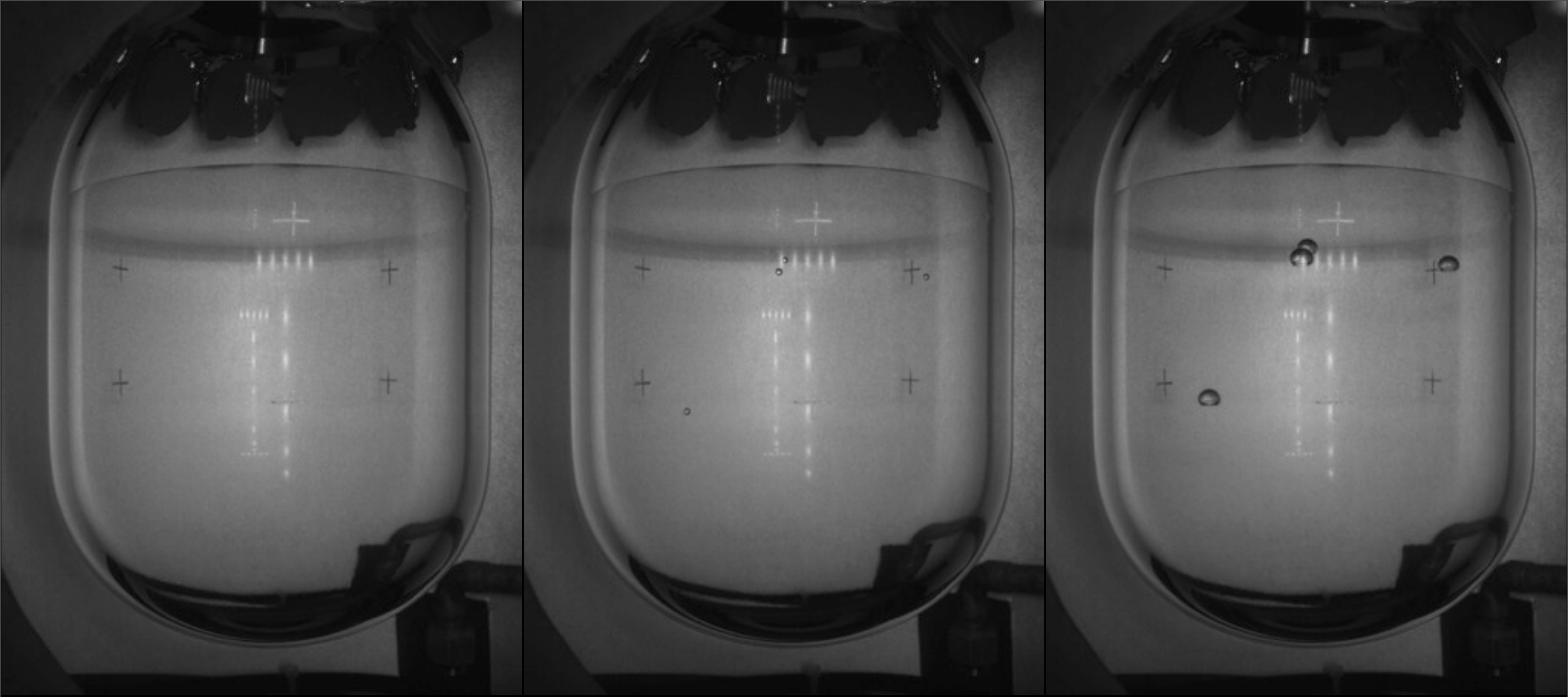


Searching for Dark Matter in a Bubble Chamber

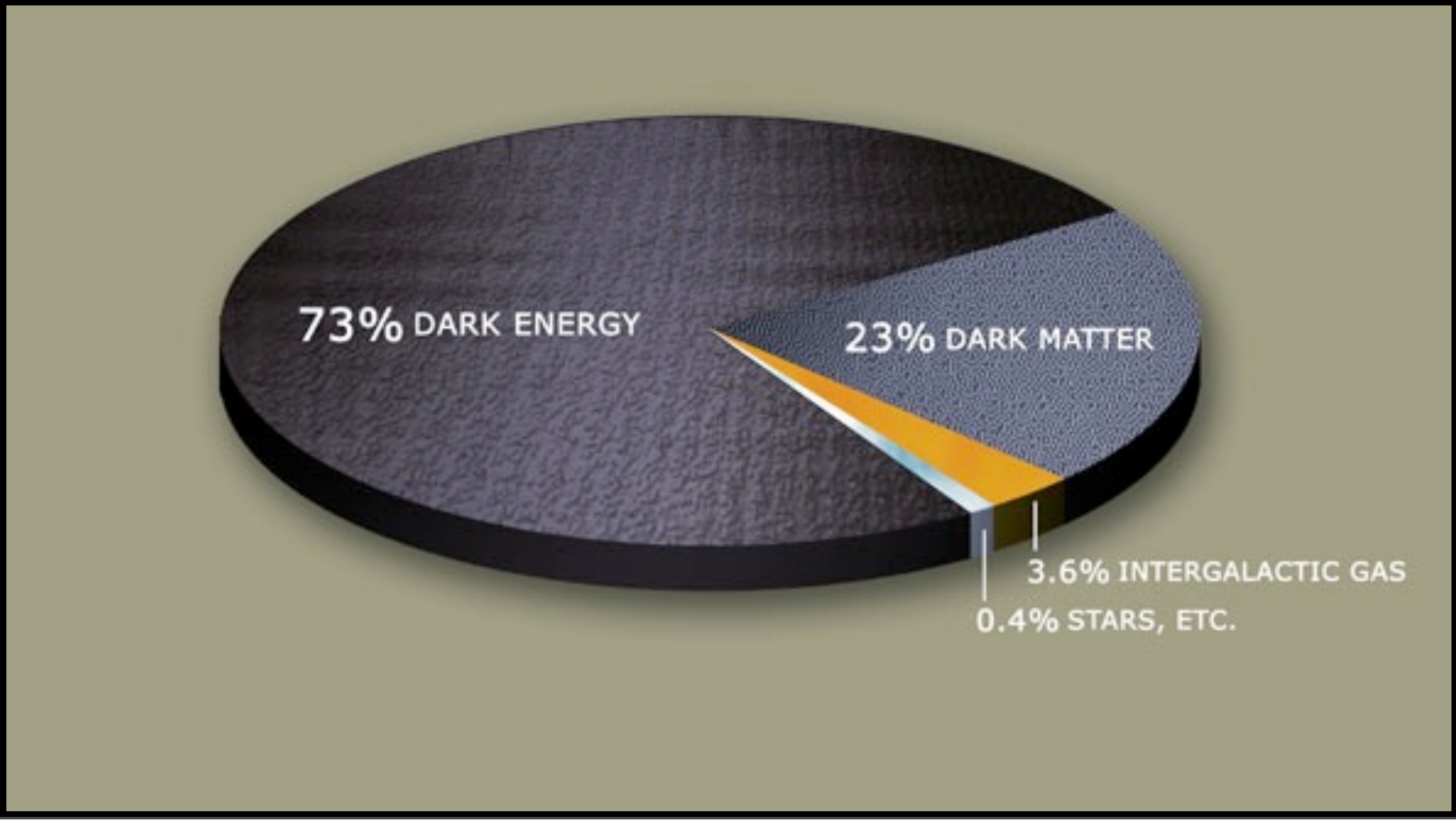
Hugh Lippincott, Fermilab

Southern Methodist University

March 4, 2013

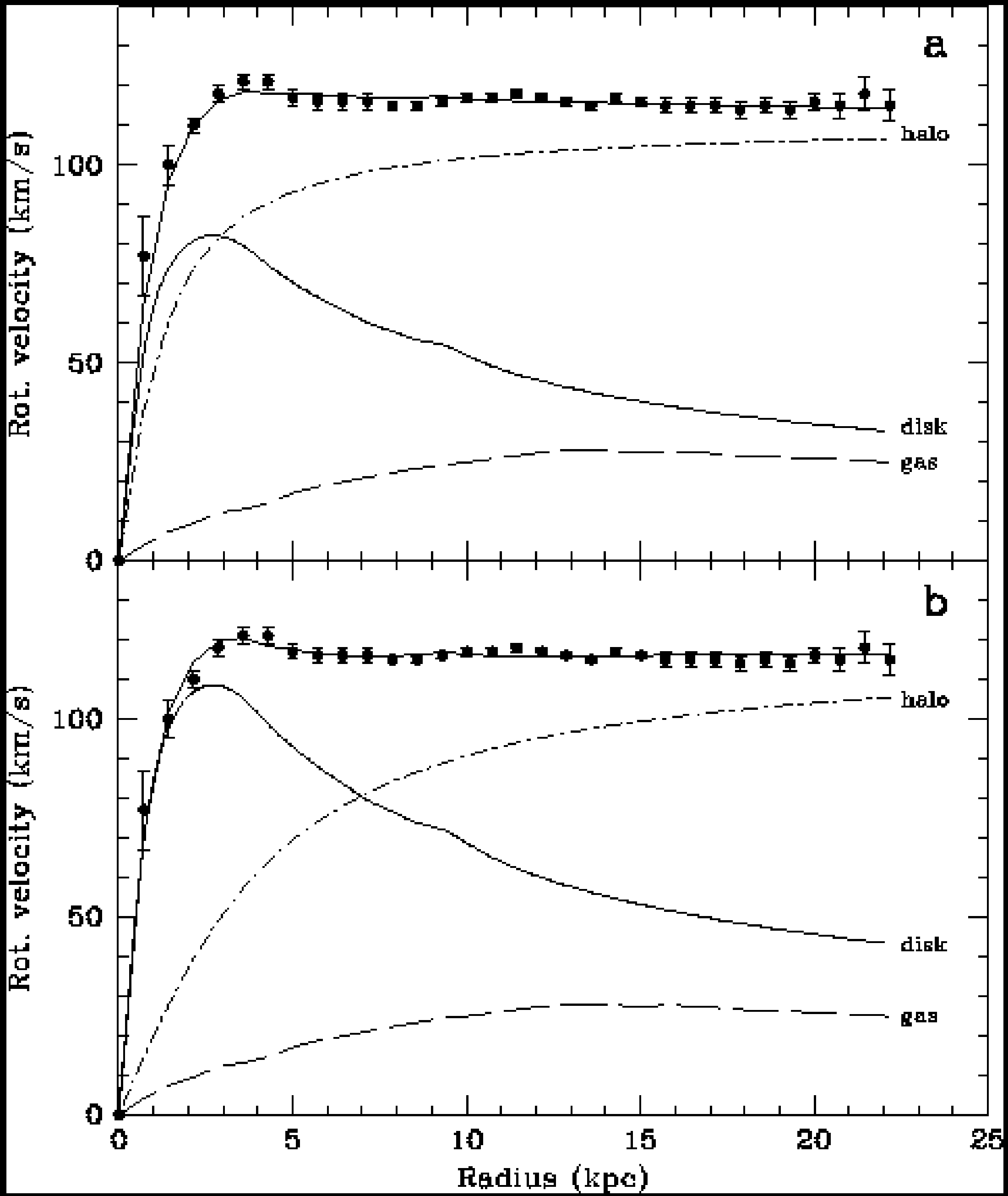
There is pretty strong consensus regarding how much stuff there is in the universe

By that same consensus, we only understand 4% of it



Dark matter - evidence?

- Galaxy rotation curves



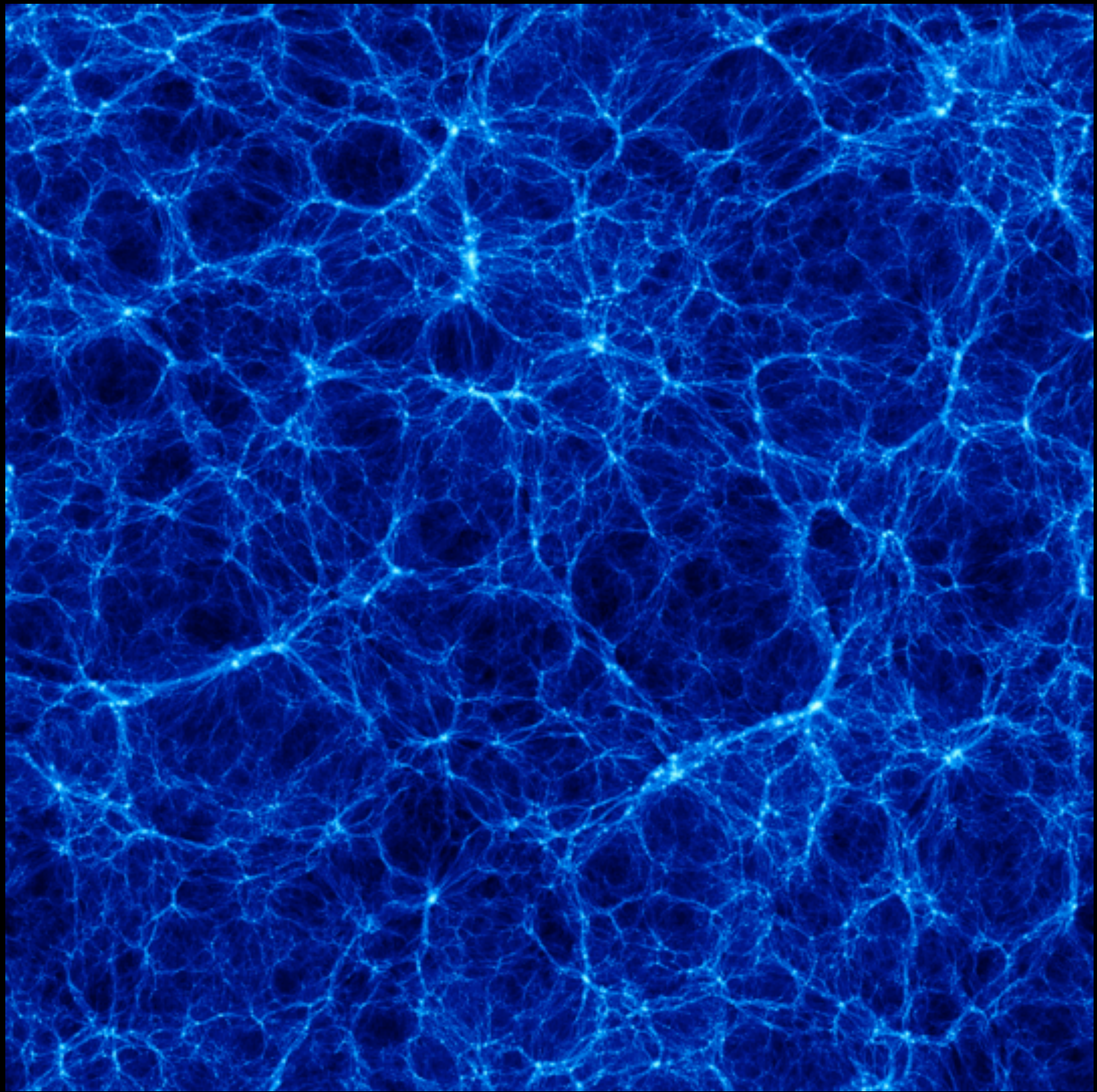
Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters

Fritz Zwicky, 1930

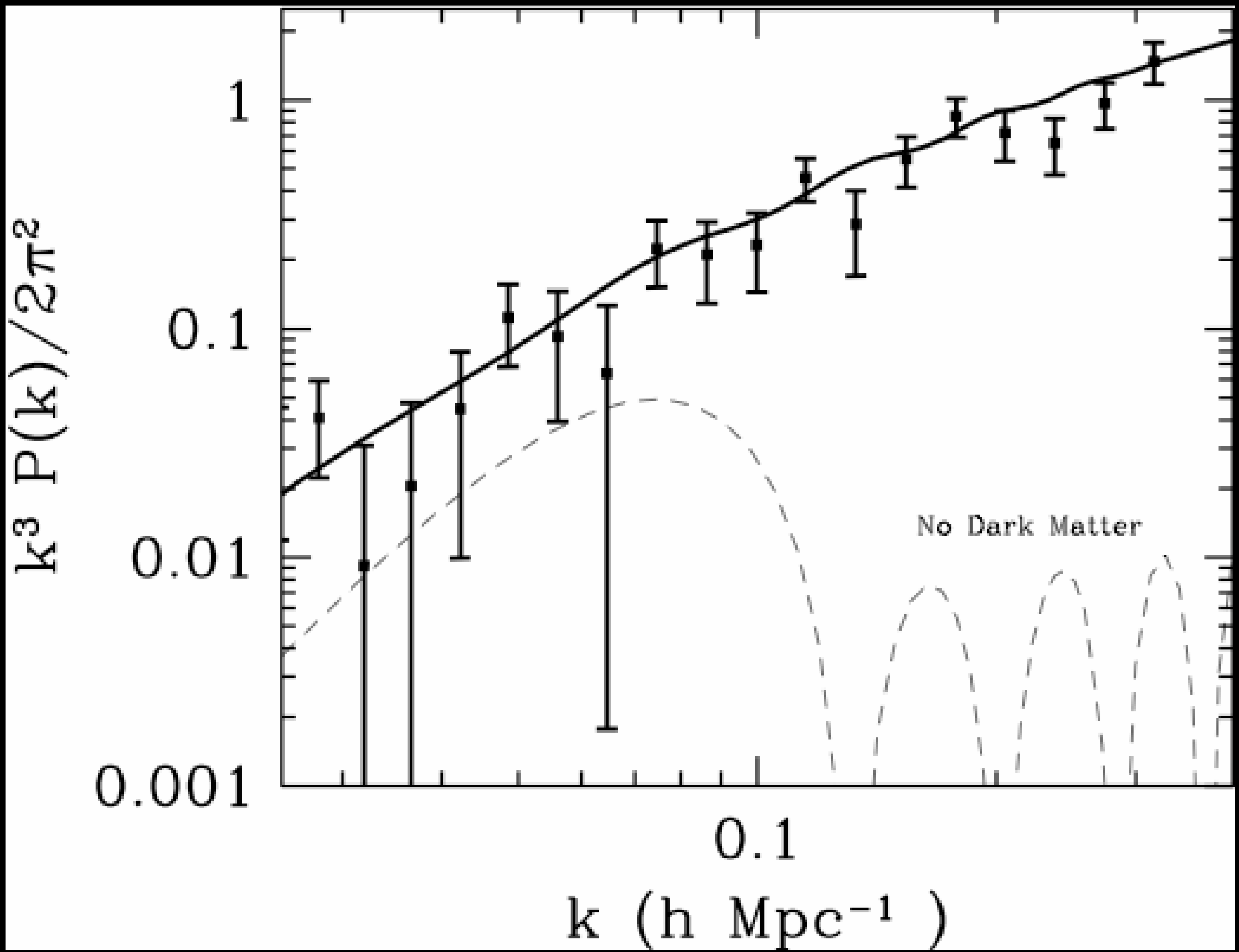
Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters



Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters

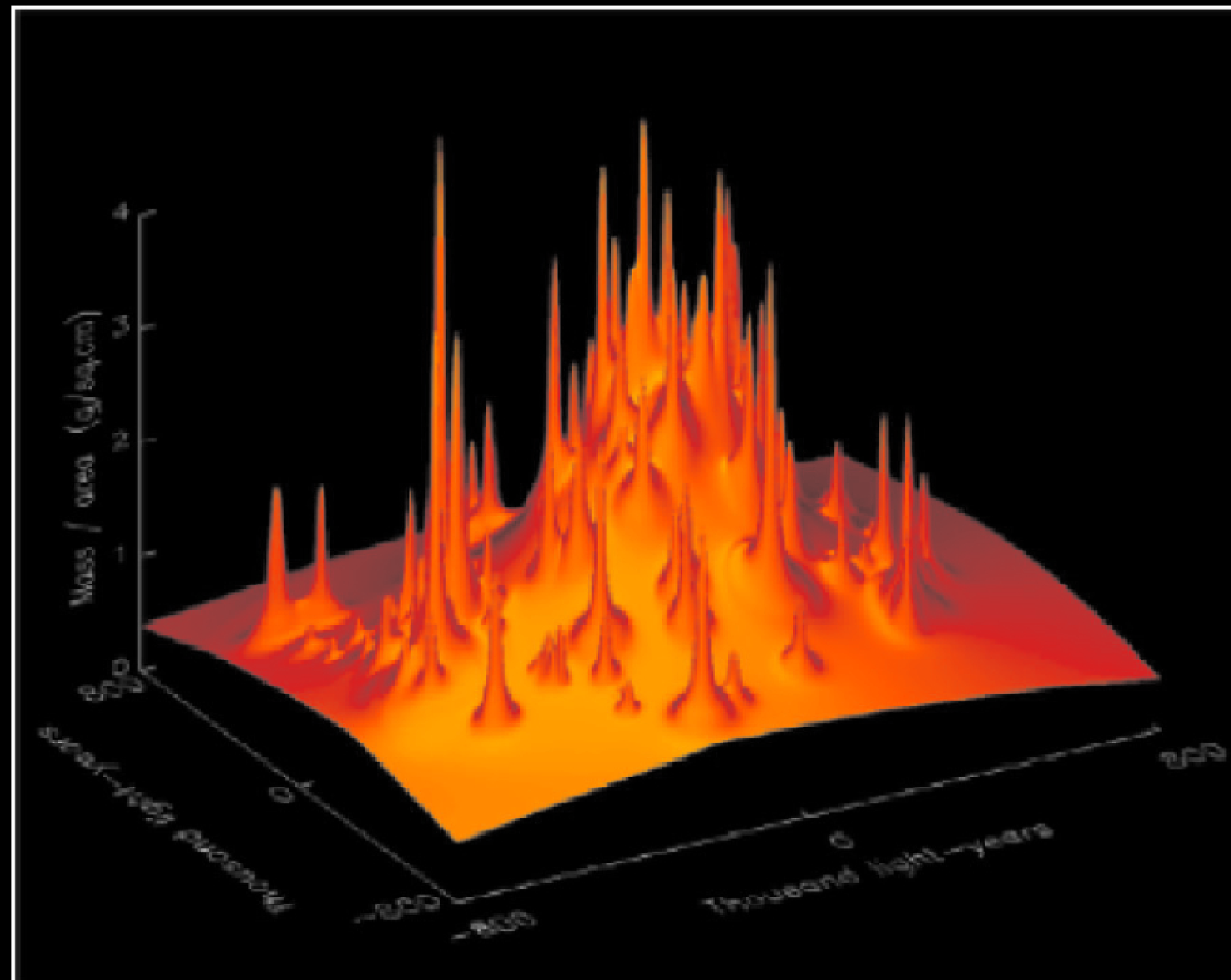


Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters
- Gravitational lensing

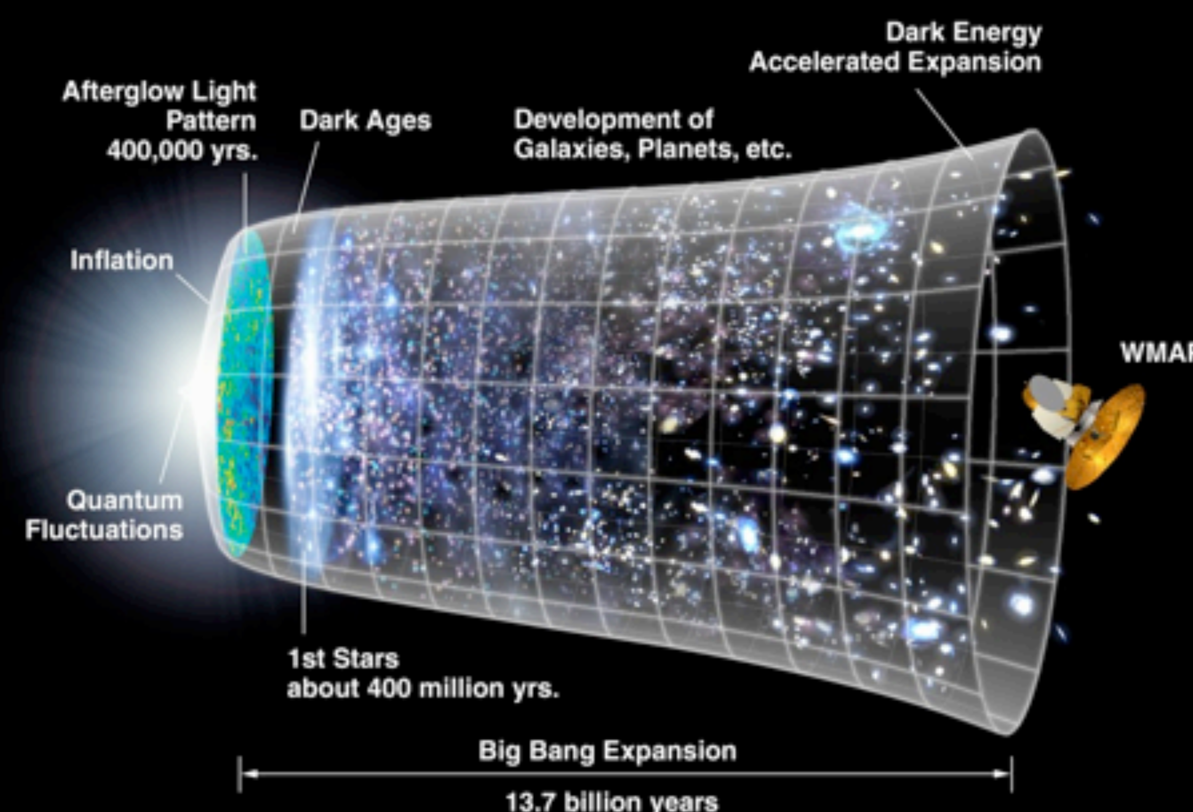
Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters
- Gravitational lensing



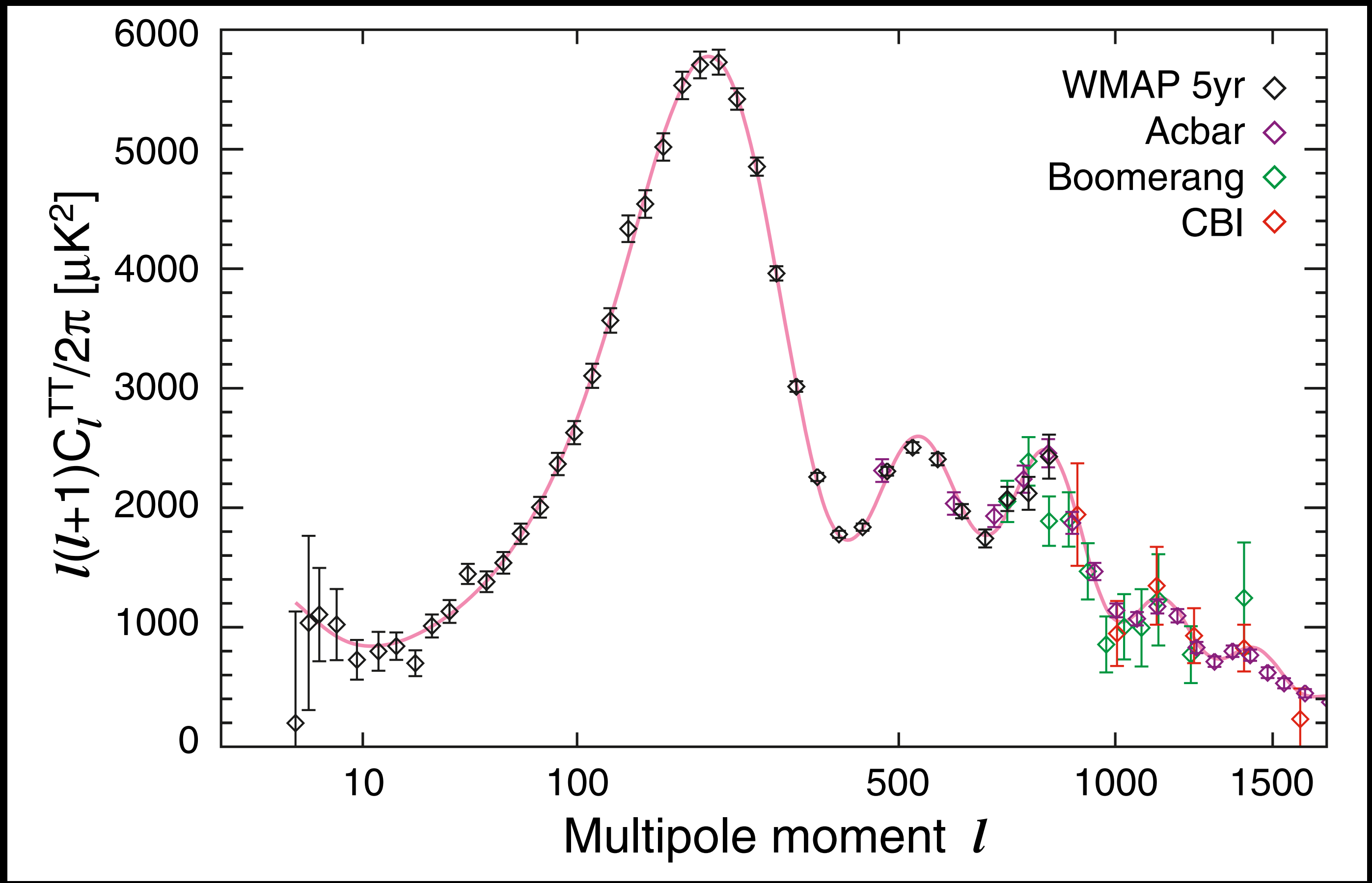
Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters
- Gravitational lensing
- Cosmic microwave background



Dark matter - evidence?

- Galaxy rotation curves
- Galaxy clusters
- Gravitational lensing
- Cosmic microwave background



Dark matter - evidence?

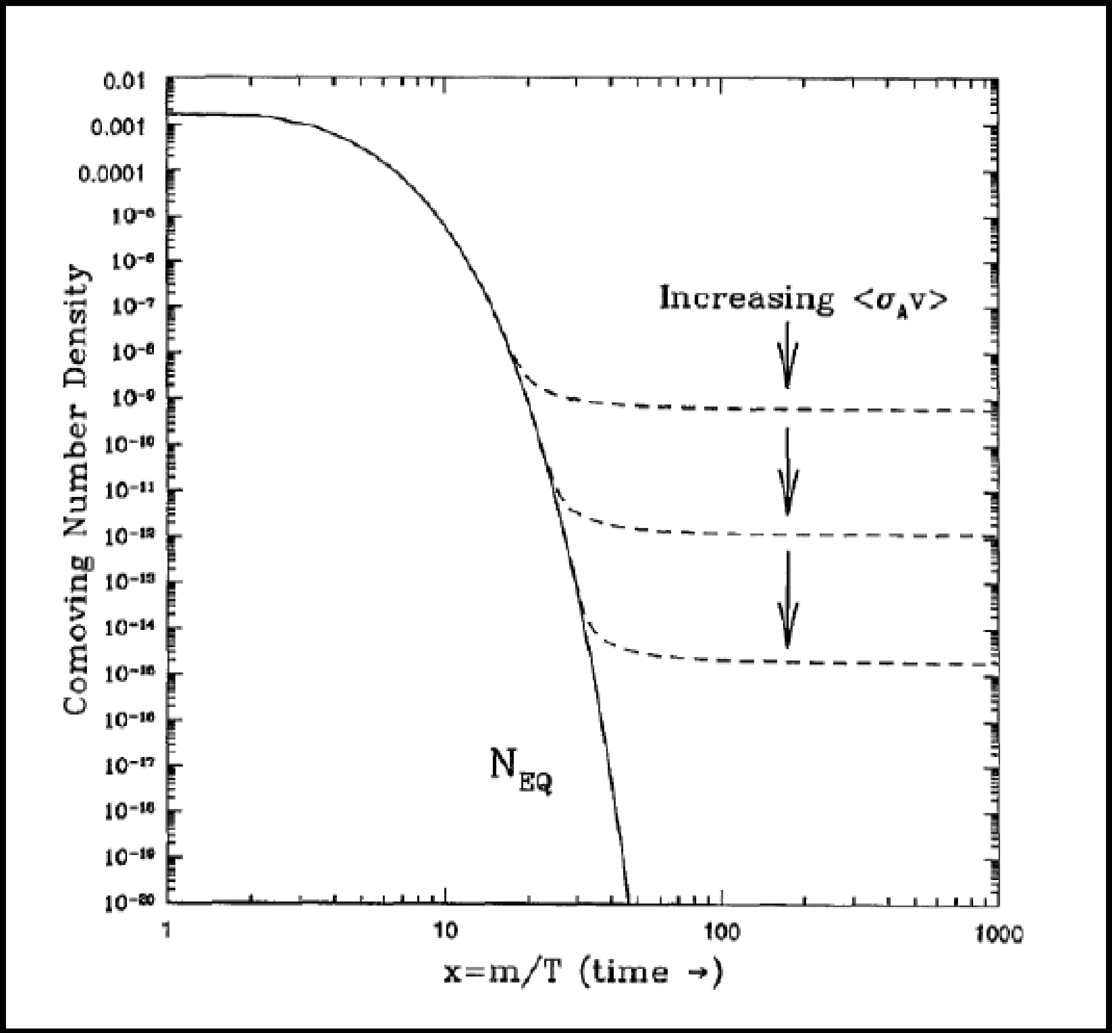
- Galaxy rotation curves
- Galaxy clusters
- Gravitational lensing
- Cosmic microwave background
- Galactic collisions

So what is it?

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

WIMPs

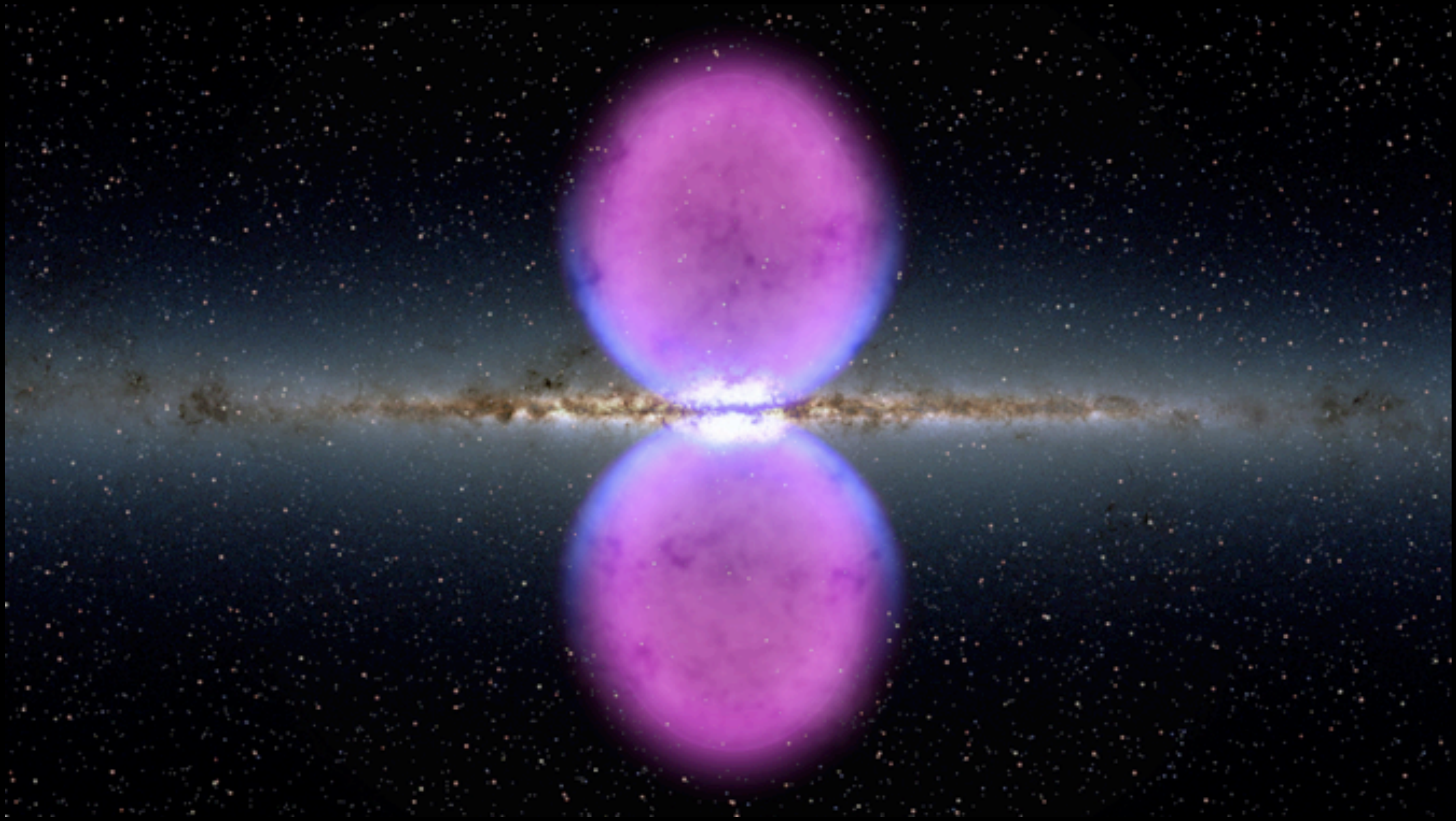
- Most discussed candidate is Weakly Interacting Massive Particle
  - Produced during big bang
  - Decouples from ordinary matter as the universe expands and cools
  - Still around today with densities of about a few per liter



- Supersymmetry produces a theoretical candidate in the lightest supersymmetric partner, but others exist

How do we find it?

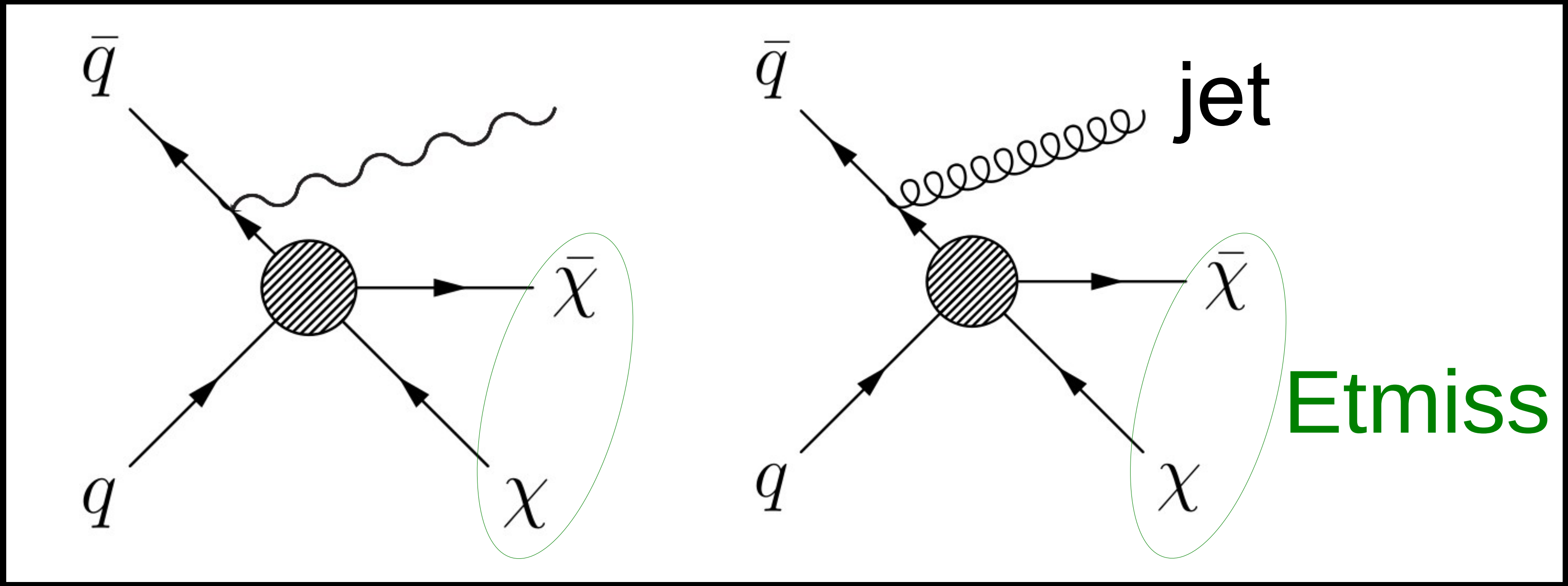
- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy



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

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

Rate calculation

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

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

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

Rate calculation

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

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

- Dark matter density component, from local and galactic observations with historically a factor of 2 uncertainty
- The unknown particle physics component, hopefully determined by experiment
  - Proportional to A^2 for most models

Rate calculation

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

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

- Dark matter density component, from local and galactic observations with historically a factor of 2 uncertainty
- The unknown particle physics component, hopefully determined by experiment
  - Proportional to A^2 for most models
- The nuclear part, approximately given by $F^2(Q) \propto e^{-Q/Q_0}$ where $Q_0 \sim \frac{80}{A^{5/3}}$ MeV

Rate calculation

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

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

- Dark matter density component, from local and galactic observations with historically a factor of 2 uncertainty
- The unknown particle physics component, hopefully determined by experiment
  - Proportional to A^2 for most models
- 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, and $v_m = \sqrt{Q/2m_r^2}$

The energy scale

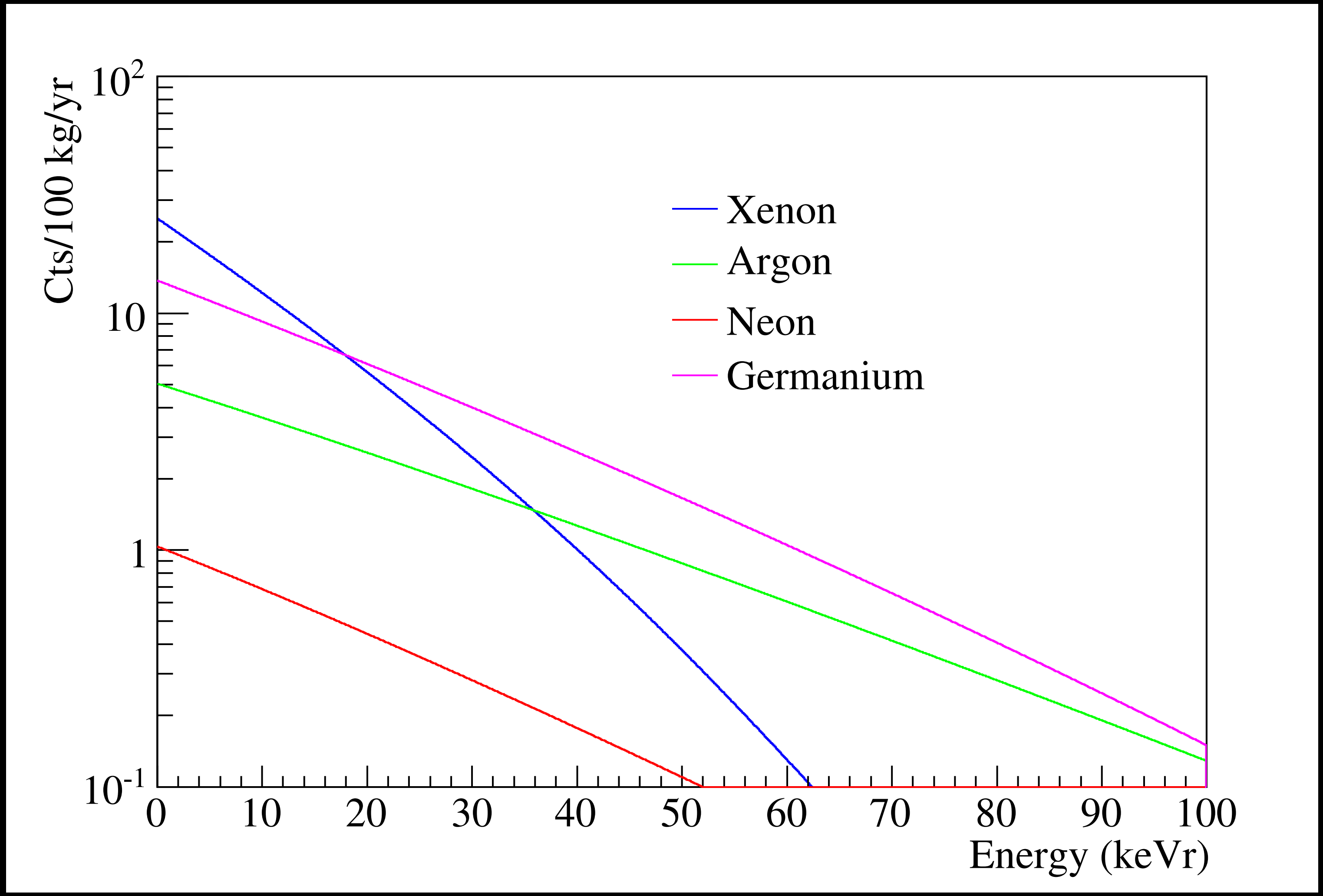
- Energy of recoils is tens of keV
- Entirely driven by kinematics, elastic scattering of things with approximately similar masses (100 GeV) and v ~ 0.001c (270 km/s)

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

Rate calculation

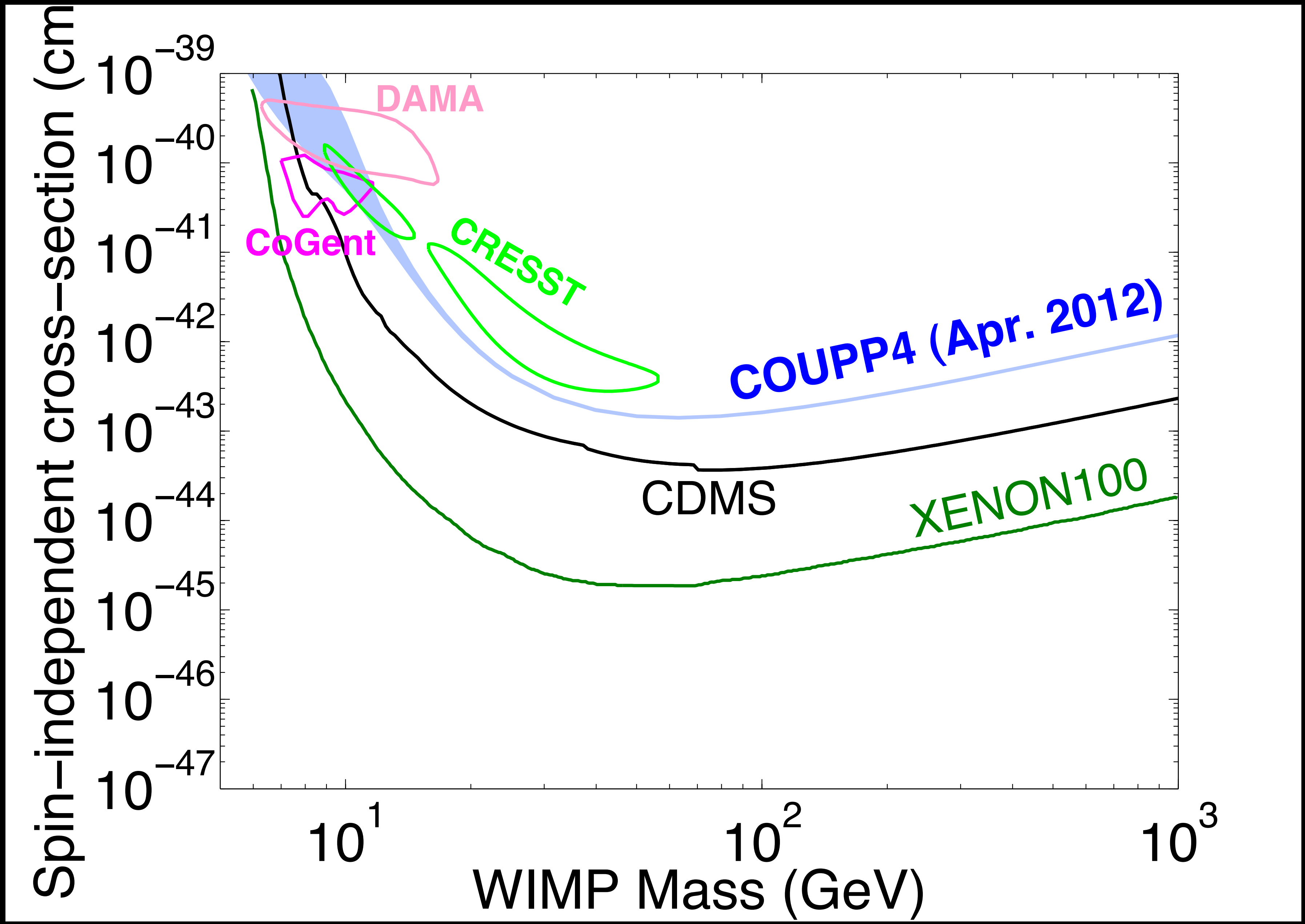
- Integrated rate above threshold, 100 GeV WIMP, $\sigma_0 = 10^{-45}$ cm^2

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



- Looking for a handful of events

The canonical plot



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

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

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 these days to get away from cosmic rays



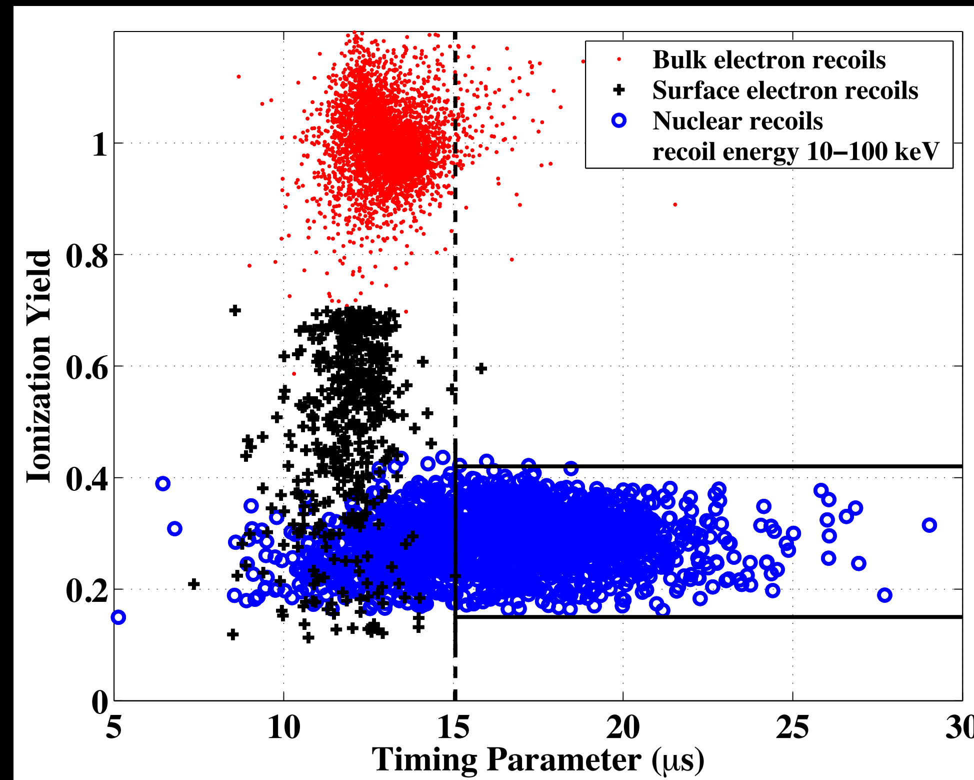
Background sources

- Cosmic rays are constantly streaming through
  - All experiments have to go underground these days to get away from cosmic rays
- Radioactive contaminants - rock, radon in air, impurities
  - Emphasis on purification and shielding

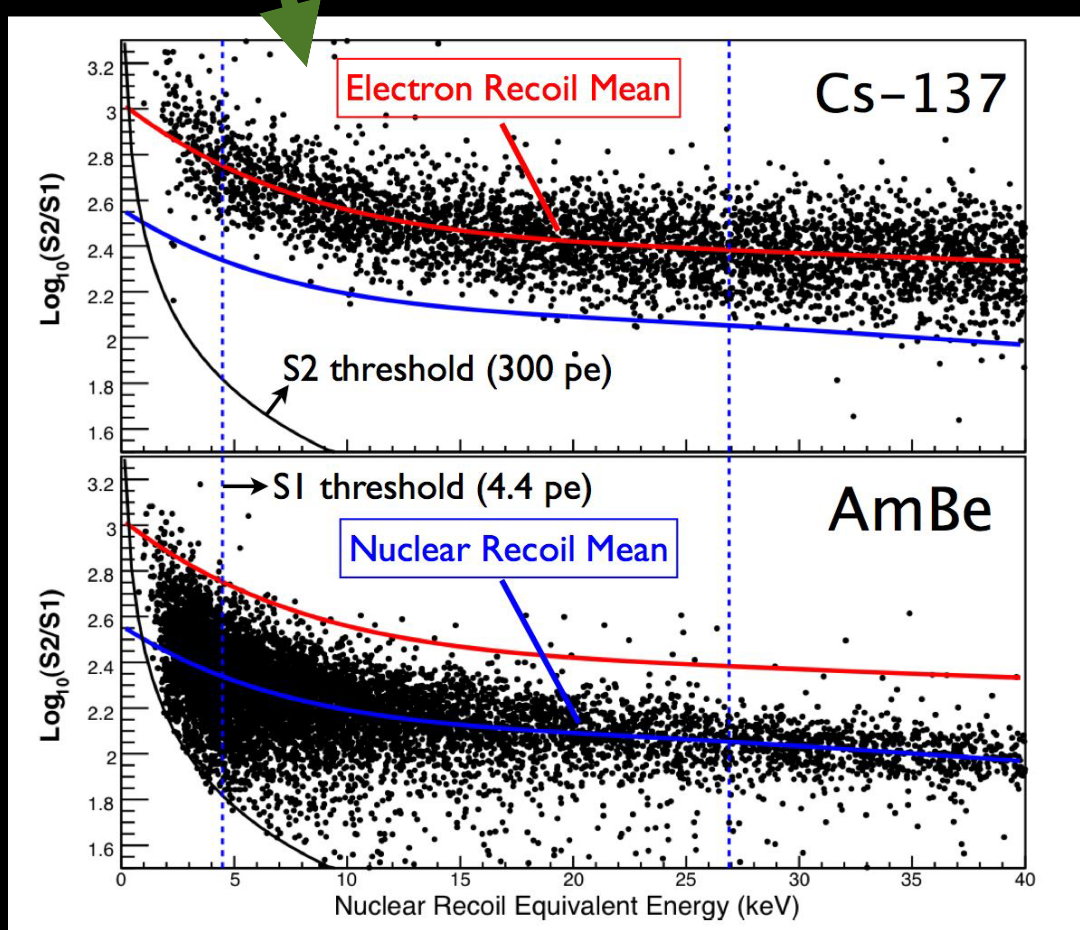
Background sources

- Cosmic rays are constantly streaming through
  - All experiments have to go underground these days to get away from cosmic rays
- Radioactive contaminants - rock, radon in air, impurities
  - Emphasis on purification and shielding
- The detector itself - steel, glass, detector components
  - Discrimination - can you tell signal from background using some microscopic physics that distinguishes the two?

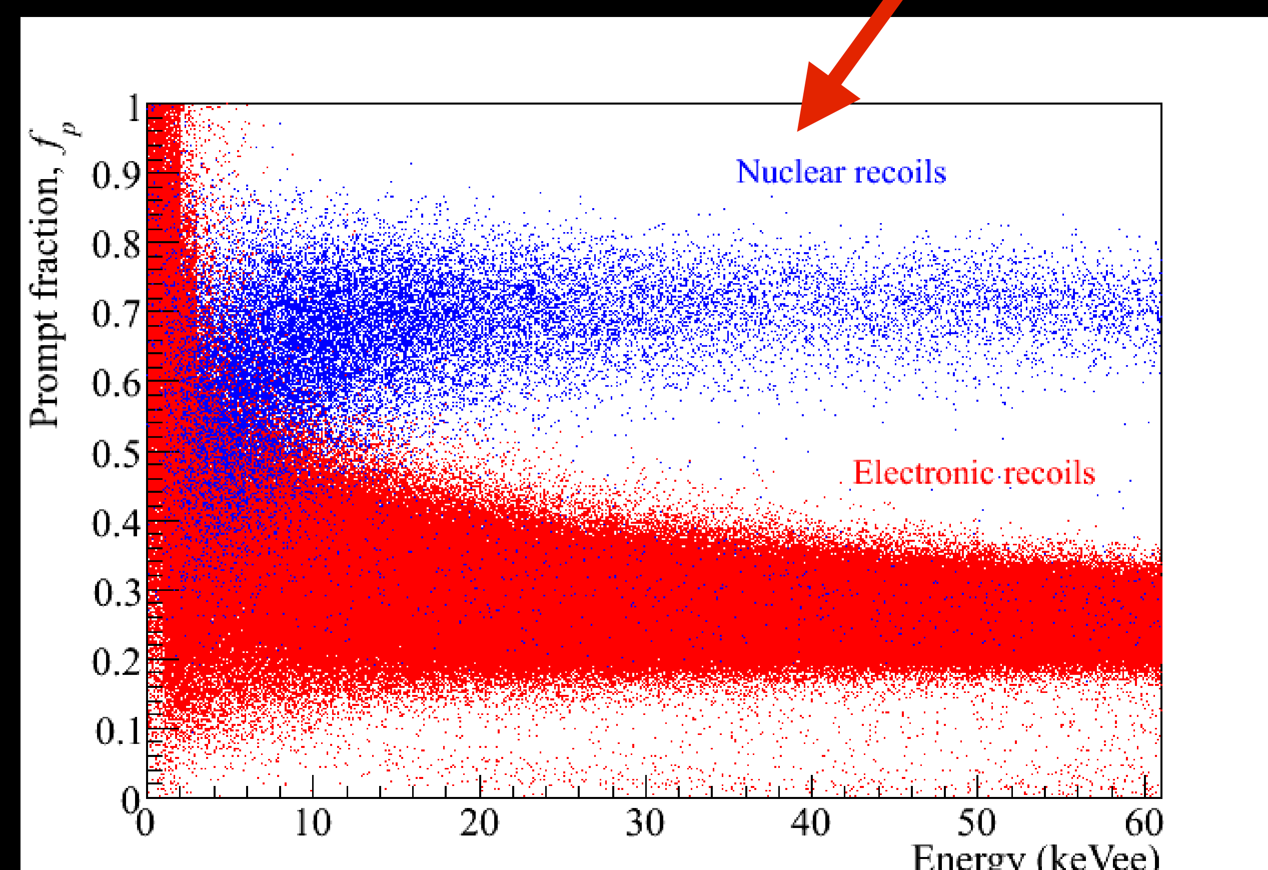
CDMS - Charge to heat



Xenon - Charge to light



Argon - Pulse shape discrimination



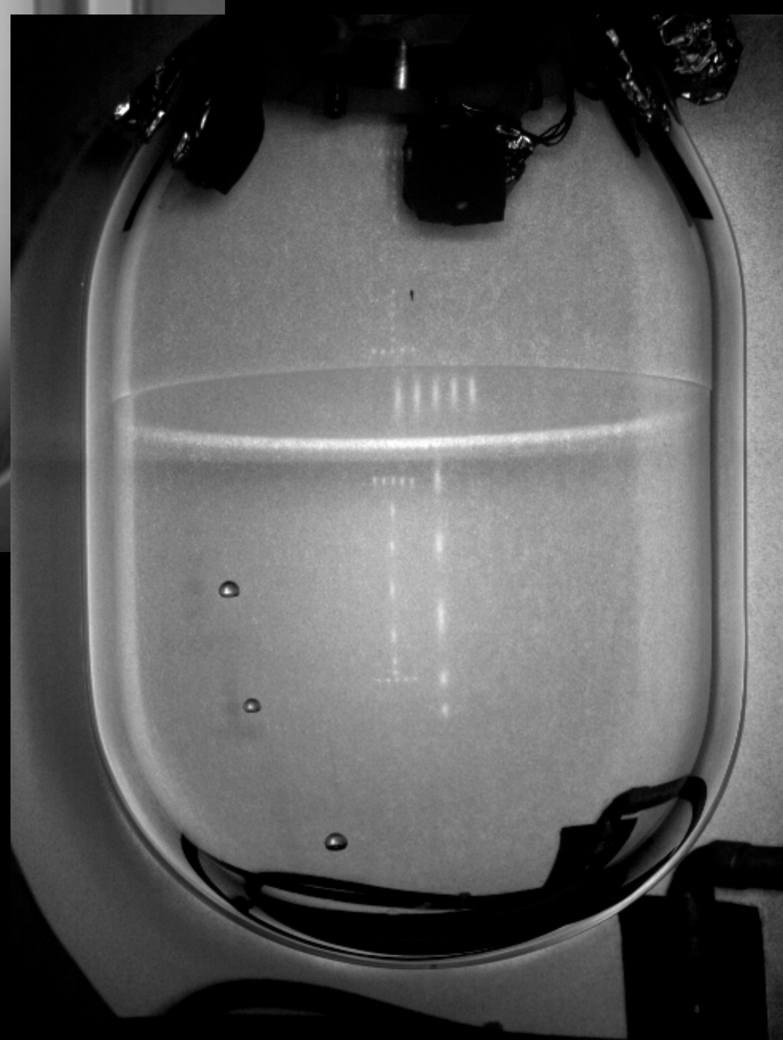
Background sources

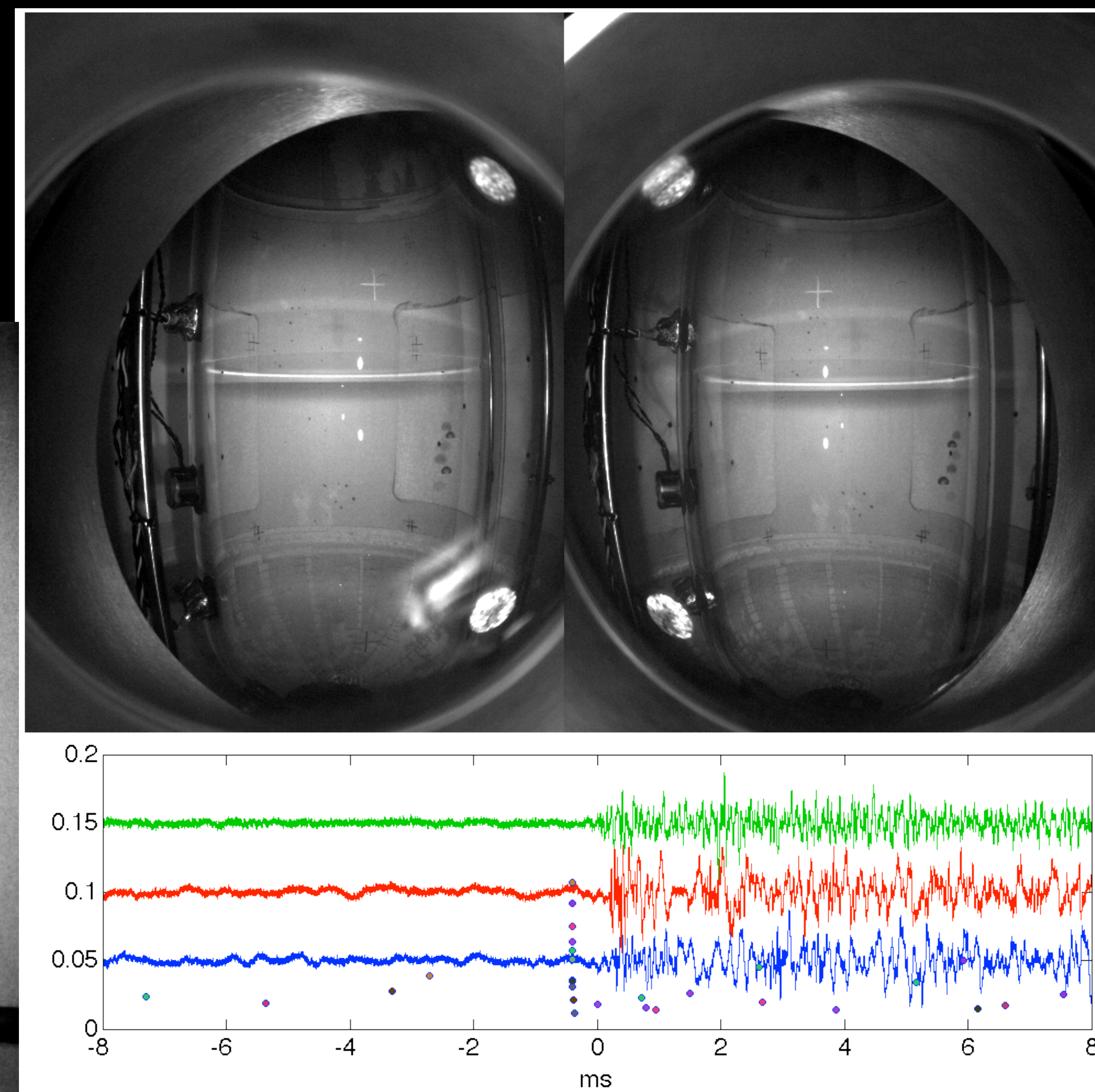
- Cosmic rays are constantly streaming through
  - All experiments have to go underground these days to get away from cosmic rays
- Radioactive contaminants - rock, radon in air, impurities
  - Emphasis on purification and shielding
- The detector itself - steel, glass, detector components
  - Discrimination - can you tell signal from background using some microscopic physics that distinguishes the two?

Bubble Chambers!

Chicagoland Observatory for Underground Particle Physics (COUPP)

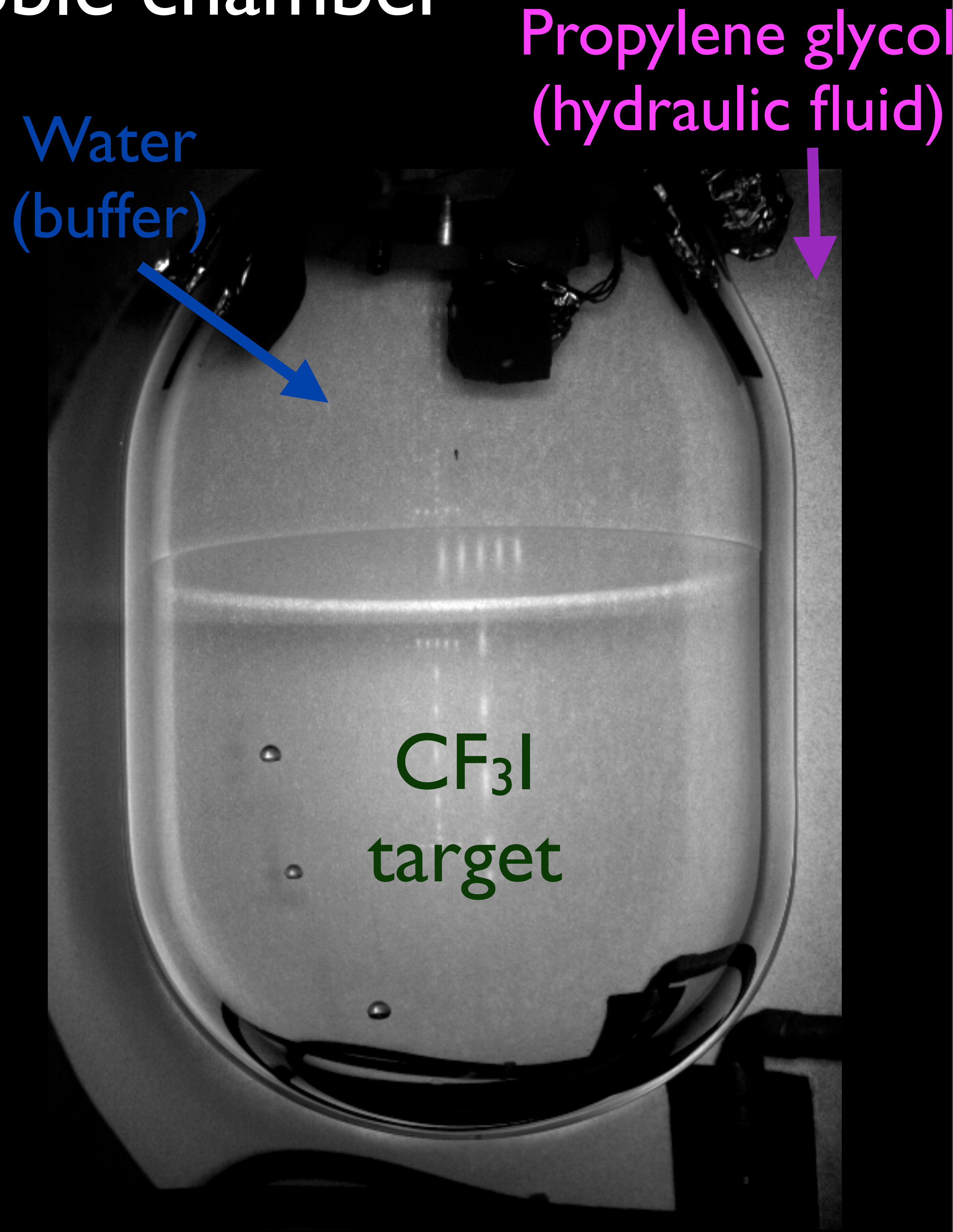
[Some debate over the pronunciation (should the Ps be silent?)]





COUPP bubble chamber

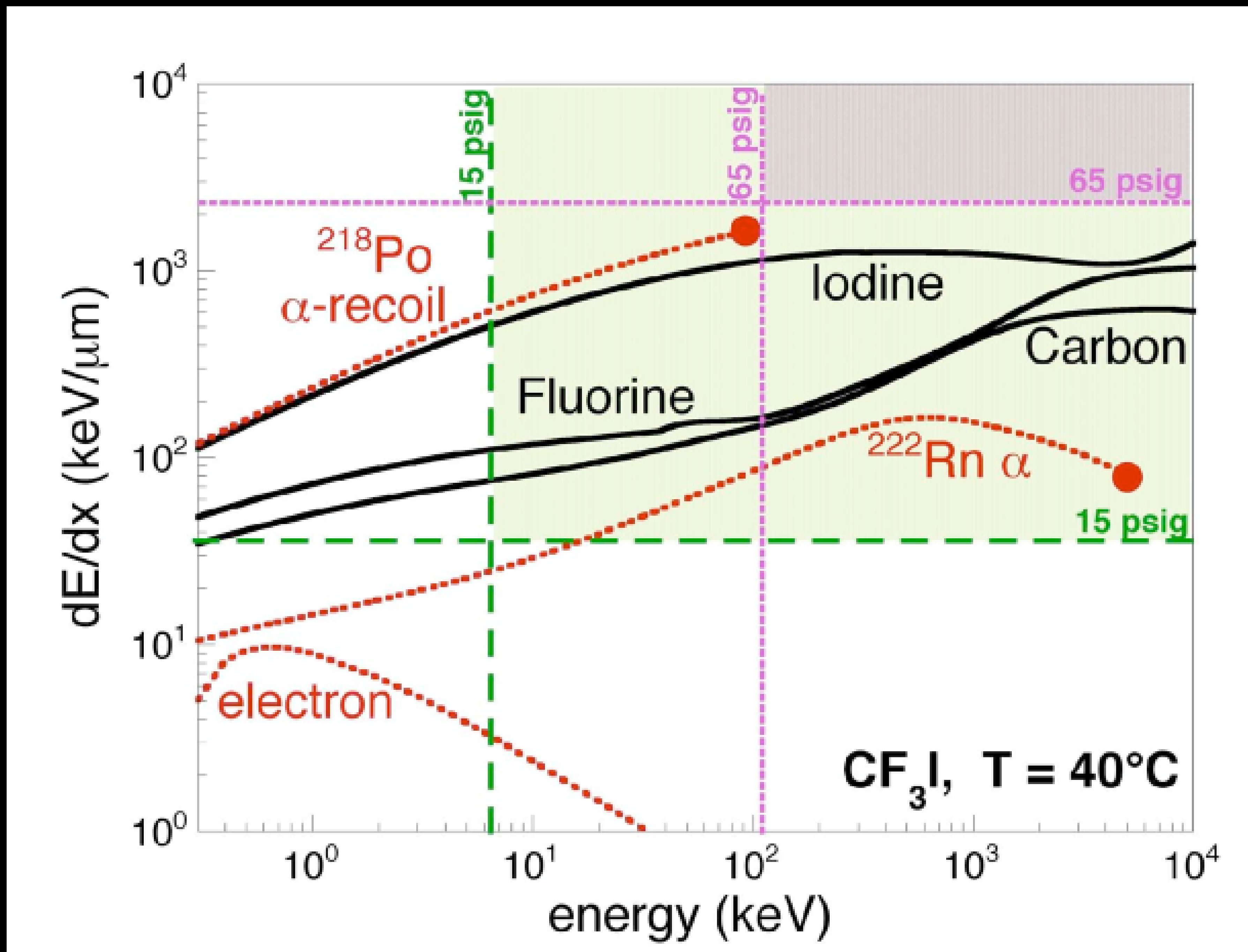
- Pressure expansion creates superheated fluid, CF_3I
  - F for spin-dependent
  - I for spin-independent
  - Alternatives - e.g. C_3F_8
- Particle interactions nucleate bubbles
- Cameras see bubbles
- Recompress chamber to reset



Why bubble chambers?

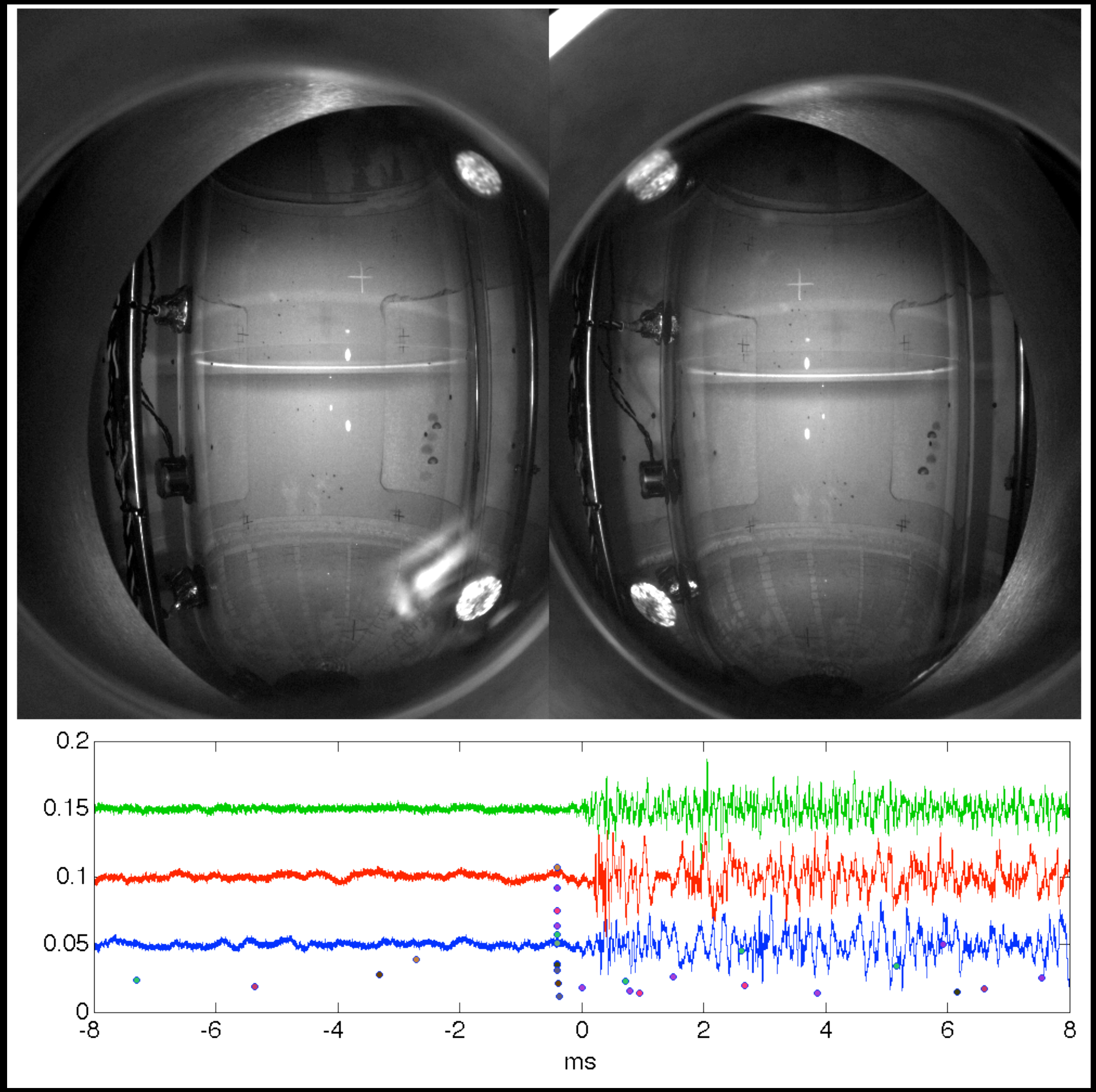
- To form a bubble requires two things
  - Enough energy
  - Enough energy density - length scale must be comparable to the critical bubble size
- By choosing superheat parameters appropriately (temperature and pressure), bubble chambers are blind to electronic recoils

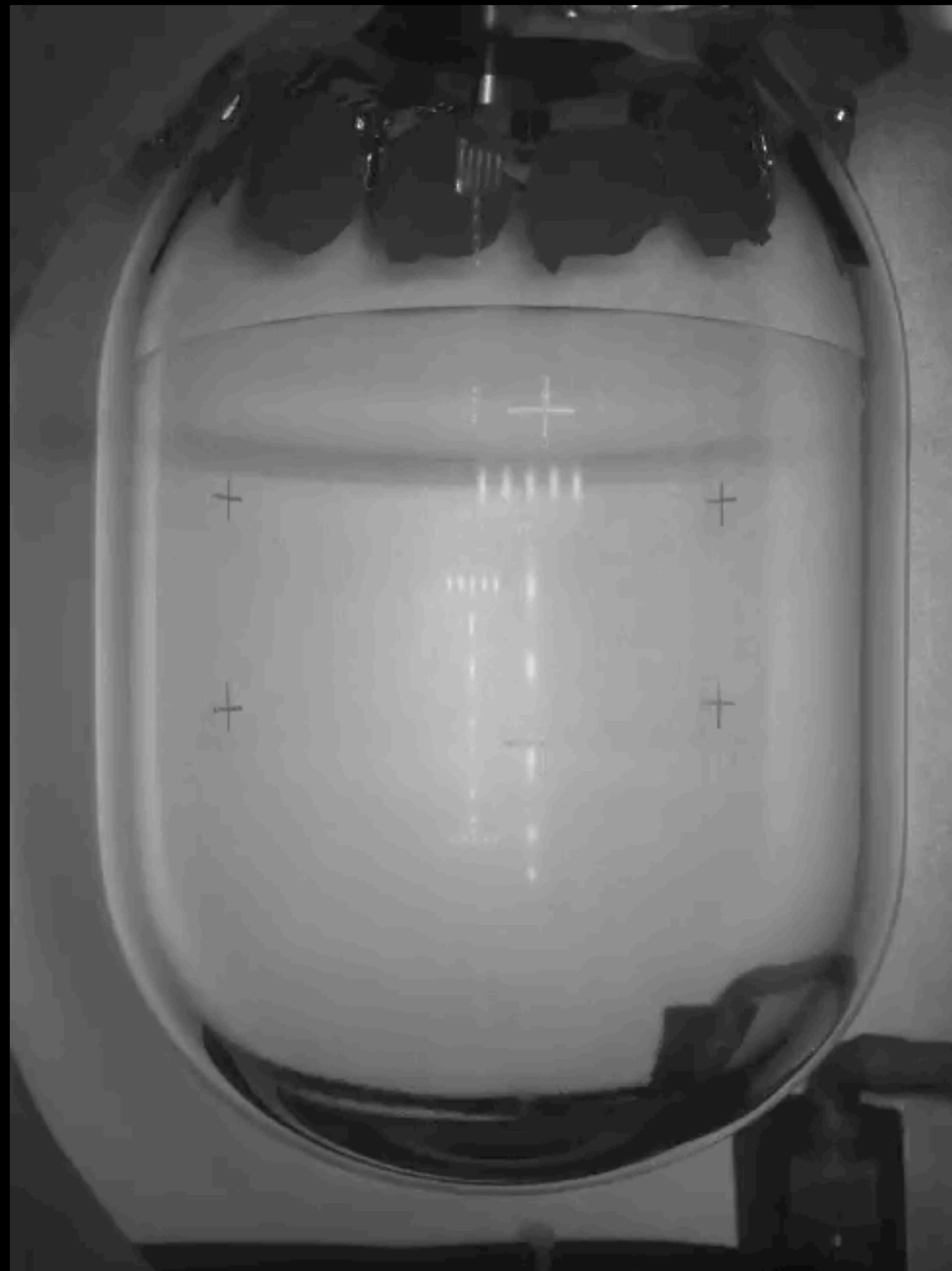
Why bubble chambers?



Why bubble chambers

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



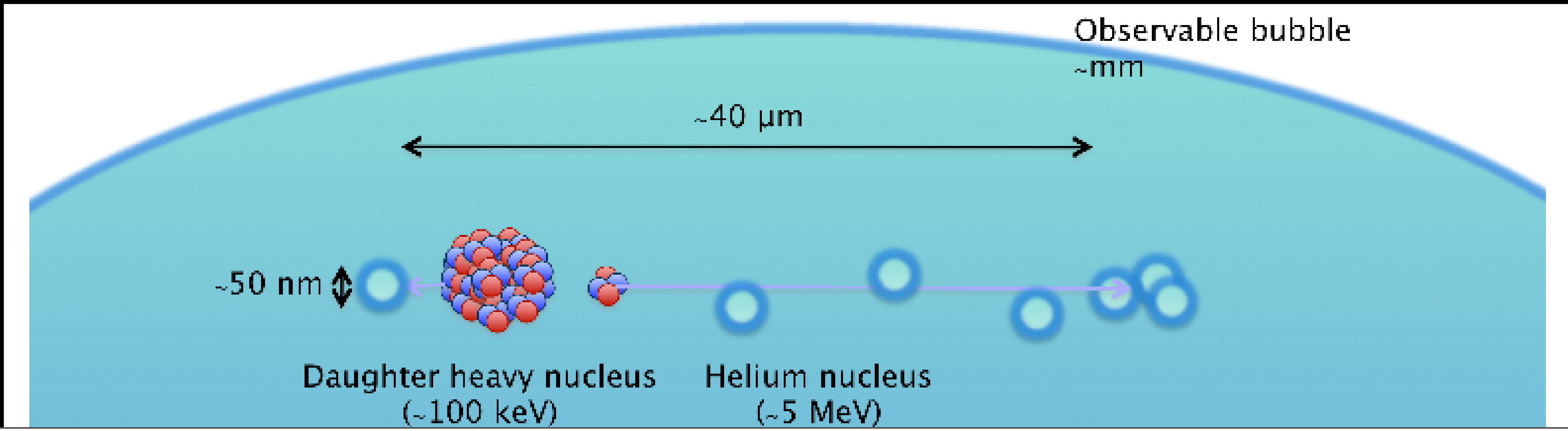


Why not bubble chambers?

- Threshold detectors - no energy resolution
  - Harder to distinguish some backgrounds
    - Alphas 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

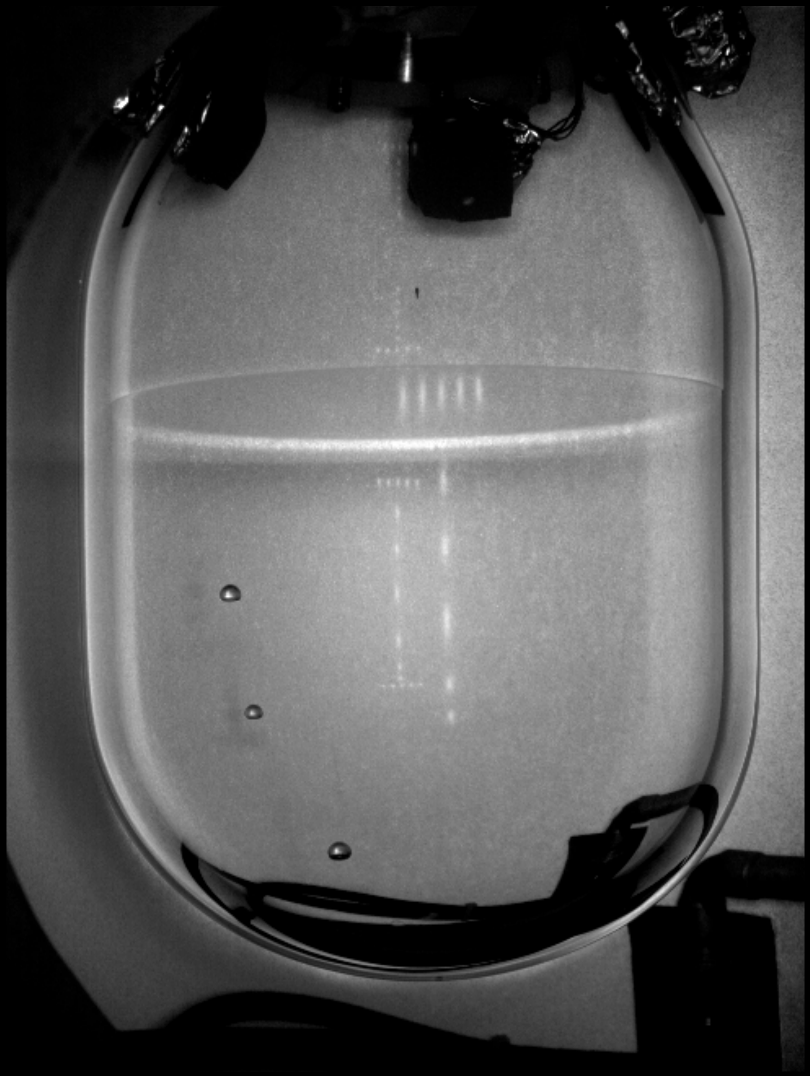
About those alphas

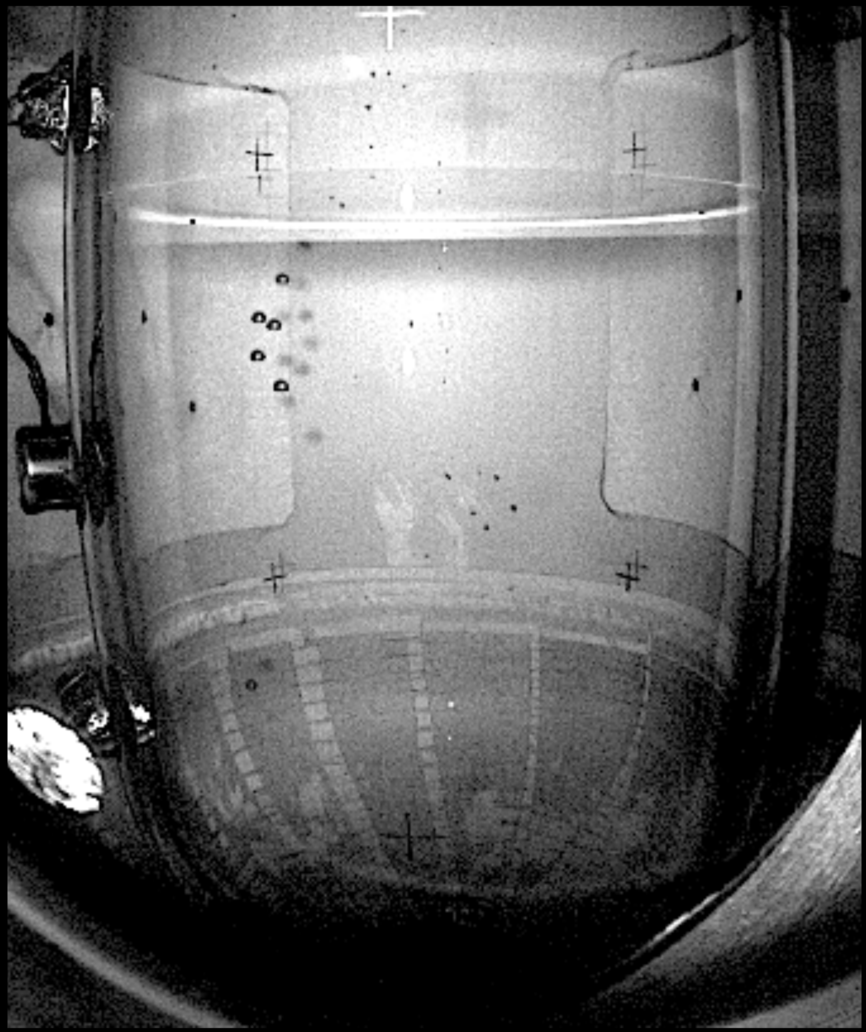
- Discovery of acoustic discrimination against alphas by PICASSO (Aubin et al, New J. Phys 10:103017, 2008)
  - Alphas deposit energy over tens of microns
  - Nuclear recoils deposit theirs in tens of nanometers
- In COUPP bubble chambers, alphas are several times louder



The COUPP program

- COUPP4: A 2-liter chamber operating at SNOLAB since 2010
- COUPP60: Up to 40 liters, commissioning at SNOLAB now
- COUPP500: Ton scale detector, funded by NSF and DOE, at SNOLAB in 2015?

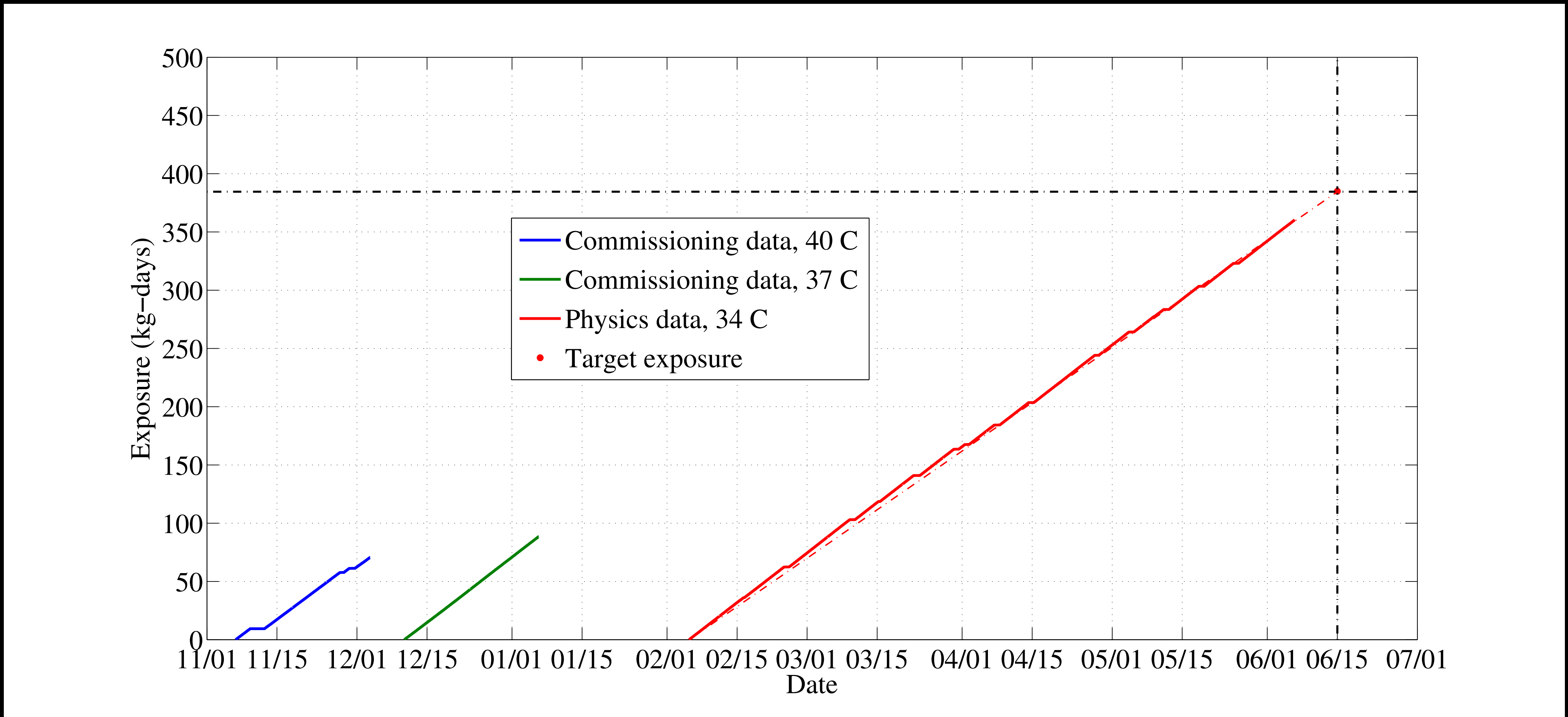




COUPP-4

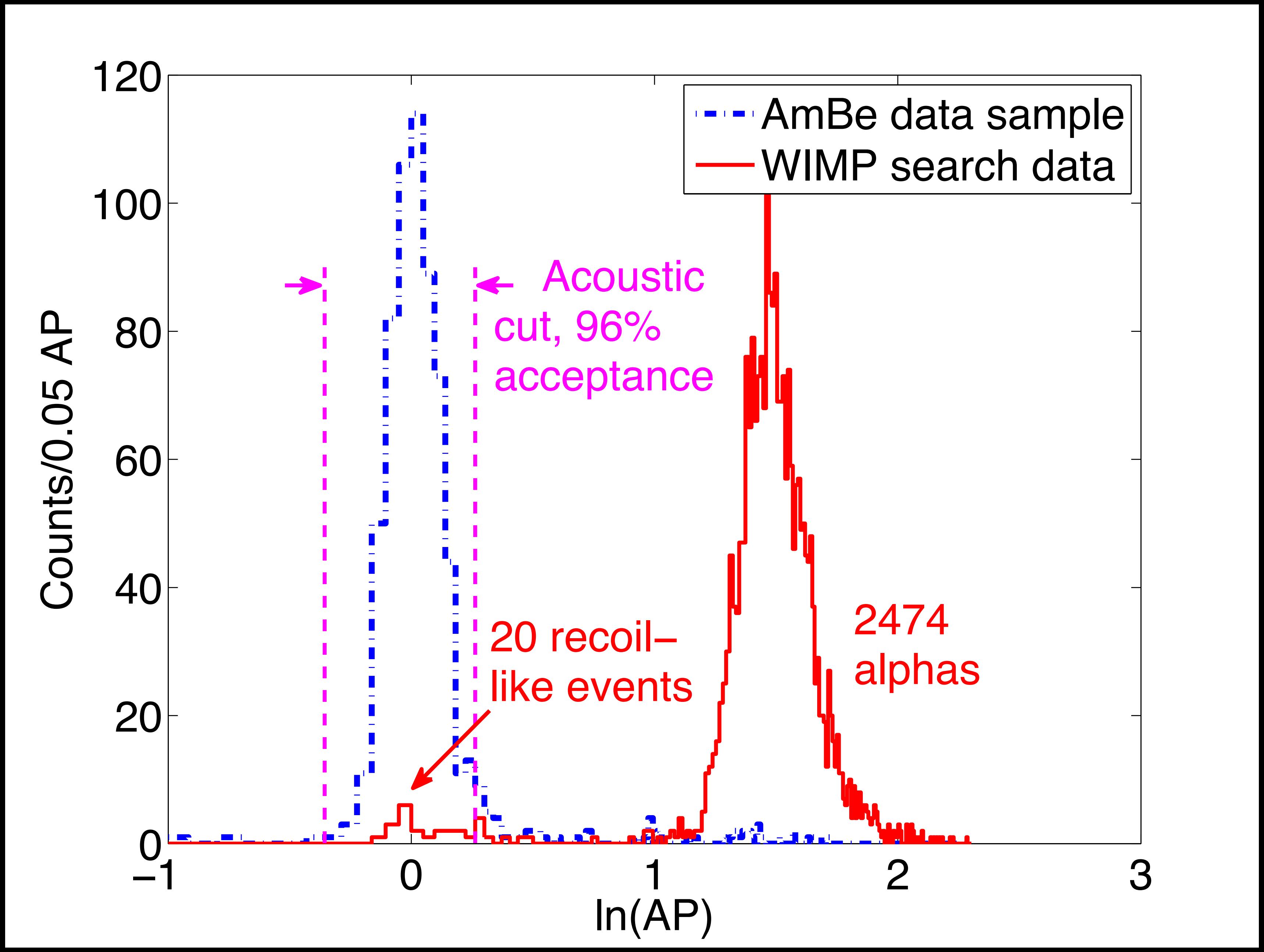
COUPP4: First run 2010-2011

- 17.4 live days at 8 keV threshold
- 21.9 live days at 11 keV threshold
- 97.3 live days at 16 keV threshold
- 79% acceptance for nuclear recoils after all cuts (including fiducial)

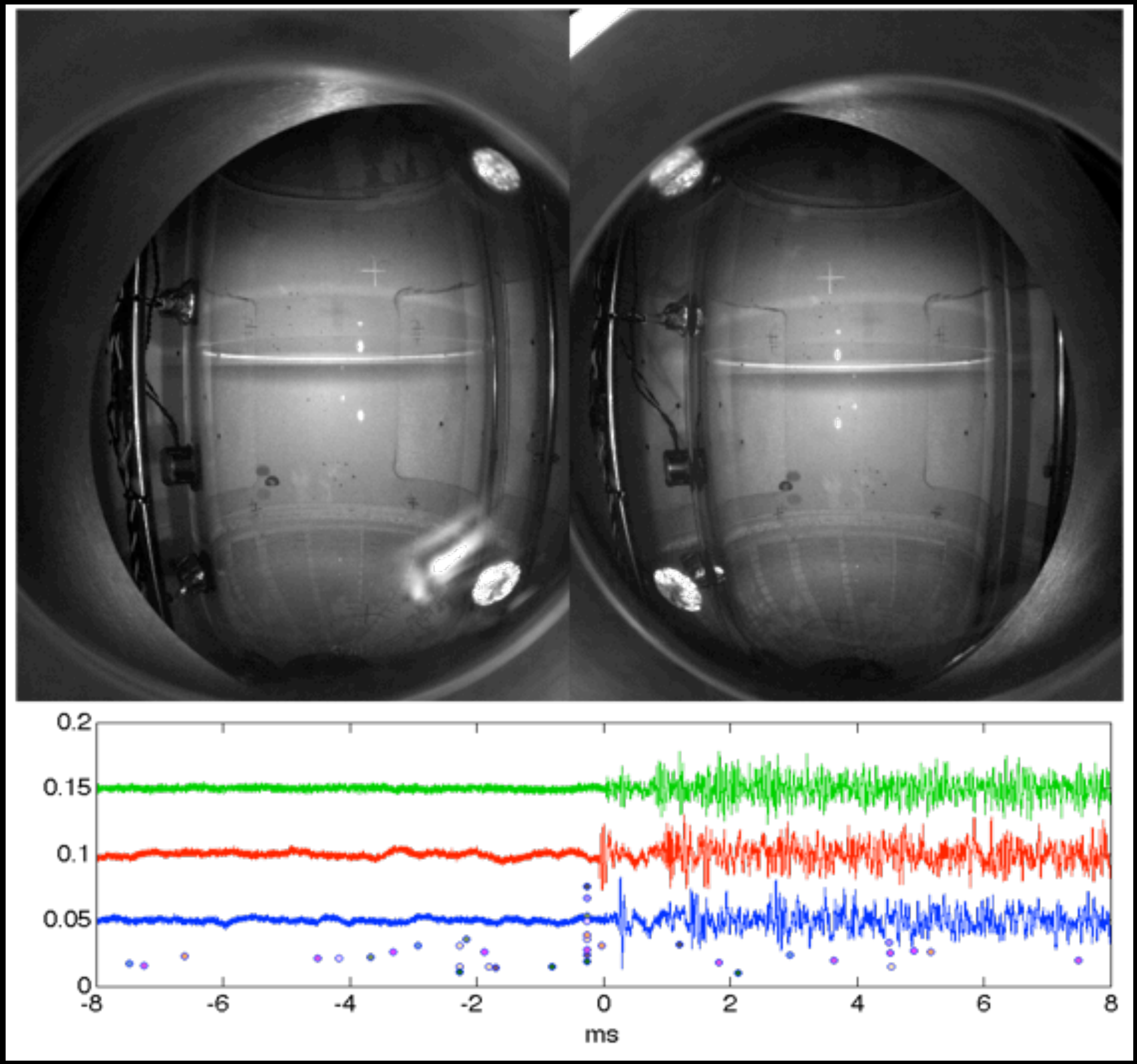


COUPP4: Acoustic discrimination

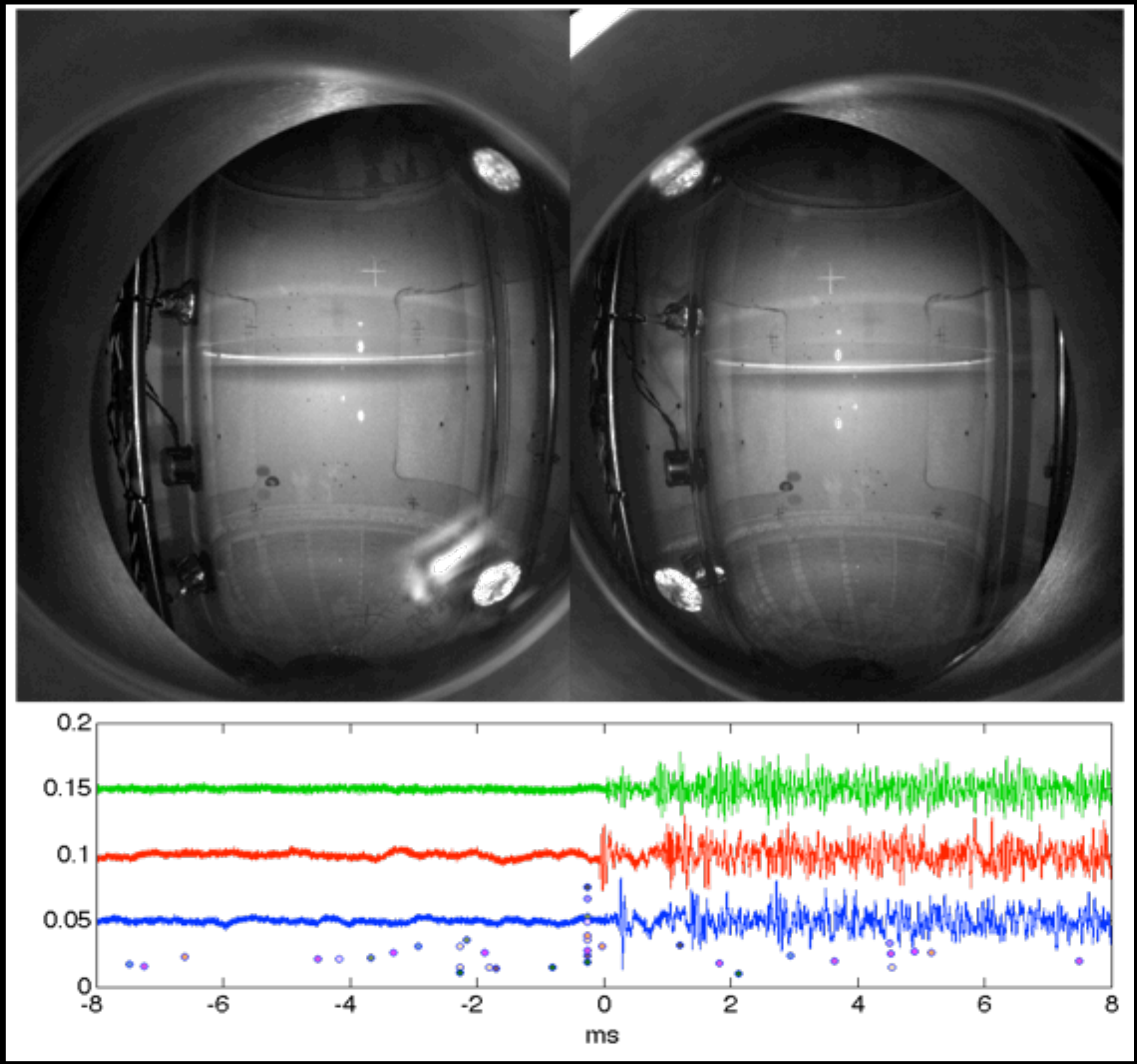
- Better than 99.3% rejection against alphas at 16 keV threshold
  - Limited by statistics, and backgrounds



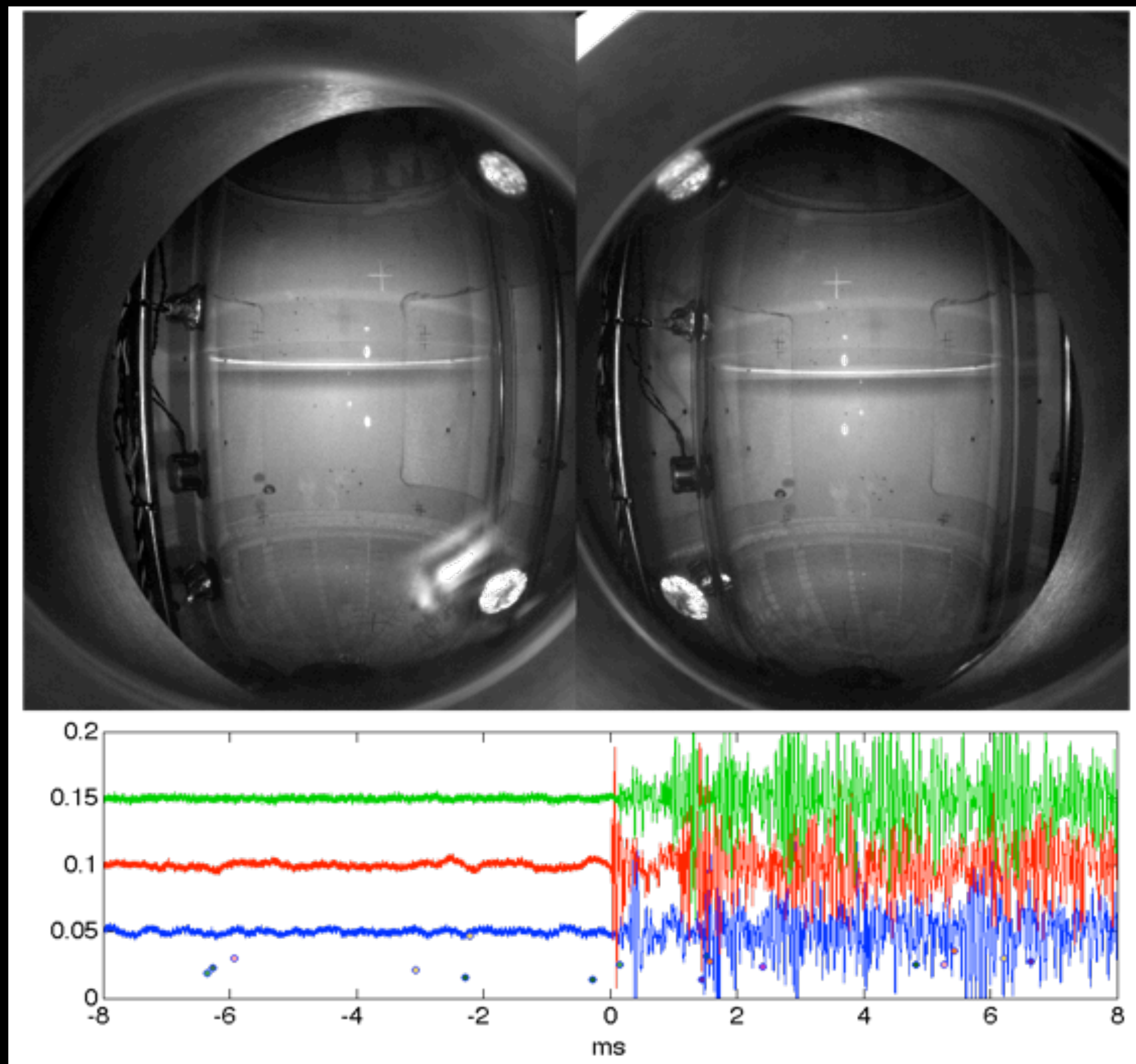
This is what dark matter would sound like



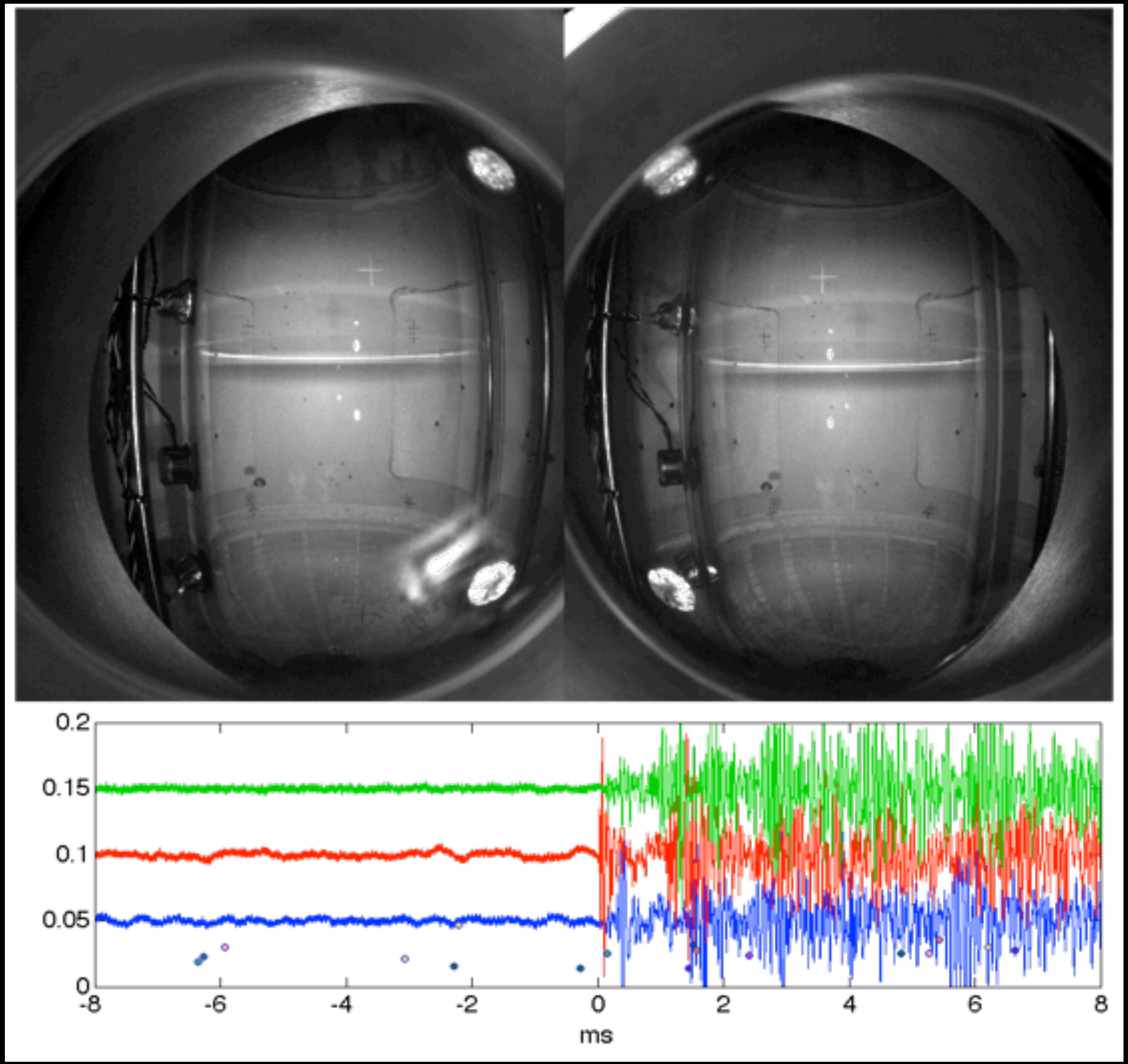
This is what dark matter would sound like



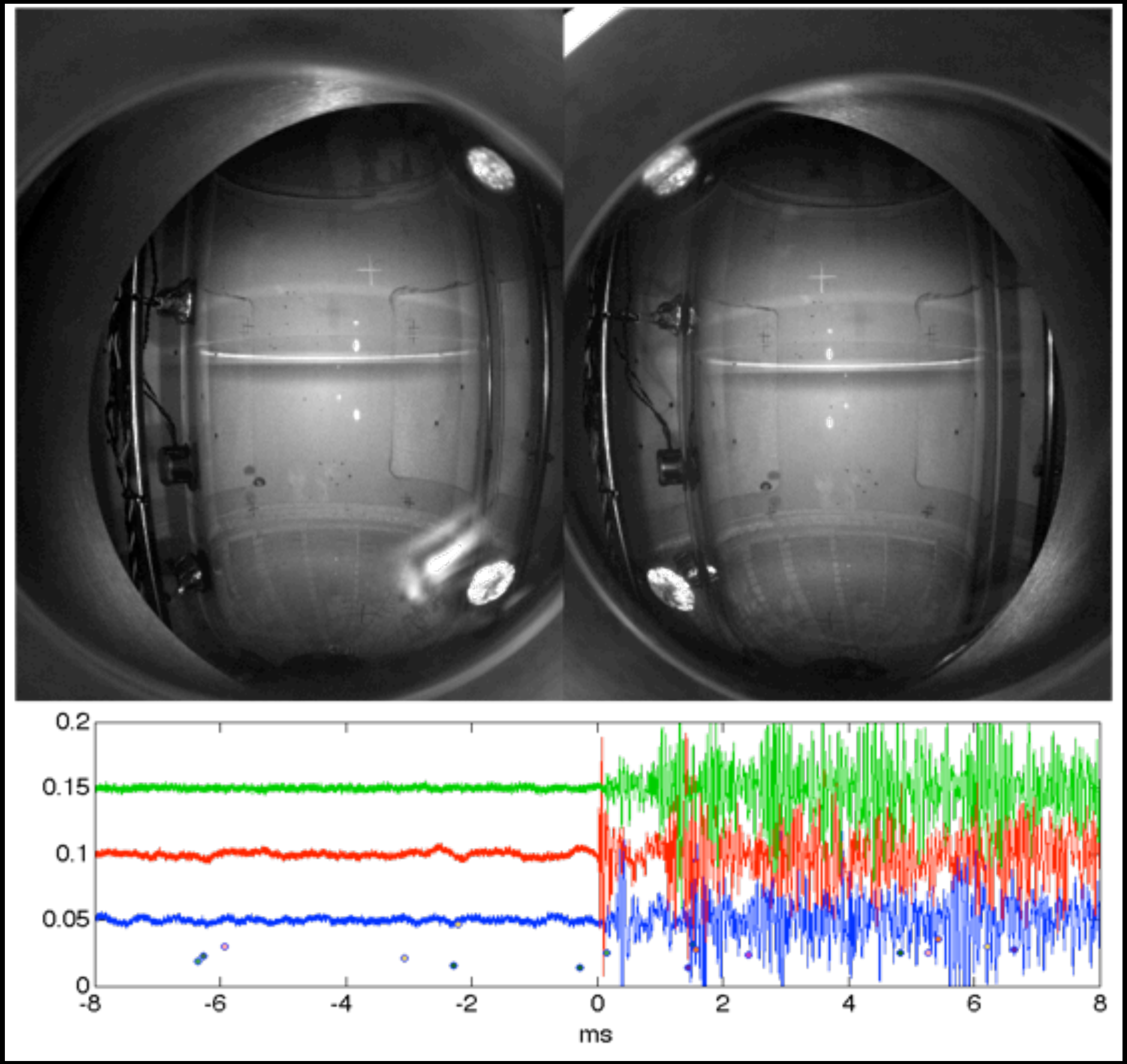
This is what an alpha sounds like



This is what an alpha sounds like



Both together, just to hear the difference



COUPP4: Results and sensitivity

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

COUPP4: Results and sensitivity

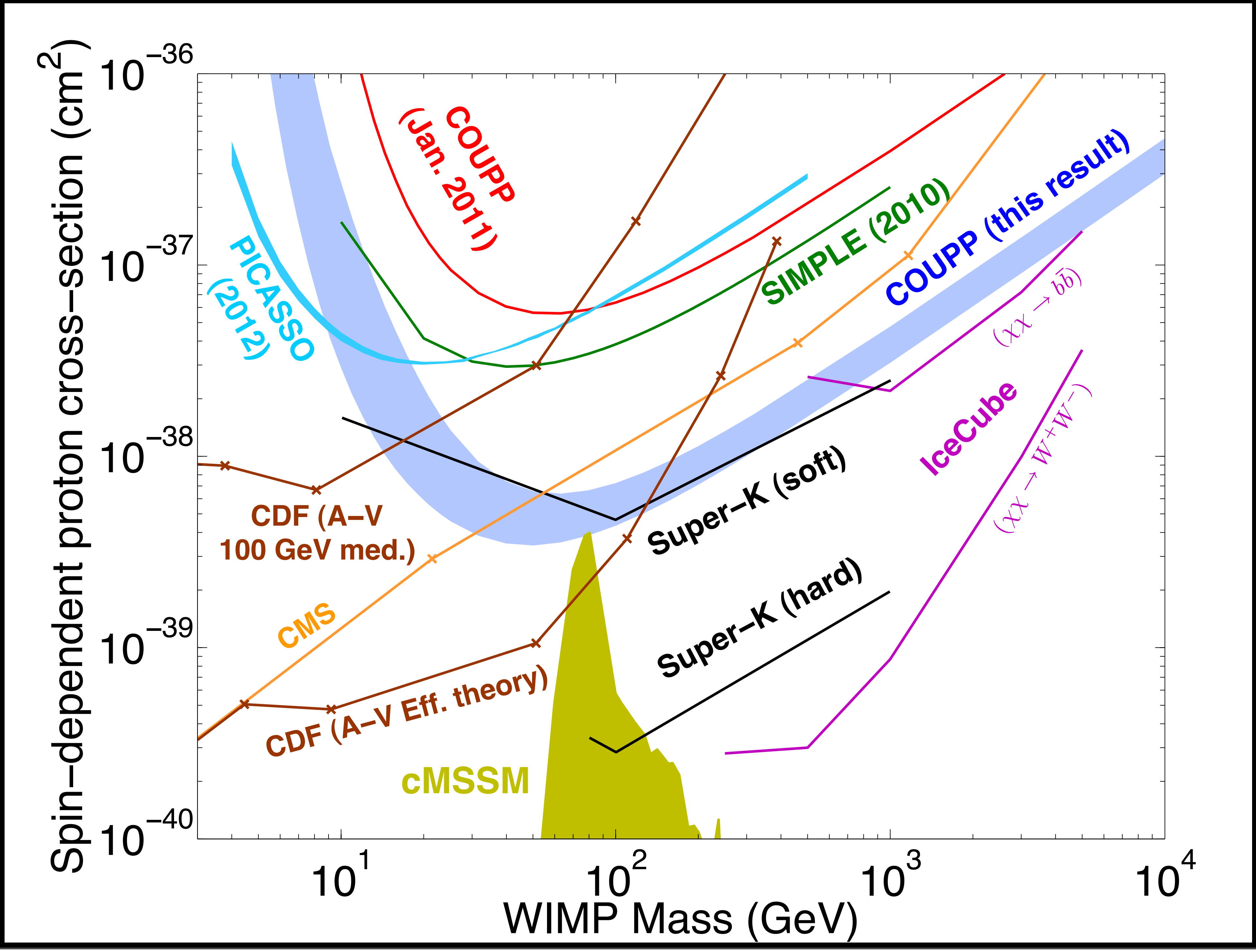
- 20 WIMP candidates (8 at 8 keV, 6 at 11 keV, 8 at 16 keV)
  - 3 multiple bubble events imply neutrons
  - U, Th in the piezo-acoustic sensors and the viewports

COUPP4: Results and sensitivity

- 20 WIMP candidates (8 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

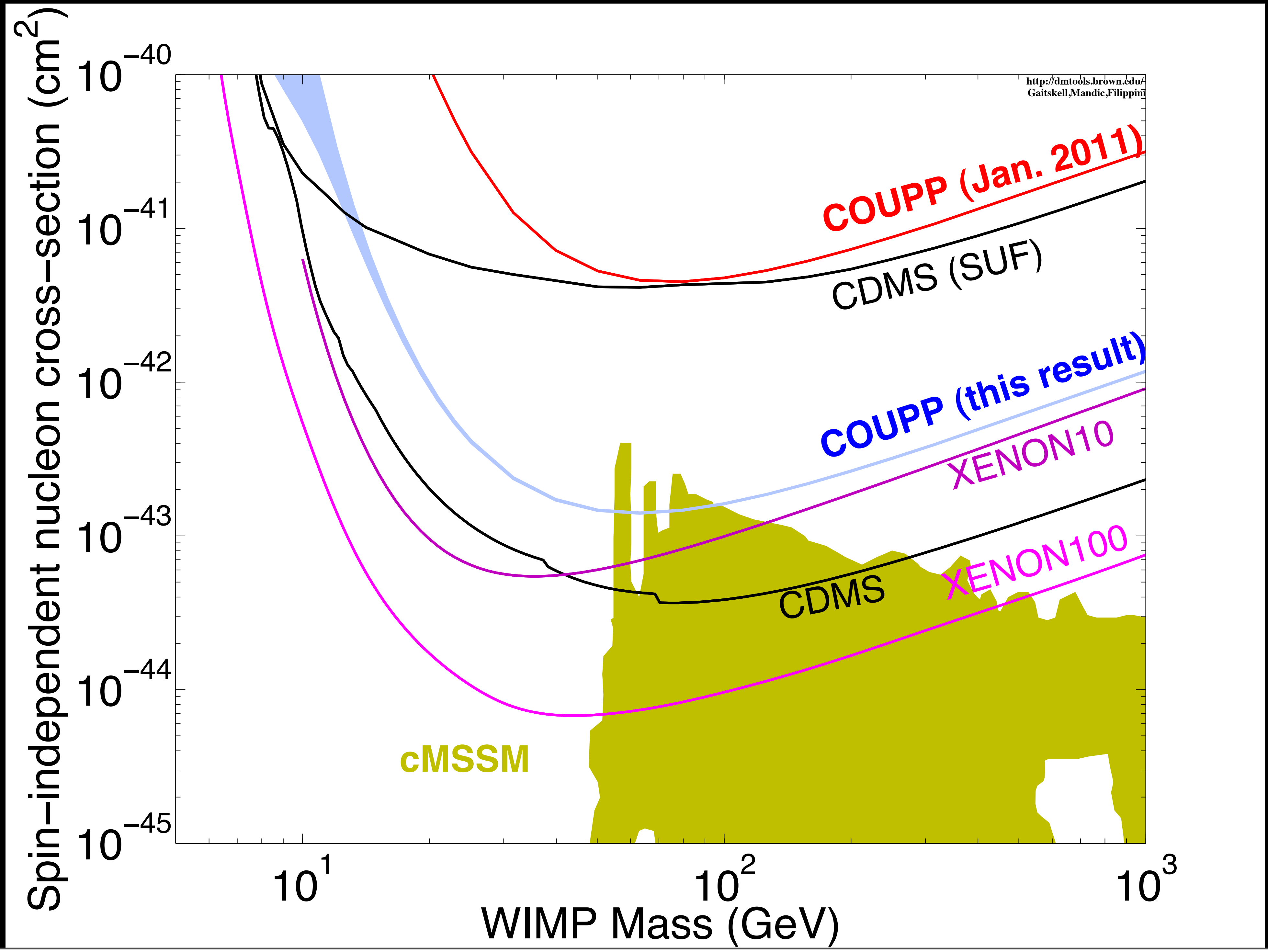
COUPP4: Results and sensitivity

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



COUPP4: Results and sensitivity

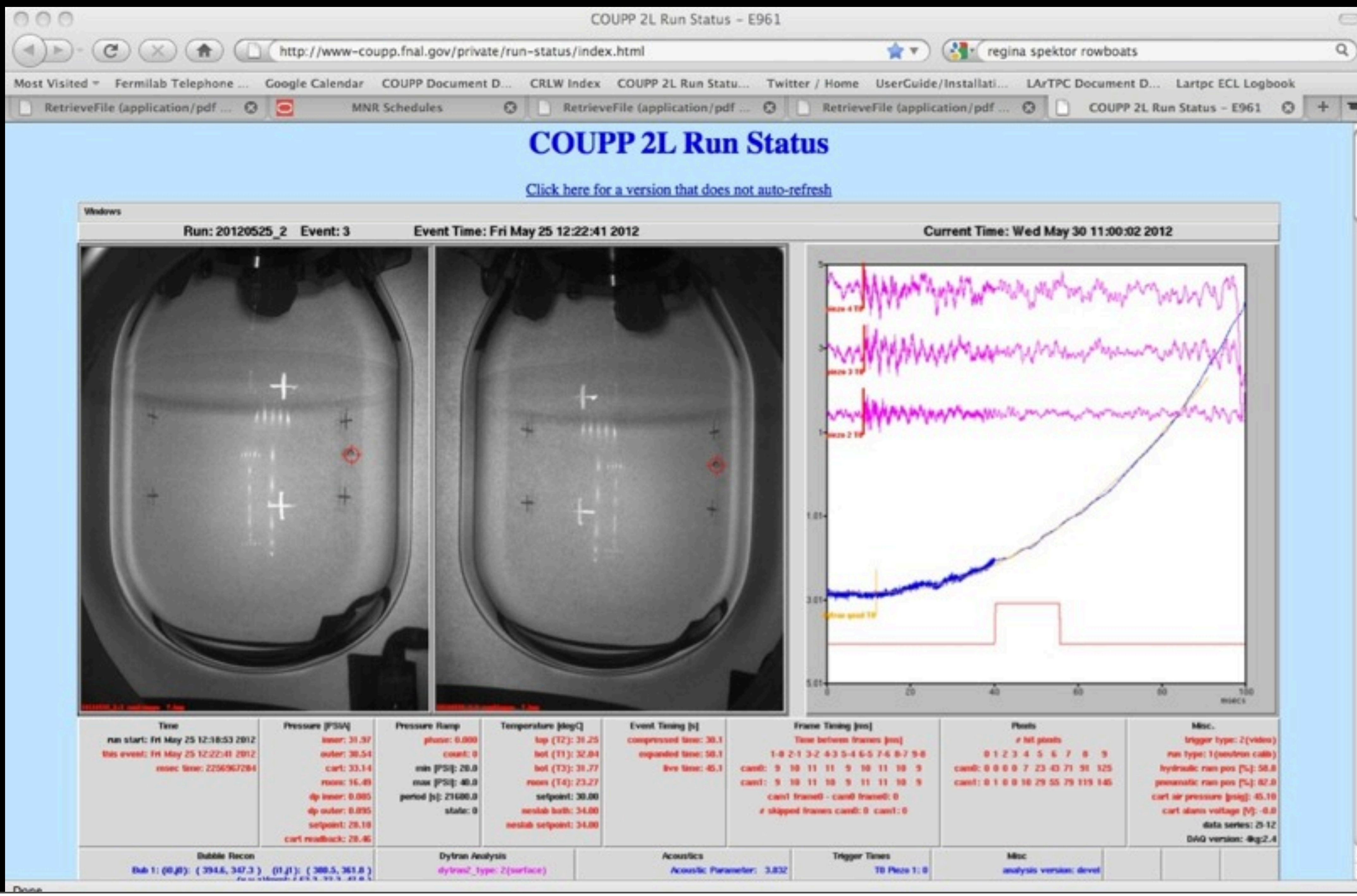
- Given uncertainties on backgrounds, no background subtraction: PRD 86:052001 (2012)



COUPP4: Results and sensitivity

- Removed known neutron sources and improved fluid purification

- Second run ended last November



Threshold and efficiency

- Threshold determined from Seitz, Phys. of Fluids **1**, 2 (1958)

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

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

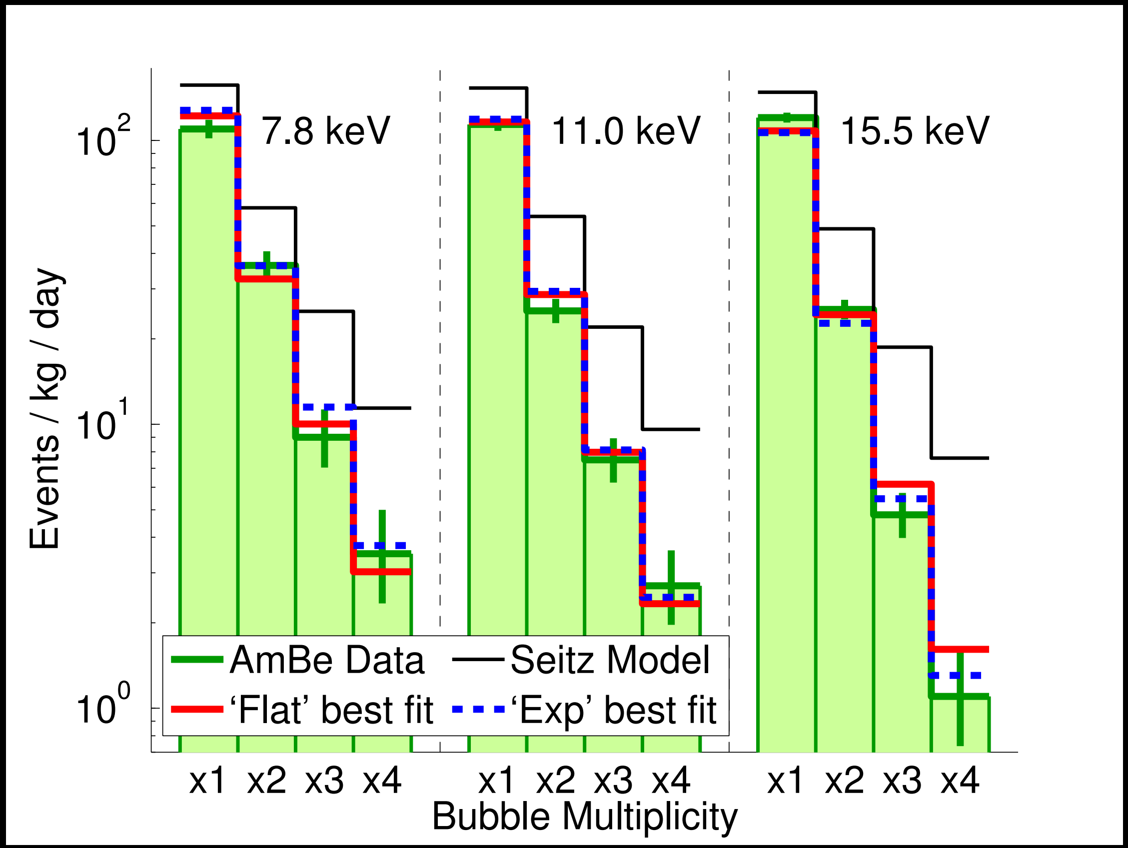
Surface energy

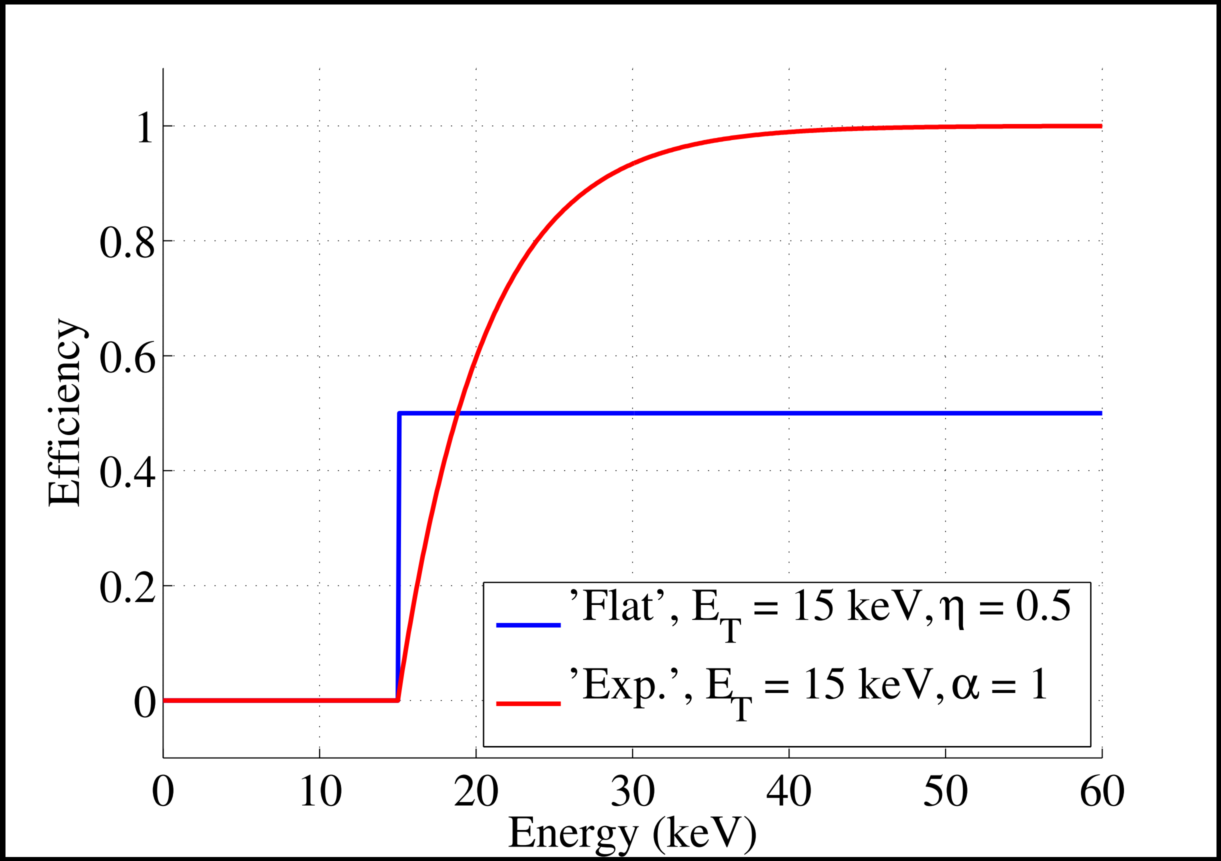
Latent heat

- Calibration required to validate this model
  - Complicated by three different types of recoils in CF_3I

Carbon and fluorine

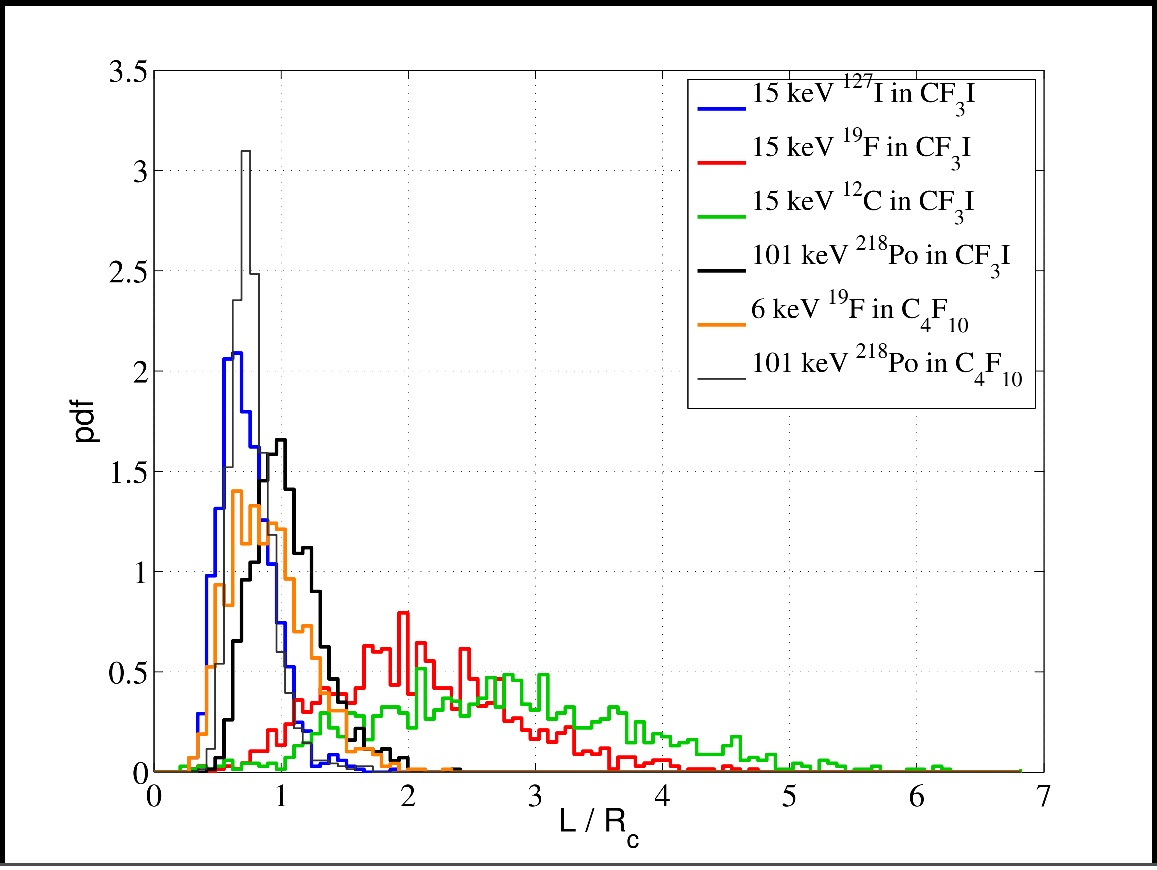
- Use neutron calibration sources at SNOLAB
- Compare MCNP-predicted rates of single, double, triple and quadruple bubble events with observation
- Data show a shortfall of events compared to simulation of the Seitz Model- i.e. the threshold is not a step function

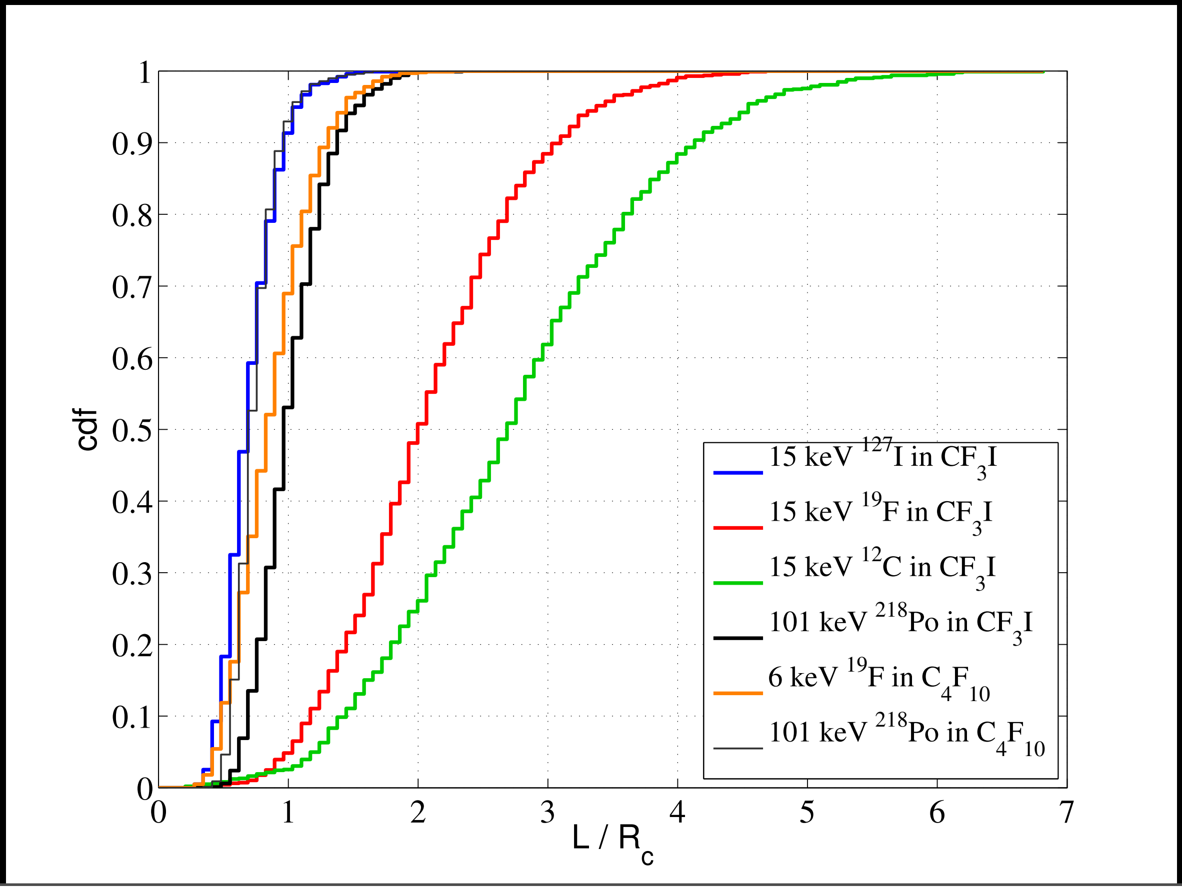




What about iodine?

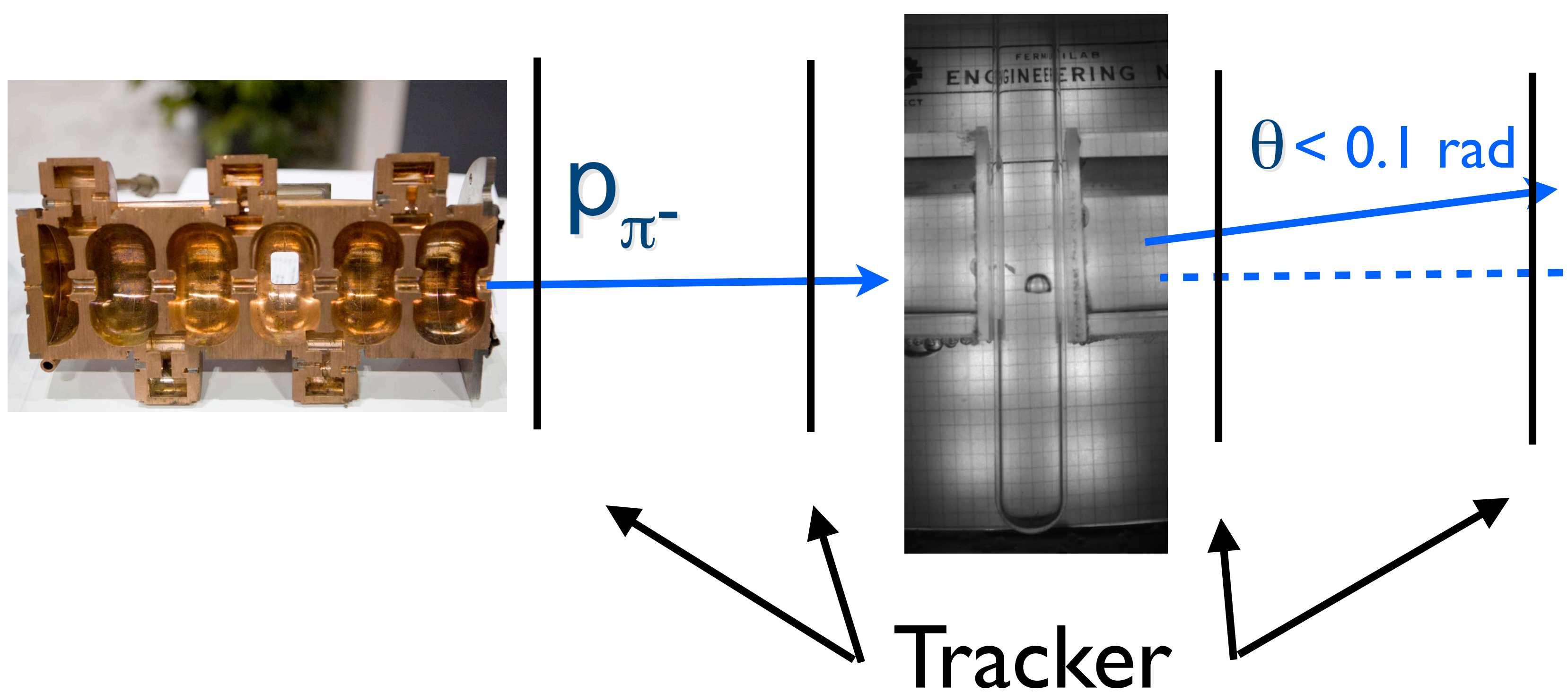
- Main sensitivity to spin independent dark matter from iodine
  - 85% of neutron source interactions are with C and F
  - Heavy radon nuclei are a proxy, but we'd like a direct calibration
- Why does the nucleus matter? Recall that the recoil track length L must be comparable to the bubble radius R_C





COUPP Iodine Recoil Threshold Experiment

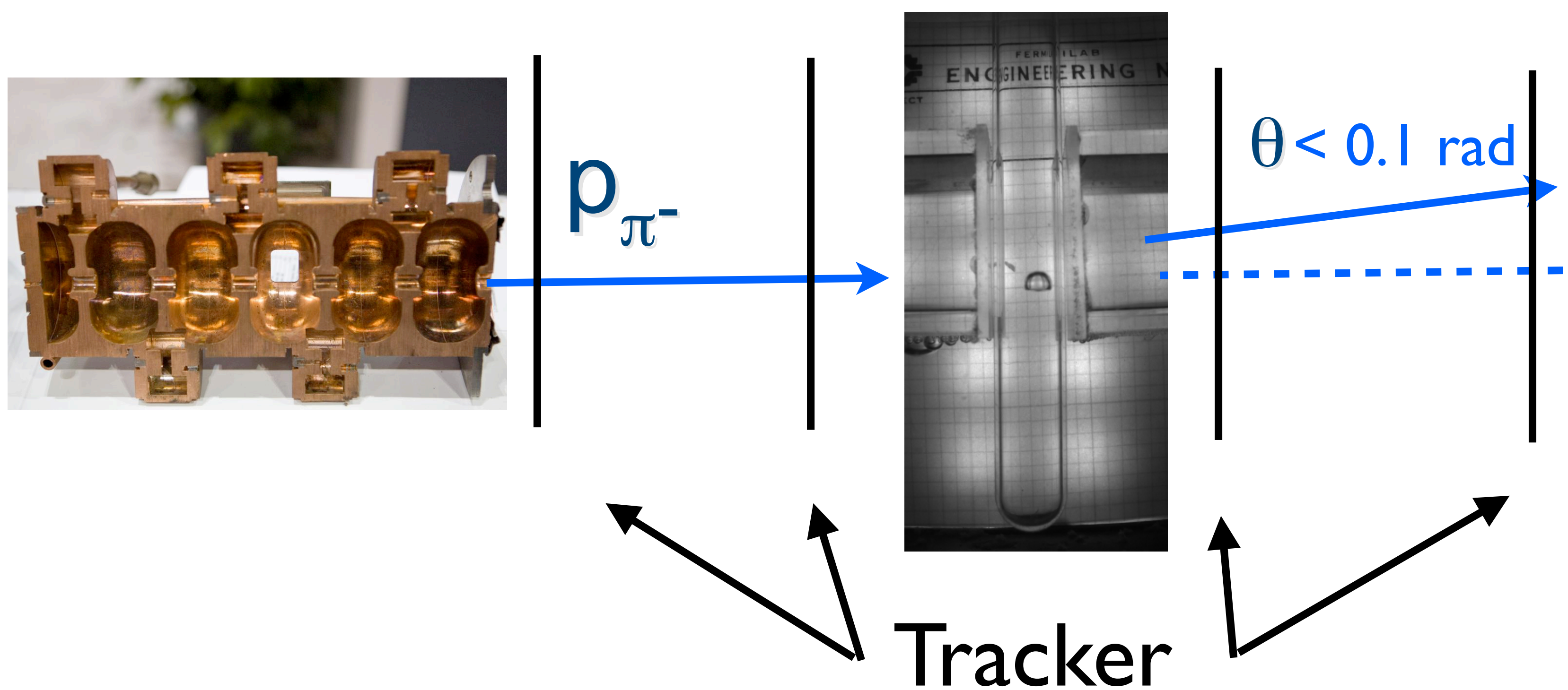
- Bubble chambers are insensitive to MIPs
  - Elastic scattering of charged particles can be tracked with very high precision



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

COUPP Iodine Recoil Threshold Experiment

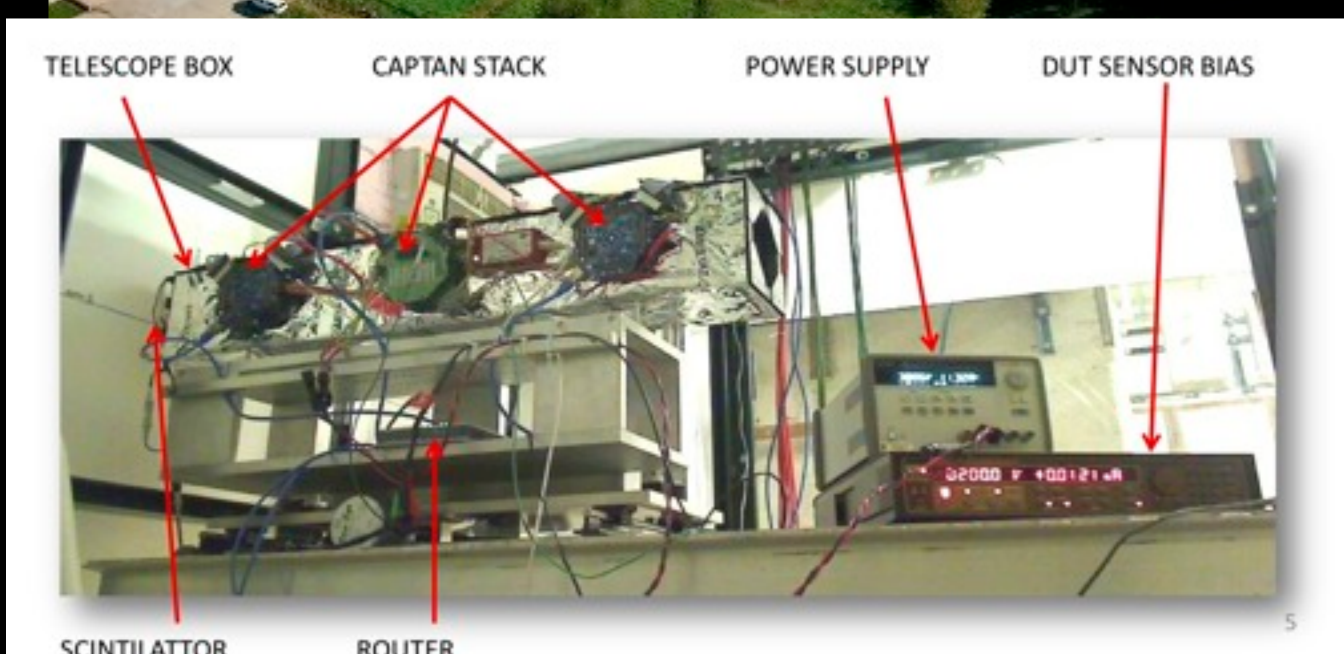
- Provides event by event energy information bubble chambers normally can't provide

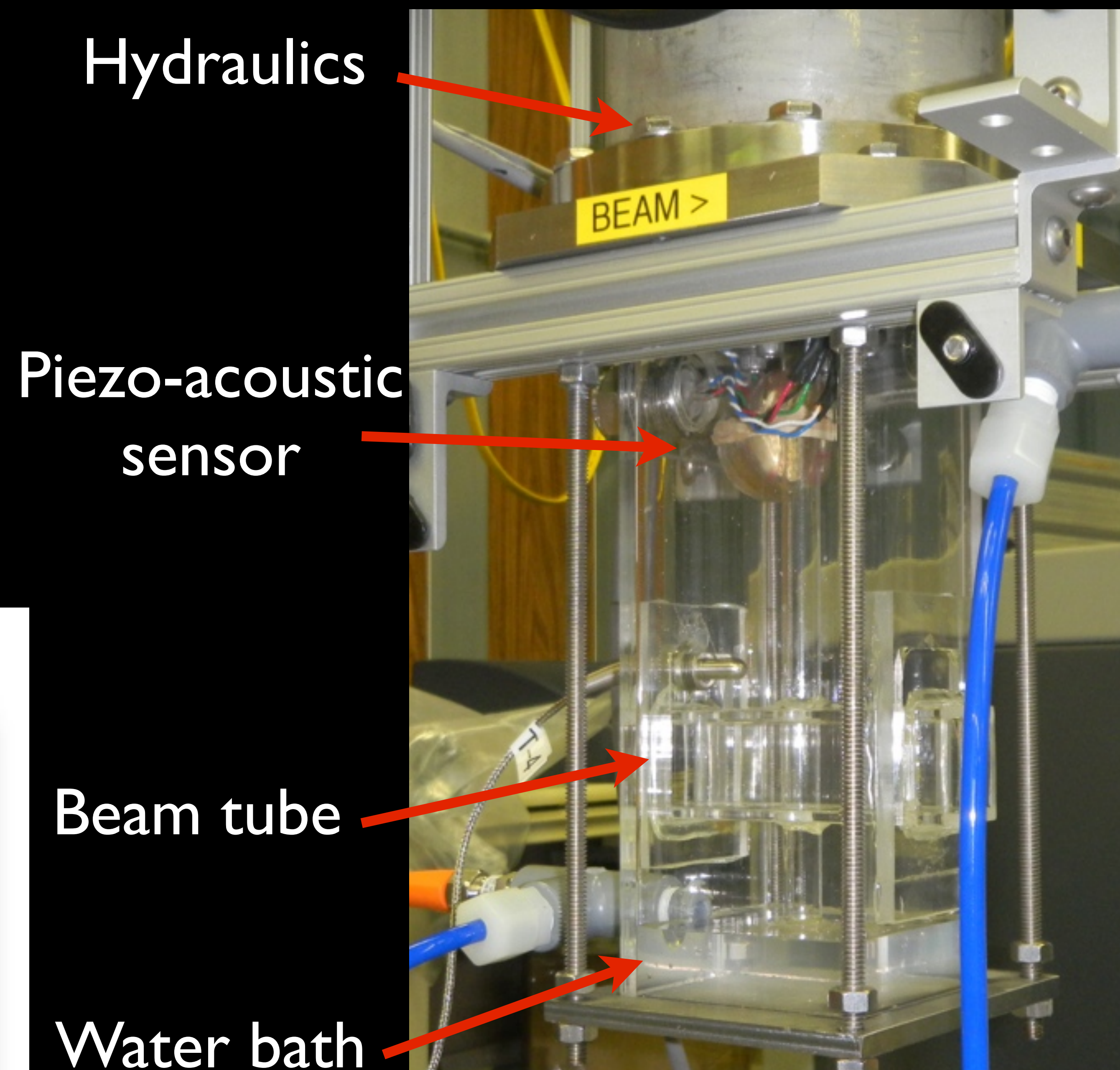


$$T = E_{recoil} = \frac{(p\theta)^2}{2m_r}$$

COUPP Iodine Recoil Threshold Experiment

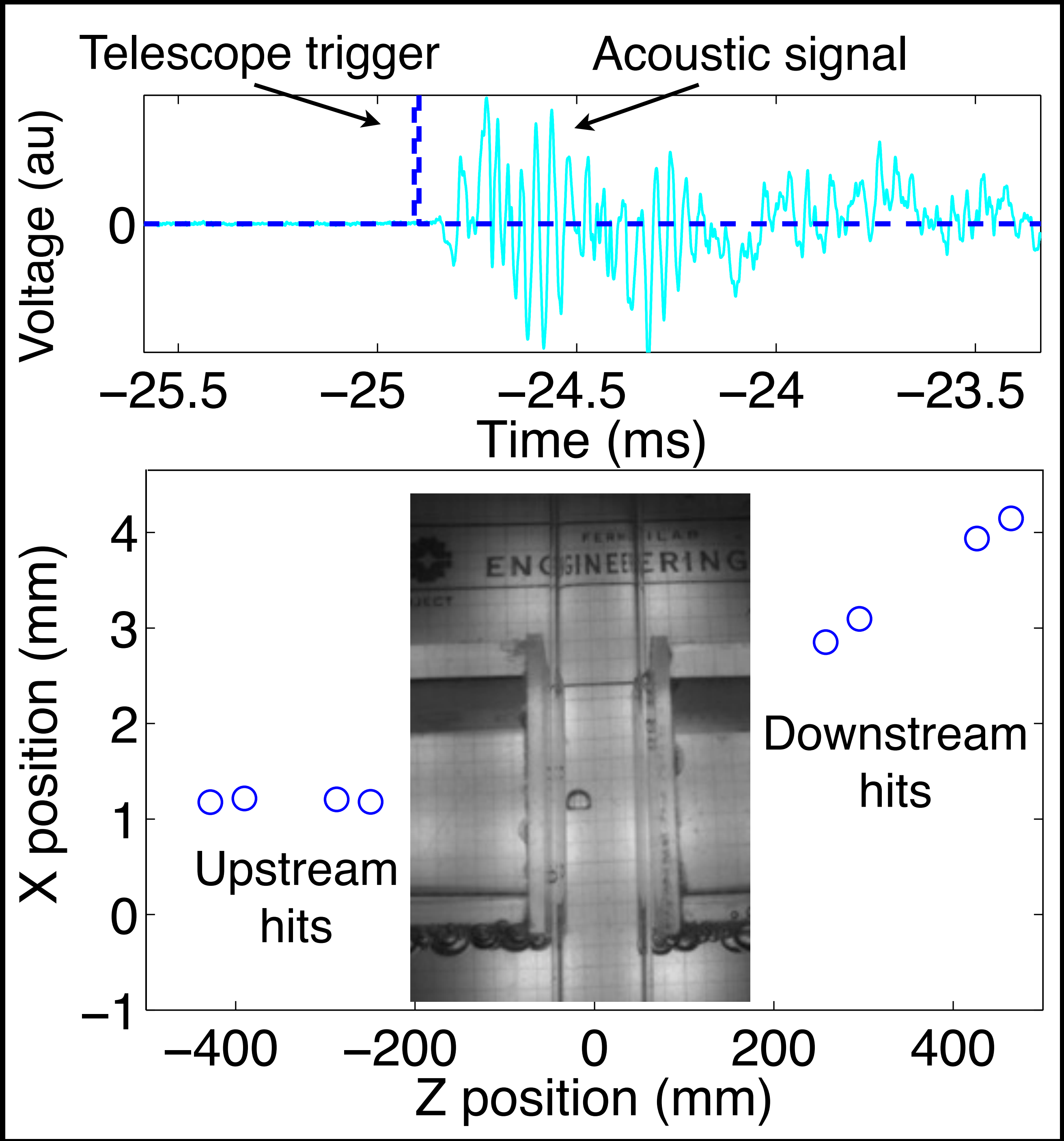
- Test beam at Fermilab with a silicon pixel telescope
- Designed a new test tube sized bubble chamber

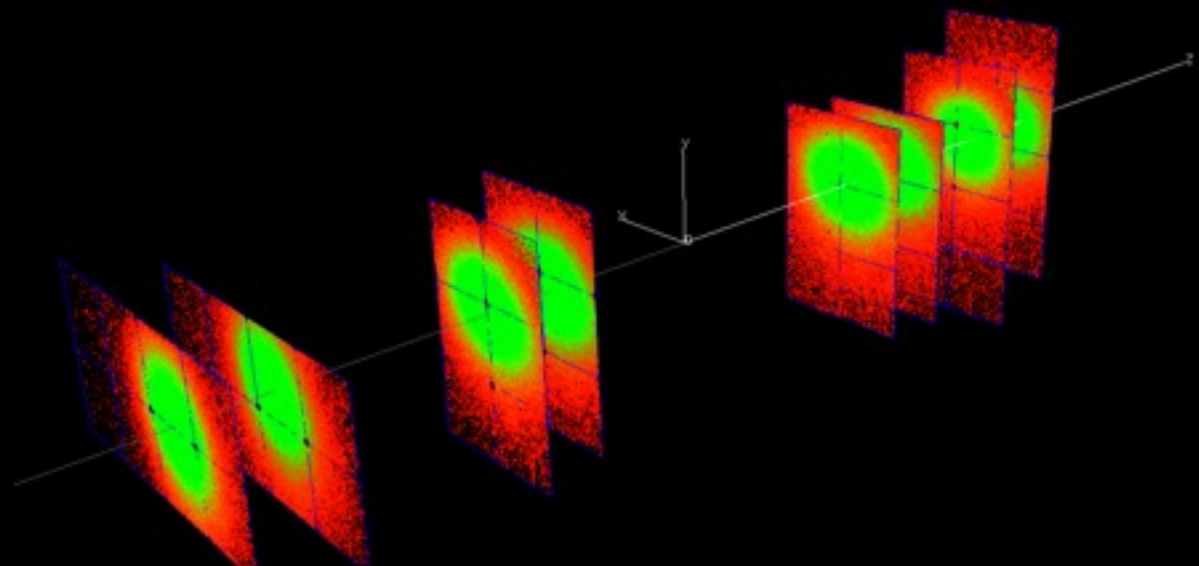


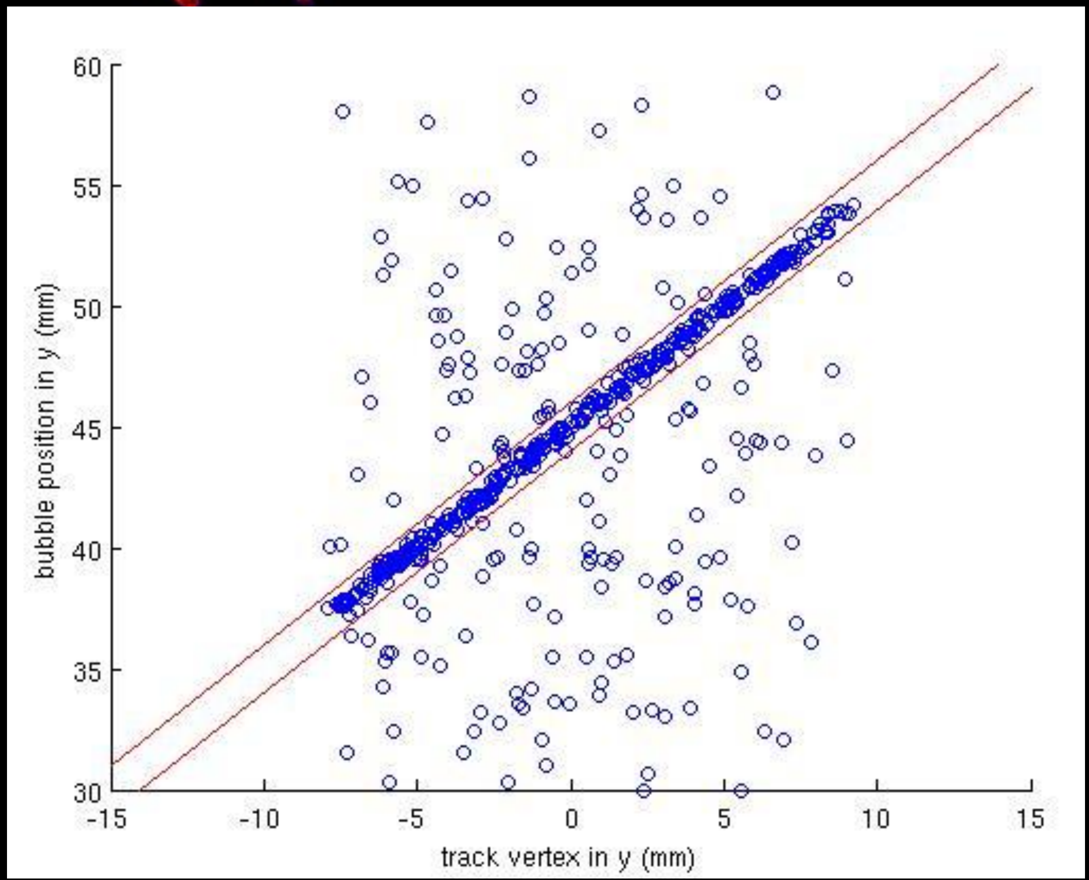


COUPP Iodine Recoil Threshold Experiment

- Beam run at Fermilab in March, 2012

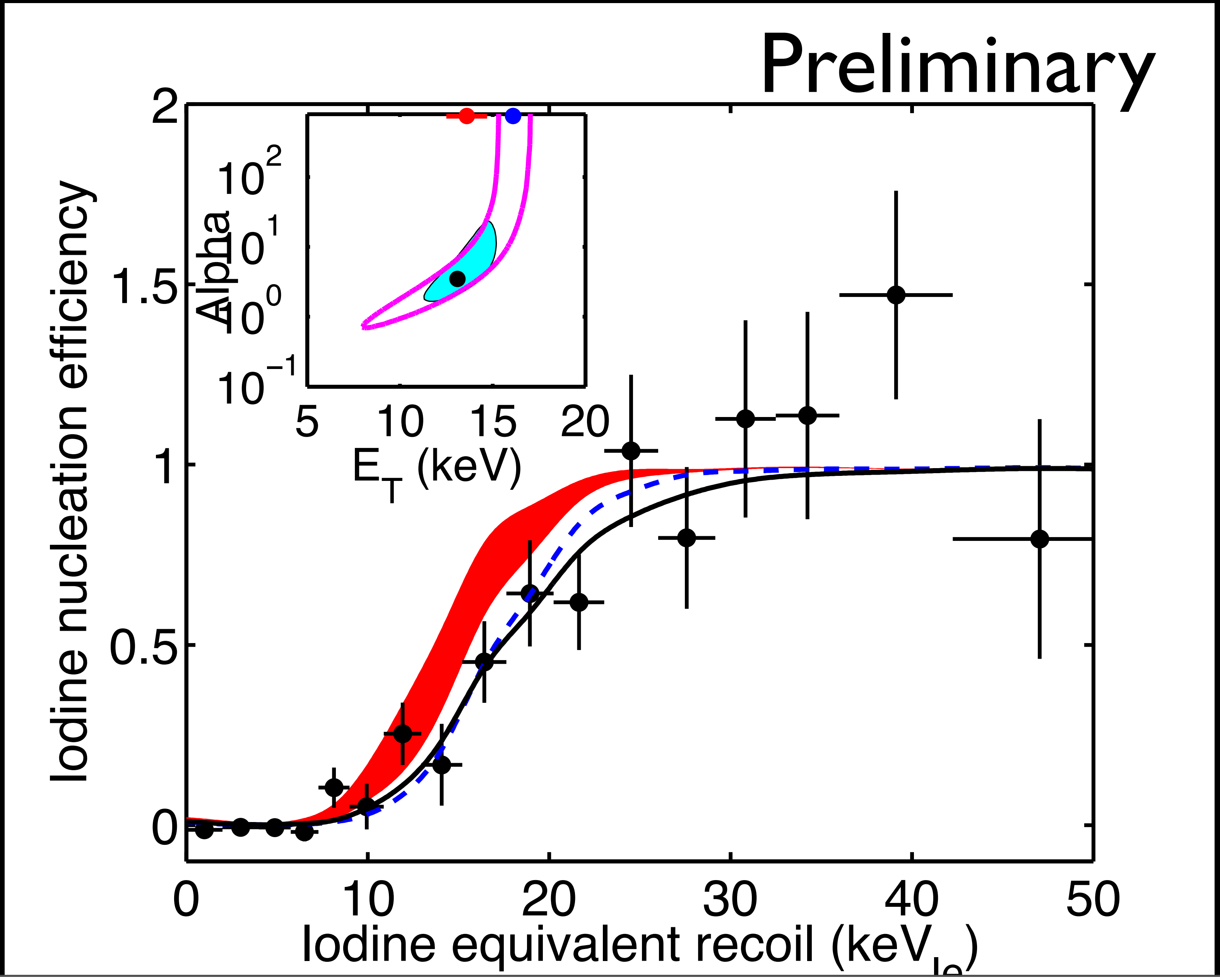






COUPP Iodine Recoil Threshold Experiment

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

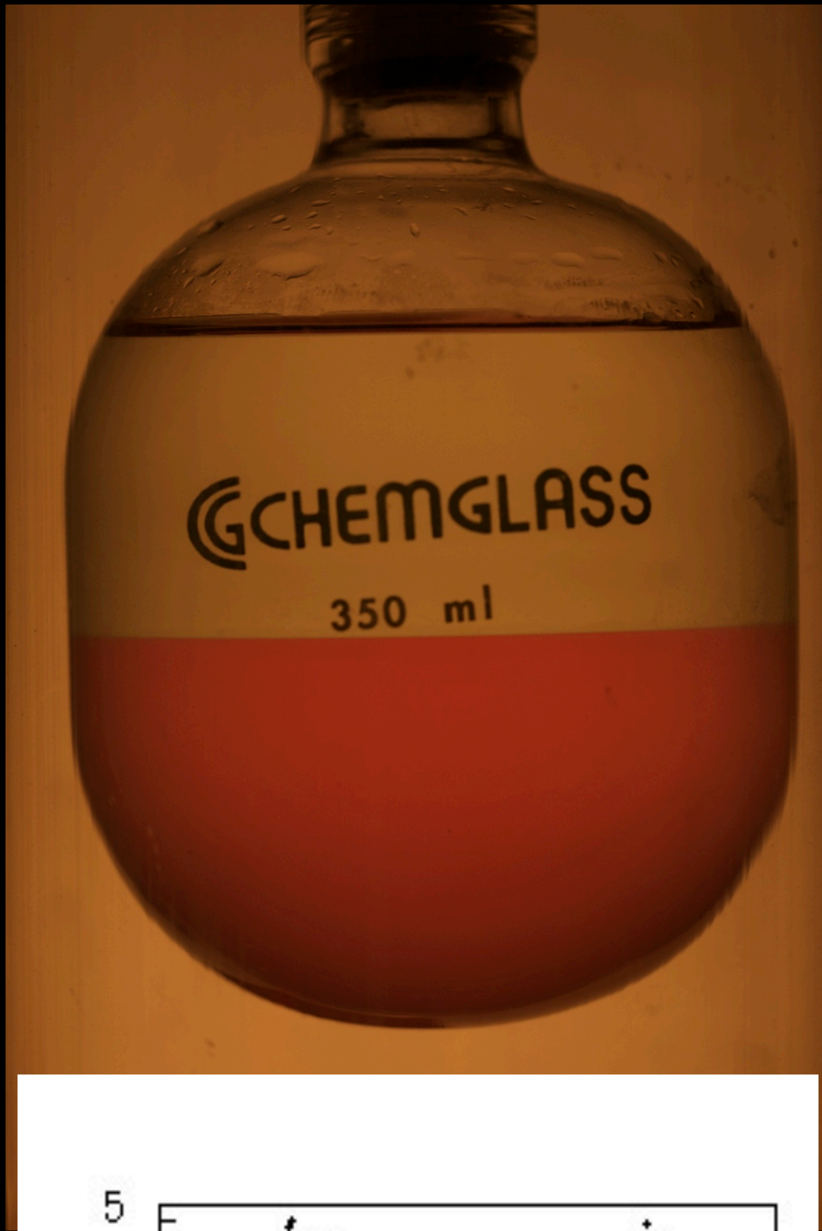


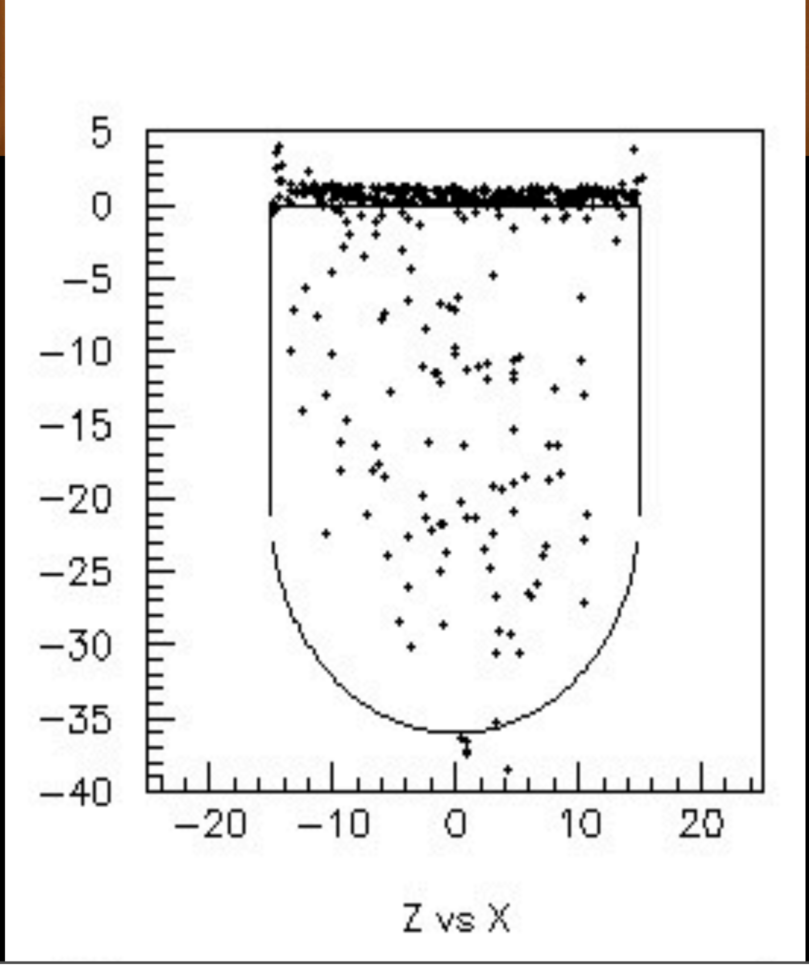
COUPP60

- 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





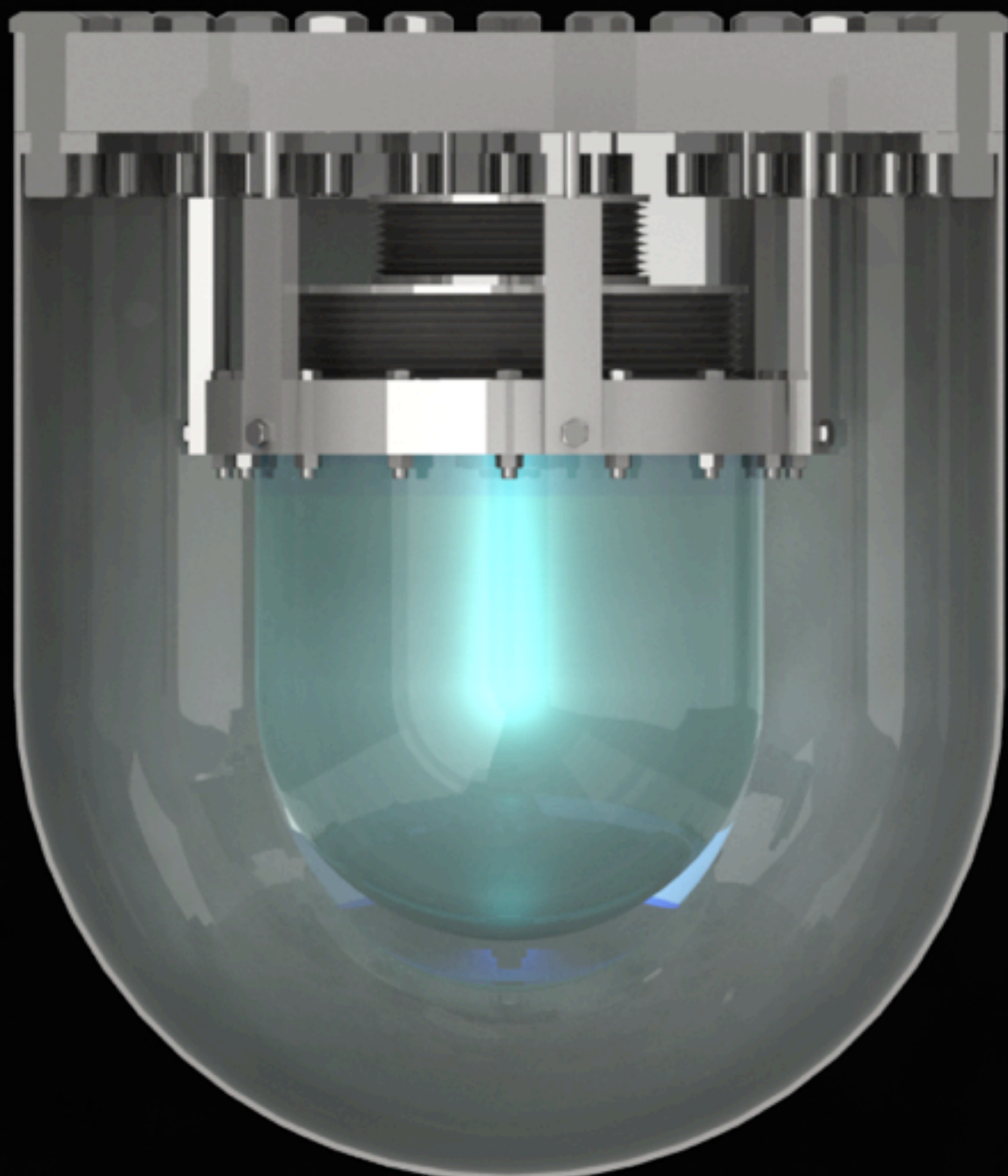
COUPP60

- Engineering run at shallow site in 2010
  - Low backgrounds and acoustic discrimination
  - Fluid darkening due to photodissociation of iodine
  - Excessive surface rate
- Solutions tested in second run November, 2011
- Moving to SNOLAB since last summer


CYLINDER
EMPTY
IN USE


Running by
end of month?

COUPP500

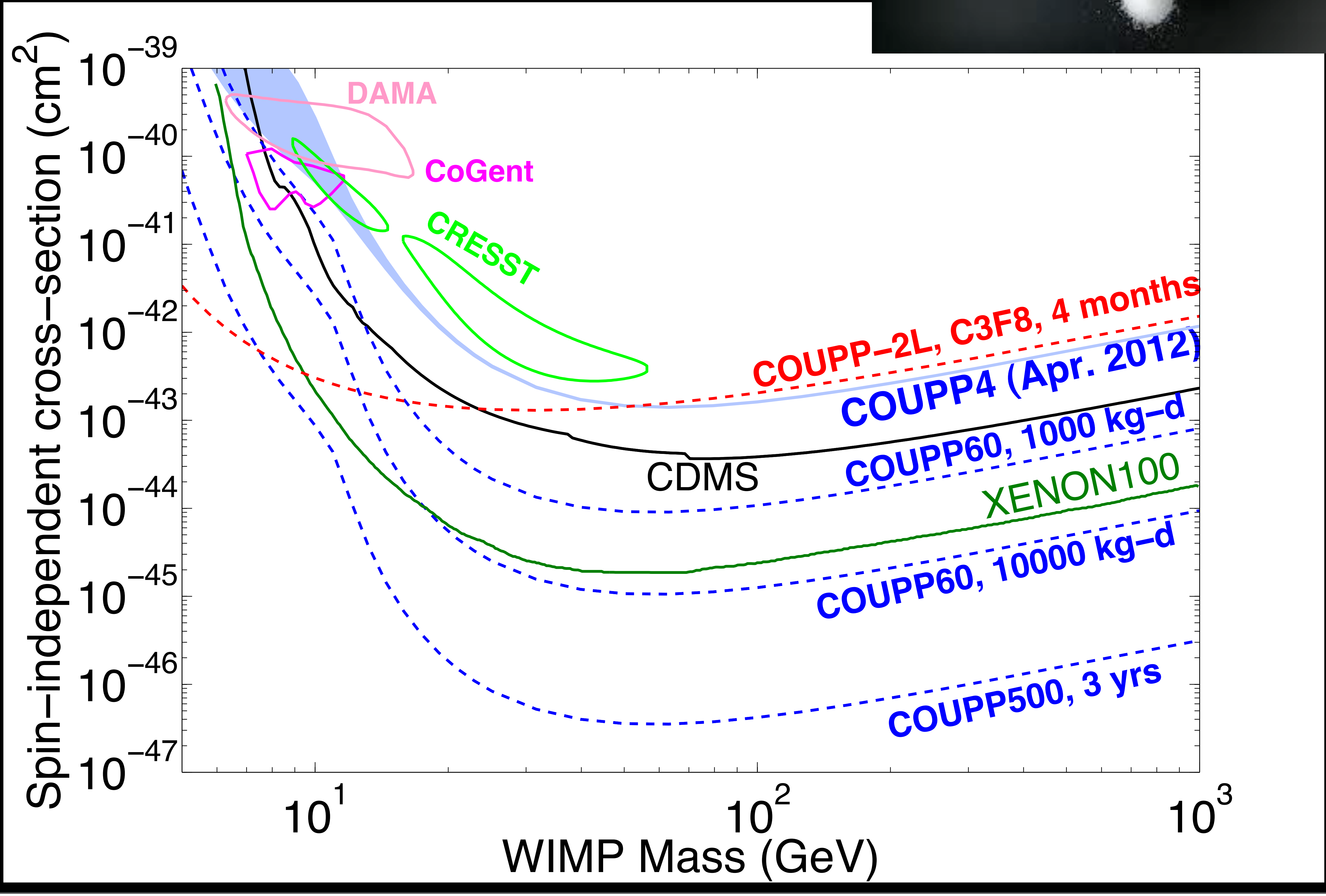


- Funded by NSF and DOE (not construction)
- Engineering well underway
- Merger with PICASSO collaboration for ton scale experiment
- Construction 2014-2015?

COUPP4 redux

- Alternate fluid - C_3F_8
  - Lower threshold (down to 3 keV in test stand)
  - Improved sensitivity at low WIMP mass
  - Improved SD sensitivity
- First effort in concert with the PICASSO collaboration
- Possible use in COUPP500 chamber

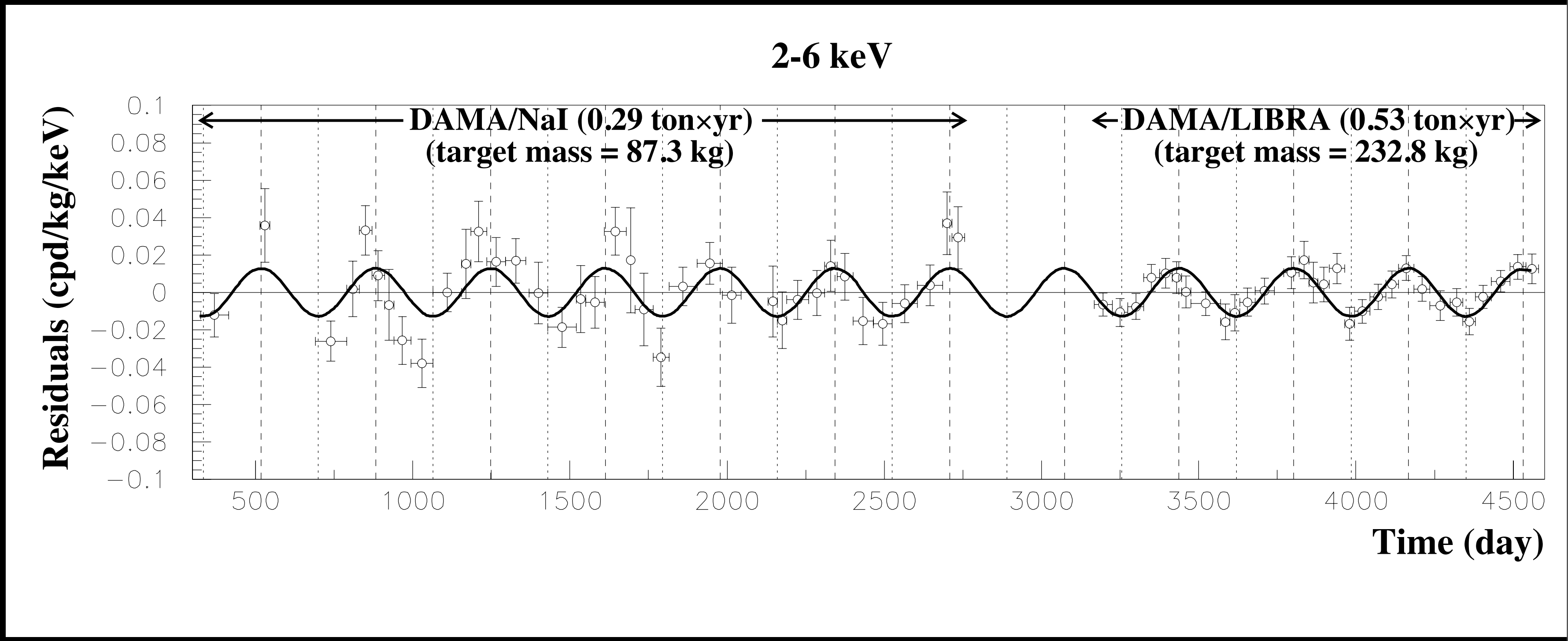
Projections



Bubble chambers are fun!

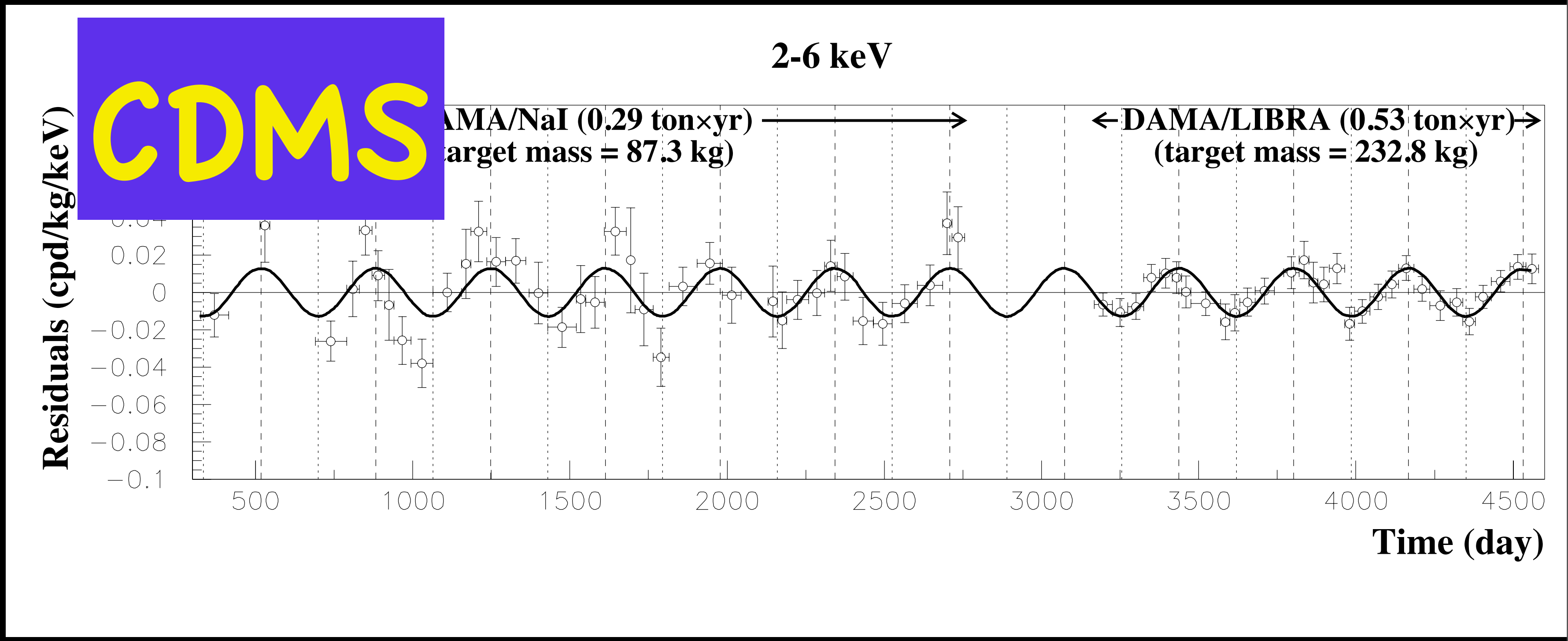
Dark matter controversies

DAMA - positive claim for 10 years!



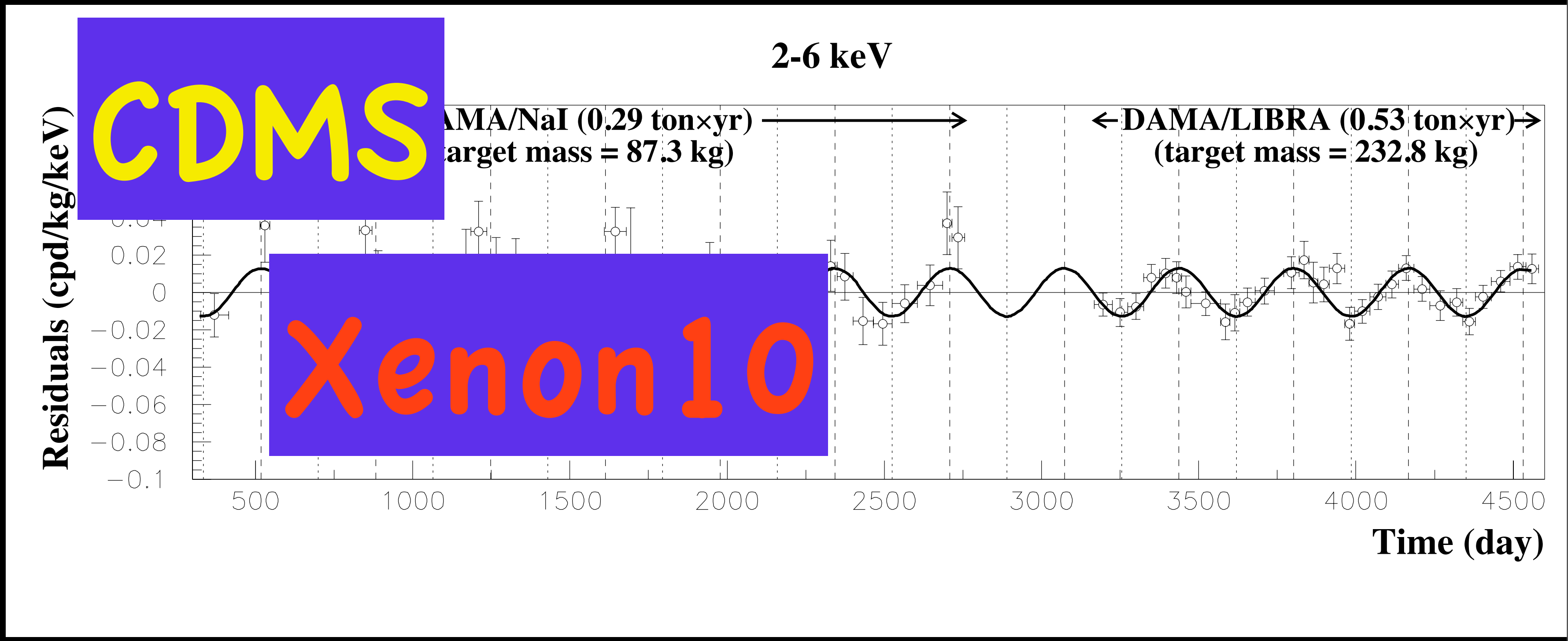
Dark matter controversies

DAMA - positive claim for 10 years!



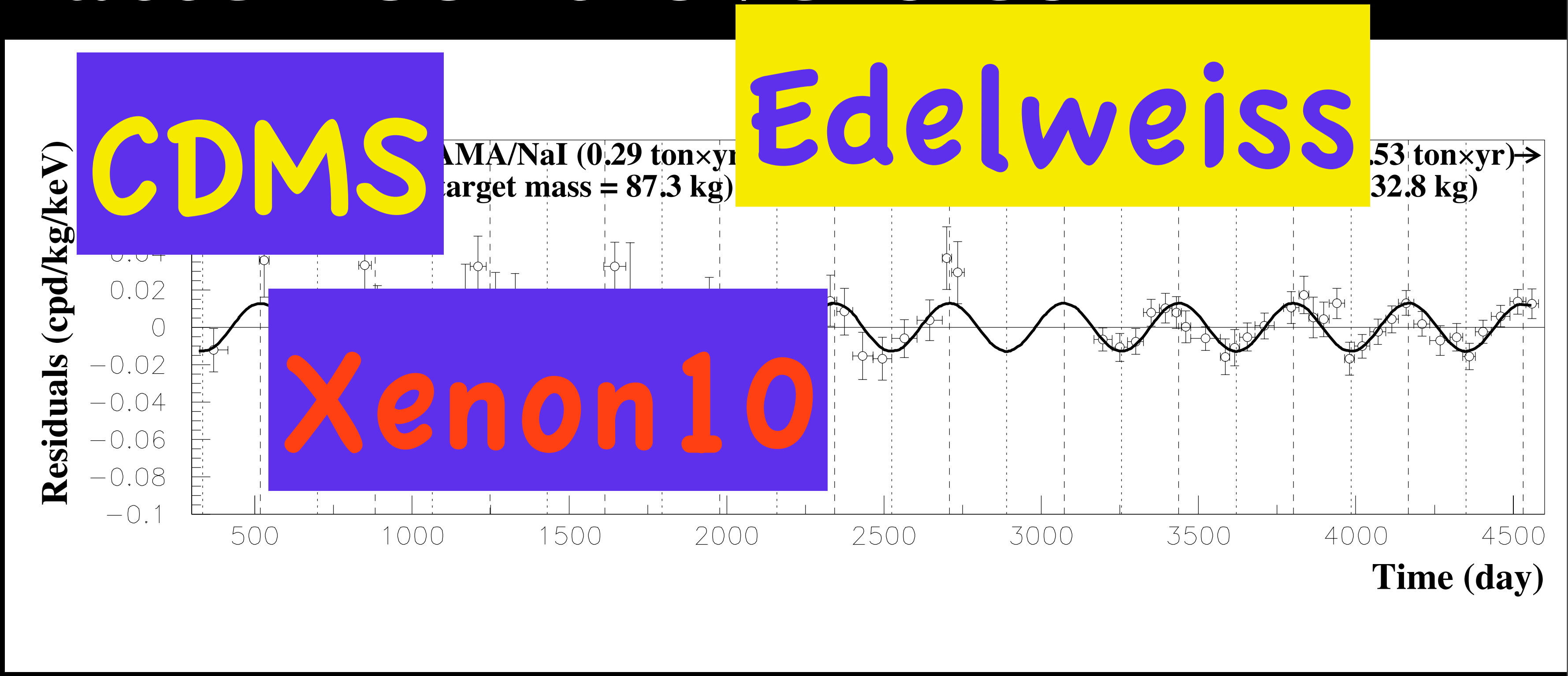
Dark matter controversies

DAMA - positive claim for 10 years!



Dark matter controversies

DAMA - positive claim for 10 years!



Dark matter controversies

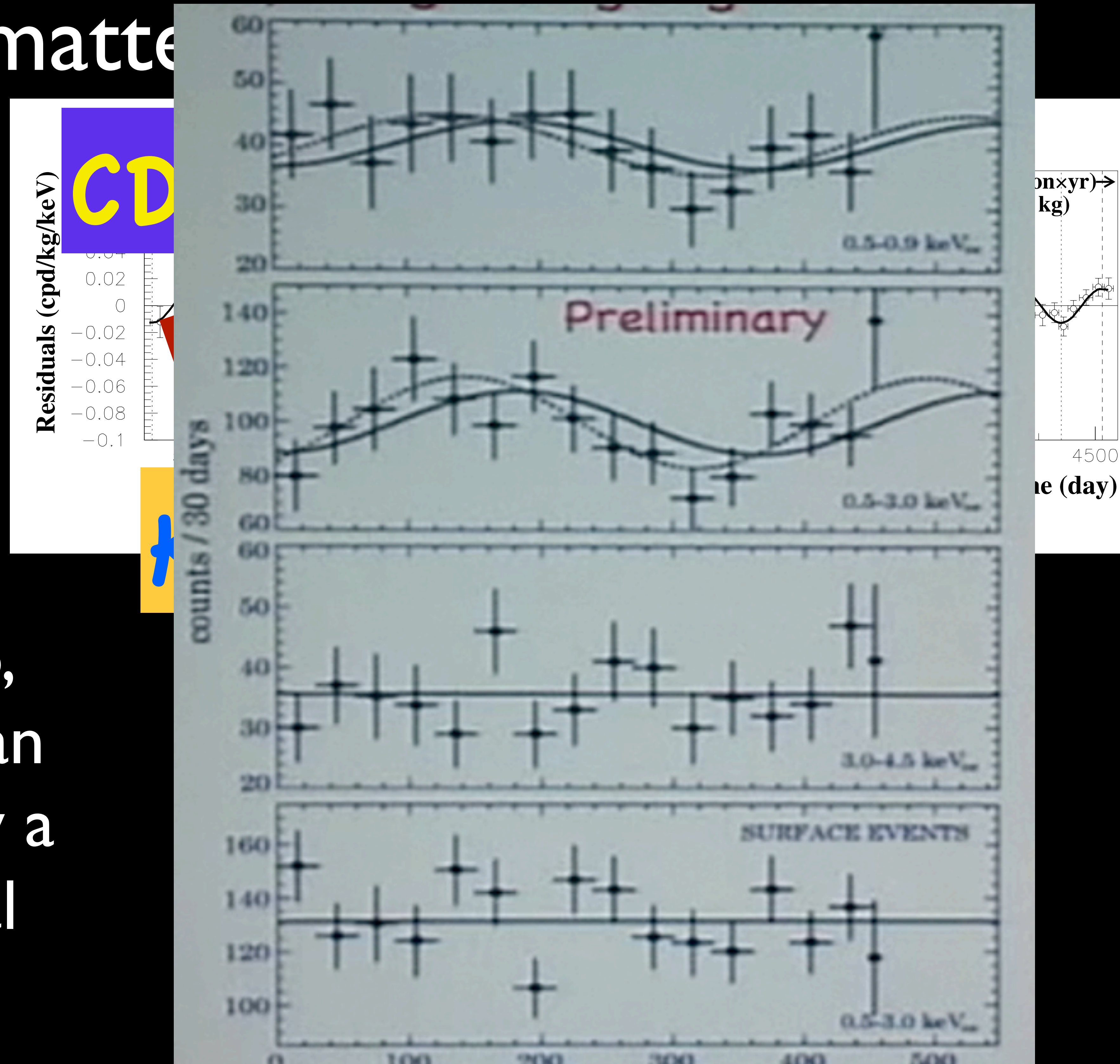
DAMA - positive claim for 10 years!

Dark matter controversies

DAMA - positive claim for 10 years!

Dark matte

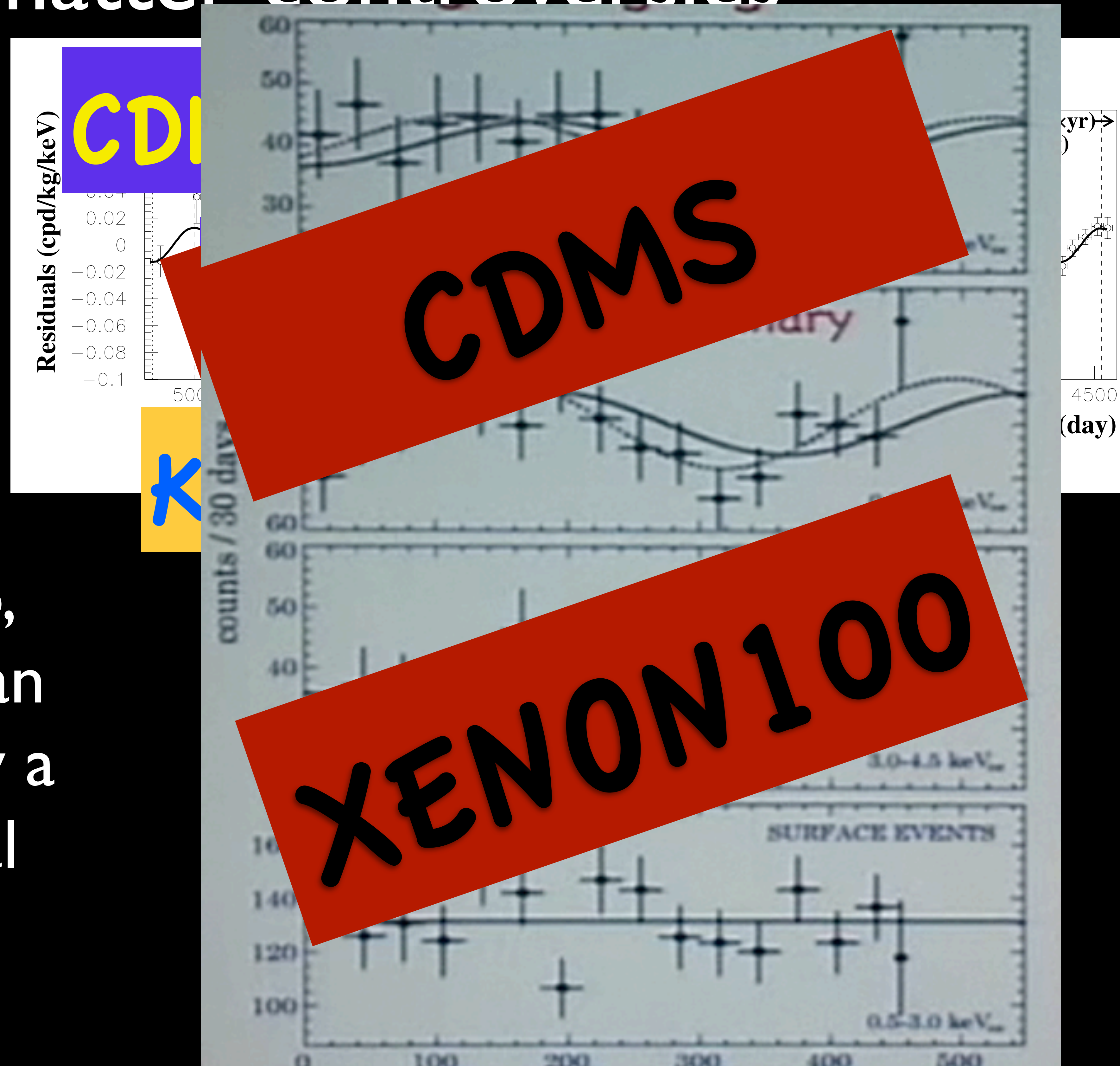
DAMA - positive claim for 10 years!



Two years ago, CoGeNT saw an excess and now a possible annual modulation

Dark matter controversies

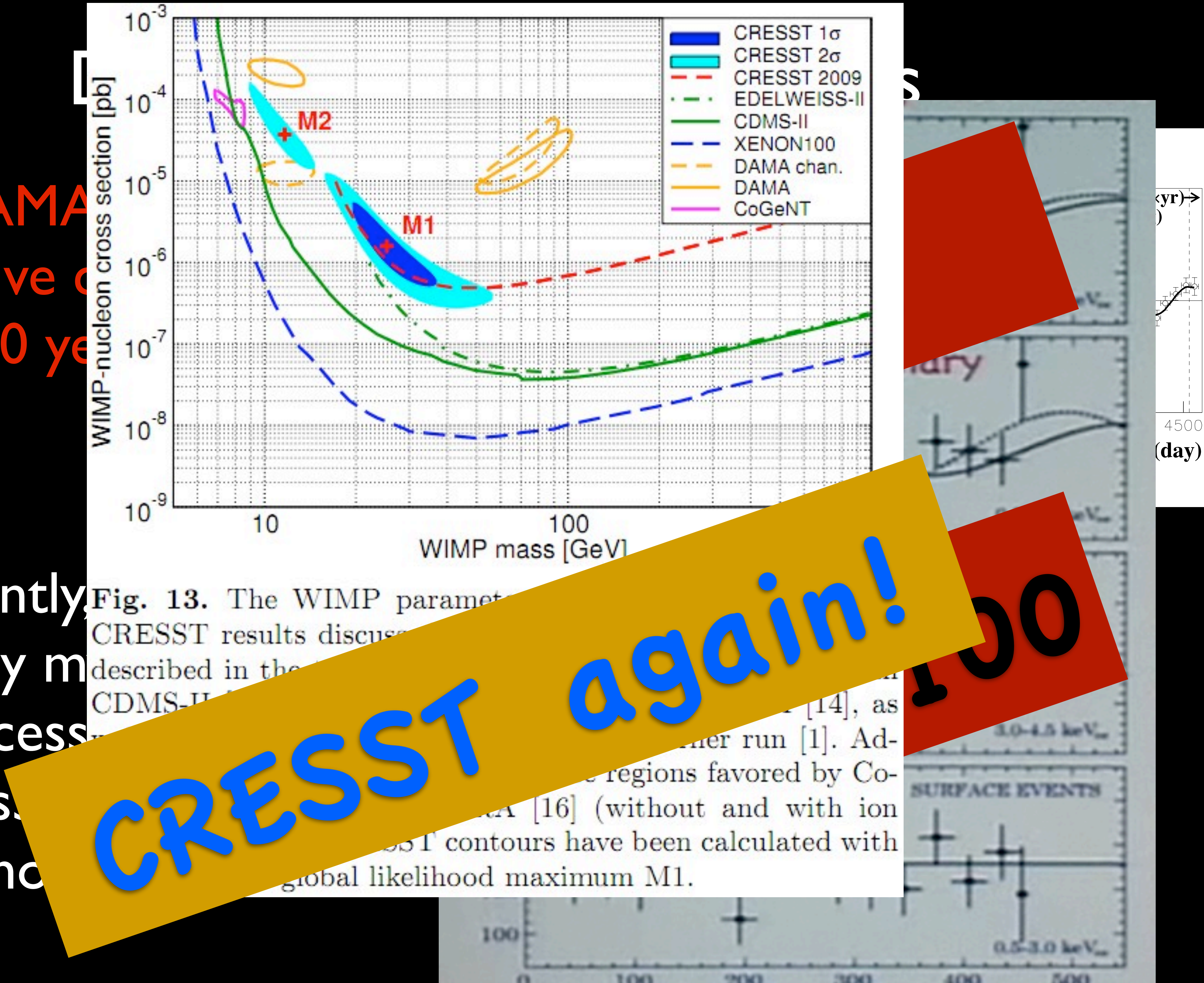
DAMA -
positive claim
for 10 years!

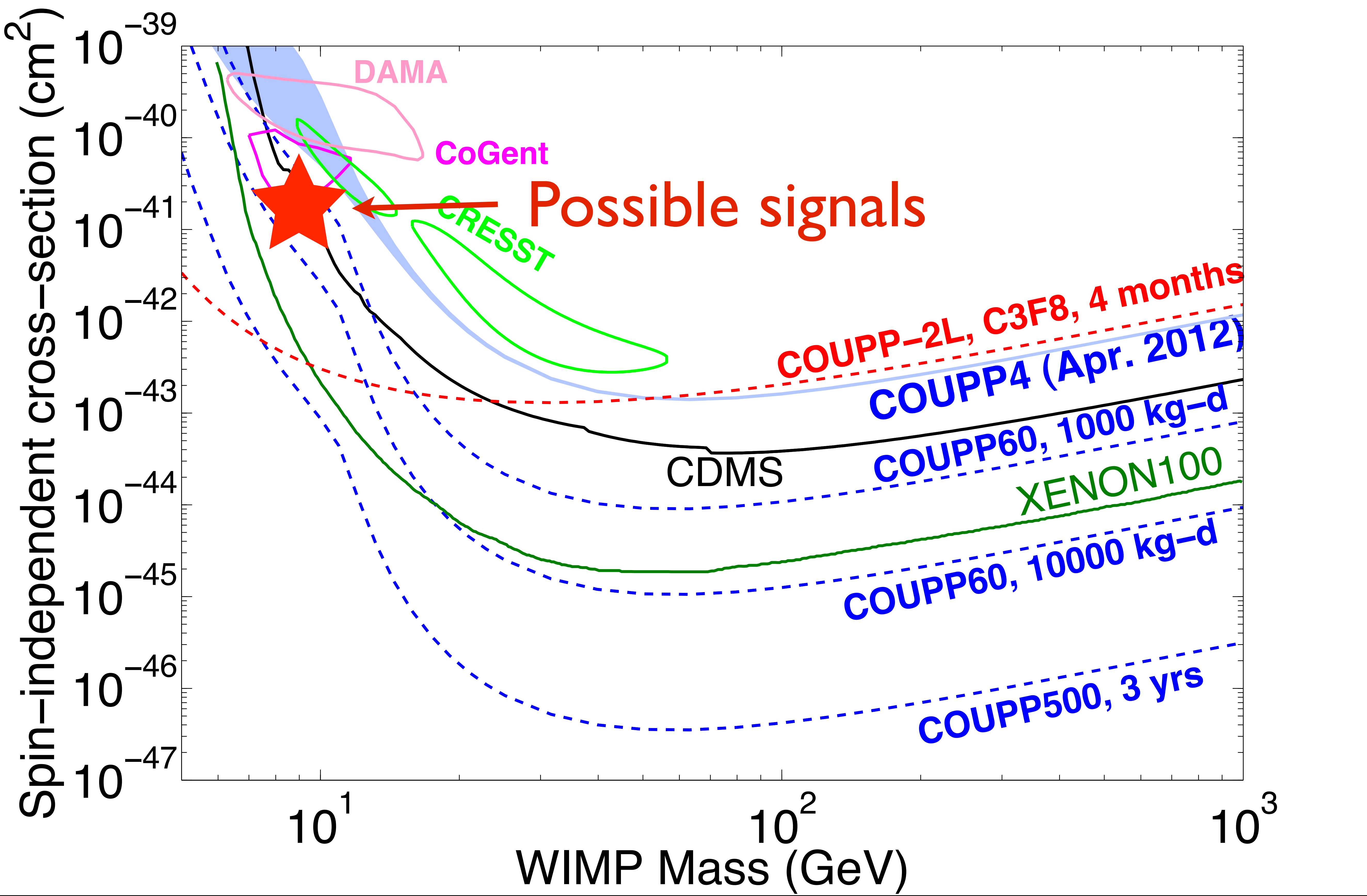


Two years ago,
CoGeNT saw an
excess and now a
possible annual
modulation

DAMA
positive c
for 10 ye

Recently,
(run by m
an excess
pos
mo




Spin-independent cross-section (cm^2)
WIMP Mass (GeV)
DAMA
CoGent
CRESST
Possible signals
COUPP-2L, C3F8, 4 months
COUPP4 (Apr. 2012)
COUPP60, 1000 kg-d
CDMS
XENON100
COUPP60, 10000 kg-d
COUPP500, 3 yrs

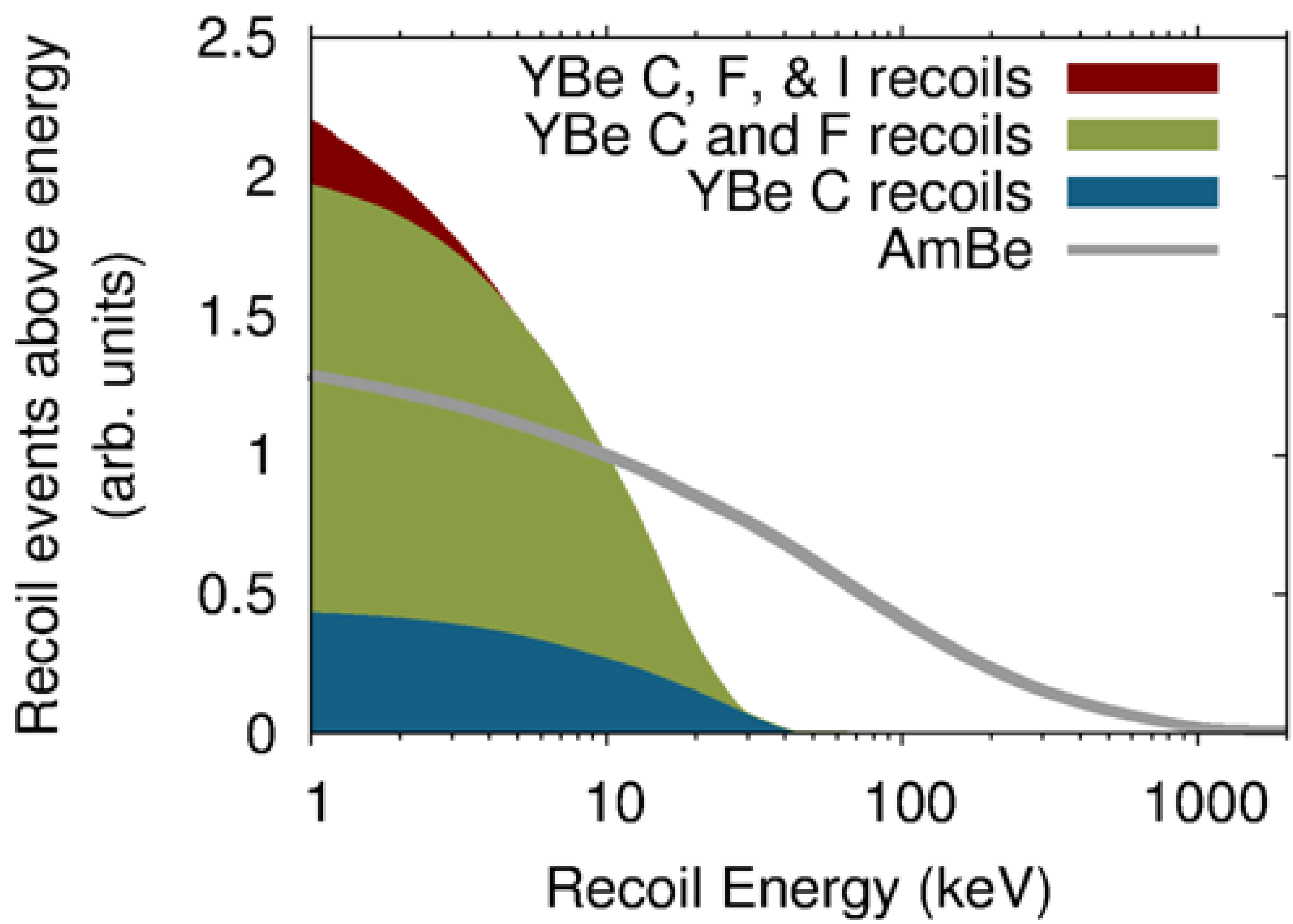
^{88}YBe (γ,n) neutron source

Mono-energetic 152 keV neutron source.

TABLE 3. Results of present measurements

E_γ (keV)	$\sigma(E_\gamma)$ (mb)
1674.7	0.88±0.16
1705.2	1.33±0.24
1724.9	1.10±0.20
1778.9	0.73±0.13
1836.0	0.47±0.09
2167.6	0.18±0.04

M. Fujishiro et al., Can. J. Phys. **60,** 1672 (1982).



WIMP-nucleon scattering

Spin-independent

Spin-dependent

$$\sigma_0 = \frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2 + \frac{32 G_F^2 \mu^2}{\pi}\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

Nucleus	Z	Odd Nucleon	J	$\langle S_p\rangle$	$\langle S_n\rangle$	C_A^p/C_p	C_A^n/C_n
^{19}F	9	p	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.20×10^{-1}	1.68×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.60×10^{-5}	6.76×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.53×10^{-2}	3.56×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.20×10^{-2}	5.56×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.45×10^{-1}	1.04×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.00×10^{-6}	3.29×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}