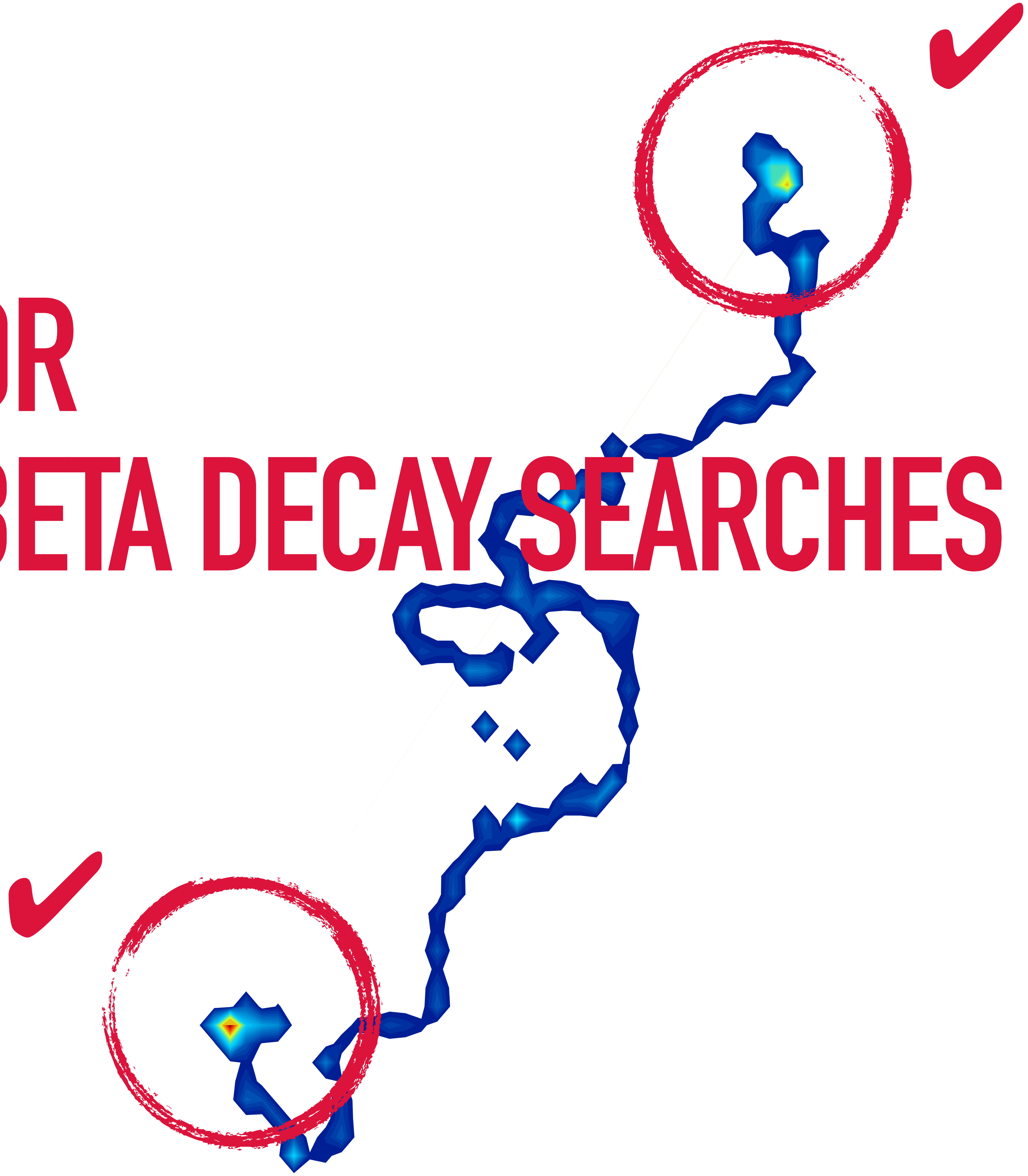
THE NEXT EXPERIMENT FOR NEUTRINOLESS DOUBLE BETA DECAY SEARCHES



Justo Martín-Albo
Instituto de Física Corpuscular (IFIC)

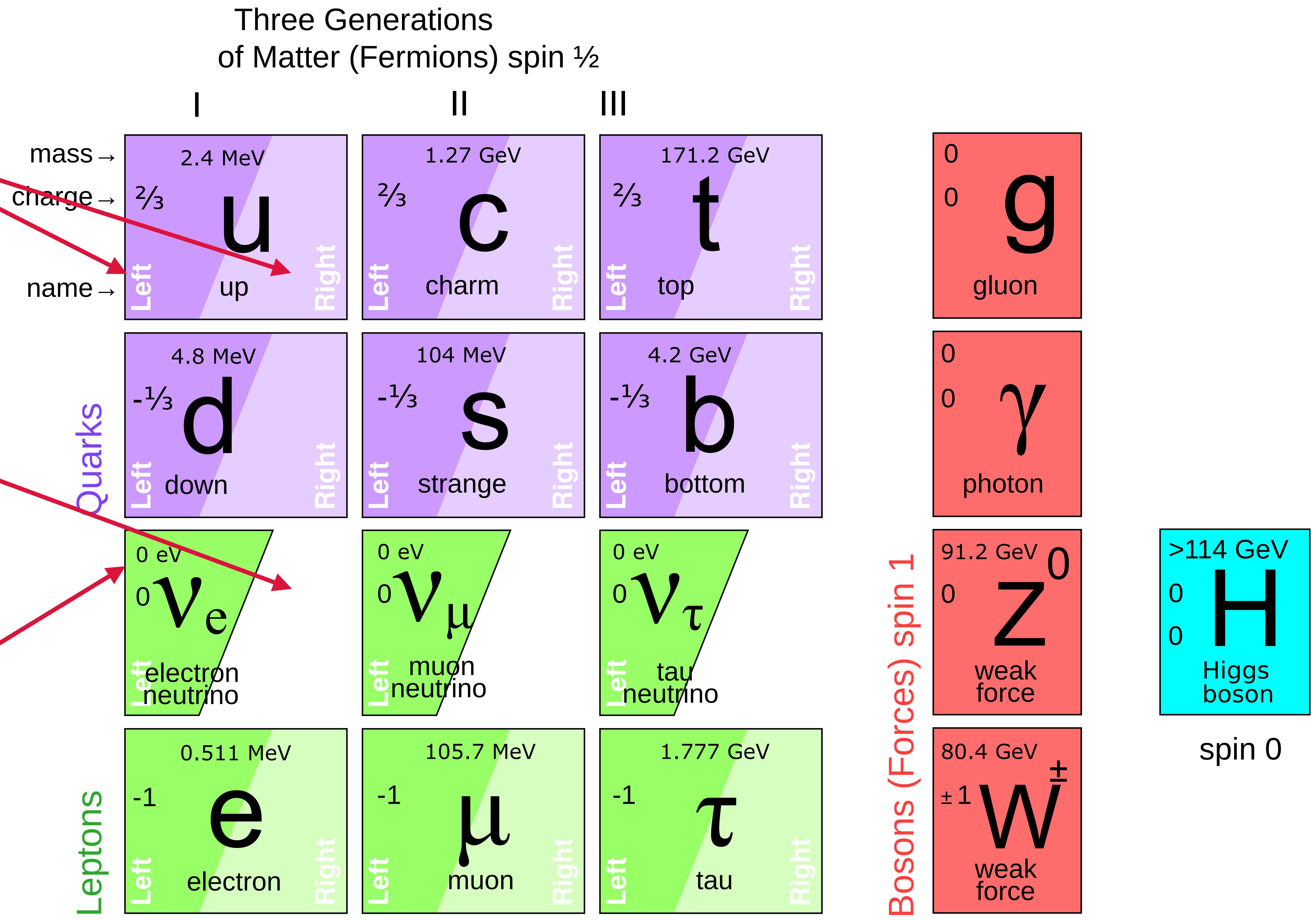
HEP Seminar, University of Liverpool | 15 July 2020

NEUTRINOS IN THE STANDARD MODEL

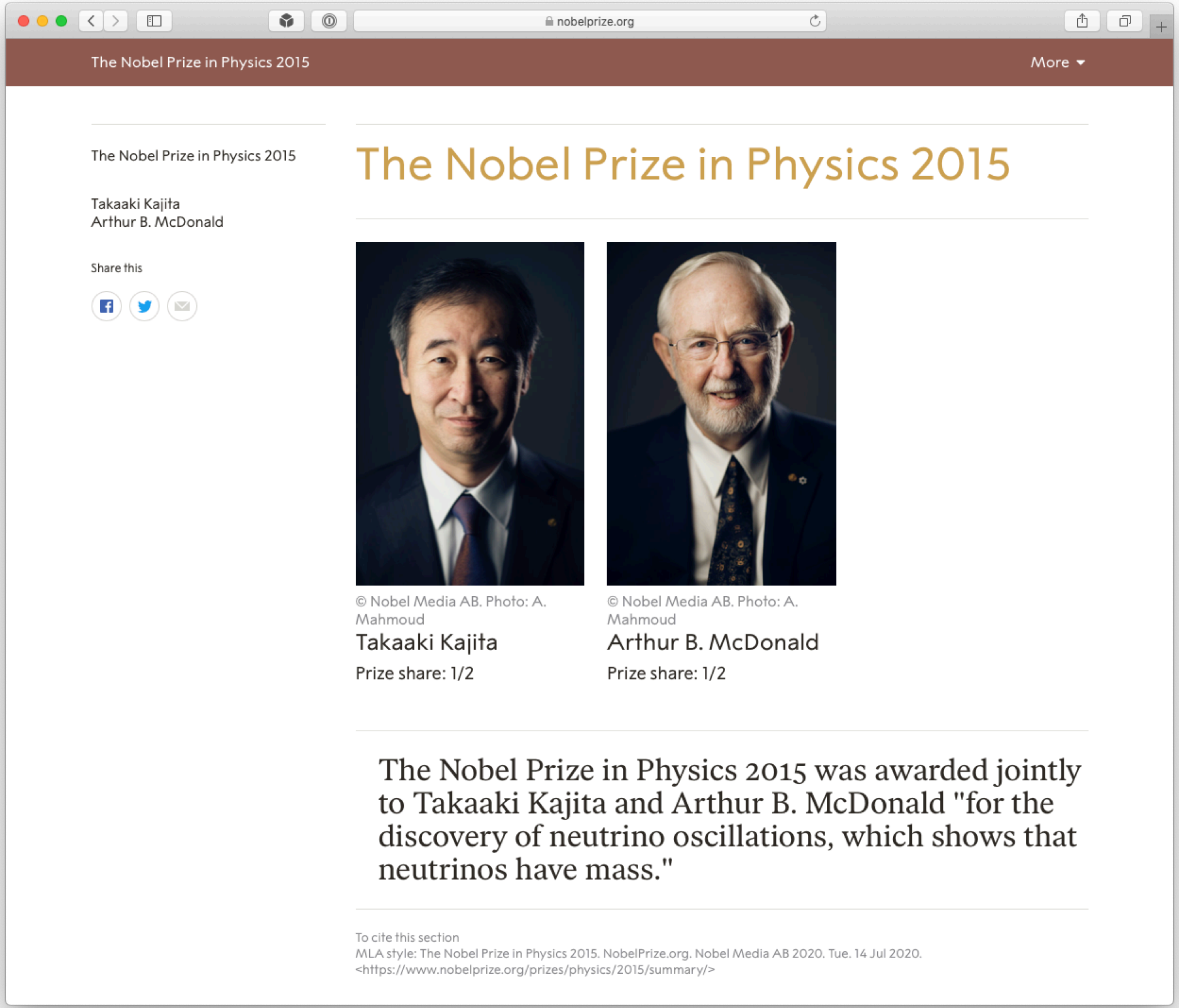
Fermion masses arise from the couplings of their left-handed and right-handed fields to the Higgs field.

The Standard Model does not contain right-handed neutrino fields (they'd be sterile, since they can't couple to the W weak boson).

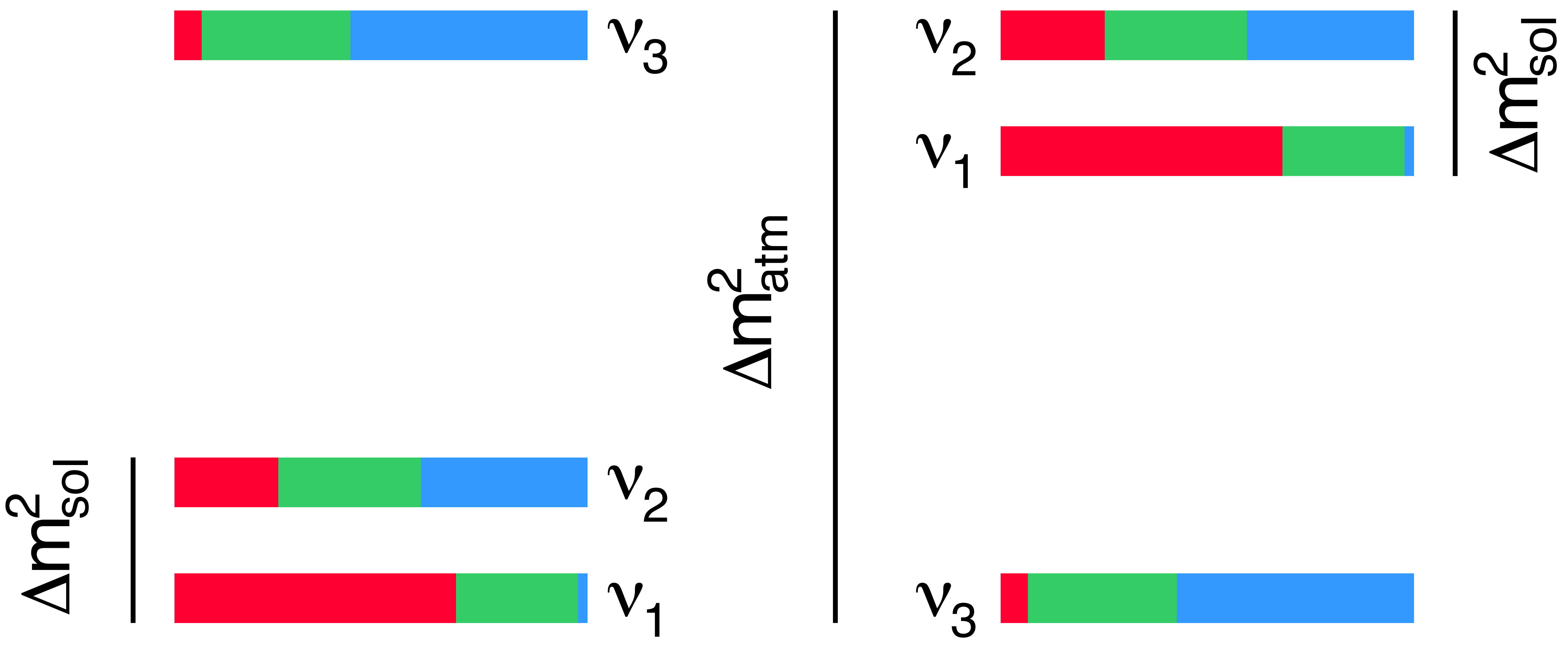
Therefore, neutrinos are left **massless** in the Standard Model.



NEUTRINO OSCILLATIONS

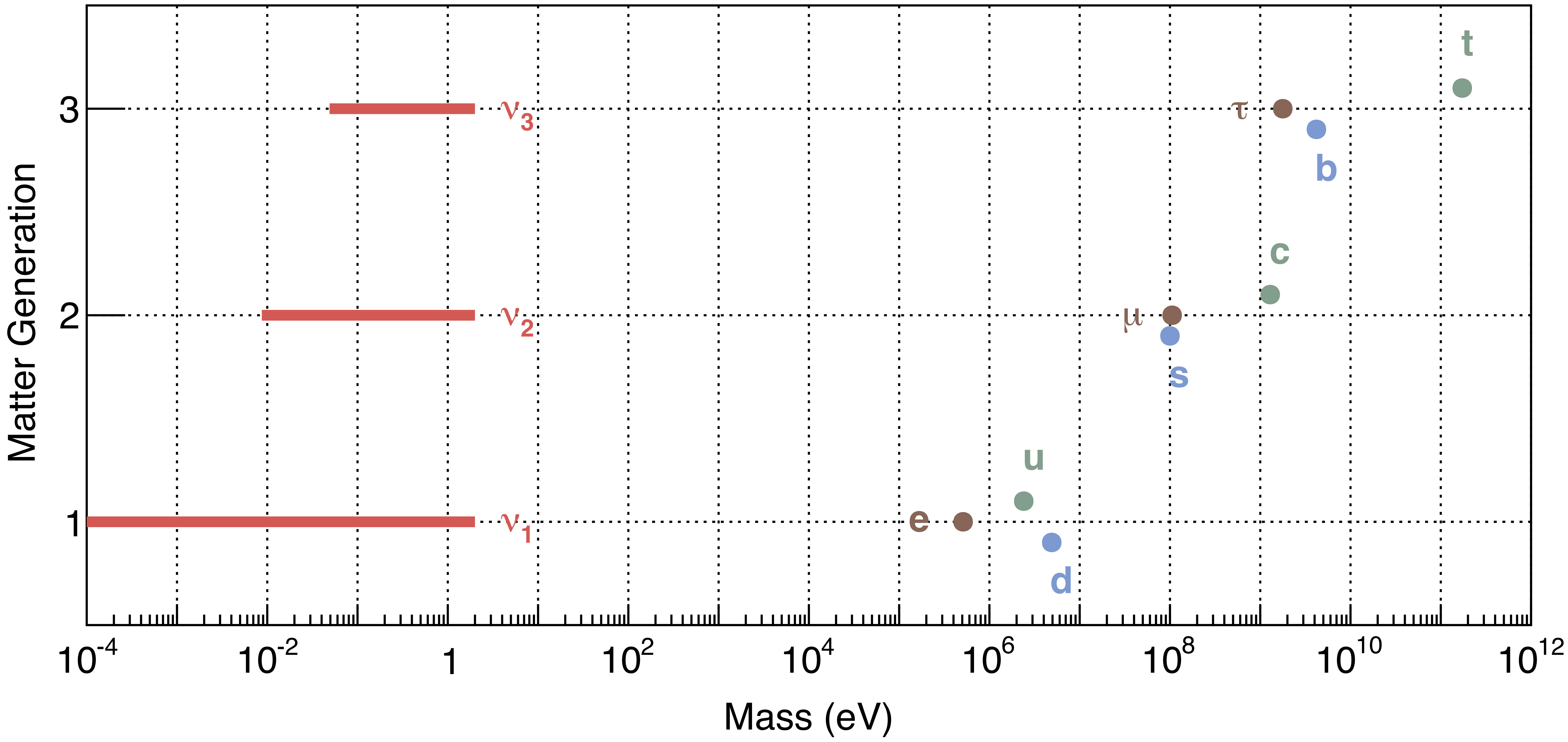


NEUTRINO MASSES AND MIXING



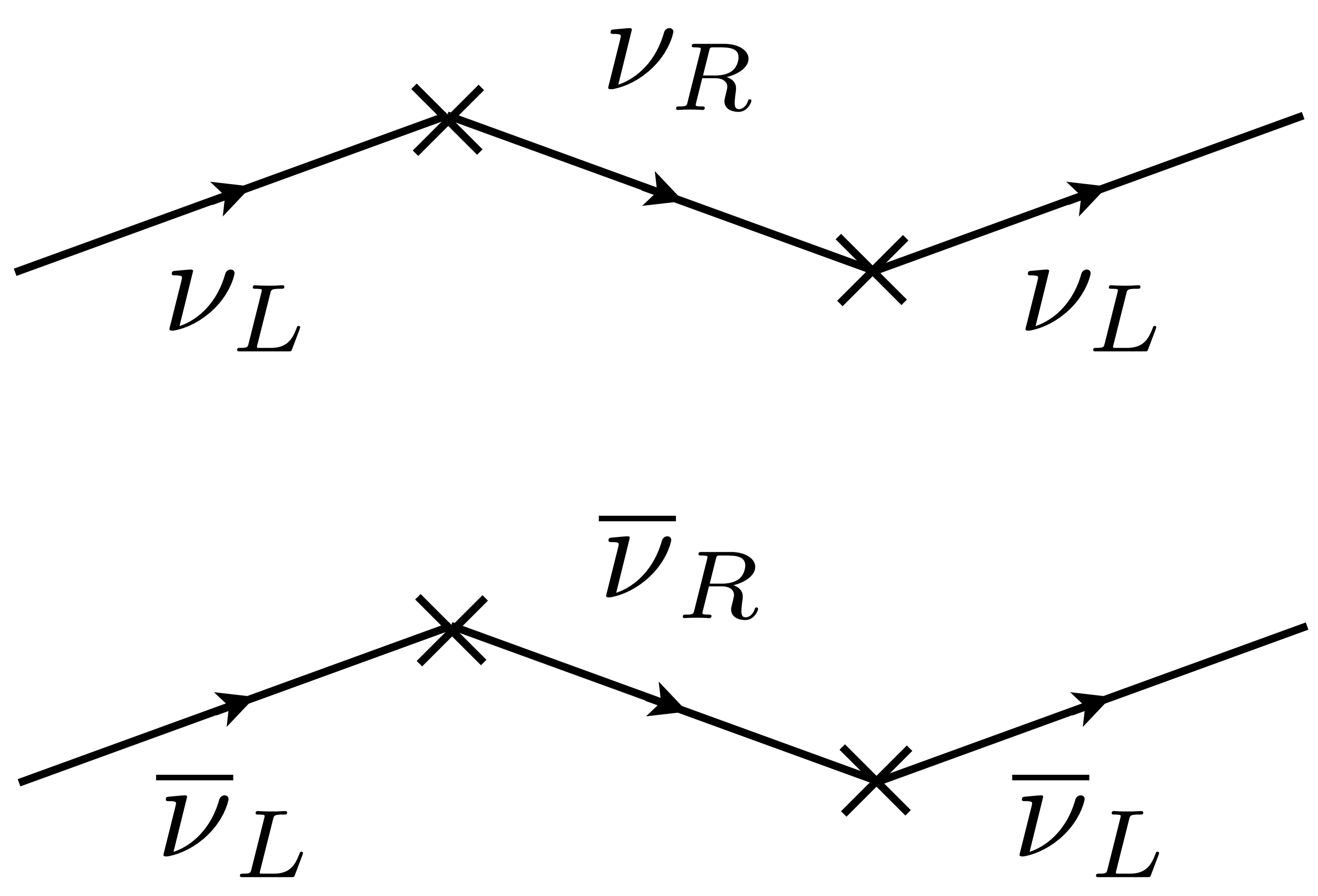
Oscillation experiments have established that neutrinos are massive particles and that the neutrino states participating in the weak interaction (*flavour eigenstates*) are different from the states controlling free-particle evolution (*mass eigenstates*).

FERMION MASS SPECTRUM

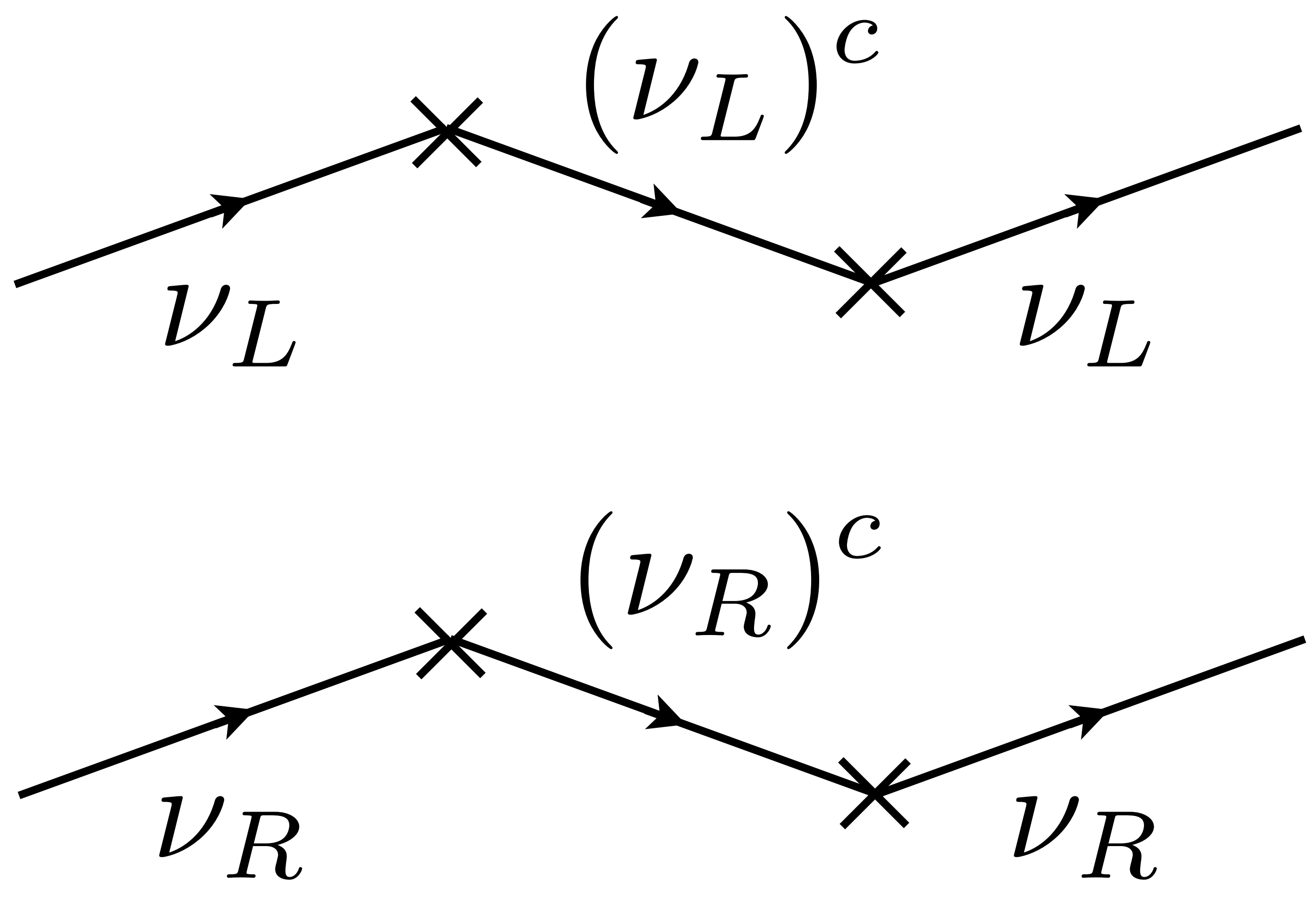


RECIPES FOR A NEUTRINO MASS

Dirac mass term



Majorana mass term



RECIPES FOR A NEUTRINO MASS

Dirac mass term

$$-\mathcal{L}_{\mathrm{D}} = m_\nu \, \overline{\nu_L} \, \nu_R + \mathrm{H.c}$$

- Mass term analogous to those of charged leptons.
- Sterile right-handed fields added to SM.
- Conserves lepton number.

Majorana mass term

$$-\mathcal{L}_{\mathrm{M}} = m_\nu \, \overline{\nu_L} \, \nu_L^c + \mathrm{H.c}$$

- Requires an expanded Higgs sector.
- Implies lepton number violation.
- Neutrinos and antineutrinos are identical.

RECIPES FOR A NEUTRINO MASS

Dirac mass term

$$m_\nu \sim y_\nu\, v$$

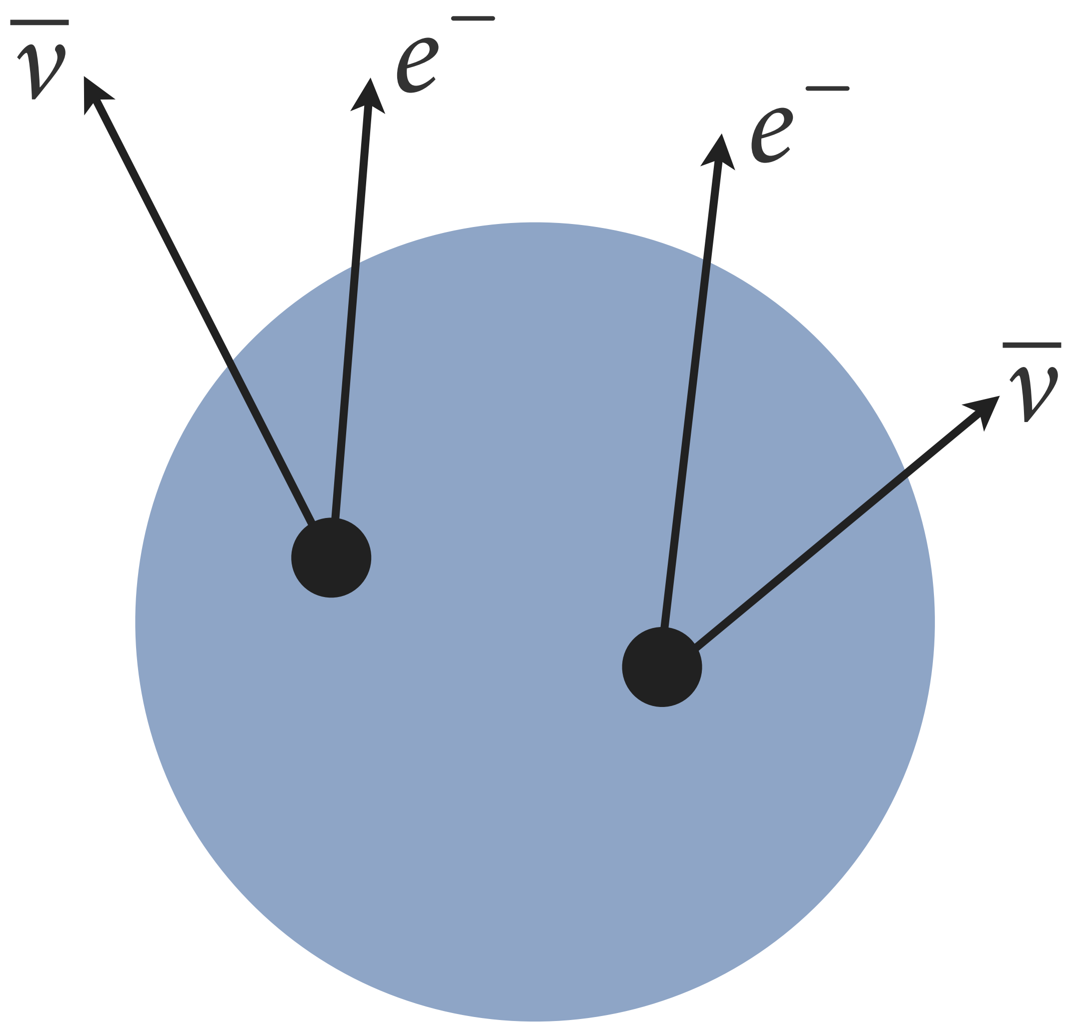
- Mass proportional to Higgs VEV.
- Very small couplings (unexplained) needed to account for observed neutrino masses.

Majorana mass term

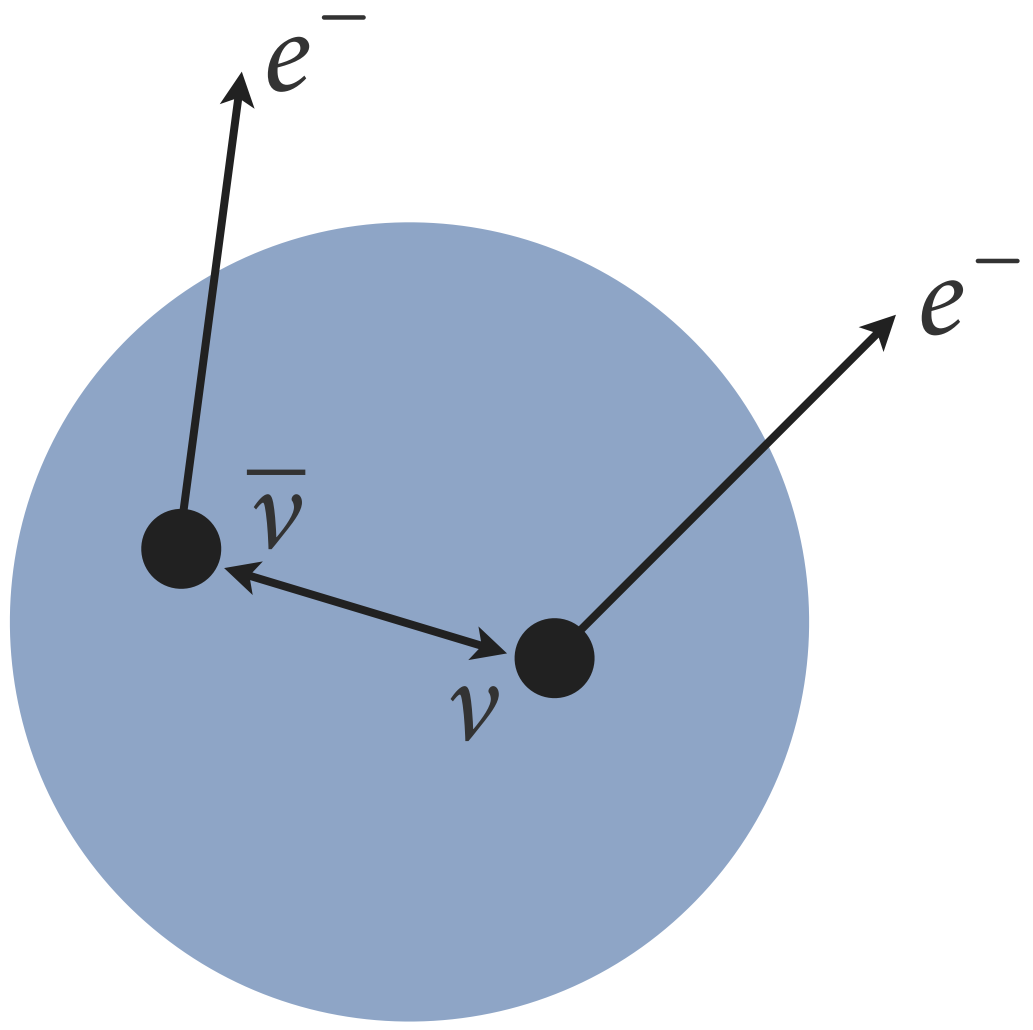
$$m_\nu \sim y_\nu\, v^2/M$$

- Hint of a new physics scale responsible for the strong hierarchy between neutrino and charged-lepton masses (cf. Weinberg operator and seesaw mechanism).

DOUBLE BETA DECAY



$2\nu\beta\beta$

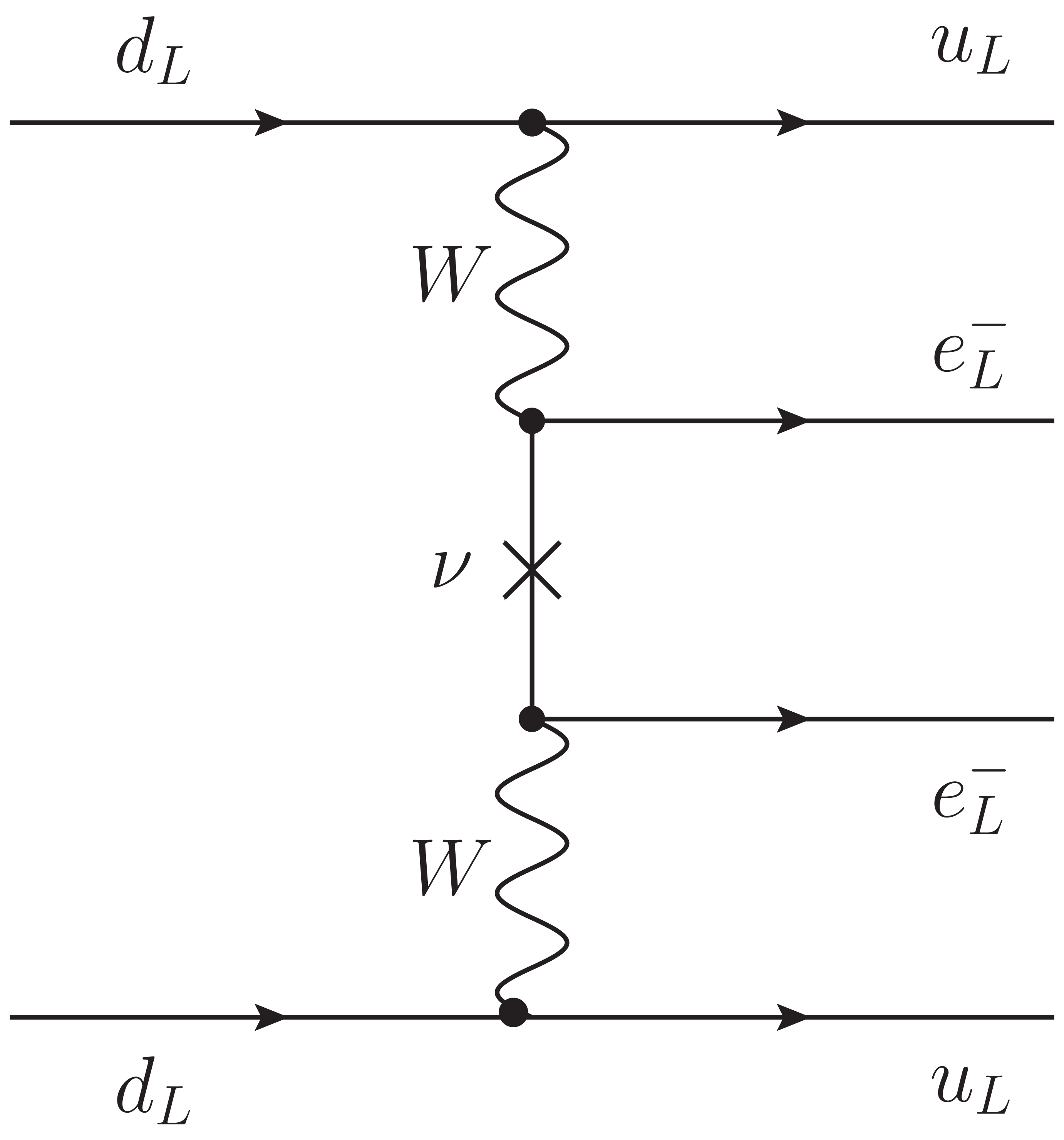


$0\nu\beta\beta$

SM-allowed process. Observed in several isotopes with half-lives of order 10^{18}–10^{22} years.

Forbidden in SM. Violates total lepton number (ΔL=2). Half-life longer than 10^{25} years.

DOUBLE BETA DECAY AND MAJORANA NEUTRINOS



The simplest underlying mechanism for neutrinoless double beta decay is the virtual exchange of a light Majorana neutrino. However, irrespectively of the mechanism, the existence of neutrinoless double beta decay implies a Majorana mass term for neutrinos.

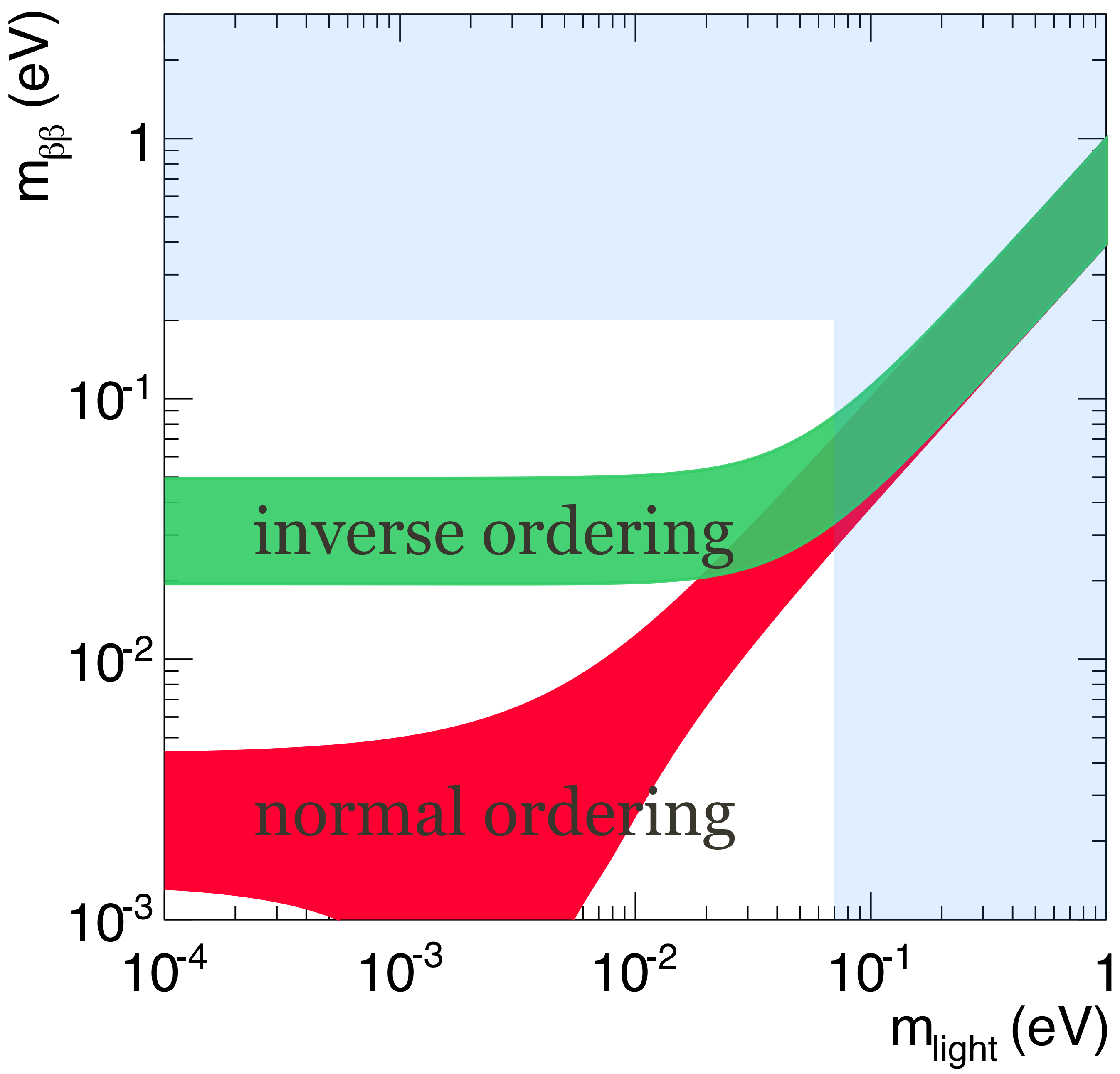
DECAY RATE

Nuclear matrix element
(nuclear physics)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\ \left|M^{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Phase-space integral
(atomic physics)

Effective Majorana mass
(particle physics)



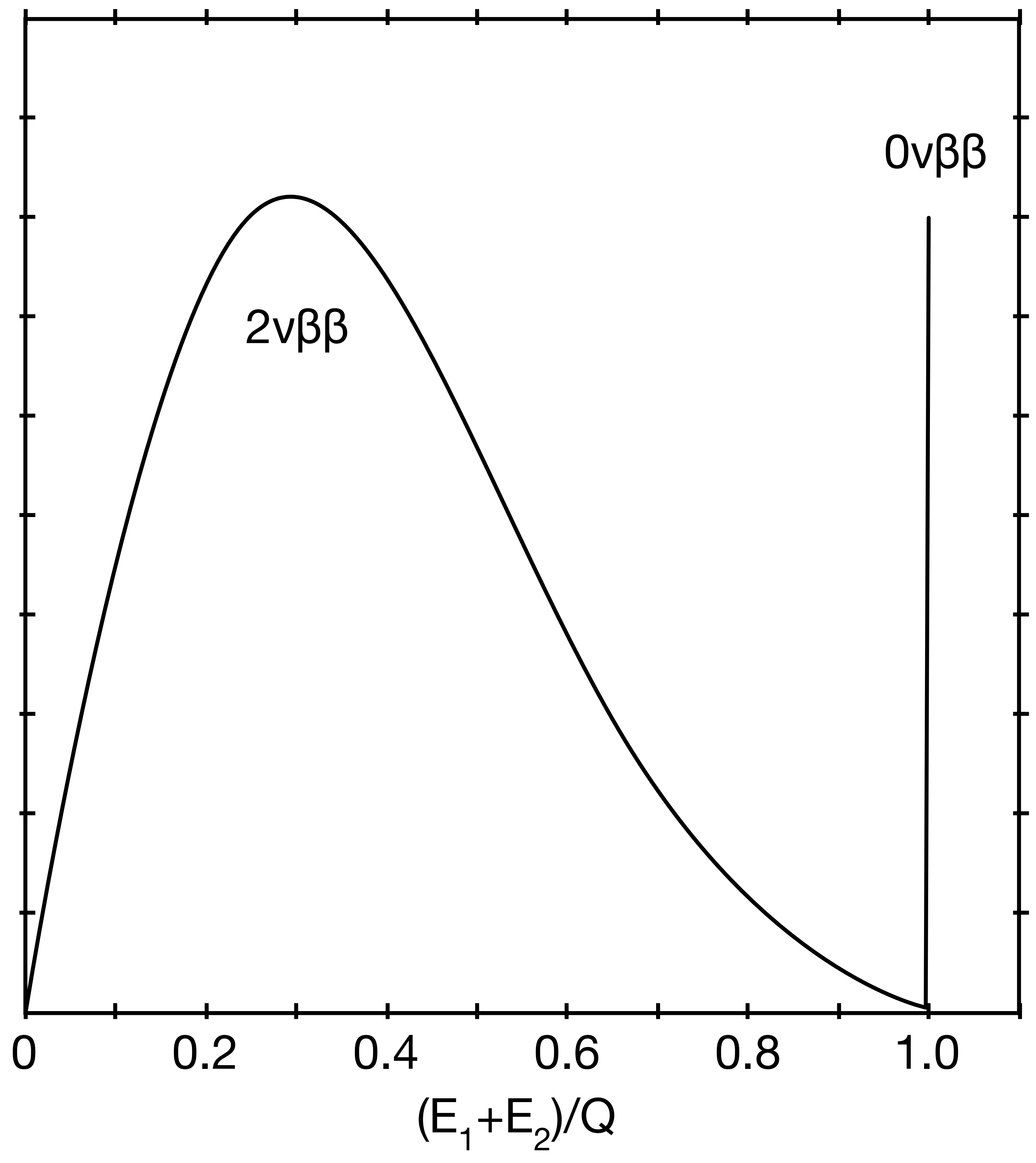
$$m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2\ m_i\right|$$

(If light neutrino exchange is the dominant underlying mechanism.)

BUILD YOUR OWN EXPERIMENT

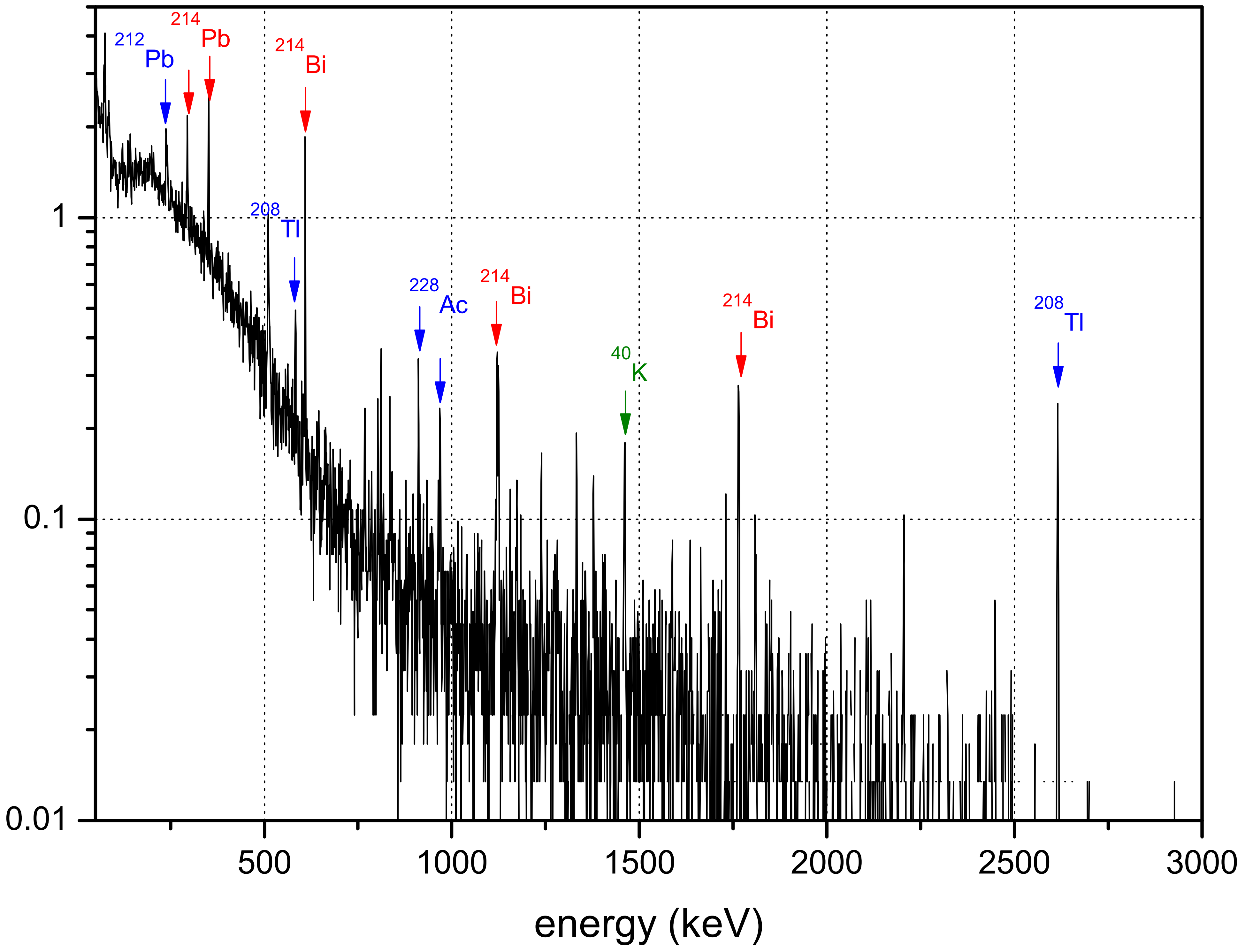
1. Acquire a large mass (M) of a double-beta emitter and a calorimeter with perfect resolution and efficiency.
2. Measure the energy of the radiation emitted by the source to separate the two double beta decay modes.
3. Count the number of neutrinoless decays (N) that have occurred in a given time (t) and calculate the corresponding half-life:

$$T_{1/2} = \log 2 \, \frac{N_A}{W} \, \frac{M\,t}{N}$$



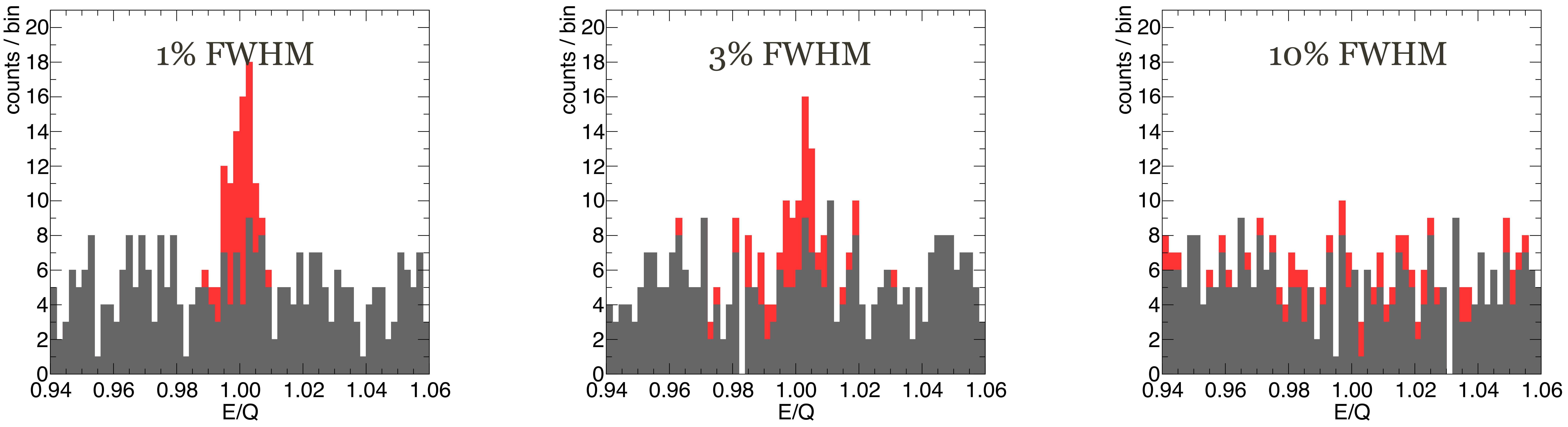
BACKGROUNDS

NEXT Collaboration (Álvarez et al.), *JINST* **8** (2013) T01002



Natural radioactivity is the most common background for neutrinoless double beta decay experiments. The figure shows a typical energy spectrum of a high-purity germanium calorimeter.

ENERGY RESOLUTION

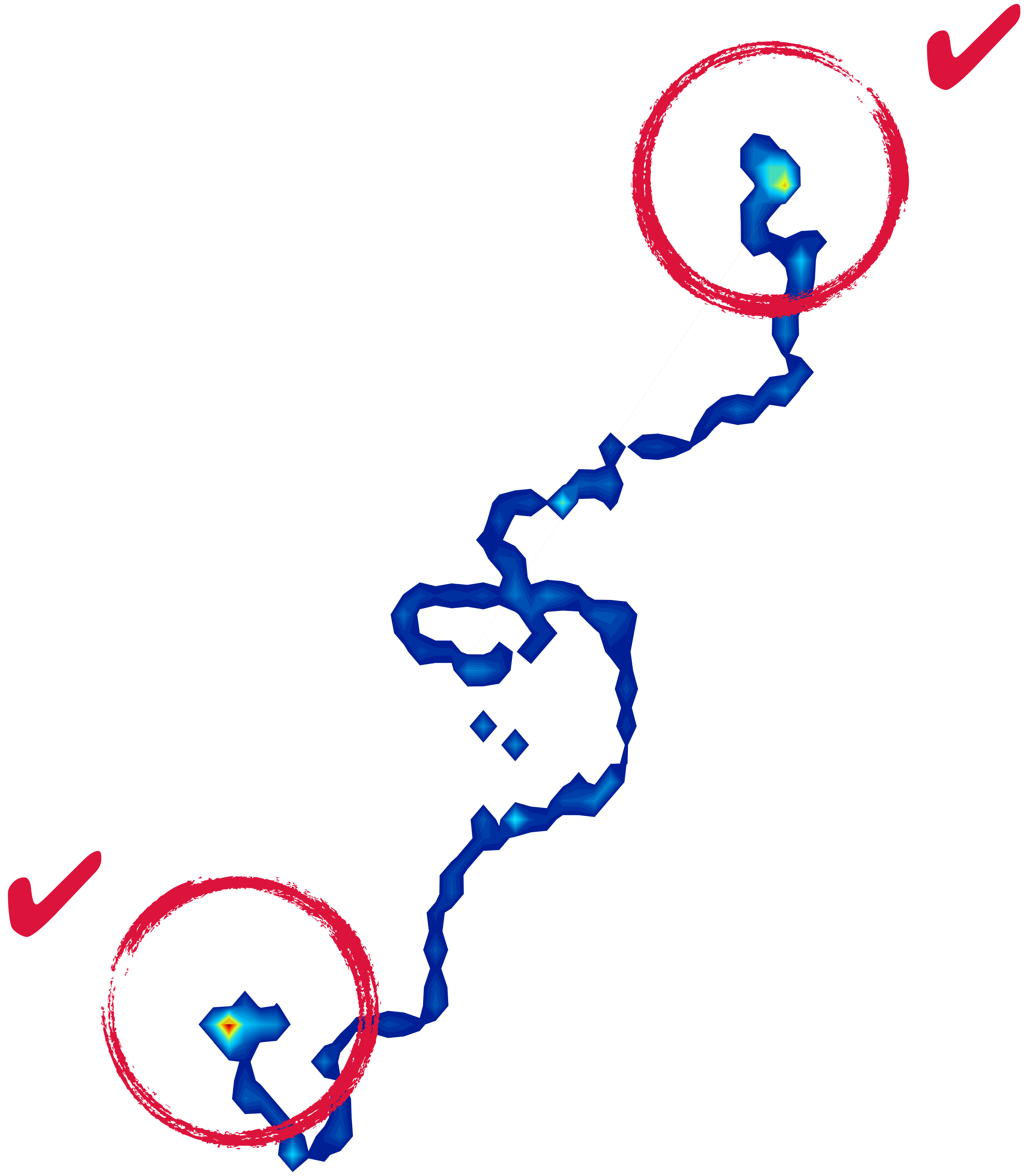


Good energy resolution is essential: it increases the signal to noise ratio and is the only protection against the standard two-neutrino decay mode.

RADIOPURITY

Detectors are being built with materials with activities as low as 10^{-6} Bq/kg.
(Compare that with typical activity of human body of about 100 Bq/kg.)

EVENT IDENTIFICATION



All experiments look for extra signatures (e.g. event topology or pulse-shape discrimination) to differentiate signal and background events.

EXPERIMENTAL FIGURE OF MERIT

$$\mathcal{S}(m_{\beta\beta}) \propto \sqrt{\frac{1}{\varepsilon M t}}$$

Background-free experiment

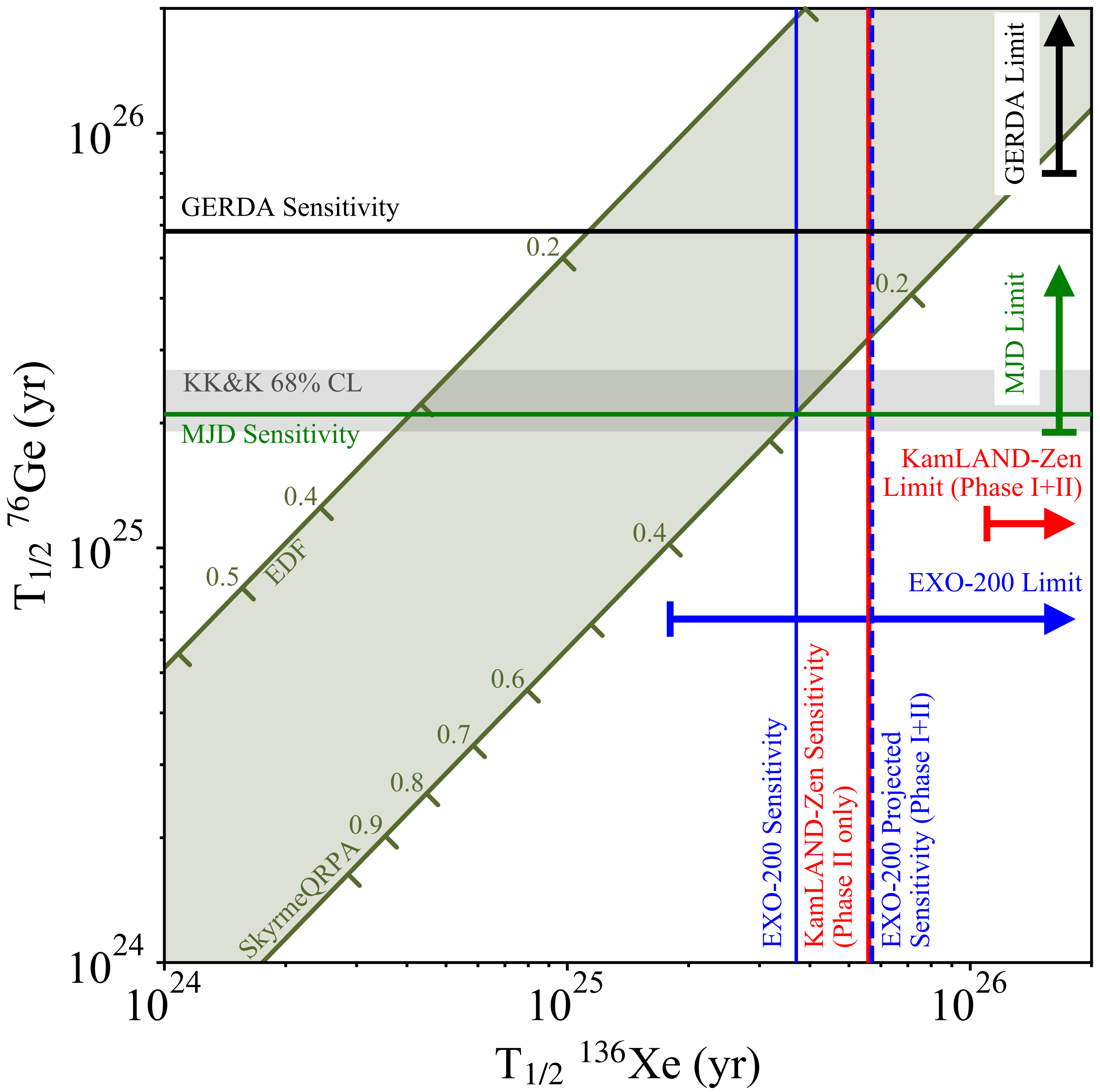
$$\mathcal{S}(m_{\beta\beta}) \propto \sqrt{1/\varepsilon} \left(\frac{b \, \Delta E}{M \, t}\right)^{1/4}$$

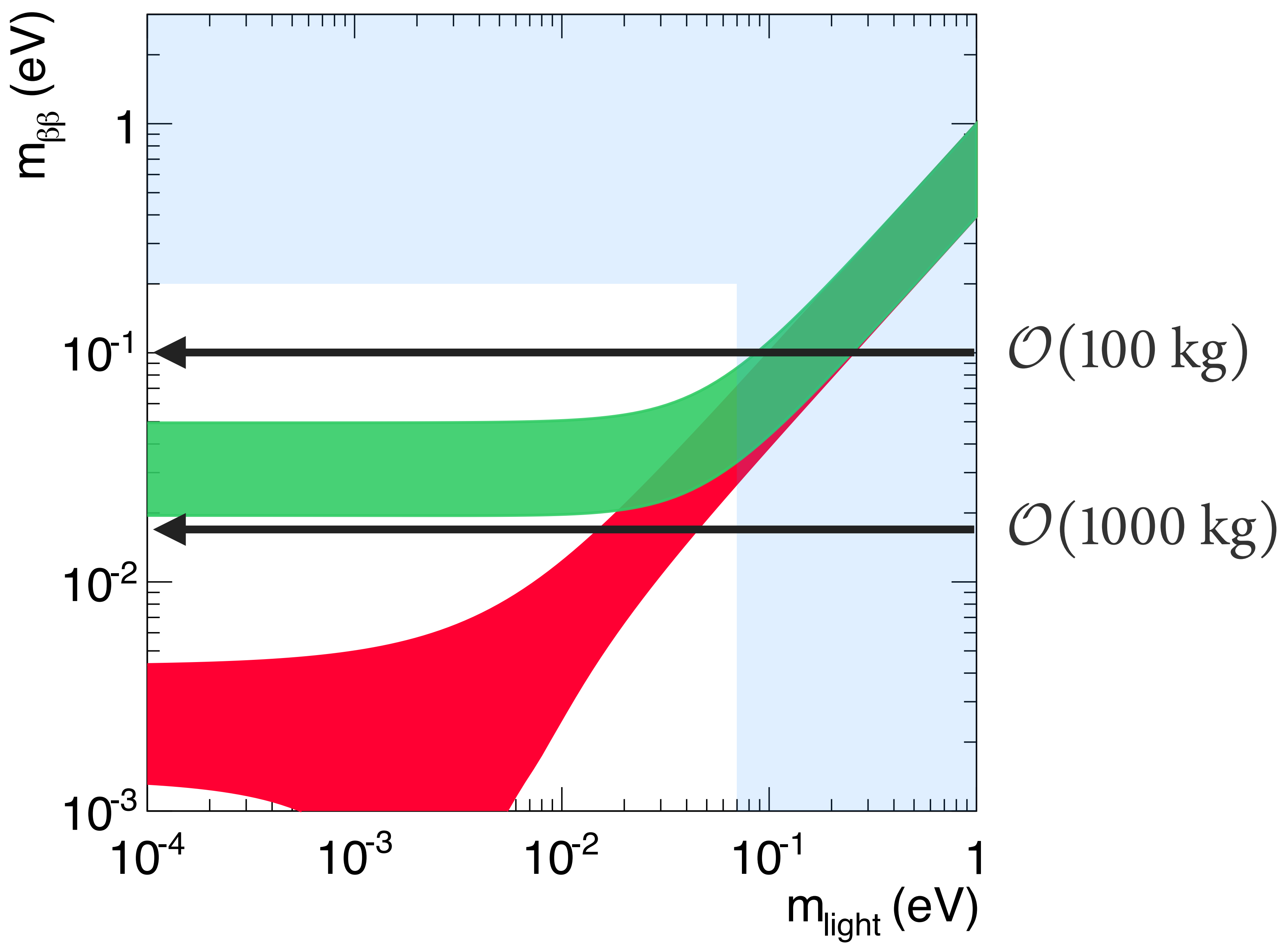
Background-limited experiment

CURRENT EXPERIMENTAL STATUS

Current best limits to 0νββ half-life:

- KamLAND-Zen (^{136}Xe): >1.07×10^{26} years (90% CL).
- GERDA (^{76}Ge): >0.90×10^{26} years (90% CL).





CURRENT EXPERIMENTAL STATUS

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
Majorana Demonstrator	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

R&D | Construction | Operating | Complete


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

THE NEXT COLLABORATION

🇪🇸 DIPC • U. de Girona • IFIC • U. Autónoma de Madrid • U. de Santiago de Compostela • U. Politécnica de Valencia • U. de Zaragoza

🇺🇸 ANL • U. Texas at Arlington • FNAL • Harvard U. • Iowa State U. • LBNL • Texas A&M U.

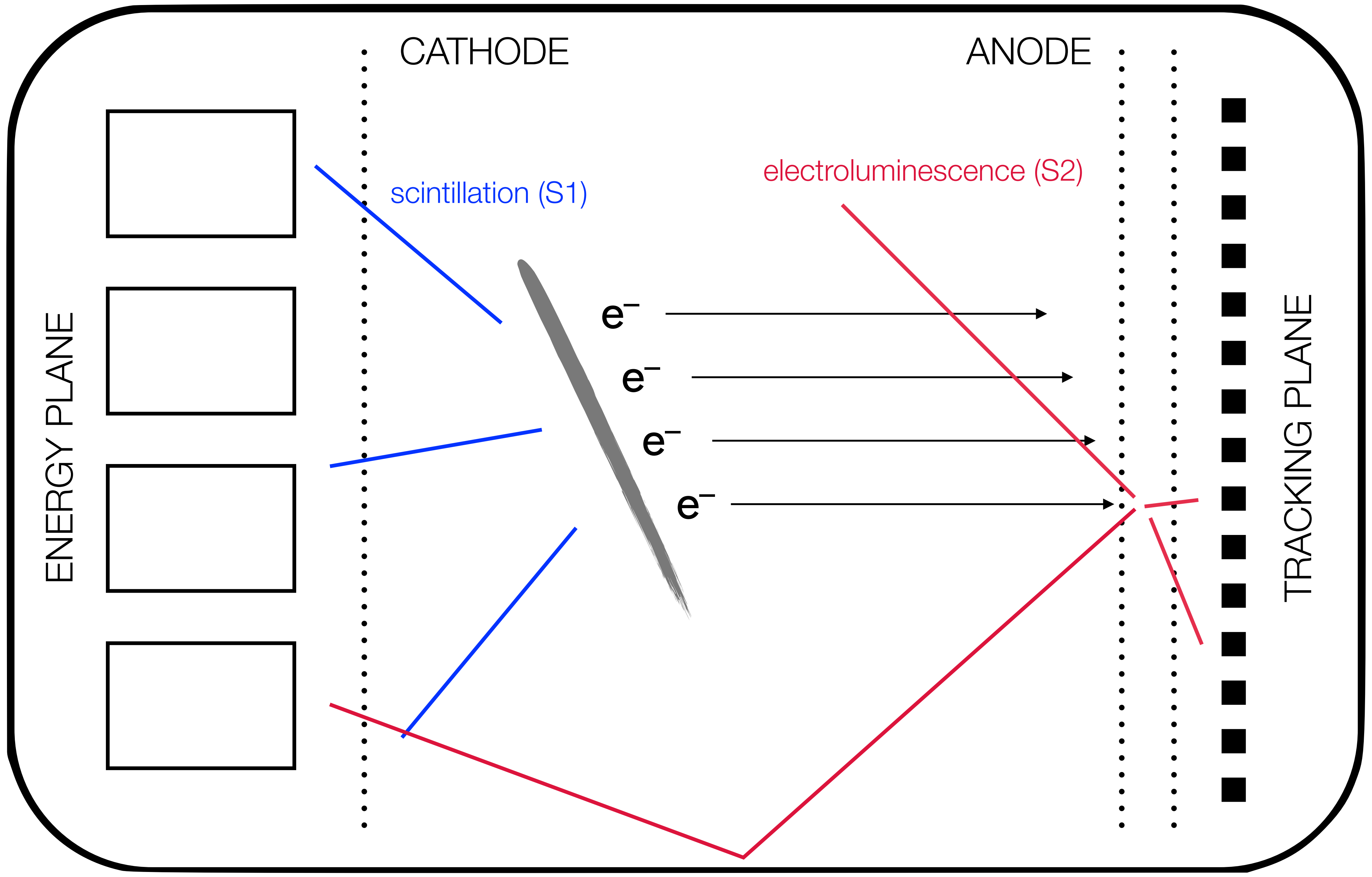
🇵🇹 U. de Aveiro • U. de Coimbra

🇮🇱 Ben-Gurion U. of the Negev

🇨🇴 U. Antonio Nariño

Co-Spokespeople: Prof. J.J. Gómez Cadenas (DIPC)
Prof. D. R. Nygren (UTA)

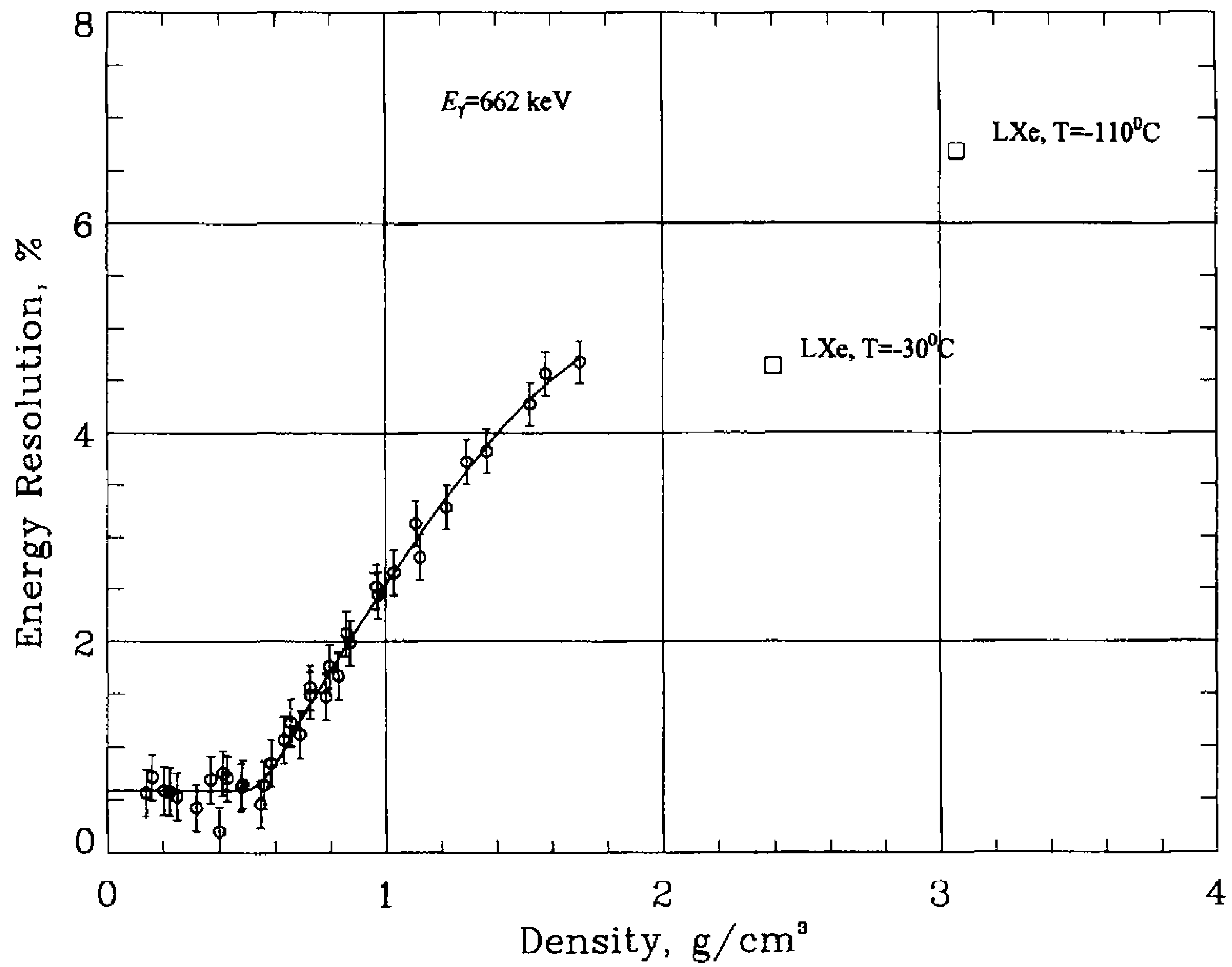
DETECTOR CONCEPT



Xenon gas time projection chamber with electroluminescent amplification.

- Primary scintillation (S1) establishes the start-of-event time.
- Secondary scintillation (S2) is used for calorimetry and tracking.
- Specialized sensor arrays for each measurement.

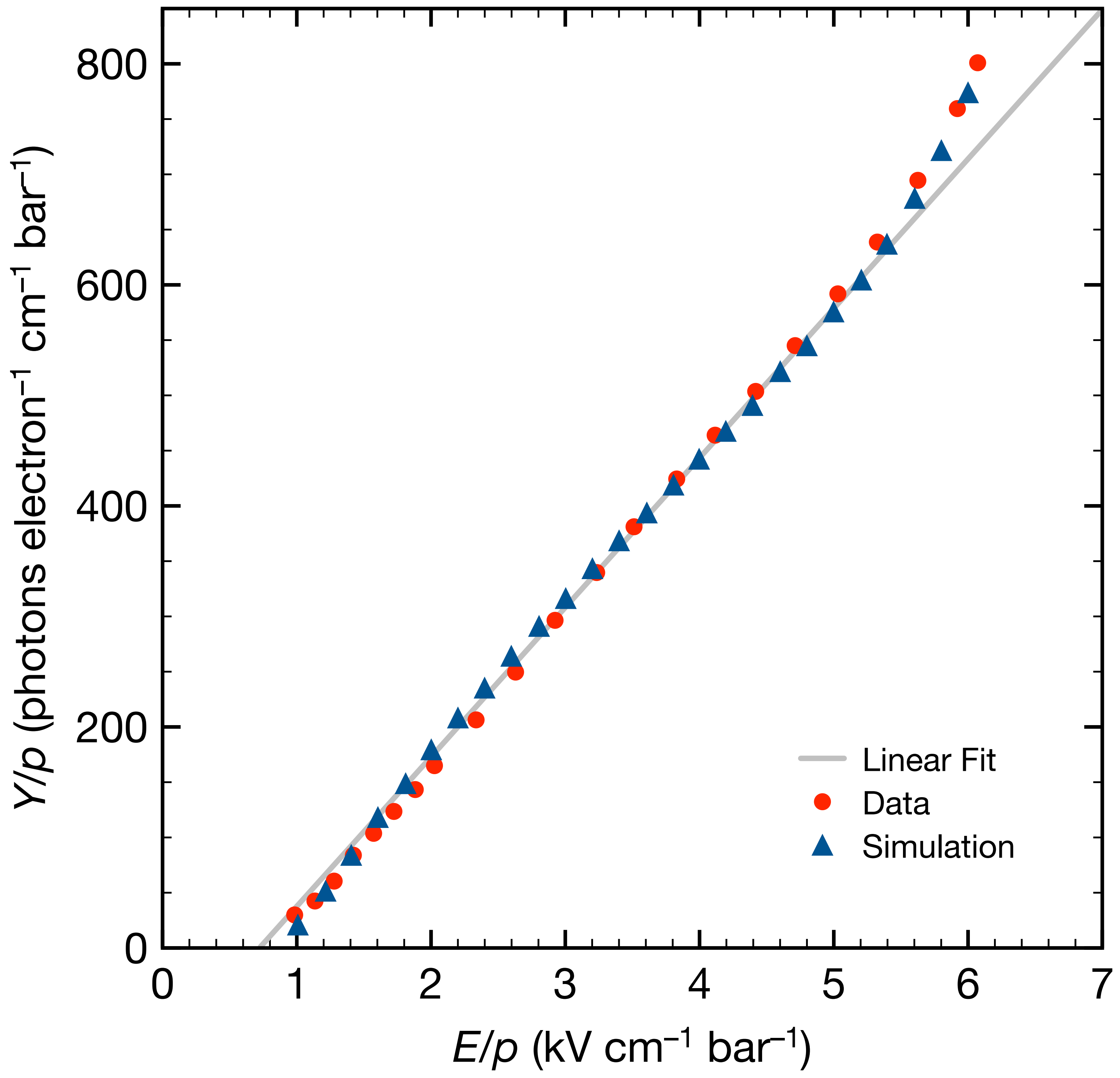
ENERGY RESOLUTION IN XENON

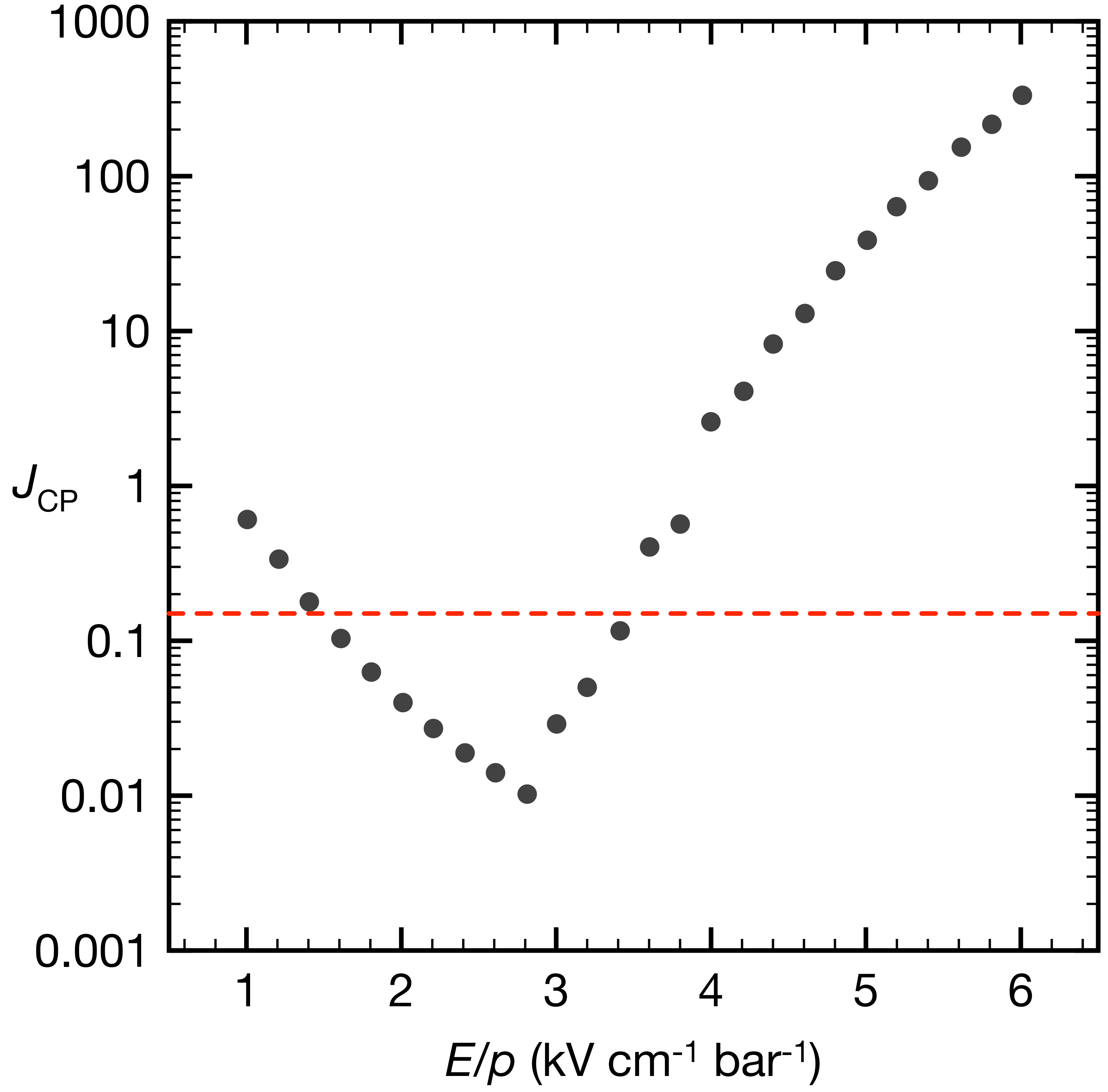


Bolotnikov and Ramsey, *NIM A* **396** (1997) 360

Intrinsic energy resolution of xenon gas close to 0.3% at 2.5 MeV.
Fano factor of xenon significantly smaller in gaseous phase than in liquid.

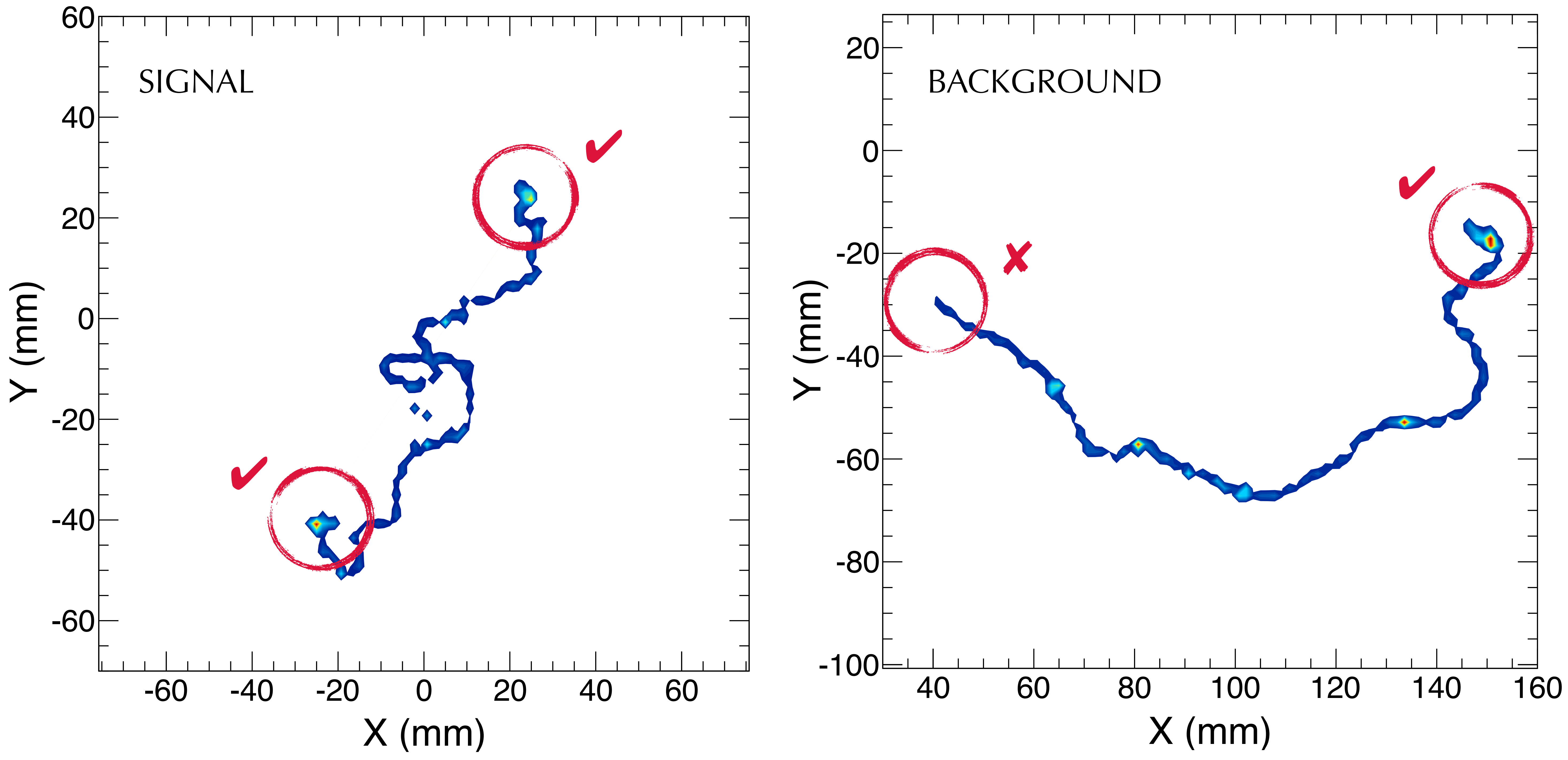
ELECTROLUMINESCENCE





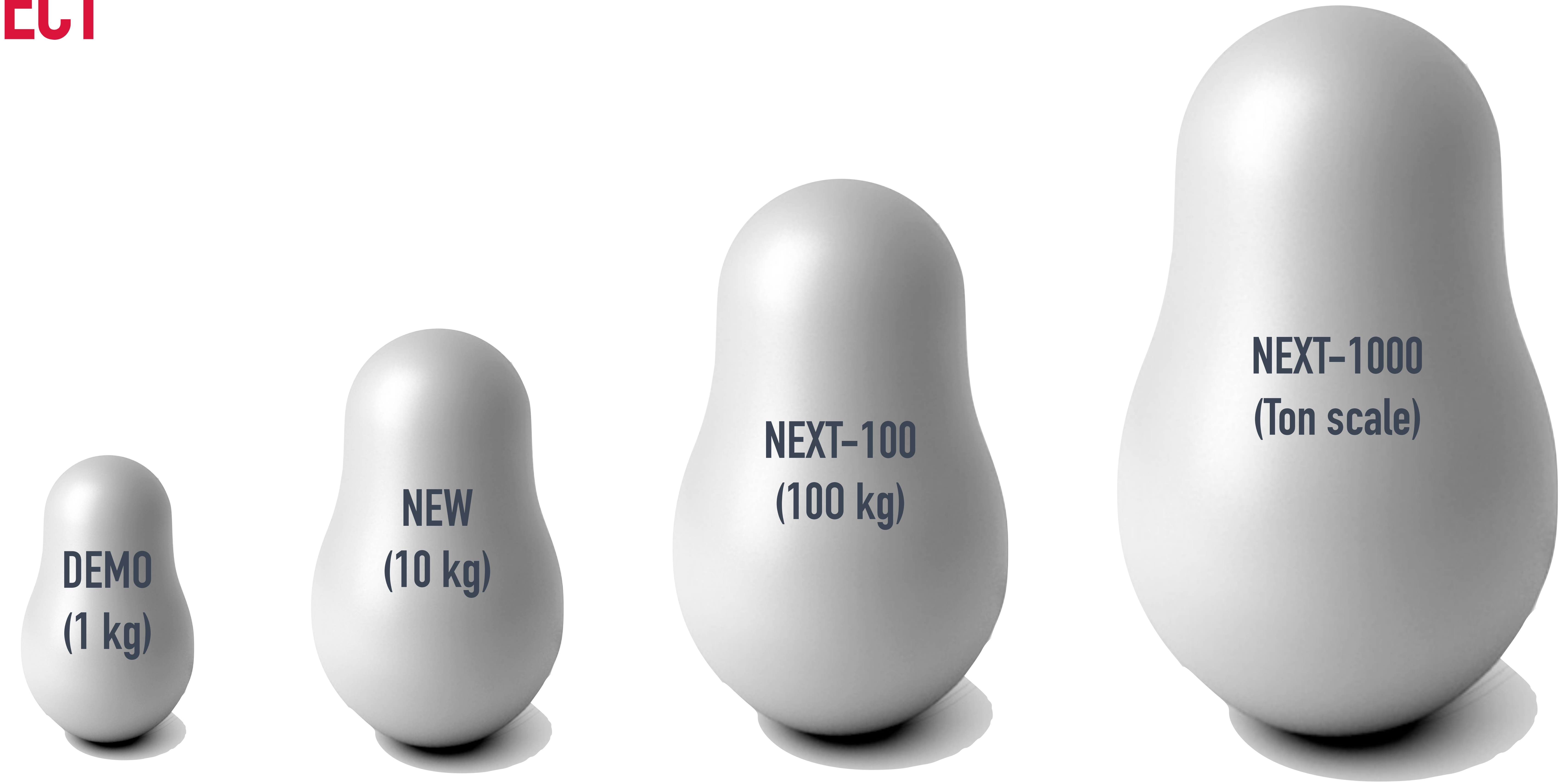
Emission of scintillation light by atoms excited by a charge accelerated by an electric field.
High, linear amplification gain with sub-Poisson fluctuations.

TRACK TOPOLOGY



Signal events (two electron tracks with a common vertex) feature high dE/dx blobs at both ends, unlike most common background events (single electrons).

THE PROJECT



(2010–2014)
Prototyping of detector concept

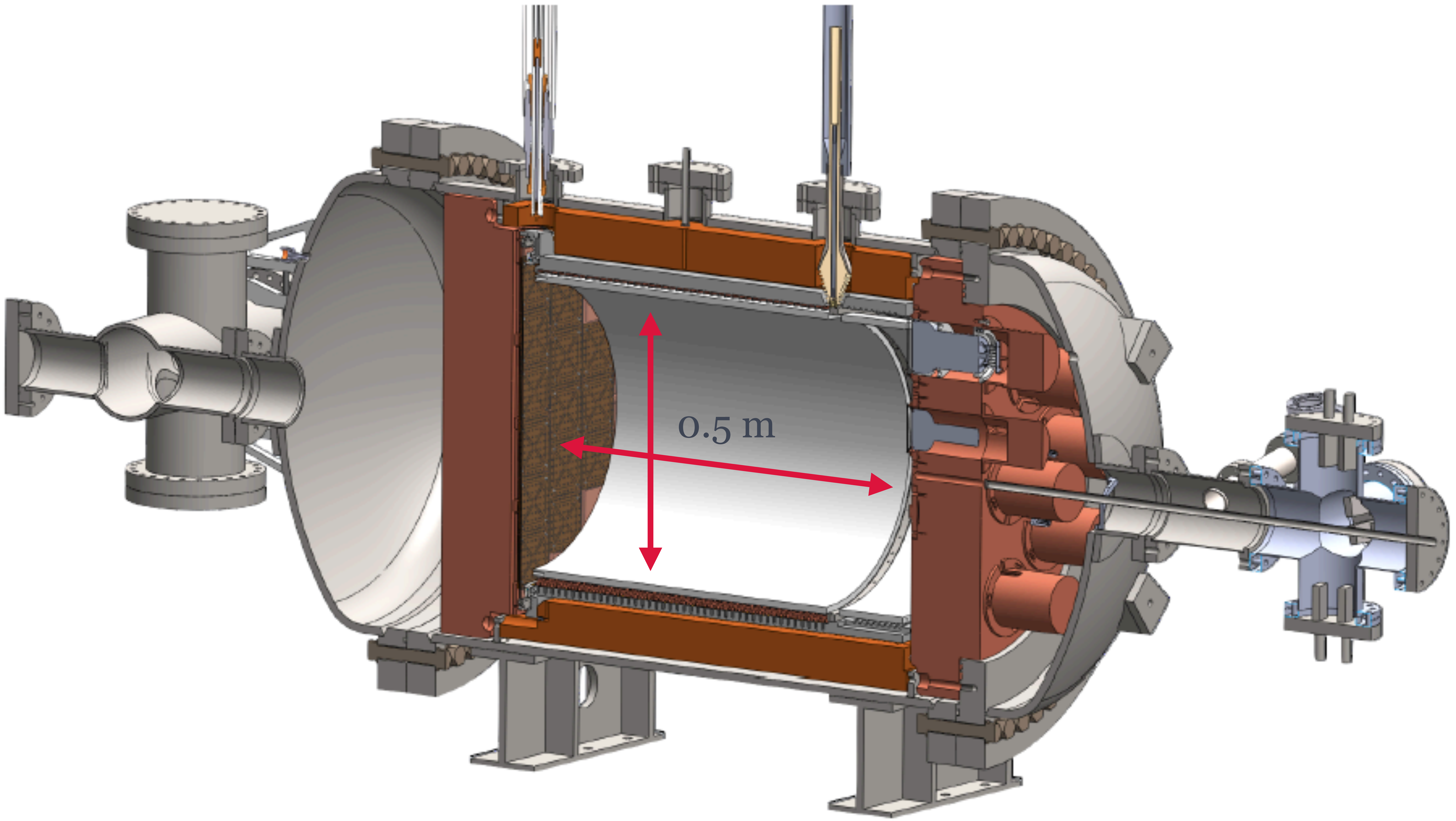
(2015–2018)
Test underground, radiopure operation

(2019–2021)
Neutrinoless double beta decay searches

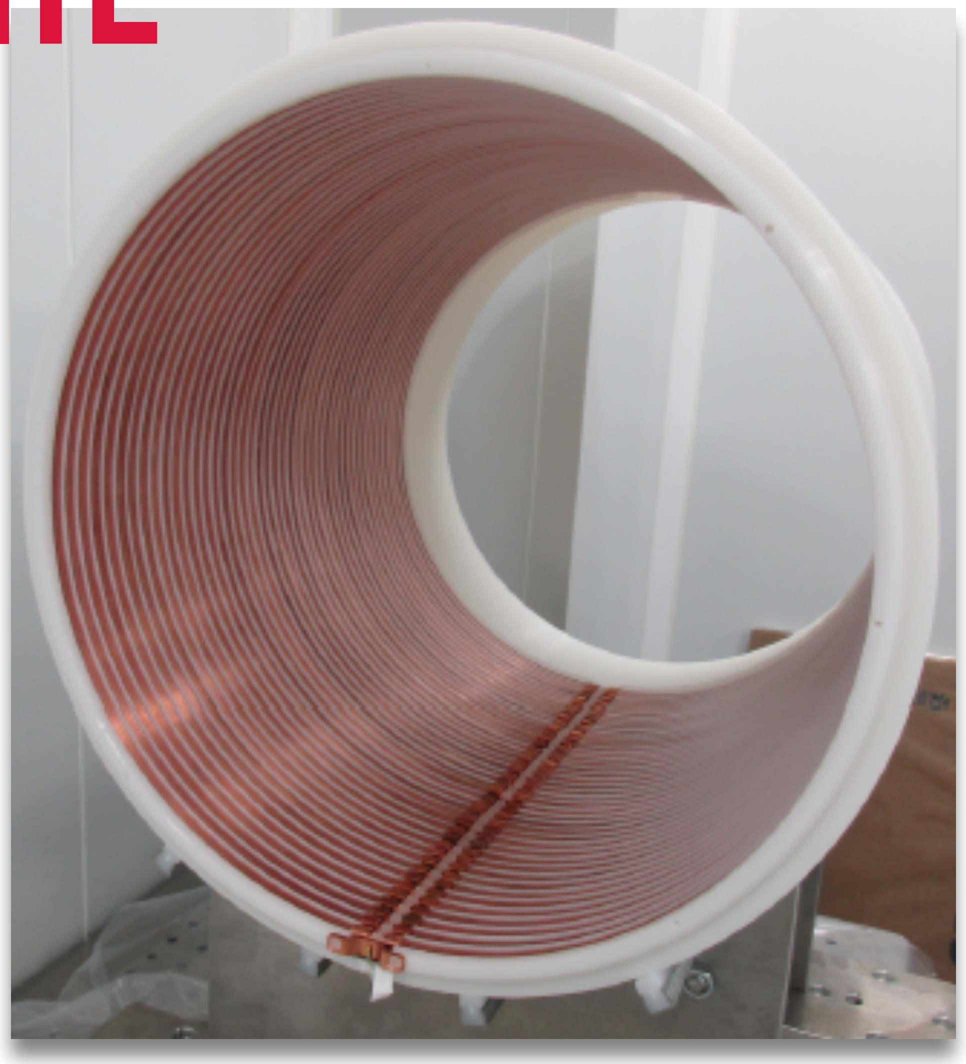
(2021– ...)
Discovery?

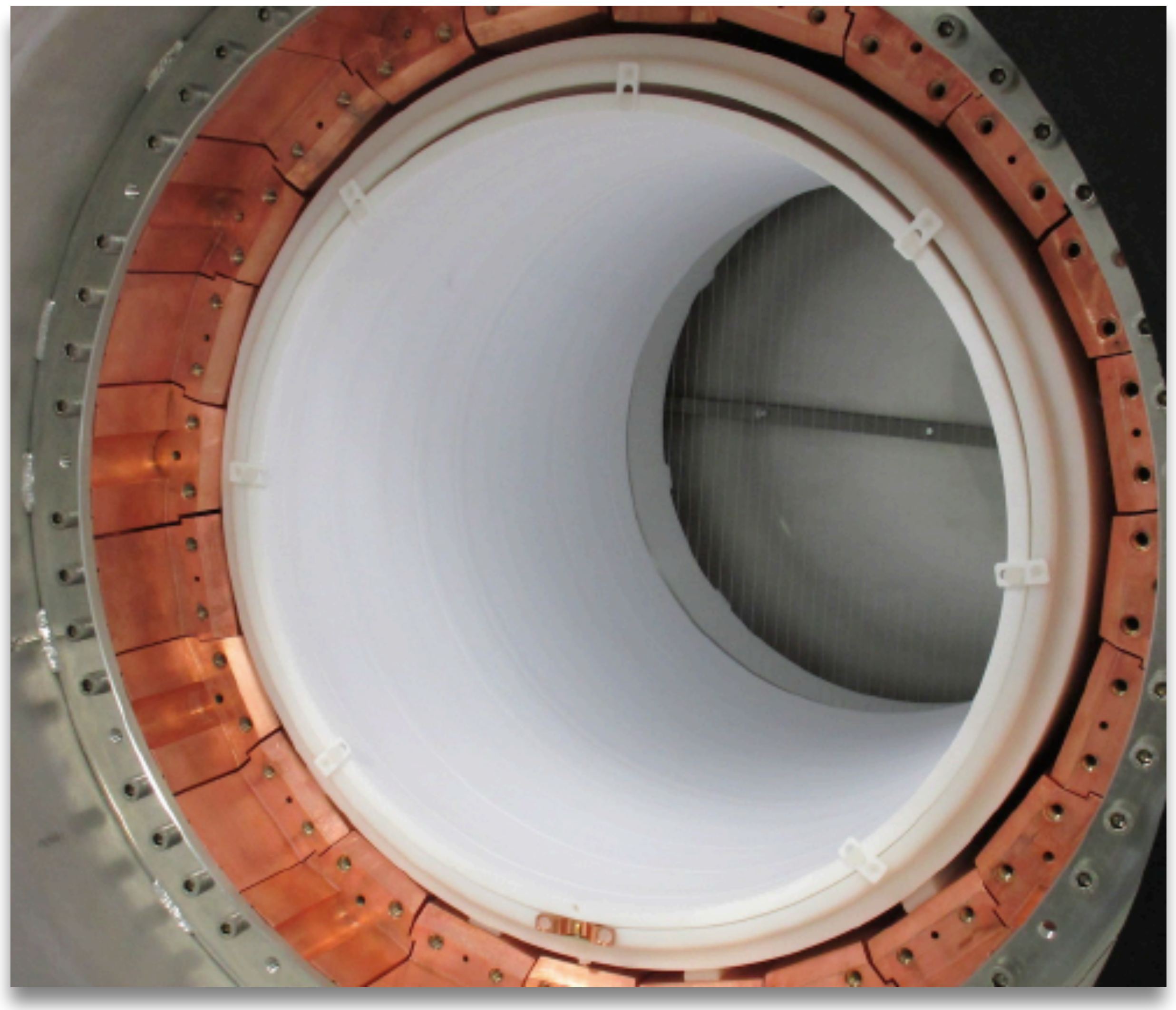

NEXT-WHITE

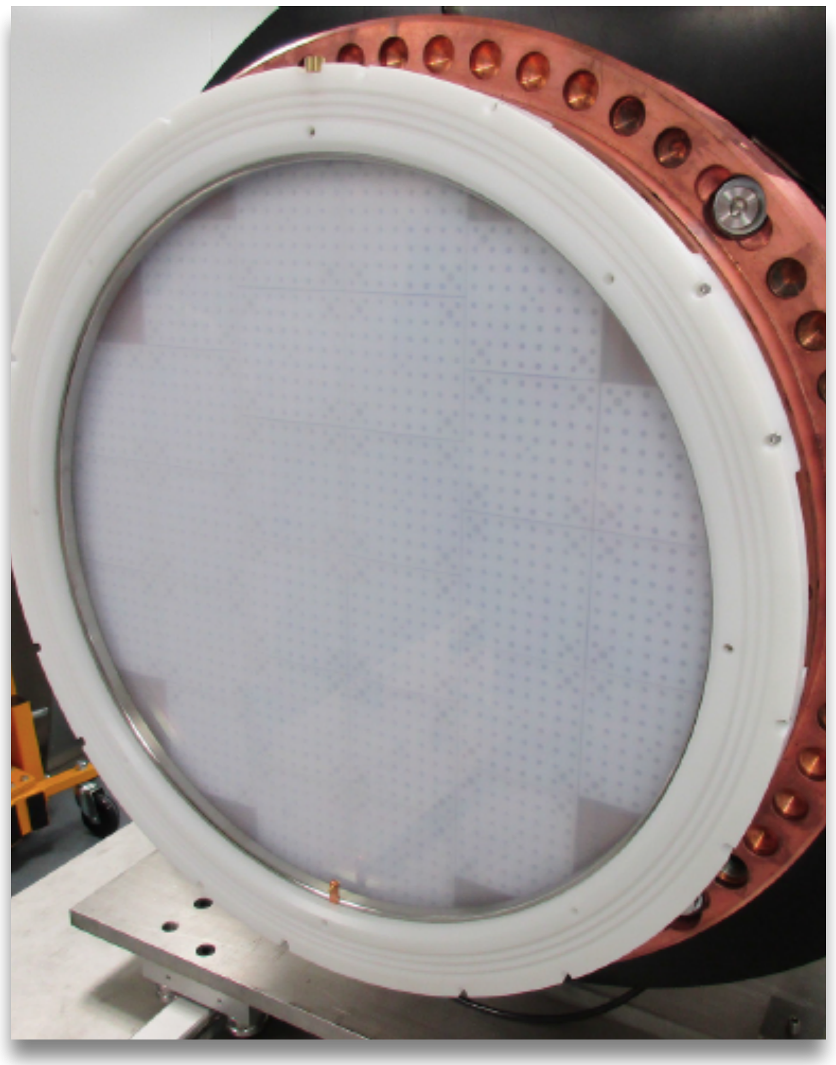
NEXT-WHITE



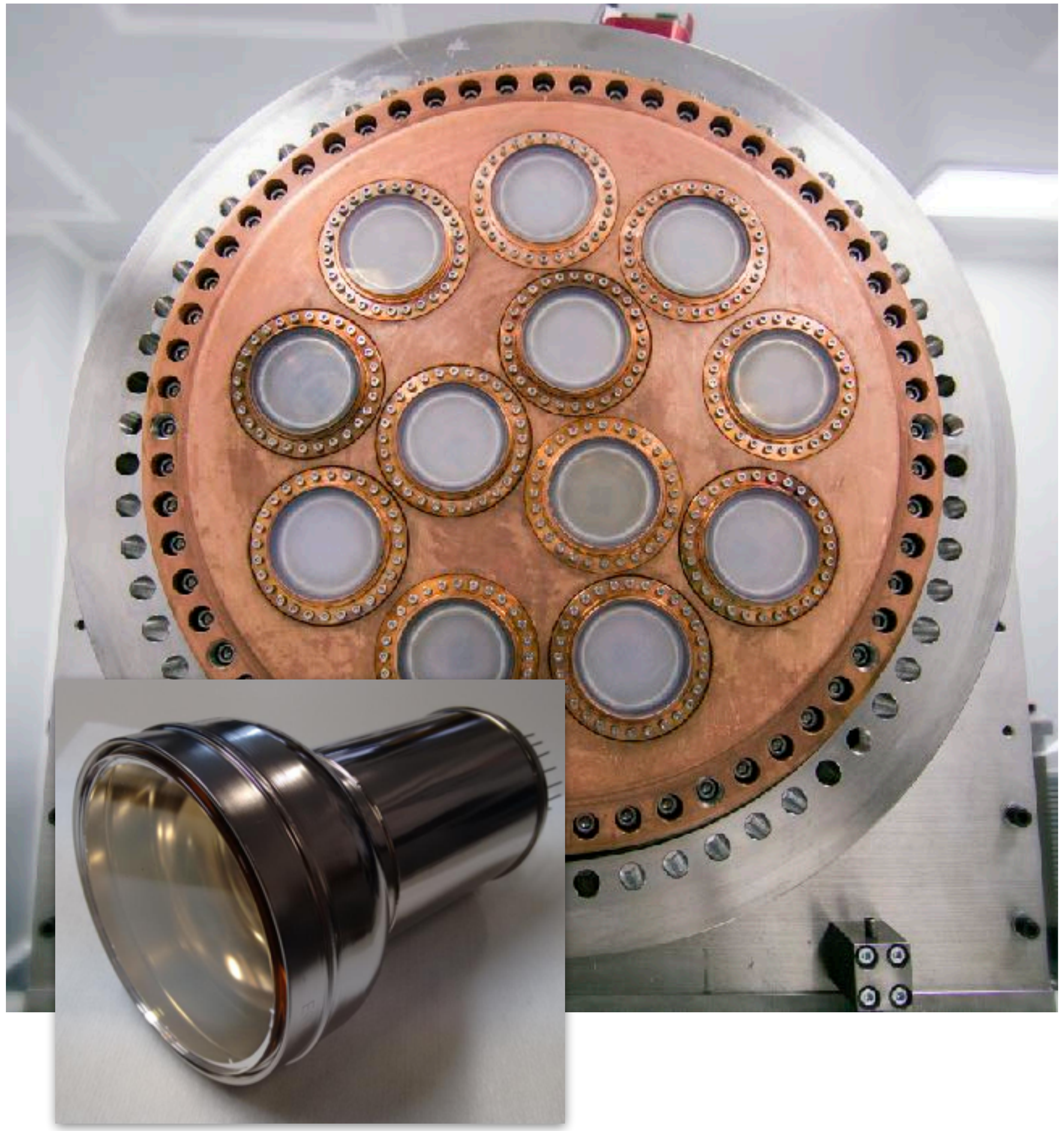
NEXT-WHITE



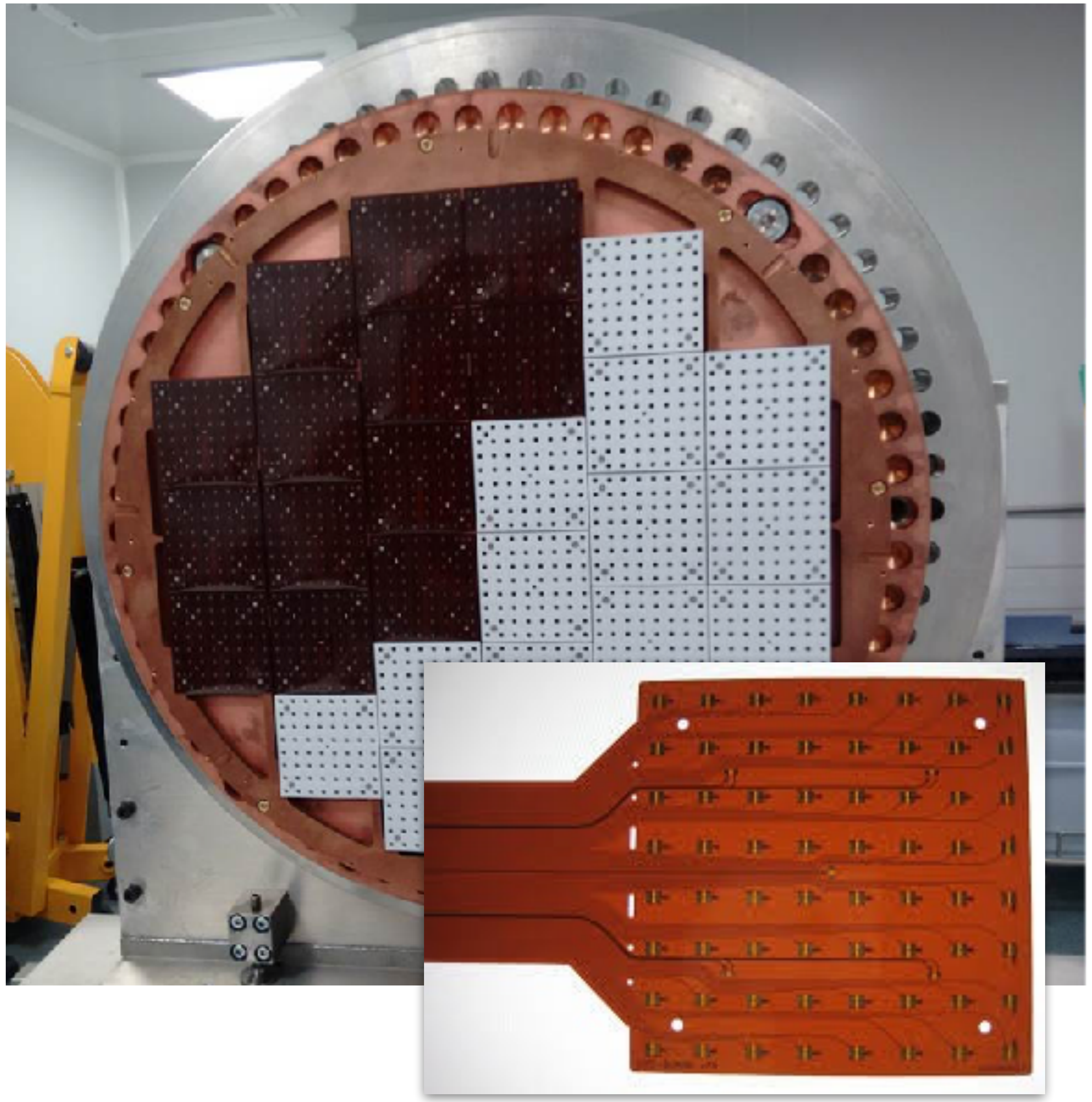




NEXT-WHITE

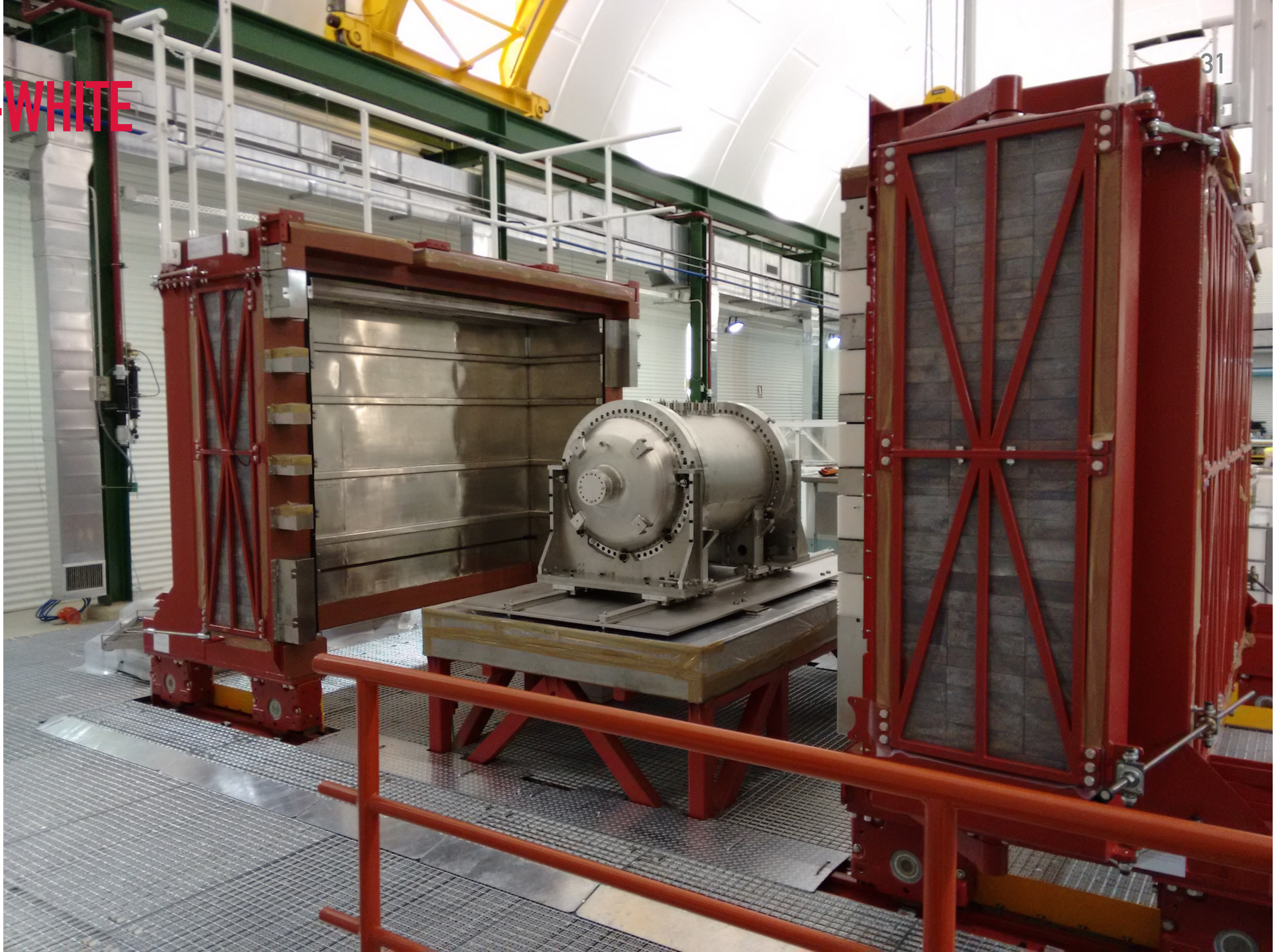


12 Hamamatsu R11410



2000+ SensL 1-mm² SiPMs

NEXT-WHITE



NEXT-WHITE

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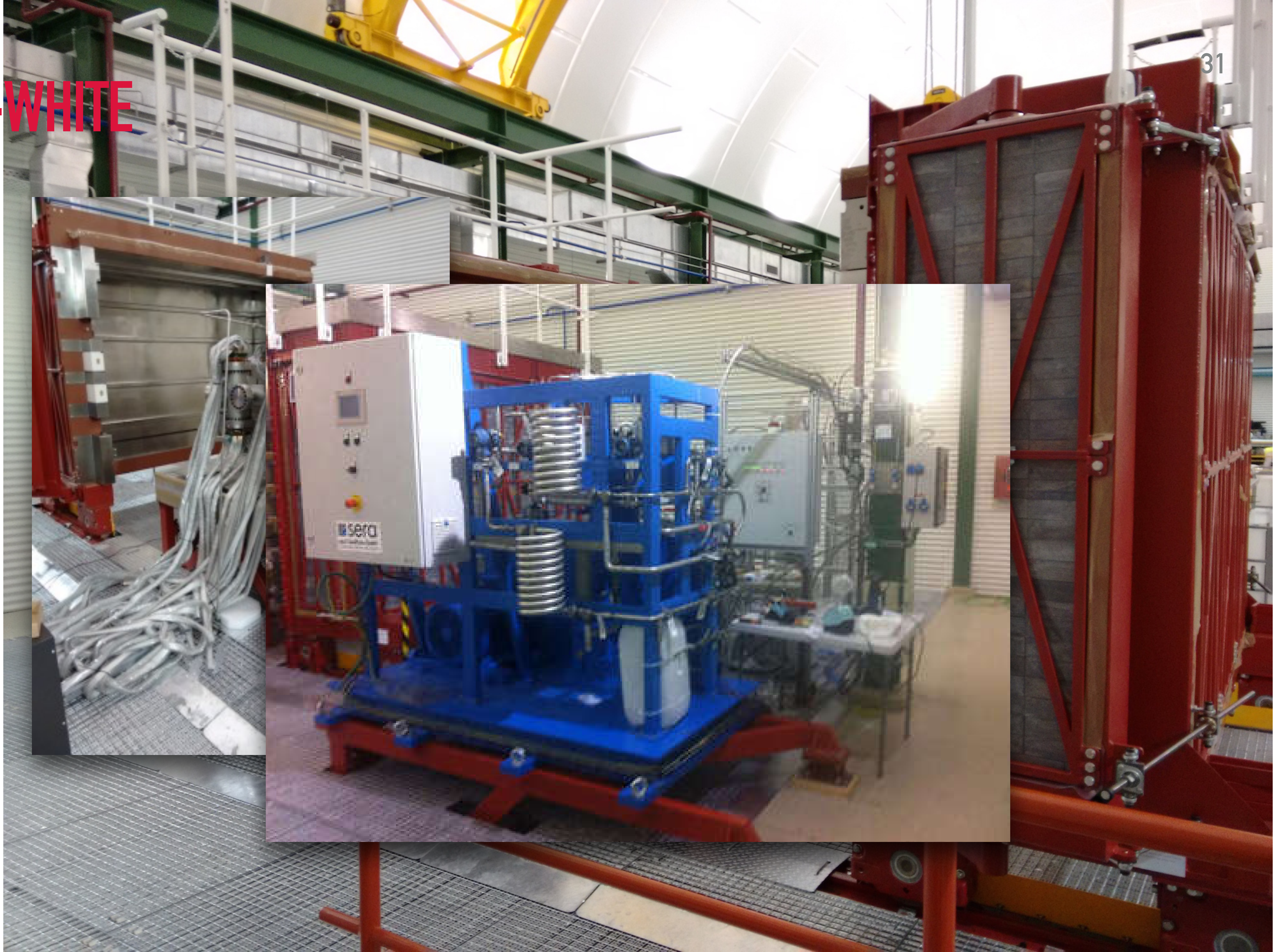

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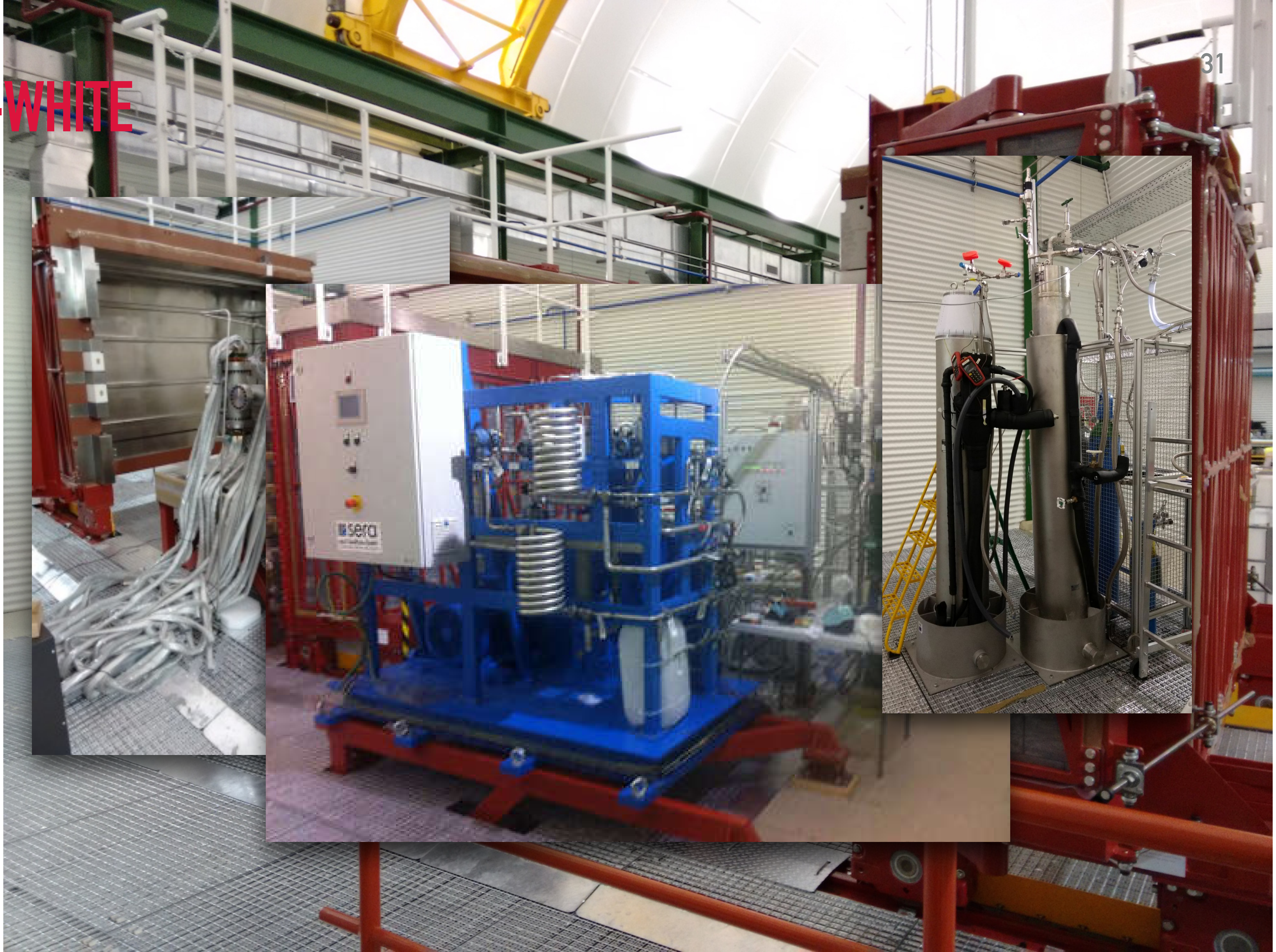
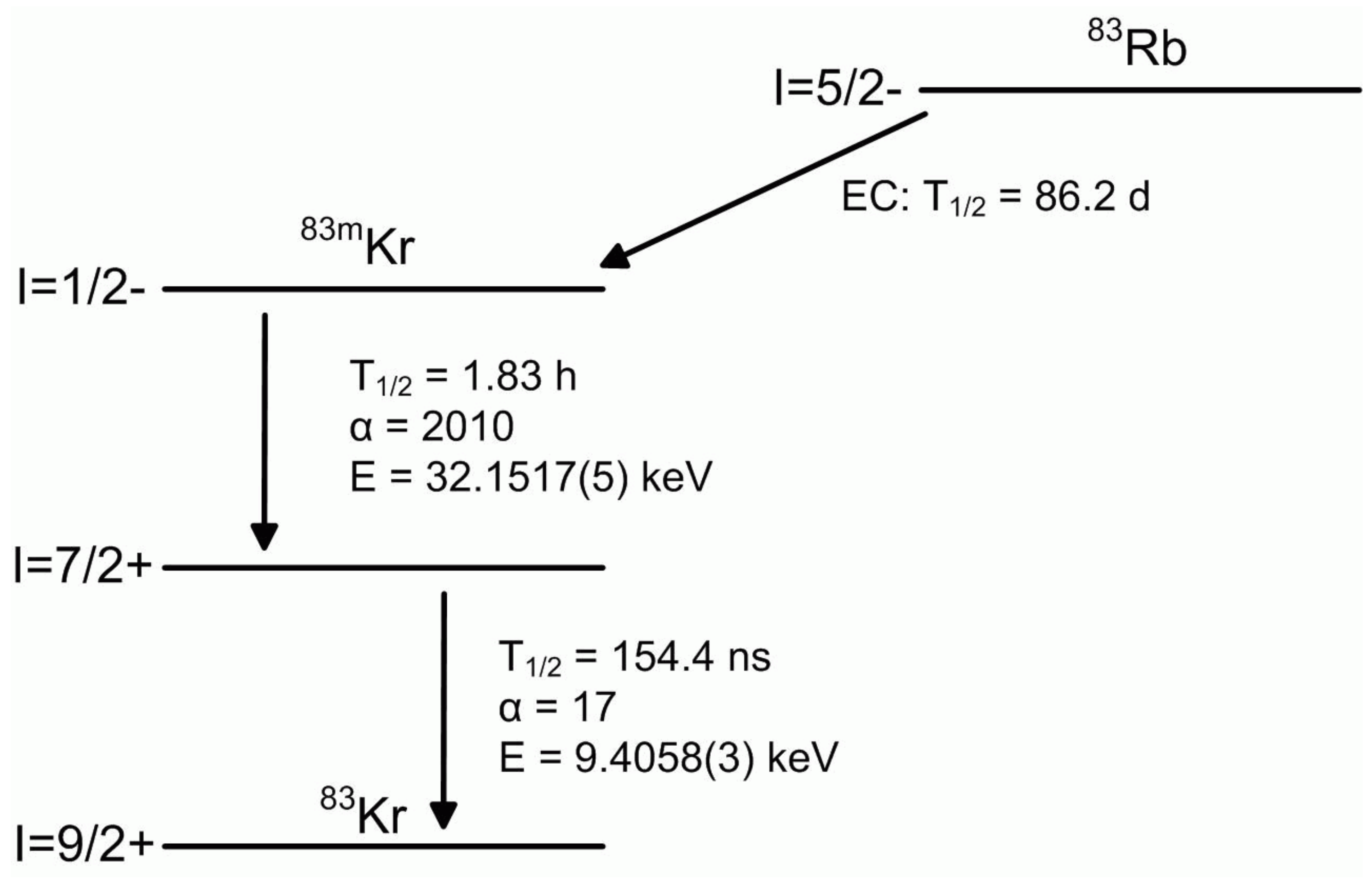
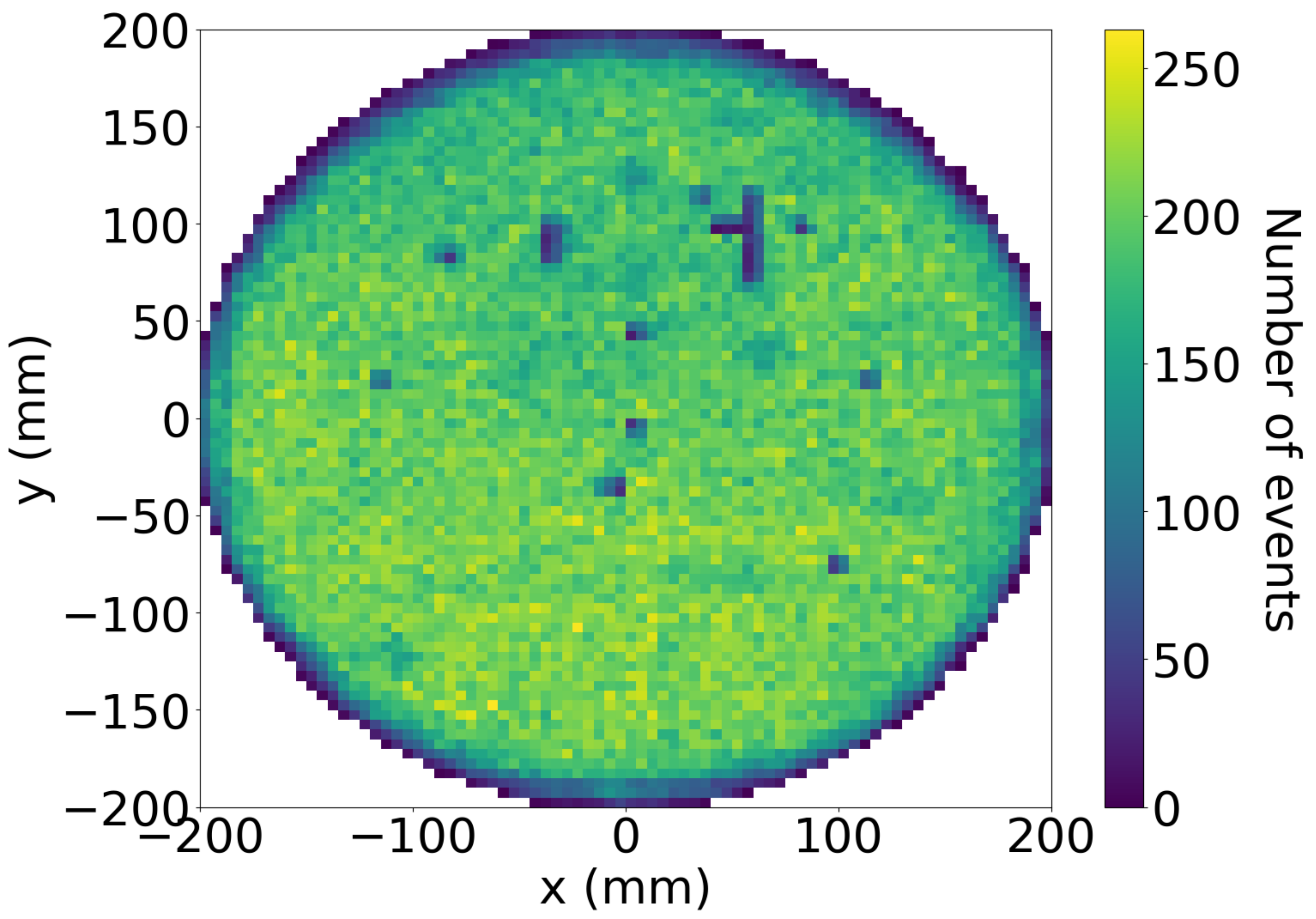


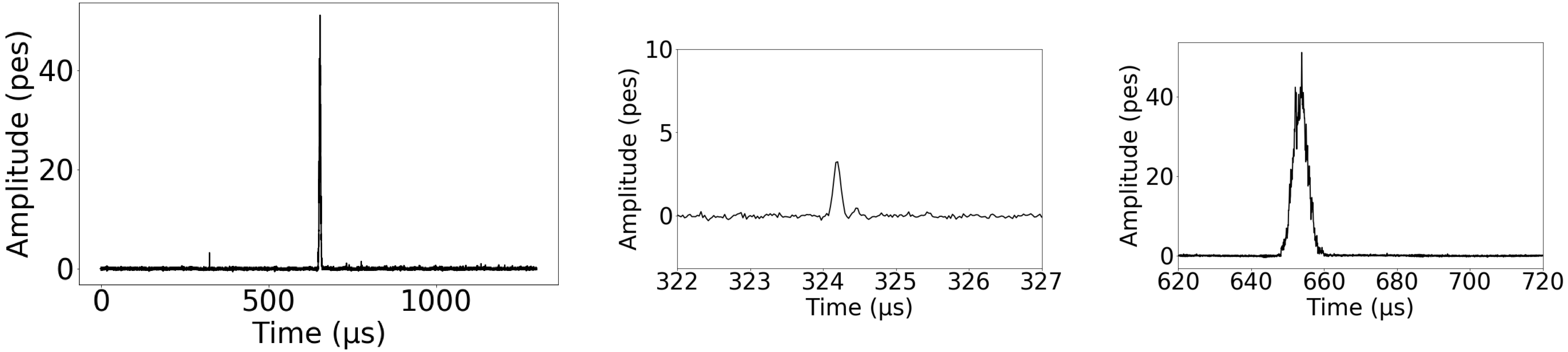
NEXT-WHITE

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

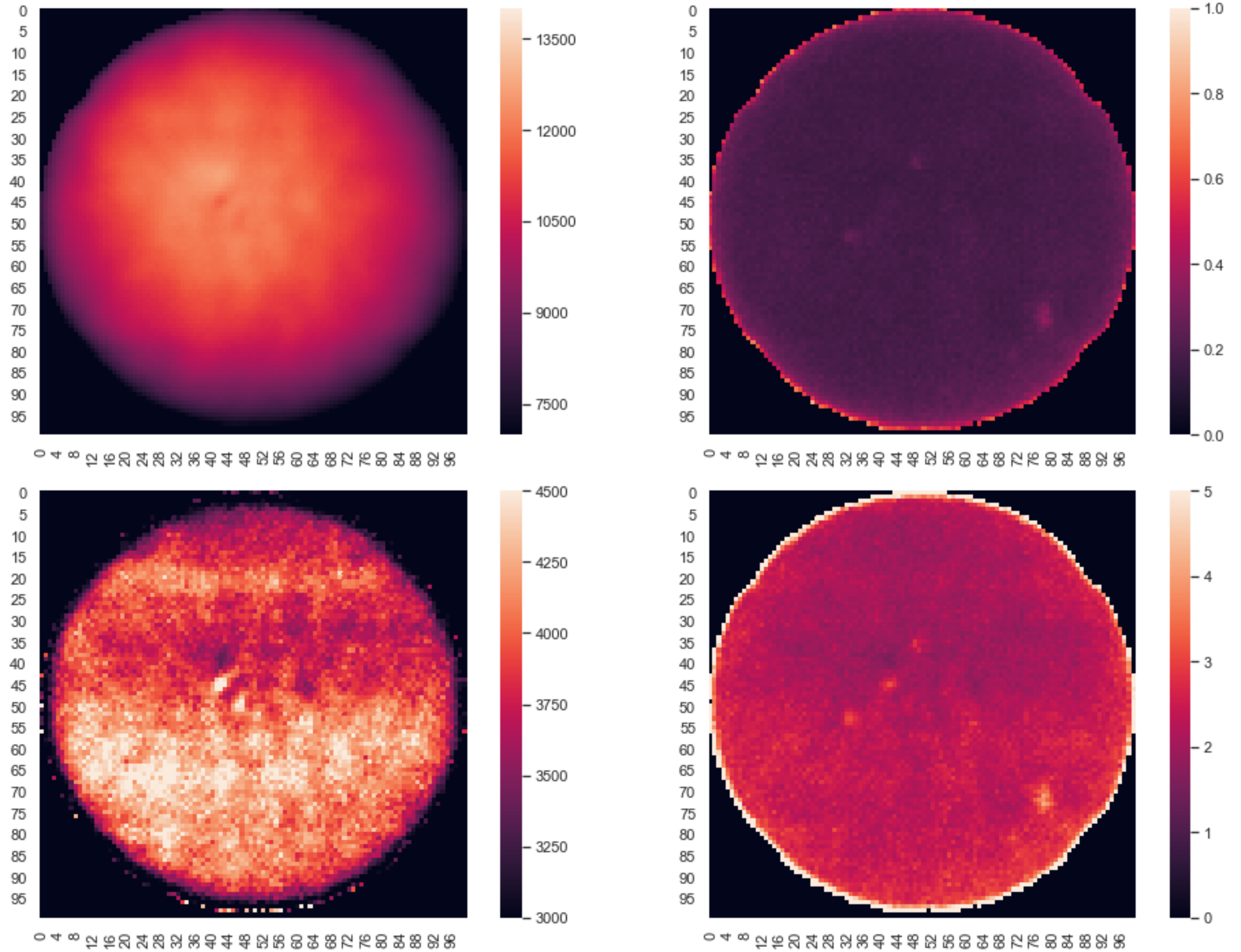
NEXT-WHITE: CALIBRATION WITH KRYPTON-83



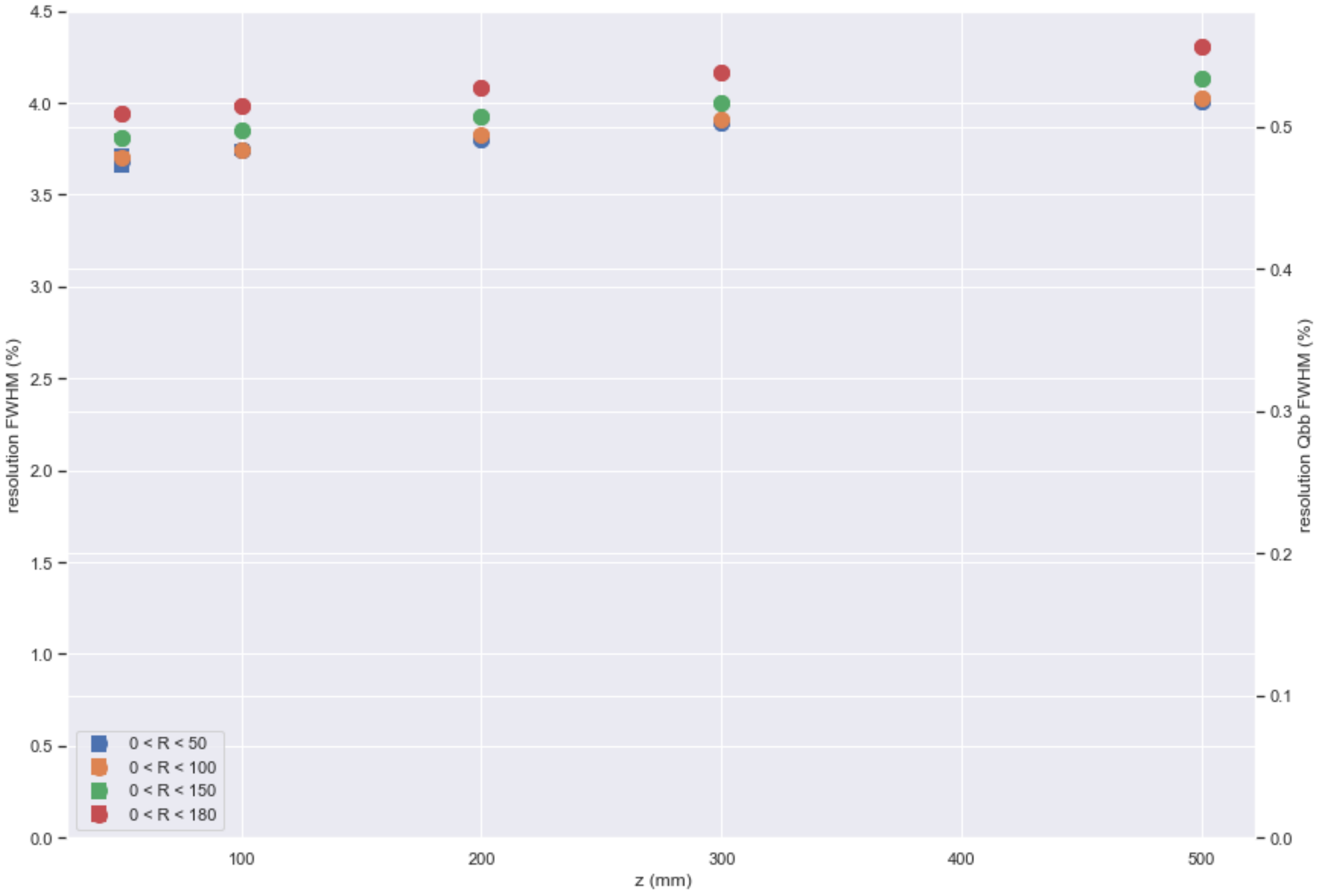




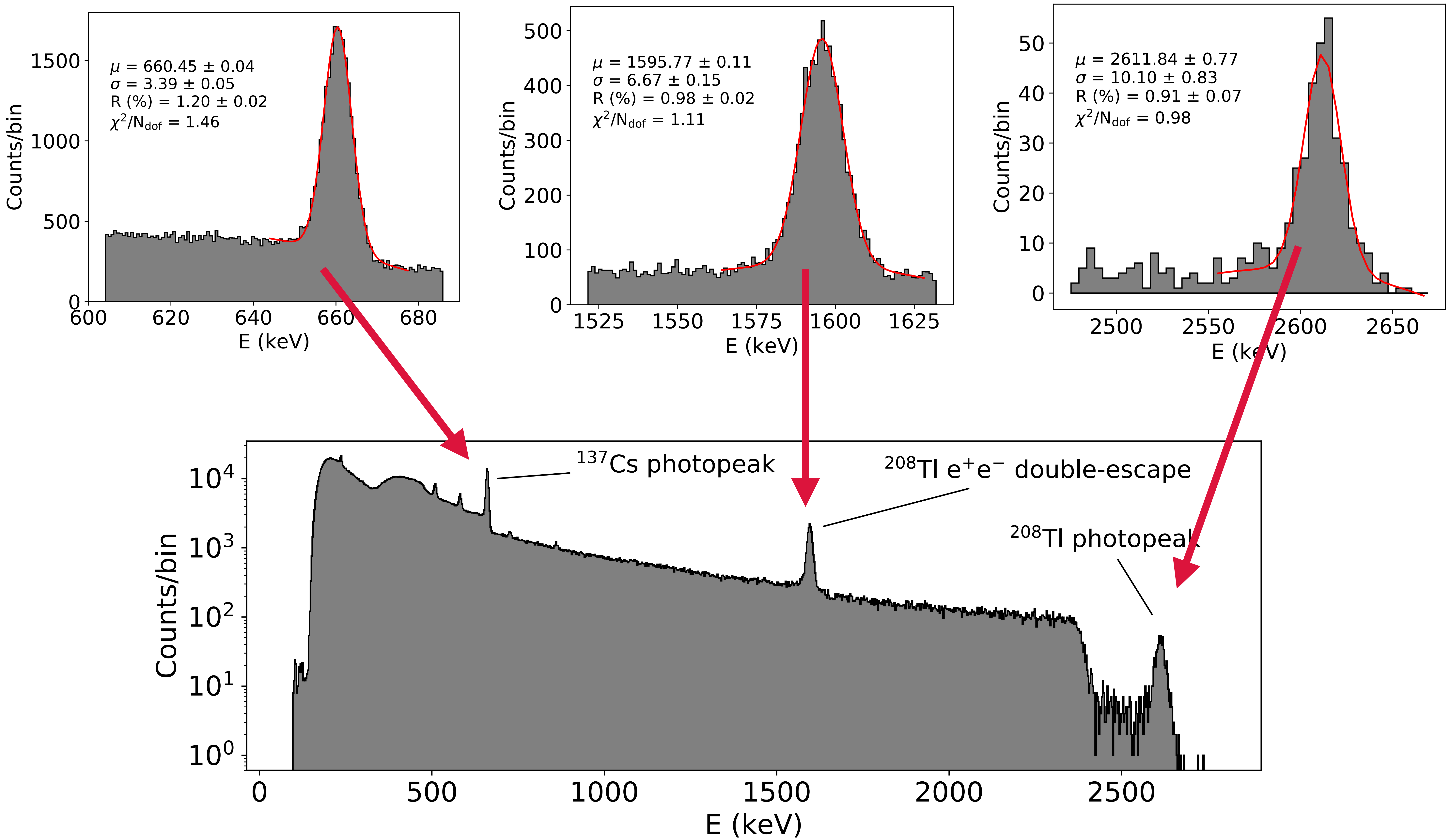
NEXT Collaboration, *JINST* **13** (2018) P10014



NEXT Collaboration, *JINST* **13** (2018) P10014


4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
resolution FWHM (%)
0.5
0.4
0.3
0.2
0.1
0.0
resolution Qbb FWHM (%)
100
200
300
400
500
z (mm)
0 < R < 50
0 < R < 100
0 < R < 150
0 < R < 180

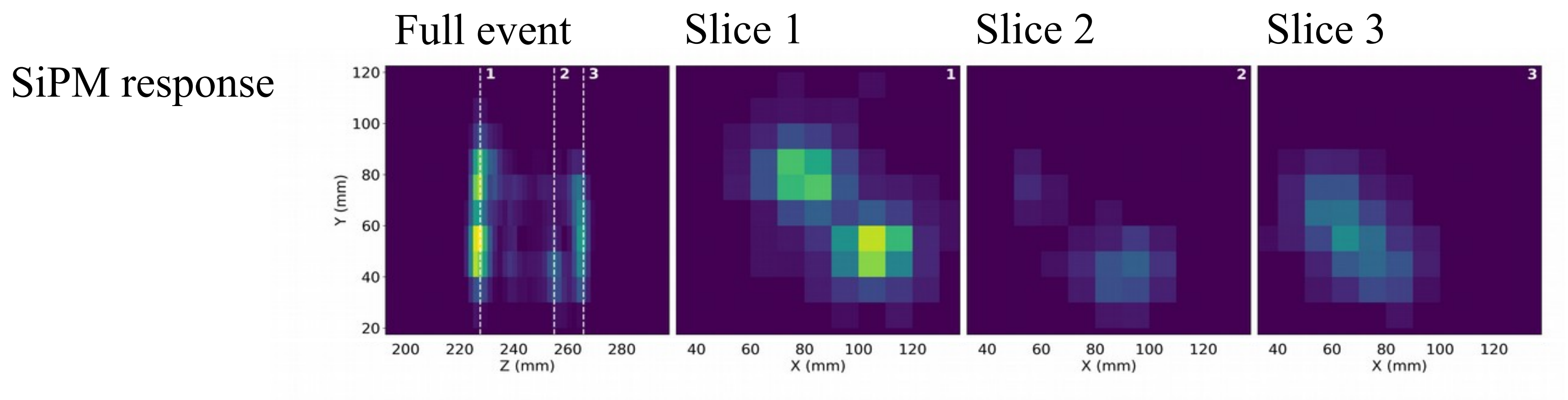
NEXT-WHITE: ENERGY RESOLUTION



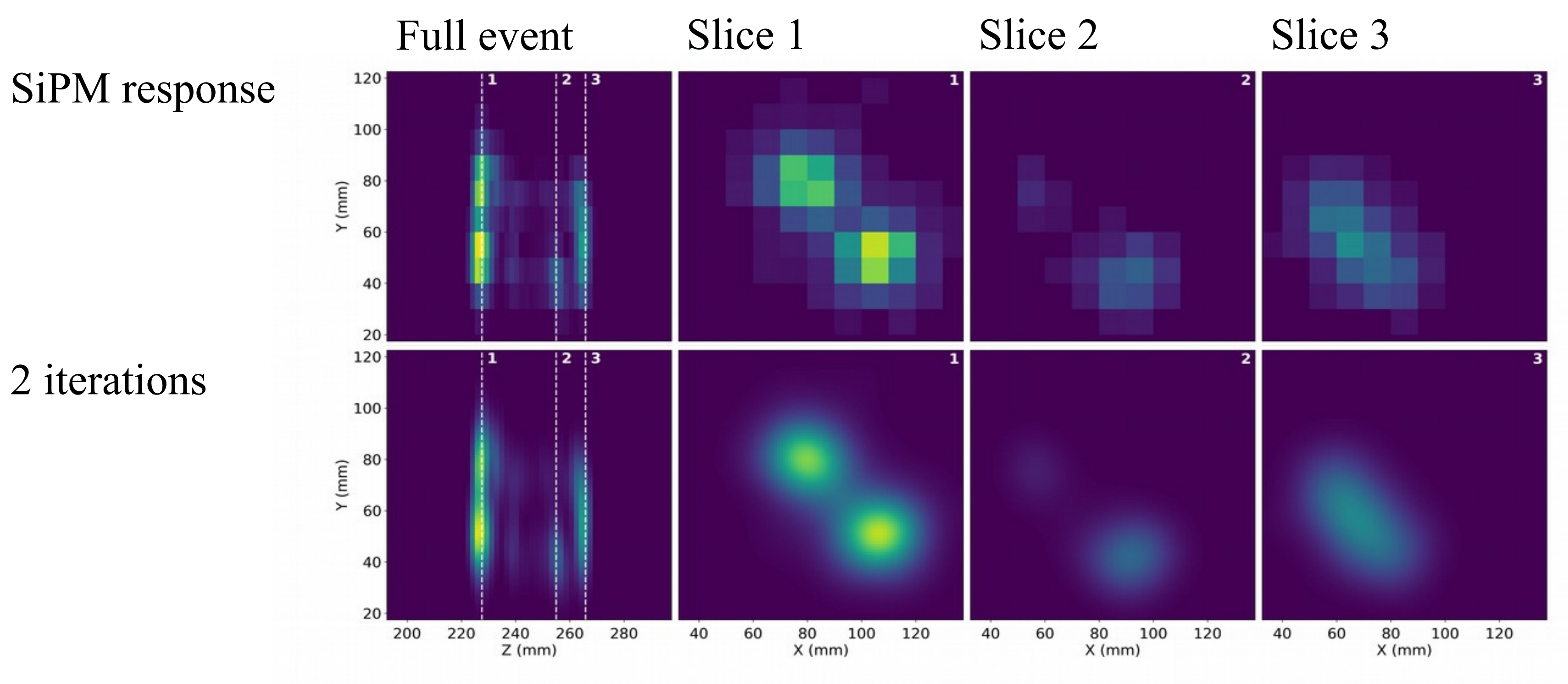
NEXT Collaboration, *JHEP* **10** (2019) 230.

NEXT-WHITE: EVENT TOPOLOGY

NEXT-WHITE: EVENT TOPOLOGY



NEXT-WHITE: EVENT TOPOLOGY



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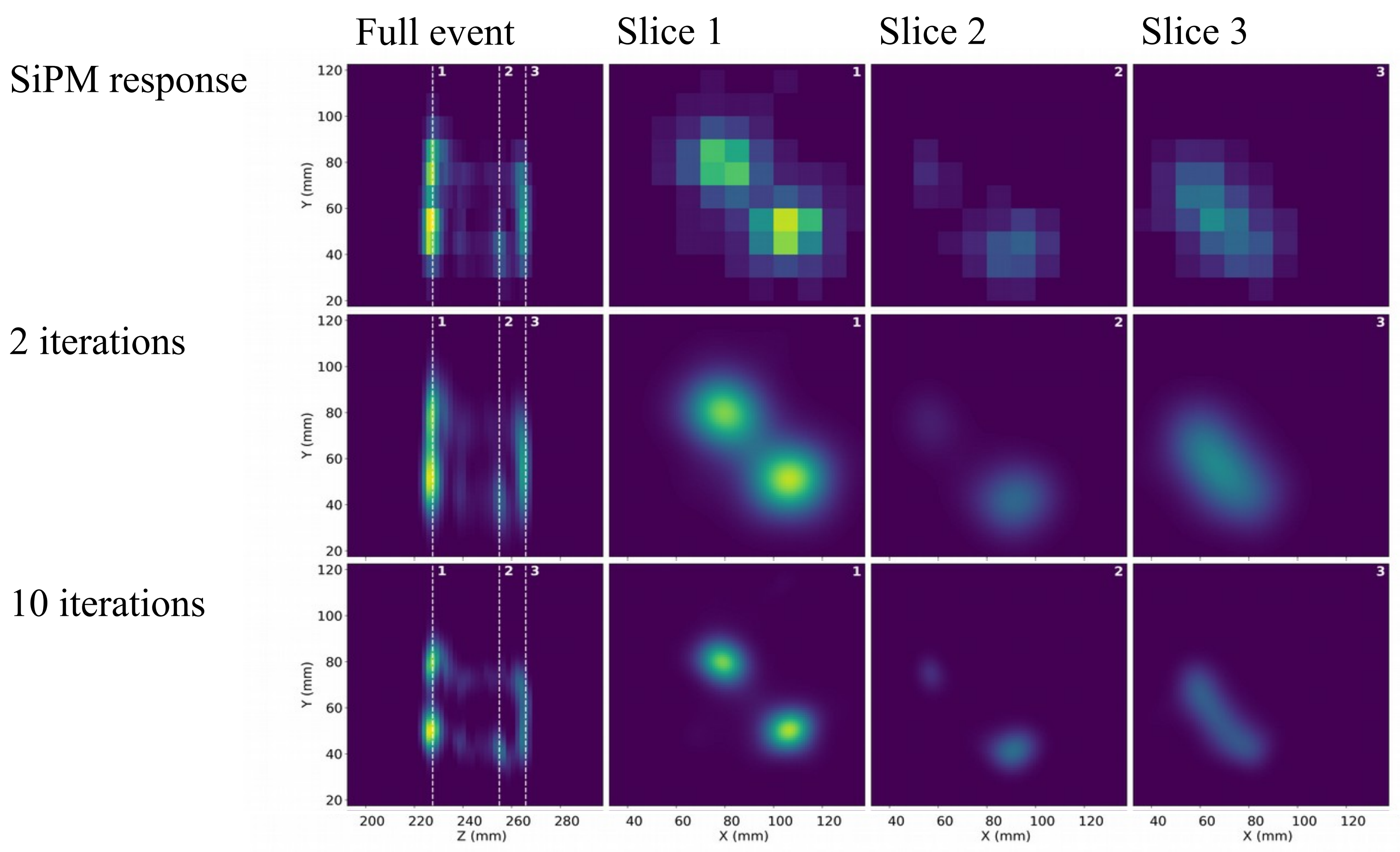

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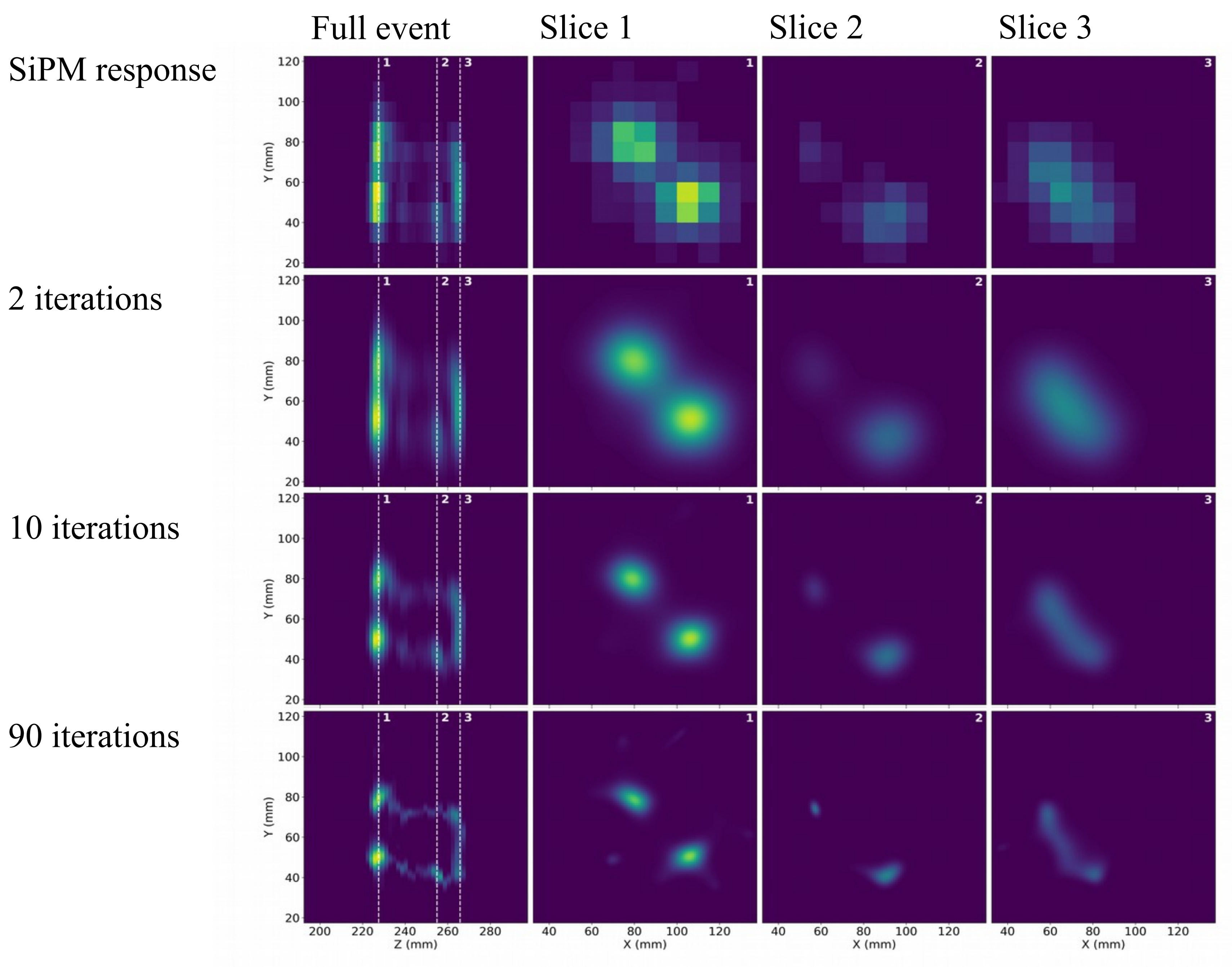

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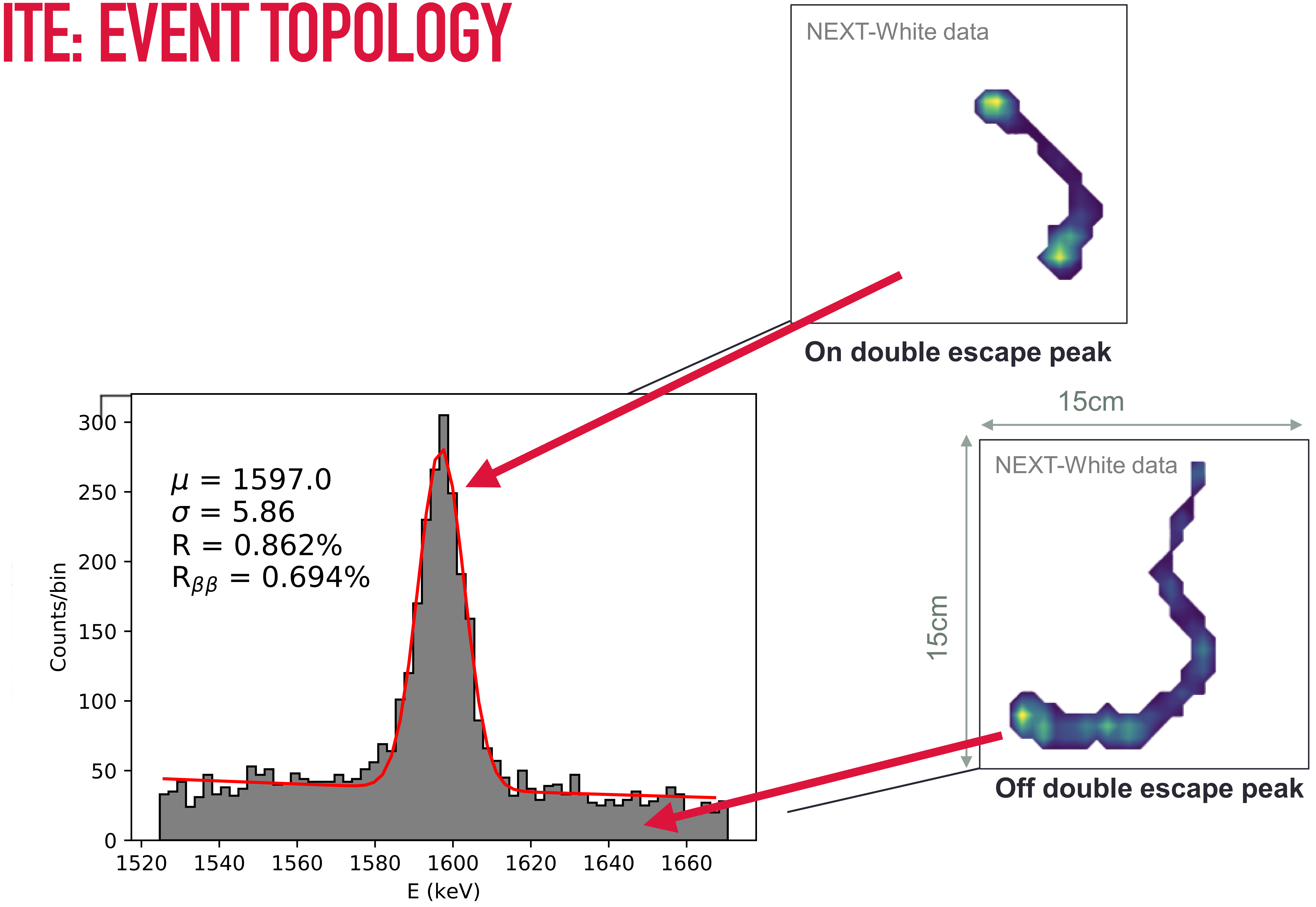
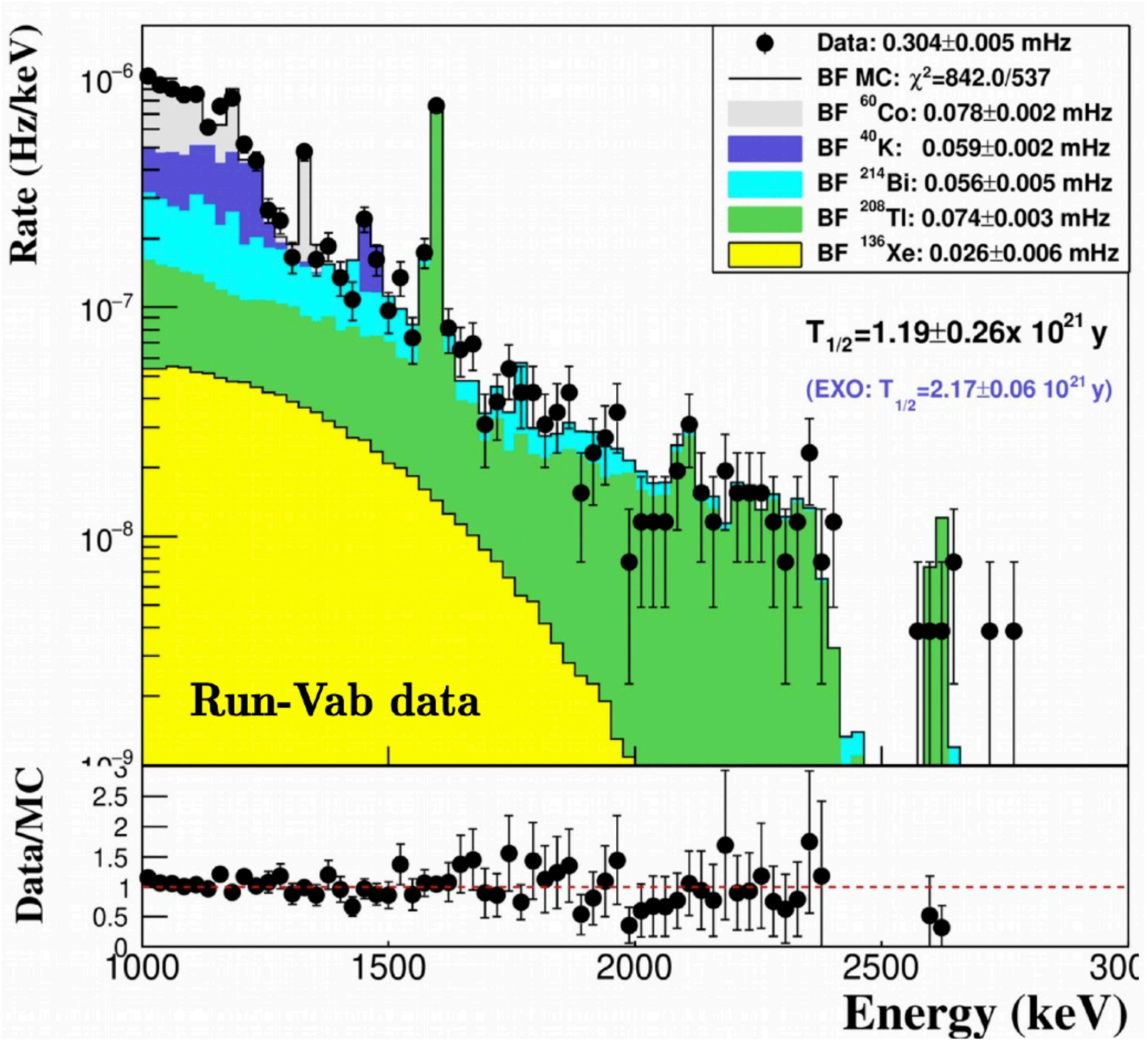


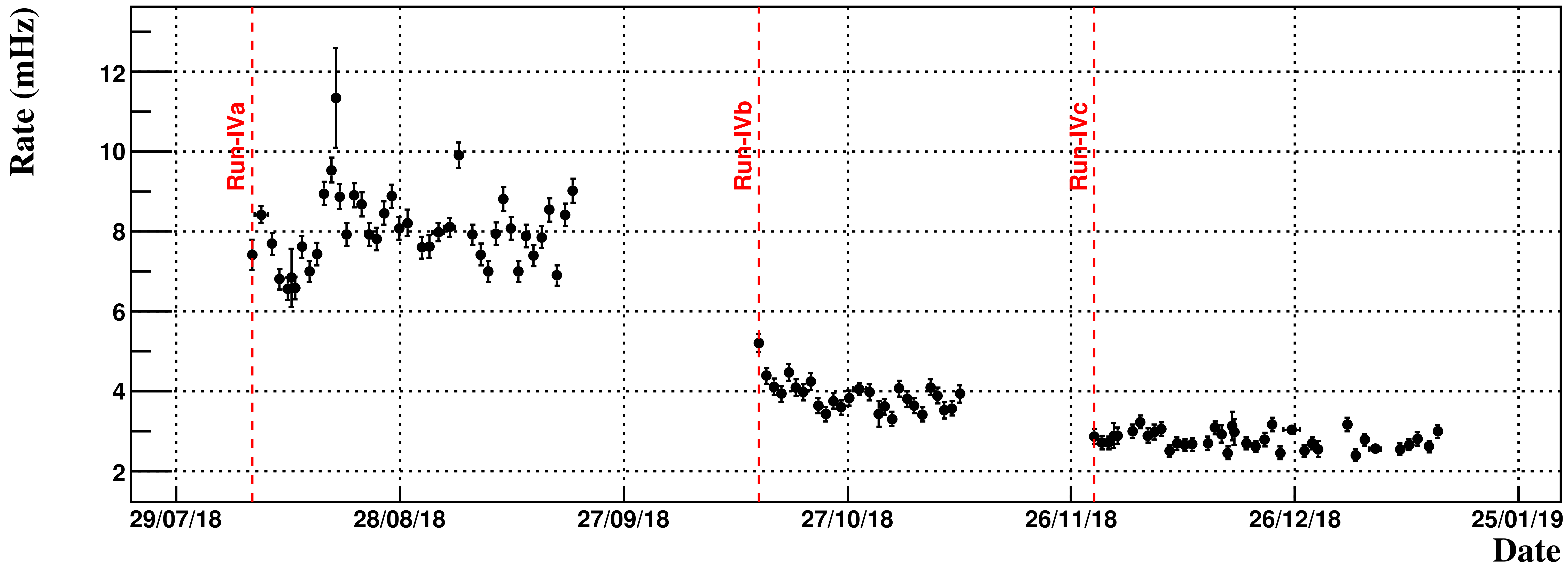
NEXT-WHITE: BACKGROUNDS

Low-background data taking proceeding after detector calibration campaign. NEXT background model assessed using these data.

Several improvements in the setup have reduced the background in a factor of ~4 over the last 2 years.

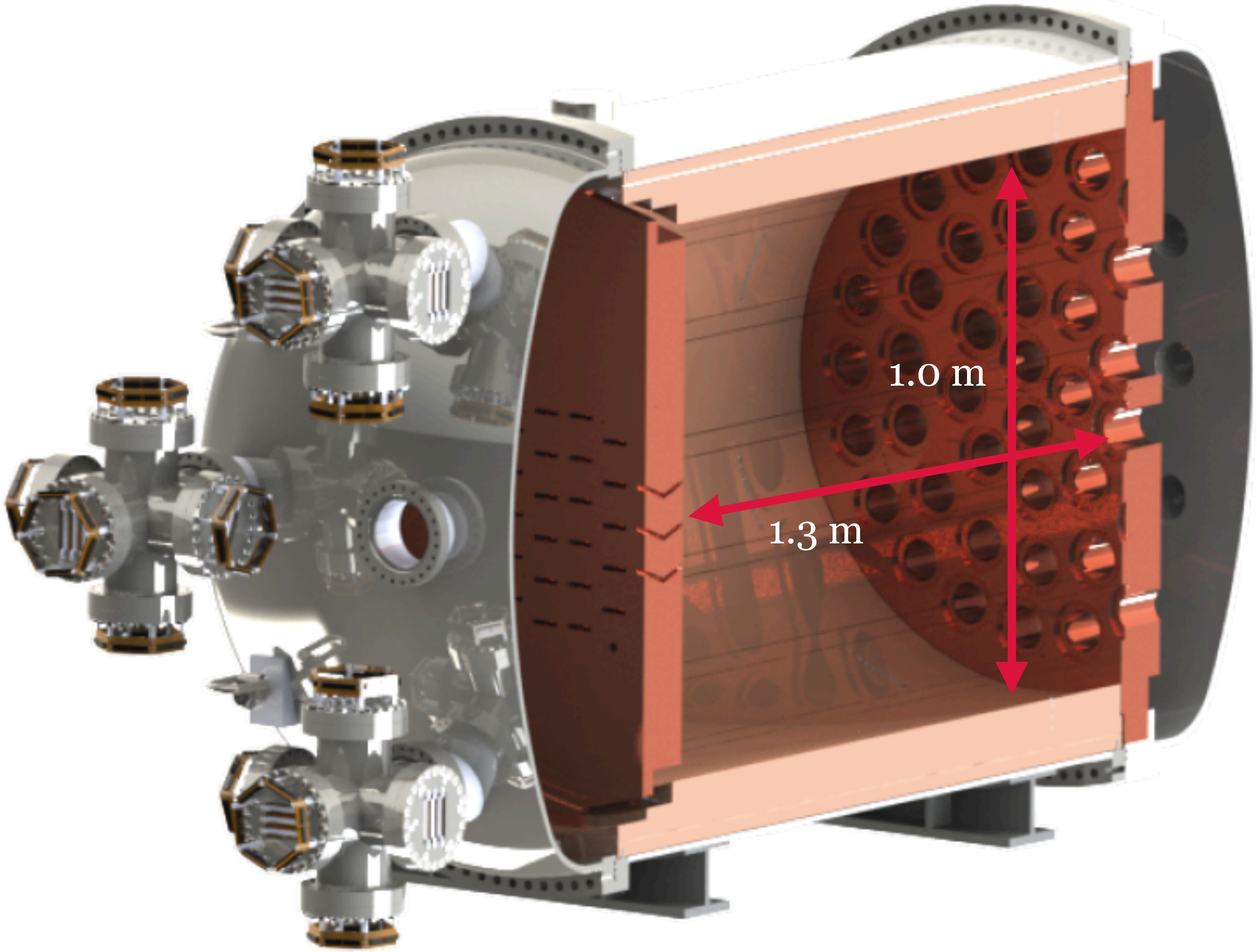
Measurement of the two-neutrino half-life is ongoing.



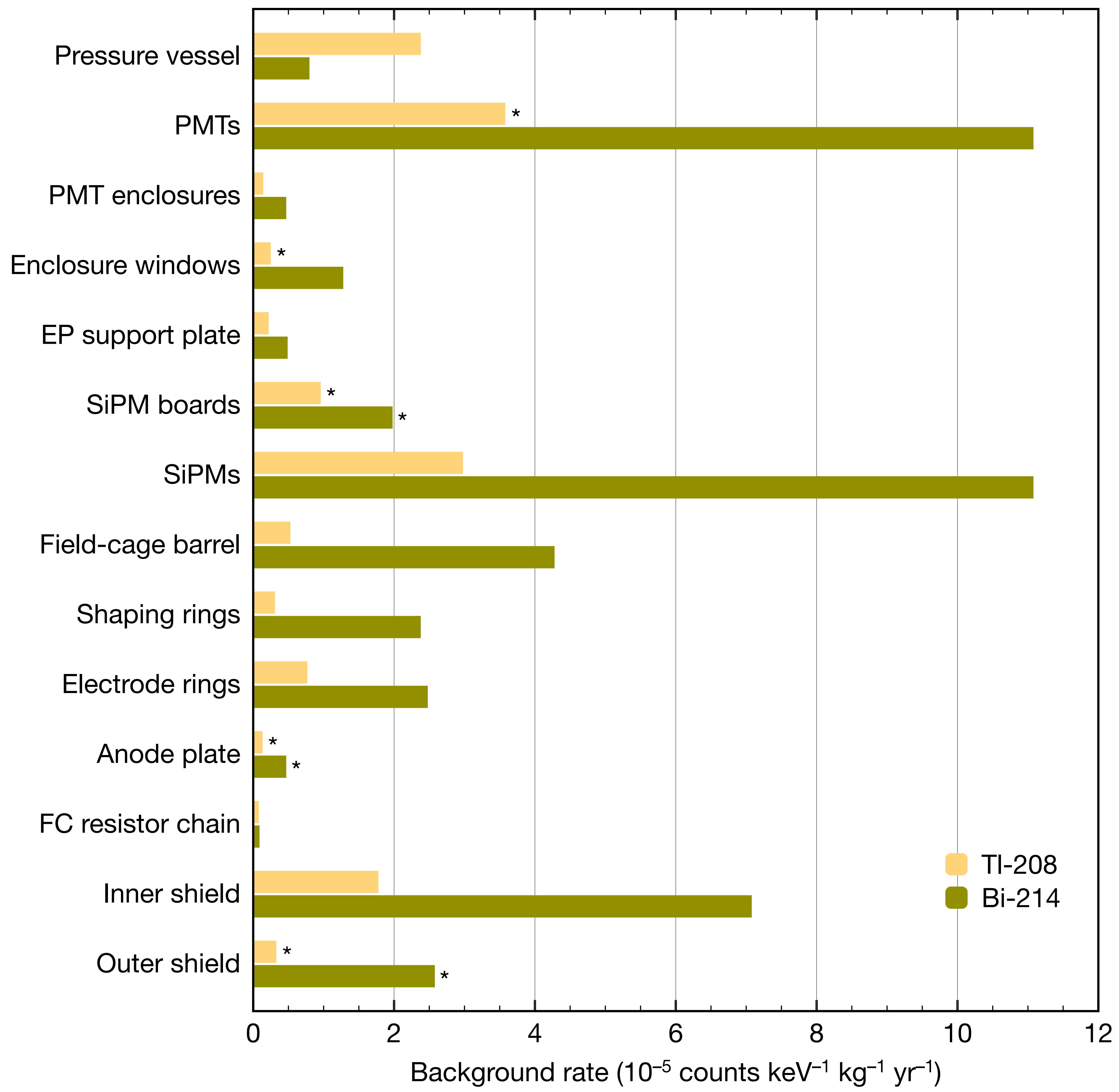


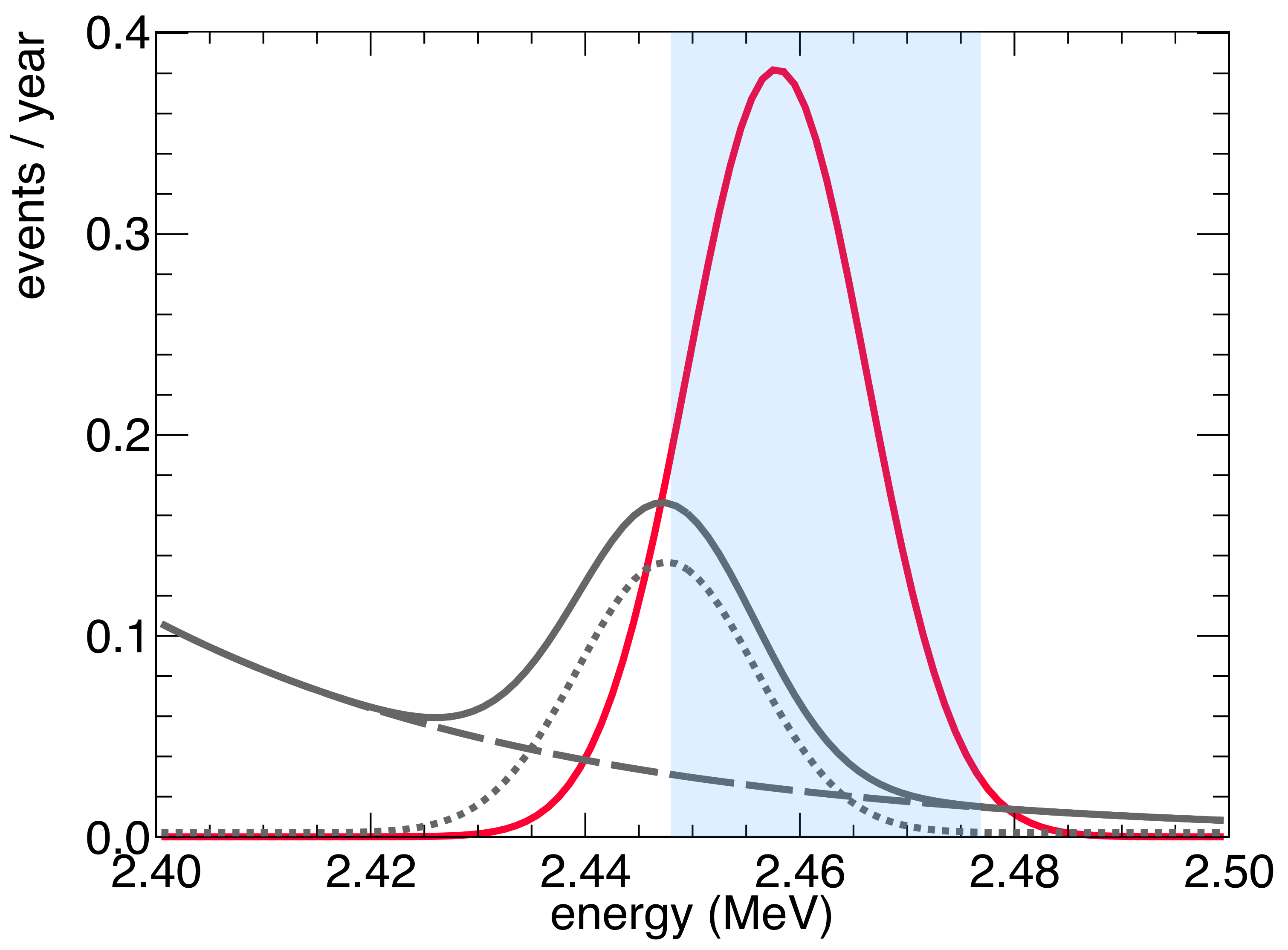
NEXT Collaboration, arXiv:1905.13625

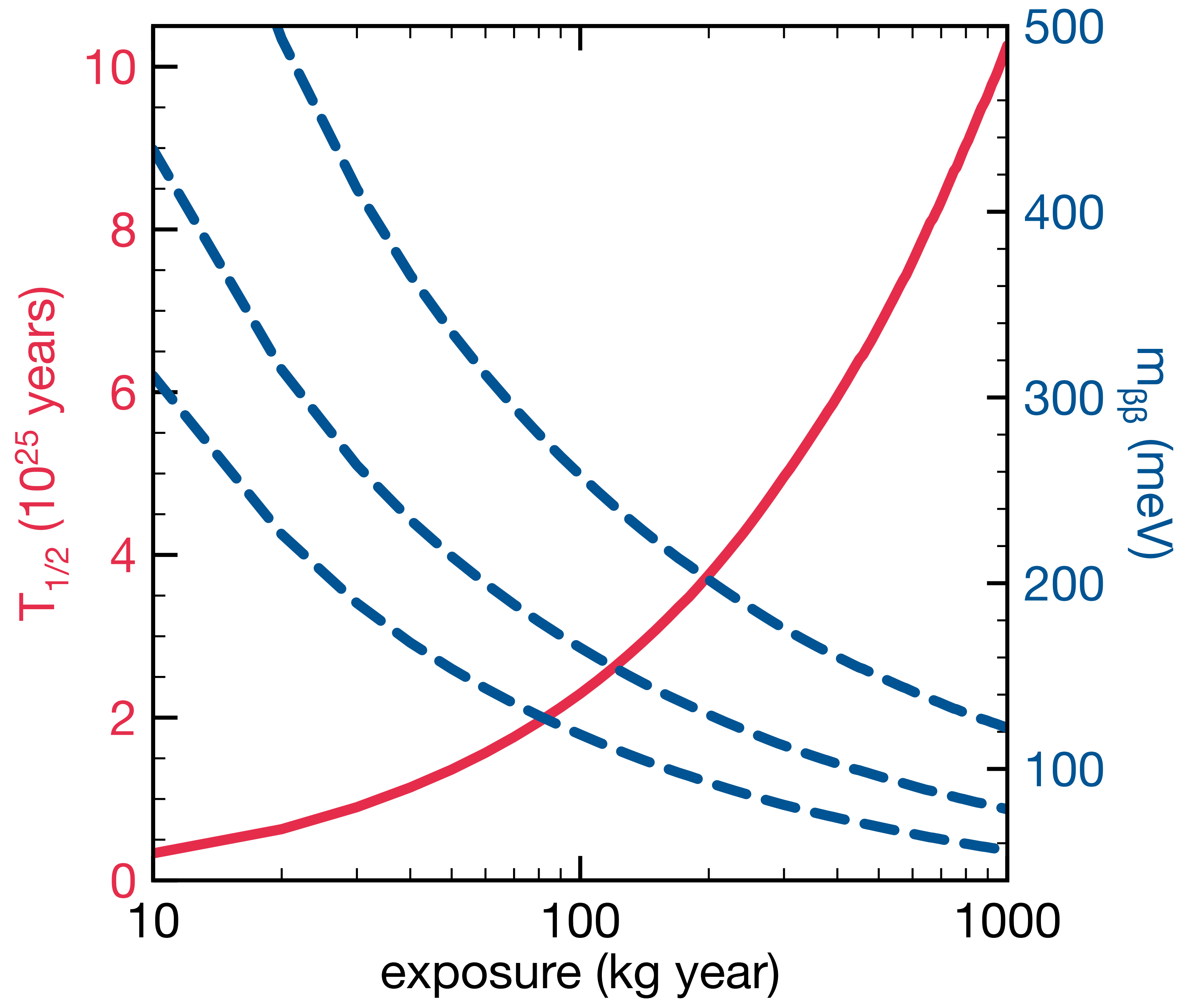
NEXT-100



NEXT-100: SENSITIVITY

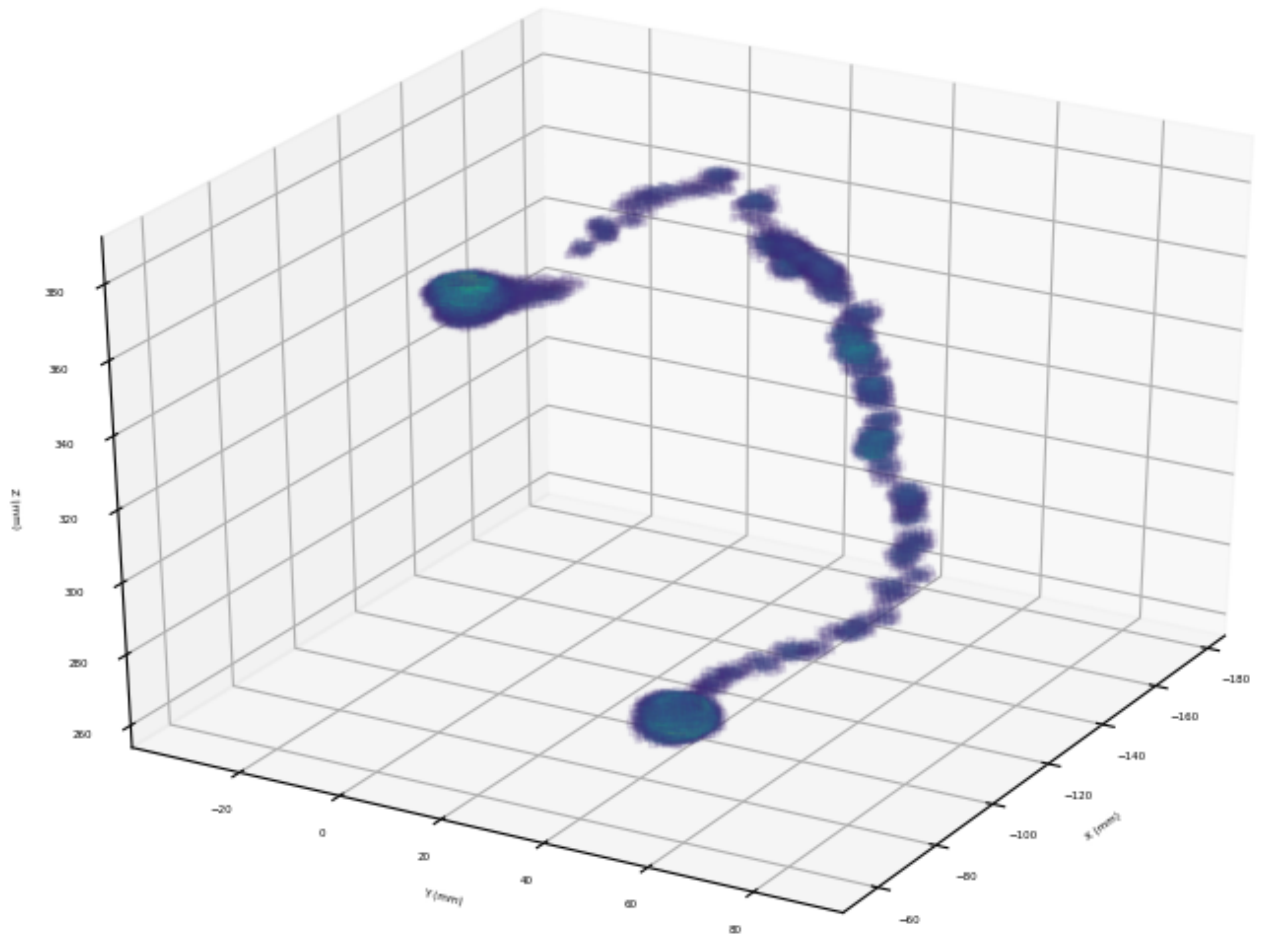


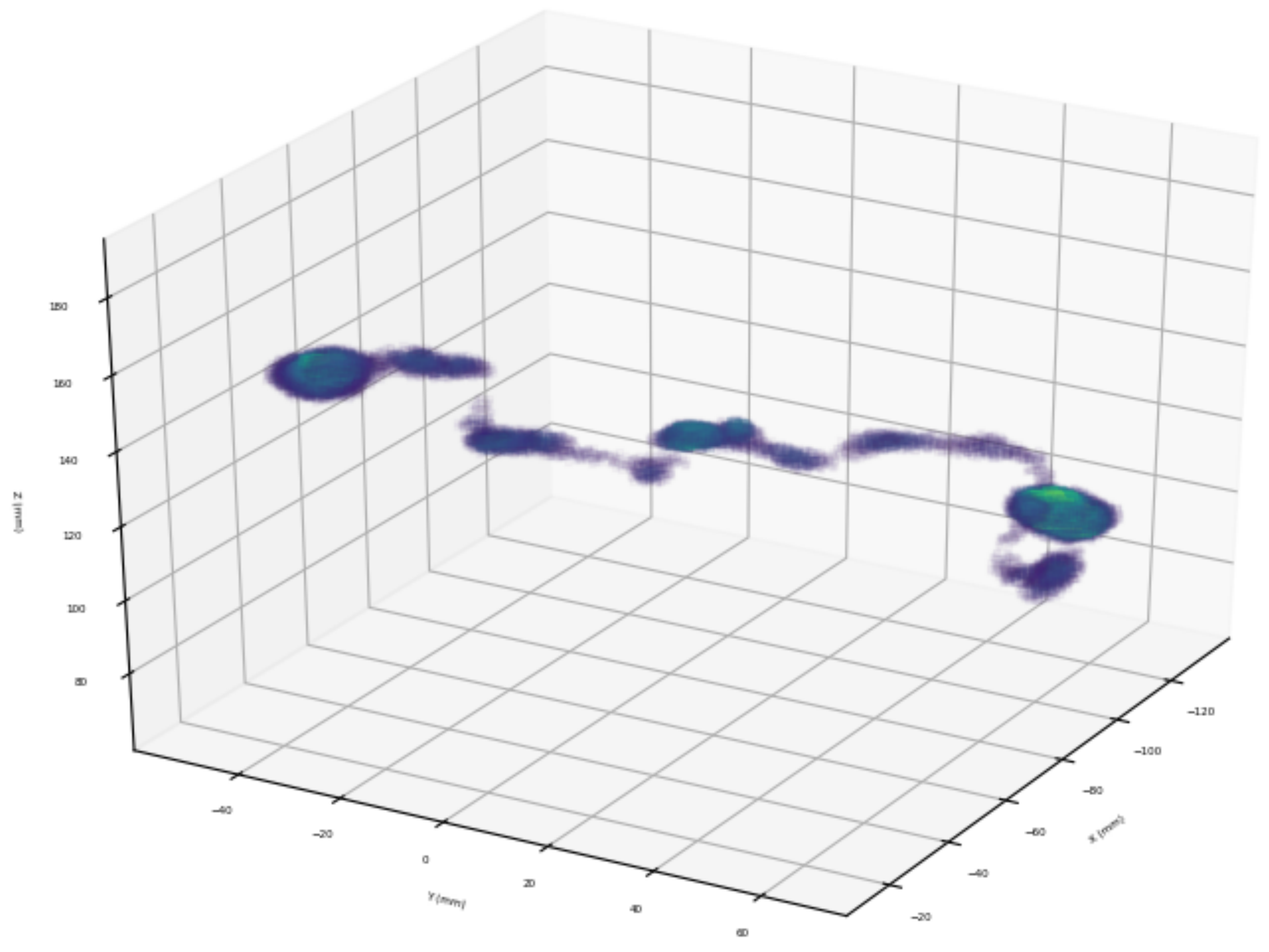




NEXT Collaboration, *JHEP* **1605** (2015) 159

NEXT-100: EVENT TOPOLOGY





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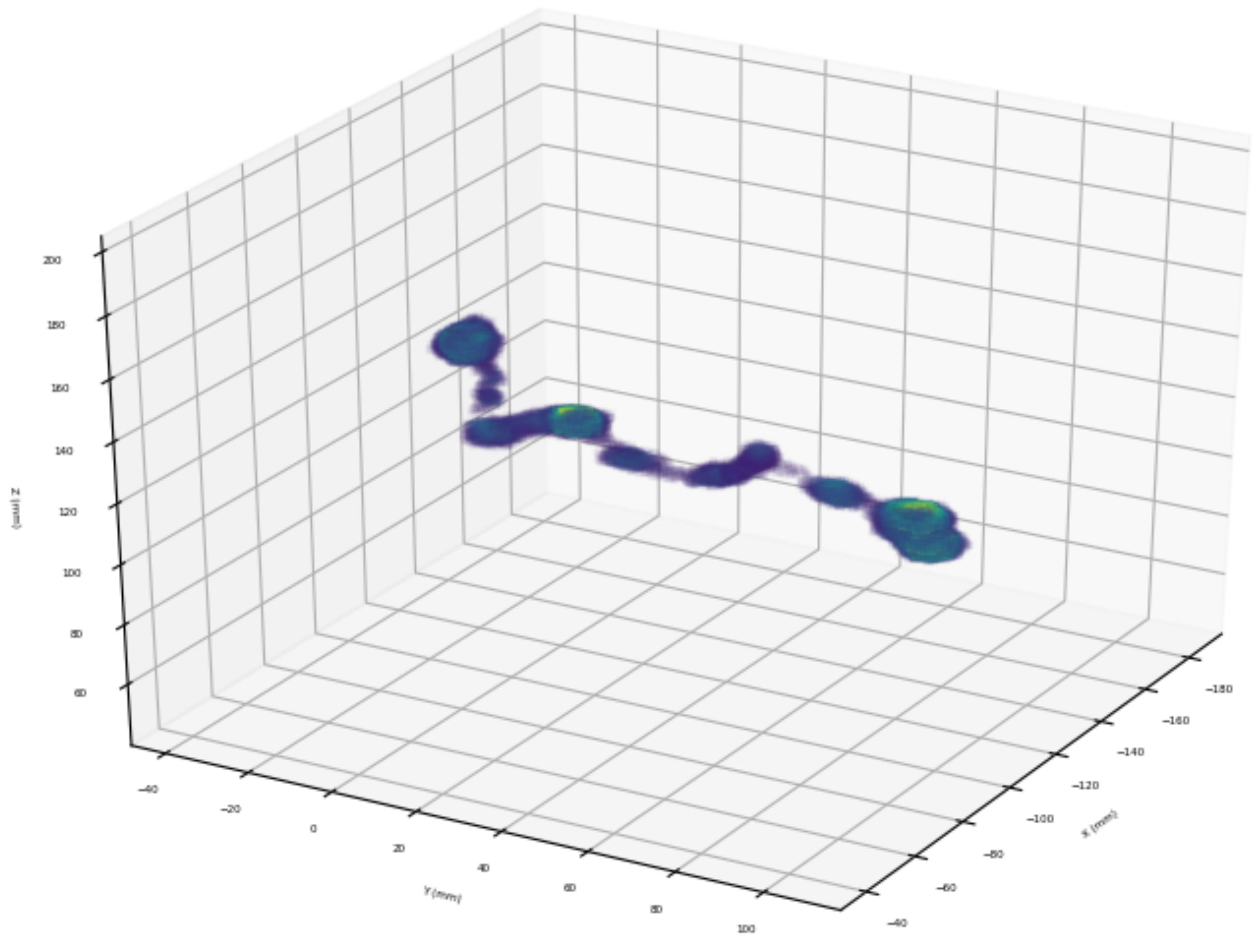

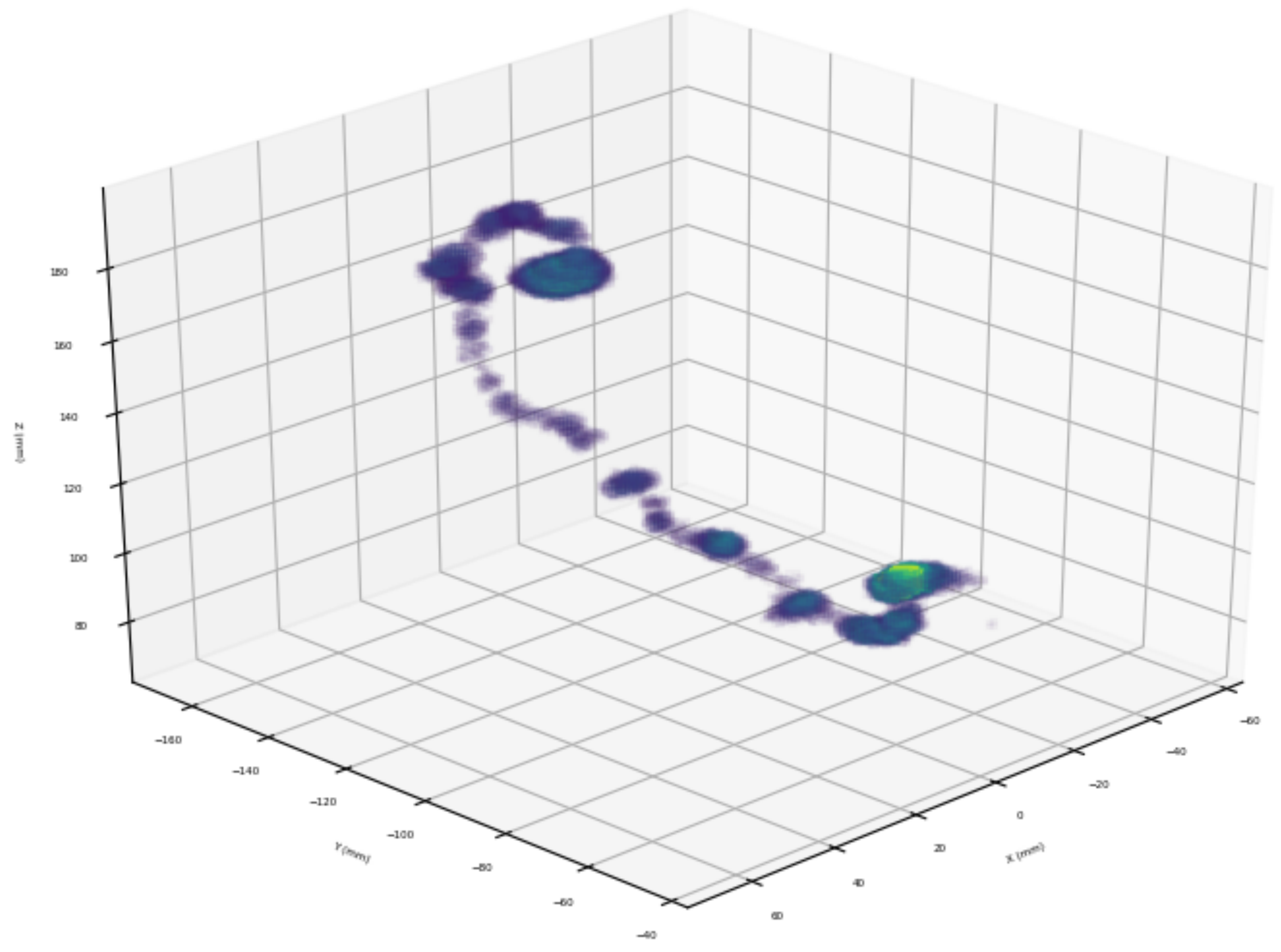

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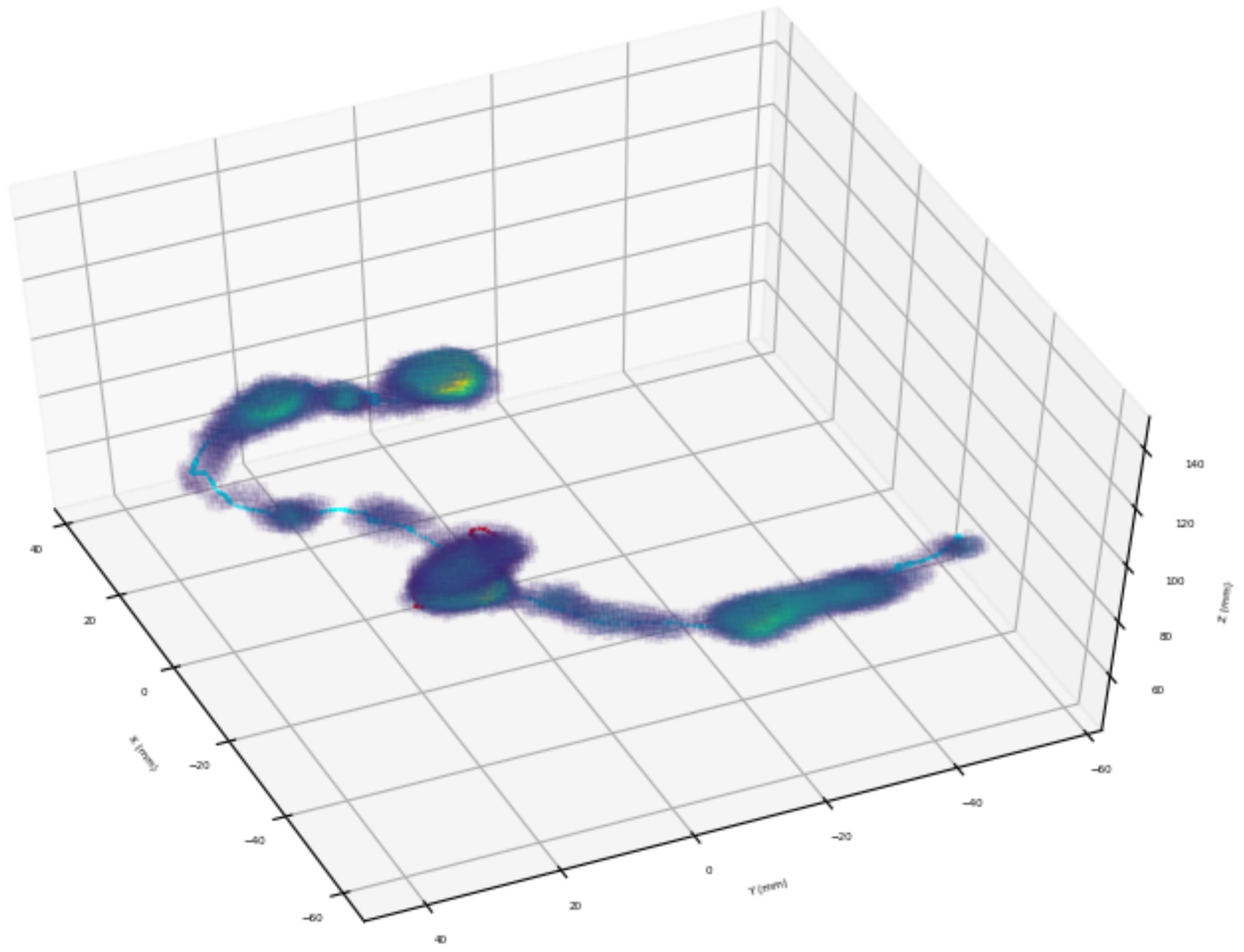
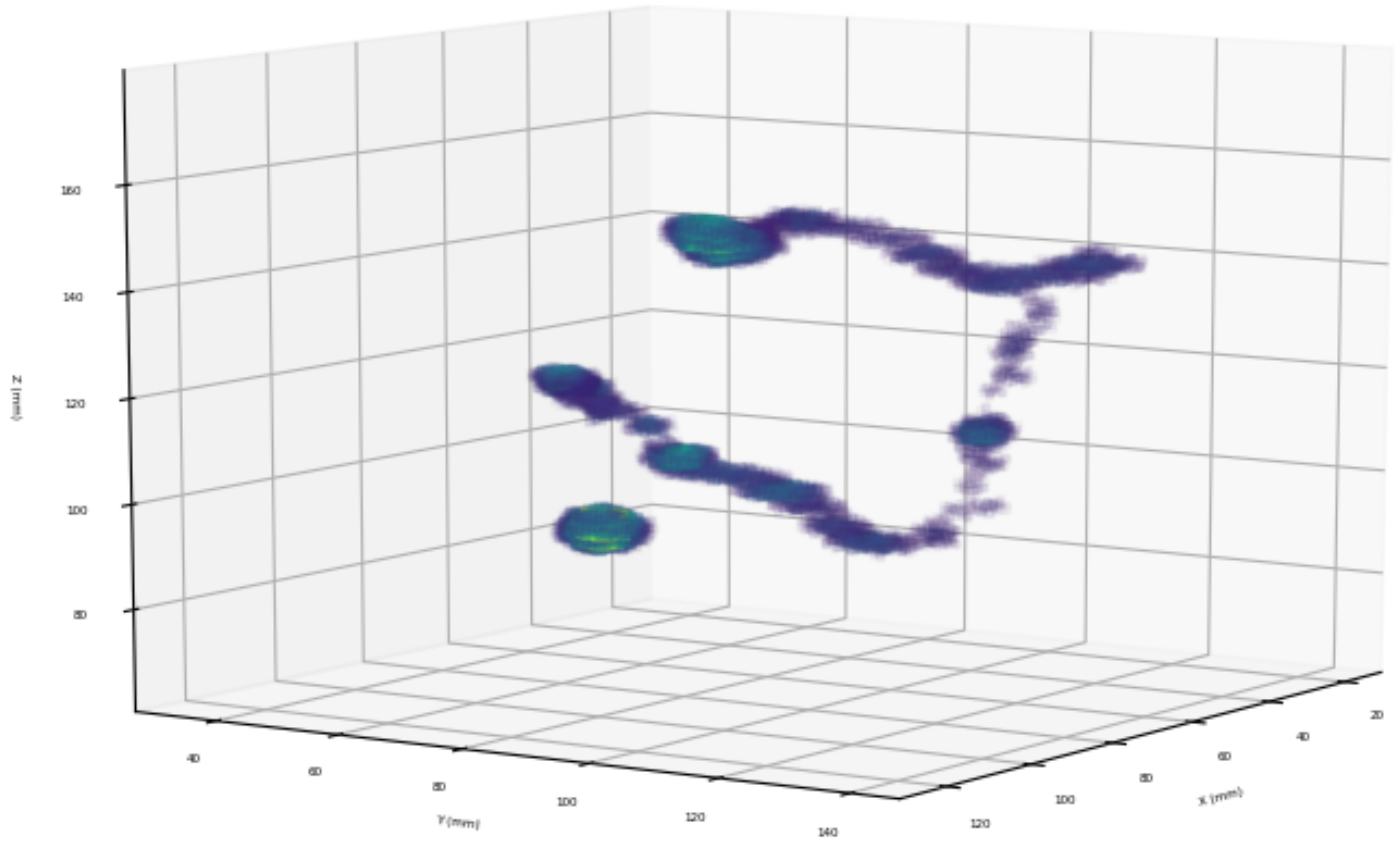
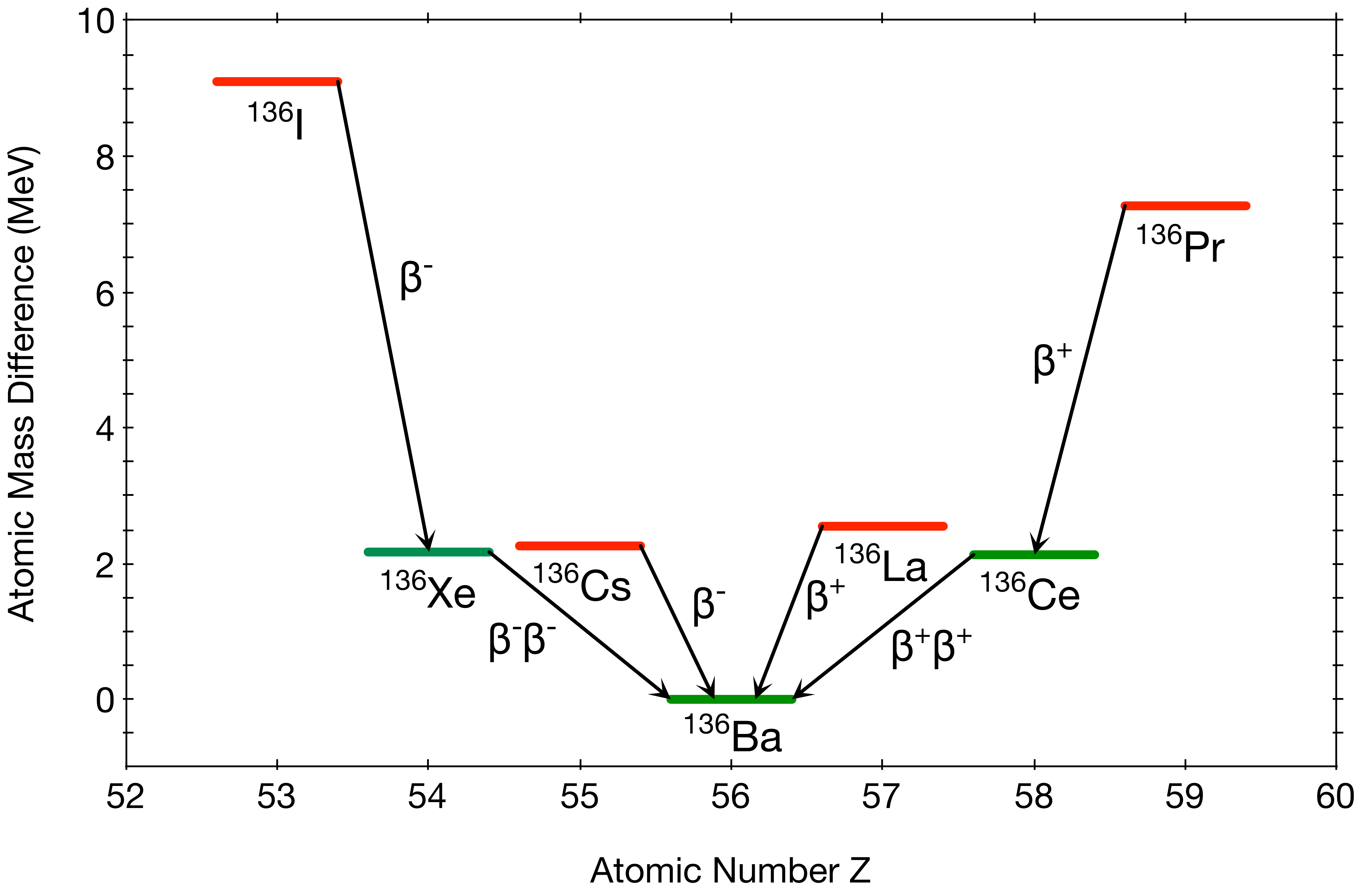


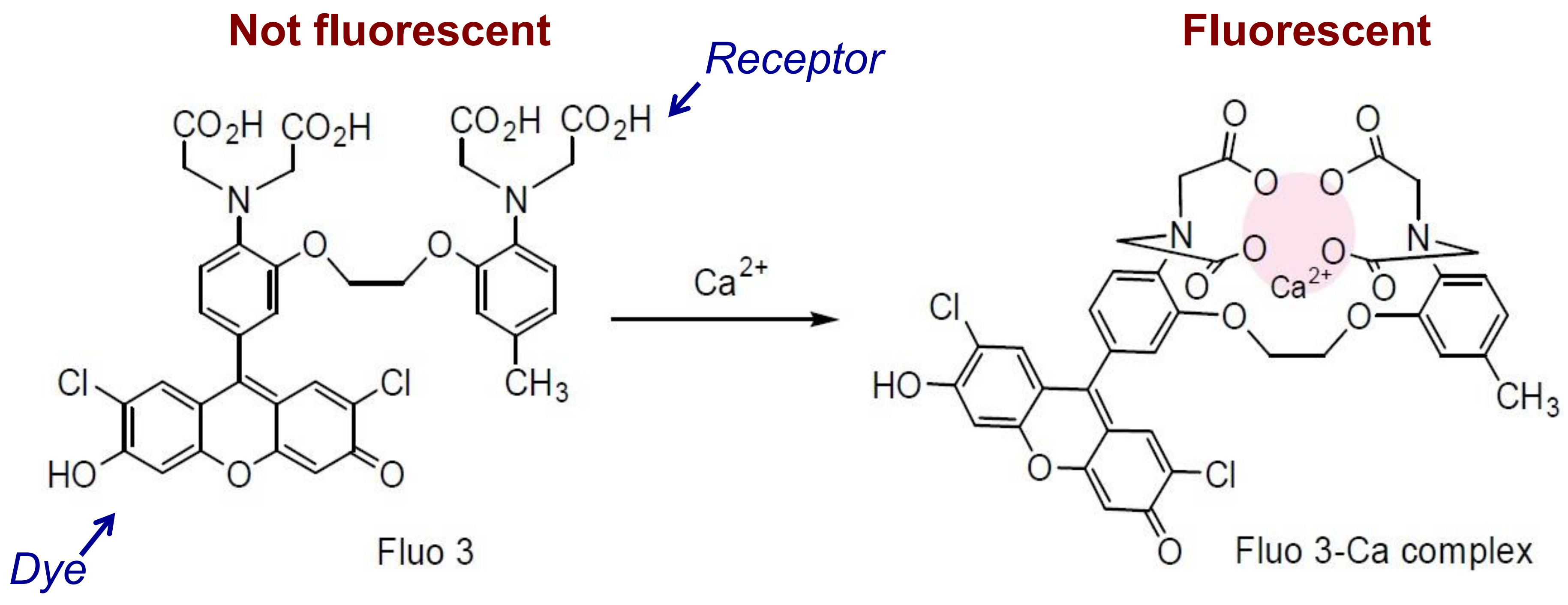


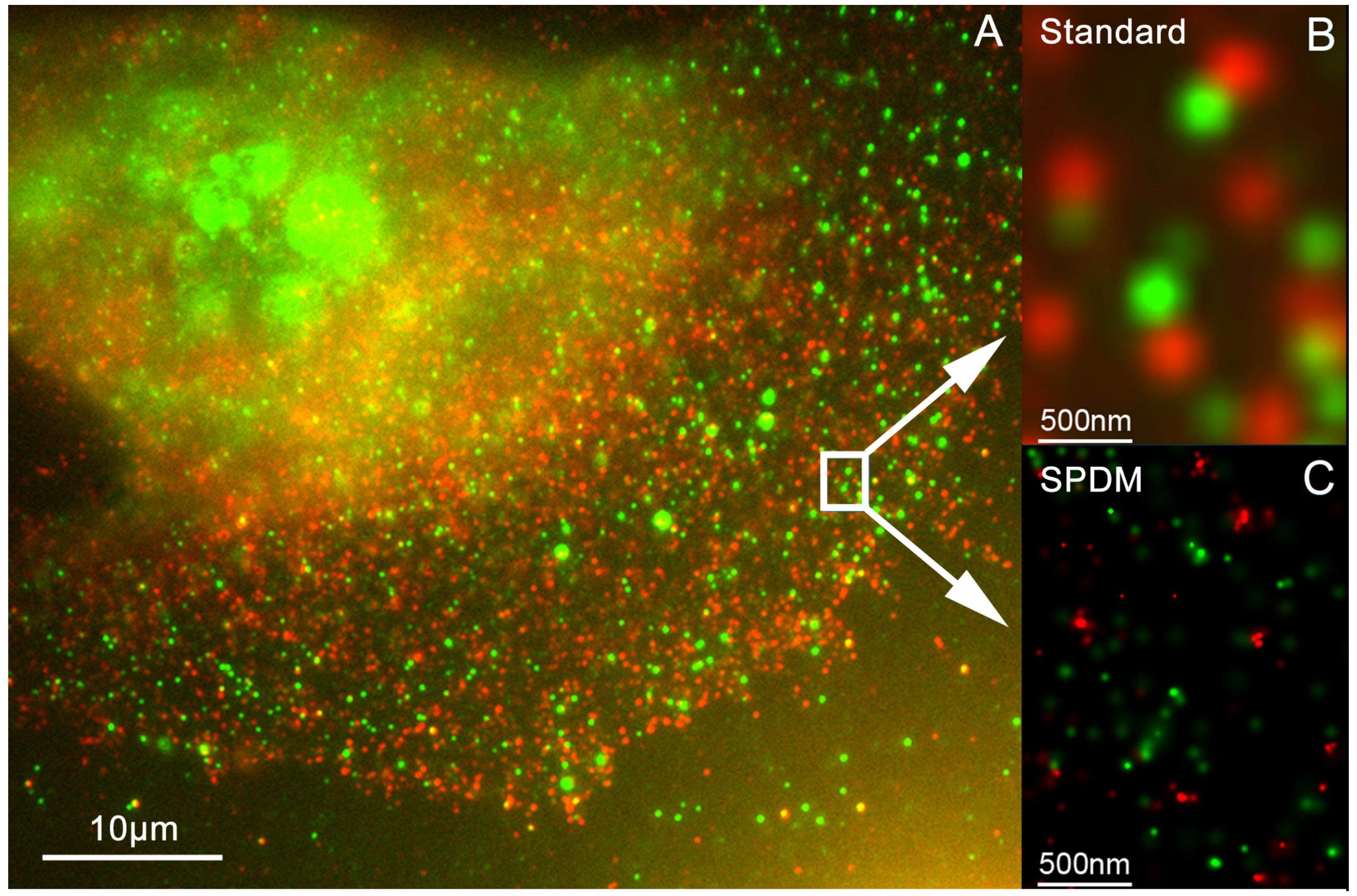
TOWARDS THE TONNE SCALE: BA TAGGING



Tagging of the Ba ion produced in a double beta decay would result in a *zero-background* experiment. It has been actively explored in gaseous and liquid xenon for 15+ years.

TOWARDS THE TONNE SCALE: BA TAGGING

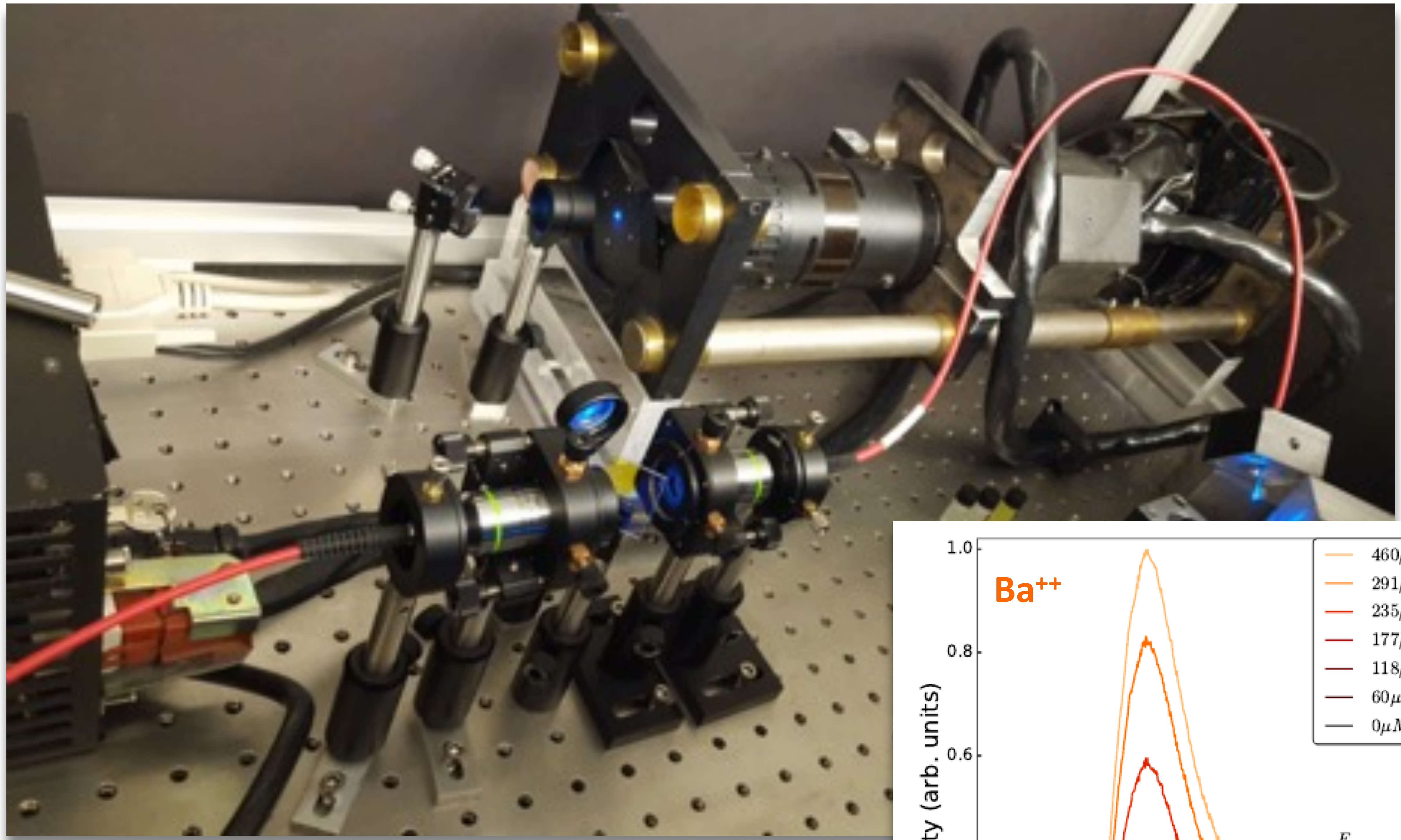


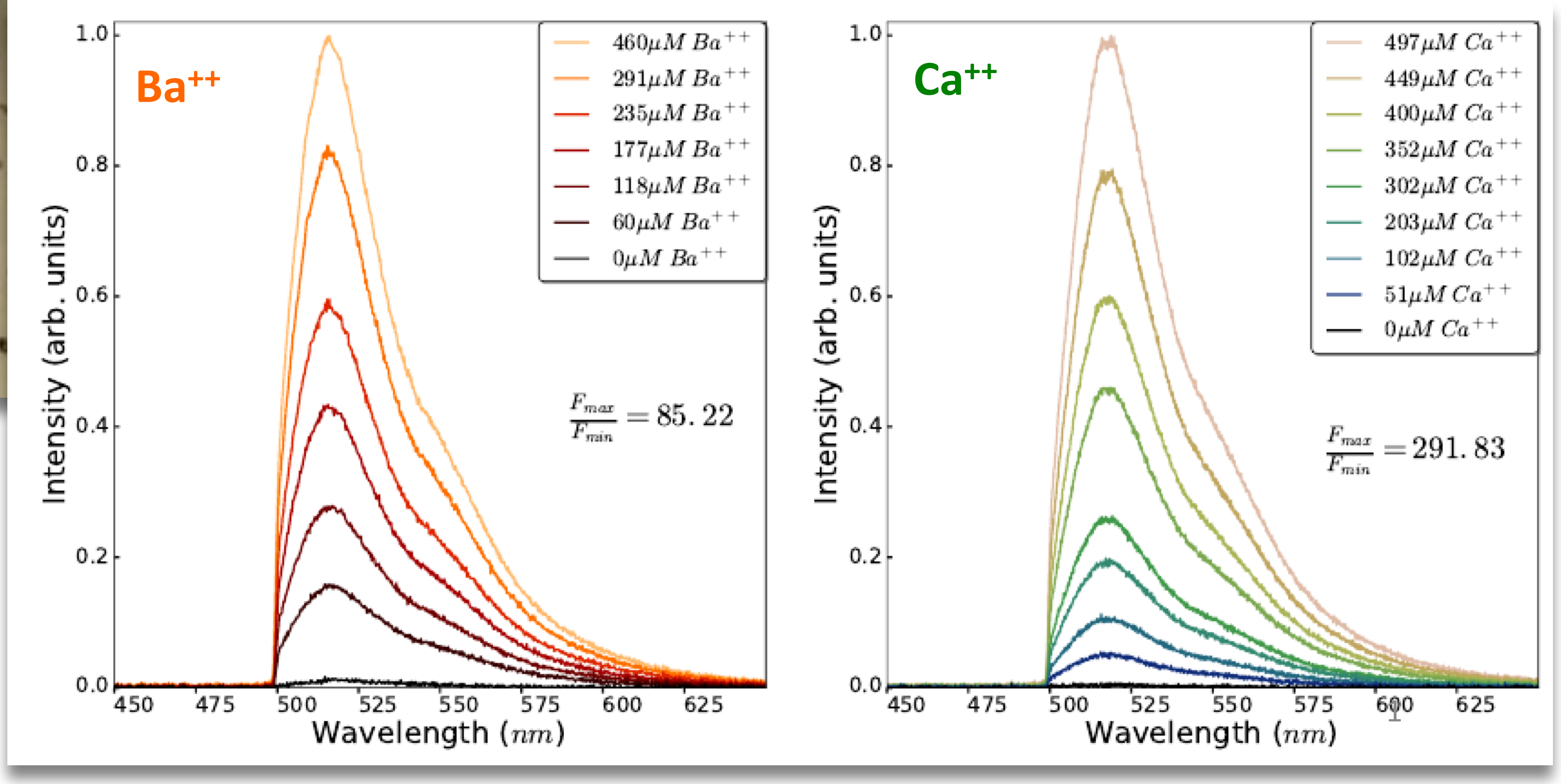


SMFI is a technique from biochemistry with proven single-ion resolution that was awarded a Nobel prize in chemistry in 2014. A non-fluorescent molecule becomes fluorescent upon chelation with an incident ion.

Calcium and barium are congeners: many dyes developed for Ca are also expected to respond to Ba. Can we use SMFI to identify a single Ba ion in a xenon gas volume?

D.R. Nygren, *J. Phys. Conf. Ser.* **650** (2015) 012002





Strong fluorescence from Fluo3 and Fluo4 under chelation with Ba++ ions.

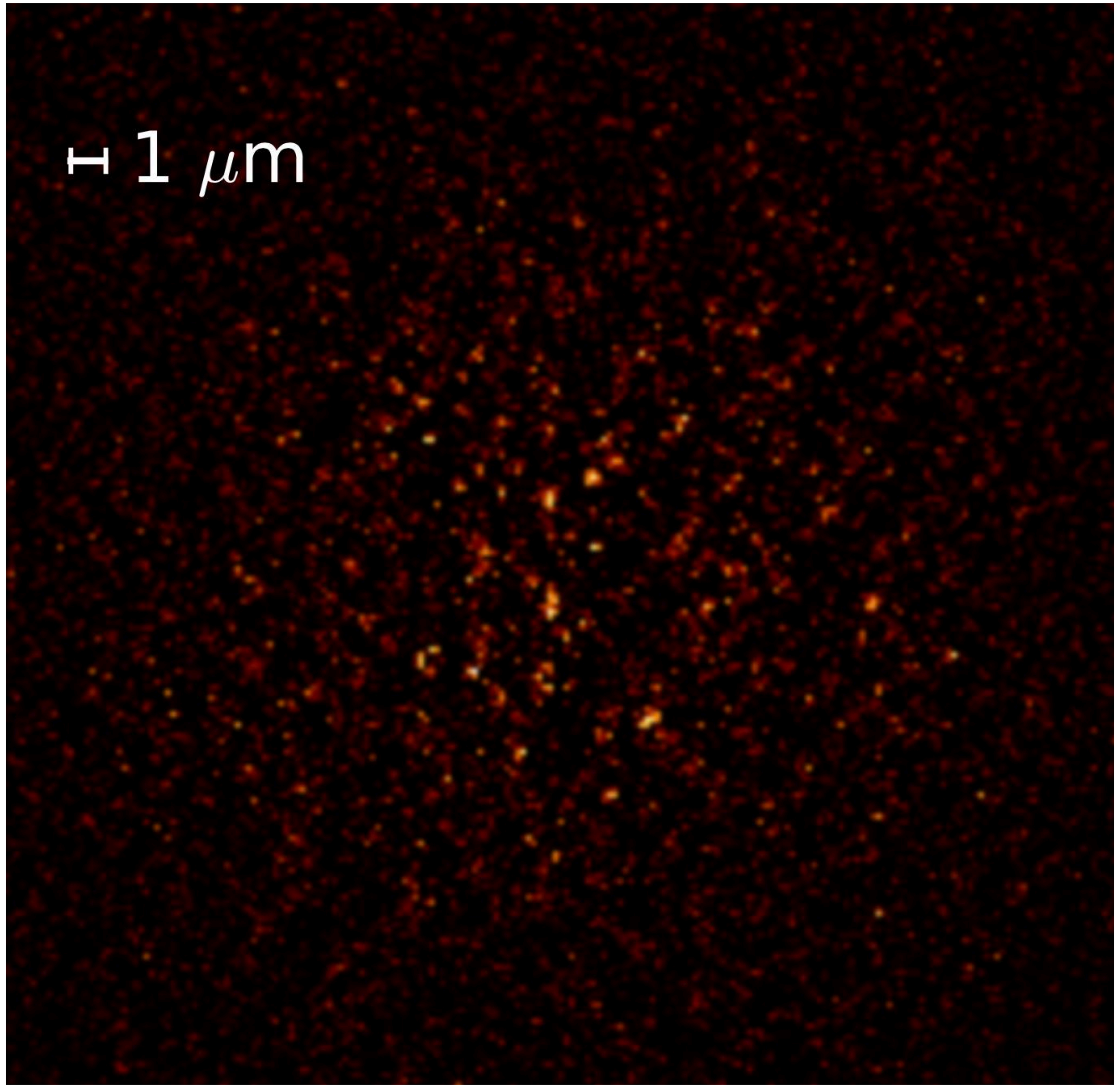
Jones, McDonald, Nygren, *JINST* **11** (2016) P12011

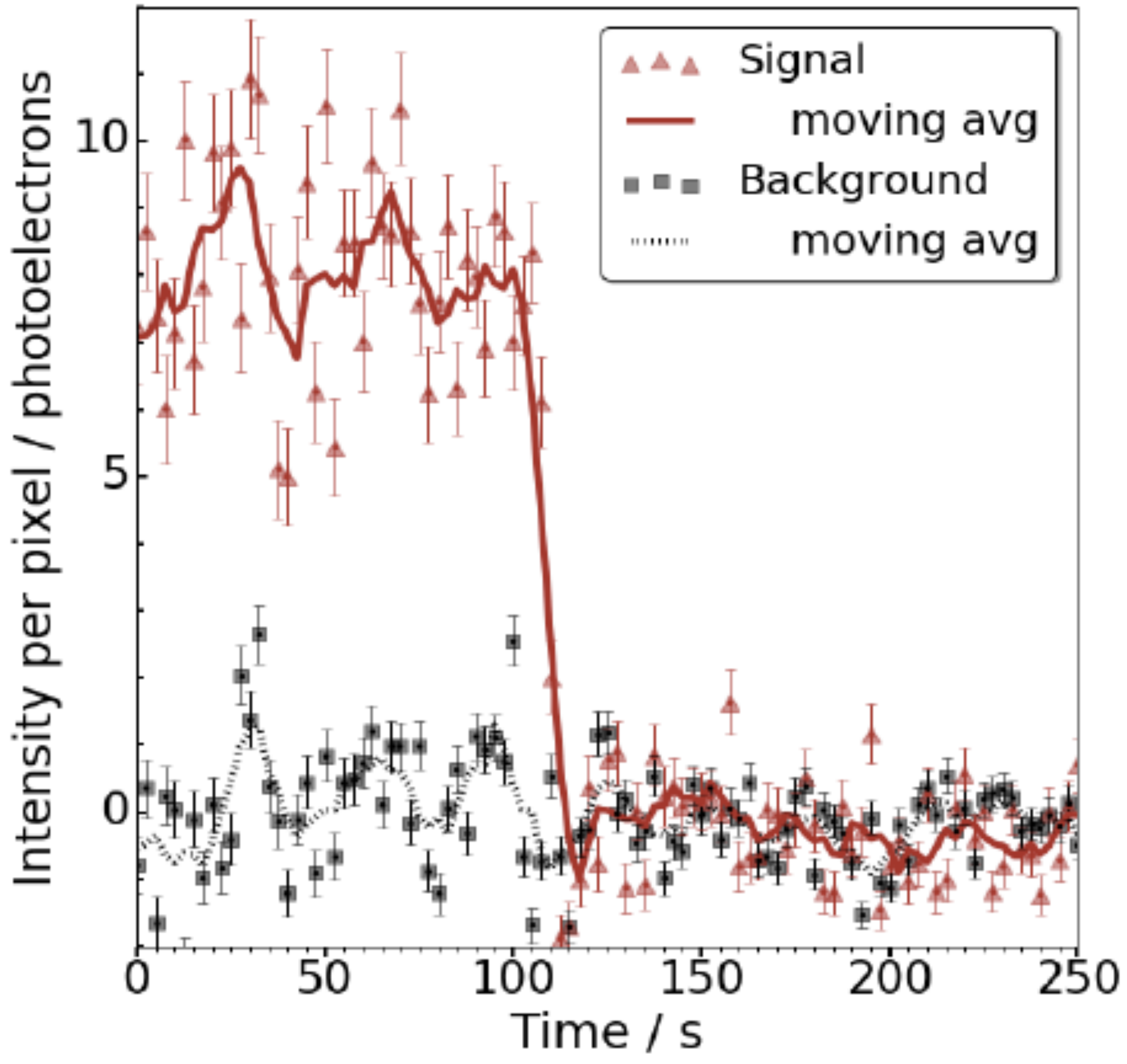
The image shows a weak solution of barium perchlorate salt on a total internal reflection microscope developed at UTA.

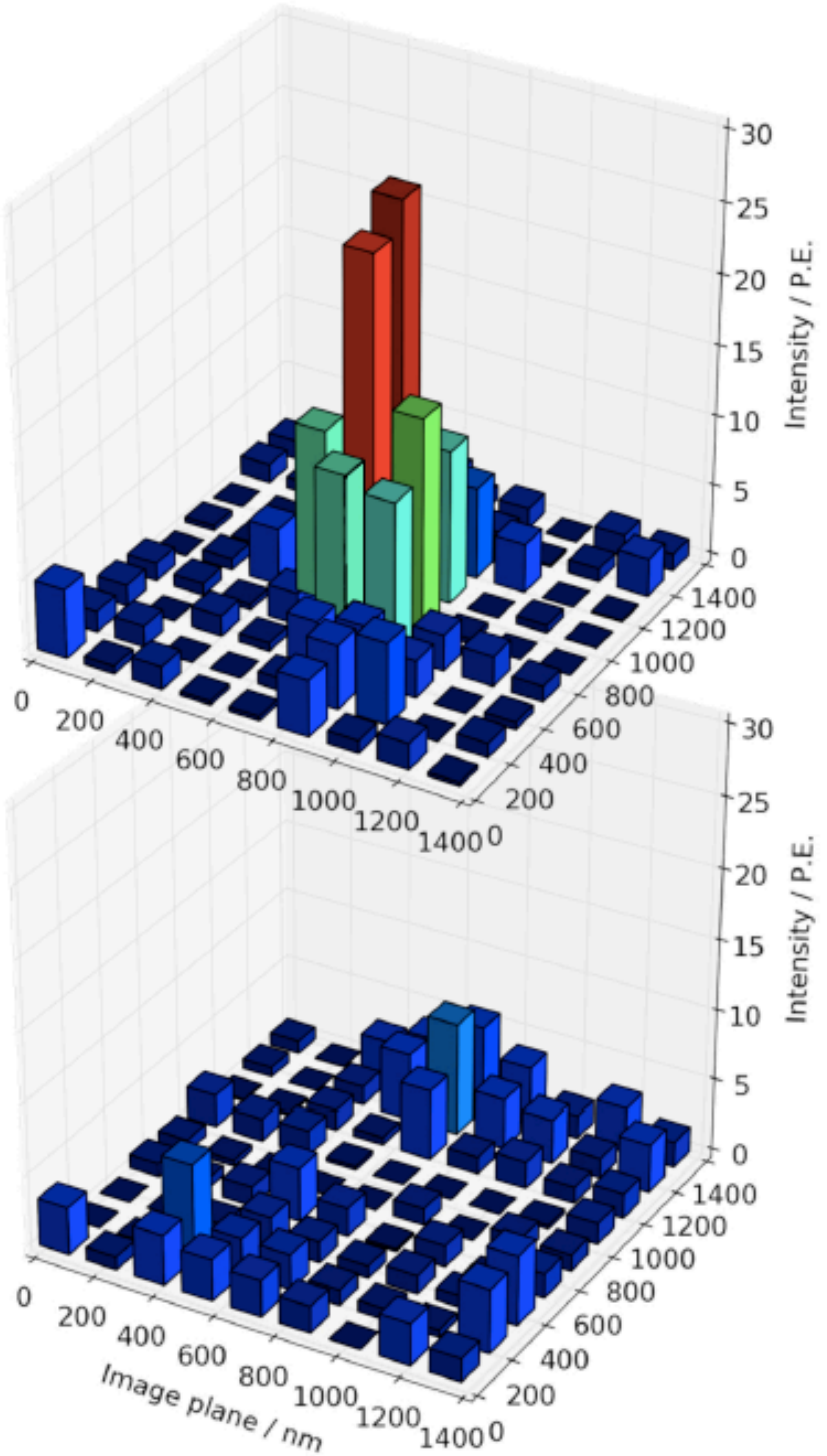
Each spot is a single barium ion.

Brighter spots are near the microscope surface, dimmer ones are deeper in the sample.

In a xenon detector, dye would be deposited as a monolayer: only brightest spots at constant depth expected.







First demonstration of single barium ion resolution!

NEXT Collaboration, *Phys. Rev. Lett.* **120** (2018) 132504

SUMMARY

Neutrinoless double beta decay searches are the most promising (likely the only) way to establish that neutrinos are Majorana particles.

The current generation of experiments is exploring the degenerate region of neutrino masses. Going forward, double beta decay experiments will require exposures well above 10^3 kg yr and background rates below 1 counts tonne^{-1} yr^{-1}.

NEXT has proven that a GXe TPC can provide both high energy resolution and tracking for event identification. NEXT-100 will probably be the most sensitive experiment using ^{136}Xe, according to the background rate measured in NEXT-White.

There's a clear path to improve NEXT towards the ton scale: reach energy resolutions close to the intrinsic limit (<0.5% FWHM) and improve the rejecting power of the tracking signature.

R&D on chemical tagging of Ba ions undergoing, with very promising results so far.