High energy physics searches in XENONnT and future LXe experiments

Cotutelle IMT Atlantique – The University of Melbourne

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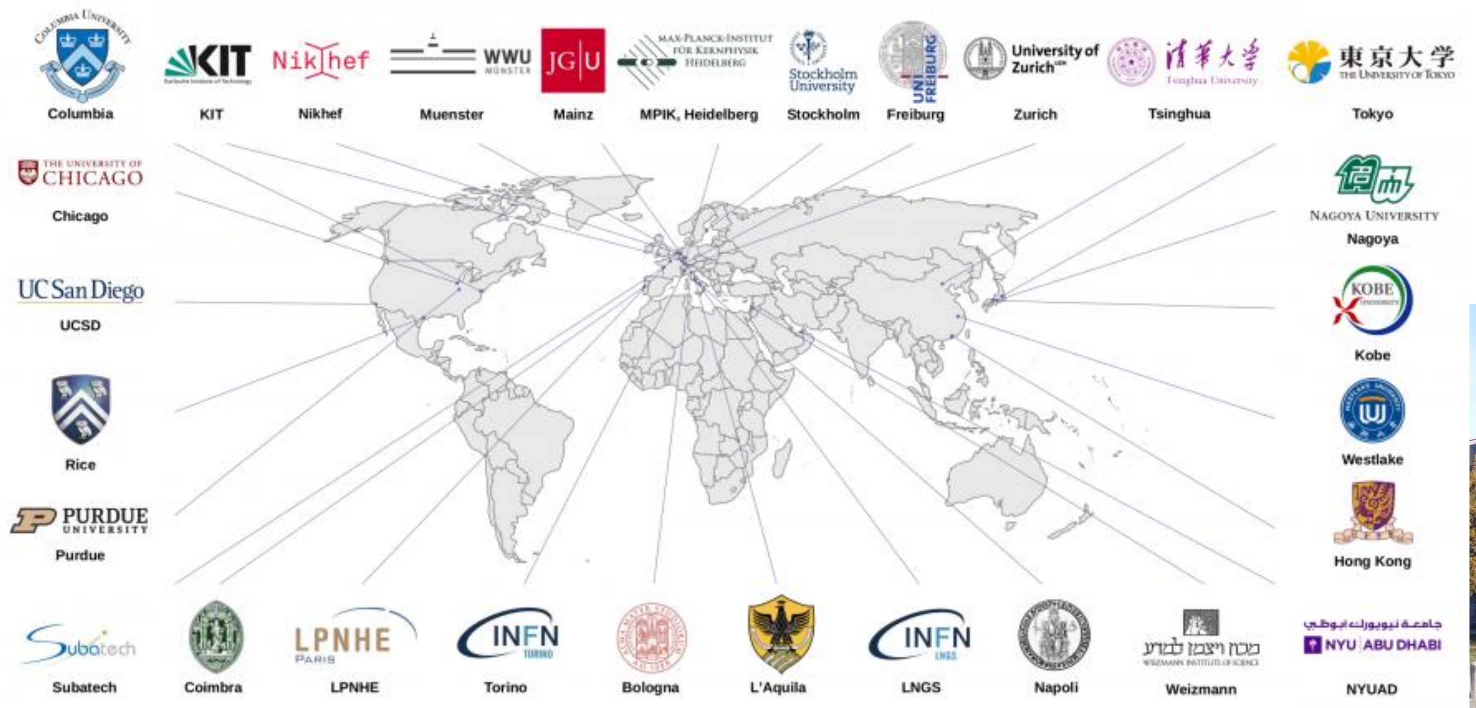
Xenon group, Subatech

Marina Bazyk

July 2023

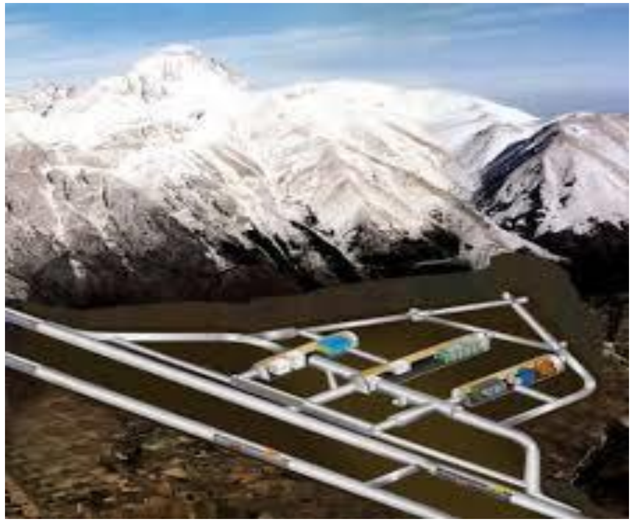
XENON collaboration



12 countries
27 institutions
200+ scientists

XENONnT experiment

Laboratori Nazionali del Gran Sasso (LNGS), Italy *2020 - present*



Rock shielding [3600 m.w.e]

General view

XENON experiments

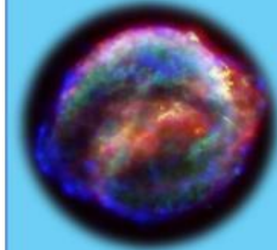
primary goal: direct dark matter detection

Rare events search = Low **BG** & high **target mass**

My contribution

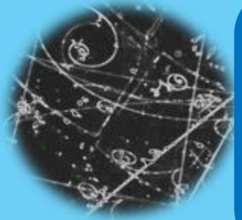
- WIMP-search
  - Spin-independent
  - Spin-dependent
- Sub-GeV
- Dark photons
- Axion-like particles

- Solar neutrinos
  - Boron-8
  - pp neutrinos
- Solar axions
- CEvNS



- Supernova neutrinos
- Actively communicate with SNEWS
- Multi-messenger in DM experiments

My contribution



- Neutrino properties
  - Double beta decay of ^{136}Xe
  - Double-electron capture in ^{124}Xe
  - Neutrino magnetic moment

XENON detectors: evolution

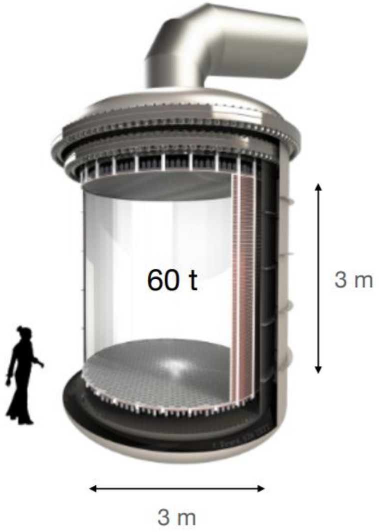
You're here → XENONnT

Time →

	XENON10	XENON100	XENON1T	XENONnT	DARWIN XLZD
Mass:	15 kg	161 kg	3.2 t	8.6 t	~60 t
Exposure:	0.87 kg × yr	48 kg × yr	1 t × yr	20 t × yr	200 t × yr
BG ER rate: [events / (t yr keV)]	~2M	~1800	~82	~16.1	



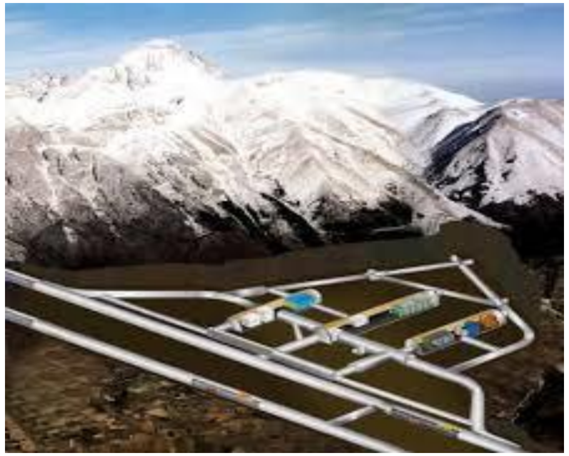


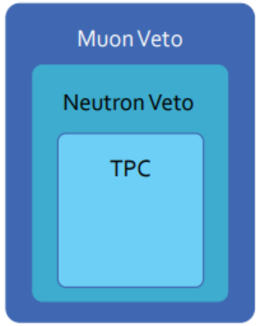


XENONnT experiment

Laboratori Nazionali del Gran Sasso (LNGS), Italy *2020 - present*

Low **BG** & high **target mass**





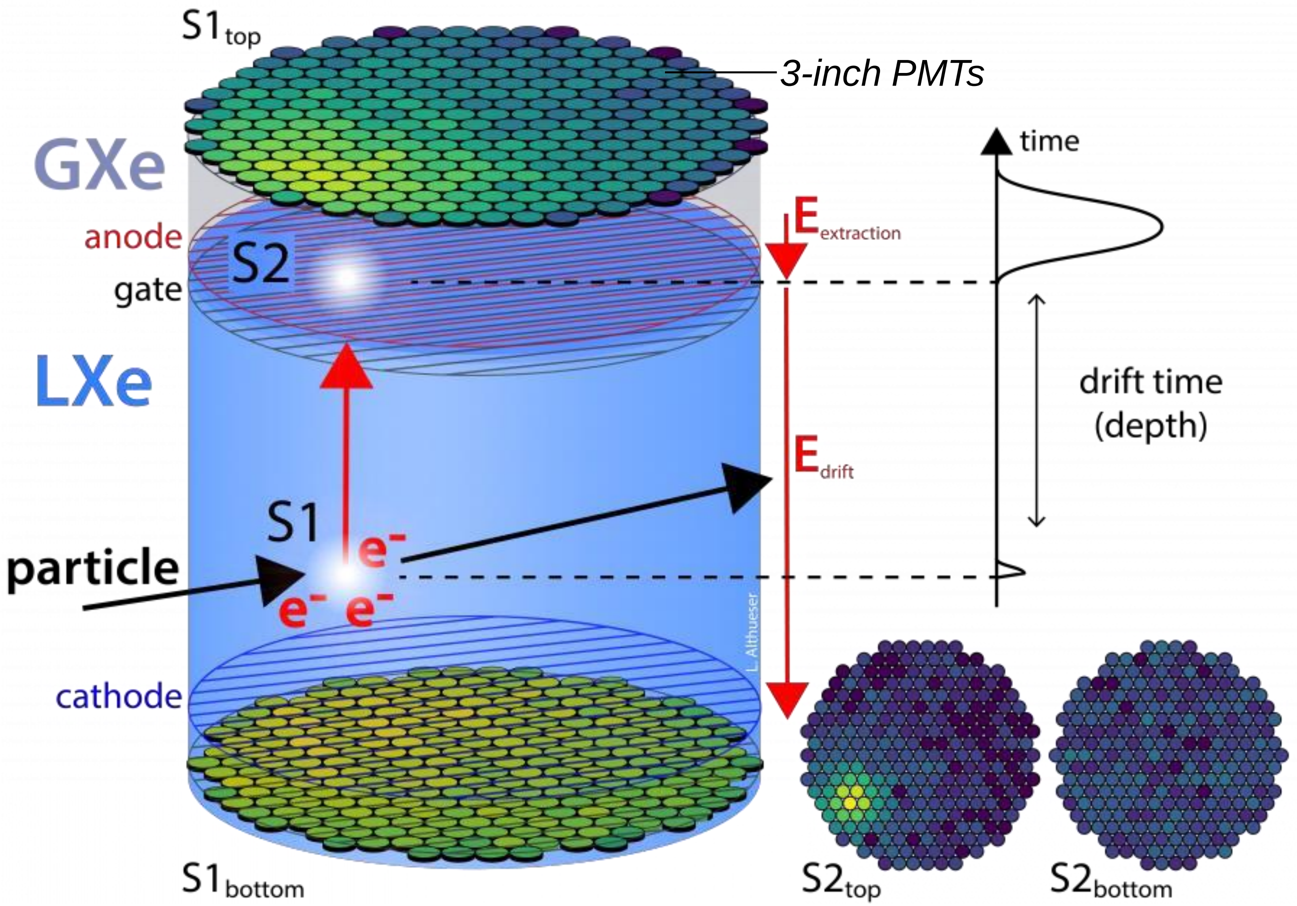
TPC
1.5 m height
1.3 m diameter

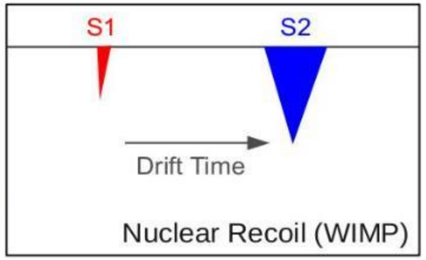
Maintenance of the detector operating conditions in the 27/7 mode is carried out by people on-site and Shifters
[My shift 3-15 March 2022]

- **Detector:** dual-phase LXe TPC
  [+ Muon Veto + Neutron Veto] [external BG]
- **Mass:** 5.9 t active LXe [3x XENON1t]
- **Exposure time:** 1.16 tonne-years ['so far', planned **20** t ×y]
- **BG ER rate achieved**: ~<u>16.1 events</u> / (t × year × keV)

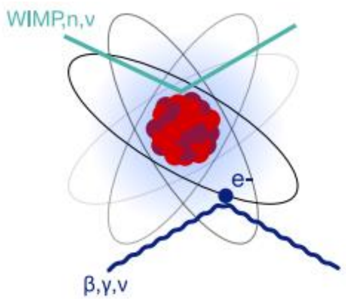
- LXe purification [avoid impurities] [external BG]
- Radon distillation column [primary BG source] [internal BG]
- Rock shielding [3600 m.w.e: cosmic rays - low energy BG] [external BG]
- Fast DAQ [>100x faster XENON1T]

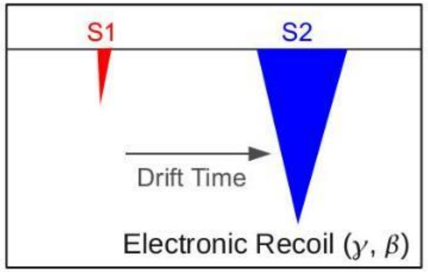
Dual-phase LXe TPC of XENONnT:
Detection principle



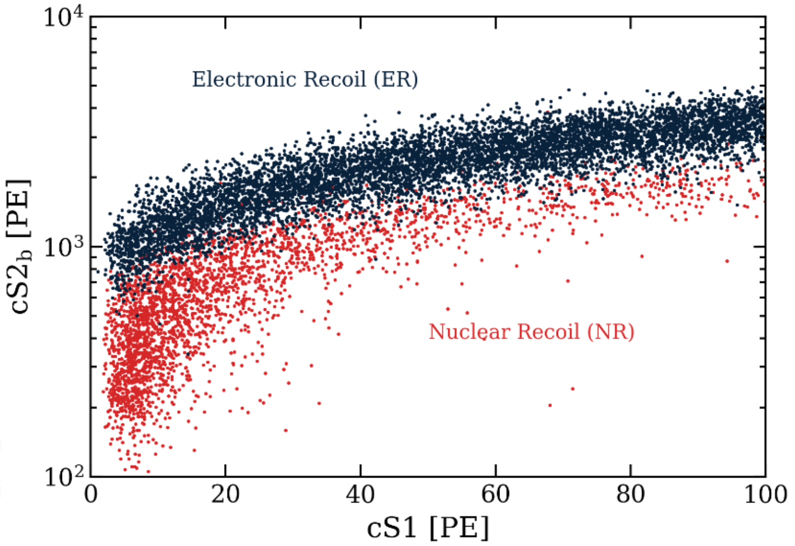


WIMPs, neutrons





β, γ



3D position reconstruction:

- **X** and **Y** via PMT pattern
- **Z** via drift time

~253 PMTs on the top
~241 PMTs at the bottom

Energy reconstruction:

- Via **S1** and **S2**

XENONnT working groups

ANALYSIS GROUPS:

NUCLEAR RECOIL
rare nuclear recoil signals search
- ❑ *Solar Boron-8 CEvNS*
- ❑ *Standard spin-independent/dependent WIMP*
- ❑ *Mirror DM*
- ❑ *Other events*

LOW ENERGY ELECTRONIC RECOIL
electronic recoil signals in low energy region search
- ❑ *Solar axions*
- ❑ *Neutrino magnetic moment*
- ❑ *Bosonic dark matter*
- ❑ *Solar-pp neutrino*
- ❑ *Other events*

HIGH ENERGY ELECTRONIC RECOIL
electronic recoil signals in high energy region search
- ❑ *Xe-136 0v/2vbb*
- ❑ *Xe-134 0v/2vbb*
- ❑ *Solar neutrino ER*
- ❑ *Other events*

My contribution

S2-ONLY
Analysis on S2 signals
- ❑ *Dark Photons*
- ❑ Migdal
- ❑ Solar boosted DM
- ❑ *DM-neutrino scattering*

ANALYSIS TOOLS
Analysis framework development

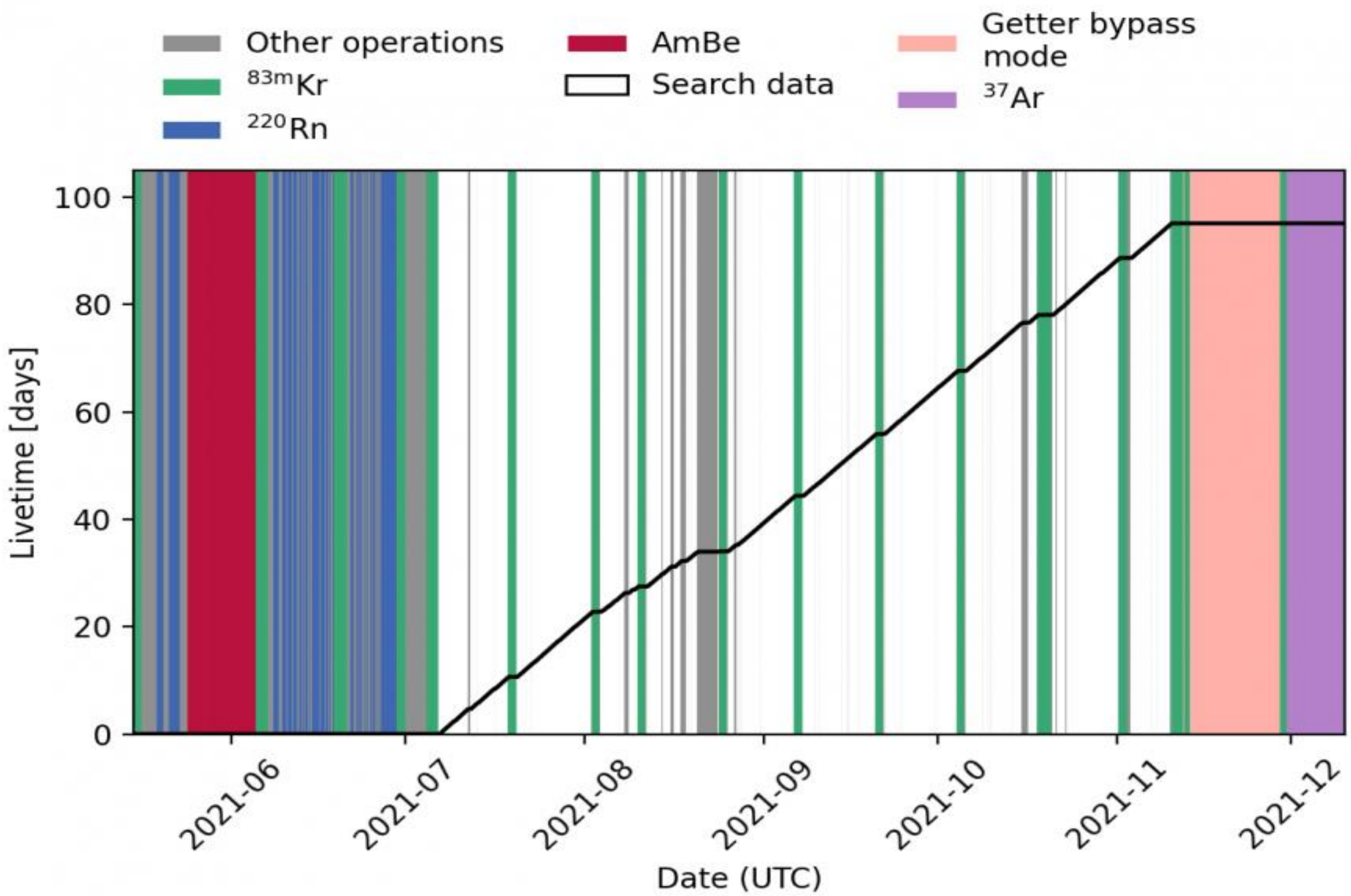
SIGNALS AND DETECTOR
Signal, particle type, energy reconstruction

My contribution

SIMULATIONS AND MODELING
Detector simulation, background estimation

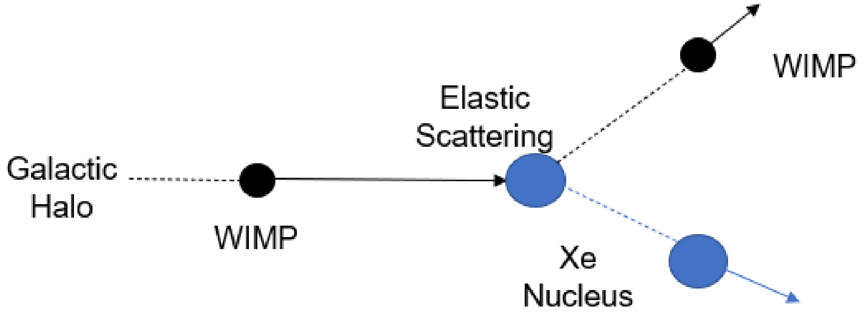
Collaboration via (bi)-weekly meetings

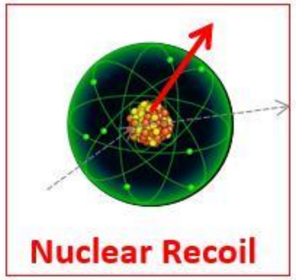
XENONnT calibration



Calibration sources: low energy

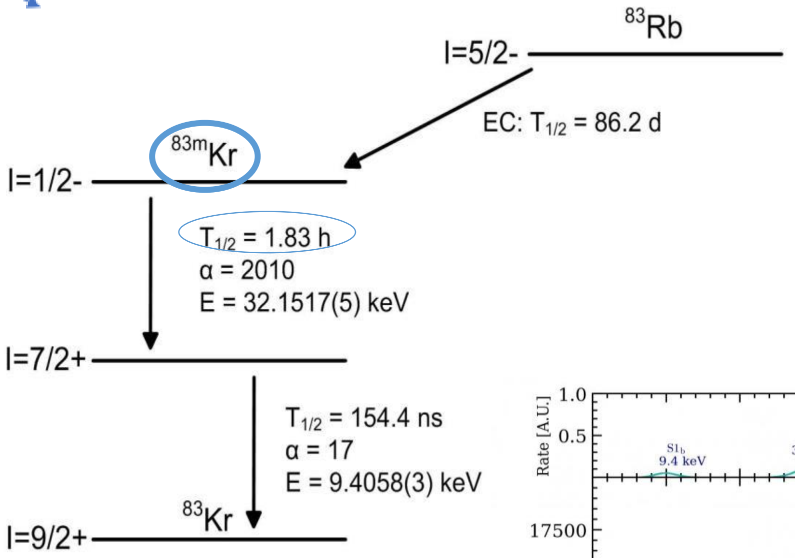
energy range: Weakly Interacting Massive Particles [WIMPs]

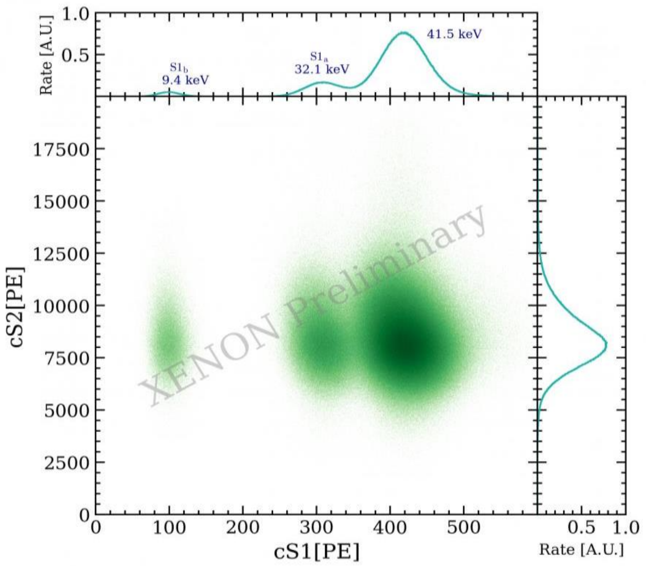




E_{recoil}: 10 ~ 100 keV

- Source ^{83m}**Kr** injected every 14 days
- Suitable half-life [$T_{1/2}$ = 1.83 h], hence…
- … fast restart of BG data taking
- Distributed uniformly in LXe
- Measure: response to low-energy events: **expected for WIMPs**

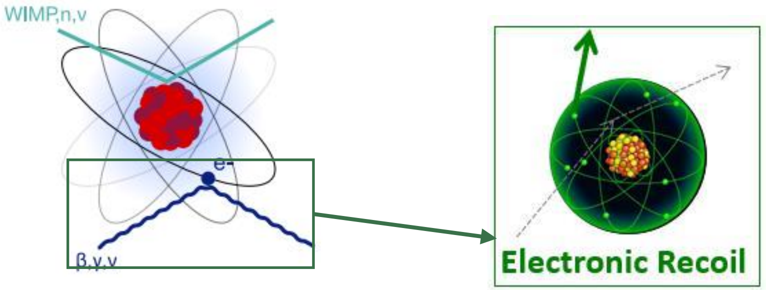




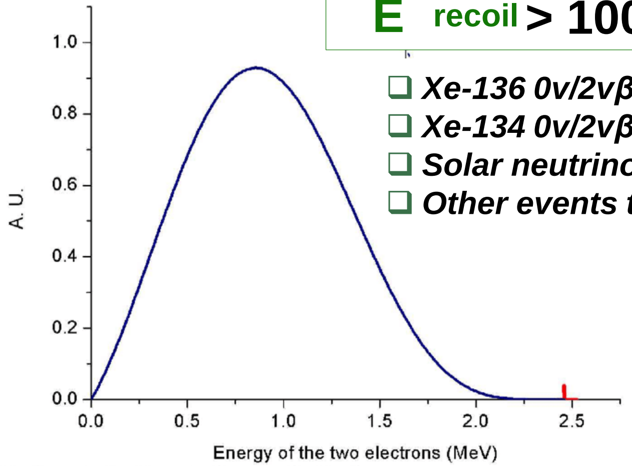
My contribution

Cuts selections
= validation of cuts applied to calibration results datasets

Calibration sources: high energy



E_{recoil} > 100 keV

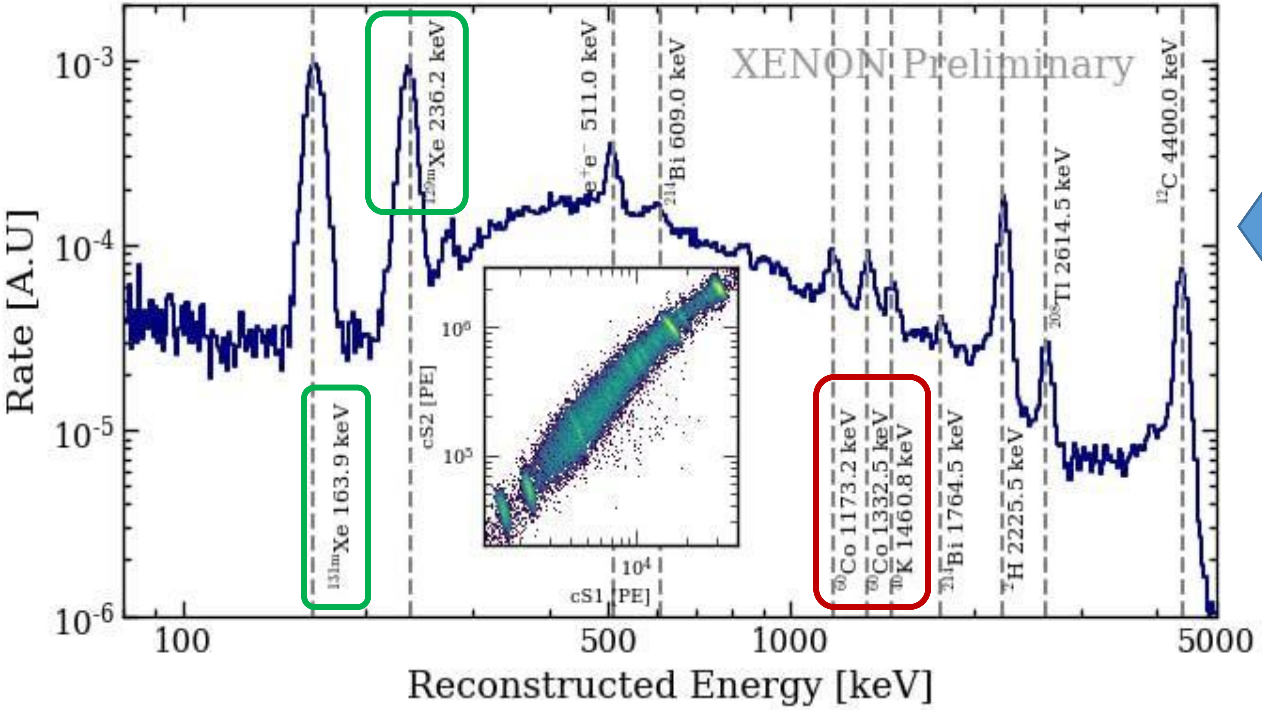


- ❑ *Xe-136 0ν/2νββ*
- ❑ *Xe-134 0ν/2νββ*
- ❑ *Solar neutrino ER*
- ❑ *Other events this ROI*

High energy sources

My contribution

- ❑ **Sources**: detector **materials, Xe-intrinsic**
- ❑ Always present
- ❑ Measure: response to high-energy events: **expected for double β-decay**



Isotope	Energy (keV)
^{131m}Xe	164
^{129m}Xe	236
^{60}Co	1173
^{60}Co	1332
^{40}K	1460

Light and Charge Yields
LY & CY

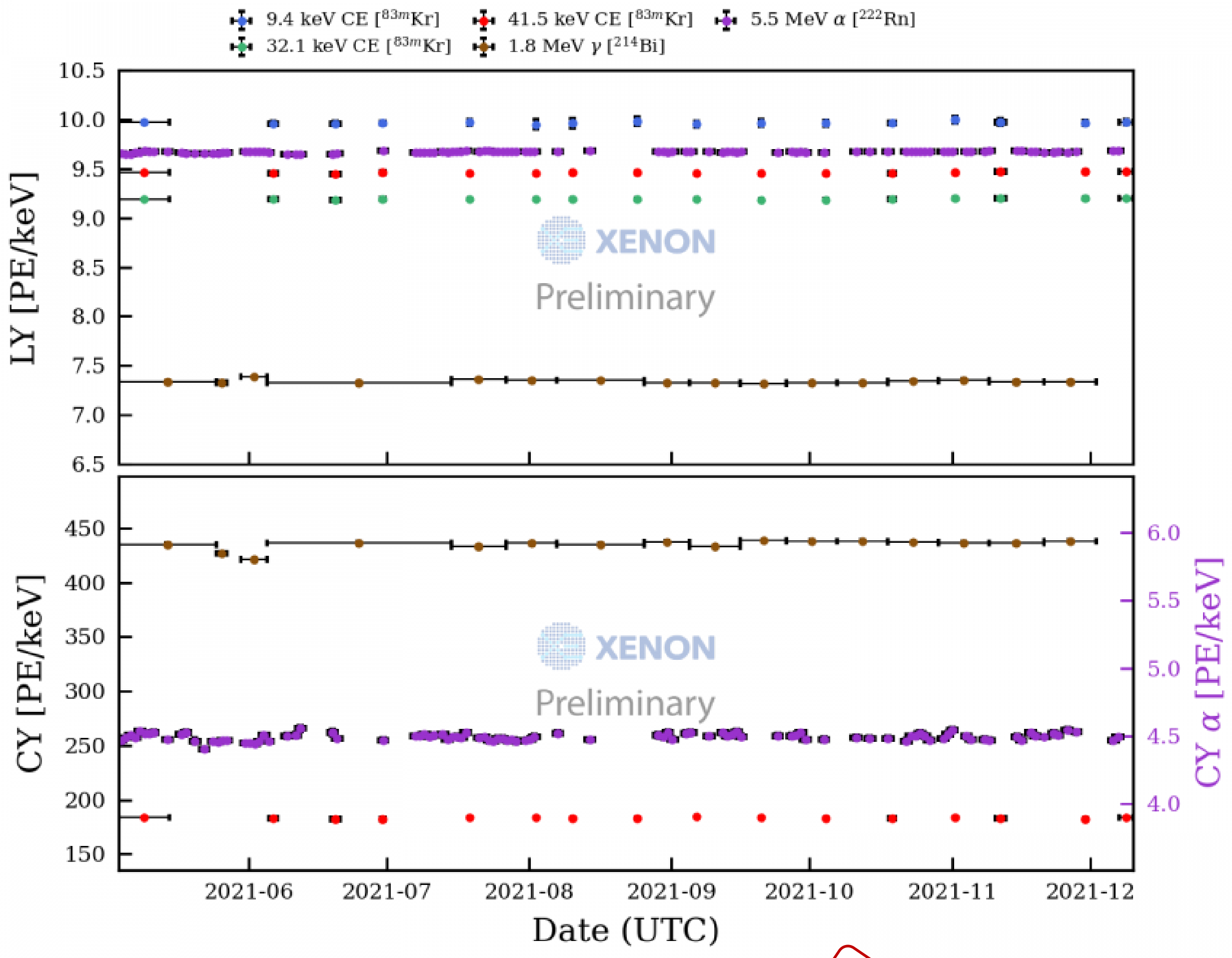
Group: SIGNALS AND DETECTOR
Signal, particle type, energy reconstruction

$$LY = \frac{S_1}{E} \text{ [PE/keV]}$$

$$CY = \frac{S_2}{E} \text{ [PE/keV]}$$

Importance of monitoring S1 and S2 signals:

- ❑ stability of Light and Charge Yields
  over a long period of detector operation
- ❑ can change with time
  depending on the operating conditions



My contribution

estimation of **systematic uncertainties** on LY and CY [upcoming…]

Known sources with known energies are usually used to estimate LY and CY.

Systematic uncertainties estimation

"Why is it important to estimate them?"

- ❑ To correctly **account** for all the uncertainties on LY and CY measurements
- ❑ To correctly **monitor** the LY and CY variations during data taking

Before this work:

Only statistical uncertainties have been accounted for

This work:

My contribution

1. Systematic uncertainties study of LY & CY for isotopes of Xe, Co and K based on the fitting model
2. Fixed and Adaptive Kernel estimation systematic uncertainties approaches [KDE & AKDE] for Xe isotopes

1. Systematic uncertainties study of Light and Charge Yields of isotopes of Xe, Co and K based on Gaussian fit input parameters

Systematic uncertainties study of LY&CY of Xe, Co, K based on Gaussian fit input parameters

detector **materials** & **Xe-intrinsic**
[slide 8]

2D Gaussian fit

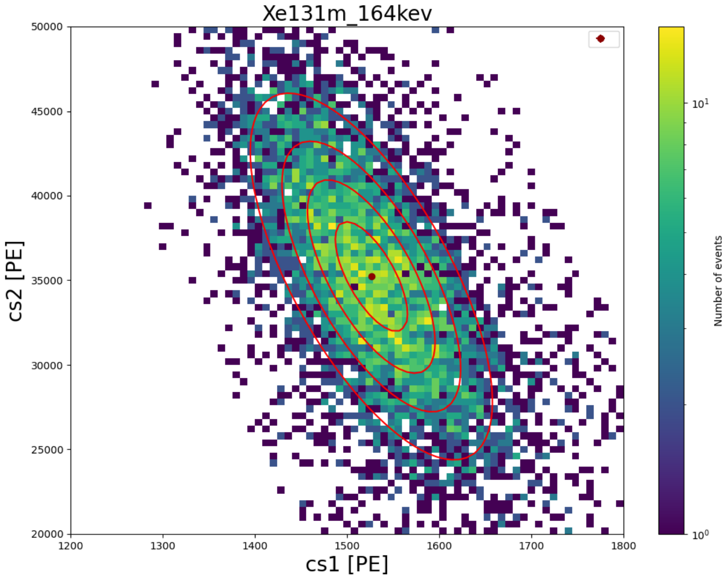
$$f(x,y) = A_0 \cdot \exp\left(-\frac{[(x-\mu_x)\cdot\cos\theta - (y-\mu_y)\cdot\sin\theta]^2}{2a^2} - \frac{[(x-\mu_x)\cdot\sin\theta + (y-\mu_y)\cdot\cos\theta]^2}{2b^2}\right) + bkg$$

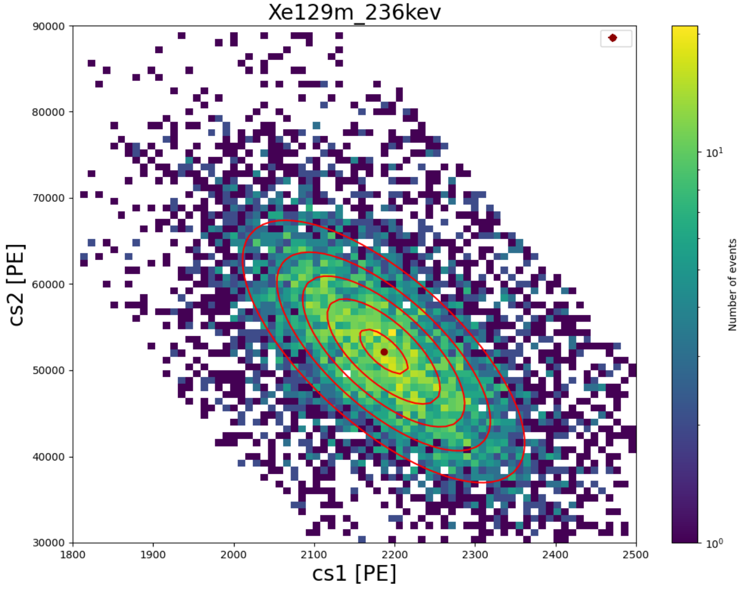
APPLY FIT TO:

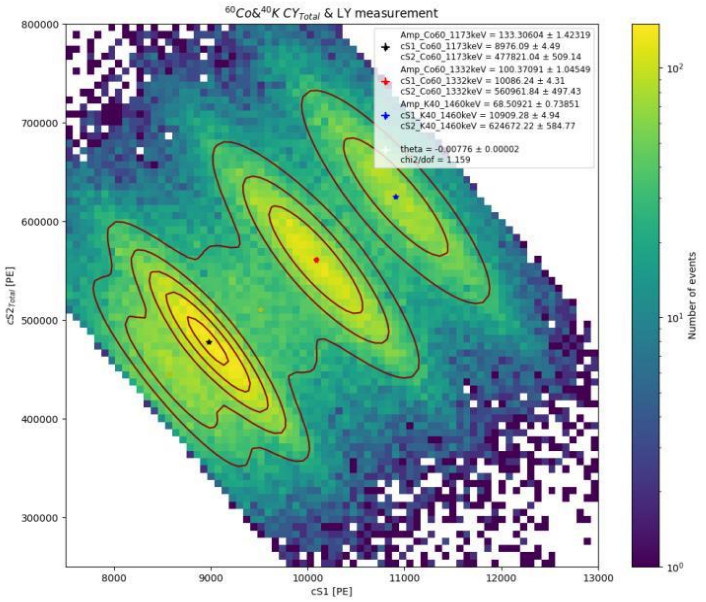
- ❑ Data: events measured [Science Run 0]
- ❑ May – November 2021
- ❑ Data division into groups

RESULTS MIGHT DEPEND ON:

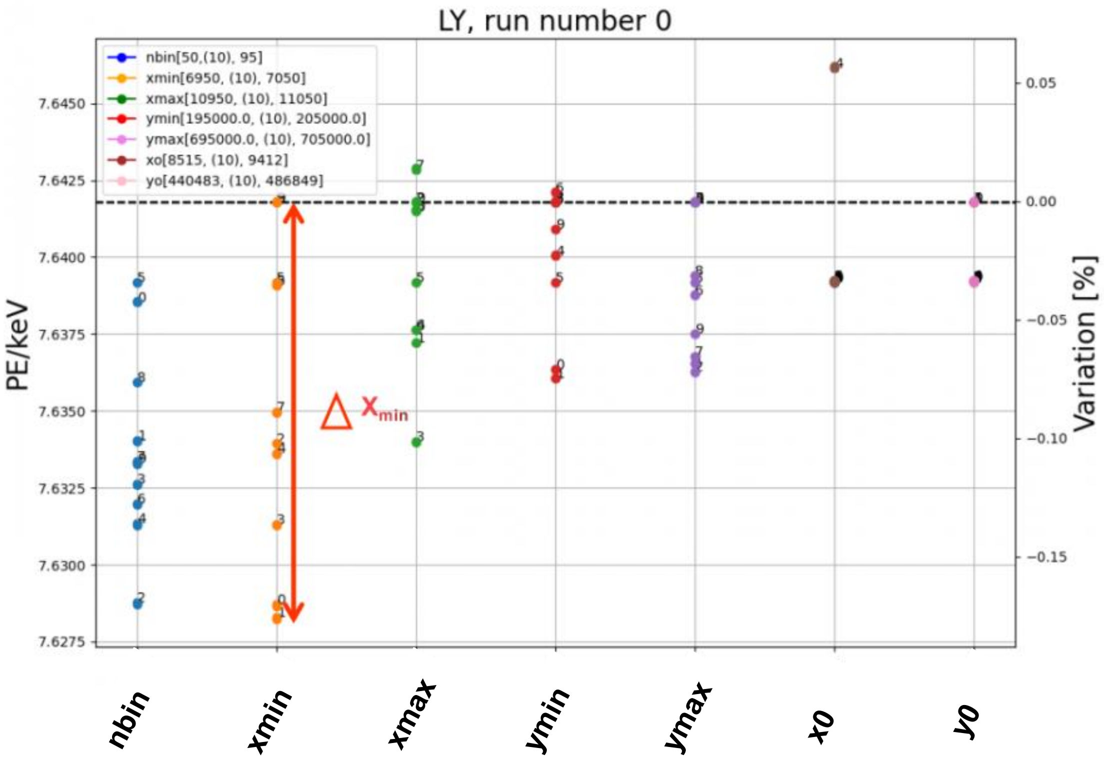
- ❑ *Number of bins*
- ❑ X_{min}
- ❑ X_{max}
- ❑ Y_{min}
- ❑ Y_{max}
- ❑ μ_x
- ❑ μ_y

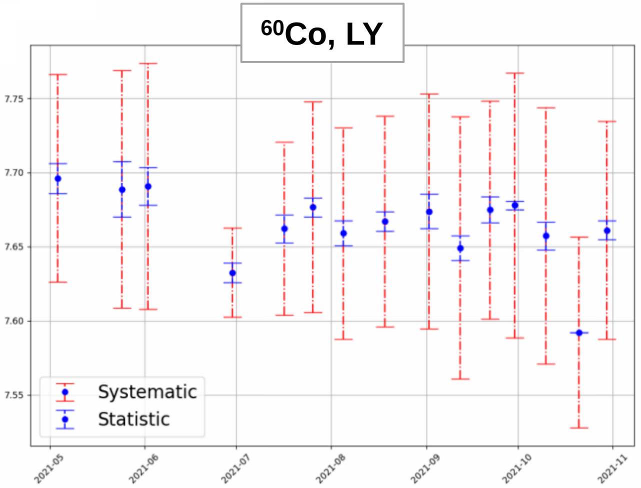






Uncertainties estimation





$$\delta_{LY(CY)} = \sqrt{\Sigma[\delta_{Parameter}(max)]^2}$$

RESULTS

Orders of magnitude of the **systematic** uncertainties:

- ❑ **for Xe: LY ~ 0,3% , CY ~ 1,3%**
- ❑ **for Co and K: LY ~ 1% , CY ~ 2%**

- ❑ Results: internal note and code integrated to collaboration work

My contribution

Internship co-supervision

“Measurements of Light and Charge Yields of ^{60}Co”

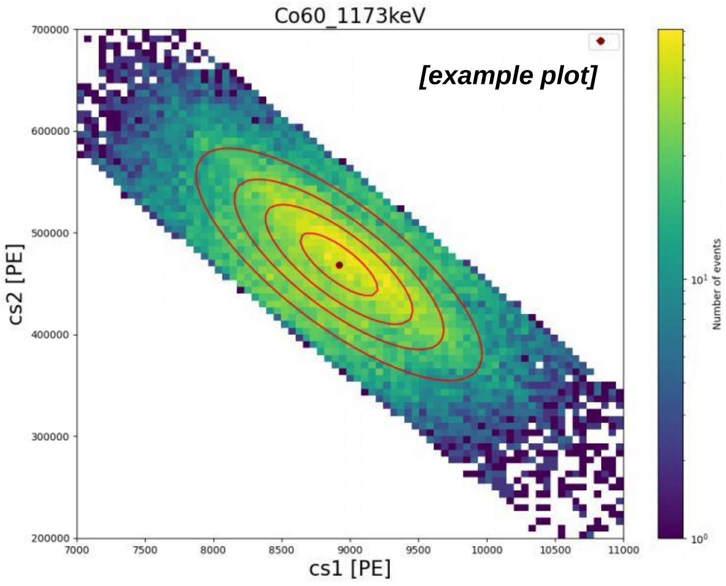
[Co-supervision: info]

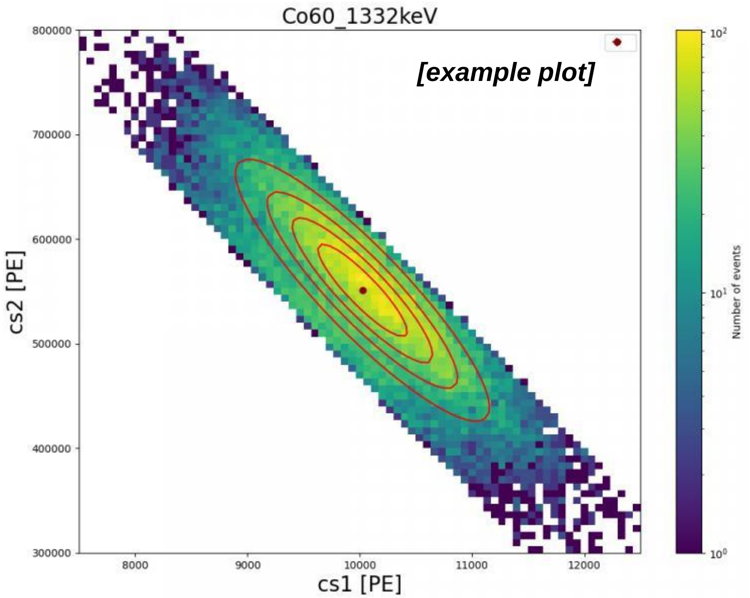
*With **Yajing Xing** and **Sara Diglio***

- ❑ **Two L3 students** “in binome” (University of Nantes)
- ❑ Active guidance in skills & knowledge obtaining
- ❑ Work & reports assessment
- ❑ Defended in March 2023

[Work done: summary]

- ❑ **Data analysis basics** with instruments used in XENON
- ❑ Measurements of **LY and CY of ^{60}Co** (1173 keV and 1332 keV)
- ❑ Implement **specific data cuts**
- ❑ Make **2D Gaussian Fits** for signals S1 and S2 (real data)





2. Systematic uncertainties study of Light and Charge Yields of Xe isotopes with KDE and AKDE approaches

Systematic uncertainties study of Light and Charge Yields of Xe isotopes with KDE and AKDE approach

Due to **lack of statistics*** (2000 events) **^{129m}Xe** and **^{131m}Xe** we try to artificially increase it by:

1. Building **PDF**
2. Producing **1000** Monte-Carlo data samples with the PDF obtained
3. Estimating **uncertainties** with the results obtained

For this algorithm use KDE or AKDE

** ^{131m}Xe and ^{129m}Xe events are mainly generated from the AmBe calibration period with neutron capture of Xe130 and Xe128 and quickly decay with half-life ~ 12 and ~9 days*

Systematic uncertainties study of Light and Charge Yields of Xe isotopes with KDE and AKDE approach

Kernel Density Estimation = *process of estimating an unknown probability density function using a kernel function.*

*While a histogram counts the number of data points in somewhat arbitrary regions, a **KDE** is a function defined as the sum of a kernel function on every data point.*

Fixed Kernel Estimation

$$\widehat{f}_h(x) = \frac{1}{n}\sum_{i=1}^{n} K_h(x - x_i) = \frac{1}{nh}\sum_{i=1}^{n} K\Big(\frac{x - x_i}{h}\Big)$$

Here: K – kernel function (non-negative) function, h - bandwidth

Adaptive Kernel Estimation

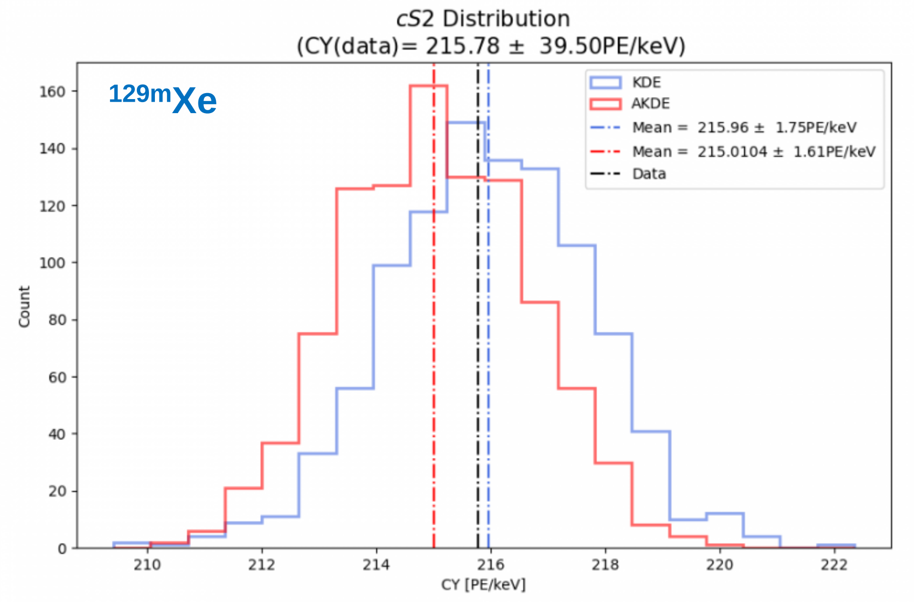
*The only difference in the adaptive kernel technique (**AKDE**) is that a bandwidth parameter is no longer a global quantity. In regions of high density we can accurately estimate the parent distribution with narrow kernels, while in regions of low density we require wide kernels to smooth out statistical fluctuations in our empirical probability density function.*

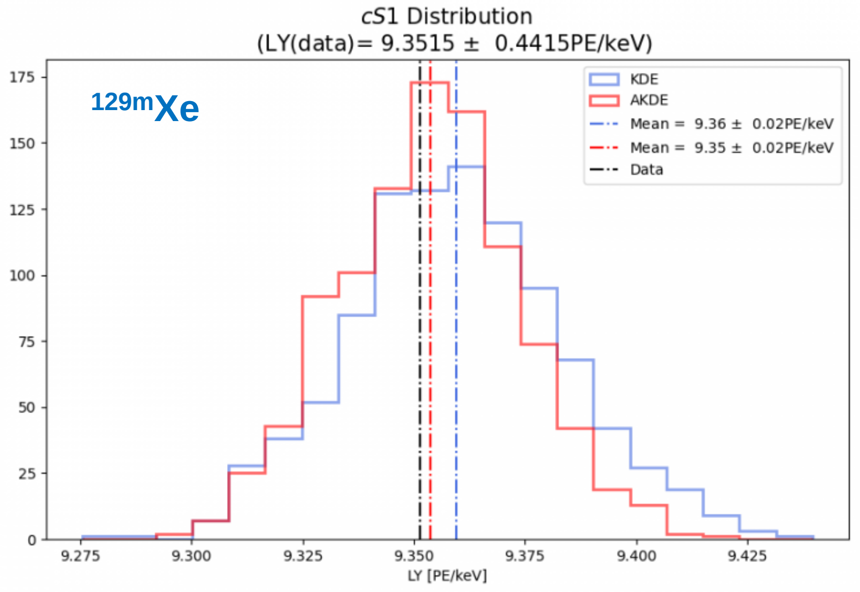
To do so, we use: $$h_i = \frac{h}{\sqrt{\widehat{f}_h(x_i)}}$$

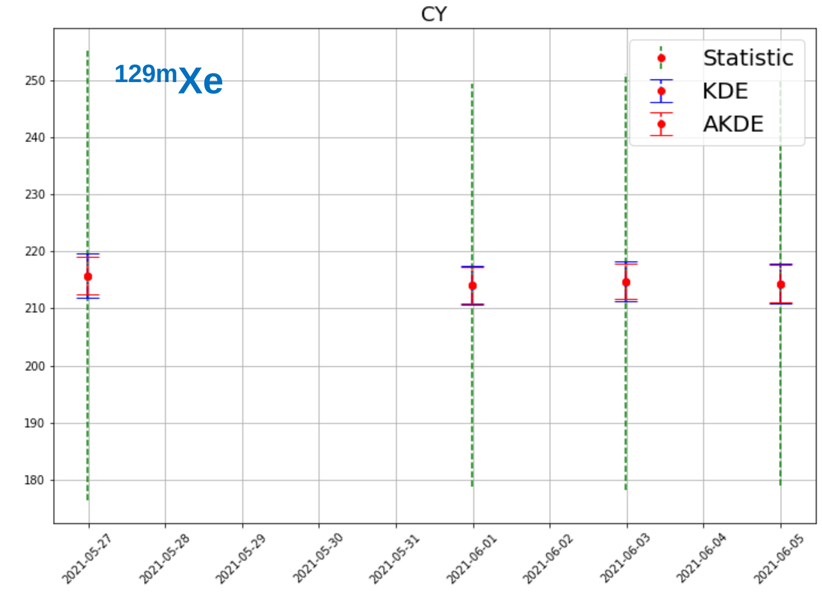
Distributions of LY & CY

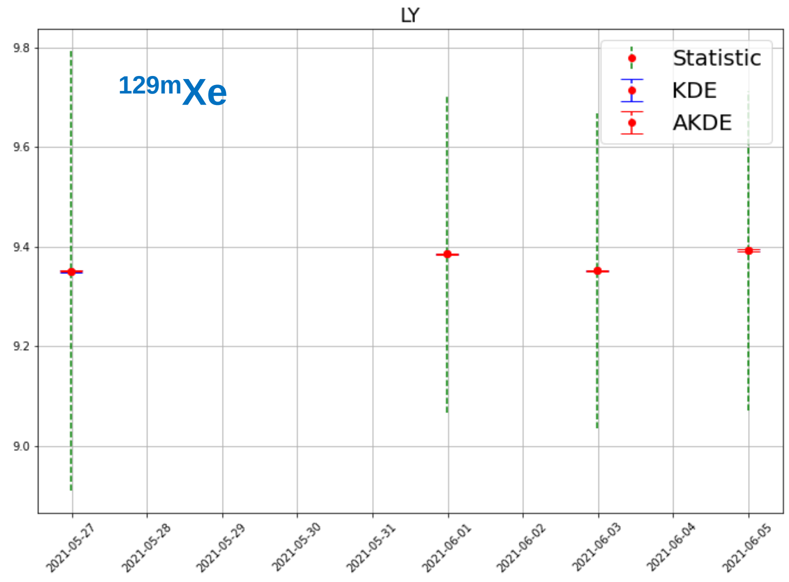
^{131m}Xe (not shown here)

Once **KDE** and **AKDE PDFs** were built, **1000 MC data samples** from these PDFs for each group of events **were produced**









KDE and **AKDE** showed
similar results
AKDE requires
more calculations resources

Stop on KDE approach

3. INFERENCE framework development in frame of High Energy ER Group

Just started!

Just started!

High-Energy Bootcamp @ Weizmann Institute of Science

- *Build the foundation of the High-Energy Analysis framework*

[May 2023]

- Signal Reconstruction
- MC – Development
- Background Model

Inference framework
for High Energy region

Motivation:

- *To draw conclusions and make predictions based on available evidence or observations*
- *To assess the validity of hypotheses and evaluate the support for proposed predictions*

Just started! *

Working packages

Data collection
Ensure data quality

Background modeling
Understanding and characterizing the expected background

MC-simulations

Templates building

INFERENCE

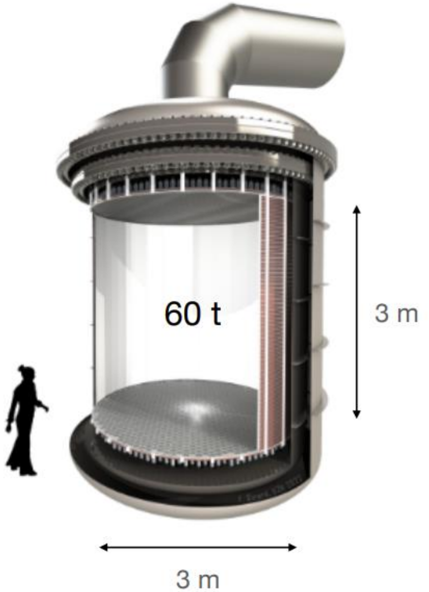
Extract the analysis limits

** The work began during the Workshop on High Energy events in WIS in Israel [May 2023]*

4. Future Liquid Xenon experiments

DARWIN & XLZD

Reminder: **rare-events** search → very low BG experiment, high target mass

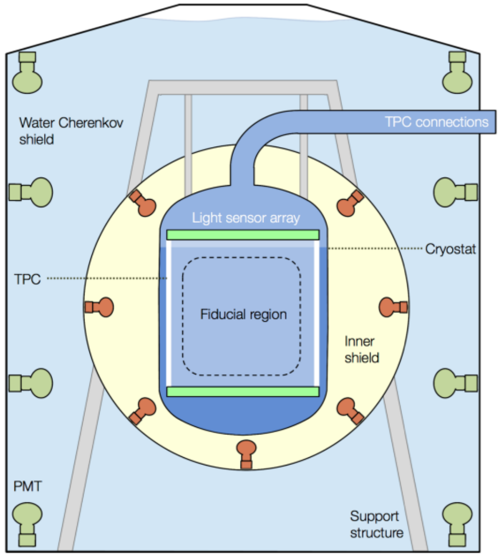


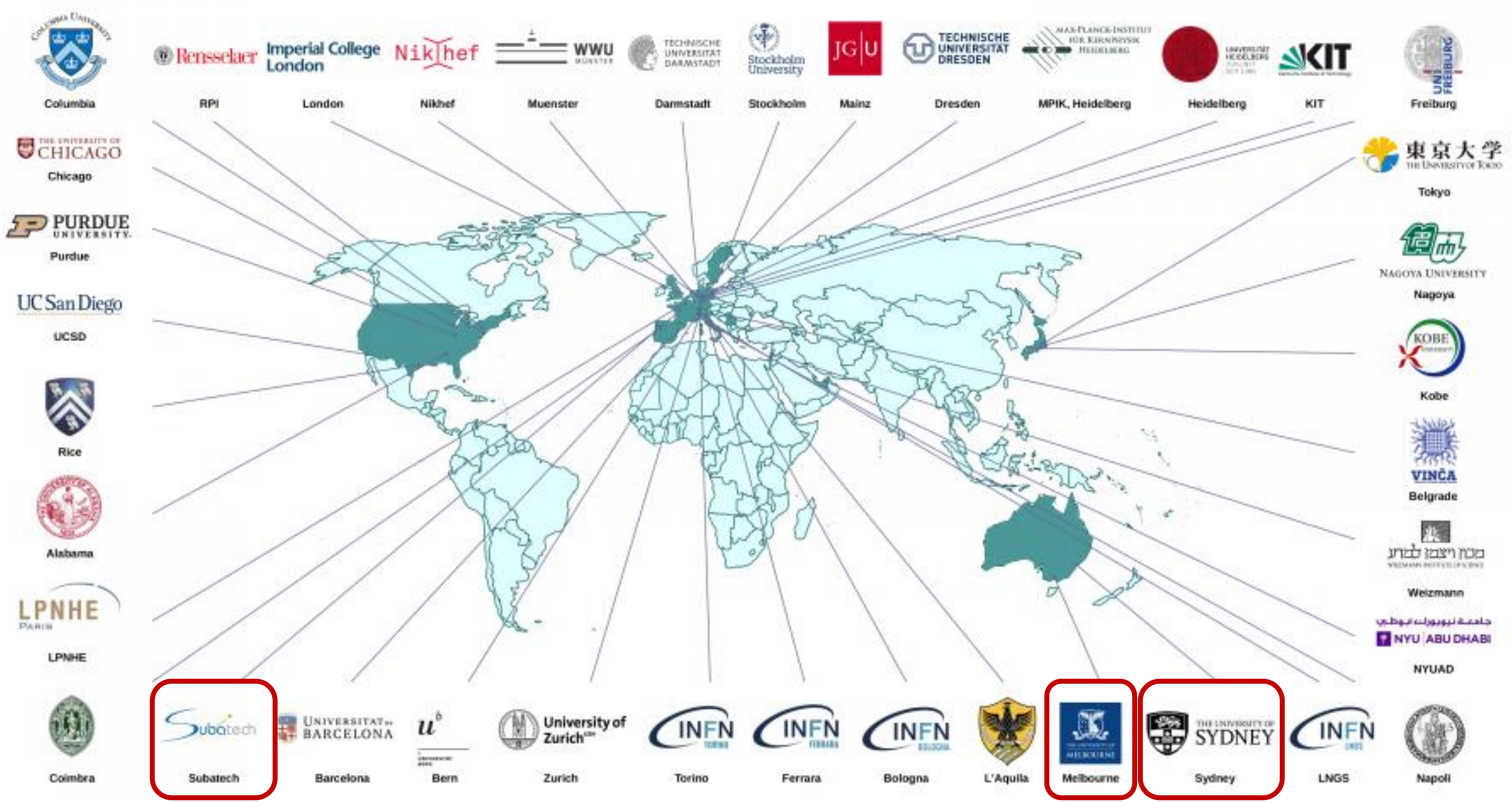
In progress…

- **Detector:** dual-phase LXe TPC
- **Volume:** 40 t - 60t - 80t of LXe!
- **R&D is ongoing**

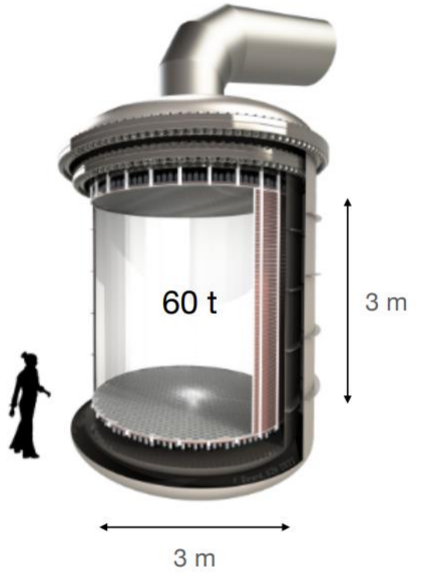
WIMPs, but also…

- low-energy solar neutrinos (ν)
- axions- and axion-like particles
- ν-less 2ββ decay of ^{136}Xe
- other rare nuclear processes
- coherent ν-nucleus scattering
- detection of ν from galactic supernovae, with sensitivity to all ν flavors, etc.z





DARWIN & XLZD



R&D ongoing right now

- ❑ Design still to be fixed
- ❑ **Simulations,** sensitivity
- ❑ PMTs to be selected:
- ❑ Full-Scale Demonstrators
- ❑ DAQ challenges
- ❑ Cryogenics distillation, material coating, radiopurity assays, etc.

- Software development
- Sensitivity studies for specific signal models

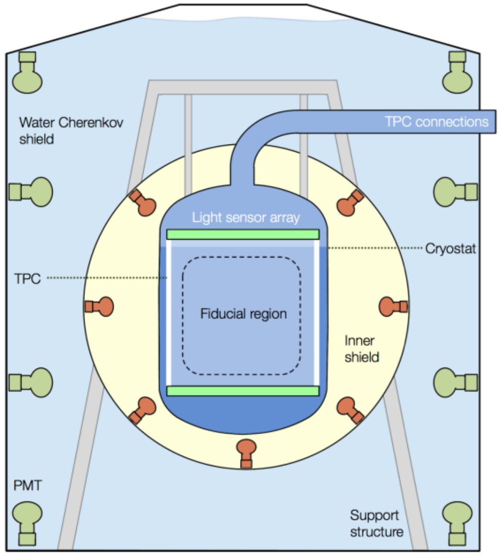
- What R&D is needed and where can we contribute?

- WG 1 - Science, Sims and Software: various topical areas (NR, ER, DBD) and tools
- WG 2 - Detector Performance & Pathologies - Xe microphysics, anomalies, materials issues
- WG 3/4 - Detector design, large scale testing, R&D planning
- WG 5 - Siting and underground requirements

- Studies on existing data (if we can find and agreement how to share), how to include in simulations etc, results from test stands

Participation in monthly France-Australia meetings

*[**discuss joint contributions**: future LXe experiments R&D and theory models]*



My possible contribution

- ❑ PMTs testing in Melbourne
- ❑ Sensitivity studies at high energies for different detector design

Summary

Done: Shift to XENONnT

^{83m}Kr cuts selection

Estimation of systematical uncertainty:

- ❑ Statistical uncertainties are dominant when we do not have enough statistics
- ❑ We can "increase" the statistics by using KDE approach

The order of magnitude of the **systematic uncertainty:**

- ❑ for Xe: **LY ~ 0,3% , CY ~ 1,3%**
- ❑ for Co and K: **LY ~ 1% , CY ~ 2%**

Ongoing: Inference framework development in High Energy:

- ❑ Development of "Template builder" for future **INFERENCE**

Anticipated: Contribution to Future Liquid Xenon experiments:

- ❑ PMTs testing in Melbourne
- ❑ Sensitivity studies at high energies for different detector design

Thanks
for your attention.

Methodology

Idea: By changing initial parameters see the variation of **LY and CY** *for* **Gaussian fit** *performed. The variation of parameters was chosen in such a way as to assure the ability to build Gaussian fit.*

- ❑ *Algorithms development from scratch*
- ❑ *High demand of computing recourses*

Other parameters set to constant while varying one of them in 10 steps

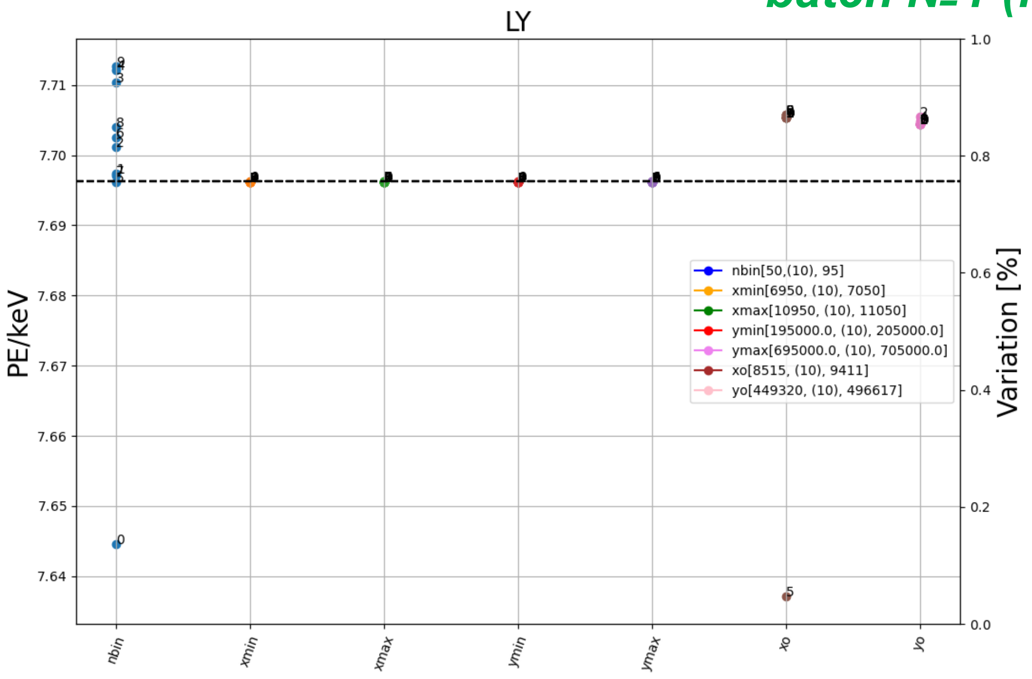
Parameter	Variation
$Number\ of\ bins$	50,..(10 steps)..,95
x_{min}	$initial$ - 50,..(10 steps)..,$initial$ + 50
x_{max}	$initial$ - 50,..(10 steps)..,$initial$ + 50
y_{min}	$initial$ - 5000,..(10 steps)..,$initial$ + 5000
y_{max}	$initial$ - 5000,..(10 steps)..,$initial$ + 5000
μ_x	$cS1mean - 5\%$, ..(10 steps).., $cS1mean + 4.5\%$
μ_y	$cS2mean - 5\%$, ..(10 steps).. , $cS2mean + 5\%$

Variation monitoring

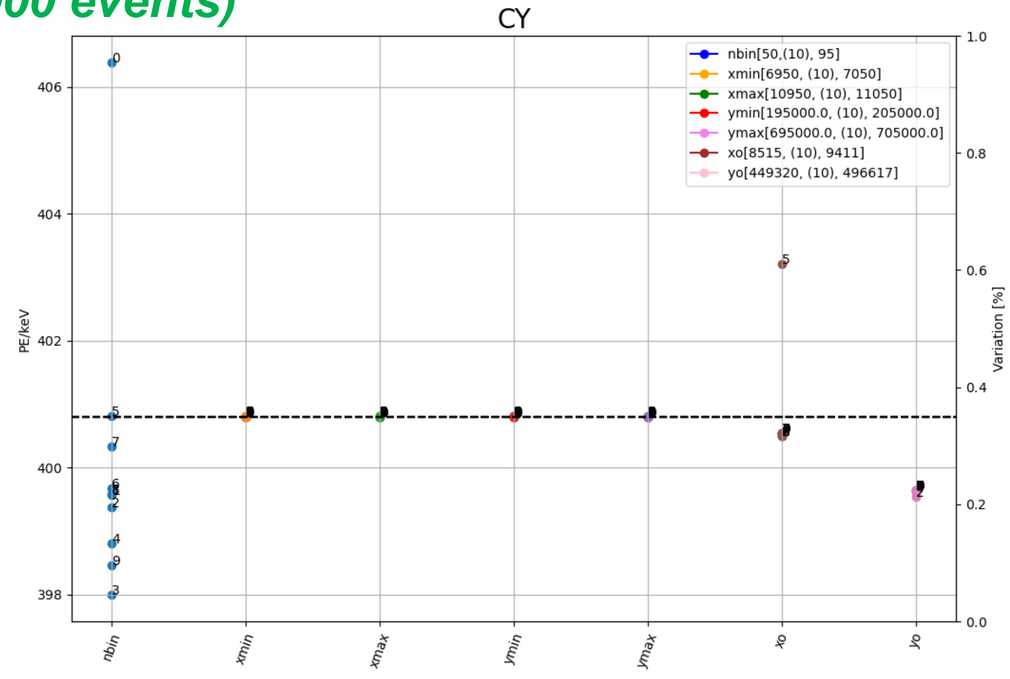
[example plots]

> 100 plots produced and analyzed

variation of signals from ^{60}Co (1173 keV)
batch №1 (first 20000 events)



dashed line represents the reference value



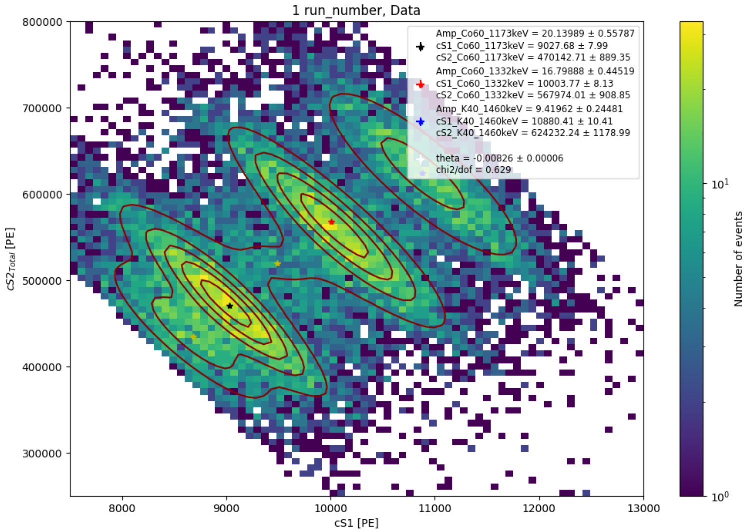
number indicated near the dot corresponds to a number of step of change

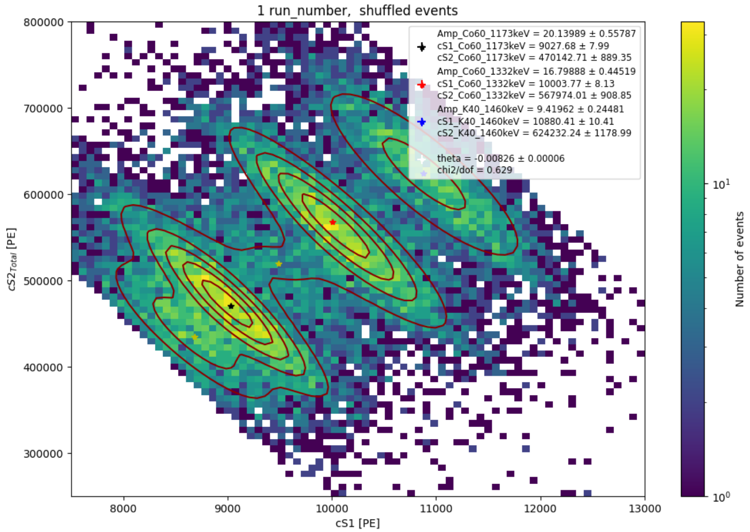
Observed:
- ❑ the smallest (or the largest) number of step of change **does not always correspond** to the smallest (or the largest) value of **LY** or **CY**.
- ❑ Hardly possible to determine which parameter **affects the results more**

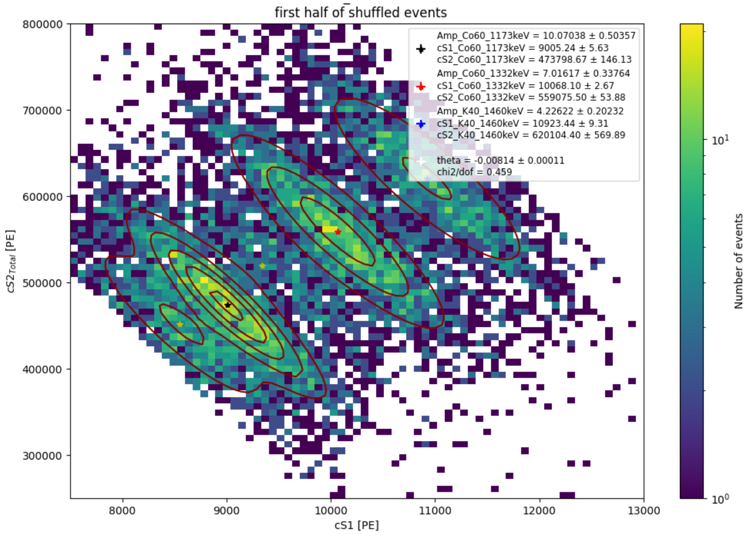
Determine from the plots :
- ❑ **most significant** variation only
- ❑ **variation of which parameter** caused such change

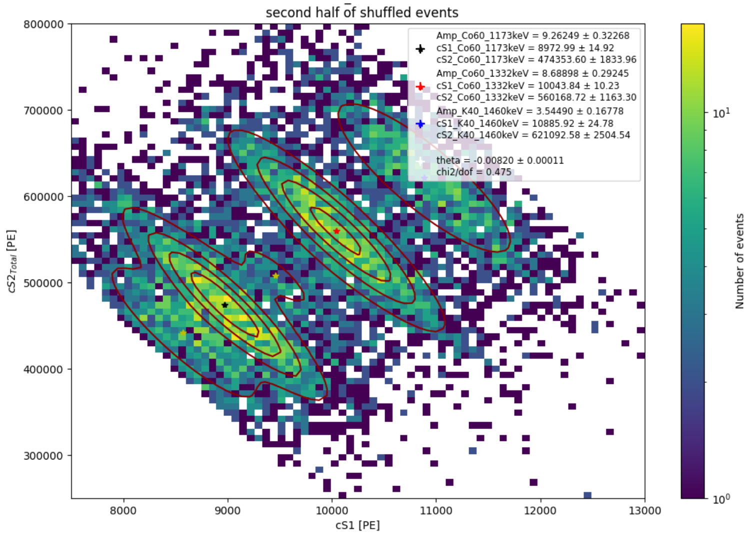
Check of ^{60}Co and ^{40}K signals statistics

We took data for each run of ***^{60}Co*** *(1173keV),* ***^{60}Co*** *(1332keV)* ***^{40}K*** *(1460keV), shuffled events and divided them into two groups of events.*
For each set of events - build Gaussian Fit and equal





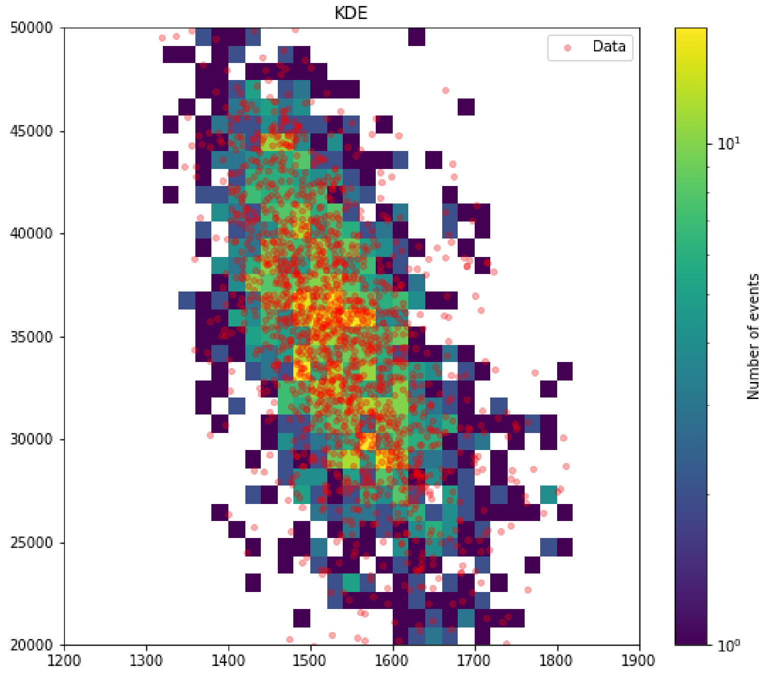


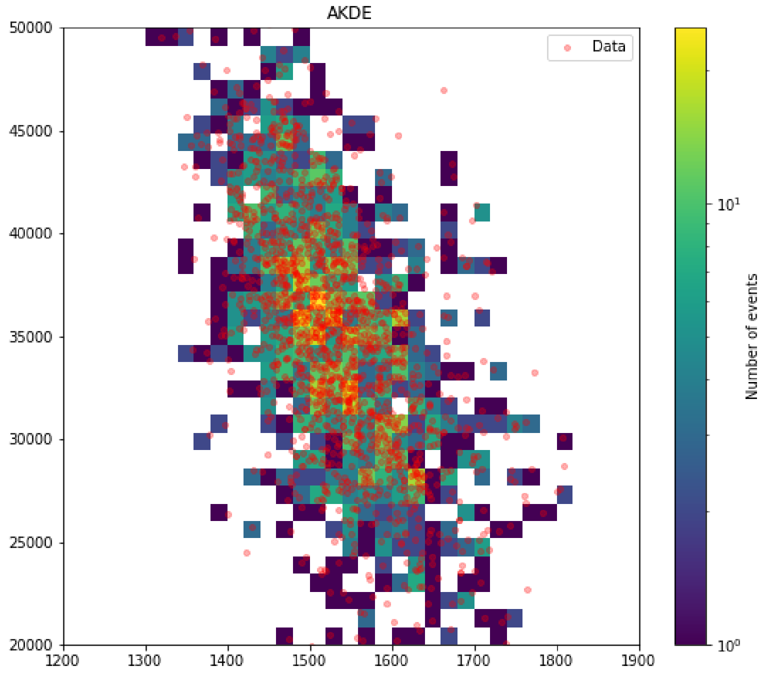


KDE and AKDE comparison

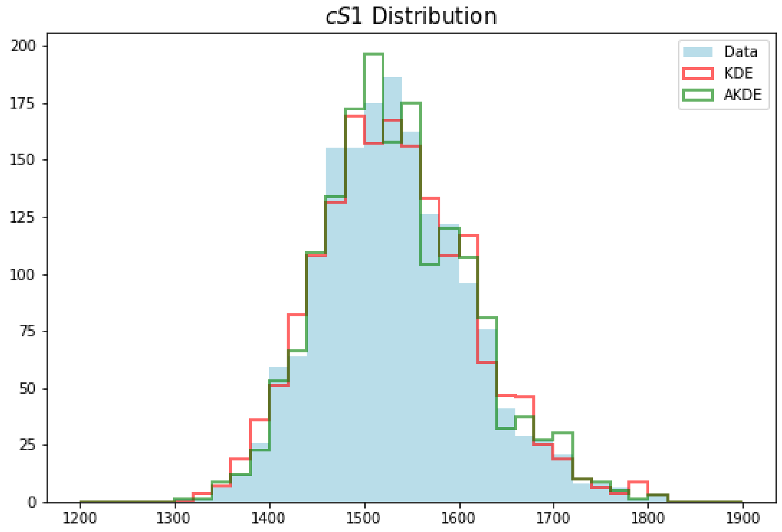
Plots represent data with ***KDE/AKDE*** *for the first group of 2000 events for* ^{131m}***Xe***

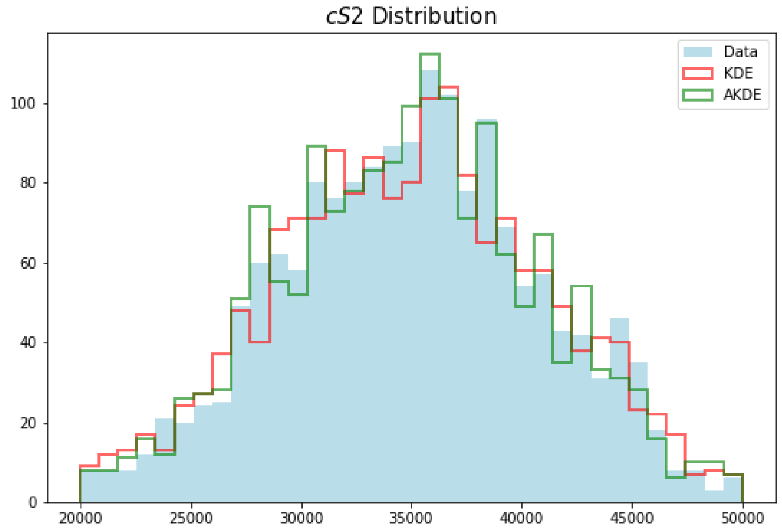
2D





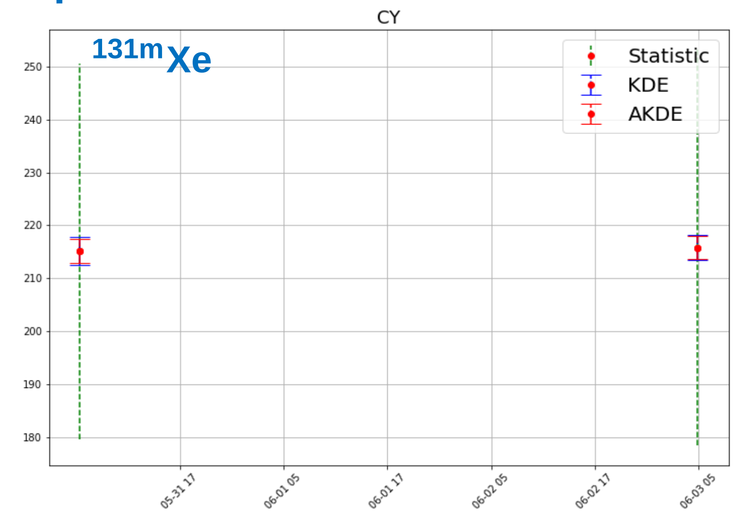
1D

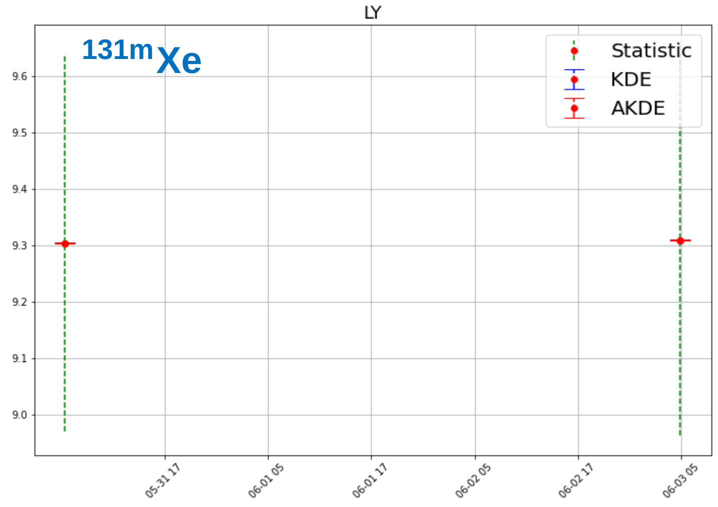


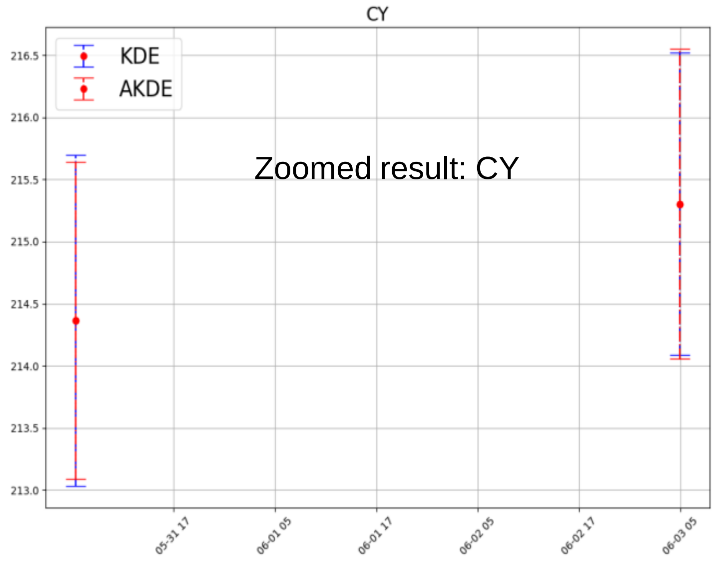


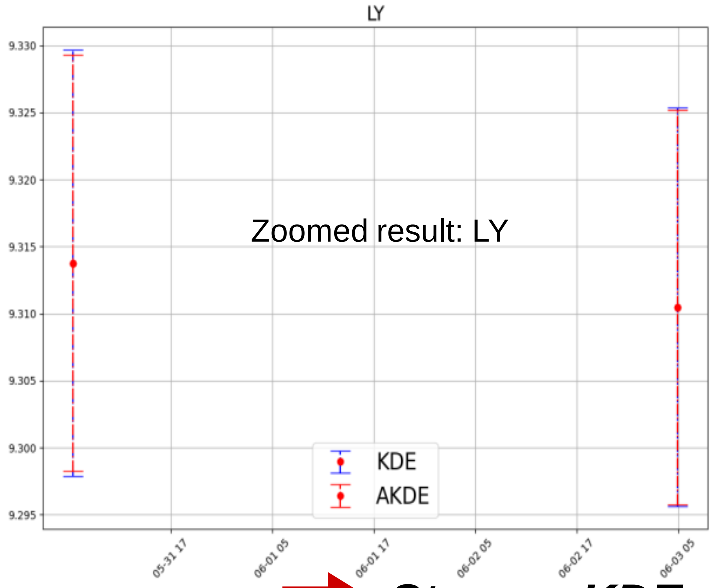
KDE and AKDE comparison

^{131m}Xe example: difference KDE/AKDE – in the zoomed version









KDE and **AKDE** show **similar results** (see *), but **AKDE** requires **more time** for calculations → ***Stop on KDE***

WIMP Sensitivity