Lesson 3

2-phase xenon detectors for WIMP search

Alexandre Lindote, 15th March 2024

Outline

Lesson 1: Evidence and Candidates

- **Evidence**
  - First hints
  - More evidence
  - The Big Picture
- **DM Candidates**
  - Candidates
  - The WIMP paradigm
  - Supersymmetry
- **Our Dark Milky Way**
  - The Standard Halo Model

Outline

Lesson 2: Detection Methods

- **Production in colliders**
- **Indirect detection**
- **Direct detection**
    - Principles
    - Kinematics and expected rates
    - Nucleon scattering cross sections
    - Modulation and directionality
    - Expected WIMP signal and background sources
- **Direct detection technologies**
    - Cryogenic experiments
    - Room temperature detectors
    - Liquid noble element experiments

Outline

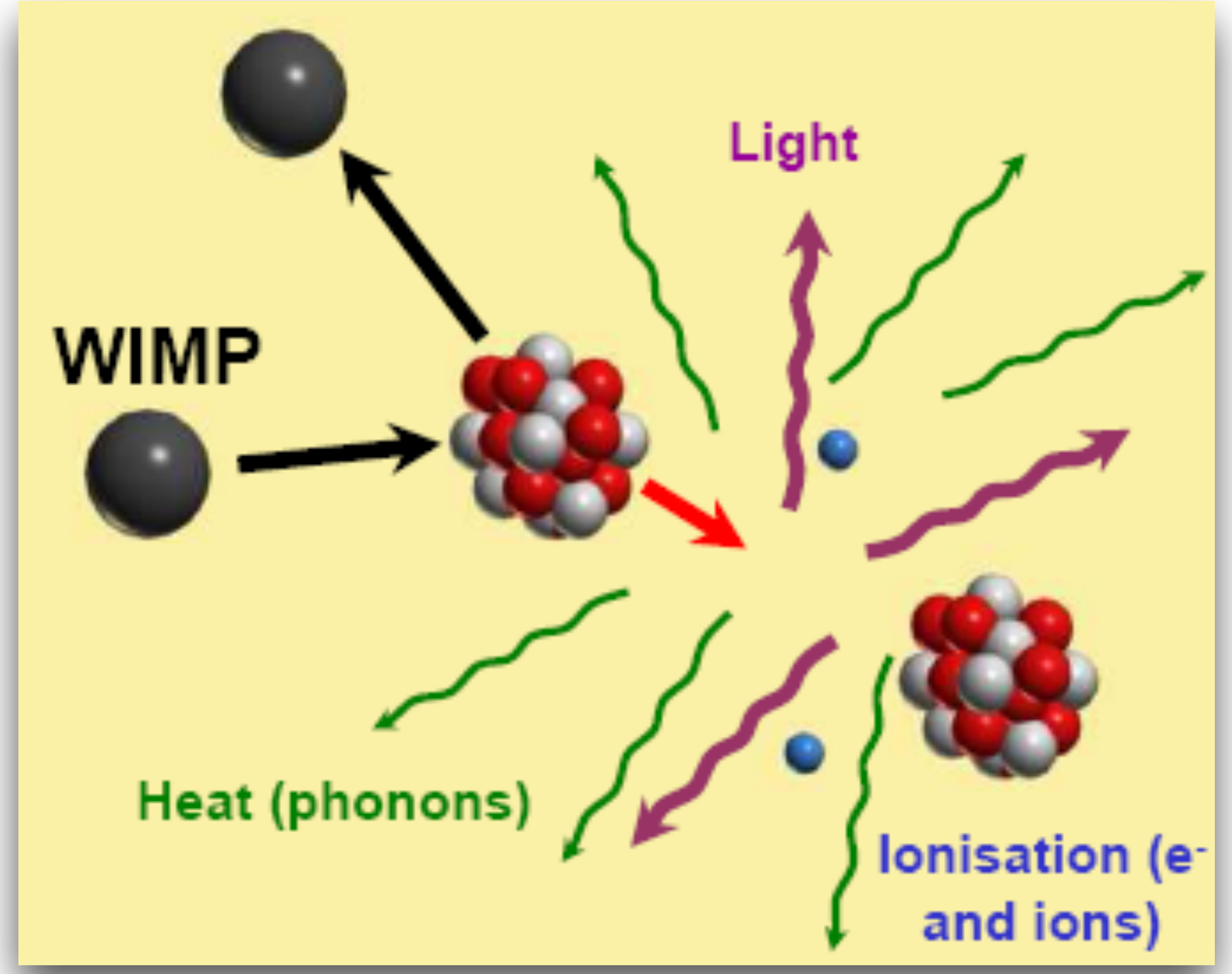
Lesson 3: Direct detection

- 2-phase xenon TPC experiments

Detection technologies

The technological landscape

Will focus on xenon TPCs, but argon based are similar



Interactions produce:

- light
- charge (electrons and ions)
- heat

Energy distribution between the 3 channels depends on the type of interaction (ERs/NRs)

Liquid noble element TPCs

Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, Argo, LUX, WARP, DarkSide, DARWIN, Panda-X, XENON, ZEPLIN, LZ

cold (LN_2)

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

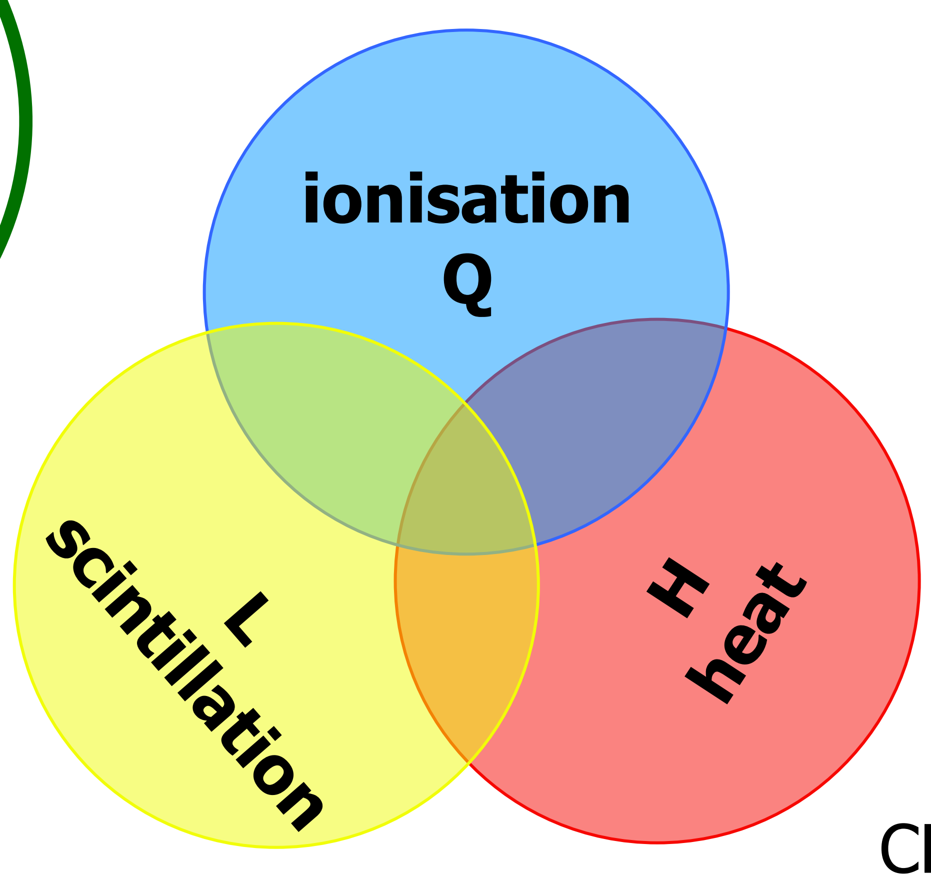
CoGeNT, CDEX, D3, DAMIC, DRIFT, DM-TPC, GENIUS, IGEX, MIMAC, NEWAGE, NEWS, TREX

Heat & Ionisation Bolometers

Targets: Ge,Si

CDMS, EDELWEISS, SuperCDMS

cryogenic (<50 mK)



Scintillators

Targets: NaI, Xe, Ar

ANAIS, MiniCLEAN, DAMA, ZEPLIN-I, DEAP-3600, DM-ICE, KIMS, LIBRA, PICOLON, NAIAD, SABRE, XMASS

Bolometers

Targets: Ge, Si, Al_2O_3, TeO_2

CRESST-I, CUORE, CUORICINO

Light & Heat Bolometers

Targets: $CaWO_4$, BGO, Al_2O_3

CRESST, ROSEBUD

cryogenic (<50 mK)

Bubbles & Droplets

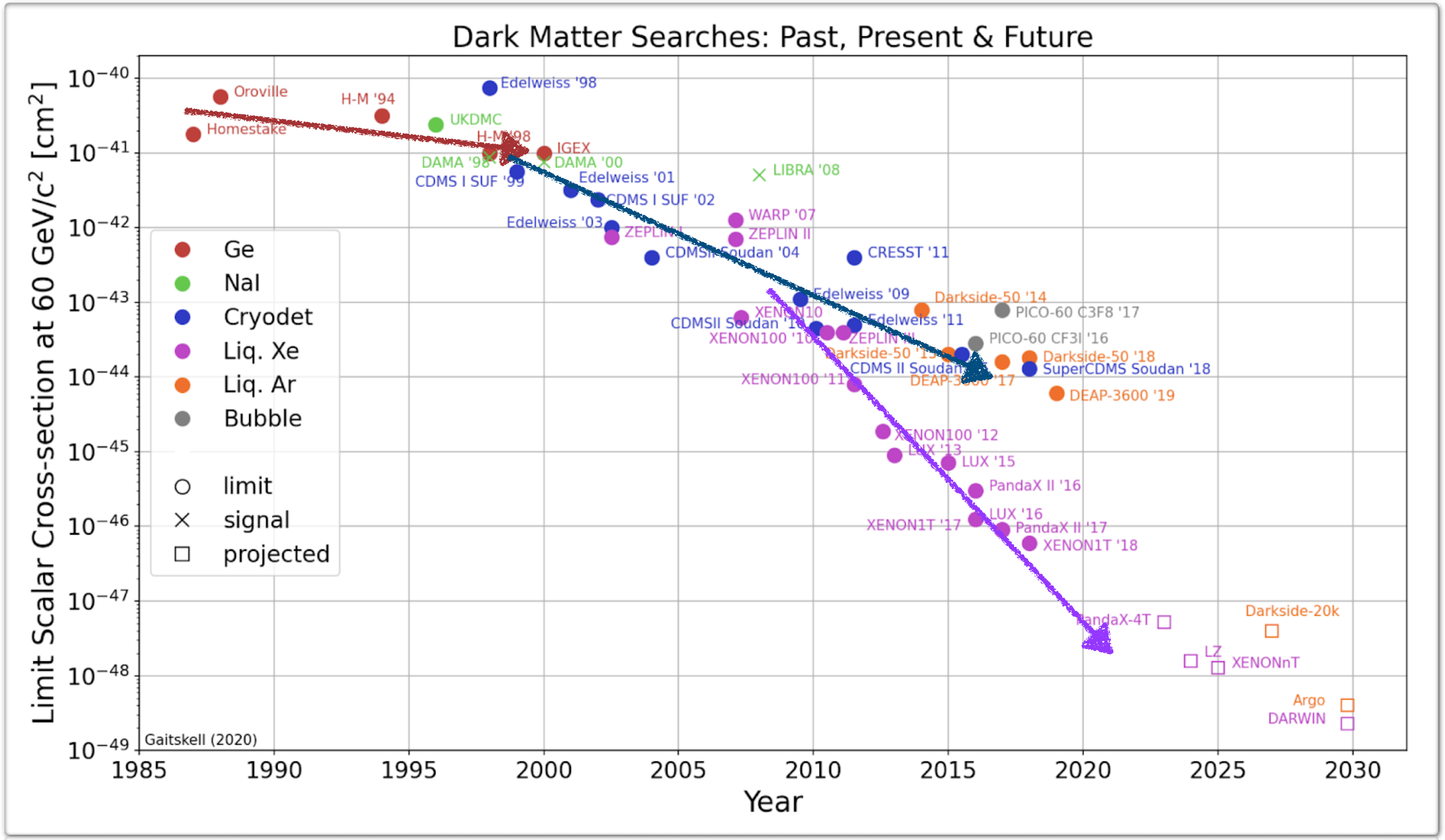
CF_3Br, CF_3I, C_3F_8, C_4F_{10}

COUPP, PICASSO, PICO, SIMPLE

Measuring two channels simultaneously allows for discrimination between ERs (backgrounds) and NRs

Detection technologies

The effect of new technologies

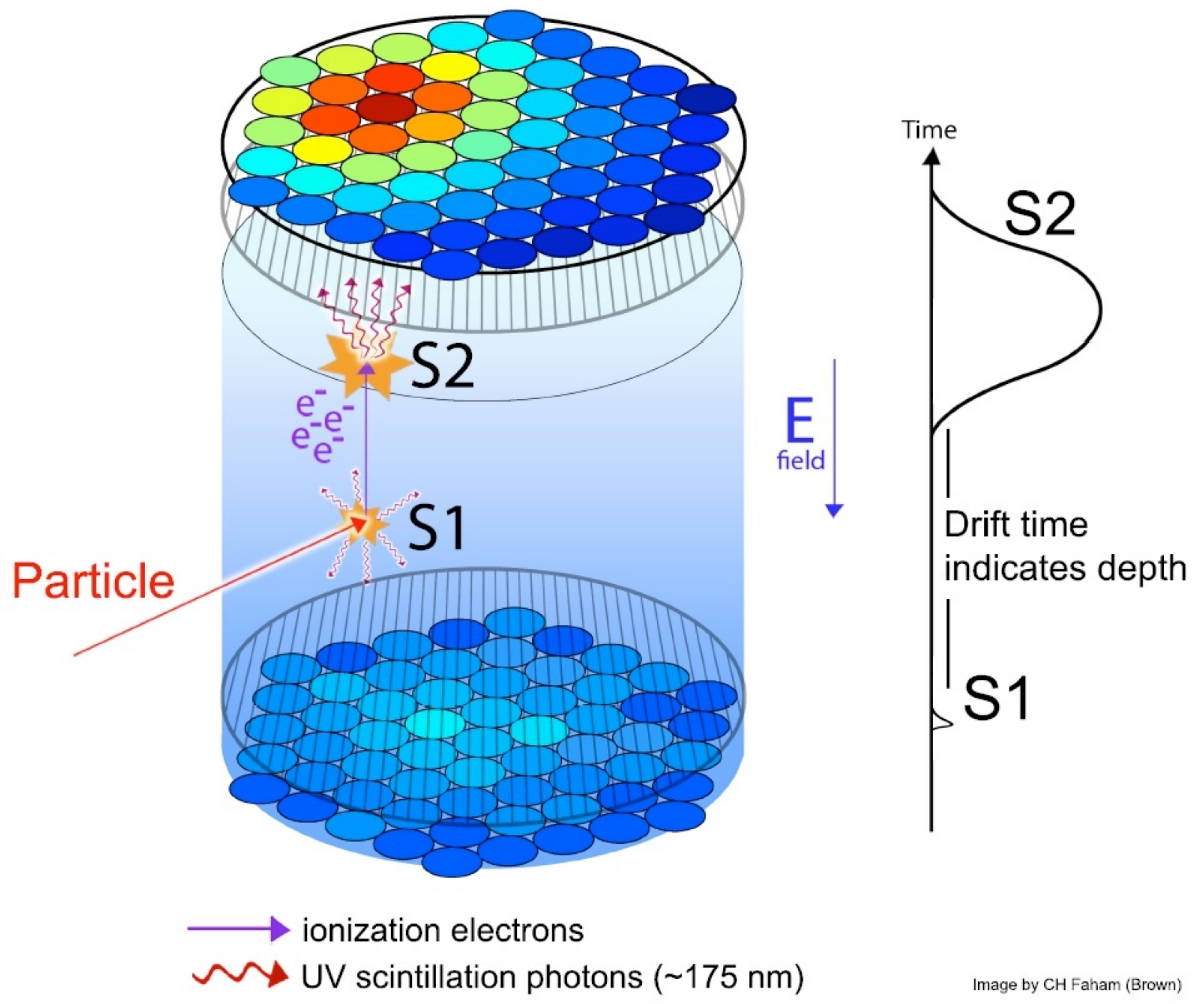


Even faster than the computing power evolution: a factor of 10 every 5 years

Operation principles

2-Phase Xenon TPCs

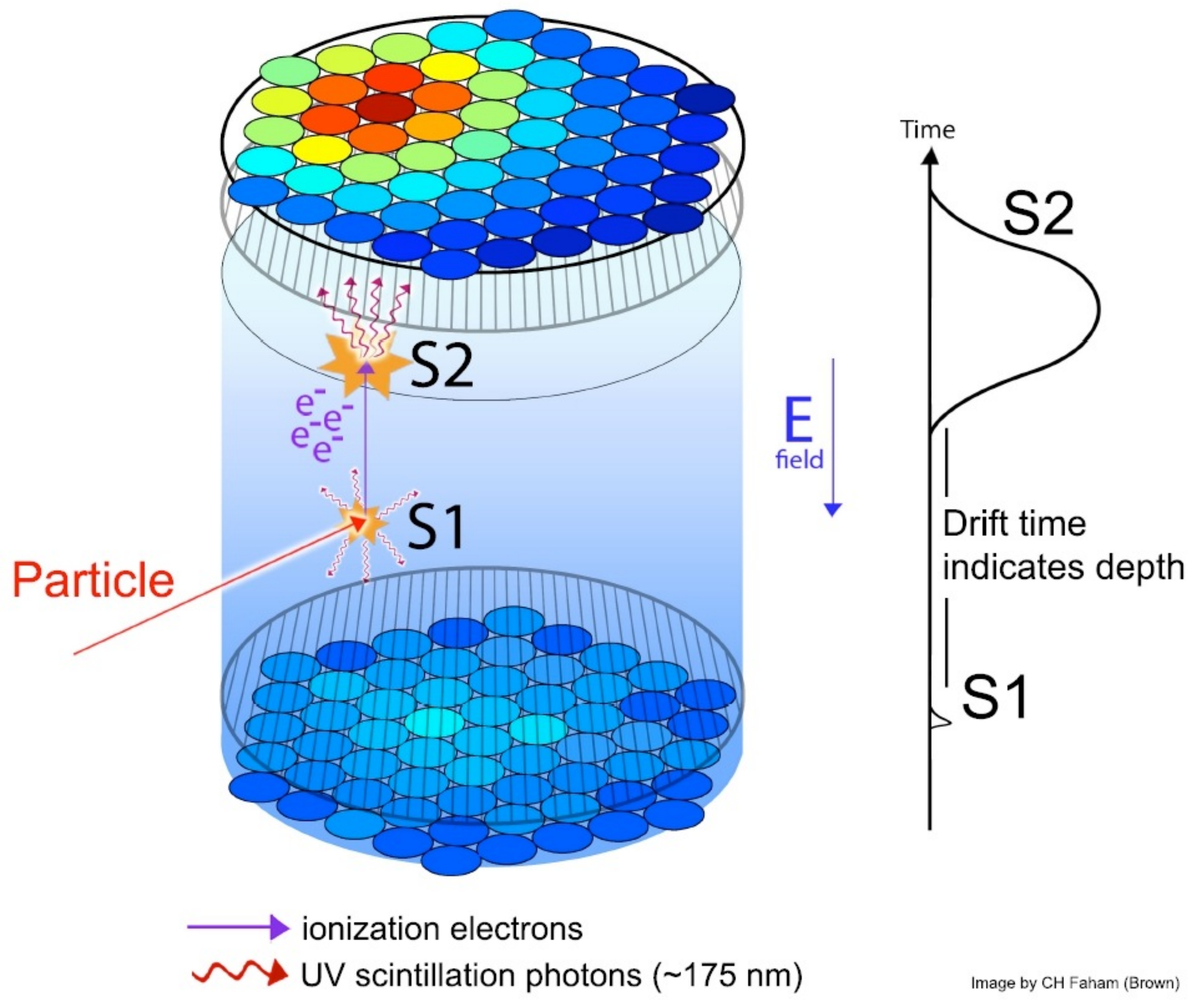
Working principle



- TPC → Time Projection Chamber
- A volume of liquid topped by a layer of gas ~(-100 C, 1.5 bar)
- An electric field is applied in the liquid, to drift ionisation electrons to the gas
- A stronger electric field is applied in the gas, to extract electrons and accelerate them

2-Phase Xenon TPCs

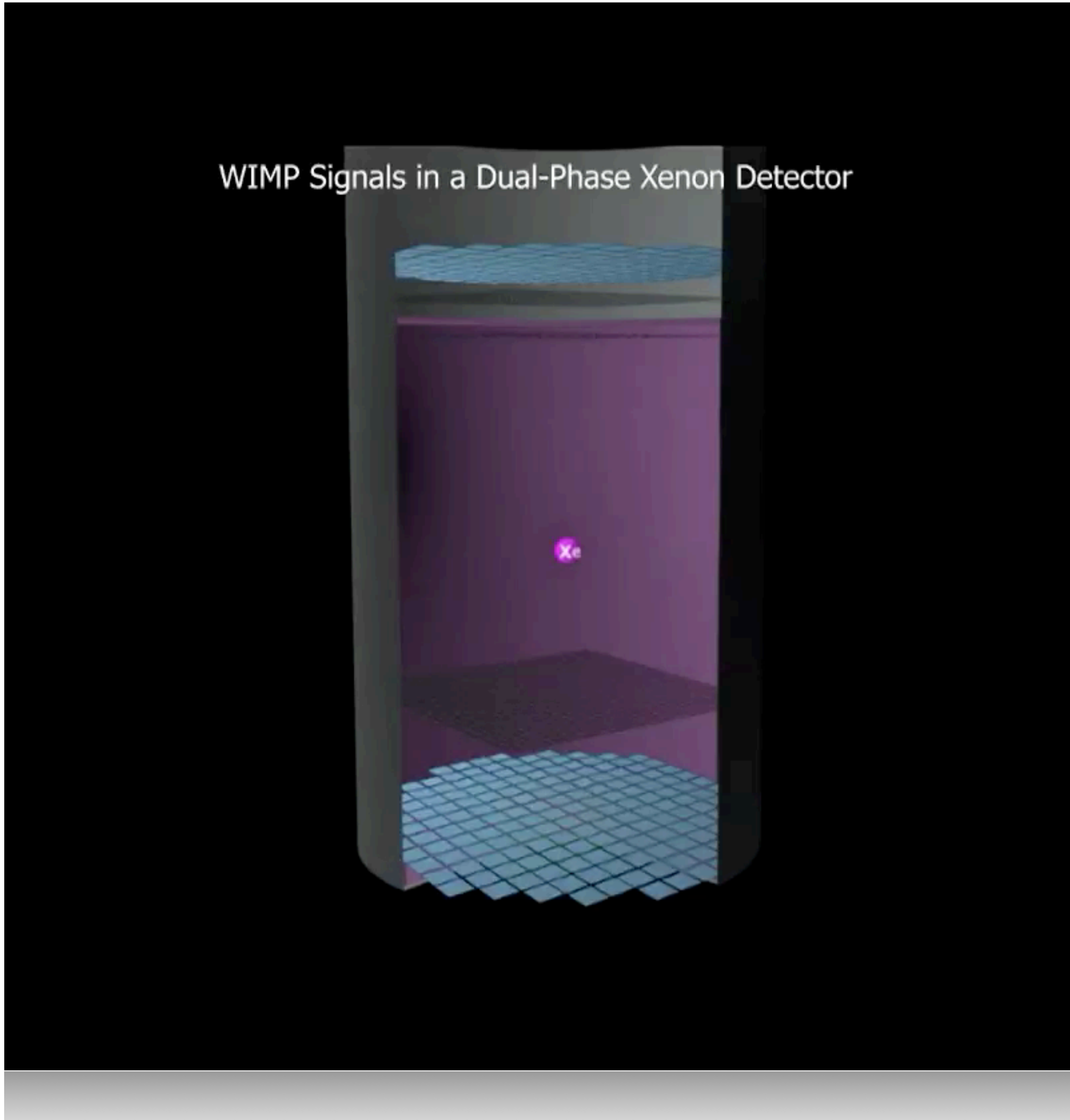
Working principle



- Each particle interaction produces two signals:
  - S1 - prompt scintillation light in the liquid
  - S2 - electroluminescence in the gas (much larger than S1)
- These signals are observed by one or two light sensor arrays
- From these 2 signals we get:
  - energy of the interaction
  - 3D position reconstruction
  - Nuclear/electron recoil discrimination

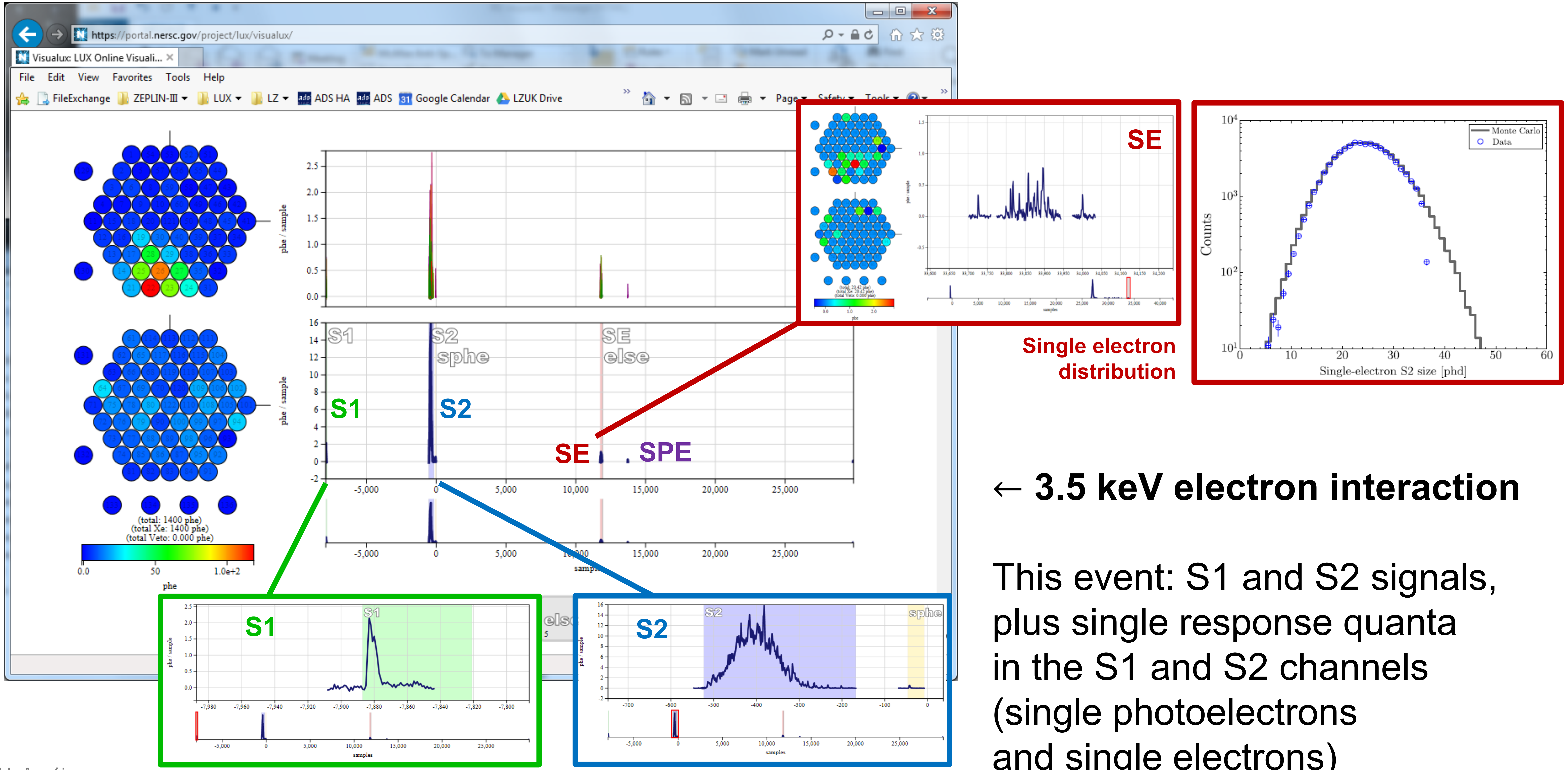
2-Phase Xenon TPCs

Interactions in a xenon TPC



2-Phase Xenon TPCs

Example event — from the LUX detector



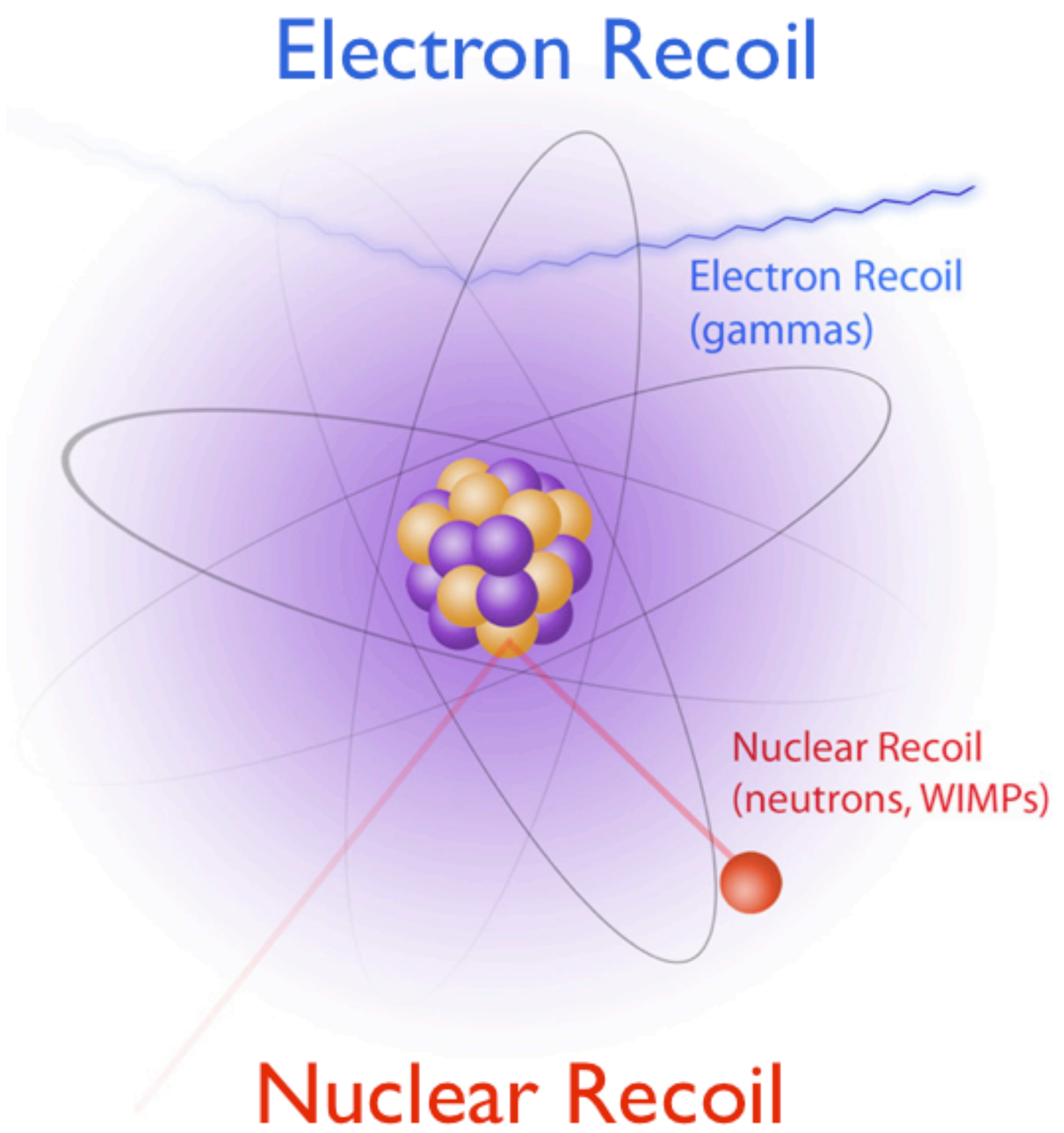
← **3.5 keV electron interaction**

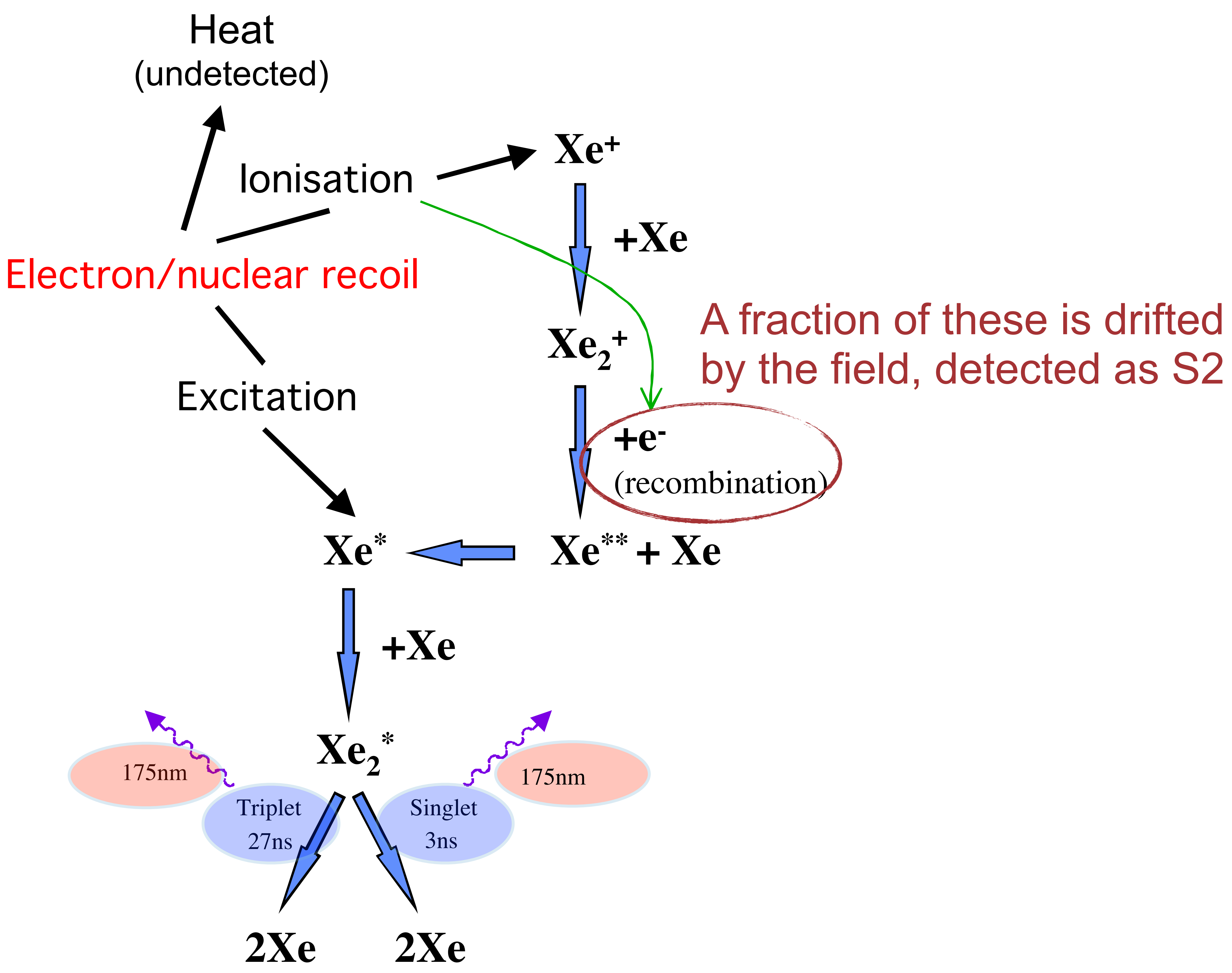
This event: S1 and S2 signals, plus single response quanta in the S1 and S2 channels (single photoelectrons and single electrons)

H. Araújo

2-Phase Xenon TPCs

Energy reconstruction





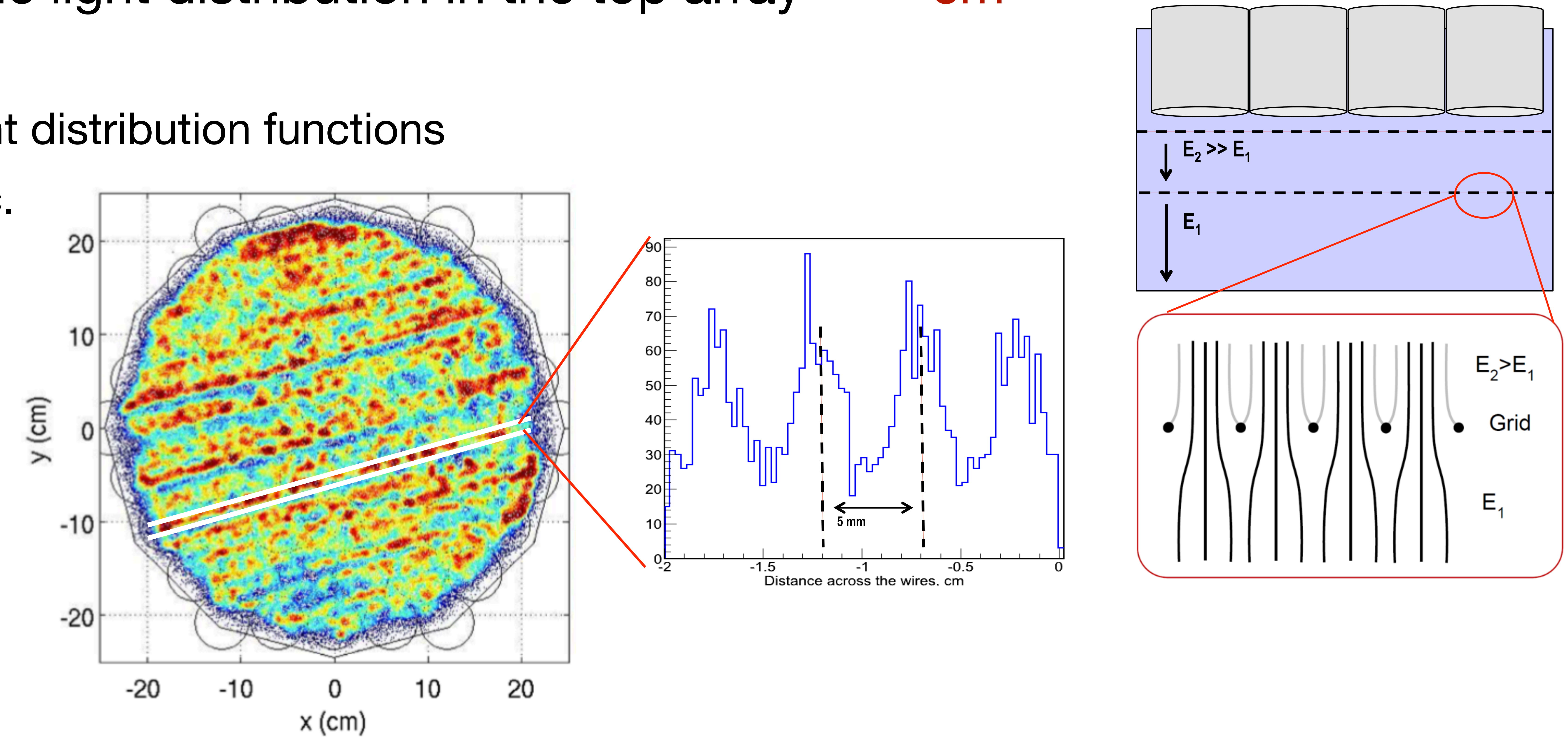
$$E_{\text{total}} = W \cdot (n_e + n_\gamma) = W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2} \right)$$

In NRs a larger fraction of the energy goes to the heat channel — a "quenching" factor must be applied

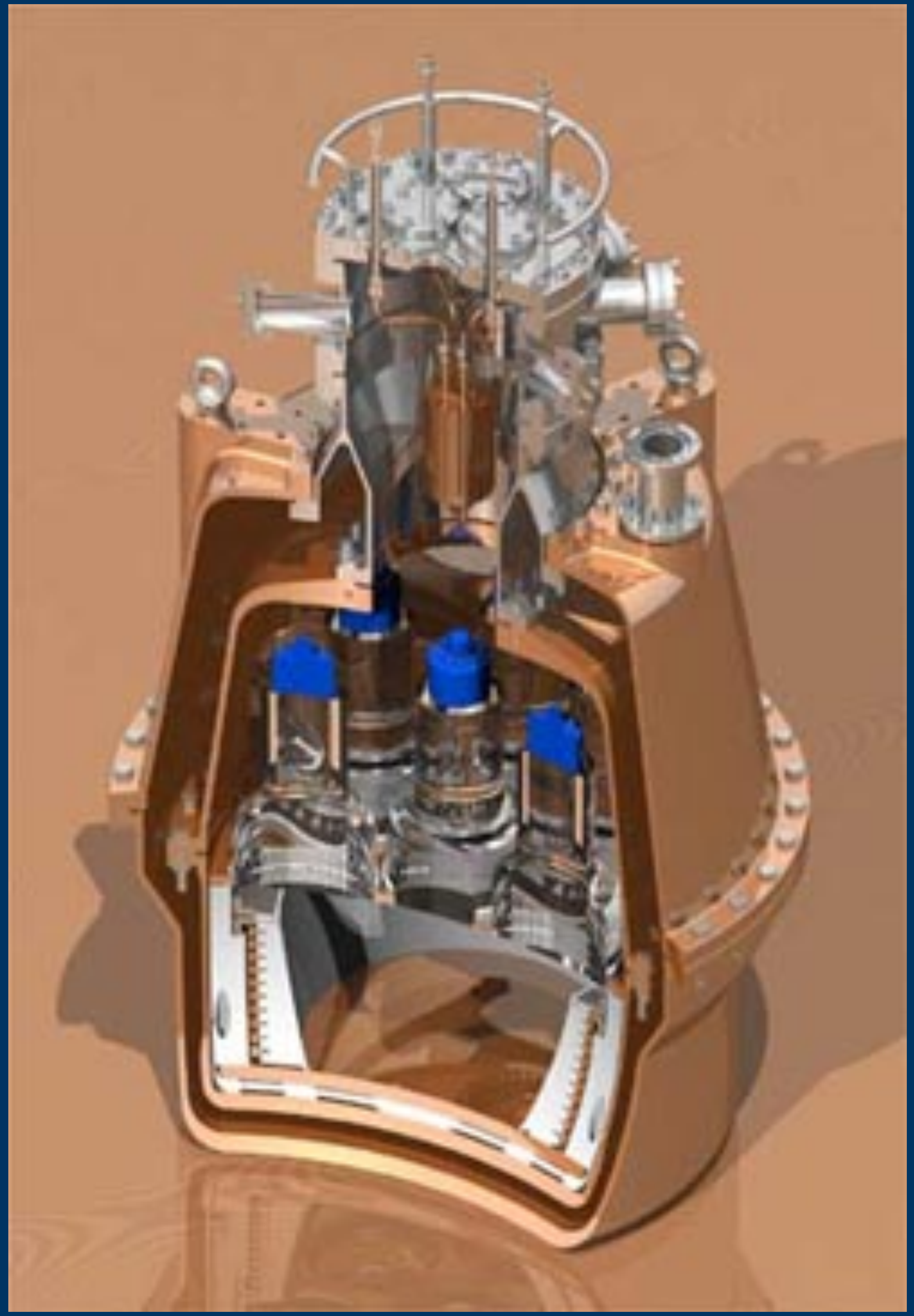
2-Phase Xenon TPCs

3D position reconstruction

- **Z position:** obtained from the time difference between the 2 signals — ~ mm (electron cloud drift time x drift speed)
- **XY position:** from the light distribution in the top array — ~ cm
  - Simple centroid
  - Minimisation with light distribution functions
  - Machine learning, etc.



Real examples

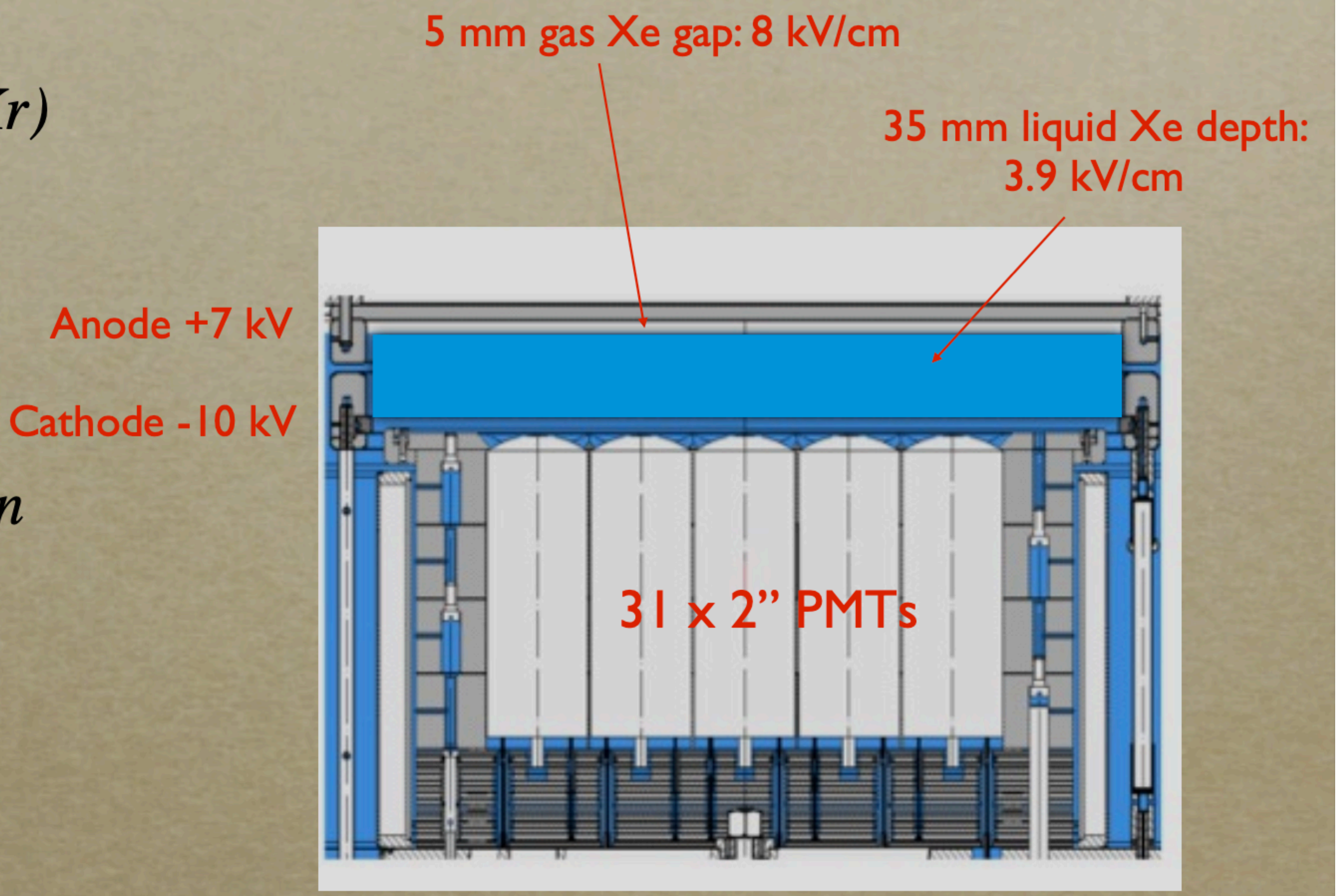


ZEPLIN-II — first 2-phase xenon TPC used for WIMP search

2-Phase Xenon TPCs

Real examples — ZEPLIN-III (2008-2011)

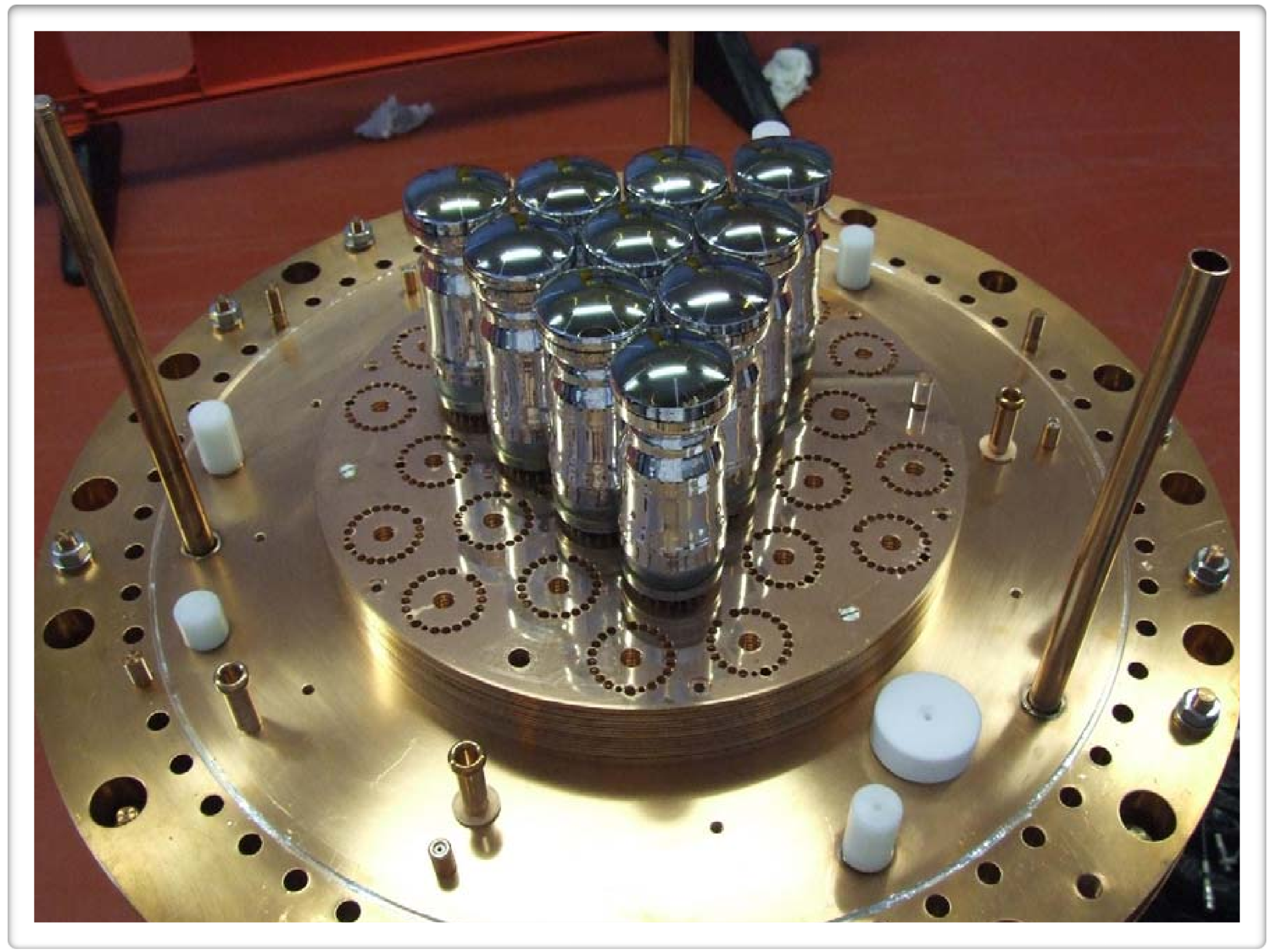
- *Active volume with 12 kg of low background LXe (40 yr old - low Kr)*
- *Open plan with no surfaces (fiducial volume from position reconstruction)*
- *High field, improved discrimination*
- *Construction in oxygen free Cu (electron beam welded)*
- *31 2" PMTs (QE ~ 30%) in the liquid:*
  - *improved primary light collection*



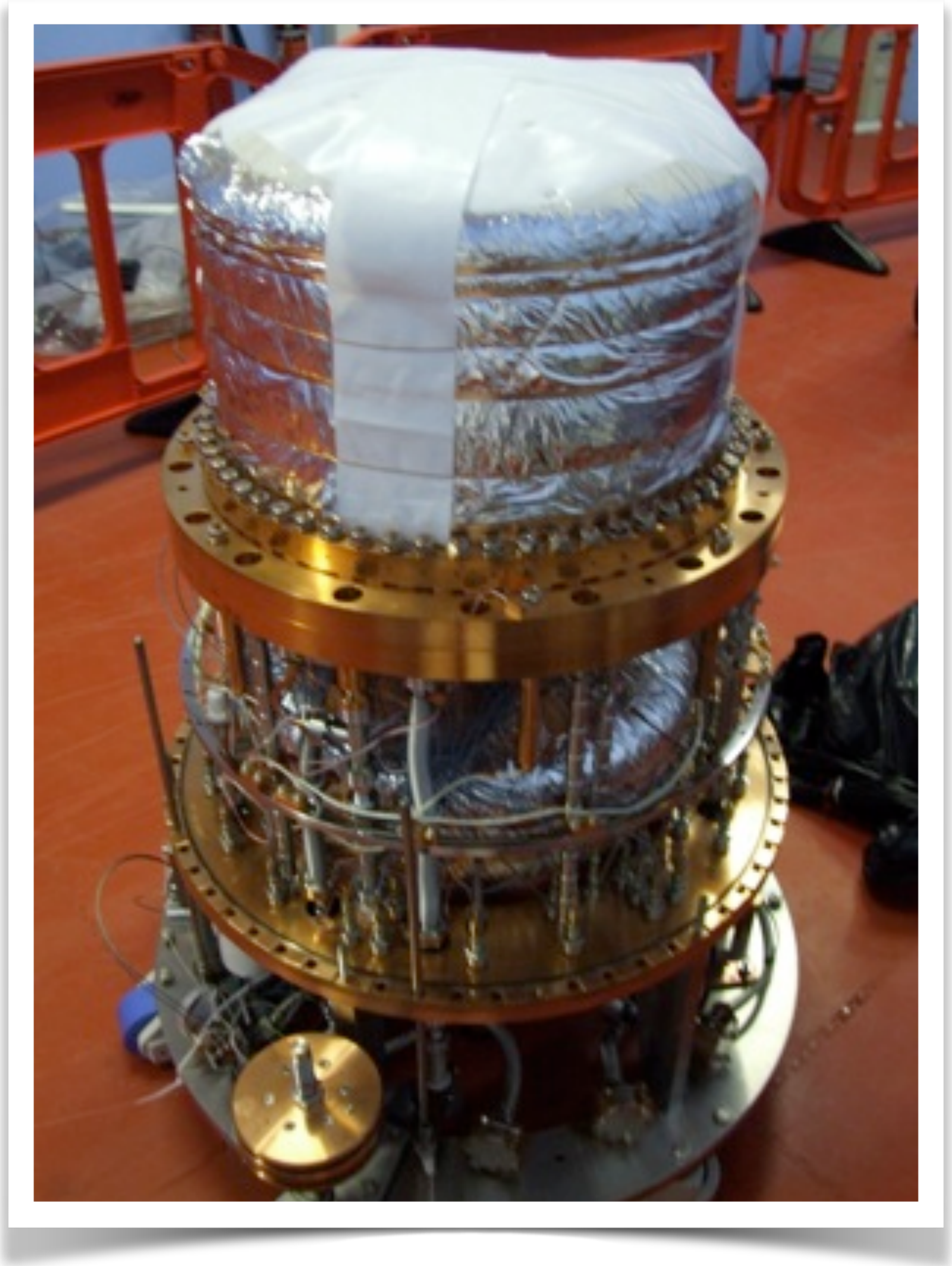
2-Phase Xenon TPCs

Real examples — ZEPLIN-III (2008-2011)

31 PMTs



Installed in the Boulby lab (UK), 1100 m deep

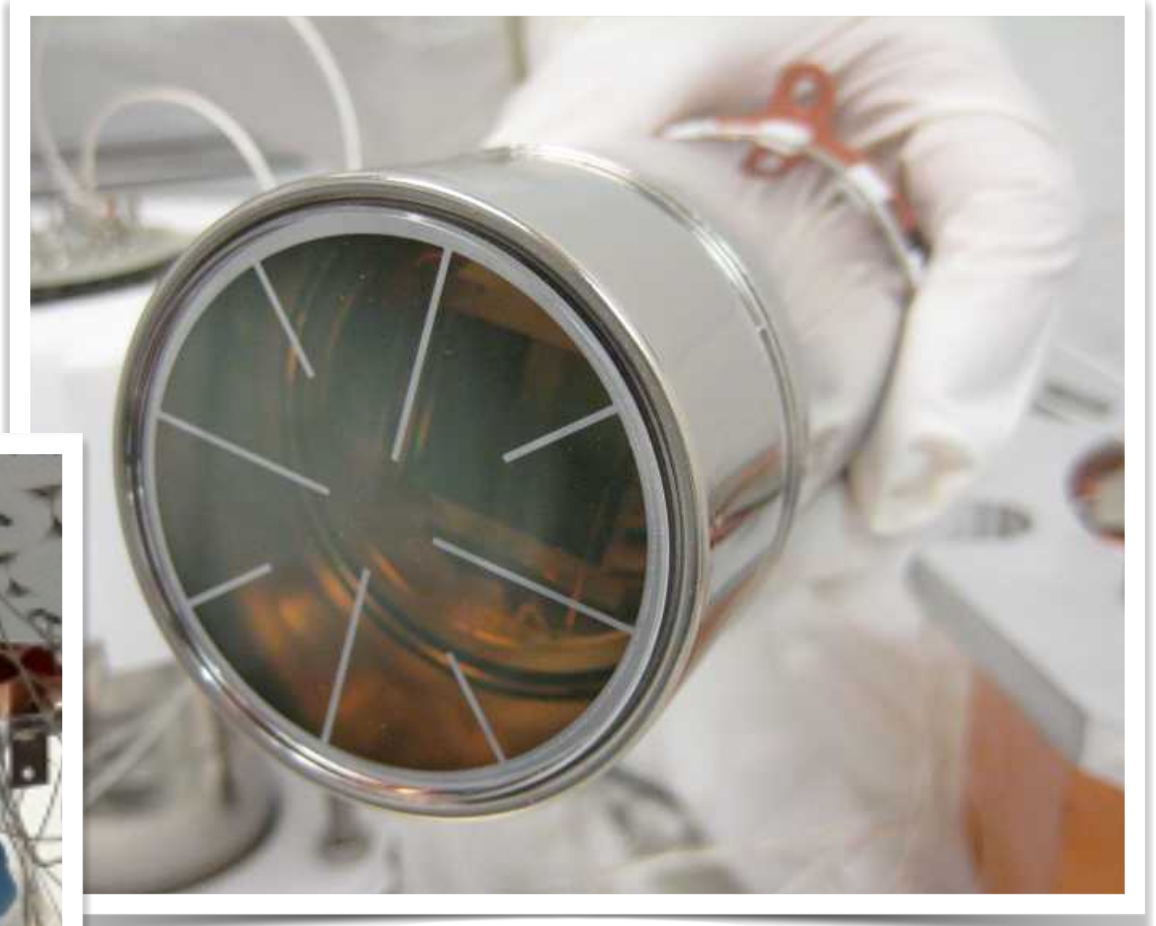


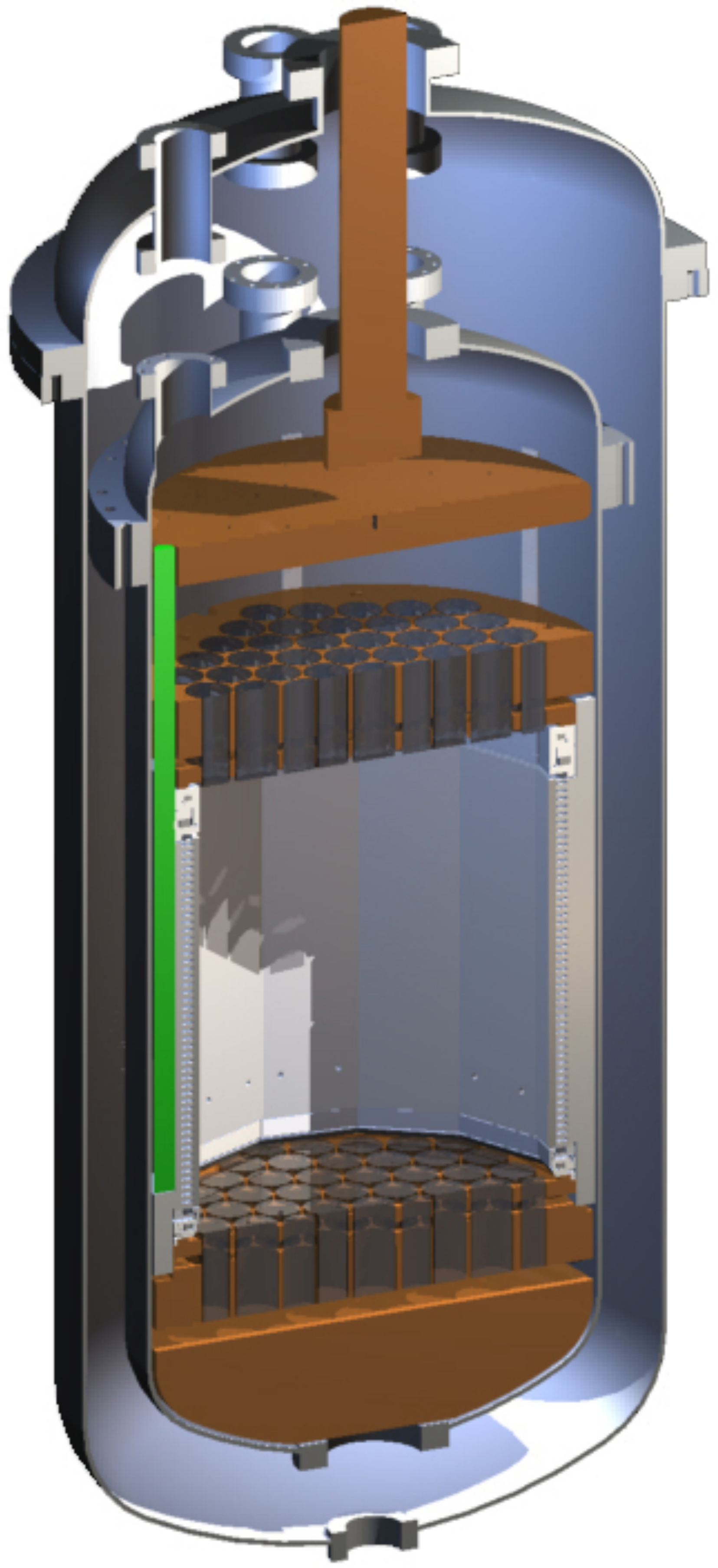
12 kg of liquid xenon

2-Phase Xenon TPCs

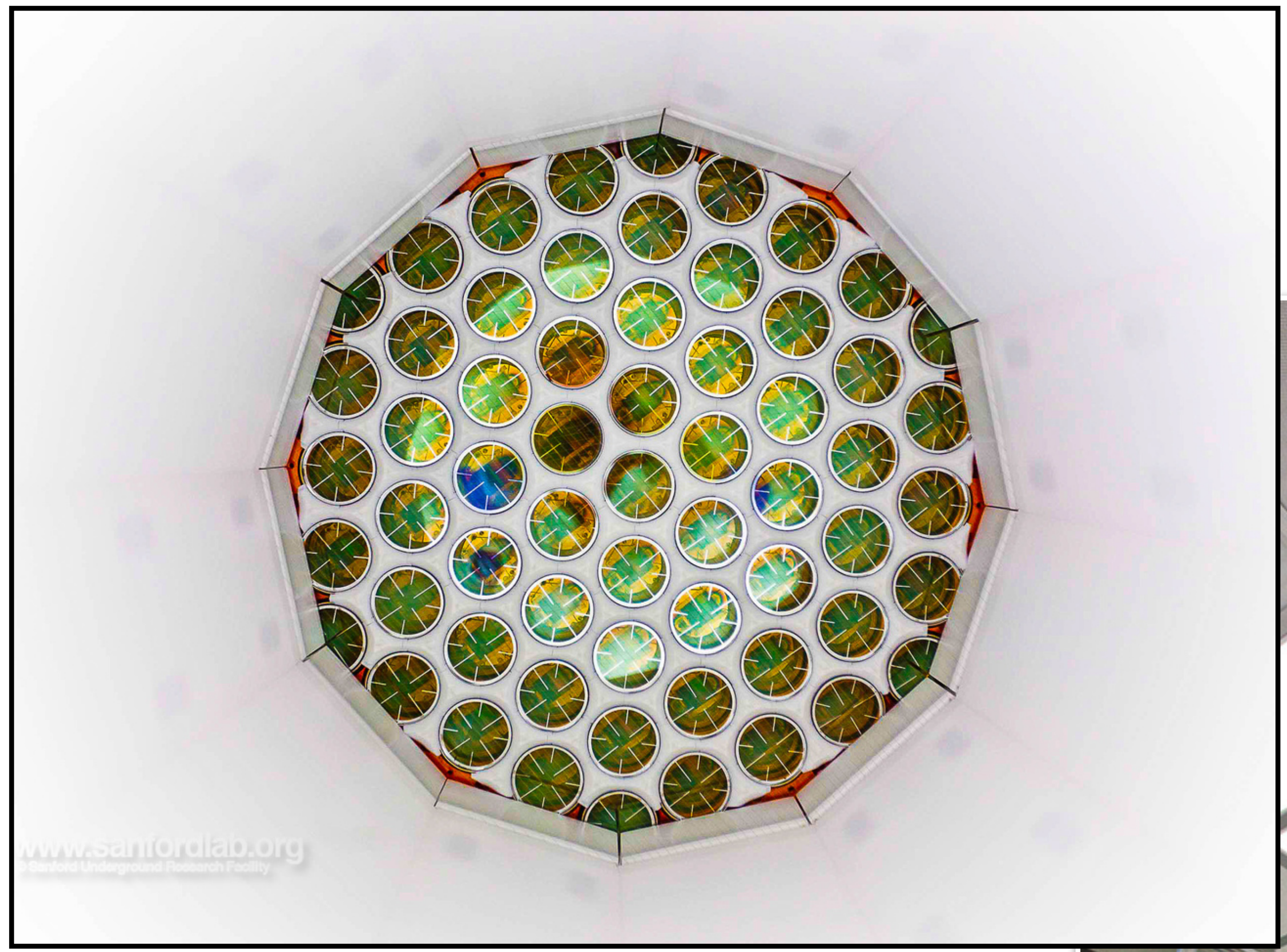
Real examples — the LUX detector (2013-2016)

122 PMTs





370 kg of liquid xenon



All inner surfaces in PTFE

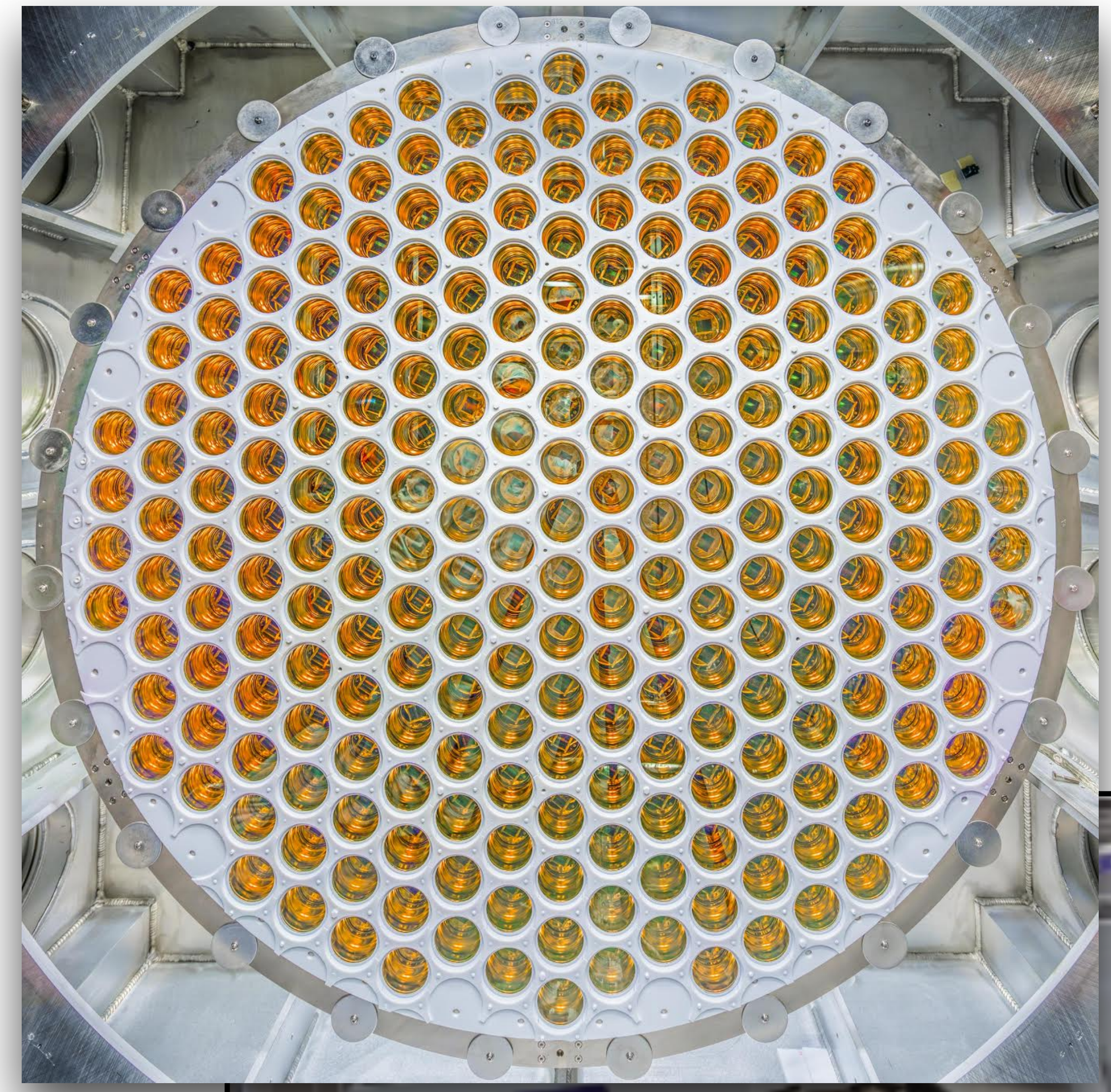
Installed at SURF (USA), 1500 m deep

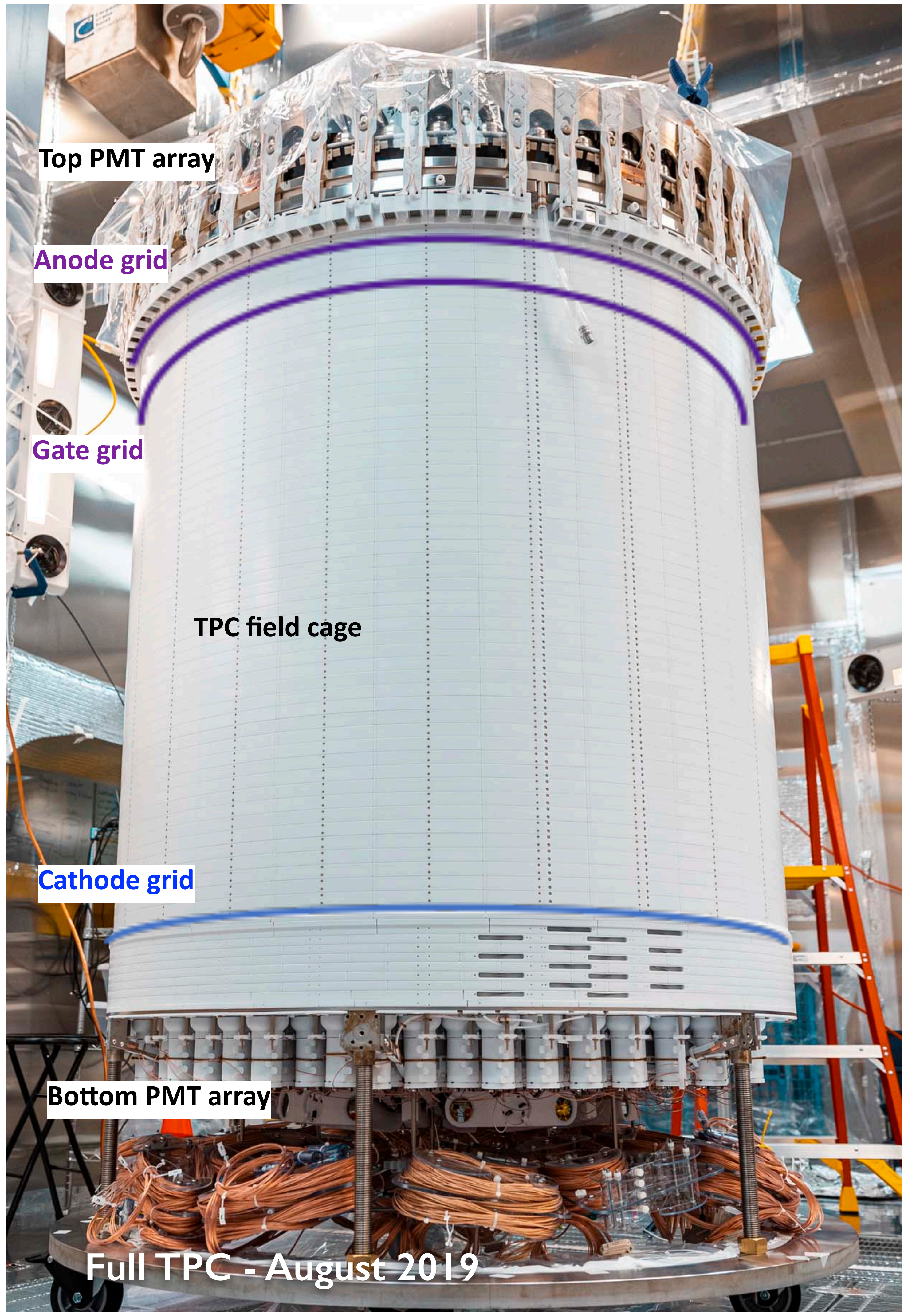
Also installed at SURF (USA), 1500 m deep

2-Phase Xenon TPCs

Another example — the LUX-ZEPLIN detector

- 7 tonnes of active mass
  - 10 tonnes total Xe
  - 1.5 m diameter × 1.5 m height
- 494 3” PMTs
- All inner surfaces in PTFE

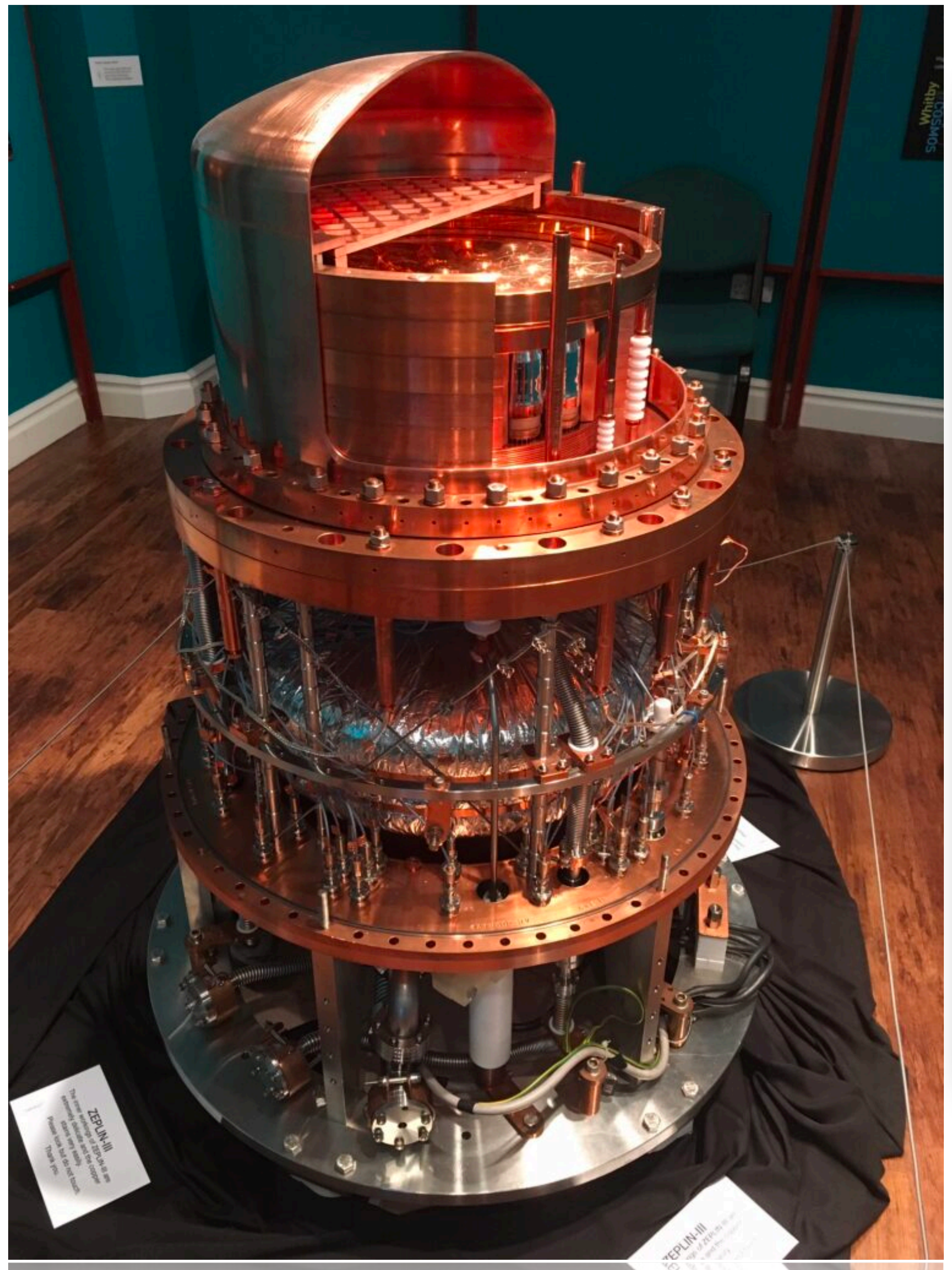




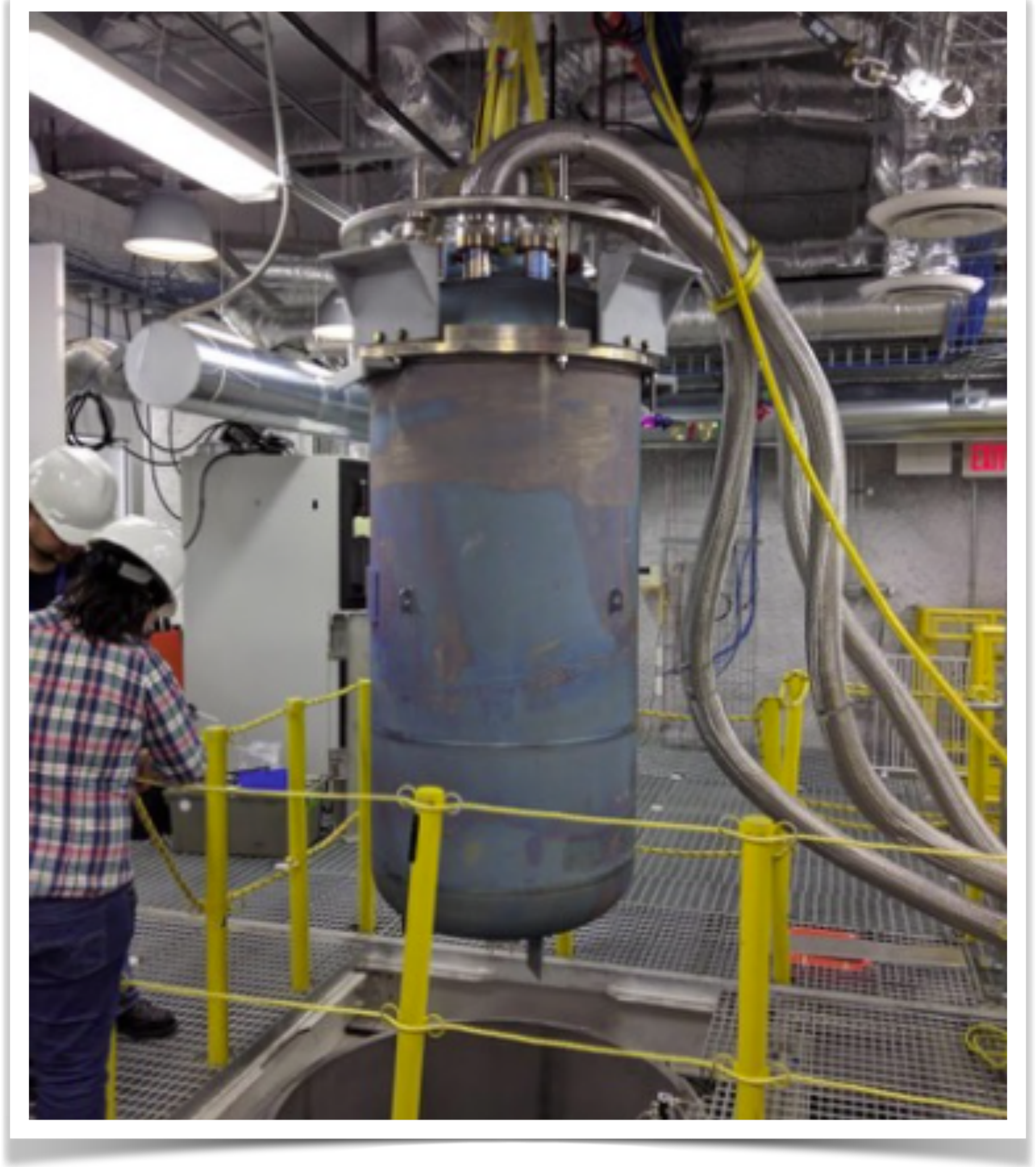
What happens to old detectors?

Golden retirement

ZEPLIN-III on display at the Whitby Museum



LUX decommissioning (end of 2016)



LUX in exhibition at the Homestake Visitor's Center

Advantages for WIMP detection

With the examples of the LUX and LZ detectors

Background reduction strategies

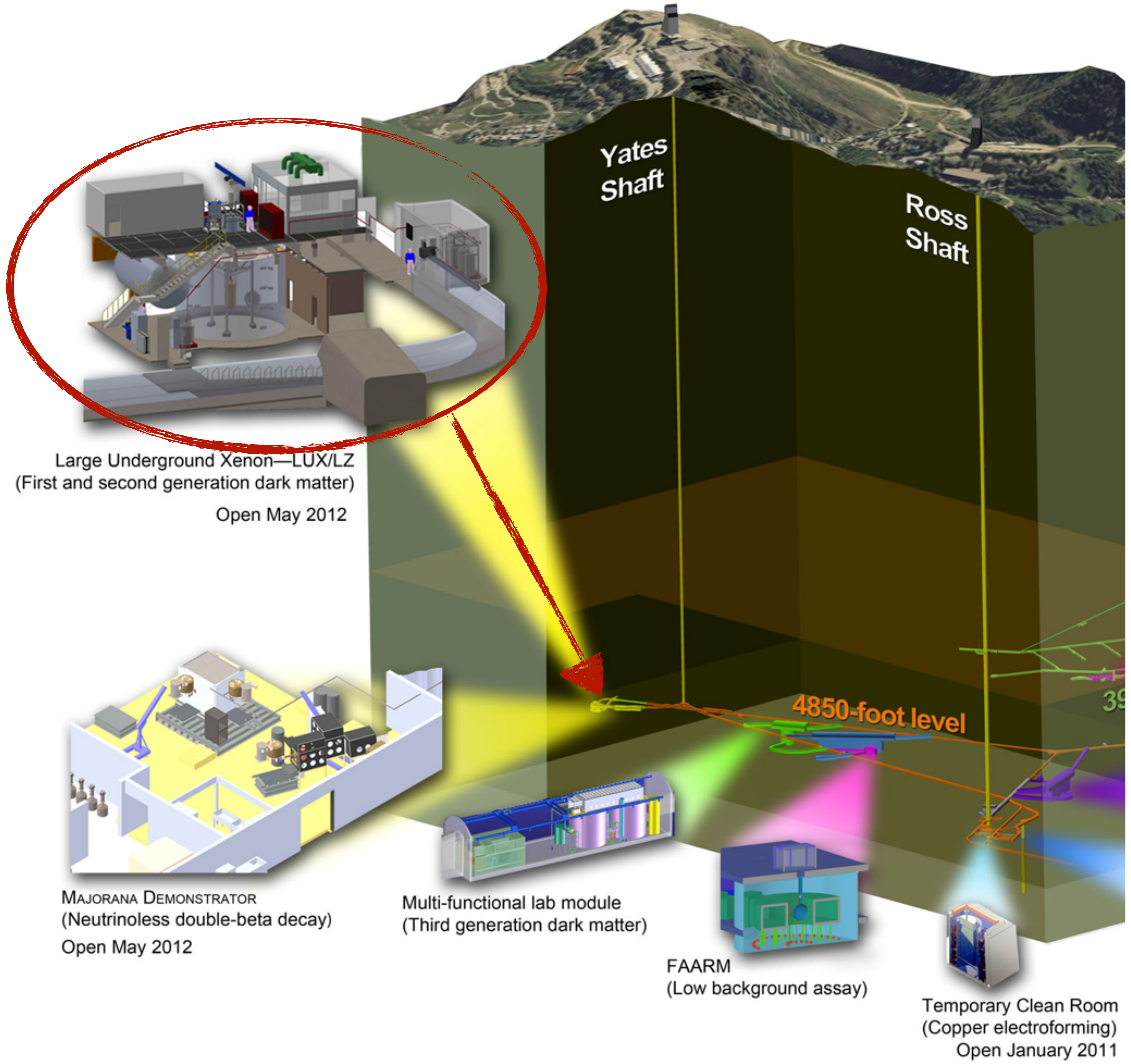
Underground deployment

Sanford Underground Research Facility (SURF)

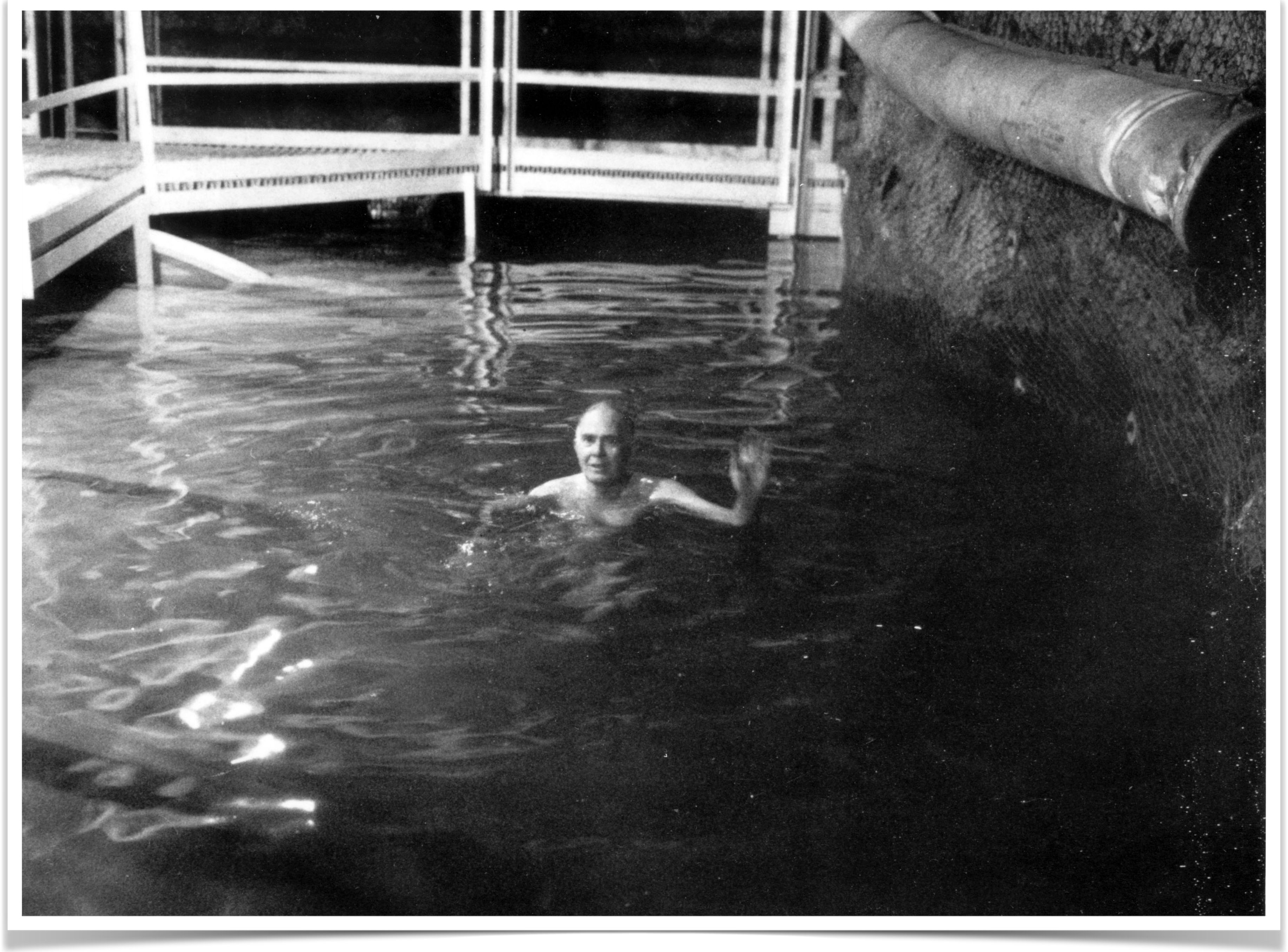
- Deepest gold mine in North America (1.5 km and 2.5 km levels)
- Abandoned due to the lower gold price at the end of the 1990's
- Bought by the state of South Dakota for a symbolic amount
- A millionaire (D. Sanford) donated $80M to convert it for science!

Background reduction strategies

Underground deployment



- 1478 m deep (4.2 km w.e., 10^7 μ flux reduction)
- 1 muon / hand surface / 3 months
- Same cavern where Ray Davis installed his Solar Neutrino Experiment in the 1960’s



Background reduction strategies

Underground deployment

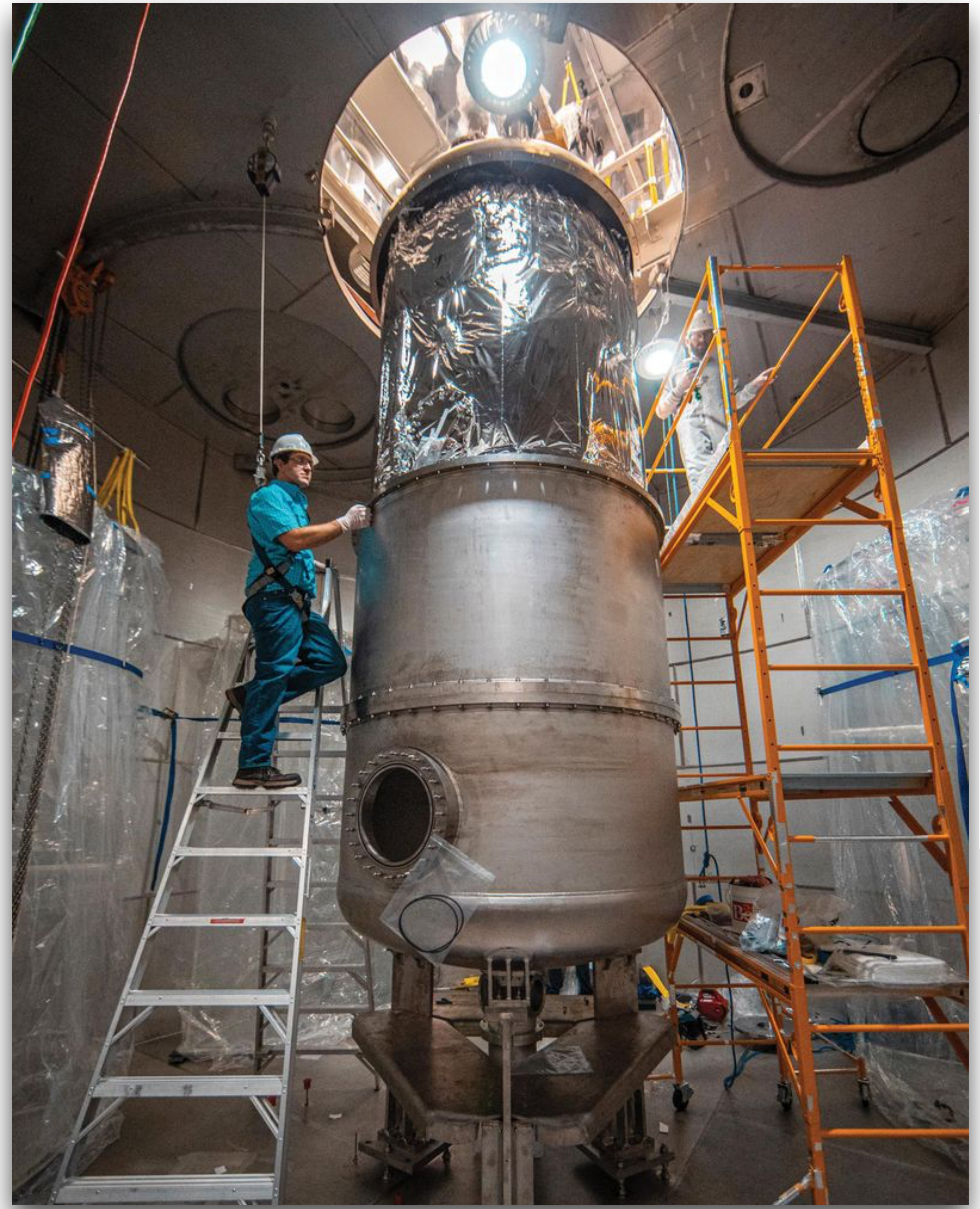
Background reduction strategies

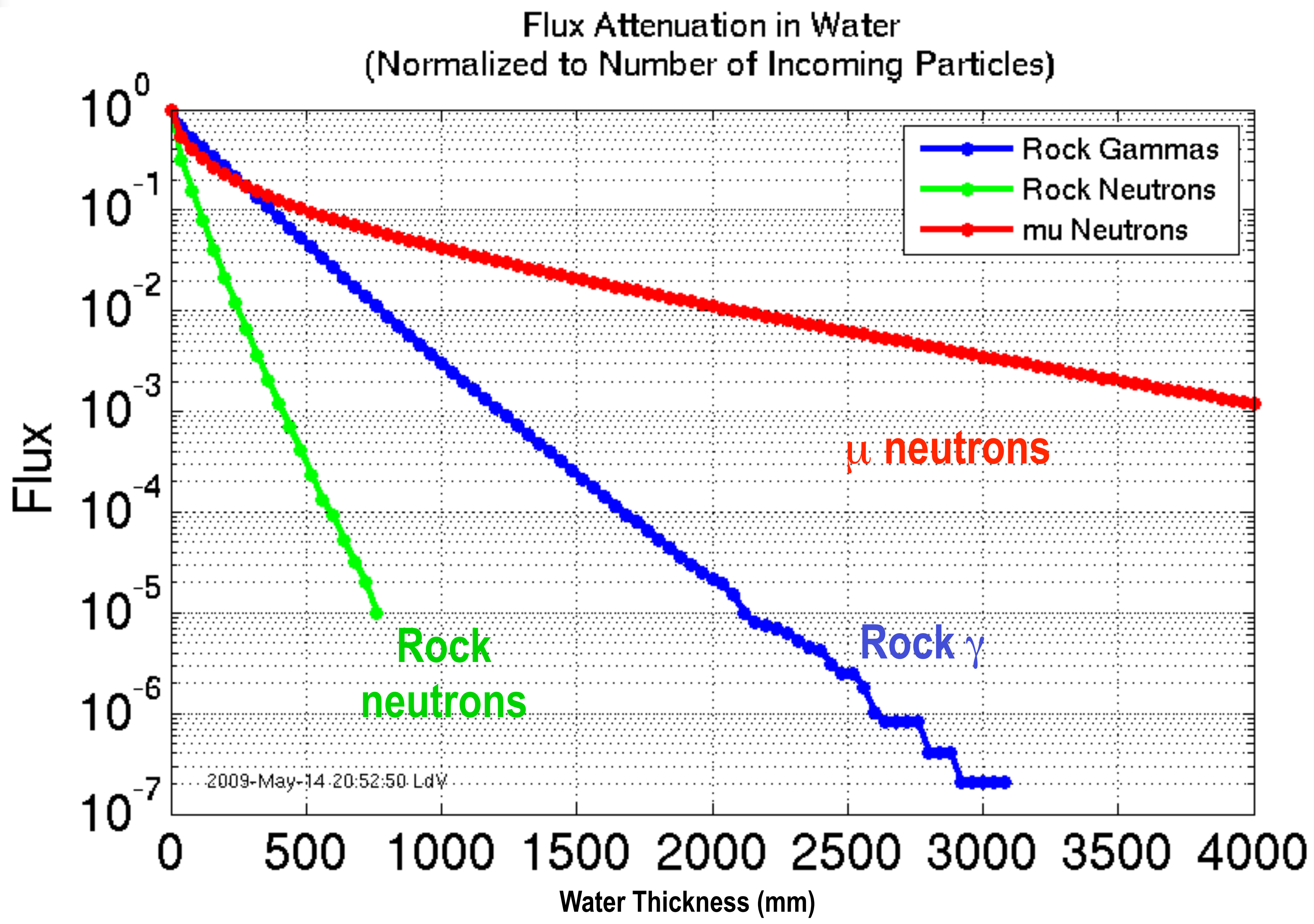
Shielding and vetoes

Background reduction strategies

Shielding and vetoes

Installing the inner cryostat of the LZ detector

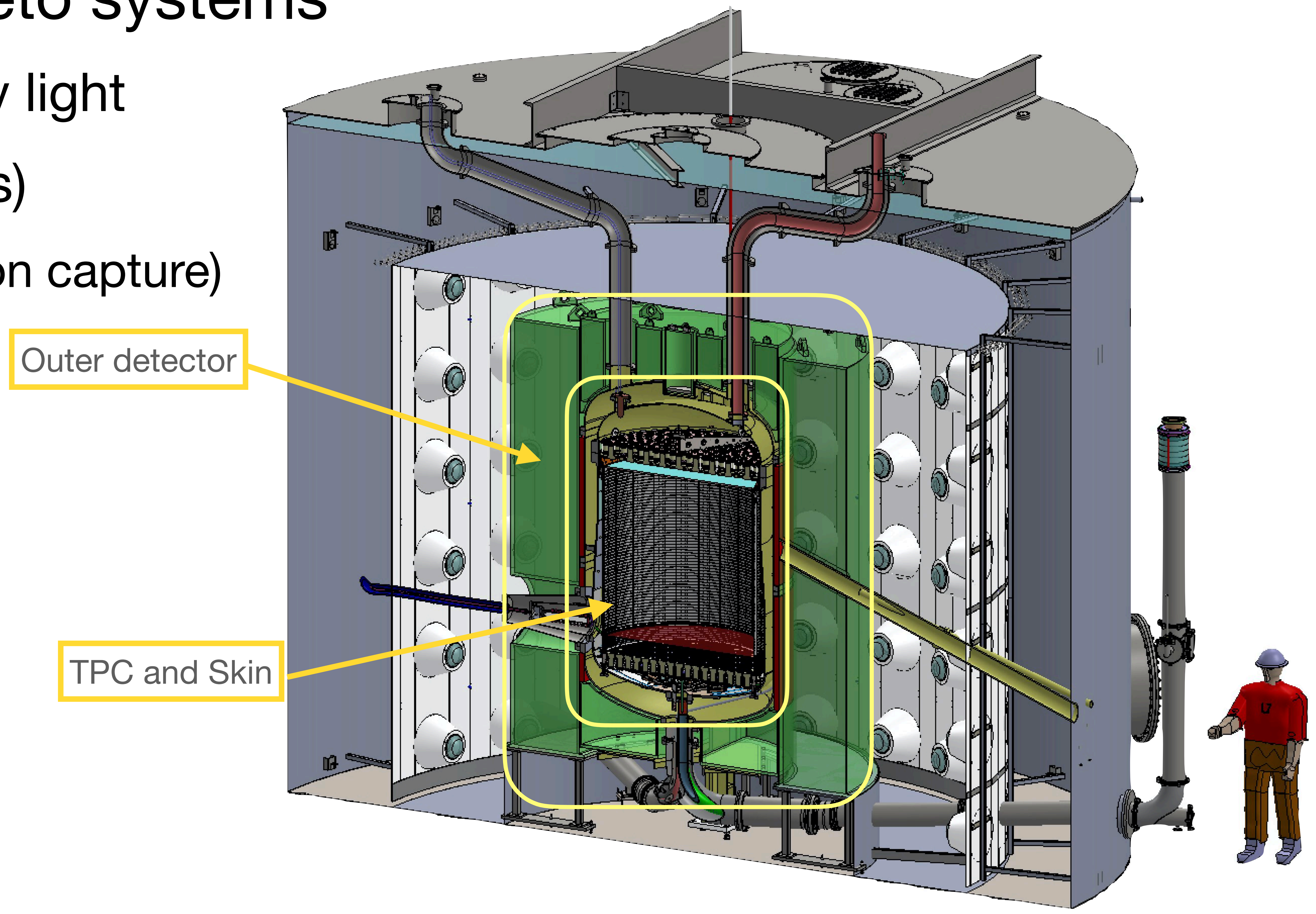




Background reduction strategies

Shielding and vetoes

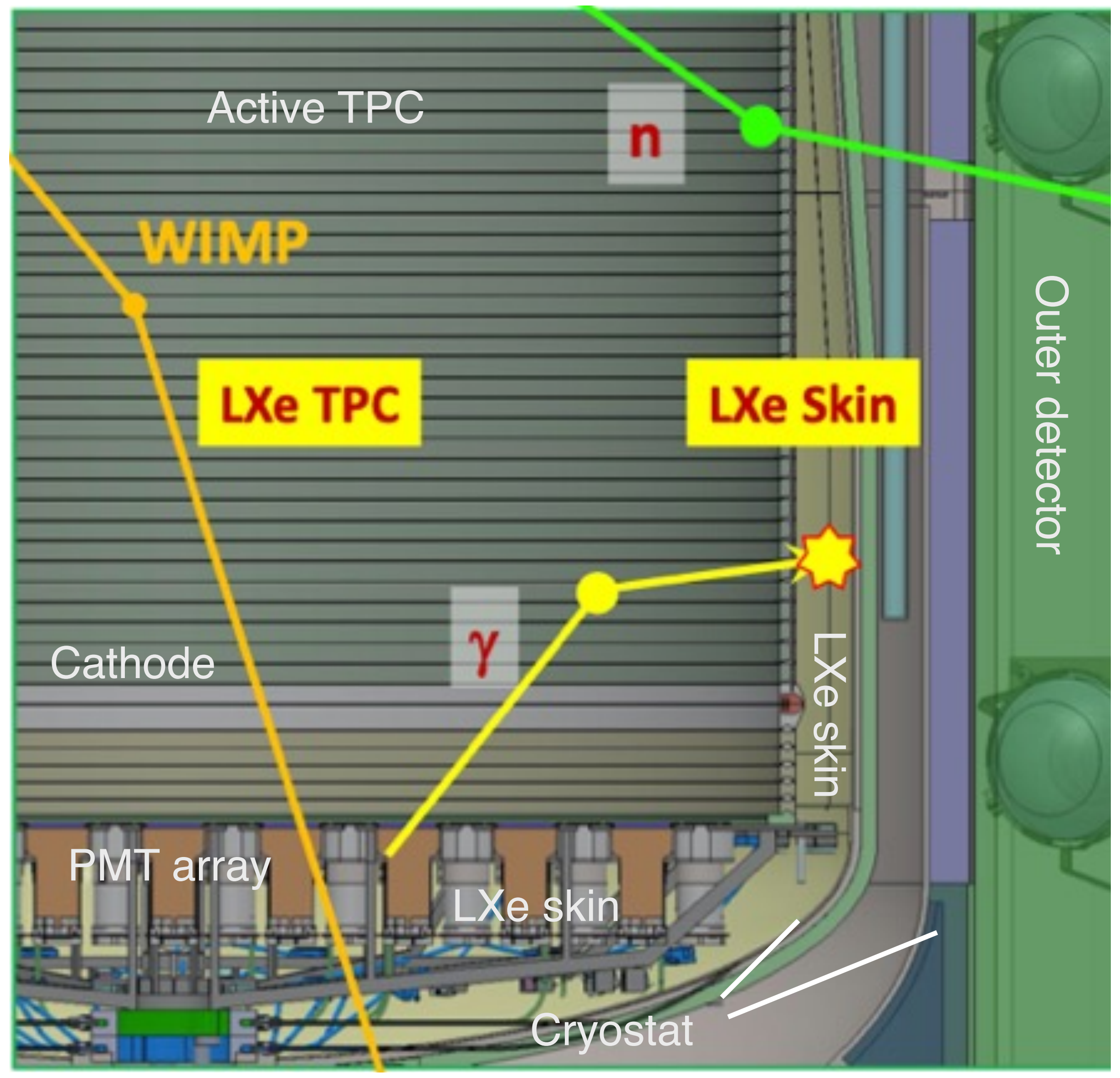
- Example: the LZ detector uses three veto systems
  - The water tank detects muon via Cherenkov light
  - A liquid scintillator outer detector (17 tonnes)
    - Loaded with Gd (high cross section for neutron capture)
  - A liquid xenon “skin” (2 tonnes)

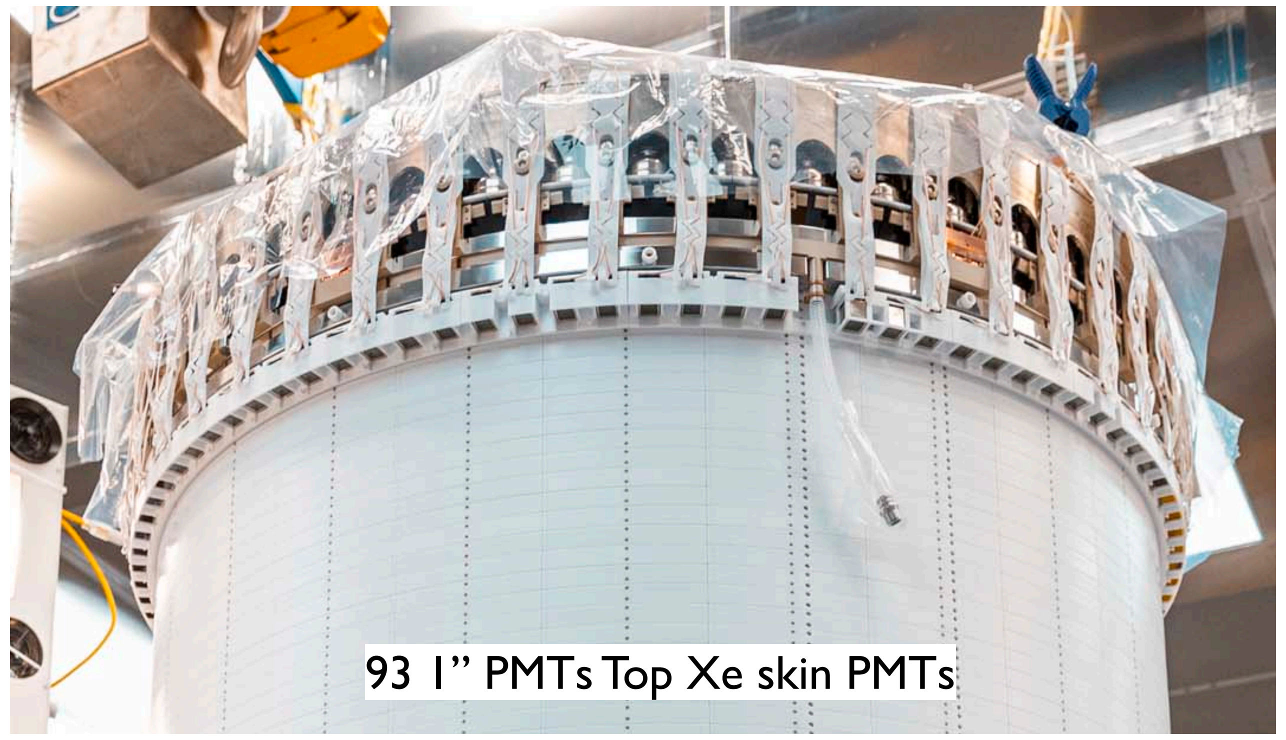


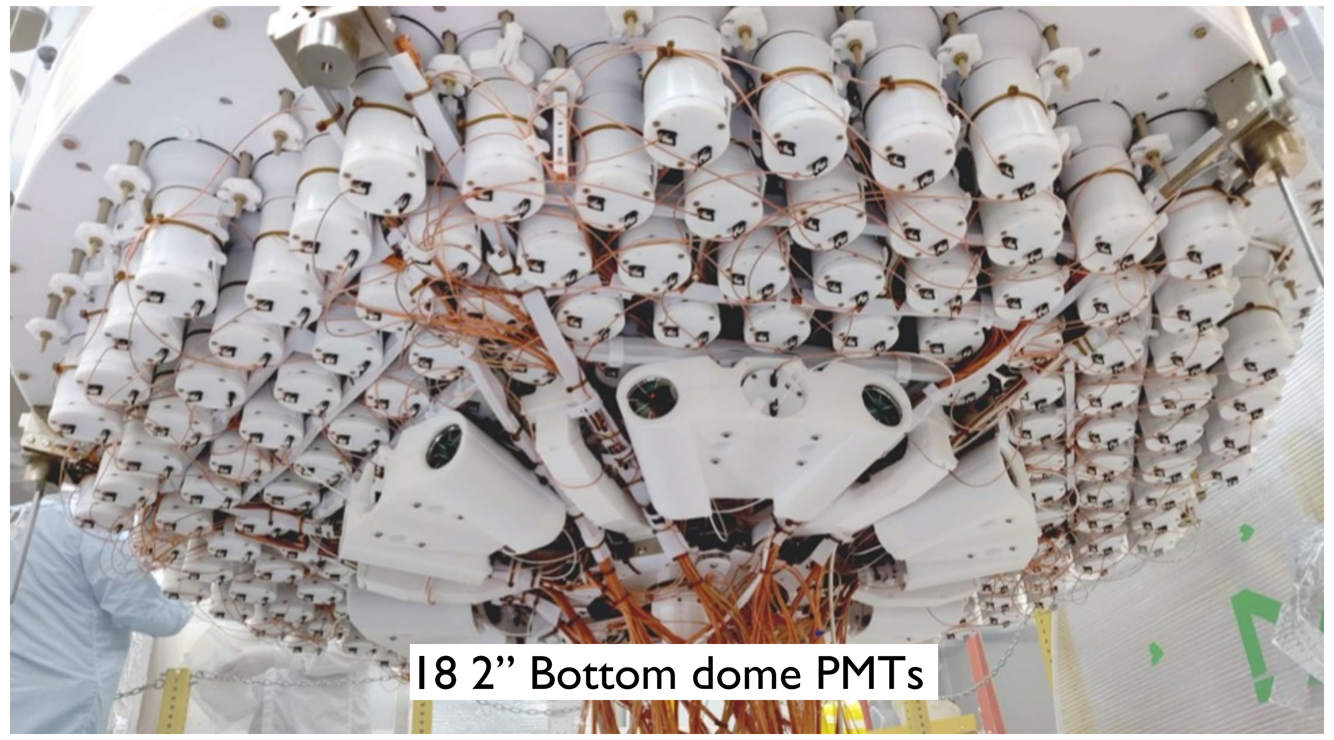
Background reduction strategies

Shielding and <u>vetoes</u>

- **The LZ xenon "skin"**
- 2 t of LXe surrounding the TPC
- Optically isolated from the TPC
- Instrumented with 1" (side) and 2" (bottom) PMTs
- All surfaces covered in PTFE to maximize light collection



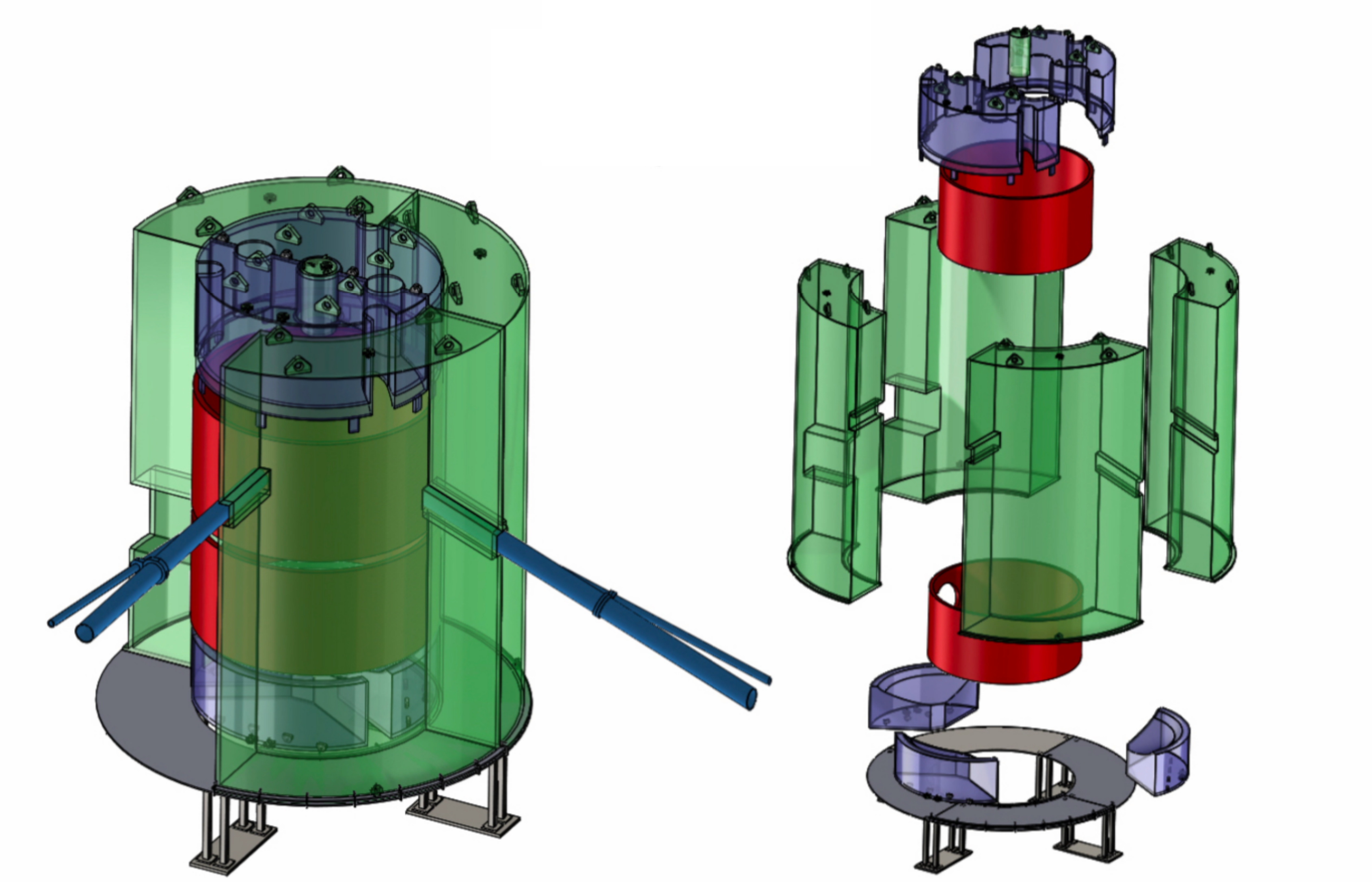


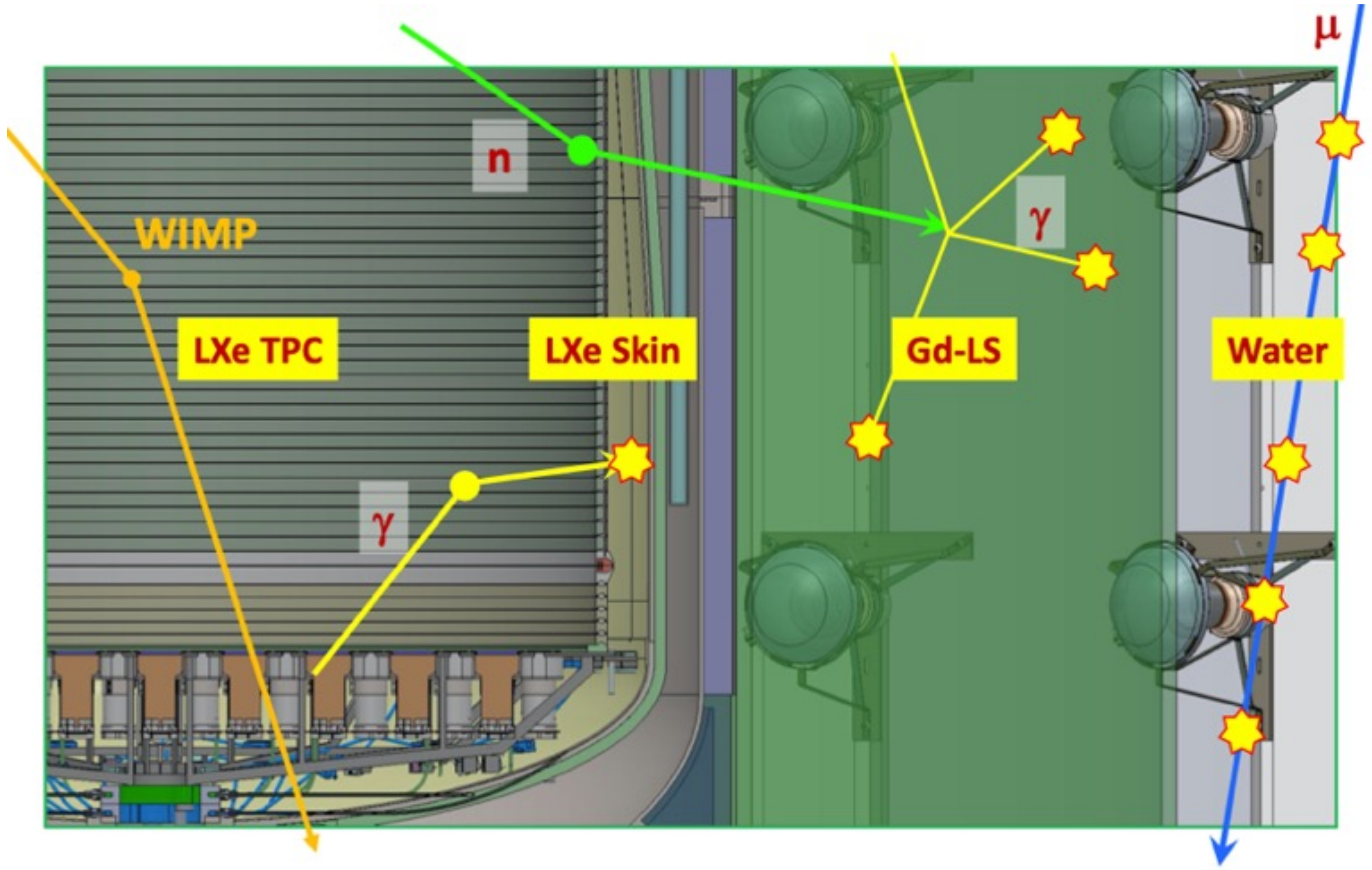


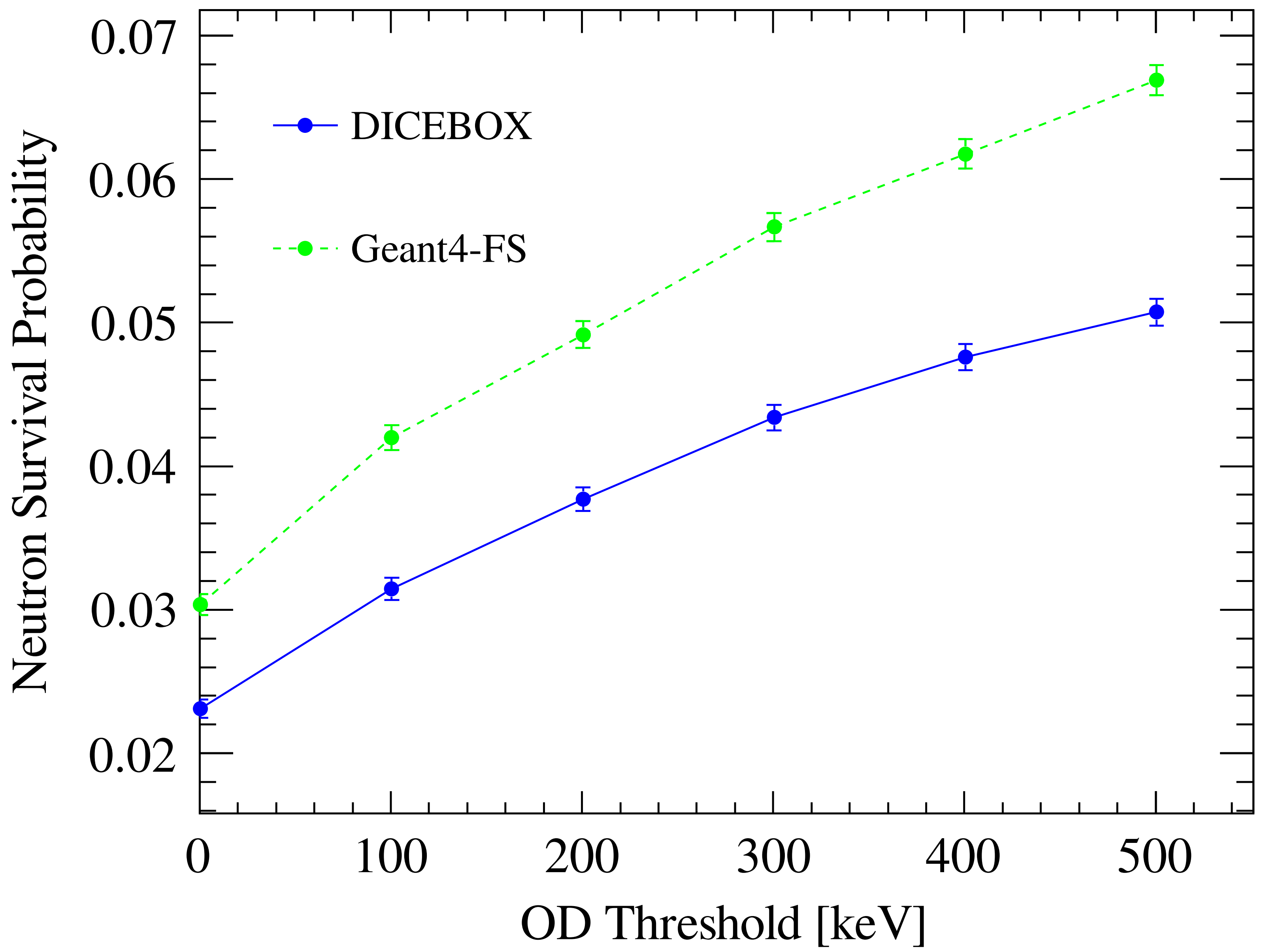
Background reduction strategies

Shielding and <u>vetoes</u>

- **The LZ outer detector**
- Suppress neutron induced background
- 17 t Gd-loaded liquid scintillator in acrylic tanks
- Surrounded by 120 8” PMTs
- ~8 MeV γ-rays following neutron capture
- 95% design efficiency for tagging neutrons







Background reduction strategies

Shielding and <u>vetoes</u>

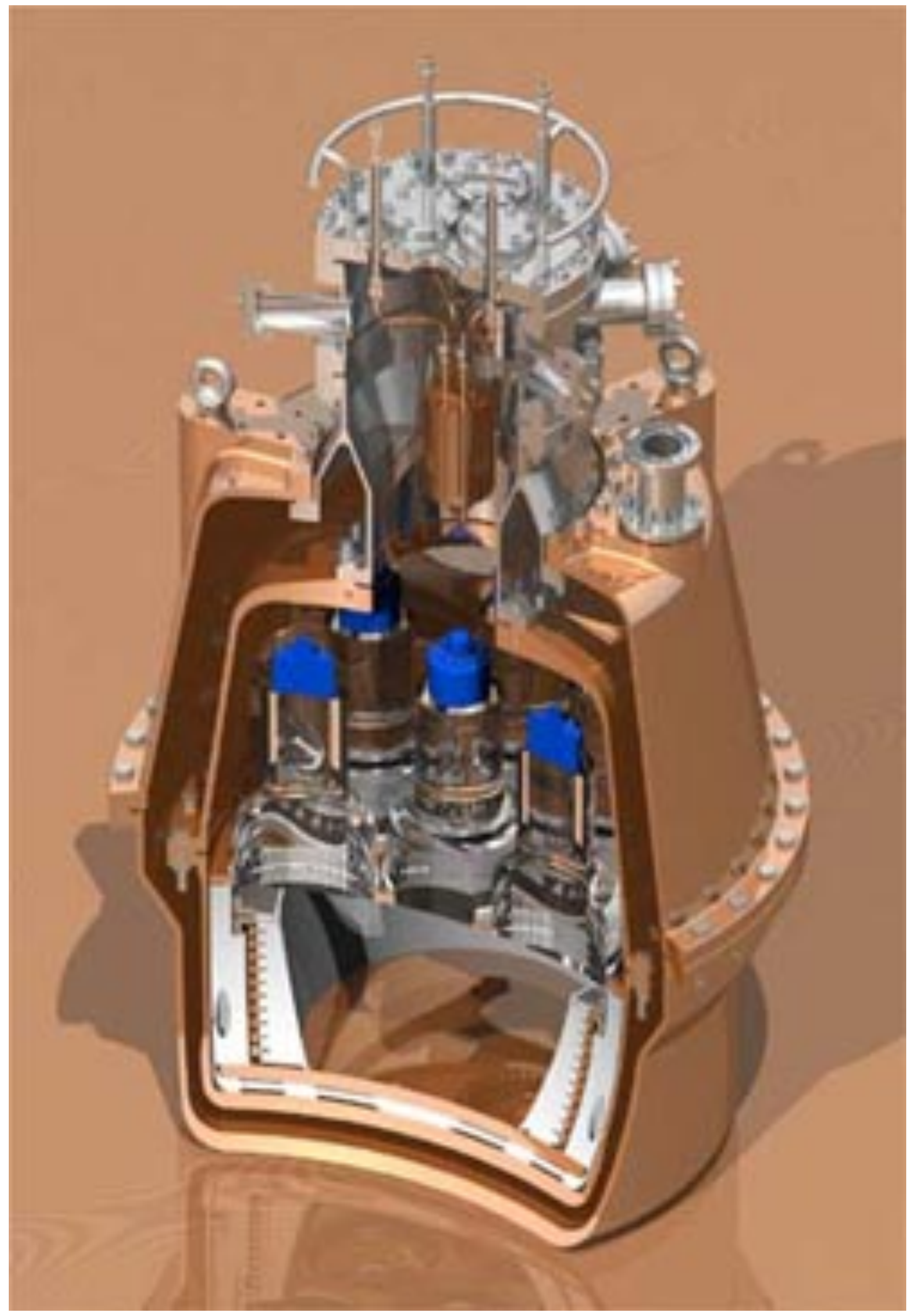
Background reduction strategies

Shielding and <u>vetoes</u>

Advantages for WIMP detection

Scalability — same technology

15 years ago…

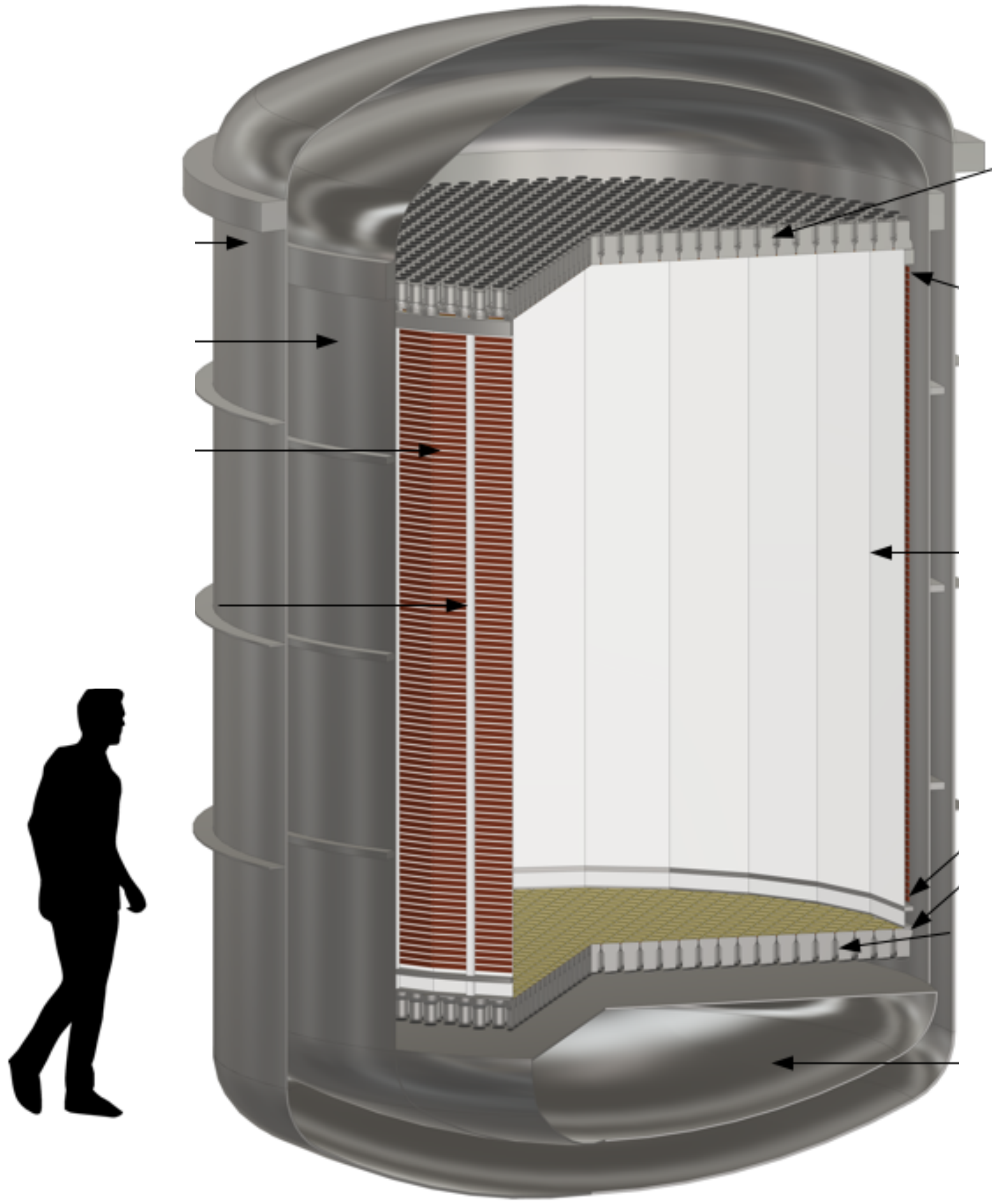


ZEPLIN-II
32 kg

Now

LUX-ZEPLIN (LZ)
10 tonnes

Future (2028 -)



Next generation detector
40-80 tons

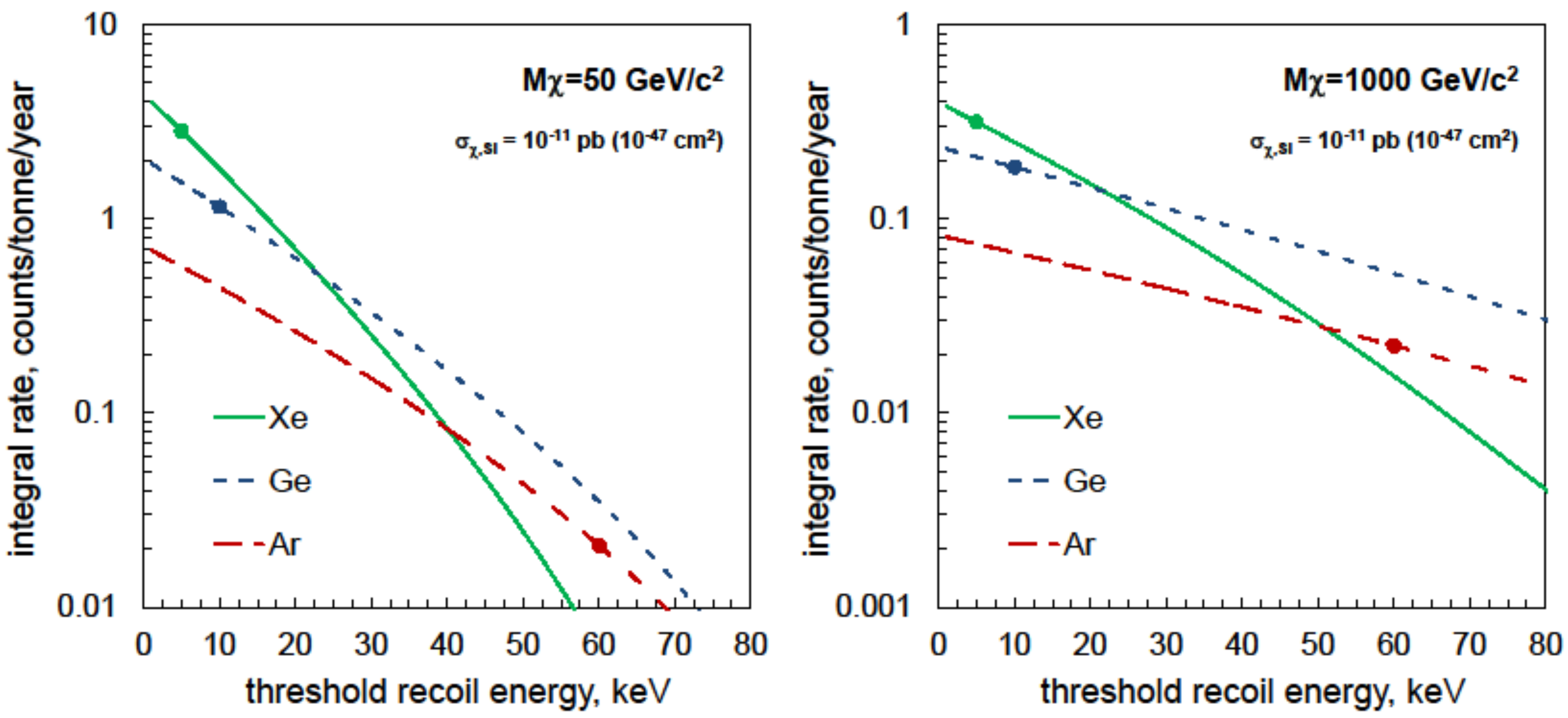
Large target mass → Increased interaction probability

Advantages for WIMP detection

Interaction rate and recoil spectrum

Expected WIMP recoil spectra: $\sigma_A^{SI}(q \to 0) = \frac{4\mu_A^2}{\pi}[Zf_p + (A-Z)f_n]^2 \approx \frac{\mu_A^2}{\mu_p^2}\sigma_p A^2$

Sensitivity is mostly at <u>low energies</u>

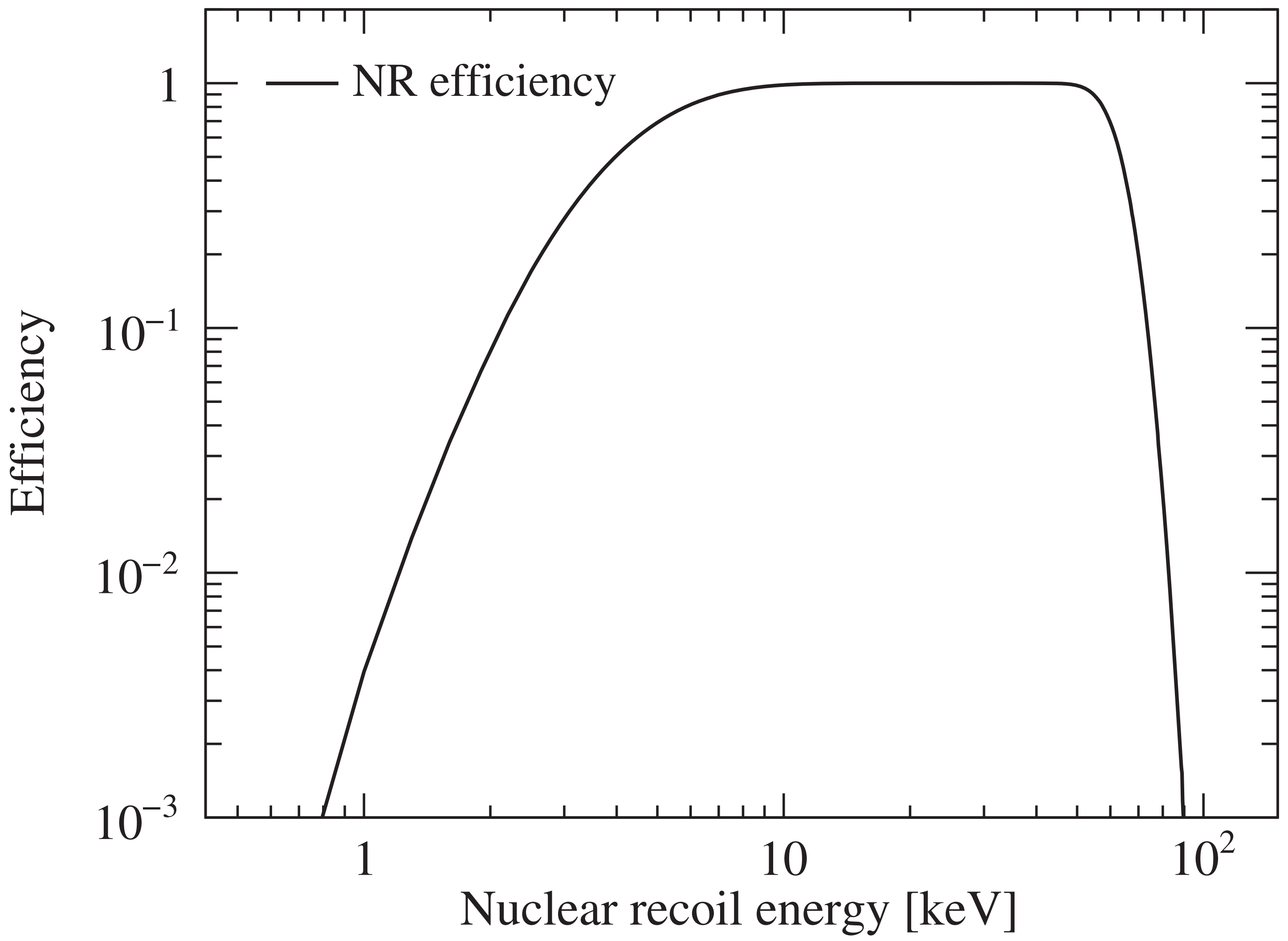


High A → Increased interaction rate

Advantages for WIMP detection

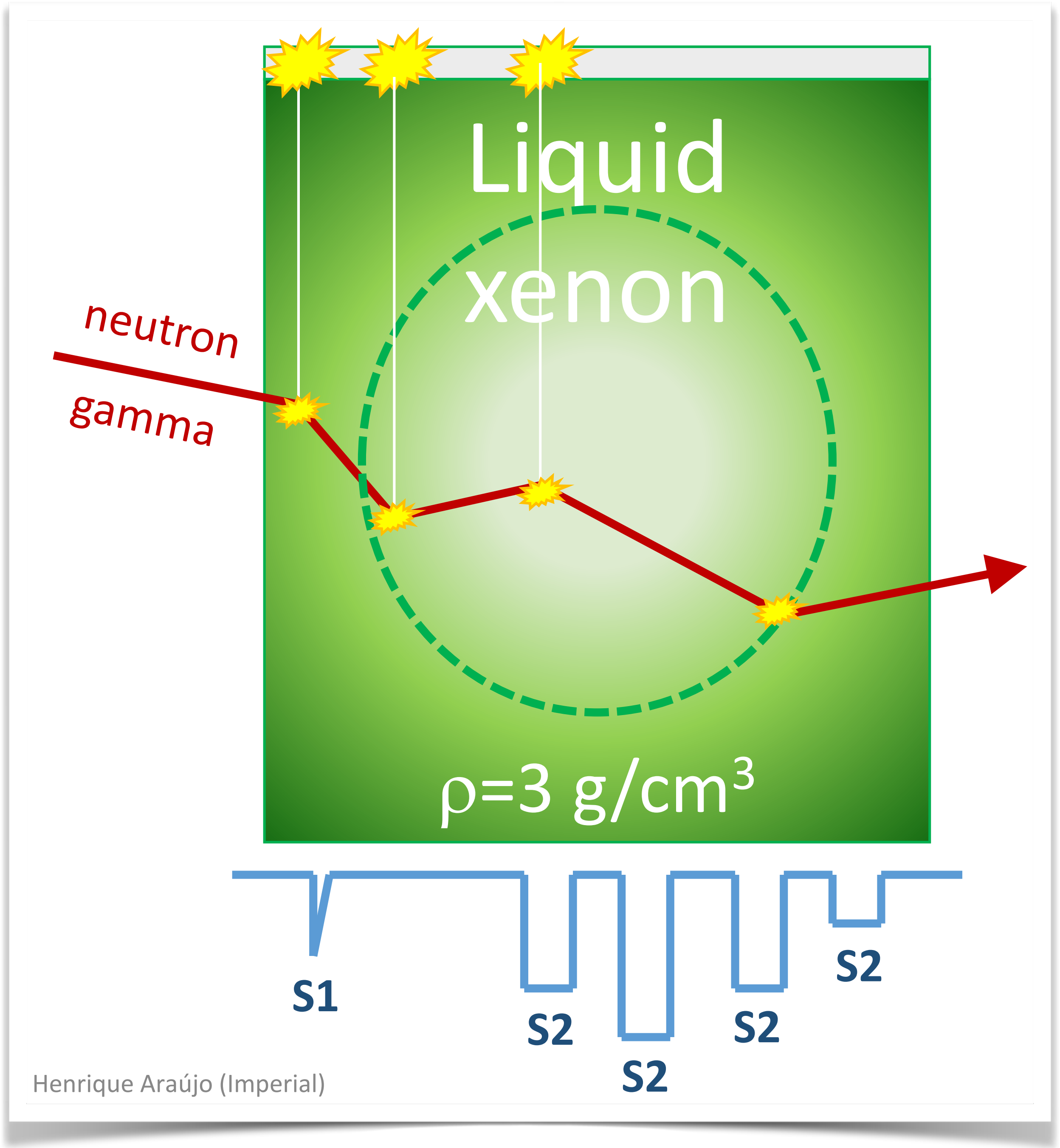
Low threshold

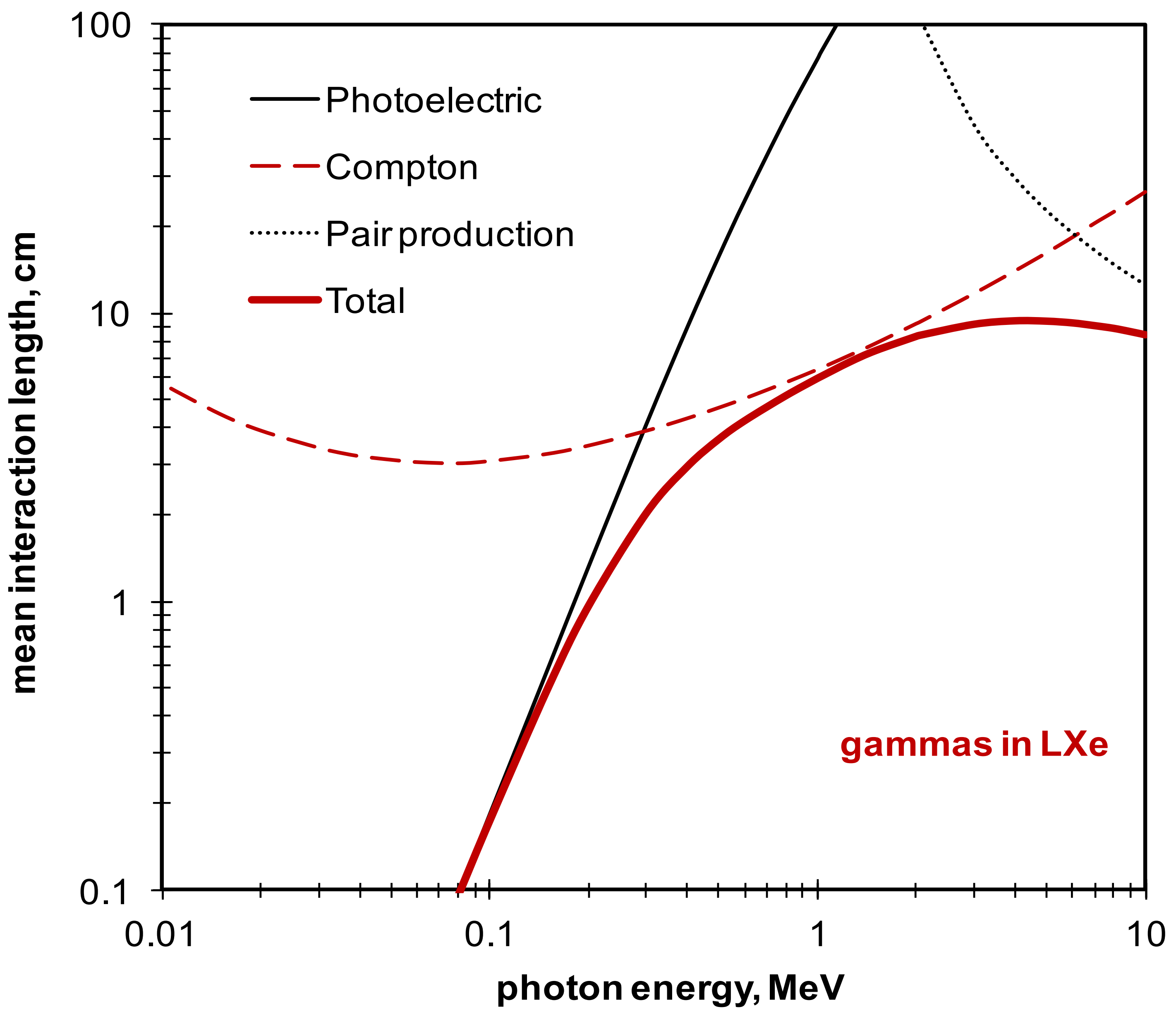
- The energy threshold is driven by the scintillation (S1) signal — can be as low as 2 photons detected!
    - Each event must contain an S1 and an S2
- Strategy: cover all the inner surfaces with highly reflective PTFE (R>97%)
- Light sensors (PMTs) can detect single photons (Q_{eff} ~ 30%)
- Detection efficiency:
  ~10% @ 2 keV$_{nr}$
  ~50% @ 3 keV$_{nr}$

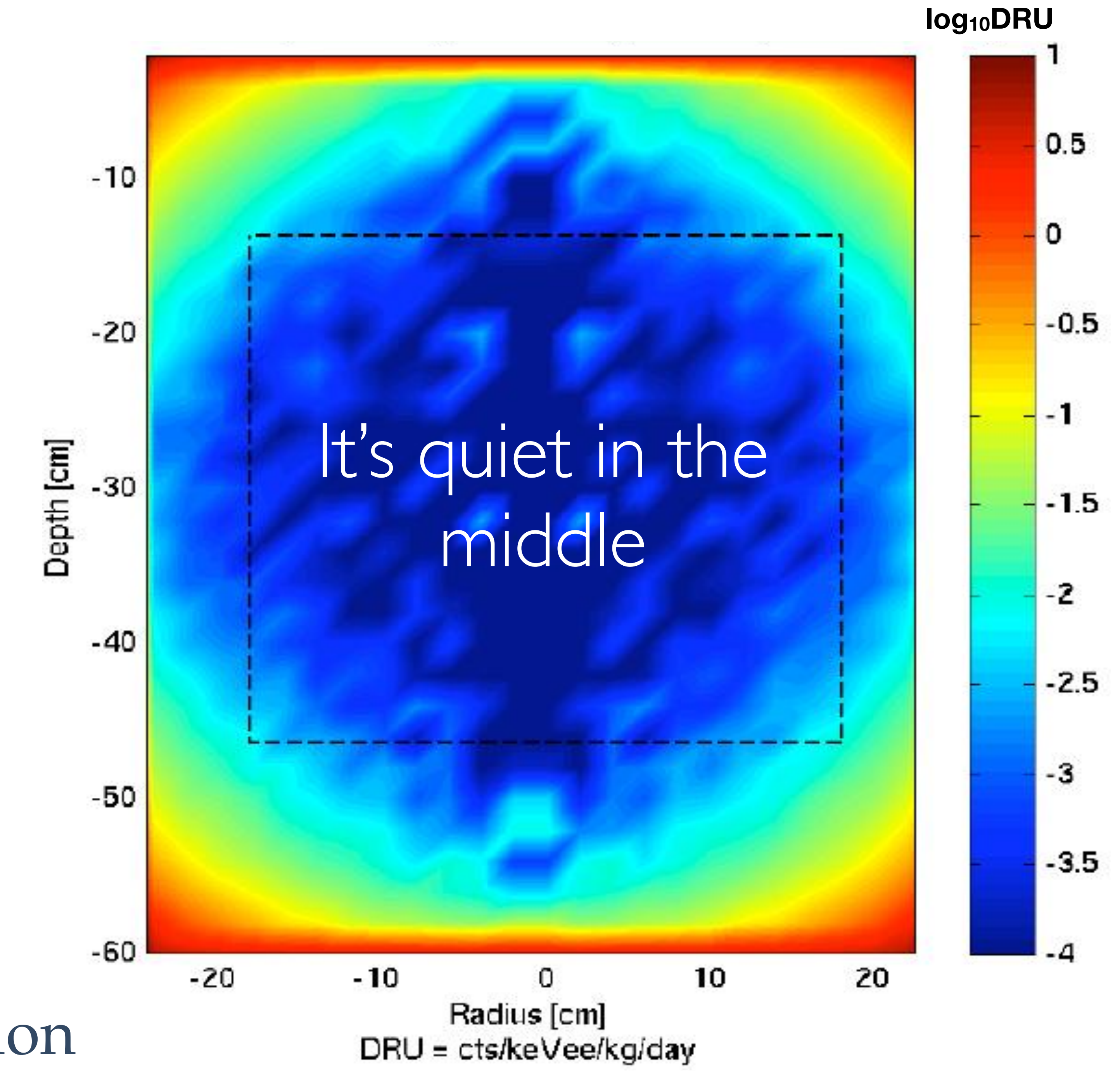


Advantages for WIMP detection

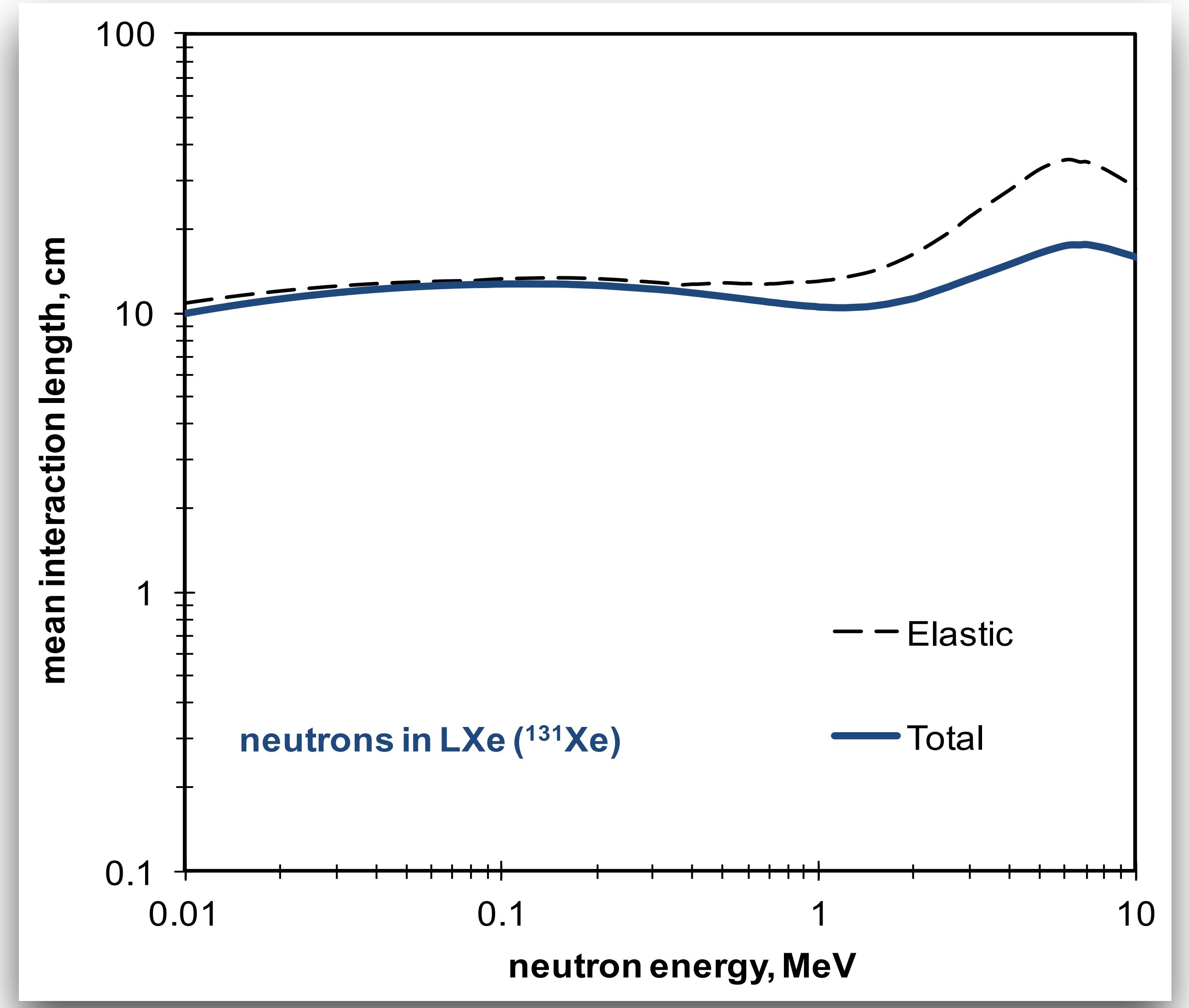
Self shielding







Mean interaction length

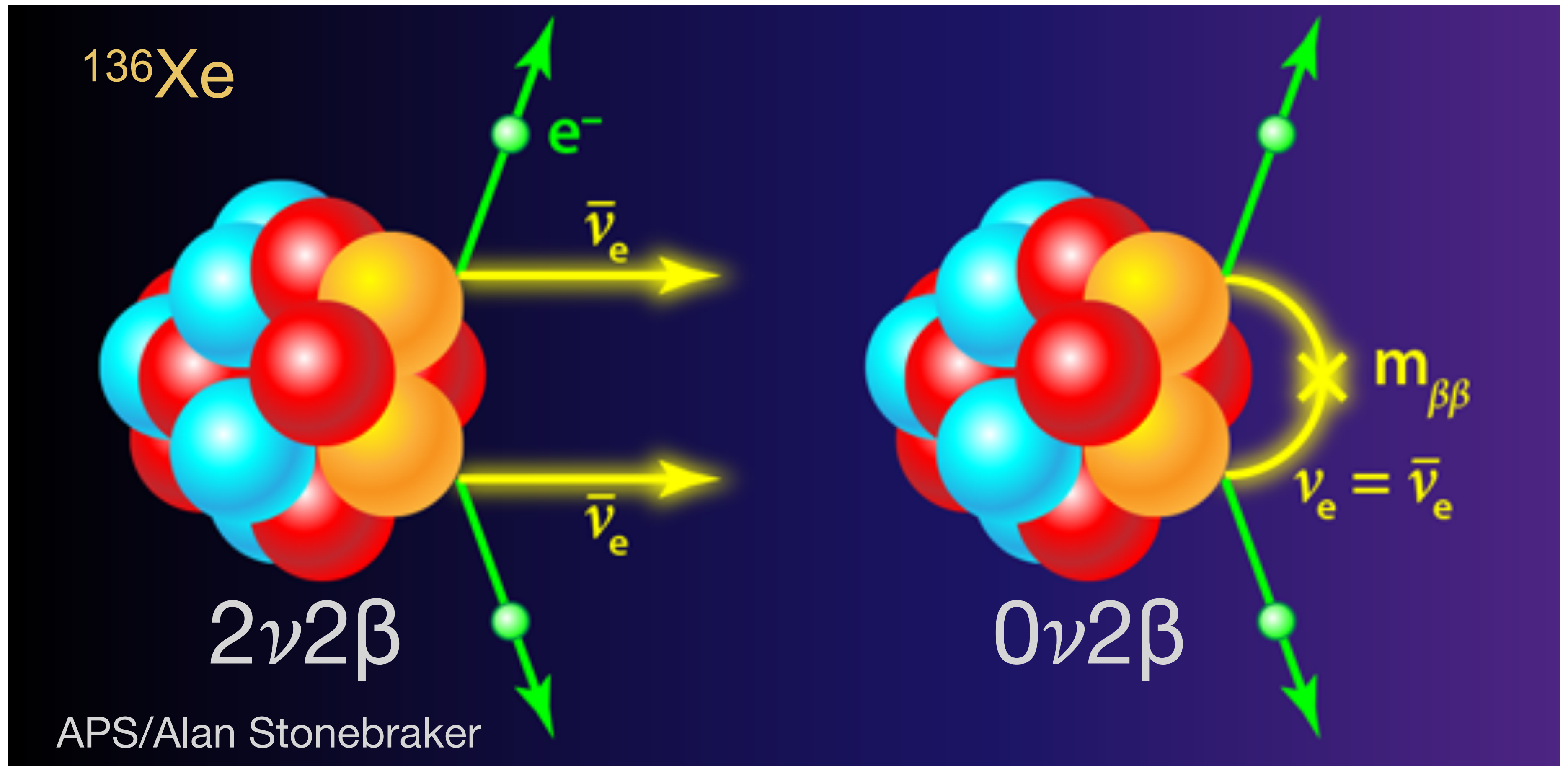


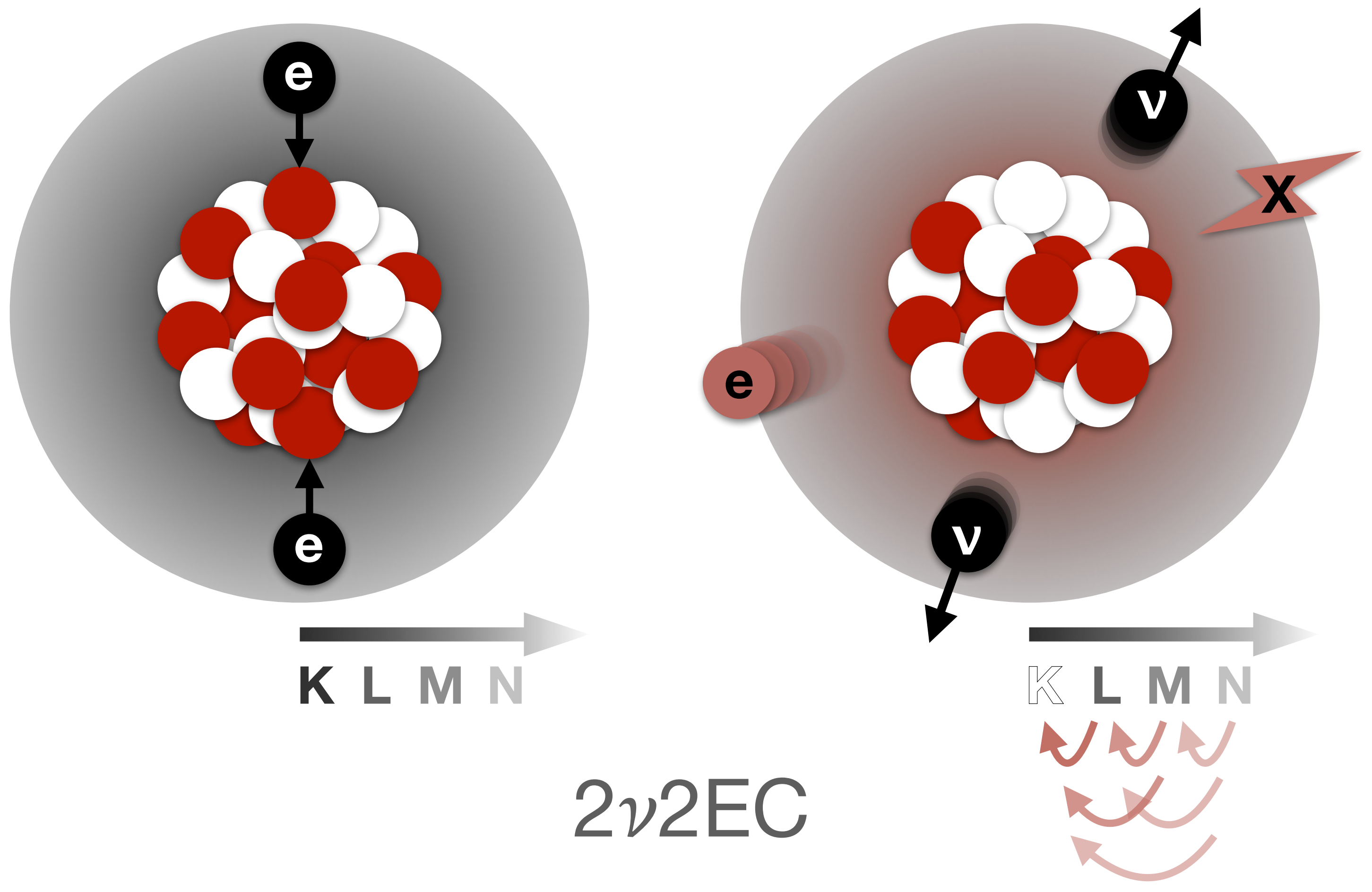
- External radiation will mostly interact in the outer regions — the high density of xenon (~3 g/cm^3) maximizes this effect compared to other targets
- γ-rays and neutrons will likely interact multiple times **(but WIMPs only interact once! — single scatters)**

Advantages for WIMP detection

No intrinsic backgrounds

- No short lived radioactive isotopes → no intrinsic backgrounds!
  - excellent for rare search experiments (DM, neutrinos, rare nuclear decays)
- Very long lived decays with physical interest on their own
  - ^{136}Xe ($2\nu\beta\beta$) has a half-life of 10^{21} years — compare with the age of the Universe (10^{10} yr)!
  - Possible to search for the neutrino less mode too ($0\nu\beta\beta$)
    - Never observed, $T_{1/2} > 10^{26}$ yr
    - Beyond the SM physics:
      - Majorana nature of the neutrinos (own anti-particle)
      - Neutrino mass hierarchy
      - Leptonic contribution to the observed matter/anti-matter asymmetry
  - ^{124}Xe (2ν2EC), half-life of 10^{22} years — test nuclear models

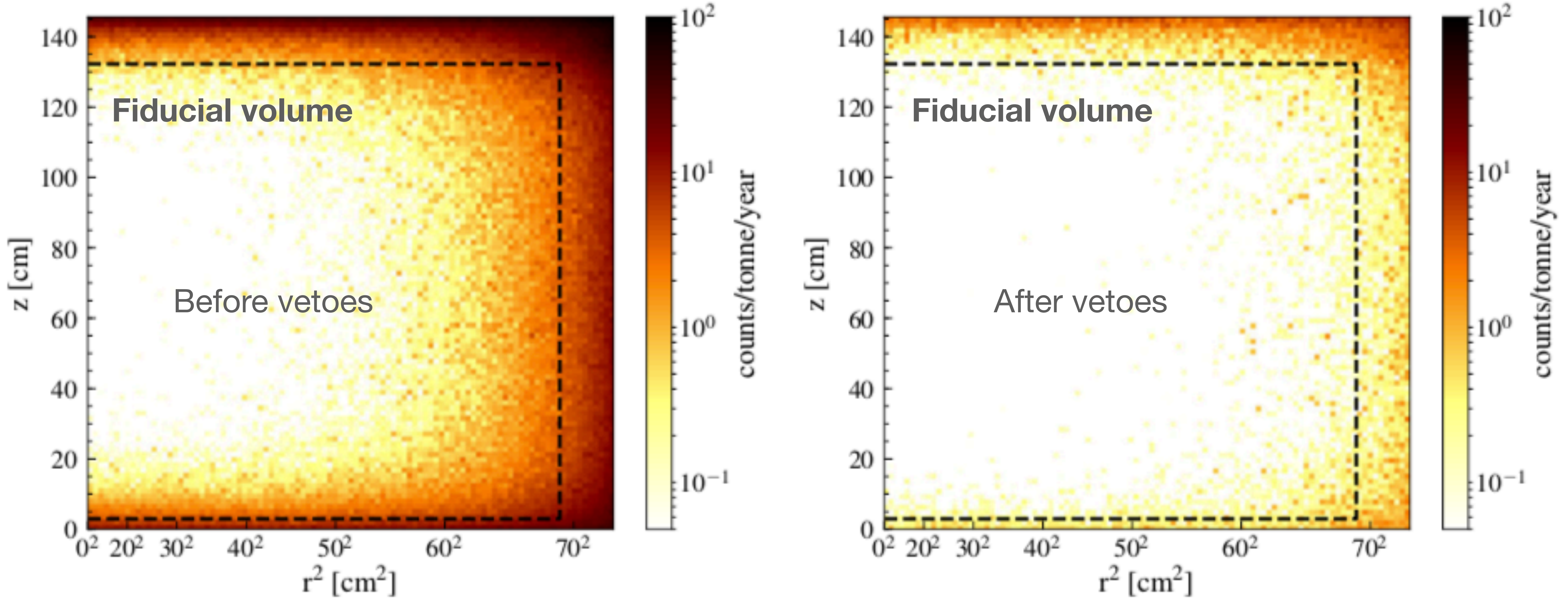




Advantages for WIMP detection

Fiducialization

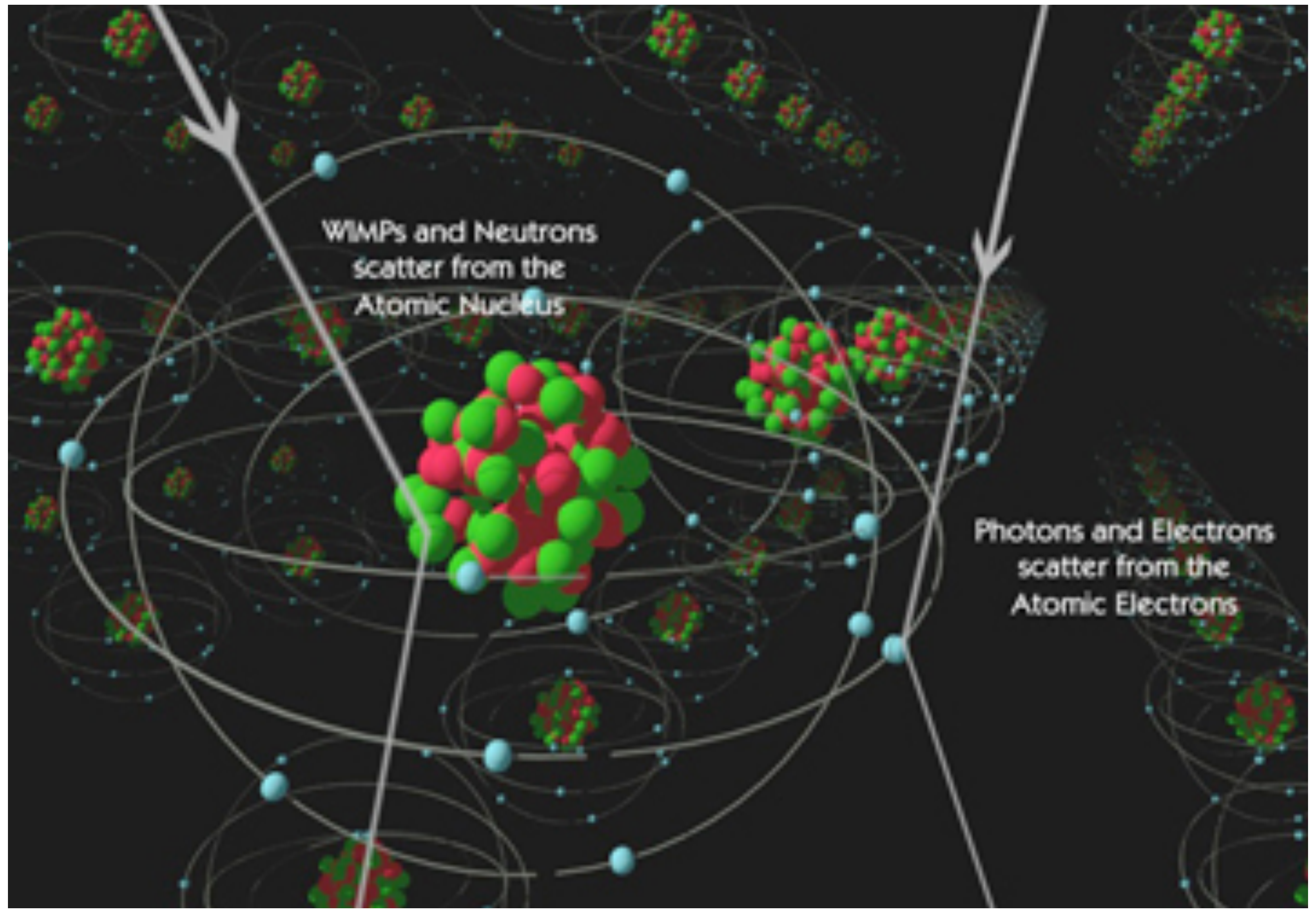
- A (very useful) side effect of self-shielding
  - Most of the background interactions occur in the outer regions of the detector
  - Using 3D position reconstruction, we can define an inner region with lower background rate



Simulated rate of nuclear recoils in the energy region of interest for WIMP search in the LZ detector due to neutrons emitted from detector building materials before (left) and after (right) excluding events with coincident signals in the vetoes

Advantages for WIMP detection

ER/NR discrimination

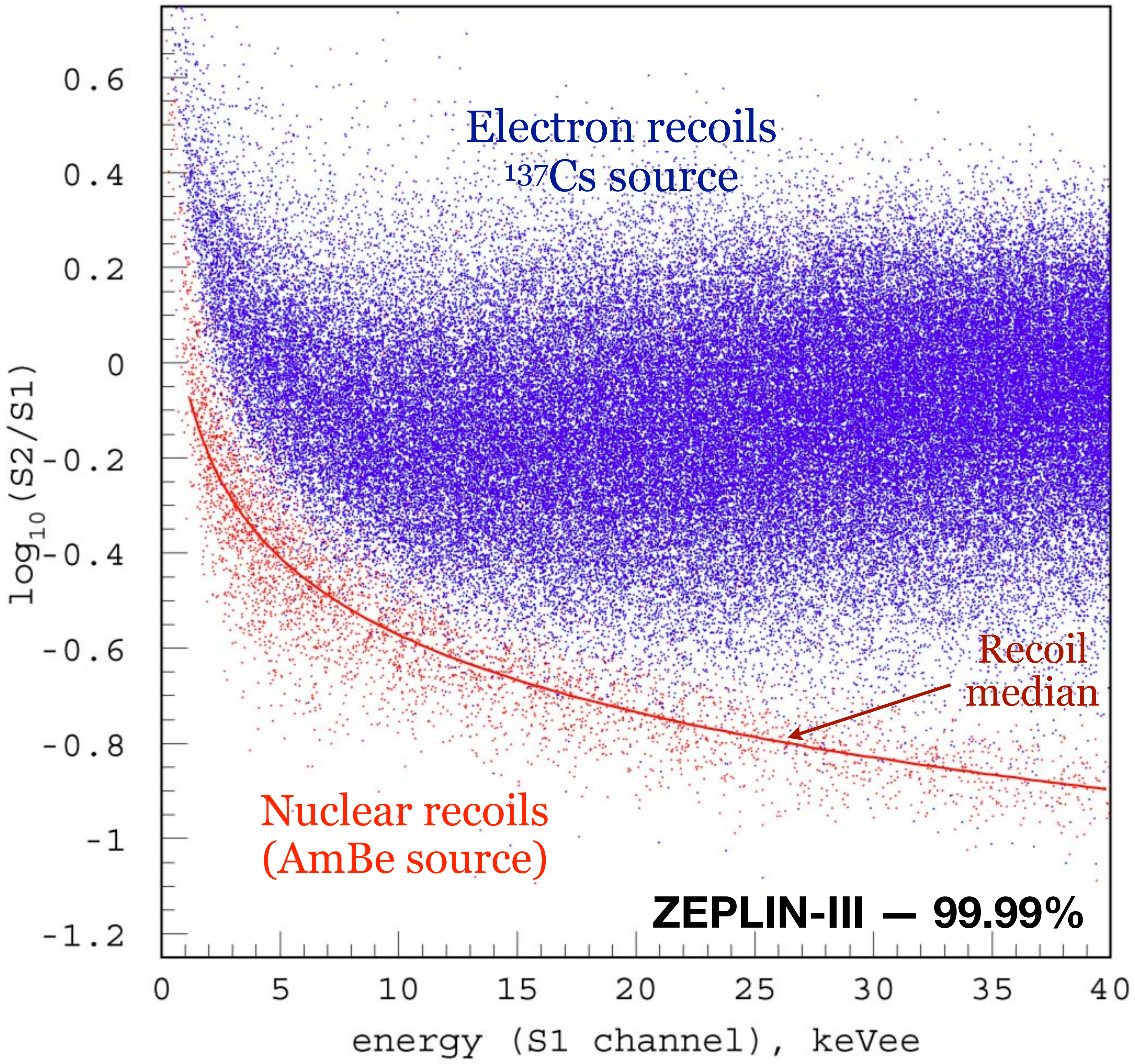


- Electron recoils: γ, β, ν
  (interactions with the atomic electrons)
- Nuclear recoils: WIMPs, neutrons, ν
  (interactions with the nucleus)

Larger energy fraction converted to heat (**undetected**)

Lower charge/light ratio

$(S2/S1)_{ER} > (S2/S1)_{WIMP}$



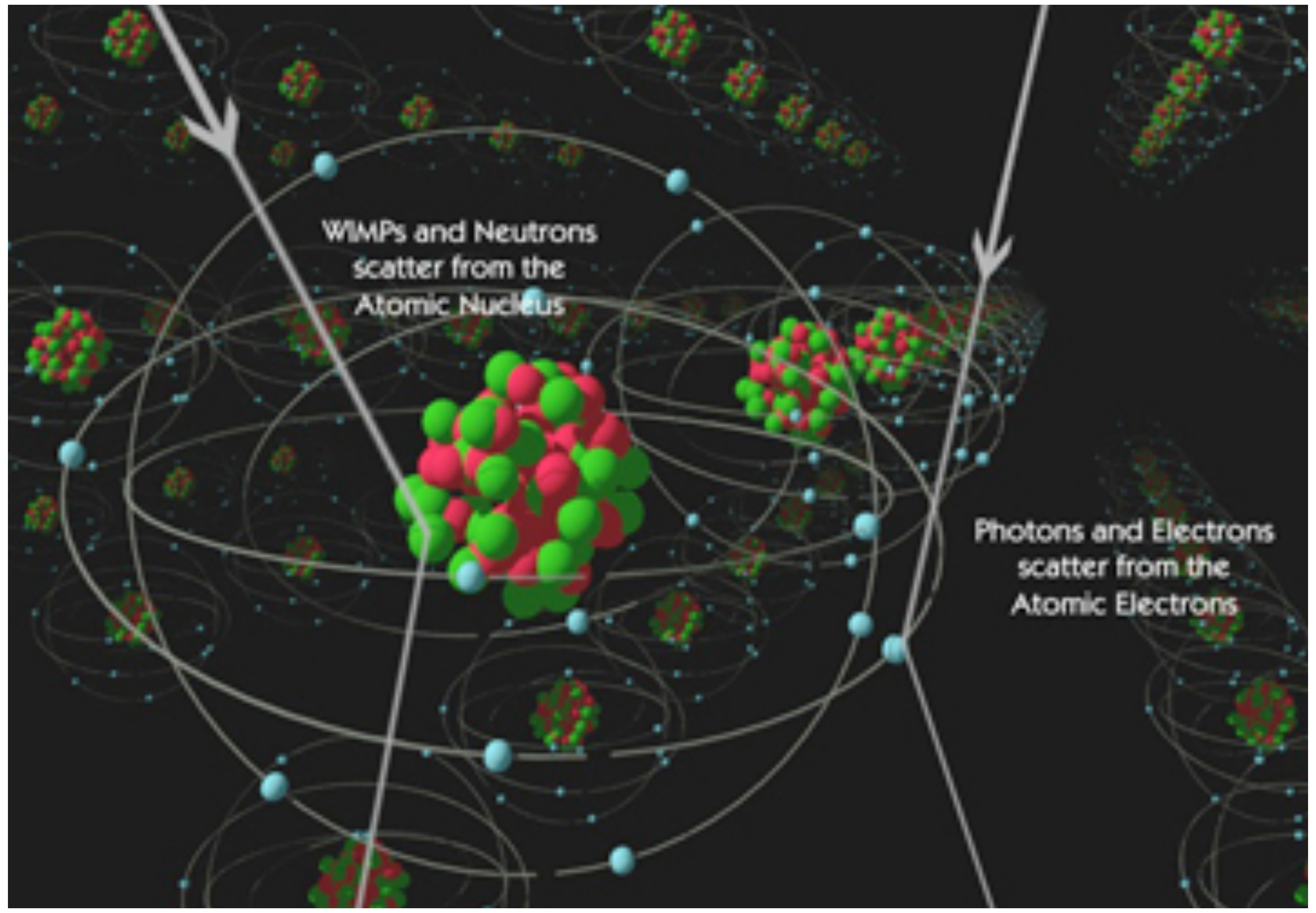
>99.8% ER discrimination

<u>>500x reduction in ER background</u>

Advantages for WIMP detection

ER/NR discrimination

$(S2/S1)_{ER} > (S2/S1)_{WIMP}$



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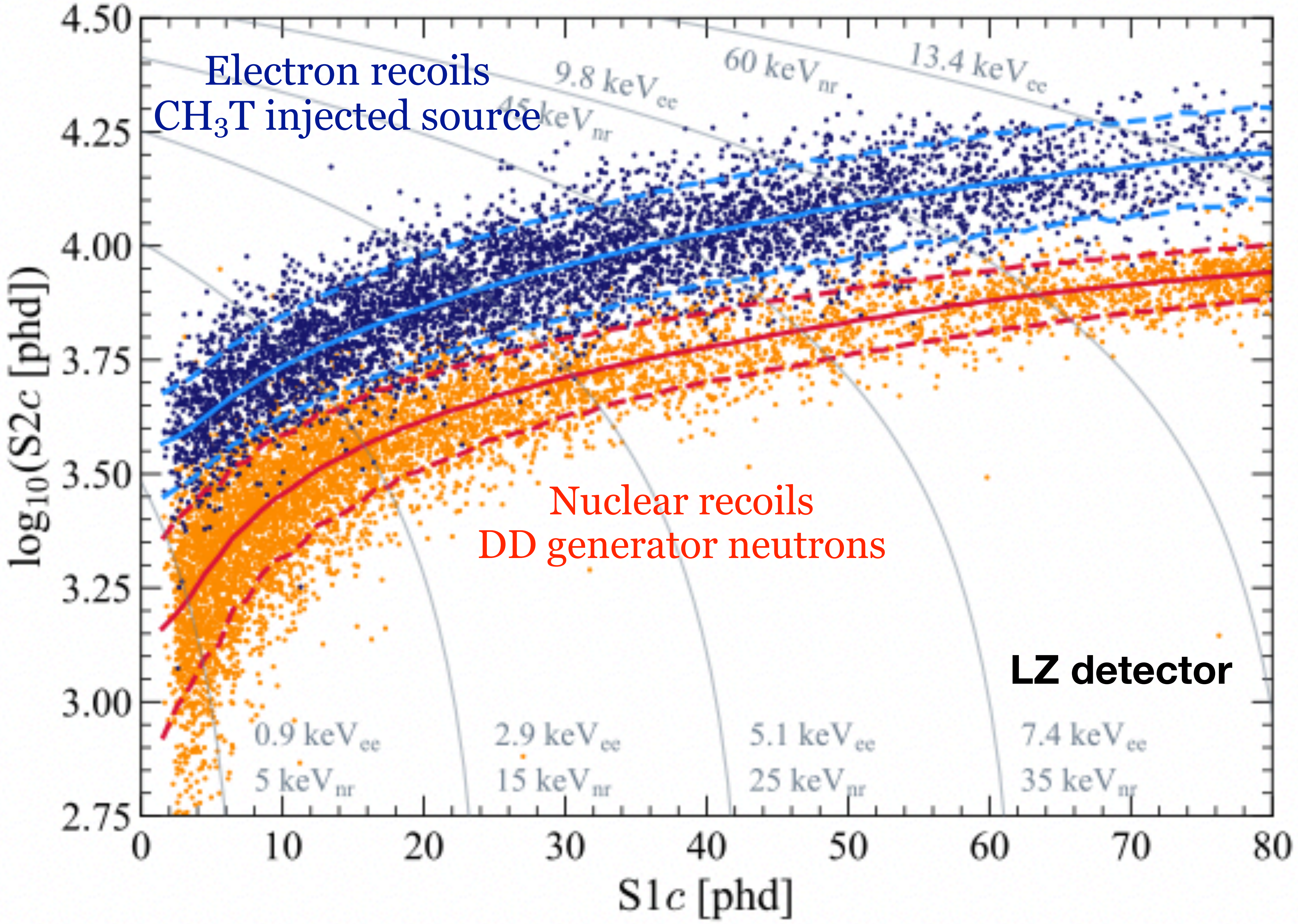


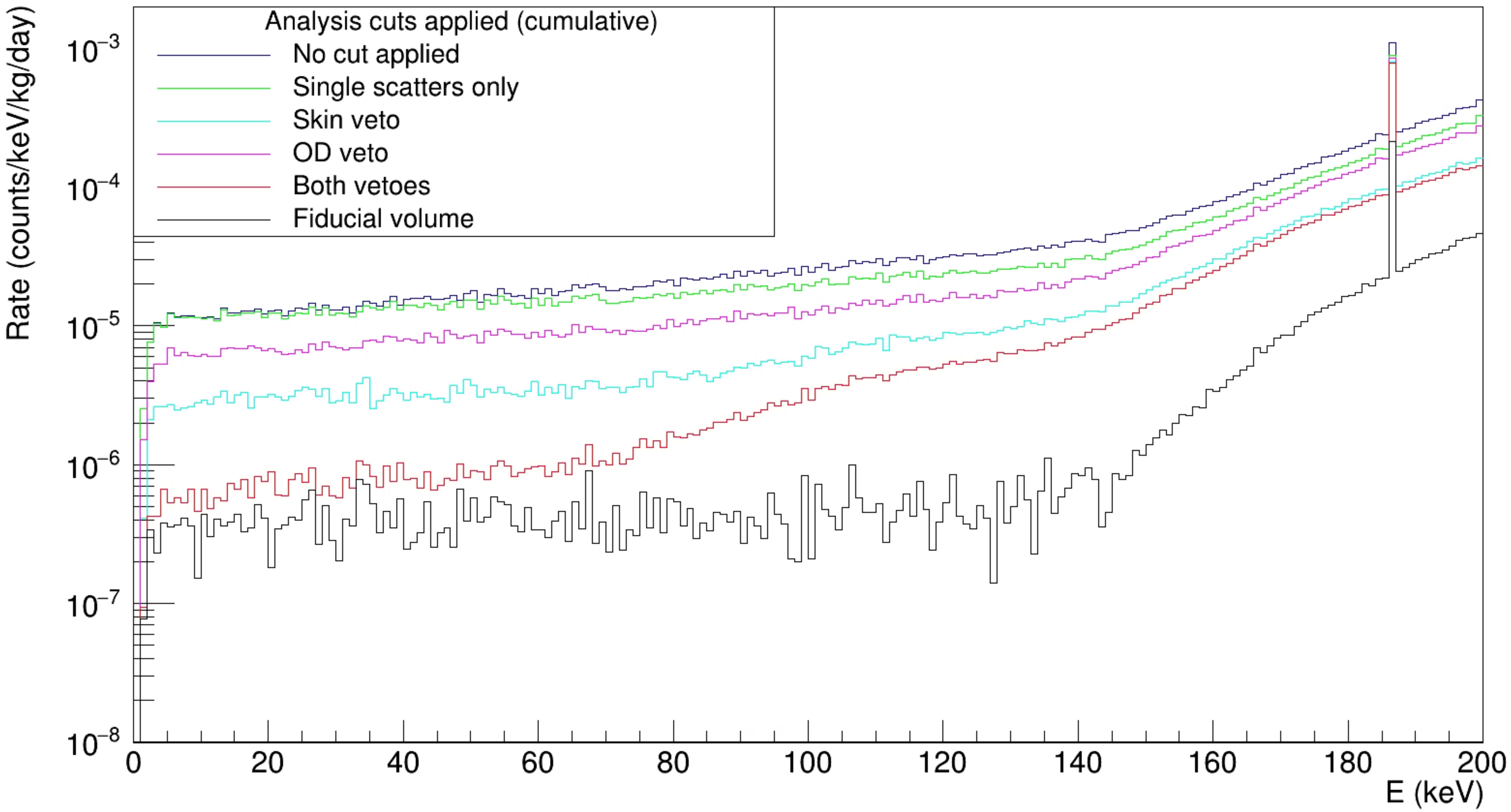
>99.8% ER discrimination

<u>>500x reduction in ER background</u>

Projections

Background model

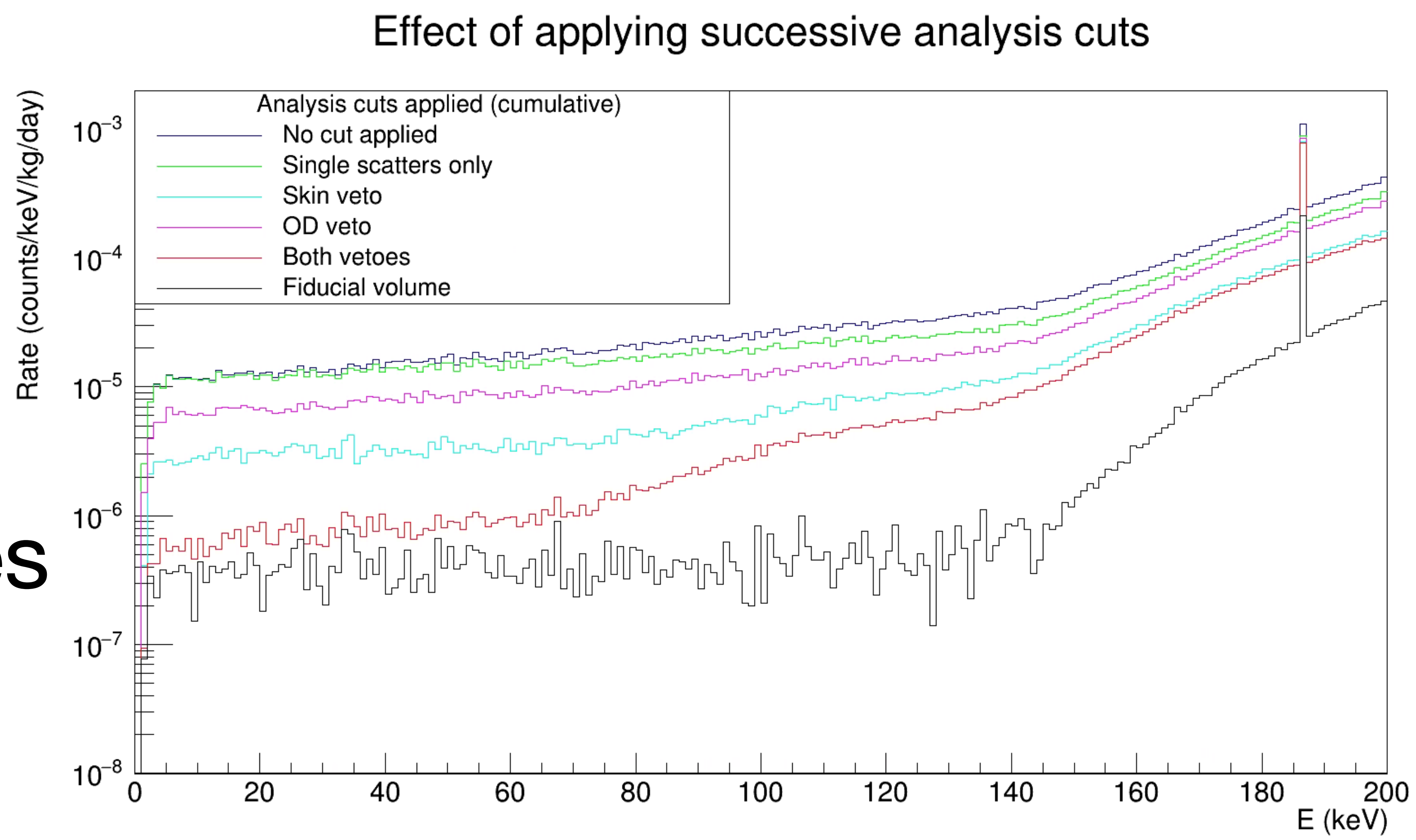
- Reduction of the external gamma background with successive analysis cuts



Projections

Background model

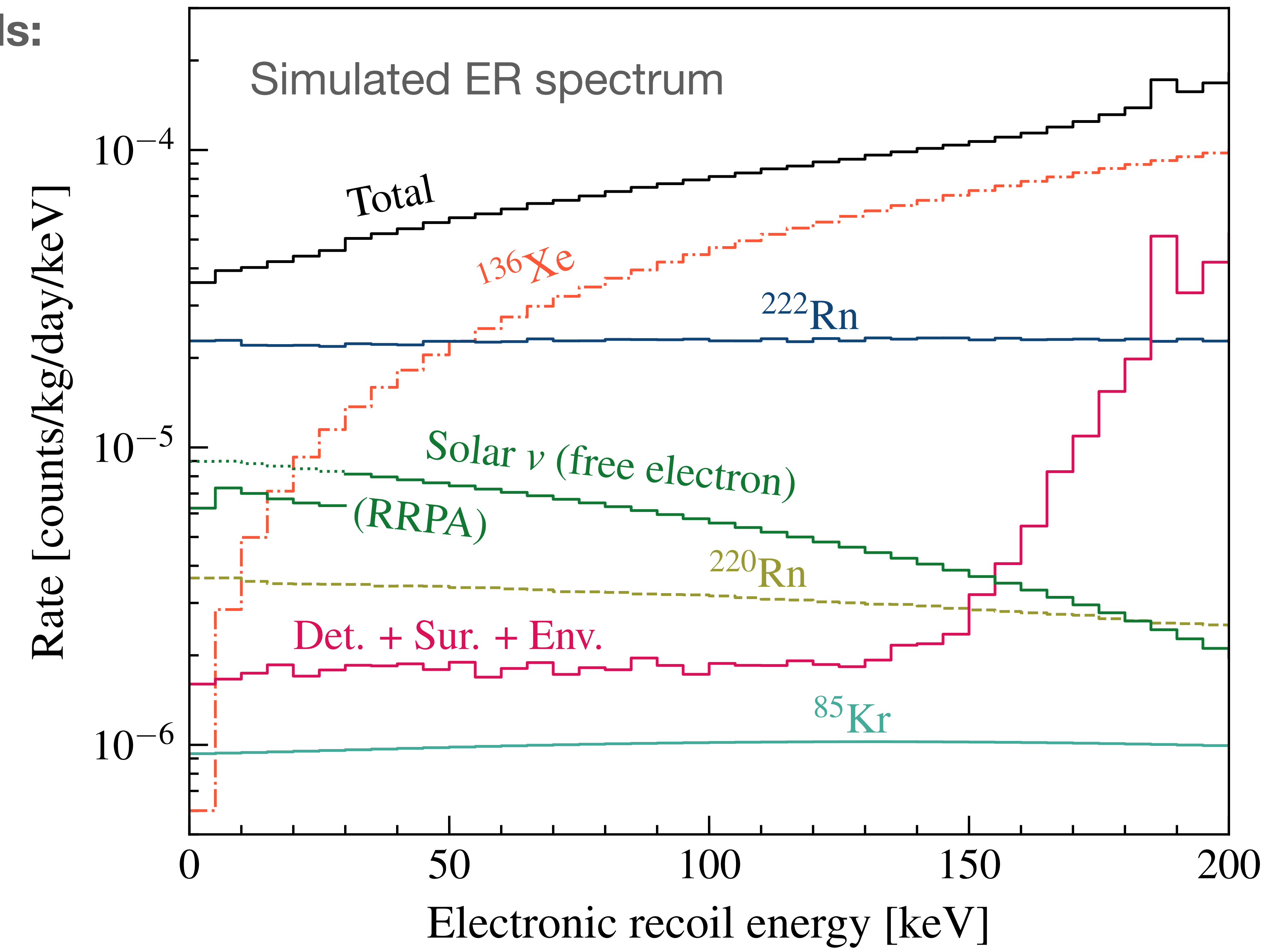
- Example for LZ, after all BG mitigation strategies
  (except discrimination of ERs)

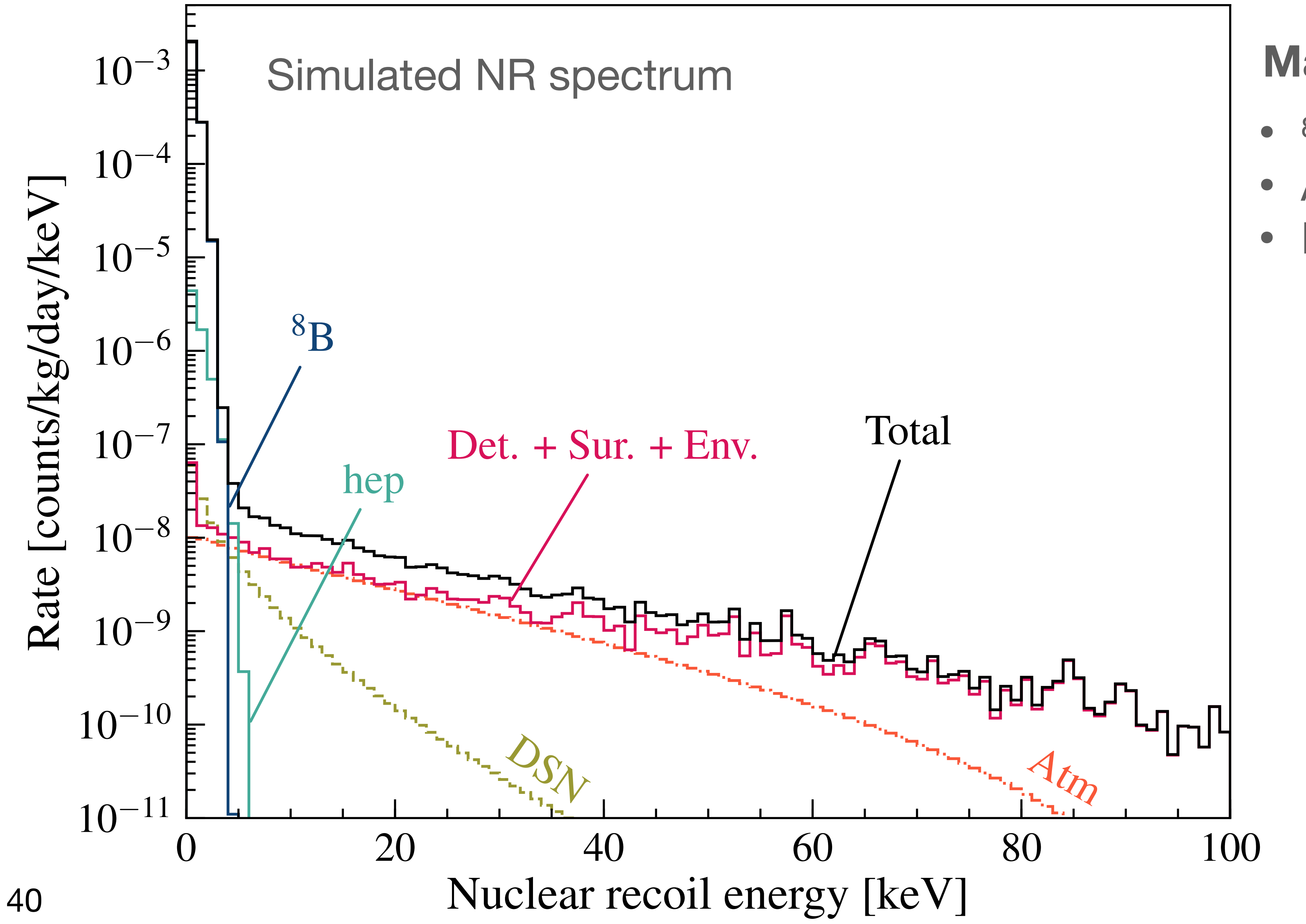


Note the difference in the rate scales!

Main ER backgrounds:

- Rn mixed in the Xe
- Solar neutrinos
- ^{136}Xe $2\nu\beta\beta$
- External gammas



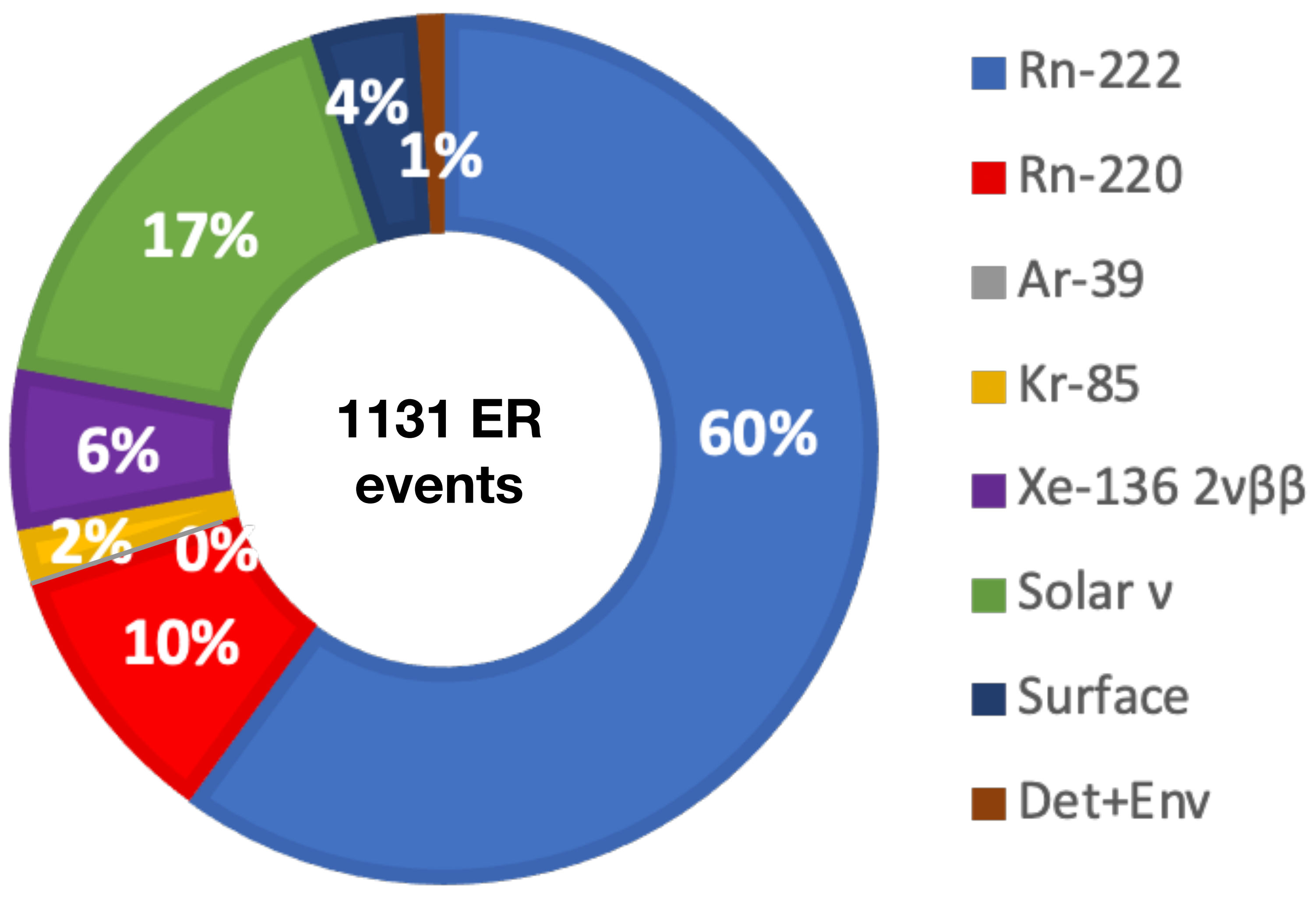


Main NR backgrounds:

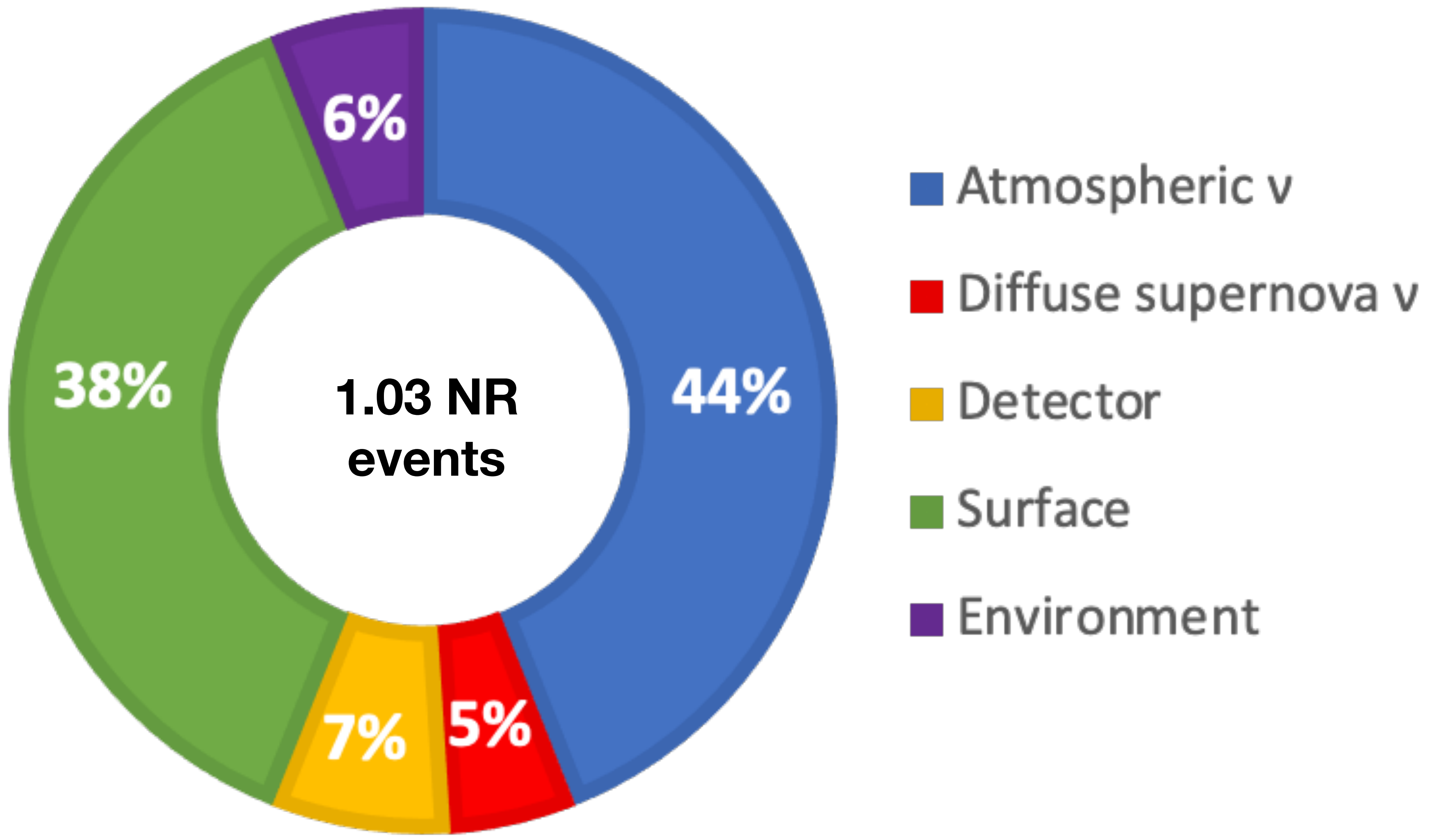
- ^{8}B+hep neutrinos
- Atmospheric neutrinos
- Detector neutrons

Projections

Projected backgrounds of the LZ detector



5.66 events after
99.5% ER discrimination

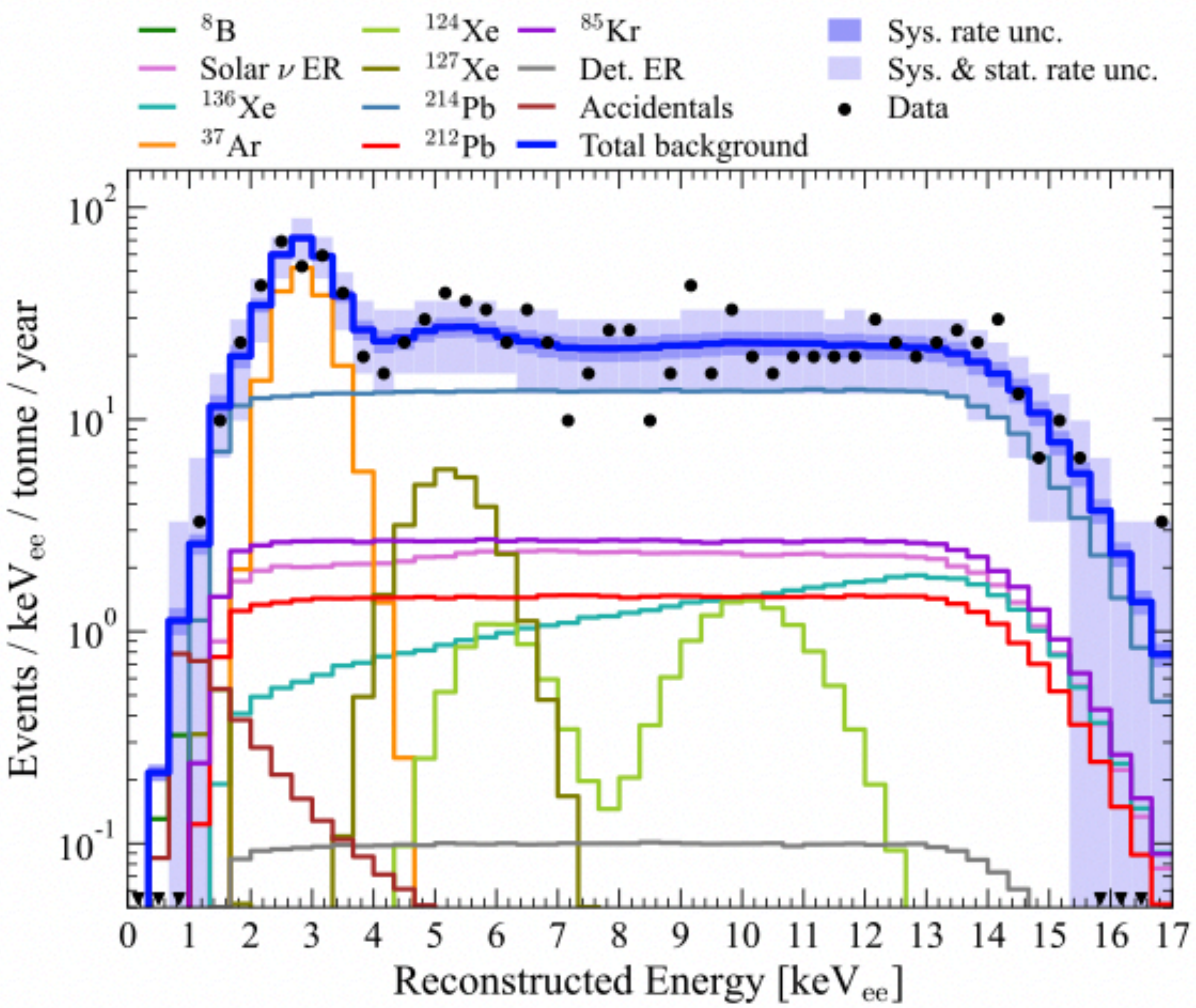


0.52 events after
50% NR acceptance

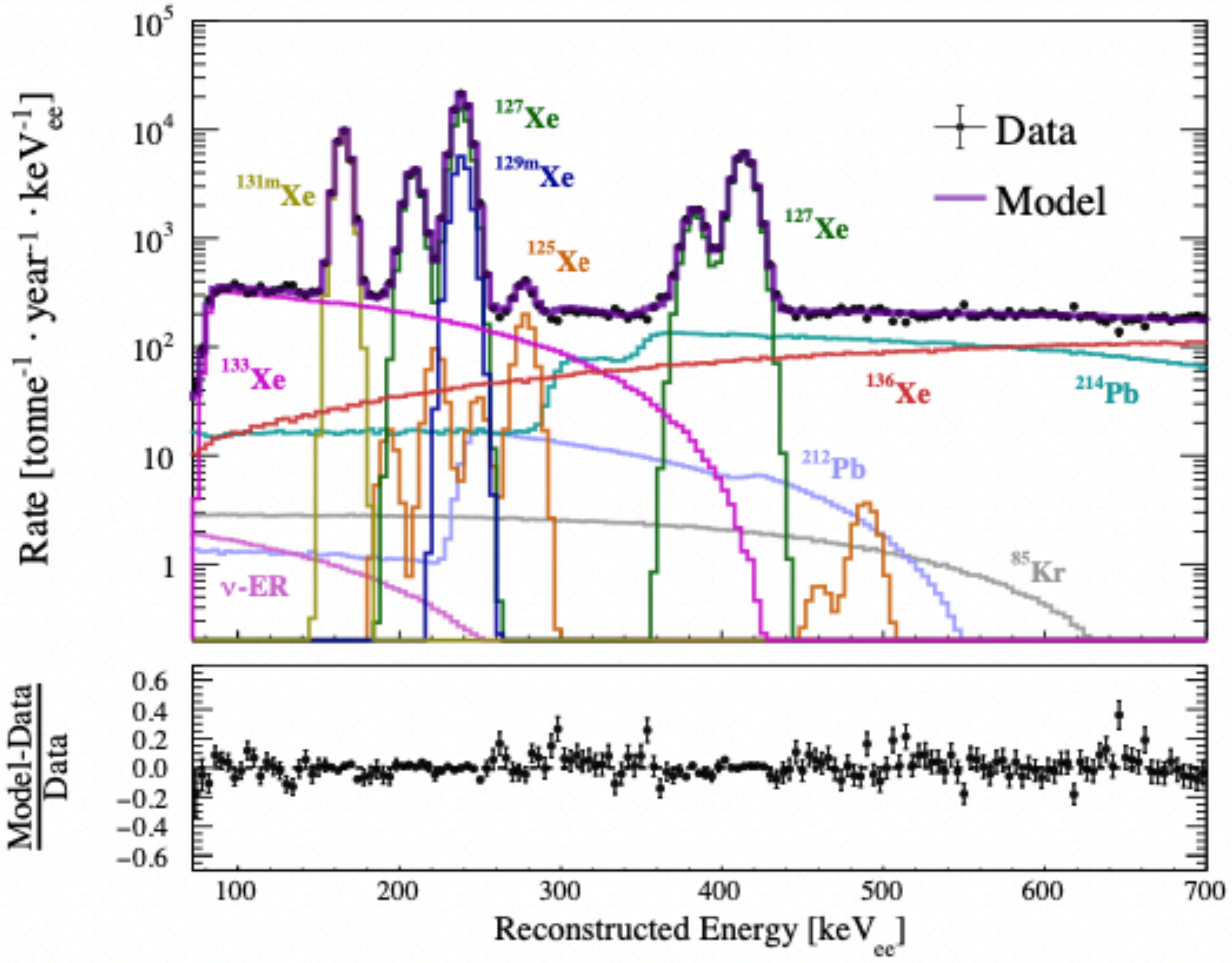
Results

LZ started operating at the end of 2021 (24/12/21)

- Observed backgrounds — low energy (arXiv:2211.17120)



Short lived isotopes from cosmogenic and neutron activation

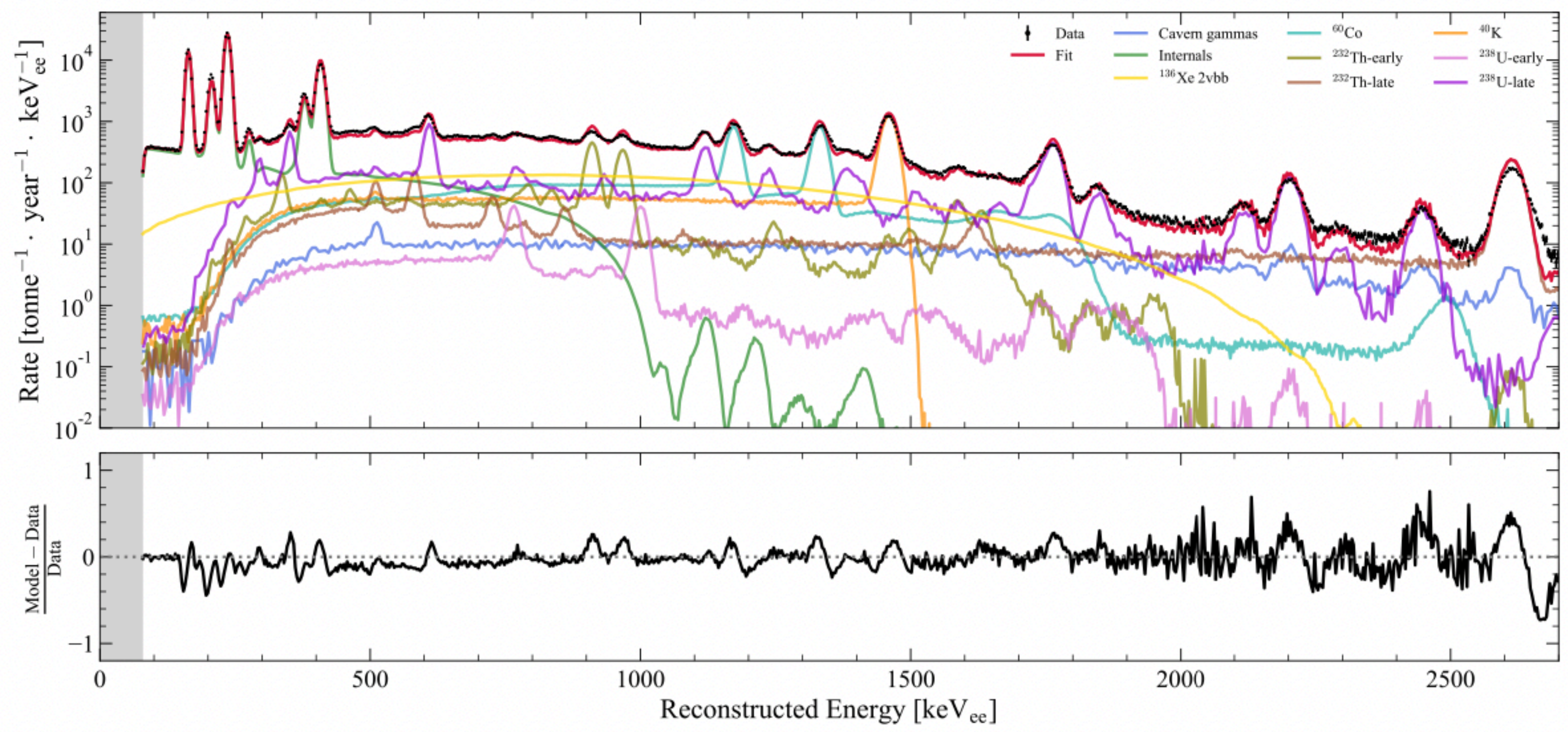


Component	Half-life [days]	Pre-DD Fit [μBq/kg]
^{127}Xe	36.4	92.88 ± 0.38
^{131m}Xe	11.8	18.87 ± 0.13
^{129m}Xe	8.9	4.91 ± 0.23
^{133}Xe	5.2	2.01 ± 0.11
^{125}Xe^a	0.7	-
^{214}Pb	-	3.05 ± 0.12
^{212}Pb	-	0.13 ± 0.01
^{136}Xe	-	3.89 ± 0.18
^{85}Kr	-	$(4.21 \pm 0.42)\cdot 10^{-2}$

Results

LZ started operating at the end of 2021 (24/12/21)

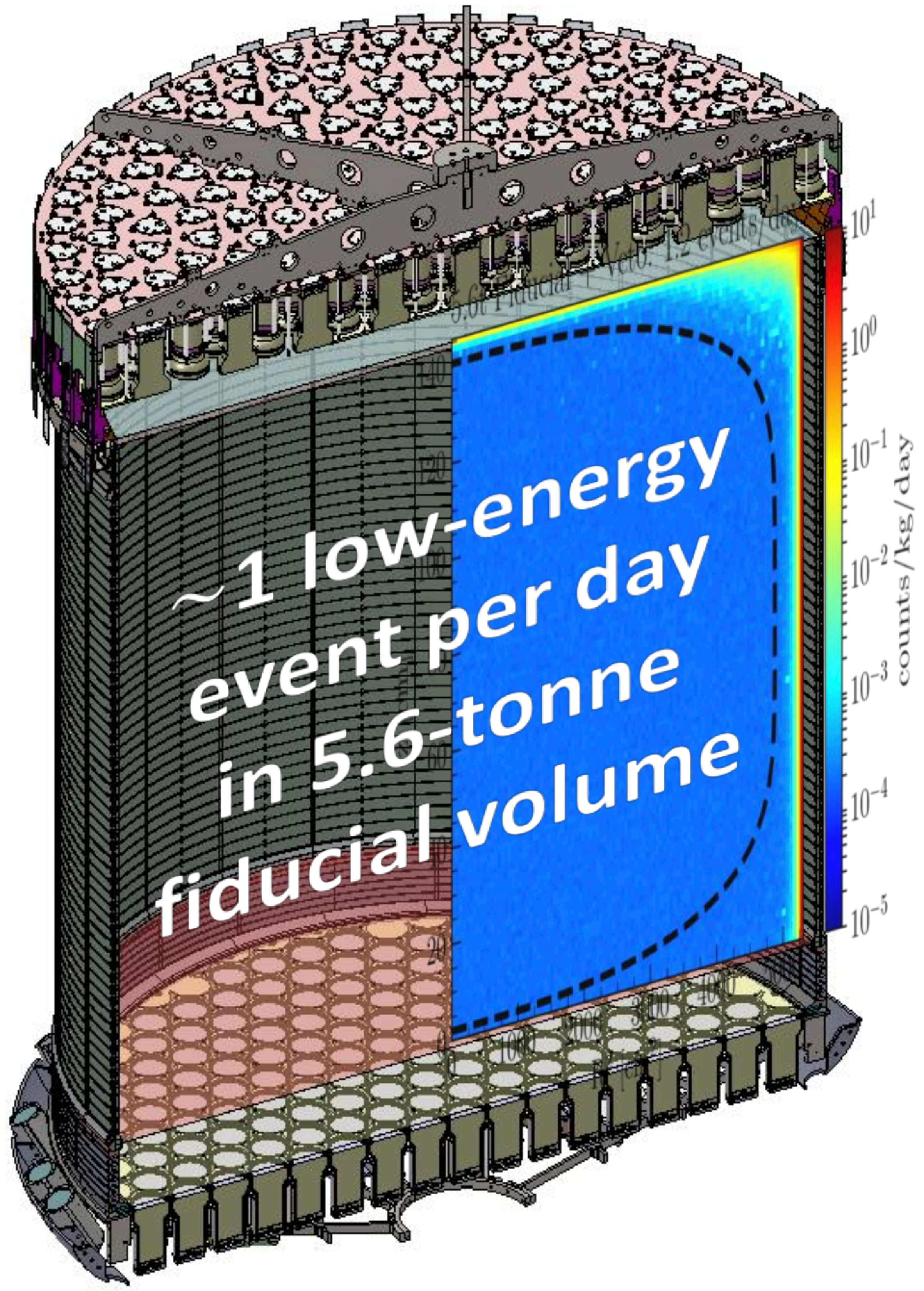
- Observed backgrounds — high energy (arXiv:2211.17120)

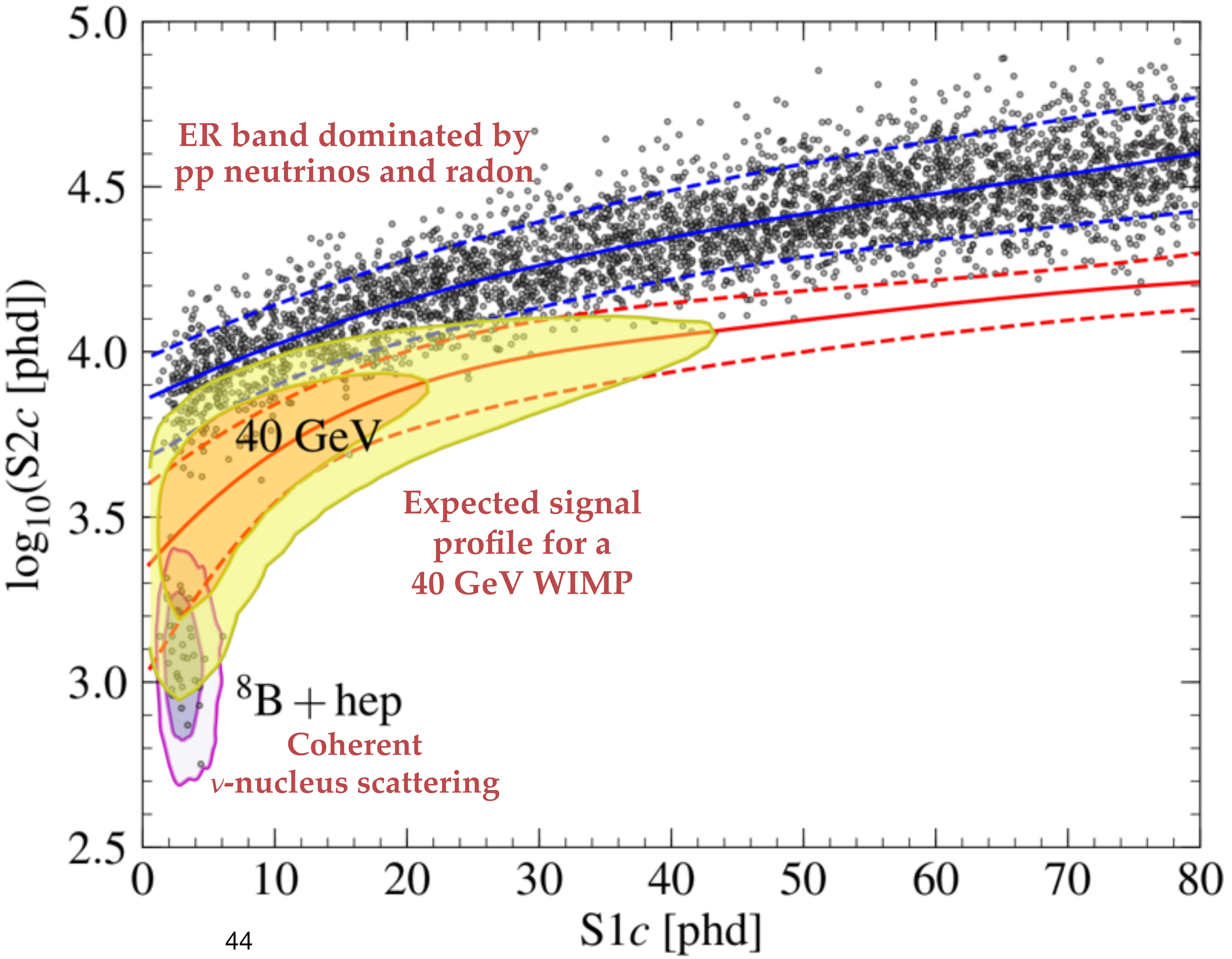


Projections

Discrimination plot

- Expected science data from the LZ detector, after a simulated 1000 day exposure

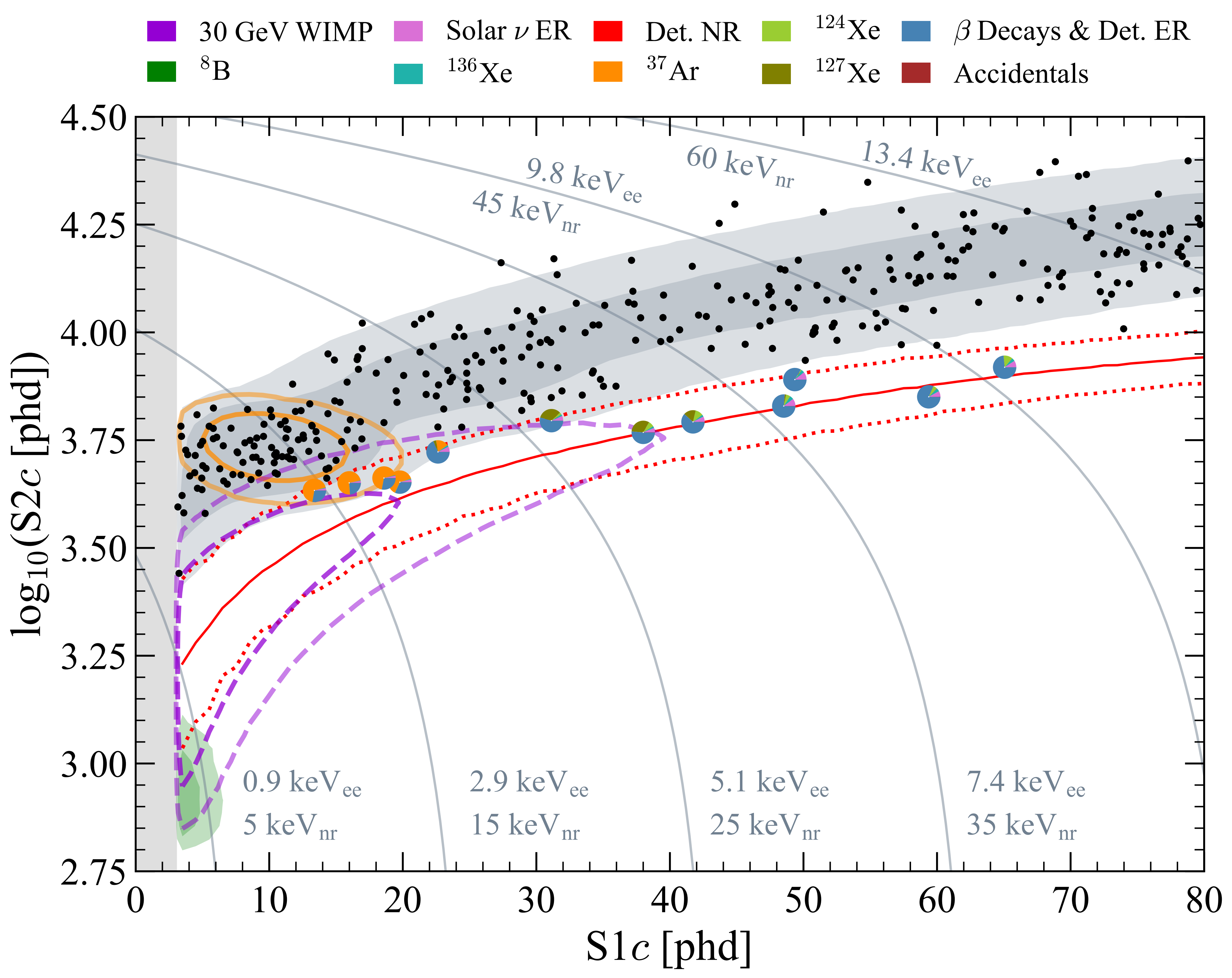


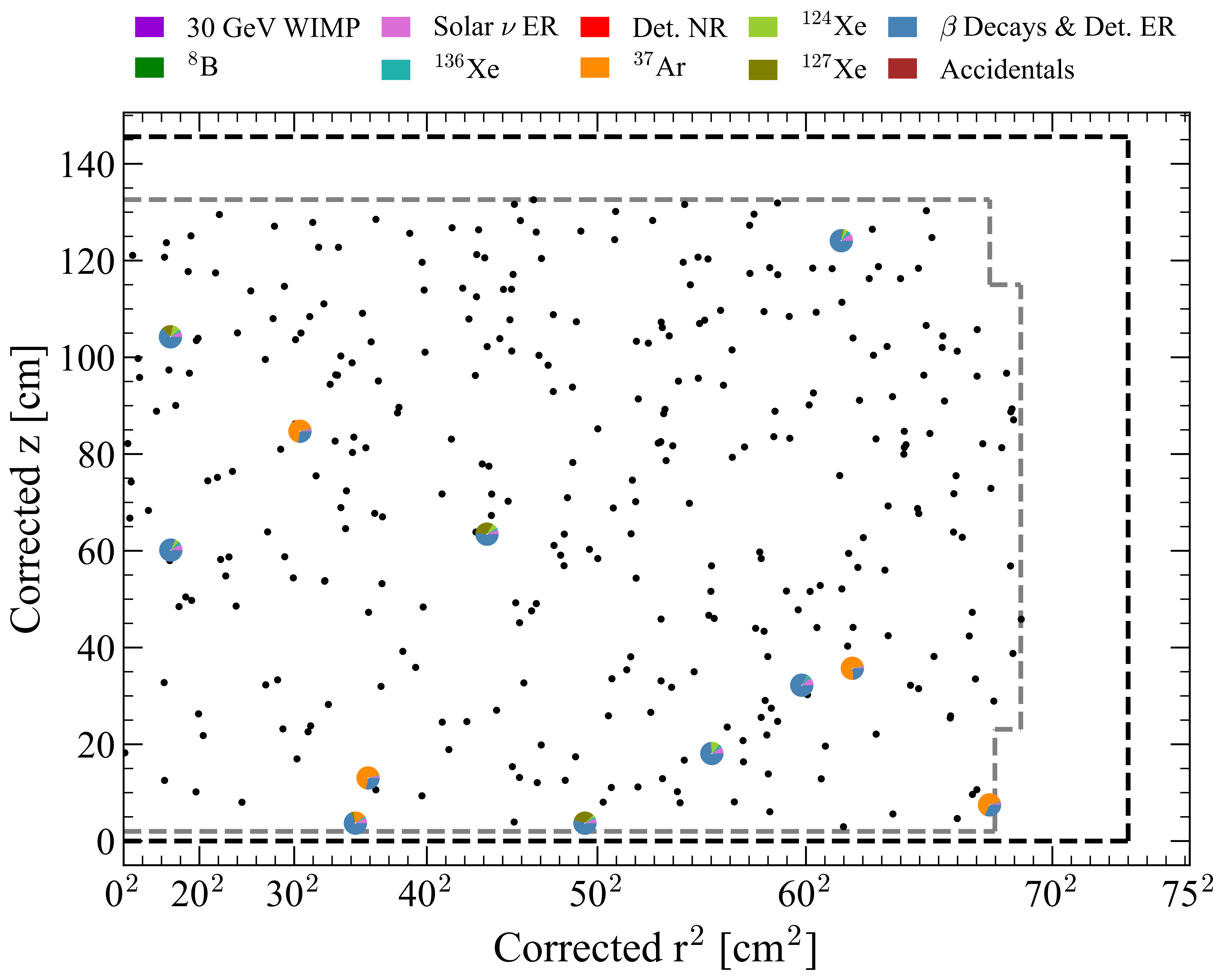


Results

LZ started operating at the end of 2021 (24/12/21)

- Observed data during 90-day science run

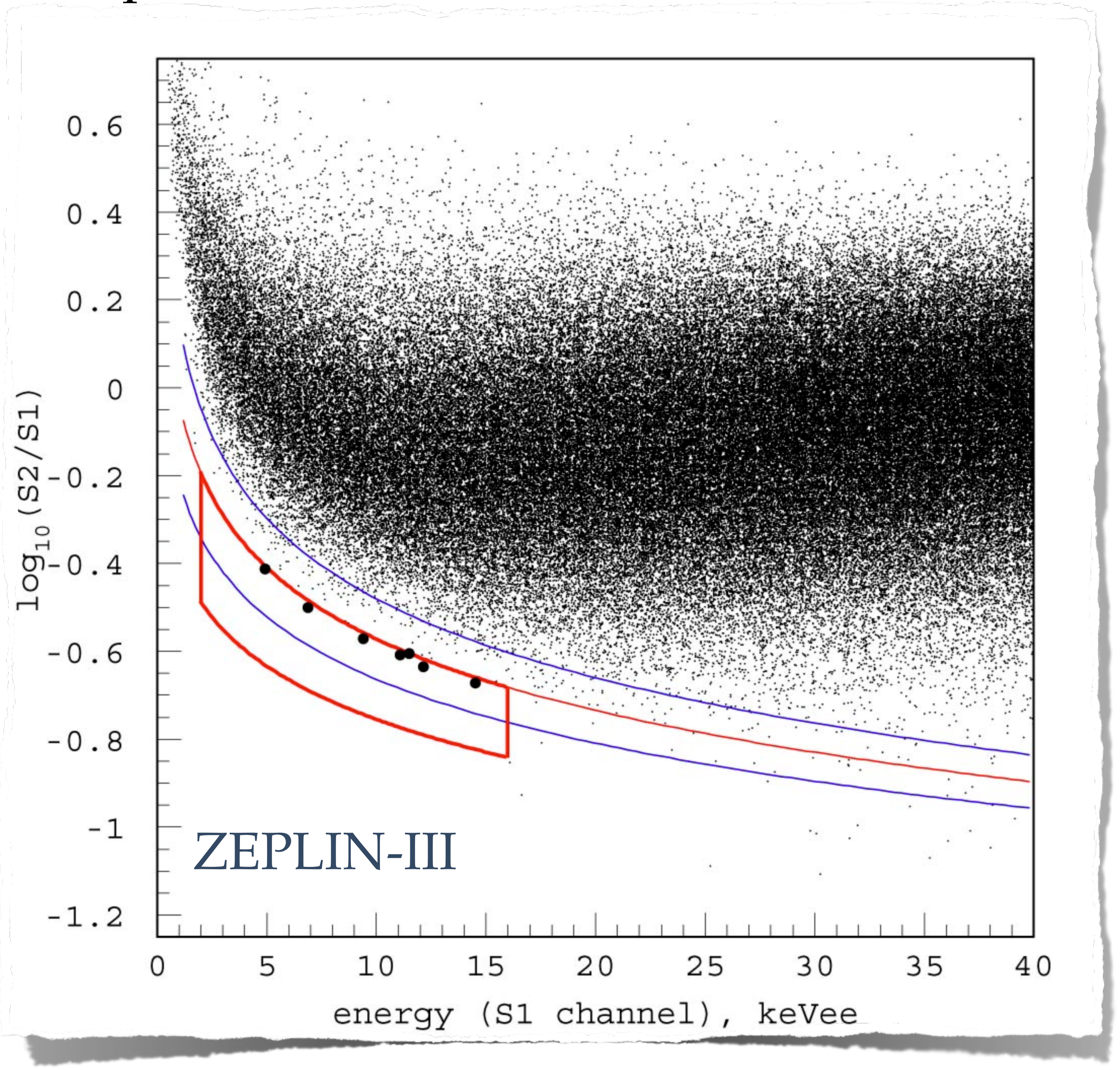




Analysis

Statistical analysis strategies

- Approach 1 (older publications):
  - define region of interest (ROI) for WIMP search
  - estimate BG counts in ROI from BG model
  - compare observed with expected
  - determine statistical significance (if observed compatible with BG or not)



Analysis

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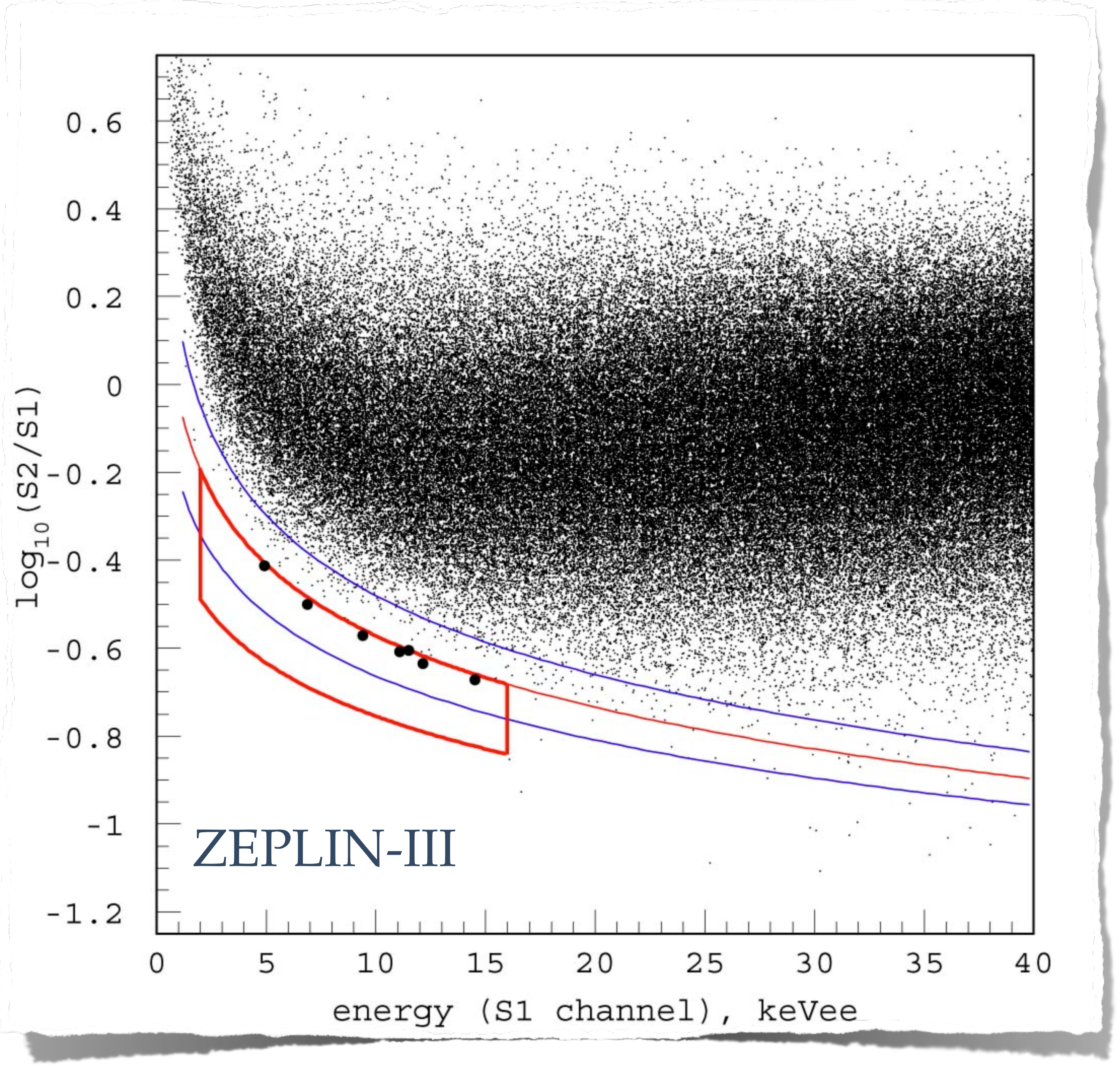
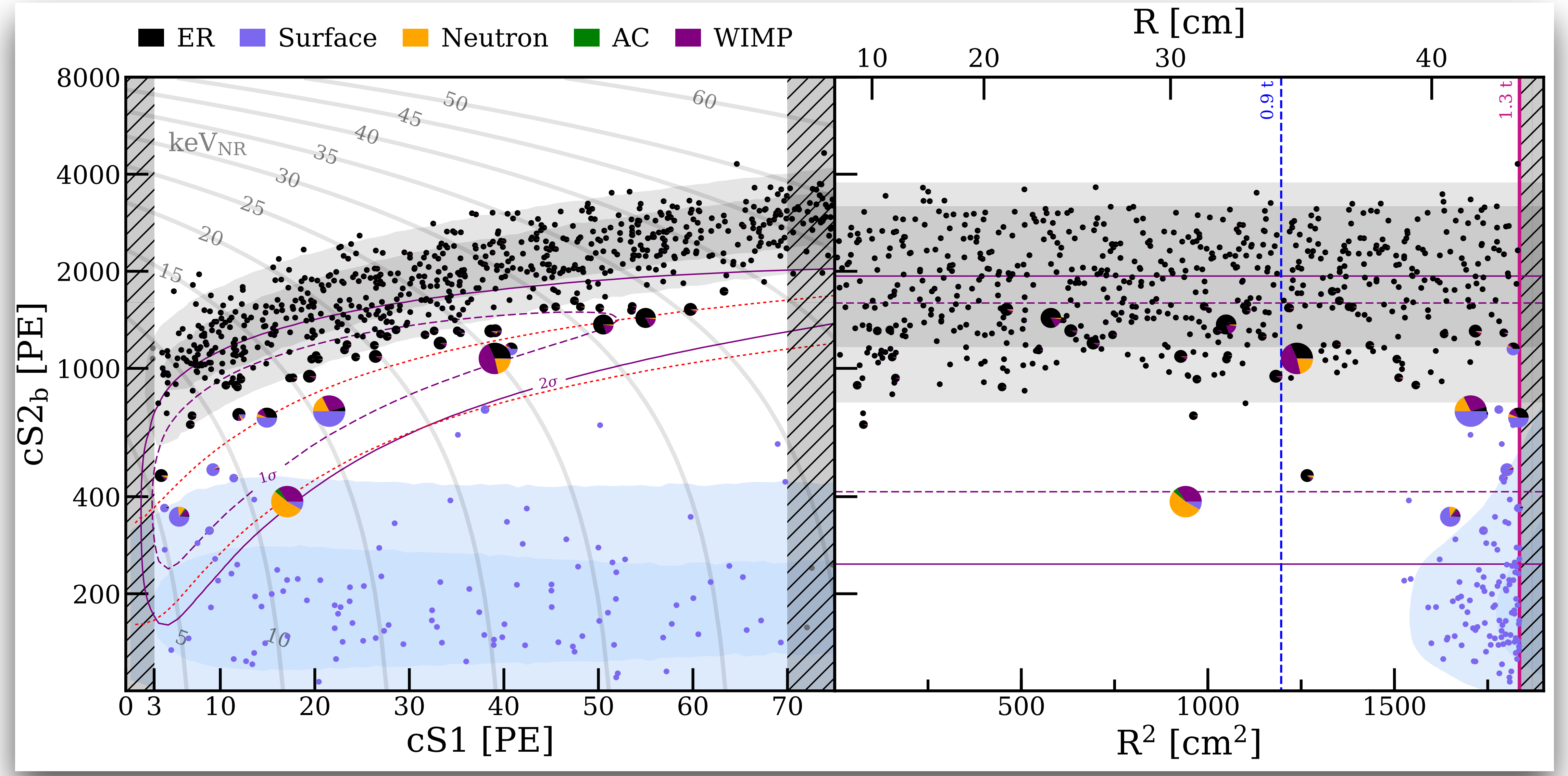


- Approach 2:
  - select set of observables (S1, S2, R, Z)
  - fully characterise BG populations in those observables
  - develop signal model
  - apply a Profile Likelihood Ratio statistical analysis to the observed data

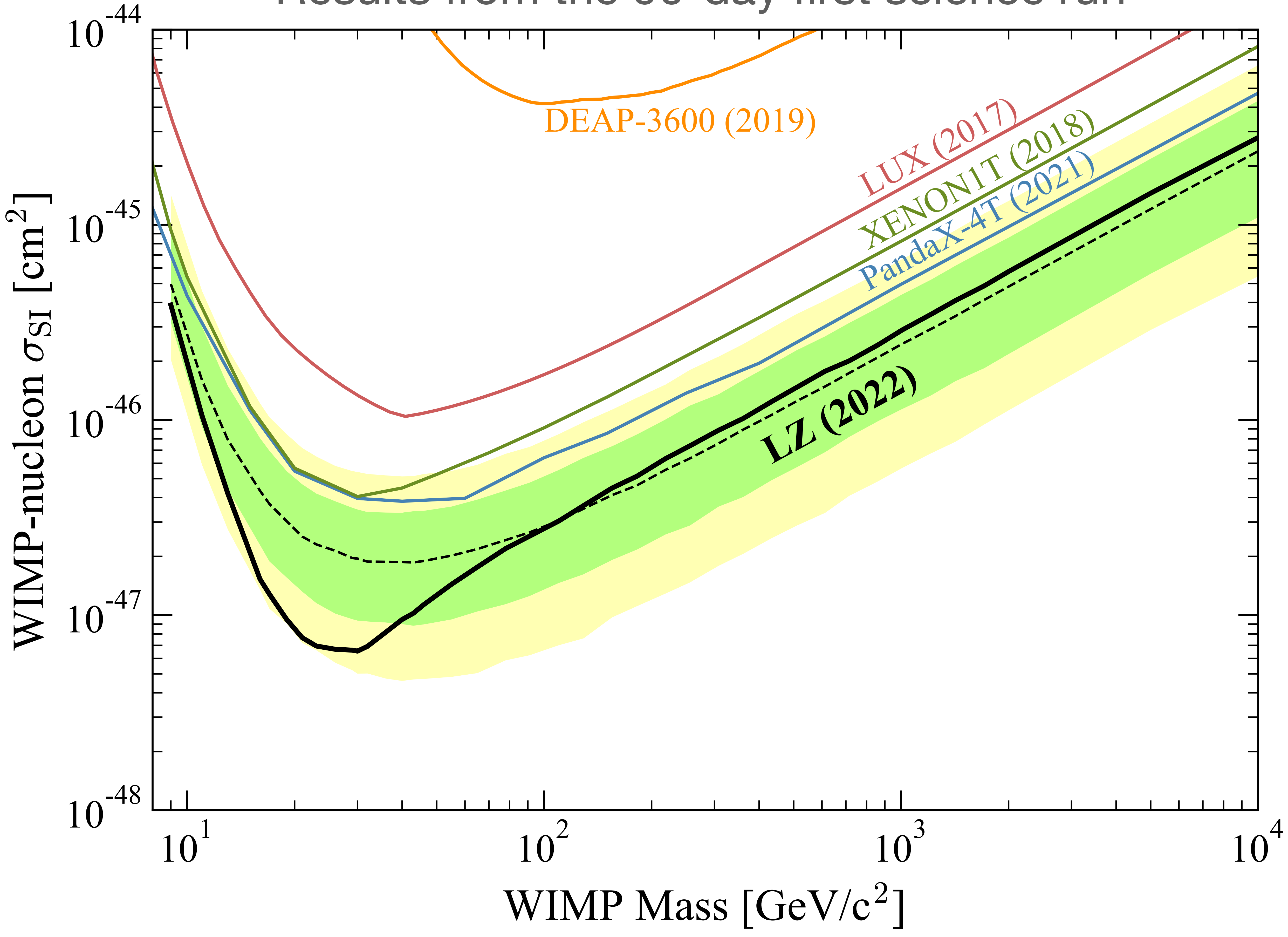


XENON1T

Results

LZ started operating at the end of 2021 (24/12/21)

Results from the 90-day first science run

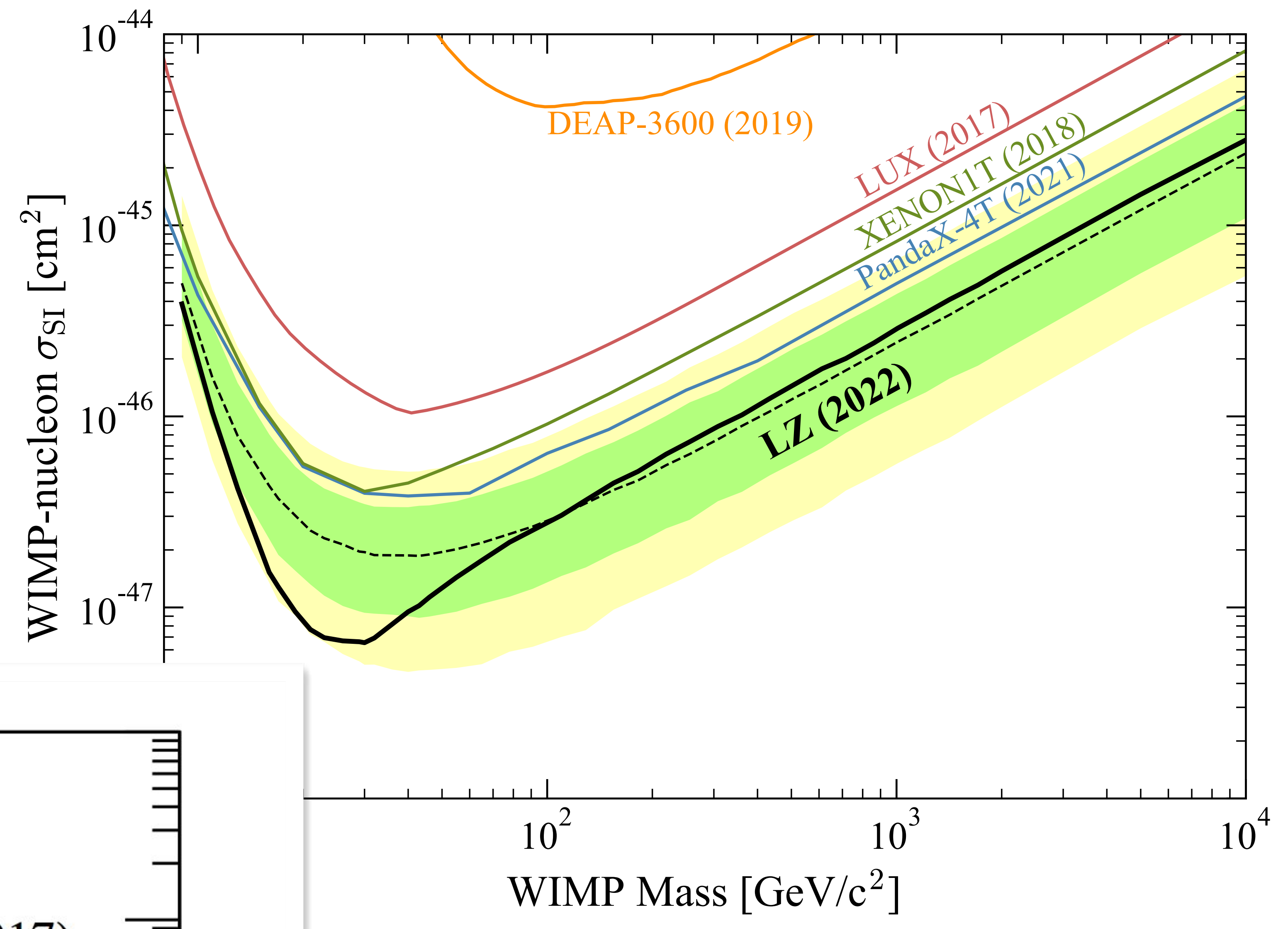


Source	Expected Events	Fit Result
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

https://arxiv.org/pdf/2207.03764.pdf

Projections

Exclusion curve

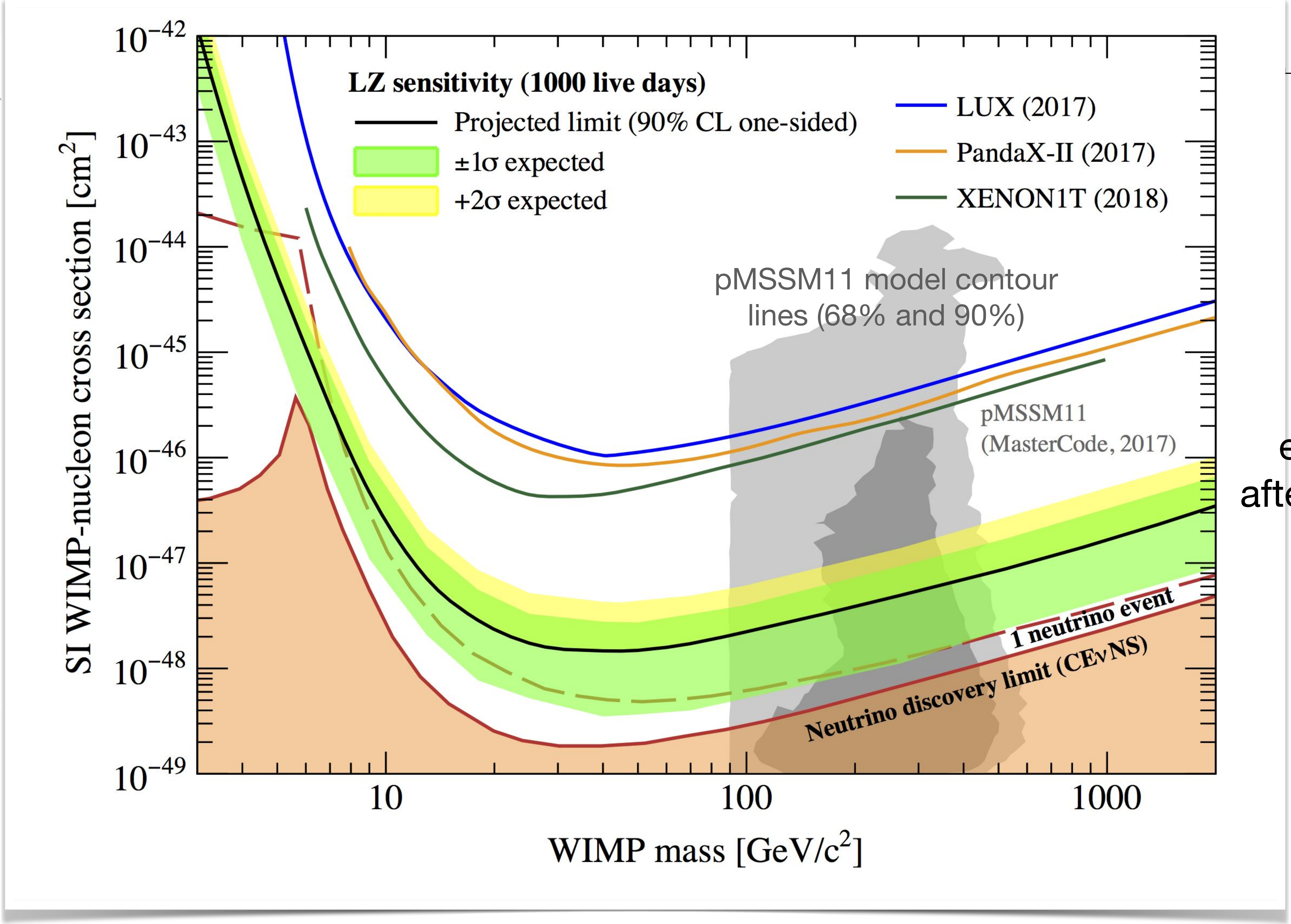


Commonly used prefixed versions

Multiples and sub-multiples[5][6]

Unit	Symbol	m²	cm²
megabarn	Mb	10^{-22}	10^{-18}
kilobarn	kb	10^{-25}	10^{-21}
barn	b	10^{-28}	10^{-24}
millibarn	mb	10^{-31}	10^{-27}
microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb	10^{-52}	10^{-48}

Wikipedia

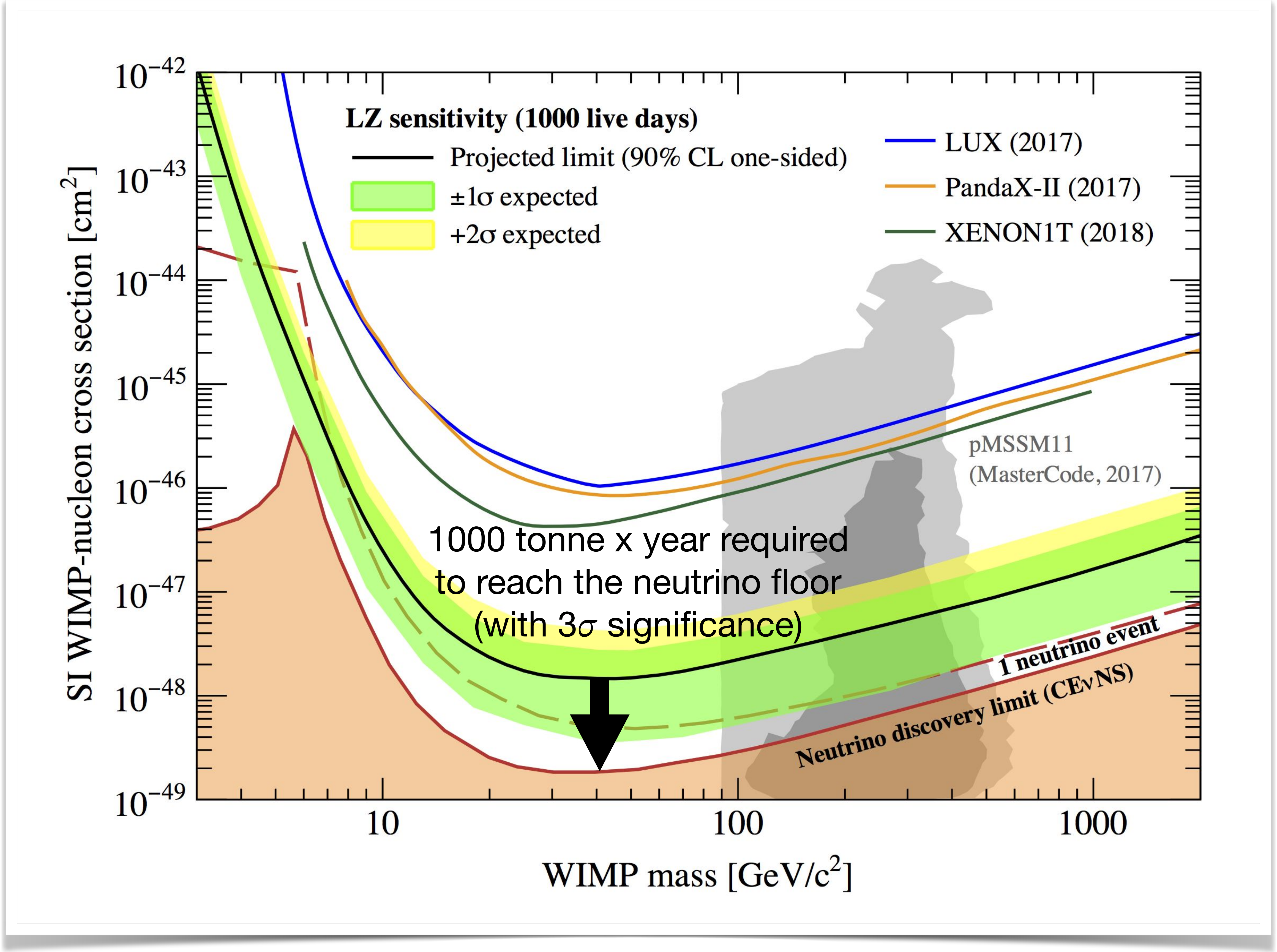


Expected LZ exclusion curve after a 1000 day run

The Future

40 — 80 tonne detector

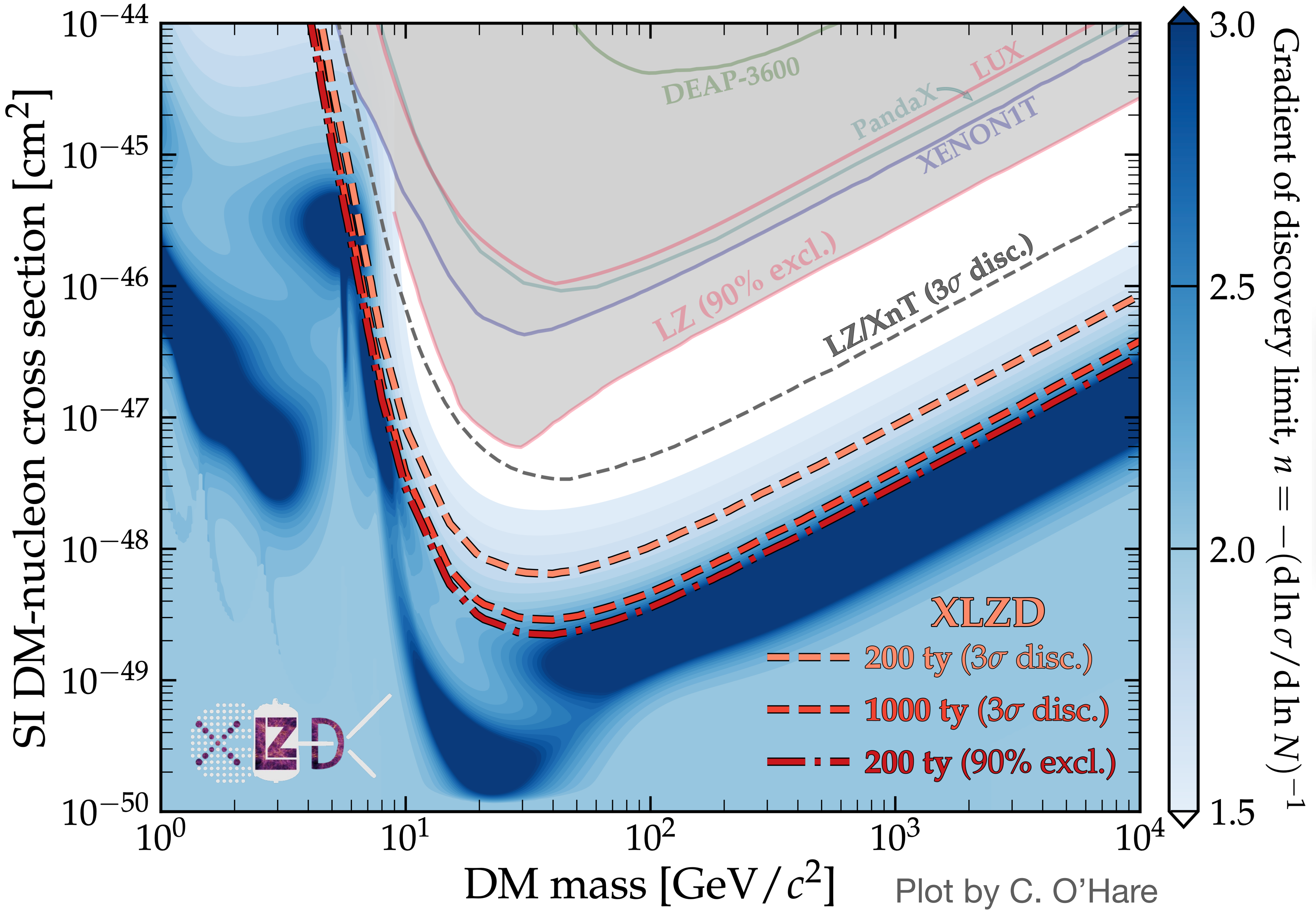
- Goal is to cover the remaining phase space down to the neutrino floor



The Future

40 — 80 tonne detector

- What happens when we "hit the floor"?



Plot by C. O'Hare

Dark Matter Direct Detection on the Moon

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[2] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada*

Direct searches for dark matter with large-scale noble liquid detectors have become sensitive enough to detect the coherent scattering of local neutrinos. This will become a very challenging background to dark matter discovery in planned future detectors. For dark matter with mass above 10 GeV, the dominant neutrino backgrounds on the Earth are atmospheric neutrinos created by cosmic ray collisions with the atmosphere. In contrast, the Moon has almost no atmosphere and nearly all cosmic rays incident on the Moon first collide with the lunar surface, producing a very different neutrino spectrum. In this work we estimate the total flux and spectrum of neutrinos near the surface of the Moon. We then use this to show that a large-scale liquid xenon or argon detector located on the Moon could potentially have significantly greater sensitivity to dark matter compared to an equivalent detector on the Earth due to effectively reduced neutrino backgrounds.

https://arxiv.org/abs/2305.04943

Conclusions

- Multi-tonne noble liquid detectors are currently the best technology to search for WIMPs in the 10 GeV — 100 TeV mass range
- Experiments starting to run now will be able to improve existing results by more than an order of magnitude
- The next generation of such experiments, with target masses approaching 100 tonnes, will be able to cover the remaining parameter space down to the neutrino floor
- They will be sensitive enough to be competitive in other physics studies (e.g. search for the BSM process $0\nu2\beta$, study neutrino properties, etc.)

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- “*TASI lectures on dark matter models and direct detection*”, by Tongyan Lin, arXiv:1904.07915.
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