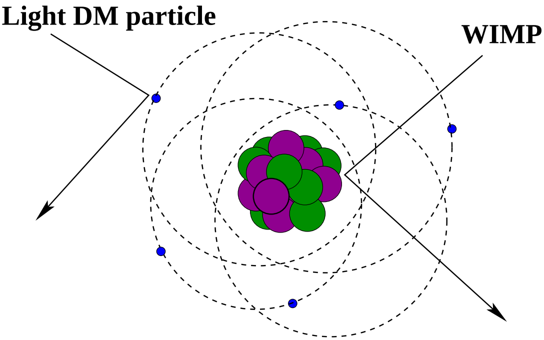
Direct dark matter search with XENON

Teresa Marrodán Undagoitia
On Behalf of the XENON100 Collaboration

Patras workshop on Axions, WIMPs and WISPs,
Mainz, June 2013

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Direct dark matter detection

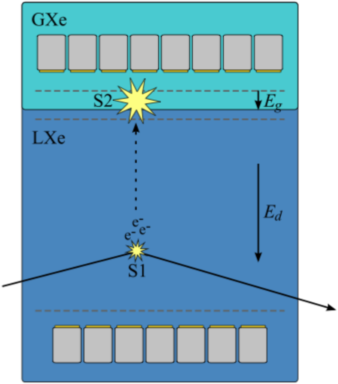


Detection via elastic scattering off
nuclei → nuclear recoils
electrons → electronic recoils

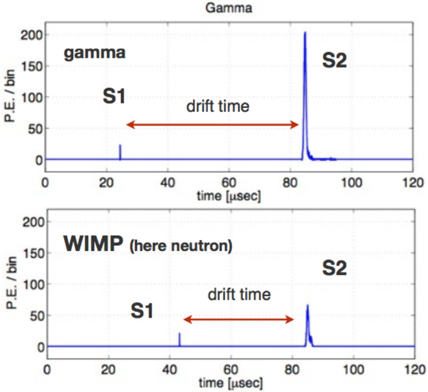
Liquid xenon as detection medium

- High stopping power → good self-shielding
- Scintillation at 178 nm → no wavelength shifter required
- Sensitivity to spin-independent and spin-dependent interactions (^{129}Xe and ^{131}Xe)

Two phase xenon TPC



- Scintillation signal (S1)
- Proportional signal (S2)

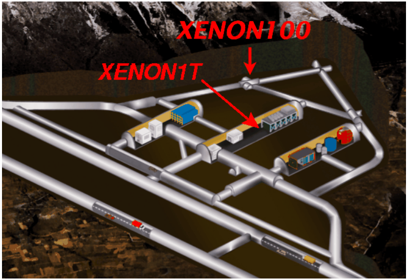


→ Electronic/nuclear recoil discrimination

- Energy scales for NR and ER to-date based on S1!
- Quenching processes are different for NR and ER

The XENON program

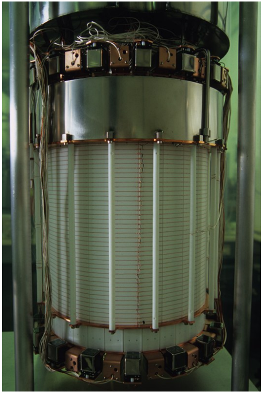
- XENON10: 15 kg active mass
- XENON100: 62 kg active mass
  - Currently running
- XENON1T: $\sim$2.2 T active mass
  - construction just started!



Laboratori Nazionali del Gran Sasso (Italy)

$\sim$ 3 650 m.w.e. shielding

XENON100 TPC



- 30 cm length and 30 cm $\varnothing$
- 161 kg LXe (30 – 50 kg FV)
- Selected low radioactivity materials

XENON100, Astropart. Phys. 35 (2012) 573

The XENON Collaboration

Columbia

Rice

UCLA

Zürich

Coimbra

LNGS

INFN

Bologna

US, Switzerland, Portugal, Italy, Germany, Holland, France and Israel

Subatech

Mainz

Münster

Weizmann

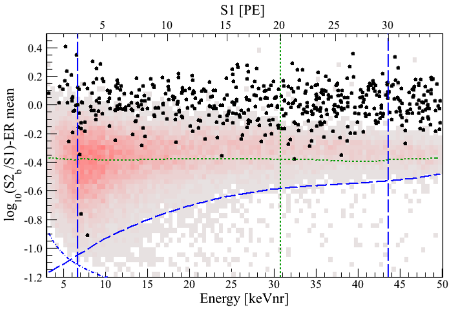
Heidelberg

Nikhef

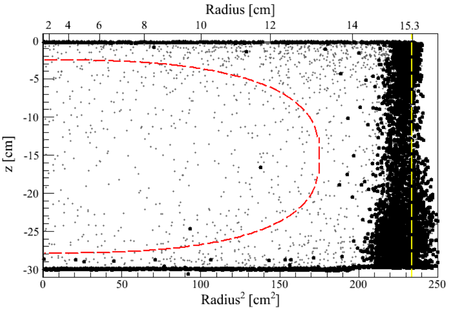
Purdue

Bern

Results from 225 live days data (2012)



Science data



Spatial distribution of events

- No significant signal over expected background

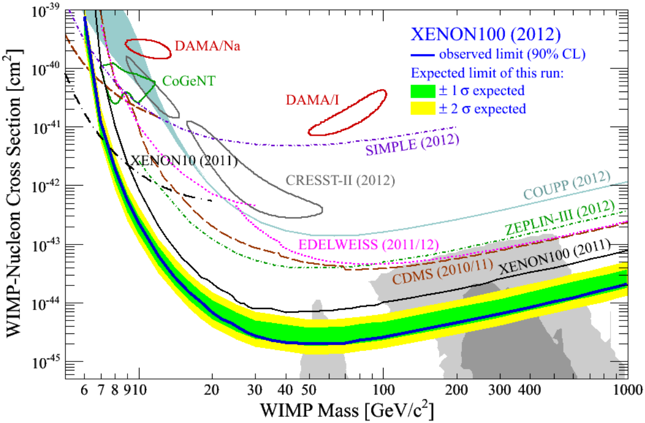
→ Exclusion limit derived using profile likelihood method

Electronic and nuclear recoil backgrounds considered

Recent publication of the neutron background estimation, XENON100 (2013) arXiv:1306.2303

- BG expectation in the benchmark region: (1.0 ± 0.2) events

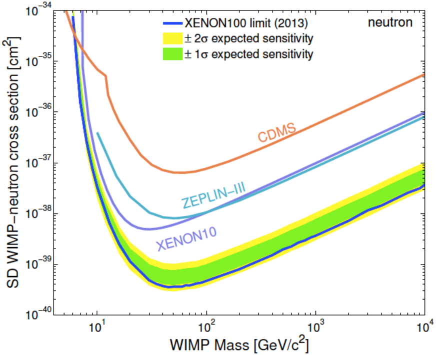
Results from XENON100

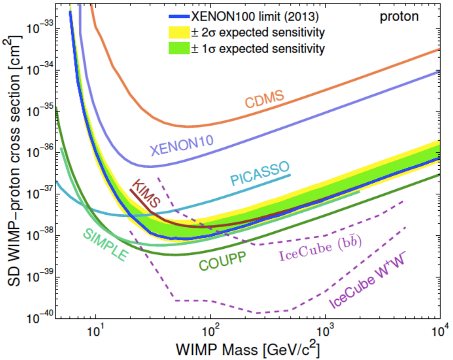


- Spin-independent best sensitivity: $\sigma = 2 \times 10^{-45}$ cm^2 at 55 GeV/c^2 WIMP mass
- Results in tension with signal indications at low WIMP masses

XENON100, Phys. Rev. Lett. 109 (2012) 181301

Spin-dependent results





- Spin-dependent best sensitivity for neutron coupling: 3.5×10^{-40} cm^2 at 45 GeV/c^2 WIMP mass
- Isotopes with a non zero nuclear spin (^{129}Xe & ^{131}Xe)
- Nuclear physics new calculations from Menendez *et al.* used

XENON100, arXiv:1301.6620 (2013) accepted at PRL

Verification of nuclear recoil energy scale

→ XENON100 NR energy scale includes all measurements of direct neutron scattering experiments

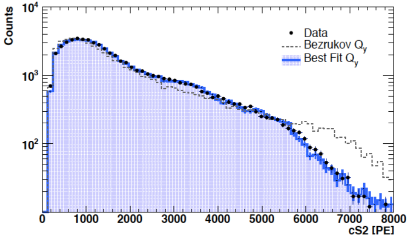
Monte Carlo simulation of neutron source

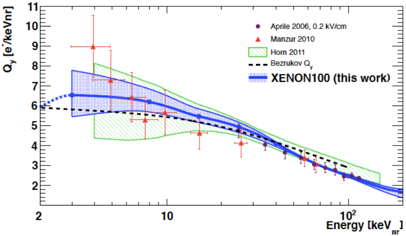
XENON100, arXiv:1304.1427

- Input AmBe spectrum (ISO 8529-1 standard). Analysis robust against variations of this spectrum
- Source strength measurement (PTB): (160 ± 4) n/s
- Complete Monte Carlo description of the detector including detector shield (water, lead, polyethylen and copper)
- E_{dep} is converted to S1 and S2 including thresholds, resolutions and acceptances from data

MC simulation of neutron source

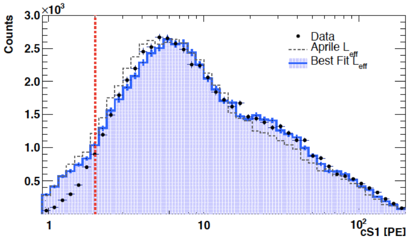
- Step 1: Using L_{eff} from direct measurements, reproduce S2 spectrum → obtain optimum Q_y
- Step 2: Using the obtained Q_y, reproduce S1 spectrum → obtain a new L_{eff}

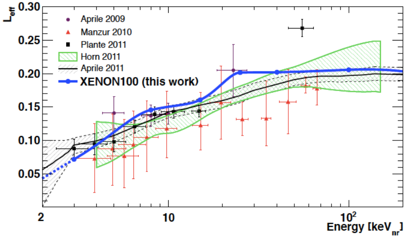




Best fit of source strength: 159 n/s

MC simulation of neutron source

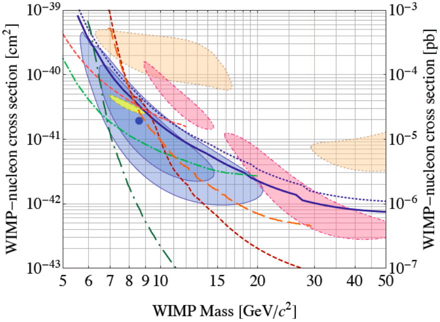


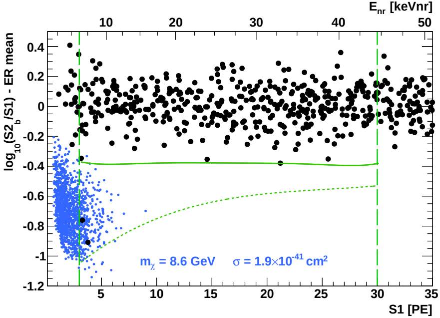


- Poor agreement below 2 PE due to unknown efficiencies below threshold
- Good overall agreement. Best fit L_{eff} matches previous measurements

$\longrightarrow$ Results of XENON100 remain unchanged using this L_{eff}

Recent CDMS signal indication and XENON100





Likelihood analysis: 0.19 % probability that the known-background-only hypothesis

- Best fit at 1.9×10^{-41} cm^2 at 8.6 GeV/c^2 WIMP mass

CDMS, arXiv: 1304.4279

Event distribution that XENON100 would observe for the best fit point of CDMS

(Note that the number of events below threshold are acceptance corrected)

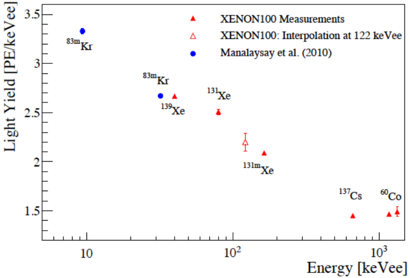
Dark matter particles producing electronic recoils

Knowledge on the ER energy scale and detector threshold required:

- ^{83m}Kr provides monoenergetic lines at 9.4 keV and 32.1 keV

  Manalaysay *et al*, Rev. Sci. Inst. **81**, 073303 (2010)

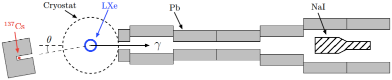
Electronic recoil scale in XENON100

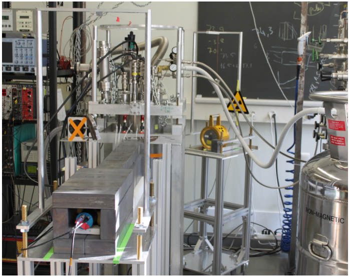


→ 9.4 keV is still a high energy

DAMA oscillation signal is in the (2 – 5) keV energy region

Compton measurement to determine LXe light yield down to ∼ 2 keV

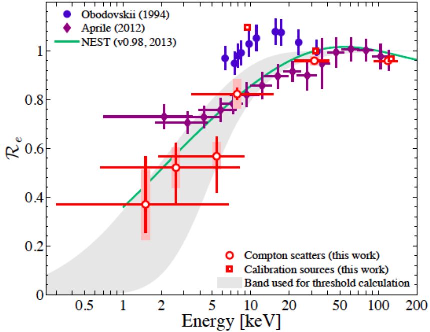


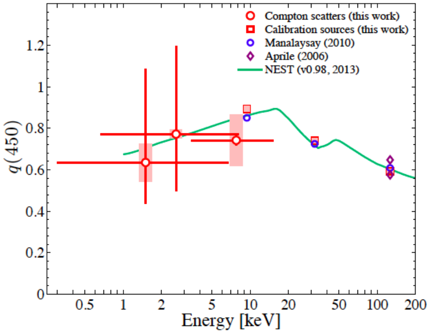


Setup at the University of Zurich

Similar setup at Columbia University: uses Ge as coincidence detector instead of NaI

Results of the Compton experiments





- Light yield decreases at 0-field below 50 keV
- Field quenching $\sim$ 75% at low energies
- Derived XENON100 energy threshold: 2.3 keV
  $\rightarrow$ sensitive to DAMA signal! Results coming soon

Columbia results: Aprile *et al.*, Phys. Rev. D 86, 112004 (2012)

Zurich results including field quenching: Baudis *et al.*, Phys. Rev. D 87, 115015 (2013)

XENON1T

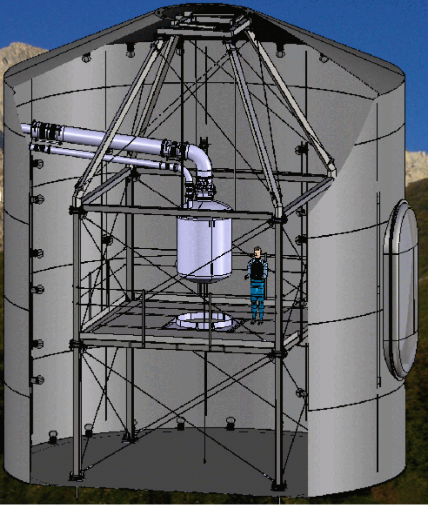
~1 ton fiducial mass (total >3 ton)

1 m drift length

100x less background than in XENON100

Shielding: water-Cherenkov muon veto

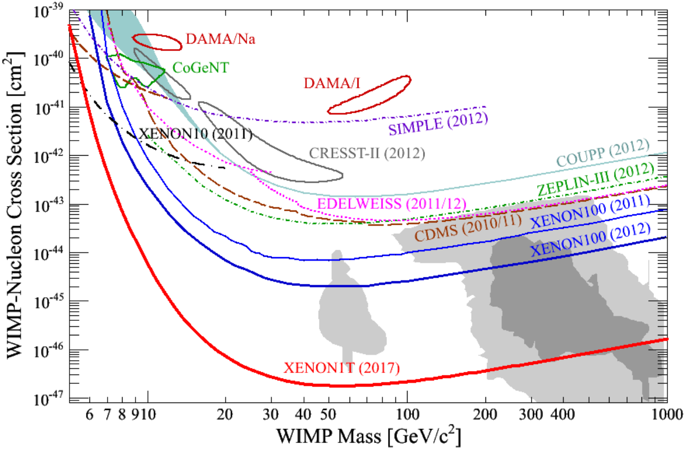
Low radioactive PMTs with <QE>=37%



Construction started in June 2013!

Commissioning by end 2014

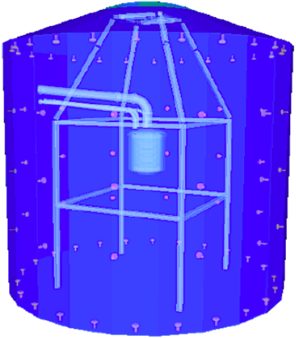
XENON1T sensitivity goal



- Sensitivity goal: $\sigma = 2 \times 10^{-47}\,\text{cm}^2$ for 50 GeV WIMP mass (calculated for 1.1 ton FV)
- Hopefully a WIMP detection!

XENON1T background and suppression

Muon veto design



- Background rejection power:

  $> 99.5\%$ neutrons with a μ tagged in the veto

- Requirement: < 1 event in the full exposure
  - External γ's: suppression via self-shielding ($\rho_{\mathrm{LXe}} \sim 3\,\mathrm{g/cm^3}$) + material screening and selection
  - Internal BGs (Rn and ^{85}Kr): removal using an adsorption tower (Rn) + a cryogenic distillation column (Kr)

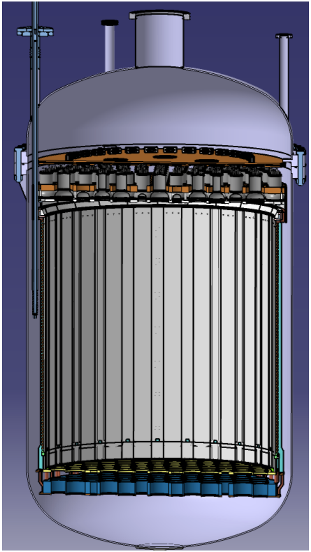
    < 1 ppt nat. Kr in Xe achieved in XENON100!
  - Neutrons: muon veto + material selection

    Low U and Th contaminations $\rightarrow$ low α and (α,n) production

    Example: Development of a low radioactive PMT with Hamamatsu: < 1 mBq/PMT in U and Th!

XENON1T status

XENON1T current TPC design

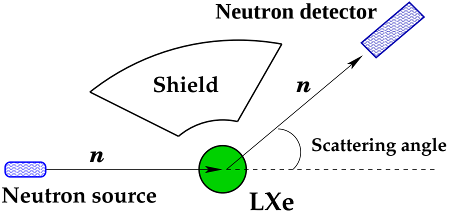


- Construction started in HallB at LNGS
  - Currently support building
  - Next construction of the water tank
- Detector design
  - Teflon UV reflector + high transparent meshes
  - Cooling using pulse tube refrigerators
  - Purification rate $\sim$ 100 s.l.p.m.
  - 1 m e^--drift and 100 kV HV demonstrated

Summary

- Scattering of WIMPs off nuclei
  - XENON100 excludes the current indications of DM
  - Energy threshold (L_{eff}) verified with MC/data comparison of an AmBe neutron source
- Scattering of light dark matter particles off electrons
  - XENON100 threshold is at $\sim 2.3\,\text{keV}$
  - XENON100 analysis of time variations of the background rate ongoing
- XENON1T constructions starts this year
  - Aimed sensitivity of $2 \times 10^{-47}\,\text{cm}^2$ for 50 GeV WIMP mass
  - Construction ongoing + optimisation of TPC design
  - Planned start of science run: early 2015

L_{eff} direct measurements



Nuclear recoil energy (E_{nr}):

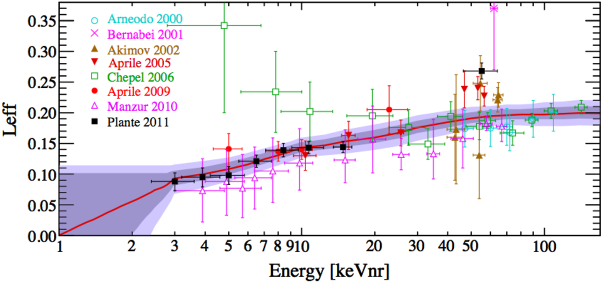
$$E_{nr} = \frac{S1}{L_y L_{eff}} \times \frac{S_e}{S_r}$$

$S1$: measured signal in p.e.

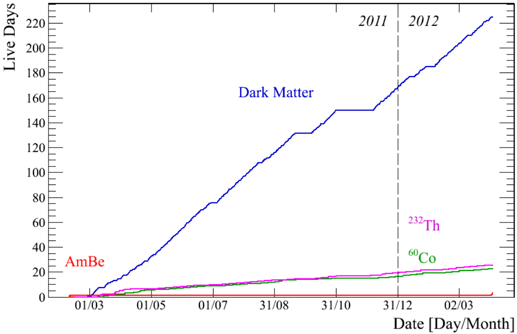
L_y: LY for 122 keV γ in PE/keV

S_e/S_r: quenching for 122 keV γ/NR due to drift field

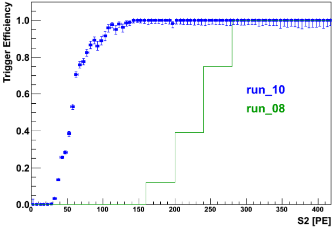
$$L_{eff} = q_{nucl} \times q_{el} \times q_{esc}$$



Dataset: 225 live days

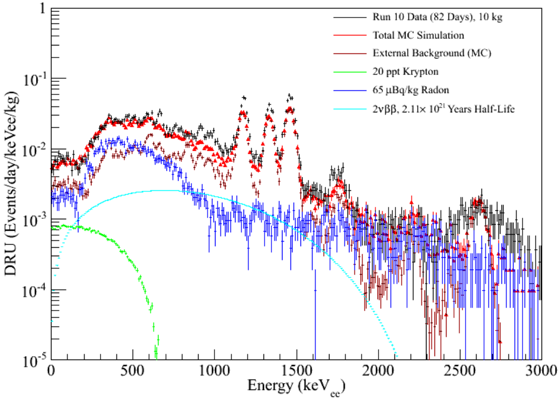


- Lower S1 threshold at 3 PE $\sim$ 6.6 keV$_{nr}$
- S2 trigger efficiency improved at 100% above 150 PE



$\longrightarrow$ More than one year continuous operation, detector stable during the whole run

Electronic recoil spectrum



- ^{85}Kr concentration reduced: dedicated LXE distillation column
- RGMS measurements $\rightarrow (19 \pm 4)$ ppt
- Radon contamination: delayed coincidence and α-tagging
- Radioactivity of materials is a dominant contribution

$\longrightarrow$ Background level: $(5.3 \pm 0.6) \cdot 10^{-3}$ events/(keV kg day) in 34 kg

Data analysis

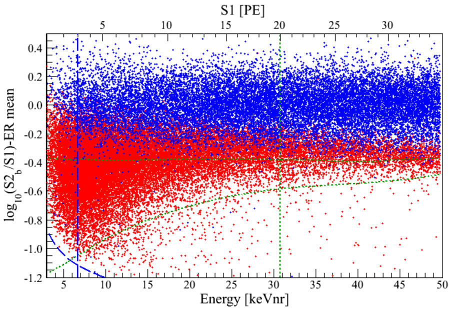
- Blind analysis:

$\rightarrow$ data selection based on calibration/non-blinded science data

- Data stability:
  $\rightarrow$ Selection of periods with stable HV, low radon level, stable thermodynamics of the detector (P, T, ...)
- Selection of physical interactions:
  $\rightarrow$ Noise cuts, stability of PMTs, width of S2 pulses, S2 pulse above threshold and S1 pulse seen by at least 2 PMTs
- Selection of single scatters:
  $\rightarrow$ Single S1 and single S2, S1 PMT pattern, cut on position reconstruction, veto cut
- Fiducial volume and WIMP search region:
  $\rightarrow$ 34 kg elliptic volume, $(3 < \mathrm{S1} < 30)$ PE and S2/S1 $> 3\sigma$ contour of the NR distribution

Analysis paper: XENON100 (2012), arXiv:1207.3458

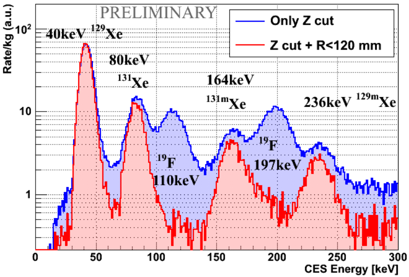
Calibration data



- Main analysis based on a profile likelihood method
  XENON100, Phys. Rev. D 84, 052003 (2011)
- Benchmark WIMP region

- Electronic recoil band: defined with ^{60}Co and ^{232}Th sources
- Nuclear recoil band: defined with AmBe neutron source

→ ER lines during n-calibration:



Background prediction in the benchmark region

- Electronic recoil background
  - Gaussian and anomalous leakage

  → determined using non-blinded background data and MC and data from ^{60}Co/^{232}Th calibration sources
  - (0.79±0.16) events
- Neutron background prediction
  - Muon-induced fast neutrons (70% of the total)
  - $\alpha - n$ reactions and spontaneous fission
  - $(0.17^{+0.12}_{-0.07})$ events
- Total BG: (1.0±0.2) events in 225 d