Dark matter search with DEAP-3600

Dr. Tina Pollmann
for the DEAP collaboration
MPP Colloquium
Nov 5th 2019

The DEAP collaboration. ~90 researchers from Canada, UK, Mexico, Germany, Russia, Italy, Spain

DEAP 3600

UNIVERSITY OF ALBERTA

Laurentian University
Université Laurentienne

SNOLAB

INFN
Istituto Nazionale di Fisica Nucleare

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

Queen's UNIVERSITY

US
University of Sussex

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

Carleton UNIVERSITY

ROYAL HOLLOWAY UNIVERSITY OF LONDON

TRIUMF

PRINCETON UNIVERSITY

Technical University of Munich
TUM

iF
Instituto de Física

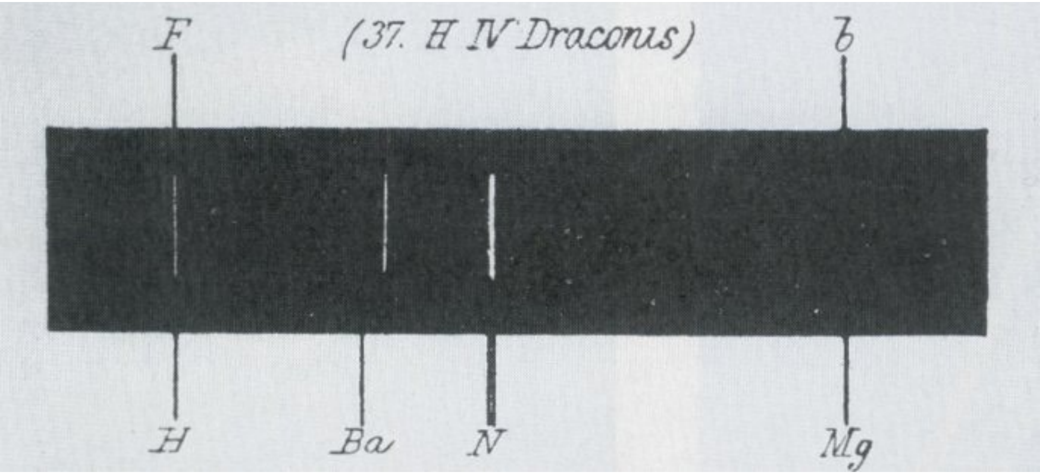
Particle Physics
Rutherford Appleton Laboratory

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat

Overview

- The Dark Matter problem and challenges in direct detection of Dark Matter
- The DEAP-3600 detector
  - Design and construction
    - Material screening
    - Radio-clean construction
    - Passive shielding
    - Active shielding (veto)
    - Particle identification
  - Results

160 years ago, the Huggins' discovery of stellar spectra lines gave foundation to the idea that objects throughout the universe are governed by the same physical laws and types of matter we find on earth.



http://stars.astro.illinois.edu/sow/n6543.html#spec

Historic spectrum of NGC 6543 (Cat's Eye Nebula)

William and Margaret Huggins

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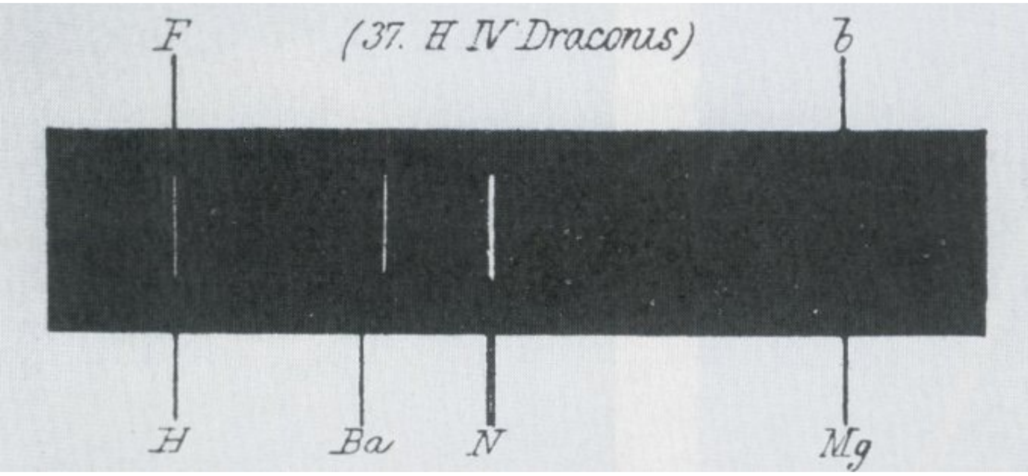

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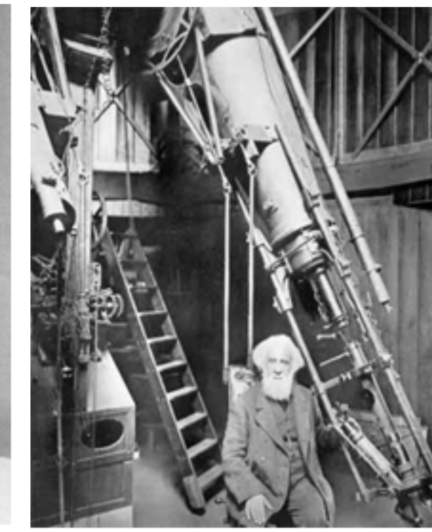
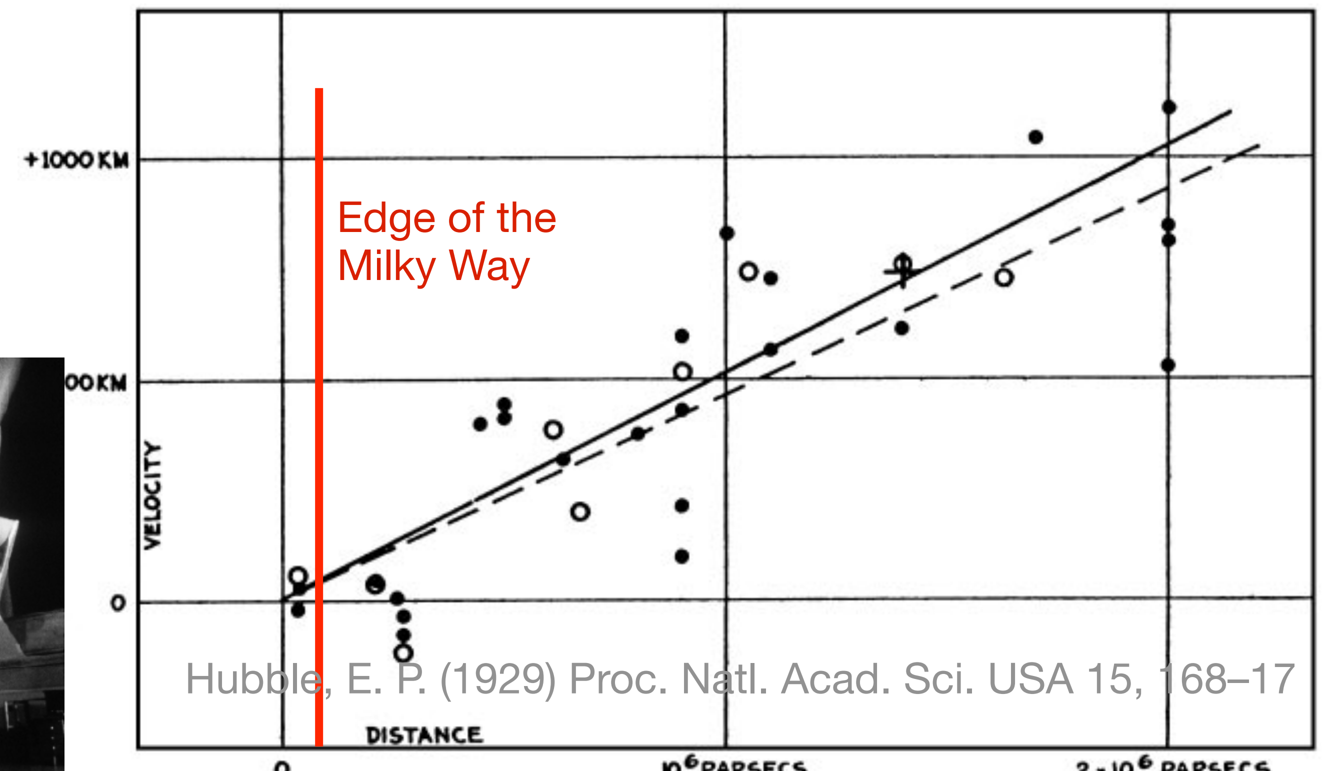


William and Margaret Huggins

90 years ago, numerous observations led to the then shocking conclusion that the universe was much bigger than our own galaxy, and that the universe is expanding

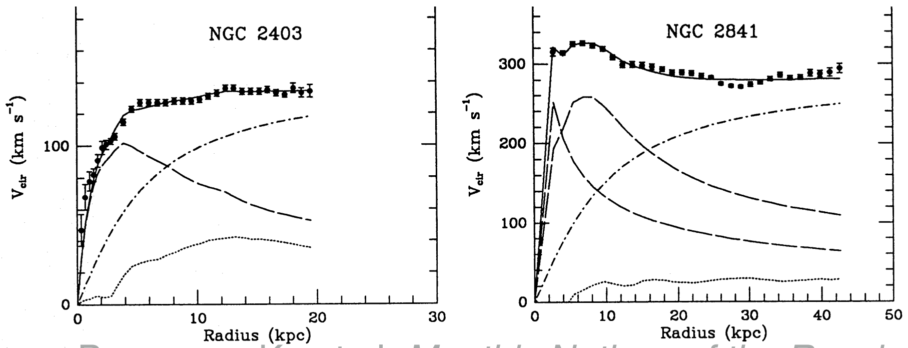
"The great spirals, with their enormous radial velocities and insensible proper motions, apparently lie outside our Solar system."

- Edwin Hubble, 1920



Hubble, E. P. (1929) Proc. Natl. Acad. Sci. USA 15, 168–17

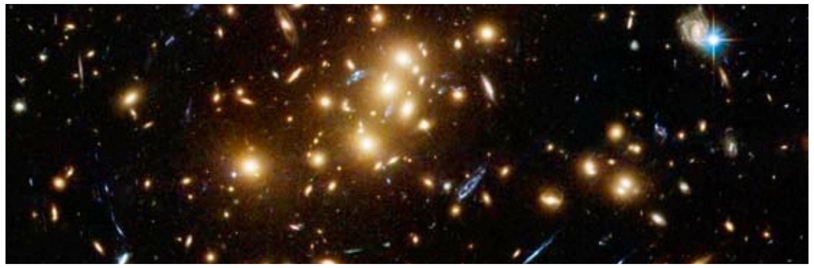
But observations quickly showed that some objects do not behave as predicted by our physical laws.



Begeman, K., et al. *Monthly Notices of the Royal Astronomical Society* **249,** 523–537 (1991).

Galactic rotation curves

Velocity of galaxies in clusters

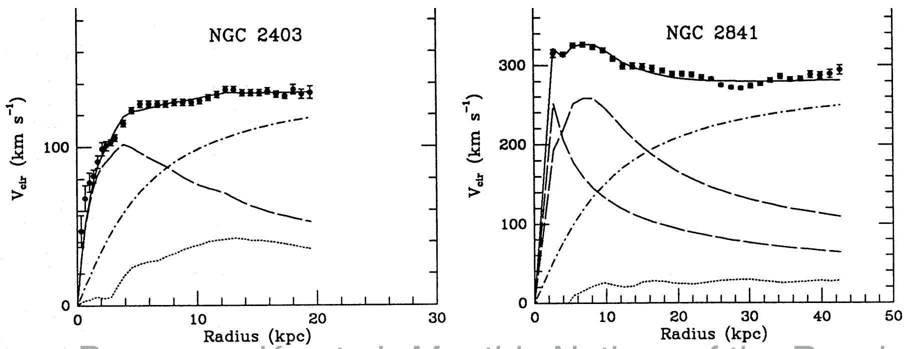


Hubble telescope image archive

"In a spiral galaxy, the ratio of dark-to-light matter is about a factor of ten. That's probably a good number for the ratio of our ignorance-to-knowledge."

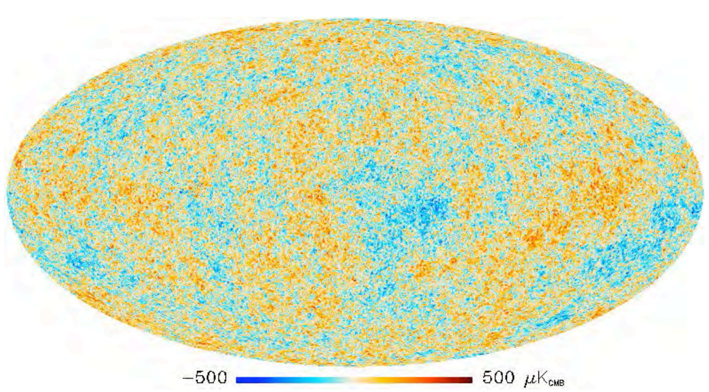
- Vera Rubin

And we kept finding objects whose motion does not follow the predicted path.



Begeman, K., et al. *Monthly Notices of the Royal Astronomical Society* **249,** 523–537 (1991).

NASA/CXC/CfA/M.Markevitch et al.; NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.; NASA/STScI; Magellan/U.Arizona/D.Clowe et al



Larson, D. et al. The Astrophysical Journal Supplement 192, 16 (2011).

Galactic rotation curves

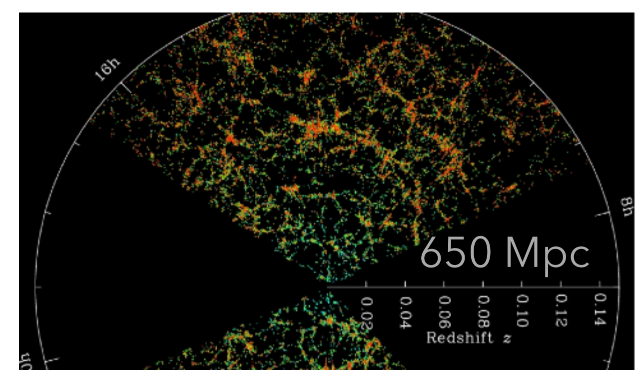
Velocity of galaxies in clusters

Lensing/microlensing

Structure formation in the universe

Cosmic microwave background

Hubble telescope image archive



Sloan Digital Sky Survey

What do we make of the fact that some objects do not move as we expect them to?

Options:

a) Our physical laws are not universal

b) Our physical laws are not correct for large distances (but are still universal)

c) There are particles and forces we have not observed yet

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Experimentally ruled out to large precision

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Possible, but cannot explain all observations

Most simple explanation for all effects. (And historically the right one)

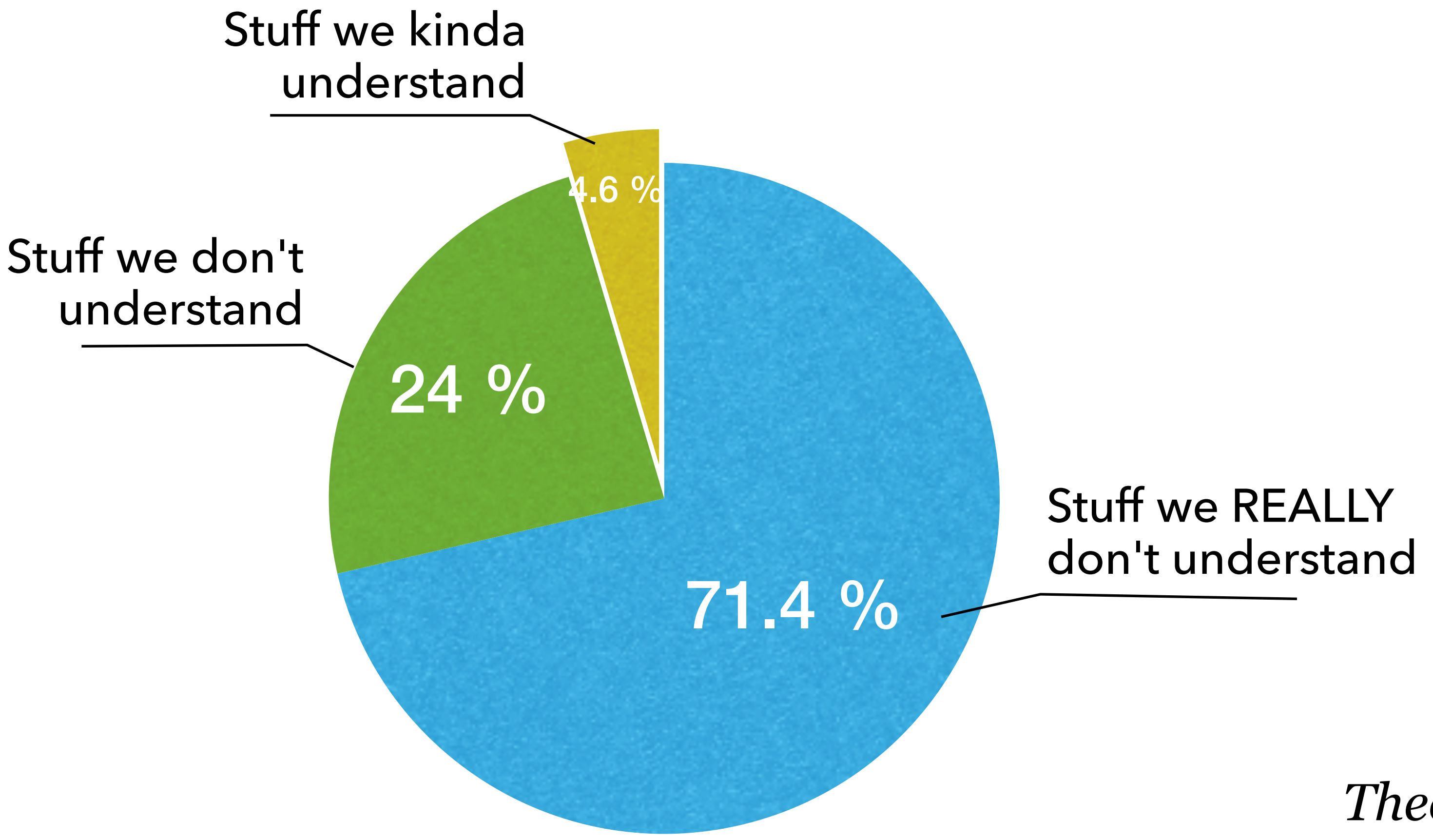
What do we make of the fact that some objects do not behave as we expect them to?

Options:

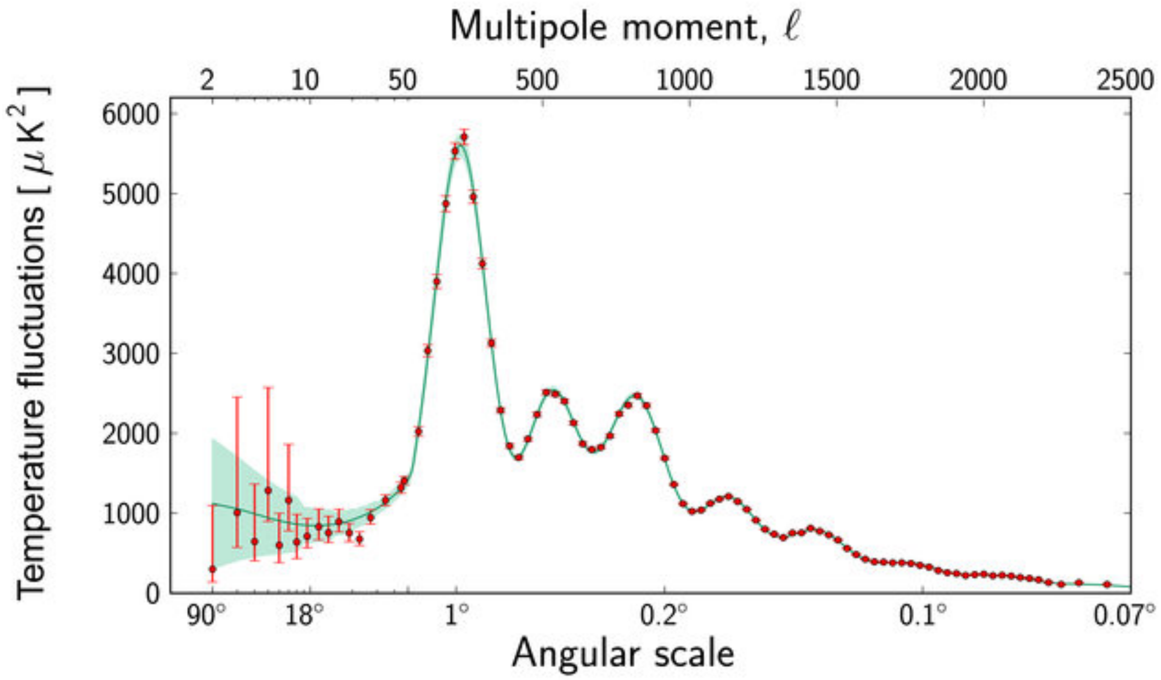
a) Our physical laws are not universal — *Experimentally ruled out to large precision*

b) Our physical laws are not correct for large distances (but are still universal) — *Possible, but cannot explain all observations*

c) There are particles and forces we have not observed yet — *Most simple explanation for all effects (and historically the right one)*



Adapted from Renée Spiewak



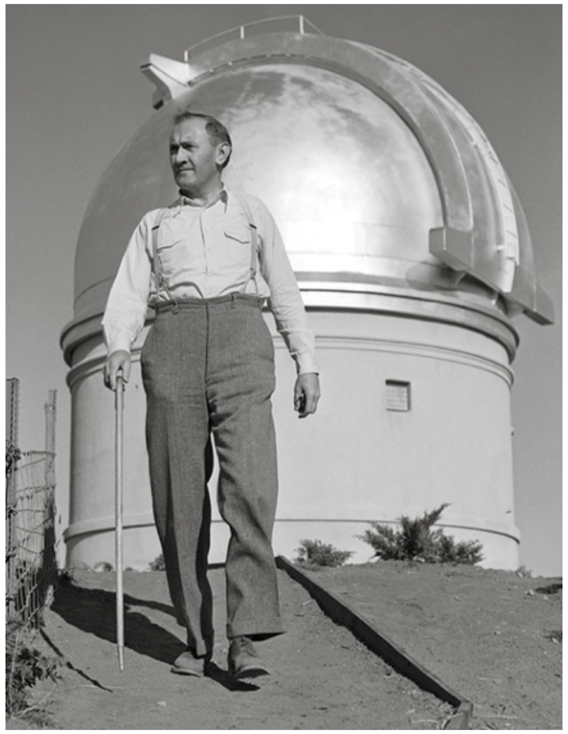
"There should be a more friendly name than ΛCDM […] I recommend the simple name "Double Dark Theory" for the modern cosmological standard model."
- Joel R. Primack

If we posit that a new particle is the solution to the problem, we should try to detect it in a manner more direct than through its gravitational pull.

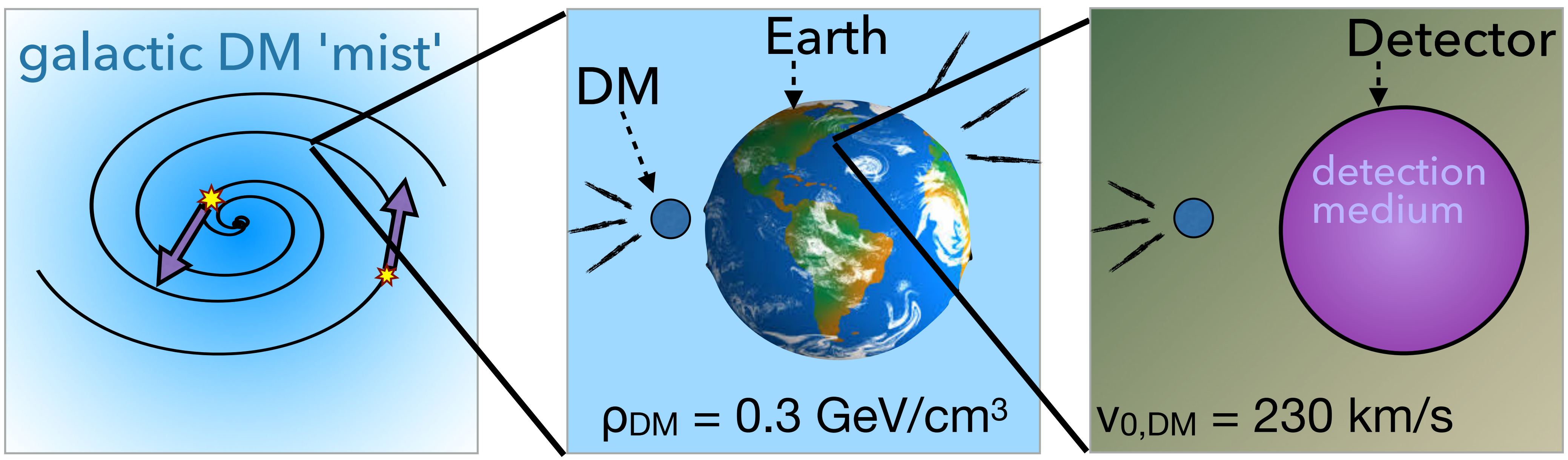
Direct detection of DM particles from our galactic halo scattering in a teresstrial detector

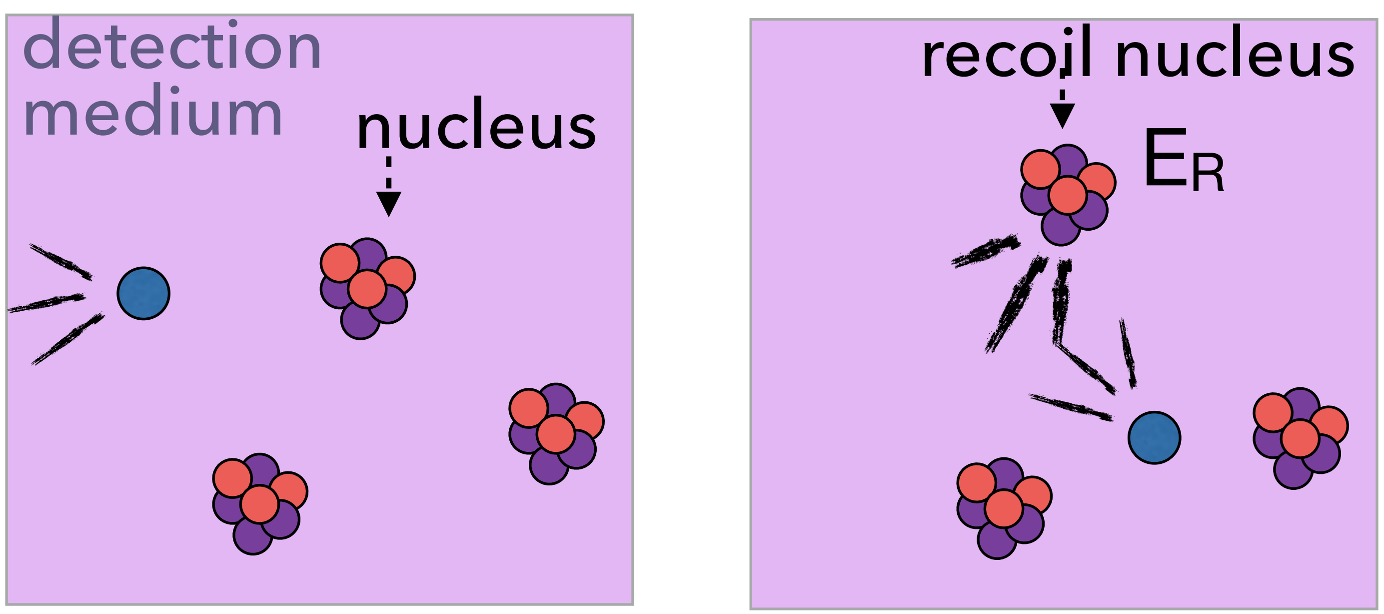
"I soon became convinced [...] that all the theorizing would be empty brain exercise and therefore a waste of time unless one first ascertained what the population of the universe really consists of. "

- Fritz Zwicky



Direct dark matter searches look for nuclear recoils in response to elastic scattering of a dark matter particle on a detector nucleus.





The signal we look for is a nuclear recoil.

These don't travel far so target == detector.

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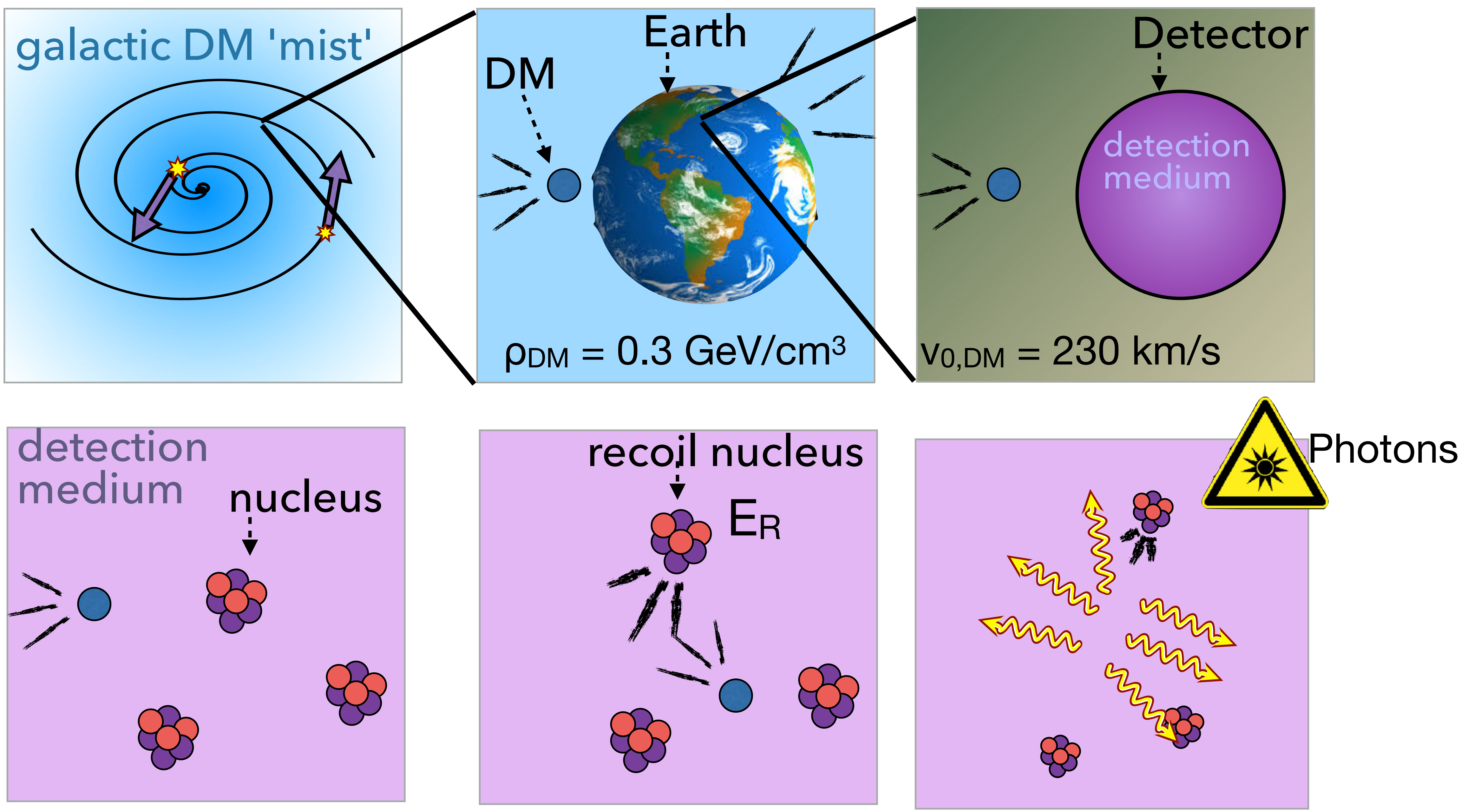
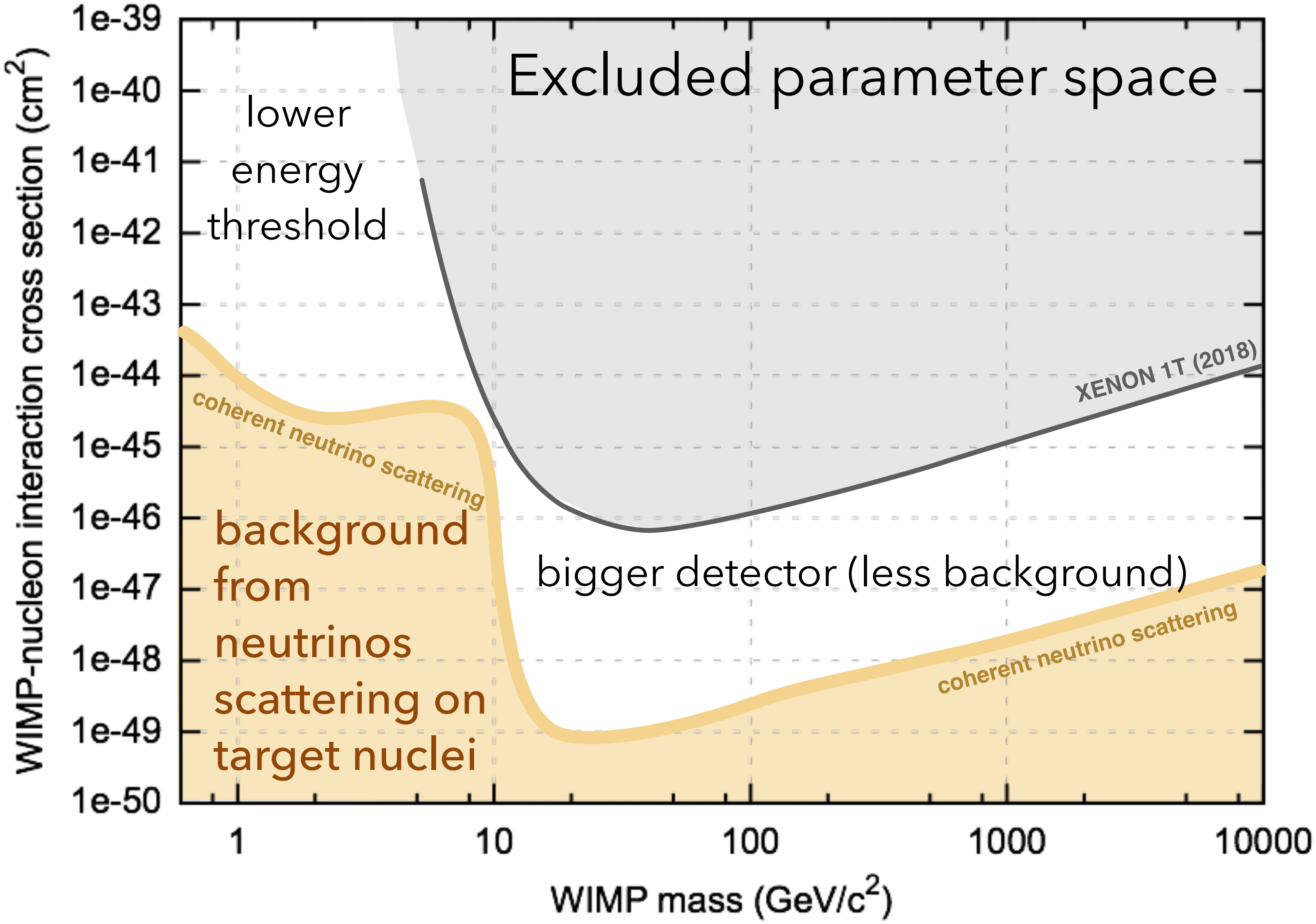


Challenge in direct detection: 1) to cover more parameter space, extreme measures must be taken to reduce backgrounds from known particles.



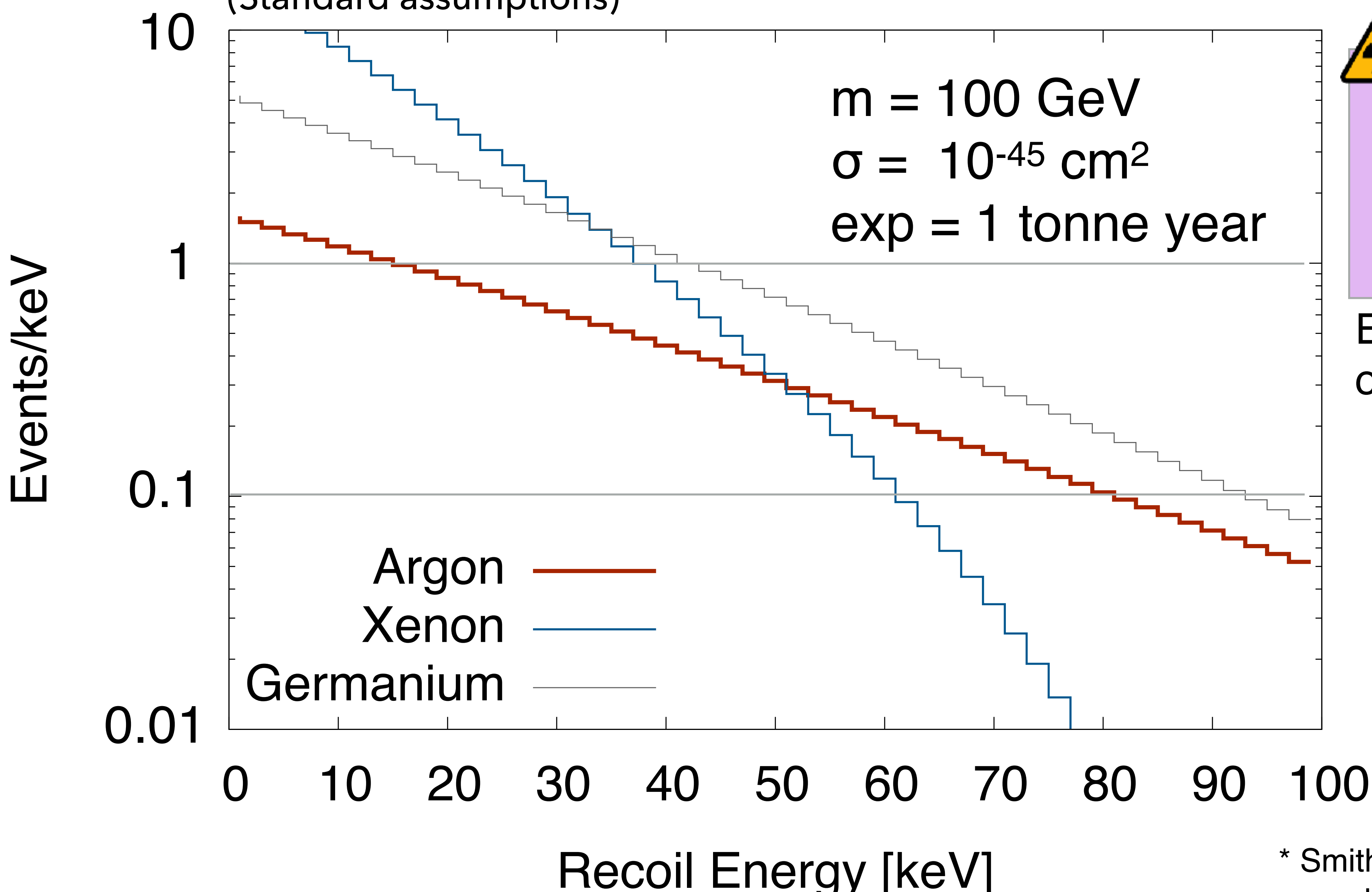
Interaction	Cross section [cm^2]
electron/muon/ photon - argon	1e-19 to 1e-15
neutron - argon	1e-24 to 1e-22
neutrino-nucleon	1e-38 to 1e-35
WIMP-nucleon (SD)	< 1e-42
WIMP-nucleon (SI)	<1e-46

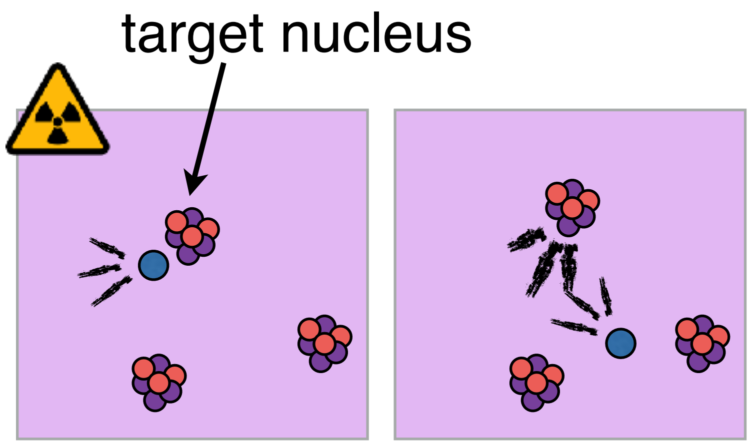
rough estimates

Challenge in direct detection: 2) small signal rates and low energies

Differential 'WIMP' dark matter recoil spectrum.

(Standard assumptions)*

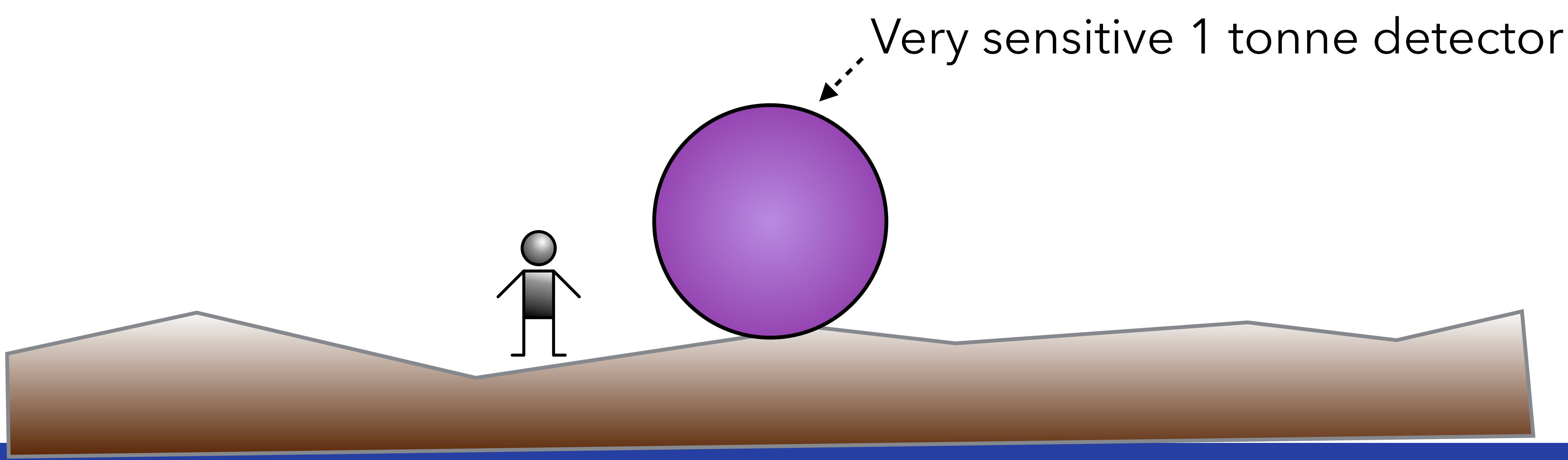


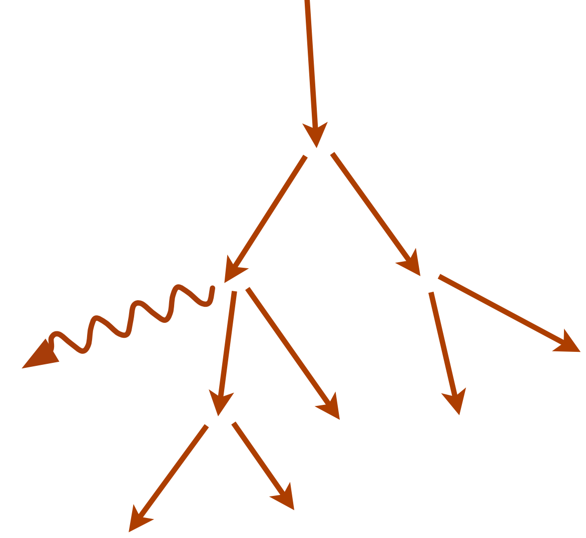


Elastic scattering of WIMP on target nucleus

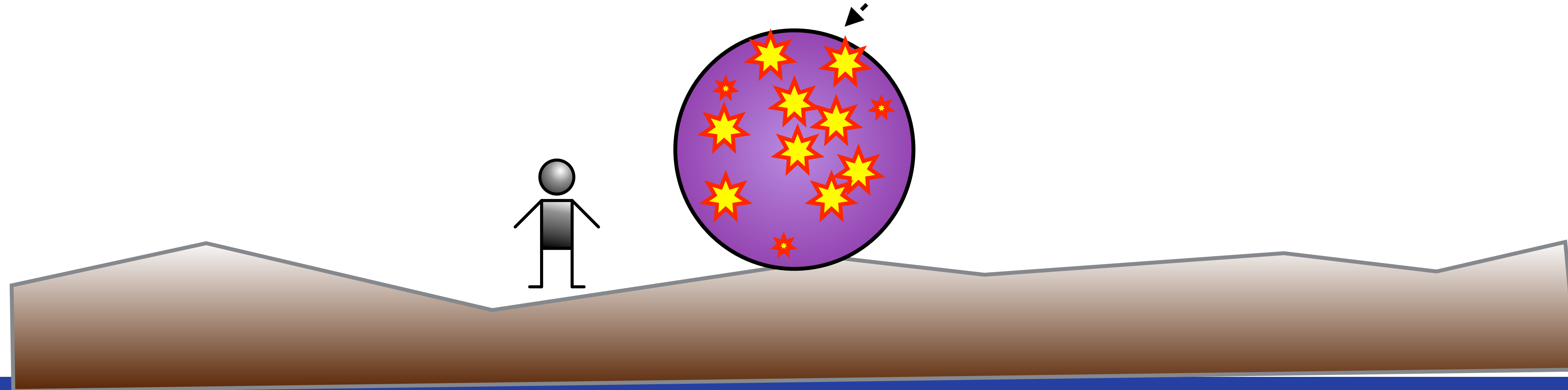
* Smith, P. F., & Lewin, J. D. (1990). Dark matter detection. *Physics Reports*, *187*(5).

	Particles passing through detector [1/s]	Signals in the detector.
Dark matter	10^6 - 10^{12}	< 1/month

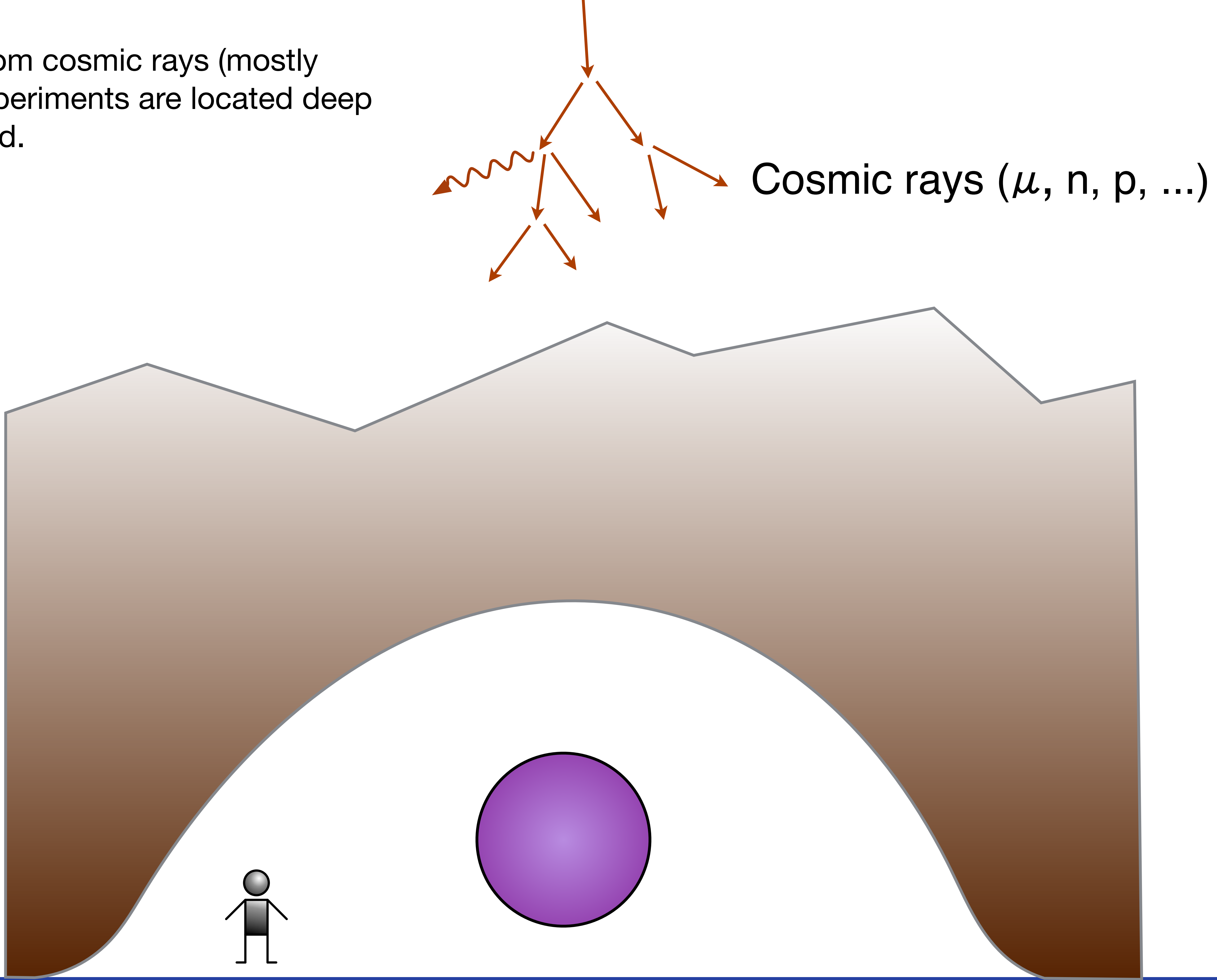




	Particles passing through detector [1/s]	Signals in the detector.
Dark matter	10^6 - 10^{12}	< 1/month
Muons	10^5	~10^5/second



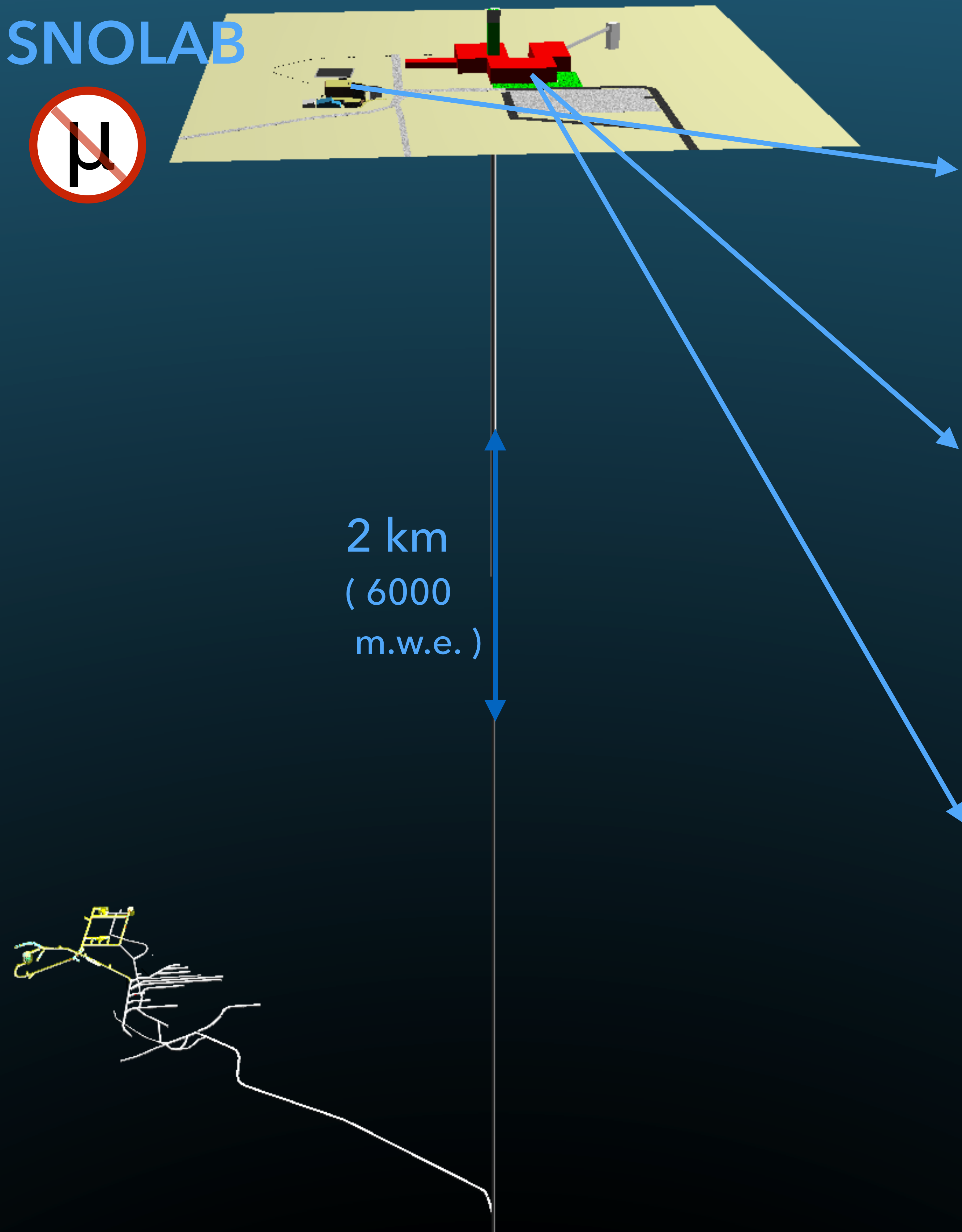
To shield from cosmic rays (mostly muons), experiments are located deep underground.



To shield against cosmic radiation, the DEAP-3600 detector is located 2 km underground at the SNOLAB research facility.

5:50am, ready to go underground.

SNOLAB

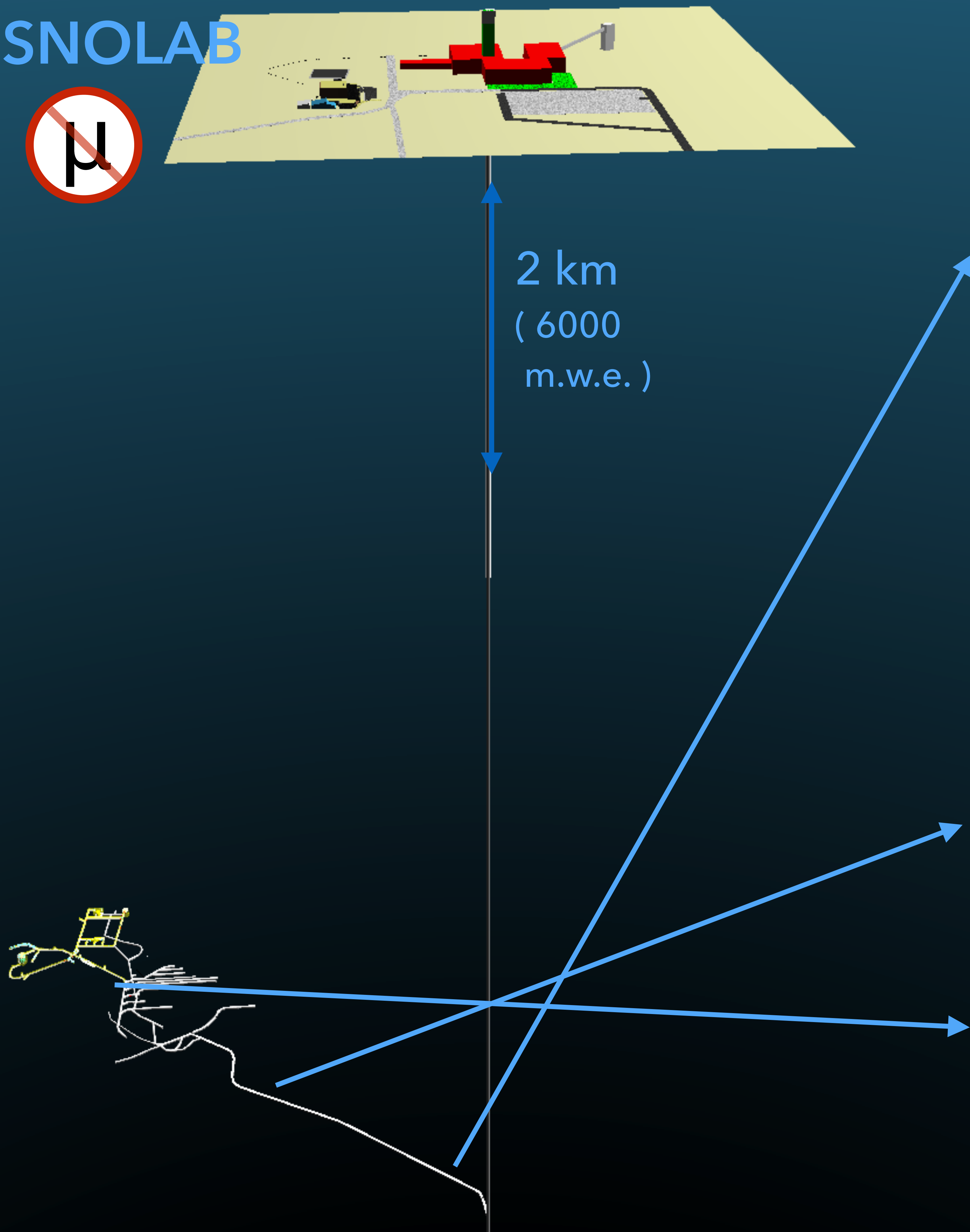


Surface facility.

Waiting for the cage.

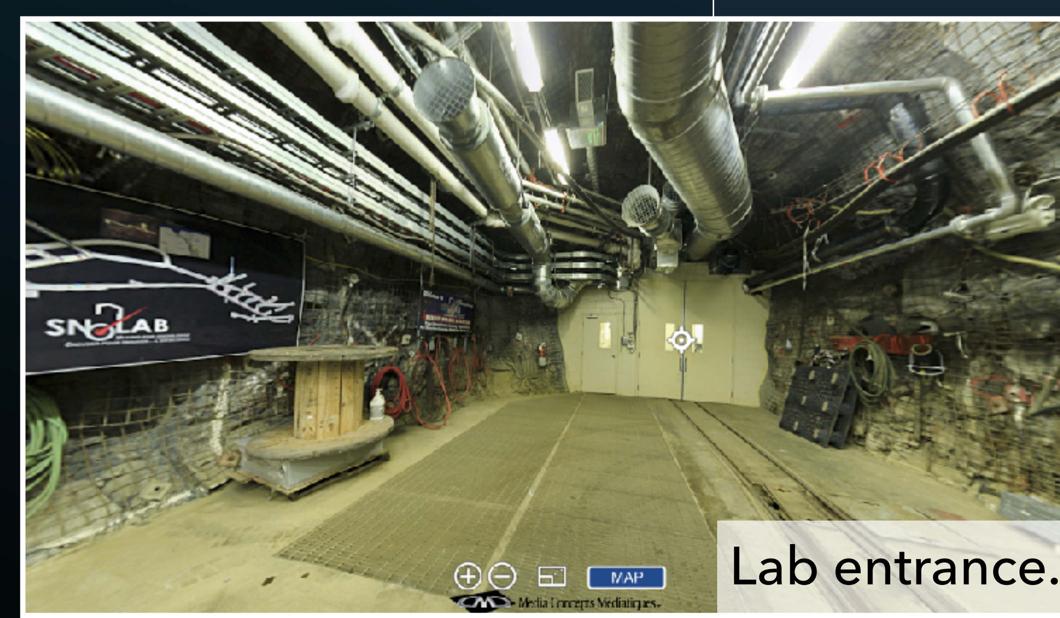
Surface shaft station.

SNOLAB

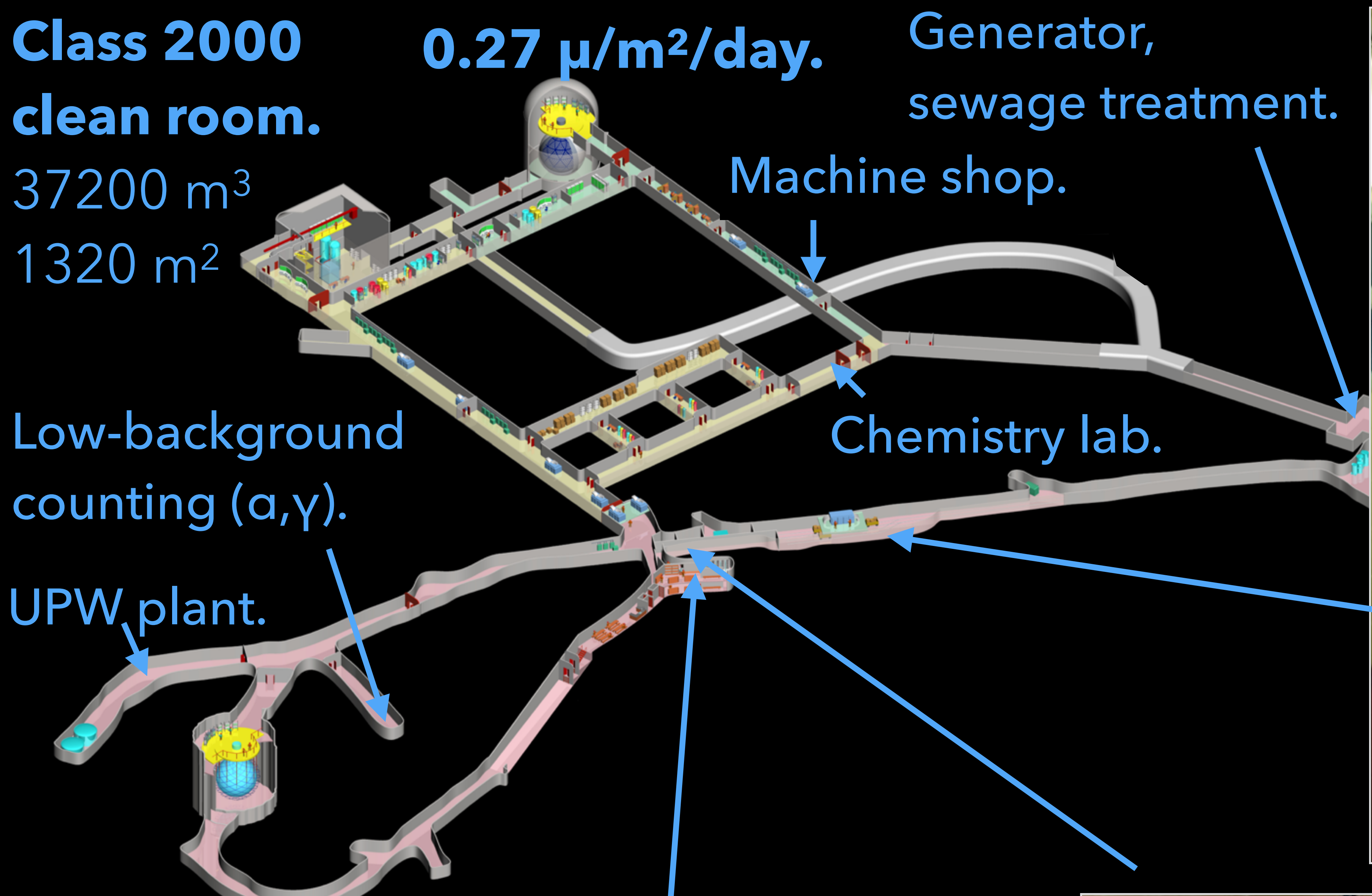


Underground tunnels.

Underground tunnels.



Lab entrance.

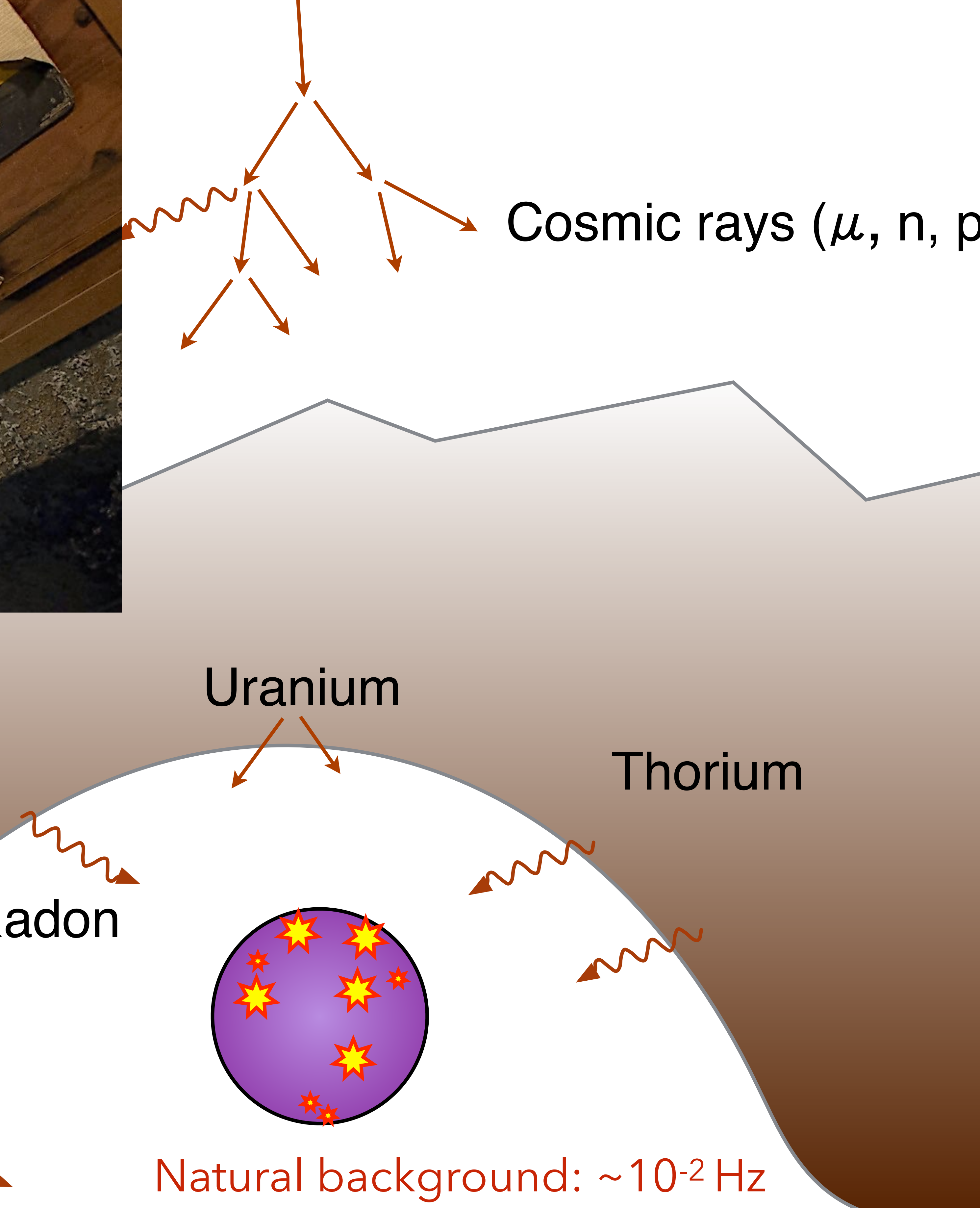

Class 2000
clean room.
37200 m³
1320 m²
0.27 μ/m²/day.
Generator,
sewage treatment.
Machine shop.
Chemistry lab.
Low-background
counting (α,γ).
UPW plant.


"Dirty" side of lab.


"Clean" side of lab. Lunch room.


Showers.

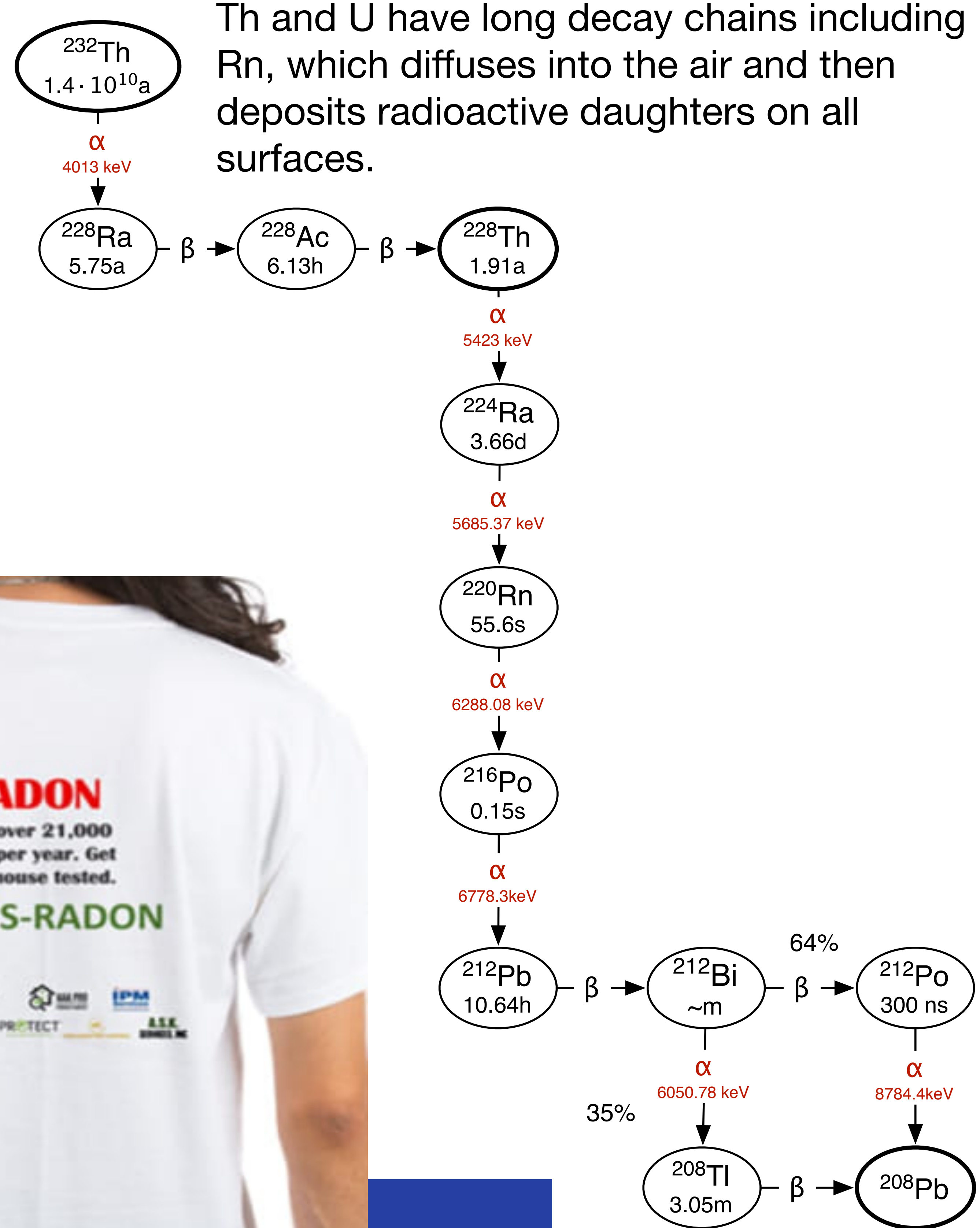
Elaborate shielding and material cleaning is necessary to reduce background from radioactive isotopes near the detector.

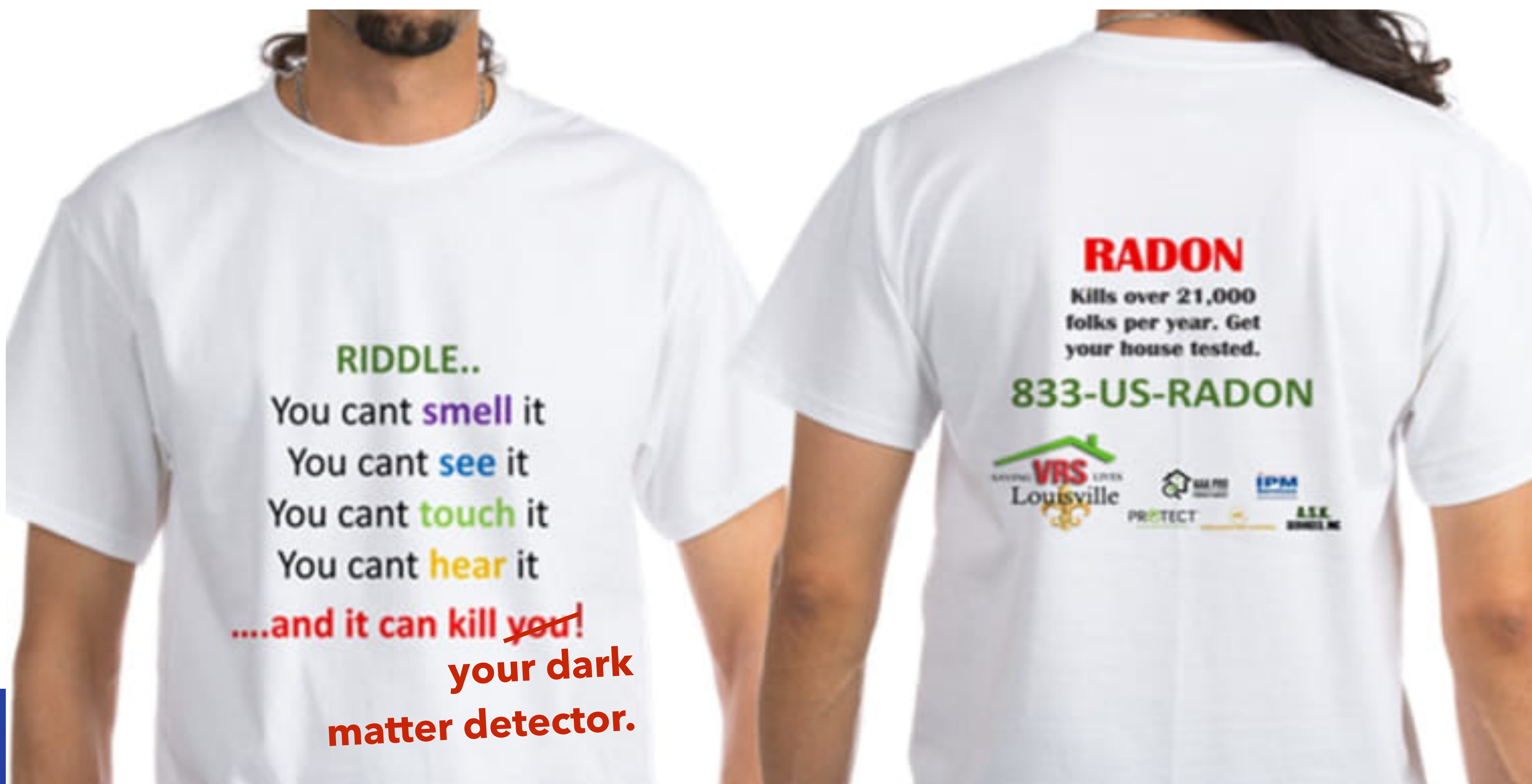


Radioactive isotopes are everywhere and in everything.

Primordial isotopes and their daughters:
Mostly Th-232, U-238, U-235, and K-40

Th and U have long decay chains including Rn, which diffuses into the air and then deposits radioactive daughters on all surfaces.





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Cosmogenic (cosmic ray activation)
E.g.: Ar-39, C-14

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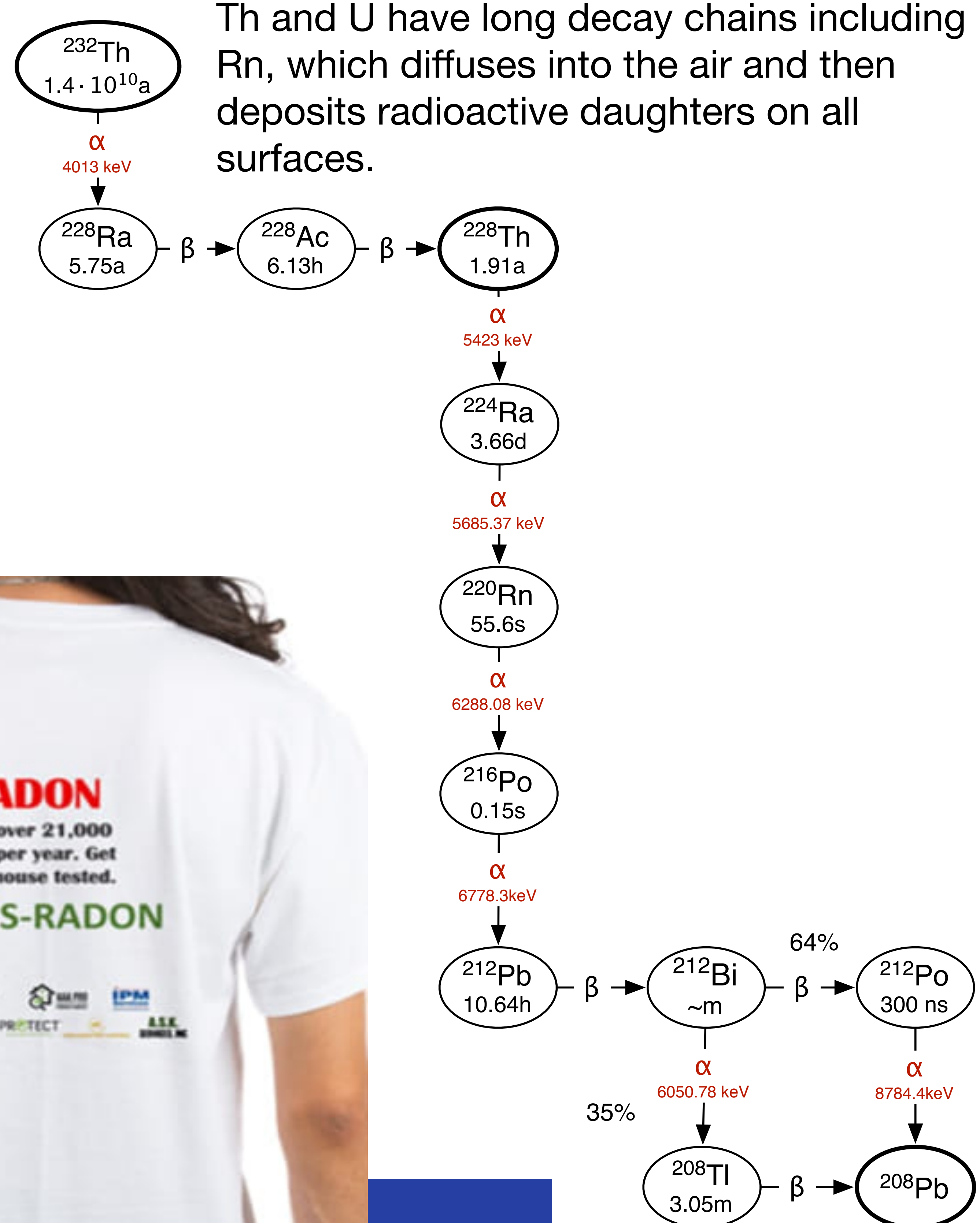

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Primordial isotopes and their daughters:
Mostly Th-232, U-238, U-235, and K-40

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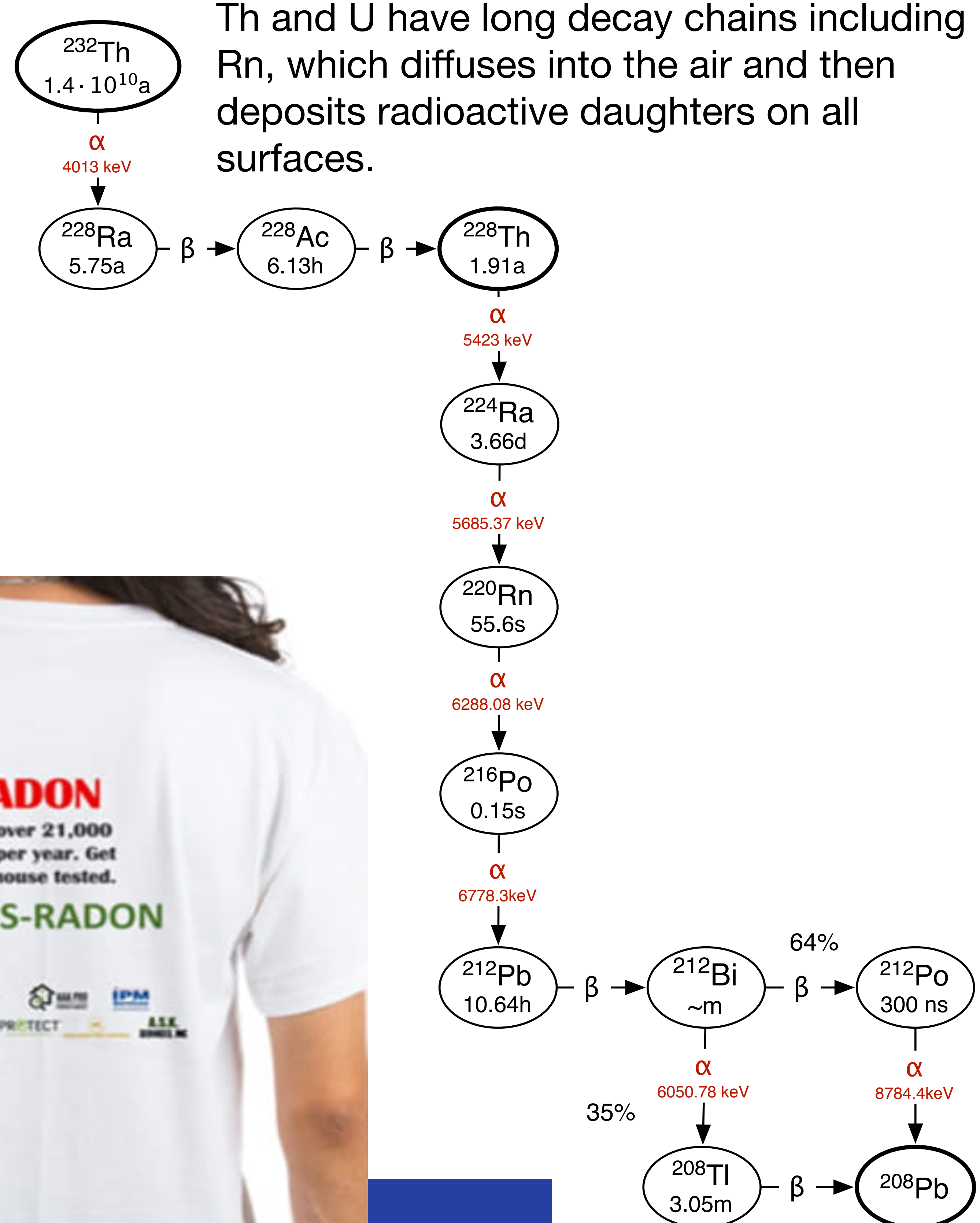
E.g.: Ar-39, C-14

Anthropogenic (man made)
E.g.: Cs-137, I-129

Th and U have long decay chains including Rn, which diffuses into the air and then deposits radioactive daughters on all surfaces.



Mitigation:

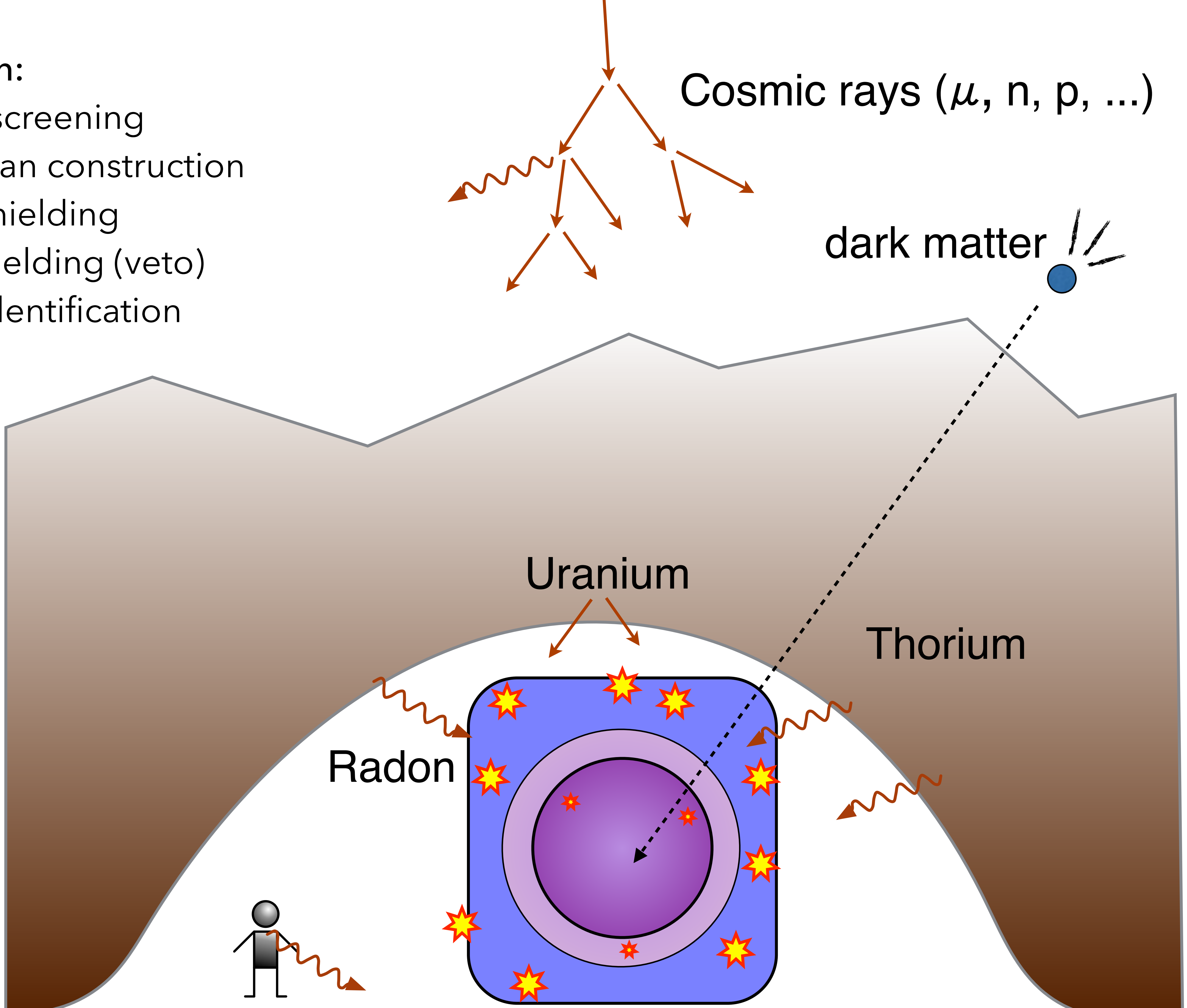
Material screening

Radio-clean construction

Passive shielding

Active shielding (veto)

Particle identification



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All materials used are screened for concentration of radioactive isotopes, and for rate of radon emanation. If the levels are not low enough, as determined from simulation, a different material must be found.

Component	$^{238}U_{lower}$ [mBq/kg]	$^{238}U_{upper}$	^{232}Th	^{235}U
Methyl methacrylate monomer (LG bonding)	1.4 ± 1.0	< 15	< 0.9	< 1.8
AV acrylic	< 0.1	< 2.2	< 0.5	< 0.2
Acrylic beads (RPT)	< 3.1	16 ± 15	0.8 ± 0.3	0.6 ± 0.5
LG acrylic	< 0.1	< 9.0	< 0.3	< 0.6
304 welded stainless steel (steel shell)	1.4 ± 1.1	< 5.0	4.7 ± 1.5	< 3.3
304 stainless steel stock (steel shell)	2.1 ± 1.1	< 112	1.9 ± 1.1	< 5.4
316 stainless steel bolts (steel shell)	< 6.1	< 315	94 ± 9	< 17
Carbon steel (stock)	2.0 ± 0.7	111 ± 43	10.0 ± 1.0	8.6 ± 1.9
Invar steel (neck)	4.5 ± 1.5	120 ± 77	2.5 ± 1.5	< 3.6
R5912 HQE PMT glass	921 ± 34	225 ± 114	139 ± 7	25 ± 3
R5912 HQE PMT ceramic	978 ± 56	15500 ± 2800	245 ± 28	503 ± 51
R5912 HQE PMT feedthrough pieces	1140 ± 60	2350 ± 1460	430 ± 32	38 ± 9
R5912 HQE PMT metal components	< 5.5	-	< 3.3	-
RG59 PMT cable (Belden E82241)	4.5 ± 1.3	91 ± 46	1.2 ± 0.9	3.4 ± 1.4
PMT mount PVC (Harvel)	72 ± 5	232 ± 130	18.6 ± 2.5	5.6 ± 1.5
PMT mount copper	< 0.5	< 10	< 0.8	< 1.3
Neck Veto PMT glass	1230 ± 620	-	407 ± 203	57 ± 29
Filler block polyethylene	0.4 ± 0.3	< 14	< 0.1	< 0.15
Filler block Styrofoam [42]	33.5 ± 3.4	115 ± 64	< 1.5	< 1.4
White Tyvek paper (diffuse reflector)	< 0.3	50 ± 37	1.3 ± 0.8	< 2.2
Black Tyvek paper (LG wrapping)	< 1.8	< 127	5.6 ± 2.3	< 3.8
Black polyethylene tube (upper neck)	13.7 ± 1.8	< 60	3.2 ± 1.1	2.6 ± 1.4
TPB (Sigma Aldrich)	< 3.9	-	< 8.7	-
Purification System Welding				
TIG weld sample	7.7 ± 5.7	< 27	25.2 ± 7.8	< 16
SMAW weld sample	< 23	< 1255	51.9 ± 12.2	< 13
Welding electrodes A (Blue Demon TE2C-116-10T)	221 ± 65	< 493	1890 ± 184	< 56
Welding electrodes B (Blue Demon TE2C-116-10T)	66.6 ± 42.6	< 1300	710 ± 103	< 138
Welding electrodes C (Blue Demon TE2C-116-10T)	86.1 ± 21.8	< 642	911 ± 73	< 108
Weld filler rods	< 4.8	< 157	3.0 ± 2.5	< 1.8
Inner AV Sanding				
Brazed diamond sanding pad (Superabrasives)	141 ± 24	< 845	49.8 ± 17.9	[illegible]
Plated diamond sanding pad (Superabrasives)	4680 ± 283	< 4130	6180 ± 300	218 ± 64

Source	Emanation Rate
	[mBq/m^2]
Filler blocks	1.6 ± 0.5
FINEMET PMT magnetic shielding [40]	0.8 ± 0.2
ESR film reflector[a]	< 2.2
Tyvek diffuse reflector	< 0.1
Black tyvek absorber	0.4 ± 0.2
PMT mount PVC (McMaster-Carr stock)	< 0.7
PMT polyethylene foam	< 0.9
Teflon sheets (McMaster-Carr stock)	0.4 ± 0.2
High density polyethylene pipe	3.5 ± 0.8
304 Stainless Steel (McMaster-Carr stock)	< 1.6
Carbon steel (McMaster-Carr stock)	0.6 ± 0.1
White PMT mount adhesive styrofoam sheet	< 1.5
Stycast 1266 A/B (Emerson & Cuming)	< 4.2
	[mBq/m]
RG59 PMT cable (Belden E82241)	0.026 ± 0.001
Steel shell EPDM O-ring	16.1 ± 1.8
Viton O-ring	1.3 ± 0.2
Buna 451 O-ring	17 ± 2
	[mBq/unit]
Hamamatsu R5912 PMTs	< 0.3
PMT mount O-ring	0.3 ± 0.1

P.A. Amaudruz et al. (The DEAP collaboration) "Design and construction of the DEAP-3600 dark matter detector." Astroparticle Physics **108** *arXiv:1905.05811* (2019).

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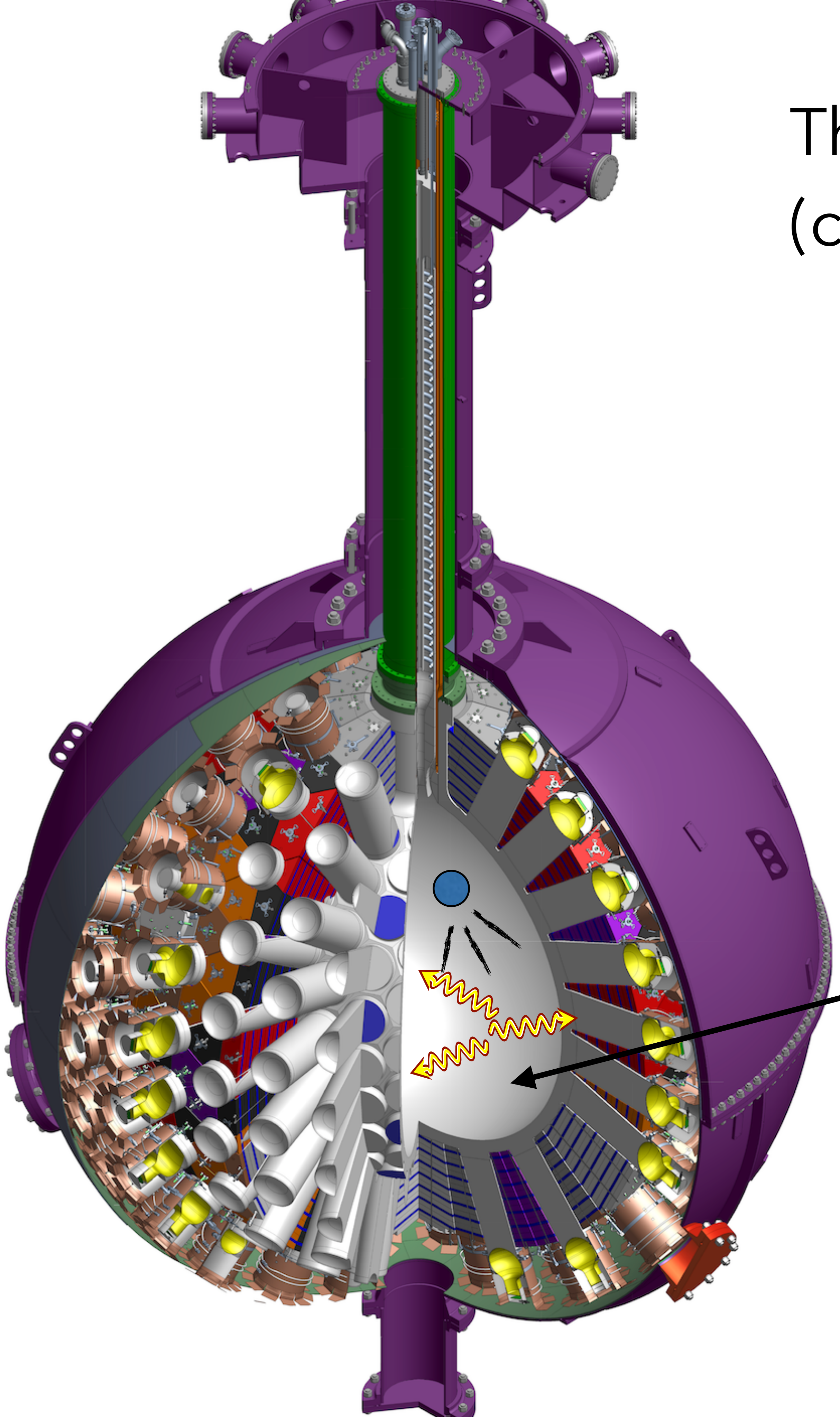
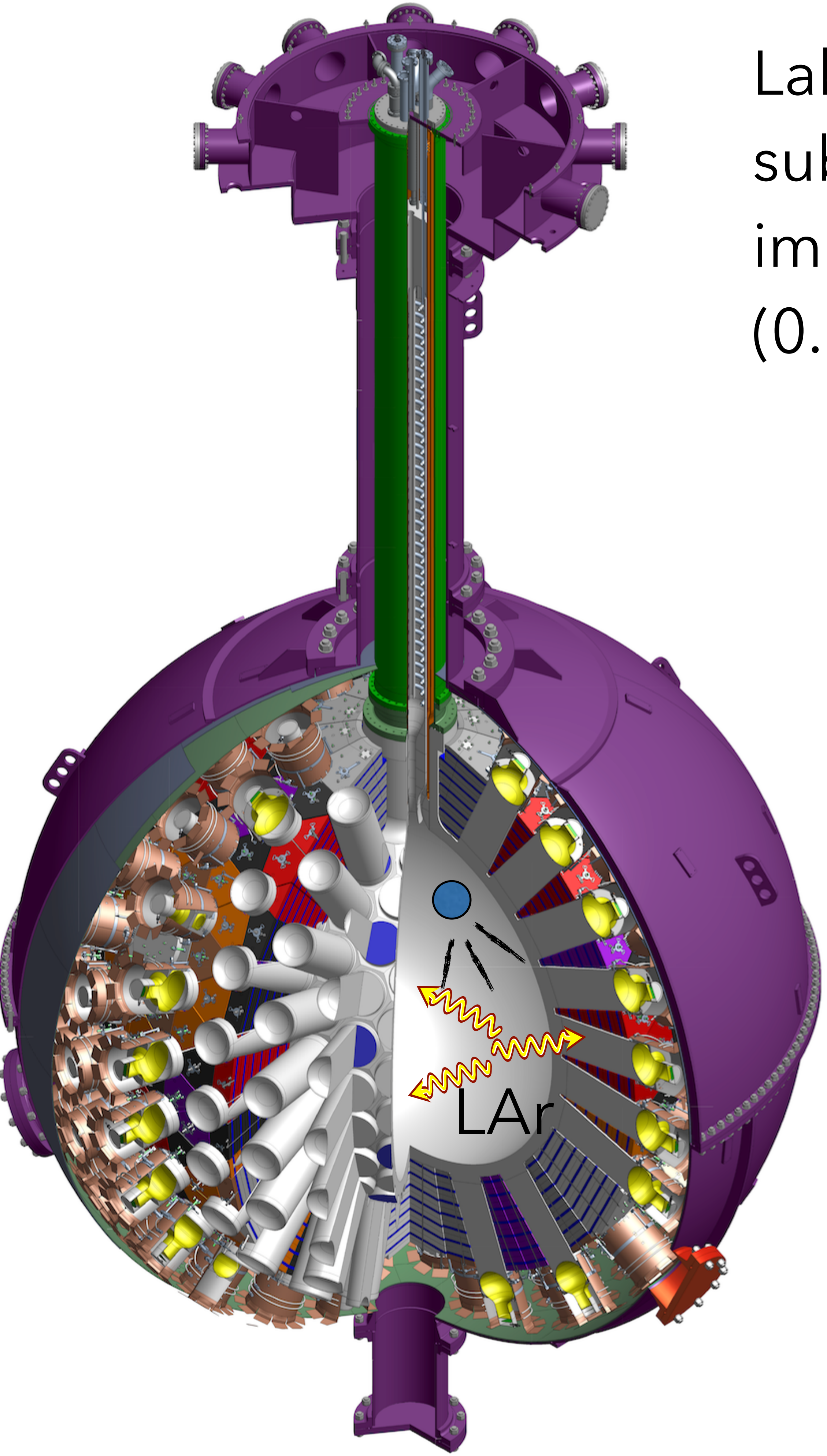
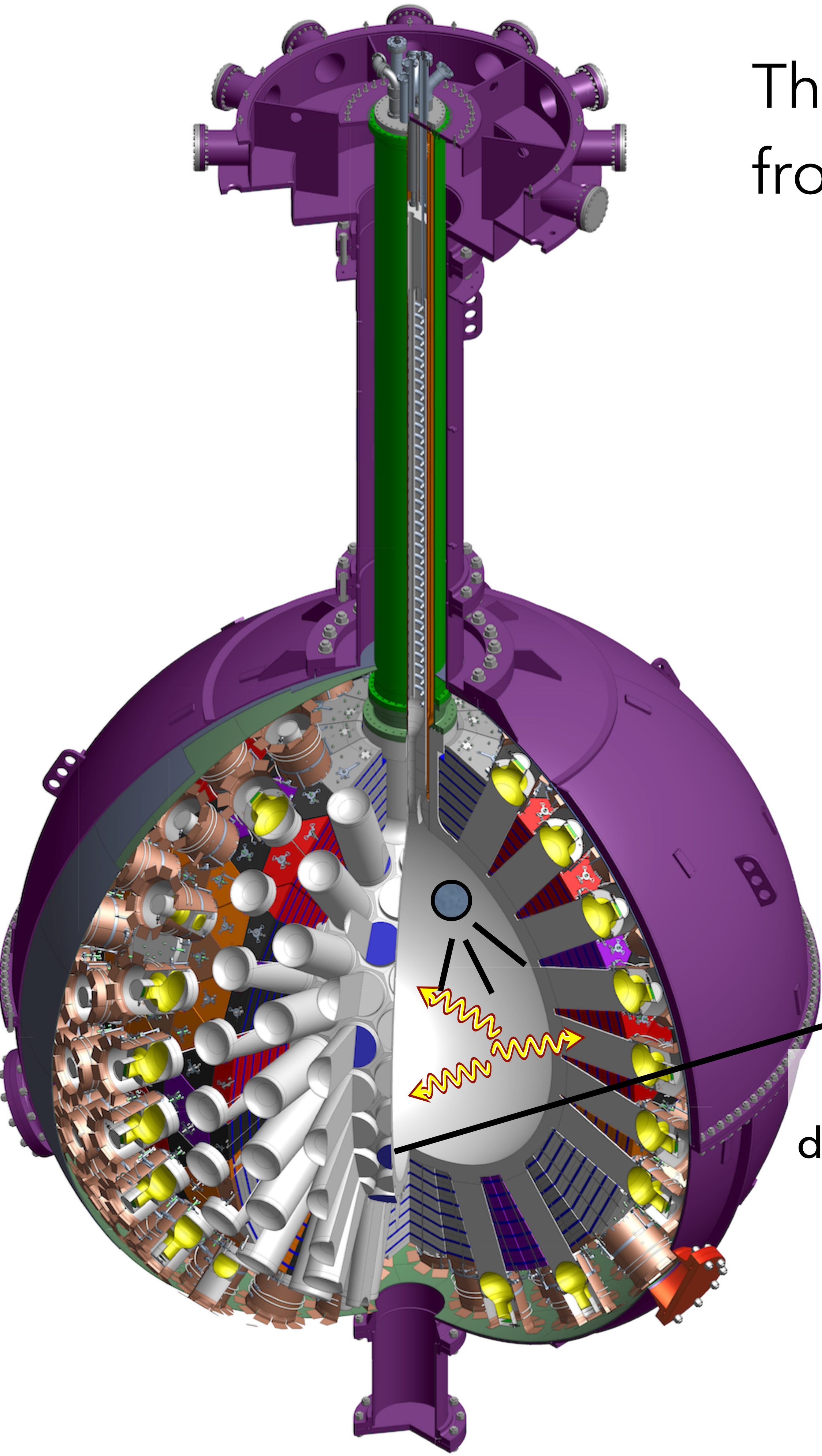
The heart of the detector is a 3.6 (currently 3.3) tonne LAr volume.

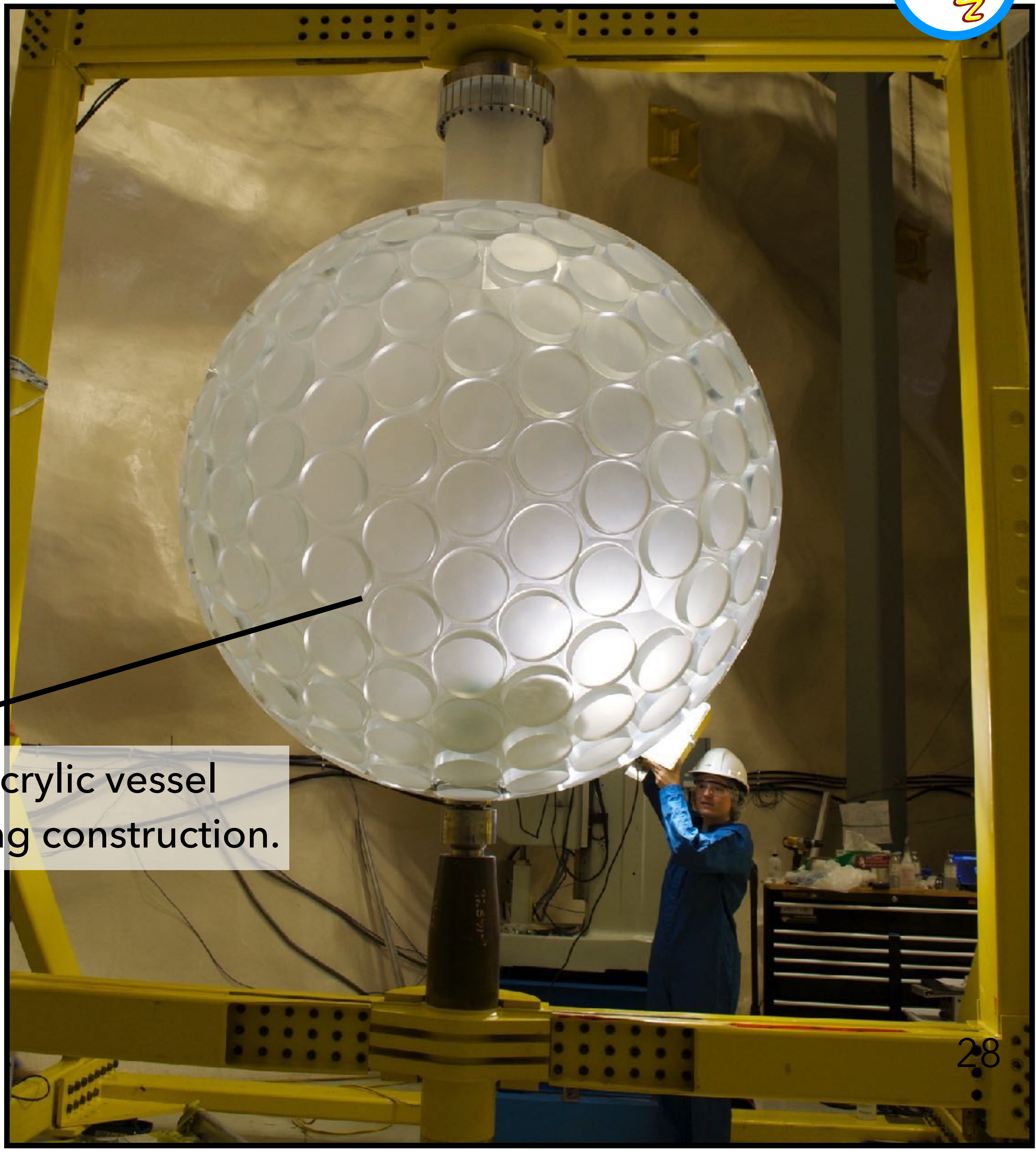




Lab-grade argon is further purified to sub-ppb levels of electronegative impurities (O_2, N_2, ...) and 10^{-26} g/g (0.15 μBq/kg) Rn^{222} (custom Rn trap).

The LAr target is held in a cryostat made from ultra-pure acrylic.





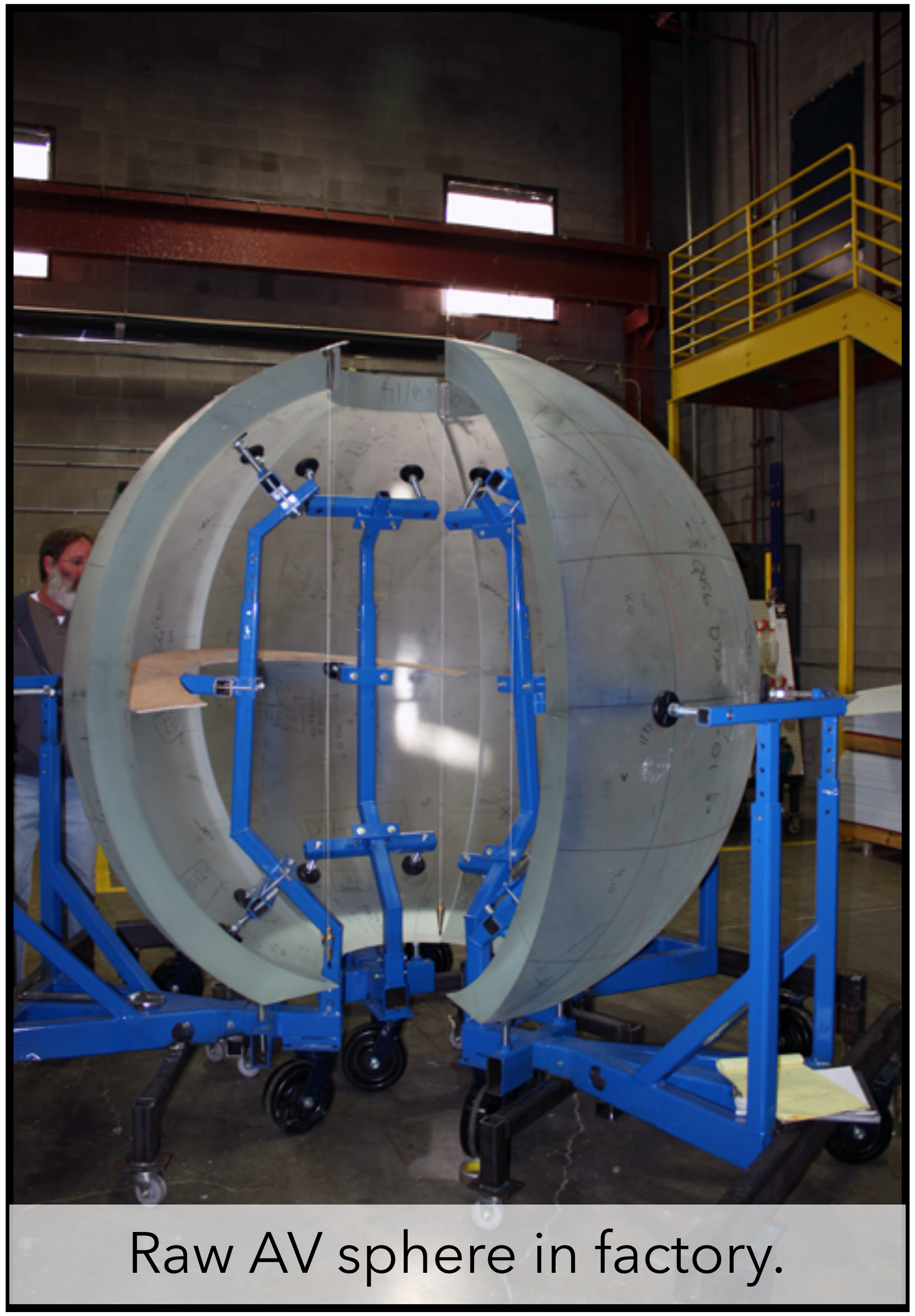
Acrylic vessel during construction.

Raw AV sphere in factory.

Source acrylic sheet.

Underground bonding

AV from custom-made clean (**$<10^{-19}$g/g ^{210}Pb, ~ppt U and Th**) acrylic, assembled u/g.



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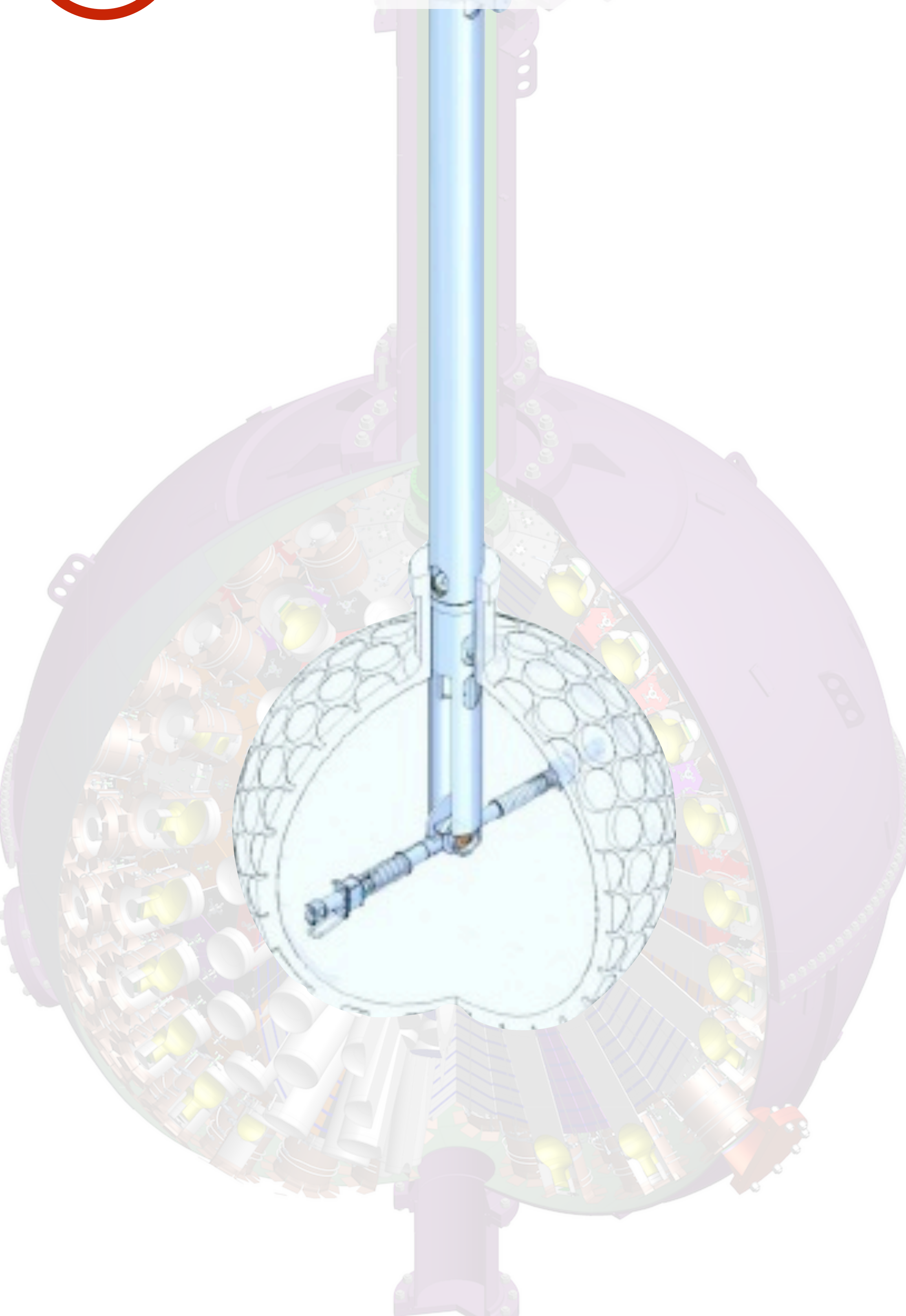
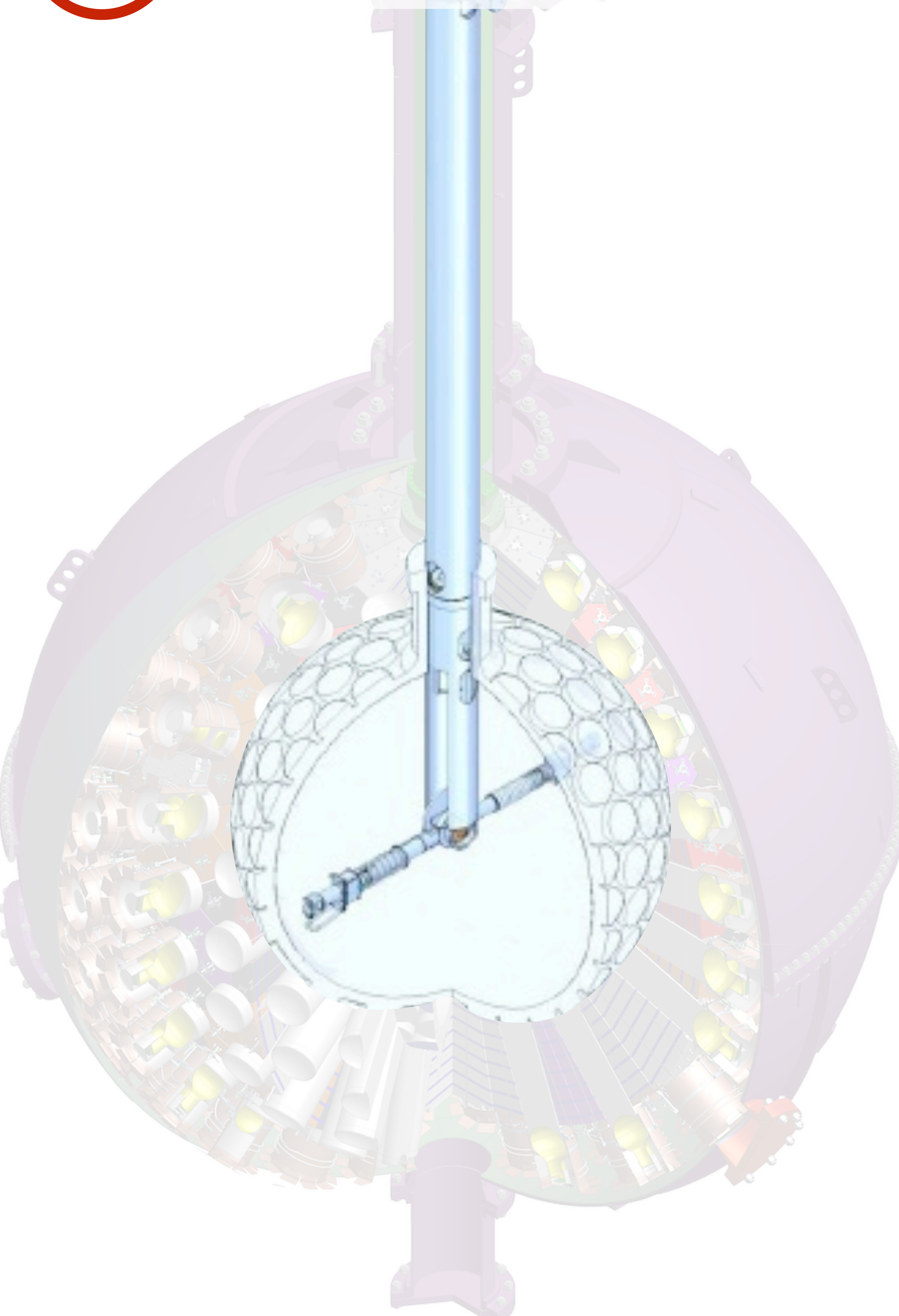
Underground bonding

AV from custom-made clean (**$<10^{-19}$g/g ^{210}Pb, ~ppt U and Th**) acrylic, assembled u/g.

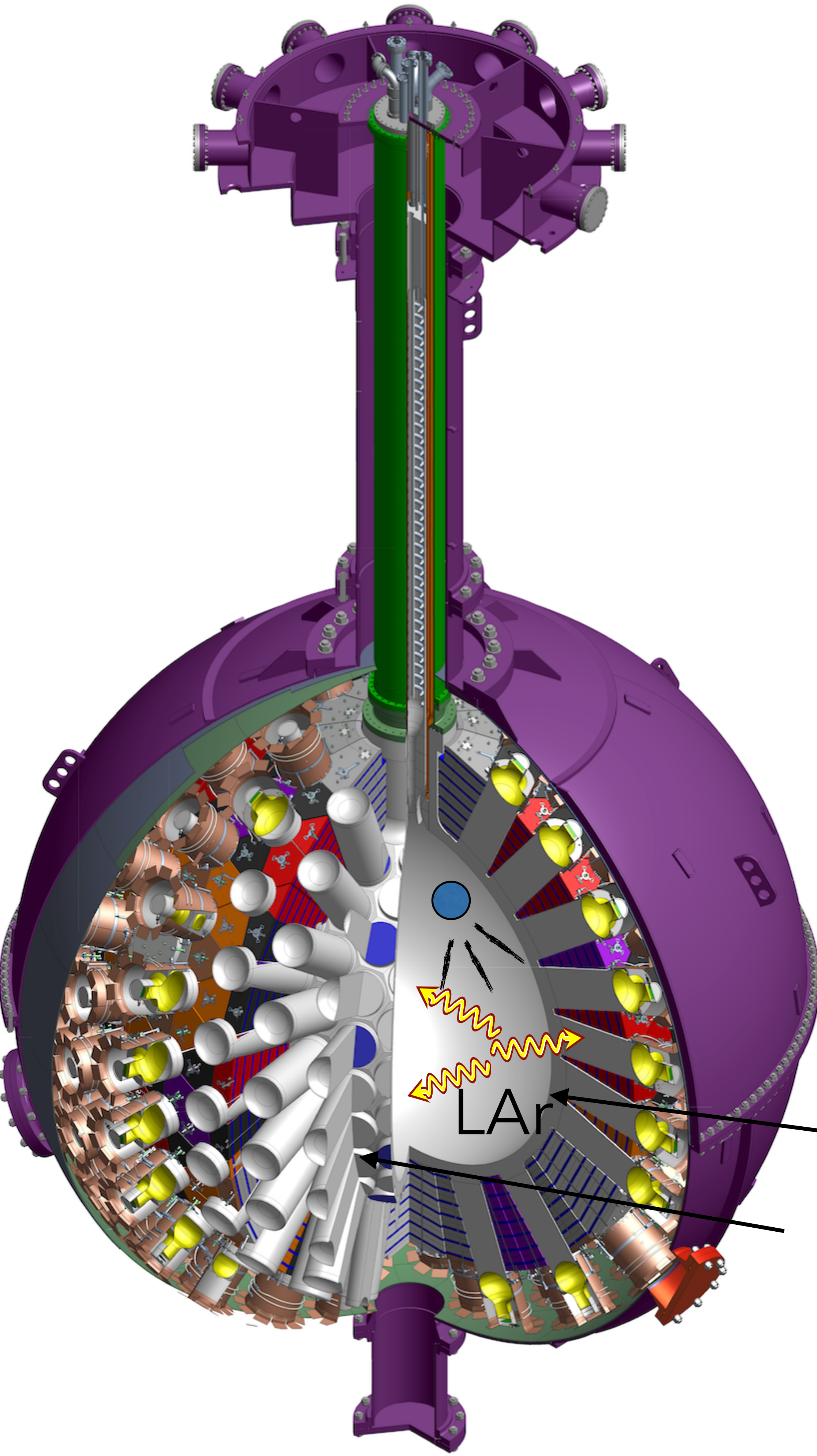
Under air-tight conditions, resurfacer removed fraction of a mm off the acrylic cryostat's inside, reducing radon daughter activity to < 10 α/m²/day.



Under air-tight conditions, resurfacer removed fraction of a mm off the acrylic cryostat's inside, reducing radon daughter activity to < 10 α/m²/day.

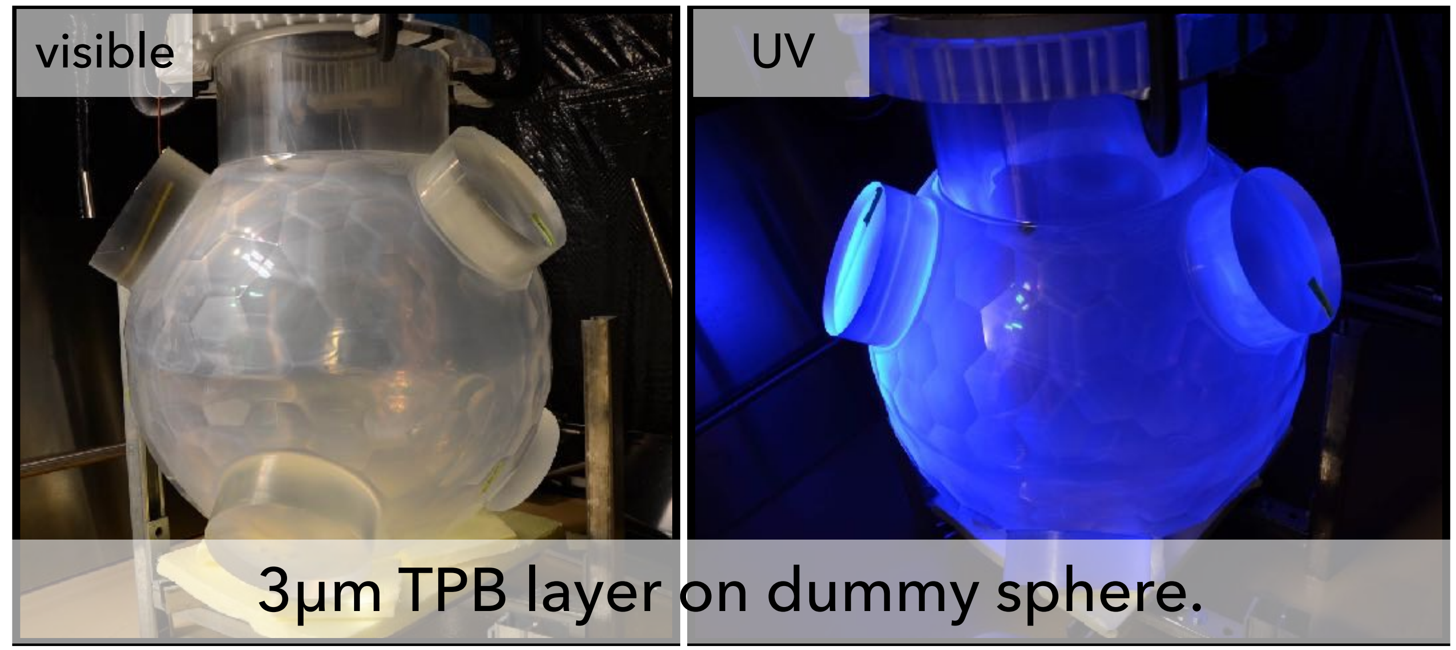


A coating of TPB makes the LAr scintillation visible.



TPB wavelength shifter.

Acrylic vessel.



128 nm →

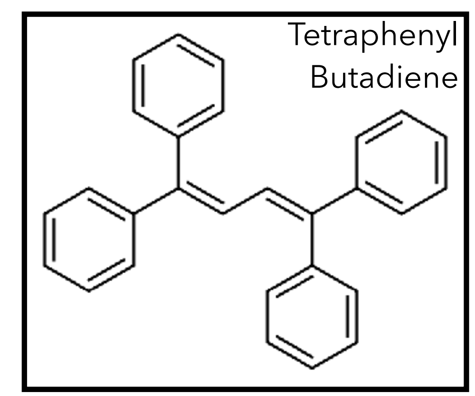
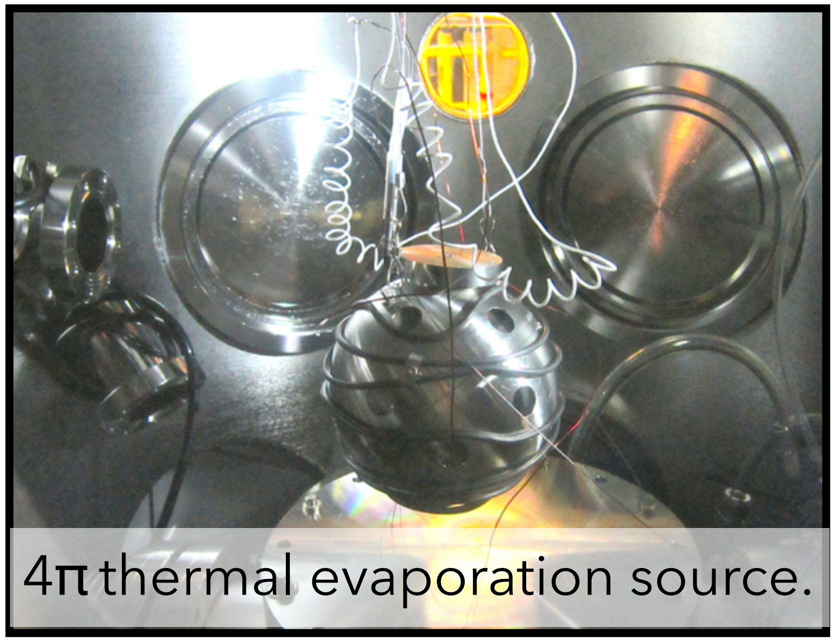
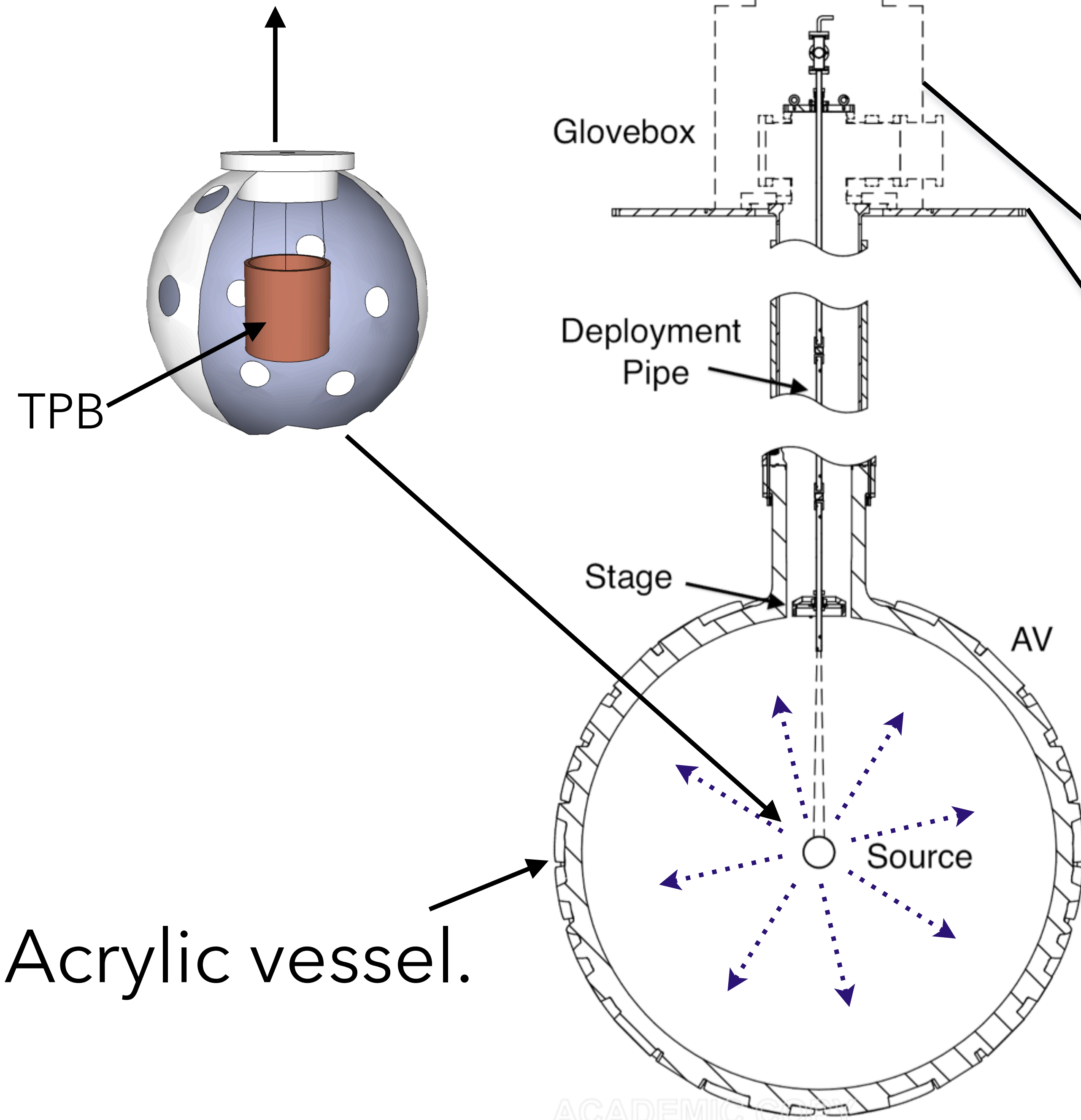


Image credit: Wikipedia

→ 420 nm

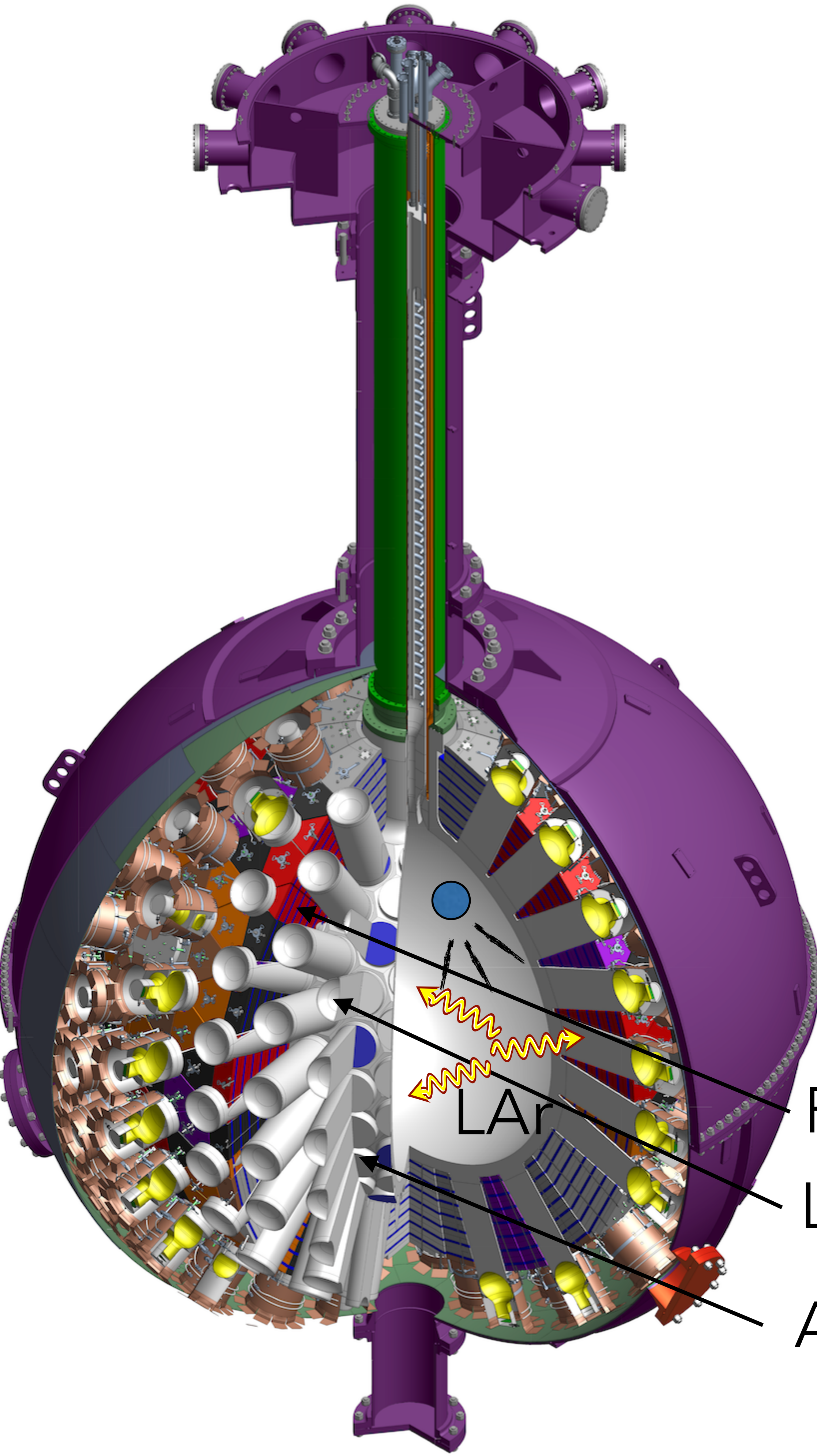
Broerman, B, et al. "Application of the TPB Wavelength Shifter to the DEAP-3600 Spherical Acrylic Vessel Inner Surface ." JINST 12 (2017)


4π thermal evaporation source.



TPB deposition system being installed under air-tight conditions.

50 cm of plastic provide thermal isolation and neutron shielding.



255 Hamamatsu R5912-HQE PMTs view the LAr volume at 71% surface coverage. PMT temperature > -40C.

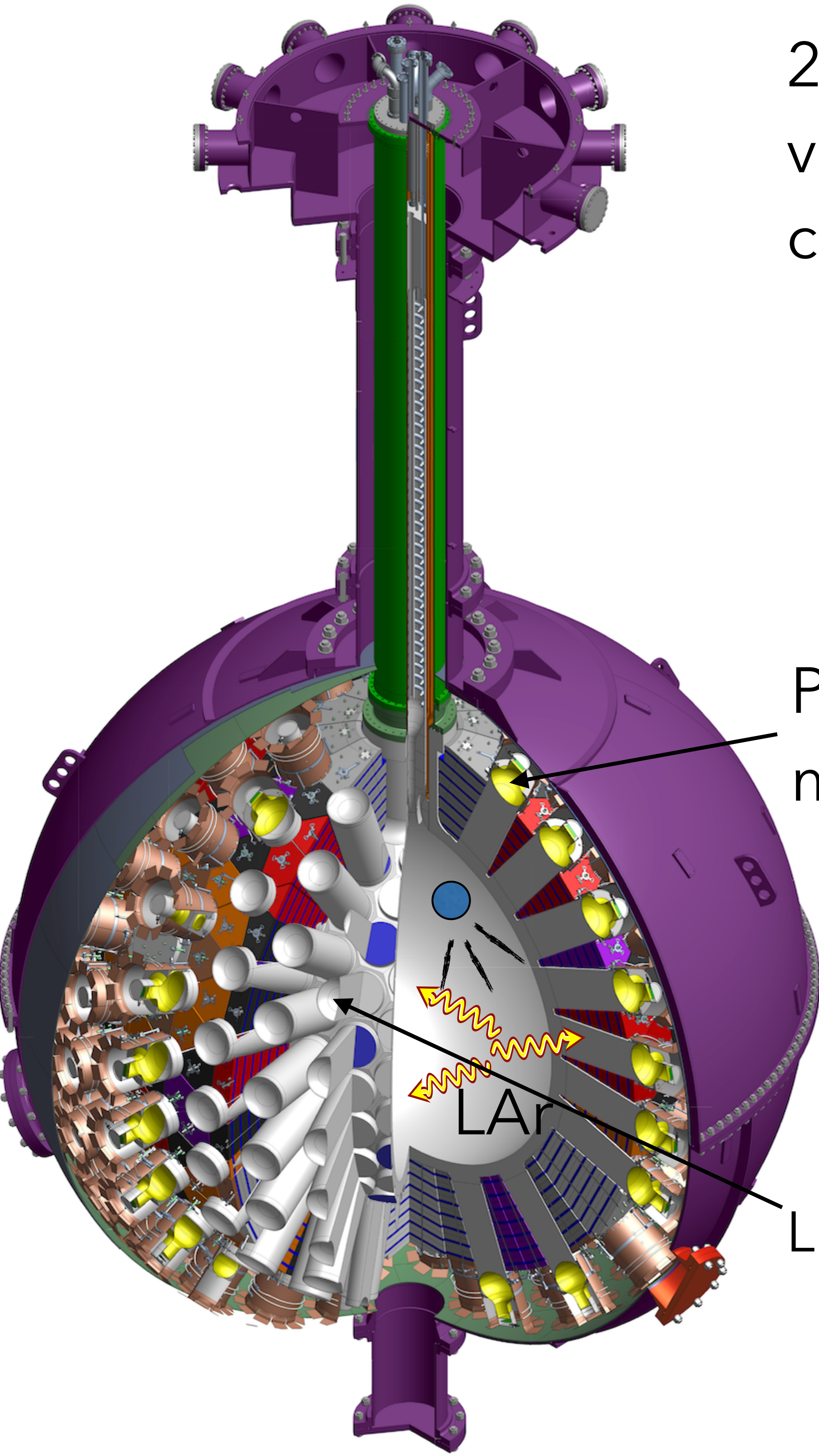


Photo multiplier.

Light guide.

Ron Calls on his years of experience....and freezes at the controls > Attila Nagy
2/06/16 7:09am

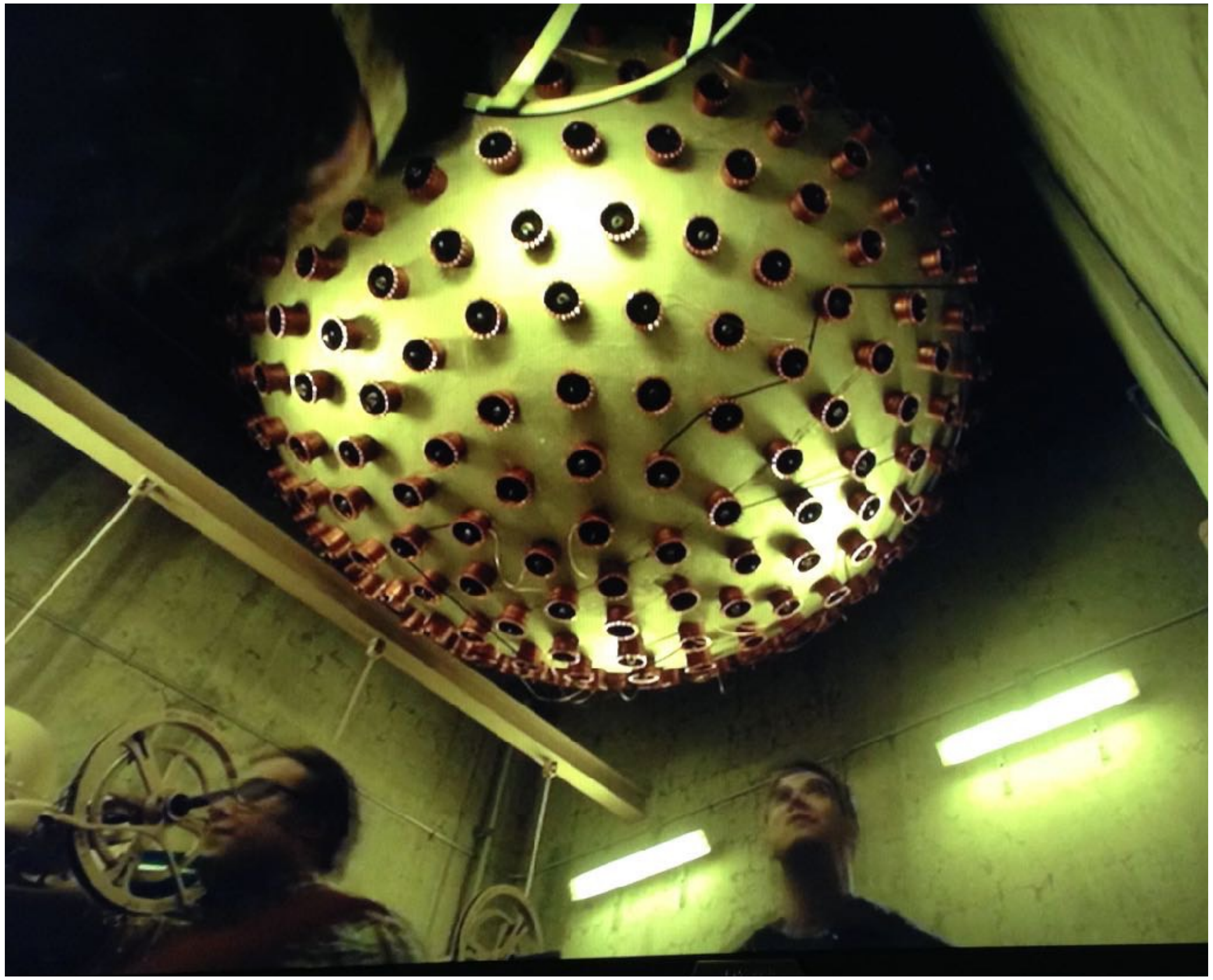
1

These gadgets looks so cool and movie prop-ish that it's a little hard to beleive they're real.haha

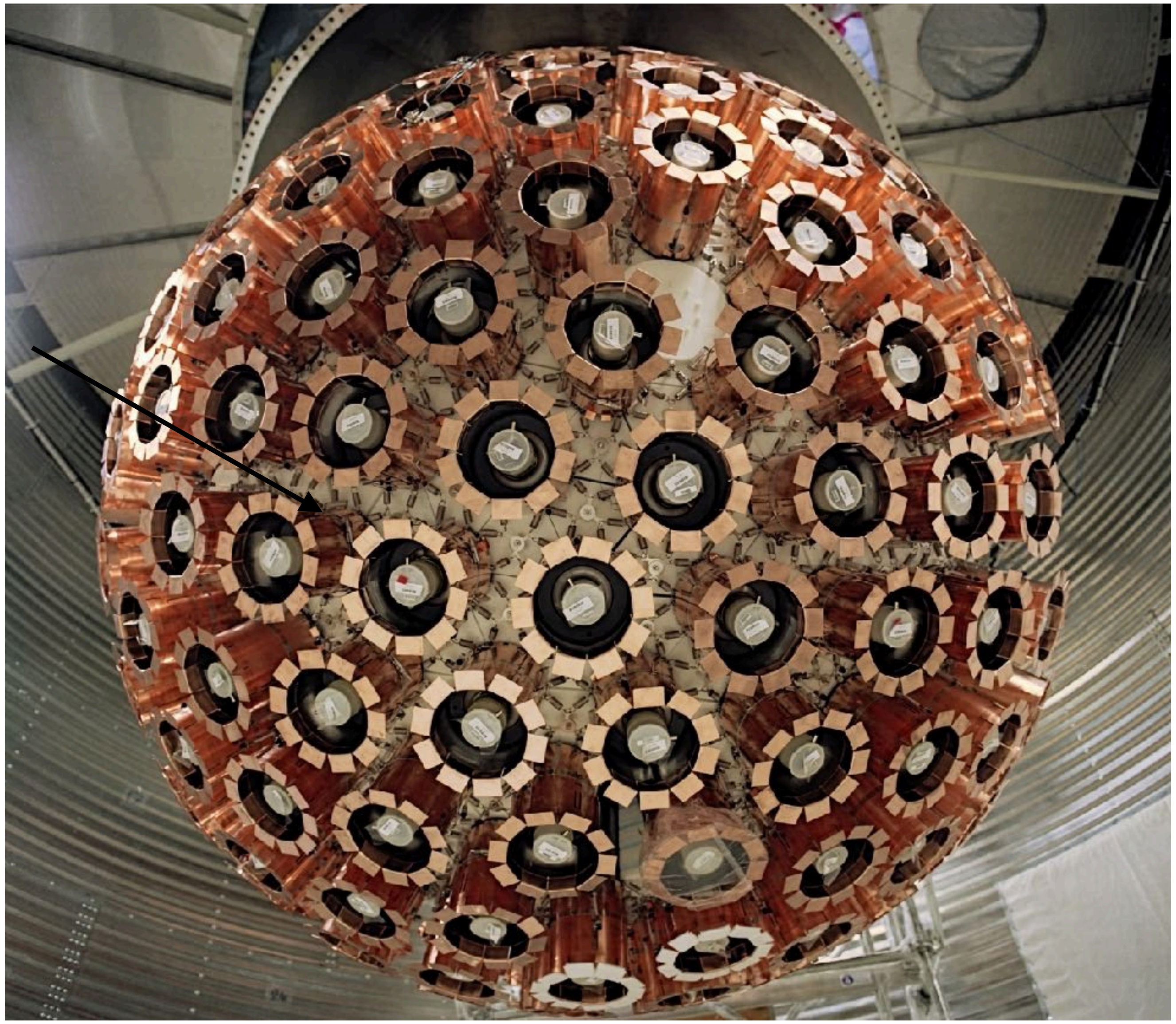
Reply

User comment to Gizmodo article about SNOLAB.

Replica from CBS TV show 'Scorpion'.



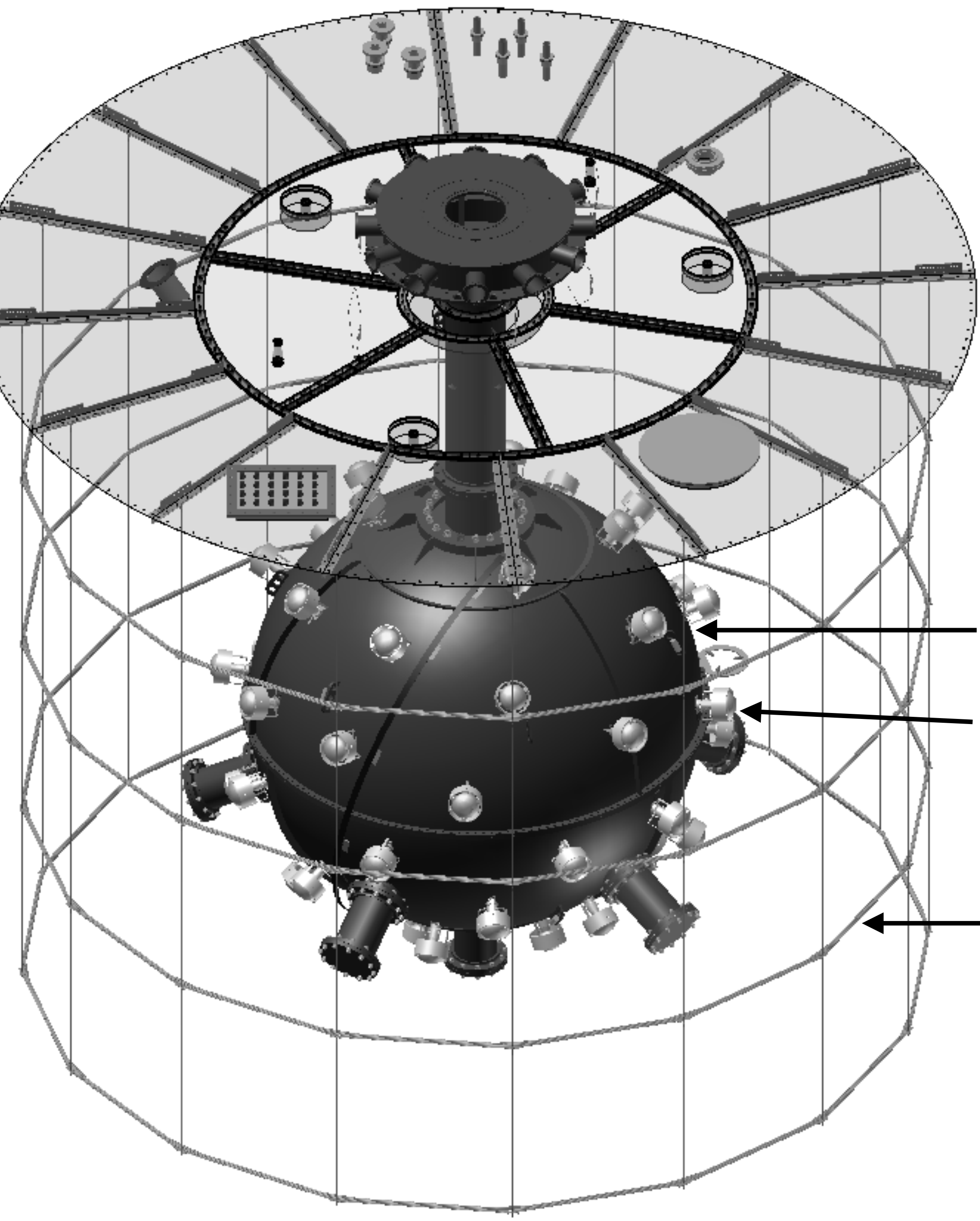
Real detector.

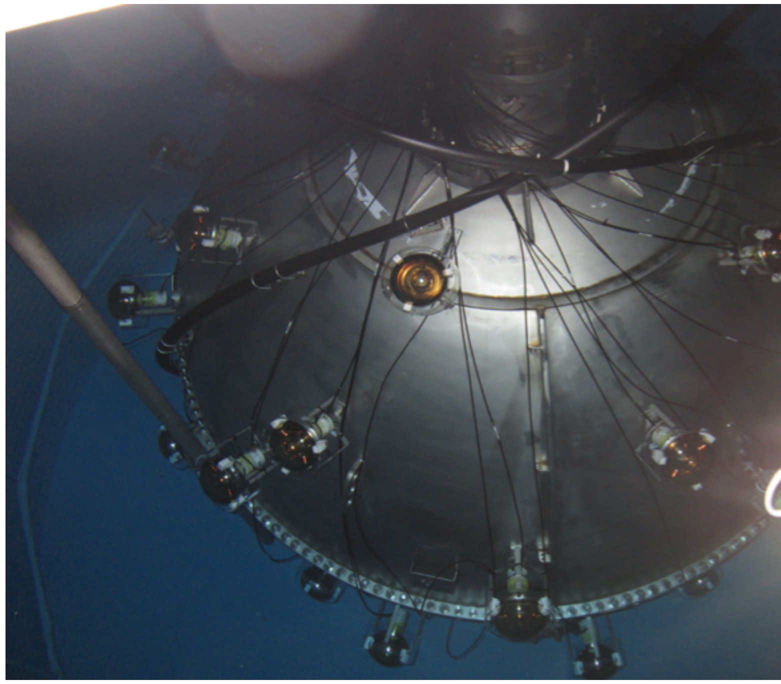


Overview

- The Dark Matter problem and challenges in direct detection of Dark Matter
- The DEAP-3600 detector
  - Design and construction
    - Material screening
    - Radio-clean construction
    - Passive shielding
    - **Active shielding (veto)**
    - Particle identification
  - Results

The detector is housed in a steel shell and submerged in a water-Cherenkov veto tank for active and passive neutron shielding.





Steel shell.

Veto PMT.

(Earth) magnetic field compensation coils

Overview

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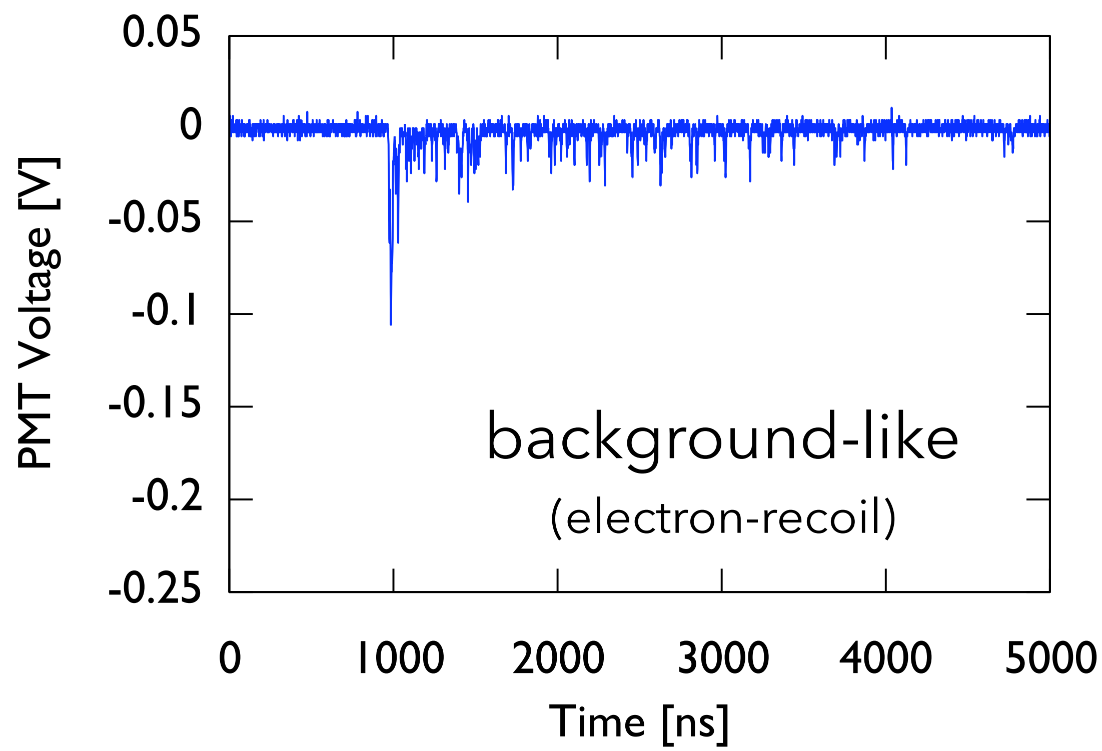
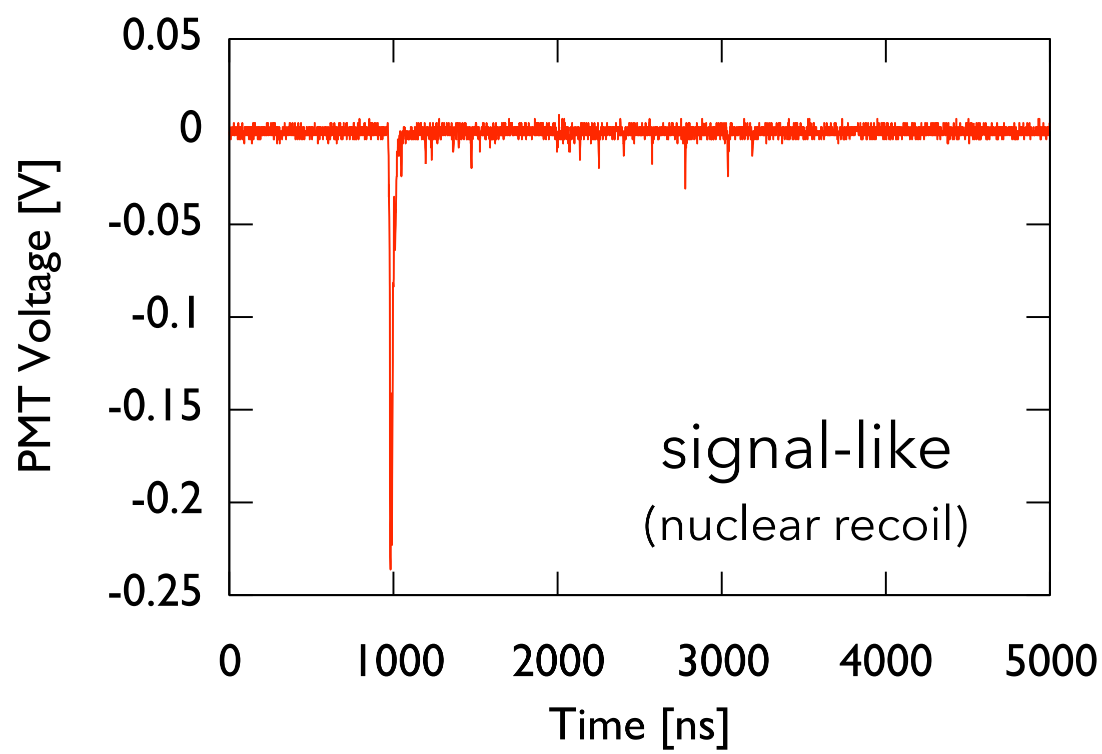
    - Active shielding (veto)
    - **Particle identification**
  - Results

Background suppression in LAr relies on pulse shape discrimination (PSD), and works well because of the large difference in the lifetimes of the two excimer states.





Pulse shapes are driven by argon singlet (6 ns) and triplet (1.3 μs) decay, and singlet/triplet ratio depends on linear energy transfer from exciting particle.

Overview

- The Dark Matter problem and challenges in direct detection of Dark Matter
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  - Design and construction
    - Material screening
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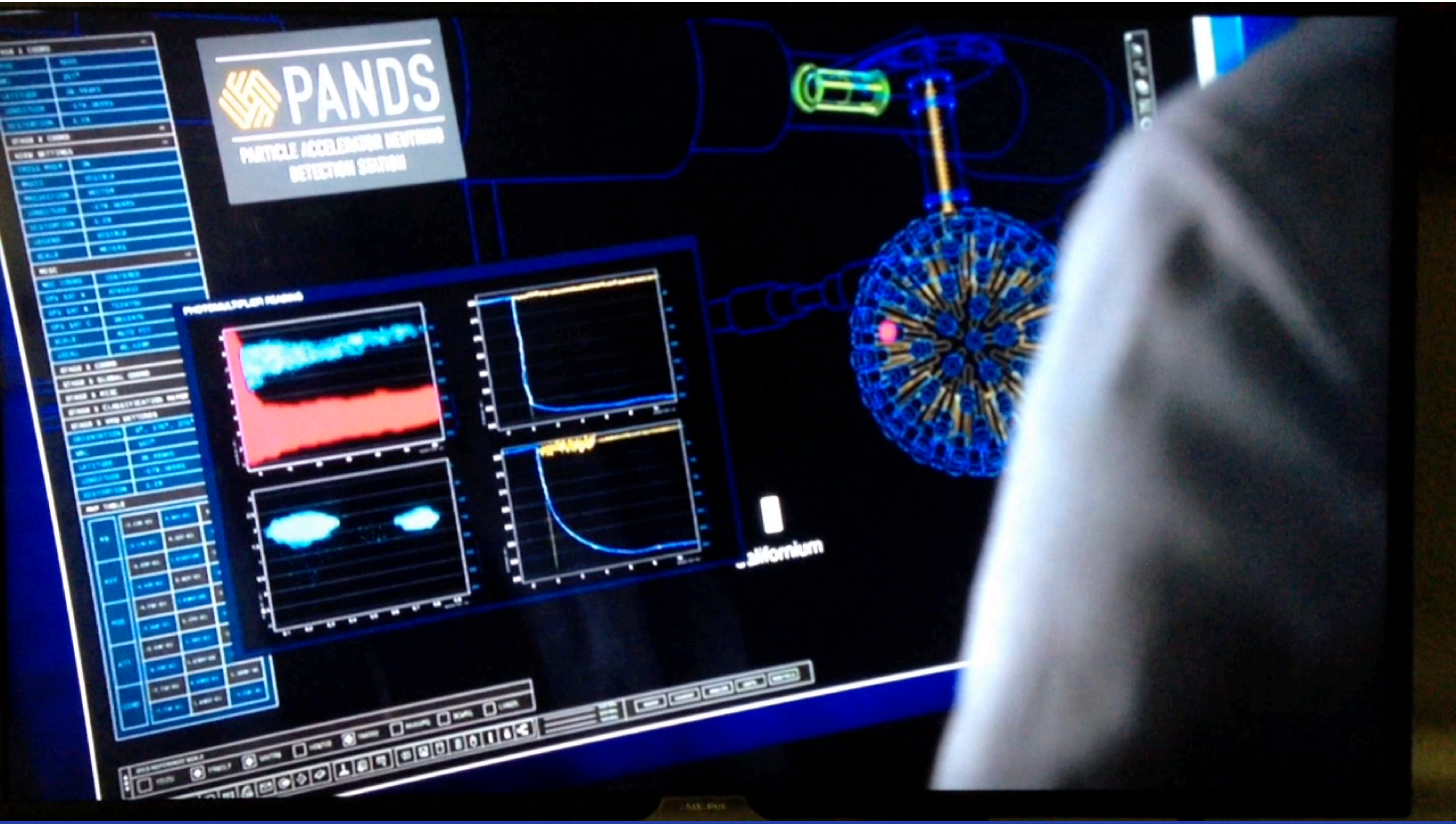
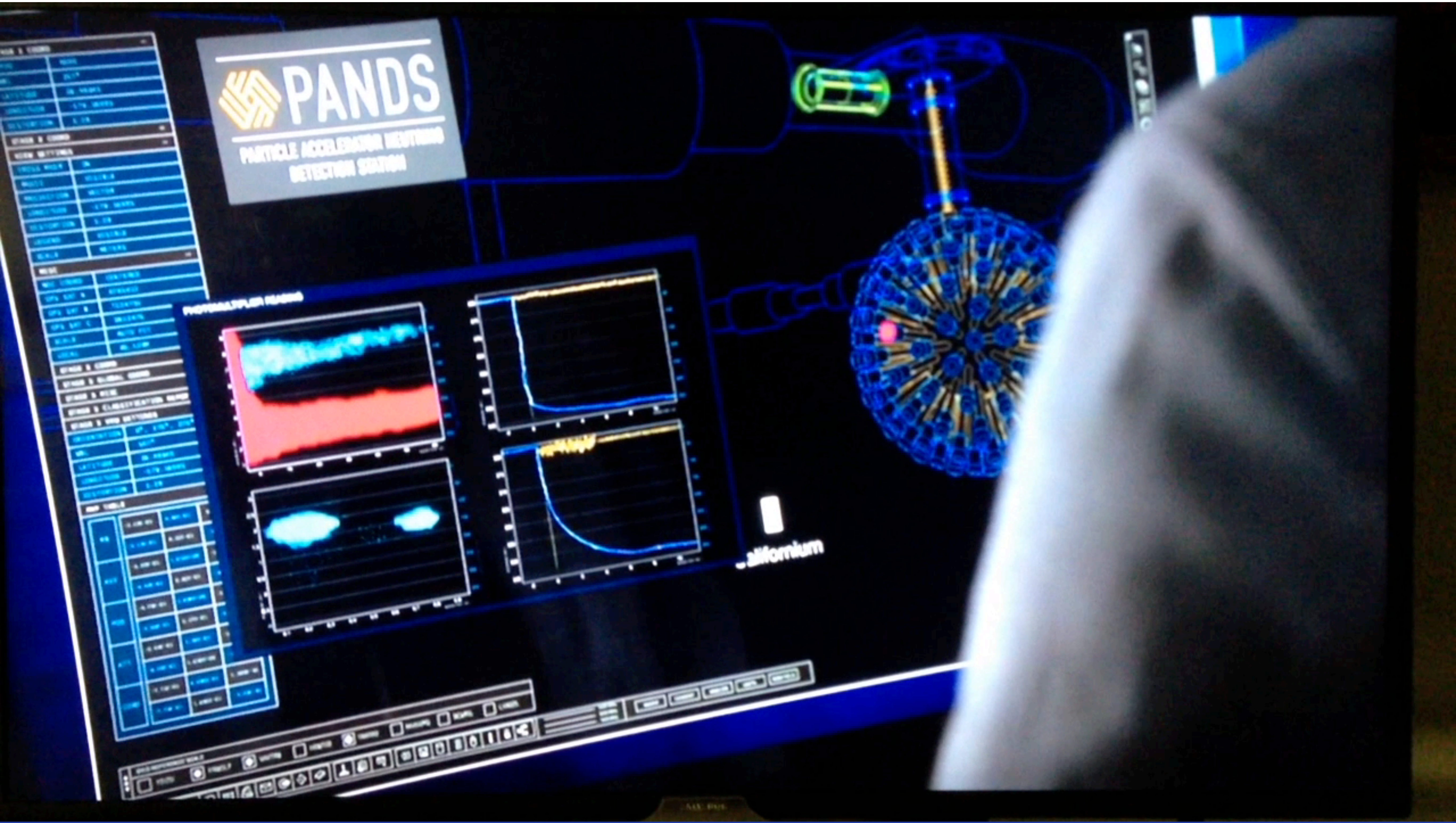
    - Passive shielding
    - Active shielding (veto)
    - Particle identification
  - **Results**

Hollywood predicts that DEAP finds Dark Matter



Credits: CBS, Scorpion. They made creative use of the DEAP detector design so they can't complain about the creative use of their material here.

Hollywood predicts that DEAP finds Dark Matter



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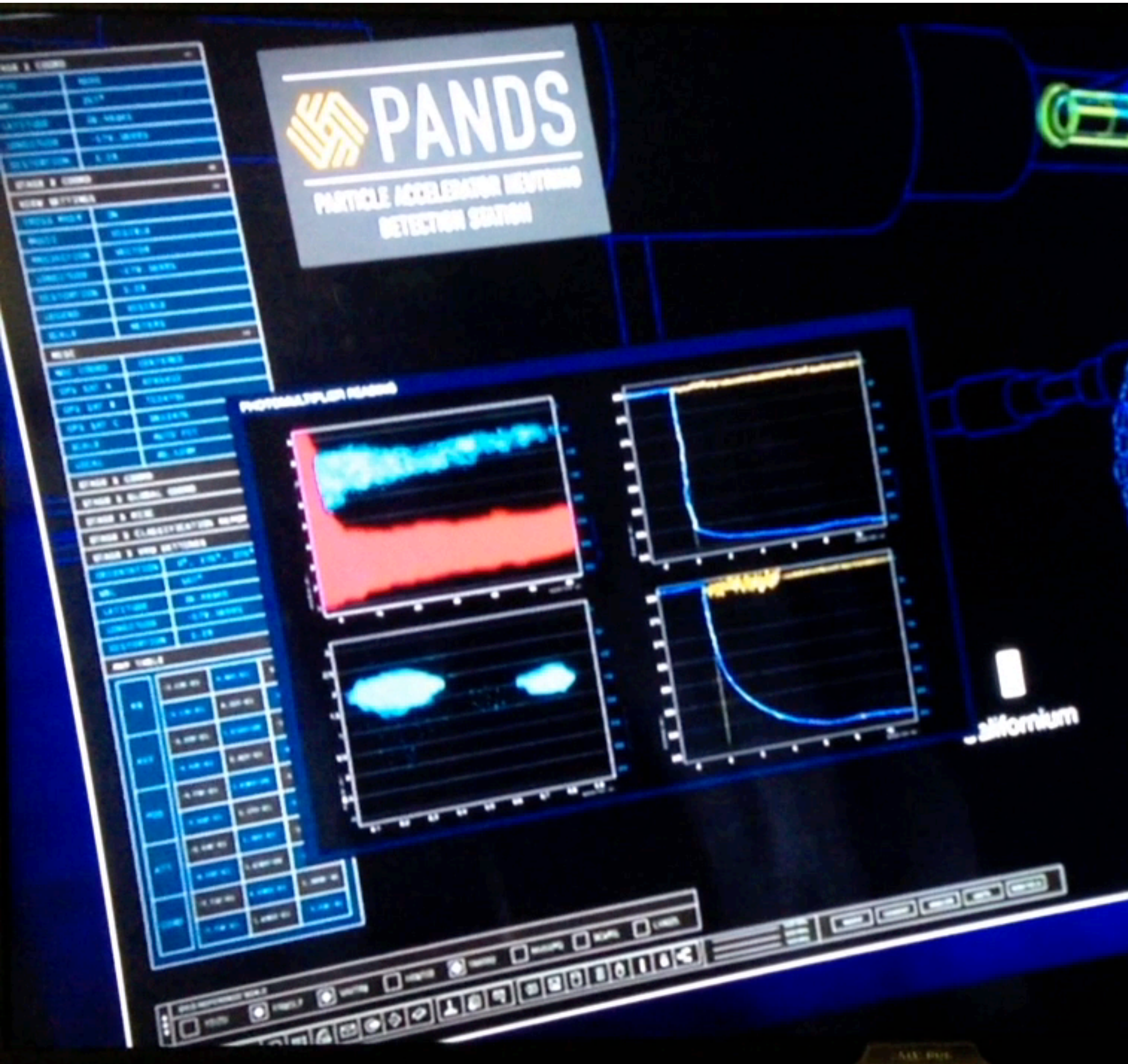
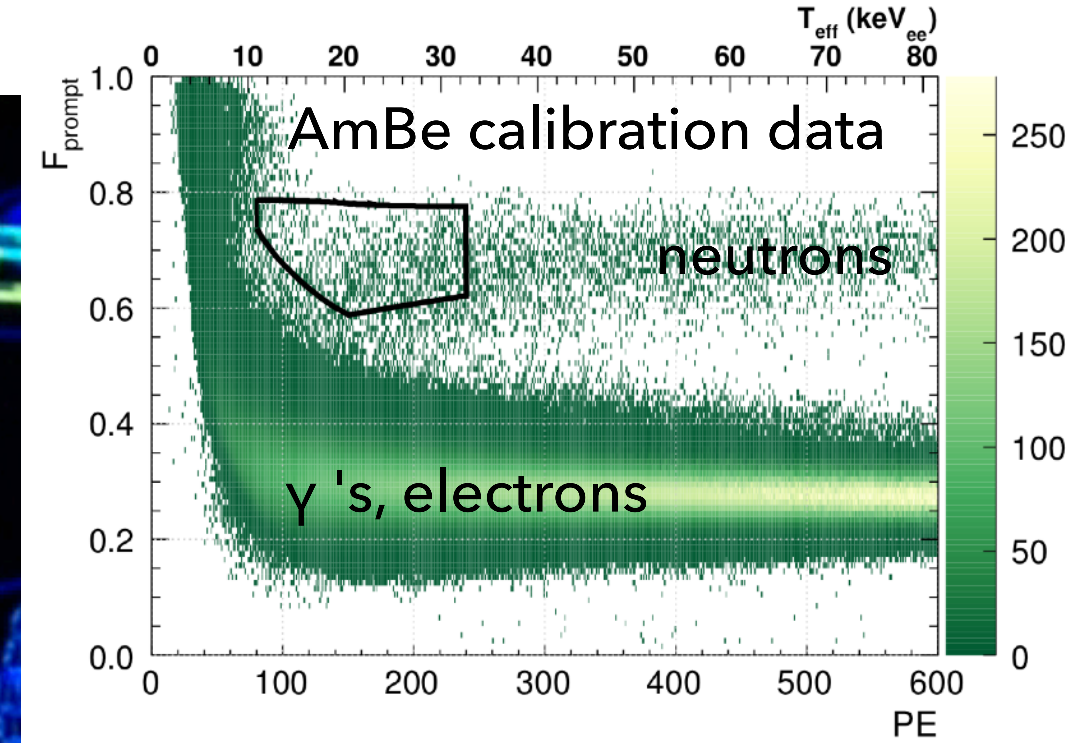
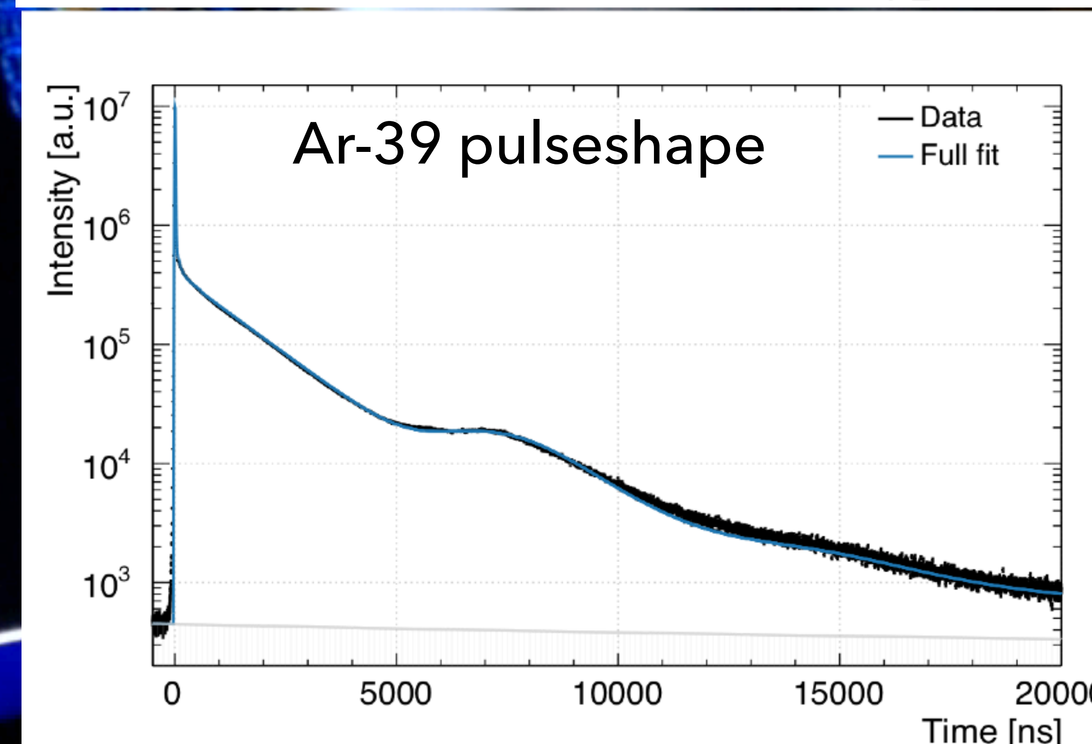


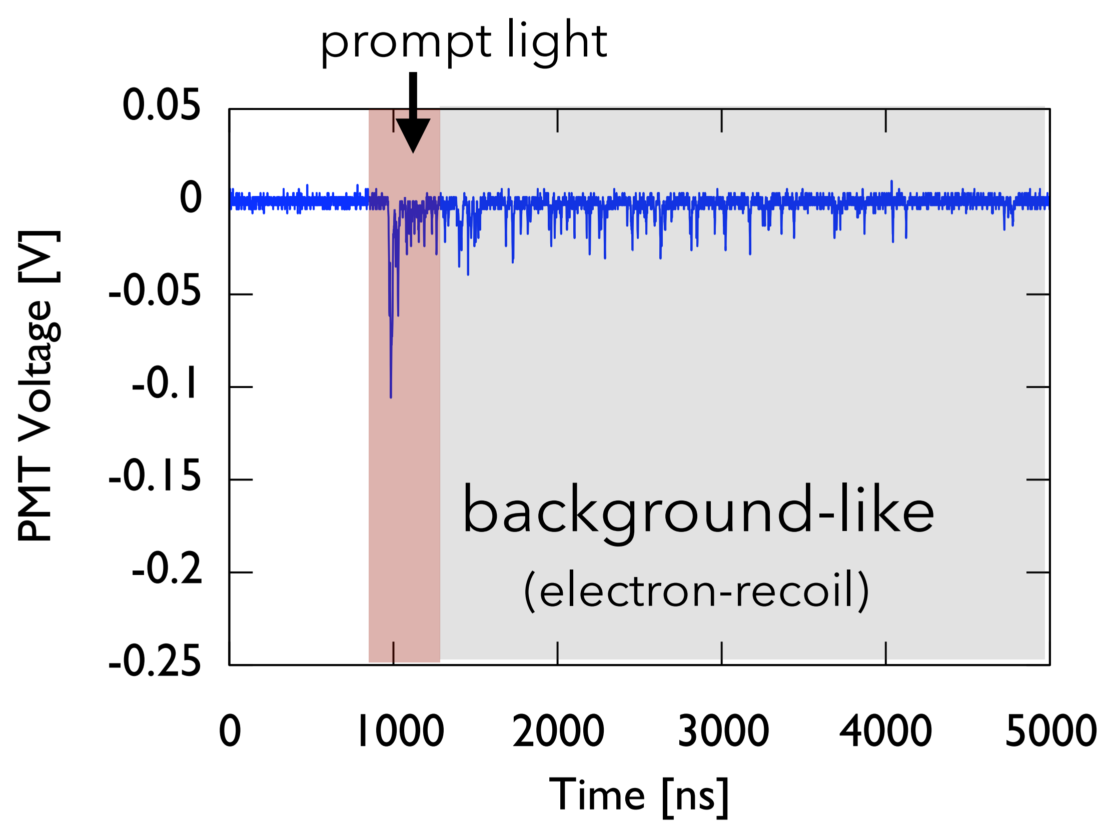


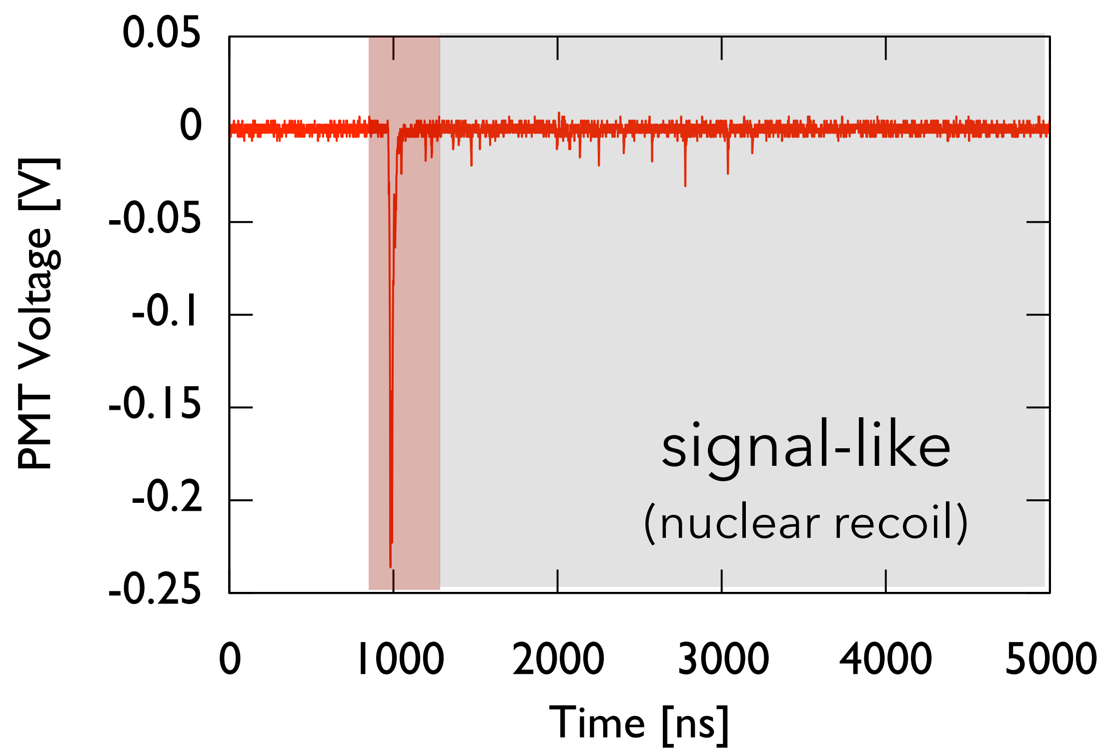


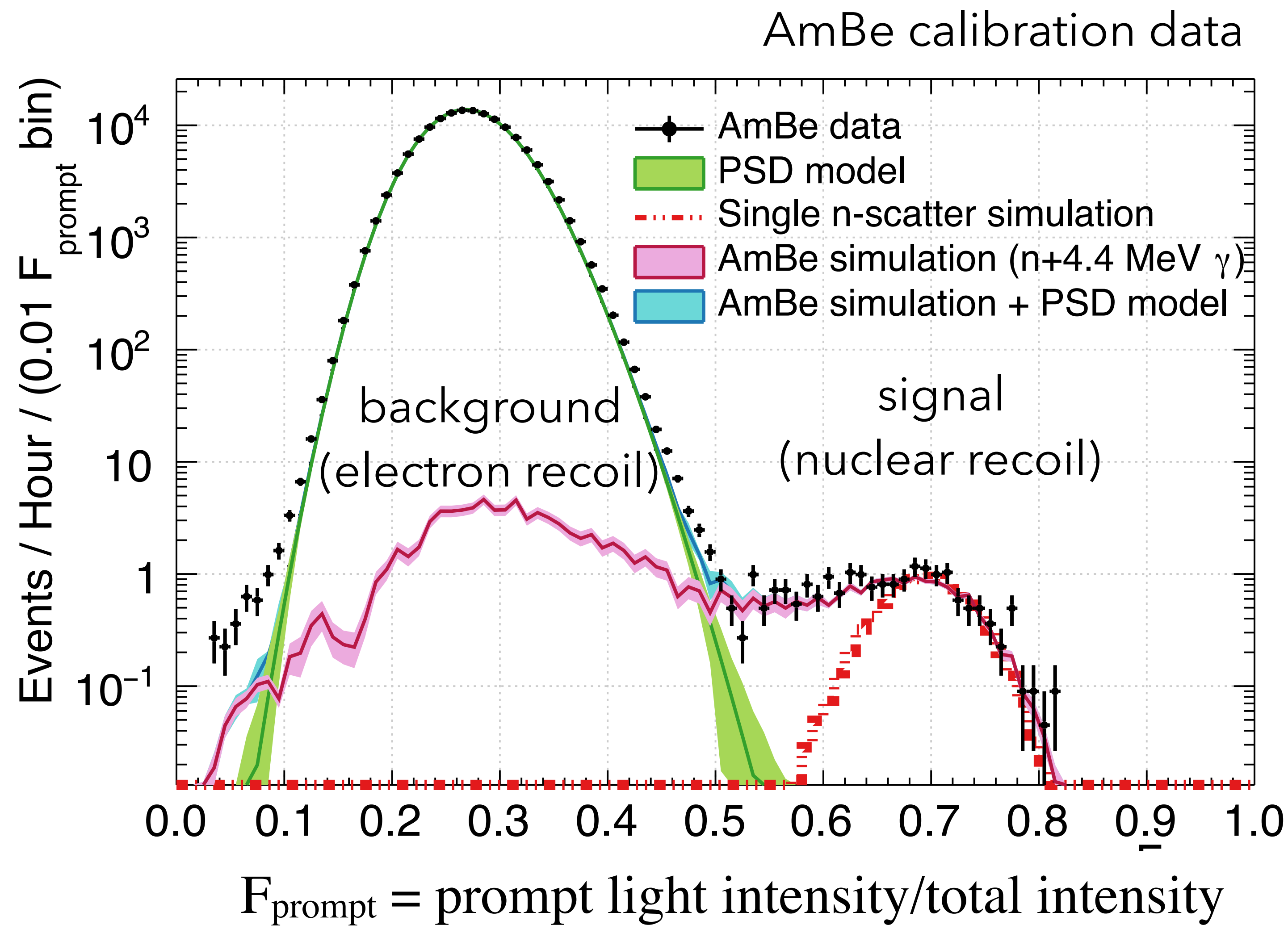
Phys. Rev. Lett. 121, 071801 (2018)
PRD 100 (2019); arXiv:1902.04048

Credits: CBS, Scorpion. They made creative use of the DEAP detector design so they can't complain about the creative use of their material here.

Simple analysis algorithms already achieve very good background identification and suppression.



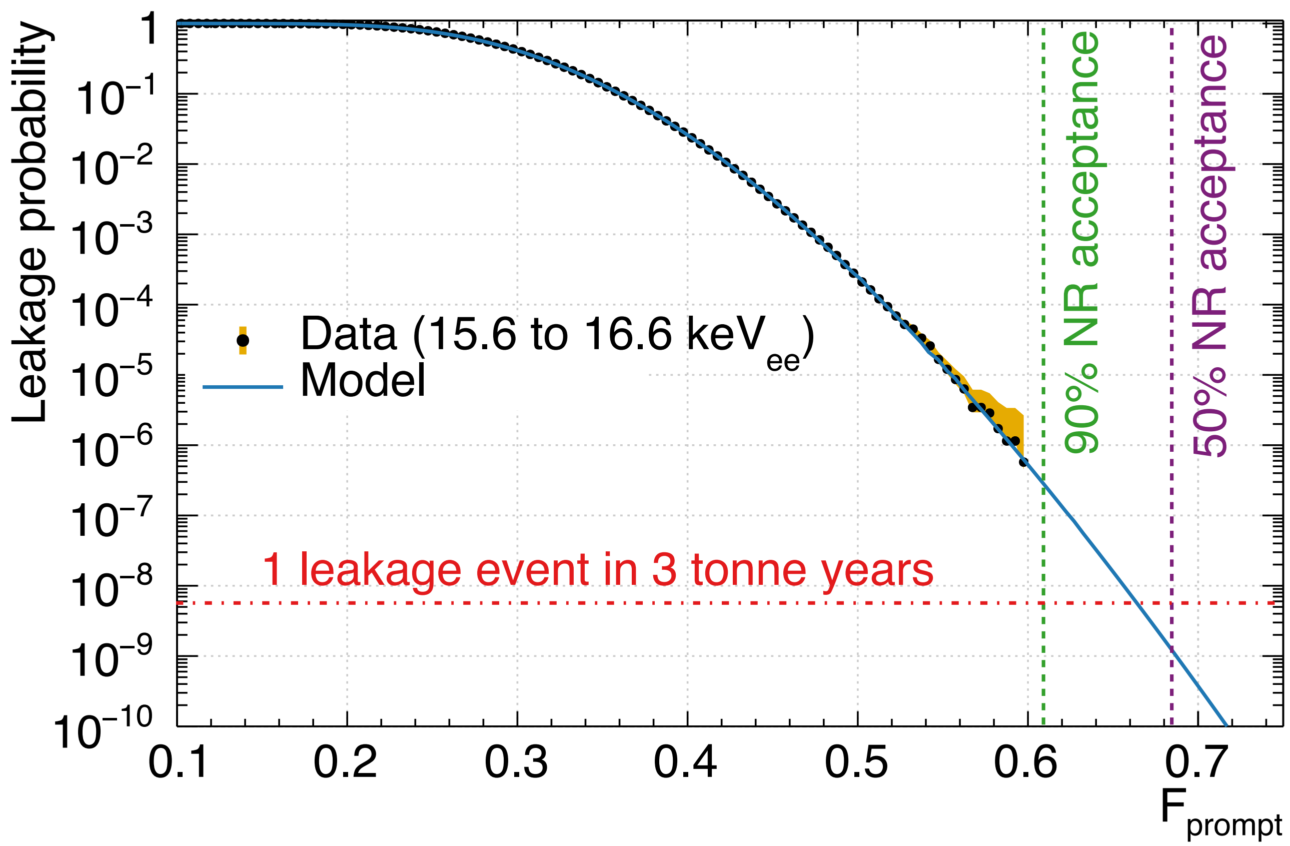




Exploiting the singlet (6 ns) and triplet (1.3 μs) lifetime difference.

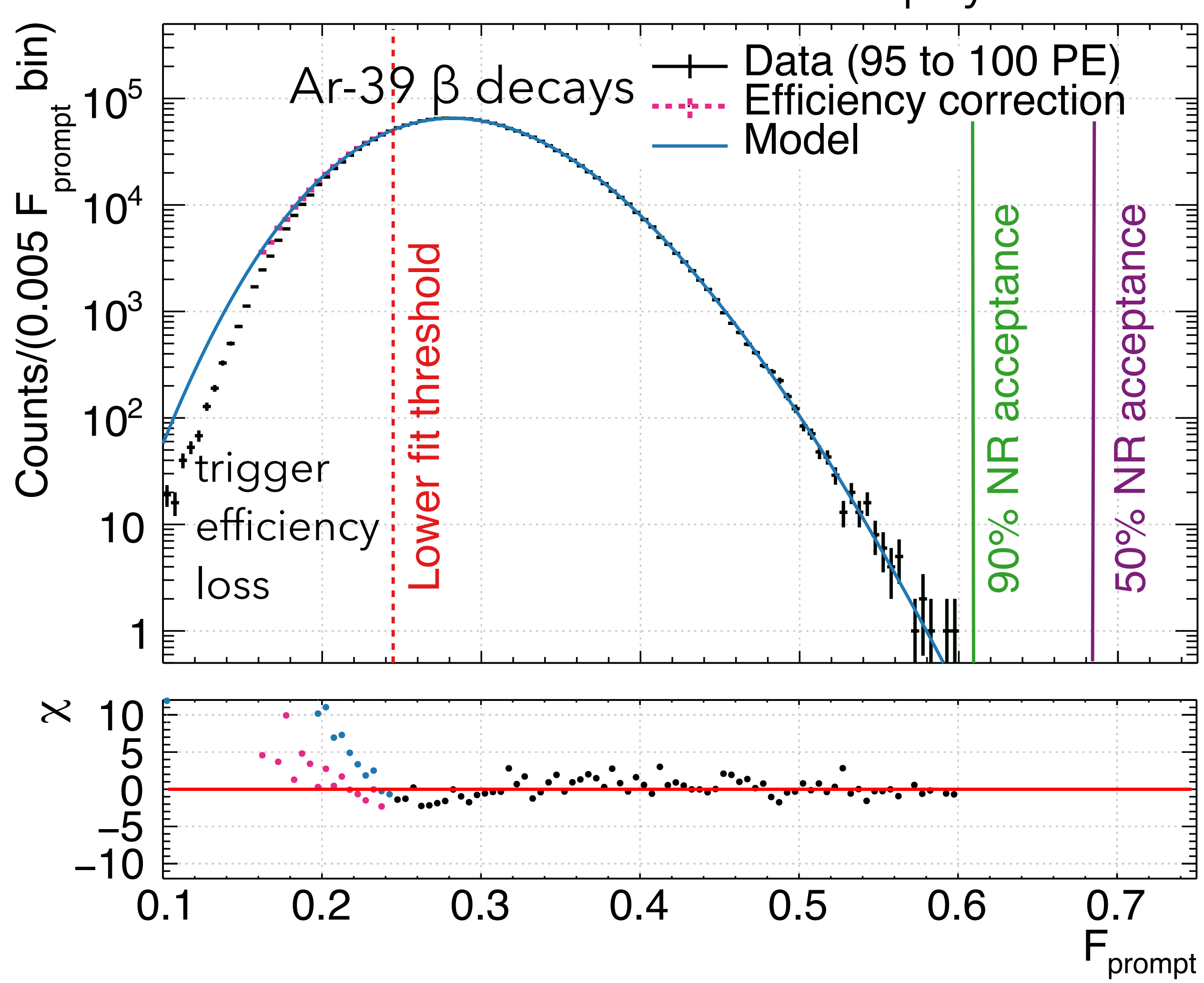
Leakage prediction for ER background @ 90% signal acceptance:
3·10^{-7} in lowest keV
4·10^{-9} in full energy ROI (~50 to 100 keVnr)

With a factor 1000 reduction in Ar-39 activity when using underground argon, a 20 kT detector can easily reach similar discrimination power, given similar light yield.



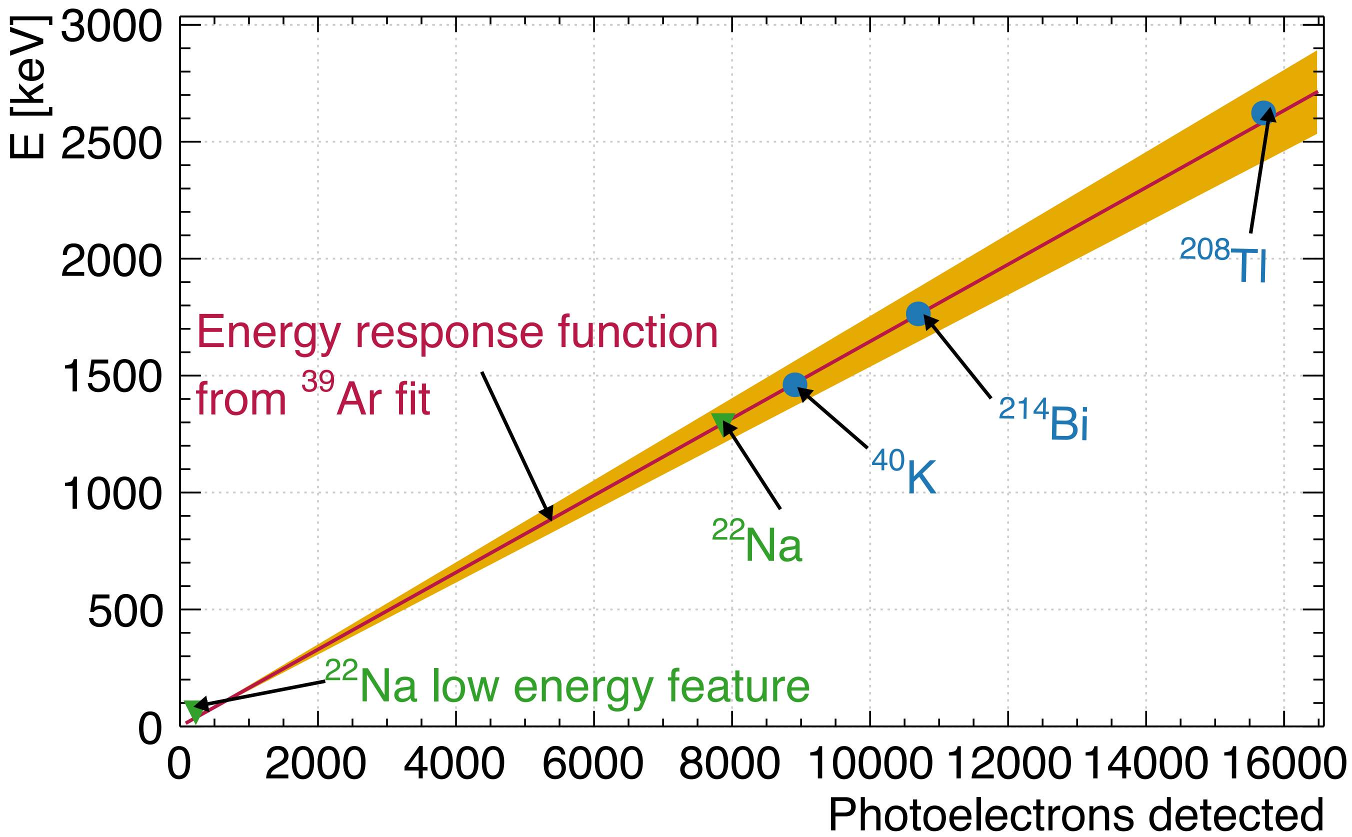
1 keV slice near low edge of energy ROI.

physics data

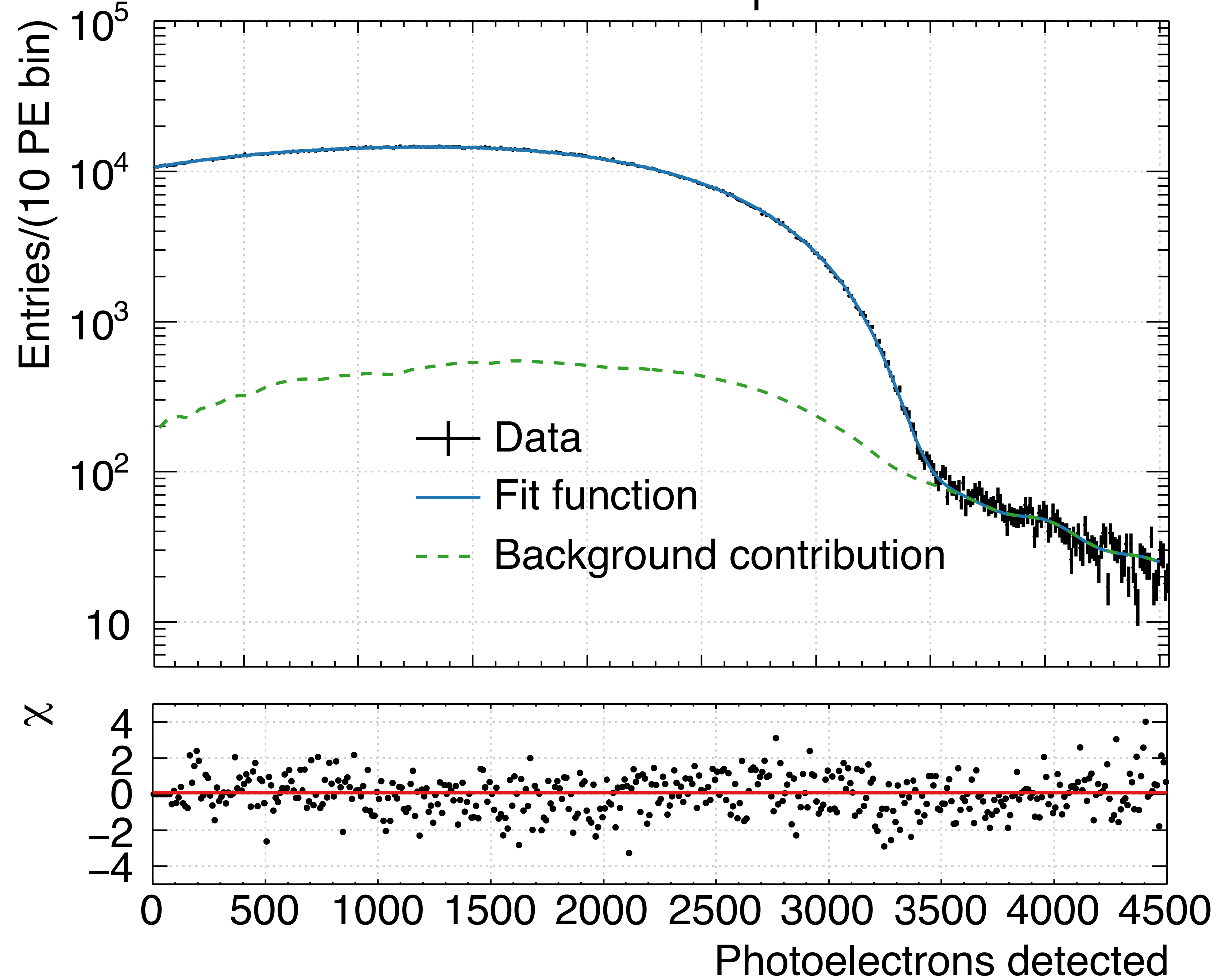


The energy response is calibrated using beta decays from the internal Ar-39 and gammas from an external Na-22 source.

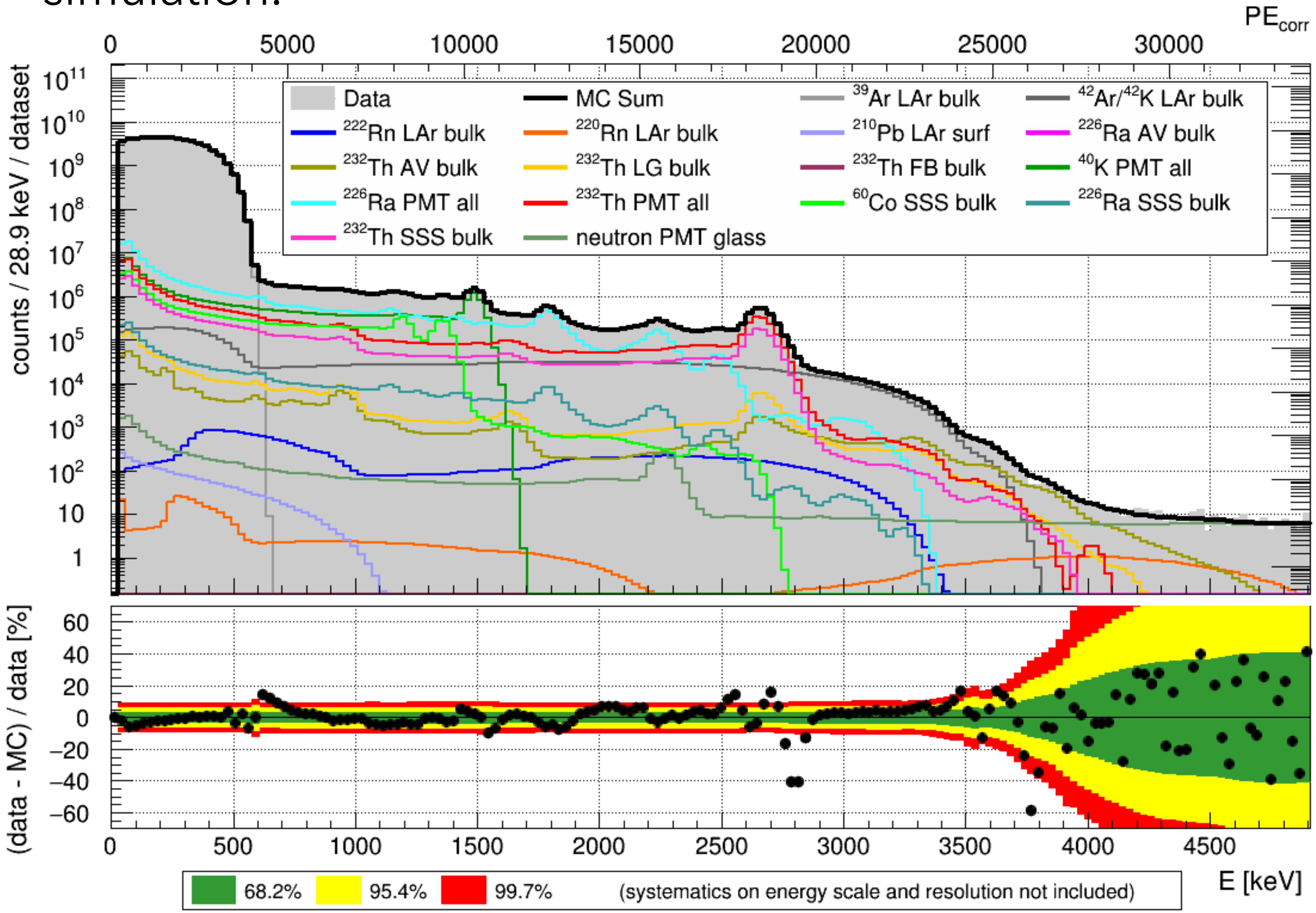
Energy response function (light yield)



Ar-39 spectrum and fit



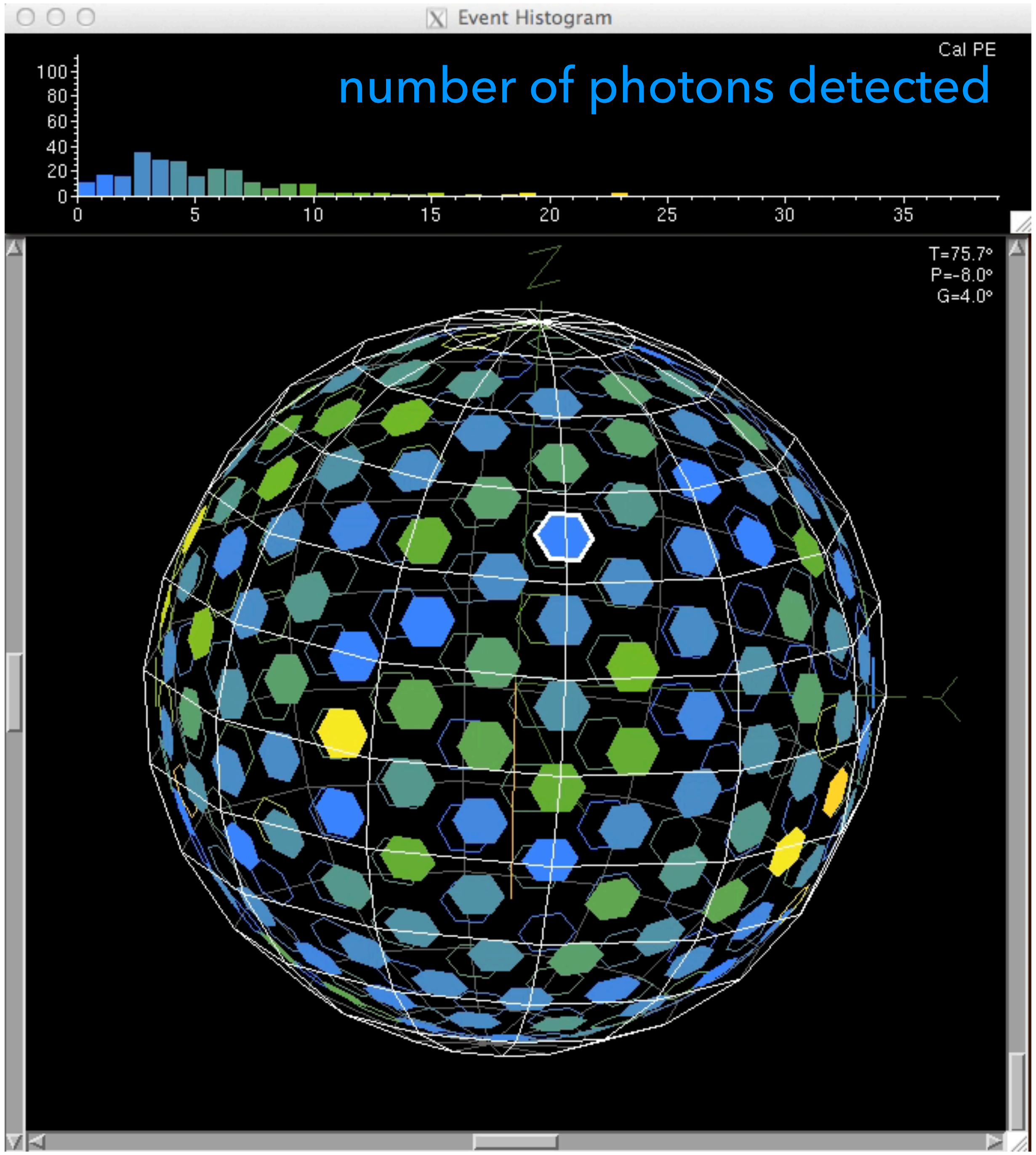
The spectrum of electromagnetic backgrounds matches what we expect from material screening results and MC simulation.



Ajaj, R, G R Araujo, et al. (The DEAP collaboration) "Electromagnetic Backgrounds and Potassium-42 Activity in the DEAP-3600 Dark Matter Detector." *arXiv:1905.05811* (2019).

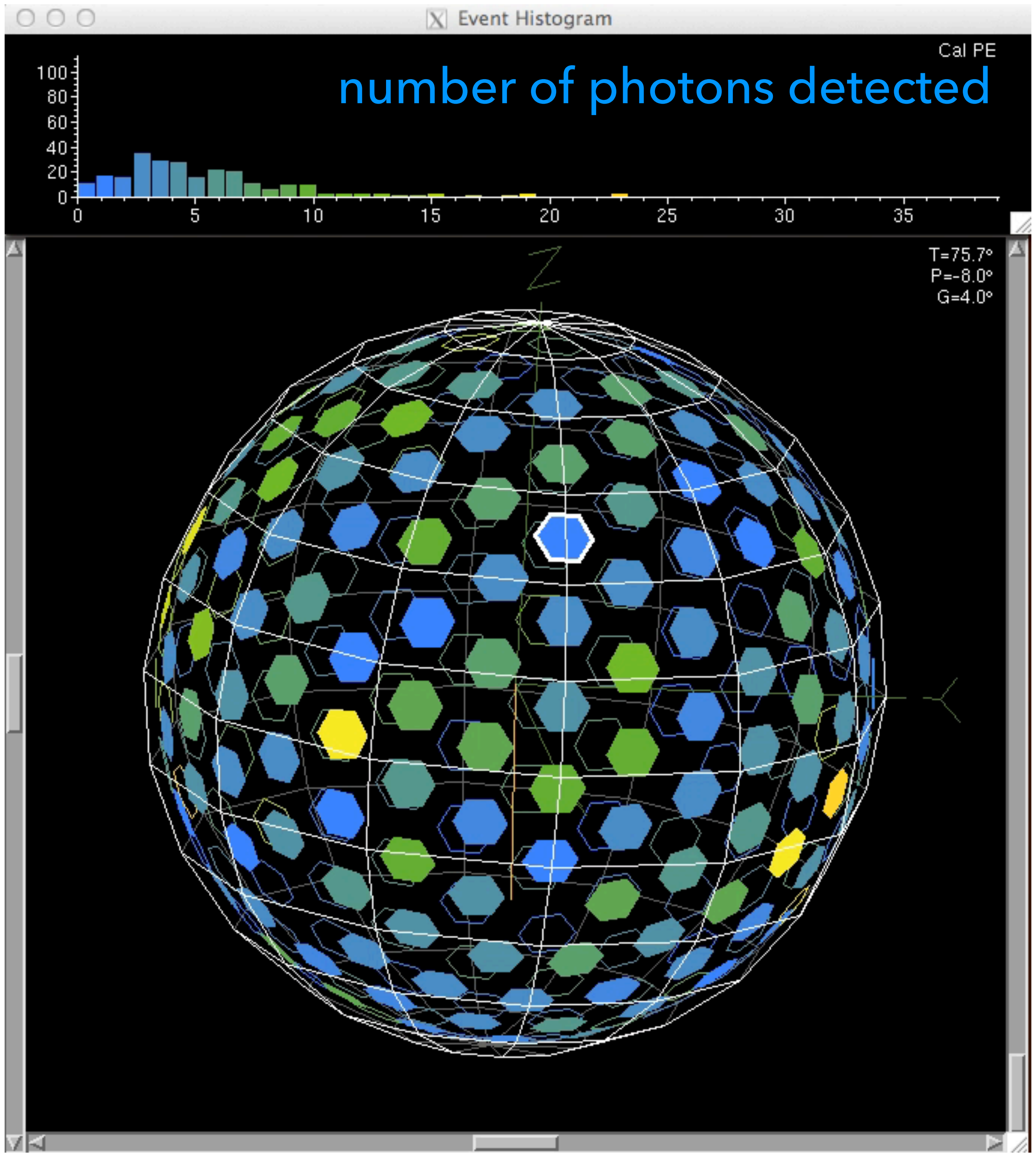
Surface backgrounds are removed by fiducialization with ~2 cm resolution position reconstruction.

"surface backgrounds"

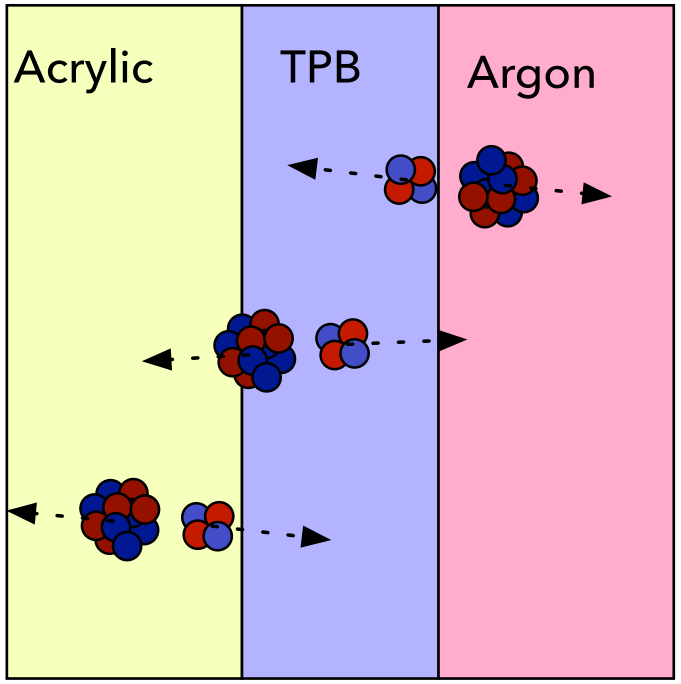


Event position is reconstructed from hit pattern across the PMT array, and photon arrival times. ~2cm resolution at border of ROI.

Surface backgrounds are removed by fiducialization with ~2 cm resolution position reconstruction.



"surface backgrounds"



Event position is reconstructed from hit pattern across the PMT array, and photon arrival times. ~2cm resolution at border of ROI.

Background rates achieved are competitive in Rn-222 level; overall dominated by unexpected contamination of flow guides.

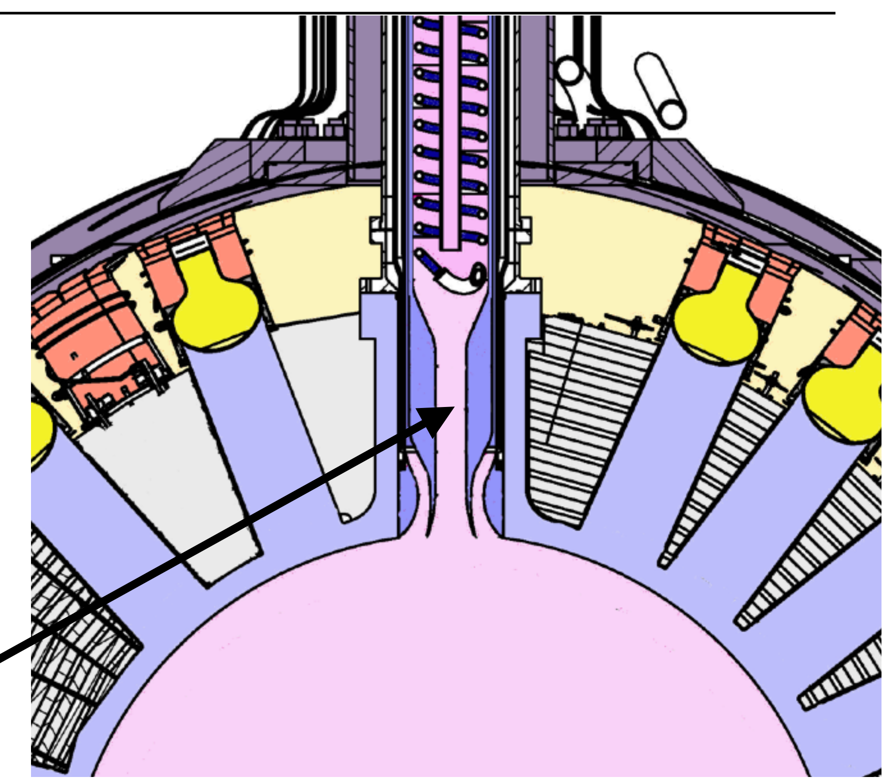
Background predictions in ROI

	Source	N^{CR}	N^{ROI}
β/γ's	ERs	2.44×10^9	0.03 ± 0.01
	Cherenkov	$< 3.3 \times 10^5$	< 0.14
n's	Radiogenic	6 ± 4	$0.10^{+0.10}_{-0.09}$
	Cosmogenic	<0.2	<0.11
α's	AV surface	<3600	< 0.08
	Neck FG	28^{+13}_{-10}	$0.49^{+0.27}_{-0.26}$
	Total	N/A	$0.62^{+0.31}_{-0.28}$

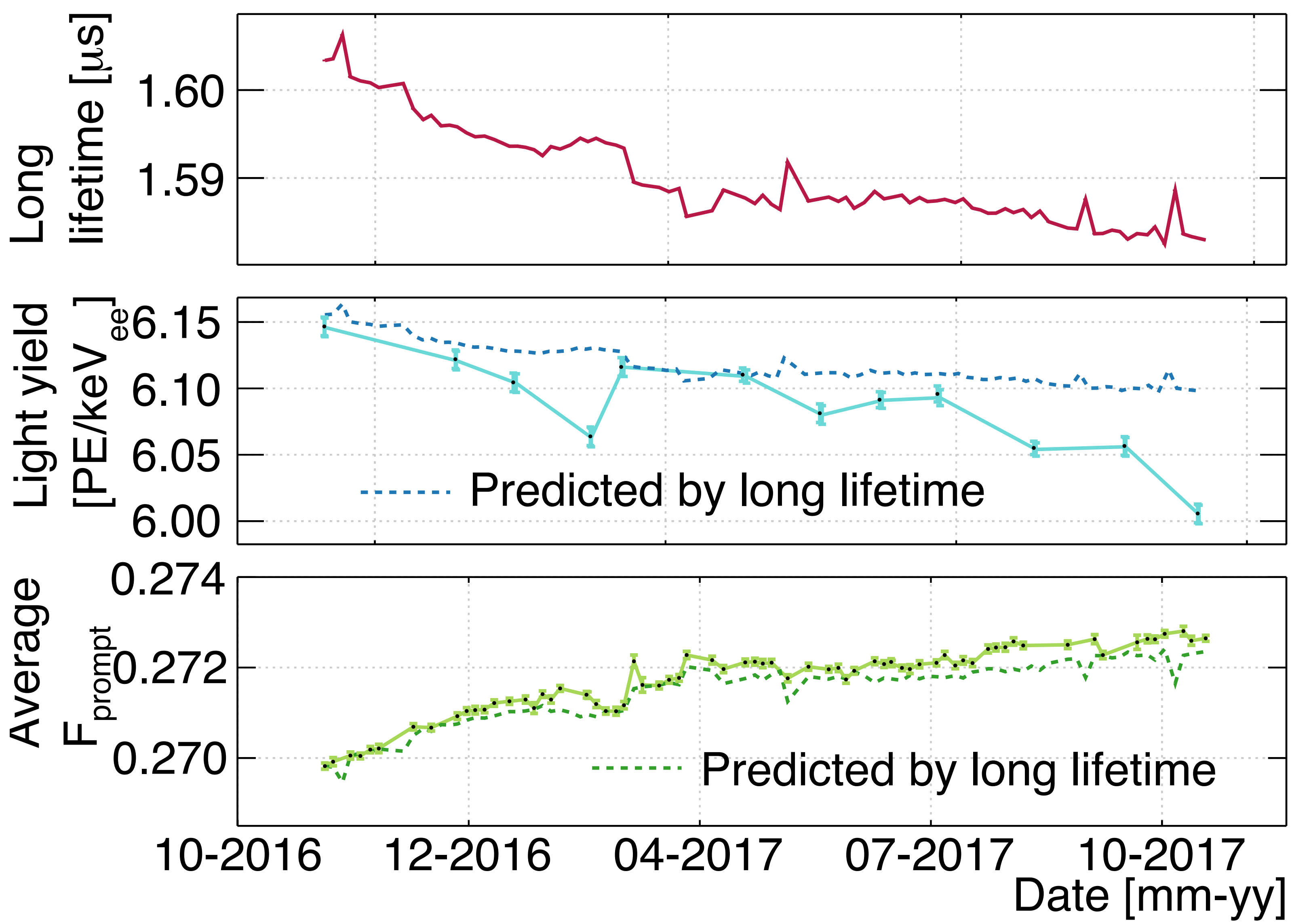
Rn-222 in the bulk target material (measured)

	^{222}Rn activity
DEAP-3600	0.15 µBq/kg
PandaX-II	6.6 µBq/kg
LUX	66 µHz/kg
XENON1T	10 µBq/kg

- PandaX-II: PHYSICAL REVIEW D 93, 122009 (2016)
- LUX: Physics Procedia 61 (2015) 658 – 665
- XENON1T: XeSAT 2017 talk



Detector response stable to better than 5% over a year of data taking.



Observed lifetime of LAr triplet state is very sensitive to LAr purity.

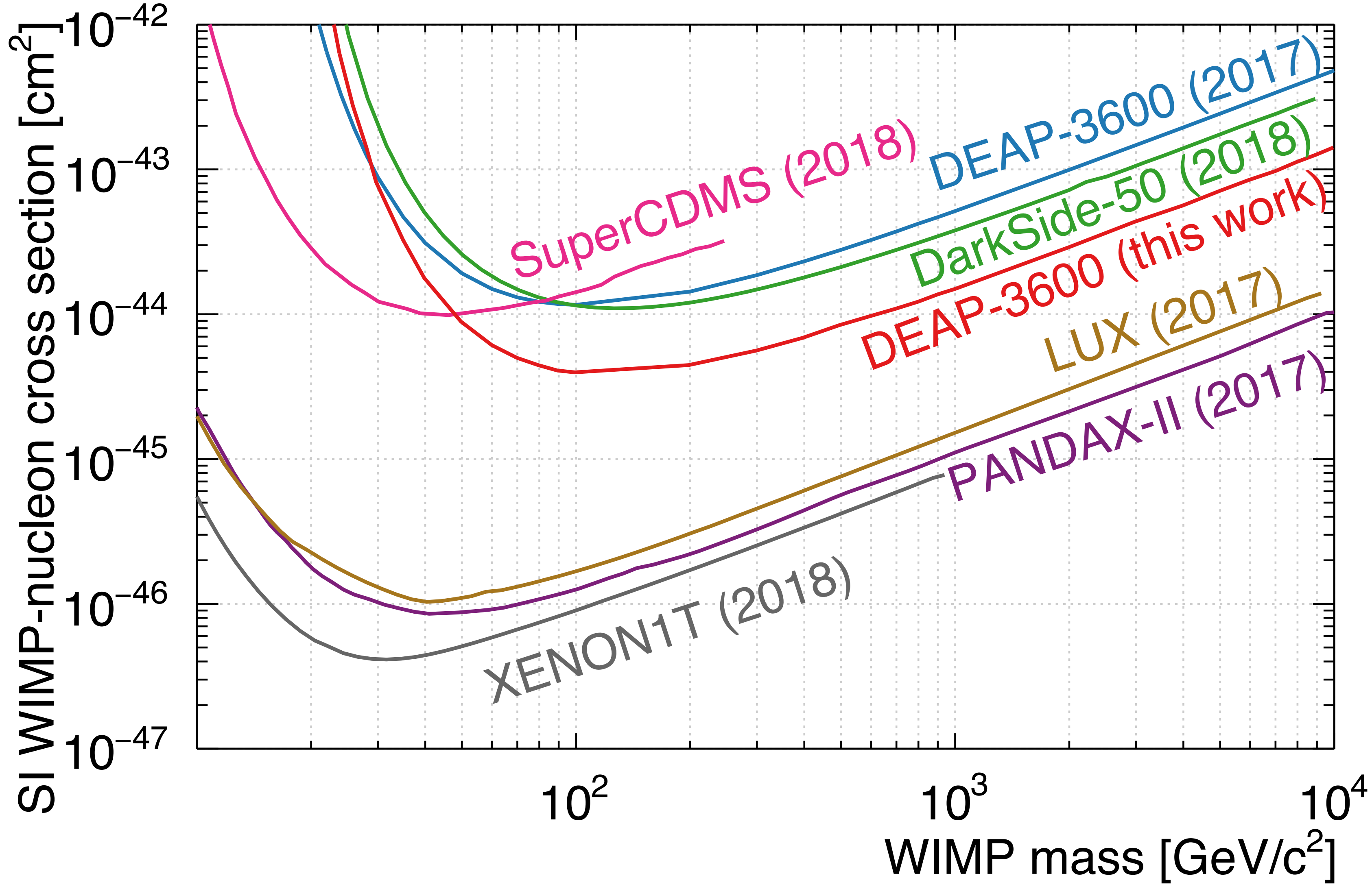
The number of observed photons per energy deposit is sensitive to LAr purity and optical response of detector.

The position of the background population in the PSD parameter

"Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600' at SNOLAB"
PRD 100 (2019); arXiv:1902.04048

Background-free (0.62 background events expected in ROI) search with 758 tonne-days (231 live days) exposure.

Most sensitive limit on LAr above 30 GeV.



"Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600‘ at SNOLAB"
PRD 100 (2019); arXiv:1902.04048

Multiple smaller collaborations with extensive R&D background on detectors based on liquid argon technology have joined to build DarkSide-20k and Argo.

Present

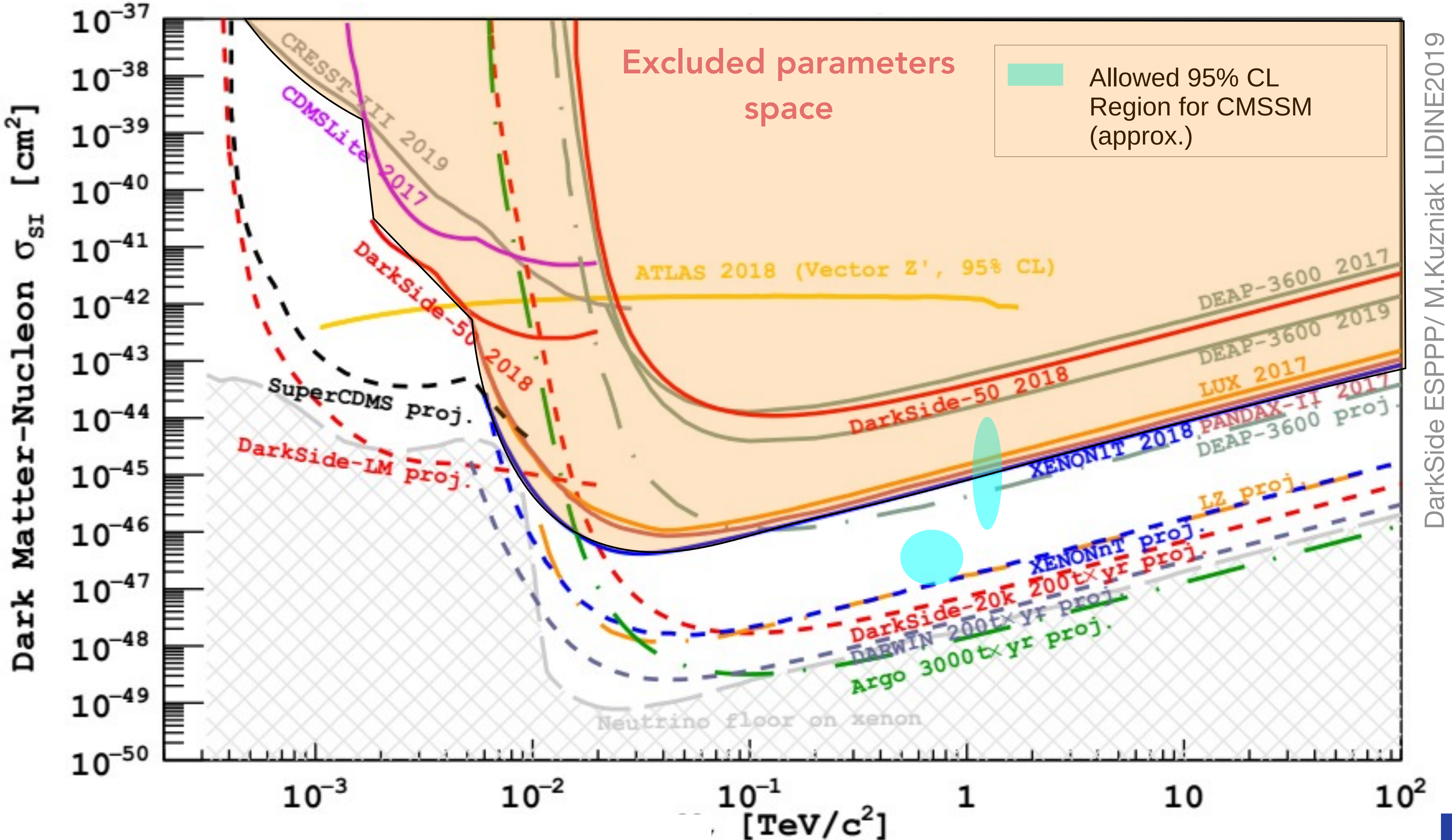
Group	Location	Detector	Target mass	Status/results
DEAP	SNOLAB (Canada)	DEAP-1	7 kg	R&D
		DEAP-3600	1000 kg	running
CLEAN	Yale	MicroCLEAN	4.3 kg	R&D
	SNOLAB	MiniCLEAN	150 kg	decommissioning
DarkSide	LNGS (Italy)	DS-10	10 kg	R&D
		DS-50	46 kg	6E-44
ArDM	Canfranc (Spain)	ArDM-1t	1000 kg	R&D

~350 physicists

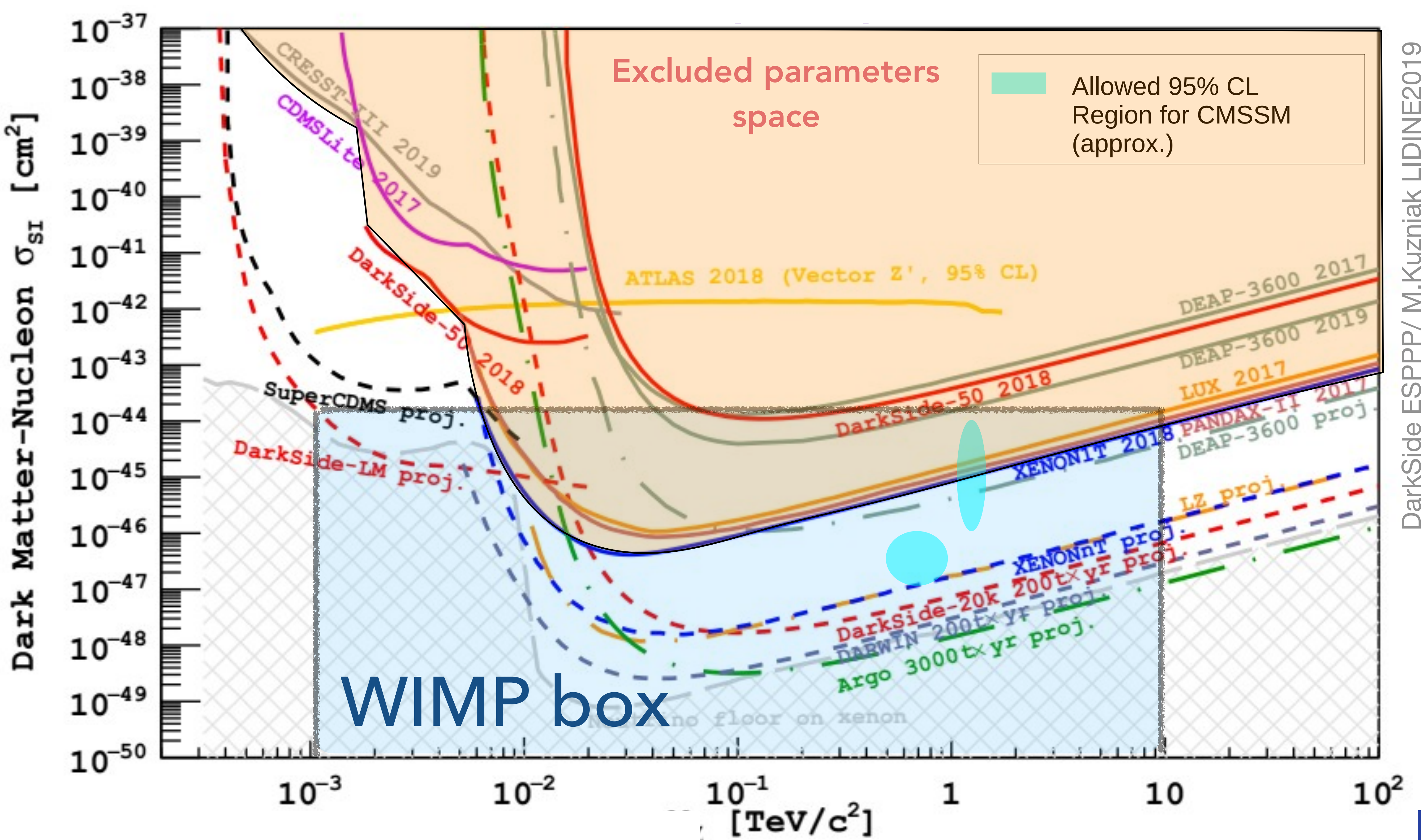
Future

DS-20k @LNGS ~2022 → Argo $\mathcal{O}$(100t) @SNOLAB

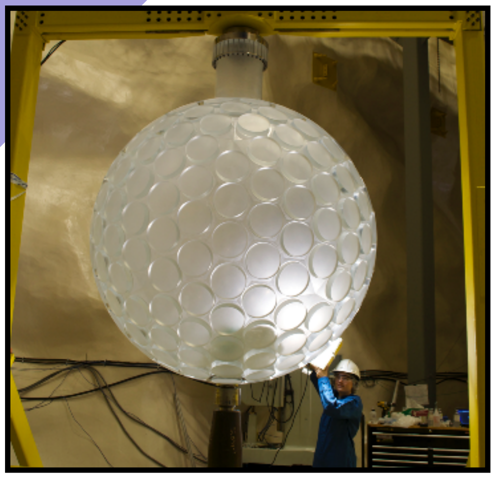
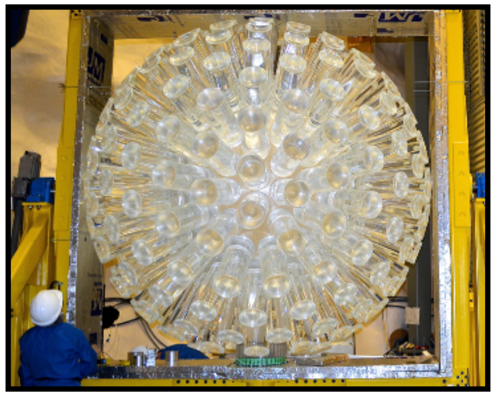
Both argon and xenon-based detectors are proceeding to cover the parameter space down to the "neutrino floor" in the 'high mass region'.

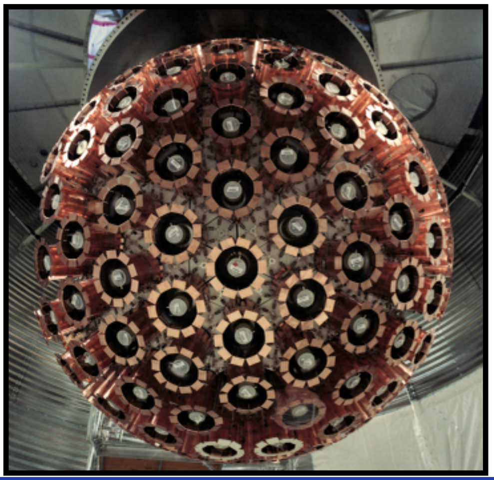


The parameter space for WIMPs has not been fully probed through direct detection.

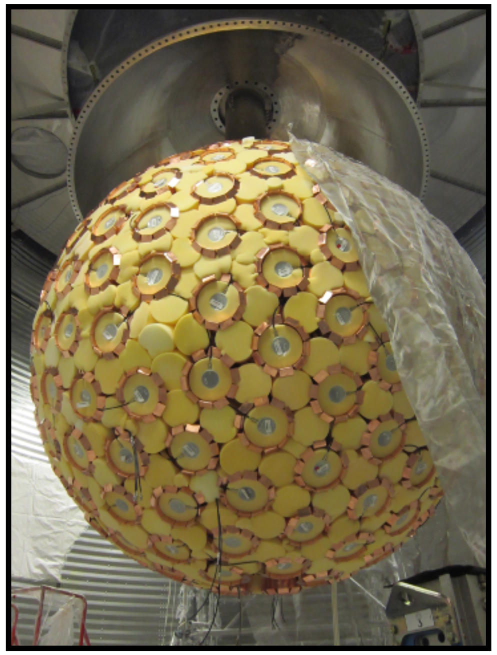


Summary and Outlook



- DEAP is a tonne-scale single-phase LAr detector operated under 6 km water-equivalent rock shielding.
- Analyzed 1 year open dataset (Nov 2016 - Oct 2017)
  - ~758 tonne-day exposure (after data quality cuts) with stable detector conditions
  - Most radon-pure noble gas ever achieved
  - Best PSD on LAr ever demonstrated
  - Background-free search for WIMP-nucleon cross section limit $<3.9\times10^{-45}$ cm^2 @100 GeV/c^2 (90% CL)
- Blind data since Jan 2018




DEAP 3600