Dual-phase xenon TPCs for rare events search

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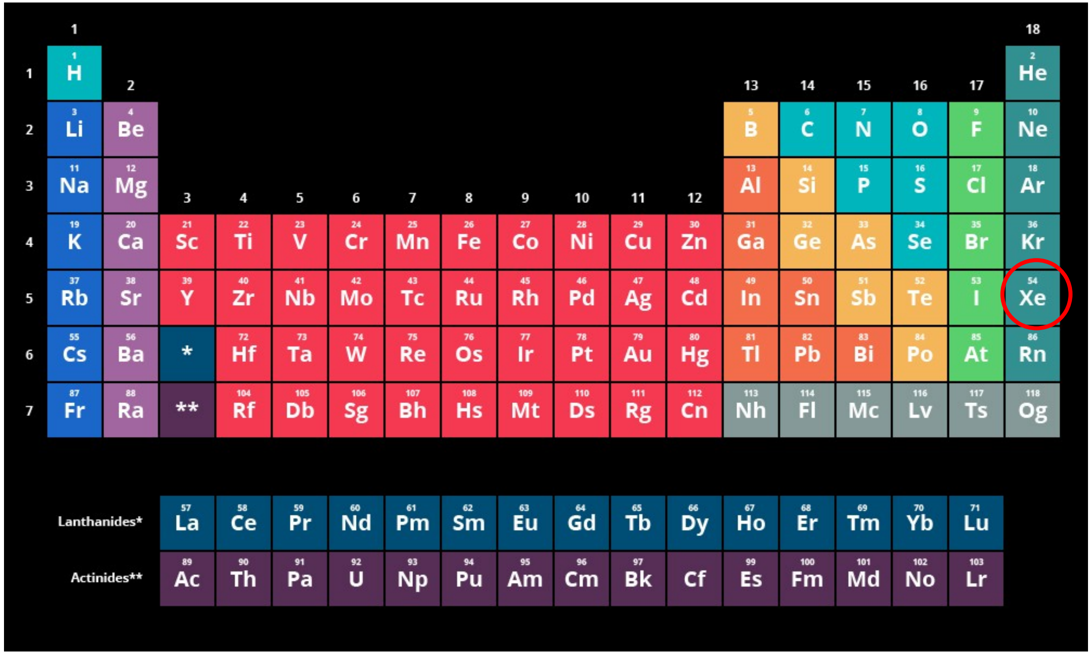
Outline

- Liquid xenon properties
- Dual-phase TPC concept
- A concrete example: XENONnT
- The ancillary systems
- Calibration
- Background and its mitigation
- Science cases
- Currently operating and future detectors

Liquid xenon properties

Introducing xenon (Xe)



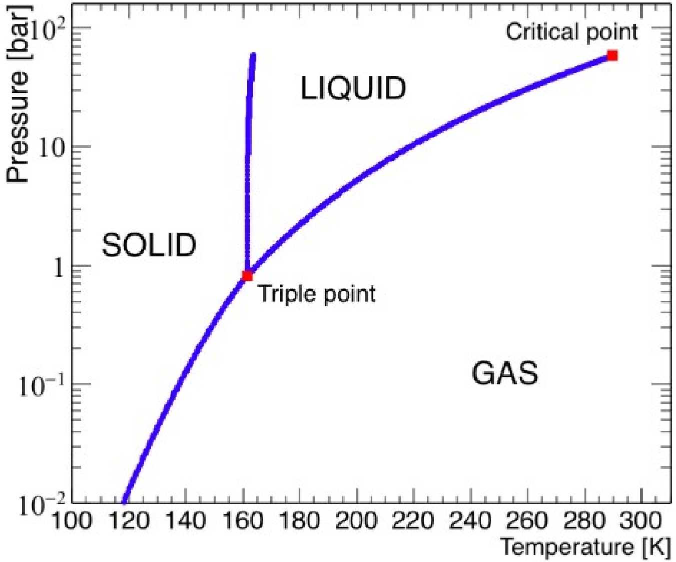
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
Lanthanides*			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
Actinides**			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

- Xenon (Xe) is the 5th noble gas
- It can be found in traces in the atmosphere (0.05 ppm)

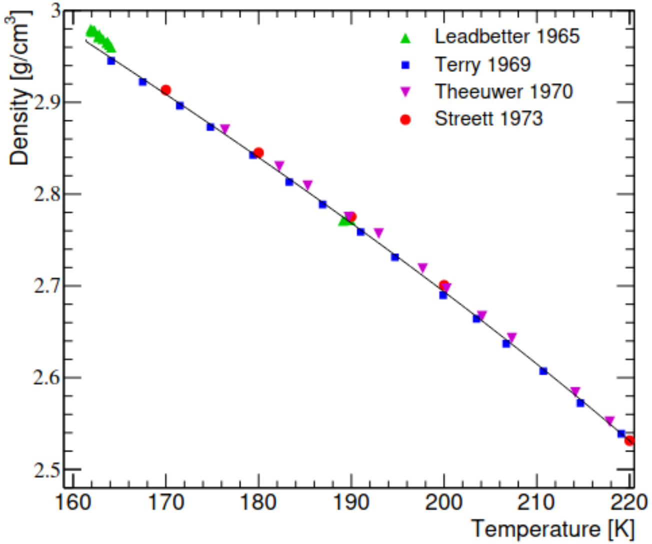
Property	Value
Atomic number, Z	54
Molar mass	$131.29\,\mathrm{g\,mol^{-1}}$
Isotopic abundances	^{124}Xe (0.095%), ^{126}Xe (0.089%), ^{128}Xe (1.91%) ^{129}Xe (26.4%), ^{130}Xe (4.07%), ^{131}Xe (21.2%) ^{132}Xe (26.9%), ^{134}Xe (10.4%), ^{136}Xe (8.86%)
Gas density (273 K, 1 atm)	$5.8971\,\mathrm{g\,L^{-1}}$
Liquid density (165.05 K, 1 atm)	$3.057\,\mathrm{g\,cm^{-3}}$
Melting point, (1 atm)	161.4 K
Boiling point, (1 atm)	163.05 K
Triple point	161.31 K, 0.805 atm, $3.08\,\mathrm{g\,cm^{-3}}$
Critical point	289.74 K, 57.65 atm, $1.155\,\mathrm{g\,cm^{-3}}$
Latent heat of fusion	$17.29\,\mathrm{kJ\,kg^{-1}}$

- Xe has 7 stable isotopes
- Most abundant isotopes: ^{129}Xe, ^{131}Xe, ^{132}Xe
- ^{124}Xe decays through double e- capture
- ^{136}Xe undergoes ββ decay

Liquid Xe (LXe) properties



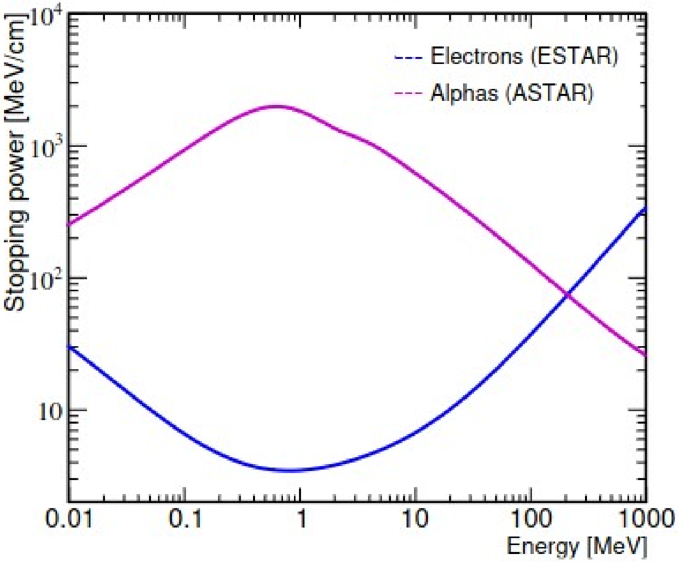
Data from the online Air Liquide encyclopedia

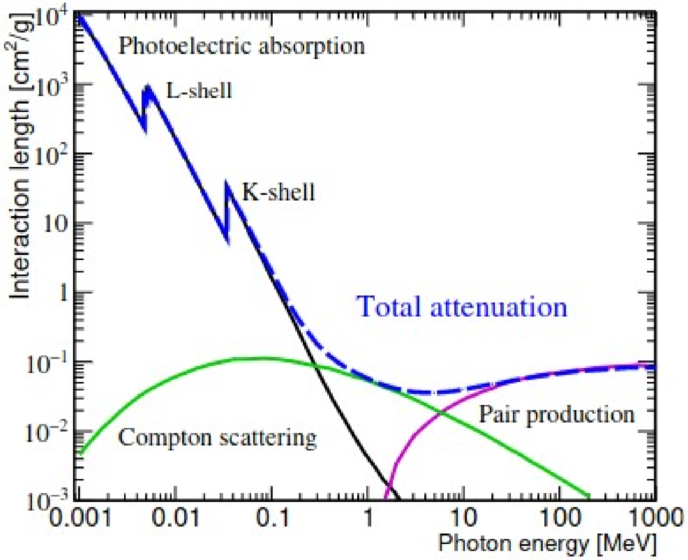


Data from various experiments & black curve from the online Air Liquide encyclopedia

- Xe is liquid (LXe) above its triple point at 161.4 K and 0.817 bar
- Typically operated at ~2 bar and at 170-180 K
- **High density** in liquid phase: ~2.85 g/cm^3

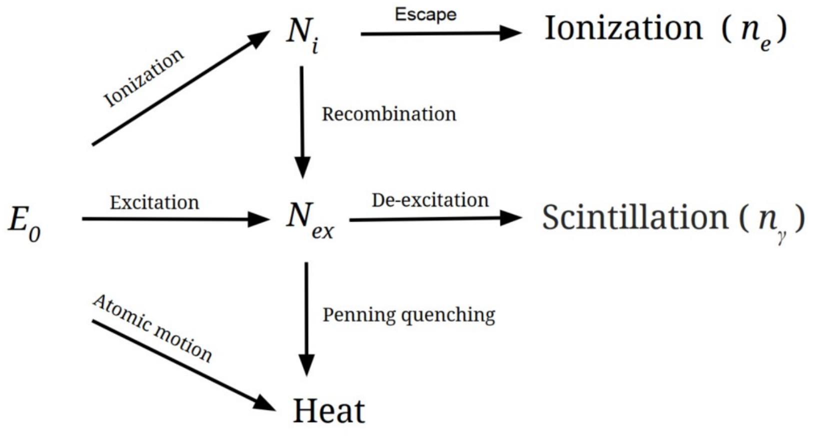
Particle interactions

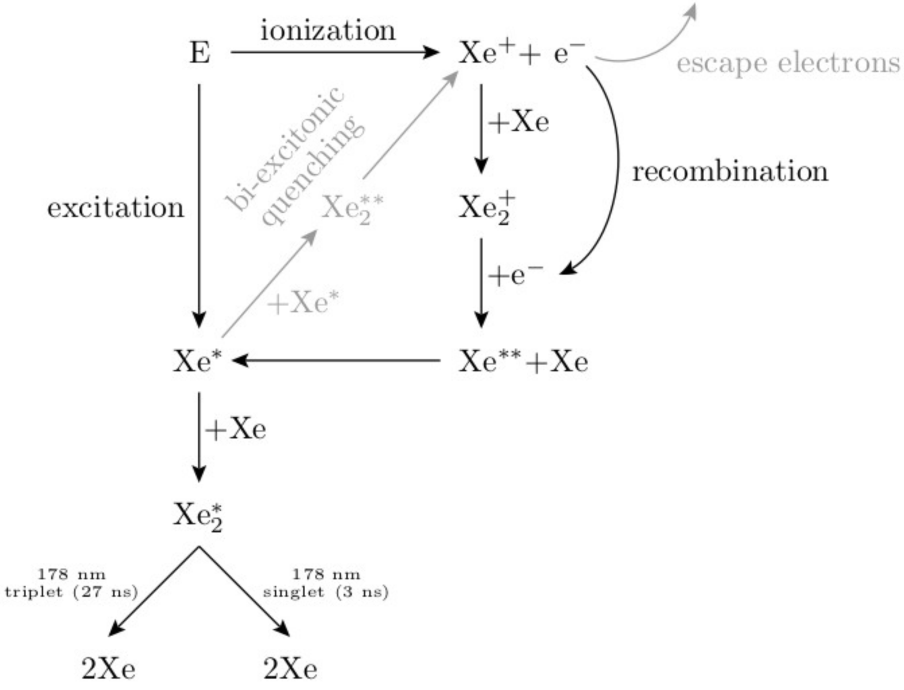




- Alpha particles with energies (5-8) MeV have *O*(μm) range
- MeV electrons reach *O*(cm) range
- LXe has a great self-shielding capability

LXe scintillation process



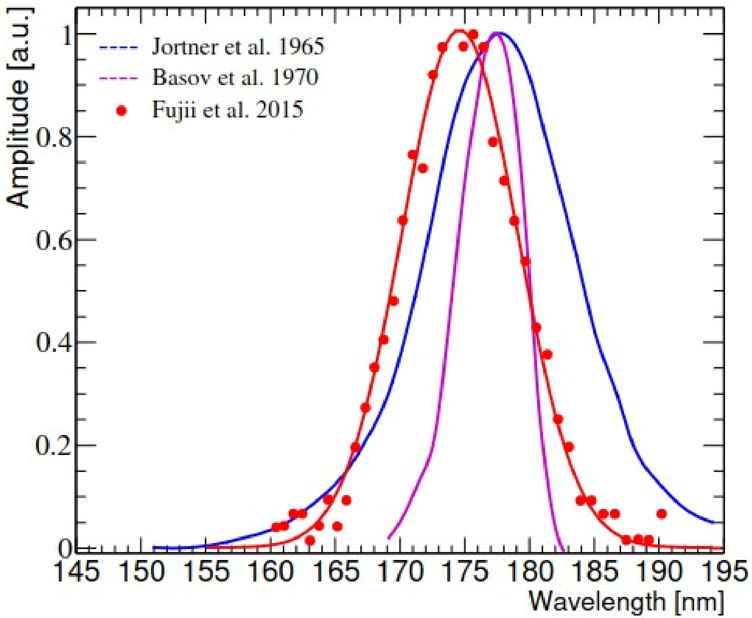


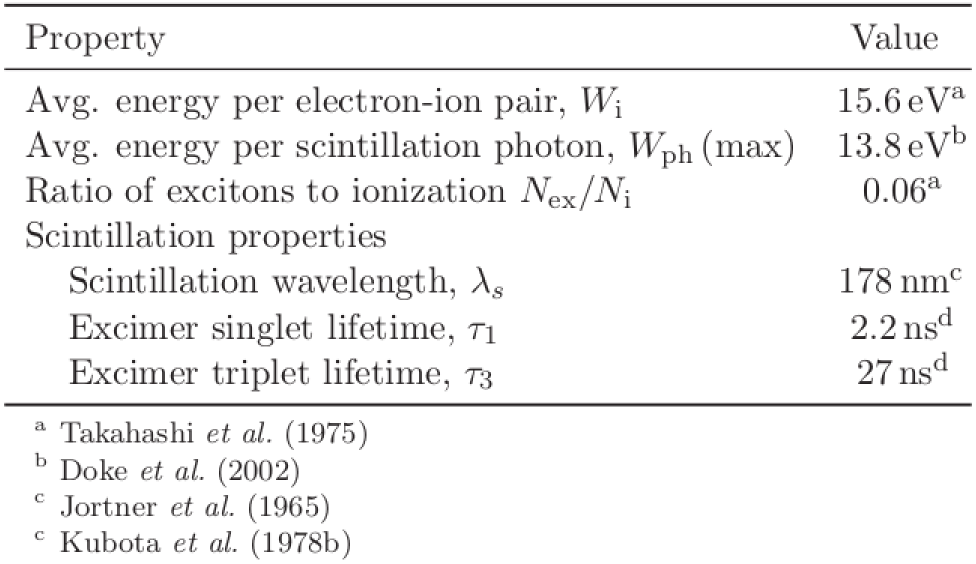
- LXe is an excellent scintillator:
  ~45x10^3 photons/MeV for relativistic e- ,
  it is transparent to its own scintillation light

- Only Ionization and Scintillation signals are detectable in dual-phase XENON TPCs

LAr: triplet 1.6 µs – singlet 5 ns
LNe: triplet 15 µs – singlet 19 ns

LXe scintillation spectrum





Property	Value
Avg. energy per electron-ion pair, W_i	15.6 eV[a]
Avg. energy per scintillation photon, W_ph (max)	13.8 eV[b]
Ratio of excitons to ionization $N_\mathrm{ex}/N_\mathrm{i}$	0.06[a]
Scintillation properties	
Scintillation wavelength, λ_s	178 nm[c]
Excimer singlet lifetime, τ_1	2.2 ns[d]
Excimer triplet lifetime, τ_3	27 ns[d]

[a] Takahashi *et al.* (1975)
[b] Doke *et al.* (2002)
[c] Jortner *et al.* (1965)
[c] Kubota *et al.* (1978b)

- LXe scintillation at (**174.8** ± 0.1 (*stat.*) ± 0.1 (*syst.*)) **nm** [Fujii 2015]
- UV regime, still possible to detect directly (no wavelength shifting)
- LAr emits at 125 nm and LNe at 78 nm

Decay time constants

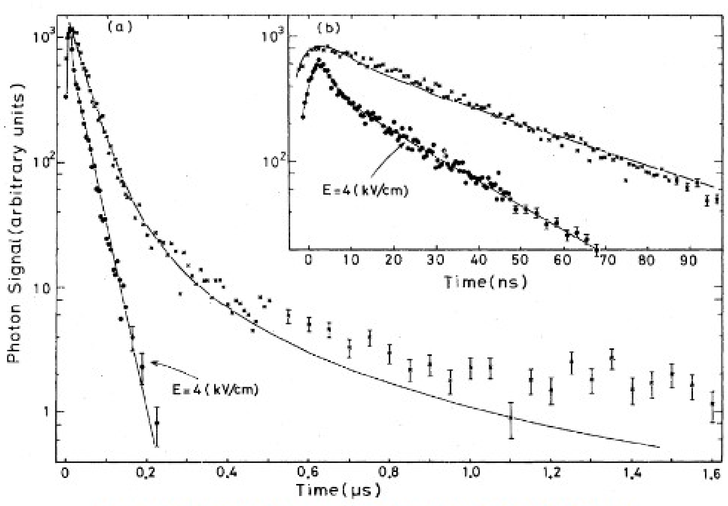


Figure from S. Kubota et al., Phys. Rev. B 20 (1979) 3486.

$$F(t) = \frac{f_s}{\tau_s} \exp\left(\frac{-t}{\tau_s}\right) + \frac{f_t}{\tau_t} \exp\left(\frac{-t}{\tau_t}\right)$$

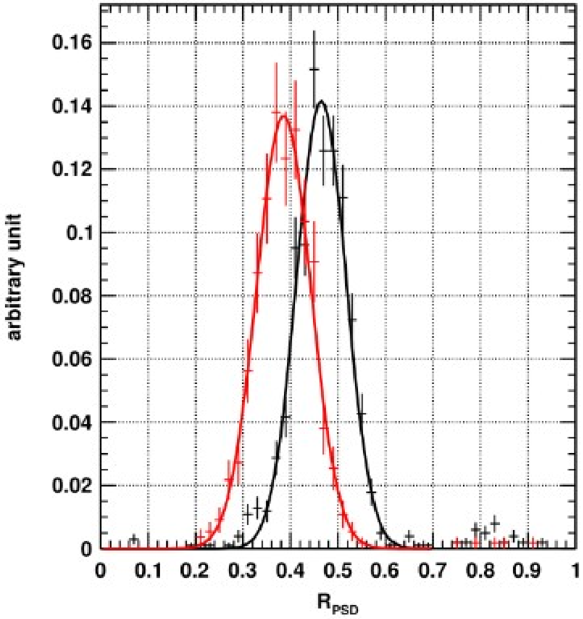


Figure from XMASS data, NIM. A659 (2011) 161

Electronic recoils from ^{137}Cs

Nuclear recoils from ^{252}Cf

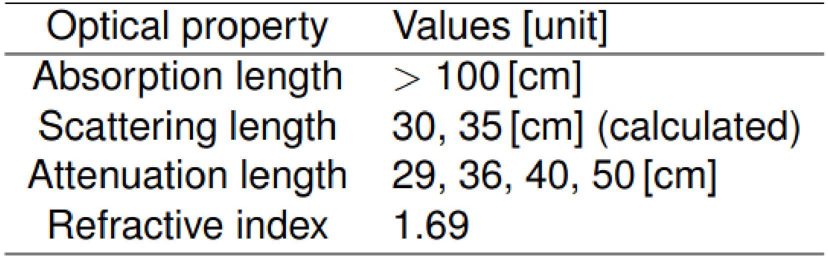
R_{PSD} is the fraction of light recorded in the first 20 ns

- Amplitudes of singlet and triplet are dE/dx dependent and also electric field dependent
- Pulse Shape Discrimination (PSD) not very effective in LXe due to similar decay constants
- PSD gets better in LAr and LNe

Optical properties

Total attenuation length, λ_{att}

$$\frac{1}{\lambda_{att}} = \frac{1}{\lambda_{abs}} + \frac{1}{\lambda_{scat}}$$



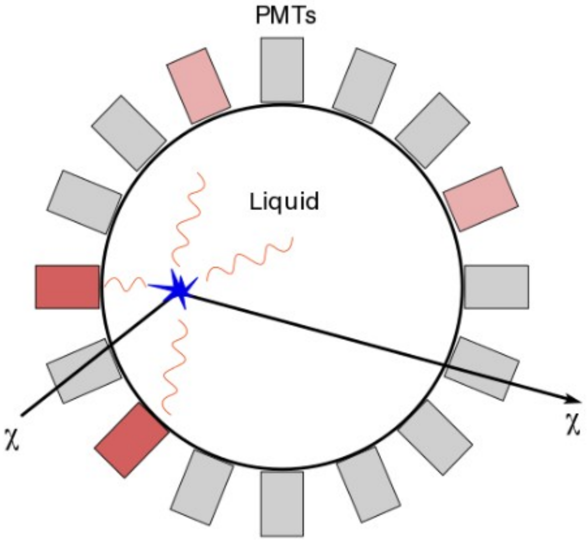
Optical property	Values [unit]
Absorption length	$>$ 100 [cm]
Scattering length	30, 35 [cm] (calculated)
Attenuation length	29, 36, 40, 50 [cm]
Refractive index	1.69

Light intensity after a distance *r*

$$I(r) = I_0 \cdot \exp^{-(r/\lambda_{att})}$$

- The short attenuation length affects the light propagation for large detectors, timing information is lost
- For dual-phase detector, **total reflection** of photons at liquid-gas interphace occurs

Single-phase (LXe) detectors



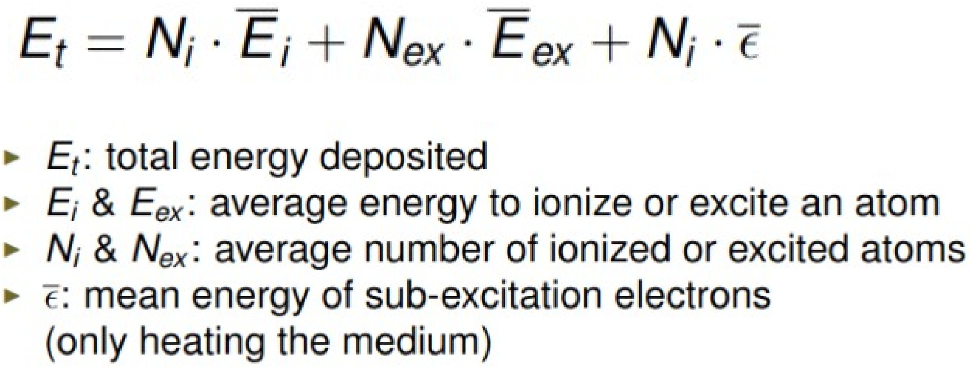
XMASS@Kamioka (Japan)

- High light yield with a 4π photosensors coverage (XMASS has 14.7 PE/keV_{ee}, E_{th} = 0.3 keV_{ee})
- Position resolution in the cm range
- PSD for particle discrimination

Dual-phase TPC concept

Ionization process

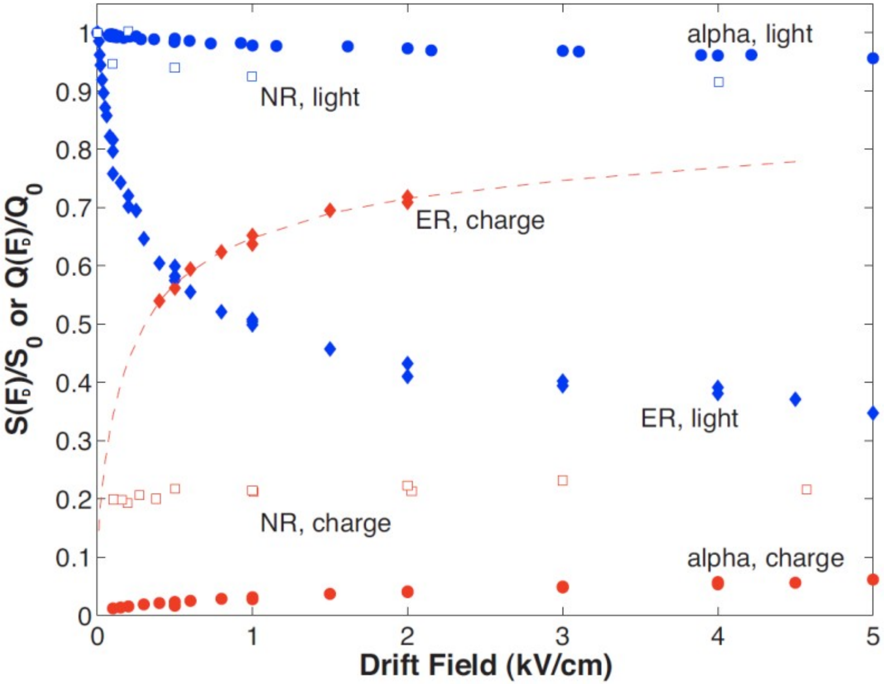
- **N_i >> N_{ex}** for electronic recoils (ER)
- **N_i ~ N_{ex}** for nuclear recoils (NR)
- Charge and light production are **dE/dX dependent**



$$E_t = N_i \cdot \overline{E}_i + N_{ex} \cdot \overline{E}_{ex} + N_i \cdot \overline{\epsilon}$$

- E_t: total energy deposited
- E_i & E_{ex}: average energy to ionize or excite an atom
- N_i & N_{ex}: average number of ionized or excited atoms
- $\overline{\epsilon}$: mean energy of sub-excitation electrons (only heating the medium)

Applying electric field

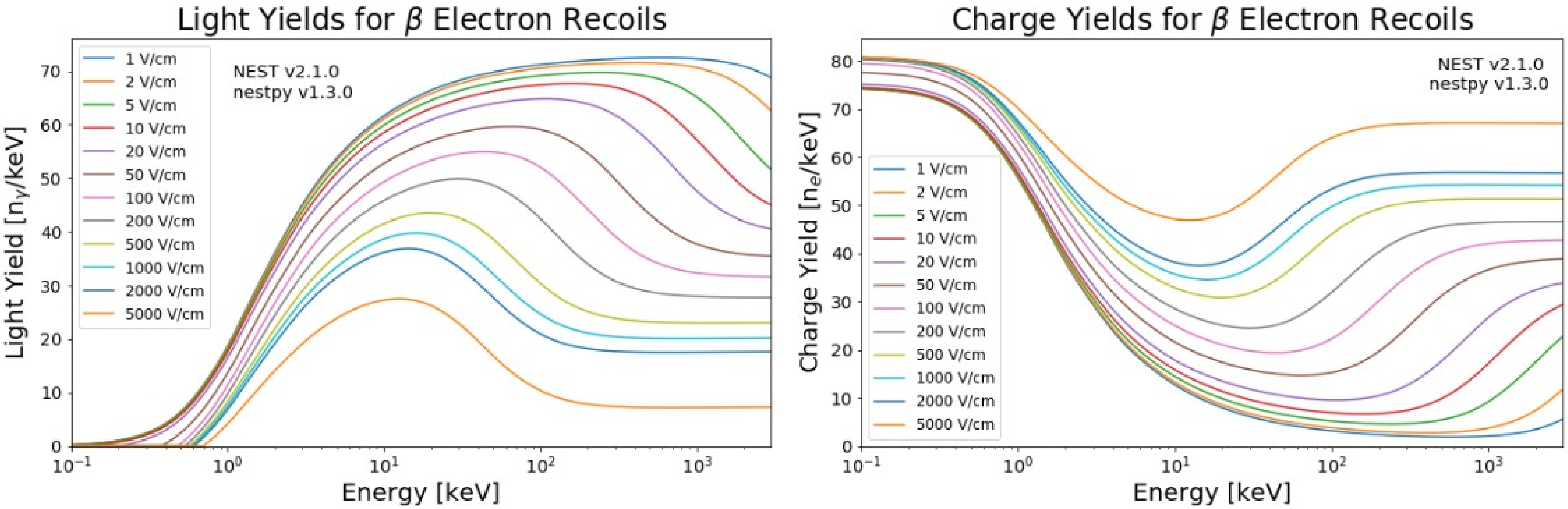


E. Aprile et al., Phys. Rev. Lett. 97 (2006) 081302

$S(F_d)/S_0$ [$Q(F_d)/Q_0$] is the light [charge] output relative to the value with no field

- **Light yield decreases** with increasing electric field
- **Charge yield increases** with increasing electric field
- Very low field-quenching for α and NR

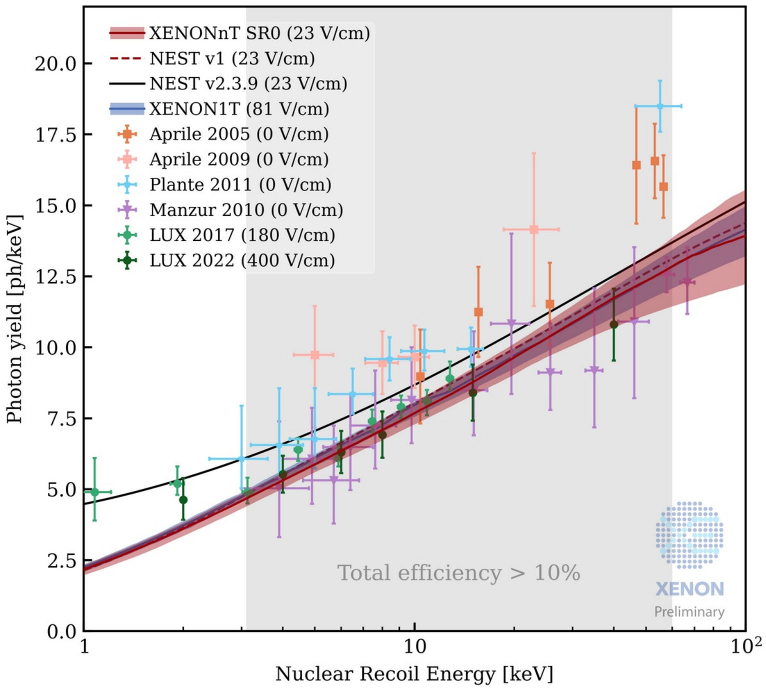
Signal yields

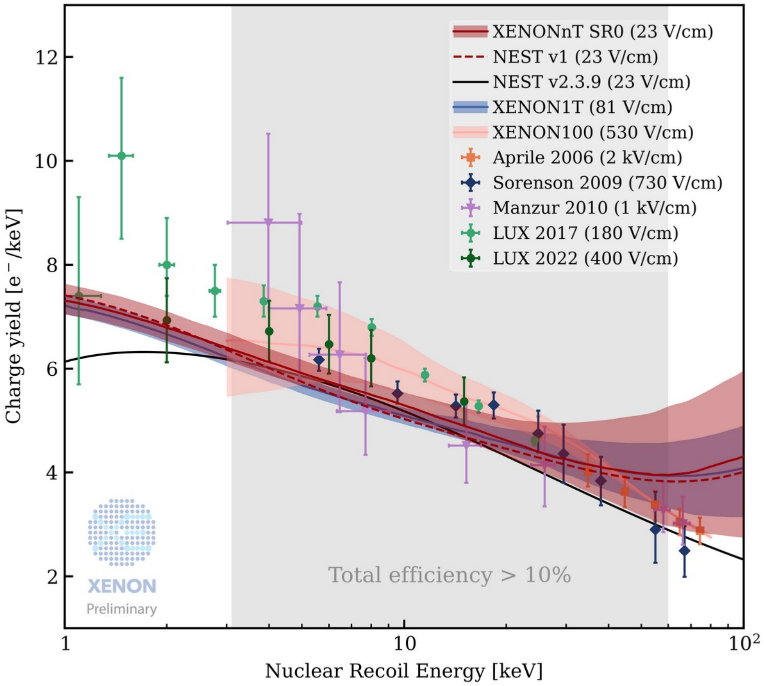


Figures from the NEST noble element simulation technique

- Energy-dependent yields for ER, NR and α particles
- Electric field dependence of the yields

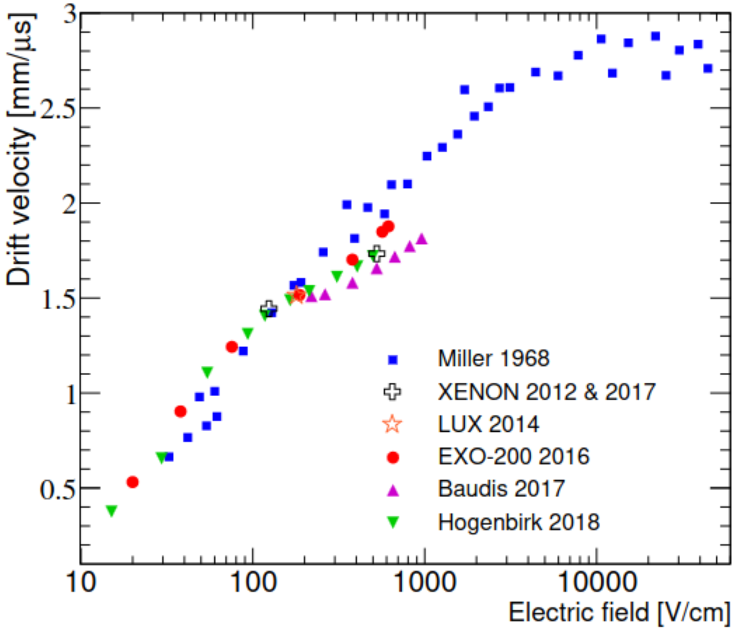
Yields for NR

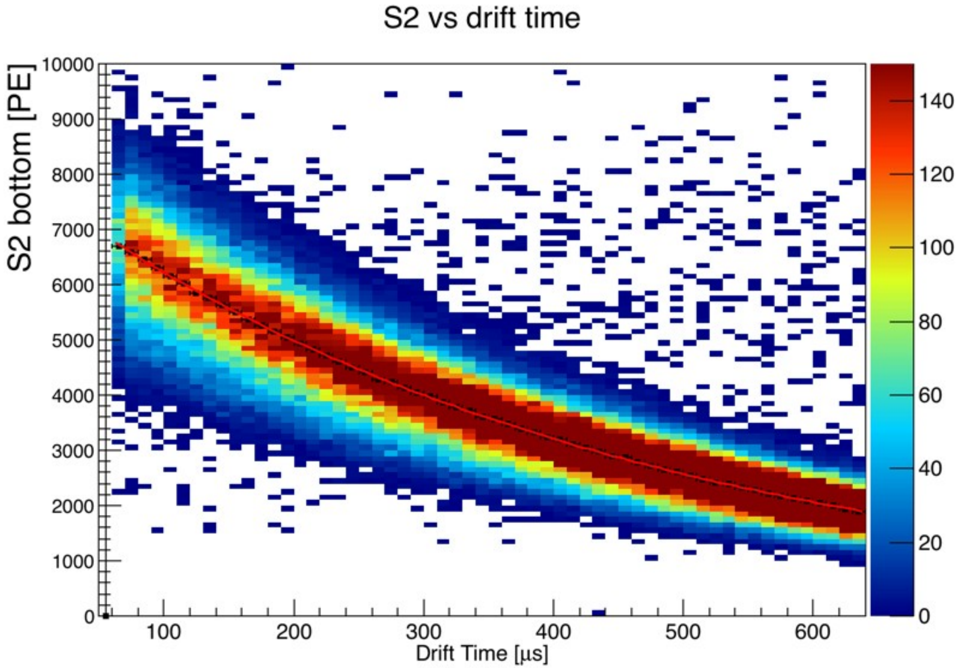




- Quenching for NR due to energy lost to heat

Electrons drift velocity and absorption





- Higher drift field gives higher electrons drift velocity
- Drifting electrons are absorbed by electronegative impurities

$S2(t_D) = S2(0)*\exp[-t_D/\tau]$

τ is “*electron lifetime*”

Electrons diffusion

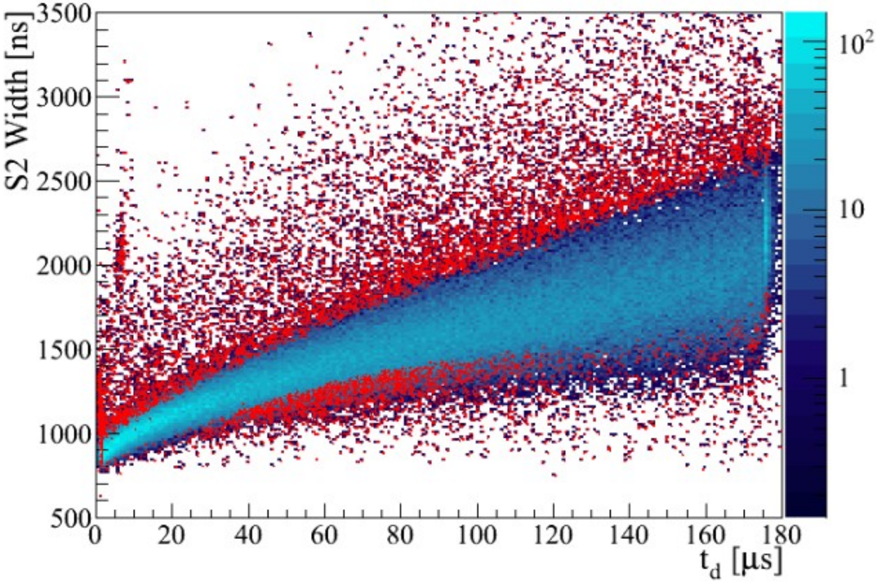


Figure from XENON100, Astropart. Phys. 54 (2014) 11

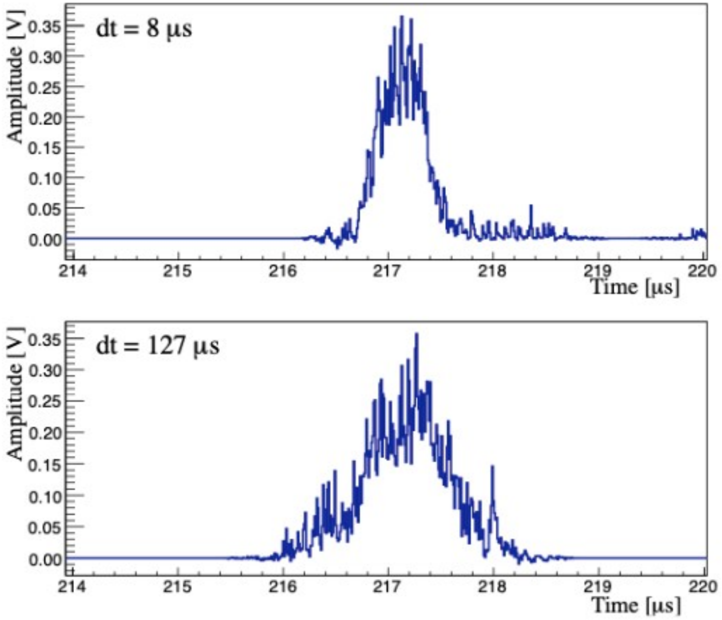
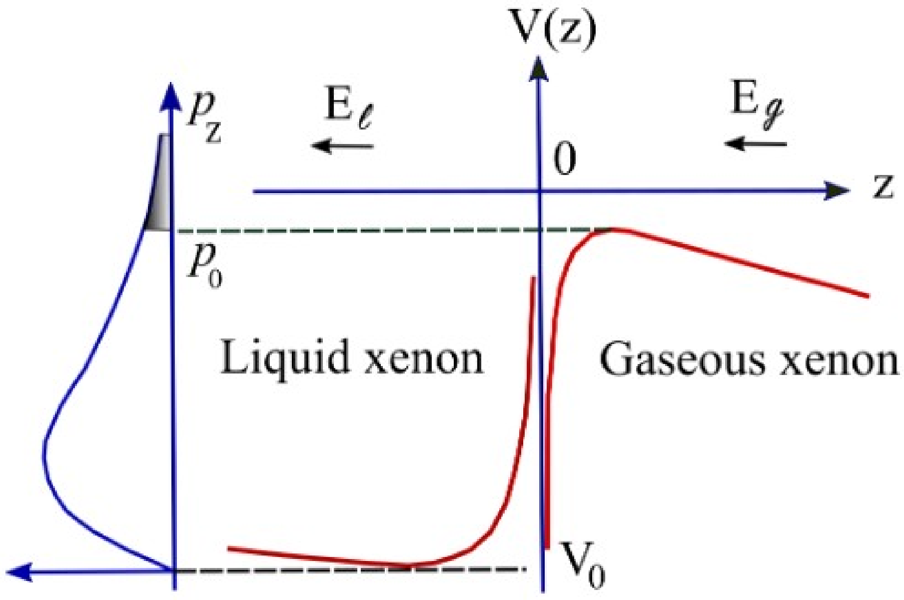
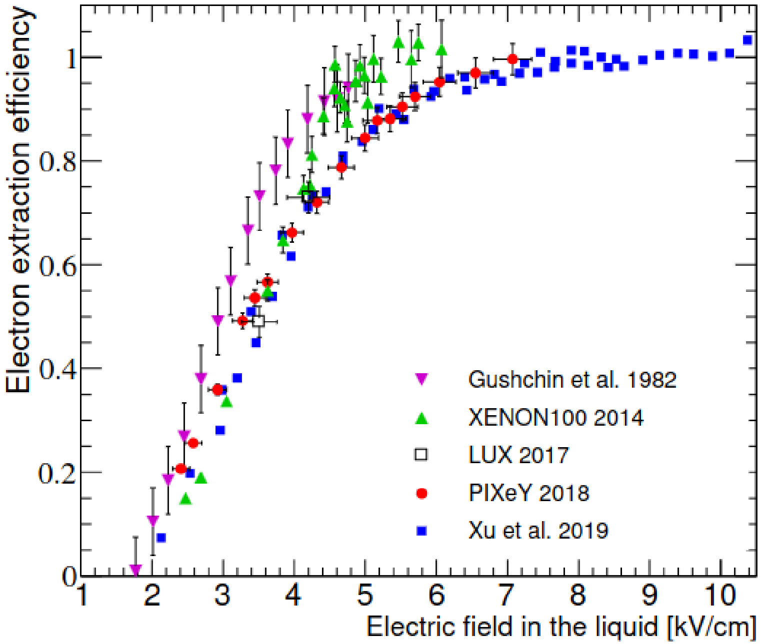


Figure from XENON100, Astropart. Phys. 54 (2014) 11

- Diffusion increases the relative distance of the drifting electrons
- The width of S2 increases due to diffusion

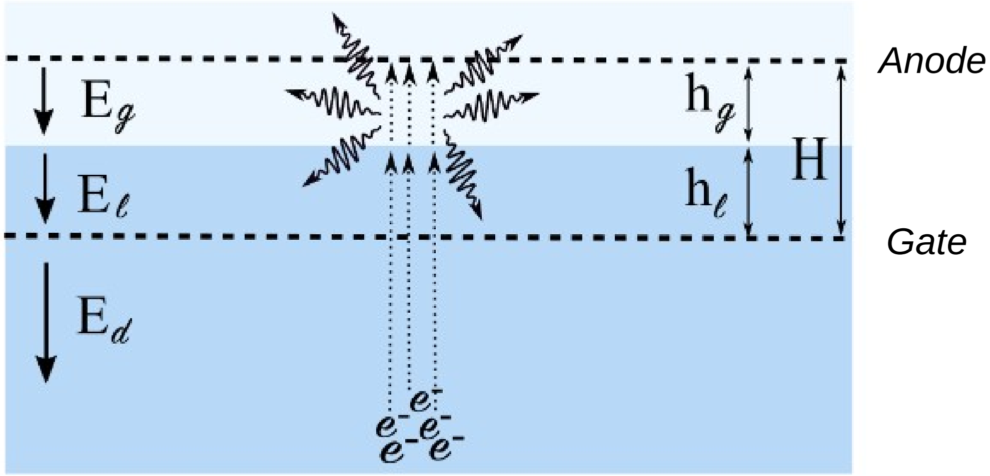
Electrons extraction





- Electrons have to overcome potential barrier: (0.65 – 0.85) eV
- Large extraction field (~5-10 kV/cm) has to be applied

Proportional scintillation



- Field in the gas phase E_g

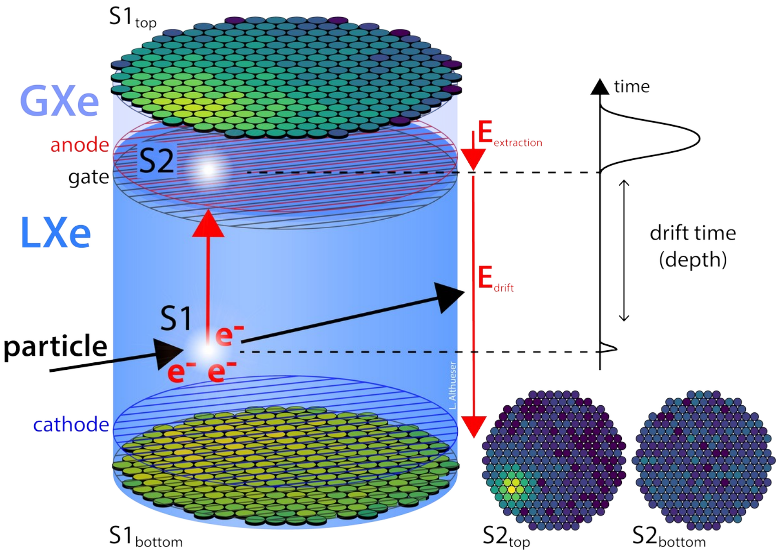
$$E_g = \frac{\epsilon_\ell \cdot \Delta V}{h_g \cdot (\epsilon_\ell - 1) + H} \quad \text{with} \quad \epsilon_\ell = 1.95$$

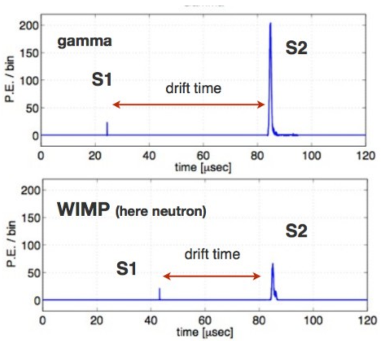
- Yield

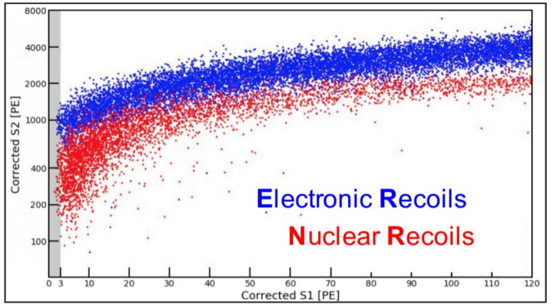
$$Y = \left(a \cdot \frac{E_g}{P_g} + b \right) \cdot h_g \cdot P_g$$

- Important to keep the liquid level stable over the whole surface
- **Amplification:** typically 20-30 PE for each electron extracted

A good idea: dual-phase Xe TPC





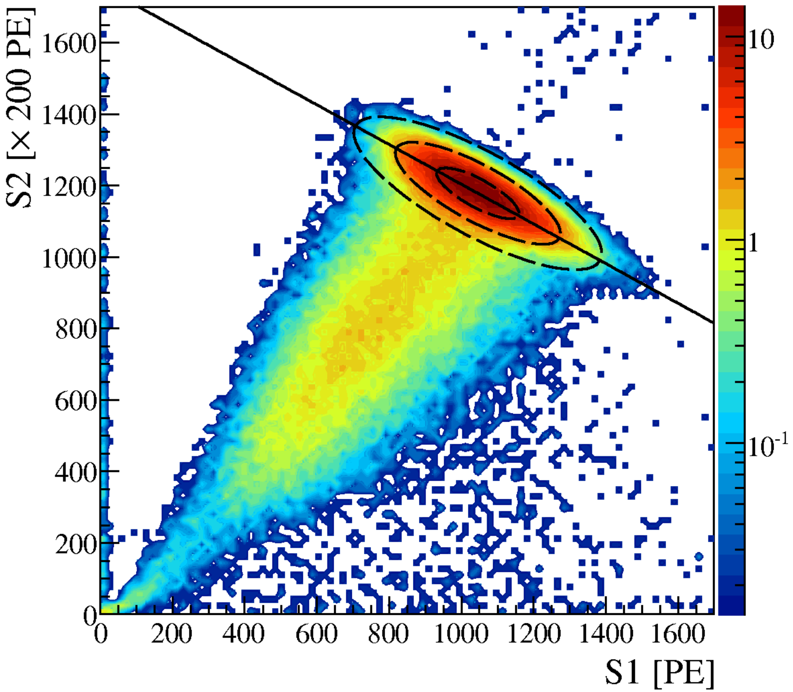


- A prompt scintillation signal (**S1**)
- Electrons from ionization drift under electric field E_{drift}
- They are extracted in gas phase and produce proportional signal (**S2**)
- Array of photosensors on top and bottom

- Drift time provides depth (*z*) of interaction
- S2 light pattern on top array gives (*x*,*y*)
- Position reconstruction with few mm resolution
- ER/NR discrimination with S2/S1 ratio

Anti-correlation of light and charge signals

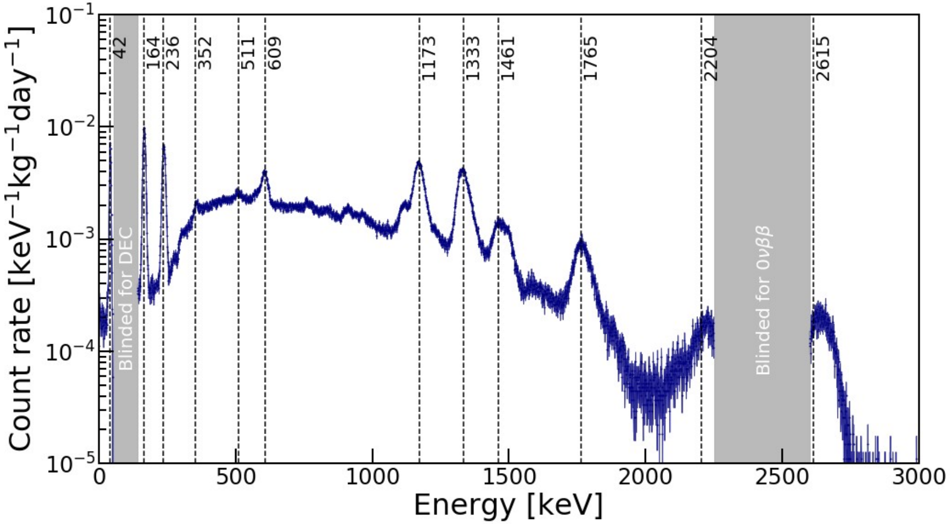
^{137}Cs calibration

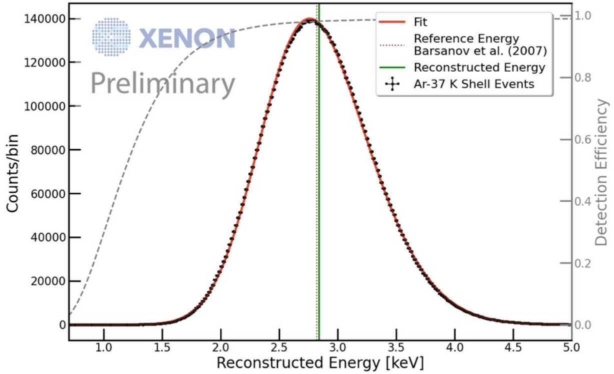


XENON100, Astropart. Phys. 35 (2012) 573

- The total number of quanta get shared between scintillation photons (S1) and electrons (S2)
- Fluctuations in the number of photons and electrons are anti-correlated: more photons implies less electrons available, and vice-versa
- This is apparent when plotting S2 vs S1 for monoenergetic signals

Energy reconstruction



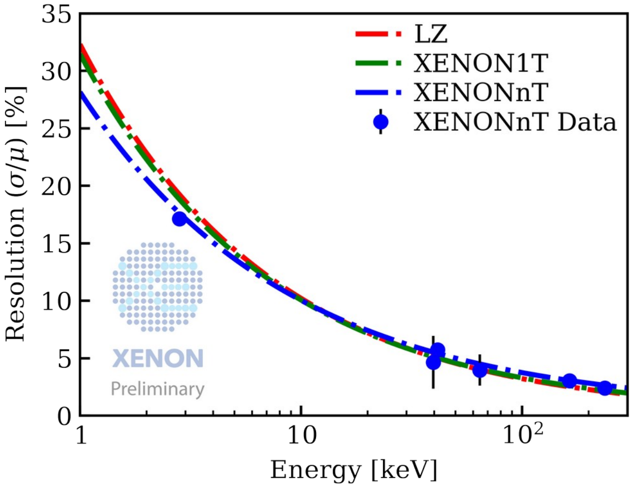


- A **combined energy scale** is commonly used

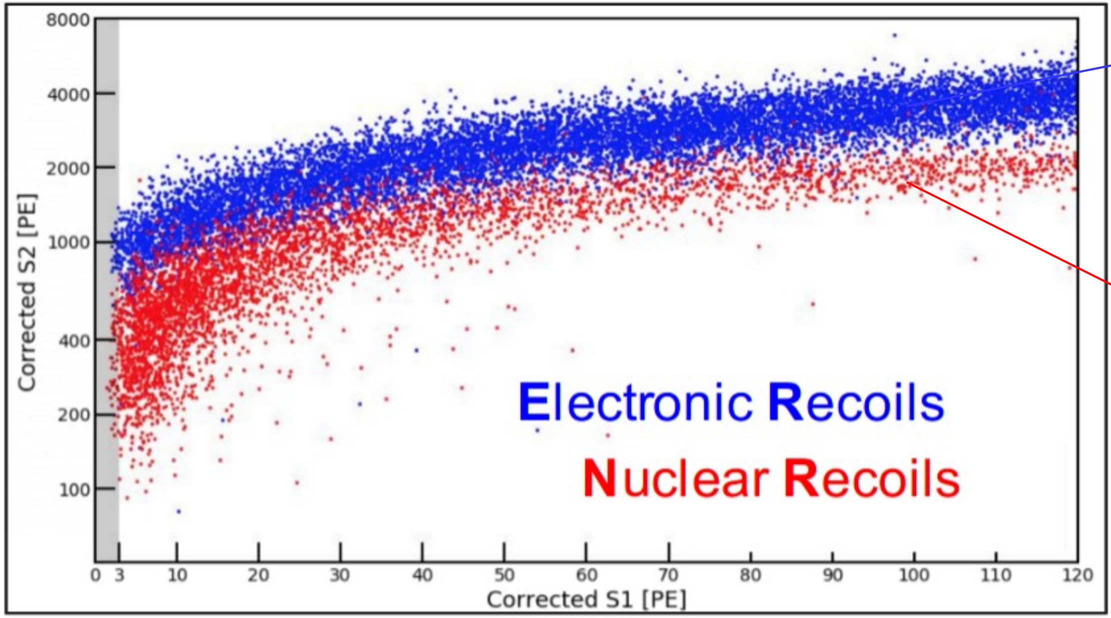
$$\hat{E} = W\left(\frac{\mathrm{cS1}}{g_1}+\frac{\mathrm{cS2}}{g_2}\right)$$

W = 13.7 eV
g1, g2 detector-dependent gains

- Energy threshold down to few keV
- Different energy scales for ER (keV$_{ee}$) and NR (keV$_{nr}$)



Particle identification



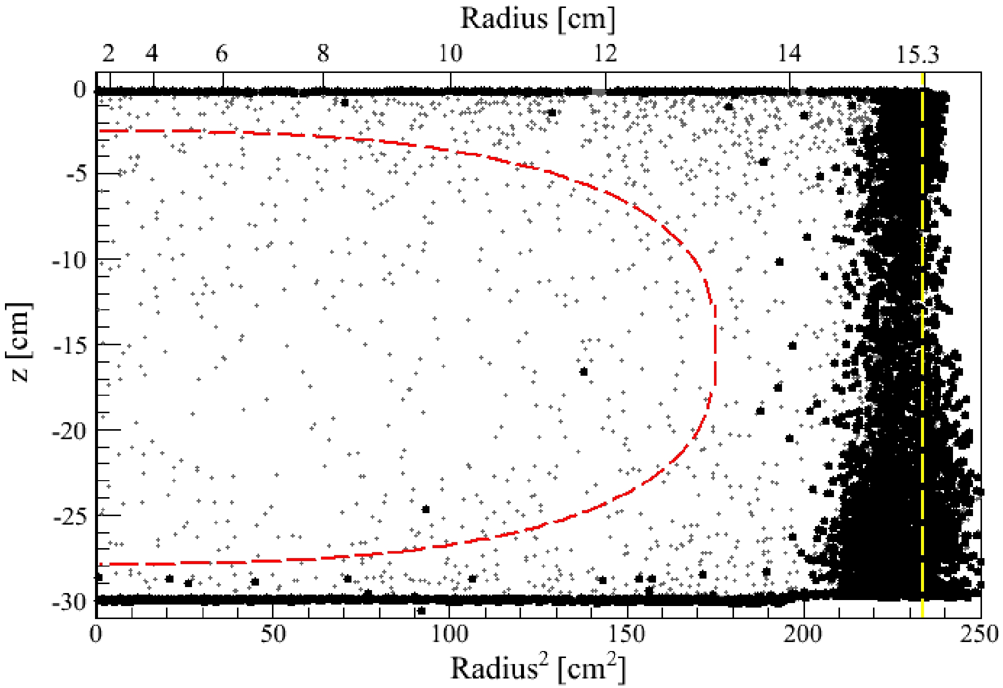
Calibration data from the XENON100 detector

ER: Calibrated with ^{220}Rn source (β-decays of ^{212}Pb)

NR: Calibrated with AmBe source or neutron generator

- Typical **ER rejection power** is 99.5% for 50% NR acceptance

Volume fiducialization



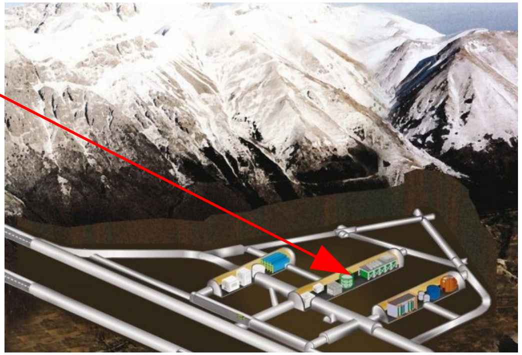
E. Aprile et al., Phys. Rev. Lett. 109, 181301 (2012)

- The possibility to define an inner fiducial volume greatly decreases the external background contribution (for example from material radioactivity)

A concrete example: XENONnT

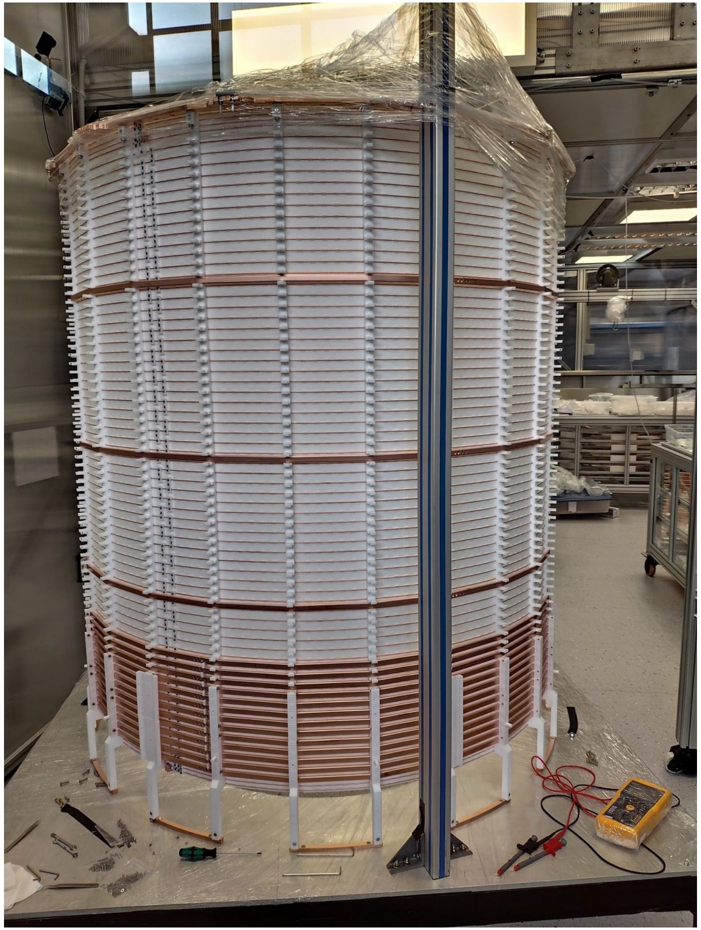
XENONnT

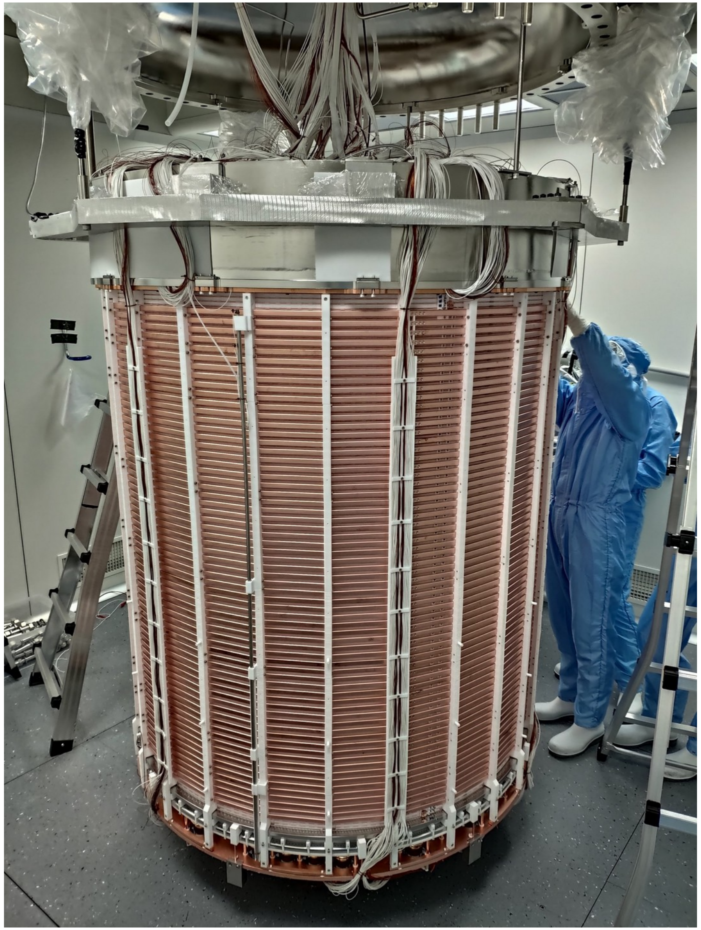
- XENONnT is a dual-phase TPCs operating underground at INFN Laboratori Nazionali del Gran Sasso (Italy)
- Main goal is the direct detection of dark matter



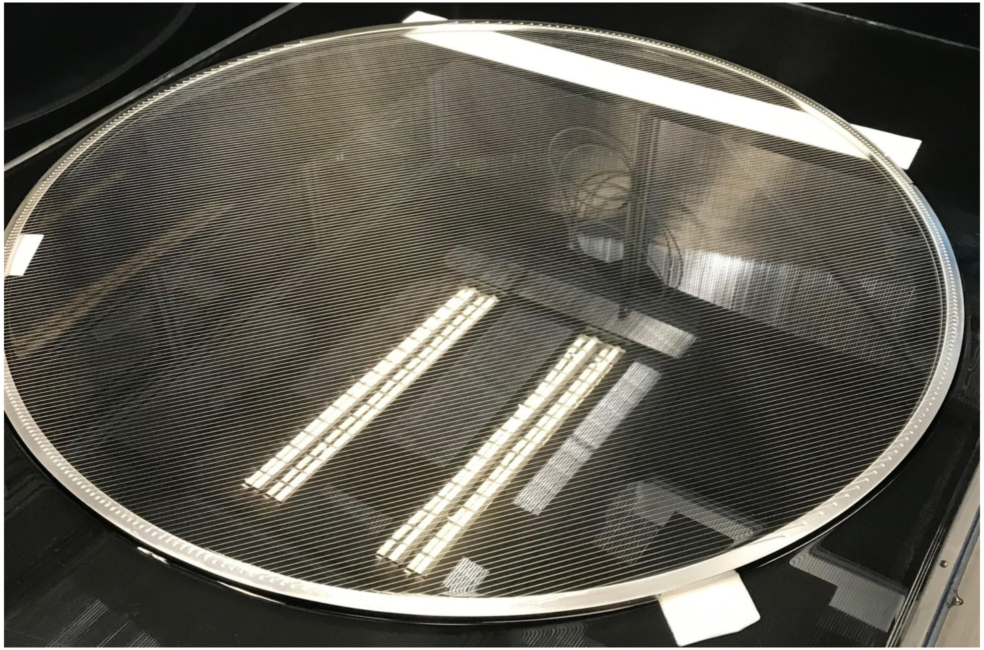
- XENONnT contains 5.9 t of Xe
- It is currently taking science data

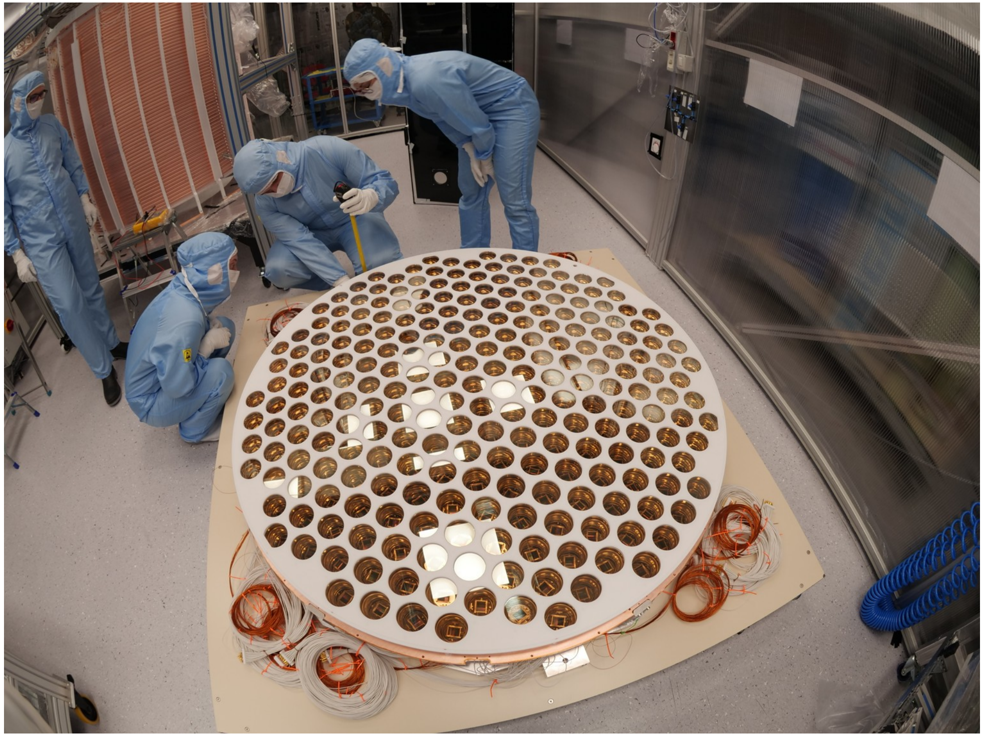
XENONnT construction: TPC structure



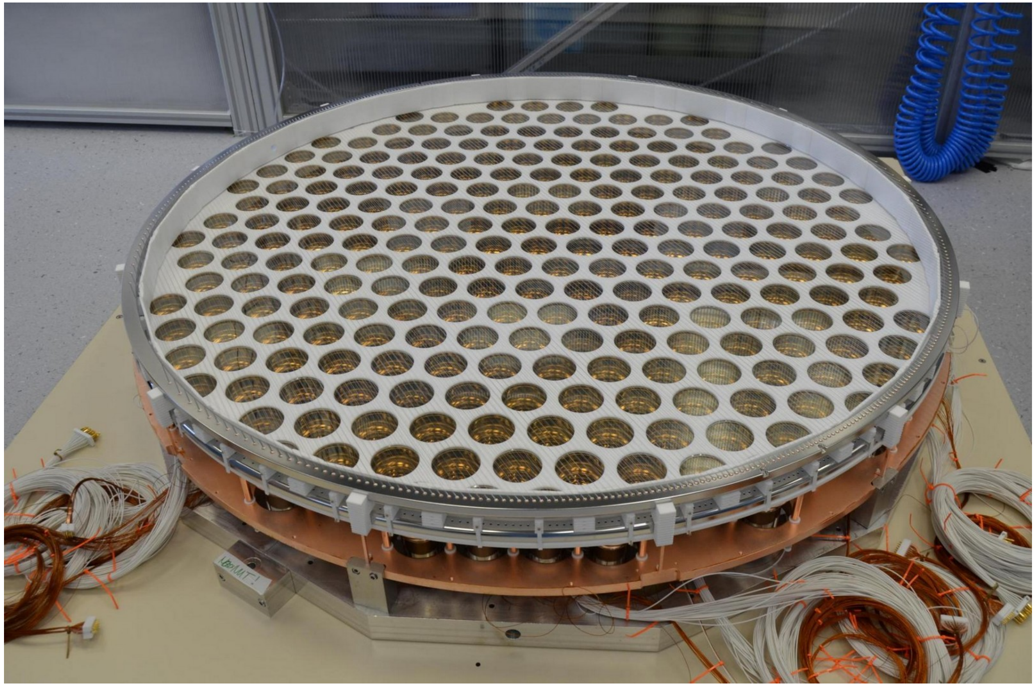


XENONnT construction: electrodes and PMTs

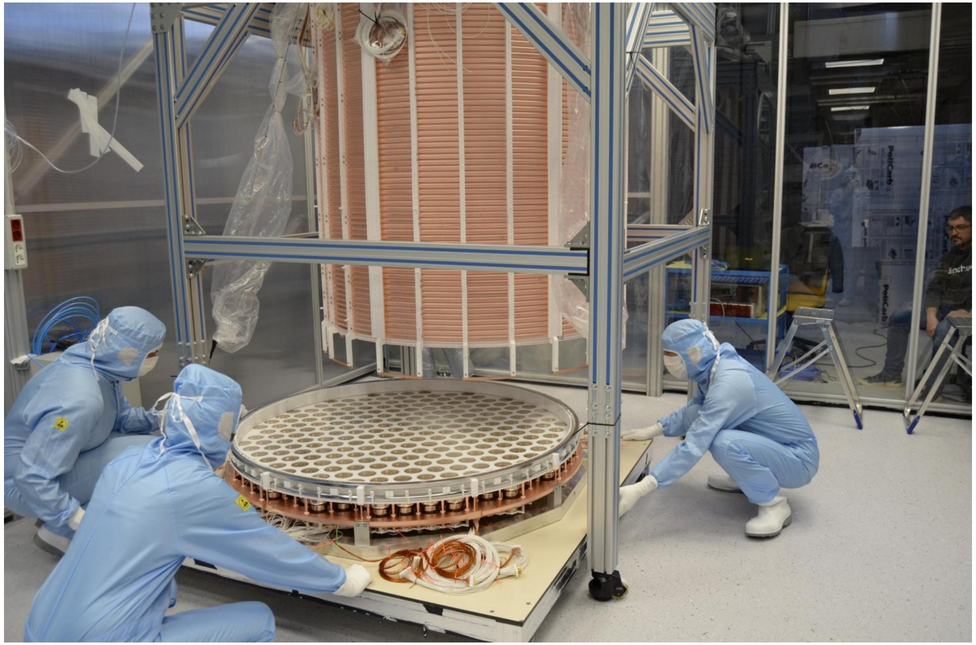


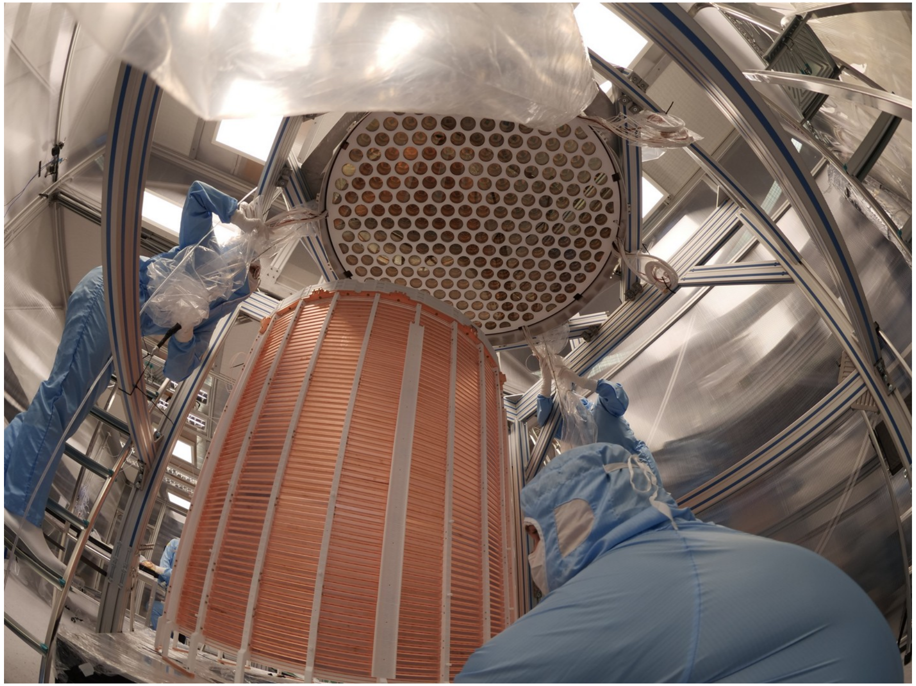


XENONnT construction: electrodes and PMTs



Putting all together

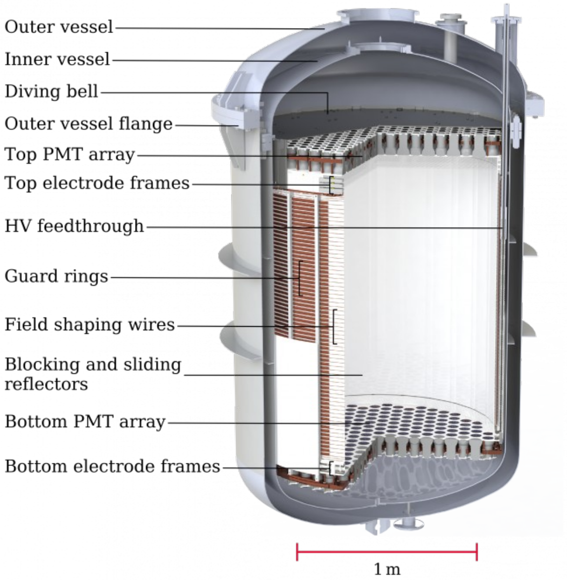


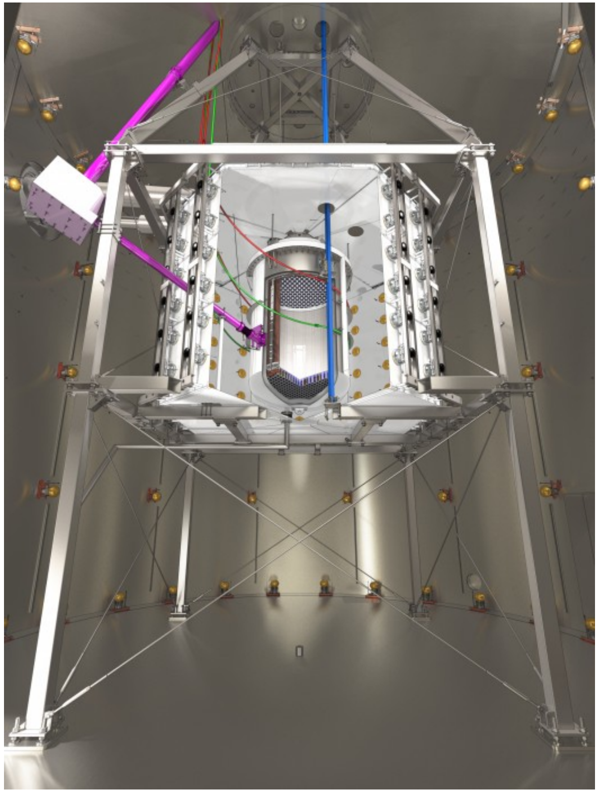


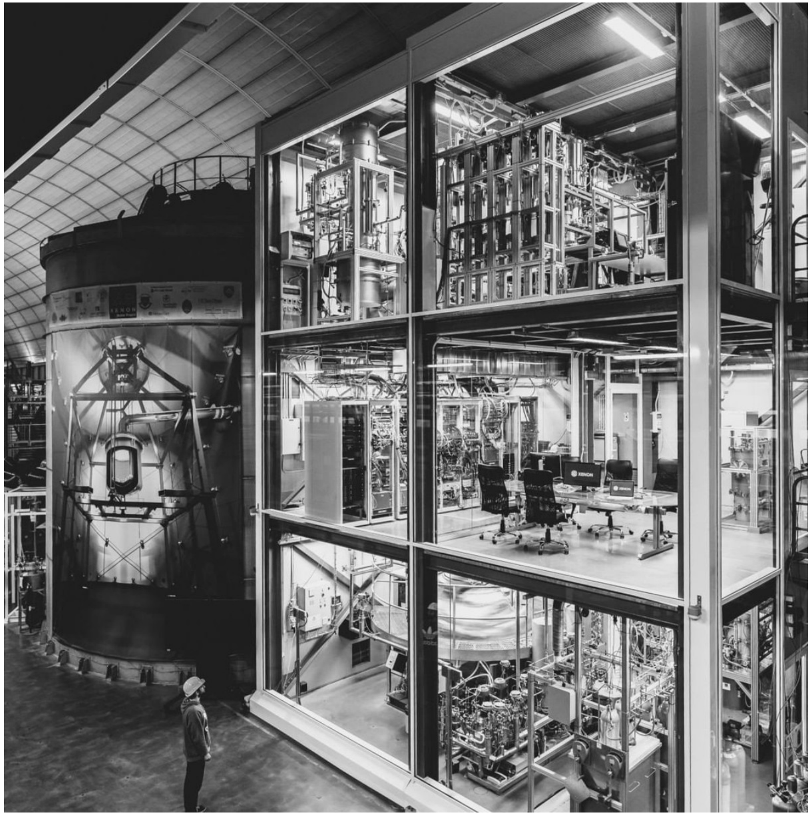
Et voilà!

The ancillary systems

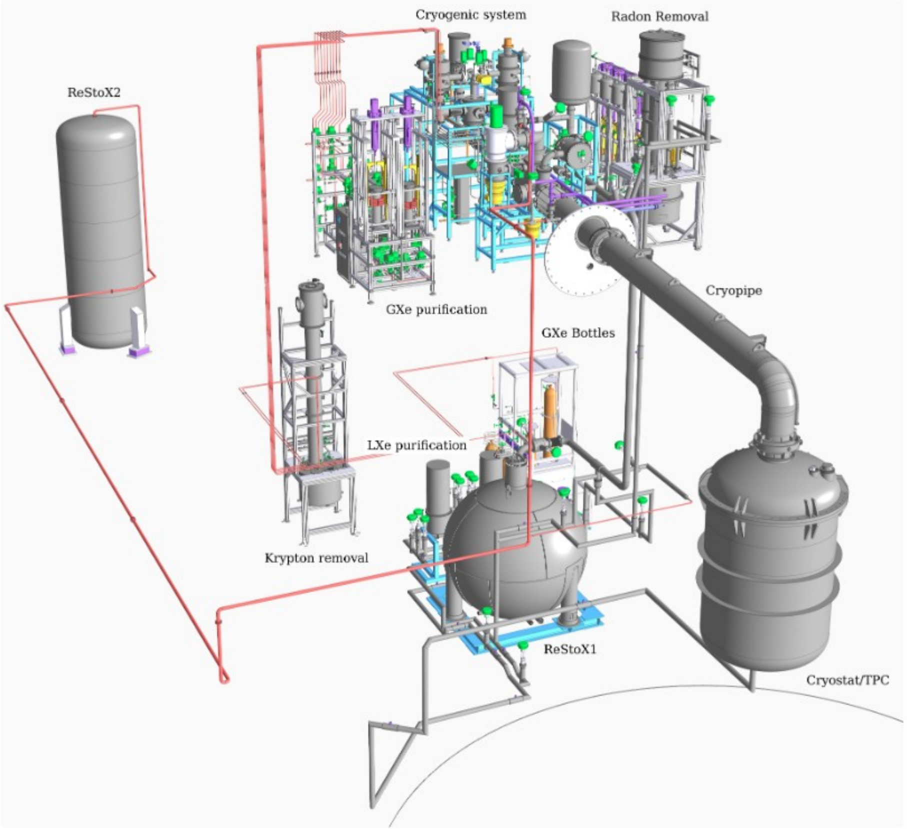
Infrastructure underground





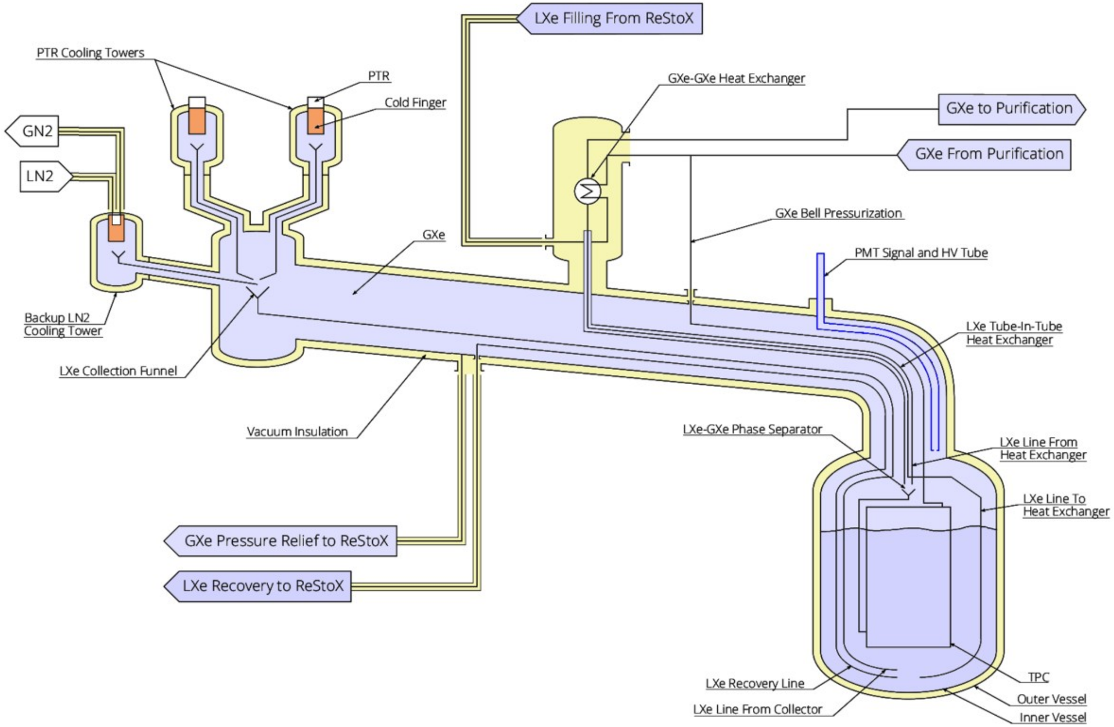


General view



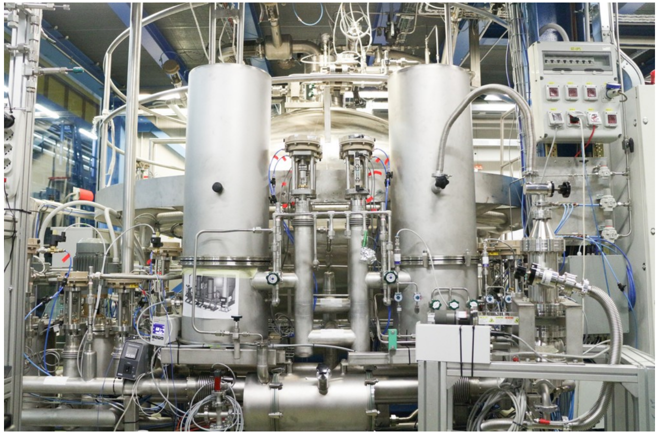
- **Cryogenic system:** it keeps the detector cold
- **GXe/LXe purification:** it purifies Xe from electronegatives
- **Krypton/Radon removal:** distillation columns to reduce the ^{85}Kr and ^{222}Rn contaminations
- **ReStoX1/ReStoX2:** Xe storage and fast recovery system

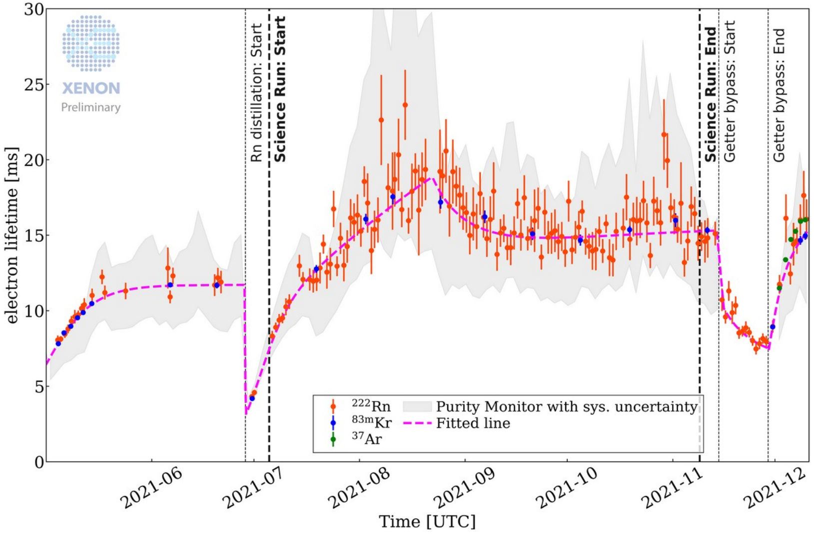
The cryogenic system

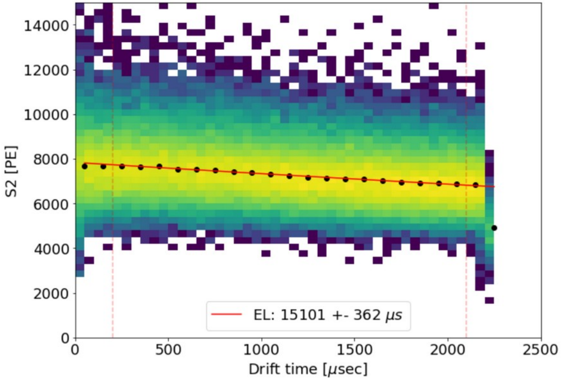


- It is based on LHe-cooled Pulse Tube Refrigerators (PTR)
- Two PTRs to ensure redundancy
- A backup LN2 system
- Installed in the service building, away from the TPC
- Cooled Xe flows back in the detector through the cryopipe

GXe/LXe purification system

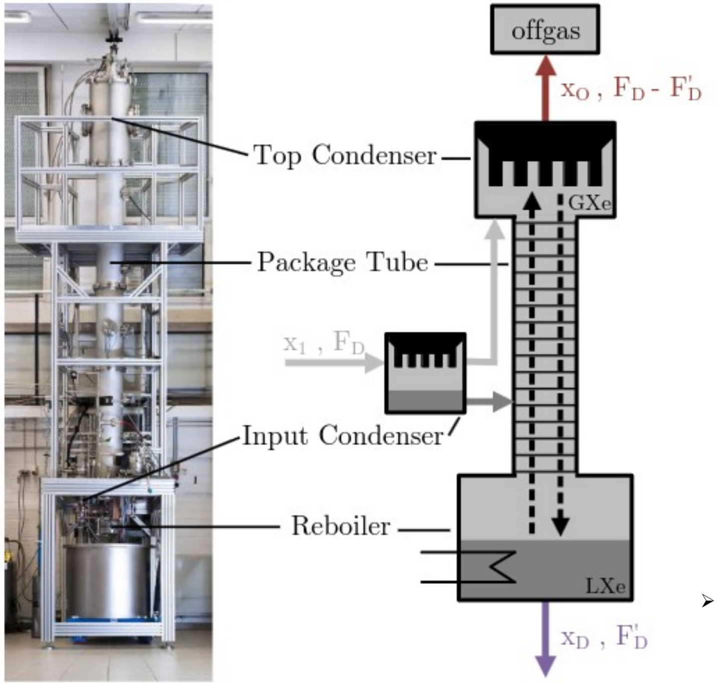


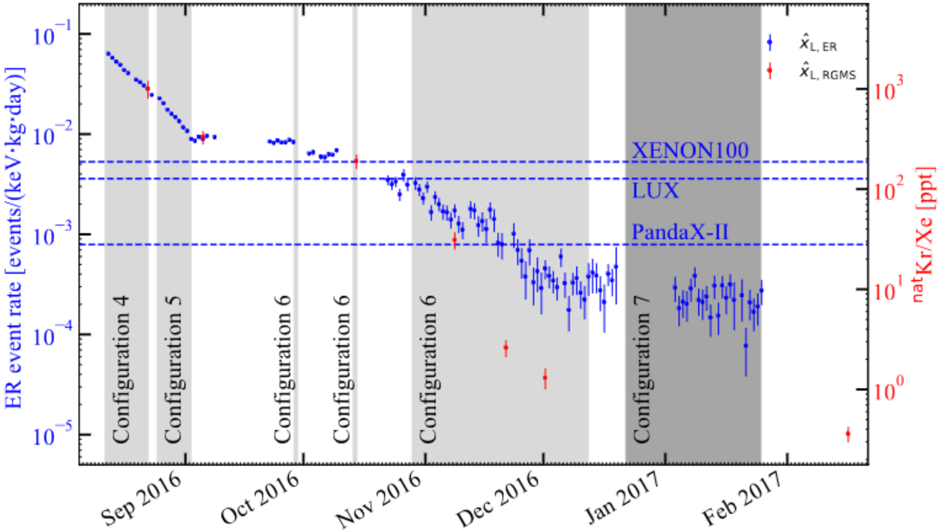




- Xe is continuosly circulated through getters to reduce the level of impurities
- This is crucial to reach a large electron lifetime, i.e. less electron absorption during drift
- The purification ability greatly increases moving from a GXe to a Lxe circulation system

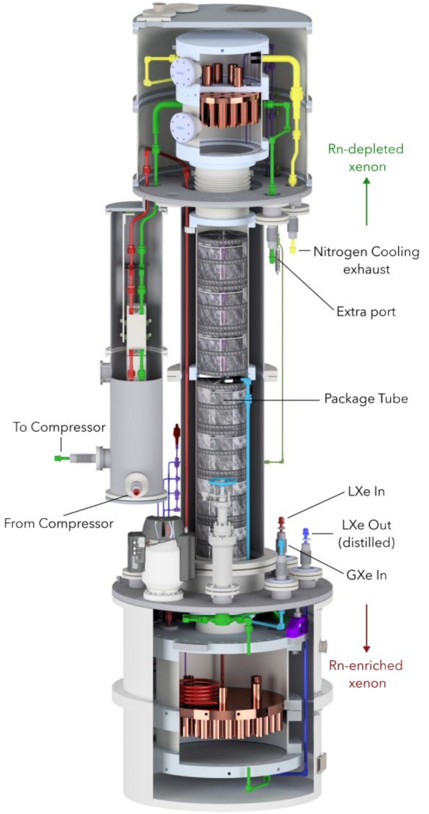
Krypton removal

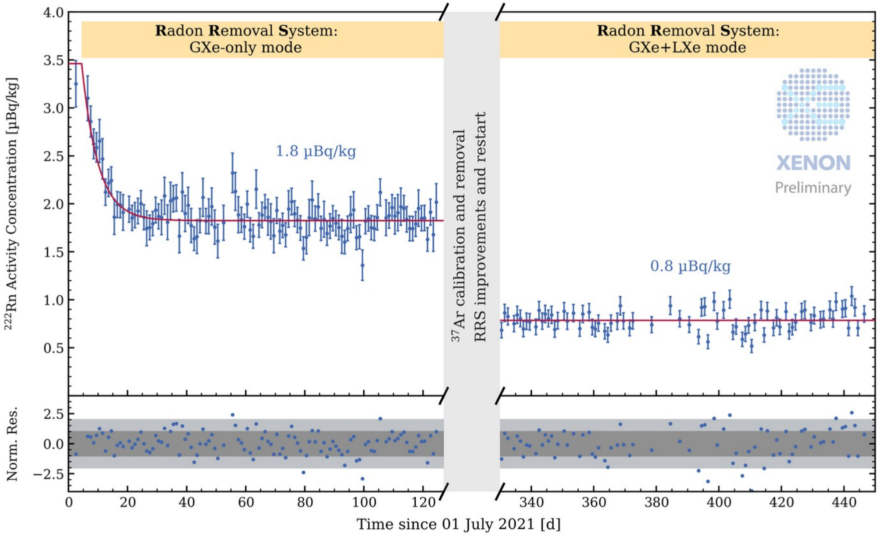




- ^{85}Kr produces β-decays with a long half-life (10.7 y)
- Kr level in Xe has to be reduced with a dedicated distillation column
- The distillation is very efficient and the Kr/Xe level gest reduced by 3 orders of magnitude (< 1 ppt)

Radon Removal System

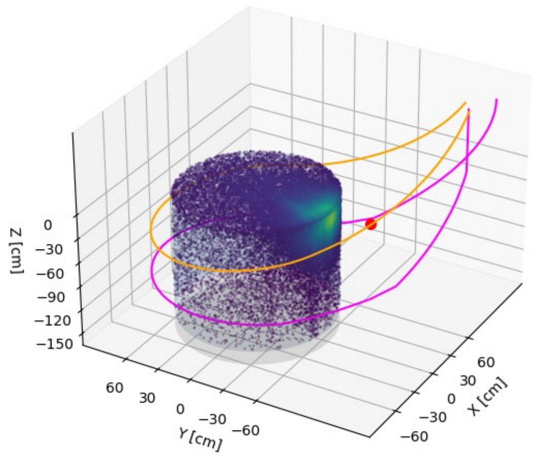


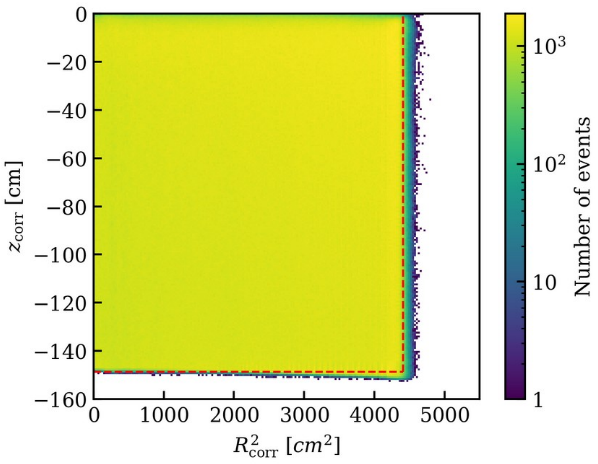


- After Kr is removed, the main background is from the decay chain of ^{222}Rn, in particular β-decay of ^{214}Pb
- ^{222}Rn is continuously emanated from the material surfaces
- Its level is reduced to a lower equilibrium point (< 1 µBq/kg) with a dedicated distillation column

Calibration of dual-phase xenon TPCs

Internal vs external calibration sources





- *External calibration sources* do not provide a uniform events distribution in the TPC

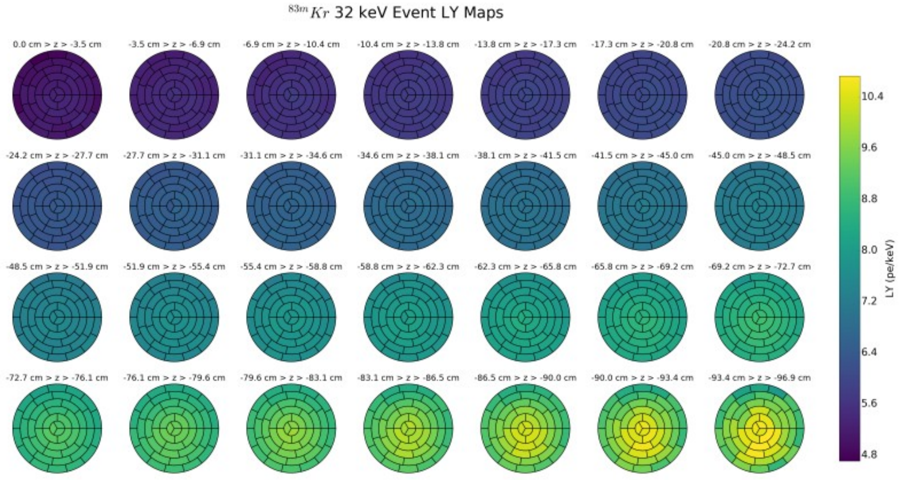
- This is due to the high shielding power of Lxe

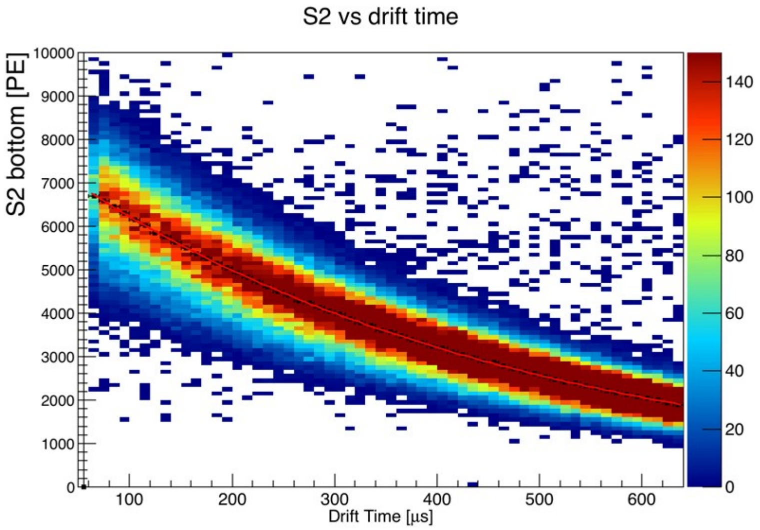
- Typically used:
  ^{57}Co, ^{137}Cs, ^{60}Co, ^{232}Th, AmBe

- *Internal calibration sources* can be used:
  elements which are diffused in the LXe volume

- Typically used in dual-phase xenon TPCs:
  ^{220}Rn (continuous), ^{83m}Kr, ^{37}Ar, ^{129m}Xe, ^{131m}Xe, ^{127}Xe (monoenergetic)

Position-dependent correction maps



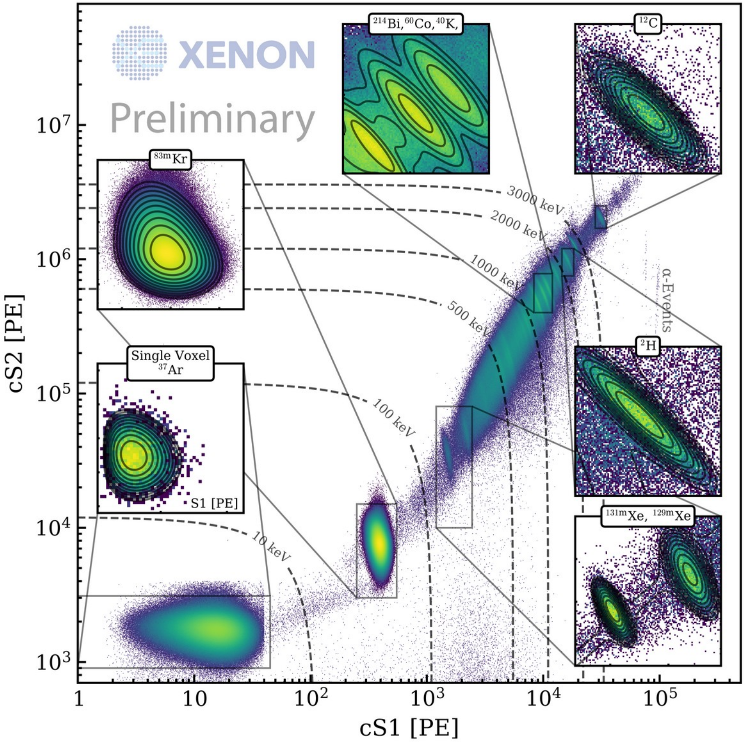


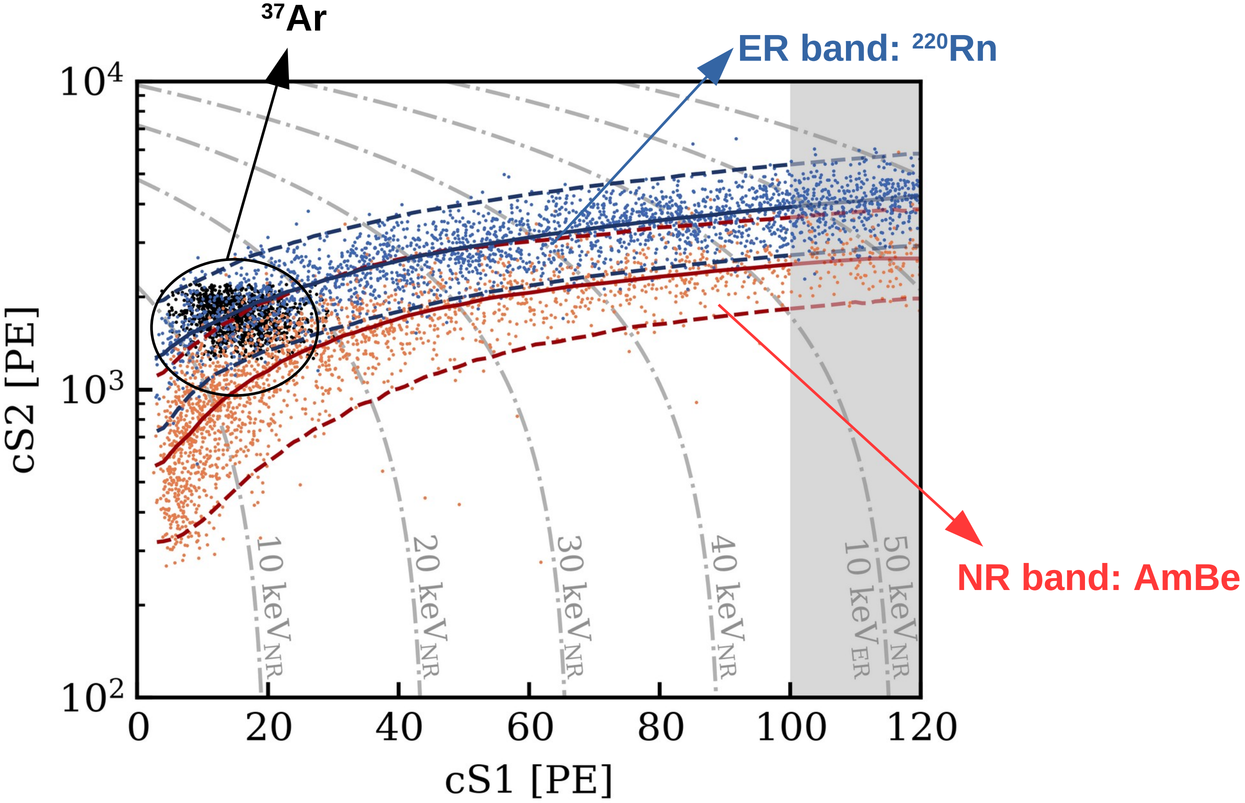
XENON1T S1 correction maps

XENON1T S2 electron lifetime measurement

- ^{83m}Kr is uniform and monoenergetic, it is ideal to build position-dependent correction maps
- ^{37}Ar is also useful for this task

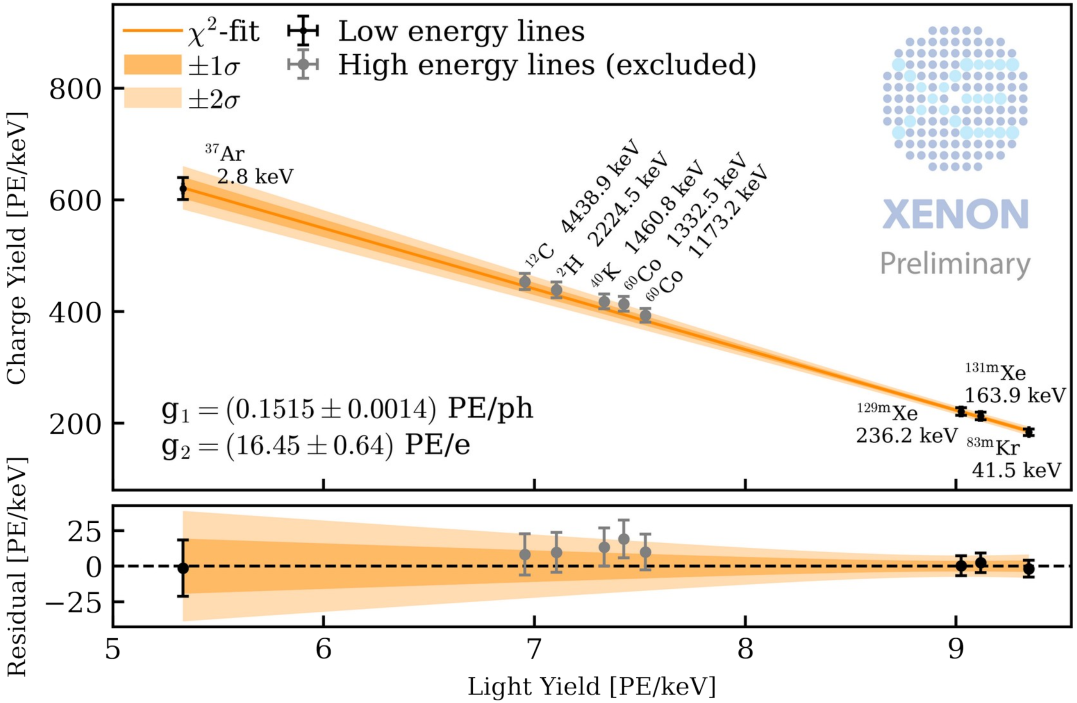
Results of calibration





'c' indicates corrected quantity
cS1: corrected for position-dependent light collection efficiency
cS2: corrected for electron lifetime

Measuring g_1 and g_2

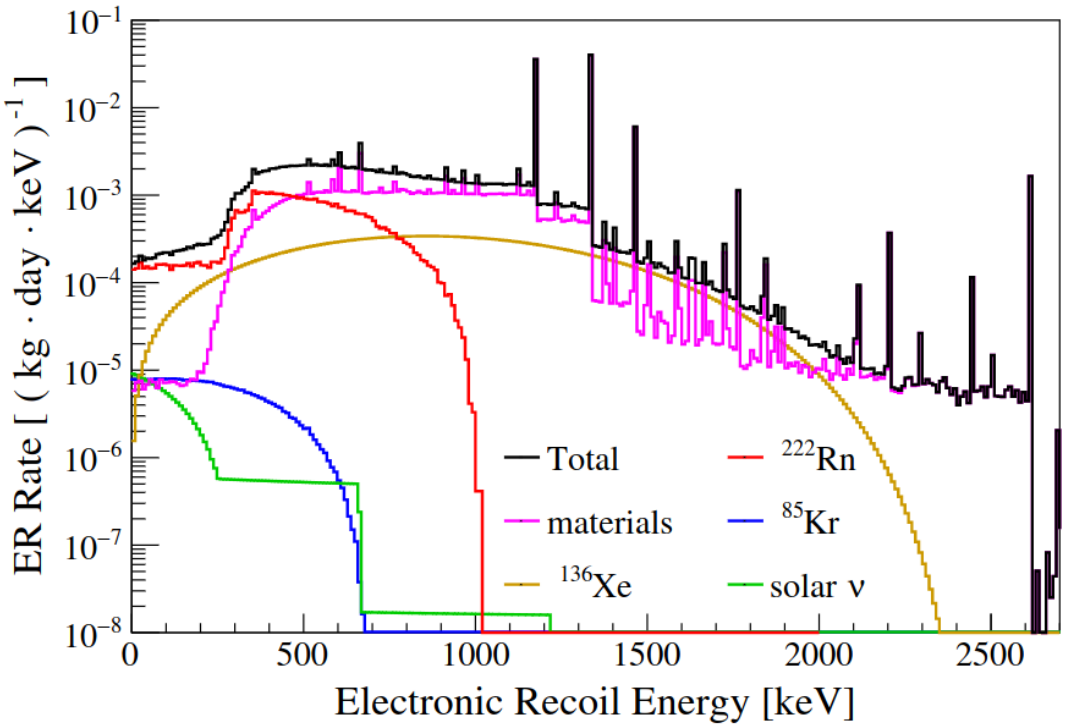


- The detector-dependent parameters are determined using charge and light yields from different sources
- g_1 and g_2 enters the combined energy scale definition

$$\hat{E} = W \left(\frac{\mathrm{cS1}}{g_1} + \frac{\mathrm{cS2}}{g_2} \right)$$

Background and mitigation strategies

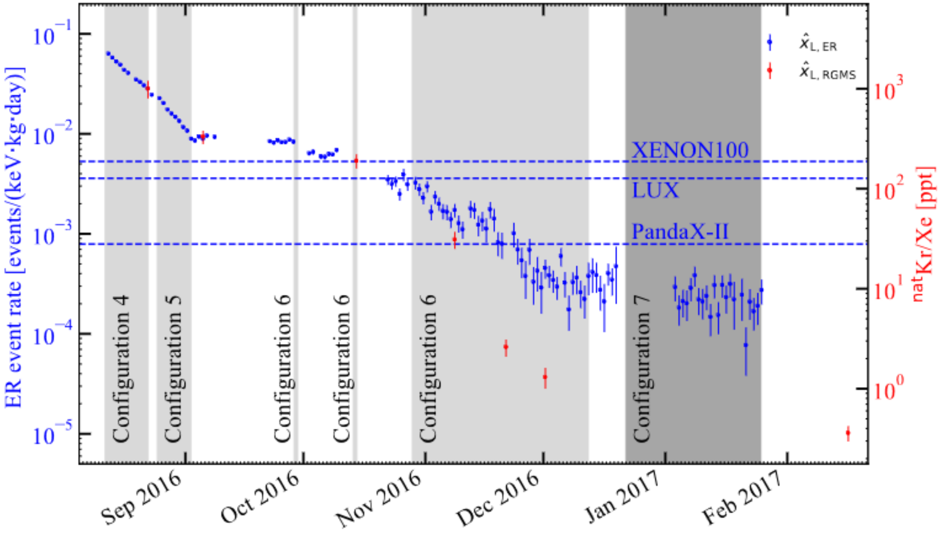
ER background components

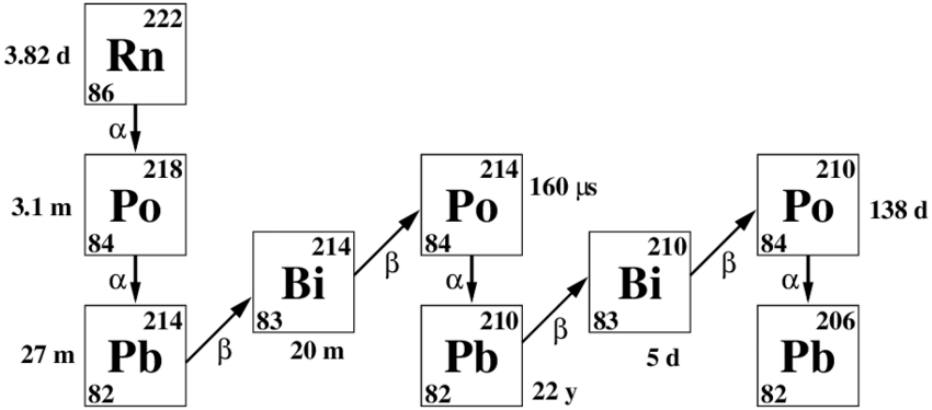


XENON1T, JCAP04 (2016) 027, arXiv:1512.07501

- **External sources:**
  materials radioactivity
- *Mitigation:*
  fiducial volume, screening of materials
- **Internal sources:**
  ^{222}Rn, ^{85}Kr, ^{136}Xe, solar ν
- *Mitigation:*
  it depends on the source, fiducial volume not effective

Kr and Rn mitigation





- Reduction of Kr and Rn level with dedicated distillation columns
- The α decays of the Rn chain can be easily excluded (high energy), possible to tag BiPo coincidence decay
- Only problematic contribution is the ^{214}Pb decay

^{136}Xe and neutrino mitigation

- ^{136}Xe (8.9% abundance) undergoes ββ decay, $t_{1/2} = 2.2 \times 10^{21}$ y

  $$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2e^{-} (+2\bar{\nu})$$

- Peak at spectrum endpoint **$Q_{\beta\beta}$ = 2.458 MeV**

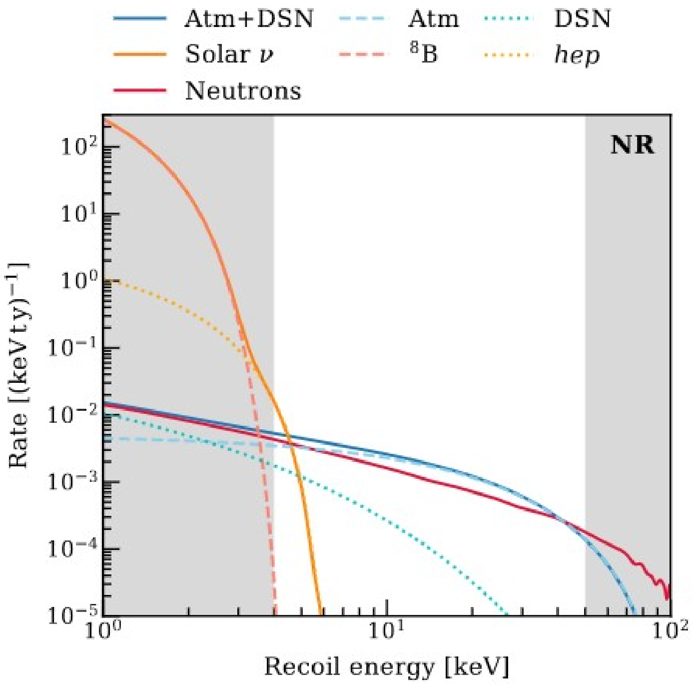
- Solar ν scattering off electrons

  $$\nu + e^- \rightarrow \nu + e^-$$

- Mainly pp ν with energies up to 420 keV

- It’s not possible to reduce these backgrounds as done for ^{85}Kr and ^{222}Rn
- As mentioned, fiducial volume doesn’t help here
- Strategy is to precisely describe them and include in background model
- Both backgrounds are not dominant in the low energy region

NR background components



`XENON Collaboration, JCAP 11 (2020) 031`

- NR background much smaller than ER background, but important since it mimics WIMP interaction

- **Neutrons from material**
Fiducial volume, exclusion of multi-scatter events, tagging with a Neutron Veto

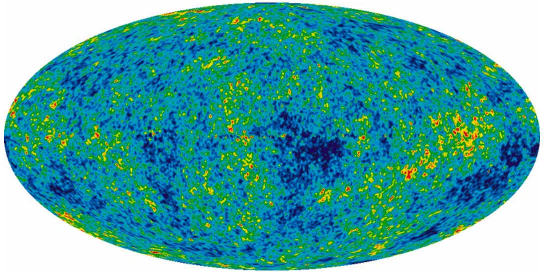
- **Coherent Elastic ν-Nucleus Scattering (CEνNS)**
From solar ν (^{8}B, hep), atmospheric ν and diffuse supernova ν
- This is an irreducible background, need a good modeling

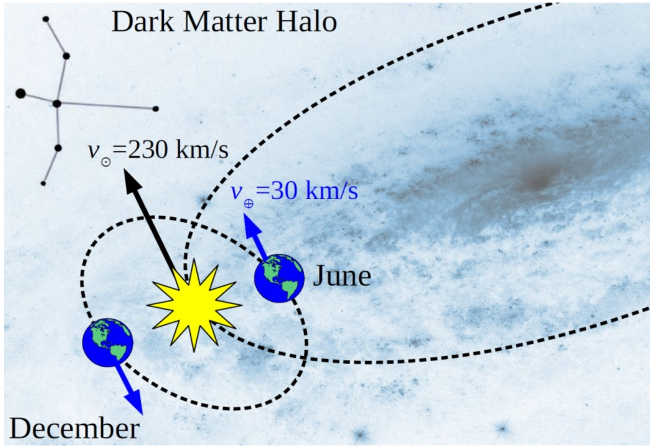
- **Cosmogenic neutrons**
These are muon-induced neutrons, they represent a negigible contribution with the help of a Muon Veto

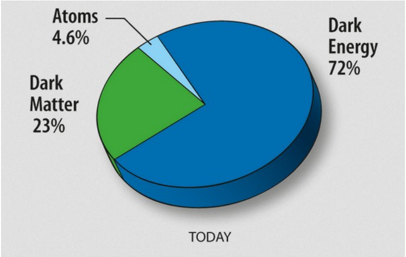
Science cases for dual-phase xenon TPCs

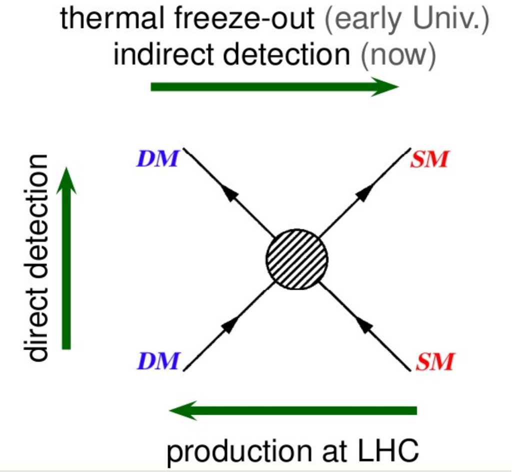
Science cases for dual-phase xenon TPCs

The problem of dark matter



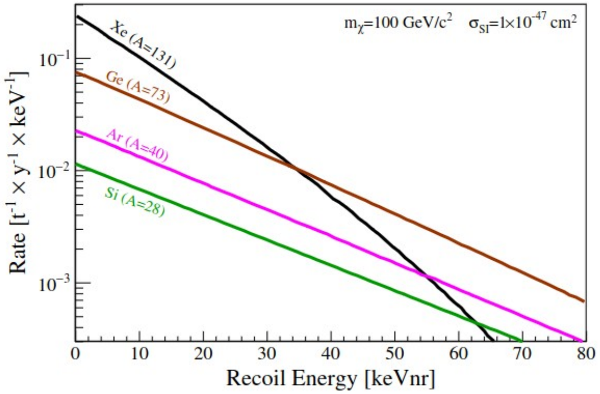


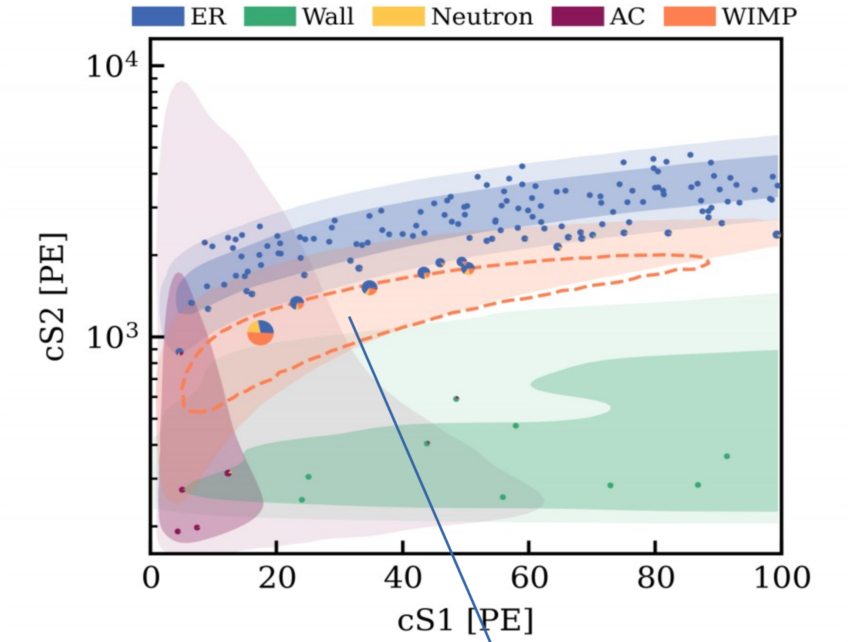




- Dark Matter is made of new particles beyond the standard model
- WIMPs are a class of candidates
- We can search for WIMP scattering on nuclei of ordinary matter

Xe pros in the search for dark matter

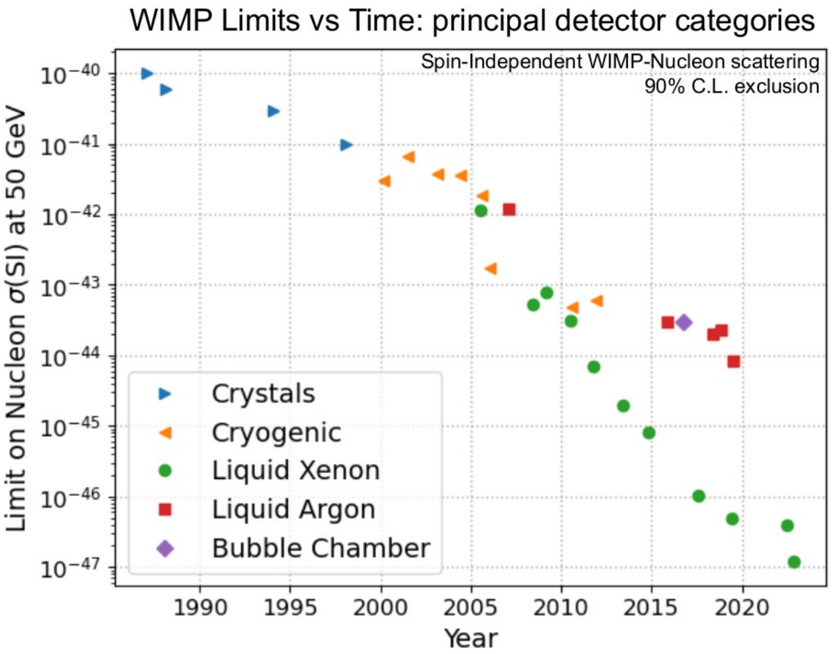




- Large masses and homogenous targets
- Low energy threshold (few keV)
- Very low intrinsic background
- Volume fiducialization
- Heavy nucleus → large expected interaction rate

WIMP search in the NR region with almost no background

Leading technology



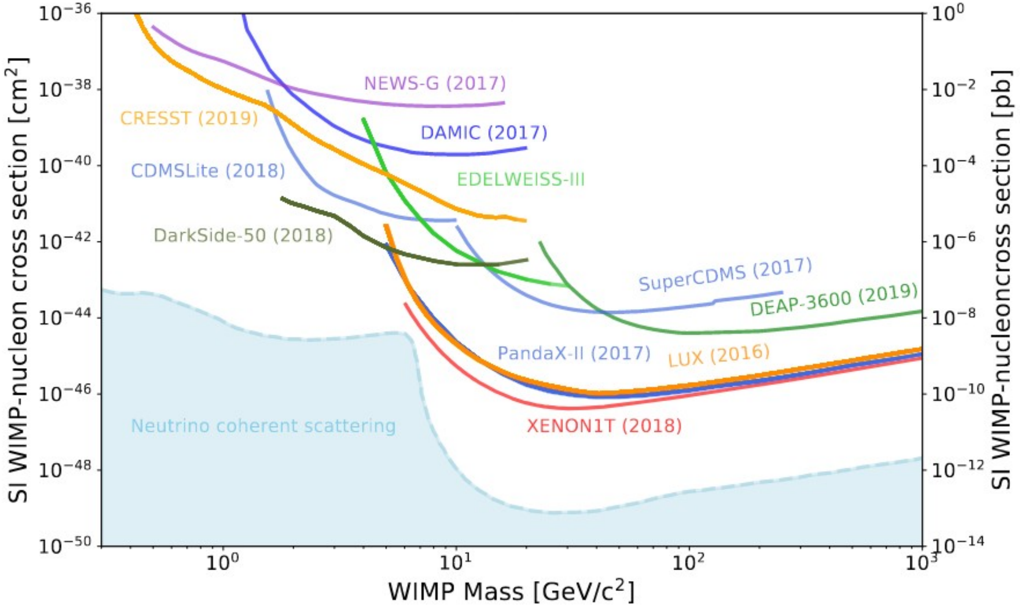
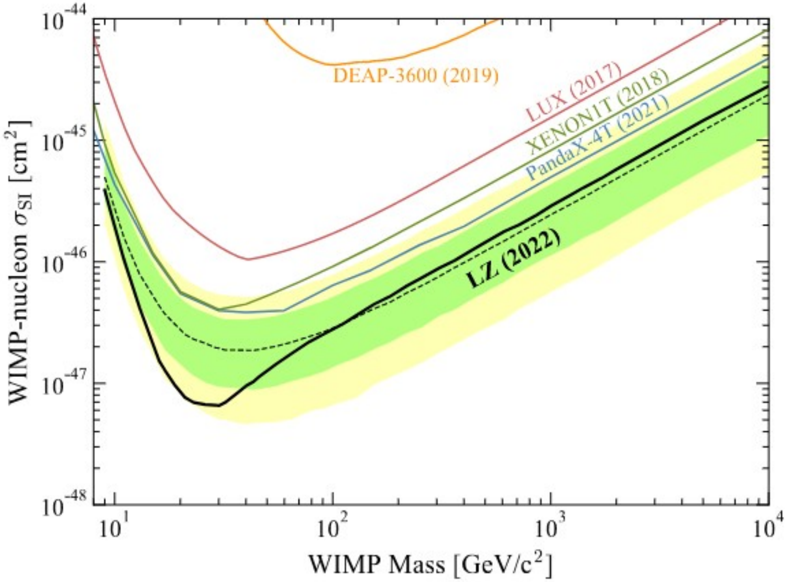


Figure from P.A. Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

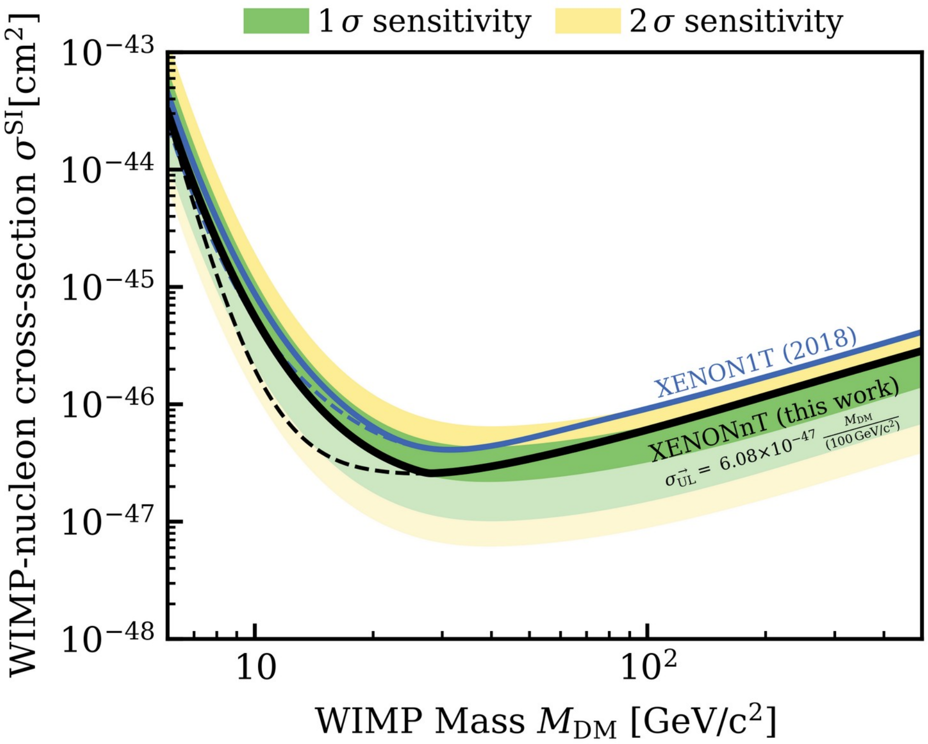
D.Akerib, Noble Gas Based Direct Detection & G3 (XLZD Proposal)

- Dual-phase Xe TPCs are currently the leading technology in the direct search for dark matter

WIMP search best limits

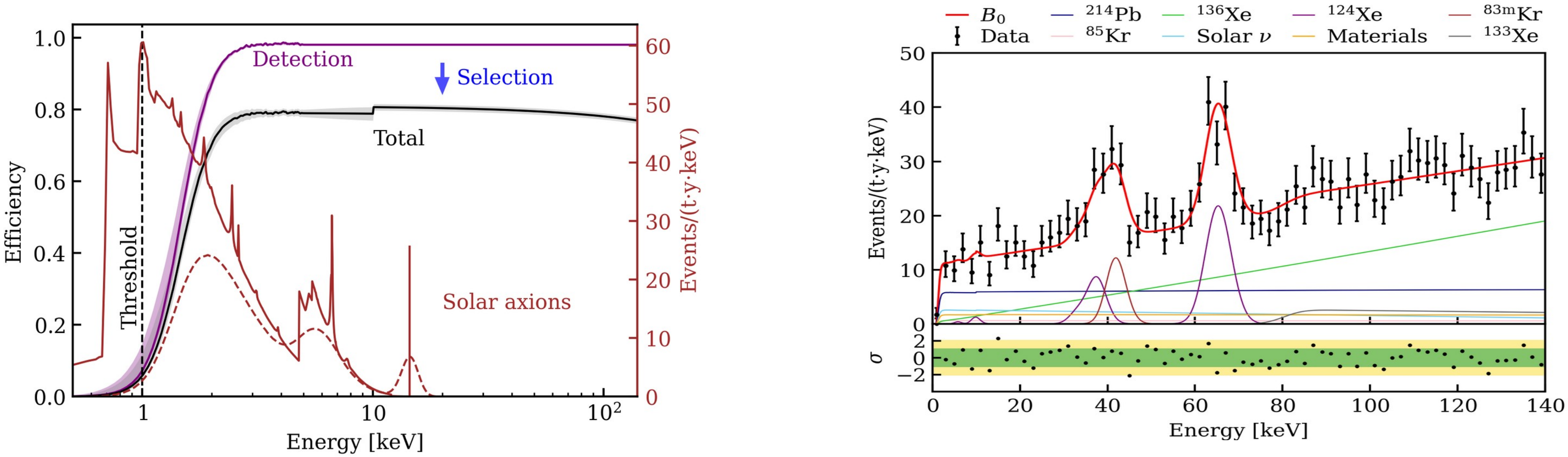


LZ Collaboration, 2022



XENON Collaboration, 2023

ER searches



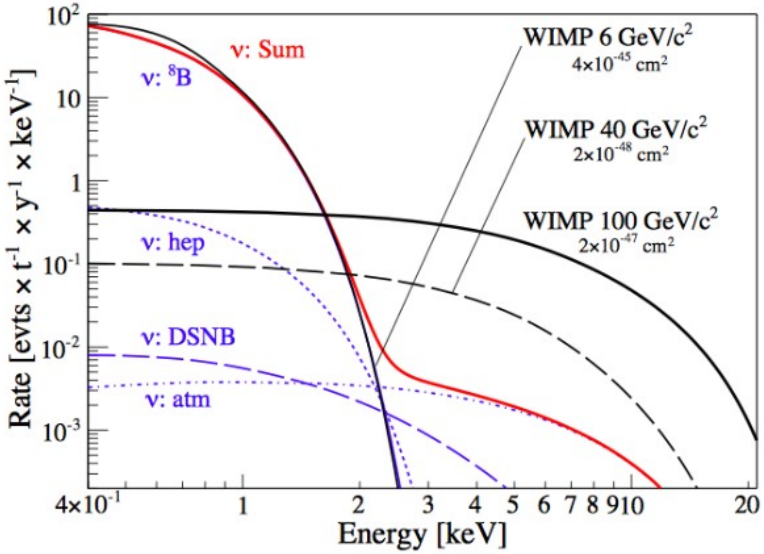
XENON Collaboration, Phys. Rev. Lett. 129, 161805 (2022)

- Thanks to extremely low background in ER, it’s possible to search for other dark matter candidates (axions, ALPs, dark photon)
- Look for excess above a known background level
- Background shape dominated by 2nd order processes

Solar and Supernova neutrinos

Science cases for dual-phase xenon TPCs

Coherent ν-nucleus scattering



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

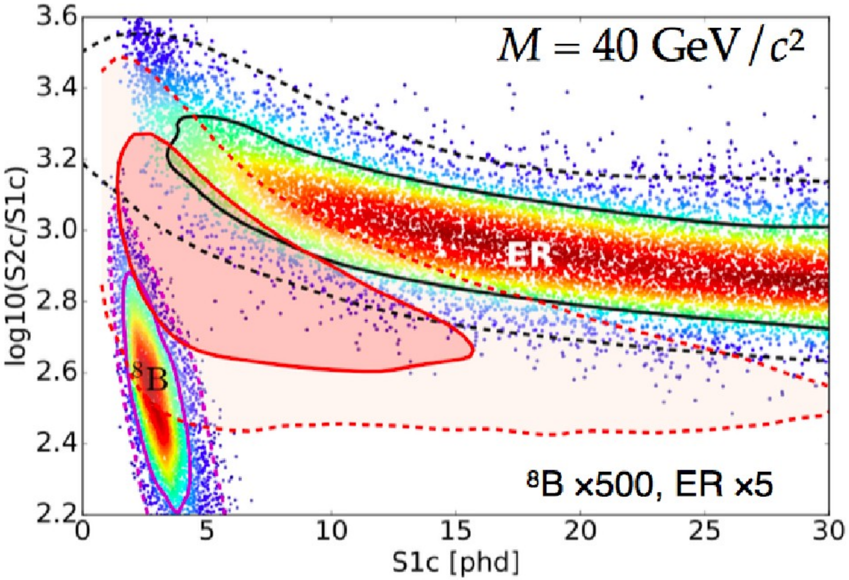
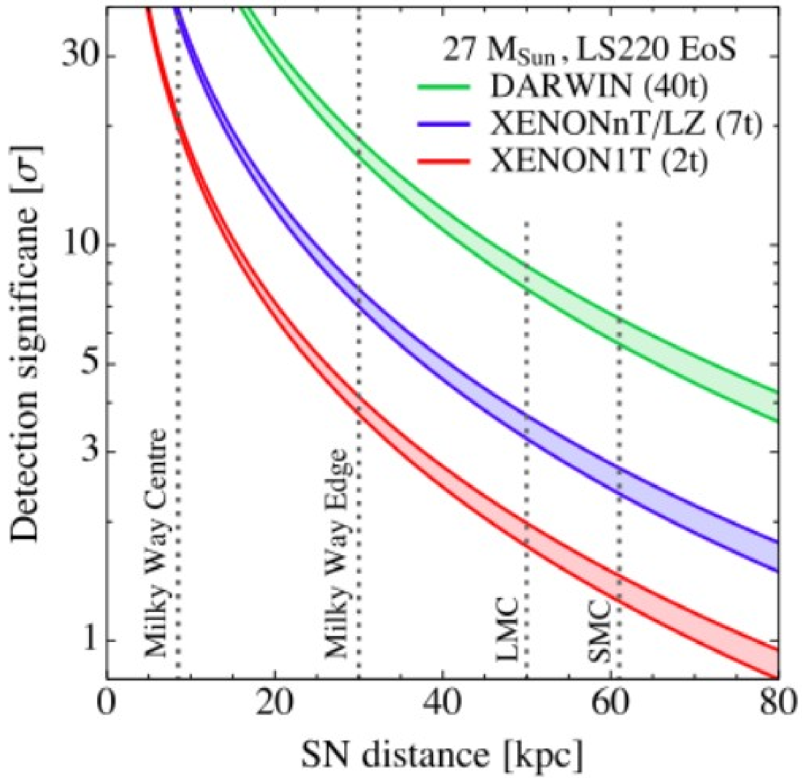


Figure from the LZ collaboration, see also arXiv:1802.06039

- CEνNS constitute an irreducible background, but they also represent an interesting signal to study
- XENONnT will attempt the first detection of ^{8}B solar ν with CEνNS

Supernova neutrino



Lang *et al.*, Phys. Rev. D 94, 103009 (2016)

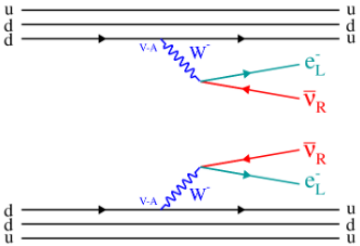
- If a supernova happens in our Galaxy, an intense ν burst will be detected by several detectors
- Dual-phase Xe TPC can observe CEνNS induced by these supernova neutrino
- Interesting point is that this channel is independent of ν oscillation effect (this is not the case for other interaction channels as the IBD)

Neutrinoless ββ decay

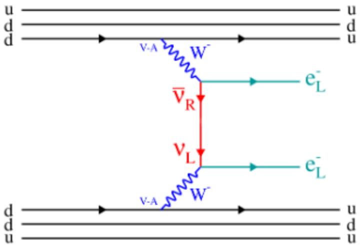
Science cases for dual-phase xenon TPCs

ν-less ββ decay

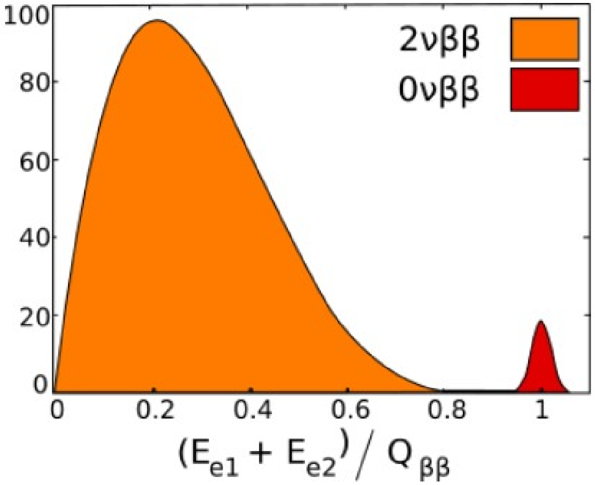
Standard process



New process



- A process violating lepton number conservation
- It would imply ν is a Majorana particle (ν and anti-ν are the same particle)

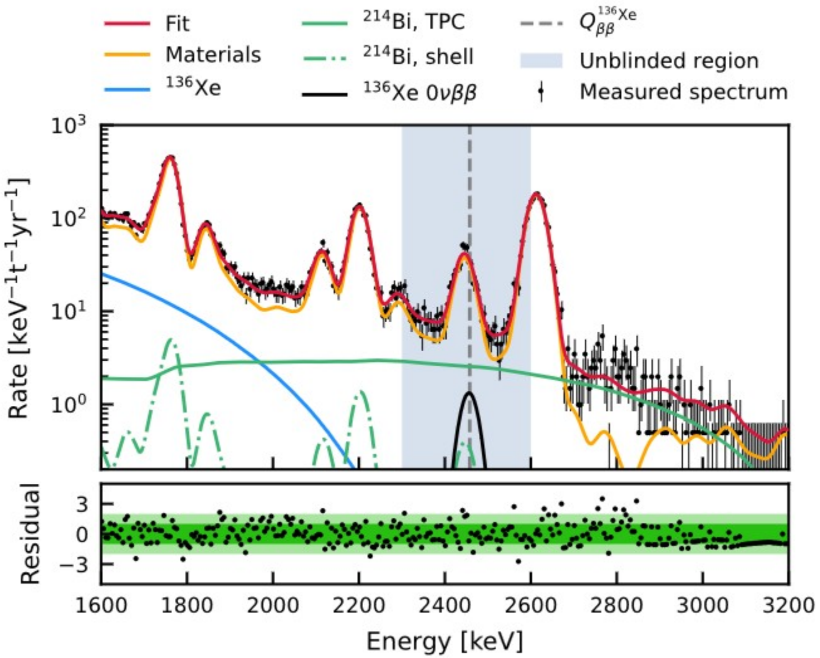


- ^{136}Xe (8.9% abundance) undergoes ββ decay (with 2 anti-ν)

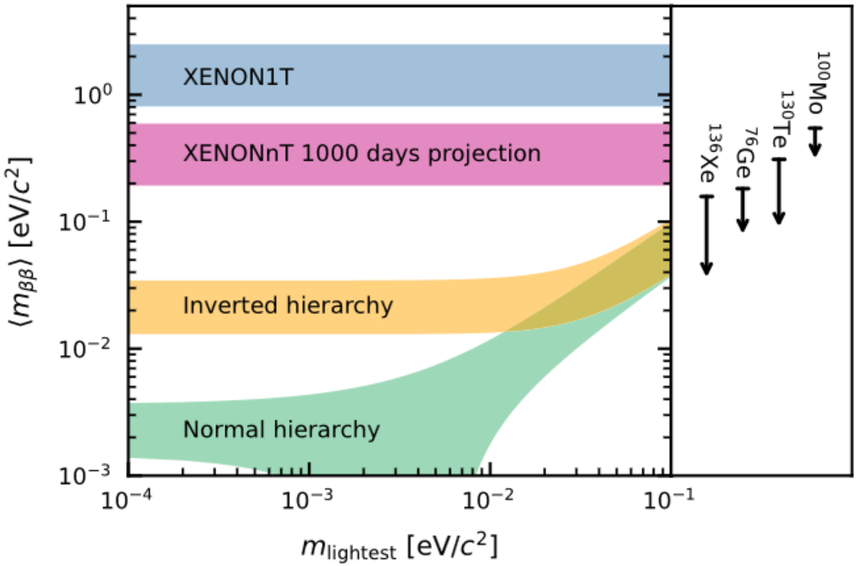
$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2e^{-} (+2\bar{\nu})$$

- Candidate for ν-less ββ decay
- Peak at spectrum endpoint **$Q_{\beta\beta}$ = 2.458 MeV**

Search for ν-less ββ decay



XENON Collaboration, Phys. Rev. C 106, 024328 (2022)



- Good energy resolution at $Q_{\beta\beta}$ (< 1%) is crucial to reach a good sensitivity

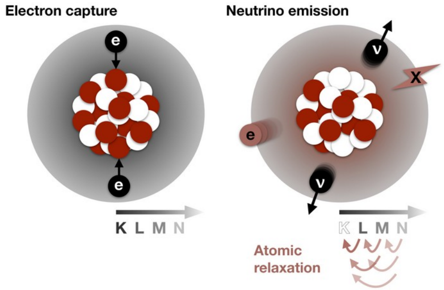
$$S_{0\nu} \propto \epsilon \cdot \frac{\alpha}{A} \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot b}}$$

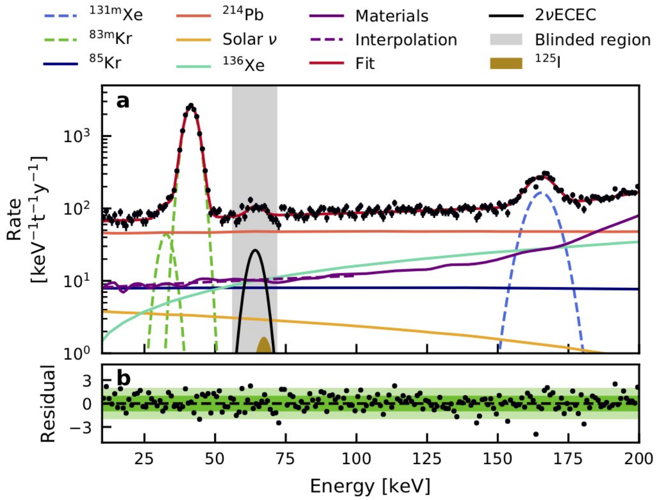
ϵ: detection eff., A: atomic mass, ΔE: energy resolution & b: background level

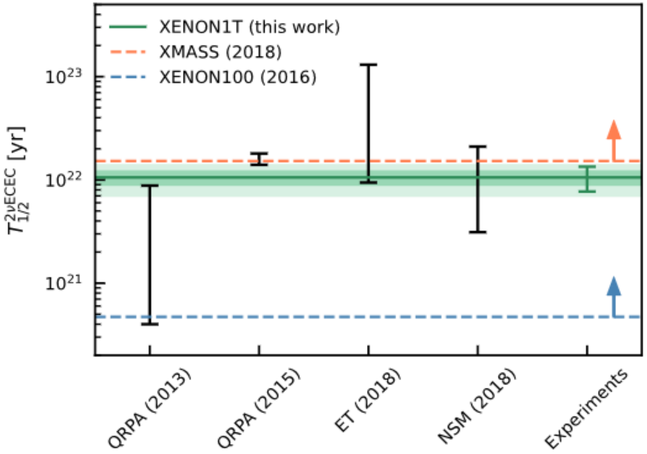
Science cases for dual-phase xenon TPCs

Rare decays

Observation of ^{124}Xe decay







- ^{124}Xe undergoes a very rare decay via double electron capture

$$^{124}\text{Xe} + 2e^{-} \rightarrow {}^{124}\text{Te} + 2\nu_{e}$$

- Observed for the first time in XENON1T (2019)
- **Longest half-life ever measured** $(1.1 \pm 0.2_{stat} \pm 0.1_{sys})\text{x } 10^{22}$ y

E. Aprile et al. (XENON), Nature 568 (2019), no. 7753, 532-535

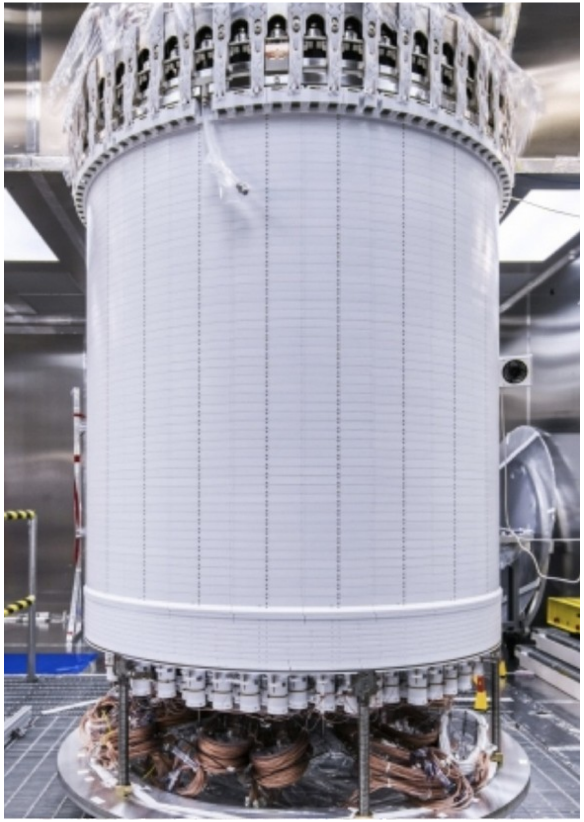
Currently operating and future dual-phase xenon TPCs

XENONnT

XENON

- ***Where:*** Laboratori Nazionali del Gran Sasso (Italy)
- ***Target mass:*** 6 t
- ***Status:*** Taking science data

LUX-ZEPLIN (LZ)



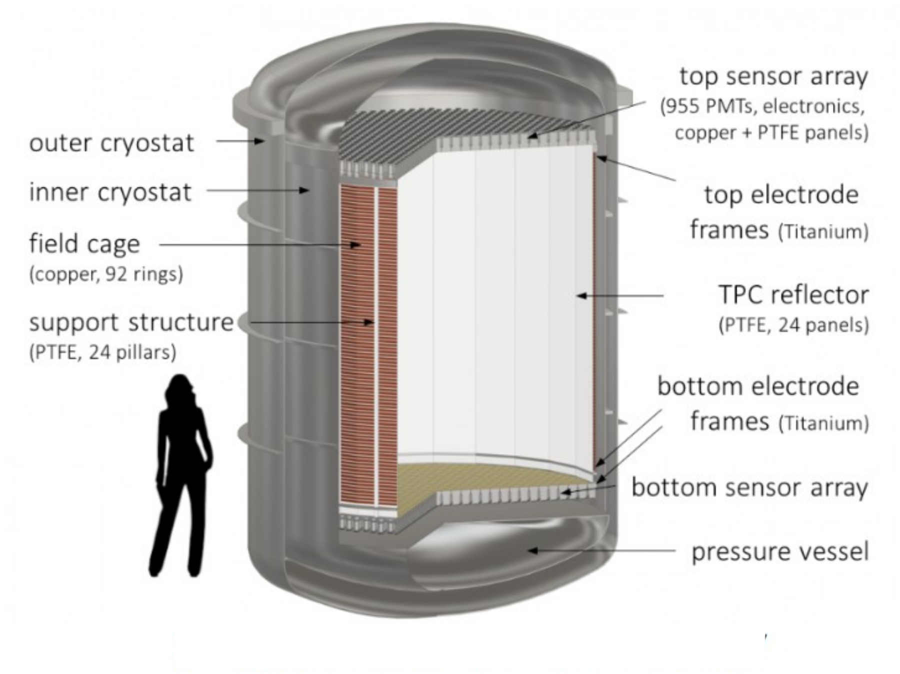
- ***Where:*** Sanford Underground Research Facility (SD, USA)
- ***Target mass:*** 7 t
- ***Status:*** Taking science data

PANDAX-4T

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

- ***Where:*** China Jinping Underground Laboratory (China)
- ***Target mass:*** 4 t
- ***Status:*** Taking science data

The future: DARWIN



DARWIN, JCAP 1611 (2016) 017

- R&D and design study ongoing for a large LXe dark matter detector
- **50 t LXe total** (40 t in the TPC)
- TPC of 2.6 m diameter and 2.6 m drift length
- It will continue the search for dark matter
- It will be a large observatory for astroparticle physics, ν-less ββ decay and rare processes

Final summary

Final summary

- Dual-phase xenon TPCs are detectors with many interesting properties:
  energy reconstruction, low energy threshold, position reconstruction, ER/NR discrimination
- They feature a very low background, in particular in the NR region
- For this reason, they are well suited for the direct detection of dark matter, for which they are currently the leading technology
- They are employed also in other rare events search: neutrino interactions, rare decays