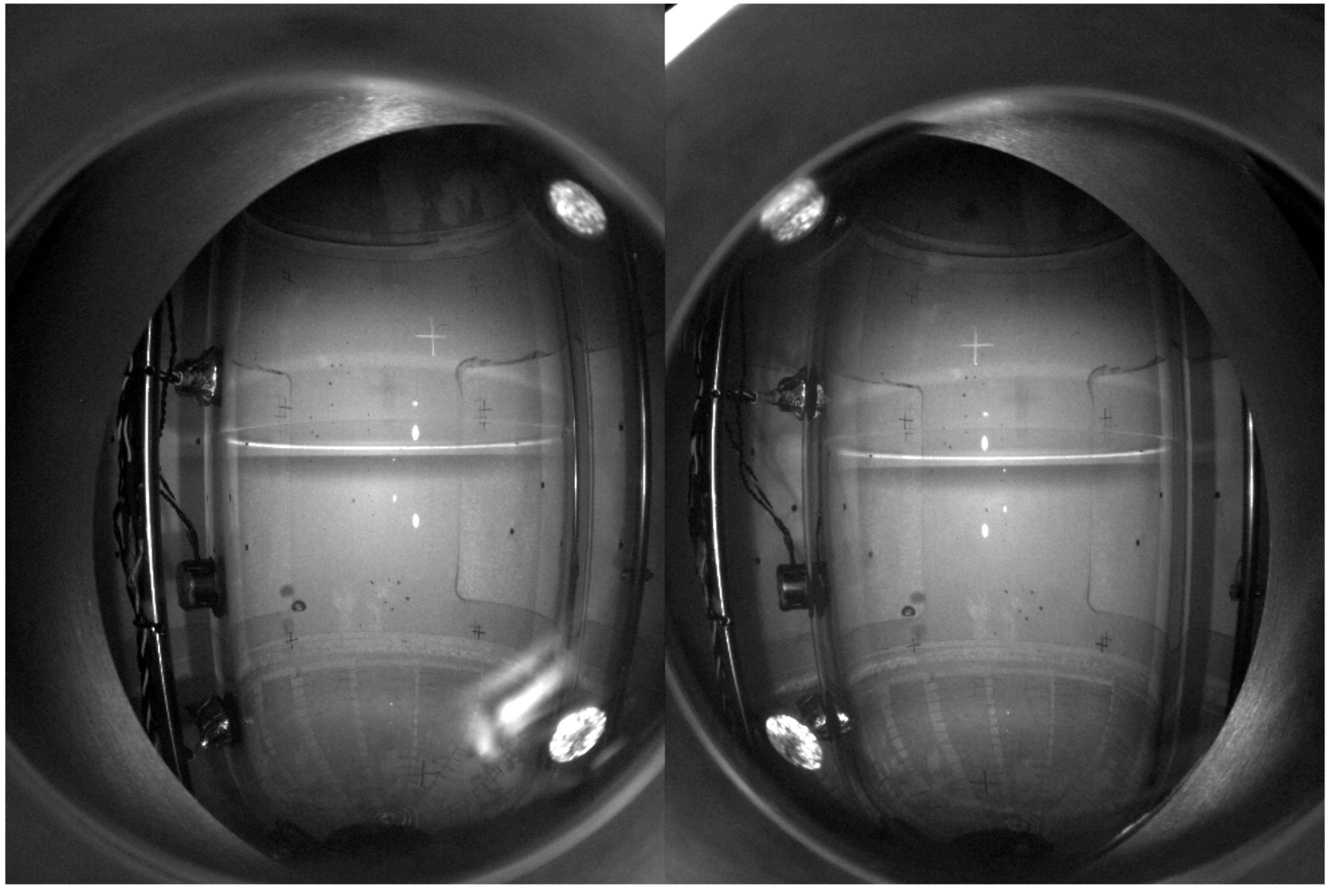

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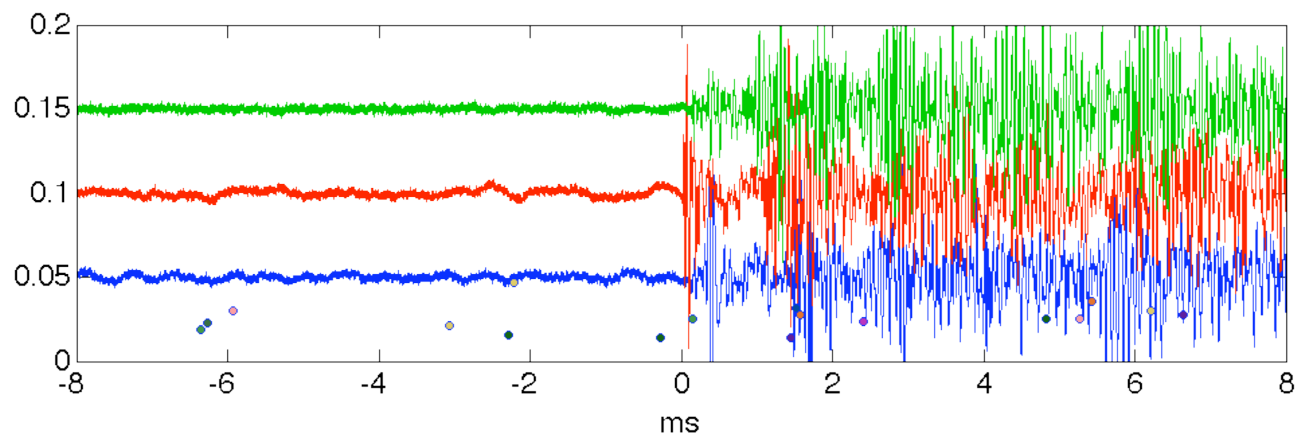


n, α

Sudbury, Ontario

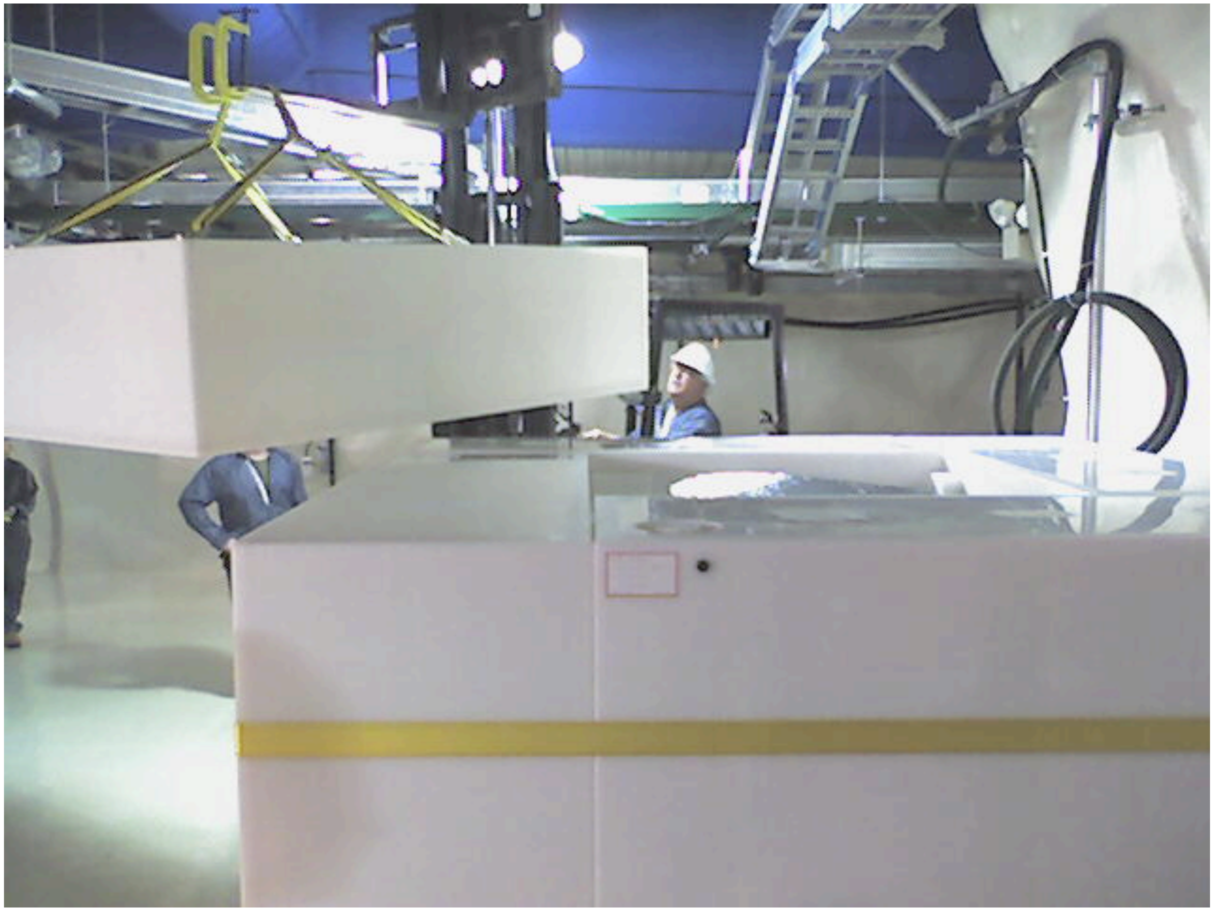
6800 Feet (2.0 Km) Down

COUPP 4kg @ SNOLAB

July 27, 2010, DAQ and Pressure Control Move Underground

Installation Begins:
July 27, 2010

COUPP 4kg @ SNOLAB

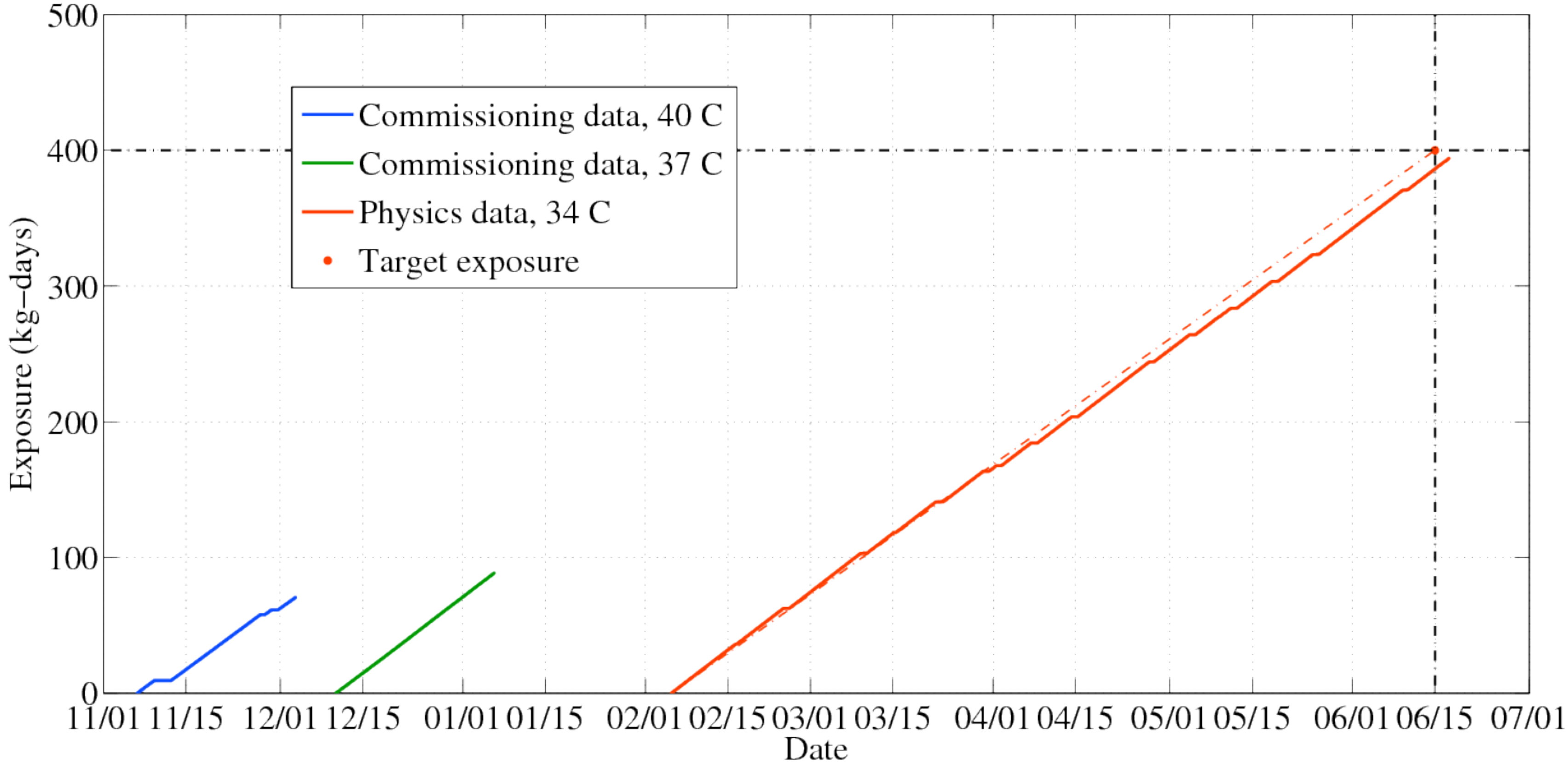


Nov 3, 2010, Shield is completed
Physics data begins!

One leaky accumulator, a few leaky plumbing lines, a slightly overstretched bellows, and one unusual occurrence report later…

Installation Ends: Nov 3, 2010

COUPP 4kg @ SNOLAB, WIMP search log

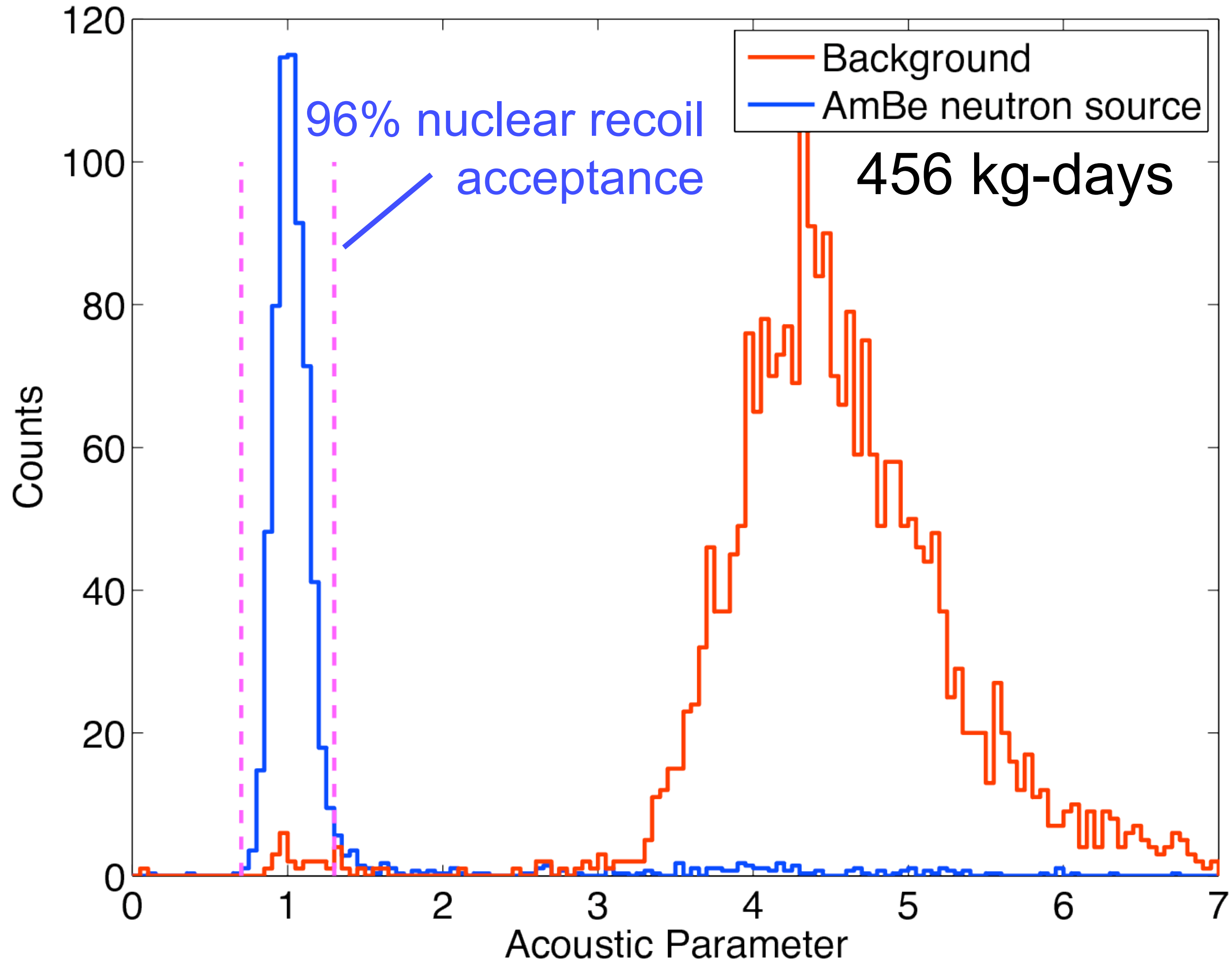


- 17.4, 21.9, 97.3 live-days at 8, 10, 15 keV thresholds
- 4.048 kg target, 79% cut-efficiency for nuclear recoils
  - 90% quality cuts, 92% fiducial cut, 96% acoustic cut

COUPP 4kg @ SNOLAB

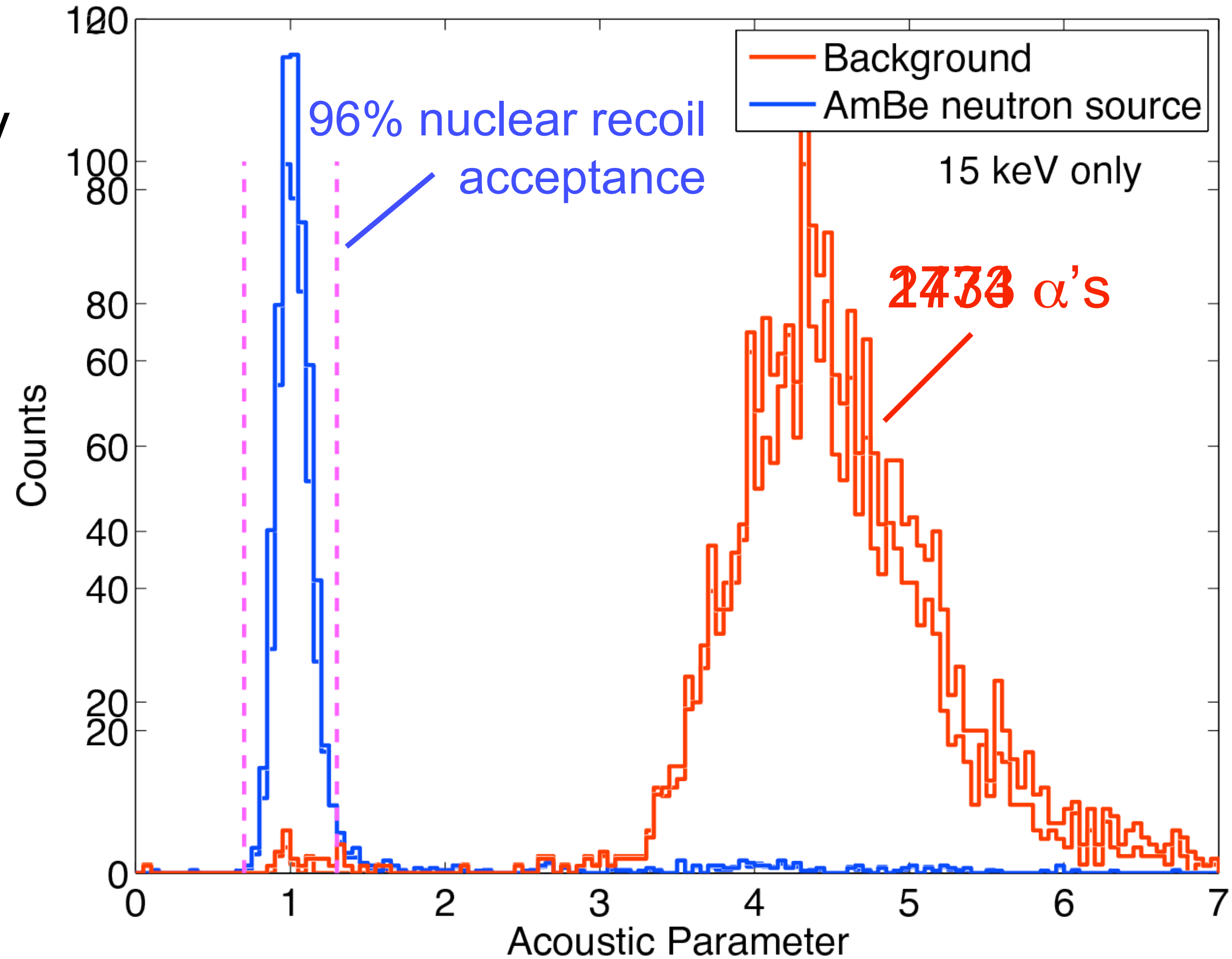
"Acoustic Parameter"

- $(Amp \bullet \omega)^2$
  (Normalized and position-corrected)
- Measure of acoustic energy deposited in chamber



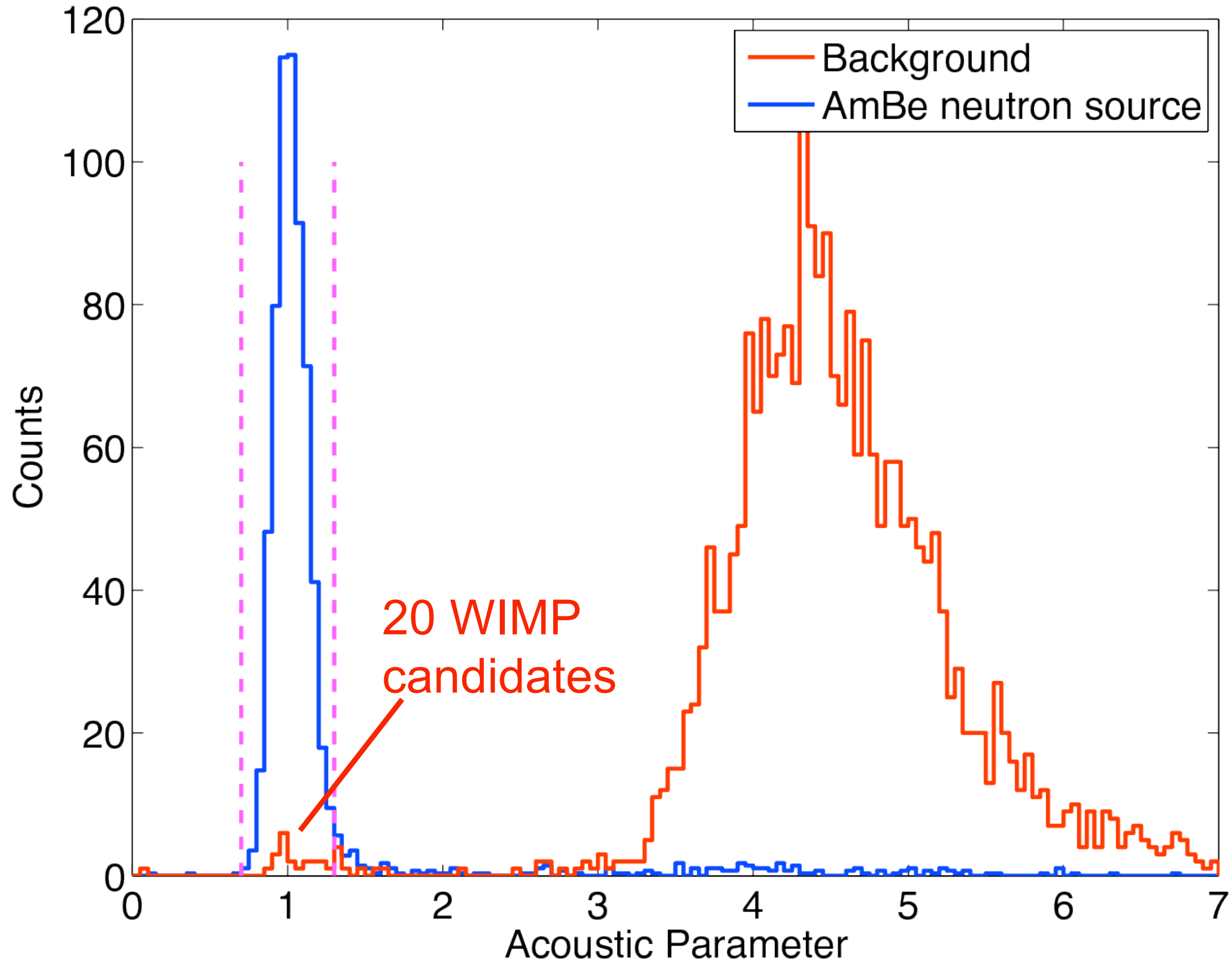
COUPP 4kg @ SNOLAB

- 5.3 alpha-decays / kg-day
  - 95% ^{222}Rn, ^{218}Po, ^{214}Po triplets
- >98.9% alpha rejection
- >99.3% alpha rejection in 15 keV data



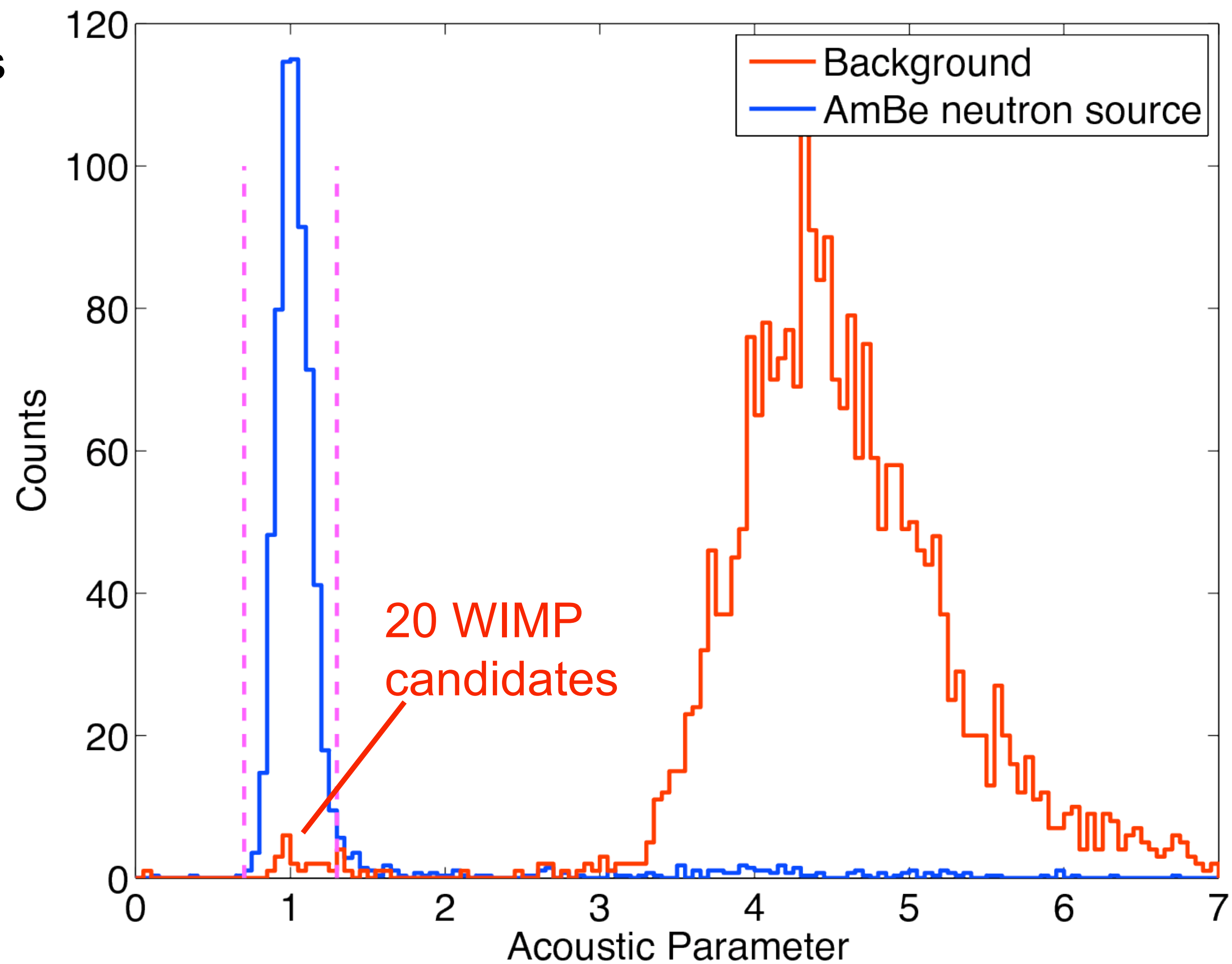
COUPP 4kg @ SNOLAB

- At 8 keV:
  - 6 WIMP candidates
- At 10 keV:
  - 6 WIMP candidates
  - 2 three-bubble events
- At 15 keV
  - 8 WIMP candidates
  - 1 two-bubble event



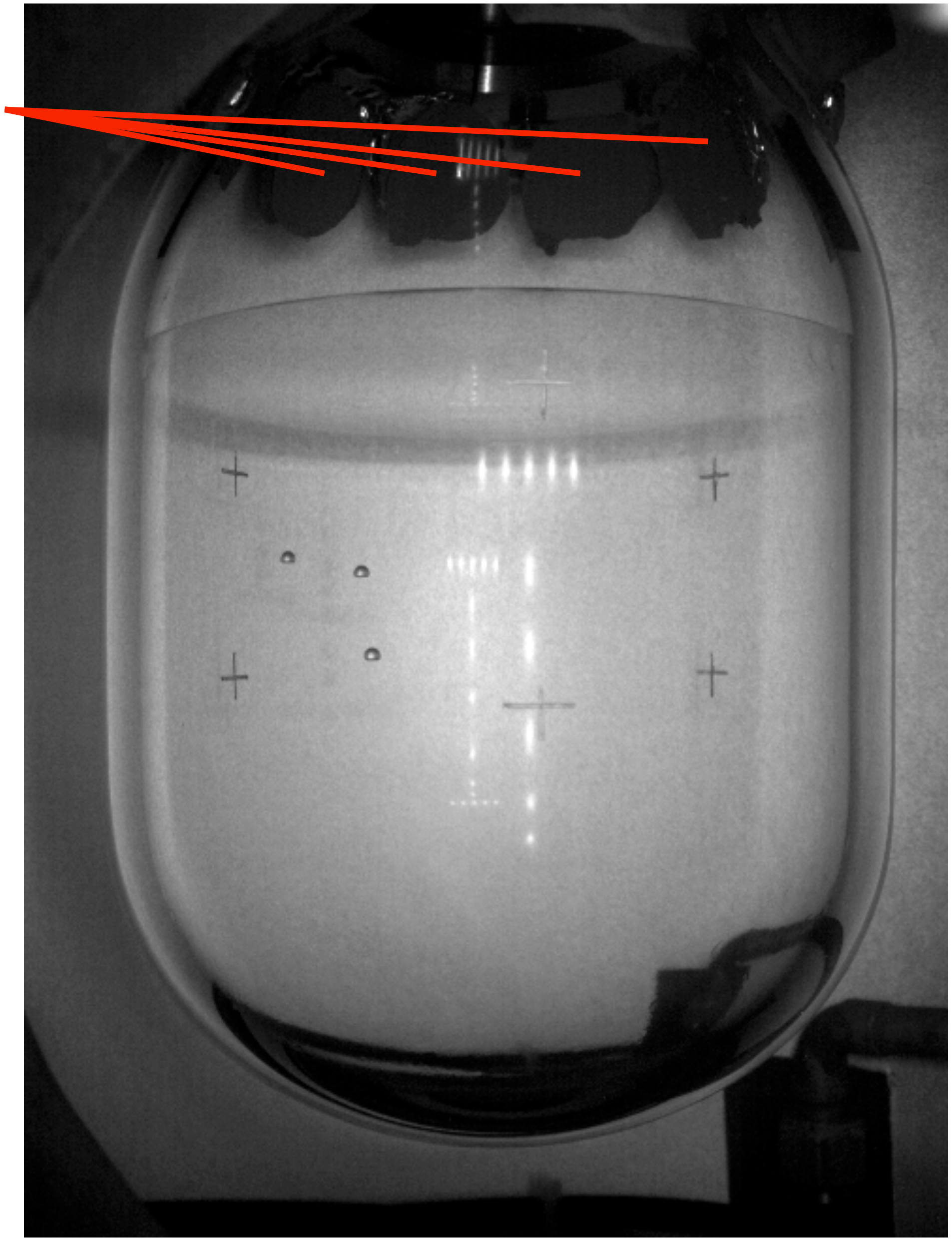
COUPP 4kg @ SNOLAB

- Multi-bubble events mean Neutron Background!
- Calibration gives 3:1 ratio for singles:multiples
  - 3 – 25 singles from neutrons
- *O*(0.1) per year from cosmic muons, cavern walls

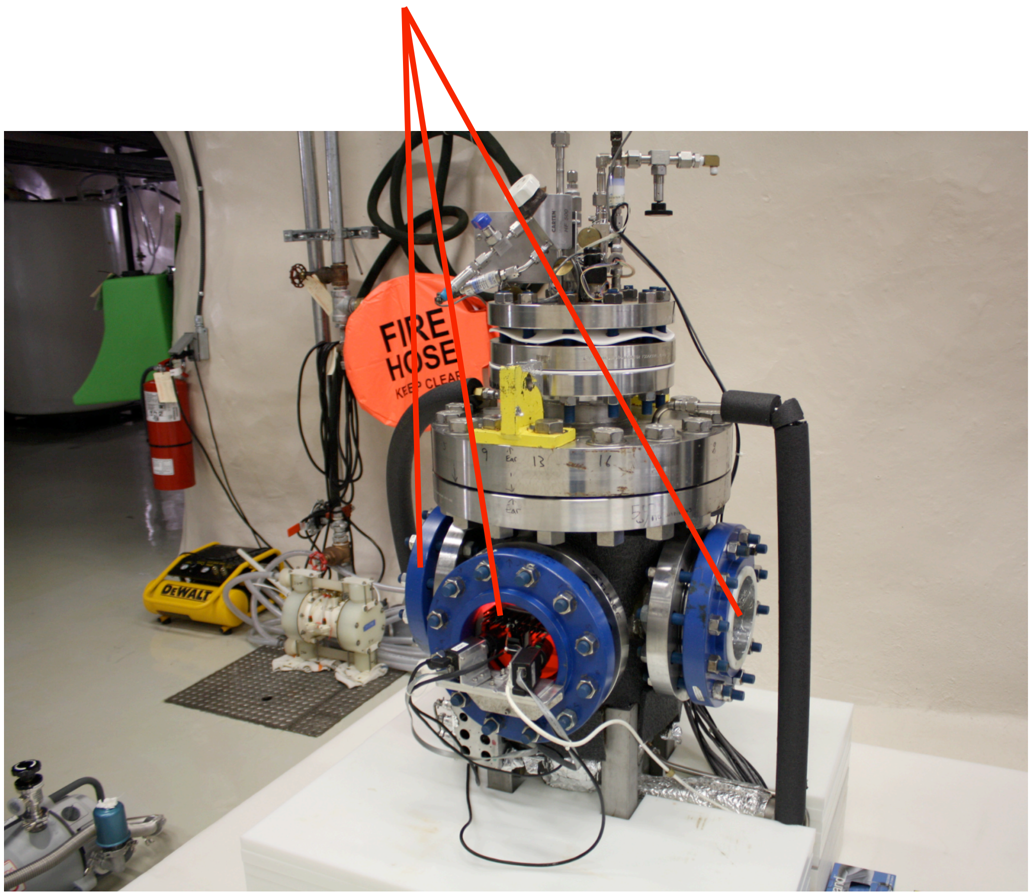


Neutron sources!

- Piezoelectric element is ceramic PZT
  (Lead zirconate titanate)
- 4.0 ppm ^{238}U
  1.9 ppm ^{232}Th
  plus lots of modern lead with ^{210}Pb
- Both fission and (α,n) on light elements
- Accounts for ~1 background single



More Neutron sources!

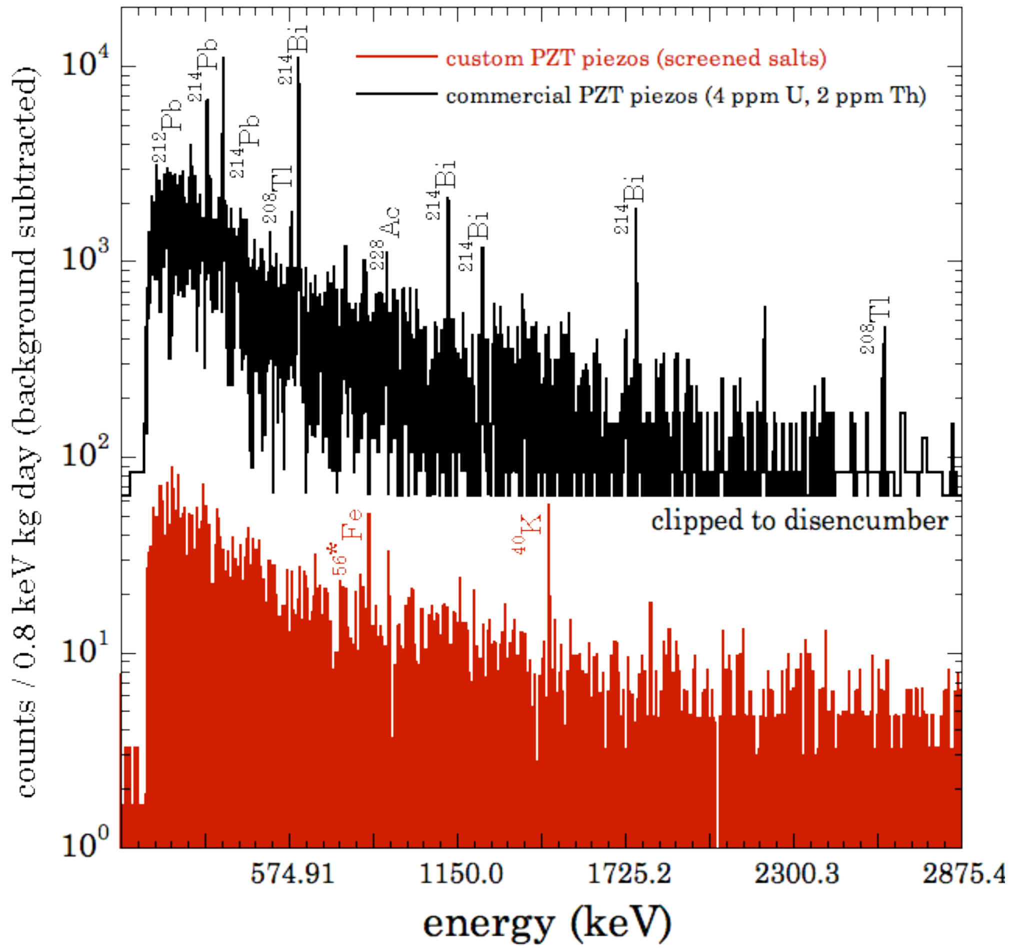


- Camera Viewports
  - Proprietary formulation, probably soda-lime glass
- 0.5 ppm ^{238}U
  0.8 ppm ^{232}Th
- Lots of (α,n) on light elements

- Accounts for ~4 background singles

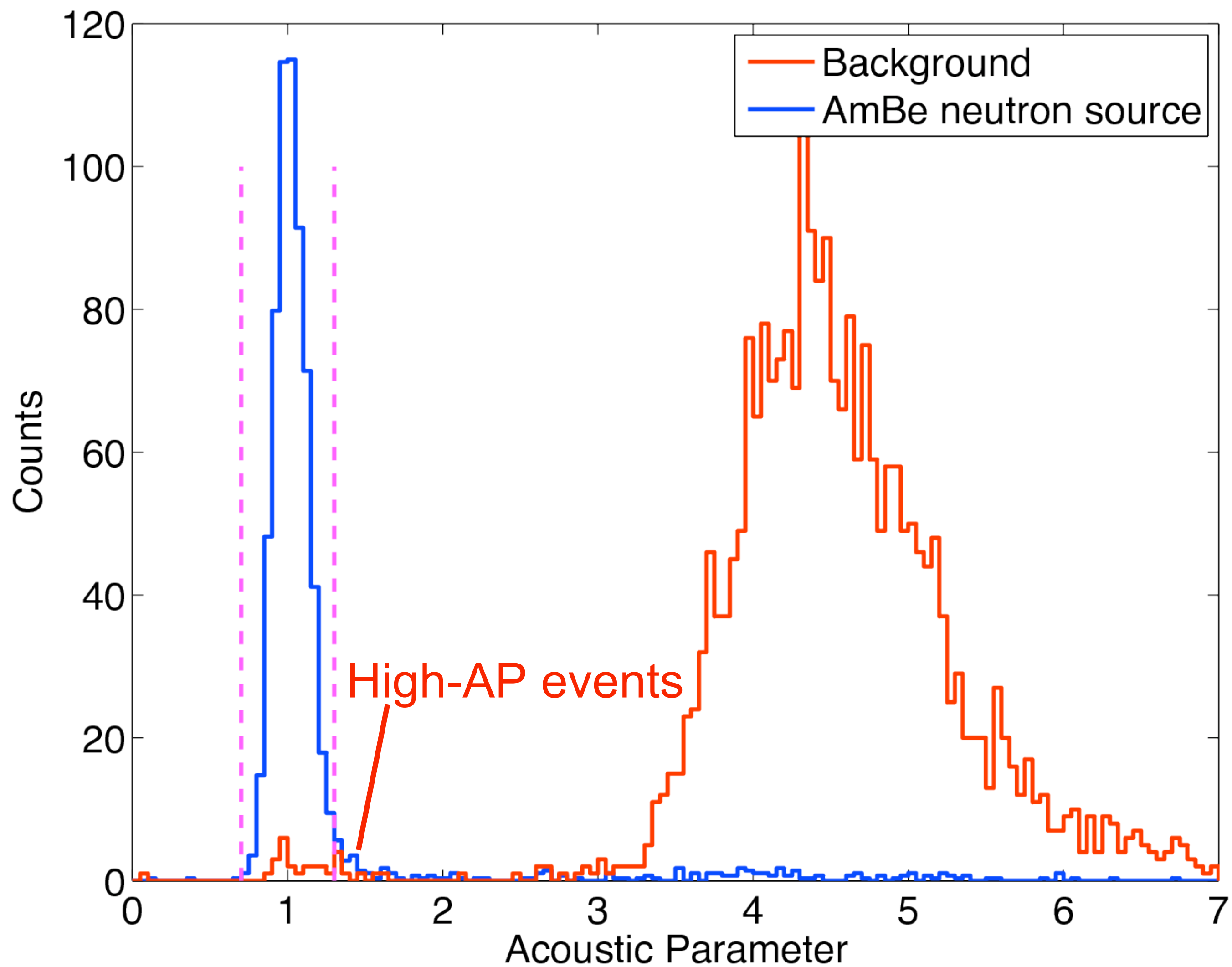
Now that we know…

- New piezos made with low-background salts
- New viewport made with synthetic silica
- Next COUPP 4 run begun May 2012



A Second Background?

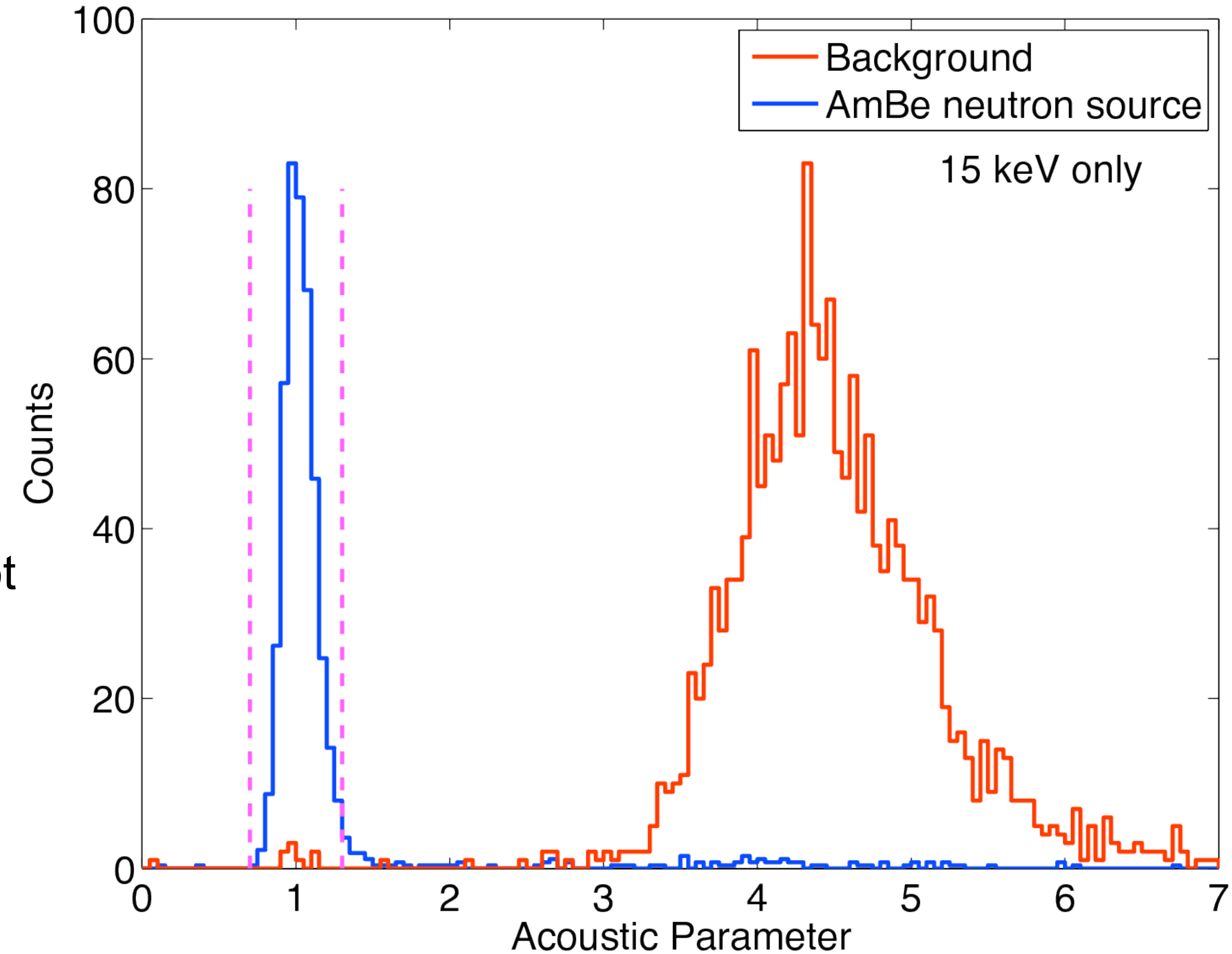
- High AP
  - 4 evts at 8 keV
  - 2 evts at 10 keV
- Clustered in time at 8 keV
  - 3 High-AP evts in 3 hours
  - 4 evts (1 High-AP) in 9 hours
- <10 minutes after normal events
  - At 8 keV: 4/6 "WIMP"s and all High-AP evts
  - At 10 keV: 3/6 "WIMP"s and 1/2 High-AP evts



A Second Background?

- No anomalous background at 15 keV
- Still investigating source of this background
- Almost certainly not WIMPS!

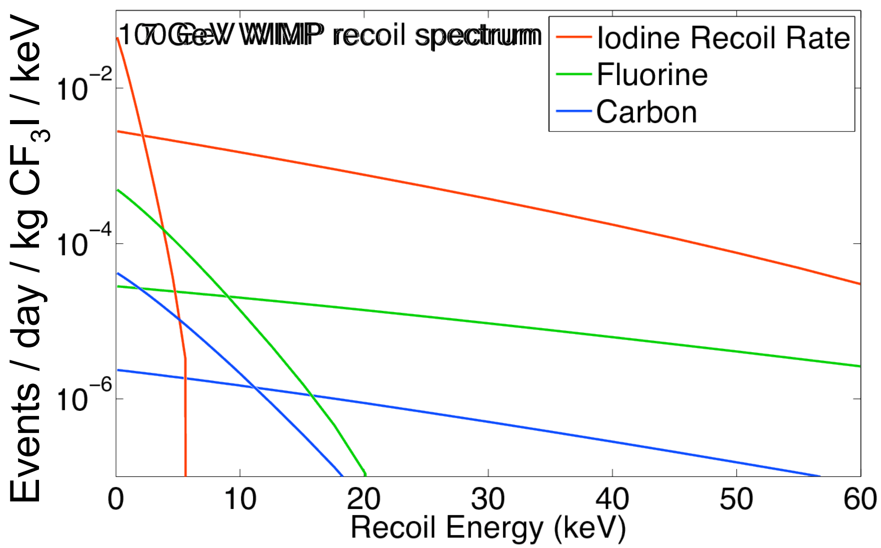
  (But counted as WIMP candidates in limit calculation)



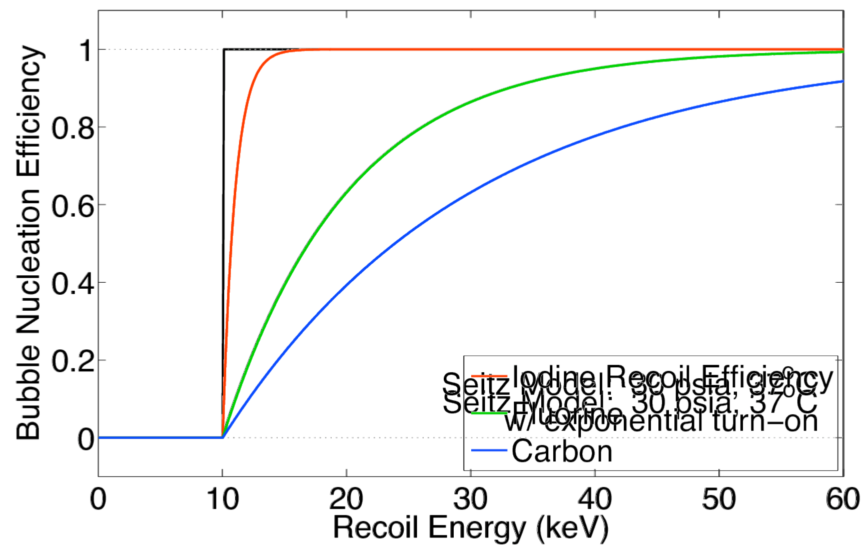
Threshold and Efficiency

WIMP sensitivity =

$\int$ WIMP recoil spectrum x Bubble Nucleation Efficiency



x



Threshold and Efficiency

- Classical Thermodynamics says-

$$p_v - p_l = \frac{2\sigma}{r_c}$$

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

Surface energy — Latent heat

- Energy deposition of E_{th} inside length r_c will nucleate bubble *(Seitz "Hot-Spike" Model)*

Threshold and Efficiency

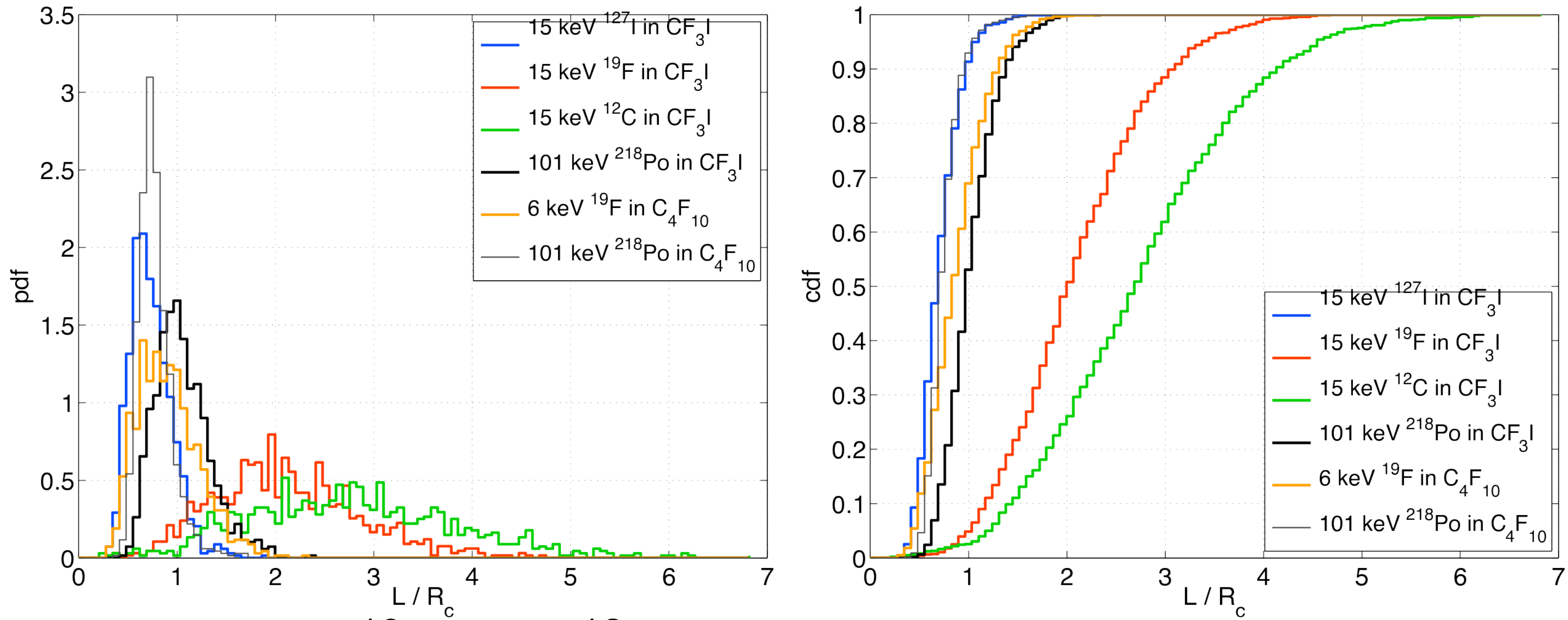
- Seitz Model Works for:
  - 6 keV ^{19}F recoils in C_4F_{10} [PICASSO Collaboration, arXiv 1011.4553]
  - 101 keV ^{218}Po recoils in C_4F_{10} [PICASSO Collaboration, arXiv 1011.4553]
  - 101 keV ^{218}Po recoils in CF_3I

Threshold and Efficiency

- Seitz Model doesn't work for:
  - Generic *O*(10) keV recoils in CF_3I
  - Neutron calibrations with AmBe and ^{252}Cf source consistently give
    - ~50% the expected rate from MCNP and Geant4 simulations
    - Lower ratio of multiples:singles than simulations

Threshold and Efficiency

- Which recoils cause problems…



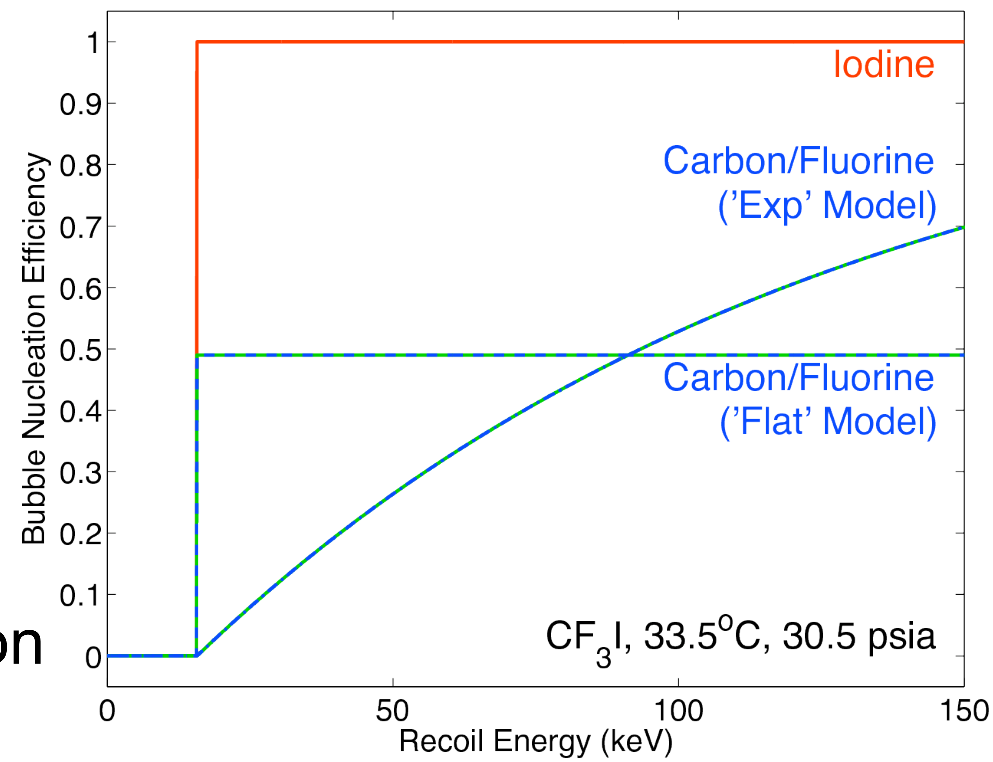
- 15 keV ^{19}F and ^{12}C in CF_3I have tracks significantly longer than critical radius

Threshold and Efficiency

- Current Best Guess
  - Seitz model for ^{127}I recoils
  - Lower efficiency for ^{19}F and ^{12}C recoils

- Either of these efficiencies for ^{19}F and ^{12}C will reproduce rates and multiplicities observed in calibration

- Need new measurements to answer efficiency question

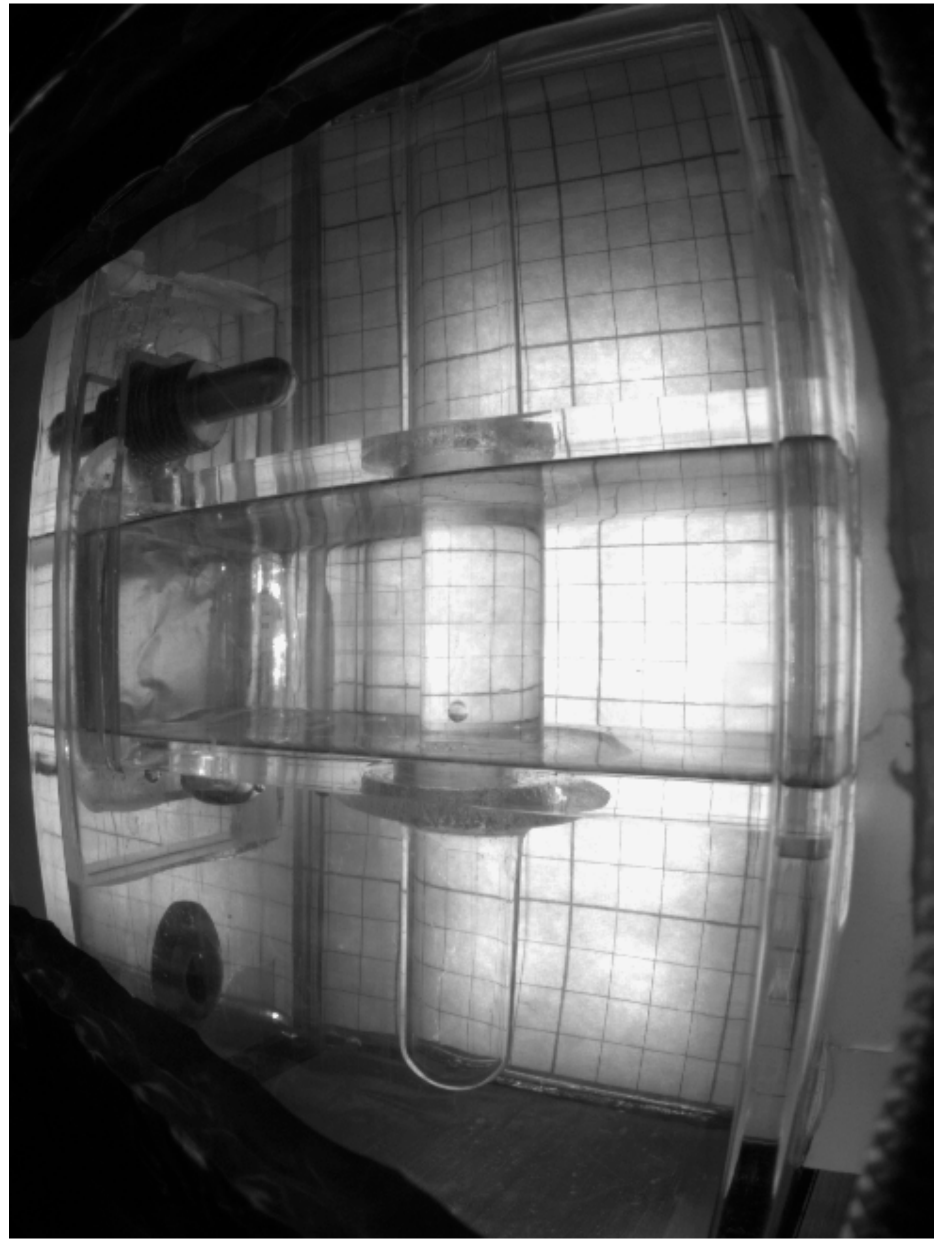


CIRTE
March 2012

- T-1017
- Fermilab Test

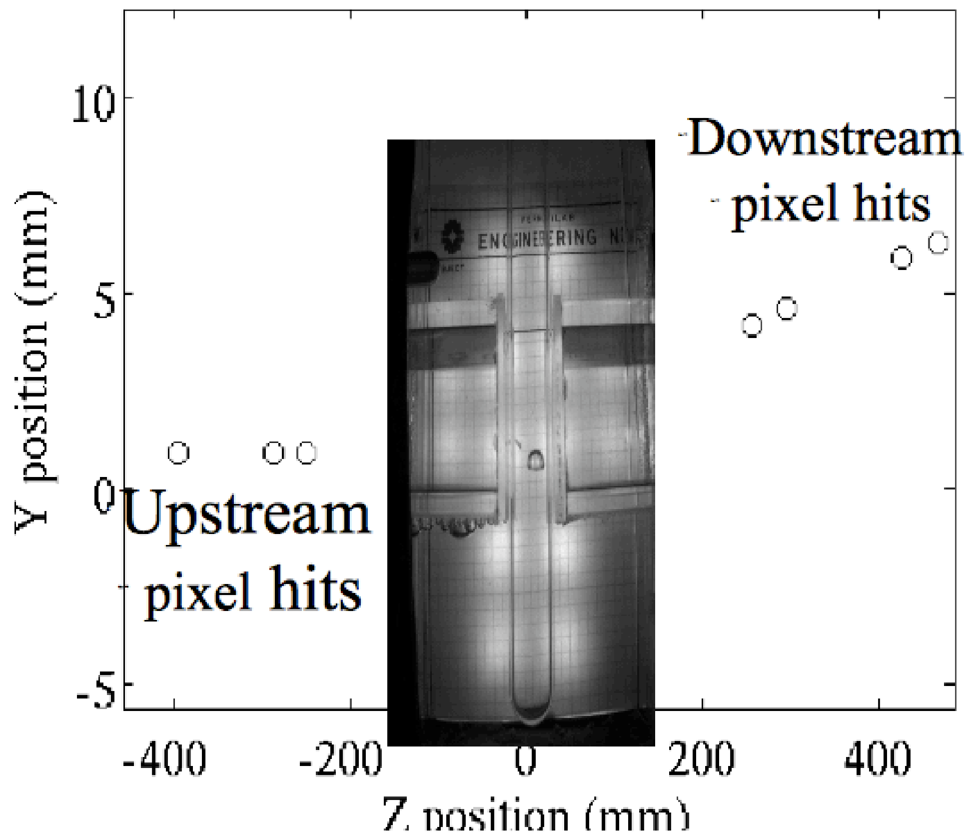
Beam Facility(M6)

COUPP
Iodine
Recoil
Threshold
Experiment



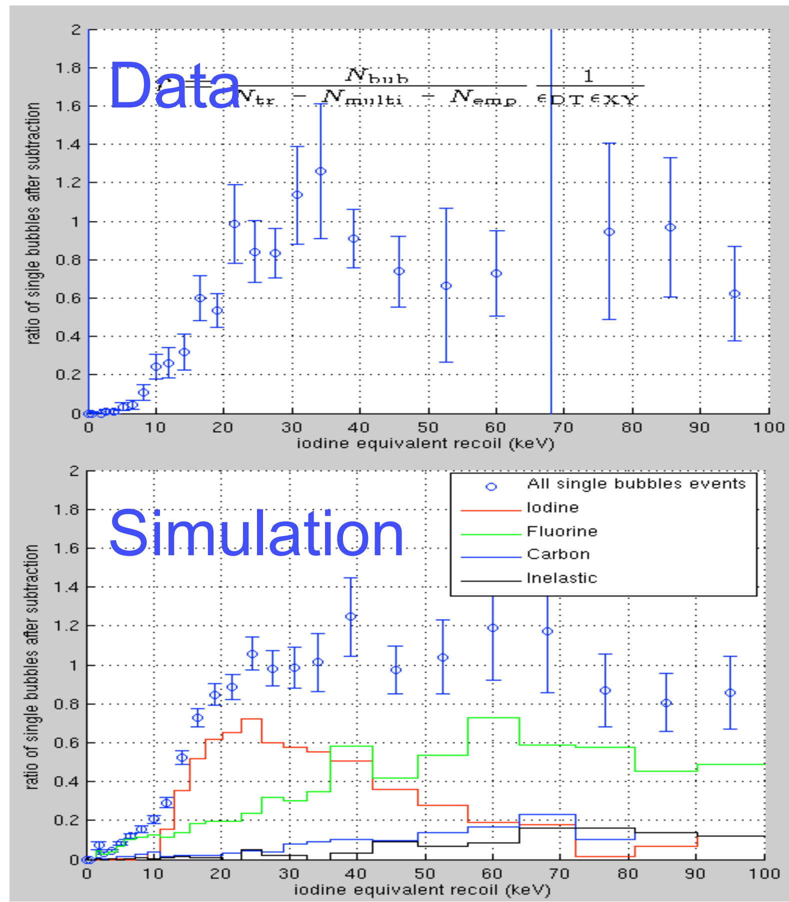
Pion Elastic Scattering $\pi^- I \rightarrow \pi^- I$

- 2 week run
- 12 Gev/c π^-
  - $T = (P\theta)^2/2M_I$
  - 10KeV : 5 mRad
- pixel tracking
- one bubble/spill

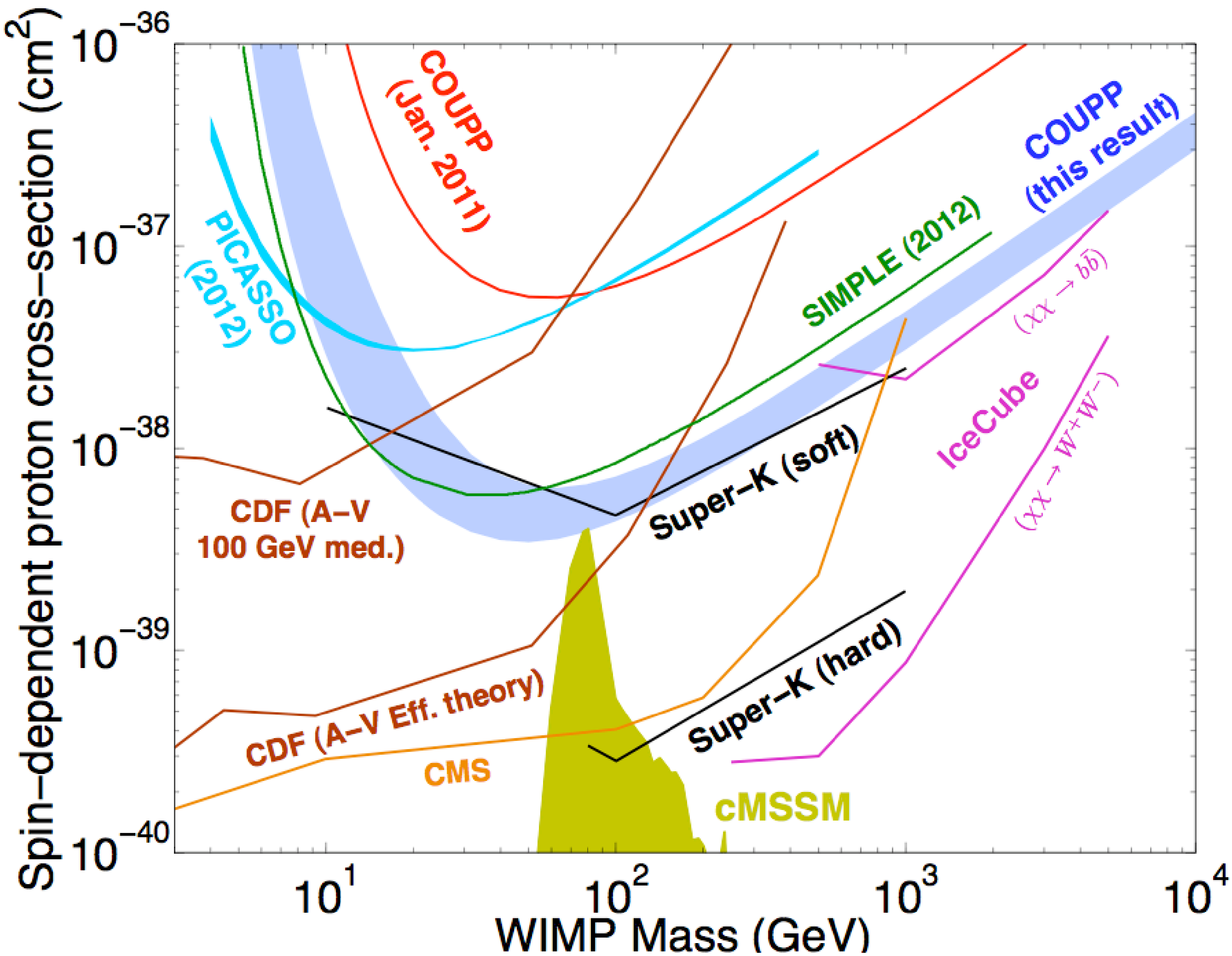


CIRTE Preliminary Results

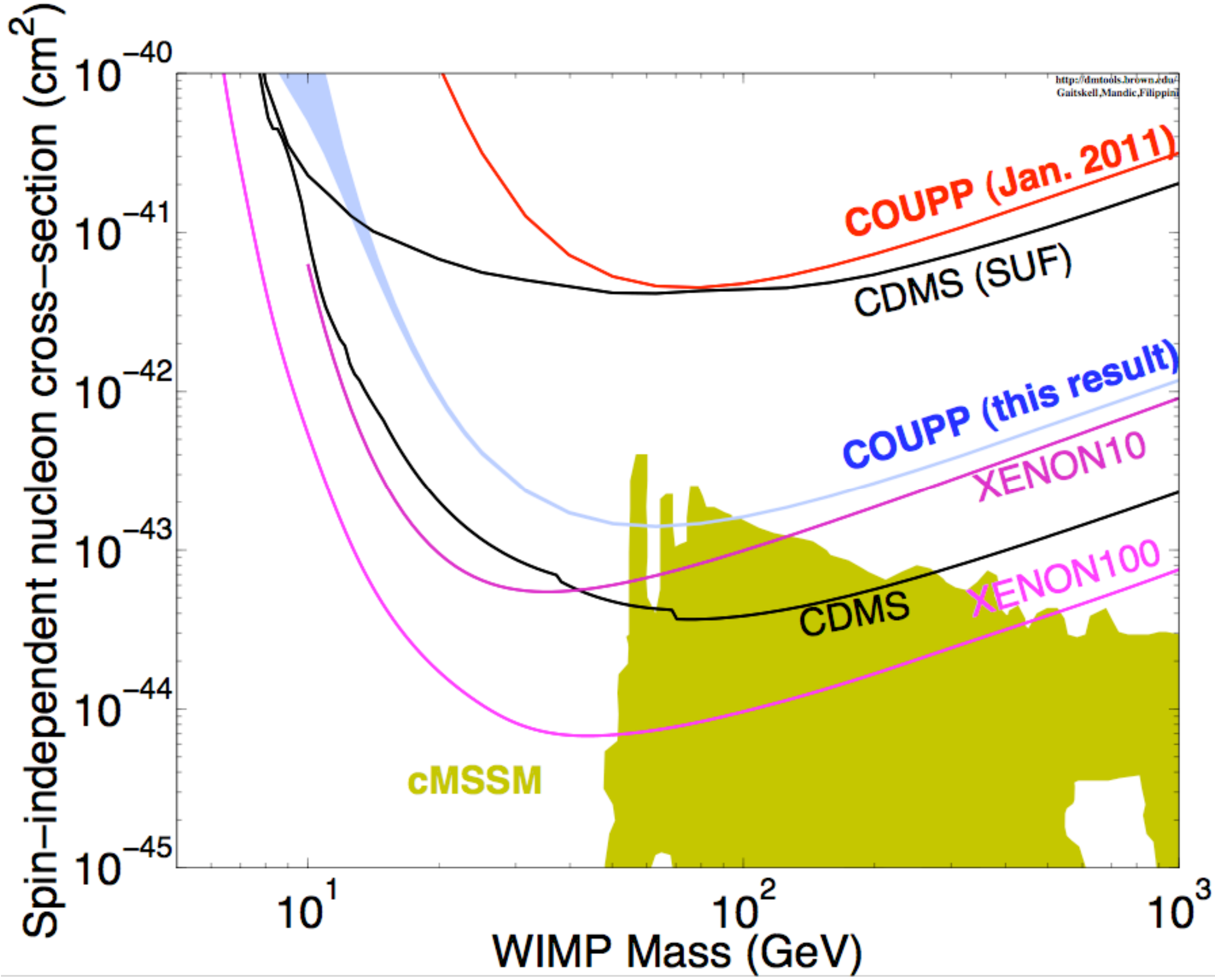
- Analysis in progress
- 15 Kev Threshold data
  - Few days of data
  - 300 good bubbles
- $\varepsilon = dN/dT_{\text{bubbles}} / dN/dT_{\text{all}}$
- looks quite good.



COUPP 4kg @ SNOLAB



COUPP 4kg @ SNOLAB



Summary & Plans

- 437 kg-days underground
- >99.3% acoustic alpha rejection
- Clear path to lower neutron background
- Next 4kg run begun in May
- COUPP60 commisioned at SNOLAB later in 2012
- COUPP500 proposal submitted
- The bubble chamber remains a competitive and cost effective tool to search for Dark Matter.