# RESULTS FROM A 1 TONNE YEAR EXPOSURE WITH XENON1T

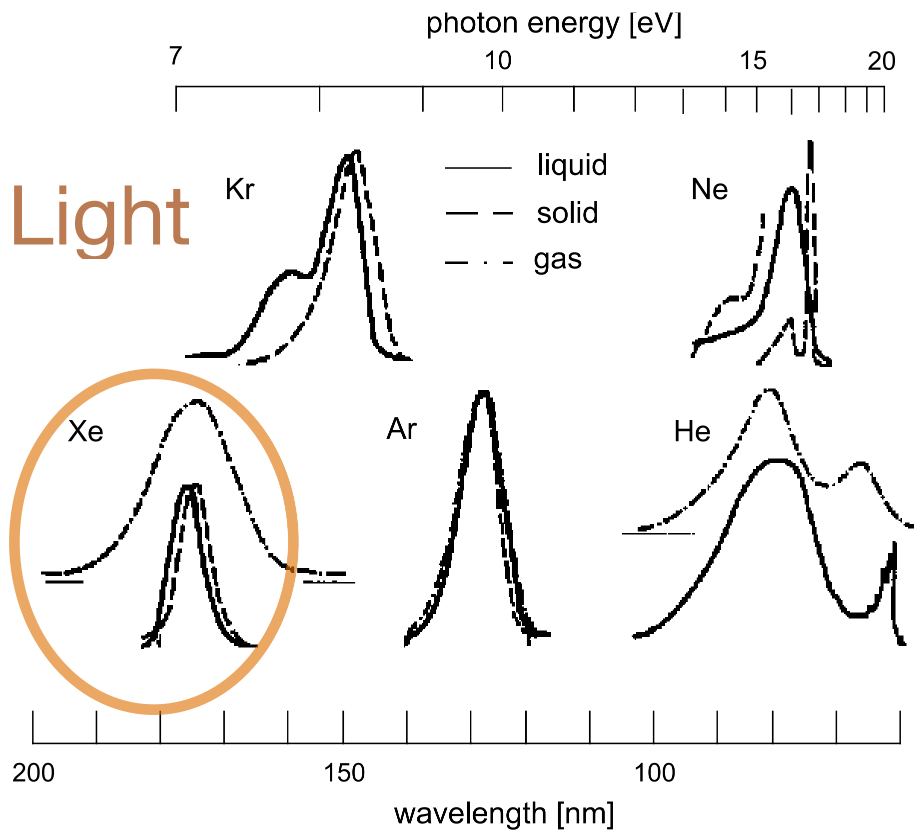
LAURA BAUDIS
UNIVERSITY OF ZURICH

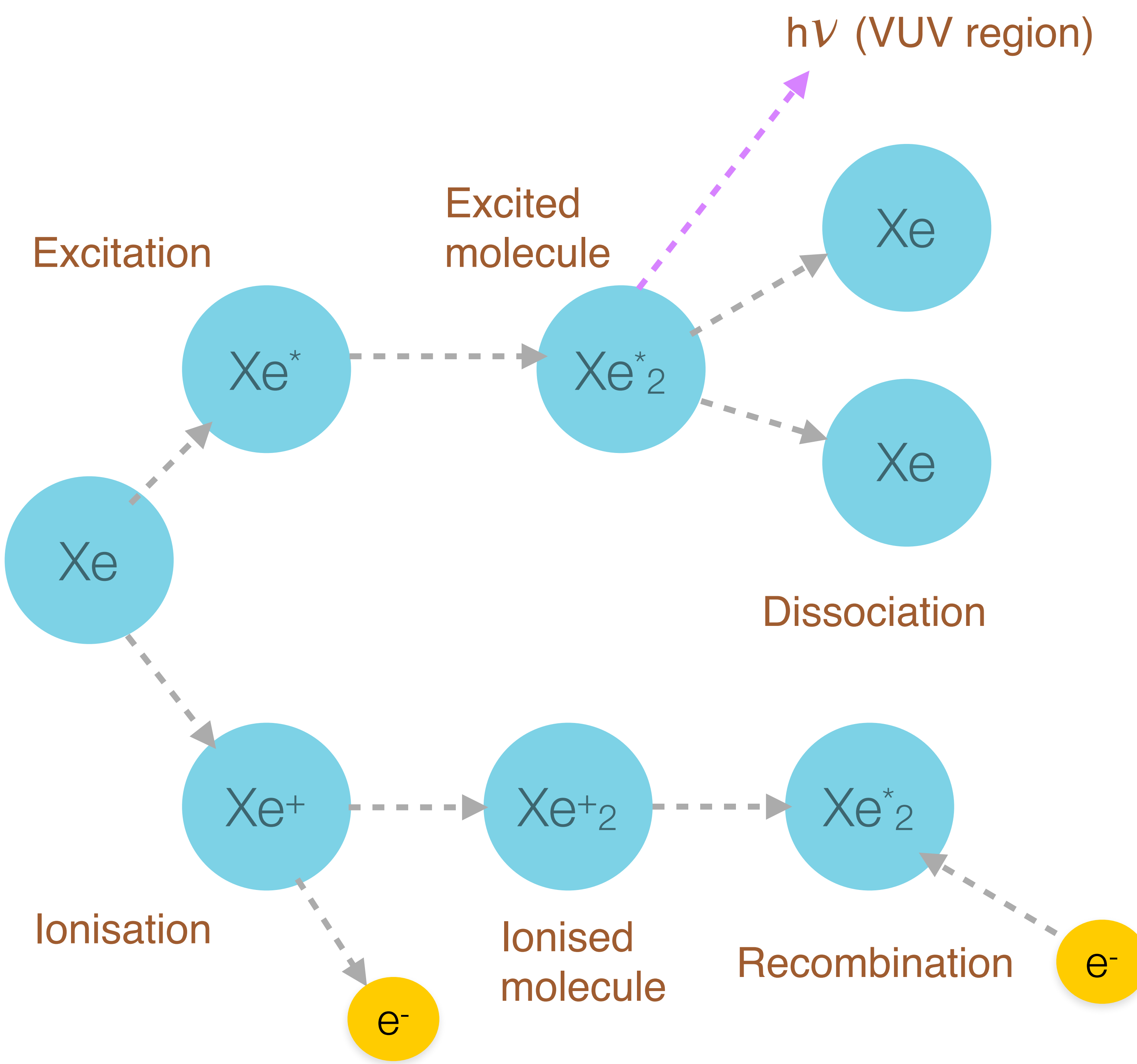
KITP COLLOQUIUM, MAY 30, 2018

xenon1t.org

# XENON ("THE STRANGE ONE") AS A NOBLE GAS

- Discovered by William Ramsay, student of Bunsen & professor at UCL
- Nobel prize 1904 in Chemistry



# A XENON TIME PROJECTION CHAMBER

- 3D position resolution via light (S1) and charge (S2) signals
- S2/S1 depends on particle ID
- Fiducialisation
- Single versus multiple interactions

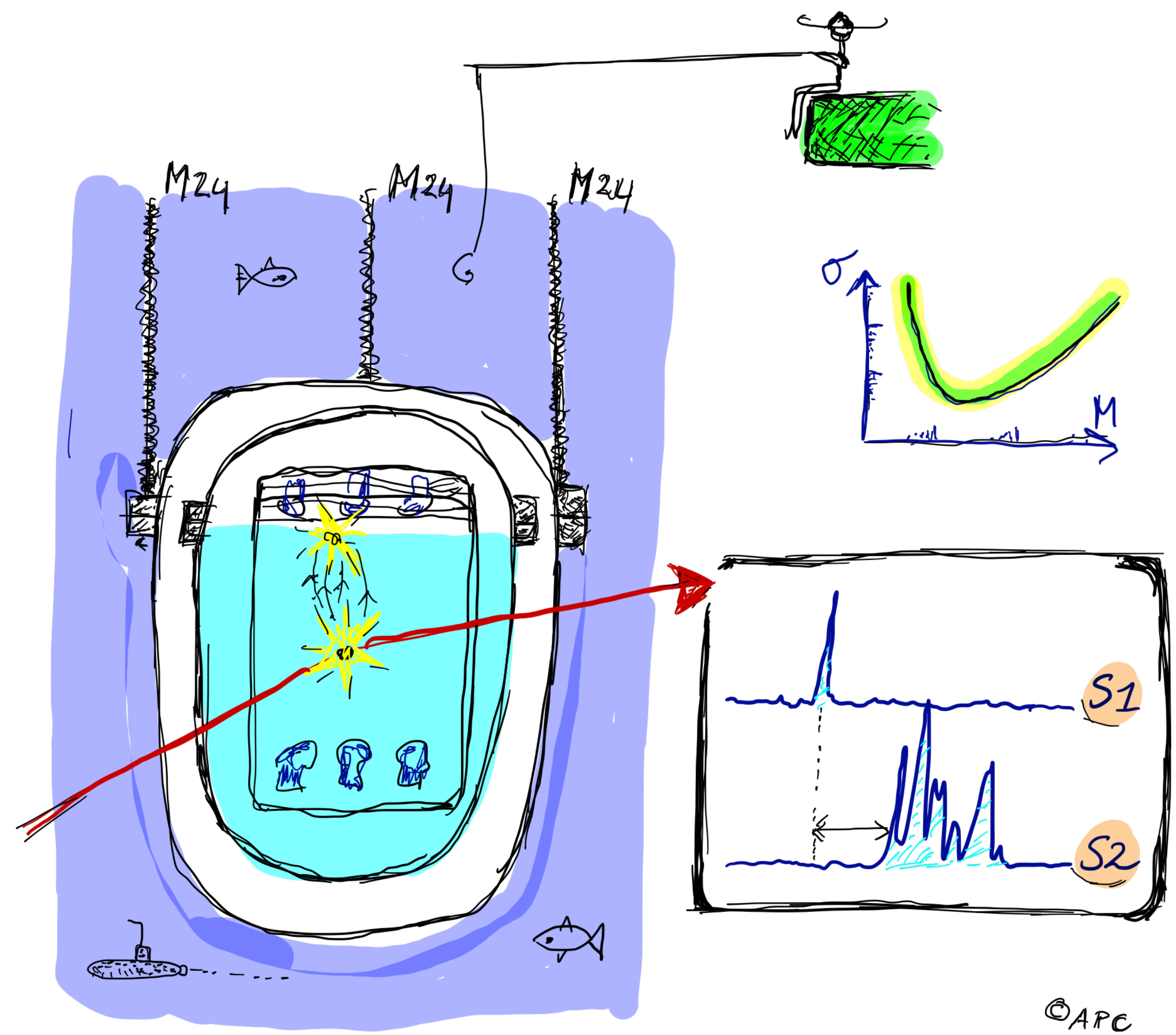
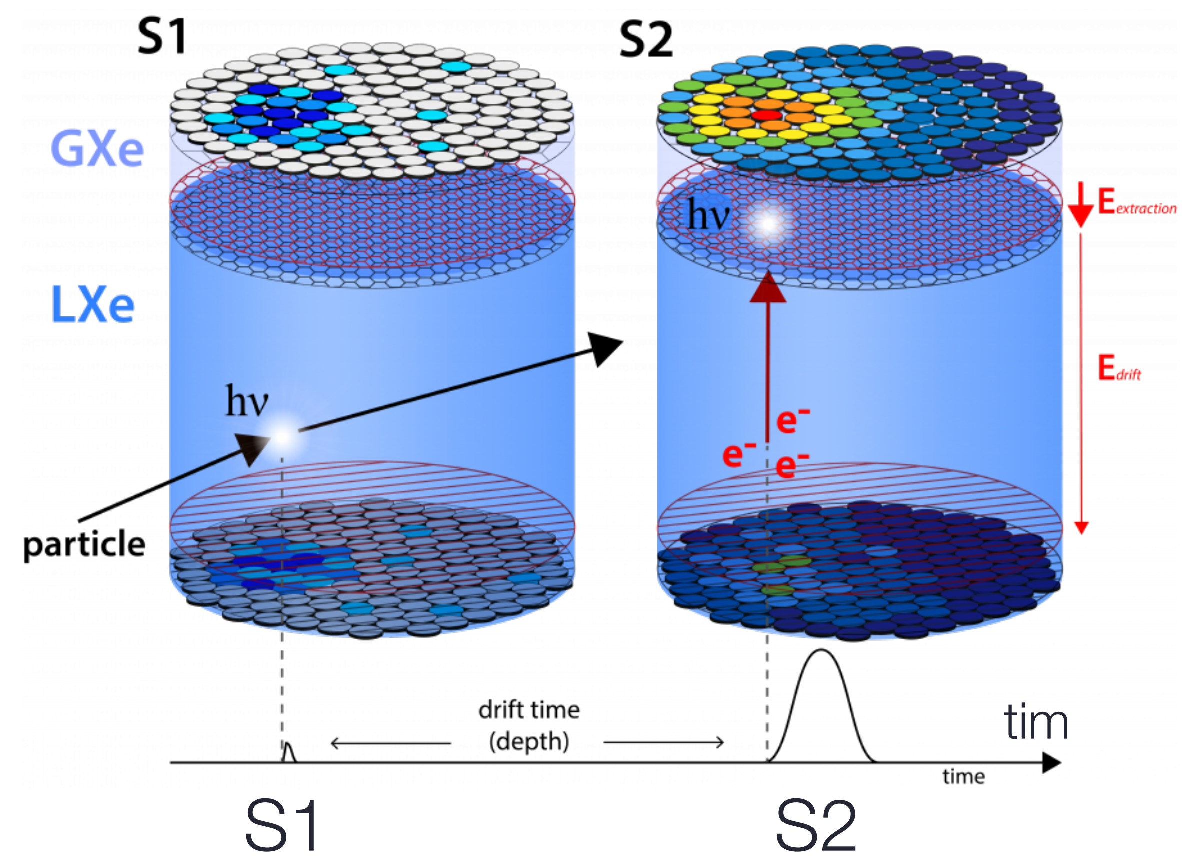
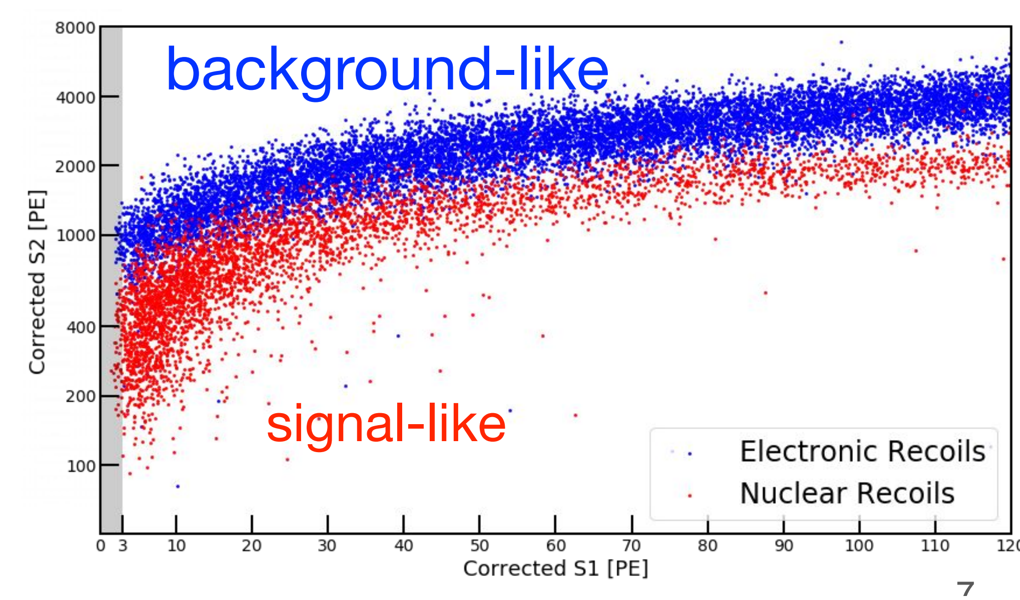



Figure by Auke-Pieter Colijn

# A XENON TIME PROJECTION CHAMBER

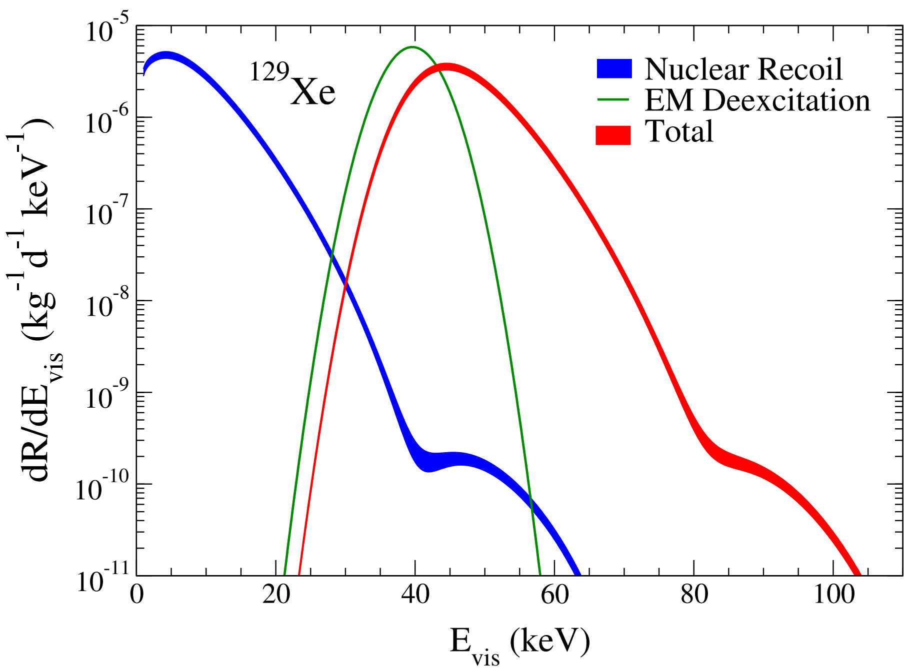
- 3D position resolution via light (S1) and charge (S2) signals
- S2/S1 depends on particle ID
- Fiducialisation
- Single versus multiple interactions



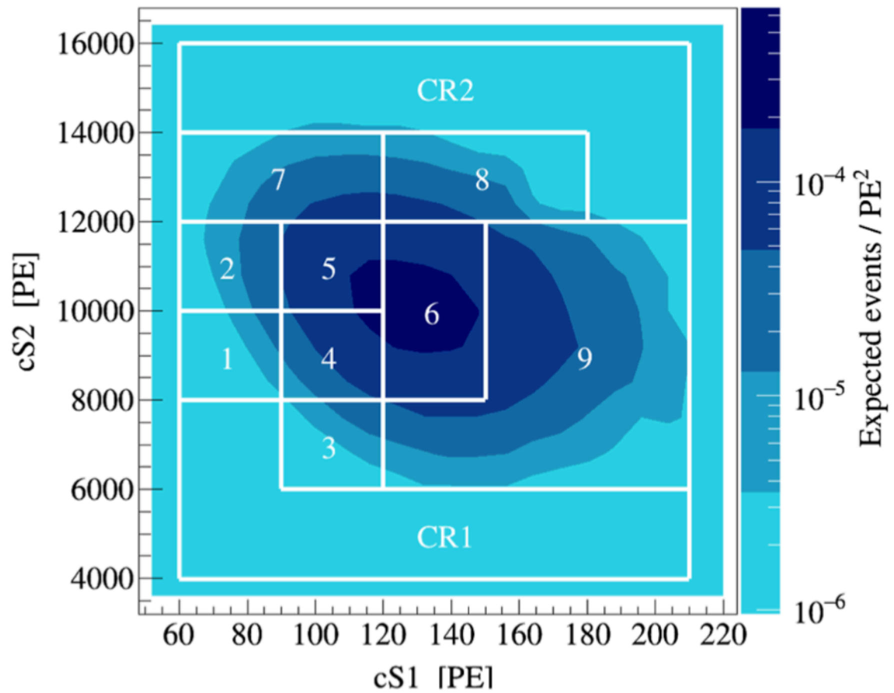



# WIMP PHYSICS WITH XENON NUCLEI

- SI elastic scatters $^{124}$Xe, $^{126}$Xe, $^{128}$Xe, $^{129}$Xe, $^{130}$Xe, $^{131}$Xe, $^{132}$Xe (26.9%), $^{134}$Xe (10.4%), $^{136}$Xe (8.9%)
- SD elastic scatters $^{129}$Xe (26.4%), $^{131}$Xe (21.2%)
- Inelastic, SD scatters: $\chi + ^{129,131}Xe \rightarrow \chi + ^{129,131}Xe^* \rightarrow \chi + ^{129,131}Xe + \gamma$



L. Baudis et al, Phys. Rev. D 88, 2013

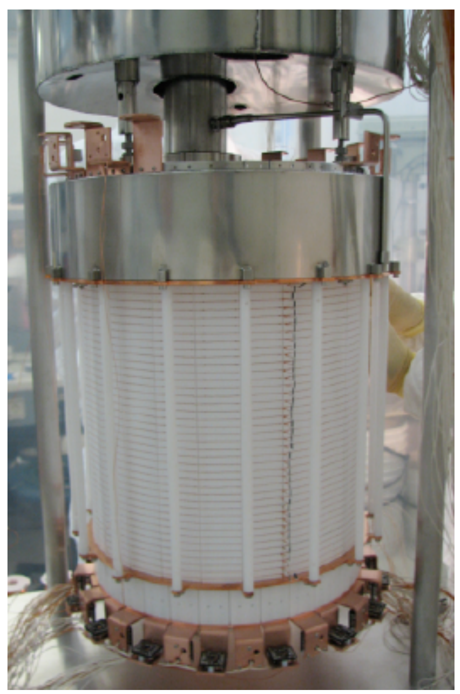


XENON collaboration, Phys. Rev. D 96, 2017

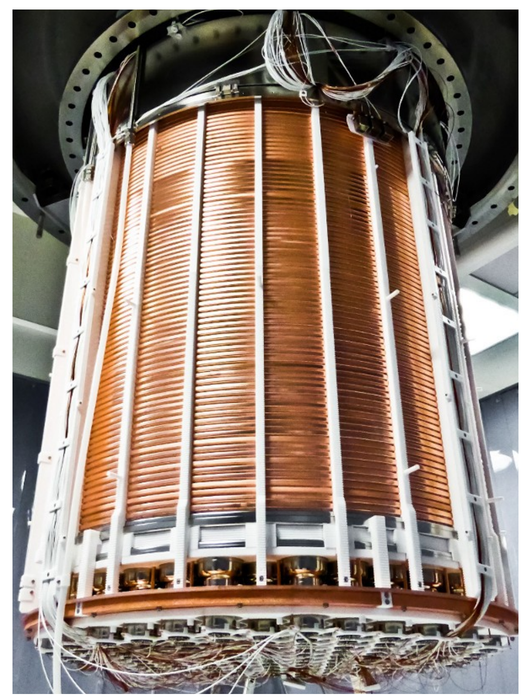
# THE XENON (&DARWIN) TIMELINE

XENON10

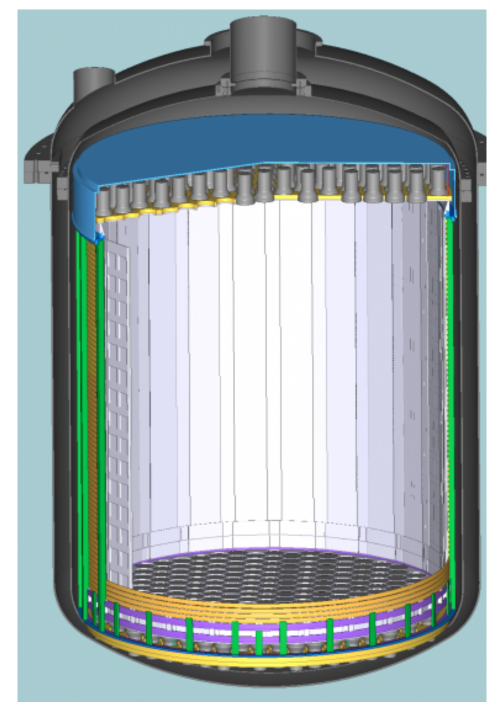
XENON100



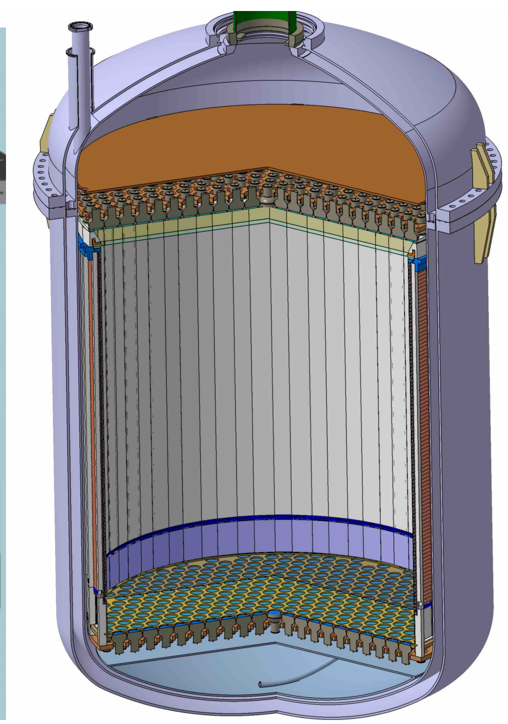
XENON1T



XENONnT

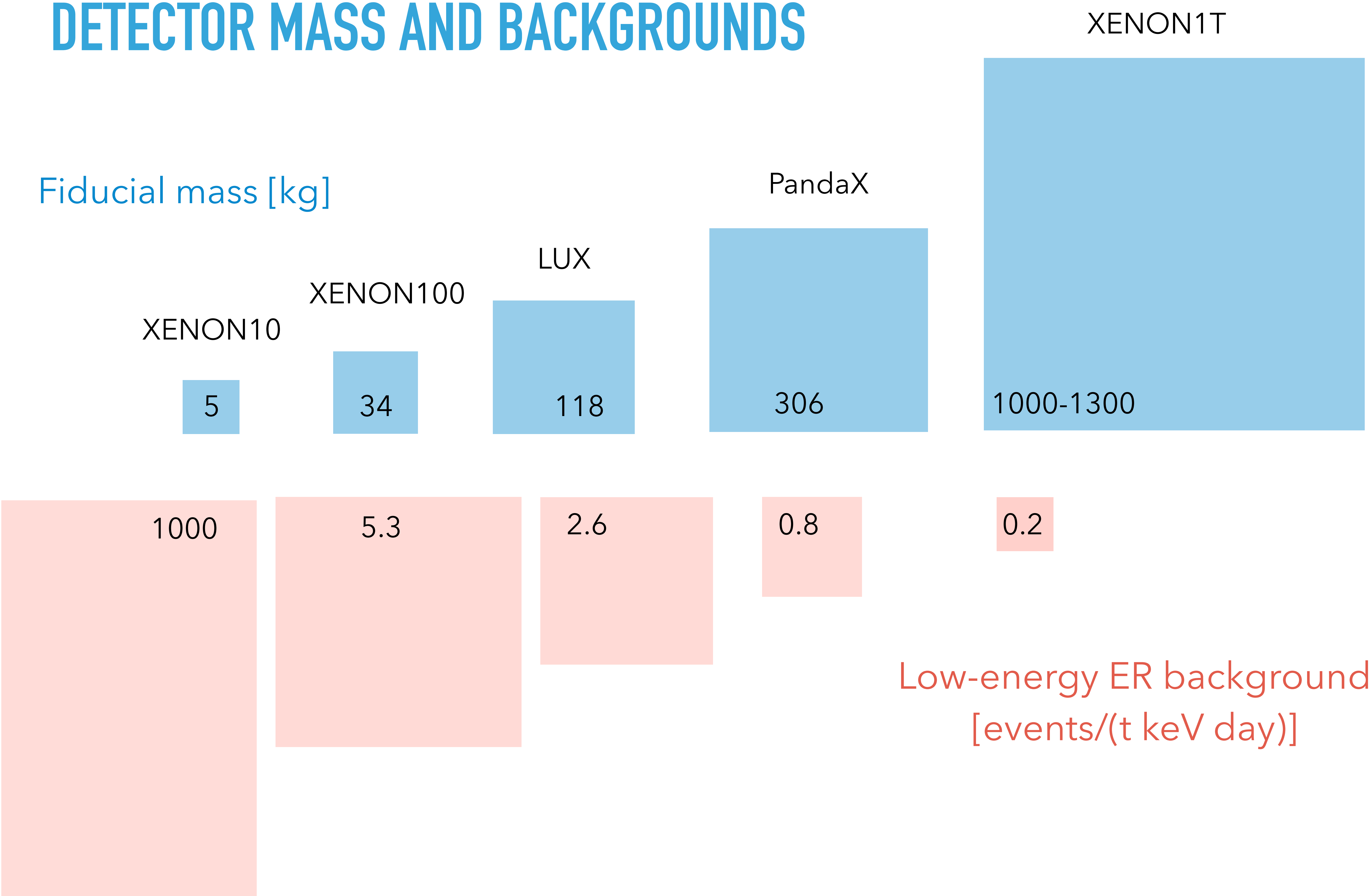


DARWIN



| | | | | |
|---|---|---|---|---|
| 2005-2007 | 2008-2016 | 2012-2018 | 2019-2023 | 2020+ |
| 15 kg | 161 kg | 3200 kg | 8200 kg | 50 tonnes |
| $\sim 10^{-43}$ cm$^2$ | $\sim 10^{-45}$ cm$^2$ | $\sim 10^{-47}$ cm$^2$ | $\sim 10^{-48}$ cm$^2$ | $\sim 10^{-49}$ cm$^2$ |

# DETECTOR MASS AND BACKGROUNDS



# GO UNDERGROUND

- Bad news: you can't shield neutrinos
- Good news: eventually these will be one of your signals

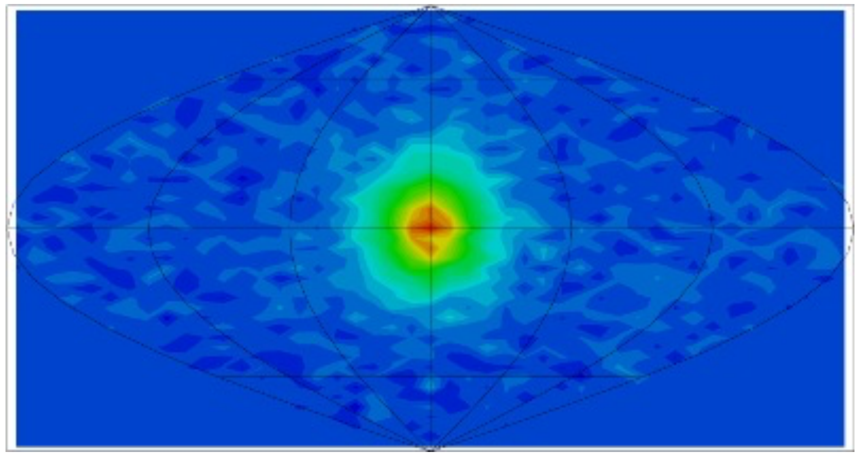
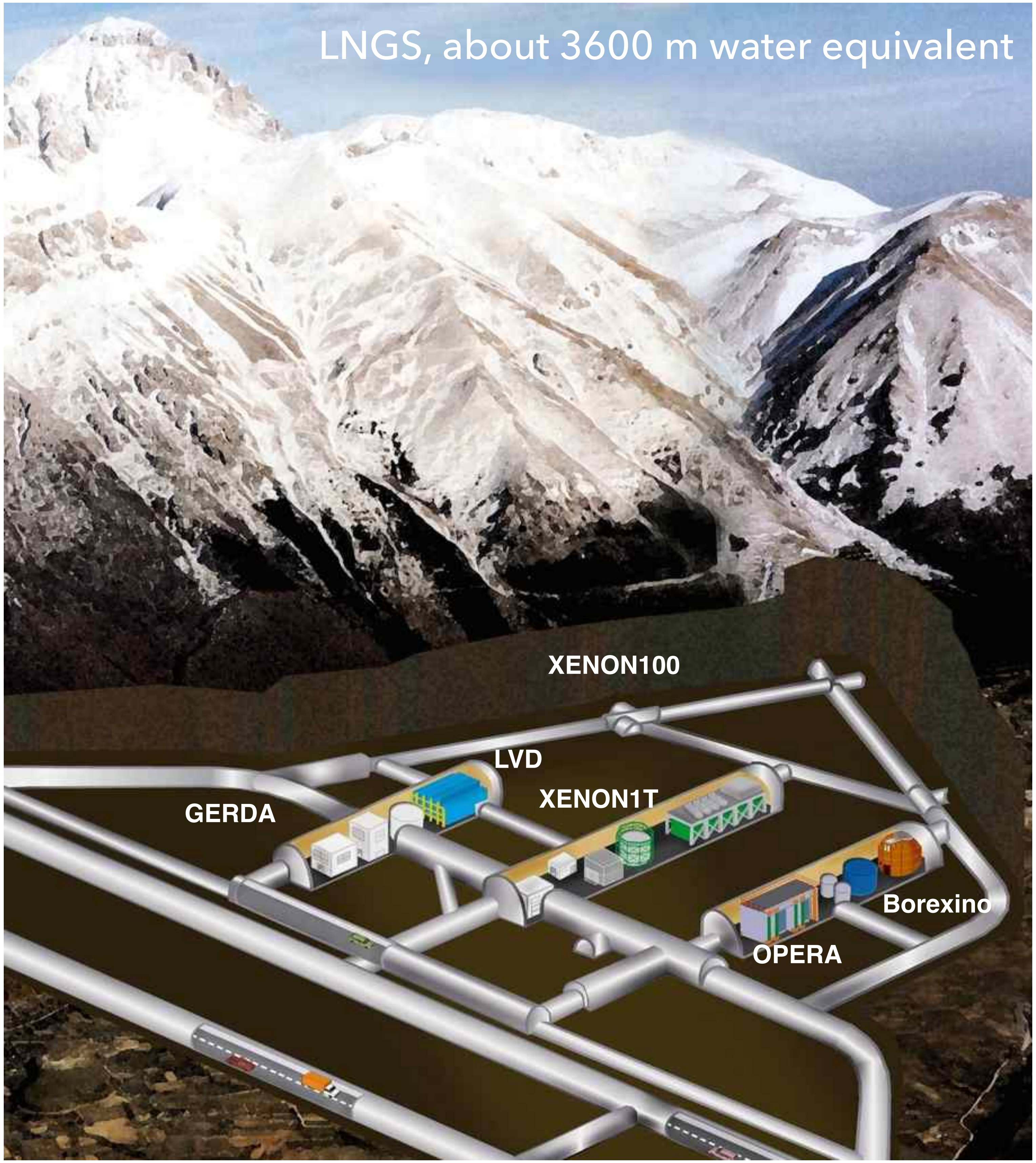


Figure by SuperKamiokande

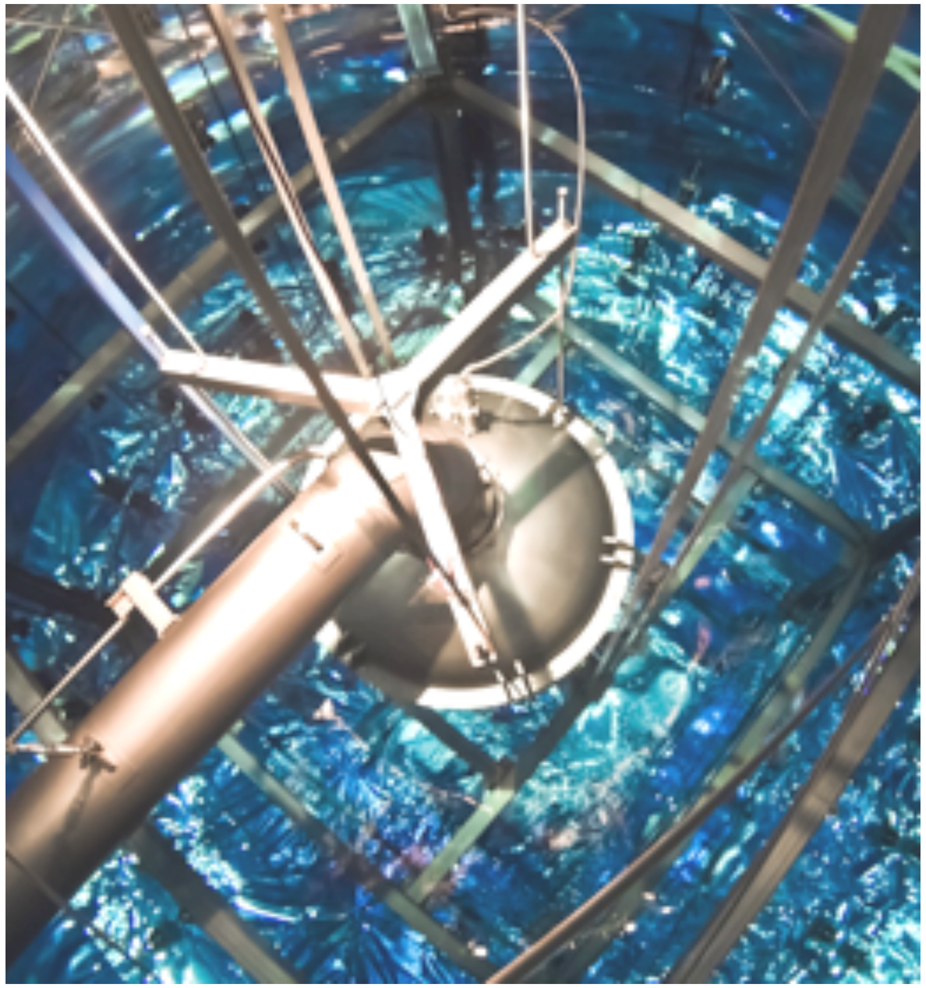


# SHIELD, SHIELD, SMARTER SHIELD

XENON10

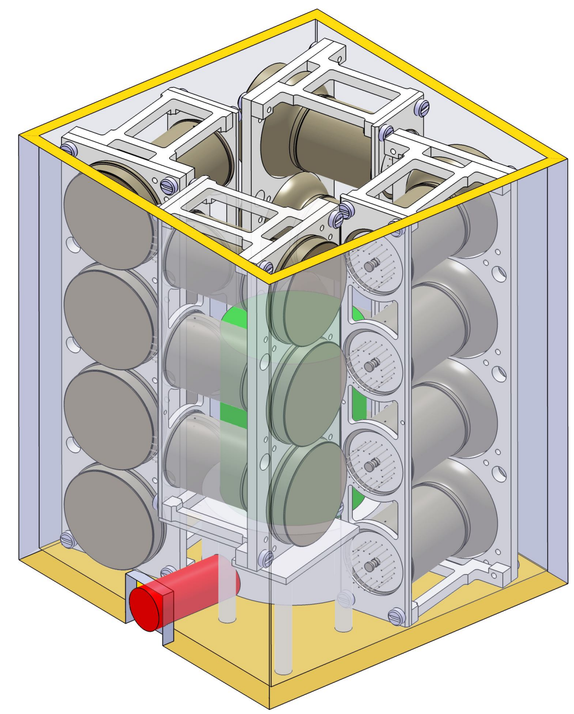
XENON100

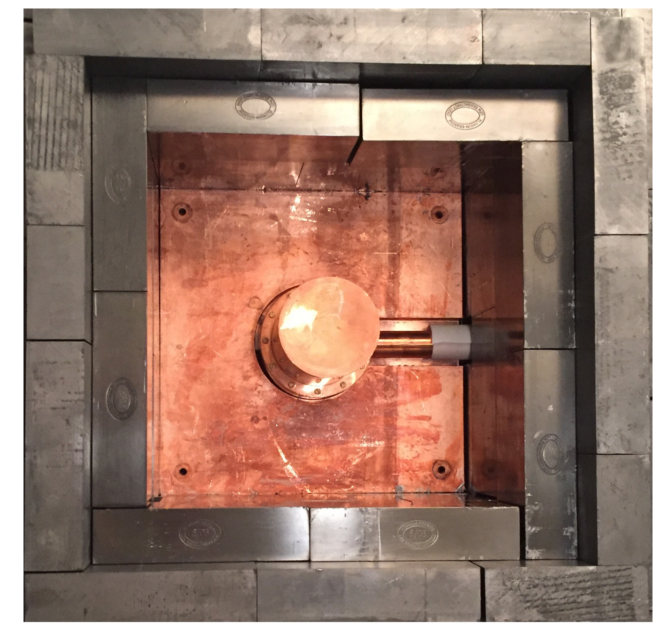
XENON1T



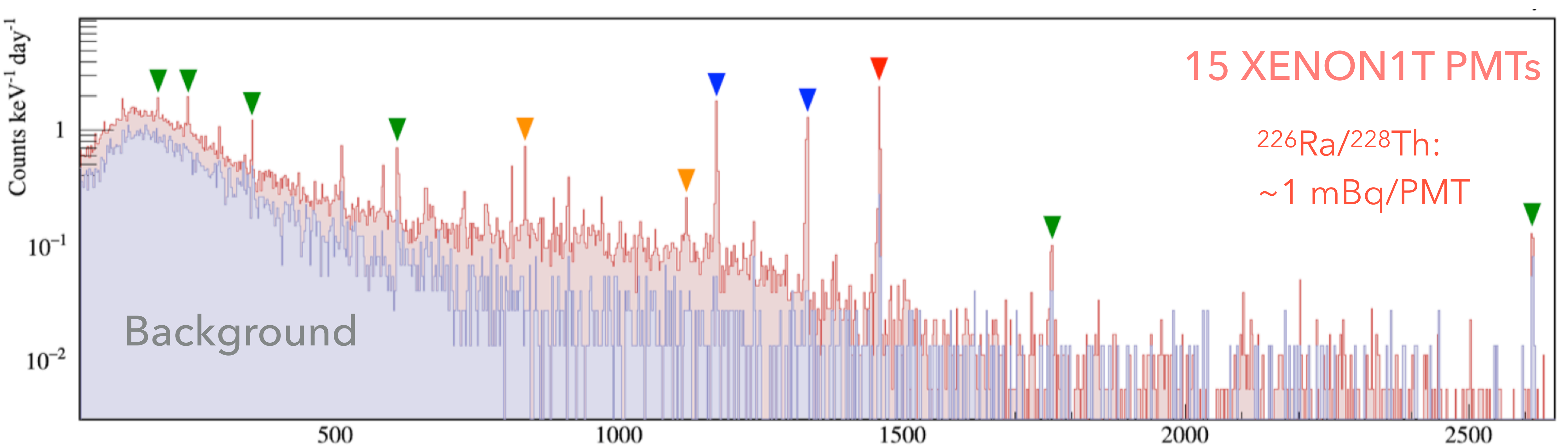
# MATERIAL SCREENING AND SELECTION

- Ultra-low background, HPGe detectors
- Mass spectroscopy
- Rn emanation facilities





L. Baudis et all, JINST 6, 2011

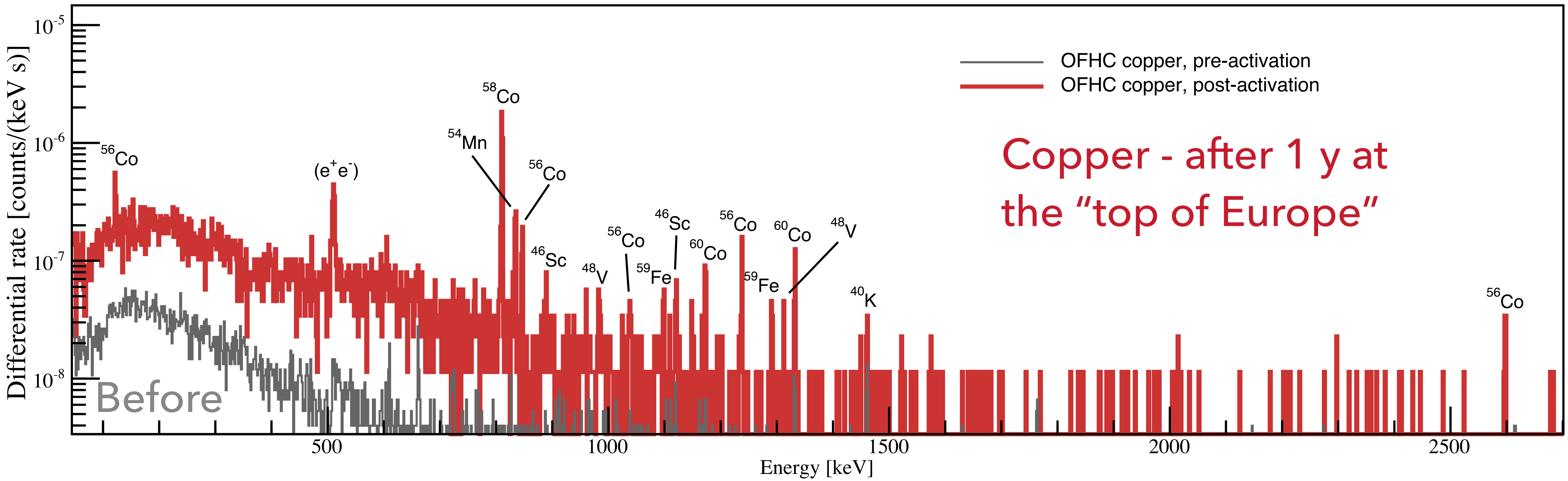



XENON collaboration, EPJ-C 75 (2015) 11

# AVOID EXPOSURE TO COSMIC RAYS

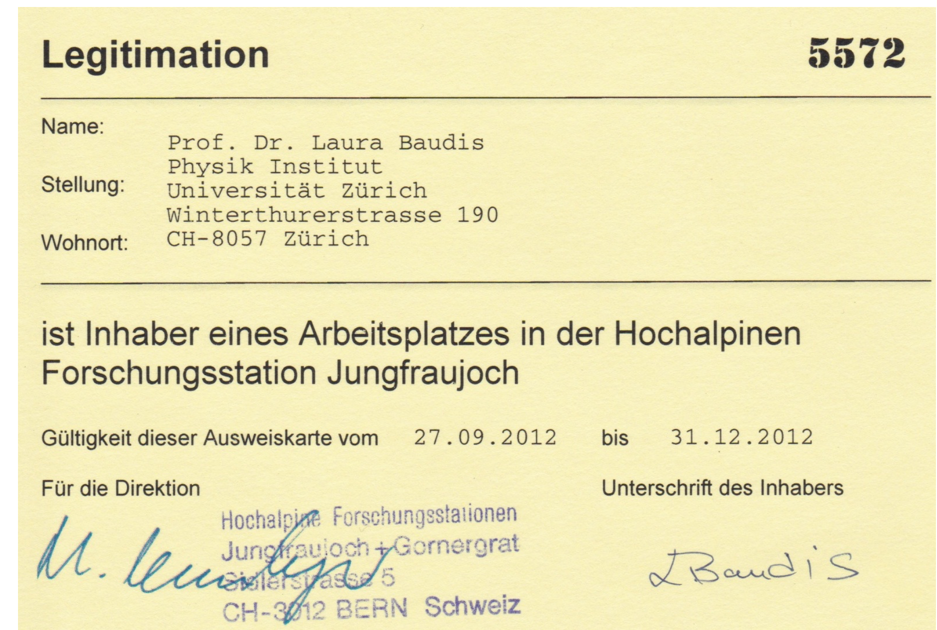
- Spallation reactions can produce long-lived isotopes
- Activate and compare with predictions (Activia, Cosmo, etc)


L. Baudis et al., Eur. Phys. J. C75 2015

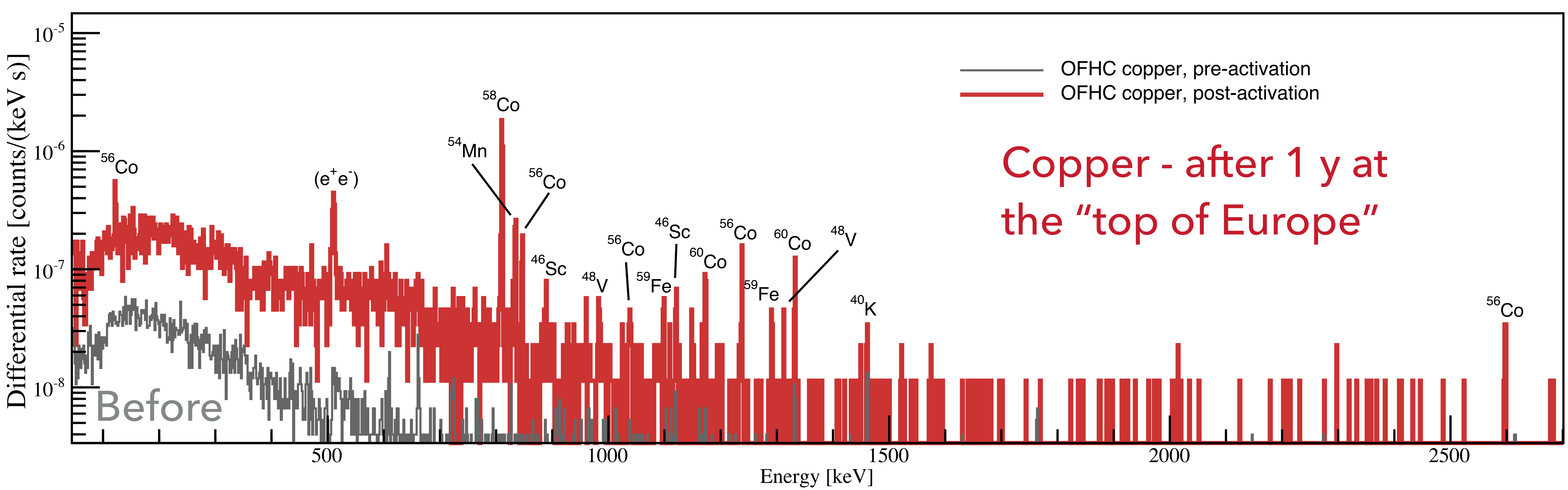


# AVOID EXPOSURE TO COSMIC RAYS

- Spallation reactions can produce long-lived isotopes
- Activate and compare with predictions (Activia, Cosmo, etc)



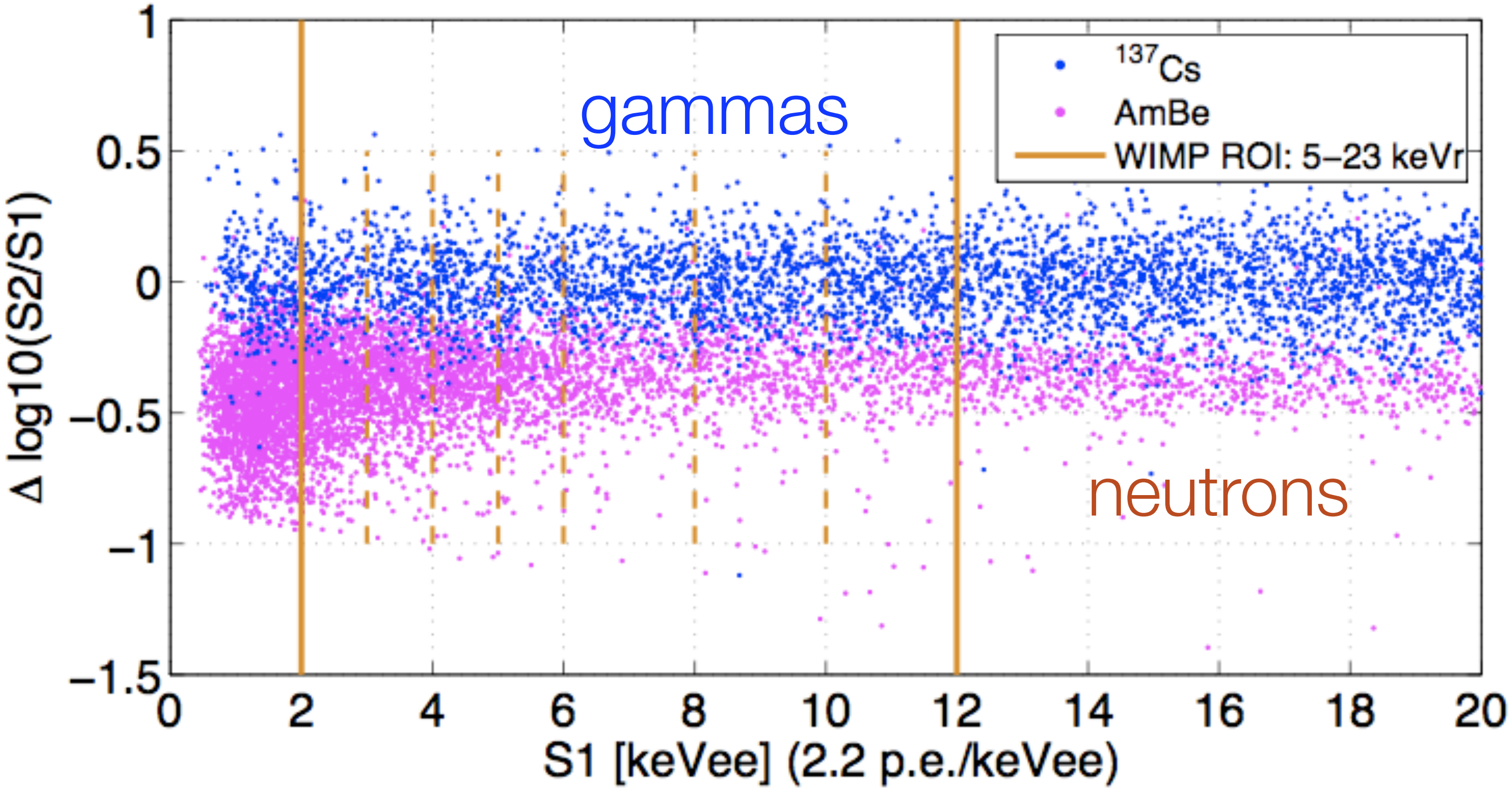

L. Baudis et al., Eur. Phys. J. C75 2015

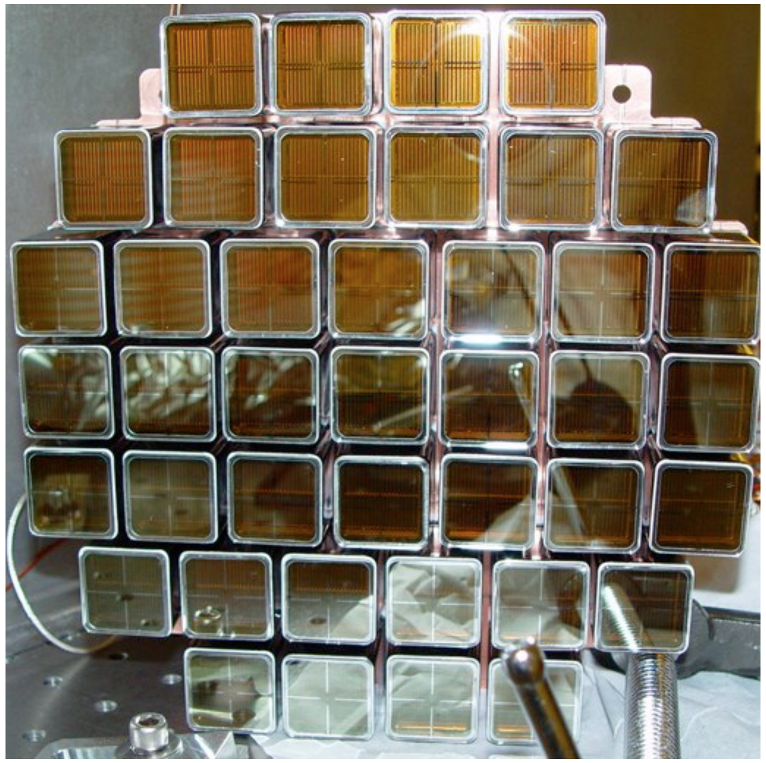


XENON collaboration, Astroparticle Physics 34, 2011 

# XENON10: 2005–2007

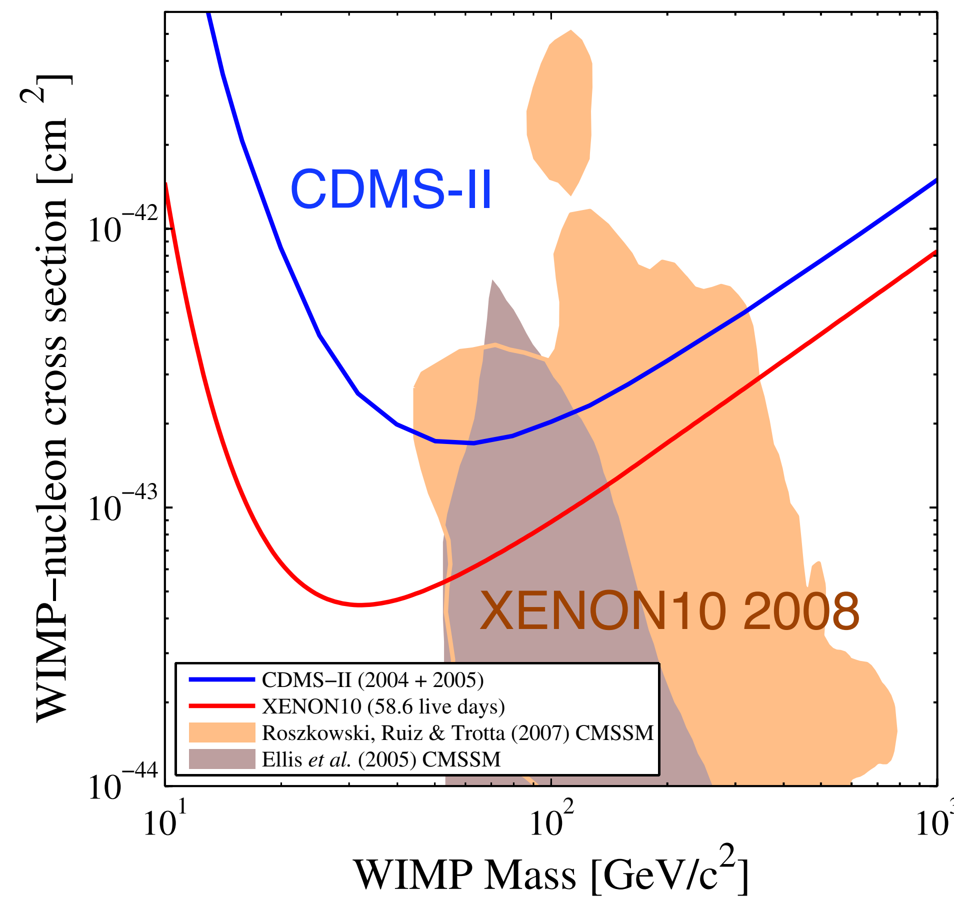
- Pathfinder TPC: 22 kg LXe
- 20 cm diam, 15 cm drift
- 89 1-inch PMTs



# XENON10: 2005–2007

- Pathfinder TPC: 22 kg LXe
- 20 cm diam, 15 cm drift
- 89 1-inch PMTs



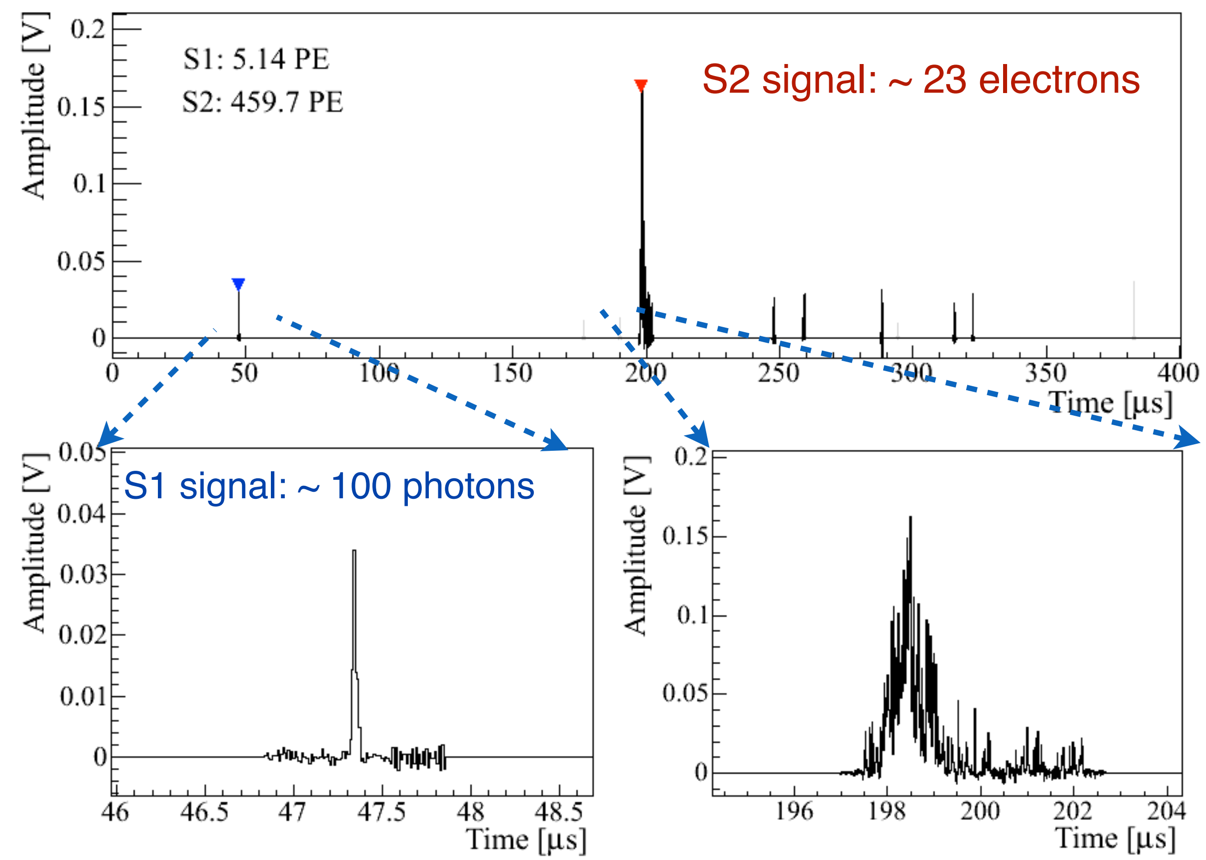

PRL **100,** 021303 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

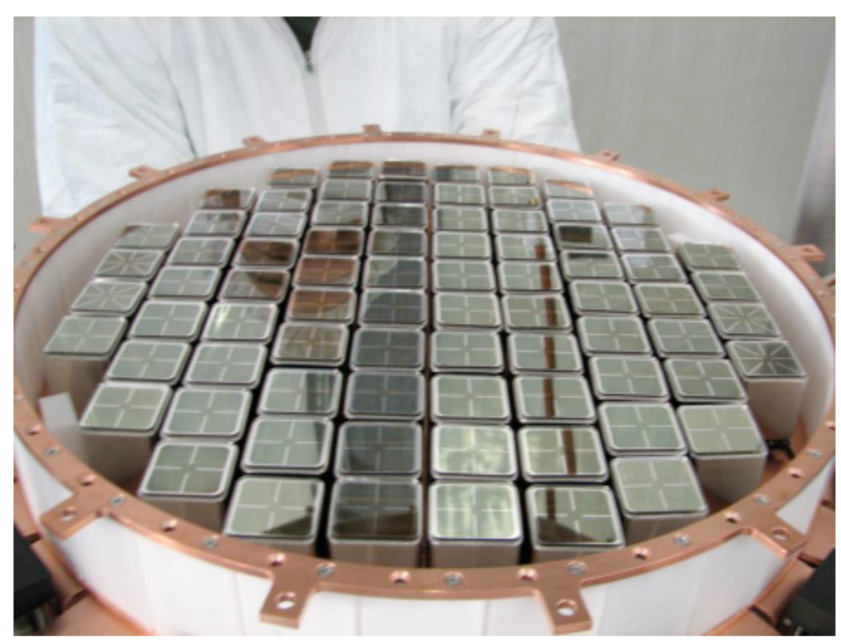
**First Results from the XENON10 Dark Matter Experiment at the Gran Sasso National Laboratory**

J. Angle,[1,2] E. Aprile,[3,*] F. Arneodo,[4] L. Baudis,[2] A. Bernstein,[5] A. Bolozdynya,[6] P. Brusov,[6] L. C. C. Coelho,[7] C. E. Dahl,[6,8] L. DeViveiros,[9] A. D. Ferella,[2,4] L. M. P. Fernandes,[7] S. Fiorucci,[9] R. J. Gaitskell,[9] K. L. Giboni,[3] R. Gomez,[10] R. Hasty,[11] L. Kastens,[11] J. Kwong,[6,8] J. A. M. Lopes,[7] N. Madden,[5] A. Manalaysay,[1,2] A. Manzur,[11] D. N. McKinsey,[11] M. E. Monzani,[3] K. Ni,[11] U. Oberlack,[10] J. Orboeck,[2] G. Plante,[3] R. Santorelli,[3] J. M. F. dos Santos,[7] P. Shagin,[10] T. Shutt,[6] P. Sorensen,[9] S. Schulte,[2] C. Winant,[5] and M. Yamashita[3]

# XENON100: 2008–2016

- Factor ~10 more LXe
- 30 cm drift, 30 cm diam
- 98+80 1-inch PMTs, LXe veto
- Selected low-radioactivity materials
- Factor 100 lower backgrounds

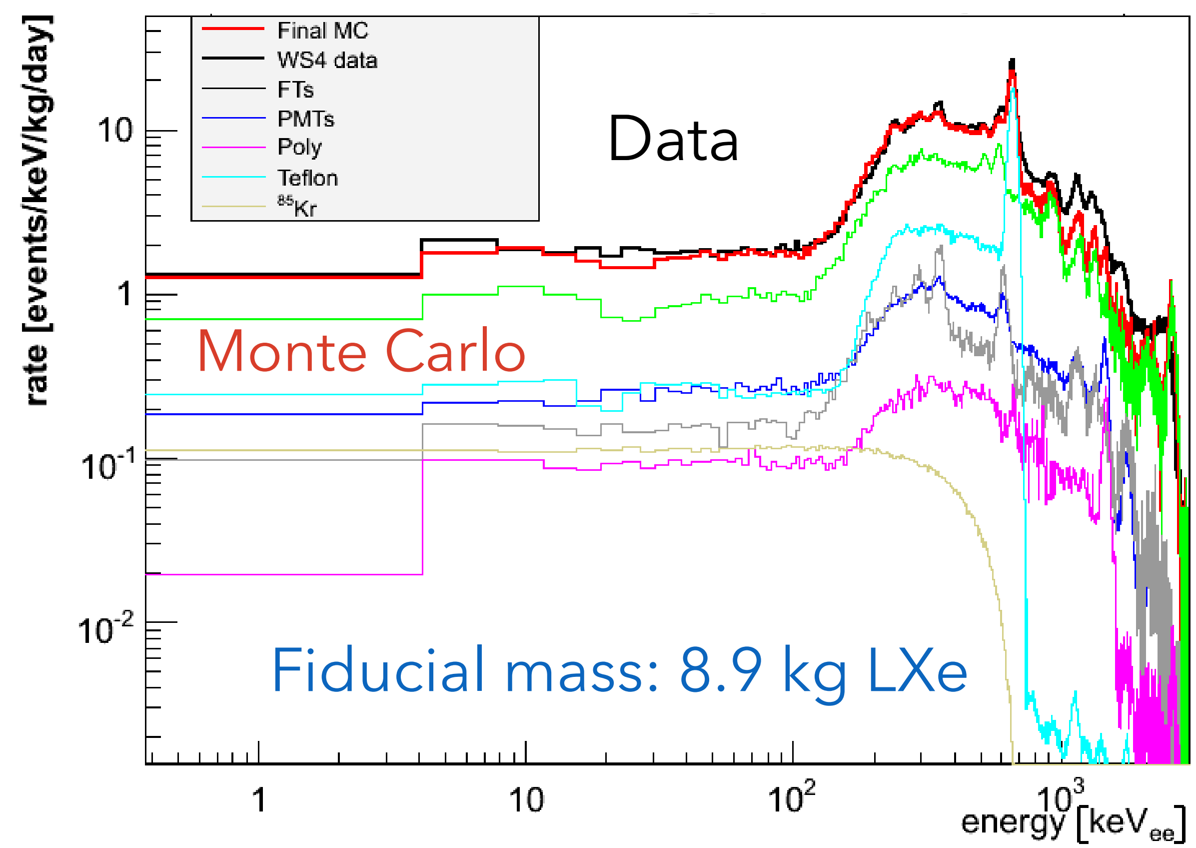


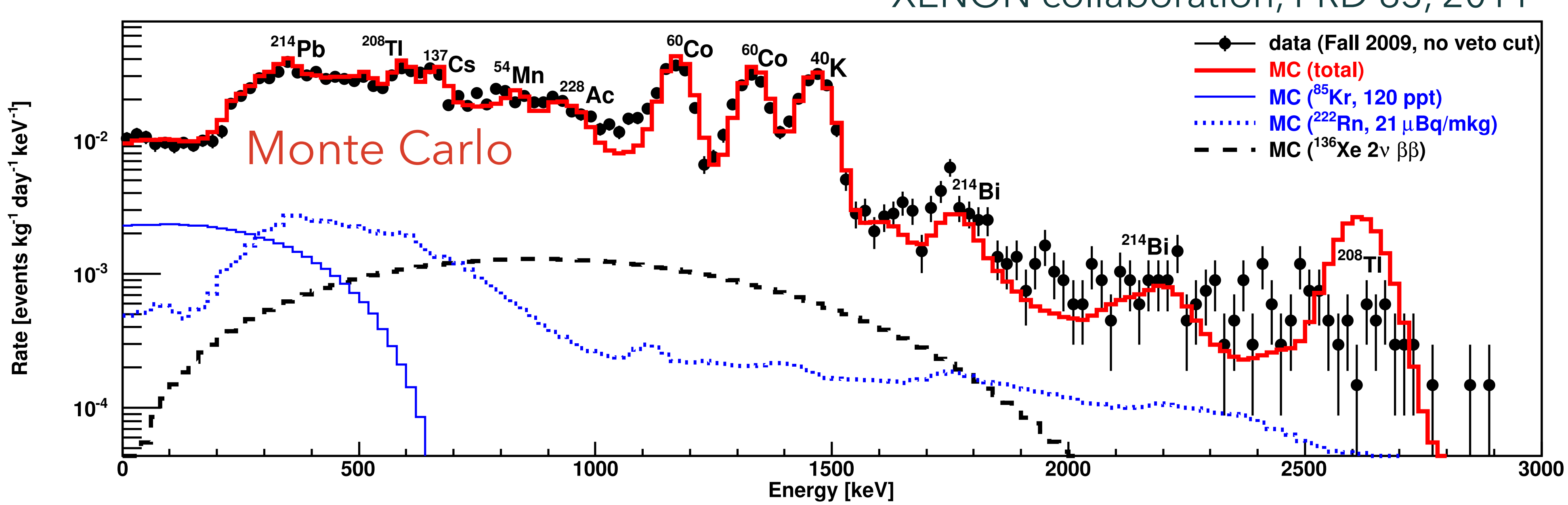
# XENON100: 2008–2016

- Factor ~10 more LXe
- 30 cm drift, 30 cm diam
- 98+80 1-inch PMTs, LXe veto
- Selected low-radioactivity materials
- Factor 100 lower backgrounds

XENON10




XENON collaboration, PRD 83, 2011




XENON100

# XENON10

LNGS, May 2006

# XENON100

LNGS, April 2011

# XENON1T/NT

170 scientists

25 institutions

11 countries


# XENON1T AT THE GRAN SASSO LABORATORY

Water tank and Cherenkov muon veto

Cryostat and support structure for TPC

Time projection chamber

Cryogenics pipe (cables, xenon)

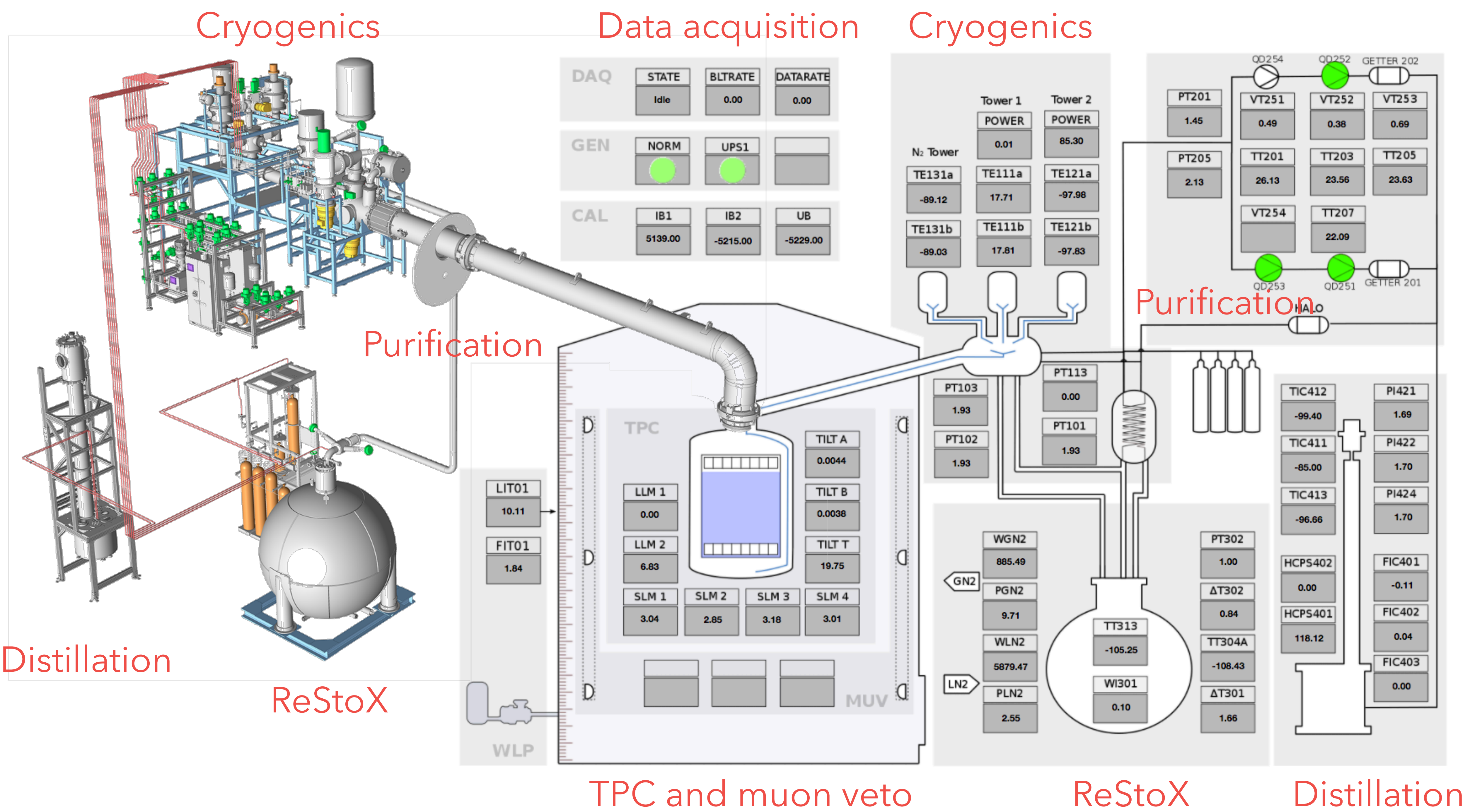
Cryogenics and purification

Data acquisition and slow control

Xenon storage, handling and Kr removal via cryogenic distillation

 XENON collaboration, EPJ-C 77 (2017) 12 

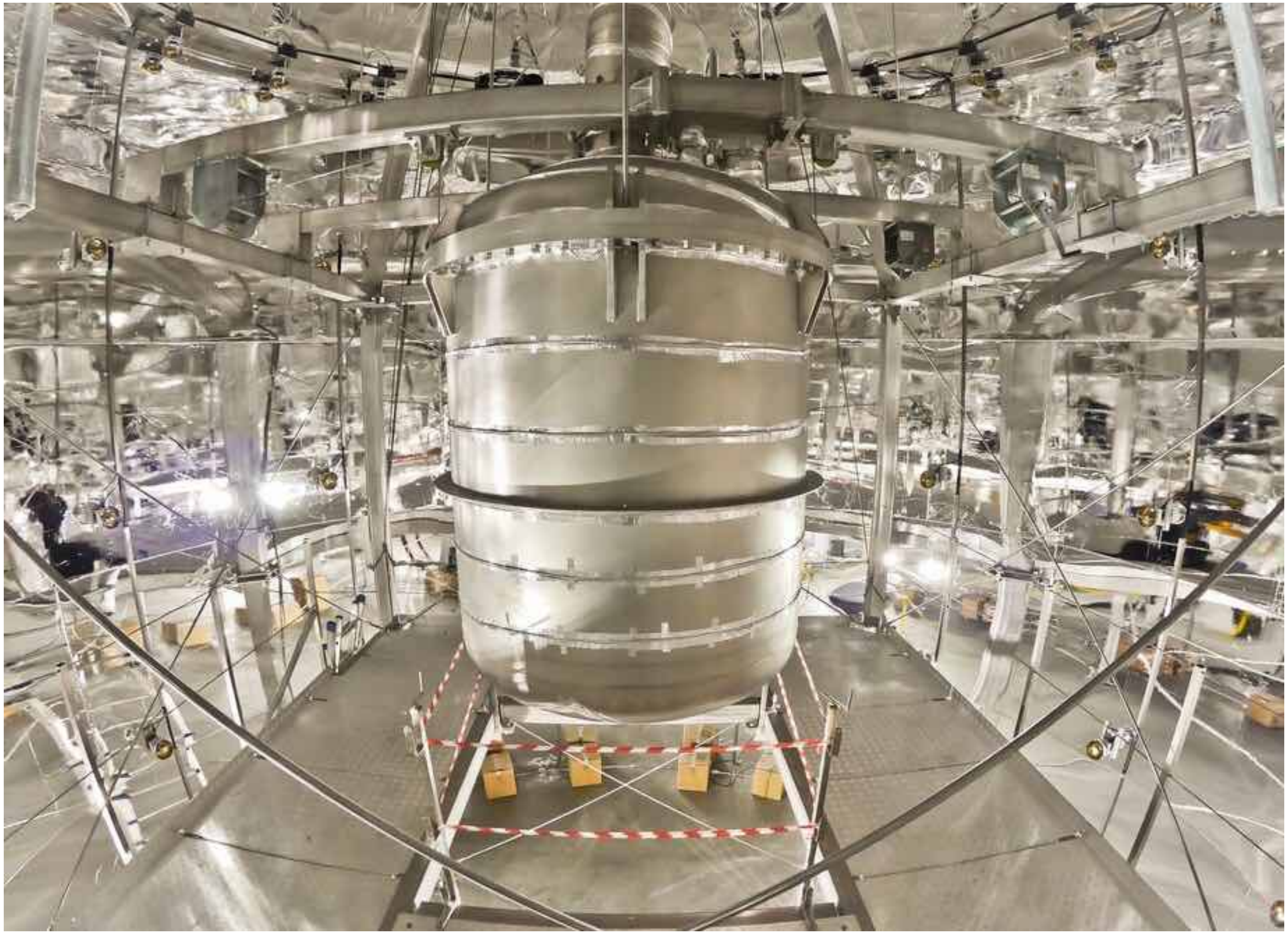
# XENON1T AT THE GRAN SASSO LABORATORY



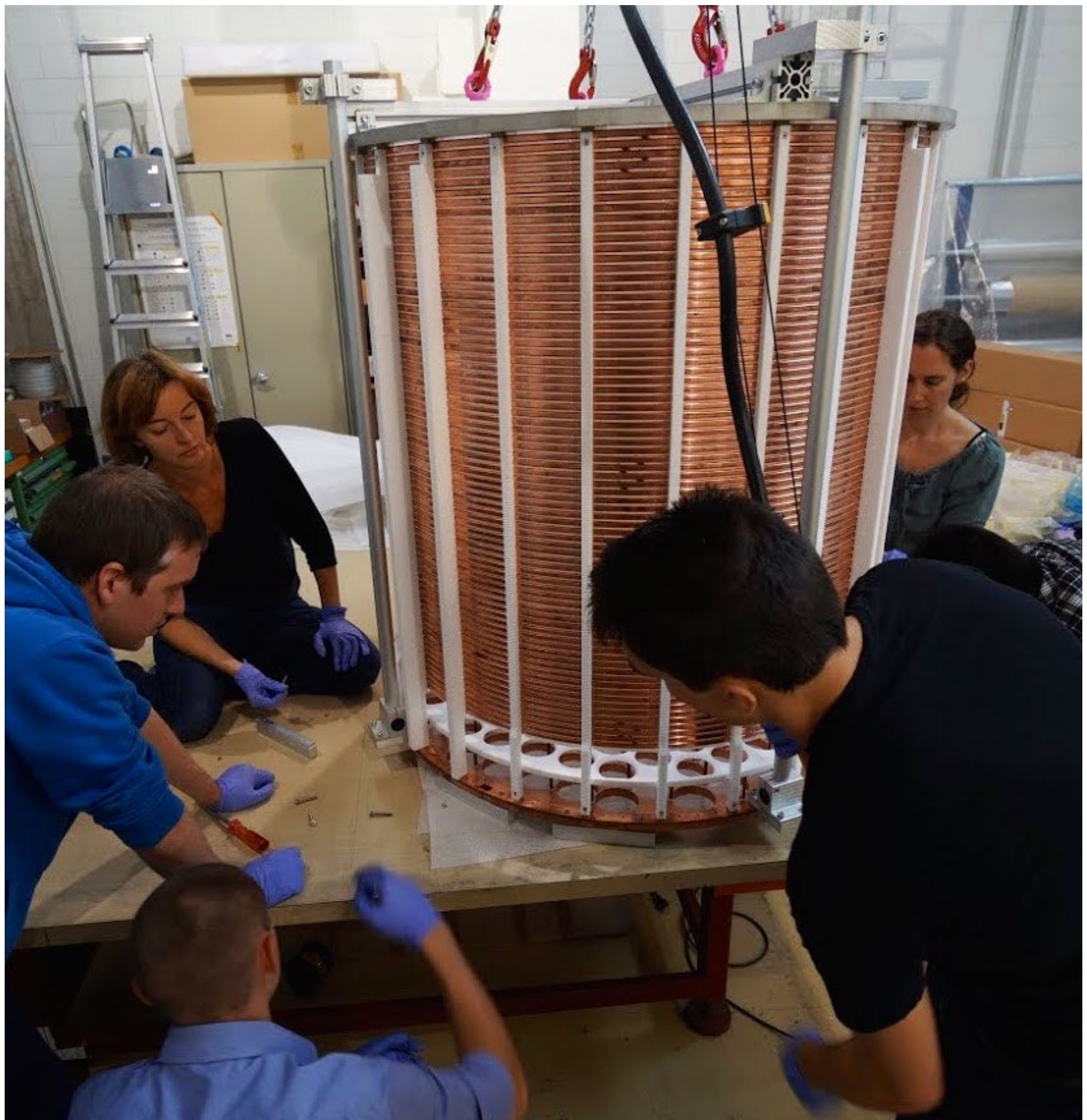
XENON collaboration, JINST 9, 2014

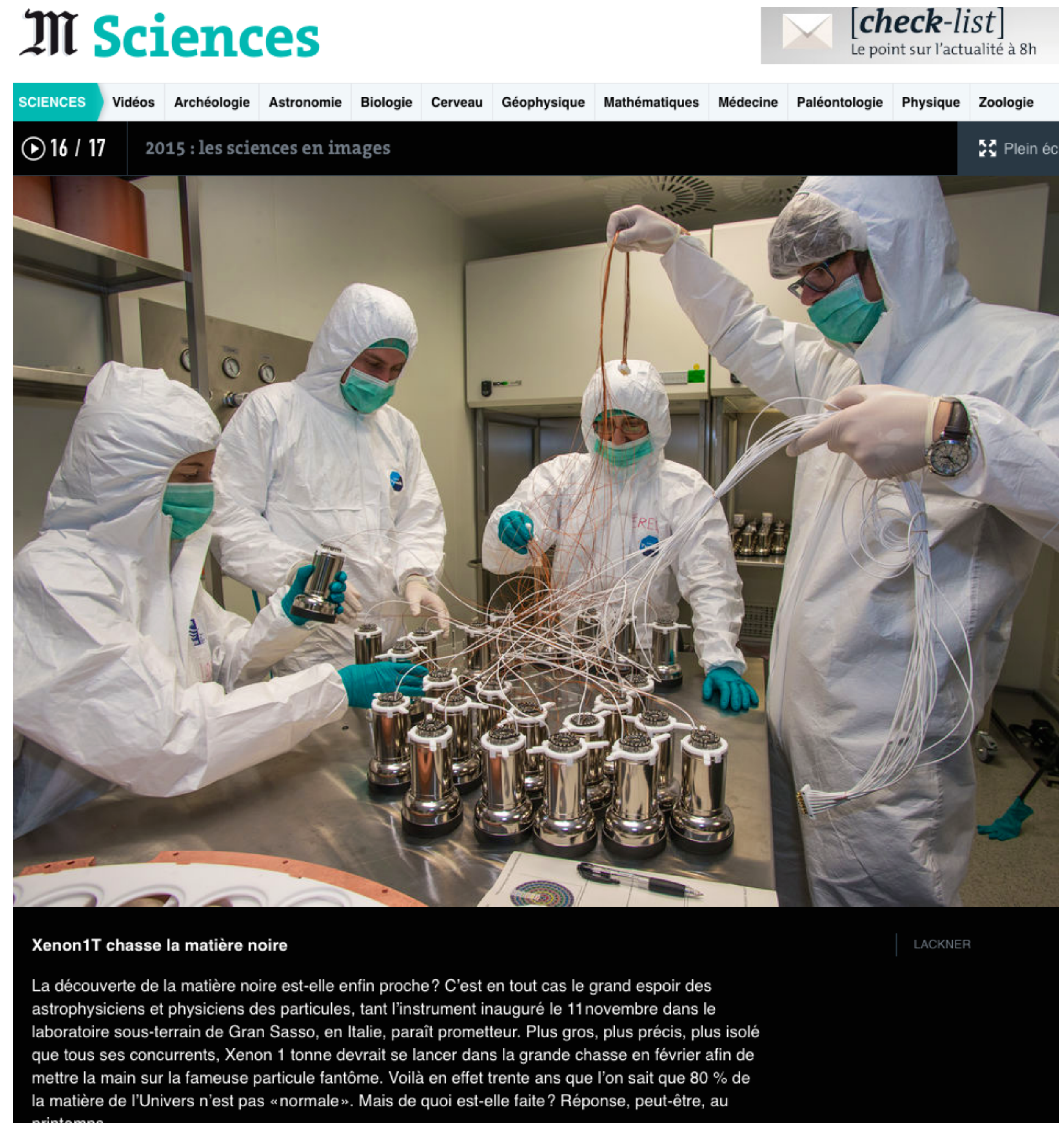


# CRYOSTAT AND WATER CHERENKOV SHIELD



# TPC AND PMT ARRAYS FIRST ASSEMBLY & TESTS





Sciences

[check-list]
Le point sur l'actualité à 8h

SCIENCES | Vidéos | Archéologie | Astronomie | Biologie | Cerveau | Géophysique | Mathématiques | Médecine | Paléontologie | Physique | Zoologie

16 / 17 2015 : les sciences en images

Plein éc

**Xenon1T chasse la matière noire**

LACKNER

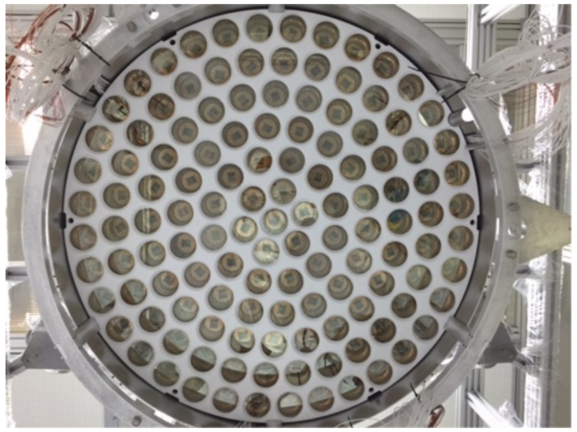
La découverte de la matière noire est-elle enfin proche? C'est en tout cas le grand espoir des astrophysiciens et physiciens des particules, tant l'instrument inauguré le 11 novembre dans le laboratoire sous-terrain de Gran Sasso, en Italie, paraît prometteur. Plus gros, plus précis, plus isolé que tous ses concurrents, Xenon 1 tonne devrait se lancer dans la grande chasse en février afin de mettre la main sur la fameuse particule fantôme. Voilà en effet trente ans que l'on sait que 80 % de la matière de l'Univers n'est pas «normale». Mais de quoi est-elle faite? Réponse, peut-être, au printemps.

# THE XENON1T TPC IN THE CLEANROOM AT LNGS

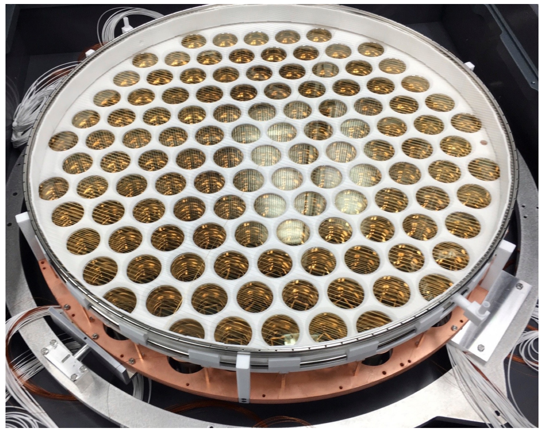
# THE TIME PROJECTION CHAMBER

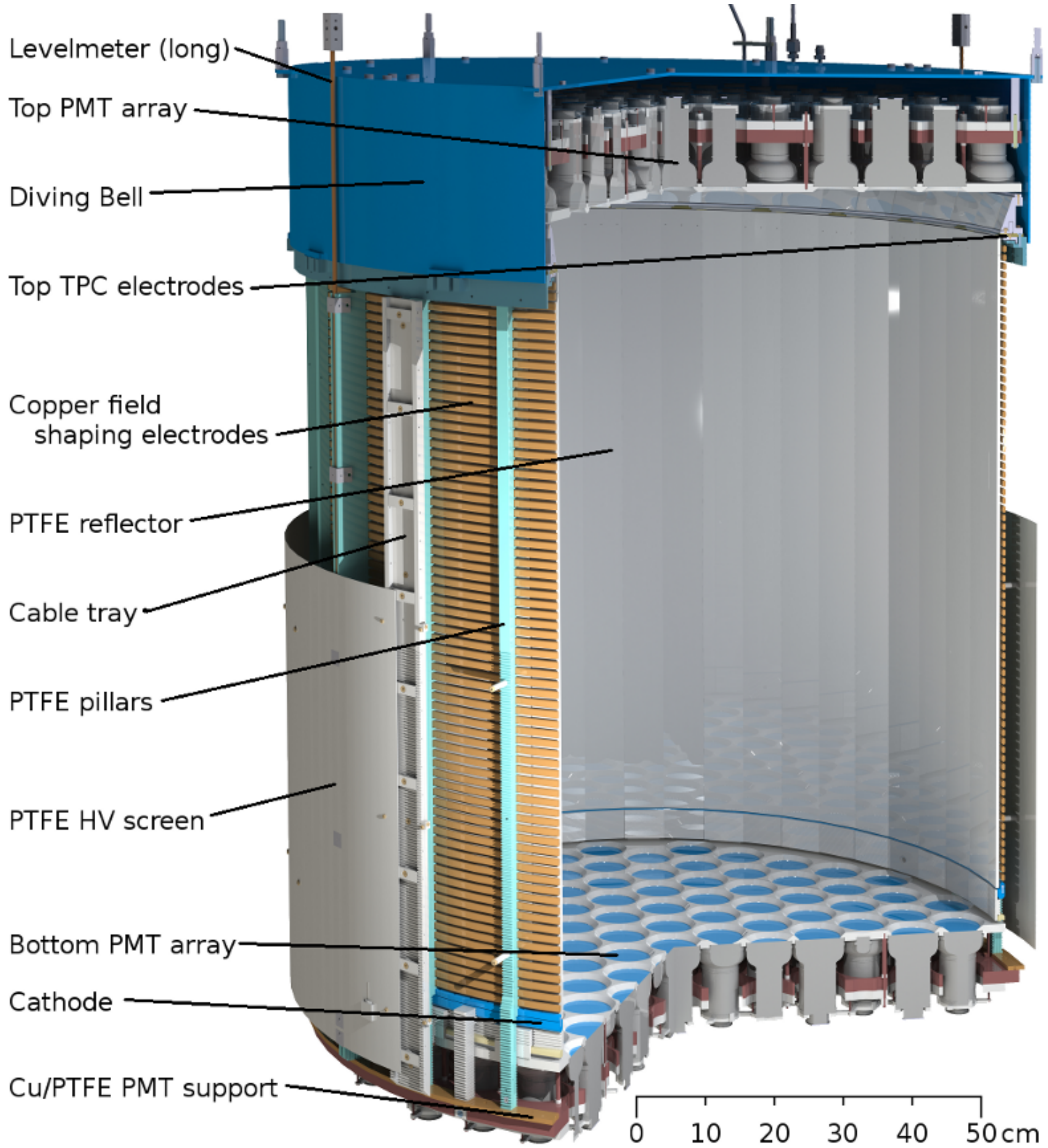
- 3.2 t LXe in total, 2 t in the TPC
- 97 cm drift, 96 cm diameter
- 248 3-inch PMTs
- 74 Cu field shaping rings, 5 electrodes, 4 level meters

127 PMTs top array



121 PMTs bottom array



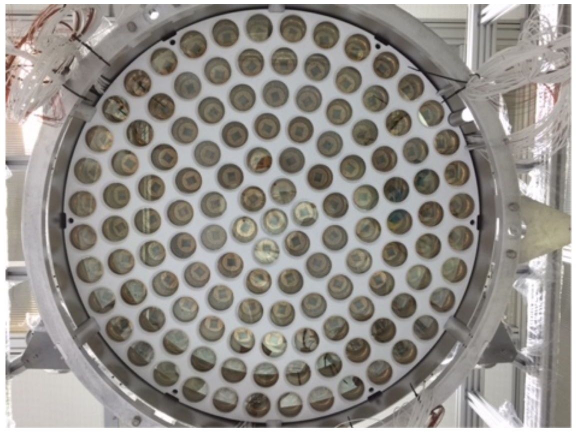


 XENON collaboration, EPJ-C 77 (2017) 12 

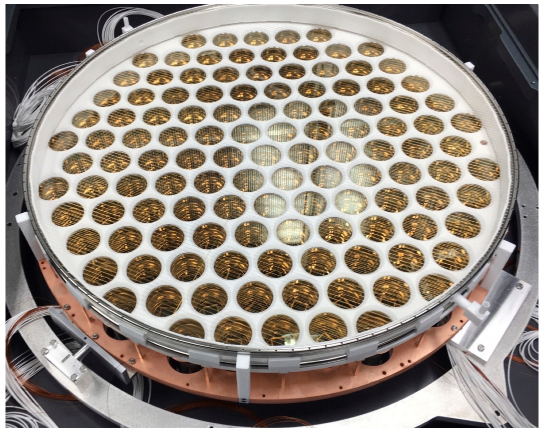
# THE TIME PROJECTION CHAMBER

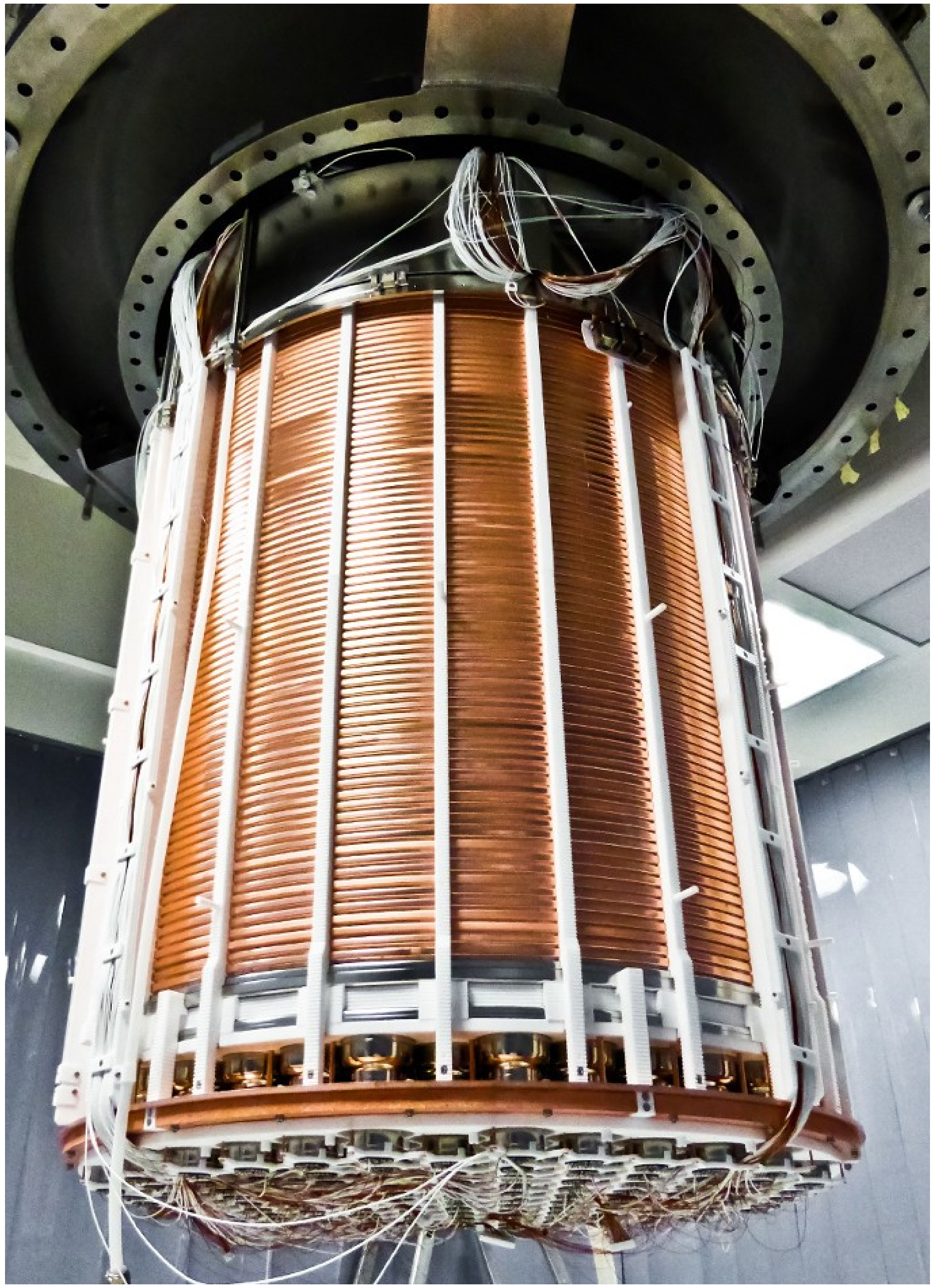
- 3.2 t LXe in total, 2 t in the TPC
- 97 cm drift, 96 cm diameter
- 248 3-inch PMTs
- 74 Cu field shaping rings, 5 electrodes, 4 level meters

127 PMTs top array



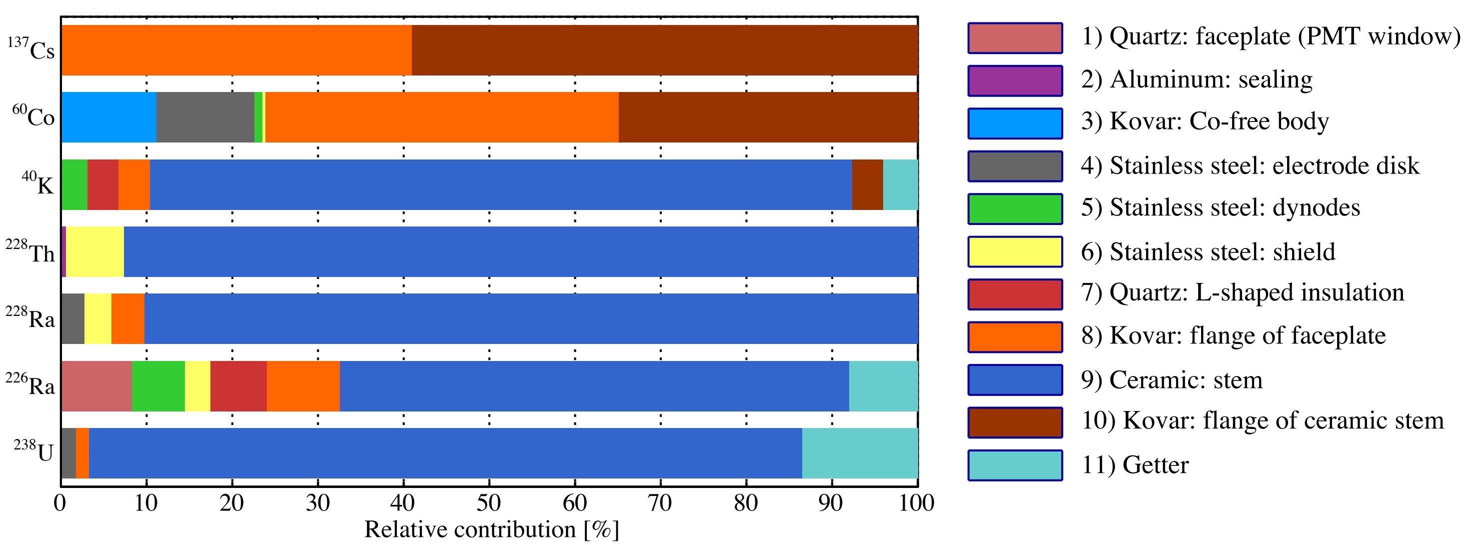
121 PMTs bottom array





# THE LIGHT DETECTION SYSTEM

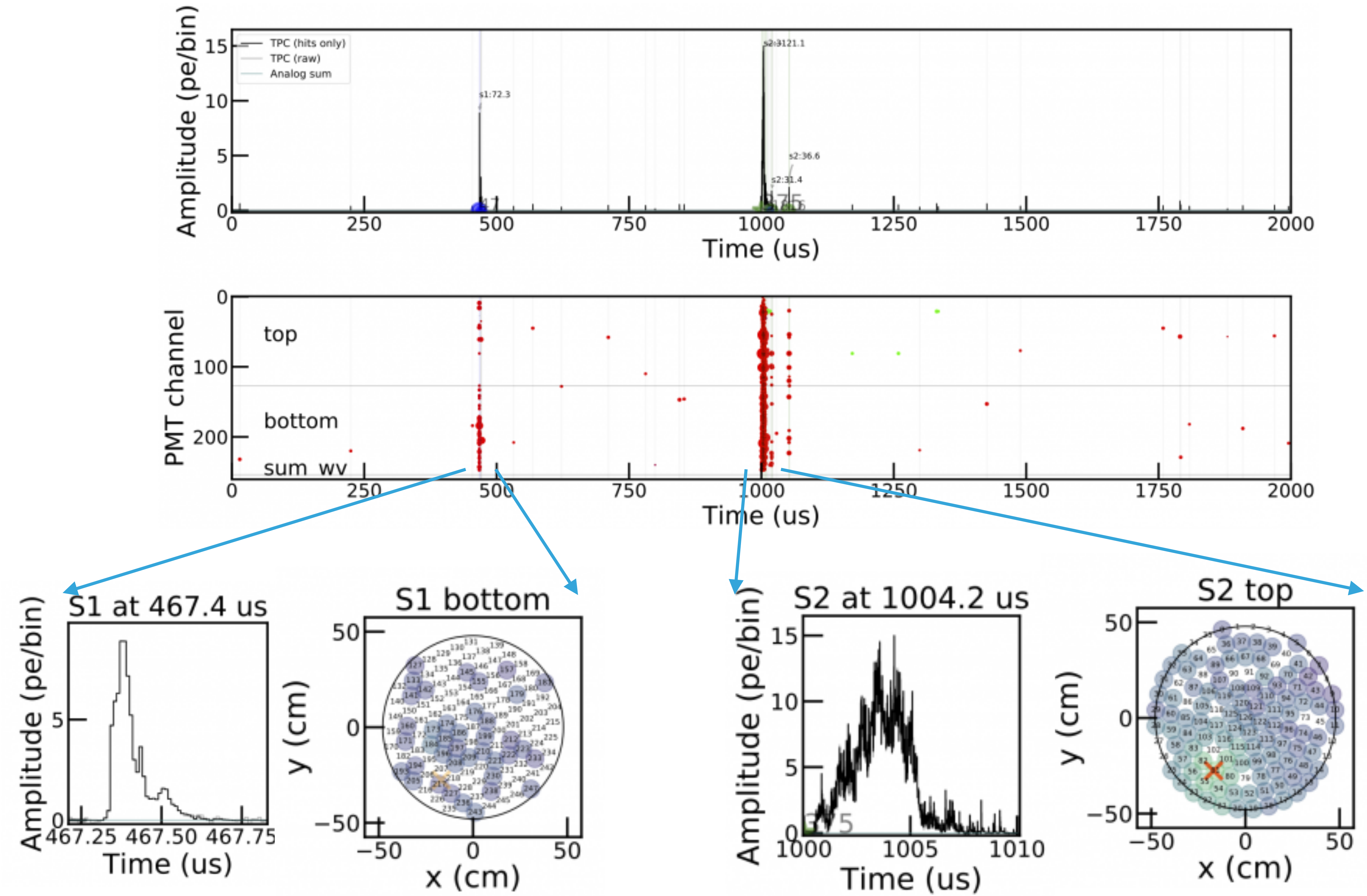
- 248 low-radioactivity, Hamamatsu R11410-21 3-inch PMTs
- Average QE@175 nm: 36%, average gain: 2e6 @ 1500 V
- Tests in cold $N_2$ gas and in GXe & LXe (P. Barrow et al., JINST12, 2017)




First: screening of all PMT materials

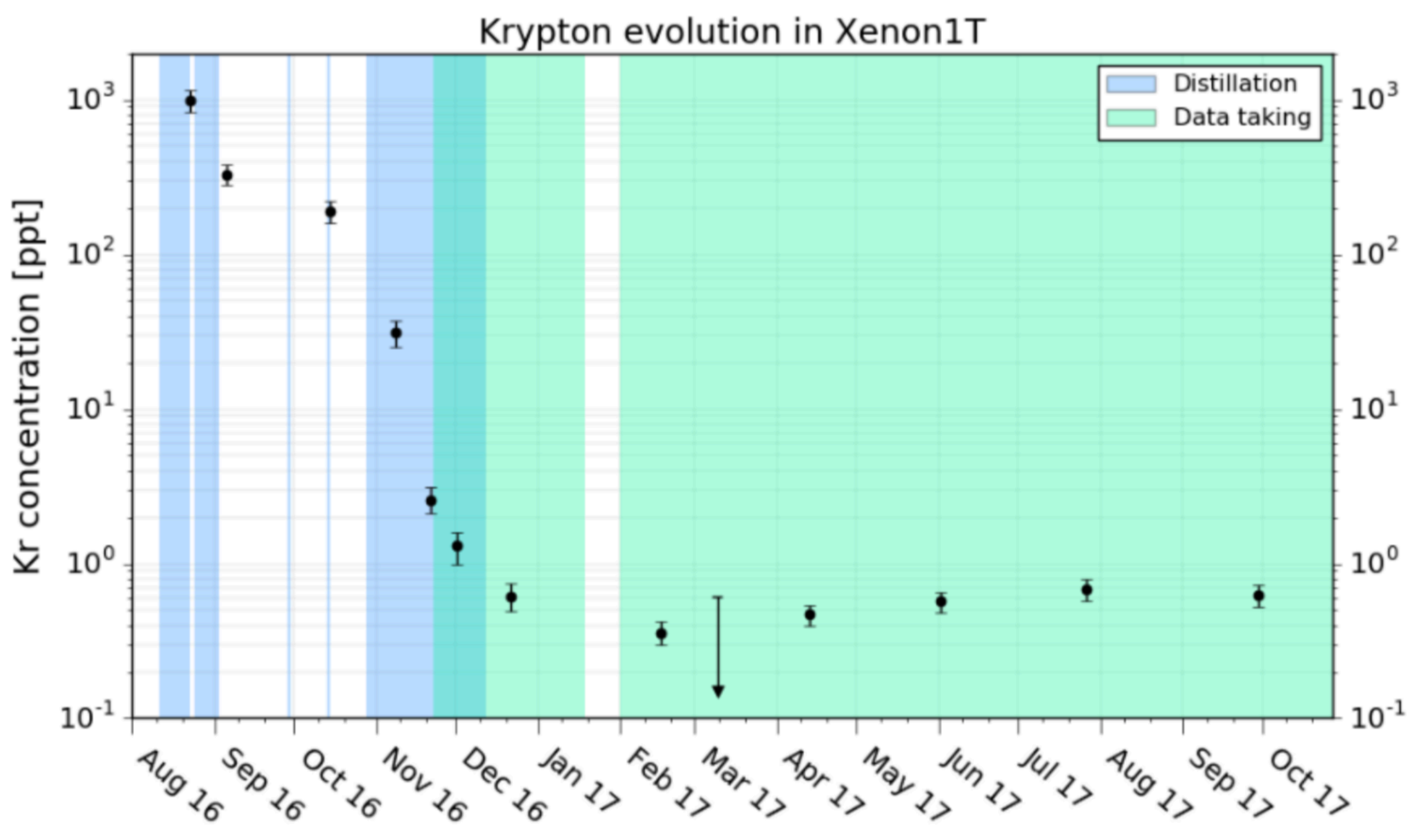
Second: screening of final products

# EXAMPLE OF A LOW-ENERGY EVENT IN THE TPC



# THE KRYPTON DISTILLATION COLUMN

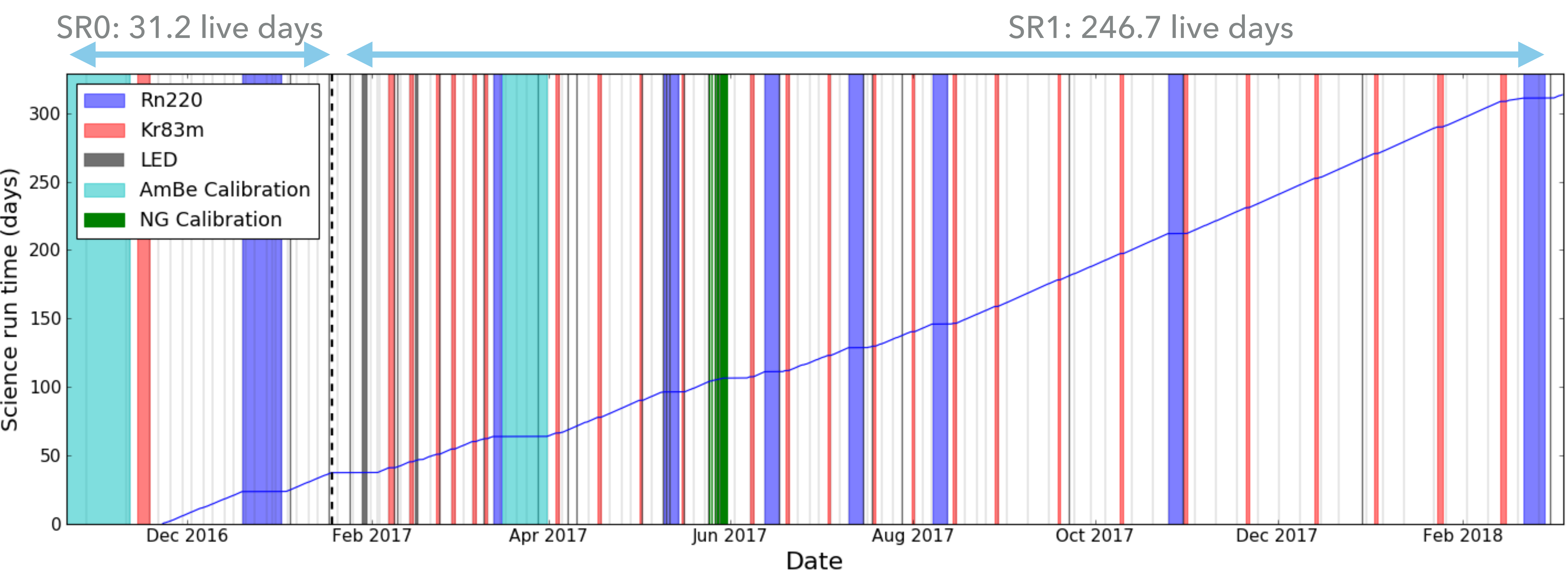
- Commercial Xe: 1 ppm - 10 ppb $^{nat}$Kr
- $^{85}$Kr is unstable ($T_{1/2}$ = 10.8 y, Q-value = 687 keV)
- XENON1T sensitivity demands 0.2 ppt $^{nat}$Kr
- Solution: 5.5 m distillation column, 6.5 kg/h output > 6.4e5 separation, to < 48 ppq




For Rn removal - see XENON collaboration, EPJ-C 77 (2017) 6

# DATA OVERVIEW

- First science run: Oct 2016 - Jan 2017
- Second science run: Feb 2017 - Feb 2018



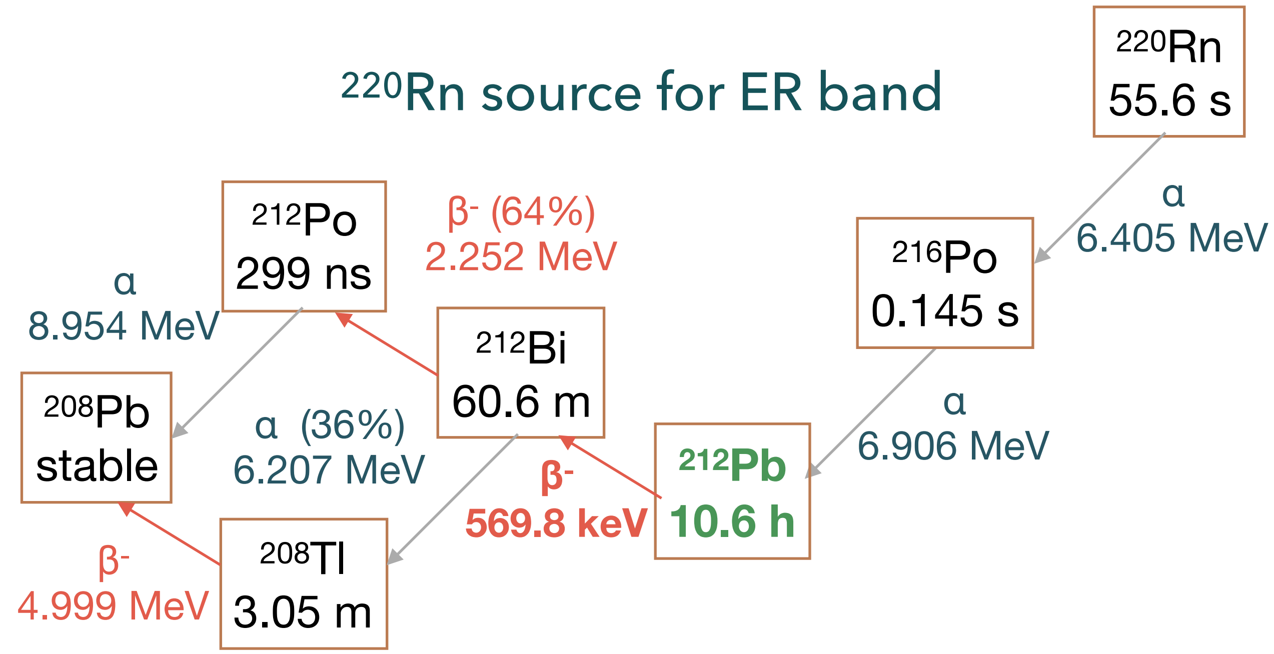

PRL 118, 2017

Earthquake
mag 5.7

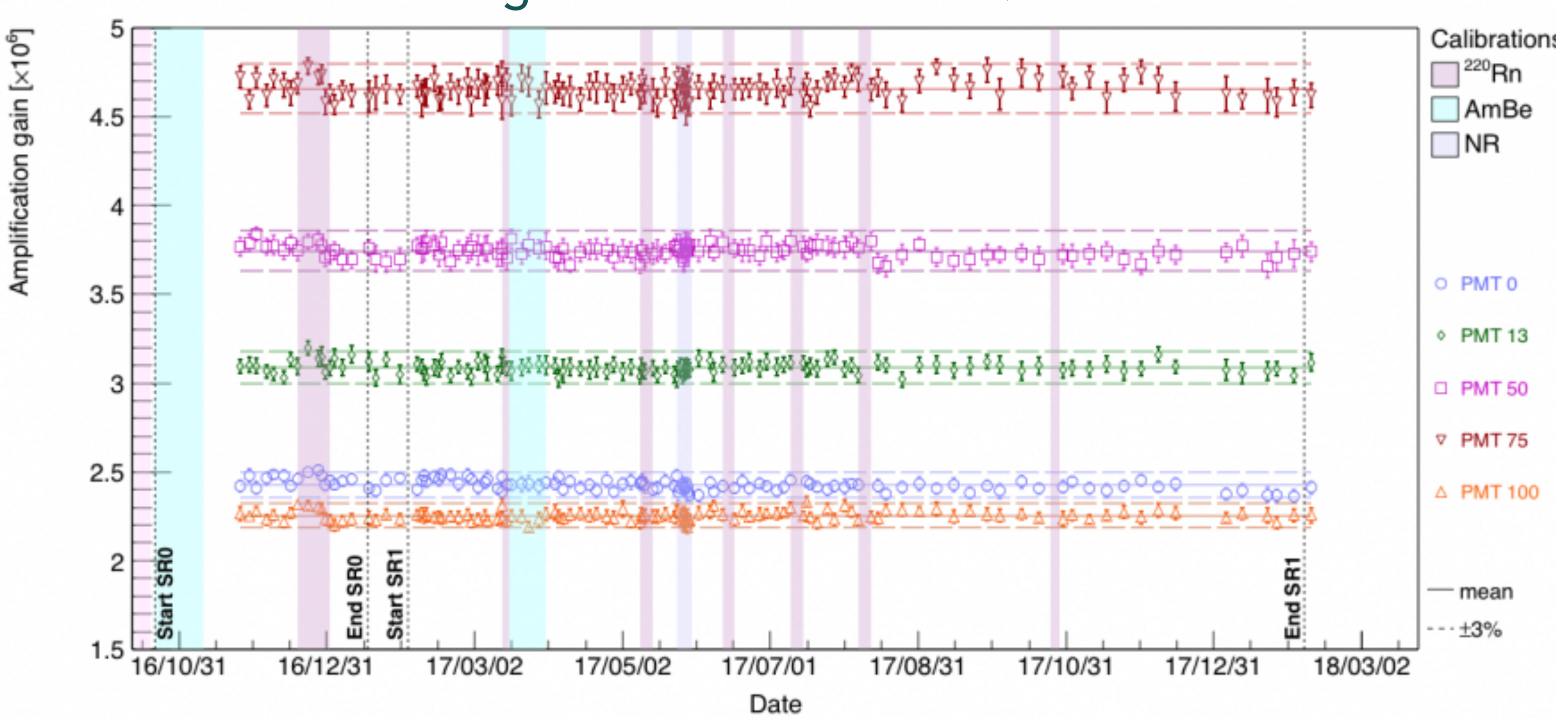
# CALIBRATION

- Energy scale: $^{83m}$Kr ($T_{1/2}$ = 1.85 h)
- ER band: $^{220}$Rn ($T_{1/2}$ = 56 s); NR band: AmBe, D-D fusion n-generator
- PMT gains: LED light via optical fibres

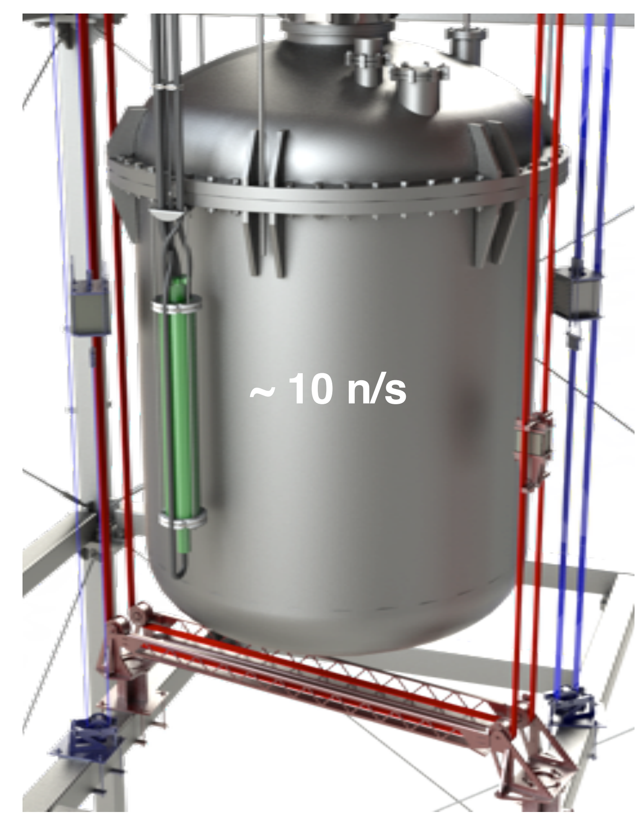
$^{220}$Rn source for ER band




PMT gains stable within 1-2%



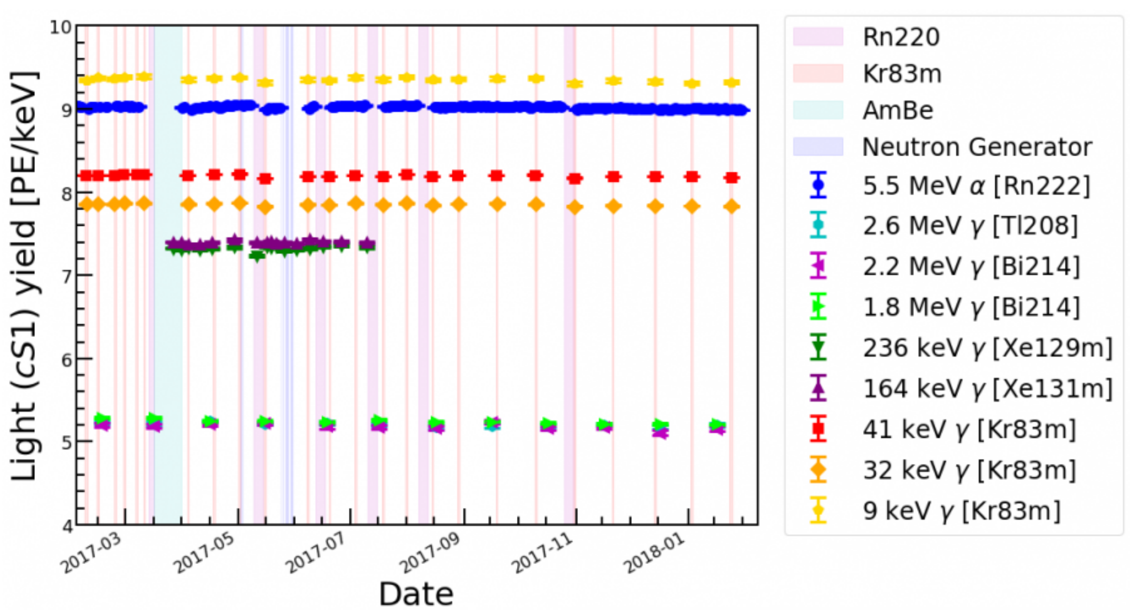

Neutron generator for NR band

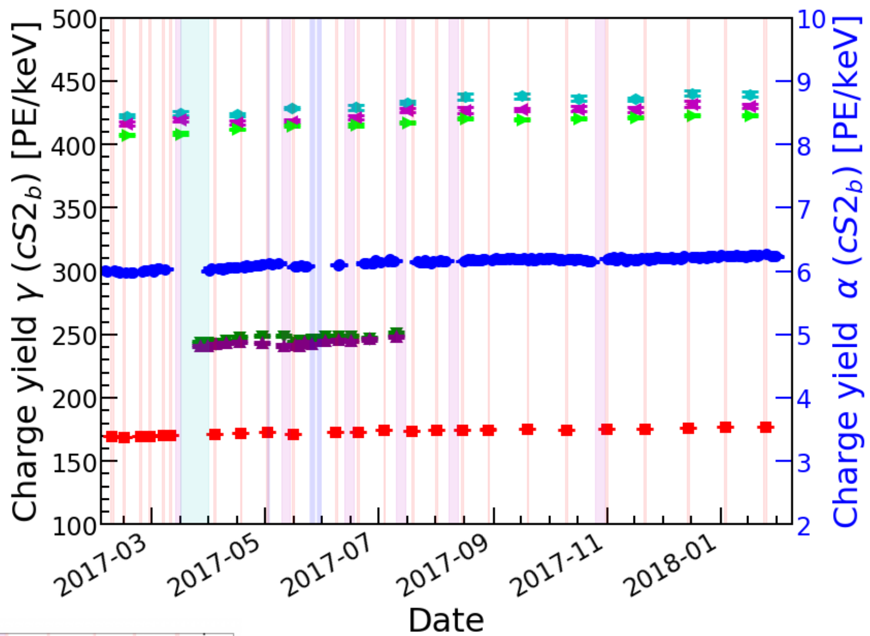



d + d -> $^3$He + n (2.45 MeV)

# LIGHT AND CHARGE YIELD VERSUS TIME

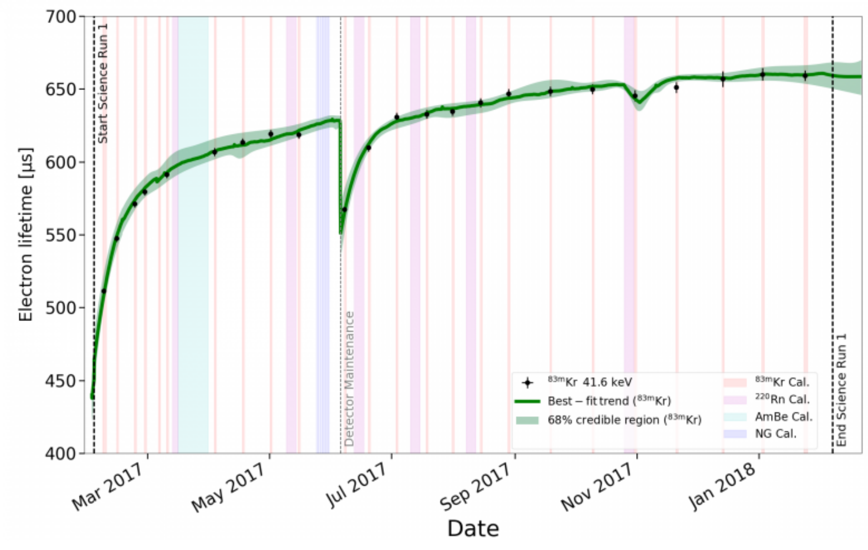
- Light yield: stable within 0.16% ($^{83m}$Kr) and 0.18% ($^{222}$Rn)
- Charge yield: slightly increasing for all sources, 1.4% ($^{83m}$Kr) and 1.2% ($^{222}$Rn)




Electron lifetime ($\tau_e$)

mean time until an electron is absorbed by an impurity in the liquid xenon



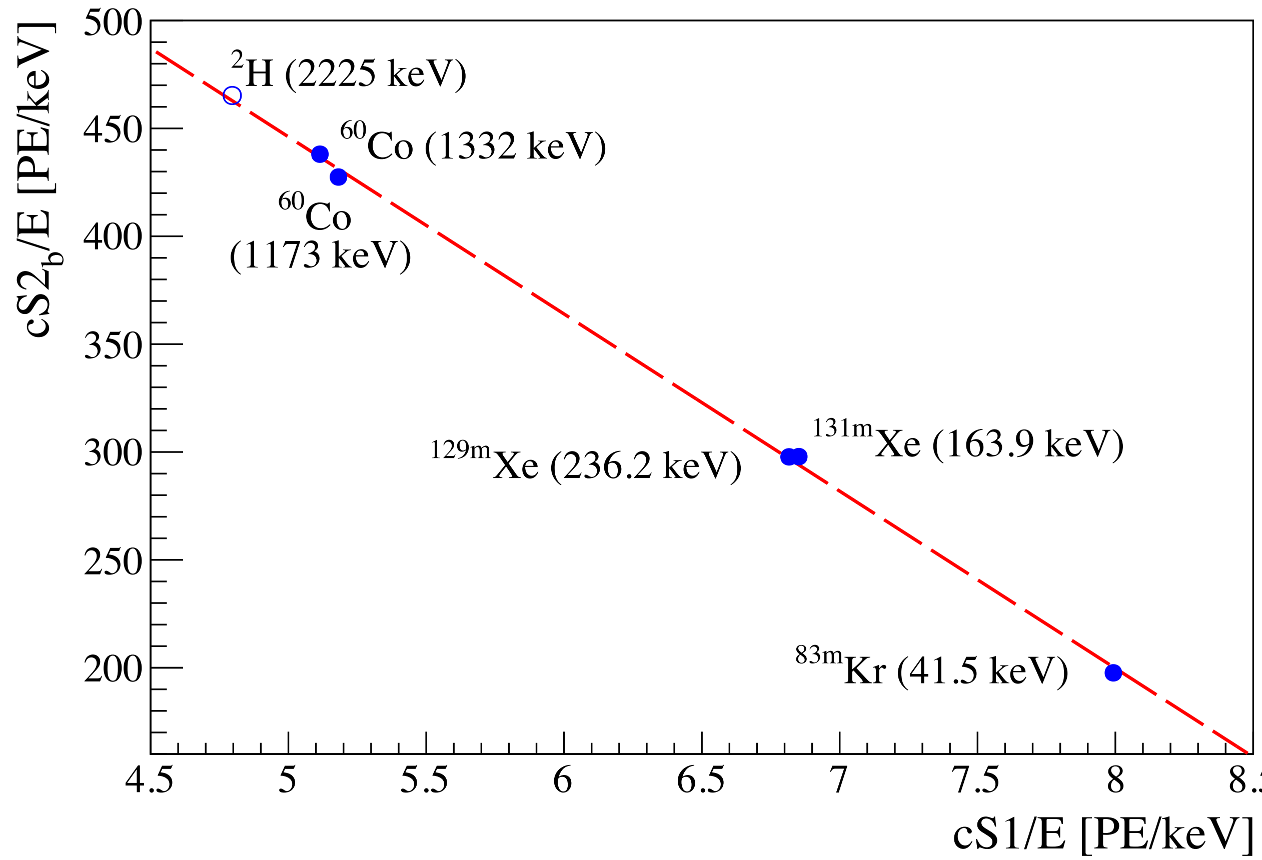

$$S_2(t) = S_2(t_0)e^{(-t/\tau_e)}$$

# ENERGY RESPONSE

$L_y$ = (8.02±0.06) pe/keV at 41.5 keV

$Q_y$ = (198.3±2.3) pe/keV at 41.5 keV

- Excellent linearity with electronic recoils up to 2.2 MeV
- Photon gain
  - $g_1$ = (0.144±0.007) pe/photon
- Electron gain
  - $g_2$ = (11.5±0.8) pe/electron



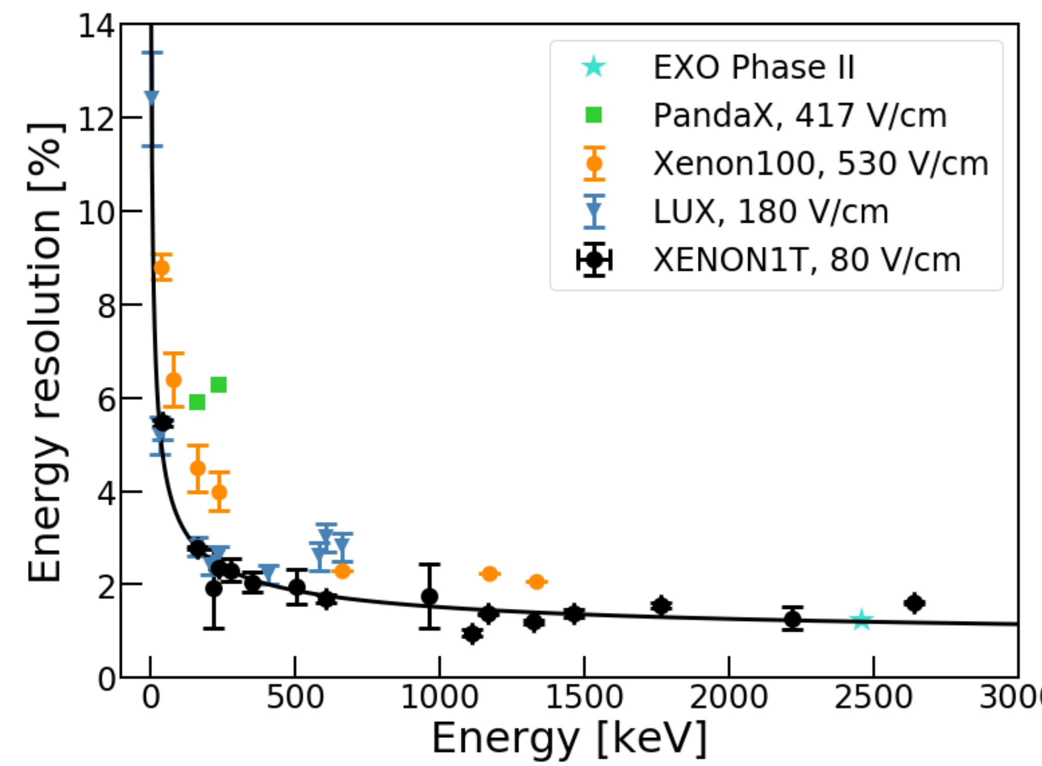

$$E = (n_{ph} + n_e) \cdot W = \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \cdot W$$

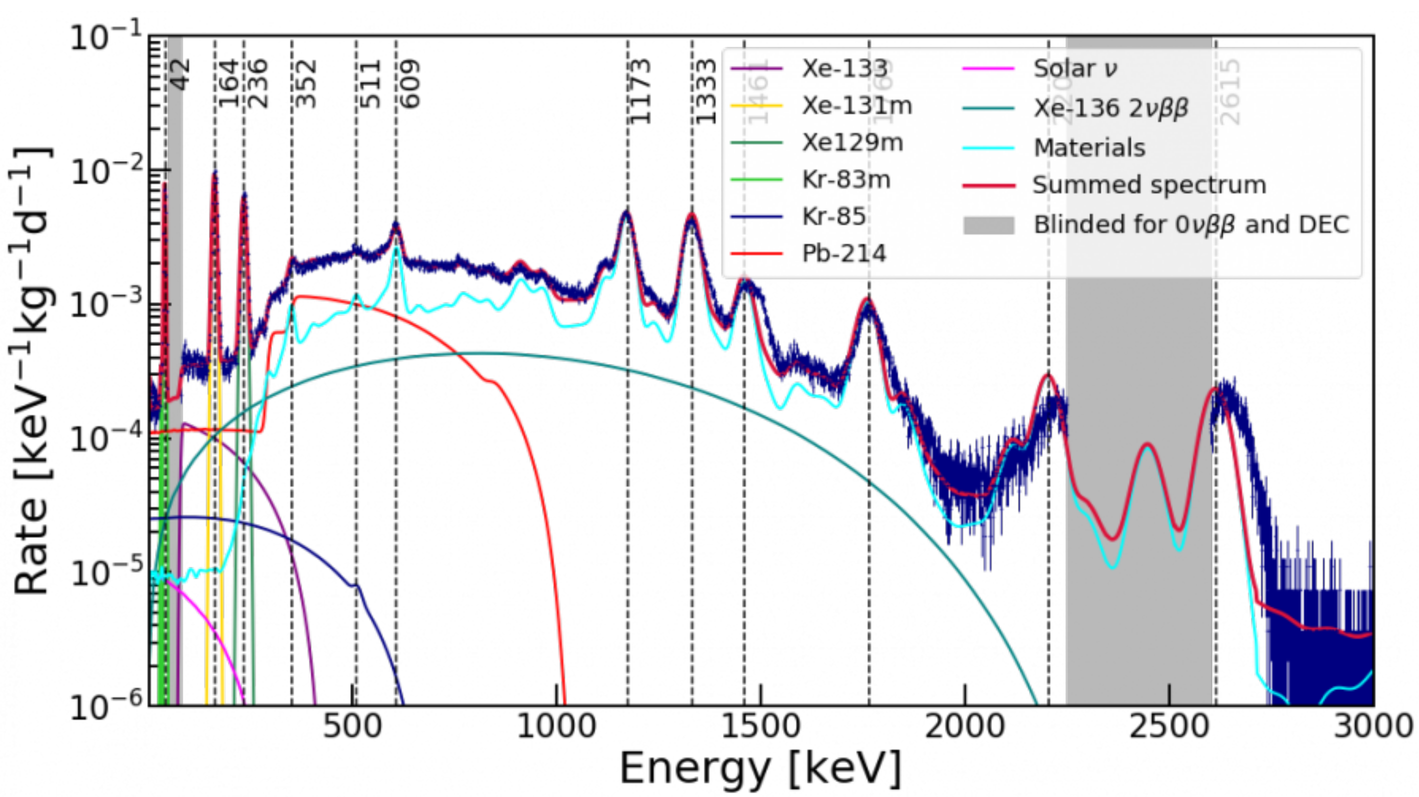
W-value = 13.7 eV

# ENERGY RESOLUTION

- One of the best among Xe-TPCs
- Covers large energy range
- Relevant for DEC ($^{124}$Xe) and 0νββ-analysis ($^{136}$Xe) & for background understanding

1.5% energy resolution at 2.5 MeV



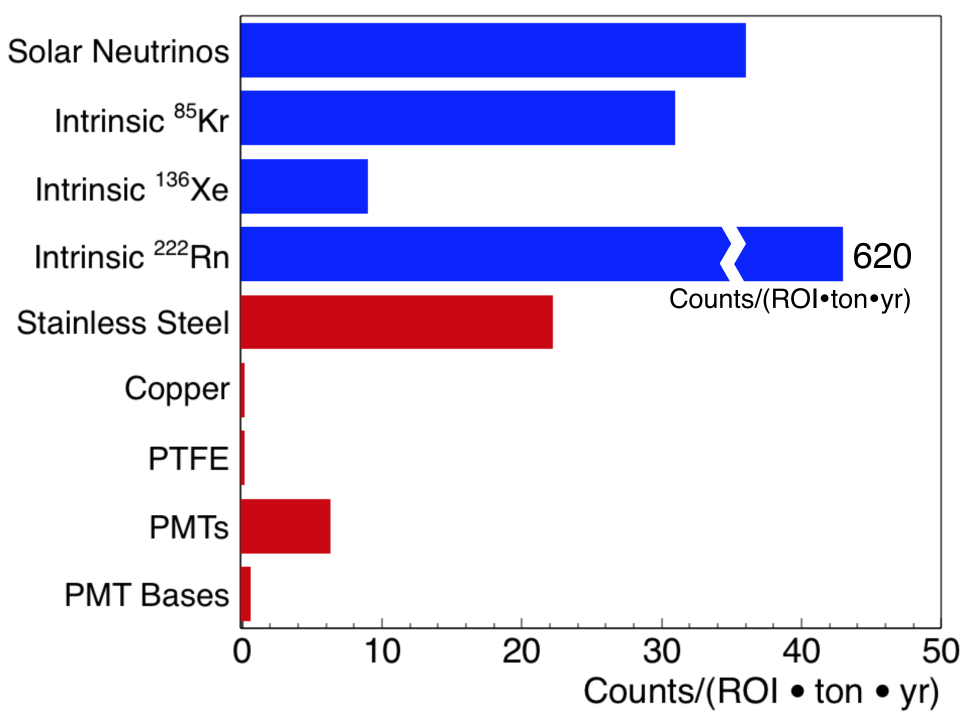

Background spectrum: data versus MC

Blinded regions: DEC and 0νββ-search

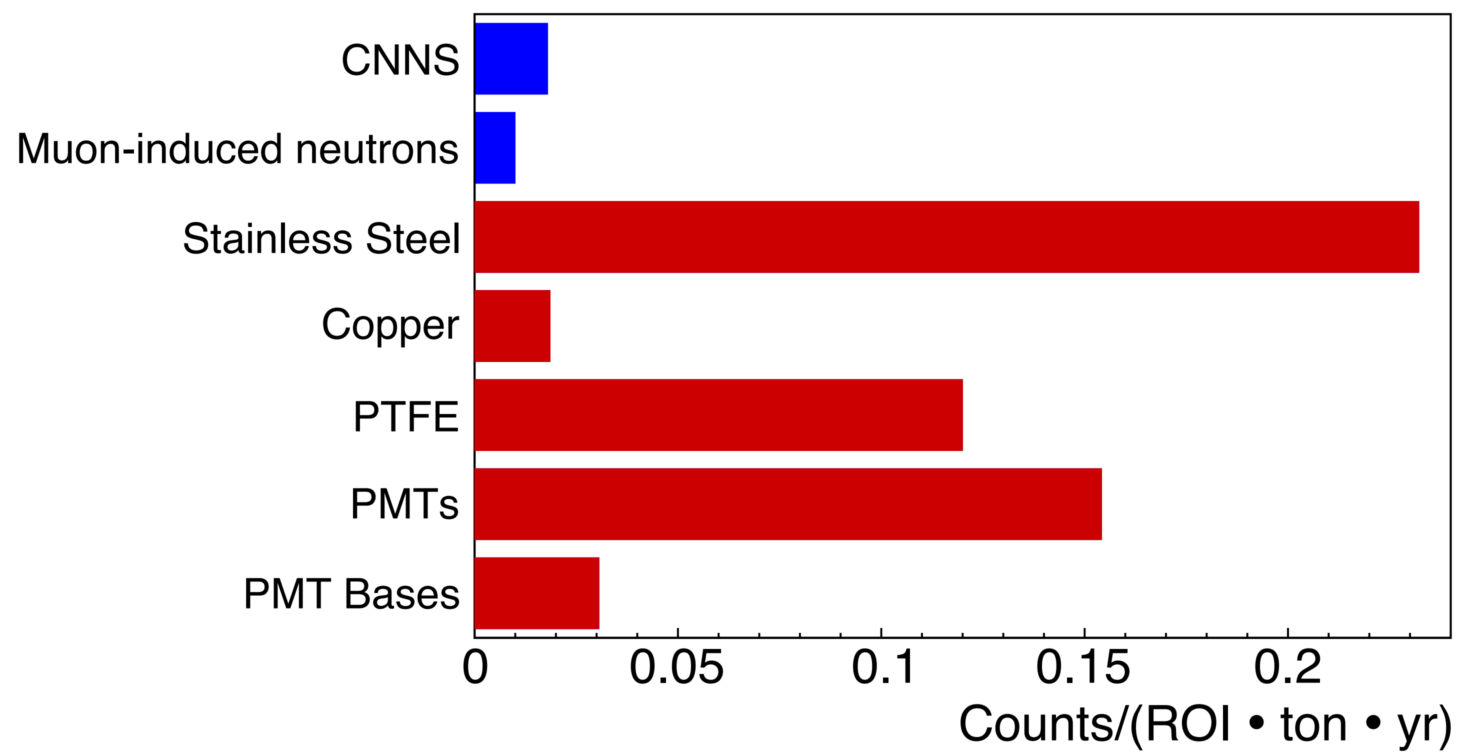
# BACKGROUND PREDICTIONS

- Based on material screening & selection
- Electronic and nuclear recoils in 1 t fiducial, 1-12 $keV_{ee}$ and 4-50 $keV_{nr}$

Electronic recoils




Nuclear recoils

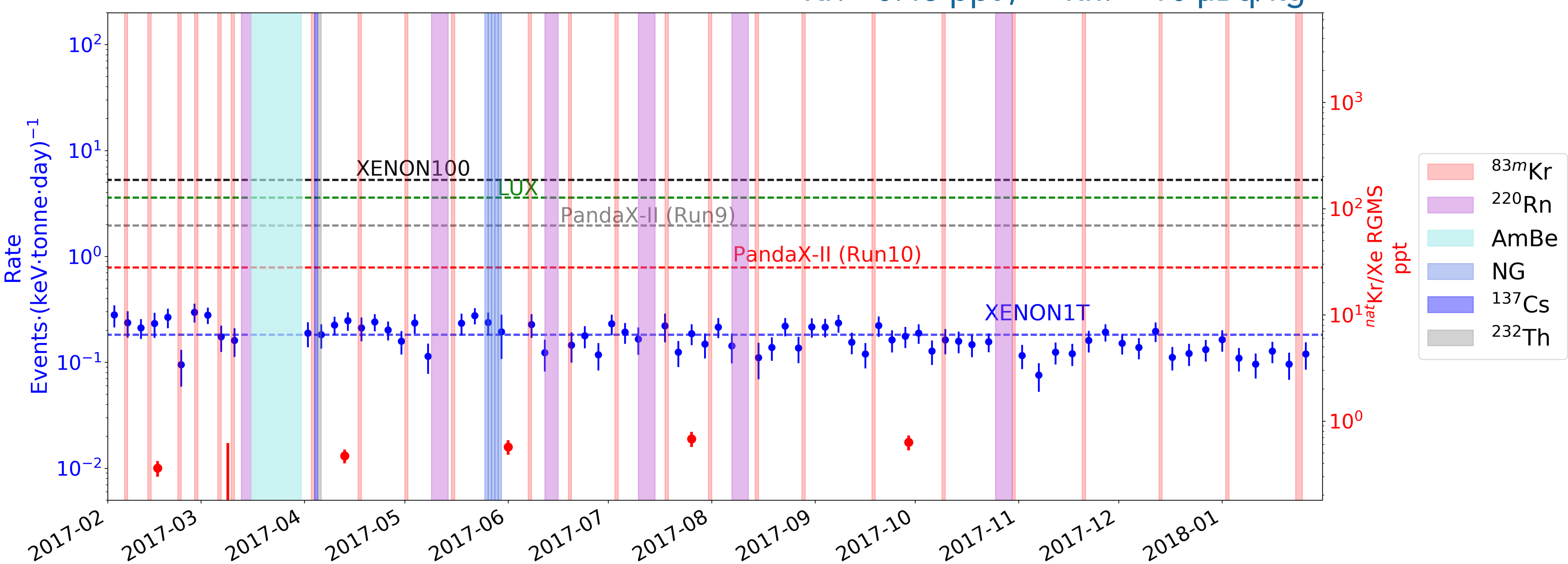



Intrinsic and neutrinos + materials

# BACKGROUND PREDICTIONS AND DATA

- ER rate: (1.7± 0.1) events/(keV t d) in 1.3 t and below 25 $keV_{ee}$
- Or: (63±2) events/(keV t y), lowest background in a dark matter detector

$^{nat}$Kr: ~0.45 ppt ; $^{222}$Rn: ~ 10 μBq/kg

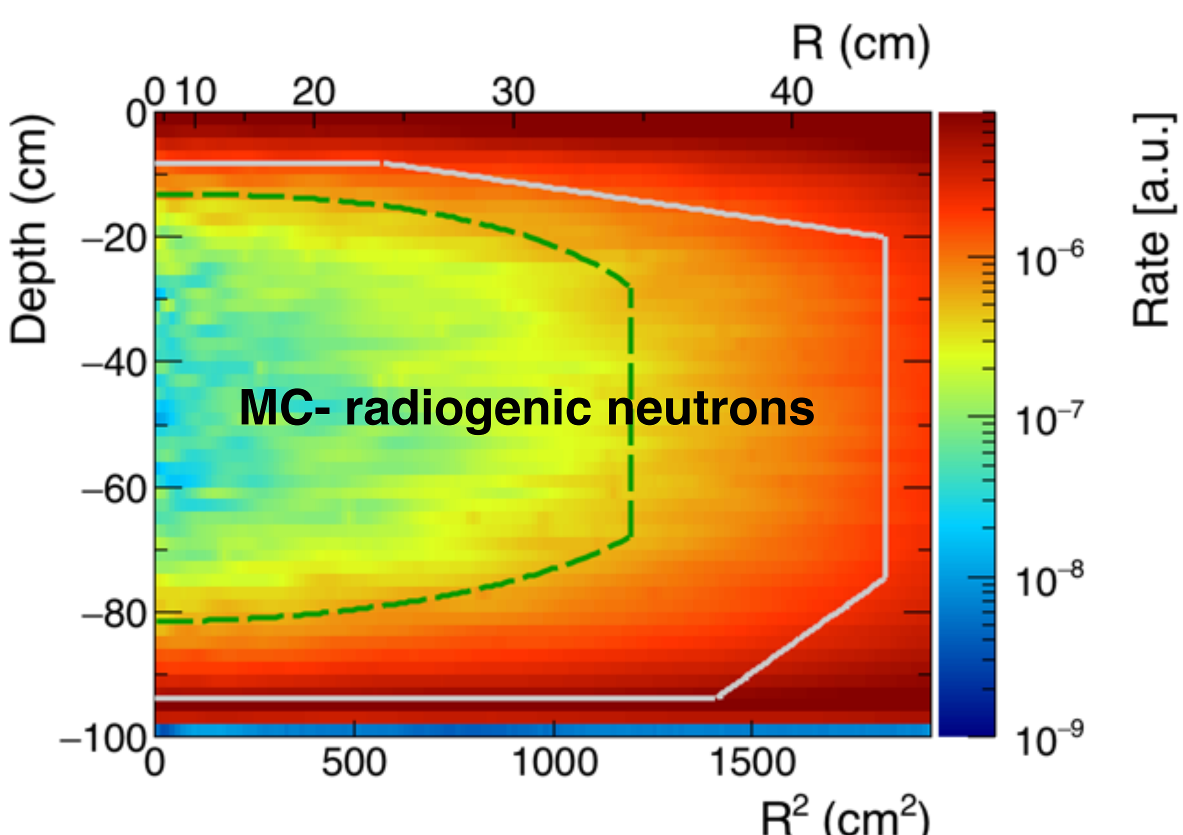



$^{222}$Rn: 85.4%, $^{85}$Kr: 4.3%, solar ν: 4.9%, materials: 4.1%, $^{136}$Xe: 1.4%

XENON collaboration: JCAP 1604 (2016) 04


# NUCLEAR RECOIL BACKGROUND

- Muon-induced neutrons: reduced by overburden and veto
- CEvNS from $^{8}B$ neutrinos: irreducible background < 1 keV
- Radiogenic neutrons from (α,n) and fission: reduced via material selection, multiplicity and fiducialisation

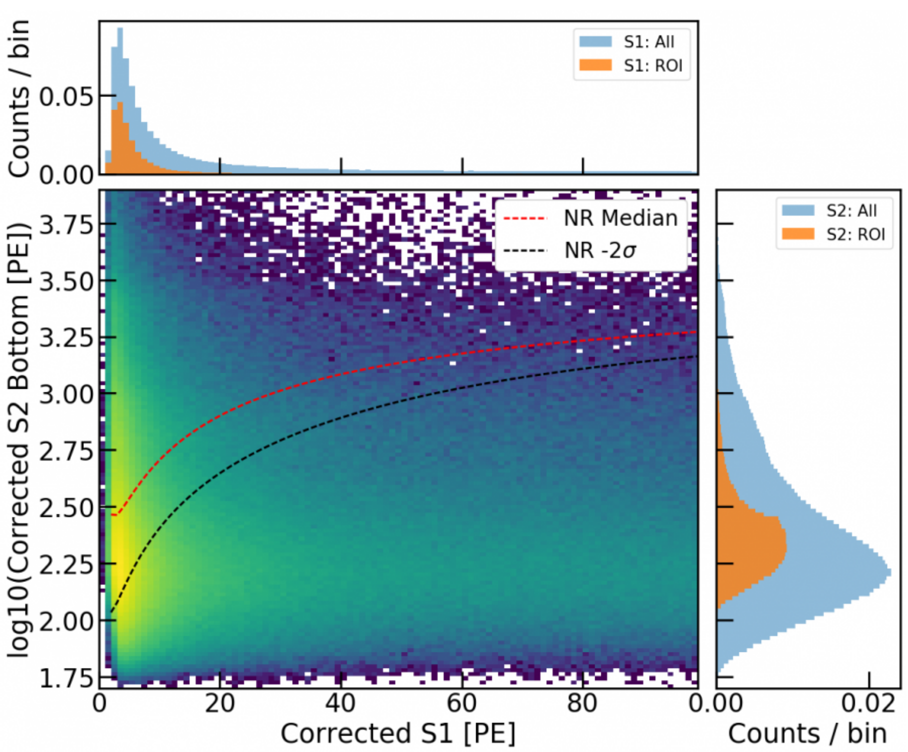



| Source | Rate [$t^{-1}$ $y^{-1}$] | Fraction [%] |
|---|---|---|
| Radiogenic | 0.6±0.1 | 96.5 |
| CEvNS | 0.012 | 2.0 |
| Cosmogenic | <0.01 | <2.0 |

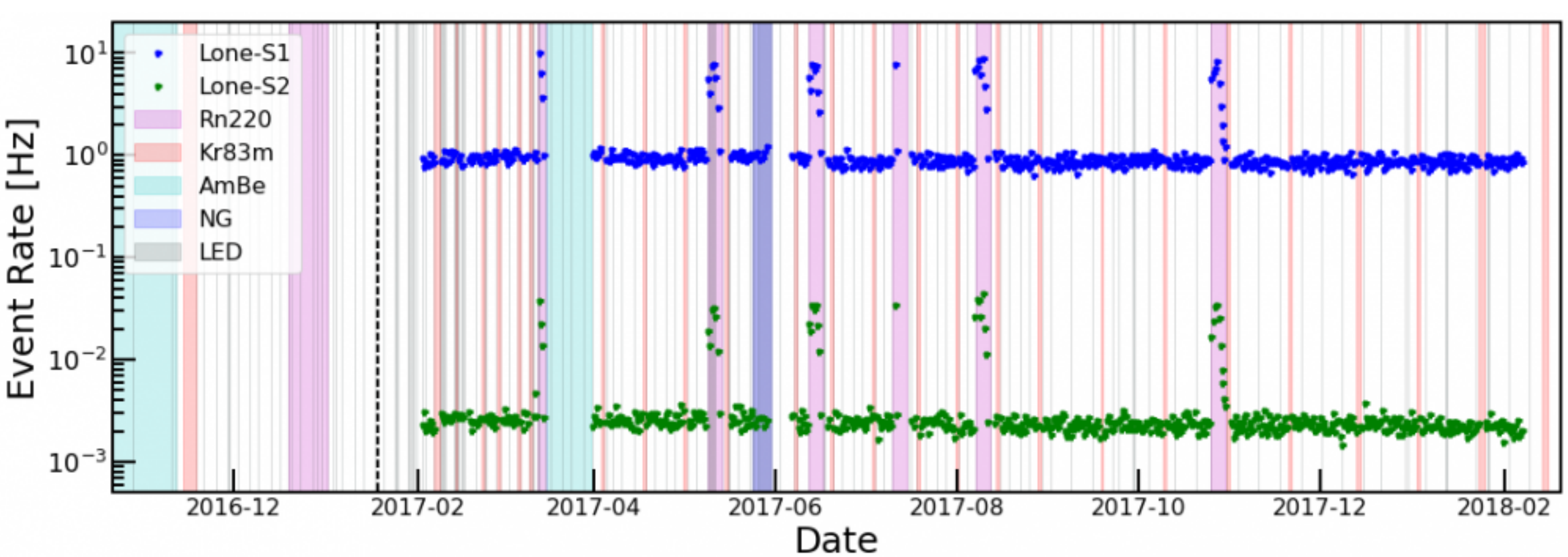
Expectation in 1tonne FV, 4-50 keV$_{nr}$ window

# ACCIDENTAL COINCIDENCE BACKGROUND

- "Lone" S1 - S2 coincidences: S1 from e.g. events below the cathode, S2 e.g. near field grids - can fake events that populate signal region
- Empirical model: select unpaired S1 [0.7,1.1] Hz – S2 (2.6±0.1) mHz from data, randomly pair to form events; apply analysis selection criteria
- Performance verified using $^{220}$Rn data and sidebands background data

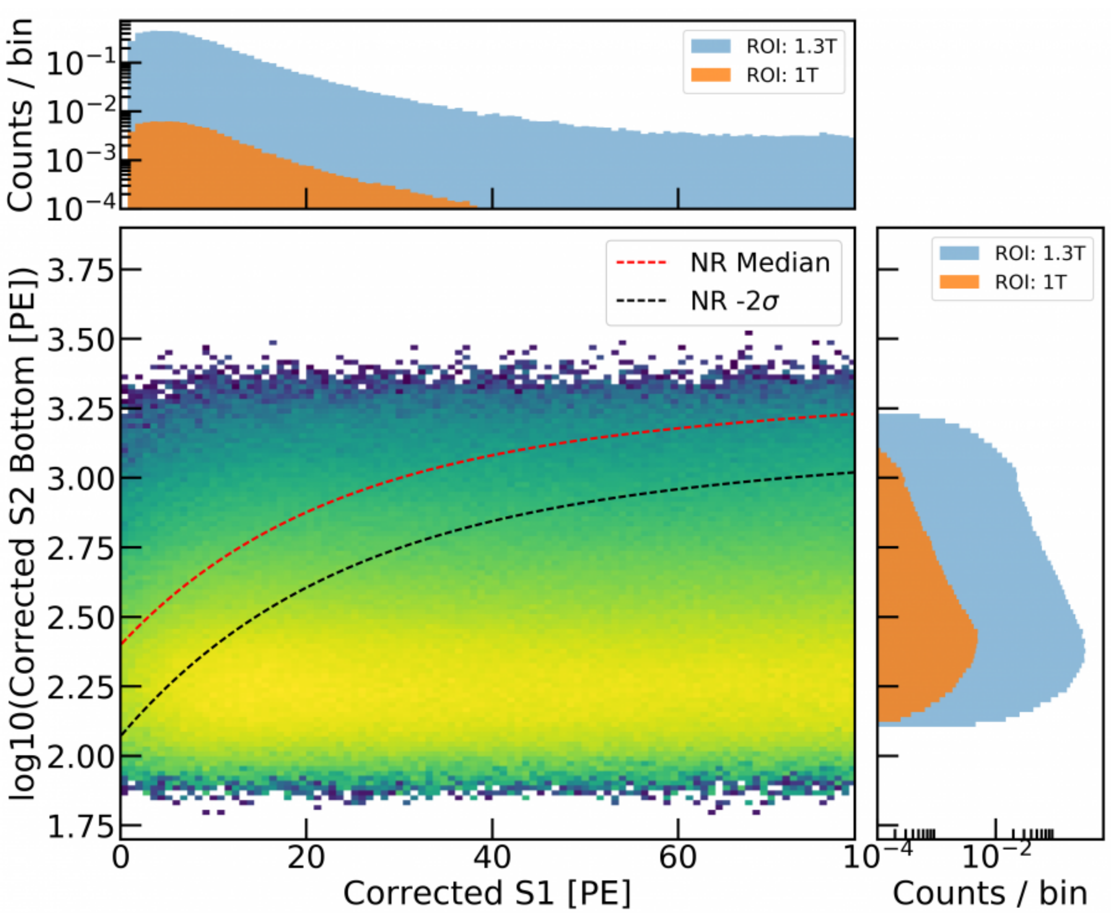


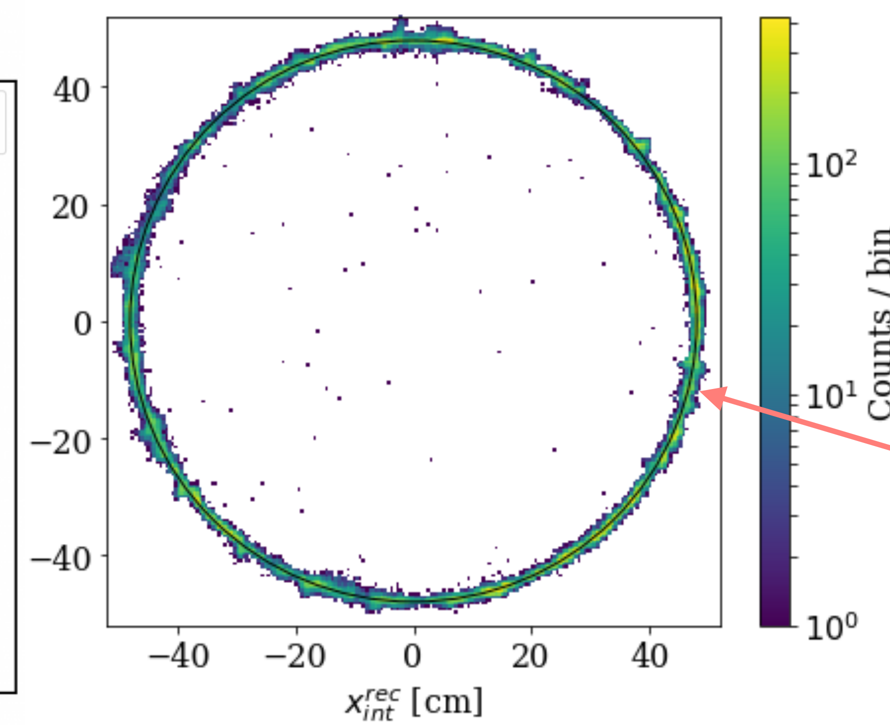

Lone S1 and S2 rates versus time



# SURFACE BACKGROUND

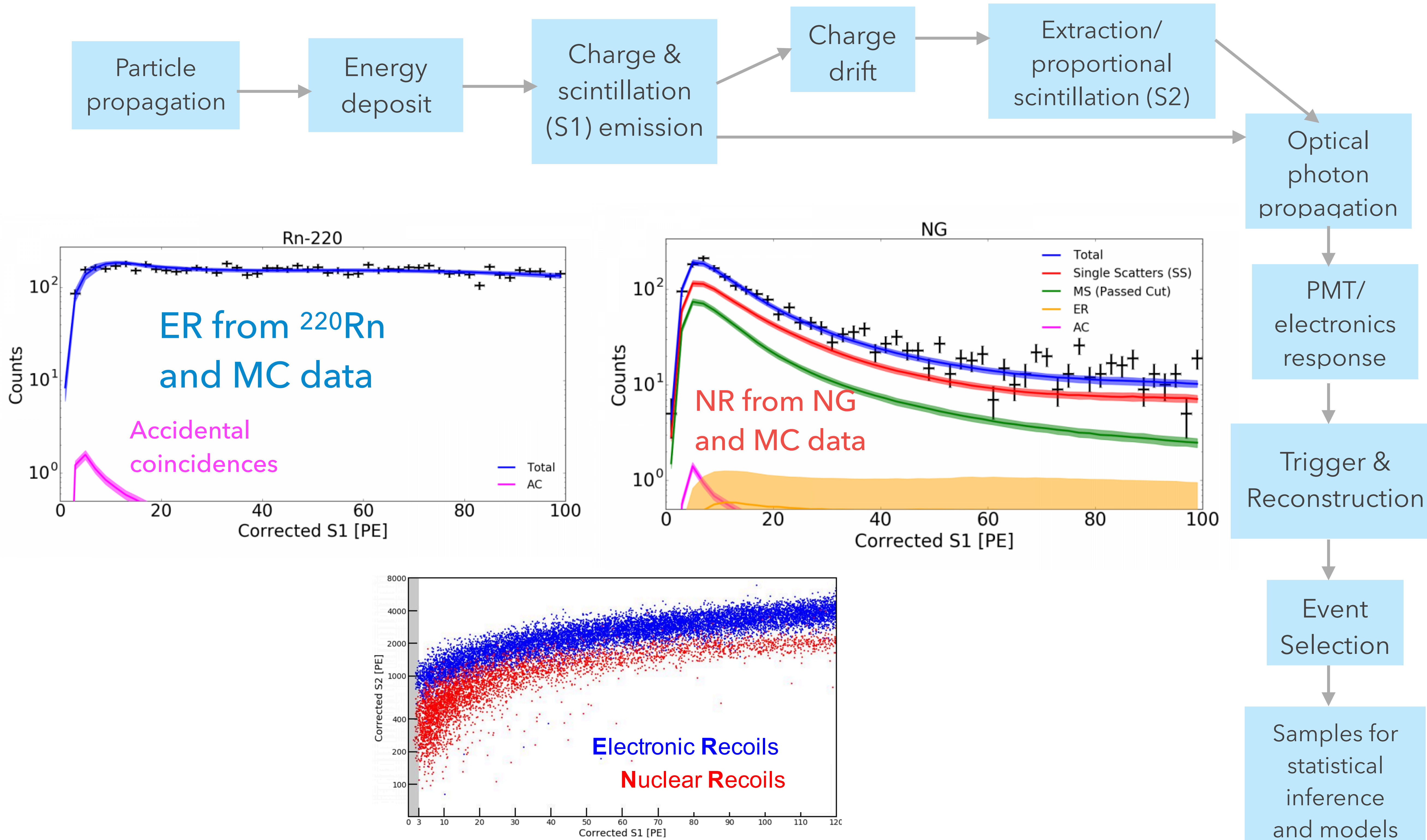
- Radioactivity on PTFE surface & charge loss: event can be reconstructed in the NR region
- Data driven model derived from surface-event samples




| | | |
|---|---|---|
| $^{222}Rn$ | 3.8 d | α ↓ 5.5 MeV |
| $^{218}Po$ | 3.05 min | α ↓ 6.0 MeV |
| $^{214}Pb$ | 26.8 min | β ↓ |
| $^{214}Bi$ | 19.9 min | β ↓ |
| $^{214}Po$ | 164 μs | α ↓ 7.7 MeV |
| $^{210}Pb$ | 22.3 y | β ↓ |
| $^{210}Bi$ | 5.0 d | β ↓ |
| $^{210}Po$ | 138 d | α ↓ 5.3 MeV |
| $^{206}Pb$ | stable | |

# SIGNAL AND BACKGROUND MODELLING



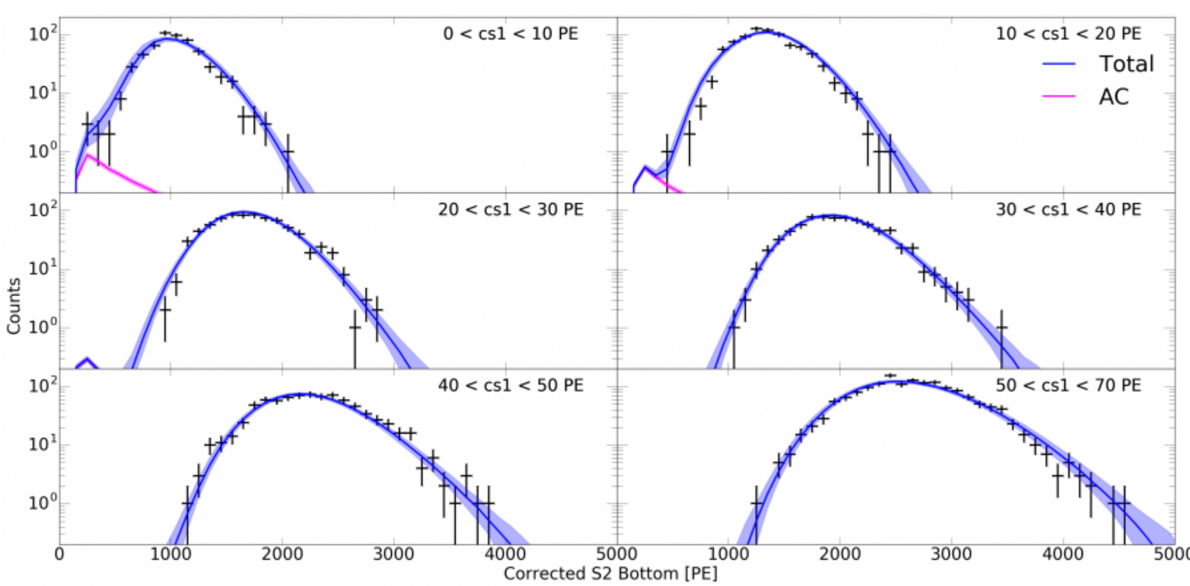
# SIGNAL AND BACKGROUND MODELLING

Particle propagation → Energy deposit → Charge & scintillation (S1) emission → Charge drift → Extraction/ proportional scintillation (S2) → Optical photon propagation

Charge & scintillation (S1) emission → Optical photon propagation

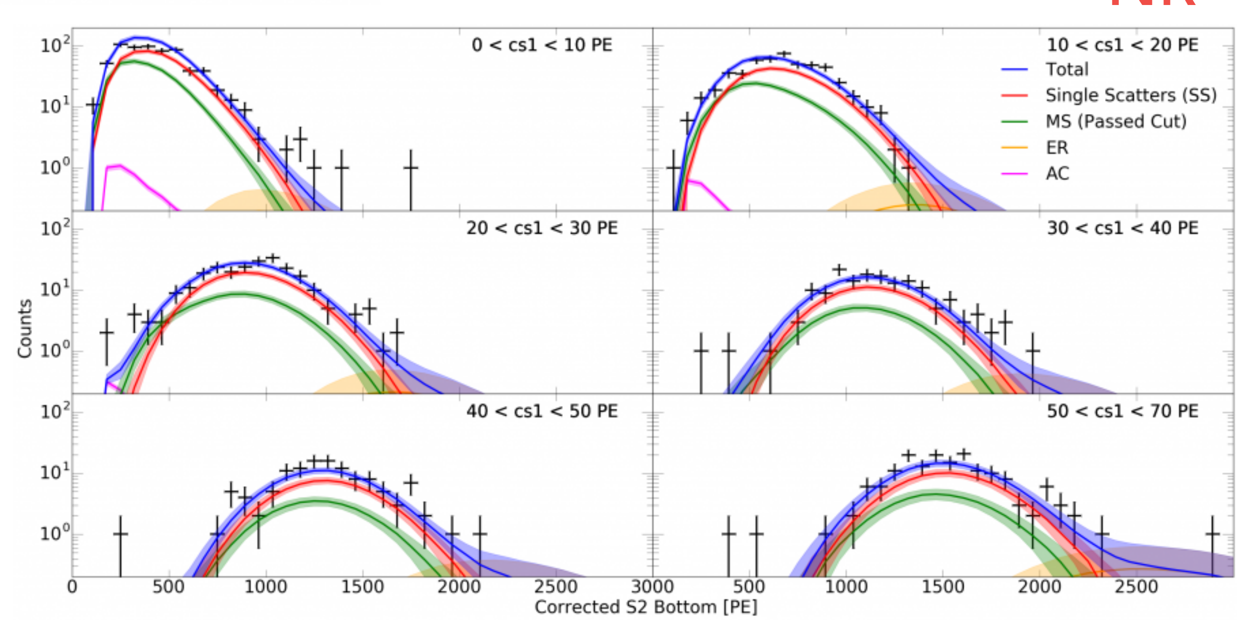
Optical photon propagation → PMT/ electronics response → Trigger & Reconstruction → Event Selection → Samples for statistical inference and models

ER




Slice in S1 & project onto S2

NR



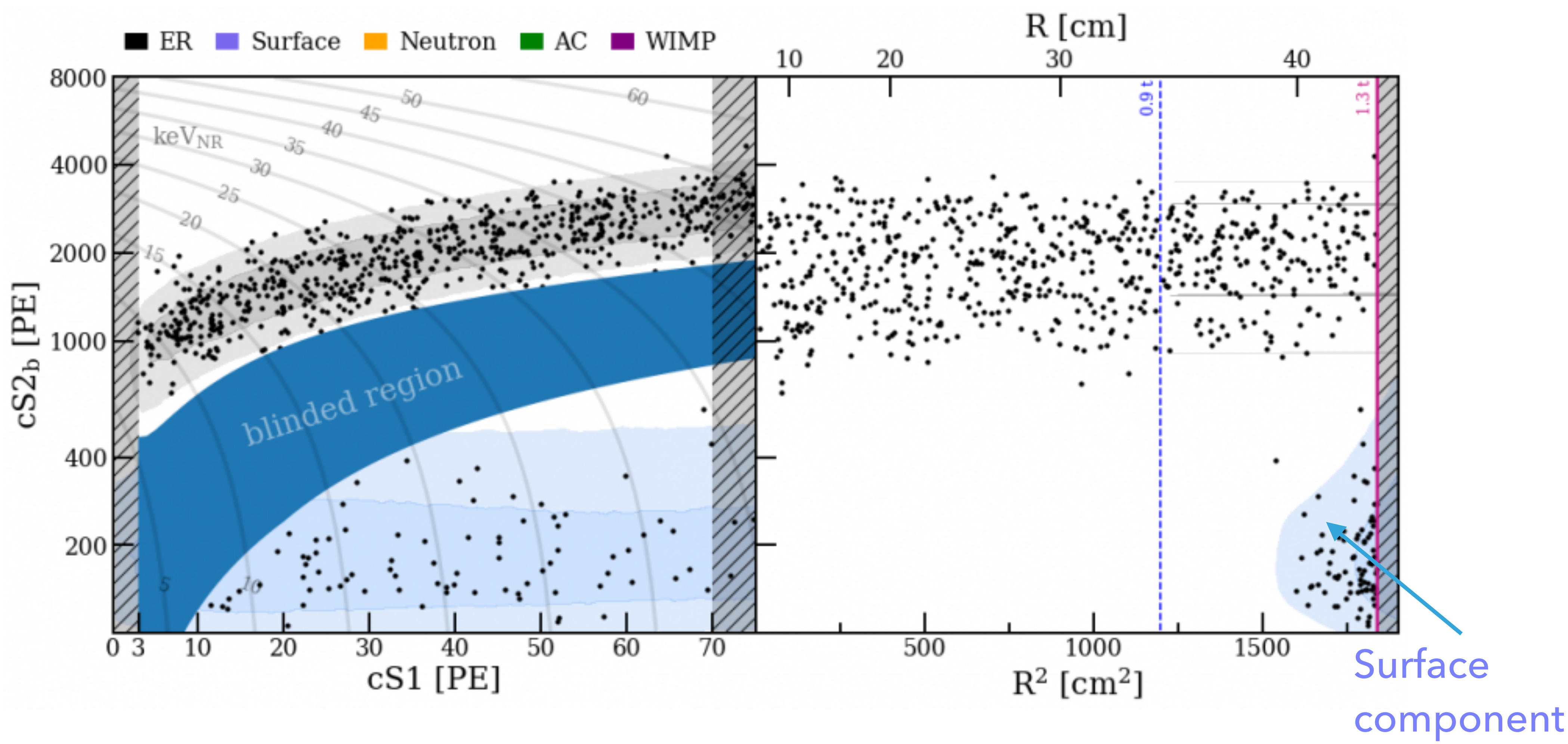

Each component (S, B) is modelled as a probability density function in ($S1$, $S2_b$, $r$, $z$)

# DARK MATTER SEARCH DATA

- Blinded: avoid bias in event selection and S/B modelling
- Salted: protect against post-unblinding tuning of cuts and background models

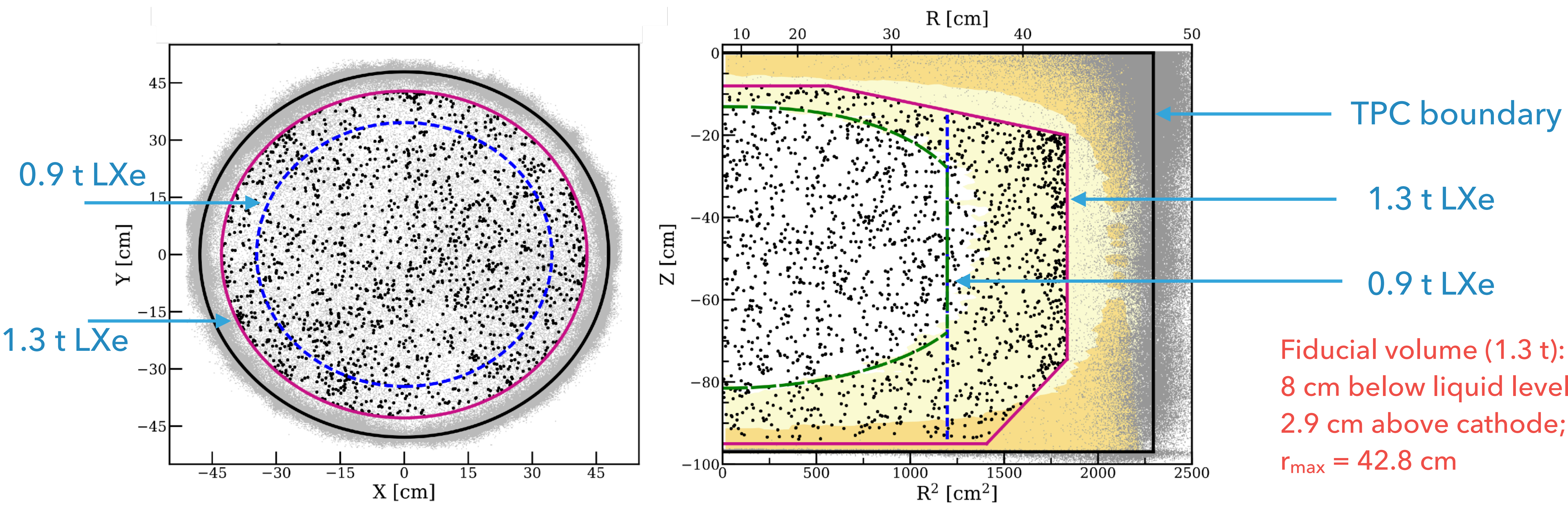
Blinded region:

- $S2 > 200$ PE
- below the ER $-2\sigma$ quantile in $S2_b$ versus S1 space



# FIDUCIAL VOLUME SELECTION

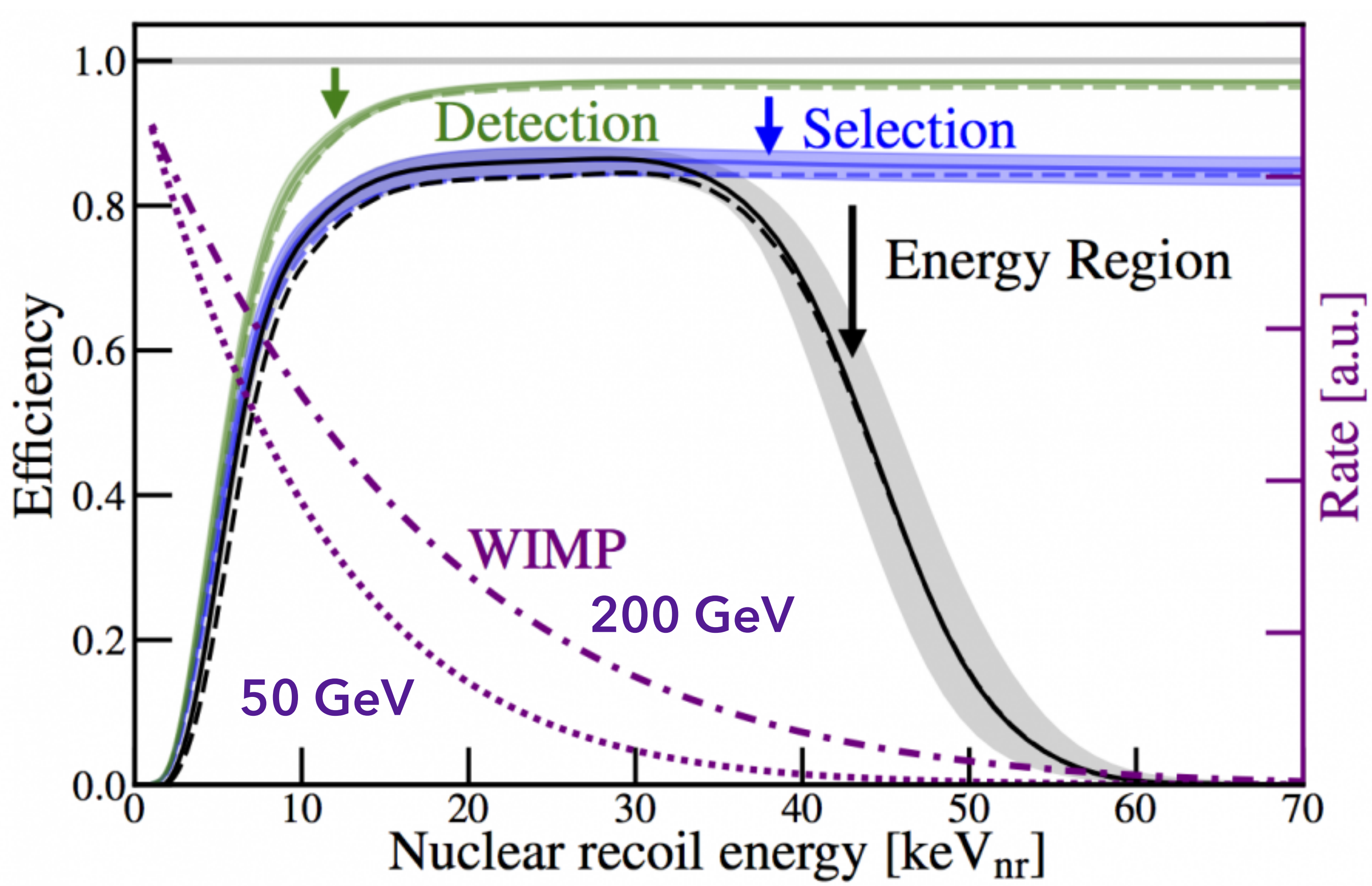
- Optimised prior to unblinding to reduce materials and surface background: 1.0 t → (1.3±0.01) t
- Included radius r in statistical inference due to surface background model; analysis in ($S1$, $S2_b$, r, z)-space




Fiducial volume (1.3 t):
8 cm below liquid level,
2.9 cm above cathode;
$r_{max}$ = 42.8 cm

# EVENT SELECTION AND DETECTION EFFICIENCY

- Detection efficiency: due to 3-fold PMT coincidence requirement
- Selection efficiencies: from MC and data control samples
- Dark matter search region: [3-70] PE in S1




Bands: 68% credible regions

ROI: [3 - 70] PE corresponds to

ER: [1.4 - 10.6] $keV_{ee}$

NR: [4.9 - 40.9] $keV_{nr}$

# BACKGROUND PREDICTION AND UNBLINDING

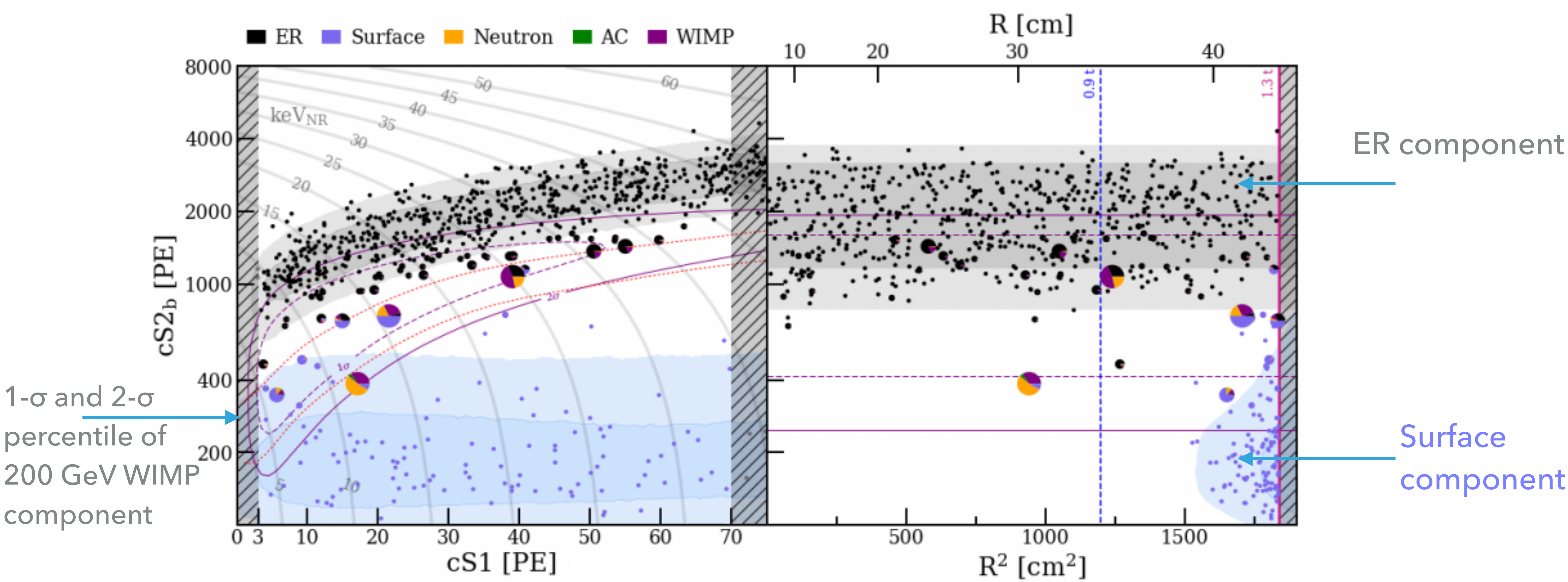
- Reference region: space between NR median and NR-2σ
- Numbers in reference region *for illustration only*, statistical inferences based on PL analysis in ($S1$, $S2_b$, r, z) space
- ER: most significant background, uniformly distributed
- Surface background: *most significant in reference region*

Best fit event rates with 278.8 days live-time

| Source | 1.3 tonnes | 1.3 tonnes |
|---|---|---|
| (S2, S1) | **Full ROI** | **Reference NR** |
| ER | 627±26 | 2.17±0.09 |
| Radiogenic | 1.44±0.61 | 0.75±0.30 |
| CEvNS | 0.05±0.02 | 0.02±0.01 |
| Accidental | $0.47^{+0.29}_{-0.02}$ | $0.10^{+0.06}_{-0.00}$ |
| Surface | 106±11 | 5.36±0.54 |
| **Total** | **736±28** | **8.40±0.63** |
| **Data** | **739** | **11** |
| $WIMP_{best\text{-}fit}$ 200 GeV, 4.2e-47 $cm^2$ | 3.36 | 1.55 |

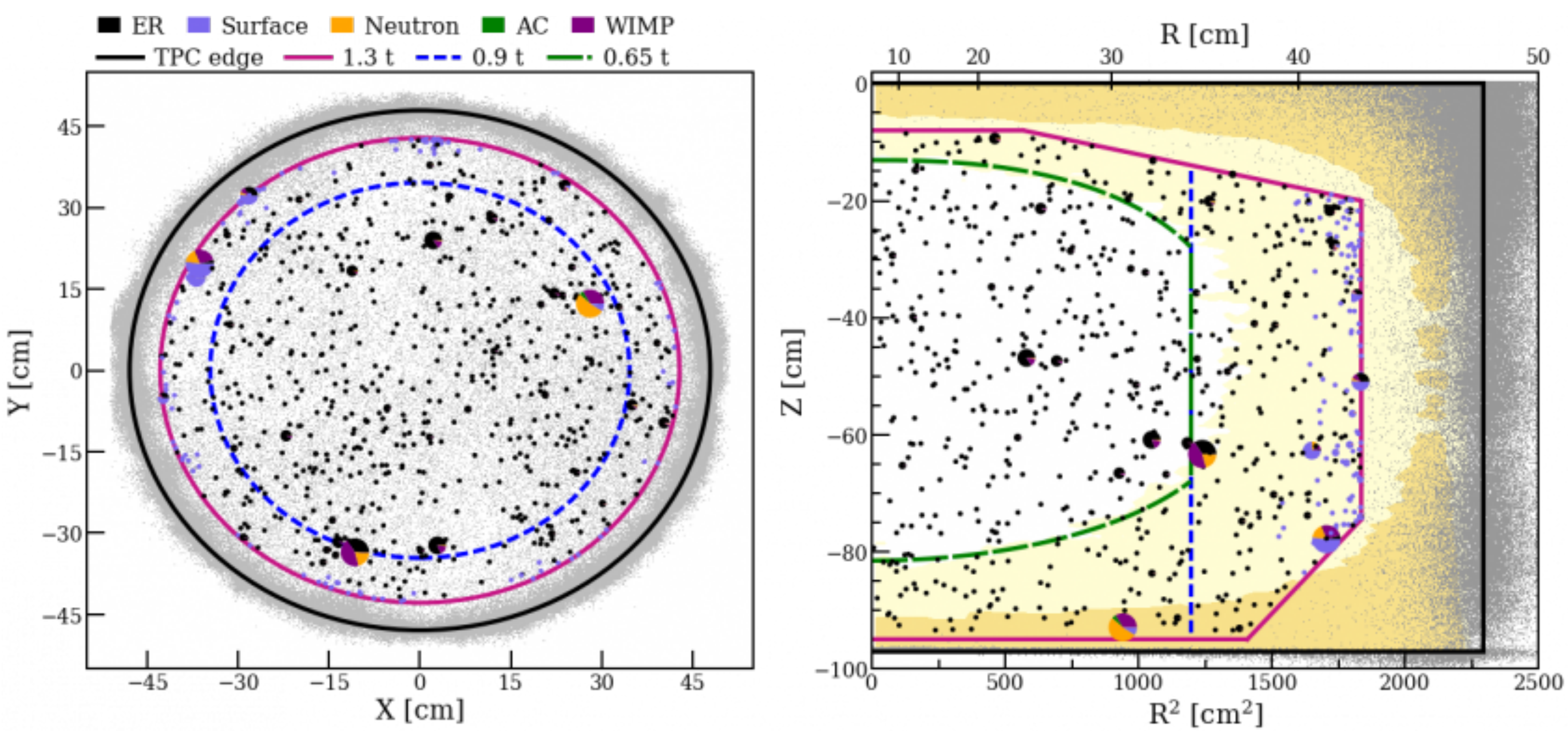
# DARK MATTER SEARCH RESULTS

- Results interpreted with unbinned profile likelihood analysis (all model uncertainties included in the likelihood as nuisance parameters)
- Piecharts: relative PDF from the best fit of 200 GeV WIMPs with $4.2 \times 10^{-47}$ cm$^2$



# SPATIAL DISTRIBUTION OF EVENTS

- Results interpreted with unbinned profile likelihood analysis (all model uncertainties included in the likelihood as nuisance parameters)
- Core volume: to distinguish WIMPs over neutron background



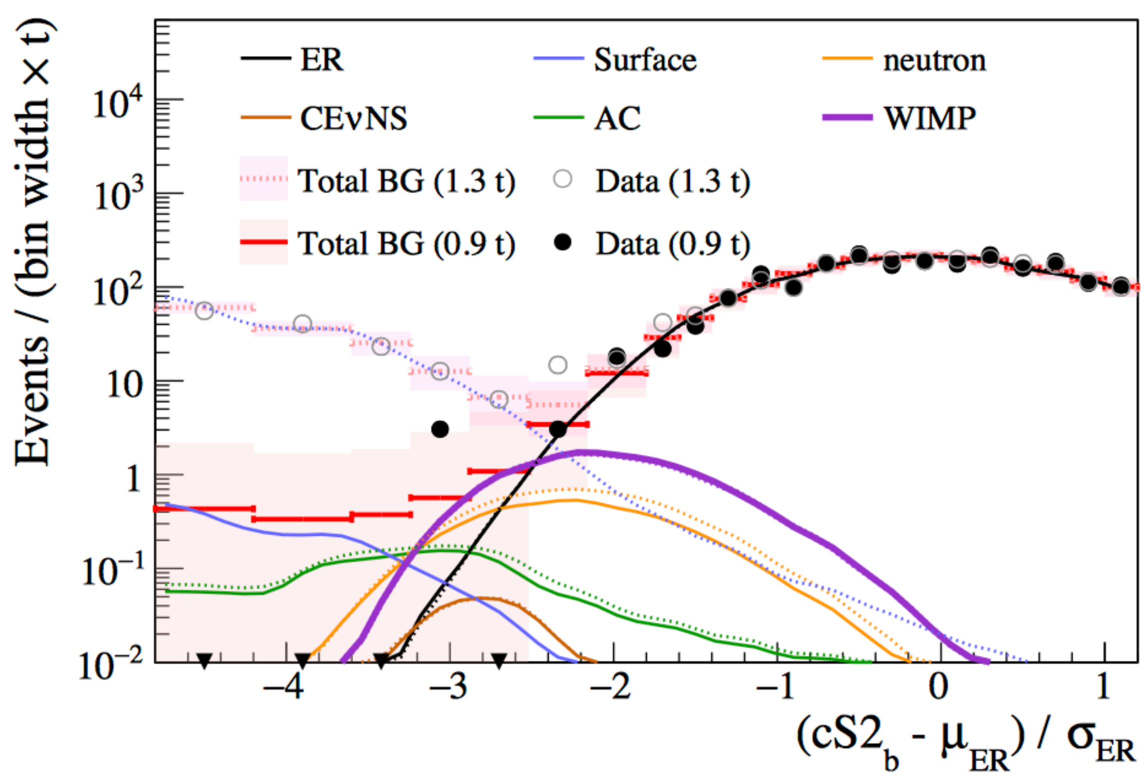

Events passing all selection criteria:

pie charts → relative probabilities of background and signal components for each event *under the best fit model* (assuming 200 GeV WIMP and $\sigma_{SI}$ = 4.2e-47 cm²)

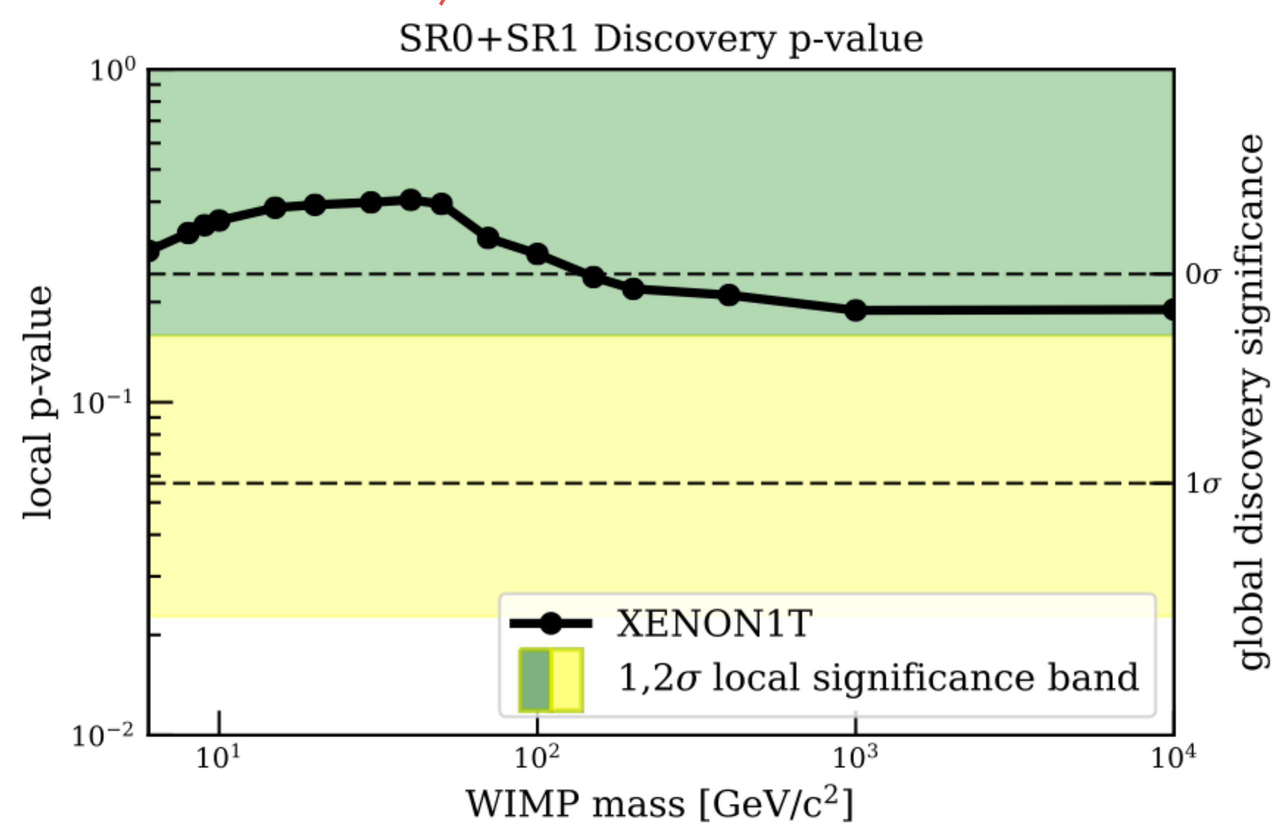
# STATISTICAL INTERPRETATION

- ER & surface background shape parameters included in the likelihood
- Safeguard to protect against background mis-modelling (N. Priel et al., JCAP 5, 2017)
- No 3-σ excess at any WIMP mass, background-only hypothesis accepted (p-value is 0.41 at 50 GeV, and 0.22 at 200 GeV)

Background and 200 GeV WIMP signal best-fit predictions compared to data in 1.3 t and 0.9 t

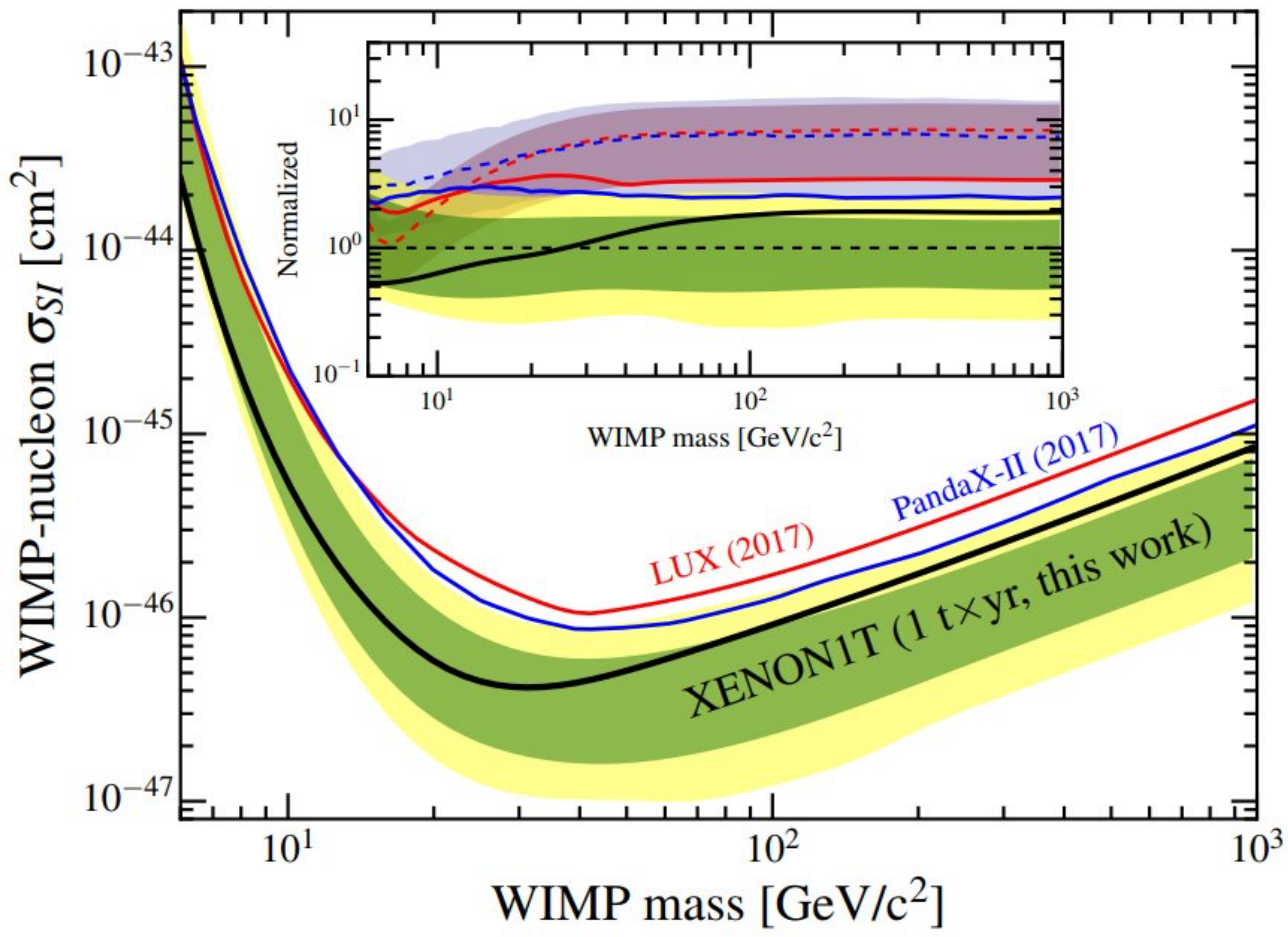



Probability that the no-signal hypothesis could have produced a dataset at least as "extreme" (in terms of log likelihood ratio)



# NEW CONSTRAINTS ON WIMPS

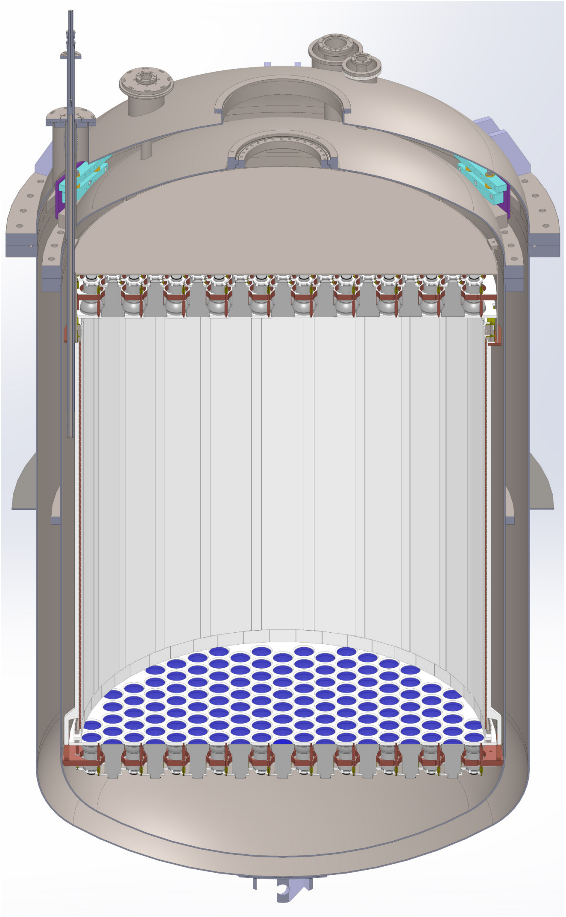
- Strongest upper limit (at 90% CL) on SI WIMP-nucleon cross sections > 6 GeV
- Median sensitivity: factor 7 higher than for previous experiments (LUX, PandaX-II)
- 1-σ fluctuation at higher WIMP masses could be due to background or signal

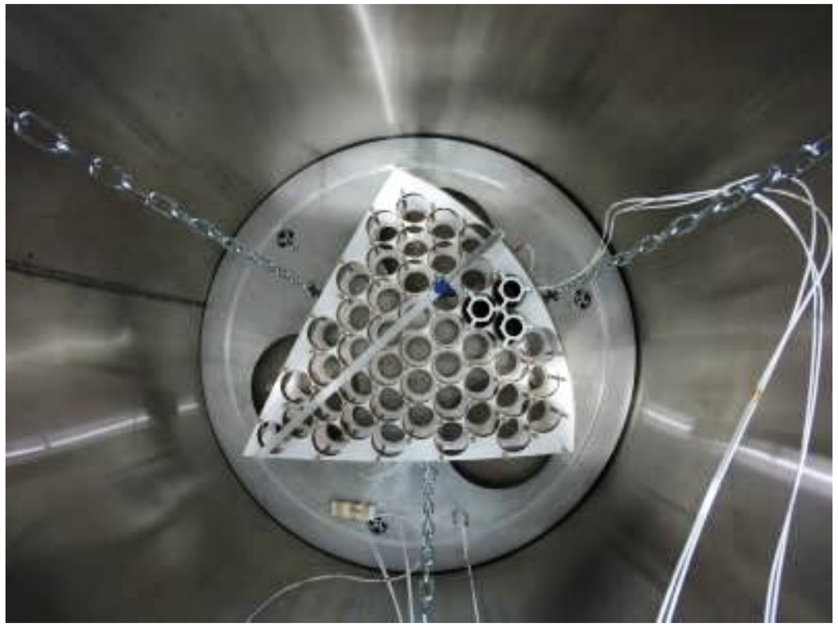



$$\sigma_{\rm SI} < 4.1 \times 10^{-47} {\rm cm}^2 \ \text{at} \ 30\,{\rm GeV/c^2}$$

# XENONNT

- Rapid upgrade to 8.2 t total mass, 6 t in the TPC
- Most sub-systems in place from XENON1T
- New inner cryostat, new TPC, 476 PMTs (most of these tested & screened)
- Neutron veto, Rn removal tower, additional storage system
- Installation at LNGS scheduled to start in late 2018, commissioning in 2019





# SUMMARY AND OUTLOOK

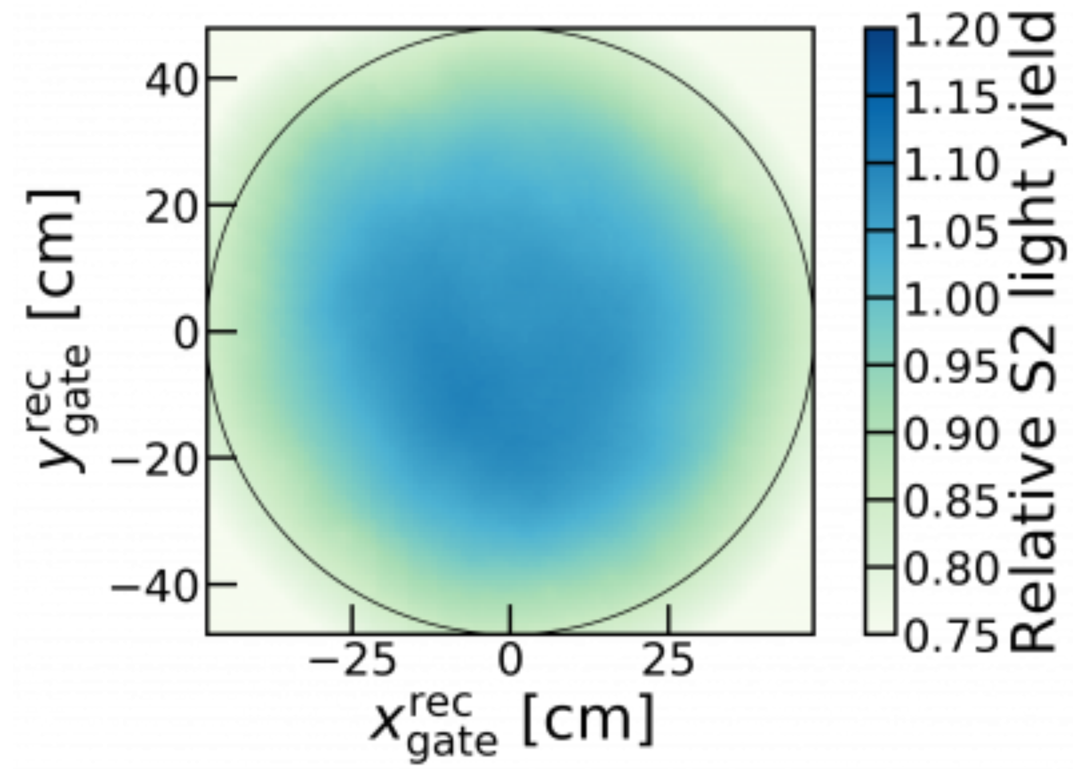
- The first multi-ton scale LXe-TPC was operated > 1 y
- Achieved the lowest background in a dark matter detector
- Result from an analysis of 1 tonne year exposure: the strongest upper limit on SI WIMP-nucleon cross sections for masses > 6 GeV, with $4.1 \times 10^{-47}$ $cm^2$ at 30 GeV
- XENON1T acquires more data until its upgrade, XENONnT, is ready for installation at LNGS
- Many analyses in the pipeline (DEC, 0νββ-decay, annual modulation, low-mass WIMPs, bosonic SuperWIMPs, etc)
- XENONnT is designed for a factor 10 increase in sensitivity

# BACKUP SLIDES

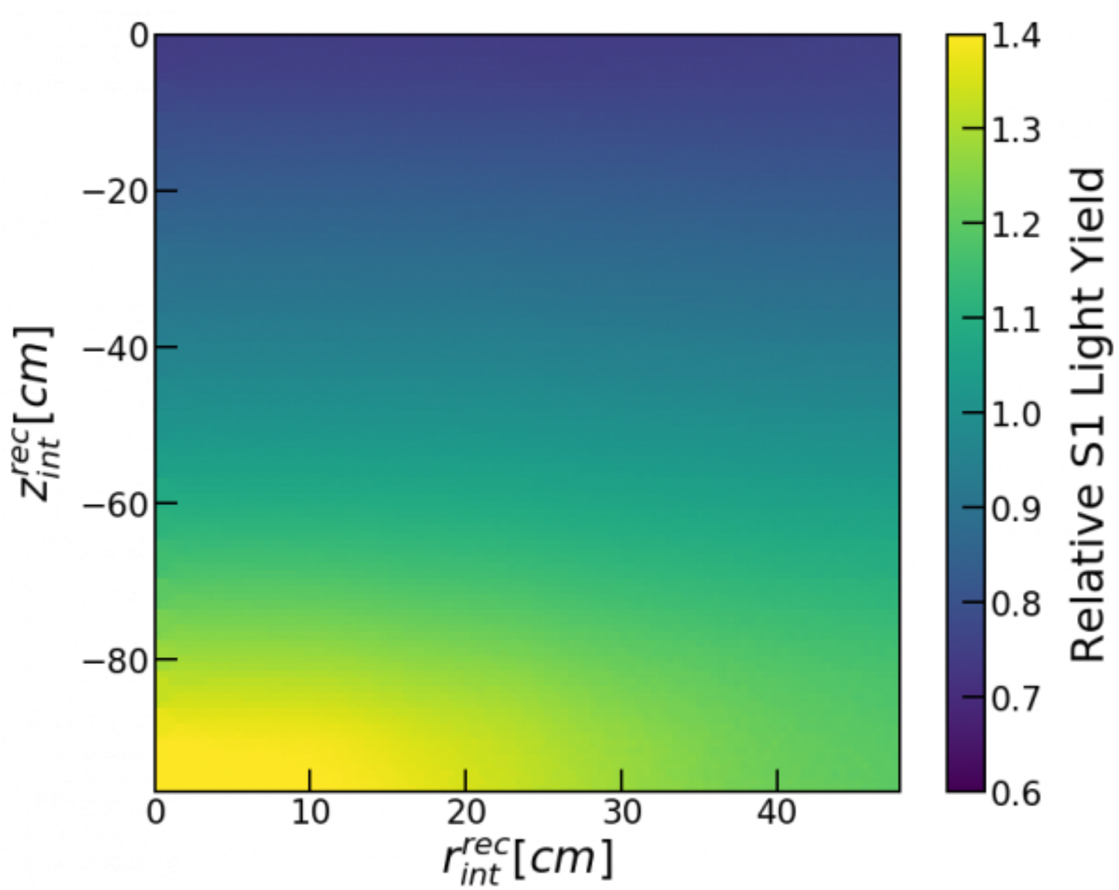
# CORRECTION MAPS

- Multiplicative corrections applied to S1s (light) and S2s (charge), depending on their position in the TPC

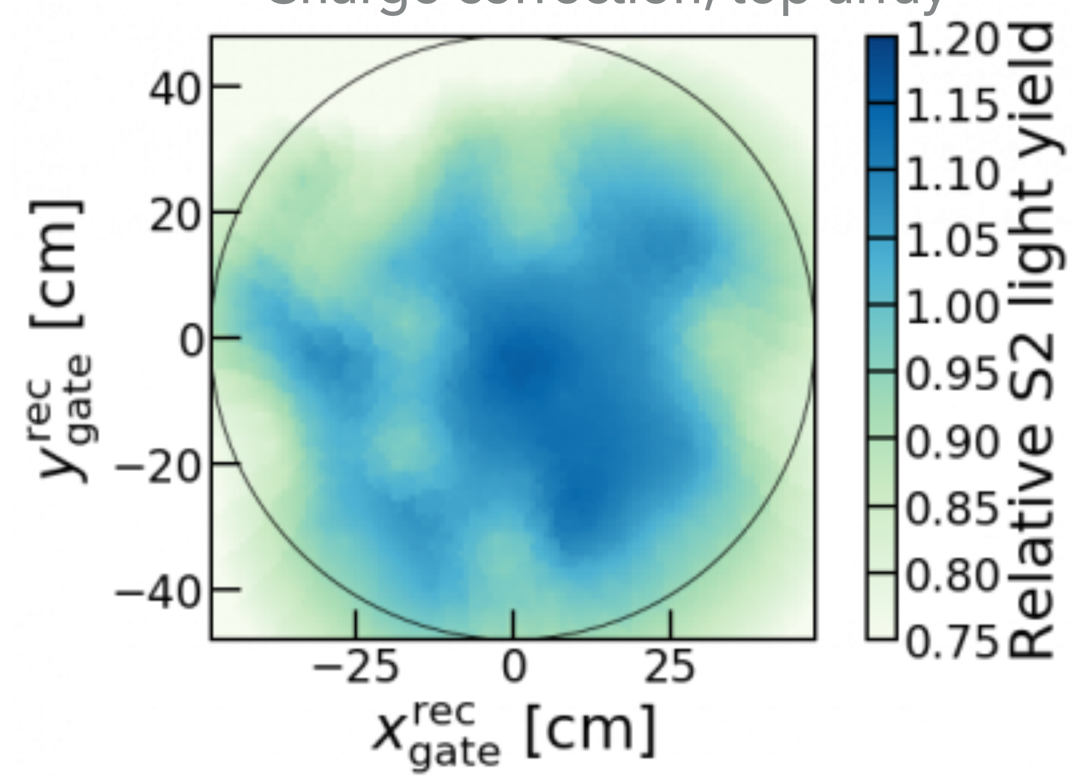
Charge correction, bottom array




Light collection efficiency correction

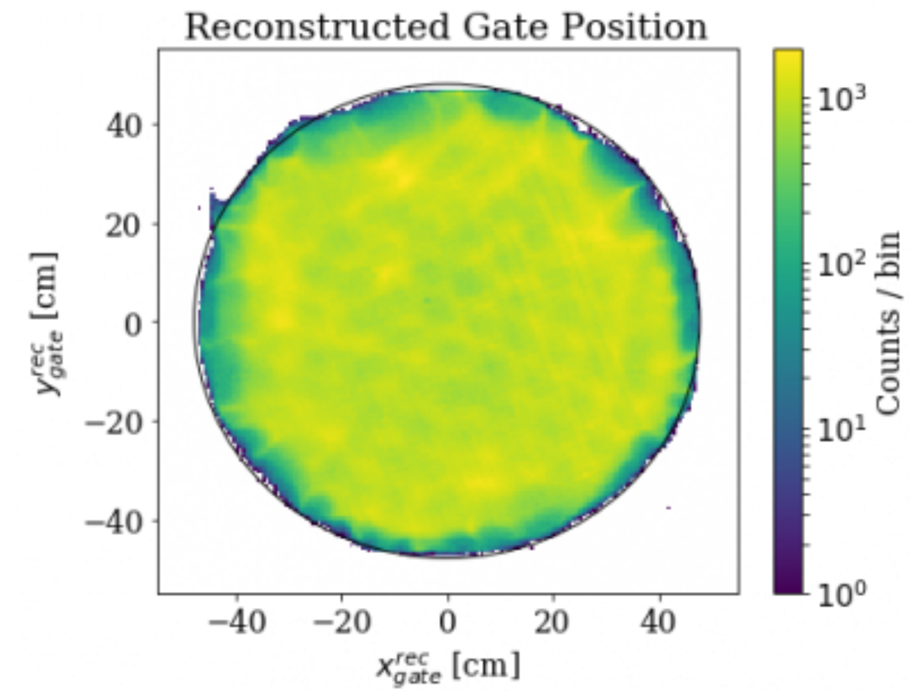


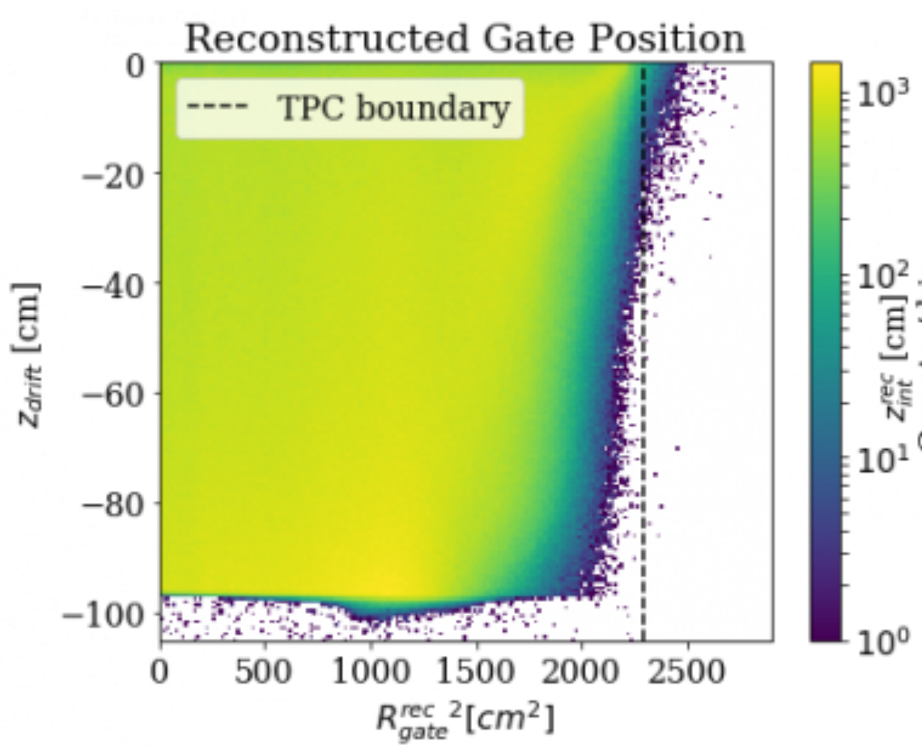

Charge correction, top array

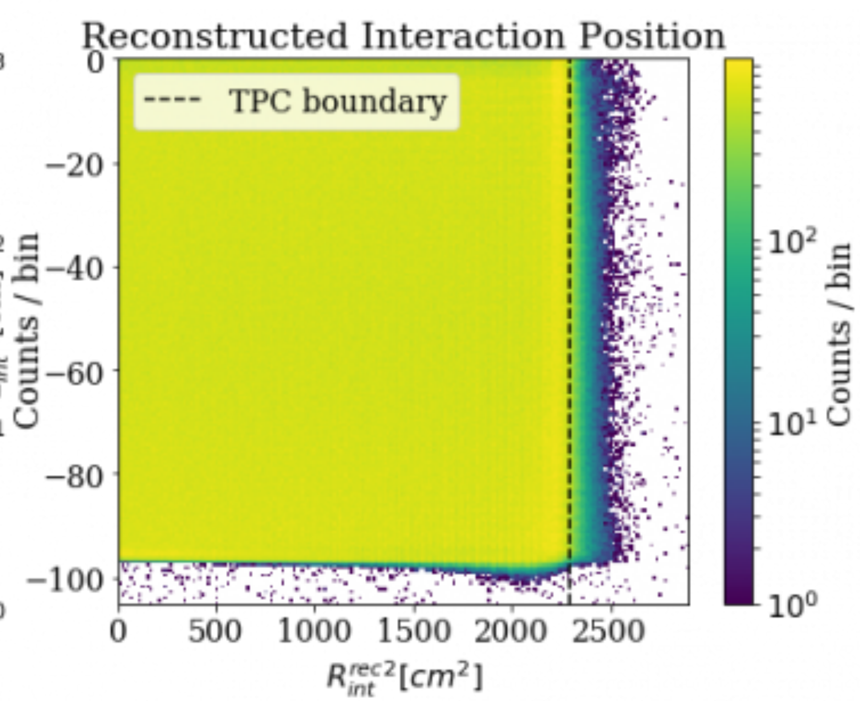


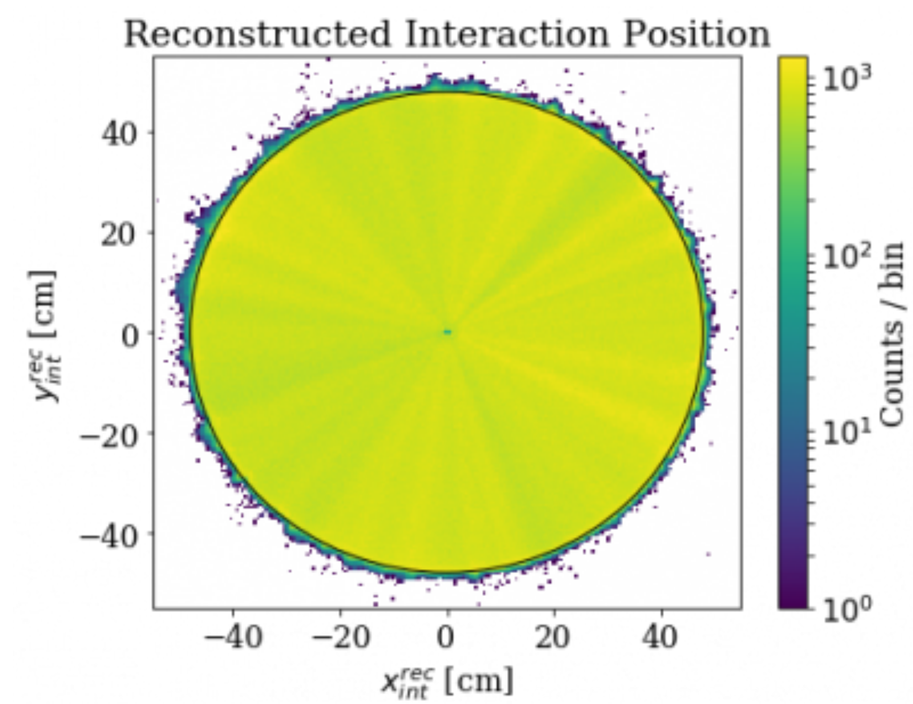
# POSITION RECONSTRUCTION & CORRECTION

- Here shown using $^{83m}$Kr data
- Reconstructed positions at gate and interaction positions, as determined via artificial NN algorithms (x-y resolution: 1-2 cm)
- Shown are positions before & after corrections



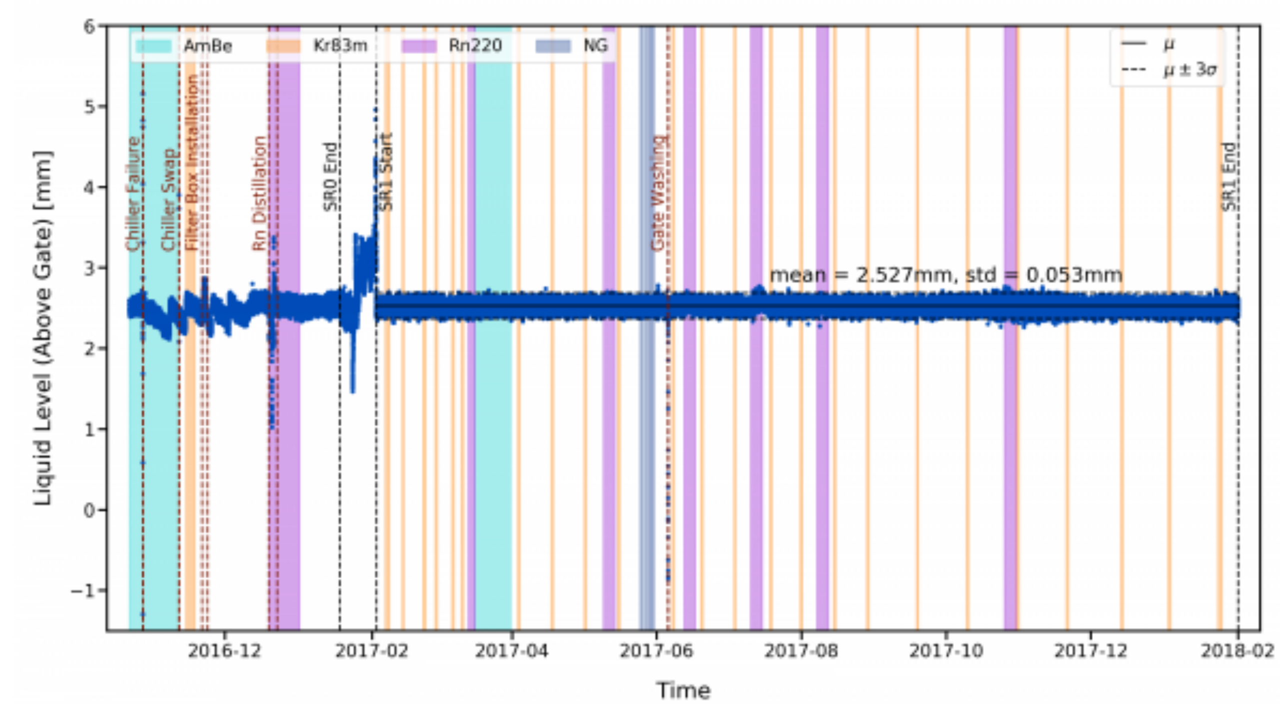



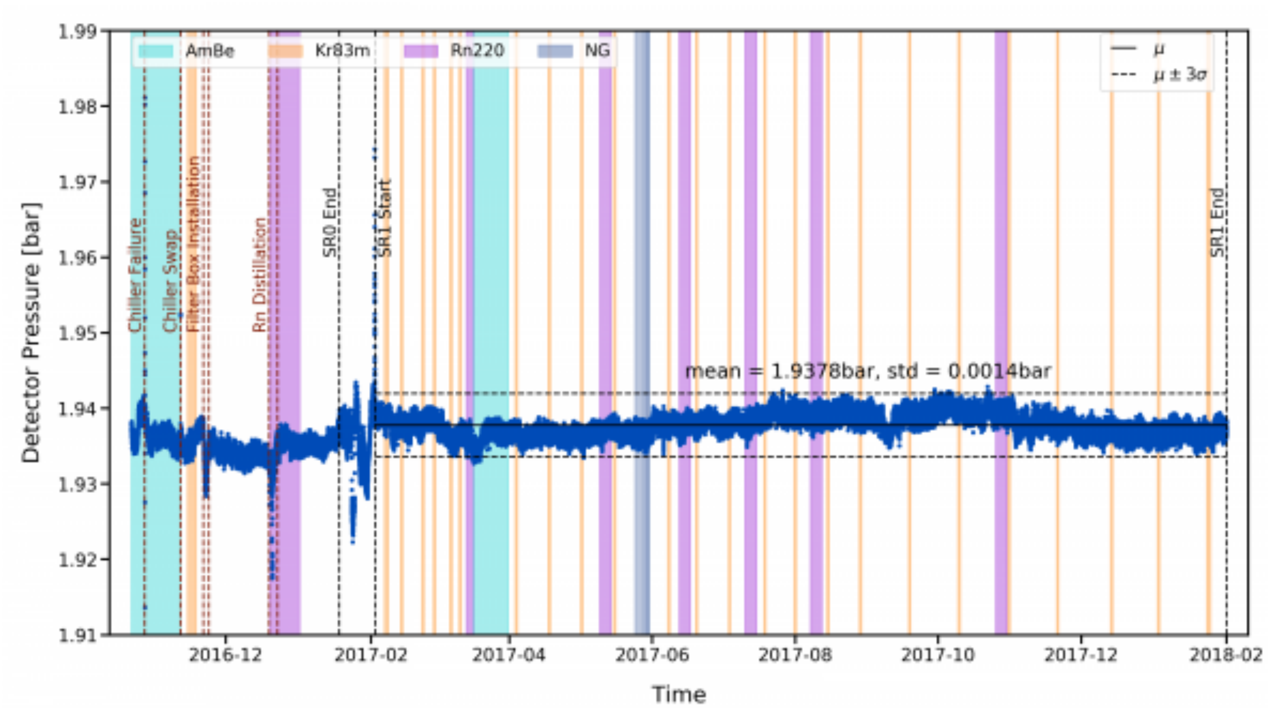



# DETECTOR STABILITY

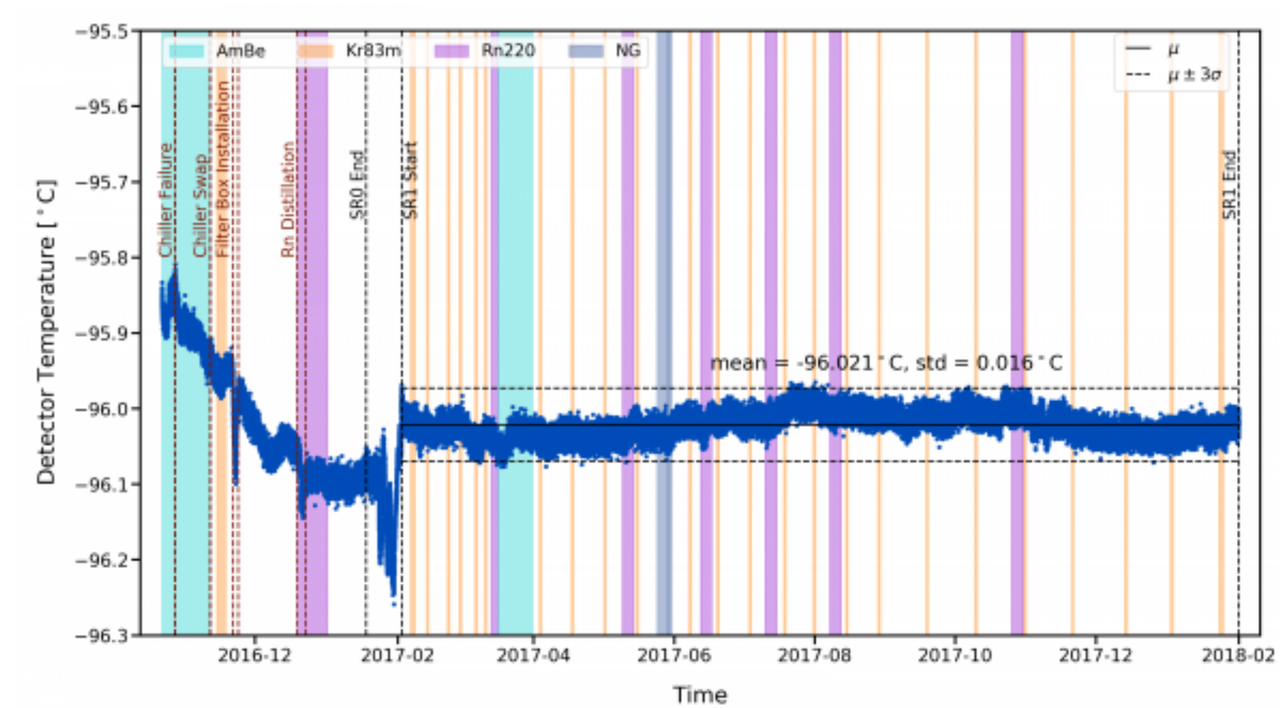
- The TPC pressure (1.94 bar), temperature (-96°C) and liquid xenon level (2.5 mm above gate) were stable during normal operation

Liquid xenon level in mm above gate



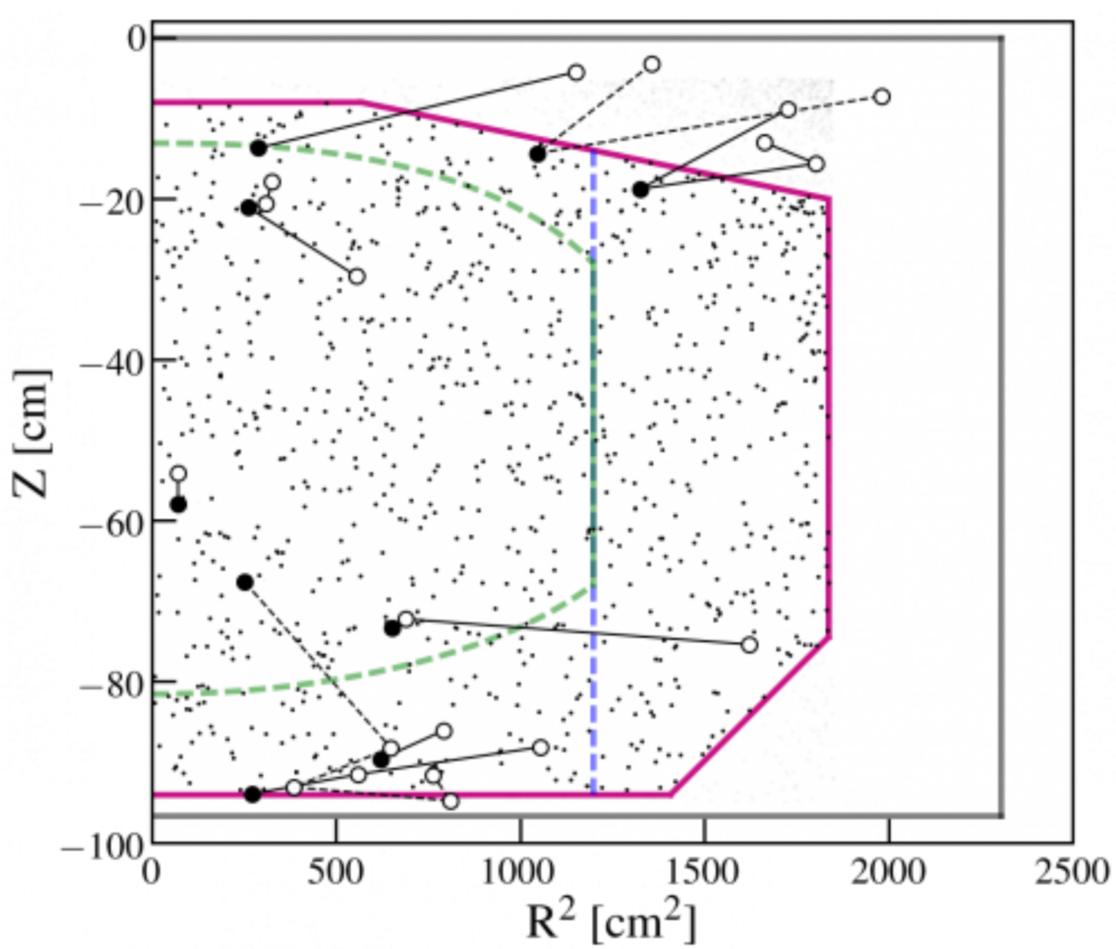

Pressure in the TPC

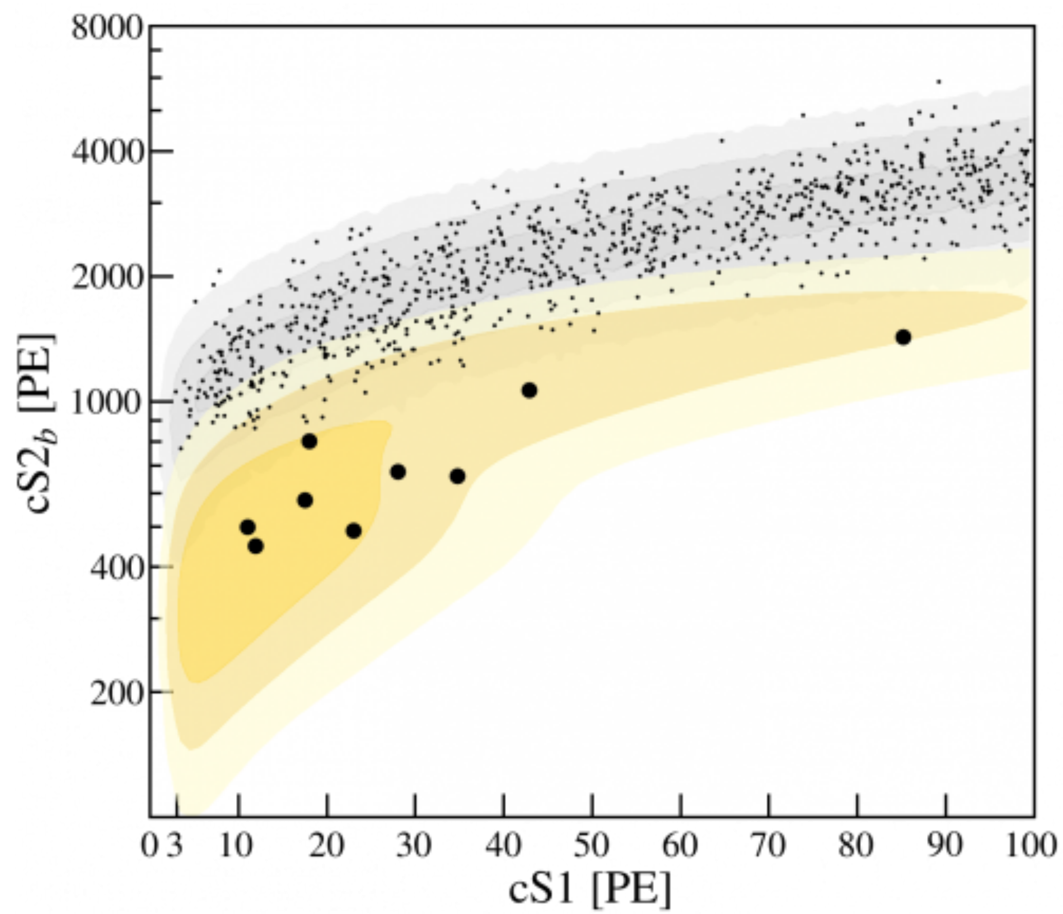



Temperature in the TPC

# MULTIPLE SCATTERS

- Expected rate of MS: about 5 x higher than single scatters
- Data: 9 candidates; MC prediction: (6.4±3.2) events
- Used to constrain the number of expected single scatter in the data

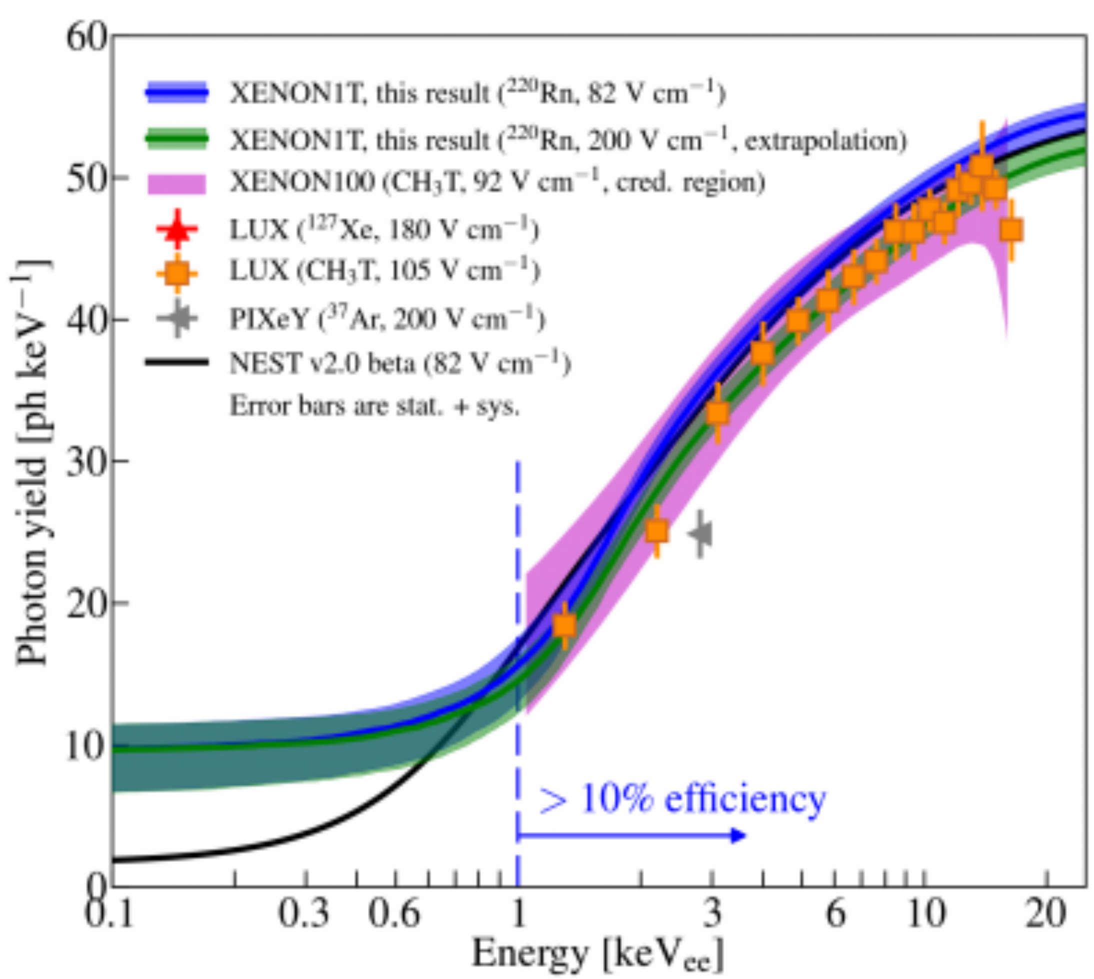


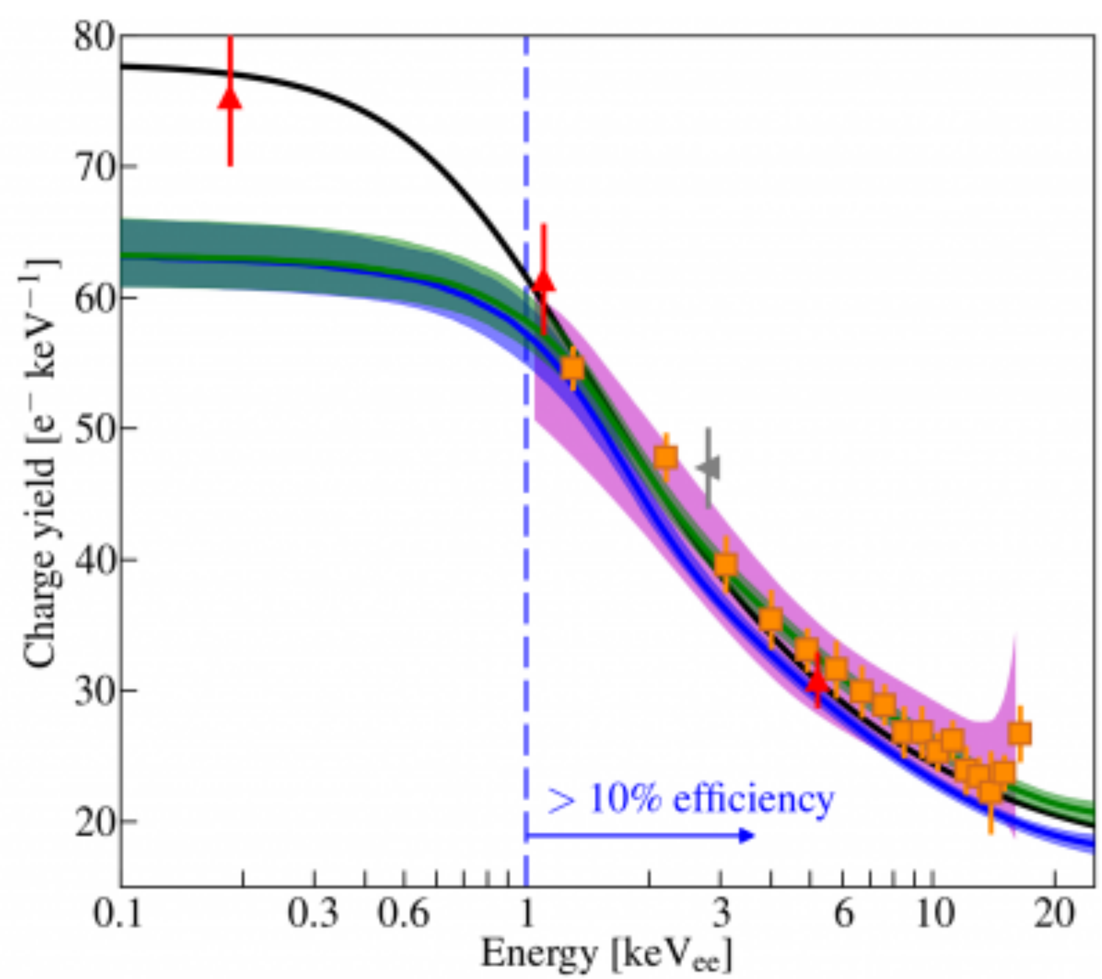
# MODELLING THE LIGHT AND CHARGE YIELD

- Electronic recoil photon and charge yields [0.1, 25] $keV_{ee}$
- XENON1T best-fit (SR1) together with other experiments (LUX, XENON100) and NEST predictions

Photon yield



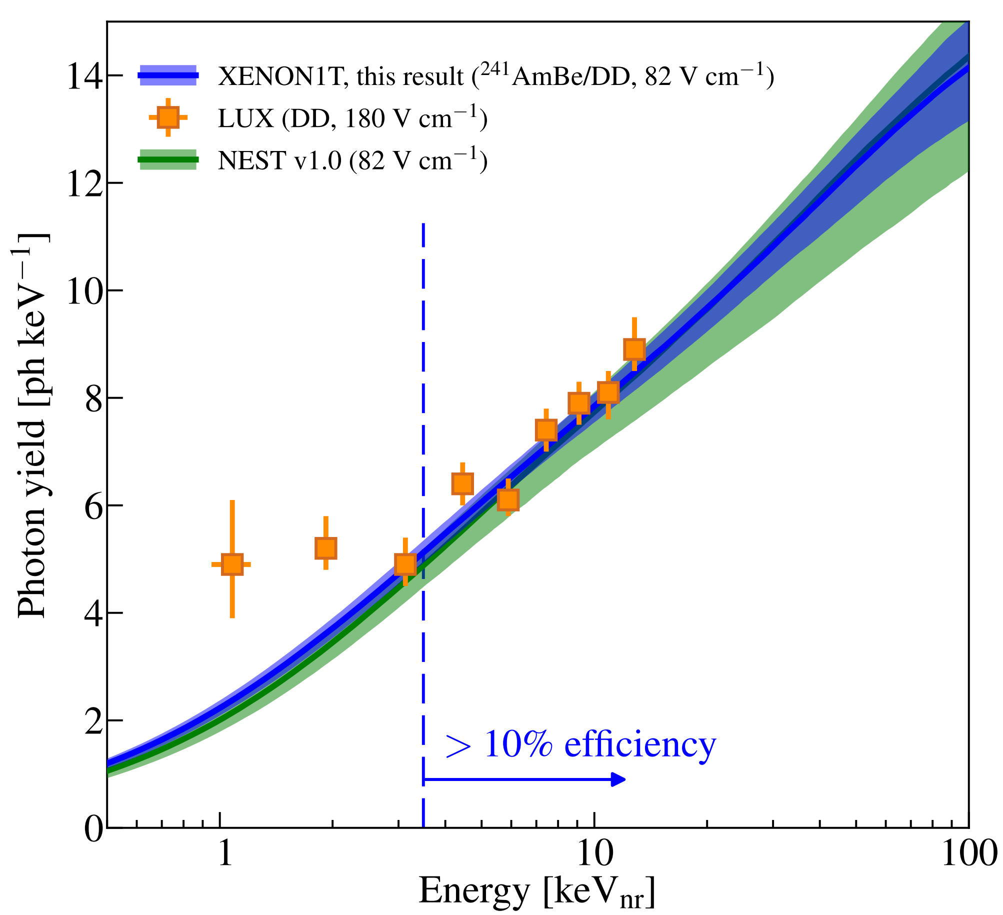

Charge yield



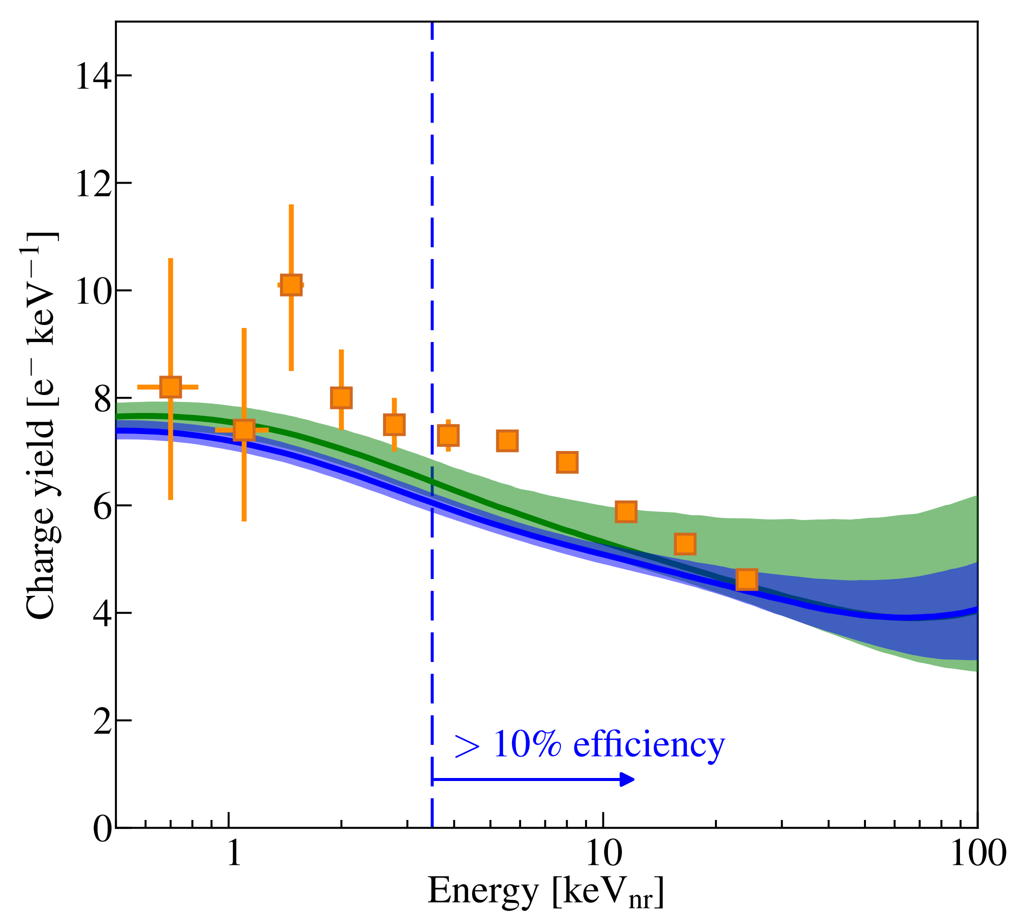
# MODELLING THE LIGHT AND CHARGE YIELD

- Nuclear recoil photon and charge yields [0.5, 100] $keV_{nr}$
- XENON1T best-fit (SR1) together with LUX and NEST predictions

Photon yield




Charge yield

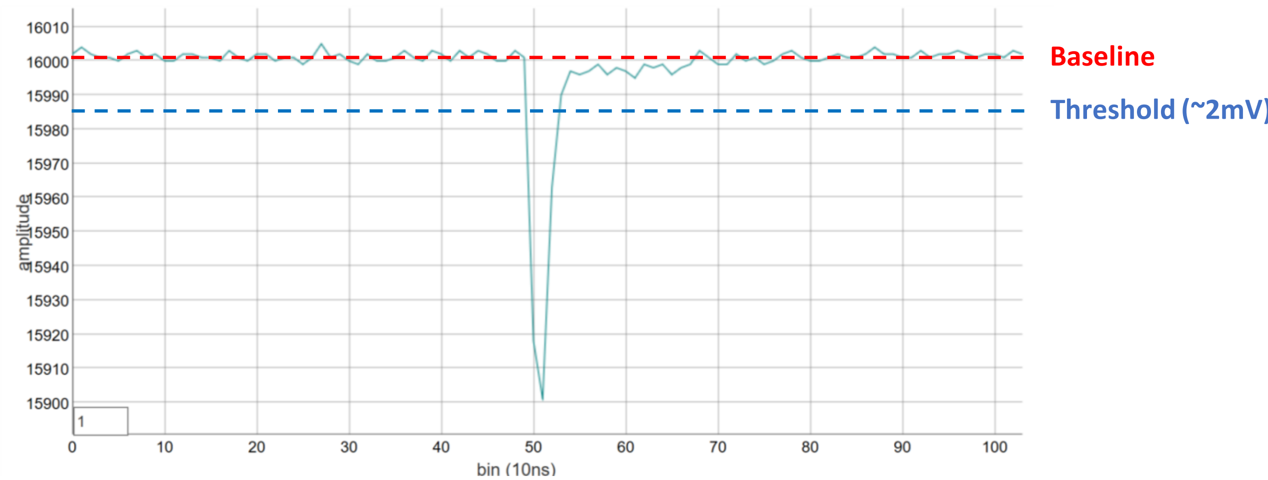


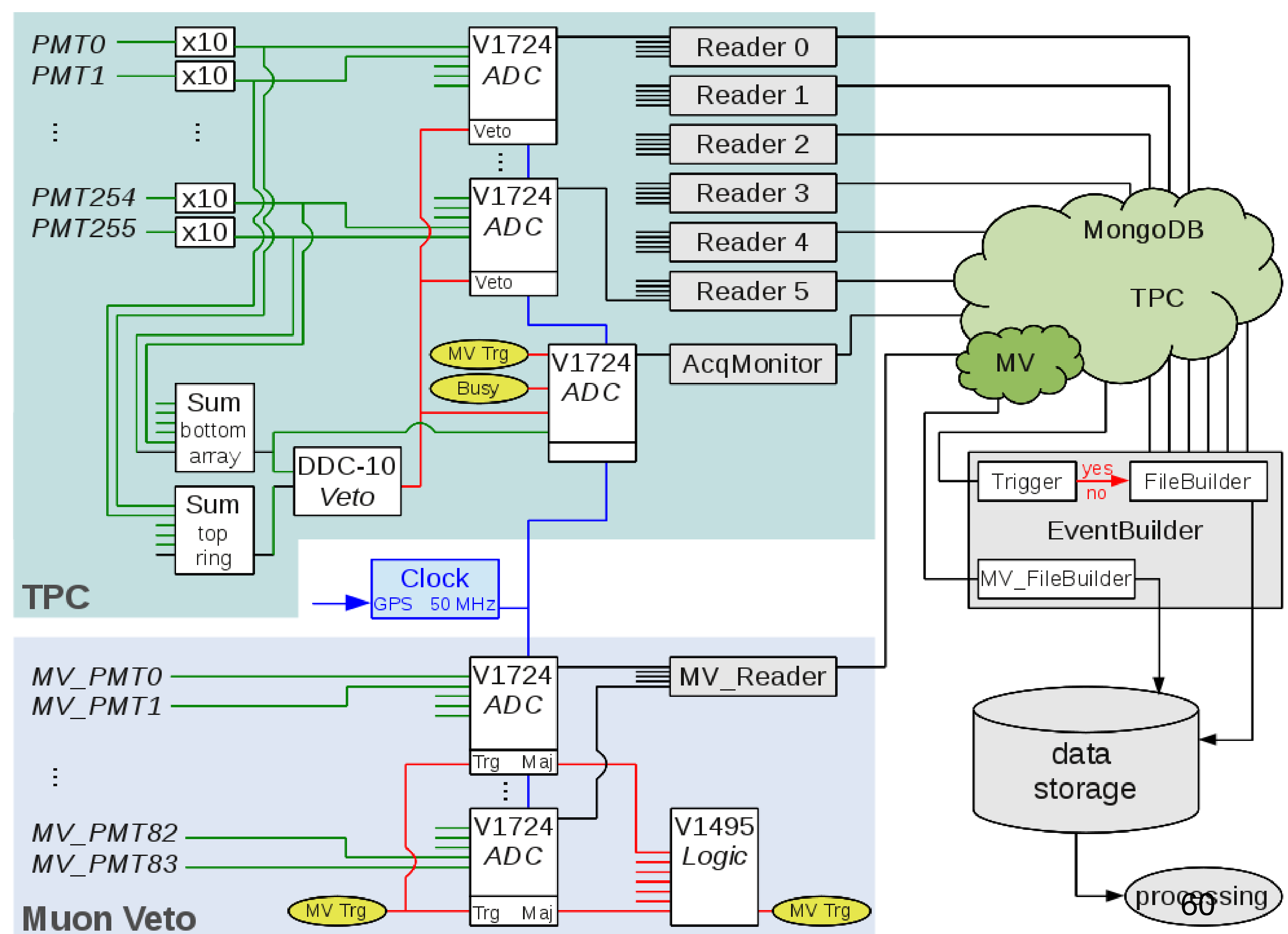
# BACKGROUND RATES IN TIME

- The $^{222}$Rn induced rates are stable in time
- Shown are the α-rates from $^{222}$Rn, $^{218}$Po and the $^{214}$BiPo β-α coincidence rate
- These give upper & lower limits on the $^{214}$Pb (naked β-decay, largest contribution to the ER rate uniformly distributed in the TPC)

# The Data Acquisition System

- PMT signals: amplified x 10, and digitised by 100 MHz flash ADCs with 14 bit resolution
- Every TPC pulse > 0.33 PE is recorded
- 6 computers read out the 32 ADCs in parallel, at max rate of 300 MB/s (1 kHz in calibration mode)
- Time-stamped digitised pulses are stored in MongoDB
- A multi-core machine groups the data into causally connected events and stores to file
- Various software trigger configurations are available



DARWIN

European Research Council
Established by the European Commission

# darwin-observatory.org

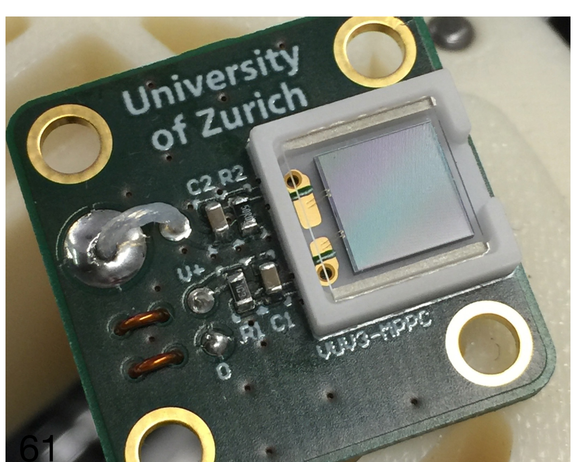
DARWIN collaboration, JCAP 1611 (2016) 017

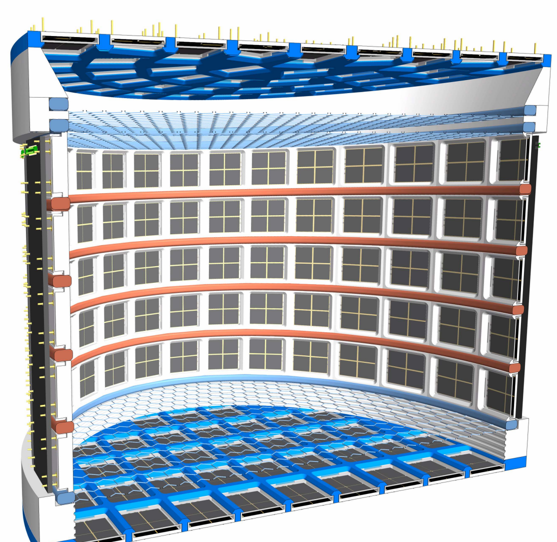
## “Ultimate” WIMP detector

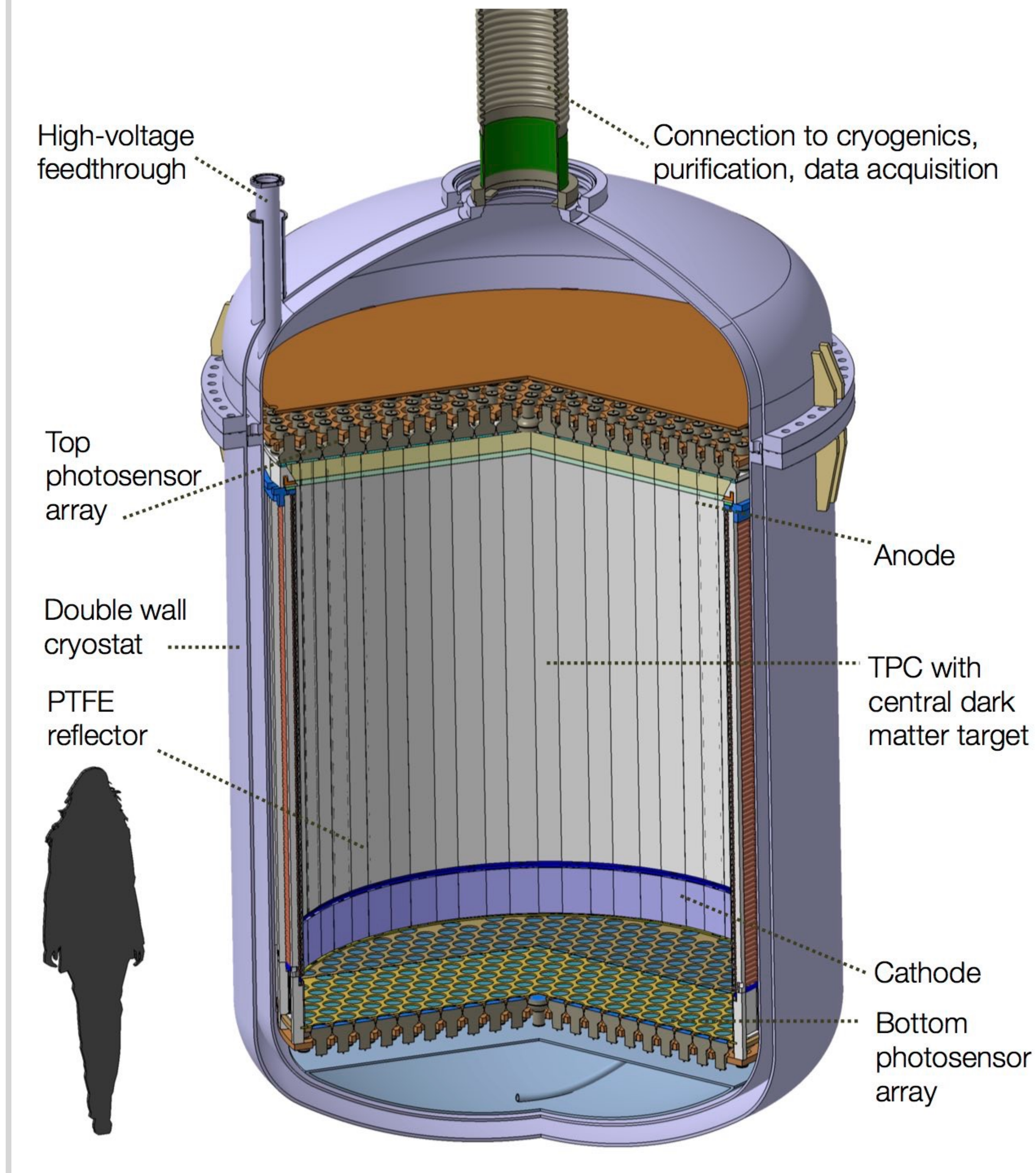
---

50 tonnes liquid xenon

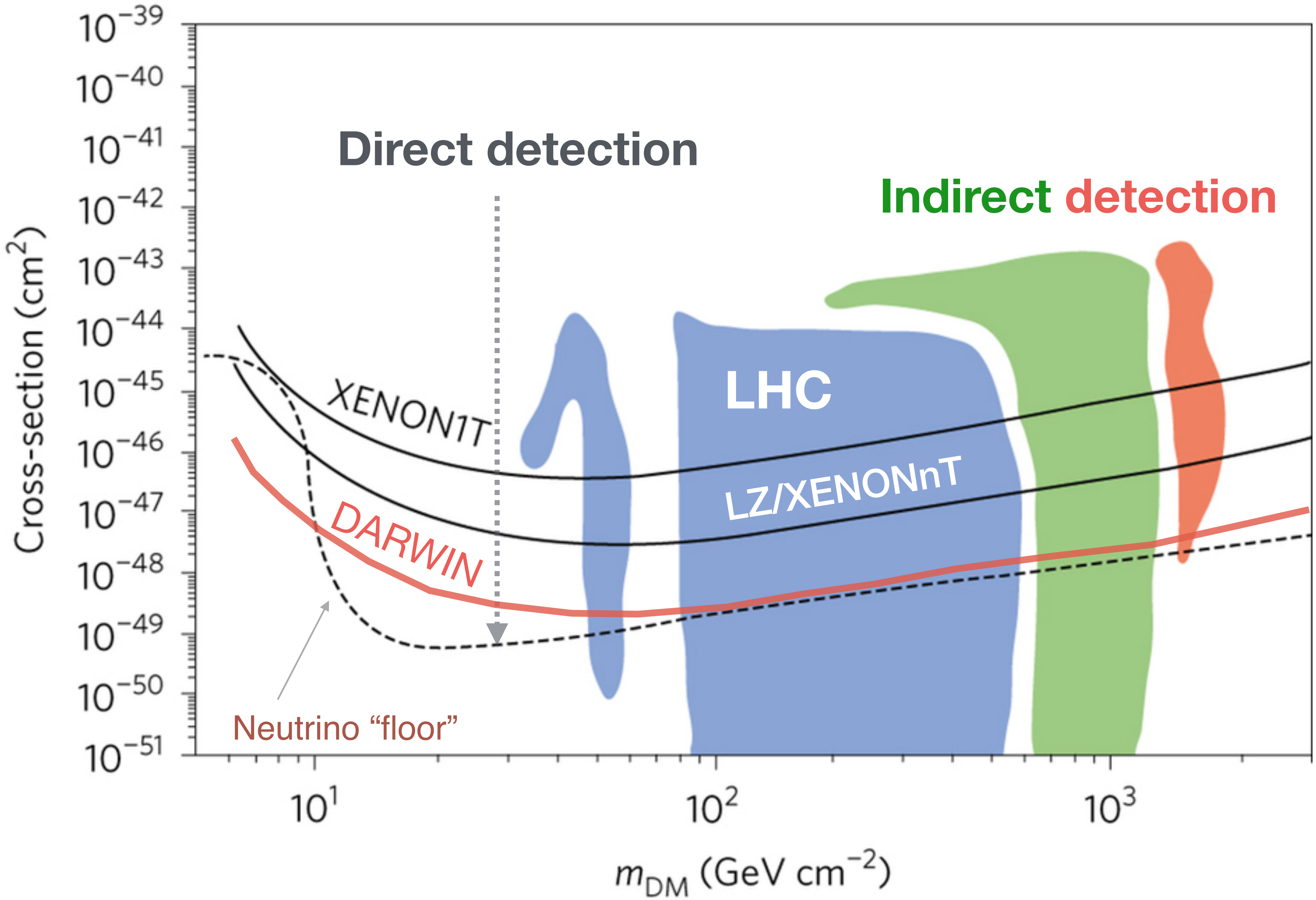
R&D and prototypes supported by two ERC grants: Ultimate (Freiburg) and Xenoscope (Zürich)





# WIMP Physics: Direct, indirect detection, and LHC




**After Nature physics, March 2017**

# Direct detection versus time

- Sensitivity: about a factor of 10 increase every ~ 2 years