Calibration of XENON1T for the search of new physics

DARK MATTER AND MORE

Outlook

XENON Project

I) Dark Matter

II) Detector principle and background

III) Dark matter search with XENON1T

- I) Calibration at low energies using a ^{83m}Kr source
- II) XENON1T : 1 ton x year results

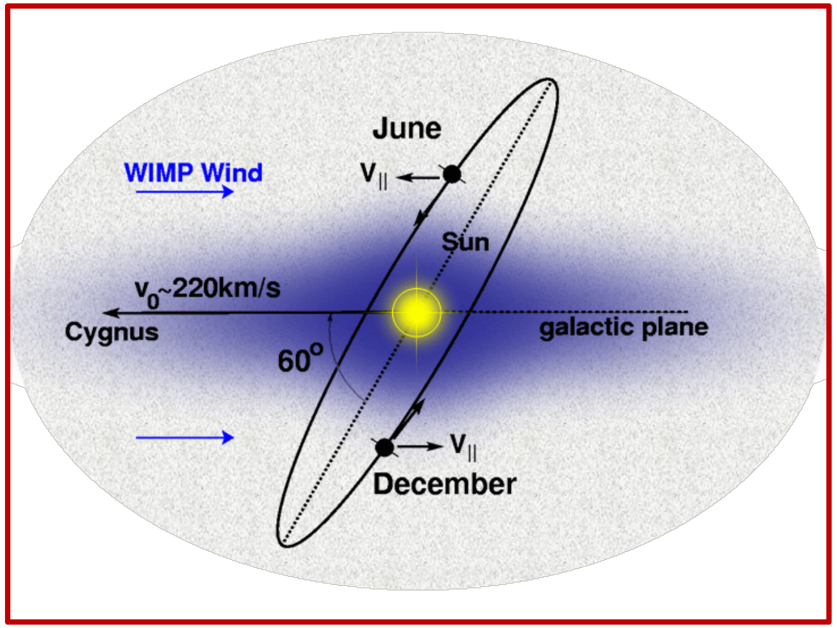
IV) Neutrinoless Double β decay :

- I) Expected signal
- II) Energy reconstruction at high energy

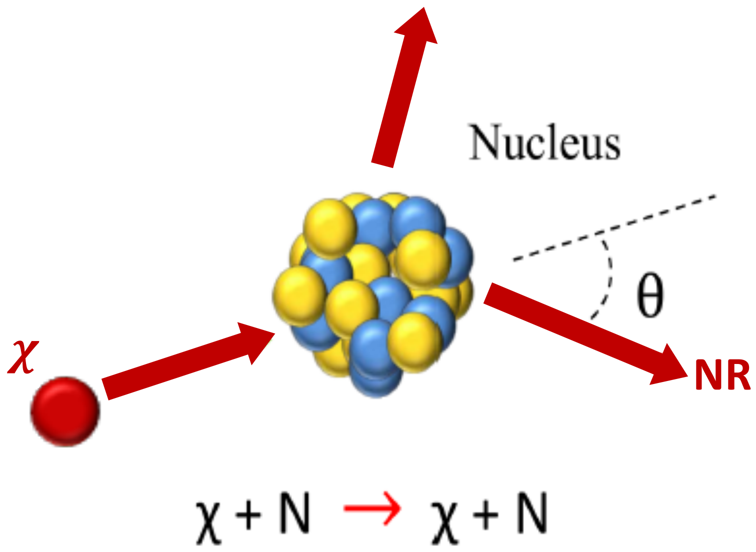
Dark matter interaction

Dark matter halo around galaxies = WIMP wind

→ WIMP (χ)—Nucleus Scattering **(Nuclear Recoil (NR))**



WIMP = **Weakly Interactive** Massive Particle



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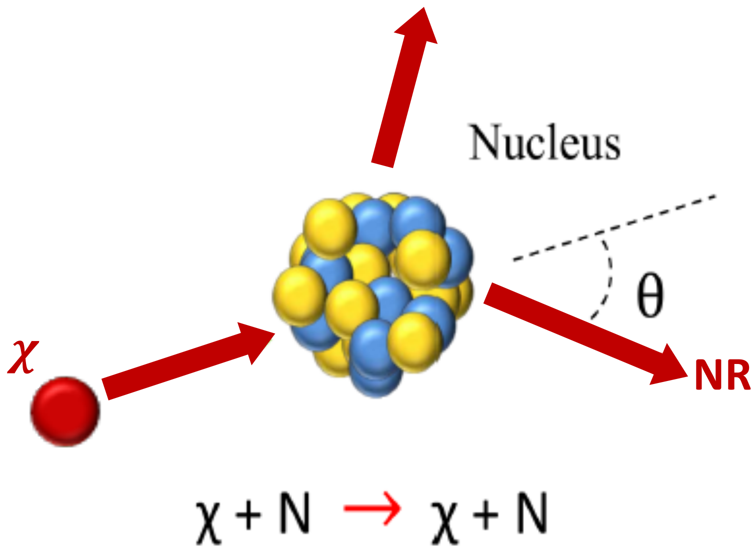
$$E_{nr} = \frac{m_\chi v^2}{2} \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} \cos^2\theta$$

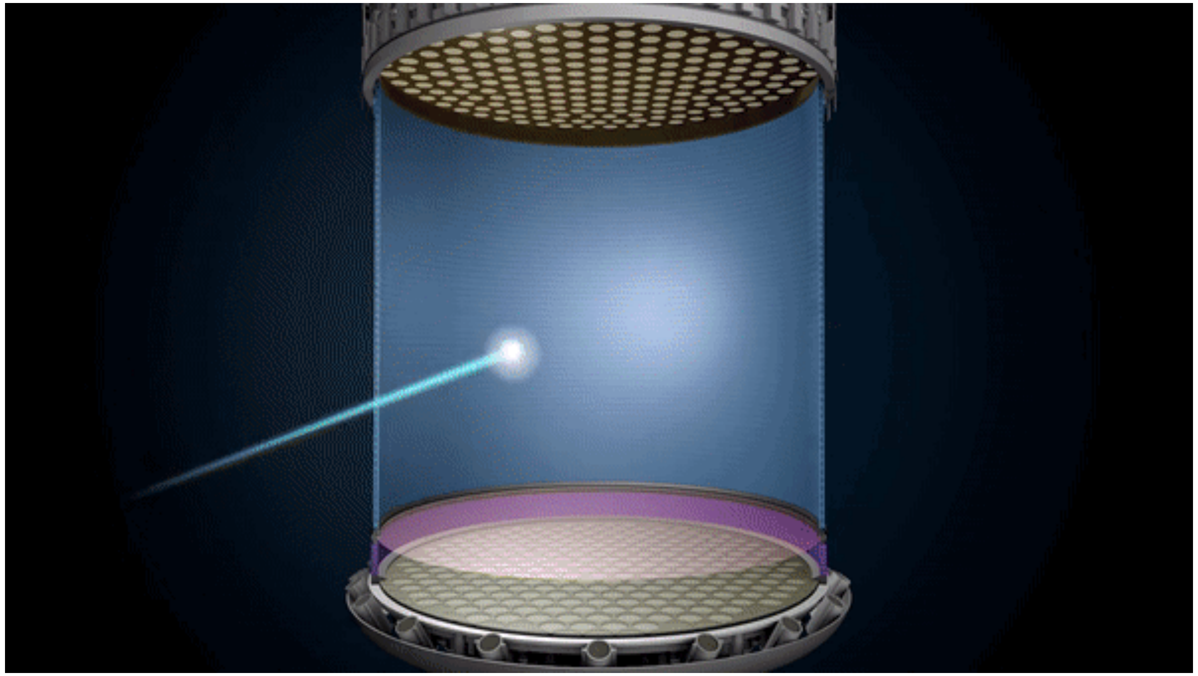
$If:\ m_N = 131\,u\ ;\ \theta = 0\ ;$
$v = 230\ km/s\ ;\ \ m_\chi = 200\,GeV/c^2$
Then : $\boldsymbol{E_{nr}^{MAX} = 55\ keV}$

→ Low energy



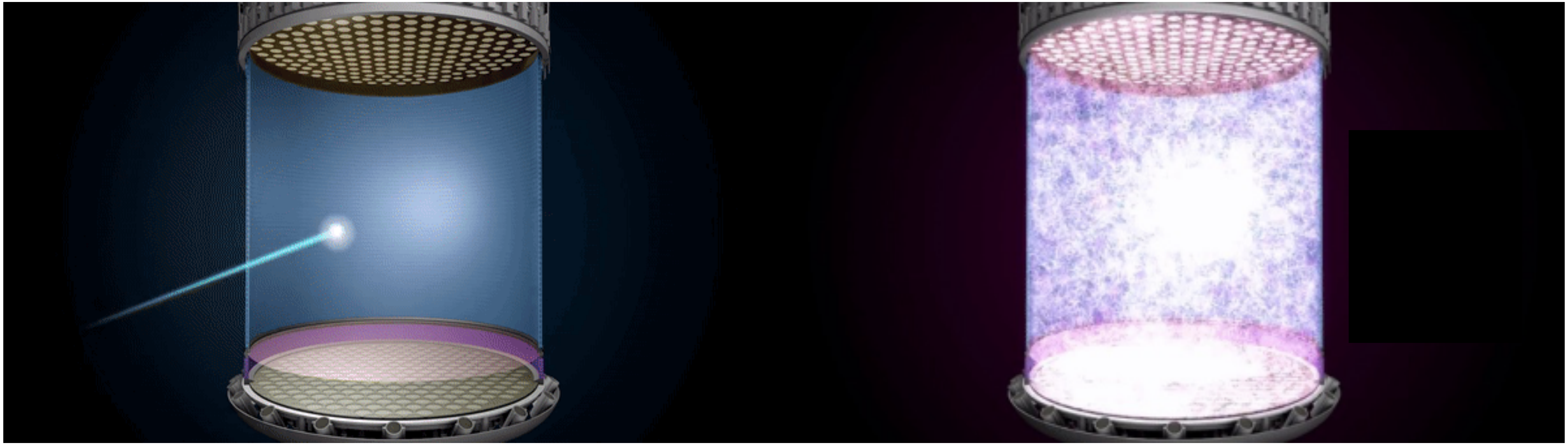
Dark matter direct detection

Rare interaction with low energy signal!



Dark matter direct detection

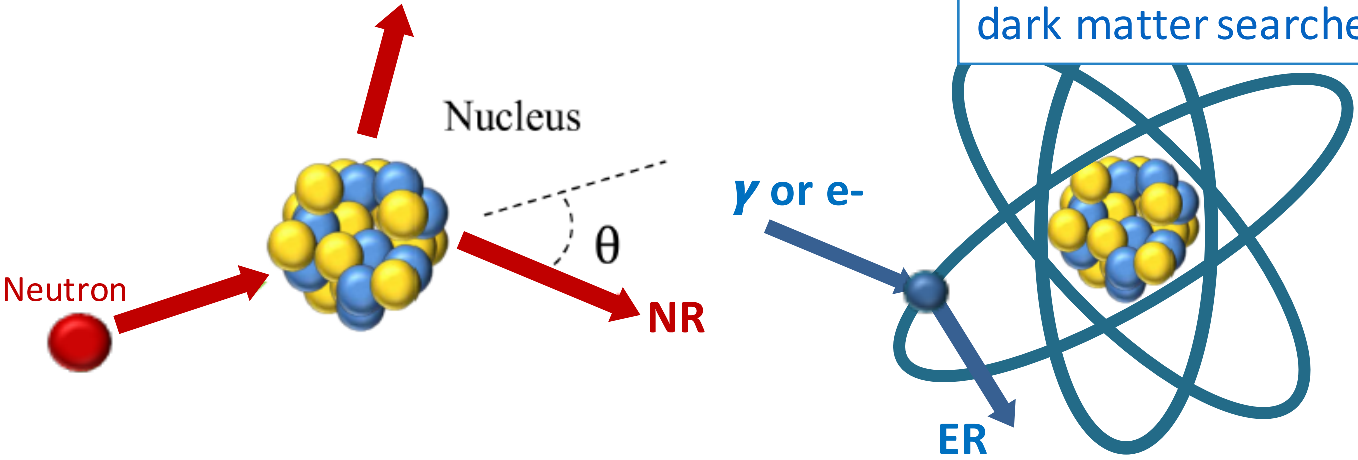
Rare interaction with low energy signal!
+ several background sources



Background

Main background for dark matter search:

- Cosmic rays
- Ambient radioactivity
  - from the laboratory
  - from the detector itself !
- Intrinsic radioactivity
  - ^{85}Kr
  - daughter of ^{222}Rn (emanation from material detector)



Main background for dark matter searches

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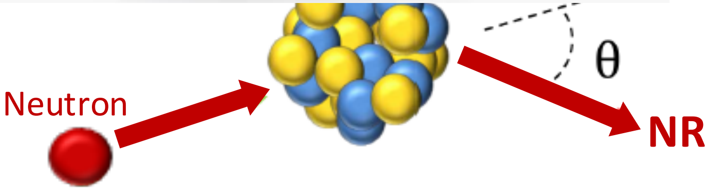

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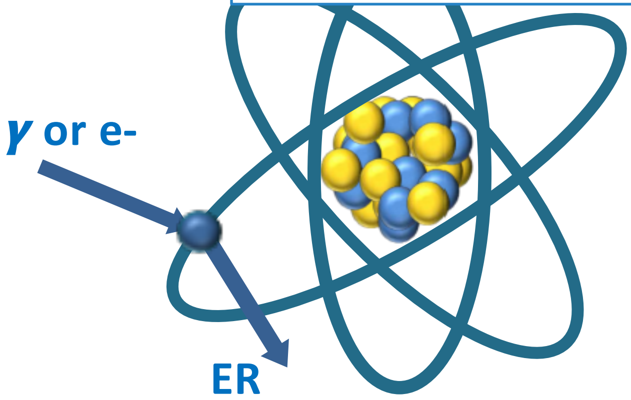

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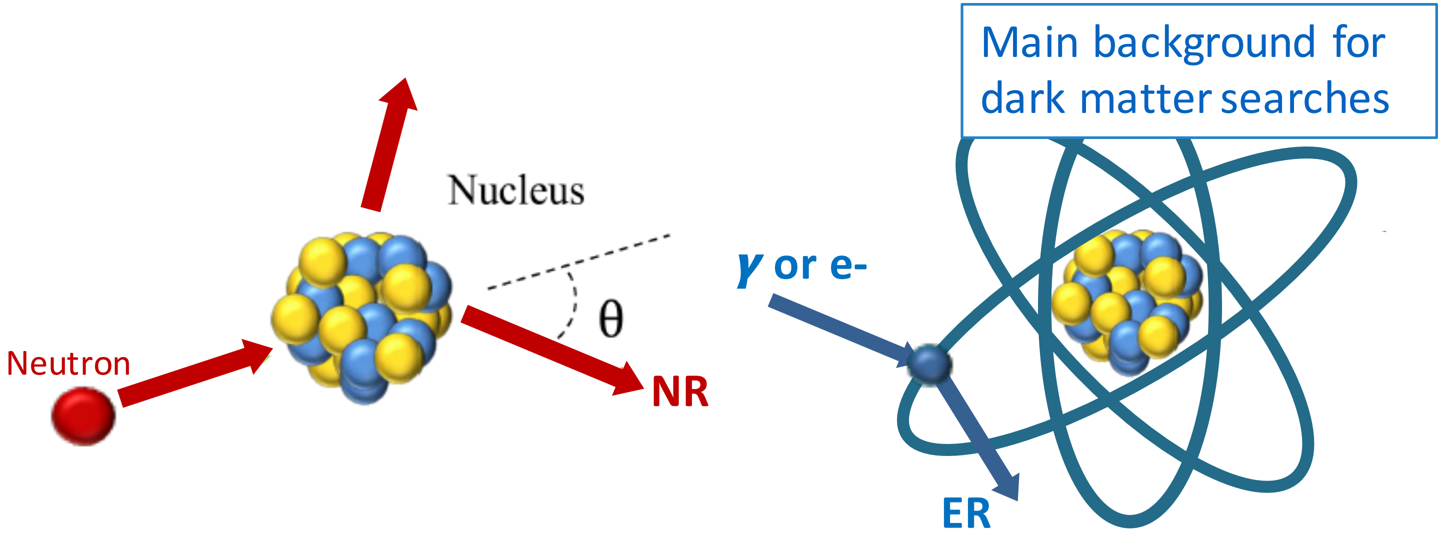

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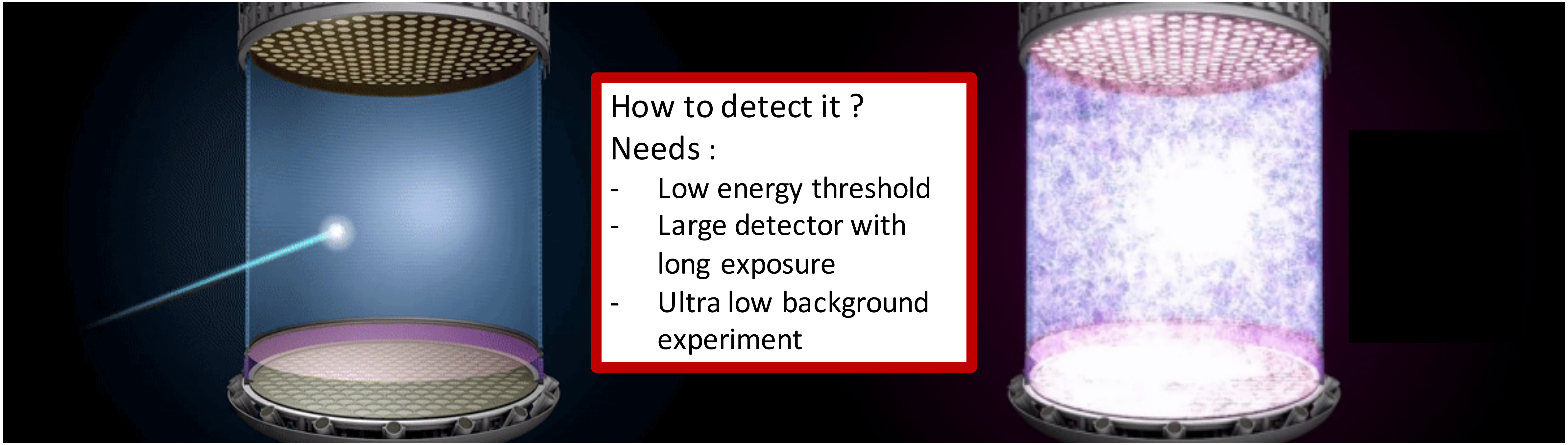


How to detect it ?

Needs :

- Low energy threshold
- Large detector with long exposure
- Ultra low background experiment

Why using liquid xenon?

WIMP-nucleus interaction probability increase:

- Large mass number A ($\sigma^{\text{WIMP-nucleus}} \propto A^2$)
- High density
- Liquid = scalable to large mass

Low energy event detection :

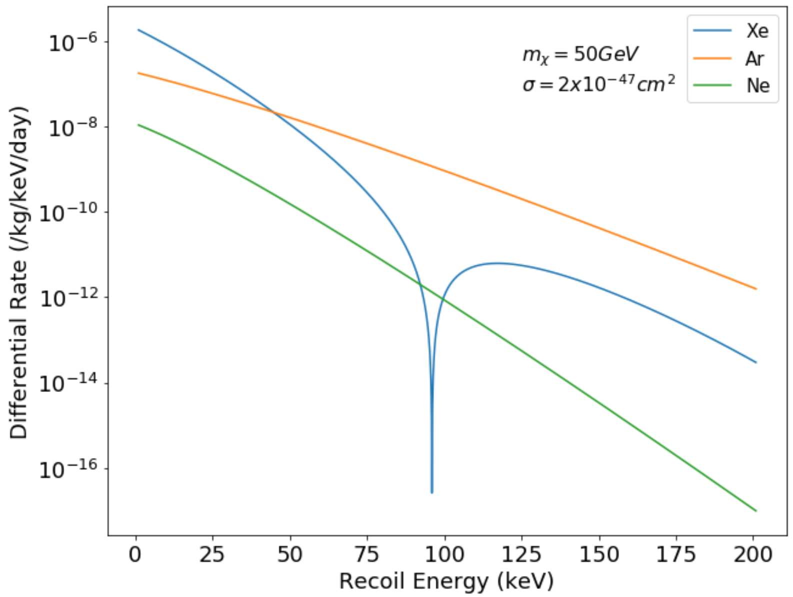
- Efficient scintillator (178 nm UV)

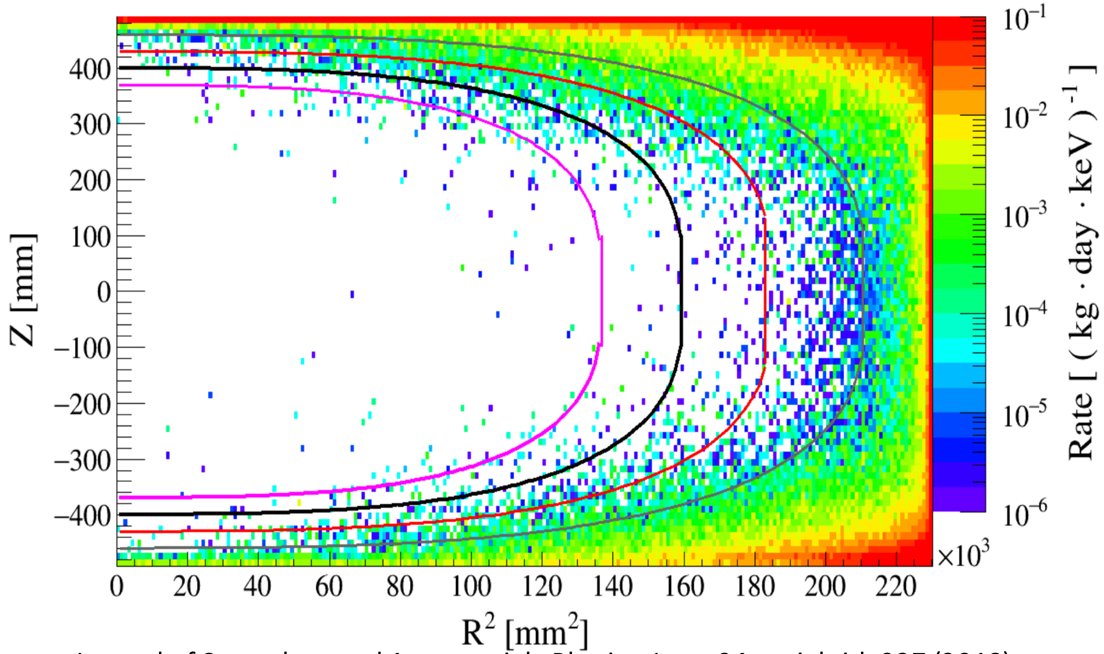
Reducing the background :

- No intrinsic radioactivity (except ^{136}Xe – long half-live)
- High stopping power (= self-shielding)

+ 3D position = fiducial volume

- Simultaneous measurement of scintillation and ionization = NR/ER discrimination





Journal of Cosmology and Astroparticle Physics, Issue 04, article id. 027 (2016)

Background reduction

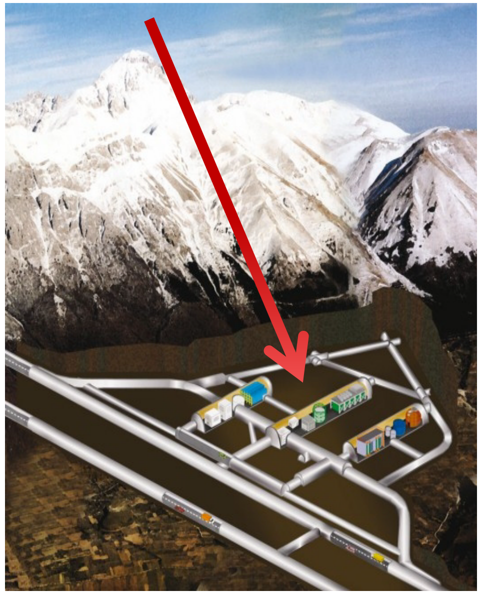
Cosmic rays : Underground laboratory

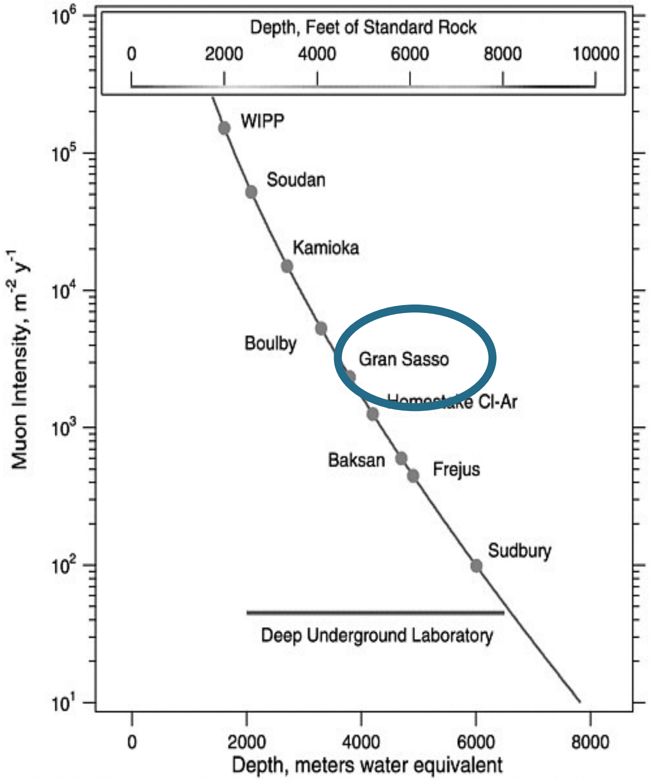
Laboratory of Gran Sasso (Italy)

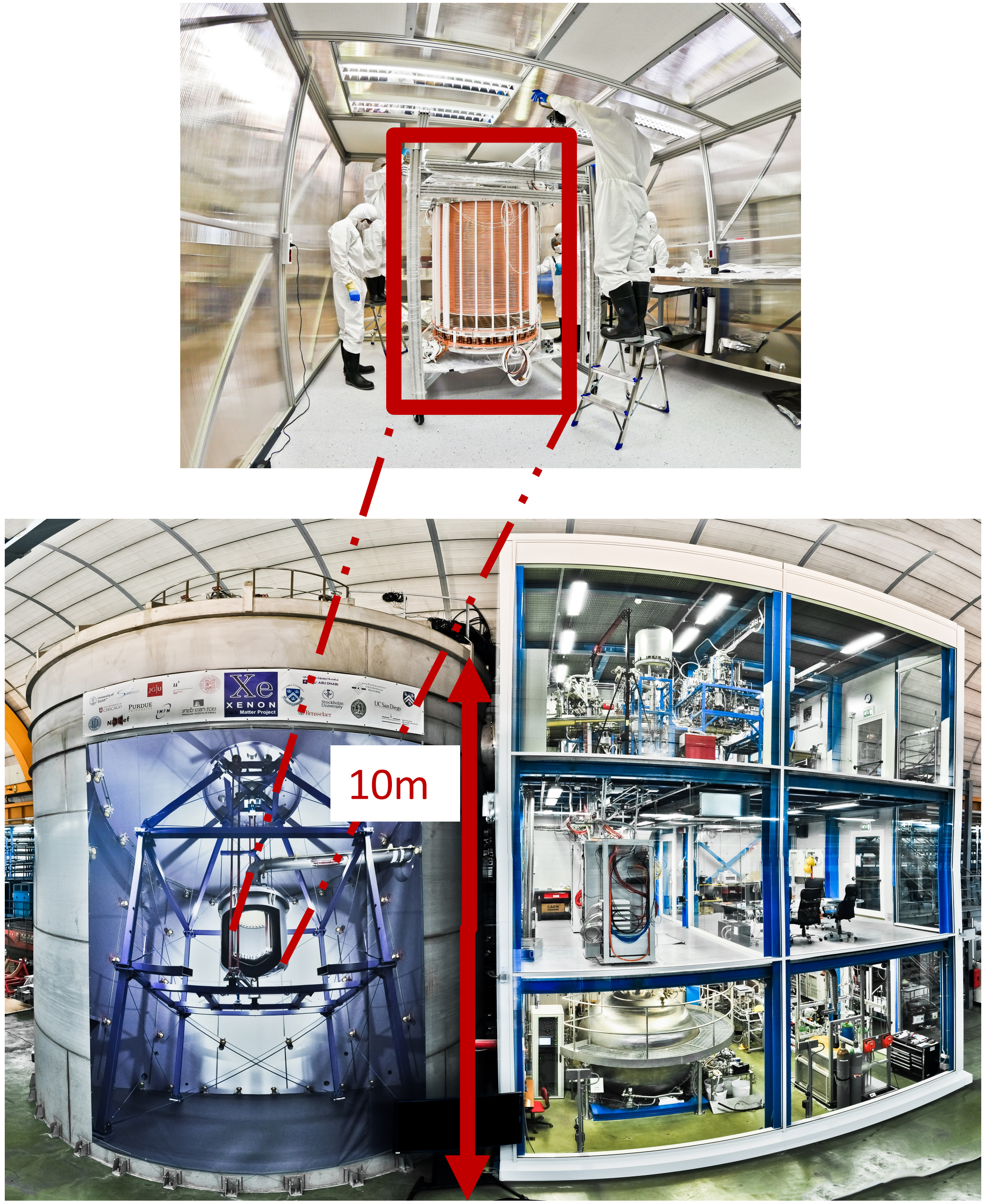
- 3 200 m water equivalent
- Reduction of a factor 10^3 of the muon flux

Muon veto

- Water shield + PMTs







Background reduction

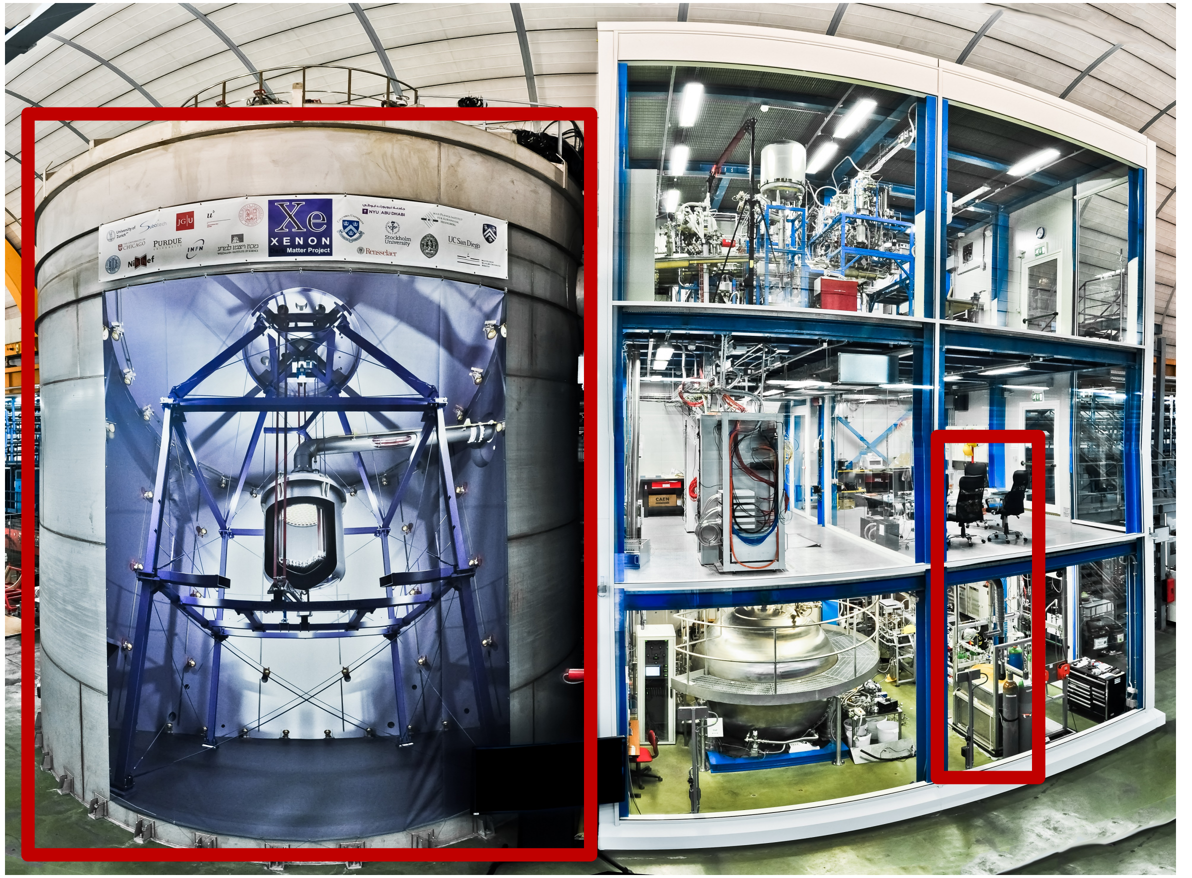
Ambient radioactivity:
- Water shield

Material radioactivity:
- Careful screening and characterization of materials
- Fiducial volume
- NR/ER discrimination

^{85}Kr:

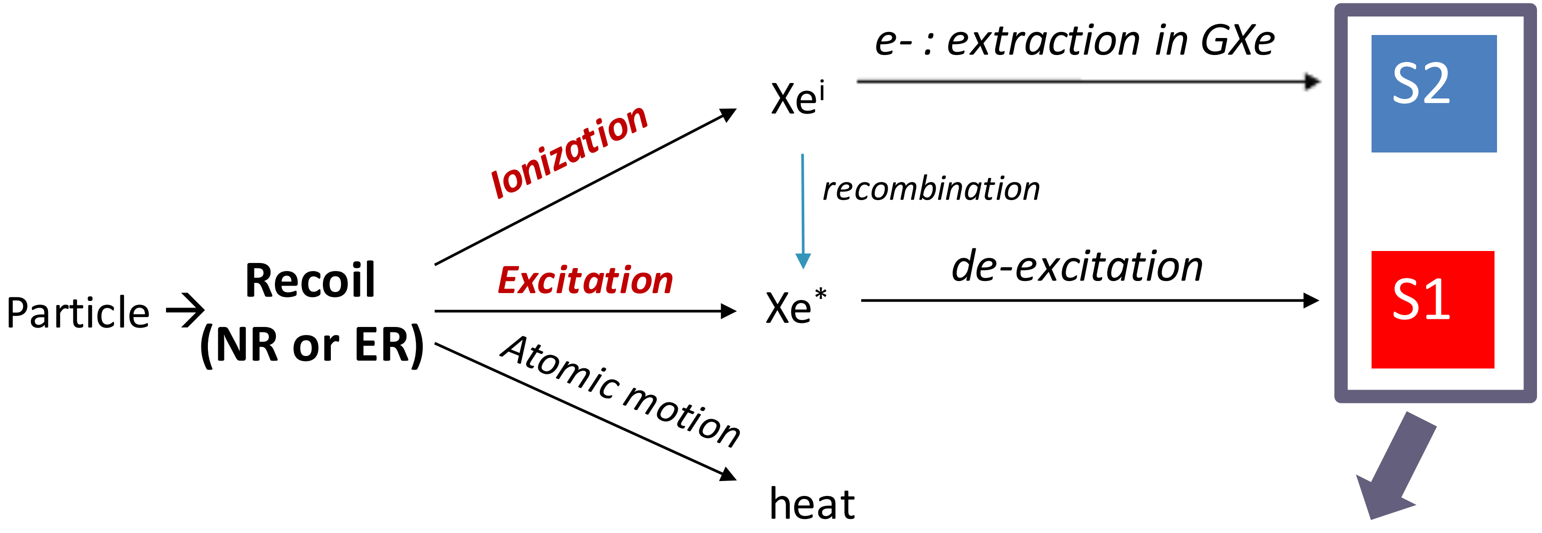
Distillation column to remove

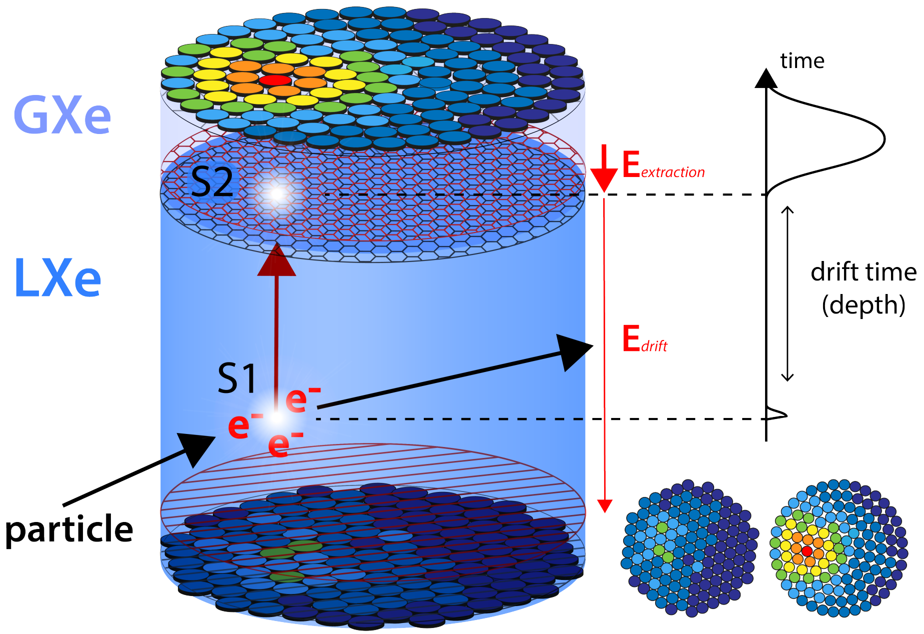
ER background rate = ~ 80 event/t.y.keV
(in the ROI for dark matter search)
Lowest background ever achieved in dark matter direct detection experiment



Detector Principle

XENON = dual phase (liquid – gas) TPC filed with LXe



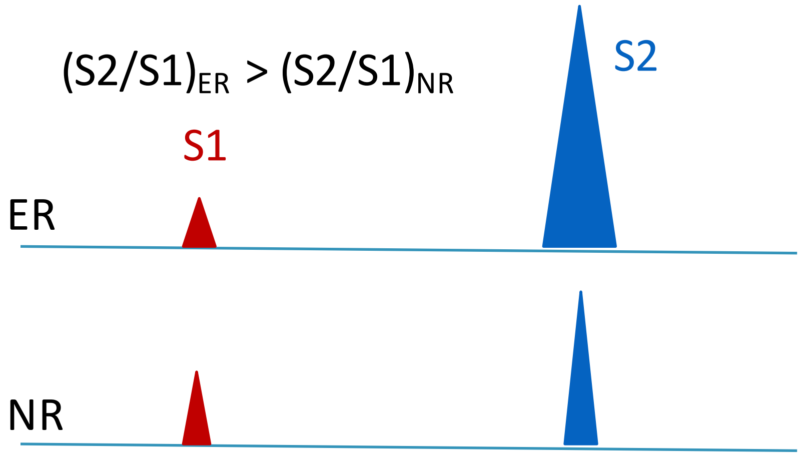


Detectable Signals

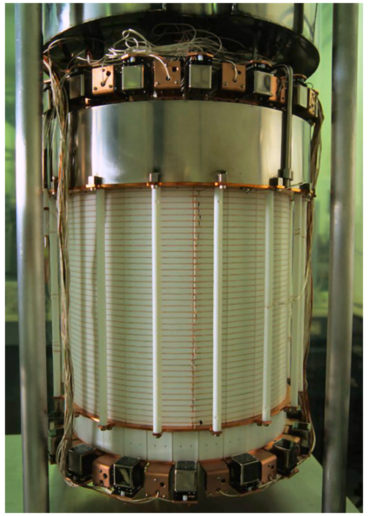
3D position

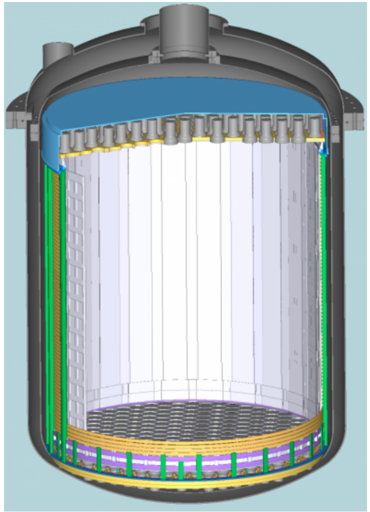
Energy

NR/ER discrimination



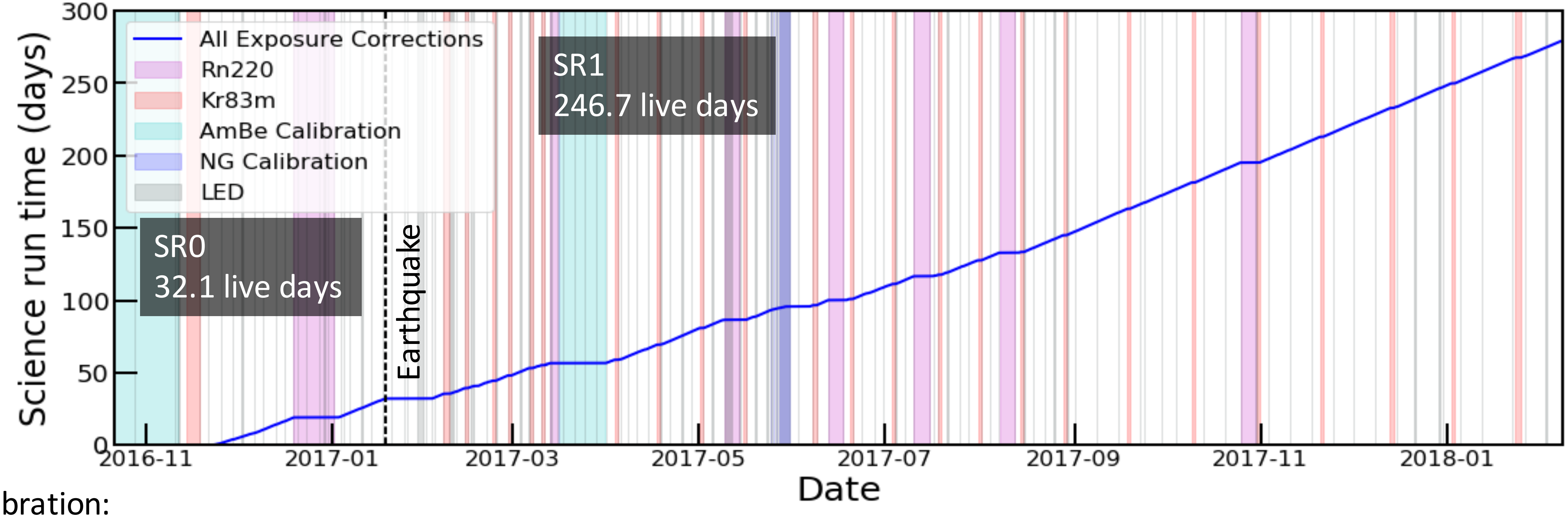
XENON Project





	XENON10	XENON100	XENON1T - Actual	XENONnT
Total mass	25 kg	162 kg	3.2 t	8 t
Active target	14 kg	62 kg	2 t	6 t
Dimension	H ~ 15 cm ⌀ ~ 20 cm	H ~ 30 cm ⌀ ~ 30 cm	H ~ 1m ⌀ ~ 1m	H ~ 1.5 m ⌀ ~ 1.4 m

Dark Matter Search with XENON1T

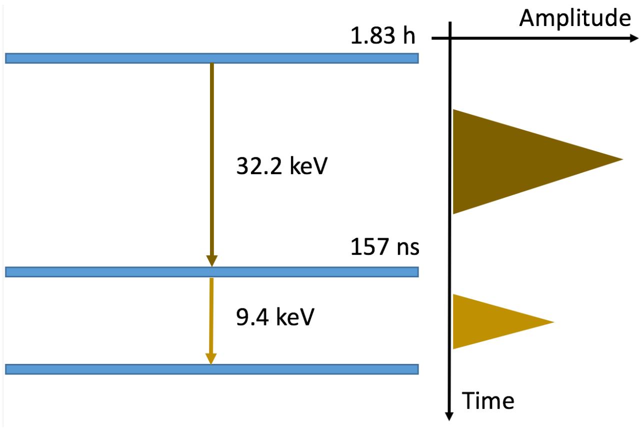


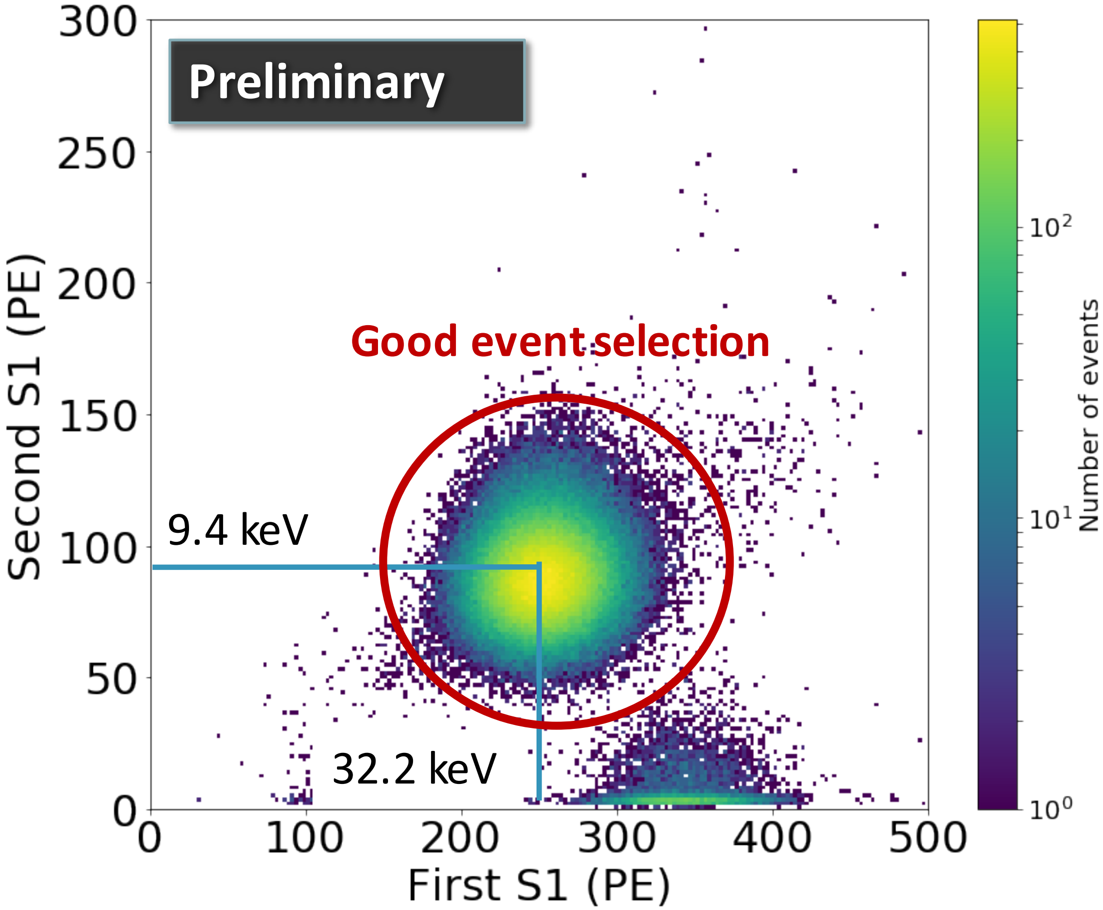
Calibration:

- LED → PMT gain monitoring
- **^{83m}Kr → Corrections, detector stability monitoring**
- ^{220}Rn → Low energy electronic recoils: ER-bands
- ^{241}AmBe and NG → Signal response: NR-bands

^{83m}Kr source

Characteristics	Advantages
Internal	Homogeneous
Short Half-life of 1.83h	Quick restart of dark matter search
2 decays at low energies	Close to the dark matter search region
Short time between the two decays	Identification



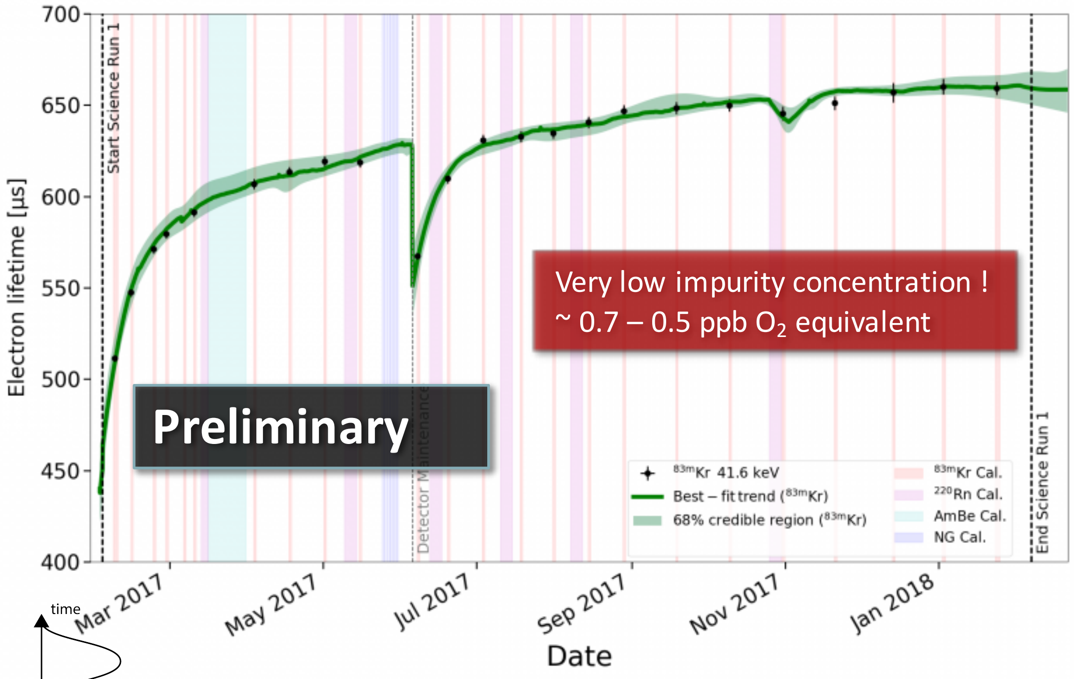


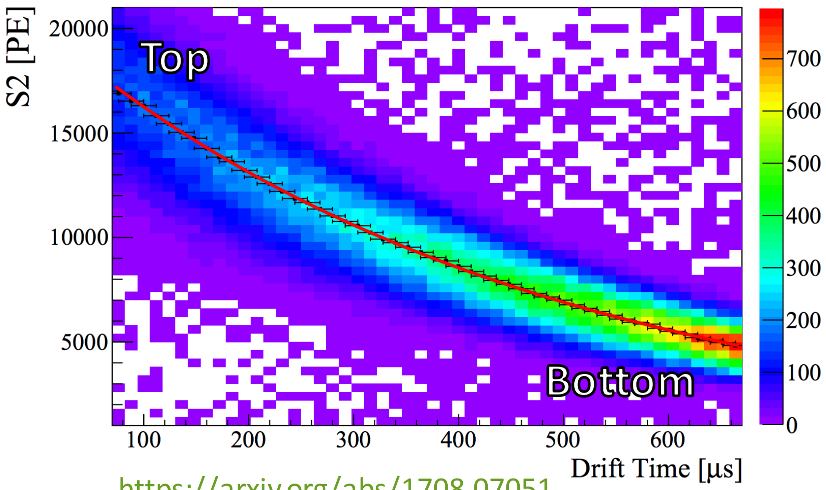
Electron Lifetime correction using ^{83m}Kr calibration

Electronegative impurities in LXe capture electrons during their drift

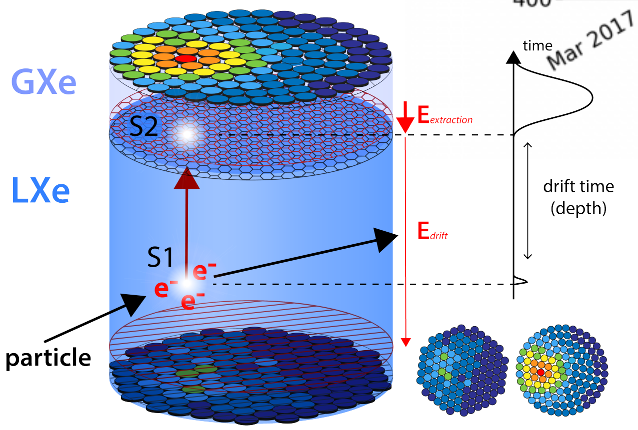
- Reduced measured S2
- Need ultra pure xenon to detect S2 = exploitable signal
- Monitoring of the impurity concentration $\propto \frac{1}{\tau}$

Correction of S2 signals with : $S2 = S2_0 \, . e^{-\Delta t/\tau}$



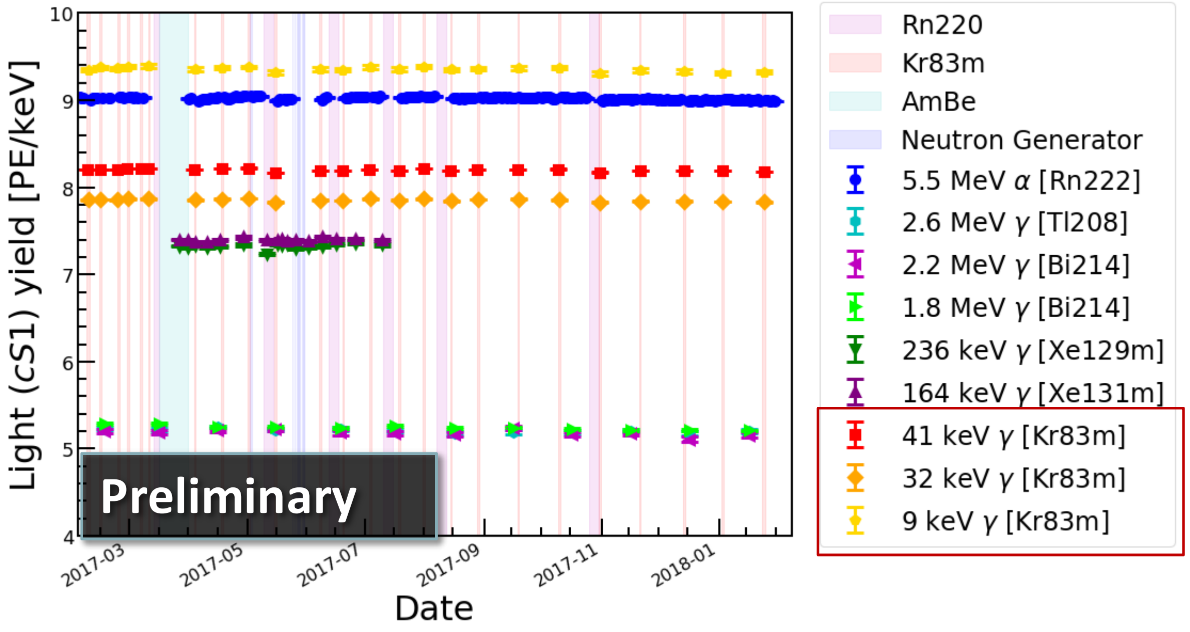


https://arxiv.org/abs/1708.07051

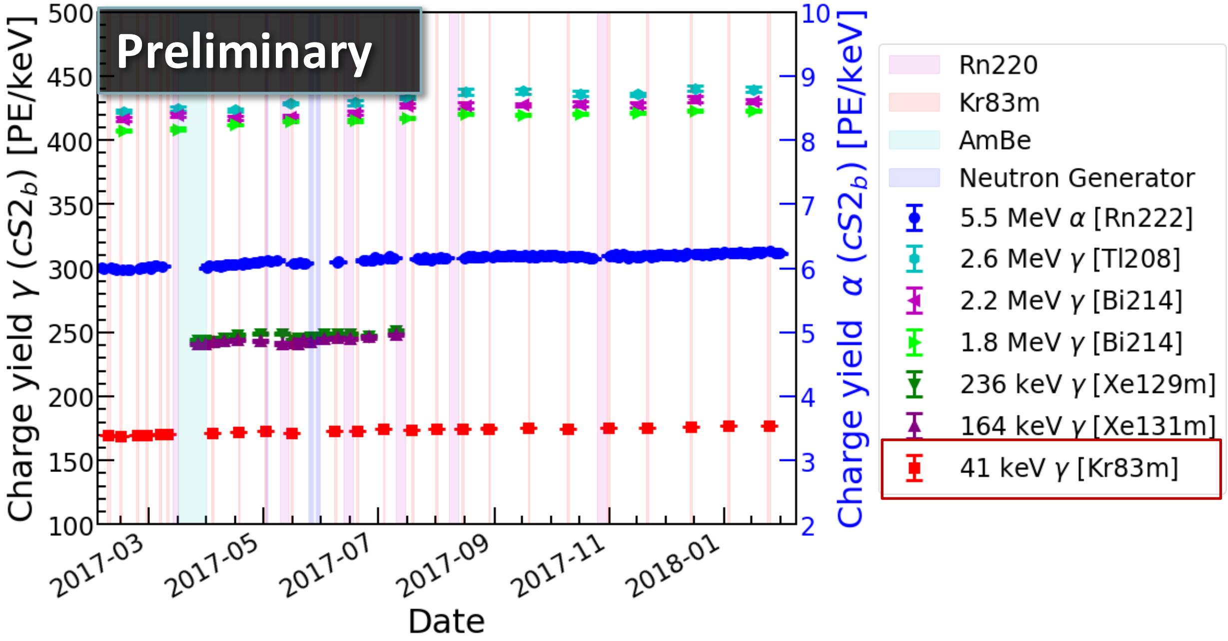


S1 and S2 monitoring using ^{83m}Kr calibration

S1 $Ly = S1 / E_{ER}$ (corrected signals)



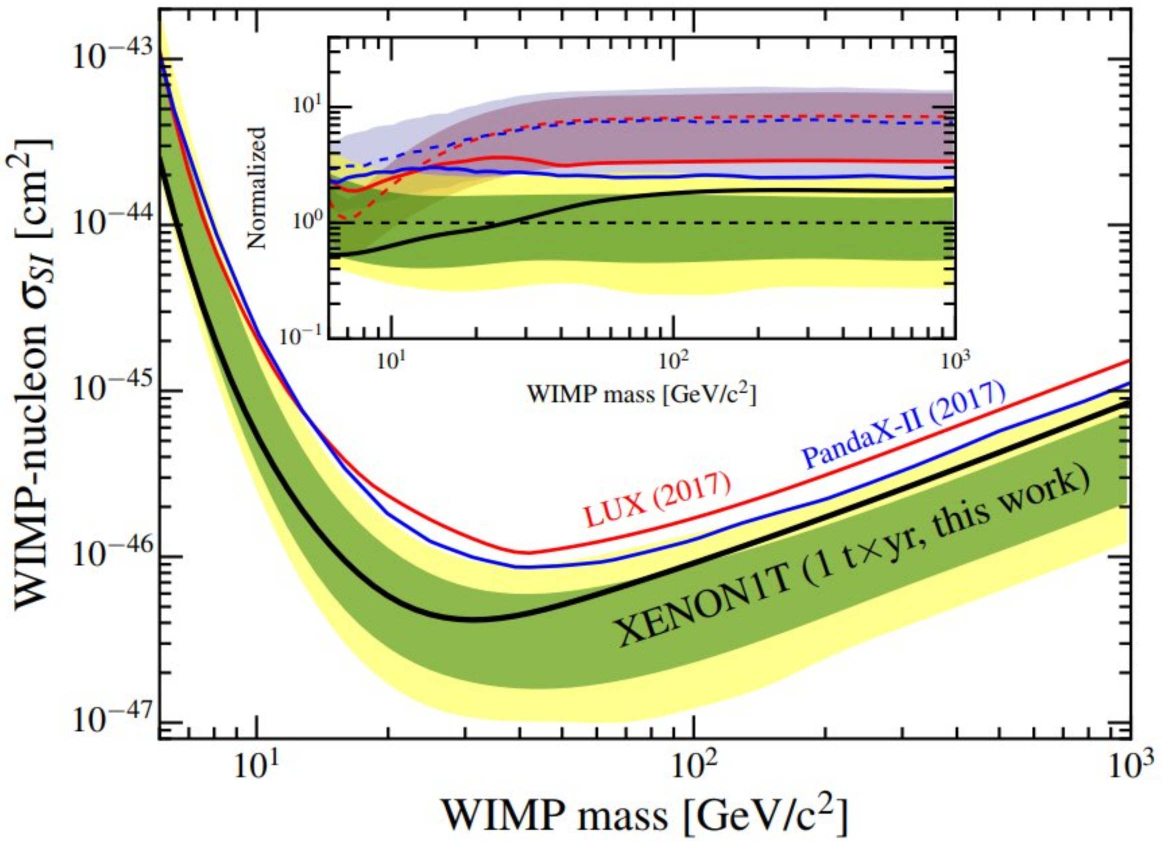
S2 $Cy_b = S2_b / E_{ER}$ (corrected signals)



Stable operation during more than one year

XENON1T results on dark matter search

- New results since May 2018
  - Phys. Rev. Lett. **121**, 111302
- **First Dark Matter experiment with an exposure of 1 ton x year**
  - Largest exposure ever achieved with liquid xenon TPC
- **Lowest background achieved in direct dark matter detection**
- Most Stringent limit on Spin Independent WIMP-nucleon cross-section for $m_{\chi} > 6$ GeV/c^2
- 7 times more sensitive compared to previous experiments (LUX, PandaX-II)



Key Numbers
1 ton x year exposure
Fiducial mass of 1.3 t
ER background rate: $(82^{+5}_{-3}\,_{sys} \pm 3_{stat})$ events/(t x yr x keVee)
Lowest limits on the SI WIMP-Nucleus cross section: σ_{SI} = 4.1 x 10^{-47} cm^2 for a WIMP of 30 GeV/c^2

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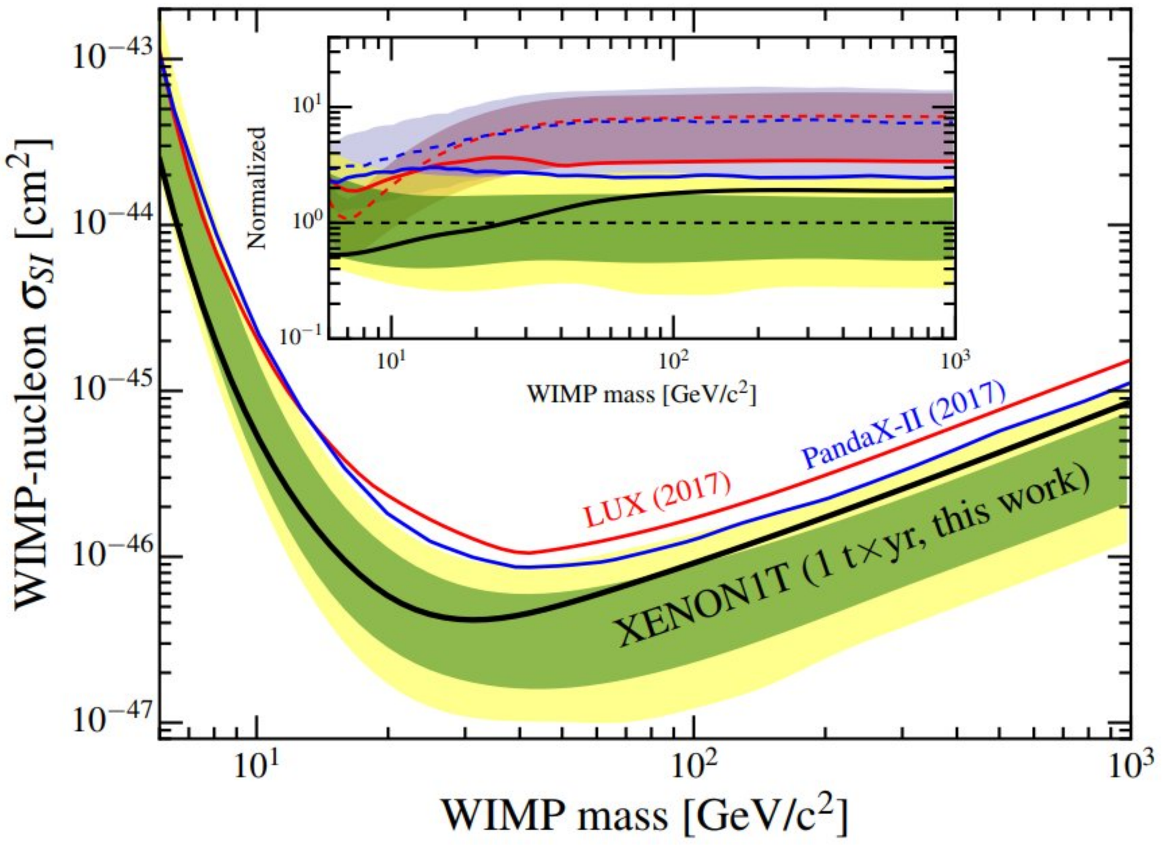
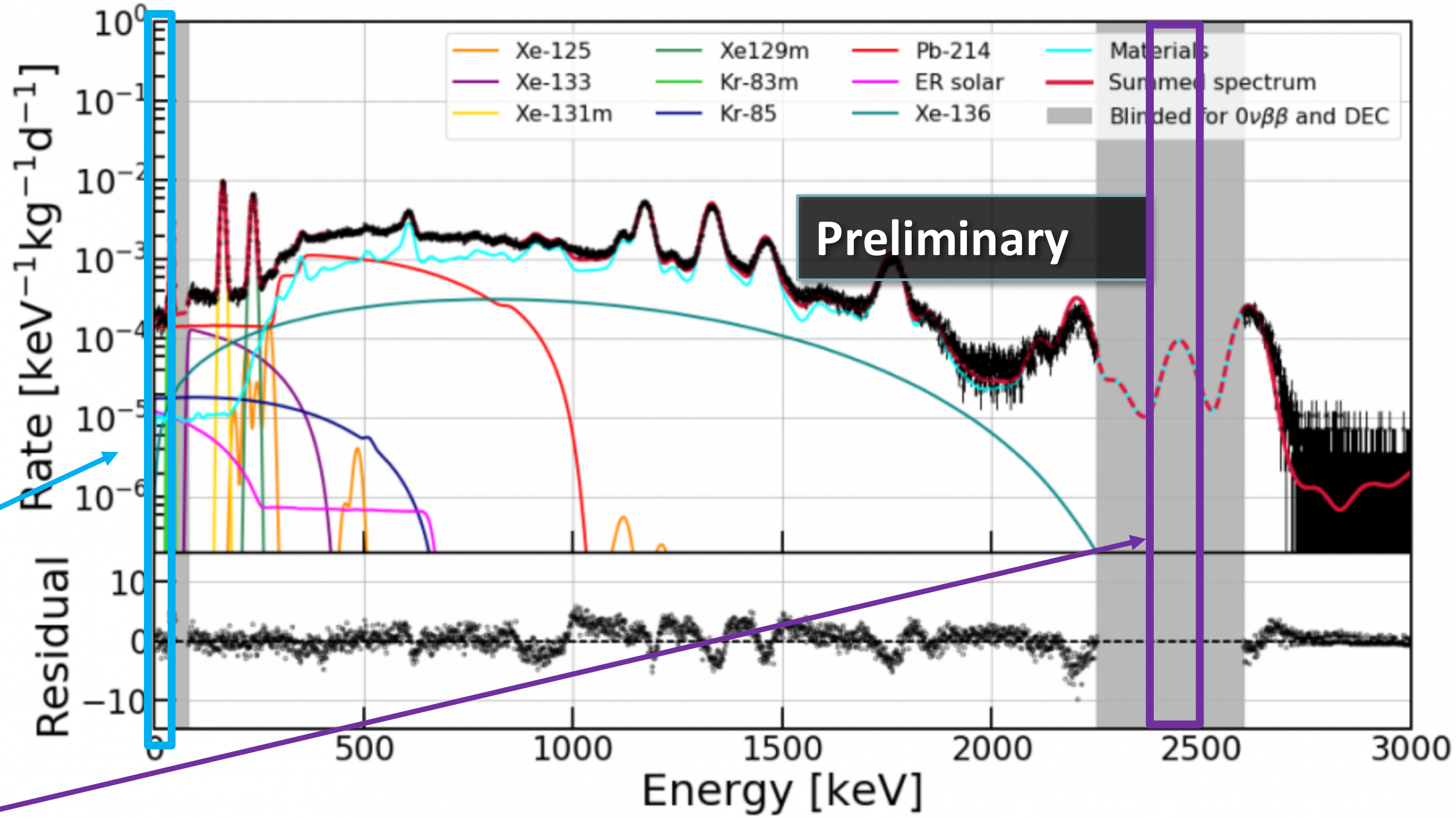


Allow for the search for other rare physics processes that required low background conditions:
E.g. Neutrinoless double β decay

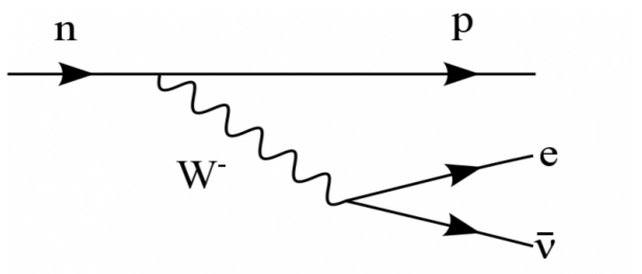
Same data for two analysis

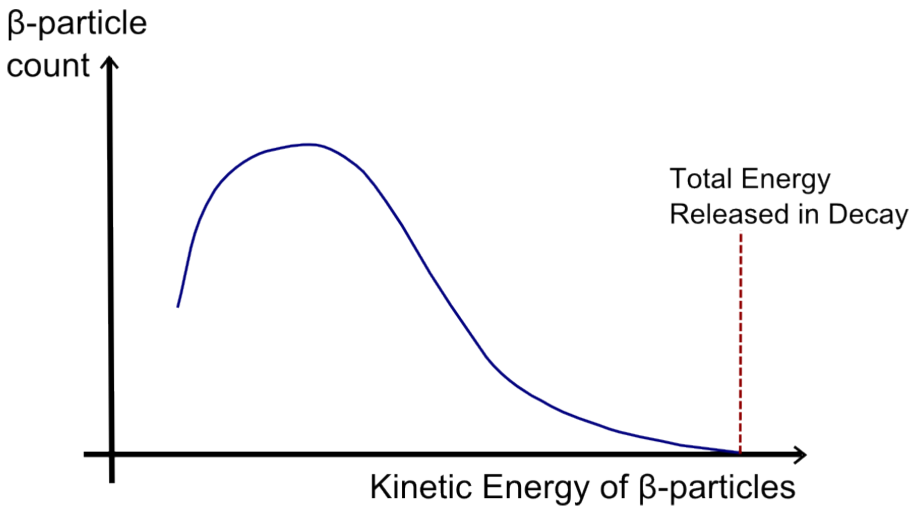
	Dark Matter	Neutrinoless double β decay
Energy region	< 100 keV	[2.4,2.5] MeV
Recoil type	NR	ER
Number of expected events	< 4 events/t.y	< 12 events/t.y



β decay

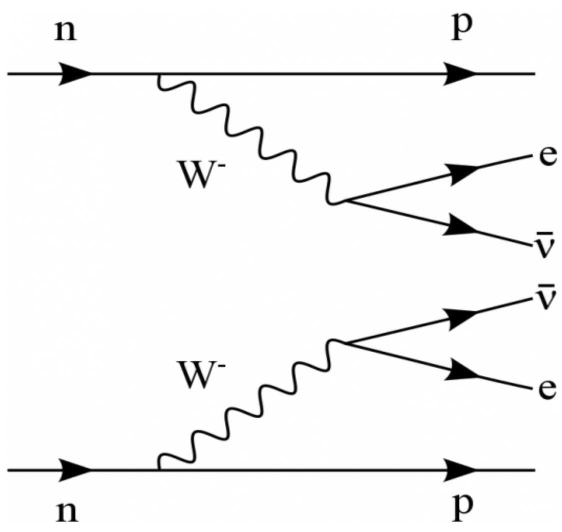
$$(Z, A) \rightarrow (Z+1, A) + 1\, e^{-} + 1\overline{\nu_e}$$





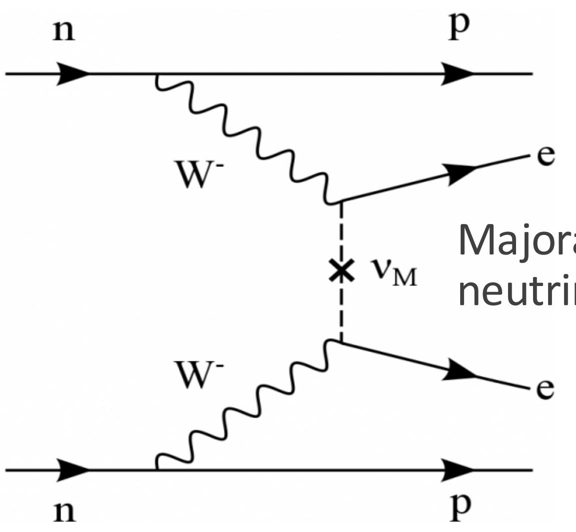
Neutrinoless Double β decay

$(Z, A) \rightarrow (Z+2, A) + 2\, e^- + 2\bar{\upsilon}_e$



Rare process :
$T^{1/2} = 21\times10^{20}$ yr = $10^{12} * T^{Univers}$
✔ Observed

$(Z, A) \rightarrow (Z+2, A) + 2\, e^-$



Majorana neutrinos

Rare process :
$T^{1/2} > 1.07\times10^{26}$ yr = $10^{18} * T^{Univers}$
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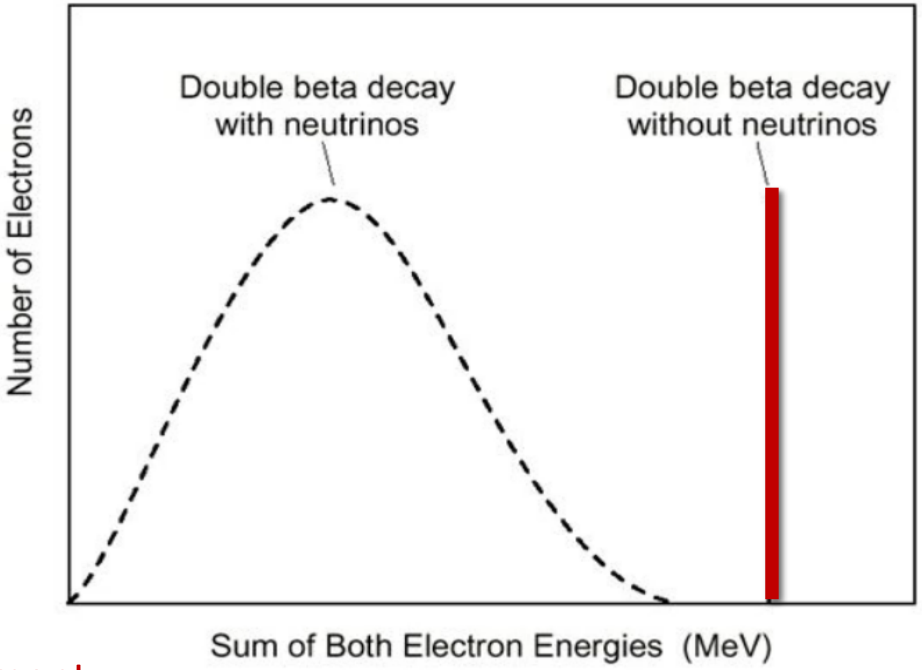

Rare event = Need a low background experiment

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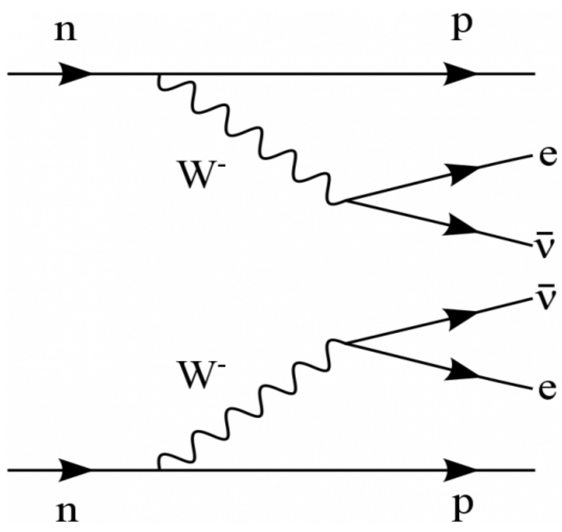

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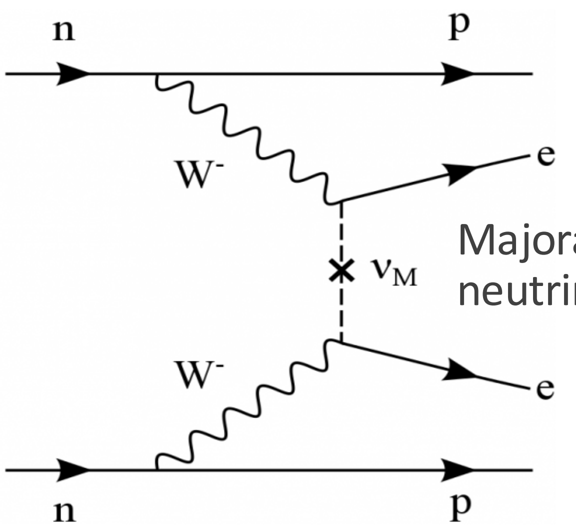

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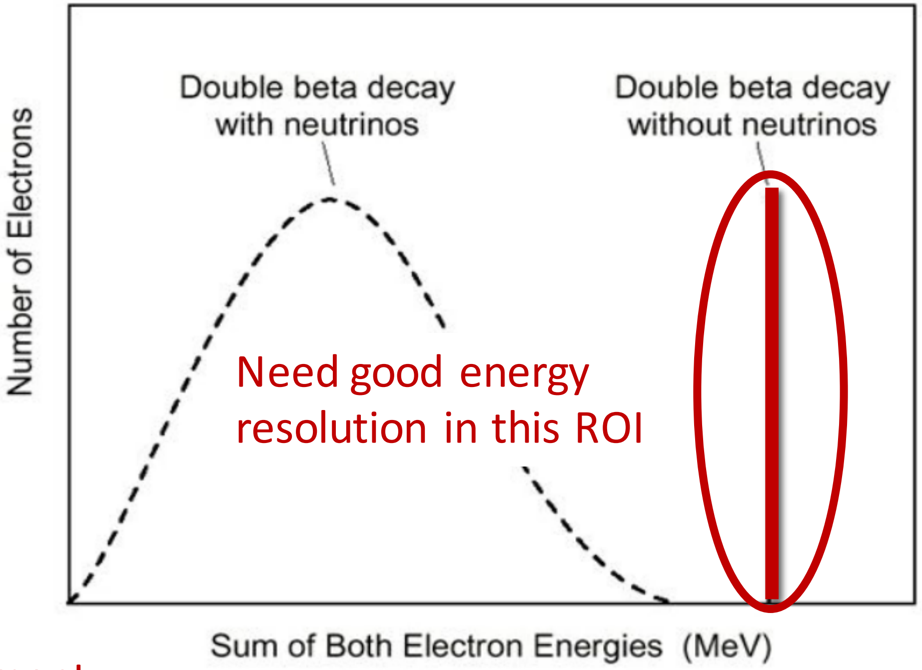
^{136}Xe isotope

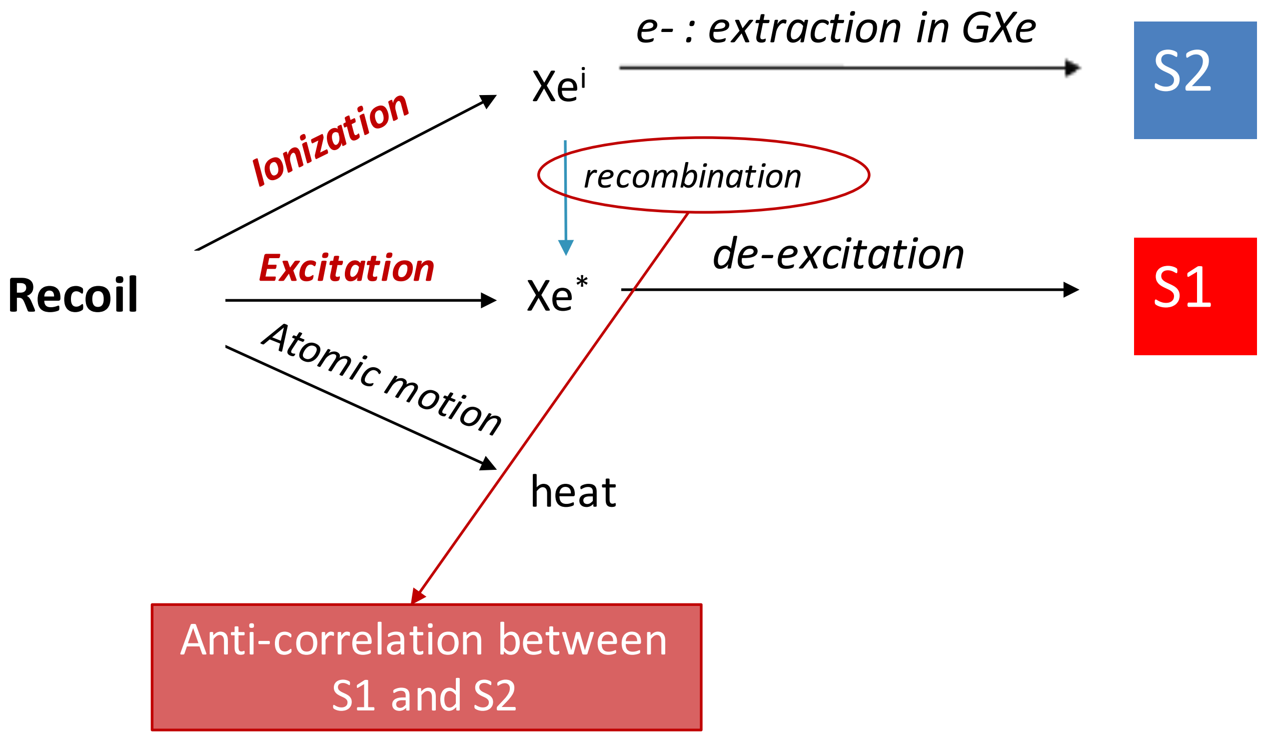
- Double β emitter
- Naturally present in XENON1T (abundance of 8.49%)

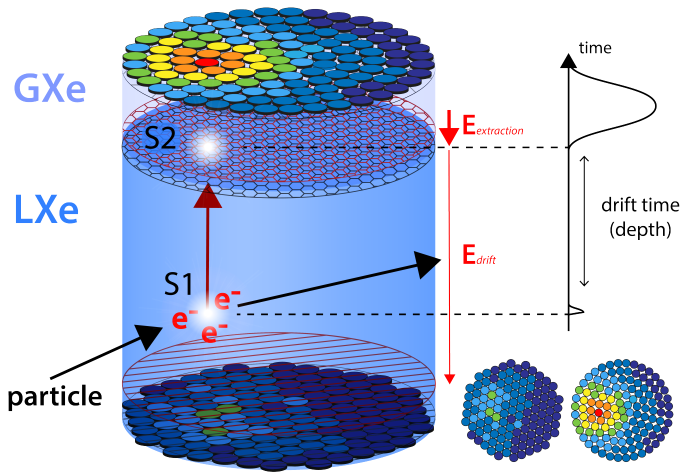


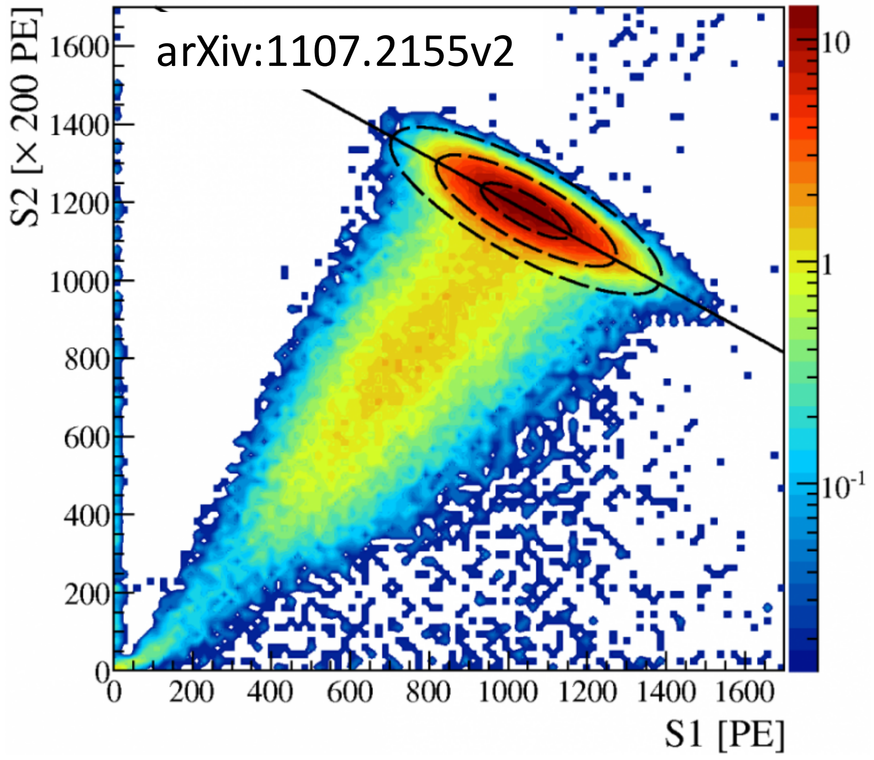
Q=2.457 MeV

Energy reconstruction

Energy deposit → S1 and S2 → Anti-correlation



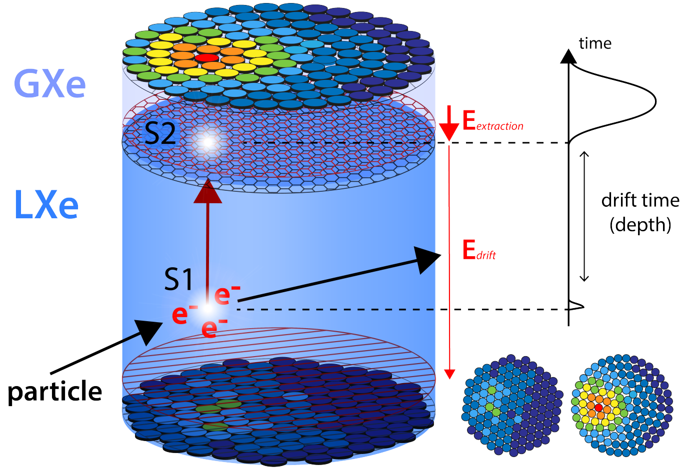


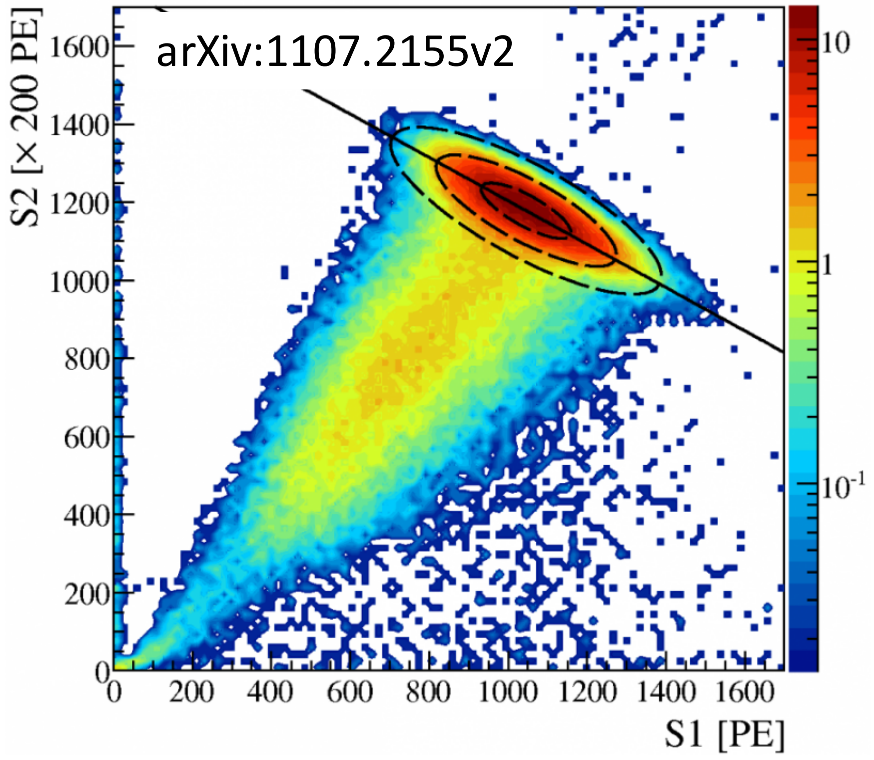


Energy reconstruction

Energy deposit → S1 and S2 → Anti-correlation :

- Combination of S1 and S2 :
  - Allow to improve the energy resolution
  - Need to take into account the repartition of S1 and S2 :
    - Scintillation gain g1
    - Ionization gain g2





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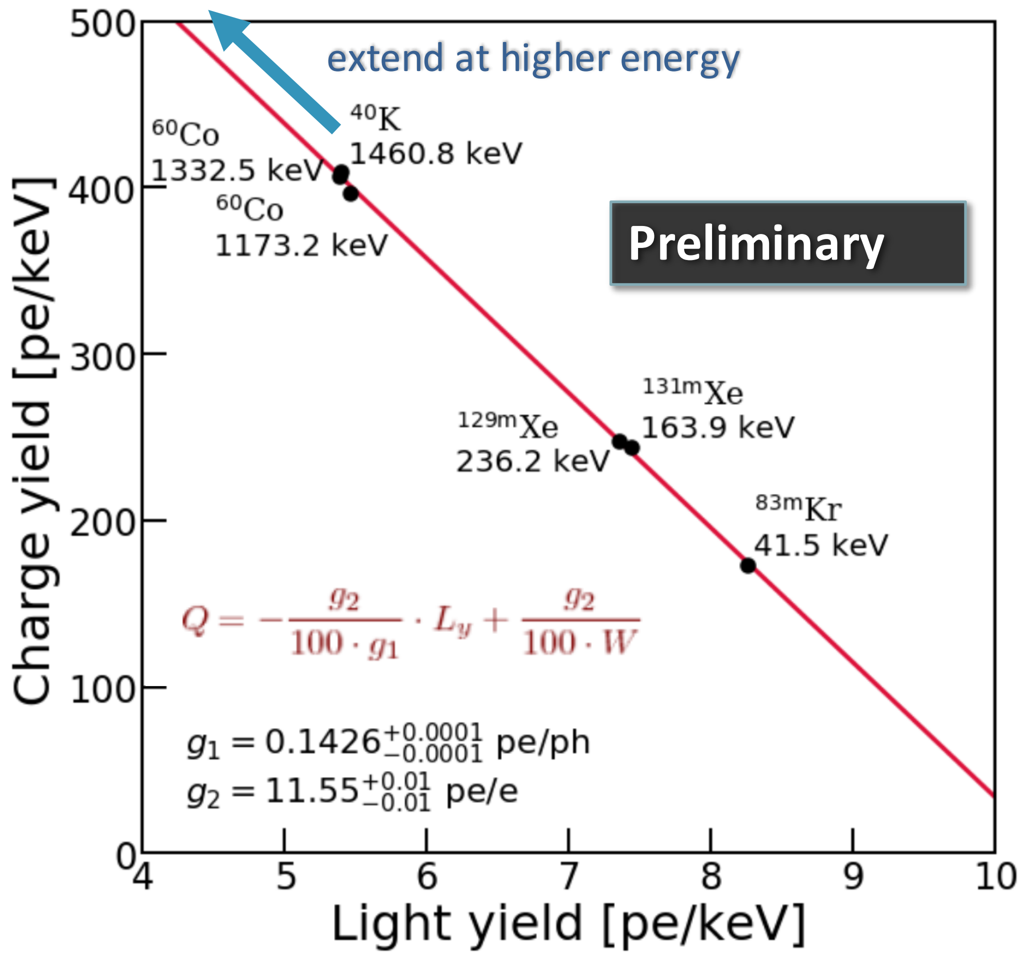
To determine g1 and g2 → Calibration :

- With known energies → light and charge yield

$$Ly = S1/E$$
$$Q = S2/E$$

- Linear correlation

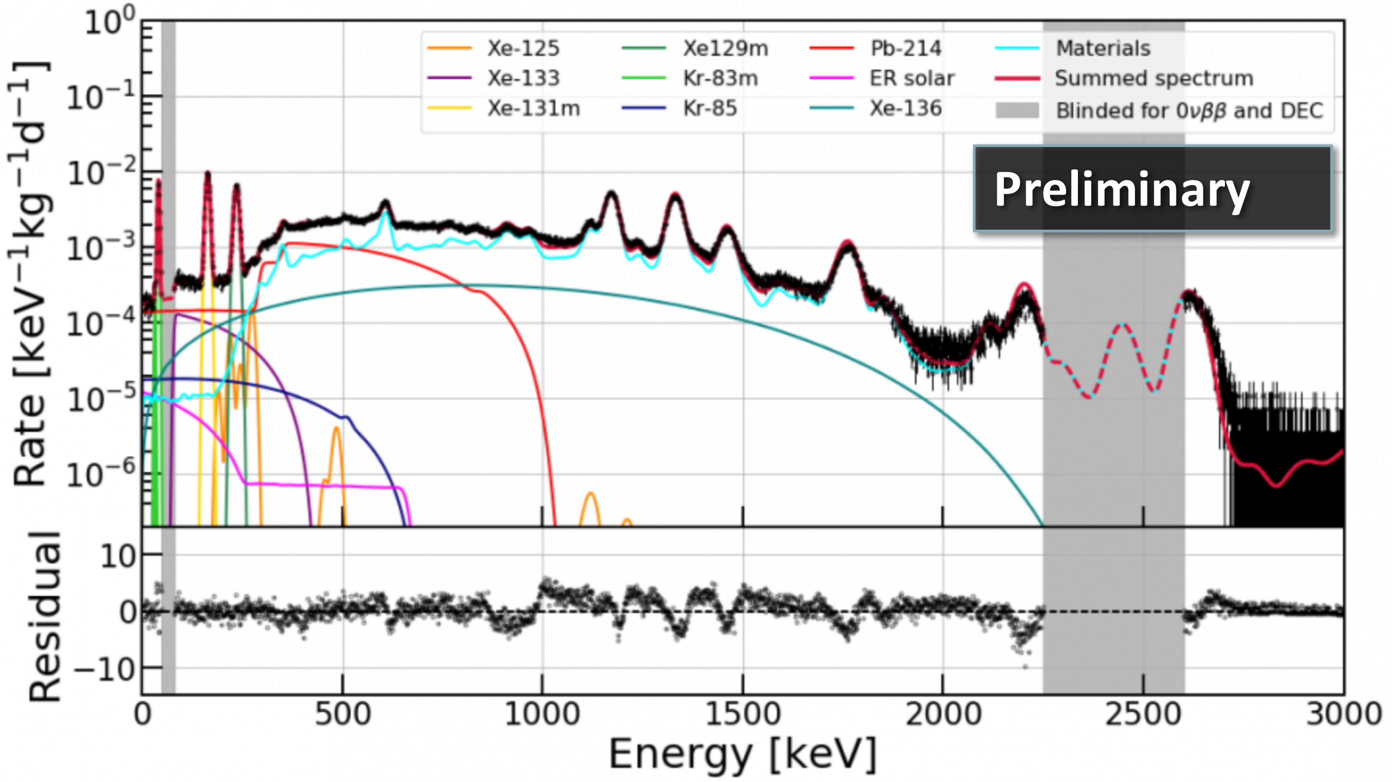
At high energy, no internal source are available so we use lines coming from material radioactive elements

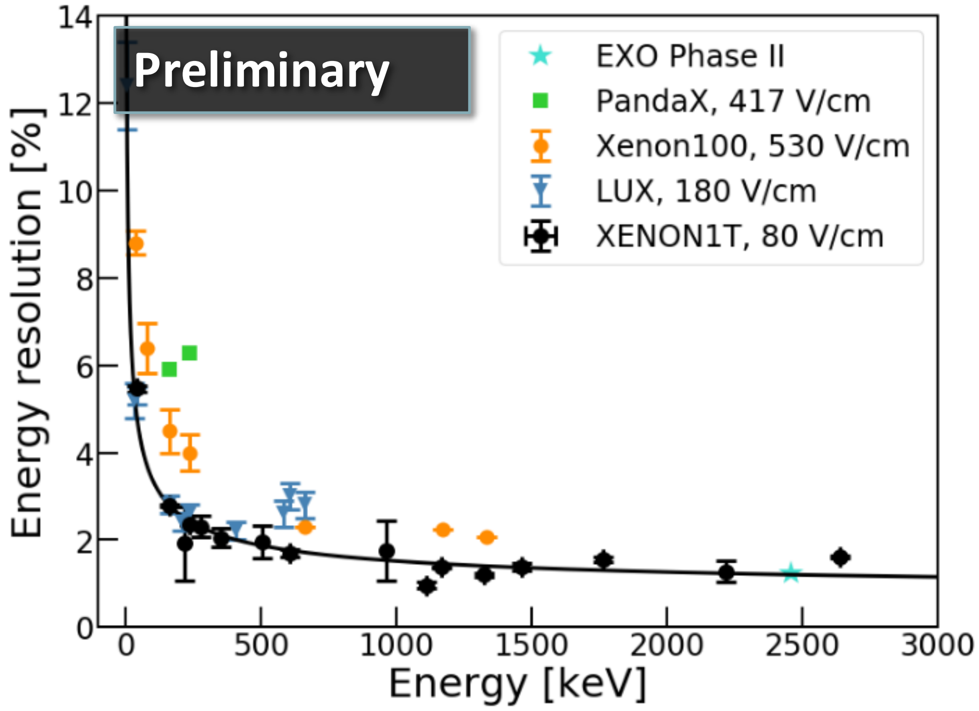


Energy reconstruction

$$E = W\left(\frac{cS1}{g1(z)} + \frac{cS2b}{g2(z)}\right)$$

With W = 13.7 eV (mean energy needed to produce one photon or electron)





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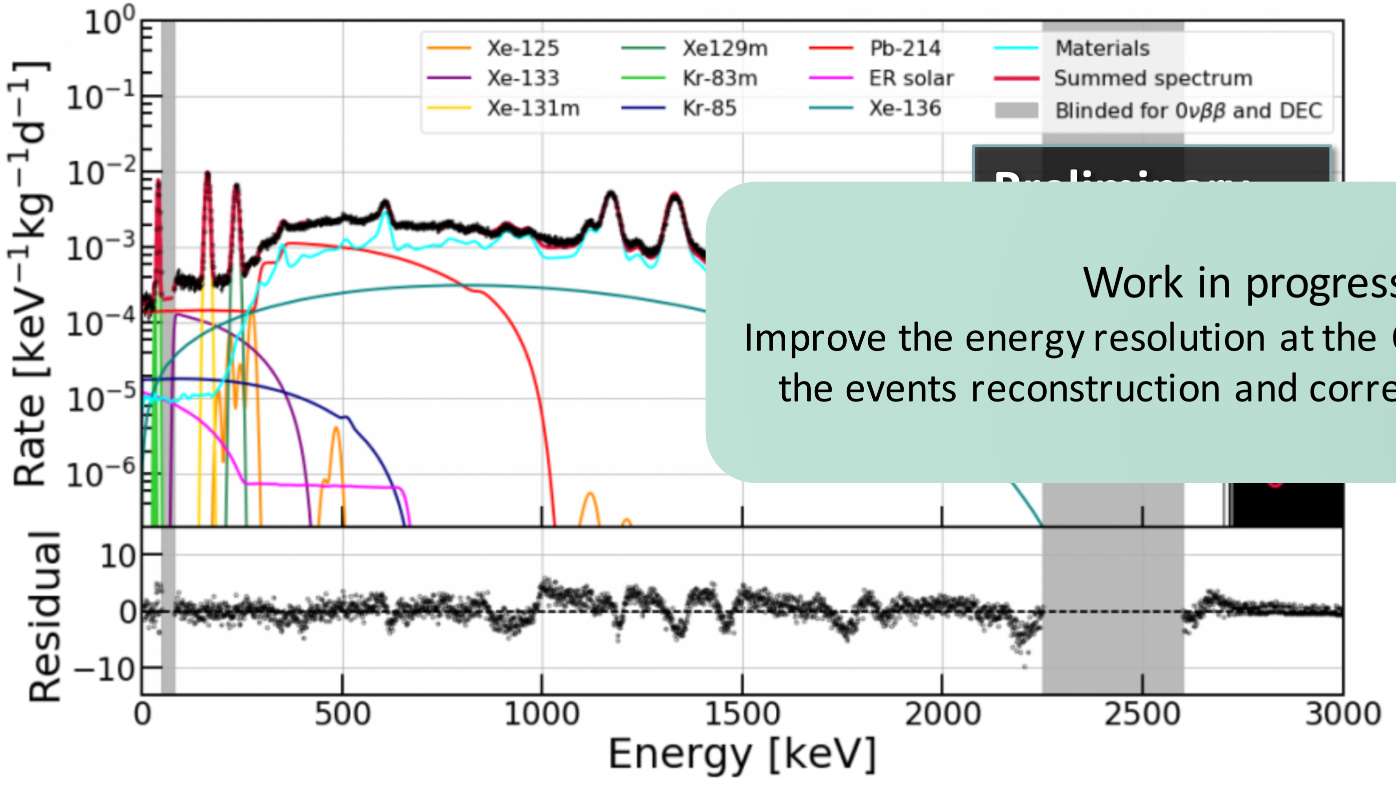
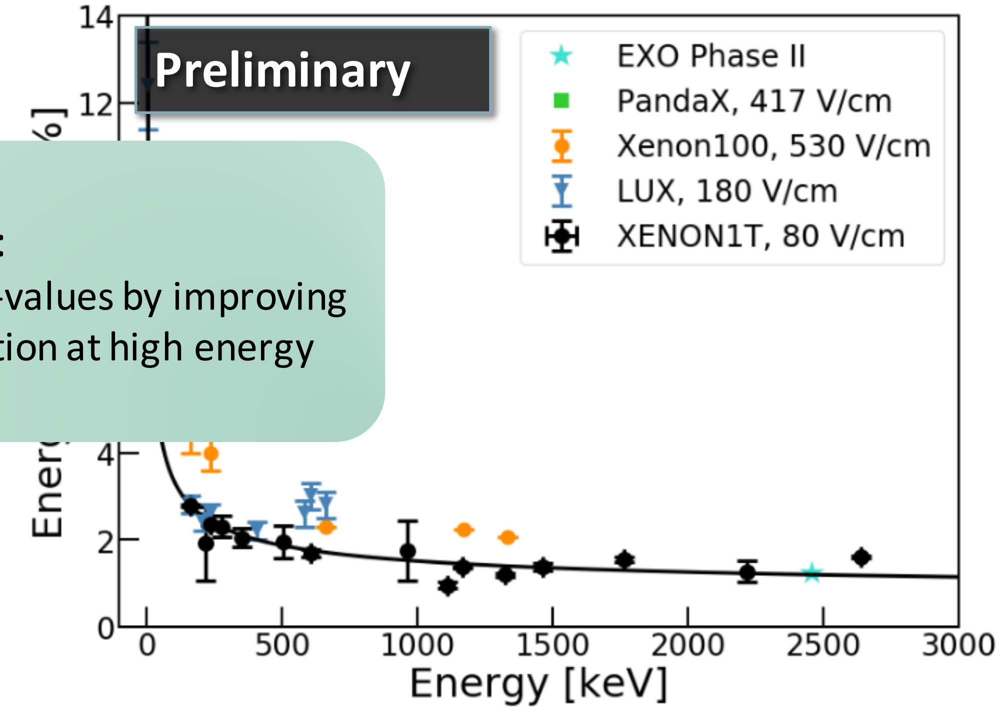




Work in progress :
Improve the energy resolution at the Q-values by improving the events reconstruction and correction at high energy

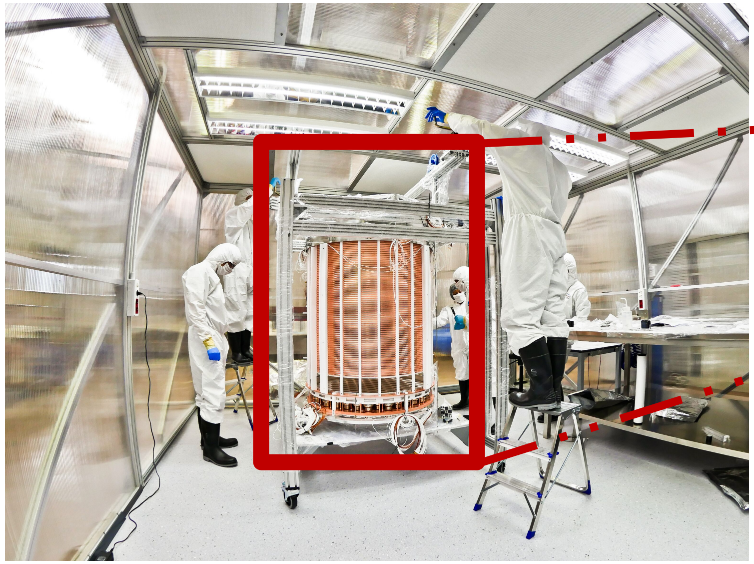
Conclusion

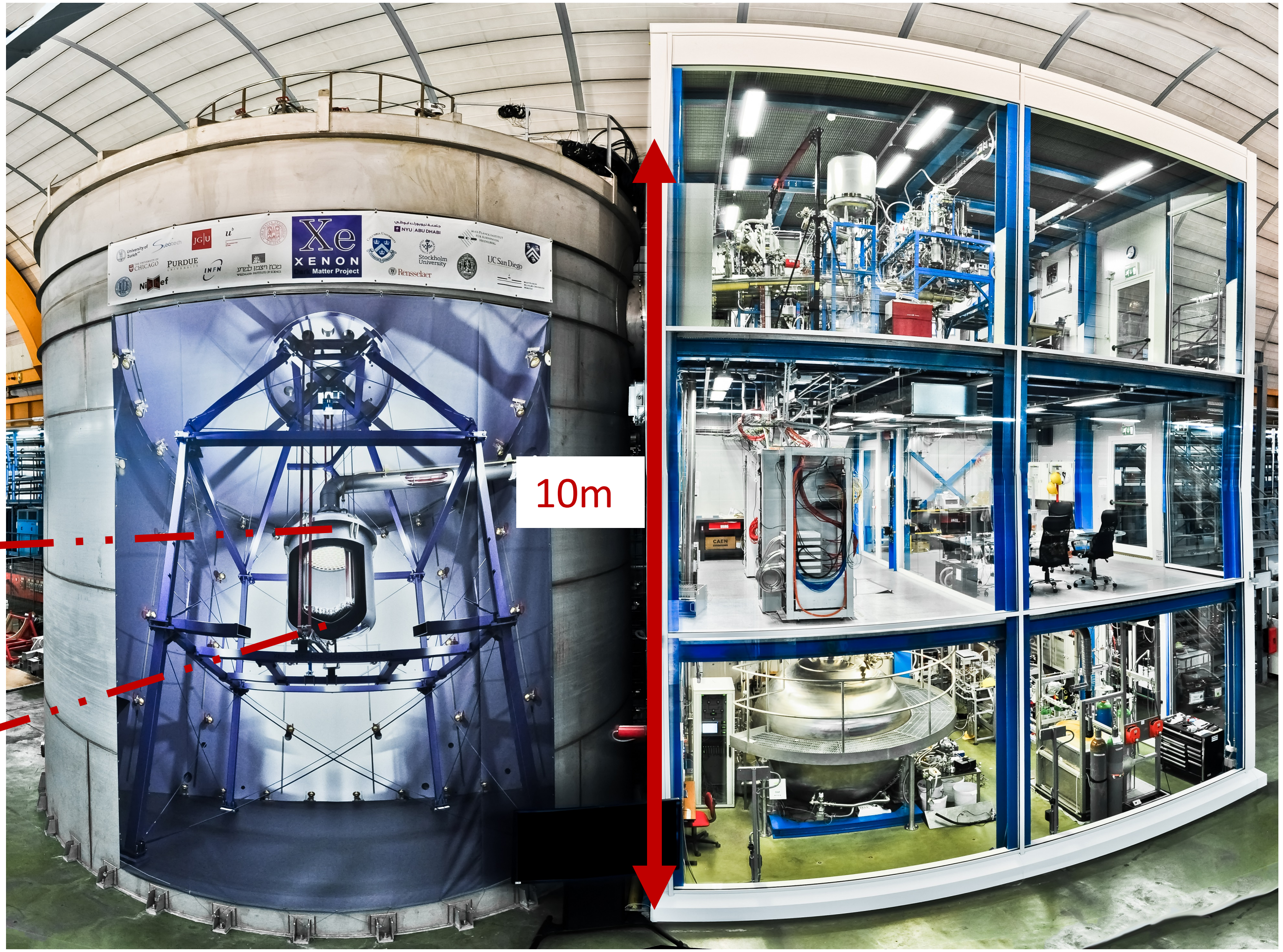
- **XENON1T is the most sensitive direct dark matter experiment with the lowest background ever achieved.**
- **Stable operation over more than one calendar year**
- Regular ^{83m}Kr calibration (24 calibration campaigns for SR1)
  - Monitoring of S1 and S2 signals
  - Monitoring of the electron lifetime
    - Monitoring of the xenon purity
    - **S2 correction → Crucial for all analysis**
- **^{83m}Kr is an excellent internal source for large xenon TPC**
  - Hard to use external source (because of LXe self-shielding)
  - Proof that it could be used for future experiments → XENON-nT (construction starting soon) and other large LXe TPC
- Thanks to the ultra-low background : neutrinoless double ß decay search
  - **New analysis – need to adapt our analysis to this all new energy region**

Backup

XENON1T

Total mass	3.2 t
Active target	2 t
Dimension	H ~ 1m / ⌀ ~ 1m

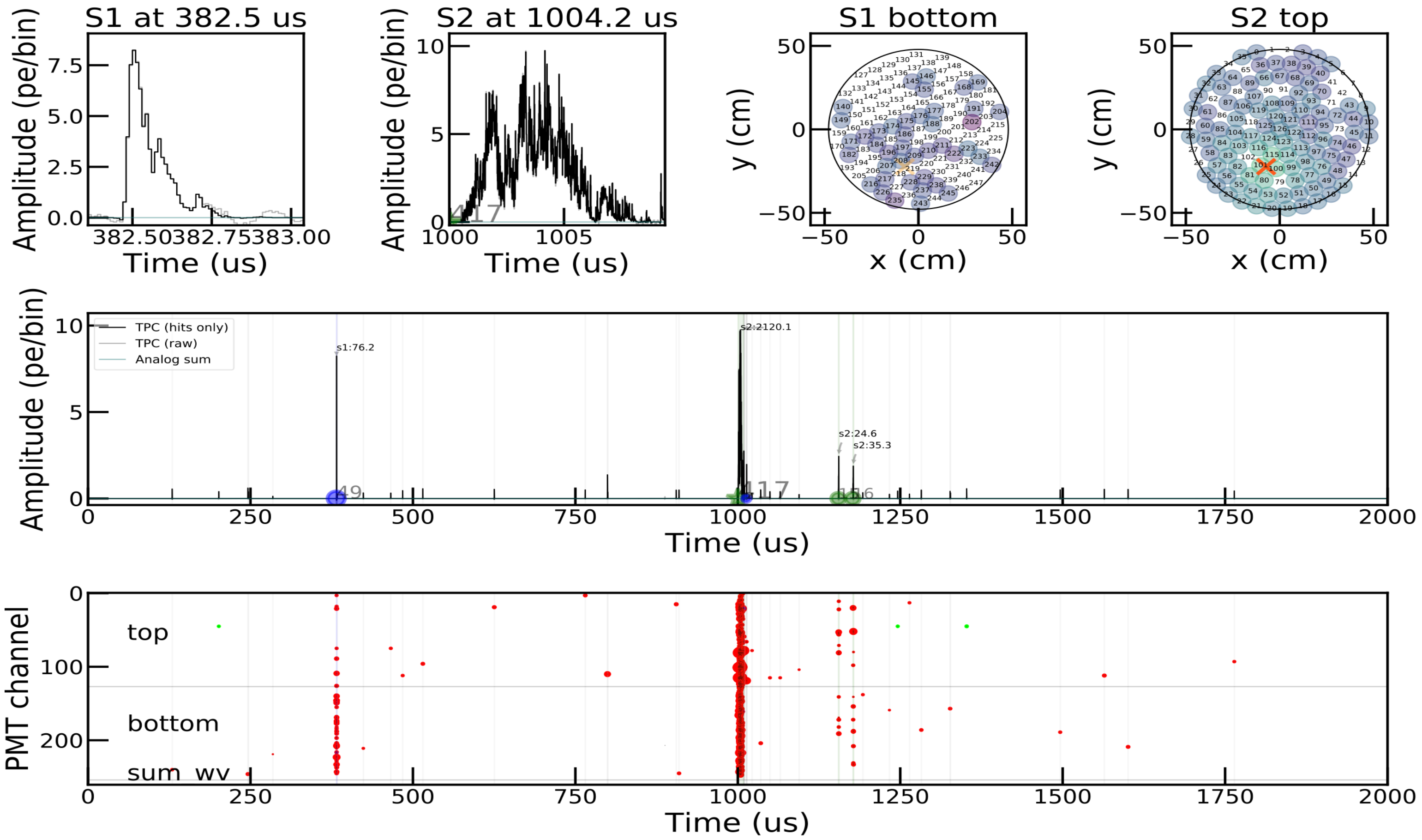


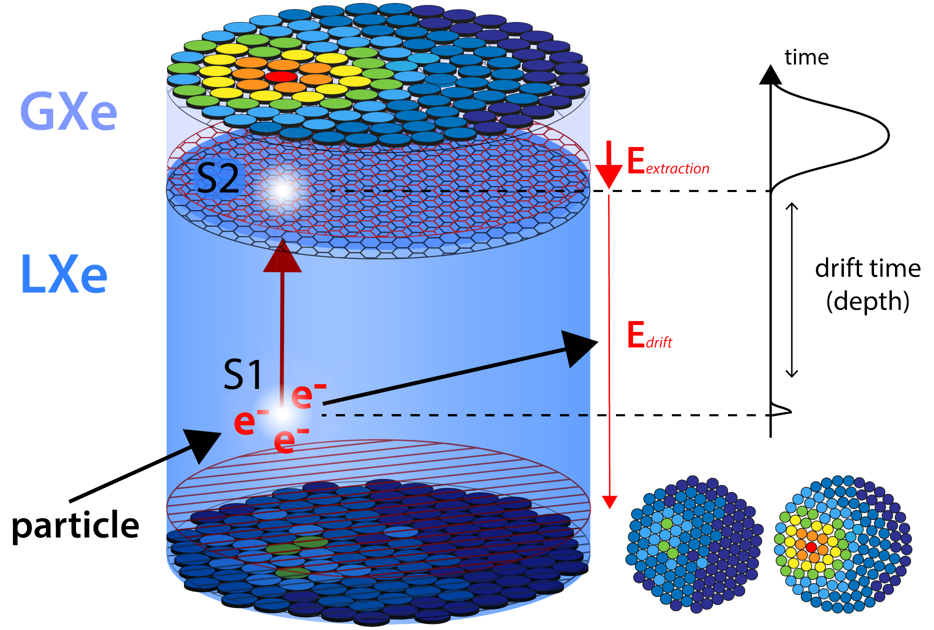


Other detector medium ?

	Neon	Argon	Krypton	Xenon
Atomic Number	10	18	36	54
Density	1.2	1.4	2.4	3
Scintillation (γ/keV)	30	40	25	42
Wavelength (nm)	85	128	150	178
Decay Time (ns)	15400	6.3, 1500	2, 91	2.2, 27, 45
Ionization (e-/keV)	46	42	49	64
Boiling Point (K)	27.1	87.3	119.8	165.0
Radioactivity	No	^{39}Ar 1Bq/kg (1mBq/kg)	Yes	^{136}Xe / Kr can be removed to ppt level
Price	$$	$ ($$$)	$$$	$$$$

Event in XENON1T





Double β decay

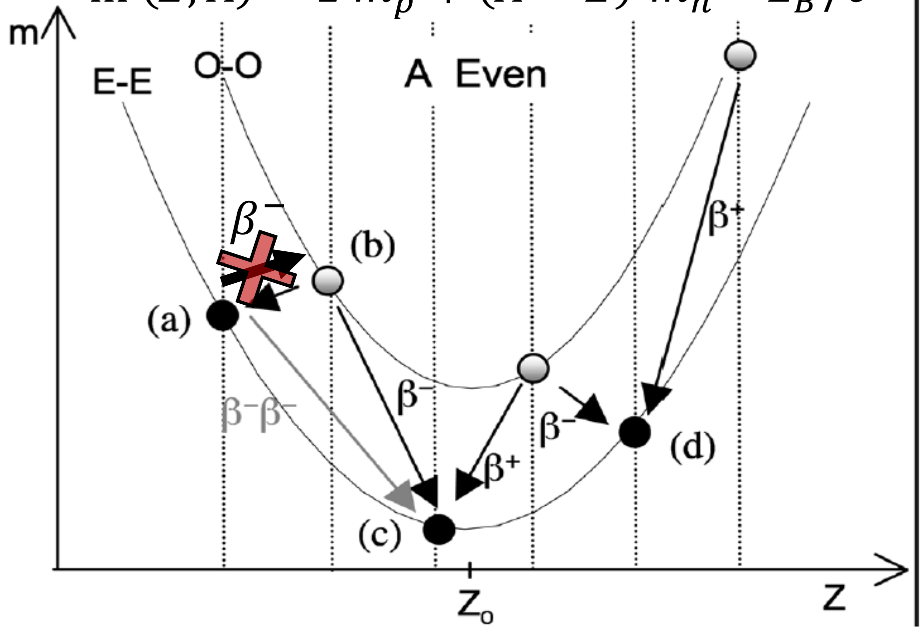
- β⁻ decay : $(Z, A) \rightarrow (Z+1, A) + e^- + \bar{\nu_e}$
- Isobaric decay (A = cte), possible if : $E_b{}^f < E_B{}^i$

$$E_B = a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z(Z-1)}{A^{\frac{1}{3}}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

$$\delta(A,Z) = \begin{cases} +\delta_0 \ if\ Z,N\ even \\ 0\ if\ A\ odd \\ -\delta_0\ if\ Z,N\ odd \end{cases}$$

- If A = even, 2 parabolic mass curves : possibility of having an E-E nucleus more stable than it Z+1 O-O neighbour = β⁻ decay is forbidden
- But double β⁻ decay is possible !
- Observed in several nuclei

$$m(Z,A) = z\, m_p + (A-Z)\, m_n - E_B/c^2$$



Isotope	nat. abund. (%)	Q-value (keV)	$T^{2\nu}_{1/2}$ (10^{20}yrs)	Experiment
^{48}Ca	0.187	4272 ± 4	$0.44^{+0.06}_{-0.05}$	CANDLES
^{76}Ge	7.8	2039.006 ± 0.050	15 ± 1	GERDA, MAJORANA
^{82}Se	9.2	2995.5 ± 1.9	0.92 ± 0.07	SuperNEMO, LUCIFER
^{96}Zr	2.8	3347.7 ± 2.2	0.23 ± 0.02	-
^{100}Mo	9.6	3034.40 ± 0.17	0.071 ± 0.004	AMoRE
^{110}Pd	11.8	2017.85 ± 0.64	-	-
^{116}Cd	7.5	2813.50 ± 0.13	0.28 ± 0.02	COBRA, CdWO$_4$
^{124}Sn	5.64	2287.8 ± 1.5	-	-
^{130}Te	34.5	2527.518 ± 0.013	$6.8^{+1.2}_{-1.1}$	CUORE
^{136}Xe	8.9	2457.83 ± 0.37	21.1 ± 2.5	EXO, NEXT
				KamLAND-Zen
^{150}Nd	5.6	3371.38 ± 0.20	0.082 ± 0.009	SNO+, DCBA