Low-Background Searches

Pawel Majewski
RAL School
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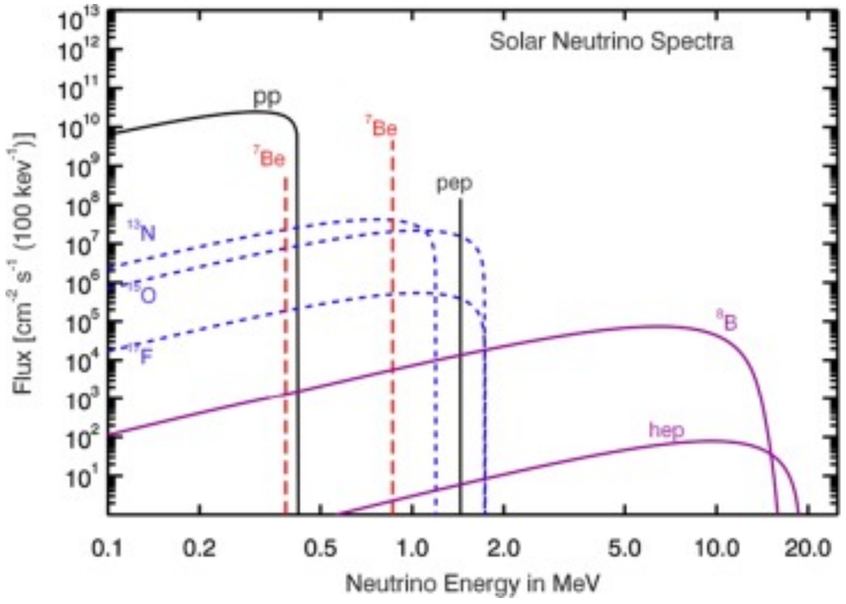
Based on lectures by Asher Kaboth from RHUL

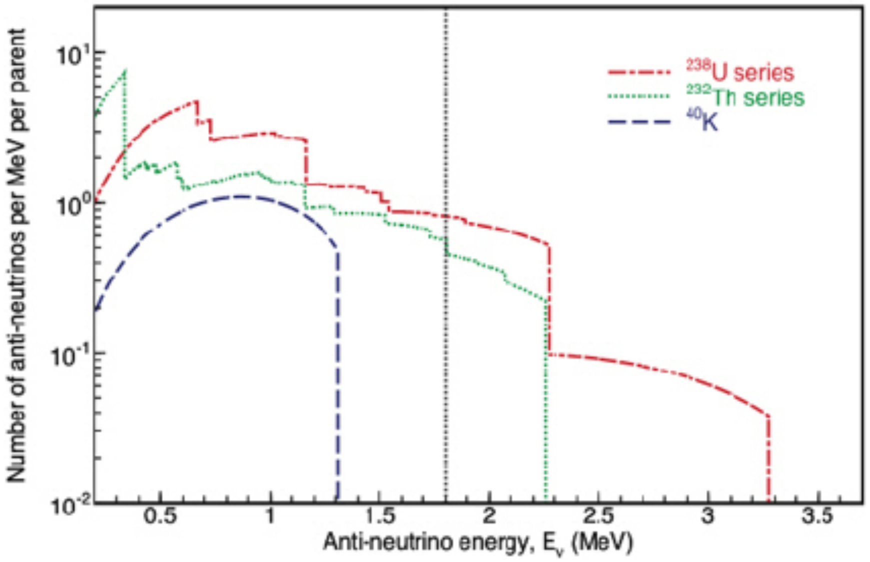
Outline

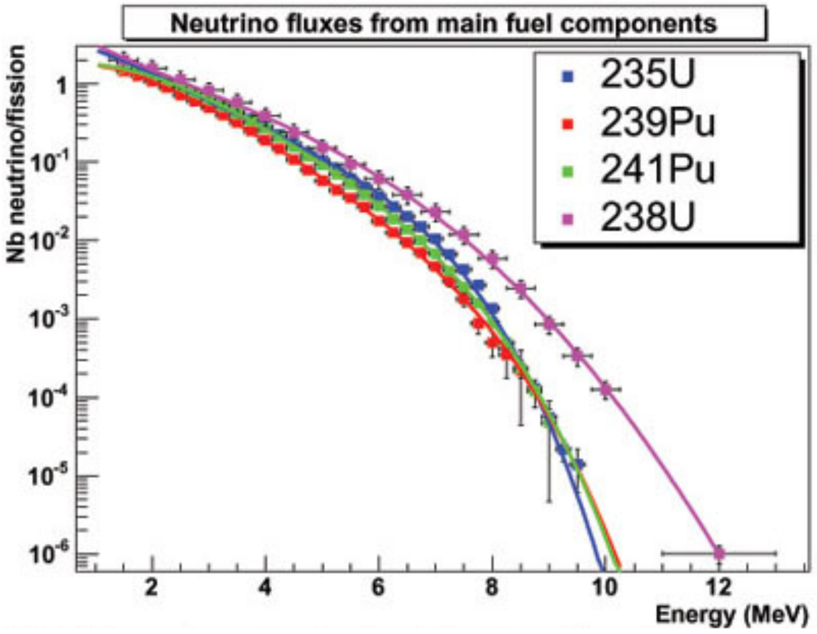
- What physics requires low background experiment
- Detector Techniques
- Contaminants and what we can do about them
- Materials & Screening
- Calibration techniques

Low Energy ν physics

- Solar Neutrinos
  - Neutrino oscillations
  - Solar modeling
- Geoneutrinos ($\bar{\nu}$)
  - Earth's core modeling
- Reactor Neutrinos($\bar{\nu}$)
  - Neutrino oscillations

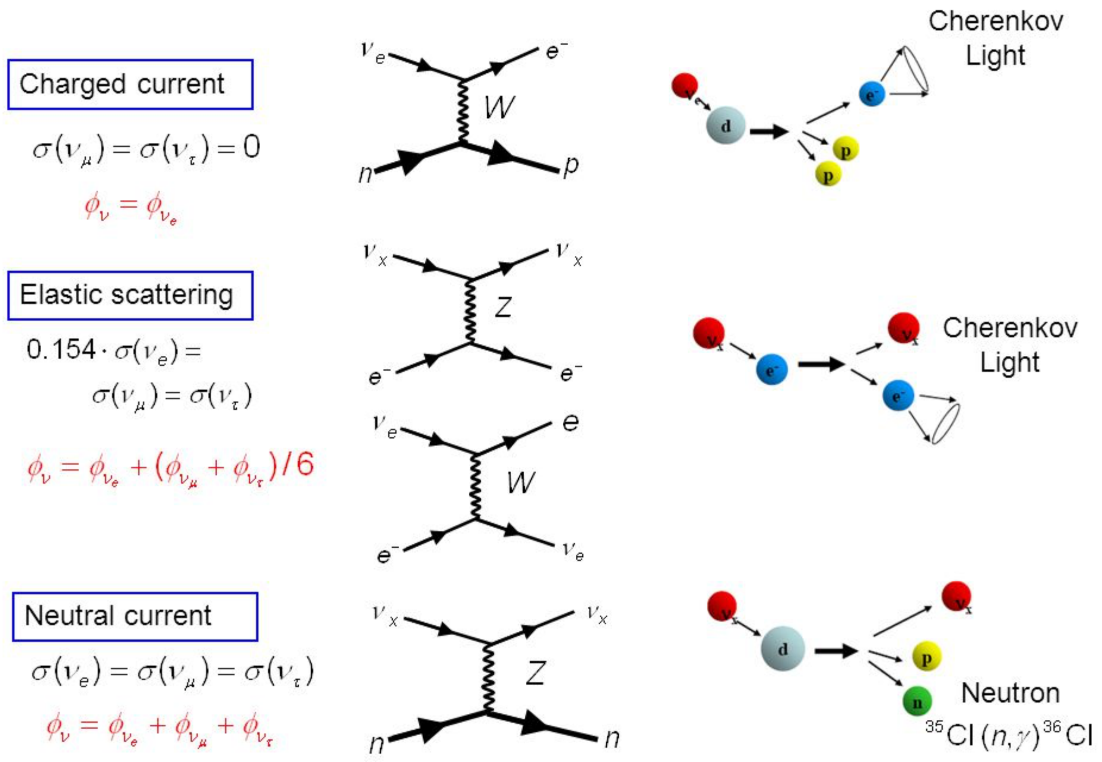


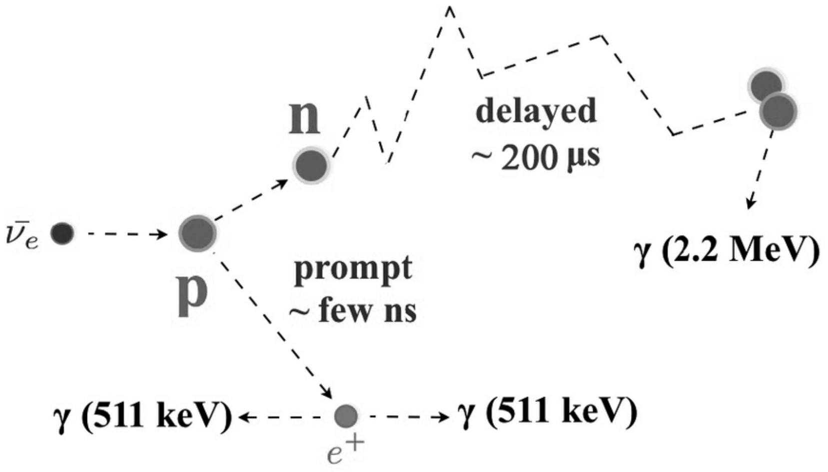




Low Energy ν Signals

$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$

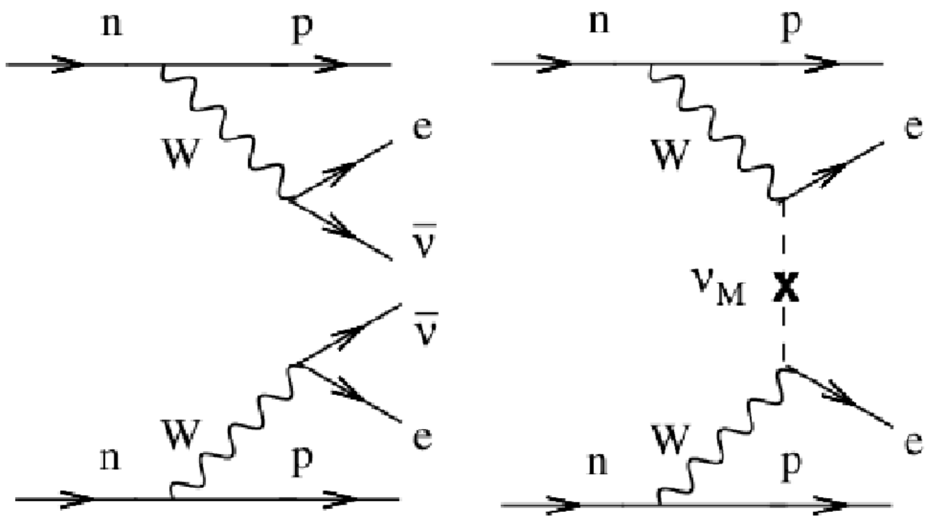


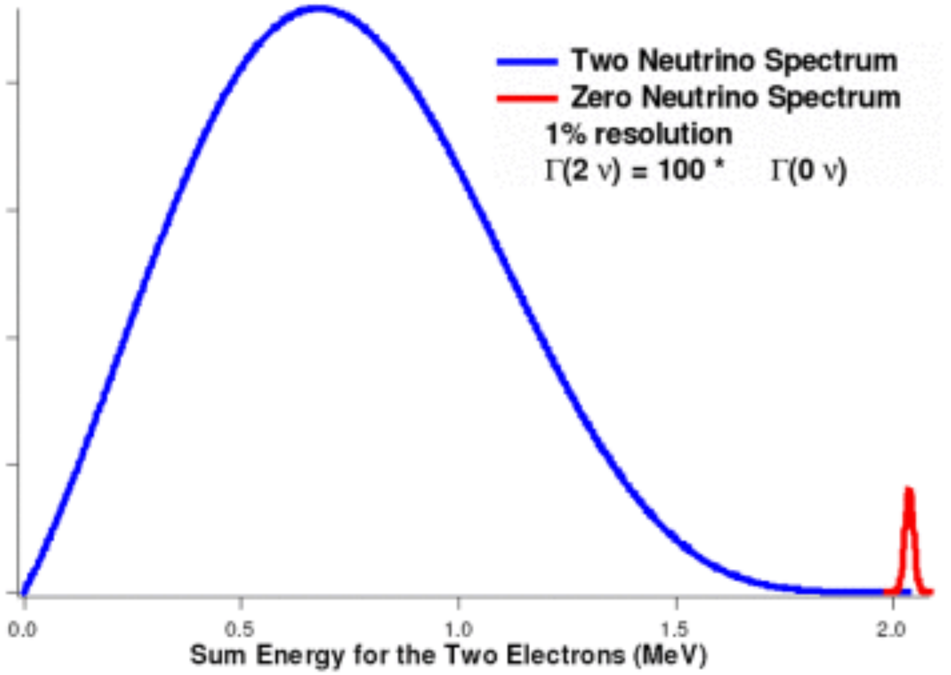


- Radiochemical processes
- CC/NC on nuclei
- Electron scattering
- Inverse beta decay

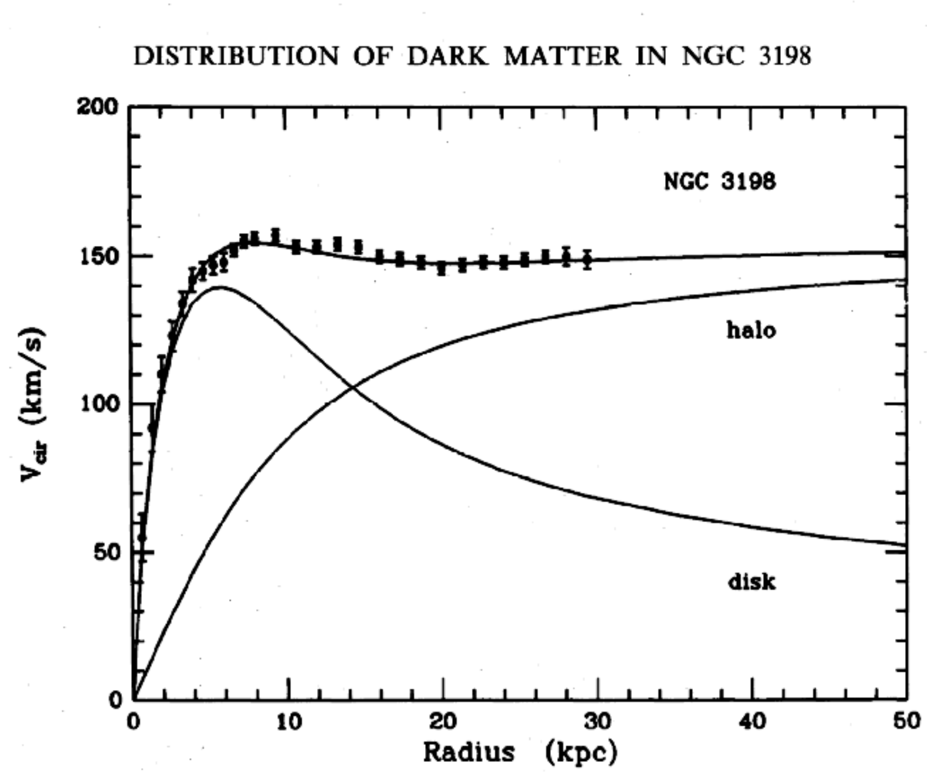
0νββ

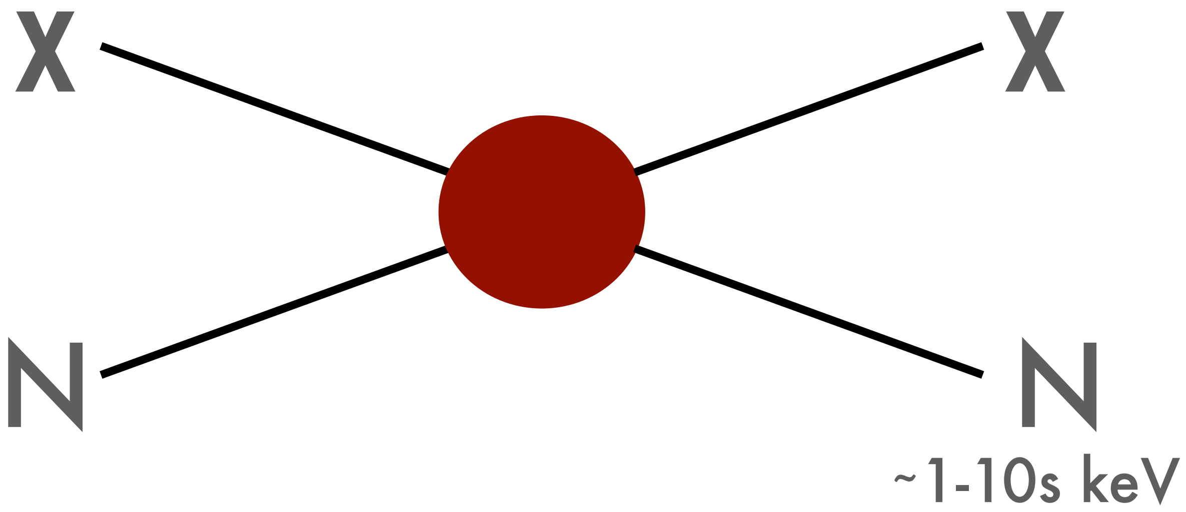
- Are neutrinos Majorana particles?
- What is the neutrino mass?
- Several different isotopes
- Signal is tiny peak at the end of the standard model 2νββ spectrum





Dark Matter

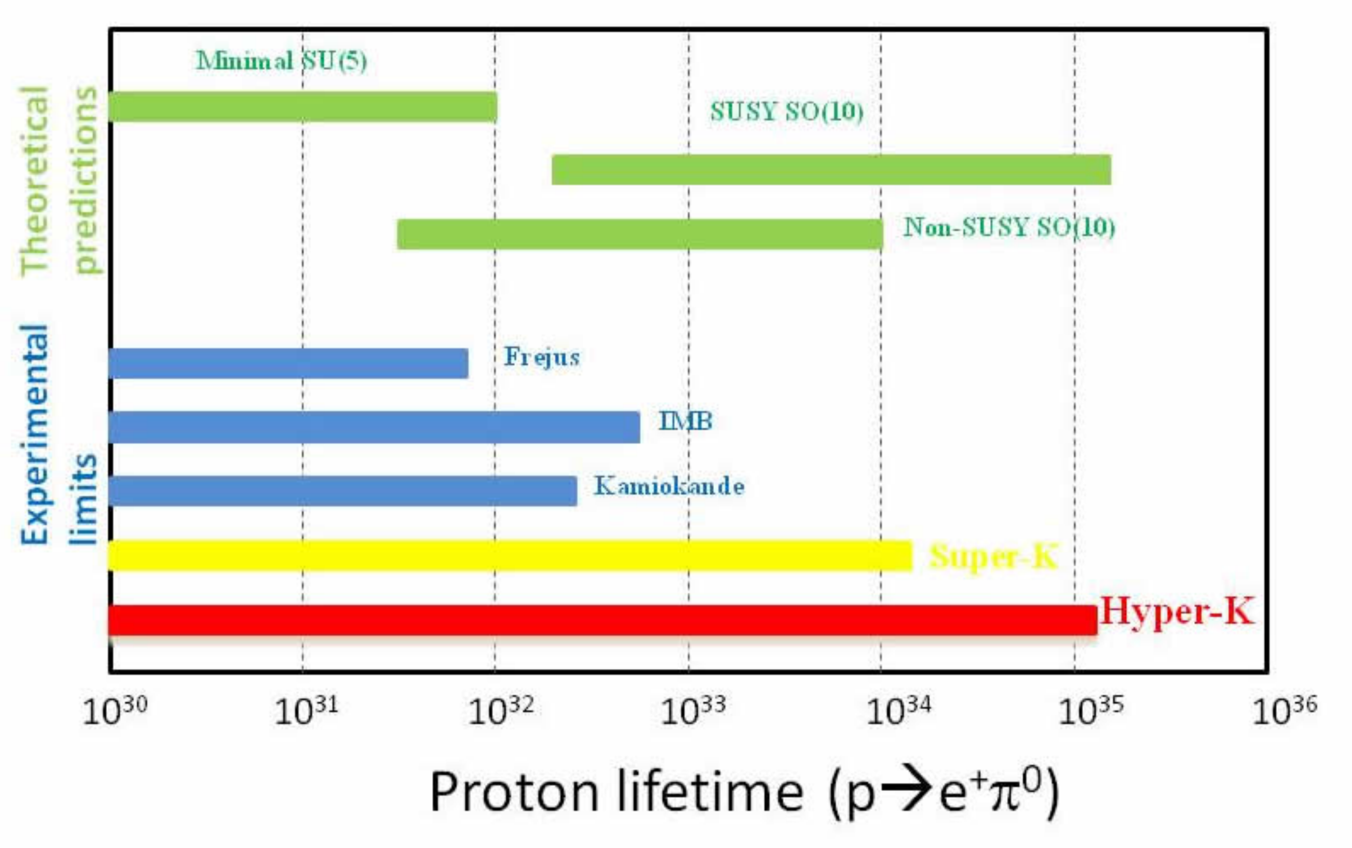


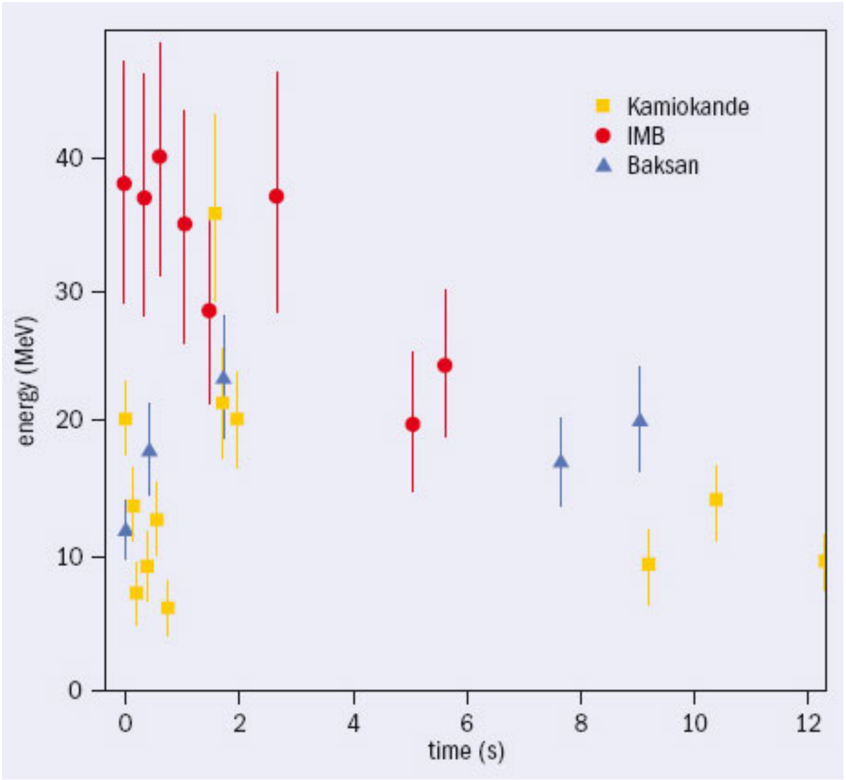


- 23% of the energy budget of the universe
- Lots of evidence from astronomy and cosmology; no evidence from particle physics
- Usually looking for some sort of weak nuclear scatter

Other Physics

- Proton Decay—how the Kamioka project began!
- Supernova Neutrino Detection—typically an add-on requirement
- Many other BSM searches



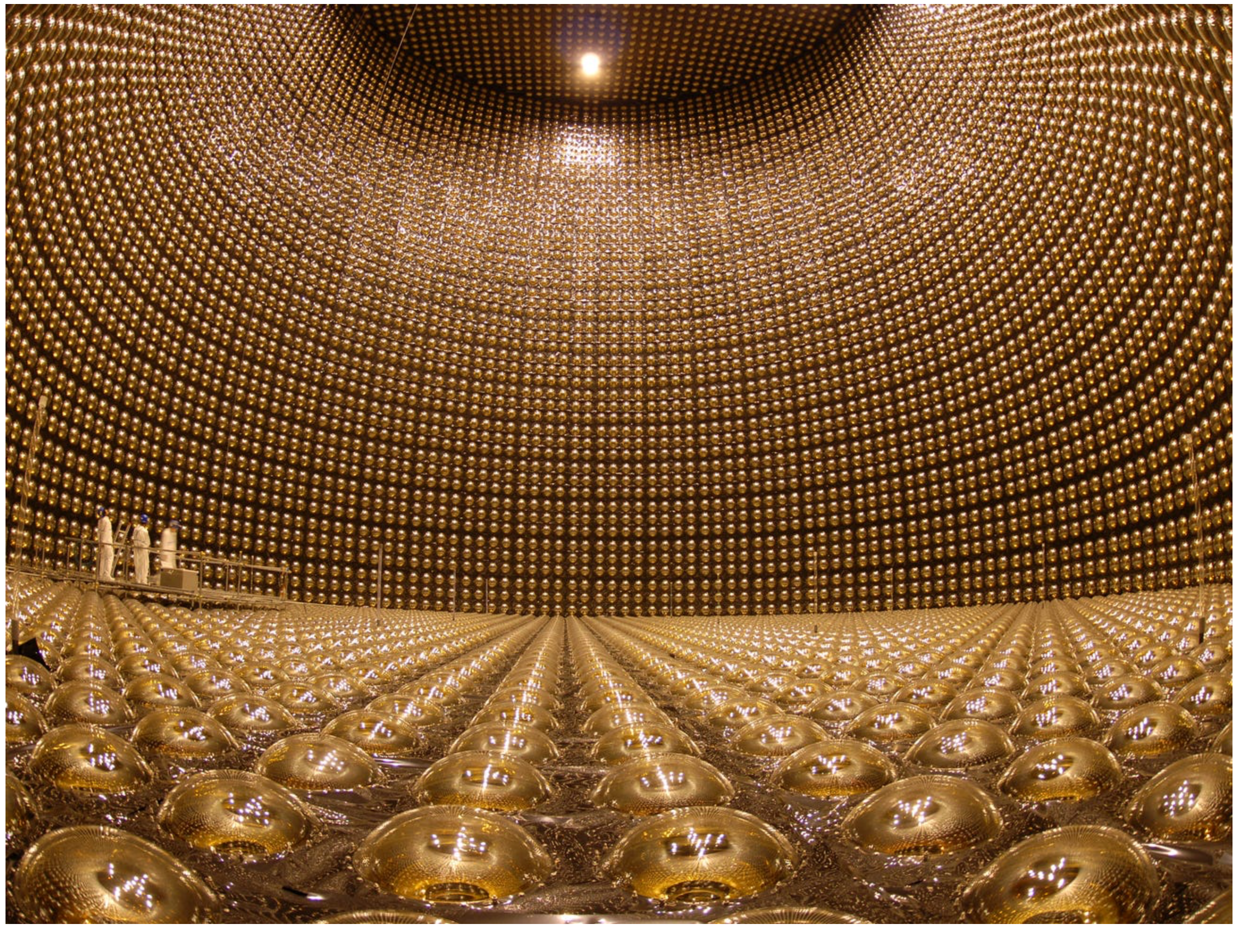


Types of Detector

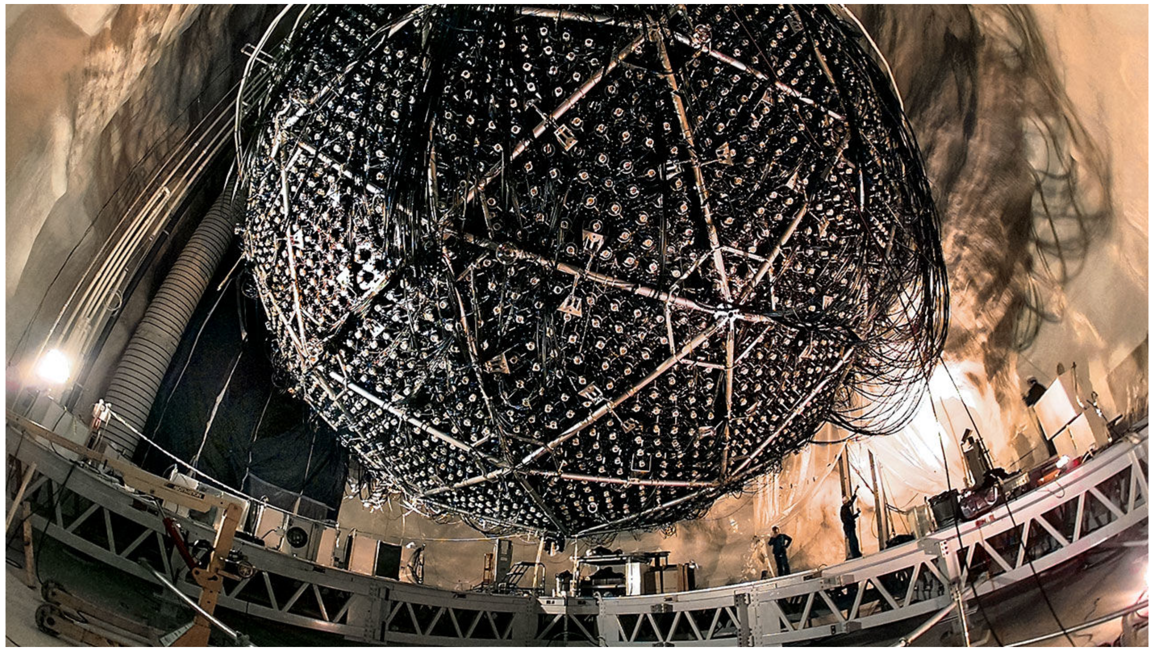
General Desirables

- BIG
- Detection medium is the same as target medium
- Background rejection as well as background elimination

Water Cerenkov



- Get a big ol' tank of water (normal or heavy)
- Put lots of PMTs around the outside
- Look for Cerenkov light
- Examples: SNO, Super-K
- Pros: water is cheap
- Cons: water has relatively high threshold



Liquid Scintillator

- Similar to WC, but medium scintillates as well as Cerenkov
- Examples: Borexino, KamLAND, SNO+, Daya Bay, RENO, Chooz
- Pros: much more light in the signal, easier to 'dope'
- Cons: Stability, cost

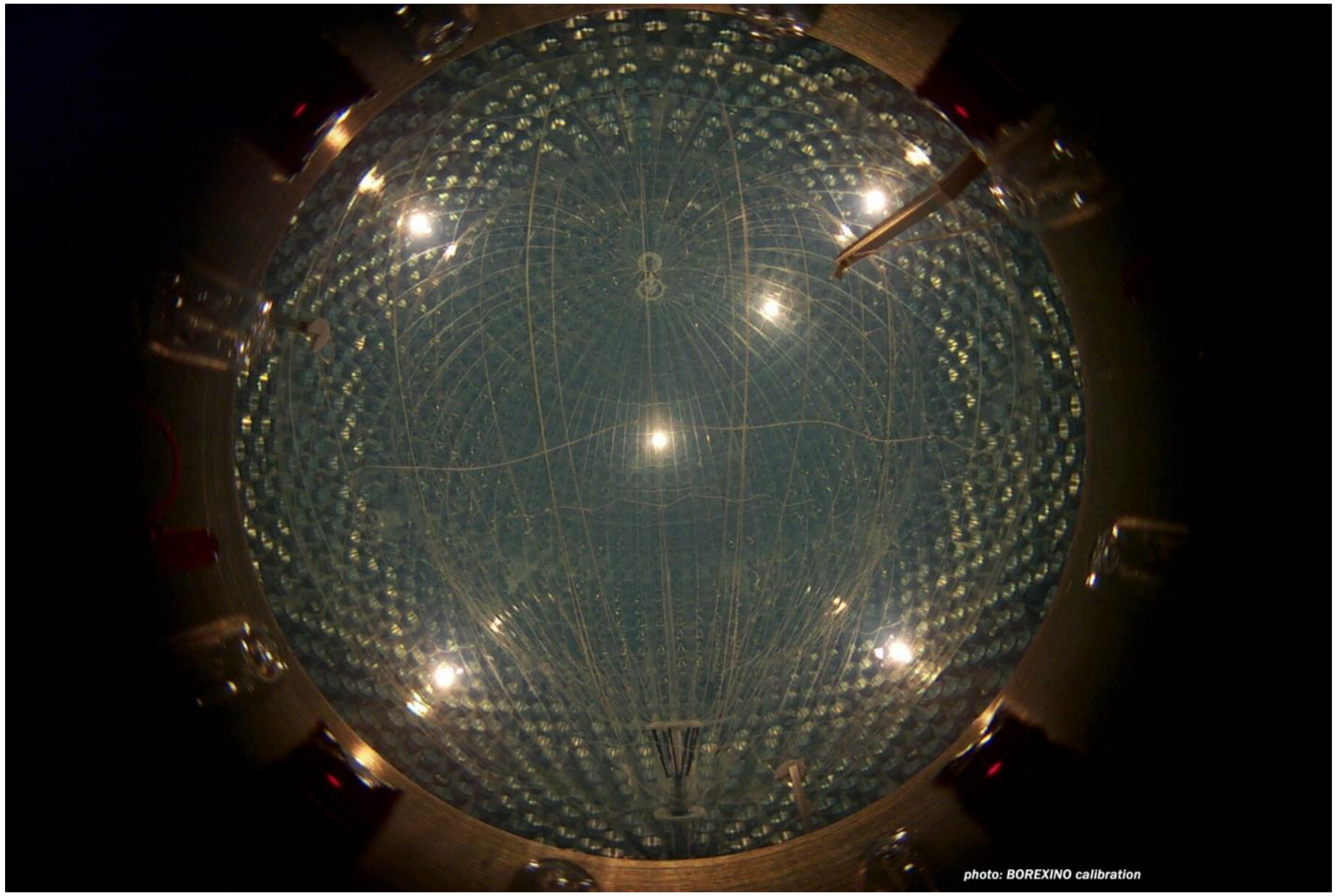


photo: BOREXINO calibration

Liquid Nobles

- Same as above, but with Xe, Ar (Ne, He explored, but uncommon)
- Single phase and dual phase versions
- Examples: EXO, Xenon, LZ, DarkSide, DEAP
- Pros: great self-shielding, lots of light, secondary discrimination
- Cons: cryogenic systems, cost

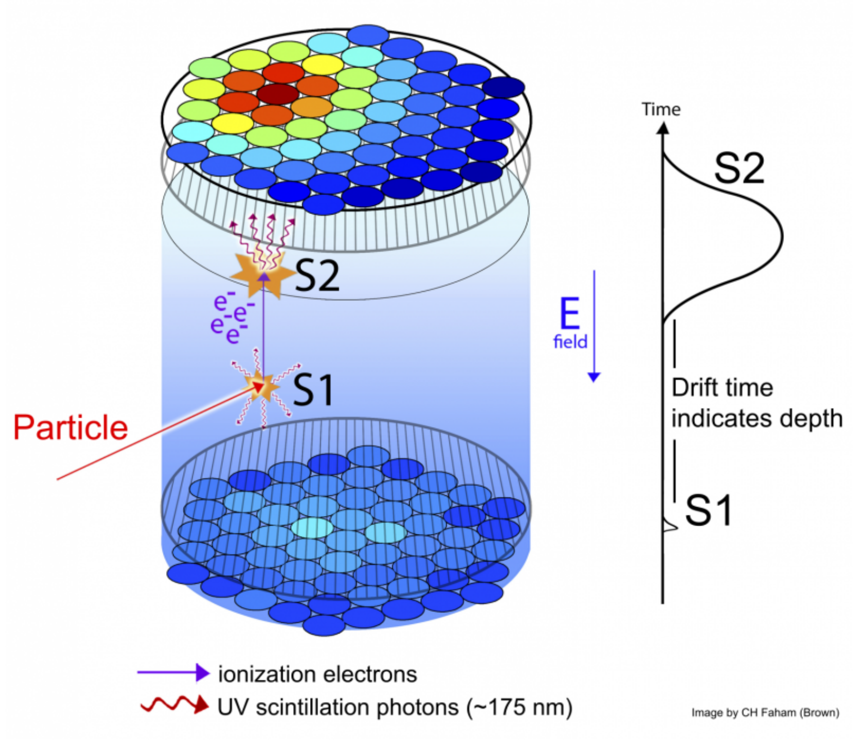
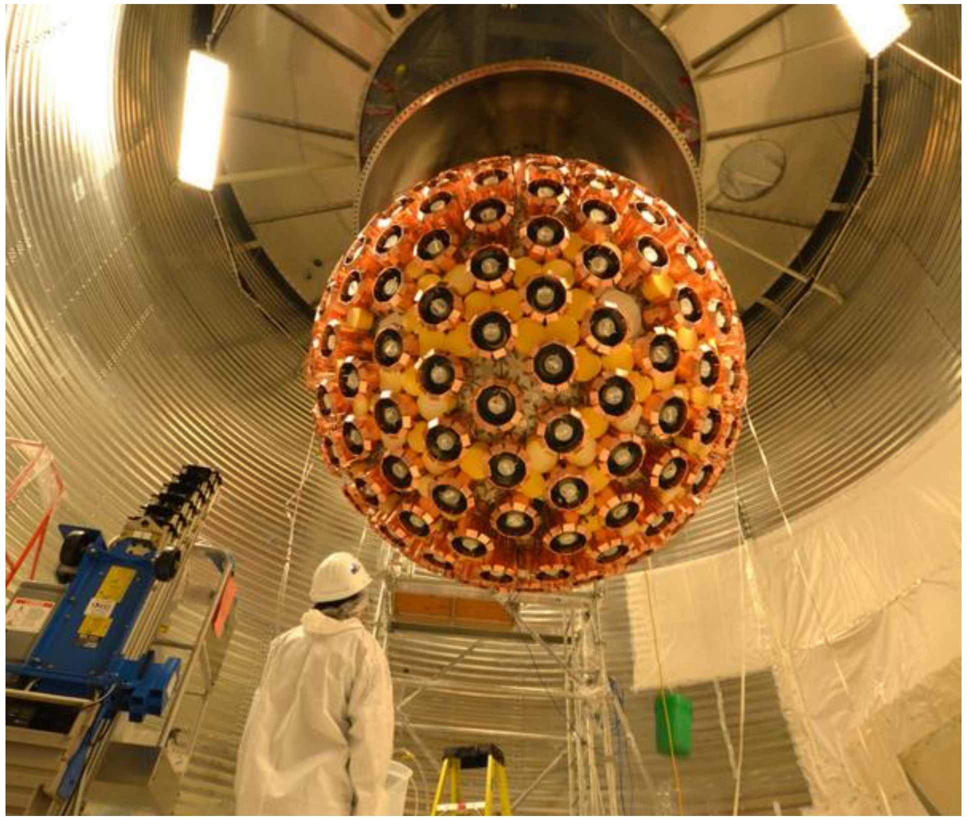
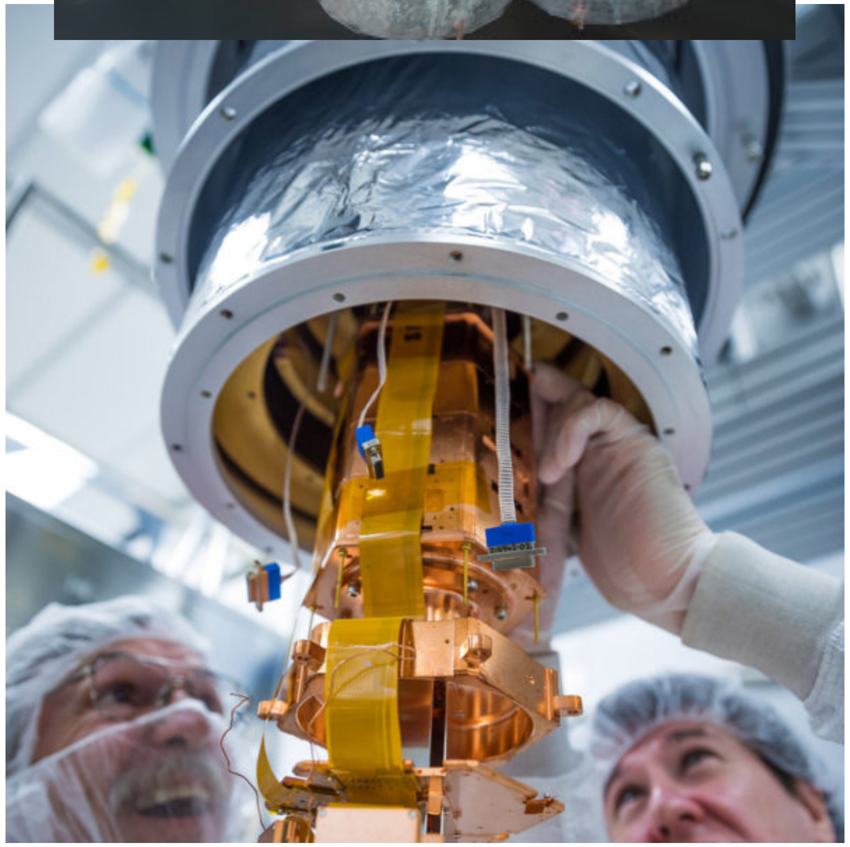


Image by CH Faham (Brown)



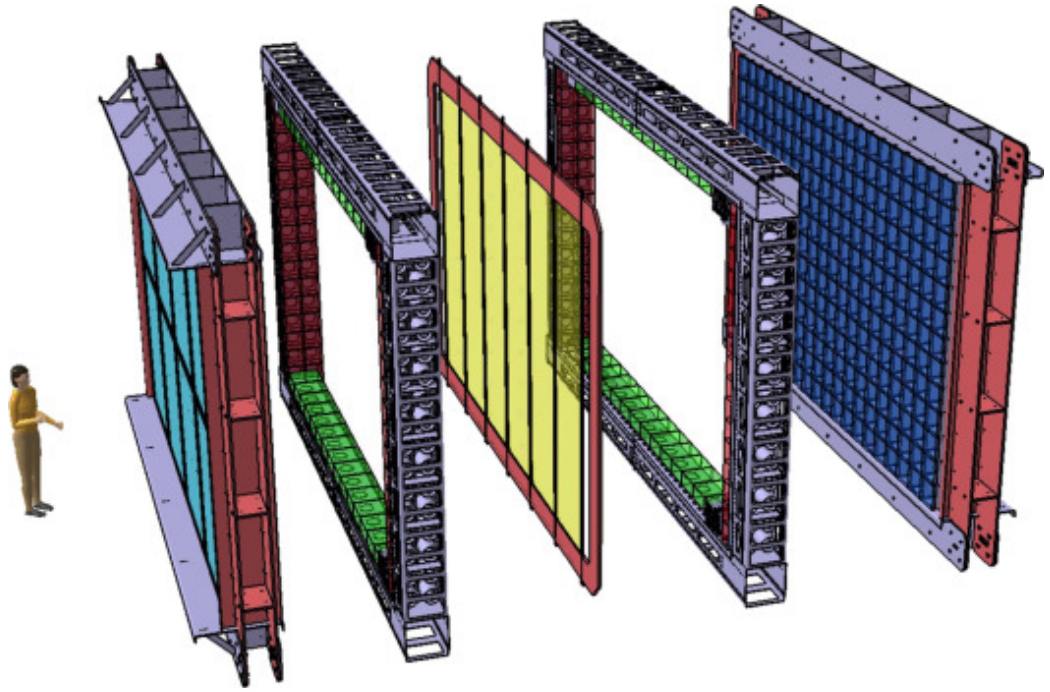
Solid Detectors

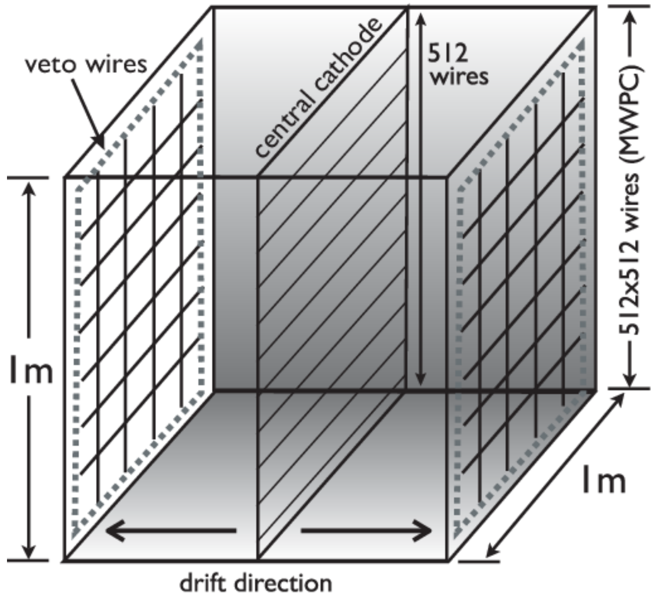
- Solid scintillating crystals of many materials: CsI, Ge, Te, Mo, Si, etc
- Detect photon, phonon, and/or ionization
- Examples: SuperCDMS, COHERENT, GERDA, MAJORANA, DAMA, etc
- Pros: extremely low thresholds, secondary discrimination
- Cons: Many small units, cryogenic, cost

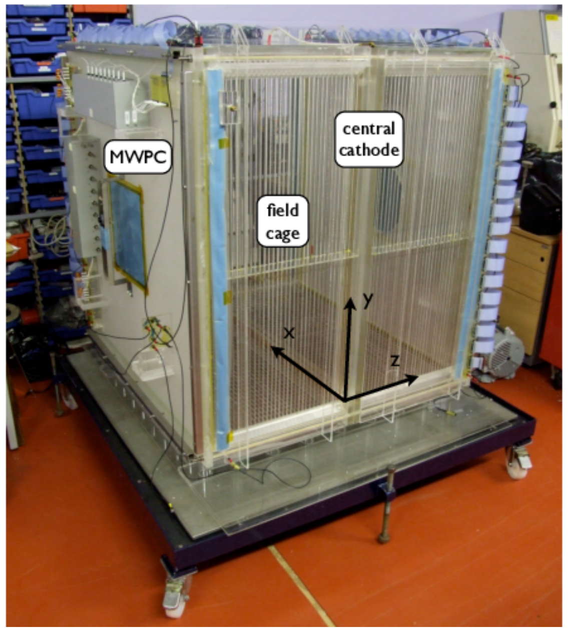


Gaseous Tracking

- Use gas for low density tracking
- Get topological information that can reduce backgrounds
- Examples: SuperNEMO, NEXT, DRIFT, DMTPC
- Pros: really detailed information about tracks
- Cons: Hard to get very large masses, little self-shielding

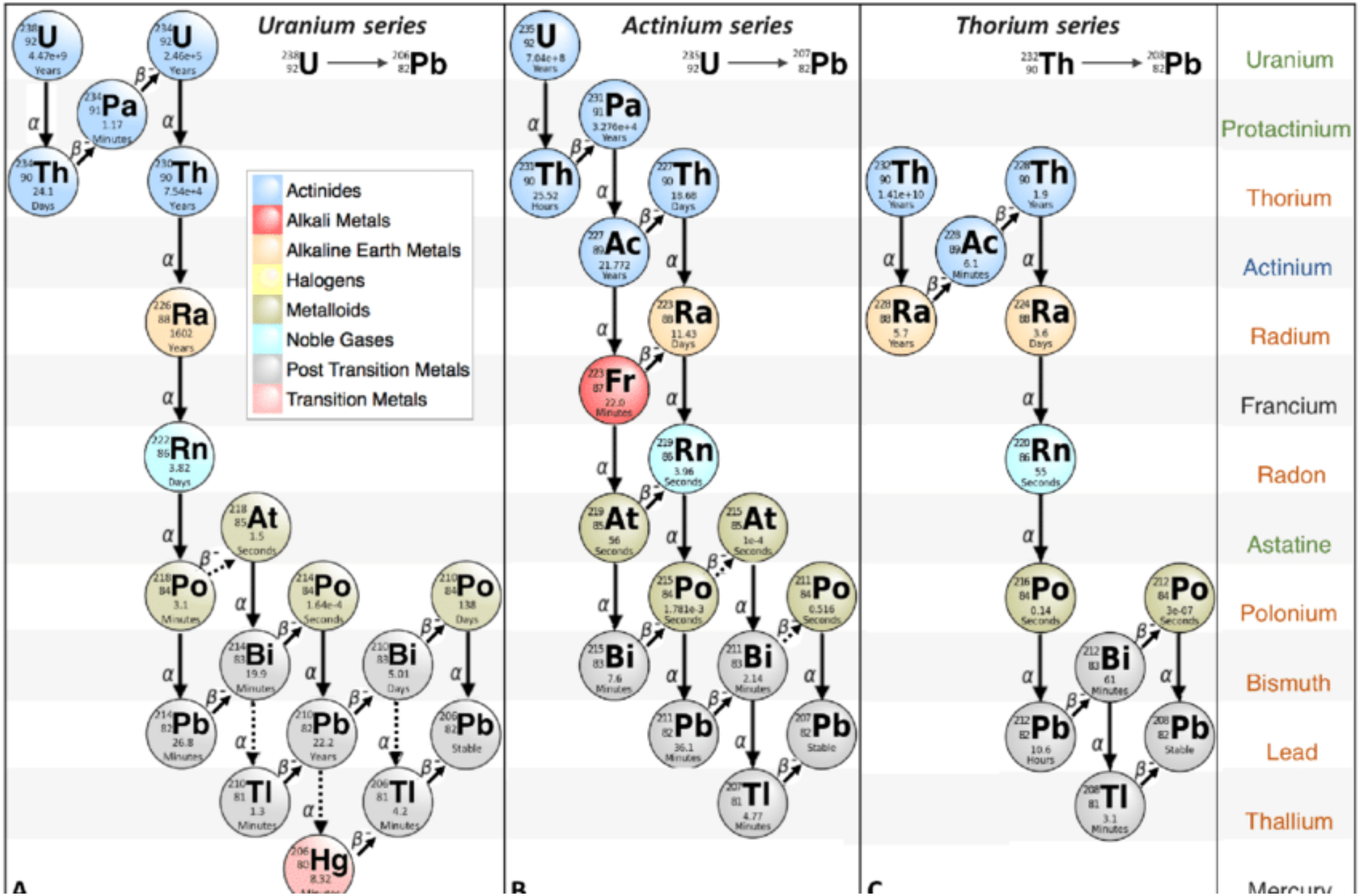






Types of Background

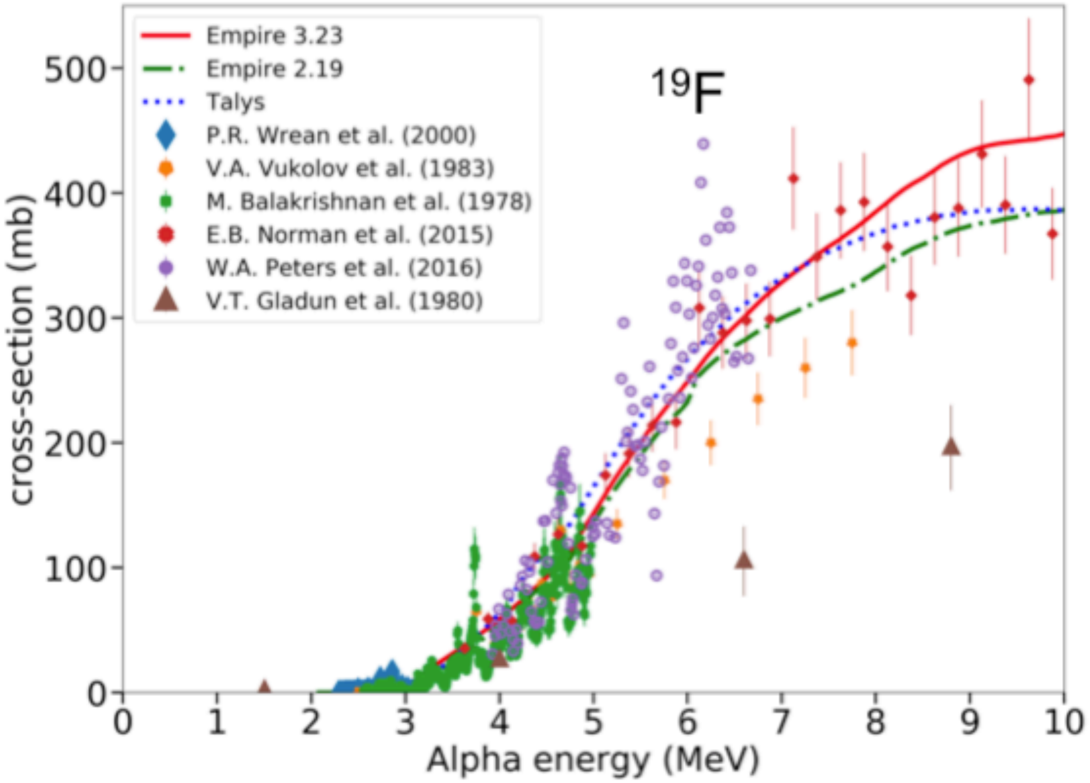
Uranium and Thorium

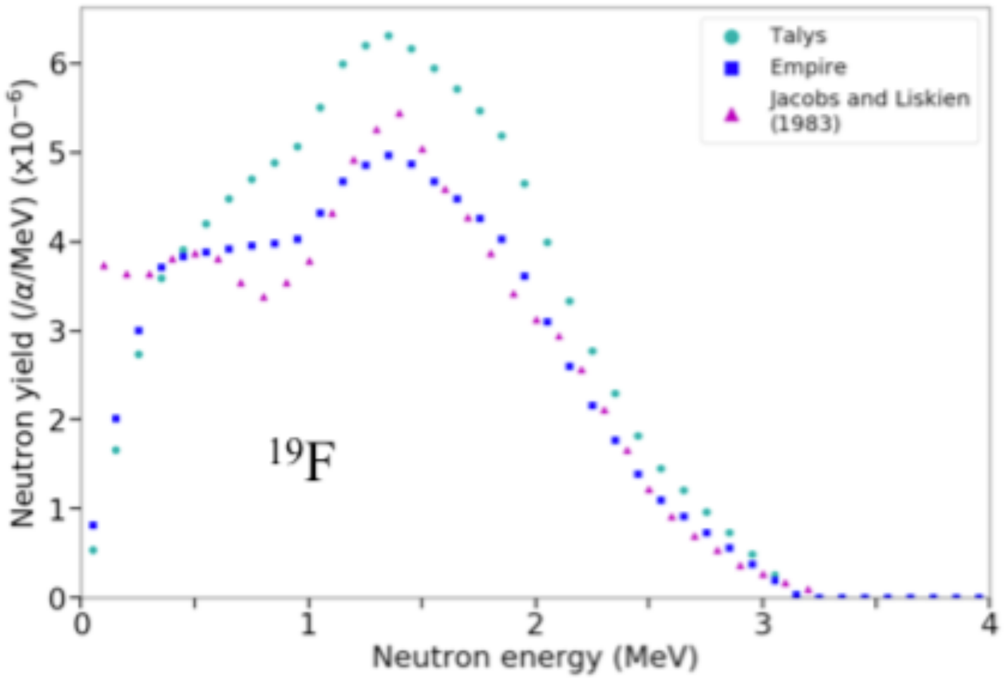


Uranium and Thorium

- Decay chains produce α, β, and γ directly
- Secondary production of neutrons
- Wide variety of energies mean these chains affect all low background experiments—something for everyone!
- Parent nuclei have extremely long lifetimes, so there is an effectively constant amount of decay products
- Basically everything has trace contamination of U/Th
- Radon is the worst because it is a gas and diffuses throughout a detector—^{222}Rn especially, with a 3.8 day half-life

Neutron production from U/Th



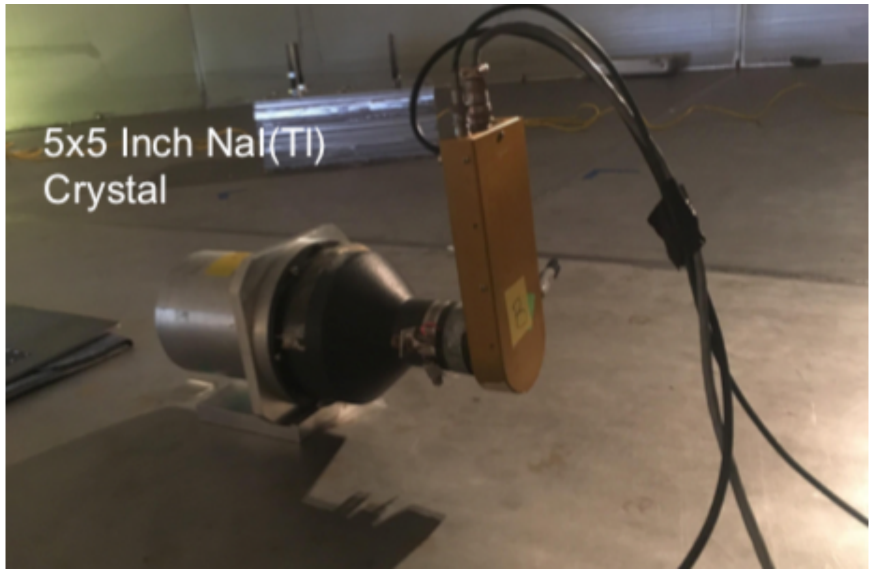


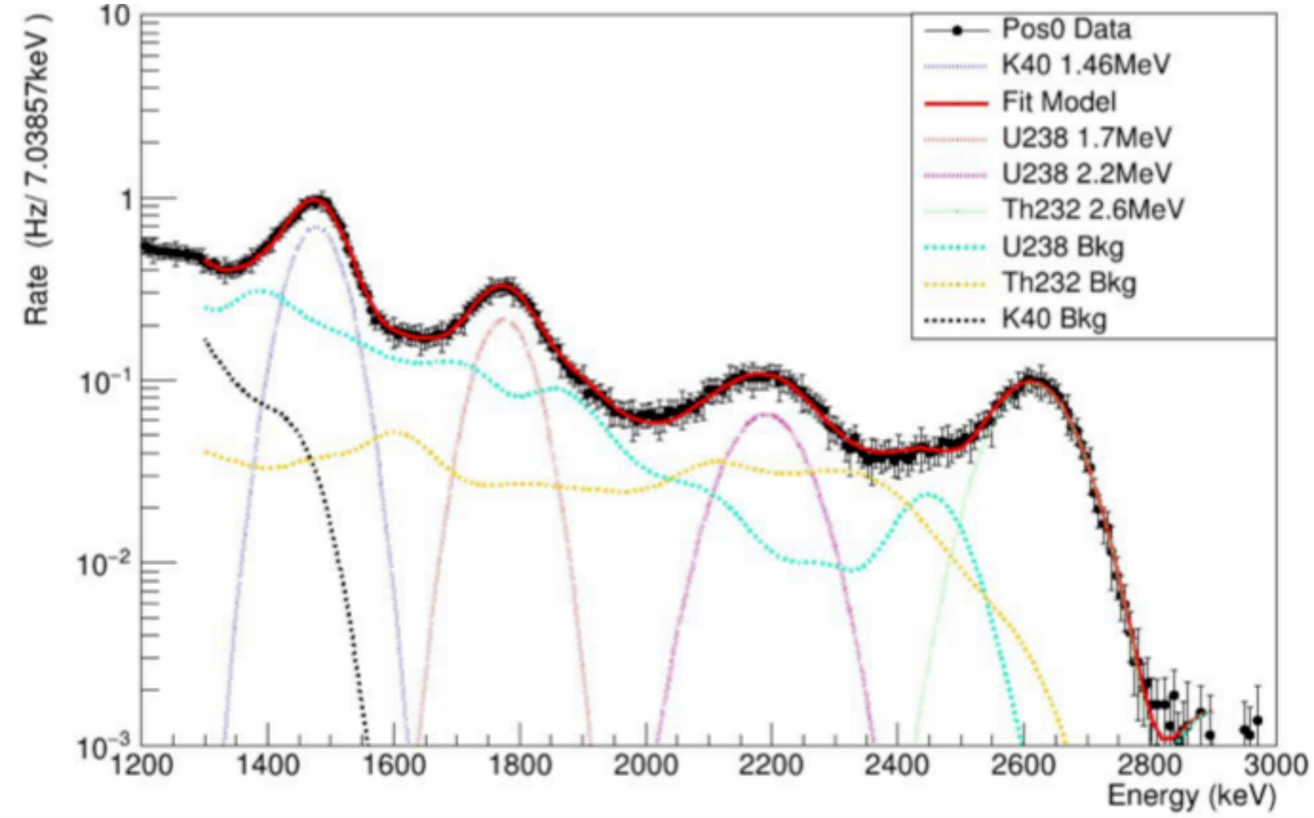
- Spontaneous fission
  - Relatively well understood
  - Usually subdominant
- (α, n) reactions
  - Uncertainty of ~20% in cross sections
  - Background contributions are dependent on detector materials

Cosmic Rays

- Cosmic rays going through detector are generally well above the physics energy of interest
- Cosmic rays can activate other materials, which have a variety of lifetimes

Cavern Rock





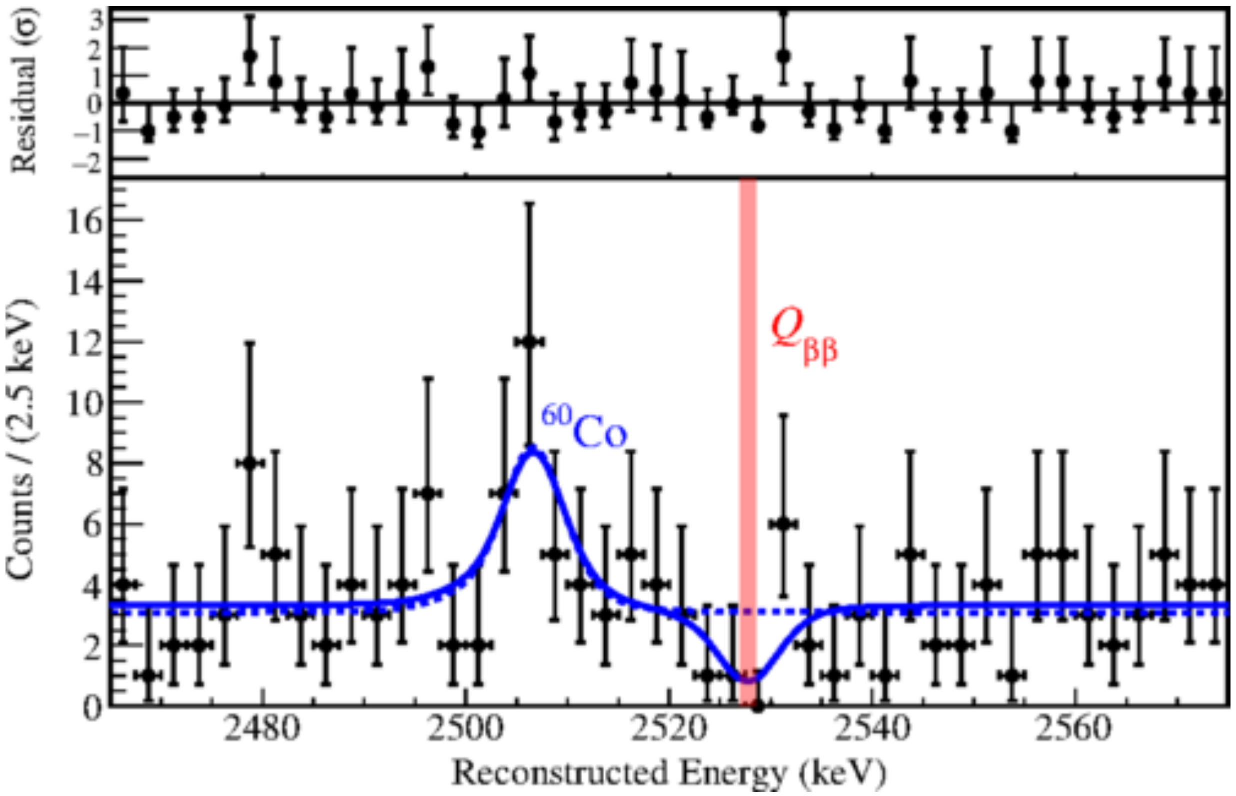
- The rock itself has intrinsic radioactivity
- Can also be activated by cosmic rays
- Can measure in-situ with auxiliary detectors

Other Radioactive Elements

- There are a wide variety of radioactive elements over a huge range of energies
- Almost every experiment has something in their ROI

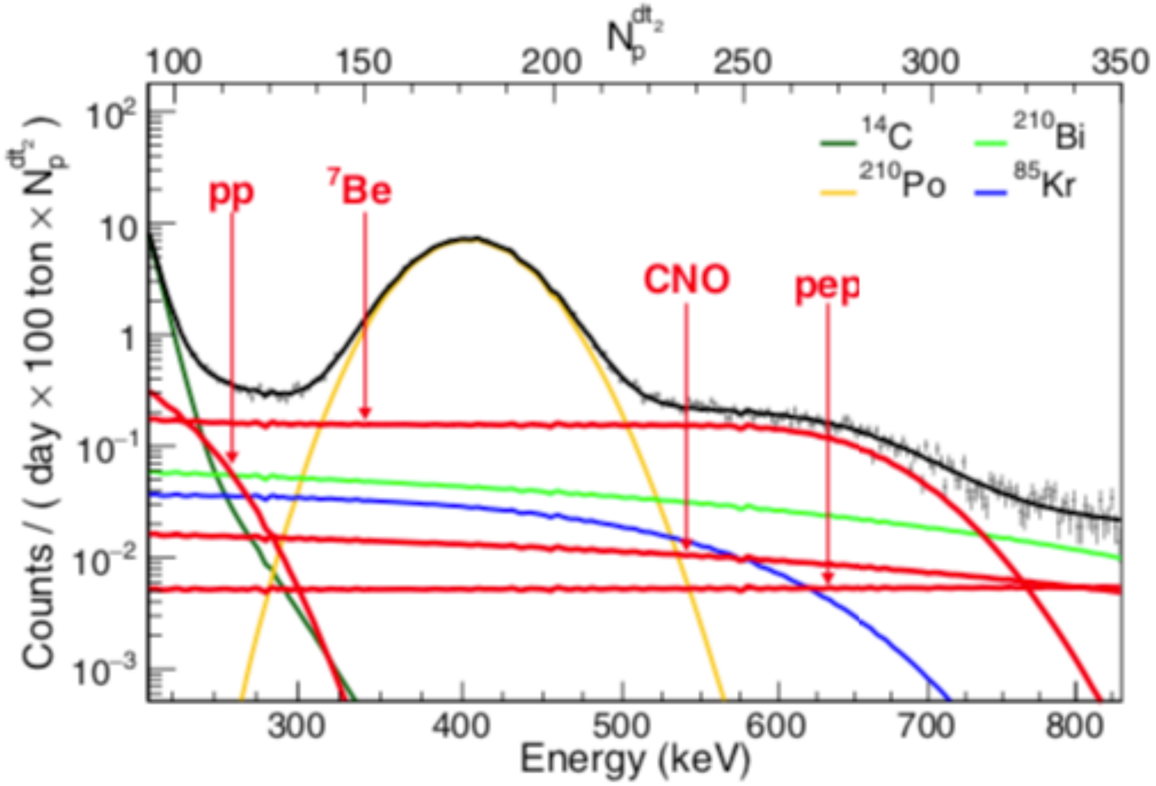
Example 1: ^{60}Co in CURORE

- CUORE is a TeO_2 bolometer $0\nu\beta\beta$ experiment
- Te has an endpoint energy of 2.528 MeV
- ^{60}Co has a peak at 2.510 MeV
- Need really good energy resolution to separate!



Example 2: ^{85}Kr in Borexino

- Sits just under the pep neutrino signal, very similar spectral shape
- Gaseous noble element produced in nuclear fuel processing
- Eleven year half life
- Can only remove from system, hard to reduce in analysis



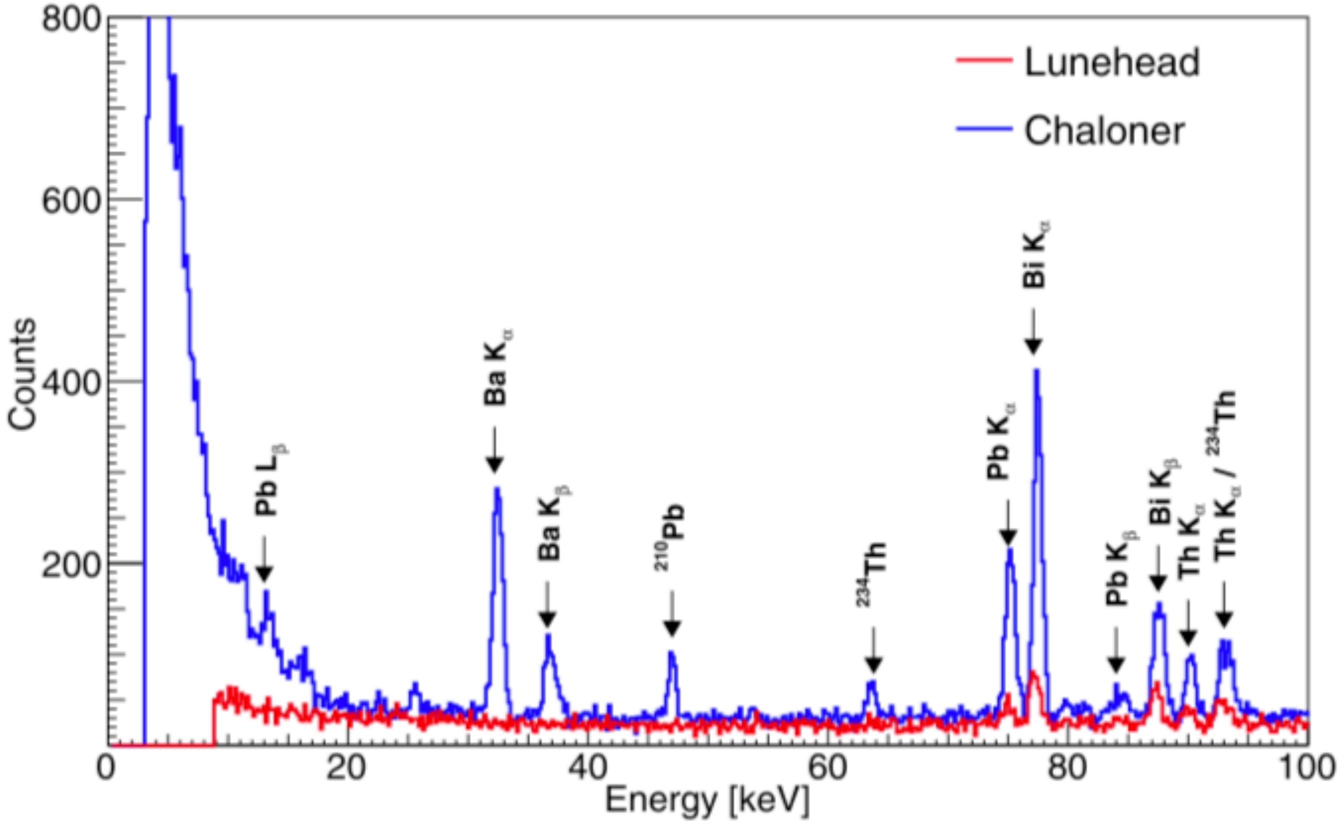
Contamination Mitigation Strategy

- Measure
- Prevent
- Eliminate

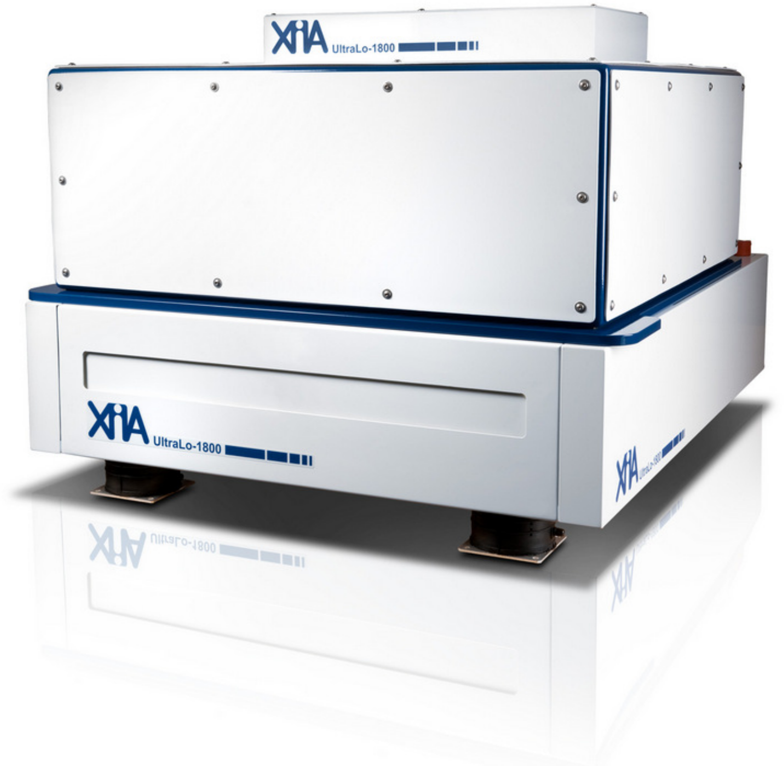
Measuring Contamination

β and γ

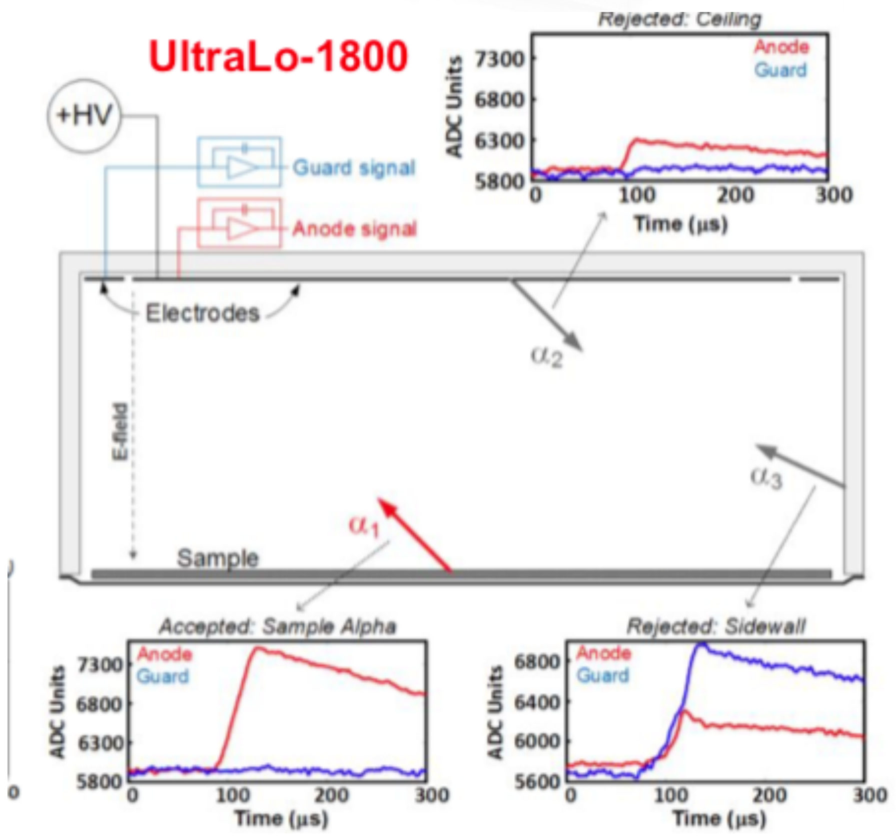
- Best measurement for β and γ sources is high-precision germanium detectors
- Typical resolution is 1 keV @ 100 keV
- Can measure relative heights of peaks to get detailed compositional measure
- Can measure down to ~few mBq/kg
- Repeat measurement to test, e.g., cleaning procedures
- UK facility in Boulby Mine near Whitby



Measuring Contamination



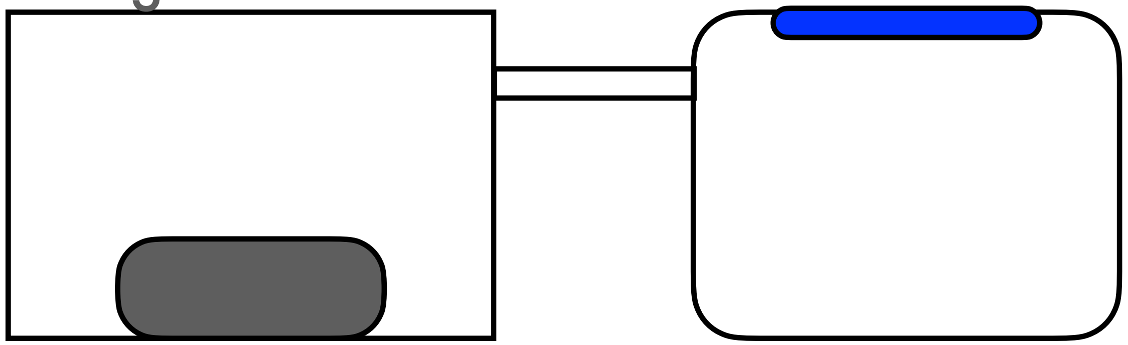
α



- Buy a fancy alpha counter from XIA
- Engineered to reject alphas from its own surfaces with pulse shape techniques
- Measure at the level of mBq/m^2

Measuring Contamination

radon



Sample under vacuum outgases radon

Detect radon daughters with Si PIN diode

Flush with ultra pure gas to detection volume

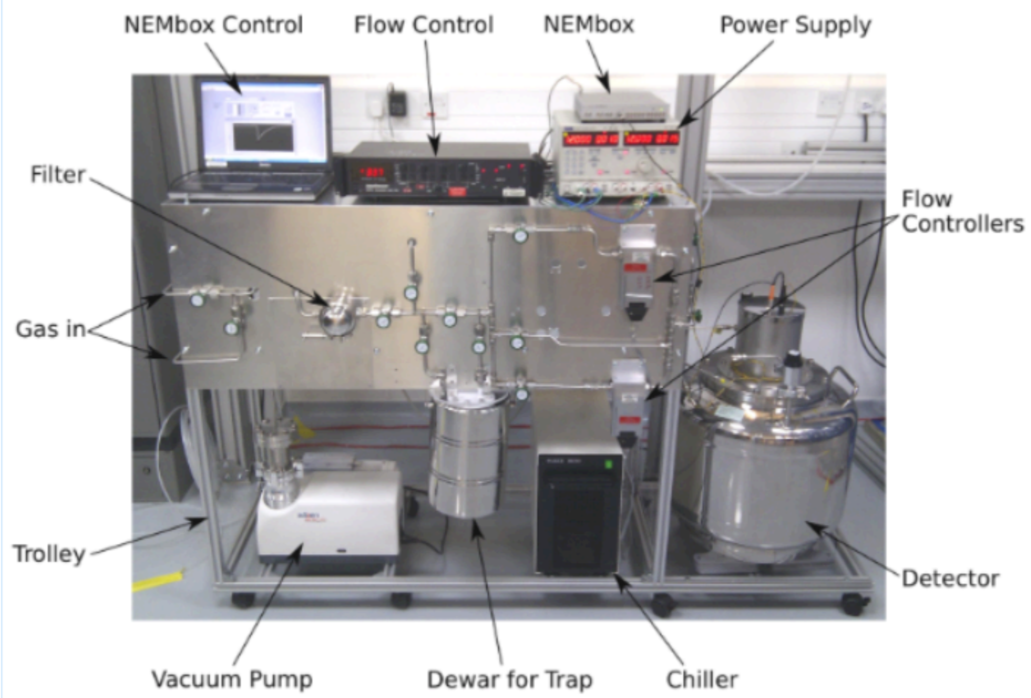


Figure 9: The radon concentration line at UCL

- Outgas radon from a sample, measure daughters
- Non-destructive, but can be a long measurement
- New facility being built at RAL—does radon emanate differently at cold temperatures?

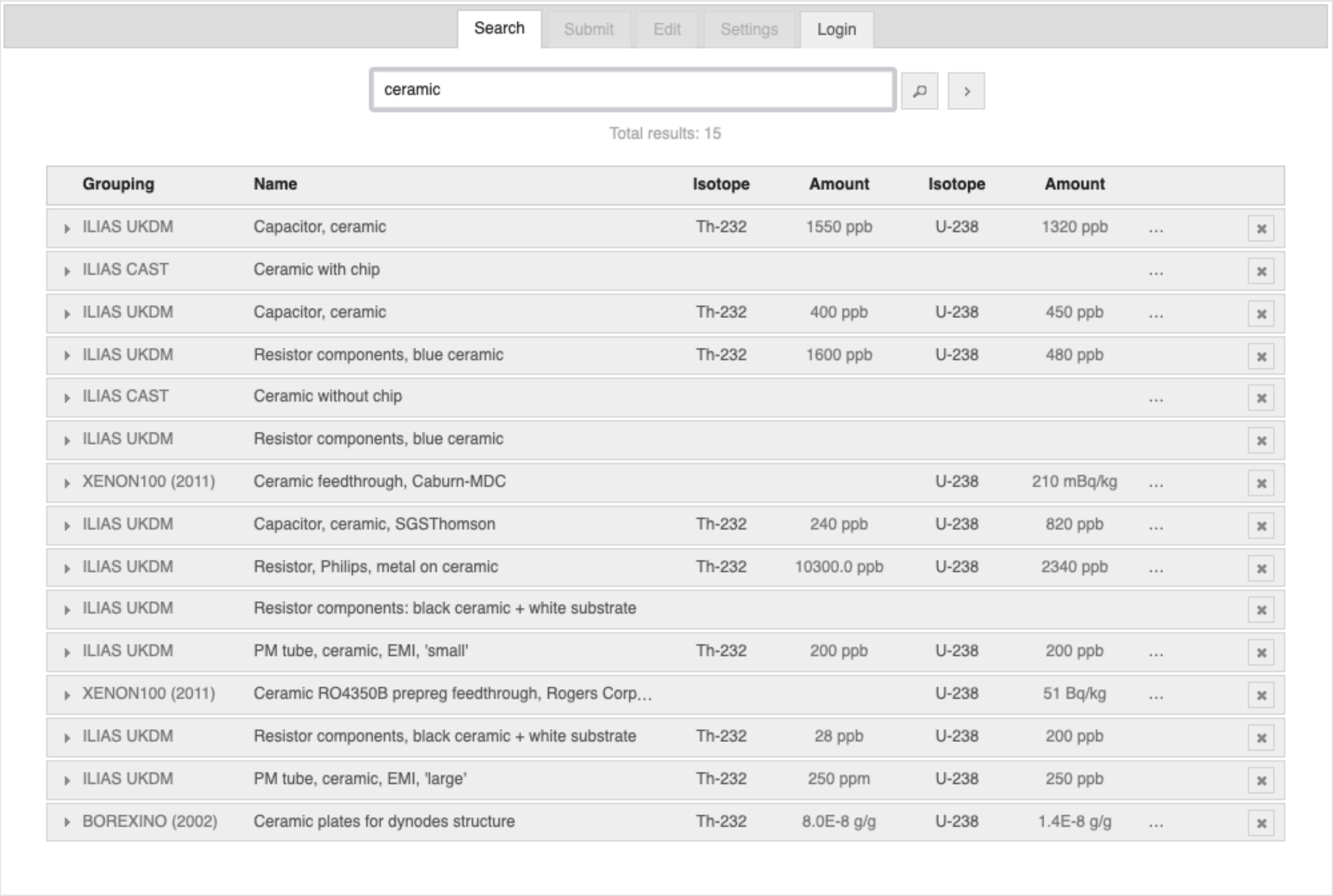
Measuring Contamination

mass spectroscopy

- Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) is a technique to atomize and ionize a sample, then do mass spectroscopy
- Destructive technique, but fast
- Precision: 10 ppt g/g in the U/Th chains

Materials Database

radiopurity.org



ceramic

Total results: 15

Grouping	Name	Isotope	Amount	Isotope	Amount	
ILIAS UKDM	Capacitor, ceramic	Th-232	1550 ppb	U-238	1320 ppb	...
ILIAS CAST	Ceramic with chip					...
ILIAS UKDM	Capacitor, ceramic	Th-232	400 ppb	U-238	450 ppb	...
ILIAS UKDM	Resistor components, blue ceramic	Th-232	1600 ppb	U-238	480 ppb	
ILIAS CAST	Ceramic without chip					...
ILIAS UKDM	Resistor components, blue ceramic					
XENON100 (2011)	Ceramic feedthrough, Caburn-MDC			U-238	210 mBq/kg	...
ILIAS UKDM	Capacitor, ceramic, SGSThomson	Th-232	240 ppb	U-238	820 ppb	...
ILIAS UKDM	Resistor, Philips, metal on ceramic	Th-232	10300.0 ppb	U-238	2340 ppb	...
ILIAS UKDM	Resistor components: black ceramic + white substrate					
ILIAS UKDM	PM tube, ceramic, EMI, 'small'	Th-232	200 ppb	U-238	200 ppb	...
XENON100 (2011)	Ceramic RO4350B prepreg feedthrough, Rogers Corp...			U-238	51 Bq/kg	...
ILIAS UKDM	Resistor components, black ceramic + white substrate	Th-232	28 ppb	U-238	200 ppb	
ILIAS UKDM	PM tube, ceramic, EMI, 'large'	Th-232	250 ppm	U-238	250 ppb	
BOREXINO (2002)	Ceramic plates for dynodes structure	Th-232	8.0E-8 g/g	U-238	1.4E-8 g/g	...

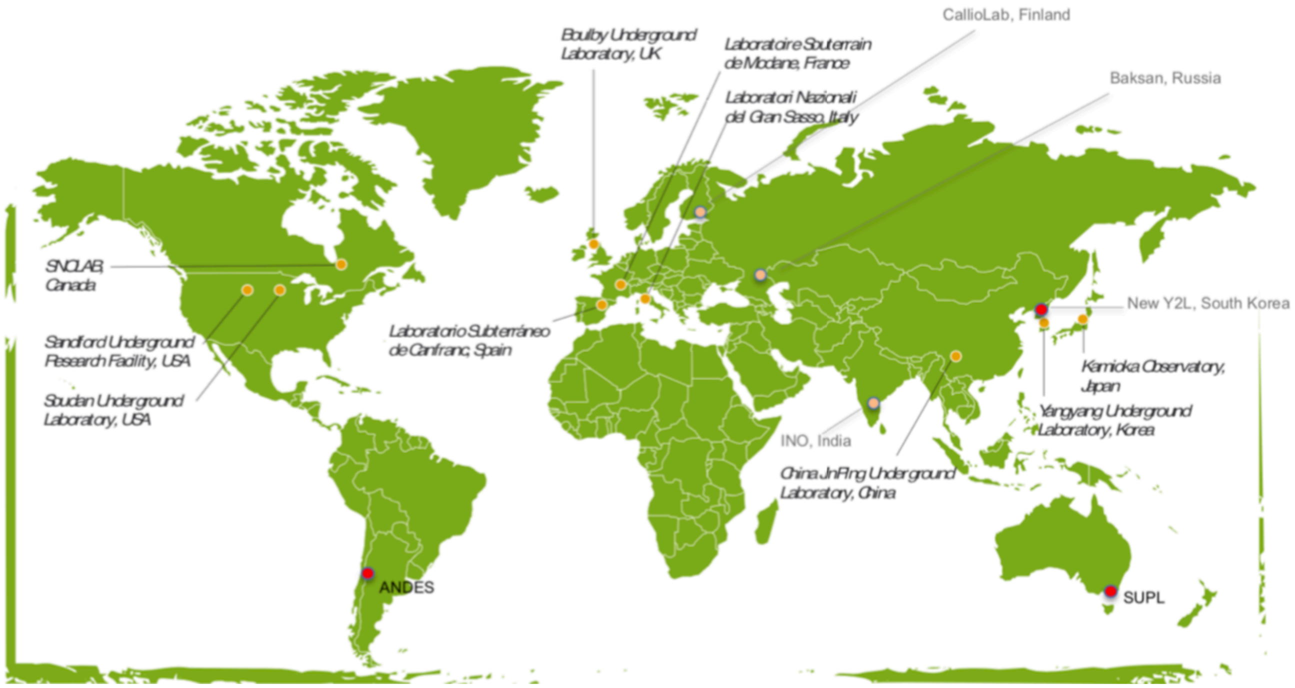
Worldwide effort to record and share information

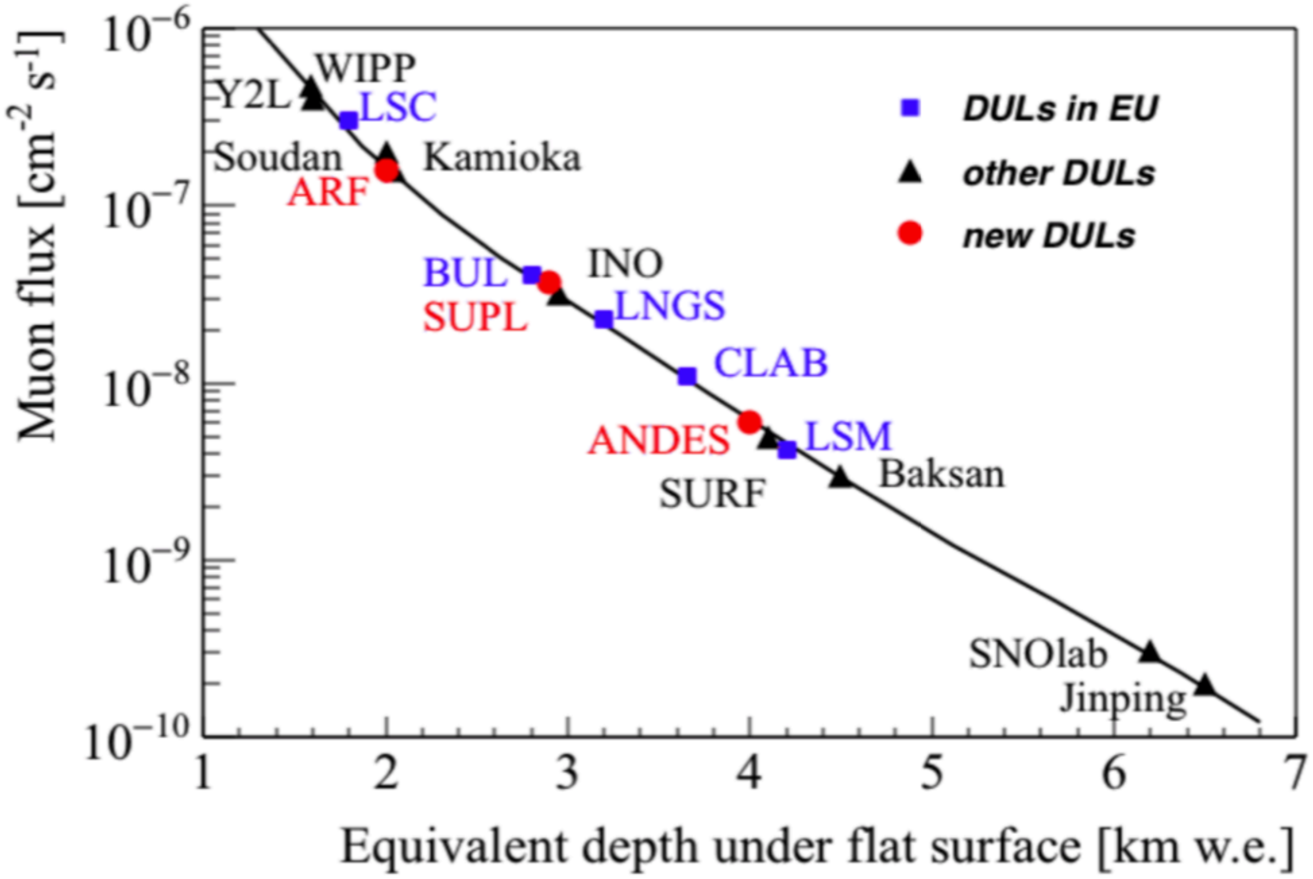
So what’s good and what's bad?

- Electronics are hard: resistors, capacitors, and cables have historically been big sources
- PMTs are hard: glass and photocathodes
- Metals are a mixed bag
- Many plastics can be made very pure

Prevention is better than the cure!

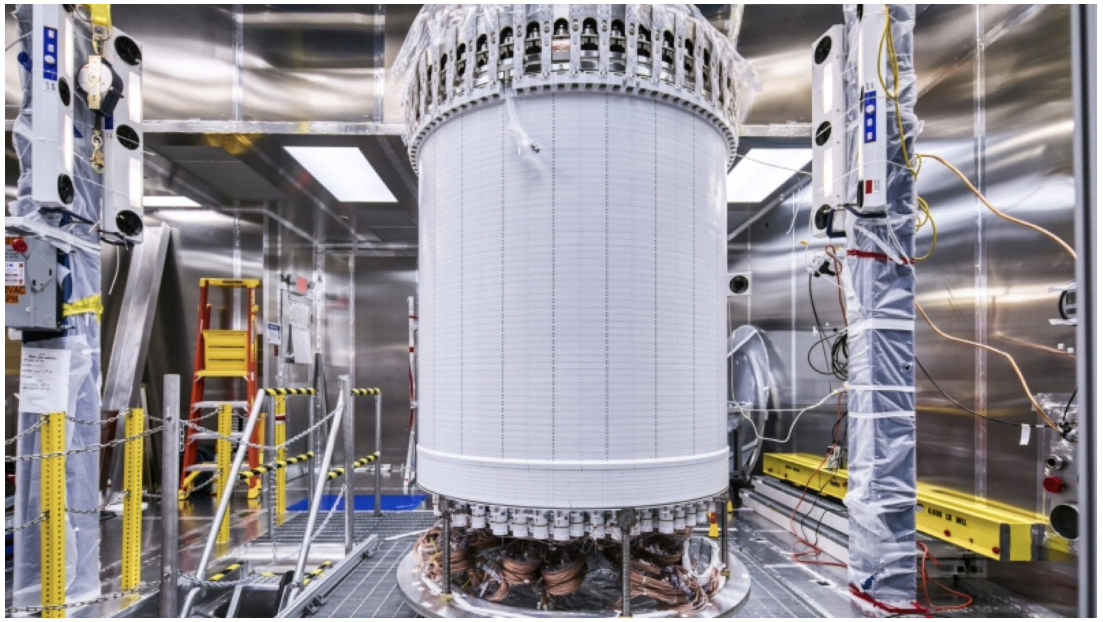
Prevention: Going Deep





- The deeper you go, the fewer cosmic rays make it to the detector or the rock around
- Typically cut 4-8 orders of magnitude
- Working underground is hard: logistically hard, physically hard, emotionally hard!

Prevention: Going Deep

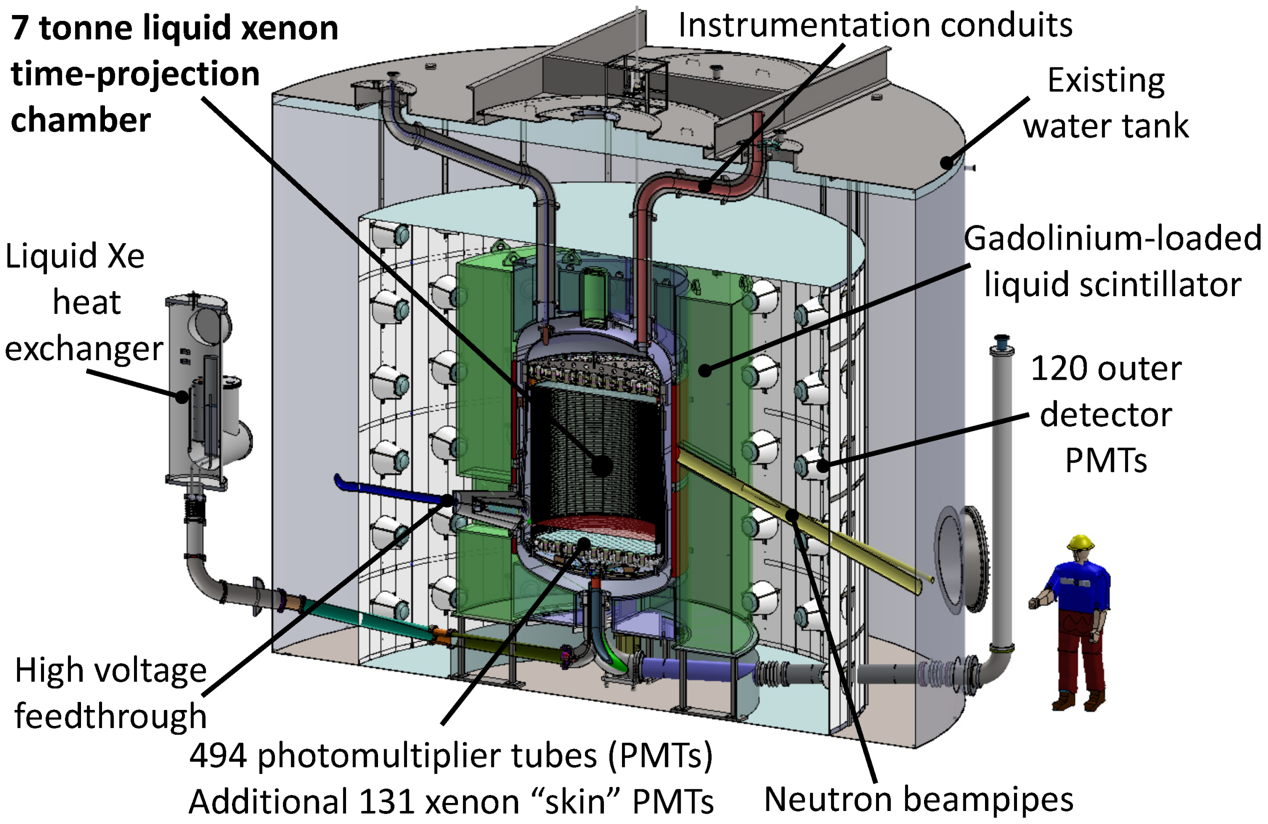


- LZ detector transportation u/g from surface clean room to underground laboratory (1490 m)

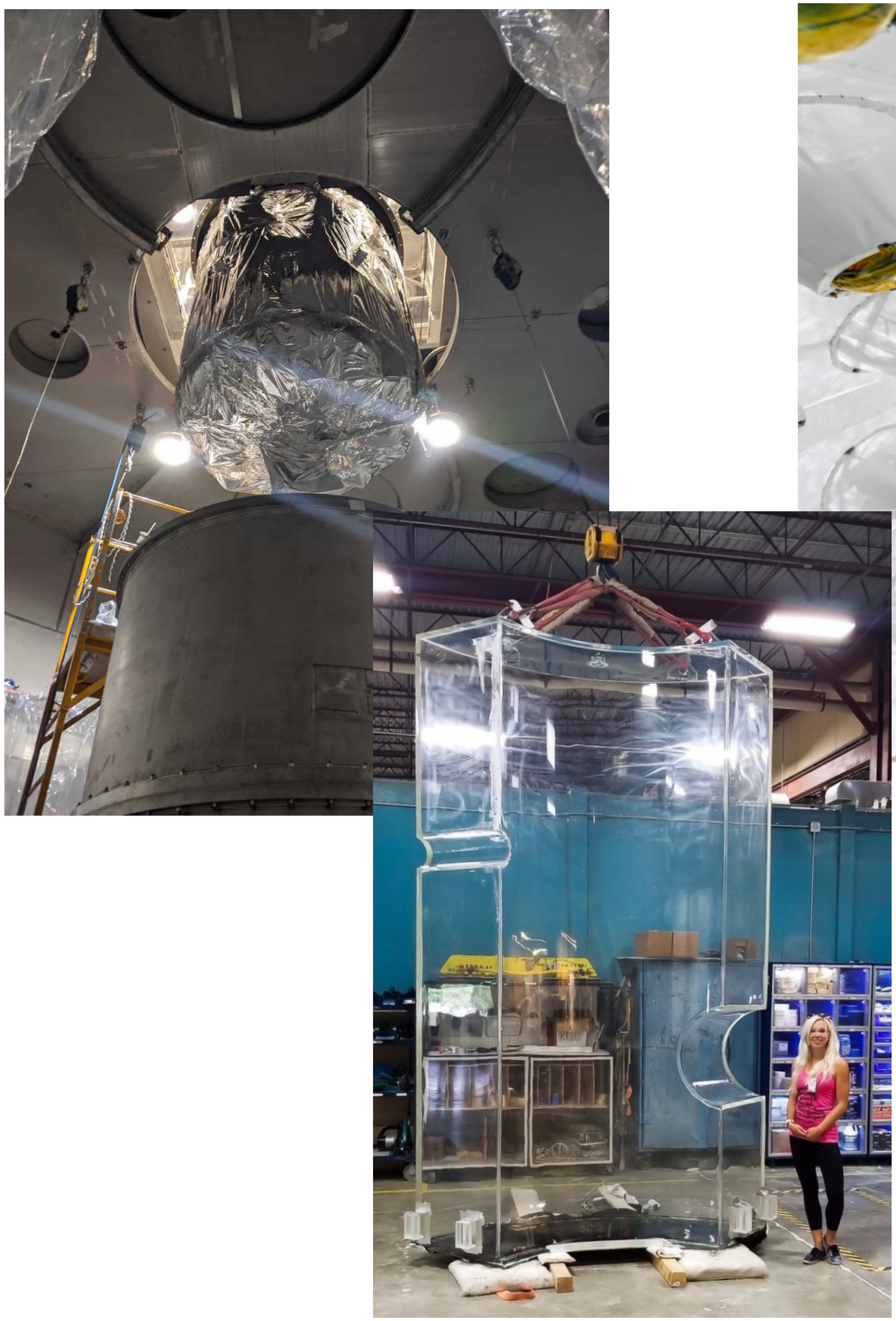
Prevention: Shielding

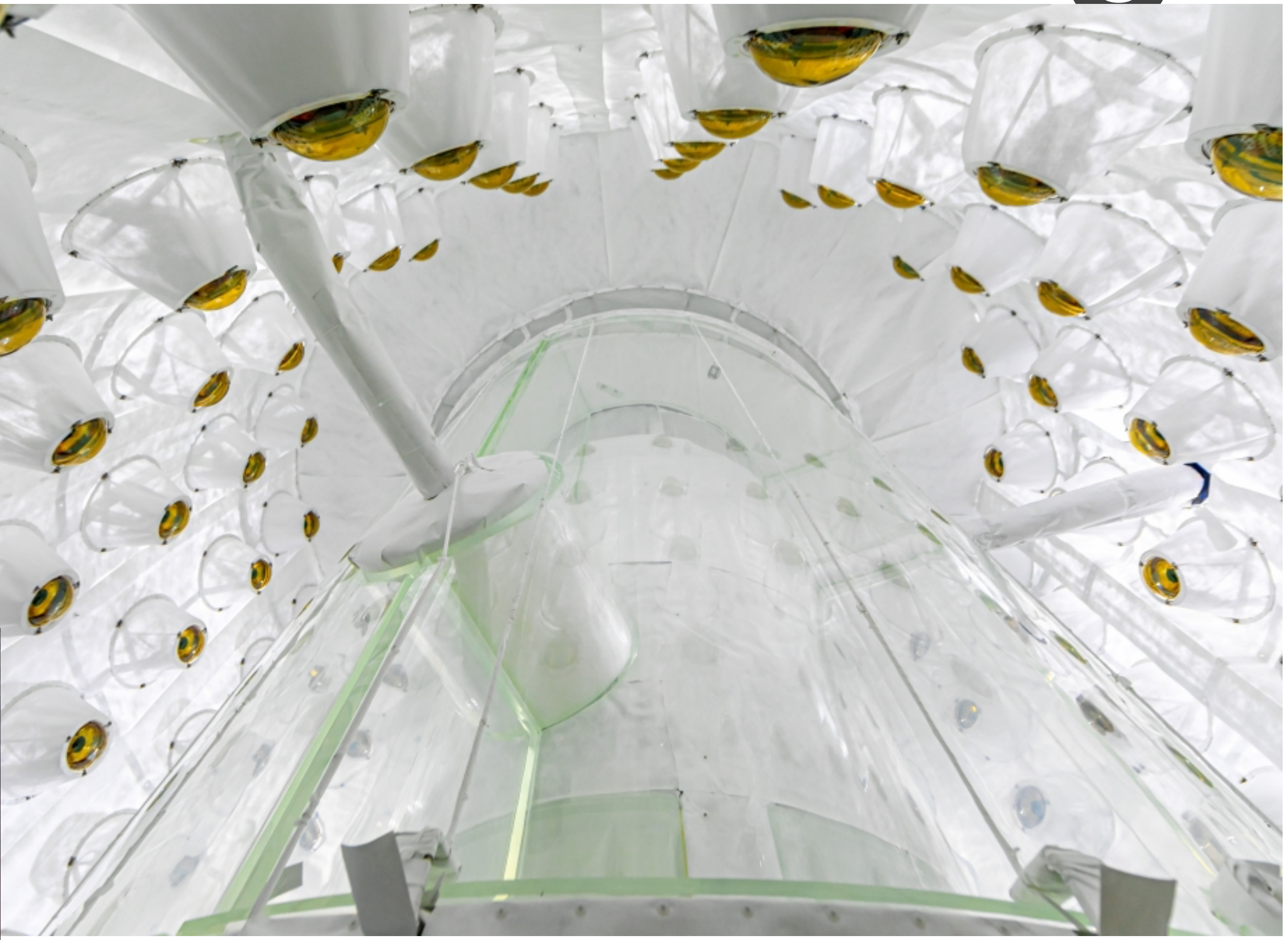
- Most experiments will have layers of shielding around the detectors
- Shields can be active or passive
- The bigger you are, the less shielding you need
- Popular materials include:
  - Water
  - Liquid scintillator
  - Copper
  - Lead (preferably Roman)
  - (Borated) plastic

The LZ Detector



Prevention: Shielding





- LZ cryostat, acrylic vessels and water tank PMTs

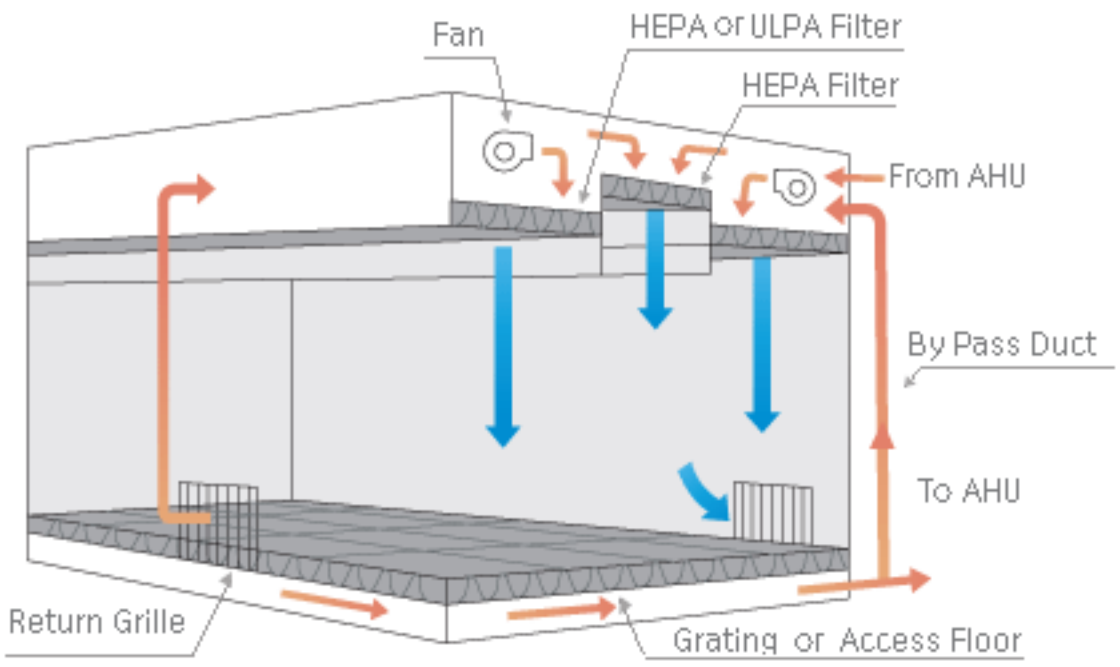
Prevention: Cleanliness

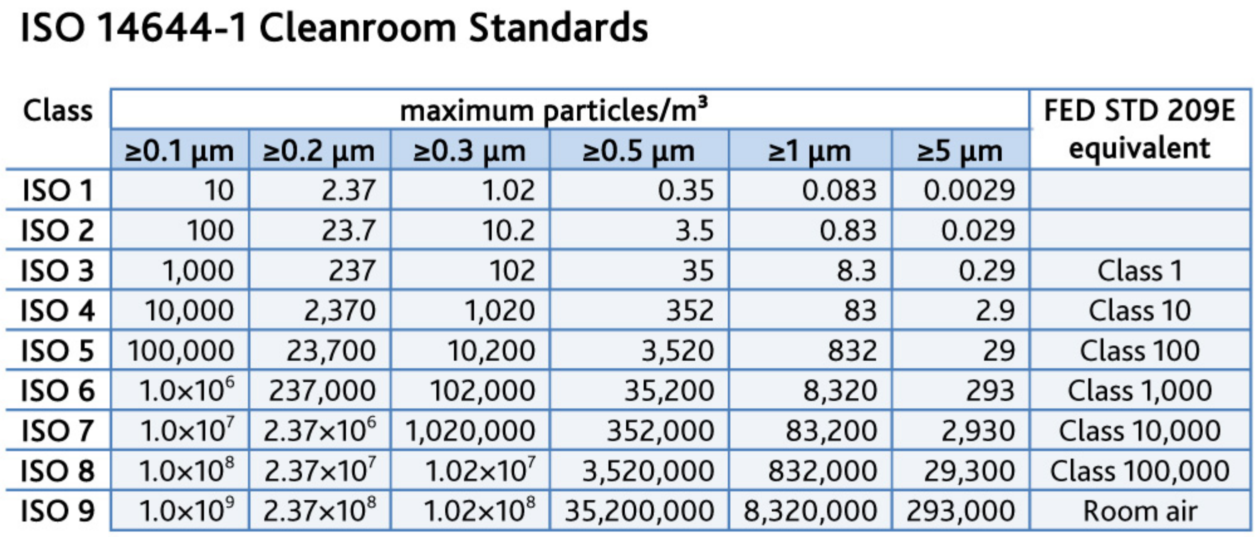
a.k.a: you are your detector's worst enemy

- You are full of radioactivity and covered in dust. You will ruin your detector.
- Your detector must be protected against you
- Most work will go on in clean rooms and with you in cleanroom gear
- Solid, cleanable surfaces
- Deionizing fans

Wearing masks before it was cool

How Clean Rooms Work



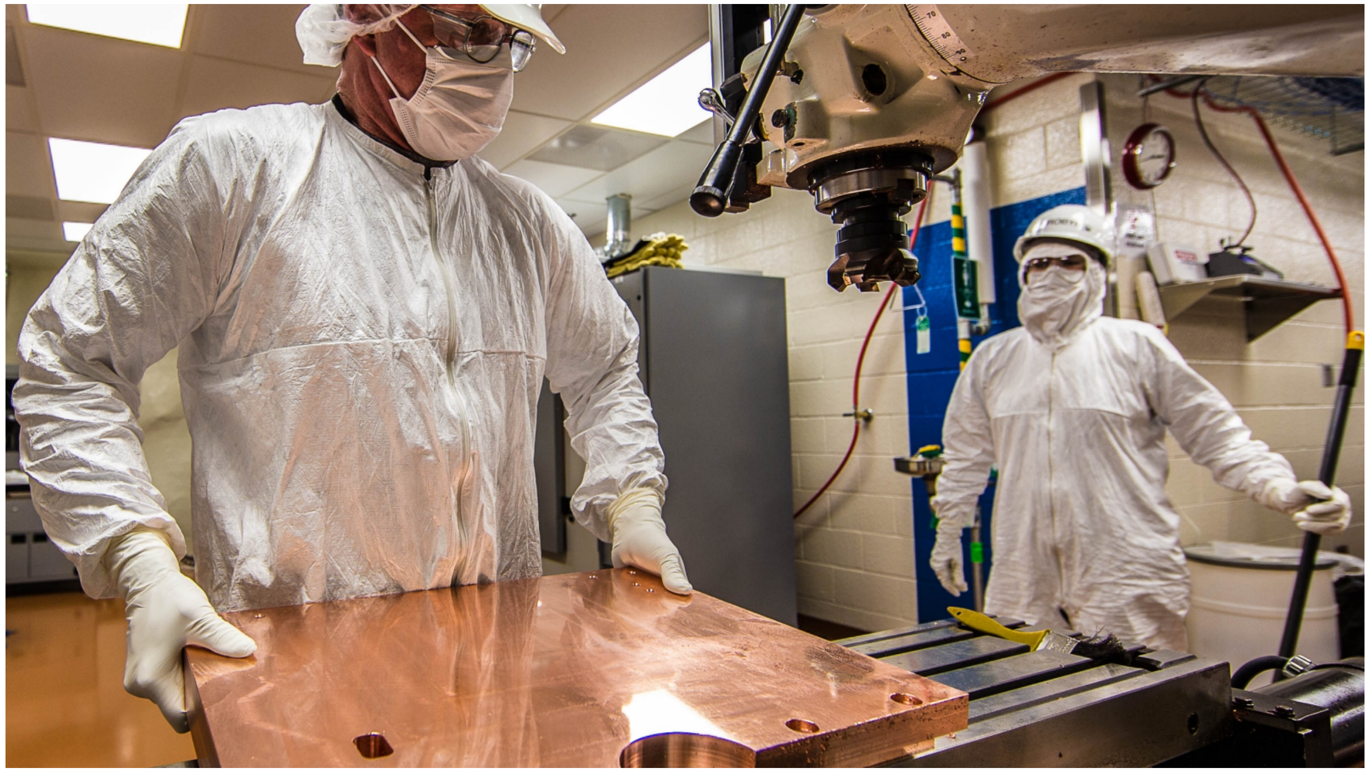


ISO 14644-1 Cleanroom Standards

Class	maximum particles/m³						FED STD 209E equivalent
	≥0.1 µm	≥0.2 µm	≥0.3 µm	≥0.5 µm	≥1 µm	≥5 µm	
ISO 1	10	2.37	1.02	0.35	0.083	0.0029	
ISO 2	100	23.7	10.2	3.5	0.83	0.029	
ISO 3	1,000	237	102	35	8.3	0.29	Class 1
ISO 4	10,000	2,370	1,020	352	83	2.9	Class 10
ISO 5	100,000	23,700	10,200	3,520	832	29	Class 100
ISO 6	1.0×10^6	237,000	102,000	35,200	8,320	293	Class 1,000
ISO 7	1.0×10^7	2.37×10^6	1,020,000	352,000	83,200	2,930	Class 10,000
ISO 8	1.0×10^8	2.37×10^7	1.02×10^7	3,520,000	832,000	29,300	Class 100,000
ISO 9	1.0×10^9	2.37×10^8	1.02×10^8	35,200,000	8,320,000	293,000	Room air

- Filtered, directed air flow
- Bring in clean air at the top, drive out less clean air at the bottom
- Air handling systems can also be made to reduce radon in the air
- Experiments often have a series of cleanrooms with different requirements for different kinds of work

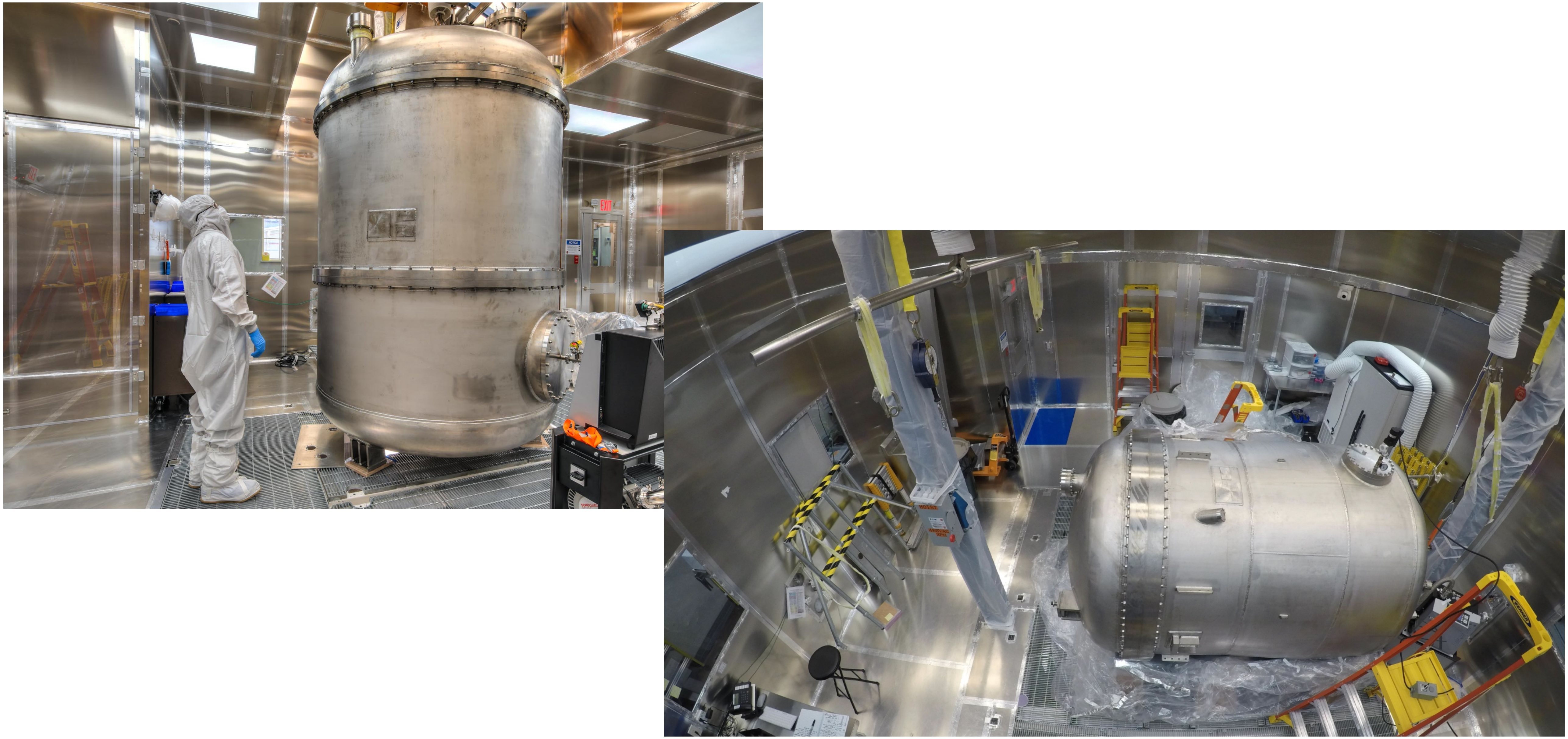
Prevention: Manufacture



- Find the cleanest materials to start with
- Manufacture in clean(er) environments
- Some experiments have whole clean machine shops

Prevention: Manufacture

- LZ cryostat made from ultra-radio pure Titanium

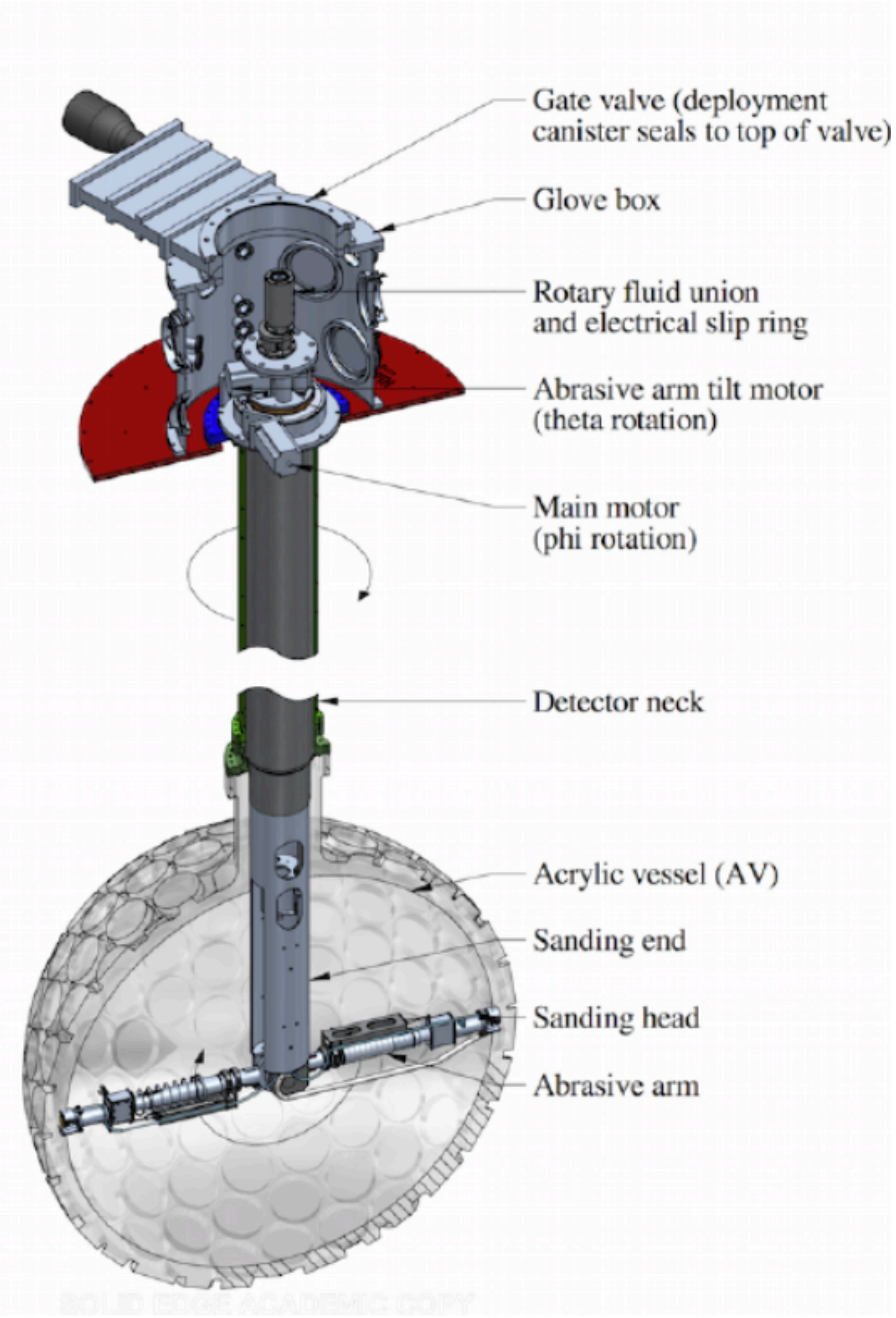


Prevention: Storage and Transport

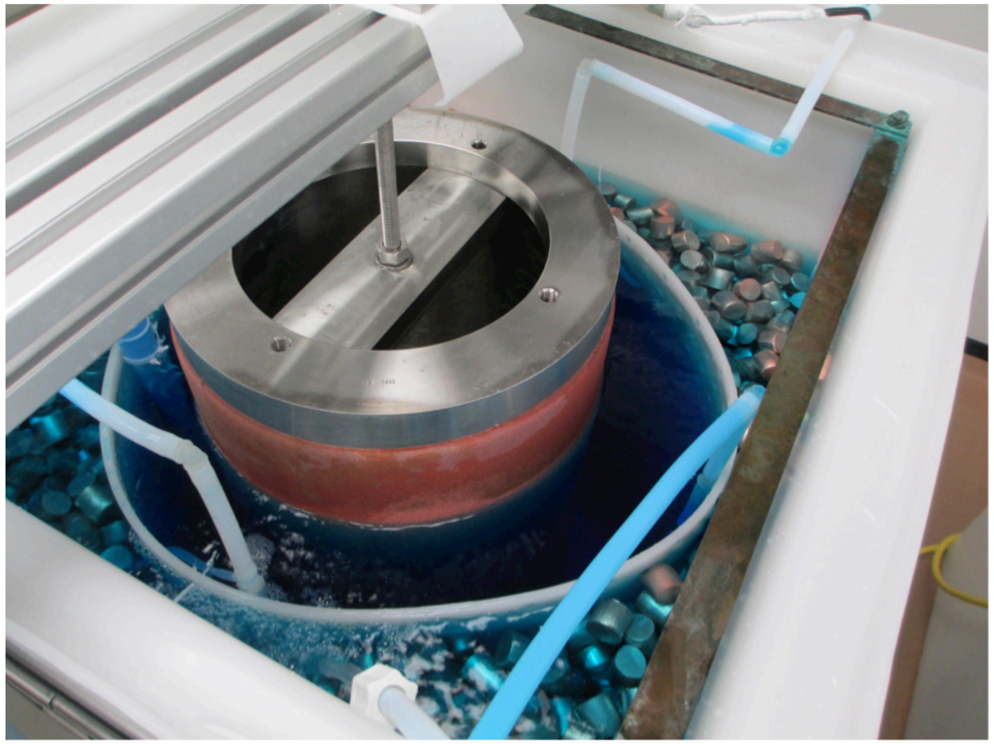
- Moving things from place to place is always a risk
- Often use ‘triple bagging’ techniques
- Minimize altitude and time
- Store things underground ASAP to prevent cosmic activation

Elimination: Cleaning

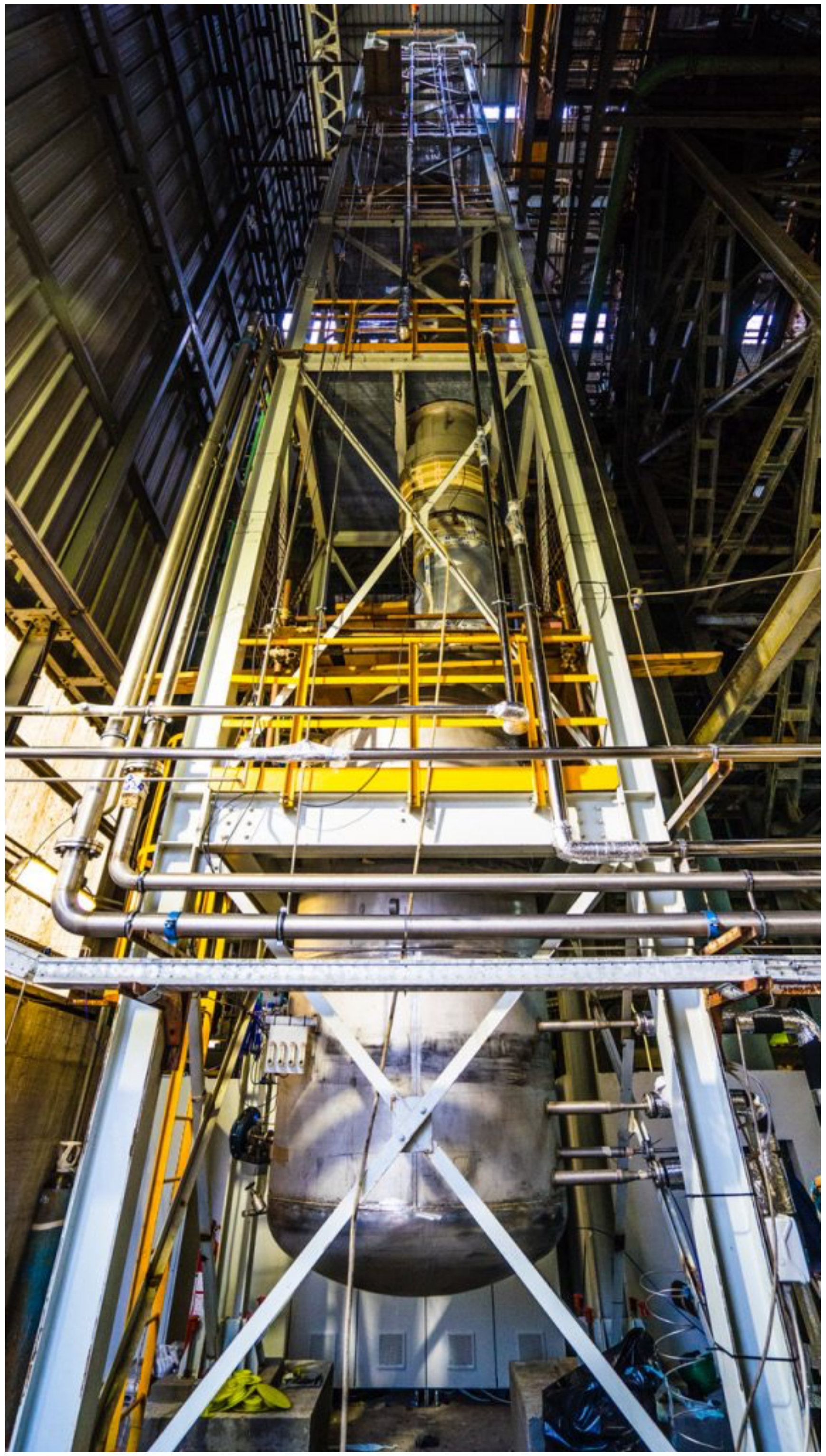
- If all else fails, clean
- Objectives are usually the removal of residual dust
- Typical techniques are ultrasonic cleaners, passivation, cleaning with alcohols
- Most extreme: DEAP resurfaced their acrylic vessel in-situ



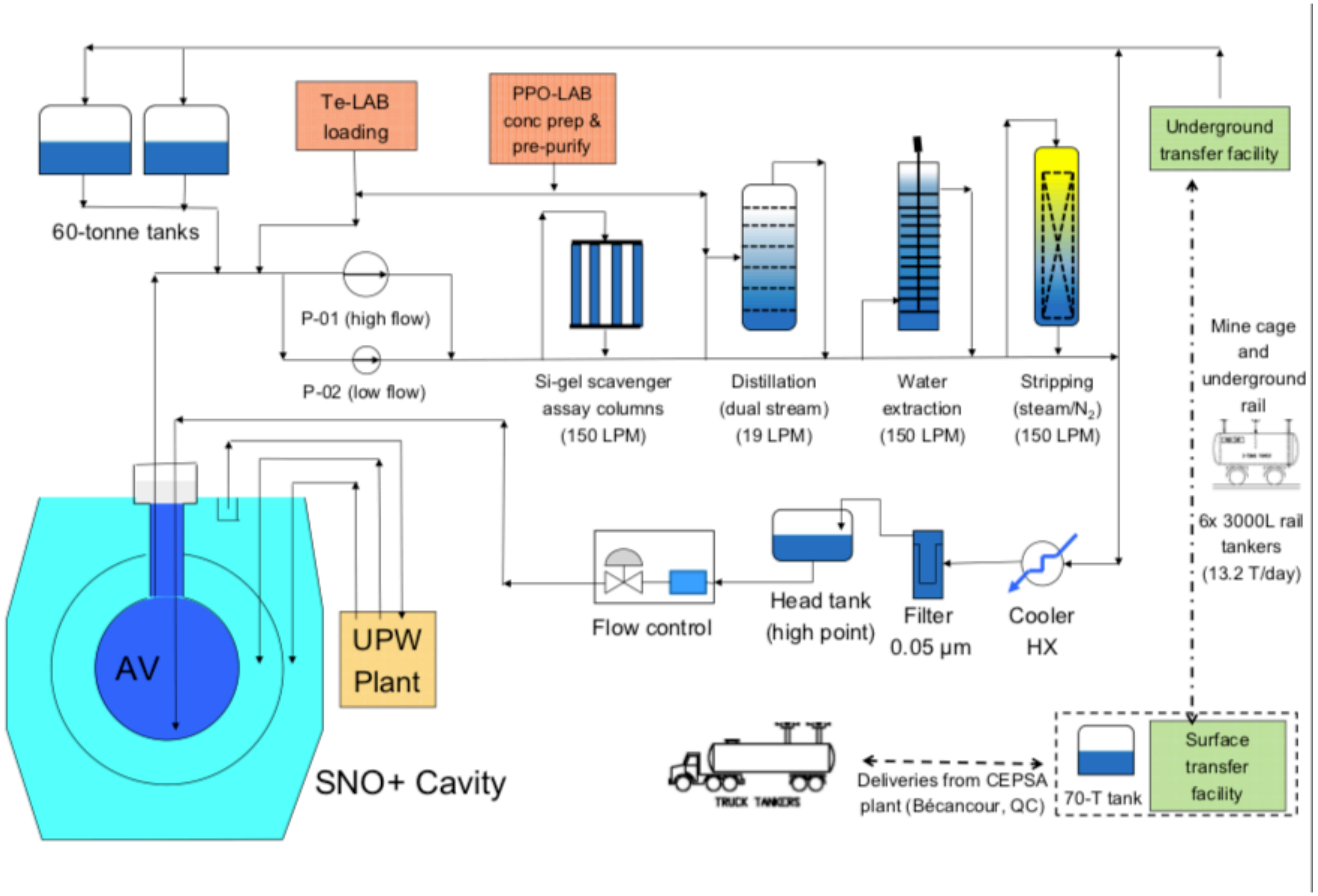
Elimination: Purification



- Materials must be purified before they're made into or put into a detector
- Example 1: Copper electroforming for MAJORANA
- Example 2: ^{39}Ar removal for DarkSide



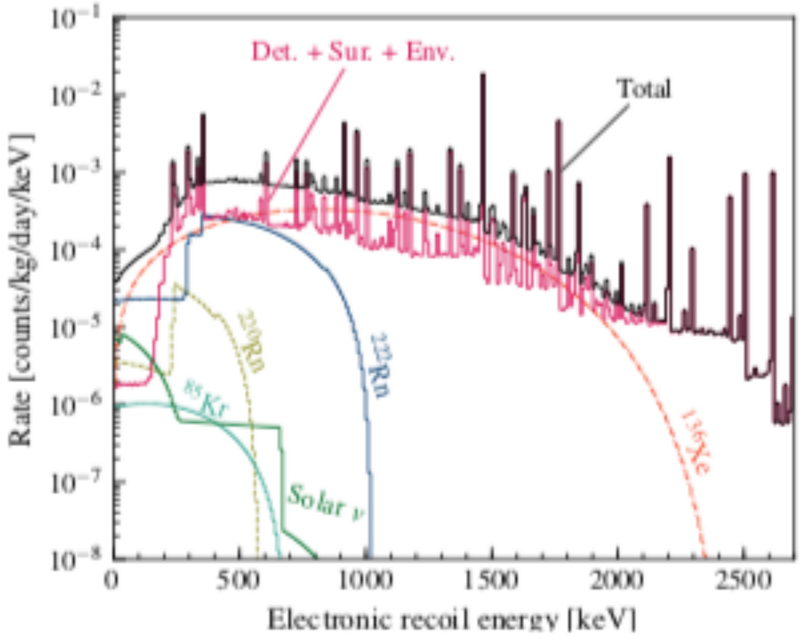
Elimination: Purification



- Any of the ‘liquid’ (water, scintillator, nobles) detectors have continuous purification of their material
- Necessary for backgrounds, but also for detector operation
- Considerable effort and expense for experiments!

Building a Background Model

- Take all your measurements and put it into GEANT (or other simulation!)
- Compare to data
- Panic! (It won't match)
- Profit!



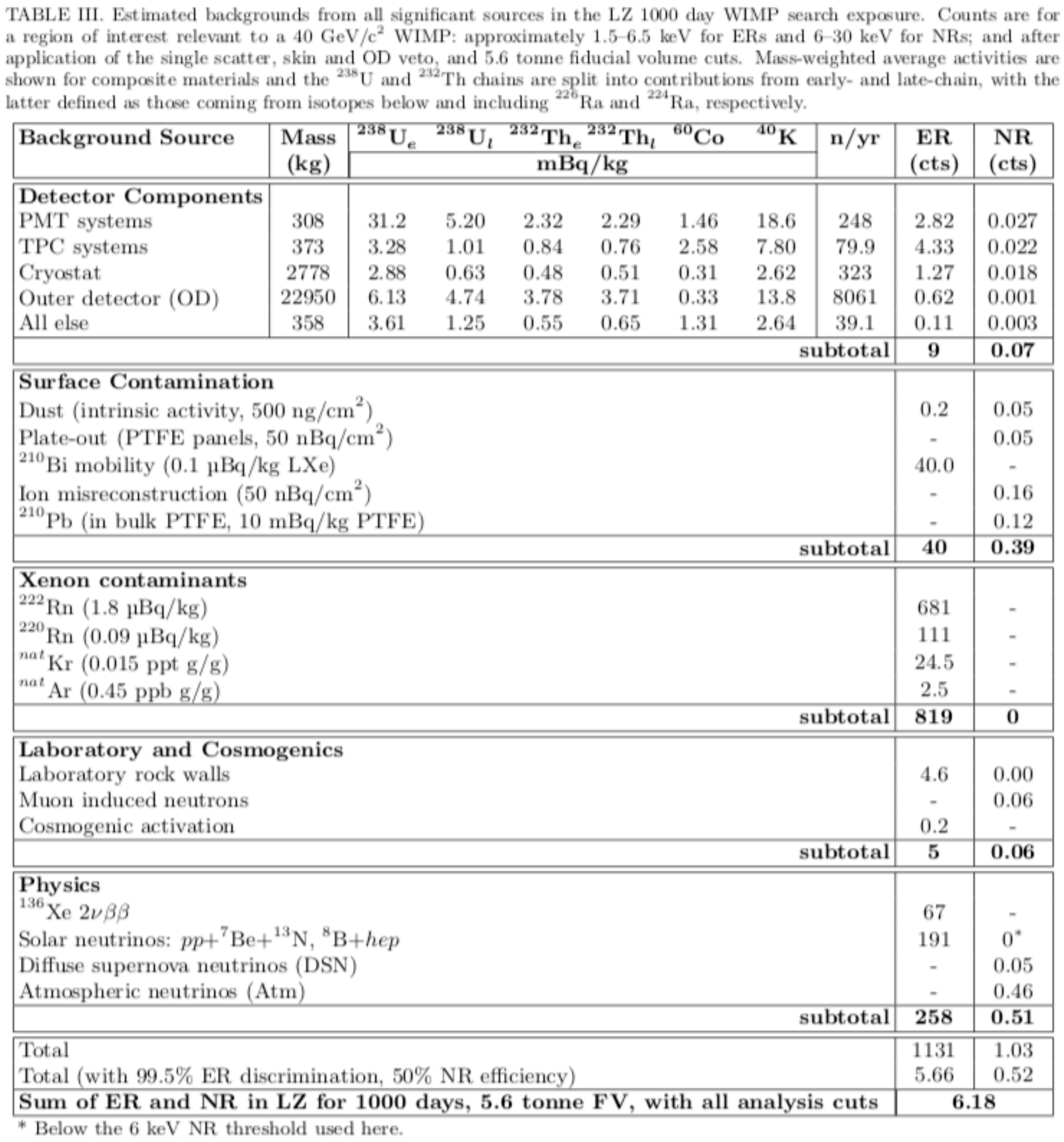


TABLE III. Estimated backgrounds from all significant sources in the LZ 1000 day WIMP search exposure. Counts are for a region of interest relevant to a 40 GeV/c^2 WIMP: approximately 1.5–6.5 keV for ERs and 6–30 keV for NRs; and after application of the single scatter, skin and OD veto, and 5.6 tonne fiducial volume cuts. Mass-weighted average activities are shown for composite materials and the ^{238}U and ^{232}Th chains are split into contributions from early- and late-chain, with the latter defined as those coming from isotopes below and including ^{226}Ra and ^{224}Ra, respectively.

Background Source	**Mass (kg)**	**^{238}U$_e$**	**^{238}U$_l$**	**^{232}Th$_e$**	**^{232}Th$_l$**	**^{60}Co**	**^{40}K**	**n/yr**	**ER (cts)**	**NR (cts)**
		mBq/kg								
Detector Components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector (OD)	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
All else	358	3.61	1.25	0.55	0.65	1.31	2.64	39.1	0.11	0.003
subtotal									**9**	**0.07**
Surface Contamination										
Dust (intrinsic activity, 500 ng/cm^2)									0.2	0.05
Plate-out (PTFE panels, 50 nBq/cm^2)									-	0.05
^{210}Bi mobility (0.1 µBq/kg LXe)									40.0	-
Ion misreconstruction (50 nBq/cm^2)									-	0.16
^{210}Pb (in bulk PTFE, 10 mBq/kg PTFE)									-	0.12
subtotal									**40**	**0.39**
Xenon contaminants										
^{222}Rn (1.8 µBq/kg)									681	-
^{220}Rn (0.09 µBq/kg)									111	-
^{nat}Kr (0.015 ppt g/g)									24.5	-
^{nat}Ar (0.45 ppb g/g)									2.5	-
subtotal									**819**	**0**
Laboratory and Cosmogenics										
Laboratory rock walls									4.6	0.00
Muon induced neutrons									-	0.06
Cosmogenic activation									0.2	-
subtotal									**5**	**0.06**
Physics										
^{136}Xe $2\nu\beta\beta$									67	-
Solar neutrinos: pp+^{7}Be+^{13}N, ^{8}B+hep									191	0*
Diffuse supernova neutrinos (DSN)									-	0.05
Atmospheric neutrinos (Atm)									-	0.46
subtotal									**258**	**0.51**
Total									1131	1.03
Total (with 99.5% ER discrimination, 50% NR efficiency)									5.66	0.52
Sum of ER and NR in LZ for 1000 days, 5.6 tonne FV, with all analysis cuts									**6.18**	

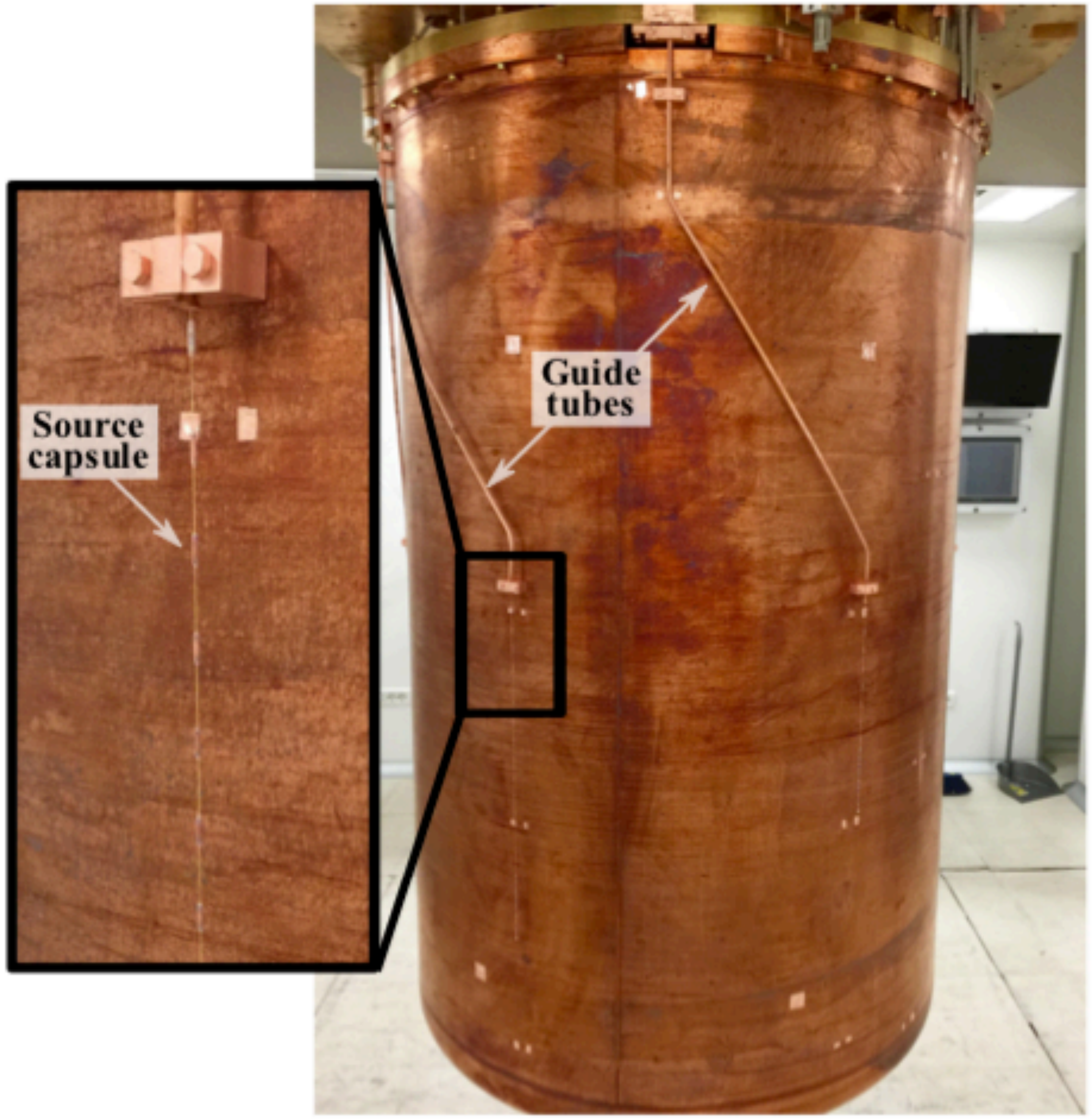
* Below the 6 keV NR threshold used here.

https://arxiv.org/pdf/1802.06039.pdf

Calibration

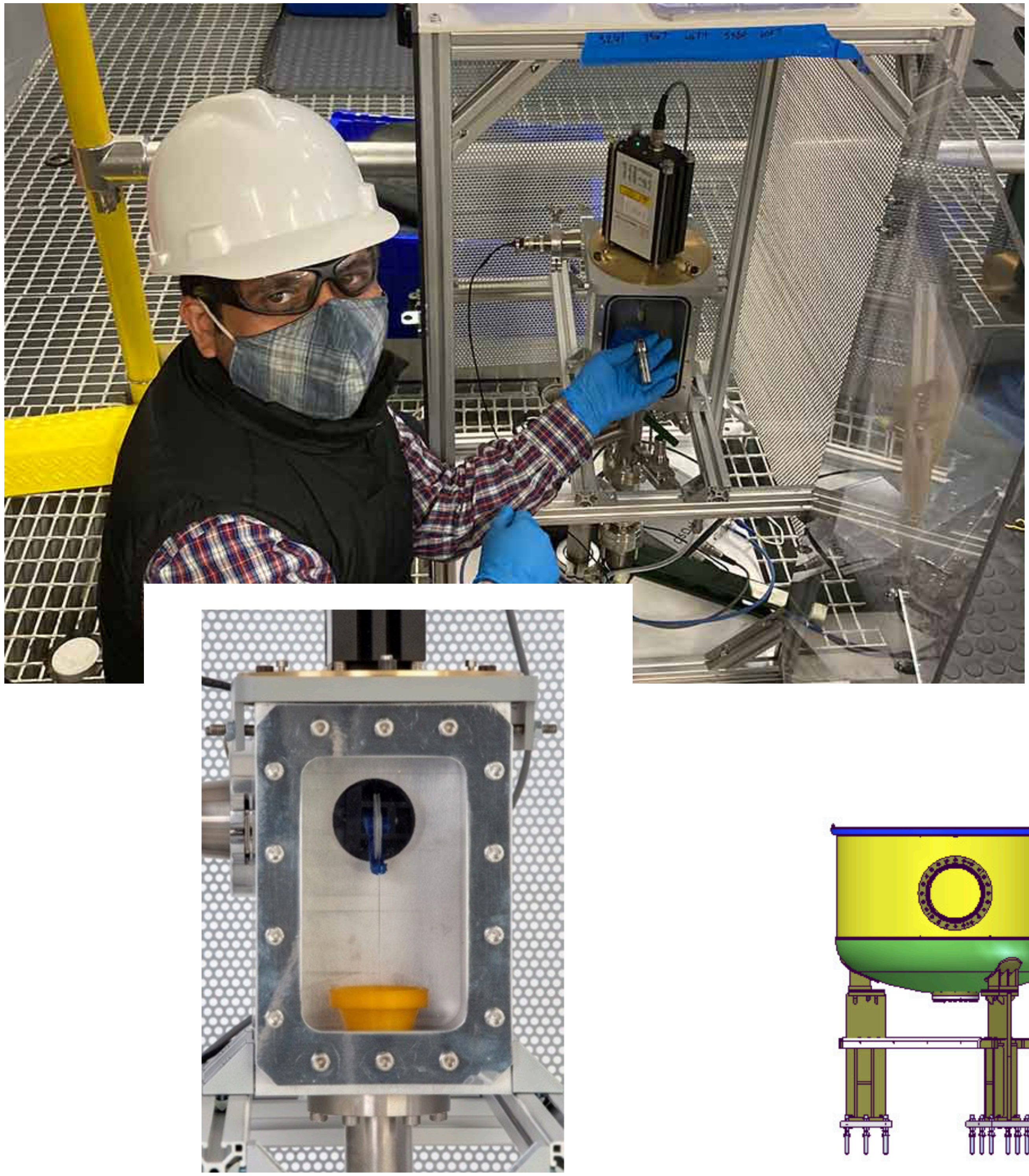
Or, when there's nothing in your detector, how can you tell what's happening?

Positional Sources

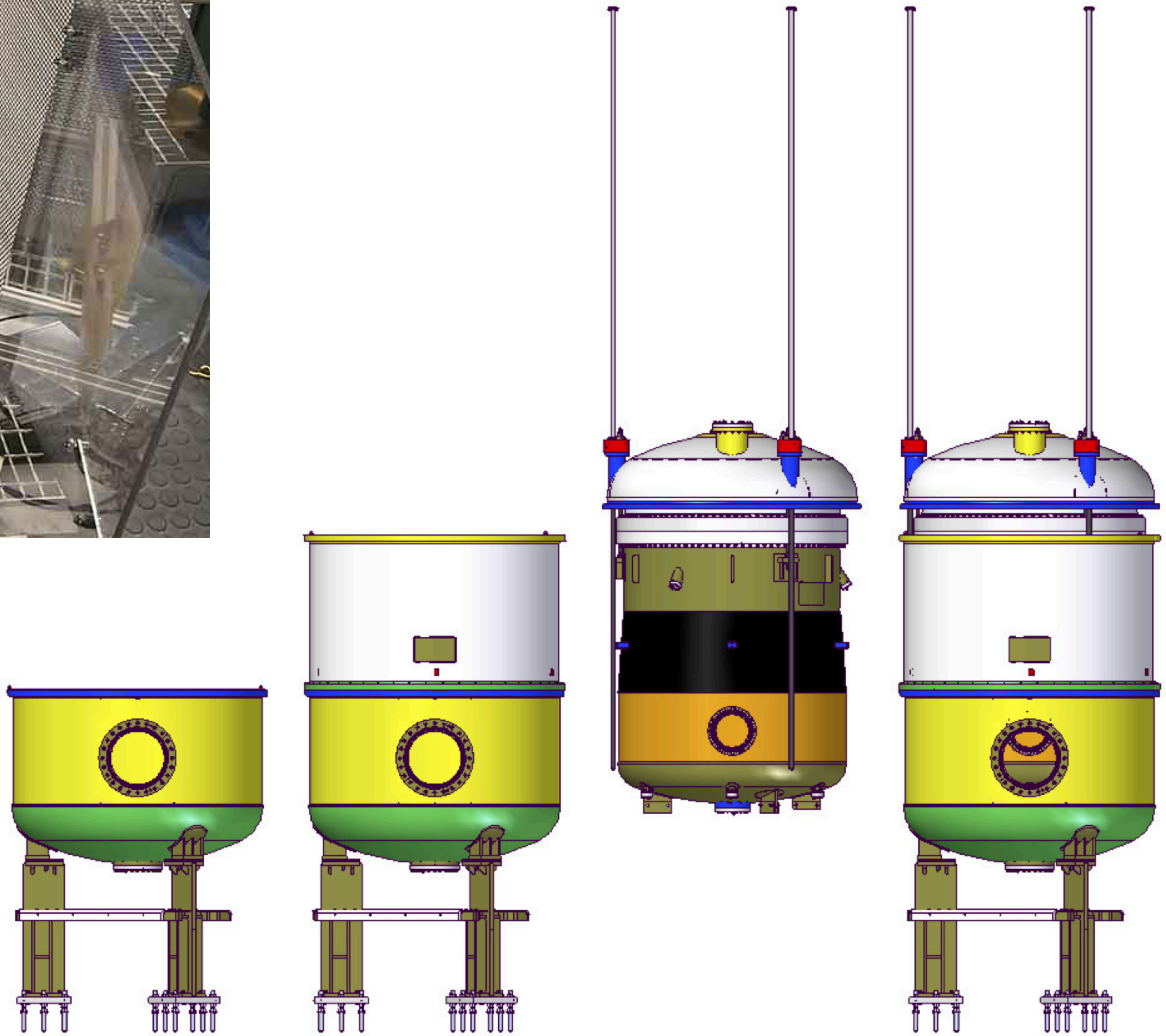


- Most experiments have a system where you can insert a source next to the detector
- Popular sources include ^{22}Na, ^{60}Co, ^{228}Th, AmBe, and many others
- Difficult to get to the center of highly self-shielded experiments!

Positional Sources

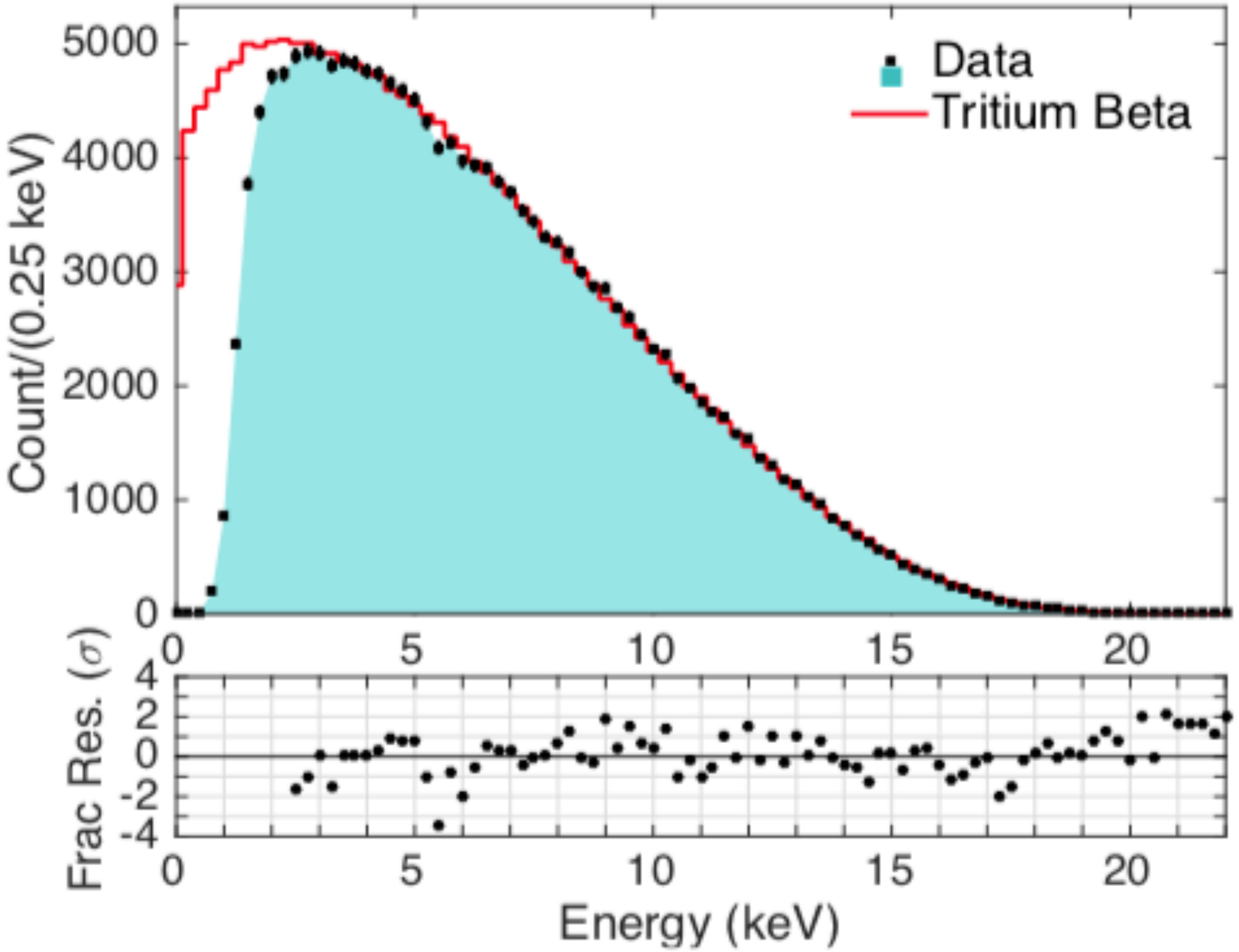


Close-up of part of the CSD system showing the CSD chamber with its deployment mechanics

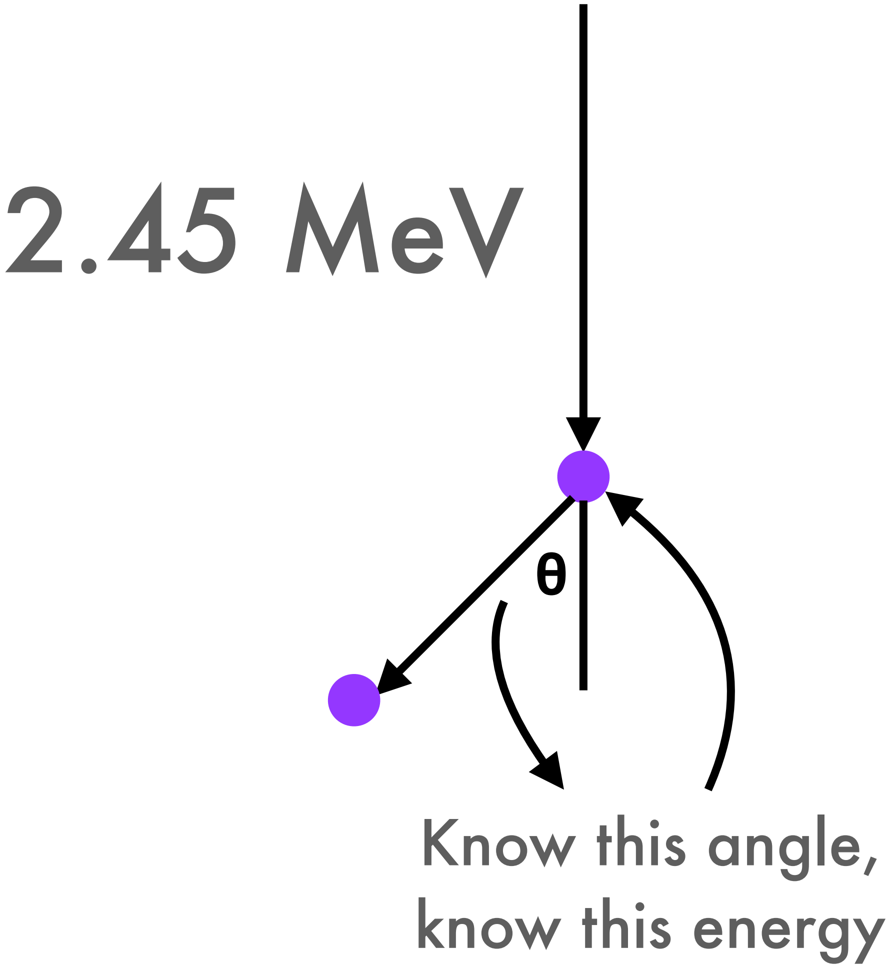


Bulk Sources

- Some liquid experiments introduce bulk sources
- Either short lifetime or easy to purify or both!
- ^{39}Ar is naturally present for Ar experiments



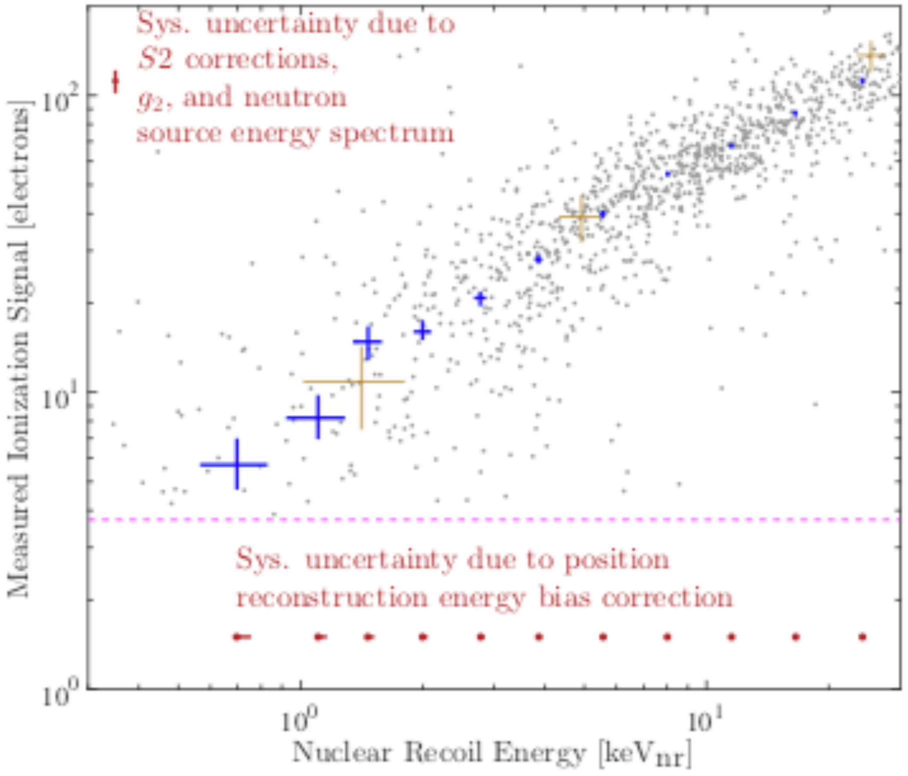
D-D Sources


2.45 MeV

θ

Know this angle, know this energy

- Deuterium-Deuterium interactions create monoenergetic neutrons
- Use multiple scatter to understand precise energy deposition



Using What's Left

- Many experiments also use everything that is left
- Stability monitoring
- Development of background models

Summary

- There's a huge variety of low-background experiments pursuing a wide variety of physics goals
- Careful measurement, prevention and elimination of natural radioactivity is necessary for their success
- Careful calibration uses removable sources and remaining background to build a model of detector operation