Nausicaa's beach

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Odysseus’s tale

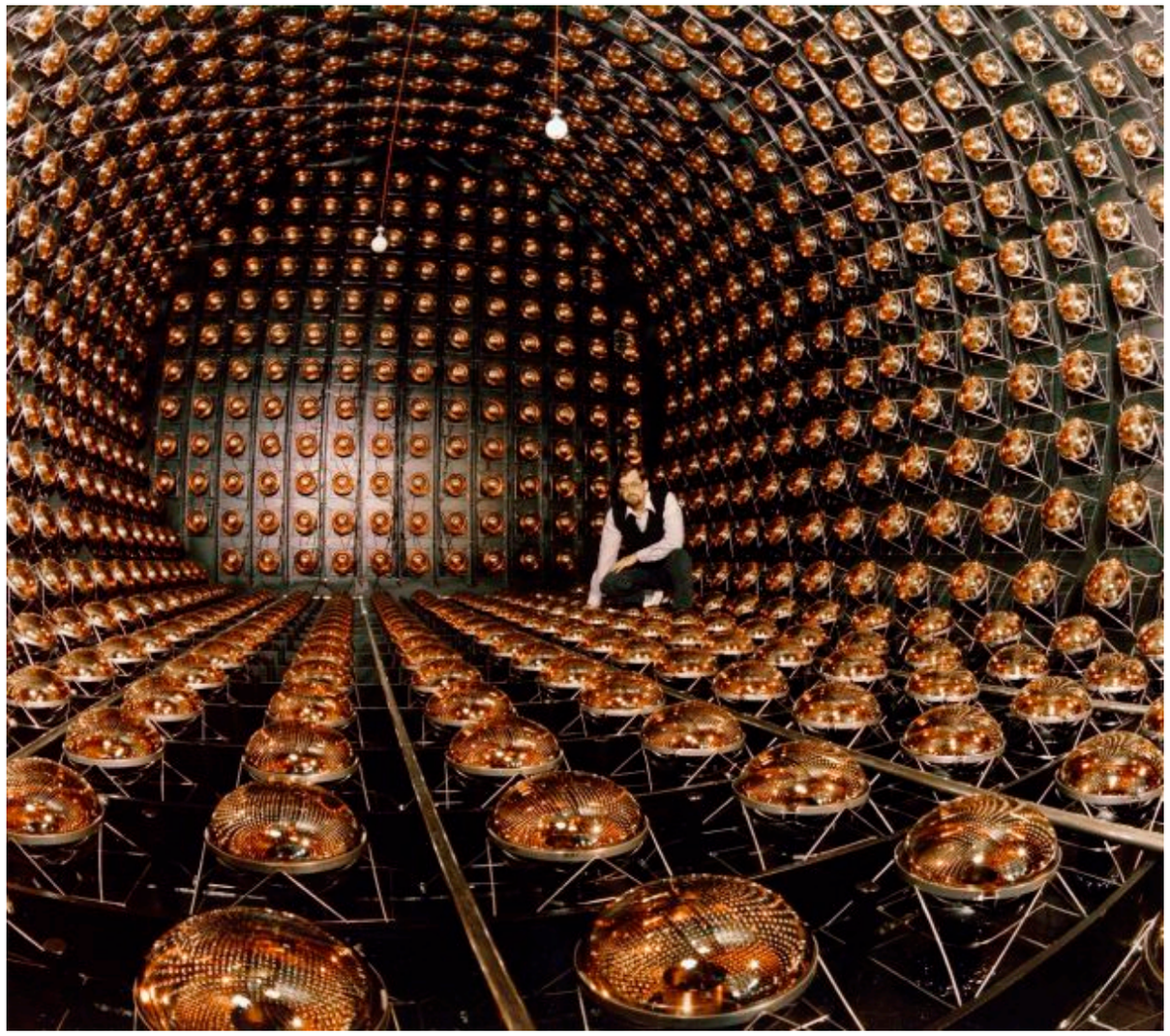
In the Odyssey, the Phaeacian princess Nausicaa goes to the river to wash her clothes and while she and her handmaidens are playing ball in the nearby beach, as their clothes dry, Odysseus wakes in the forest (after almost drowning in the sea) and encounters them. Naked himself, he humbly yet winningly pleads for their assistance, never revealing his identity.

Odysseus’s tale

A few days later, Odysseus finds himself in the palace of Nausicaa’s father, king Alcinous. A bard sang of the great deeds of Troy’s war heroes. After witnessing the sadness of Ulysses on the bard’s song, the king asks him to tell his story.

The Journey of Odysseus
BLACK SEA
GREECE
ITALY
ASIA MINOR
MEDITERRANEAN SEA
Land of the Dead (Tiresias)
8
7
Aeaea (Circe)
9
6
Laestrygonians (cannibals)
Ismarus (Cicones)
2
Dardanelles
Olympus
Troy
1
15
Phaeacia
Ithaca
16
10
Sirens
Charybdis
11
12
Scylla
SICILY
Cyclops
Aeolus (god of the winds)
5
4
13
Thrinacia (island of the sun god)
Ogygia Isle (Calypso)
14
3
Lotus-Eaters

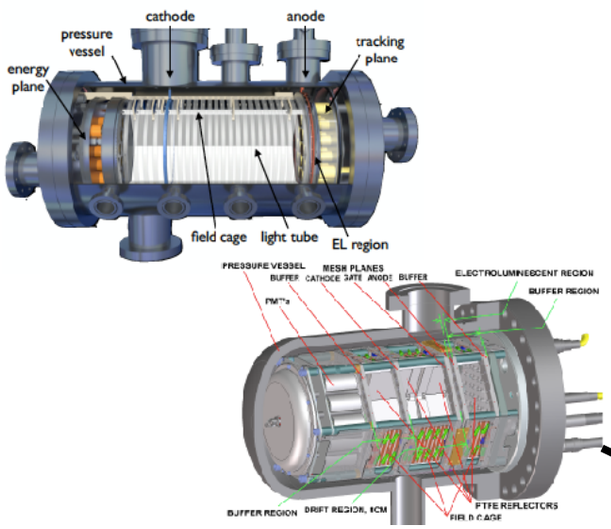
The discovery’s odyssey



The tale of discoveries in (neutrino) physics could be told as odysseys, often involving the long 20 years that Ulysses needs to return to Ithaca.

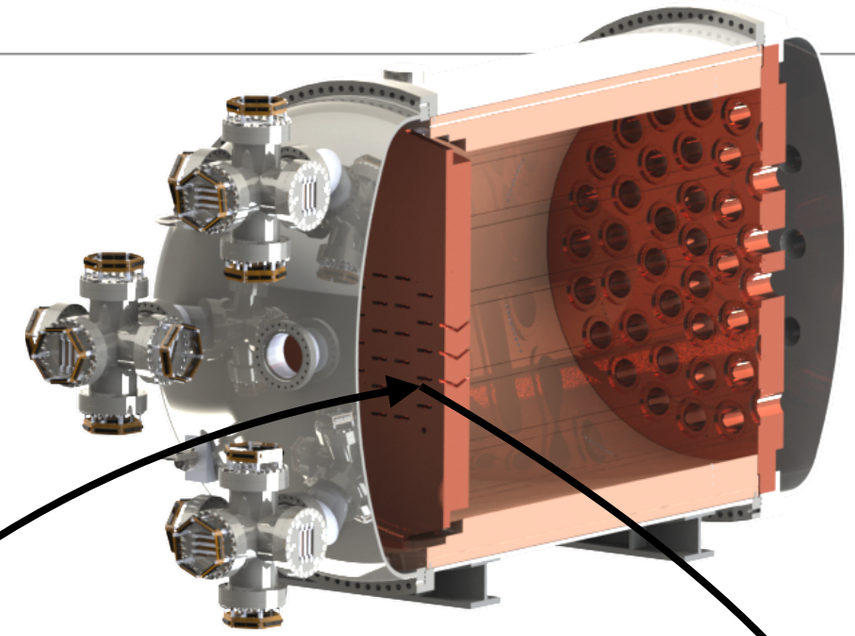
For example, the Kamioka experiment was commissioned in the early 80’s and in the 2000’s it has dramatically contributed to the discovery of neutrino oscillations.

NEXT Odyssey



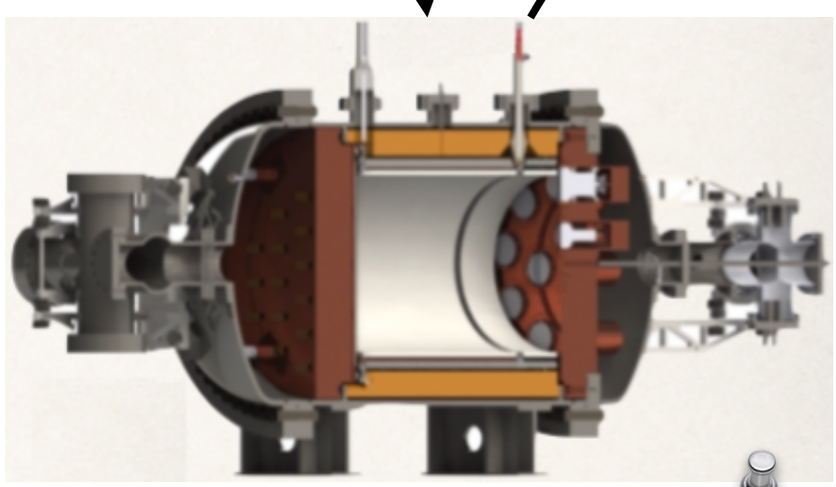
Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept



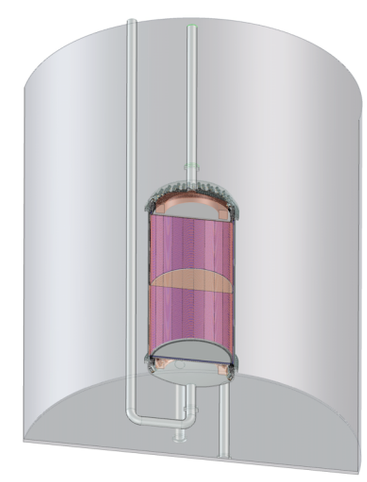
NEXT-100 (~100 kg)
[2019 - 2020's]

??



NEXT-NEW (~5 kg)
[2015 - 2018]

Underground and radio-pure operations, background, ββ2ν

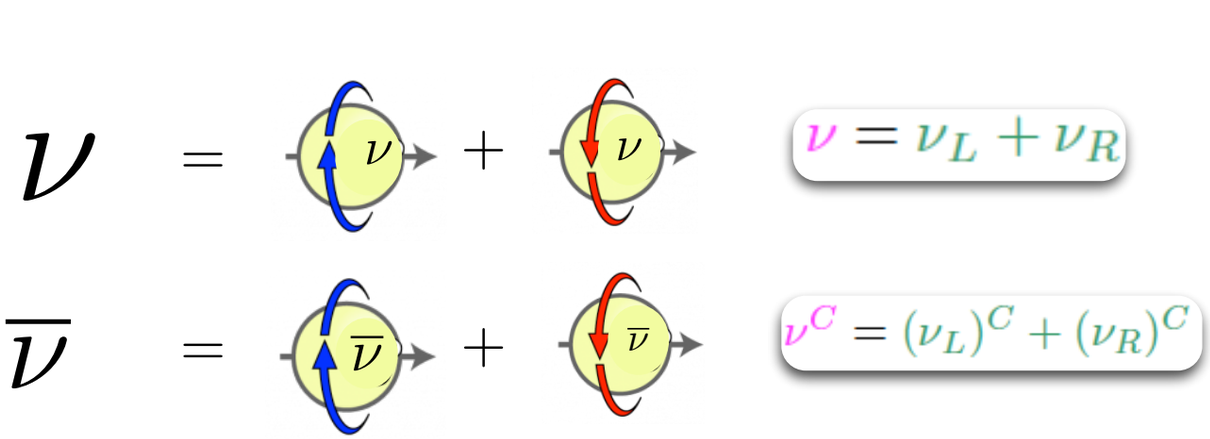


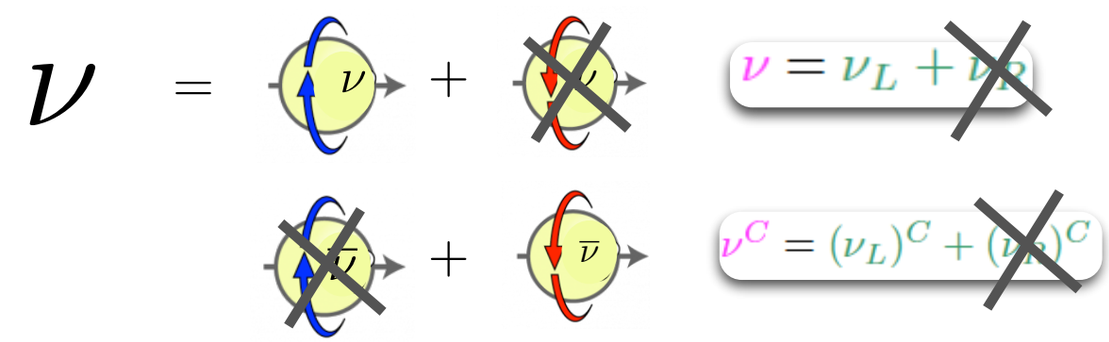
- (multi) ton mass
- ββ0ν search

Paris judgement

Why did Ulysses sail from Ithaca? Because Paris chose Aphrodite as the most beautiful of the Goddesses.

Paris judgement revisited





$\nu = \nu_L + \nu_L^C \qquad \nu^c = \nu$

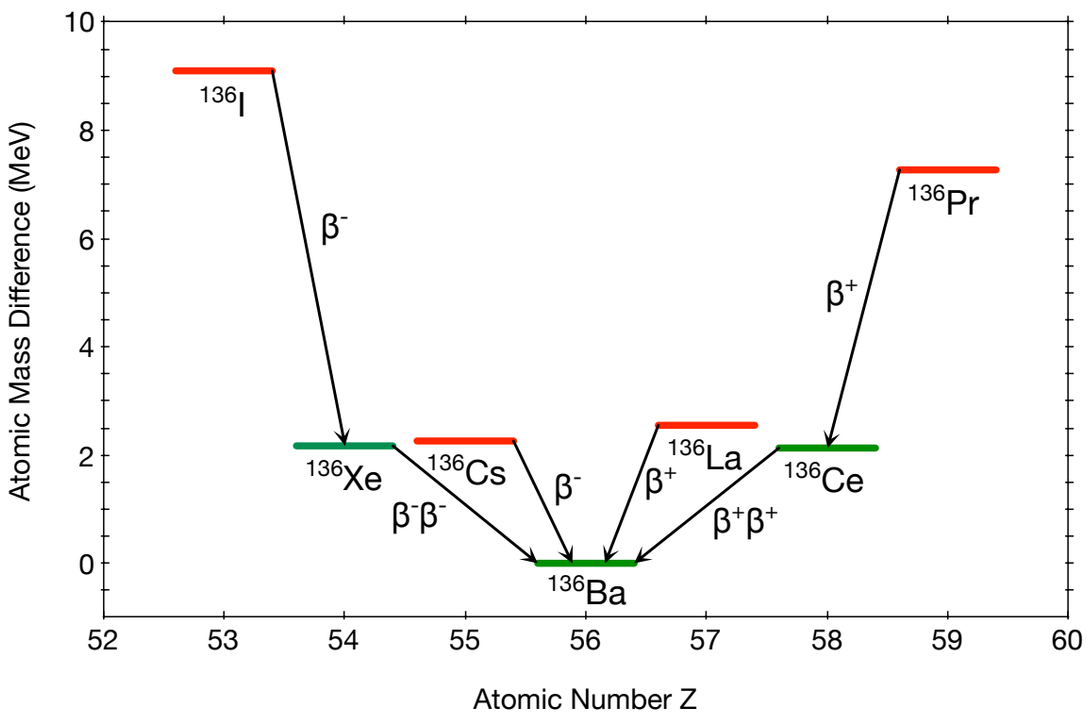
Are neutrinos their own antiparticles? Who gets the golden apple, Dirac or Majorana?

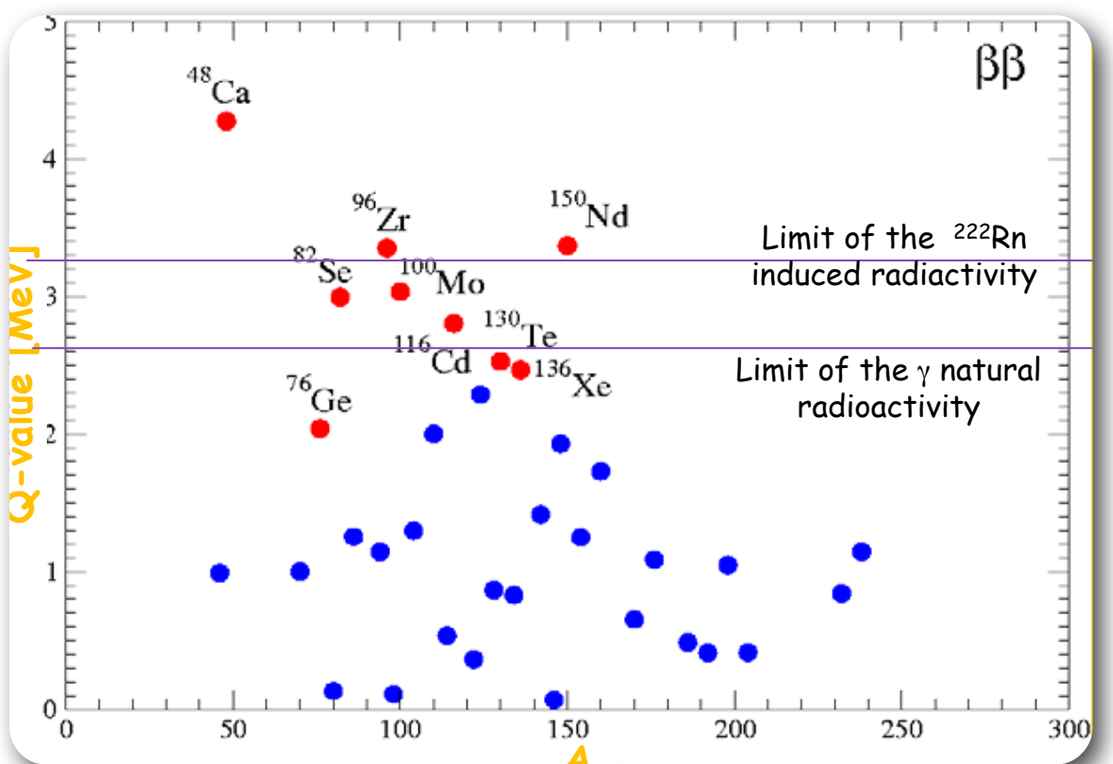
Setting sail...

Going to Troy
after Helena

Going underground after neutrinoless double beta decay.

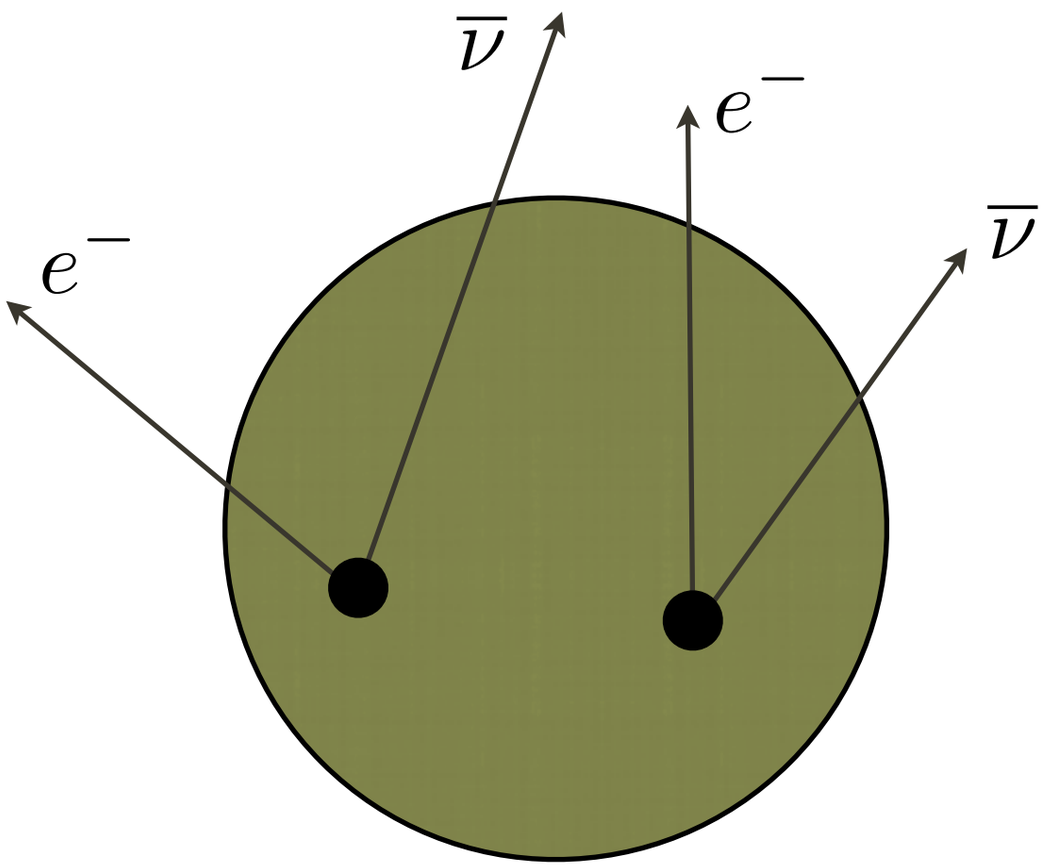
Double beta decay





- Some nuclei, otherwise quasi stable can decay by emitting two electrons and two neutrinos by a second order process mediated by the weak interaction.
- This process exists due to nuclear pairing interaction that favours energetically the even-even isobars over the odd-odd ones.

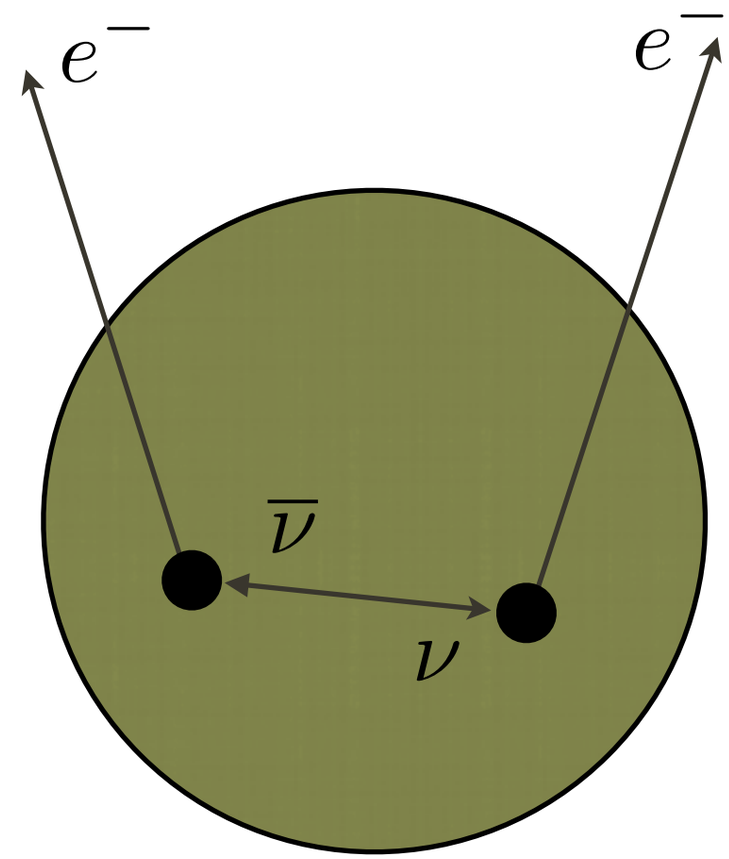
Double beta decay



$\beta\beta 2\nu$

SM-allowed process.
Measured in several nuclei.

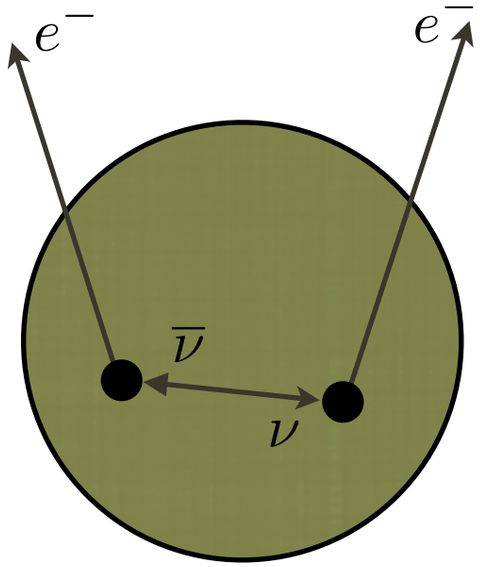
$$T_{1/2} \sim 10^{18} - 10^{20}\ \mathrm{y}$$



$\beta\beta 0\nu$

Lepton number violating process.
Requires massive, Majorana neutrinos.

$$T_{1/2} > 10^{25}\ \mathrm{y}$$



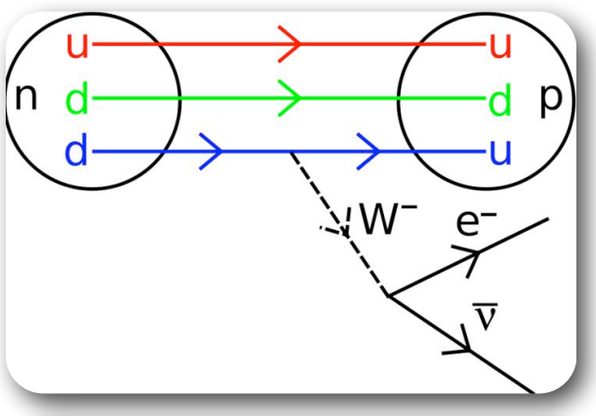
$\beta\beta0\nu$

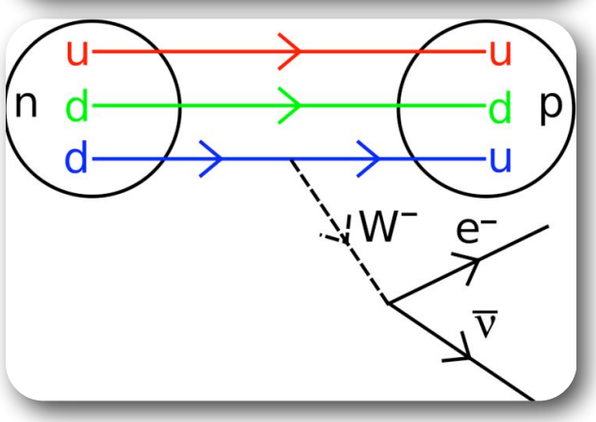
Nuclear physics

$$(T^{0\nu}_{1/2})^{-1} = \boxed{G^{0\nu}(Q,Z)}\,\boxed{|M^{0\nu}|^2}\,m^2_{\beta\beta}$$

phase-space

nuclear matrix

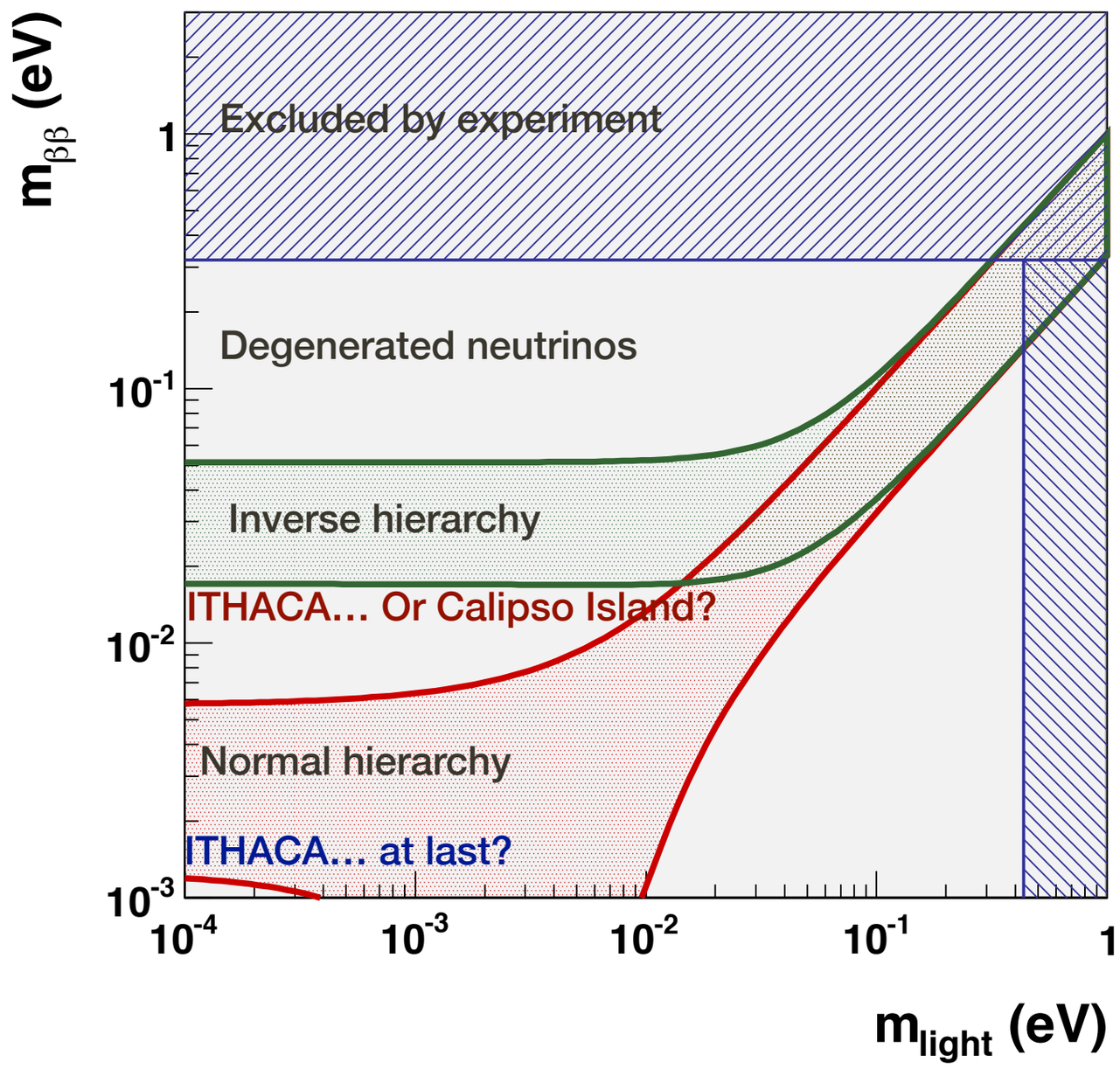




Majorana neutrino

Two protons decay simultaneously in a heavy isotope
Nuclear physics results in proportionality constants between period and the inverse of the Majorana mass squared

Sailing to Ithaca



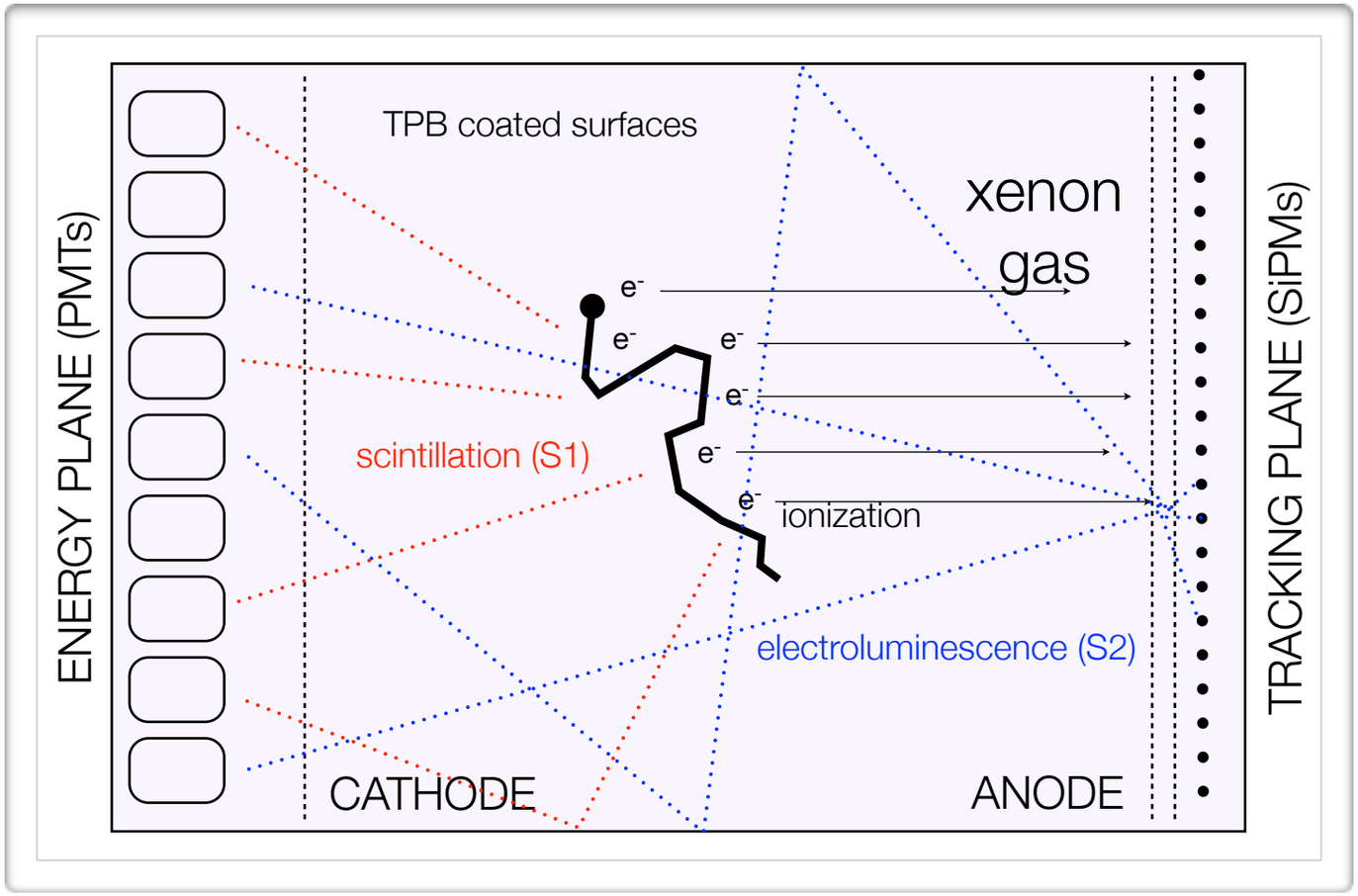
Cosmological limits and limits from previous bb0nu experiments included in this plot.

Inverse hierarchy: 20 — 50 meV (10^{26} y— 10^{27}y)

Normal hierarchy: 2 — 20 meV (10^{27} y— 10^{29} y)

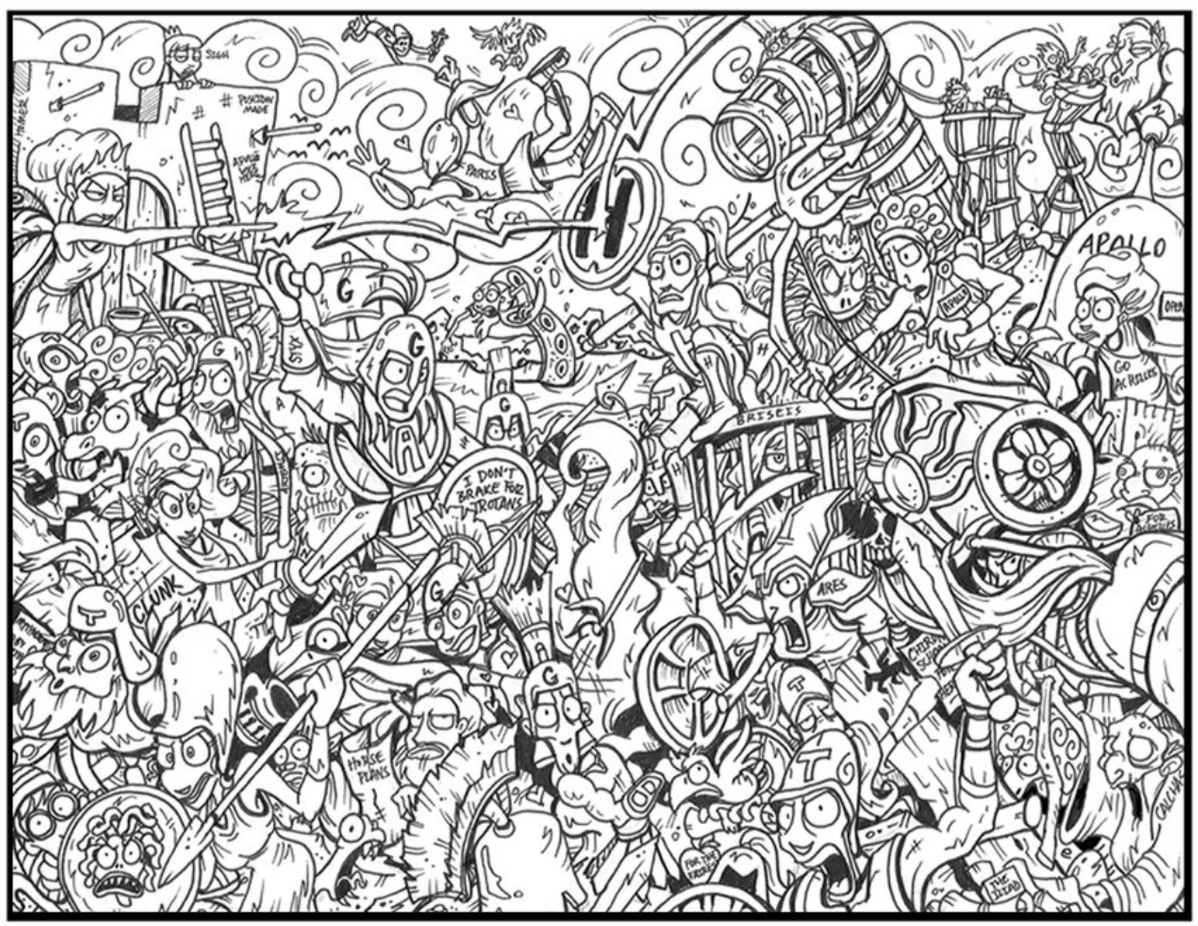
Nausicaa's beach

Every odyssey starts with a terrific idea



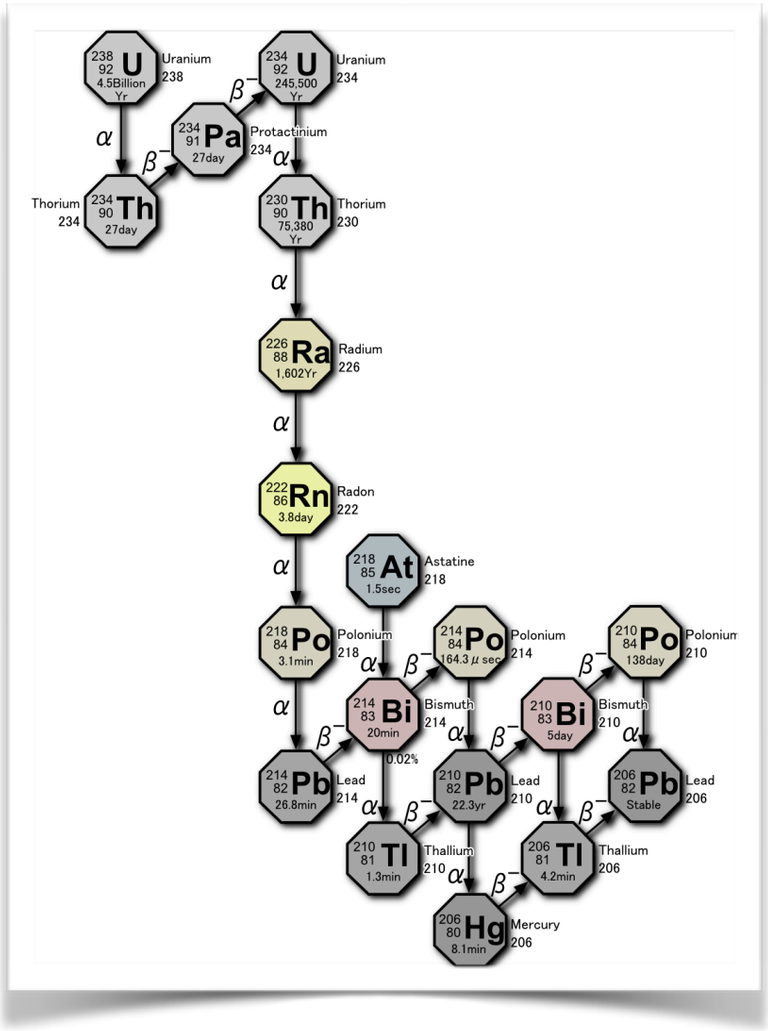
- A new device to conquer Troy
- A new device to search for ββ0ν

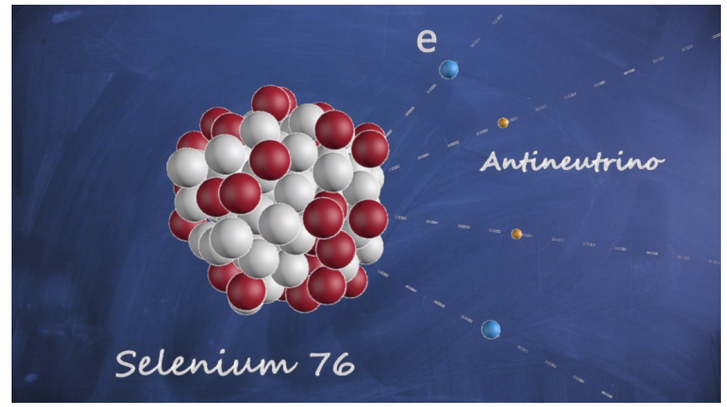
And utter ignorance of the upcoming complications…



ββ0ν searches

How hard is to reach Ithaca ?





Next generation of ββ0ν experiments aim to observe a signal whose lifetime is 10^{27} (10^{29}) y

Lifetime Bkgnd/Signal ~10^{17} (10^{19})

Earth is a very radioactive planet

Lifetime of Th-232 is of the oder of the age of the Universe (~1.4 10^{10} y)

Nausicaa's beach

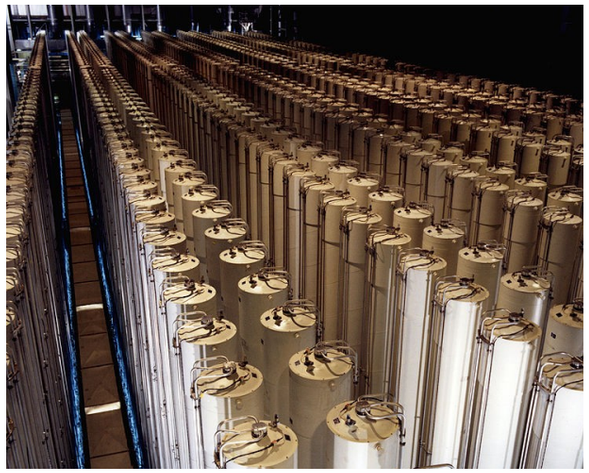
https://www.quora.com/How-many-grains-of-sand-are-there-in-a-given-stretch-of-an-average-beach

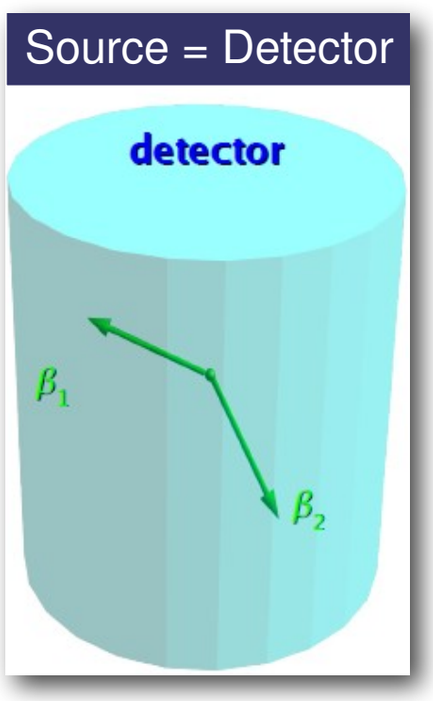
- Nausicaa's beach: A beach with 10^{17} grains of sand.
- About 1.5×10^{9} per square meter (to a depth of 3 m).
- Thus, Nausicaa's beach is 70 km long and 1 km wide.

The Achaeans

- Just as the greeks attacked Troy with many armies bb0nu experiments attack the search for neutrino less double beta decay with many experimental techniques.

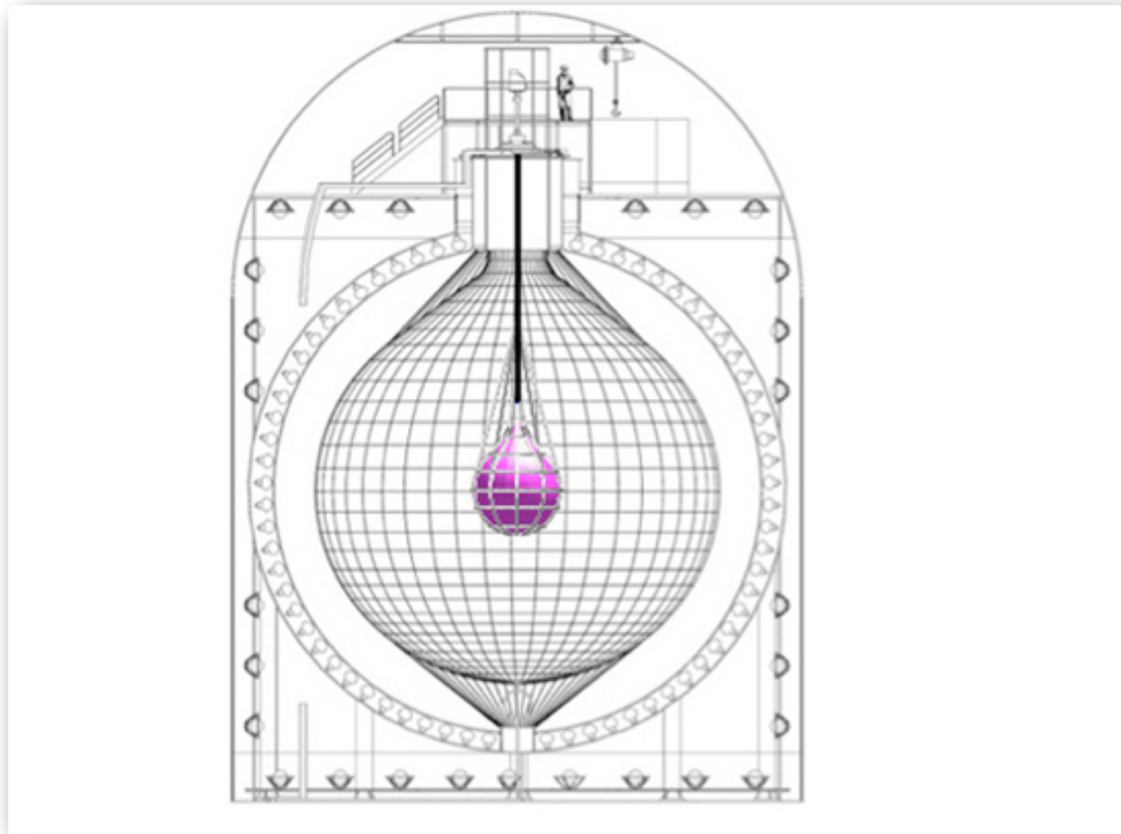
Why Xenon?

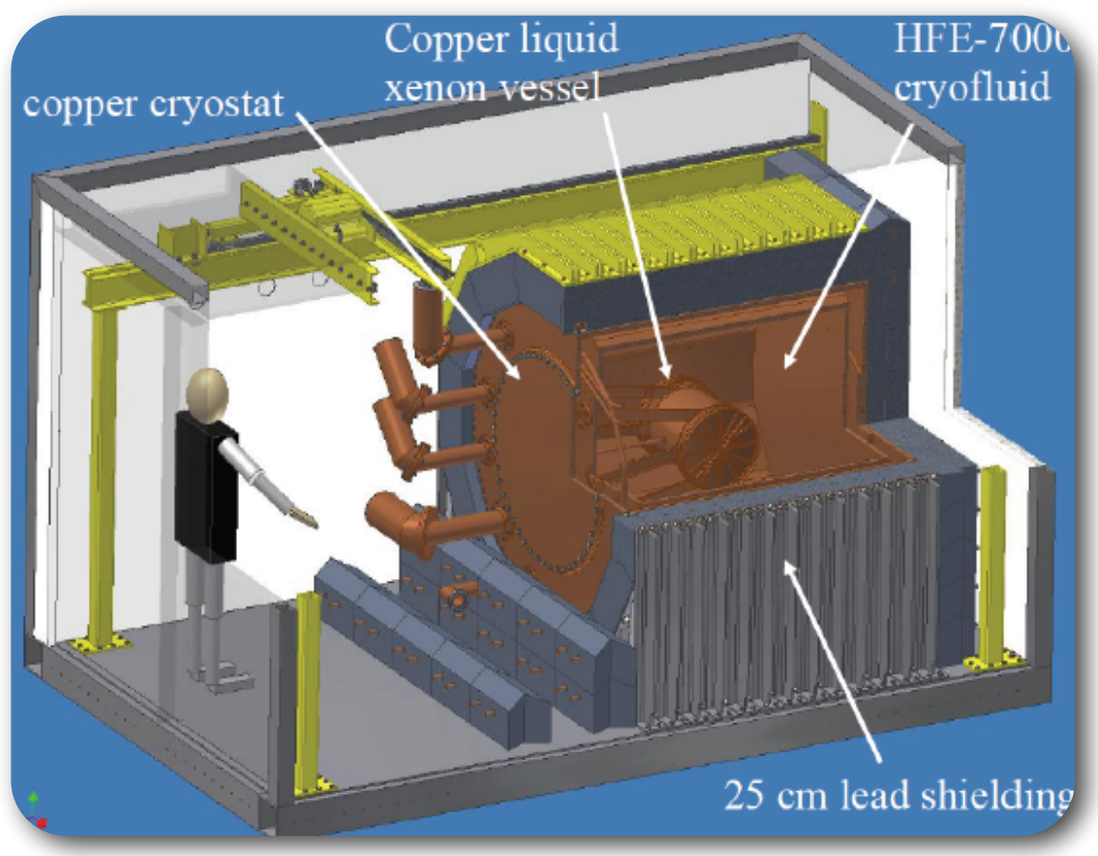




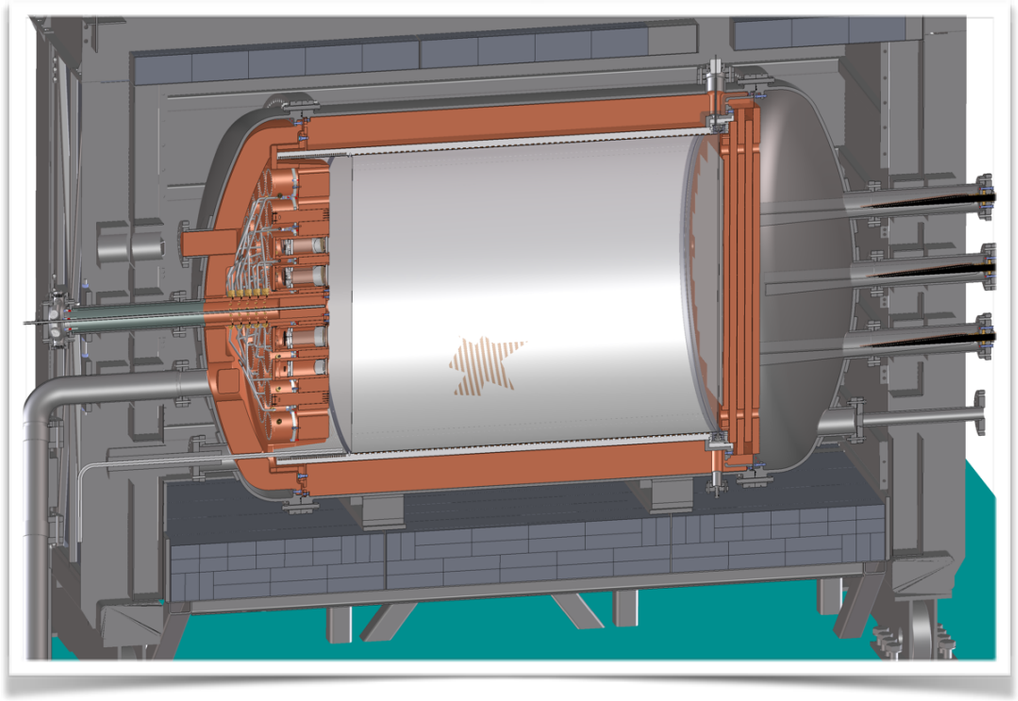
- It is a noble gas, thus ideally suited for detection (TPC, calorimetry).
- source = detector, thus scalability.
- It has no long-lived radioactive isotopes.
- It has two interesting isotopes, Xe-136 (bb0nu) and Xe-124 (2-e capture). The natural abundance of Xe-136 is OK (10%), and most importantly, being the heaviest isotope is easy (cheap) to produce enriched Xenon.
- Nuclear matrix elements, phase space and Qbb, OK.

- **There is already 1 ton of enriched Xenon in the World (mostly own by KZ)**

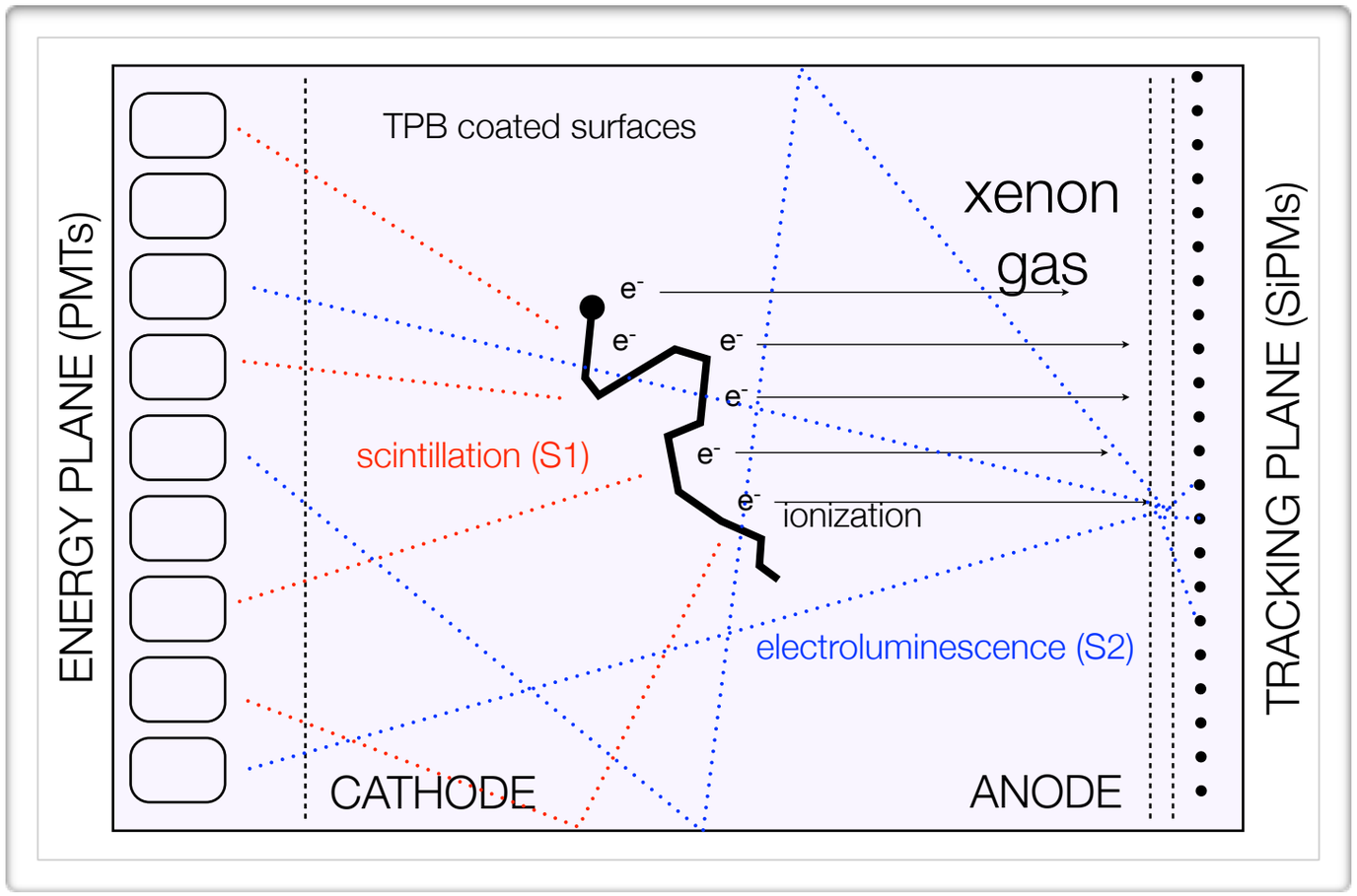



copper cryostat
Copper liquid
xenon vessel
HFE-7000
cryofluid
25 cm lead shielding

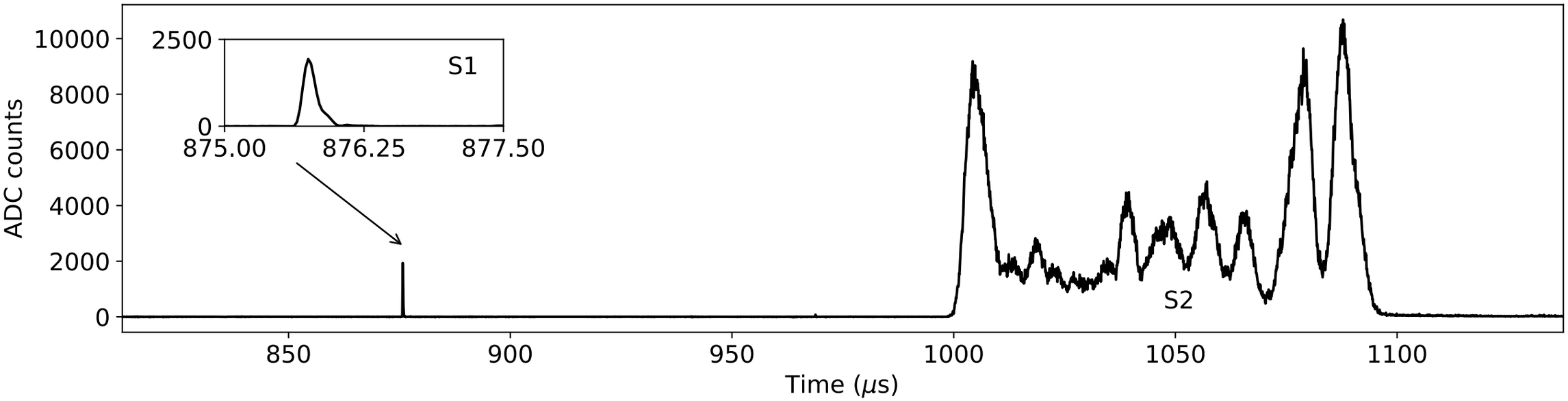
Meet Odysseus

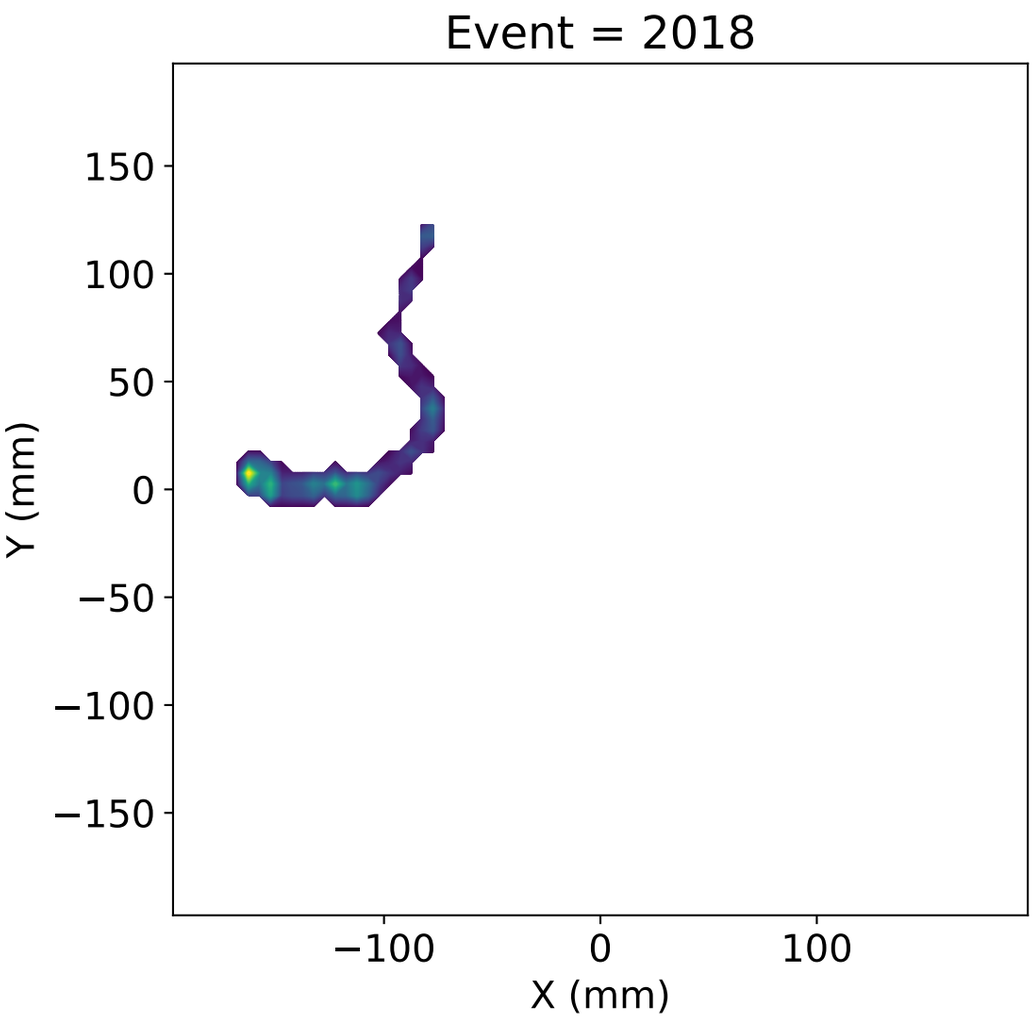


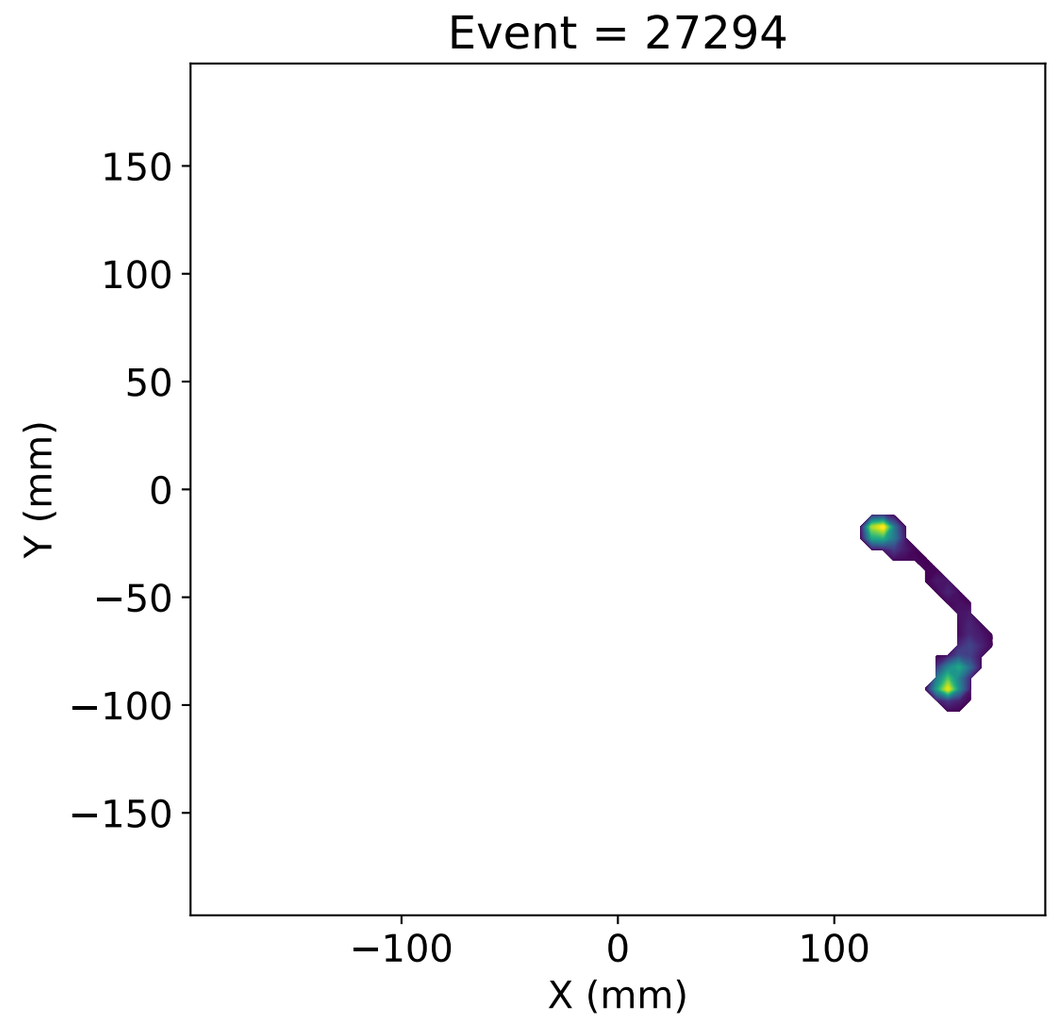
The NEXT concept



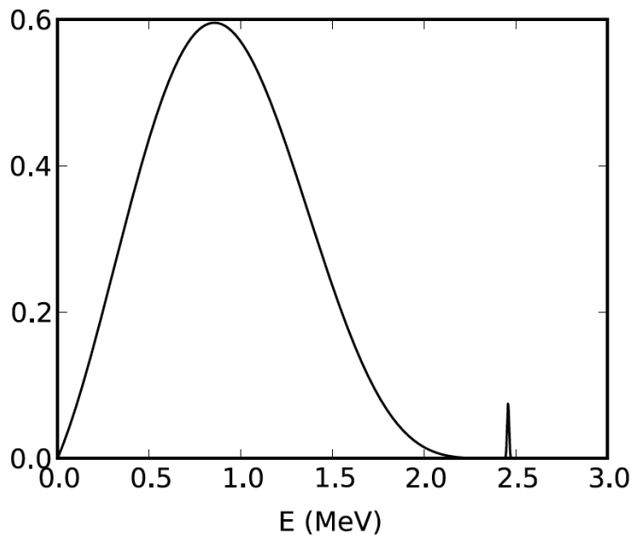
- High Pressure Xenon TPC (operation 10-20 bar)
- EL amplification to achieve excellent energy resolution (~0.5 % FWHM appears possible)
- Topological signature (observation of two electrons) to further suppress the backgrounds.
- Is built with radio pure materials.

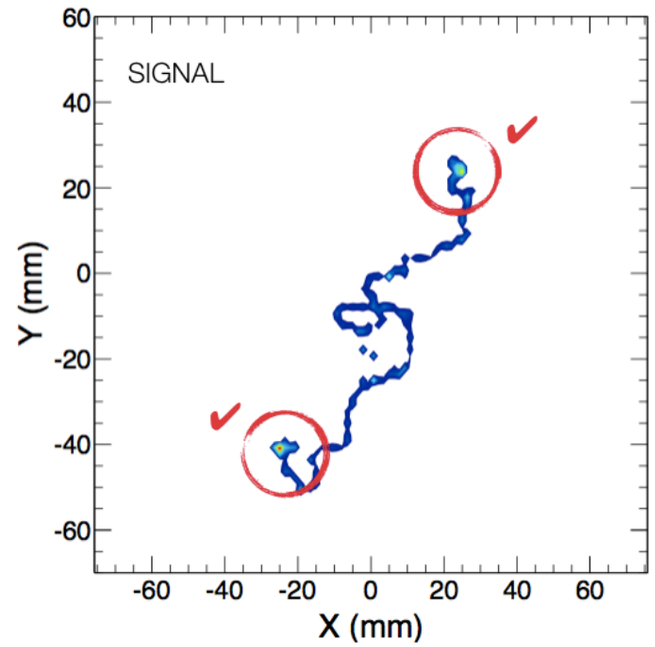

ADC counts
10000
8000
6000
4000
2000
0
2500
0
875.00
876.25
877.50
S1
S2
850
900
950
1000
1050
1100
Time (μs)

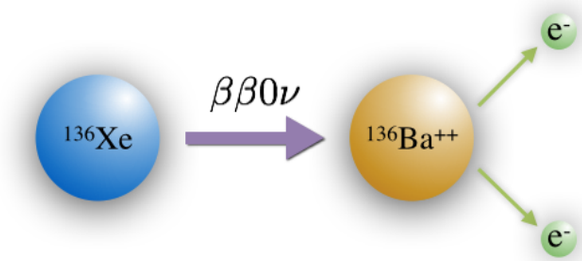

Event = 2018
150
100
50
0
−50
−100
−150
Y (mm)
−100
0
100
X (mm)

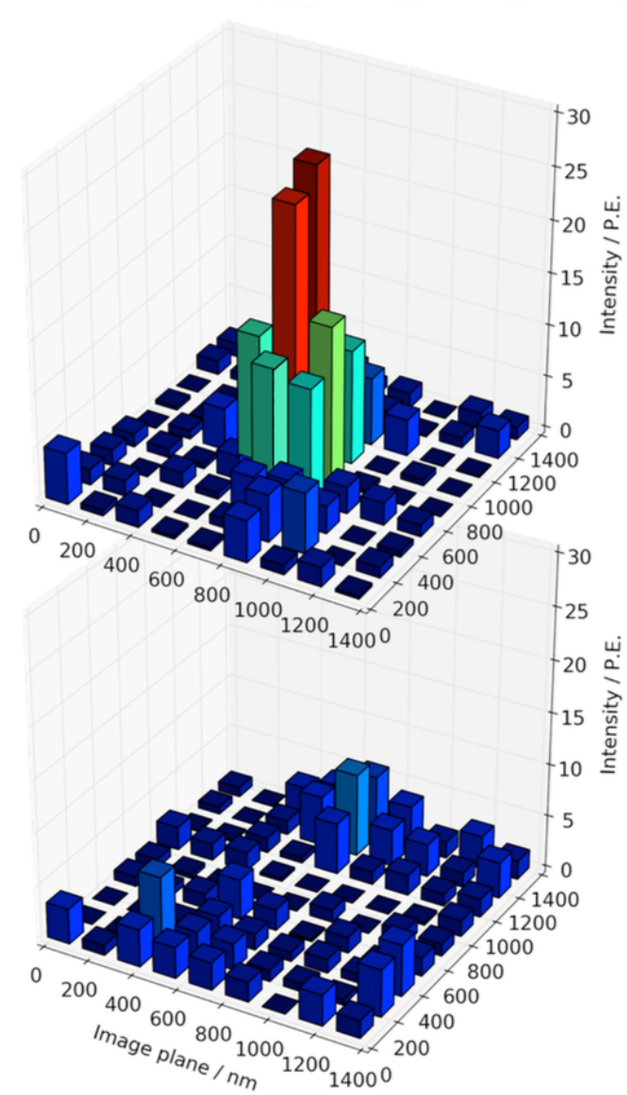

Event = 27294
150
100
50
0
−50
−100
−150
Y (mm)
−100
0
100
X (mm)

Advantages of HPX-EL technology

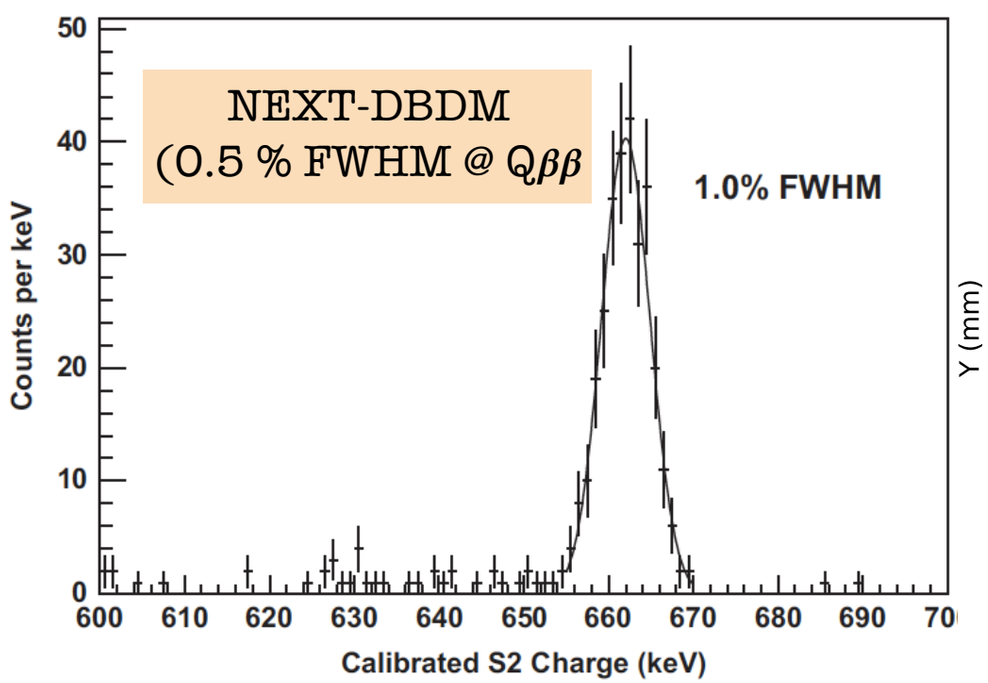


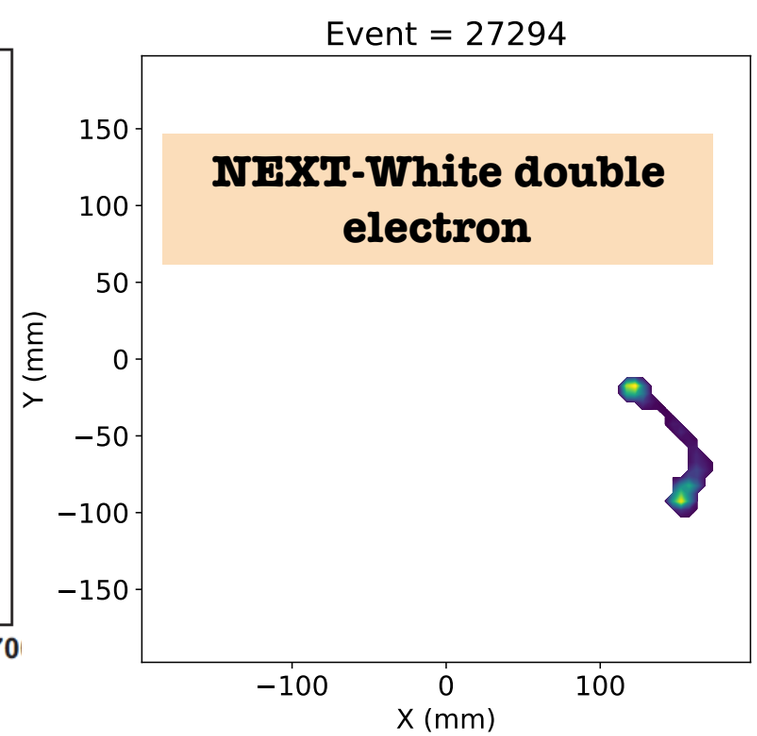






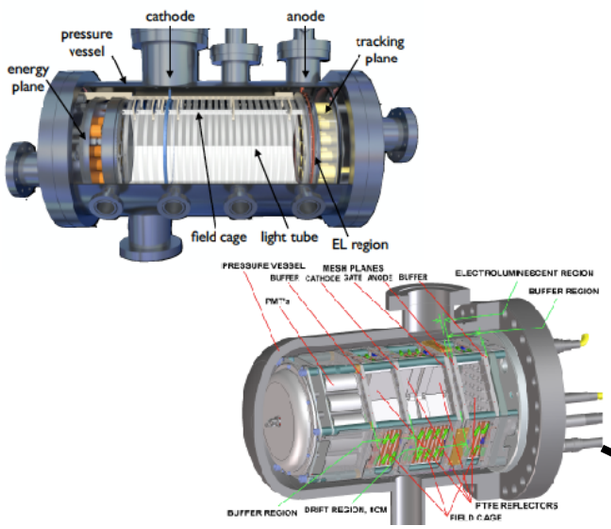
NIM A708. 101 (2014) [arXiv:1211.4474]





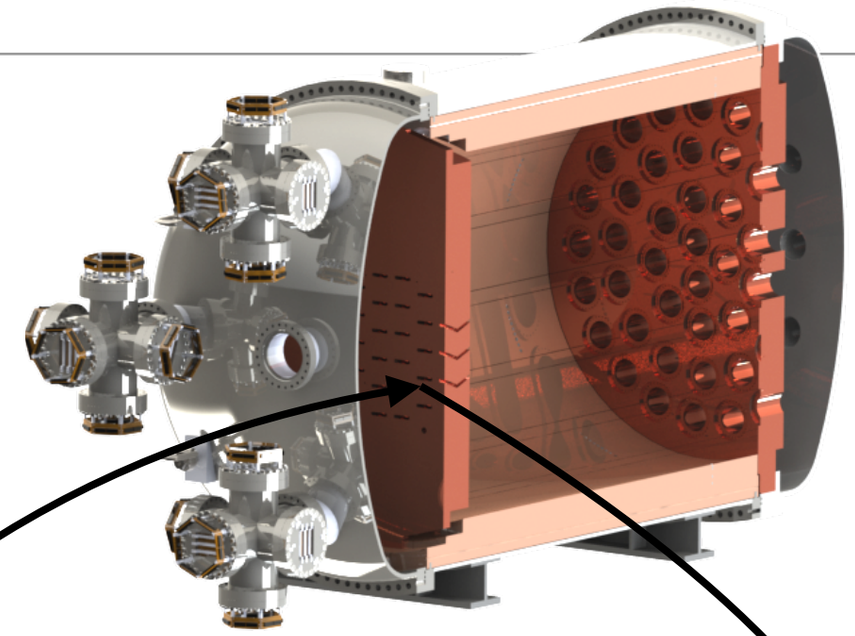
Electroluminescent High pressure Xenon gas optical TPC

NEXT phases



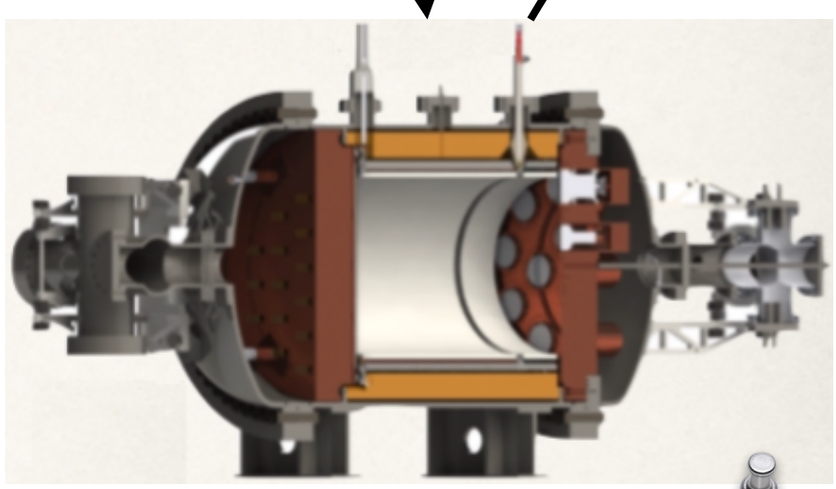
Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept



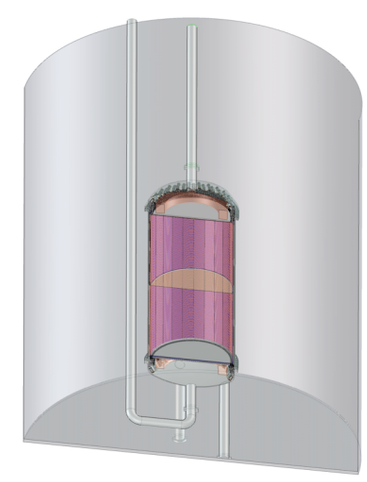
NEXT-100 (~100 kg)
[2019 - 2020's]

??



NEXT-NEW (~5 kg)
[2015 - 2018]

Underground and radio-pure operations, background, ββ2ν



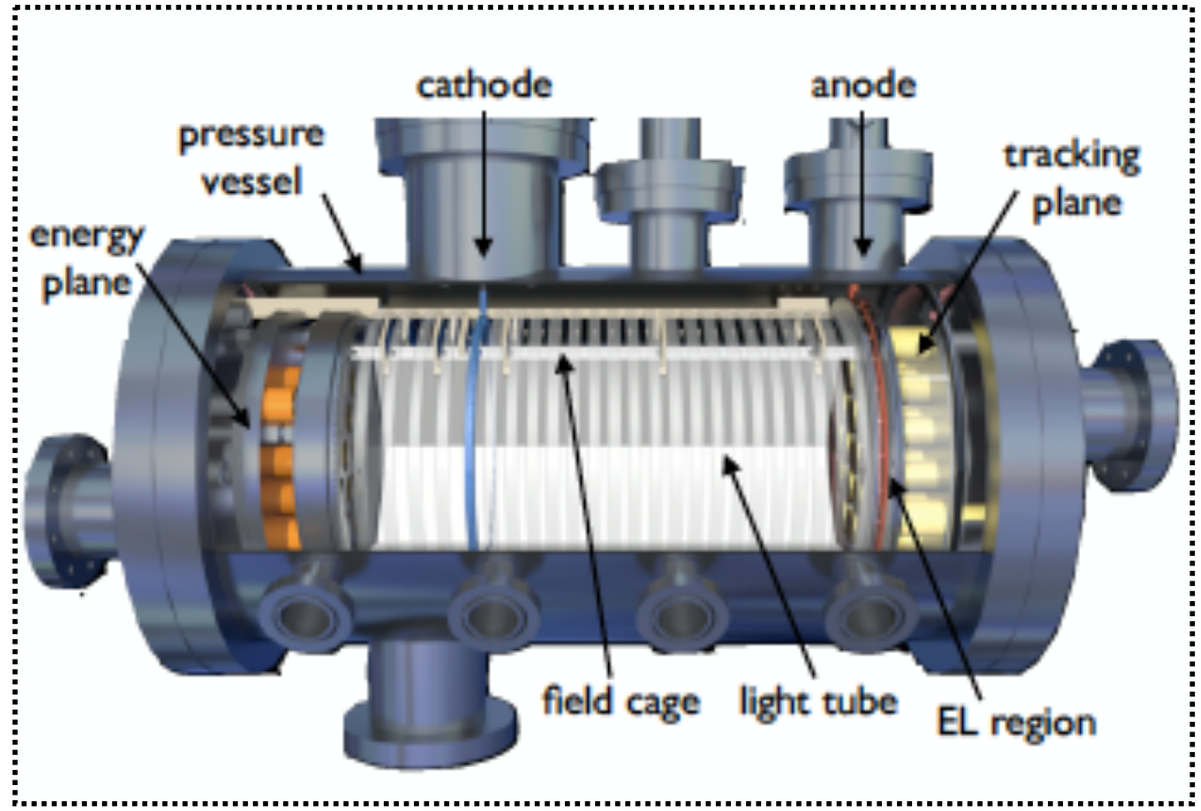
- (multi) ton mass
- ββ0ν search

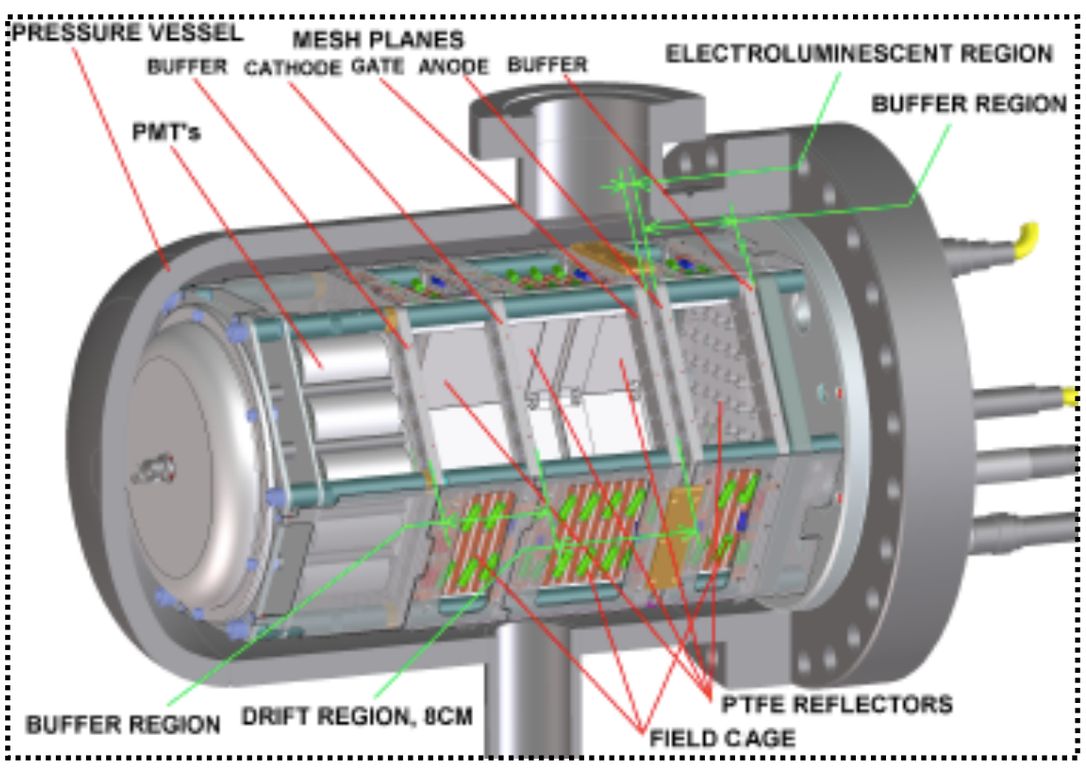
NEXT Prototypes

NEXT-DEMO (IFIC)

- Energy resolution (19 1” PMTs)
- Tracking (256 SiPMs)
- ~1.5 kg Xe gas at 10 bar

Publications: **JHEP 01, 104 (2016) [arXiv:1507.05902]**
JINST 10, P03025 (2015) [arXiv:1412.3573]
JINST 9, P10007 (2014) [arXiv:1407.3966]
JINST 8, P04002 (2013) [arXiv:1211.4838]
JINST 8, P05025 (2013) [arXiv:1211.4508]
JINST 8, P09011 (2013) [arXiv:1306.0471]



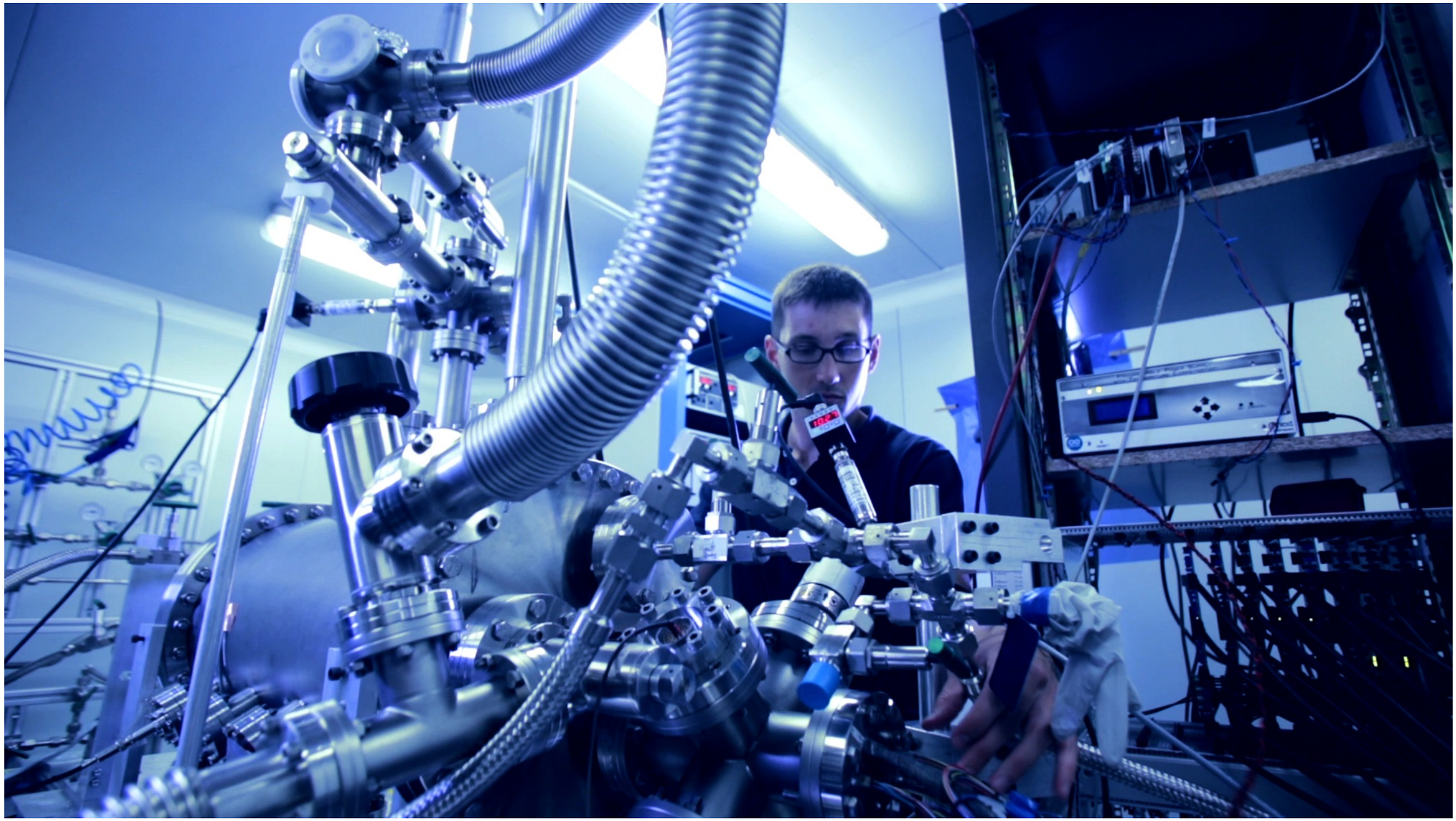


NEXT-DBDM (LBNL)

- Energy resolution (19 1” PMTs)
- ~1 kg Xe gas at 10-15 bar
- Also measured response of HPXe to nuclear recoils

Publications: **NIMA 793, 62 (2015) [arXiv:1409.2853]**
NIMA 708, 101 (2013) [arXiv:1211.4474]

A young Odysseus…

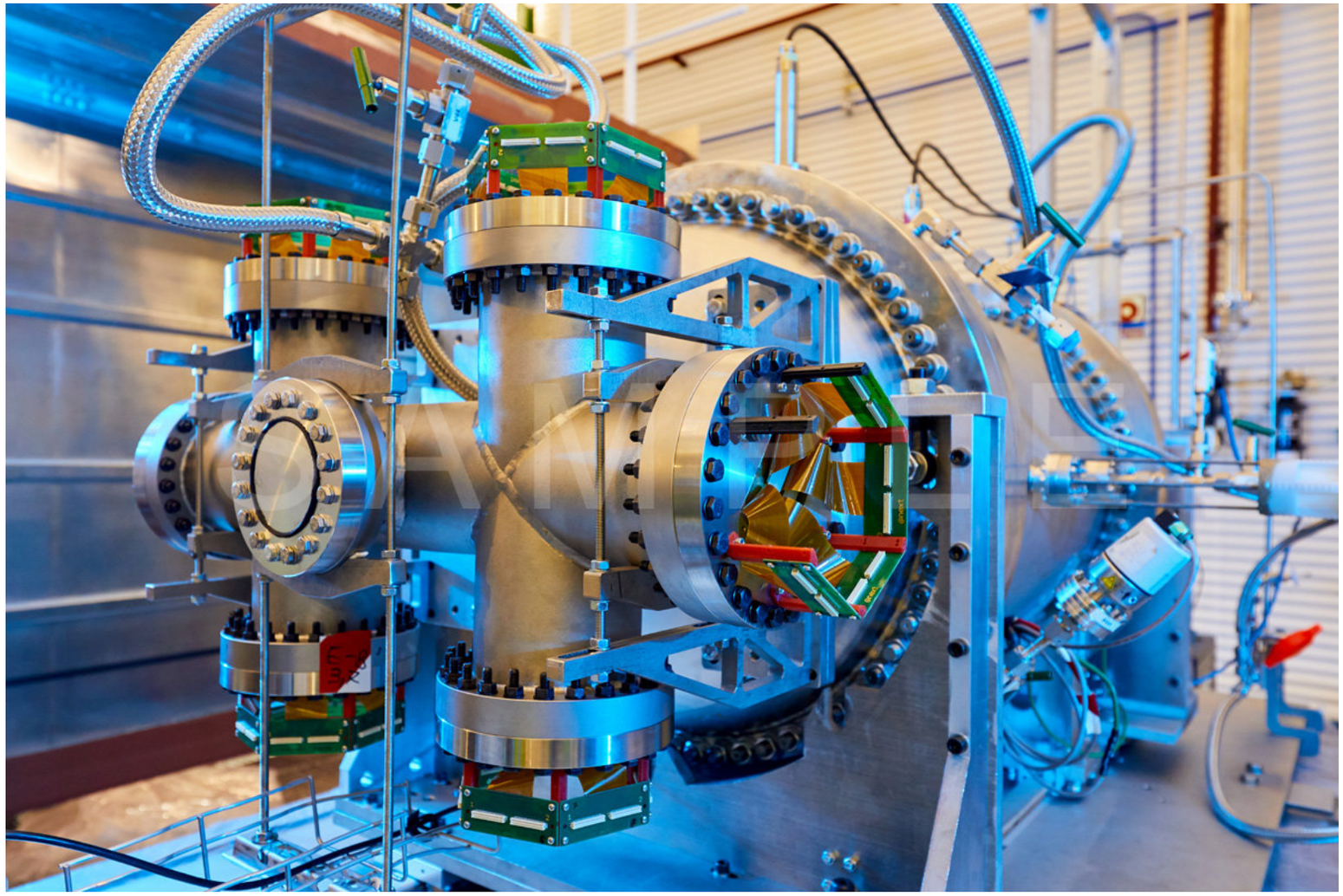


NEXT-DEMO: Started in 2011, first HPXeEL in the World.

A few years later…

NEXT-White: Already operating at the LSC

NEXT-White



- Scaled version (1:2 in longitudinal dimensions) of NEXT-100
- Technology development, radio purity, setting up infrastructures (shielding, gas system)
- Measures energy resolution, topological signature, background index, bb2nu mode.

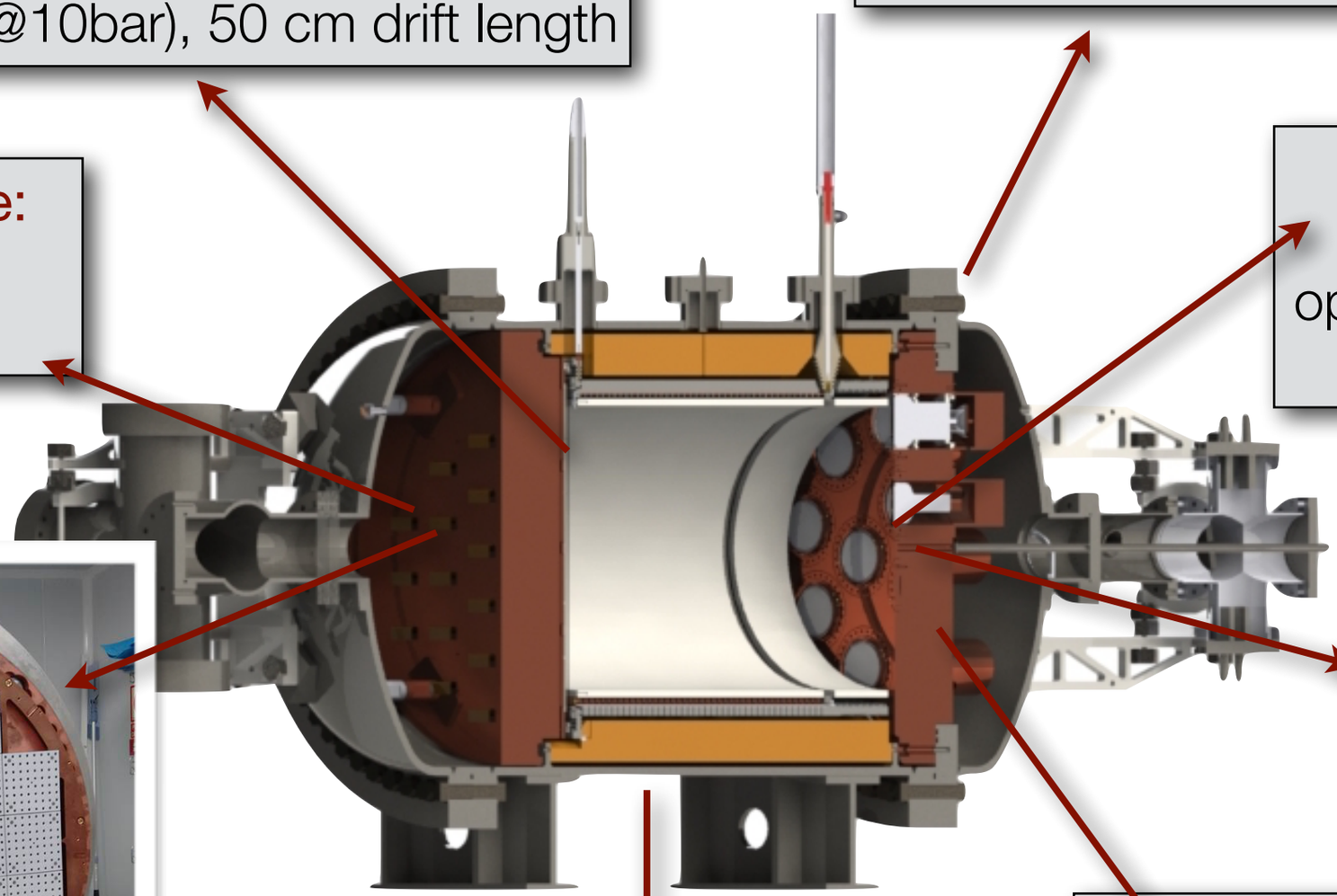
NEW (NEXT-WHITE) at glance

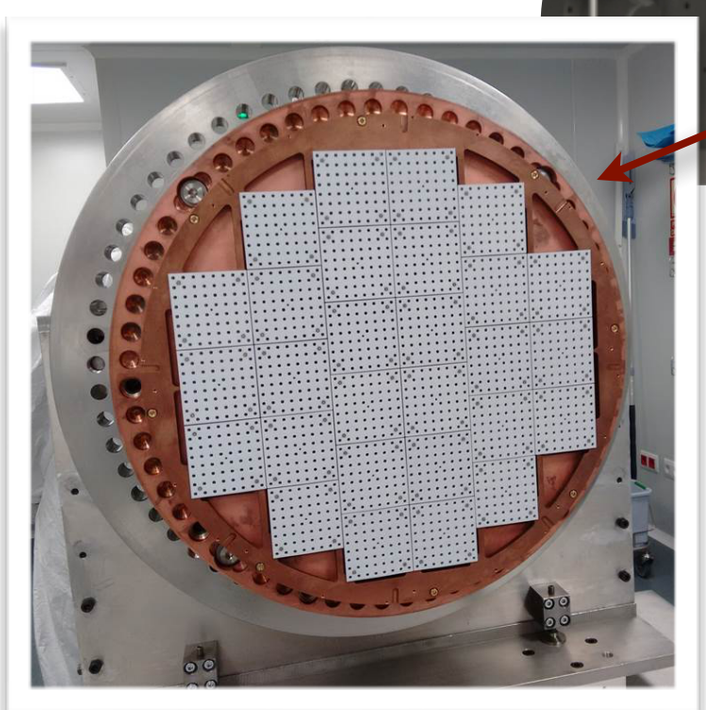
Time Projection Chamber:
5 kg active region(@10bar), 50 cm drift length

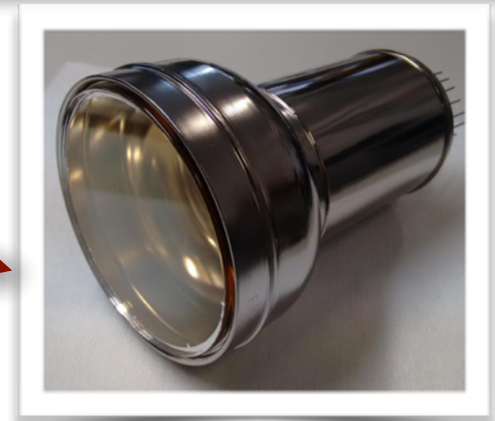
Pressure vessel:
316-Ti steel, 30 bar max pressure

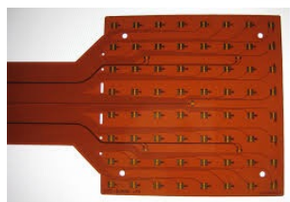
Tracking plane:
1792 SiPMs,
1 cm pitch

Energy plane:
12 PMTs,
operating at vacuum.
30% coverage





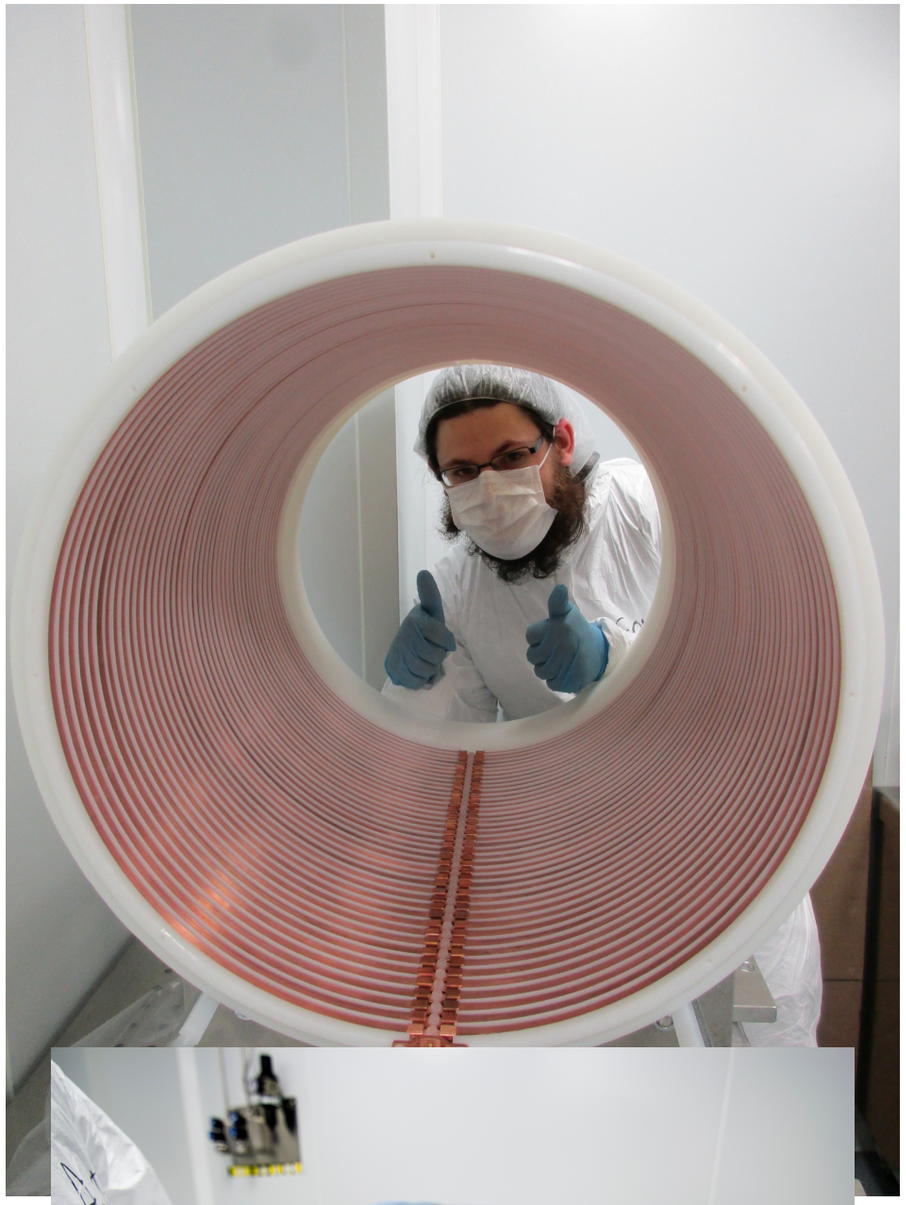


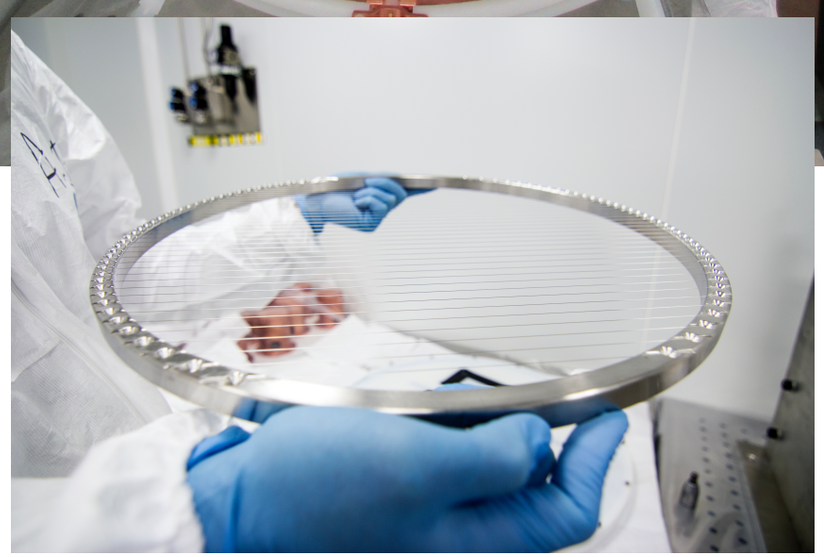


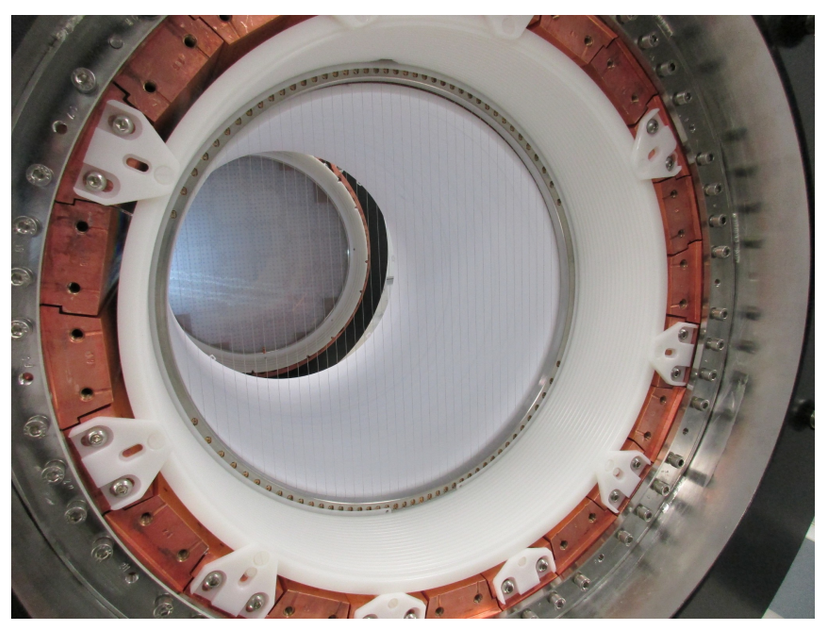
Inner shield:
copper, 6 cm thick

Mother can:
12 cm copper plate that separates pressure from vacuum and ads shielding.

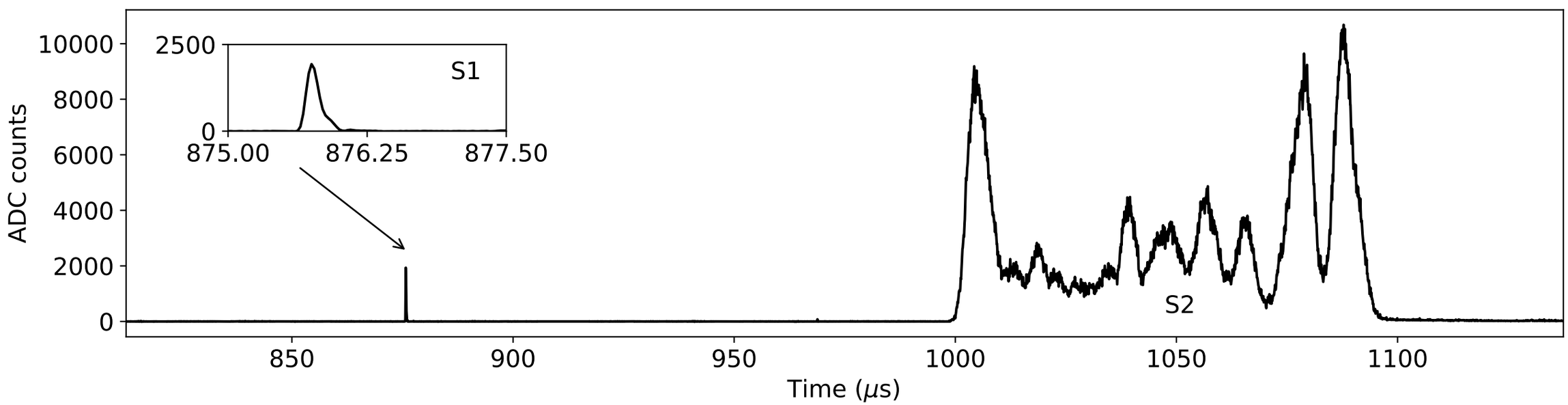
Field cage



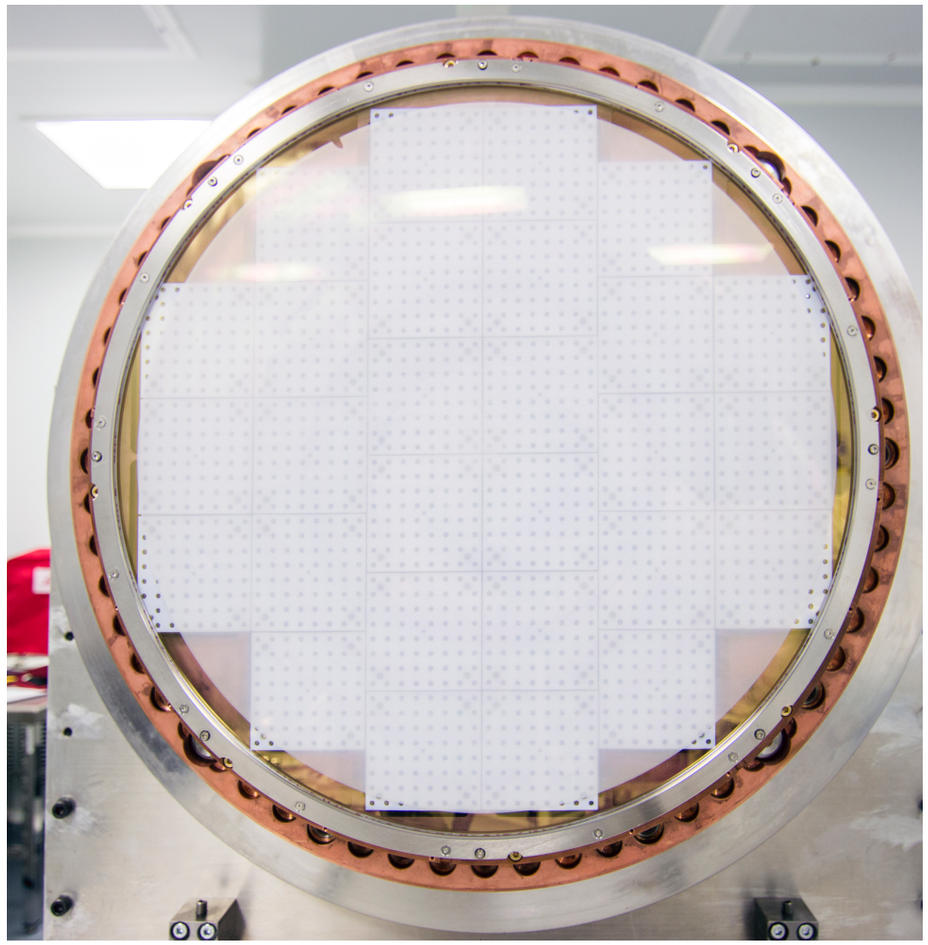


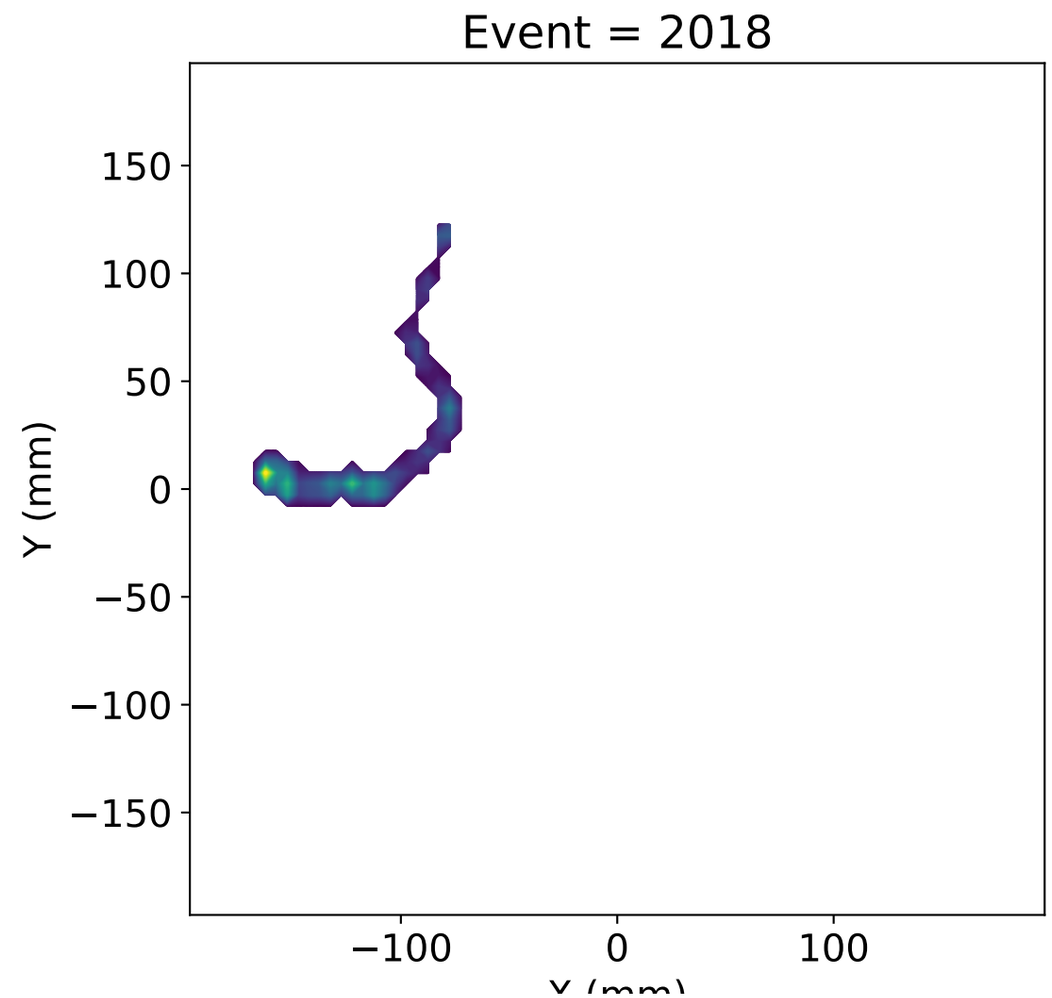


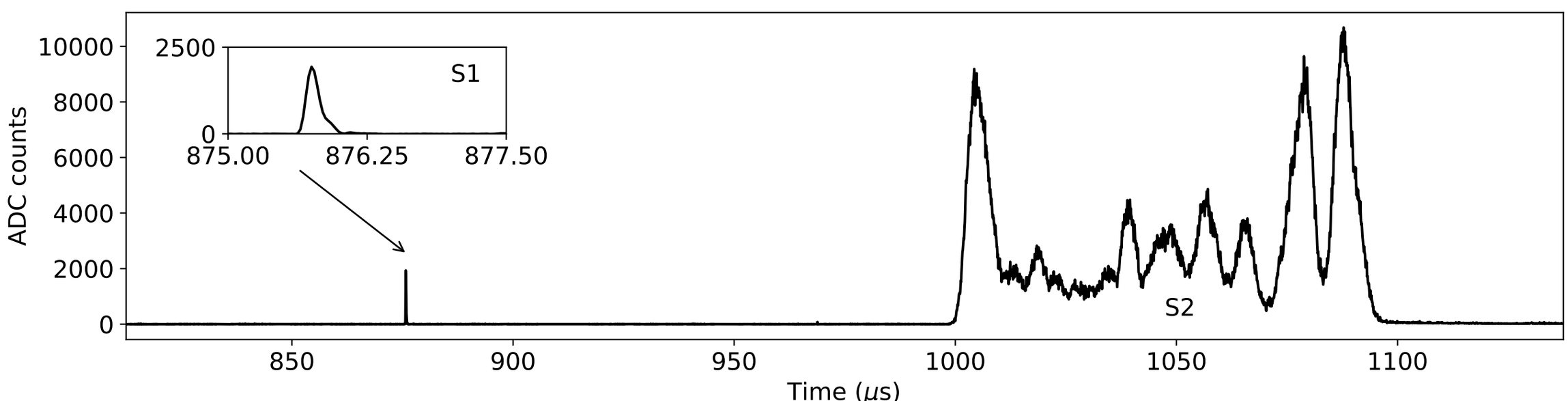
Energy plane



Tracking plane





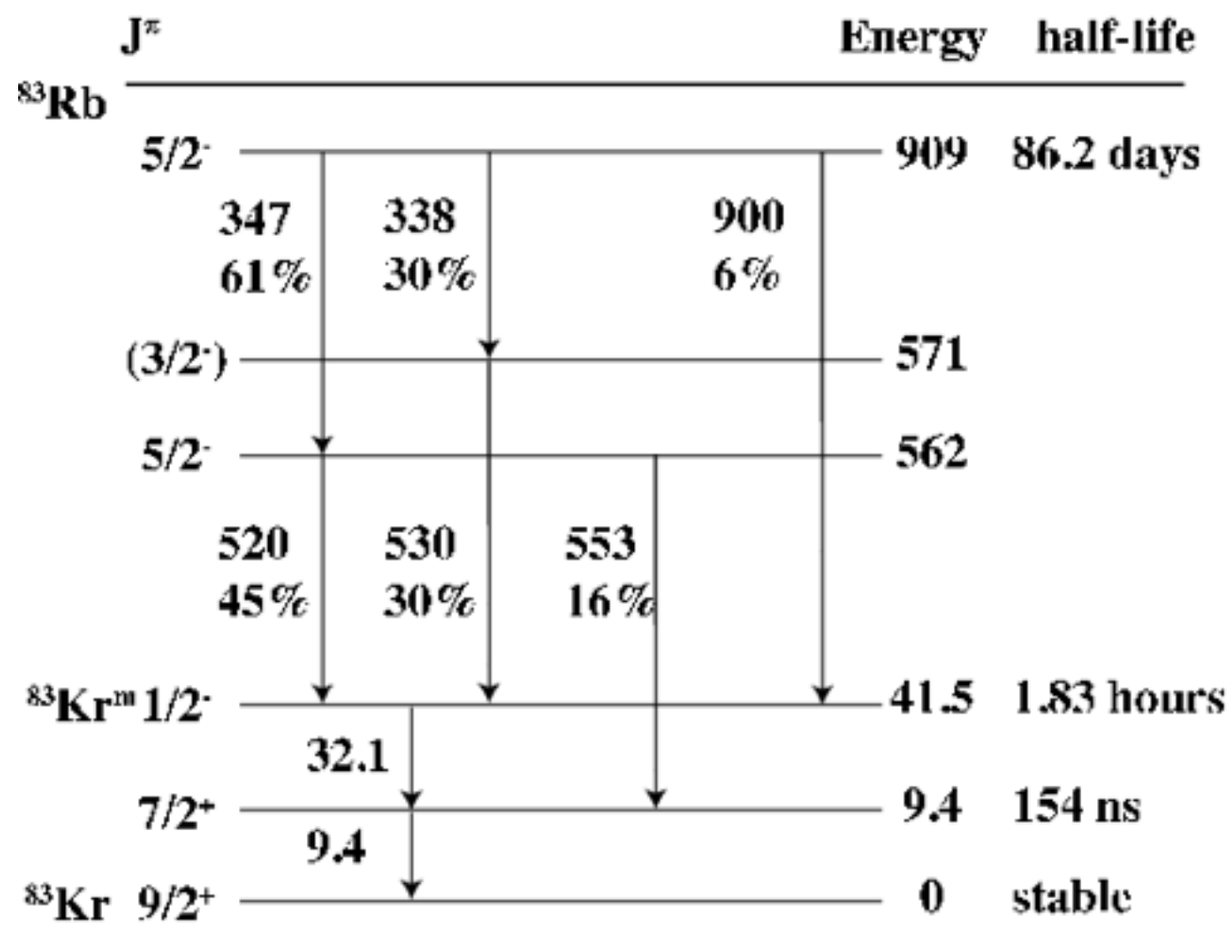


LSC (Huesca, Spain)

NEW at the LSC

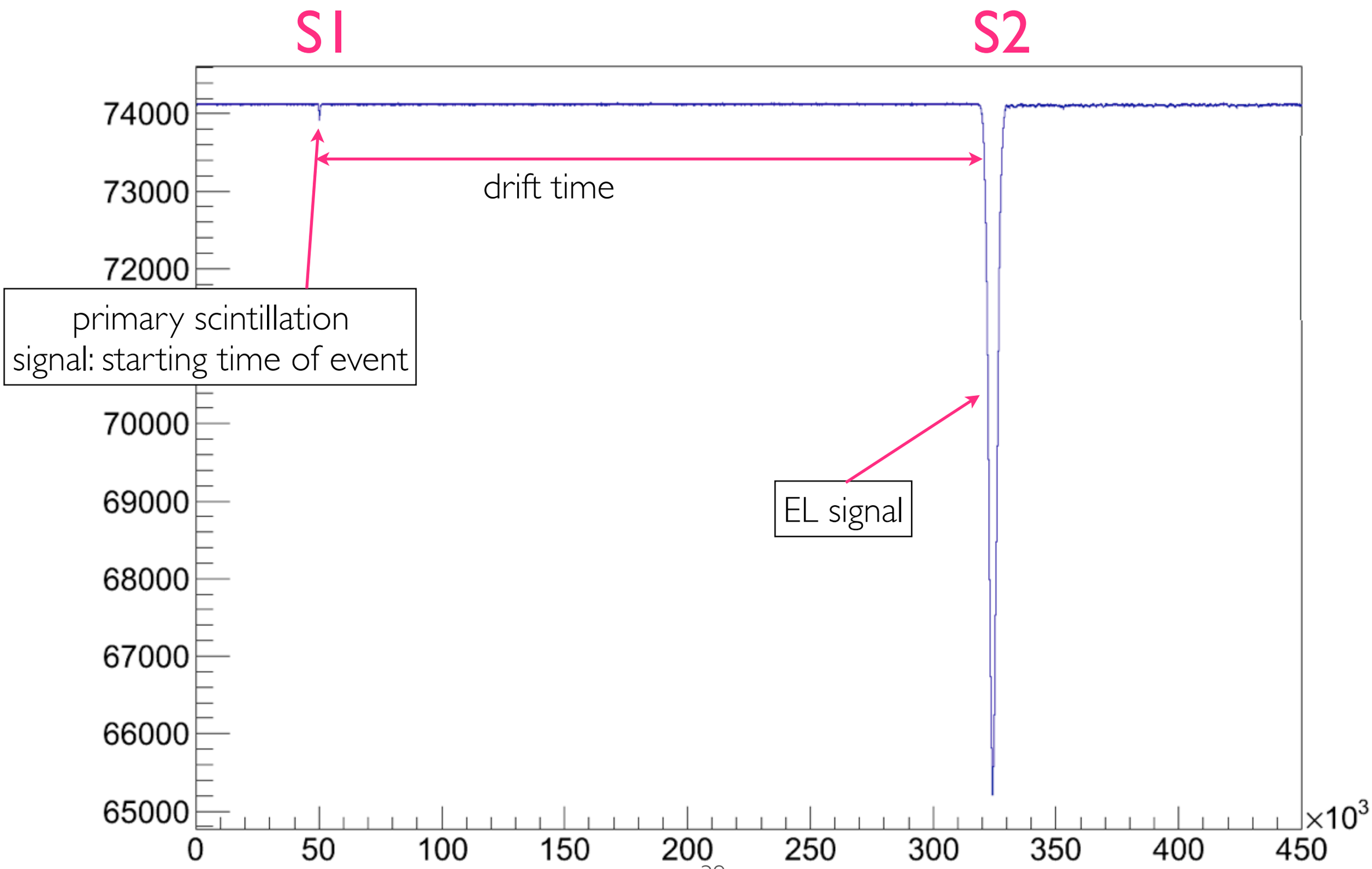
$^{83}Kr^{m}$ as calibration source

- ^{83}Rb decays 75% of the time to a metastable state of ^{83}Kr through internal conversion with a lifetime of 86 days.
- The metastable state decays to ground with a lifetime of 1.83 h emitting two conversion electrons of 32.1 and 9.4 keV.
- These low energy electrons create a very short signal, useful for calibration.

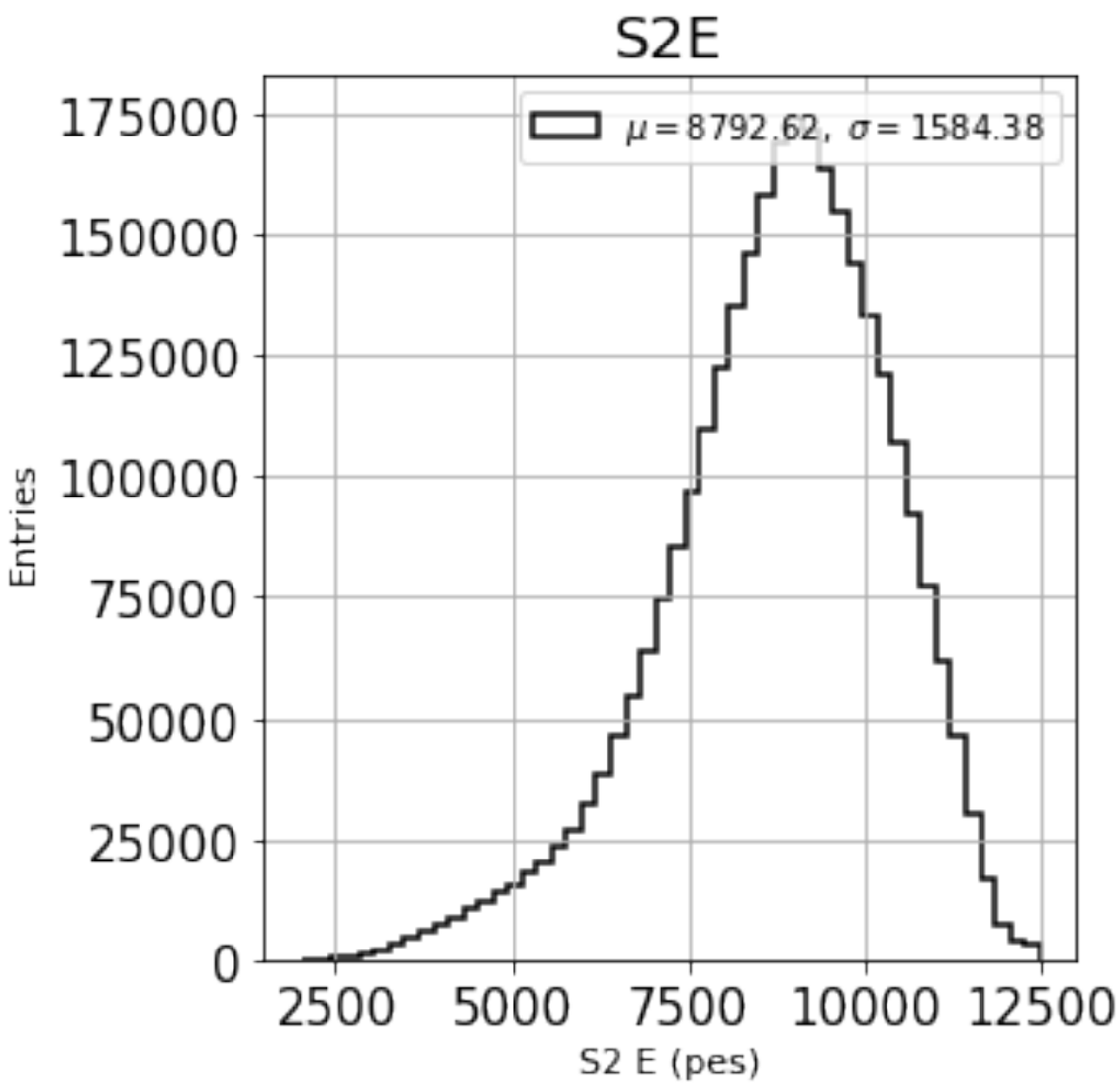


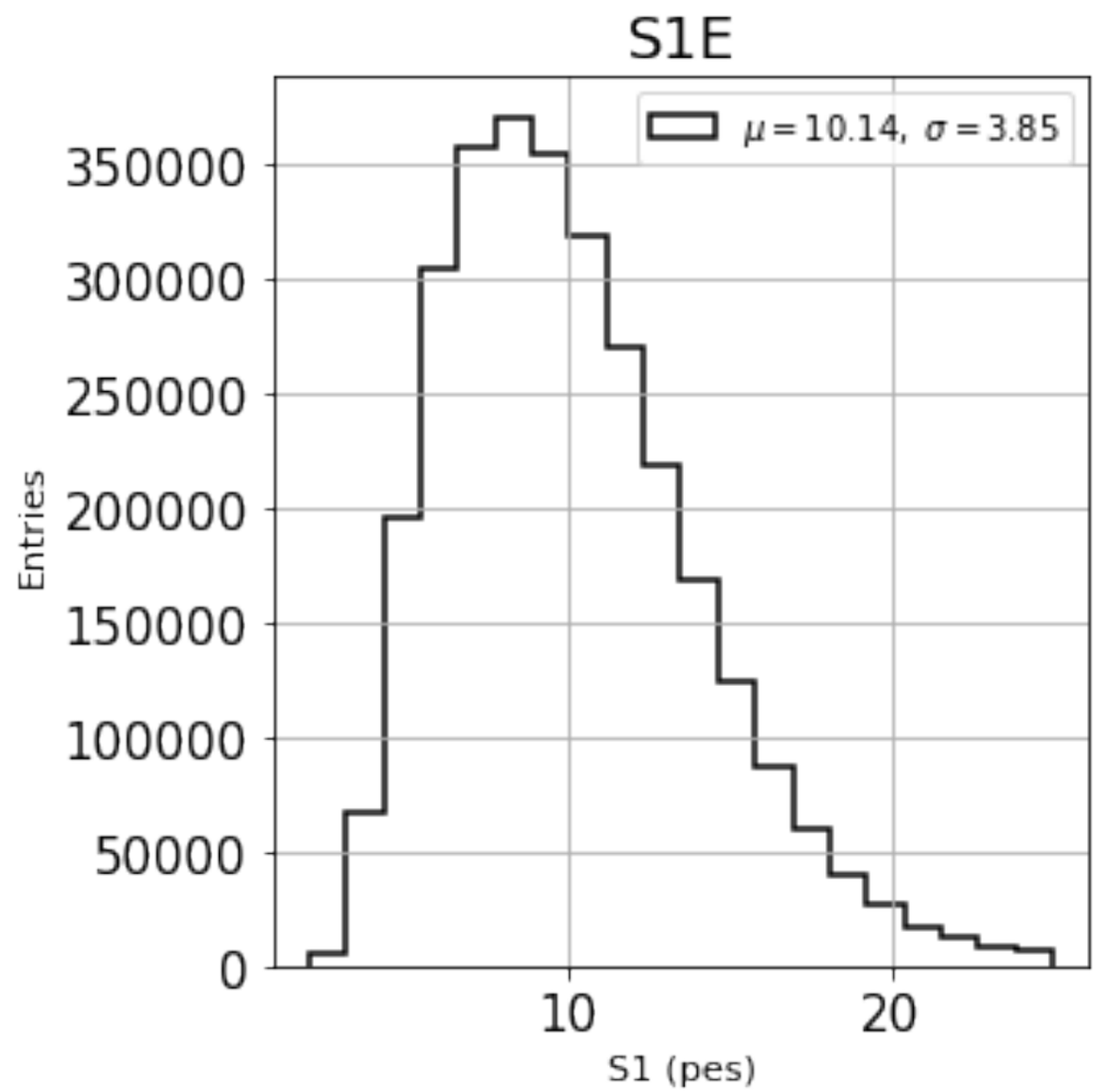
With these events we can map the light collection along X, Y and Z.

Kripton waveforms

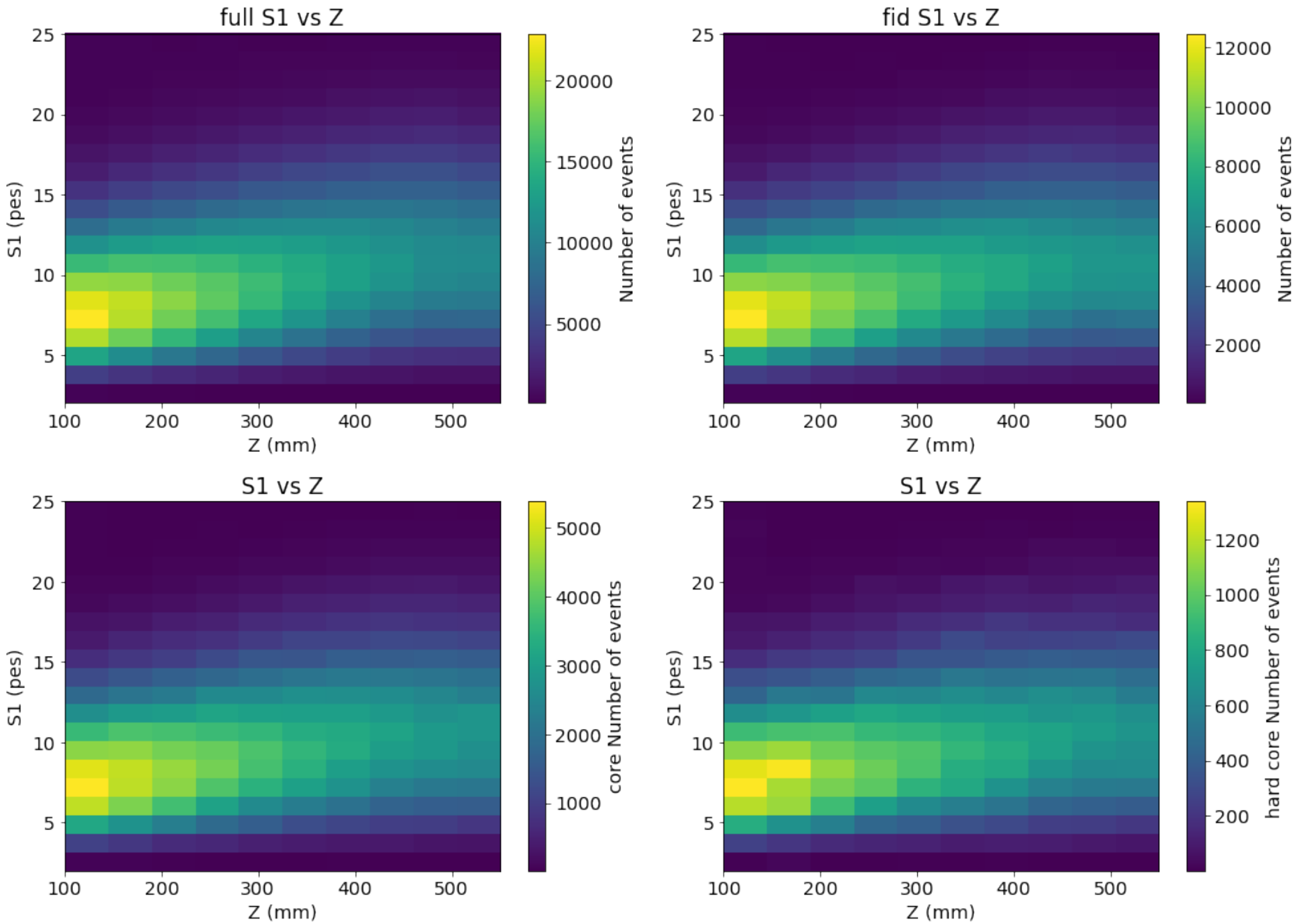


Raw energy distributions

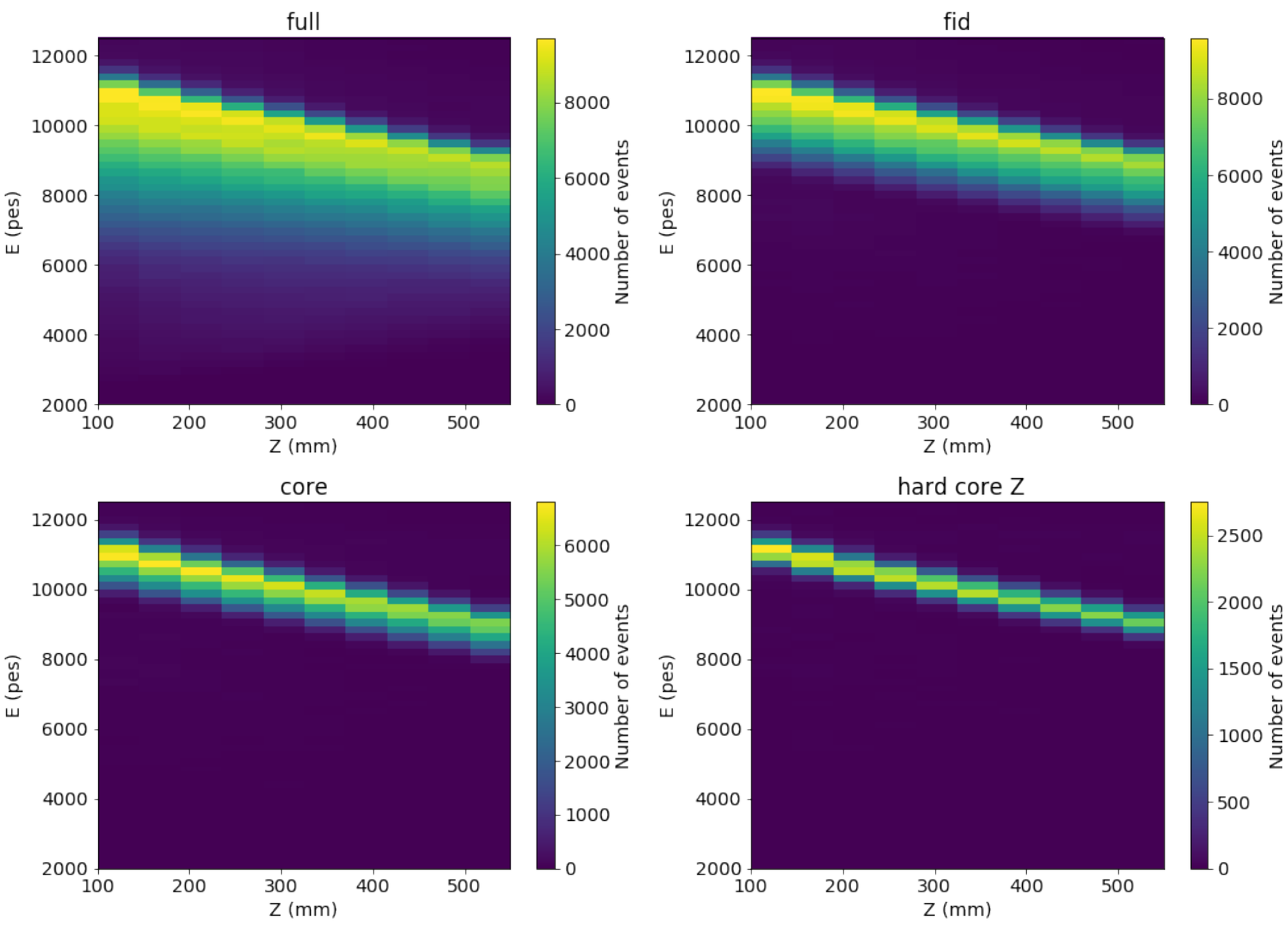




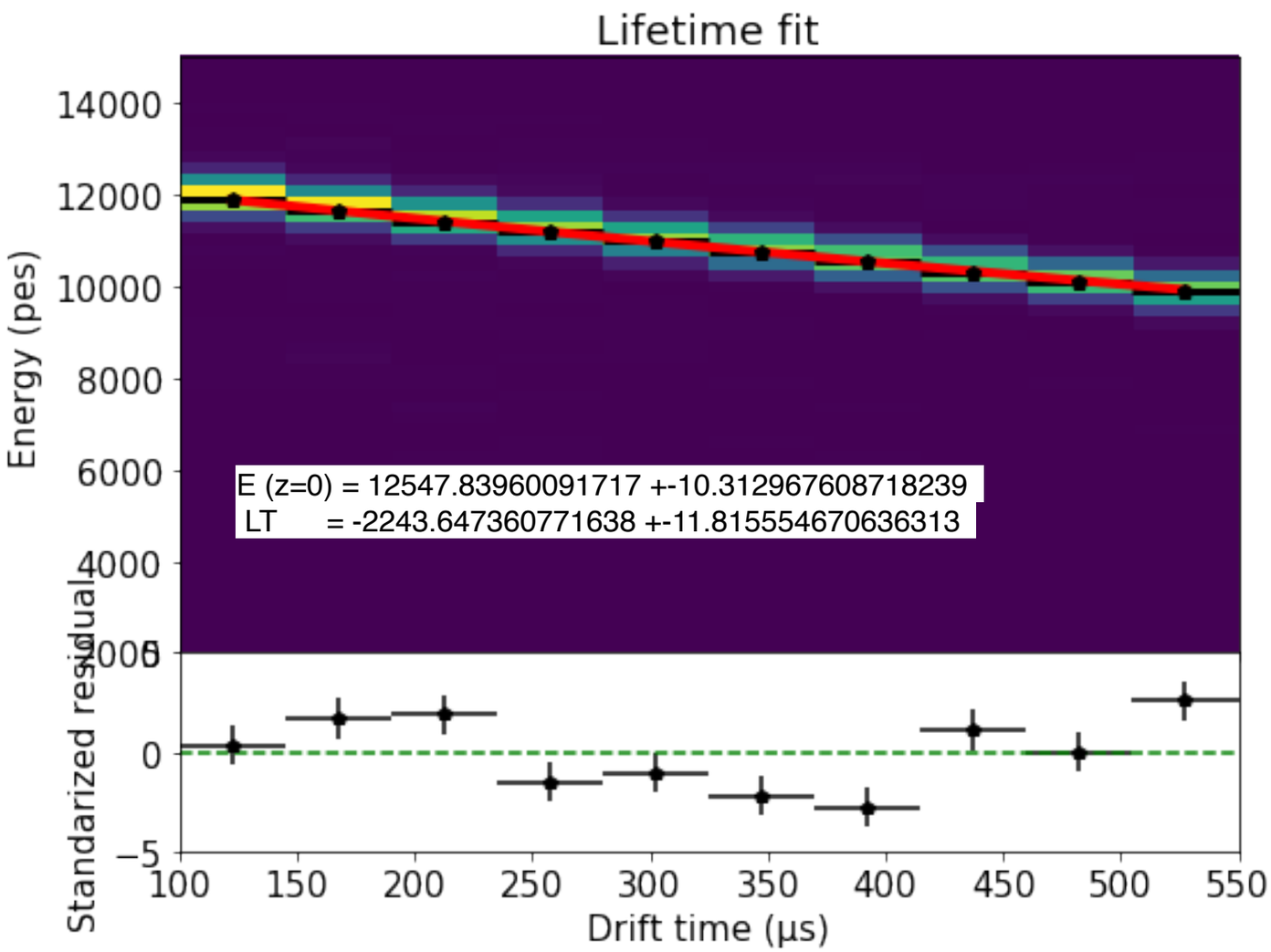
S1 depends of geometry and lifetime



S2 depends of geometry and lifetime



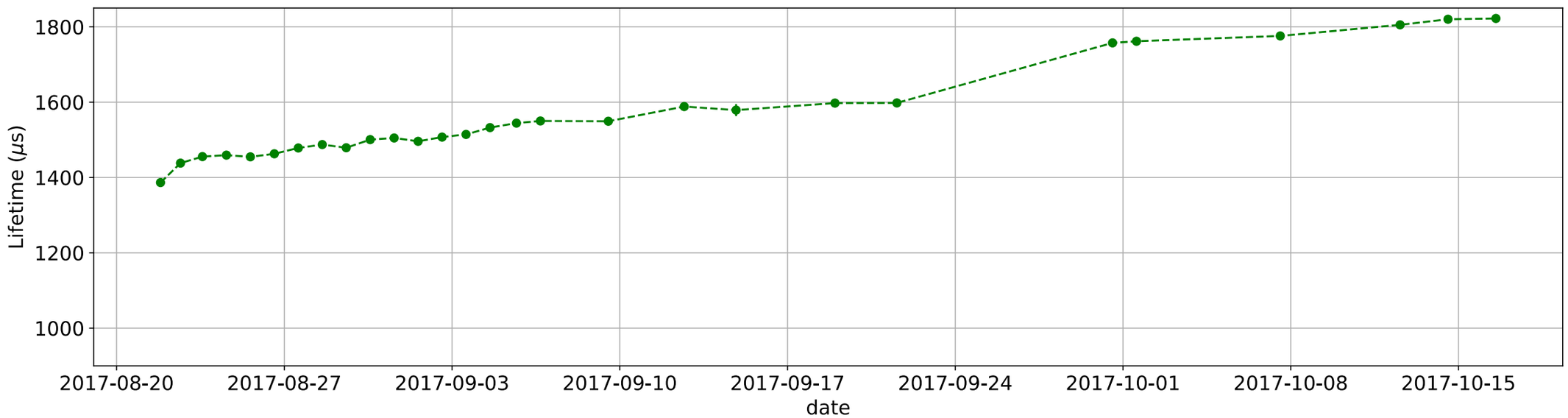
Measurement of lifetime

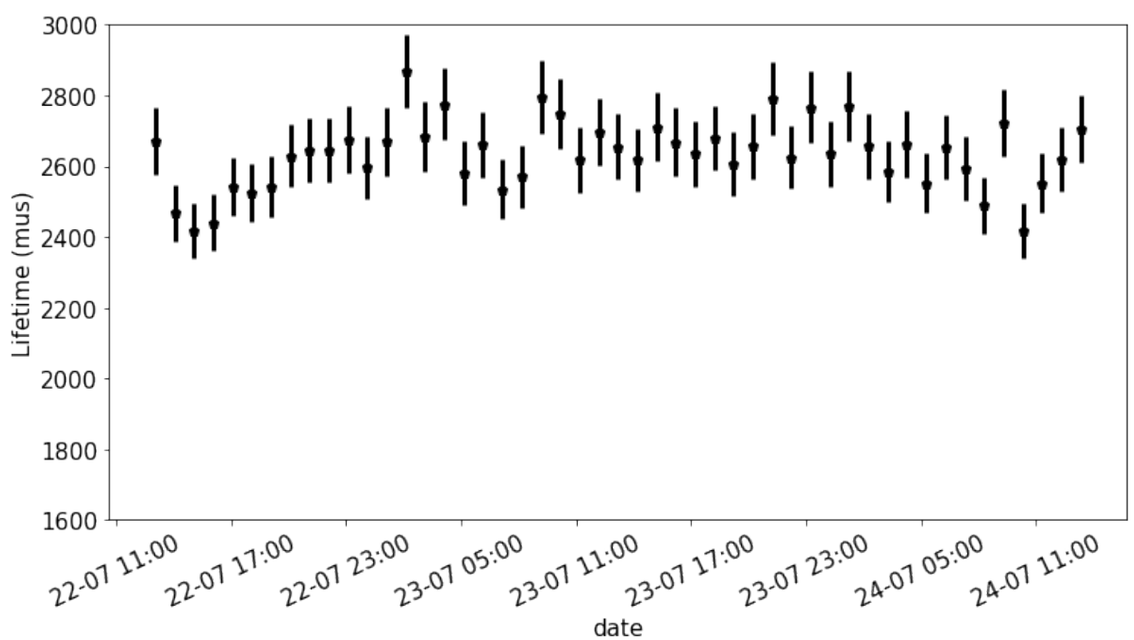


- To measure lifetime, one must know the drift time.
- Without t0, drift time cannot be measured and the lifetime cannot be computed
- Assuming that a large HPXe (ton scale) can achieve “infinite” lifetime (e.g., 10 times drift length) may not be realistic.

Lifetime evolves with time

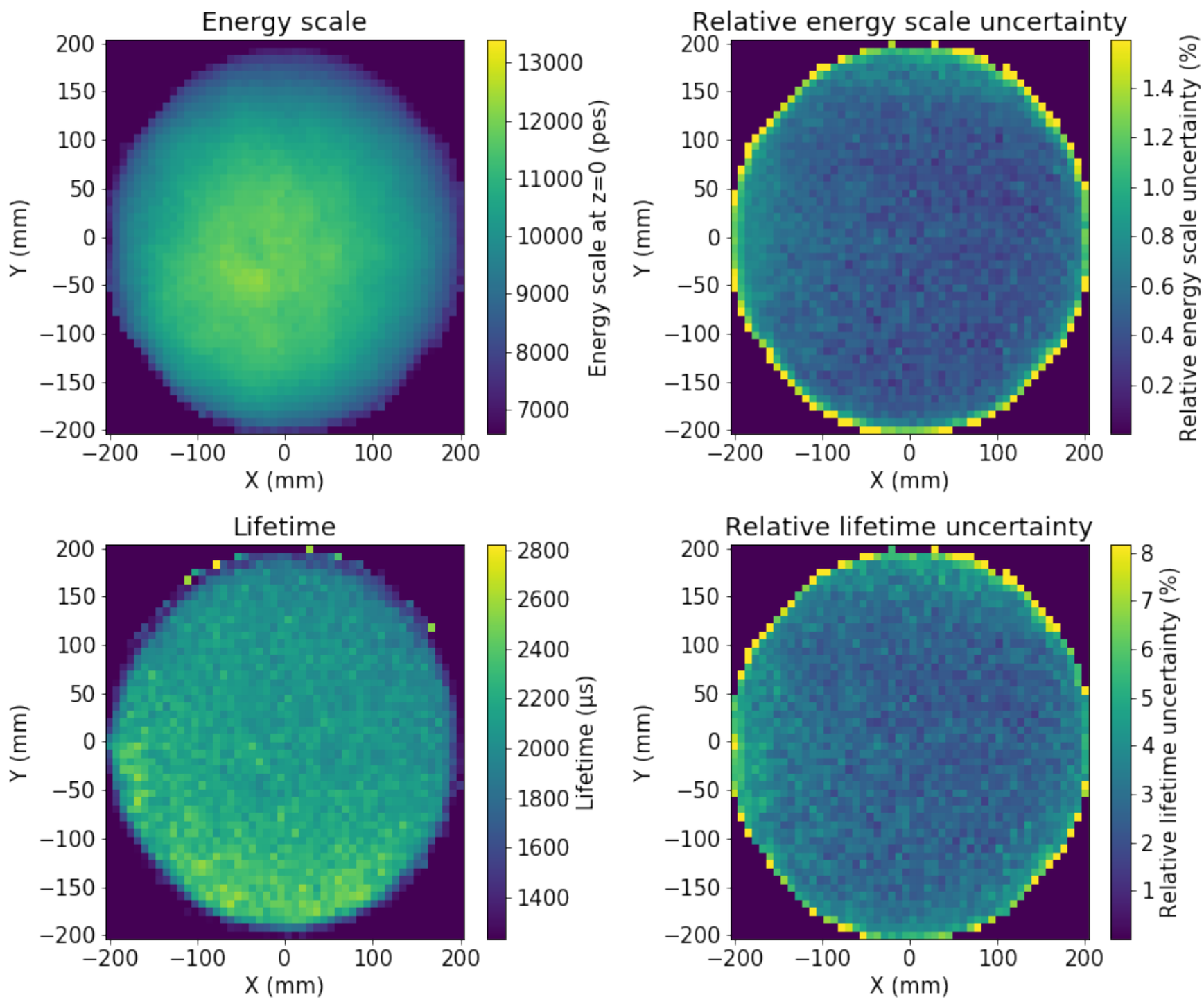
Evolution of lifetime during Run II





evolution of lifetime Run IV

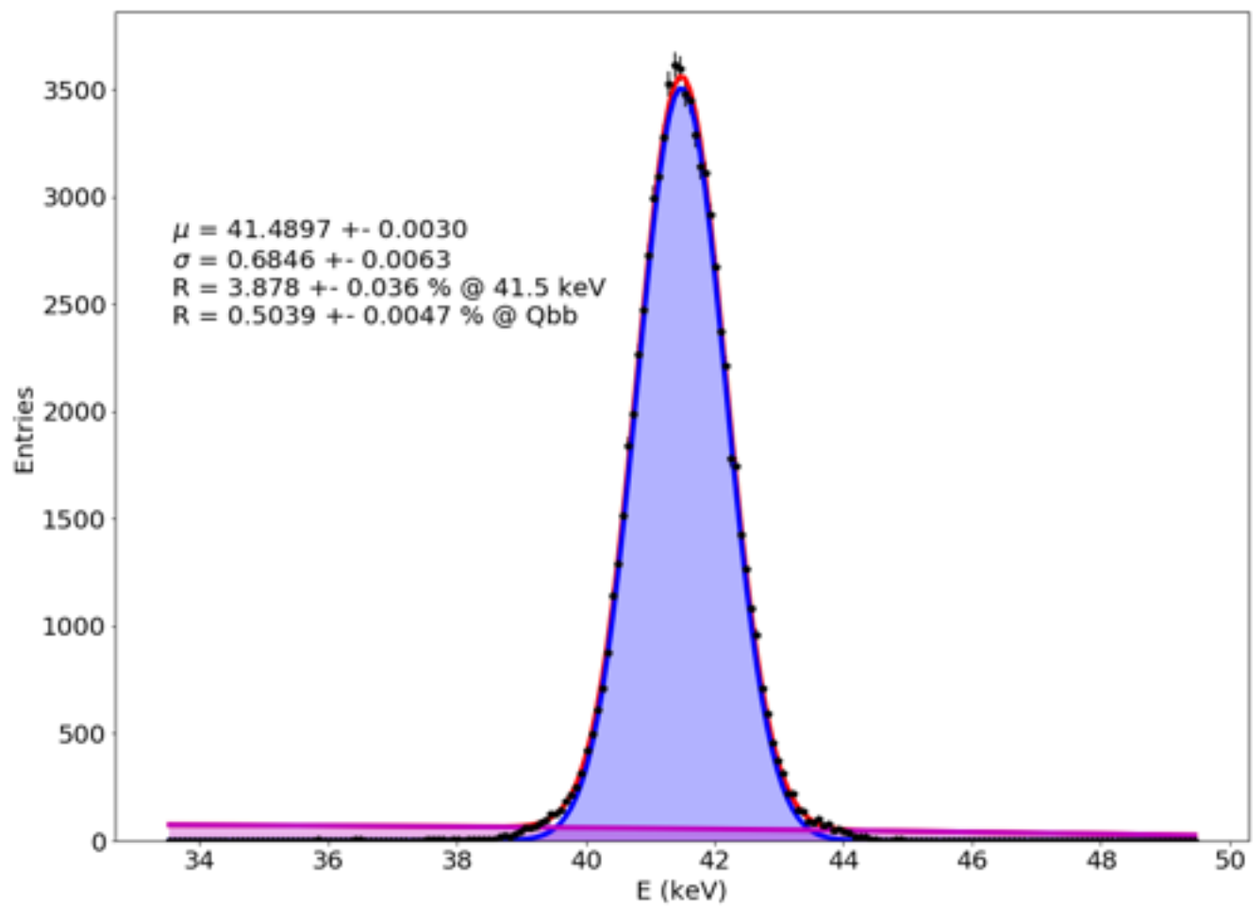
Lifetime and geometry maps



Energy resolution

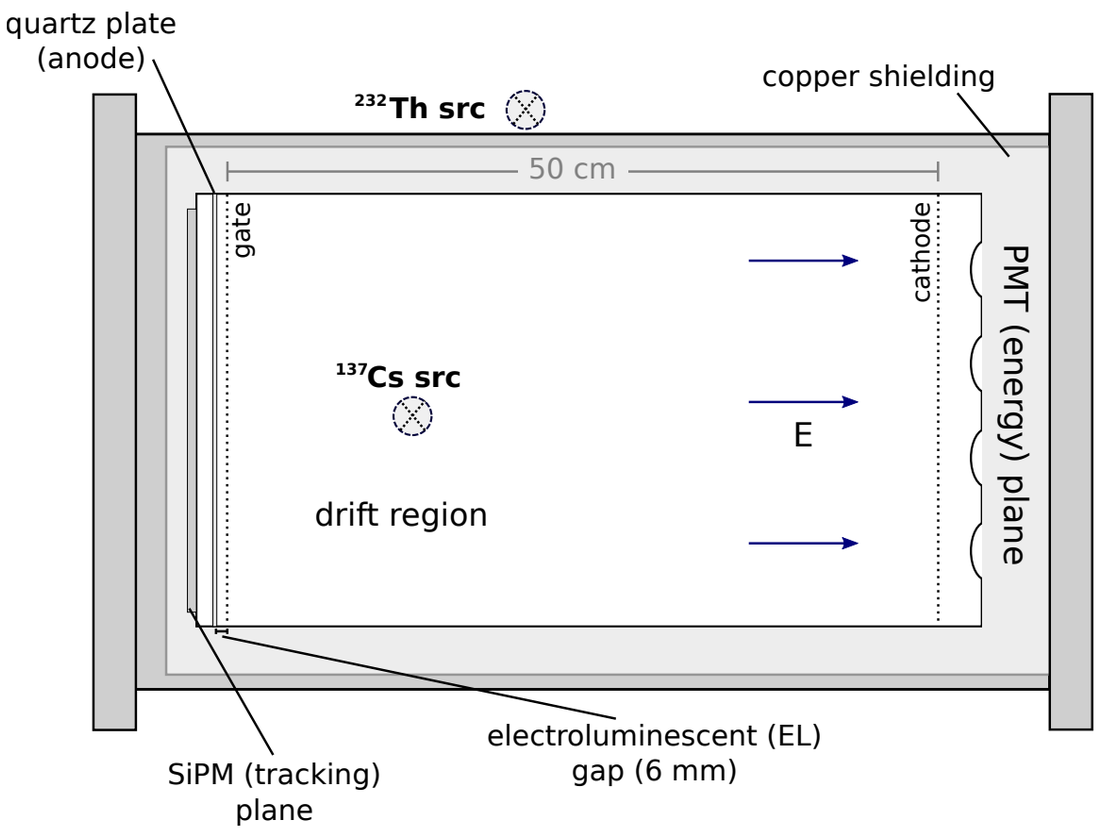
- The resolution is best when the light-reduction effects are minimal, i.e. short drift and close to the center.
- The measured resolution ***<u>in a fiducial volume</u>*** is (3.878 ± 0.036 (stat)) % FWHM @ 41.5 keV
- The extrapolated ($1/\sqrt{E}$) resolution is (0.5039 ± 0.0047 (stat)) % FWHM @ $Q_{\beta\beta}$.

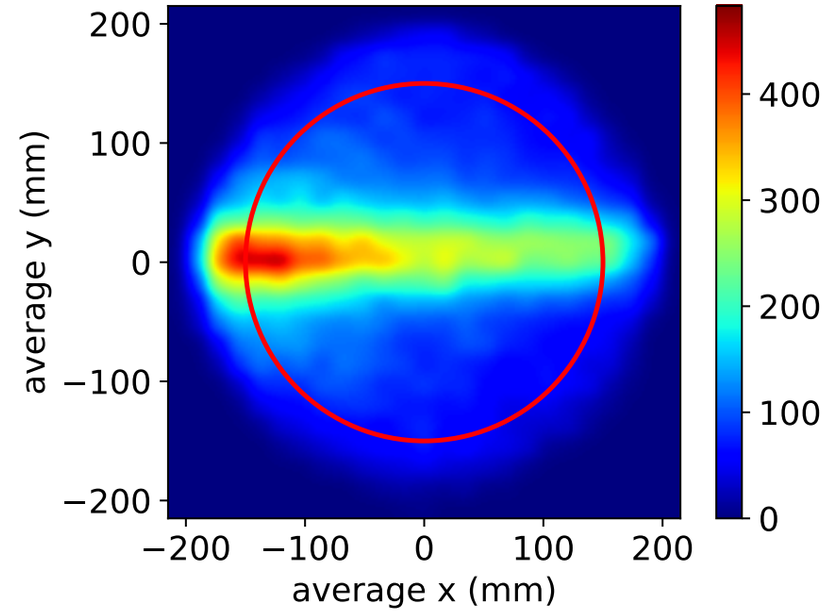
R < 150 mm
Z < 150 mm

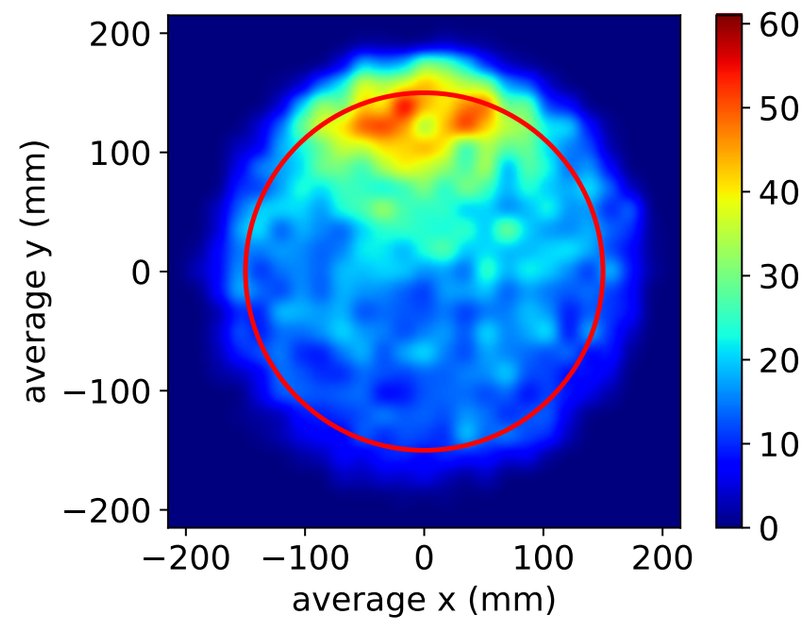


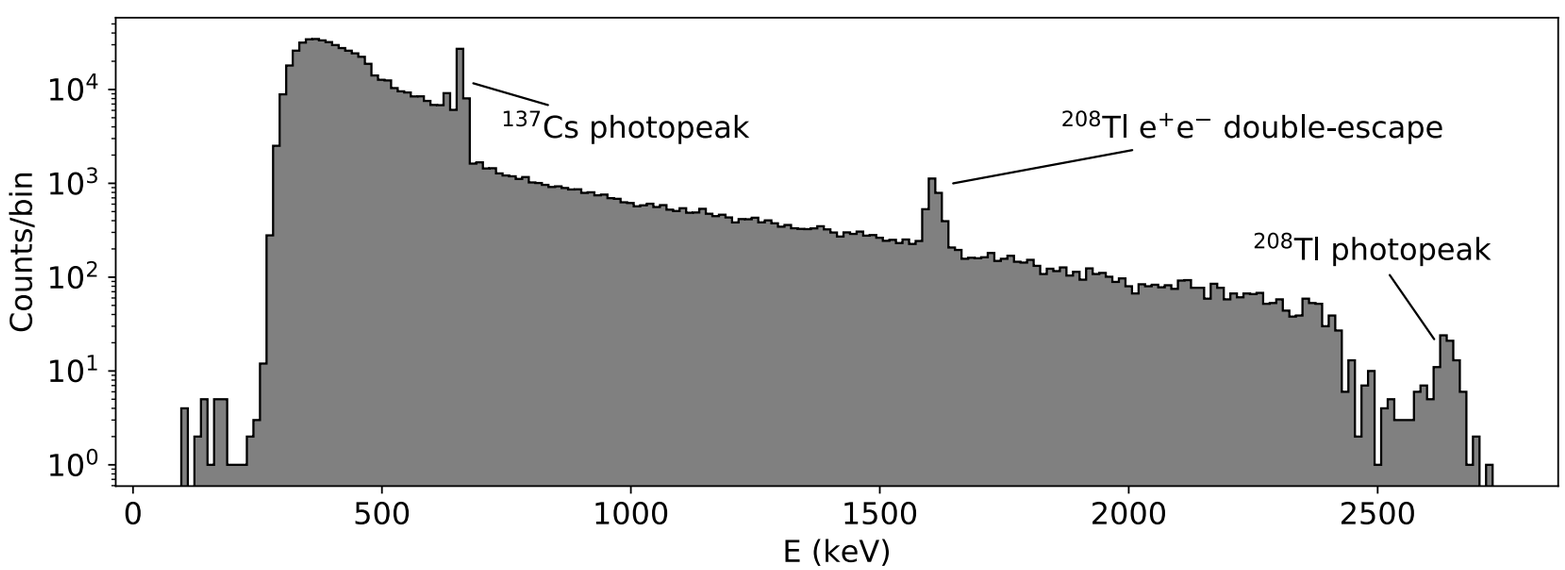
Run 4734

High energy calibrations

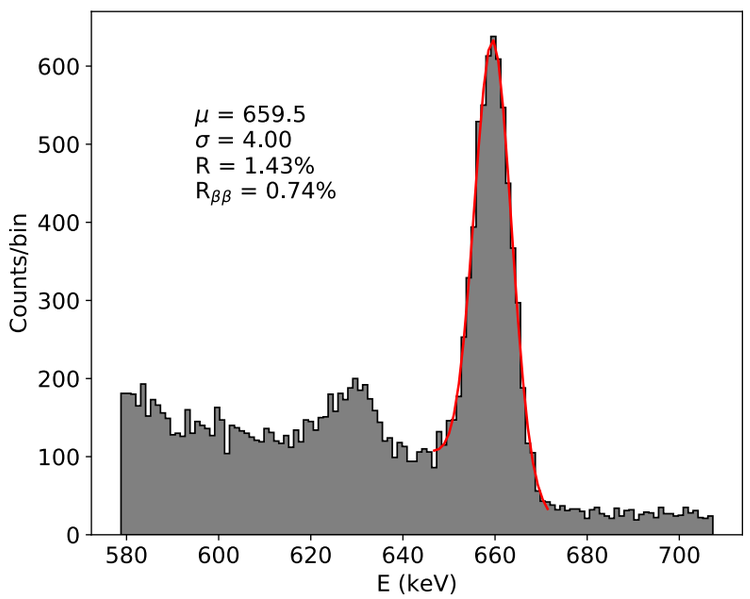


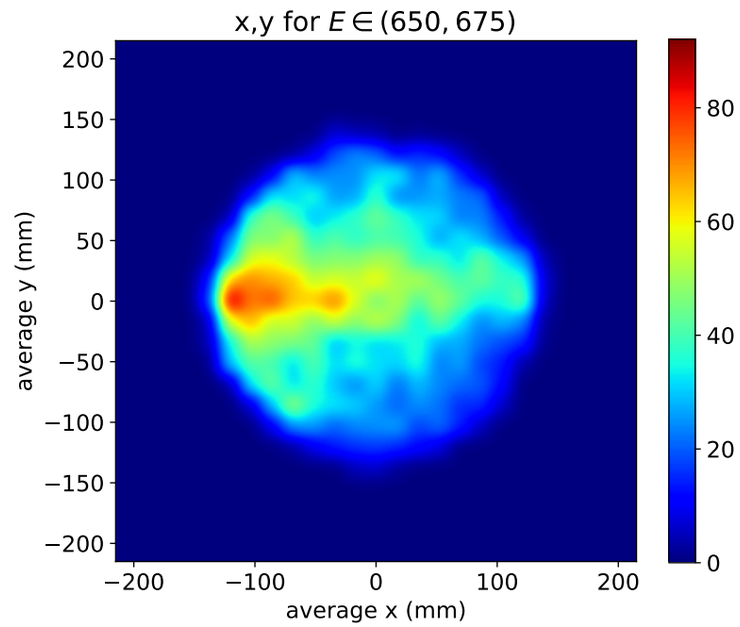


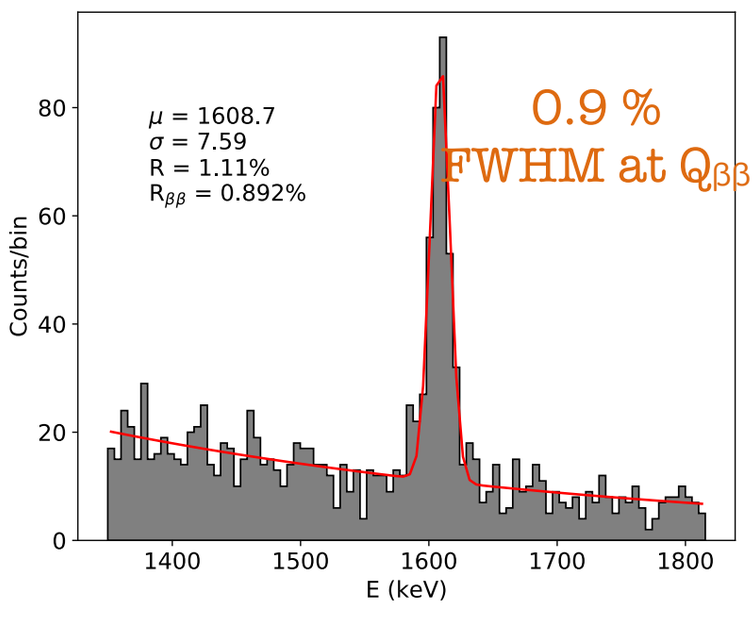


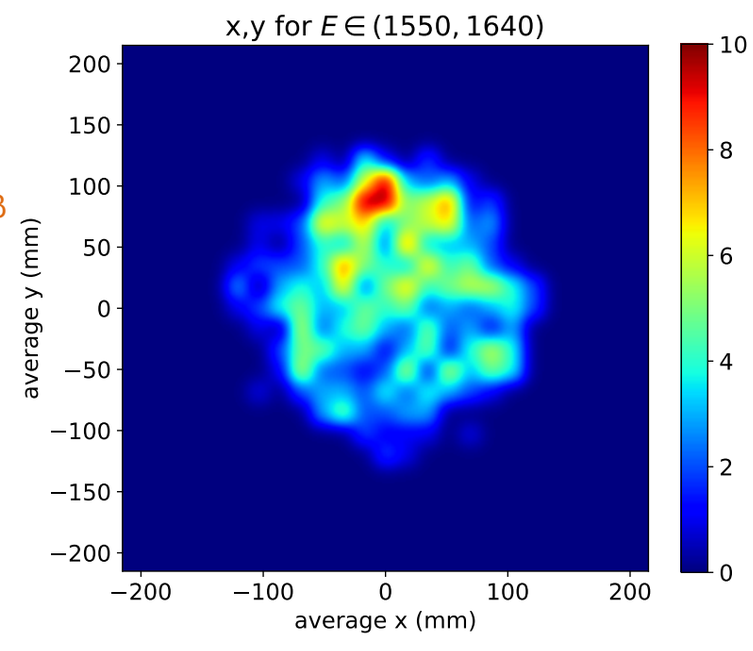


Energy resolution long tracks









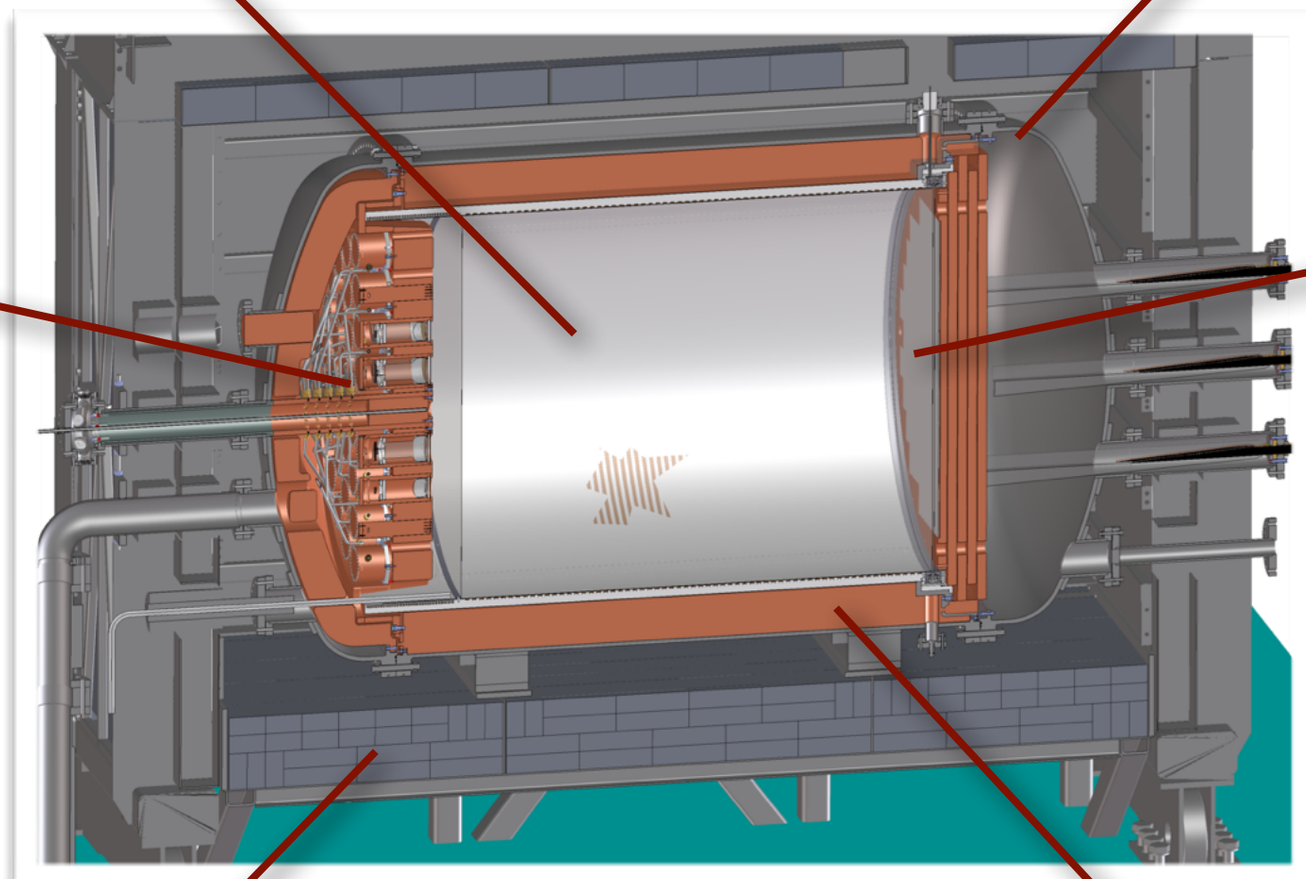
- Long tracks need to be corrected hit-by-hit
- Precise geometrical map, long lifetime and precise lifetime maps are even more important than at lower energies.
- Tl-209 double escape peak double electrons are longer in NEW at 7 bar than $Q_{\beta\beta}$ electrons in NEXT-100 at 15 bar. Expect good resolution for NEXT-100.

NEXT 100

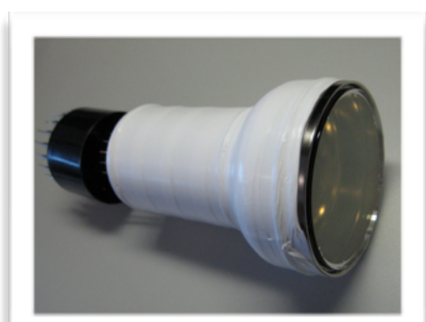
Time Projection Chamber:
100 kg active region, 130 cm drift length

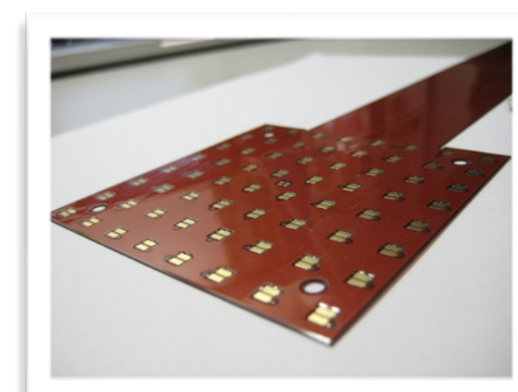
Pressure vessel:
stainless steel,15 bar max pressure

Energy plane:
60 PMTs,
30% coverage



Tracking plane:
7,000 SiPMs,
1 cm pitch?





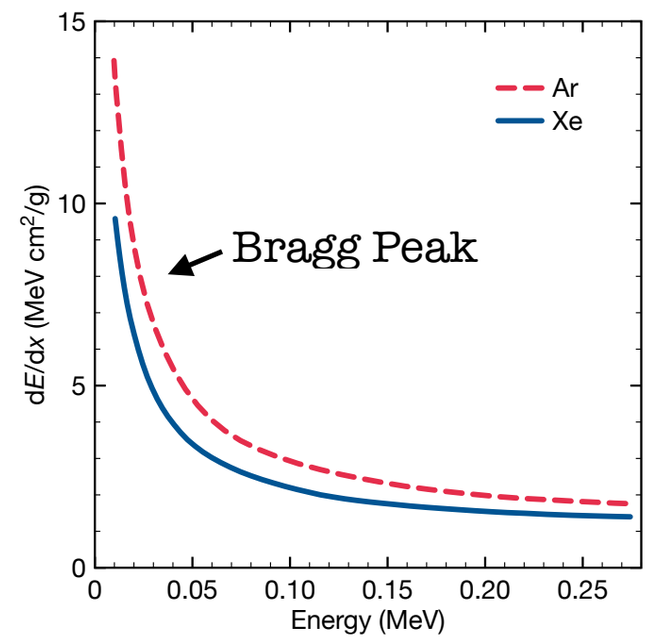
Outer shield:
lead, 20 cm thick

Inner shield:
copper, 12 cm thick

$\beta\beta_{0\nu}$ signal

$\beta\beta_{0\nu}$ signal

Two electrons from a common vertex inside the active volume with a total Edep = ^{136}Xe $Q_{\beta\beta}$.

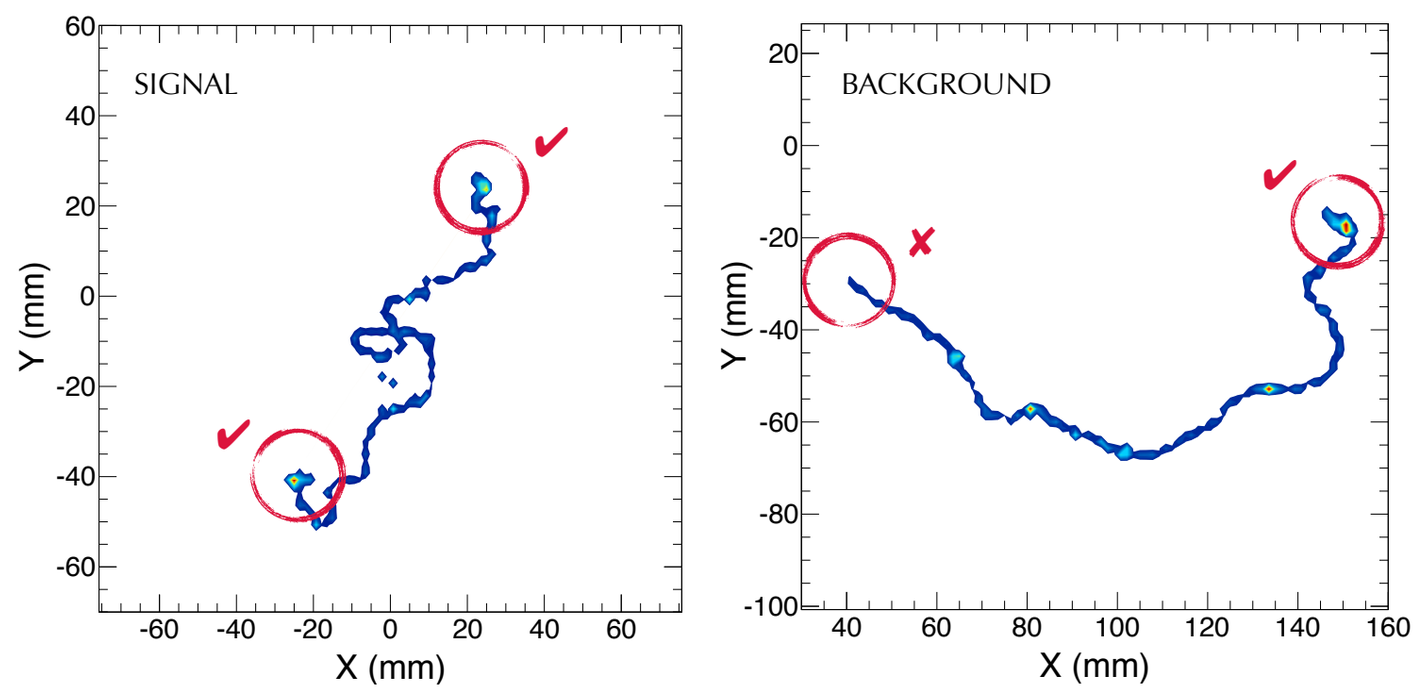


$\beta\beta_{0\nu}$ event

Energy deposition of $Q_{\beta\beta}$

Fiducial

Characteristic topology: single track + 2 blobs



$\beta\beta_{0\nu}$ backgrounds

Relevant Backgrounds	Negligible Backgrounds
Natural decay series	^{136}Xe $2\nu\beta\beta$ decays
Radon	ν_e elastic scattering
Neutrons	ν_e capture by ^{136}Xe
Cosmogenic muons	...

$$B = A * \varepsilon$$

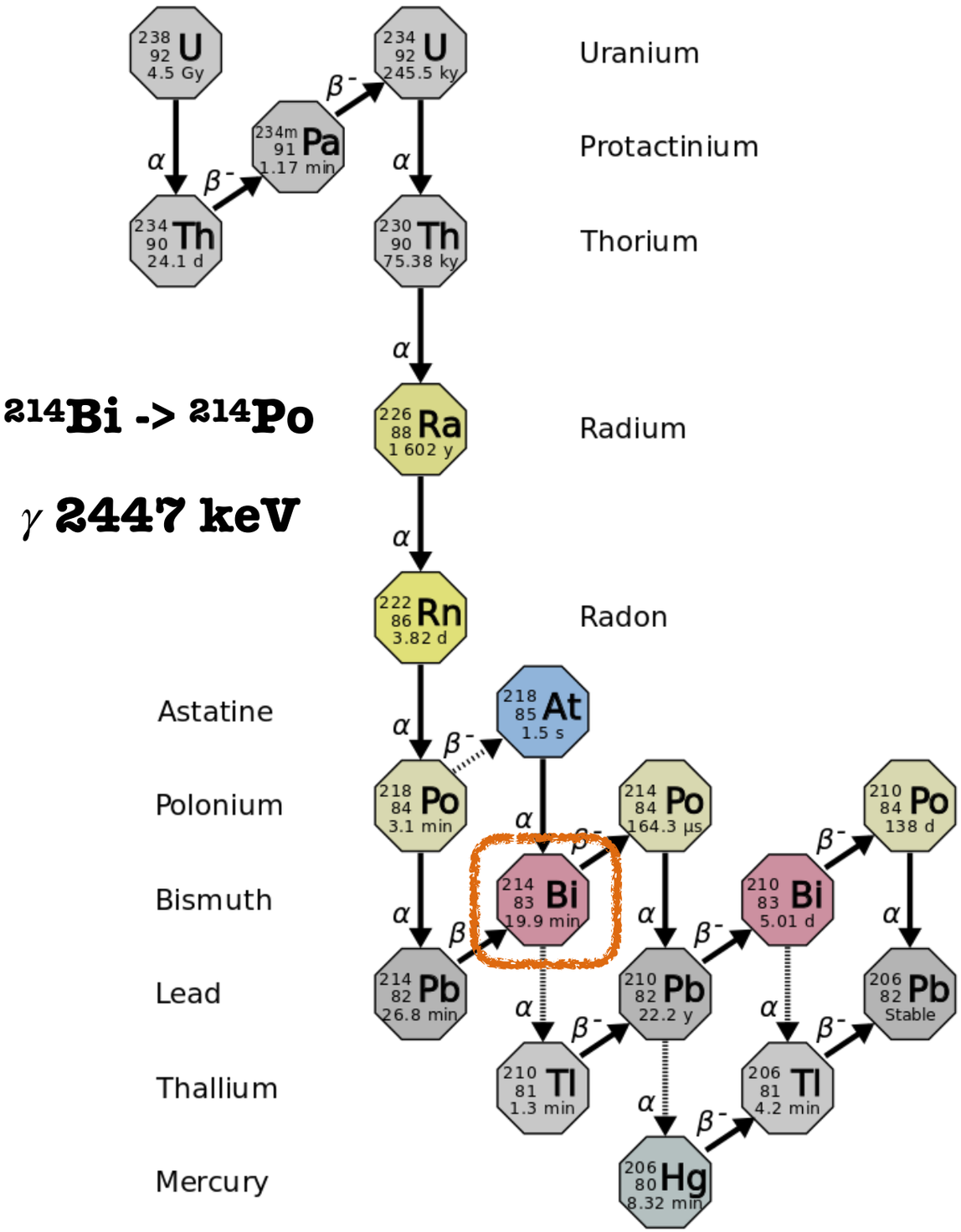
B: Predicted rate

A: Activity measured

ε: Selection efficiency from simulation + analysis

$\beta\beta_{0\nu}$ backgrounds

Natural decay series

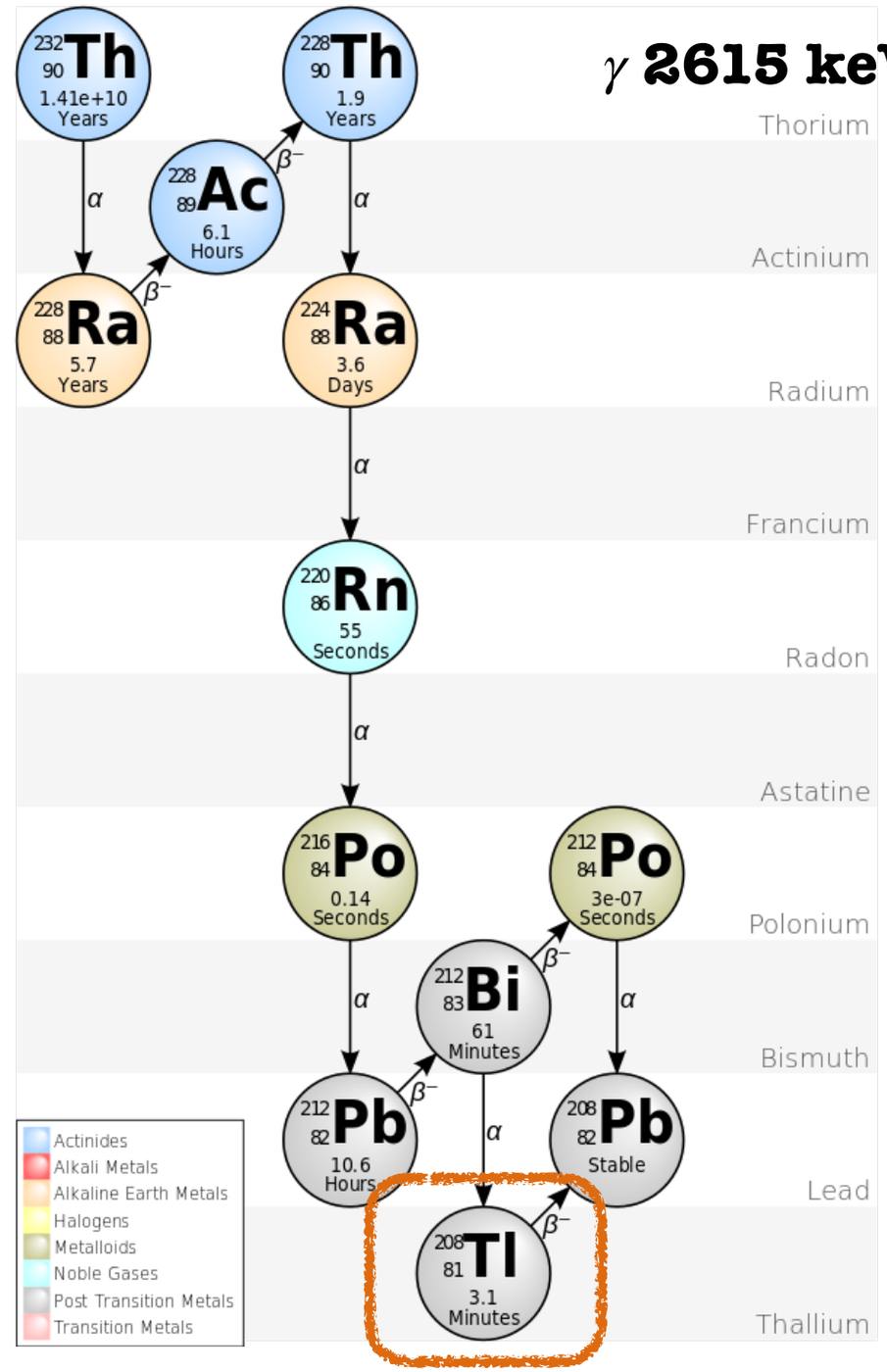


^{214}Bi -> ^{214}Po

γ 2447 keV

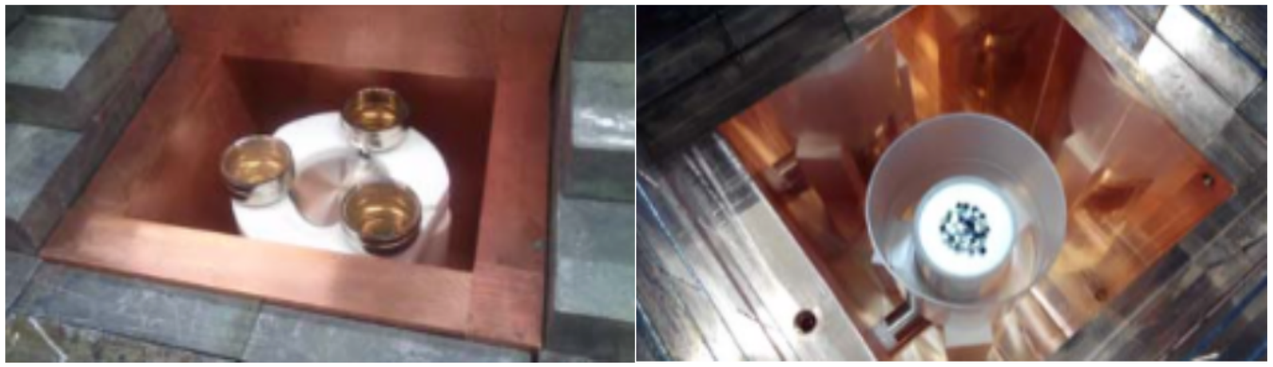
^{208}Tl -> ^{208}Pb

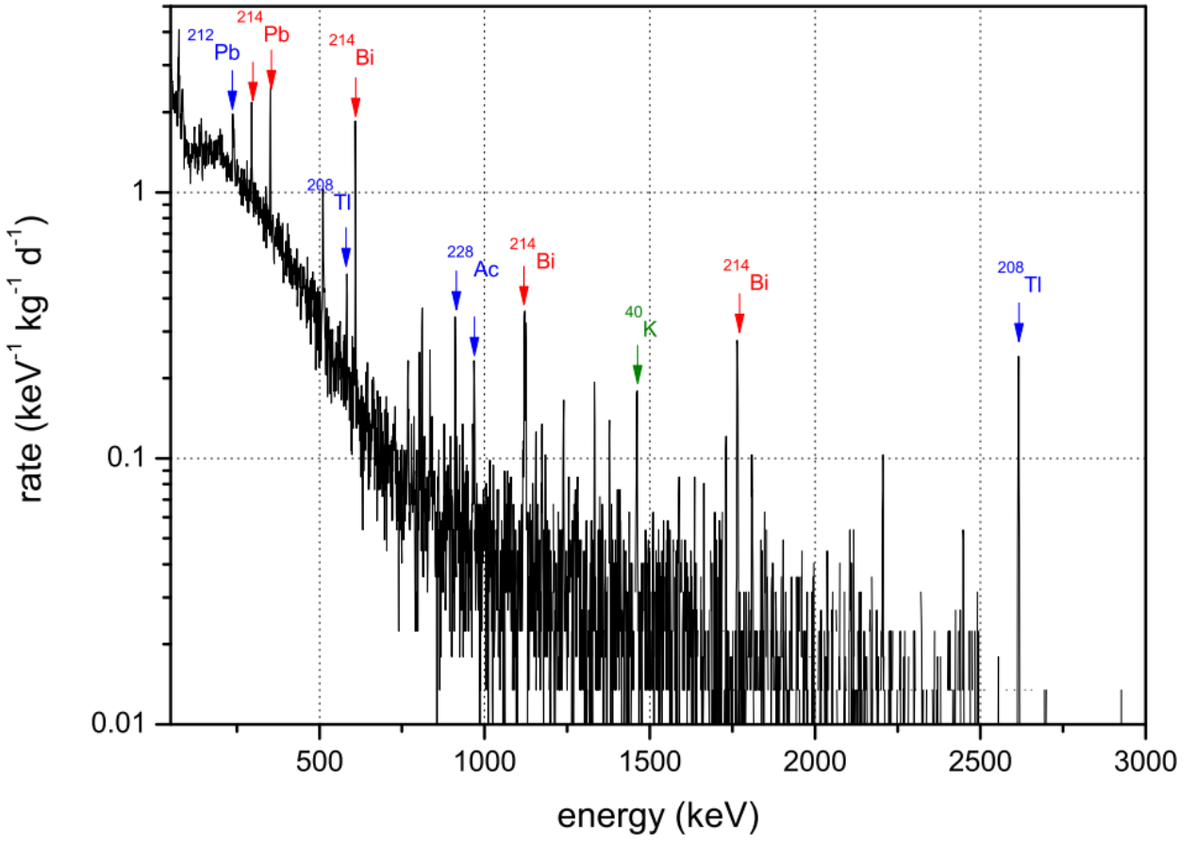
γ 2615 keV



$\beta\beta_{0\nu}$ backgrounds

Natural decay series





(activities in mBecq.)

VOLUME	^{208}Tl	^{214}Bi	**Total**
Dice Boards	1.26	8.10	9.36
DB Plugs	214	685	899
TRACKING PLANE	**215.26**	**693.1**	**908.36**
PMTs	11.4	21.0	32.4
PMT Bases	9.48	35.1	44.6
Enclos. Windows	< 1.19	< 5.34	< 6.53
ENERGY PLANE	**22.1**	**61.4**	**83.5**
Field Cage Barrel	< 1.06	< 8.59	< 9.65
Anode Quartz	0.233	1.44	1.67
FIELD CAGE	**< 1.29**	**< 10.03**	**< 11.32**
Inner Cu Shield	< 12.5	24.9	< 37.43
Tracking Support	< 0.24	0.48	< 0.71
Carrier Plate	< 0.77	1.54	< 2.30
COPPER SHIELD	**< 13.5**	**26.94**	**< 40.44**
VESSEL	**< 197**	**< 603**	**< 800**
SHIELDING CASTLE	**530**	**5460**	**5990**

JINST 12 (2017) no.08, T08003, JINST 10 P05006 (2015)

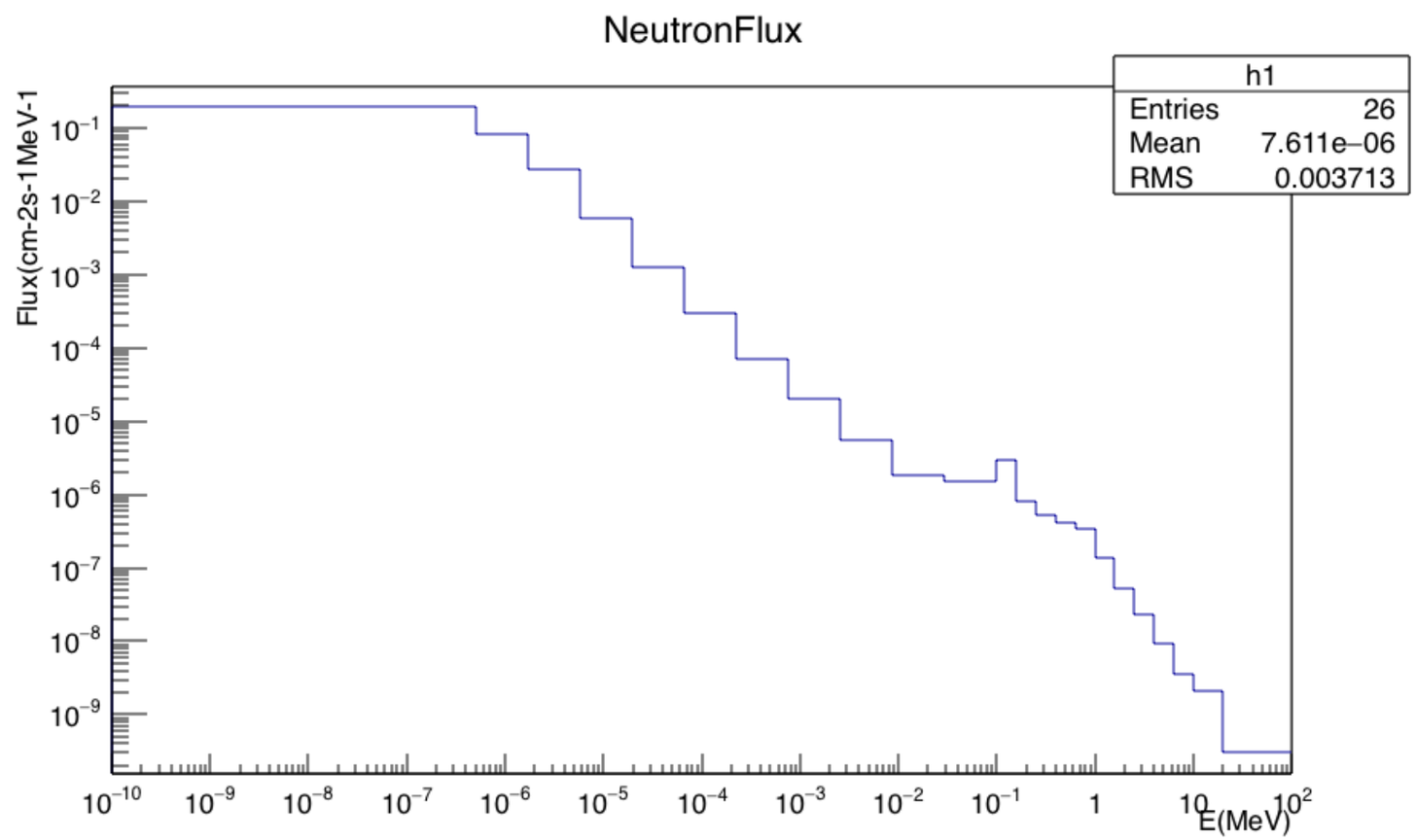
$\beta\beta_{0\nu}$ backgrounds

Neutrons

Very penetrating

Neutron captures activate different radionuclides producing myriad of gammas

^{137}Xe activation
Q = 4173 KeV.
Half-life = 3.95 min.



Total neutron flux at LSC Hall A
Origin in LSC walls

$$1.38 \pm 0.14 \times 10^{-5}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

DOI: 10.1016/j.astropartphys.2012.11.007

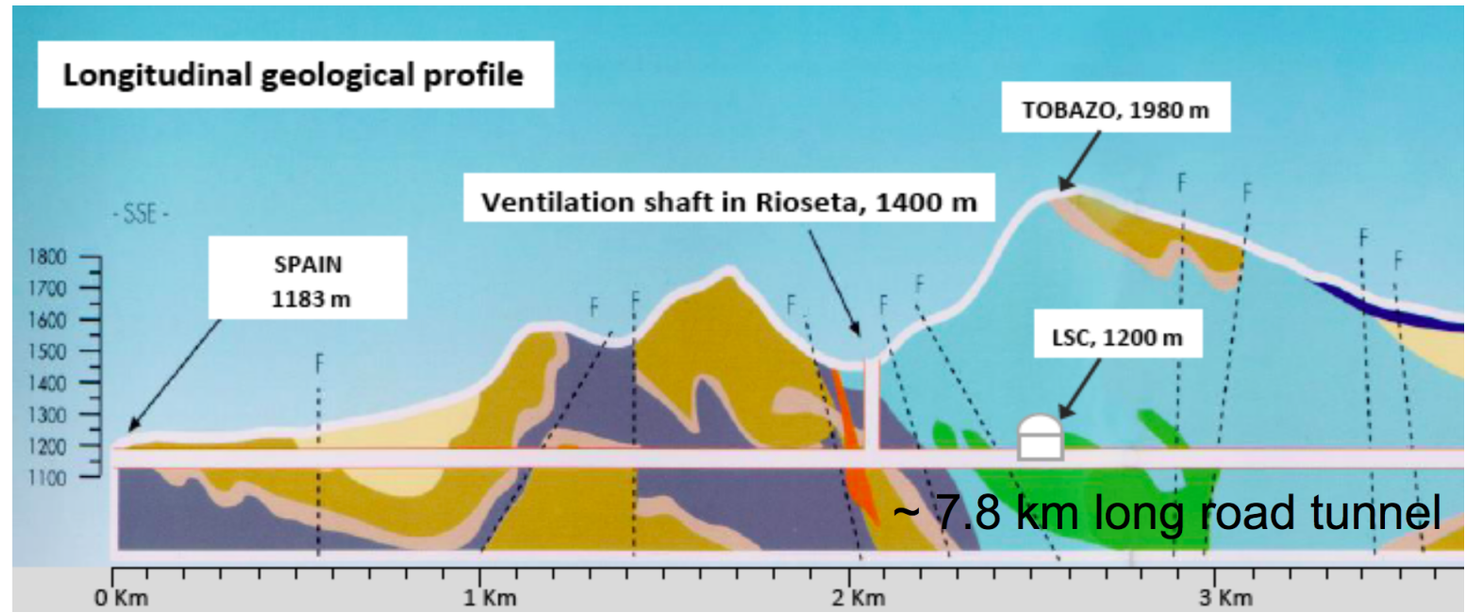
$\beta\beta_{0\nu}$ backgrounds

Cosmogenic muons

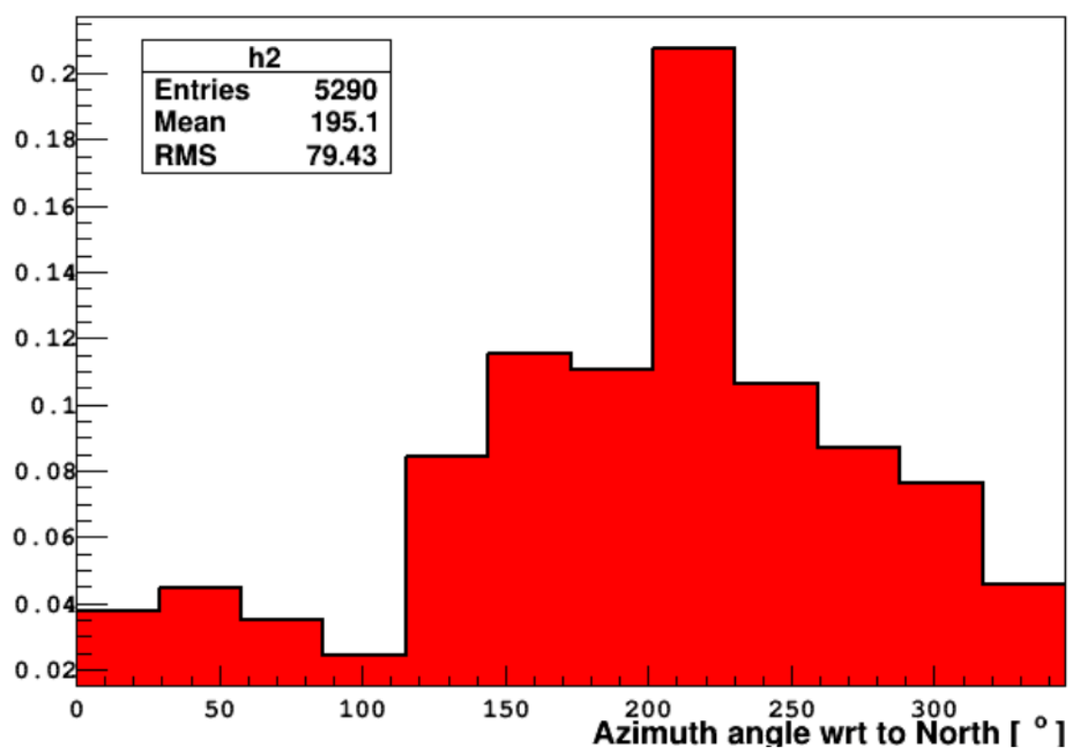
Total muon flux
at LSC Hall A:

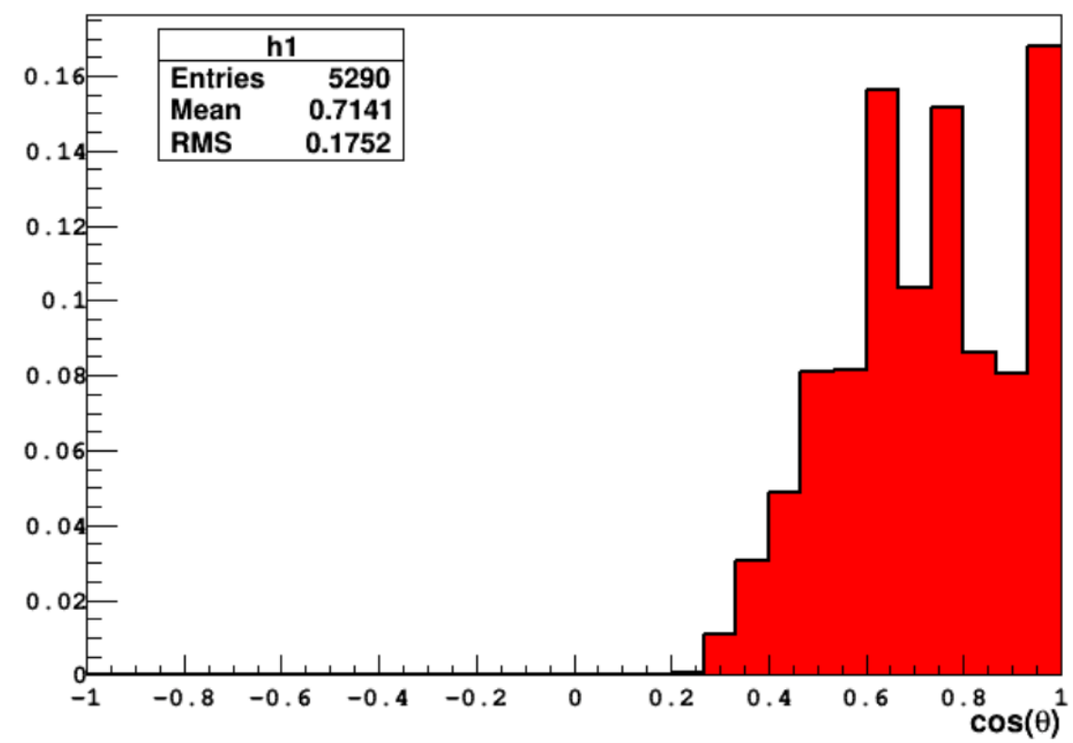
$$3 \times 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Avg. E = 220 - 245 GeV

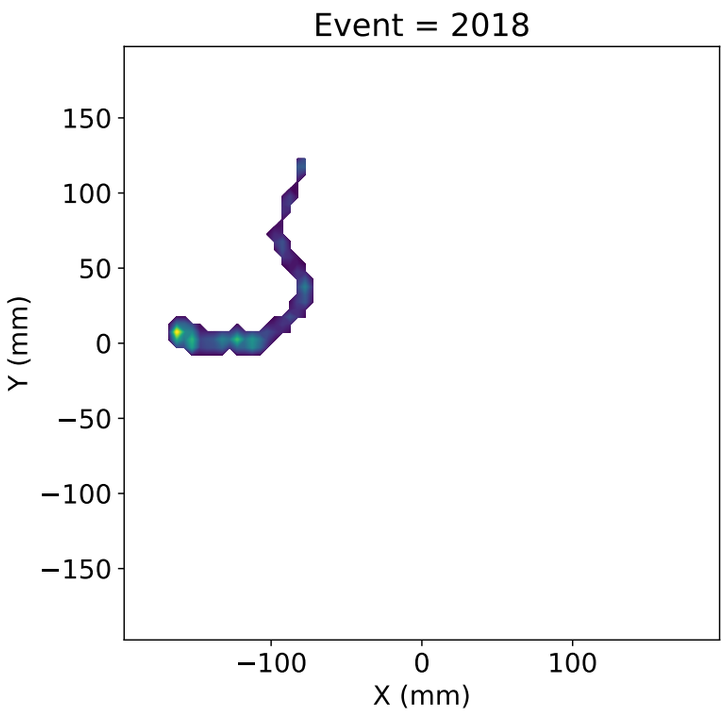


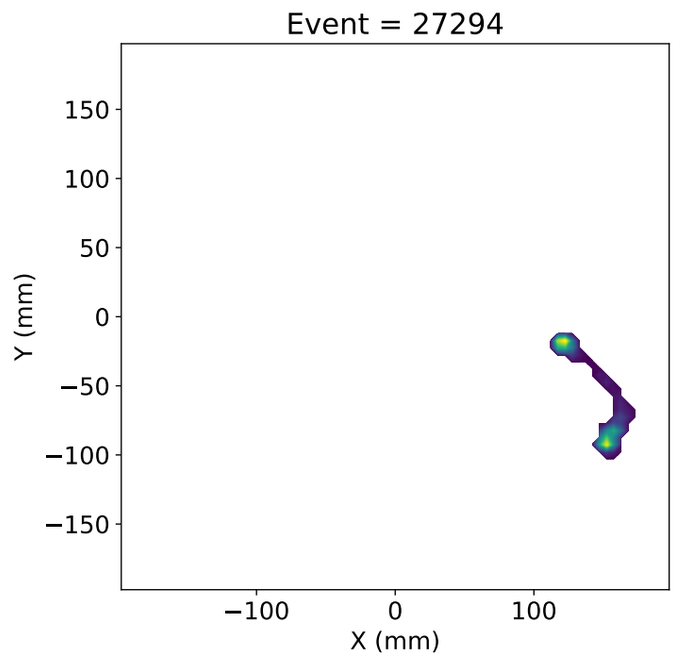
A.Ianni, *Canfranc underground laboratory*.
Private communication from workshop, 2016



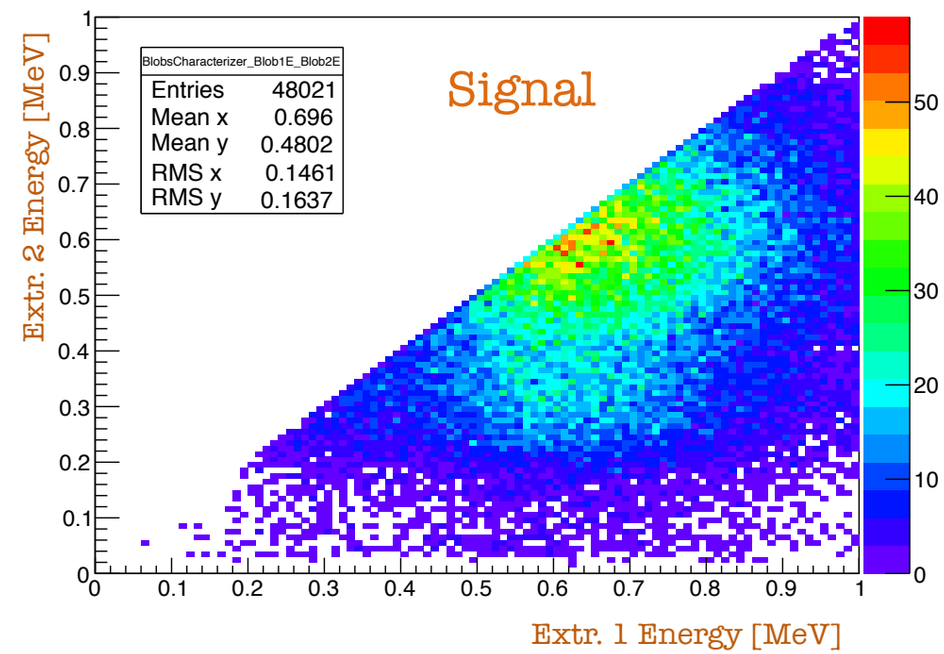


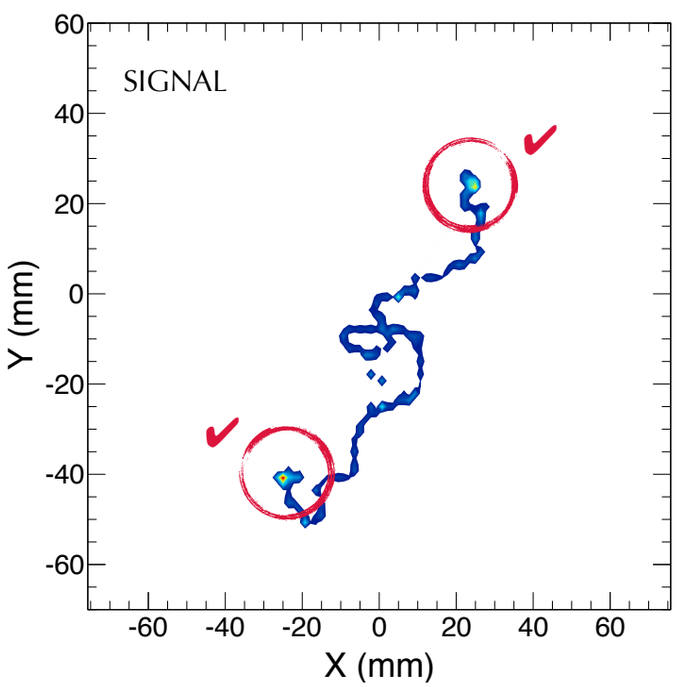
Topology Analysis

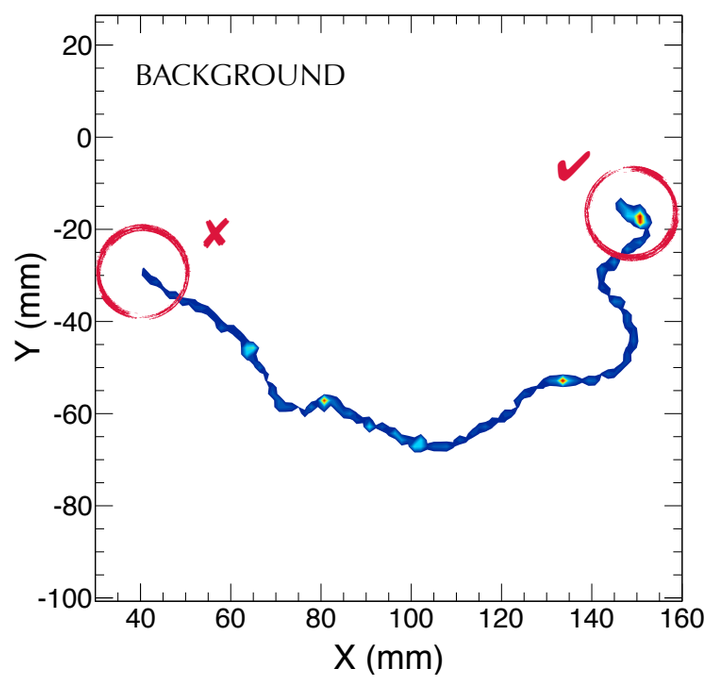


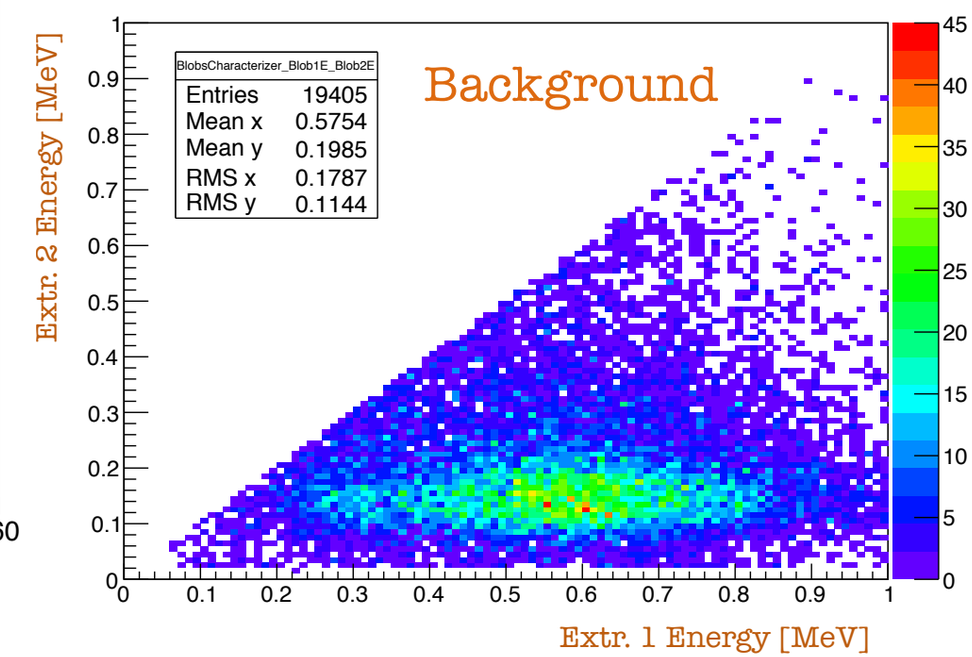


Extremes energy

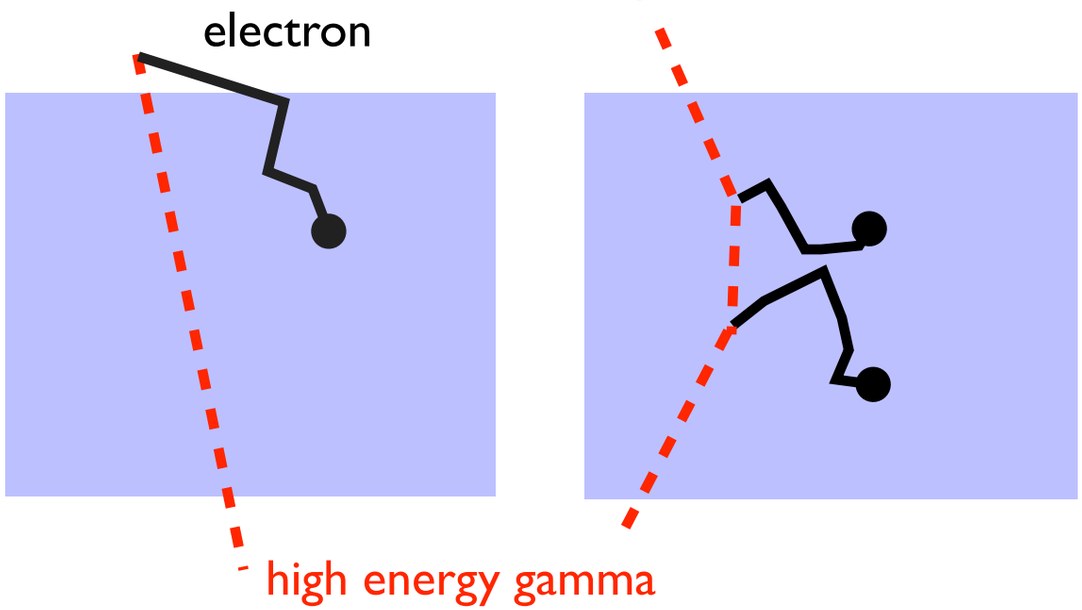








Efficiencies for signal and backgrounds



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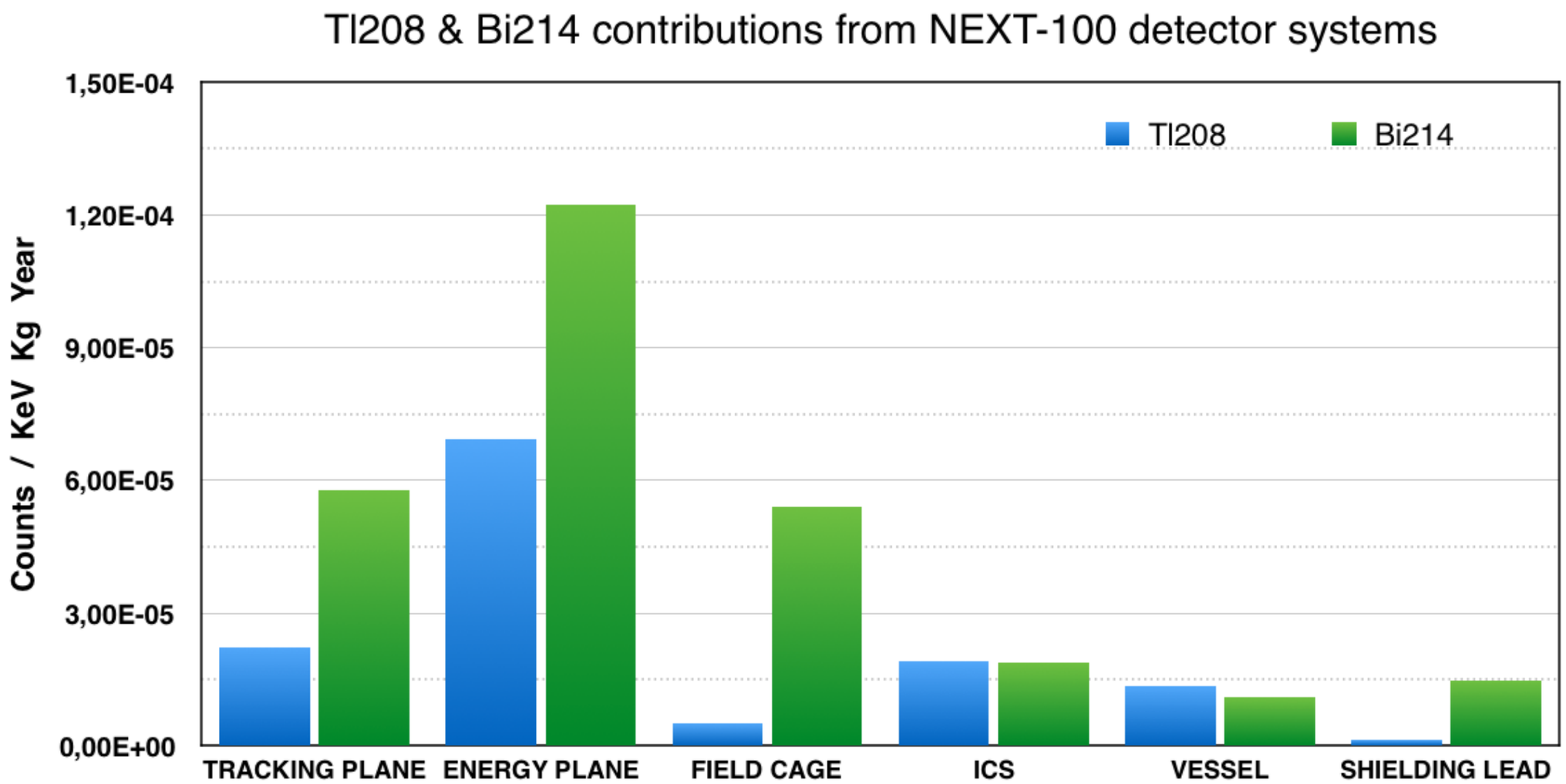
	0νββ	Tl-208	Bi-214
Fiducial + E ∈ [2.4, 2.5] MeV	0.664	3.5×10^{-4}	2.9×10^{-5}
1 track	0.476	1.41×10^{-5}	3.44×10^{-6}
2 "blobs"	0.354	1.57×10^{-6}	3.39×10^{-7}
Energy ROI	0.320	2.54×10^{-7}	1.46×10^{-7}

NEXT-100 Background model

1. Natural decay series: $< 4.09 \times 10^{-4}$ cts / keV kg year



NEXT-100 Background model

2. ^{222}Rn progeny: ≃ (0.7 - 4.4) 10^{-5} cts / keV kg year

From cathode ^{214}Bi decays

3. Neutrons: ≃ 10^{-3} cts / keV kg year **WITHOUT neutron shield**

NEXT-100 will add a shield of boron doped (5%) polyethylene slabs 20 cm thick -> neutron background becomes negligible.

4. Cosmogenic muons: ≃ 8.0 10^{-5} cts / keV kg year

^{137}Xe activations -> 10^{-5} cts / keV kg year

NEXT-100 Sensitivity

Total Background rate:

4.22×10^{-4} cts / keV kg year

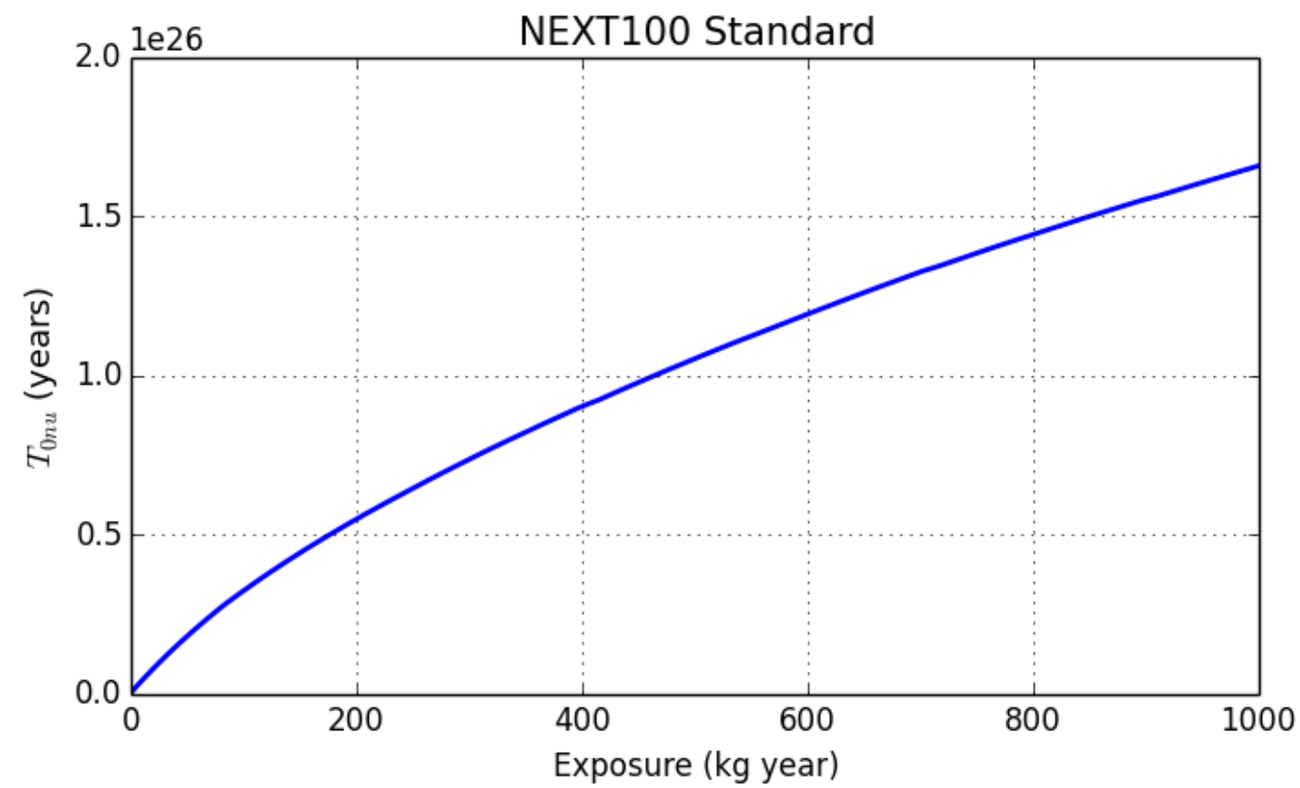
Global detection efficiency:

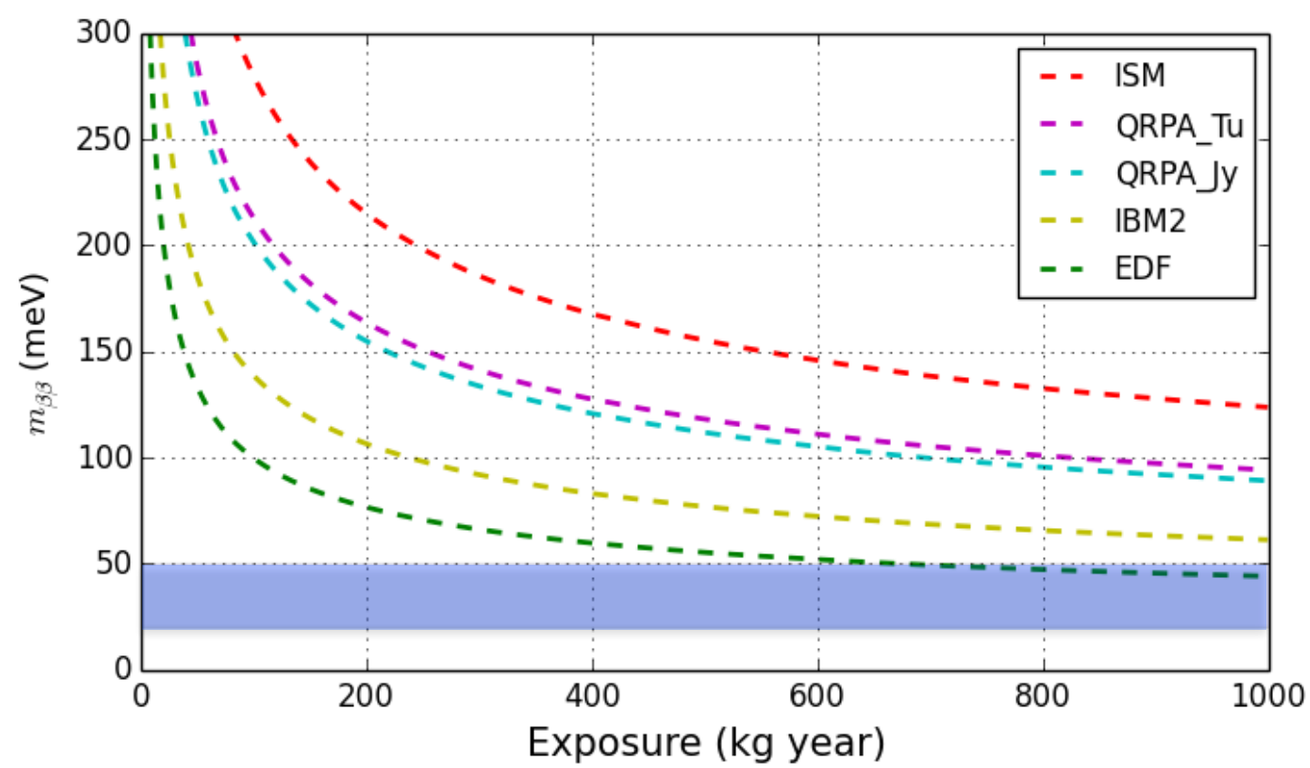
32 %

exposure of 500 kg/year:

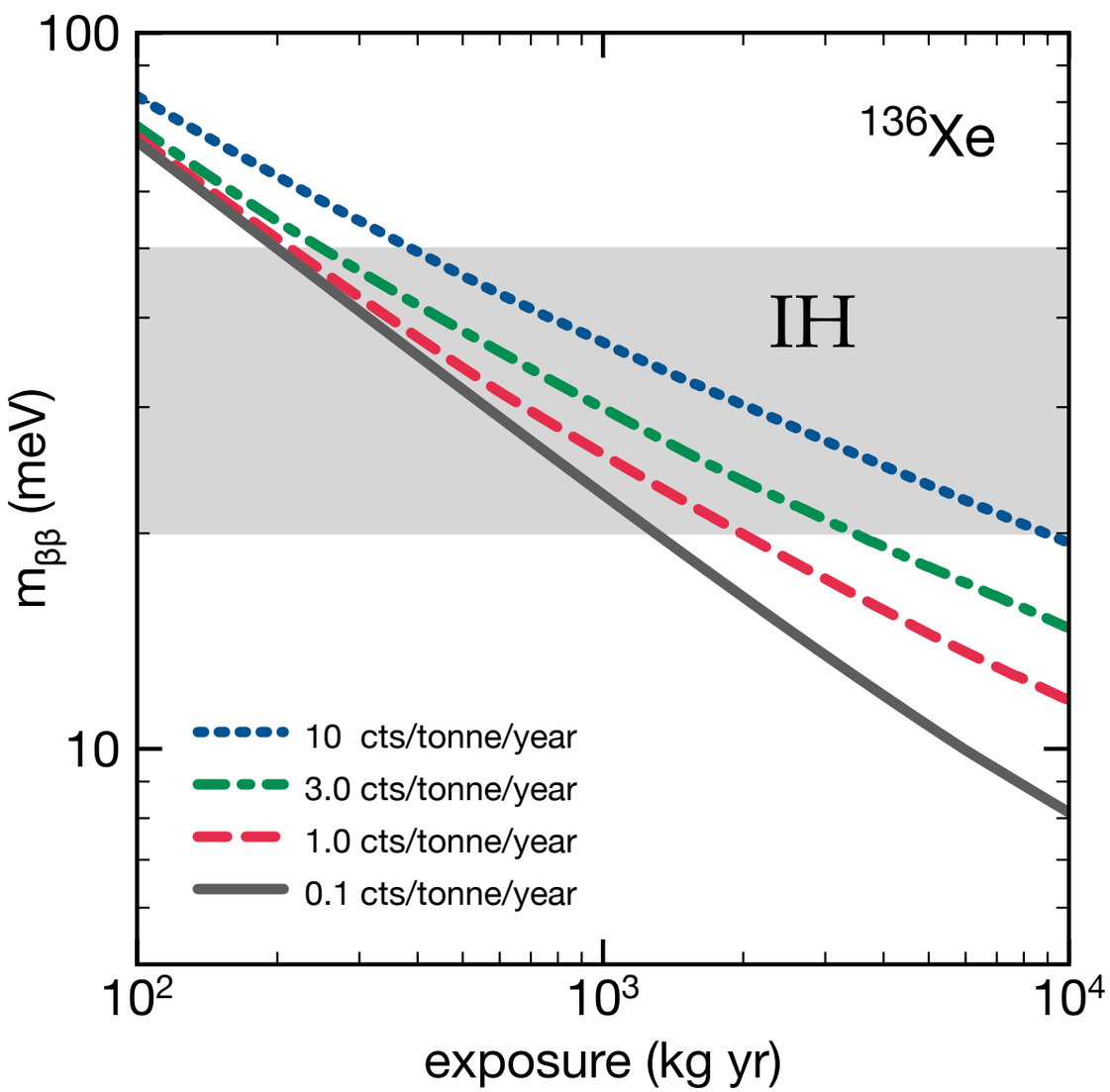
0ν half-life ≃ 1.0 10^{26} years

$m_{\beta\beta}$ = [57-161] meV



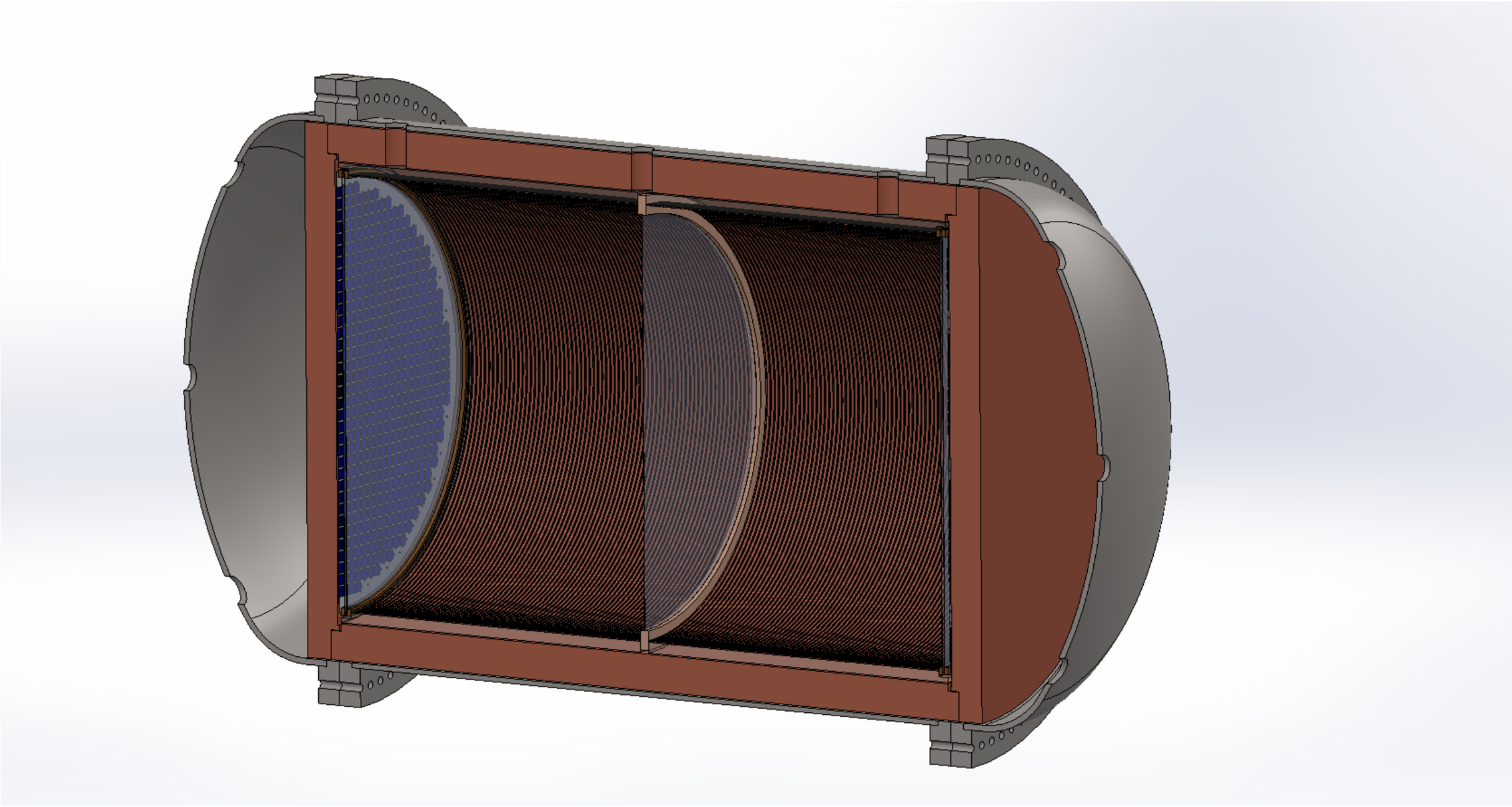


Exploring the IH

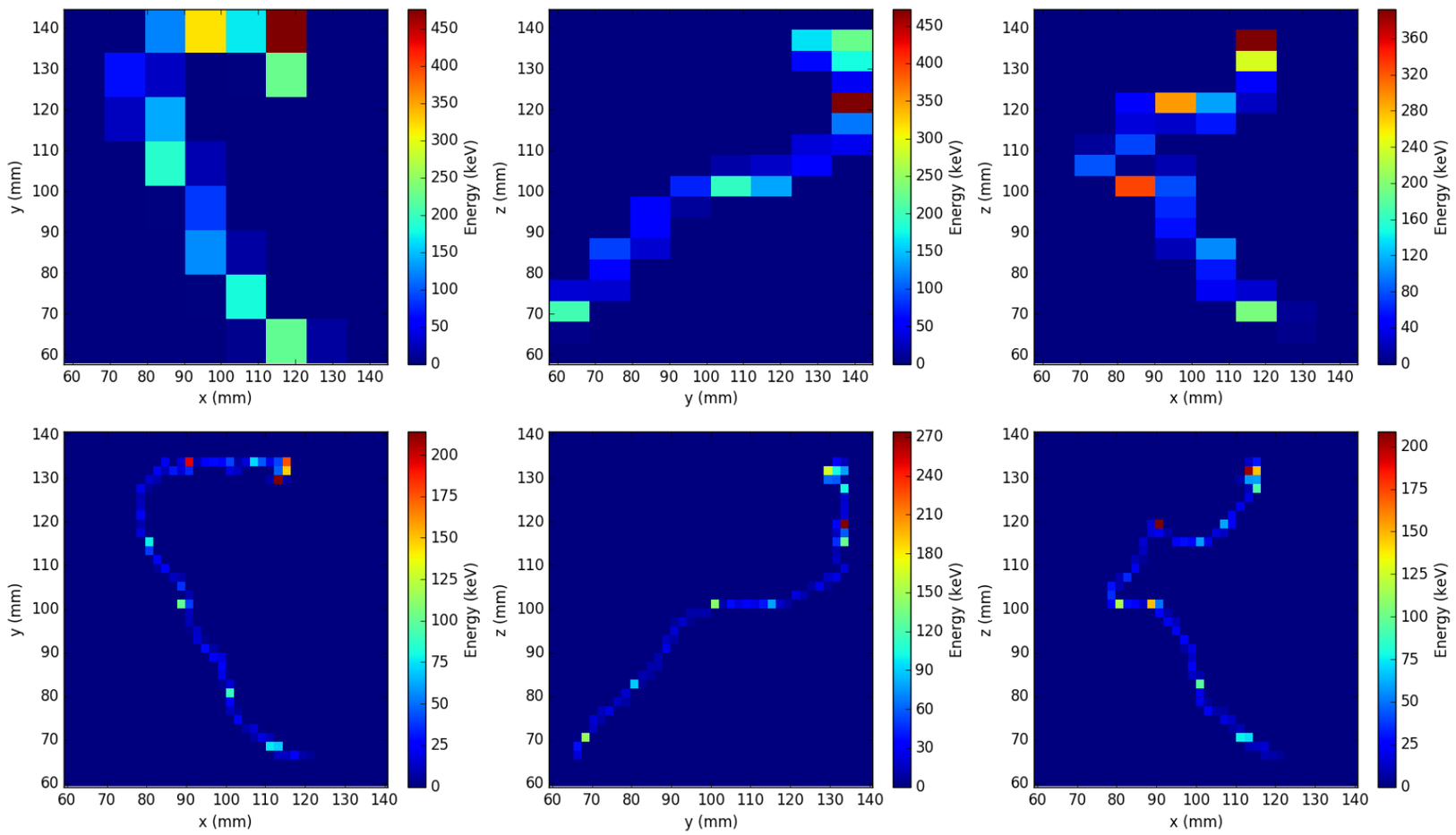


- Plot shows the sensitivity of a 100% efficient Xenon experiment (with a reasonable NME set).
- With a background ~10 cts/tonne/year and a mass of 1 ton, 10 years of run are required (e.g, 30 years for an efficiency of 30 %).
- With a background count of ~1 cts/tonne/year, "only" 2 years are required (6 years for an efficiency of 30%).

NEXT-2.0

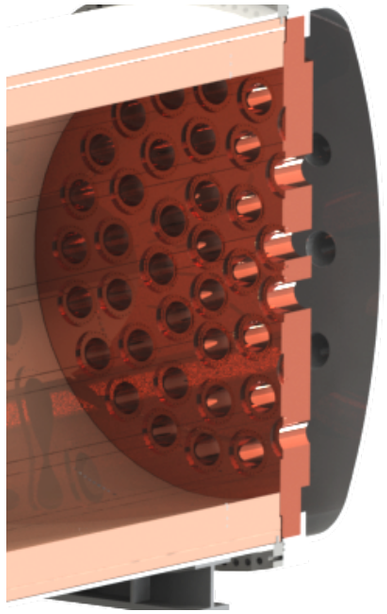


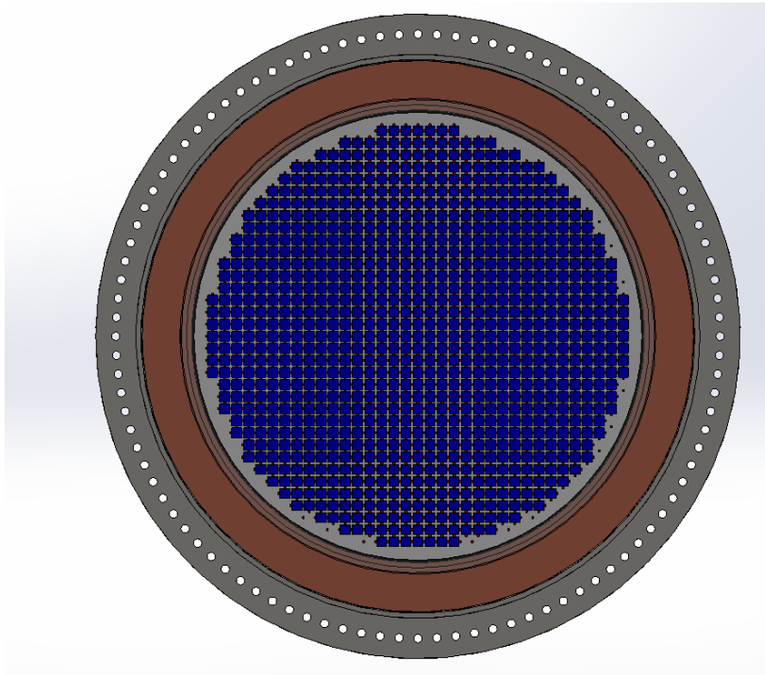
Improve topological signature



- Reduced diffusion can improve rejection power of topological signature by a factor 3.
- Requires low diffusion mixtures (Xe-He) and dense tracking.

Improve radioactive budget





- Replace PMTs by SiPMs mounted in ultra-low background substrates.
- Select ultra-low background copper (commercially available, need proper screening).
- Operate detector at -60 C (negligible dark current in SiPMs, reduced pressure for constant density)
- Radioactive budget can be cut to 1/3 of present projections.

NEXT-Ton Sensitivity

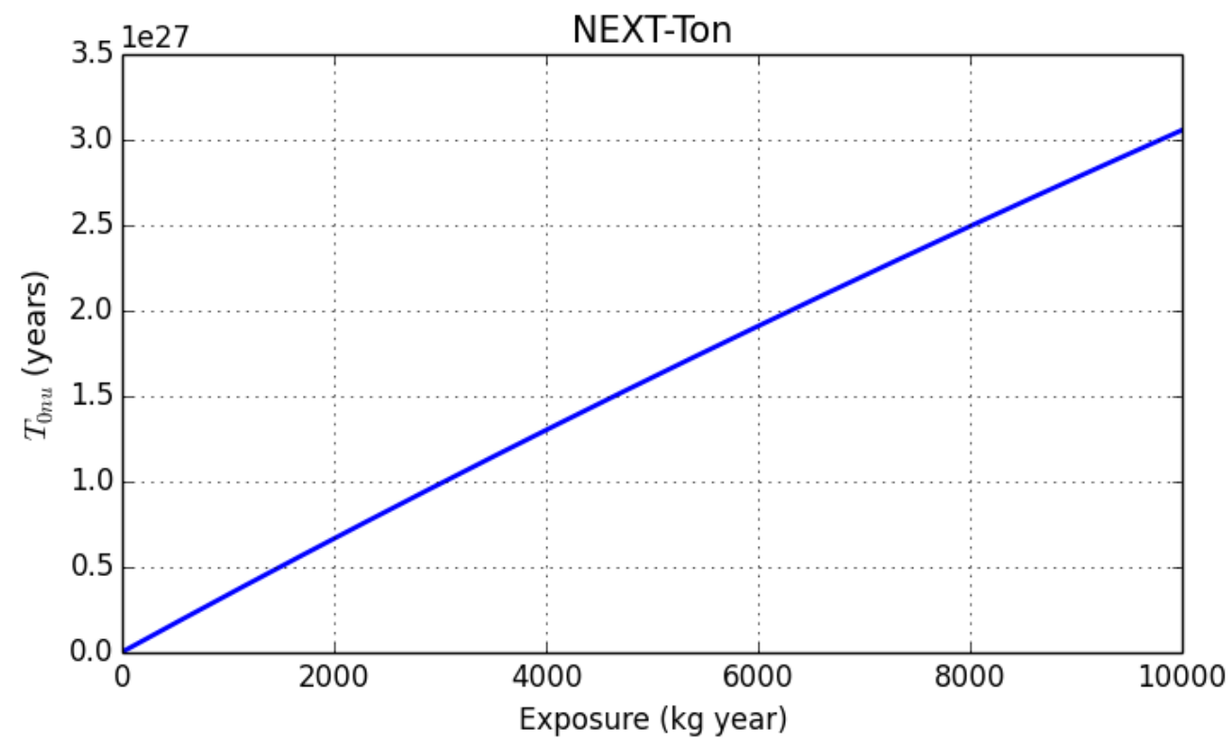
Total Background rate:

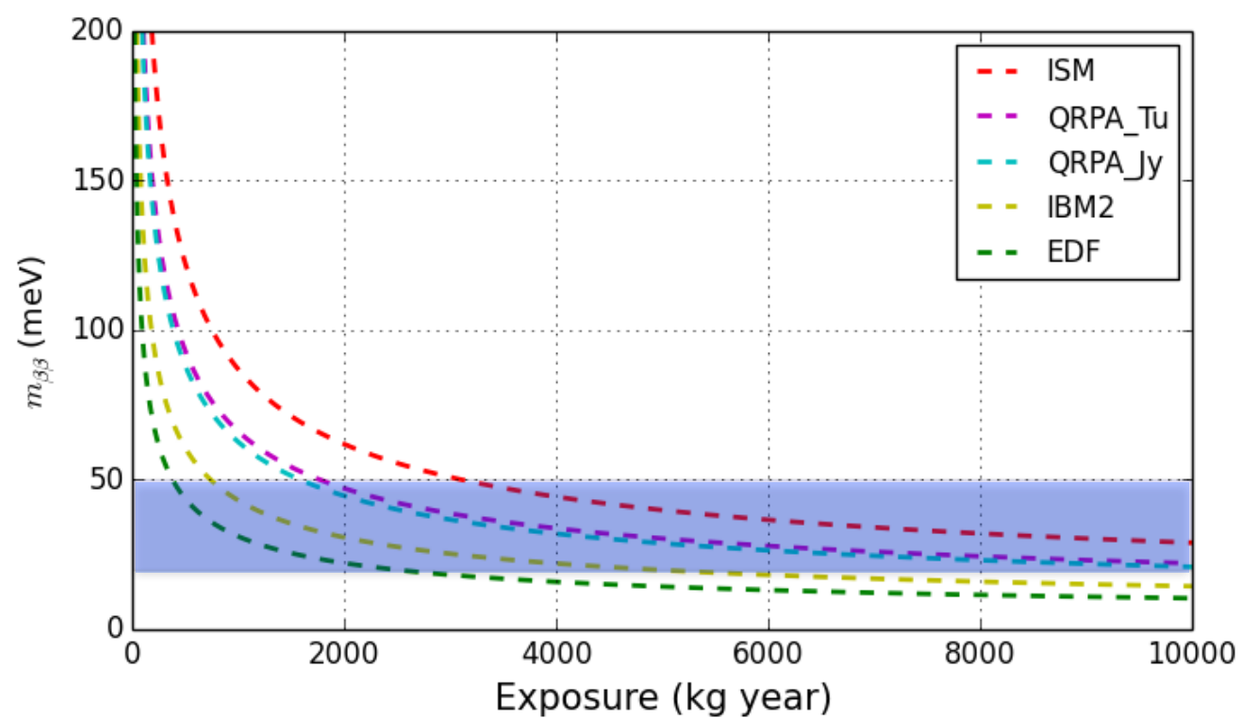
2.59×10^{-5} cts / keV kg year

Exposure of 5 ton year

0ν half-life ≃ $1.5\ 10^{27}$ years

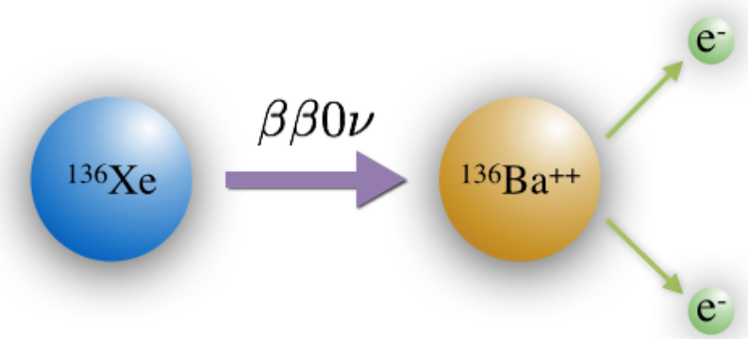
$m_{\beta\beta}$ = [15-42] meV





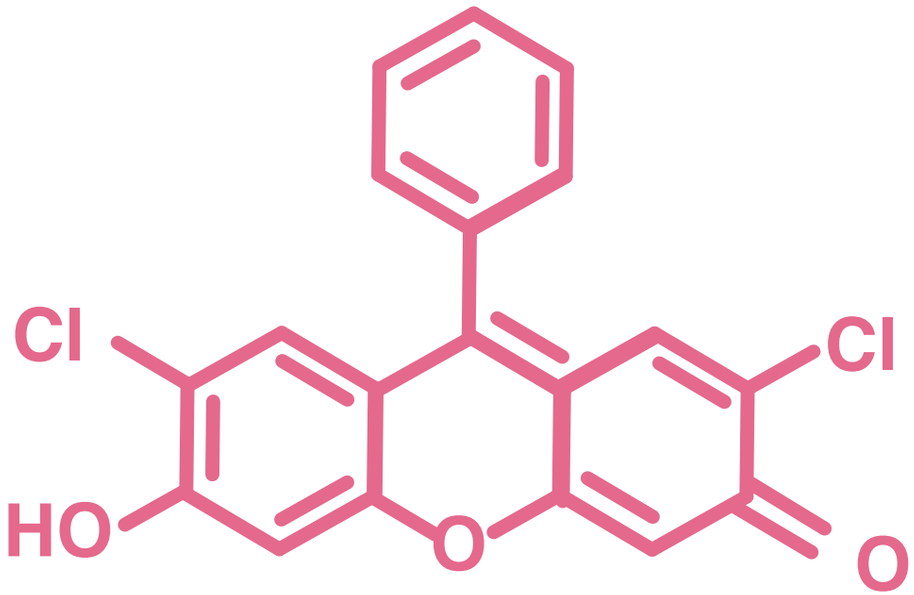
- But what if the signal is not in the IH
- Exploring the NH may be as difficult as leaving Calipso…
- Can it be done or shall we resign ourselves to watch the see and miss Ithaca forever?
- **Here is a possible way…**

BA-TAGGING

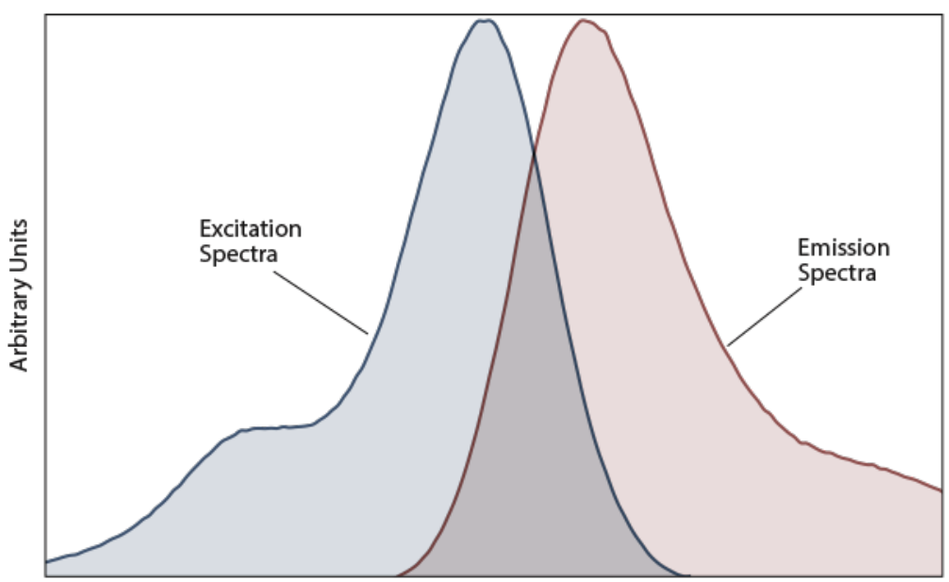


- Tagging the Ba++ atom = background free experiment, since natural radioactivity does not produce Ba++.
- But how do you “tag” de Ba++ ion?)

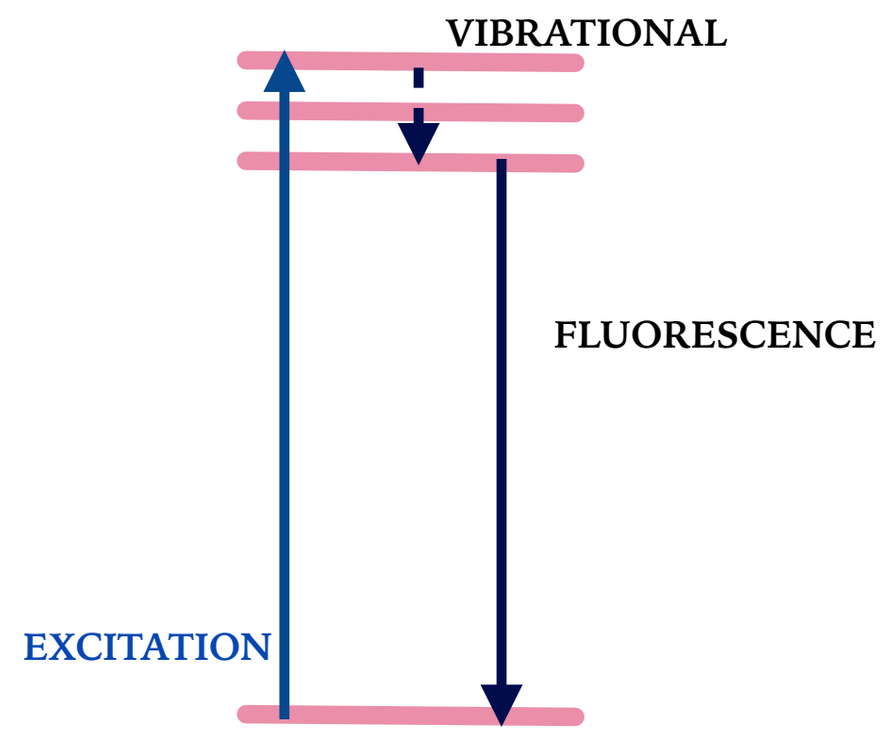
SINGLE MOLECULE FLUORESCENCE IMAGING



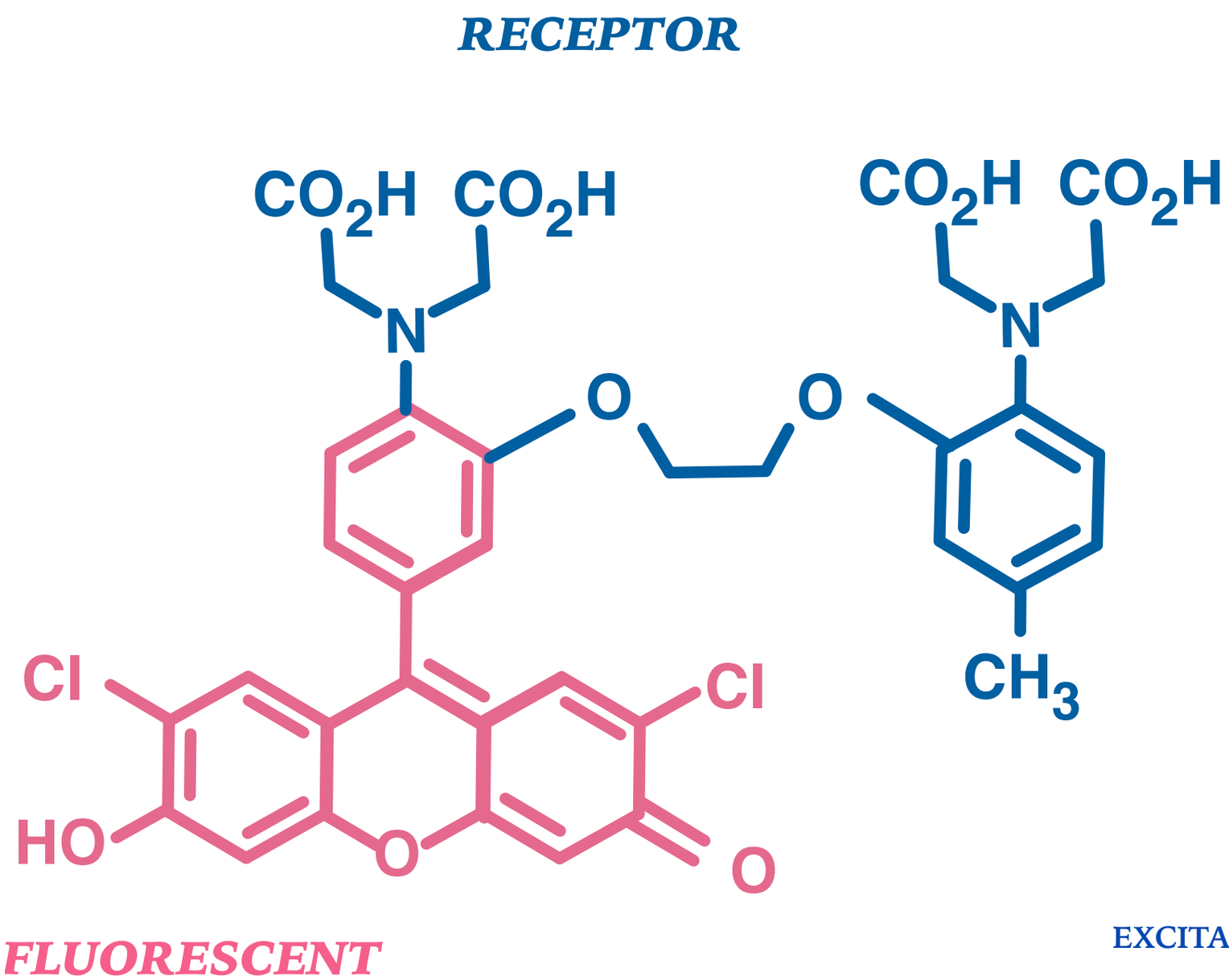
FLUORESCENT



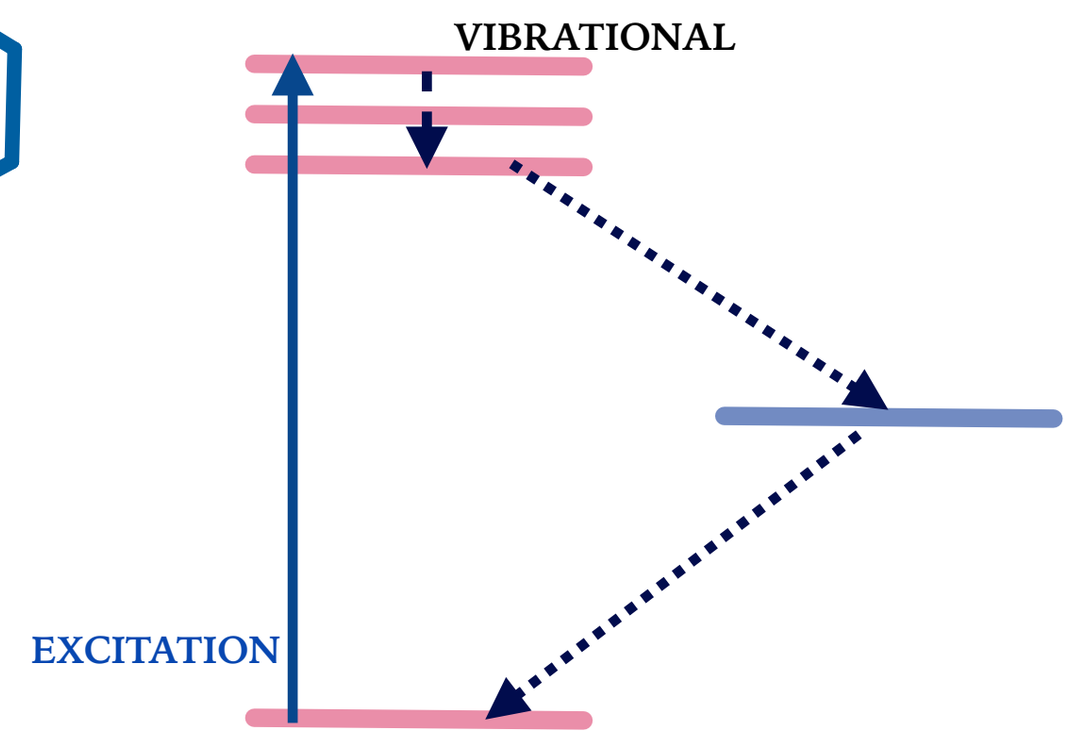
Molecule de-excites via fluorescence



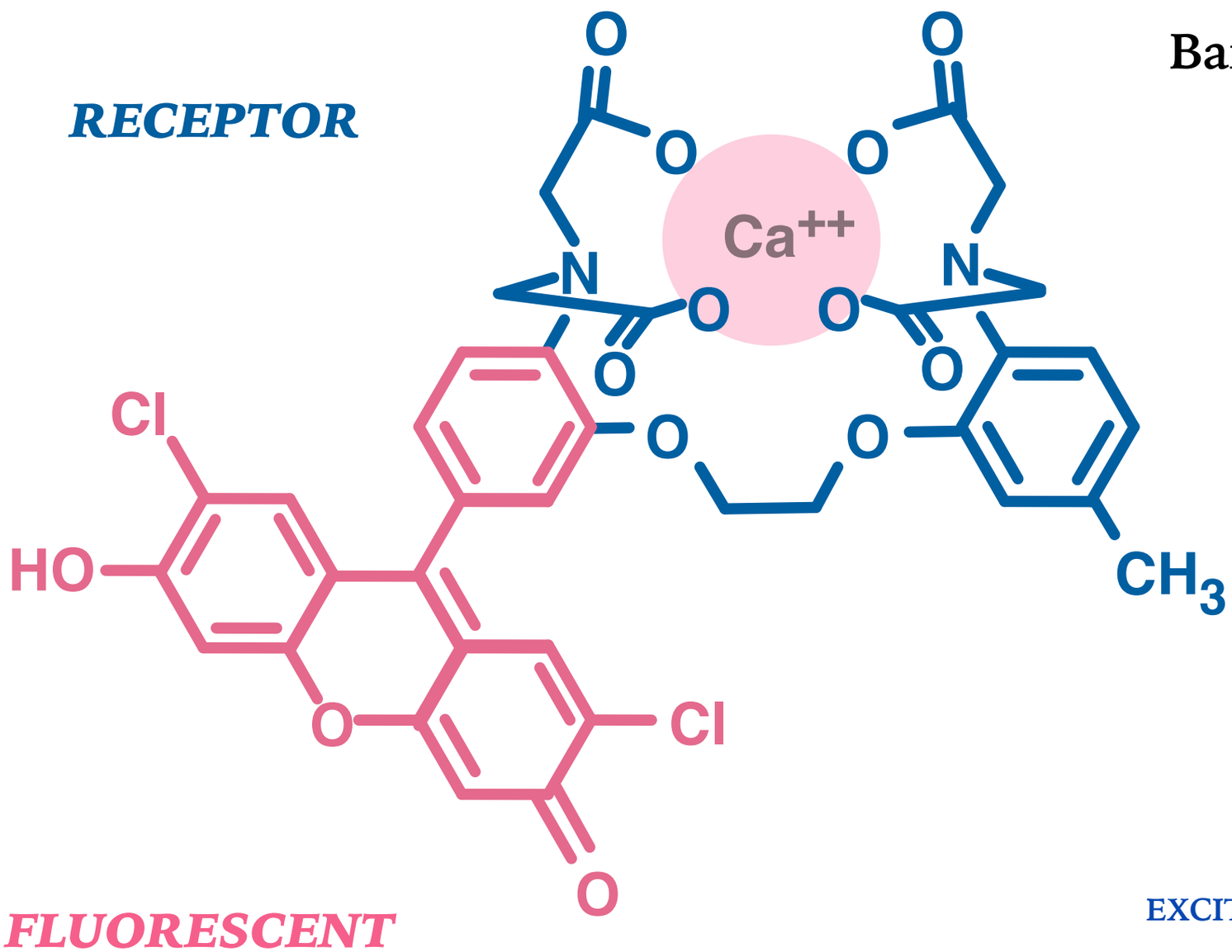
RECEPTOR-MOLECULES



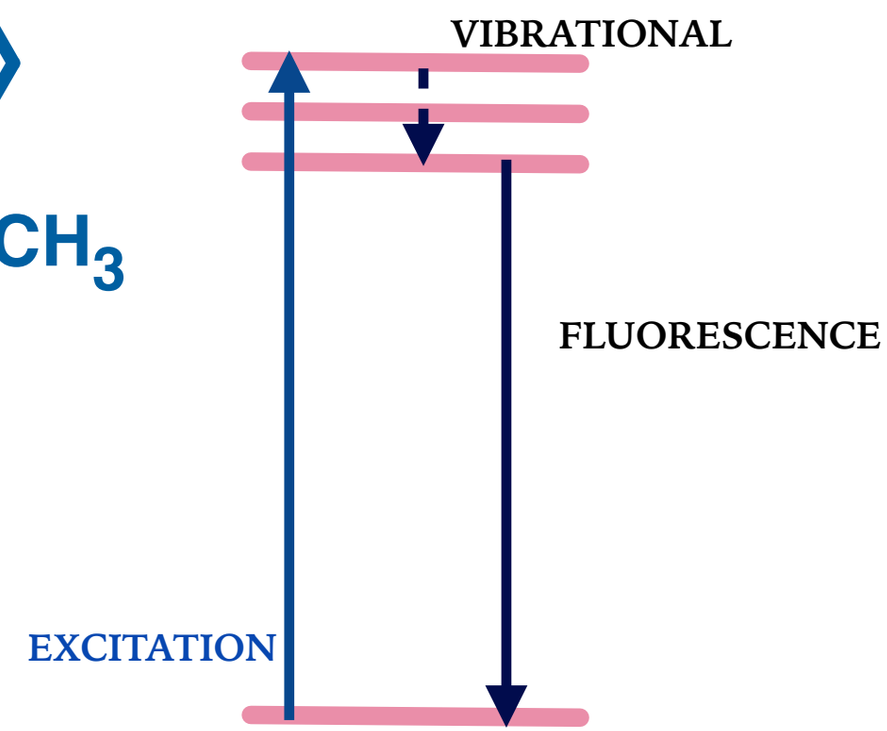
Molecular form inhibits fluorescence



CAPTURE OF MOLECULE

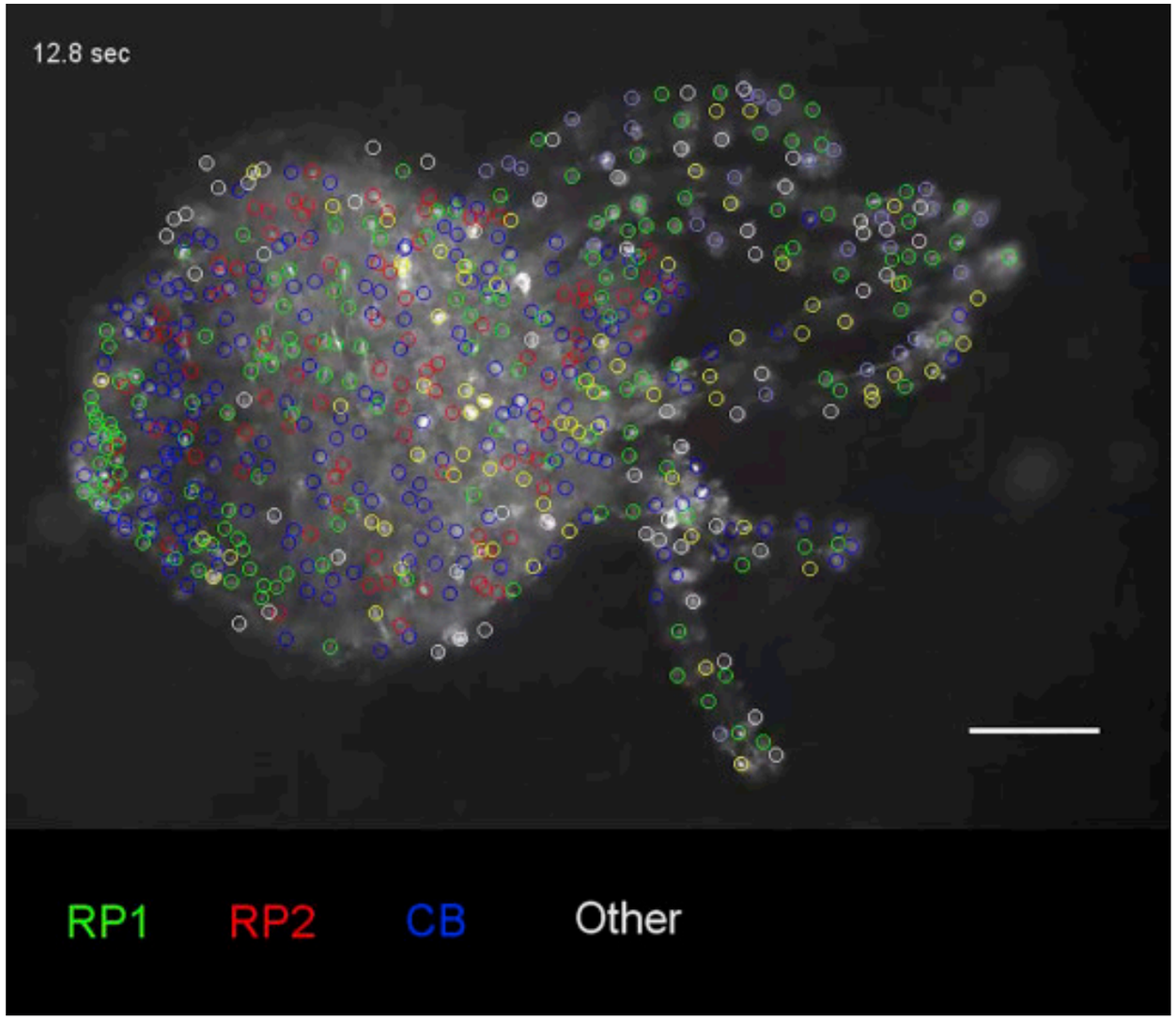


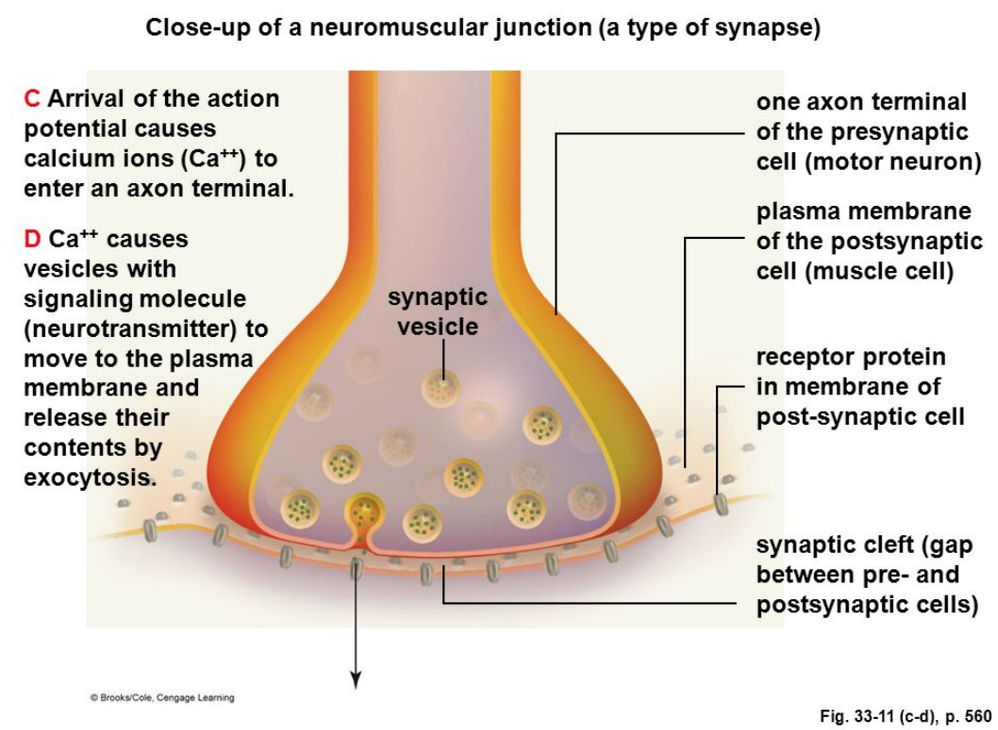
Barium trapping makes de-excitation via fluorescence available.



- **Technique works with Ca++… does it work for Ba++?**

MAKING THE HYDRA SHINE





Can single Ba^{++} ions be detected with SMFI?

PHYSICAL REVIEW LETTERS

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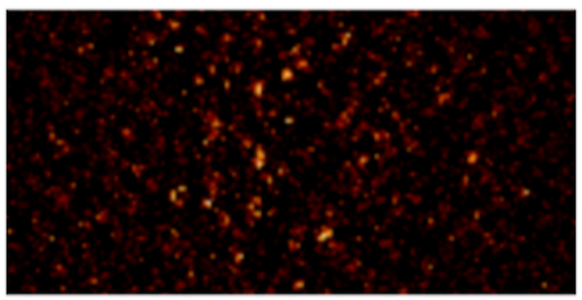


Physics NEWS AND COMMENTARY

Barium Ion Detector for Next-Generation Neutrino Studies

March 26, 2018

A device that can detect individual barium ions could be the heart of an experiment that takes the next step toward probing the nature of the neutrino.

Focus story on:
A.D. McDonald *et al.* (NEXT Collaboration)
Phys. Rev. Lett. **120**, 132504 (2018)

Demonstration of Single Barium Ion Sensitivity for Neutrinoless Double Beta Decay using Single Molecule Fluorescence Imaging

(The NEXT Collaboration)

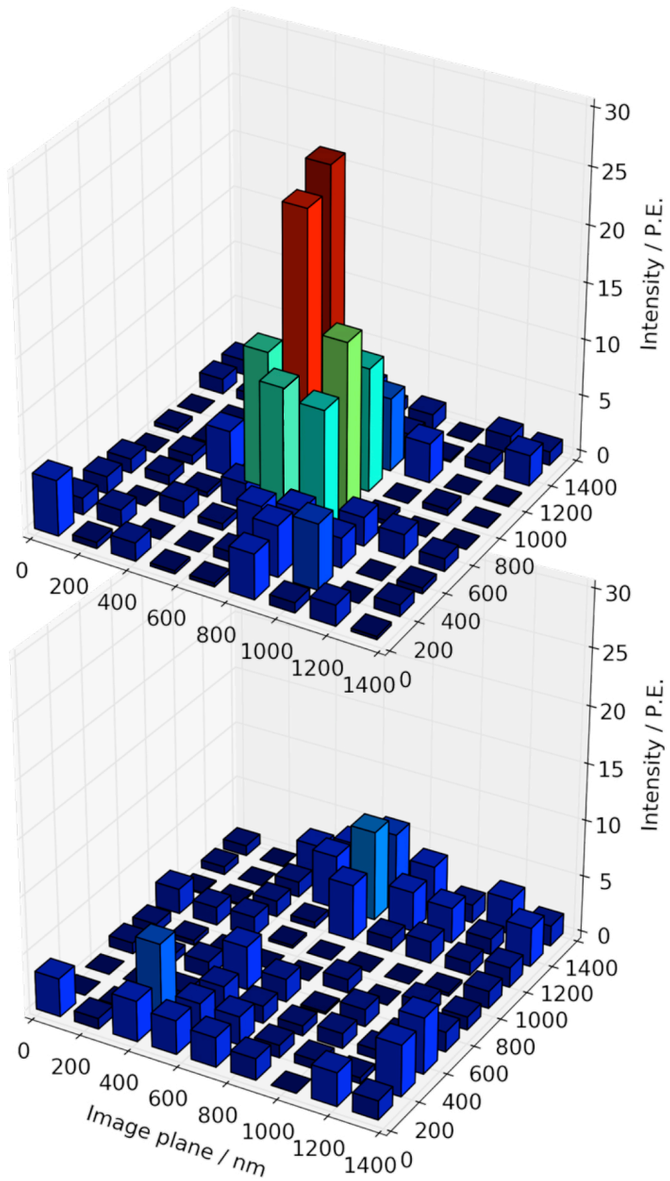


FIG. 1. A single Ba^{++} candidate. A fixed region of the CCD camera is shown with 0.5 s exposure before (top) and after (bottom) photo-bleaching transition.

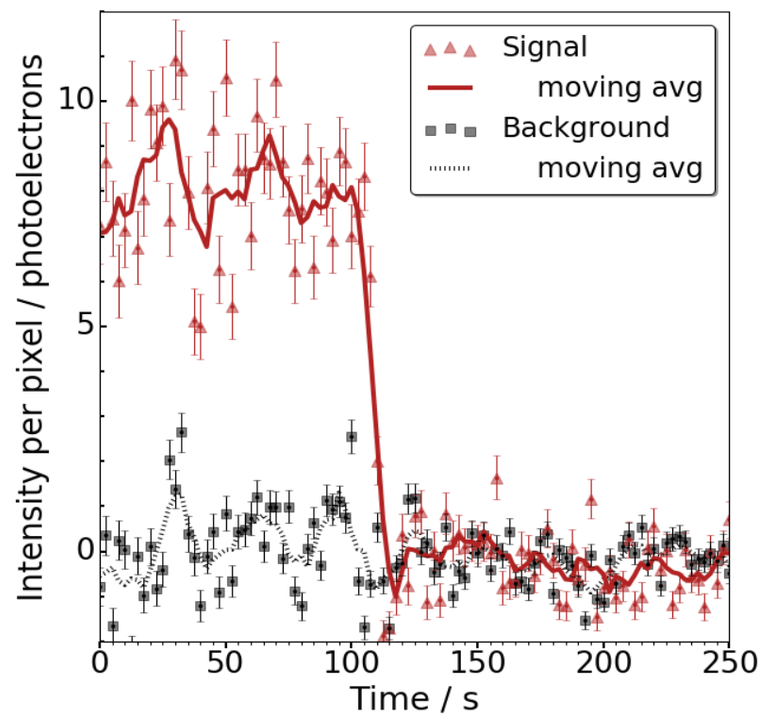


FIG. 4. Fluorescence trajectory for one candidate in a barium-spiked sample. "Signal" shows the average activity in 5x5 pixels centered on the local maximum. "Background" shows the average in the 56 surrounding. The single step photo-bleach is characteristic of single molecule fluorescence.

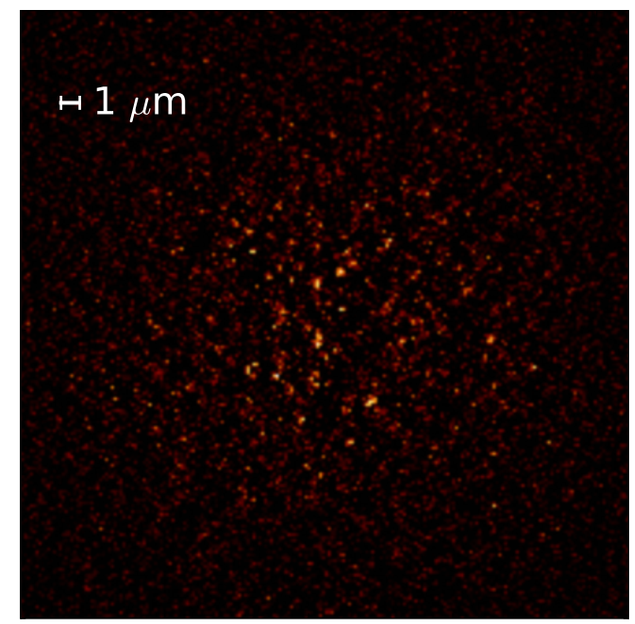
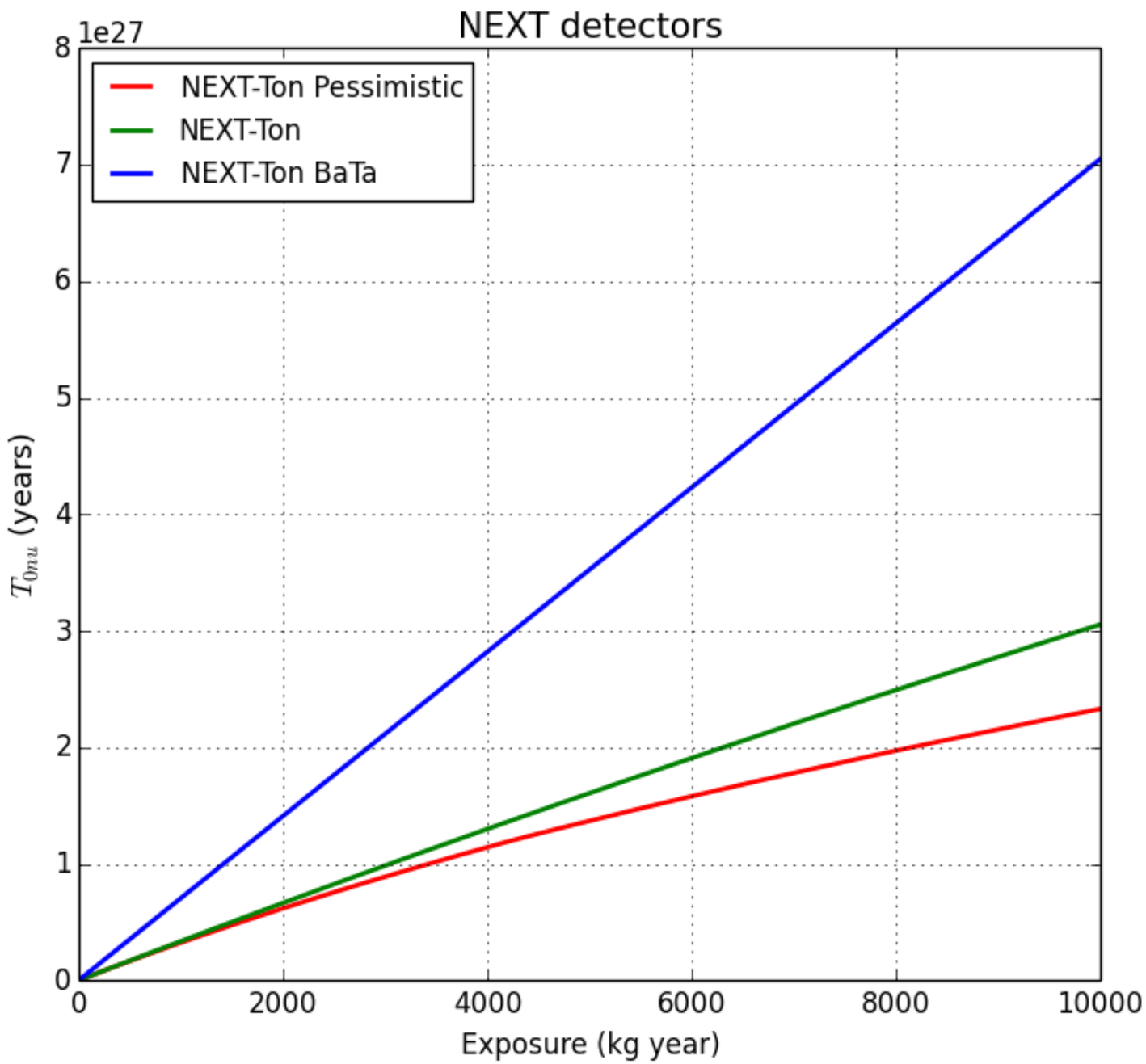


FIG. 3. A sample image from the EM-CCD in one of the barium-spiked samples showing both near-surface (bright) and deeper (dim) fluorescent molecules.

Barium tagging



After 5 years of data taking:

Next-Ton

0ν half-life = 1.47 10^{27} years

$m_{\beta\beta}$ = [15-42] meV

Next-Ton + BaTa

0ν half-life = 7 10^{27} years

$m_{\beta\beta}$ = [10-28] meV

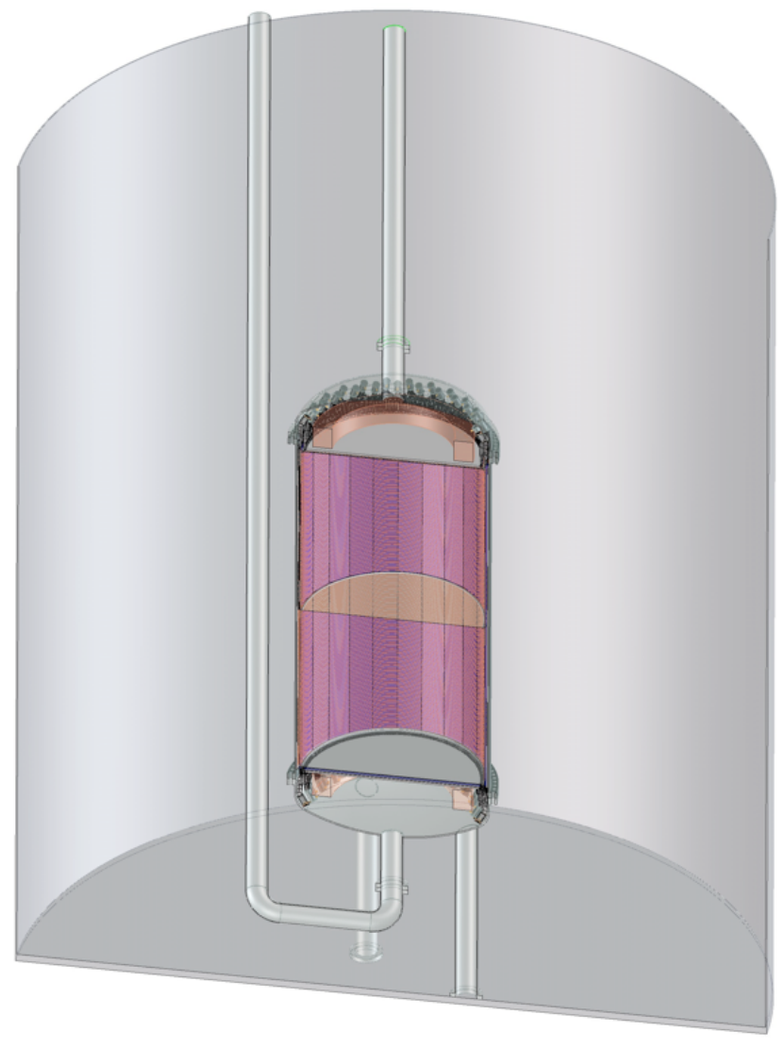
Background free, ten-ton experiment? Why not?

Summary

- The NEXT program was started 10 years ago by Dave Nygren, James White and JJGC.
- The NEXT-White demonstrator is in full operation. Background index and bb2nu measurements foreseen for next year.
- NEXT-100 will start operations in 2020.
- The NEXT program has the potential to explore lifetimes of the bb0nu mode of 10^{27} y and beyond.
- Exciting potential for a background-free experiment with Ba++ SMFI tagging.

NAUSICAA

Next apparatUS with Improved CApAbilities



Ithaca

When you set out on your journey to Ithaca,
pray that the road is long,
full of adventure, full of knowledge.

Pray that the road is long.
That the summer mornings are many, when,
with such pleasure, with such joy
you will enter ports seen for the first time;

Always keep Ithaca in your mind.
To arrive there is your ultimate goal.
But do not hurry the voyage at all.
It is better to let it last for many years;
and to anchor at the island when you are old,
rich with all you have gained on the way,
not expecting that Ithaca will offer you riches.

Ithaca has given you the beautiful voyage.
Without her you would have never set out on the road.
She has nothing more to give you.
And if you find her poor, Ithaca has not deceived you.
Wise as you have become, with so much experience,
you must already have understood what Ithacas mean.

Constantine P. Cavafy

The NEXT Collaboration

Autónoma Madrid • Girona • IFIC Valencia • Politécnica Valencia • Santiago de Compostela

ANL • FNAL • Iowa State • Ohio State • Texas Arlington • Texas A&M

Coimbra GIAN • Coimbra LIP • Aveiro

JINR

A. Nariño