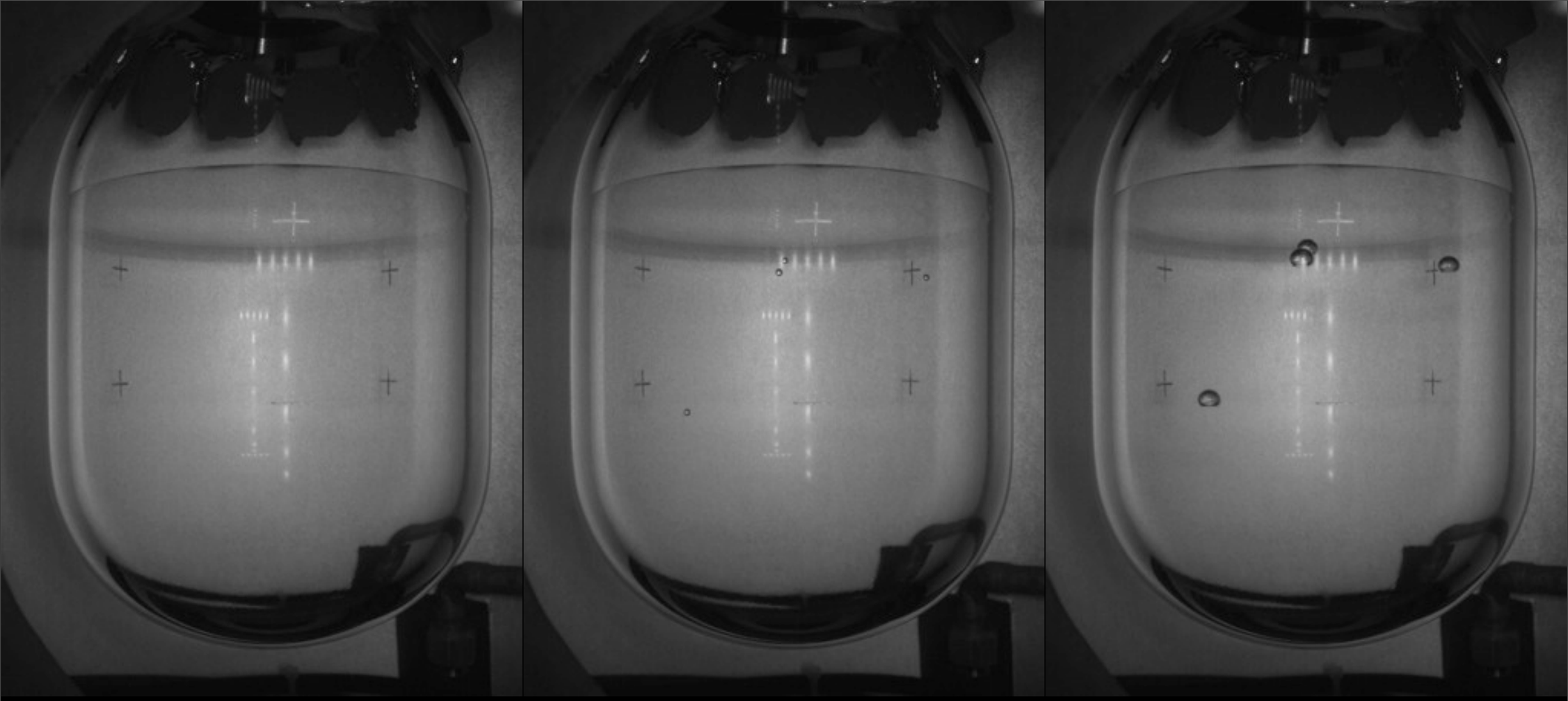

Searching for Dark Matter with Bubble Chambers

Hugh Lippincott, Fermilab

Yale University, WIDG
April 29, 2014

Weak Interaction Discussion Group History

- I was around for the founding WIDG
- I think I gave the second WIDG ever on the Klapdor 0vBB claim in January 2005
  - 8 out of 11 slides were all text
- This is my 9th

PICO Collaboration

Queen's University
C. Amole, M. Besnier, G. Caria, A. Kamaha, A. Noble, T. Xie

Universitat Politècnica de València
M. Ardid, M. Bou-Cabo

Pacific Northwest National Laboratory
D. Asner, J. Hall

Northwestern University
D. Baxter, C.E. Dahl, M. Jin

Indiana University South Bend
E. Behnke, H. Borsodi, C. Harnish, O. Harris, C. Holdeman, I. Levine, E. Mann, J. Wells

Saha Institute of Nuclear Physics, Calcutta
P. Bhattacharjee, M. Das, S. Seth

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

Kavli Institute for Cosmological Physics at the University of Chicago
J.I. Collar, R. Neilson, A.E. Robinson

Université de Montréal
F. Debris, M. Fines-Neuschild, C.M. Jackson, M. Lafrenière, M. Laurin, L. Lessard, J.-P. Martin, M.-C. Piro, A. Plante, O. Scallon, N. Starinski, V. Zacek

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

Czech Technical University in Prague
R. Filgas, S. Pospisil, I. Stekl

University of Alberta
S. Gagnebin, C. Krauss, D. Marlisov, P. Mitra

Virginia Tech
D. Maurya, S. Priya

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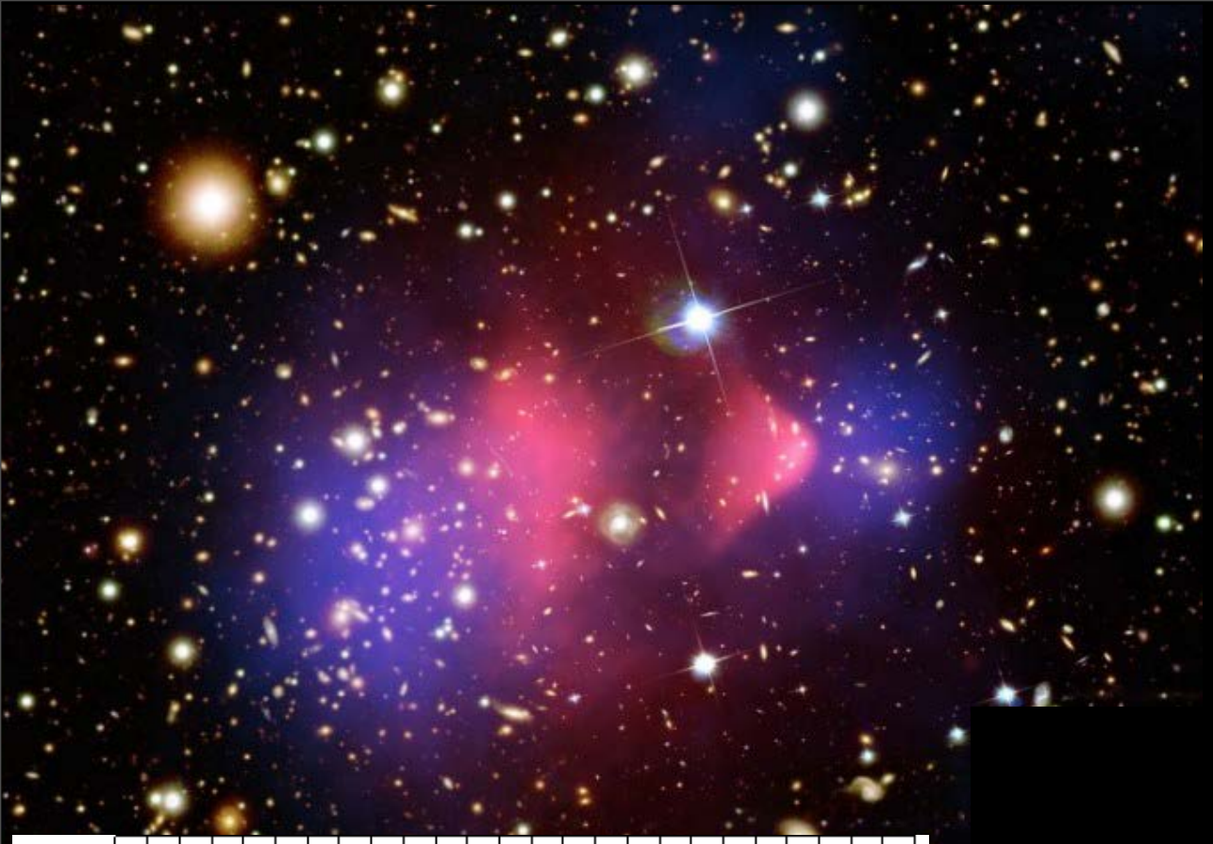
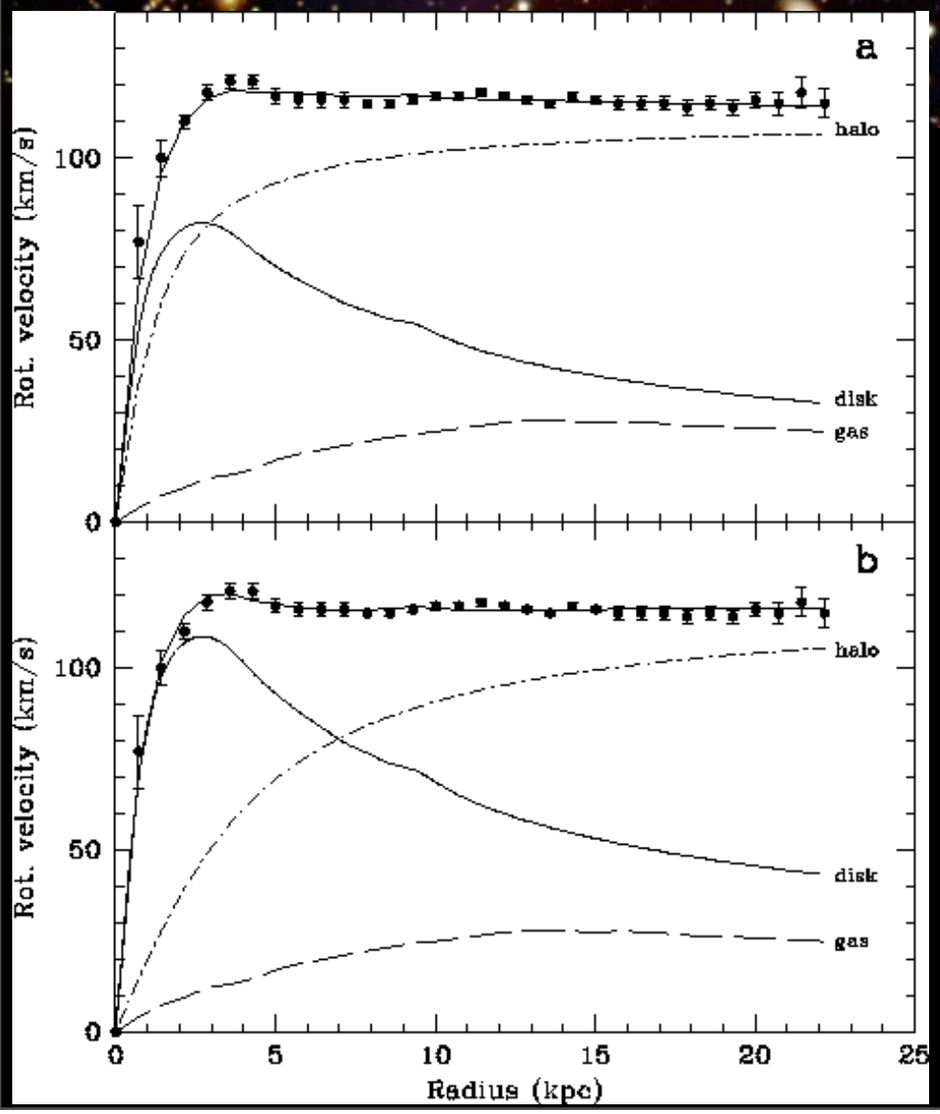
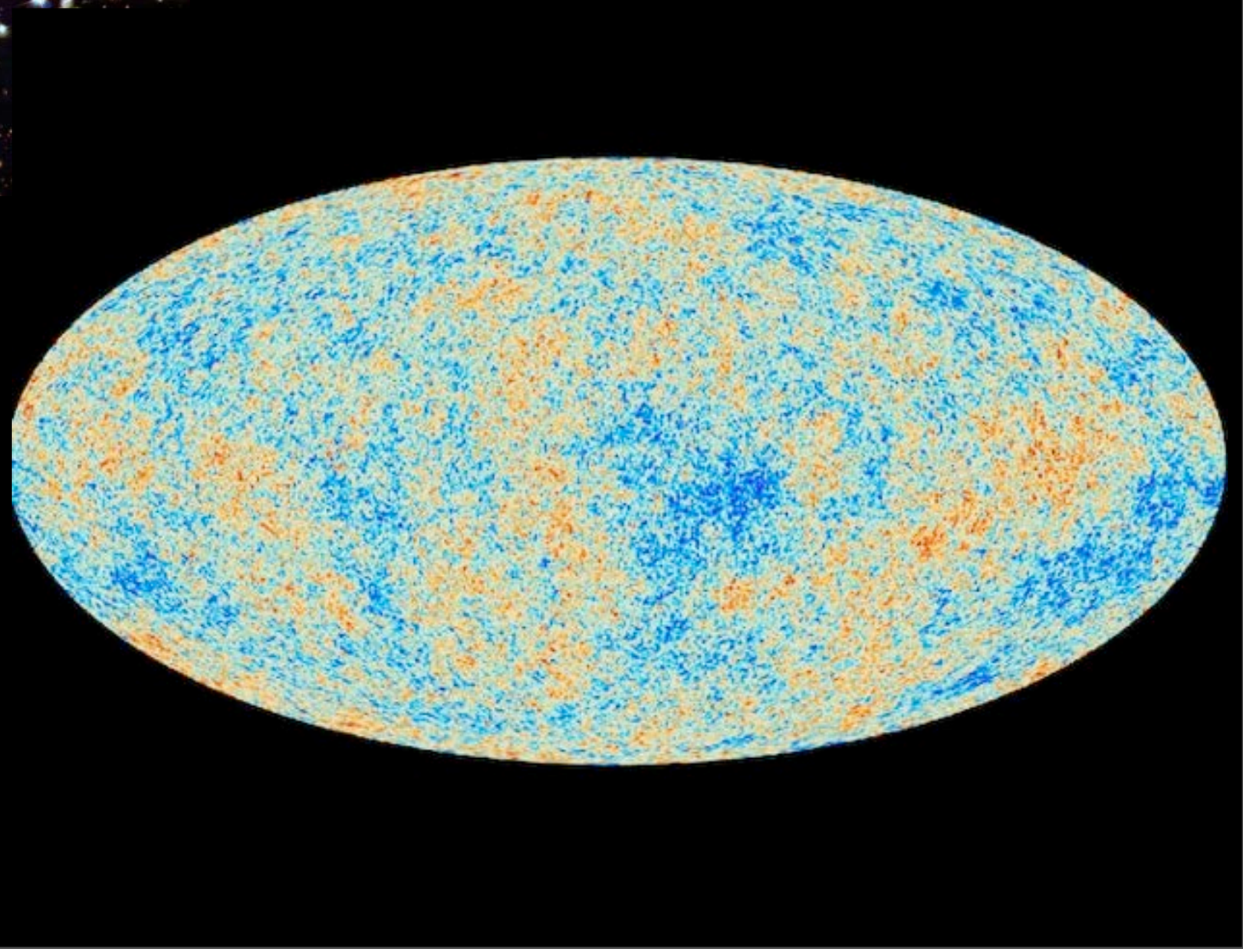
Mining for knowledge / Creuser pour trouver... l'excellence
I. Lawson, E. Vázquez Jáuregui

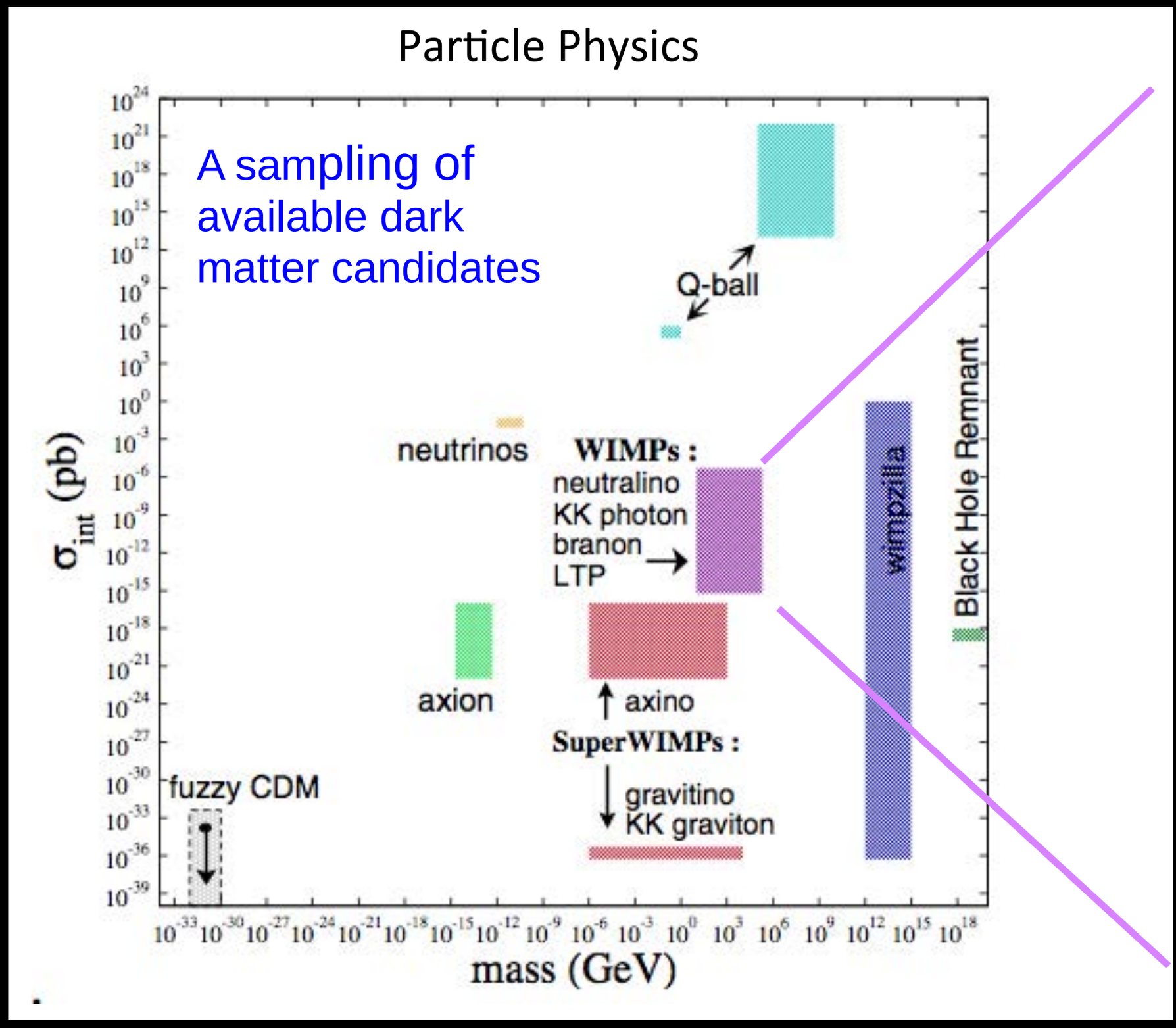




We think dark matter exists



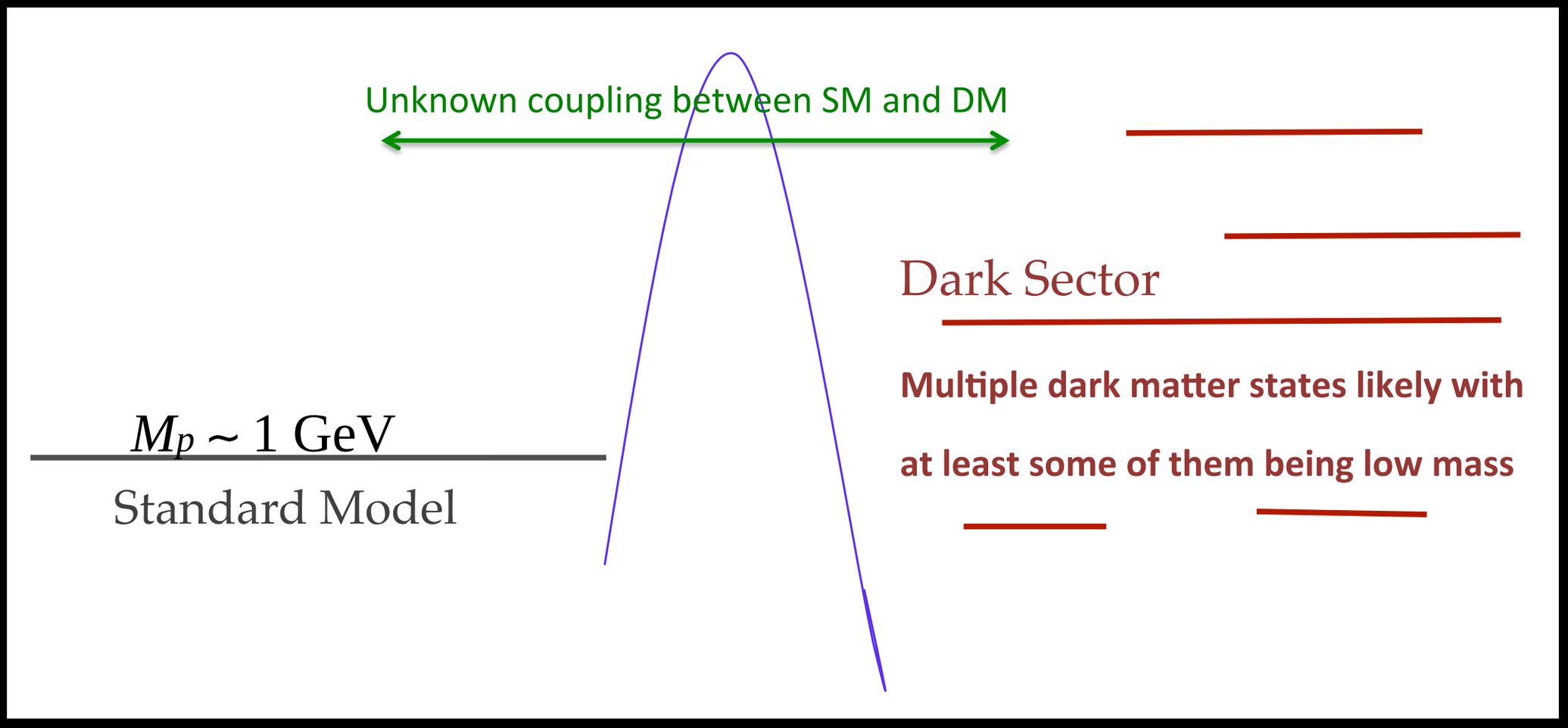
So what is it?



It's probably WIMPs, right?

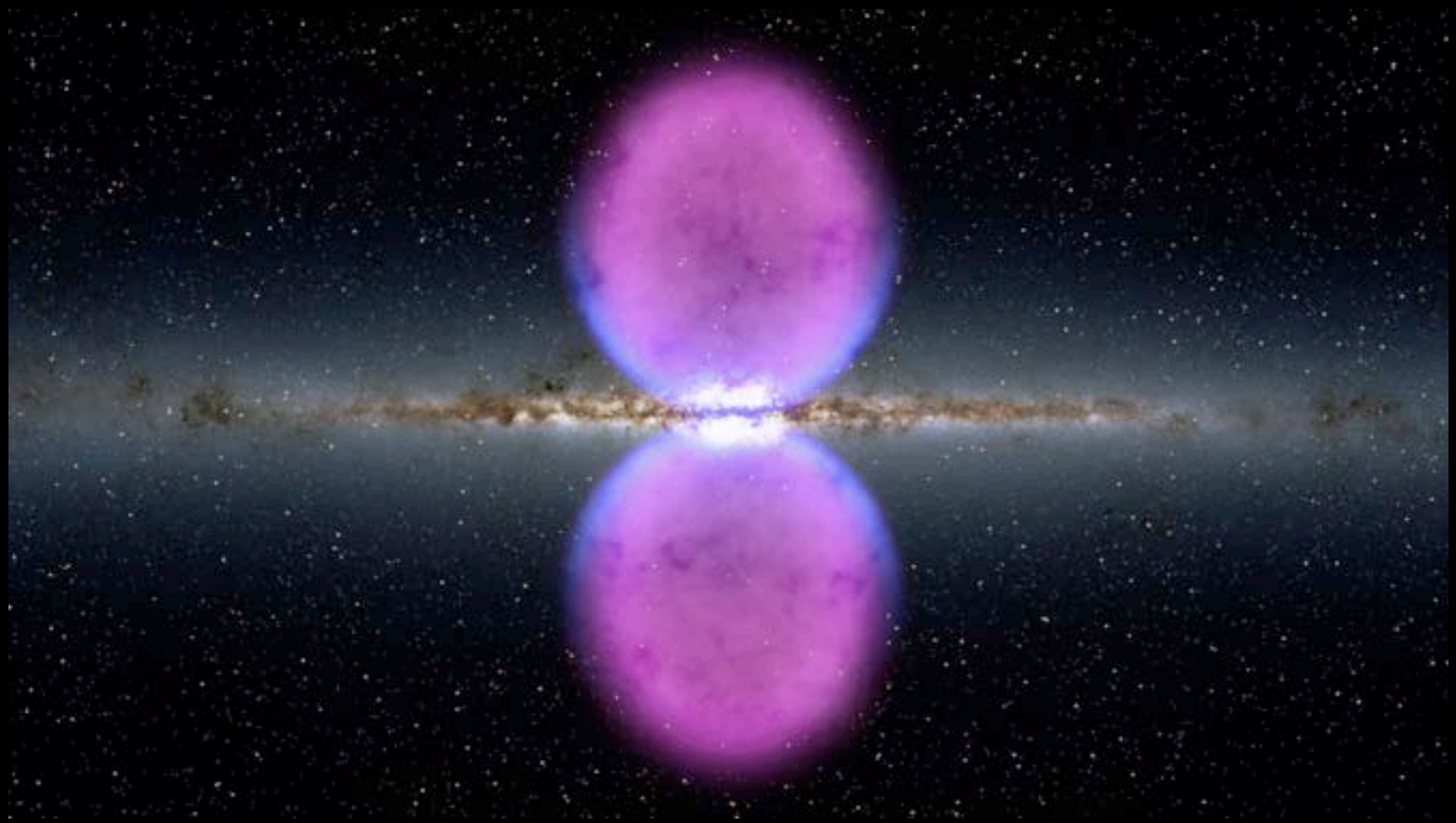
WIMPs not necessarily related to supersymmetry

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



How do we find it?

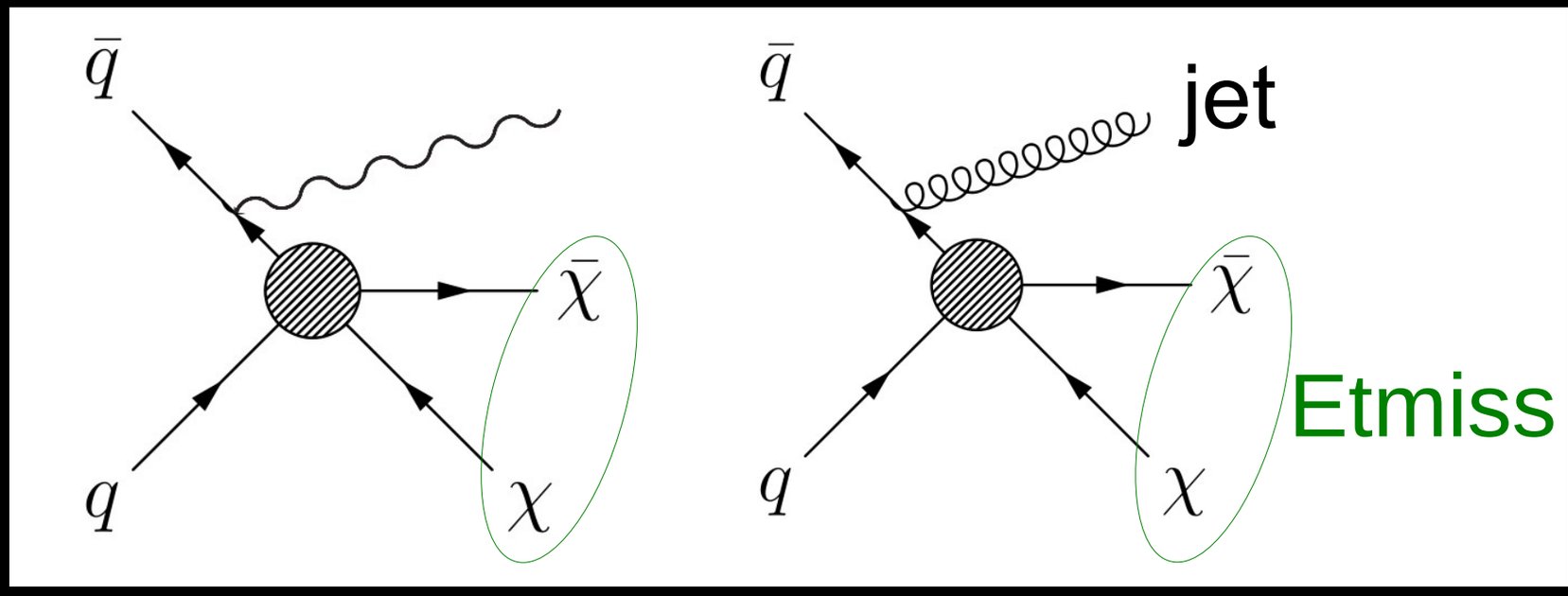
- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy



Fermi bubbles, courtesy of NASA

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



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

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

Rate calculation

- The differential cross section (for spin-independent interactions) per kilogram of target mass per unit recoil energy is

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv \qquad (1)$$

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- Dark matter density component, from local and galactic observations with historically a factor of 2 uncertainty

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- The velocity distribution of dark matter in the galaxy - of order 30% uncertainty (not-statistical), and $v_m = \sqrt{Q/2m_r^2}$

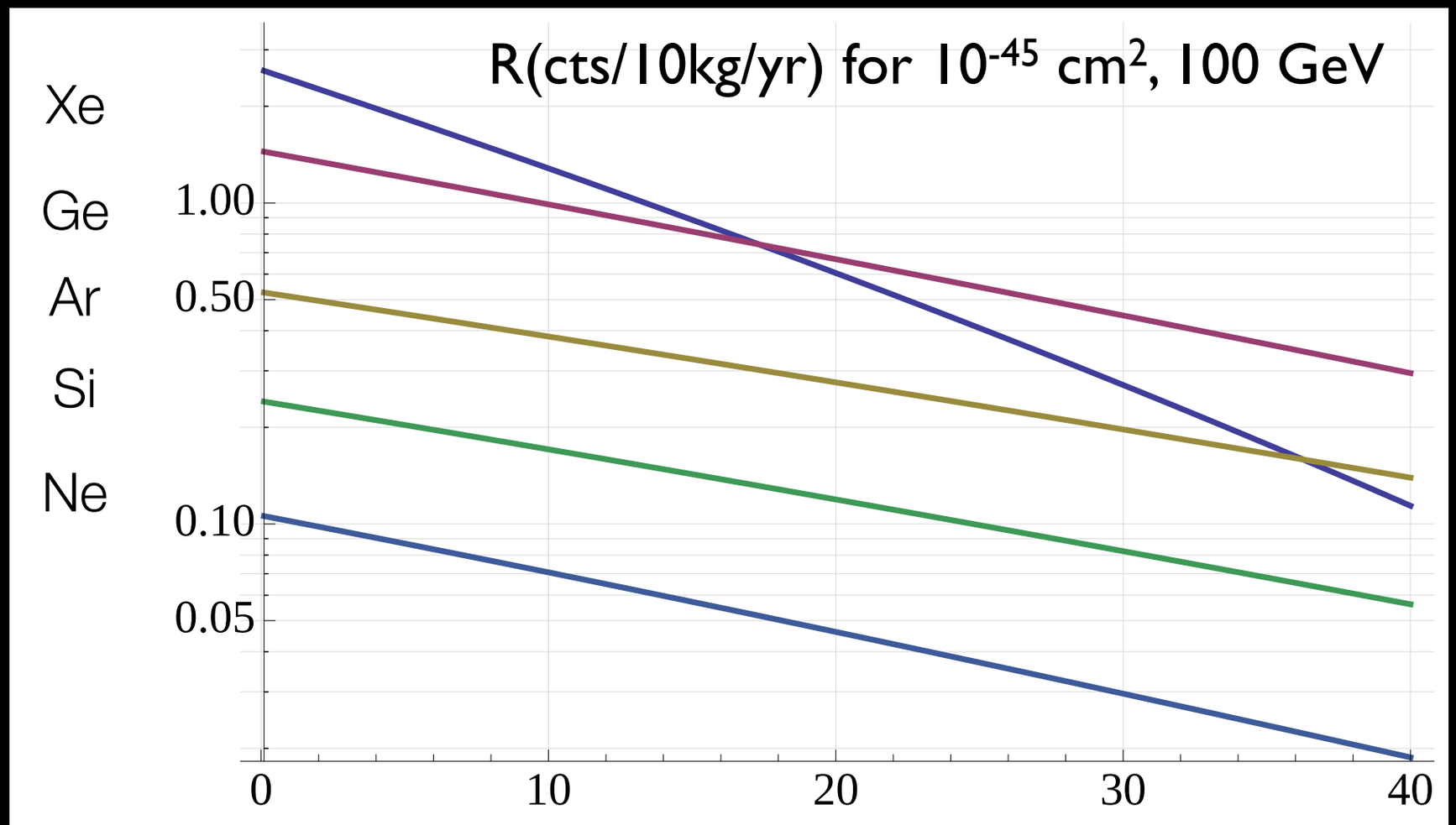
The energy scale

- 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)



- Rate depends crucially on WIMP mass and threshold

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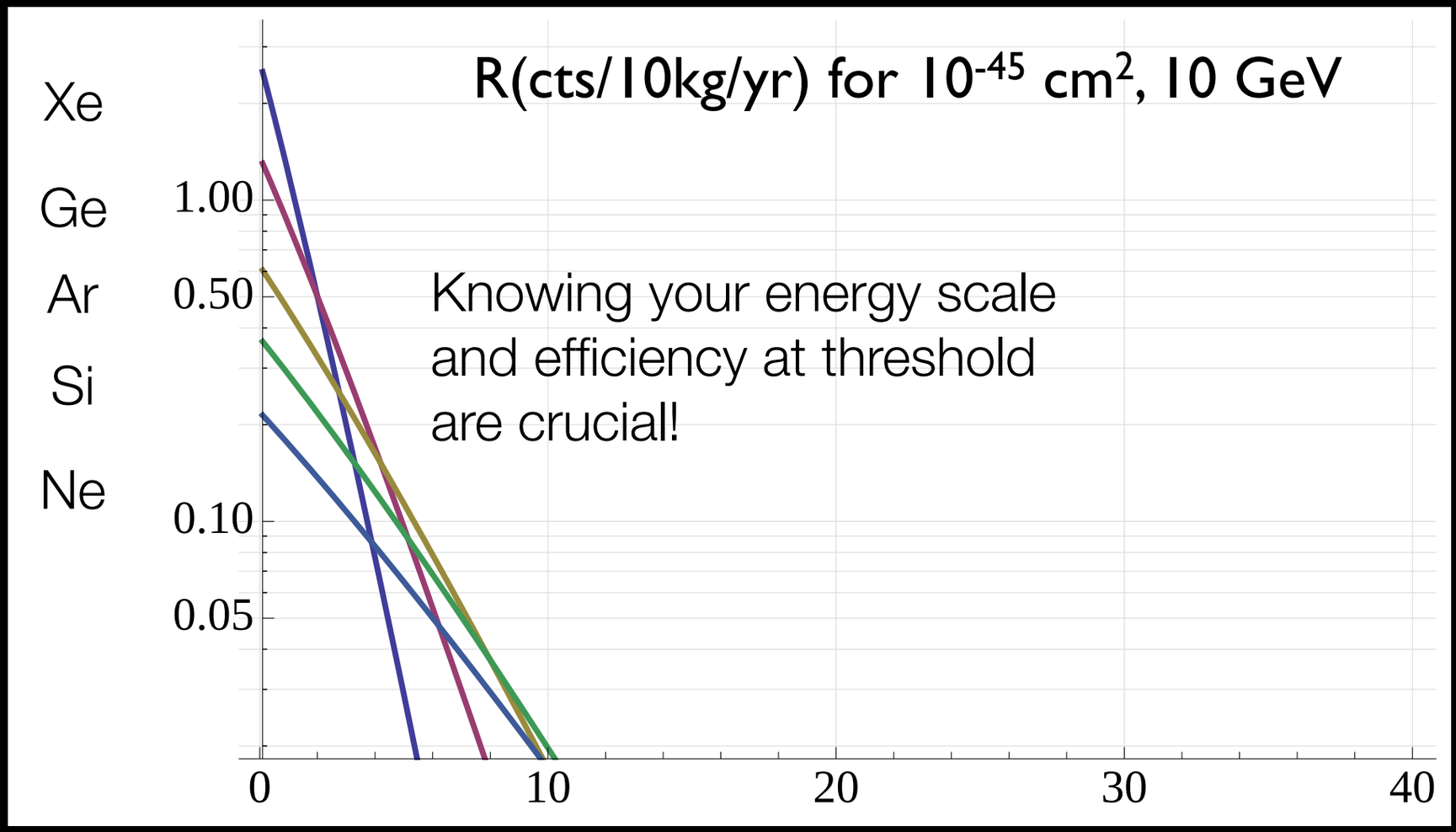
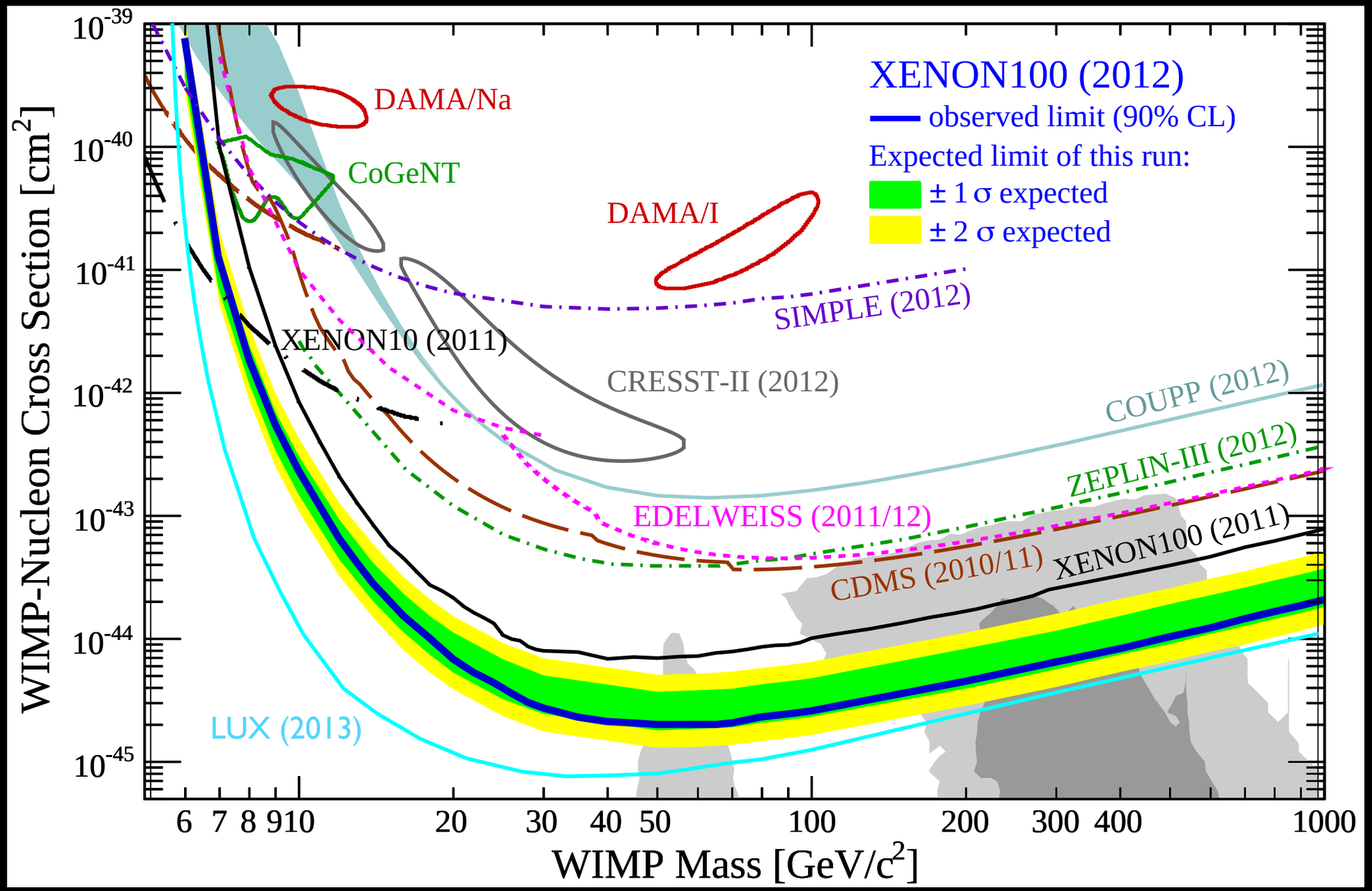


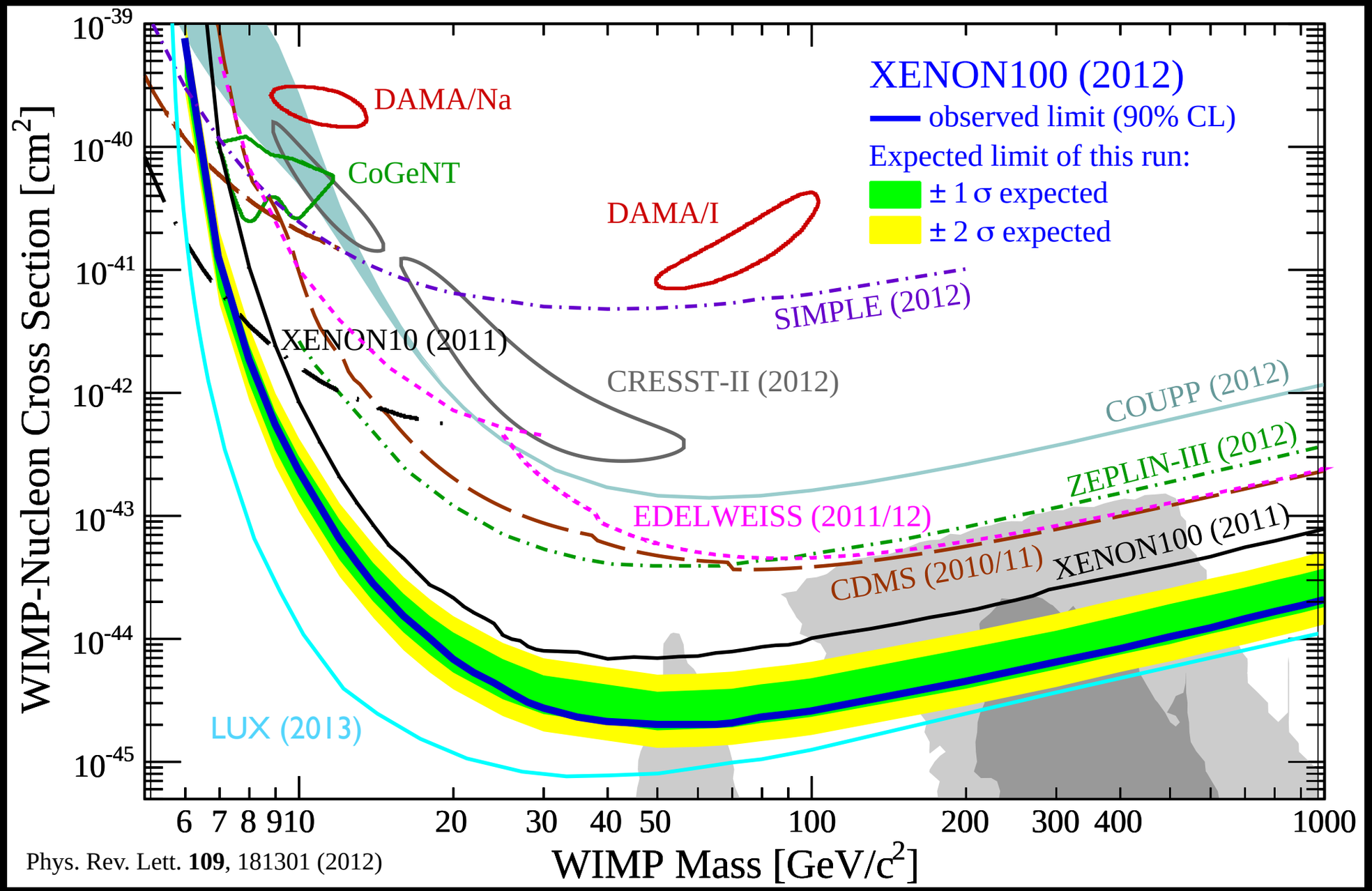
- Rate depends crucially on WIMP mass and threshold

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

So we look for WIMPs

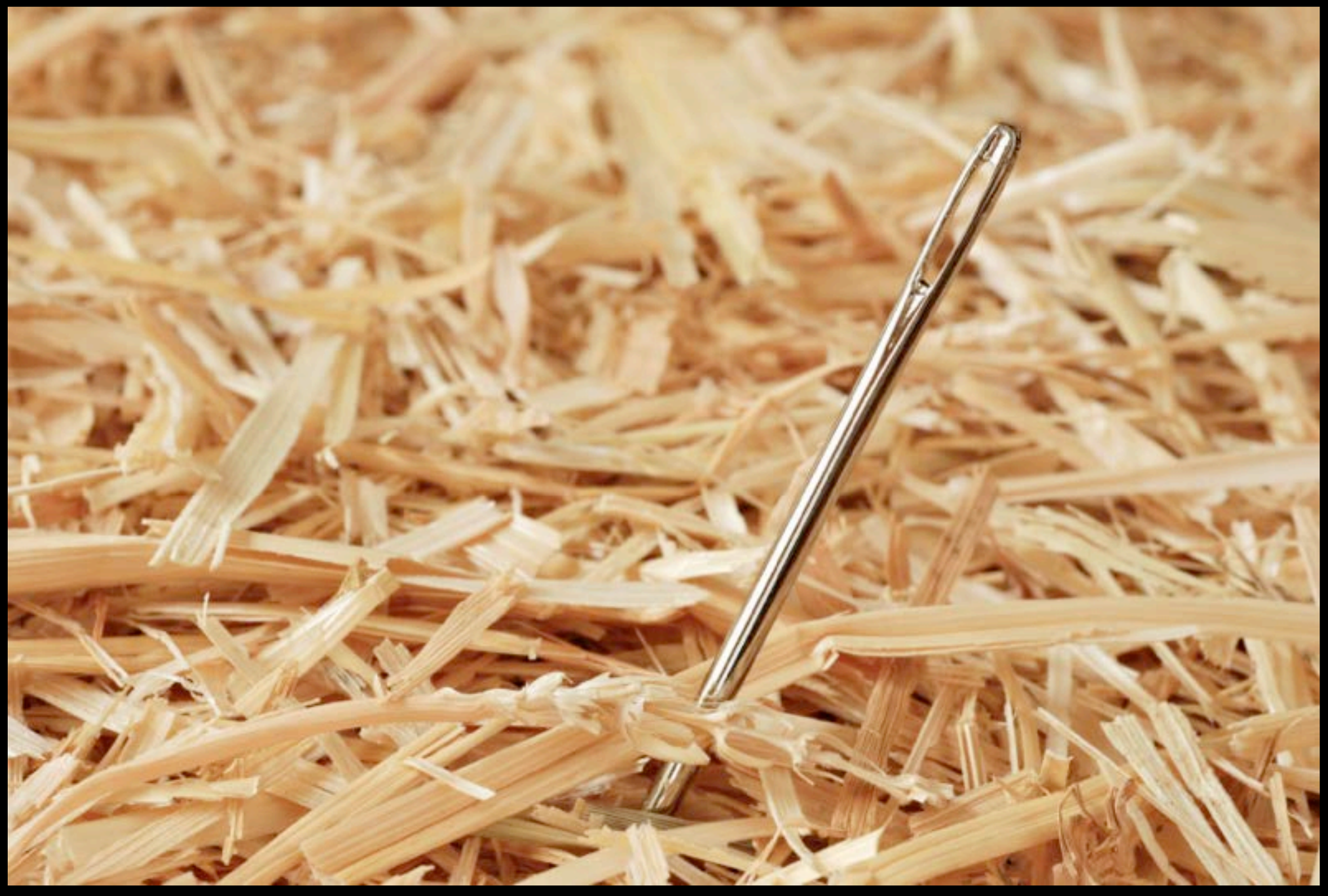
- A few hundred just passed through us, and we might expect a handful of counts in a detector per year

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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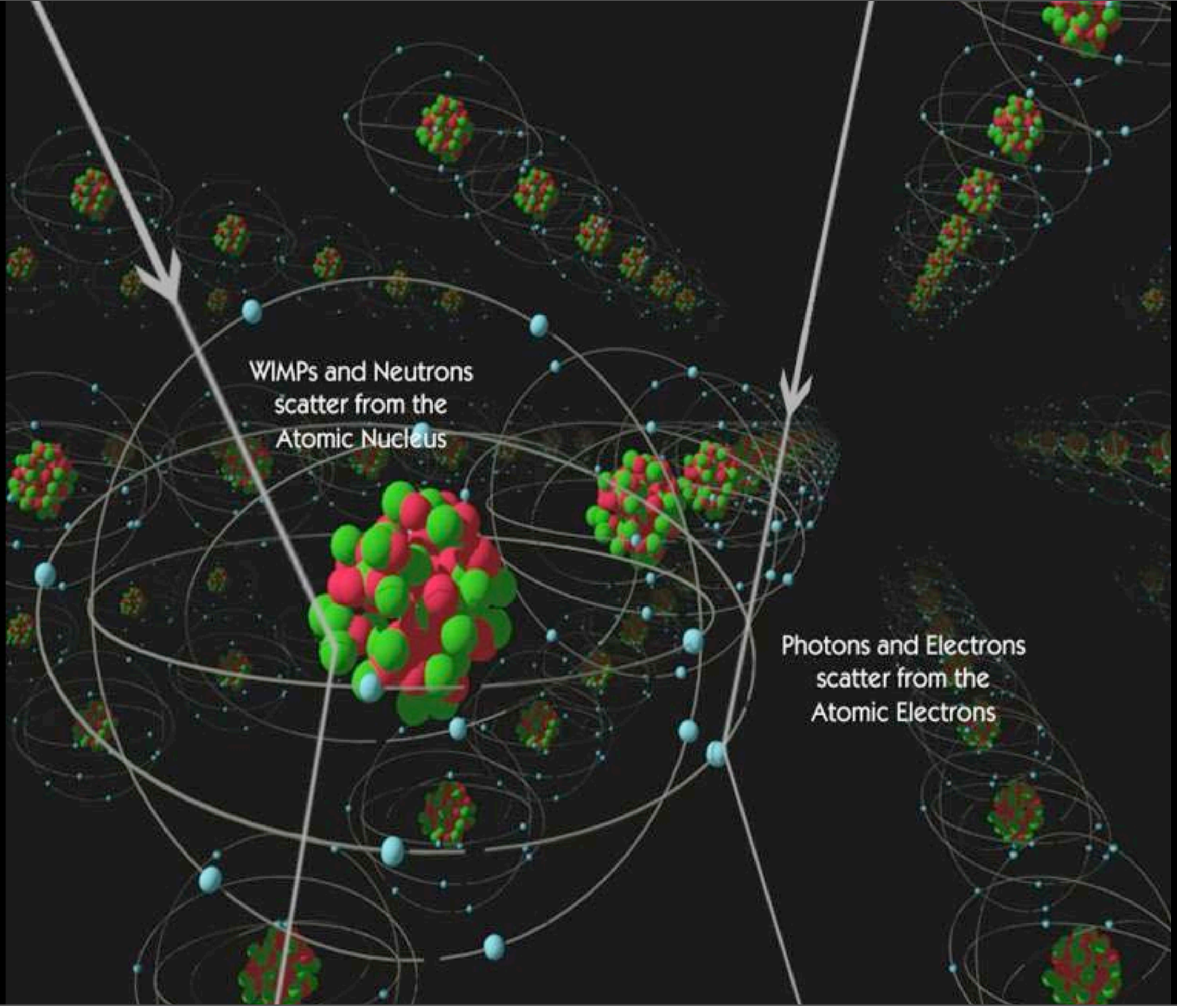
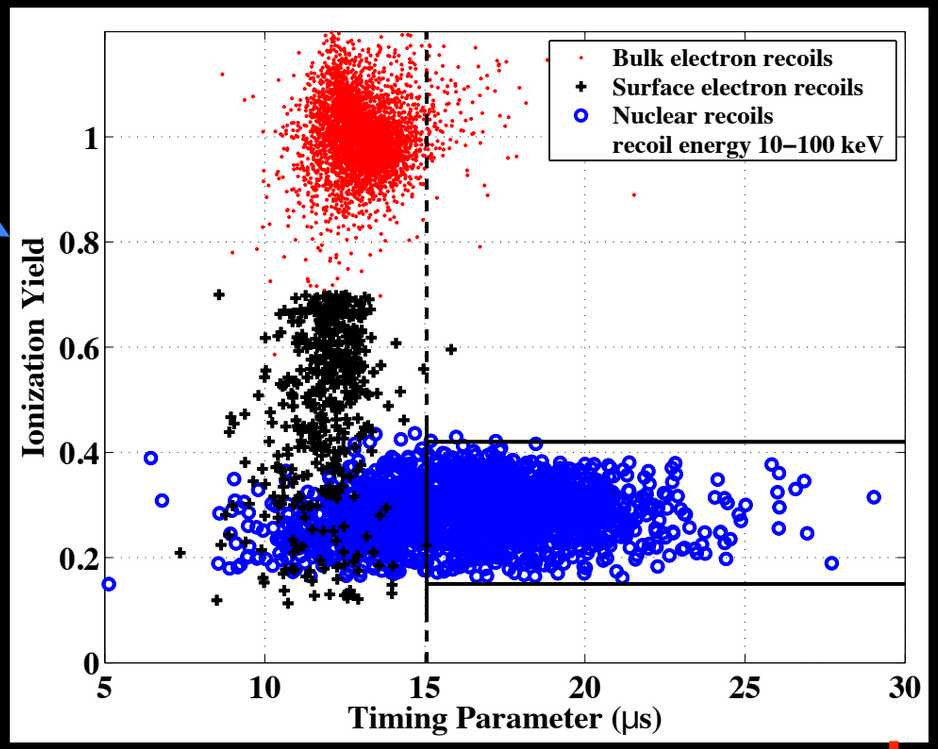
  - Discrimination - can you tell signal from background (gamma rays, alphas, neutrons, etc)?

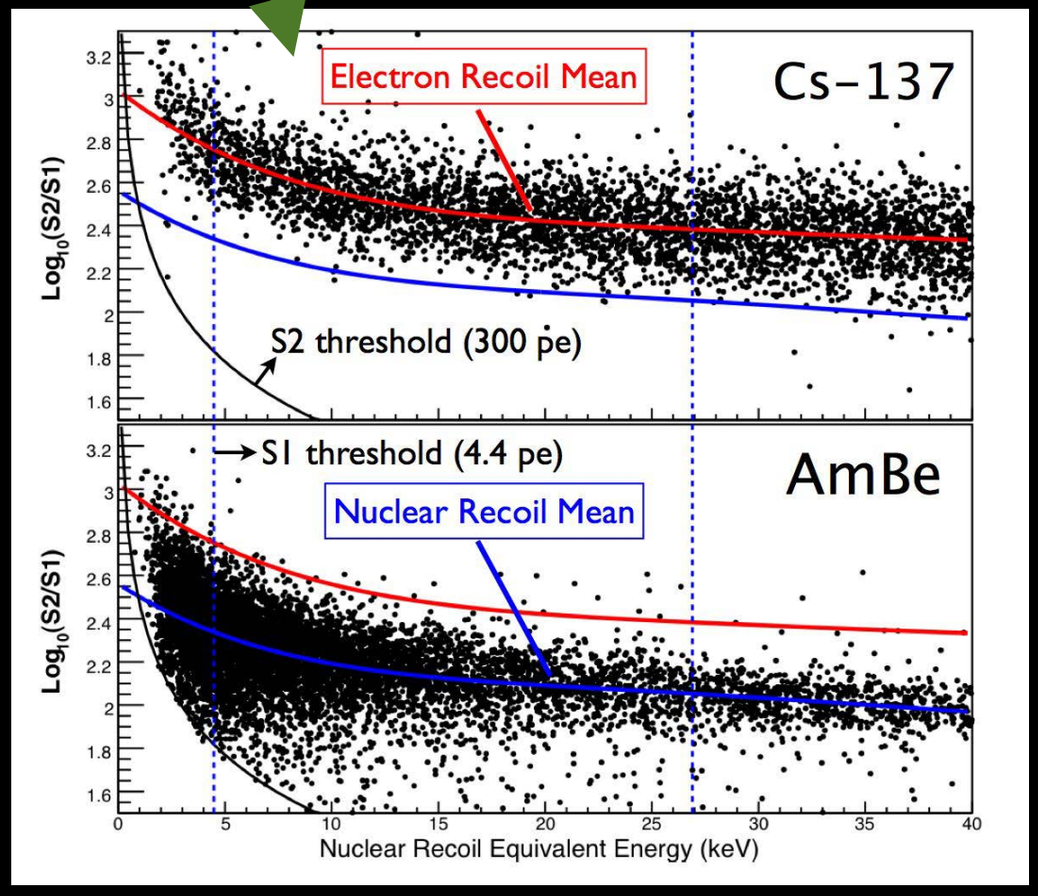

WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons

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

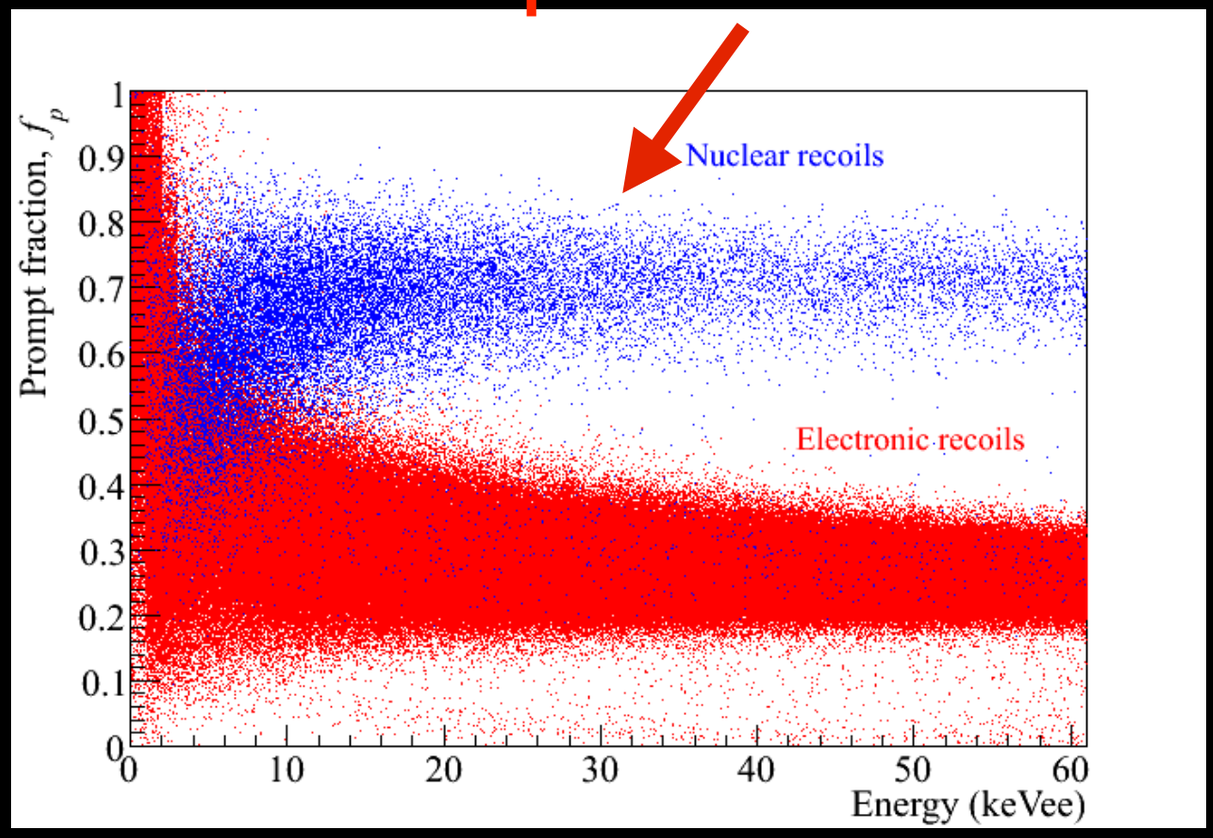
CDMS - Charge to heat



Xenon TPCs - Charge to light



Argon - Pulse shape discrimination



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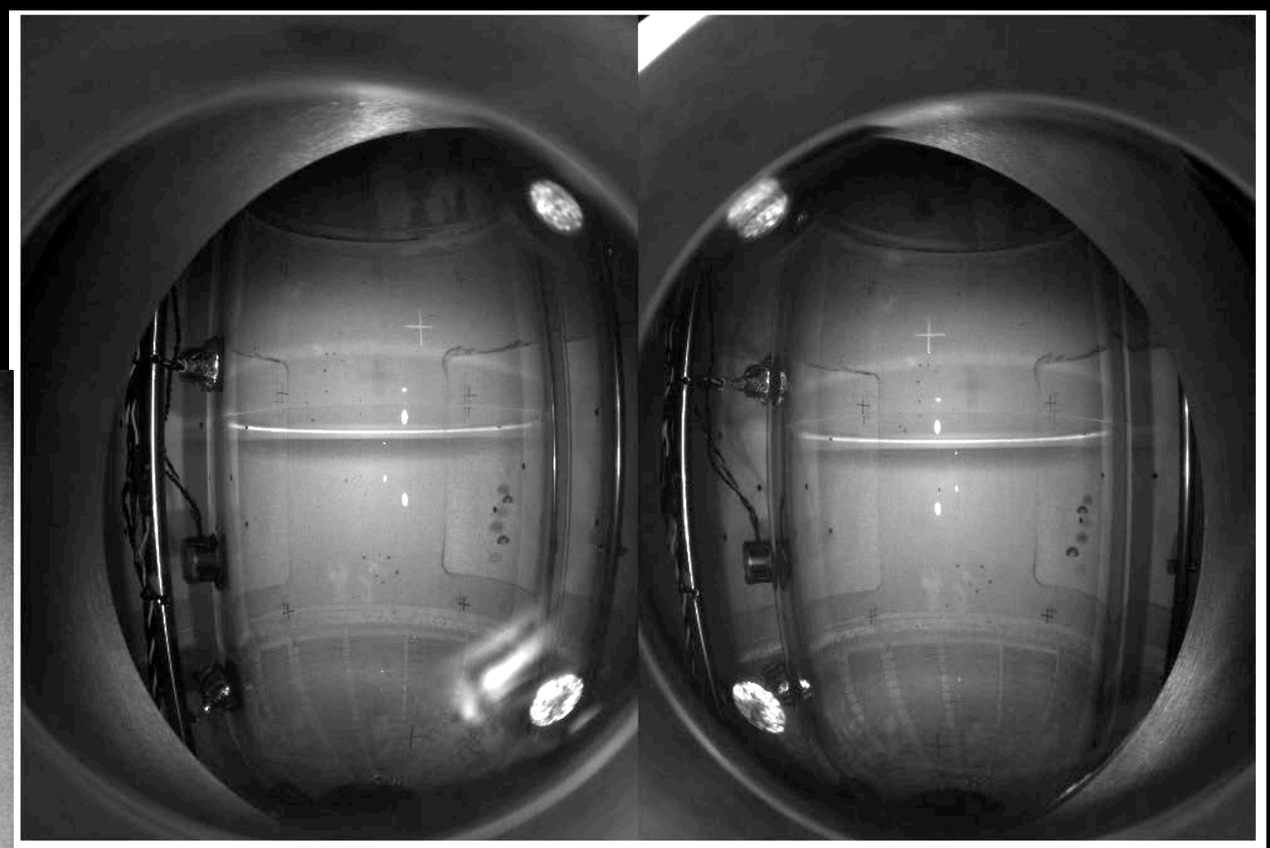
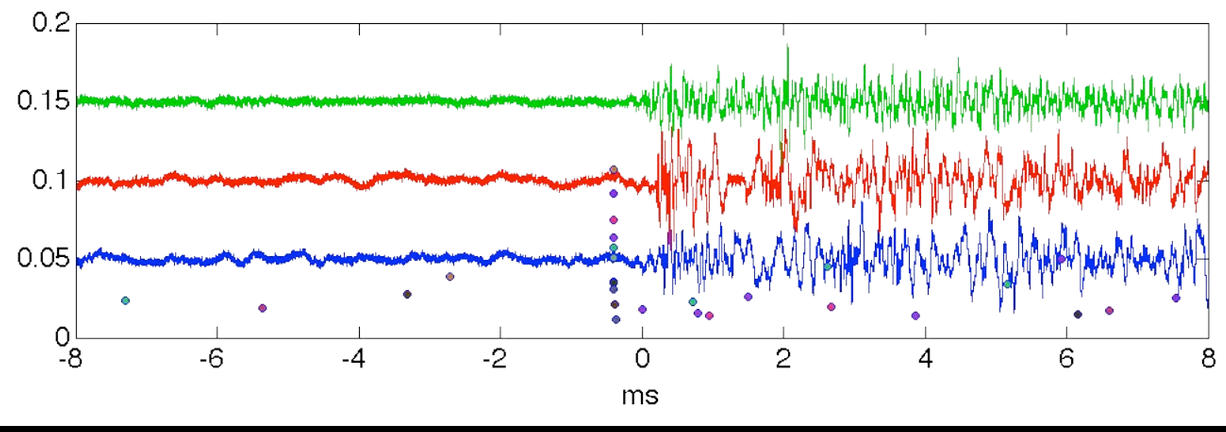
Bubble Chambers!

Chicagoland Observatory for Underground Particle Physics (COUPP)

[Some debate over the pronunciation (should the Ps be silent?)]





Chicagoland Observatory for Underground Particle Physics (~~COUPP~~ PICO)

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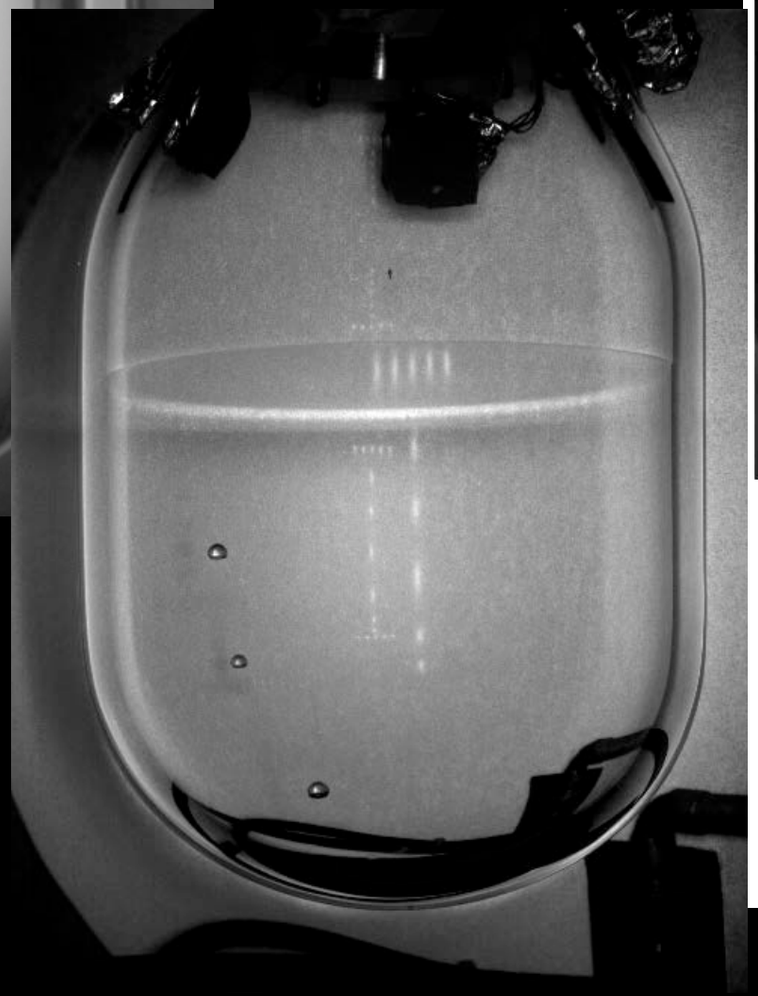
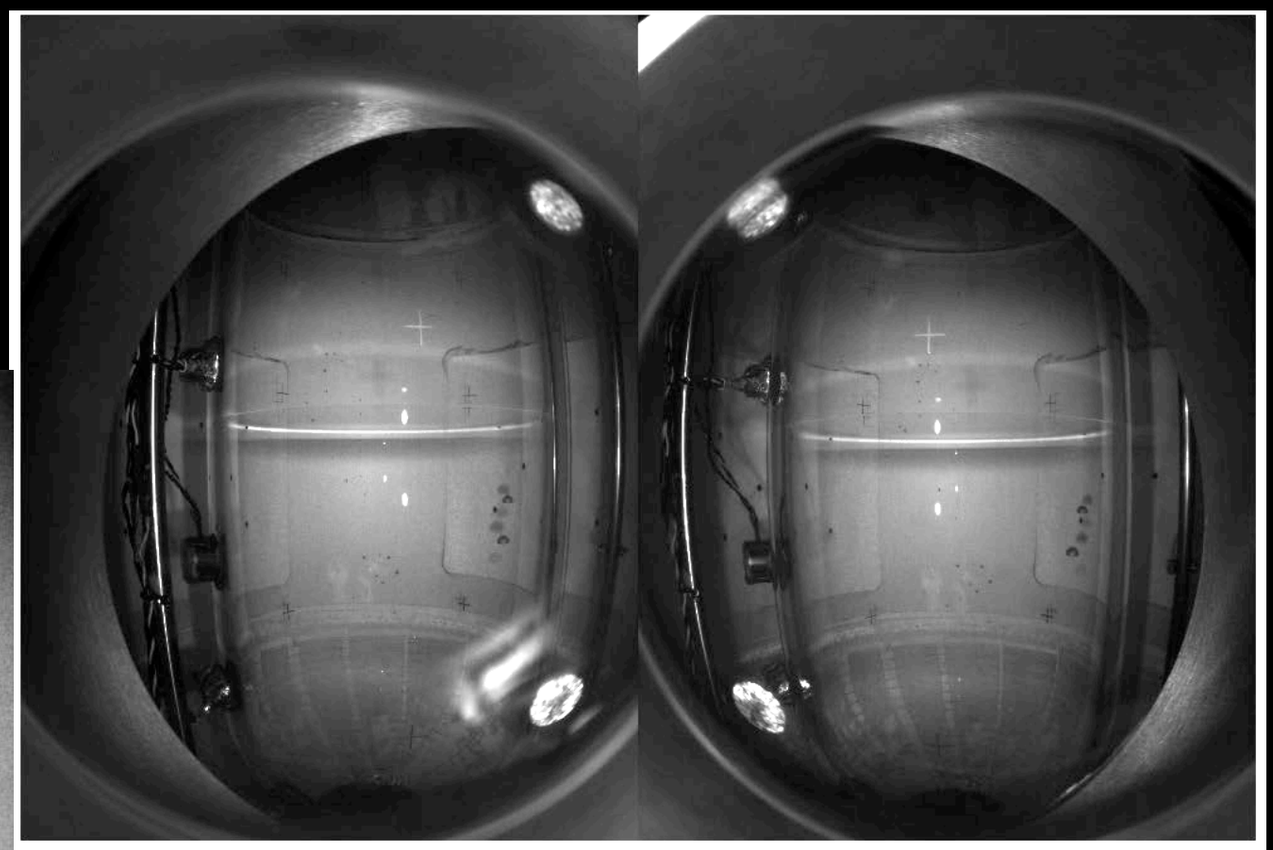
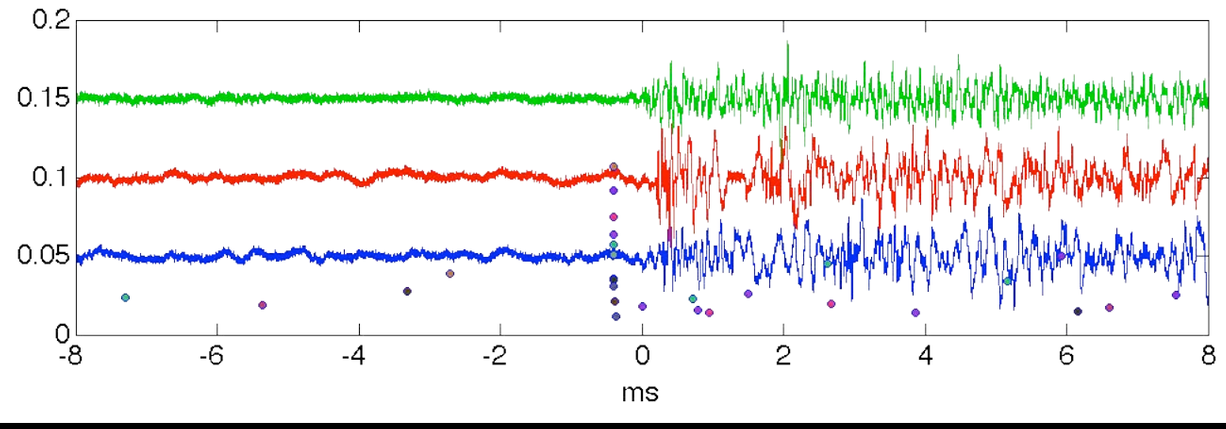
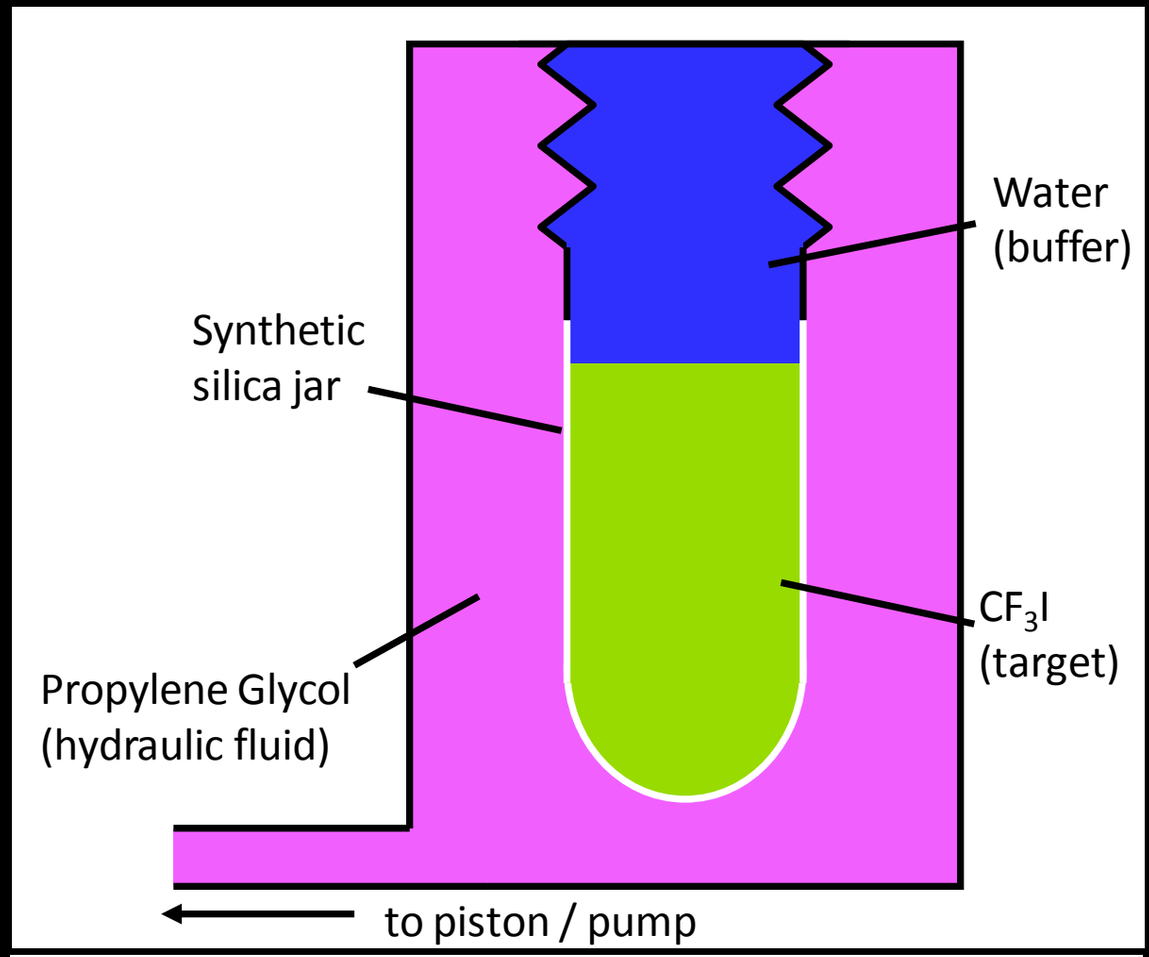


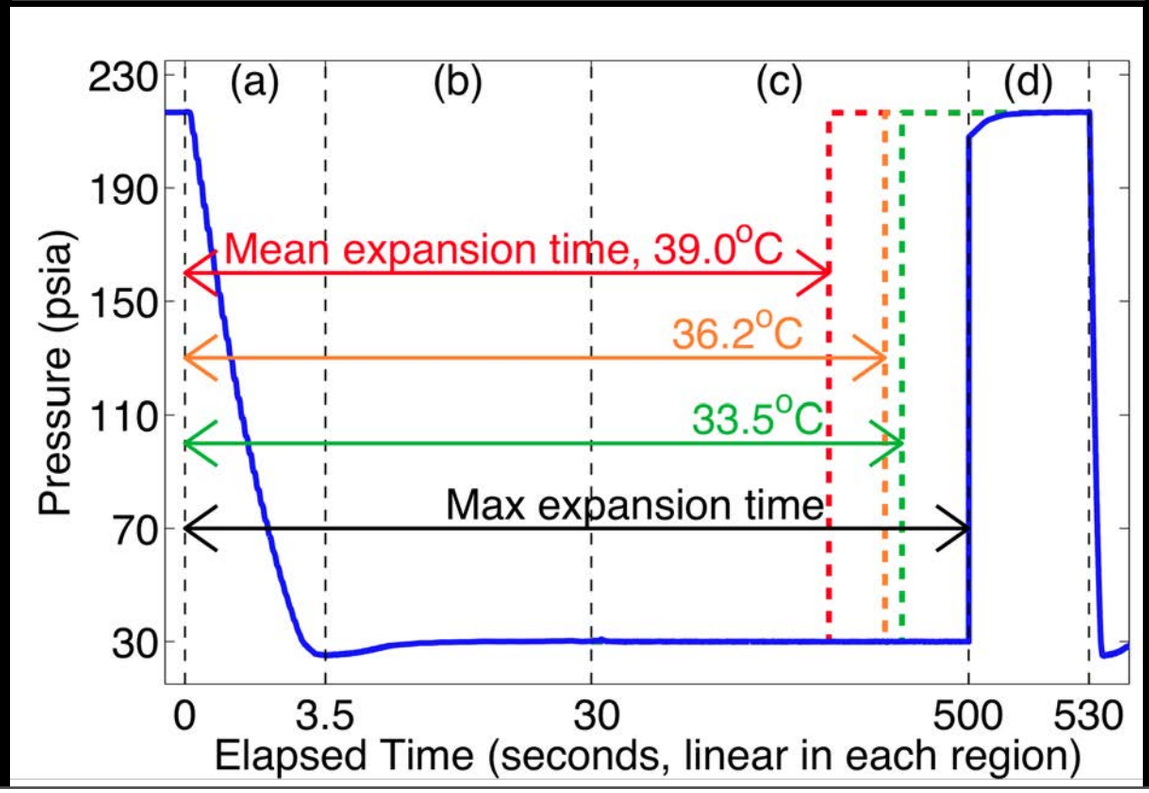




PICO/COUPP fast compression bubble chamber

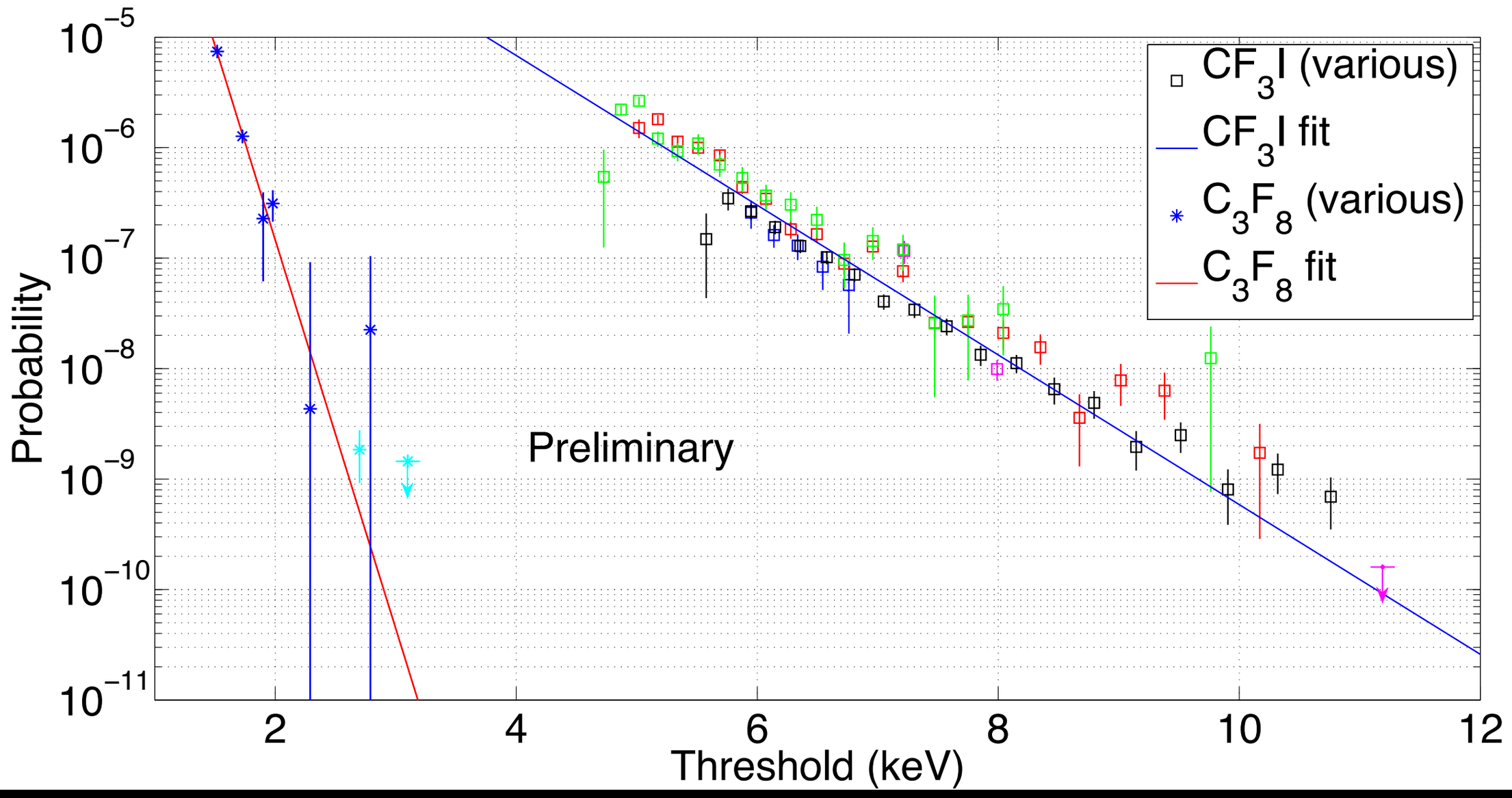
- Pressure expansion creates superheated fluid, CF_3I or C_3F_8
  - I for spin-independent
  - F for spin-dependent
- Particle interactions nucleate bubbles
- Cameras see bubbles
- Recompress chamber to reset





Why bubble chambers?

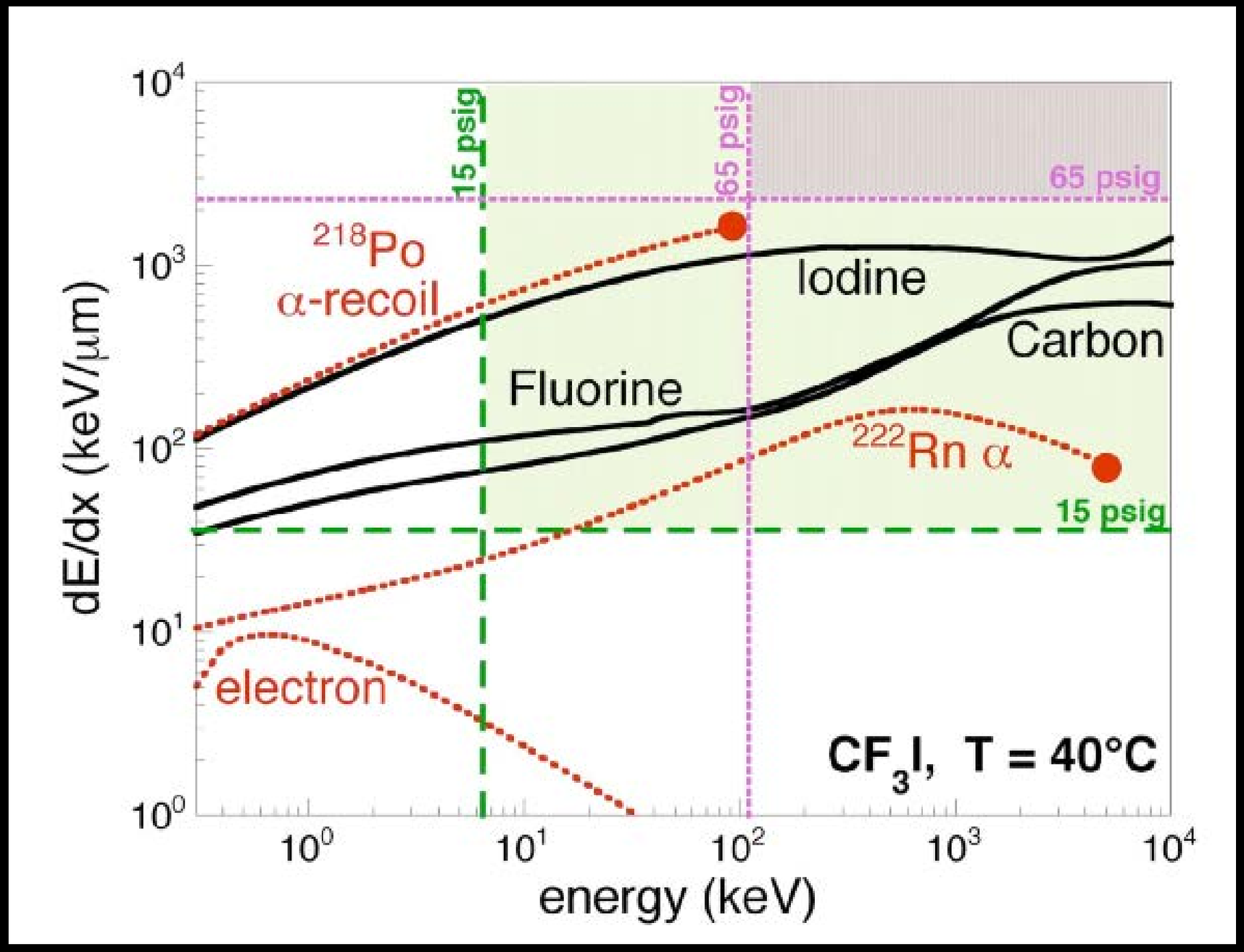
- By choosing superheat parameters appropriately (temperature and pressure), bubble chambers are blind to electronic recoils (10^{-10} or better)
  - The probability for gamma interaction to produce a bubble:



Why bubble chambers?

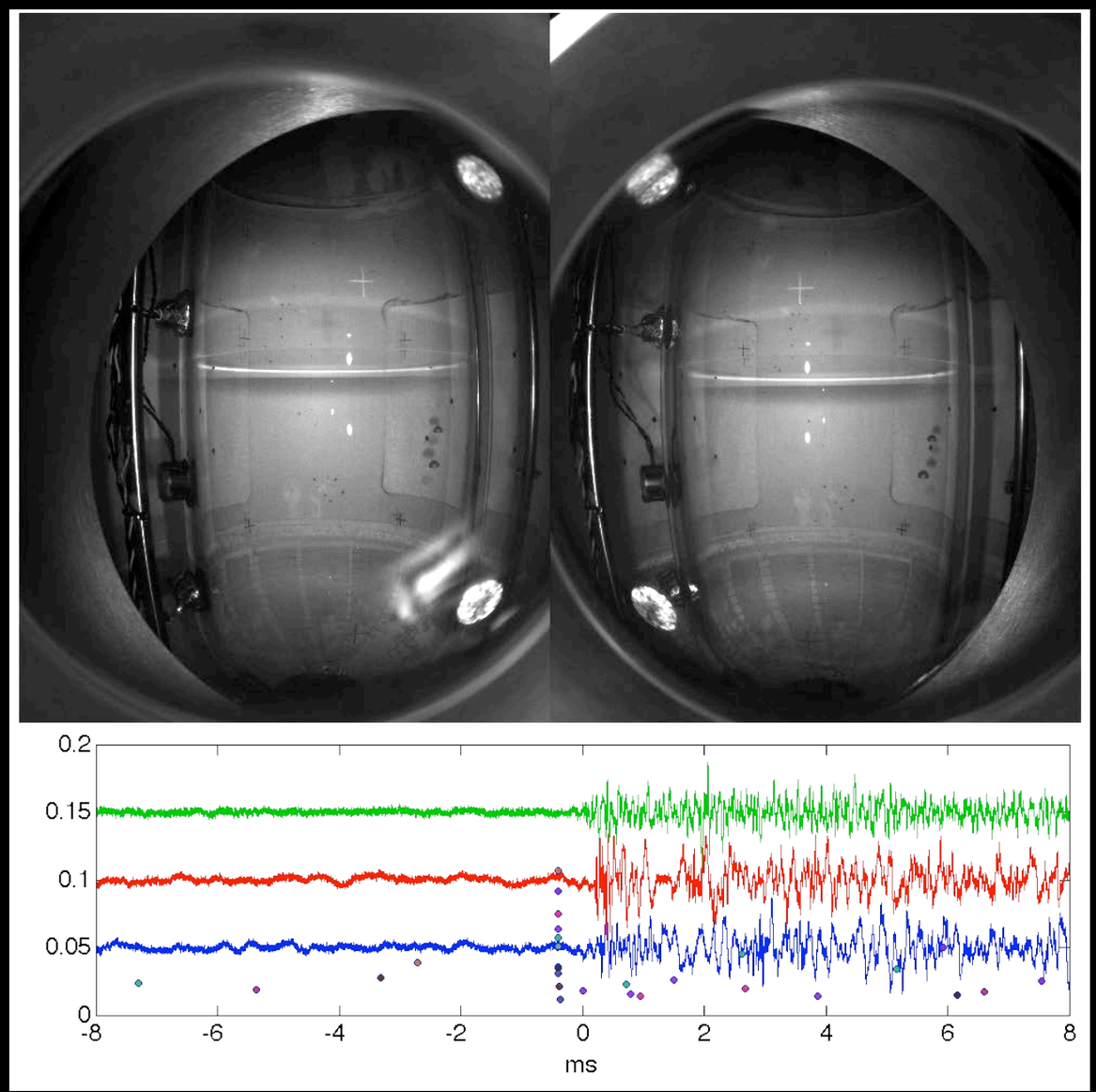
- By choosing superheat parameters appropriately (temperature and pressure), bubble chambers are blind to electronic recoils (10^{-10} or better)
- To form a bubble requires two things
  - Enough energy
  - Enough energy density - length scale must be comparable to the critical bubble size

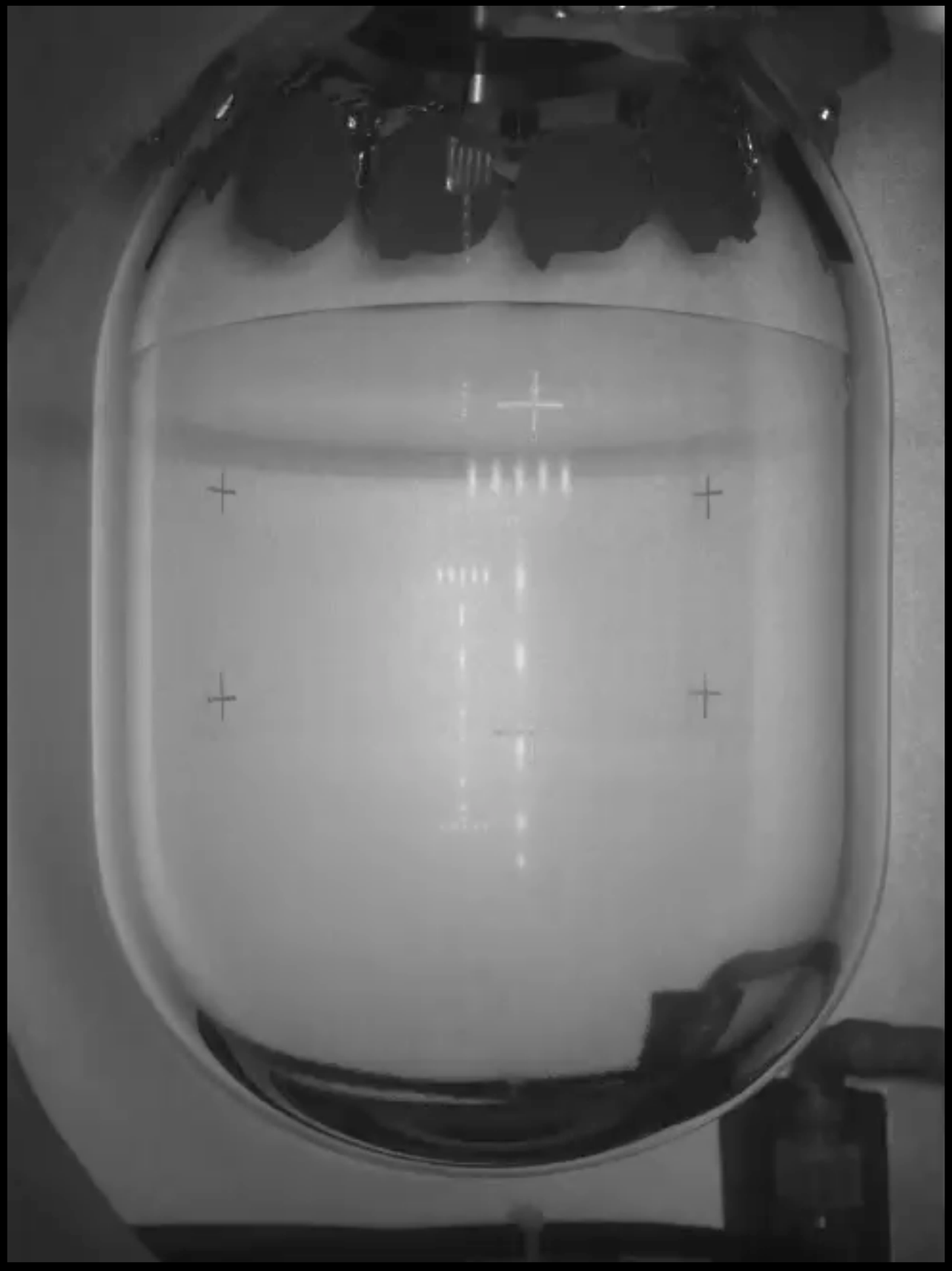
Why bubble chambers?



Why bubble chambers?

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



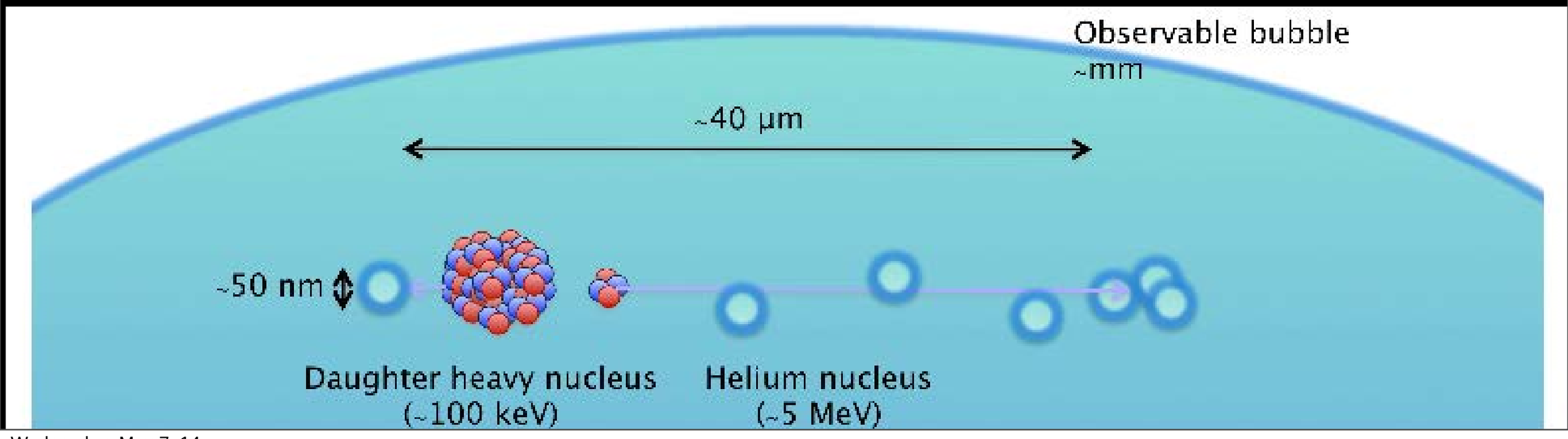


Why not bubble chambers?

- 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
- Bubble chambers are slow - about 30 s of deadtime for every event
  - Overall rate must be low

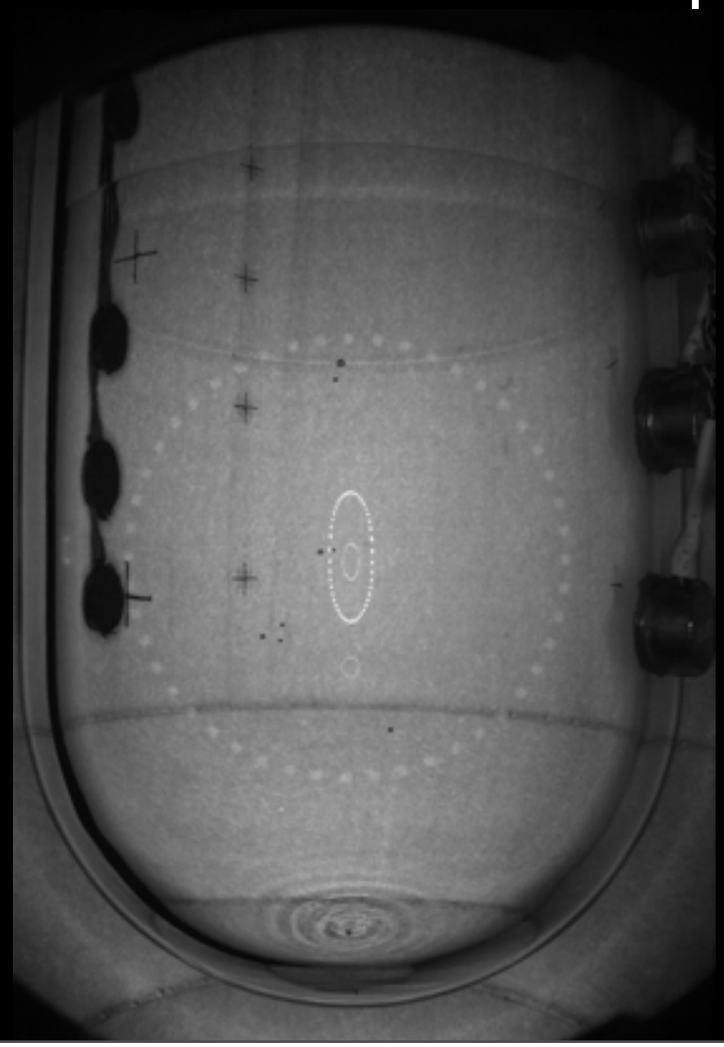
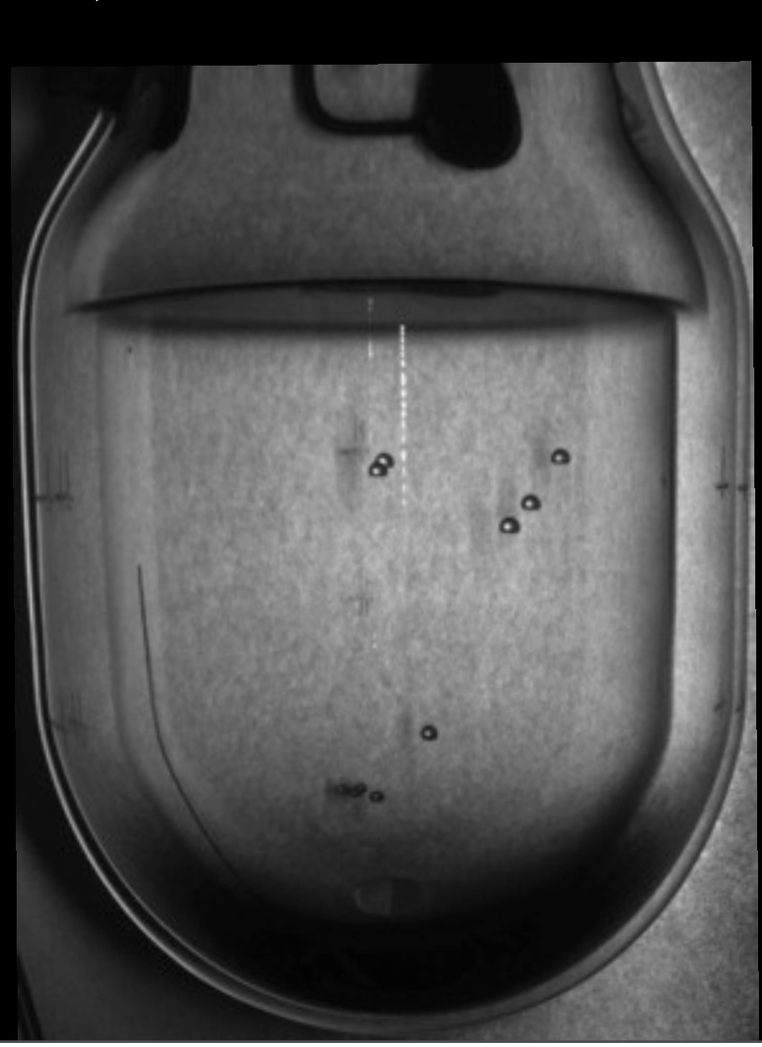
About those alphas

- 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 COUPP bubble chambers, alphas are several times louder

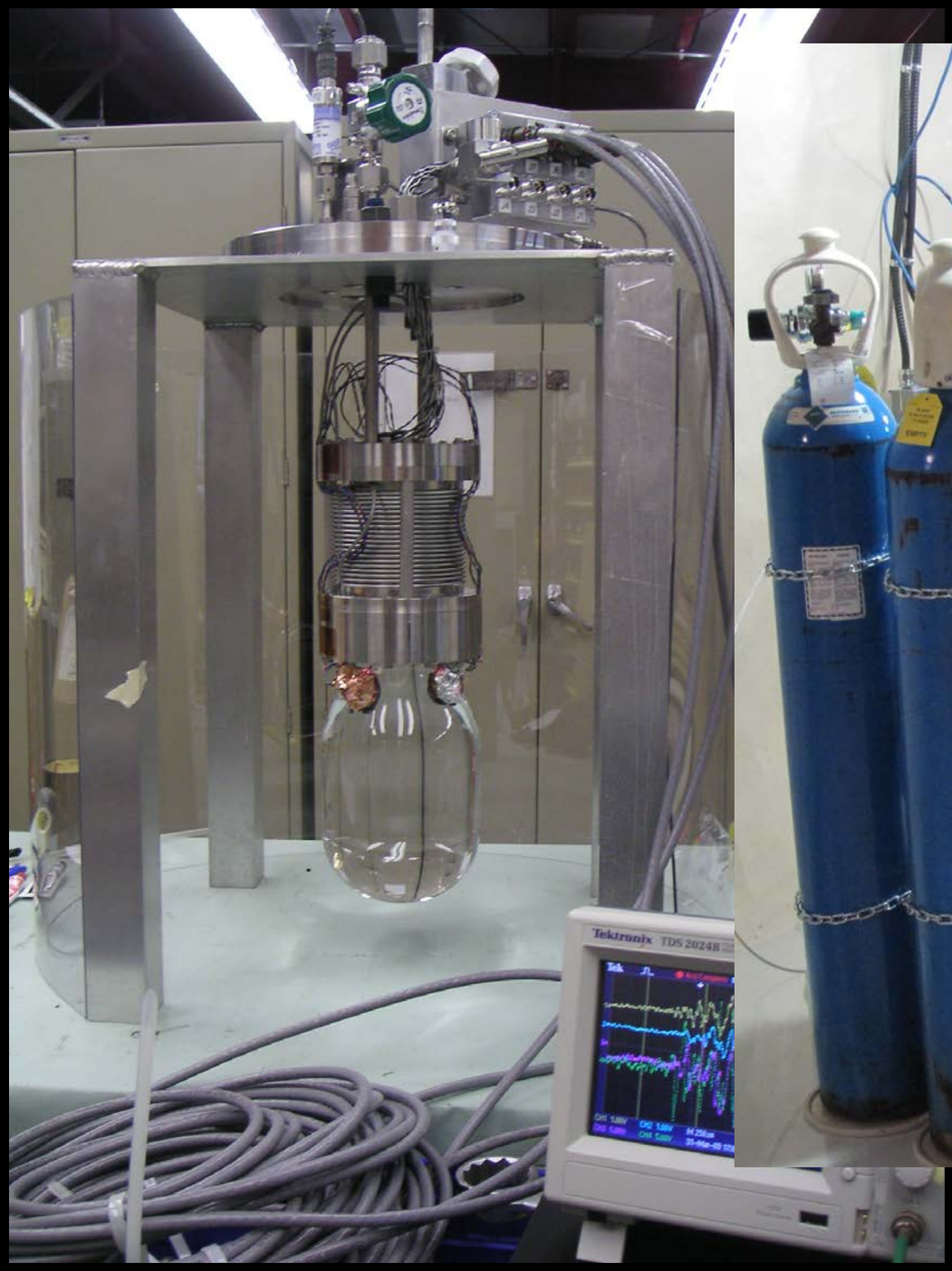


The PICO program

- COUPP4: A 2-liter chamber operated at SNOLAB from 2010-2012
- COUPP60: Up to 40 liters, running at SNOLAB now
- PICO-2L: Refurbished COUPP4 with C_3F_8, filled in October, 2013
- PICO-250L: Ton scale detector in G2 DM competition, at SNOLAB in 2016?

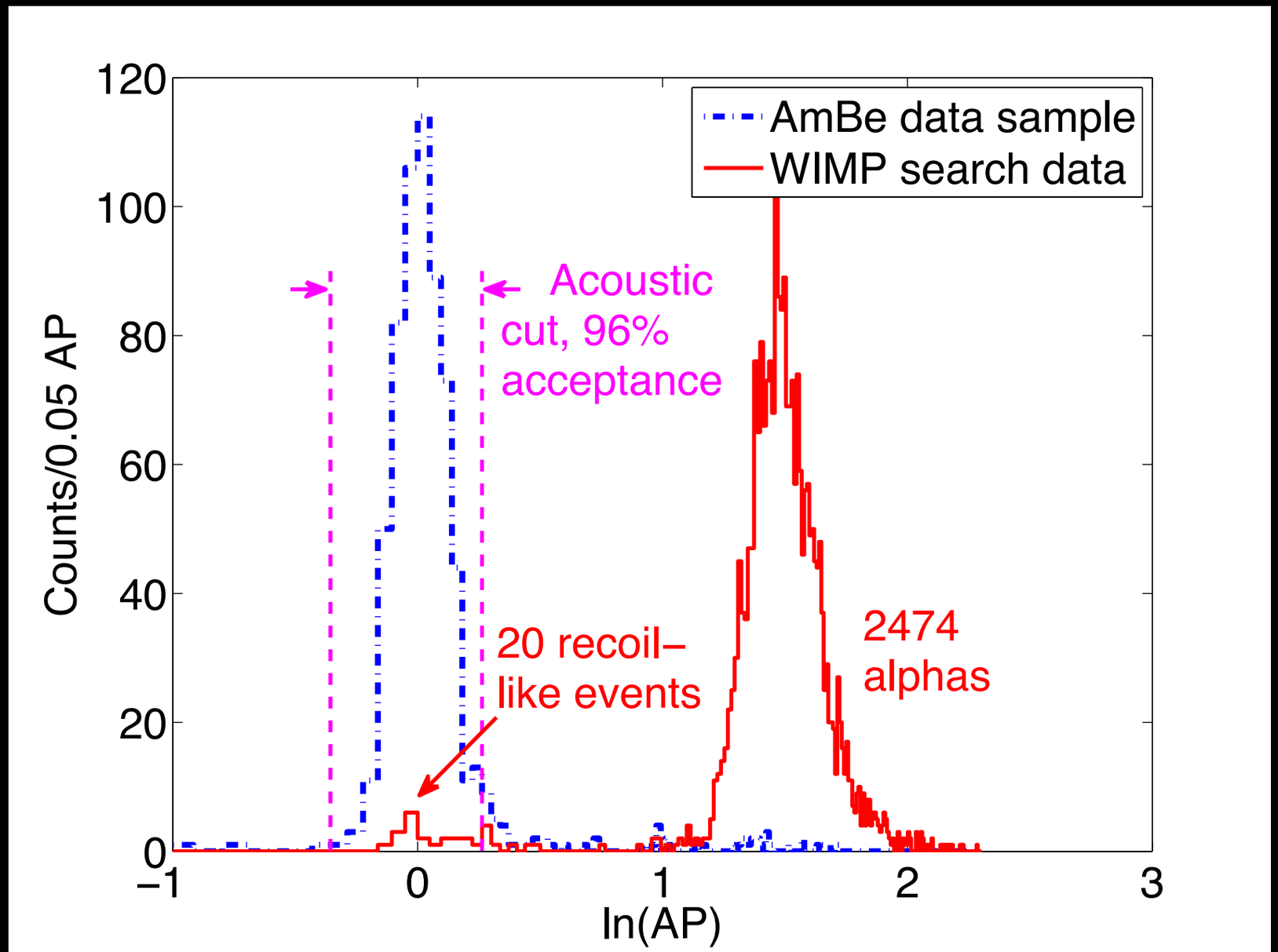
COUPP4 at SNOLAB



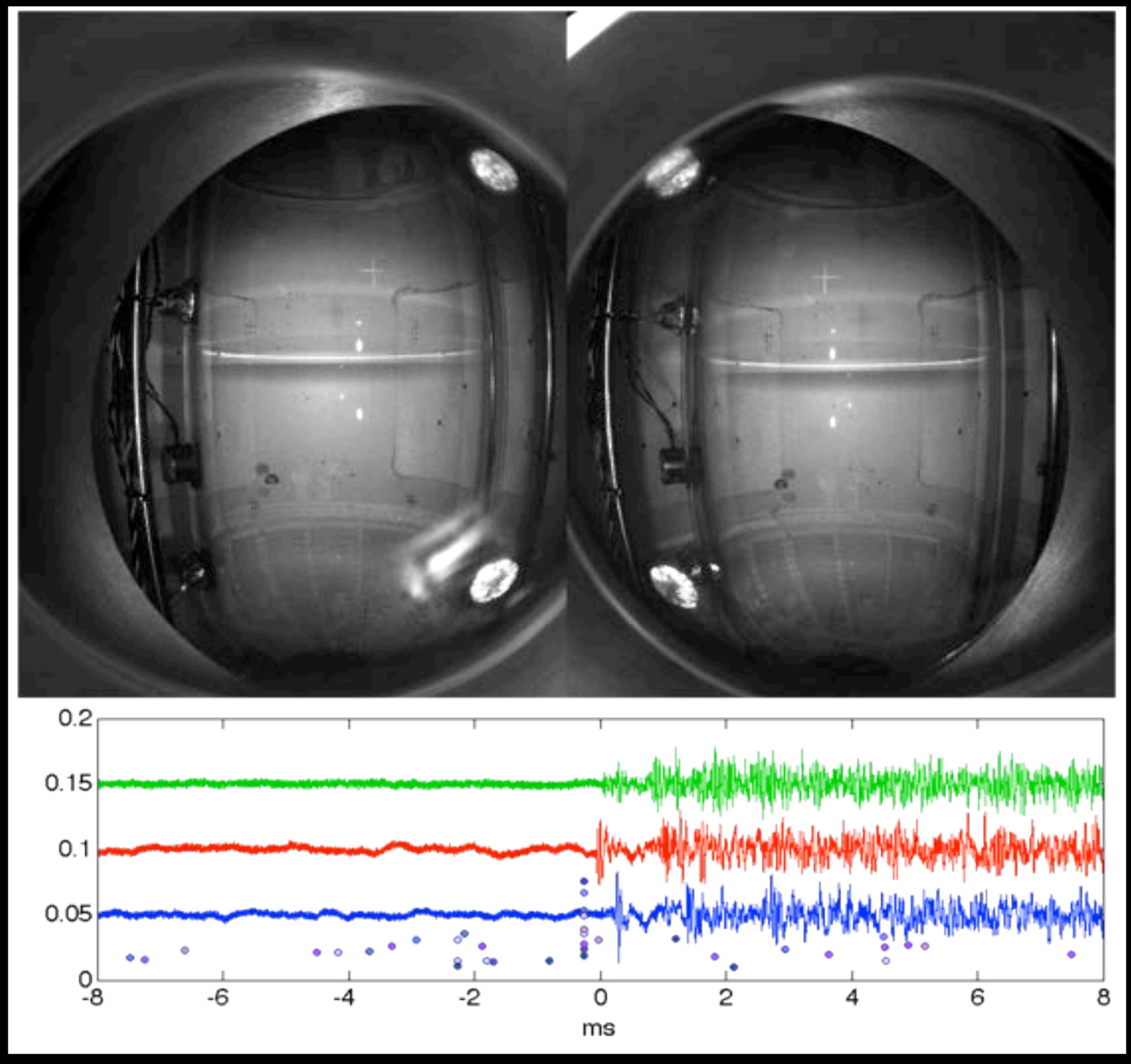
- First run at SNOLAB: About 140 live days of data, with 79% acceptance after all cuts

COUPP4: Acoustic discrimination

- Better than 99.3% rejection against alphas at 16 keV threshold
  - Limited by statistics, and backgrounds



This is what dark matter would sound like



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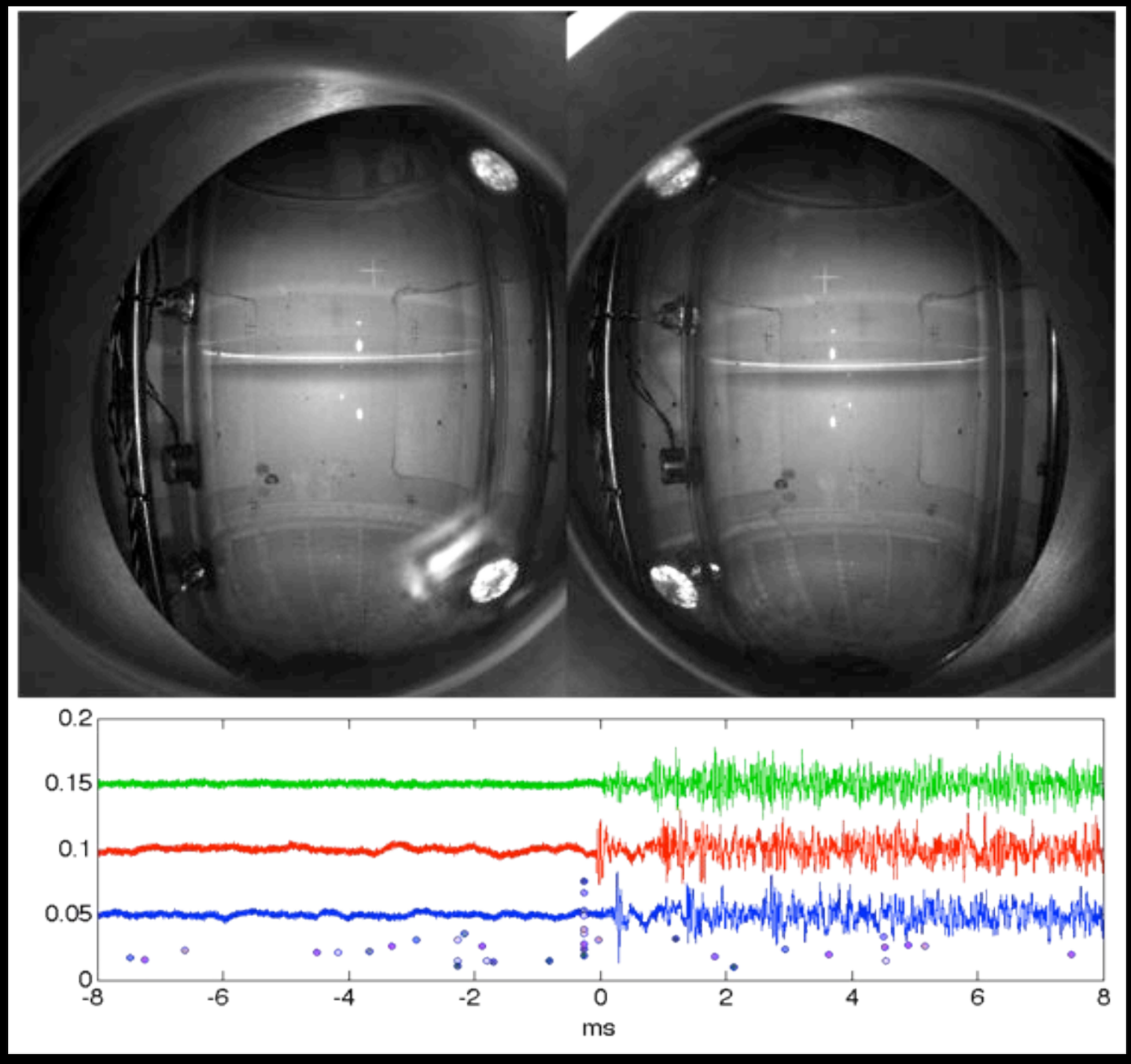
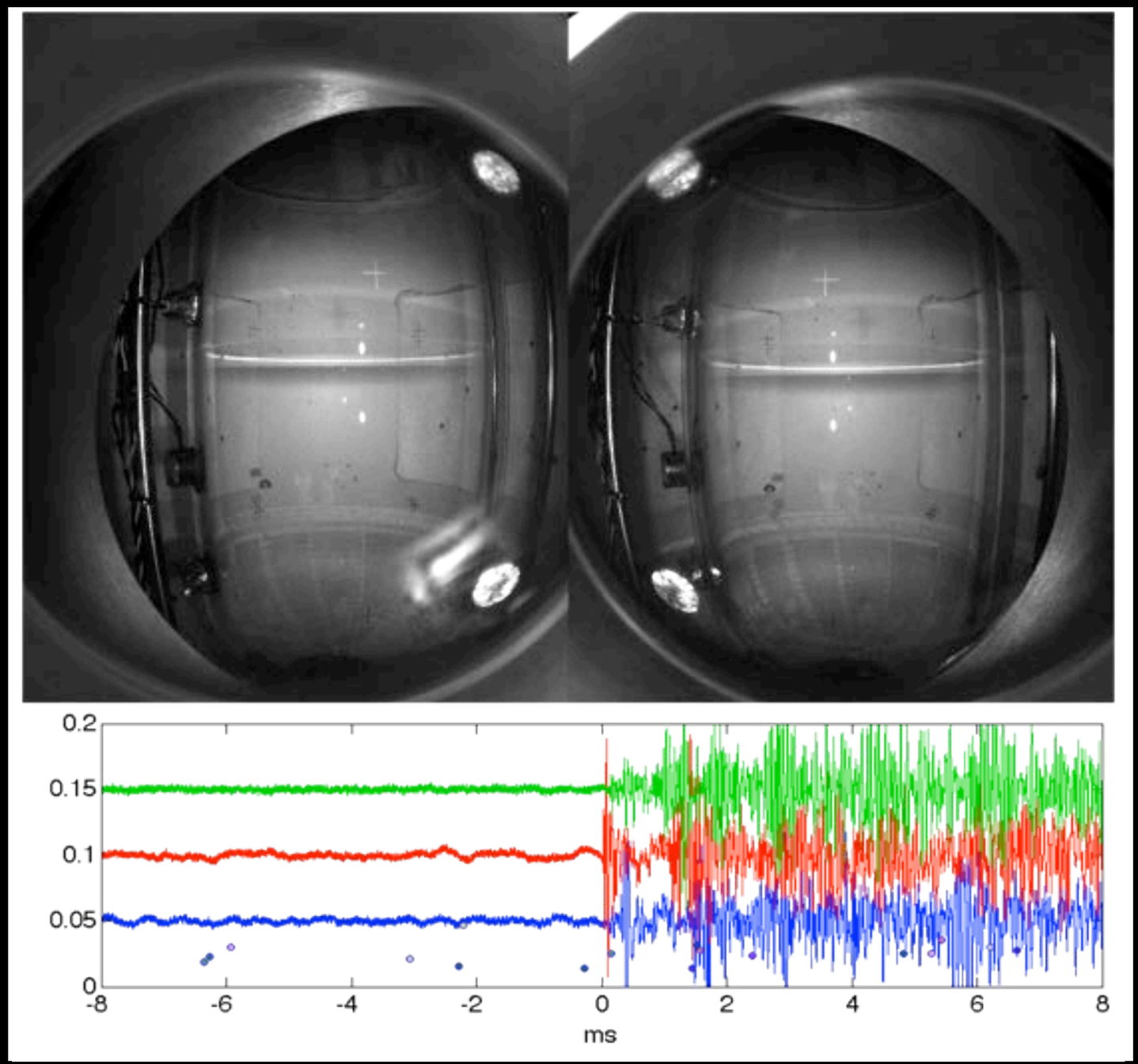


This is what an alpha sounds like



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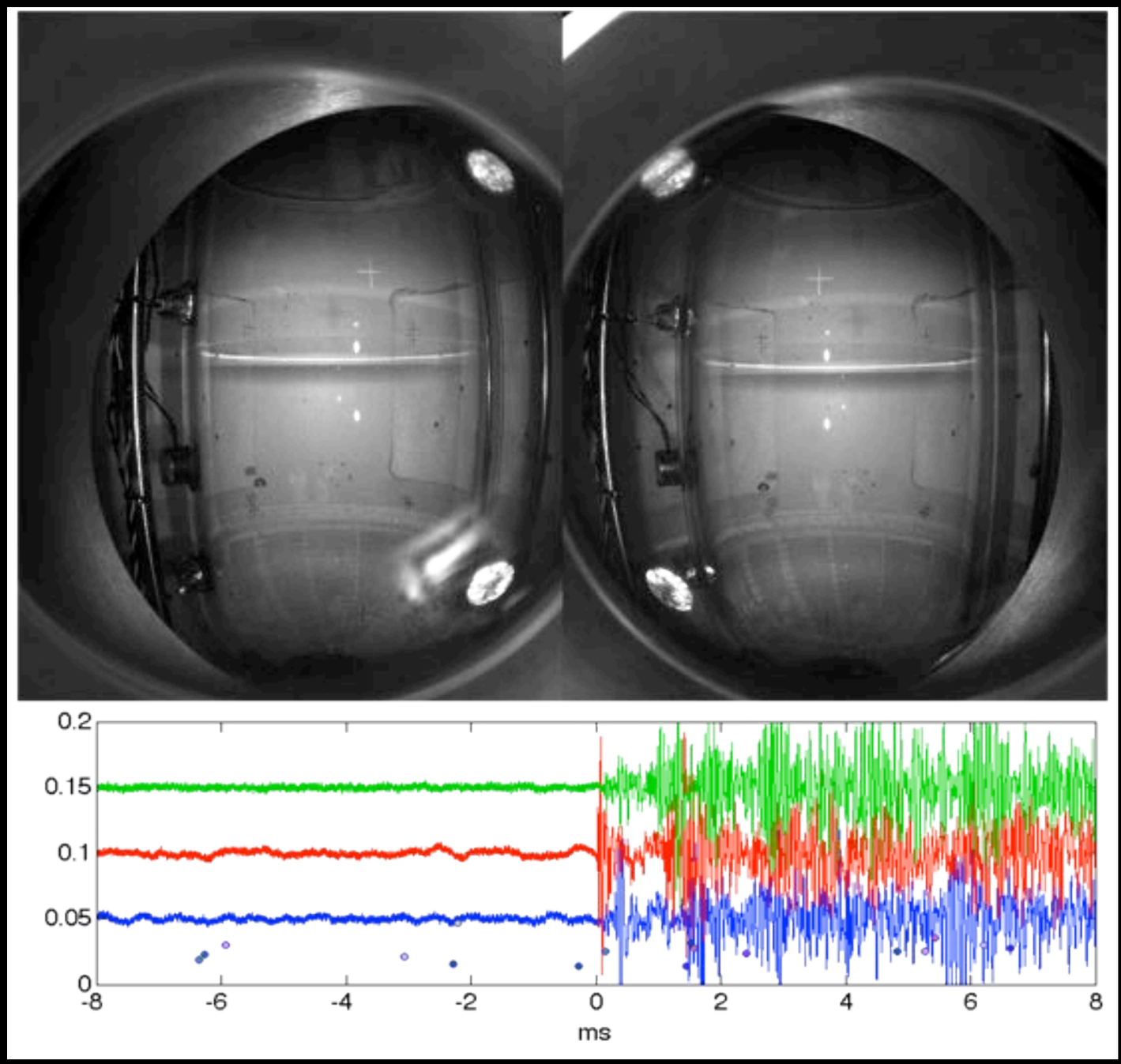
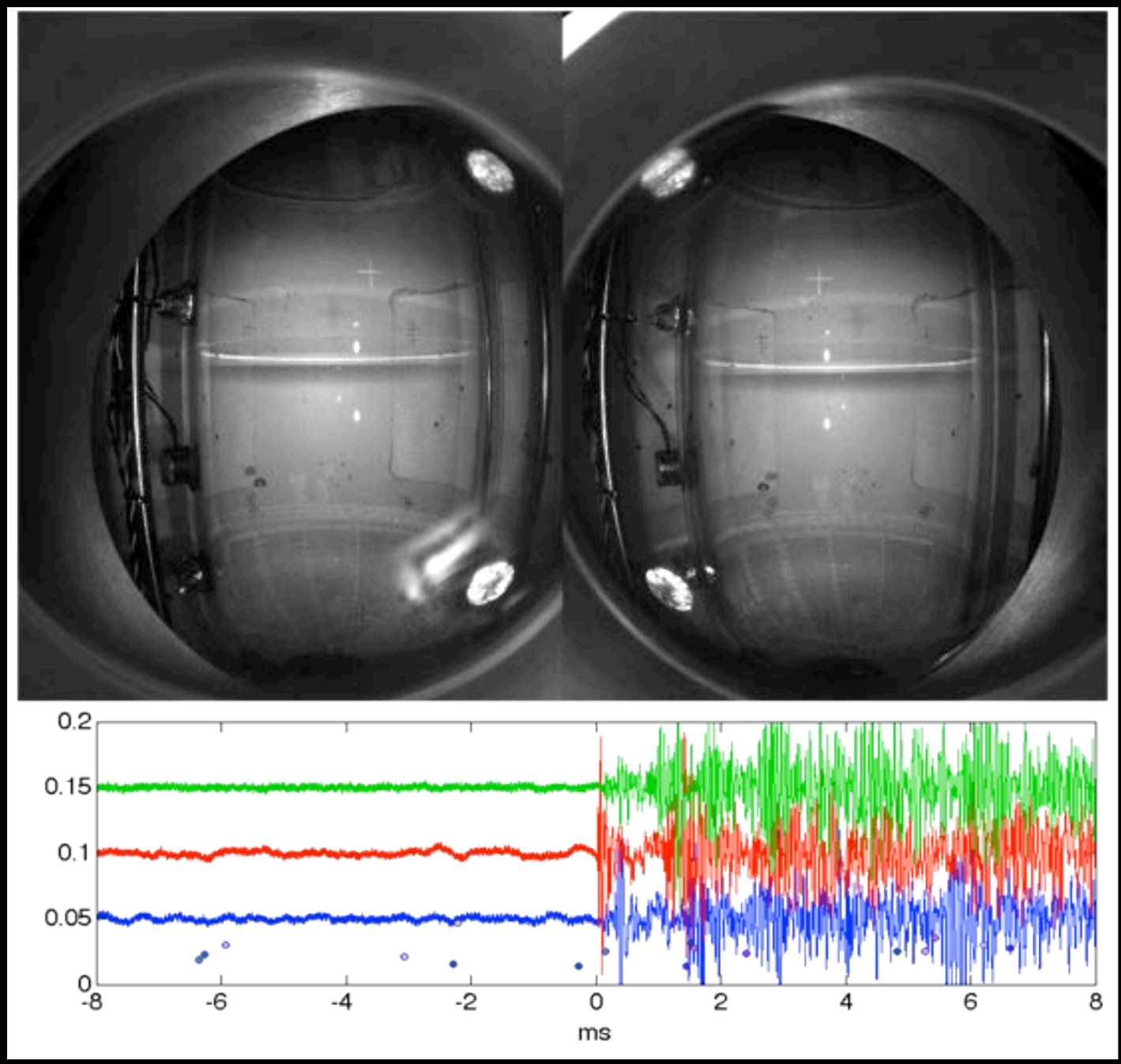


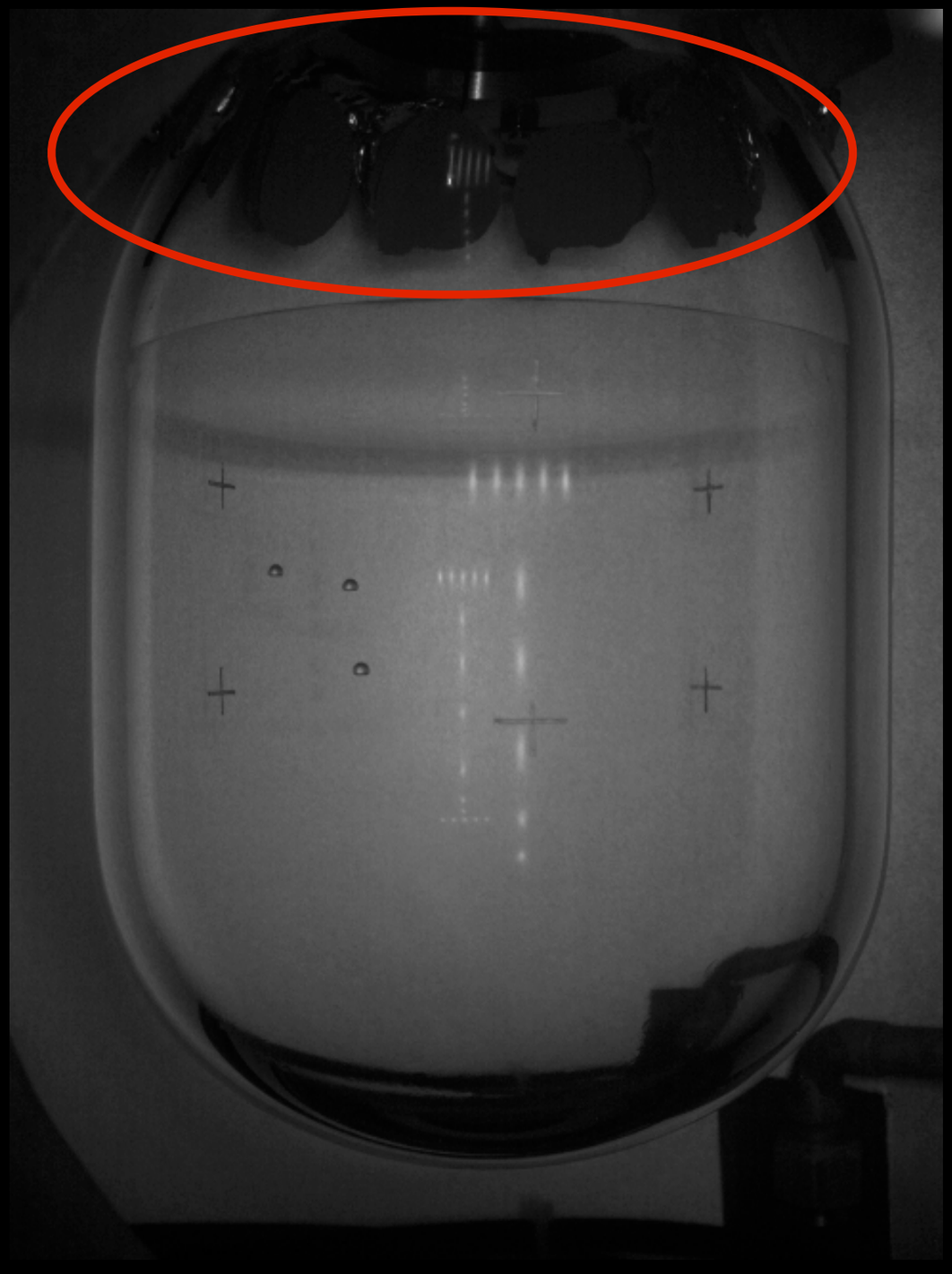
Both together, just to hear the difference



COUPP4: Results and sensitivity

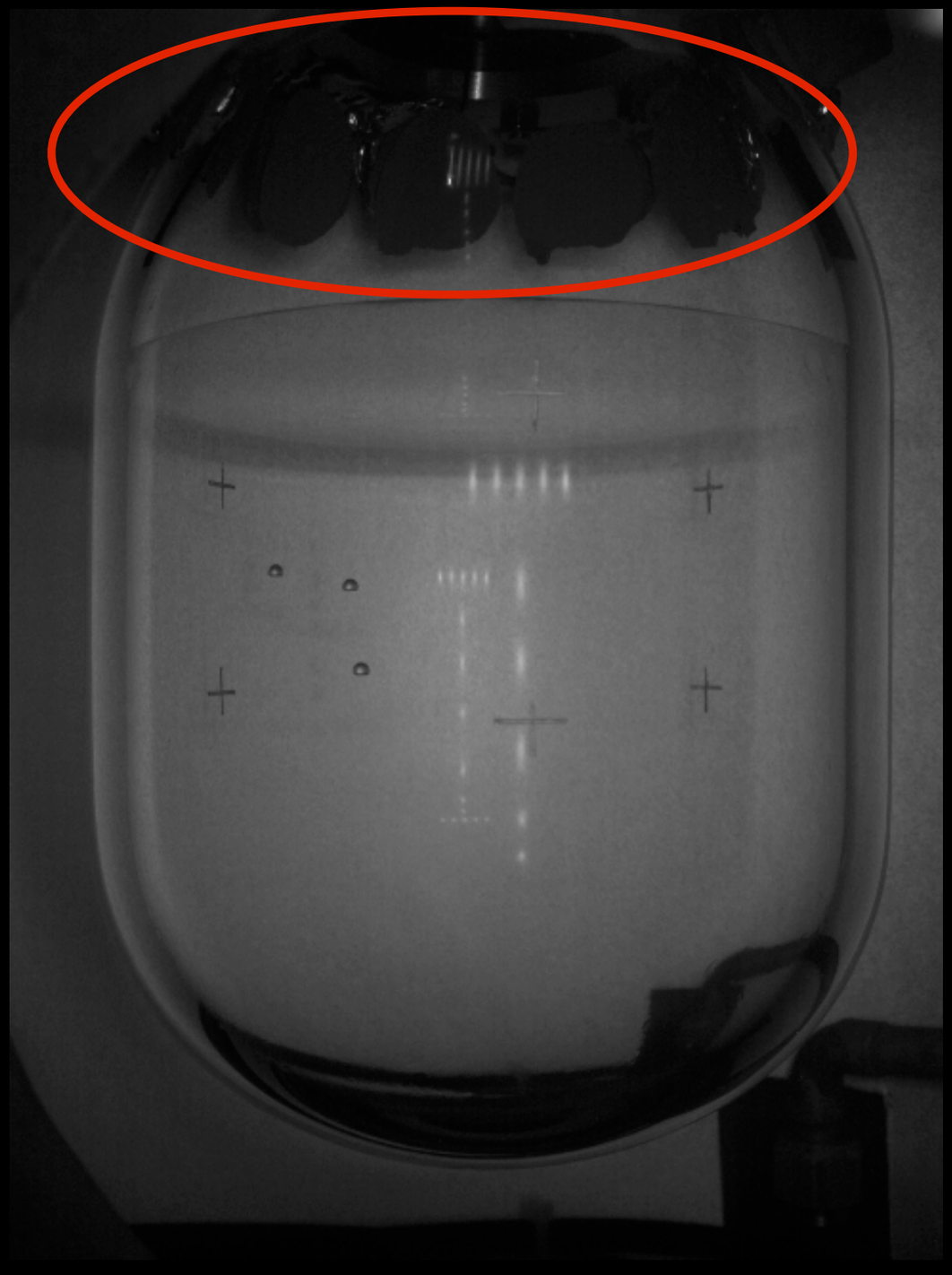
- 20 WIMP candidates (6 at 8 keV, 6 at 11 keV, 8 at 16 keV)
  - 3 multiple bubble events imply neutrons

COUPP4: Results and sensitivity



- 20 WIMP candidates (6 at 8 keV, 6 at 11 keV, 8 at 16 keV)
  - 3 multiple bubble events imply neutrons
  - U, Th in the piezo-acoustic sensors and the viewports

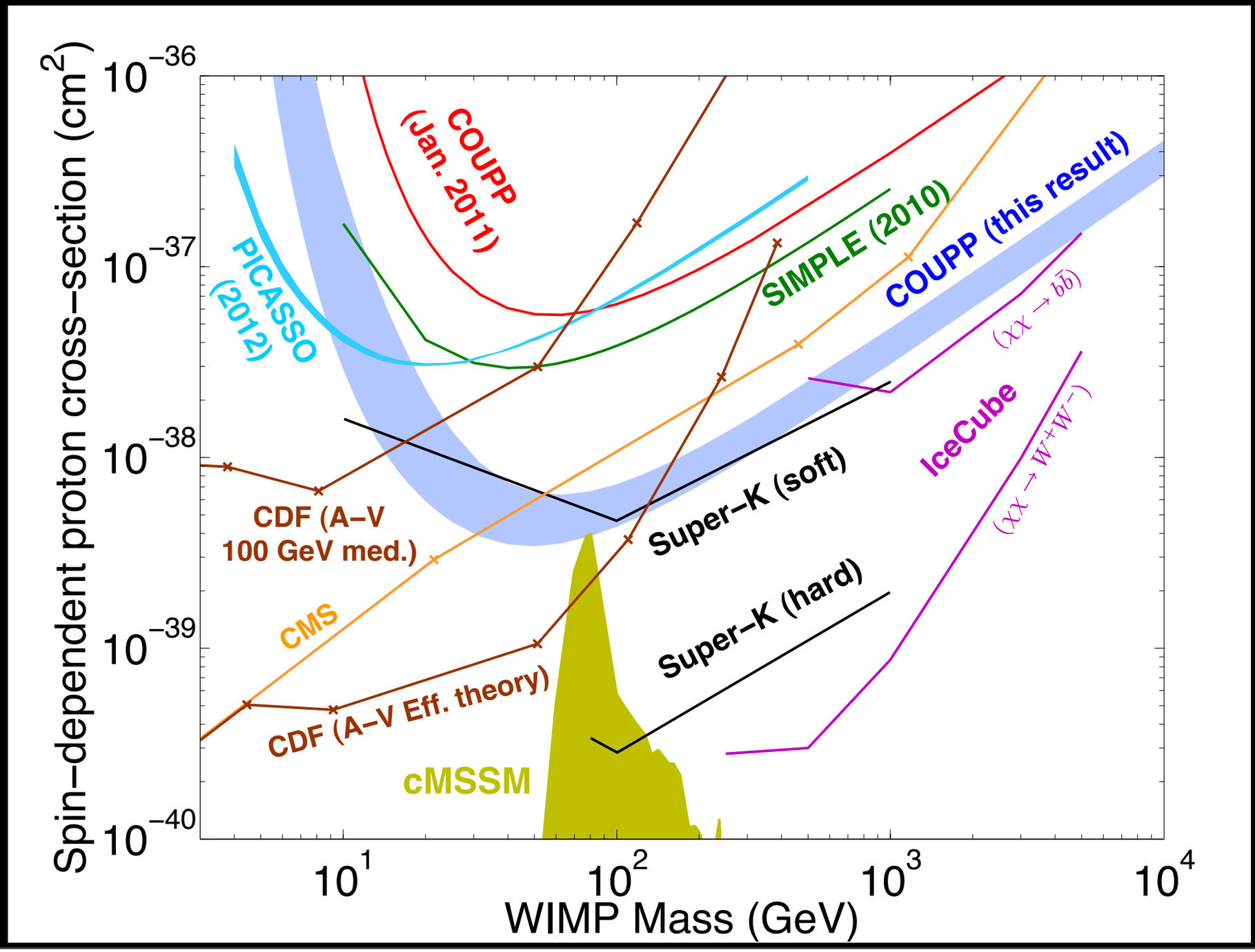
COUPP4: Results and sensitivity



- 20 WIMP candidates (6 at 8 keV, 6 at 11 keV, 8 at 16 keV)
  - 3 multiple bubble events imply neutrons
  - U, Th in the piezo-acoustic sensors and the viewports
- Remaining excess of singles at low threshold
  - Time clustering
  - Correlated with activity at water-CF_3I interface

COUPP4: Results and sensitivity

- Given uncertainties on backgrounds, no background subtraction: PRD 86:052001 (2012)



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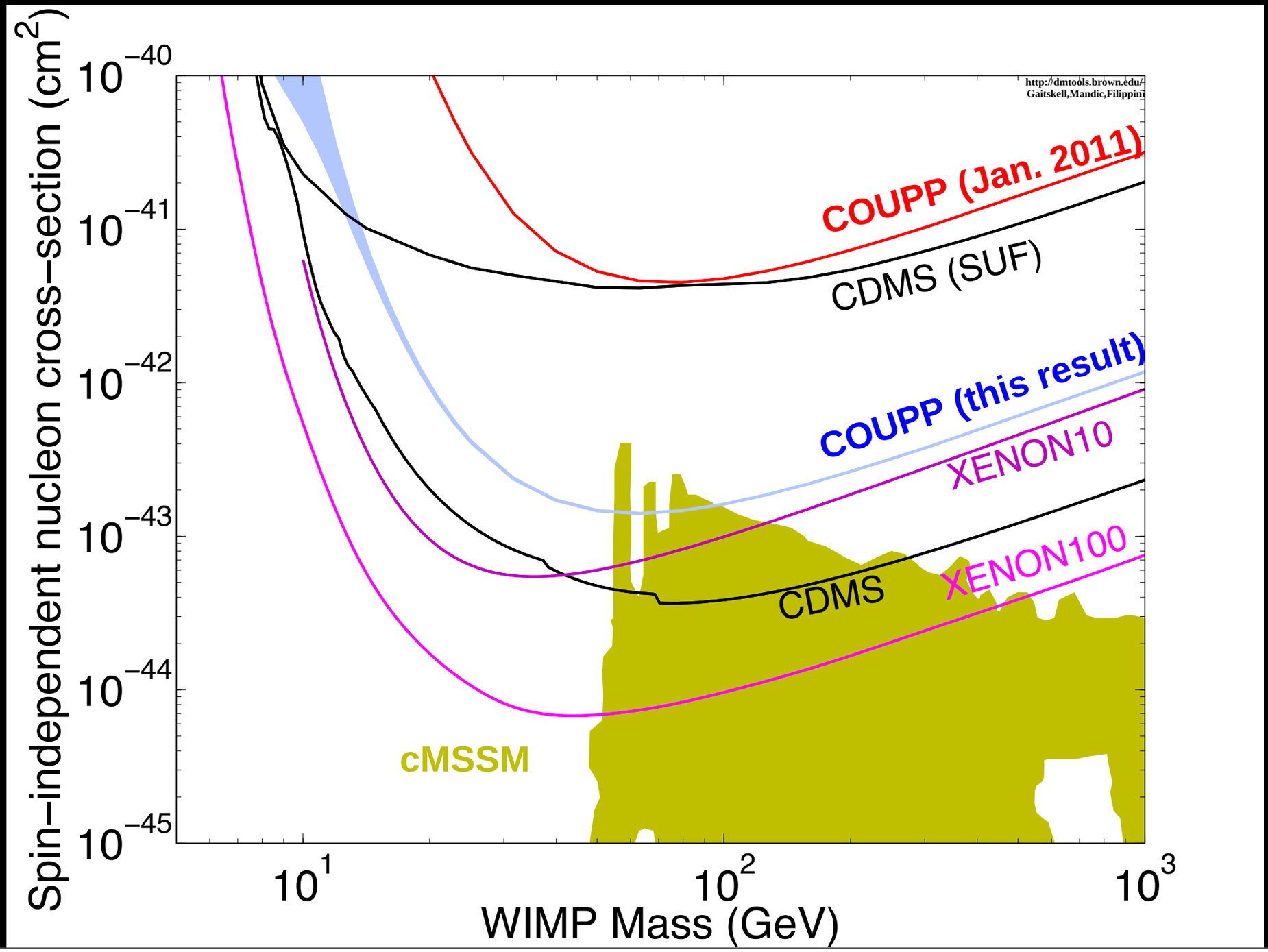
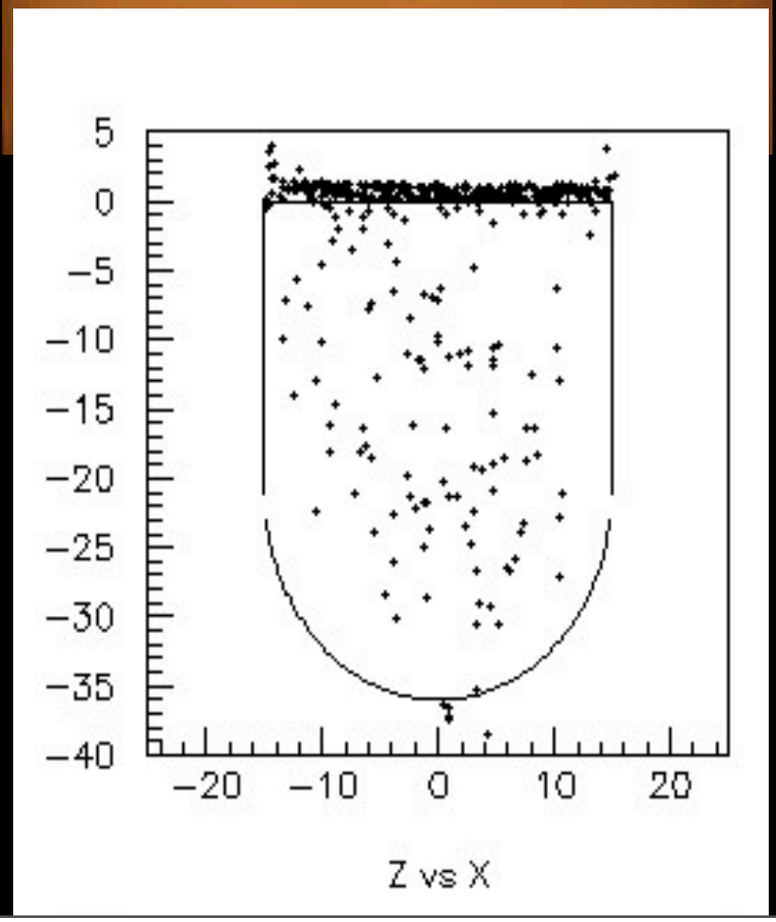


COUPP60

- Engineering run at shallow site in 2010
  - Low backgrounds and acoustic discrimination

COUPP60

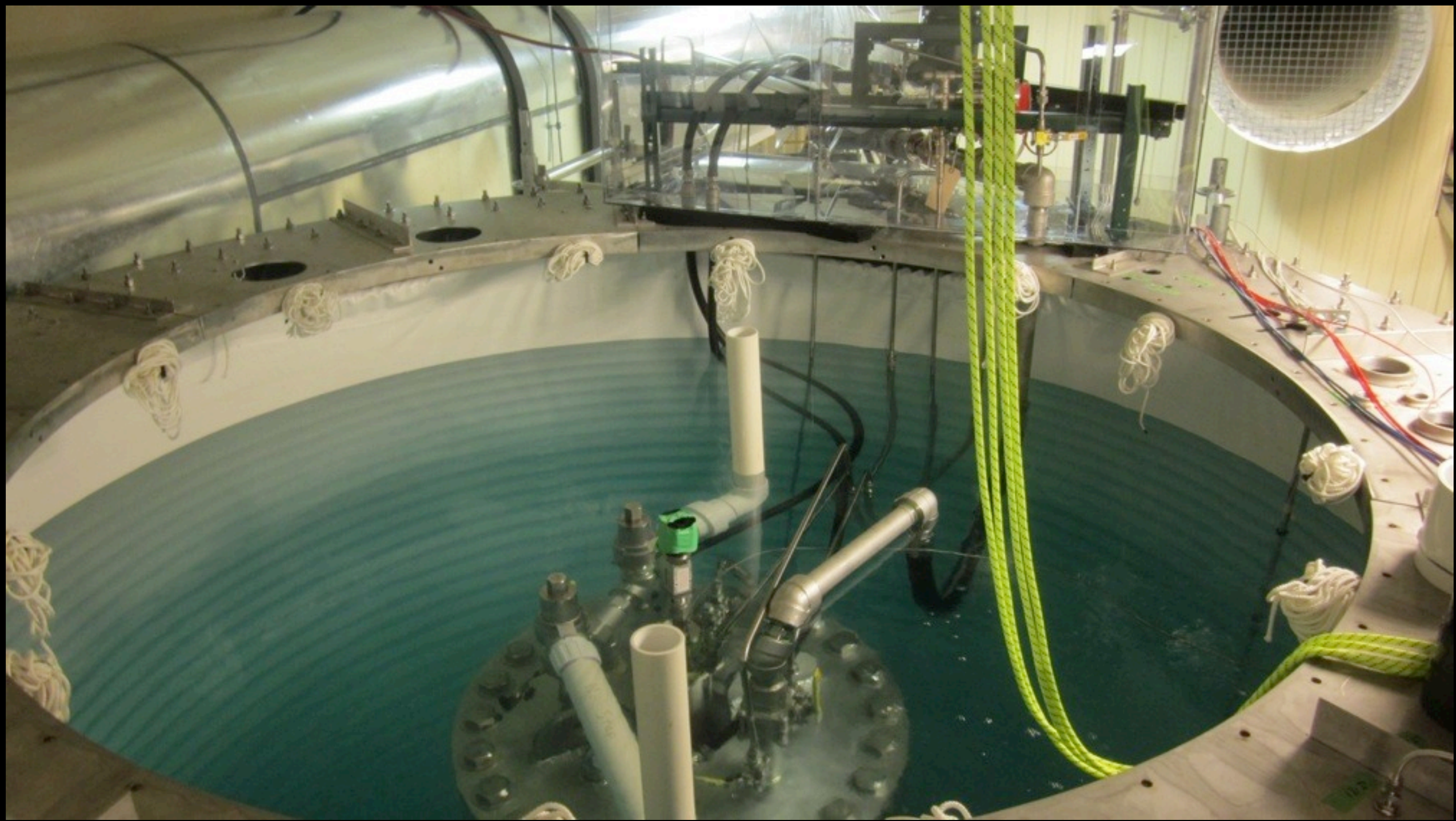
- Engineering run at shallow site in 2010
  - Low backgrounds and acoustic discrimination
  - Fluid darkening due to photodissociation of iodine
  - Excessive surface rate



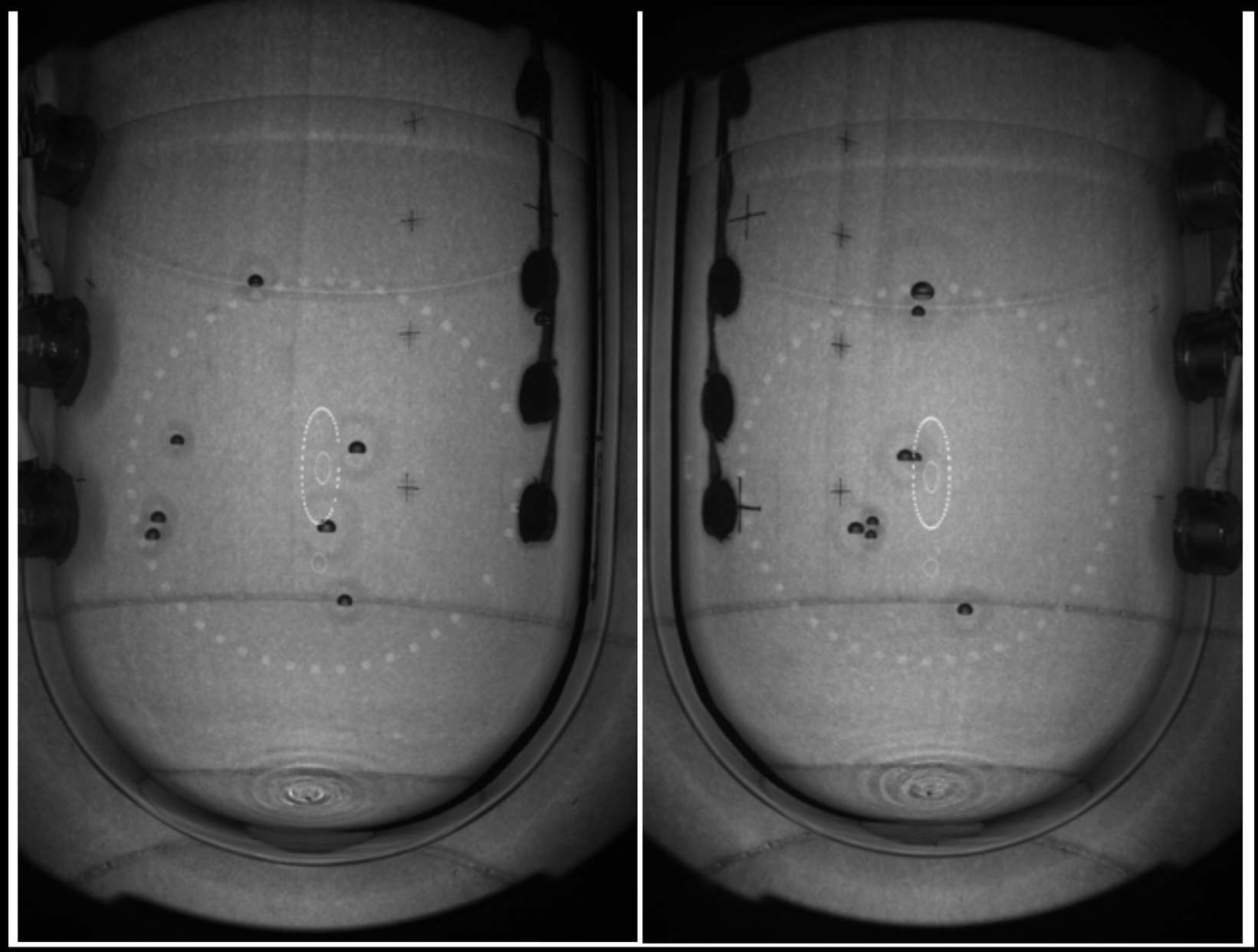
COUPP60

- Engineering run at shallow site in 2010
  - Low backgrounds and acoustic discrimination
  - Fluid darkening due to photodissociation of iodine
  - Excessive surface rate
- Improved purification and chemistry, tested in November, 2011
- Moved to SNOLAB beginning summer of 2012


CYLINDER
EMPTY
IN USE

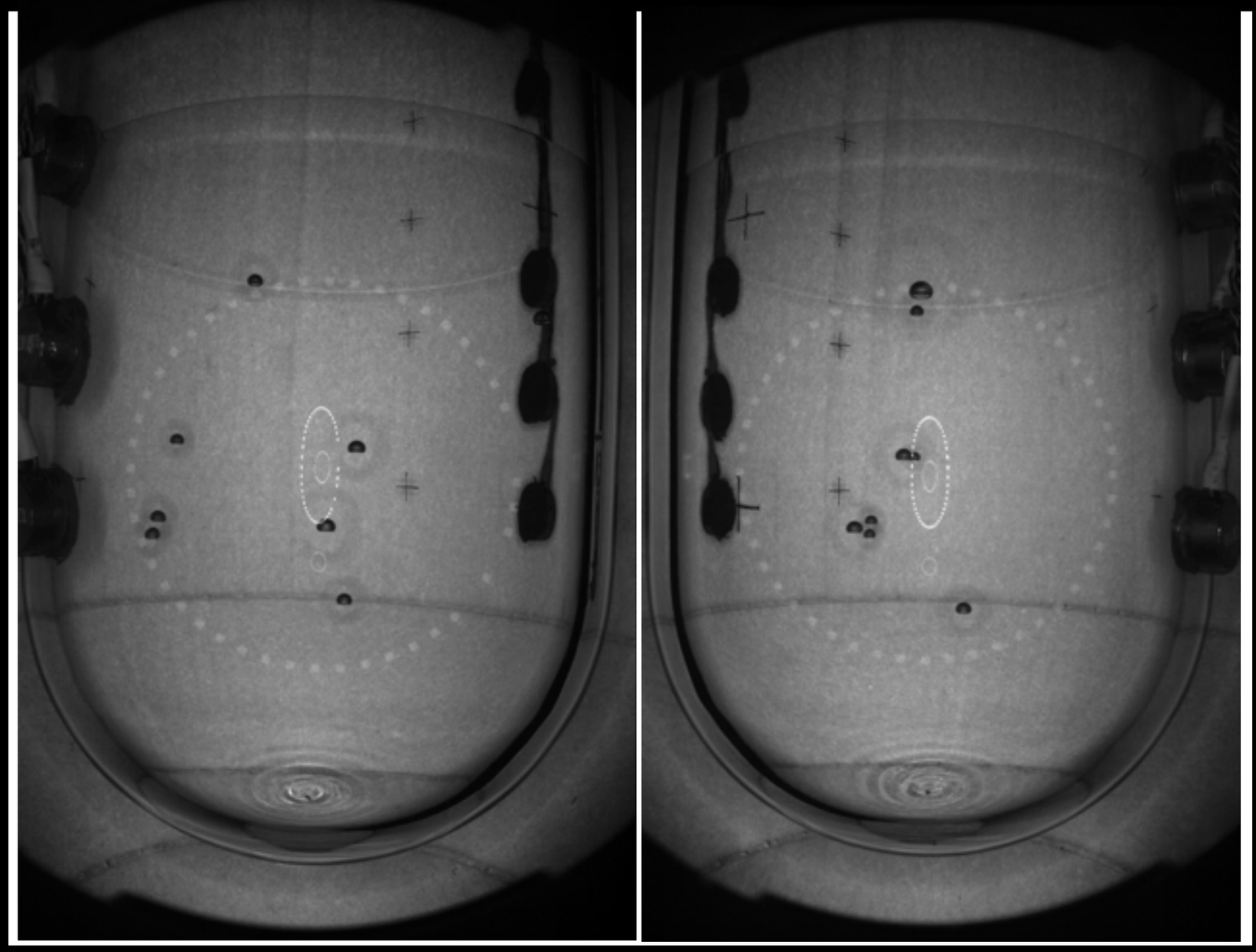


COUPP60



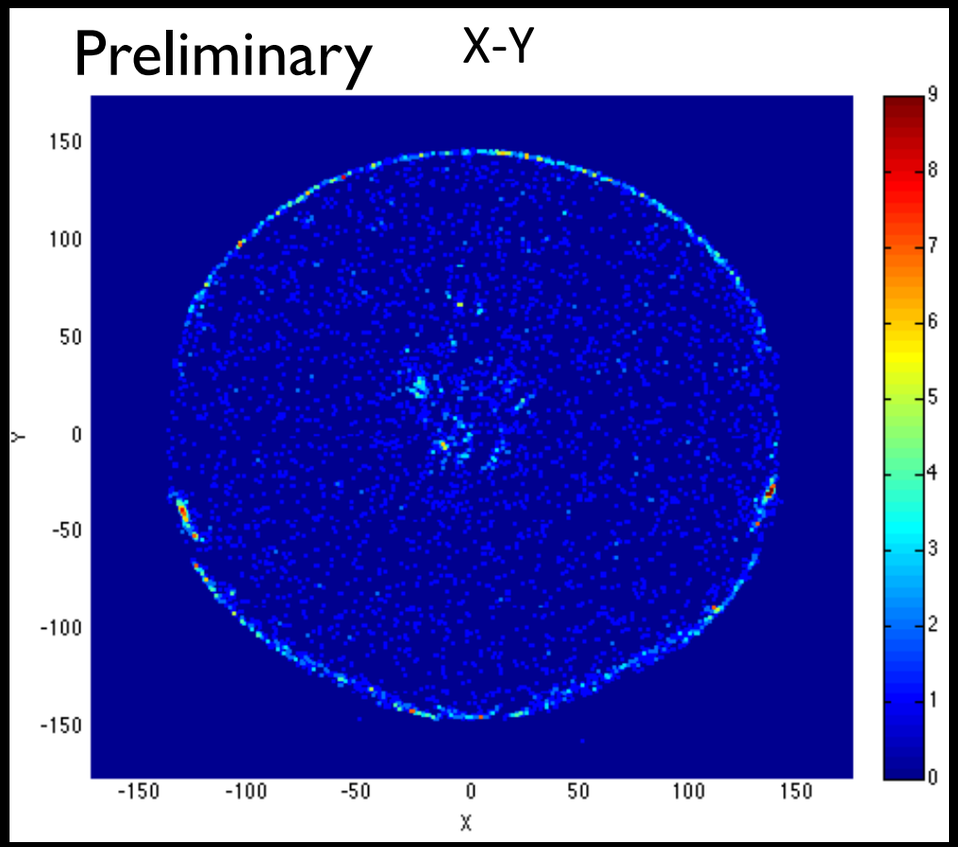
- Filled with 36.8 kg of CF_3I at end of April, 2013
- First bubble observed on May 1 (radon decay)
- Physics data started June 13

COUPP60

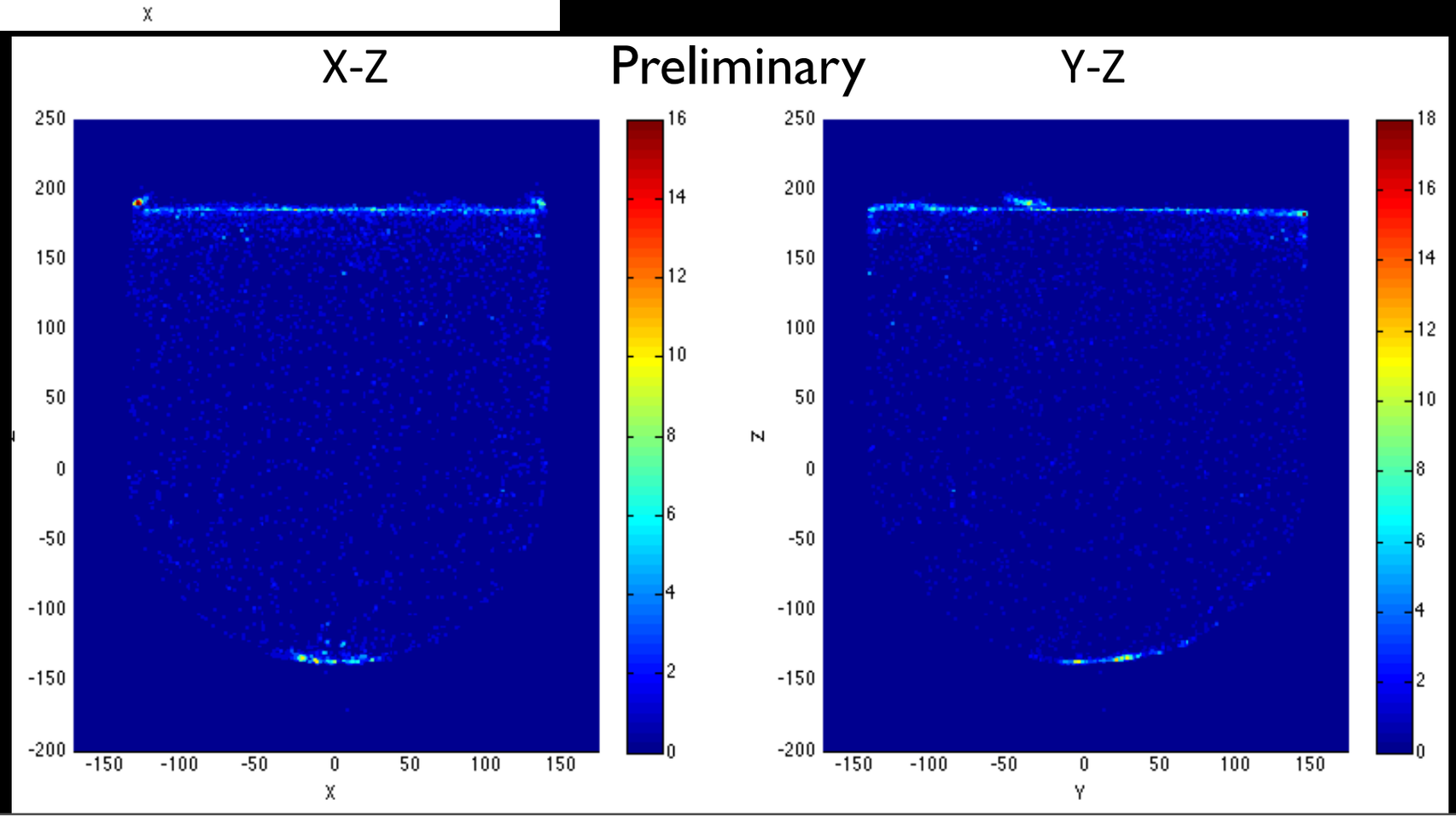


- Collected >2700 kg-days of dark matter search data between 9 and 25 keV threshold
  - Good live fraction > 80%, no darkening
- >1500 neutron source events from calibration runs

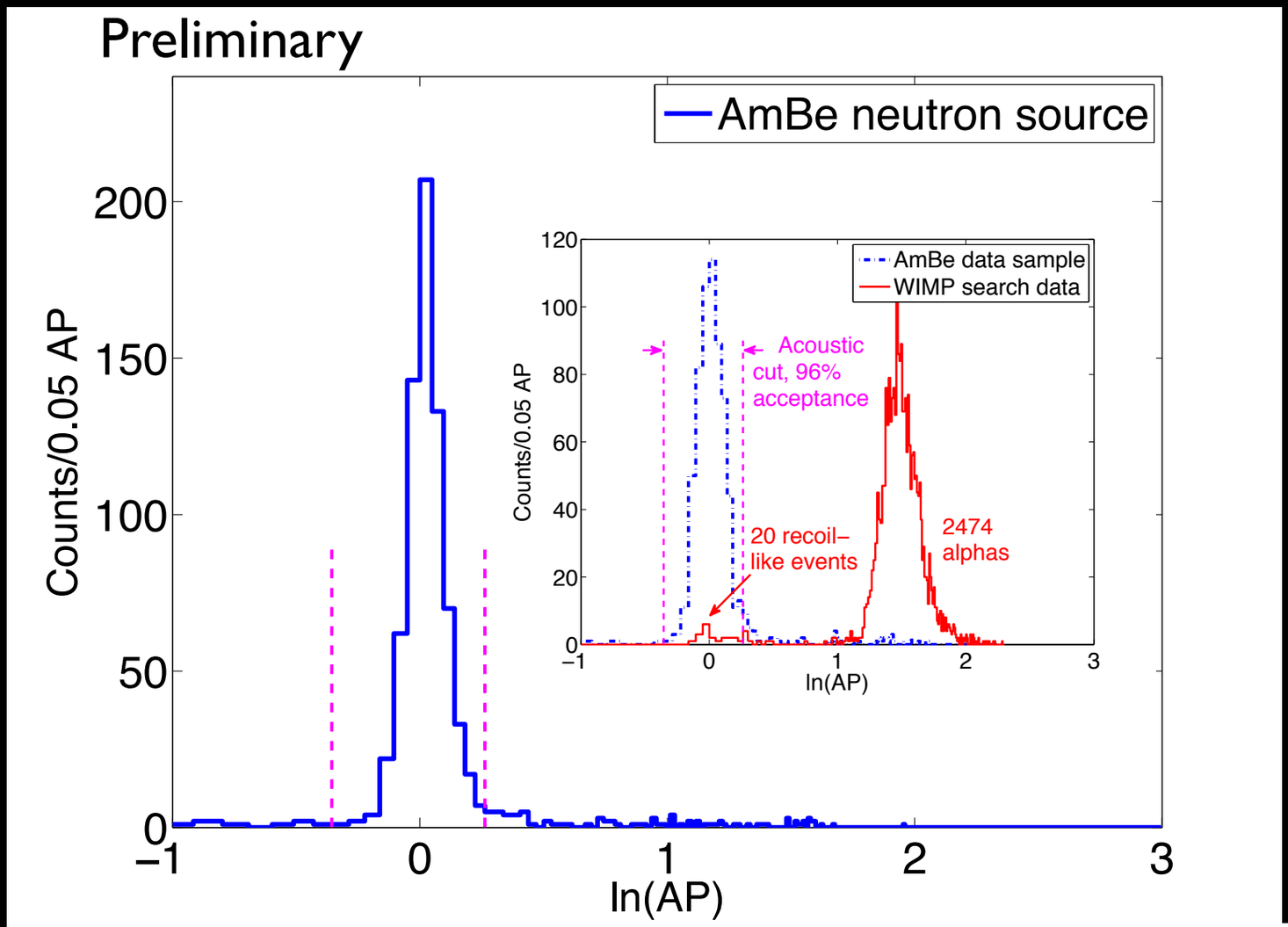
COUPP60 - the data



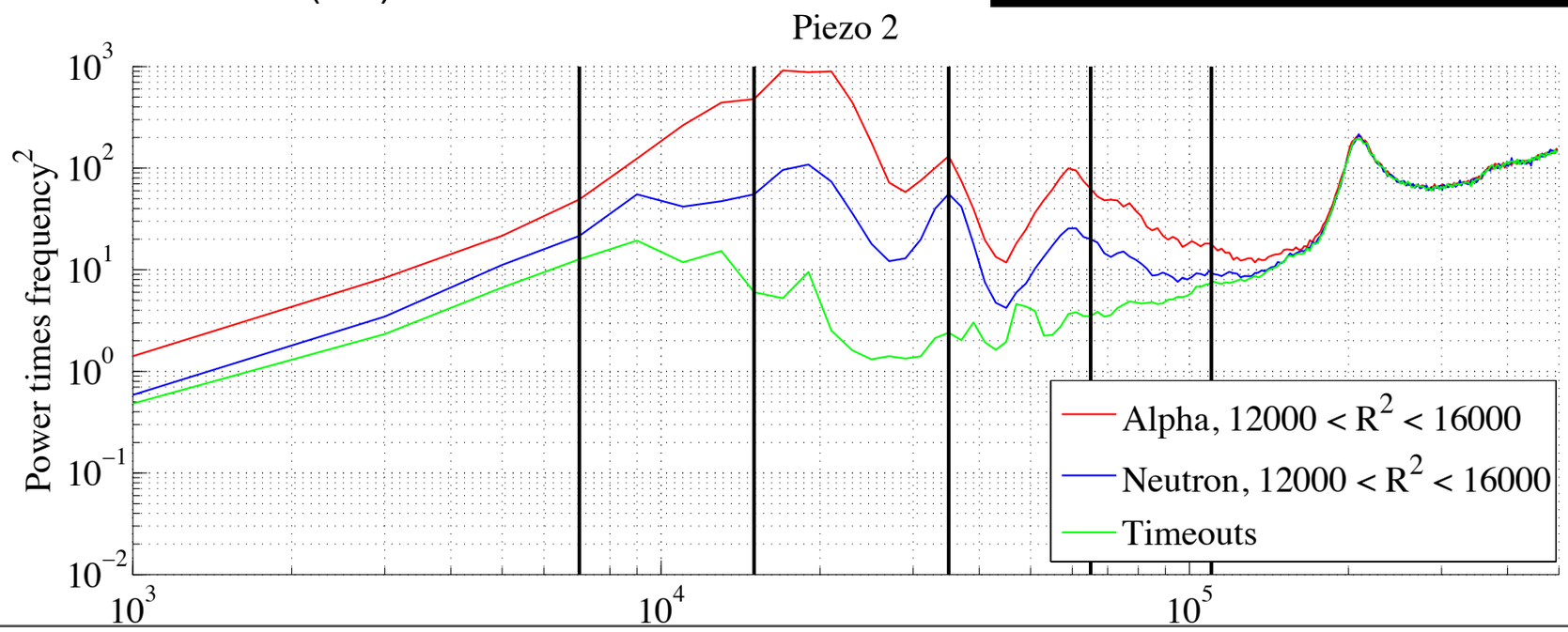
- Position reconstruction working well
- Clear set of events on surface and hemisphere
- Not a background, and rate is under control



COUPP60 - the data

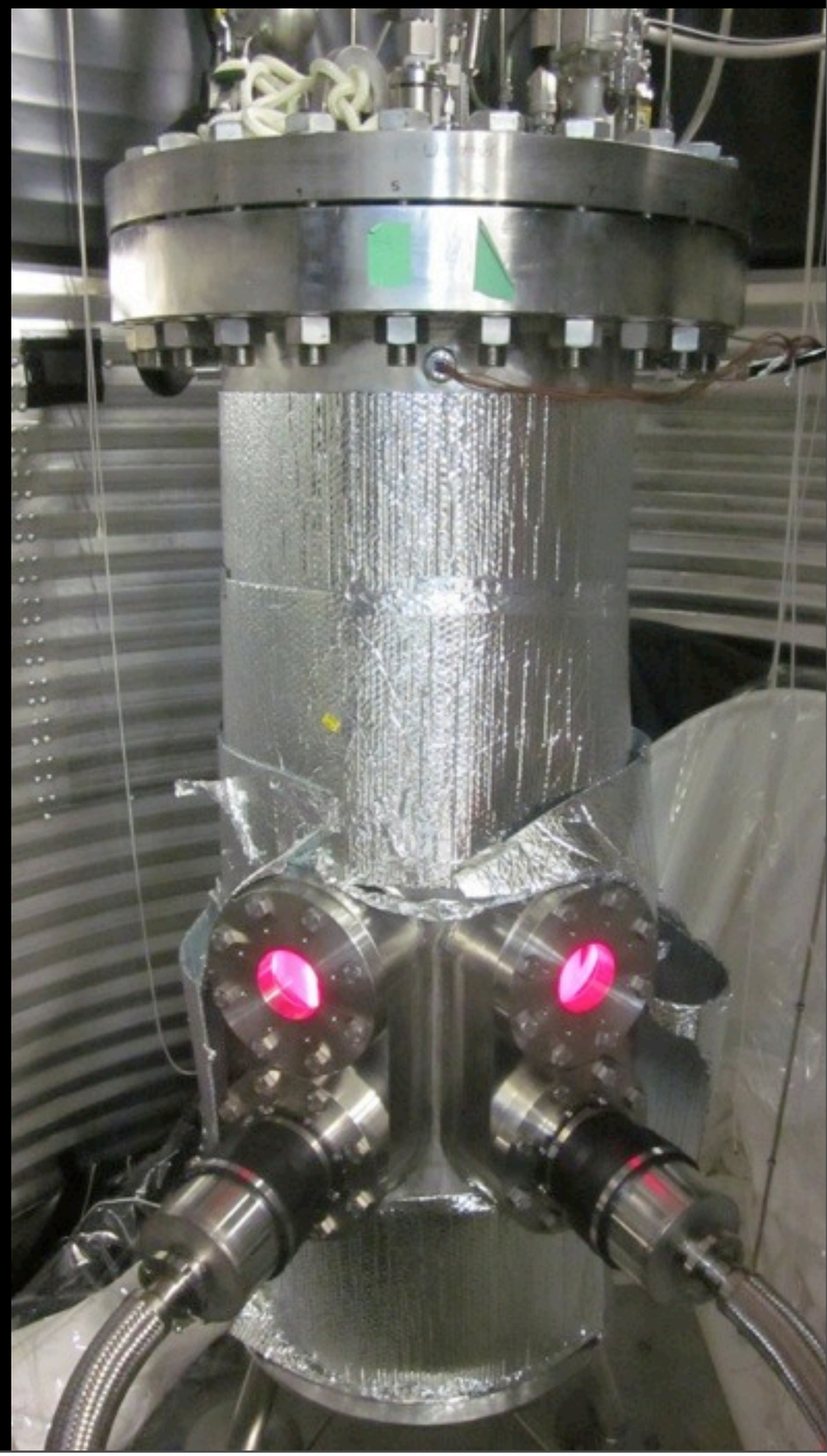


- Acoustics are working well
  - Calibration data show a narrower distribution than COUPP4
- Alpha discrimination still very strong



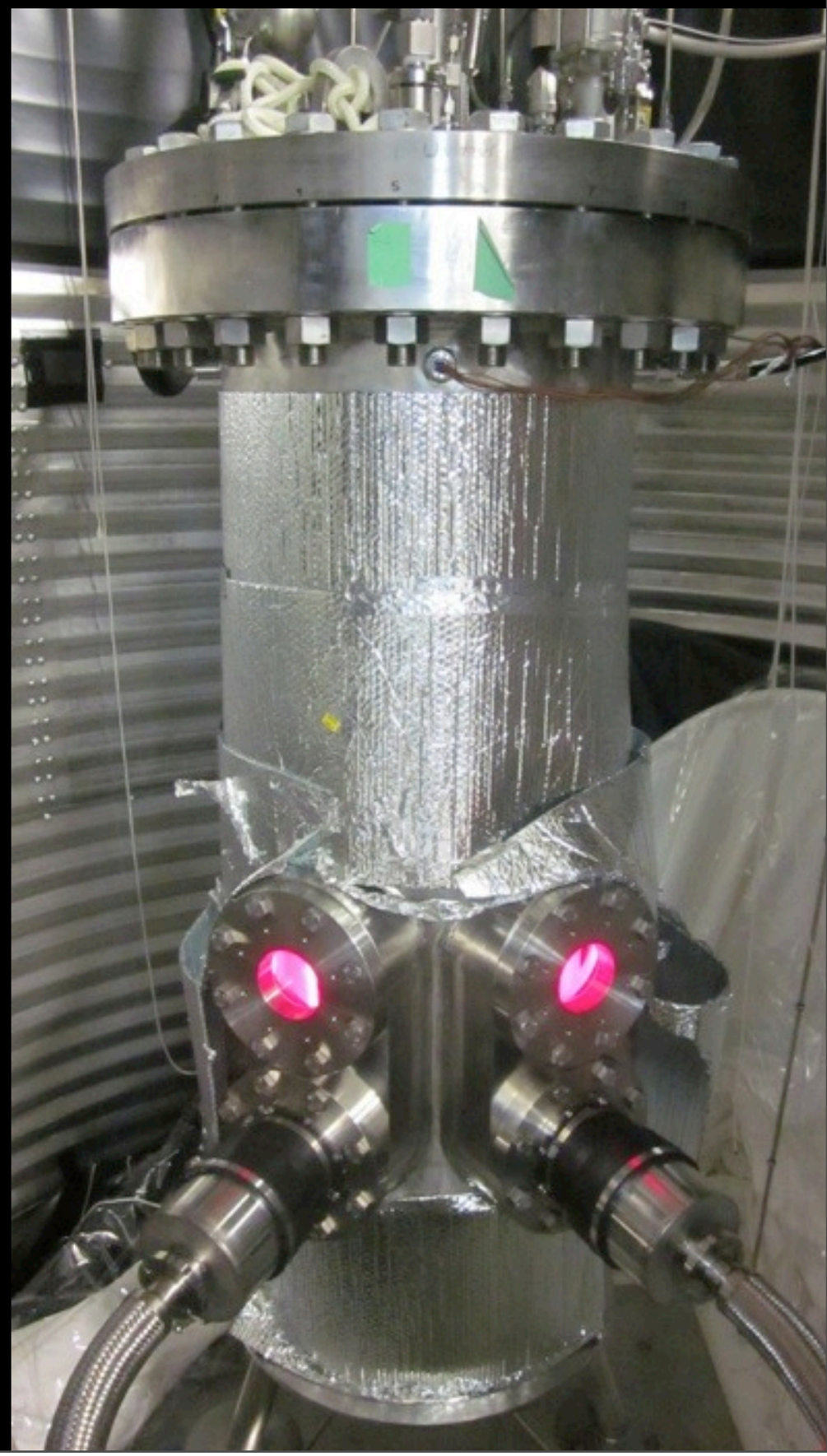
COUPP60 - the data

- Analysis still under development
- Good news:
- Bad news:



COUPP60 - the data

- Analysis still under development
- Good news: Zero multiple bubbles, no neutrons. Limit on neutron rate is factor 6 below observed rate in COUPP4
- Bad news:



COUPP60 - the data

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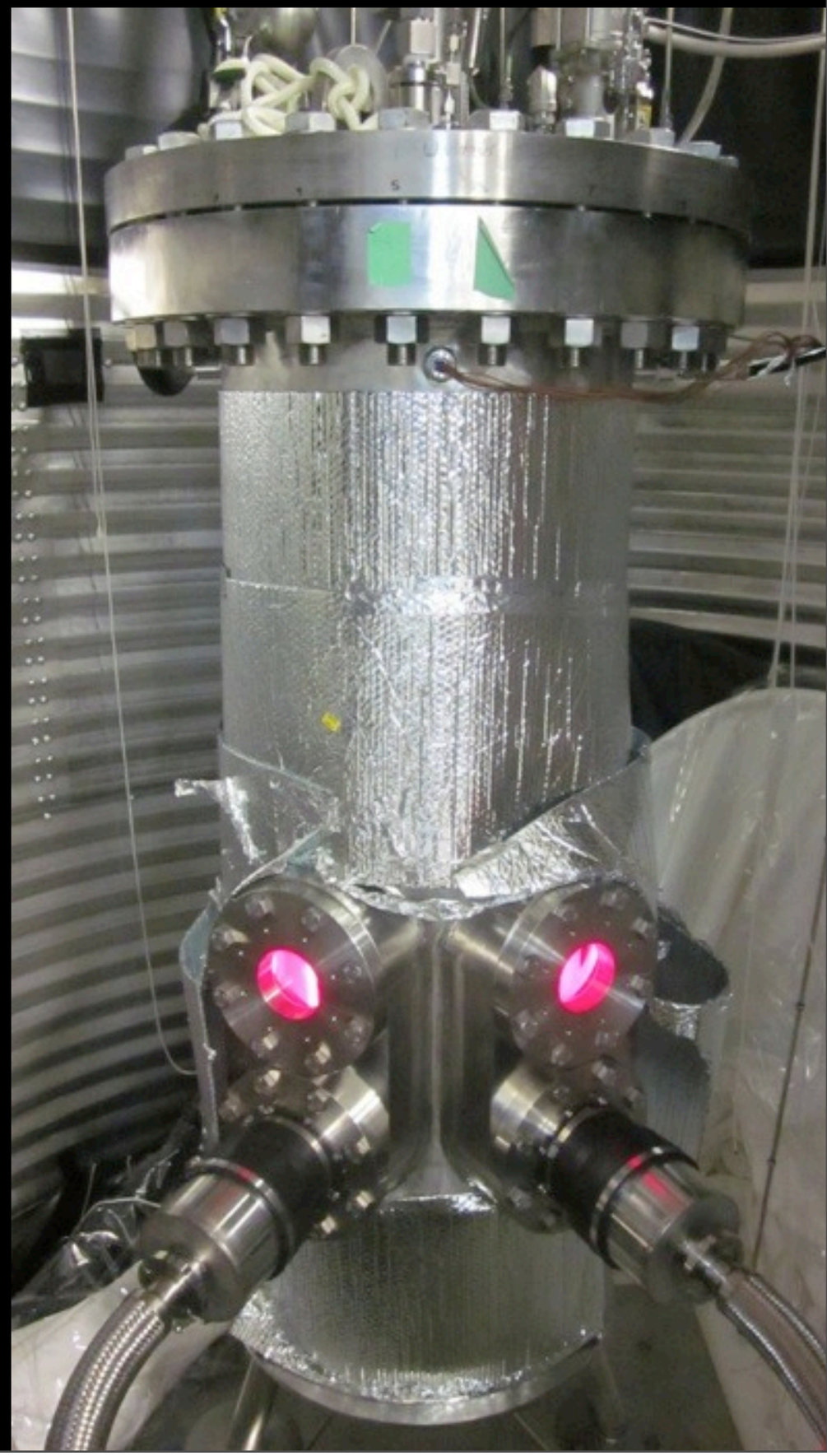
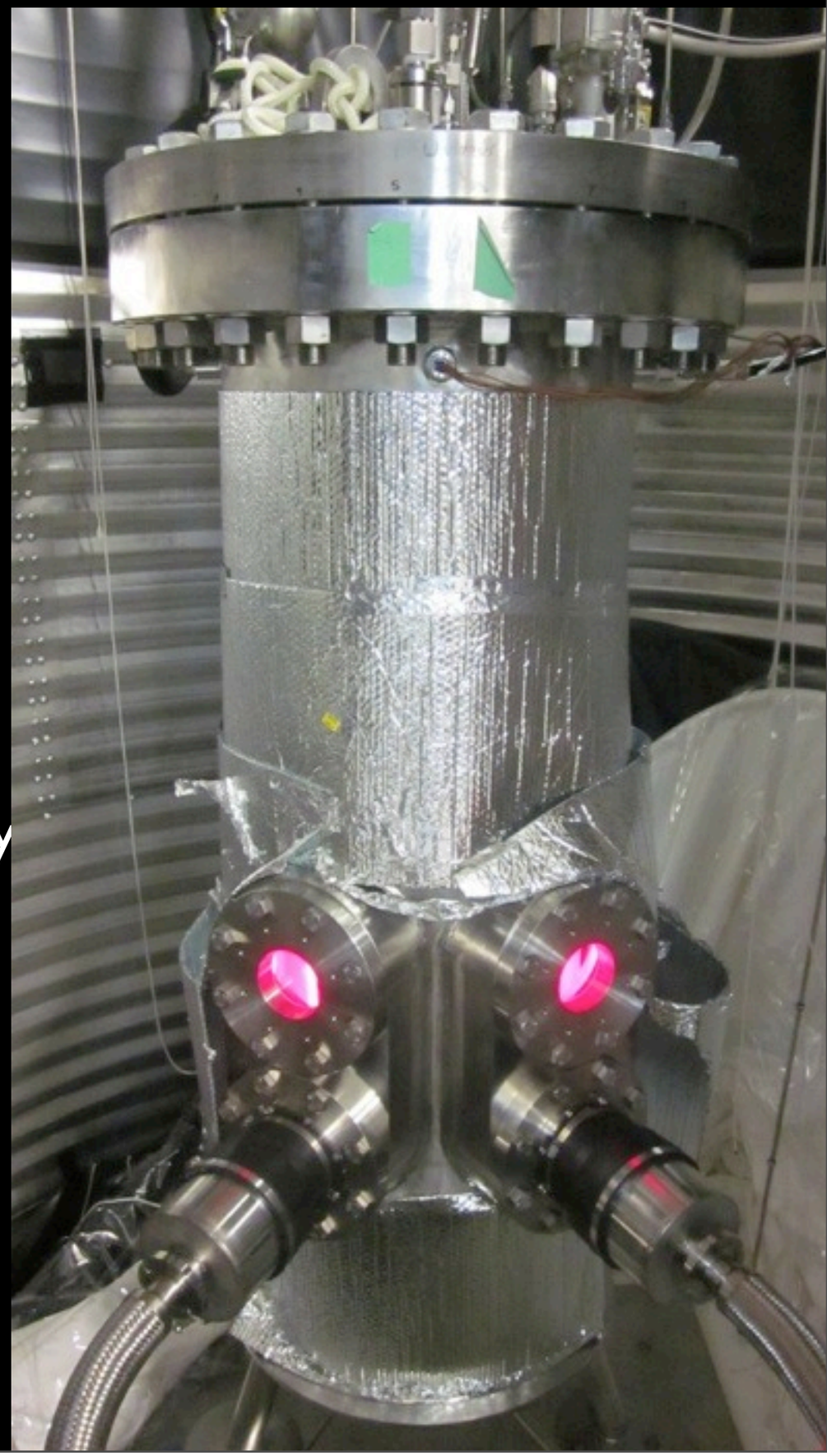
- Good news: Zero multiple bubbles, no neutrons. Limit on neutron rate is factor 6 below observed rate in COUPP4
- Bad news: Population of events that sound like nuclear recoils but are clearly not WIMPs
- Silver lining:



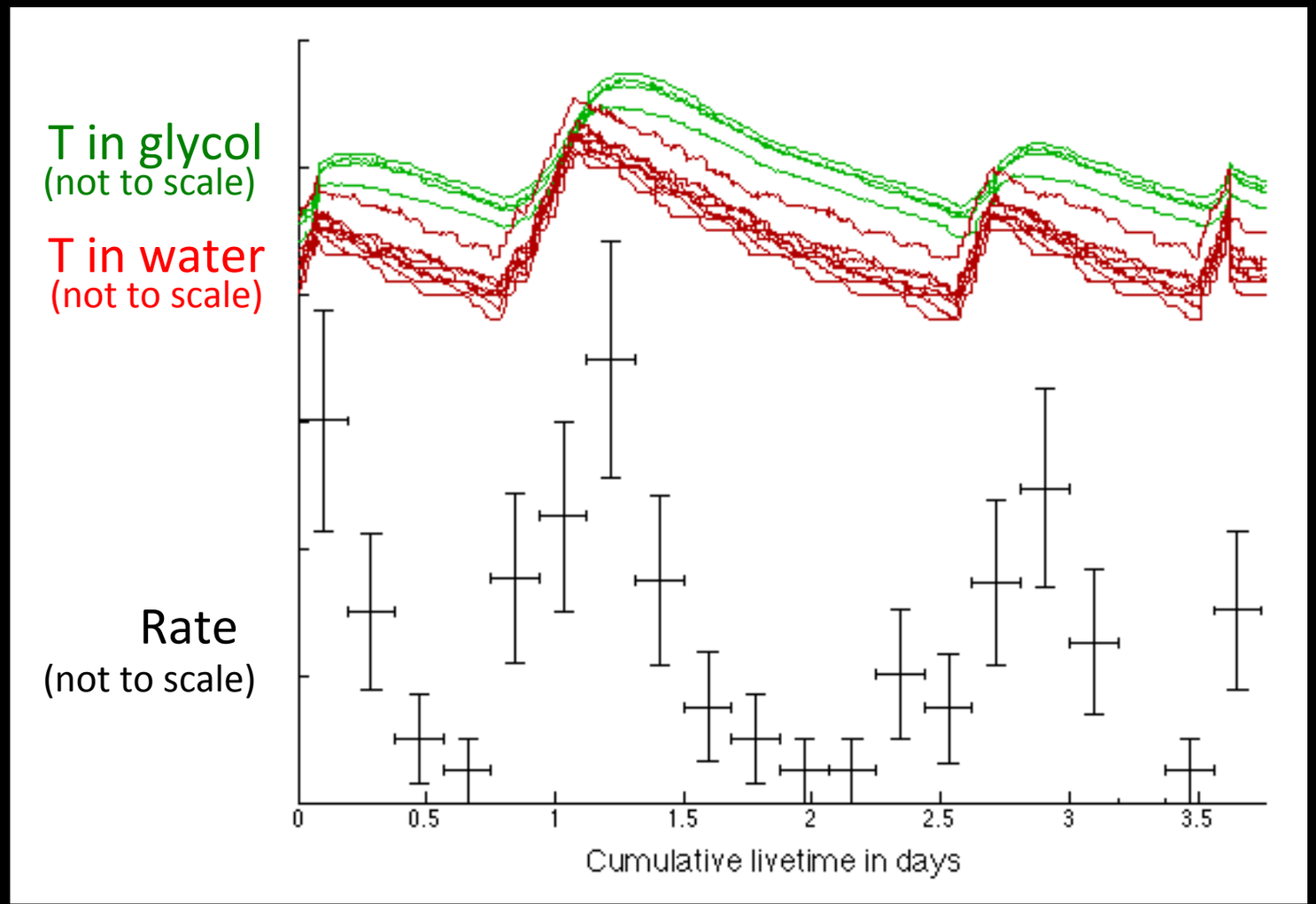
COUPP60 - the data

- Analysis still under development
- Good news: Zero multiple bubbles, no neutrons. Limit on neutron rate is factor 6 below observed rate in COUPP4
- Bad news: Population of events that sound like nuclear recoils but are clearly not WIMPs
- Silver lining: statistics - we can actually study them in detail

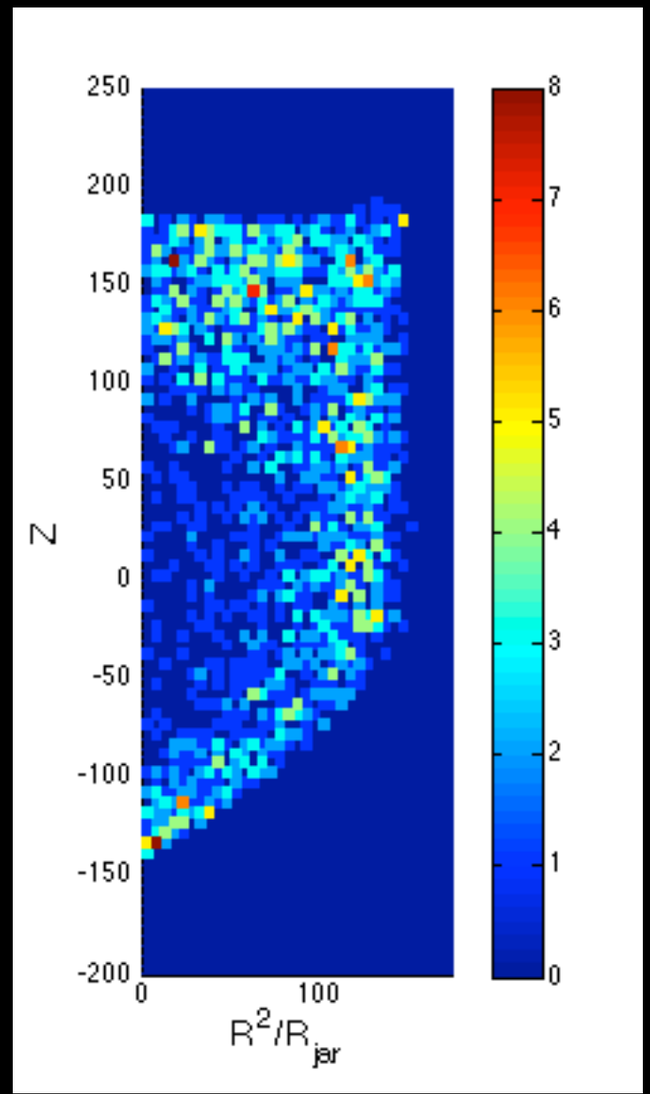


COUPP60 - the data

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

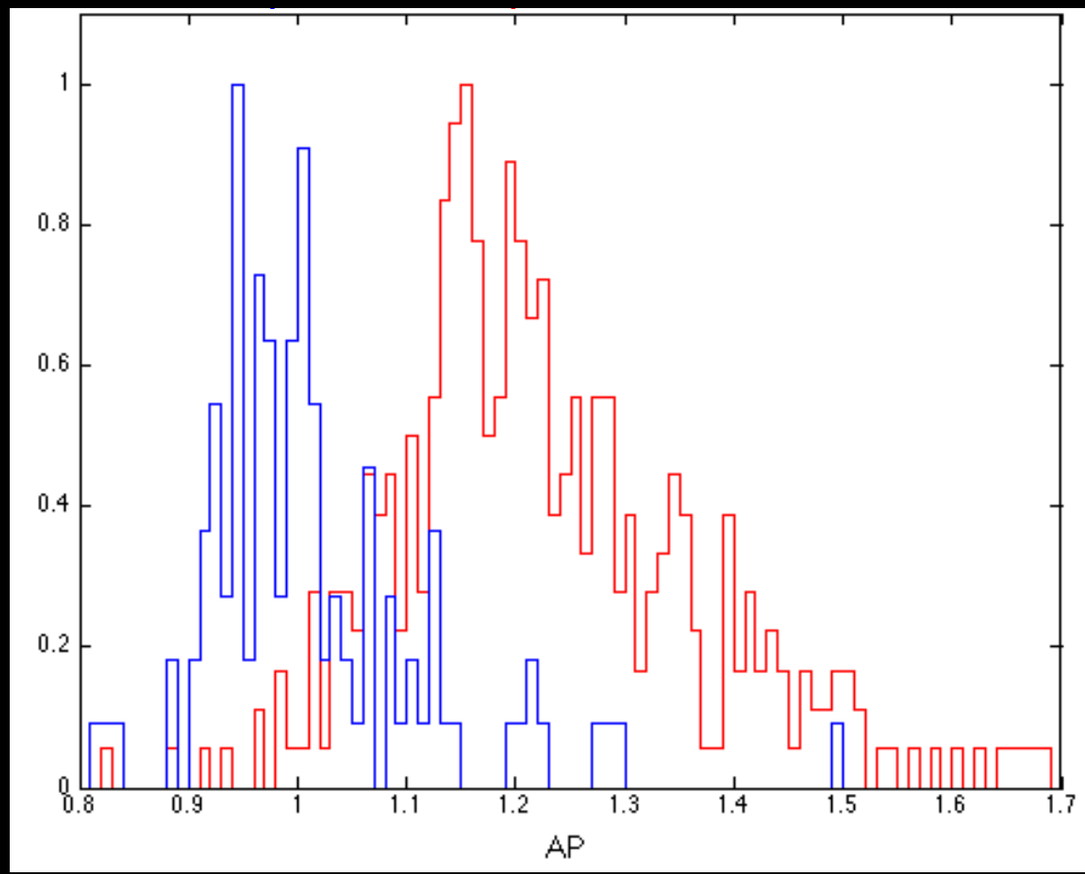


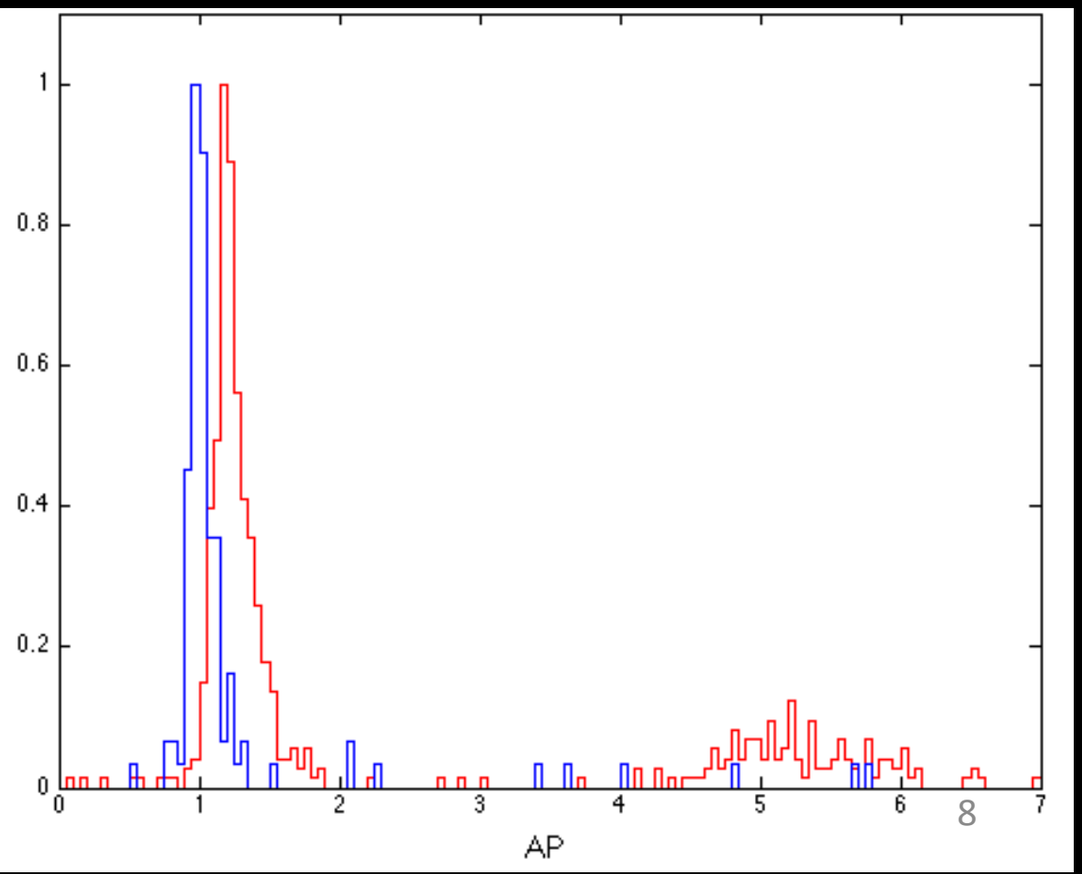
- Spatial dependence - looks temperature-related to me



COUPP60 - the data

- Clear shift in acoustics relative to neutron calibration data





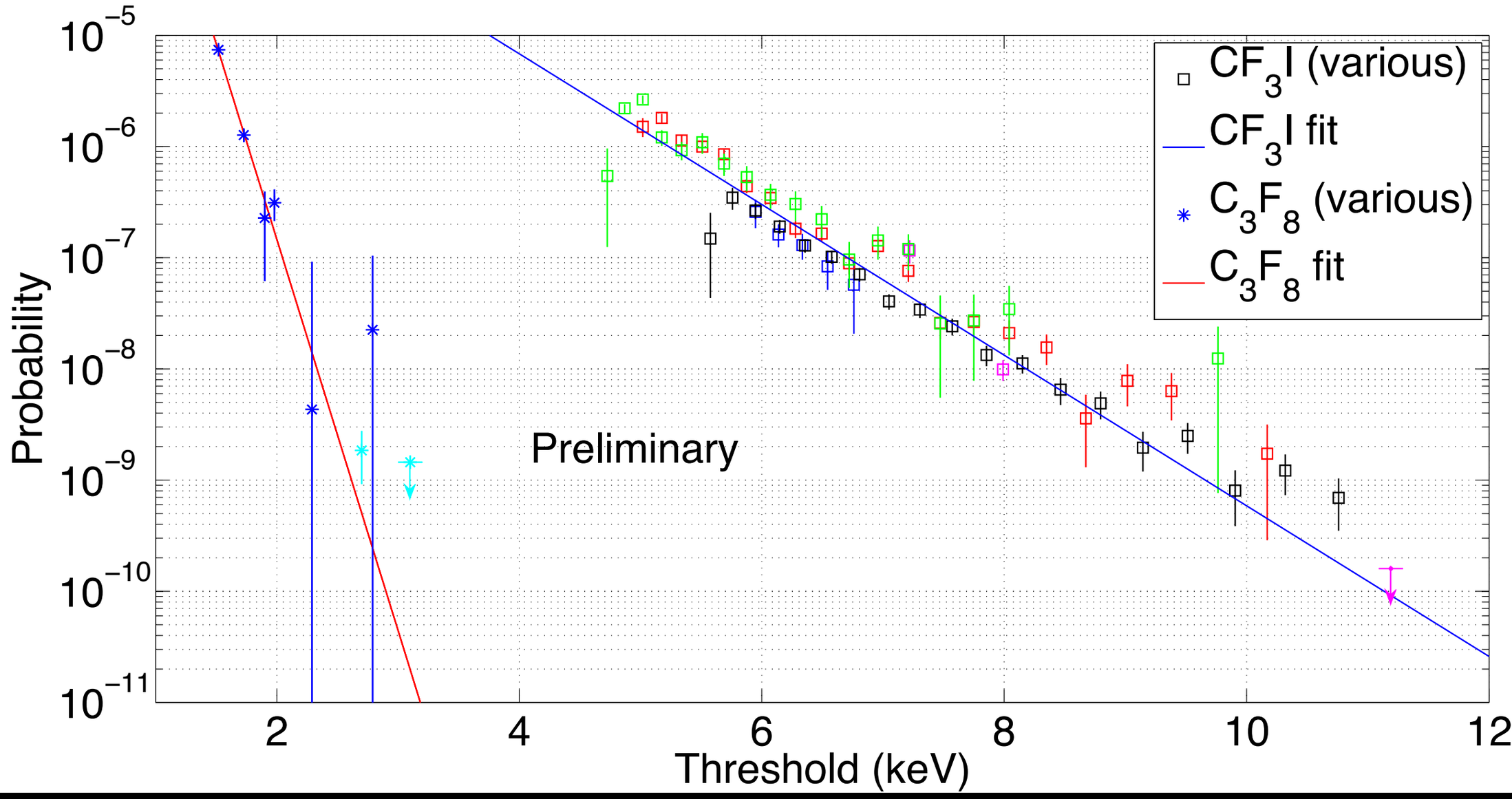
- Developing more advanced acoustic analysis that shows much better discrimination on a subset of data

PICO-2L (COUPP4 redux)

- Alternate fluid - remove the iodine - C_3F_8
  - Lower threshold (down to 3 keV in test stand)

PICO-2L (COUPP4 redux)

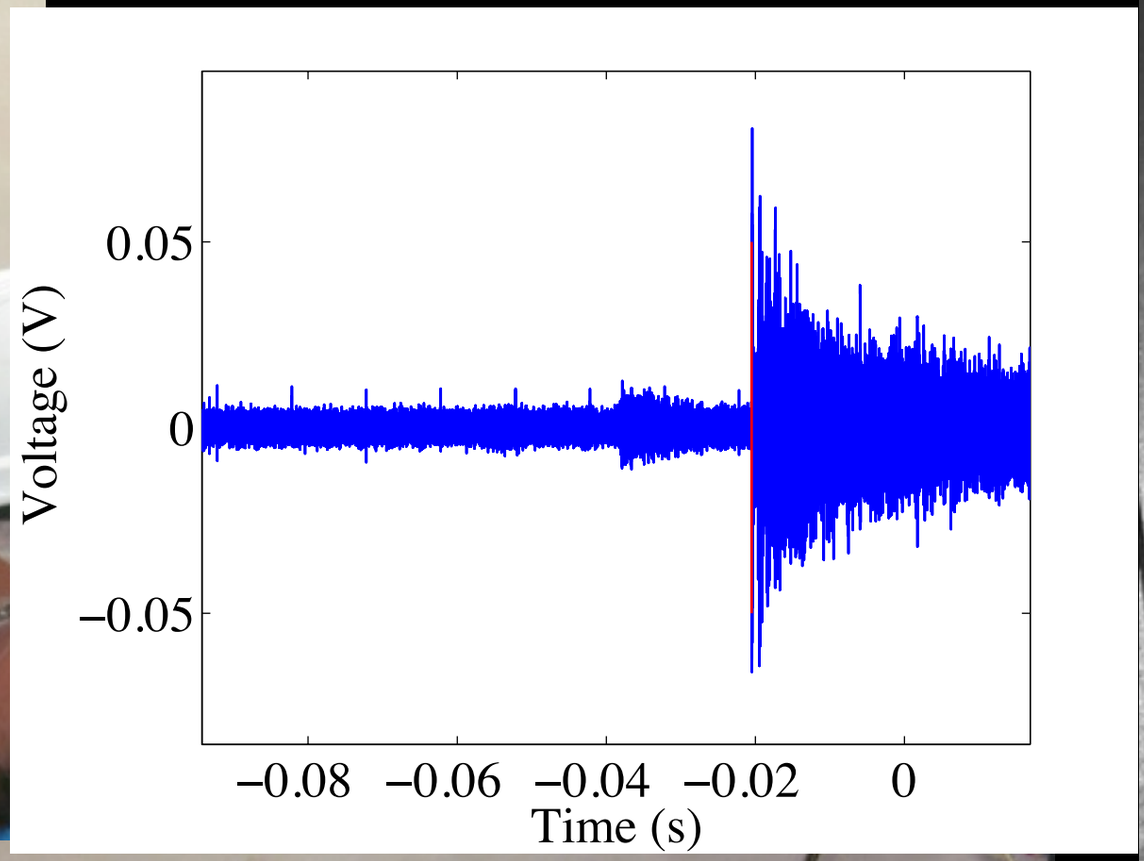
- Why C_3F_8 again? Excellent gamma rejection at a lower threshold

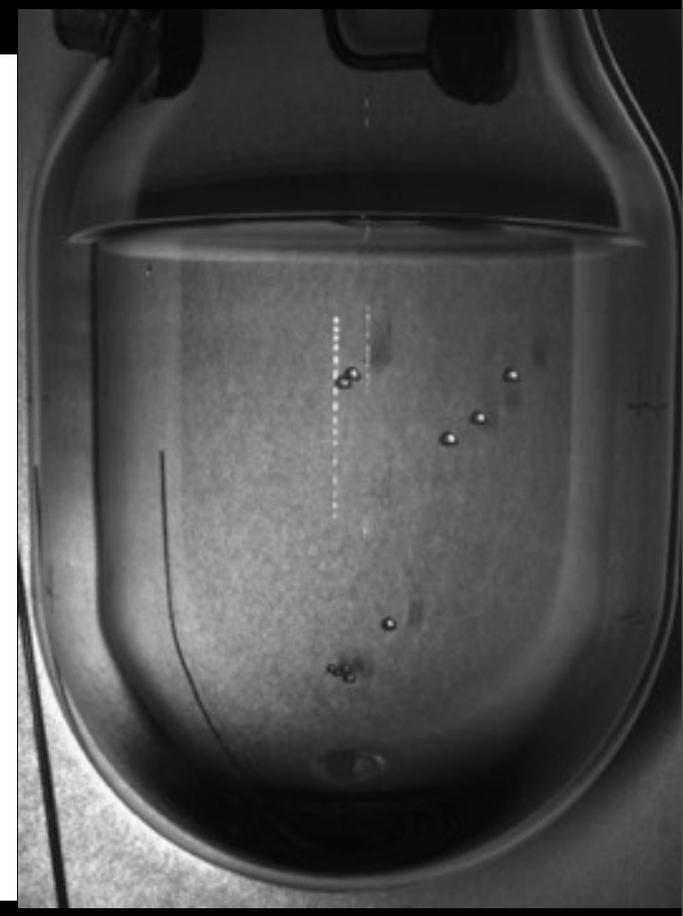


PICO-2L (COUPP4 redux)

- Alternate fluid - remove the iodine - C_3F_8
  - Lower threshold (down to 3 keV in test stand)
  - Improved sensitivity at low WIMP mass
    - ~1 event per day from recent CDMS result
  - Improved SD sensitivity
- First effort in concert with the PICASSO collaboration
- Chamber filled in October, 2013

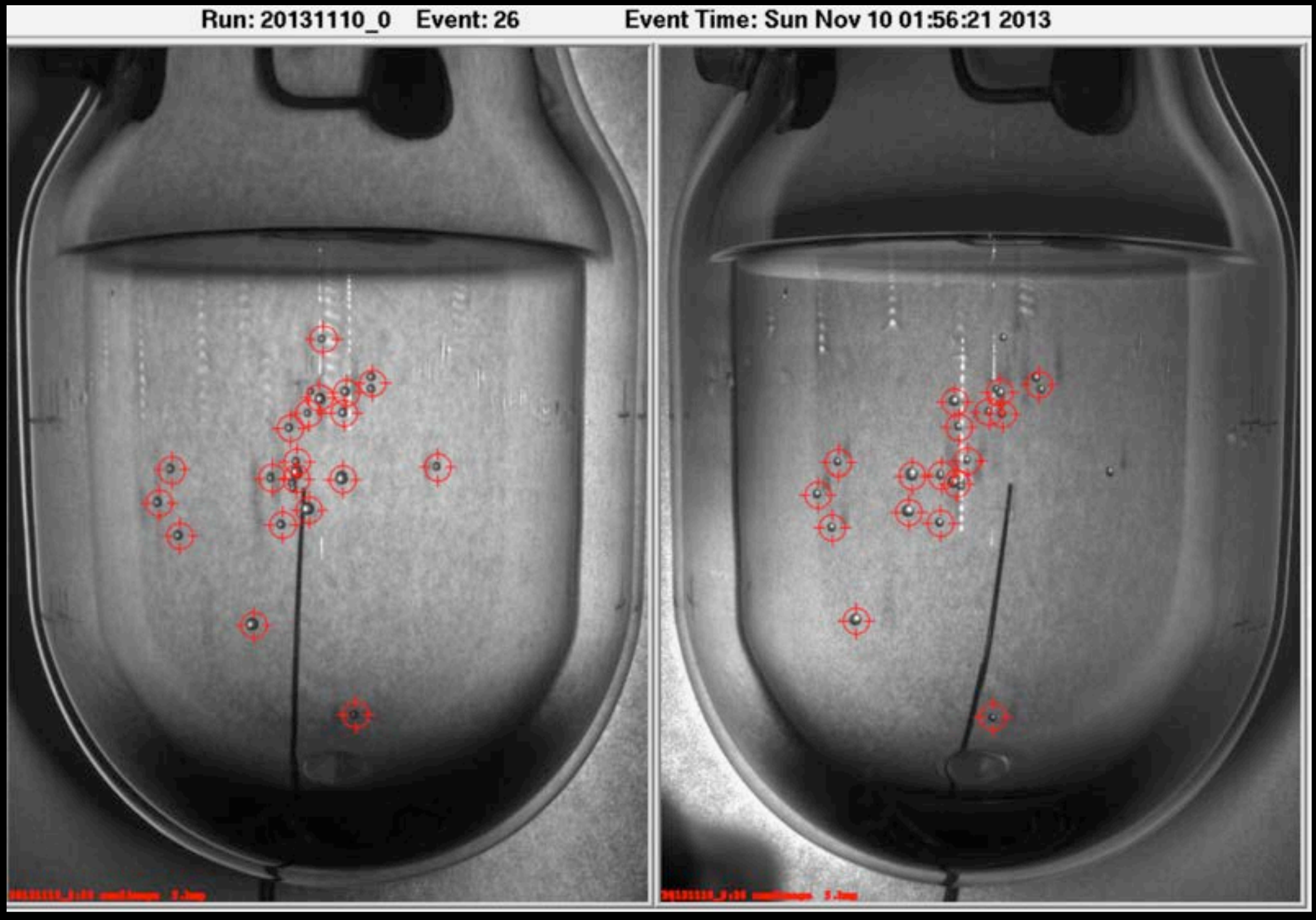
PICO-2L





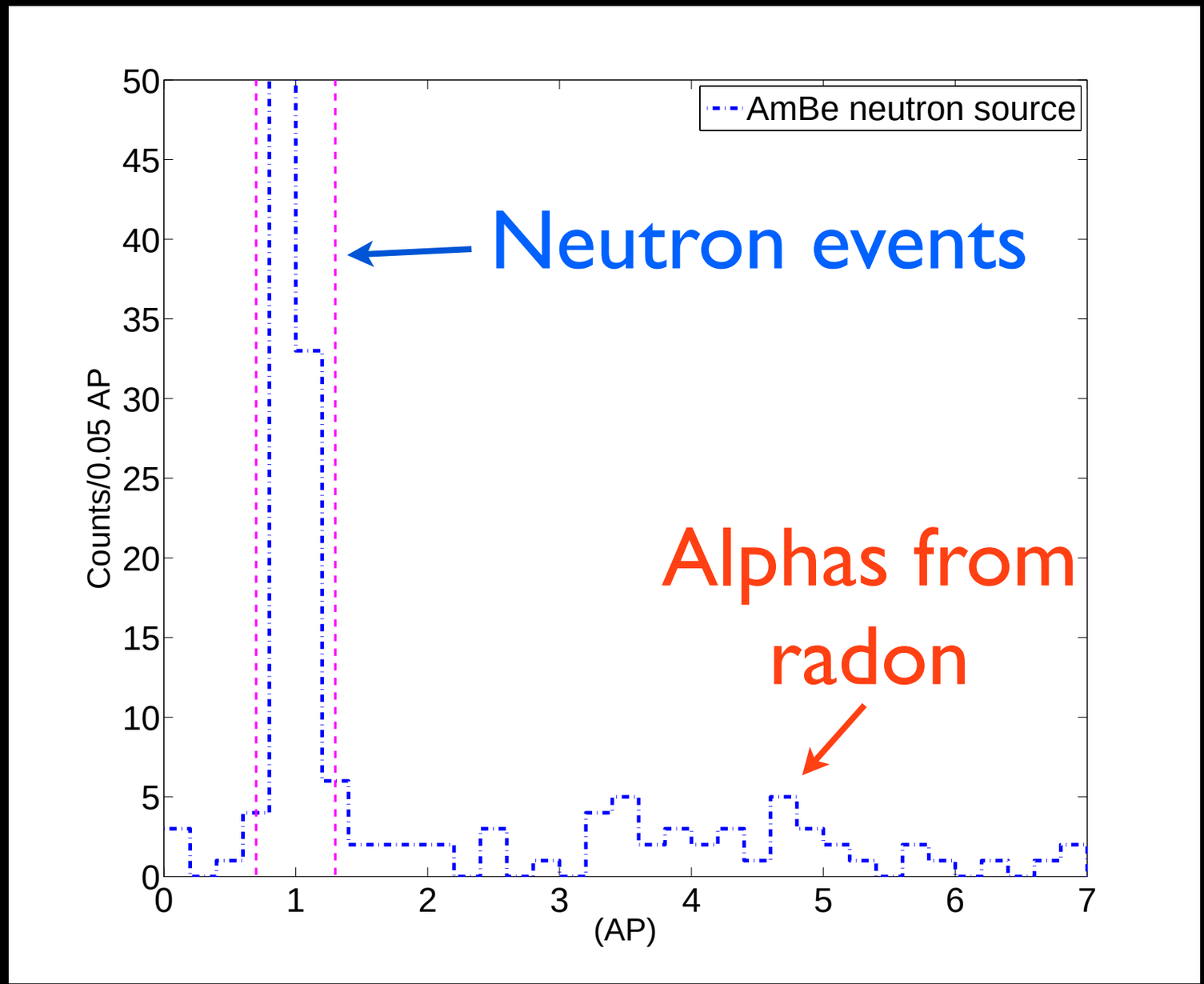
- Now taking data!

PICO-2L



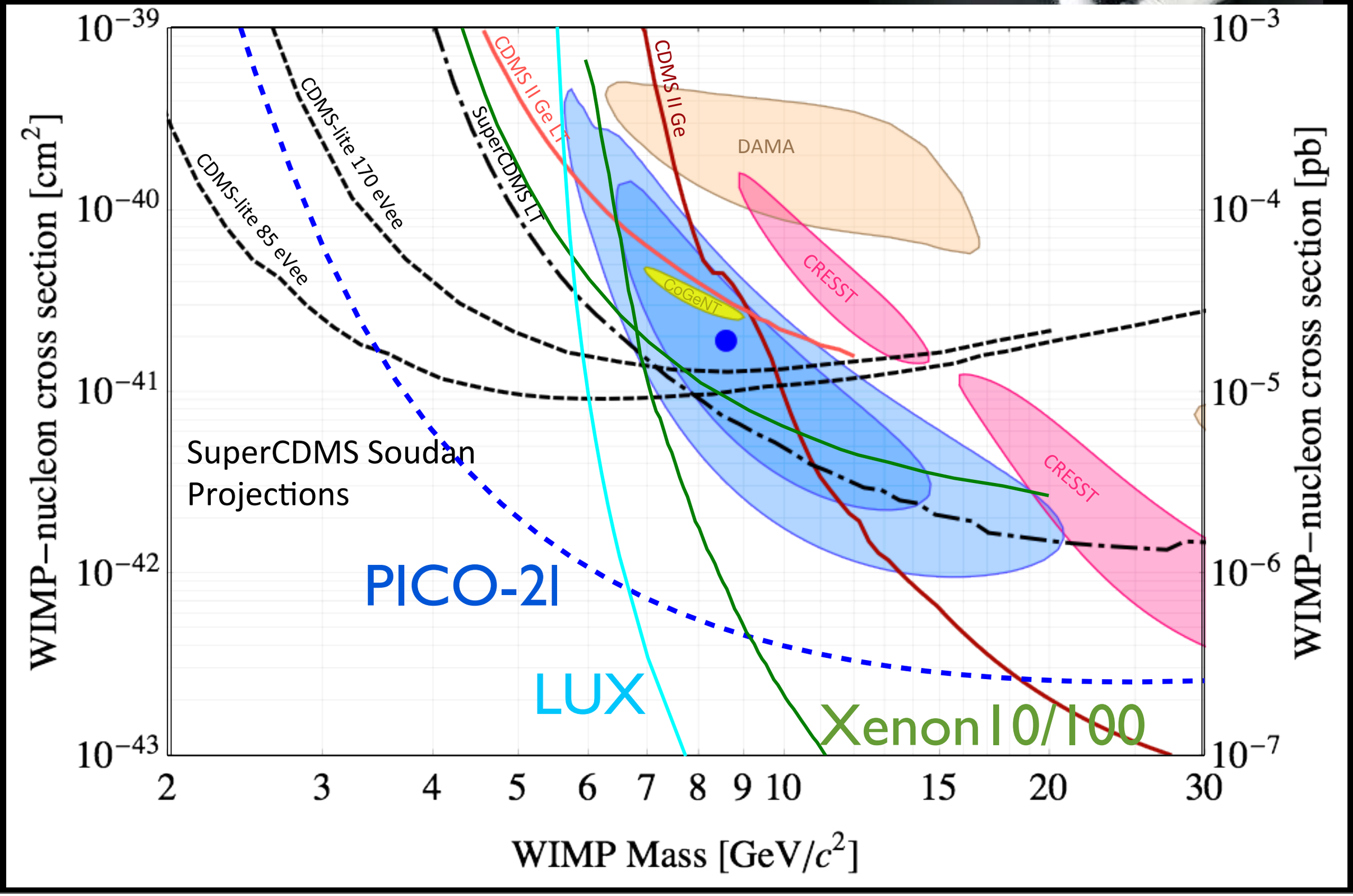
- 26 bubble event from AmBe neutron source!

PICO-2L



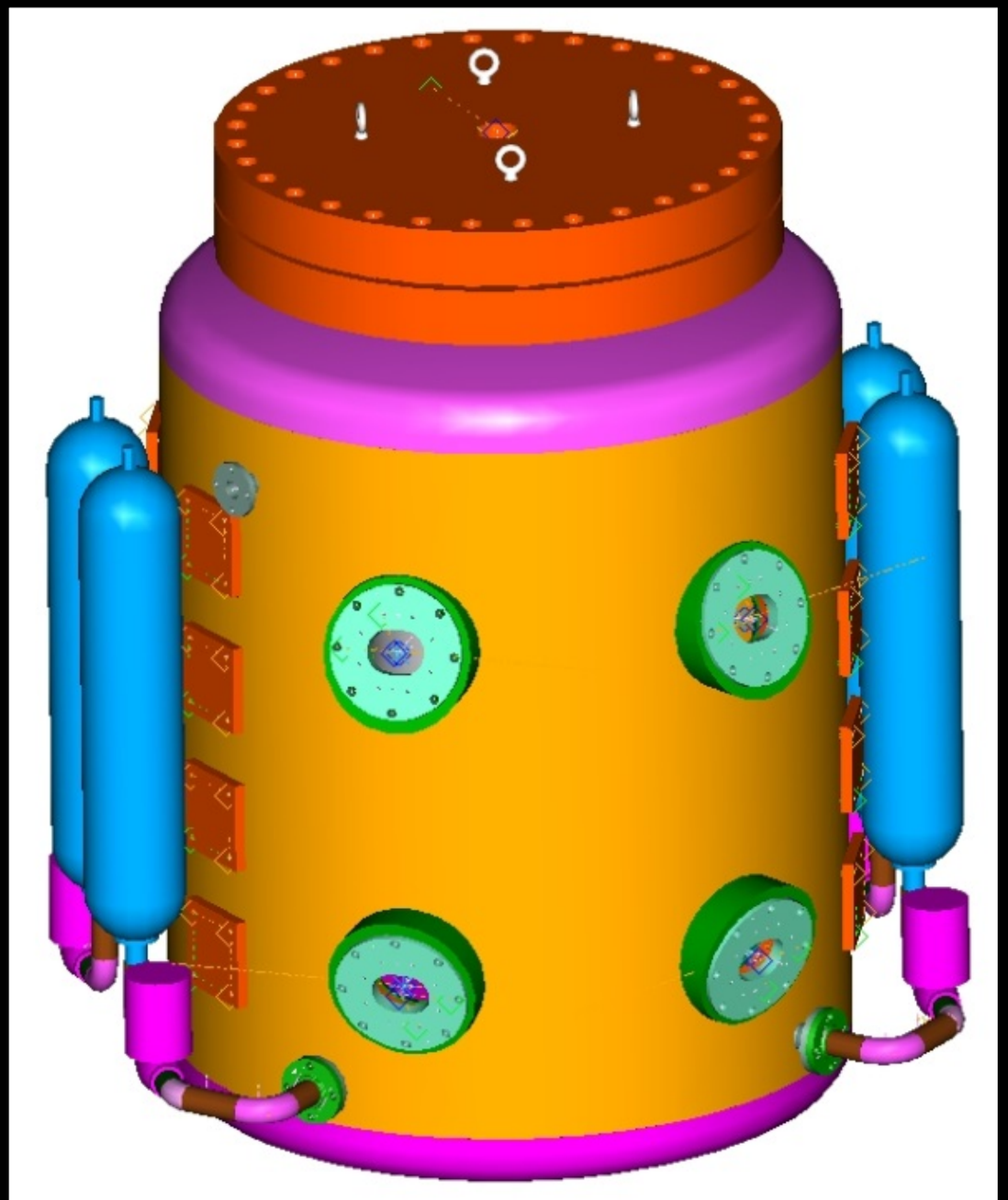
- Acoustics from commissioning data (with neutron source)
- Radon injection at start of run provides some alphas in our neutron data set

Projections

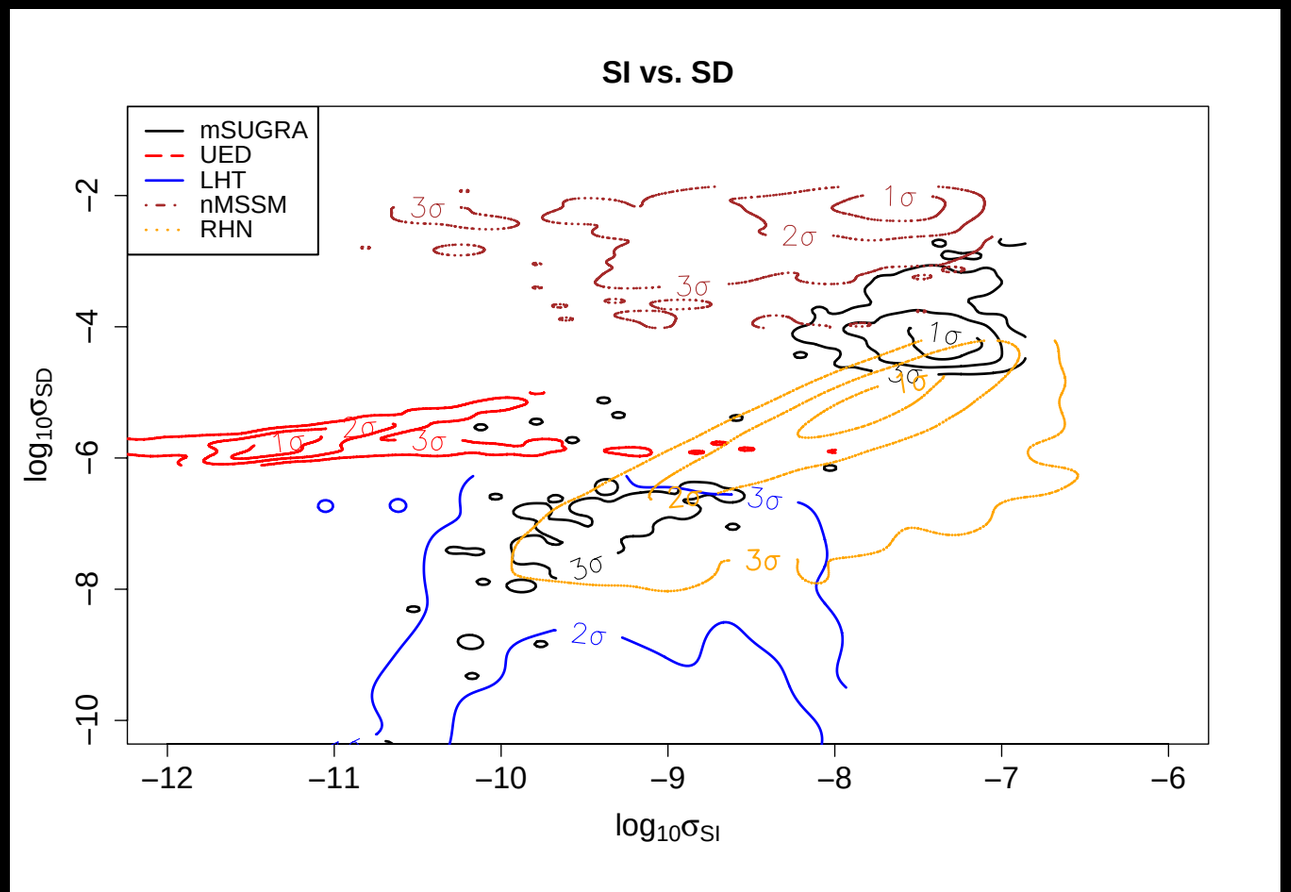


PICO-250L

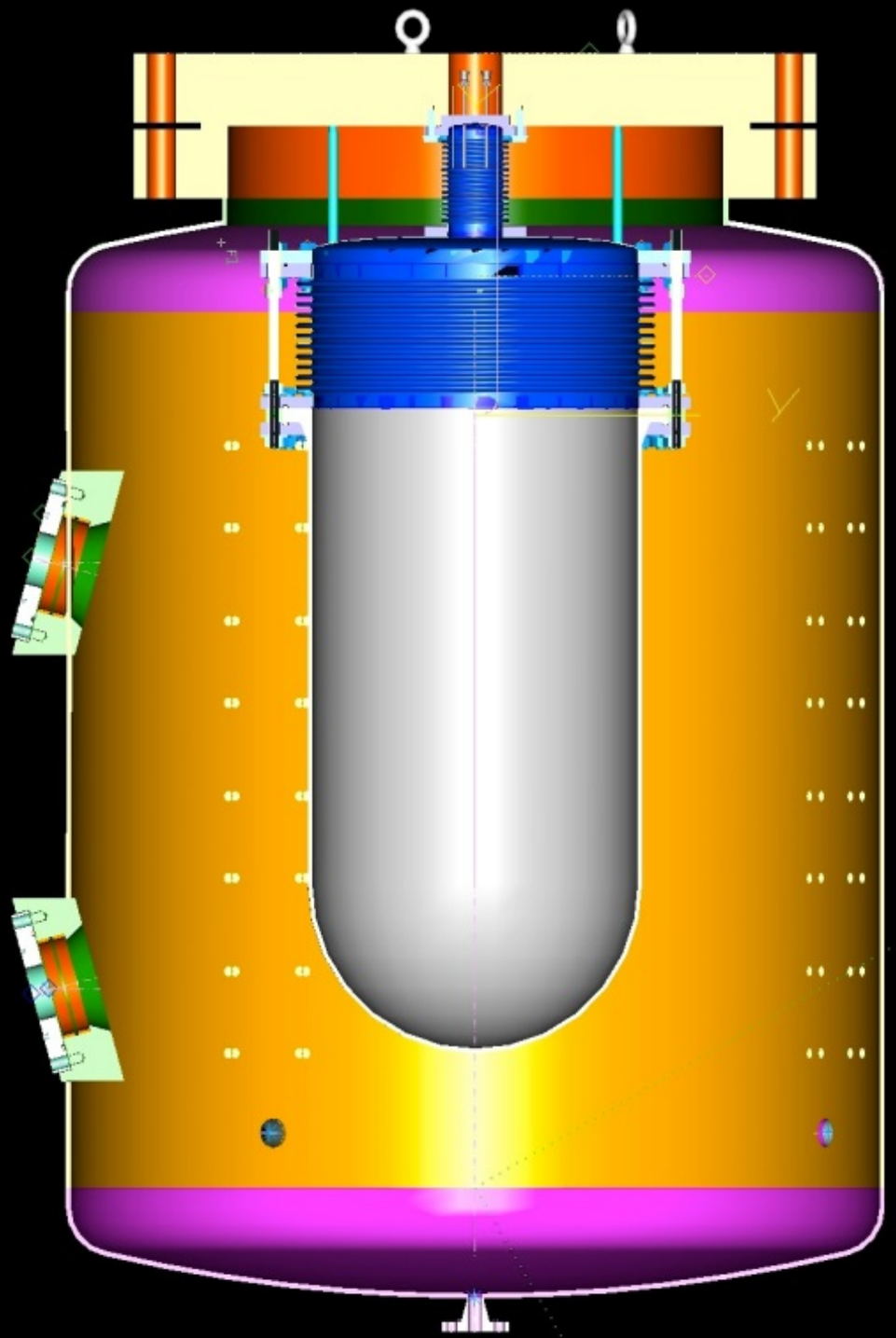
- Straightforward scale up of existing PICO-2L and COUPP60 detectors



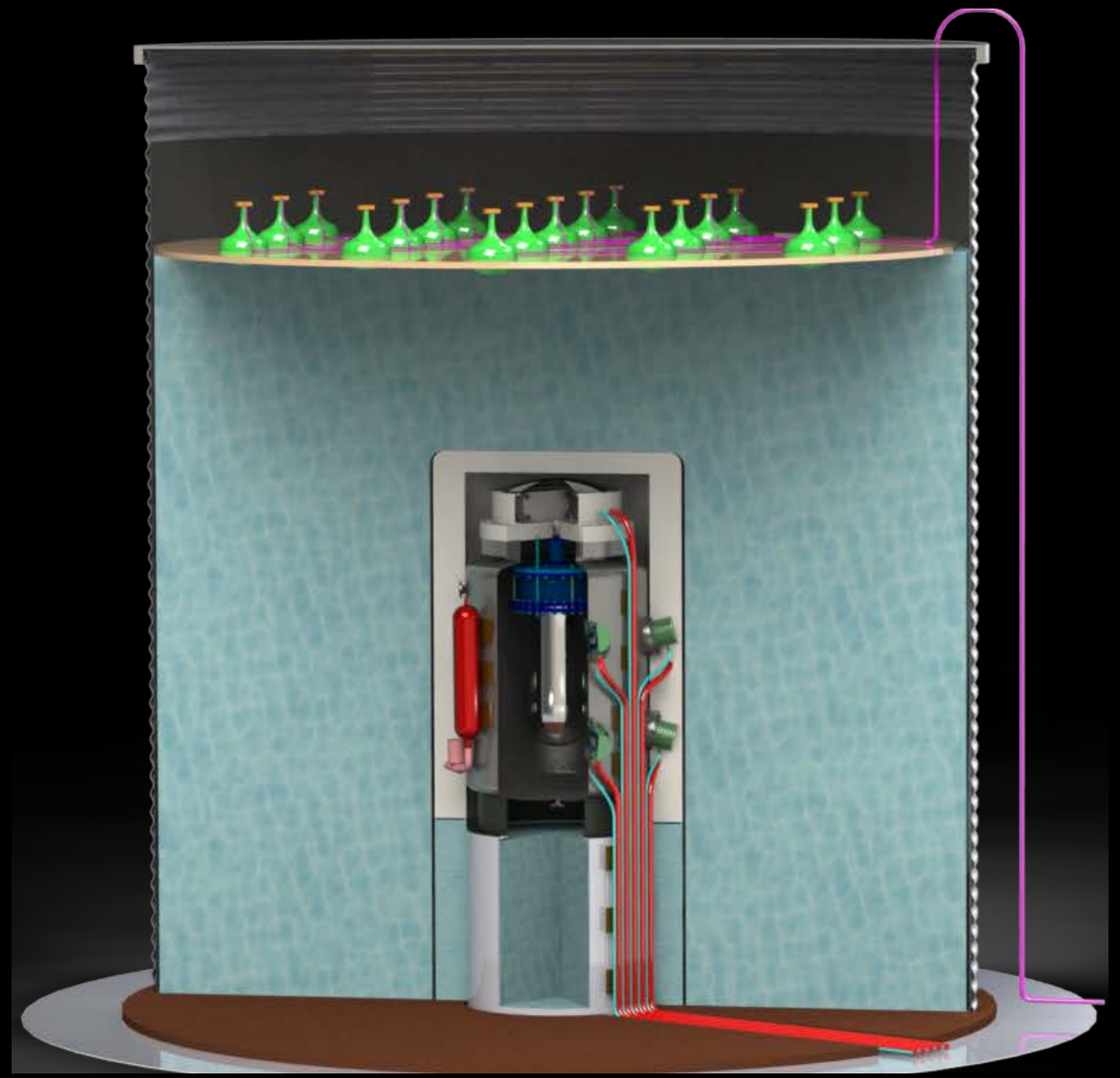
- Begin with C_3F_8 to maximize leadership potential (Spin-dependent and low masses)
- Retain flexibility to respond to developments in the field



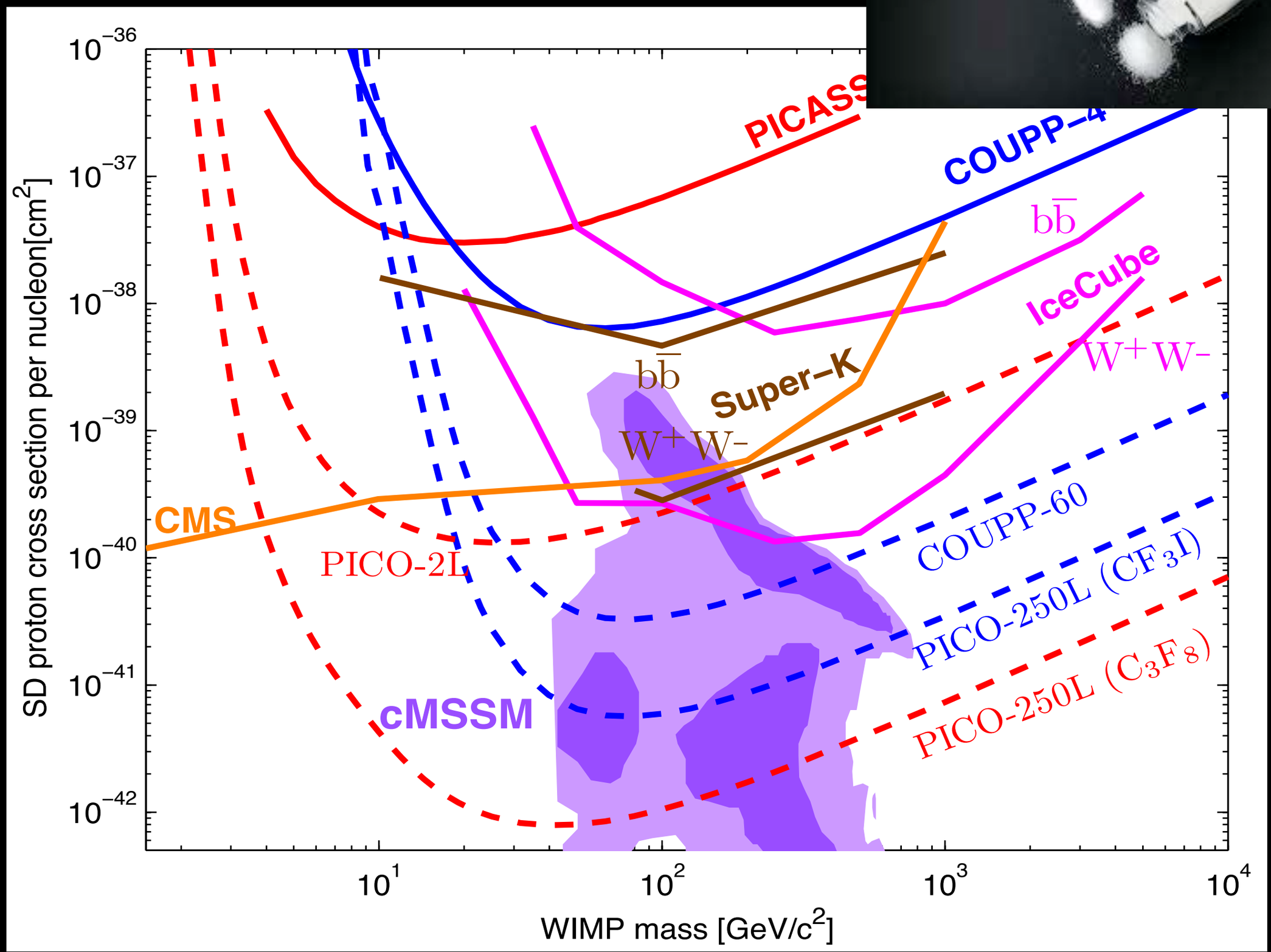
PICO-250L



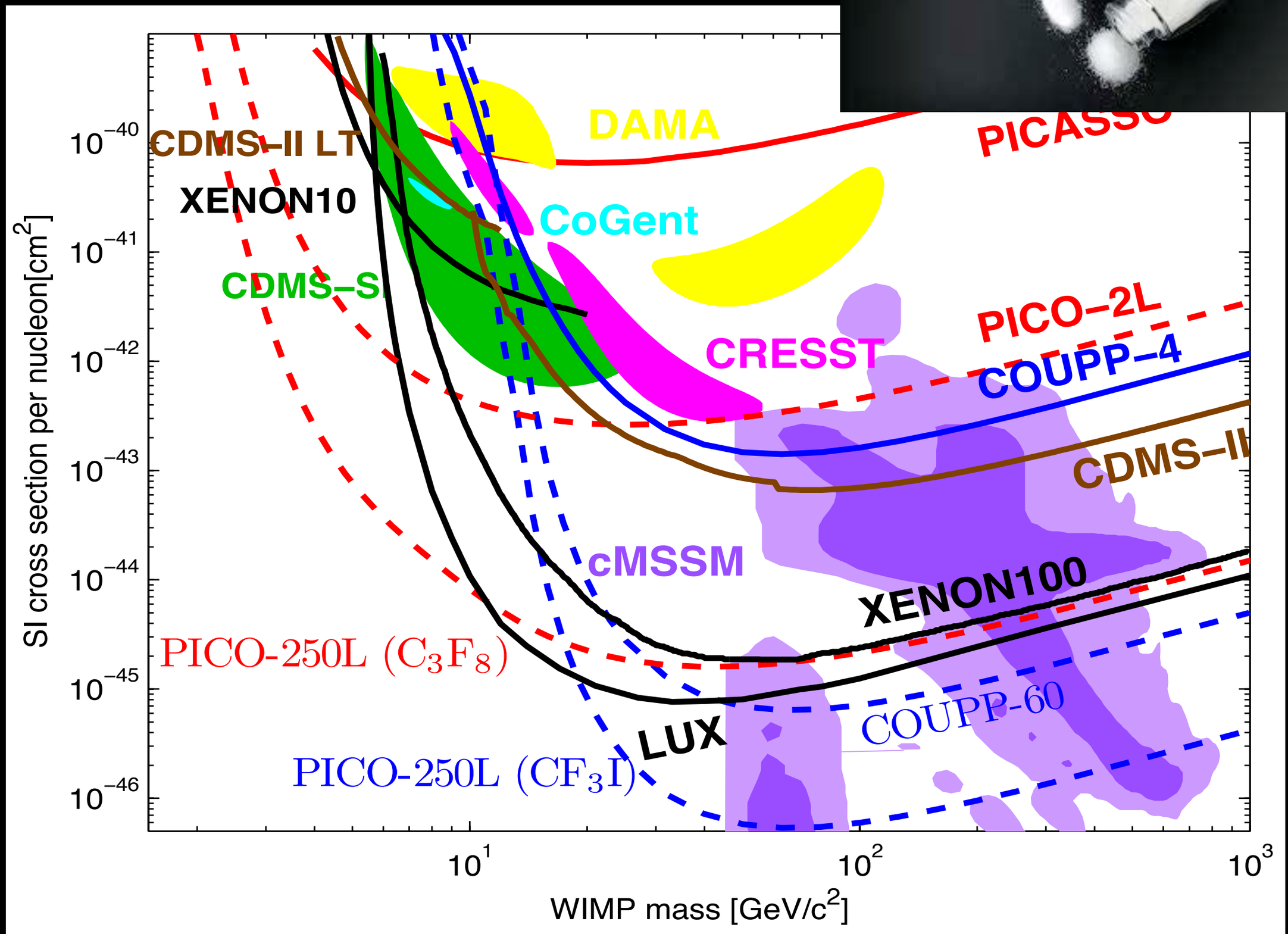
- Funded by NSF and DOE as part of G2 Dark Matter (big showdown in February)
- Engineering well underway
- Construction 2015-2016?

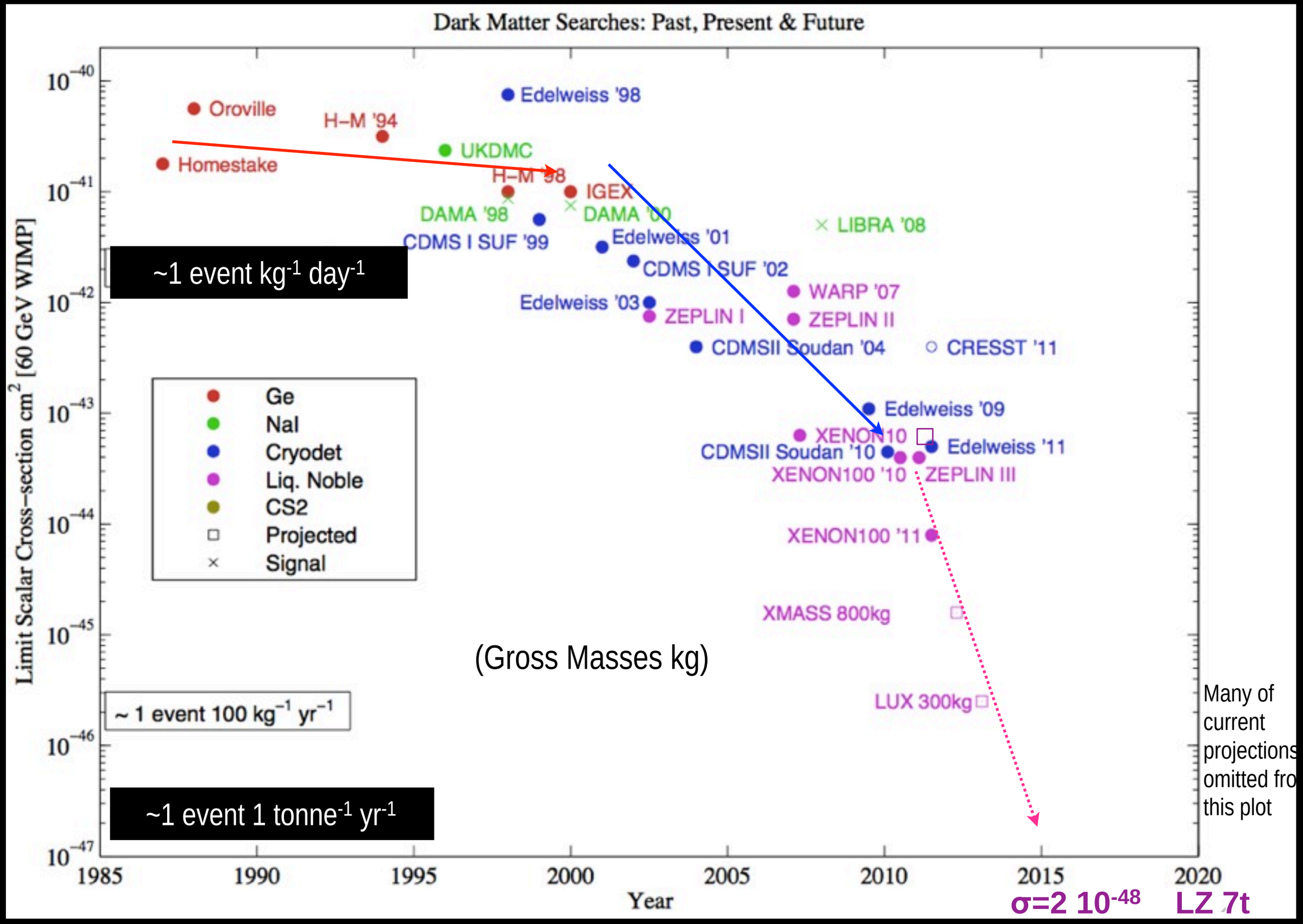


Projections



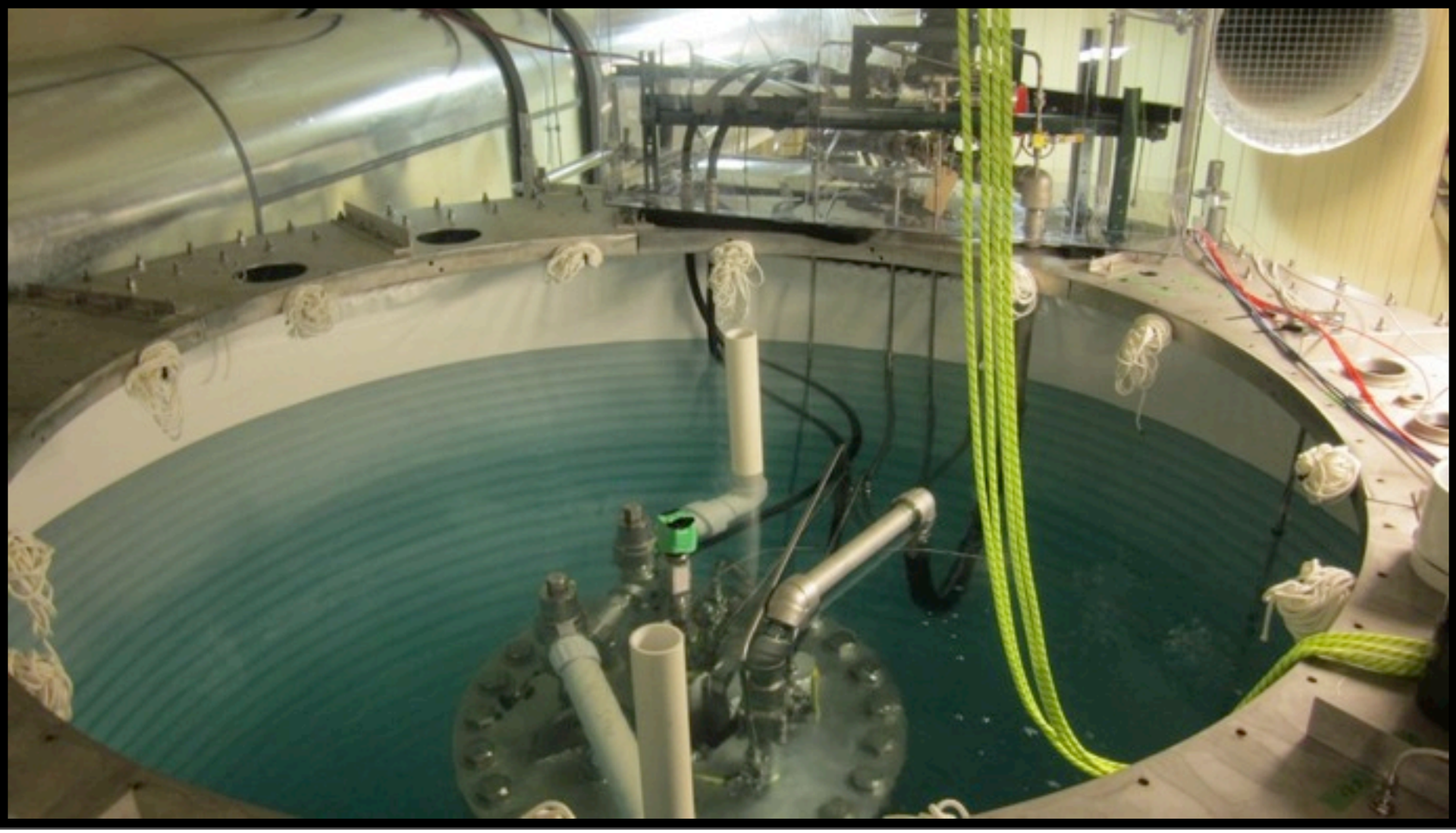
Projections

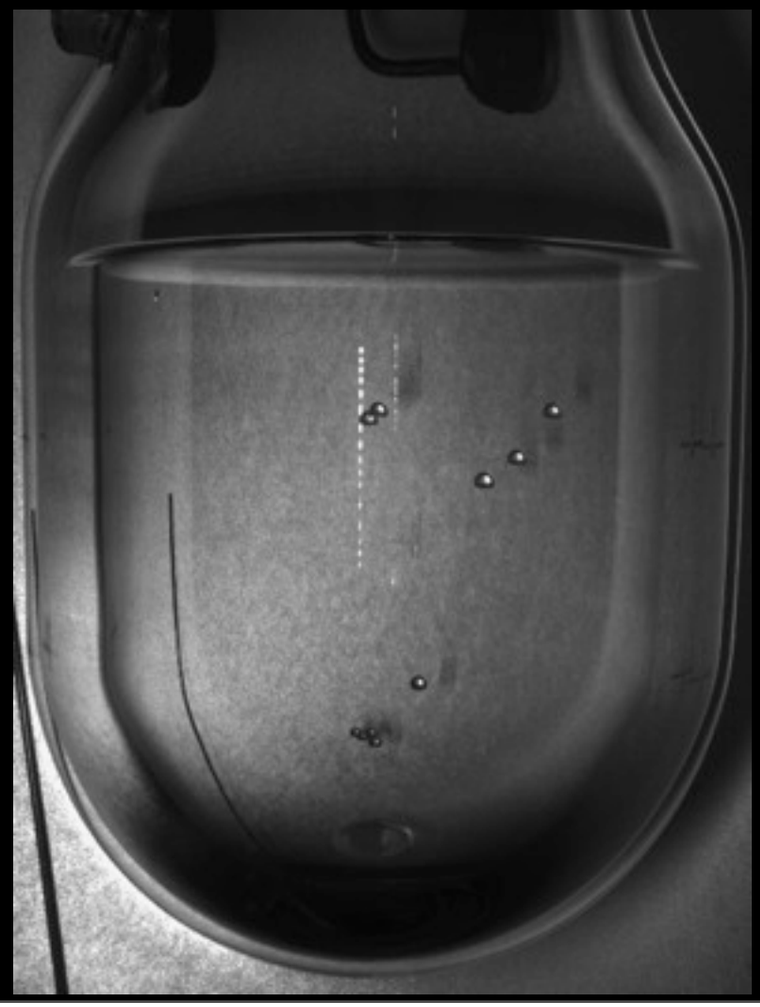


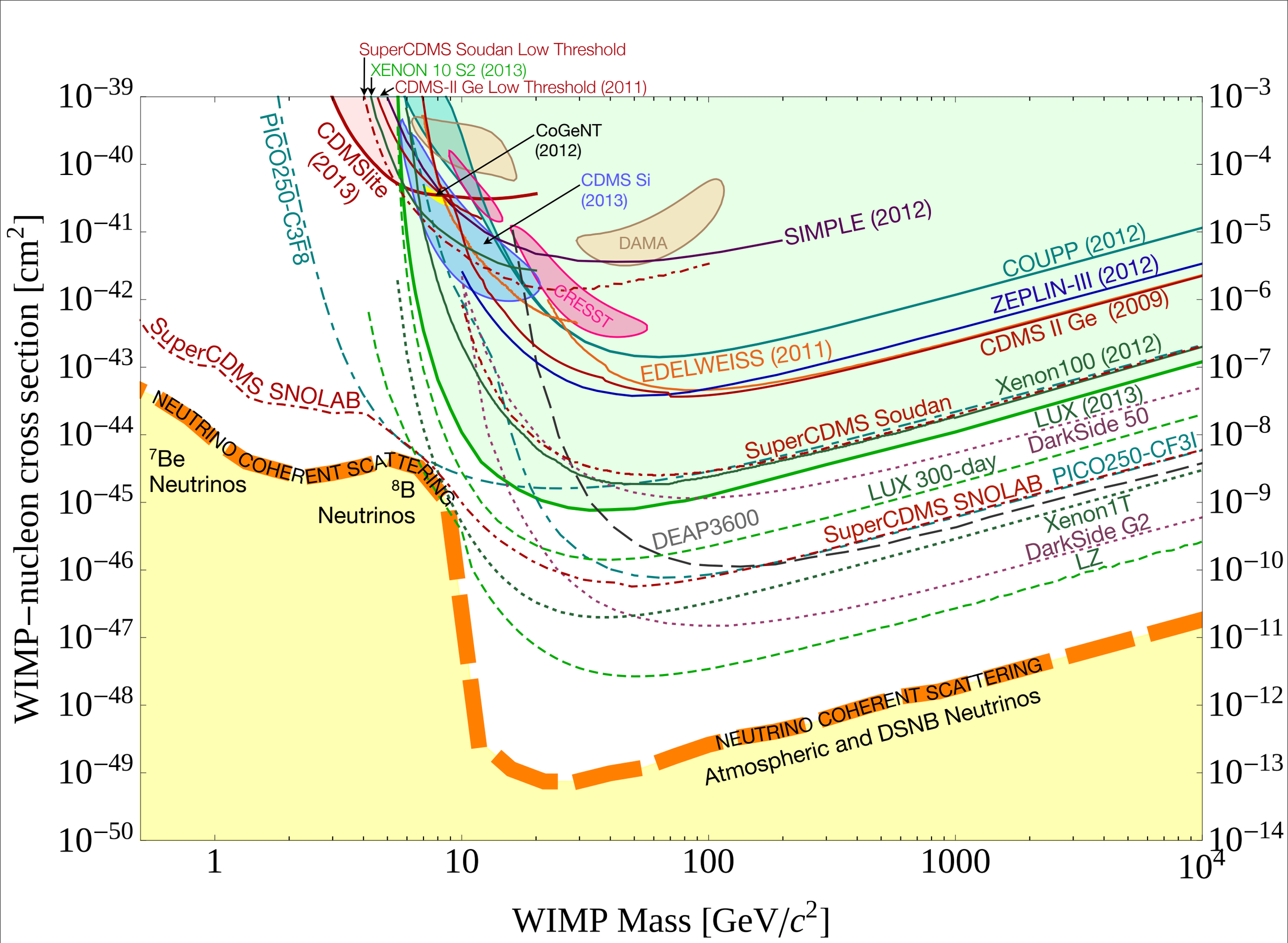

Dark Matter Searches: Past, Present & Future
Limit Scalar Cross−section cm^2 [60 GeV WIMP]
Year
Oroville
H–M '94
Homestake
UKDMC
Edelweiss '98
H–M '98
IGEX
DAMA '98
DAMA '00
CDMS I SUF '99
Edelweiss '01
LIBRA '08
CDMS I SUF '02
WARP '07
Edelweiss '03
ZEPLIN I
ZEPLIN II
CDMSII Soudan '04
CRESST '11
Edelweiss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

Conclusion

- Dark matter searches are making fast progress (indirect, accelerator and direct)
- PICO is producing the best direct detection limits on spin-dependent dark matter
- PICO bubble chambers are competitive for spin-independent searches (particularly for light dark matter)






SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
PICO250-C3F8
CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
LUX 300-day
DarkSide 50
SuperCDMS SNOLAB
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
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