THE NEXT PROGRAM FOR NEUTRINOLESS DOUBLE BETA DECAY SEARCHES

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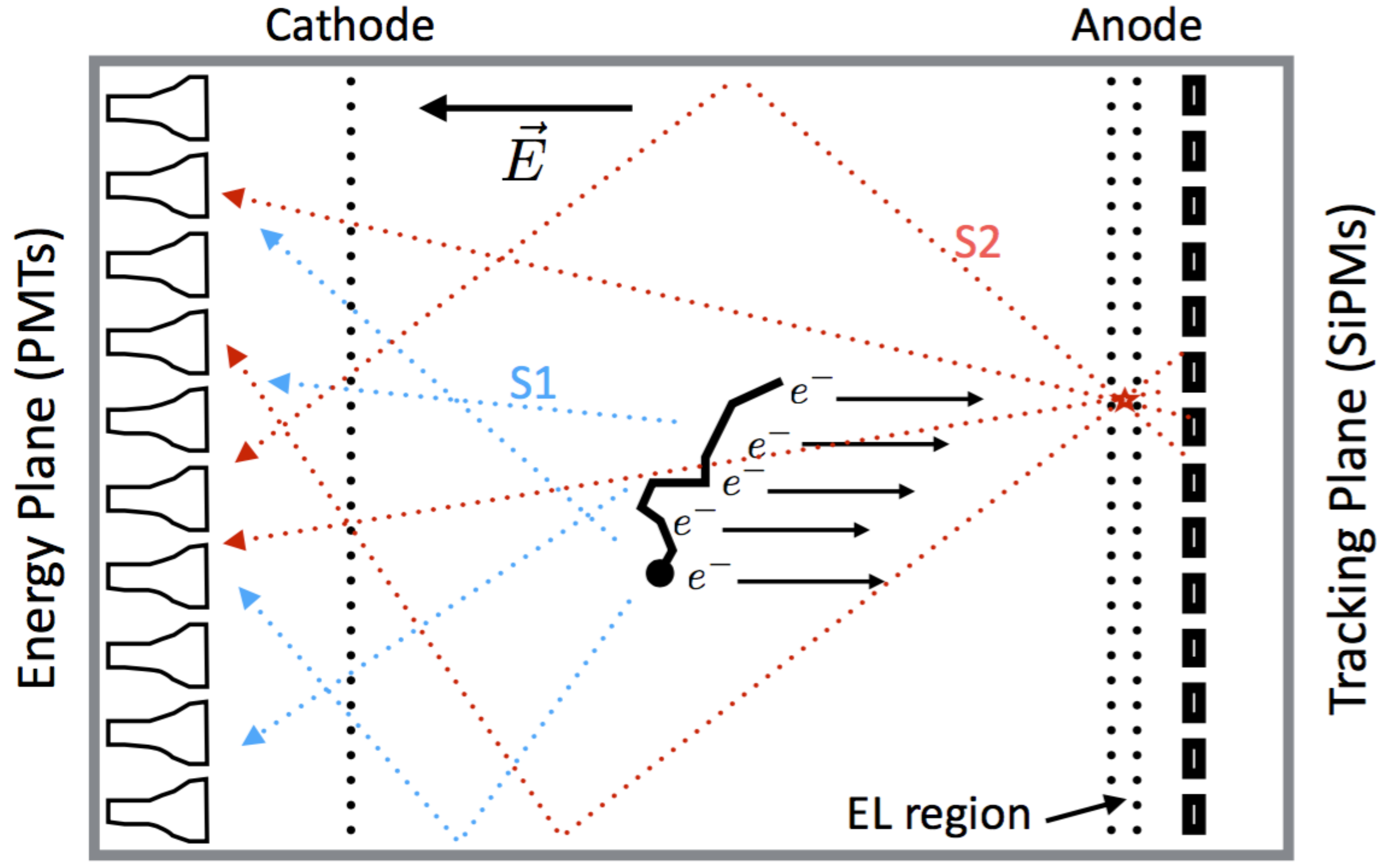
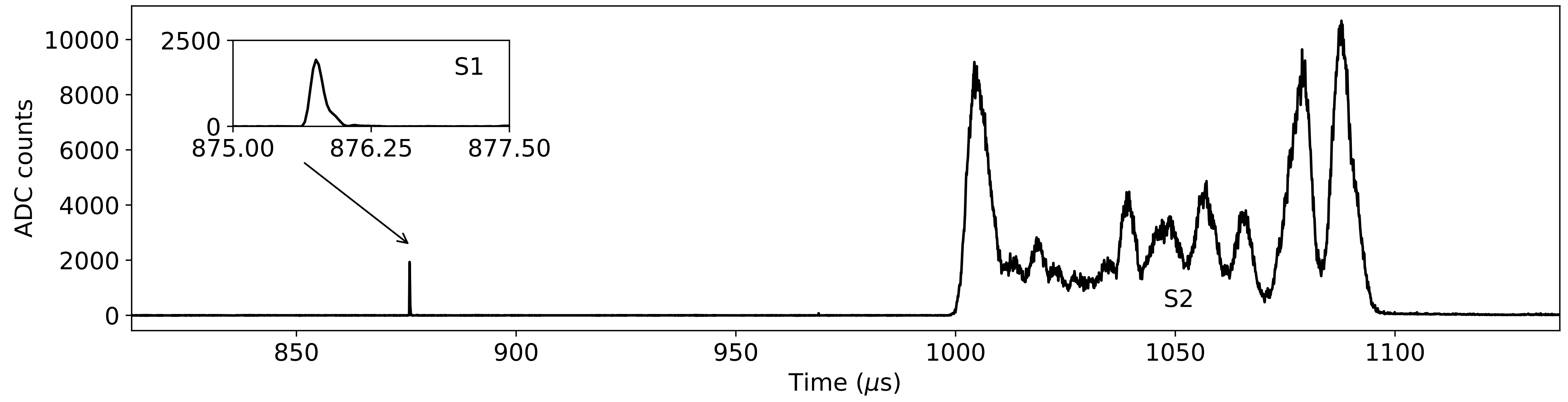
European Research Council

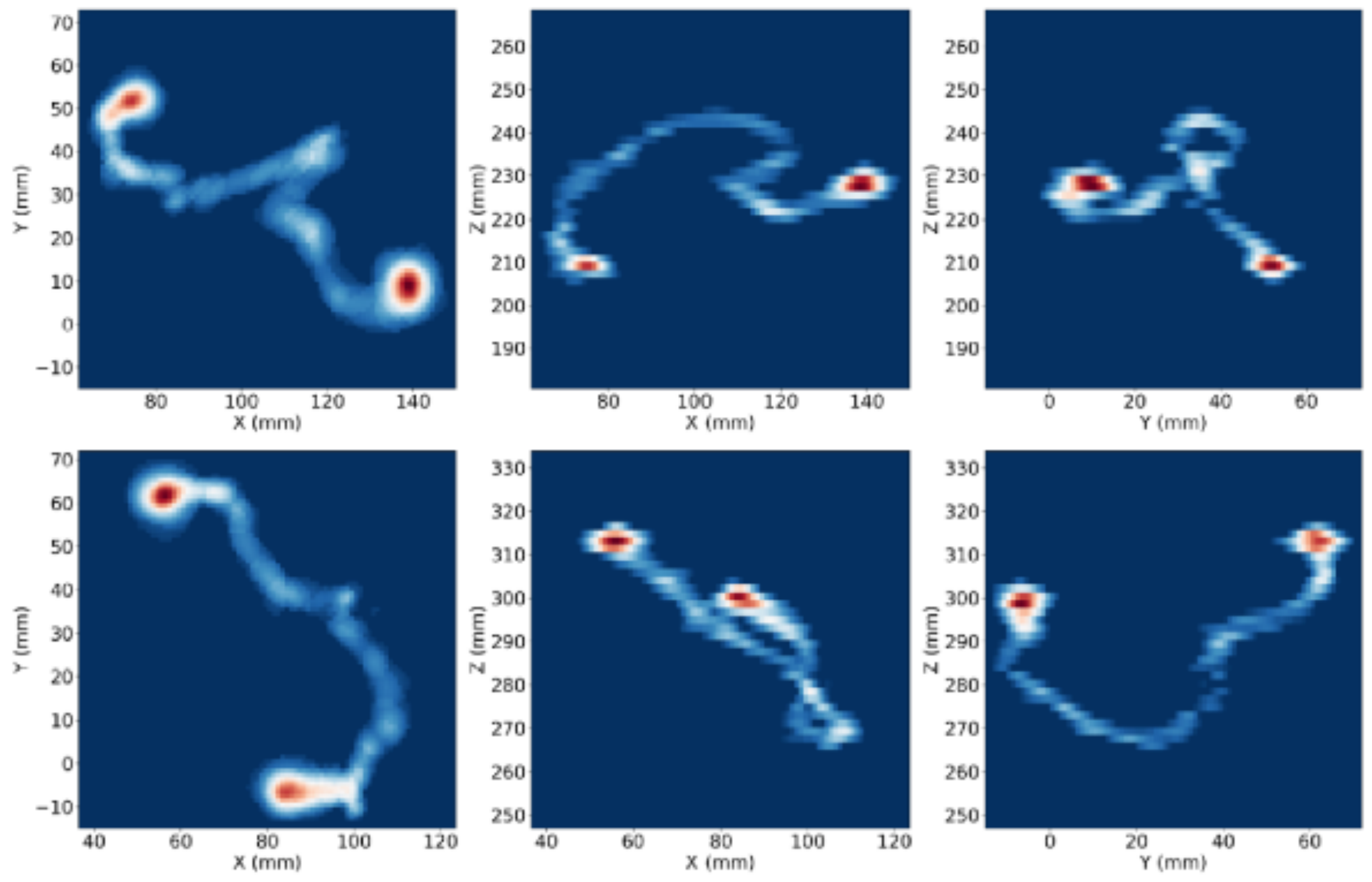
ikerbasque
Basque Foundation for Science

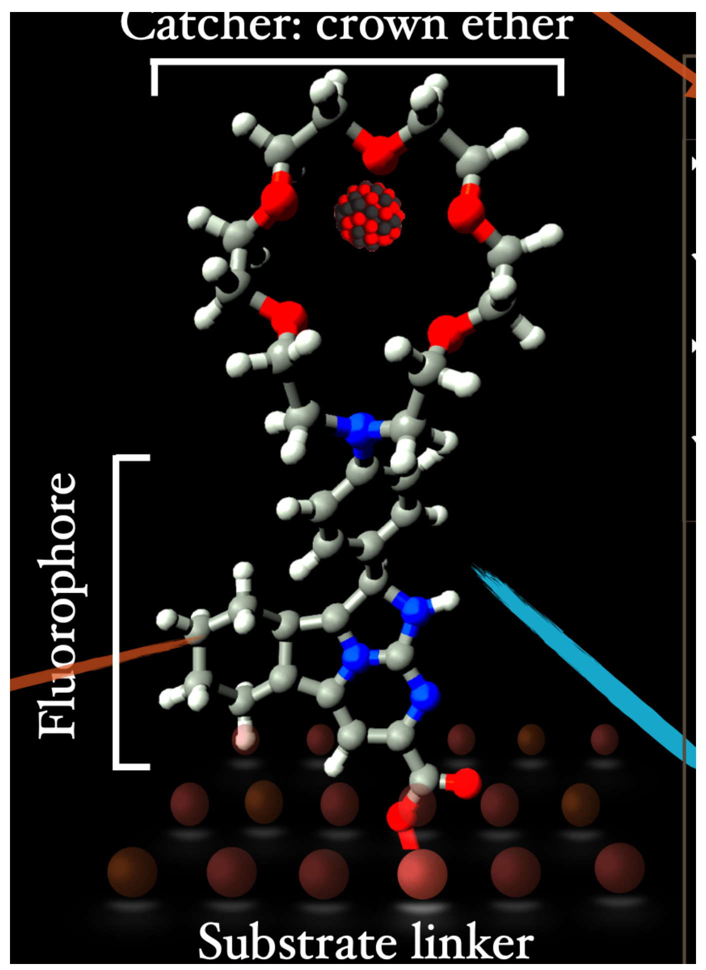
Frascati, October 2021

Detector Concept





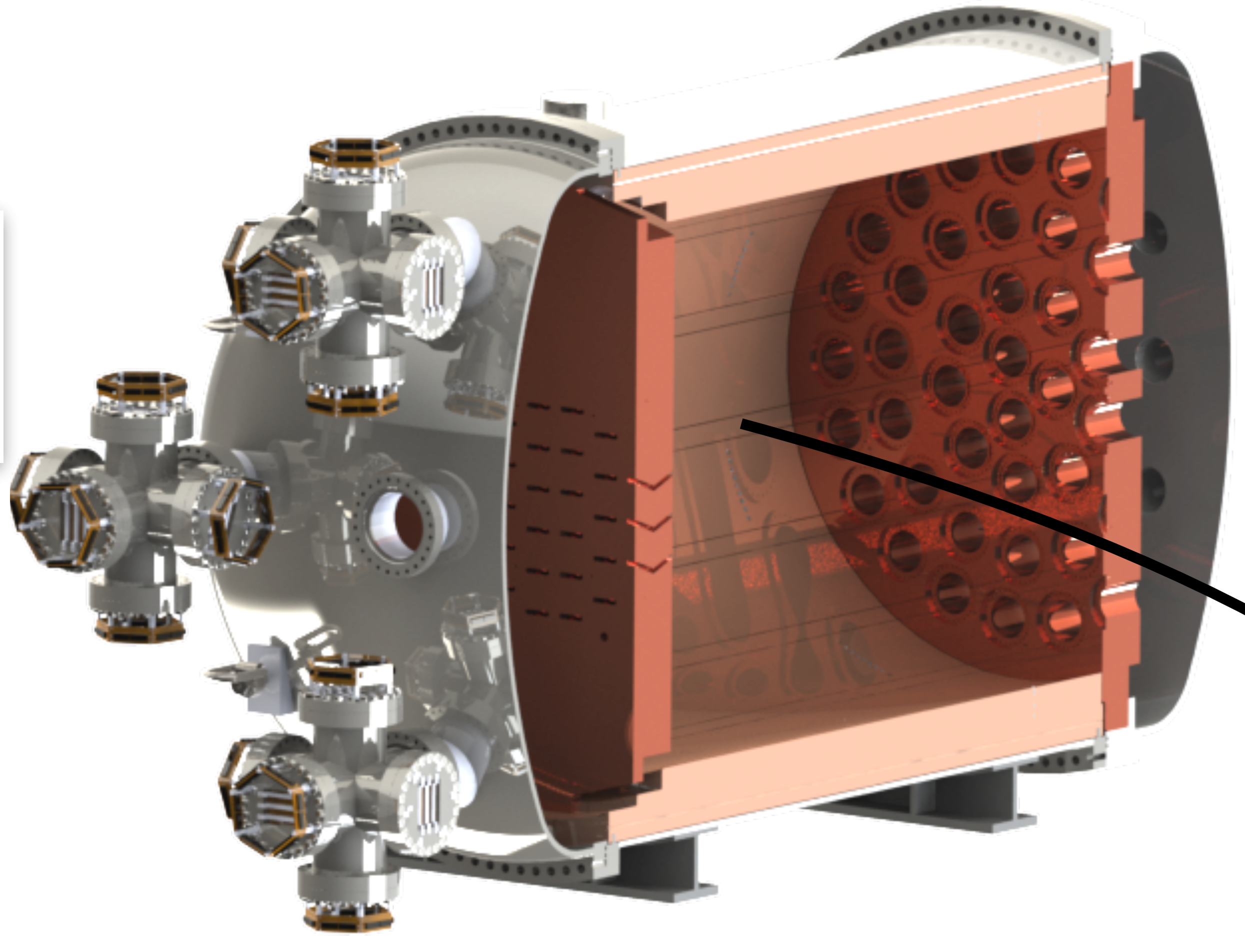




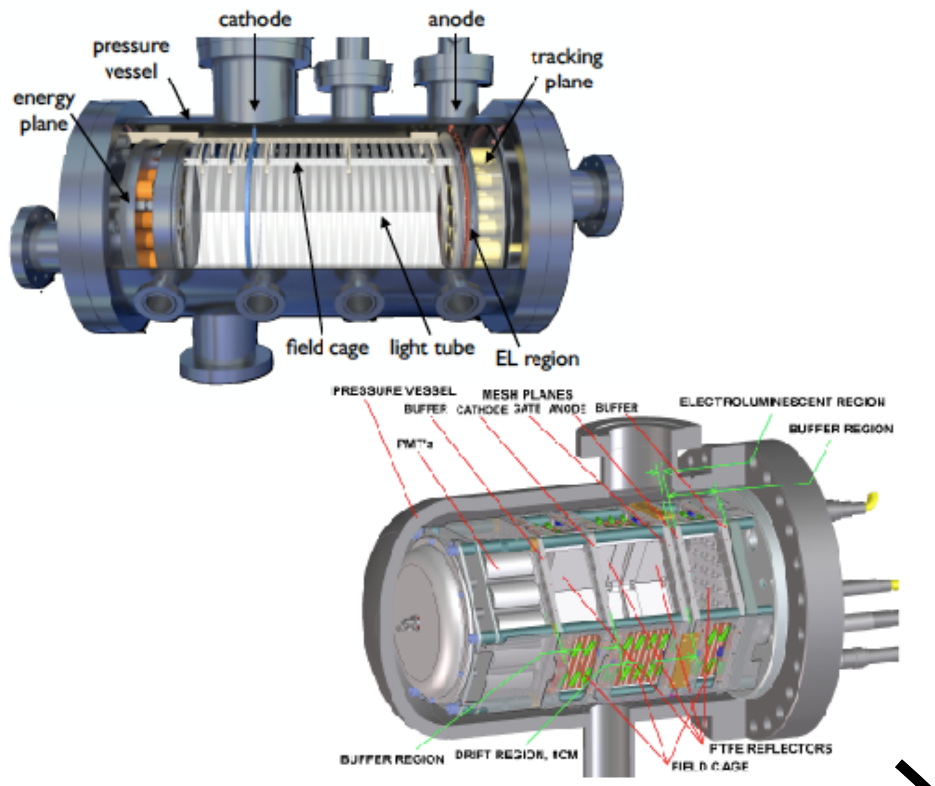
- High pressure Xenon TPC with electroluminescence amplification of the signal
- Good energy resolution (measured <1 % FWHM, feasible 0.7 % FWHM).
- Topological signature (reconstruction of electrons in event). Measured ~60 % efficiency for~1/30 background suppression
- Radiopure detector, along the lines of all other Xe TPCs
- Can be scaled to masses in the range of the tonne.
- Multi-module/multi-site possible
- Can implement Barium Tagging.

The NEXT program

NEXT-100 (~100 kg)
[2022 - 2026]



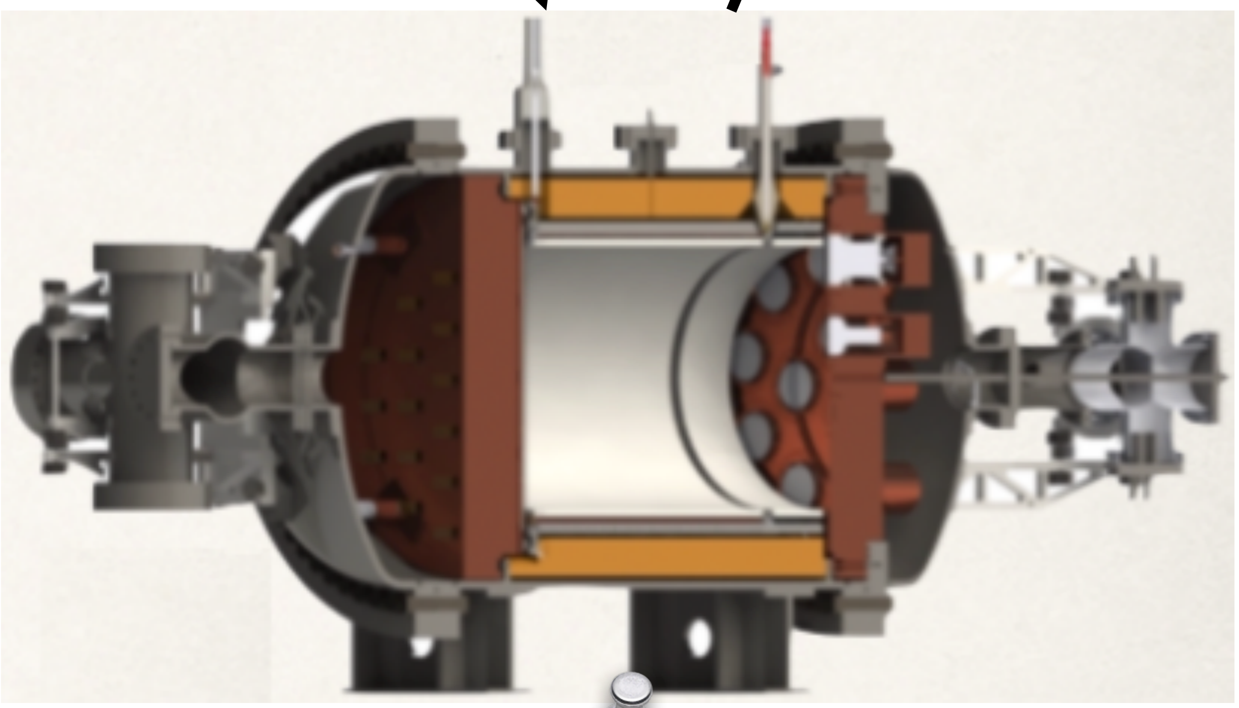
ββ0ν searches (10^{26} y)
Show extrapolation to ton scale



Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept

NEXT-White (~5 kg)
[2015 - 2021]



Underground and radio-pure operations, background, ββ2ν

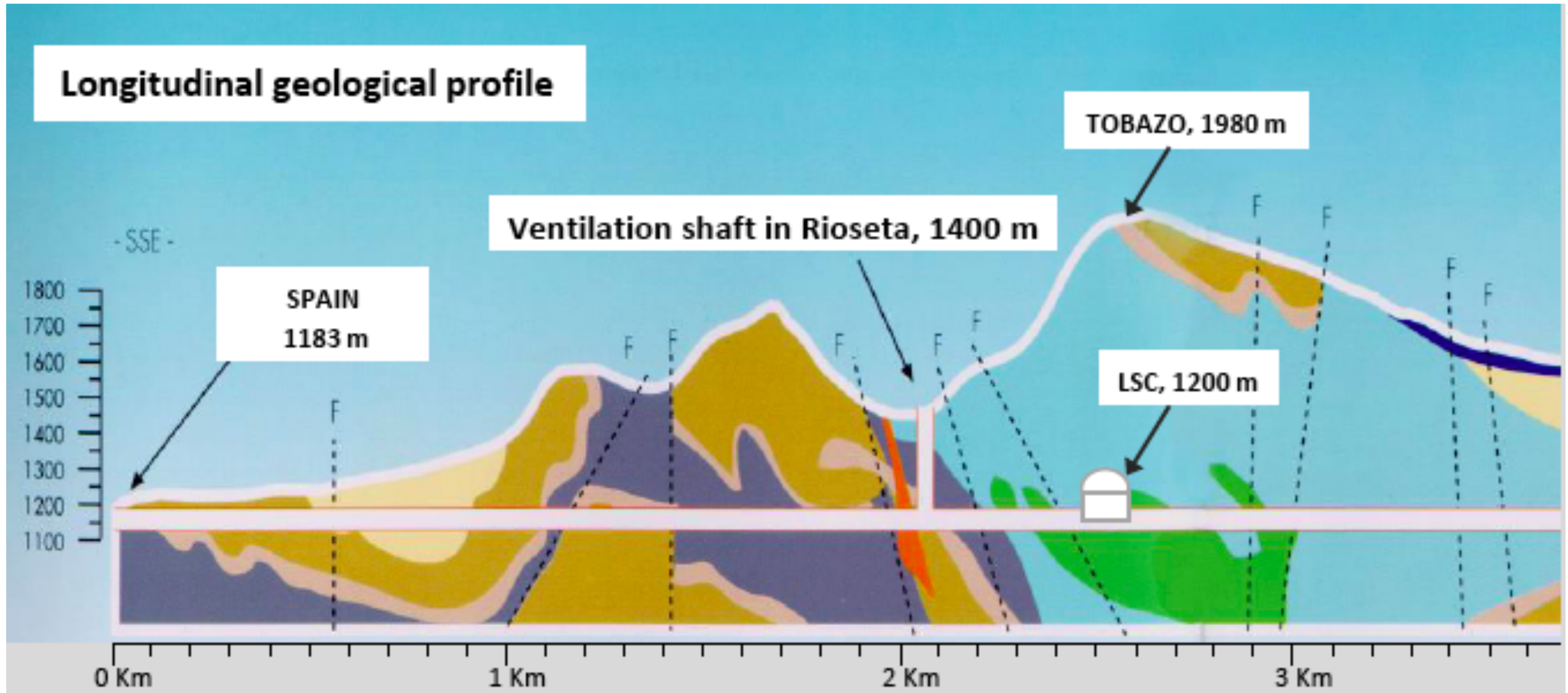
NEXT-HD/BOLD
[2026…]

ββ0ν searches (ββ0ν searches (10^{27}- 10^{28} y)


next
LSC
Laboratorio Subterráneo de Canfranc
Nantes
Cholet
Châteauroux
Bourges
Bilbao
Irun
Toulouse
Montpellier
Vitoria-Gasteiz
Pau
Béziers
Perpignan
León
Logroño
Pamplona
Girona
Zaragoza
Lérida
ESPAÑA
Barcelona
Tarragona
Madrid
Toledo
Castelló de la Plana
Valencia
Palma de Mallorca
Alicante
0
100
200
300 km

Canfranc Underground Laboratory (LSC)

Laboratorio Subterráneo de Canfranc



800 m bajo el Tobazo (~ 2500 m.w.e)
Radon 50 - 80 Bq/m^3
Neutron (<10 MeV) ~ 3×10^{-6} n/(cm^2 s)
Gamma ~ 1/(cm^2 s)

- Inlet air flux 20000 m^3/h
- Radon 50-80 Bq/m^3
- Muons $(5.3 \pm 0.2) \cdot 10^{-3}\ m^{-2}s^{-1}$
  Neutrons(<10 MeV) ~$3.5\cdot10^{-6}$ $cm^{-2}s^{-1}$
- Gamma ~ 2 $cm^{-2}s^{-1}$

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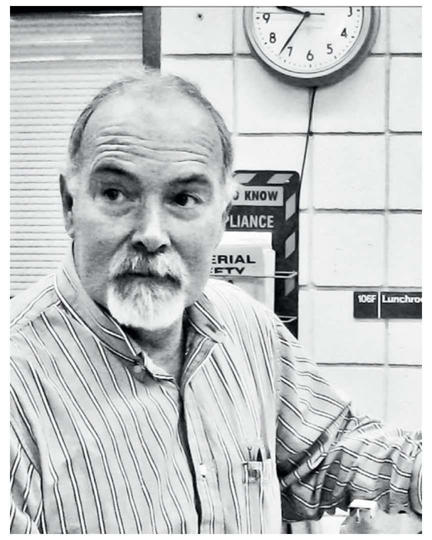
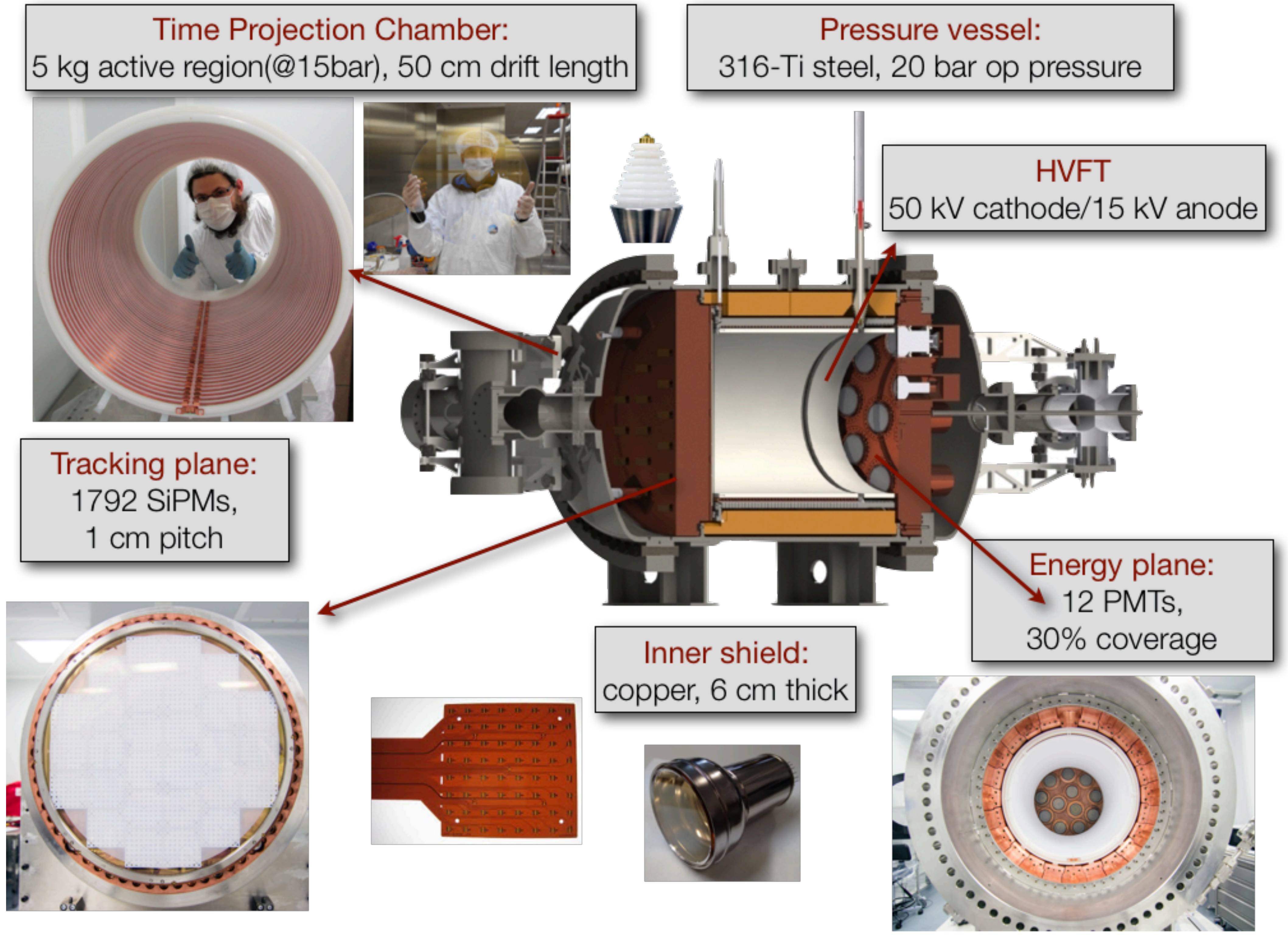
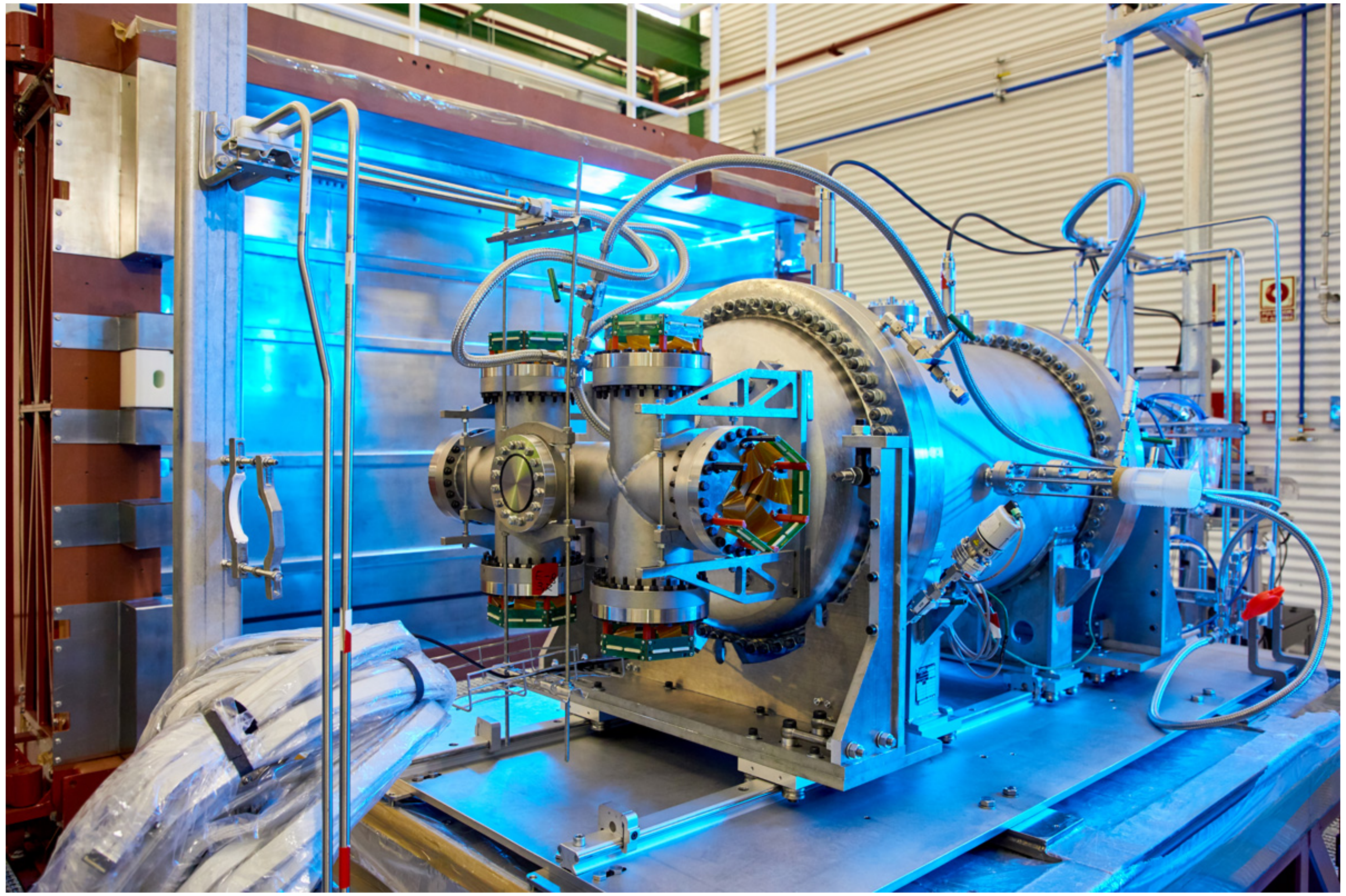
NEXT-White



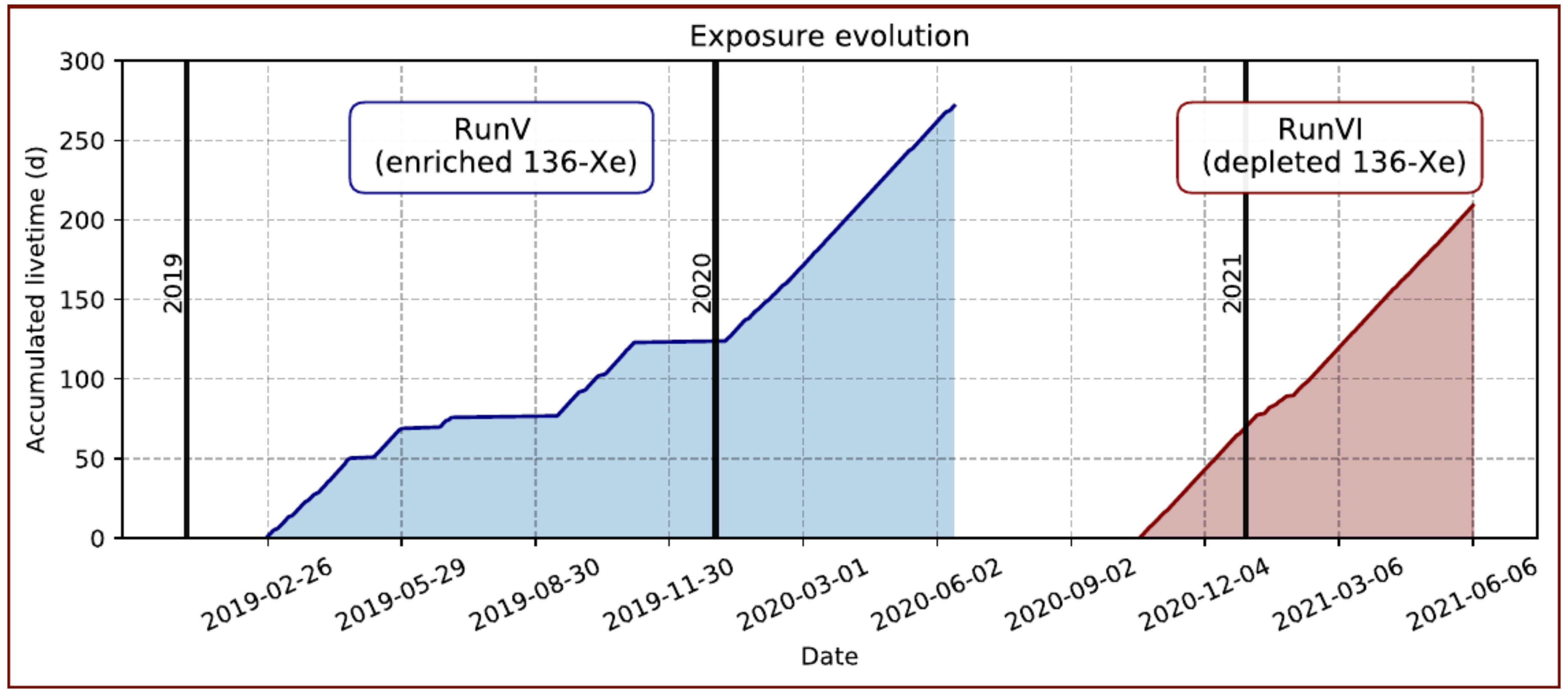
Our beloved friend
The late professor James White.



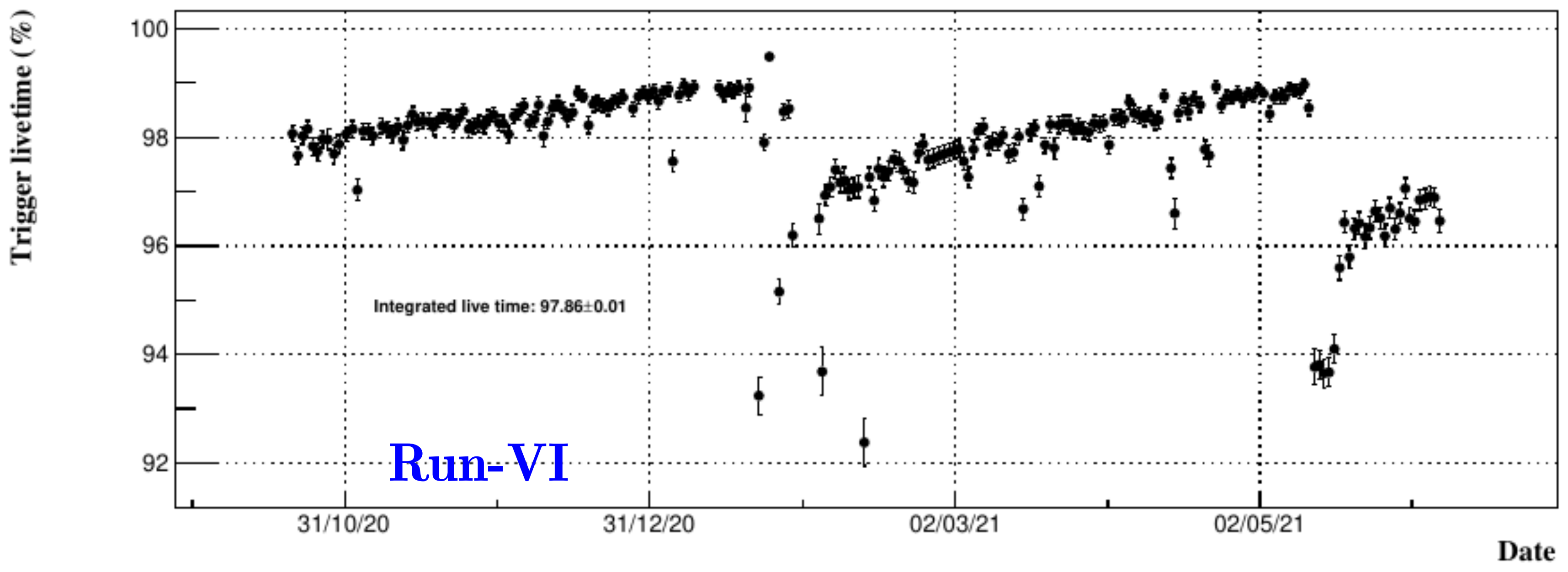


NEXT-White operation

- 2016-2018: Calibration campaigns @ 7/10 bar (Run-I – Run-III)
- 2018-2019: Background measurement with ^{136}Xe-depeleted xenon (Run-IV)
- 2019-2021: $\beta\beta2\nu$ combining ^{136}Xe-enriched (Run-V) and ^{136}Xe-depeleted (Run-VI) data:



Run period	Start Date	Run time (day)	Triggers
Run-Va	25-02-2019	75.8	617,896
Run-Vb	13-09-2019	47.1	412,902
Run-Vc	08-01-2020	148.7	1,117,101
Run-V	25-02-2019	271.6	2,147,899
Run-VI	20-10-2020	208.9	1,646,501

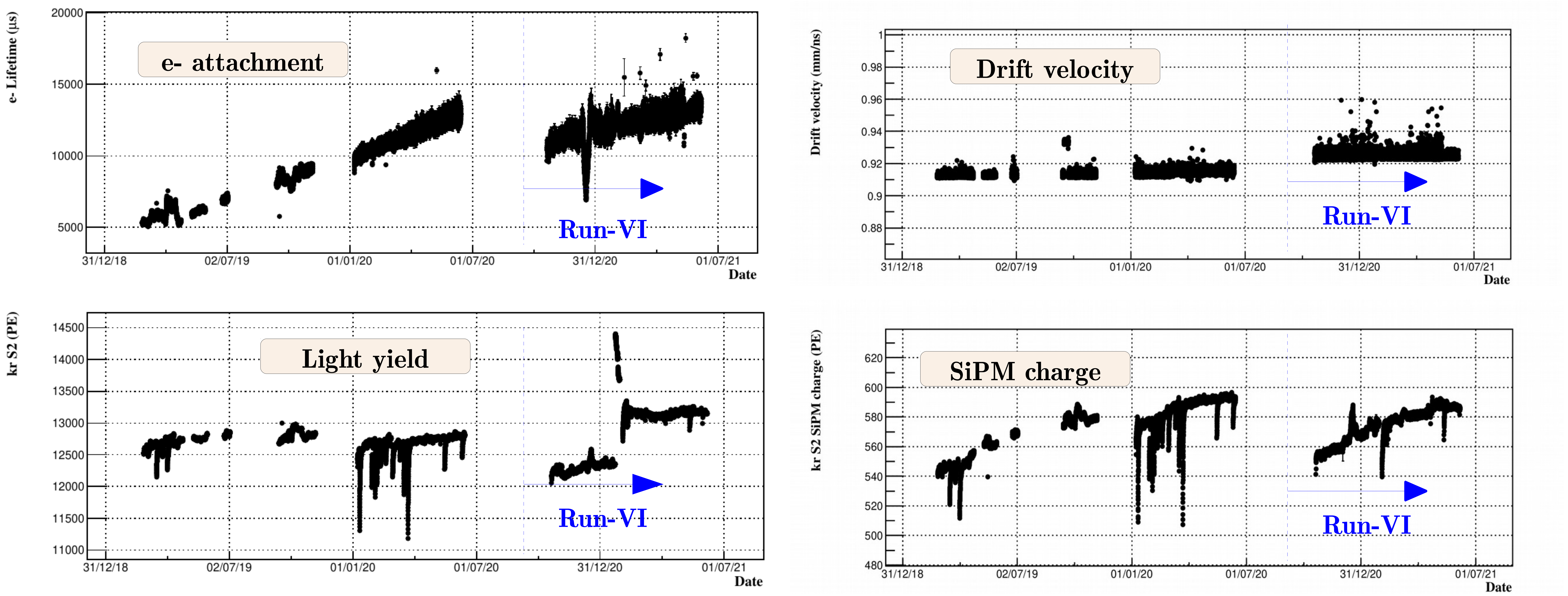


- Total run-times: 271.6 day (Run-V) and 208.9 day (Run-VI)
- DAQ dead time: ~3% @ Run-V and ~2% @ Run-VI
- Summer 2021: detector decommissioning
  - Emptied, cables disconnected, ILC removed

NEXT-White @ LSC 28th SC meeting

Continuous calibration with ^{83m}Kr

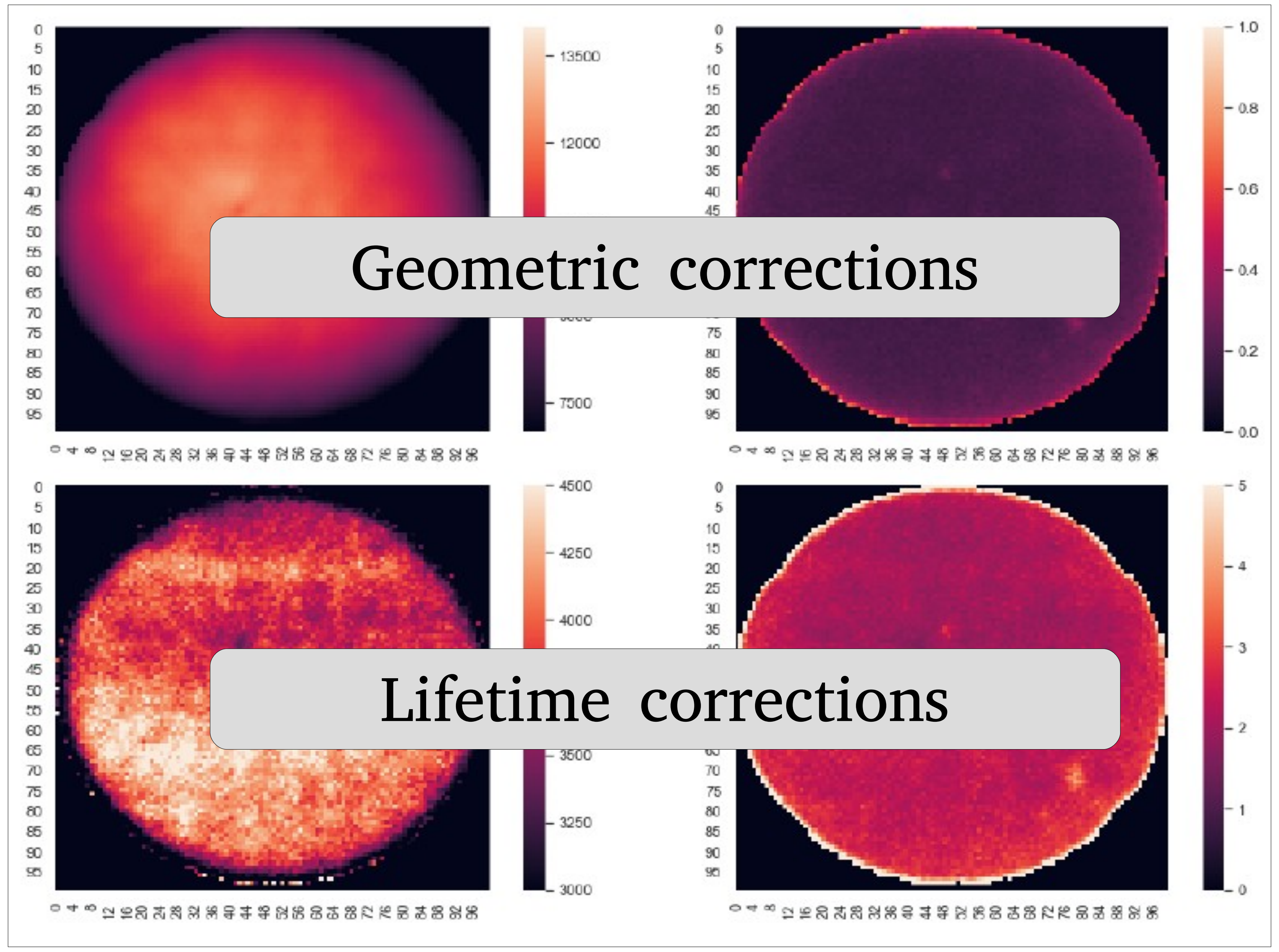
Run period	DAQ livetime (%)	ϵ_{S2} (%)	ϵ_{2PMT} (%)
Run-V	97.04±0.01	100	97.6±0.2
Run-VI	98.10±0.01	100	97.6±0.2



- Very stable operation during Run-V and particularly during Run-VI (no sparks)

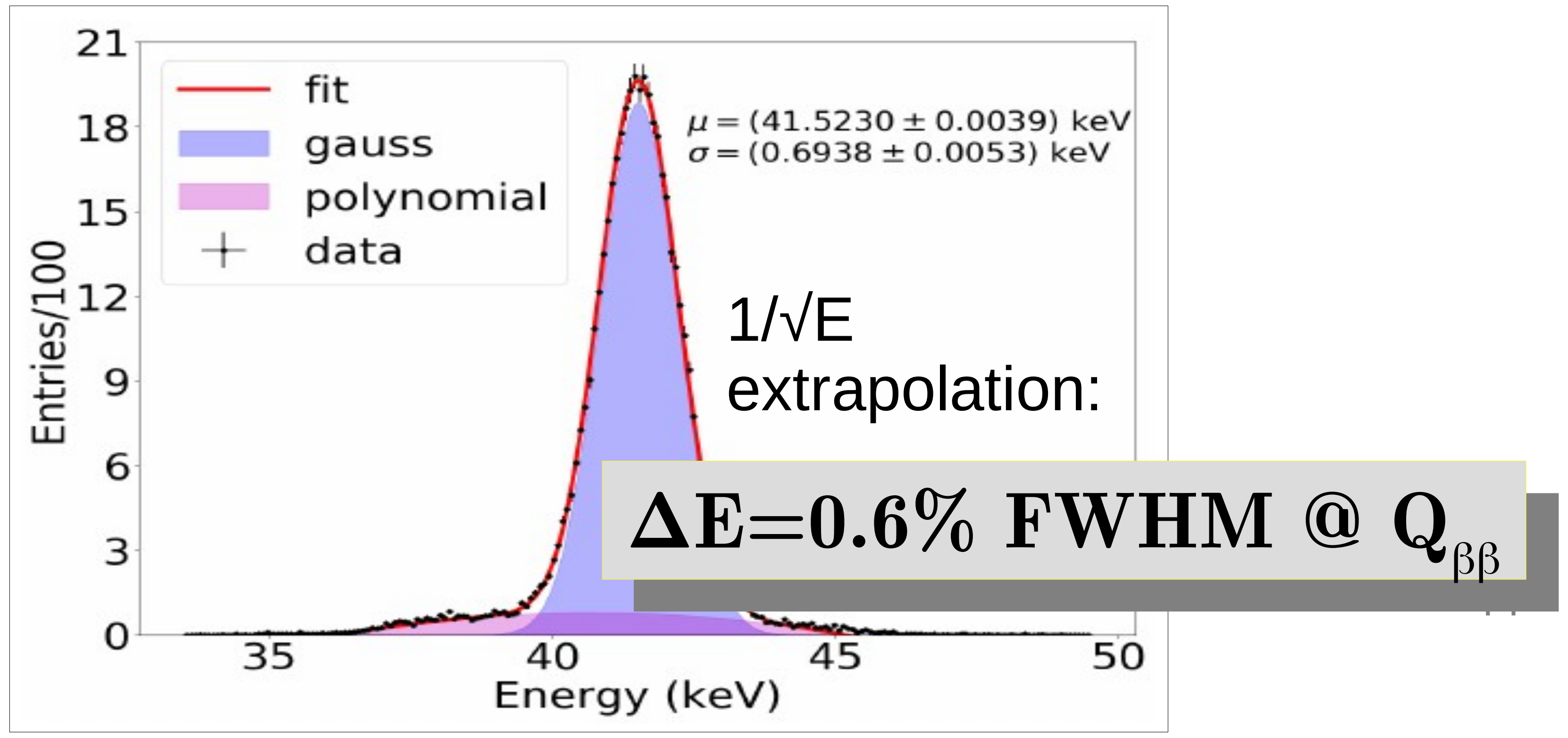
Energy maps and resolution at low energy

- **Calibration XY maps:**

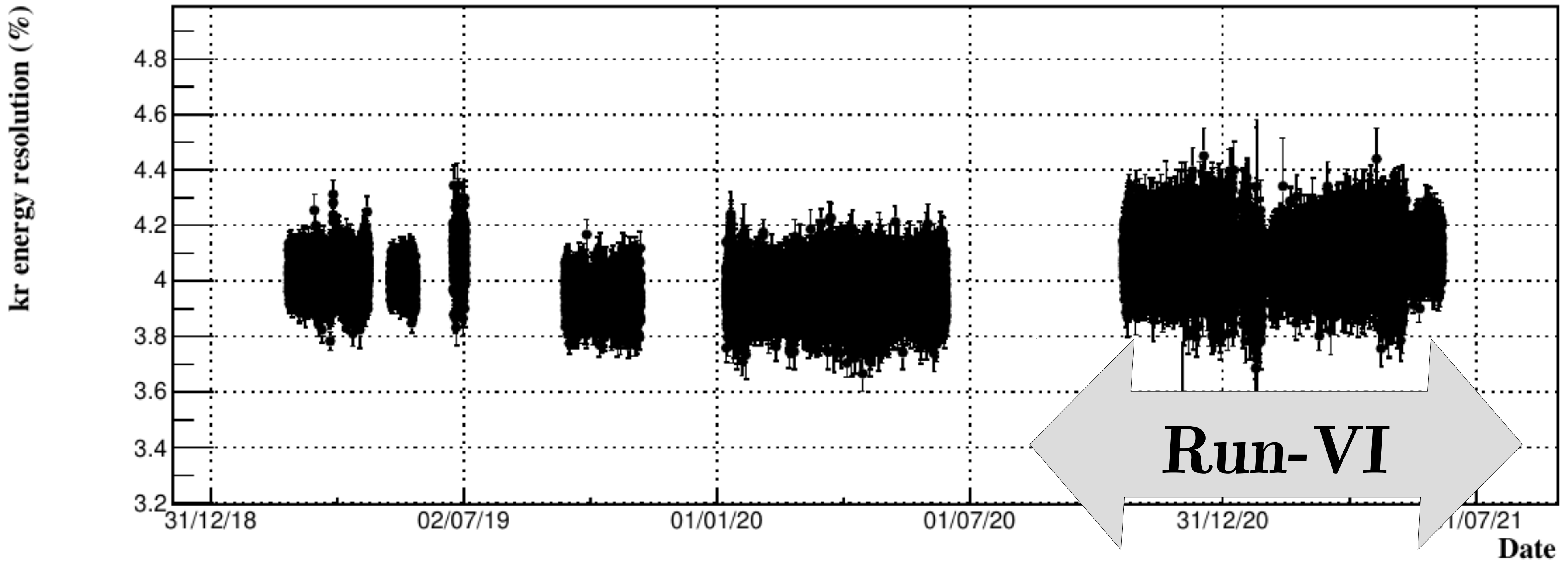


- **Detector *continuously* monitored and calibrated:**
  - **e- attachment and light yield**
- **JINST 13 (2018) no.10, P10014 (7bar)**

- **Energy resolution:**

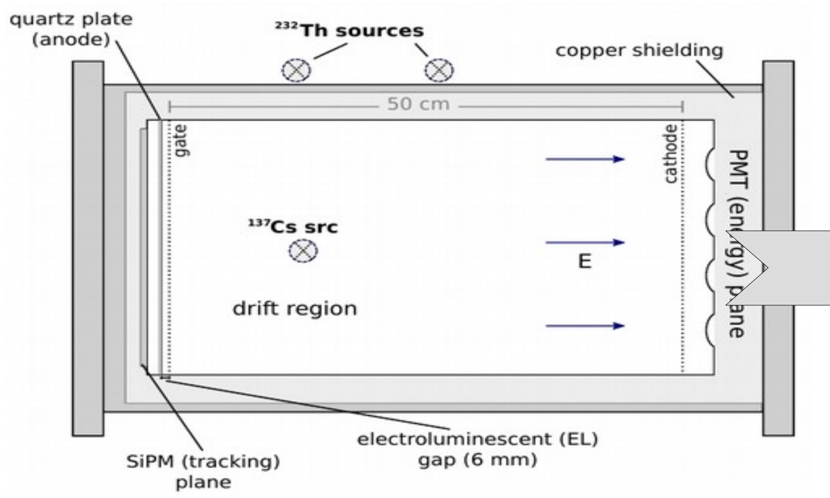


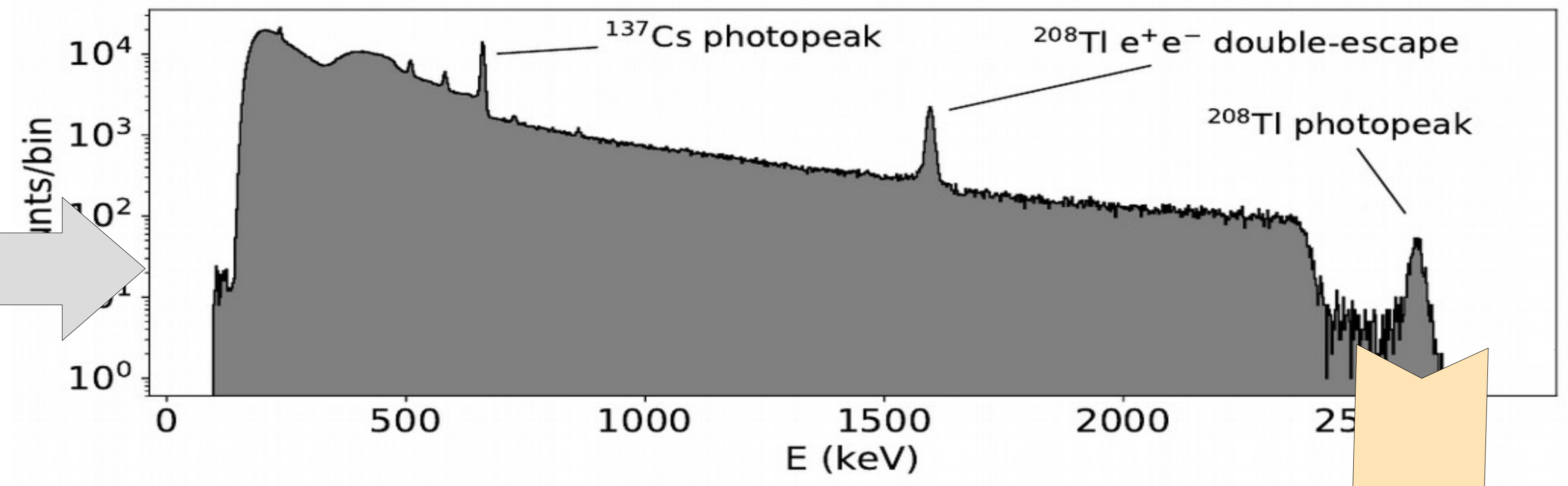
- **Monitoring of energy resolution evolution in time:**

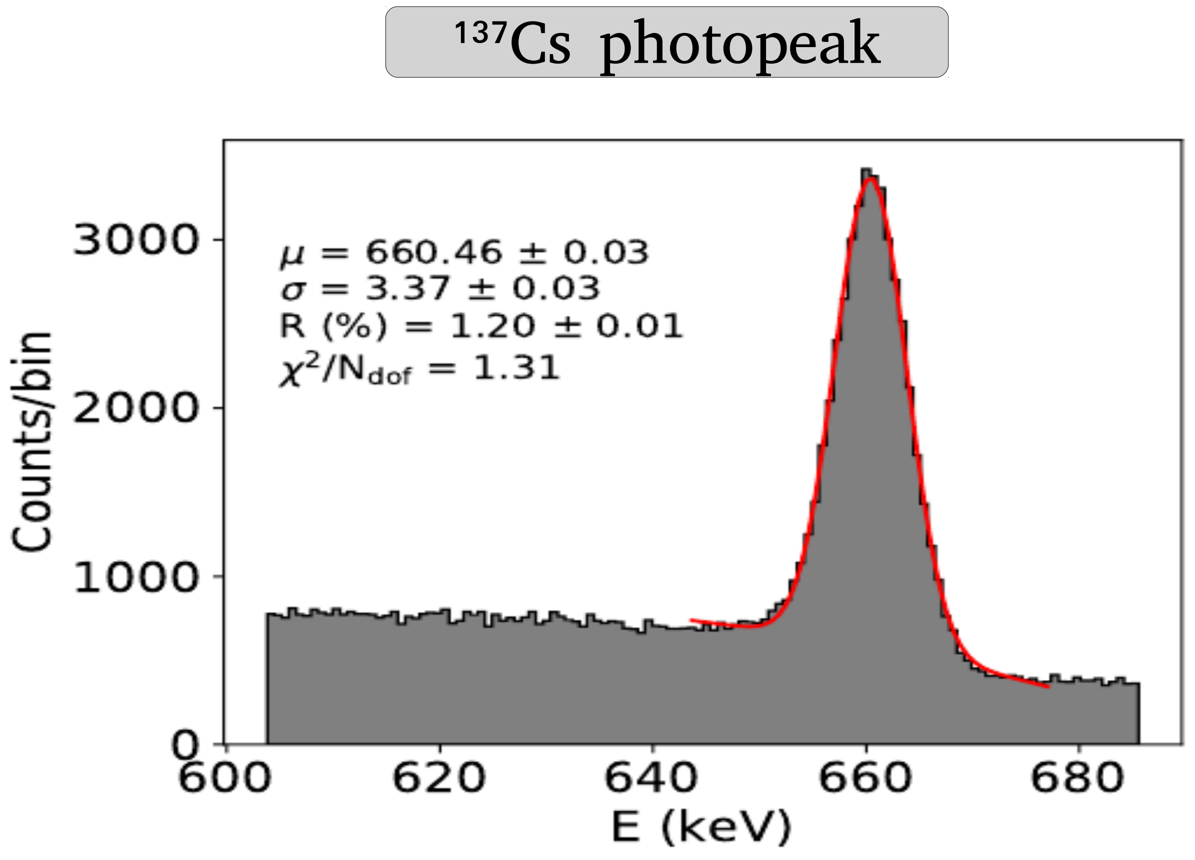


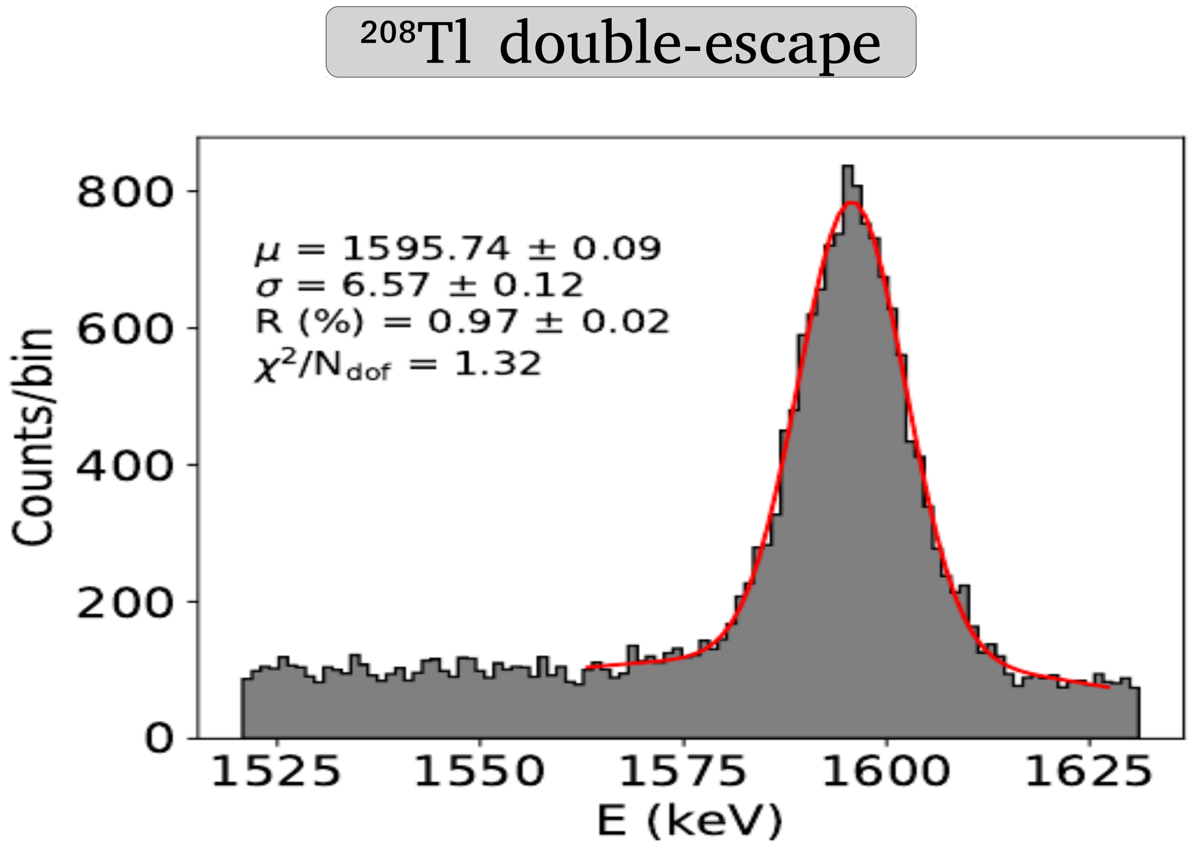
Calibration and resolution at high energy

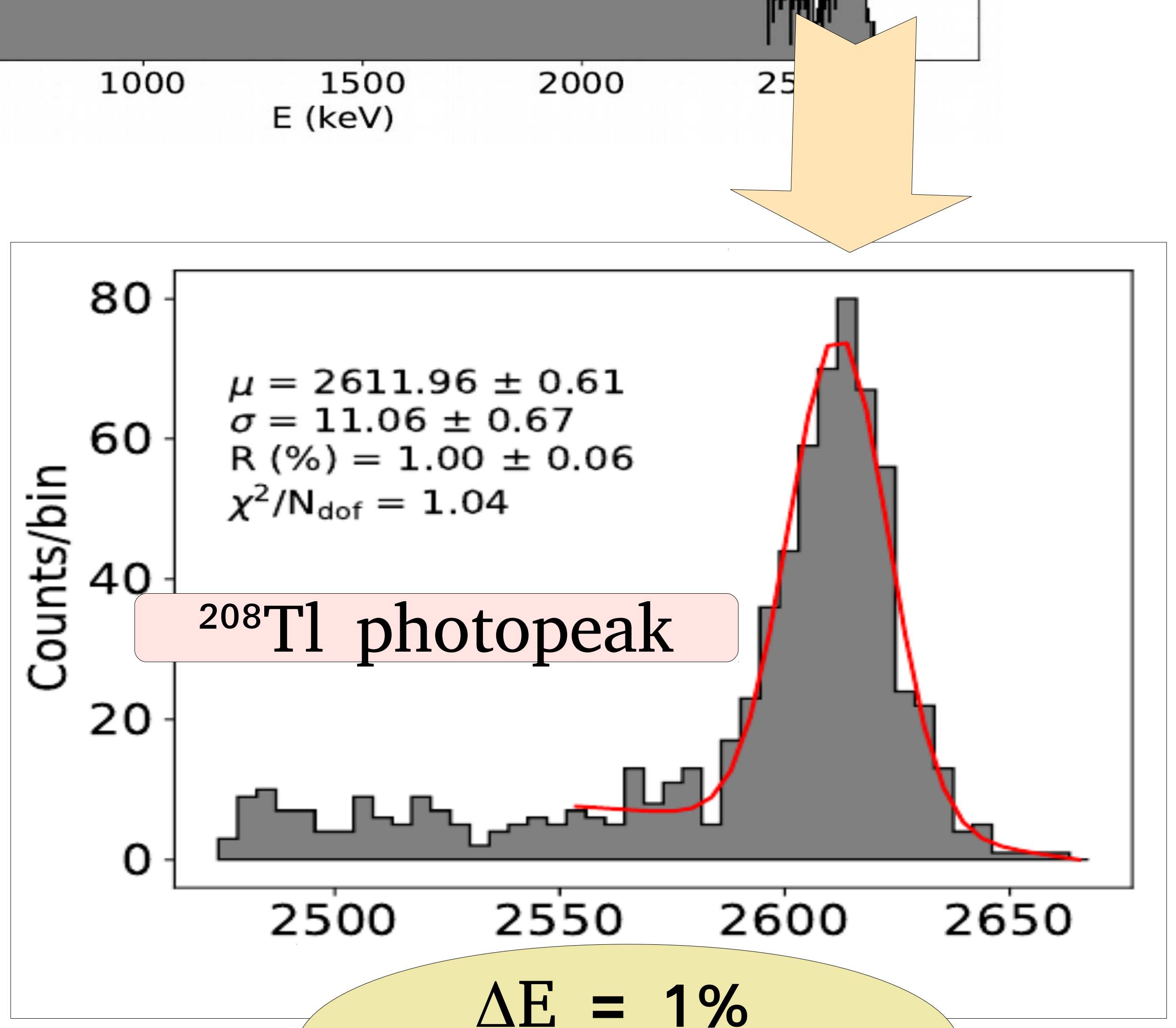
- **High energy calibration already reported to SC and published**
  - **Energy scale**
  - **Energy resolution vs E**
  - **Energy resolution @ $Q_{\beta\beta}$**









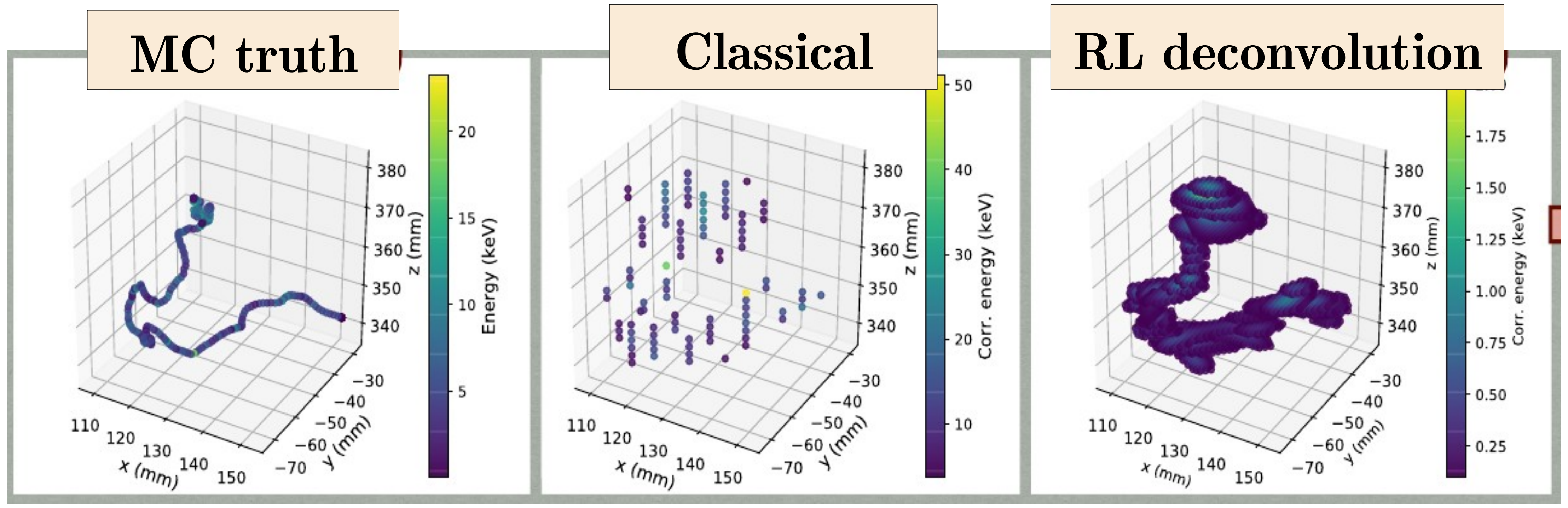


ΔE = 1%
FHWM @~$Q_{\beta\beta}$

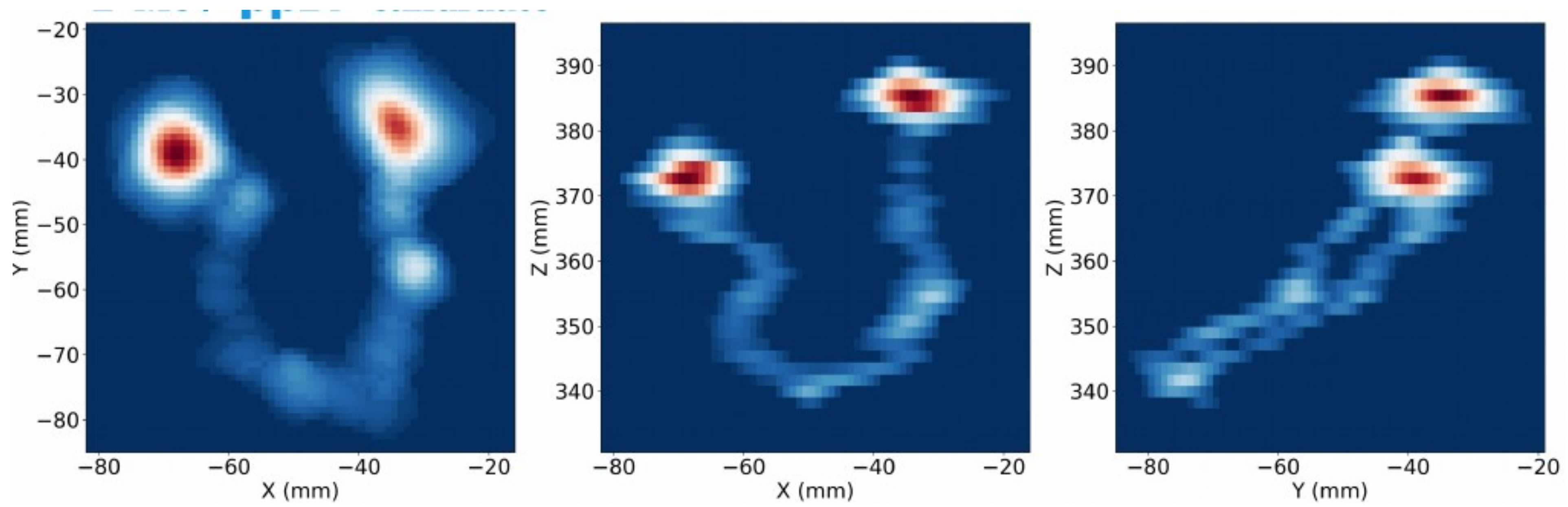
- **JHEP 10 (2019) 230**
- **JINST 13 (2018) no.10, P10020**

Topological signature

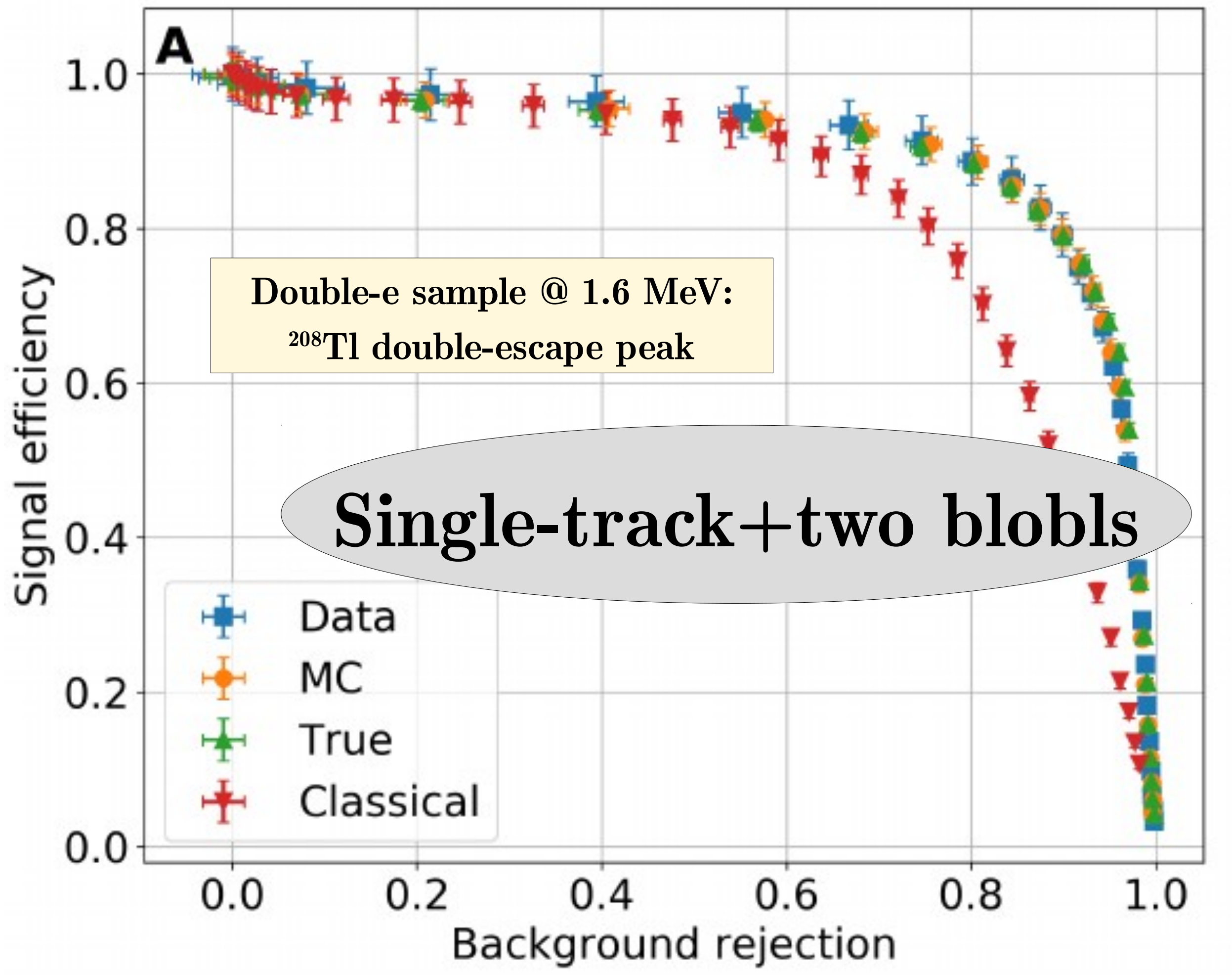
- Track reconstruction:
  - Classical analysis: corrected hits
  - RL-deconv. over corrected hits
    - Reduction in image *smearing* (diffusion, light spread, …)
  - Track reconstruction



- Richardson-Lucy performance at 1.6 MeV: JHEP 7 (2021) 146
  - ββ event candidate @ 2.0 MeV:



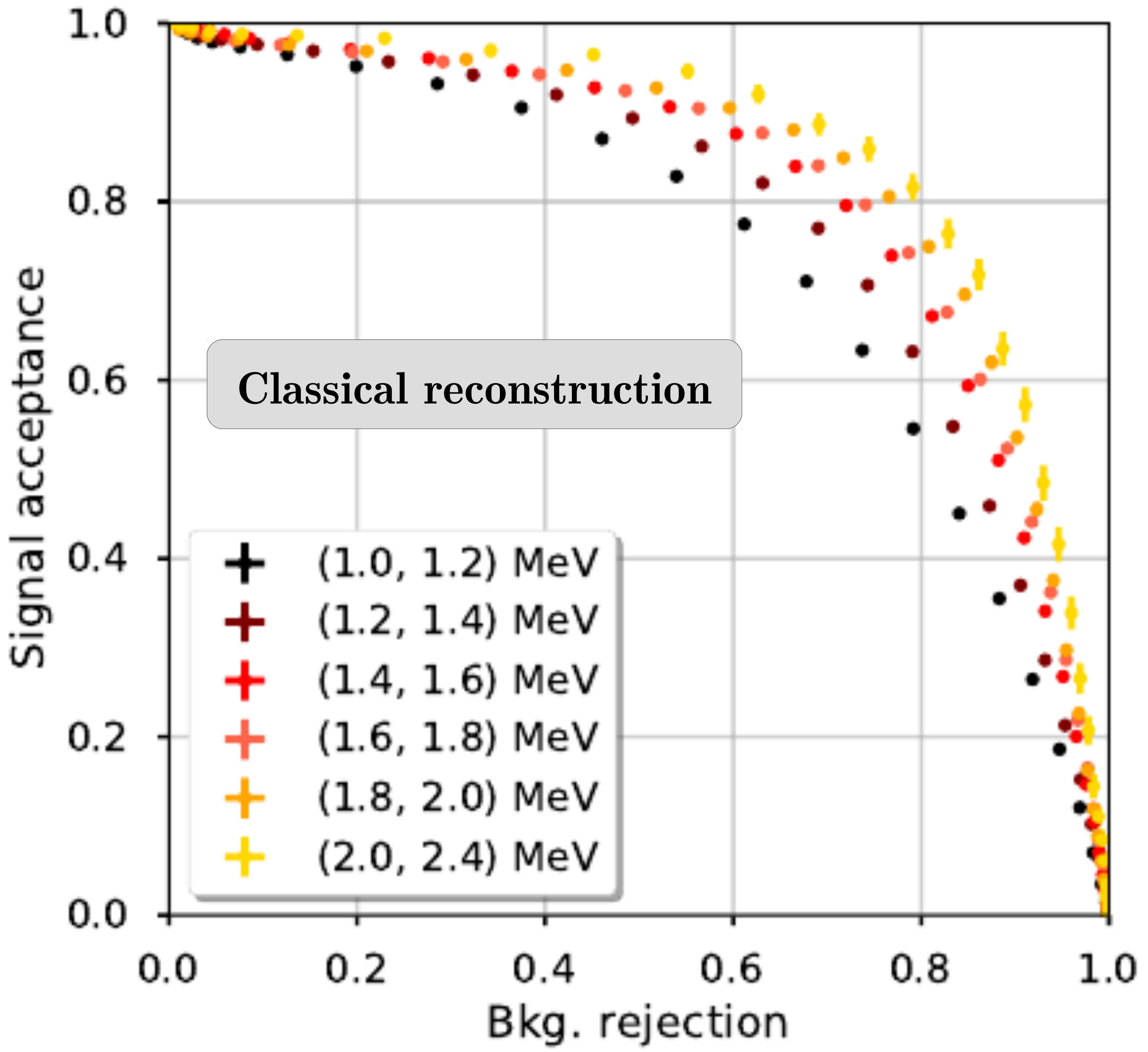
- **Selection efficiency:**
  - Sig. eff: 56.6%
    BG accept: 3.7%

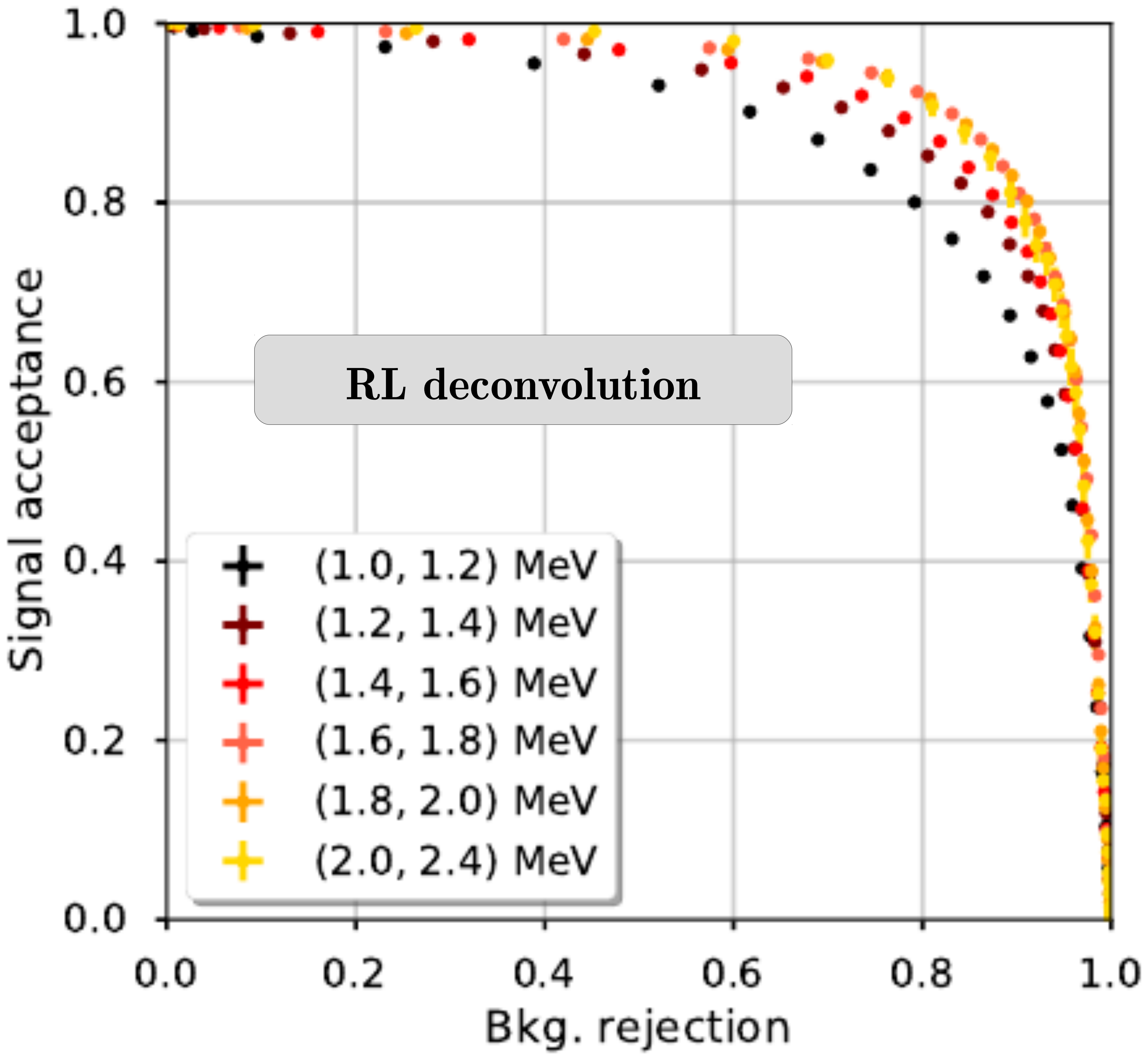


DNNs: JINST 12 (2017) no.01, T01004
SiPM: JHEP 10 (2019) 052
CNNs: JHEP 01 (2021) 189

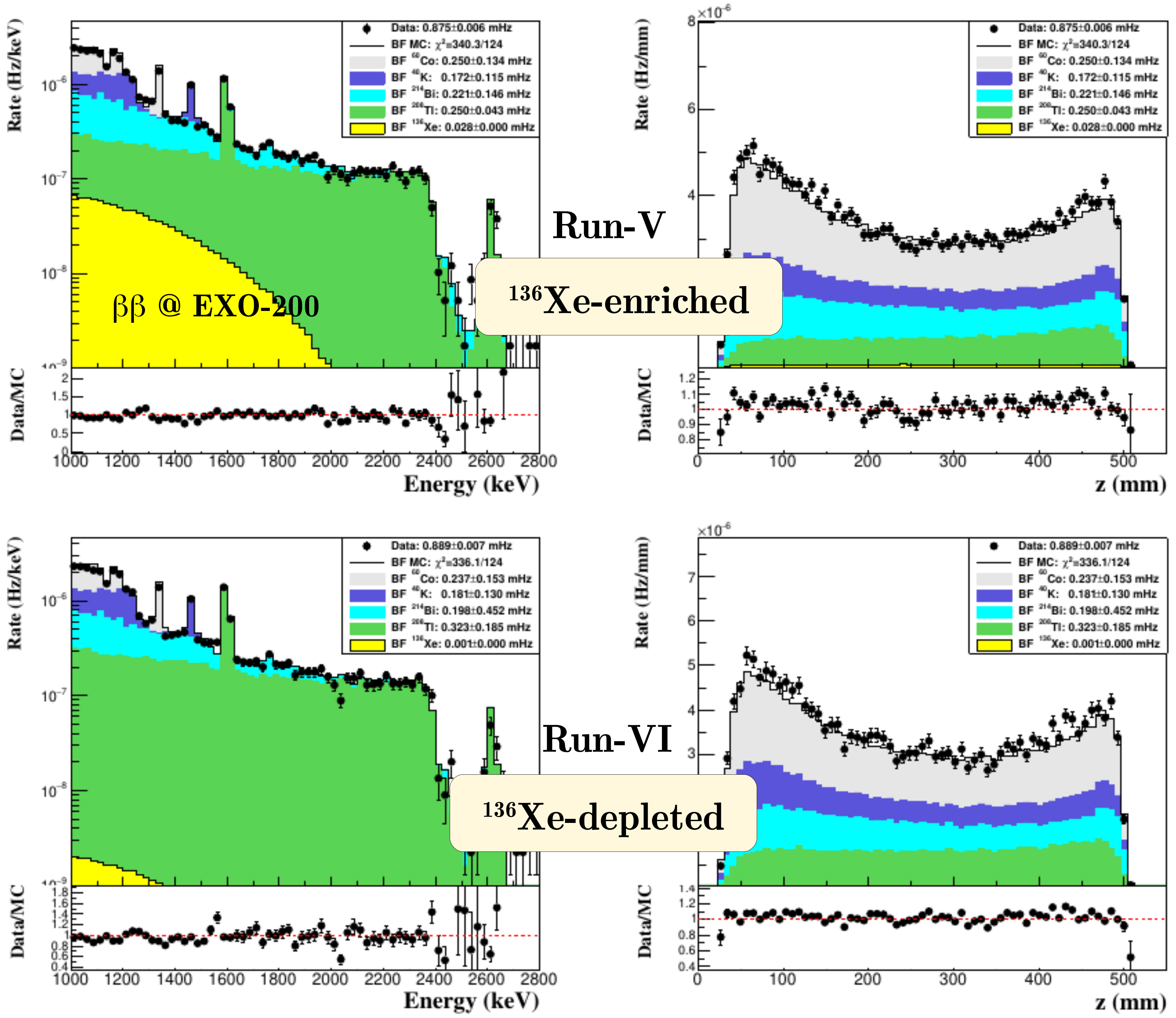
NEXT-White @ LSC 28th SC meeting

Selection efficiency



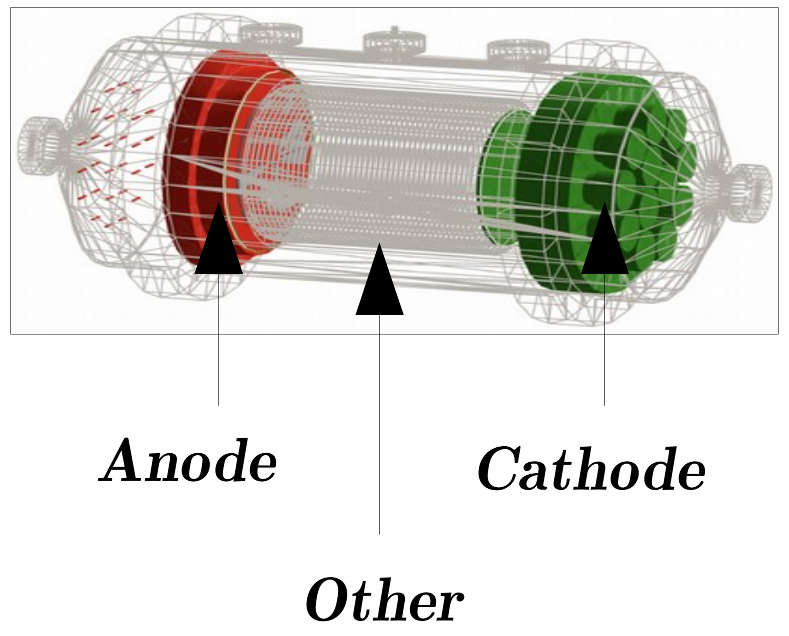


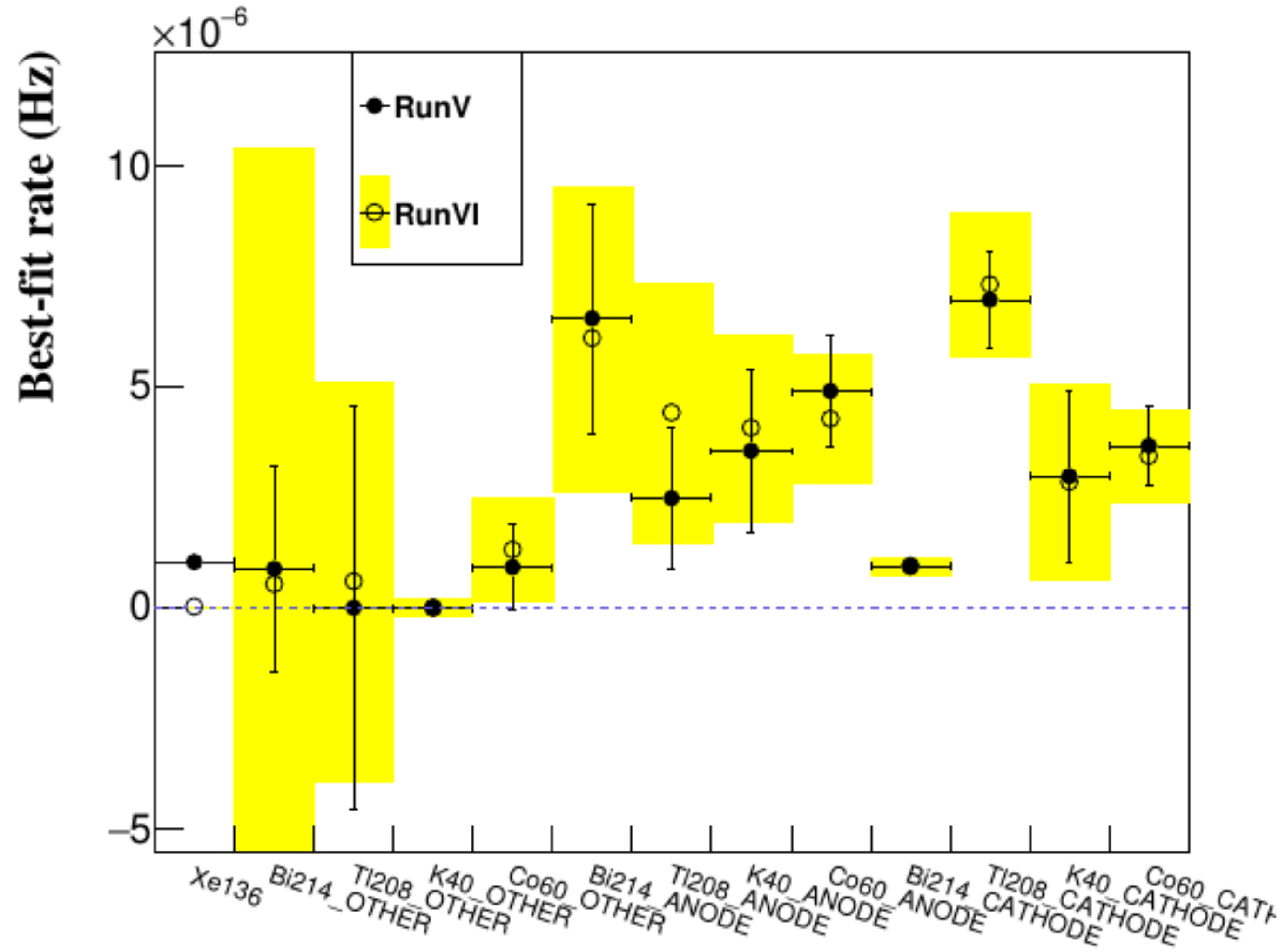
Radiogenic background



Update w.r.t. JHEP 10 (2019) 051

- BG model based on extensive radio-purity campaign
  - JINST 8 (2013) T01002, JINST 10 (2015) 05, P05006)
  - Four isotopes (^{214}Bi, ^{208}Tl, ^{60}Co, ^{40}K) and 84 sources
- Fiducial radiogenic background fit:
  - R+S(E+Z), 4 isotopes from 3 effective volumes

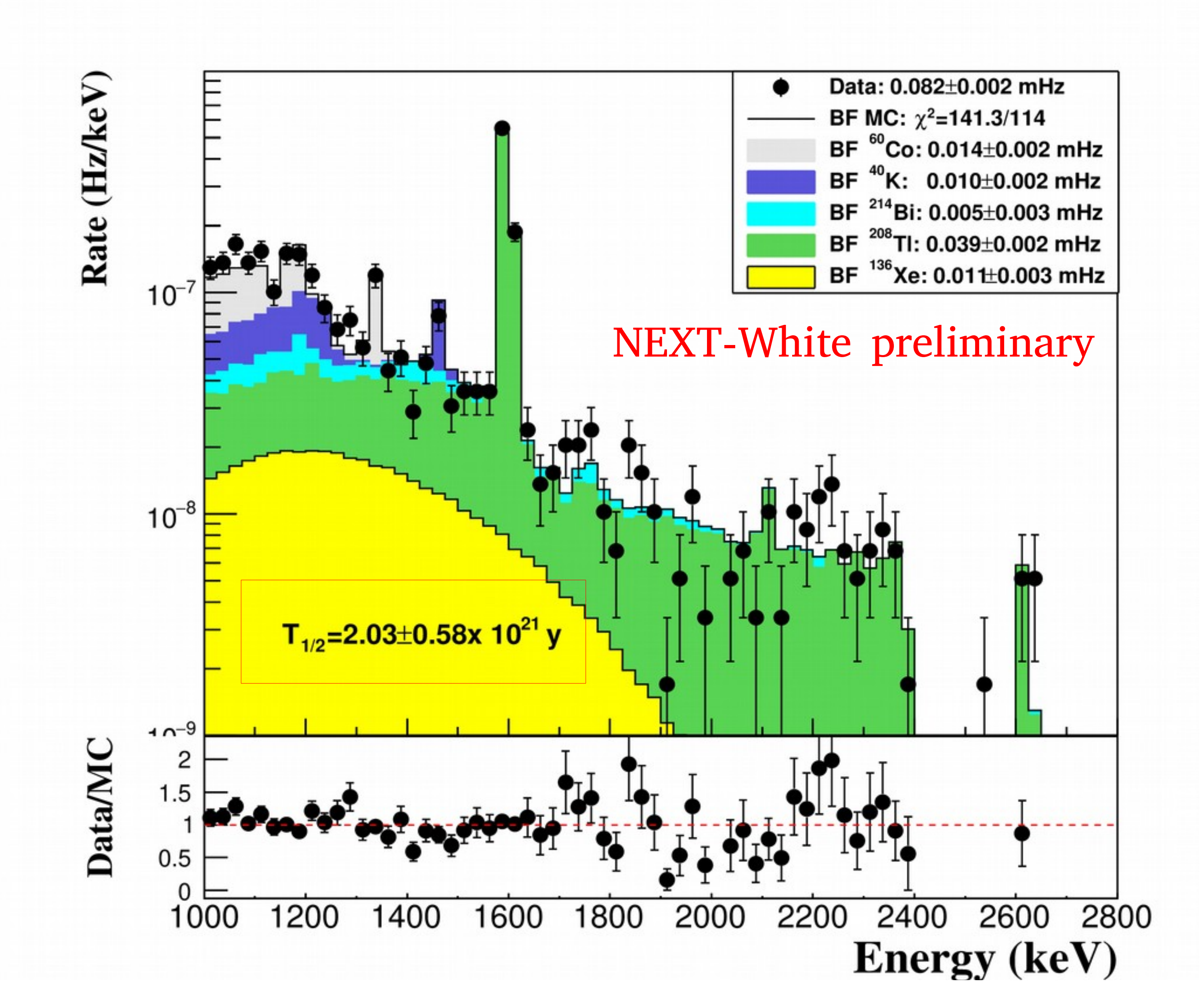


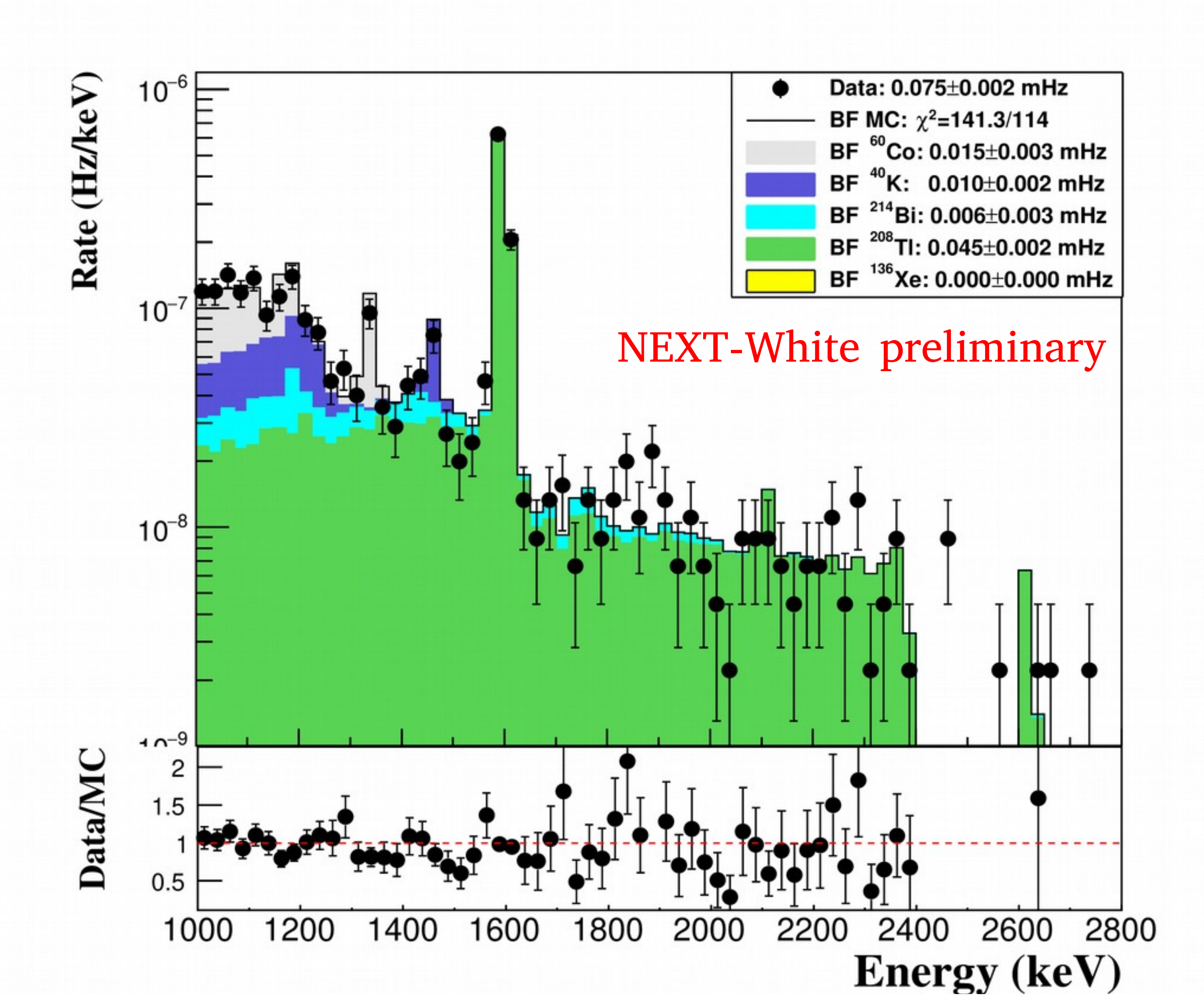


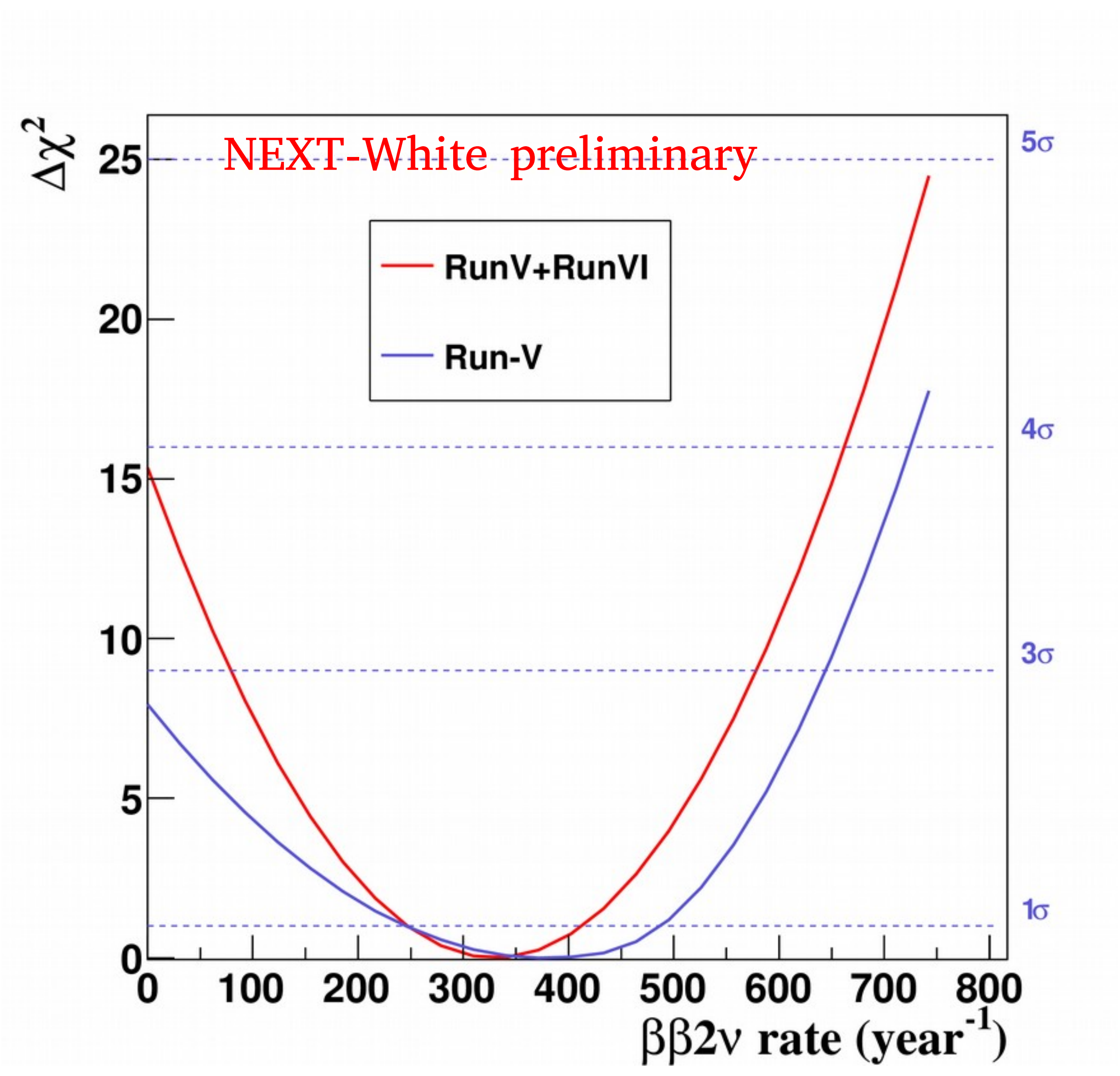
- 12 BG sources measured to be stable in time

Bβ2v: Background model-dependent fit

- Joint fit of the ^{136}Xe-enriched and the ^{136}Xe-depleted samples
- Rate of ββ events extracted along with total radiogenic background rates



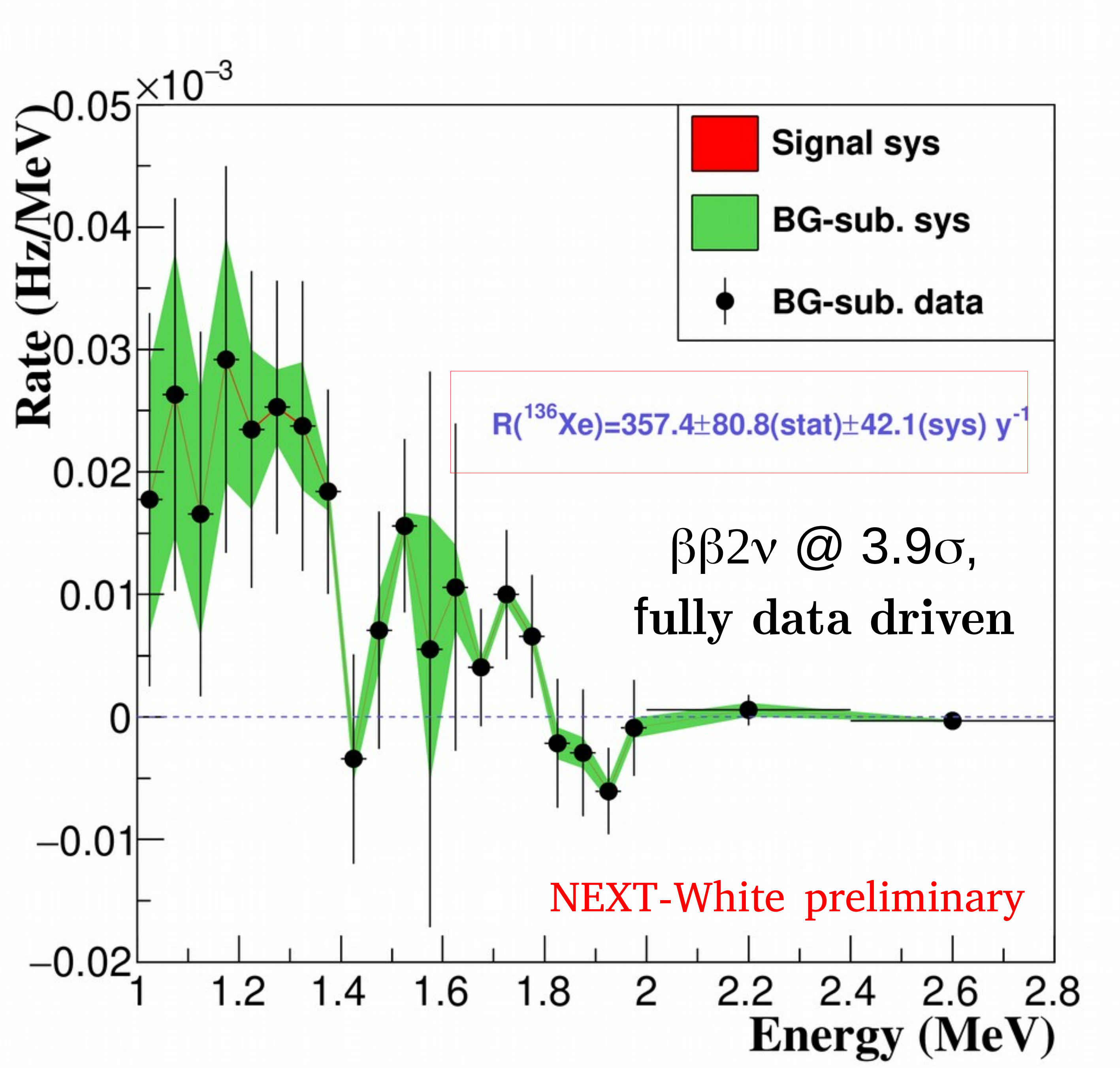


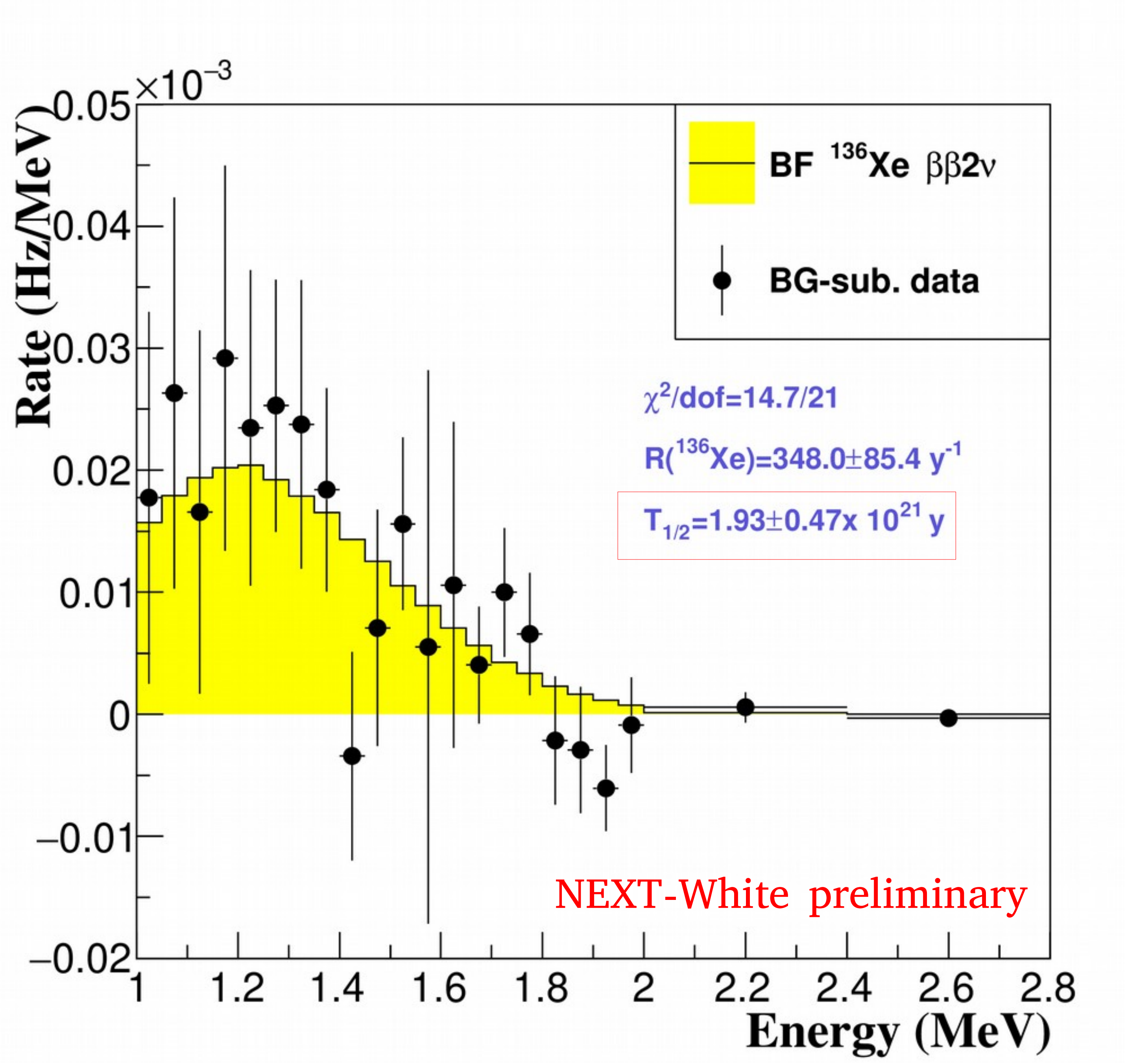


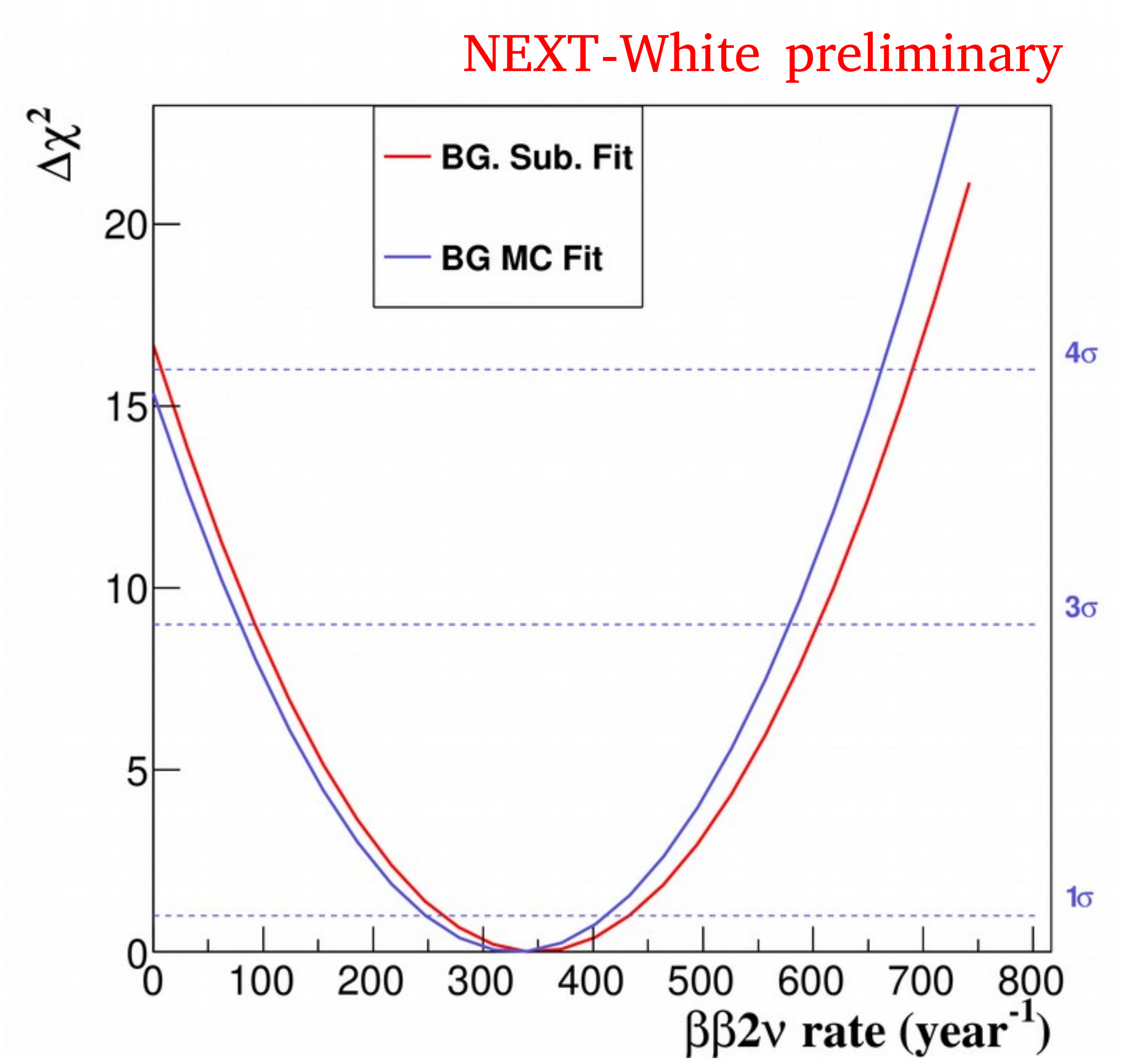
- The ^{136}Xe-depleted sample improves the precision by constraining the backgrounds
- 3.9σ measurement (4σ expected), but poor goodness of fit: χ^2/dof = 142/114, p-value = 4.2%

Bβ2v: Background subtraction fit

- Background-subtracted ββ spectrum: ^{136}Xe-enriched - ^{136}Xe-depleted (unique in NEXT!):





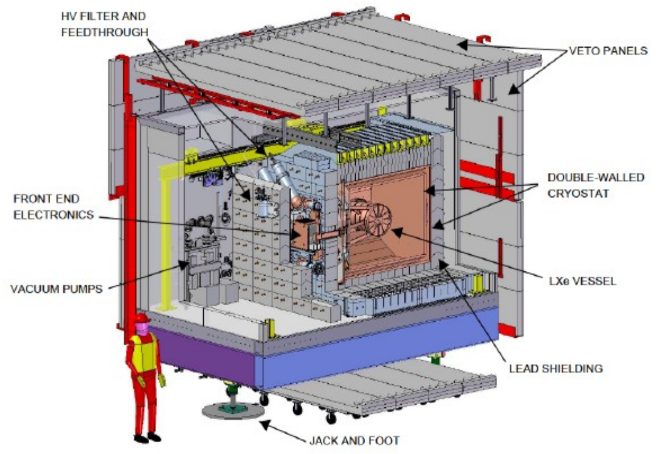


- Fit to the ββ2ν expectation (BG-model independent!): $T_{1/2}$ measured @ 4.1 sigma (3.8σ expected)
- Fully consistent with BG-model-dependent fit, but excellent goodness of fit: χ^2/dof=14.6/21

Bβ2ν: Existing and future measurements

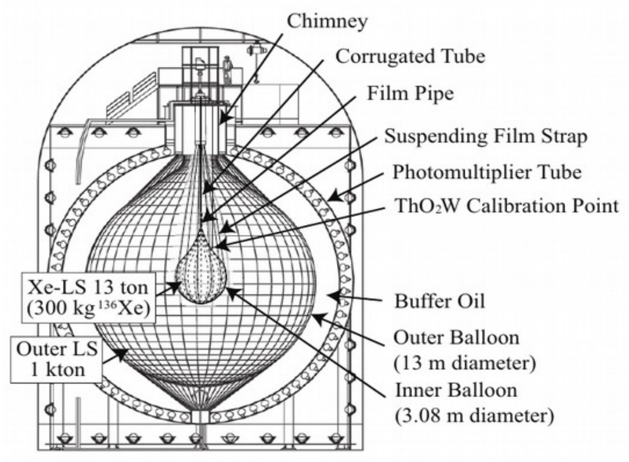
EXO-200

^{136}Xe ~142 kg



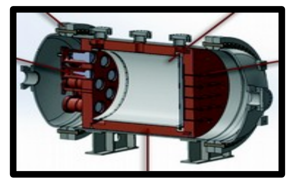
KamLAND-Zen400

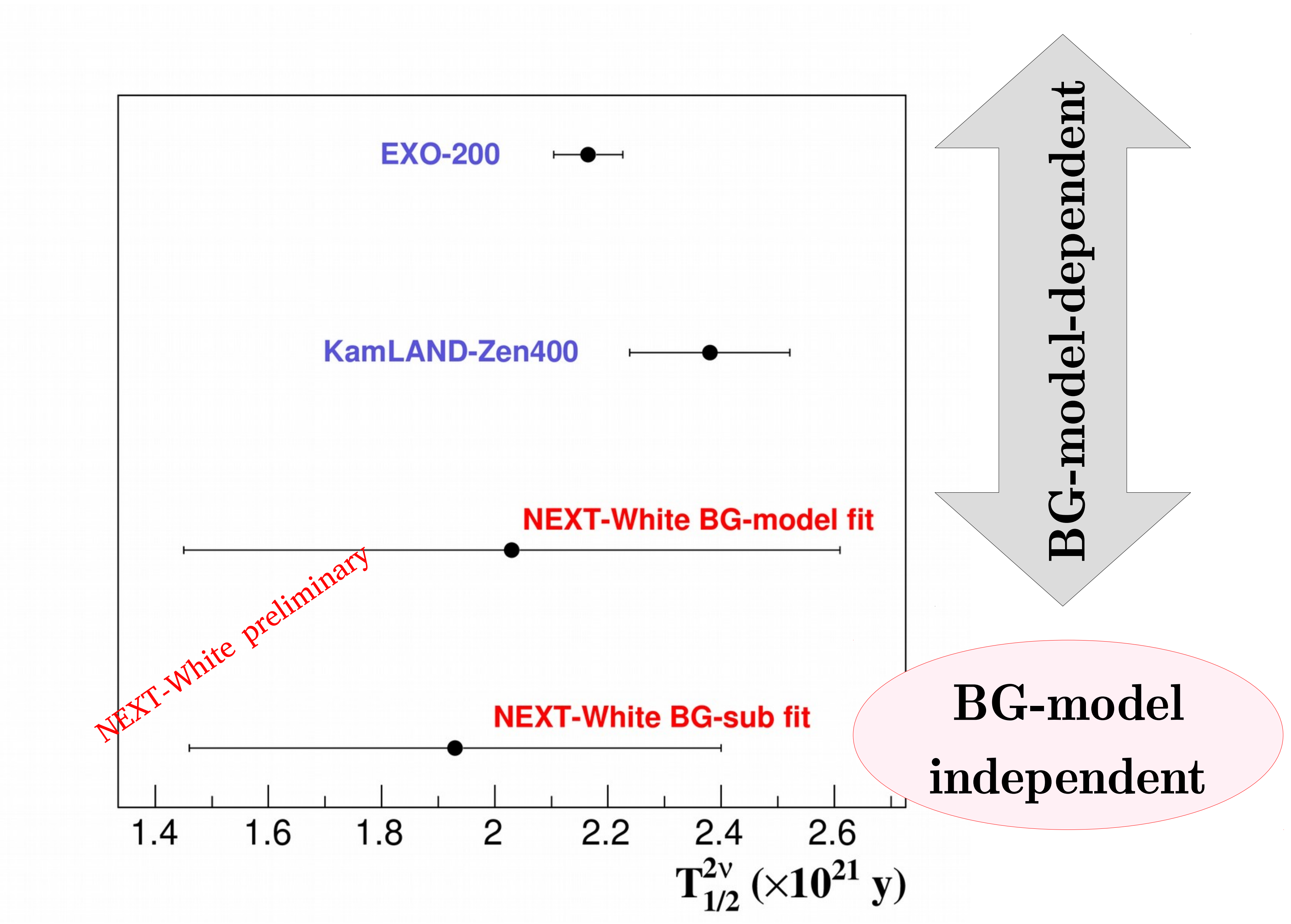
^{136}Xe ~129 kg



NEXT-White

^{136}Xe ~3.9 kg



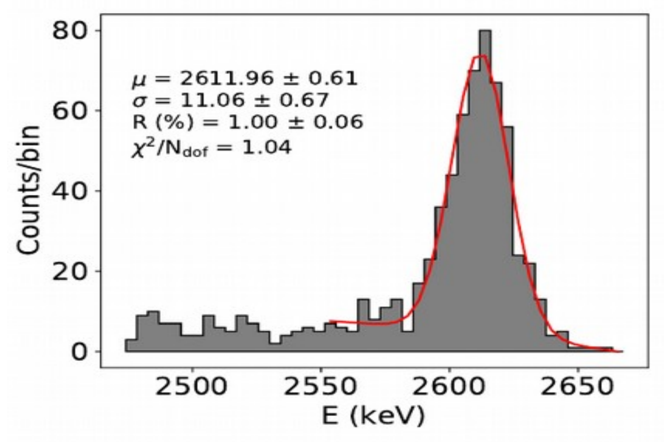


- NEXT-100: > 50 statistics (direct subtraction): reduce error by factor ~8.
- NEXT-HD: > 500, reduce error by factor > 20… Precision measurement.

NEXT-White: overview

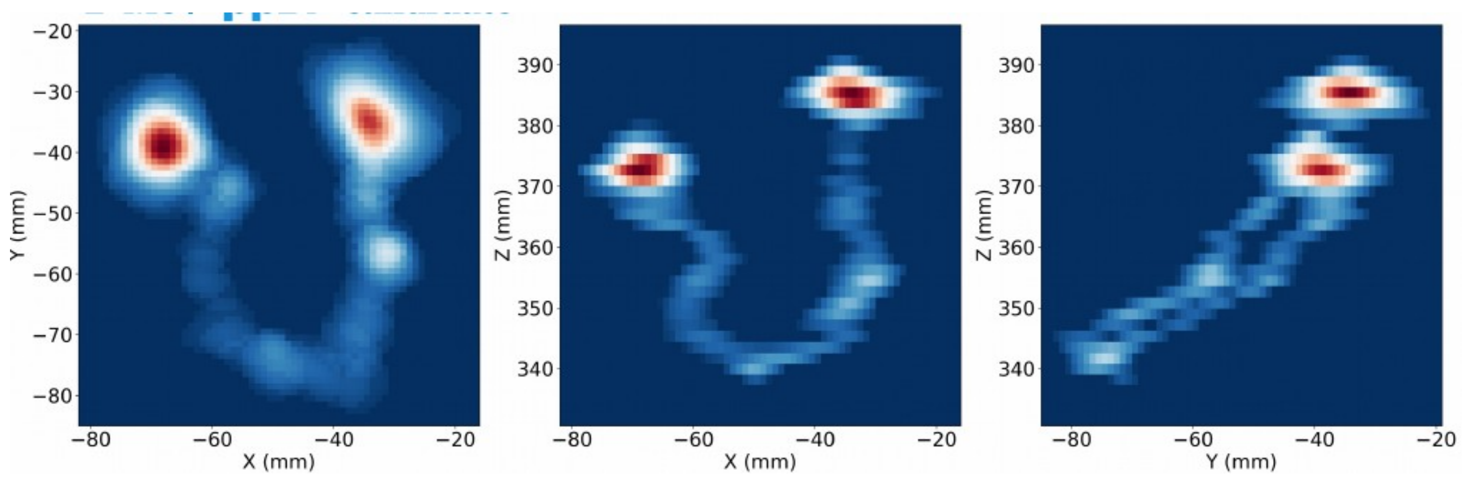
- NEXT-White has been operated with good performance from 2016 to 2021→ long term stability
- Physics program of the NEXT-White detector completed → all goals achieved:

Energy resolution: 1% FWHM @ $Q_{\beta\beta}$



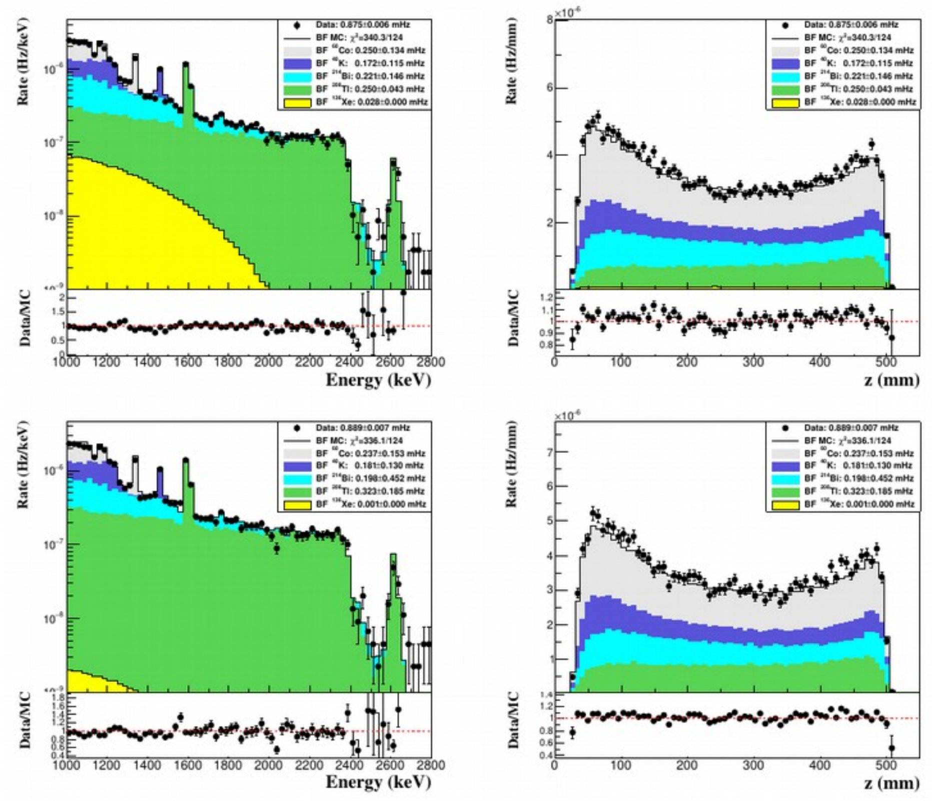
- JHEP 10 (2019) 230
- JINST 13 (2018) no.10, P10020
- JINST 13 (2018) no.10, P10014

Topology-based BG rejection



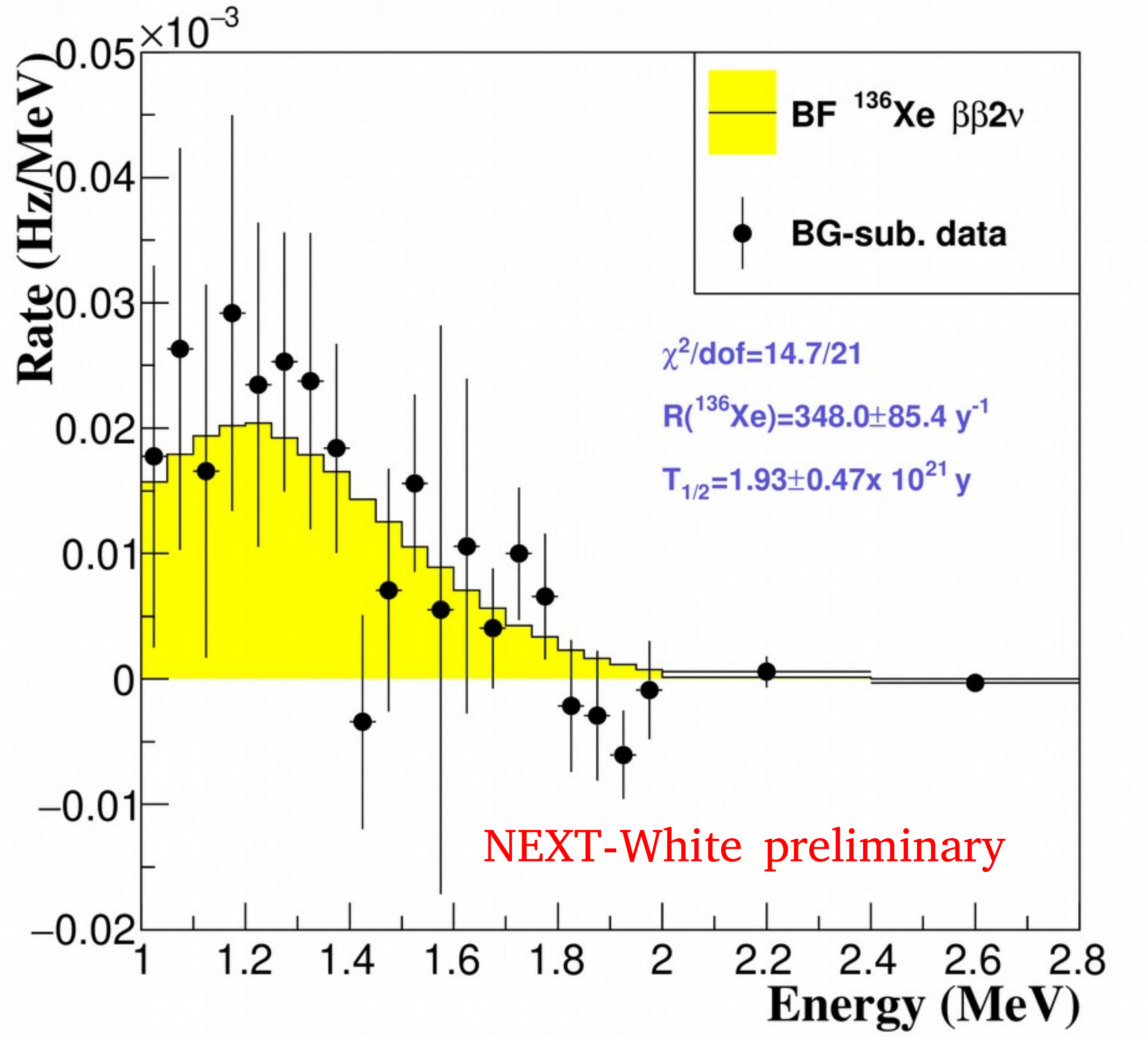
- JHEP 7 (2021) 146
- JHEP 01 (2021) 189
- JHEP 10 (2019) 052
- JINST 12 (2017) no.01, T01004

- Background measurement



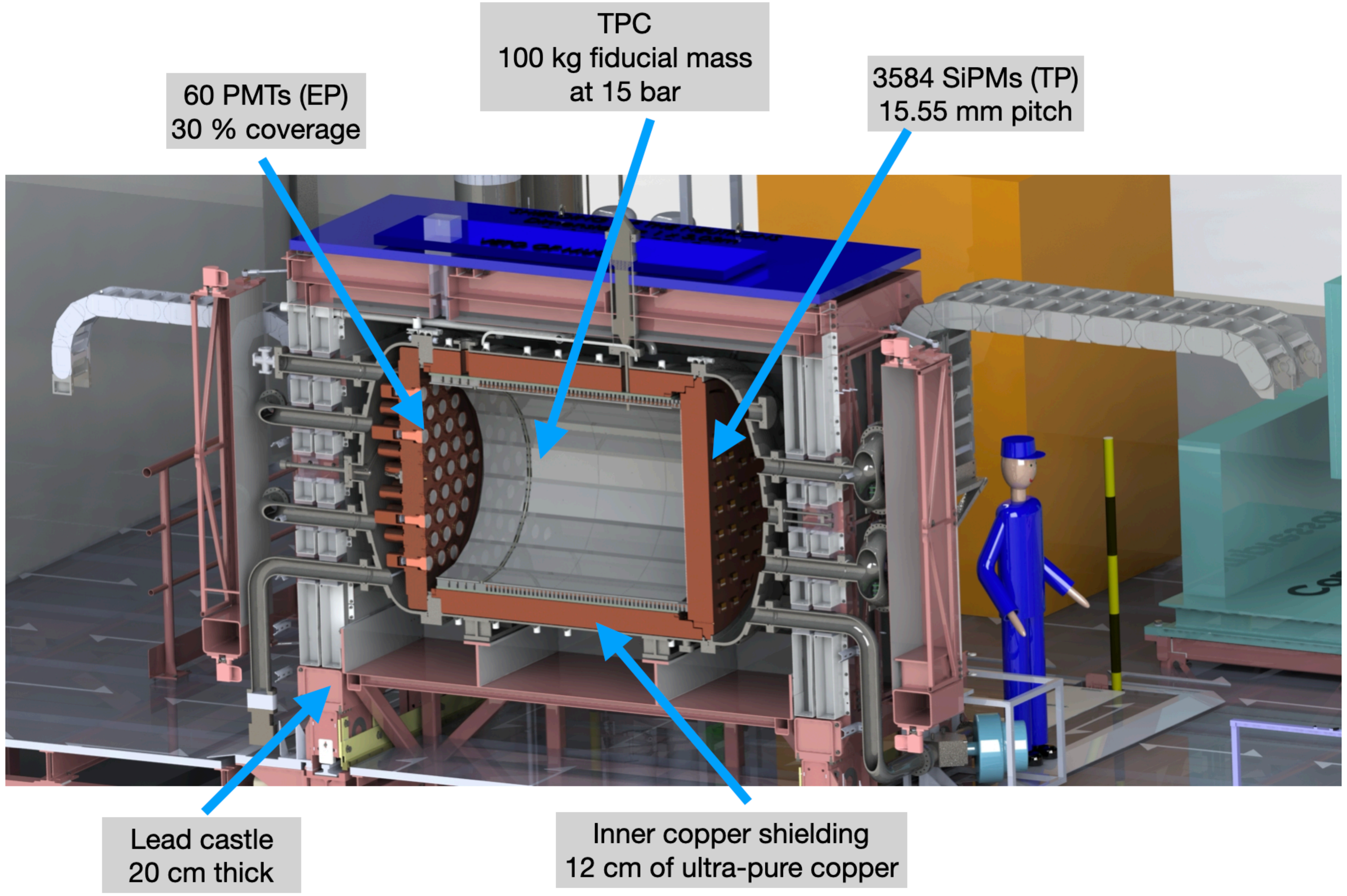
- JHEP 10 (2019) 051
- JHEP 10 (2018) 112
- Muon flux+cosmogenics paper

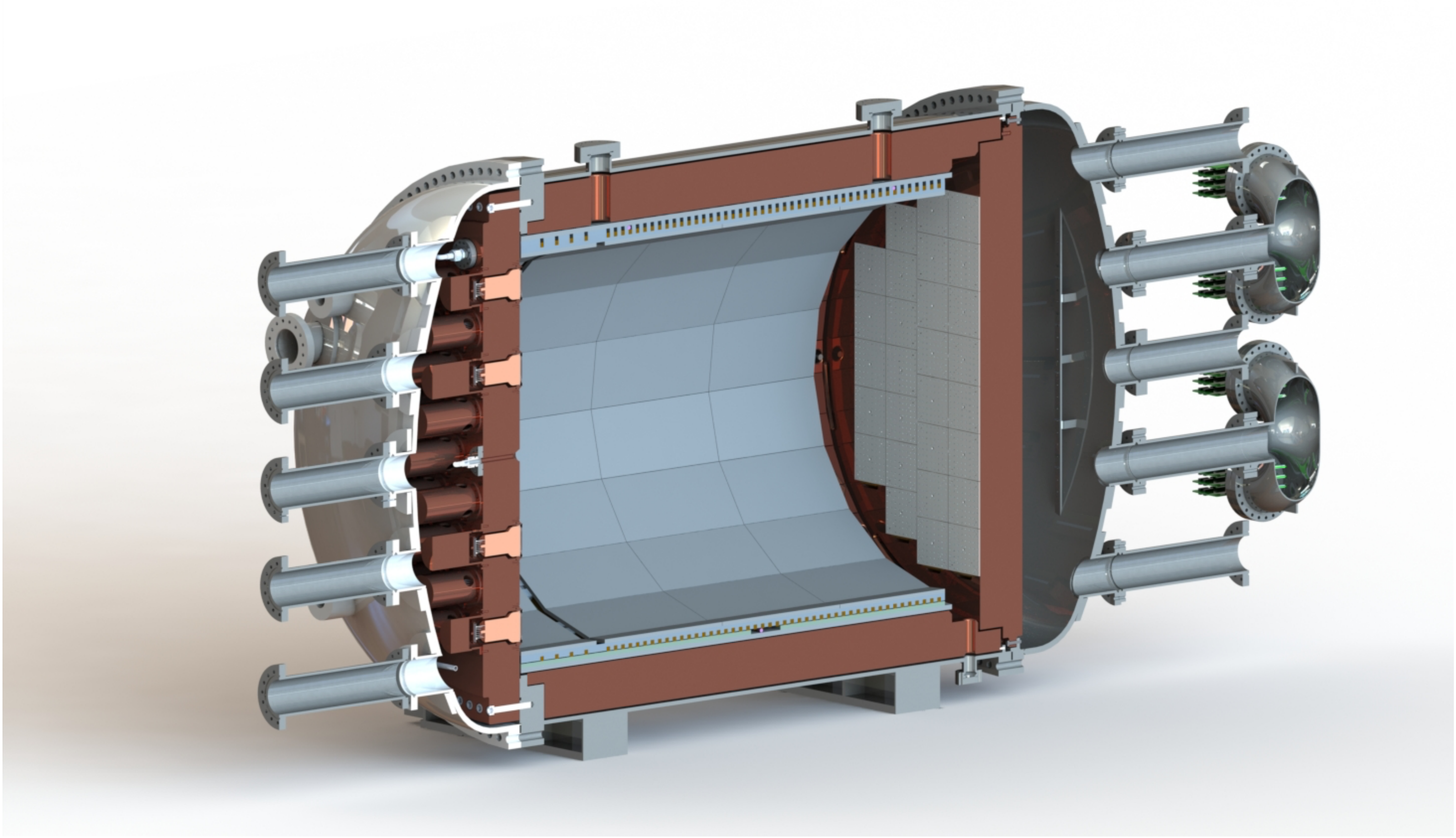
- ββ2ν measurement (x2!)



- ββ2ν paper in preparation

NEXT-100





- Detector structure like NEXT-White: Energy Plane (EP), Tracking Plane (TP) and TPC.
- Construction underway. Expect to be in operation in 2022.
- Can reach a sensitivity of ~10^{26} years, thus competing with EXO and KamLAND-Zen

ββ0ν backgrounds

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

$$B = A * \varepsilon$$

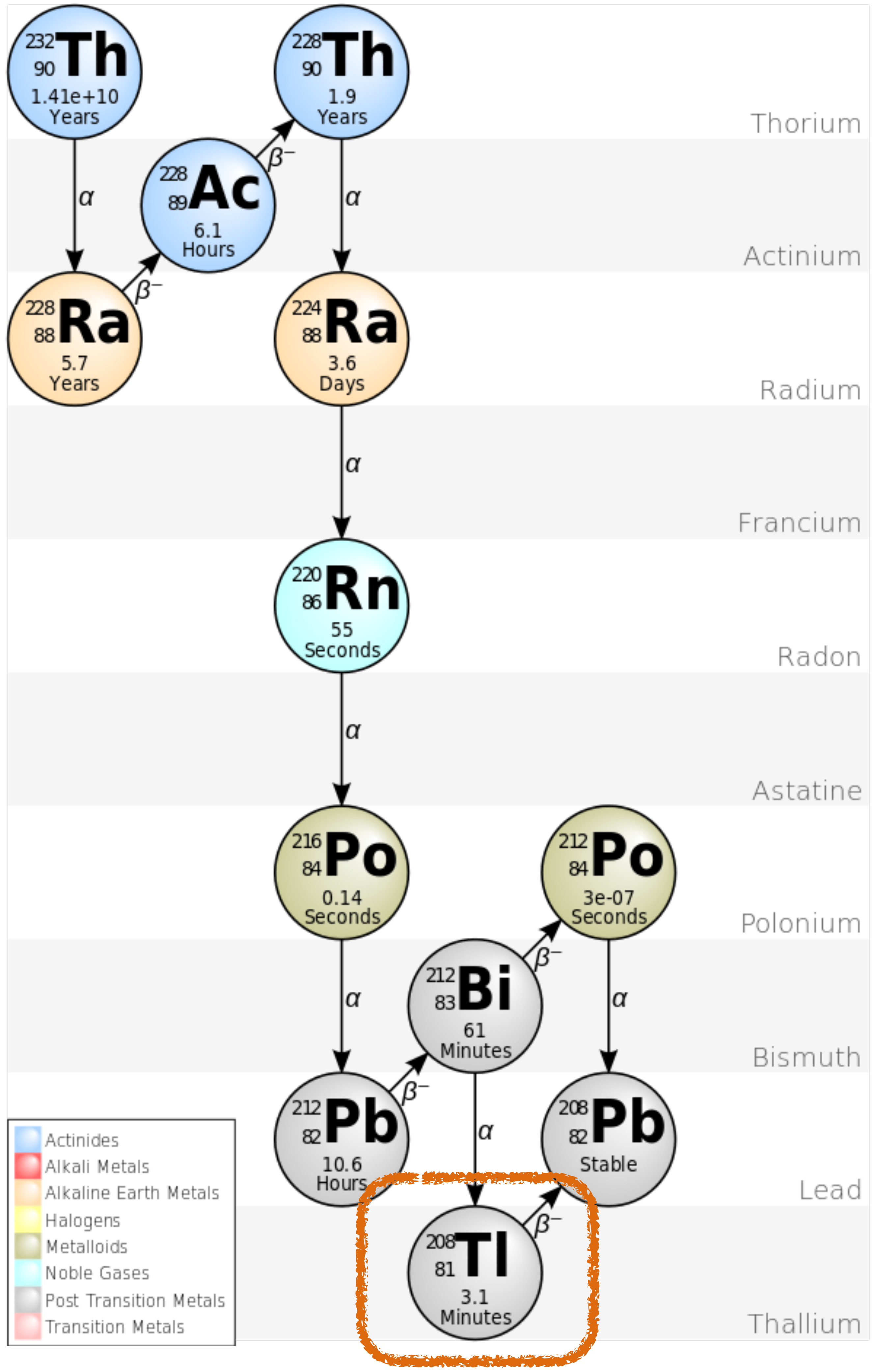
B: Predicted rate

A: Activity measured

ε: Selection efficiency from simulation + analysis

ββ0ν backgrounds

Natural decay series



From Thorium^{232}

$^{208}Tl \rightarrow {}^{208}Pb$

Gamma 2615 keV

99.75% Intensity

ββ0ν backgrounds

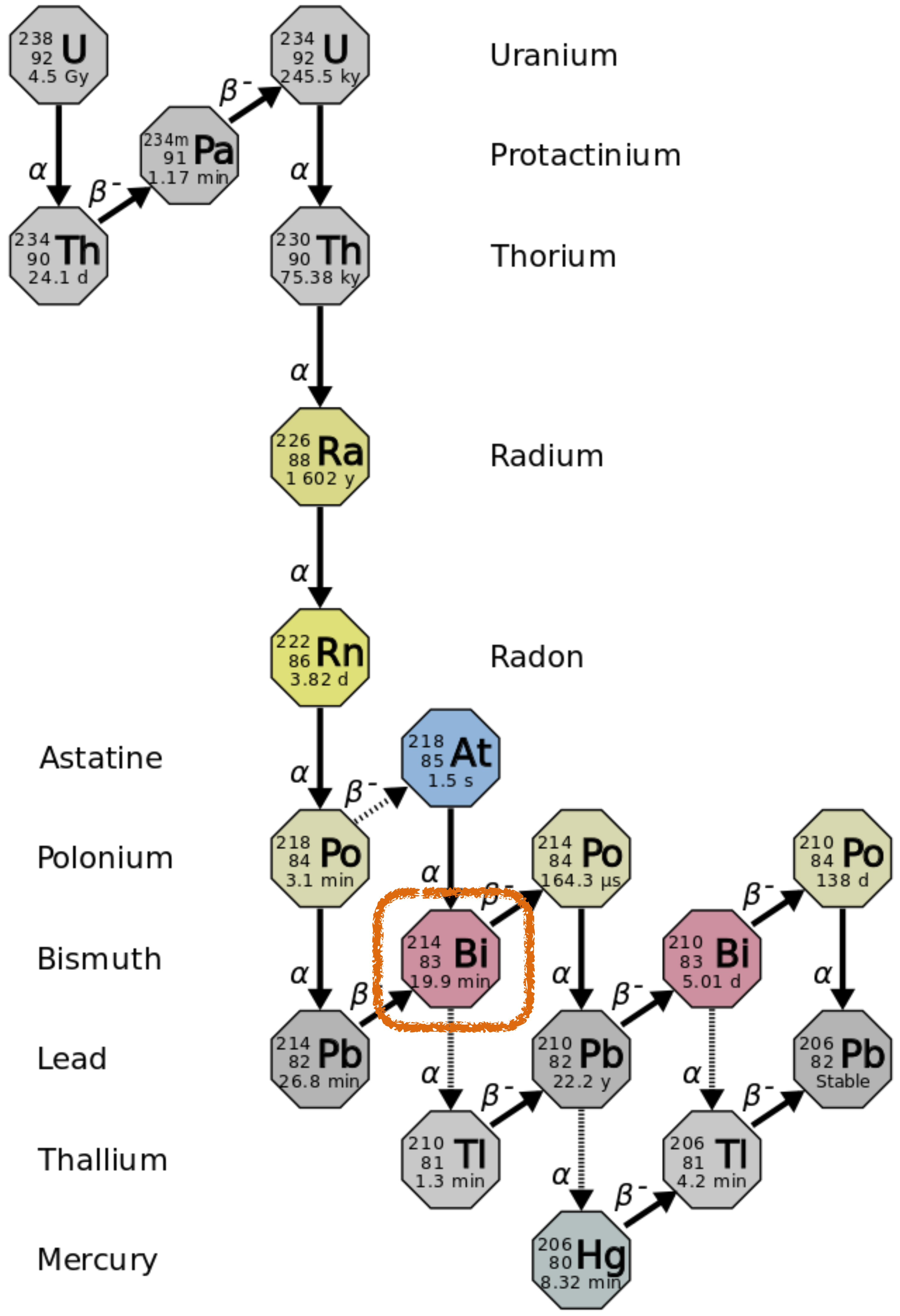
Natural decay series

From Uranium238

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

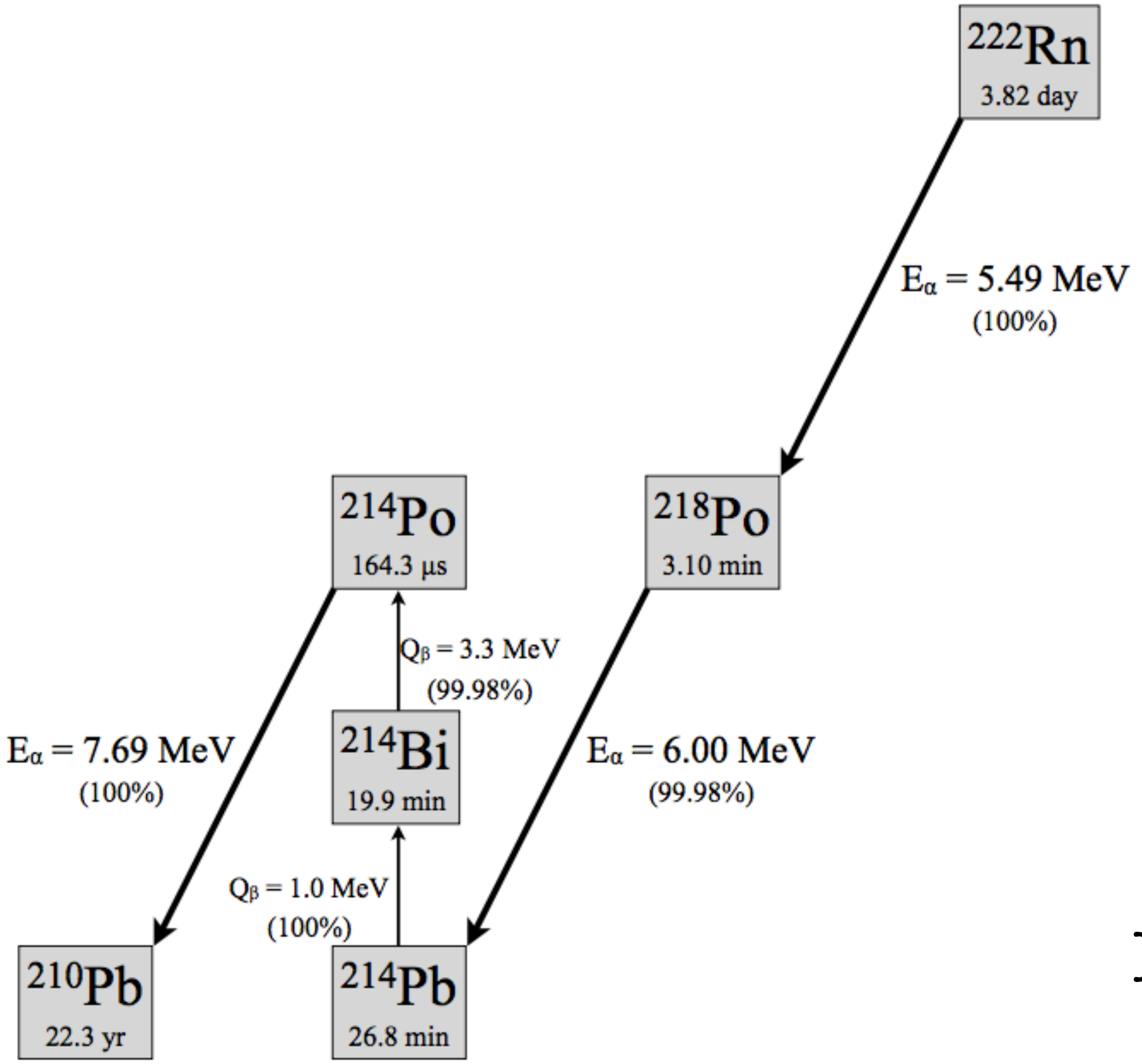
Gamma 2447 keV

1.57% Intensity



ββ0ν backgrounds

Radon



two different Rn sources

Airborne. 66 Bq/m^3
LSC abatement system

Degassing of detector materials
and gas system
1.81 mBq in NEXT-NEW

NEXT-100 Rn Activity?
Depending on main source 3-10 mBq

arXiv:1804.00471 [physics.ins-det]

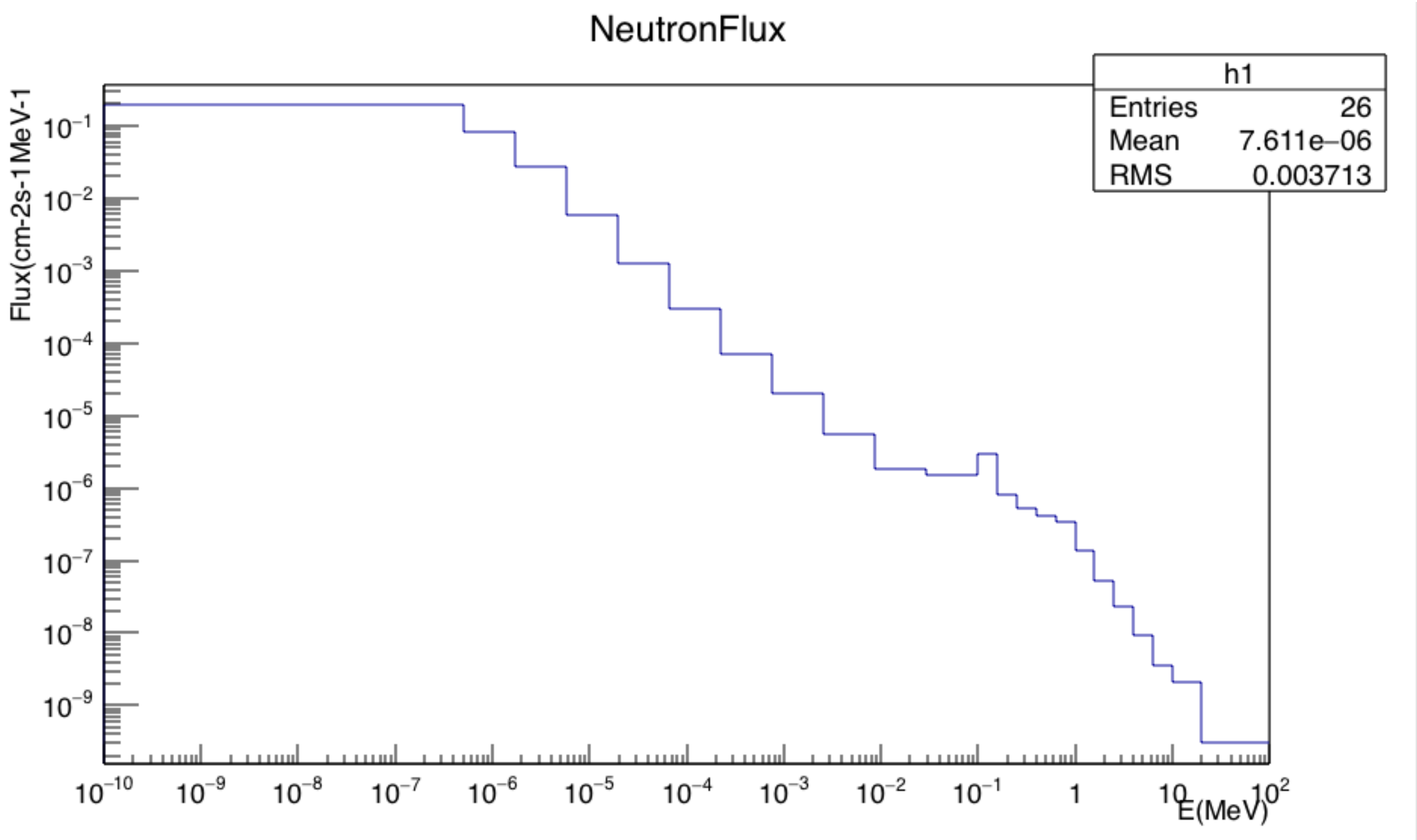
ββ0ν backgrounds

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

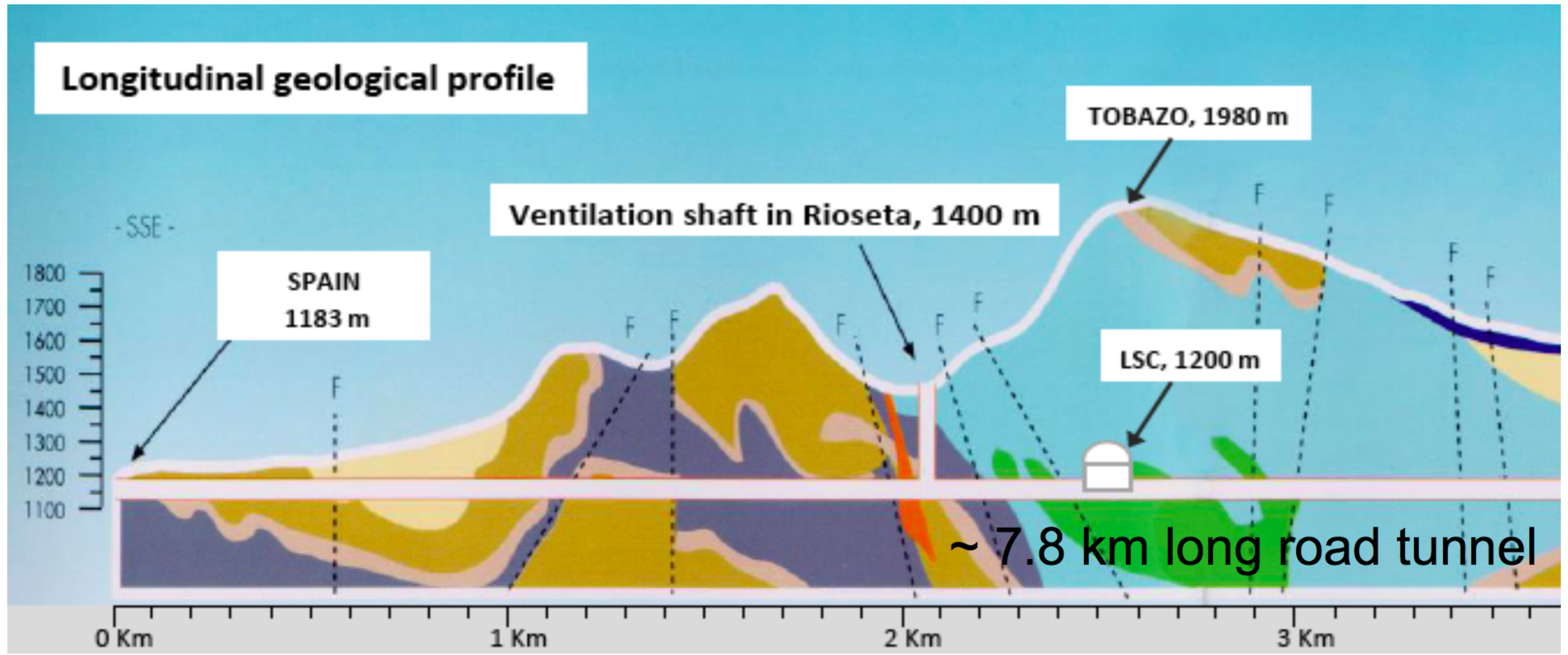
ββ0ν backgrounds

Cosmogenic muons

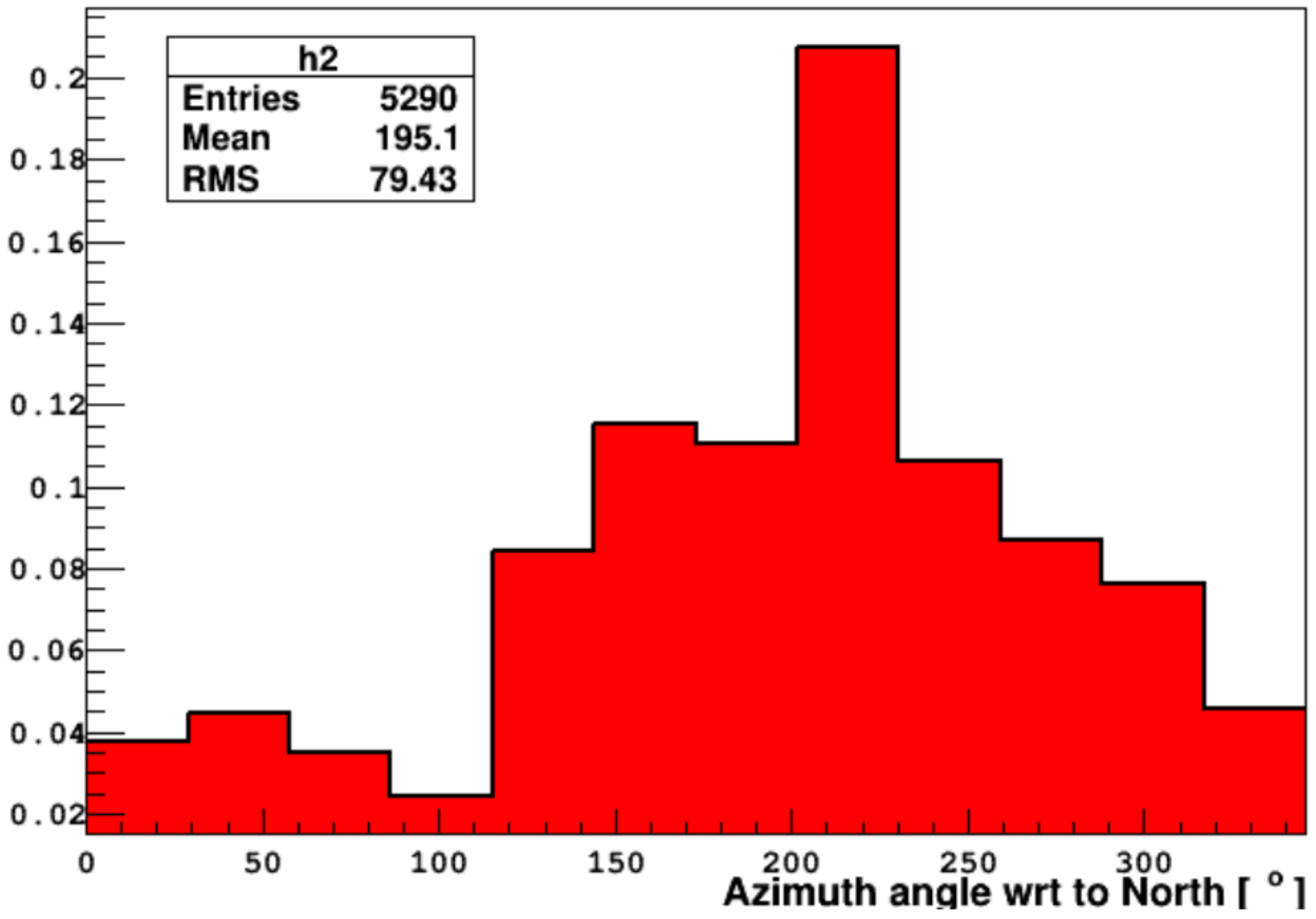
Total muon flux
at LSC Hall A:

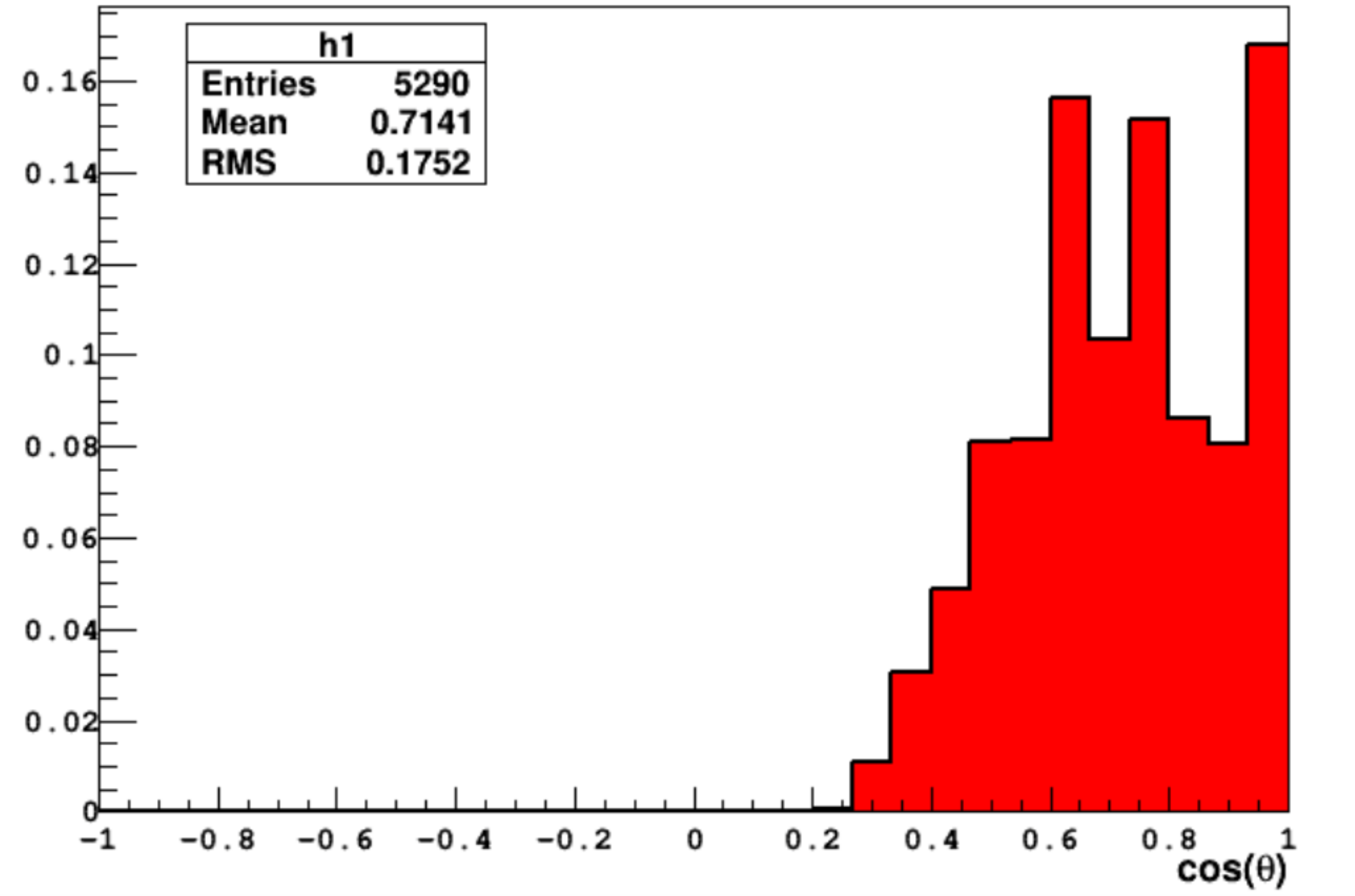
$$3 \times 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Avg. E = 220 - 245 GeV



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

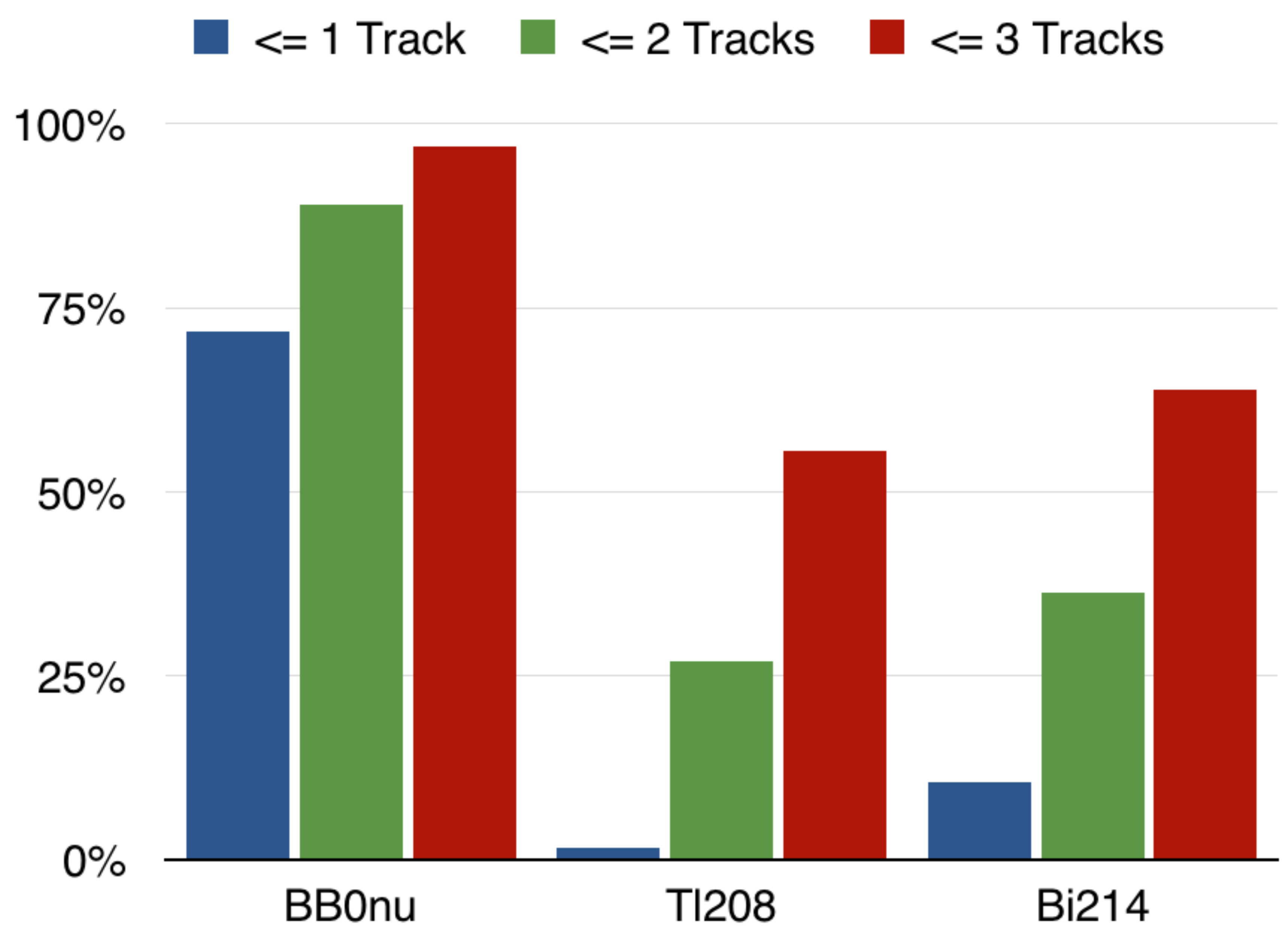




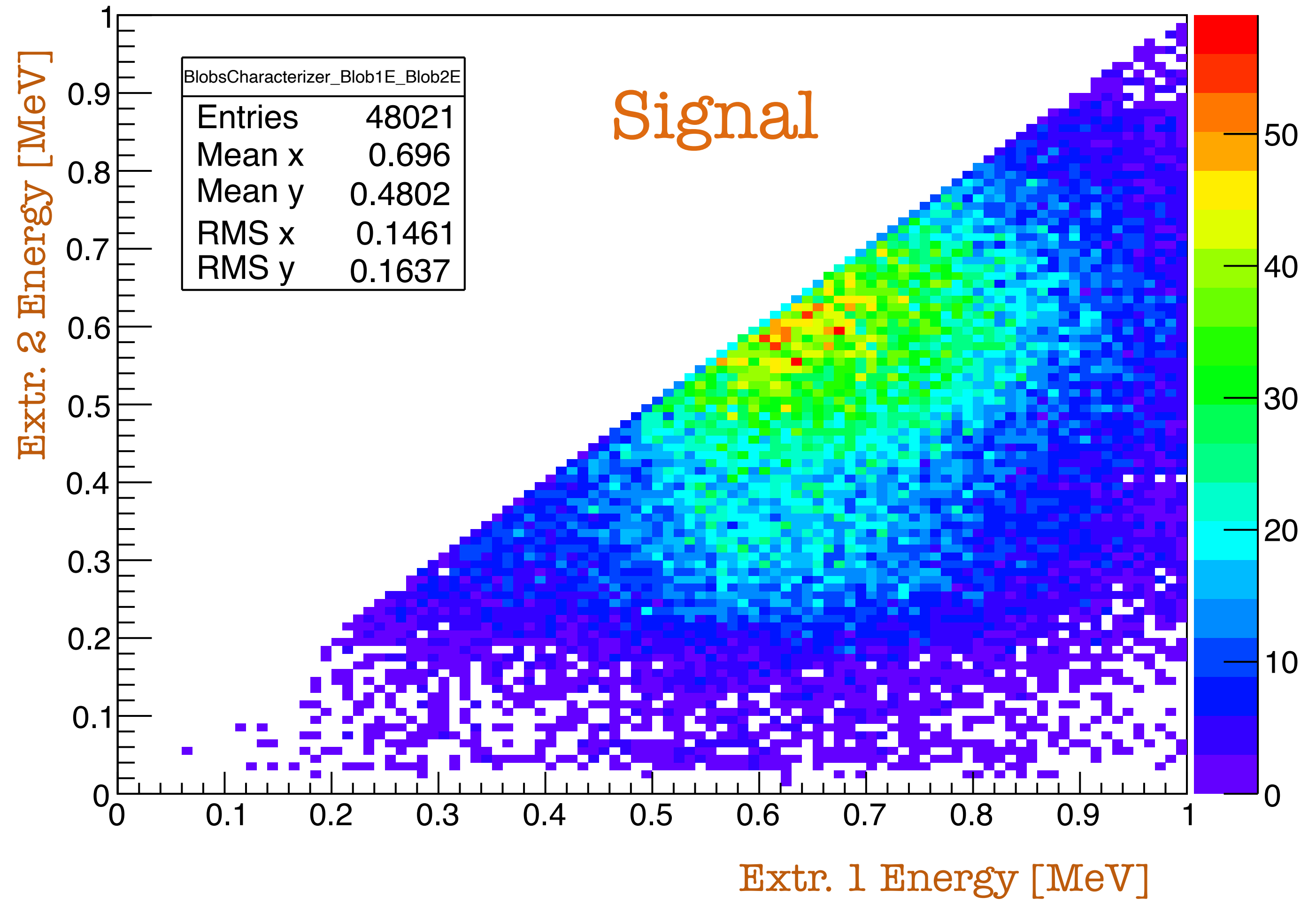
ββ0ν background suppression

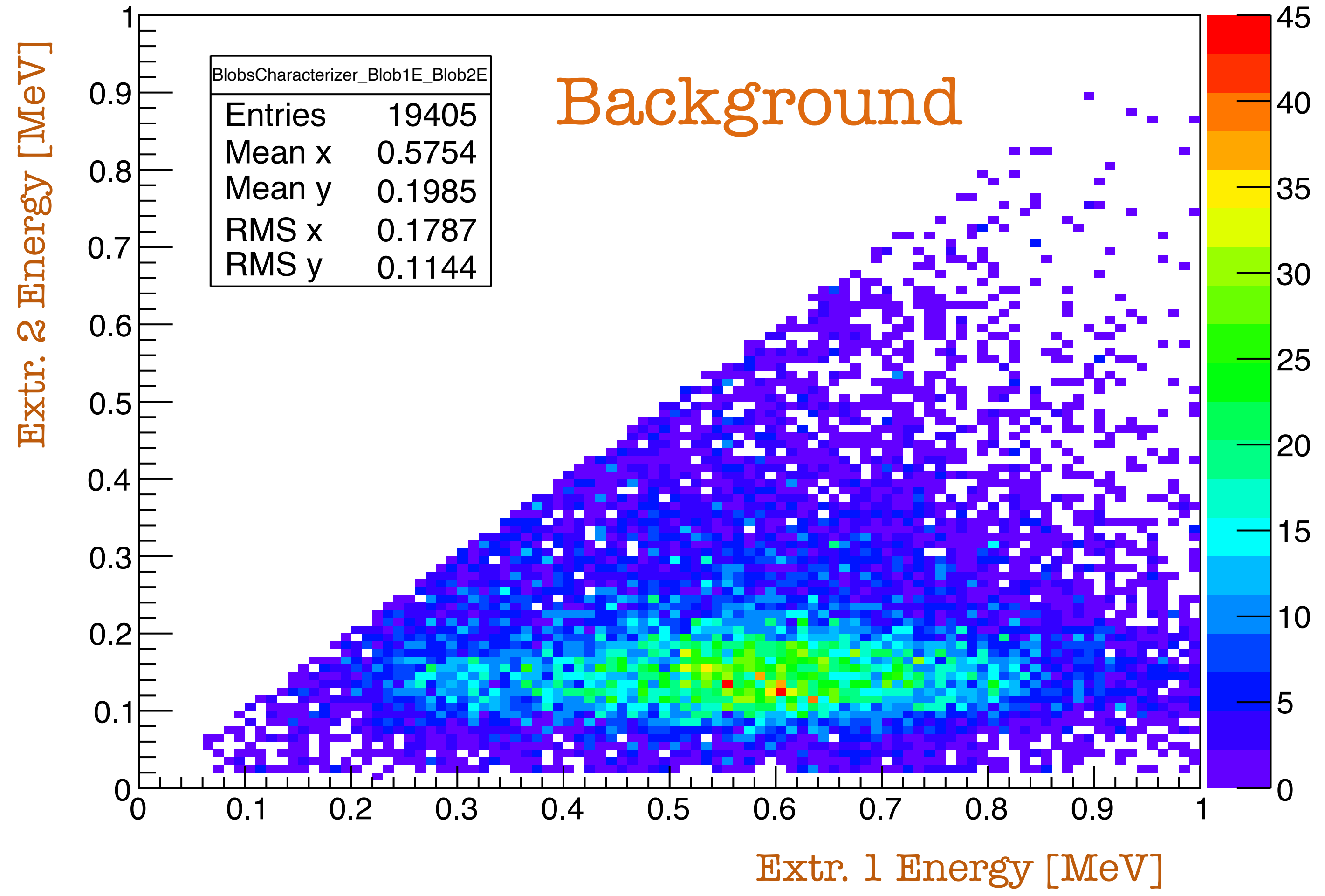
Topology. 1 Track + 2 "blobs"

Track Multiplicity



Extremes energy





ββ0ν background suppression

Efficiencies of classical selection criteria for ^{136}Xe 0νββ decays and average values for ^{208}Tl and ^{214}Bi decays from the dominant sources

Selection criteria	$0\nu\beta\beta$	^{208}Tl	^{214}Bi
Fiducial	0.68	7.72×10^{-3}	9.78×10^{-5}
$E \in [2.4, 2.5]$ MeV	0.98	1.27×10^{-1}	7.24×10^{-1}
Topology (1 Track)	0.72	2.37×10^{-2}	1.11×10^{-1}
Topology (2 Blobs)	0.74	1.14×10^{-1}	1.01×10^{-1}
Energy ROI	0.91	1.44×10^{-1}	4.45×10^{-1}
Total	0.32	3.80×10^{-7}	3.52×10^{-7}

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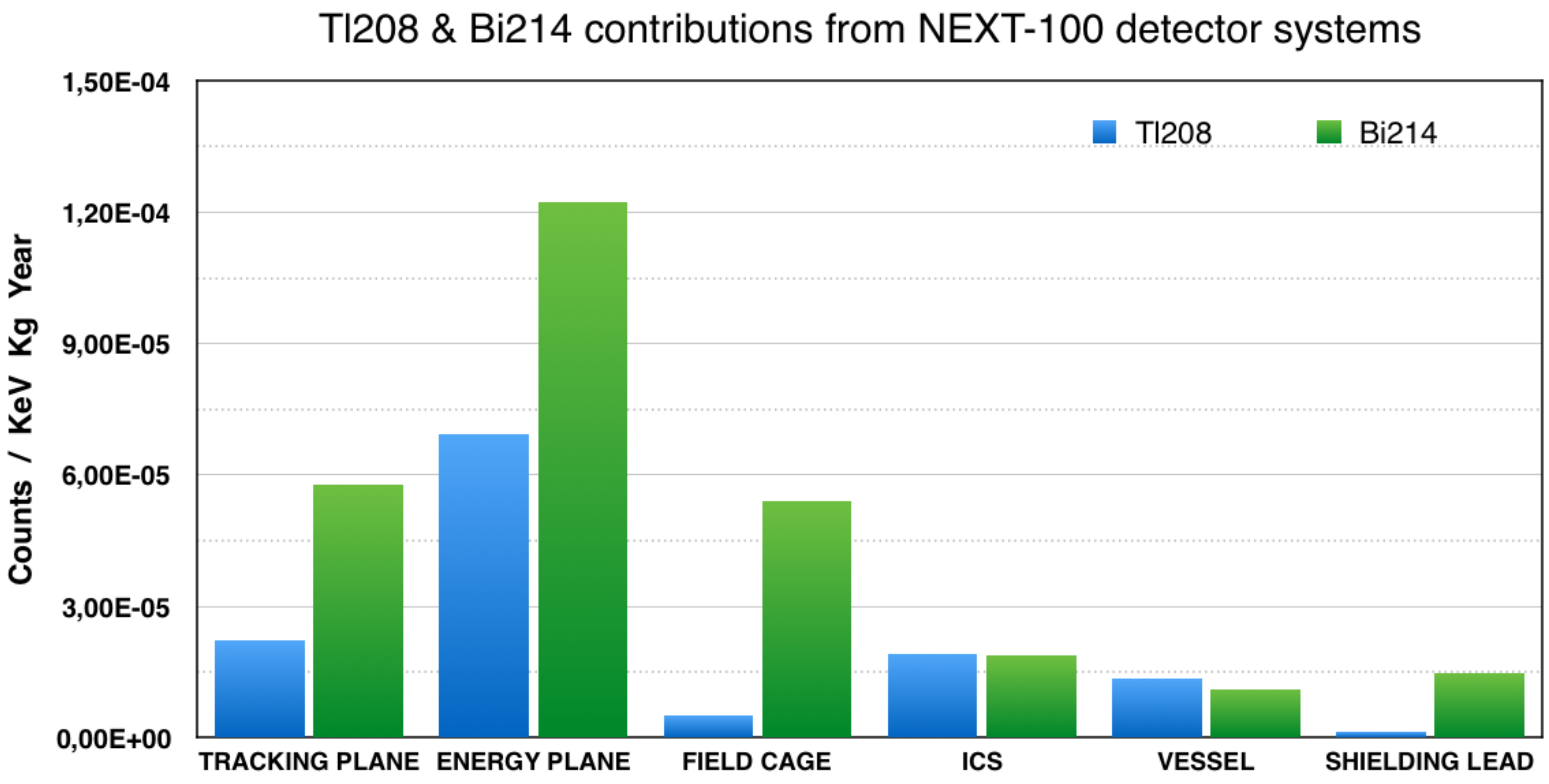
NEXT-100 Background model

Natural decay series: < 4.09×10^{-4} cts / keV kg year



Javier Muñoz Vidal

NEXT-100 Sensitivity

Total Background rate:

4.22 x 10^{-4} cts / keV kg year

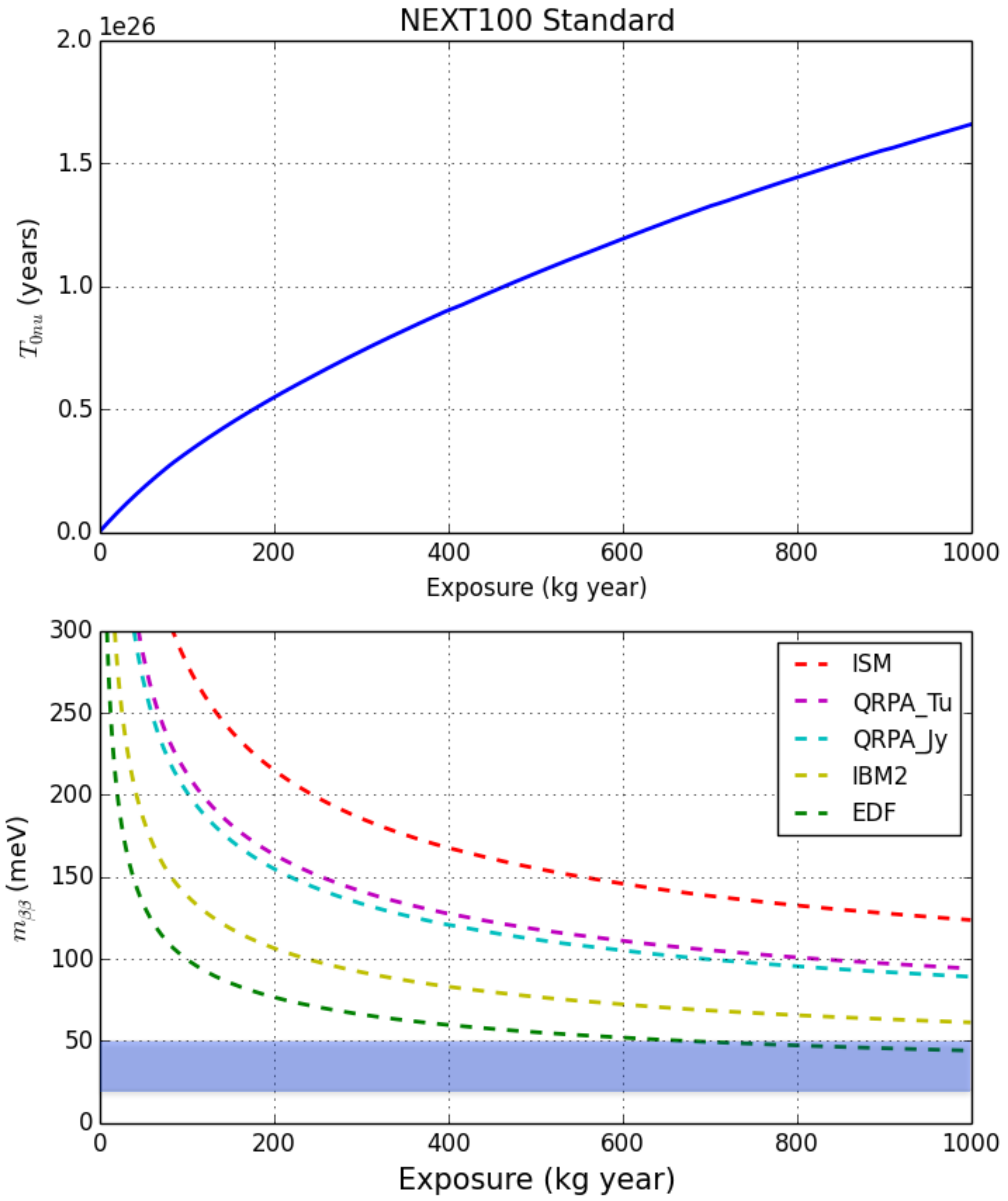
Global detection efficiency:

32 %

After 5 years of data taking:

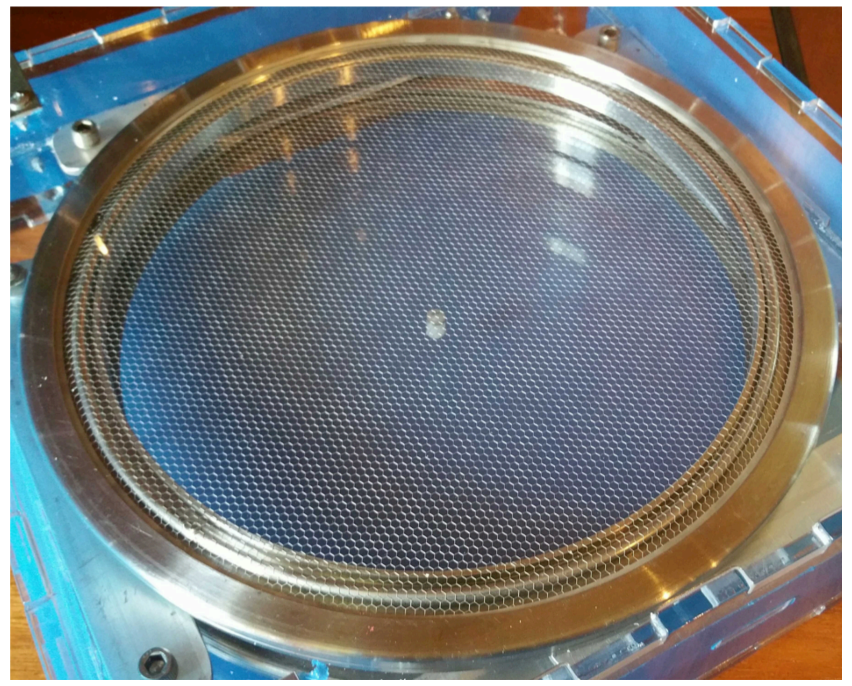
0ν half-life ≃ 1.0 10^{26} years

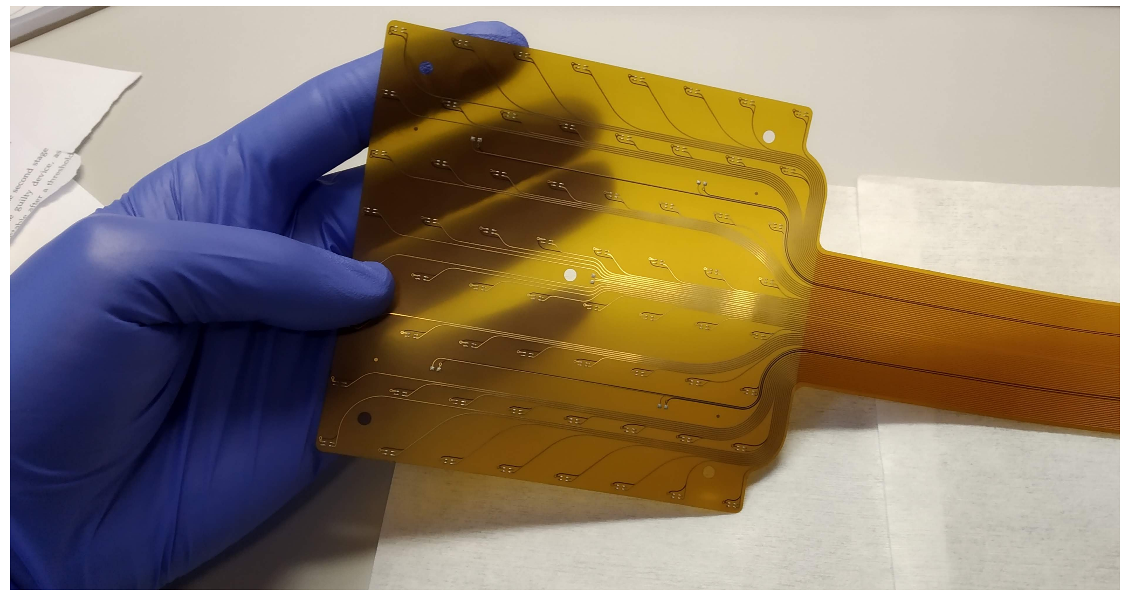
$m_{\beta\beta}$ = [57-161] meV

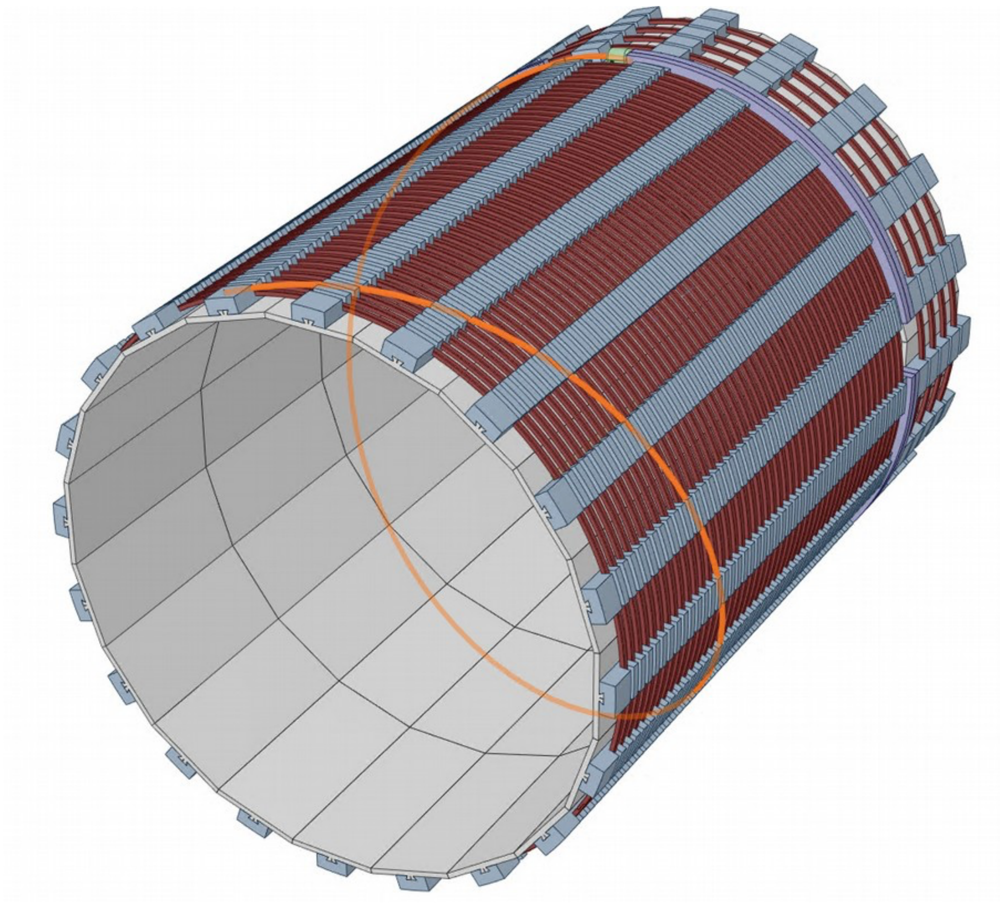


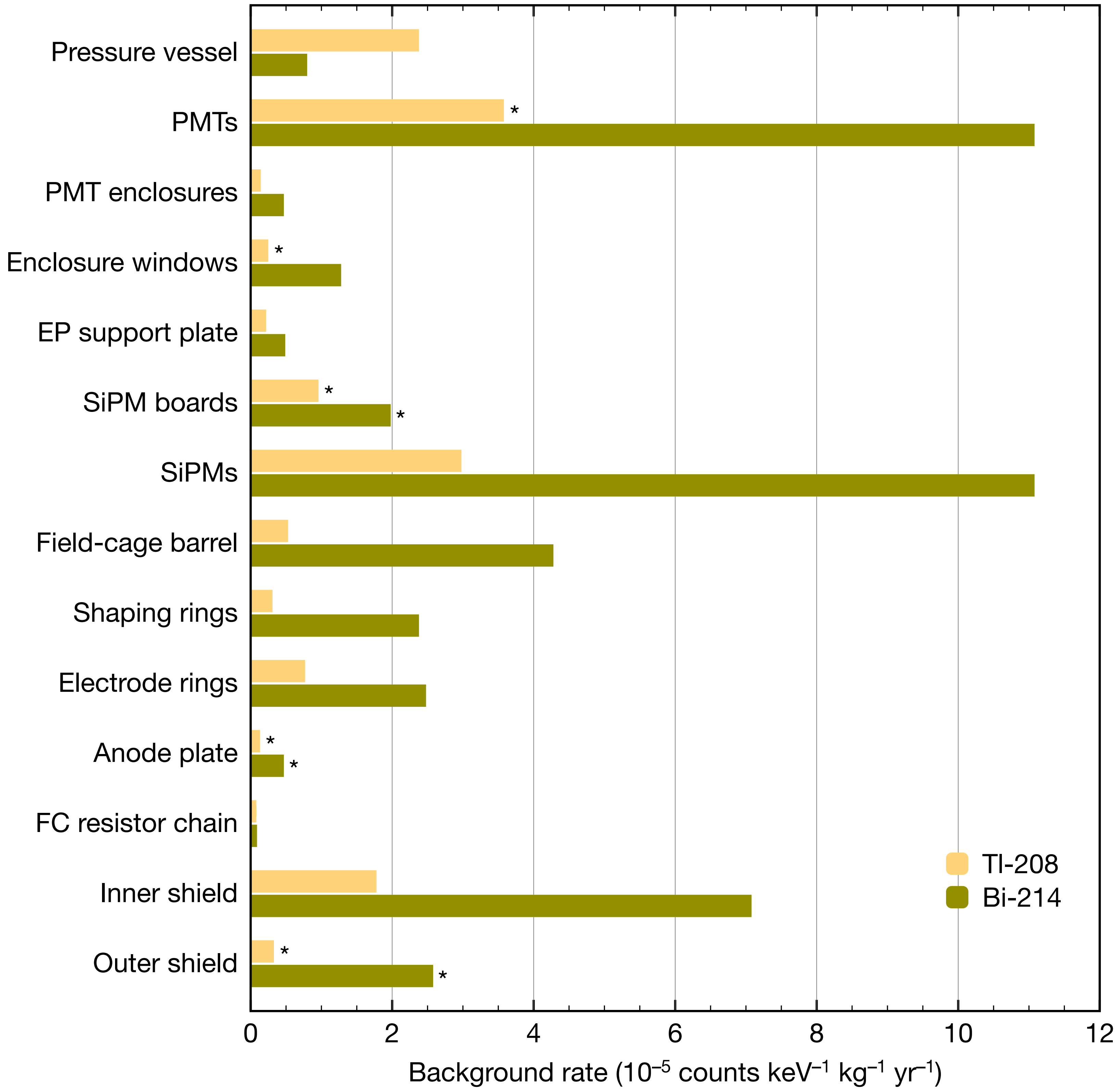
Javier Muñoz Vidal

NEXT-100: also a prototype to ton-scale



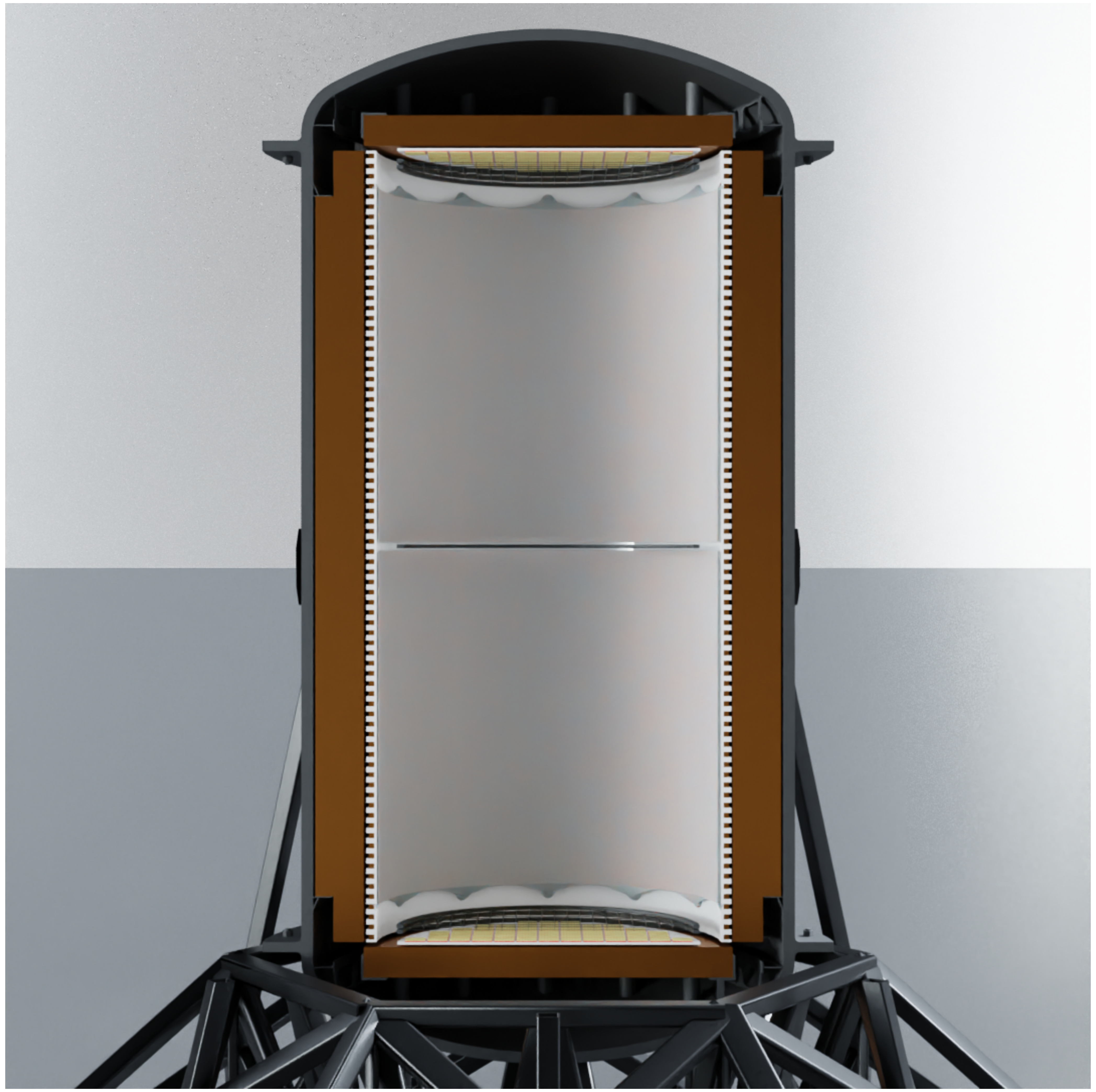






- Understand technical solutions at large scale (EL meshes, HVFT, thinner Kapton boards for SiPMs.
- Validate background model, including background near $Q_{\beta\beta}$ in a detector more radipure and better shielded than NEXT-100
- Understand further energy resolution, topological signature, direct background subtraction.
- Provide an additional physics measurement for ββ0ν searches in Xe-136

Next step: NEXT-HD



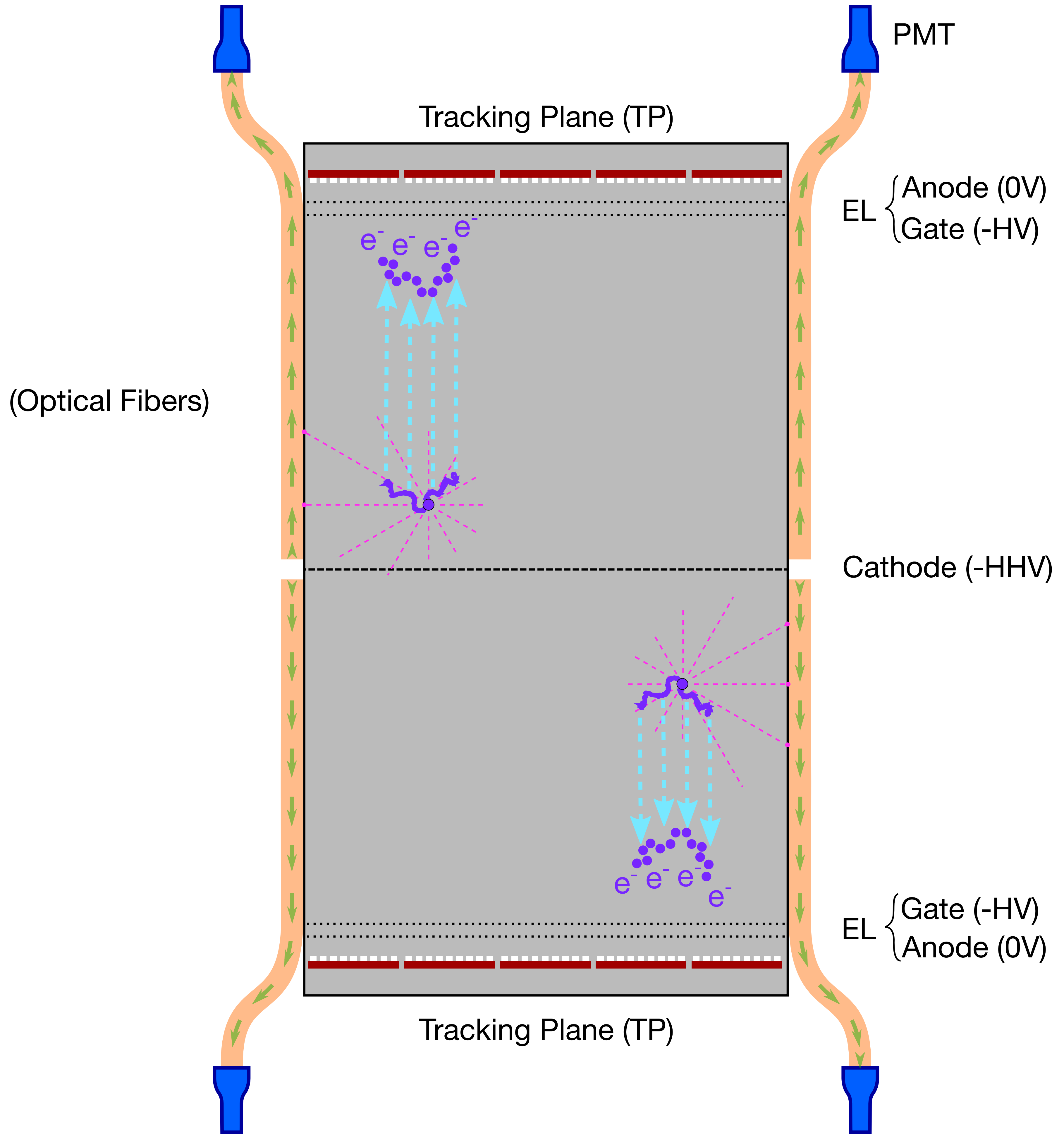
• A symmetric detector of **2 x 1.5 m length** and **2.2 m diameter**, “doubling size of NEXT-100”, holds **1 tonne at 15 bar** and allows operational voltages in the same range than those used by NEXT-100 (thus, minimising risk).

•Both anodes instrumented with dense planes of SiPMs (**DSPs**).

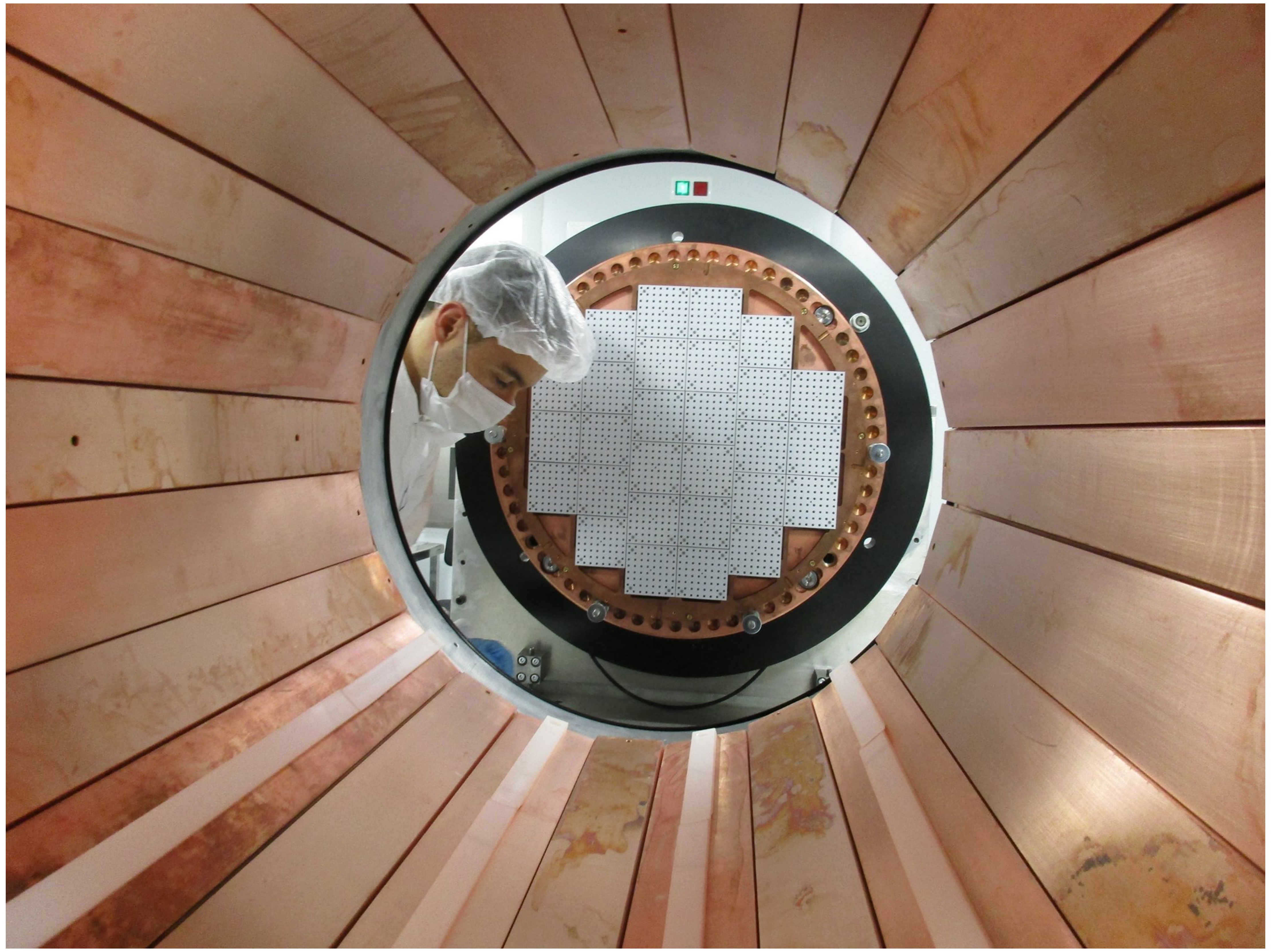
•S1 (and S2) measured by a barrel fiber detector (**BFD**).

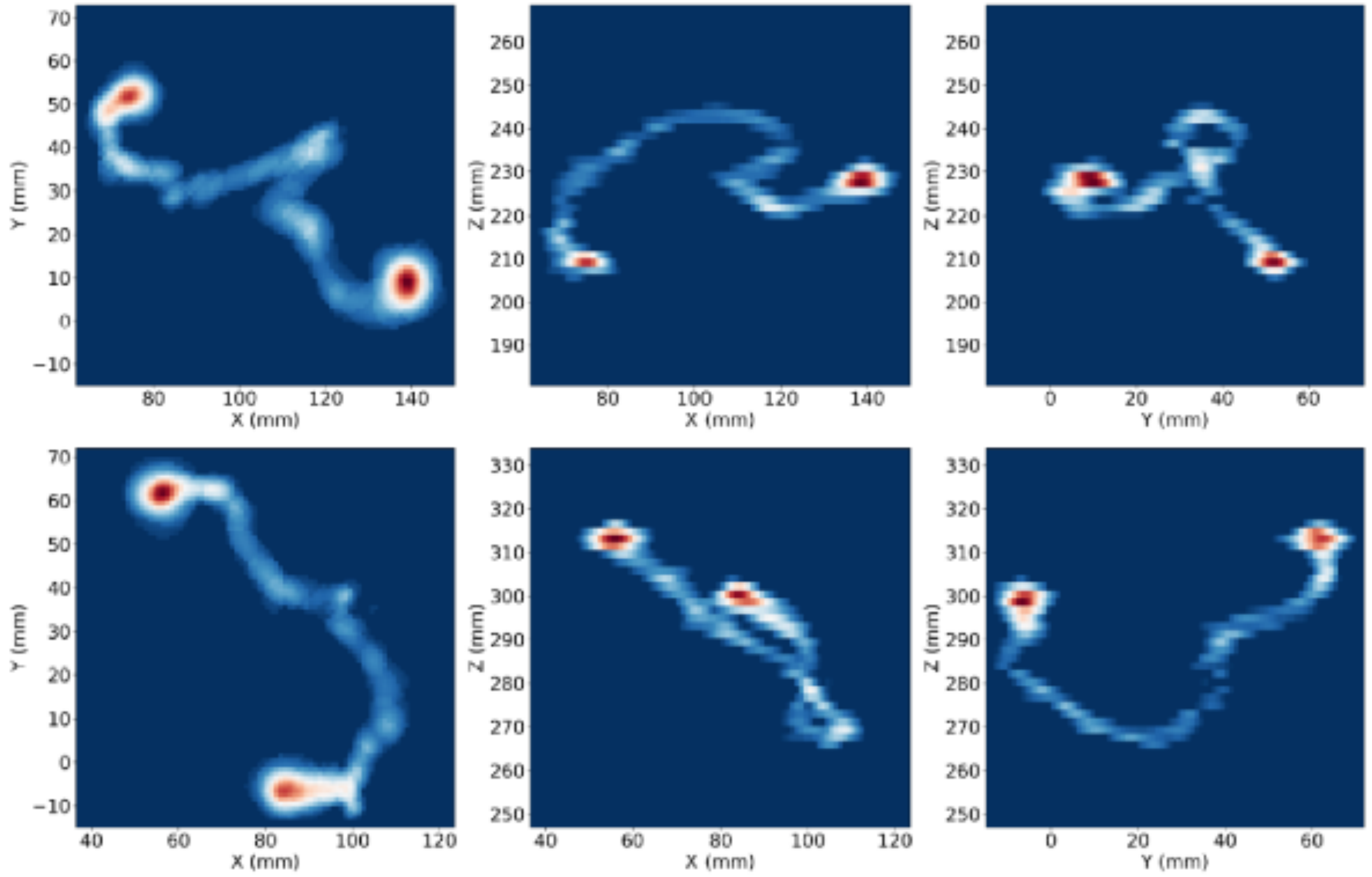
Barrel Fiber Detector

- In NEXT-White and NEXT-100, S1 and S2 are measured by the PMTs. The overall light efficiency of both systems is of the order of 1.1 %. This permits the identification of S1 for Krypton (essential for calibrations) and also a measurement of S2 with modest EL amplification (~500 photons/e).
- NEXT-HD needs to provide a system that is located in the barrel and replaces the role of the PMT plane.
- Baseline: double-clad scintillating optical fibres, coupled to PMTs (or SiPMs).
- Monte Carlo studies indicate that the optical detection efficiency will increase from 1.2% to about 3%.

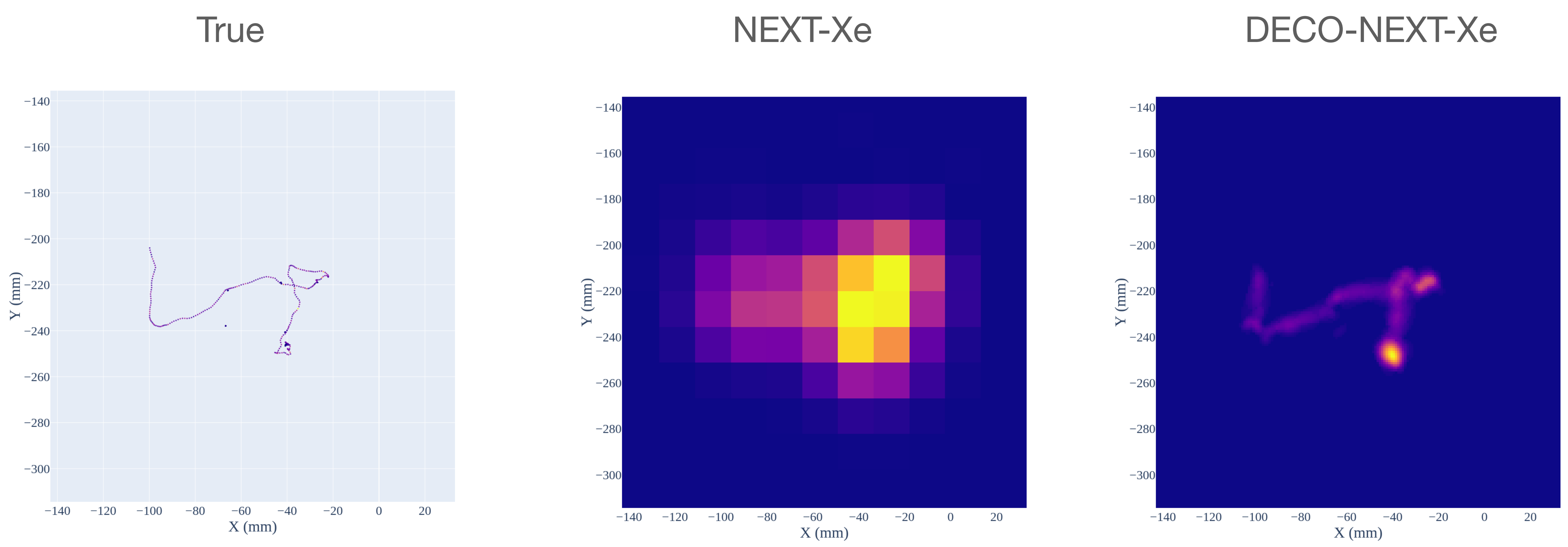


Topological signature: NEXT unique asset

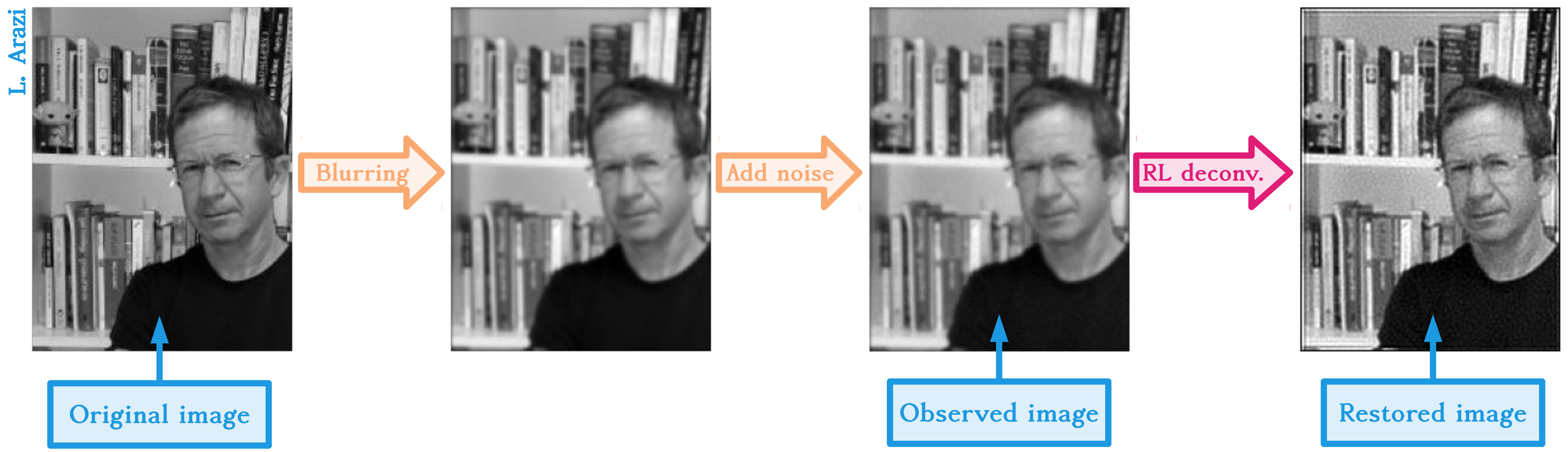




NEXT topological signature: Richardson-Lucy deconvolution



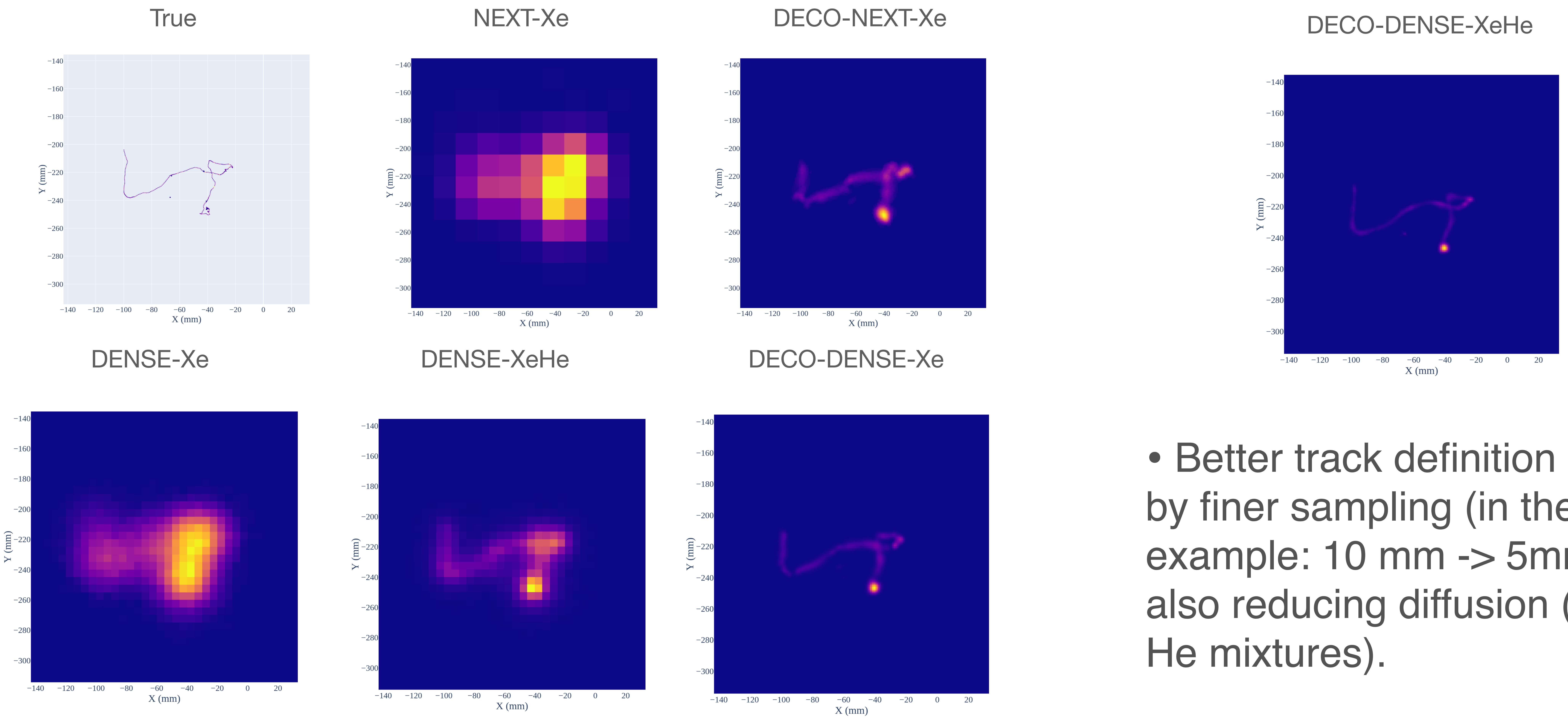
- The observed image is the result of the original image blurred by a kernel and additional noise.
- **Given a known kernel,** Richardson–Lucy (RL) deconvolution **solves the inverse problem iteratively**.
  - Described independently by W. Richardson and L. Lucy in the early 70s.



- Why DSP?

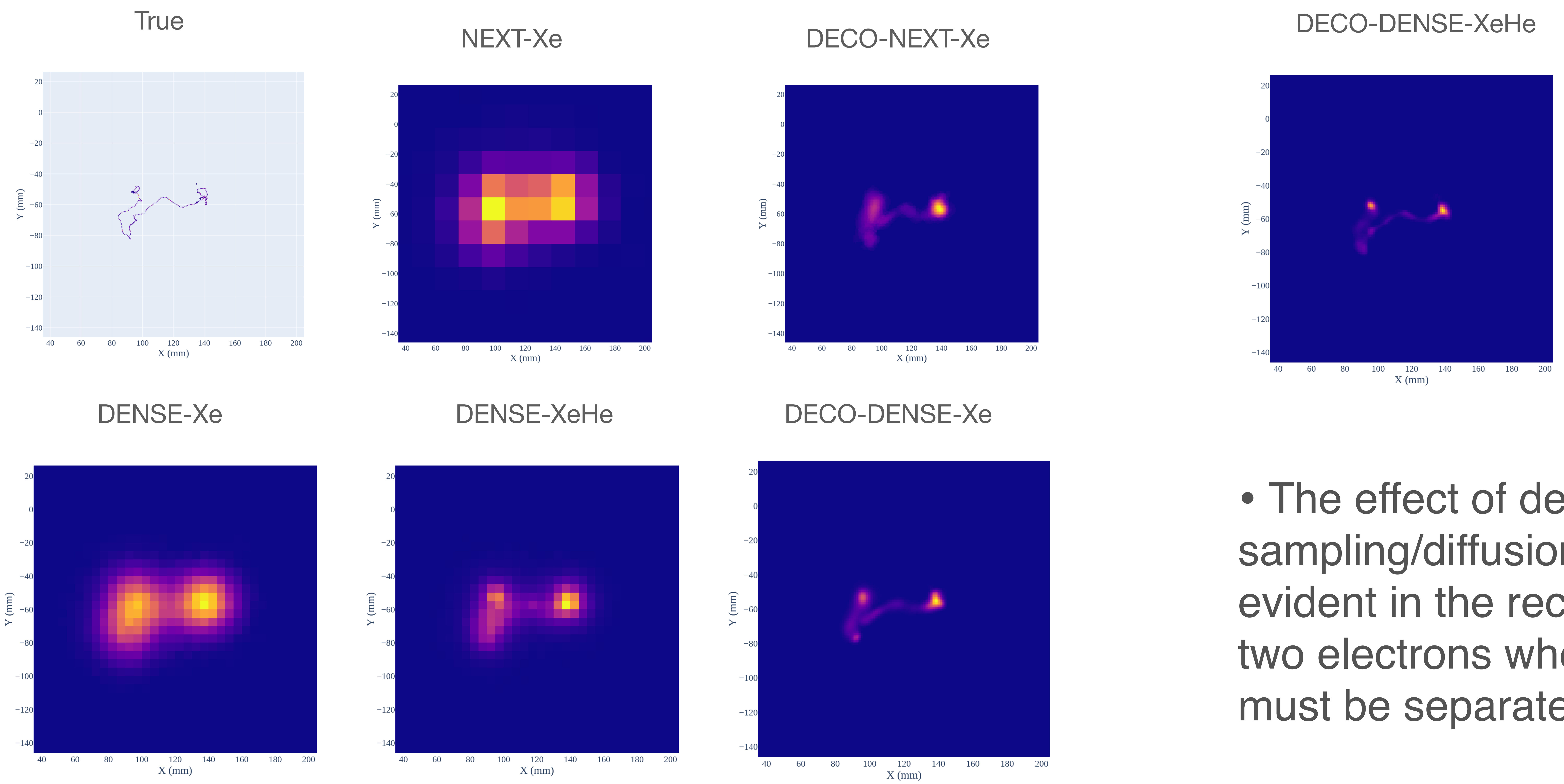
- Deconvolution requires proper sampling of image, which in turn benefits from fine-grain pixels .

High density = high definition (single electron example)



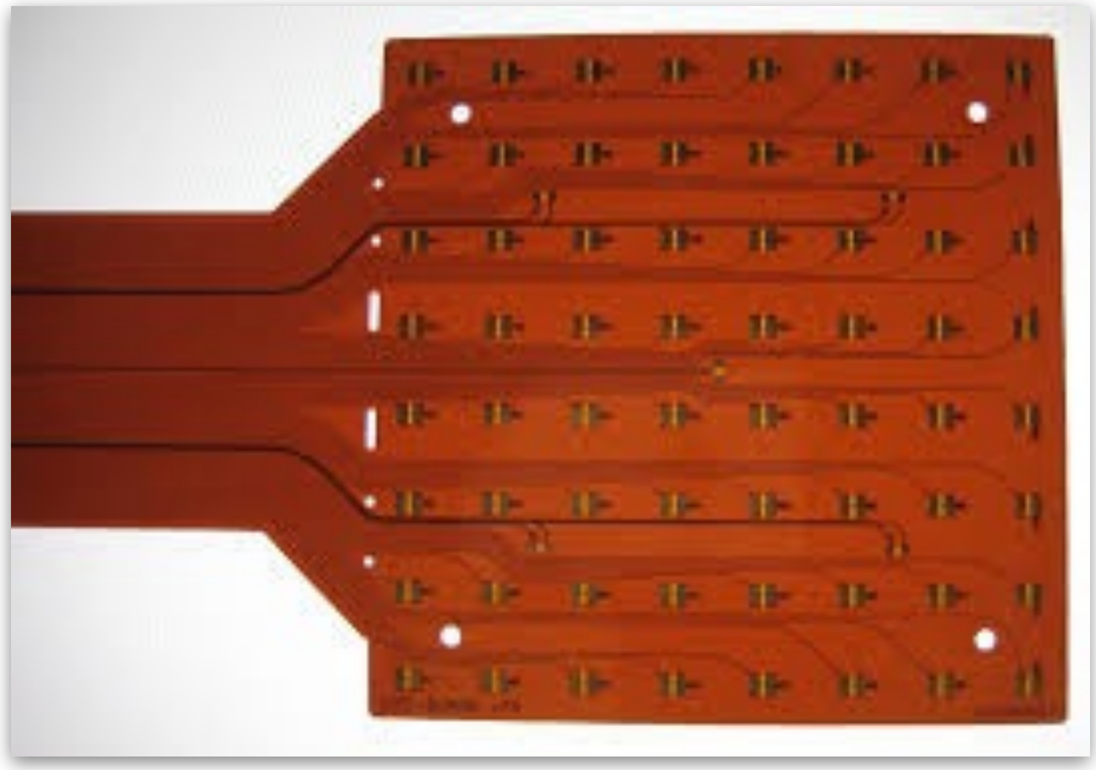
- Better track definition achieved by finer sampling (in the example: 10 mm -> 5mm) but also reducing diffusion (e.g, Xe-He mixtures).

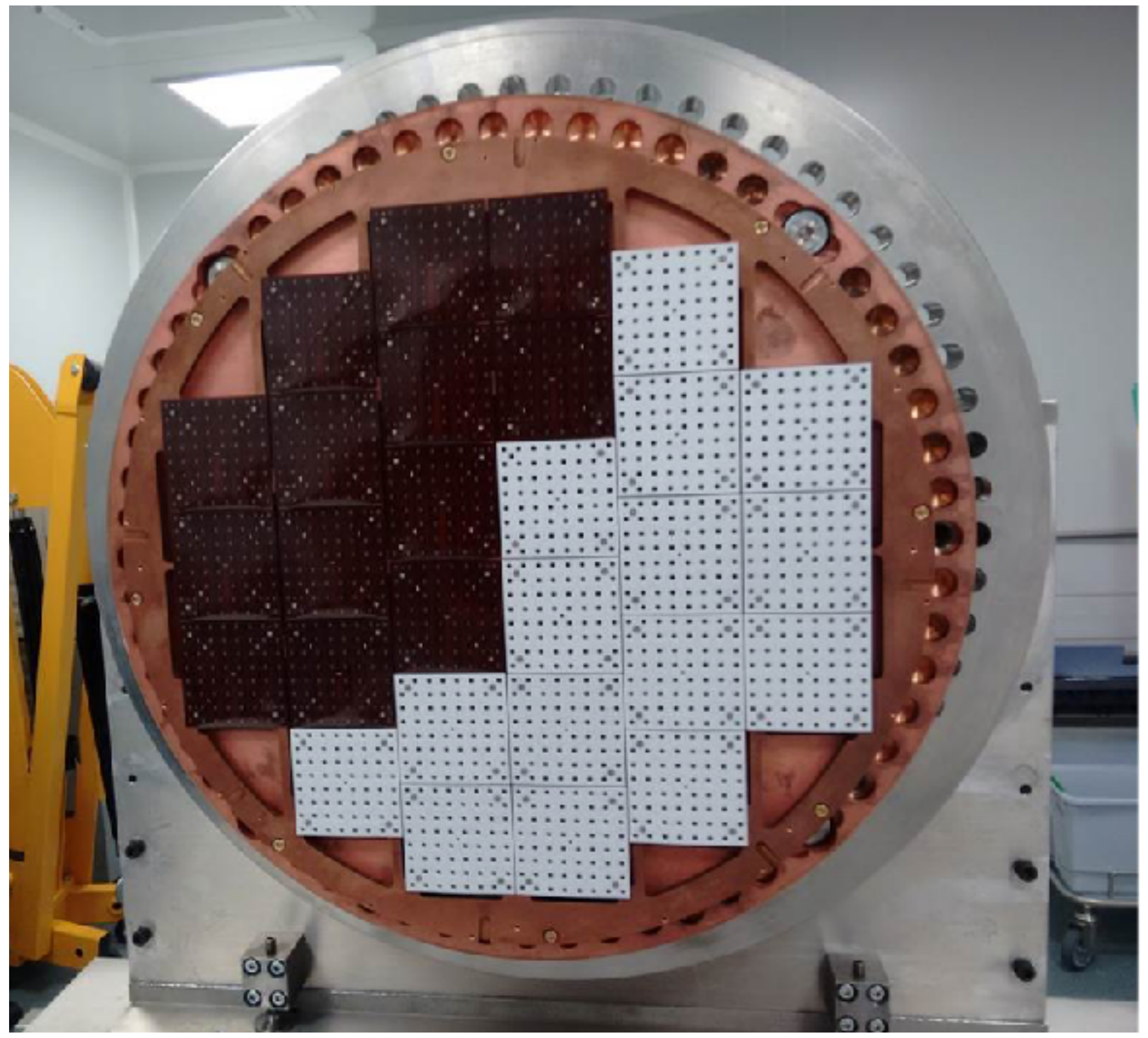
High density = high definition (double electron example)



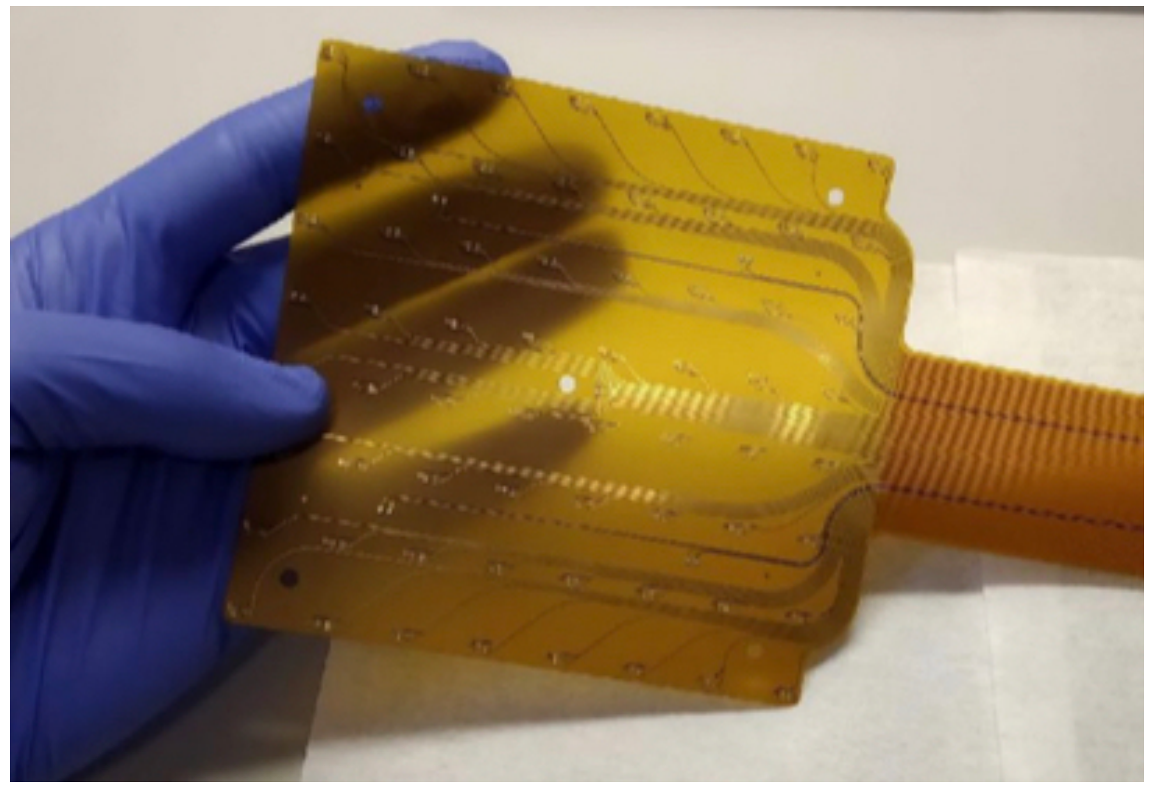
- The effect of deconvolution/sampling/diffusion is even more evident in the reconstruction of two electrons where two blobs must be separated.

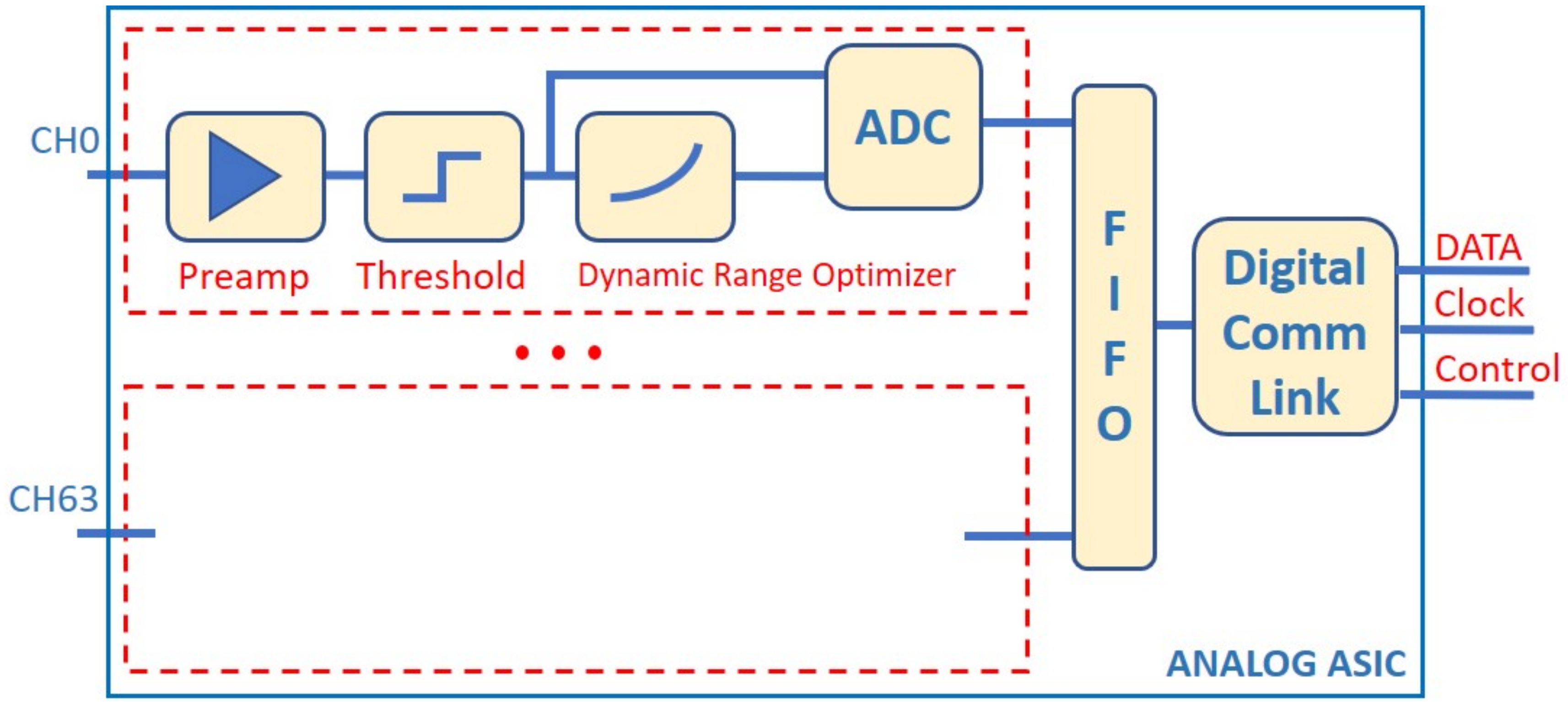
Design of the Dense Silicon Planes





Optimise pitch to maximise track reconstruction and thus background rejection.

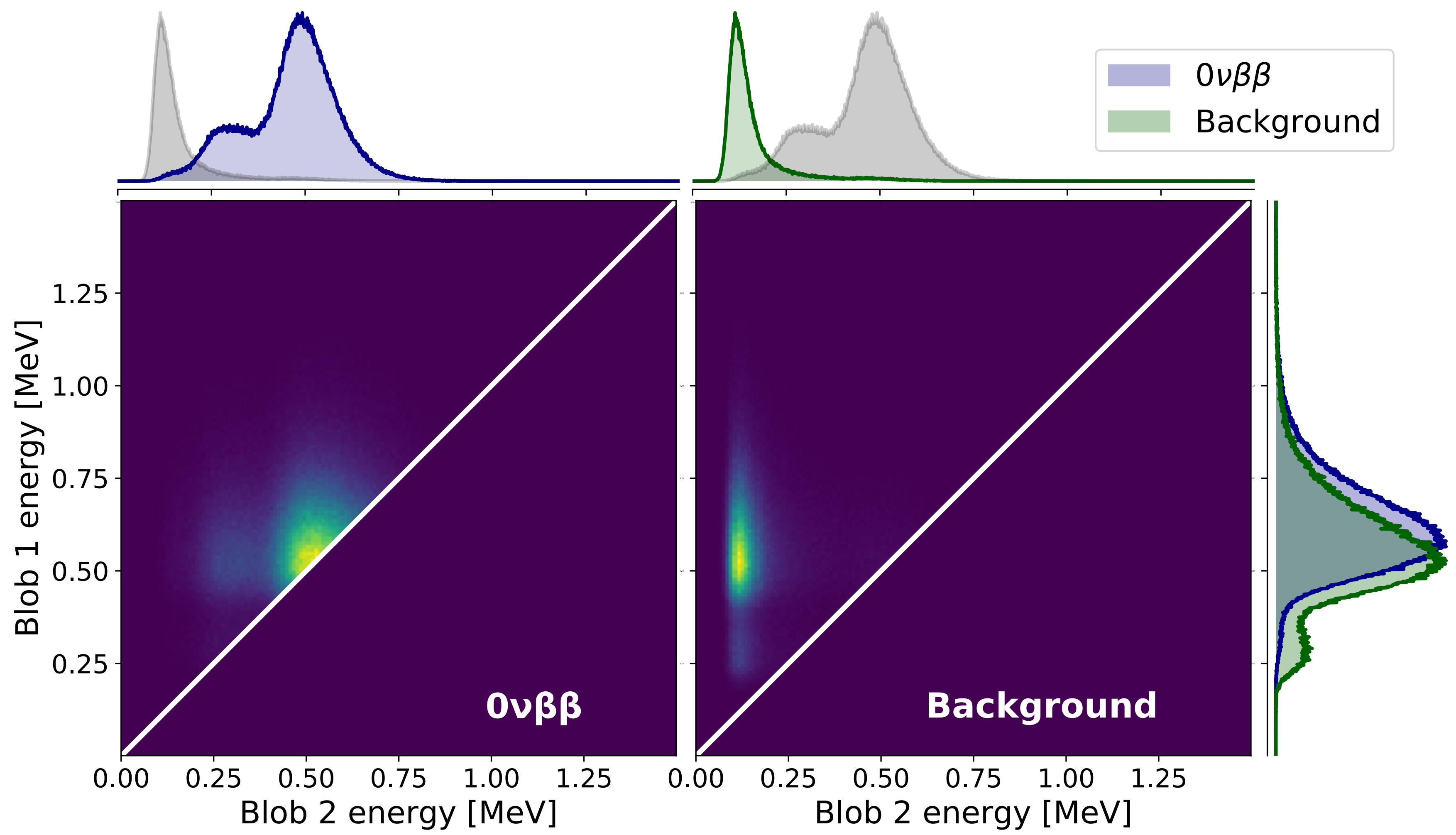


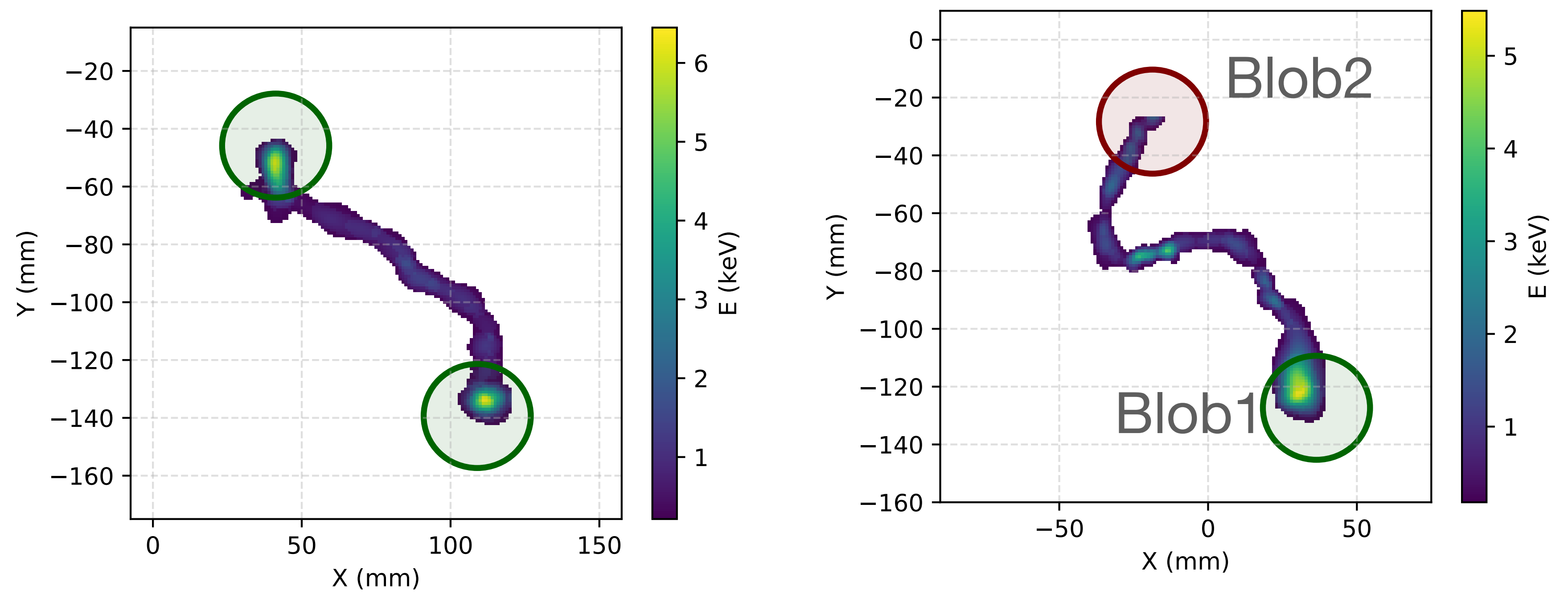


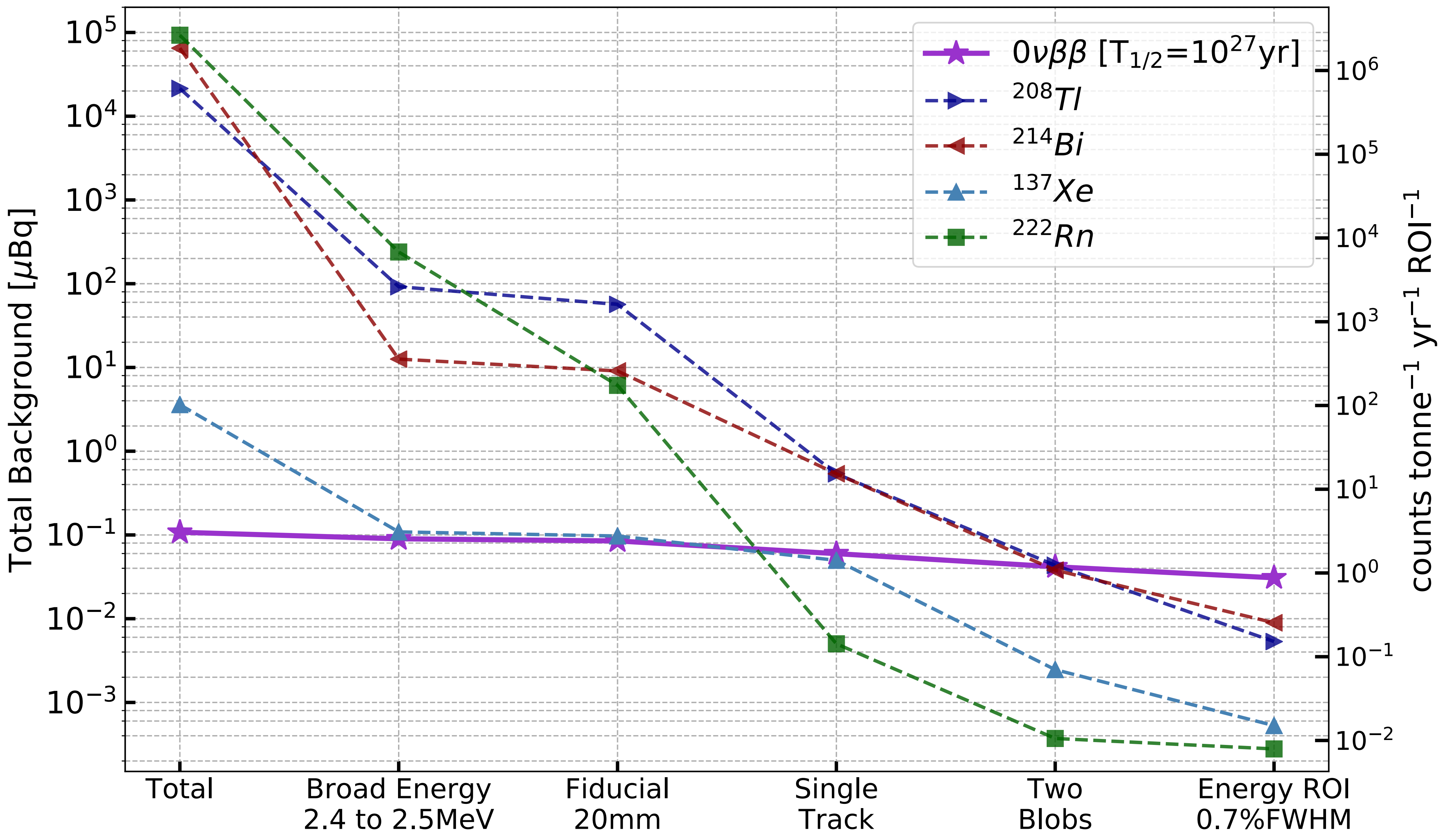
In vessel electronics (develop new ASIC or re-use/optimise existing devices).

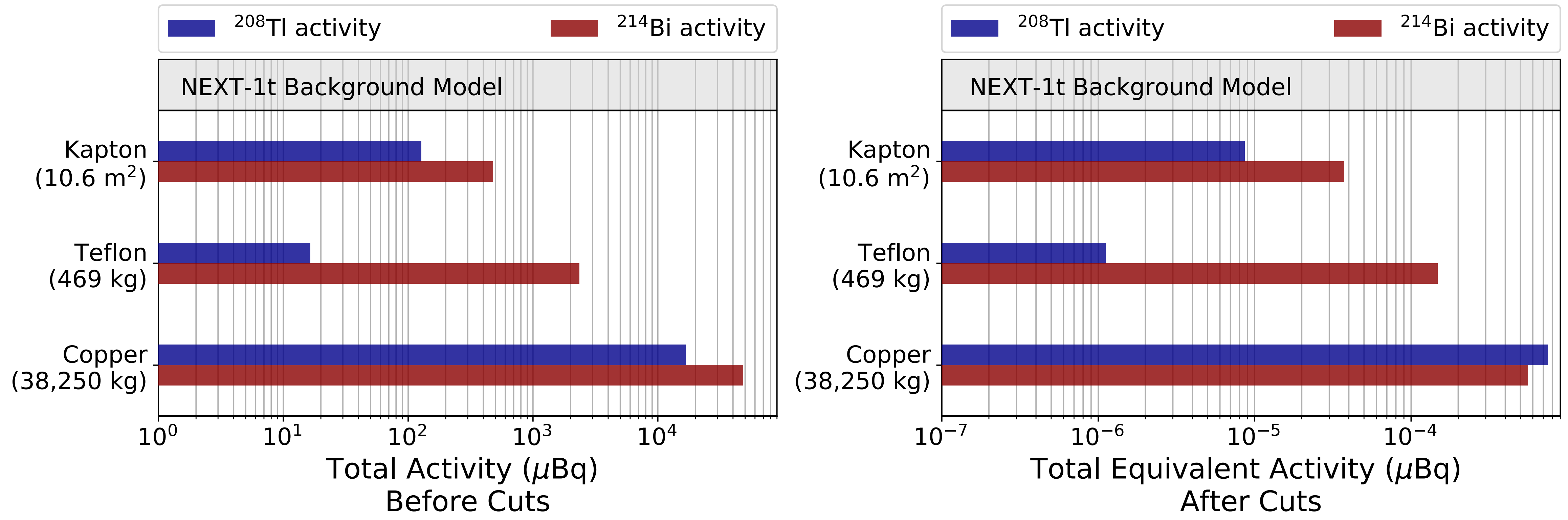
Reduce radioactive budget (thinner Kapton boards)

NEXT-HD background rejection power









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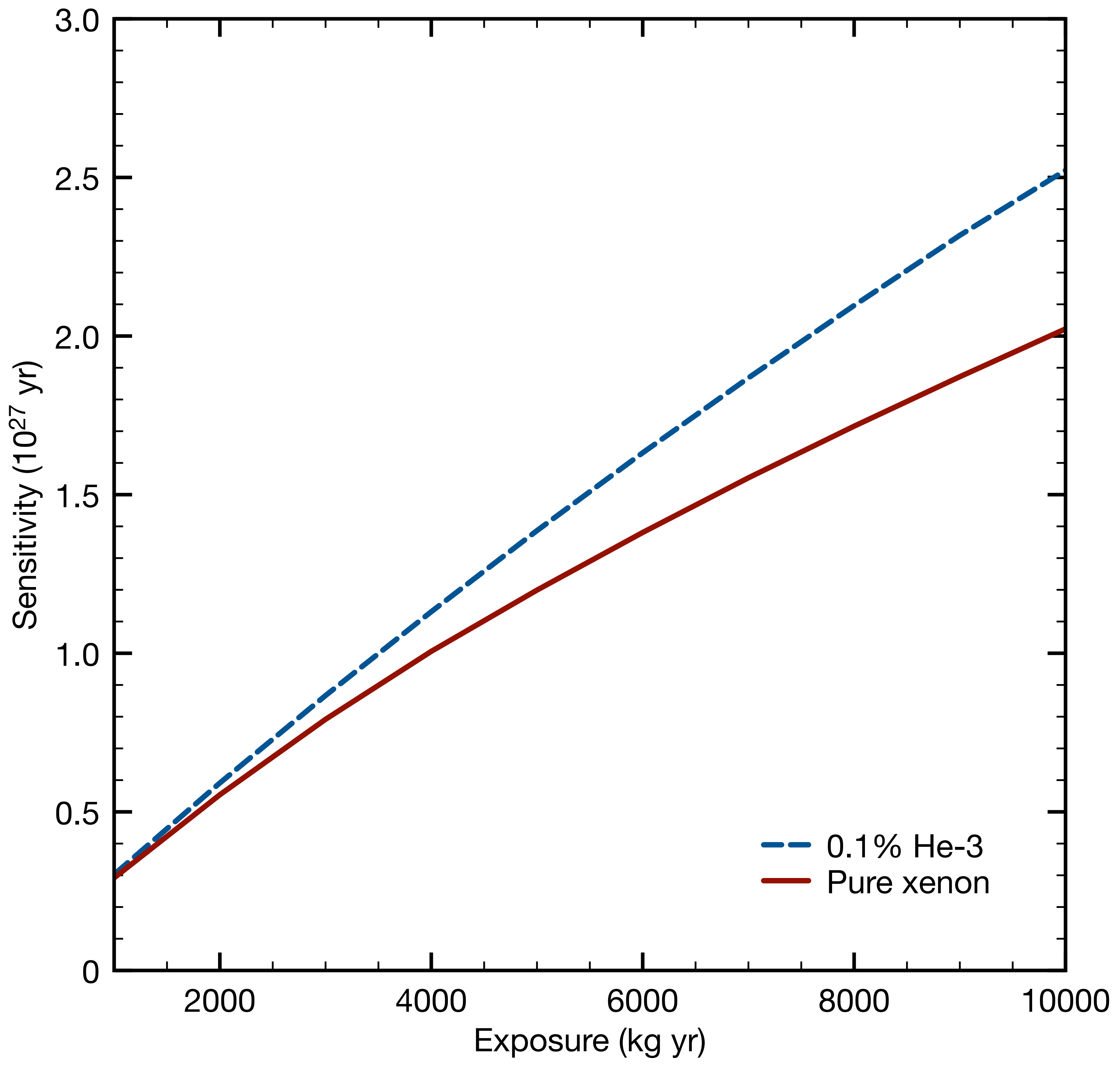
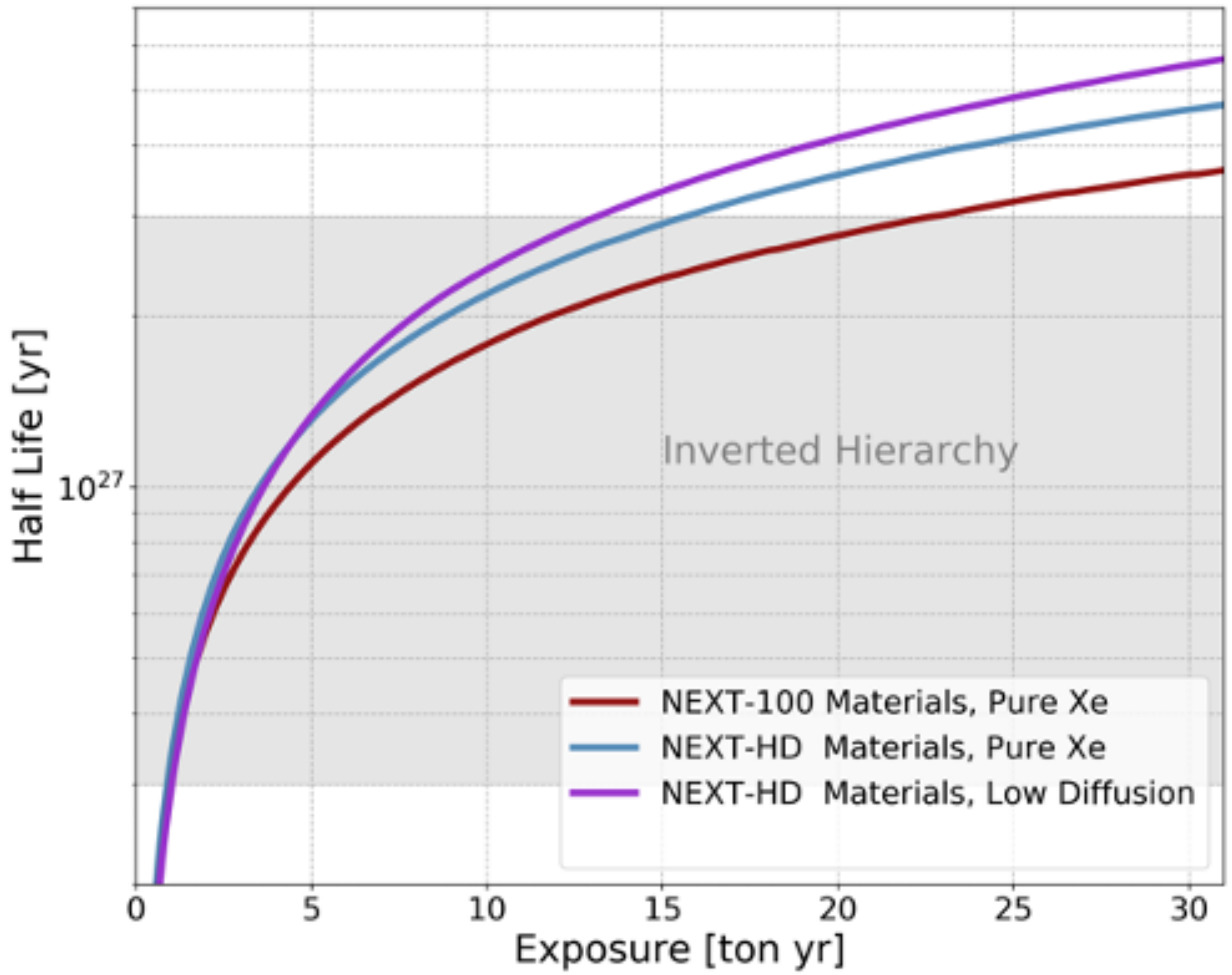
Sensitivity

First module at LSC



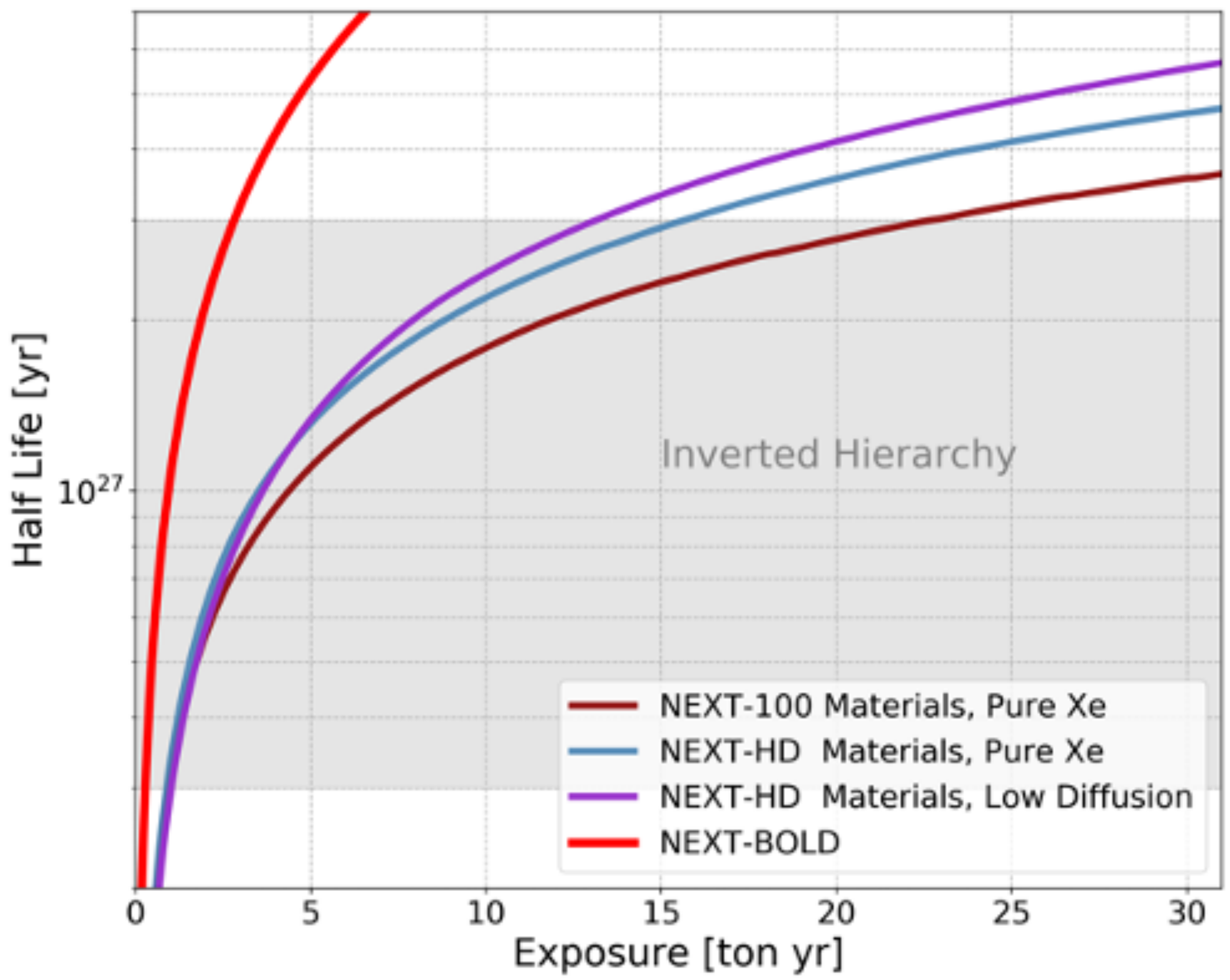
Large exposure sensitivity



• NEXT-HD first module, proposed to operate at the LSC can reach 10^{27} years with 5 ton year exposure.

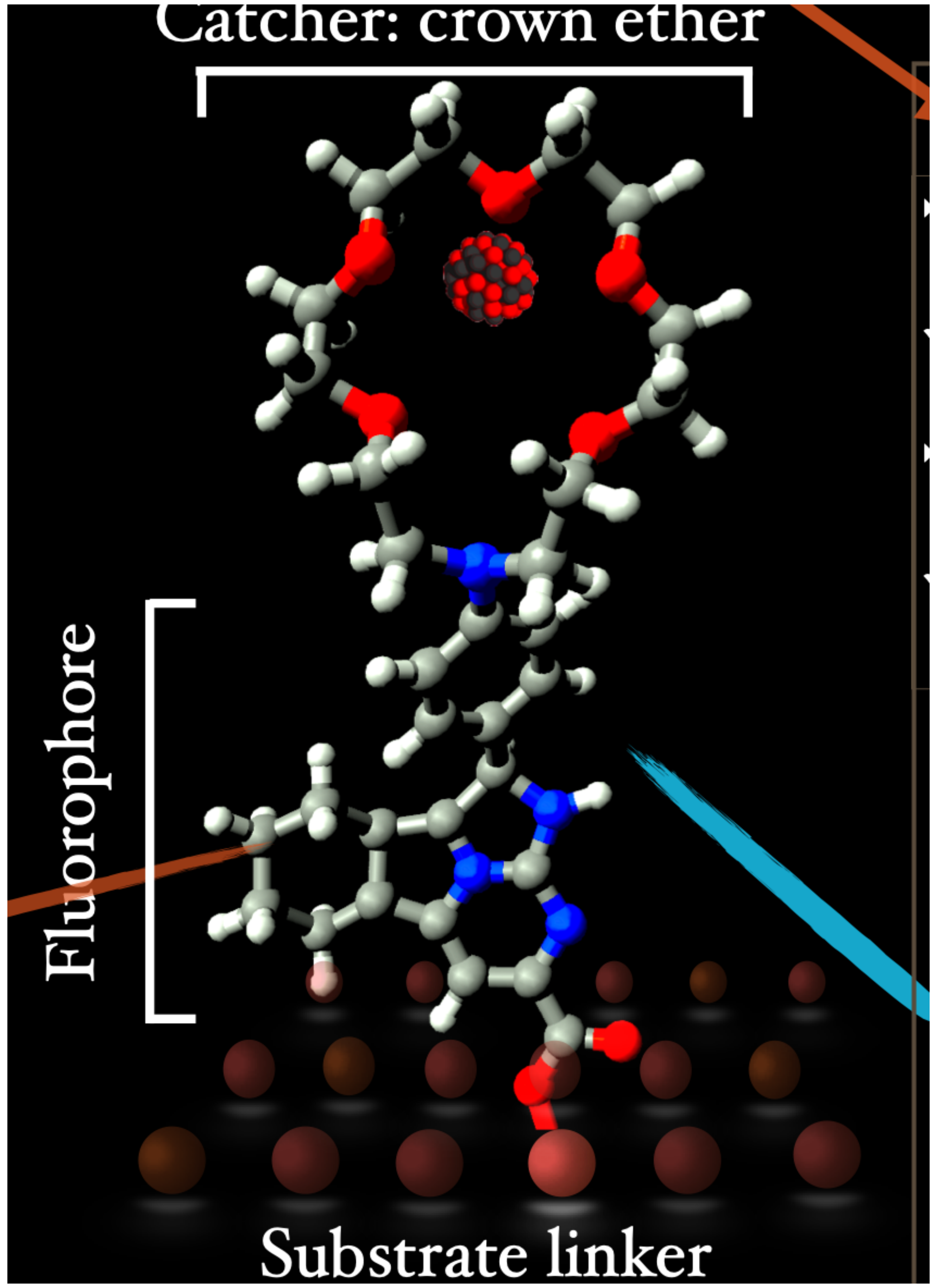
•Further modules (eventually with larger masses and operating deeper) can explore the region up to 10^{28} y.

From NEXT-HD to NEXT-BOLD



- To explore the NH (>~10^{28} year) further background reduction and higher efficiency are essential.
- Both can be achieved by NEXT-BOLD, with Barium Tagging.
- BOLD R&D program will take the next ~5 years.
- This is the time that we also need to operate NEXT-100, carry HD R&D, build and commission NEXT-HD.
- Next HD sets the stage for NEXT-BOLD, which will operate at the ton-scale with augmentation to realise barium tagging.

BOLD: Ba2+ detection using molecular indicators



D. Nygren , J.Phys.Conf.Ser. 650 (2015) no.1, 012002
JINST 11 (2016) no.12, P12011

A.D. McDonald *et al.* (NEXT Collaboration)
Phys. Rev. Lett. 120, 132504 (2017)

Sci Rep 9, 15097 (2019)

Nature 583, 48–54 (2020)

ACS Sens. 2021, 6, 1, 192–202 (2021)

- **Idea (Nygren)**: Exploit single molecule fluorescent imaging (SMFI) to visualise ("tag") a single Ba2+ ion as it arrives at the TPC cathode
- **Ba2+ sensor**: Based on molecular indicators, able to change luminous response after chelating Ba2+ cations.
- **Apparatus**: Must be able to detect in delayed coincidence the electron signal (in anode) and the cation signal in cathode.
- **Crucial bonus** : delayed coincidence pushes estimated background (and error) to very small numbers (ultimately limited by $\beta\beta2\nu$ at levels near 10^{-9} ckky). Efficiency of delayed coincidence can be measured (calibration with Ra2+ source and ββ2v events).

Ba2+ expected to chelated indicators in high pressure gas

Nature 583, 48–54 (2020)

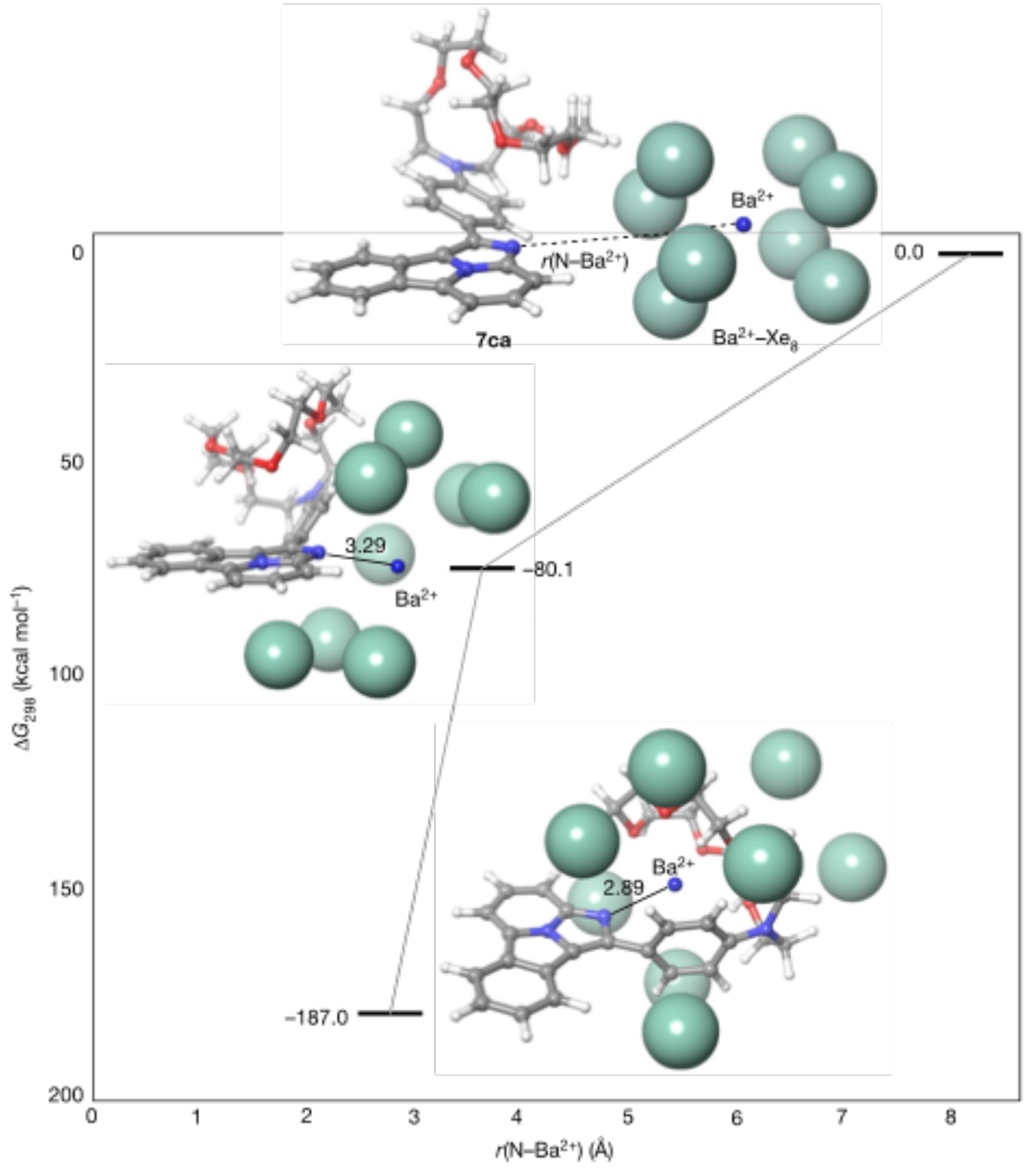
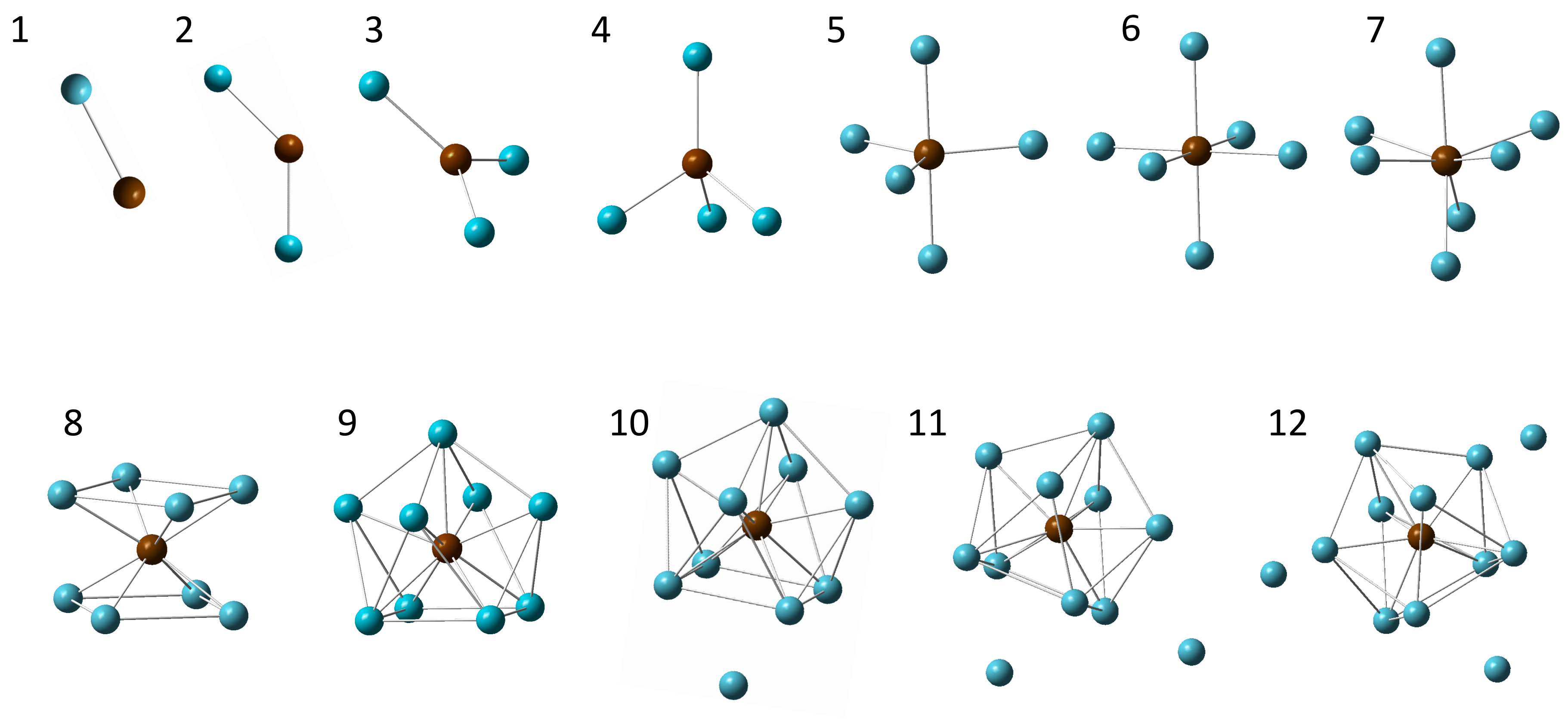
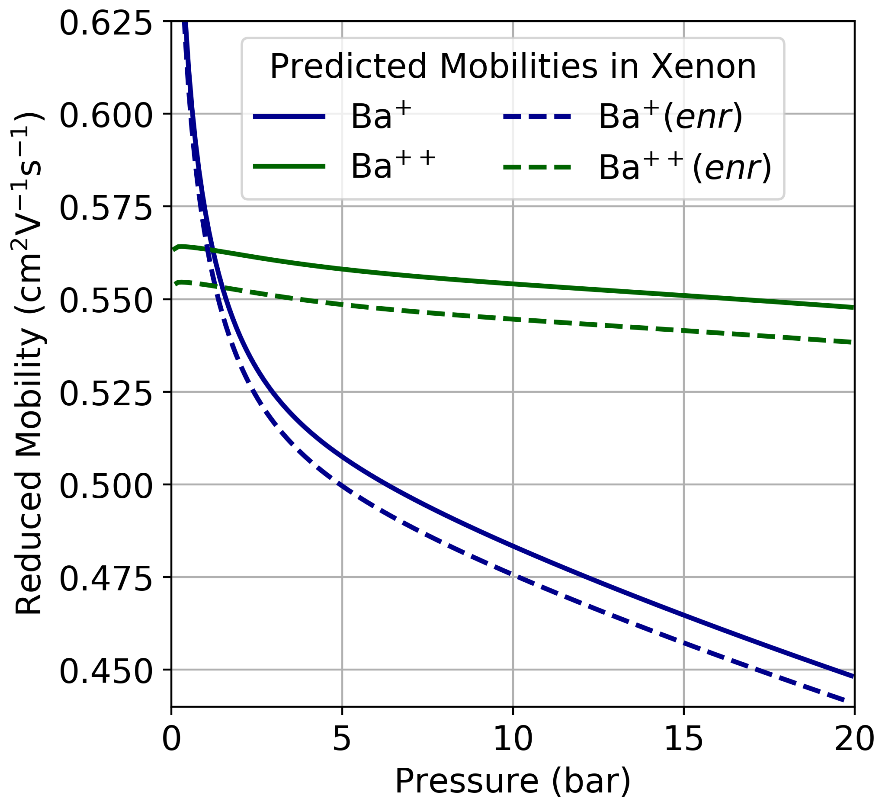


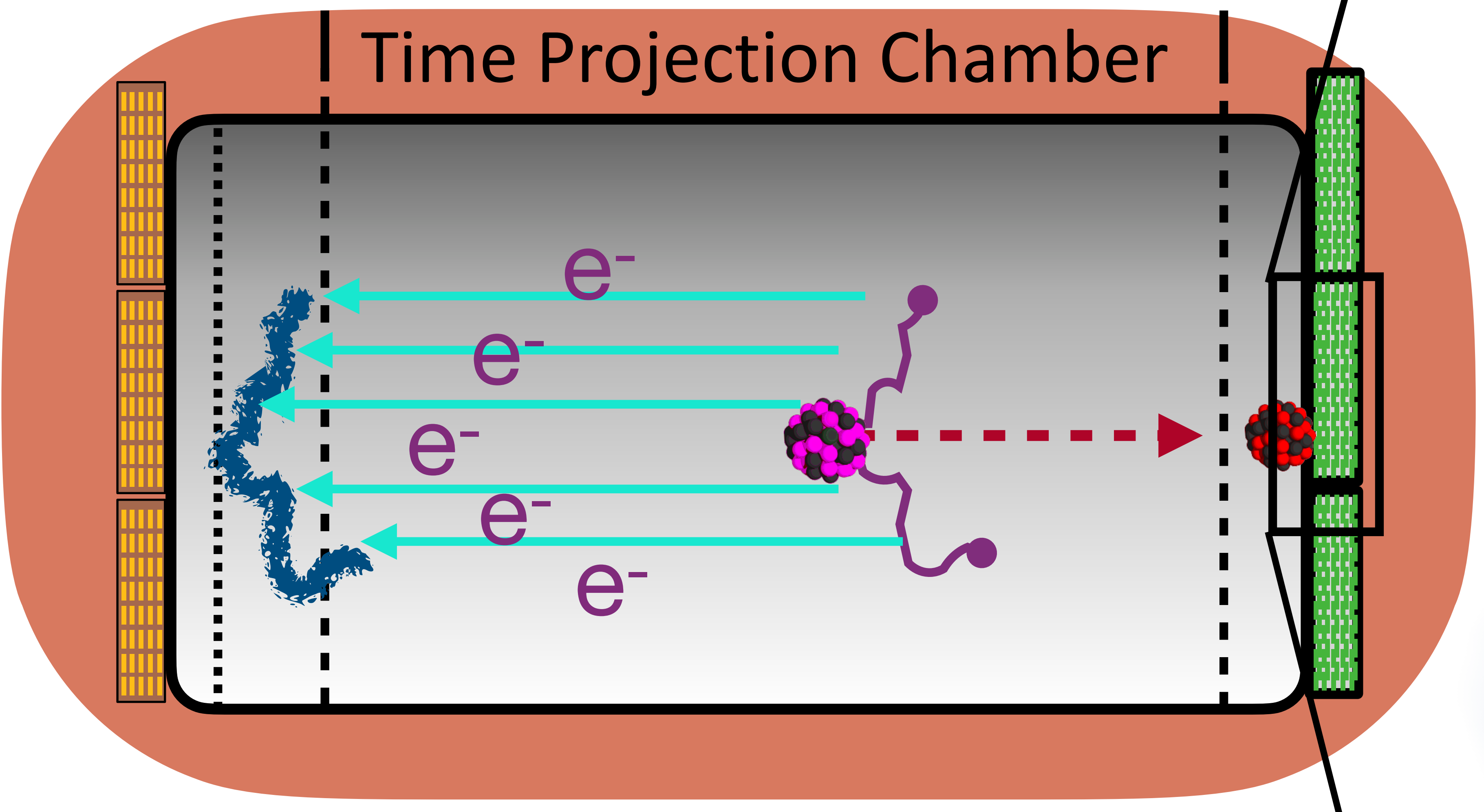
Fig. 4 | Computed structures of FBI (7ca) and a $Ba^{2+}Xe_8$ cluster at different N–Ba^{2+} distances. The geometries and energies shown were computed using DFT (see Methods for further details). Xenon atoms are represented using the Corey–Pauling–Koltun (CPK) space-filling model. The remaining atoms are represented using a ball-and-stick model and the CPK colouring code. Relative free energies (ΔG_{298}), have been computed at 25 °C (298 K).

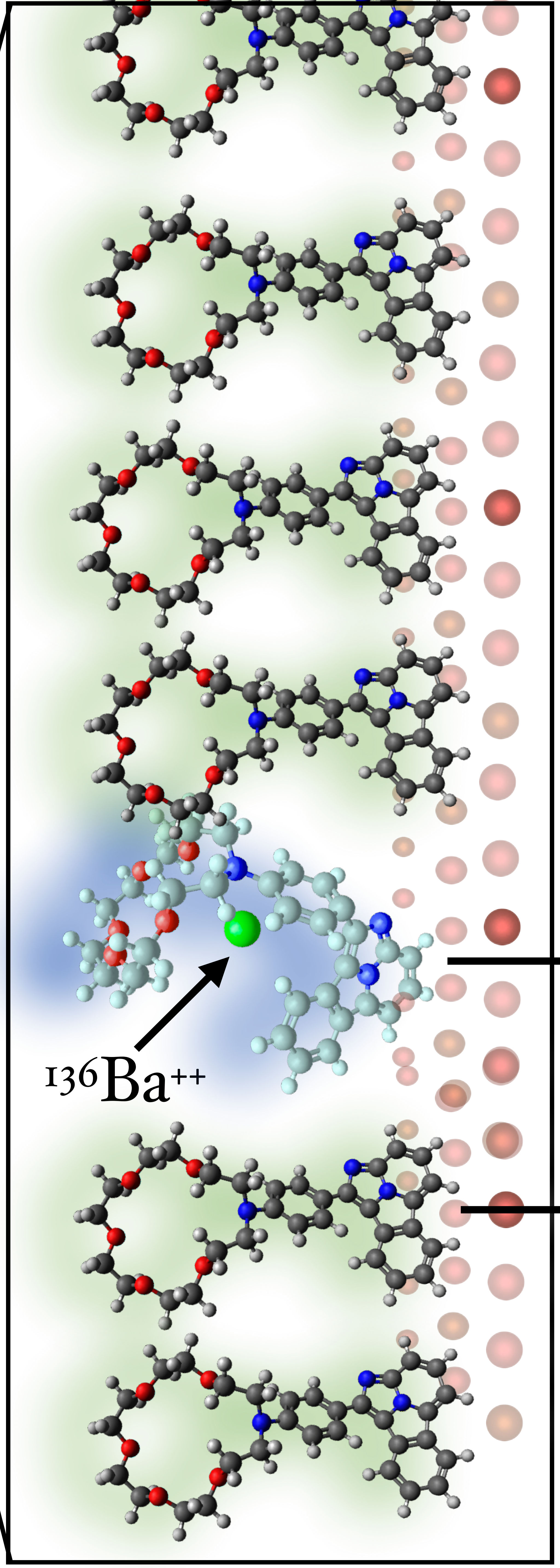
Phys. Rev. A **97**, 062509





Barium tagging in NEXT:
A ML of Fluorescent Bicolor Indicators (FBI) traps the barium ion, thereby changing its optical properties.

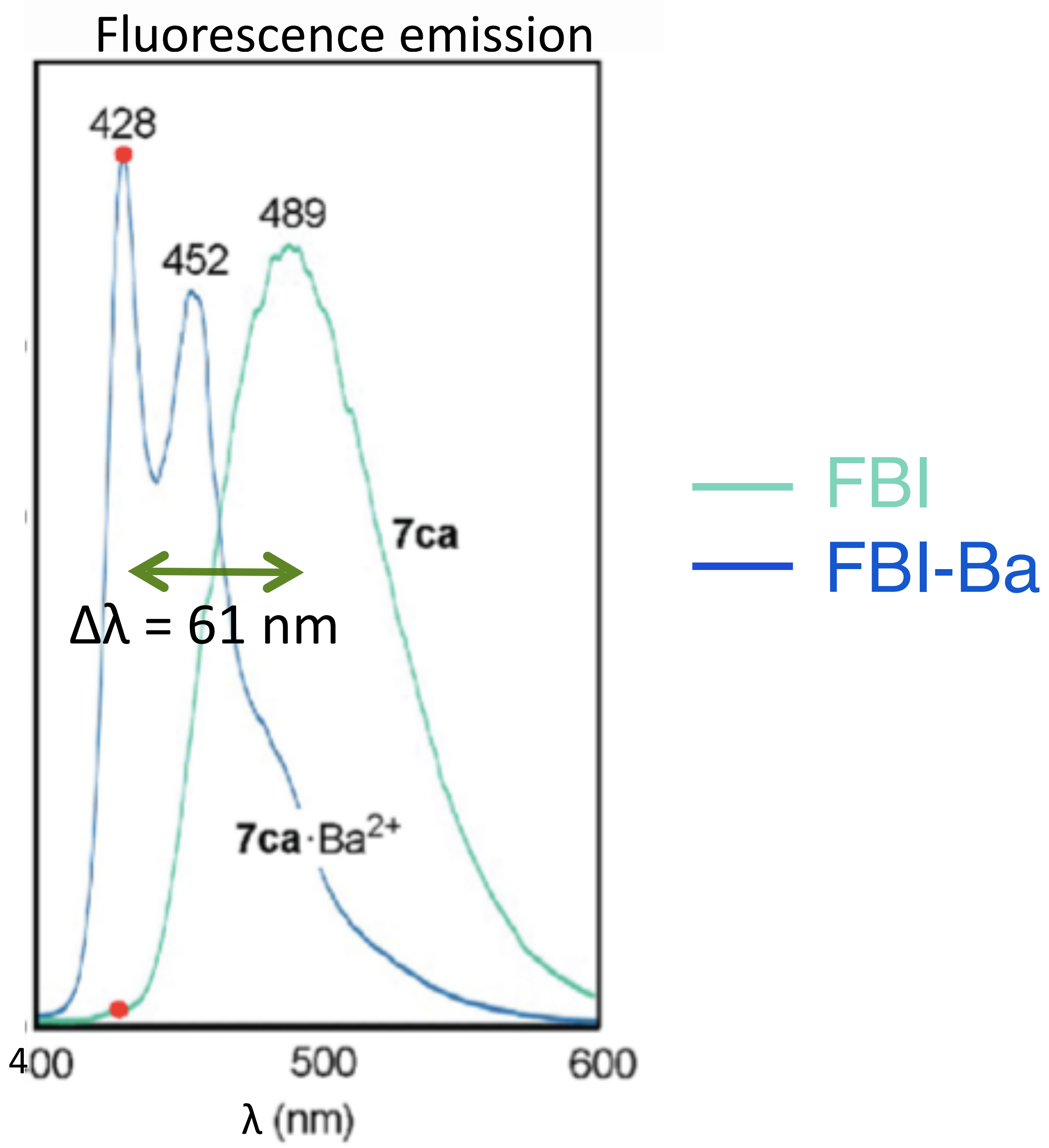


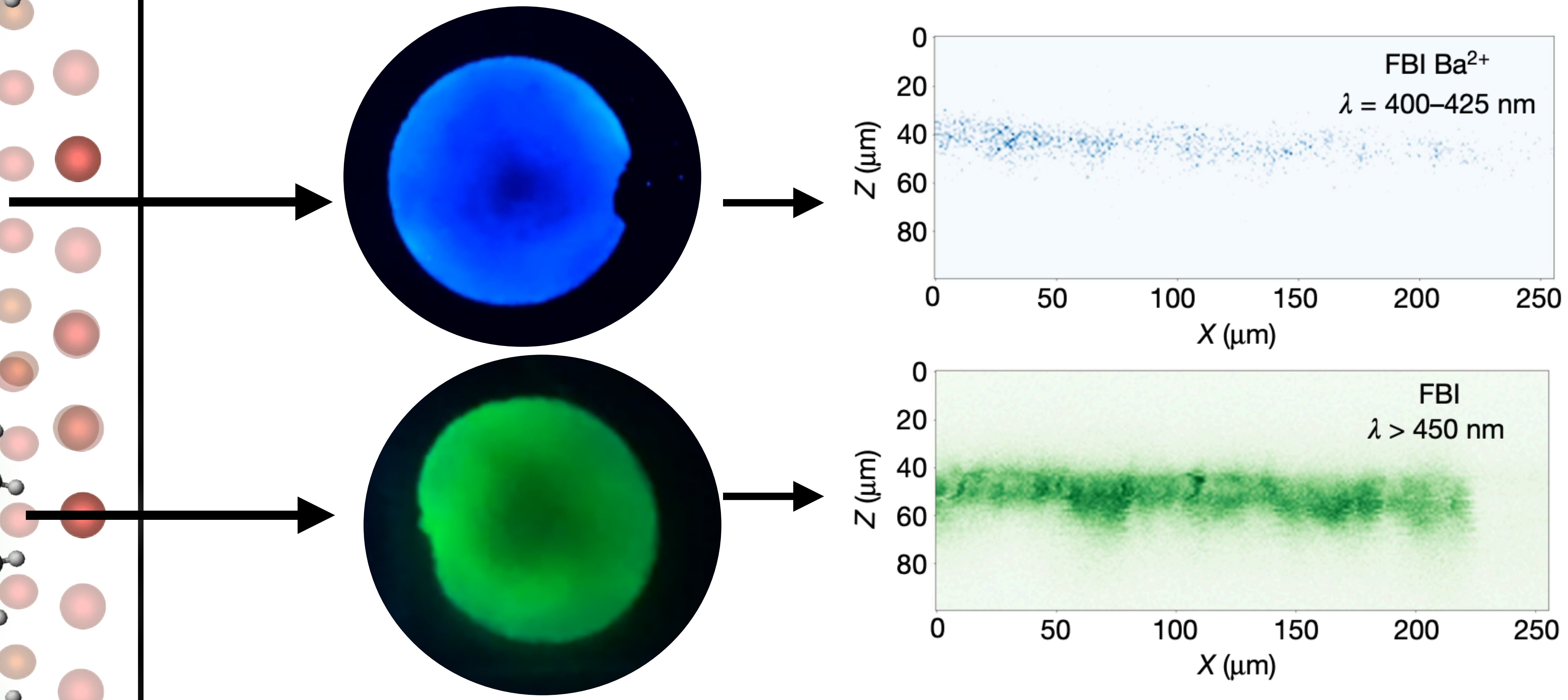


- First experiment of chelation in a dry medium:
- $Ba(ClO_4)_2$ was evaporated in UHV on silica pellets containing FBI. This changed its fluorescence from green to blue and proved that the trapping took place in UHV.

The stokes shift between free FBI (cyan) and FBI·Ba^{2+} (blue) is larger than 35 nm.

This effect is specific of Ba^{2+} chelation and does not appear for other ions.

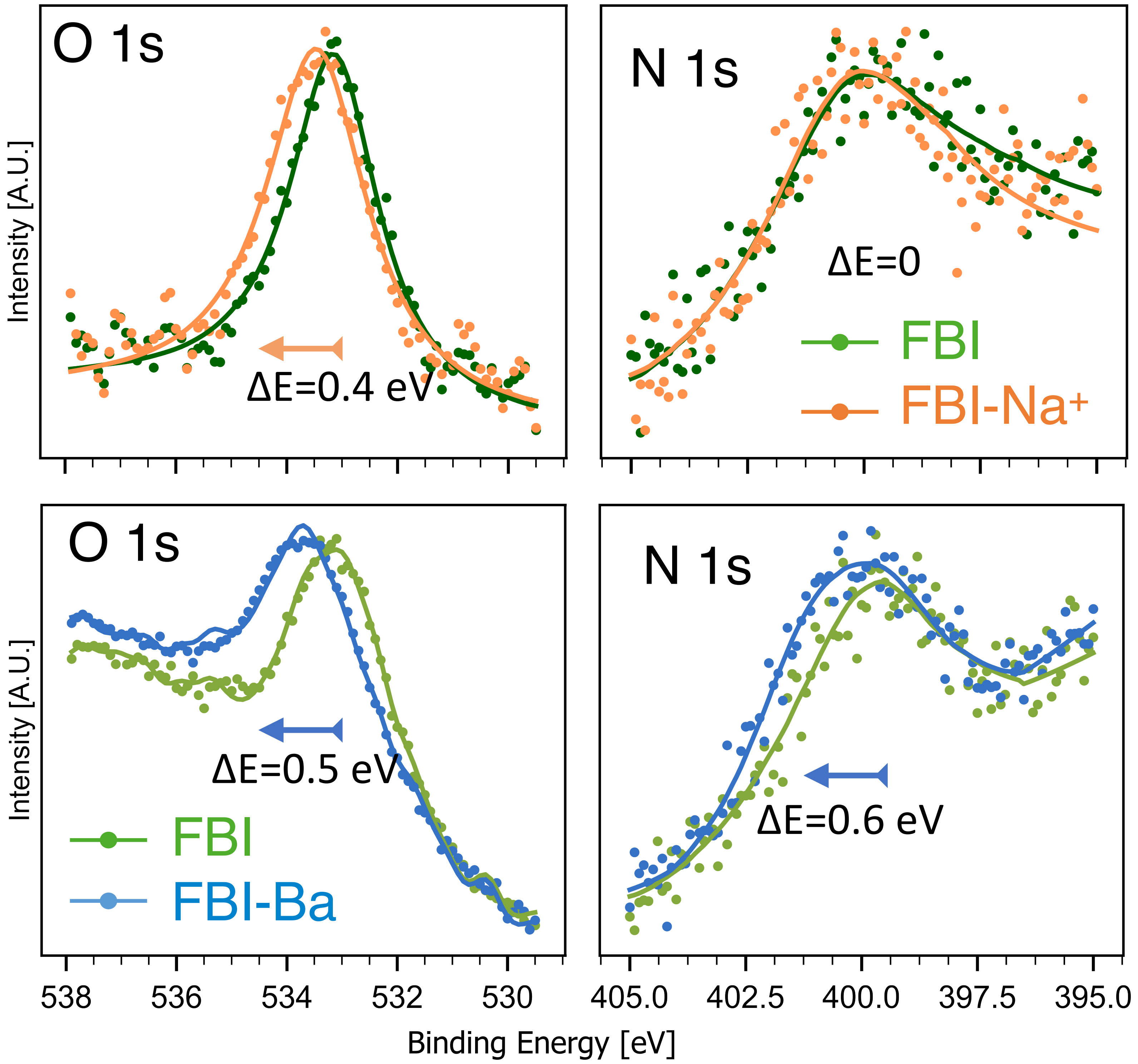




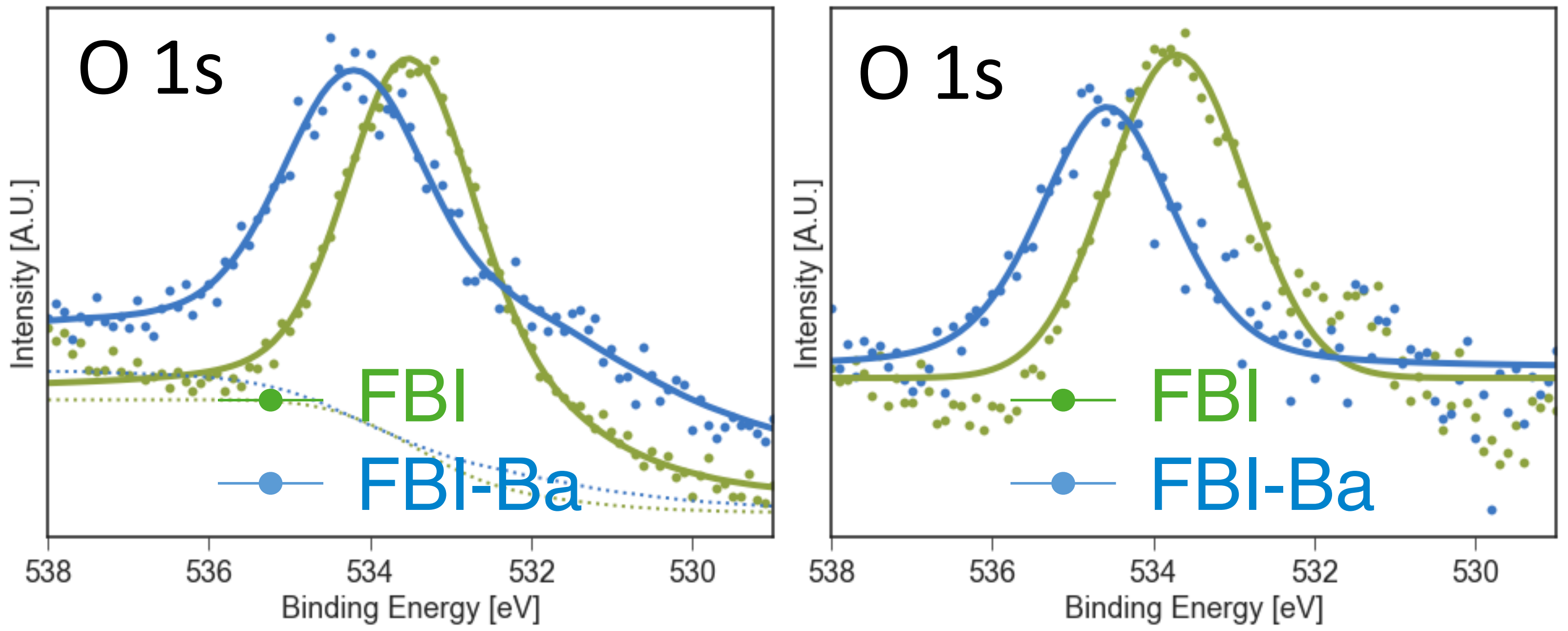
Microscopic tomographies were recorded for an unchelated (green) and a chelated (blue) pellet.

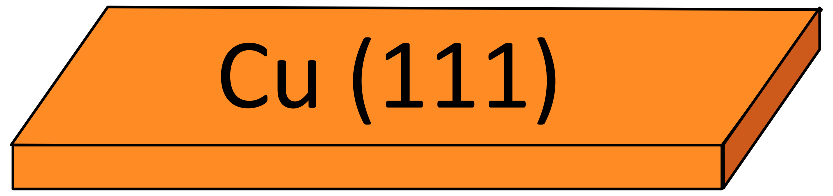
FBI was evaporated in UHV onto different surfaces, Au(111), Cu(111) and ITO. After evaporating $BaCl_2$ on them chemical and structural changes were analysed using XPS and STM.

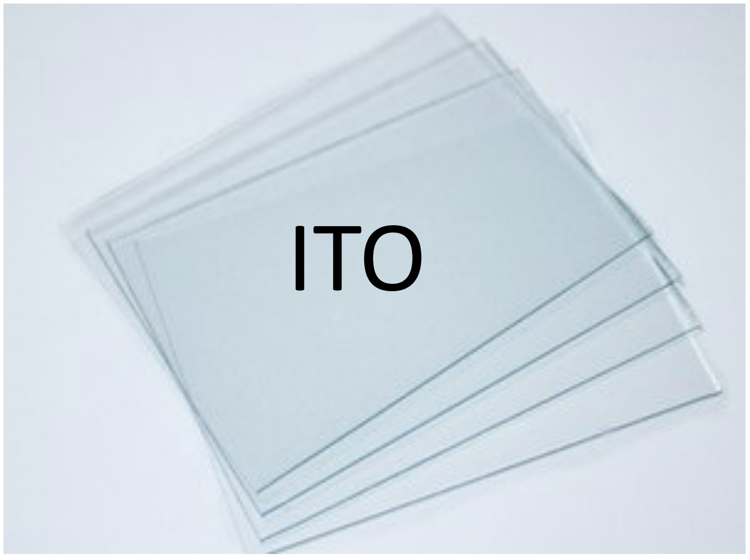
The XPS O 1s core level shifted towards lower binding energy as expected for the chelation of an ion by a crown-ether. The N 1s also shifted in Au (111) proving that the ion also interacts with one of the nitrogen atoms.

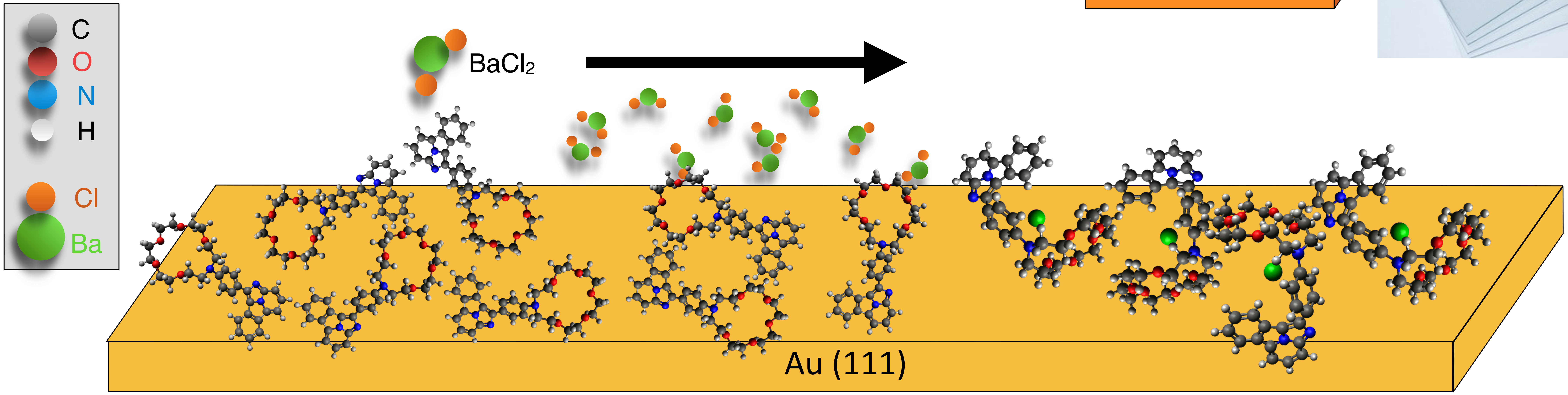


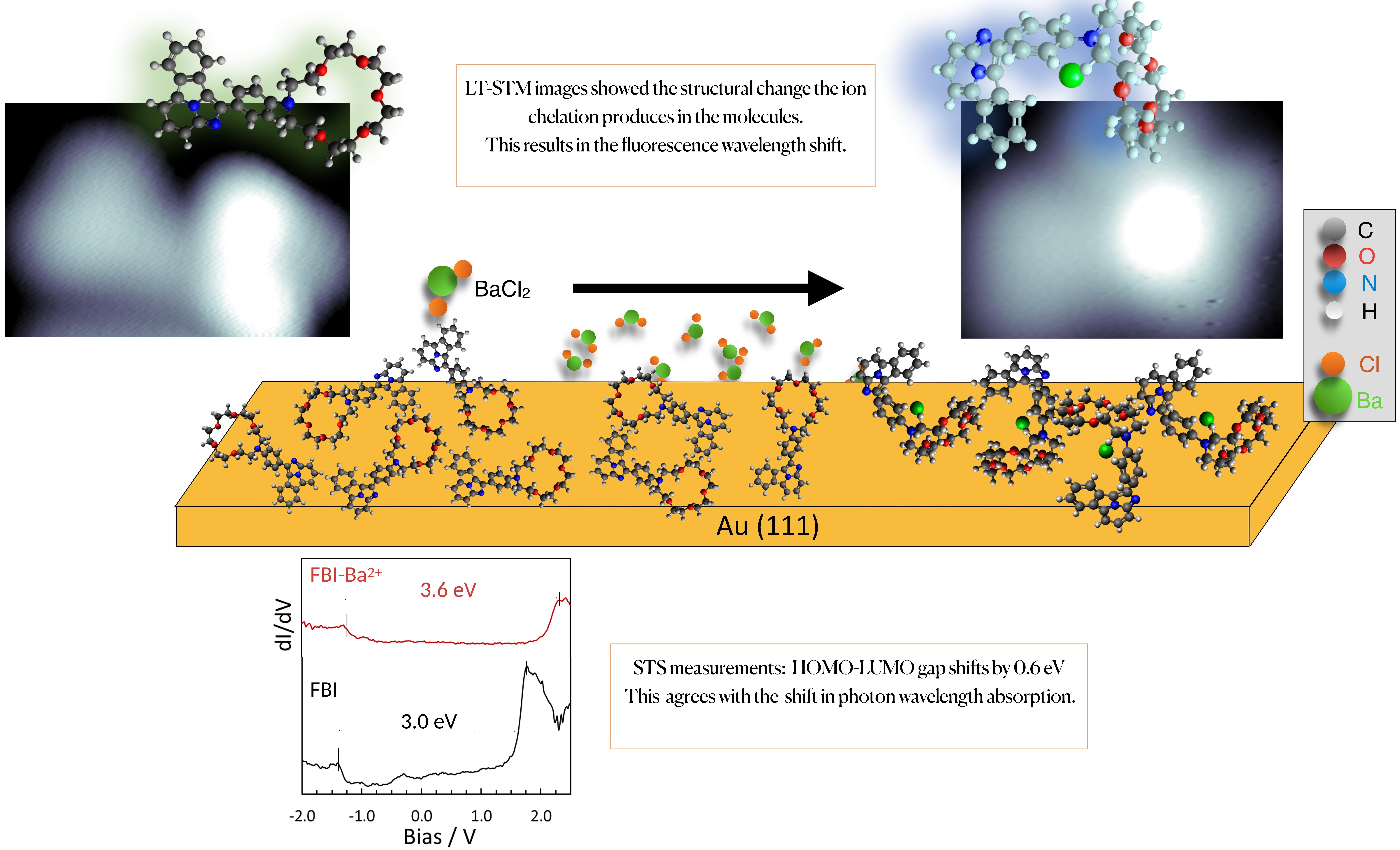
The O 1s shift also takes place for chelation with Ba^{++} on Cu(111) and ITO substrates (3).









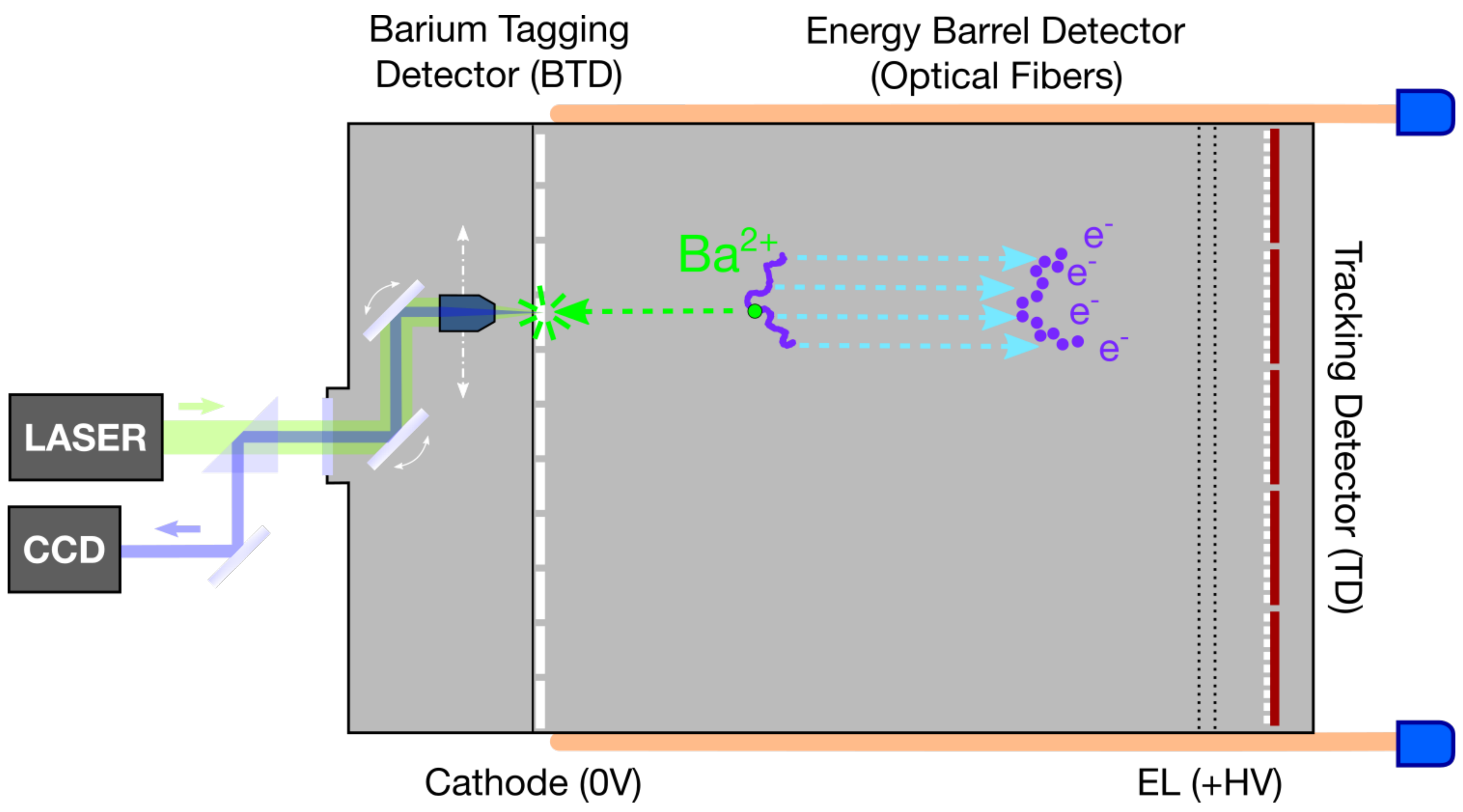


LT-STM images showed the structural change the ion chelation produces in the molecules.
This results in the fluorescence wavelength shift.
BaCl2
C
O
N
H
Cl
Ba
Au (111)
FBI-Ba2+
3.6 eV
FBI
3.0 eV
dI/dV
-2.0
-1.0
0.0
1.0
2.0
Bias / V
STS measurements: HOMO-LUMO gap shifts by 0.6 eV
This agrees with the shift in photon wavelength absorption.

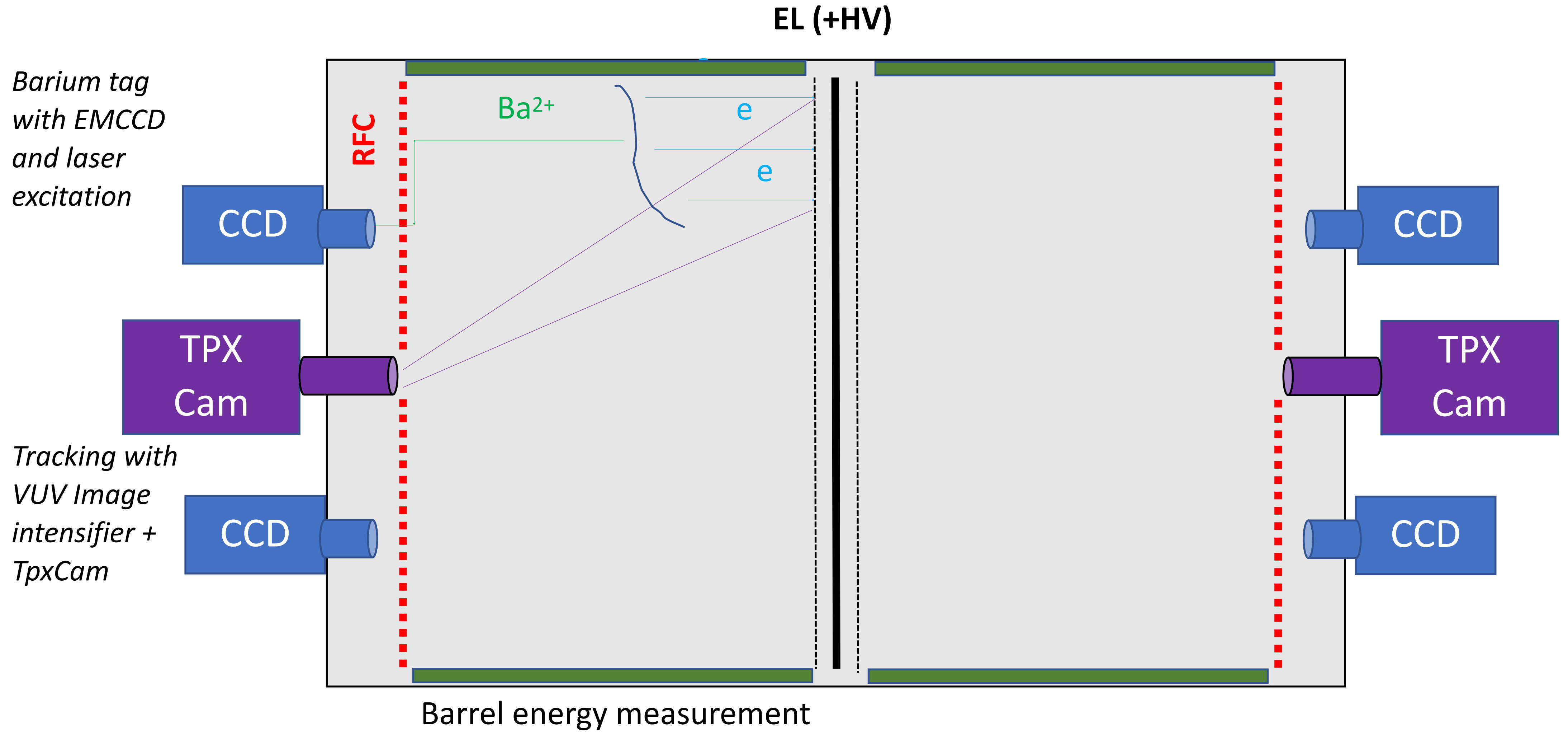
BOLD R&D

- Ion beams using $^{222}Rn^{2+}$ from thorium decay are under development for single ion test.
- Beam tests also planned at ANL CARIBU with $^{144}Ba^{2+}$ mass-selected from ^{252}Cf fission.
- The ultimate test-beam is ββ2ν !
- Demonstrator phases at 10kg-scale are being planned for ~2024-2025.
- Multiple full system concepts under exploration, to be guided by ongoing R&D.
- The program is well funded by DOE in USA and by ERC (Synergy Grant, 2020) in Europe.

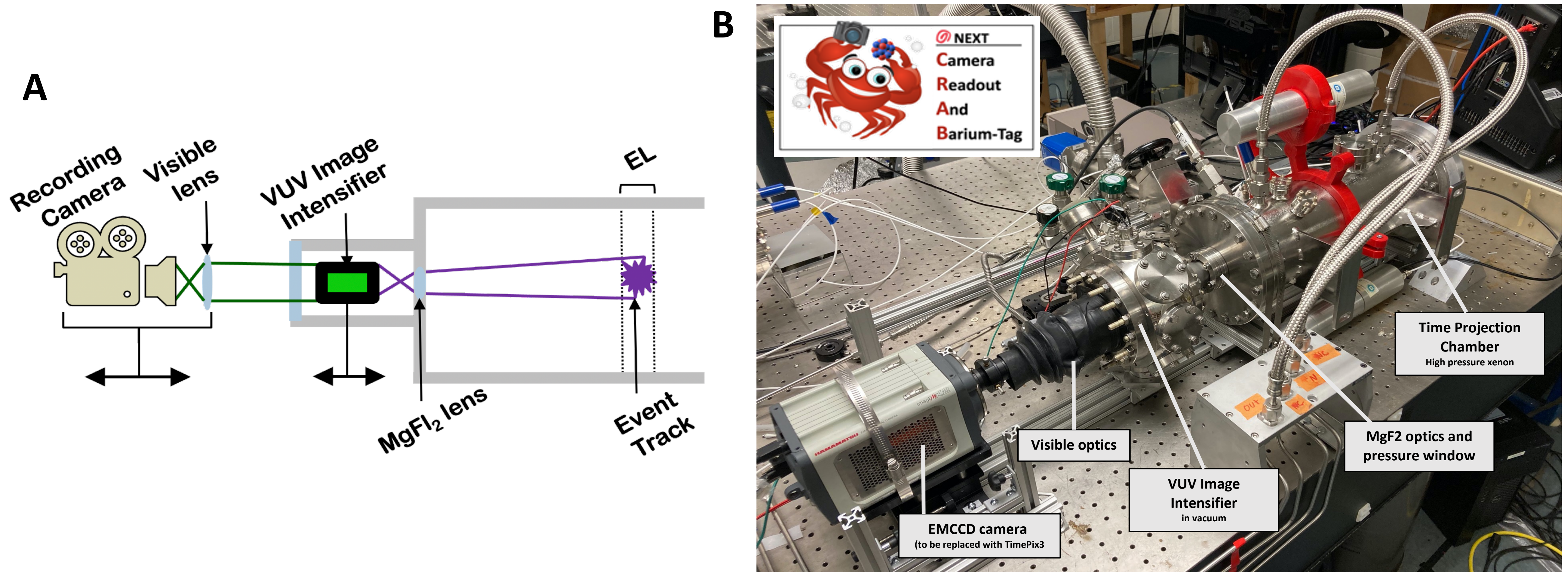
"SABAT" concept with fully active cathode, SiPM-based tracking and Energy Barrel Detector



"CRAB" concept with RF carpet concentrators and camera-based topology measurement

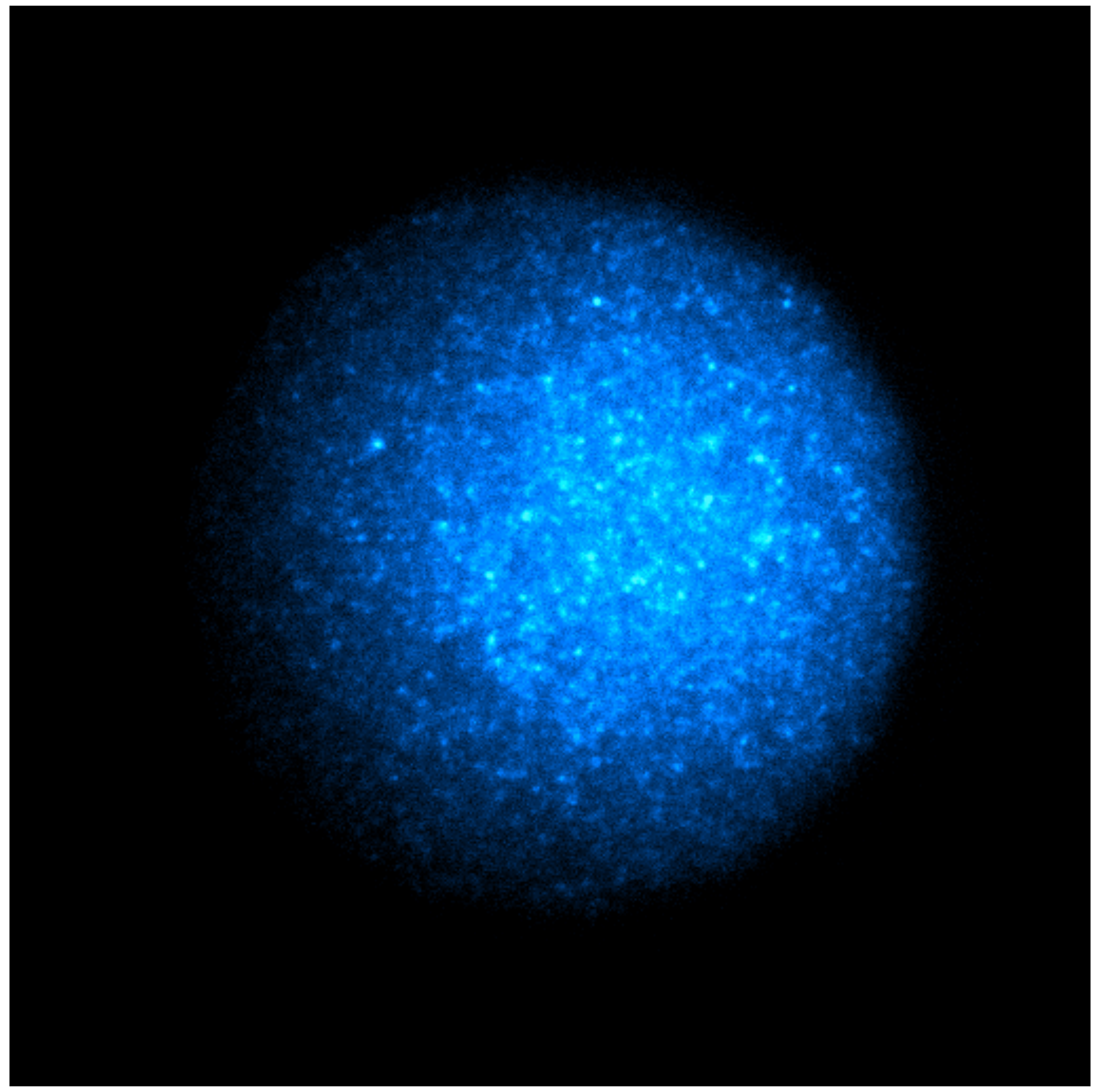


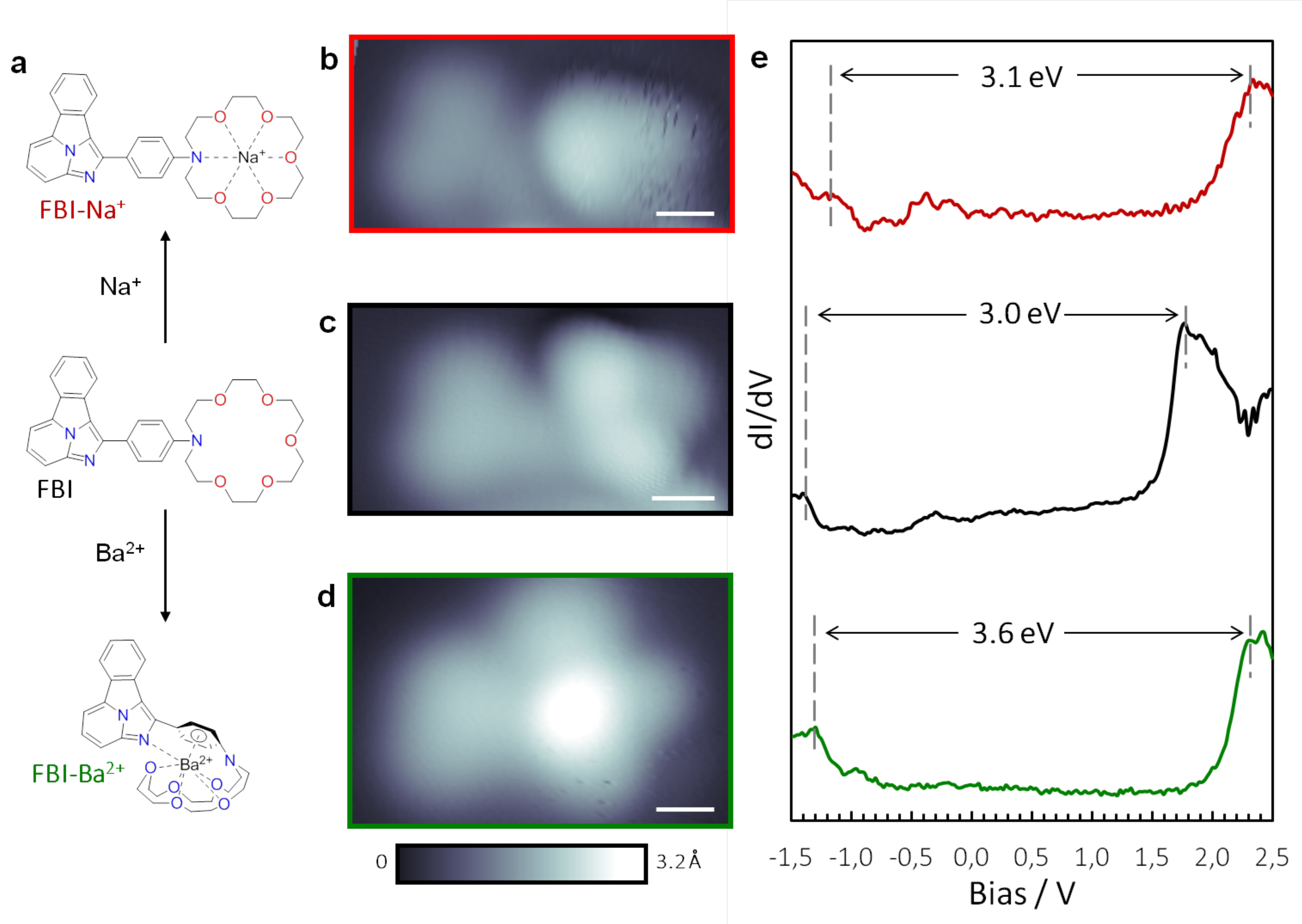
High Speed Optical Cameras



• The SiPM + ASIC solution follows the “NEXT tradition” (e.g, NEXT-White, NEXT-100), and thus can benefit from the acquired experience.
•But the number of channels grows quadratically with the pitch (and the area). The technology becomes stretched in the limit of very high density.
•An alternative (spinoff of our own R&D in Barium Tagging) would be the use of high speed optical cameras, directly sensitive to VUV from EL plane.
•First prototypes yield promising results.

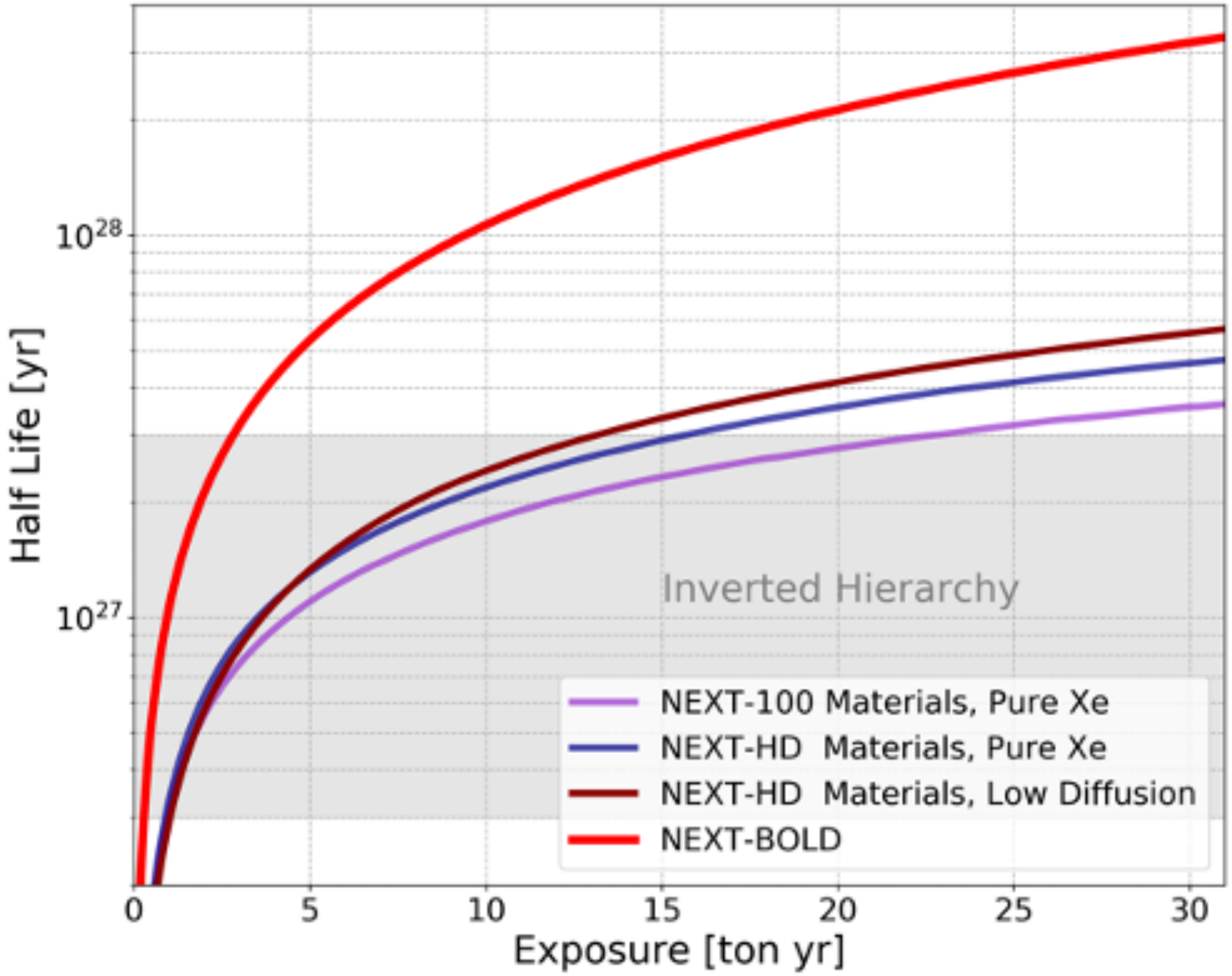
BOLD R&D program





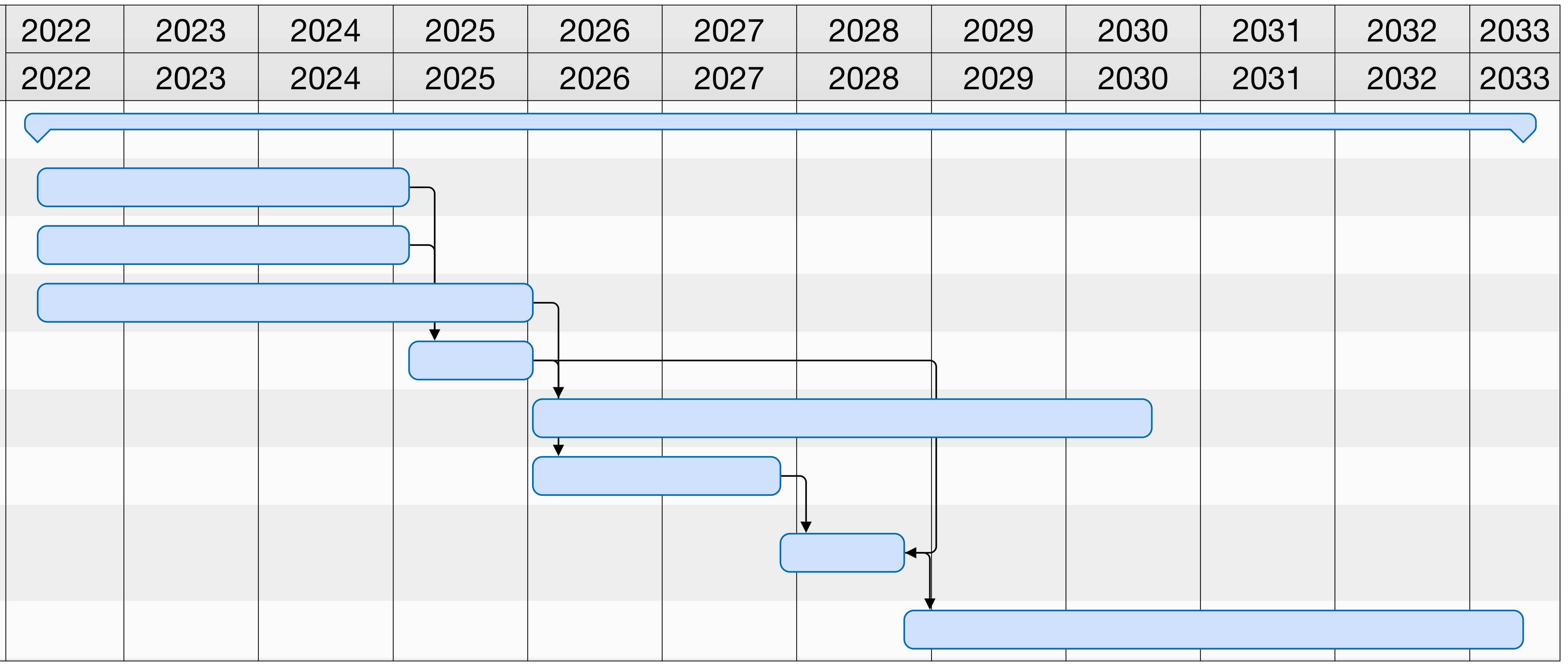
- Funded in the US (DOE Early Career Award, DOE Nuclear Physics Research Program, National Science Foundation, Welch Foundation) and in Europe (Synergy Grant ERC, Israel Science Foundation, ISF).
- Developed new “dry” chemistry, with several families of sensors able to capture Ba2+
- Developed high pressure microscopy, able to take pictures of single molecules in gas.
- Our studies suggest that Ba2+ reaches the cathode with high efficiency, and has high probability of chelating sensors.
- We have shown that our molecules chelate with Ba2+ (and STM images of the chelated molecule).
- Full scale demonstrators being planned for the next few years.

BOLD sensitivity



The project

#	Traits	Title	Given Work	Given Earliest Start	Resources	Predecessors
0		**NEXT-Project**		**12/05/2022**		
1		NEXT-100 Operation	3 years			
2		NEXT-HD R&D	3 years			
3		NEXT-BOLD R&D	4 years			
4		NEXT-HD (LSC)/ construction	1 year			1; 2
5		NEXT-HD-LSC operation	5 years			4
6		BOLD Demonstrators	2 years			3
7		BOLD/HD module 2 construction	1 year			4EE; 6
8		BOLD/HD (2) operation	5 years			7



•Operation of NEXT-100 runs in parallel with R&D for NEXT-HD and NEXT-BOLD from 2021 to 2025

•Preparation of infrastructures (water tank, gas, pressure vessel, inner copper shielding) proceeds as soon as NEXT-100 is in operation. **LSC, which enters as new group in NEXT will lead this activity.**

•Procurement of ~200 kg per year of Xe-136 from 2021 to 2026 (LSC).

•**NEXT-HD can begin operation at intermediate mass (and lower pressure) and scale up as more xenon becomes available.**

APPEC Report

SWOT table: LEGEND (^{76}Ge)

STRENGTHS

- HPGe diodes have best energy resolution (0.13% FWHM) and lowest background achieved in ROI; prerequisite for signal discovery.
- Background reduction of only a factor 6 for LEGEND-200 w.r.t. GERDA and factor 10 for LEGEND-1000 w.r.t. LEGEND-200.
- Efficient use of isotopes: total mass quasi equal to active mass given high signal acceptance efficiency.
- Efficient staging possible given design with separate payloads.
- Wide availability of Ge; procurement has no impact on global market.
- Two supplier for enrichment established and tested (Europe & Russia).
- Comparative low spread of NME (factor 2).

WEAKNESSES

- Requires deep underground laboratory and/or tagging for Ge-77m suppression.
- Underground Ar depleted in ^{42}Ar likely required for LEGEND-1000.
- Relatively low Q-value (2039 keV) implies smaller phase space factor which requires larger $T_{1/2}$ for same values of $m_{\beta\beta}$.

OPPORTUNITIES

- LEGEND-200 start in 2021; serves also as test bench for LEGEND-1000.
- Non-DBD0ν physics at low energies.
- Transatlantic cooperation and funding; opportunities for new groups.

THREATS

- Unknown background could appear at LEGEND-200 which might be difficult to mitigate.
- For LEGEND-1000 : no funding secured; poor coordination of funding agencies; DOE down-select might move ahead without European funding aligned.
- Underground argon production dependent on INFN/NSEF in context of DarkSide project.

SWOT table: CUPID (^{100}Mo)

STRENGTHS

- Enrichment at large scale with medium prices
- High Q-value (3034 keV)
- Compatible with scintillating bolometer technique
- Excellent energy resolution $Li_2{}^{100}MoO_4$: 5 keV FWHM at 2615 keV
- Low background demonstrated in large crystal: ~ 5 μBq/kg for ^{232}Th / ^{238}U; 5 mBq/kg for ^{40}K
- Source=Detector, modularity, high efficiency
- Event-type discrimination: α/β full rejection demonstrated
- Favourable Nuclear Factor of Merit (Phase Space x NME)

WEAKNESSES

- No tracking
- Short $2\nu2\beta$ half-life (potential background due to accidental pileup) $\Rightarrow$ develop faster light detector
- Scalability possible but costly; factor two looks feasible by setting up a second CUORE-like facility
- Cryogenic infrastructures are complicated and need onsite expertise

OPPORTUNITIES

- Cryogenic infrastructure well demonstrated in CUORE (space for 300 kg of ^{100}Mo-enriched detector available)
- Several crystal compounds compatible with the bolometric technique: $Li_2{}^{100}MoO_4$, $ZnMoO_4$, $CaMoO_4$
- High reproducibility of crystal quality
- Many producers on the market
- Alternative pulse shape discrimination techniques
- Second physics case (direct dark matter detection)
- New CUPID collaboration is chance for new collaborators/groups

THREATS

- Enrichment monopoly in Russia
- AMORE collaboration: 120 kg of ^{100}Mo for bolometric experiment in Korea. This can be turned into an opportunity in case of a common CUPID-AMoRE bi-site experiment
- Funding of CUPID open

SWOT table: NEXT (^{136}Xe)

STRENGTHS

- Enrichment at large scale with low prices (10 M€ per ton)
- Moderately high Q-value (2457 keV)
- Long $2\nu2\beta$ half-life
- Good energy resolution NEXT-White: 20 keV FWHM at 2457 keV
- NEXT-White: factor 20 reduction in background due to topological cuts.
- Source=Detector.
- Fiducial volume: only high energy gammas relevant, negligible background from α
- Reasonable Nuclear Factor of Merit (Phase Space x NME)
- Possibility of in-situ barium tagging, leading to a background-free experiment

WEAKNESSES

- Modest/low efficiency (30%)
- Less dense than liquid xenon
- Maximum size of modules about 500-1500 kg $\Rightarrow$ Possibility to build two modules
- Less developed than other DBD0ν technologies
- Physics potential (background index, barium tagging) still under investigation.

OPPORTUNITIES

- Full infrastructure for operation of NEXT-100 and possible upgrades available at Canfranc Underground Laboratory
- NEXT-100 is a high profile scientific project in Spain
- US plays an important role in NEXT.
- Possibility of a major future US participation.
- Possibility of reusing other major infrastructures (BOREXINO at LNGS) for ton-scale modules
- Interest in HPXe in Japan (and China) with the possibility of convergence
- Potential synergy with dark matter experiments (Dark Side, DARWIN)

THREATS

- Xenon market potentially overloaded (dark matter experiments, neXO)
- Funding not yet guaranteed beyond NEXT-100
- Intense competition with other projects may lead to the technology not being selected in the US
- Interest in HPXe in Japan (and China) but possibility of *no* convergence.

- NEXT is one of the 3 experimental approaches with strong European participation studied in the APPEC report.
- Experiments explore 3 different isotopes (a must given the large uncertainties associated to NMEs).
- Complementary Strengths/Weaknesses as well as Opportunities/Threats.

next

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