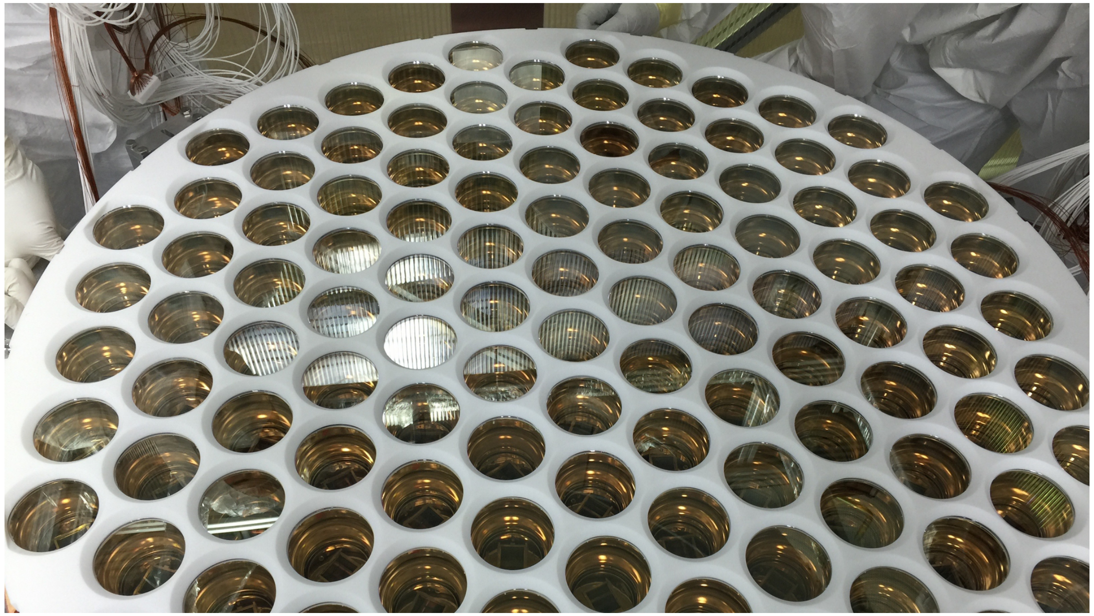
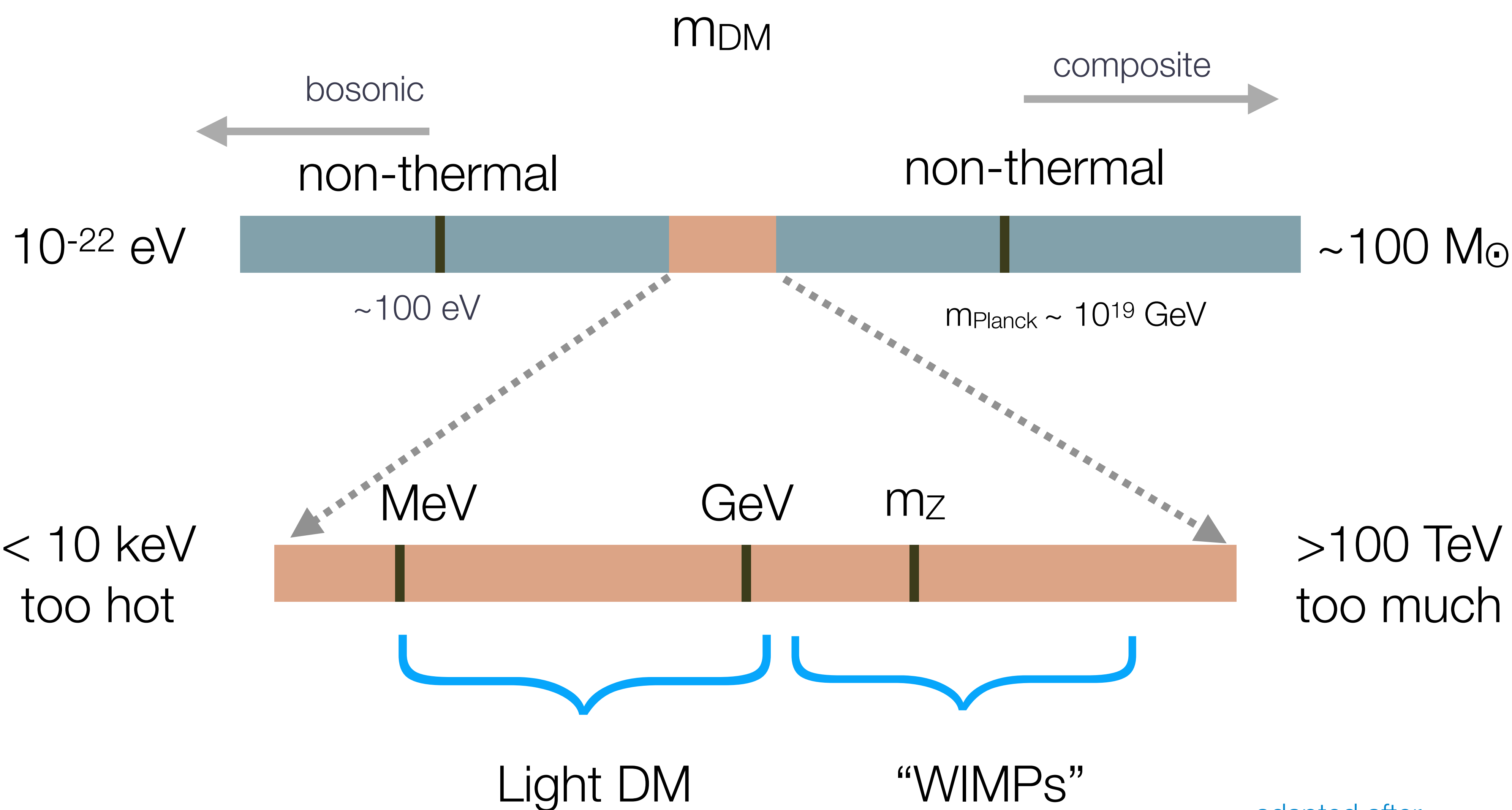
Searching for Dark Matter with the XENON1T Experiment

Laura Baudis
University of Zurich

Caltech HEP seminar
April 23, 2018

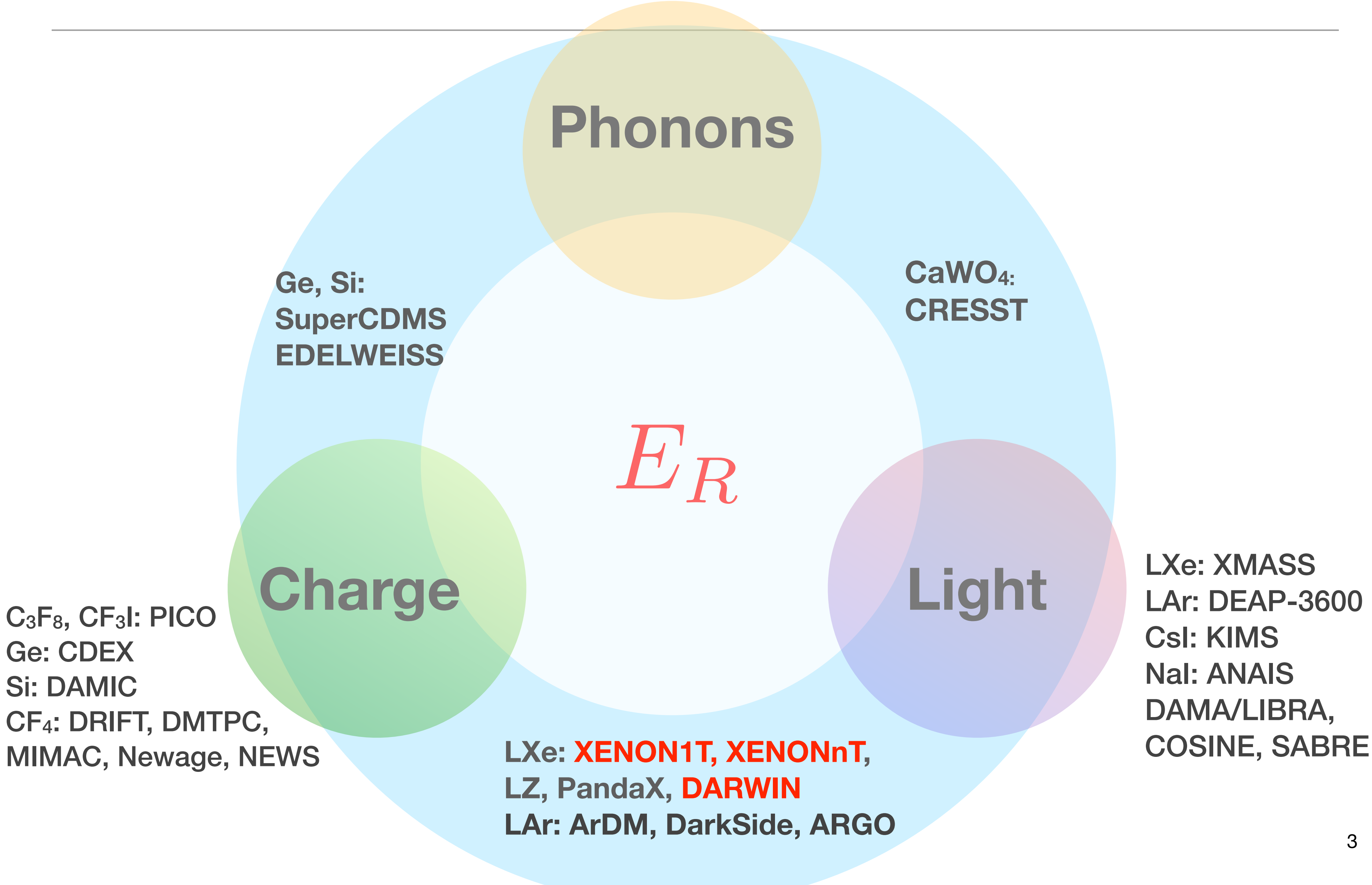


Dark Matter Candidates

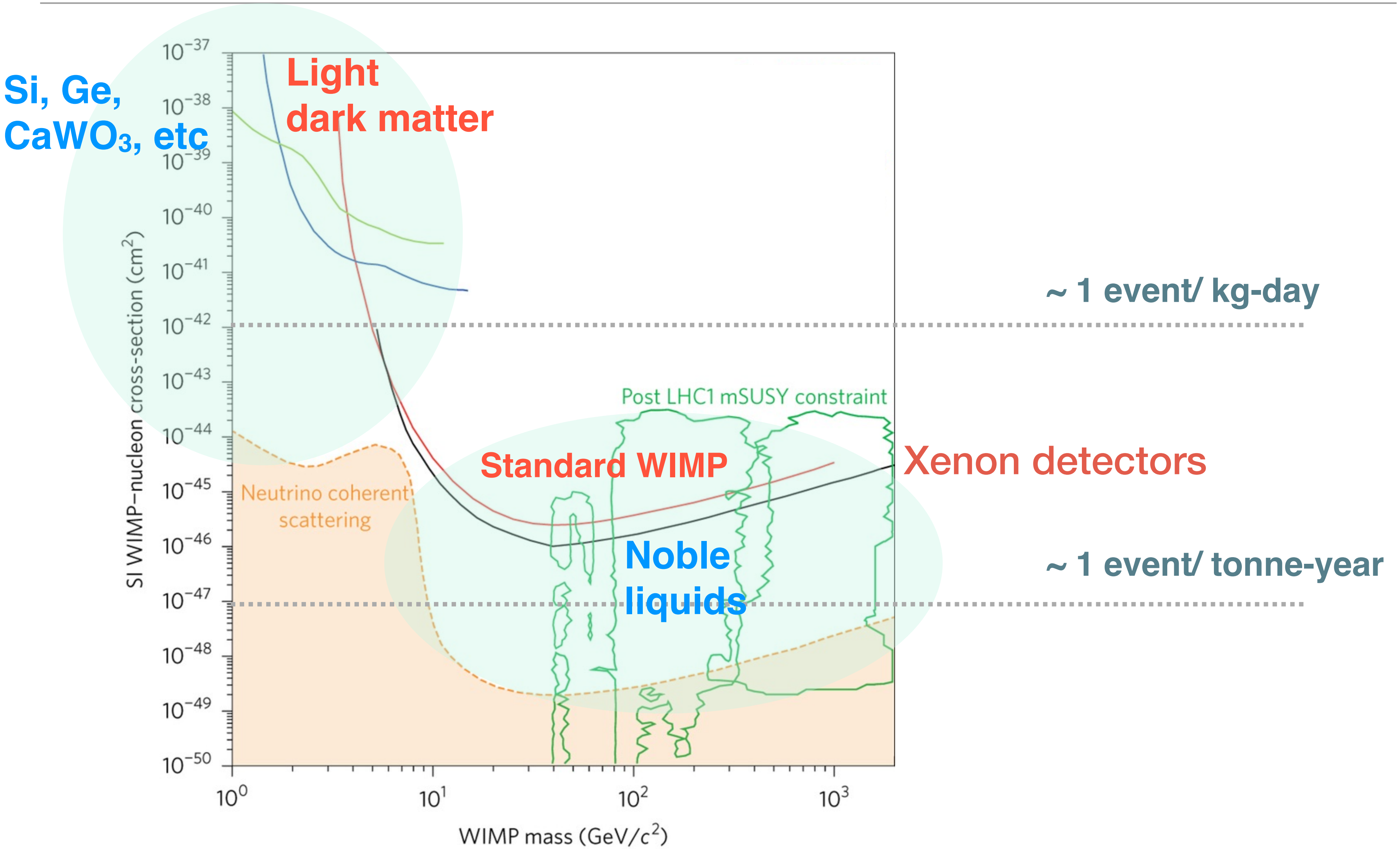


adapted after
Brian Batell,
Invisibles2017

Direct Detection Experiments



The WIMP landscape ~one year ago



Nature physics, March 2017

WIMP physics with xenon nuclei

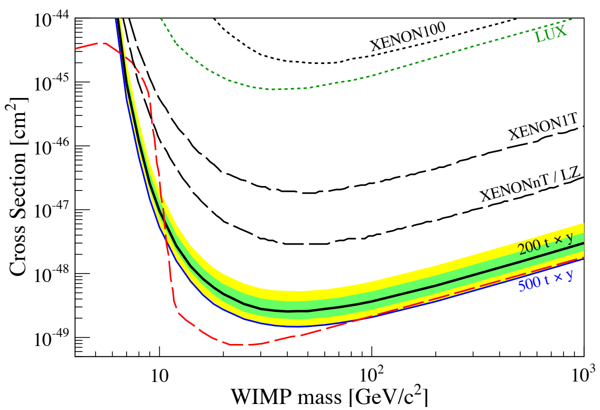
Probe WIMP-Xe interactions via:

- spin-independent elastic scattering: ^{124}Xe, ^{126}Xe, ^{128}Xe, ^{129}Xe, ^{130}Xe, ^{131}Xe, ^{132}Xe (26.9%), ^{134}Xe (10.4%), ^{136}Xe (8.9%)
- spin-dependent elastic scattering: ^{129}Xe (26.4%), ^{131}Xe (21.2%)
- inelastic WIMP-^{129}Xe and WIMP-^{131}Xe scatters $\chi + {}^{129,131}Xe \rightarrow \chi + {}^{129,131}Xe^{*} \rightarrow \chi + {}^{129,131}Xe + \gamma$

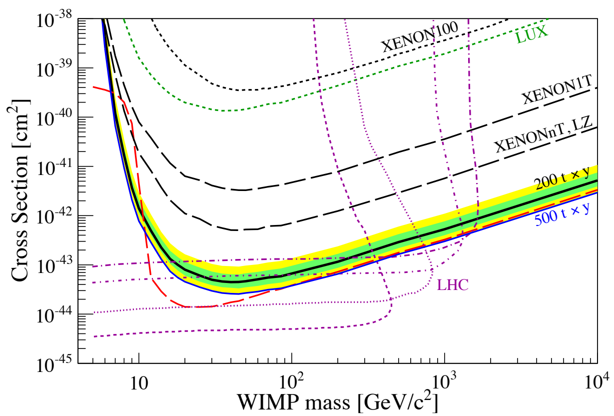
1 ns, 0.5 ns

40 keV, 80 keV

SI, elastic WIMP-nucleus

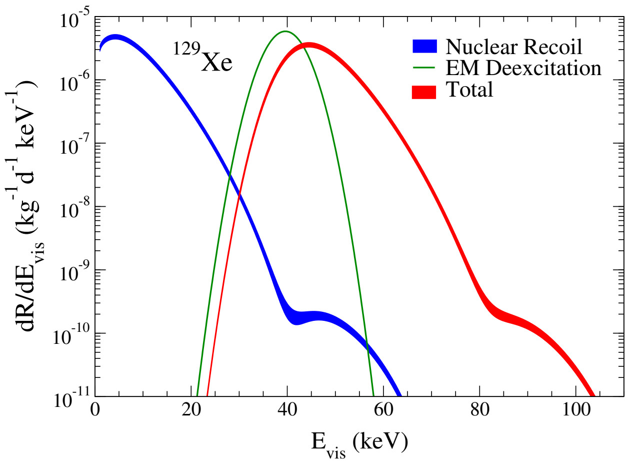


SD, elastic WIMP-nucleus



M. Schumann et al., JCAP10 (2015) 016

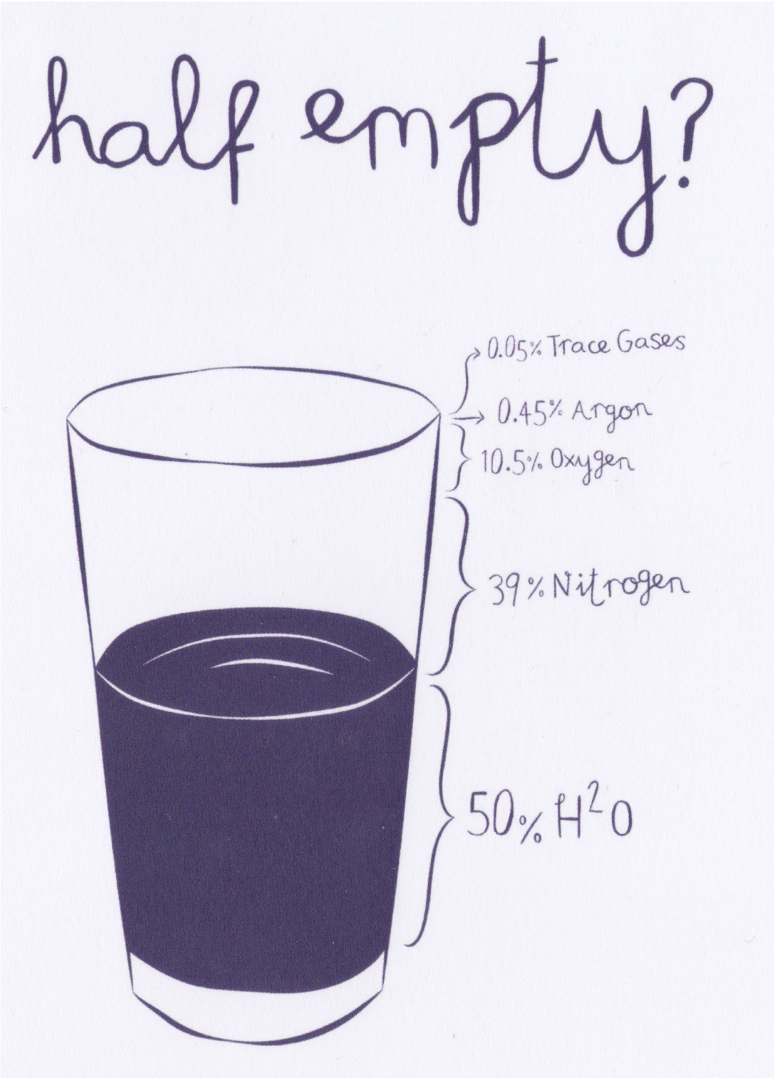
SD, inelastic WIMP-nucleus

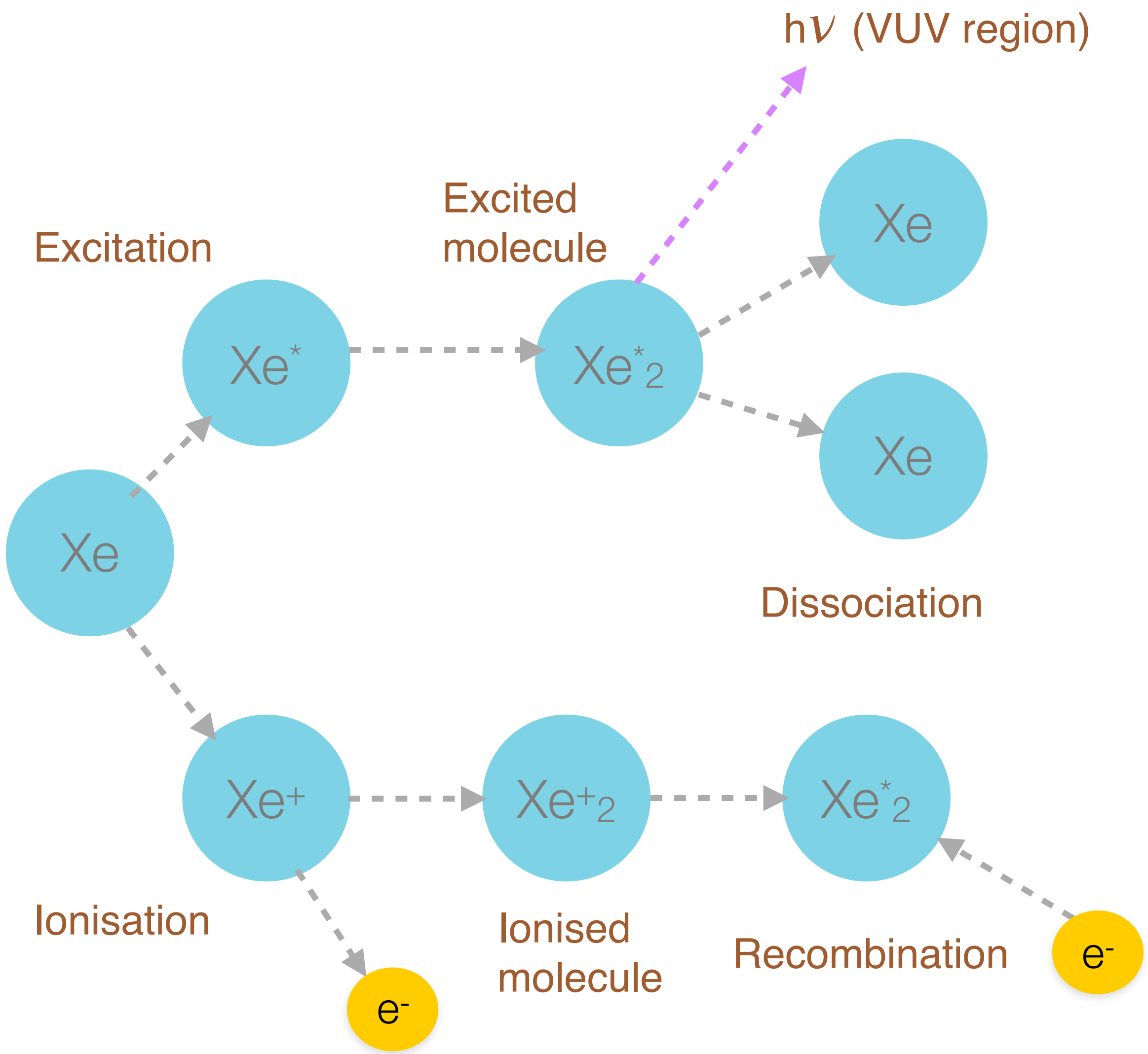


L. Baudis et al, Phys. Rev. D 88, 115014 (2013)

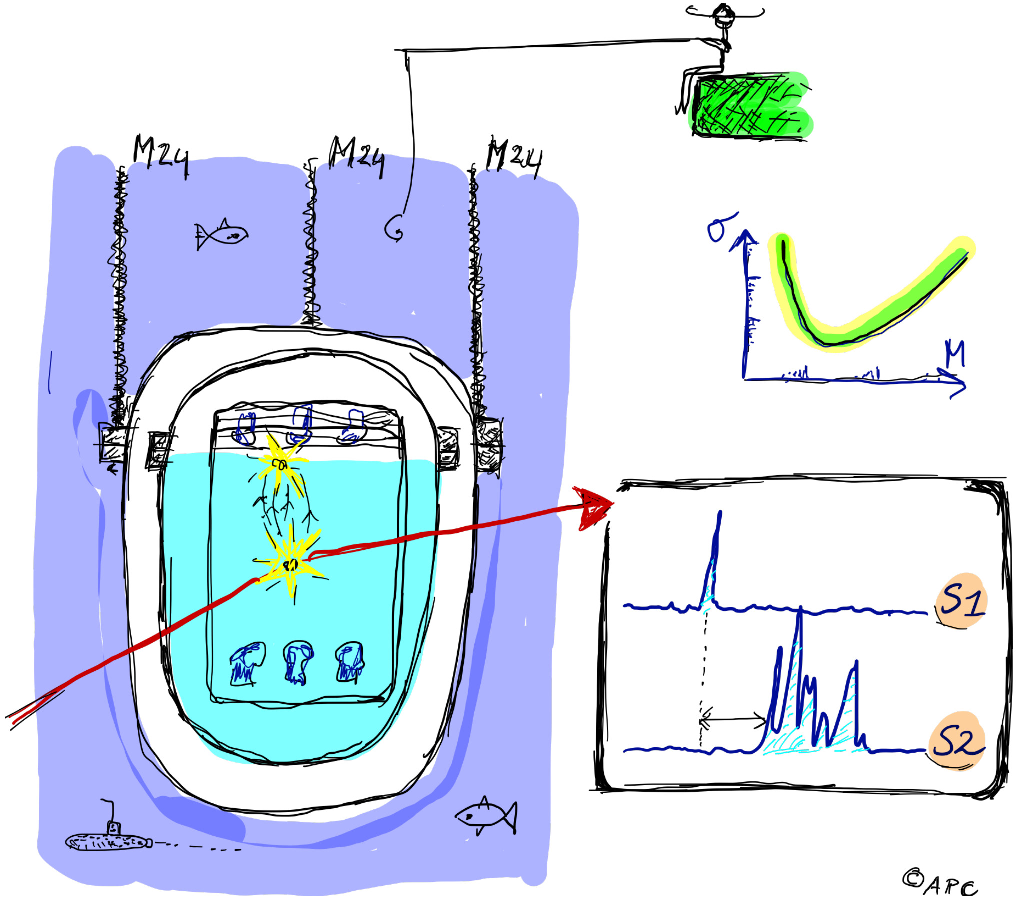
Liquefied xenon

- "The strange one"





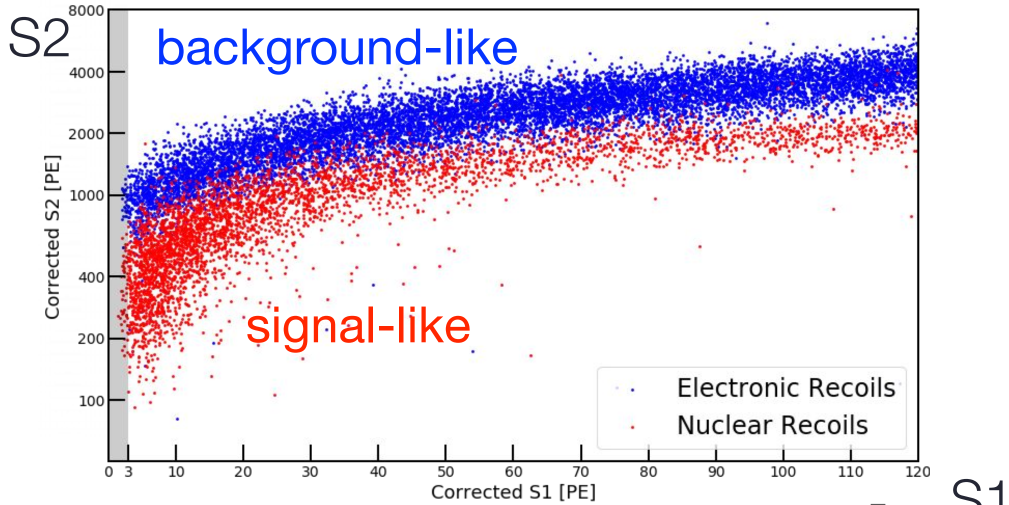
Two-phase xenon projection chambers



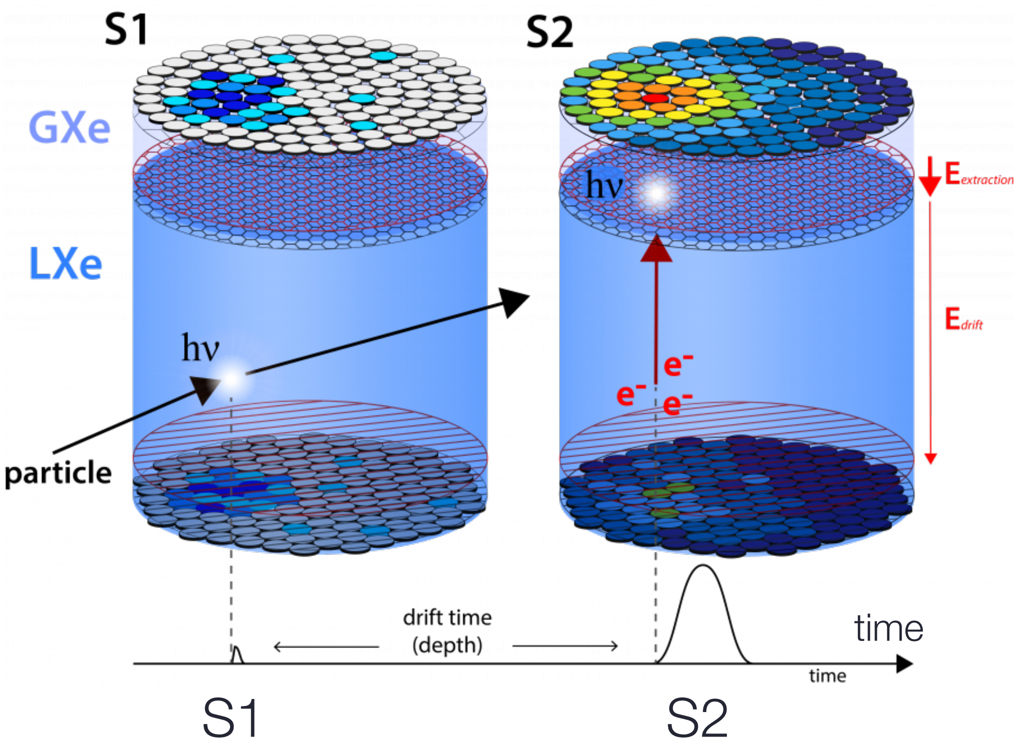
XENON100

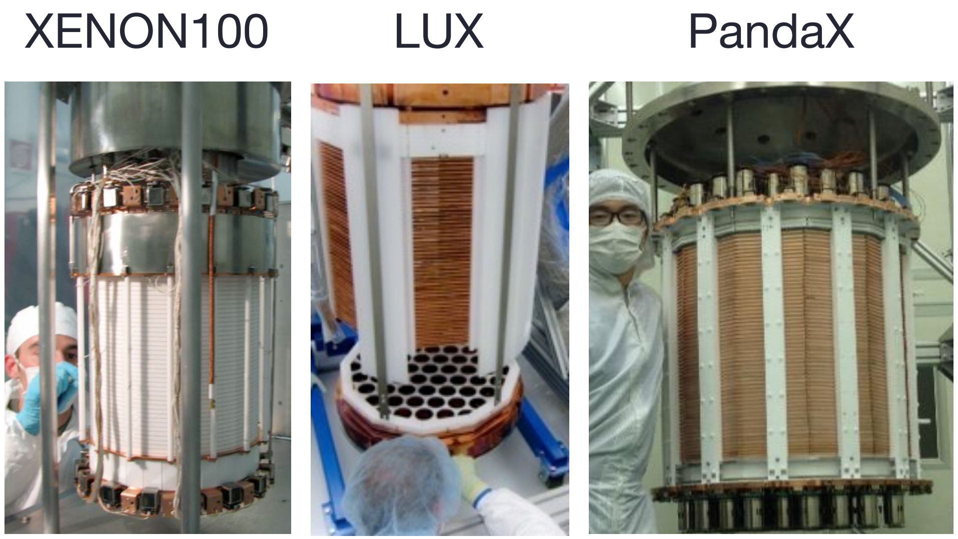
LUX

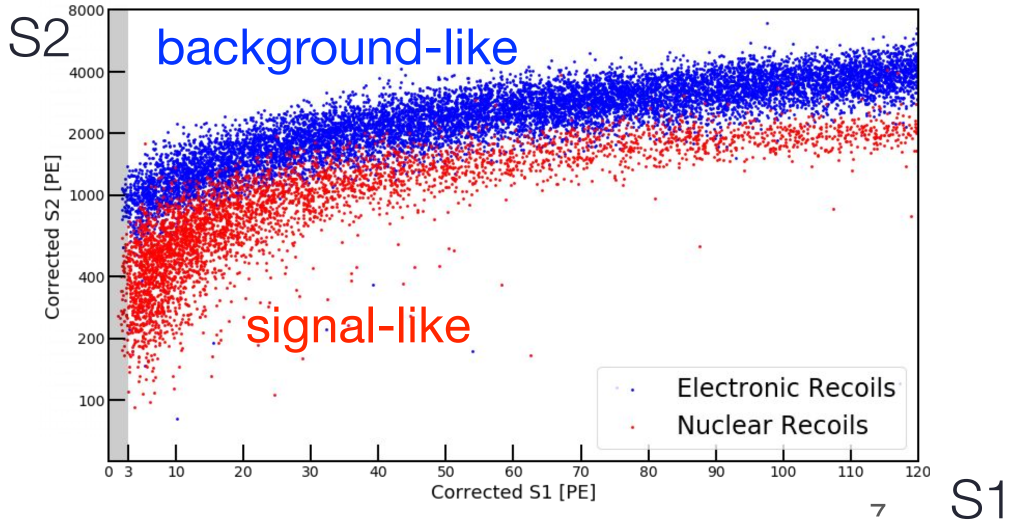
PandaX



Two-phase xenon projection chambers



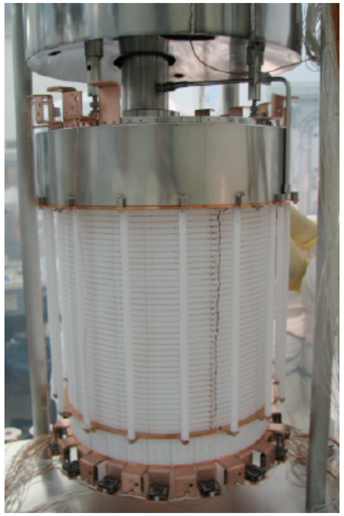




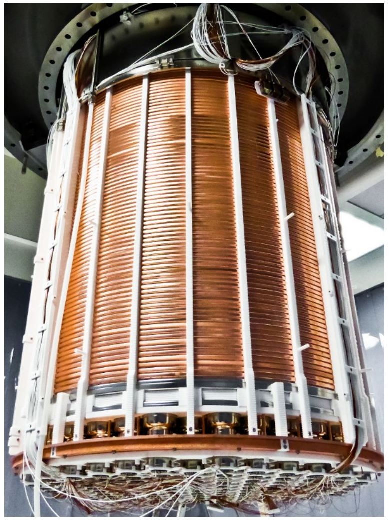
The XENON (and DARWIN) timeline

XENON10

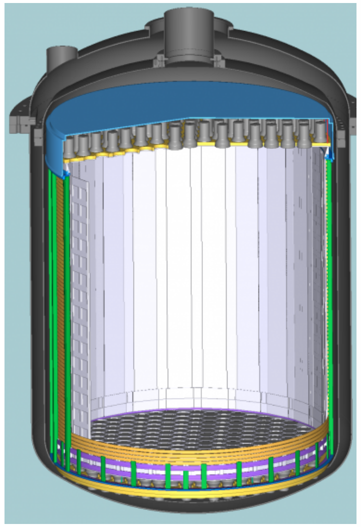
XENON100



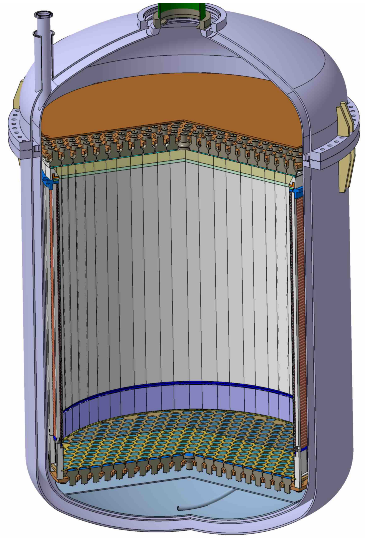
XENON1T



XENONnT

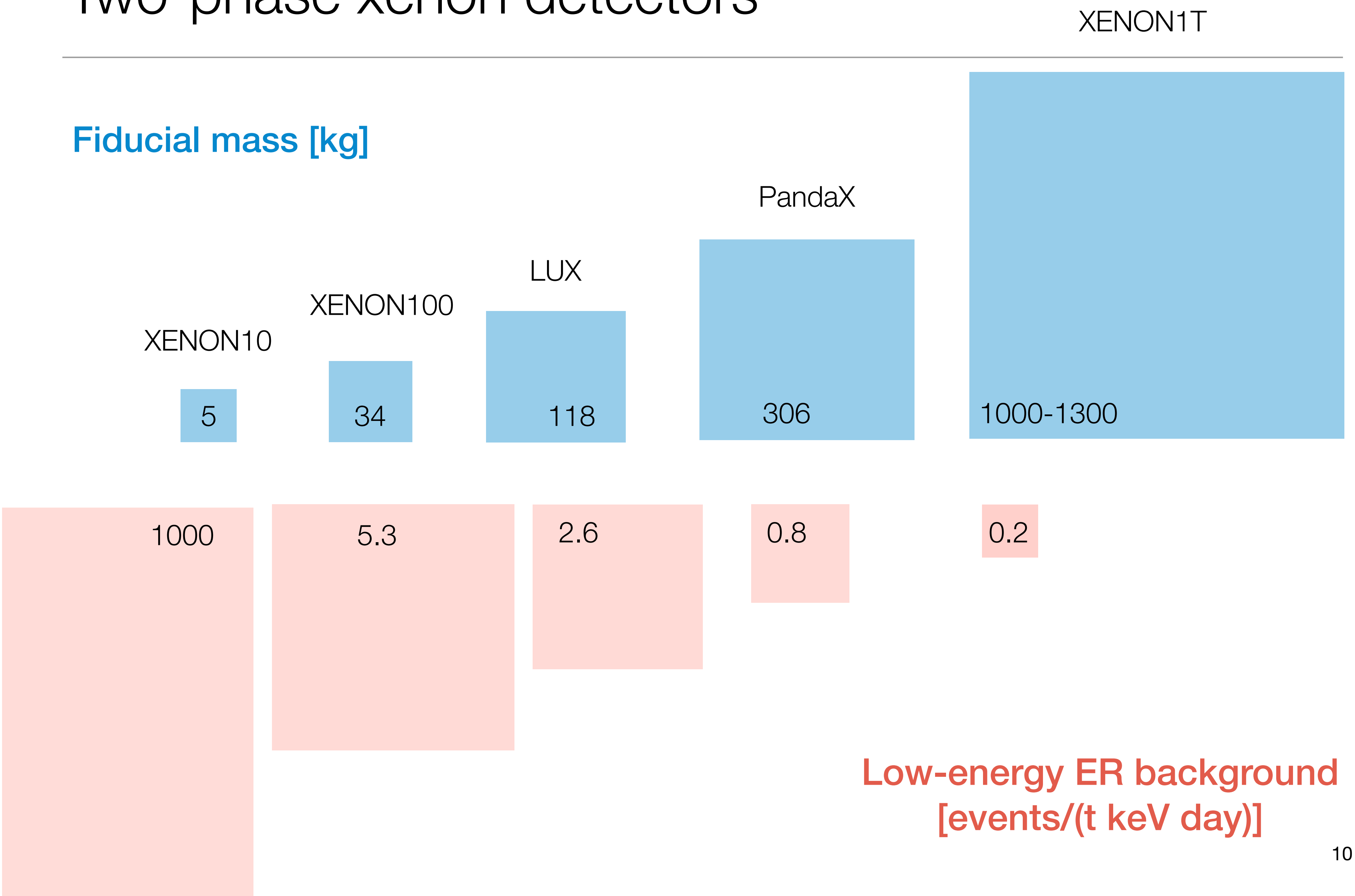


DARWIN

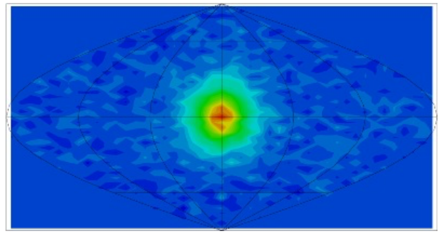


2005-2007	2008-2016	2012-2018	2019-2023	2020+
15 kg	161 kg	3200 kg	8000 kg	50 tonnes
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2	$\sim 10^{-49}$ cm^2

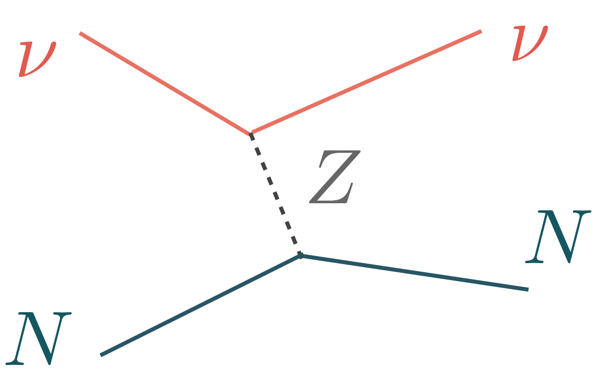
Two-phase xenon detectors

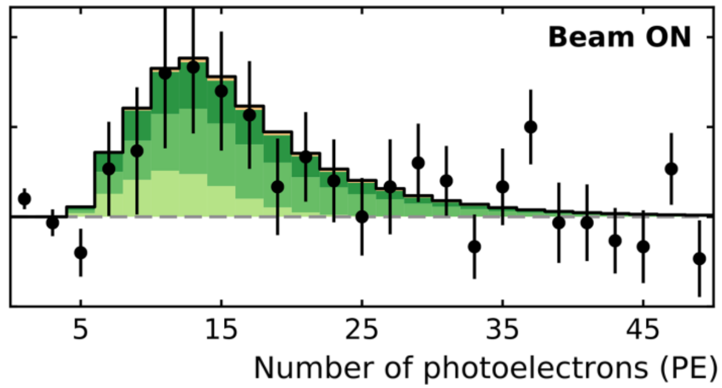


Backgrounds



- Ideally below the expected signal (< 1 event/exposure)
  - Muons & associated showers; cosmogenic activation of detector materials
  - Natural and anthropogenic radioactivity
  - Neutrinos! *Coherent neutrino-nucleus scattering exists*

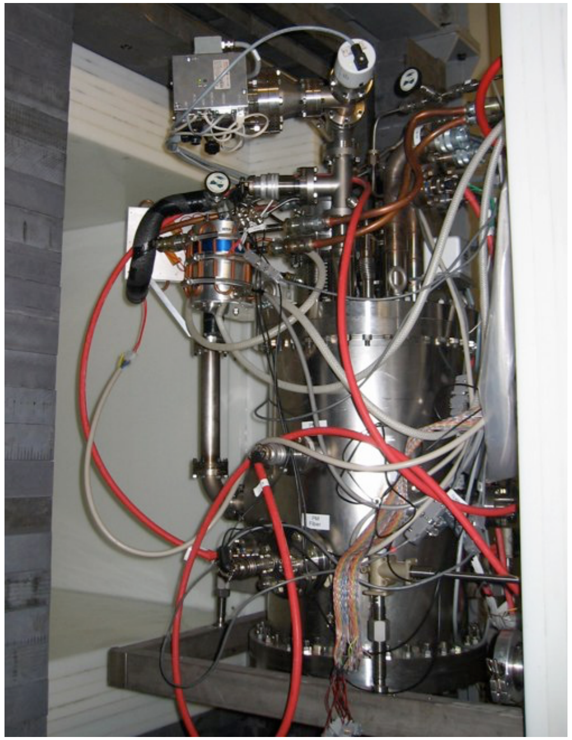




COHERENT, Science, August 3, 2017

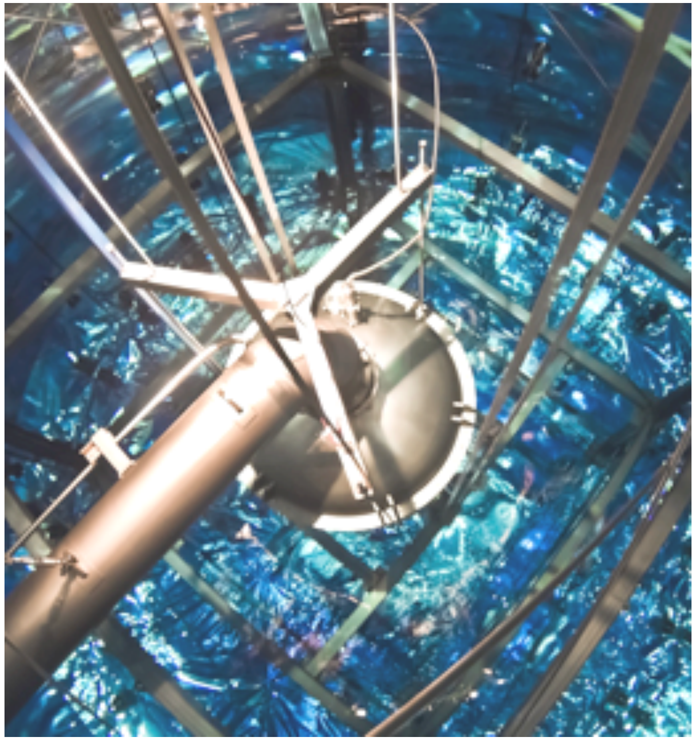
From XENON10 to XENON1T/nT

XENON10



XENON100

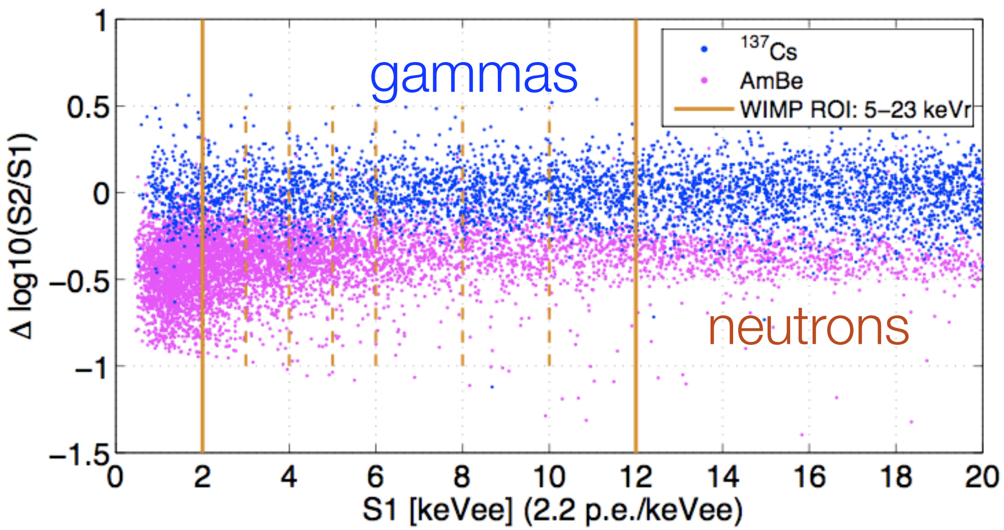
XENON1T/nT



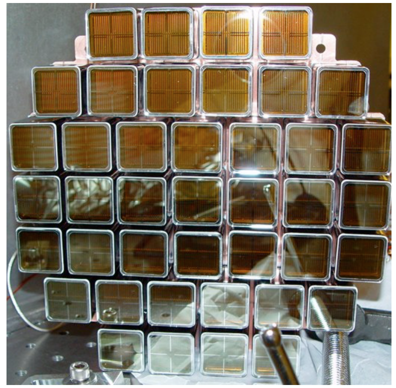
XENON10/XENON100: conventional shield, onion-like structure

XENON1T/nT (& DARWIN): large water Cherenkov shields

The XENON10 experiment: 2005-2007



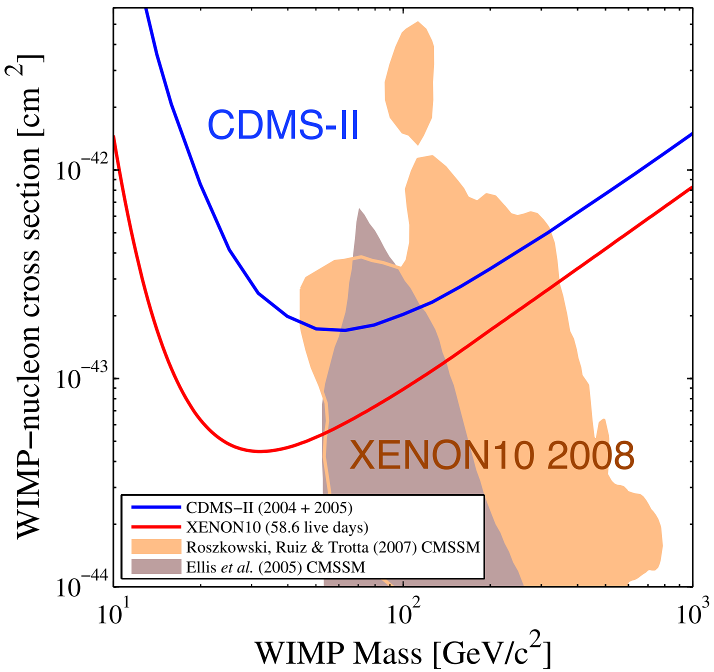
- 22 kg LXe in total
- 20 cm diam, 15 cm drift
- 89 1-inch PMTs
- 0.73 kV/cm drift field



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]



The XENON100 experiment: 2008-2016

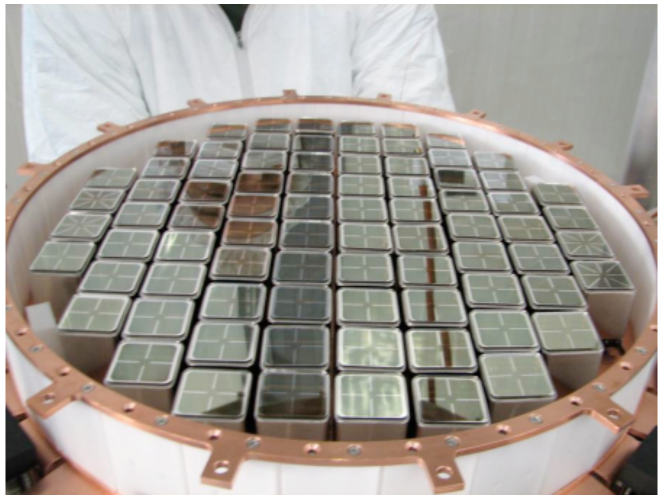
- Double phase time projection chamber with 161 kg (30-50 kg) of LXe total (fiducial), at LNGS
- 30 cm e^- drift length, 30 cm diameter
- 2 arrays of 1-inch, low-background PMTs + LXe veto
- Low radioactivity - screened/selected - materials

Instrument described in:
Astroparticle Physics 35, 2012

Material screening results in:
JINST 6, 2011

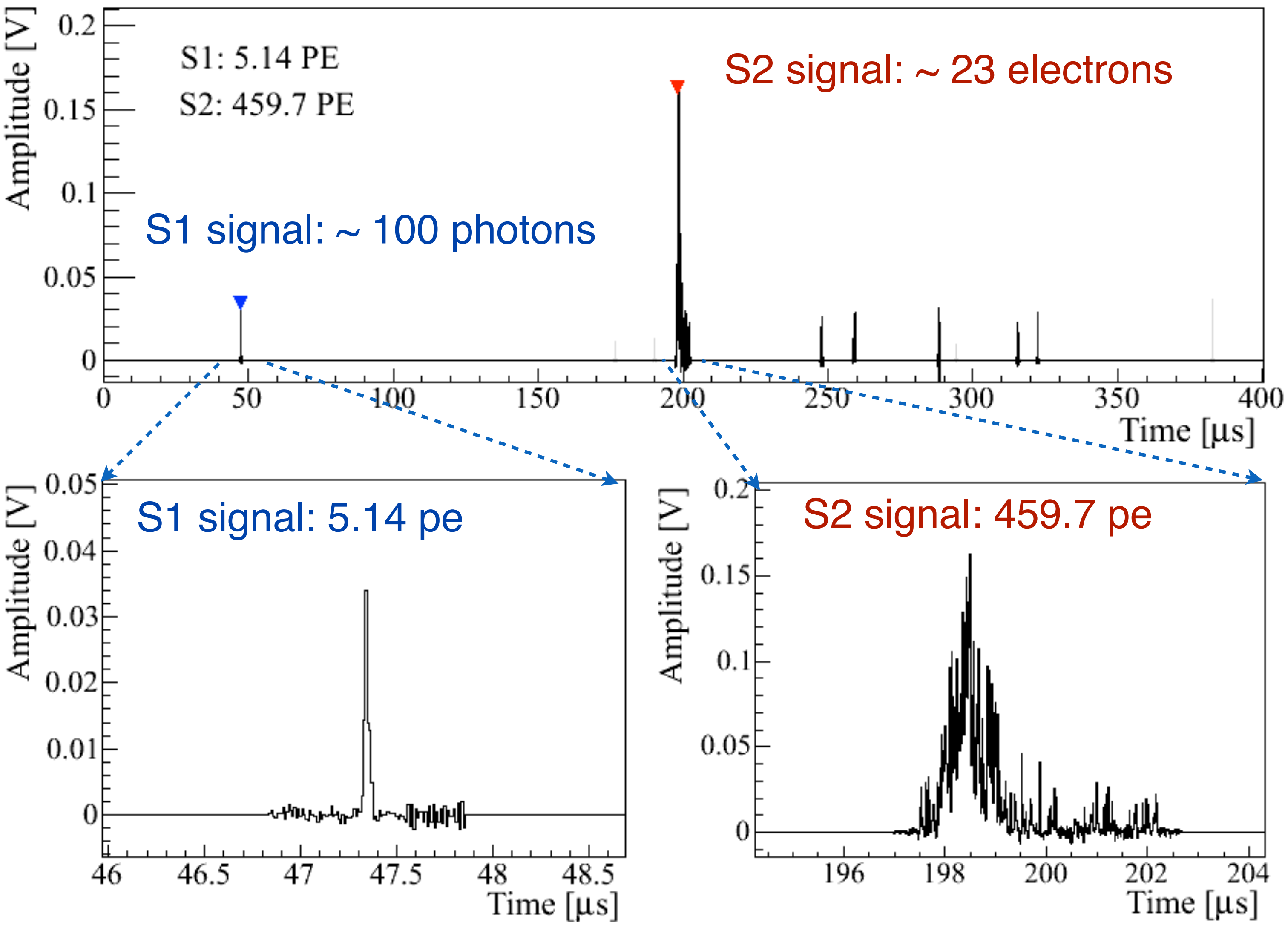
Detailed analysis paper:
Astroparticle Physics 54, 2014

Top array: 98 PMTs



Bottom array: 80 PMTs

Example of a low-energy event waveform

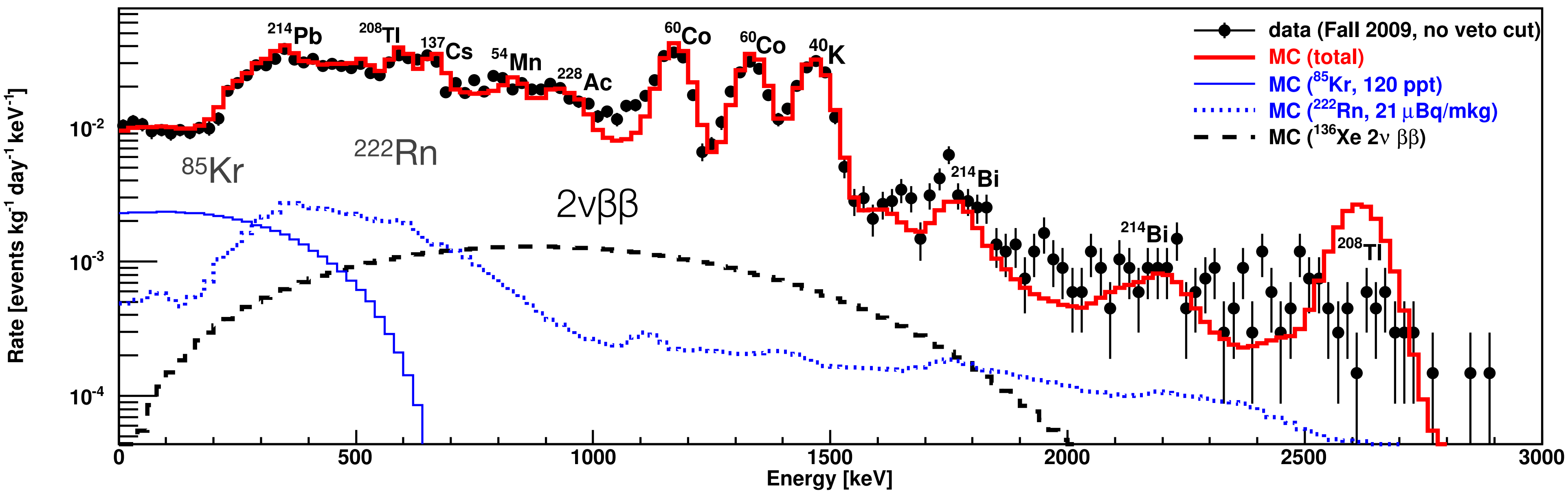


The measured background in XENON100

- **Data** and **MC** (no MC tuning; before the active LXe veto cut)
- Region above ~ 1500 keV: saturation in the PMTs
- The background met the design specifications: 5.3 x 10^{-3} events/(kg keV day)

➡ **100 times lower than in XENON10**

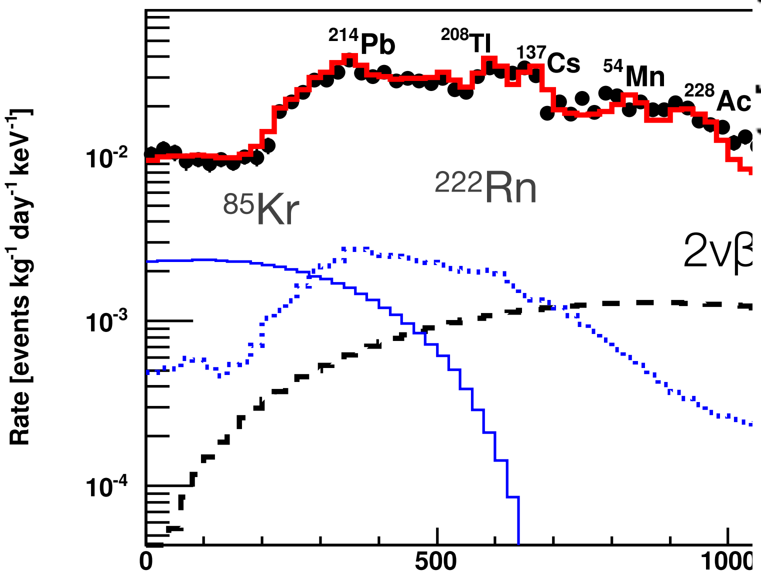
Aprile et al., XENON100 collaboration, PRD 83, 082001 (2011)

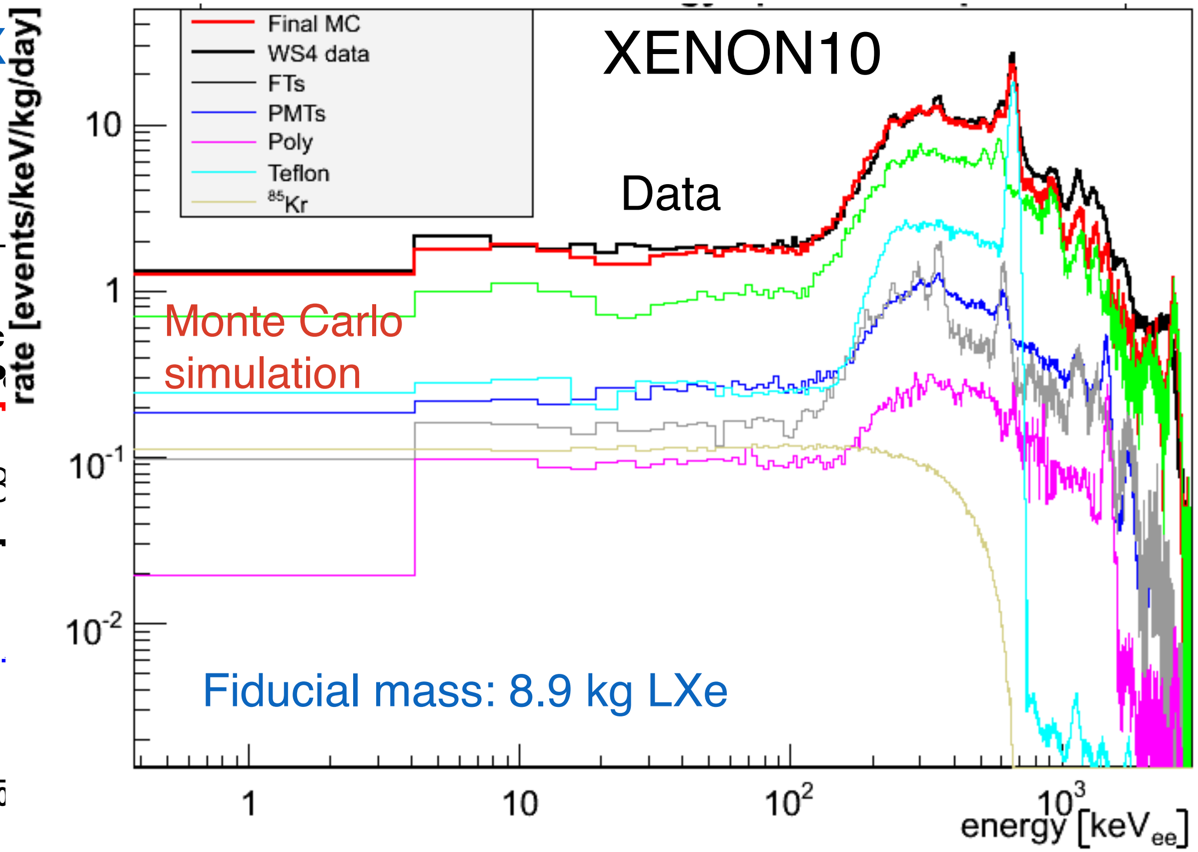


The measured background in XENON100

- **Data** and **MC** (no MC tuning; before the active LXe veto cut)
- Region above ~ 1500 keV: saturation in the PMTs
- The background meets the design specifications: 5.3 x 10^{-3} events/(kg keV day)

➡ **100 times lower than in X**





From XENON10…

LNGS, May 2006

to XENON100…

LNGS, April 2011

to XENON1T/nT

164 scientists

25 institutions

11 countries

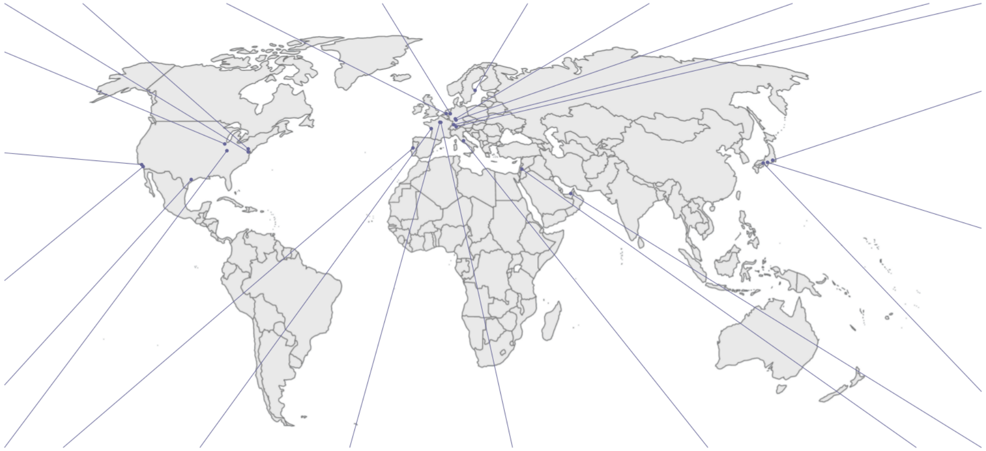
Columbia RPI Nikhef Muenster Stockholm Mainz MPIK, Heidelberg Freiburg Zurich

Chicago

UCLA

UCSD

Rice



Tokyo

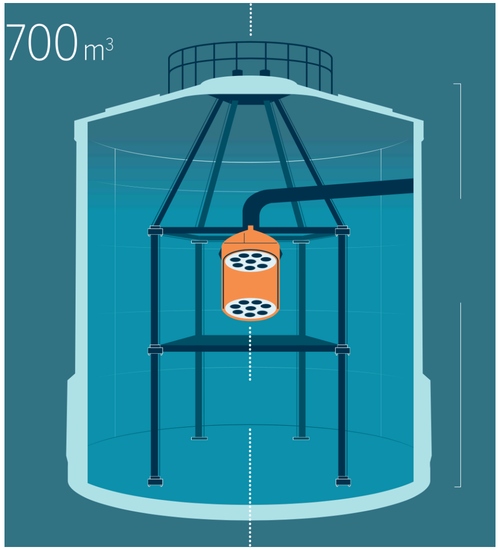
Nagoya

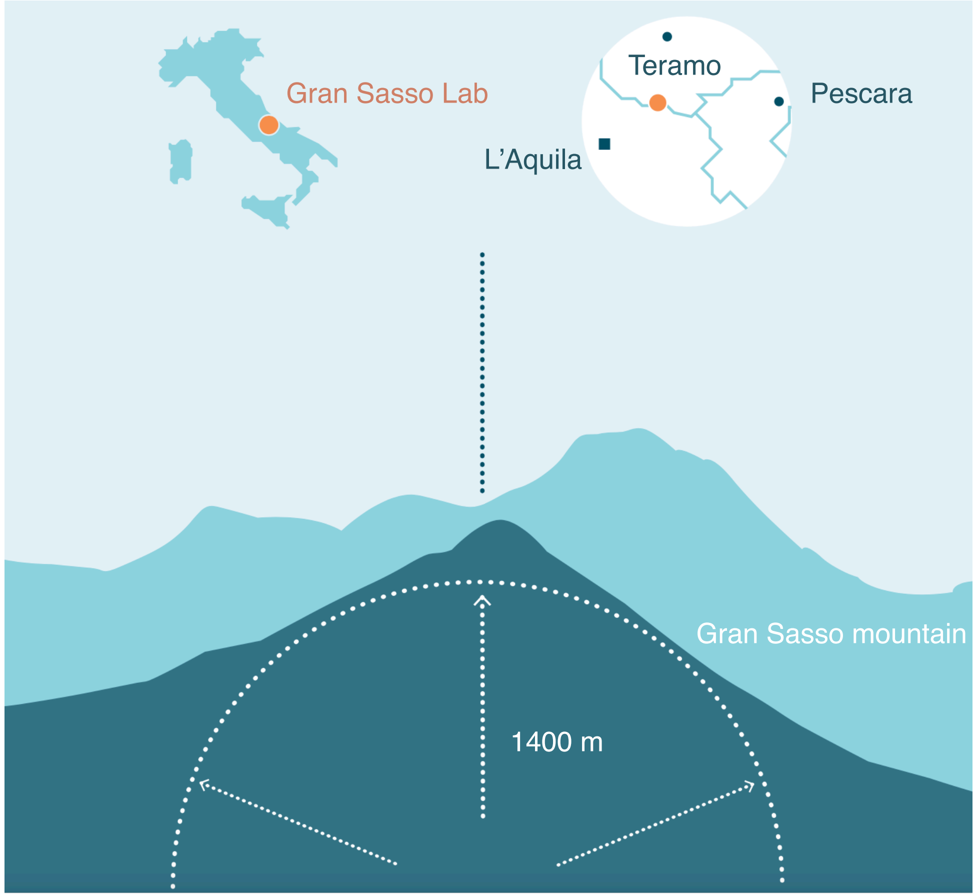
Kobe

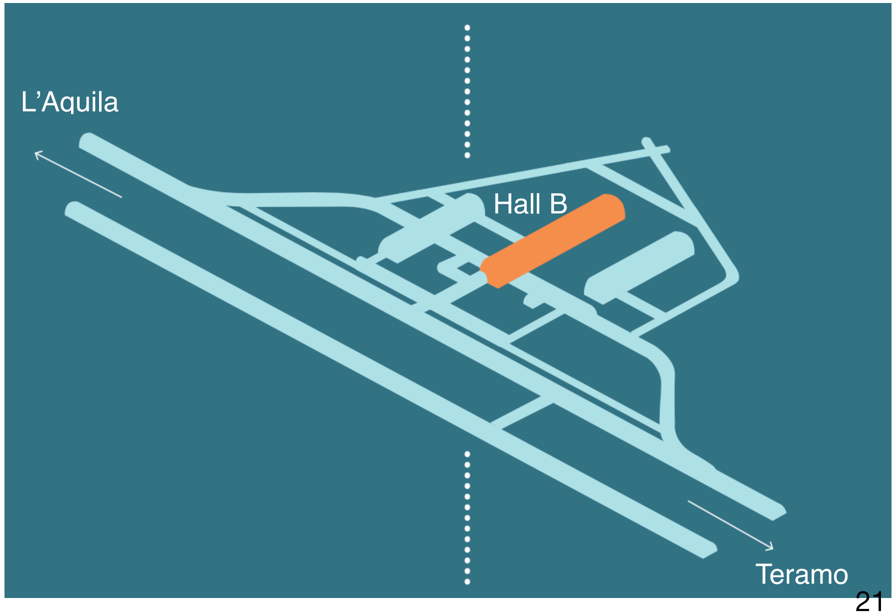
Purdue Coimbra Subatech LPNHE LAL Bologna LNGS Torino Napoli Weizmann NYUAD

XENON1T at LNGS

- Total (active) LXe mass: 3.2 t (2 t), 1 m electron drift
- 248 3-inch PMTs in two arrays







Tagesanzeiger December 2016

XENON1T Overview

XENON collaboration, EPJ-C 77 (2017) 12

Water tank and
Cherenkov muon veto

Cryostat and support
structure for TPC

Time projection
chamber

Cryogenics pipe
(cables, xenon)

Cryogenics and
purification

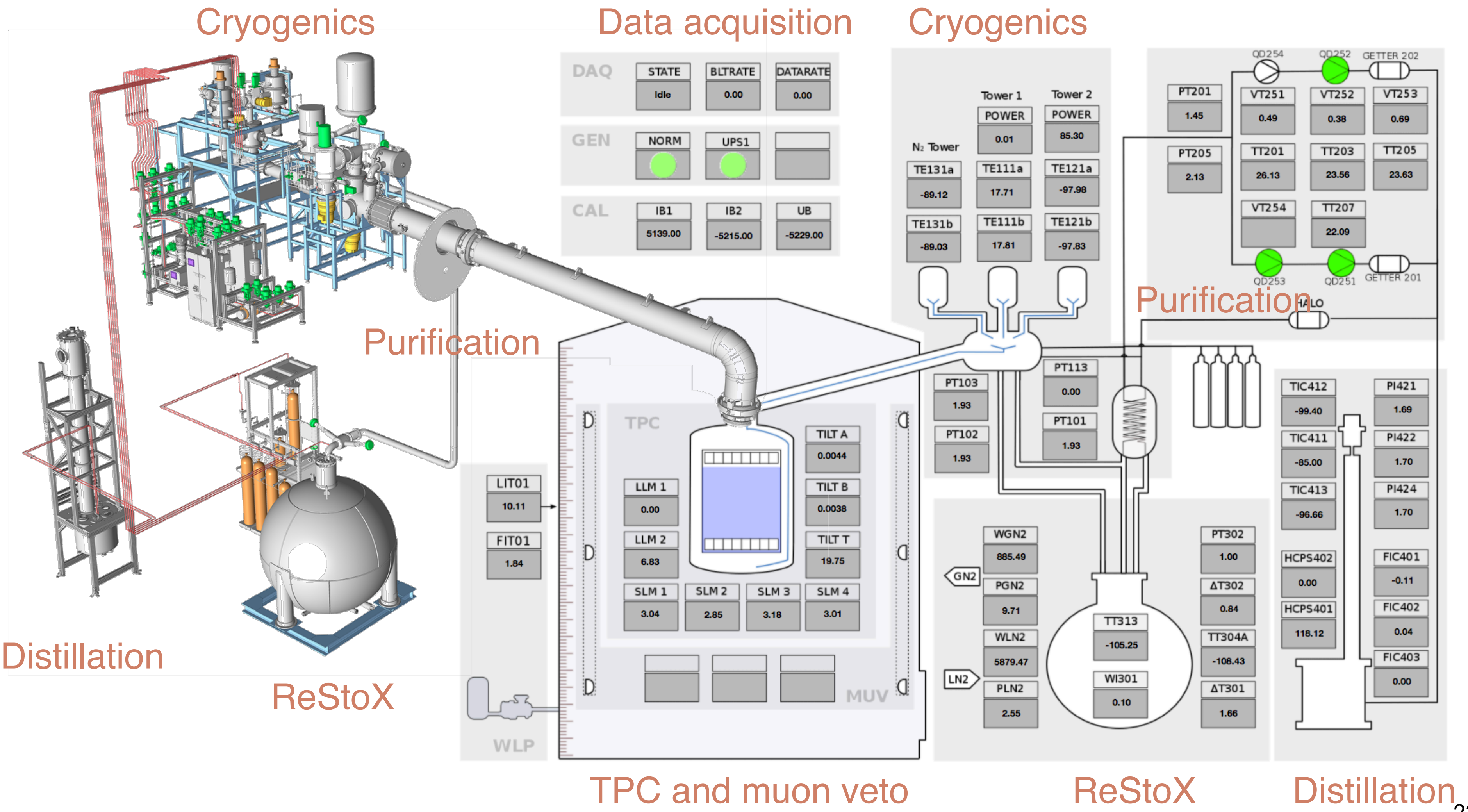
Data acquisition and
slow control

Xenon storage,
handling and
Kr removal via
cryogenic
distillation

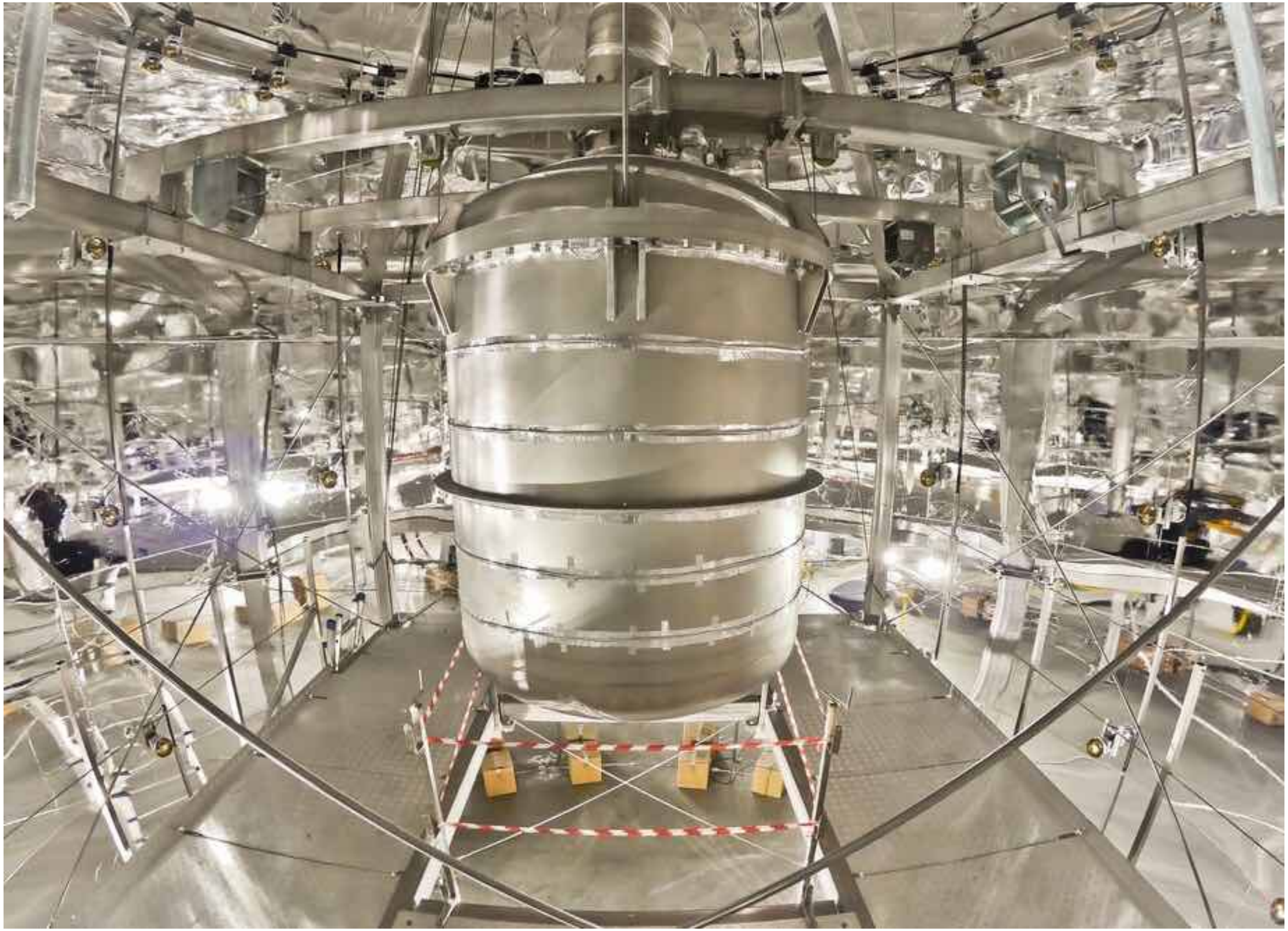
XENON1T Overview

XENON collaboration, EPJ-C 77 (2017) 12

- Slow control system: functional screens for remote monitoring and controlling



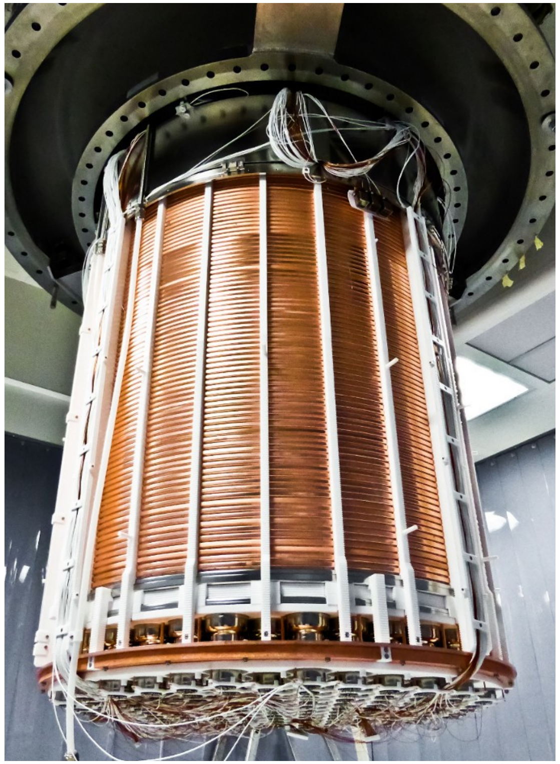
The XENON1T Cryostat and Water Shield



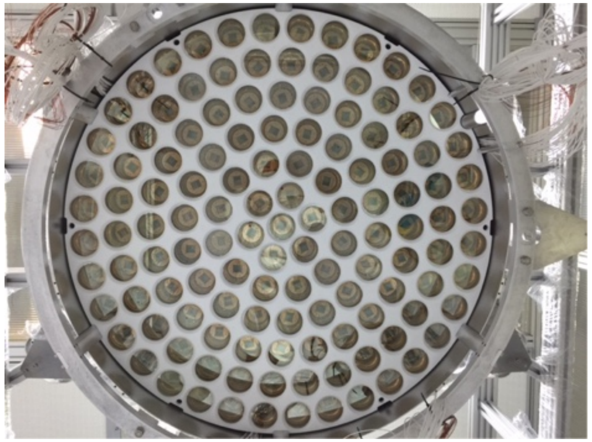
The Time Projection Chamber

- The 248 3-inch, low-radioactivity PMTs are arranged in two arrays

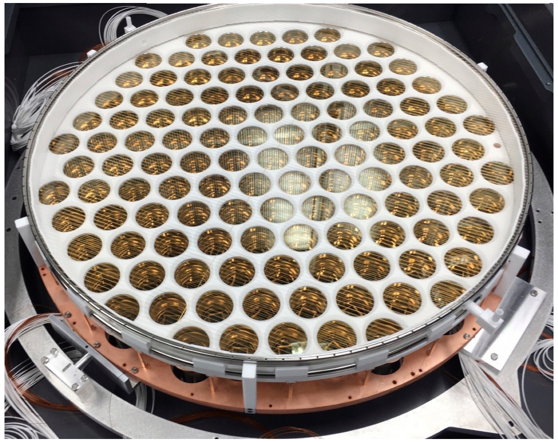
EPJC 75 (2015) 11, 546



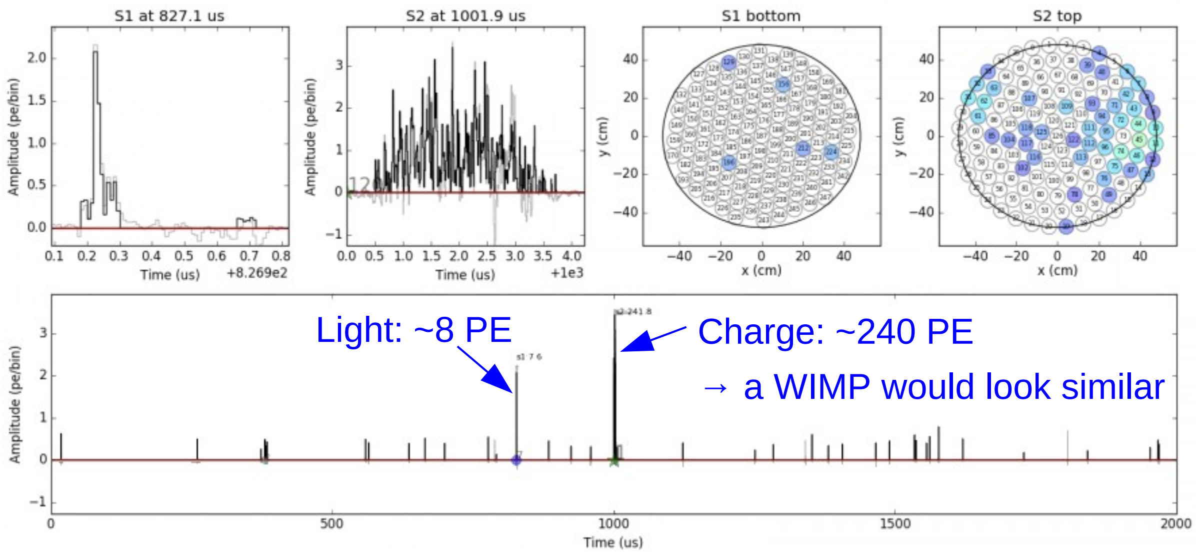
3.2 t LXe @180 K



127 PMTs in the top array



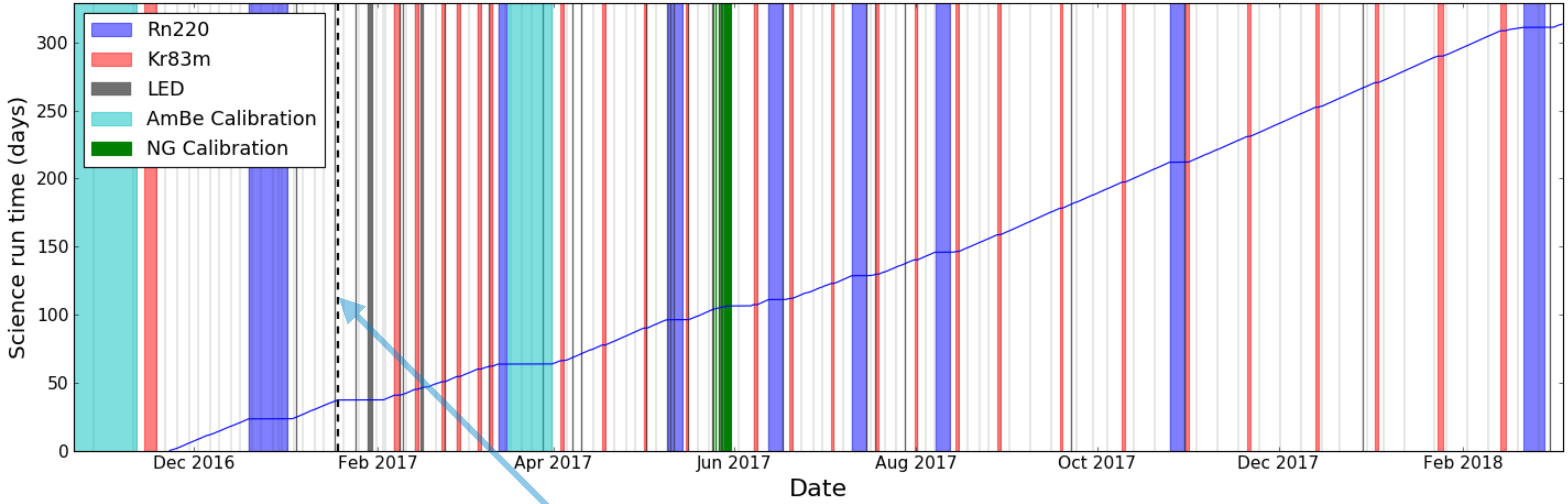
121 PMTs in the bottom array



The Time Projection Chamber at LNGS

Science and calibration data overview

- **First science run: Oct 2016 - Jan 2017 (34.2 live days)**
- Second science run proceedings smoothly (> 250 live days)
- Unblinding soon… expect new results this spring



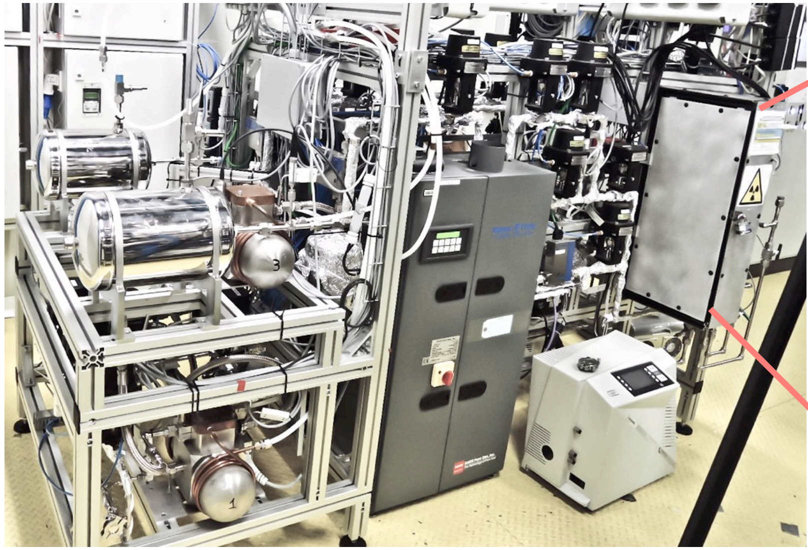
SR0
~34 live days

Earthquake

SR1
250 live days

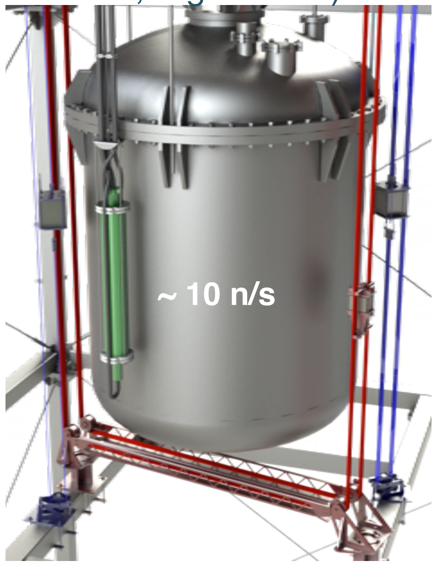
Calibration systems

Light: 4 external LEDs and optical fibres

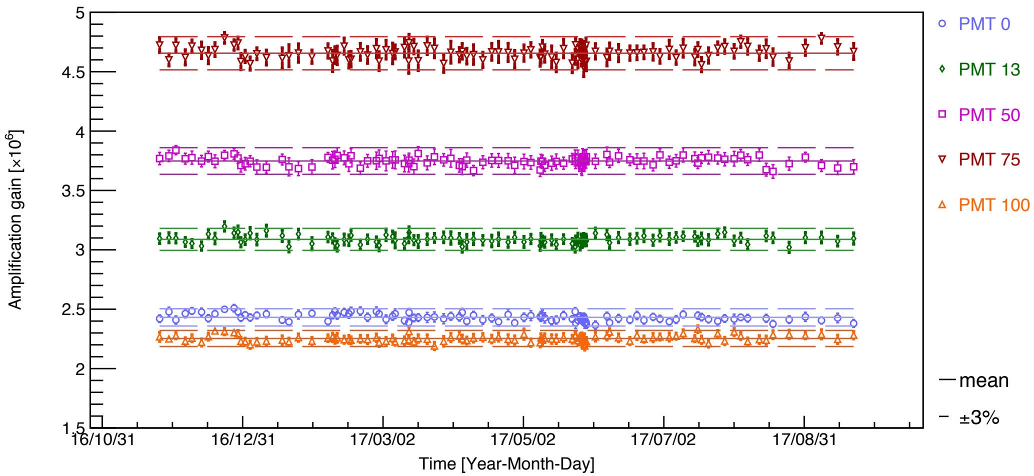


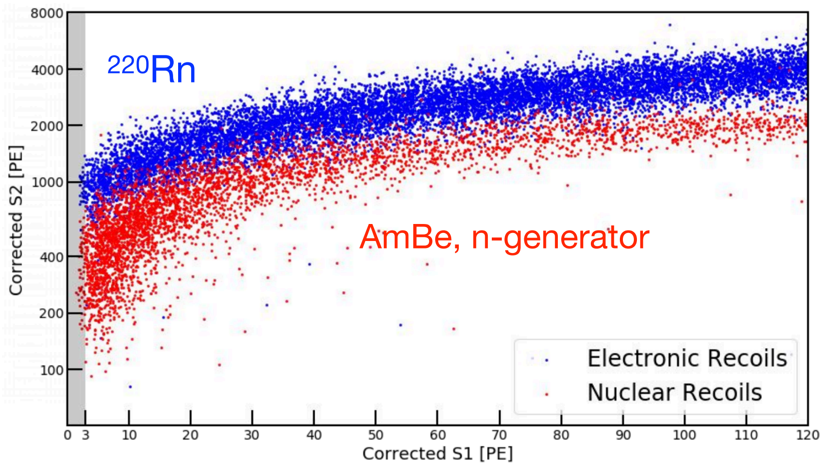
Internal sources (^{220}Rn, ^{83m}Kr)

External sources (AmBe, ^{137}Cs, n-generator)



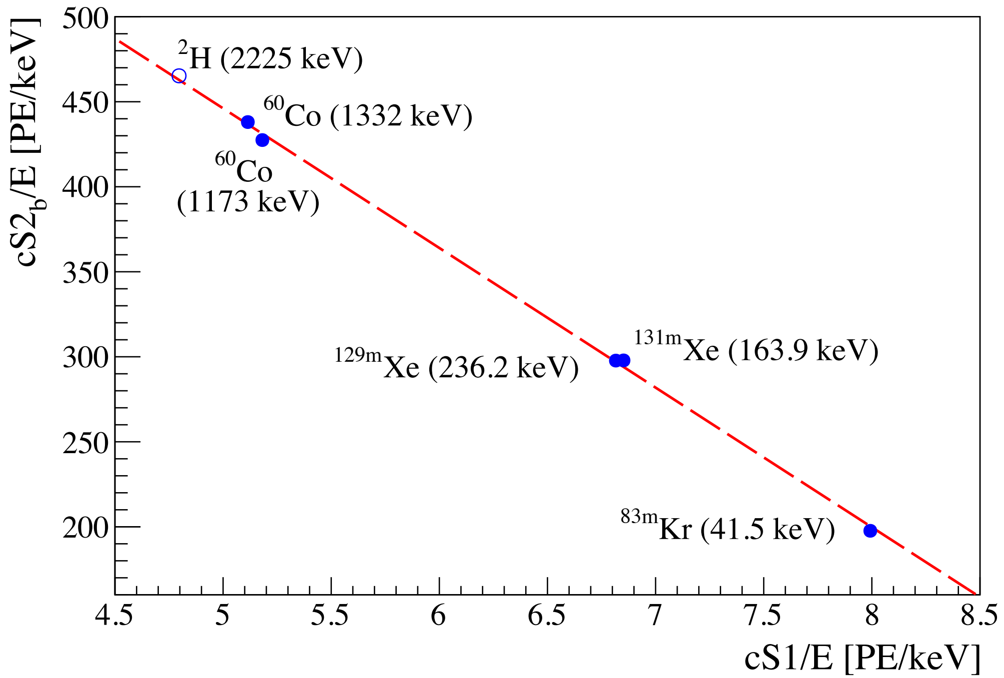
d + d -> ^{3}He + n (2.45 MeV)





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



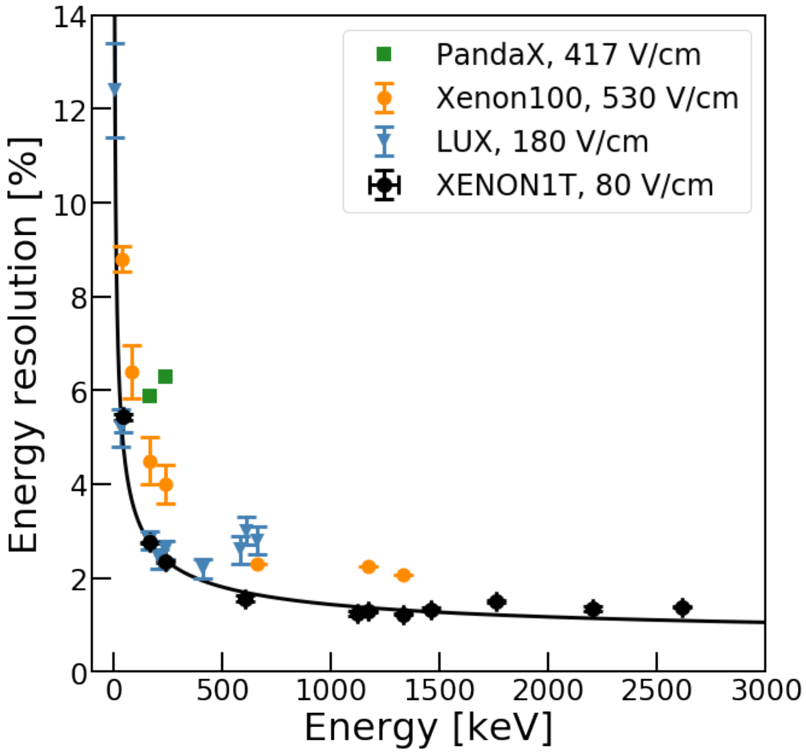
$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right) \cdot W$$

- Excellent linearity with electronic recoil energy up to 2.2 MeV
  - g_1 = photon gains
  - g_2 = electron gain
  - W-value = 13.7 eV

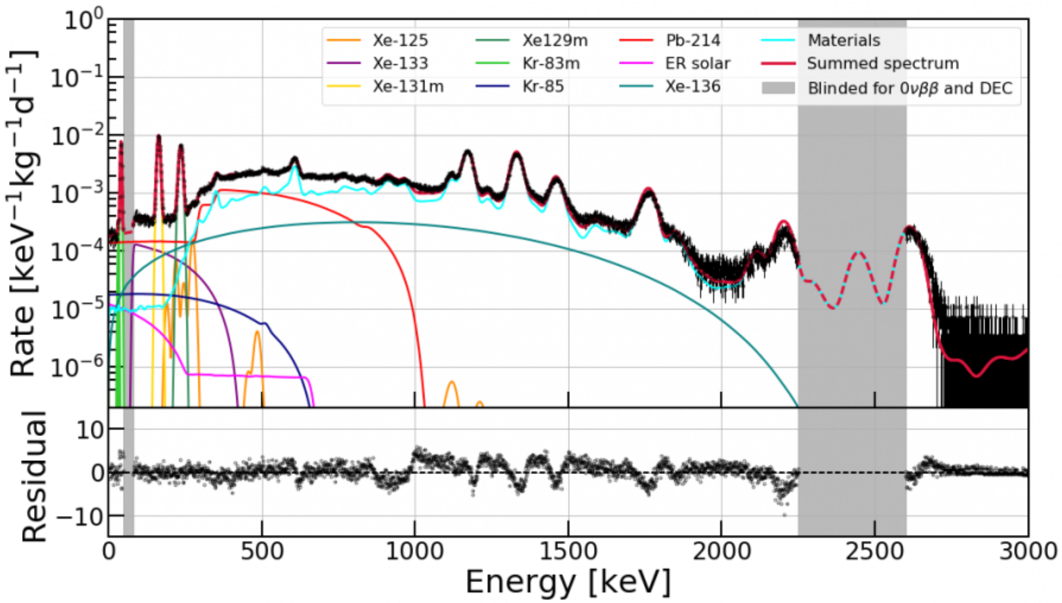
- g_1 = (0.144 ± 0.007) pe/photon
- g_2 = (11.5 ± 0.8) pe/electron

Energy resolution

- One of the best energy resolutions among all liquid xenon TPCs
- Covers large energy range (background understanding, 0νββ-decay analysis)



Relative energy resolution (σ(E)/E) versus energy

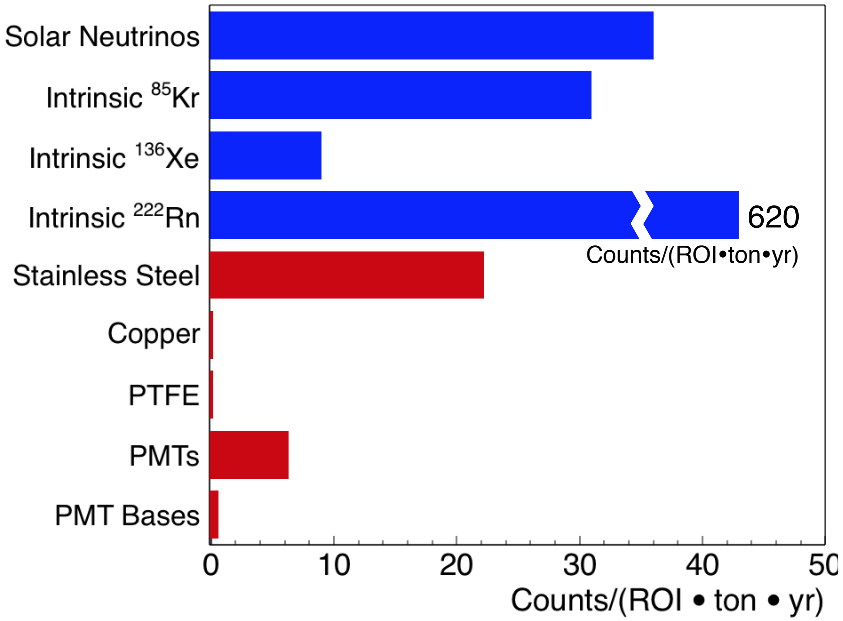


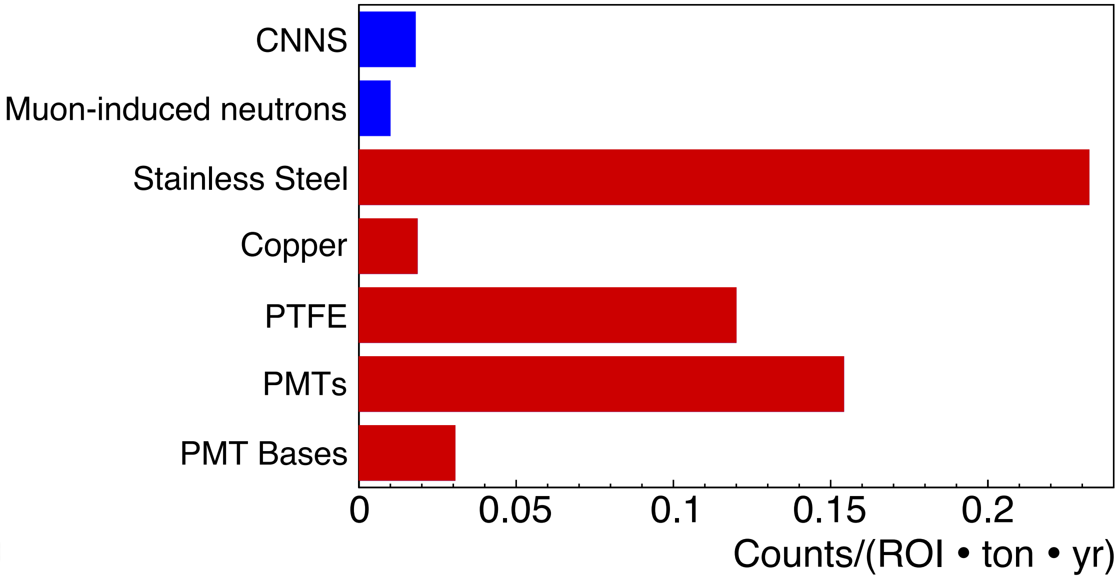
Energy spectrum of electronic recoils

Background predictions

XENON collaboration: JCAP 1604 (2016) no.04

Intrinsic and neutrinos + materials*





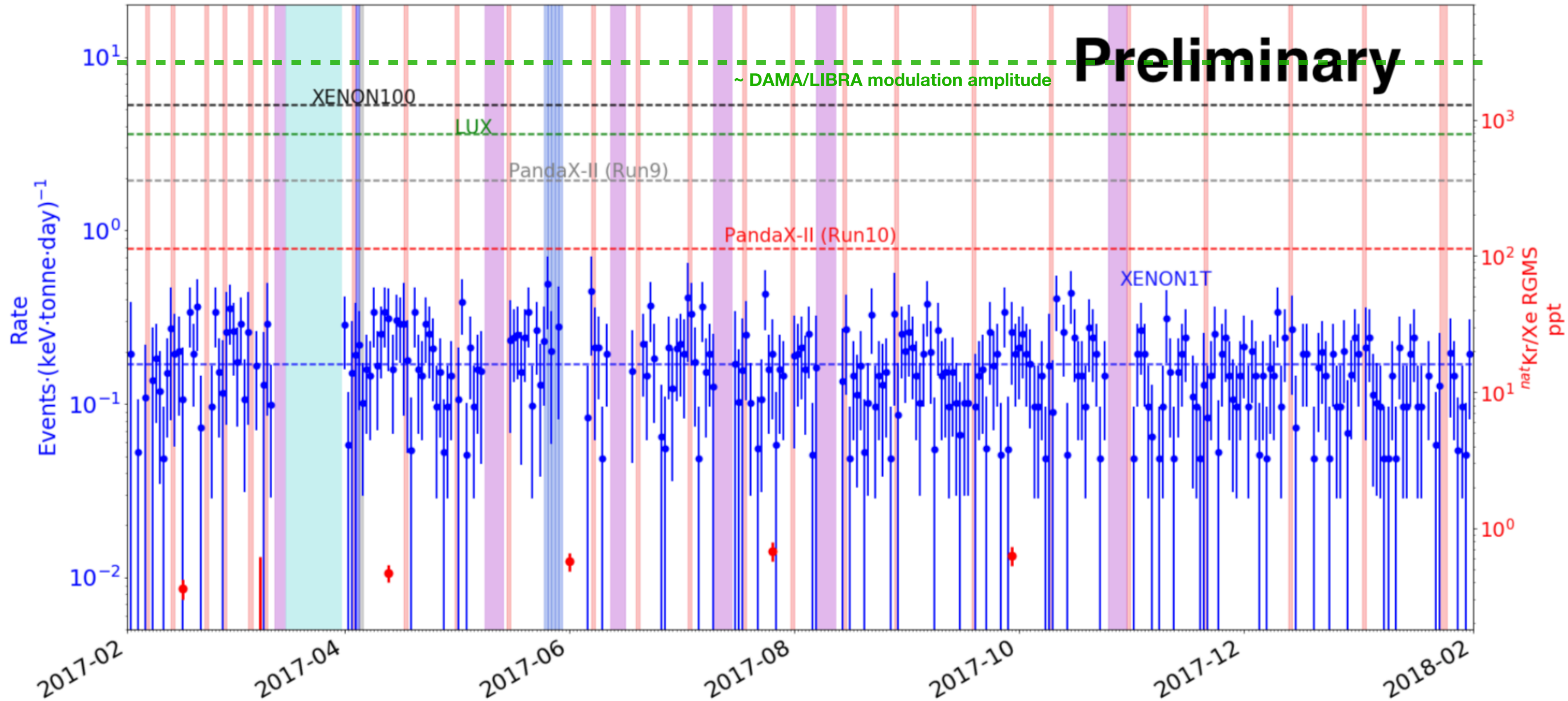
Electronic recoils in 1 t fiducial, energy region: 1-12 $\mathrm{keV_{ee}}$

Nuclear recoils in 1 t fiducial, energy region: 4-50 $\mathrm{keV_{nr}}$

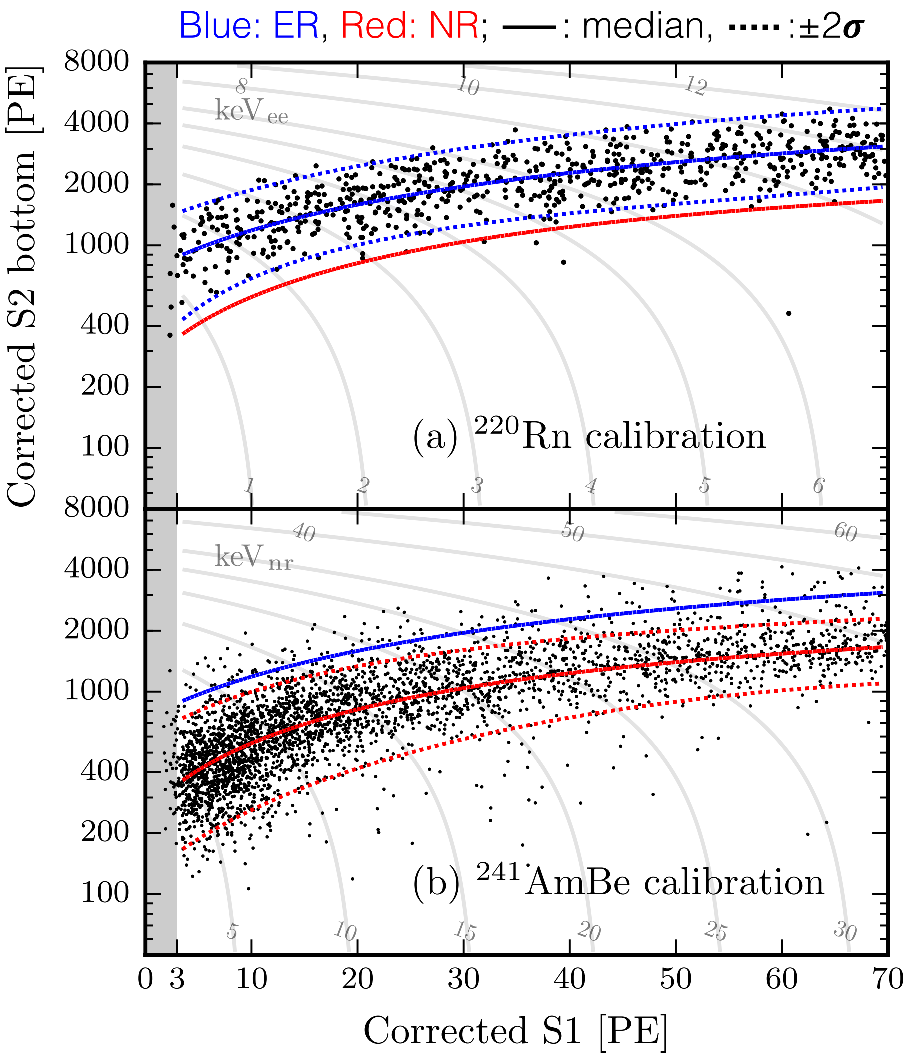
*based on screening with HPGe detectors (Gator, GeMPI etc) and ICP-MS: EPJ-C 77 (2017) no.12

Backgrounds: prediction versus data

- Prediction for ER rate: **~0.2 events/(keV tonne day)** below 10 keV; NR: subdominant
- Background reduced to ~ the predicted level (^{nat}Kr reduced from 1 ppb to ~0.4 ppt)



Science run 0: ER and NR bands

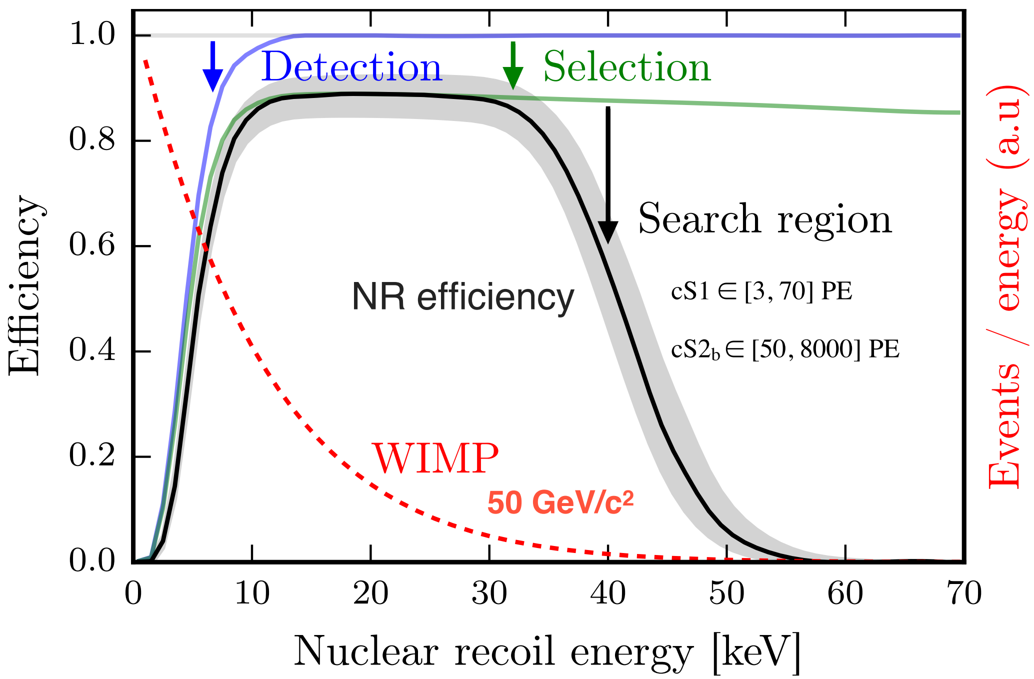


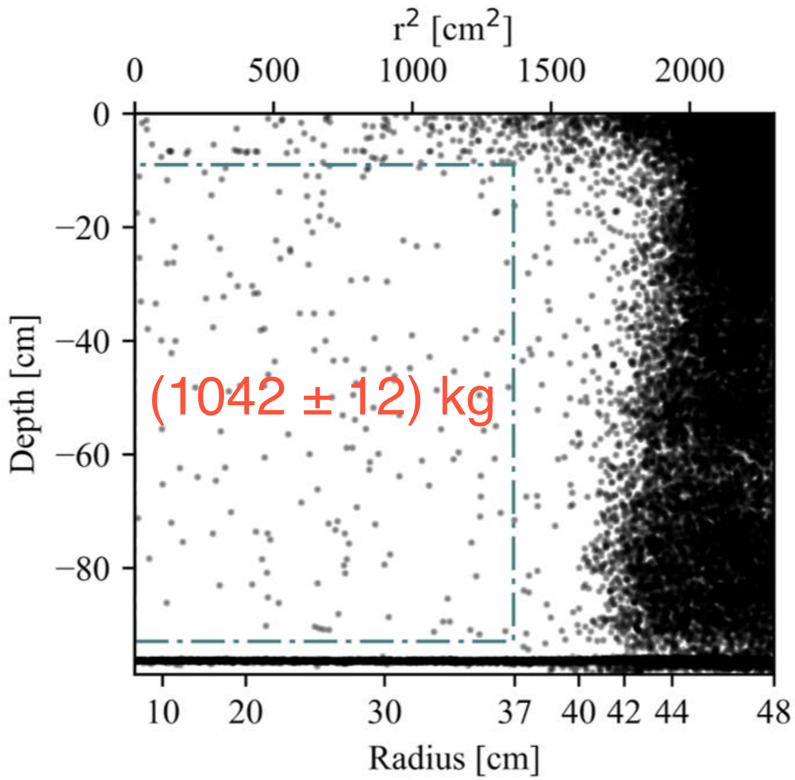
- **Electronic recoils**
  - ^{220}Rn ($T_{1/2}$ = 65 s), emanated by ^{228}Th source, directly into LXe
  - ^{212}Pb ($T_{1/2}$ = 10.6 h) buildup, decays to ^{212}Bi => low-energy ER events
- **Nuclear recoil**
  - external AmBe source
  - upgraded to D-D fusion n-generator
  - time required to calibrate: weeks -> days

Science run 0: Data selection

- Signal region blinded until selection fixed
- Single-scatter, event quality, peak quality, fiducial volume

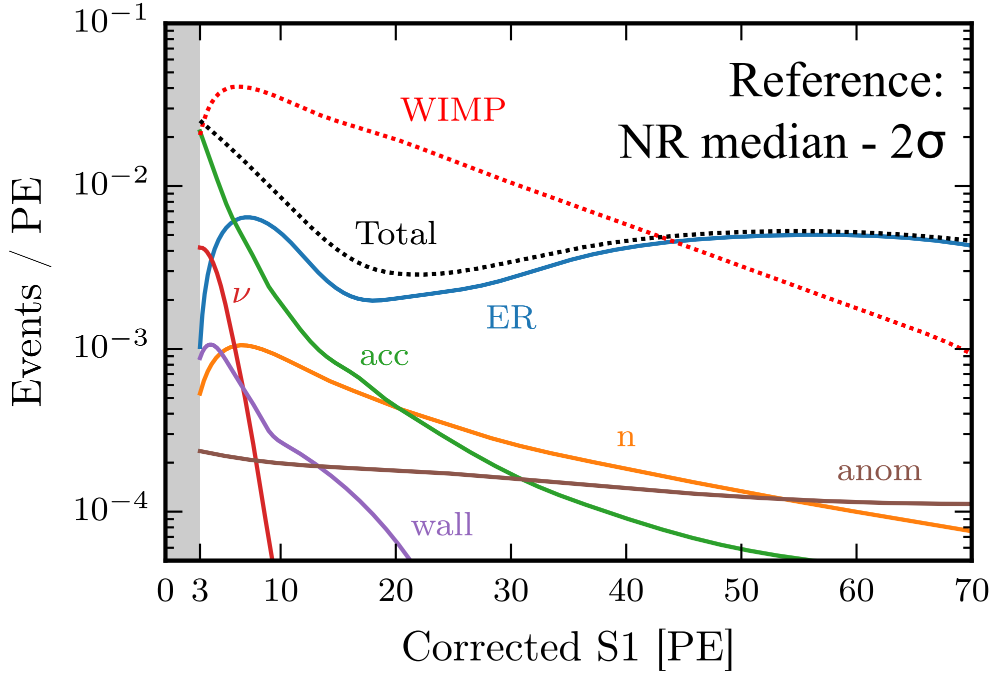
Selection criterium	Events remaining
All events (cS1<200 PE)	128144
Data quality, selection	48955
Fiducial volume	180
S1 range (3-70) PE	63





Science run 0: Total background

- ER rate is dominated by radon (emanation from detector materials)
- Target concentration of 10 µBq/kg reached
- Further reduction by Rn distillation (see EPJ C (2017) 77:358, arXiv:1702.06942)

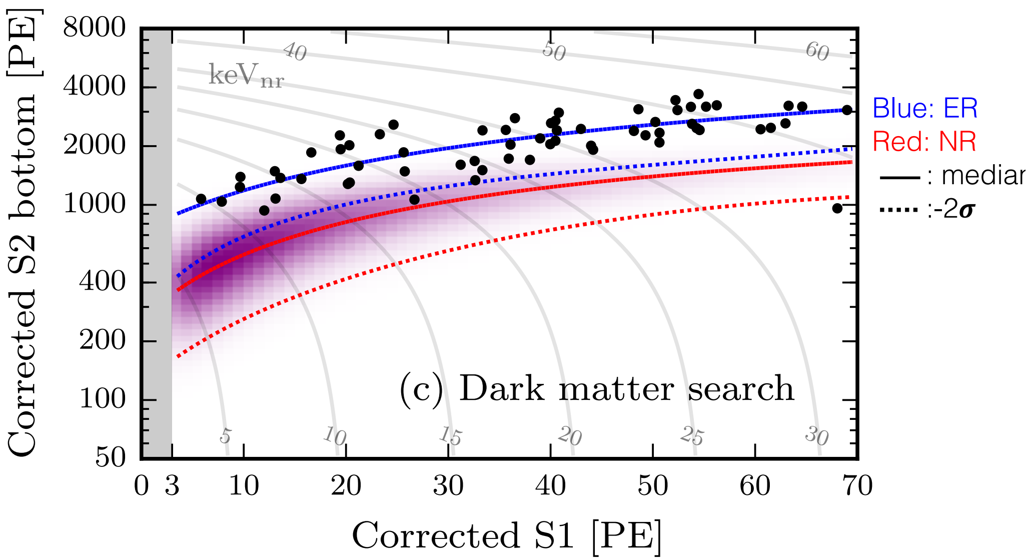


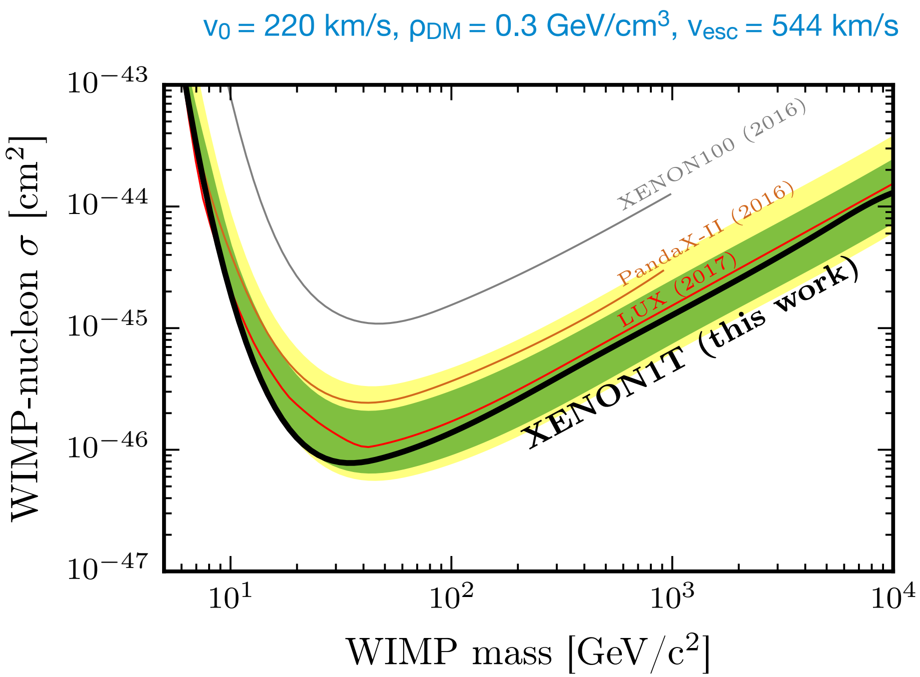
	Full	Reference
Electronic recoils (ER)	(62 ± 8)	$(0.26^{+0.11}_{-0.07})$
Radiogenic neutrons (n)	0.05 ± 0.01	0.02
CNNS (ν)	0.02	0.01
Accidental coincidences (acc)	0.22 ± 0.01	0.06
Wall leakage ($wall$)	0.5 ± 0.3	0.01
Anomalous ($anom$)	$0.10^{+0.10}_{-0.07}$	0.01 ± 0.01
Total background	63 ± 8	$0.36^{+0.11}_{-0.07}$

Observed ER rate: $(1.93 \pm 0.25) \times 10^{-4}$ events/(kg $\times$ d $\times$ keV)

SR0: Dark matter search results

- No post-unblinding changes to event selection
- Unbinned profile likelihood analysis, data consistent with background-only hypothesis
- ER/NR shape largely determined from calibration fits



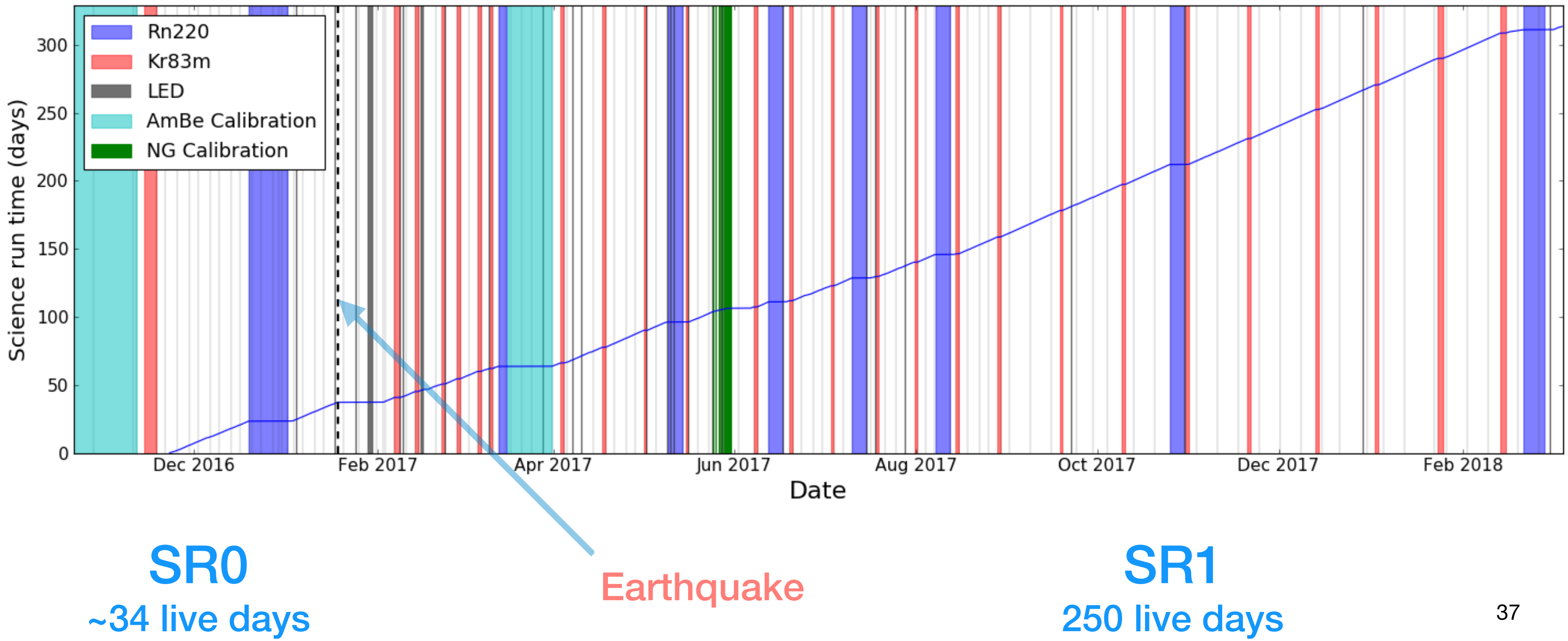


Phys. Rev. Lett. **119**, 181301, 2017

$7.8 \times 10^{-47}\,\mathrm{cm}^2$ at $35\,\mathrm{GeV/c}^2$

Science and calibration data overview

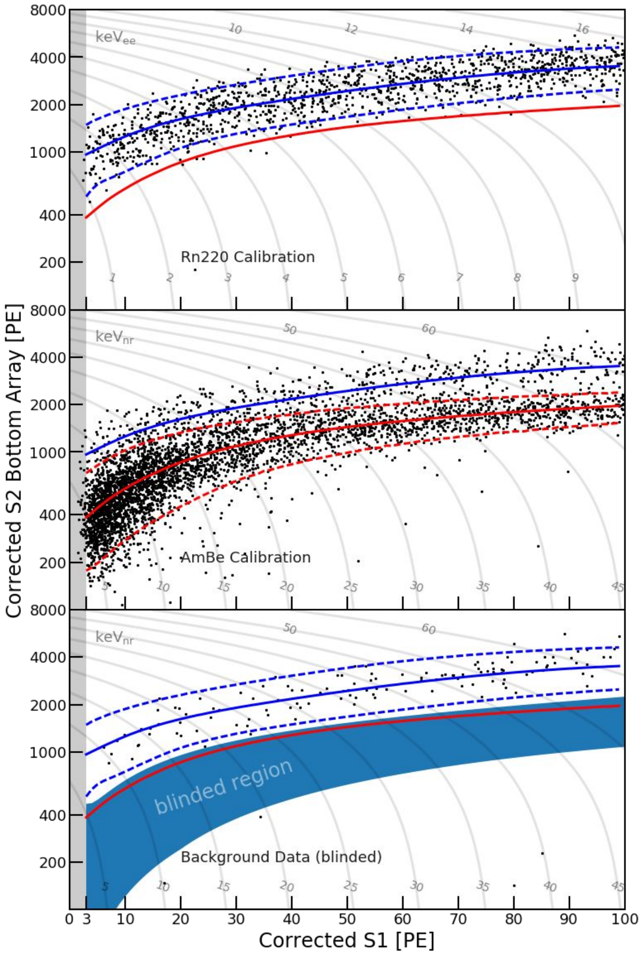
- **First science run: Oct 2016 - Jan 2017 (34.2 live days)**
- Second science run proceedings smoothly (> 250 live days)
- Unblinding soon… expect new results this spring

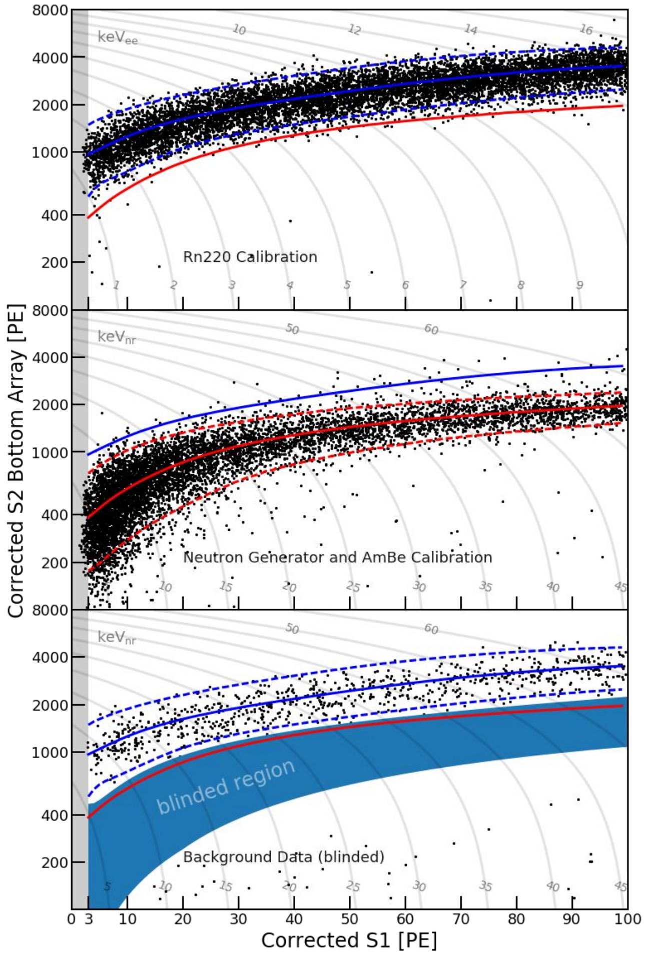


Calibration and science data

- Signal region is blinded & data is also salted (fake events added)
- Unbinned profile likelihood analysis in (S1, S2, r) space

SR0

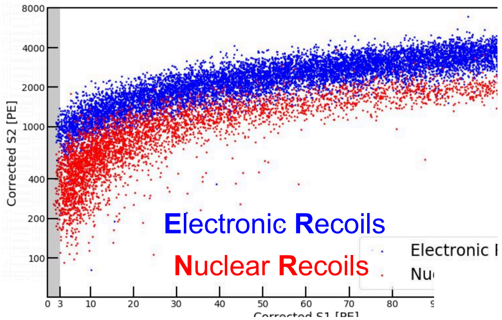


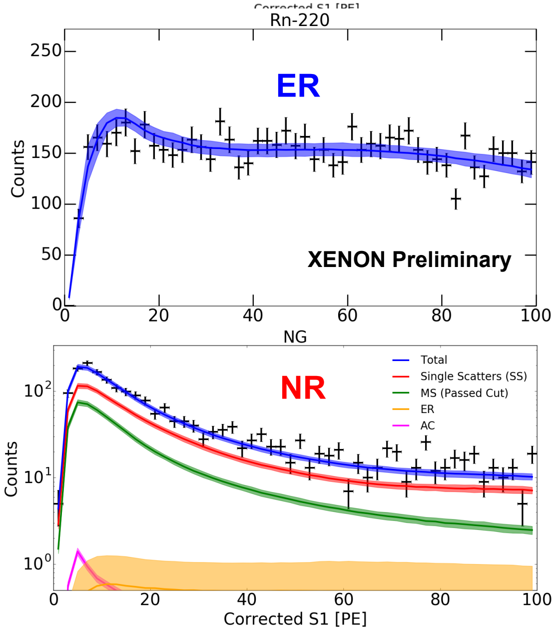


SR1

Signal and background modelling

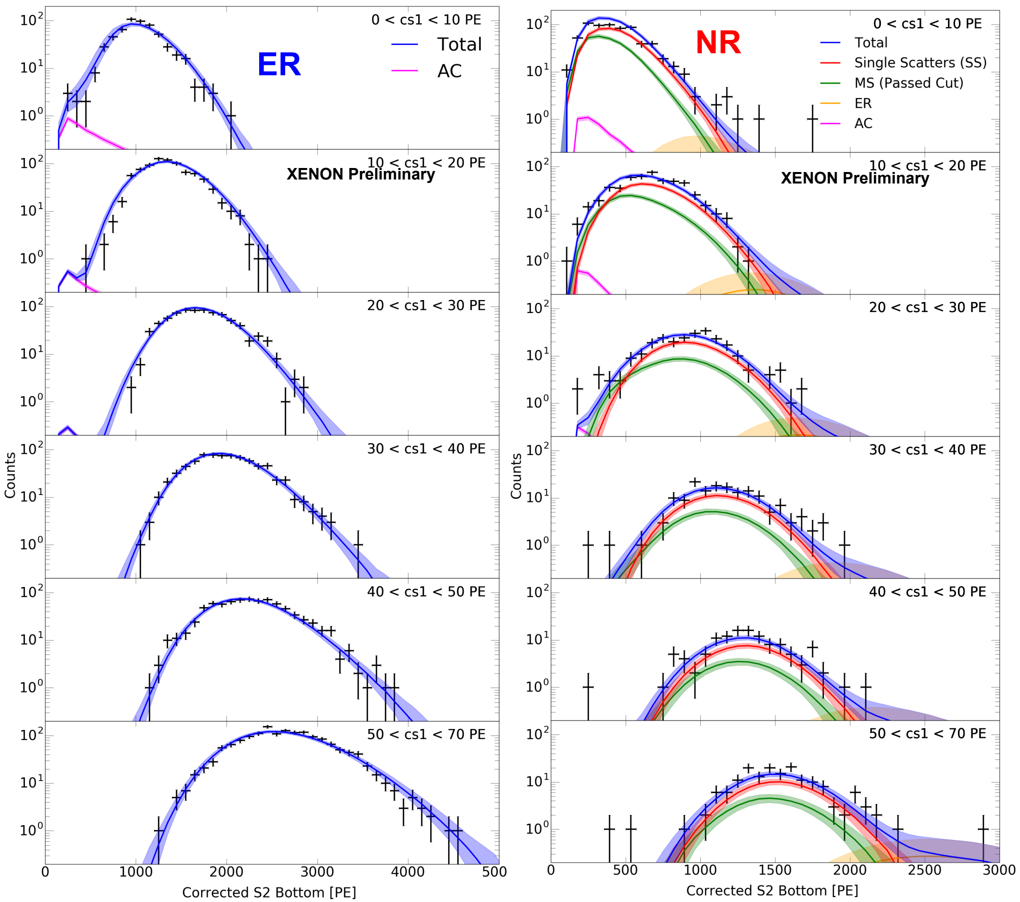
Particle propagation → Energy deposit → Charge & scintillation (S1) emission → Charge drift → Extraction/ proportional scintillation (S2) → Optical photon propagation → PMT/ electronics response → Trigger & Reconstruction → Event Selection → Samples for statistical inference and models





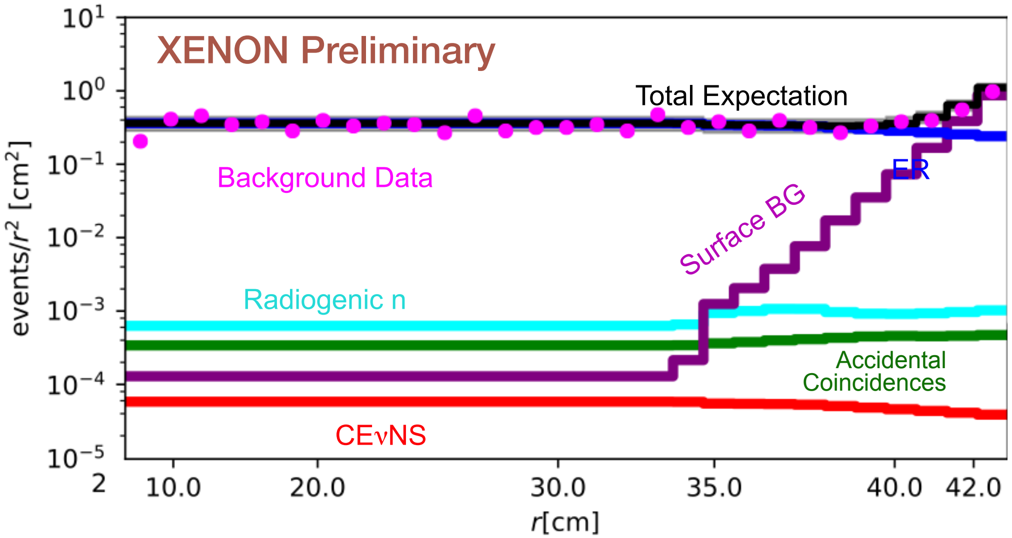
Slice in S1 & project onto S2

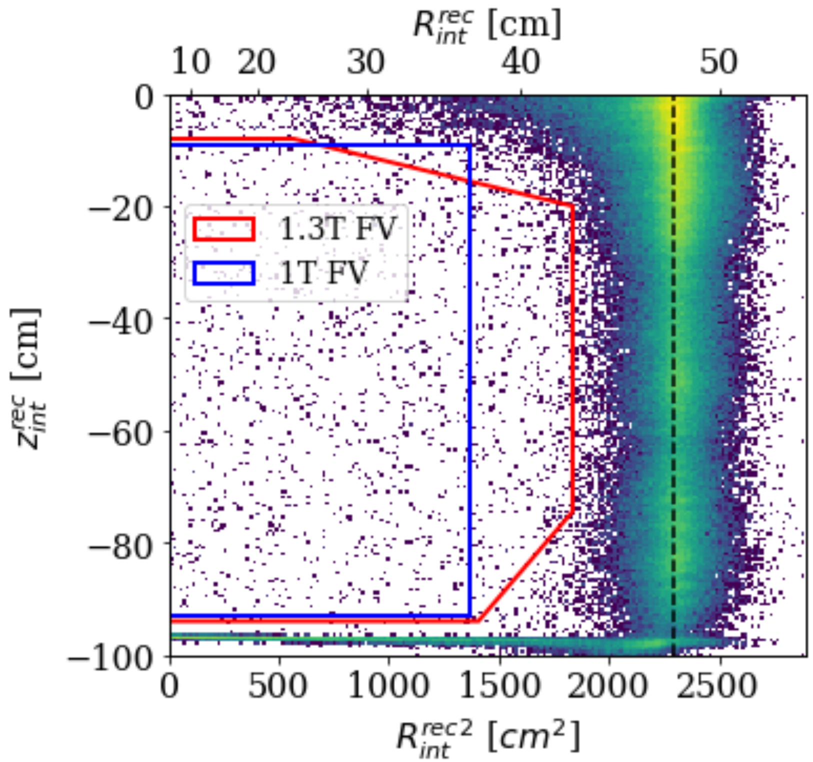
arXiv:1709.10149



Science Run 1: Increased fiducial volume

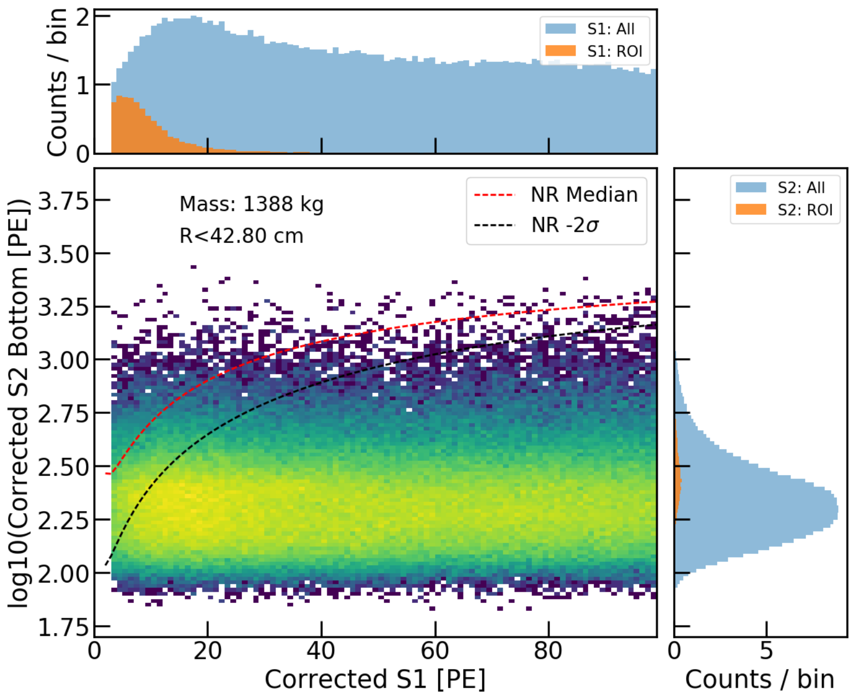
- Select FV to reduce materials and surface backgrounds
- SR0: 1 tonne
- SR1: 1.3 tonnes due to improvement in position reconstruction + new surface backgrounds model which includes radius r in statistical inference

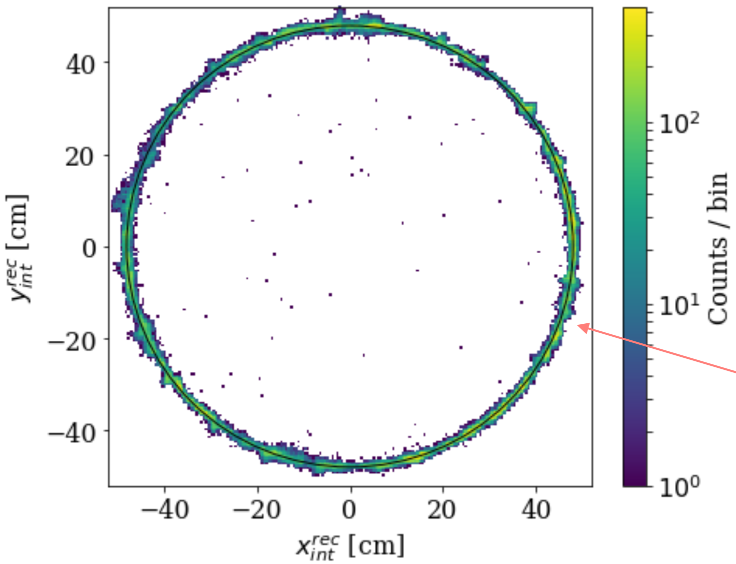




Surface background

- Radioactivity on PTFE surfaces & 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	

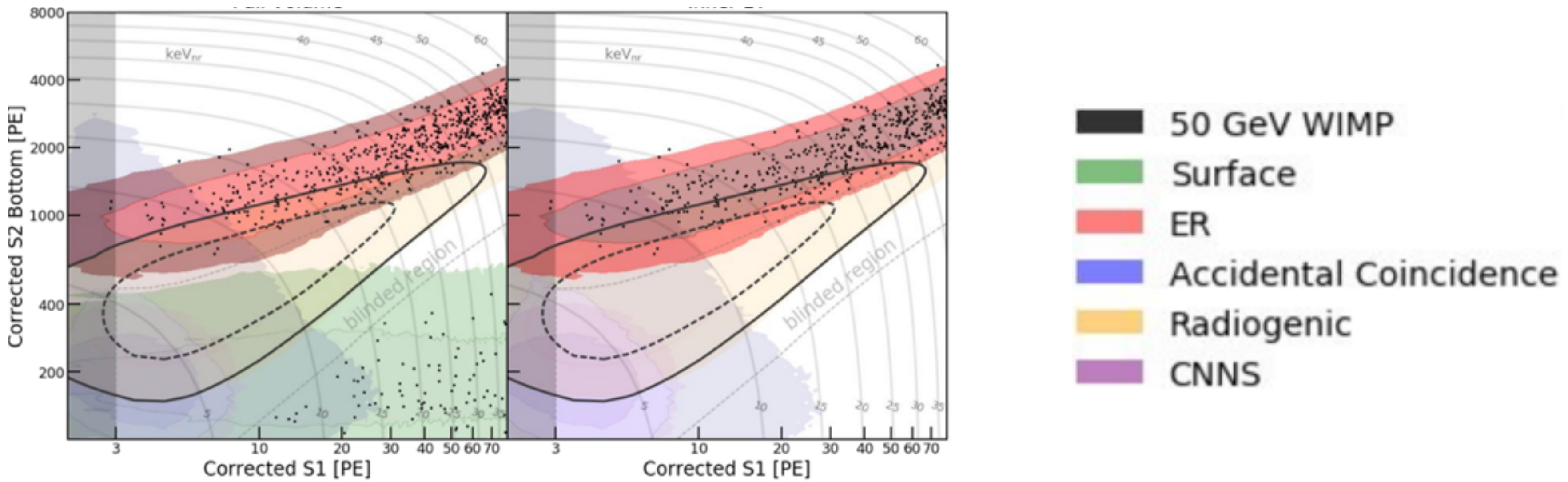
Complete background model

- Models derived in 3D space (S1, S2, r) while data is blinded

Source	1.3 tonnes	1 tonne
ER	1.8±0.2	1.4±0.2
Radiogenic	0.6±0.3	0.4±0.2
CEvNS	0.04±0.01	0.03±0.01
Accidental	0.2±0.1	0.1
Surface	6.1±0.3	0.1
Total	8.7±0.5	2.0±0.3
50 GeV, 1e-47 cm^2	0.8±0.1	0.6±0.1

1.3 tonnes volume

1.0 tonne volume

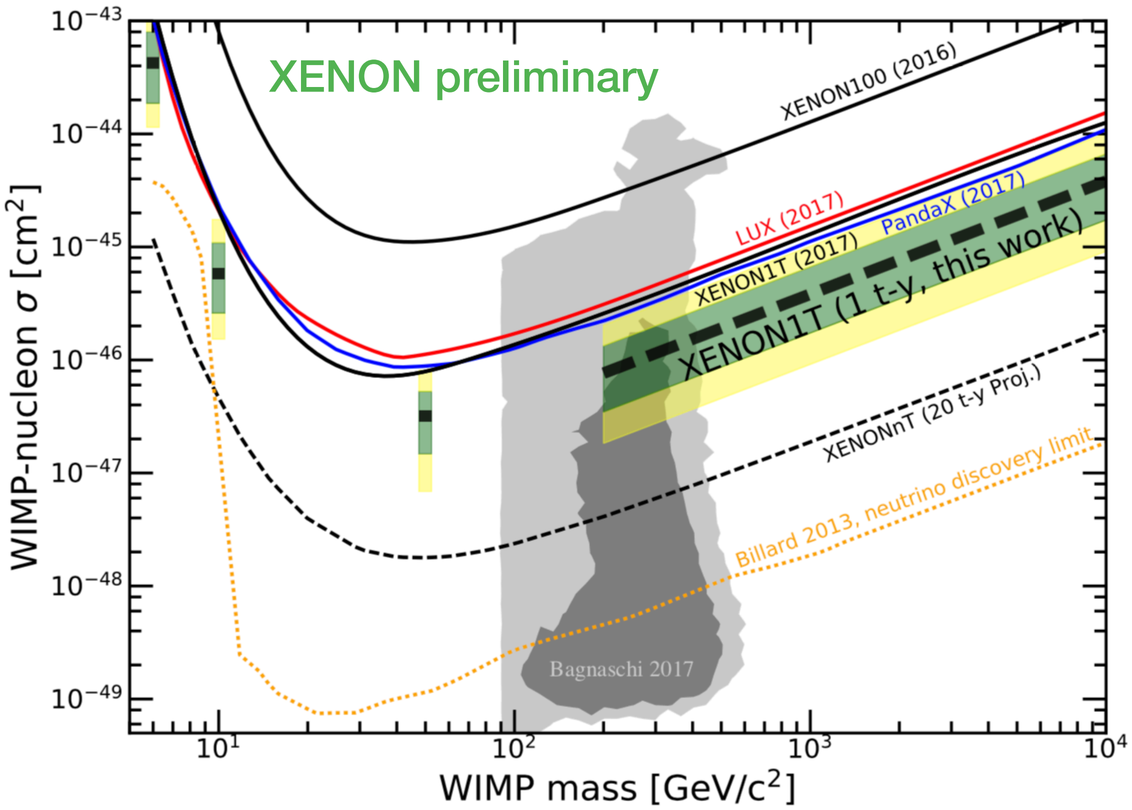


Expected sensitivity

- Factor of 3-4 improvement compared to SR0 due to

  ➡7.7 x more data, larger fiducial volume (due to improved understanding of detector)

  ➡ additional spatial information added to statistical framework



See

blog xenon1t.org

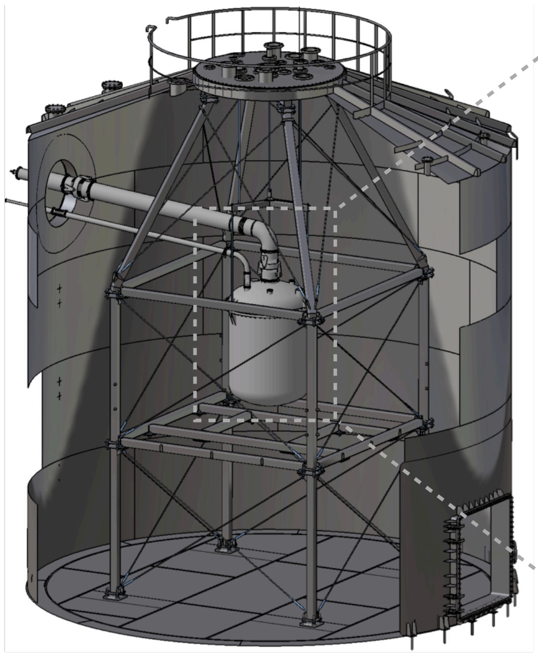
and

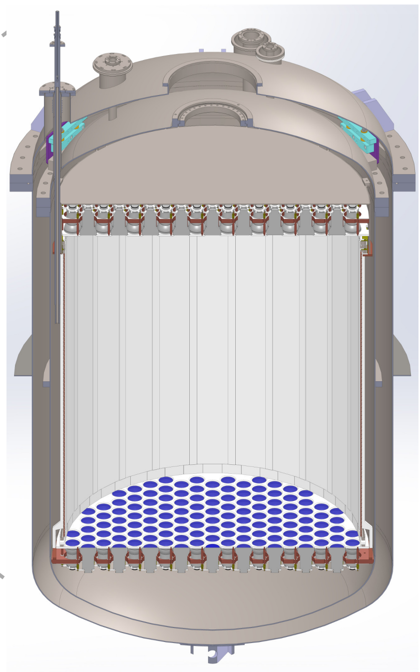
twitter: @Xenon1T

for updates

The XENONnT Experiment

- A rapid upgrade to XENON1T, with: 8 t total LXe mass, 6 t active (x3 compared to 1T)
- Most sub-systems can handle a larger detector with up to 10 t of LXe:





- Water tank + muon veto
- Outer cryostat and support structure
- Cryogenics and purification system
- LXe storage system
- Cables installed for XENONnT as well
- New inner cryostat, new TPC, 476 PMTs
- Neutron veto, Rn removal tower, additional LXe storage system

- PMTs under tests; TPC materials ordered, first batches under screening & outgassing measurements

DARWIN

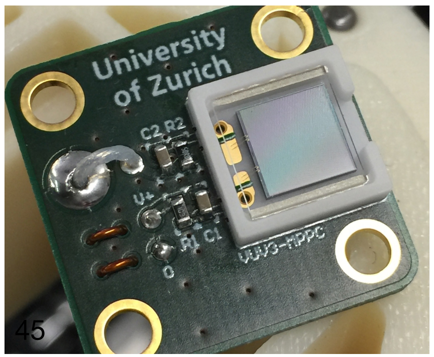
European Research Council
Established by the European Commission

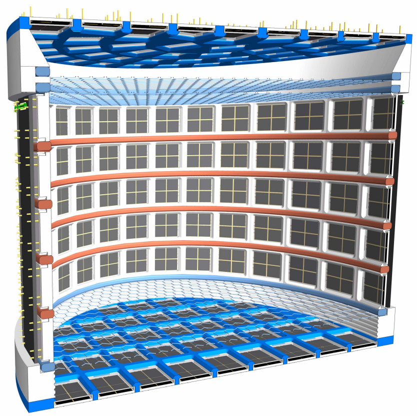
darwin-observatory.org

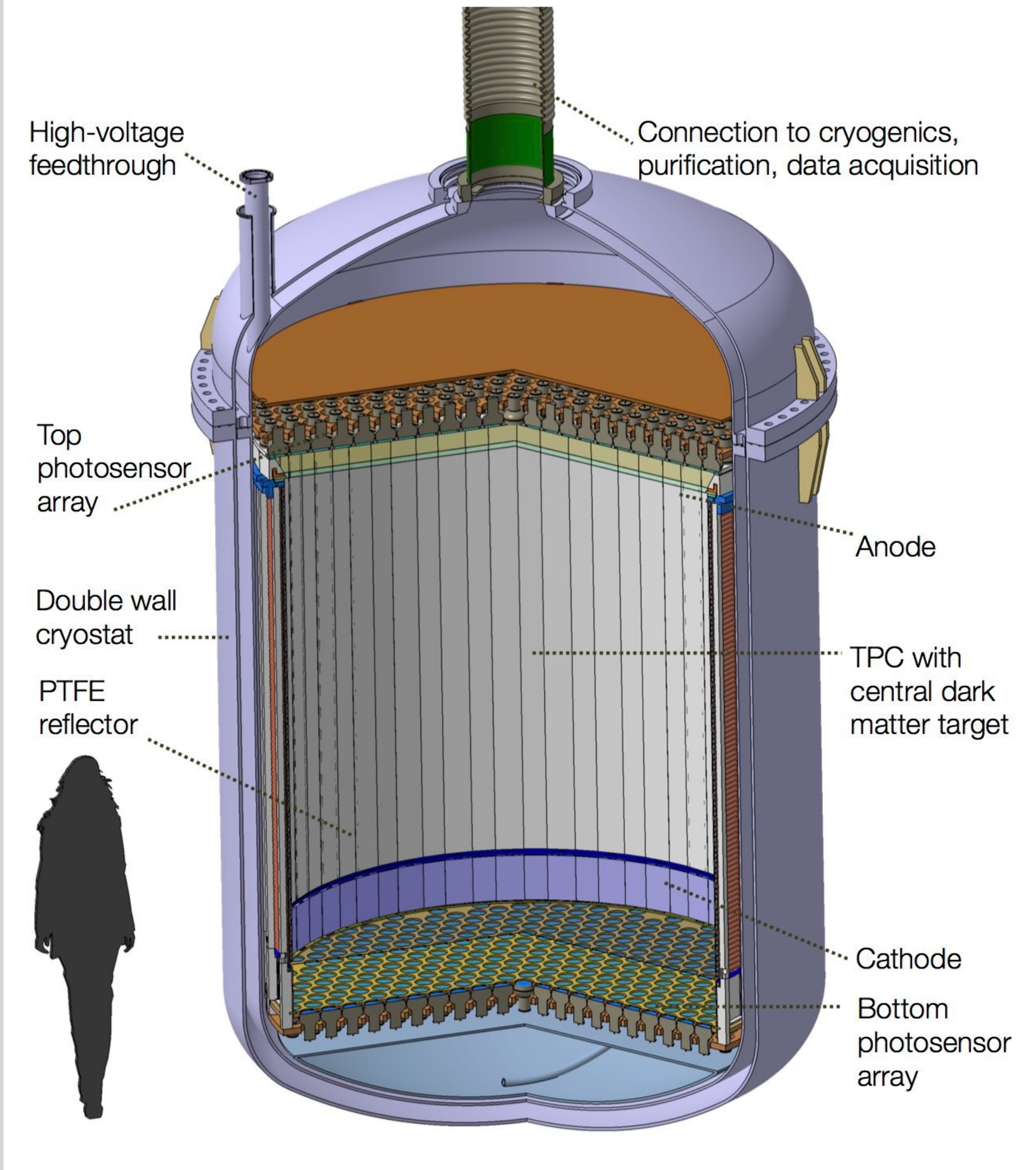
“Ultimate” WIMP detector

50 tonnes liquid xenon

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

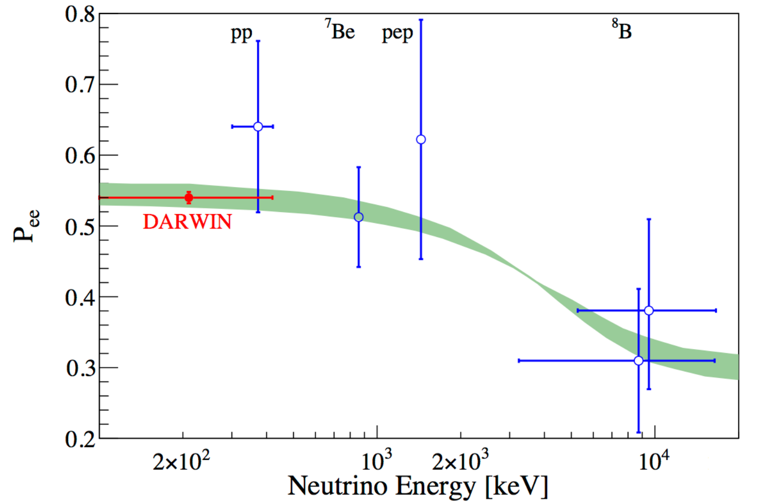


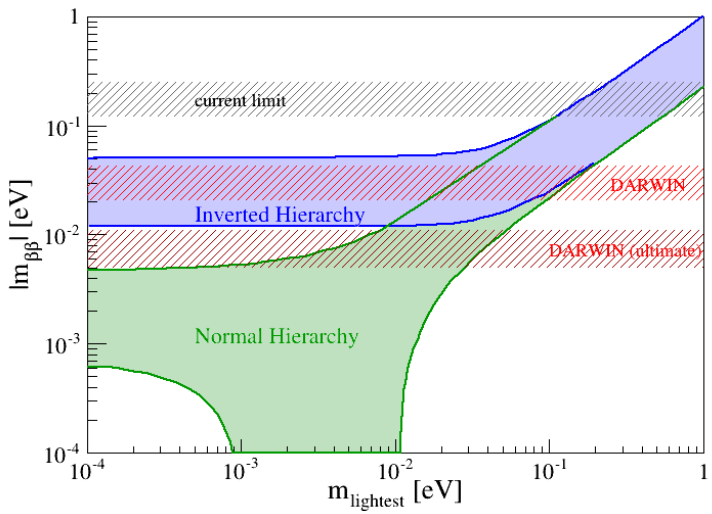




Non-WIMP Physics: a non-exhaustive list

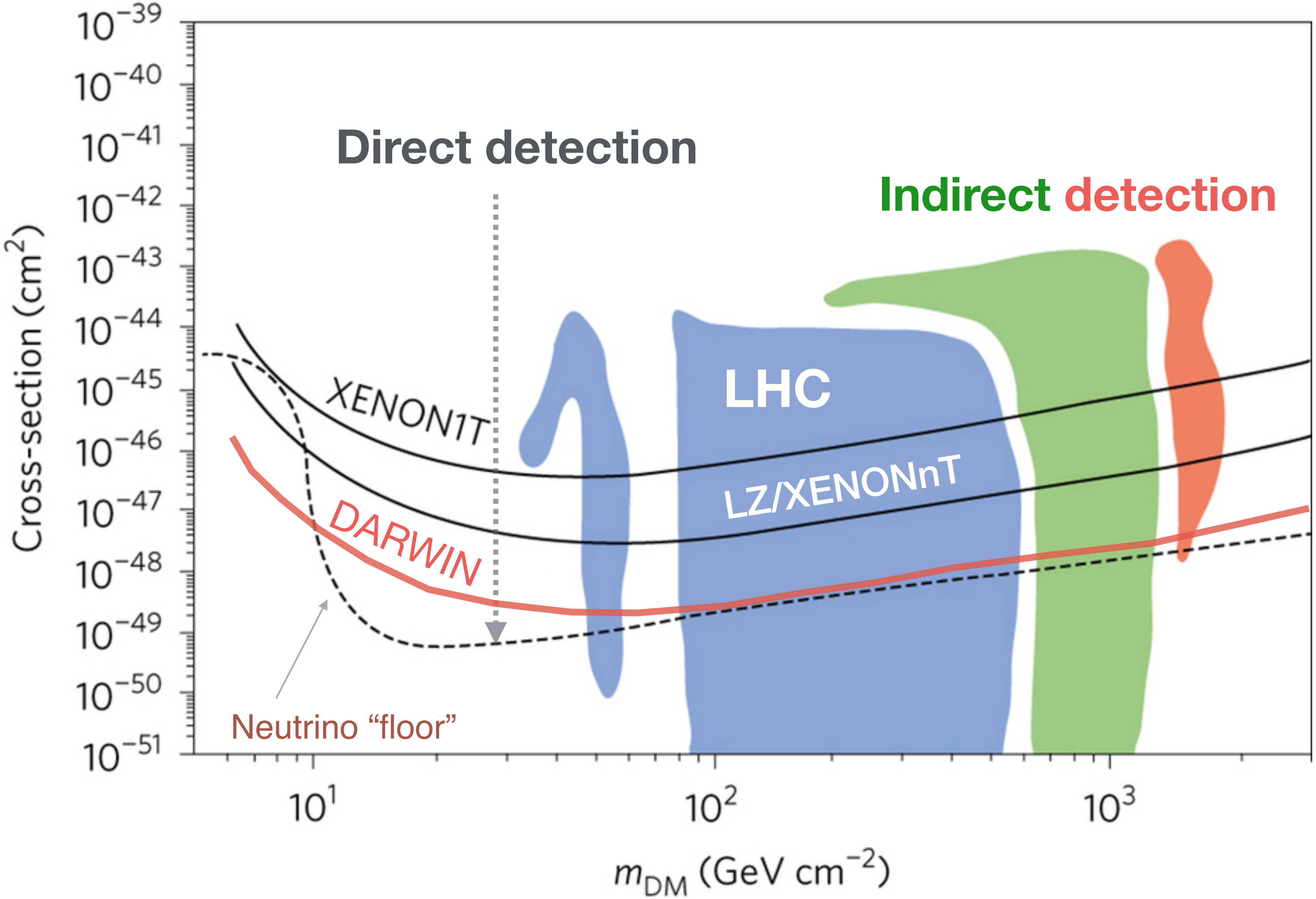
- DM scattering off electrons (leptophilic models)
- pp solar neutrinos (ν-e⁻ scattering) to ~1%
- Coherent ν-nucleus scattering (^{8}B and SN neutrinos)
- Neutrinoless double beta decay in ^{136}Xe
- Double electron capture in ^{124}Xe
- Solar axions and axion-like particles (via axio-electric effect)
- Heavy sterile neutrinos (masses in the > 10 keV range)
- Bosonic SuperWIMPs (via absorption by Xe atoms)





DARWIN collaboration, JCAP 1611 (2016) 017

WIMP Physics: Direct, indirect detection, and LHC

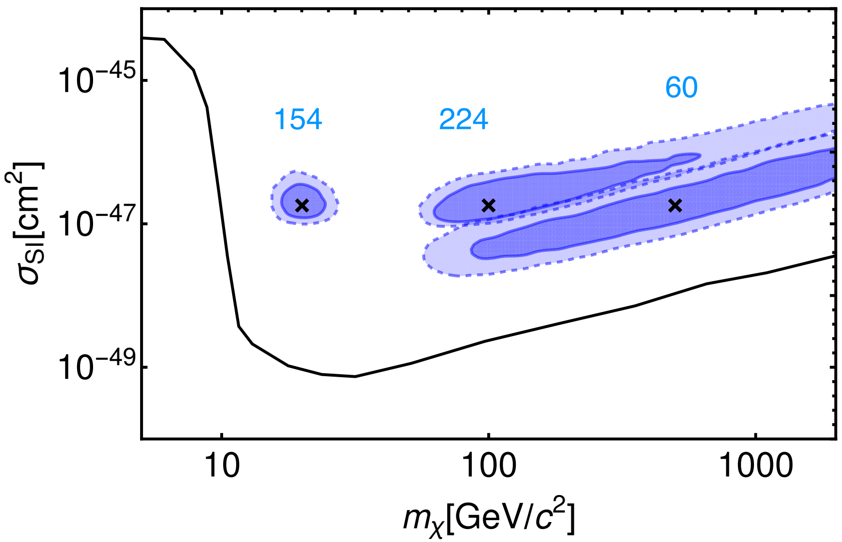


After Nature physics, March 2017

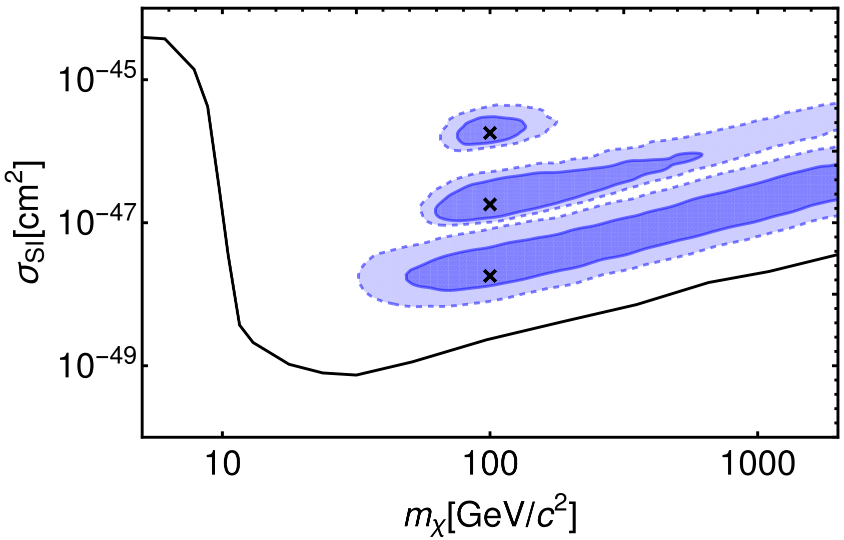
Dark matter spectroscopy

- Capability to reconstruct the WIMP mass and cross section for various masses **(20, 100, 500 GeV/c²)** and cross sections

Exposure: 200 t y



Exposure: 200 t y



1 and 2 sigma credible regions after marginalising the posterior probability distribution over:

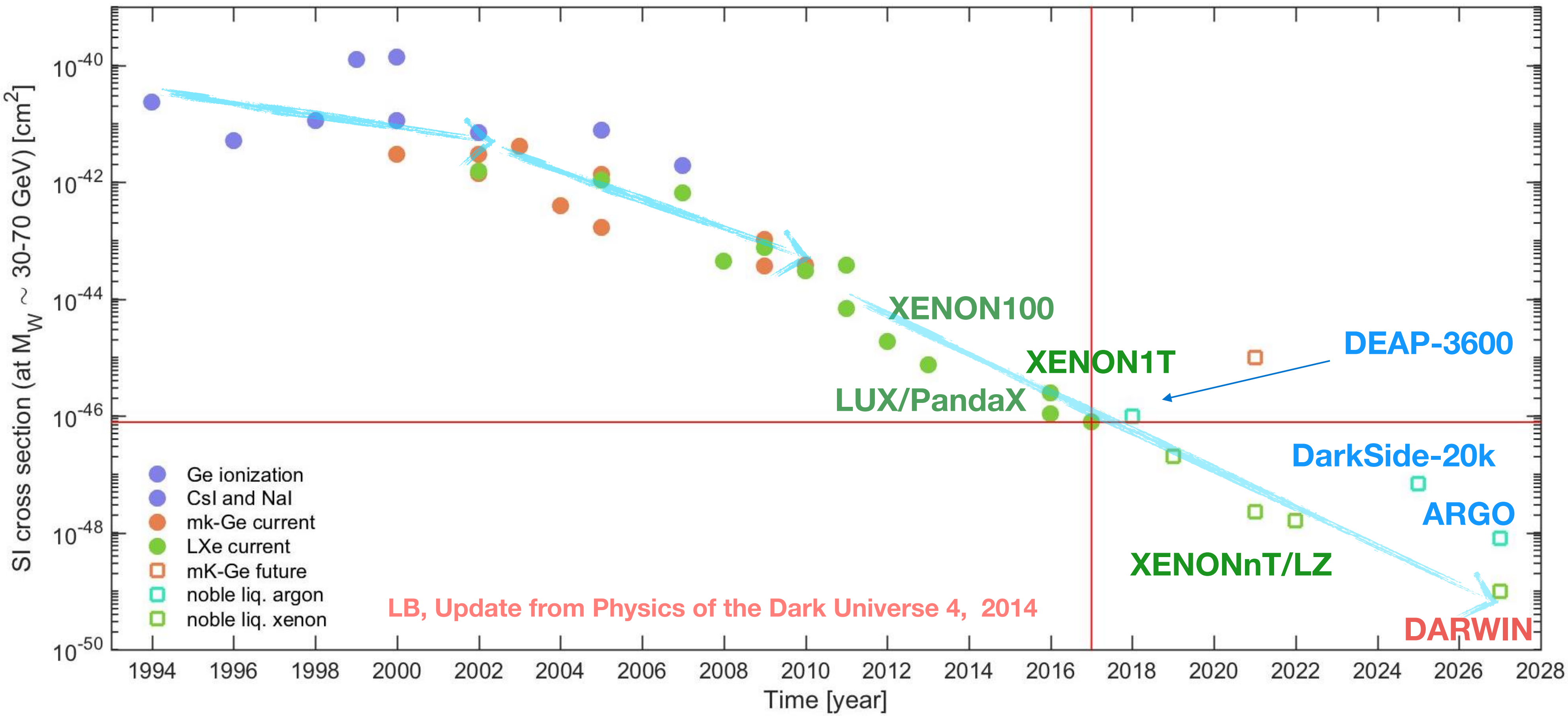
$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

Direct detection versus time

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



Conclusions and Outlook

- The XENON1T experiment operates in stable mode and showed very good data taking performance in 2017 + 2018
- **First physics results published in PRL, from 34.2 live days of data**
- Lowest background in a dark matter detector (~0.2 events/(t d keV))
- More than 250 additional live days of (blinded) science data on disk, new results expected later this spring
- Upgrade on critical path, with XENONnT TDR to LNGS submitted. Upgrade work on site at LNGS to start in late 2018
- R&D and design for ‘ultimate’ 50 t LXe detector (DARWIN) ongoing
- **Stay tuned for a wealth of interesting physics results from Science Run 1 and beyond!**