THE NEXT PROGRAM FOR NEUTRINOLESS DOUBLE BETA DECAY SEARCHES

J.J. Gómez-Cadenas (on behalf of the NEXT collaboration)
Donostia International Physics Center and Ikerbasque

Future of Double Beta Decay Workshop | Gran Sasso, September 2021 next

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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: $\sim 5\ \mu$Bq/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

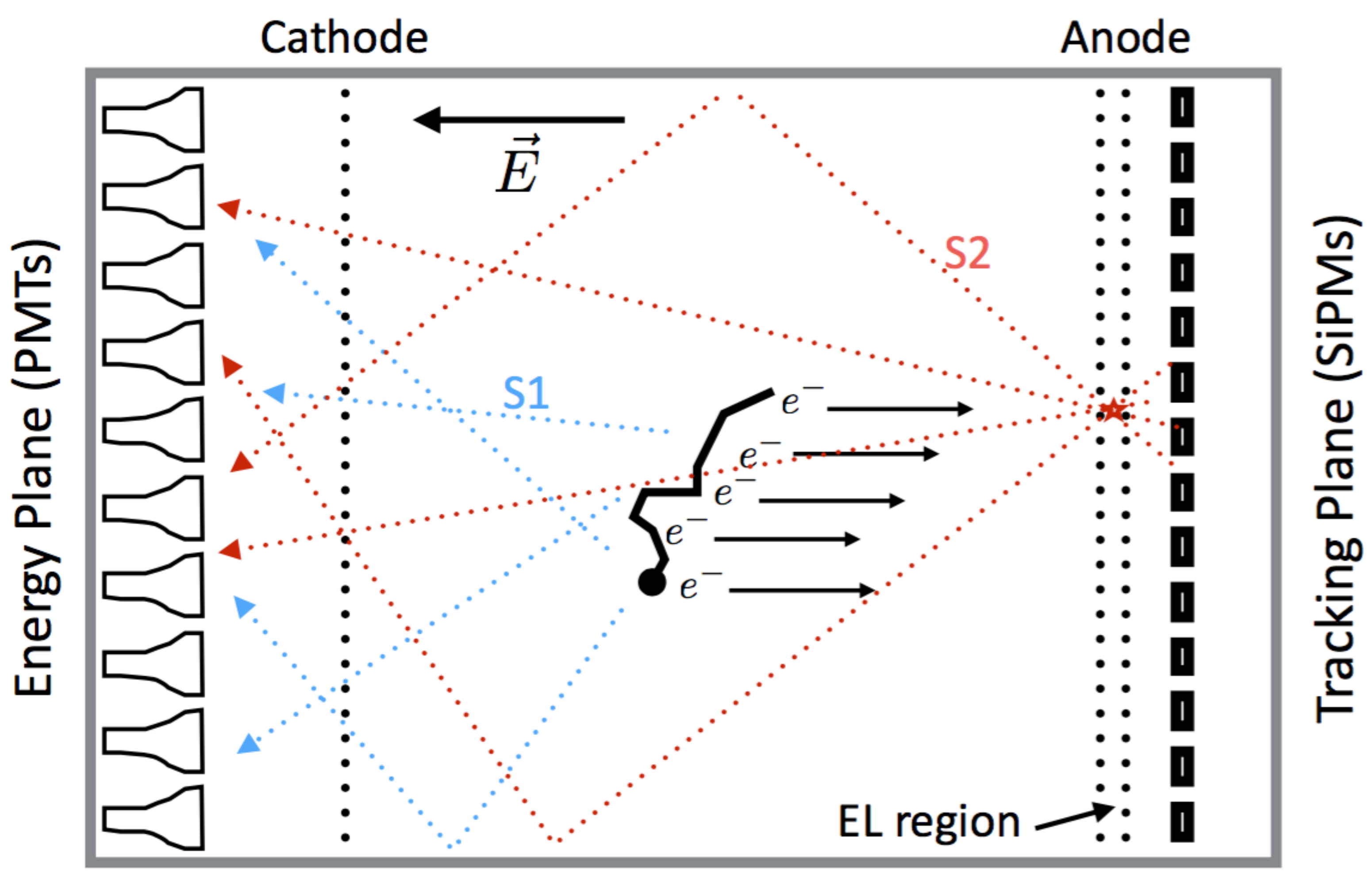
WEAKNESSES
- Modest/low efficiency (30%)
- Less dense than liquid xenon
- Maximum size of modules about 500-1500 kg $\Rightarrow$ Possibility to build two modules
- Less developed than other DBD0ν technologies
- Physics potential (background index, barium tagging) still under investigation.

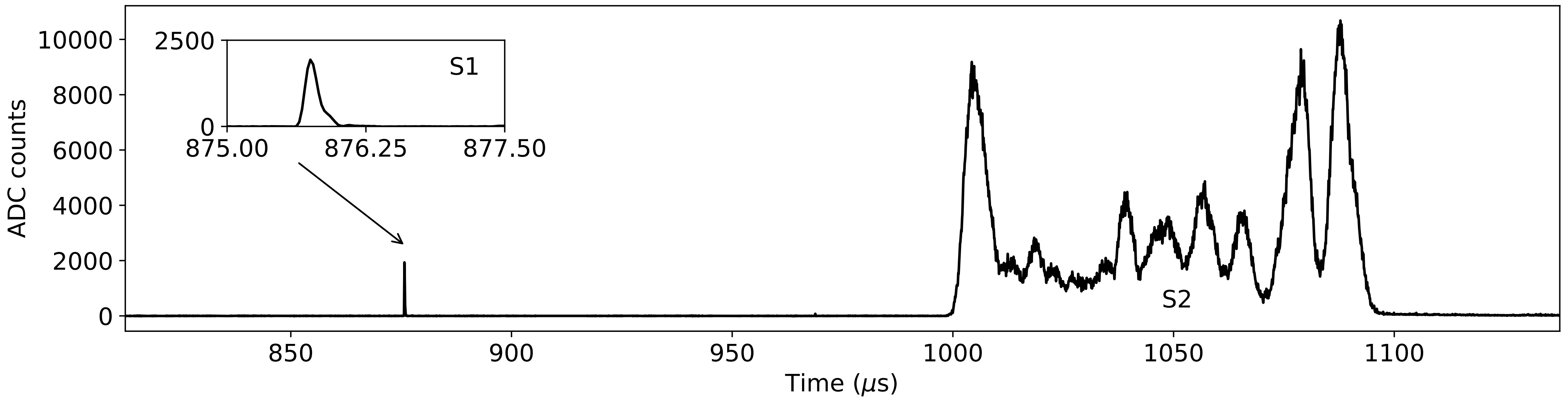
OPPORTUNITIES
- Full infrastructure for operation of NEXT-100 and possible upgrades available at Canfranc Underground Laboratory
- NEXT-100 is a high profile scientific project in Spain
- US plays an important role in NEXT.
- Possibility of a major future US participation.
- Possibility of reusing other 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)

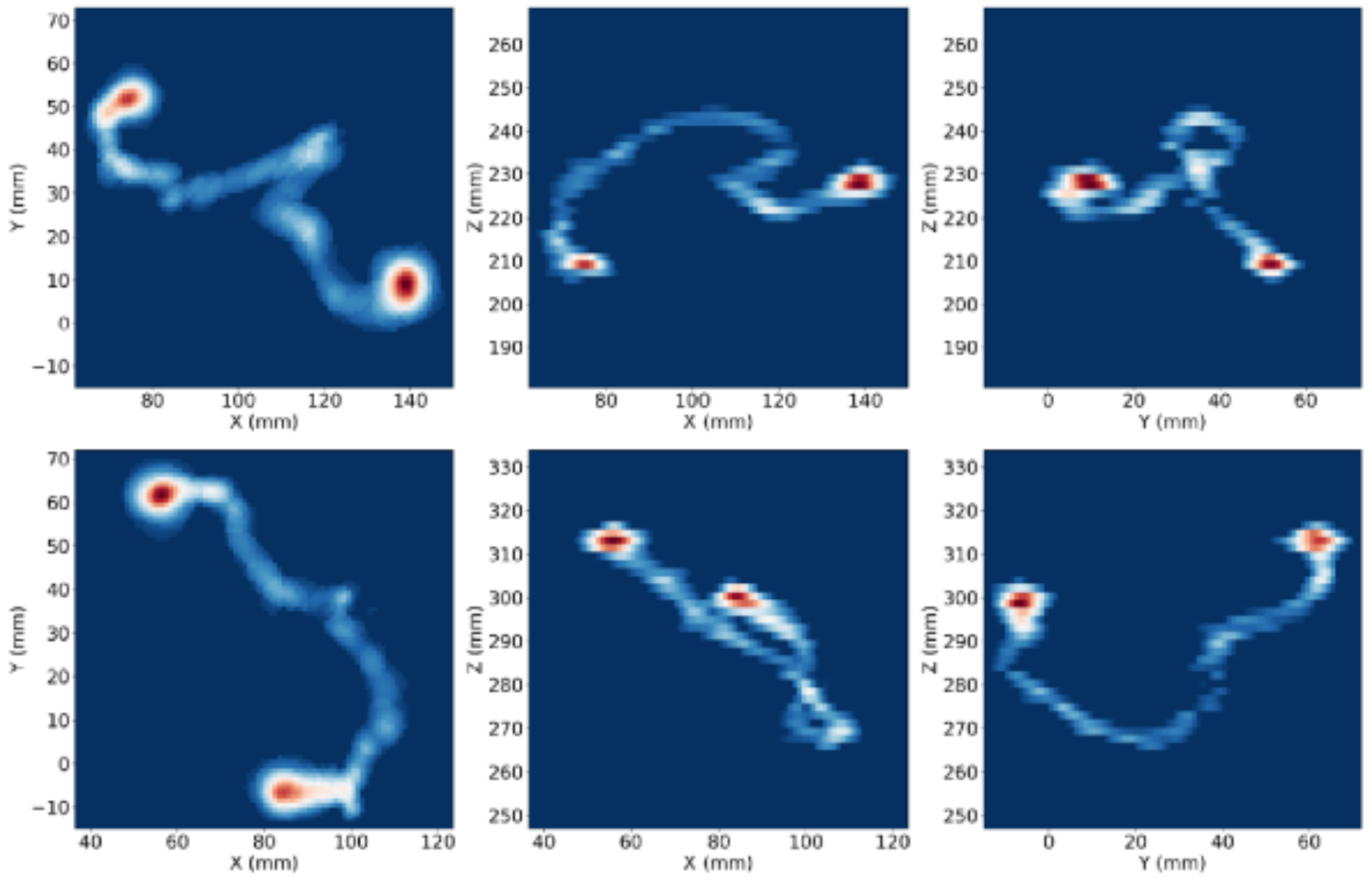
THREATS
- Xenon market potentially overloaded (dark matter experiments, neXO)
- Funding not yet guaranteed beyond NEXT-100
- Intense competition with other projects may lead to the technology not being selected in the US
- Interest in HPXe in Japan (and China) but possibility of *no* convergence.

- 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.

Detector Concept

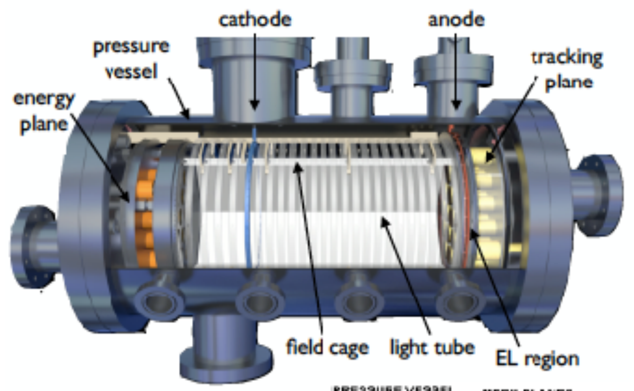


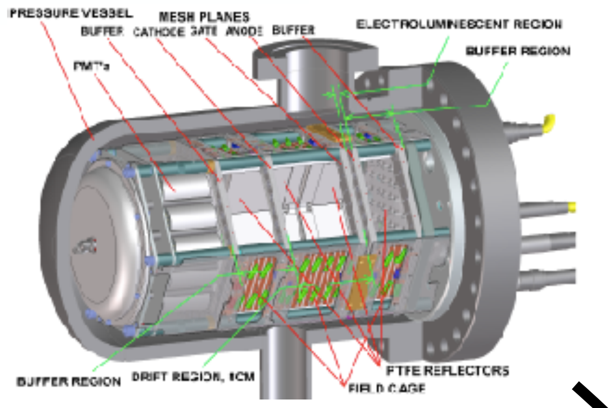




- High pressure Xenon TPC with electroluminescence amplification of the signal
- Good energy resolution (measured <1 % FWHM, feasible 0.7 % FWHM).
- Topological signature (reconstruction of electrons in event). Measured ~60 % efficiency for~1/30 background suppression
- Radiopure detector, along the 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

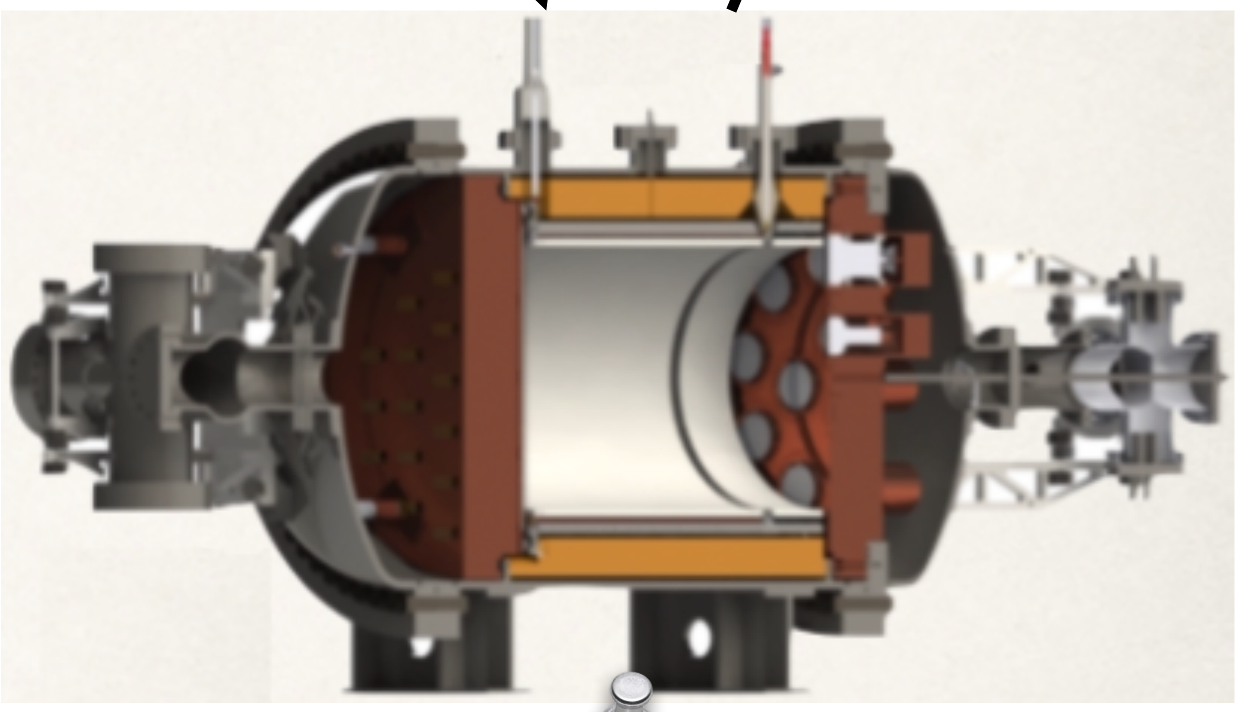




Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept

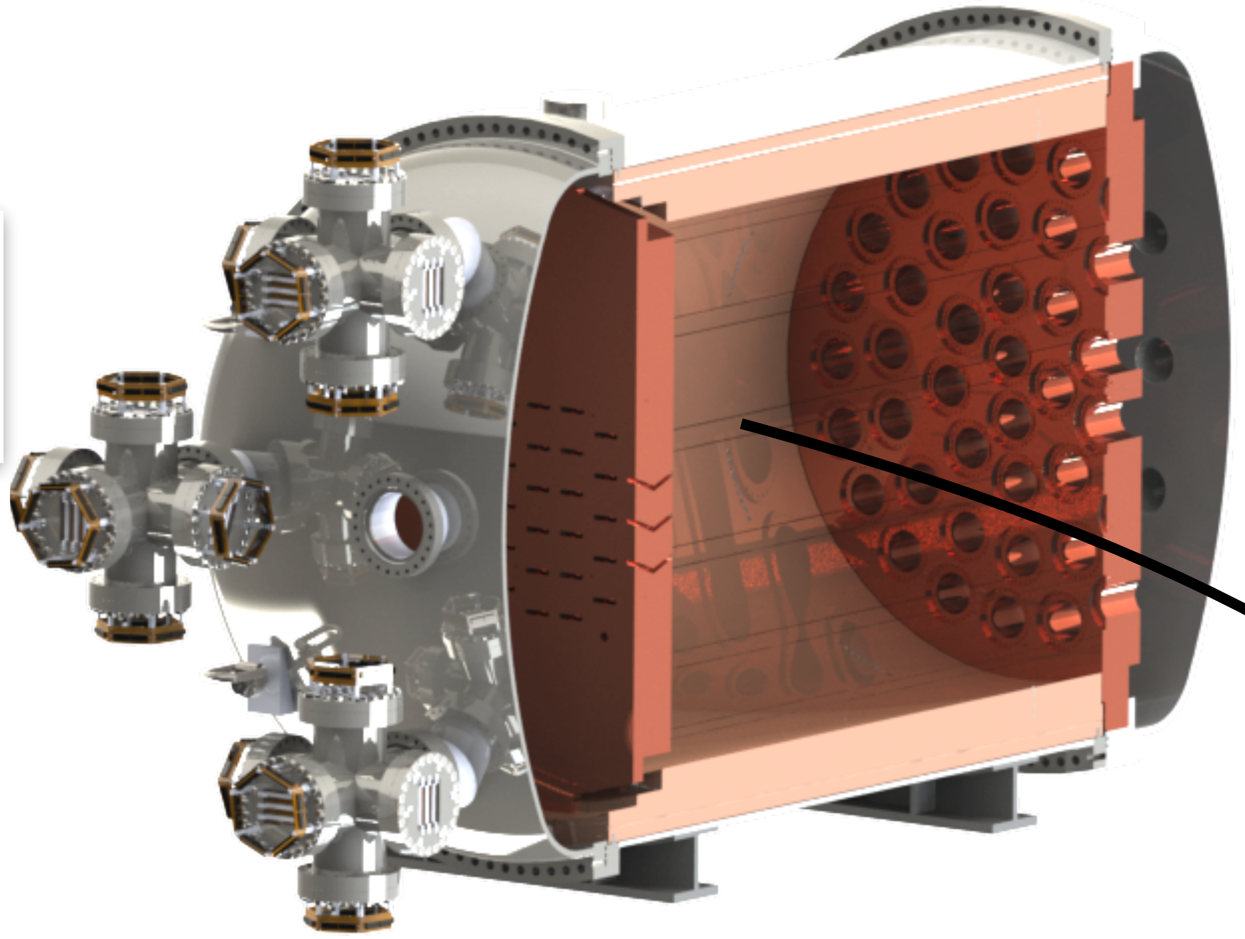
NEXT-White (~5 kg)
[2015 - 2021]



Underground and radio-pure operations, background, ββ2ν

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

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



NEXT-HD/BOLD
[2026…]

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


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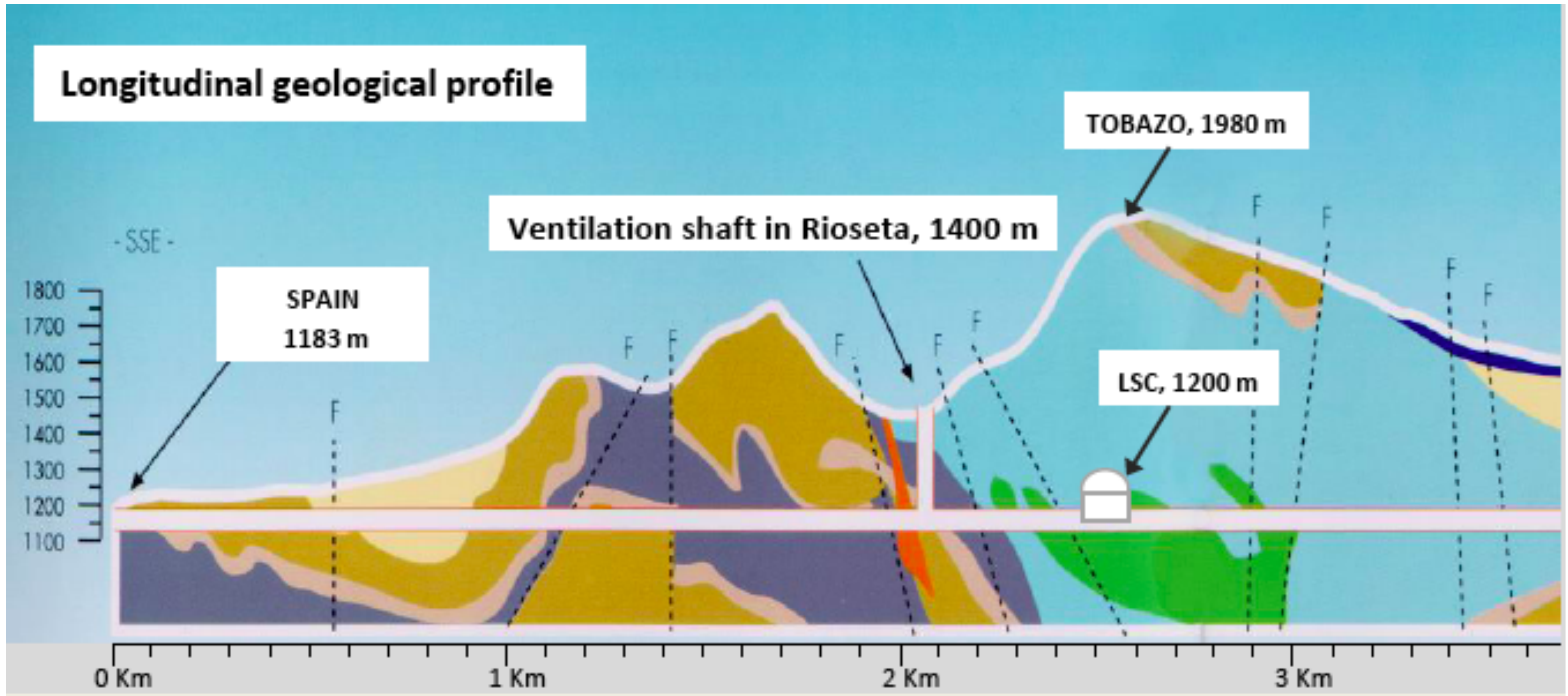
Tarragona
Barcelona
Madrid
Toledo
Castelló de la Plana
Valencia
Palma de Mallorca
Alicante
0 100 200 300 km

Canfranc Underground Laboratory (LSC)

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)

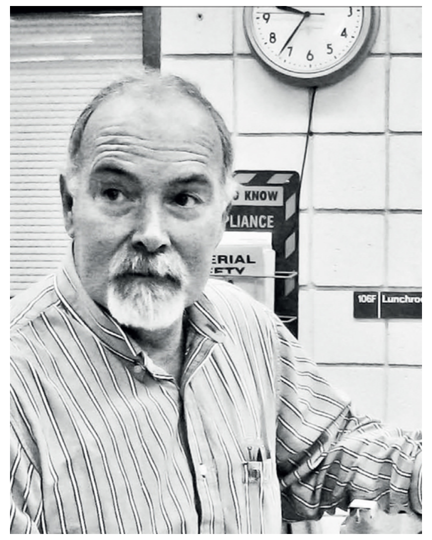
- Inlet air flux 20000 m^3/h
- Radon 50-80 Bq/m^3
- Muons (5.3 ± 0.2) ·10^{-3} m^{-2}s^{-1}
  Neutrons(<10 MeV) ~3.5·10^{-6} cm^{-2}s^{-1}
- Gamma ~ 2 cm^{-2}s^{-1}

Canfranc Underground Laboratory (LSC)

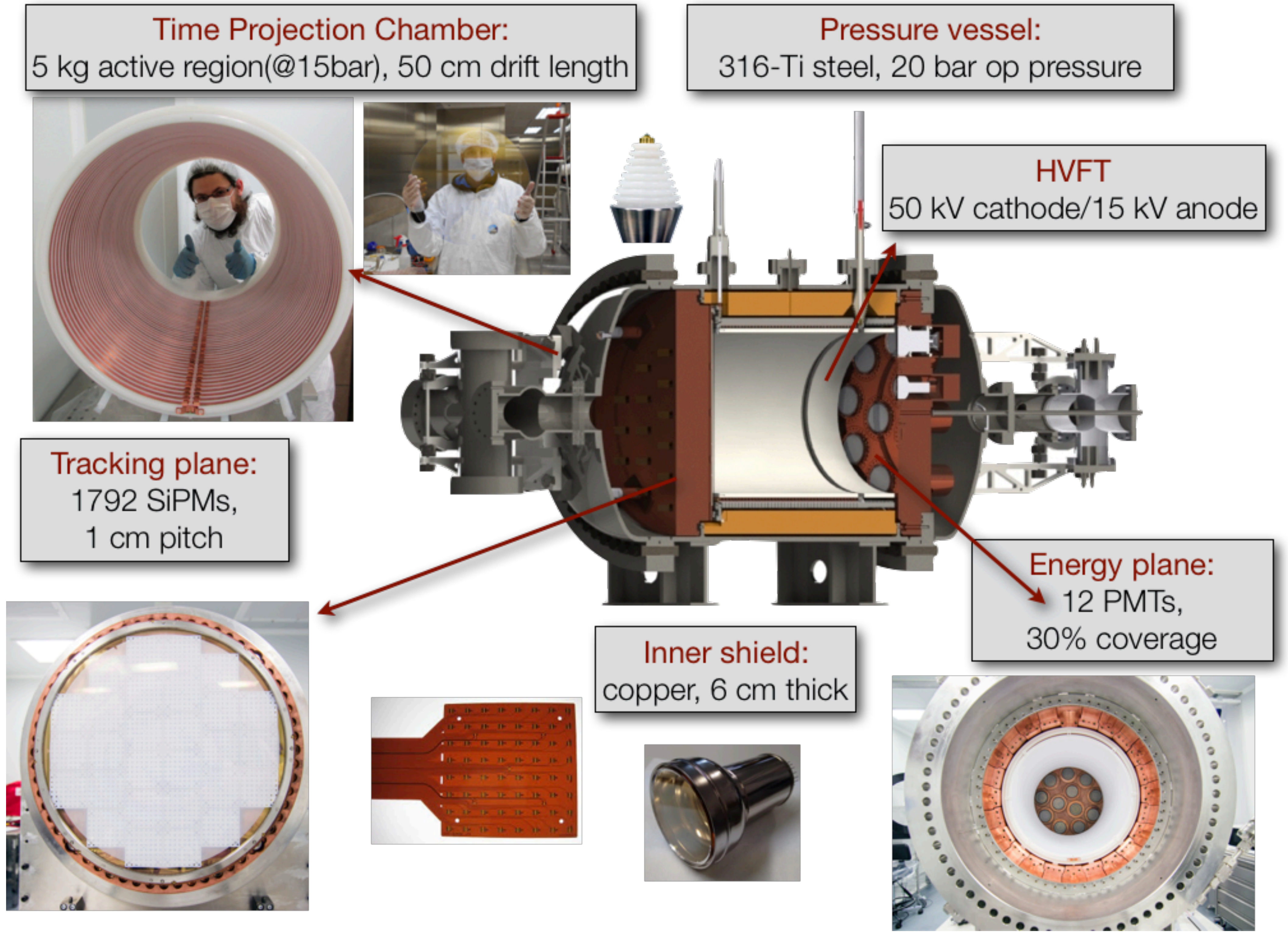
The NEXT-White setup in Hall A at the Laboratorio Subterráneo de Canfranc.

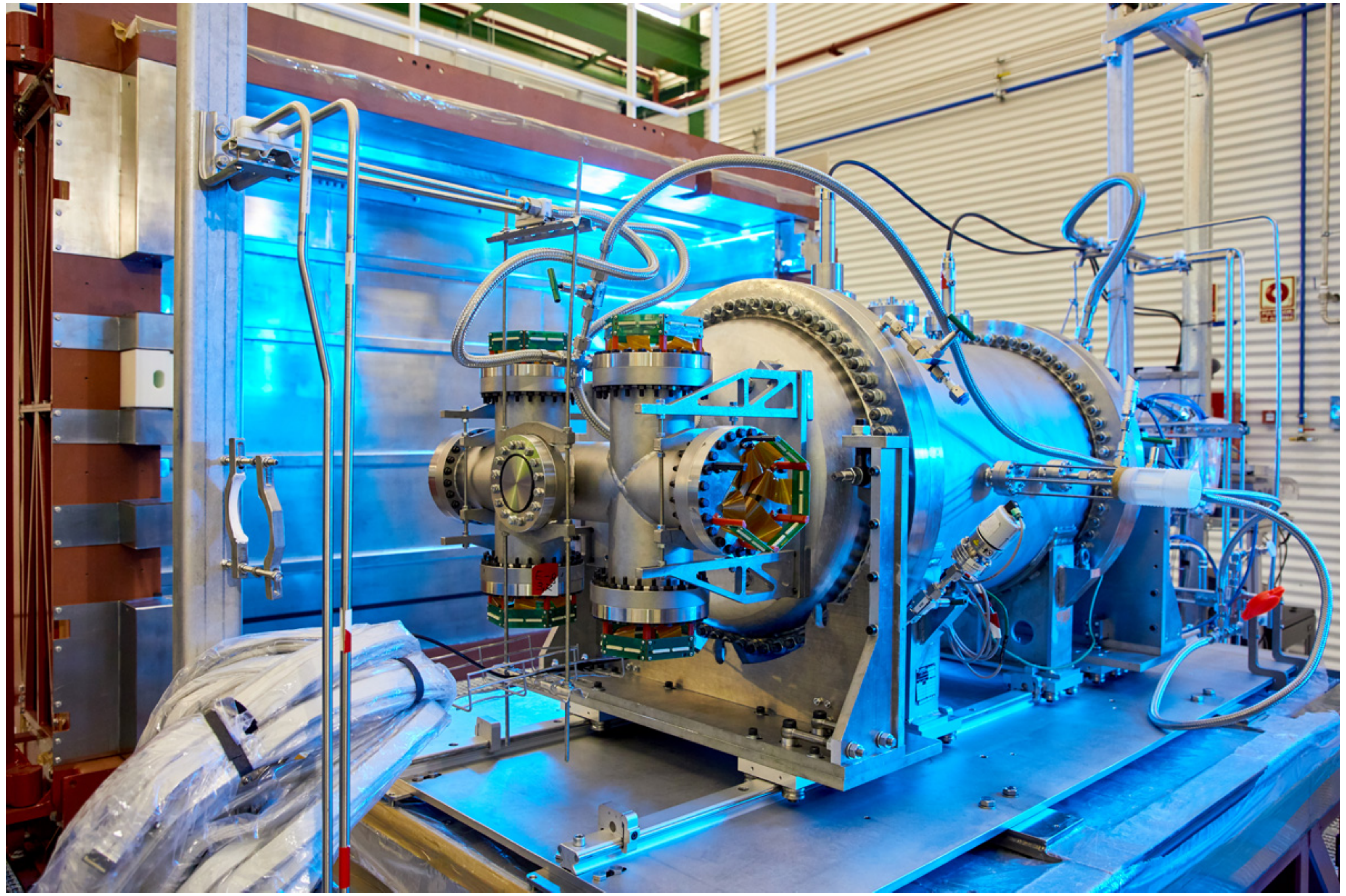
Canfranc Underground Laboratory (LSC)

NEXT-White



Our beloved friend
The late professor James White.





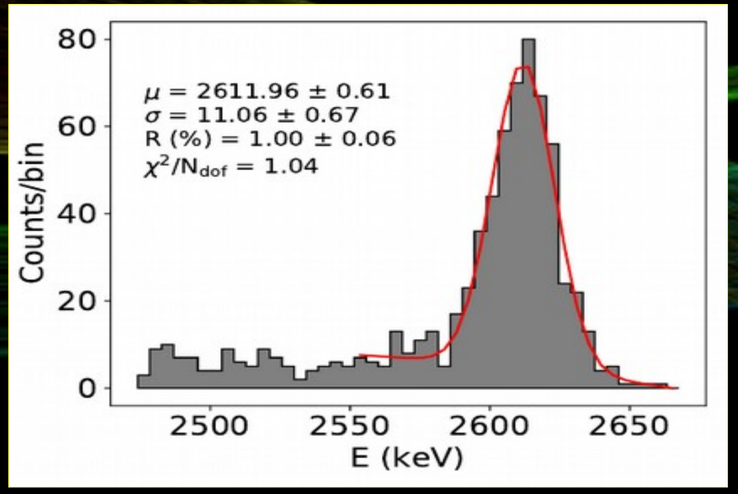
Demonstration of NEXT technology

Summary

JINST 13 (2018) 12

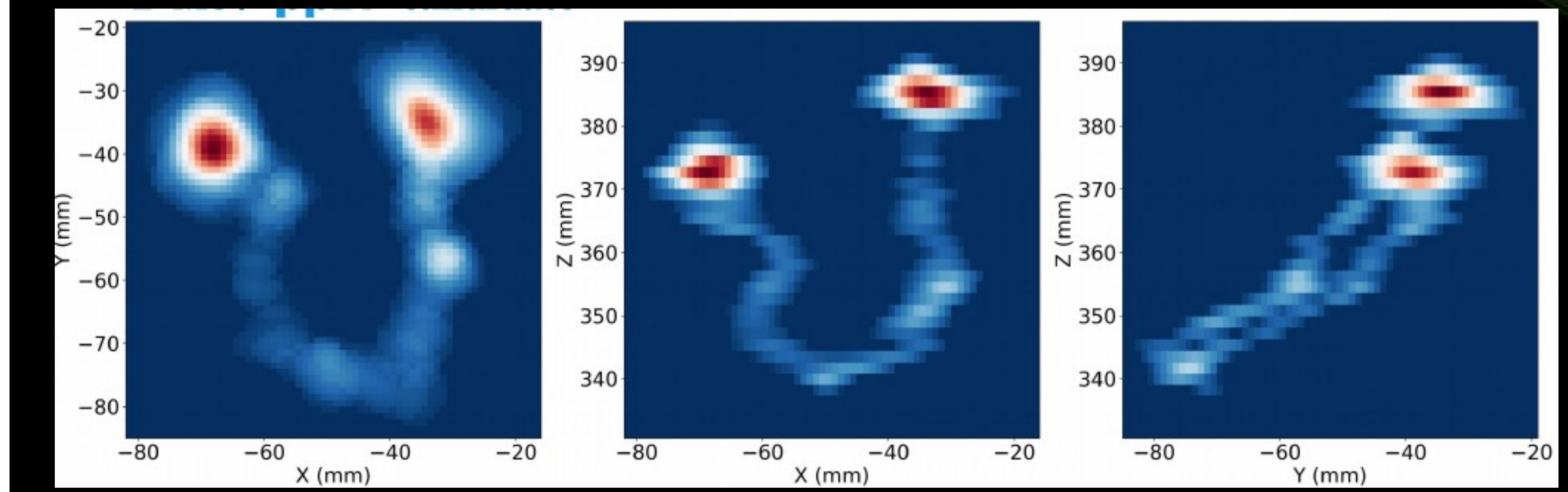
- NEXT-White has been operated with good performance from 2016 to 2021→ long term stability
- Physics program of the NEXT-White detector completed → all goals achieved:

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



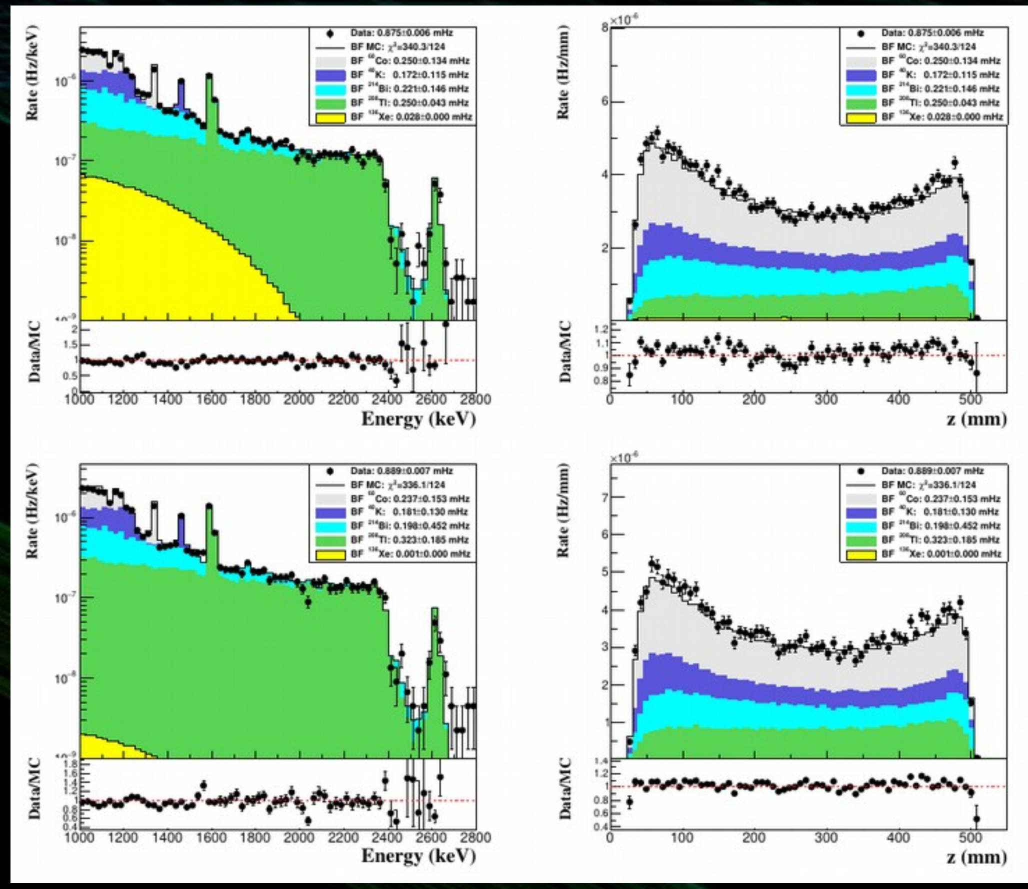
- JHEP 10 (2019) 230
- JINST 13 (2018) no.10, P10020
- JINST 13 (2018) no.10, P10014

Topology-based BG rejection



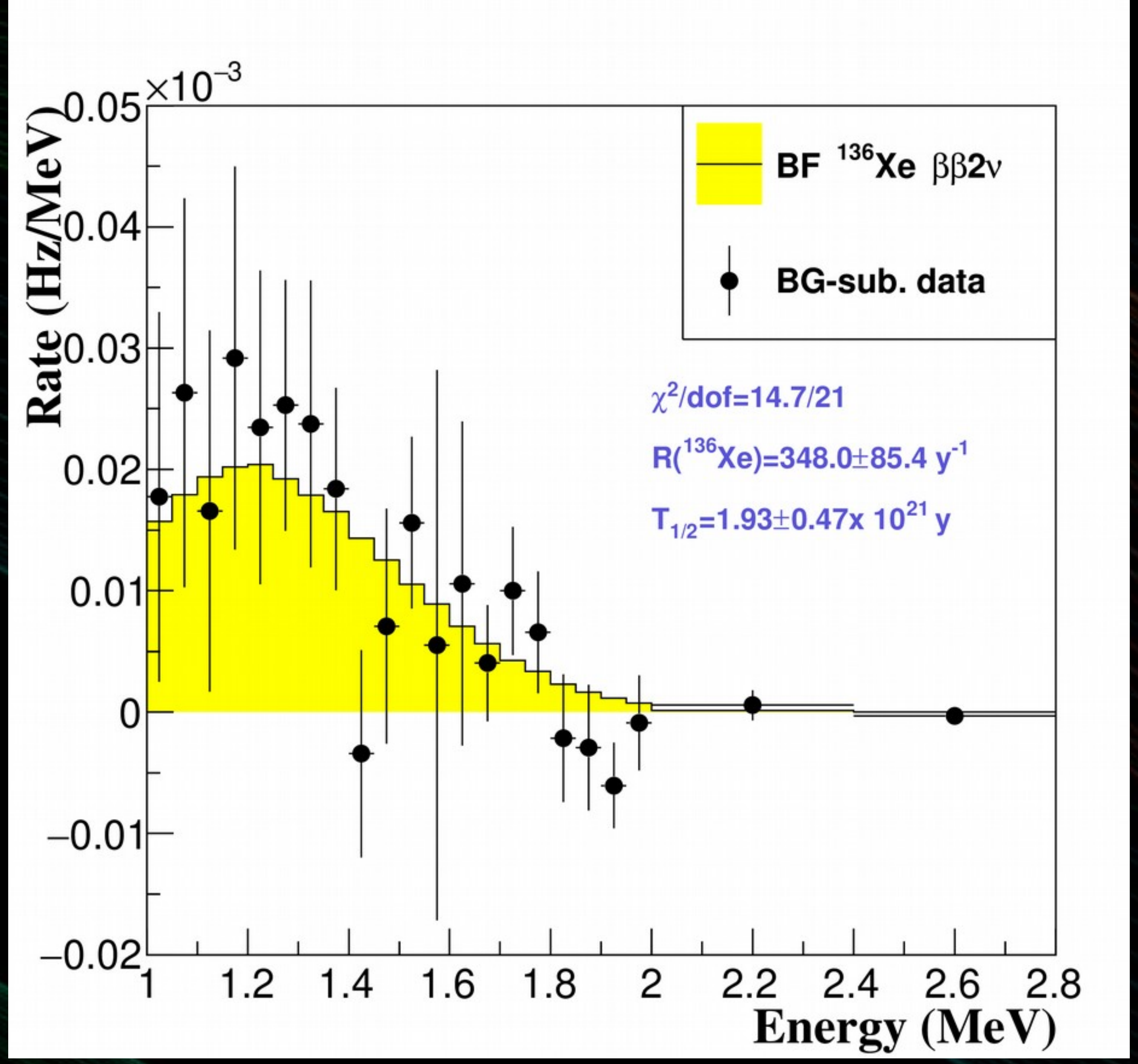
- JHEP 7 (2021) 146
- JHEP 01 (2021) 189
- JHEP 10 (2019) 052
- JINST 12 (2017) no.01, T01004

- Background measurement



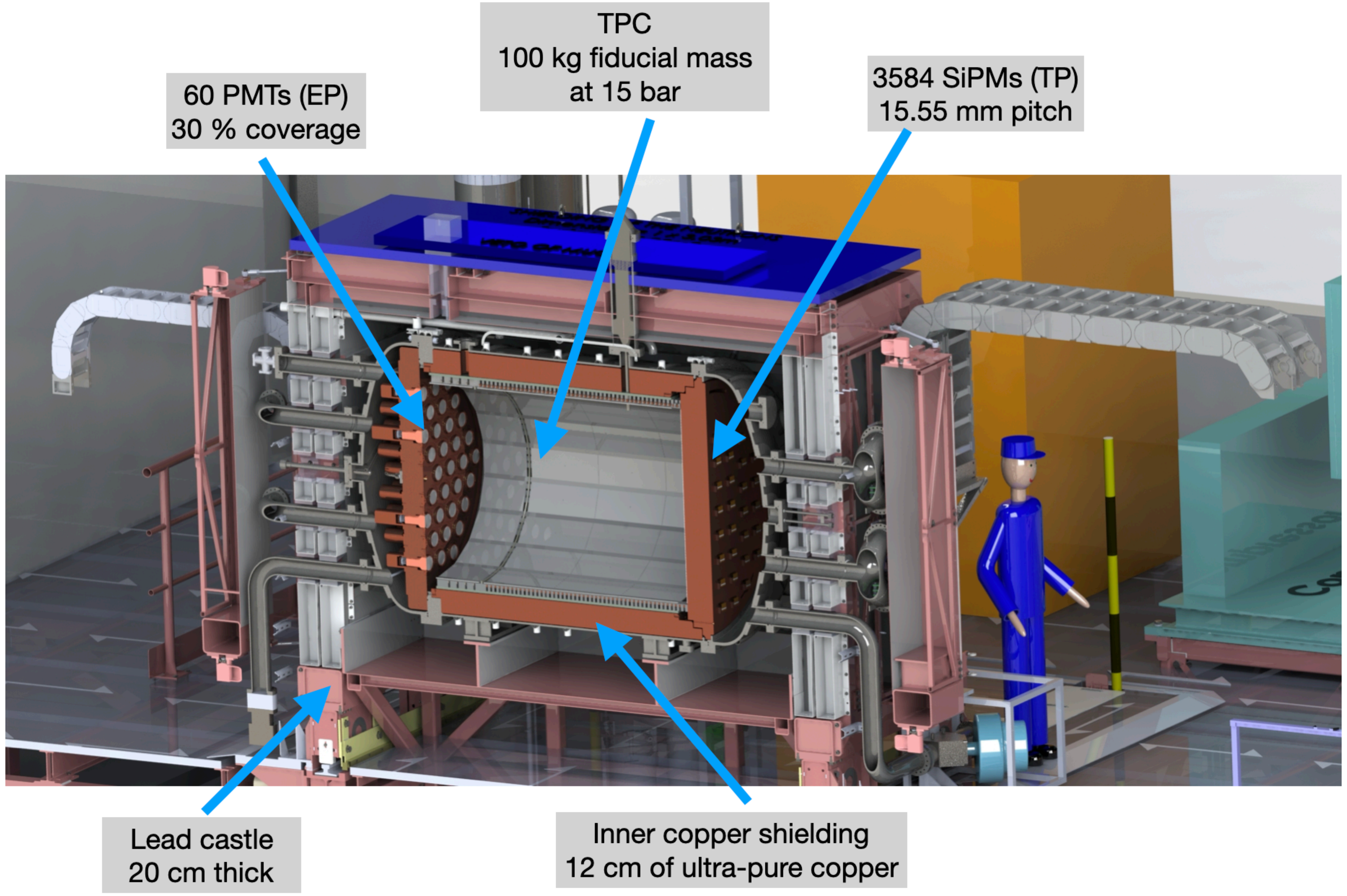
- JHEP 10 (2019) 051
- JHEP 10 (2018) 112

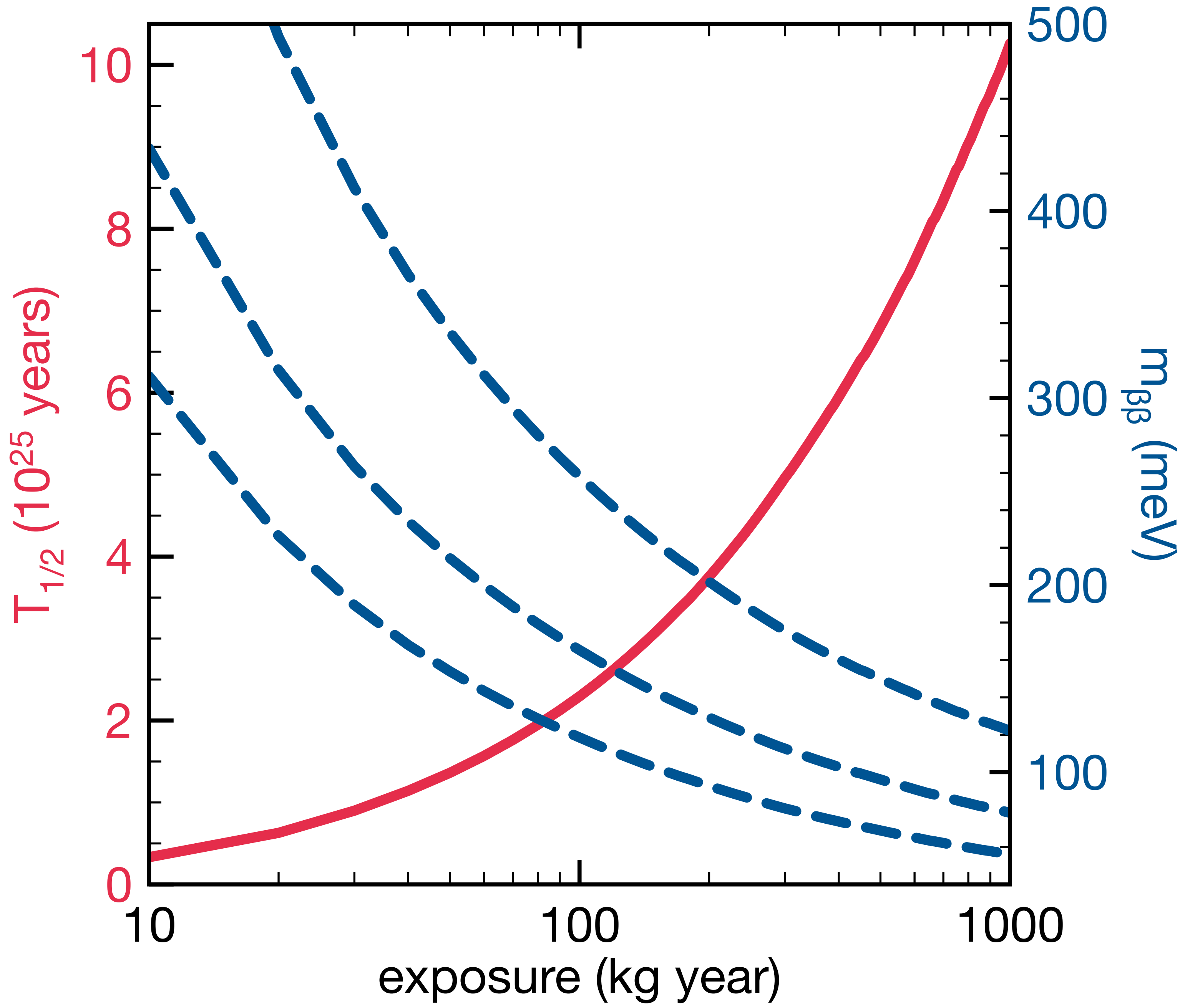
- ββ2ν measurement (x2!)



- Paper in preparation

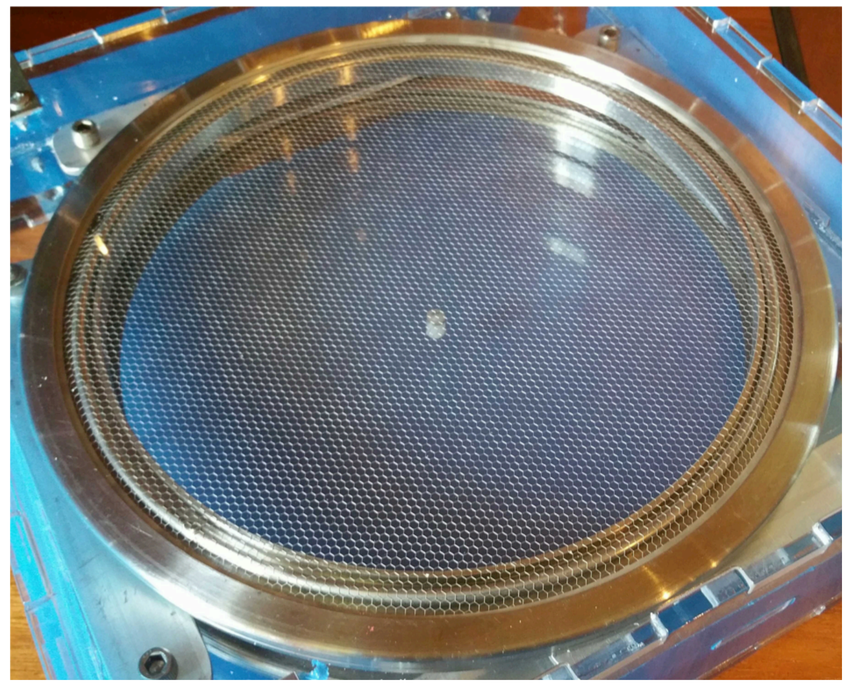
NEXT-100

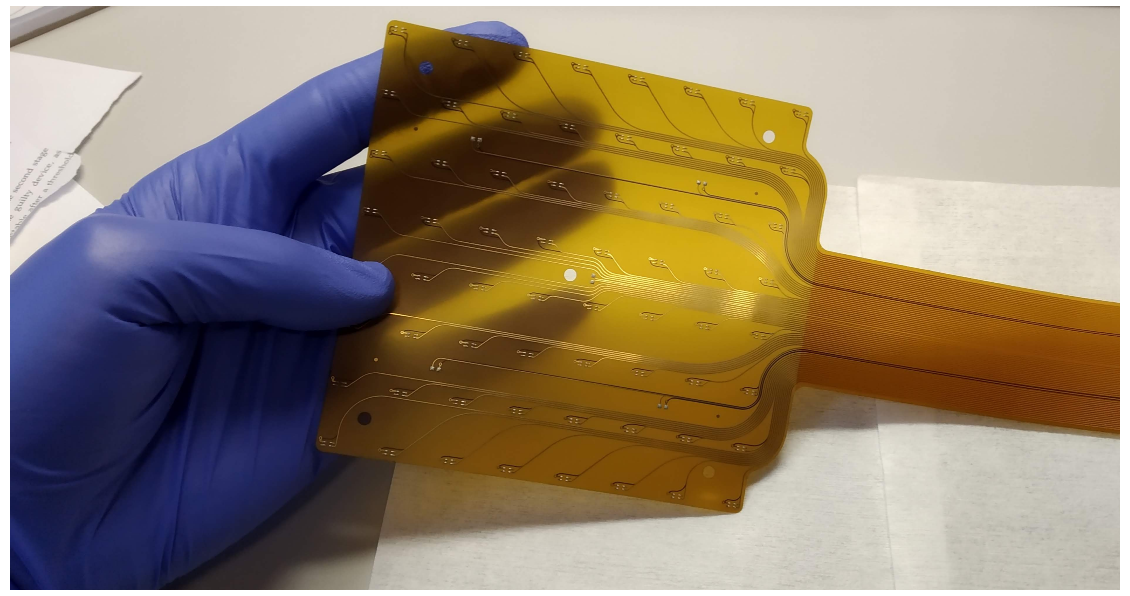


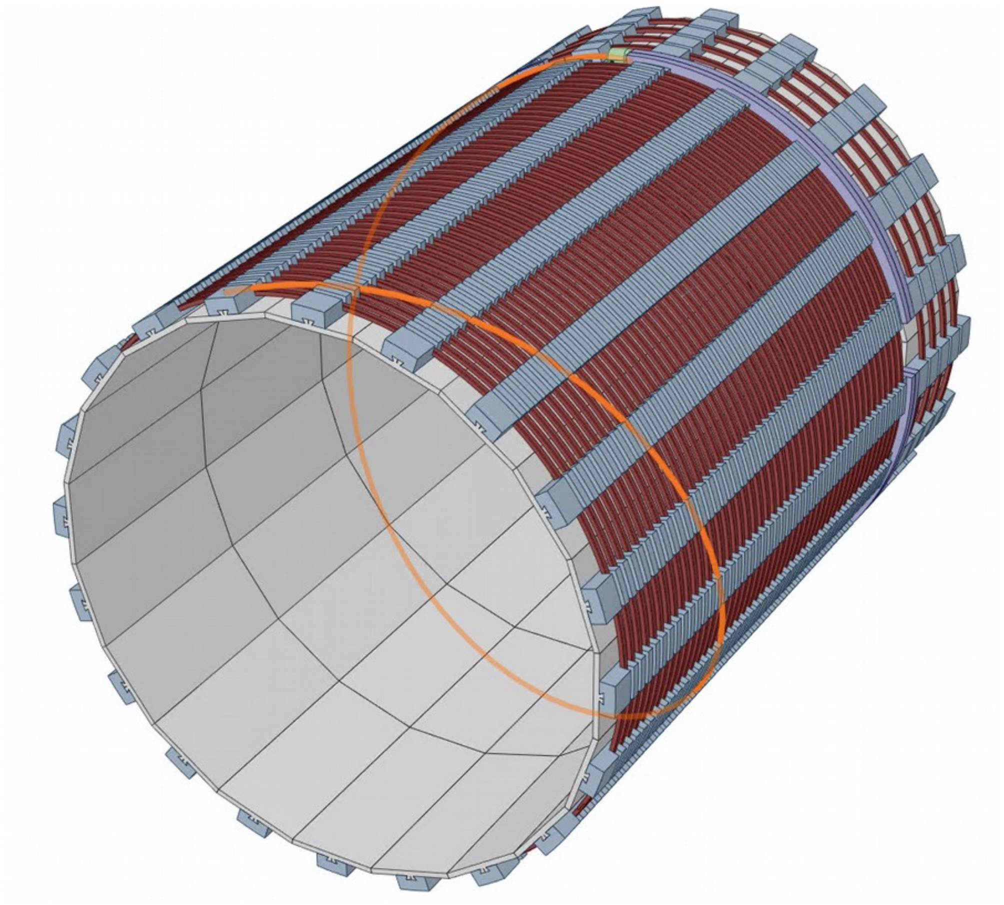


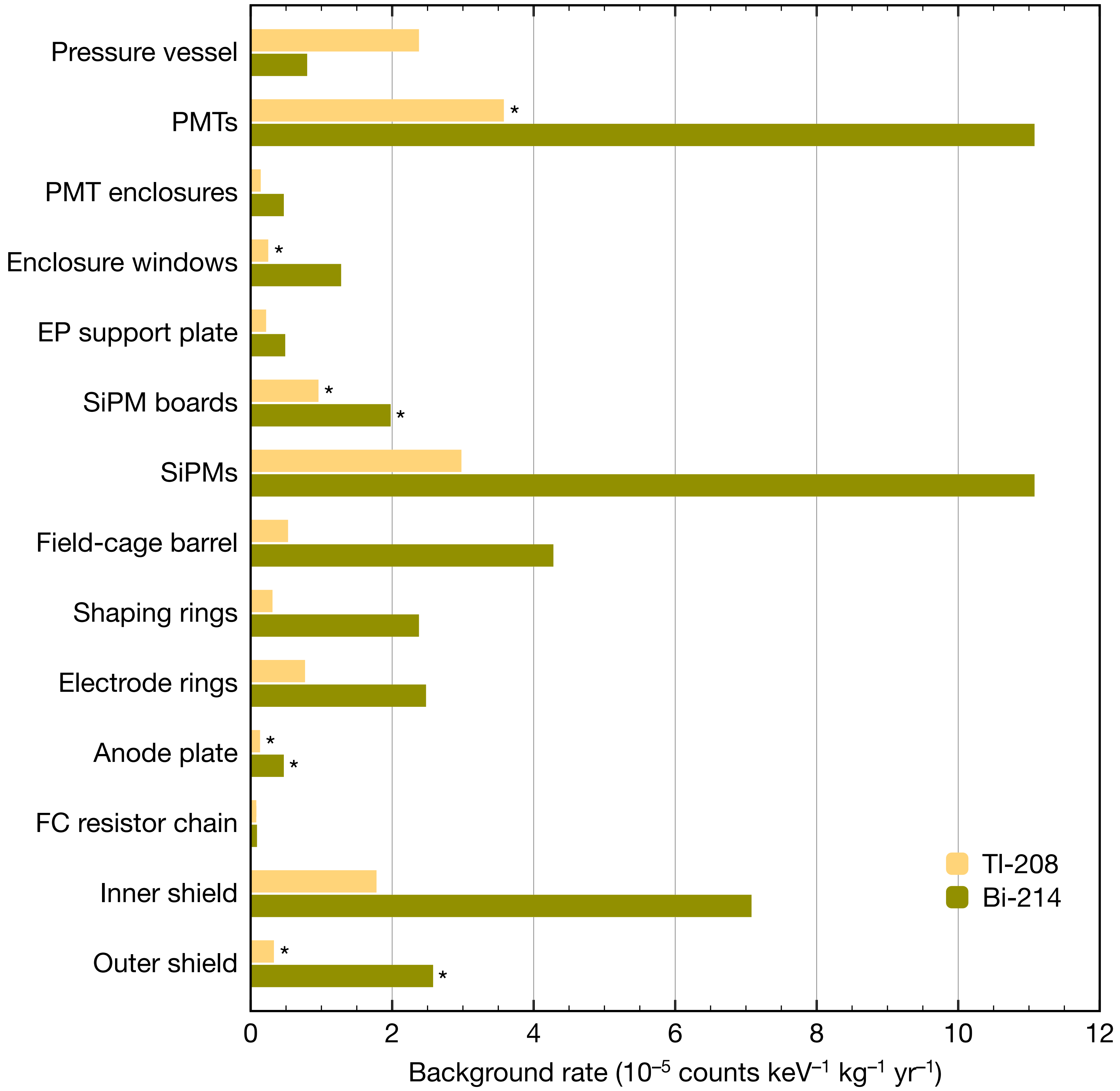
- Detector structure like NEXT-White: Energy Plane (EP), Tracking Plane (TP) and TPC.
- Construction underway. Expect to be in operation in 2022.
- Can reach a sensitivity of ~10^{26} years, thus competing with EXO and KamLAND-Zen

Why we need NEXT-100



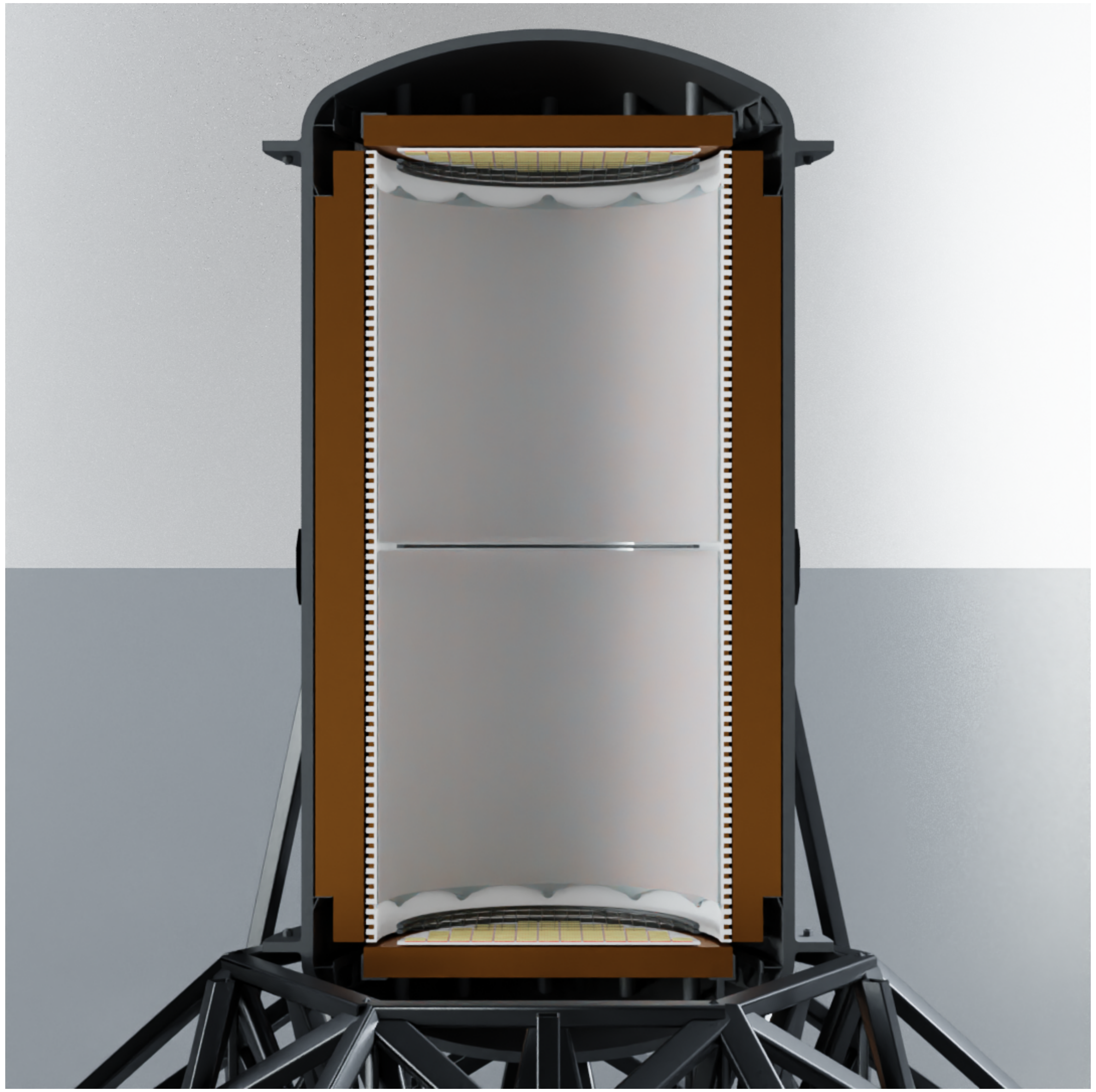






- Understand technical solutions at large scale (EL meshes, HVFT, thinner Kapton boards for SiPMs.
- Validate background model, including background near $Q_{\beta\beta}$ in a detector more radipure and better shielded than NEXT-100
- Understand further energy resolution, topological signature, direct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

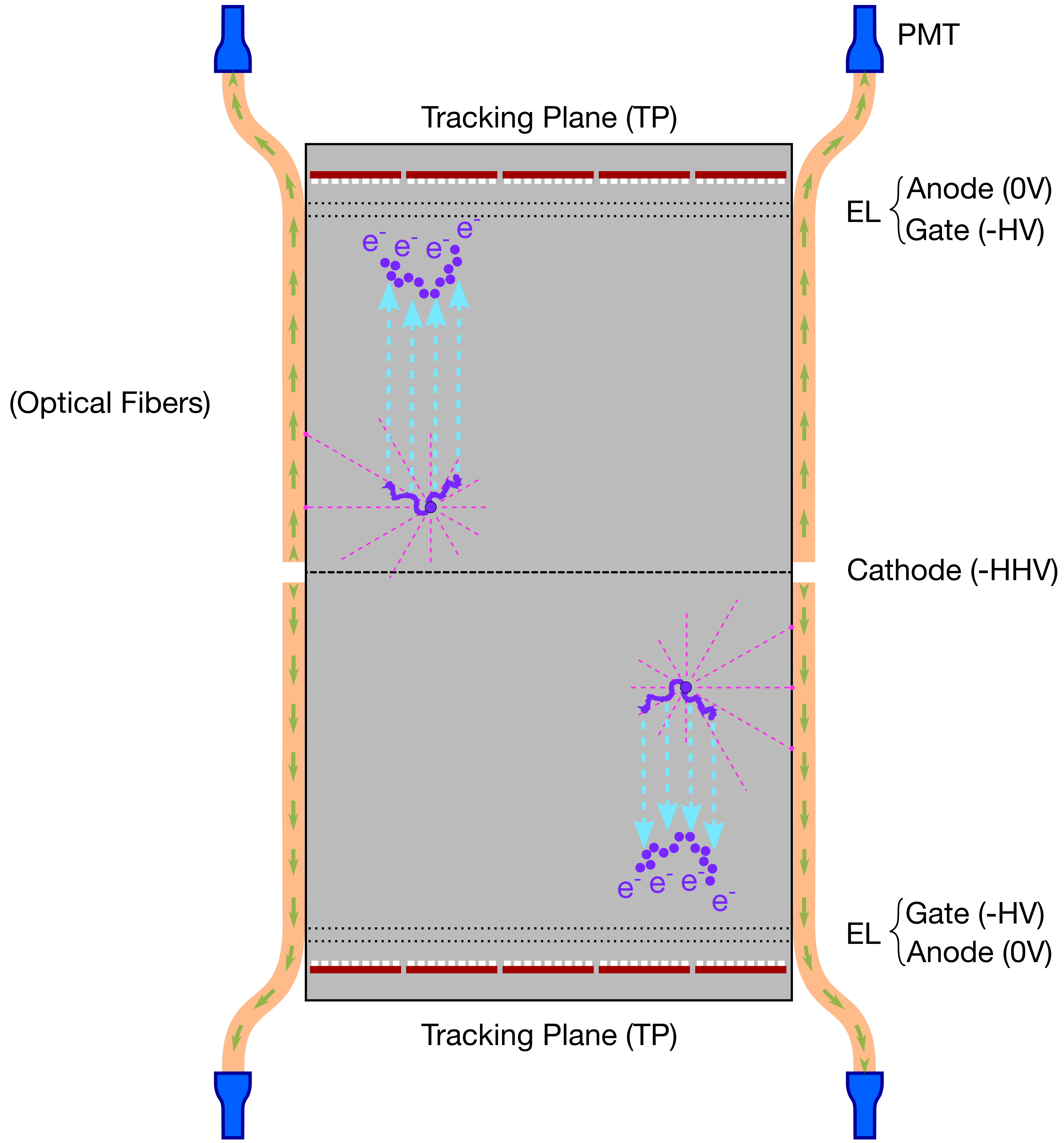
Next step: NEXT-HD



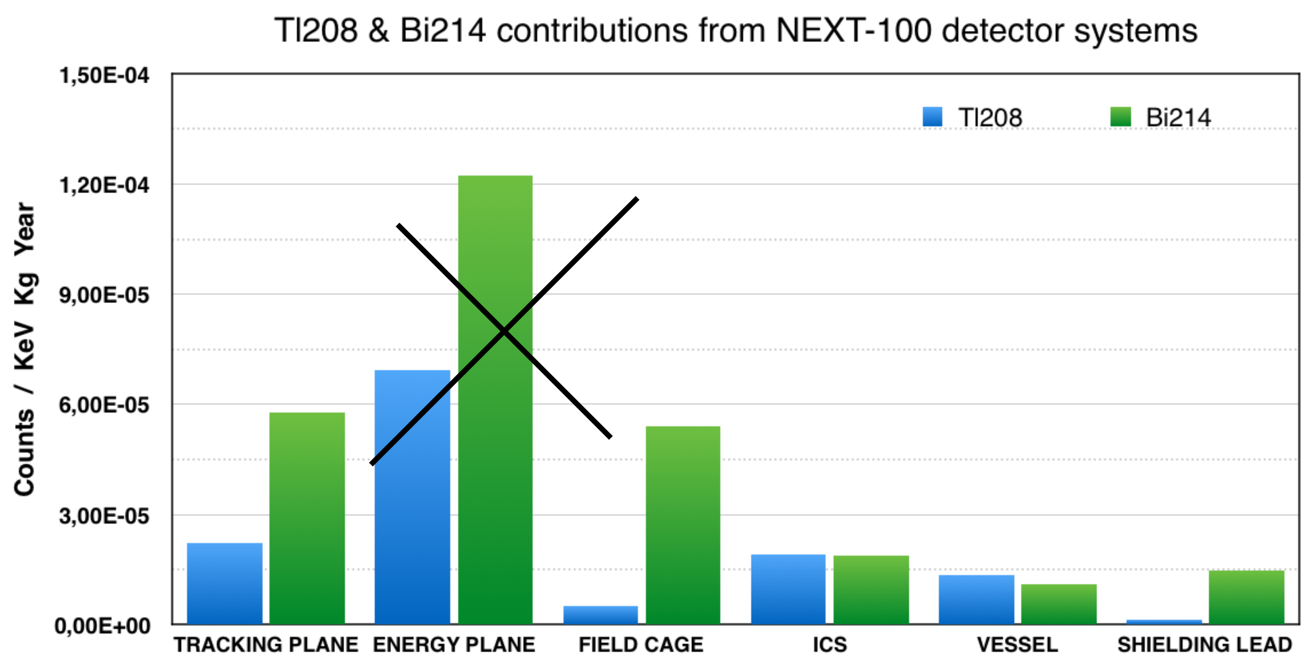
- A symmetric detector of **2 x 1.5 m length** and **2.2 m diameter**, “doubling size of NEXT-100”, holds **1 tonne at 15 bar** and allows operational voltages in the same range than those used by NEXT-100 (thus, minimising risk).
- Both anodes instrumented with dense planes of SiPMs (**DSPs**).
- S1 (and S2) measured by a barrel fiber detector (**BFD**).
- In this talk: NEX-HD refers to the upgrade of NEXT technology (without barium tagging) and also to the first module of 1 ton to be operated at the LSC. Some times we refer to this module also as NEXT-1t.

Barrel Fiber Detector

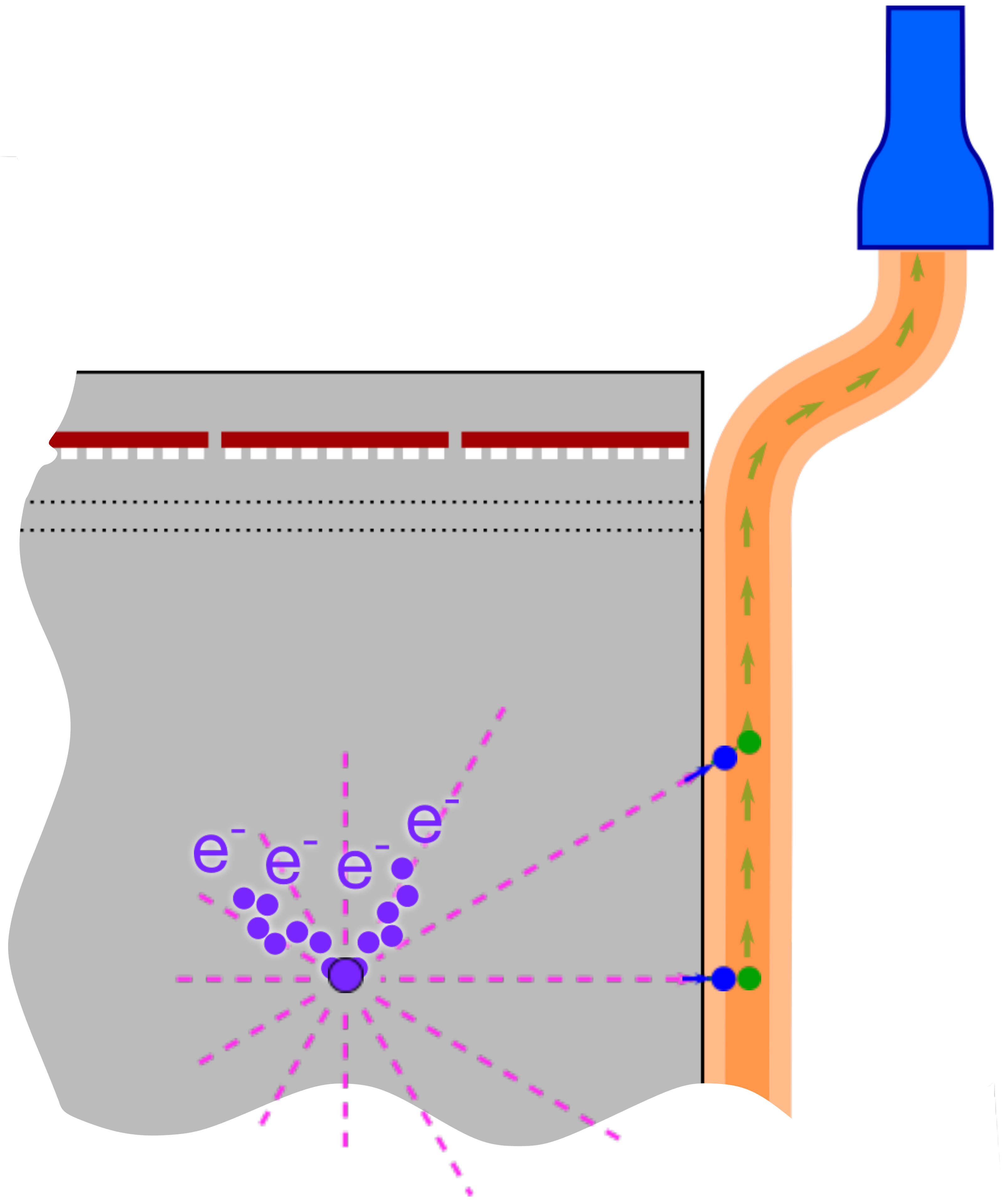
- In NEXT-White and NEXT-100, S1 and S2 are measured by the PMTs. The overall light efficiency of both systems is of the order of 1.1 %. This permits the identification of S1 for Krypton (essential for calibrations) and also a measurement of S2 with modest EL amplification (~500 photons/e).
- NEXT-HD 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%.



Principles of operation

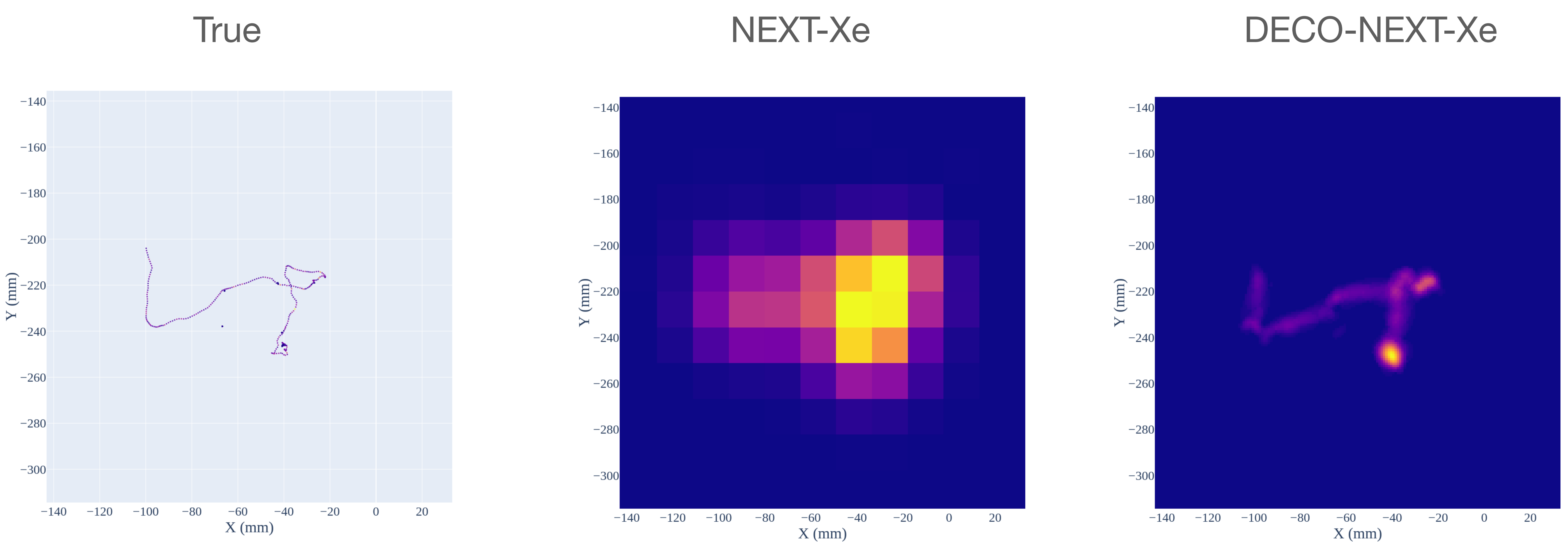


- PMTs shielded from active volume, thus eliminating the dominant background source in next

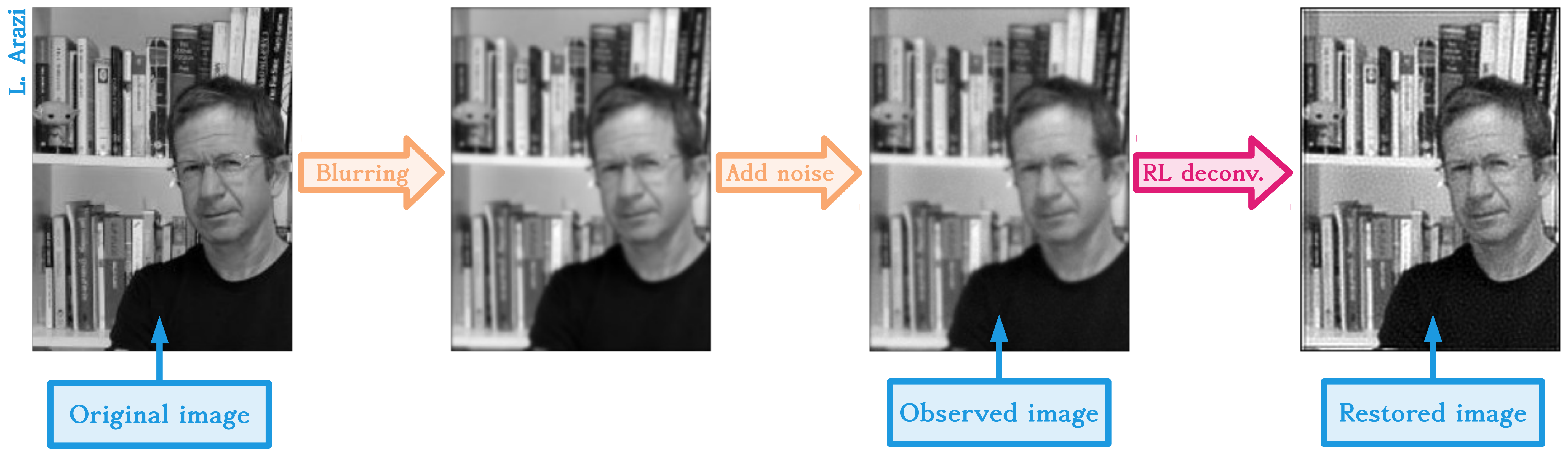


- S1/S2 VUV photons reach double-clad optical fibres (mass produced by Kurarai and St. Gobain). Optical fibres are coated with TPB, which shifts light to blue. Blue light enters the fibres and is absorbed with high efficiency, then re-emitted as green light. Finally green light propagates by total internal reflection until it reaches the sensors.

NEXT topological signature: Richardson-Lucy deconvolution

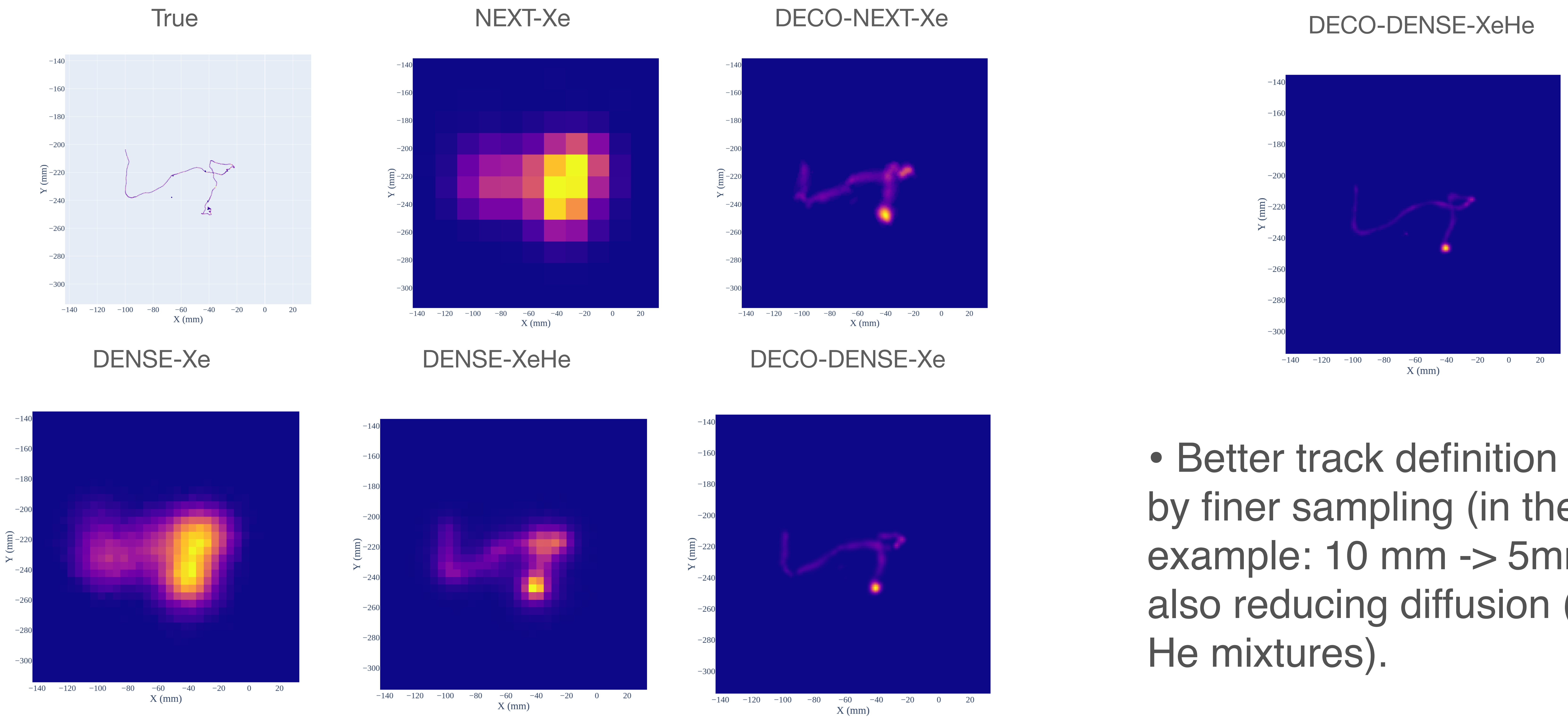


- The observed image is the result of the original image blurred by a kernel and additional noise.
- **Given a known kernel**, Richardson-Lucy (RL) deconvolution **solves the inverse problem iteratively**.
  - Described independently by W. Richardson and L. Lucy in the early 70s.



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

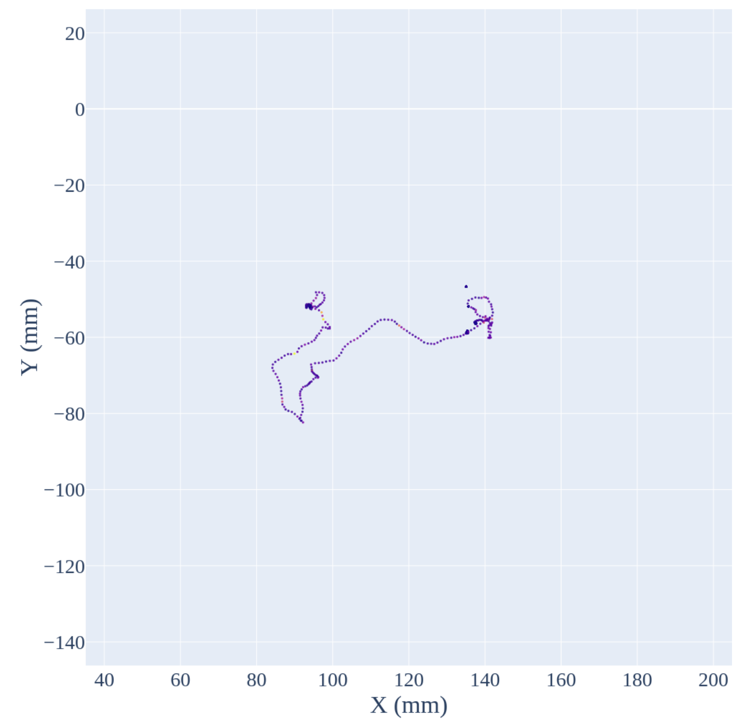
High density = high definition (single electron example)



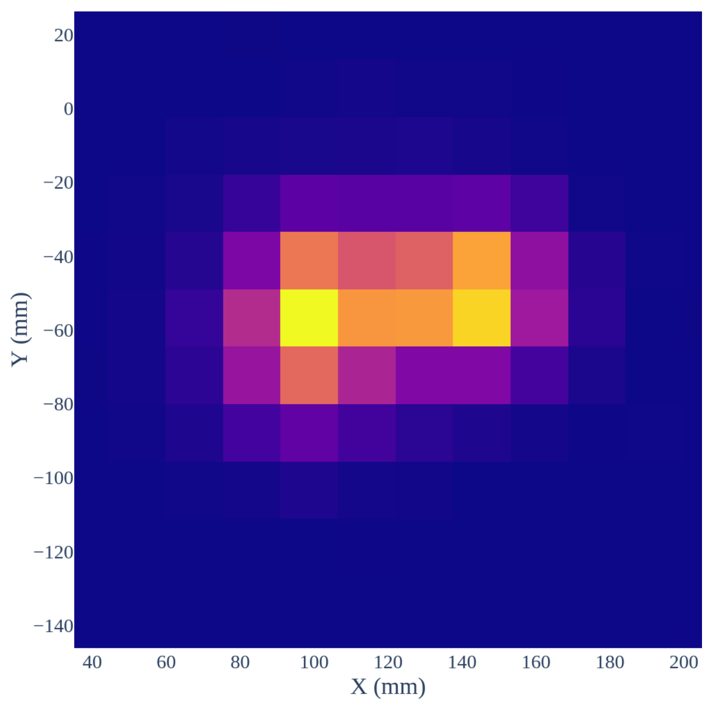
- Better track definition achieved by finer sampling (in the example: 10 mm -> 5mm) but also reducing diffusion (e.g, Xe-He mixtures).

High density = high definition (double electron example)

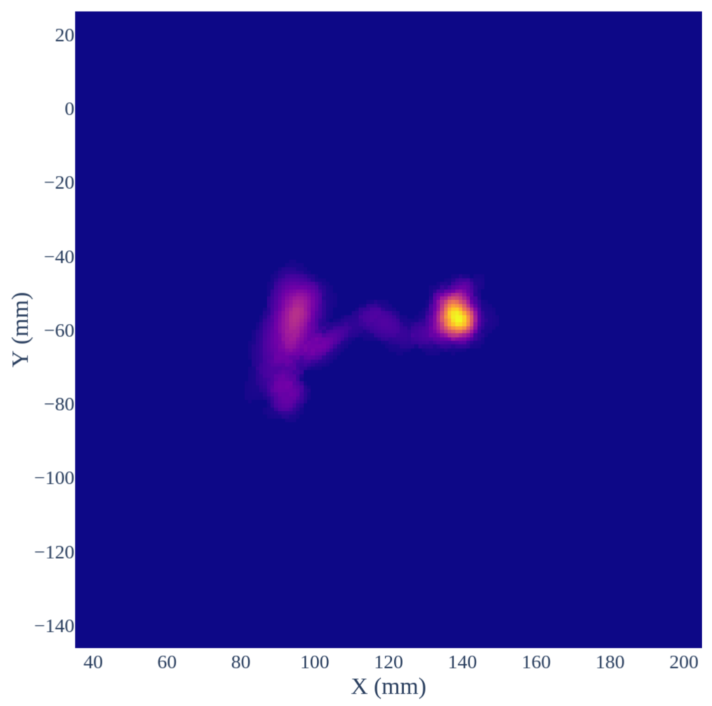
True



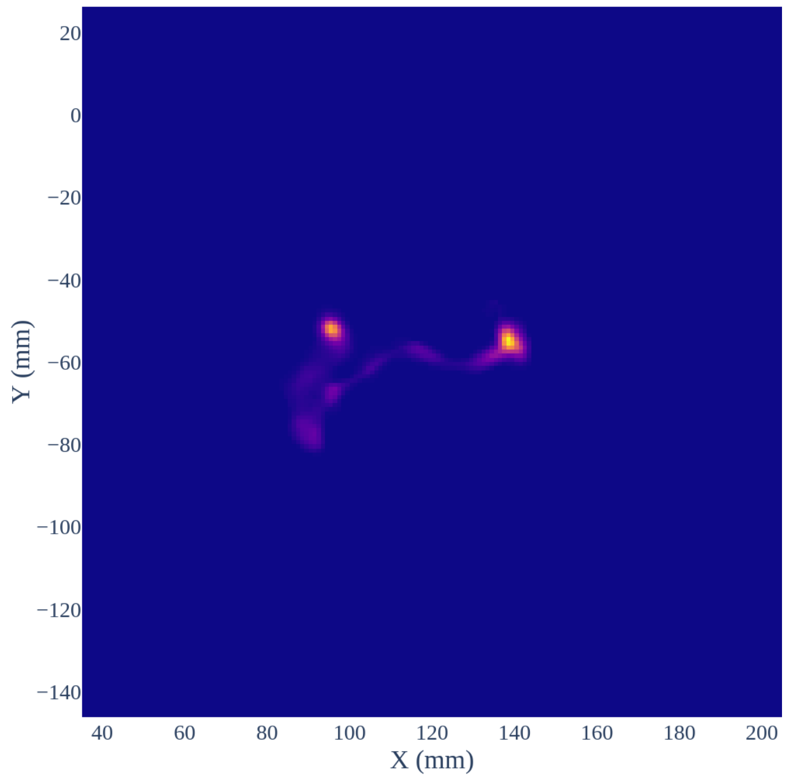
NEXT-Xe



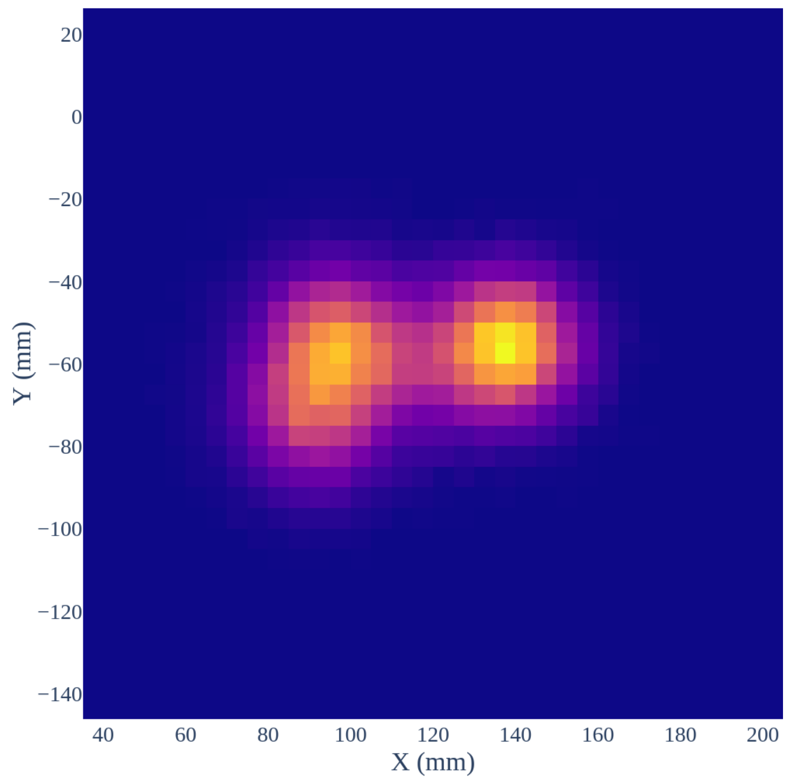
DECO-NEXT-Xe



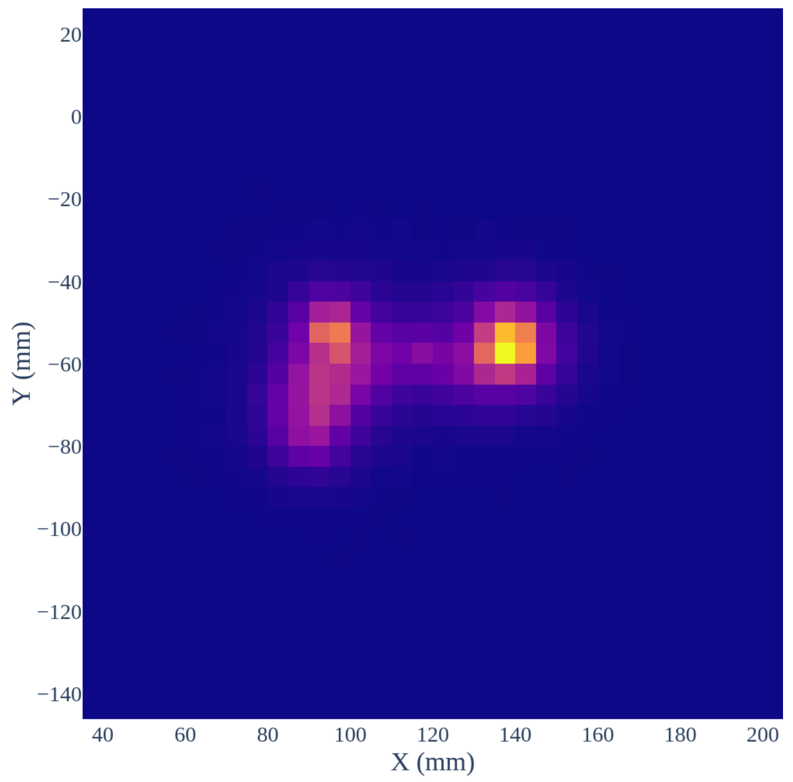
DECO-DENSE-XeHe



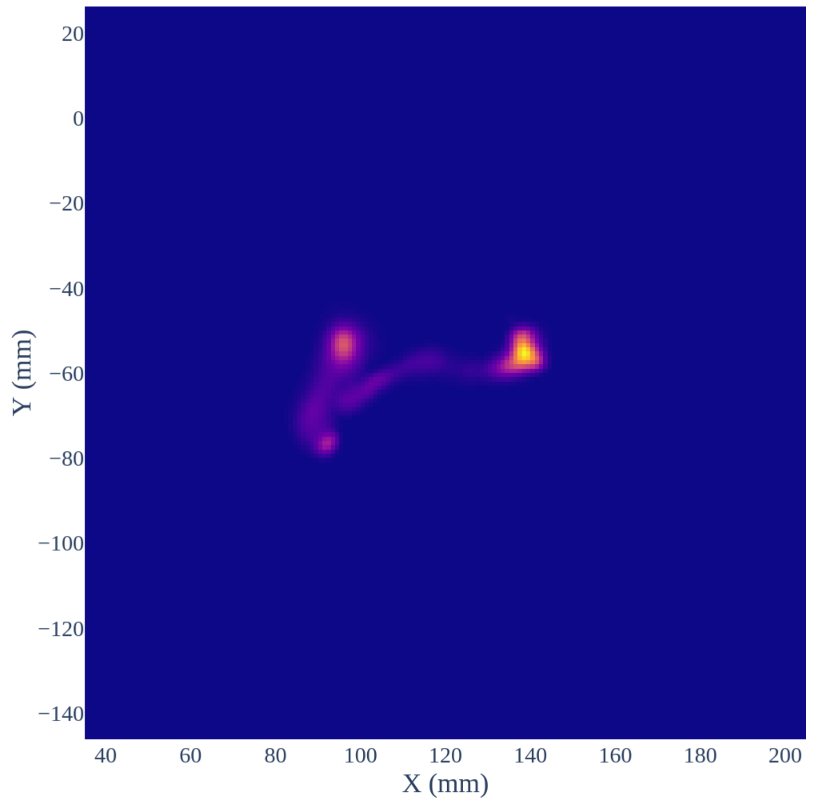
DENSE-Xe



DENSE-XeHe

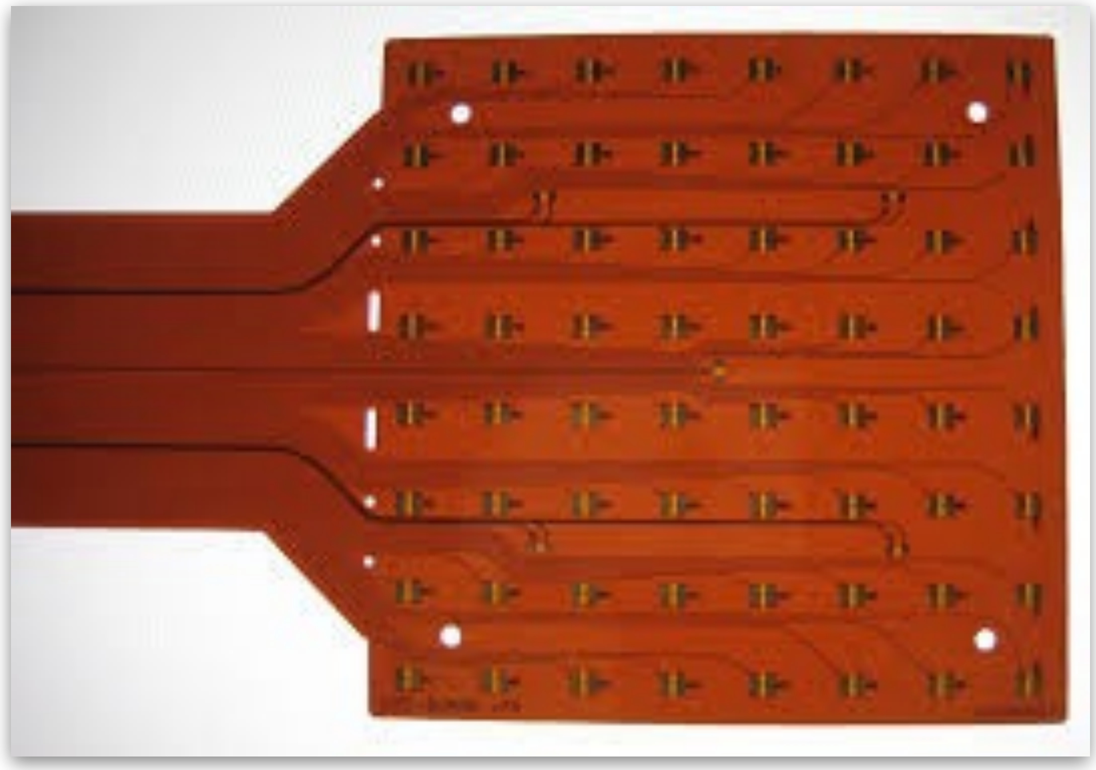


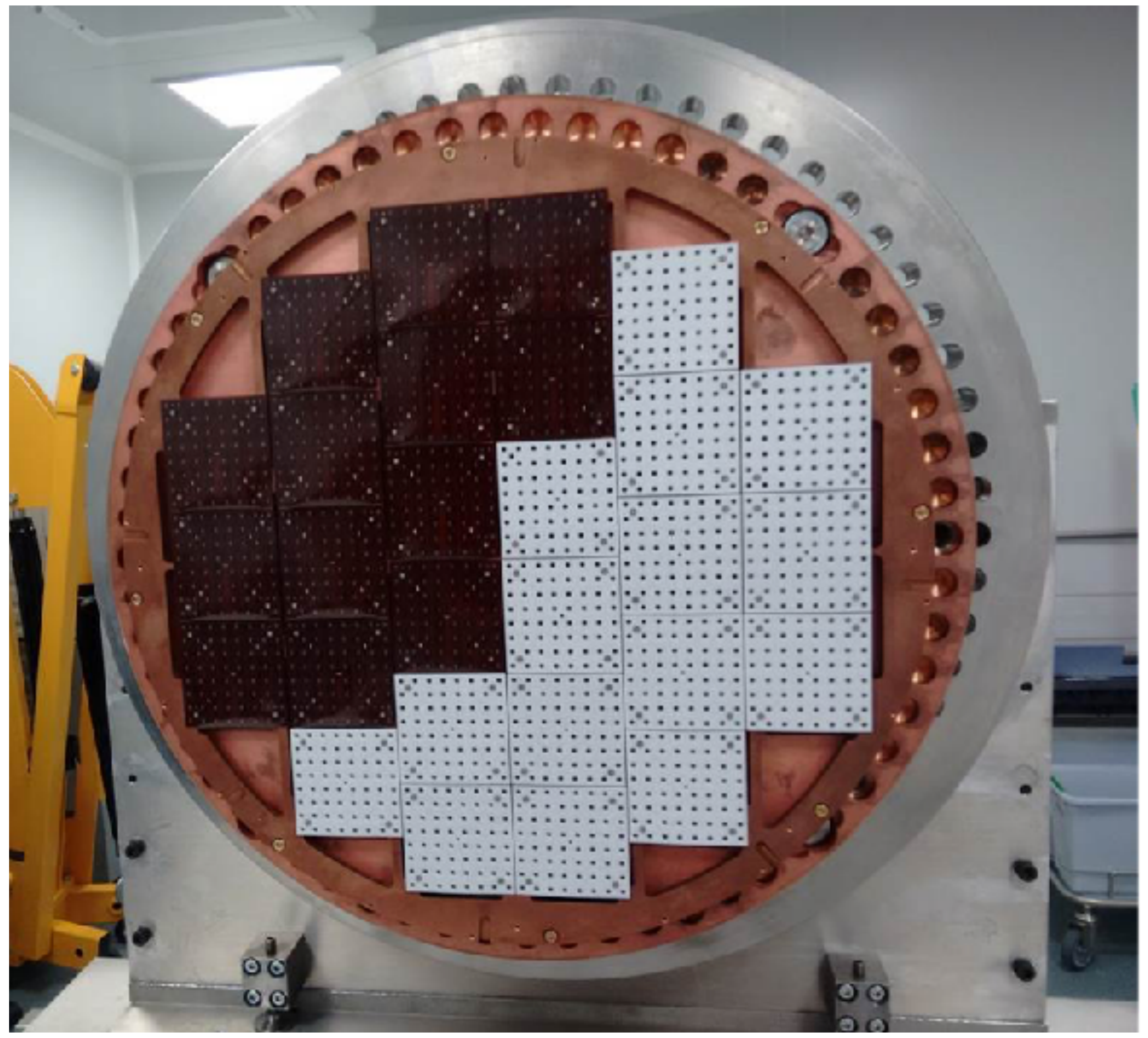
DECO-DENSE-Xe



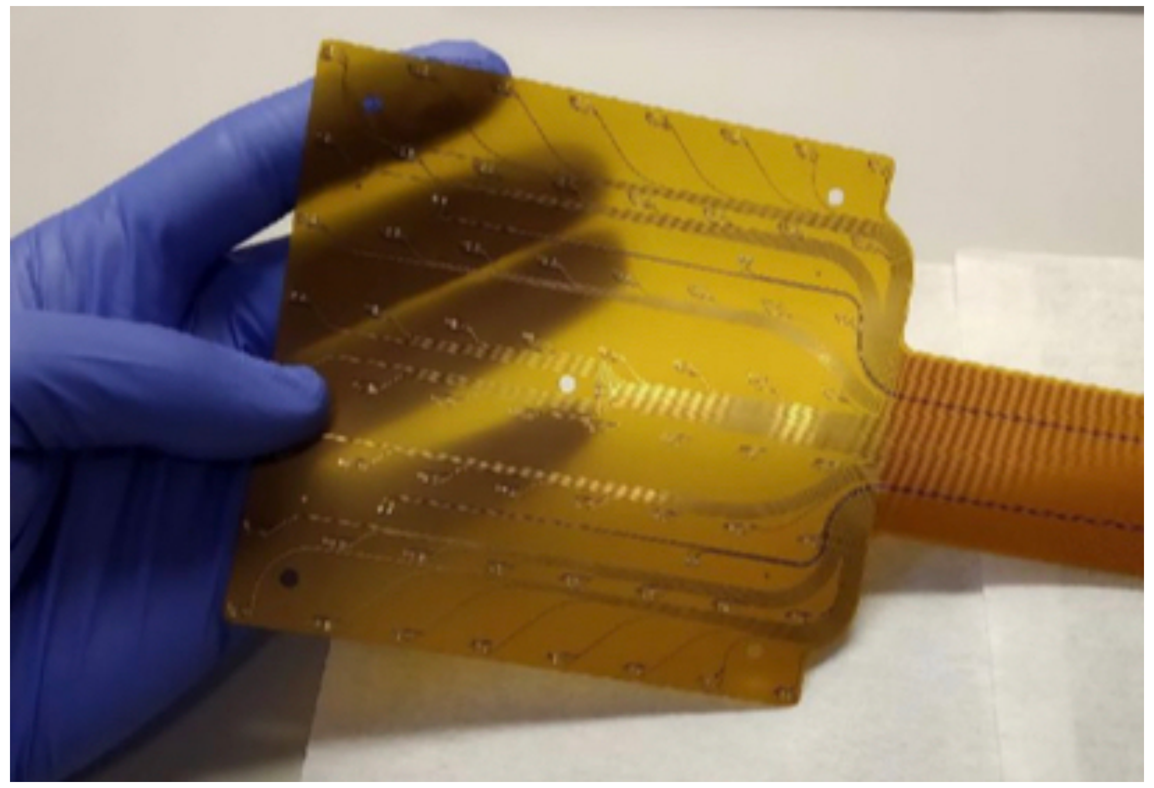
- The effect of deconvolution/sampling/diffusion is even more evident in the reconstruction of two electrons where two blobs must be separated.

Design of the Dense Silicon Planes

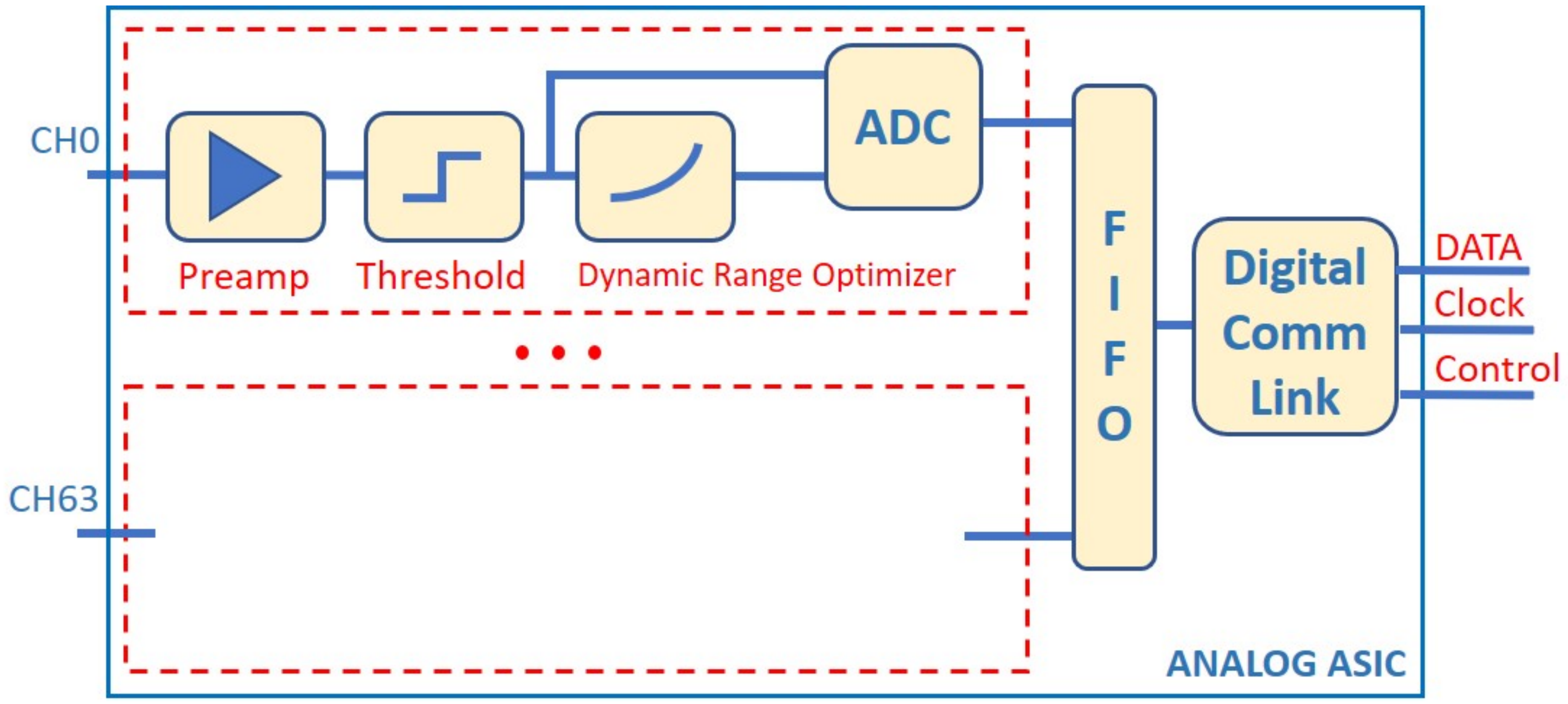




Optimise pitch to maximise track reconstruction and thus background rejection.

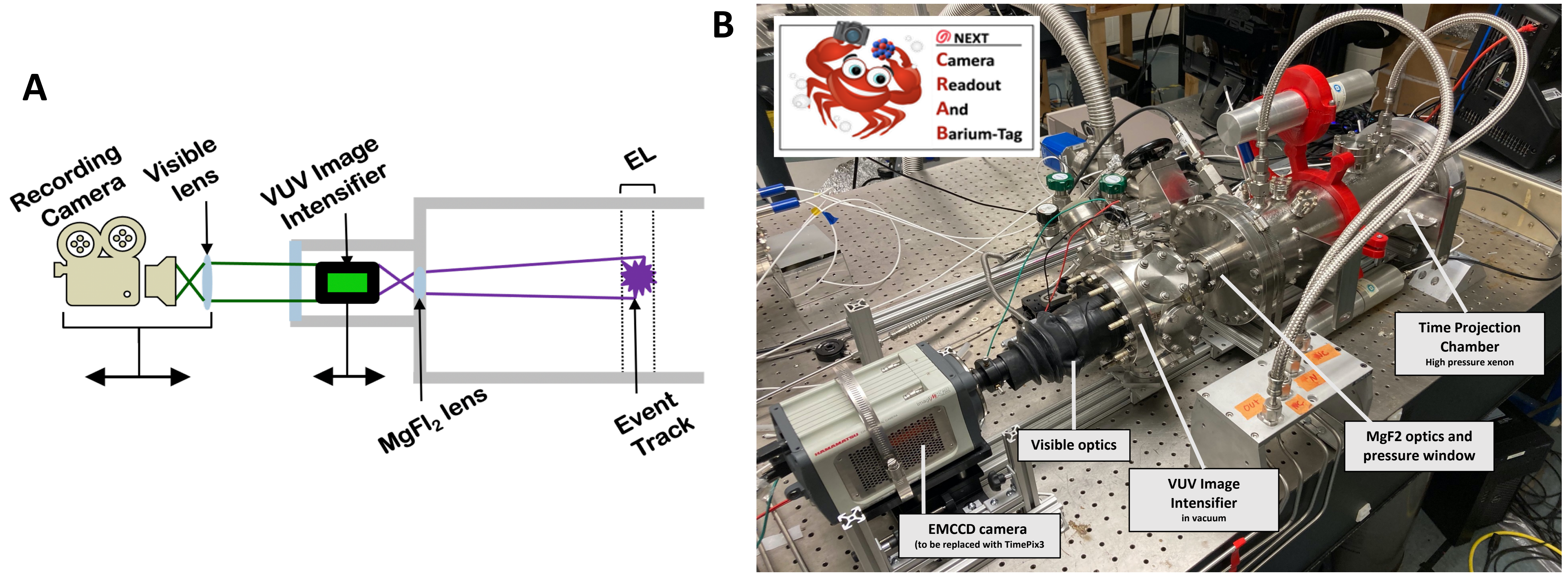


Reduce radioactive budget (thinner Kapton boards)



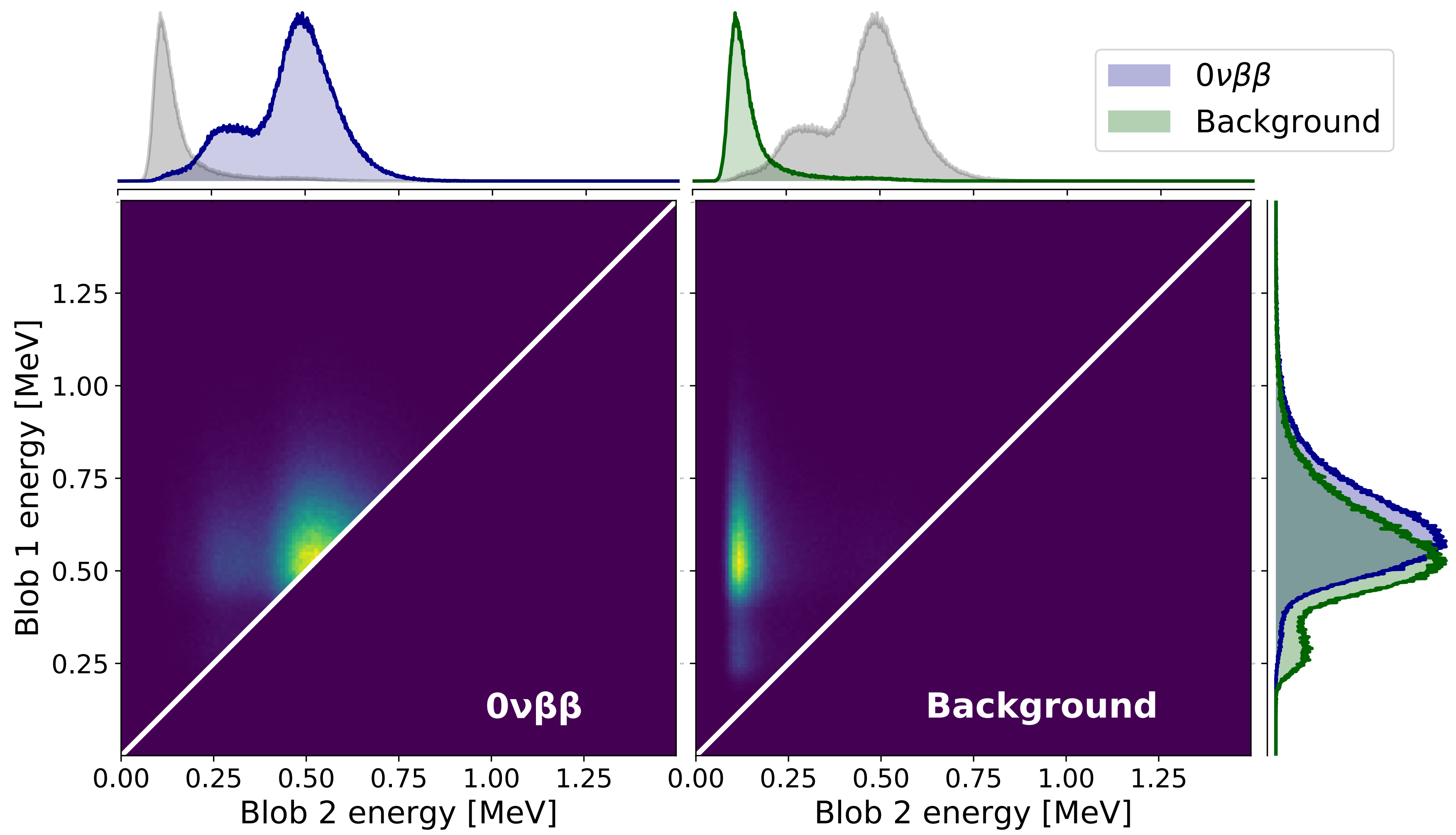
In vessel electronics (develop new ASIC or re-use/optimise existing devices).

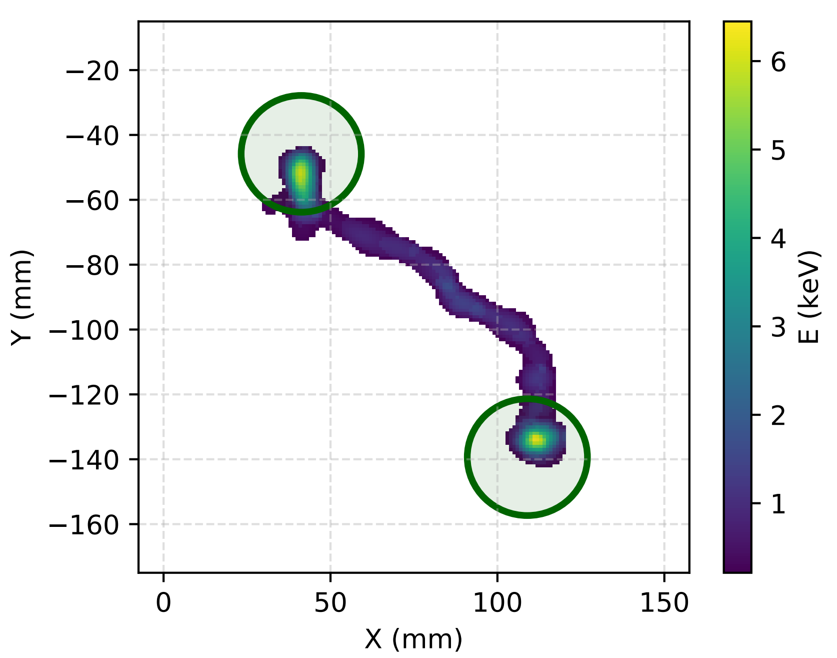
High Speed Optical Cameras

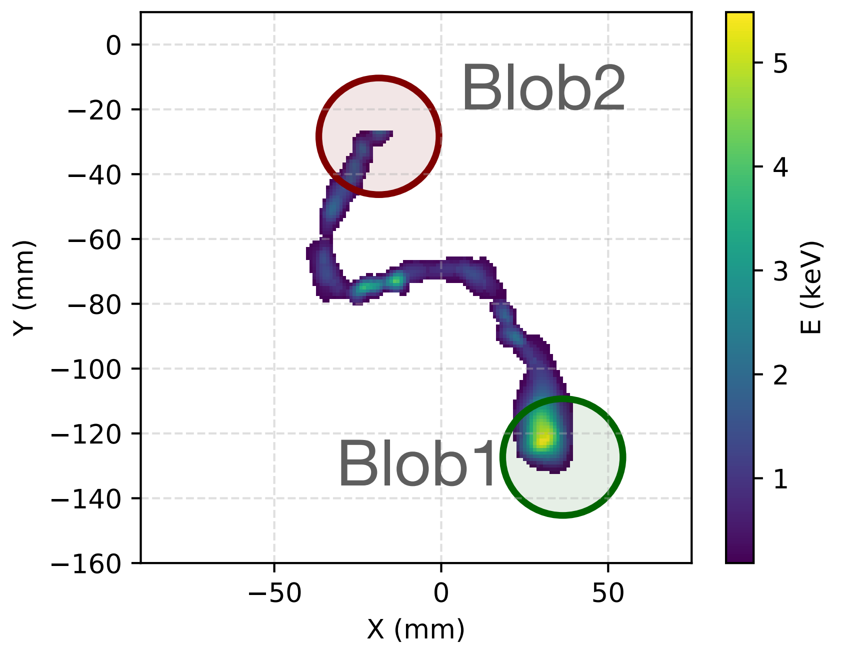


• The SiPM + ASIC solution follows the “NEXT tradition” (e.g, NEXT-White, NEXT-100), and thus can benefit from the acquired experience.
•But the number of channels grows quadratically with the pitch (and the area). The technology becomes stretched in the limit of very high density.
•An alternative (spinoff 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.

Background rejection power

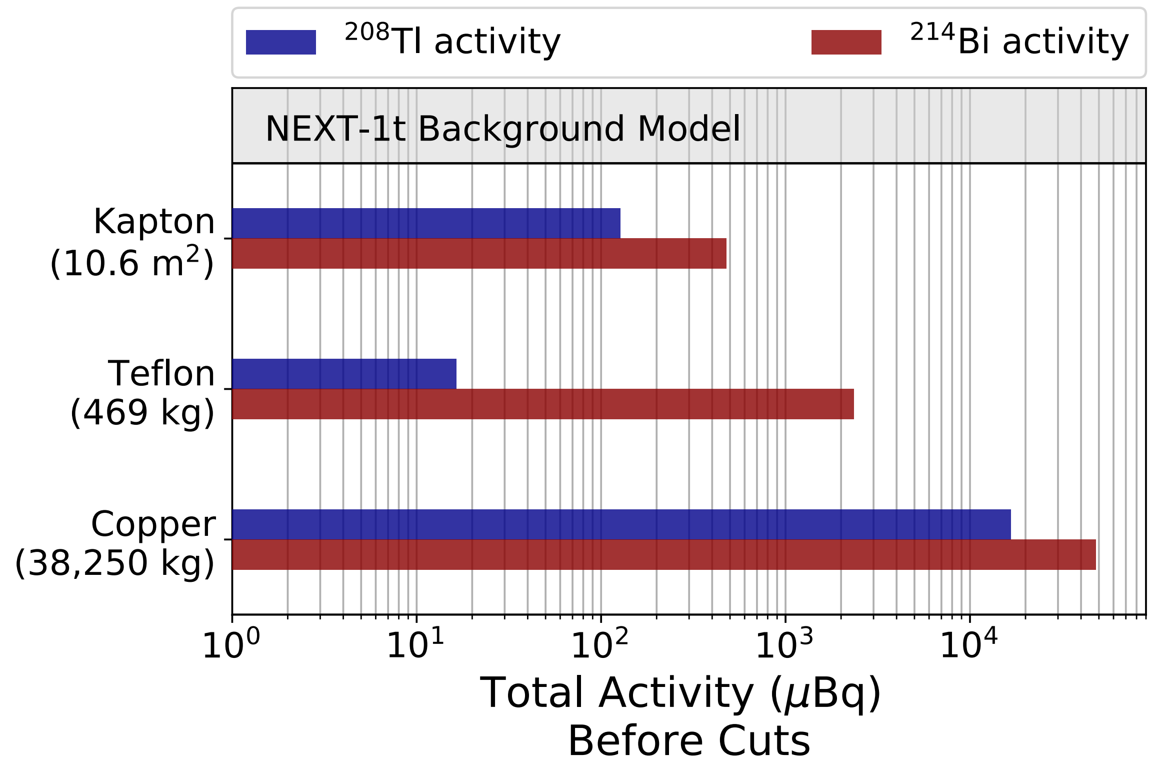


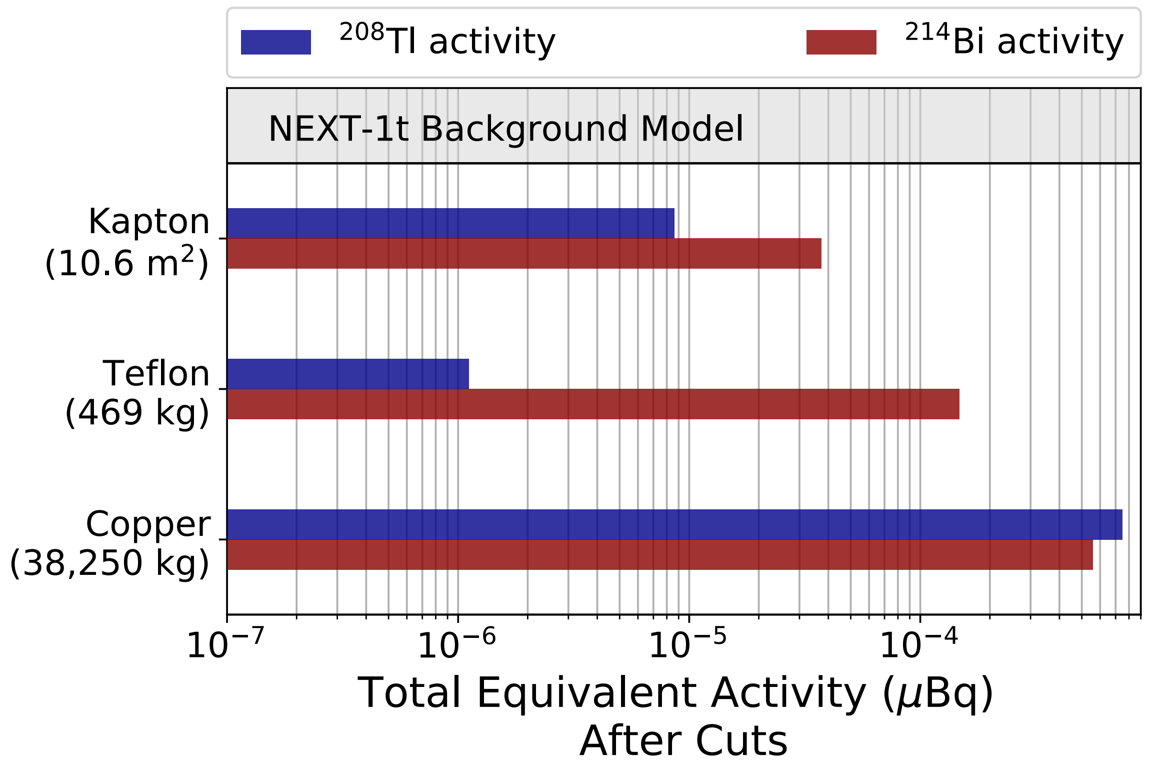




Material	Detector system	Method	Activity (μBq/kg) ^{232}Th	^{228}U	Reference
Copper	Inner shield	ICPMS	1.22 ± 0.04	1.28 ± 0.09	This work
PTFE	TPC field cage	NAA	0.103 ± 0.012	< 5	[44]
Kapton	Readout planes	ICPMS	81 ± 15	110 ± 50	[45]

Table 1. Specific activities of ^{232}Th and ^{238}U (parents of ^{208}Tl and ^{214}Bi, respectively) assumed in the background model of NEXT-1t for the most relevant materials used in the detector.





Source gas	Acceptance $[10^{-5}]$	Background index $[\text{ton}^{-1}\ \text{yr}^{-1}\ \text{ROI}^{-1}]$
Pure xenon	5.68(17)	113.49×10^{-3}
0.1% ^{3}He doping		11.78×10^{-3}

Table 3. Acceptance factor for the ^{137}Xe background and resultant contribution to the background index of NEXT-HD at the LSC.

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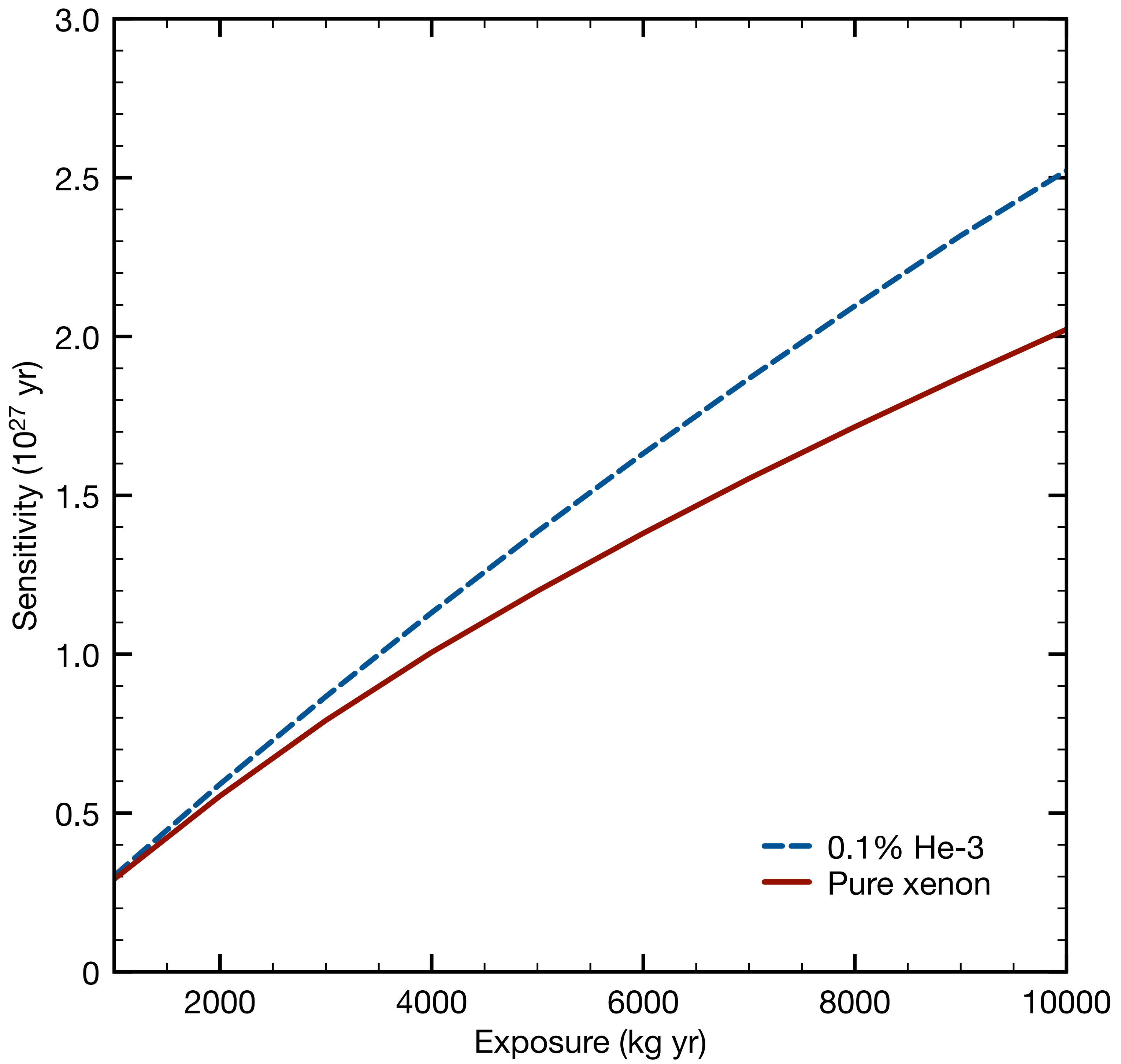
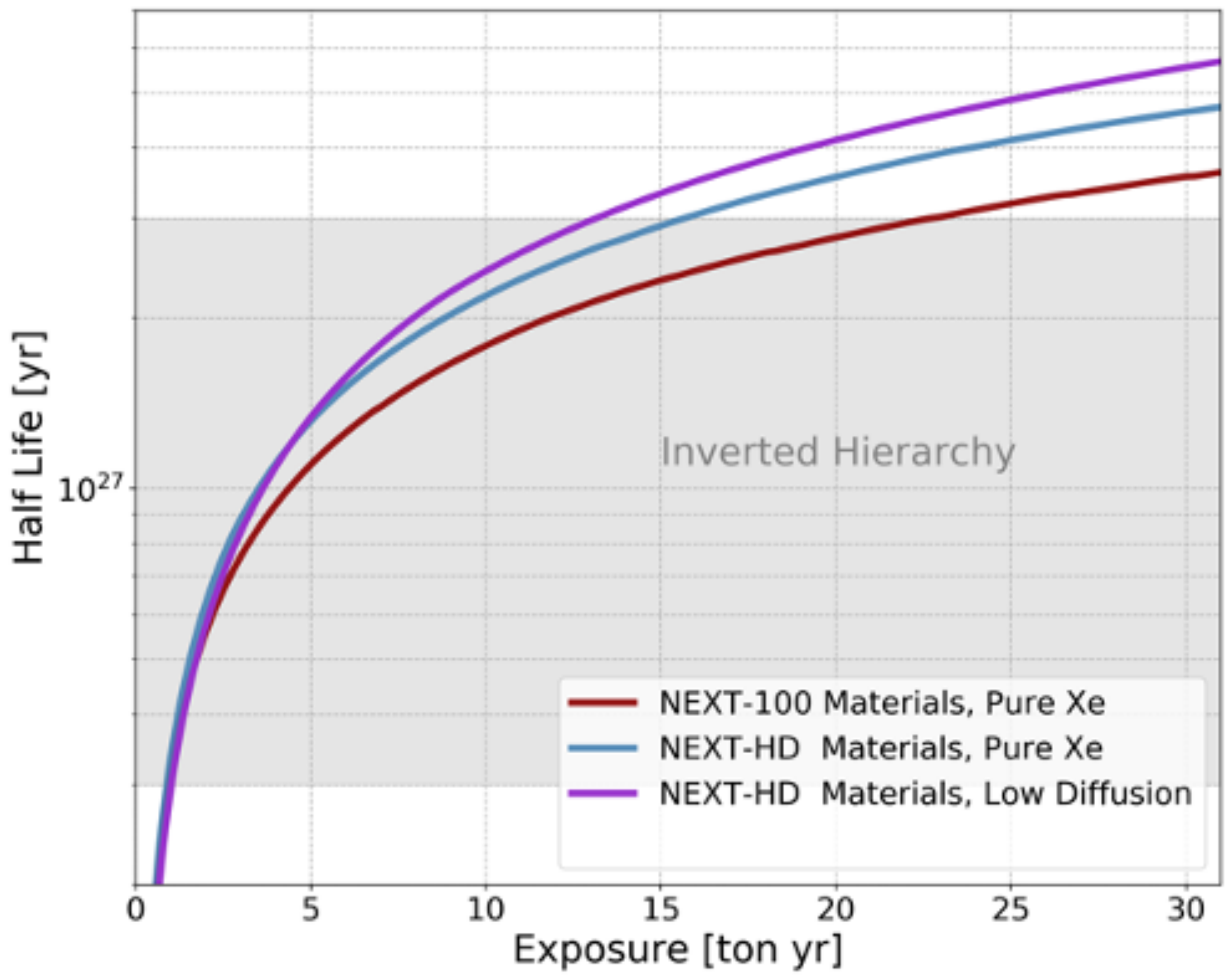
Sensitivity

First module at LSC

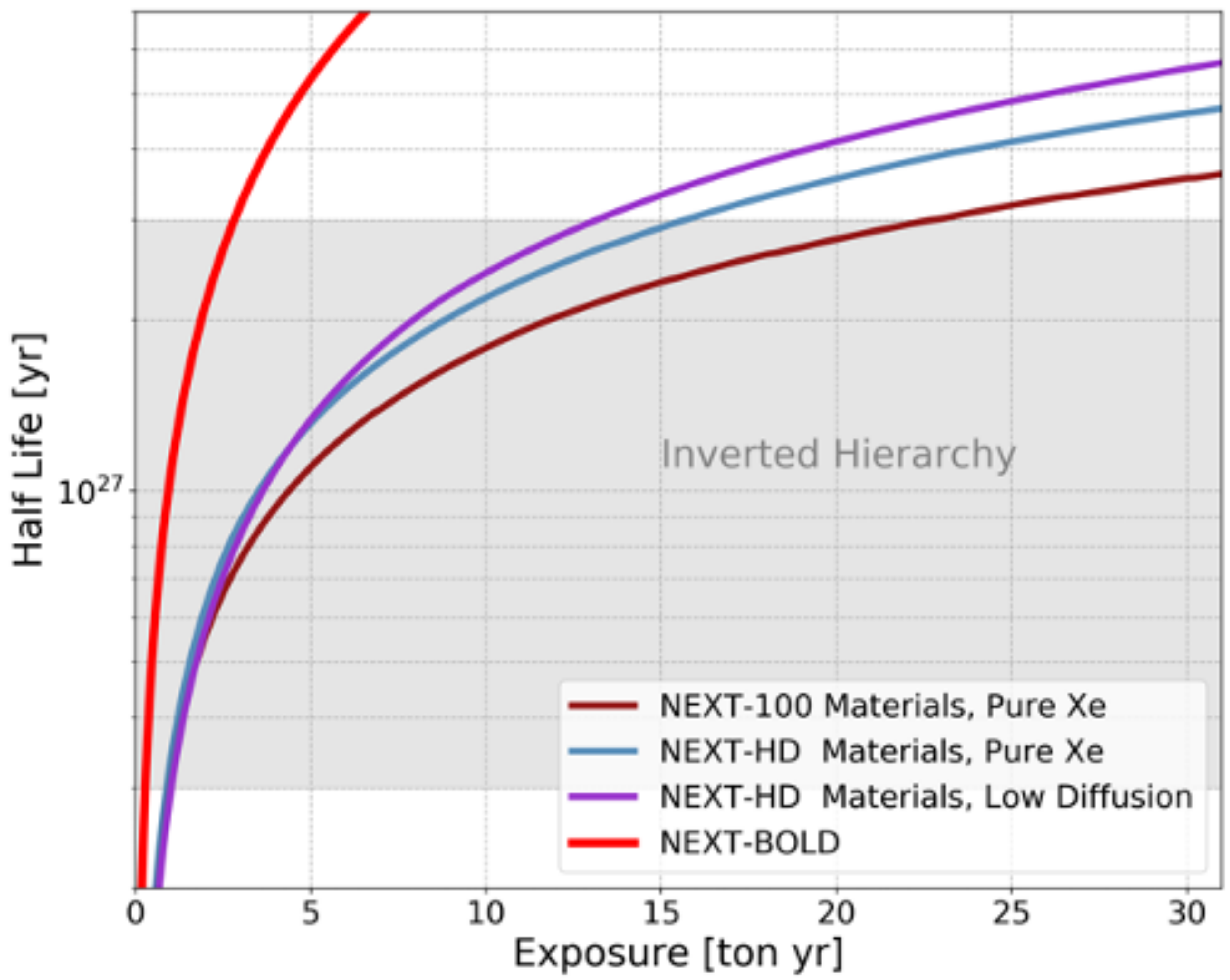


Large exposure sensitivity



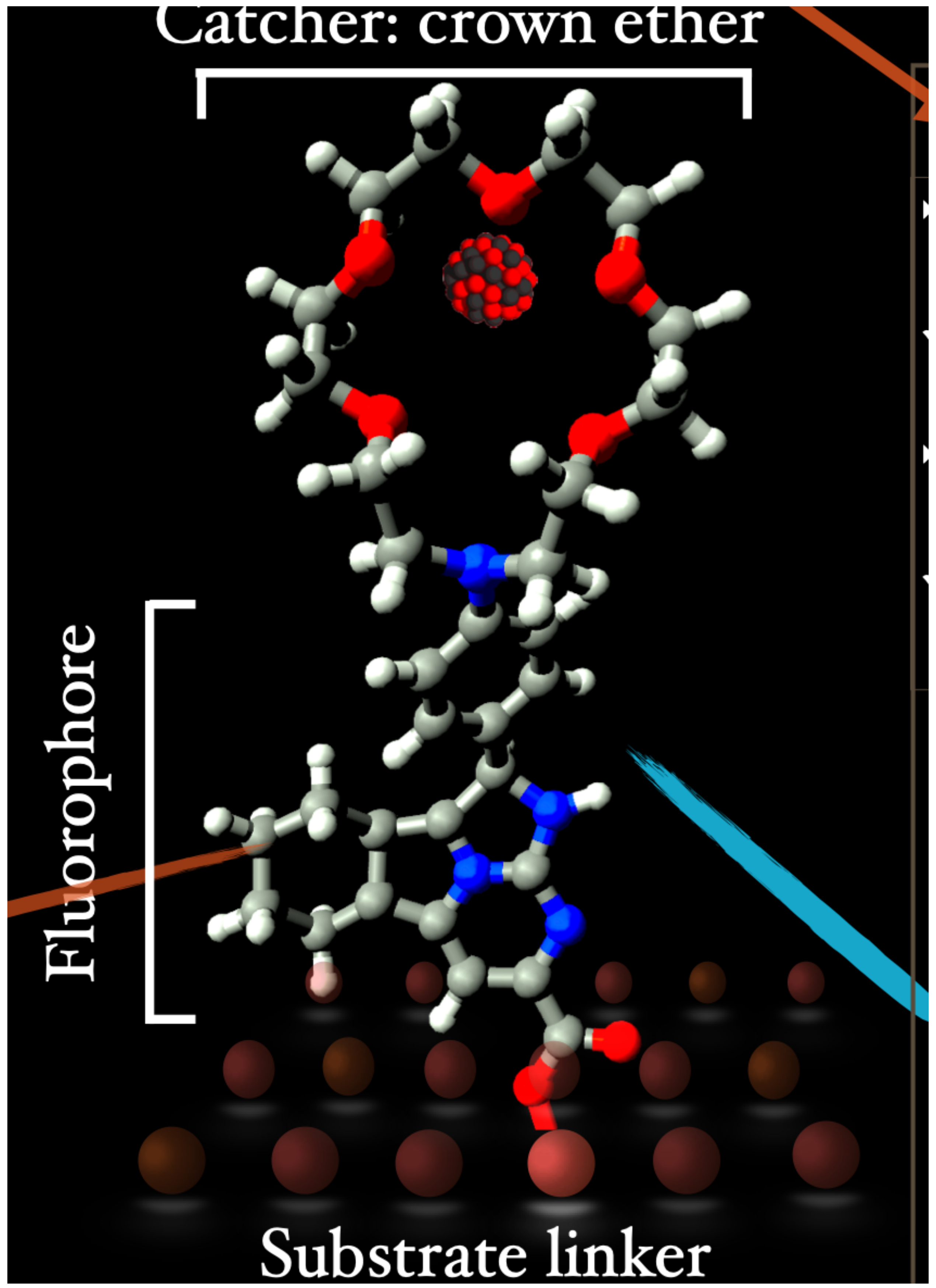
- NEXT-HD first module, proposed to operate at the LSC can reach 10^{27} years with 5 ton year exposure.
- Further modules (eventually with larger masses and operating deeper) can explore the region up to 10^{28} y.

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



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JINST 11 (2016) no.12, P12011

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

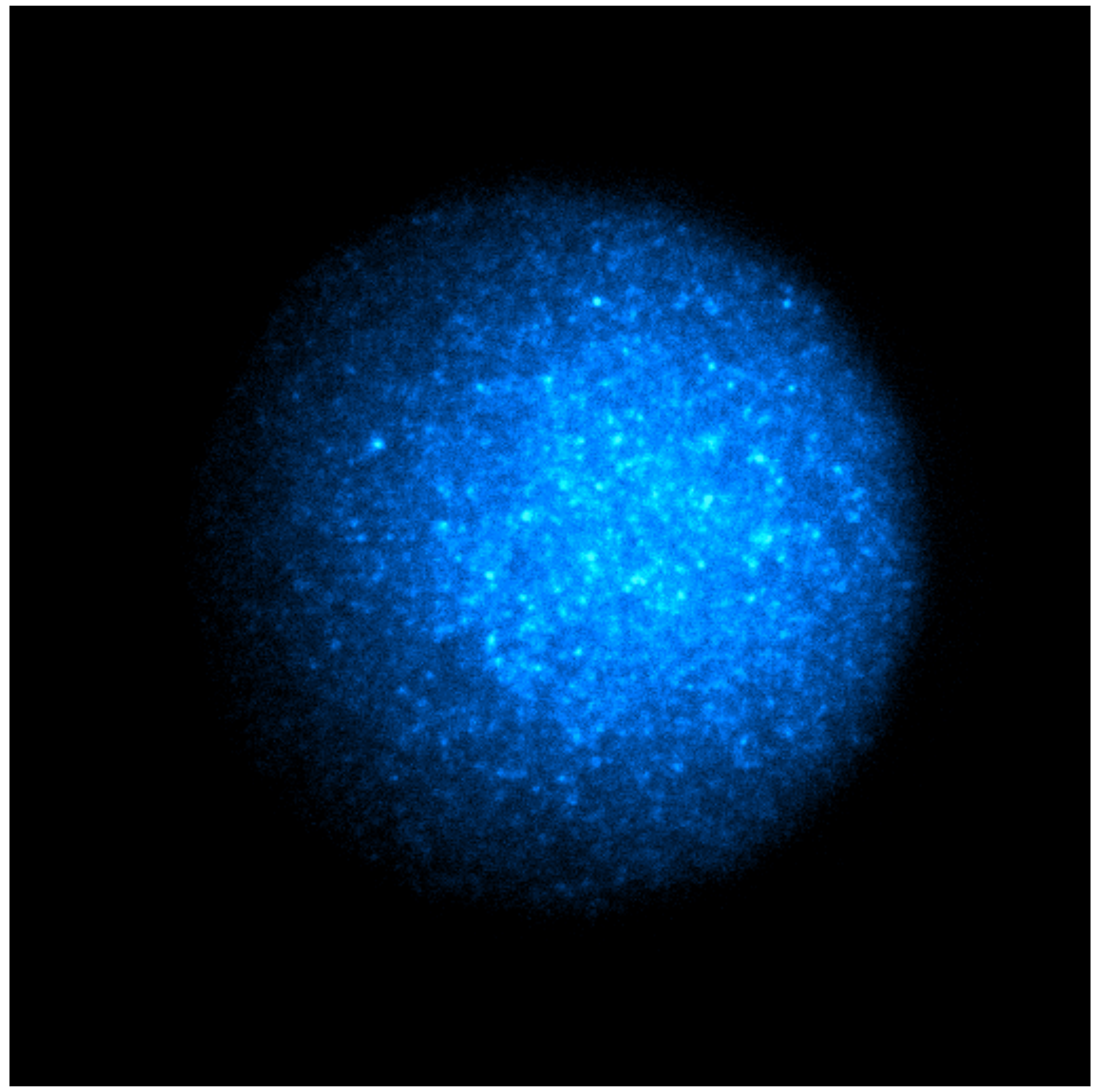
Sci Rep 9, 15097 (2019)

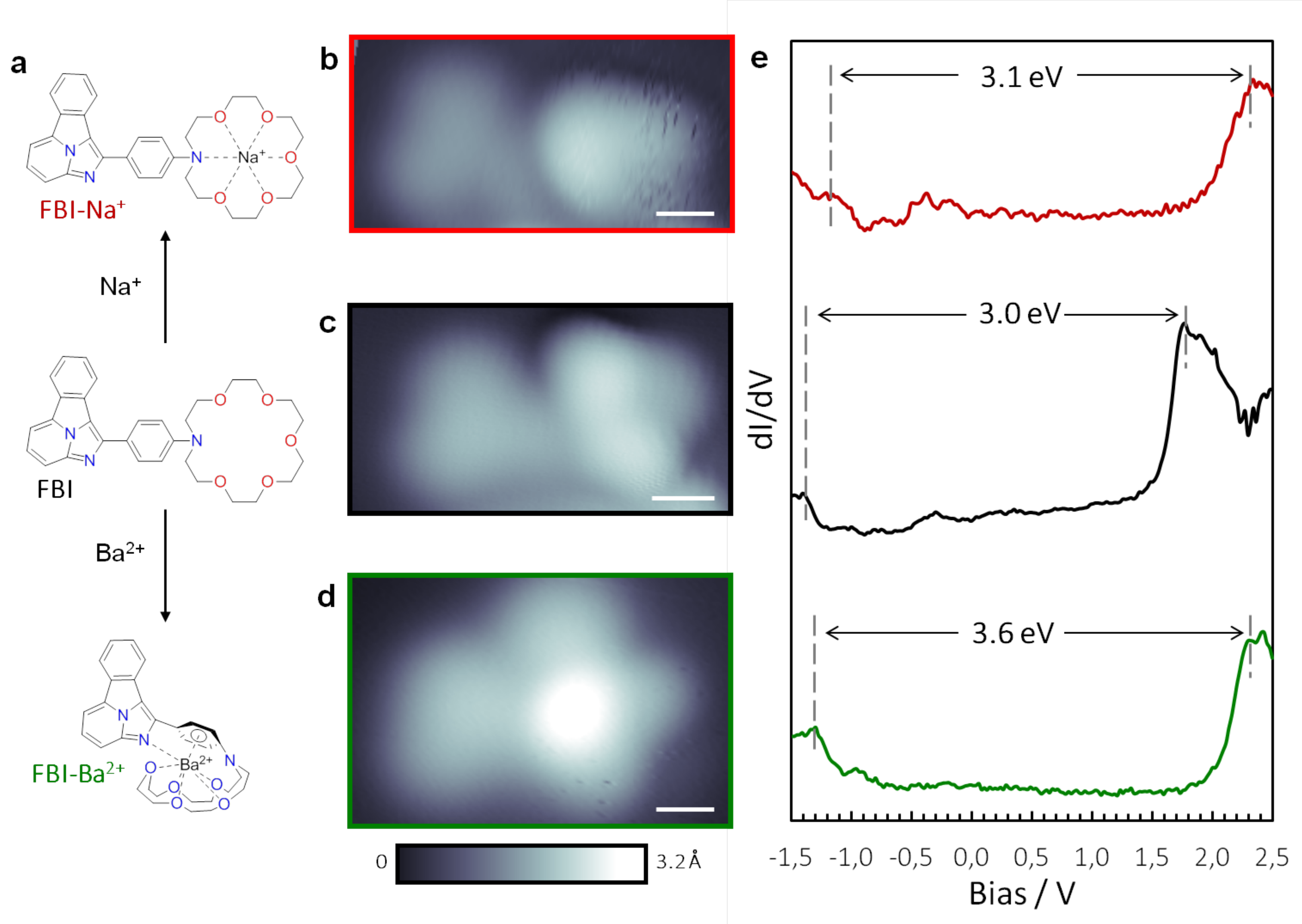
Nature 583, 48–54 (2020)

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).

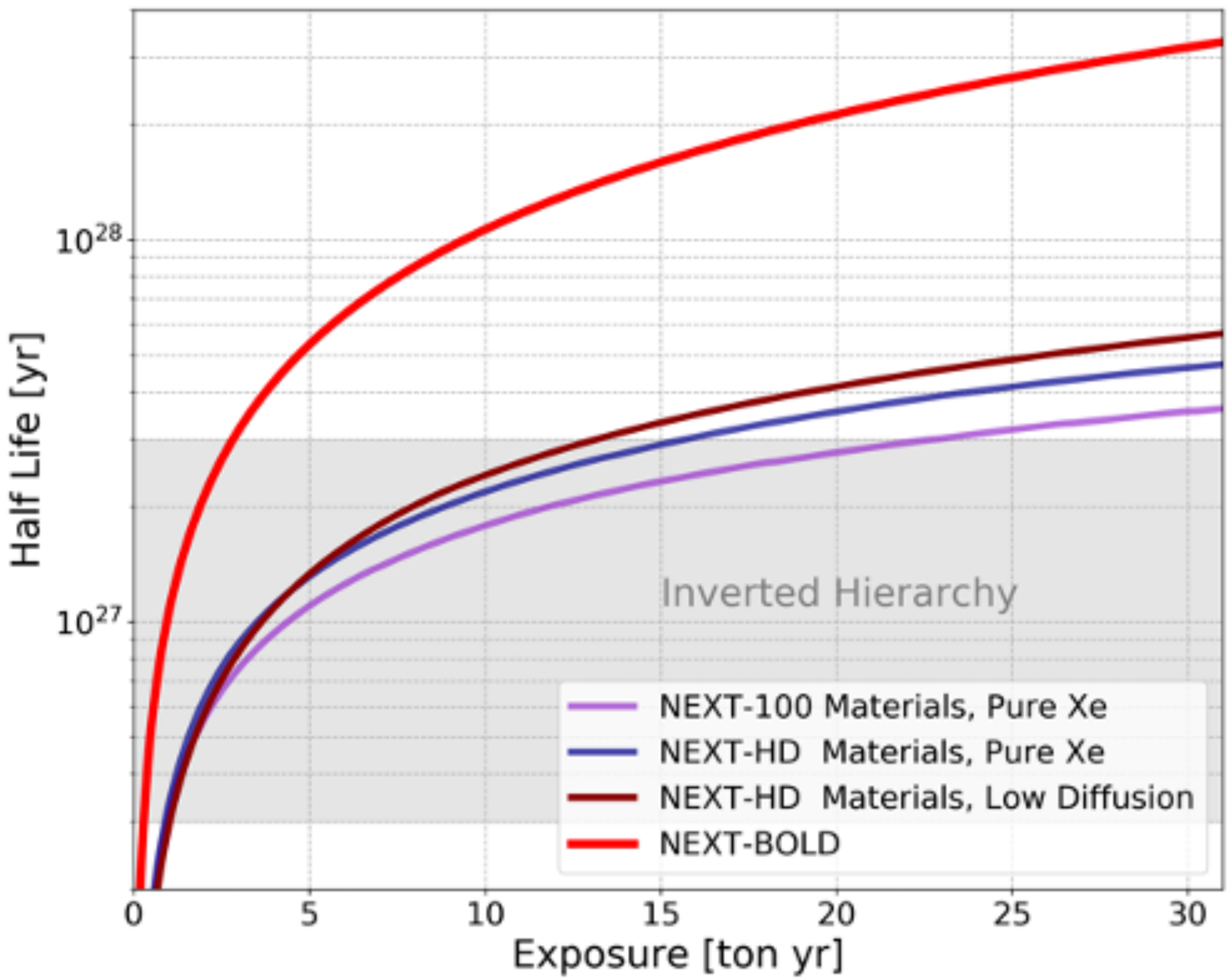
BOLD R&D program





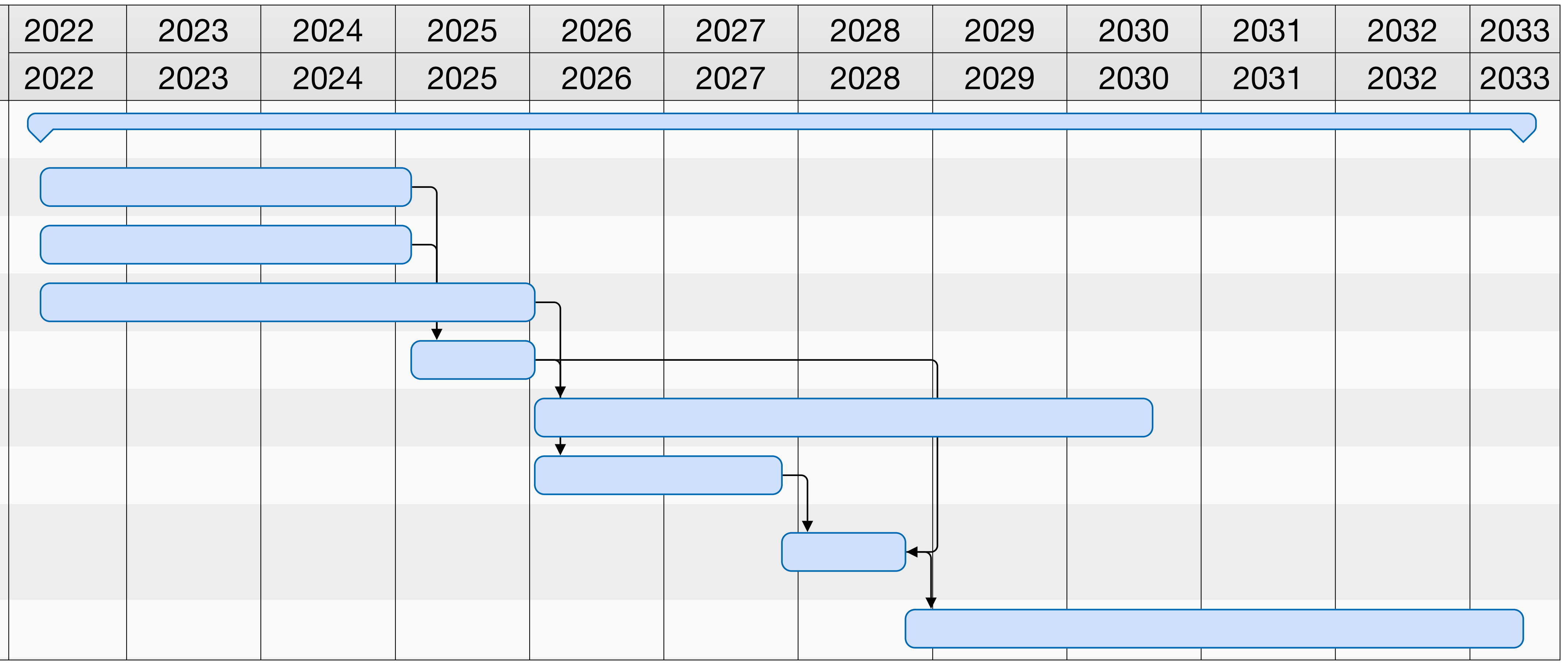
- Funded in the US (DOE Early Career Award, DOE Nuclear Physics Research Program, National Science Foundation, Welch Foundation) and in Europe (Synergy Grant ERC, Israel Science Foundation, ISF).
- Developed new “dry” chemistry, with several families of sensors able to capture Ba2+
- Developed high pressure 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.**

Outlook

- Cost of Xe-136 is uncertain: Estimation: **10 - 20 M€**. Notice: lower bound corresponds to the cost payed for NEXT-100.
- Water tank, copper shielding, pressure vessel, gas infrastructures: **5 M€**
- Detector: ~**5 M€**, cost dependes on DSP density.
- Total cost for operating 1st HD module: **20-30 M€**

- NEXT is an international collaboration, with institutions from Europe (including Israel), North and South America. Of course, plenty of opportunities for new groups interested in the program.
- Funding from several national agencies, with substantial contributions from Spain (Spanish ministry of science), Israel (ISF), US (DOE), and European Union (ERC).
- NEXT is the scientific flagship of the LSC laboratory. Involvement of LSC guarantees the development of infrastructures and the acquisition of Xe-136 (Notice that the Xe-136 used by NEXT-White and NEXT-100 is owned by LSC). It will contribute also with human resources.

- The first NEXT-HD module can be followed by a detector implementing Barium Tagging (BOLD) and/or by further HD/BOLD modules which can operate at several underground laboratories. **NEXT offers the potential of a multi-module, multi-site experiment.**