First results from the XENON1T dark matter experiment

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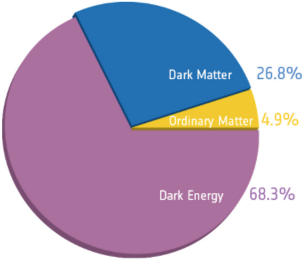
FÜR KERNPHYSIK
HEIDELBERG

DESY

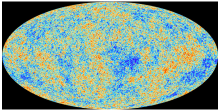
Cosmological and astronomical hints

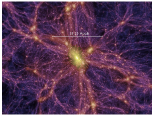
- Cosmic microwave background
- Large scale structure-formation

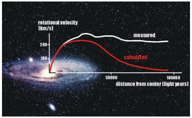
- Velocity dispersion of galaxies in clusters (F. Zwicky 1933)
- Rotation velocities of stars in galaxies (V. Rubin 1978)
- Gravitational lensing (A. Einstein 1936)
- Collisions of galaxy clusters (Bullet cluster, Abell 520 and few others)



After Planck







What is dark matter?

Early solutions to the missing mass problem:

- Modified gravitational theories e.g. MOND (Milgrom 1983)
  → fail/need unrealistic parameters for some observables (e.g. CMB)
- Massive astrophysical compact halo objects: MACHOS
  → not enough such objects found (MACHO Coll. 2001) & BBN

Well motivated theoretical approach:

WIMP

(**W**eakly **I**nteracting **M**assive **P**article)

- Predicted in theories beyond the standard model of particle physics
- Correct relic density for an annihilation rate ∼ weak scale

→ Dark matter could be non weakly-interacting or a different particle!

How can we look for dark matter?

Indirect detection

Direct detection

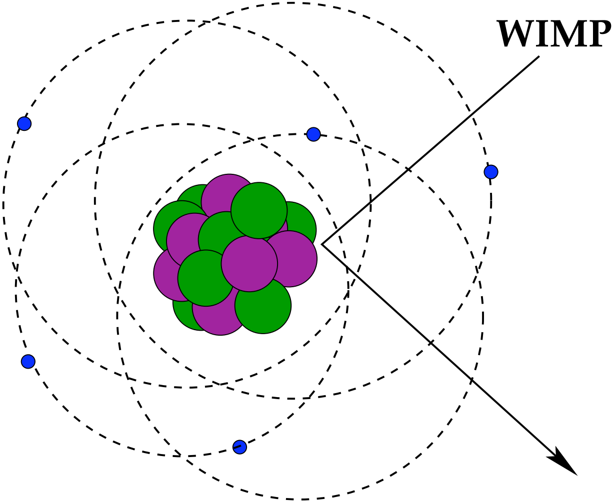
Production at LHC

$\chi\overline{\chi} \rightarrow \gamma\gamma, q\overline{q}, \ldots$

$\chi\,\mathrm{N} \rightarrow \chi\,\mathrm{N}$

$\mathrm{p} + \mathrm{p} \rightarrow \chi\overline{\chi} + \mathrm{X}$

Direct dark matter detection



$$E_{\mathrm{R}} \sim \mathcal{O}(10\,\mathrm{keV})$$

Expected interaction rates in a detector

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3 v$$

Astrophysical parameters:

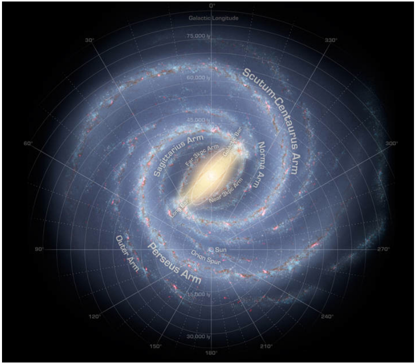
- ρ_0 = local density of the dark matter in the Milky Way

  'Standard' value: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$ $\simeq 3\,000\,\mathrm{WIMPs/m^3}$
- $f(\mathbf{v},t)$ = WIMP velocity distribution, $\langle v \rangle \sim 220\,\mathrm{km/s}$

Parameters of interest:

- m_χ = WIMP mass ($\sim 100\,\mathrm{GeV}$)
- σ = WIMP-nucleus elastic scattering cross section (SD or SI)

Figure from NASA



Cross sections for WIMP elastic scattering

- Spin-independent interactions: coupling to nuclear mass

  $\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi+m_N)^2} \cdot [Z \cdot f_p + (A-Z) \cdot f_n]^2$

  $f_{p,n}$: effective couplings to p and n.

- Spin-dependent interactions: coupling to nuclear spin

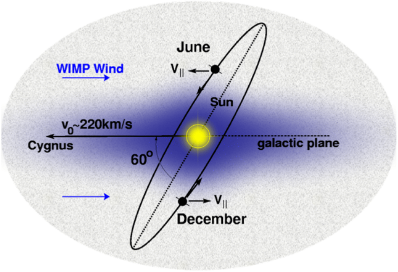
  $\sigma_{SD} = \frac{32}{\pi} \cdot G_F \cdot \frac{m_\chi^2 m_N^2}{(m_\chi+m_N)^2} \cdot \frac{J_N+1}{J_N} \cdot [a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2$

  $\langle S_{p,n}\rangle$: expectation of the spin content of the p, n in the target nuclei
  $a_{p,n}$: effective couplings to p and n.

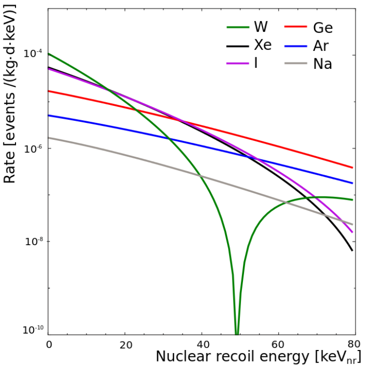
Detector requirements and signatures

- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold ∼ few keV's
  - Very low background and/or background discrimination

- Other signatures of dark matter
  - Annual modulated rate
  - Directional dependance



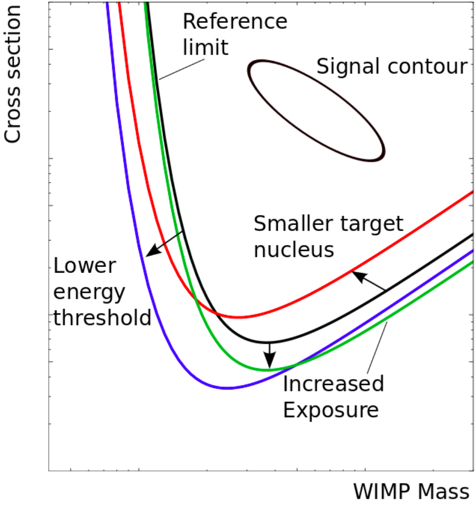
J. Phys. G: 43 (2016) 1, arXiv:1509.08767



Result of a direct detection experiment

→ Statistical significance of signal over expected background?

J. Phys. G: 43 (2016) 1, arXiv:1509.08767



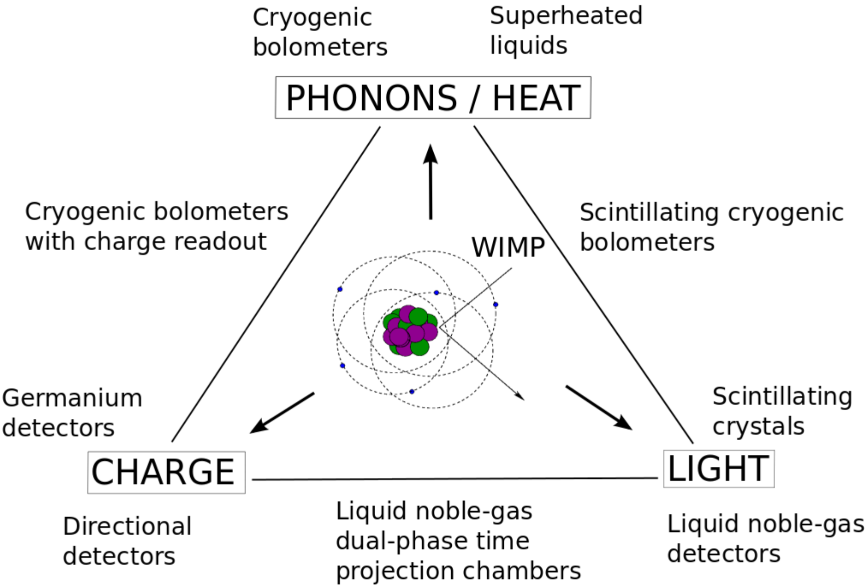
- Positive signal
  - Region in σ_χ versus m_χ
- Zero signal
  - Exclusion of a parameter region

o Low WIMP masses: detector threshold matters

o Minimum of the curve: depends on target nuclei

o High WIMP masses: exposure matters $\epsilon = m \times t$

Direct detection experiments



Cryogenic bolometers

Superheated liquids

PHONONS / HEAT

Cryogenic bolometers with charge readout

WIMP

Scintillating cryogenic bolometers

Germanium detectors

Scintillating crystals

CHARGE

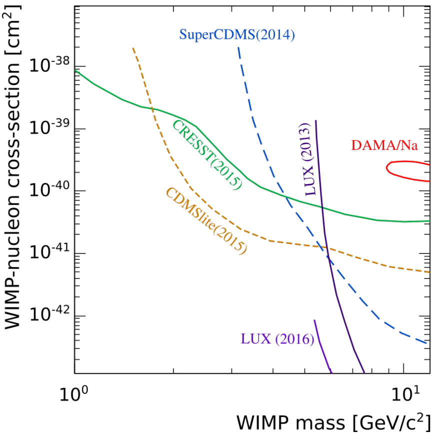
LIGHT

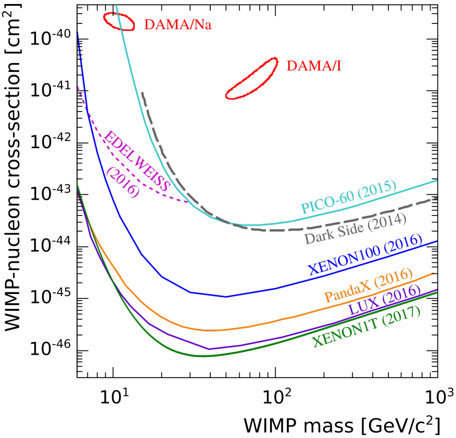
Directional detectors

Liquid noble-gas dual-phase time projection chambers

Liquid noble-gas detectors

Overview spin-independent results





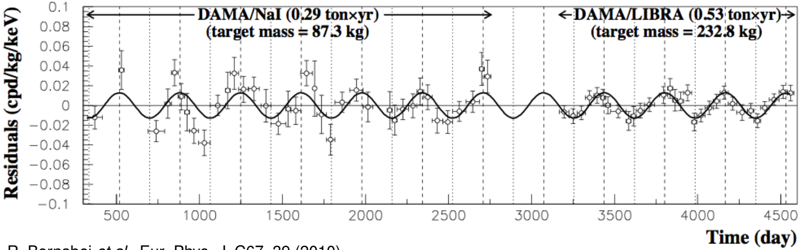
Figures from C. Hasterok

DAMA annual modulation

- Ultra radio-pure NaI crystals
- Annual modulation of the background rate in the energy region (2 – 6) keV

  9.3 σ significance!

  R. Bernabei, Eur. Phys. J. C73 12 (2013) 2648, arXiv:1308.5109
- No discrimination of electronic recoils from nuclear recoils



R. Bernabei *et al.*, Eur. Phys. J. C67, 39 (2010)

What is causing the DAMA signal?

- Results of other experiments disfavour the DAMA signal

  → SI/SD interpretations

  → XENON100 annual modulation study

  XENON100, PRL 118, 101101 (2017) & arXiv:1701.00769

- Muon-flux modulates due to the changing temperature of the atmosphere: muon-induced signal? Blum, arXiv:1110.0857

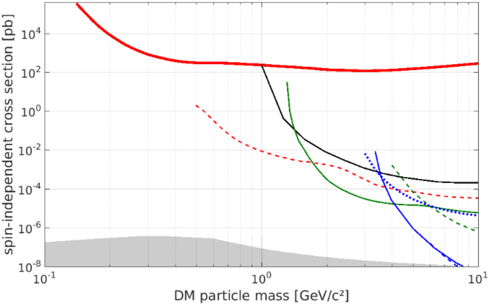
  → but this has a different phase

- Neutrinos also modulate (due to the varying Sun-Earth distance)
  → Combination of muon-induced and neutrino flux? Davis, arXiv:1407.1052

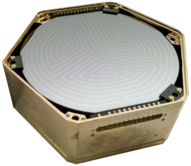
- Varying rates of background neutrons? Ralston, arXiv:1006.5255

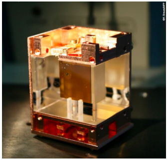
- Experimental effect?

At low WIMP masses: cryogenic bolometers



Limits curves from CRESST, CDMS & EDELWEISS, LXe detectors and DAMIC





→ Best sensitivities at low WIMP masses

- CRESST scintillating $CaWO_4$ crystals $E_{th} = 307\,\text{eV}$

  CRESST, Eur. Phys. J. C76 (2016) 25, arXiv:1509.01515

  → Recent MeV-DM results from a gram-scale detector $E_{th} \sim 20\,\text{eV}$

  arXiv:1707.06749 (2017)

- CDMSlite germanium bolometers $E_{th} = 56\,\text{eV}$

  CDMSlite, Phys. Rev. Lett. 116 (2016) and also arXiv:1707.01632 (2017)

Spin-dependent interactions & bubble chambers

- Energy depositions $> E_{th}$ $\rightarrow$ expanding bubble detected with cameras + piezo-acoustic sensors
- A bubble chamber filled with superheated fluid (C_3F_8) in meta-stable state

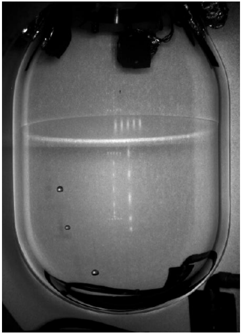
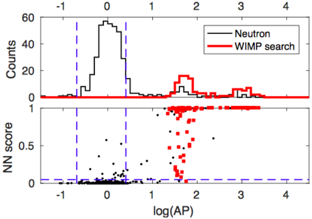


Figure from COUPP

Acoustic power (AP) and neuronal network (NN score), PICO, arXiv:1702.07666 (2017)



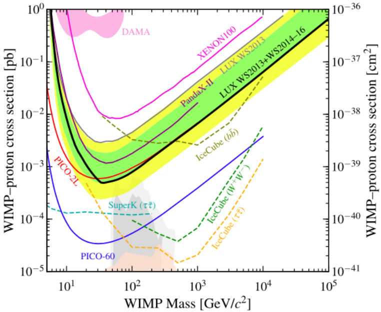


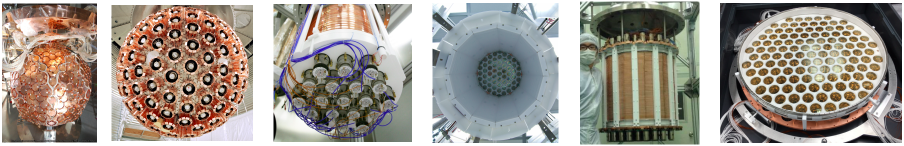
Figure from LUX, Phys. Rev. Lett. 118 (2017) 251302

Advantages of liquid noble gases for DM searches

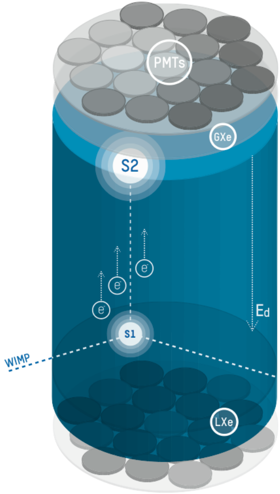
- Large masses and homogeneous targets
- 3D position reconstruction → fiducialization
- Transparent to their own scintillation light

	LNe	**LAr**	**LXe**
Z (A)	10 (20)	18 (40)	54 (131)
Density [g/cm^3]	1.2	1.4	3.0
Scintillation λ	78 nm	125 nm	178 nm
Ionization [e$^-$/keV]*	46	42	64
Scintillation [γ/keV]*	7	40	46

* for electronic recoils

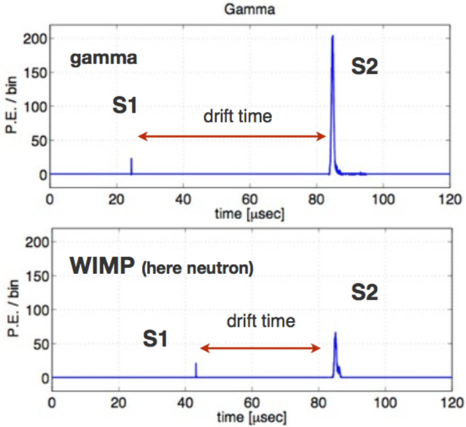


Two phase noble gas TPC



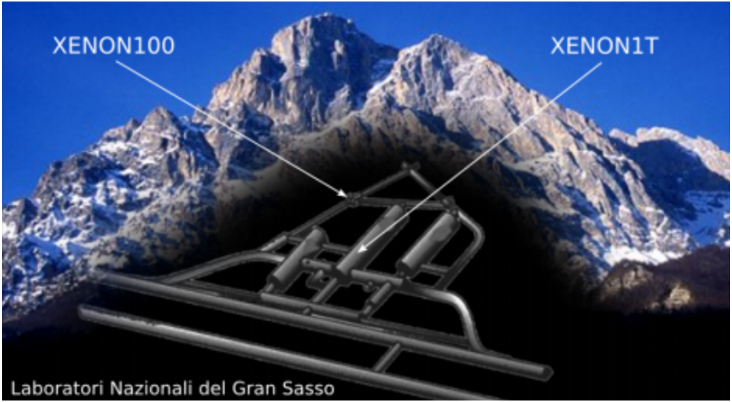
- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)

→ Electron- /nuclear recoil discrimination



- Drift field
- Electronegative purity
- Position resolution

XENON experiment



- Laboratori Nazionali del Gran Sasso (Italy) below 3 650 m.w.e. shielding
- Completed: XENON100 with 62 kg active mass
- Currently taking data: XENON1T using 2 ton active mass
- Future: XENONnT with ∼ 6 ton active mass

The XENON collaboration

Columbia
RPI
Nikhef
Stockholm
Muenster
Mainz
MPIK

Chicago
UCLA
UCSD
Rice

Freiburg
Zurich
NYUAD
Weizmann

Purdue
Coimbra
Subatech
LPNHE
LAL
Bologna
LNGS
Torino

XENON1T

XENON1T @ LNGS in Italy

XENON1T infrastructure

- Kr-distillation column,
- purification & cryogenic systems,
- storage and filling systems, ...

→ All installed and commissioned early 2016

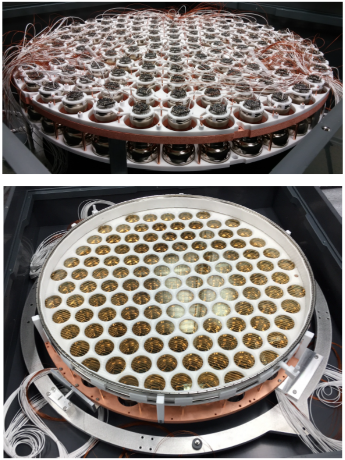
The XENON1T TPC

XENON1T TPC (Sept. 2015)

TPC design

$\sim$ 1 m height and 1 m $\varnothing$

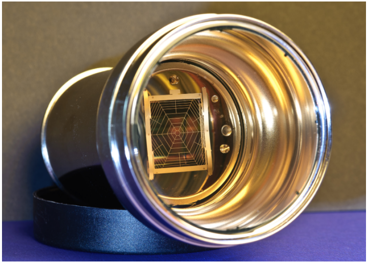
2 t LXe in the target (3.2 t total mass)



Photosensors

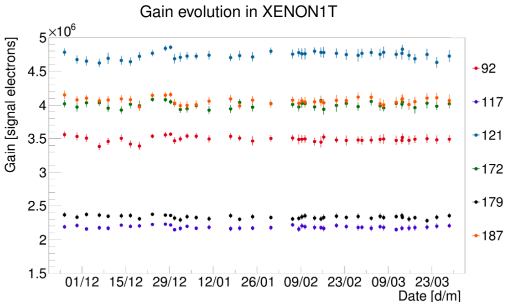
248 low-background Hamamatsu R11410 3-inch PMTs, EPJC 75 (2015) 11, 546

Low radioactivity sensor for XENON1T

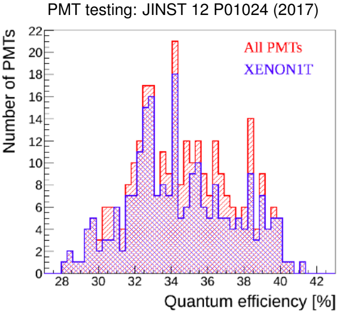


- **High QE**: $\sim 35\,\%$ at $175\,\text{nm}$
- **30%** Single PE resolution
- **Sub-mBq** activities in U & Th

  For reference: 1 Banana $\sim$ 15 Bq in ^{40}K
- **Low DC rates** in XENON1T:
  $\langle R \rangle_{top} = 12\,\text{Hz}$ & $\langle R \rangle_{bottom} = 24\,\text{Hz}$



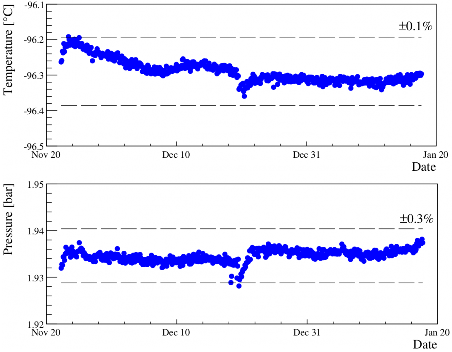
Gain evolution in XENON1T



PMT testing: JINST 12 P01024 (2017)

Detector stability and xenon purity

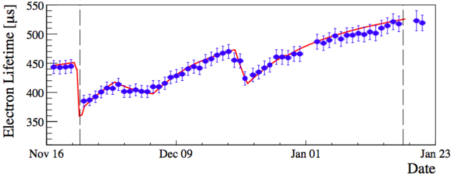
- Removal of electronegative impurities below 1 ppb (O_2 eq.)
- Continuous recirculation of xenon gas through hot getters
- Evolution of the 'electron lifetime': a measure of the number of electrons lost during the drift time



Temperature and pressure stability during SR0
XENON1T, arXiv:1708.07051

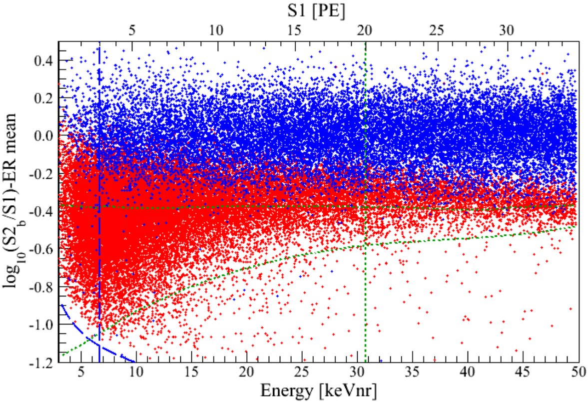
- LXe temperature: (177.08 ± 0.04) K
- GXe pressure: (1.934 ± 0.001) bar
- LXe liquid level: (2.5 ± 0.2) mm

Purity evolution during SR0
XENON1T, arXiv:1708.07051



Background reduction

- Nuclear recoil background: in the WIMP signal region
- Electronic recoil background: affects signal region due to leakage

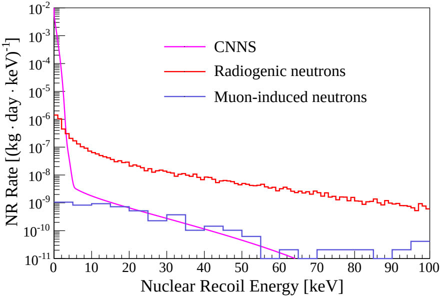


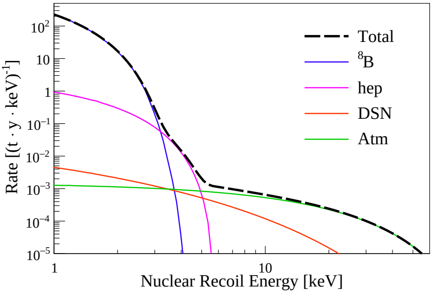
Example using calibration data from the XENON100 detector

Nuclear recoil backgrounds

- External neutrons: muon-induced, (α, n) & fission reactions
  - Underground location + active water Cherenkov veto
  - Material selection for low U and Th contaminations

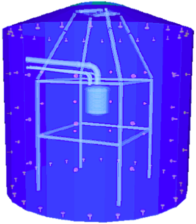
- Neutrinos: Coherent neutrino-nucleus scattering





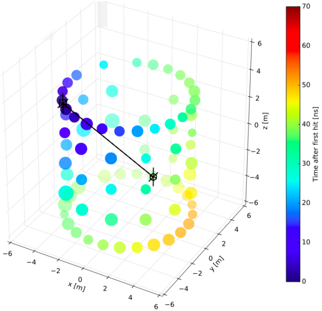
XENON1T, JCAP04 (2016) 027, arXiv:1512.07501

Water Cherenkov detector



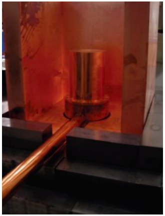
- Active water-Cherenkov muon shield
- Instrumented with 84 PMTs (8” R5912)
- Trigger efficiency $> 99.5\,\%$ for neutrons (muon in the water tank)
- Science run 0: no muon event in coincidence with the TPC events

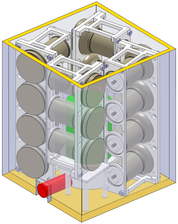
Muon veto design, JINST 9 (2014) P11006

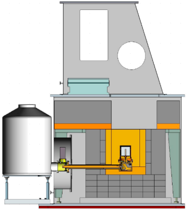


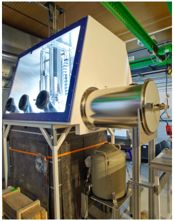
XENON1T, arXiv: 1708.07051

Material screening and selection


Inner chamber of Gator


15 PMTs inside the screening chamber


Scheme GeMPI detecor


Giove @ MPIK

- High sensitive HPGe spectrometers
  - GeMPIs and Gator detectors at LGNS with $\sim$ 10 μBq/kg sensitivity in U & Th
- Further detectors at MPIK shallow depth lab
  - Newly developed GIOVE with 'only' an order of magnitude less sensitivity

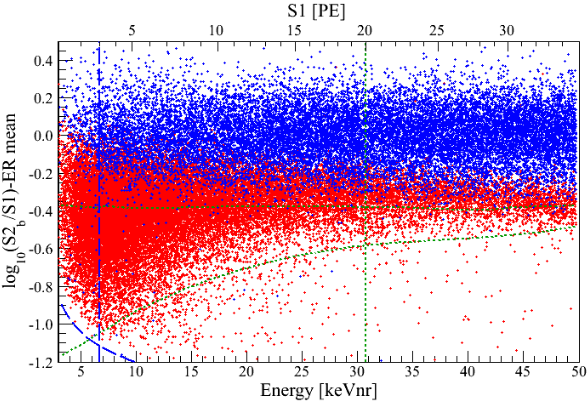
    G. Heusser *el al.*, EPJC75 (2015) 11, 531

→ Selection of cleanest materials for the XENON1T detector construction

XENON Collaboration (2017), arXiv:1705.01828

Background reduction

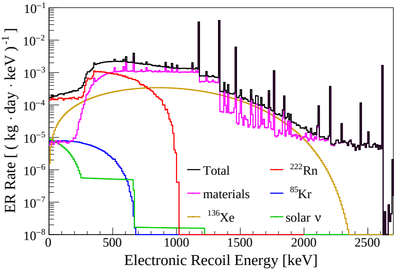
- Nuclear recoil background: in the WIMP signal region
- Electronic recoil background: affects signal region due to leakage



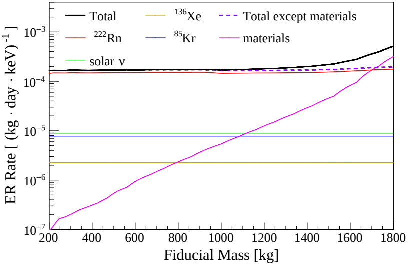
Example using calibration data from the XENON100 detector

Electronic recoil backgrounds

- External γ's: from natural radioactivity:
  - Suppression via self-shielding of the target
  - Material screening and selection
- Neutrinos: Elastic neutrino-electron scattering of ν from the Sun
- Internal contamination:
  - Xenon: ^{136}Xe $\beta\beta$ decay ($T_{1/2} = 2.3 \times 10^{21}$ y)
  - ^{85}Kr: removal by cryogenic distillation
  - Rn: Material selection + eventually online removal



Average rate in the energy range (1 — 12) keV



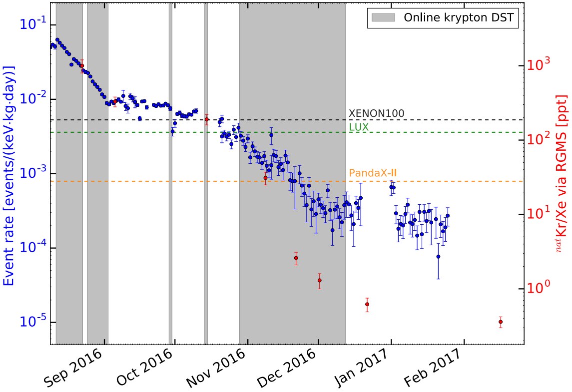
XENON1T, JCAP04 (2016) 027, arXiv:1512.07501

XENON1T background during commissioning

- Lowest background level of all LXe experiments
- Krypton background reduced by online cryogenic distillation

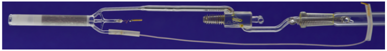
  XENON1T, Eur. Phys. J. C 77 (2017) 275
- Krypton level measured independently by RGMS

  Eur. Phys. J. C 74 (2014) 2746

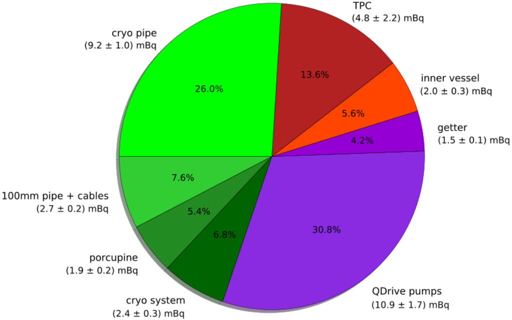


Radon budget and its reduction

- Radon emanation measurements for material selection



miniaturized proportional counter



Radon budget in XENON1T (preliminary)

- R&D on radon reduction
  - Surface cleaning/coating
  - Cryogenic distillation

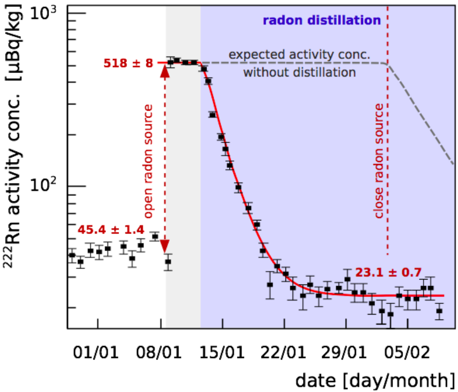
  See arXiv:1611.03737 & arXiv:1702.06942

- Prediction for XENON1T: 10 μBq/kg

Demonstration of radon distillation

→ Proof of single-stage radon distillation: $R > 4$

S. Bruenner et al. EPJC 77 (2017) 3, 143 arXiv:1611.03737



- XENON100 krypton distillation column operated in reverse mode without xenon loss

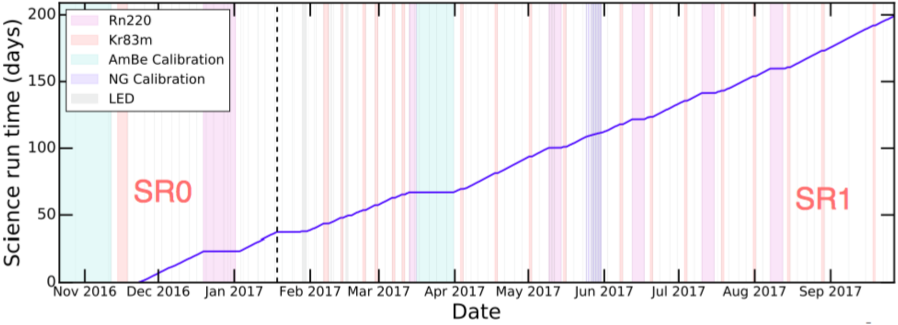
→ Two distillation runs with & without a radon source

- Reduction factor: $R > 27$ at 95% C.L.

XENON100, EPJC (2017) 77, 358 & arXiv:1702.06942

→ Distillation also tested in XENON1T using Kr-column in reverse mode: 20% reduction on radon background XENON1T, arXiv: arXiv:1705.06655

Data exposure



- SR0: 34.2 live days acquired → published
- SR1: currently on-going, more than 150 additional live days

Calibration in XENON1T

- Electronic recoil band determined from Rn220 calibration

  Injected from a ^{228}Th source, XENON100, arXiv:1611.03585

- Nuclear recoil (signal region) data from AmBe neutron source

- Background data (α-particles from ^{222}Rn decays) used to monitor the detector response

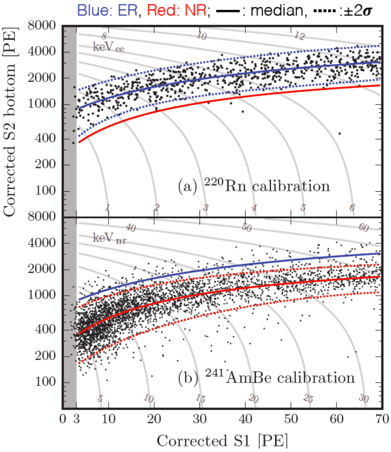
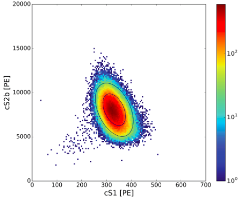
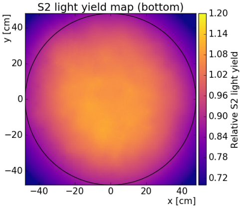


Figure from XENON1T, arXiv:1705.06655

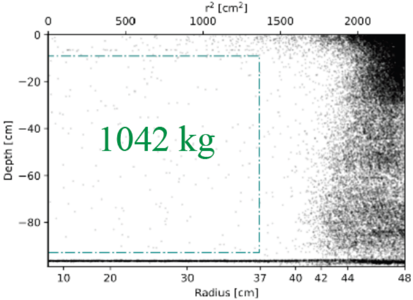


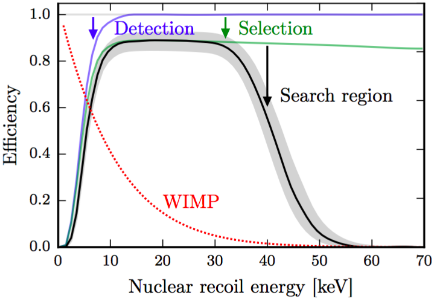


→ Data corrections and processor performance tested on ^{83m}Kr data

Event selection and efficiencies

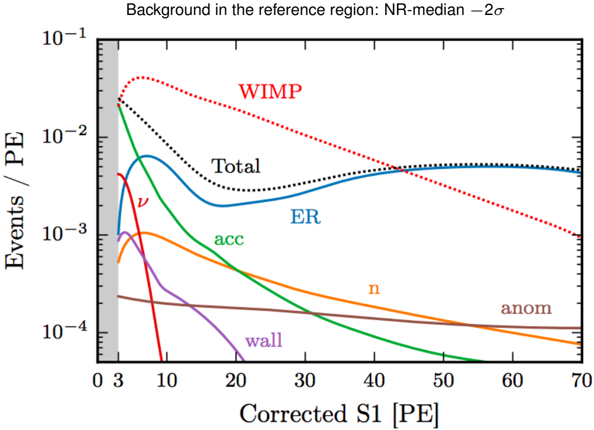
- Blind analysis: selection criteria defined on calibration data
- Energy range: $(3 < cS1 < 70)$ PE
- Analysis volume of $\sim$ 1 ton





- Detection efficiency dominated by the 3-fold coincidence requirement
- Efficiencies calculated from control samples or from simulation

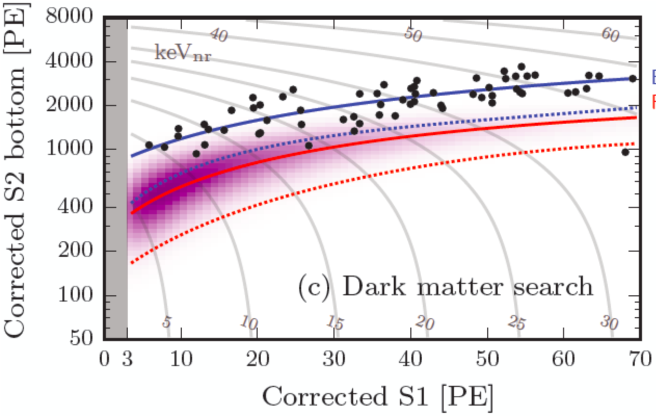
Background model



- Background modelled using calibration and science data outside the ROI
- Accidental coincidences dominate at low energies
- Radon is the main contributor above few PE

Figure from XENON1T, arXiv:1705.06655

Science data



Blue: ER

Red: NR

— : median

····· :-2σ

Figure from XENON1T, arXiv:1705.06655

XENON1T first result and future sensitivity

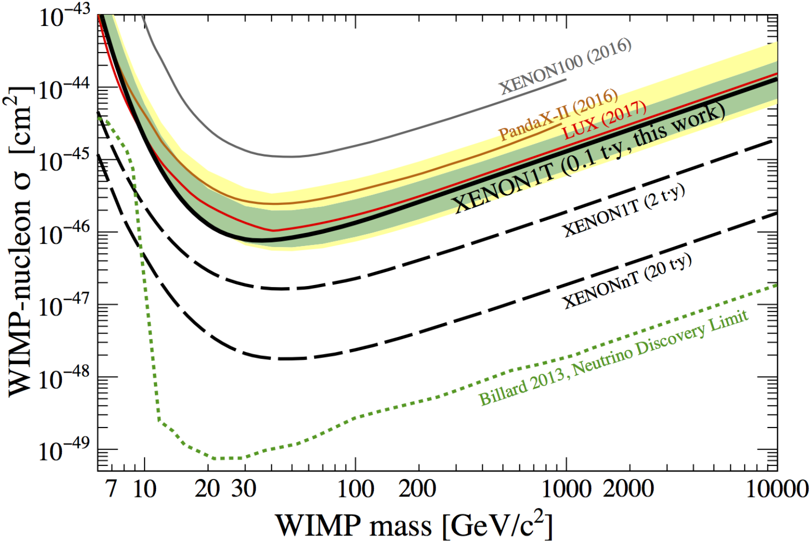
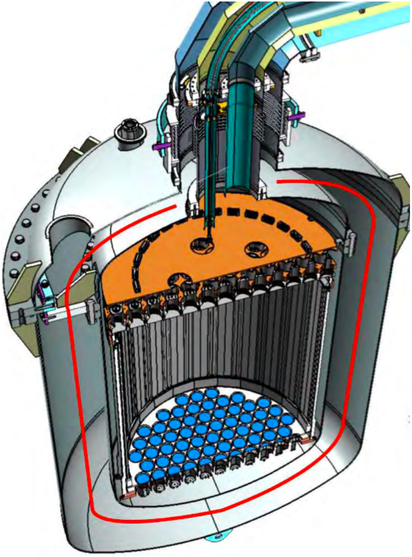


Figure updated from XENON1T, arXiv:1705.06655
(Note than the new PandaX-II result is missing here)

Upgrade to XENONnT



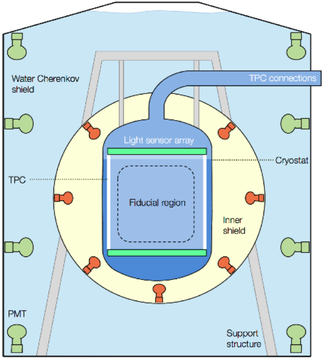
- XENONnT will contain about 6 t LXe in the target
- All infrastructure built already to accommodate XENONnT
- 'Only' xenon, 260 new PMTs and new TPC necessary
- Background expectation:
  assuming negligible material BGs
  - ER BG: 0.13 ev/t/y (dominated by solar ν's)
  - NR BG: 0.23 ev/t/y (dominated by solar ν's)
- Sensitivity: $1.6 \times 10^{-48}\,\mathrm{cm}^2$ for 50 GeV/c^2 WIMP mass
  $\rightarrow$ for 20 t×y exposure

Currently $>$ 8 t of LXe purchased and missing PMTs already being delivered and measured

DARWIN: the ultimate WIMP detector

dark matter wimp search in noble liquids

DARWIN



http://darwin-observatory.org/

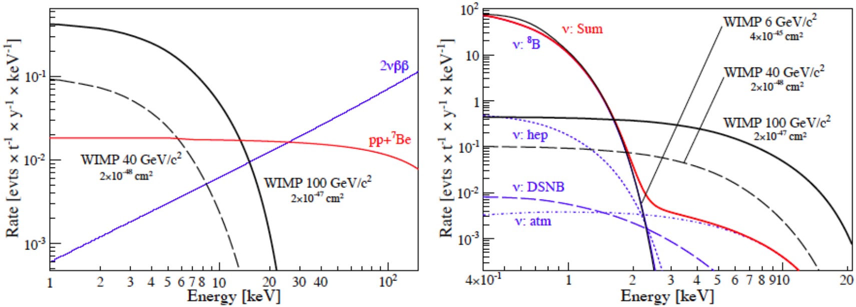
50 t LXe total (40 t in the TPC)

- R&D and design study for a liquid xenon observatory
- Design phase on-going, followed by construction and commissioning
- TPC of $\sim$2.6 m diameter & 2.6 m drift length
- 7 years necessary to exploit the complete sensitivity
- Location: possibly inside the XENON1T/nT water tank

DARWIN, JCAP 1611 (2016) 017

DARWIN physics

- Goal: measure WIMP properties / ultimate cross-section sensitivity
- Neutrino physics channels become available:
  - Electronic recoils from solar neutrinos
    $\sim$7 ev/day in 30 t and E = (2-30) keV$_{ee}$
  - 3.5 t of ^{136}Xe in DARWIN without isotopic enrichment
  - Nuclear recoils from coherent neutrino scattering:
    solar, diffuse supernova background and atmospheric ν's
    90 events/t/y from 8B-neutrinos above $\sim$ 1 keV$_{ee}$

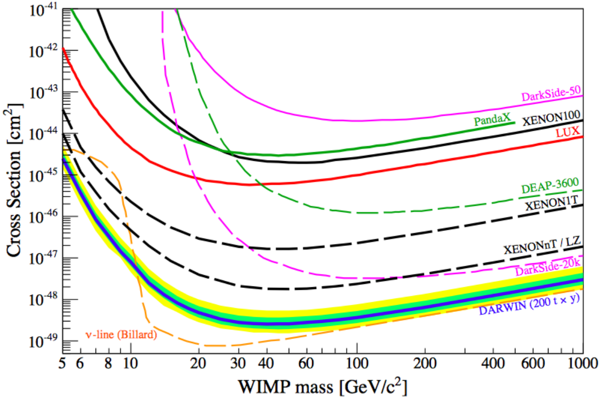


L. Baudis *et al.*, JCAP01 (2014) 044

Summary

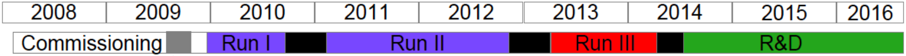
Sensitivity for dark matter searches has progressed rapidly

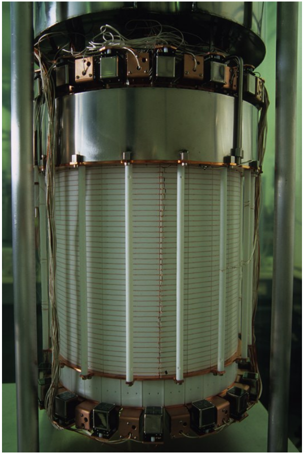
- Best sensitivities by liquid xenon detectors (above few GeV/c^2)
- XENON1T currently taking data!
- XENONnT and DARWIN are the future devices to investigate the dark matter properties and a wide variety of neutrino physics



DARWIN, JCAP 1611 (2016) no.11, 017, arXiv:1606.07001

The XENON100 experiment





- Taking data from 2009 – 2016
- 30 cm drift length and 30 cm ∅
- 161 kg LXe mass (34 – 48 kg for analysis)
- Background $\sim 5 \cdot 10^{-3}$ events/(kg·d·keV)

  → Instrument paper: Astropart. Phys. 35 (2012) 573

  → Analysis paper: Astropart. Phys. 54 (2014) 11

- Leading results during the last years

  → Spin independent result: PRL 109, 181301 (2012)

  → Spin dependent result: PRL 111, 021301 (2013)

  → Axion searches: Phys. Rev. D 90, 062009 (2014)

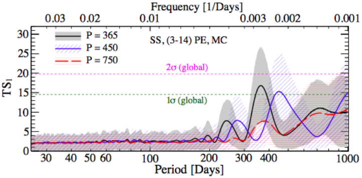
  → Rate modulation: PRL 115, 091302 (2015)
  & update 2017: PRL 118, 101101 (2017)

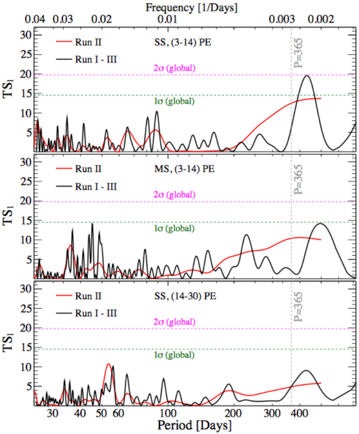
  → Leptophilic models: Science 349, 6250 pp. 851 (2015)

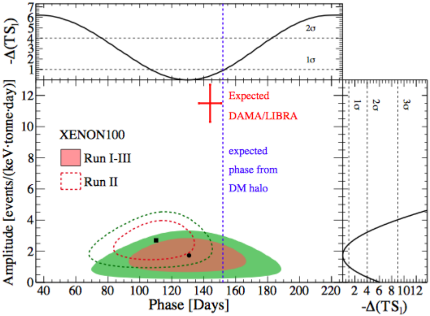
  → Final combined results: Phys. Rev. D 94, 122001 (2016)

  . . .

Data stability study



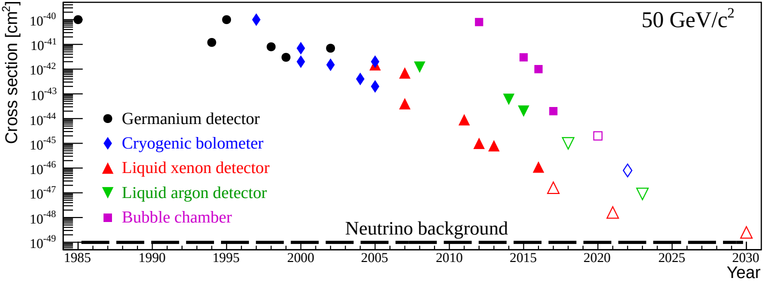


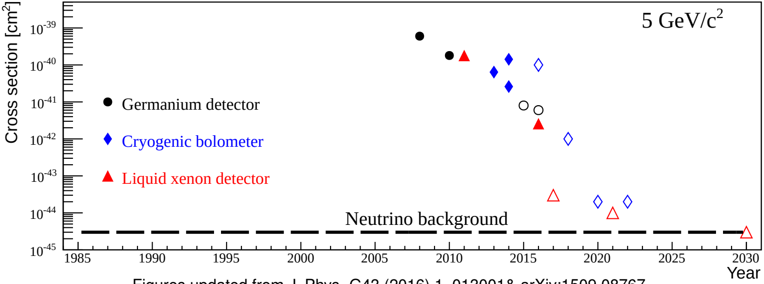


- Test of time modulation of electronic recoils of (2 – 6) keV energy
- Time span: 4 years (477 live days)
- DAMA signal excluded at 5.7 σ

XENON100, PRL 118, 101101 (2017) & arXiv:1701.00769

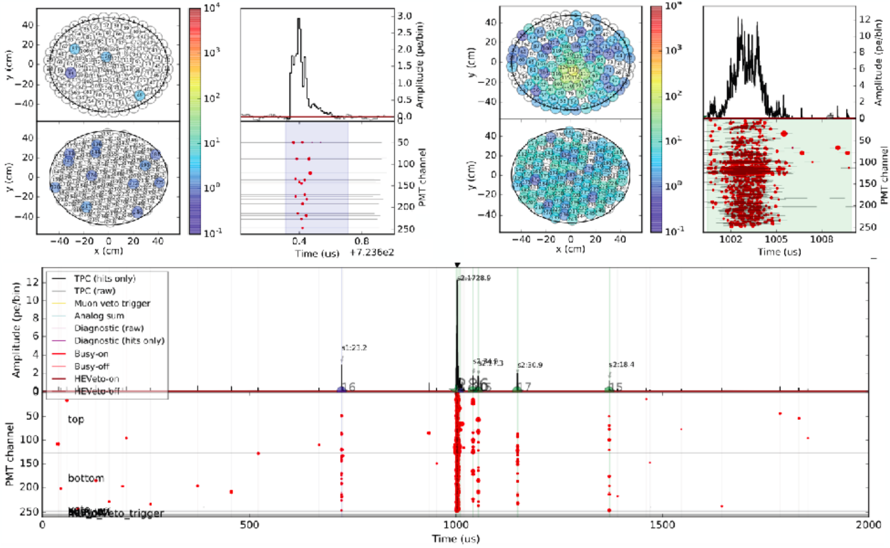
Sensitivity evolution and prospects



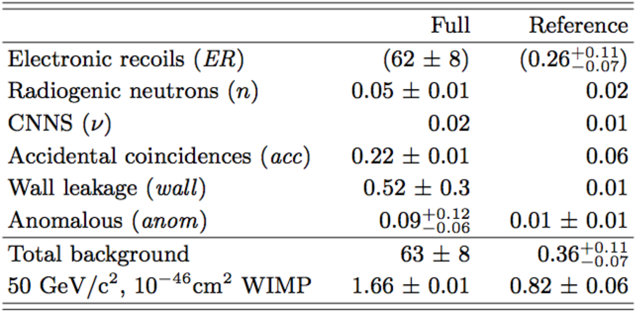


Figures updated from J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

Example of a waveform in XENON1T



Background model



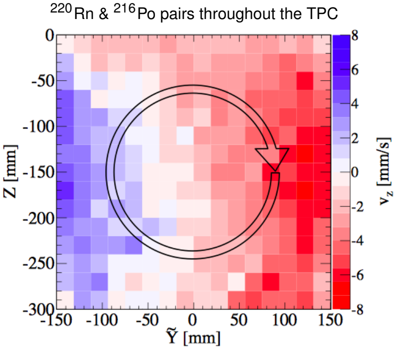
	Full	Reference
Electronic recoils (*ER*)	(62 ± 8)	$(0.26^{+0.11}_{-0.07})$
Radiogenic neutrons (*n*)	0.05 ± 0.01	0.02
CNNS (ν)	0.02	0.01
Accidental coincidences (*acc*)	0.22 ± 0.01	0.06
Wall leakage (*wall*)	0.52 ± 0.3	0.01
Anomalous (*anom*)	$0.09^{+0.12}_{-0.06}$	0.01 ± 0.01
Total background	63 ± 8	$0.36^{+0.11}_{-0.07}$
50 GeV/c^2, 10^{-46}cm^2 WIMP	1.66 ± 0.01	0.82 ± 0.06

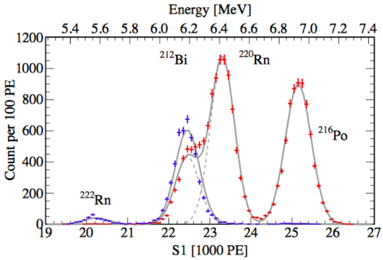
Calibration in large detectors

- Common γ-ray energies do not reach the inner volume

  → internal ^{220}Rn can be used
- Radon is injected from a ^{228}Th source
- Beta decay of ^{212}Pb used to define the background region
- No long lived isotopes in the ^{220}Rn chain → LXe doesn't need to be purified
- Use of the source tested successfully in XENON100

XENON100, PRD 95, 072008 (2017) & arXiv:1611.03585





Scintillation and ionization signals in XENNO1T