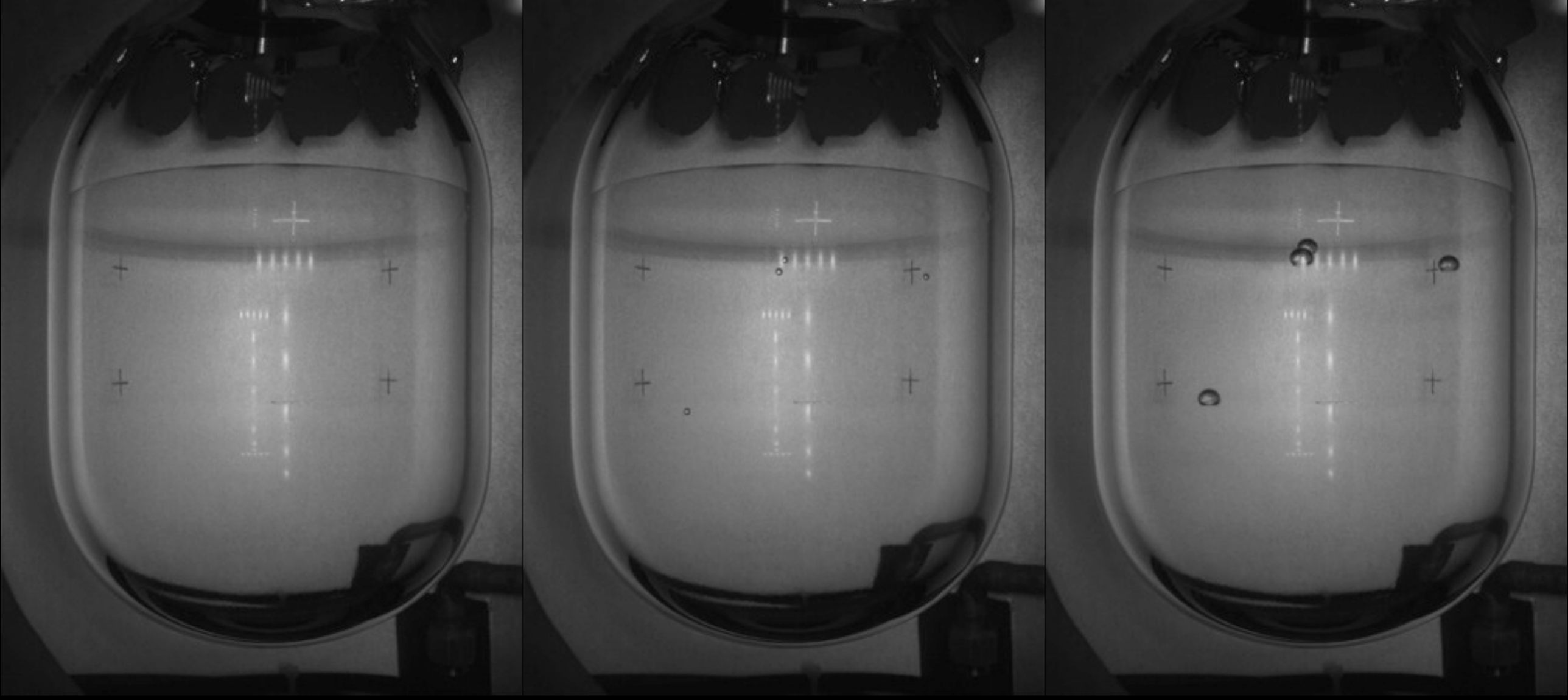

Recent Results from PICO: Searching for Dark Matter with Bubble Chambers

Hugh Lippincott, Fermilab
for the PICO Collaboration

W&C
January 30, 2015

PICO

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

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Northwestern University
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Saha Institute of Nuclear Physics, Calcutta
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R. Filgas, I. Stekl

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J.I. Collar, A.E. Robinson

Indiana University South Bend
E. Behnke, H. Borsodi, O. Harris, A. LeClair, I. Levine, E. Mann, J. Wells

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R. Neilson

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S.J. Brice, D. Broemmelsiek, P.S. Cooper, M. Crisler, W.H. Lippincott, E. Ramberg, M.K. Ruschman, A. Sonnenschein

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Queen's University
C. Amole, M. Besnier, G. Caria, G. Giroux, A. Kamaha, A. Noble

Pacific Northwest National Laboratory
D.M. Asner, J. Hall

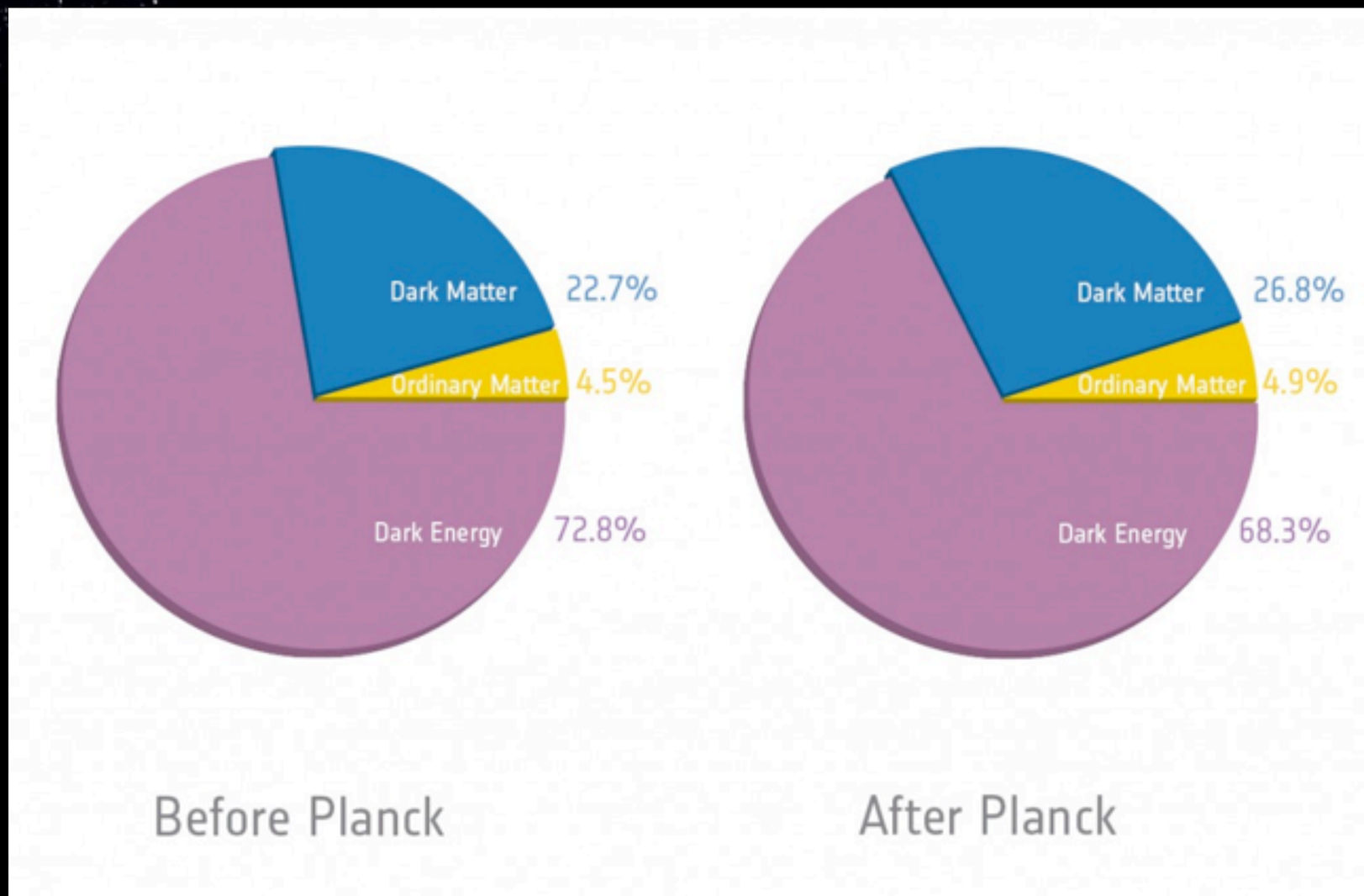
University of Alberta
S. Fallows, C. Krauss, P. Mitra

University of Toronto
K. Clark

Laurentian University / Université Laurentienne
N. Dhungana, J. Farine, R. Podviyanuk, U. Wichoski

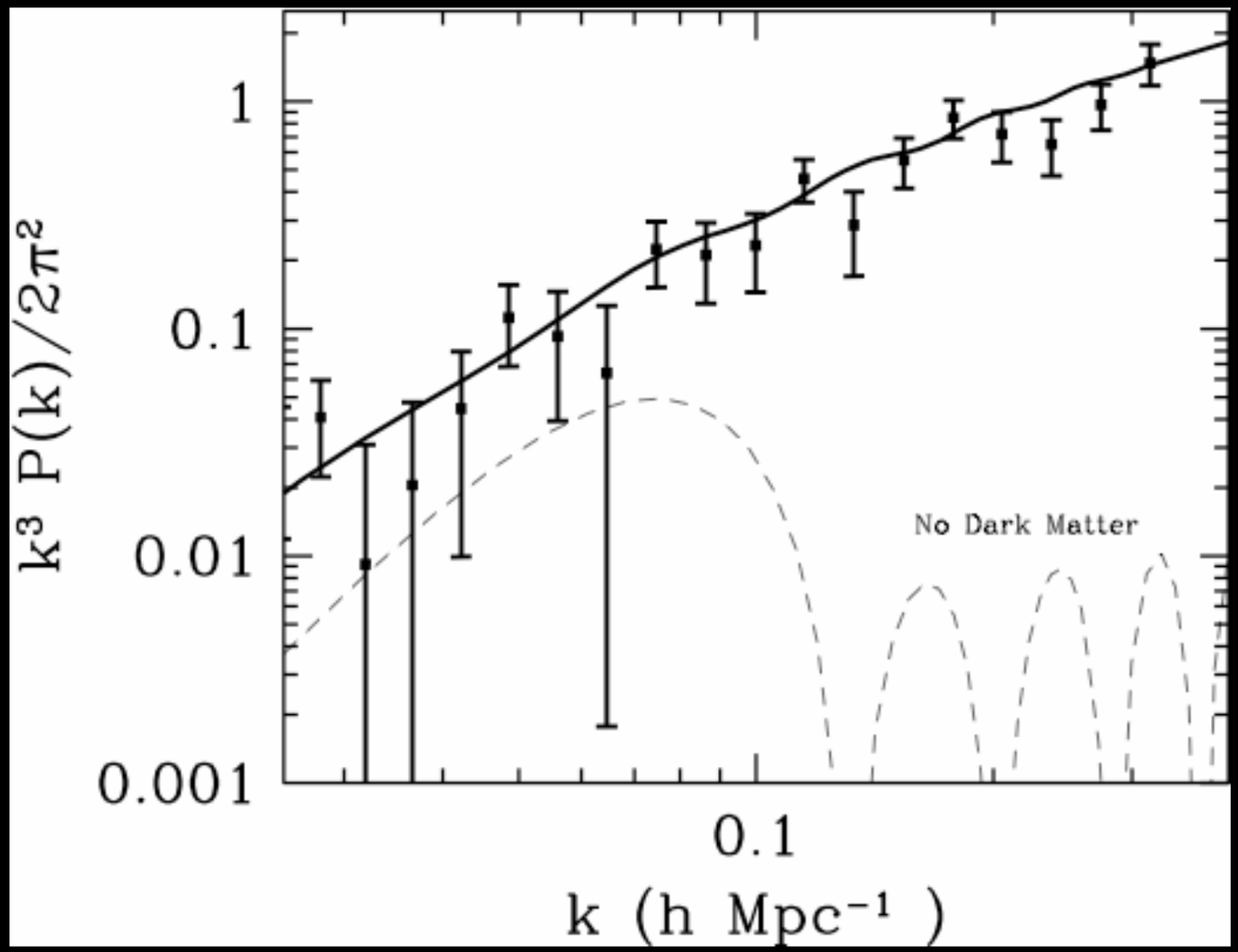
There is pretty strong consensus regarding how much stuff there is in the universe

By that same consensus, we only understand 5% of it



Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters
- Gravitational lensing
- Large Scale Structure →
- Cosmic microwave background



So what is it?

- We know it interacts gravitationally
- It is "dark" - should not interact with light or electromagnetism
- Nearly collisionless
- Slow

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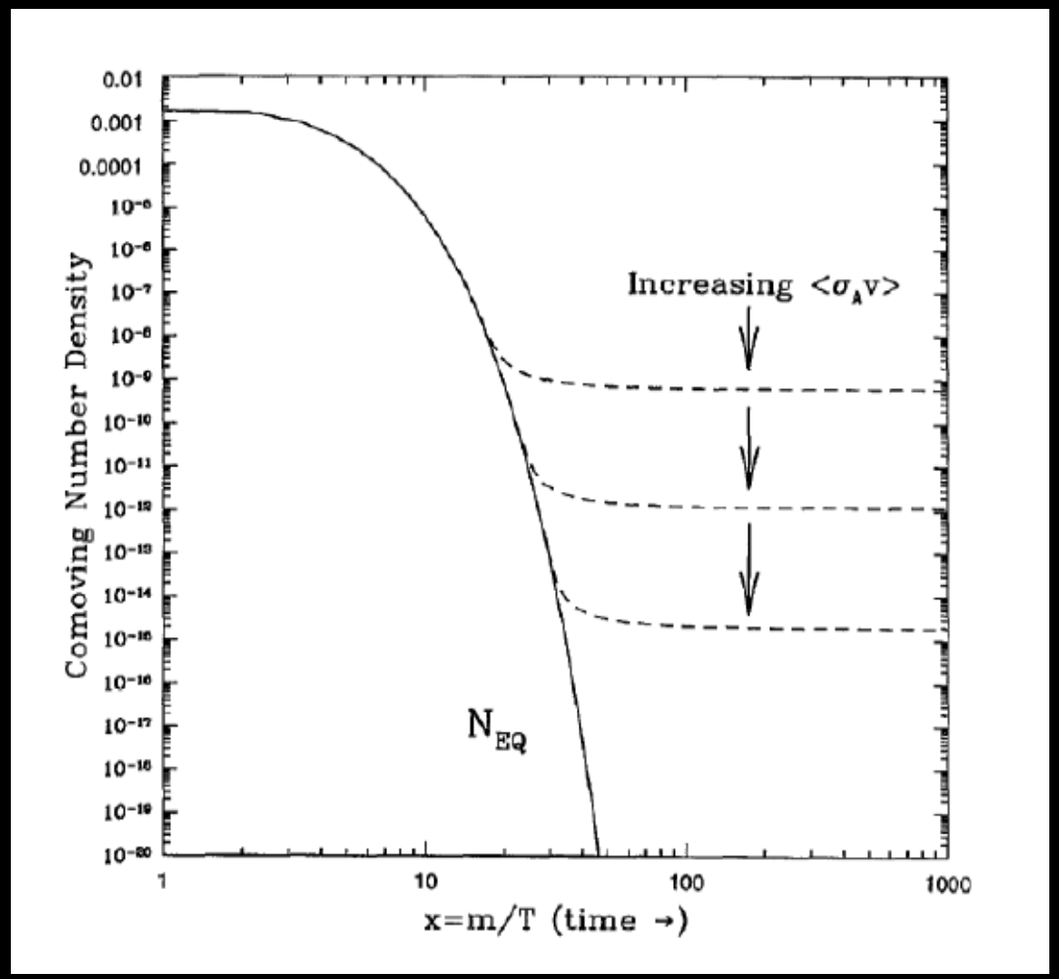
Beyond the Standard Model!

WIMPs

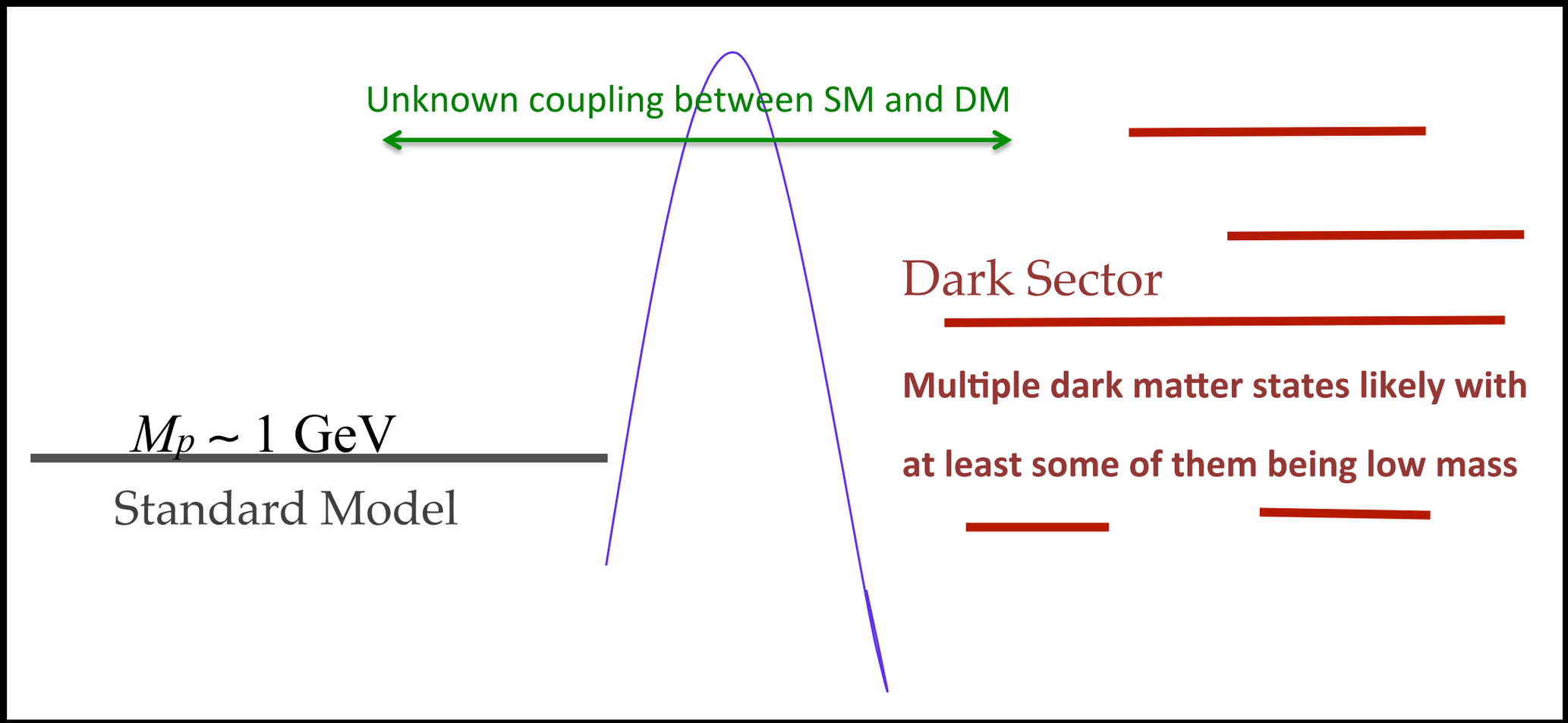
- Most discussed candidate is Weakly Interacting Massive Particle
  - Produced during big bang
  - Decouples from ordinary matter as the universe expands and cools
  - Still around today with densities of about a few per liter



- Supersymmetry produces a theoretical candidate (LSP), but others exist (e.g. Kaluza-Klein particles, ...)

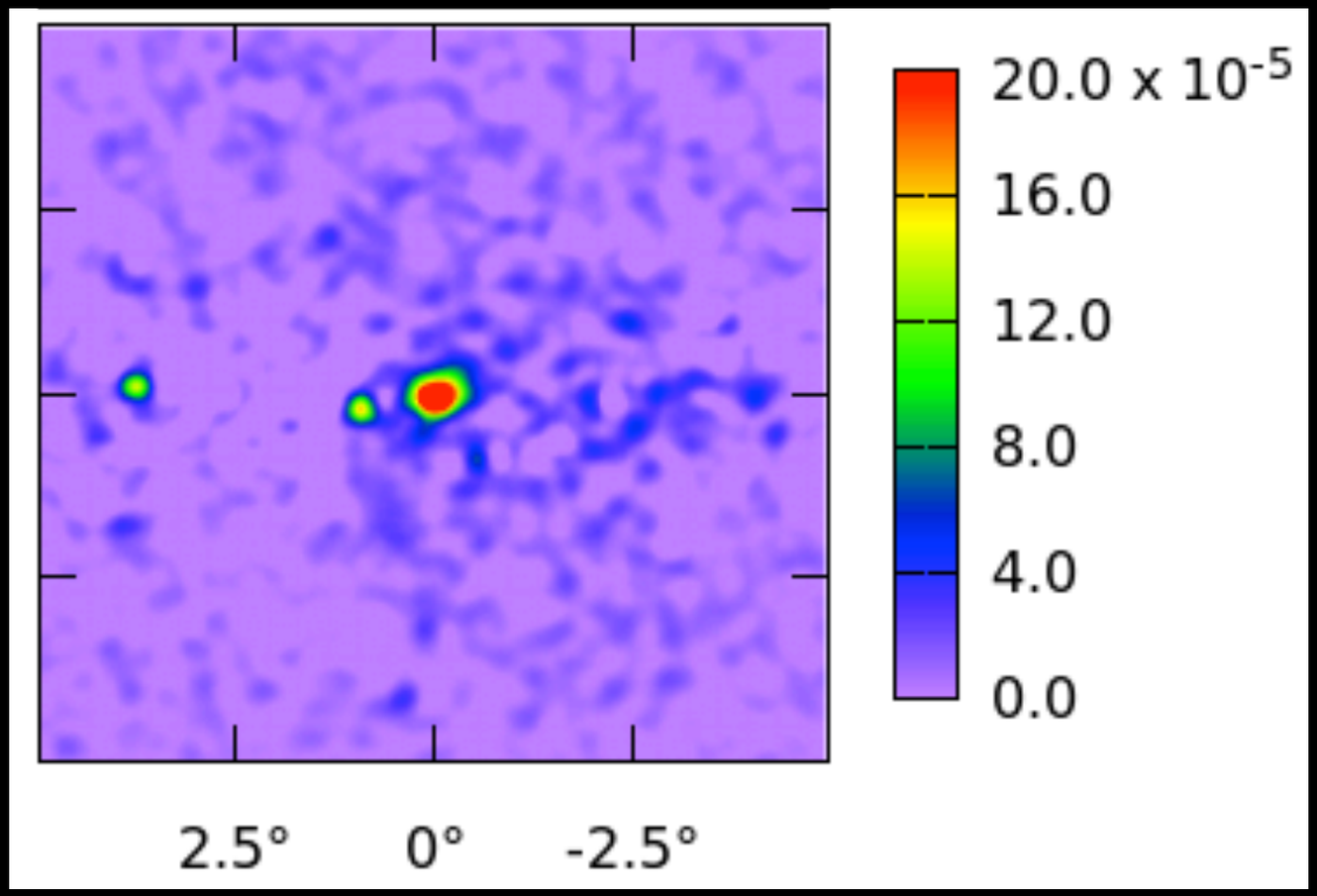
WIMPs not necessarily related to supersymmetry

- Dark sector could be as complicated as standard model
- Searches not limited by expectations from SUSY models



How do we find it?

- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy



Fermi-LAT gamma ray excess at center of galaxy
Daylan, Hooper et al., 1402.6703

How do we find it?

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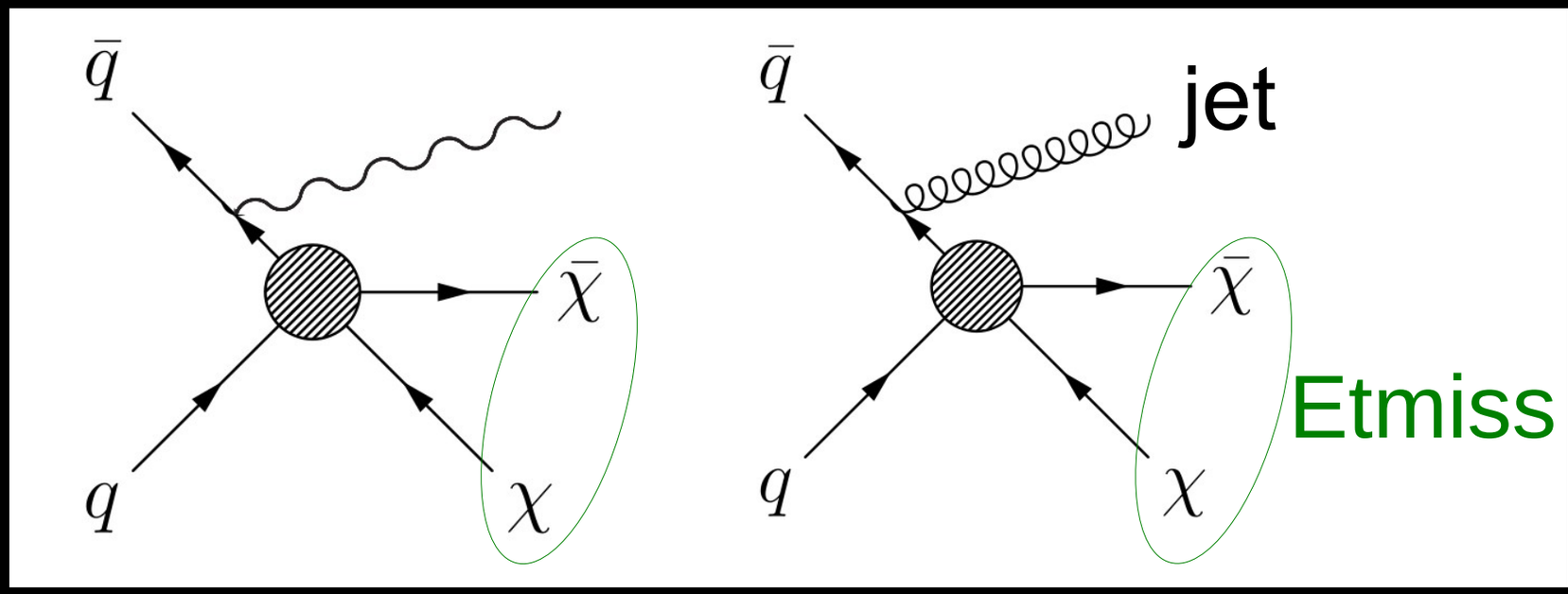
  - Missing ET and monojet searches



How do we find it?

- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy
- Accelerators - create a WIMP at the LHC
  - Missing ET and monojet searches
- Direct detection - WIMPs can scatter elastically with nuclei and the recoil can be detected

Direct Detection

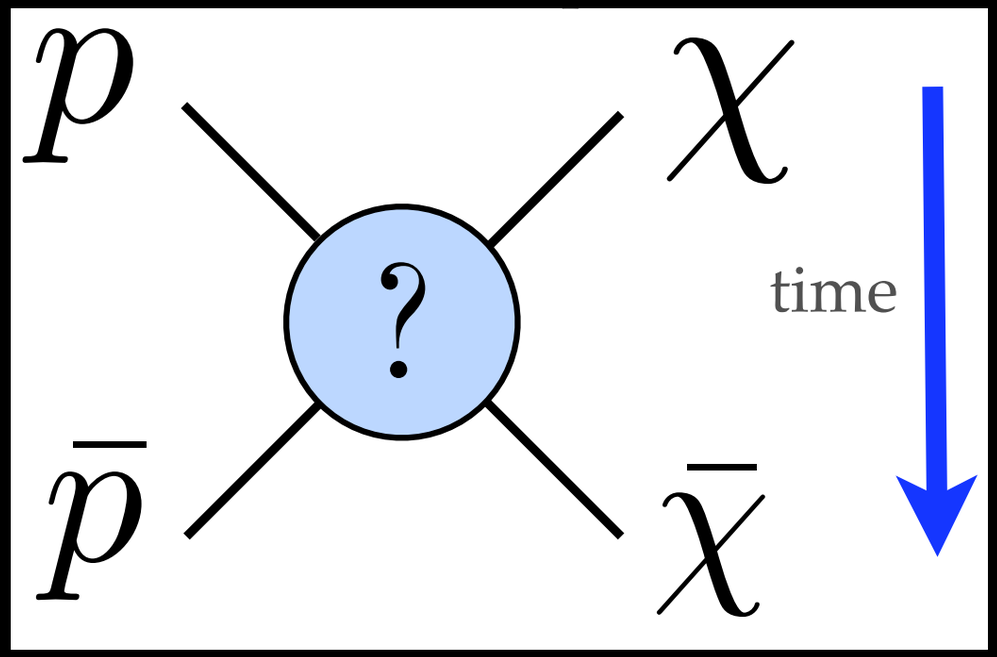
- Calculate rate based on assumptions about the dark matter distribution and interaction

- Historically two interactions are considered (by DM experimentalists)

  - Spin independent (SI) - couples to all nucleons

    - Enhancement for large nuclei

  - Spin dependent (SD) - couples to the spin of the nucleus (unpaired spin of one nucleon)



Rate calculation

- The differential cross section (for spin-independent interactions) in events/kg/keV mass per unit recoil energy is

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv \tag{3}$$

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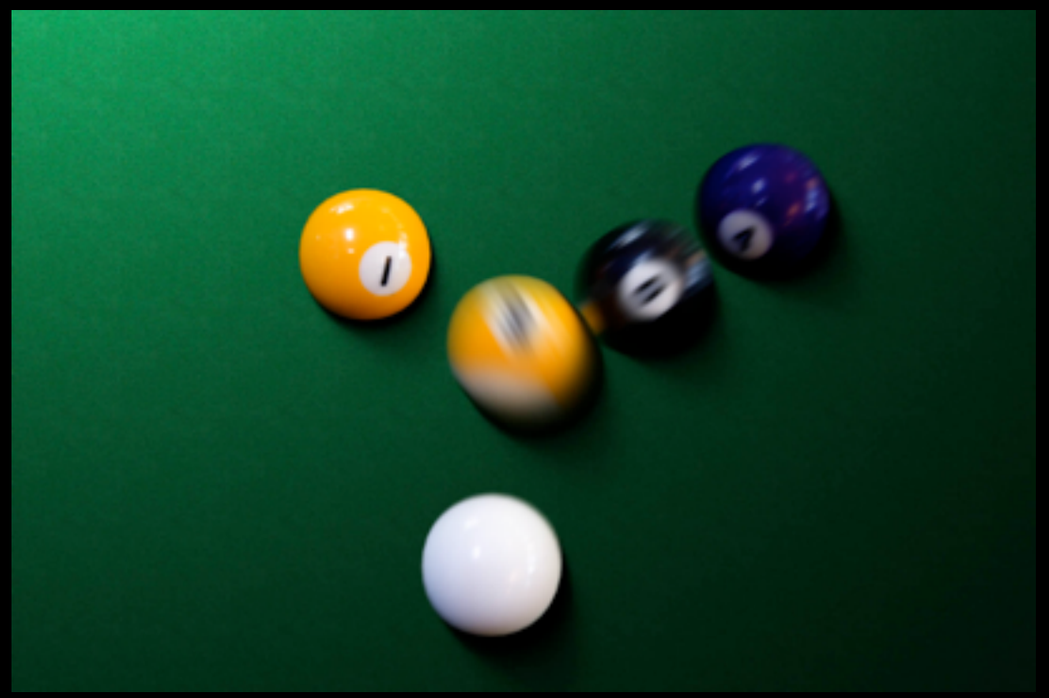
- The nuclear part, approximately given by $F^2(Q) \propto e^{-Q/Q_0}$ where $Q_0 \sim \frac{80}{A^{5/3}}$ MeV
- The velocity distribution of dark matter in the galaxy - of order 30% uncertainty (not-statistical), and $v_m = \sqrt{Qm_N/2m_r^2}$ (here $m_r = m_N m_\chi/(m_N + m_\chi)$ is the reduced mass of the nucleus)

The energy scale

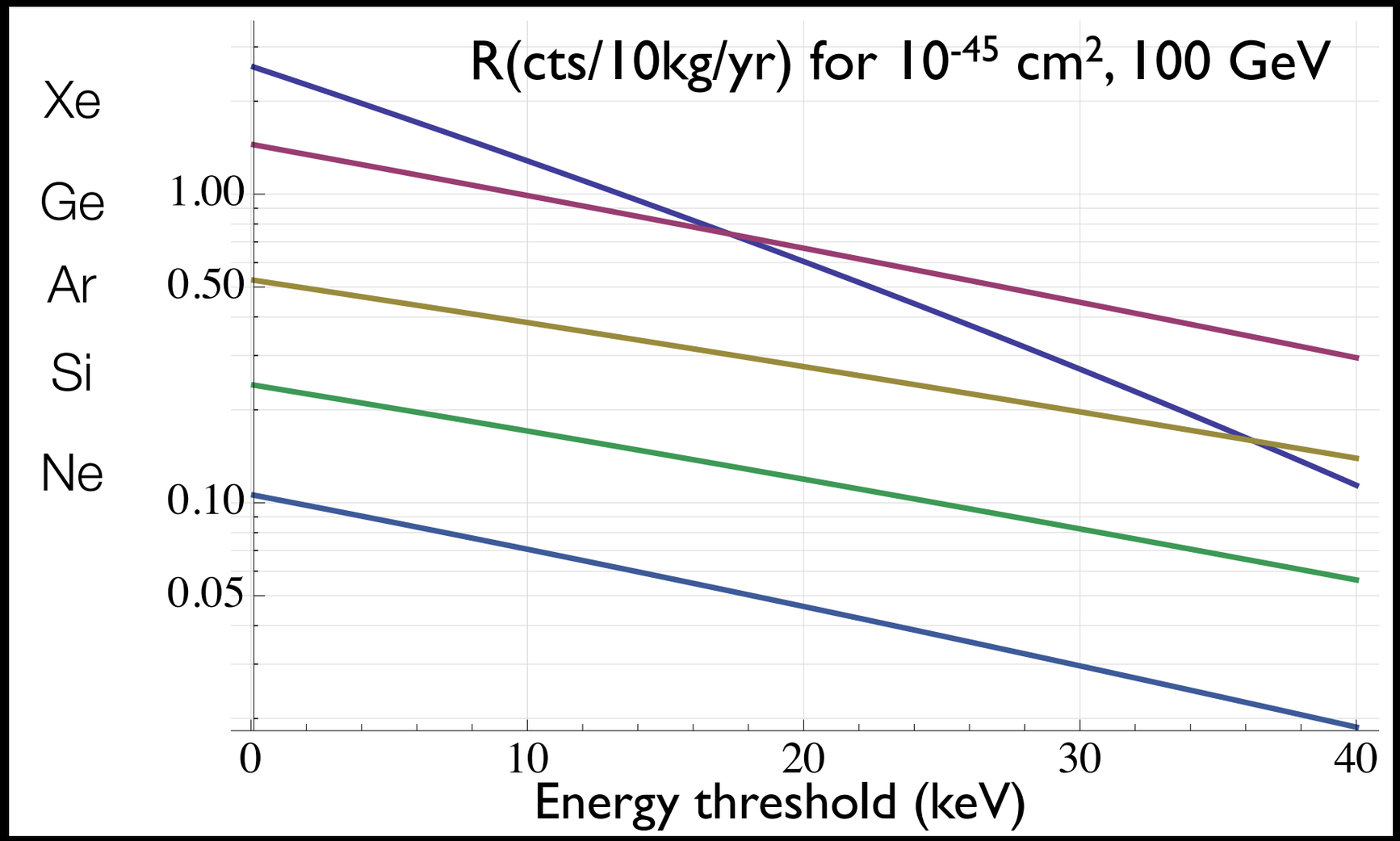
- Energy of recoils is tens of keV
- Entirely driven by kinematics, elastic scattering of things with approximately similar masses (100 GeV) and v ~ 0.001c

$$\frac{1}{2} m_N v_N^2 = \frac{1}{2} \times 100\,\mathrm{GeV} \times 10^{-6} = 50\,\mathrm{keV}$$



How do we find it?

- Very low rate process (~events/year)



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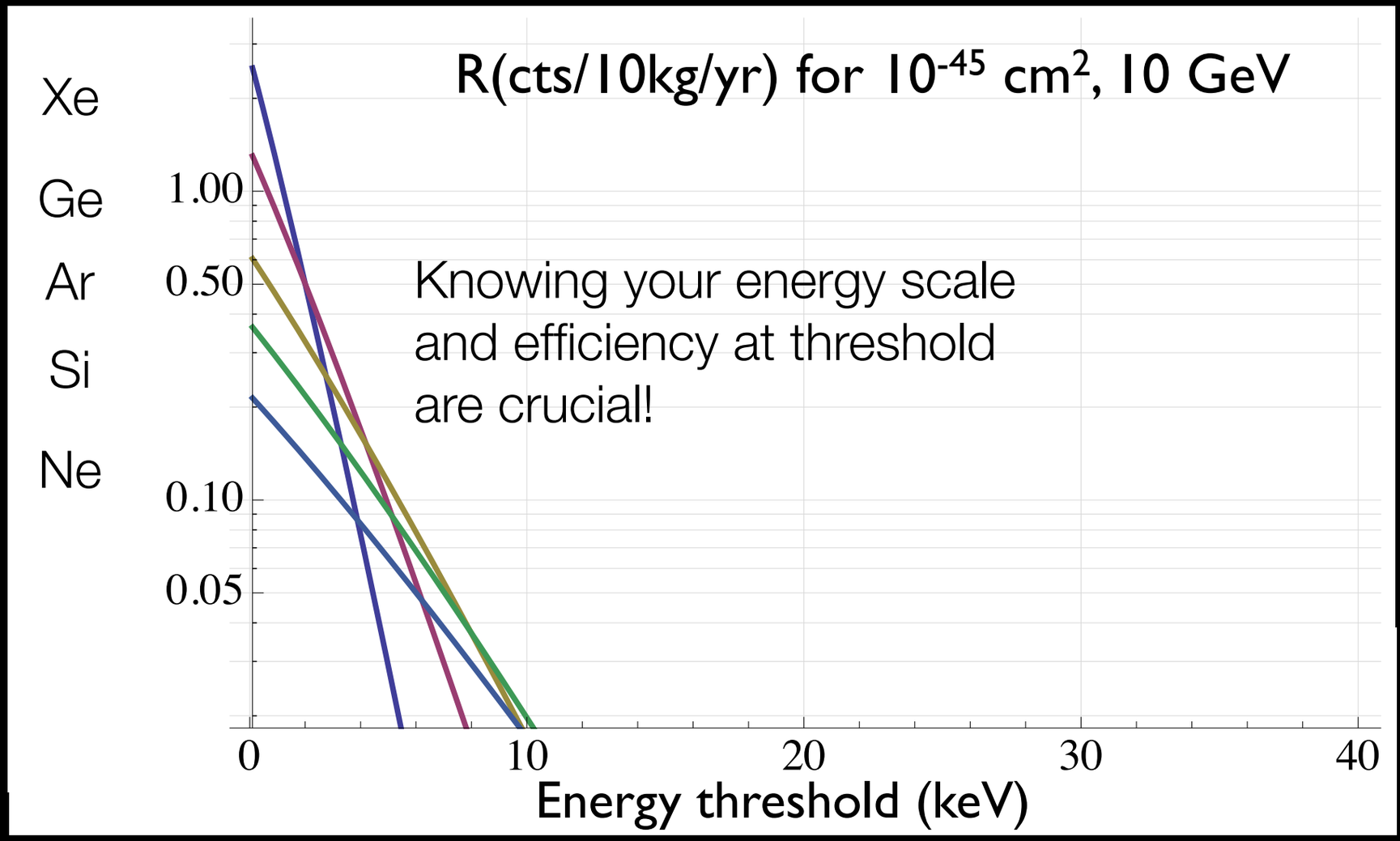
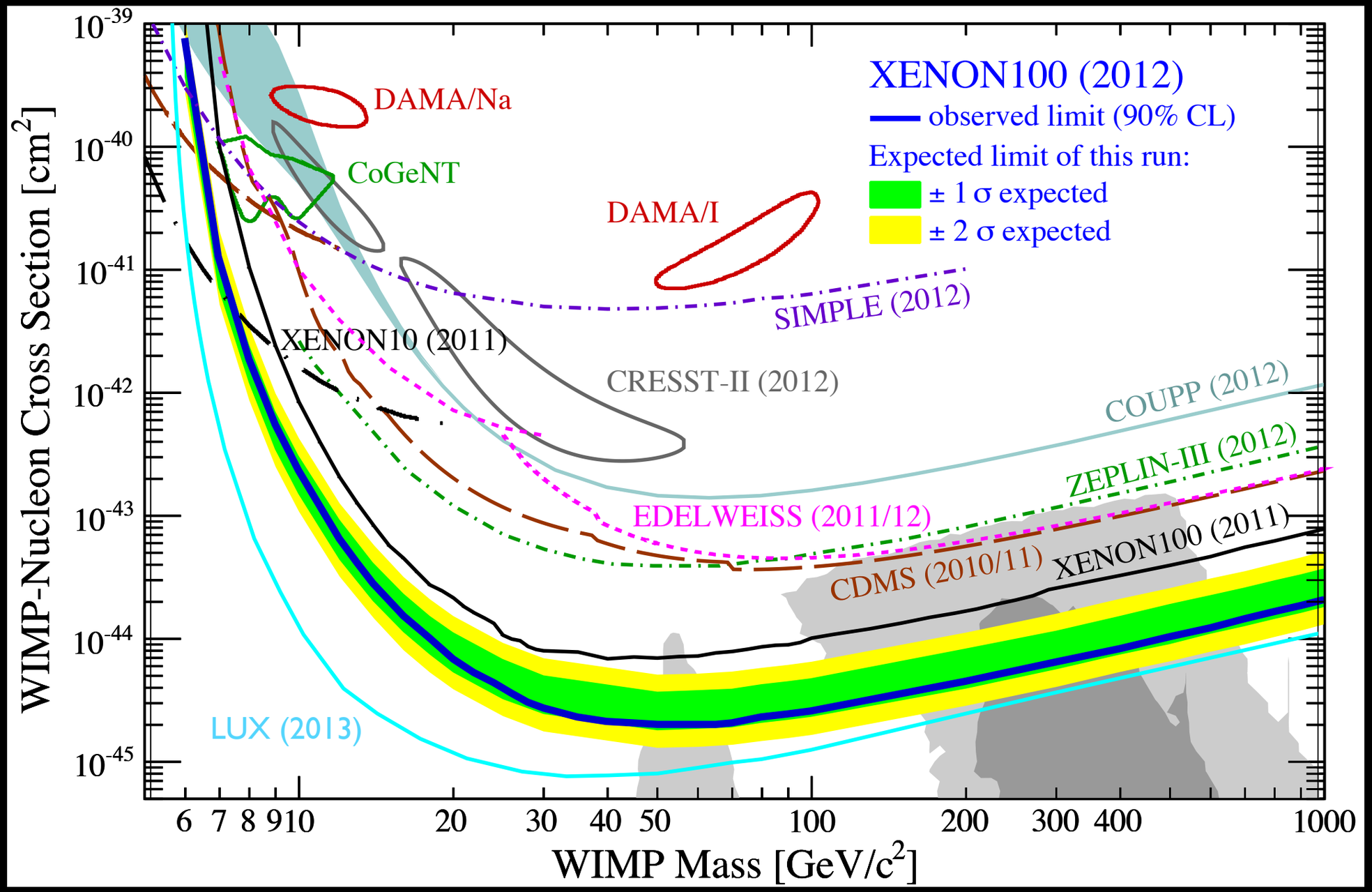


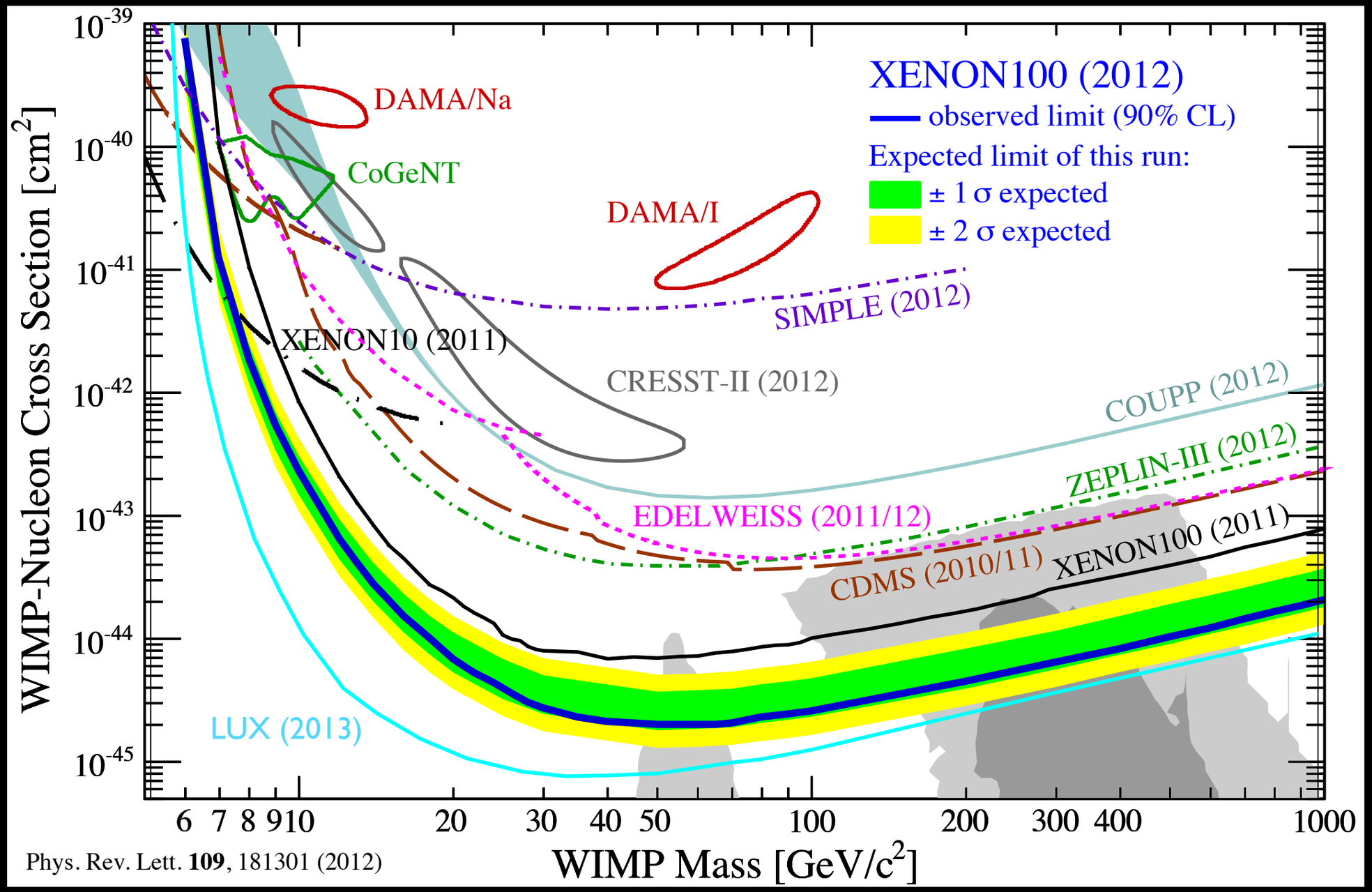
- Rate depends crucially on WIMP mass and threshold

The canonical plot



- Limited at low mass by detector threshold
- Limited at high mass by density

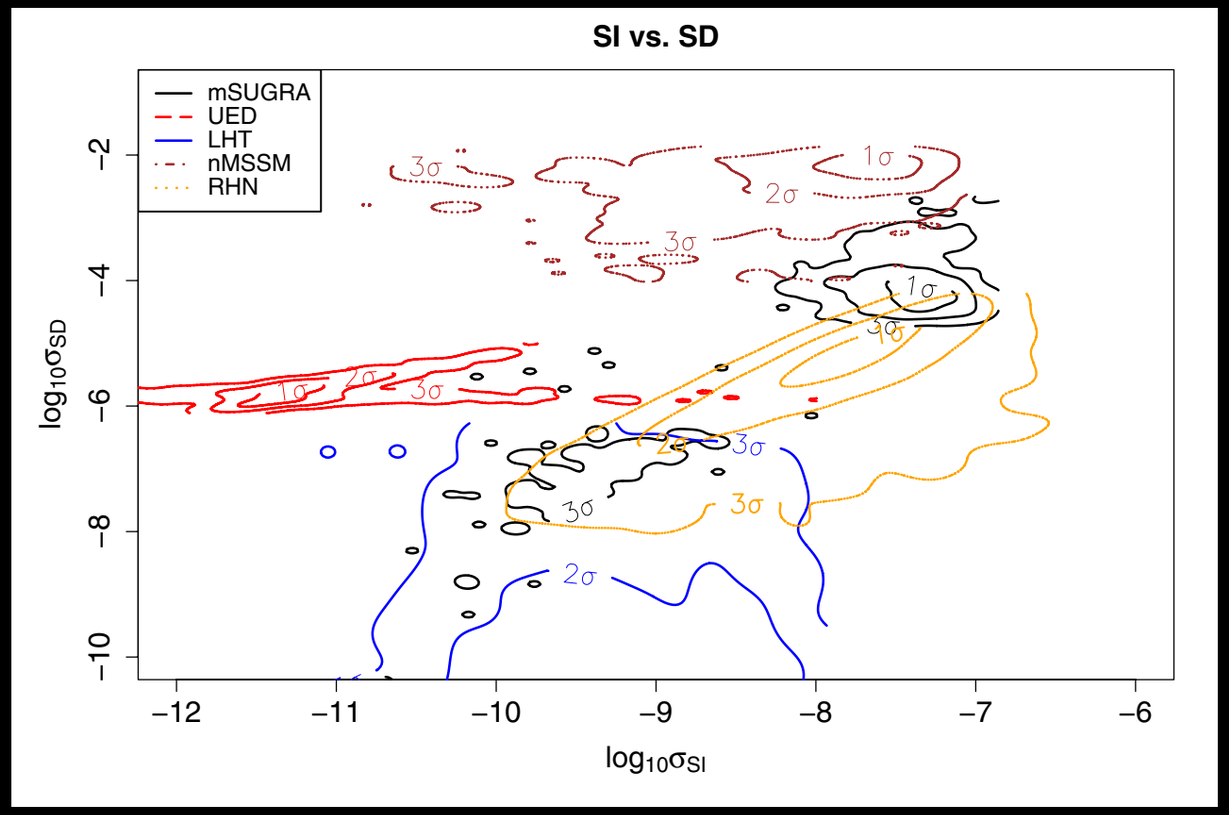
The canonical plot



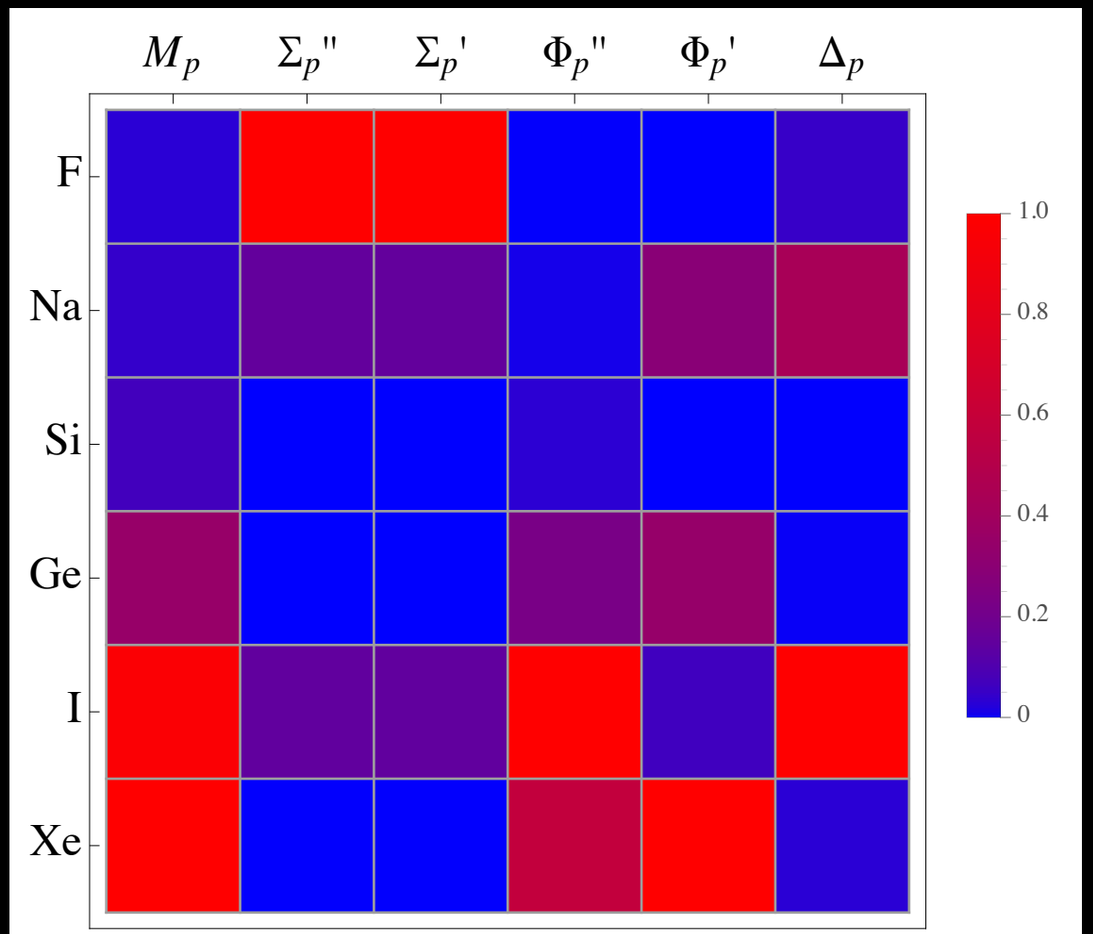
- What happened to "weakly" interacting?
- Mediation via Z was excluded long ago (~10^{-39} cm^2), but only now are we probing Higgs exchange

SI vs. SD (vs. nuclear physics)

- Spin-independent historically dominates the news because of the rate enhancement (x16000 for an atom like xenon)
- True interaction is still unknown



SD vs. SI cross section predictions for different models (Barger, PRD, 78 056007)



Sensitivity of different p-coupling operators to various nuclear targets (from L. Fitzpatrick at INT Workshop, 2014)

So we look for WIMPs

- A few hundred just passed through us, and we might expect a handful of counts in a detector per year

So we look for WIMPs

- A few hundred just passed through us, and we might expect a handful of counts in a detector per year
- The problem is that background radioactivity is everywhere!

100 events/second/kg =
3,000,000,000,000 events/year
in a ton-scale experiment

Backgrounds!

Background sources

- Cosmic rays are constantly streaming through
  - All experiments have to go underground to get away from cosmic rays


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

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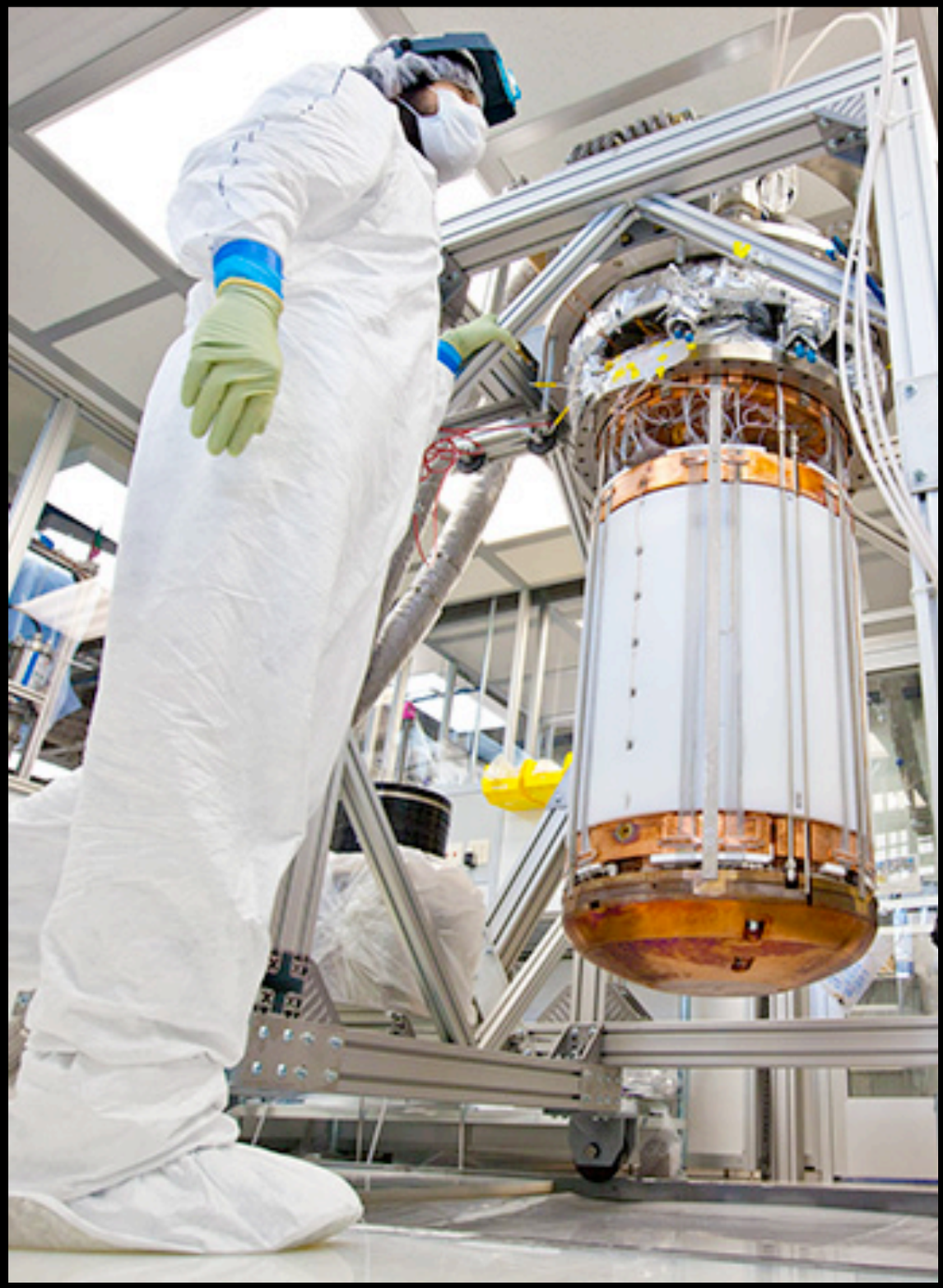

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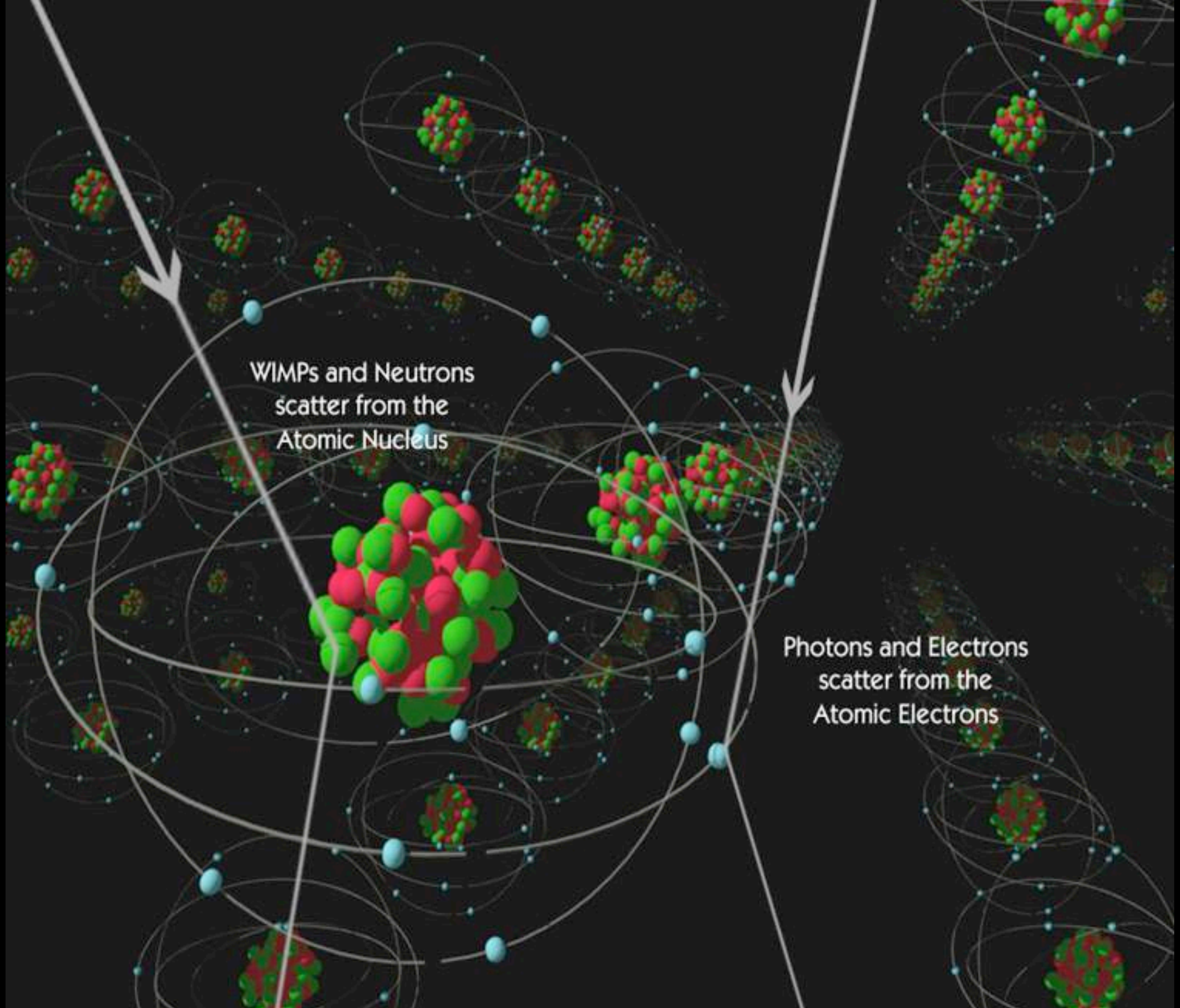
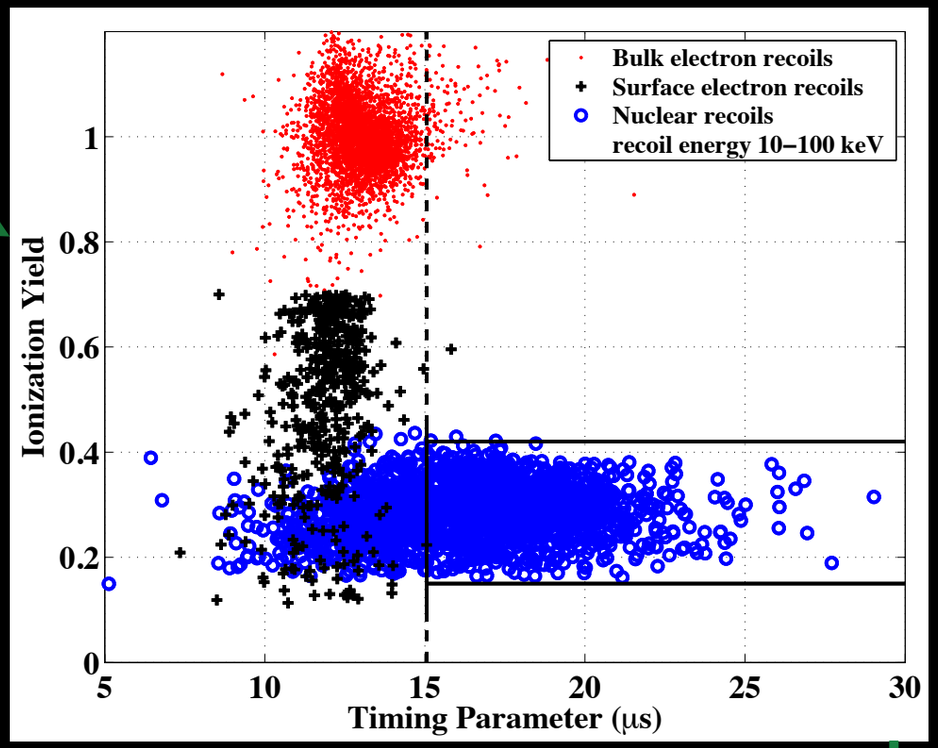
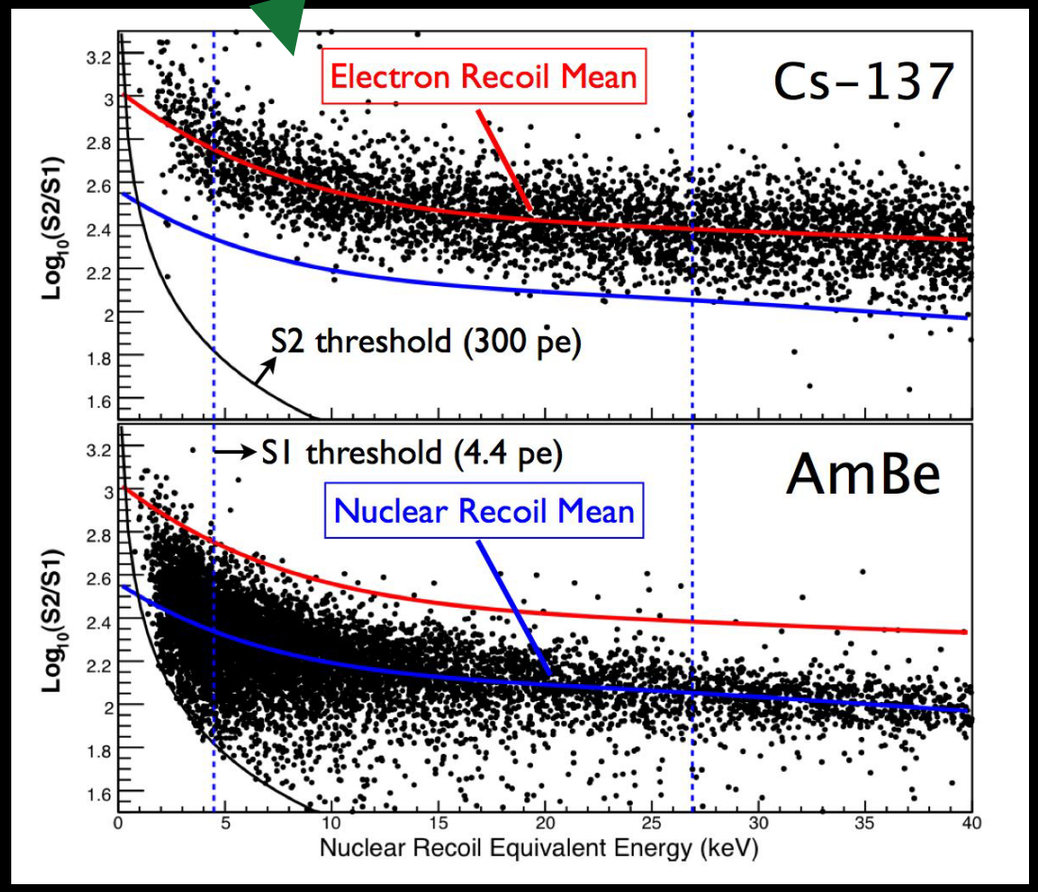

WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons

Electronic recoils (gammas) vs. nuclear recoils (WIMPs)

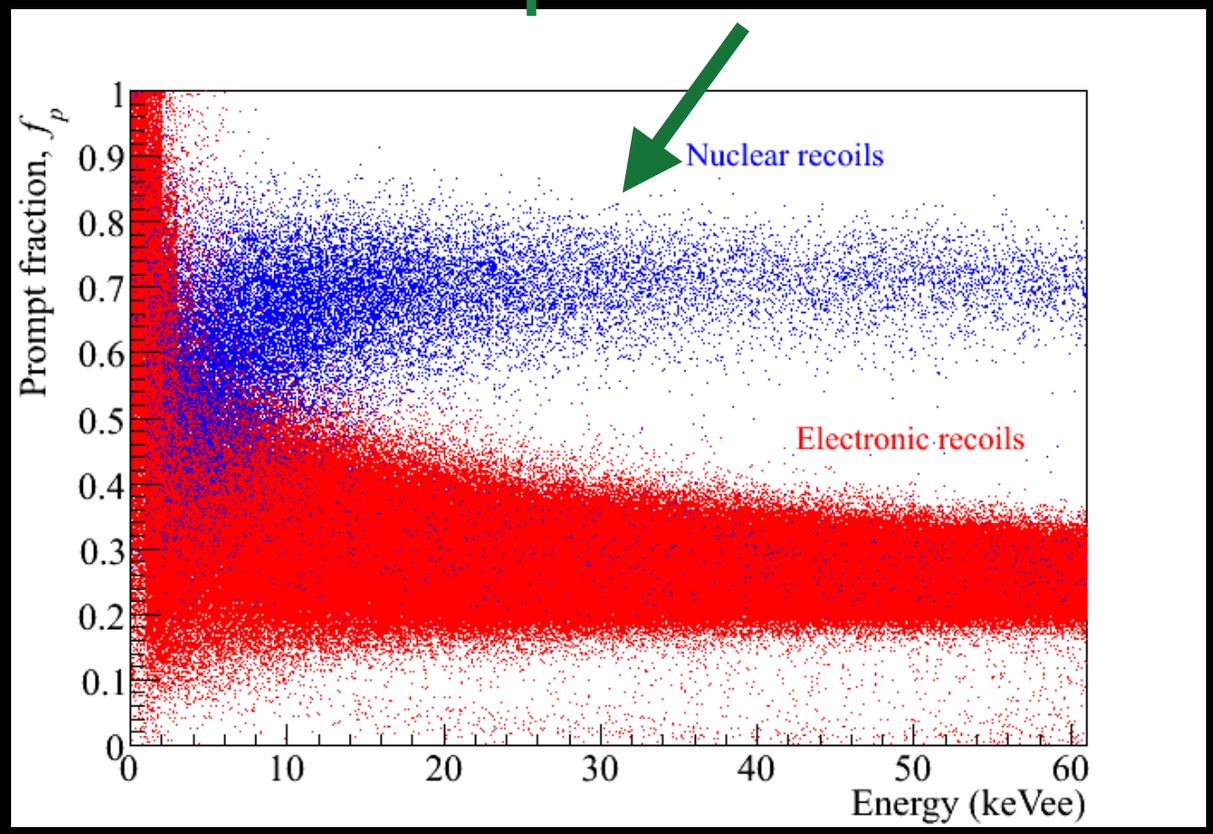
CDMS - Charge to heat



Xenon TPCs - Charge to light



Argon - Pulse shape discrimination



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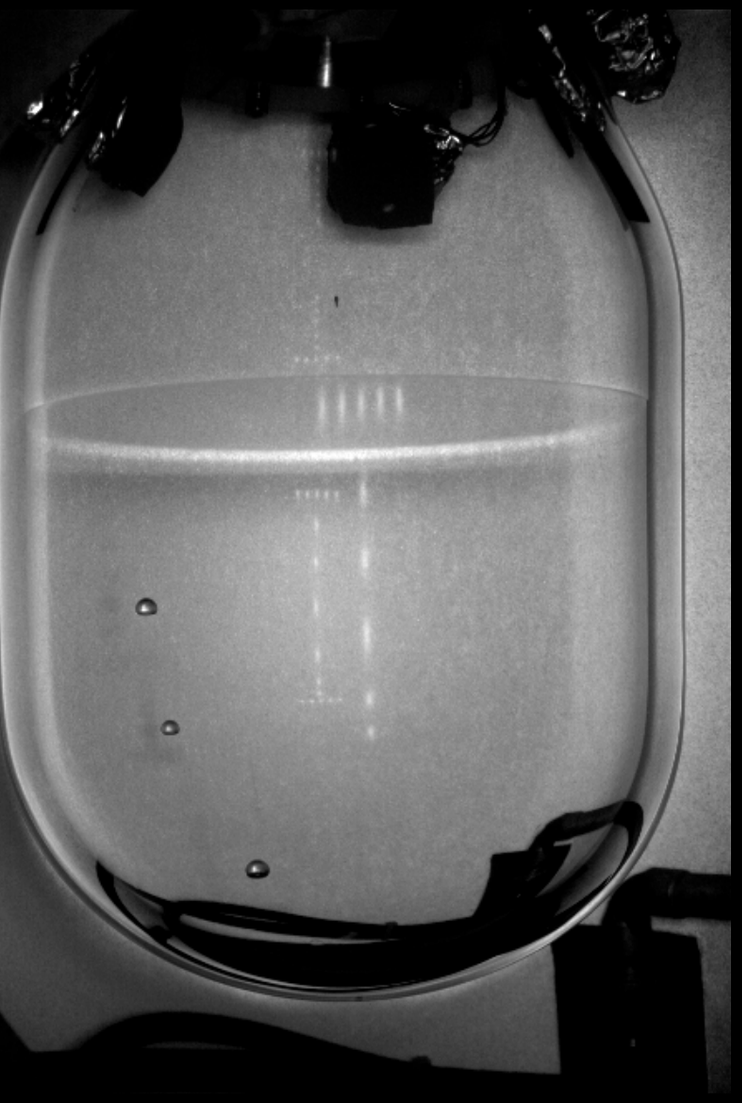
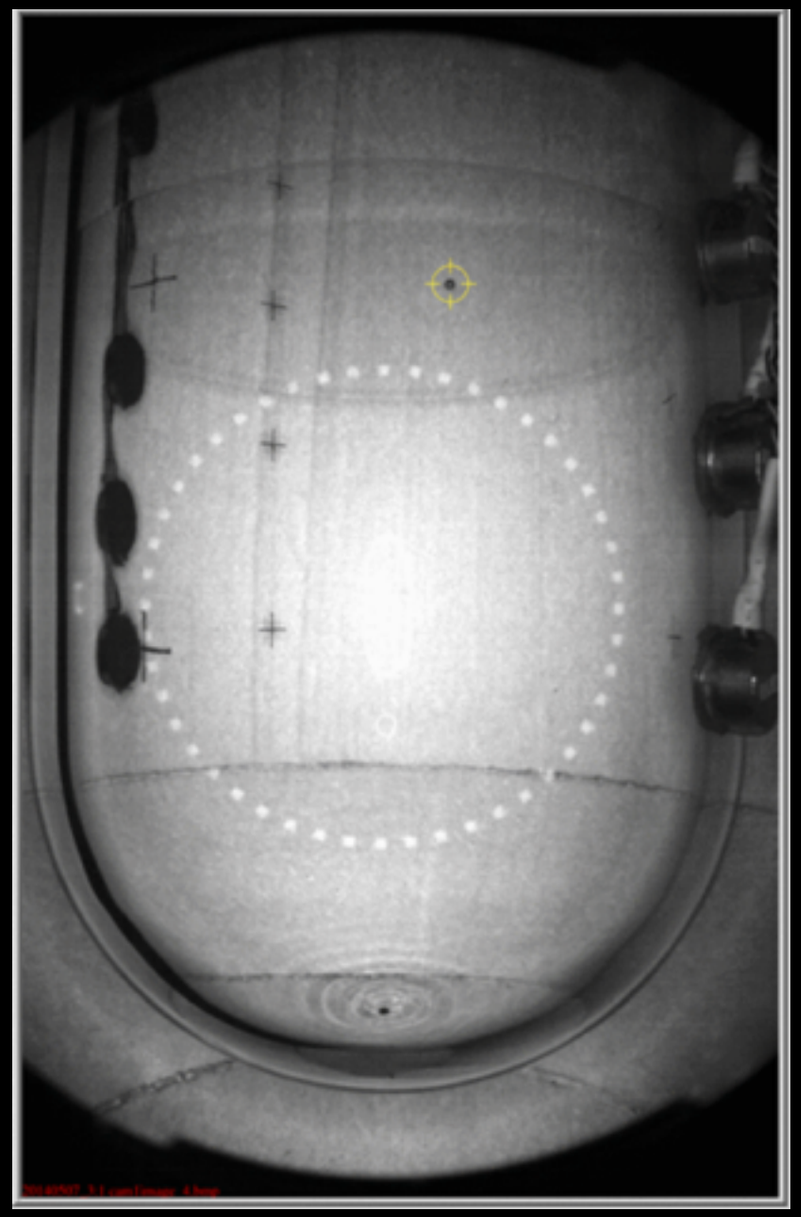
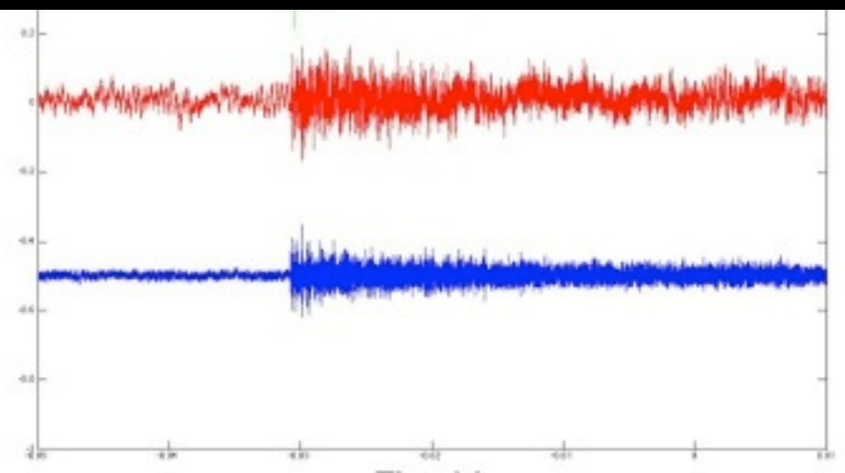
Bubble Chambers!

PICO Collaboration

(portmanteau of PICASSO and COUPP, themselves clunky acronyms)

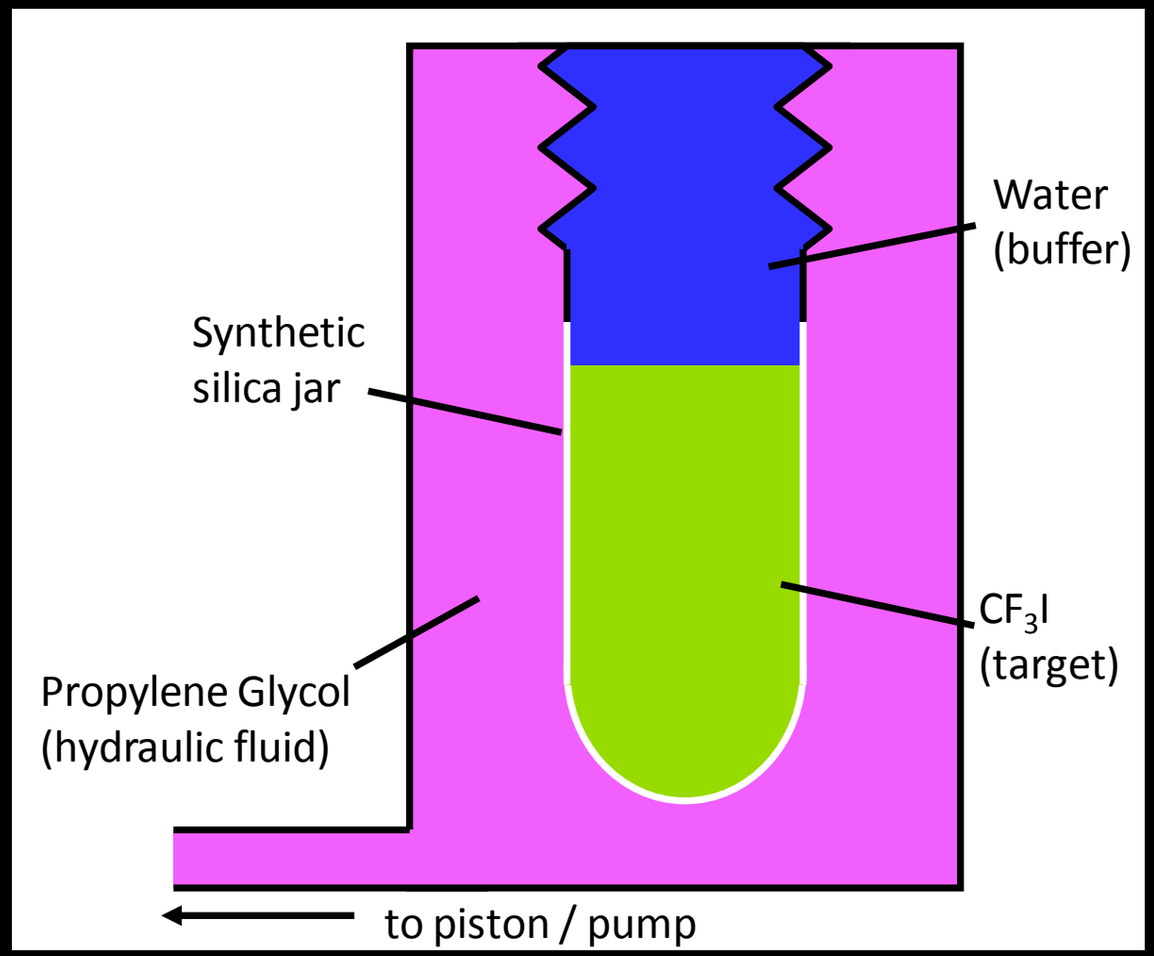


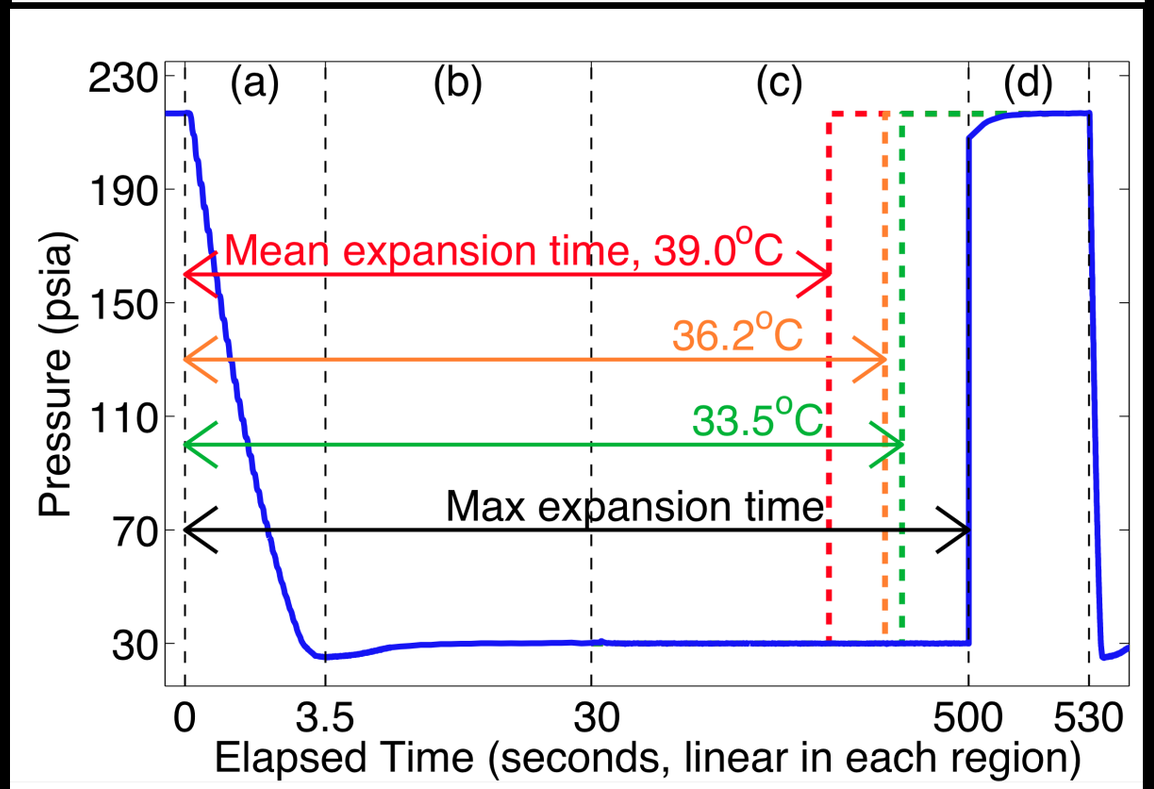


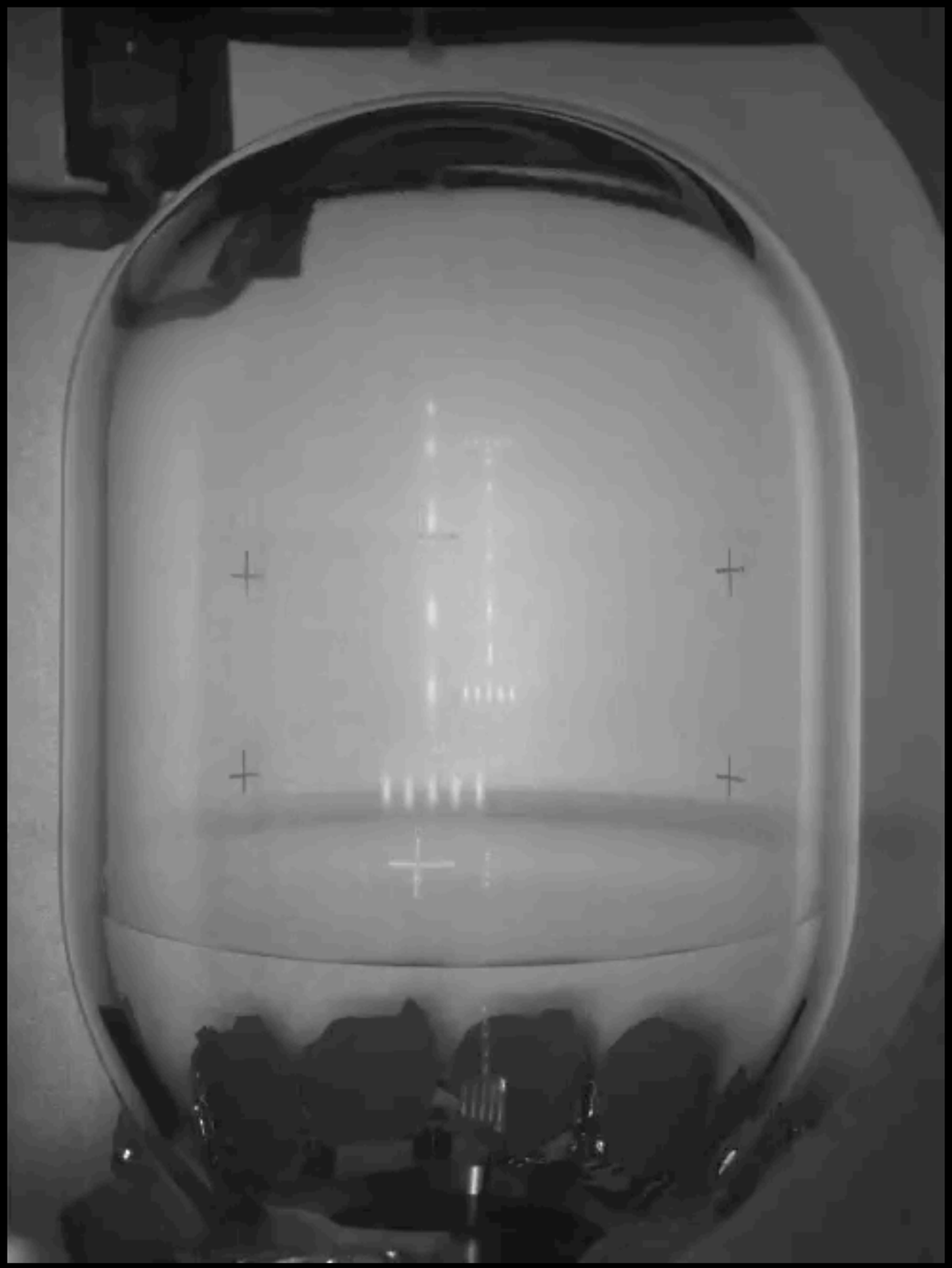


PICO fast compression bubble chamber

- Pressure expansion creates superheated fluid, CF_3I or C_3F_8
  - I for spin-independent
  - F for spin-dependent
- Particle interactions nucleate bubbles
- Cameras see bubbles
- Recompress chamber to reset

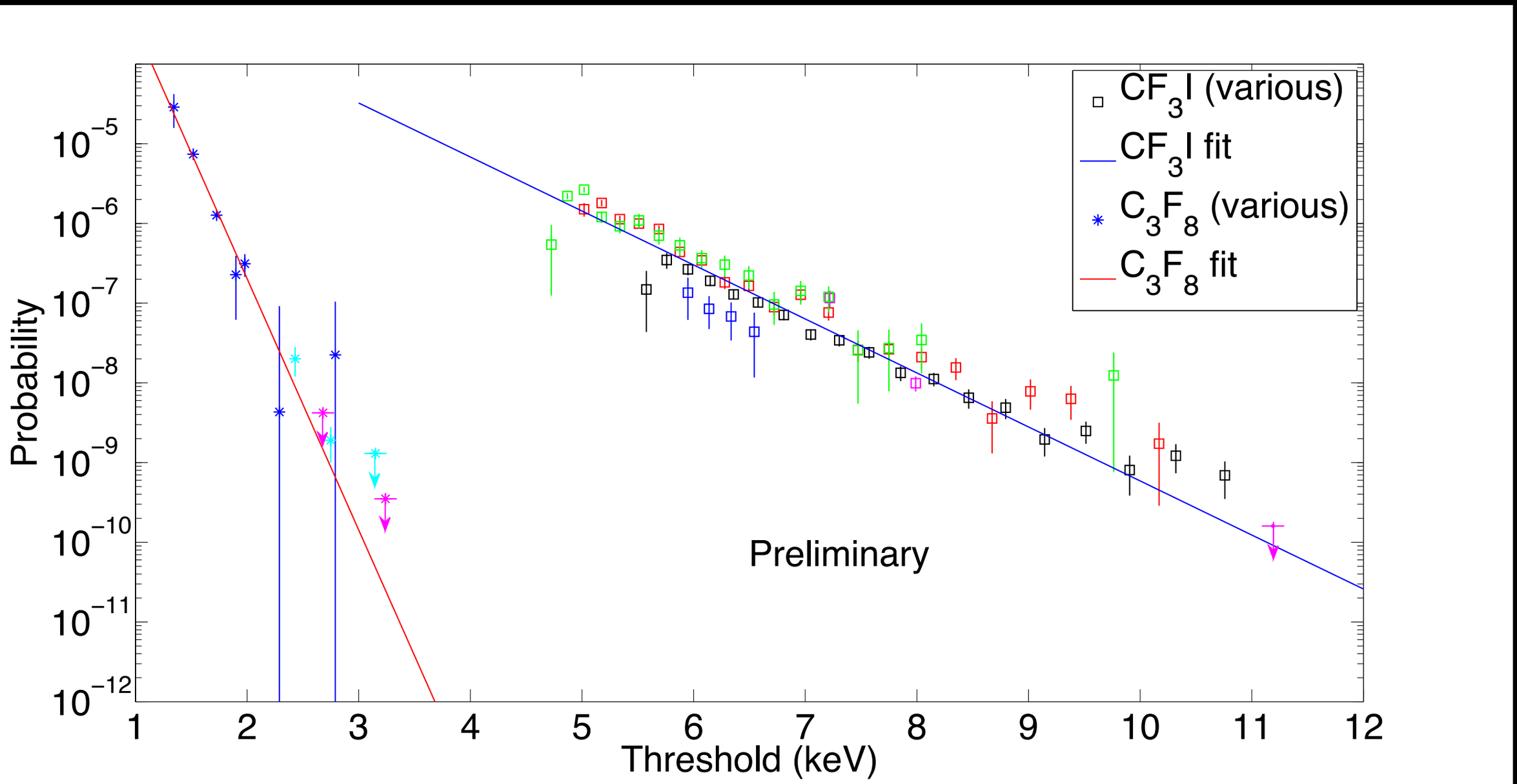






Why bubble chambers?

- By choosing superheat parameters appropriately (temperature and pressure), bubble chambers are blind to electronic recoils (10^{-10} or better)
  - The probability for gamma interaction to produce a bubble:



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  - Enough energy density - length scale must be comparable to the critical bubble size

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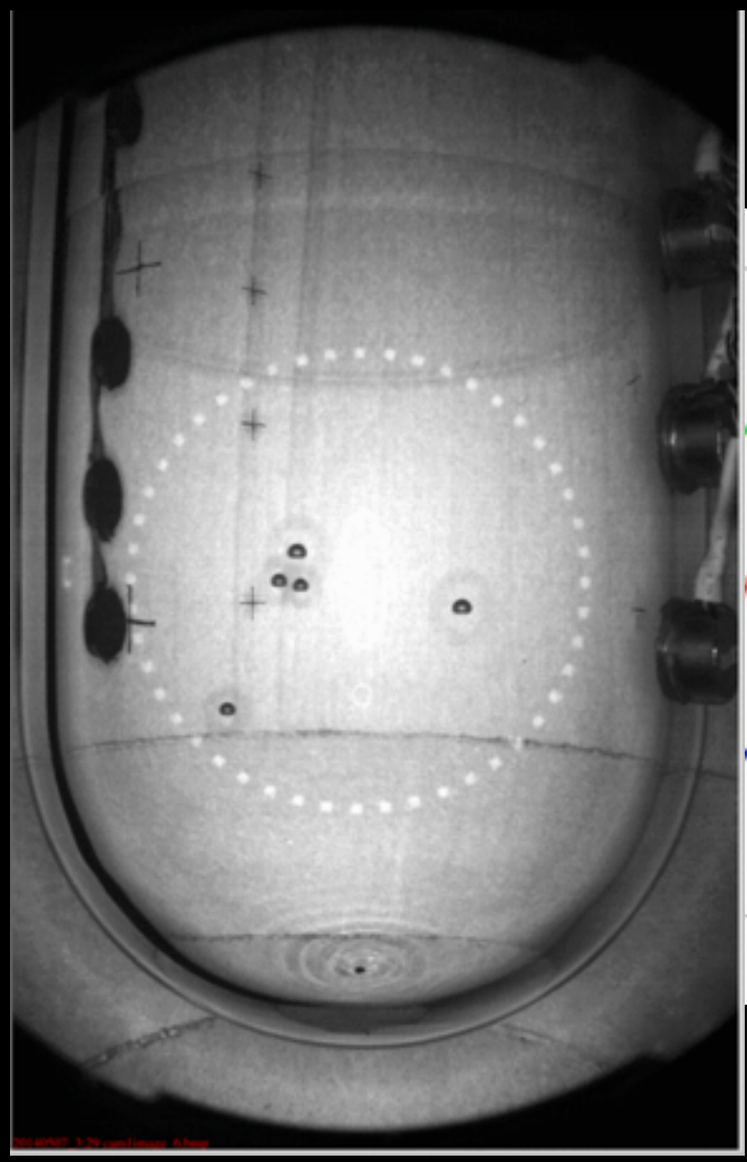
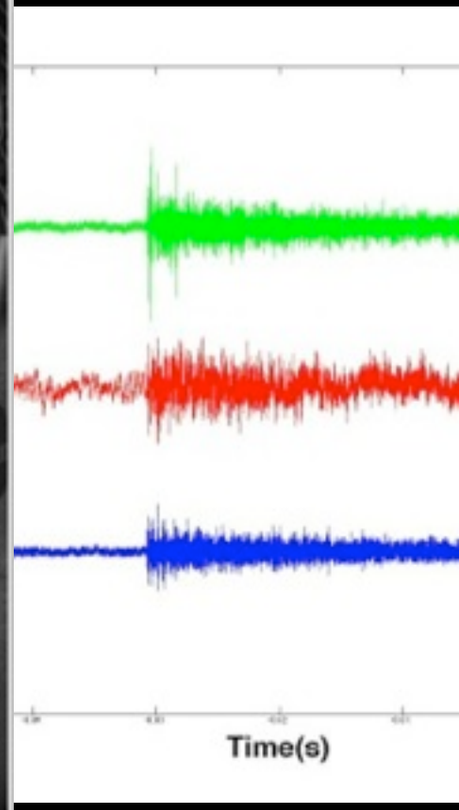
Electron energy deposition is too diffuse to nucleate a bubble!

Why bubble chambers?

- Easy to identify multiple scattering events → Neutron backgrounds
- Easy DAQ and analysis chain
  - Cameras
  - Piezos
- No PMTs, no cryogenics



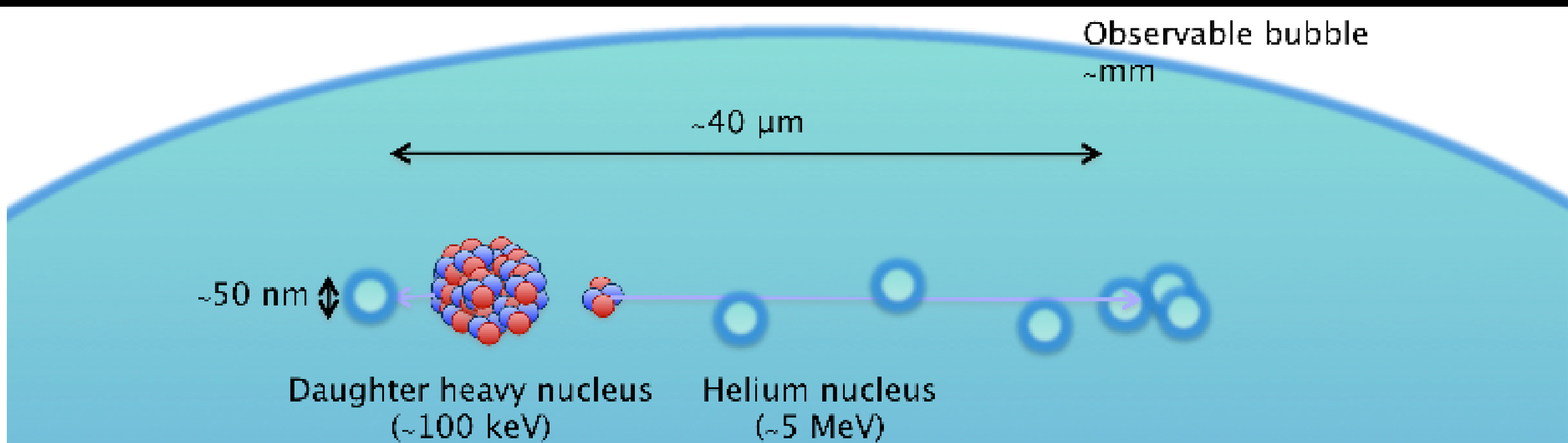


Why not bubble chambers?

- Threshold detectors - no energy resolution
  - Harder to distinguish some backgrounds, less information about any potential signal
  - Alphas (several MeV) were a big concern
- Energy threshold calibrations are hard and important

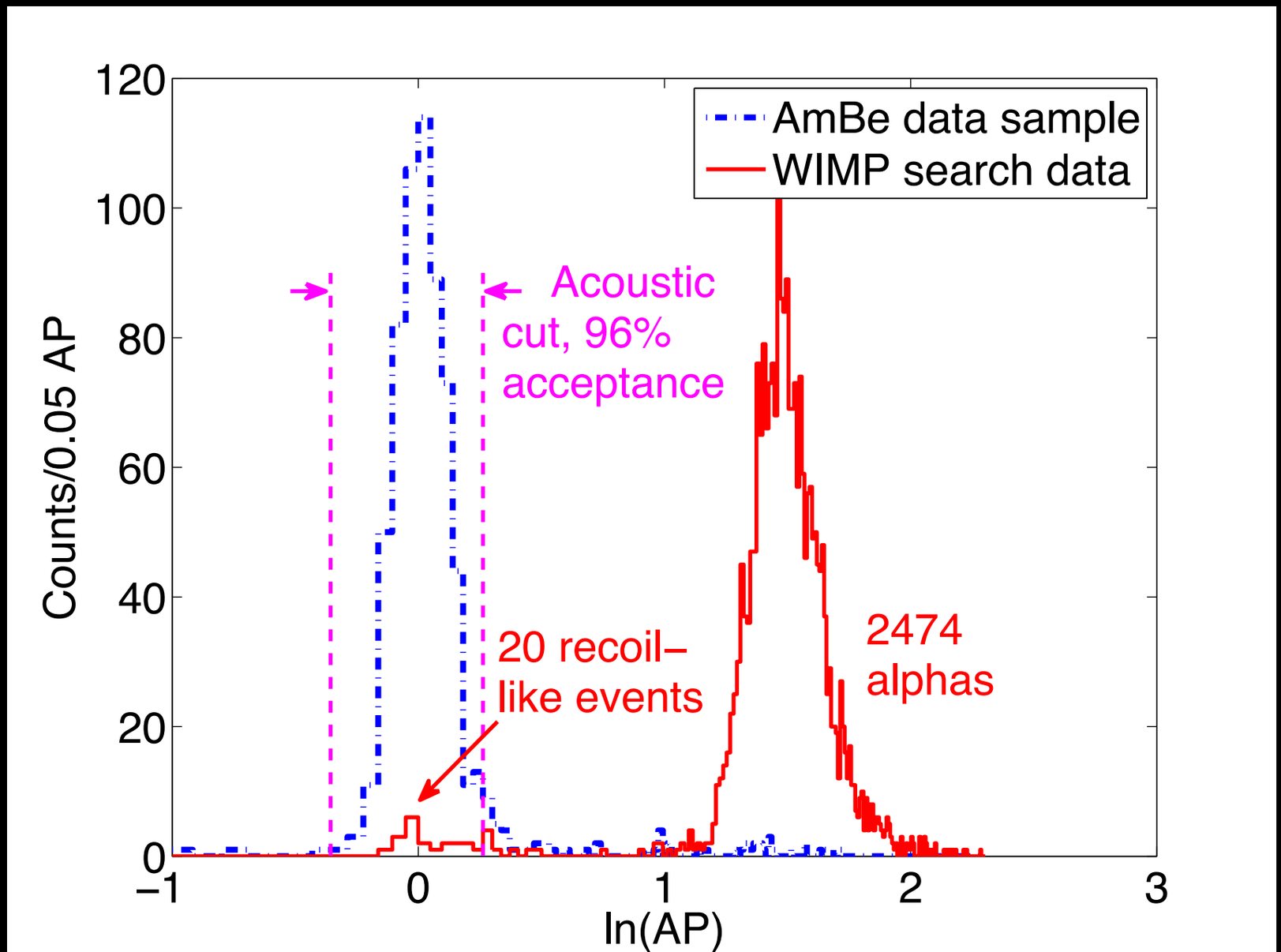
About those alphas

- Discovery of acoustic discrimination against alphas by PICASSO (Aubin et al, New J. Phys 10:103017, 2008)
  - Alphas deposit energy over tens of microns
  - Nuclear recoils deposit theirs in tens of nanometers
- In bubble chambers, alphas are several times louder

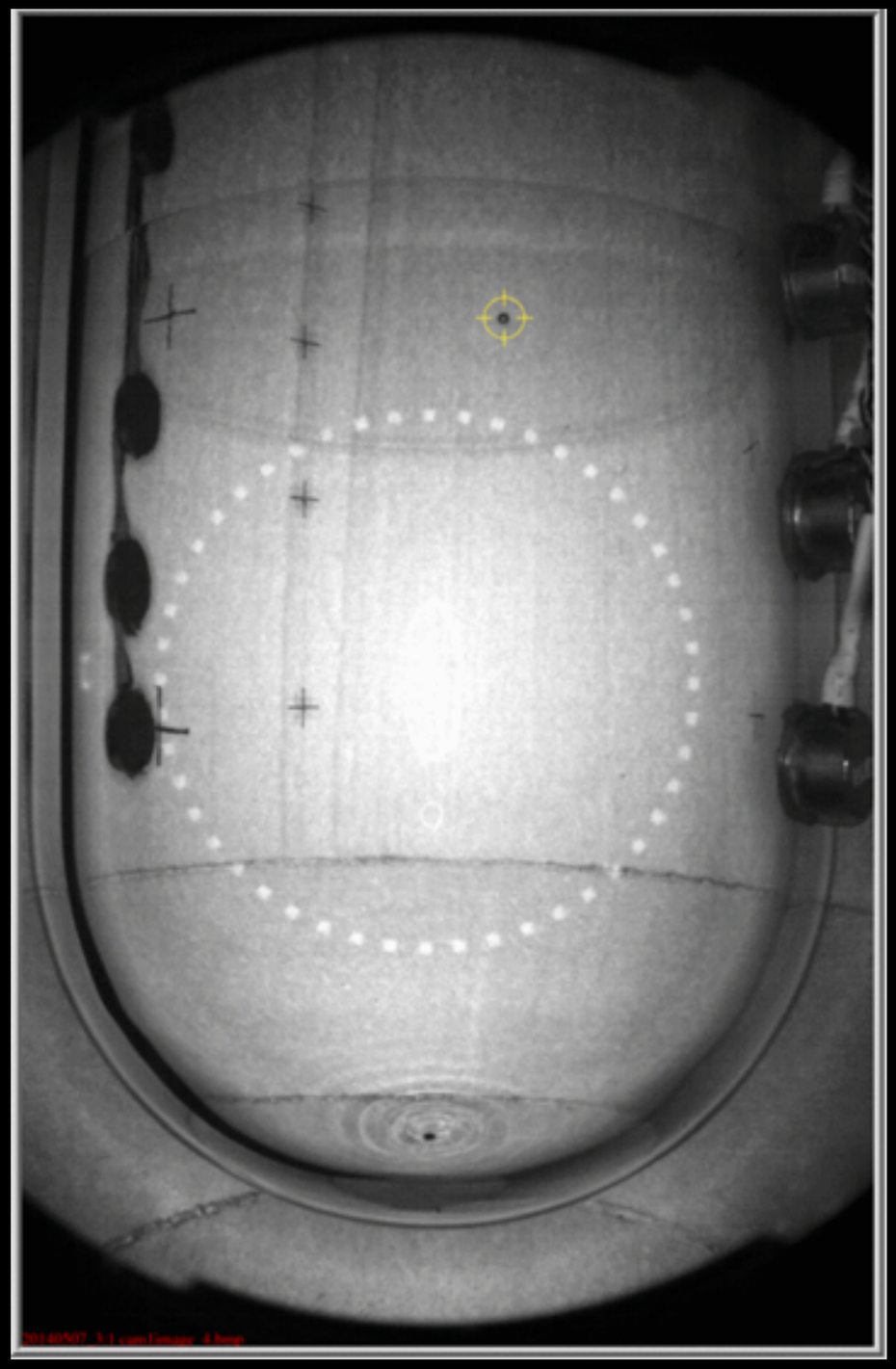


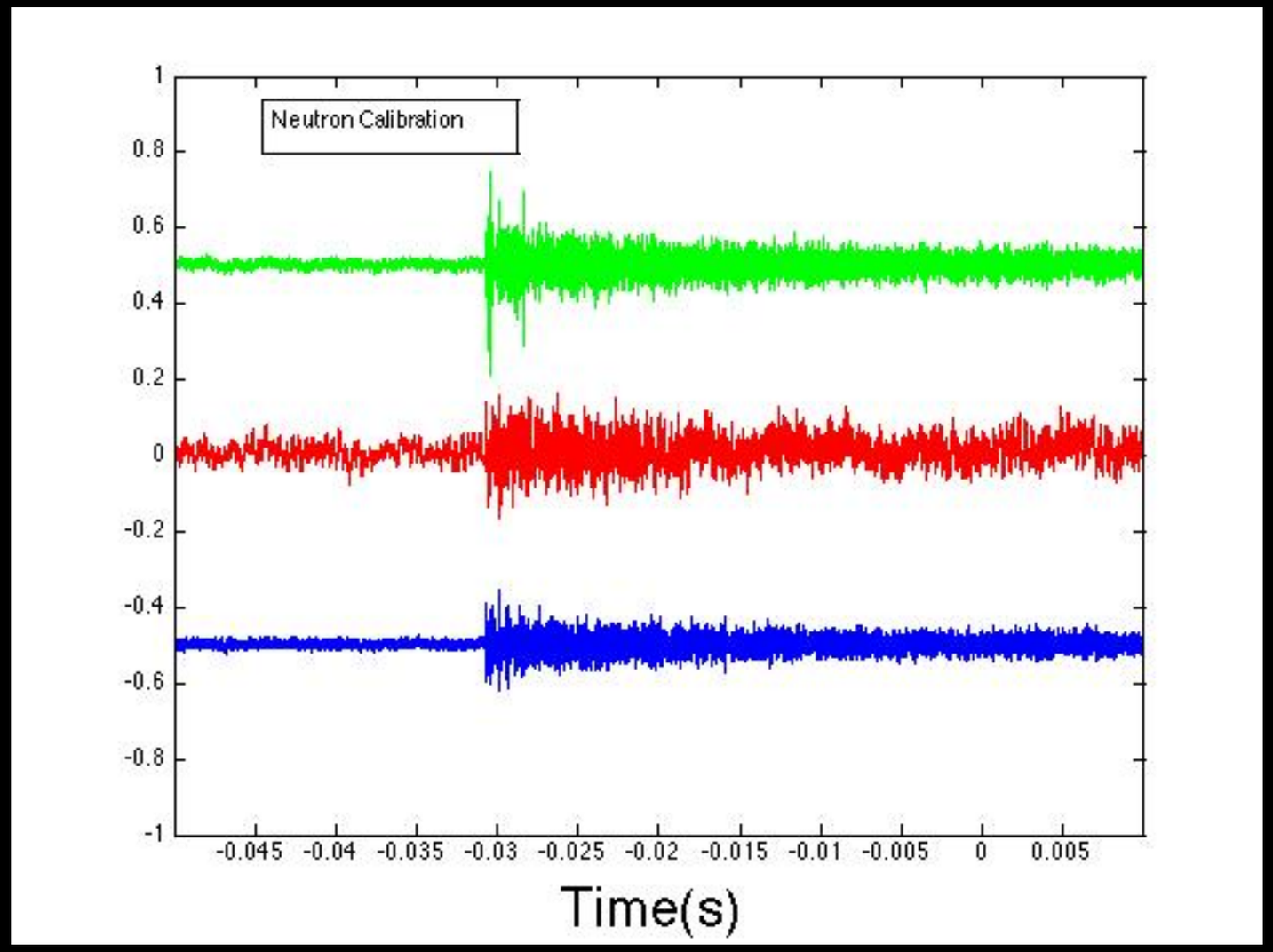
Acoustic rejection

- From COUPP4 chamber with CF_3I at SNOLAB
- Better than 99.3% rejection against alphas at 16 keV threshold
  - Behnke et al, Phys. Rev. D86, 052001 (2012)



This is what dark matter would sound like





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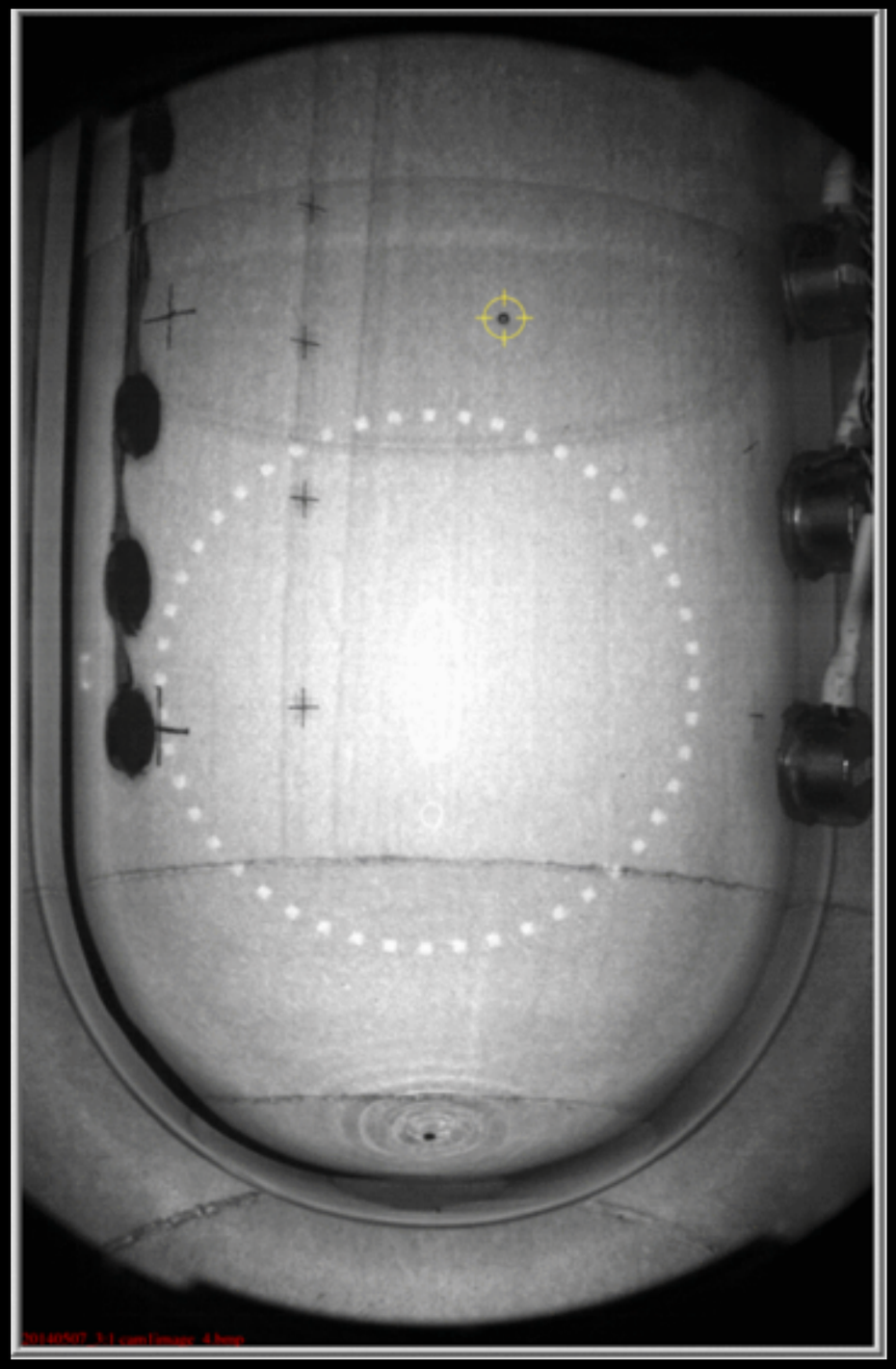
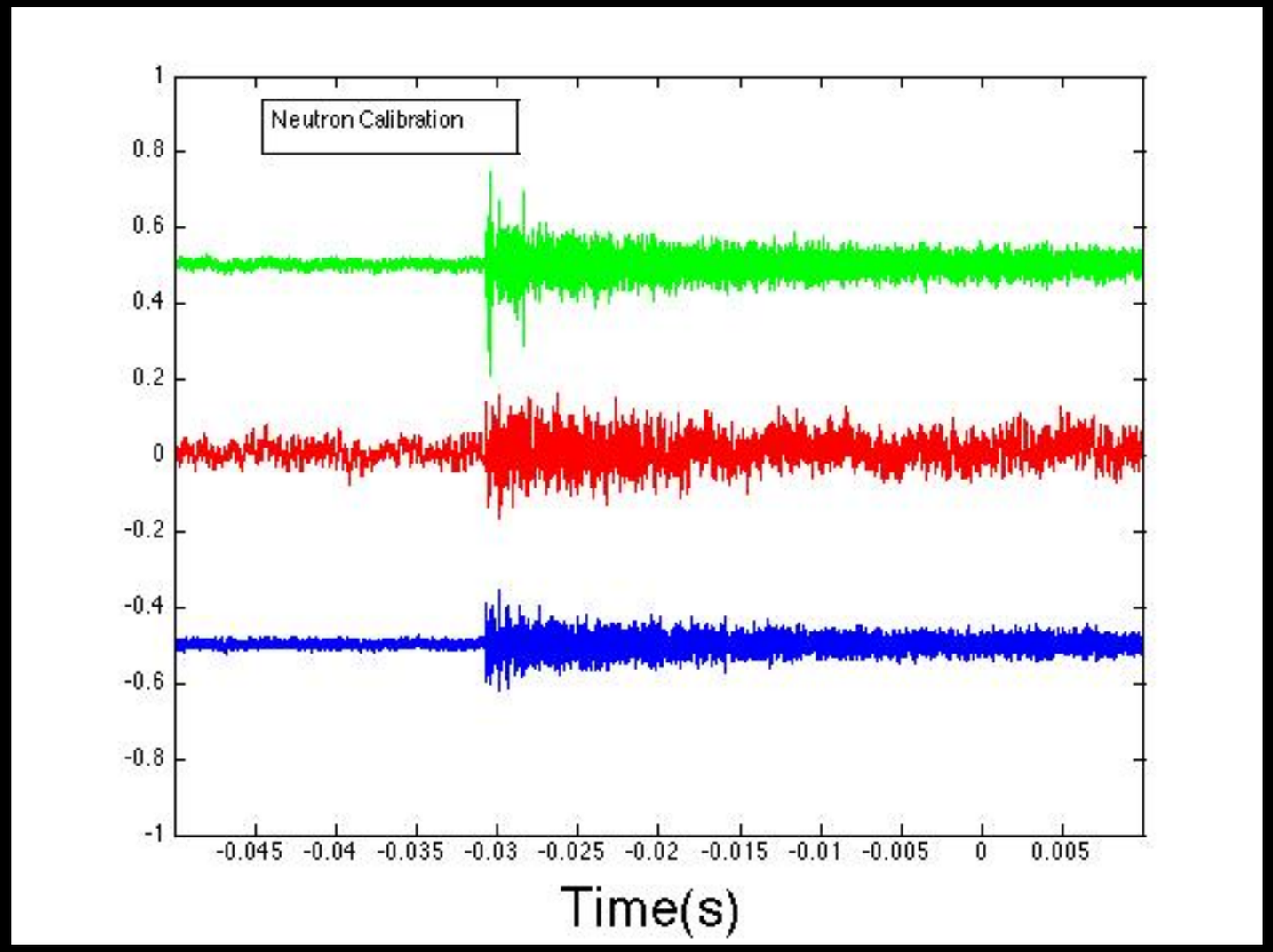
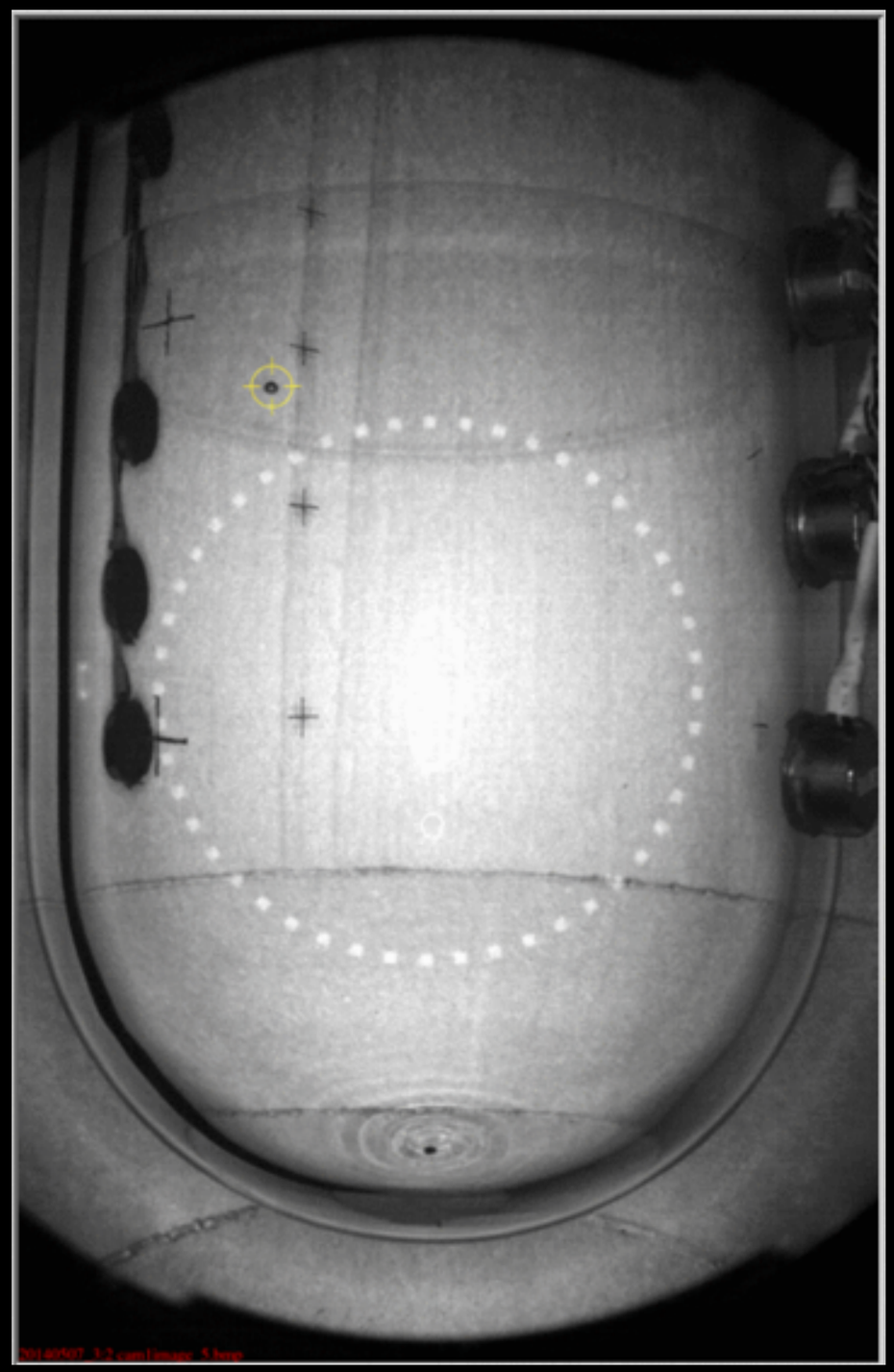
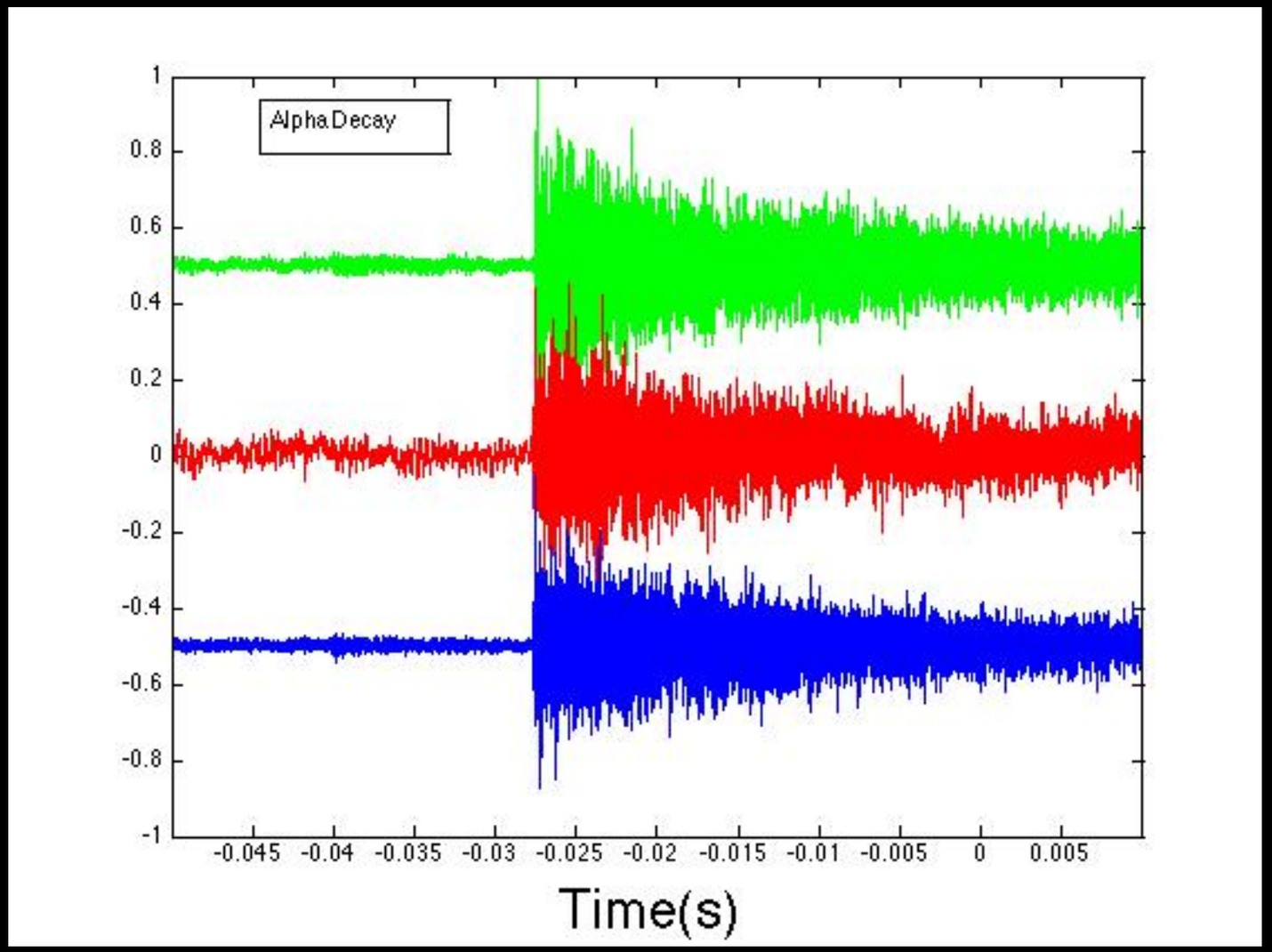


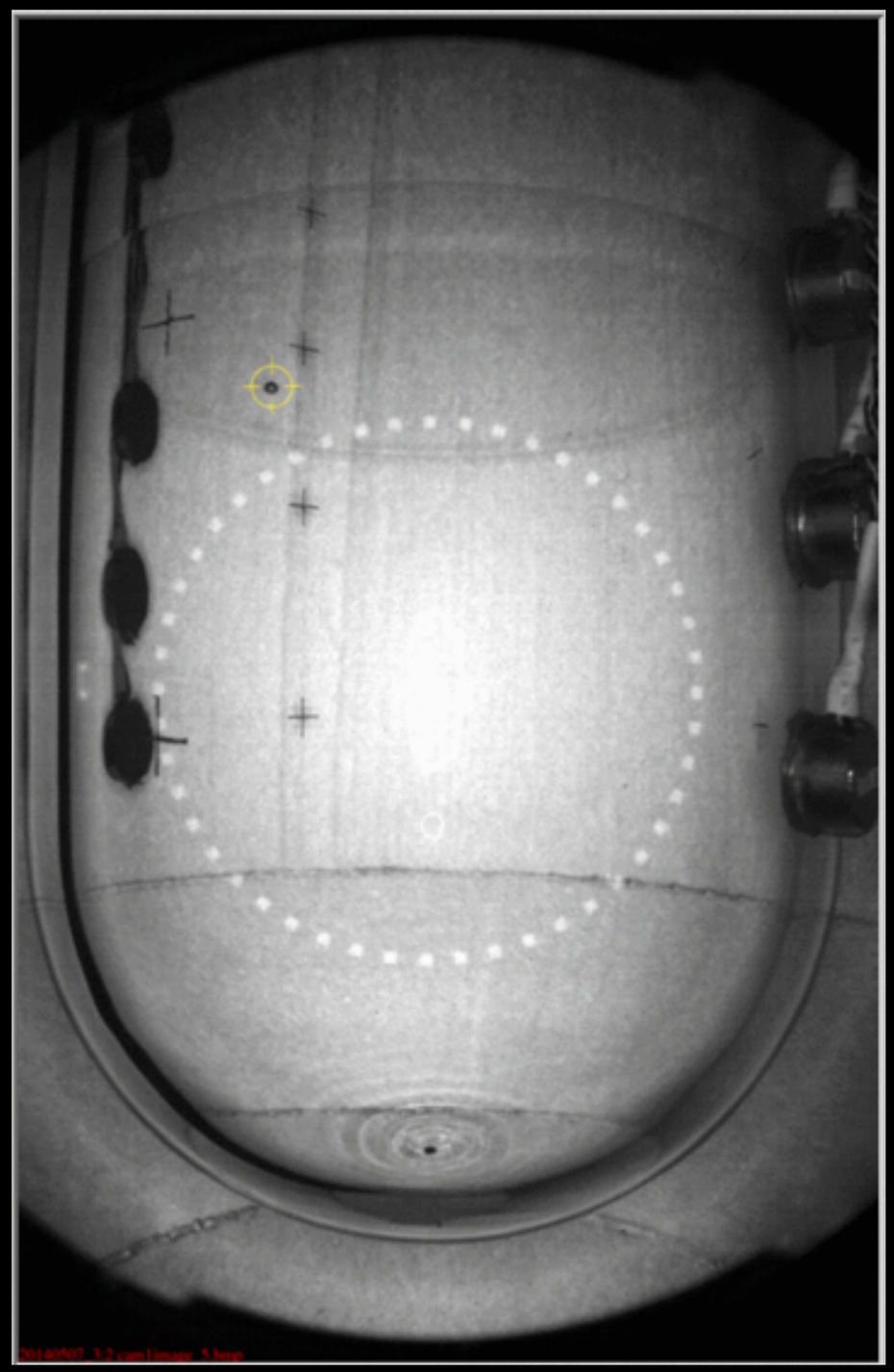


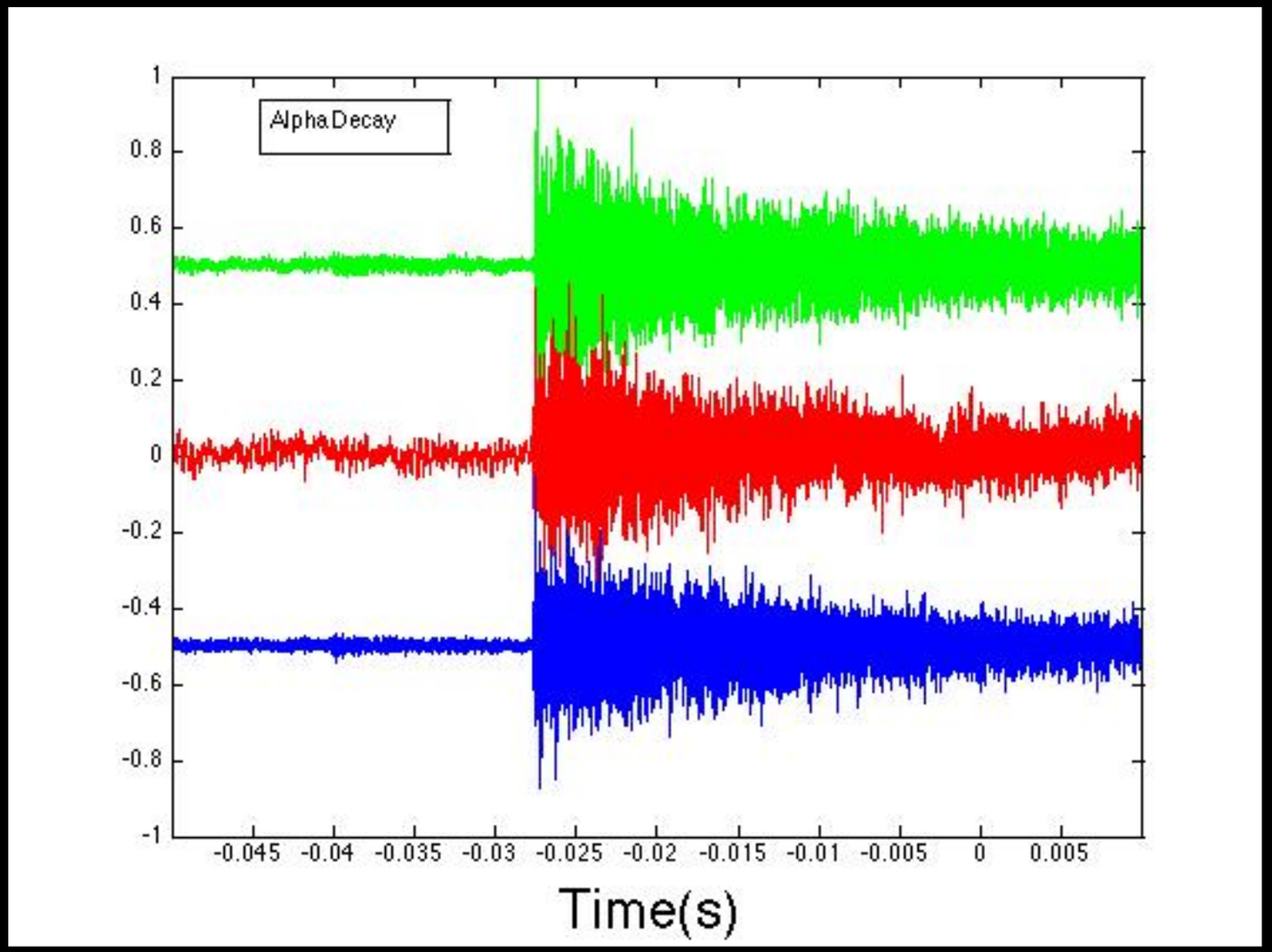
This is what an alpha sounds like



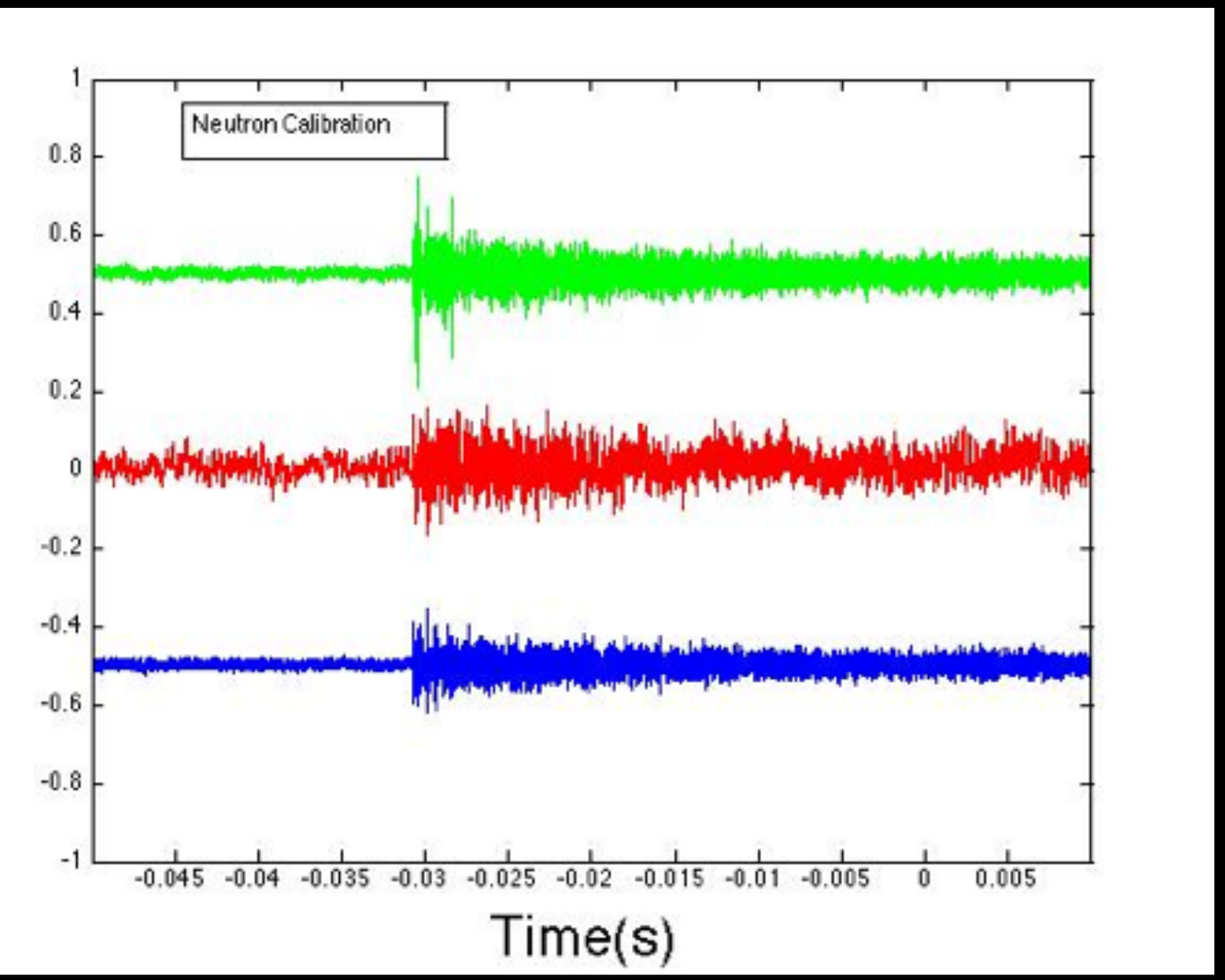


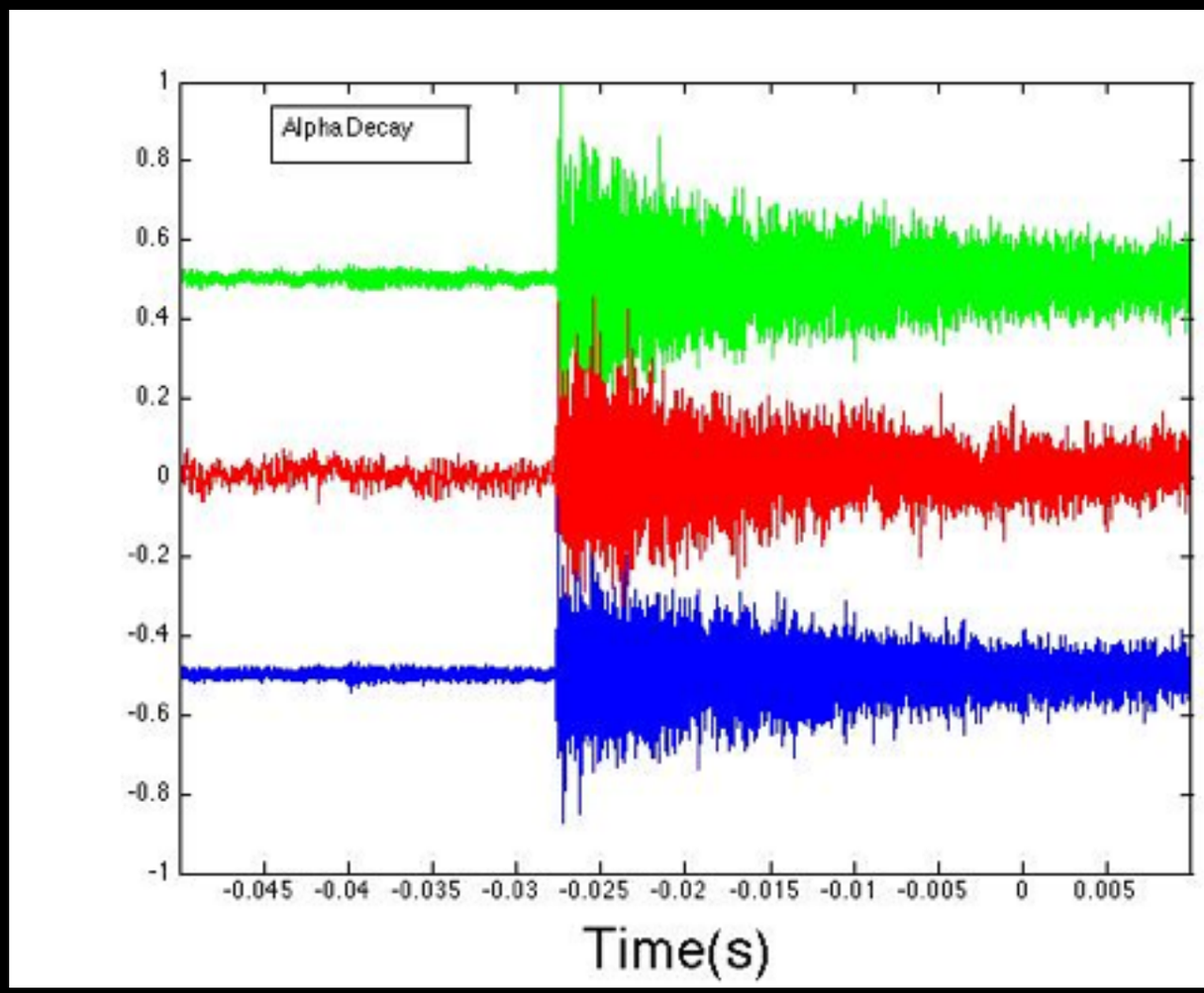
This is what an alpha sounds like





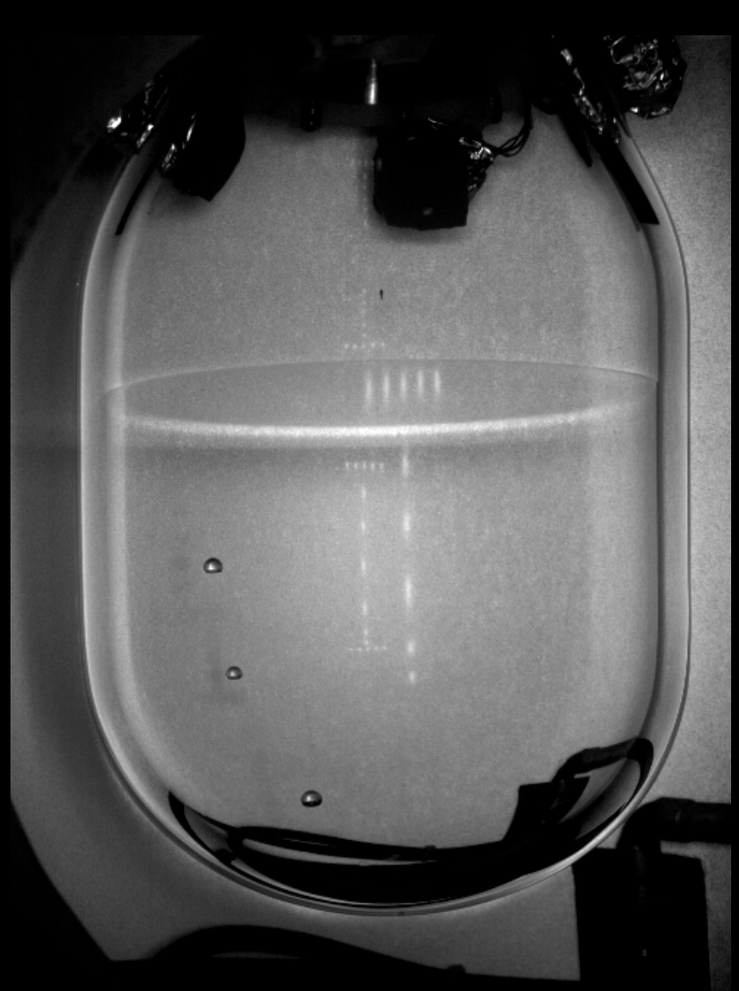
Both together, just to hear the difference

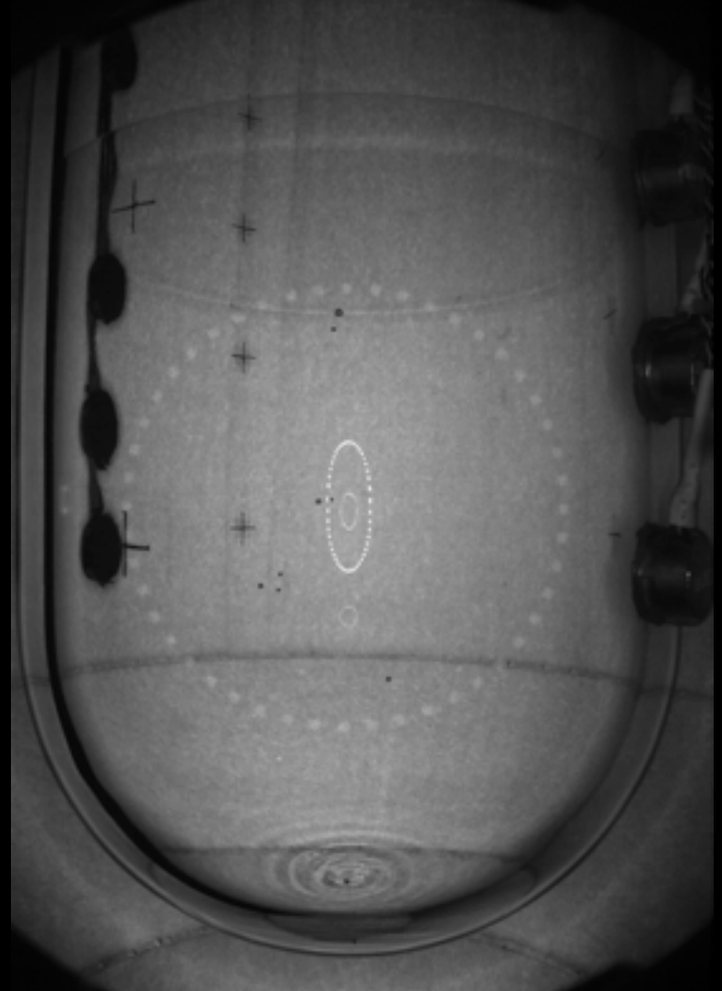


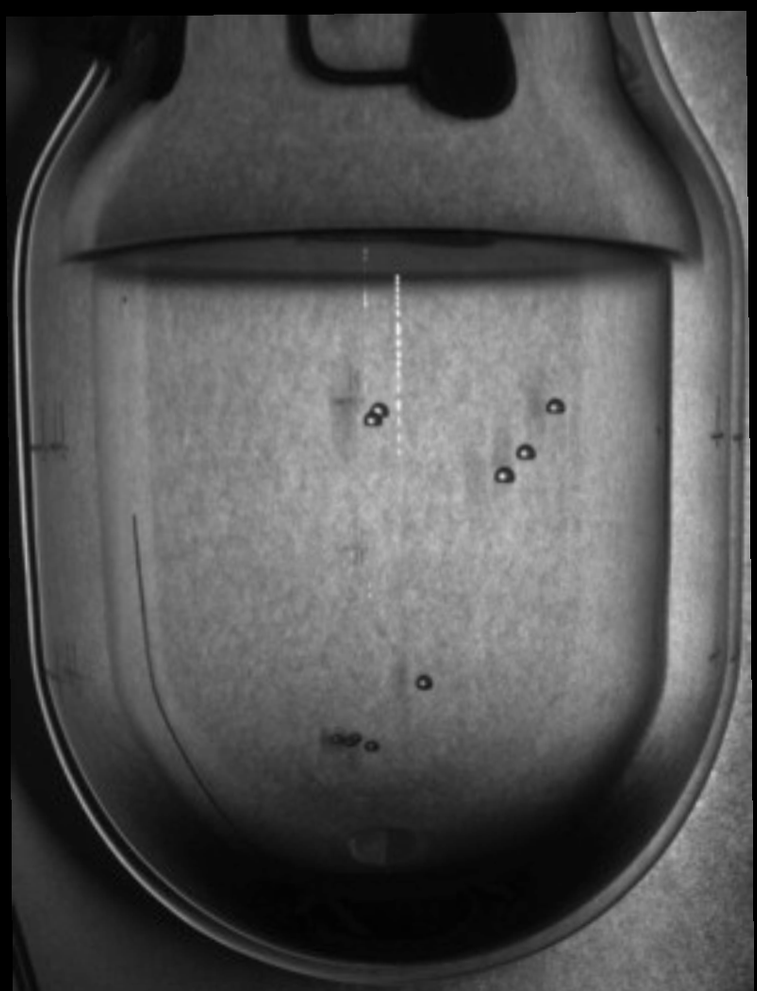


The PICO program

- PICO60: Up to 40 liters, operated with CF_3I at SNOLAB from June 2013 to May 2014
- PICO-2L: 2 liter chamber, filled with C_3F_8 at SNOLAB from October 2013 to May 2014
- PICO-250L: Proposed ton scale detector

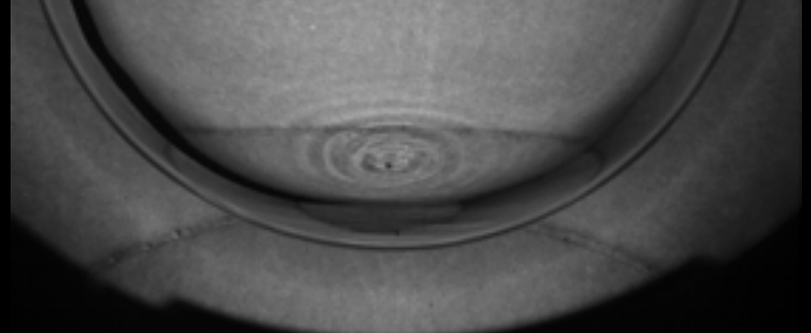




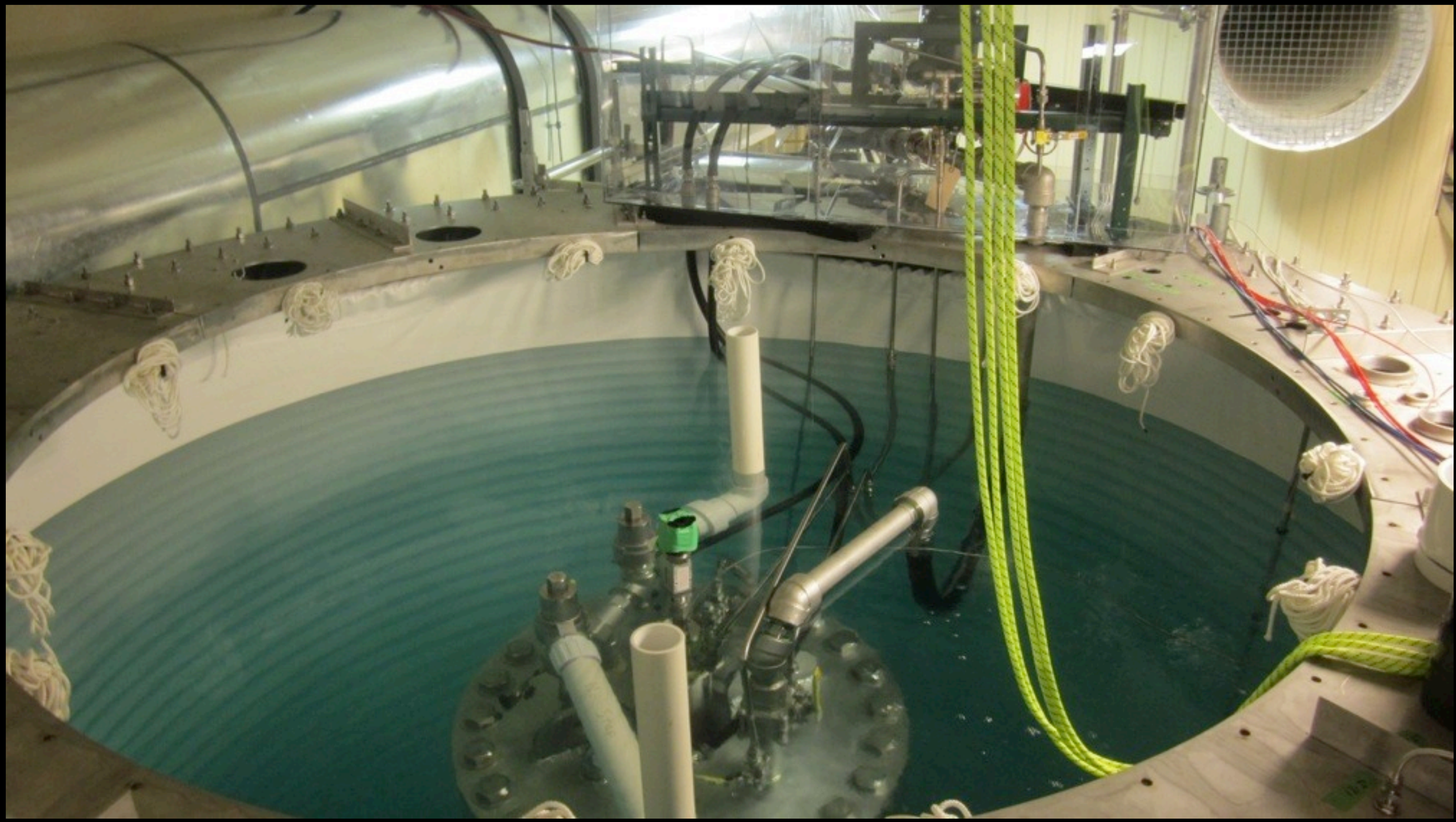


PICO60

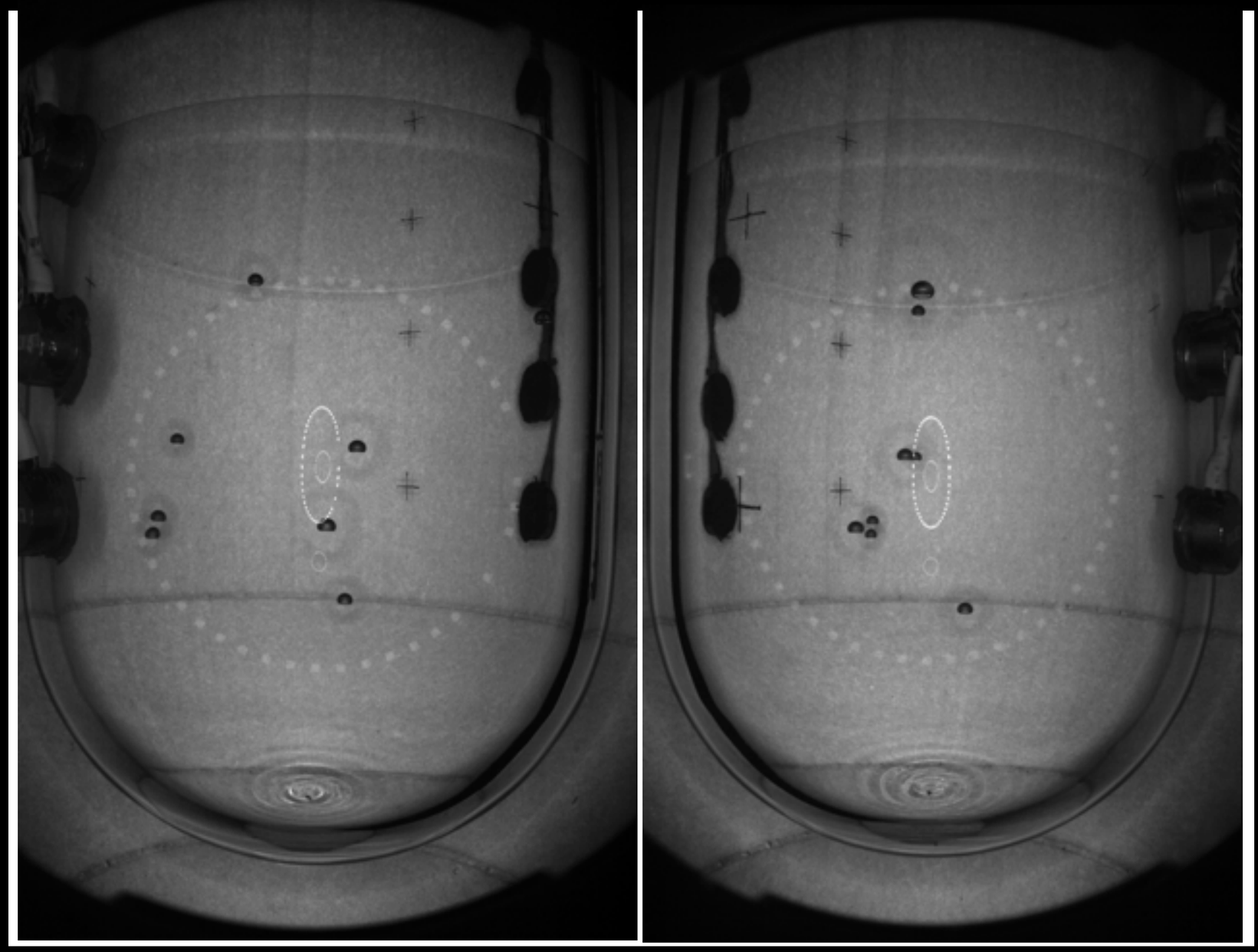
- Test runs at Fermilab from 2010-2011
- Started the move to SNOLAB beginning summer of 2012




CYLINDER
EMPTY
IN USE



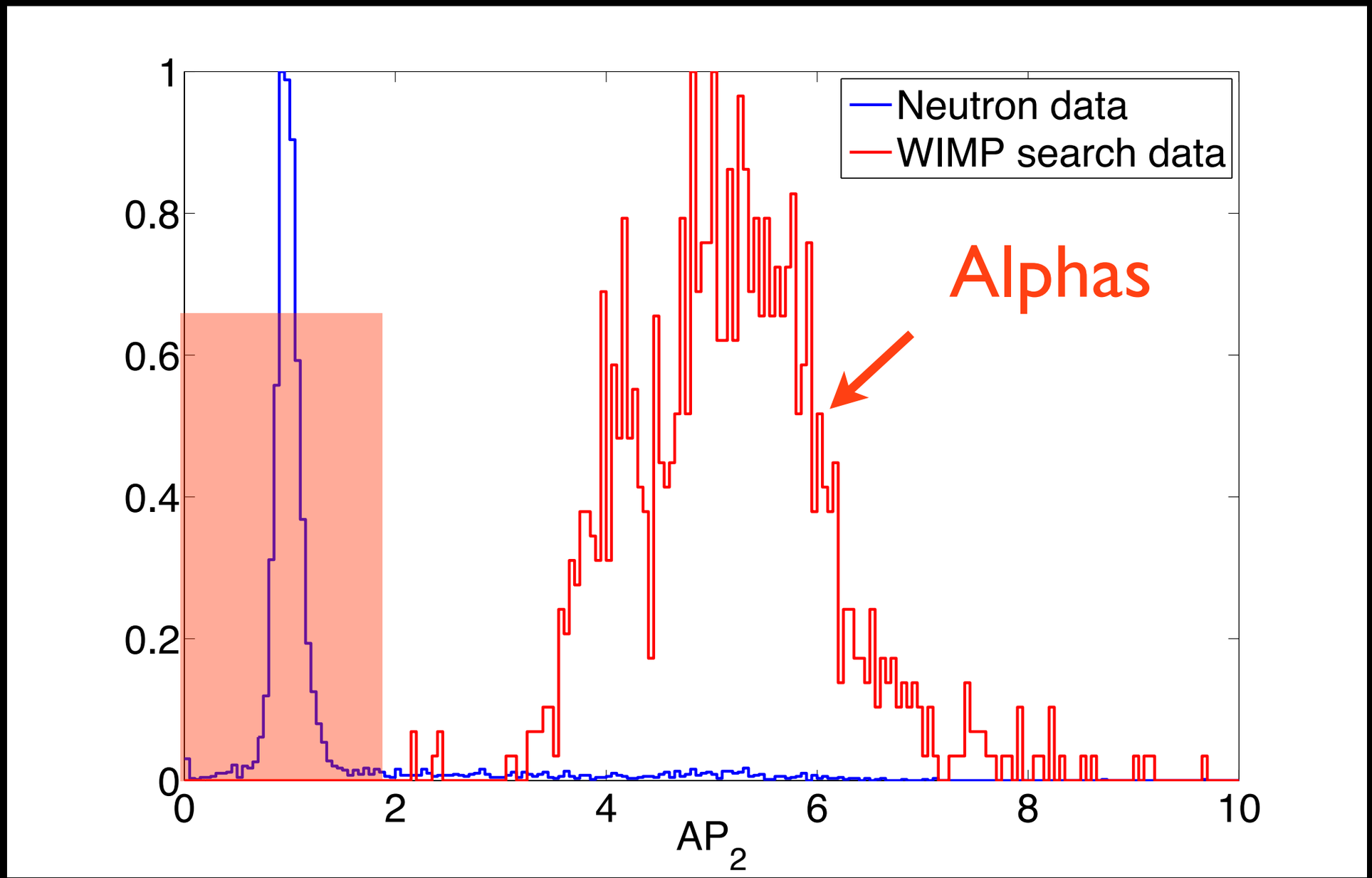
PICO60

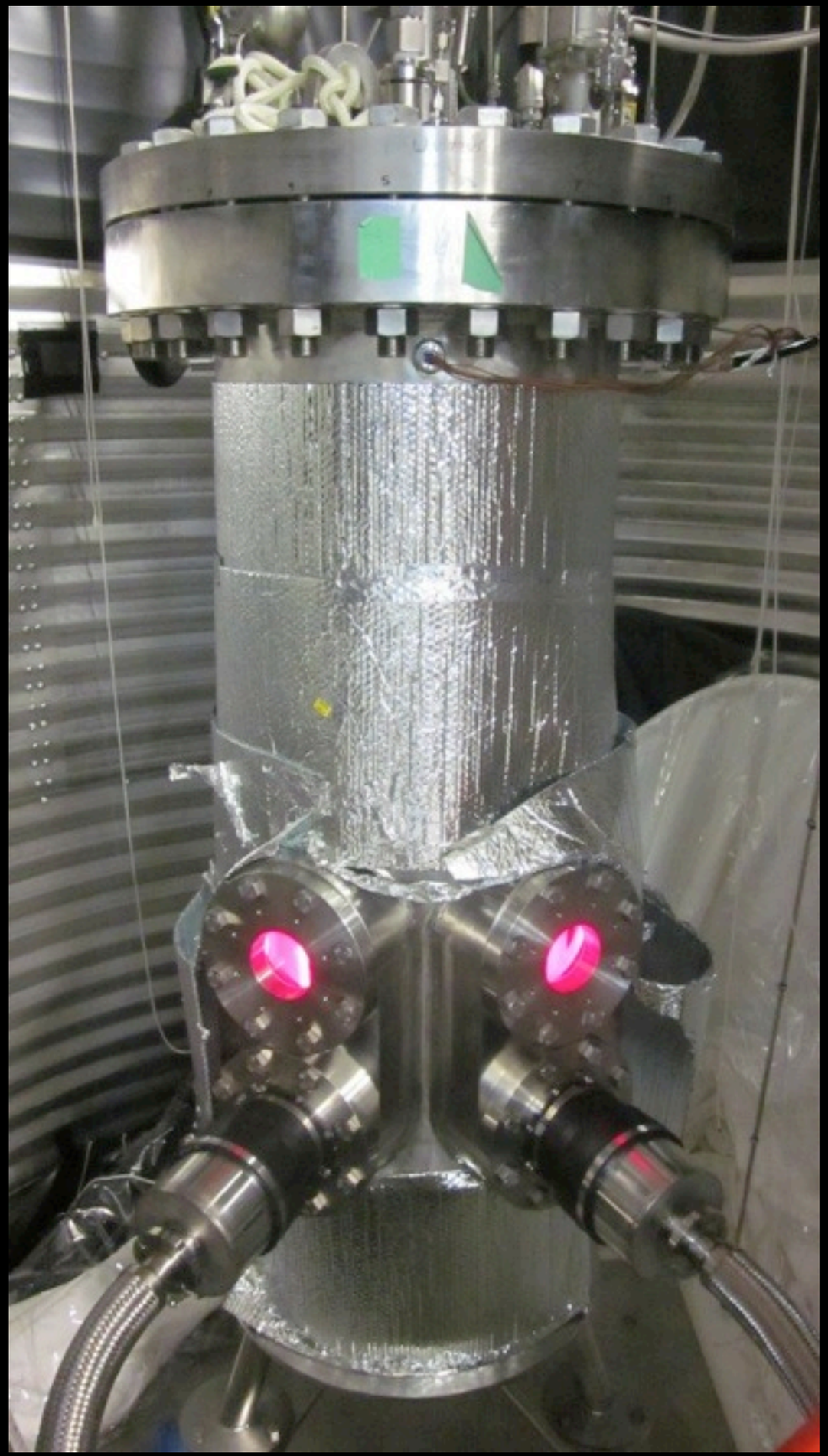


- Filled with 36.8 kg of CF_3I at end of April, 2013
- Collected ~6000 kg-days from June, 2013 to May, 2014

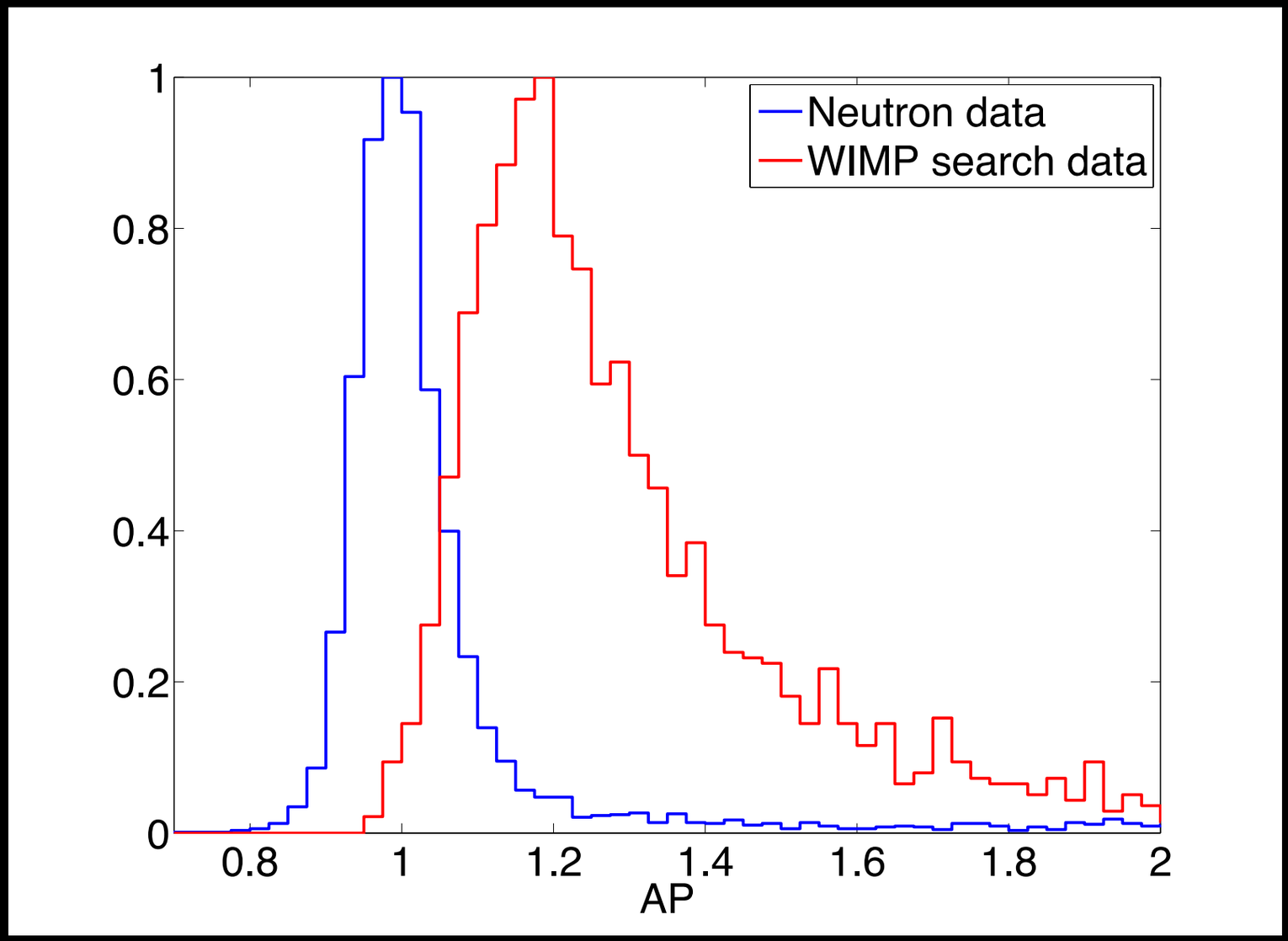
PICO60 - the good news

- Very low neutron background rate!
  - One clear multiple (5!) bubble event, likely cosmic in origin
- Alpha discrimination very strong in the large chamber!



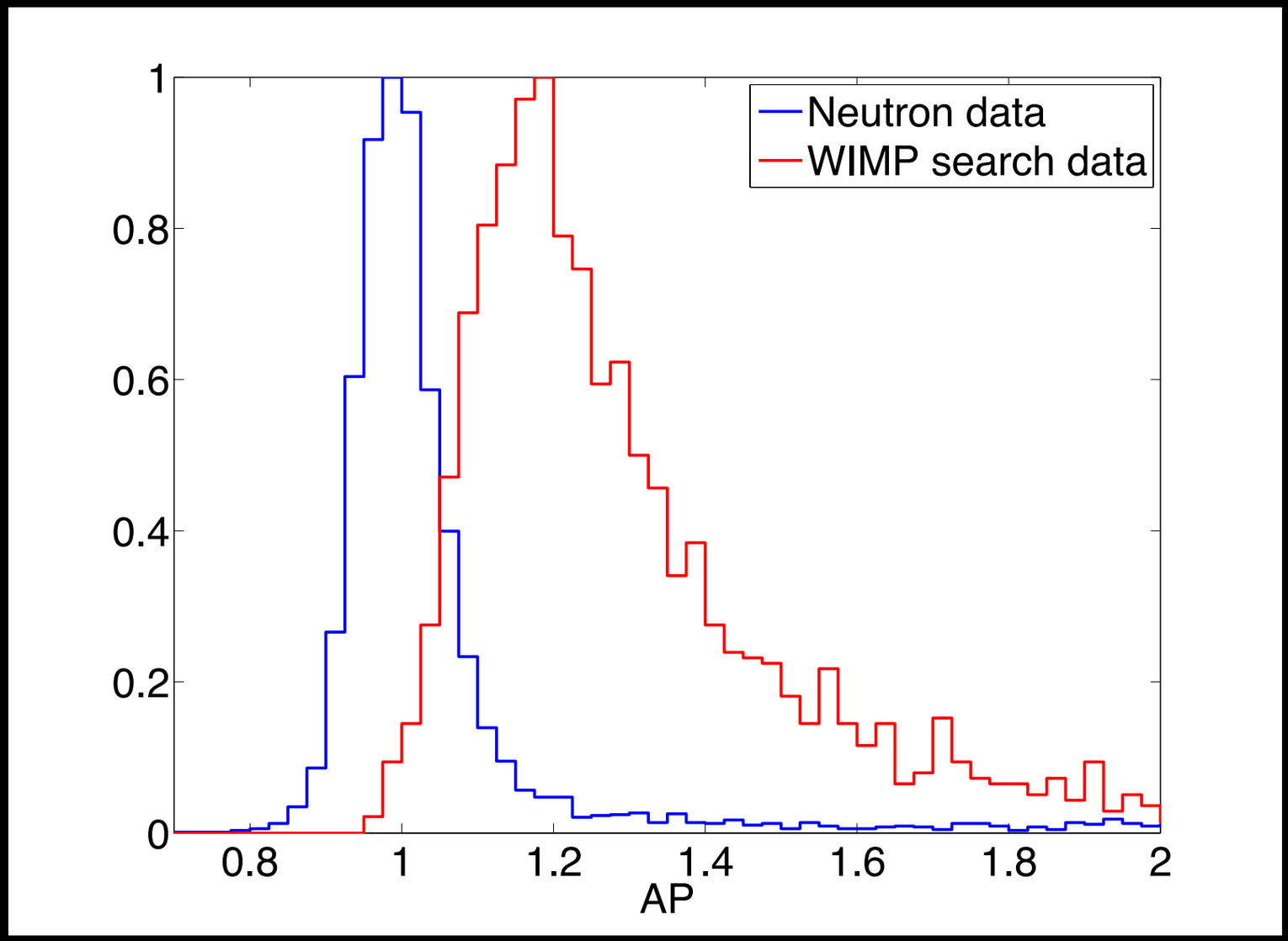


PICO60 - the bad news



- Large population of events that sound similar to (but slightly louder than) nuclear recoils
  - We've seen this before with very low statistics in COUPP4

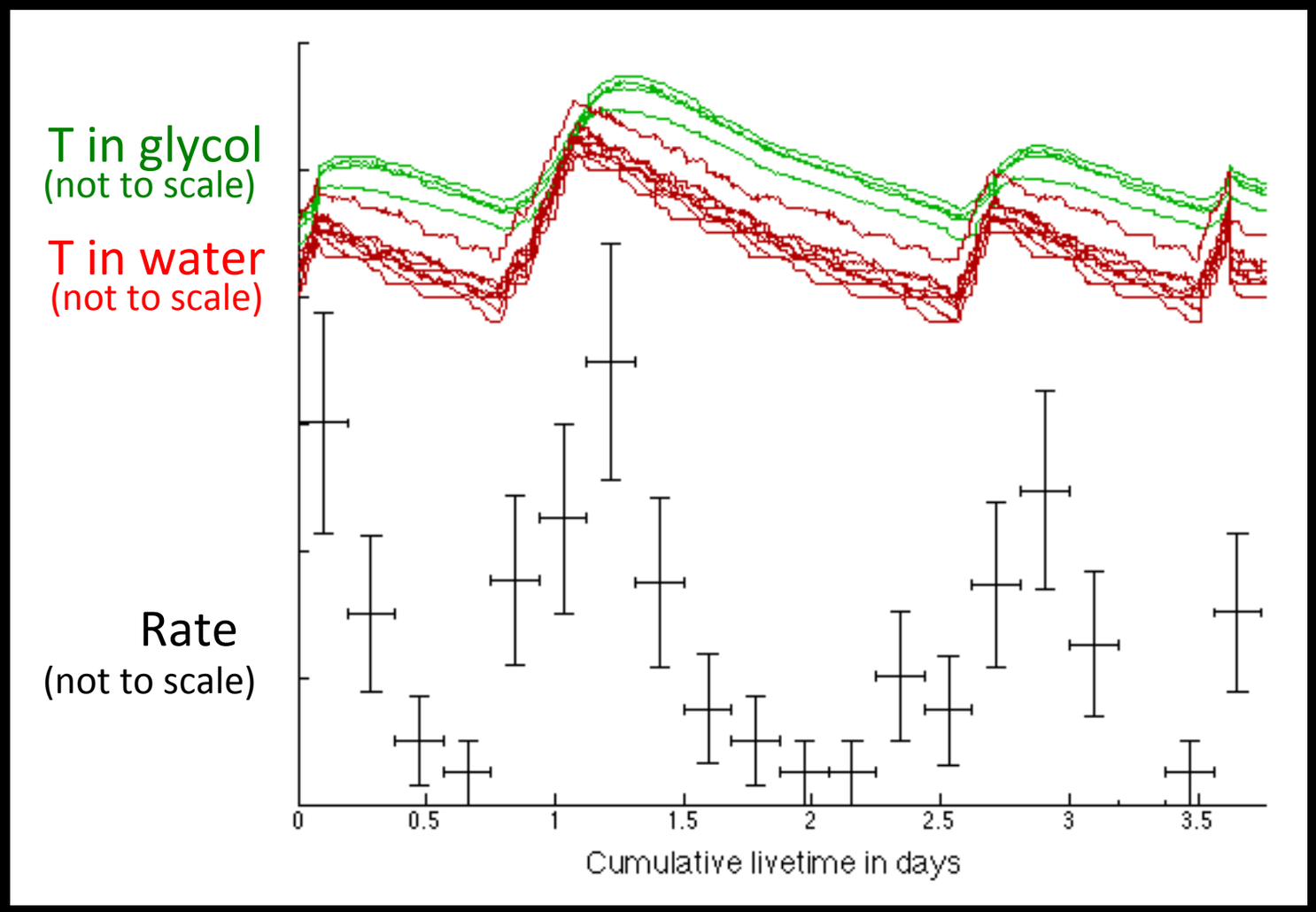
PICO60 - the bad news



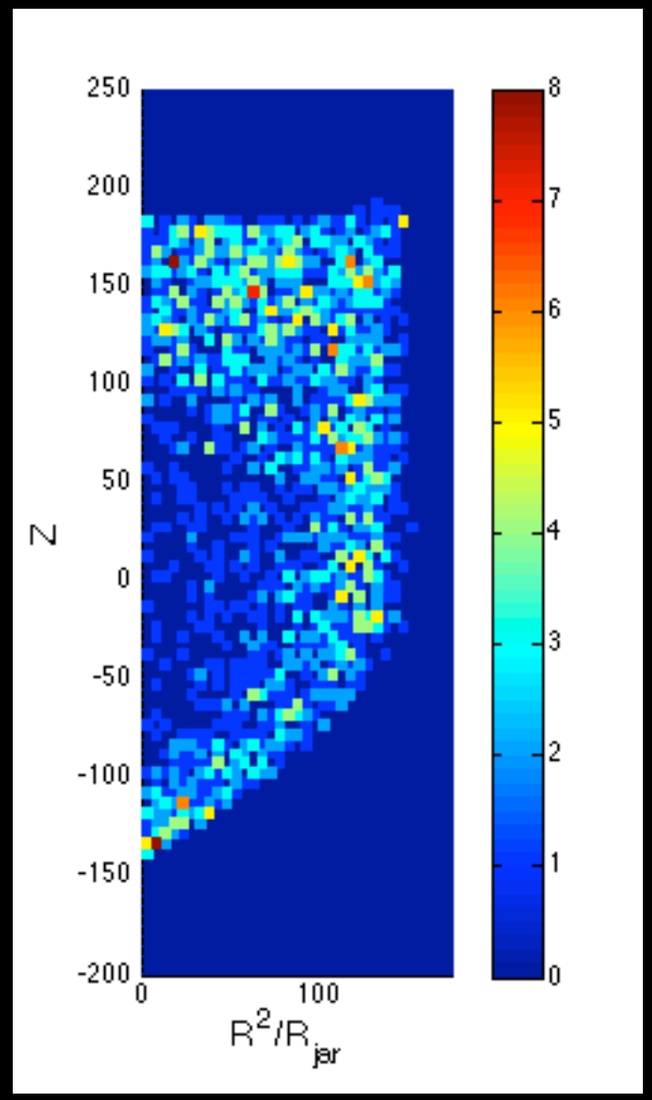
- Large population of events that sound similar to (but slightly louder than) nuclear recoils
  - We've seen this before with very low statistics in COUPP4
- Silver lining: statistics - we can actually study them in detail

PICO60 anomalous events

- Temperature dependence - more specifically, a dT/dt dependence

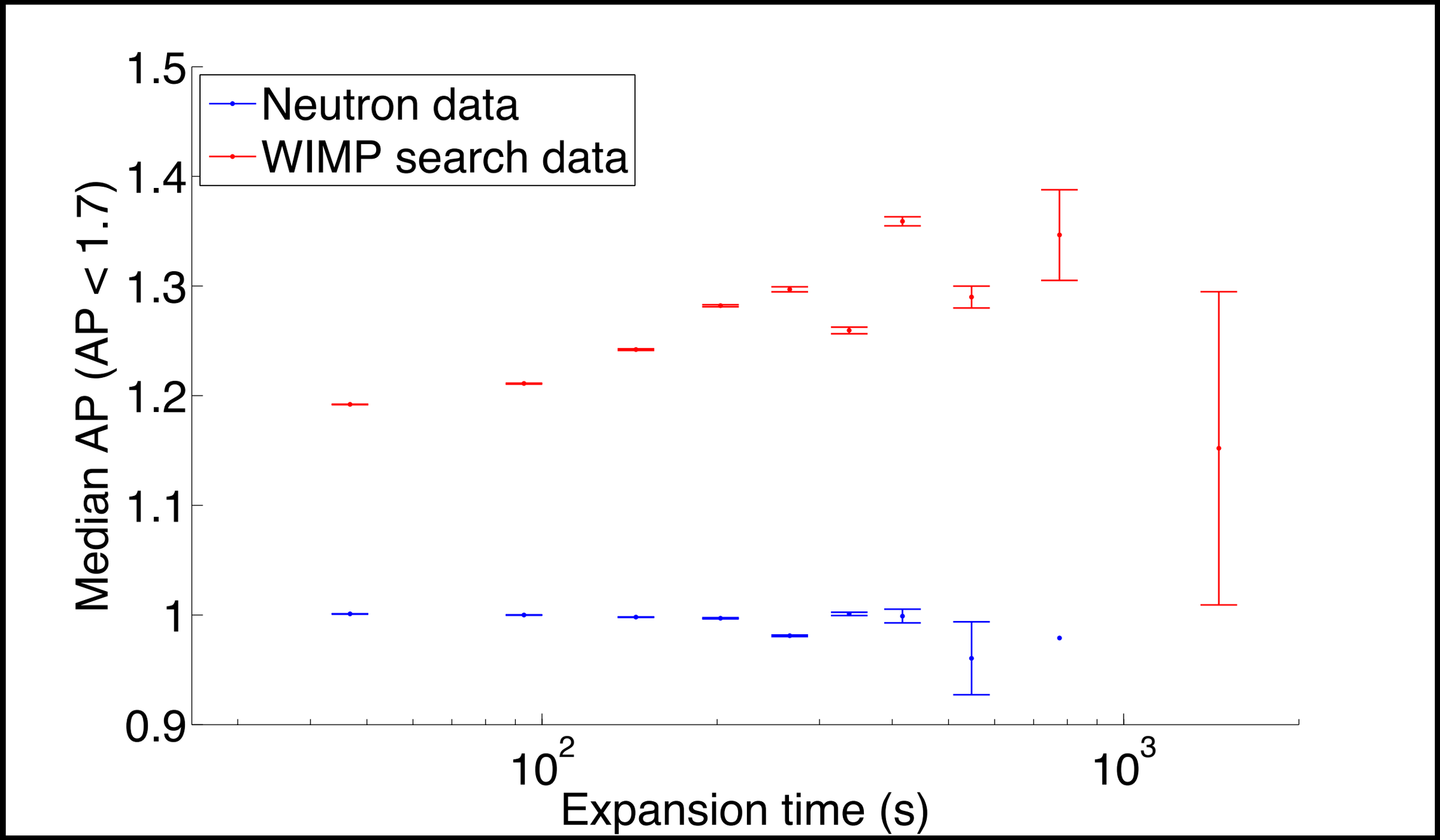


- Spatial dependence



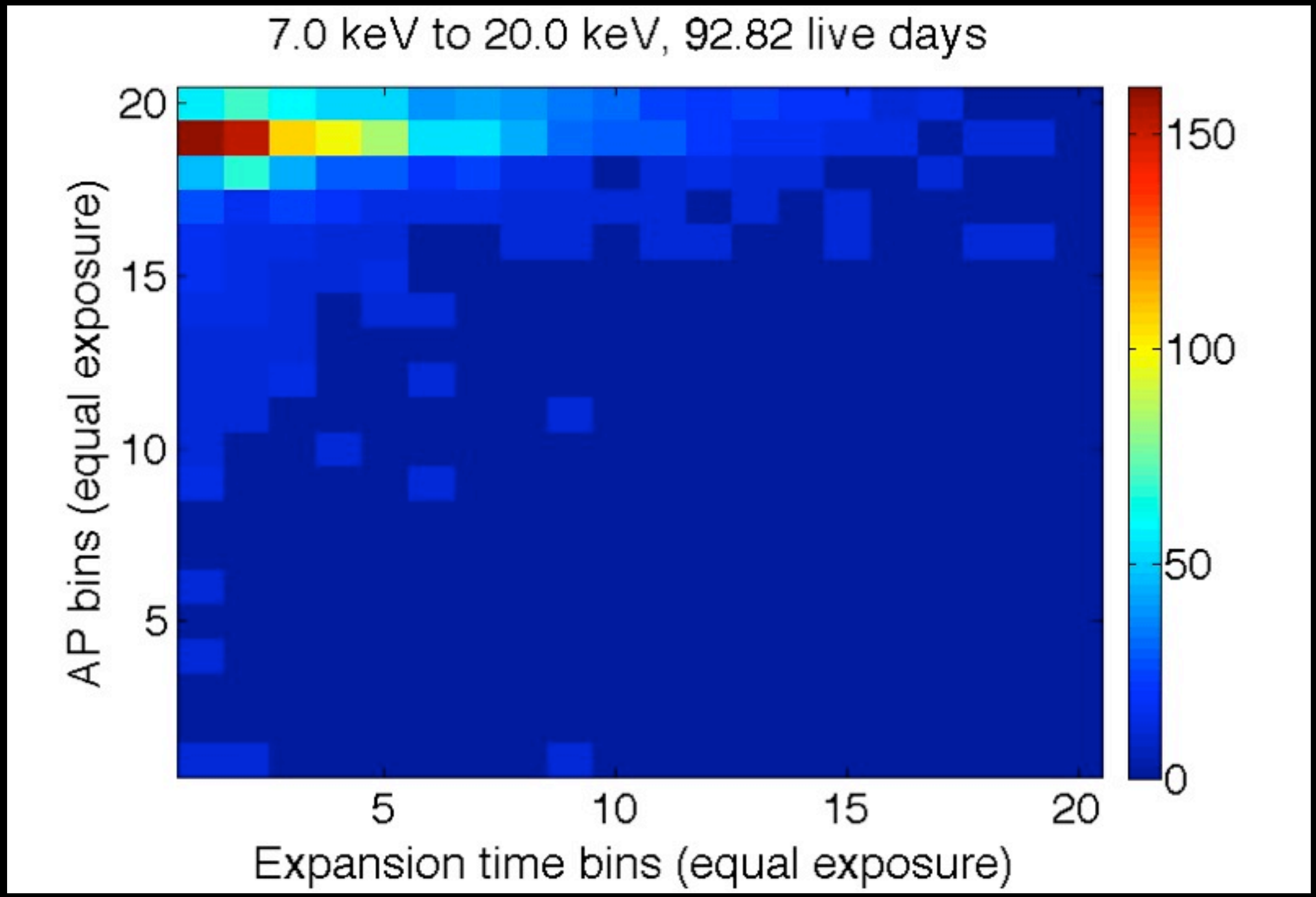
PICO60 anomalous events

- Correlation of acoustic power with expansion time



PICO60 anomalous events

- Discrimination is possible with these variables



PICO60 anomalous events

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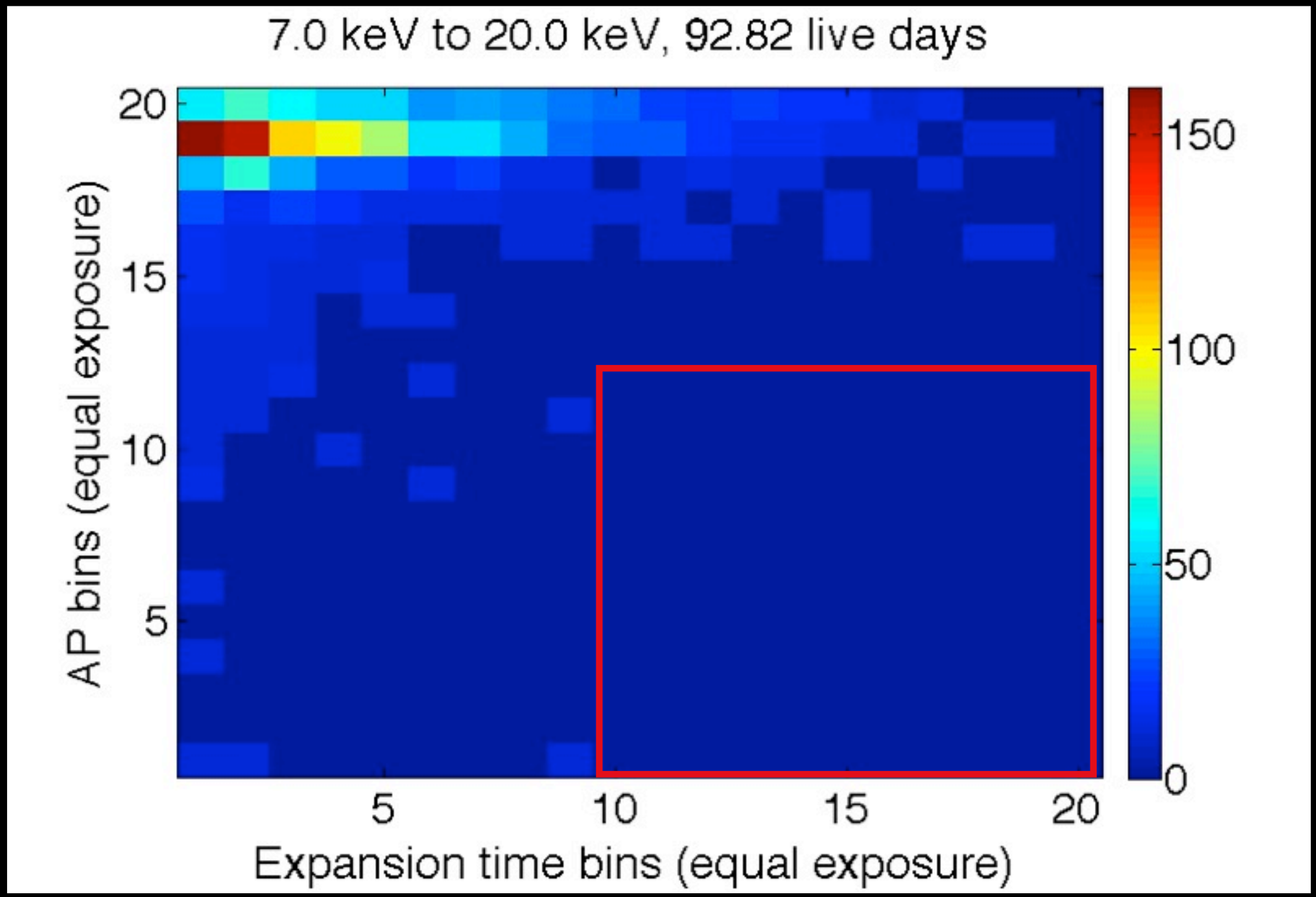

PICO60 anomalous events

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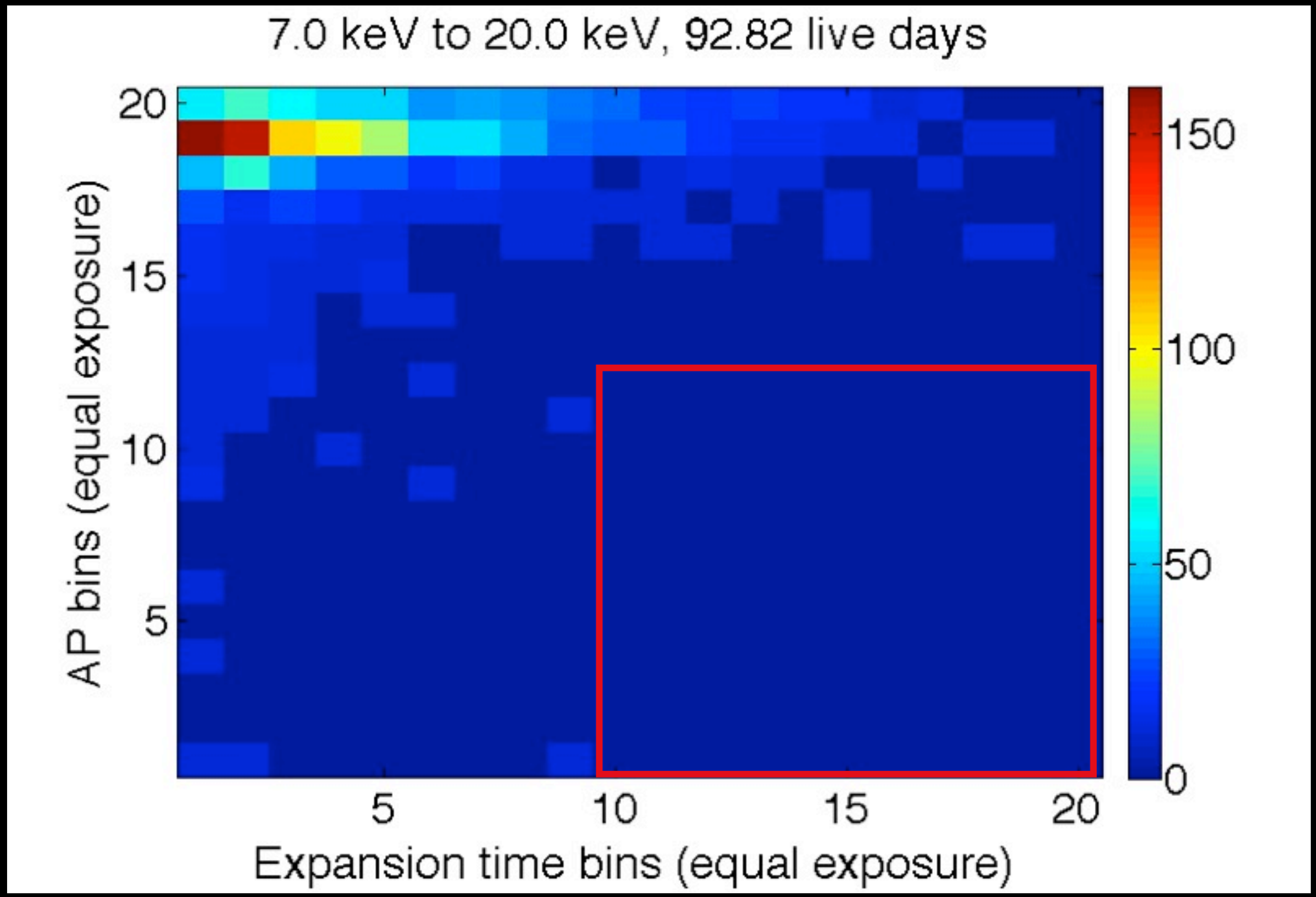
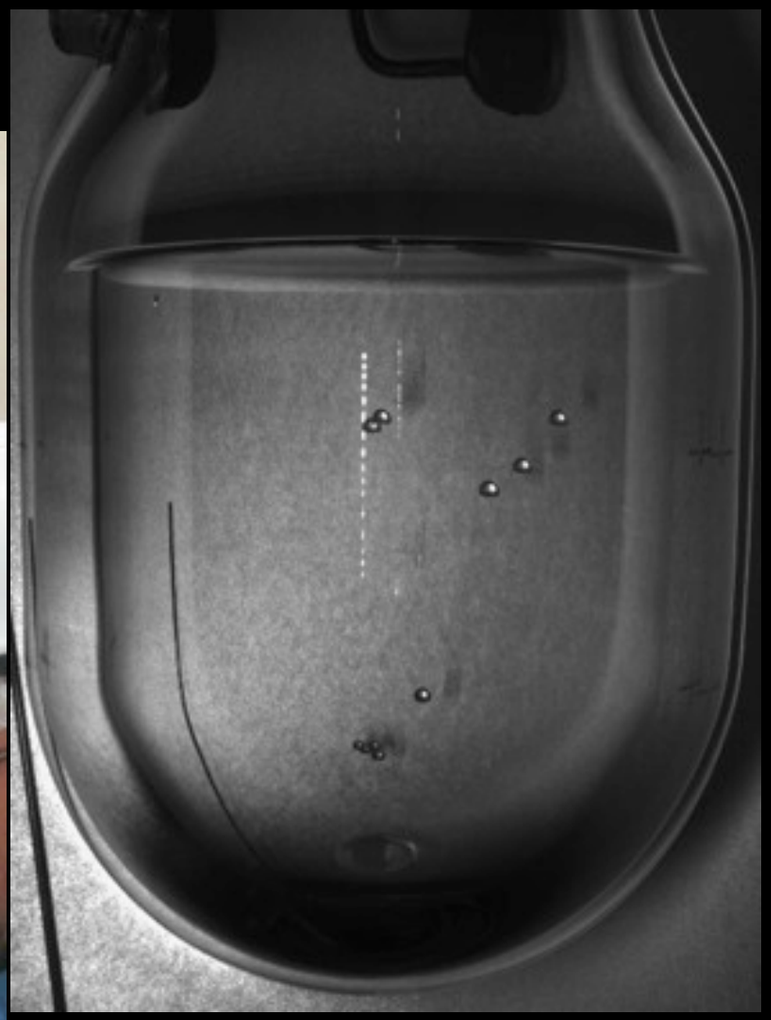
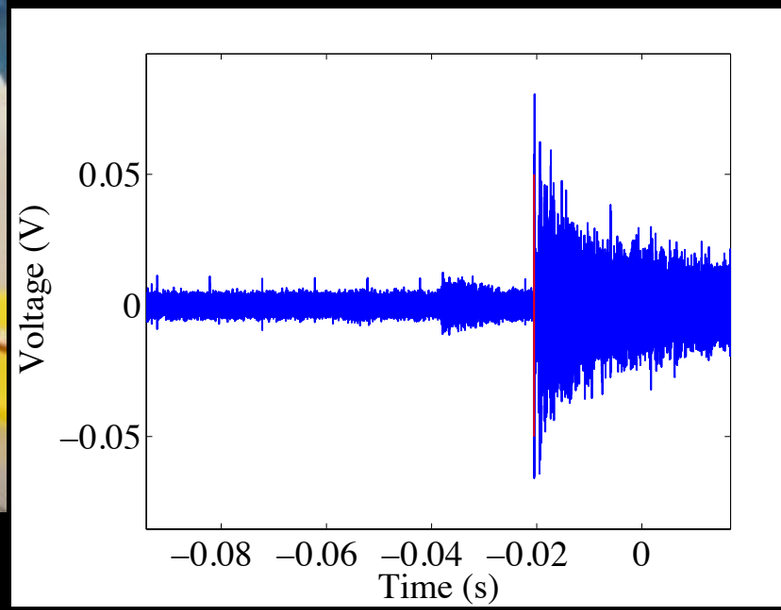


- Not blind...

PICO-2L

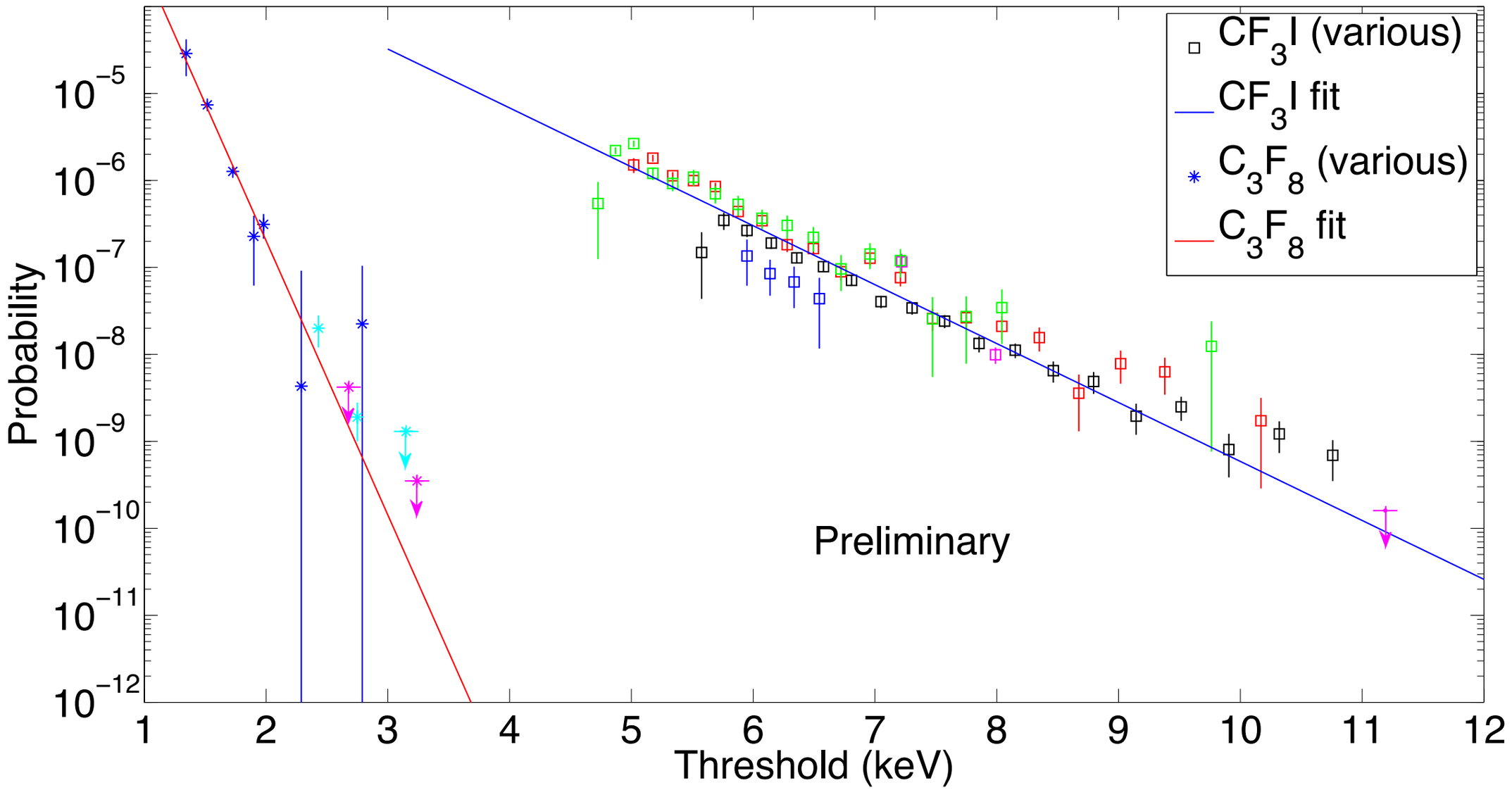
- First test of C_3F_8 as target fluid
- Run from Oct. 2013 to May 2014





PICO-2L

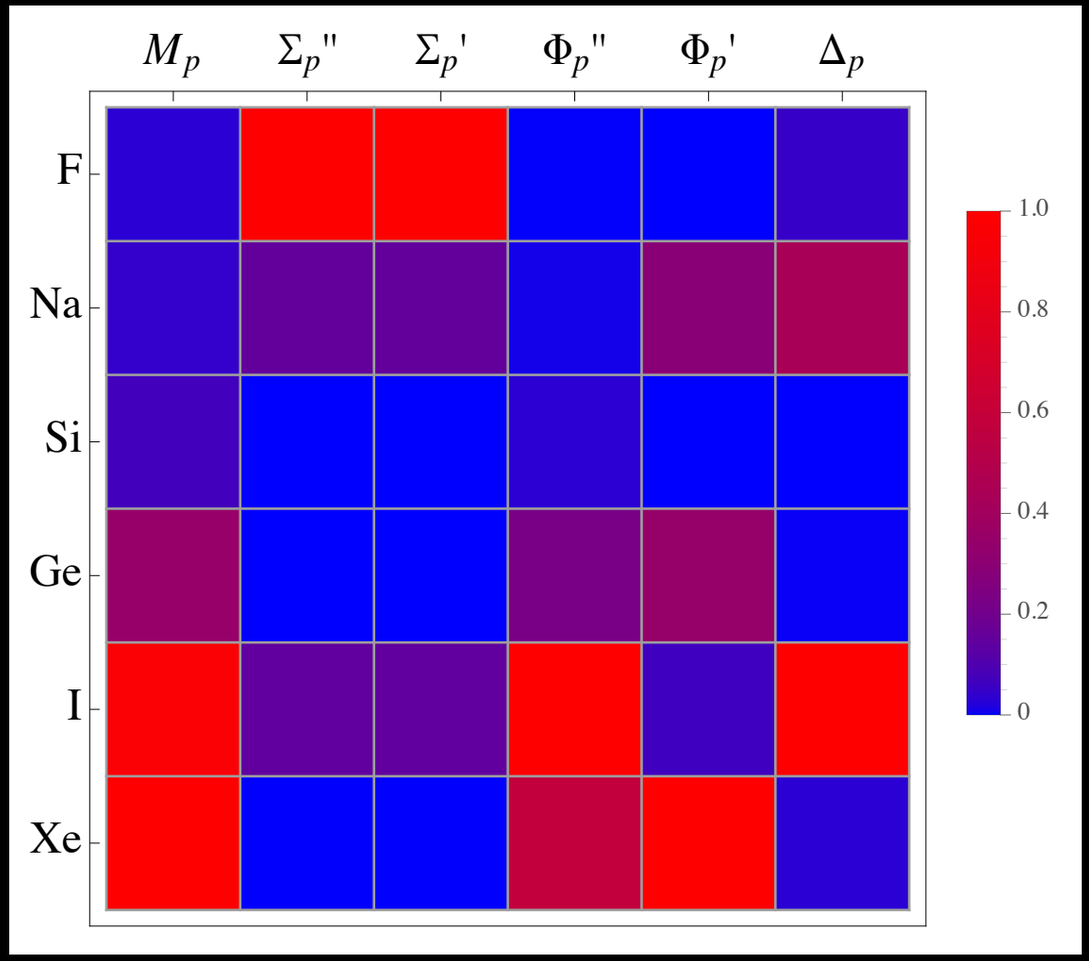
- Switch target fluid to C_3F_8 for several reasons
  - Very low operating threshold



PICO-2L

- Switch target fluid to C_3F_8 for several reasons
  - Very low operating threshold
  - Twice the fluorine density

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



PICO-2L

- Switch target fluid to C_3F_8 for several reasons
  - Very low operating threshold
  - Twice the fluorine density
  - Improved efficiency for bubble nucleation (could be a completely separate talk)

PICO-2L

- Switch target fluid to C_3F_8 for several reasons
  - Very low operating threshold
  - Twice the fluorine density
  - Improved efficiency for bubble nucleation (could be a completely separate talk)

Great for SD-proton interactions

⟶ no other direct detection target comes close

Great for light WIMPs

⟶ 1 event/day from CDMS-Si result

Detour: Threshold and efficiency

- Threshold based on theory of Seitz, Phys. of Fluids **1**, 2 (1958)

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

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

Surface energy

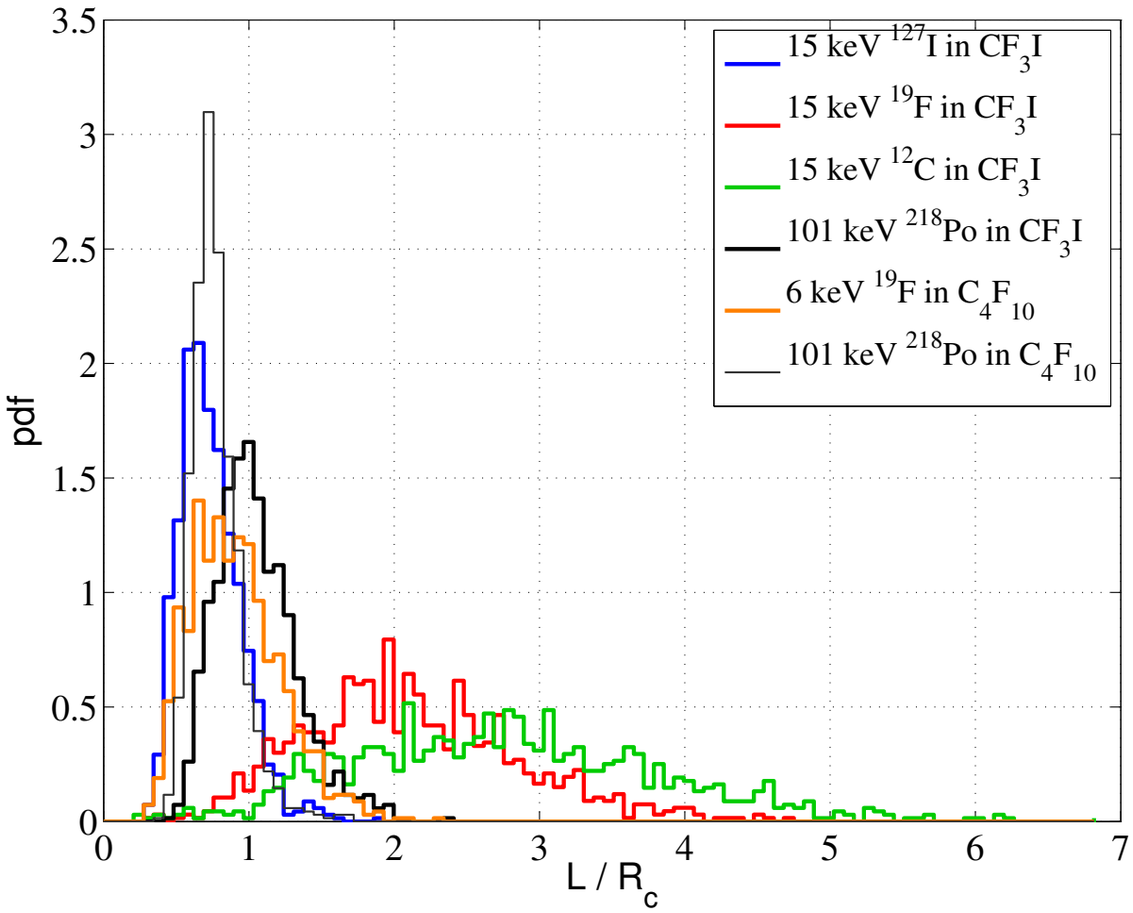
Latent heat

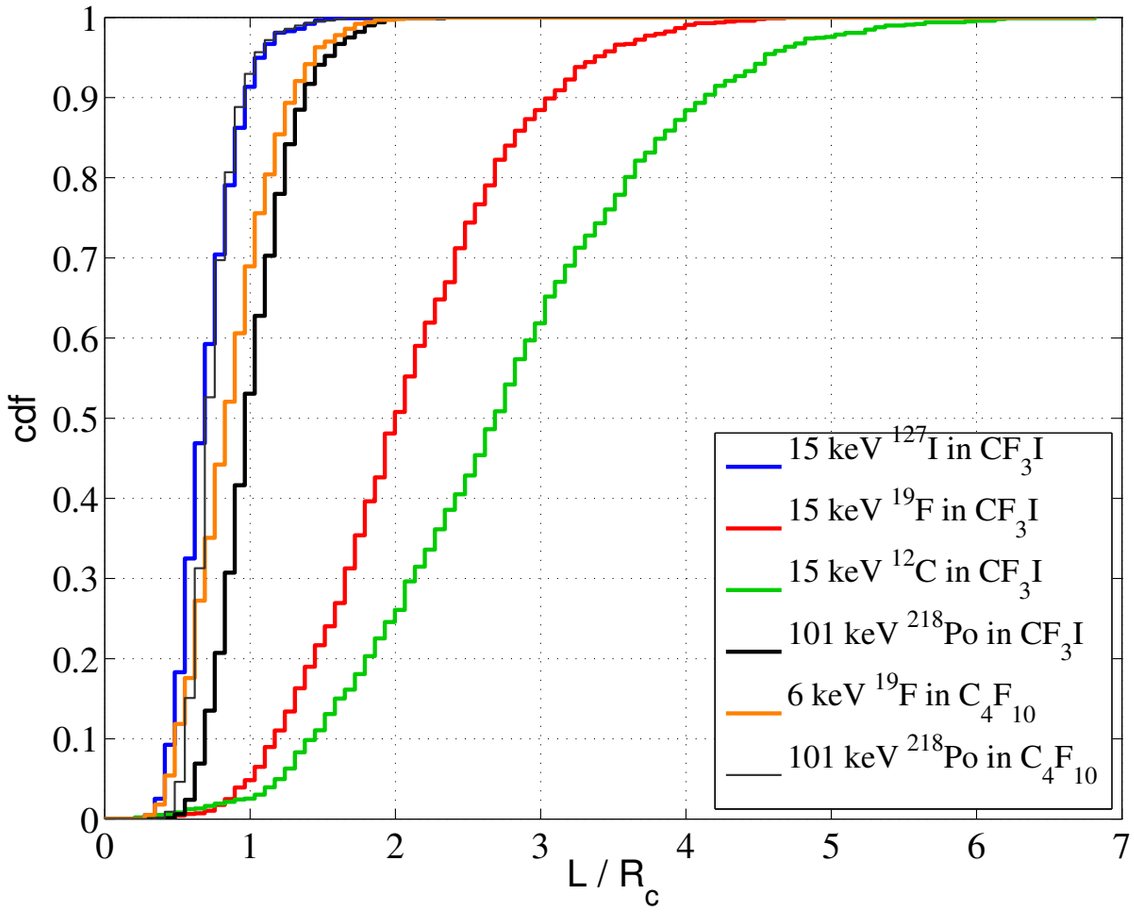
- Energy deposition E_{th} within length R_c will nucleate a bubble ("Hot Spike" or "Seitz" model)

- Seitz model assumes a step function above threshold, but the track dependence is not fully specified

Detour: Threshold and efficiency

- Complicated by molecule, CF_3I or C_3F_8
- The recoil track length, L, must be comparable to the bubble radius R_C

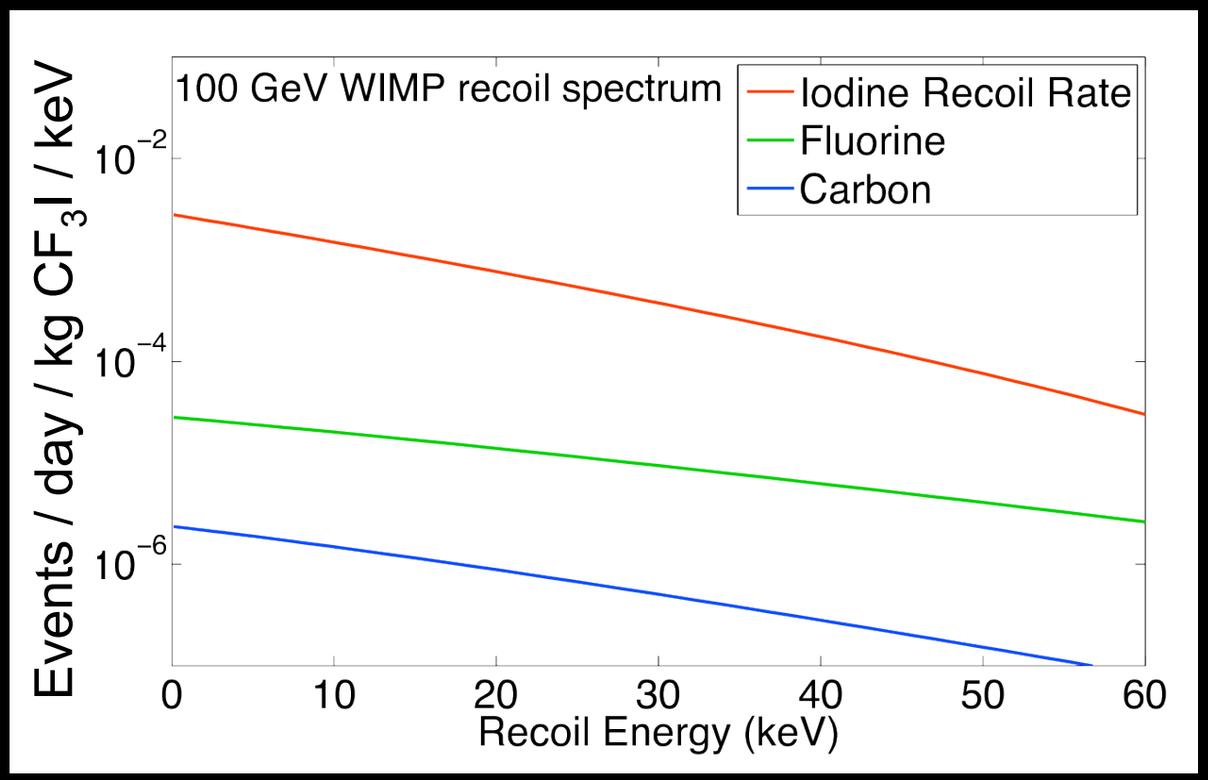


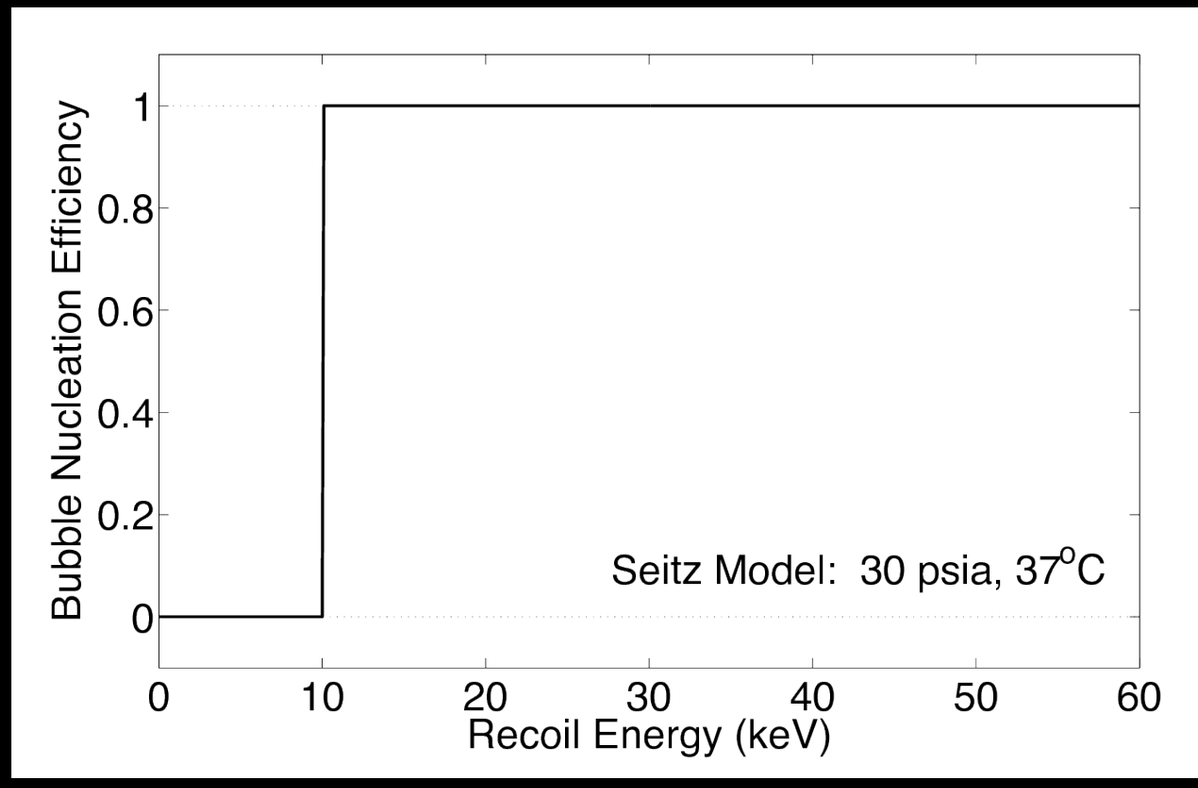


- Easy to imagine difference in behavior between C, F and I

Detour: Threshold and efficiency

$$\text{Rate} = \int \text{WIMP recoil spectrum} \times \text{Bubble nucleation efficiency}$$

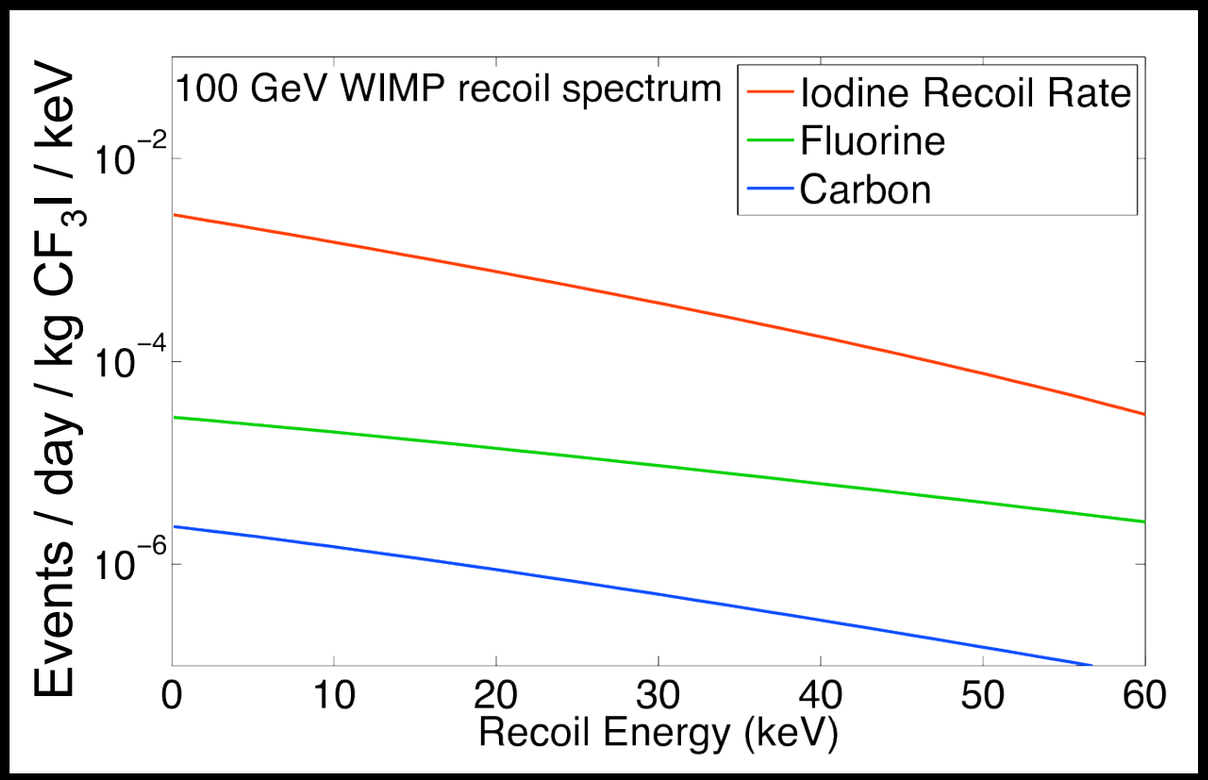


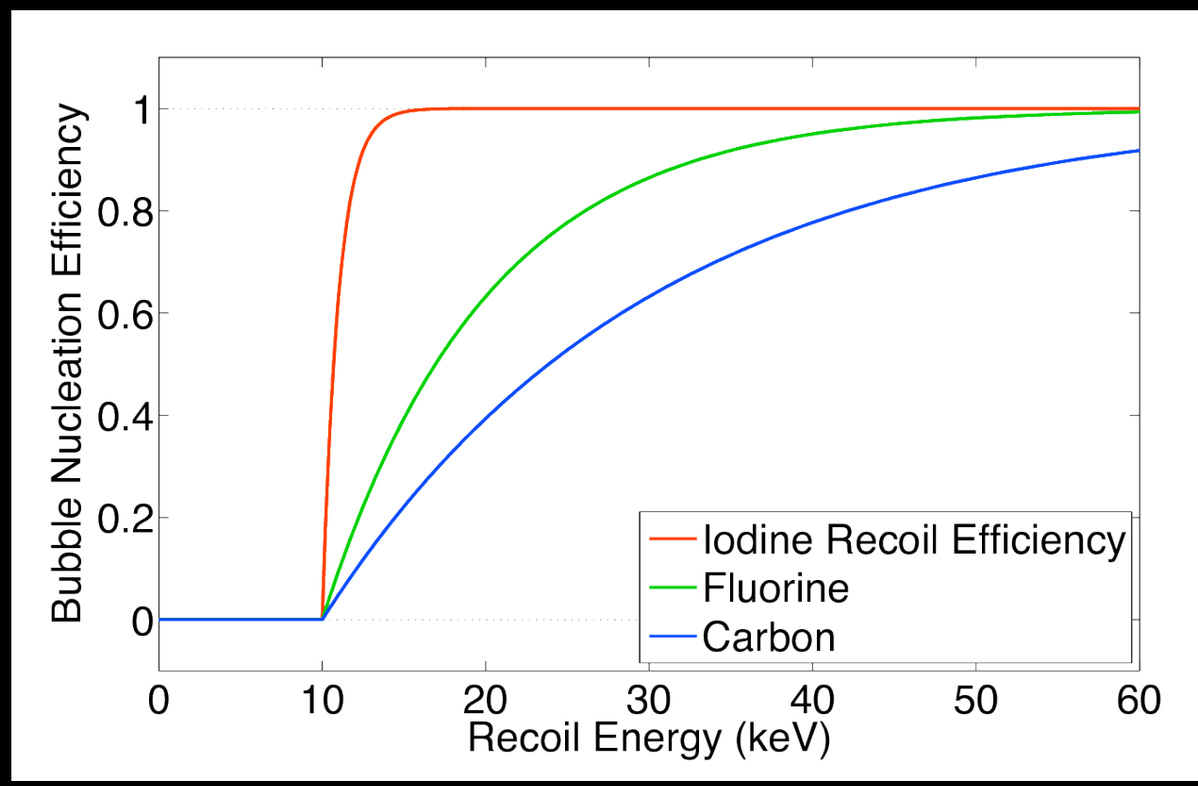


- Effect of threshold shape depends on target, WIMP mass

Detour: Threshold and efficiency

$$\text{Rate} = \int \text{WIMP recoil spectrum} \times \text{Bubble nucleation efficiency}$$





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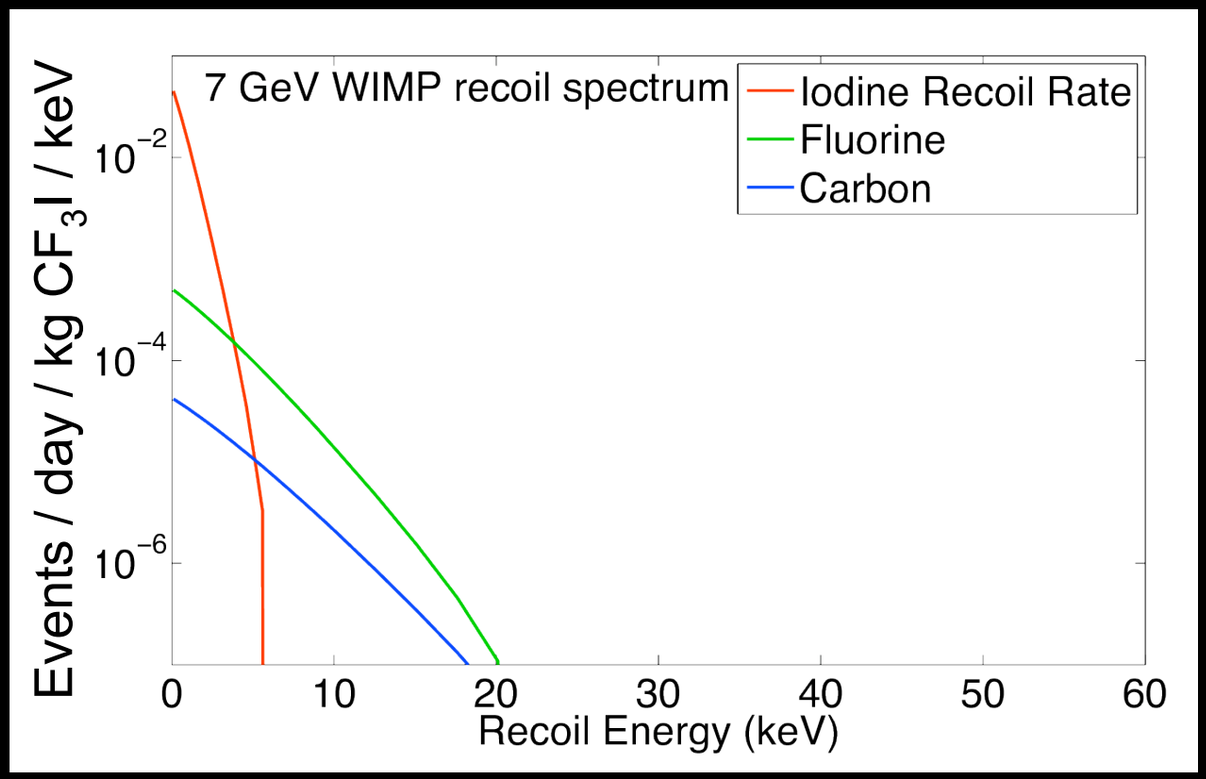
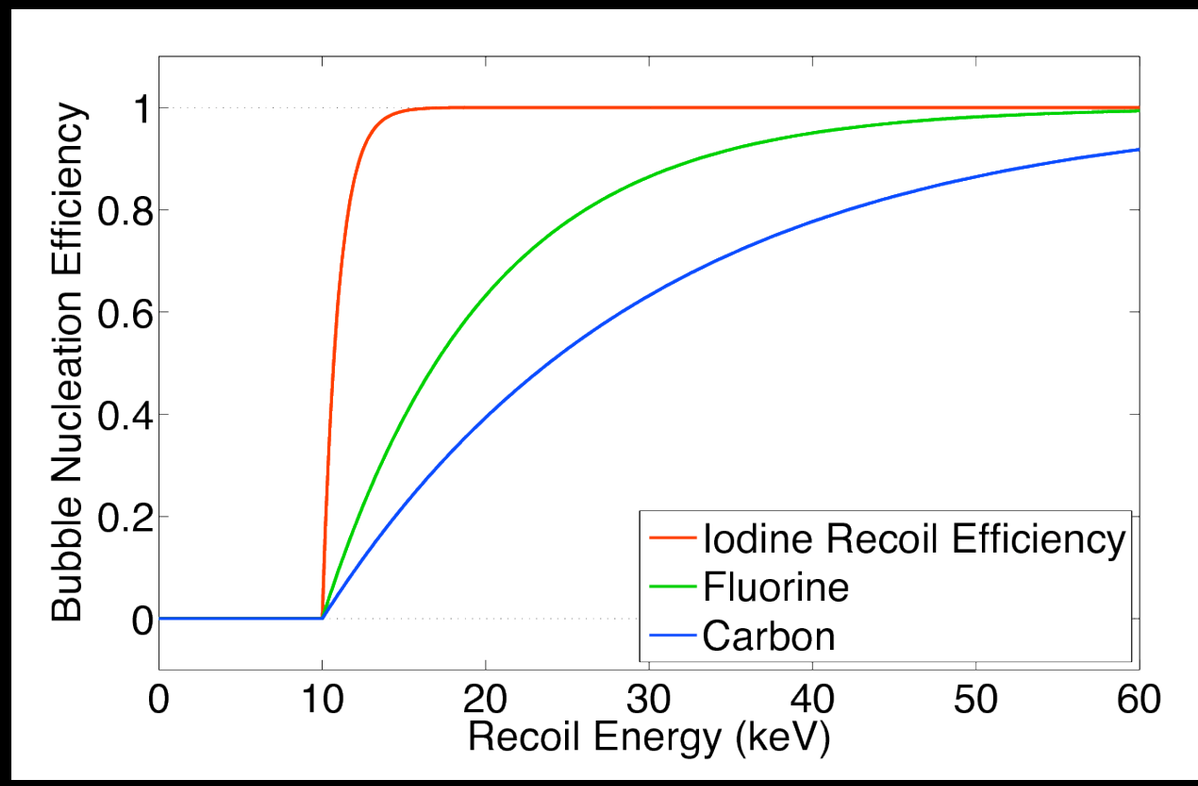


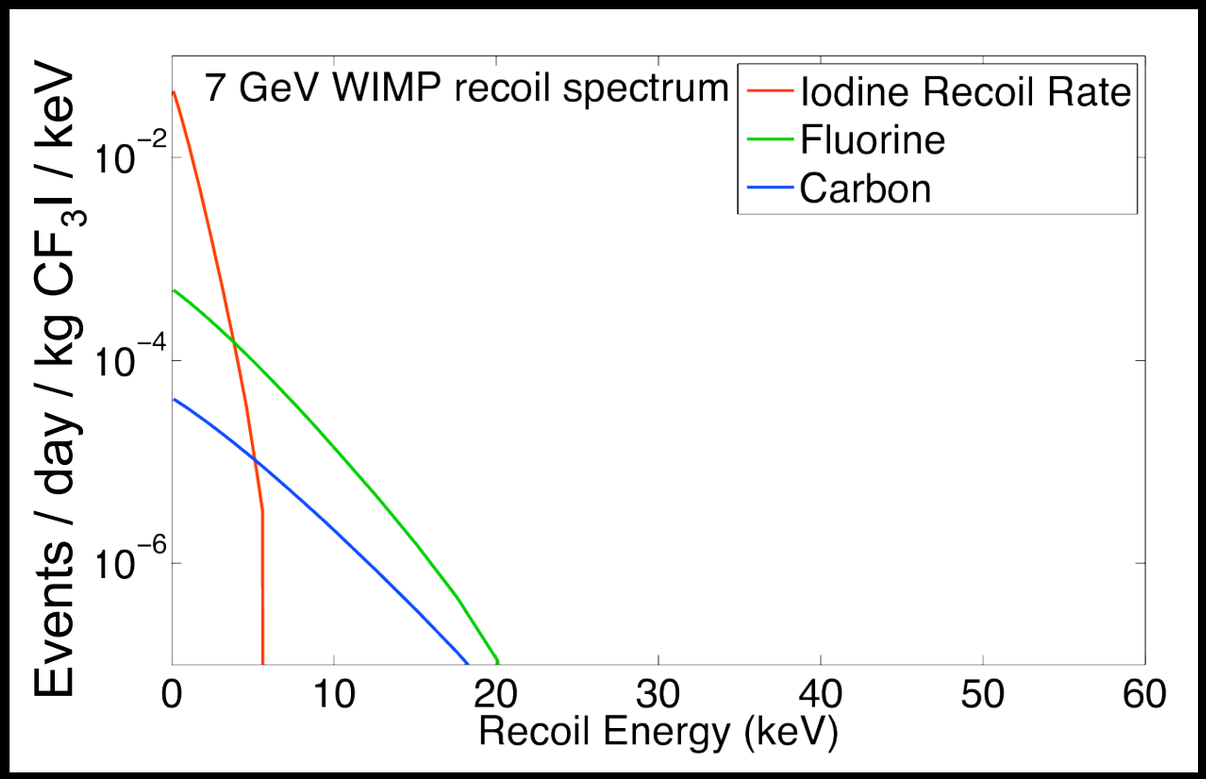


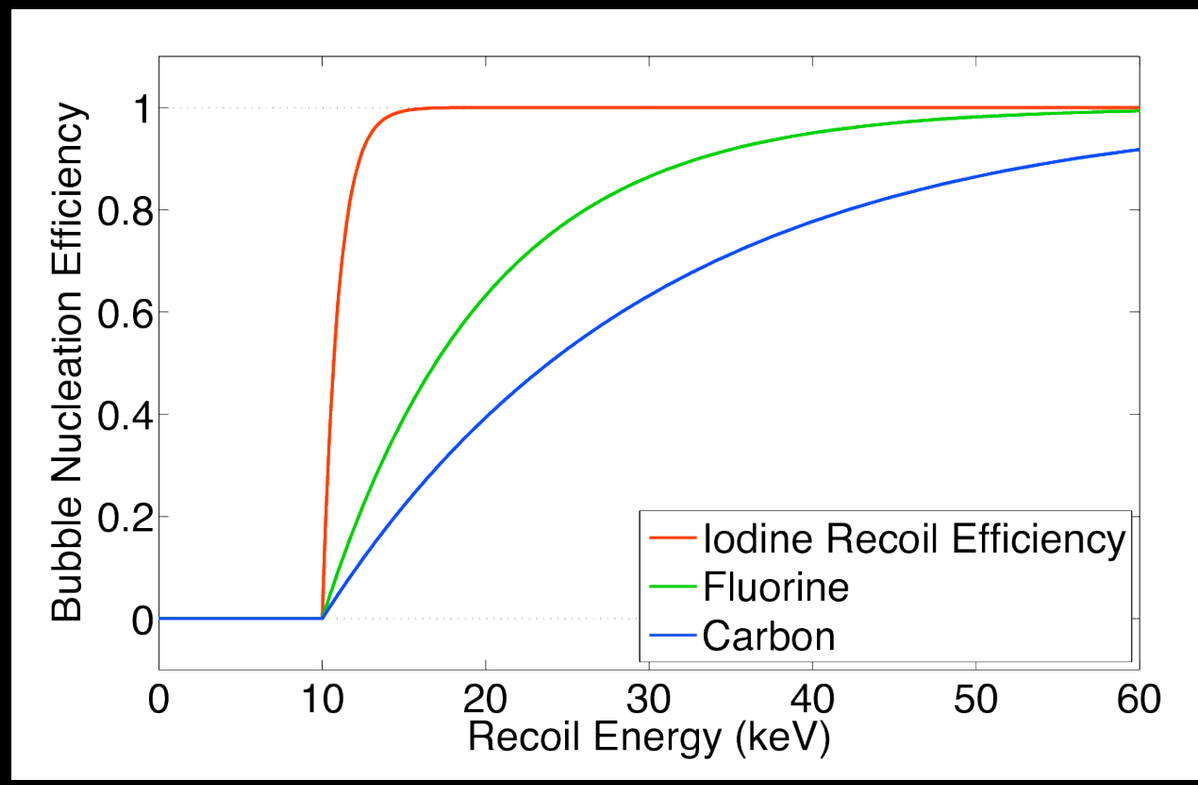
- Effect of threshold shape depends on target, WIMP mass

Detour: Threshold and efficiency

We need to calibrate!

$$\text{Rate} = \int \text{WI} \; \text{n efficiency}$$

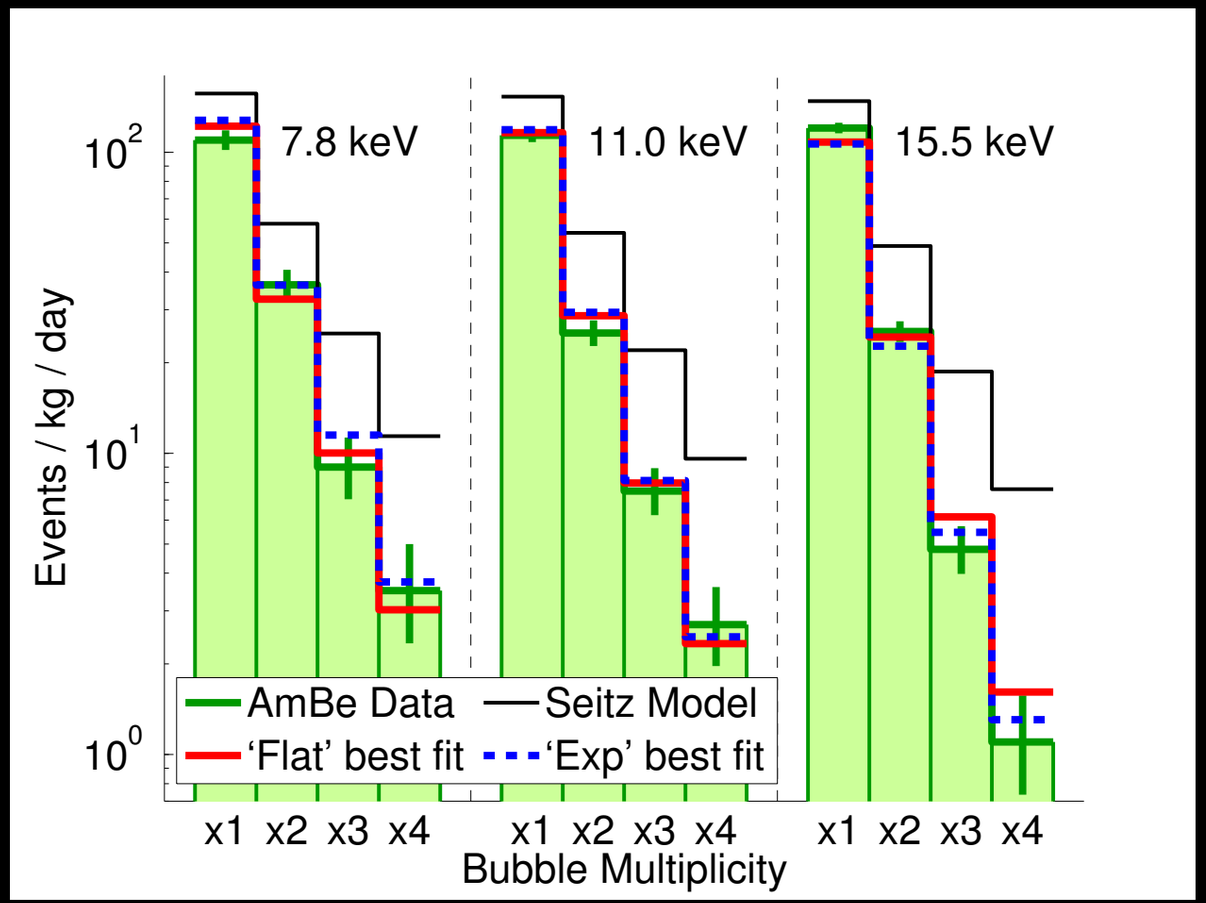


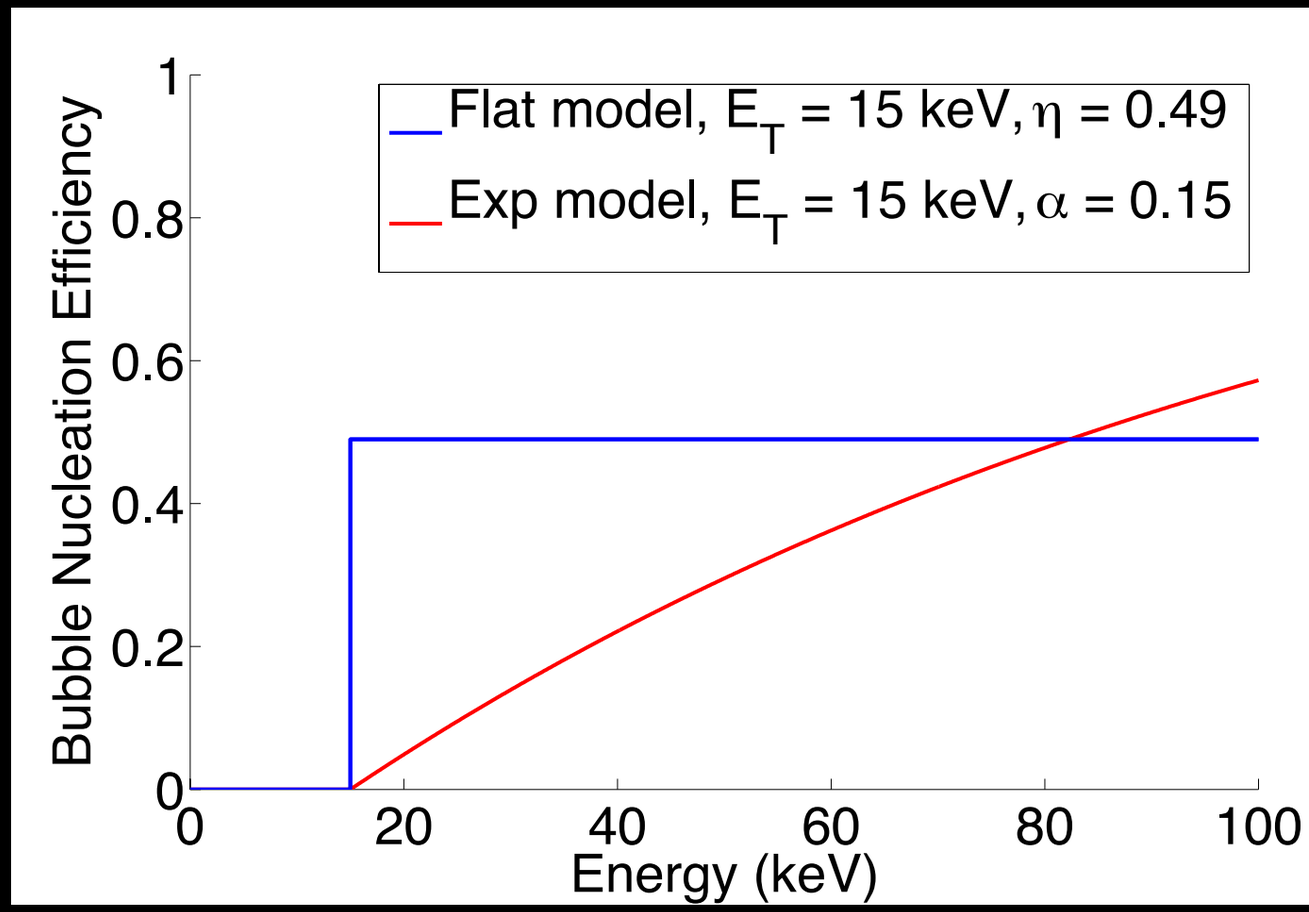


- Effect of threshold shape depends on target, WIMP mass

Is Seitz model adequate?

- Use AmBe broad spectrum neutron calibration sources at SNOLAB to measure response of carbon and fluorine
- Compare MCNP-predicted rates of single, double, triple and quadruple bubble events with observation
- Rates in CF_3I are 50% lower than simulations with a step function



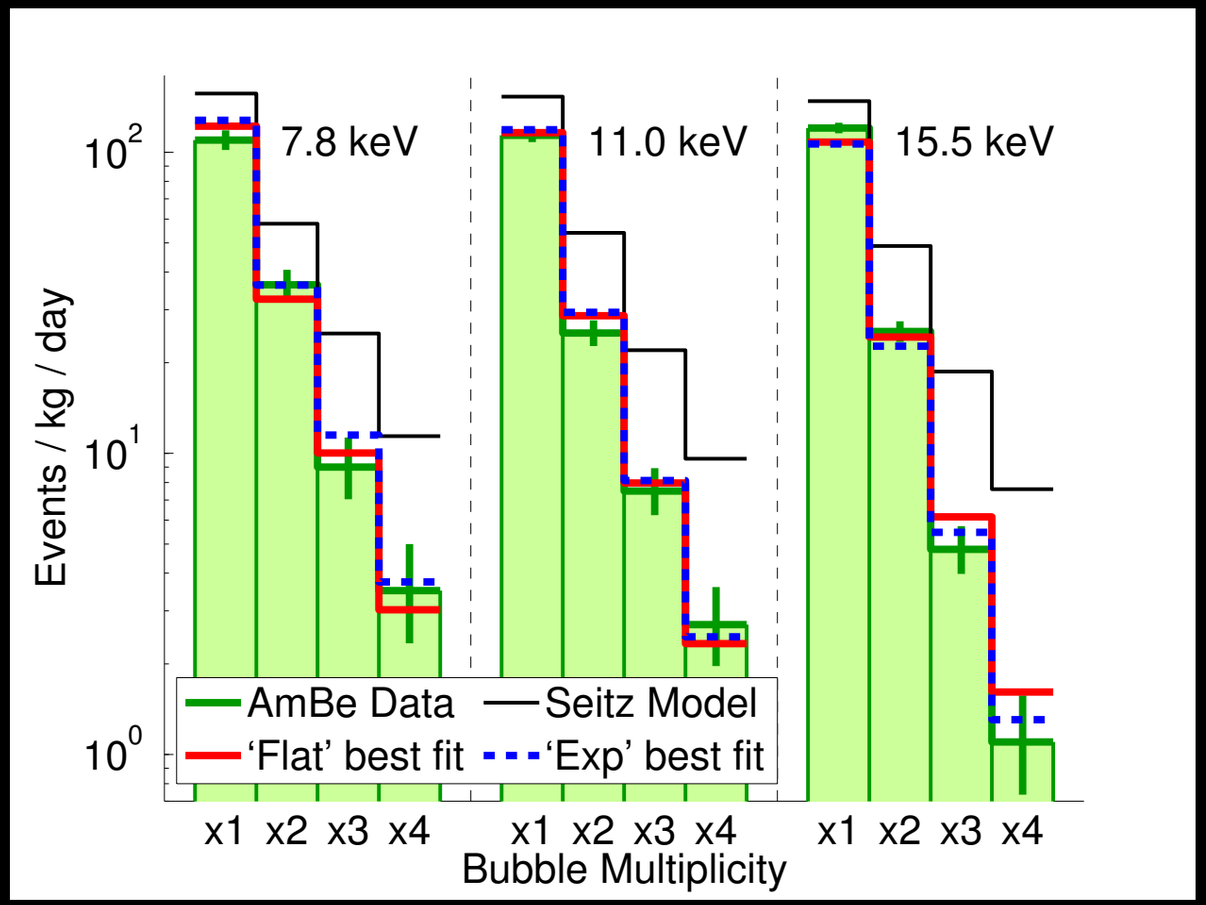


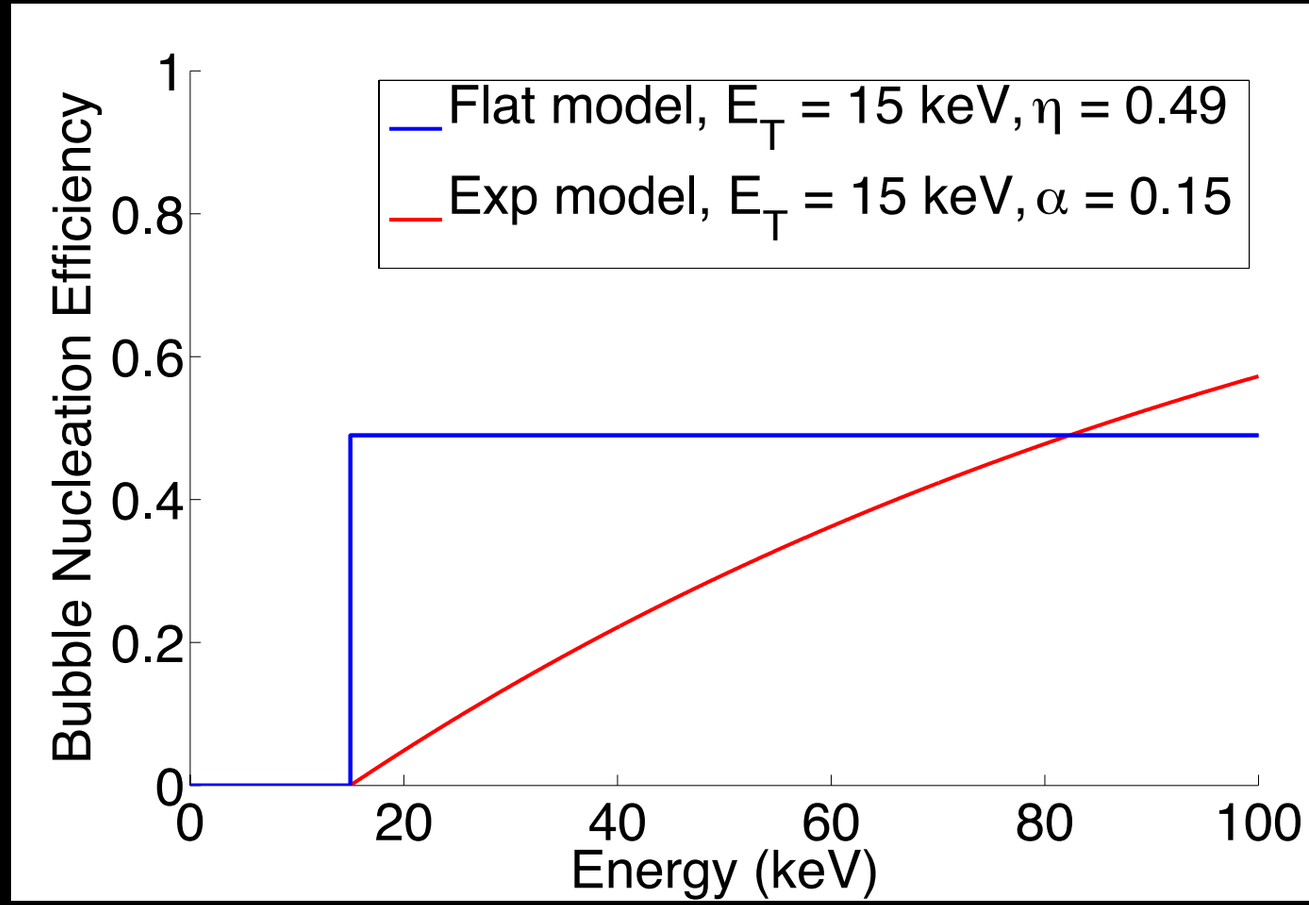
Is Seitz model adequate?

- Use AmBe [illegible] sources at SNOLAB to [illegible]uorine

Not for C and F in CF_3I!

- Compare MCNP-predicted rates of single, double, triple and quadruple bubble events with observation
- Rates in CF_3I are 50% lower than simulations with a step function



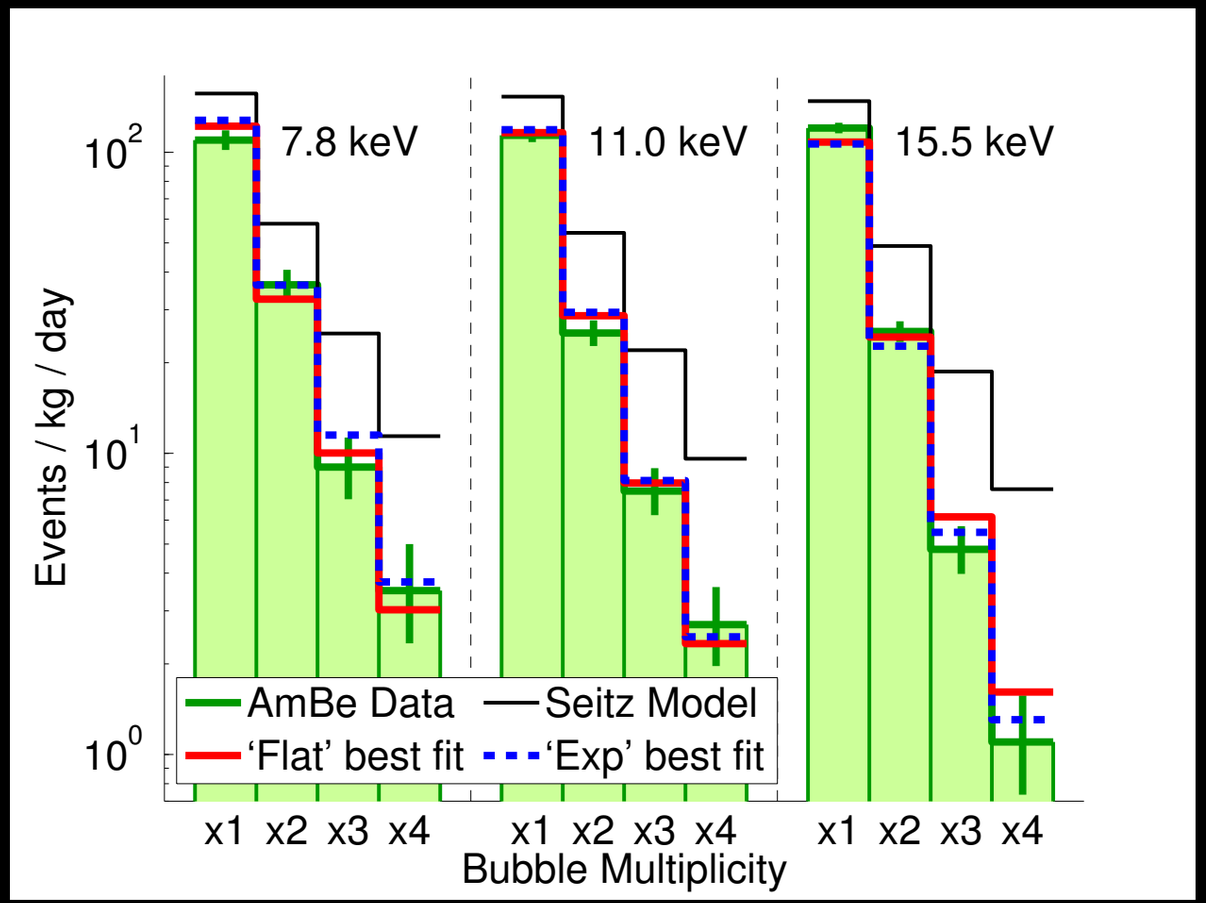


Is Seitz model adequate?

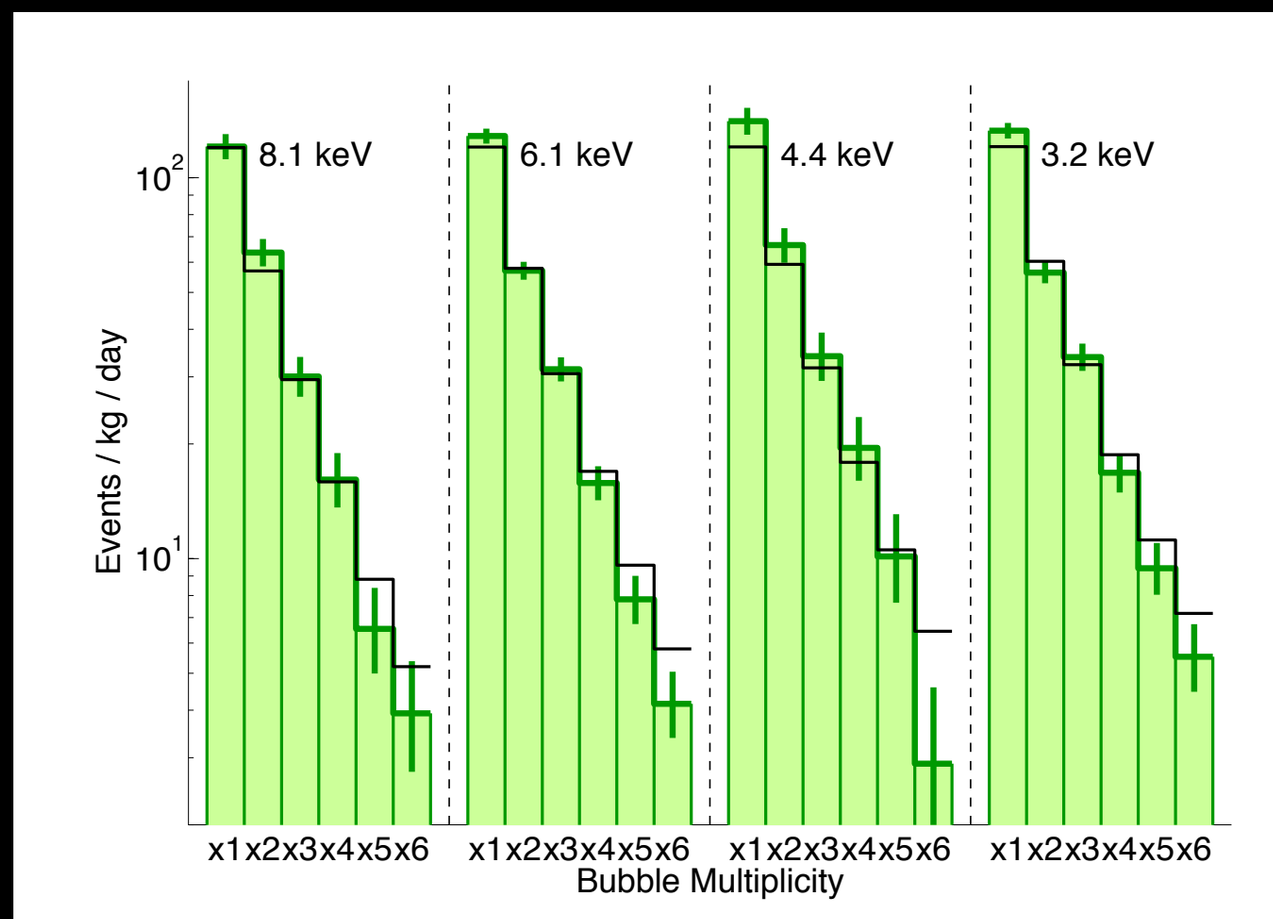
- Response is much better in C_3F_8 (C,F recoils lose energy more efficiently in non-iodinated fluid)

- The same AmBe data-MC comparison is perfect with the new target - much closer to the Seitz model

CF_3I



C_3F_8



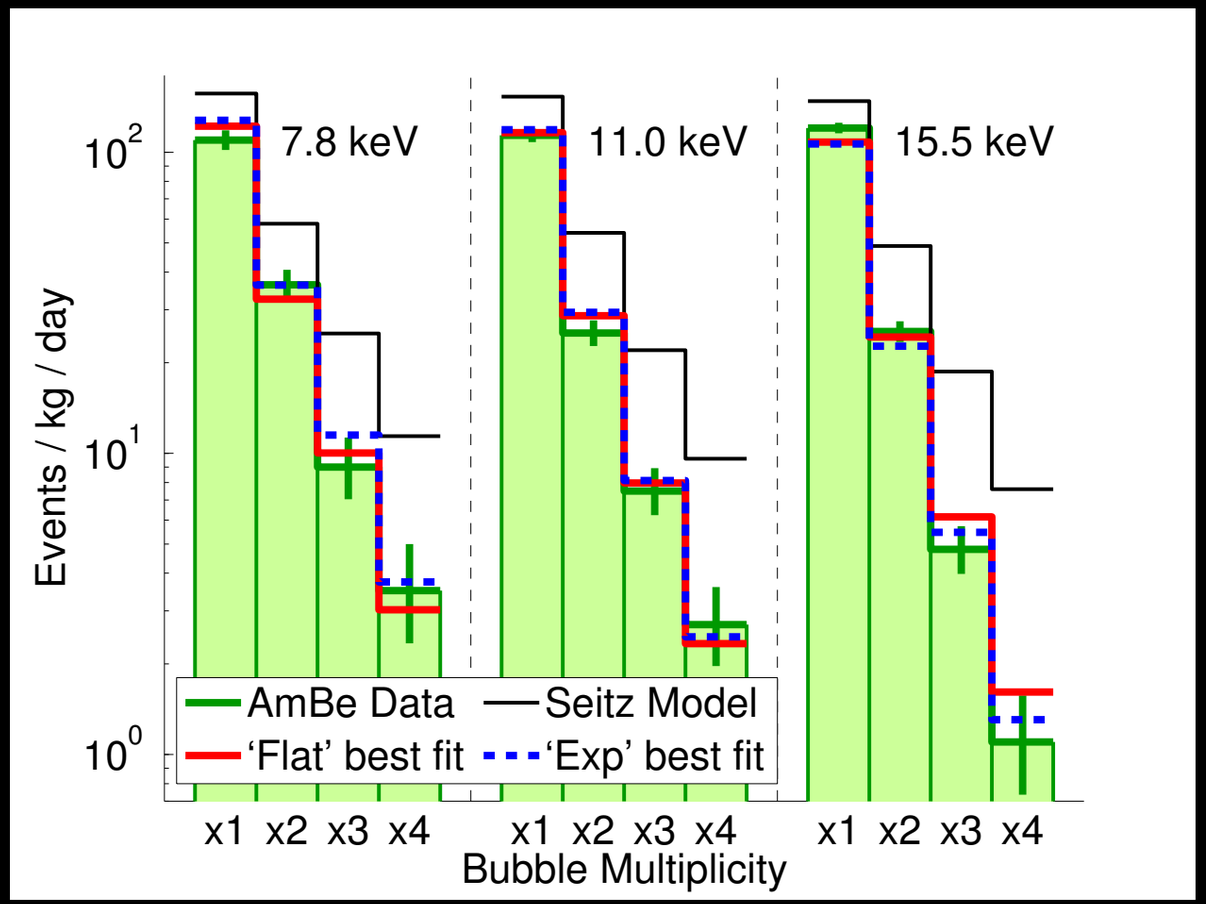
Is Seitz model adequate?

- Response is mu[illegible] ecoils lose energy more efficiently

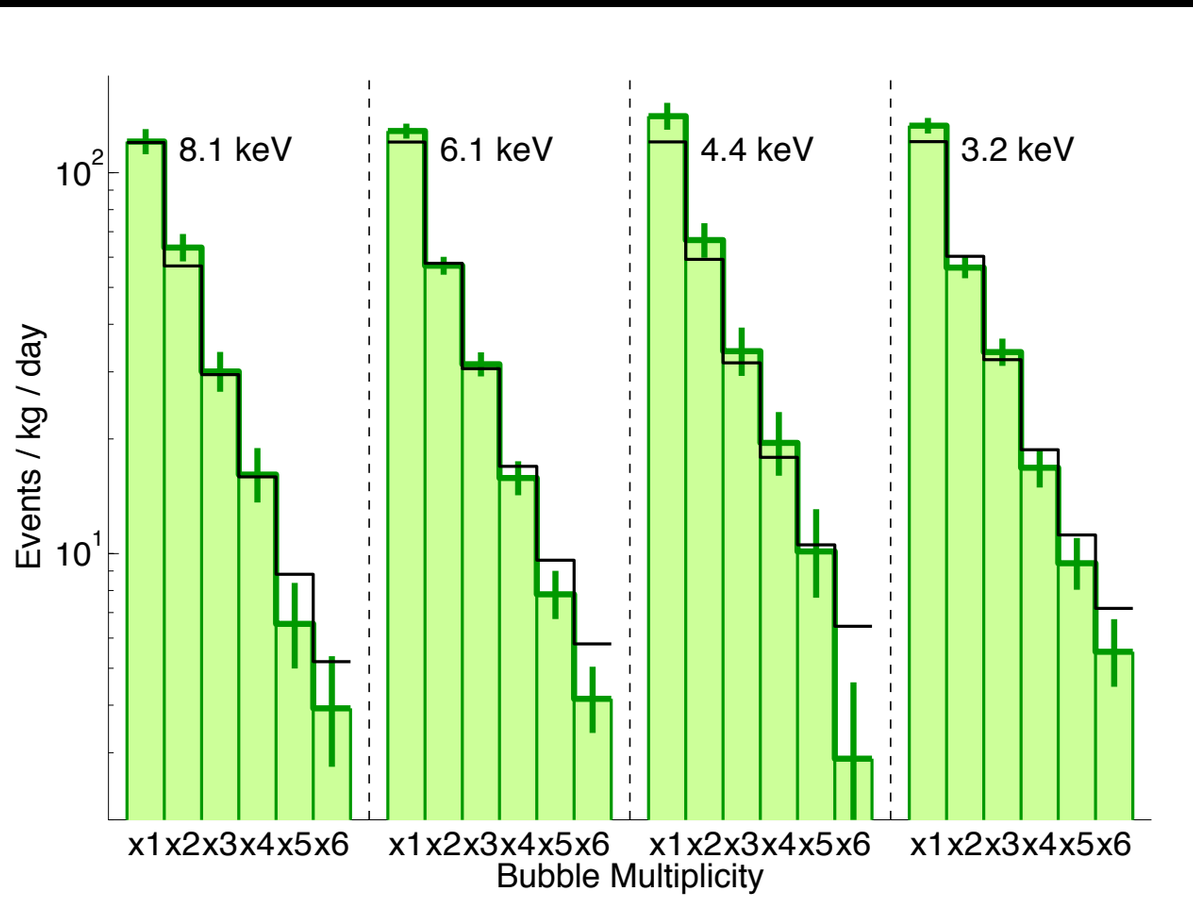
Maybe in C_3F_8!

- The same AmBe data-MC comparison is perfect with the new target - much closer to the Seitz model

CF_3I

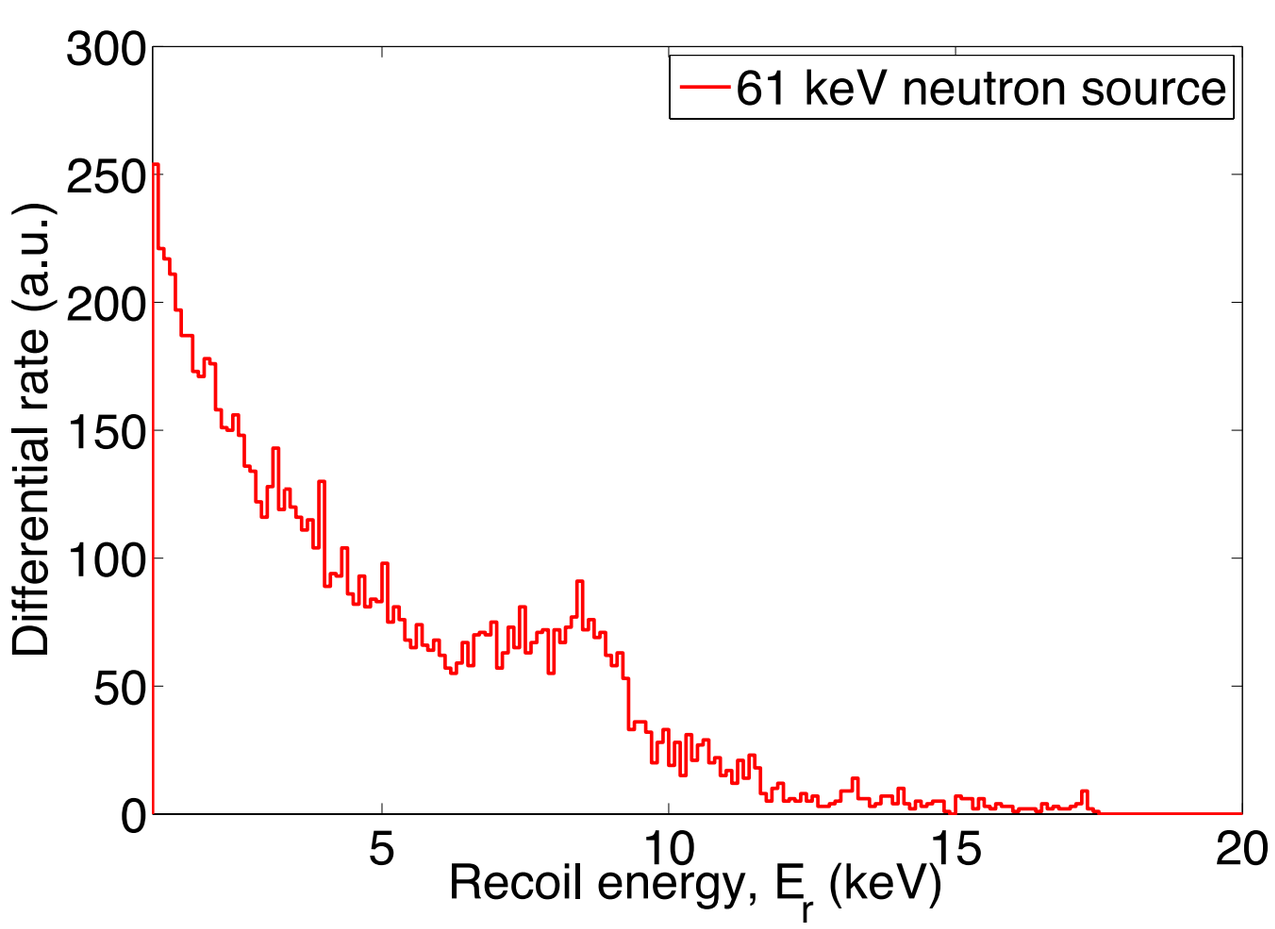


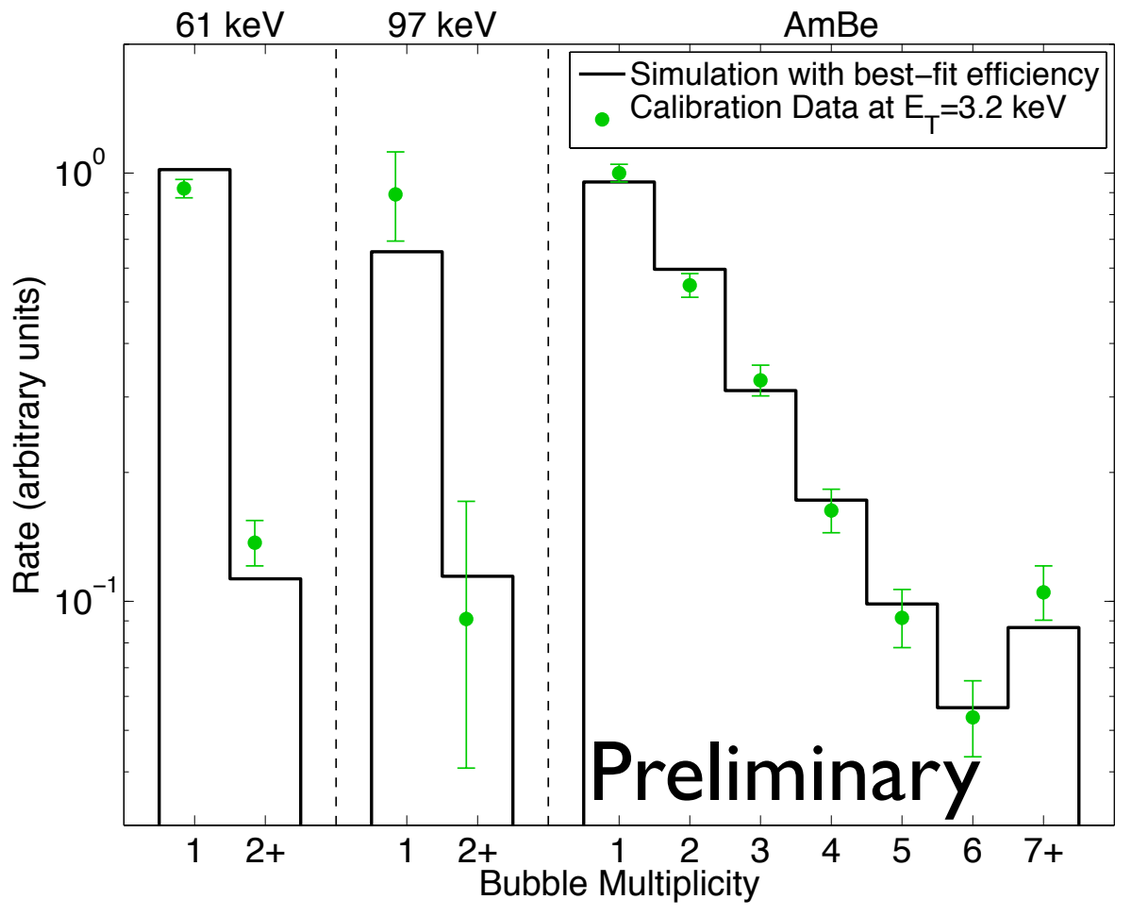
C_3F_8



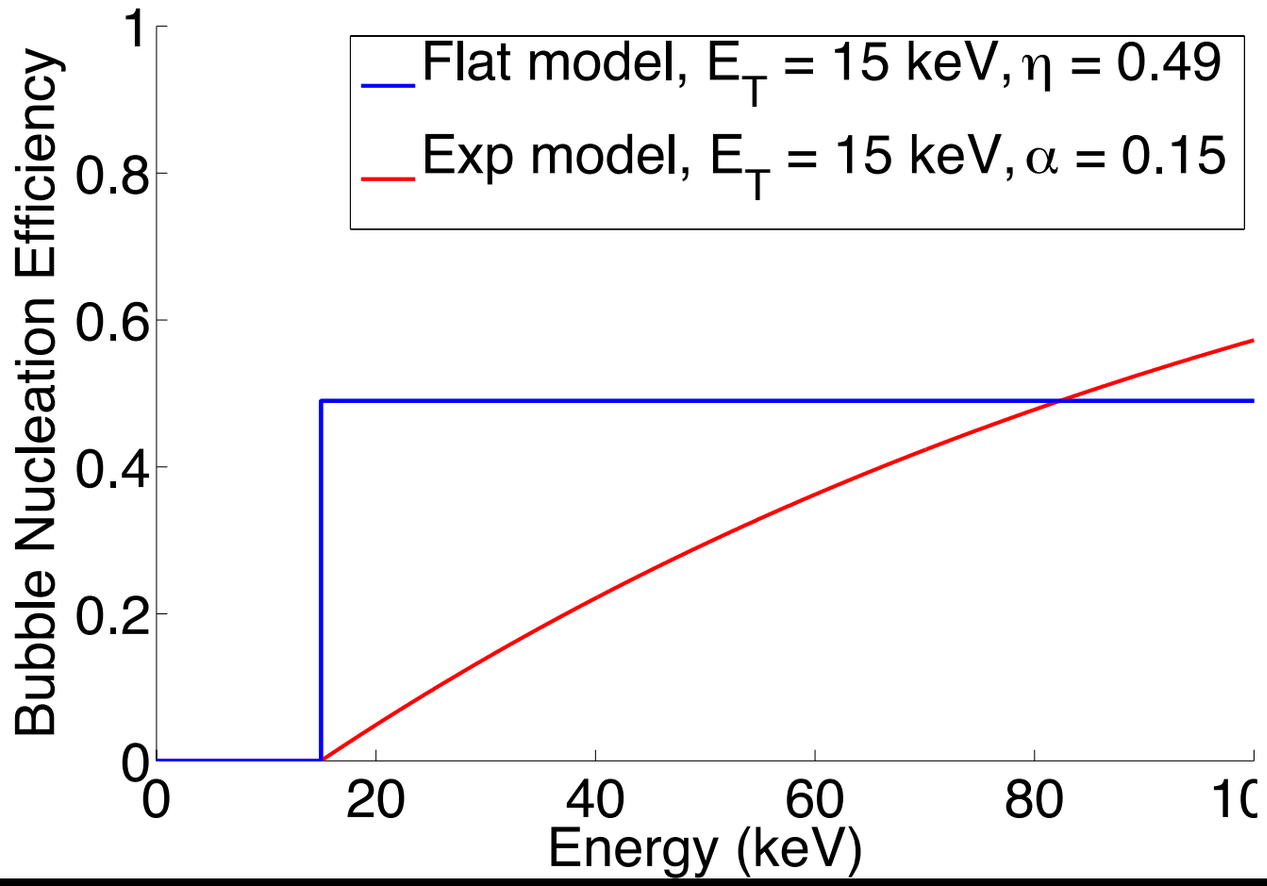
Threshold and efficiency

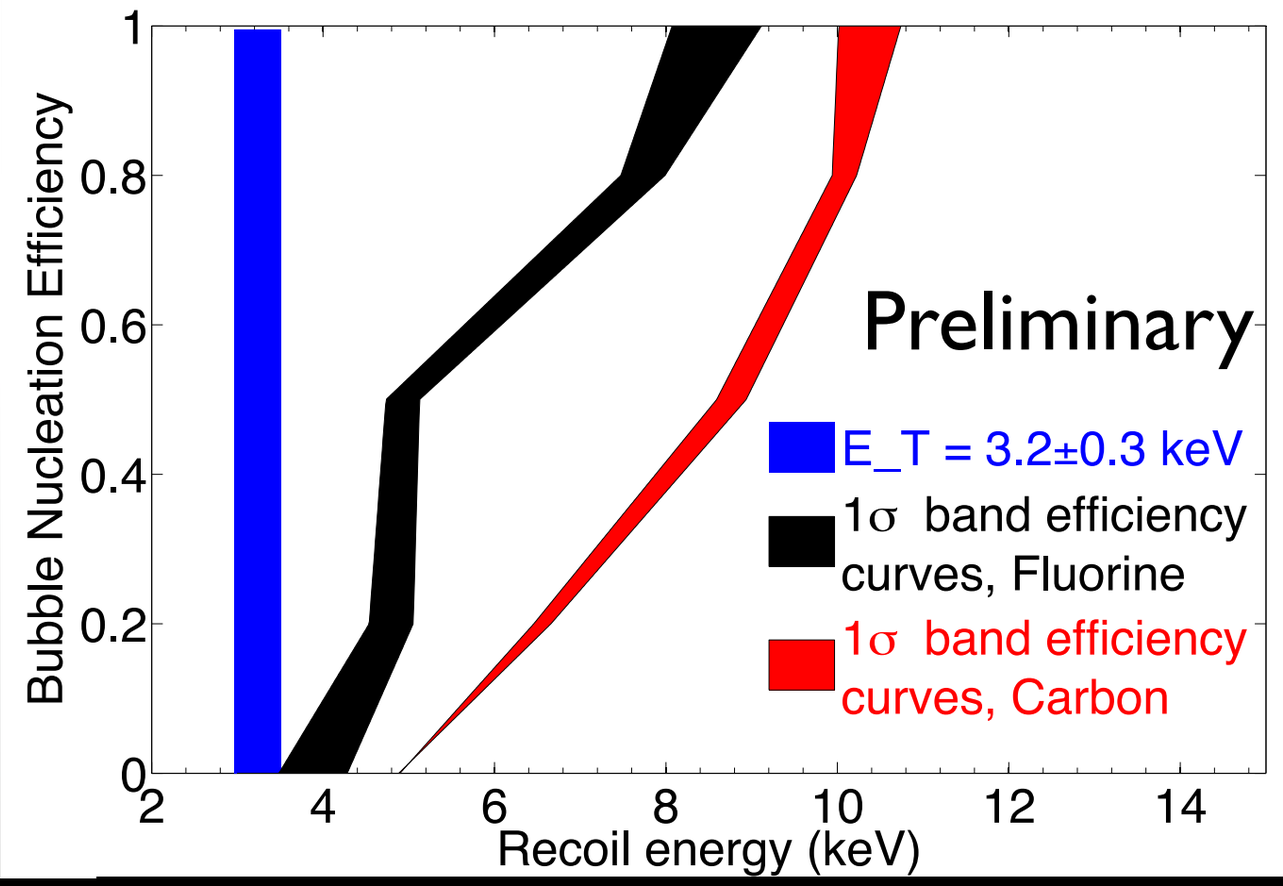
- This is important - we need to get it right
- Low energy neutron beam at University of Montreal allows us to probe very low energy recoils
  - The result agrees with the AmBe calibrations, and constrains the shape of the efficiency curve at low energy!





Threshold and efficiency

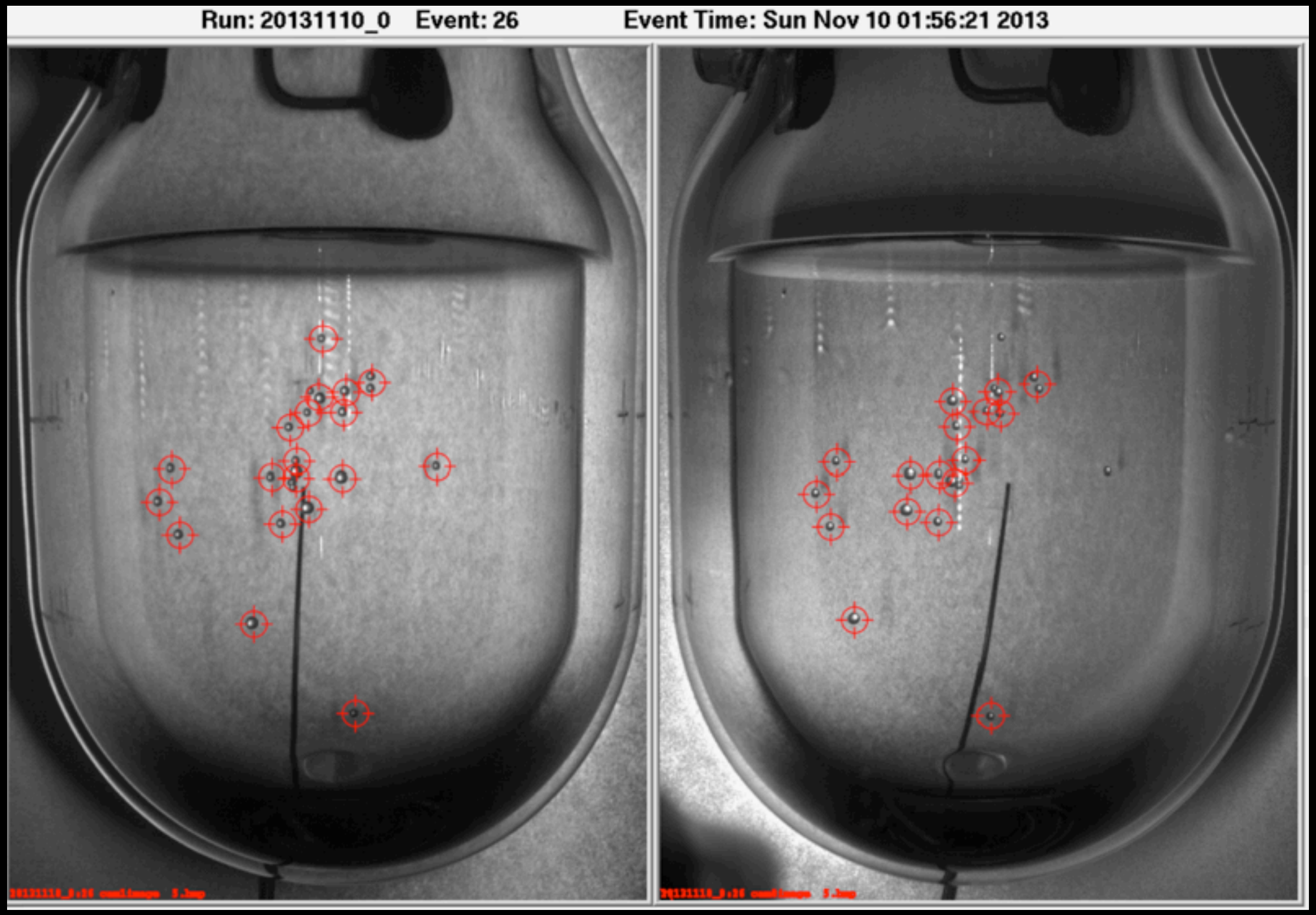




F, C response in CF_3I
Very soft turn on
Large uncertainty

New calibration on C_3F_8
Much faster turn on!
Much better constrained!

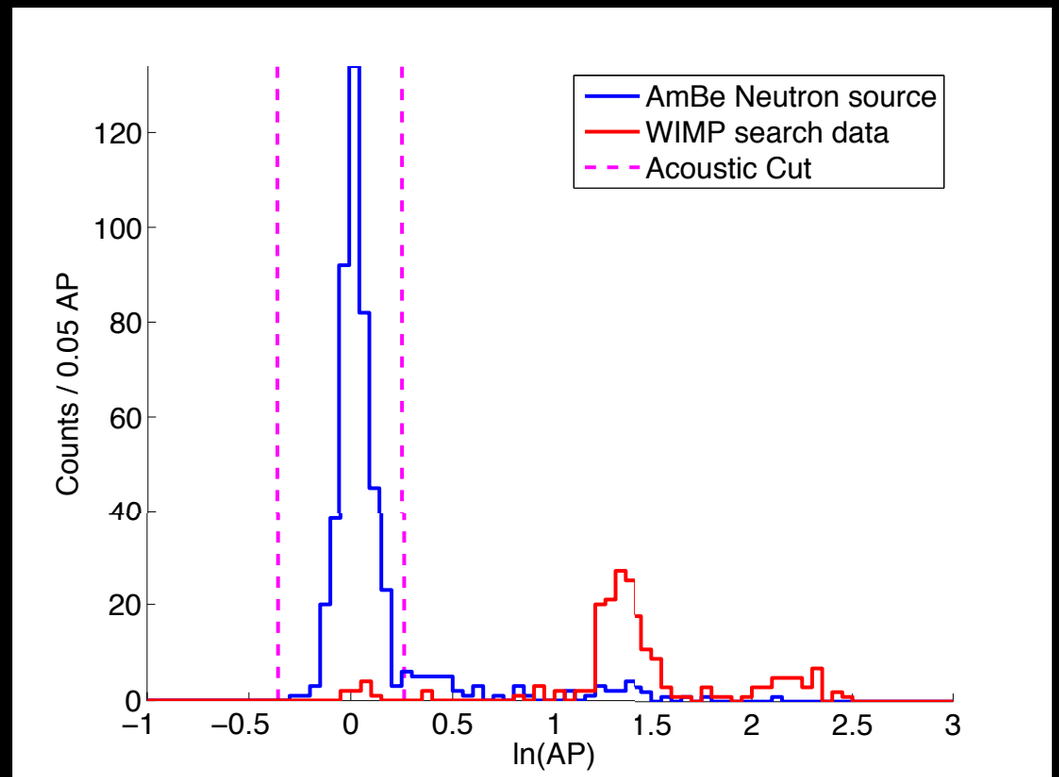
Threshold and efficiency

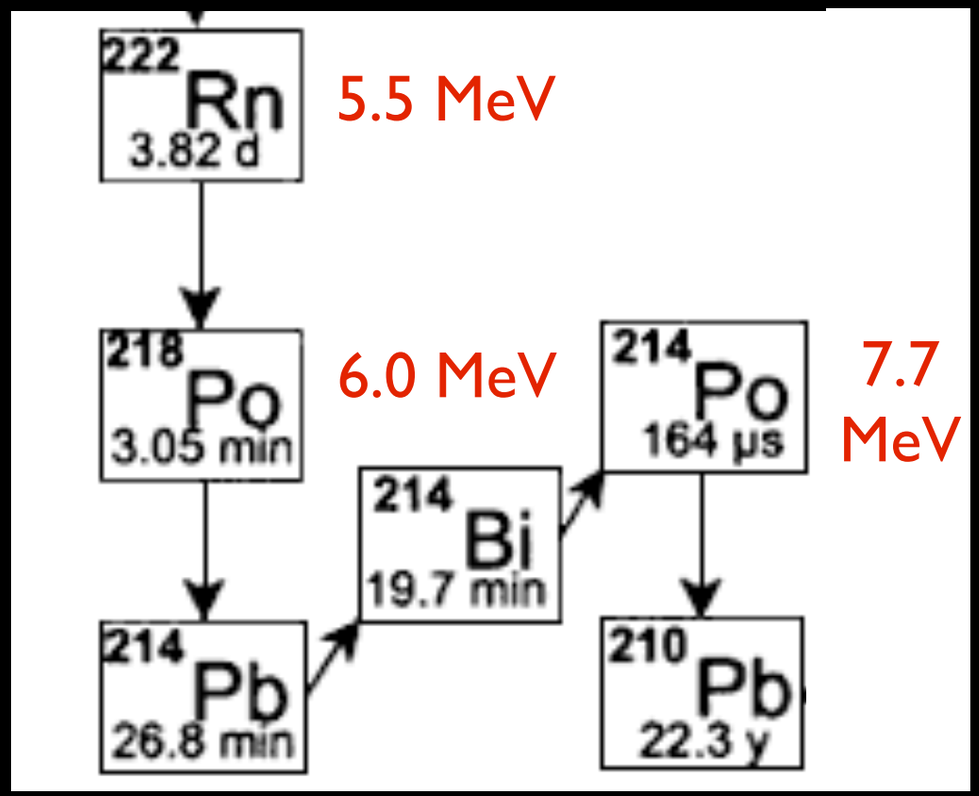


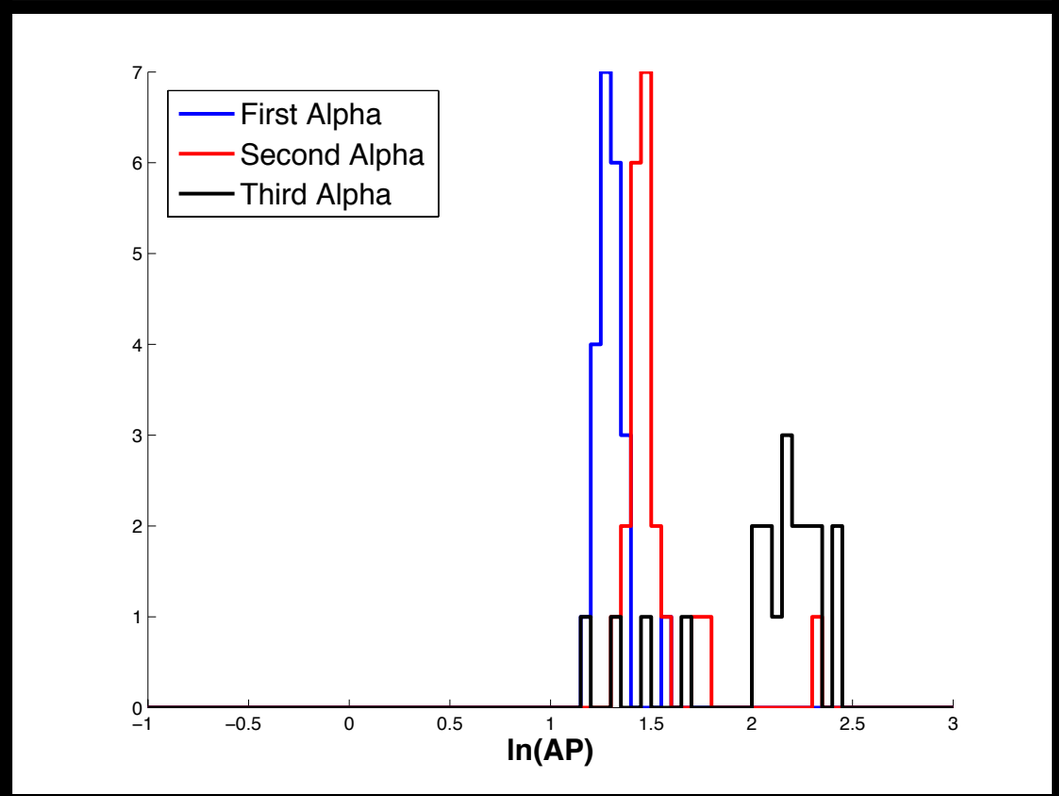
- 23 bubble event from AmBe neutron source!

PICO-2L Results

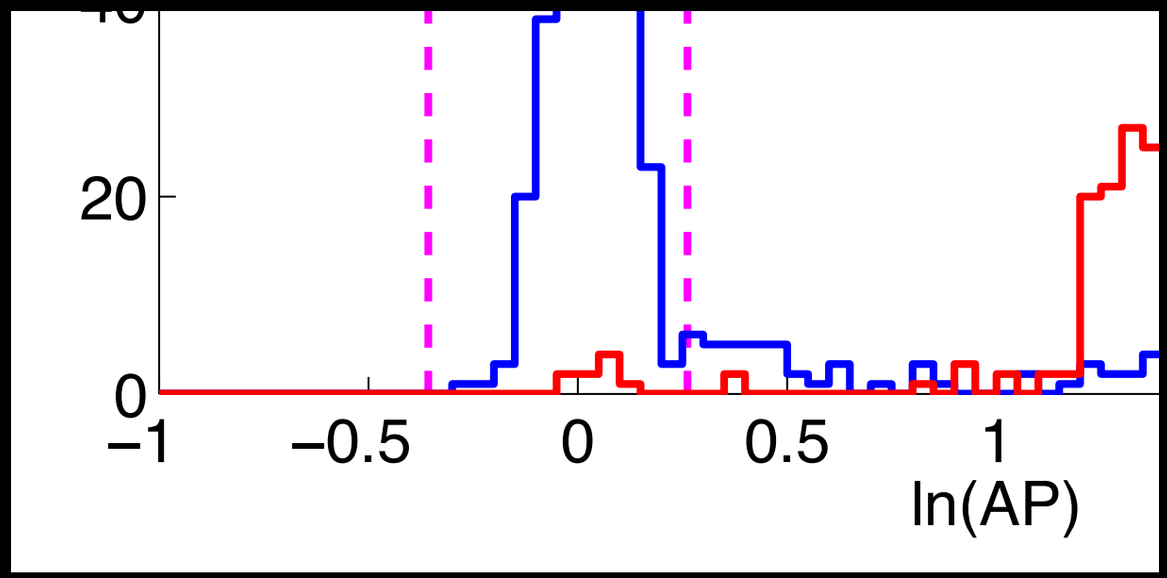
- Two distinct alpha peaks, well separated from neutron data
- Timing of events is consistent with Rn decay, and higher energy alphas are louder
- "Acoustic calorimetry"







PICO-2L Results



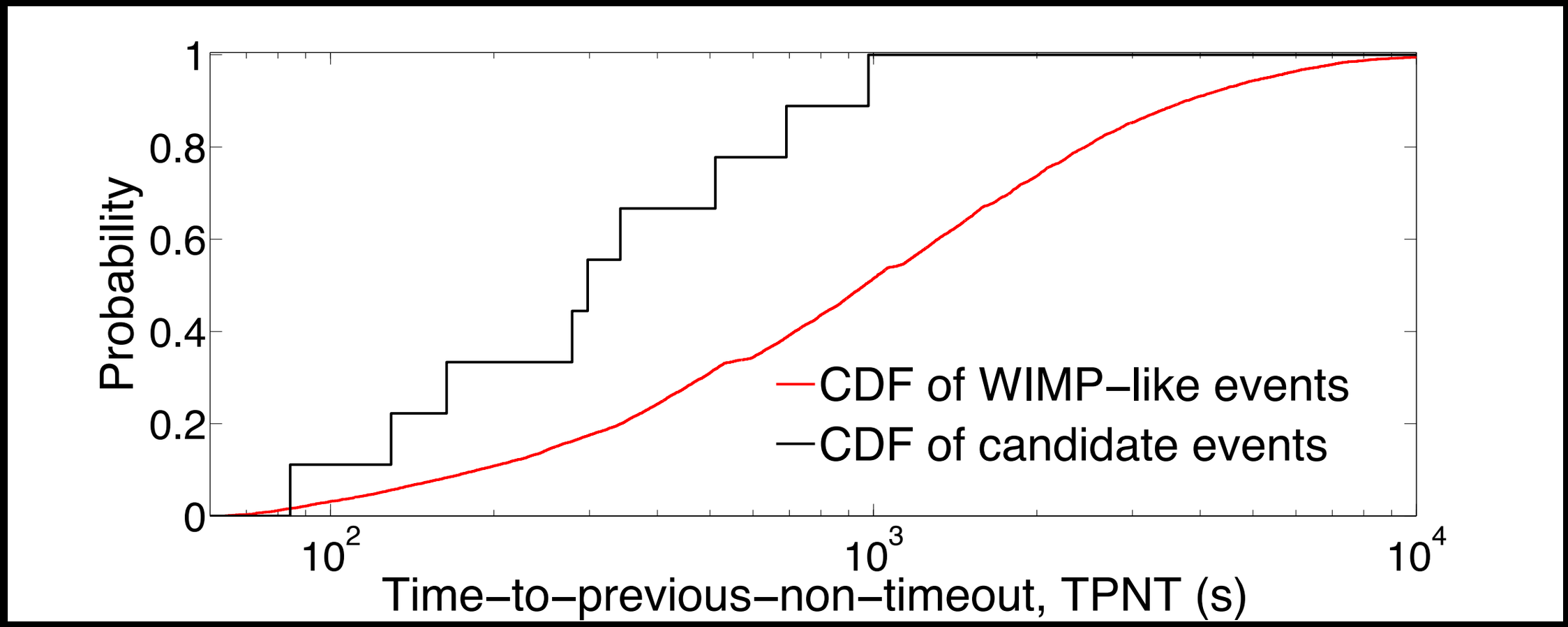
- 12 candidate events in 211.6 kg-days of exposure

Seitz threshold, E_T (keV)	Livetime (d)	WIMP exposure (kg-d)	Candidates
$3.2 \pm 0.2(\text{exp}) \pm 0.2(\text{th})$	32.2	74.8	9
$4.4 \pm 0.3(\text{exp}) \pm 0.3(\text{th})$	7.5	16.8	0
$6.1 \pm 0.3(\text{exp}) \pm 0.3(\text{th})$	39.7	82.2	3
$8.1 \pm 0.5(\text{exp}) \pm 0.4(\text{th})$	18.2	37.8	0

- Expected ~1 background event (neutrons)

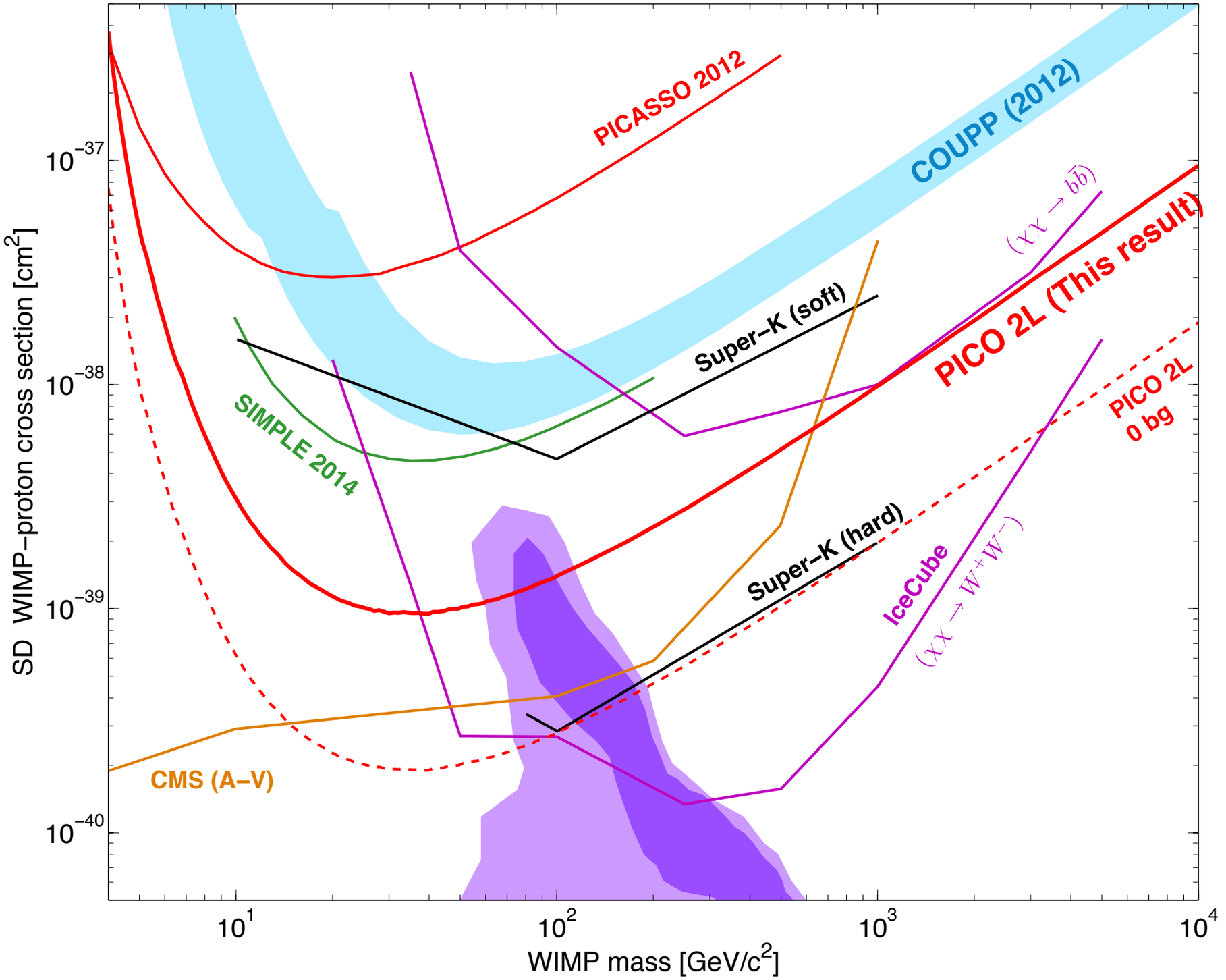
PICO-2L Results

- These events have timing correlations inconsistent with WIMPs (sounds familiar)

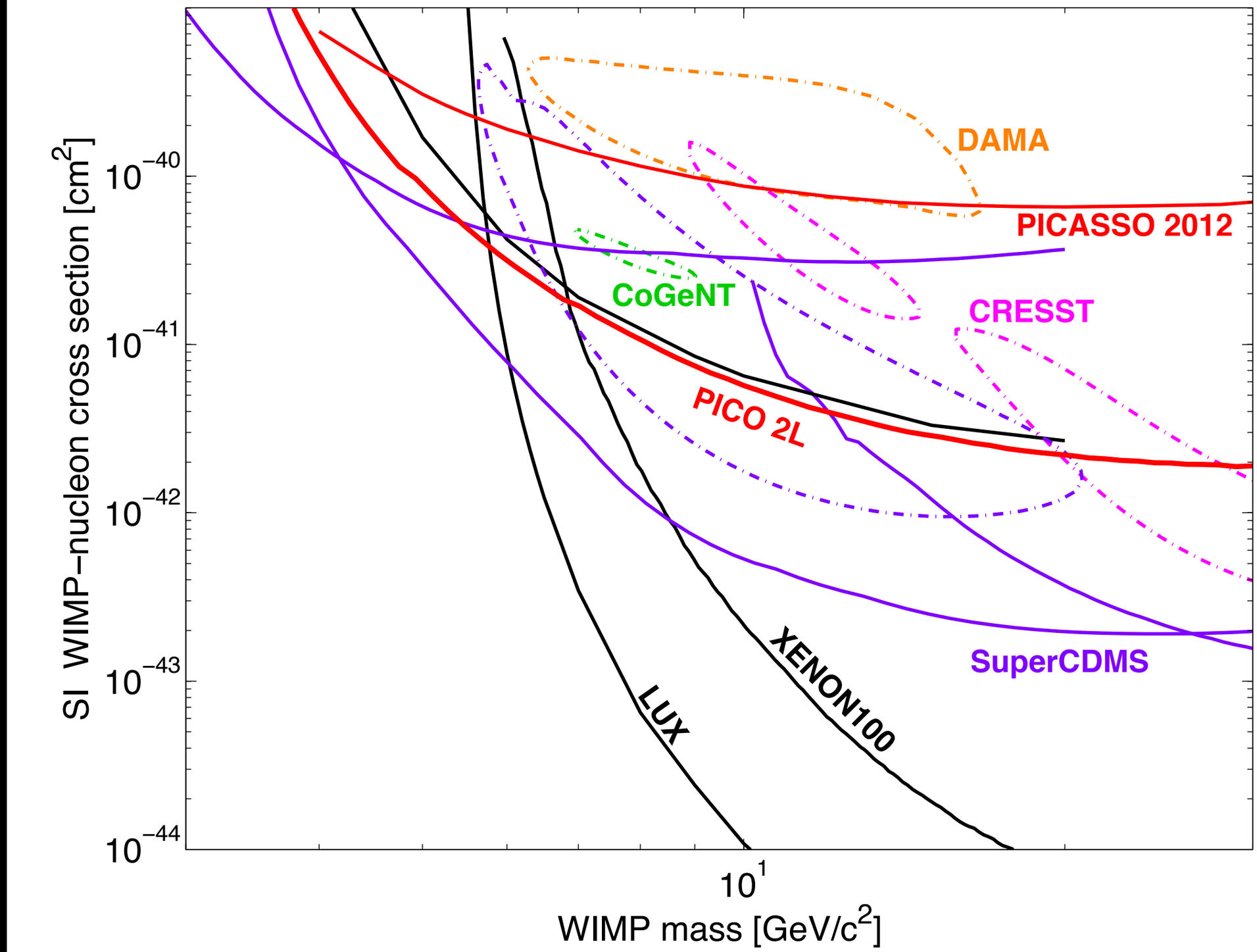


- This becomes a cut variable (method similar to optimum interval of Yellin, PRD 66,032005 (2002))

PICO-2L Results

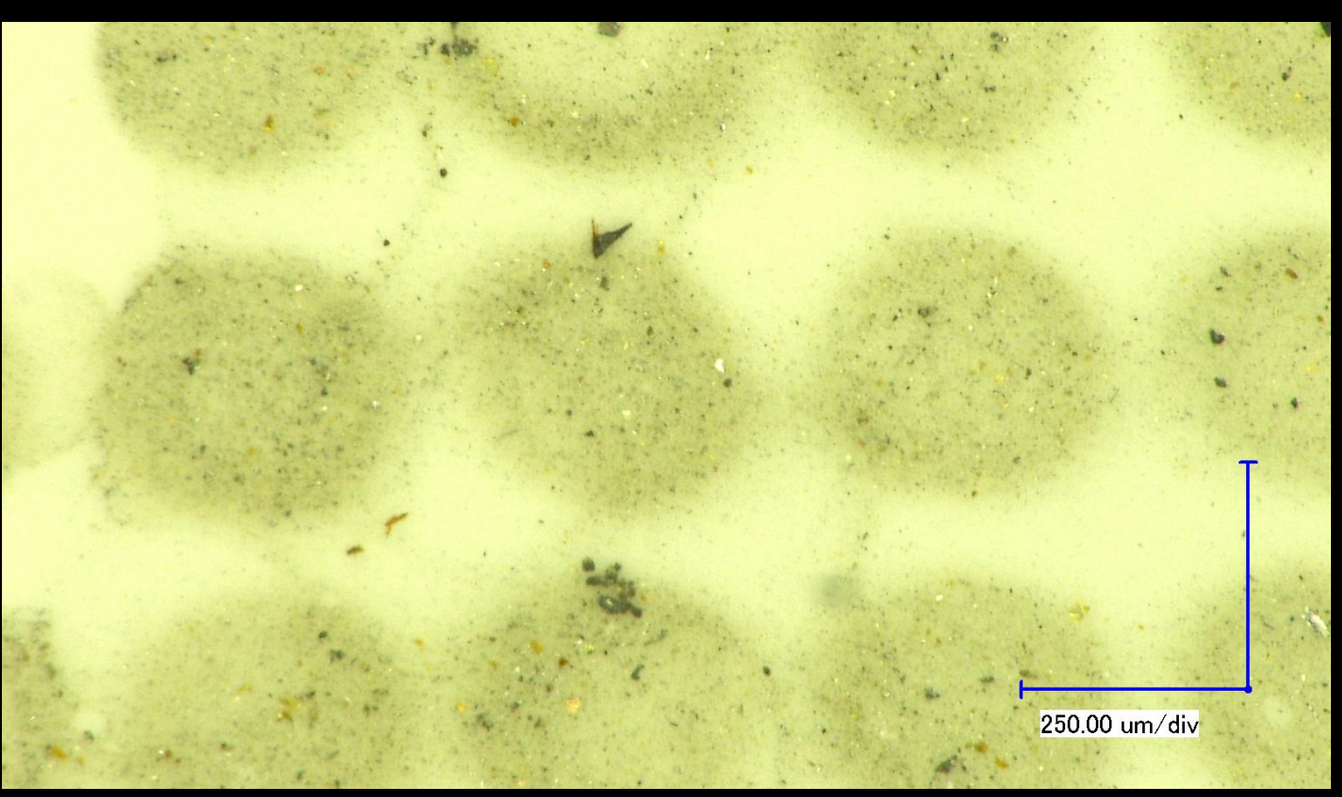


PICO-2L Results

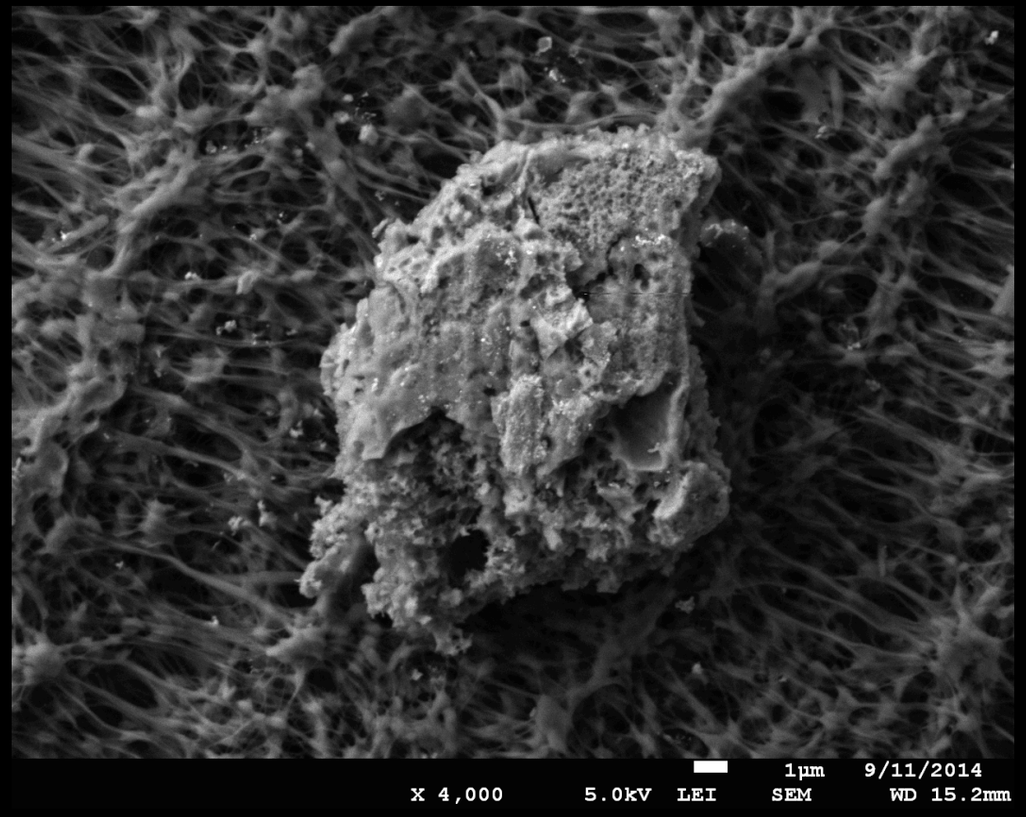


Background sources

- Leading hypothesis - particulate contamination
- In the middle of large assay program
  - XRF identified several contaminants in filters (SS, quartz, gold)
  - ICPMS has found enough thorium to explain PICO-2L rate



Filter sample from PICO-2L



SEM image of particulate

Understanding our backgrounds

- Is it particulates (or some other contaminant)?
  - Test chambers, particulate spikes

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  - Improved cleaning processes and QA (new run of PICO-2L about to begin)
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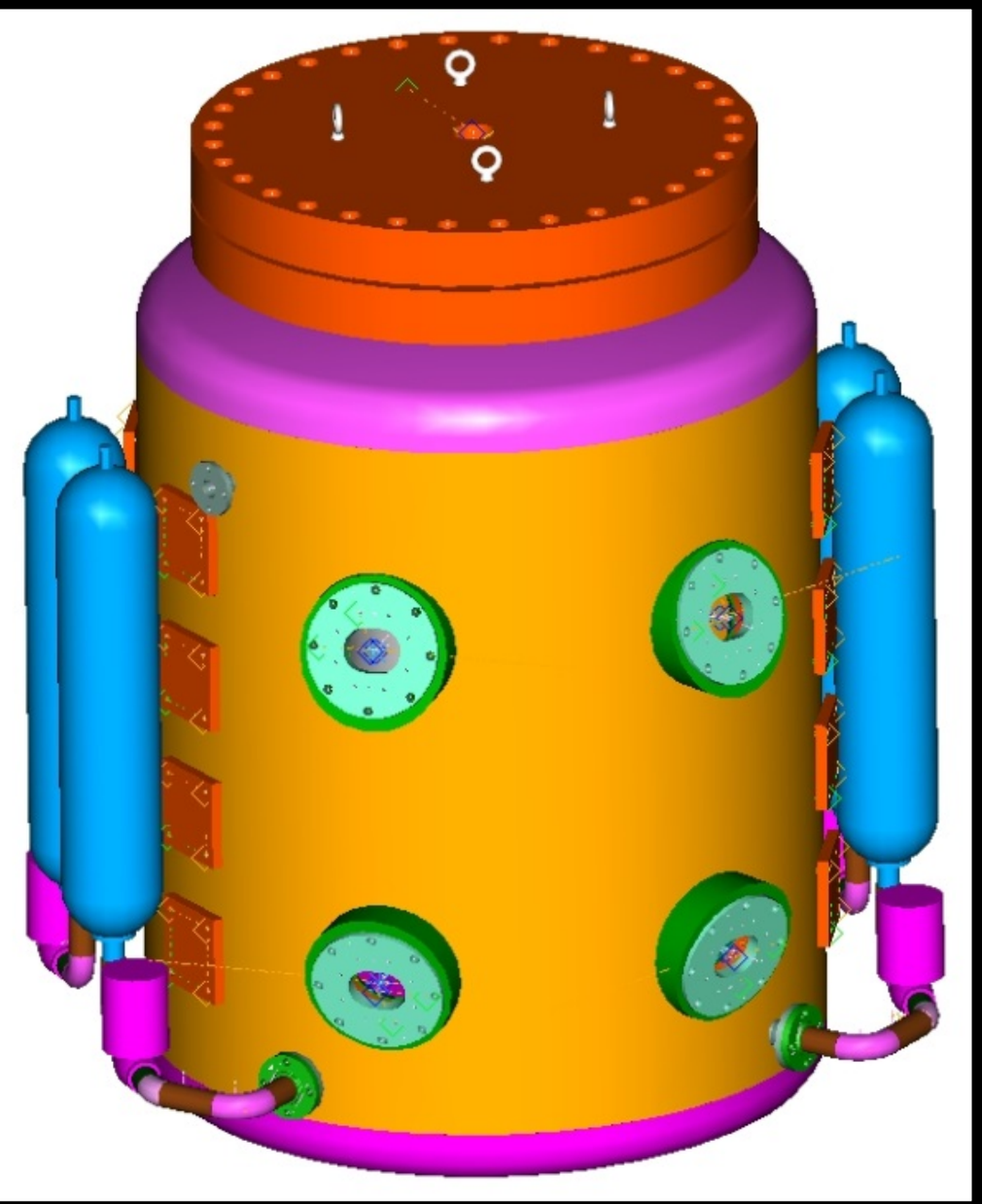
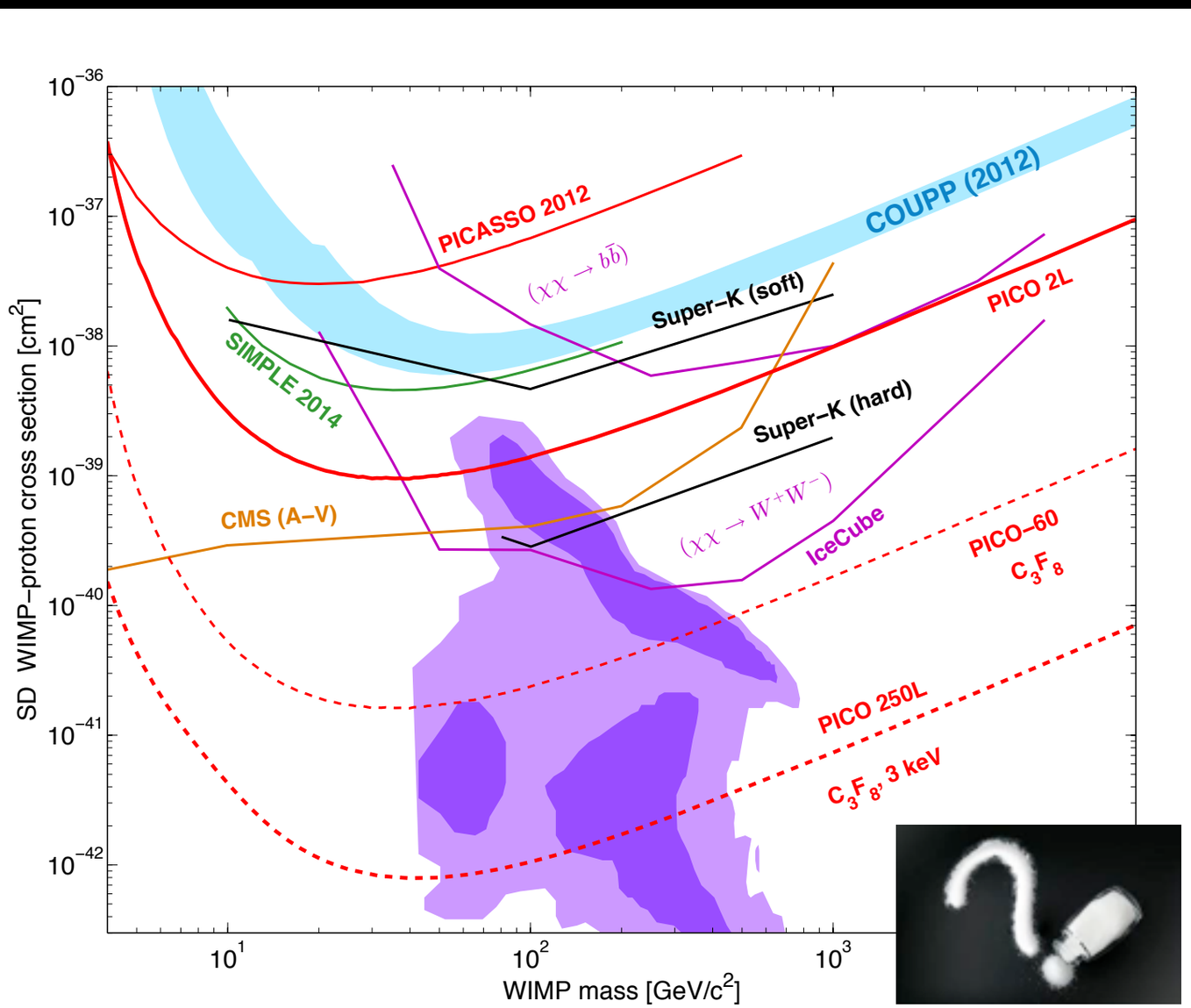
- Can we prevent it from getting in to the target?
  - Improved cleaning processes and QA (new run of PICO-2L about to begin)
  - Exploring small design modifications to isolate active fluid
- Can we filter it out of the target?
  - In-situ filtration in PICO60
  - Eliminating buffer fluid would make filtration easier...

PICO-250L

- Straightforward scale up of existing PICO-2L and PICO60 detectors

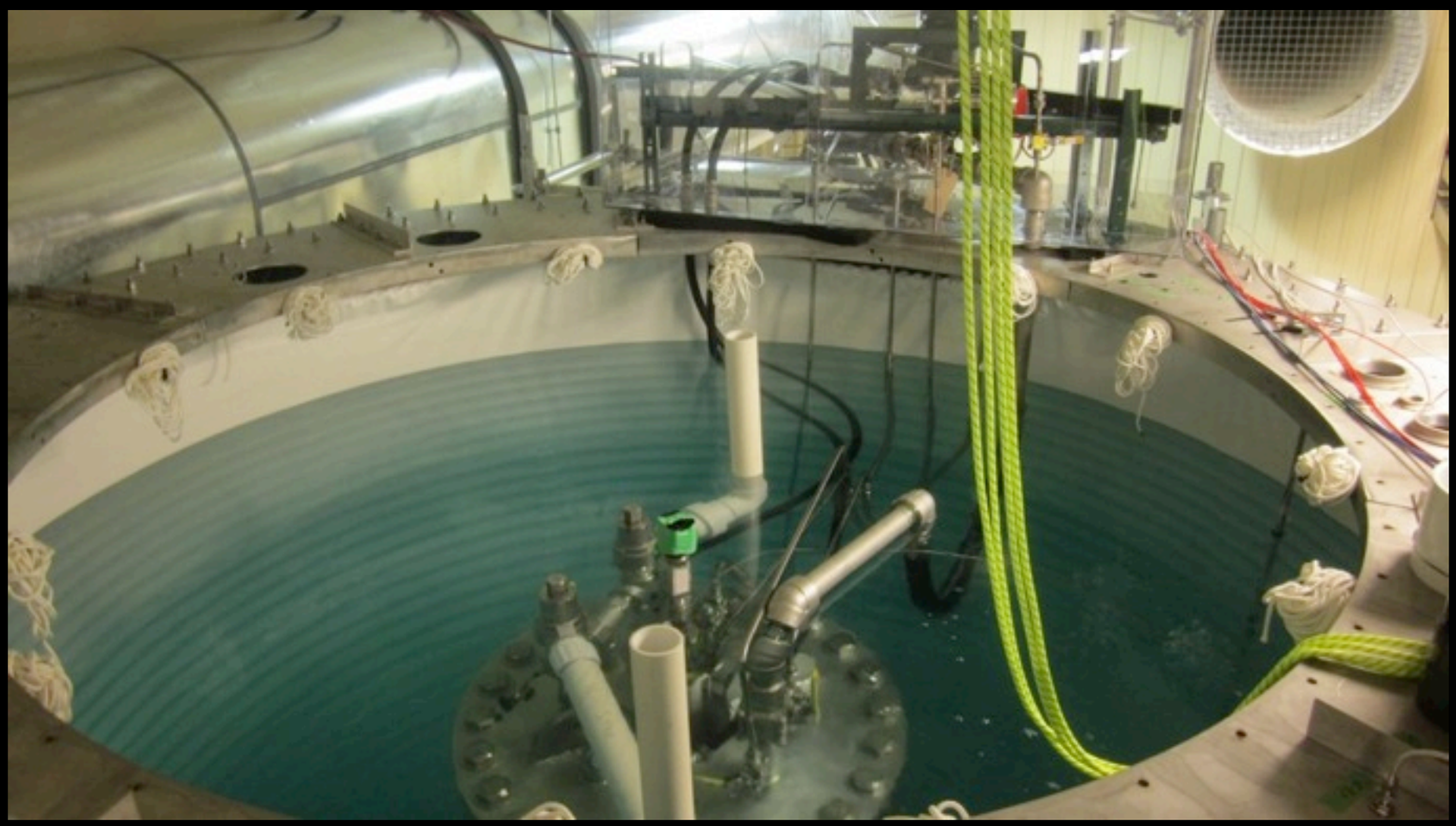


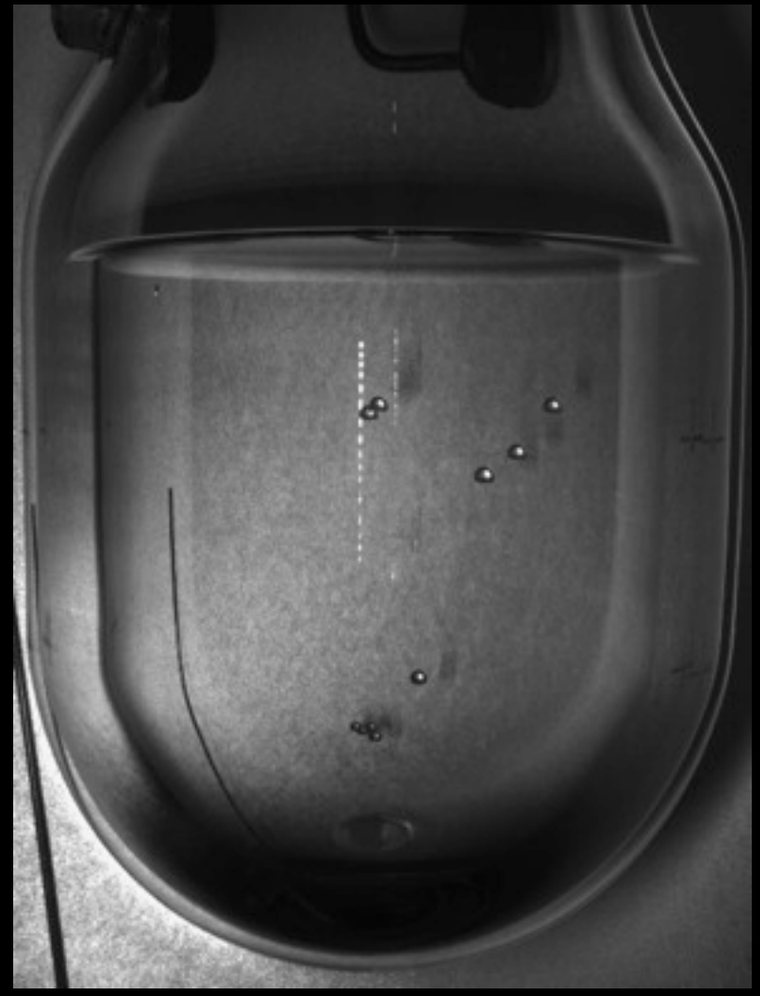
- Begin with C_3F_8 to maximize discovery potential (SD and low masses)
- Retain flexibility to respond to developments in the field - switch targets!



Conclusion

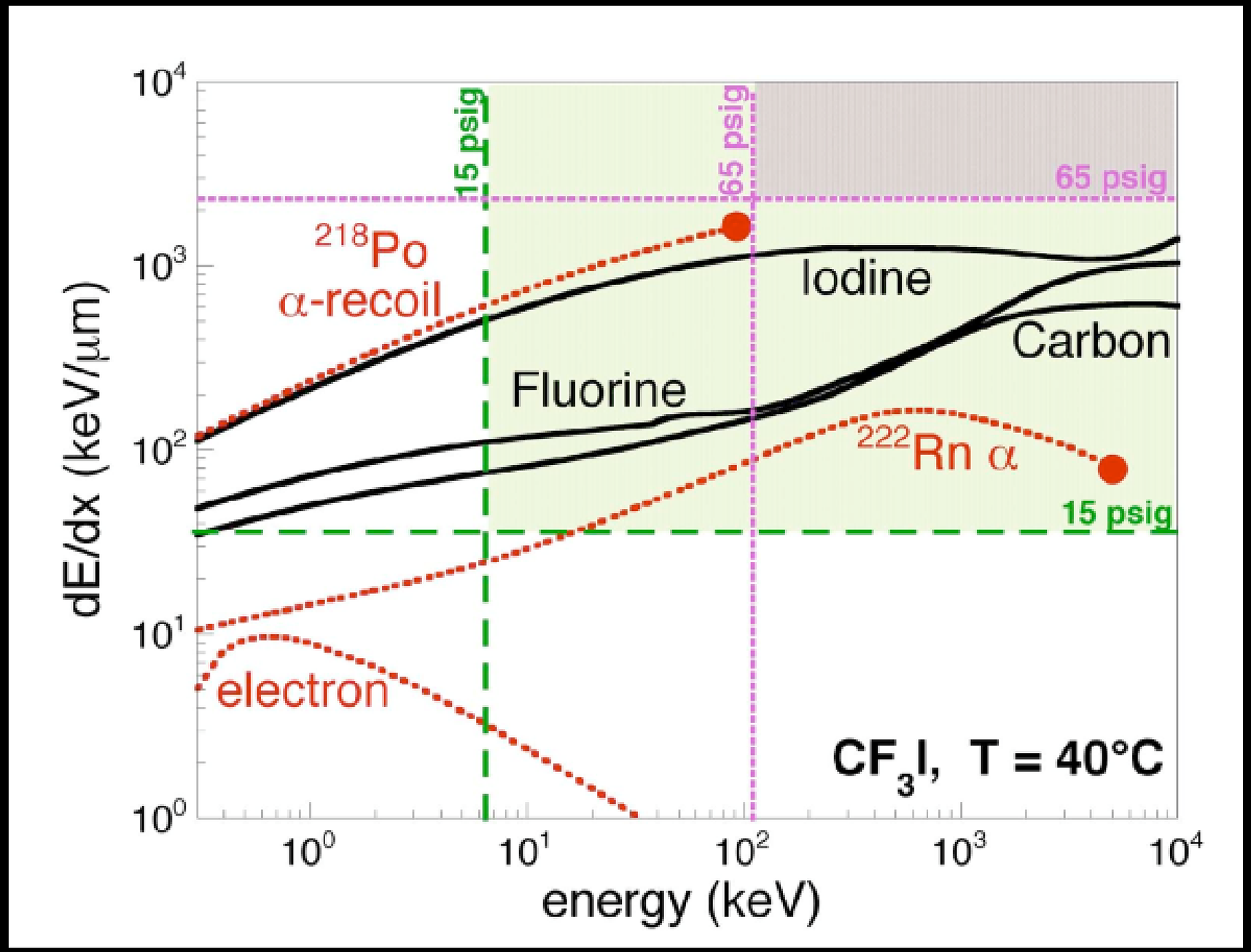
- PICO is producing the best direct detection limits on spin-dependent dark matter, with competitive sensitivity in SI channels
- The dark matter field (including PICO) makes orders of magnitude gains every few years, but we still don't know the answer
- PICO should play a unique role in the hunt for dark matter, but we have work to do before we are ready for the next stage



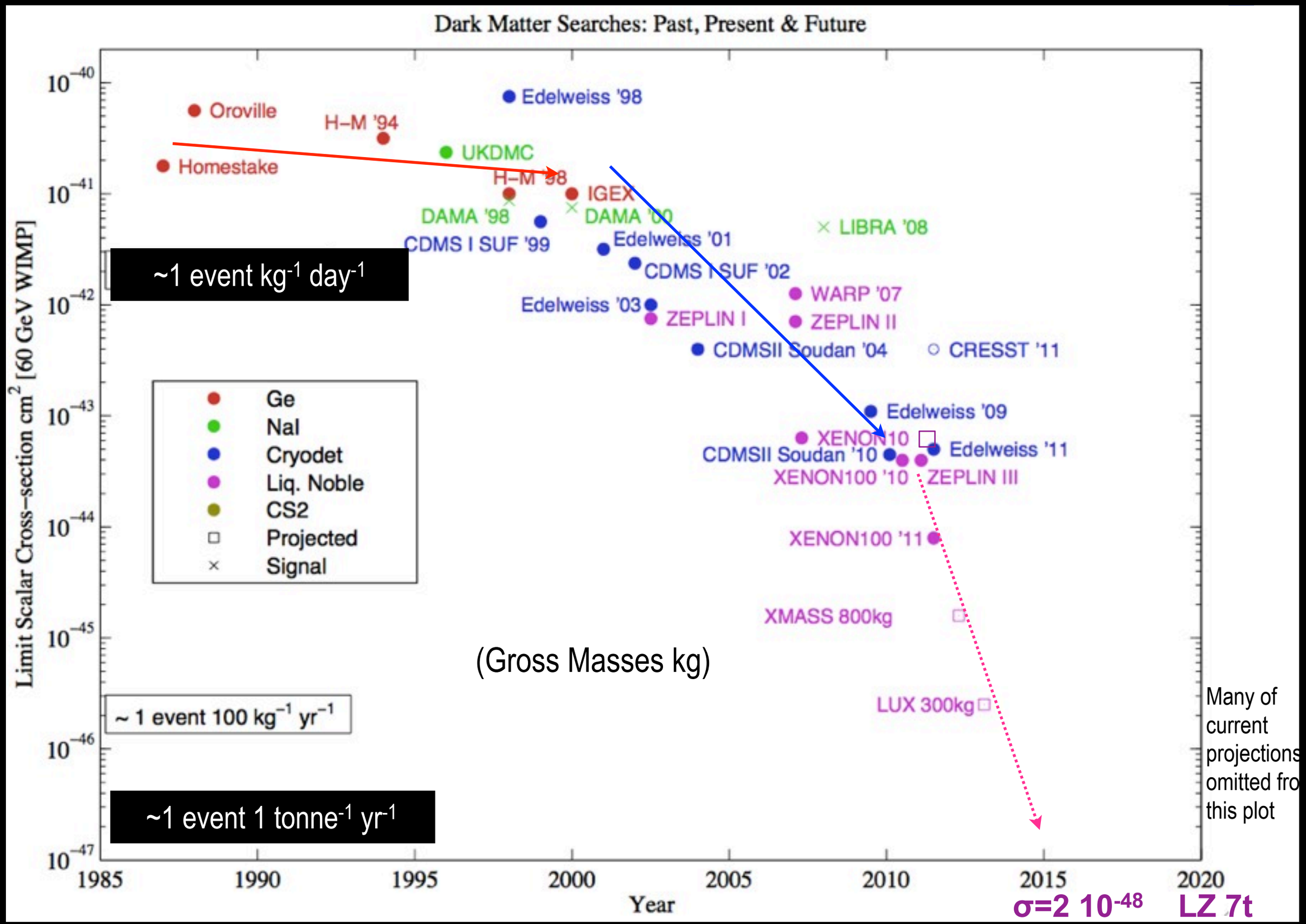


End

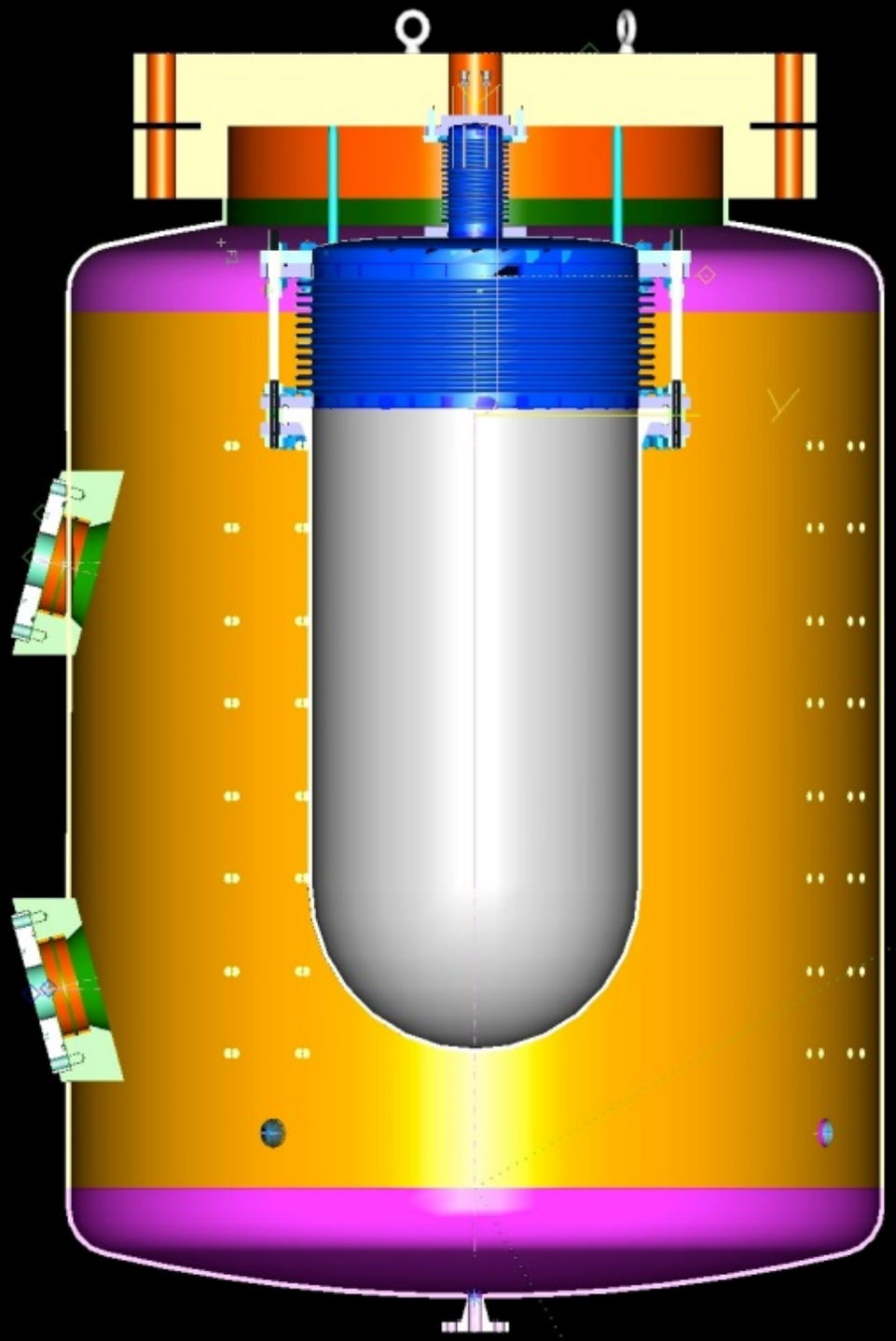
Why bubble chambers?



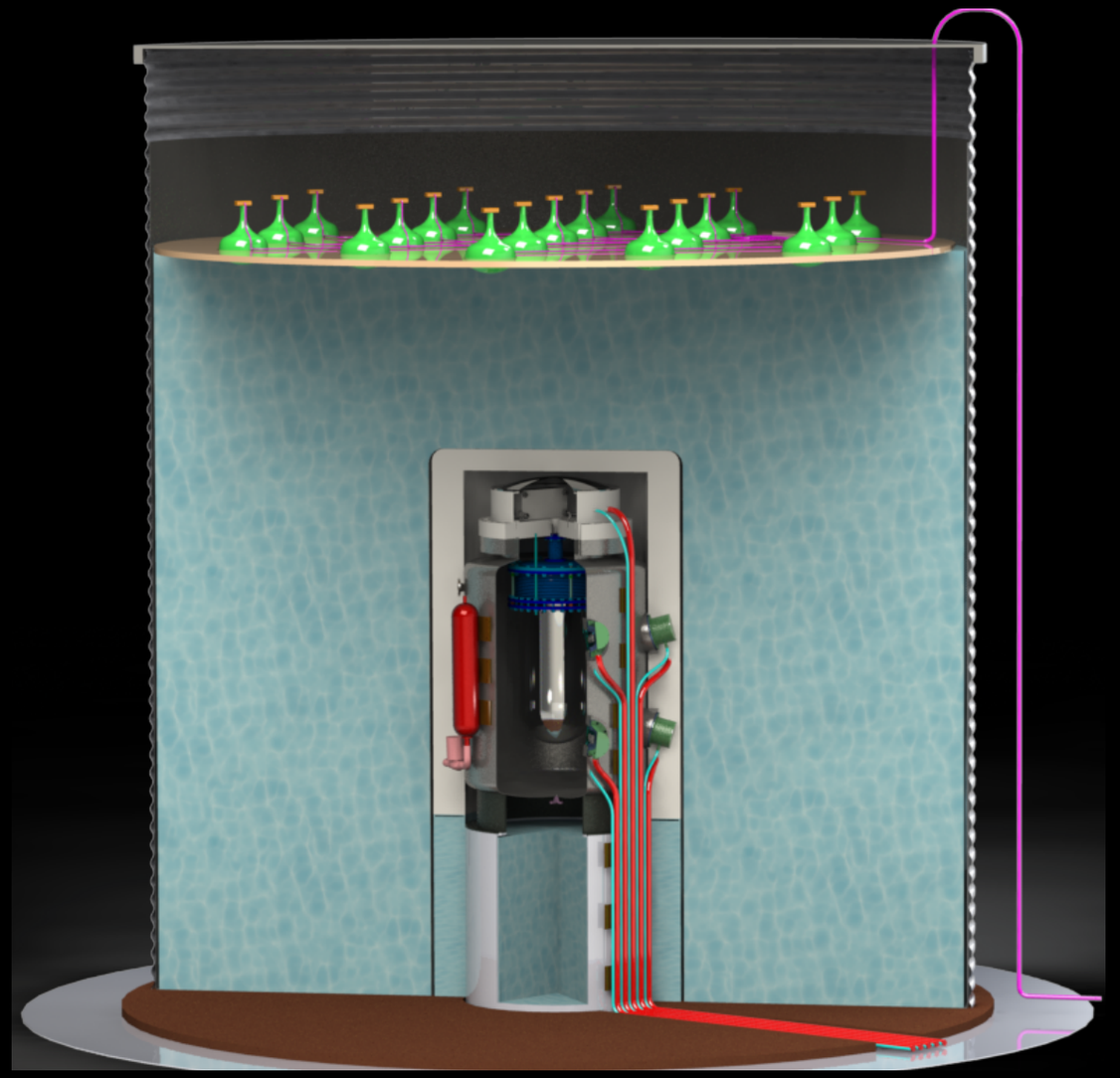
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-CF3I
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
SuperCDMS SNOLAB
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4


Dark Matter Searches: Past, Present & Future
Limit Scalar Cross−section cm^2 [60 GeV WIMP]
Year
Oroville
H–M '94
Homestake
UKDMC
H–M '98
IGEX
DAMA '98
DAMA '00
CDMS I SUF '99
Edelweiss '98
Edelweiss '01
CDMS I SUF '02
LIBRA '08
WARP '07
ZEPLIN II
Edelweiss '03
ZEPLIN I
CDMSII Soudan '04
CRESST '11
Edelweiss '09
XENON10
CDMSII Soudan '10
Edelweiss '11
XENON100 '10
ZEPLIN III
XENON100 '11
XMASS 800kg
LUX 300kg
~1 event kg^{-1} day^{-1}
Ge
NaI
Cryodet
Liq. Noble
CS2
Projected
Signal
(Gross Masses kg)
~ 1 event 100 kg^{-1} yr^{-1}
~1 event 1 tonne^{-1} yr^{-1}
σ=2 10^{-48}
LZ 7t
Many of current projections omitted fro this plot

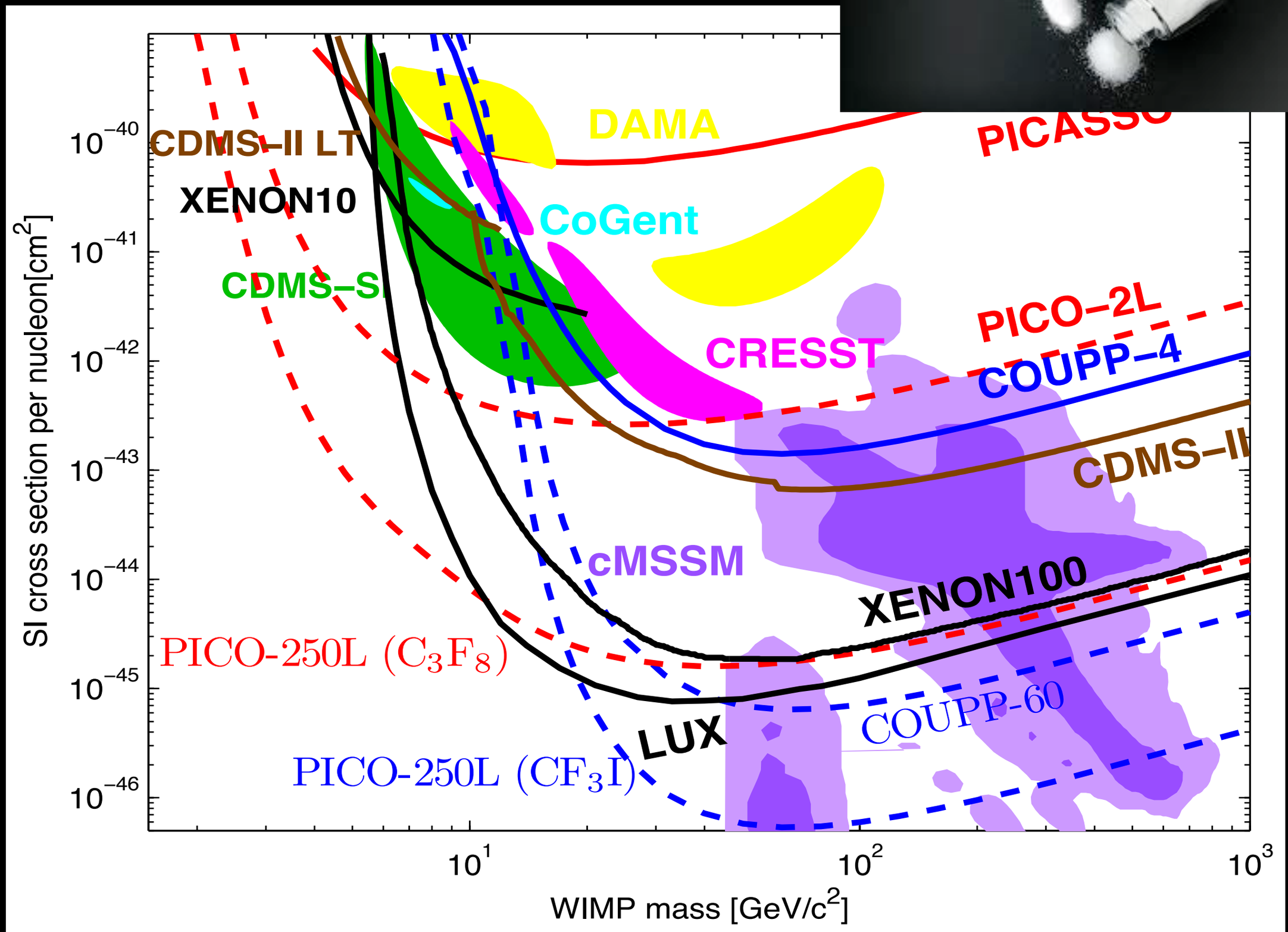
PICO-250L



- Funded by NSF and DOE as part of G2 Dark Matter but not ultimately chosen
- Engineering well underway

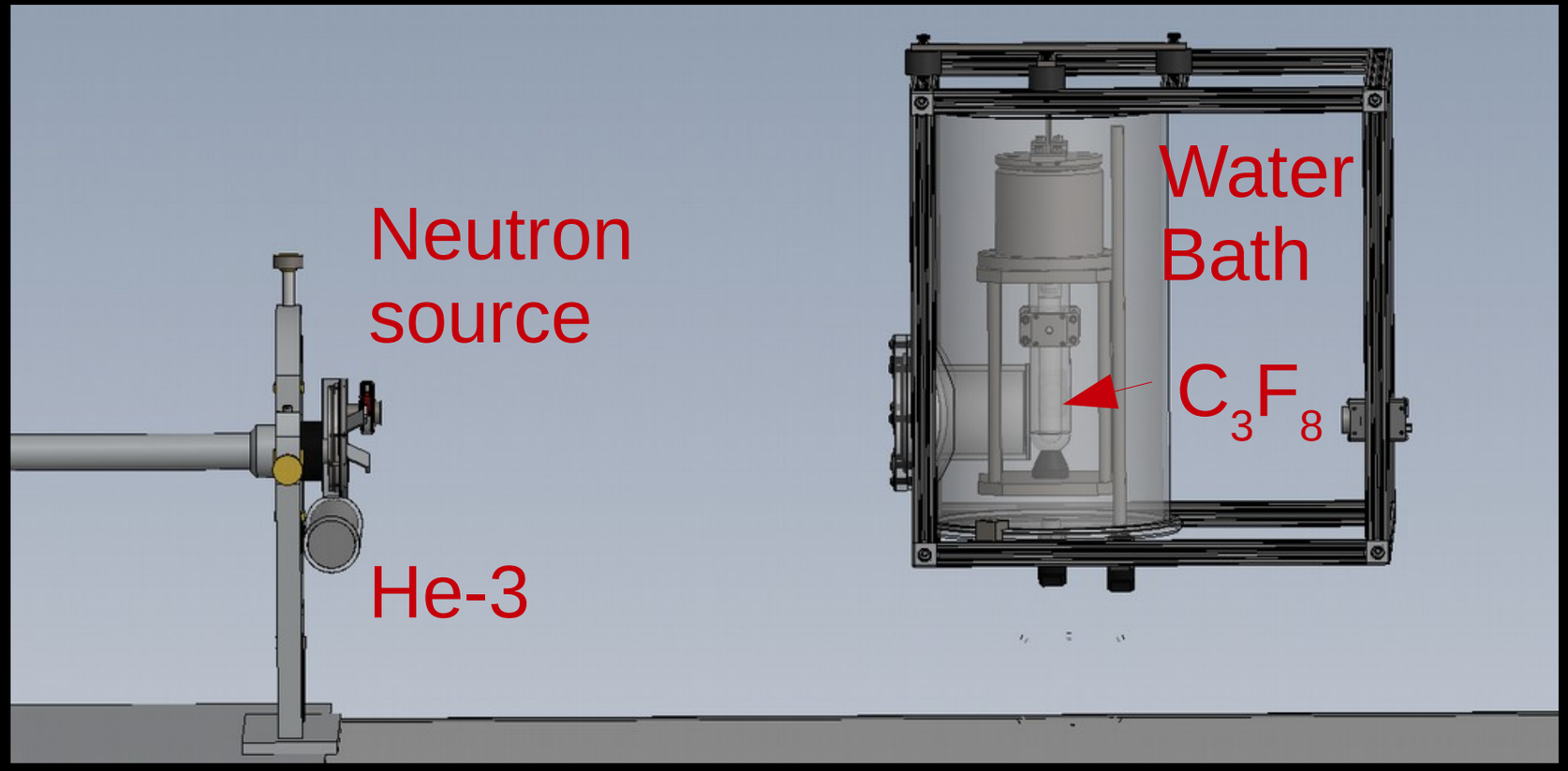


Projections



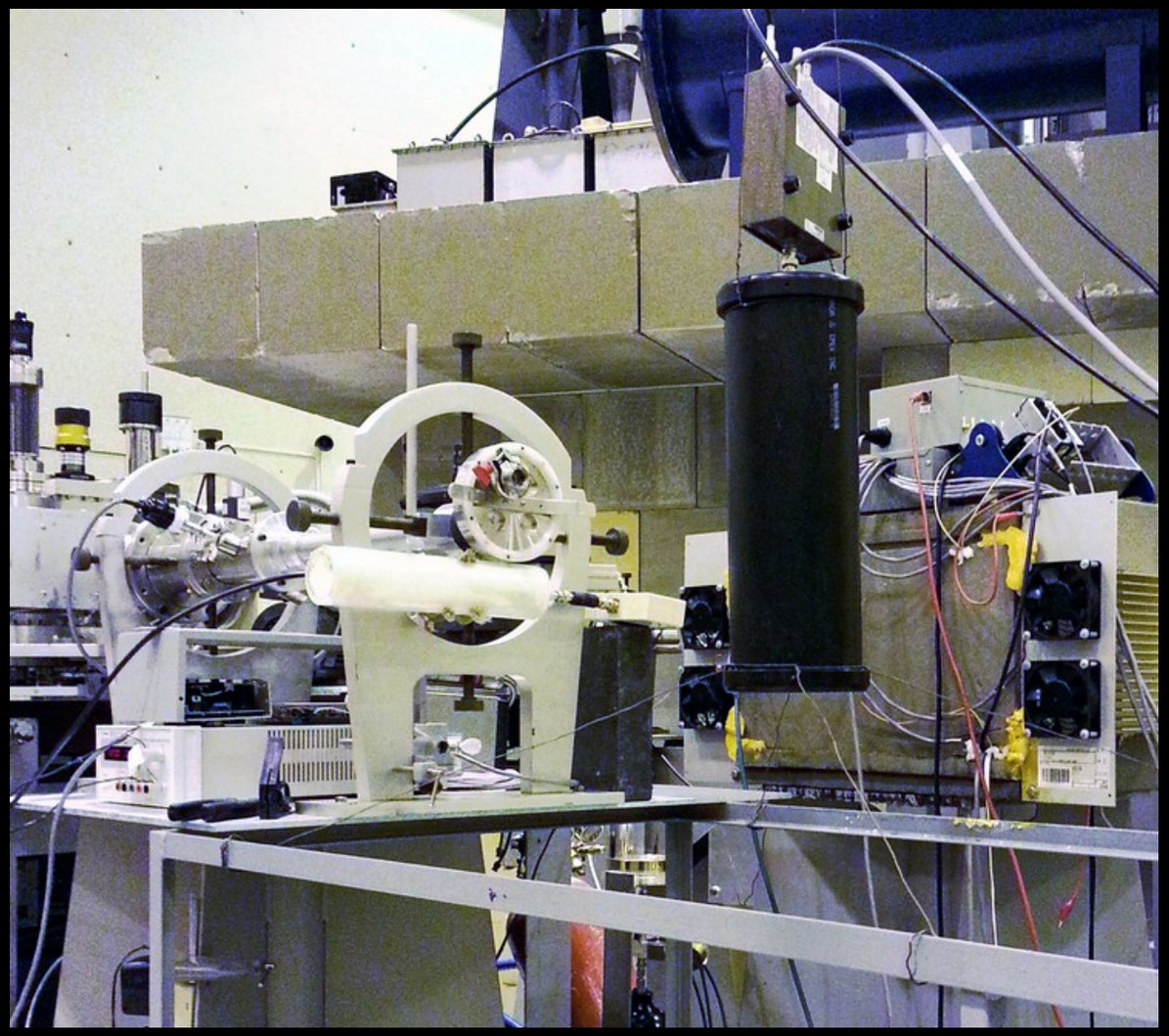
Neutron beam calibration

- Neutrons at 61 & 97 keV → 12 & 20 keV $E_{r,max}$
- Material between source and C_3F_8 minimized.



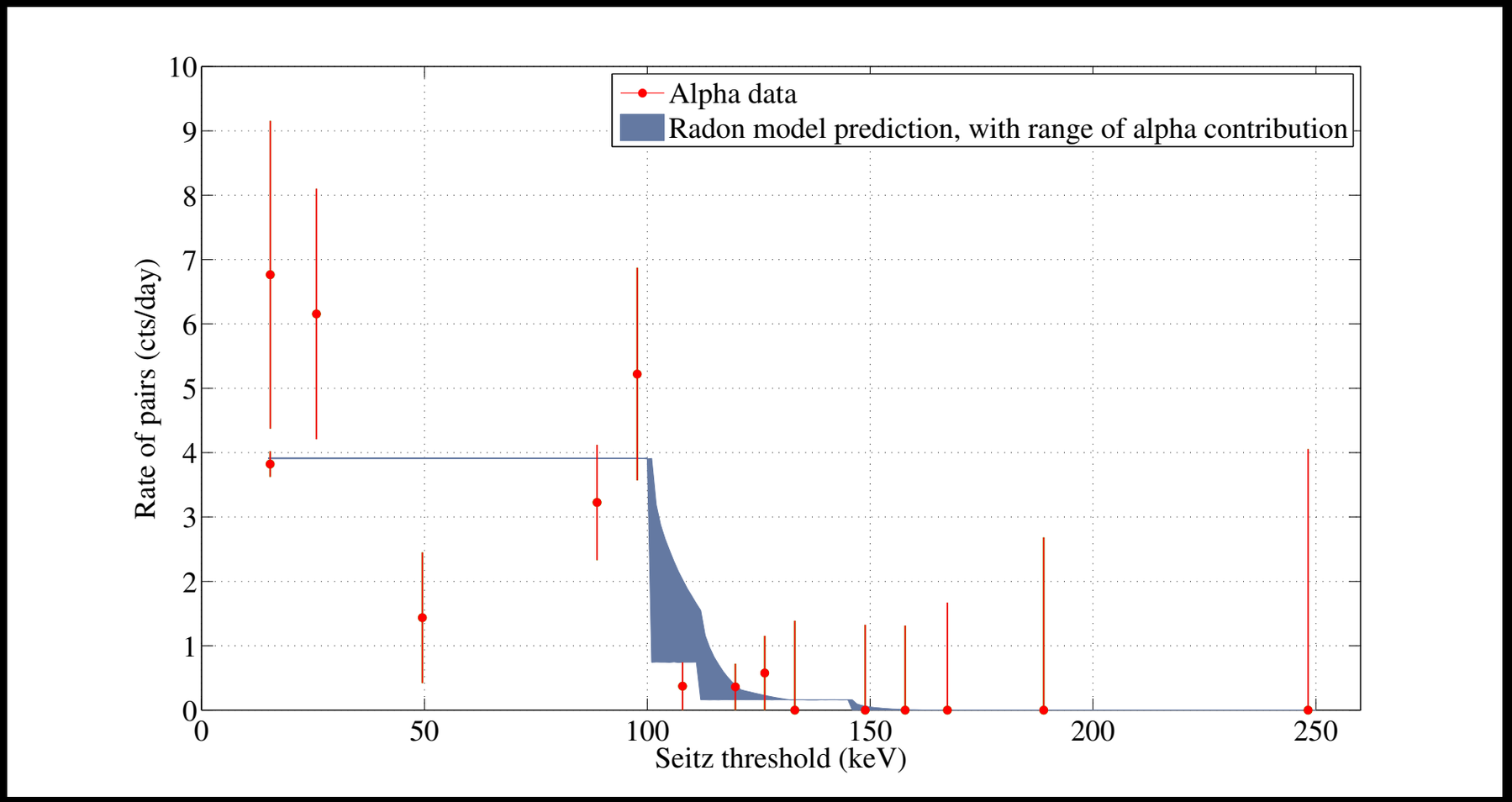
Neutron Beam Calibration

- Results normalized to He-3 at 90° to beam end.
- Cross-calibrated with 2nd He-3 in forward direction.
- Detailed neutron propagation simulations find < 10% total rate uncertainty.



What about iodine?

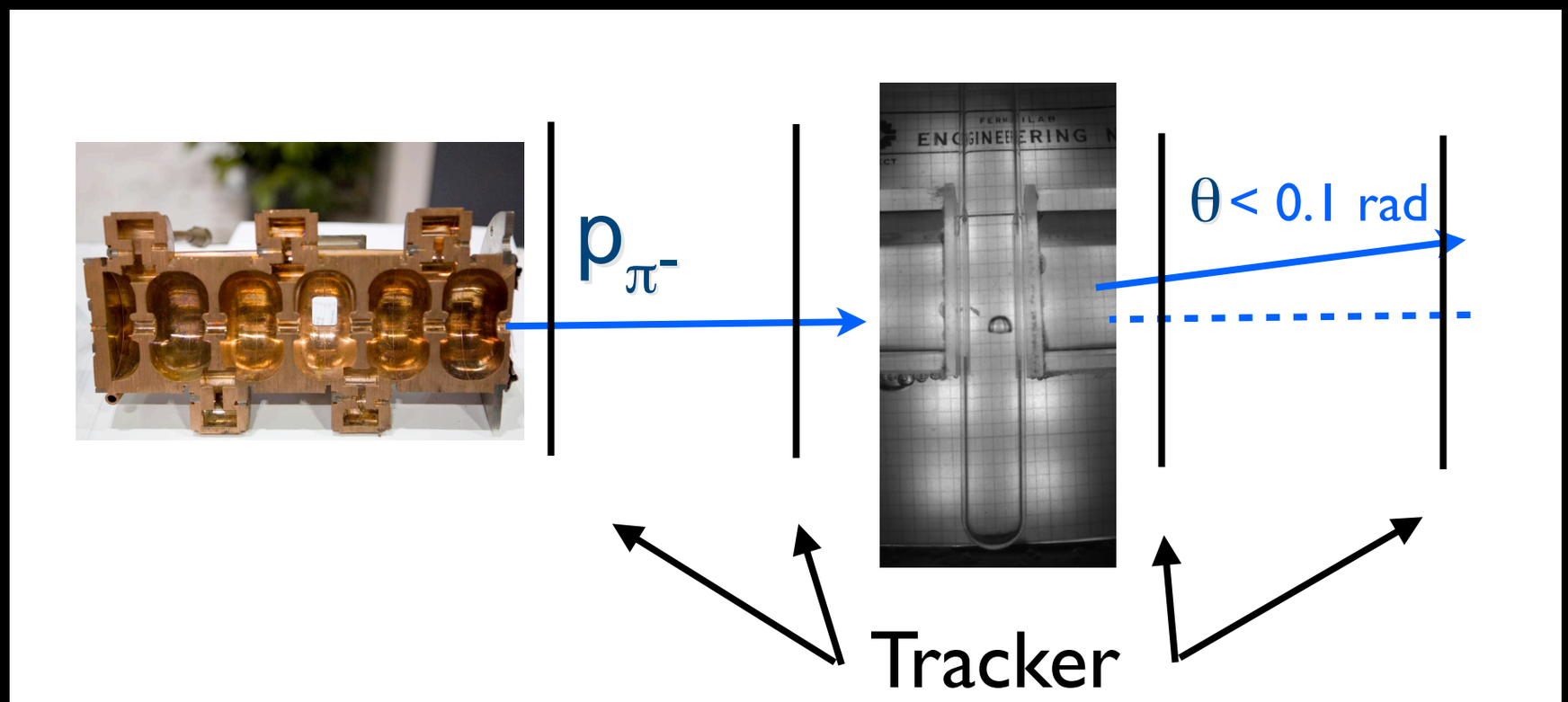
- Main sensitivity to spin independent dark matter from iodine
  - 85% of neutron source interactions are with C and F
- Heavy radon daughter nuclei are a proxy and are step-like



- We really need a direct calibration

COUPP Iodine Recoil Threshold Experiment

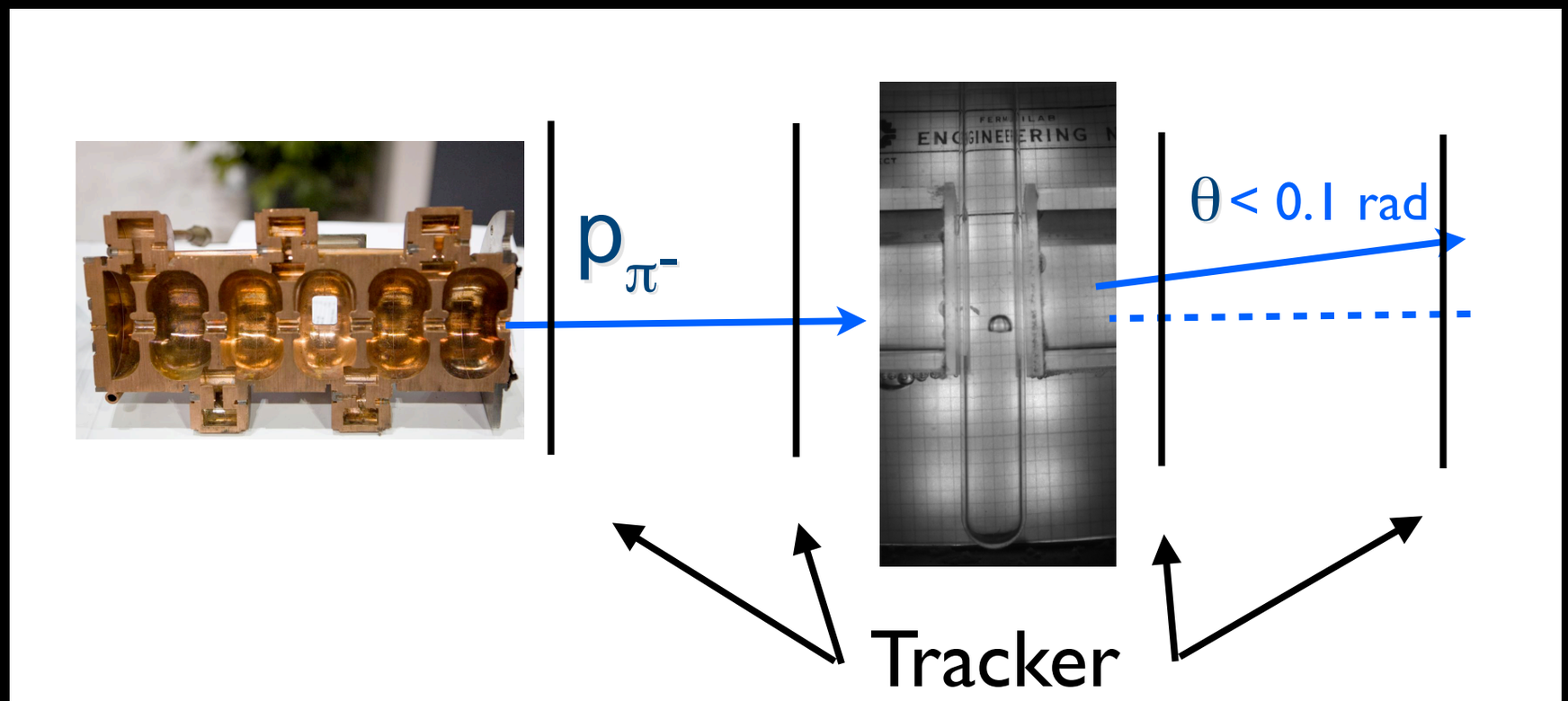
- Bubble chambers are insensitive to MIPs
  - Elastic scattering of charged particles can be tracked with very high precision



$$T = E_{recoil} = \frac{(p\theta)^2}{2m_r}$$

COUPP Iodine Recoil Threshold Experiment

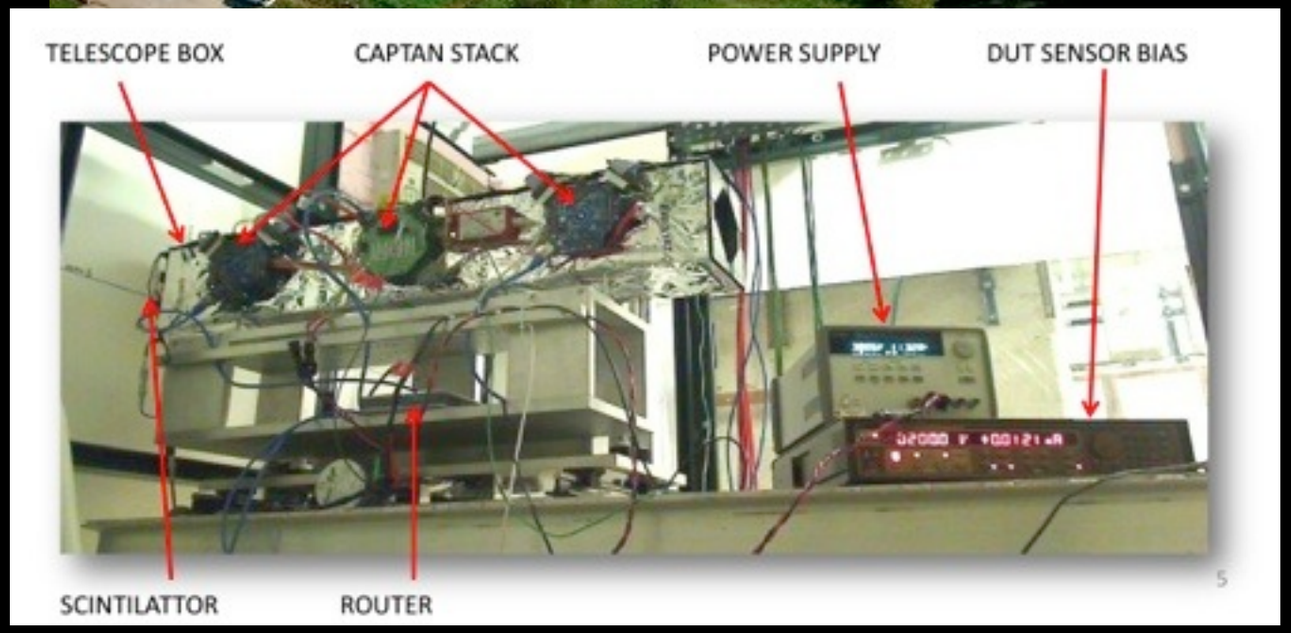
- Provides event by event energy information bubble chambers normally can't provide
- 75% of elastic scattering events with 12 GeV pions at energies relevant to dark matter involve iodine



$$T = E_{recoil} = \frac{(p\theta)^2}{2m_r}$$

COUPP Iodine Recoil Threshold Experiment

- Test beam at Fermilab with a silicon pixel telescope
- Designed a new test tube sized bubble chamber

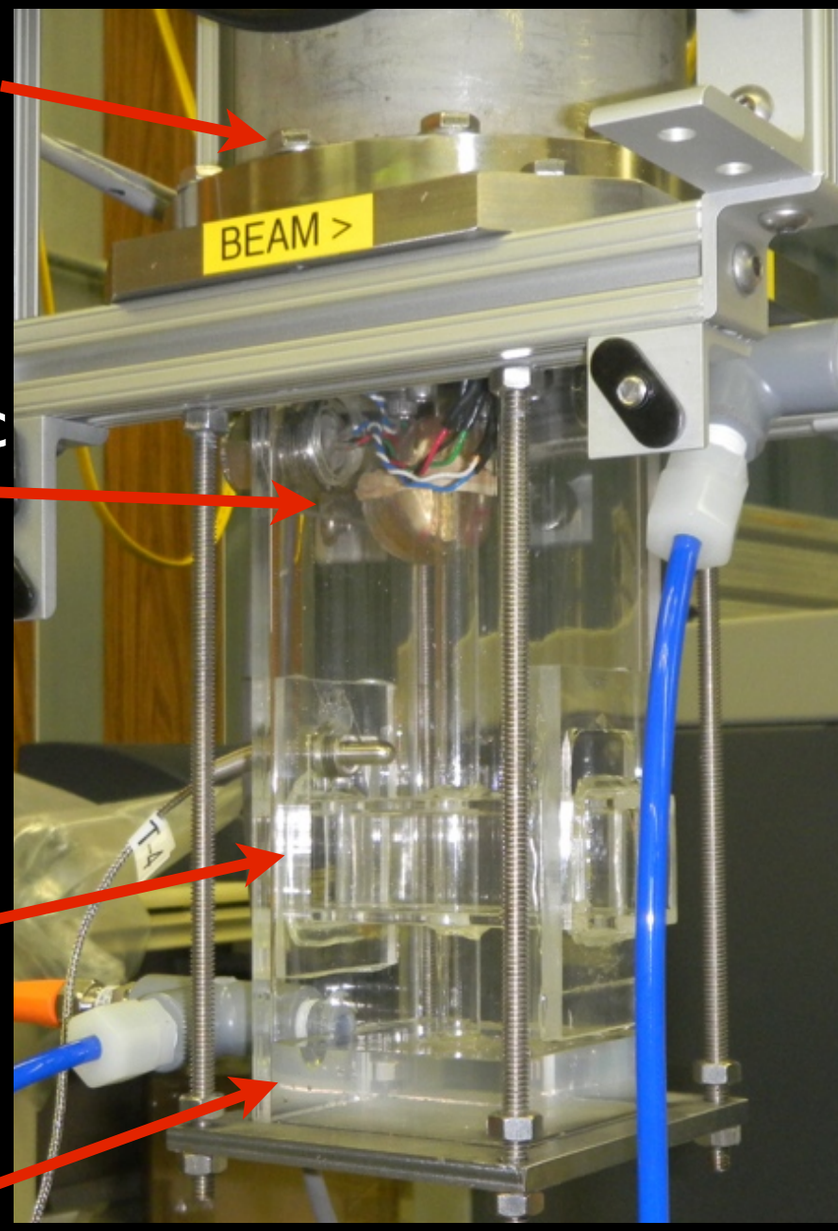


Hydraulics

Piezo-acoustic sensor

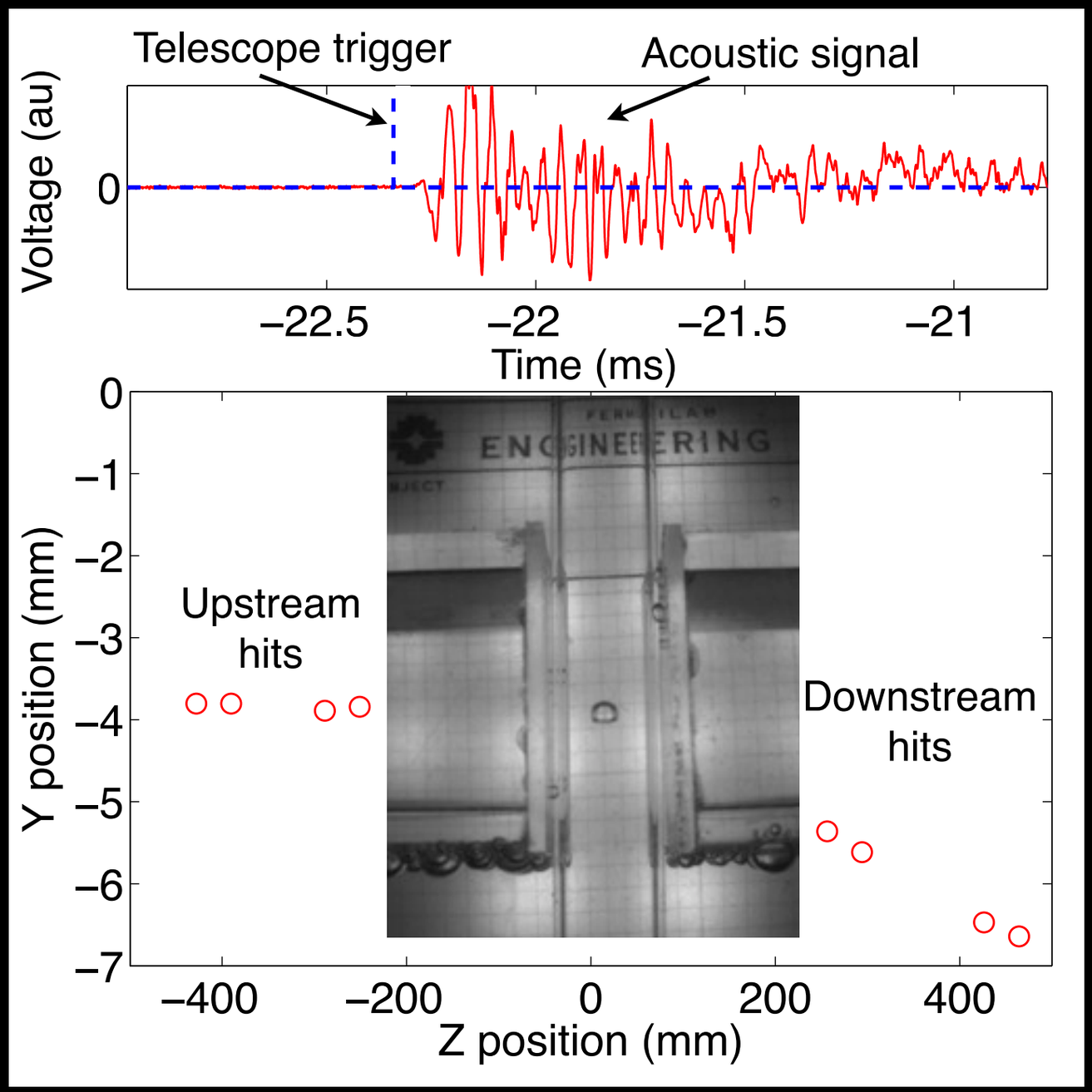
Beam tube

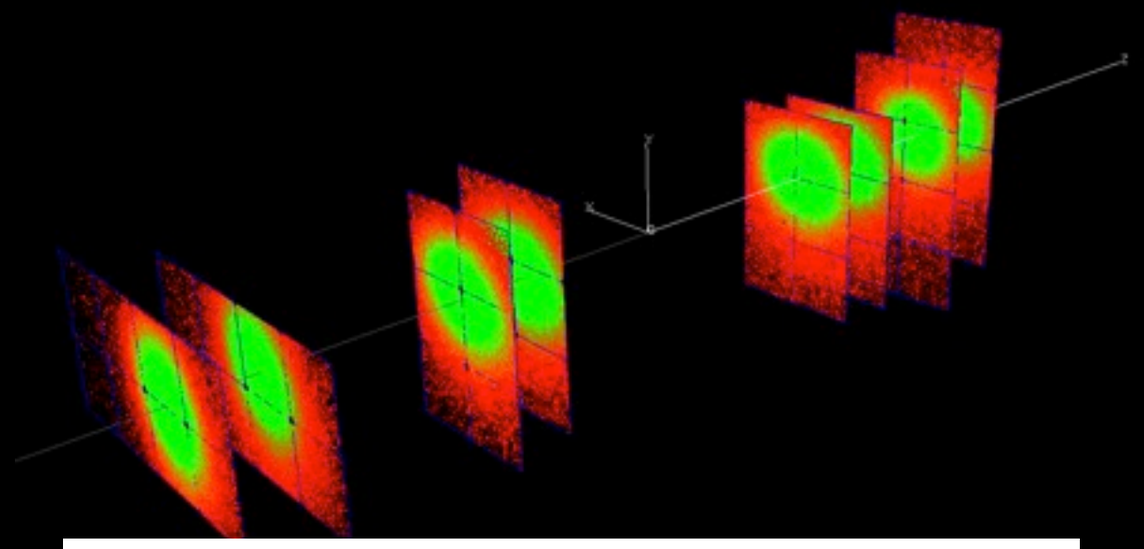
Water bath

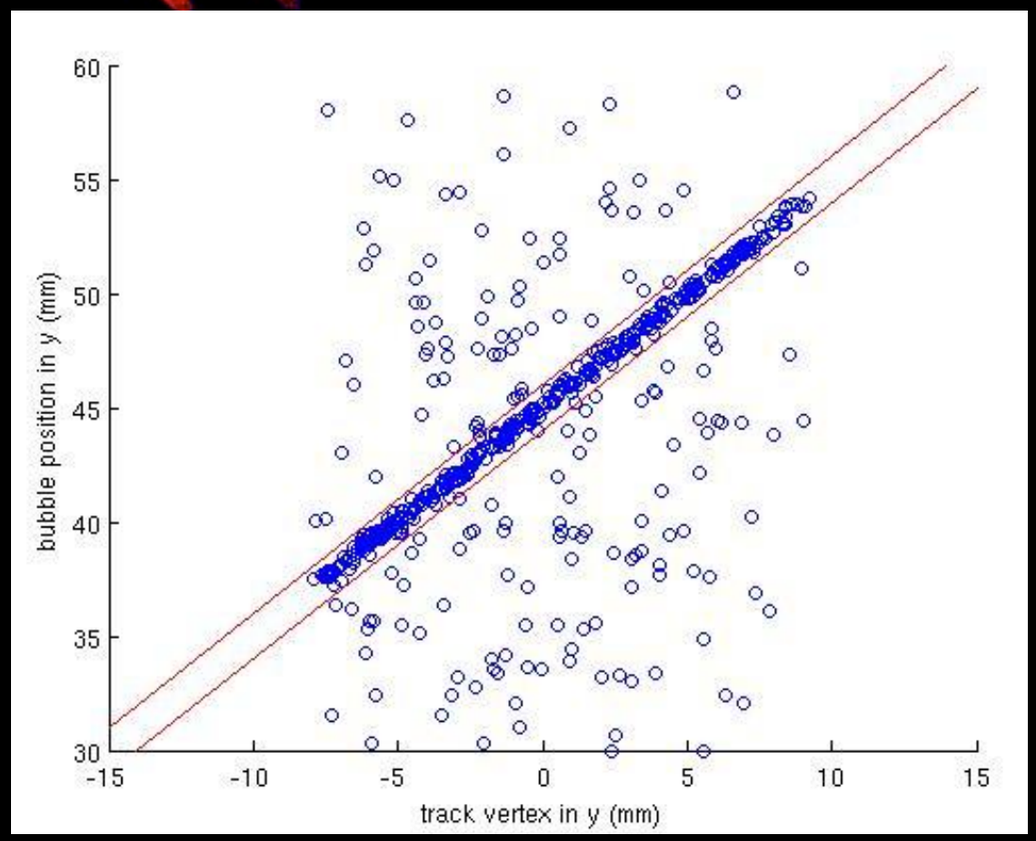


COUPP Iodine Recoil Threshold Experiment

- Beam run at Fermilab in March, 2012

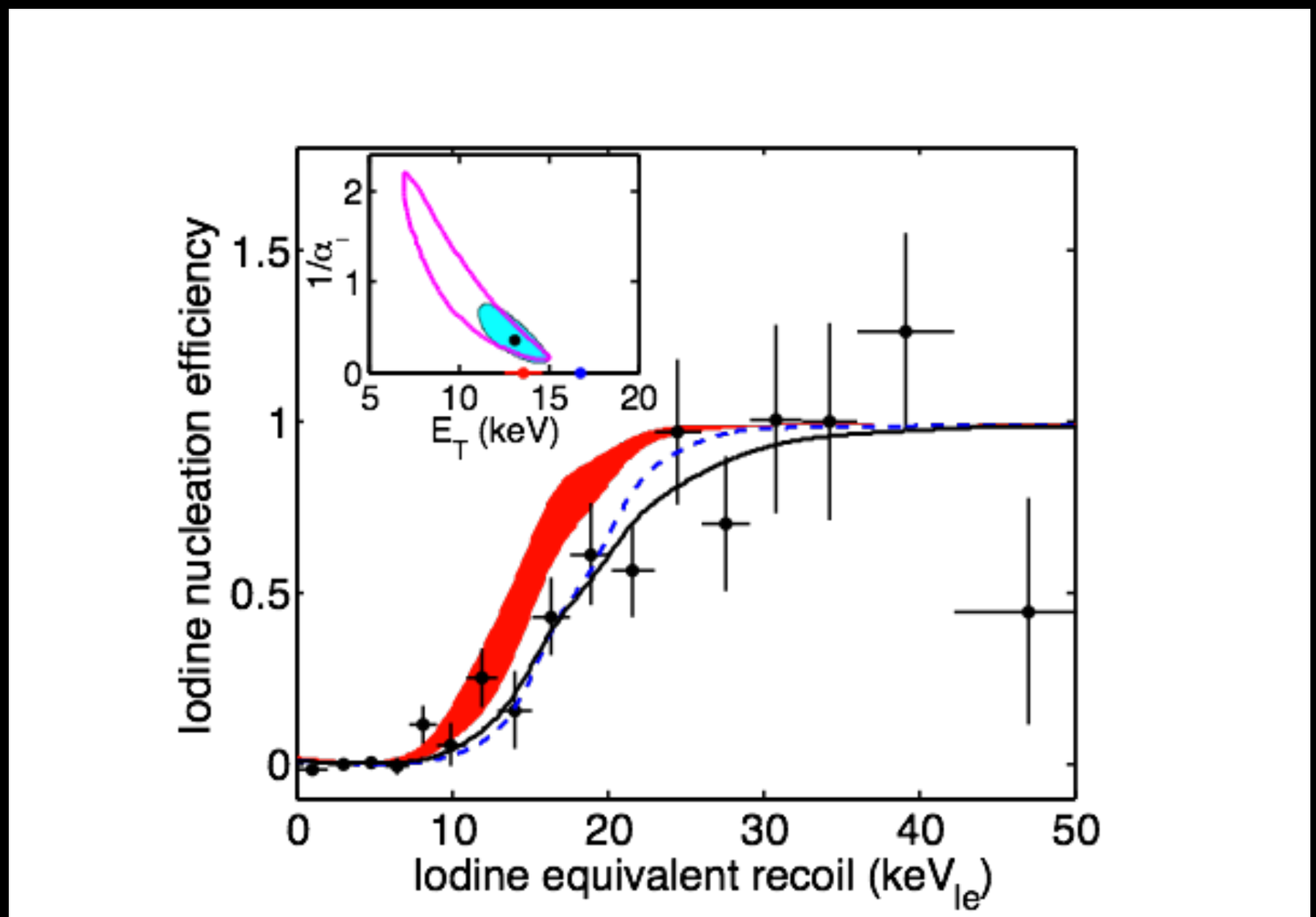






COUPP Iodine Recoil Threshold Experiment

- Analysis shows that iodine threshold is very close to a step function at the predicted energy (PRC 88:021101, 2013)
    - Limited by resolution (MCS) and statistics



Background sources

- XRF has identified many components chemically
  - Stainless steel
  - Quartz
  - Gold (from seal)
  - Silver (VCR parts?)