The NEXT experiment Status and Prospects

Lior Arazi for the NEXT Collaboration
Ben-Gurion University

XIX International Workshop on Neutrino Telescopes, 18-26 February 2021

next

USA

University of Texas Arlington · Argonne National Laboratory · Harvard · Fermilab · Texas A&M · Iowa State University · Pacific Northwest National Laboratory

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Portugal, Israel, Colombia

U C · universidade de aveiro · Ben-Gurion University of the Negev · UAN Universidad Antonio Nariño

LSC Laboratorio Subterráneo de Canfranc

Co-spokespersons:
D. Nygren
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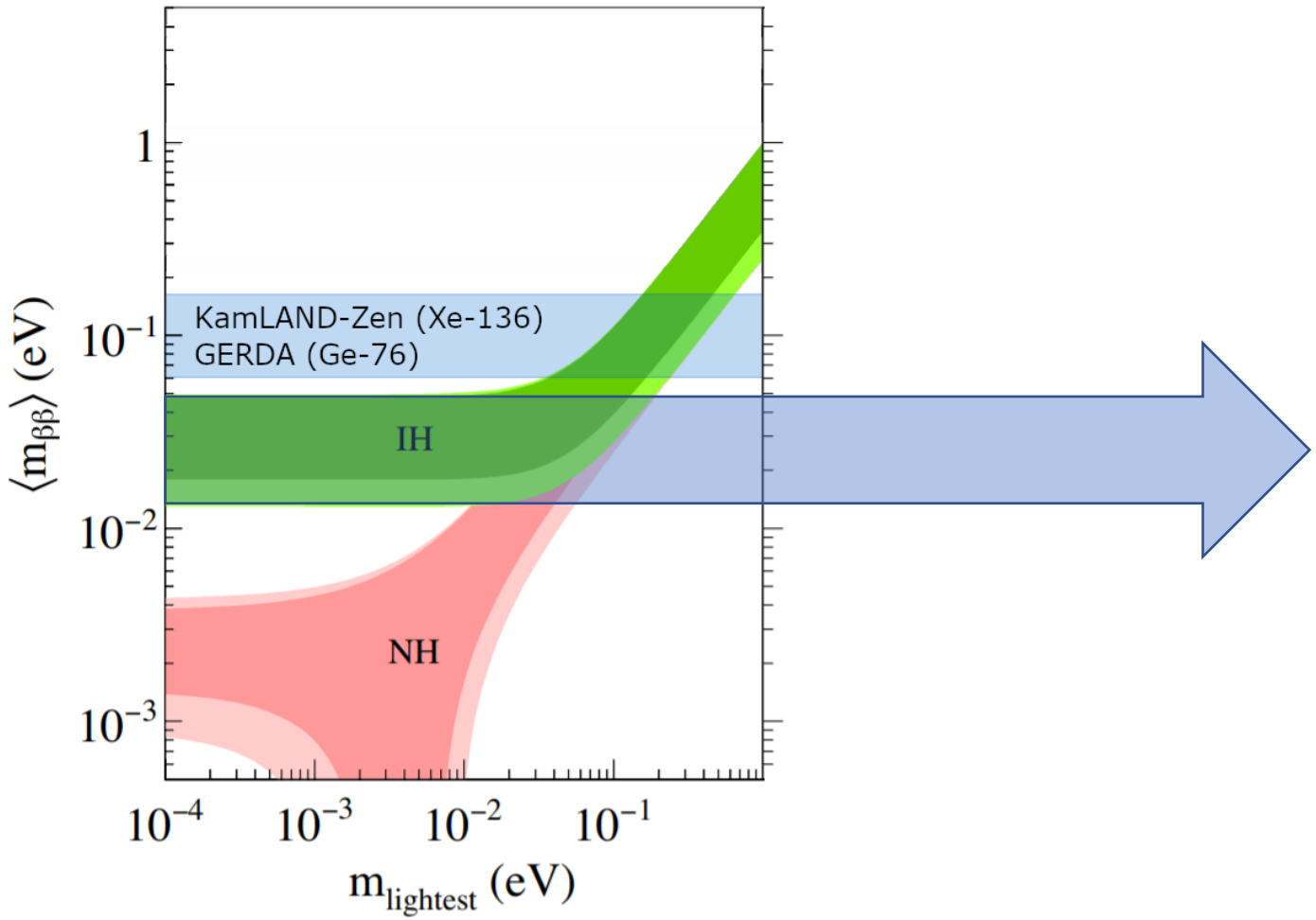
The challenge of next generation experiments



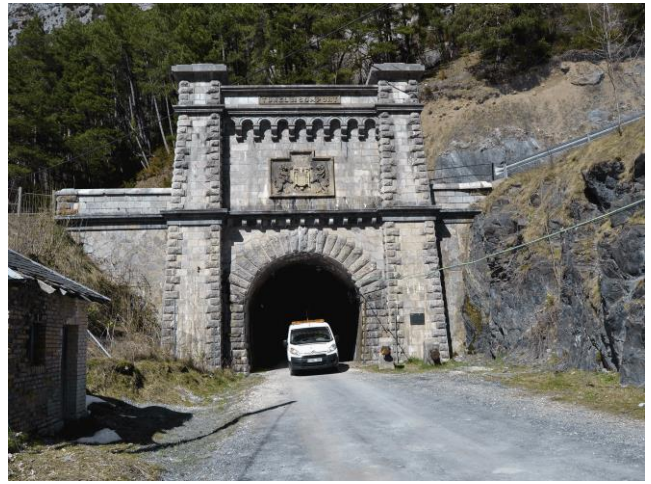
Next generation:

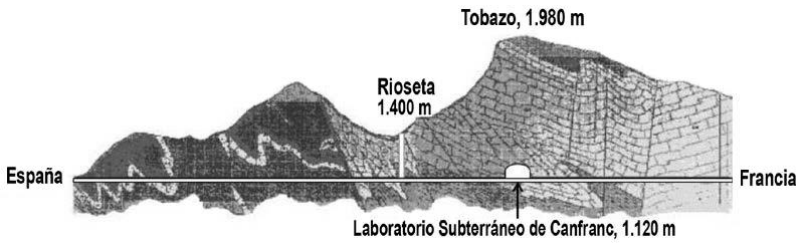
Lifetime ~10^{27}-10^{28} years. For ^{136}Xe: 0.3-3 events/tonne/yr

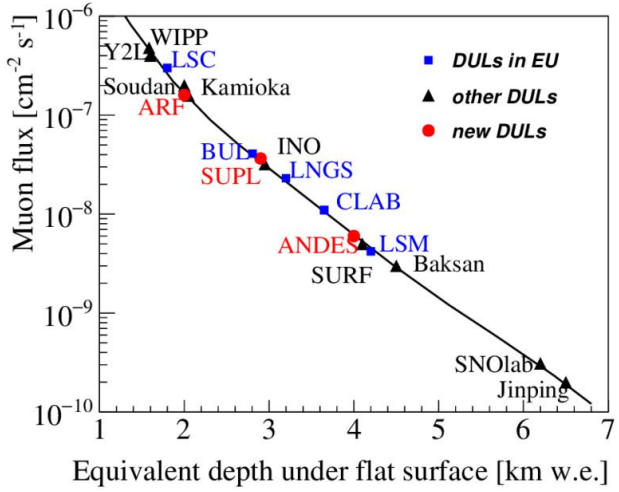
NEXT: Neutrino Experiment with a Xenon TPC

- Search for $\beta\beta0\nu$ in ^{136}Xe in a *high-pressure xenon gas* time projection chamber (TPC)
- Working in gas rather than liquid allows:
  - Excellent energy resolution with electroluminescence (demonstrated 1% FWHM at $Q_{\beta\beta}$=2.458 MeV, aiming at 0.5%)
  - Track topology: events span ~10 cm (vs. point-like in liquid) allowing signal/background discrimination based on track shape
- High pressure required to assemble enough mass in a reasonable volume
- Currently concluding 4 years of NEXT-White (~5 kg of 90% enriched Xe at 10 bar in active volume); Aims: demonstrate the technology on a large scale and measure $\beta\beta2\nu$
- NEXT-100 (97 kg enriched Xe at 15 bar in active volume) to be built this year

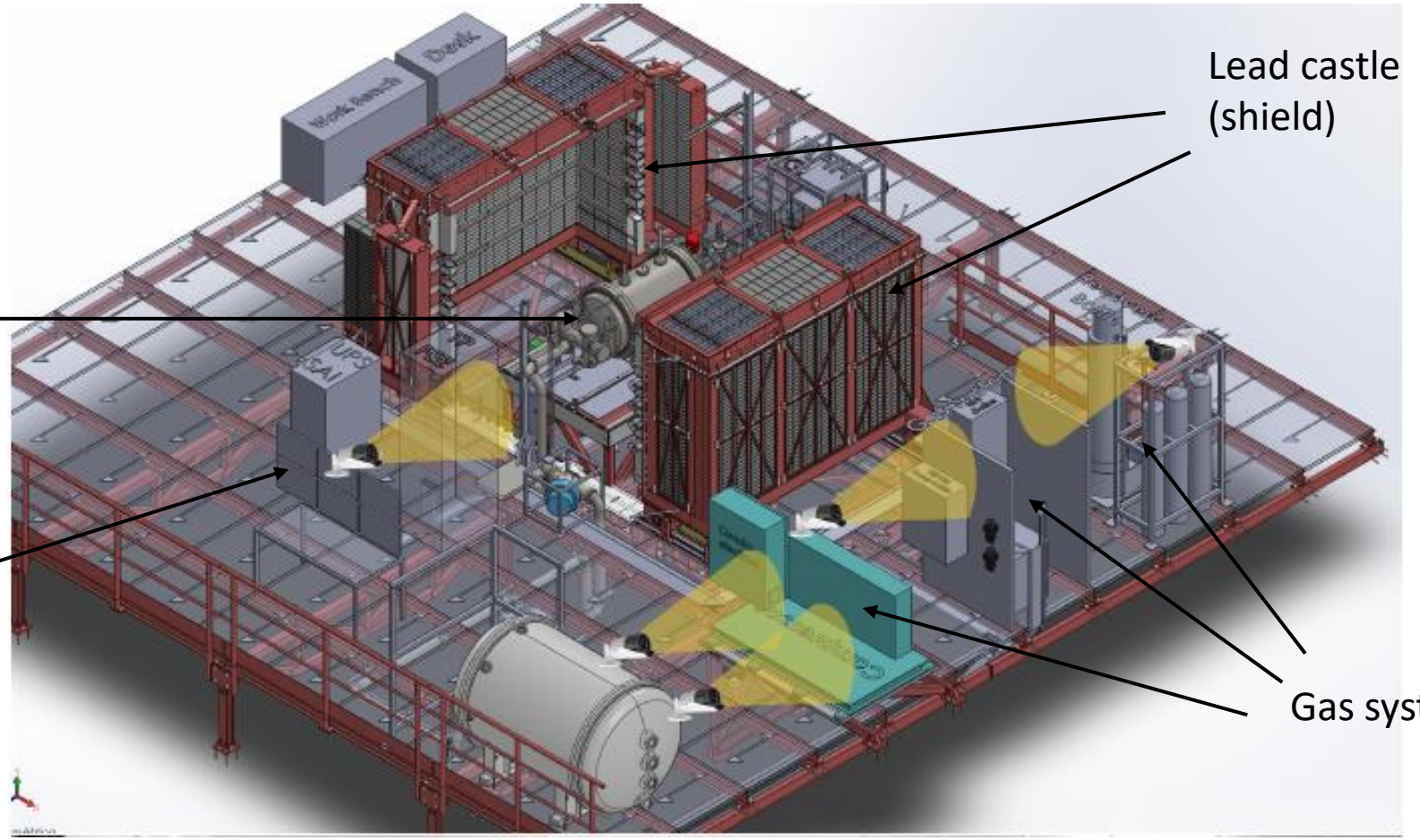
Canfranc underground laboratory (LSC)







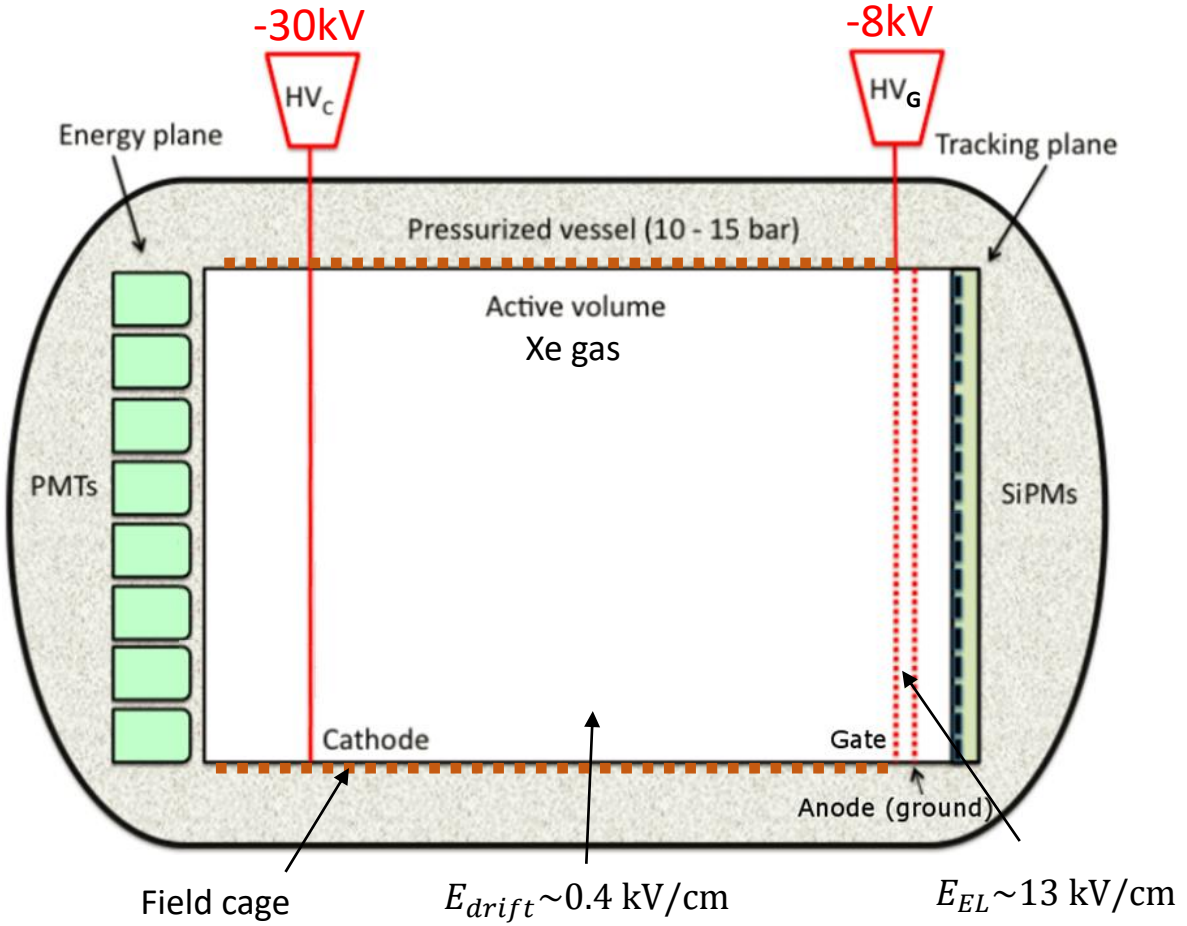
NEXT-White outside view



NEXT-White outside view

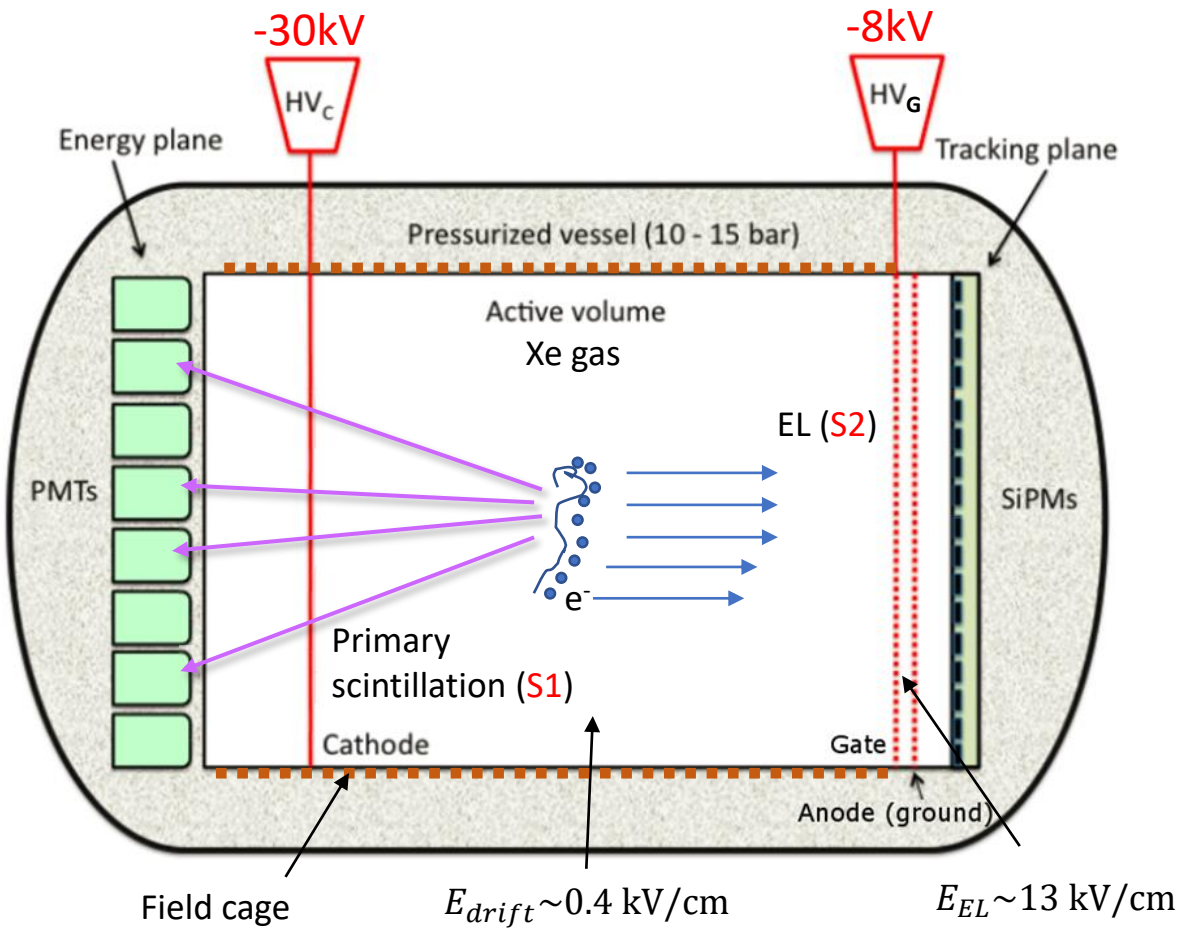
NEXT principle of operation (demonstrated in NEXT-White)

- Horizontal Time Projection Chamber (TPC)
- Full of high-purity xenon gas at 10 bar, contained in a high-pressure vessel
- Three conductive planes + peripheral "field shaping rings" define two uniform field regions:
  - The cathode and gate stainless steel grids (53 cm apart) define the drift field
  - The gate grid and anode plate (6 mm apart) define the electroluminescence (EL) field
- TPC diameter: 39.6 cm
- 12 PMTs behind the cathode form the "energy plane"
- 1792 SiPMs behind the anode define the "tracking plane"



NEXT principle of operation (demonstrated in NEXT-White)

- Particle interaction inside Xe releases a fast electron
- It excites and ionizes Xe atoms along its track
- De-excitation of excited states gives a prompt flash of UV light ("S1")
- S1 is recorded by the PMTs to give the start time of the event t_0
- The free ionization electrons drift to the EL gap



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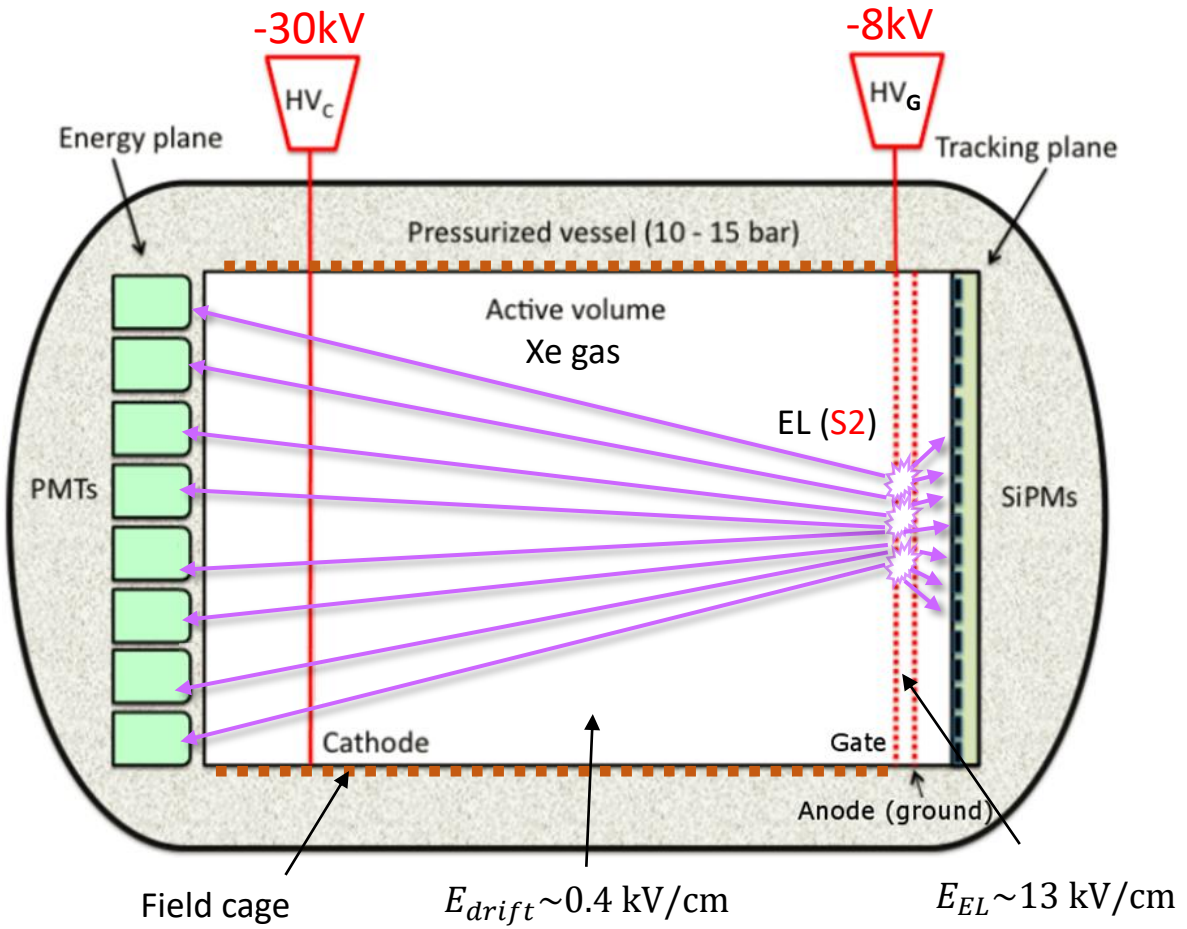
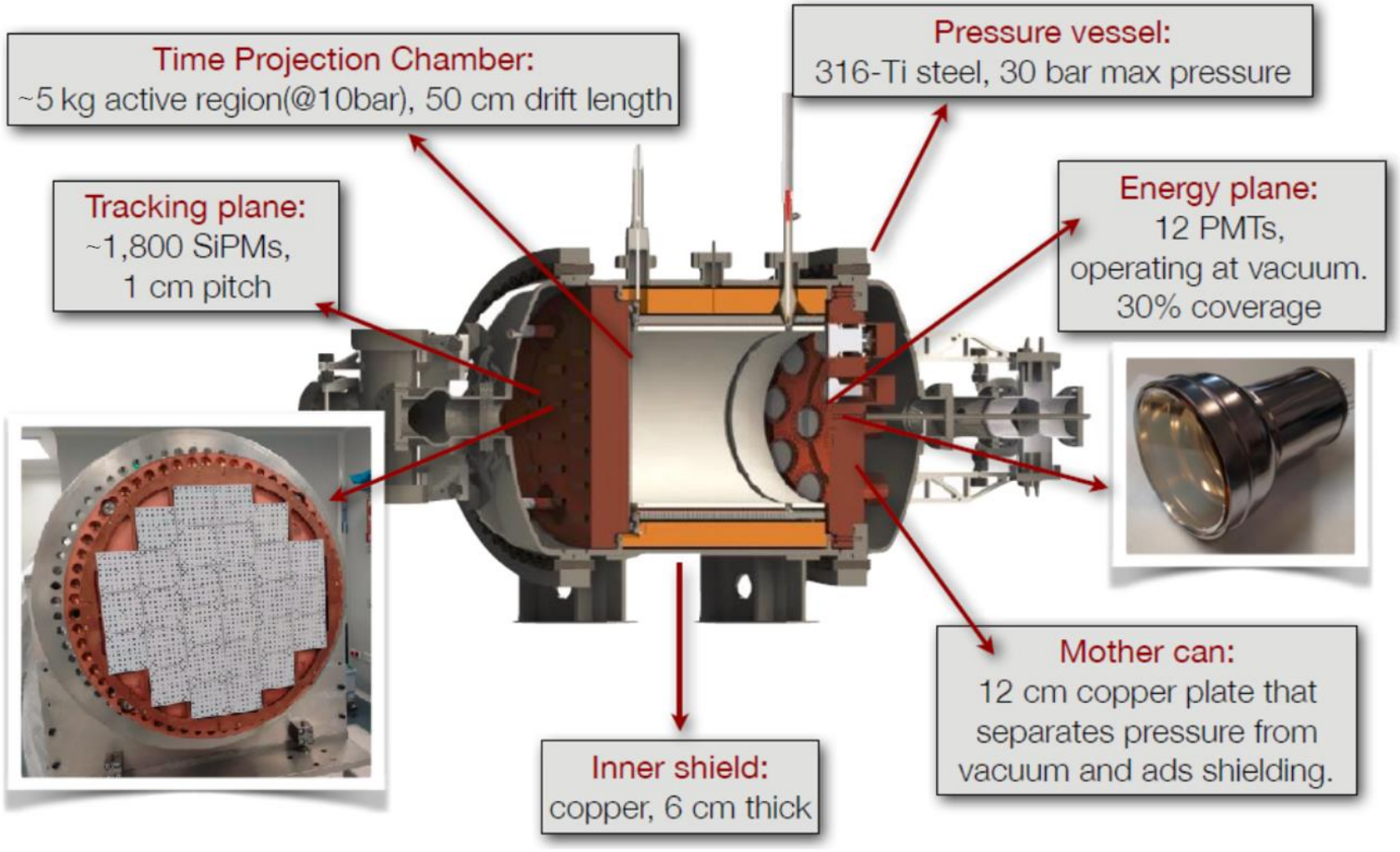
- De-excitation of excited states gives a prompt flash of UV light ("S1")
- S1 is recorded by the PMTs to give the start time of the event t_0
- The free ionization electrons drift to the EL gap
- When they cross it they produce a long pulse of EL light ("S2")
- The PMTs use S2 to find the energy of the event
- The SiPMs record the light pattern in 2D slices giving the shape ("topology") of the event

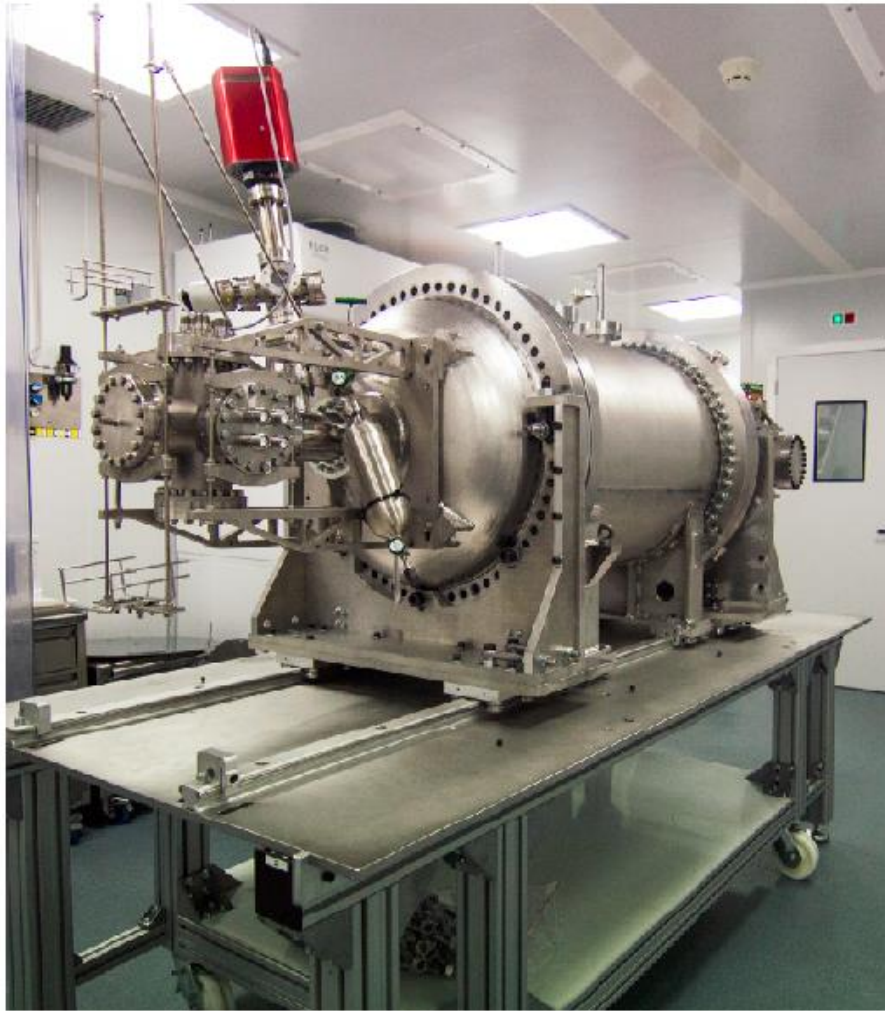


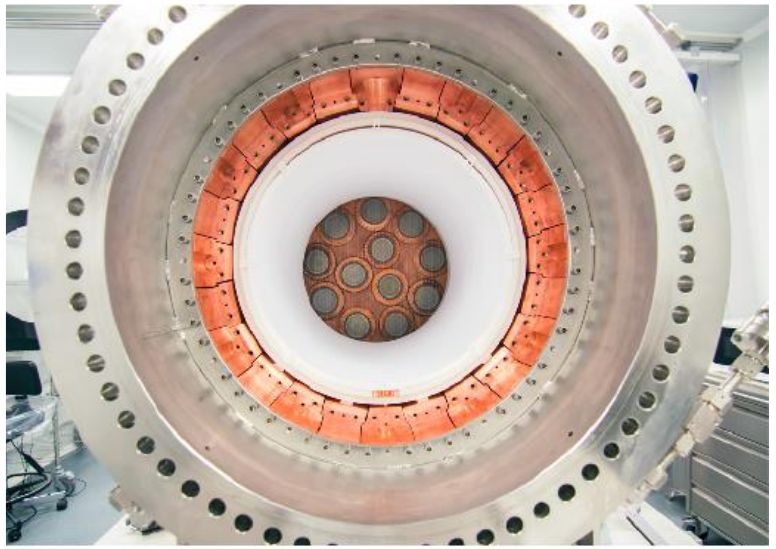
NEXT-White inner structure

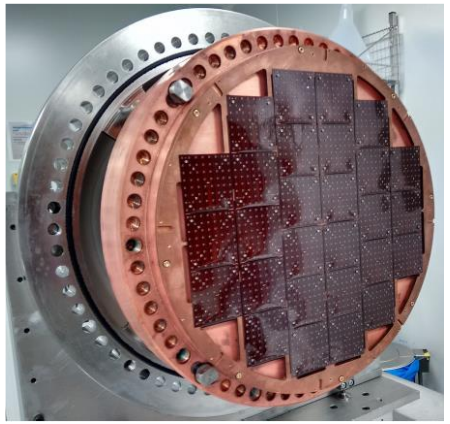


F. Monrabal *et al* 2018 *JINST* **13** P12010

NEXT-White inner structure

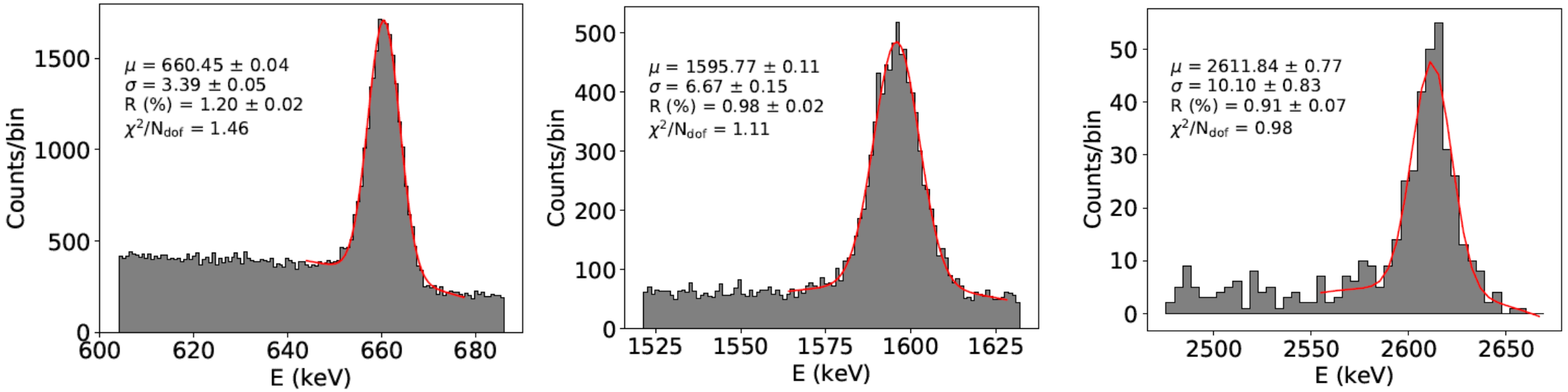






Energy resolution

- Energy resolution determined using ^{137}Cs (662 keV) and ^{208}Tl (1593, 2615 keV).
- Long tracks corrected voxel-by-voxel with ^{83m}Kr calibration maps

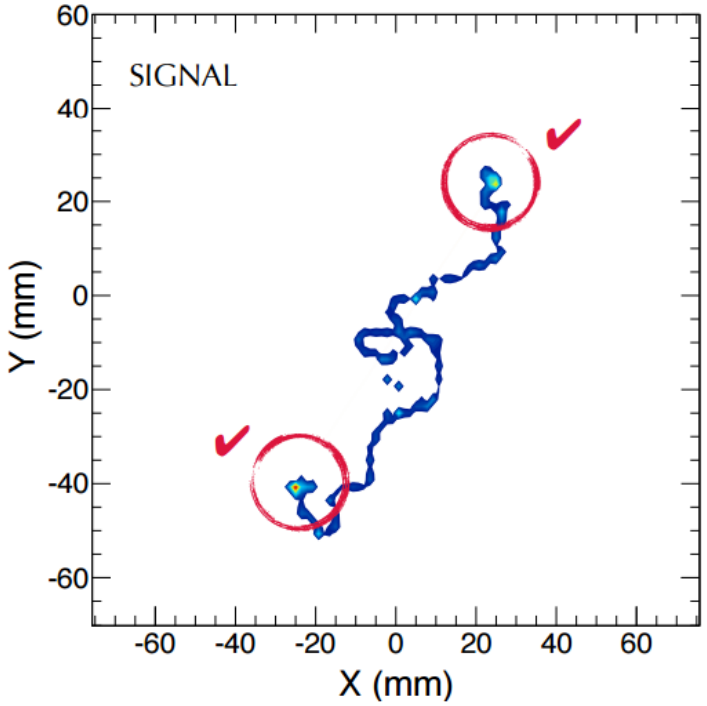


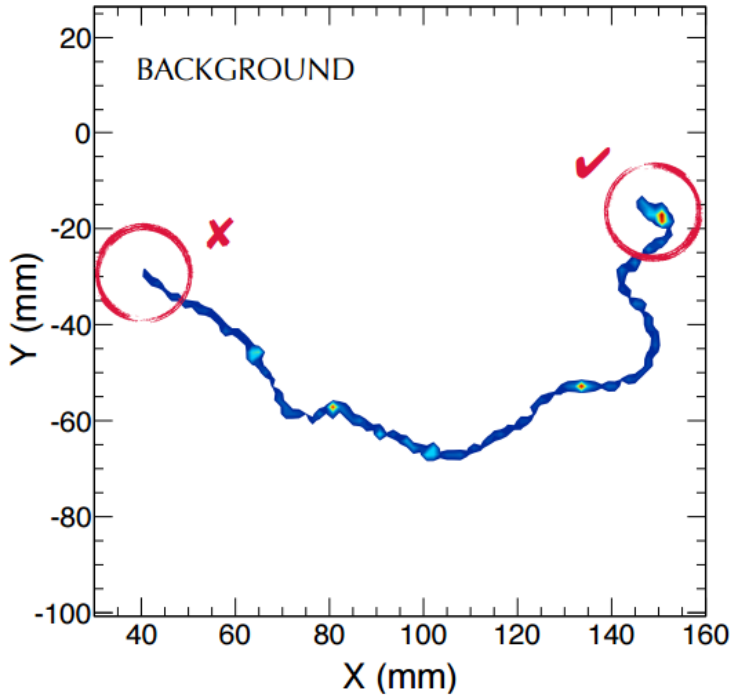
Demonstrated <1% FWHM at $Q_{\beta\beta}$ (intrinsic statistical limit = 0.3%)

J. Renner *et al* JHEP 2019 230

Topological background suppression

- Background events more likely to have multiple tracks → require a single track
- Remaining background events have a single electron, with one Bragg peak at the end
- ββ events have two Bragg peaks

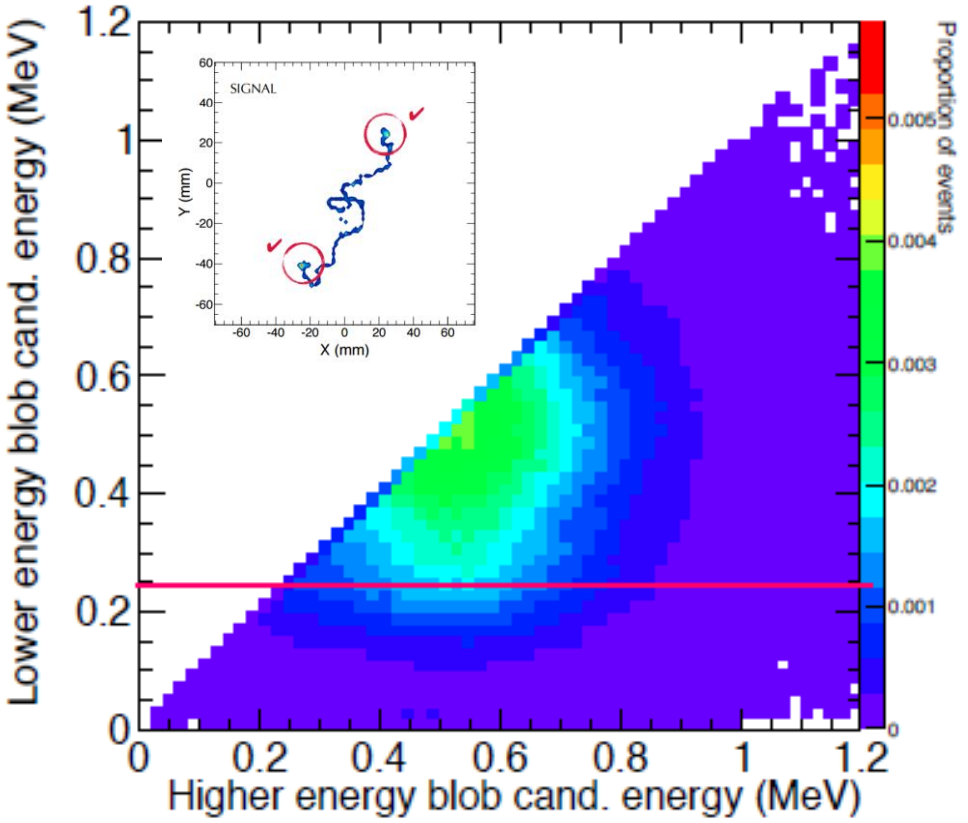




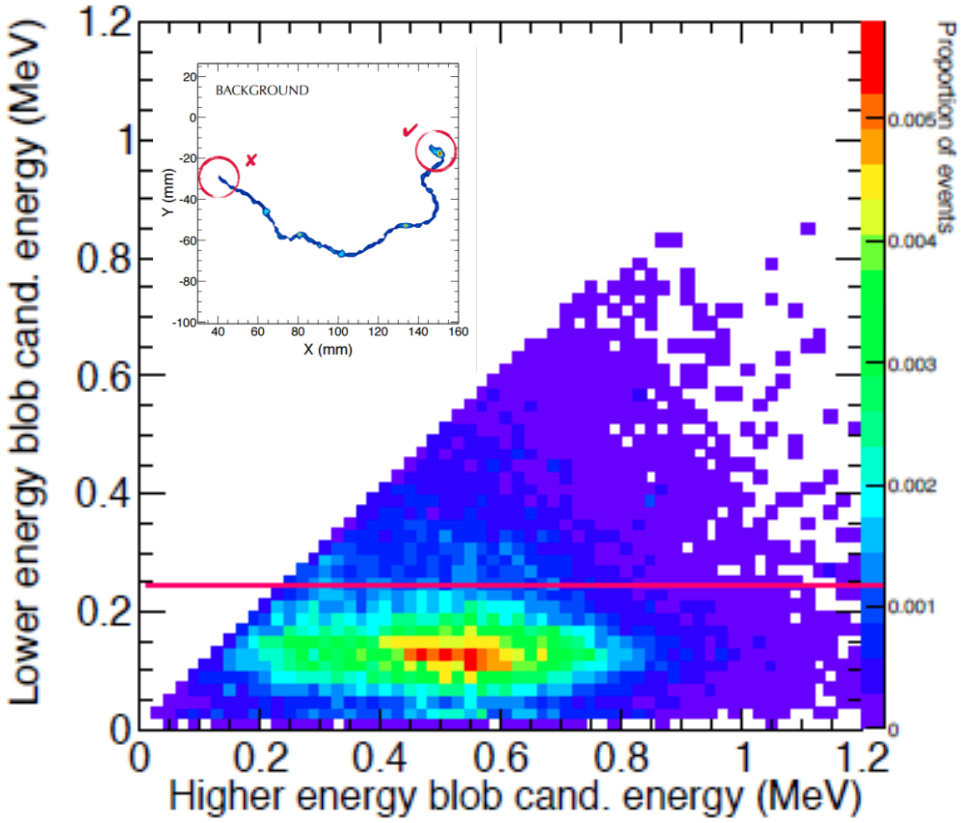
→ Signal/background discrimination by comparing the energy in spherical "blobs" at track ends

Topological background suppression (ideal MC)

Signal: both blobs have similar energy

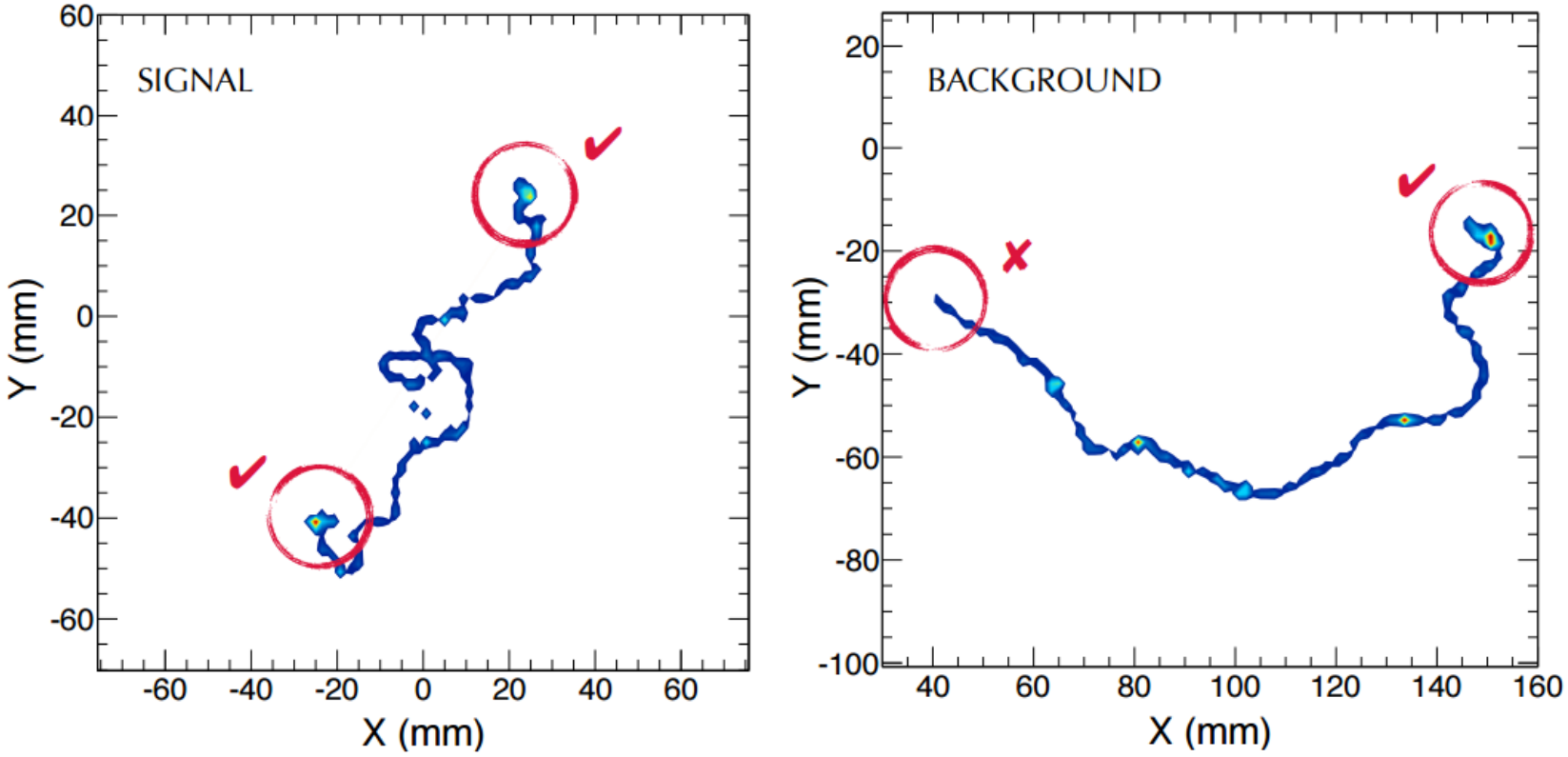


Background: one blob has low energy



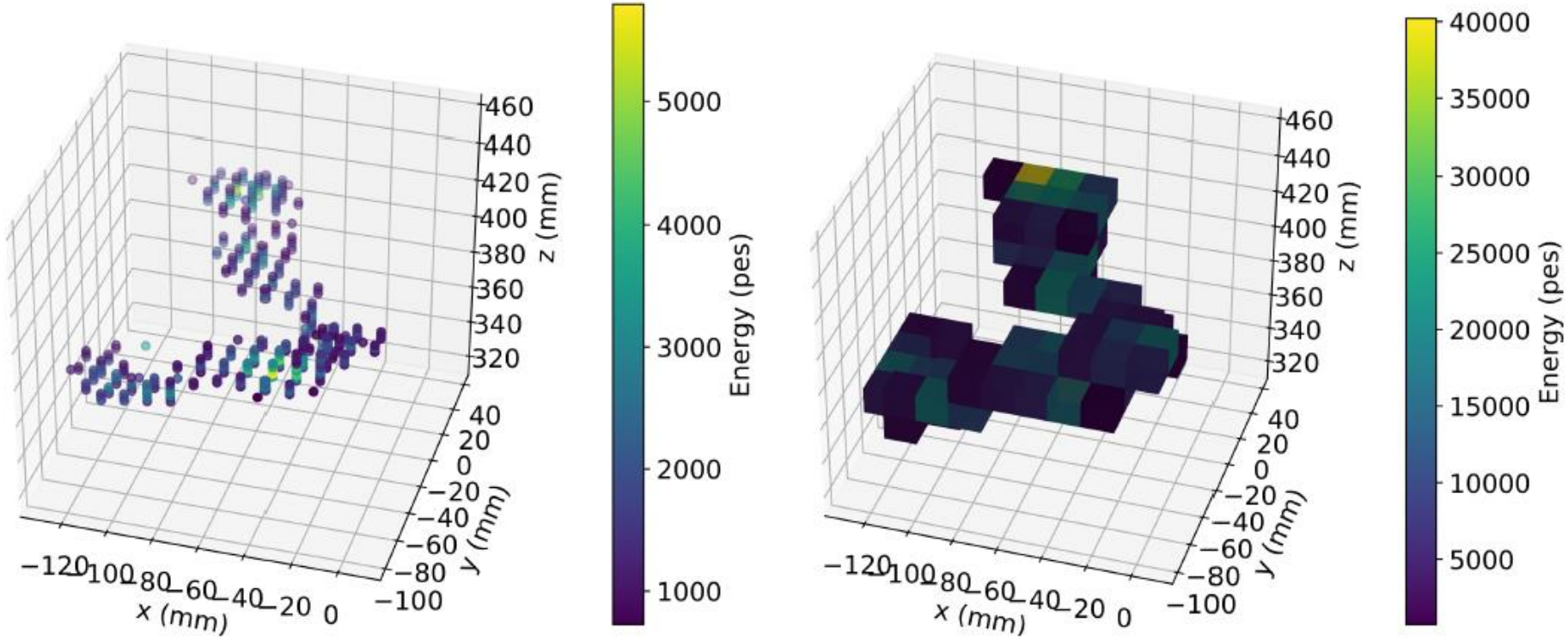
Recent progress in topological analysis

Ideally, we should have had this:



Recent progress in topological analysis

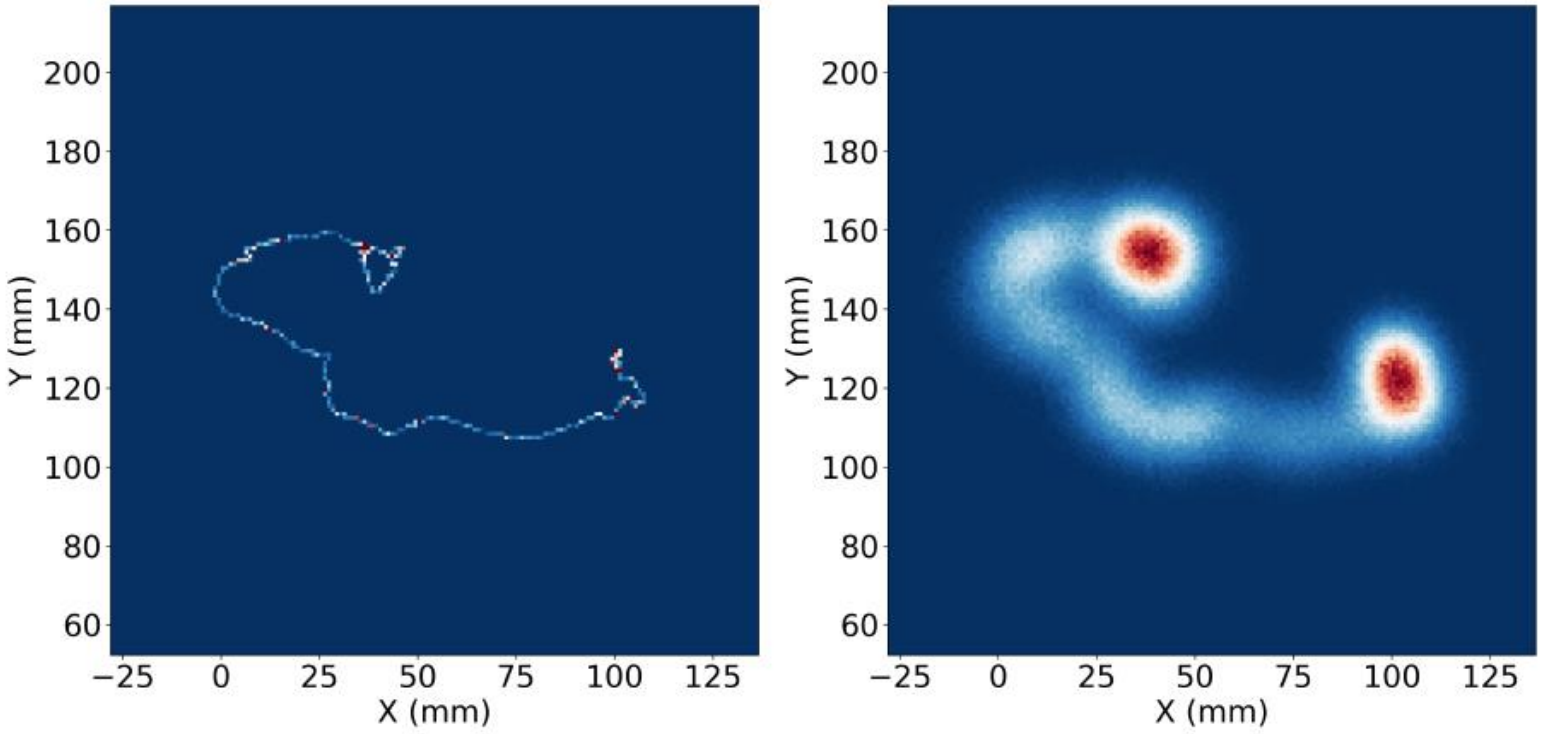
Until recently, we had this:



P. Ferrario *et al* JHEP 2019 52

Recent progress in topological analysis

This was considered ok because electron diffusion during drift smears out the track in any case:



Can we deblur the image?

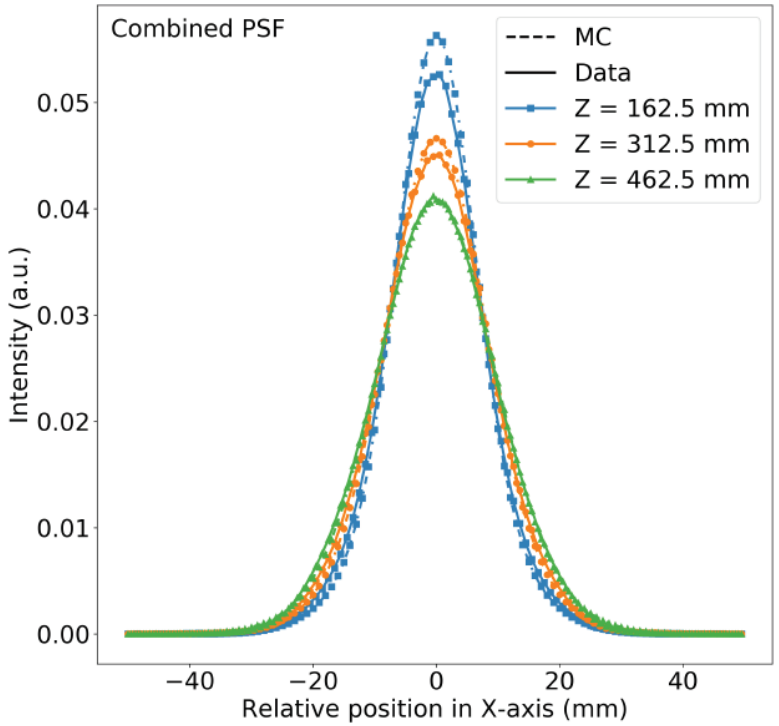
Blur:
Convolve image with Point Spread Function (PSF)

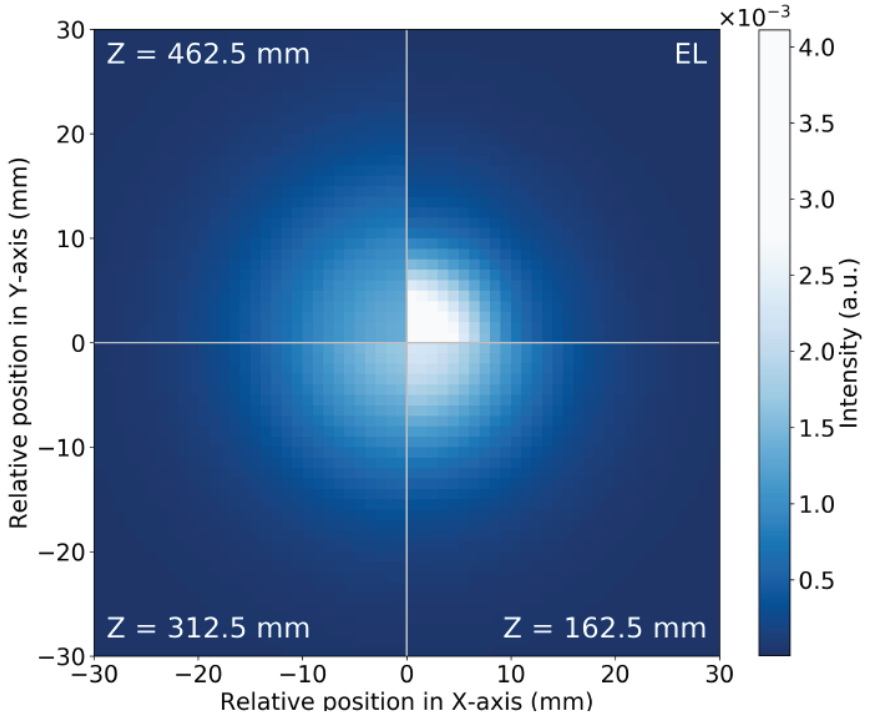
Deblur:
Deconvolve blurred image with PSF (iteratively)

Need to know the PSF!

Idea: use ^{83m}Kr to find the PSF!

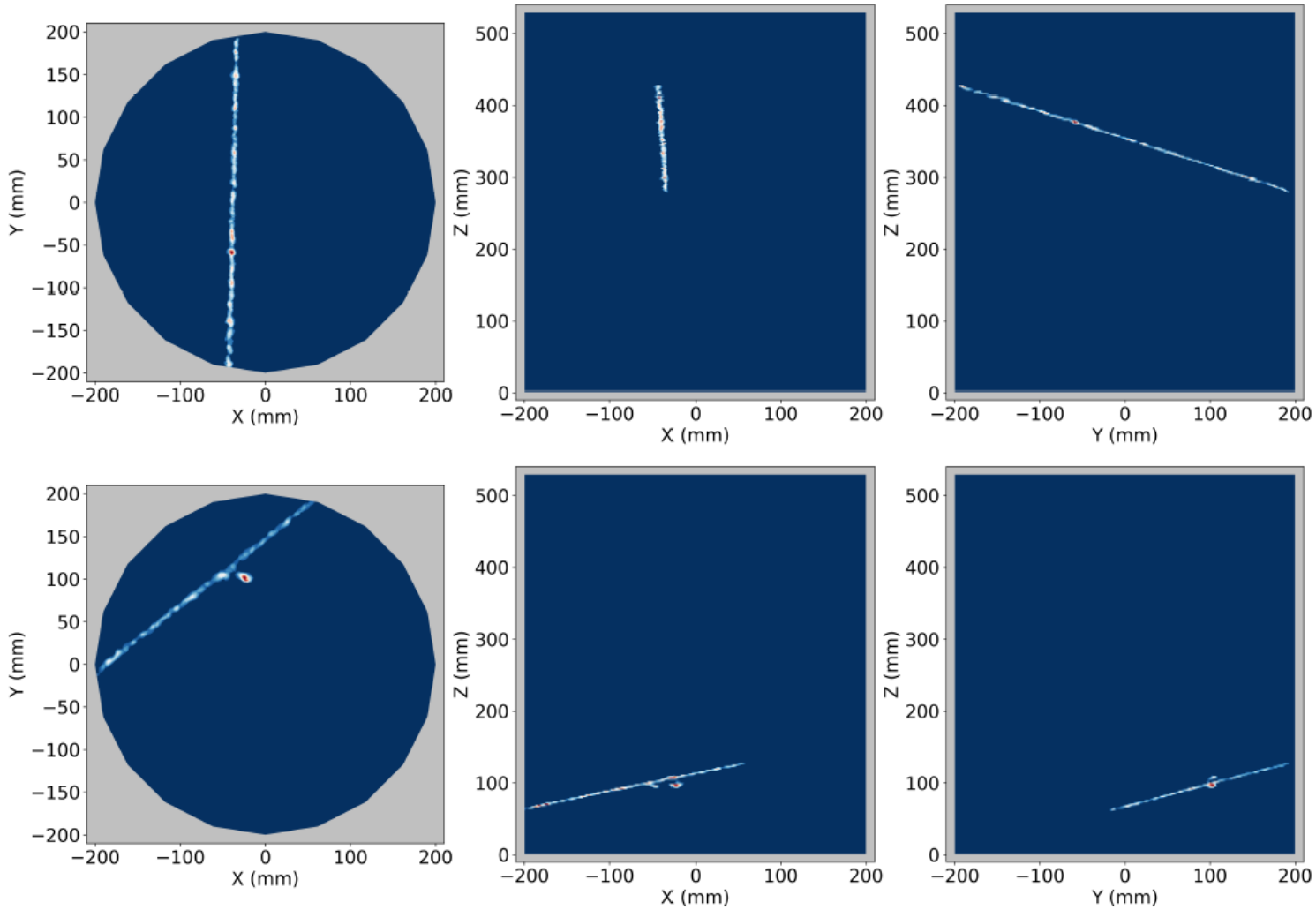
- Blurring results from diffusion + optical smearing by EL gap
- Use ^{83m}Kr point-like events at different drift distances to quantify blurring as PSF(z)





- Apply image deblurring algorithm (Richardson-Lucy) to recover original track

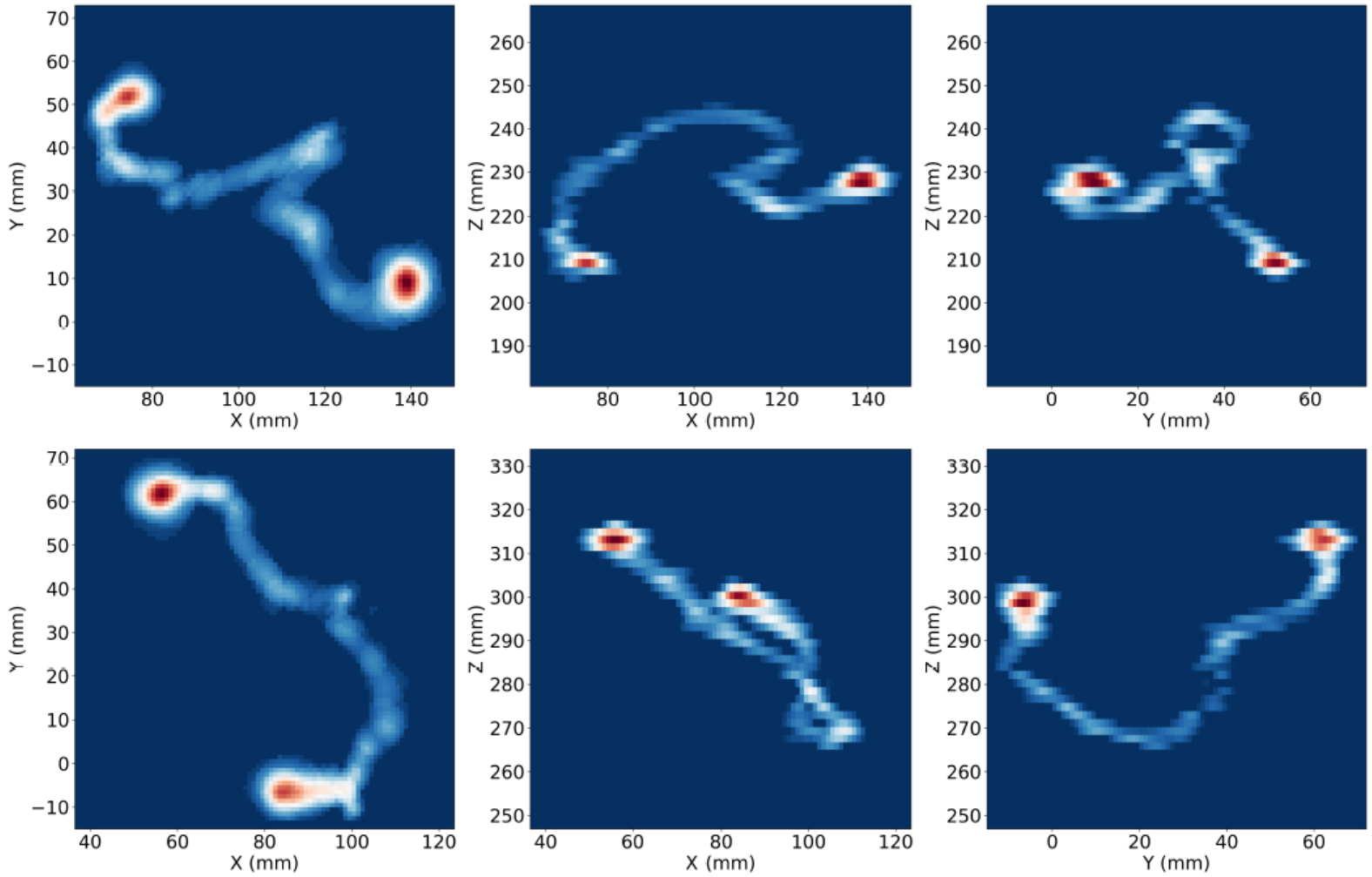
Crossing muons



A. Simón et al
2102.11931

e^-e^+ pairs at 1.6 MeV (^{208}Tl double escape peak)

Real e^-e^+ events recorded and processed by RL deconvolution in NEXT-White



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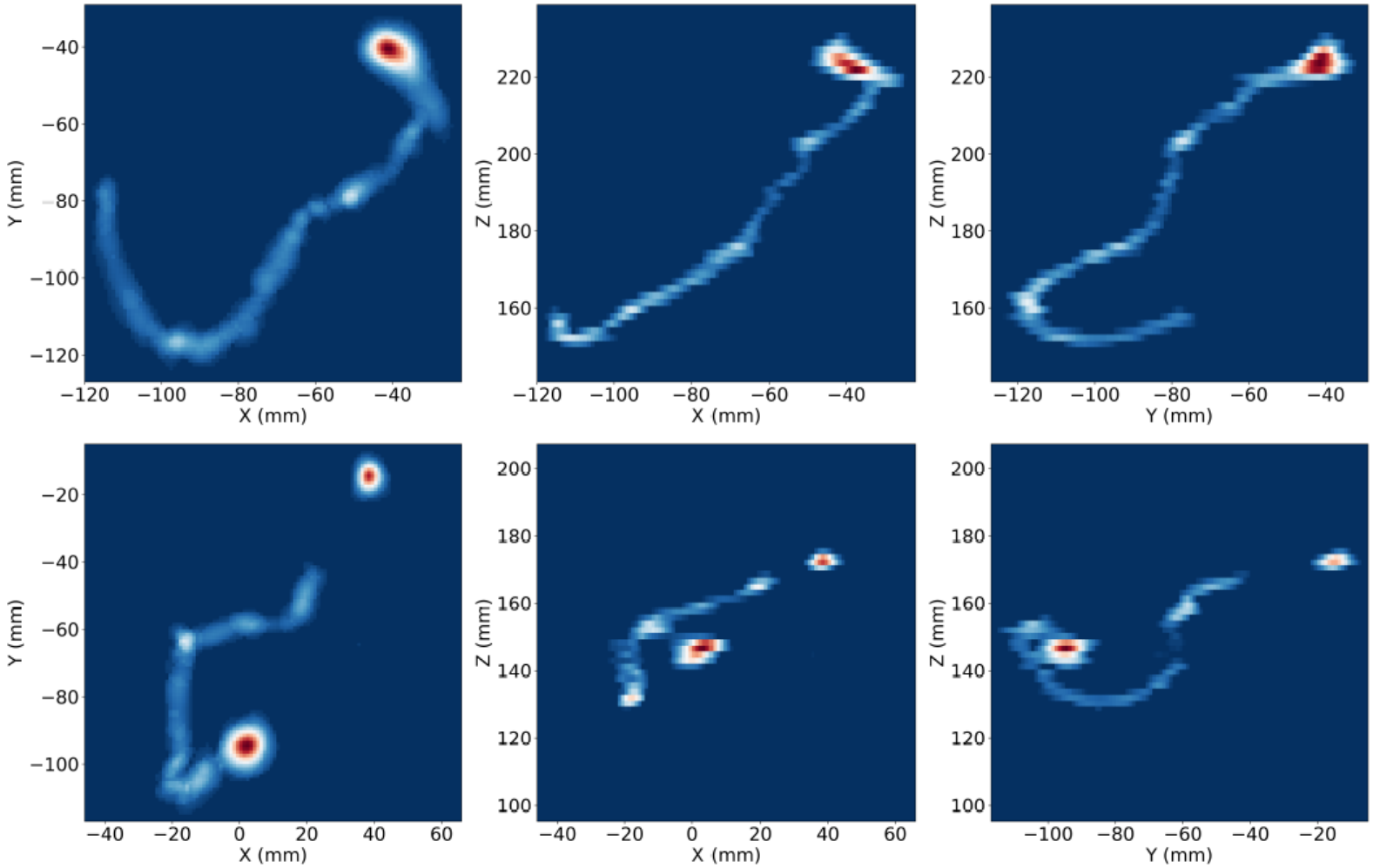
Background events at 1.6 MeV

Real Compton electrons recorded and processed by RL deconvolution in NEXT-White



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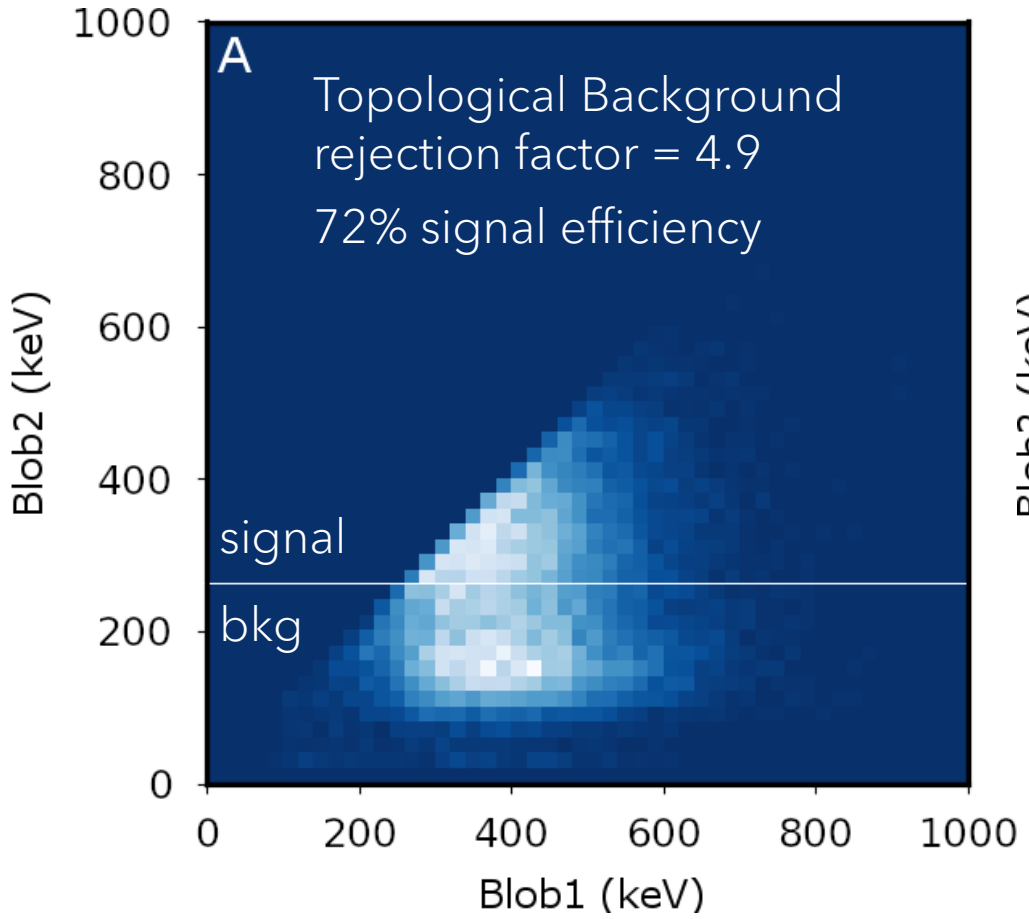
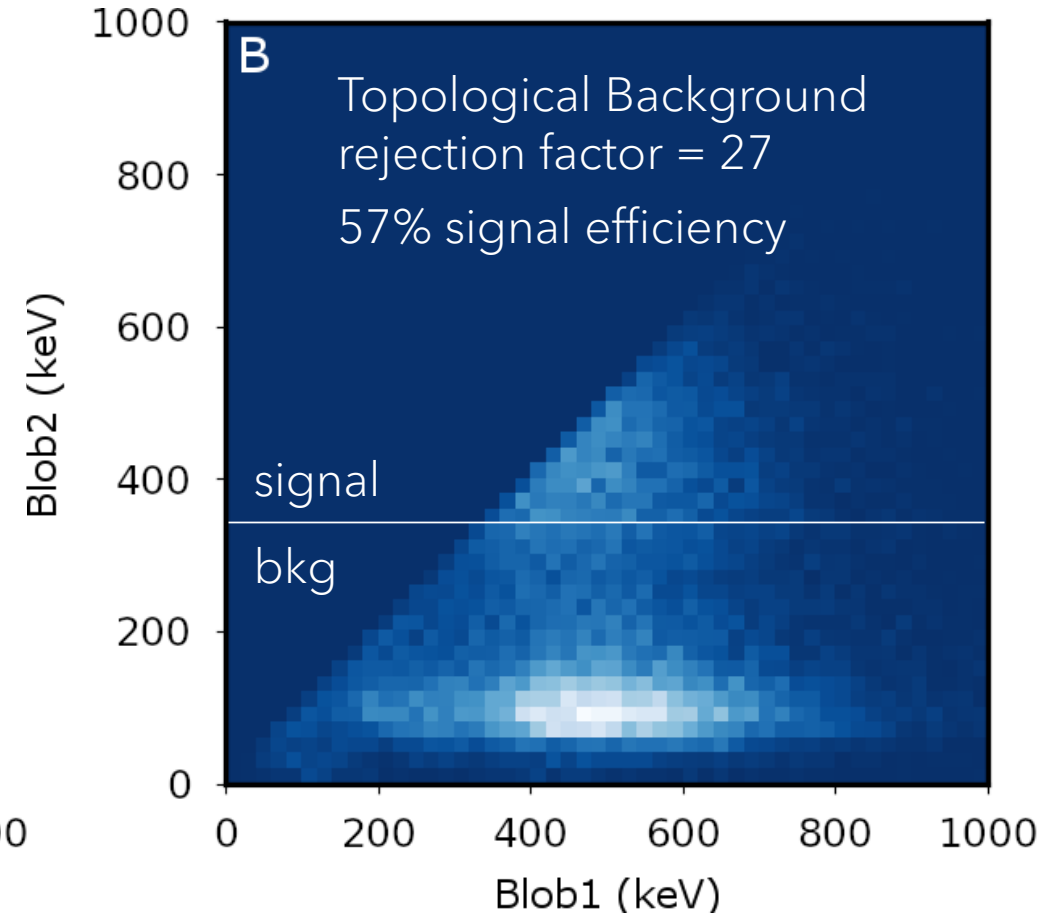
>5-fold improvement in background suppression!

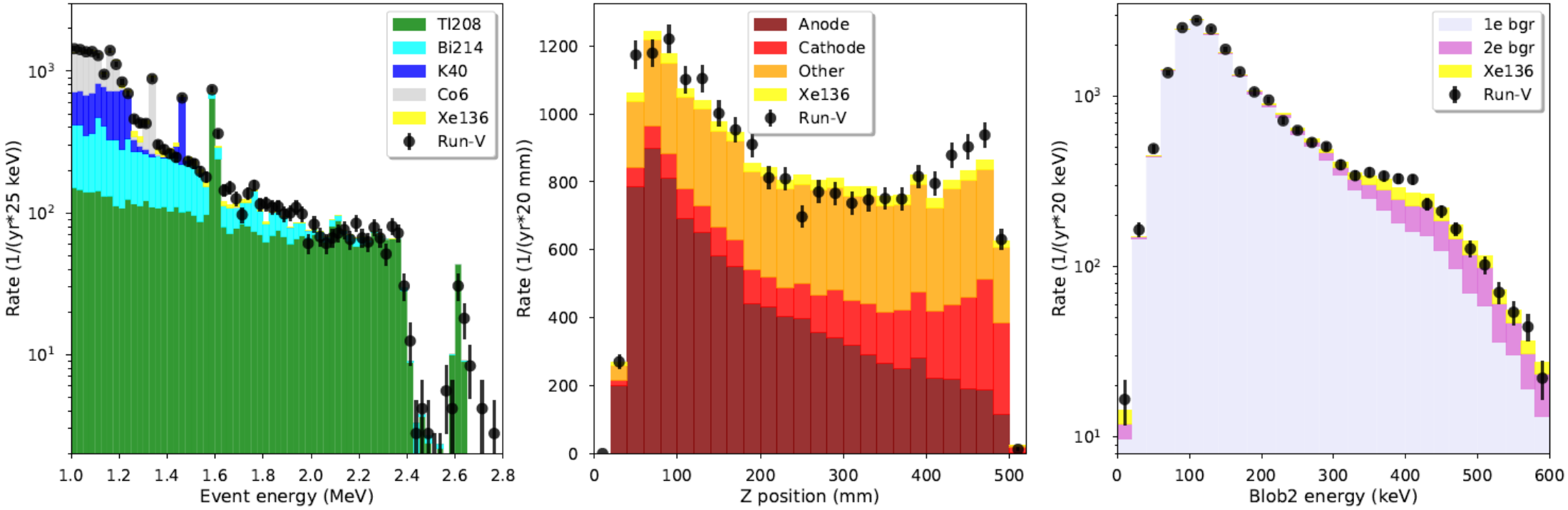
Previous state-of-the-art

New method



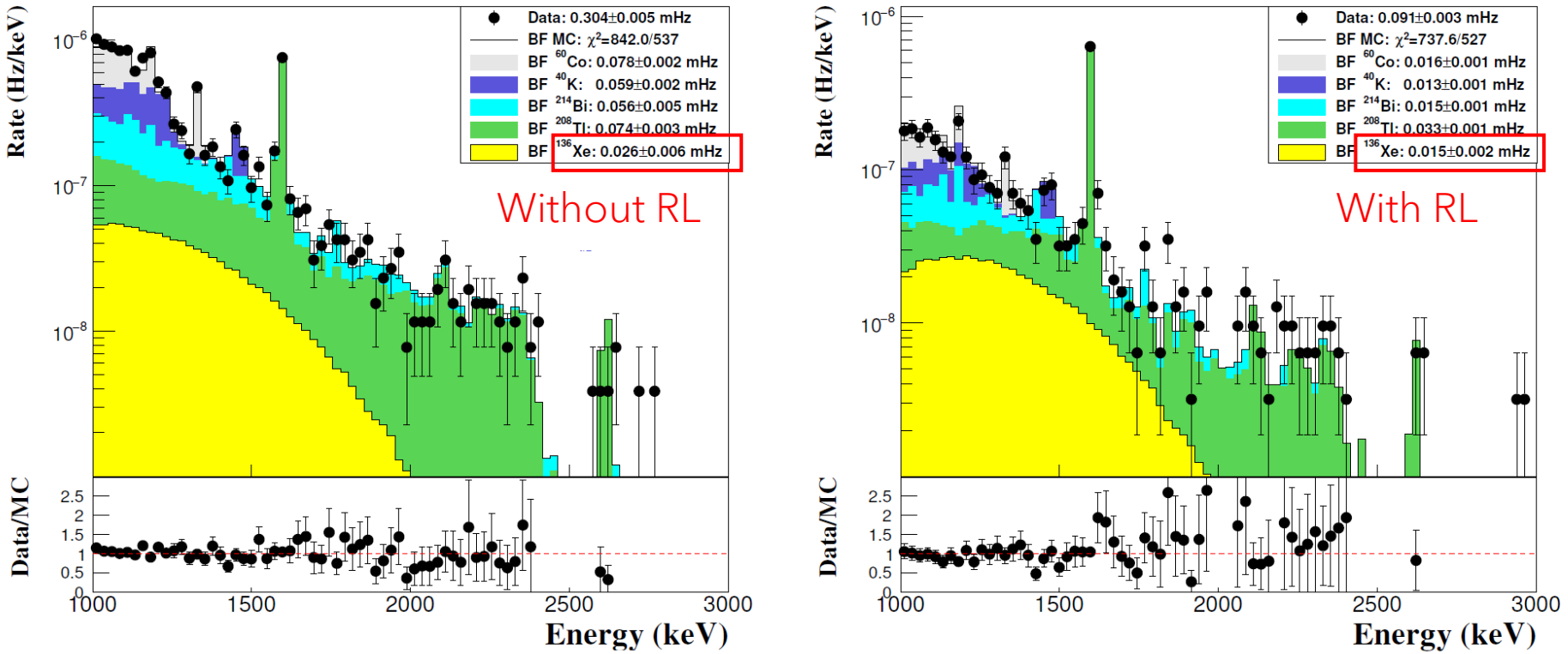


$\beta\beta 2\nu$ analysis in NEXT-White



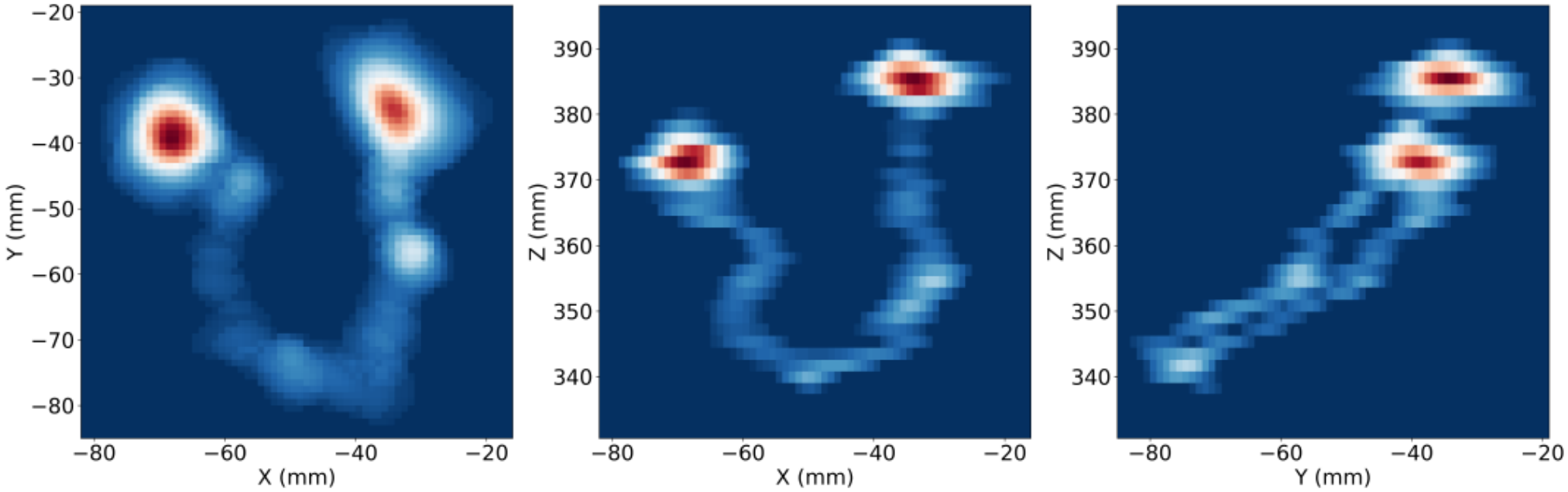
Using event energy (different isotopes), event average z, and blob2 energy information to constrain background/signal yields

$\beta\beta 2\nu$ analysis in NEXT-White



- Ongoing work: use RL deconvolution + depleted Xe run + improved background model + improved systematic error analysis
- Adding RL deconvolution improves chi square and relative error on ^{136}Xe fit

$\beta\beta 2\nu$ analysis in NEXT-White

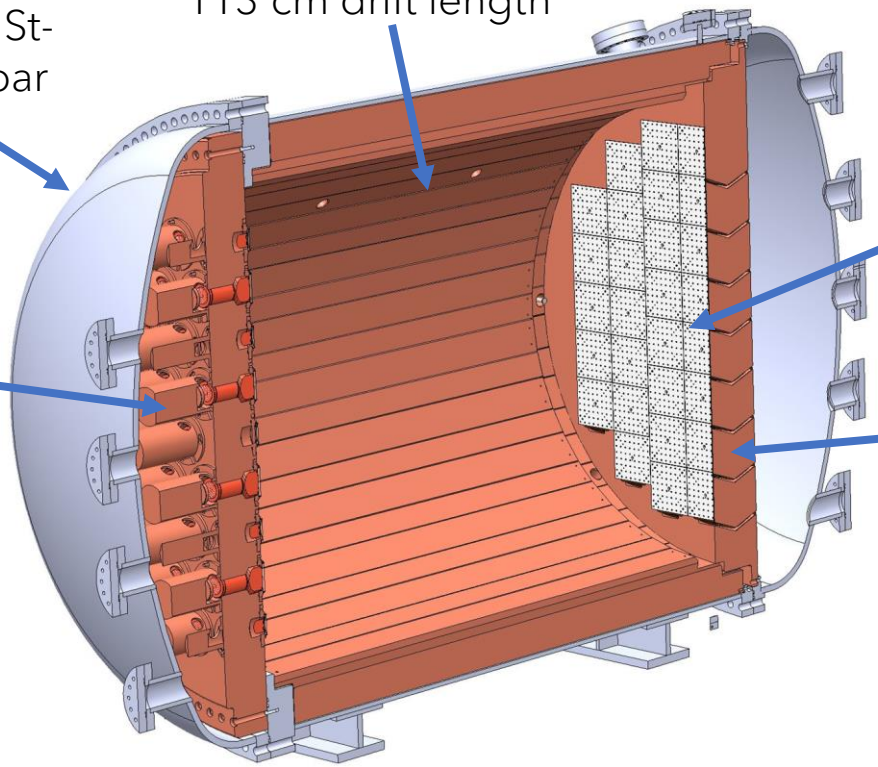


$\beta\beta 2\nu$ candidate from NEXT-White

NEXT to come: NEXT-100

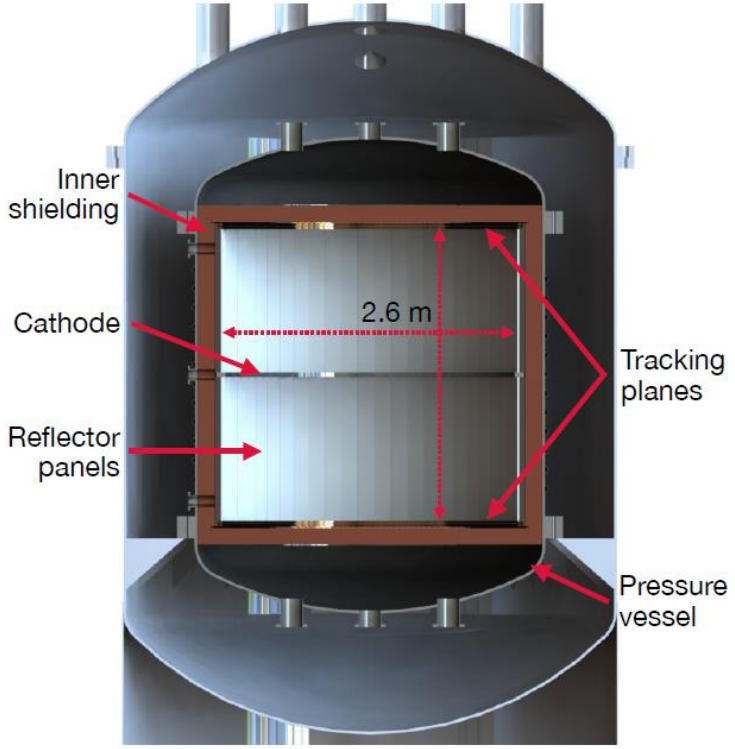
Main goal: demonstrate the technology at the 100 kg scale, expected sensitivity ~10^{26} y

Background index $\mathbf{4 \times 10^{-4}}$ counts/keV/kg/yr. Construction planned for 2021



NEXT-Tonne simulation study

- 1000 kg enriched Xe
- Bi-directional symmetric TPC
- Tracking + energy by radiopure SiPMs
- Operated at low temperature (to reduce SiPM dark count rate)
- Low-diffusion gas mixture (e.g., Xe/He 85/15) to further improve topology
- Well-understood background model dominated by radiogenic sources; cosmogenic activation of Cu and ^{136}Xe subdominant
- Expected sensitivity at 3 tonne-yr: $T_{1/2}^{0\nu} \sim 1 \times 10^{27}$ y



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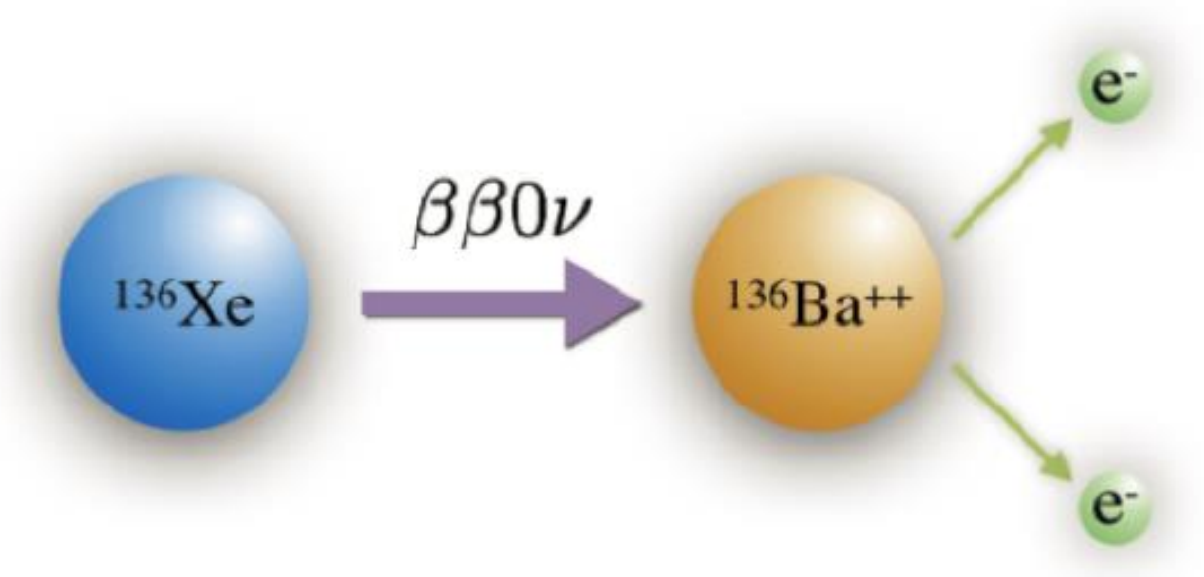
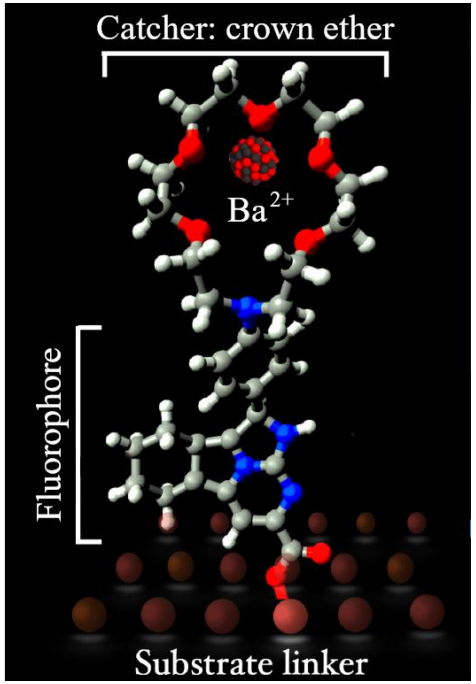
The aggressive approach: barium tagging



For NEXT, $\beta\beta2\nu$ leakage to the $Q_{\beta\beta}$ ROI is negligible

Identification of ^{136}Ba in coincidence with a signal in the $Q_{\beta\beta}$ ROI → true background-free experiment

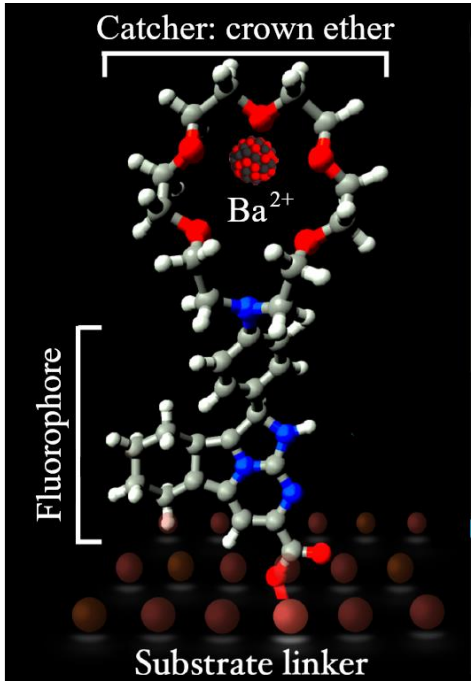
Ba^{2+} detection using molecular indicators



D. Nygren, J Phys Conf Ser 650 (2015) 012002
JINST 11 (2016) P12011
PRL 120 (2017) 132504
Sci Rep 9 (2019) 15097
Nature 583 (2020) 48-54
ACS Sens 6 (2021) 192-202

- Idea (D. Nygren): use single molecule fluorescent imaging to visualize ("tag") a single Ba^{2+} ion as it arrives at the TPC cathode
- Ba^{2+} sensor: based on molecular indicators able to change luminous response after chelating Ba^{2+} cations; must operate in dry phase
- Apparatus: must be able to detect in delayed coincidence the electron signal (at the anode) and the cation signal (at the cathode)

Ba^{2+} detection using molecular indicators



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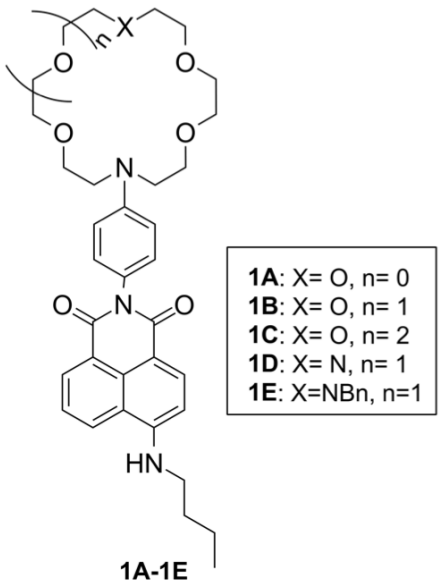
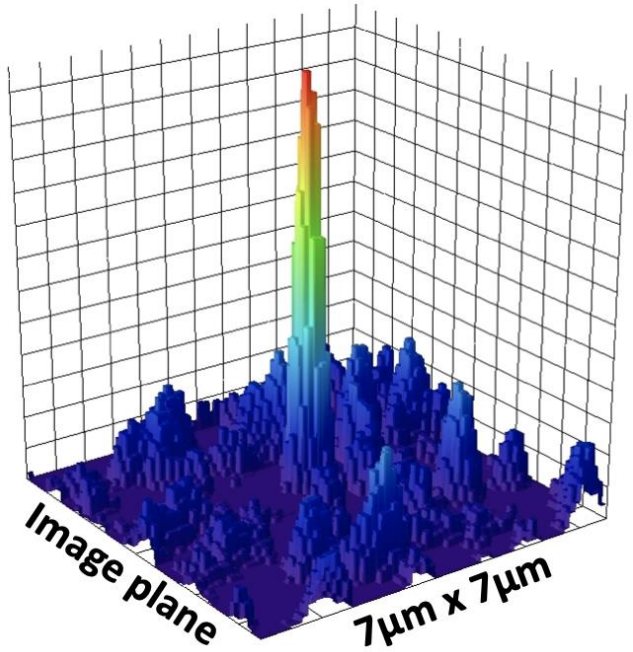
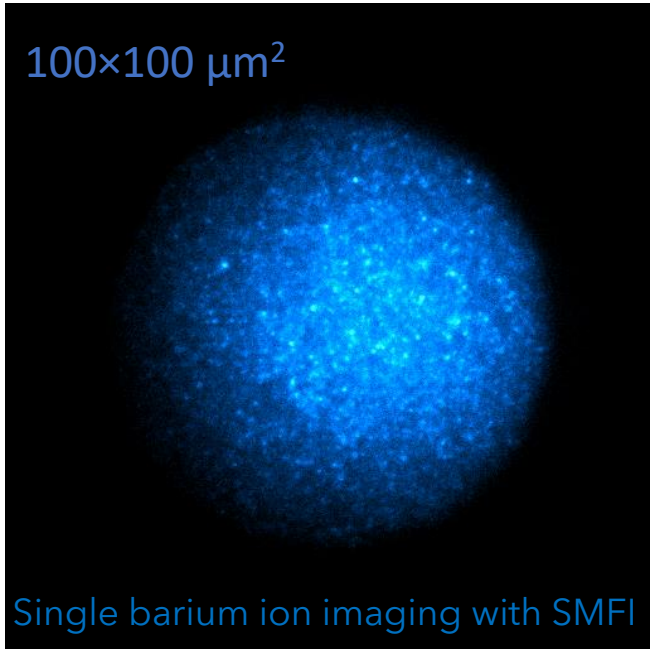
- Extensive collaboration-wide R&D program
  - Molecular indicators: bicolor, on/off, monolayers, tests with ions
  - Microscopy: two-photon absorption, high-pressure epifluorescence
  - Ion collection: RF carpets, tiled monolayers
  - Energy and tracking: metalenses, camera readout
- Goals: Prove barium tagging feasibility for a tonne-scale NEXT detector using small/medium/large-scale demonstrators in ~5 yr

Enhanced fluorescence





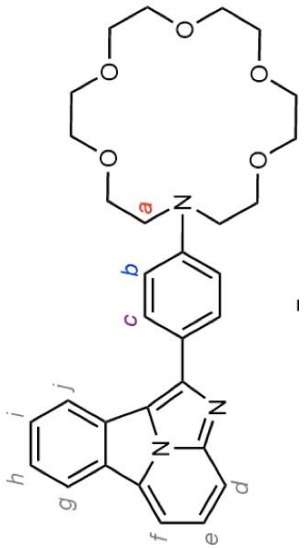


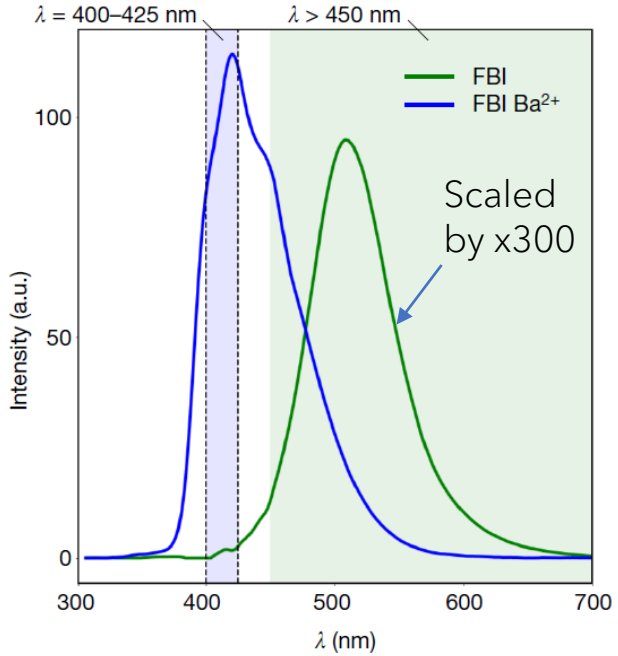
On/off molecules: dry single-molecule imaging with TPC-compatible microscopy

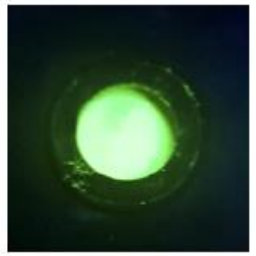
Sci Rep 9 (2019) 15097

ACS Sens 6 (2021) 192-202

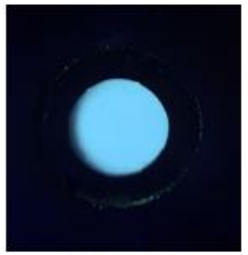
Bicolor enhanced fluorescence







FBI



FBI·Ba^{2+}

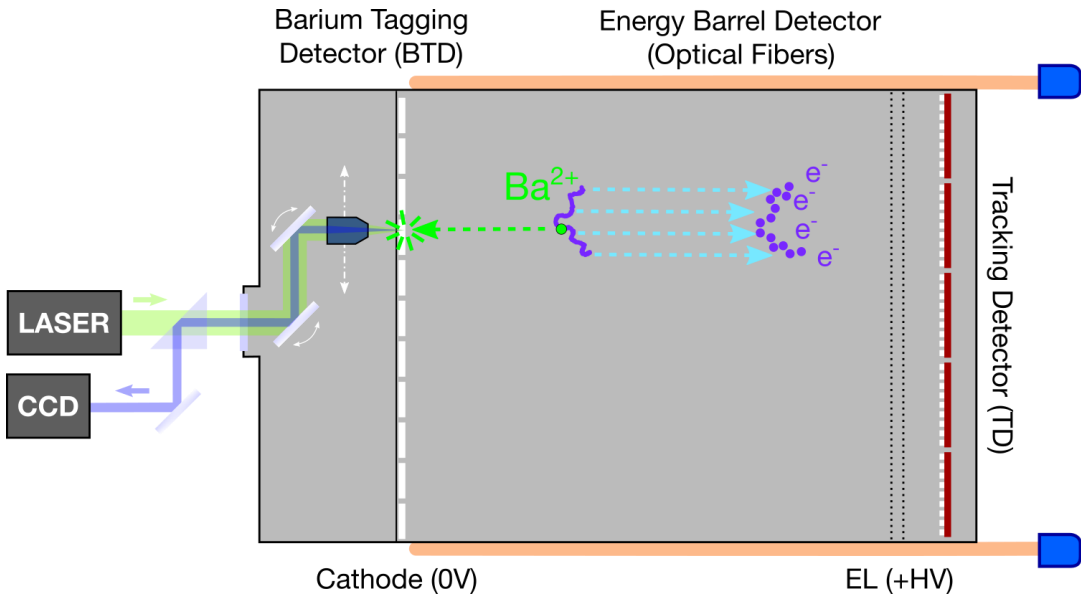
- Fluorescent Bicolor Indicators (FBI): enhanced fluorescence and spectral separation
- Overall separation factor of $\sim 10^4$ between chelated and unchelated states
- First demonstration of in-vacuo chelation
- See talk by Zoraida Freixa on the next session

Nature 583 (2020) 48-54

NEXT steps

- Ba^{2+} ion beam tests in vacuum/low pressure He and tests with $^{224}Ra^{2+}$ recoils emitted from a ^{228}Th source in high-pressure Xe
- Beam tests planned at ANL CARIBU with $^{144}Ba^{2+}$ mass-selected from ^{252}Cf fission and ^{133}Ba high-pressure plasma source
- The ultimate test beam is $\beta\beta 2\nu$!
- Demonstrator phases at 10 kg-scale planned for ~2024-2025
- Multiple full system concepts under exploration, to be guided by ongoing R&D

BOLD concept with fully active cathode, SiPM-based tracking and Energy Barrel detector

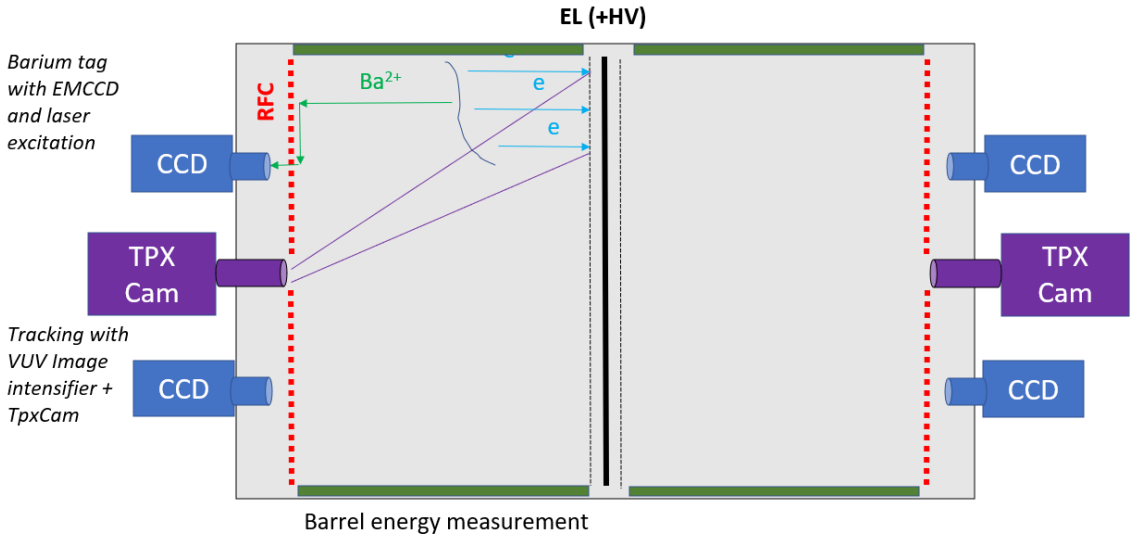


Awarded 9.3 M€ ERC Synergy grant

NEXT steps

- Ba^{2+} ion beam tests in vacuum/low pressure He and tests with $^{224}Ra^{2+}$ recoils emitted from a ^{228}Th source in high-pressure Xe
- Beam tests planned at ANL CARIBU with $^{144}Ba^{2+}$ mass-selected from ^{252}Cf fission and ^{133}Ba high-pressure plasma source
- The ultimate test beam is $\beta\beta 2\nu$!
- Demonstrator phases at 10 kg-scale planned for ~2024-2025
- Multiple full system concepts under exploration, to be guided by ongoing R&D

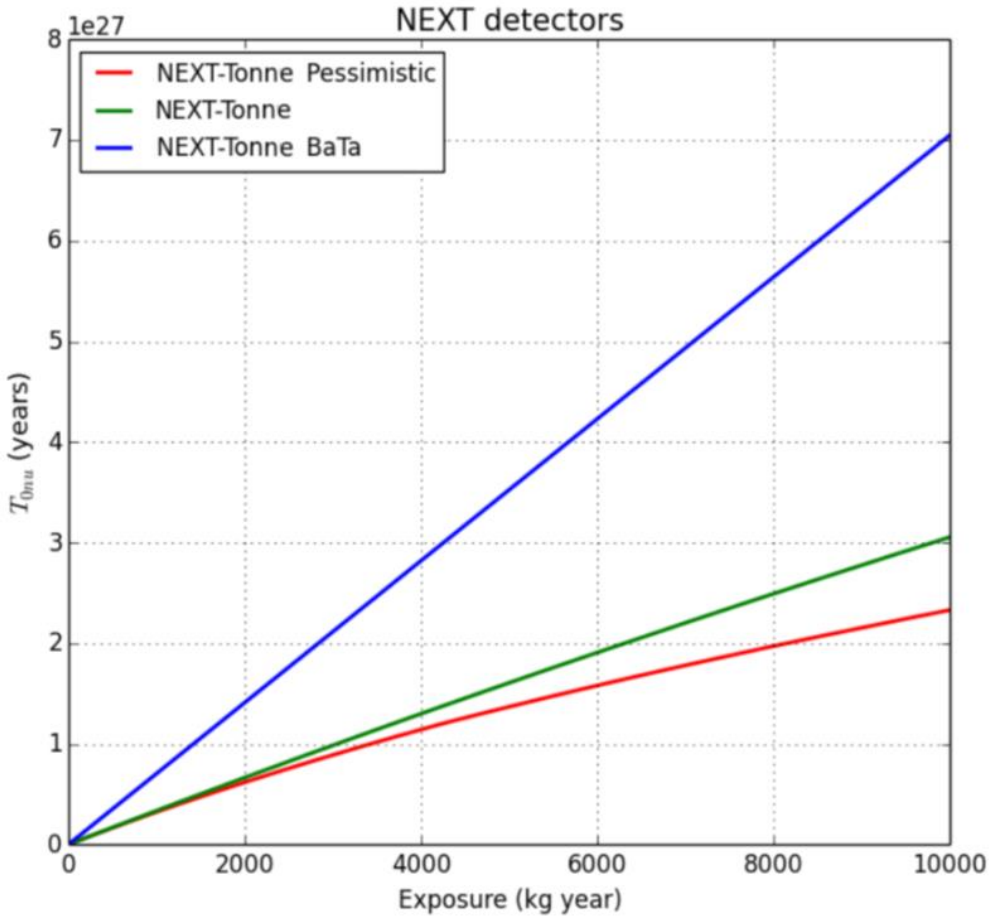
CRAB concept with RF carpet concentrators and camera-based topology measurement



Well-funded ongoing DOE-supported program

Projected sensitivities

- NEXT forward-looking sensitivity estimates for a tonne-scale detector
- Assumed background in ROI:
  - NEXT-Tonne: 0.06 counts/yr
  - NEXT-Tonne Pessimistic: 0.1 counts/yr
  - NEXT-Tonne BaTa: real background free



Summary and outlook

- NEXT concept demonstrated on a large prototype, with <1% FWHM energy resolution at $Q_{\beta\beta}$ and highly effective topological background suppression
- NEXT-100 will be up and running soon, demonstrating the technology on the 100 kg scale
- NEXT-Tonne is a reasonable extrapolation from an established technology, would be sensitive to half-lives of 10^{27} years
- Barium tagging is a central well-funded effort, with concrete plans for a demonstrator based on NEXT-White/NEXT-100
- Barium tagging on the tonne-scale can enable reaching a sensitivity of 10^{28} yr

Thank you!