Noble Liquid Detectors

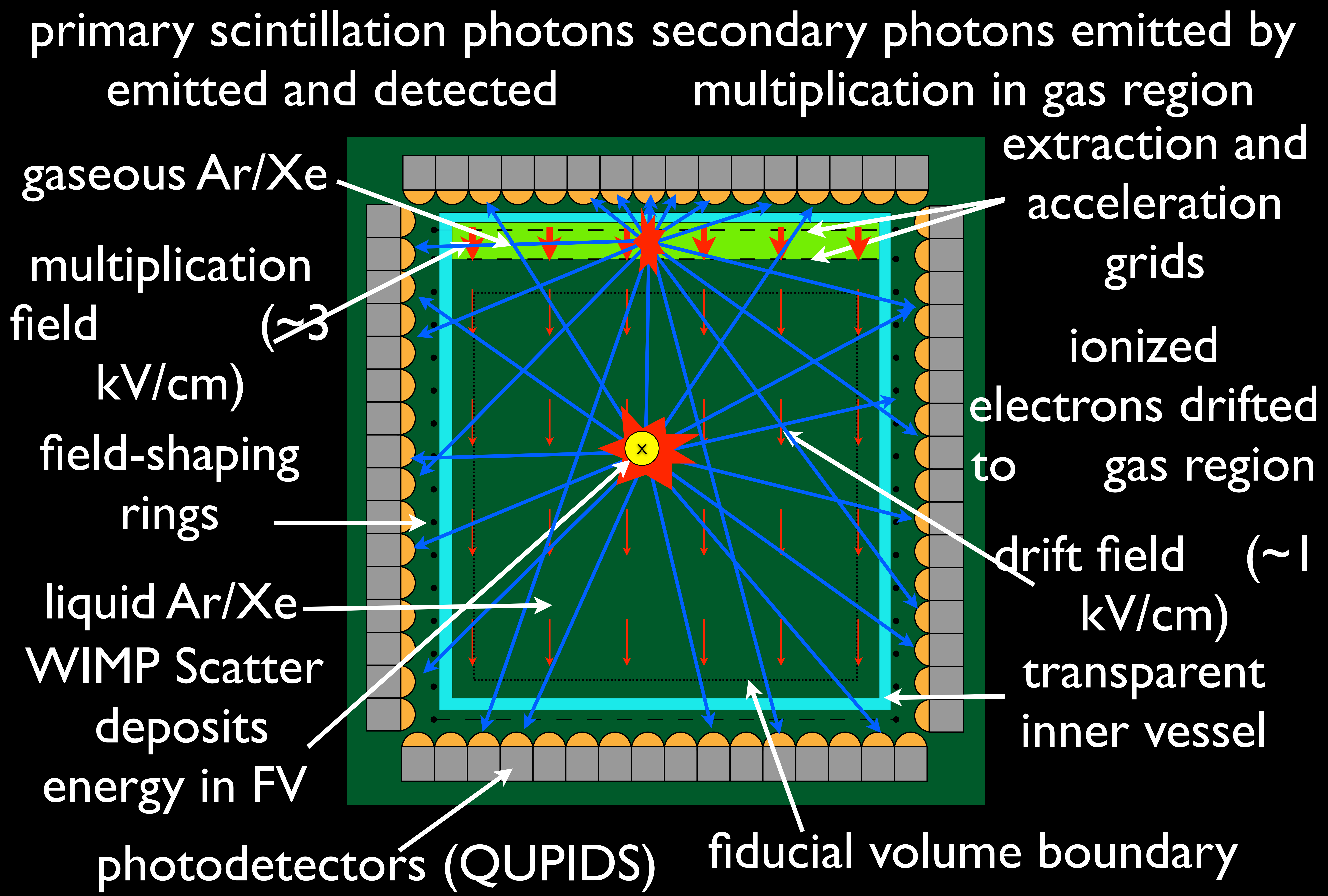
SOUP 20|21

Cristiano Galbiati - July 1, 2021

Noble Liquid Detectors

- Target = Detector
- Excellent scintillation detectors: 40 photons/keV (Ar, 128 nm), 46 photons/keV (Xe, 178 nm)
- Excellent ionization detectors: 40 electrons/keV (Ar), 64 electrons/keV (Xe)
- Photons and electrons not self-absorbed
- Easily purified
- Excellent background discrimination
- Large multi-ton detectors possible and "cheap"

TPC in Action



Discrimination in Xenon

- Fiducialization reduces the background from construction and external materials in the fiducial region
- Difference in ratio of the prompt scintillation (S1) to the drift time-delayed ionization (S2) with strongly dependent upon recombination of ionizing tracks, which in turn depends on ionization density
  - Rejection ~ 10^2-10^3
- Precise determination of events location in 3D
  - 1-5 mm x-y, 1 mm z
  - Additional rejection for multiple neutron recoils and γ background

Discrimination in Argon

- Pulse shape discrimination of primary scintillation (S1) based on the very large difference in decay times between singlet (≈ 7 ns) and triplet (1.6 μs) components of the emitted UV light
    - Minimum ionizing: triplet/singlet ~ 3/1
    - Nuclear recoils: triplet/singlet ~ 1/3
    - Theoretical Identification Power exceeds 10^8 for > 60 photoelectrons (Boulay & Hime 2004)
- Difference in ratio of the prompt scintillation (S1) to the drift time-delayed ionization (S2)
- Precise determination of events location in 3D

WARP Collaboration

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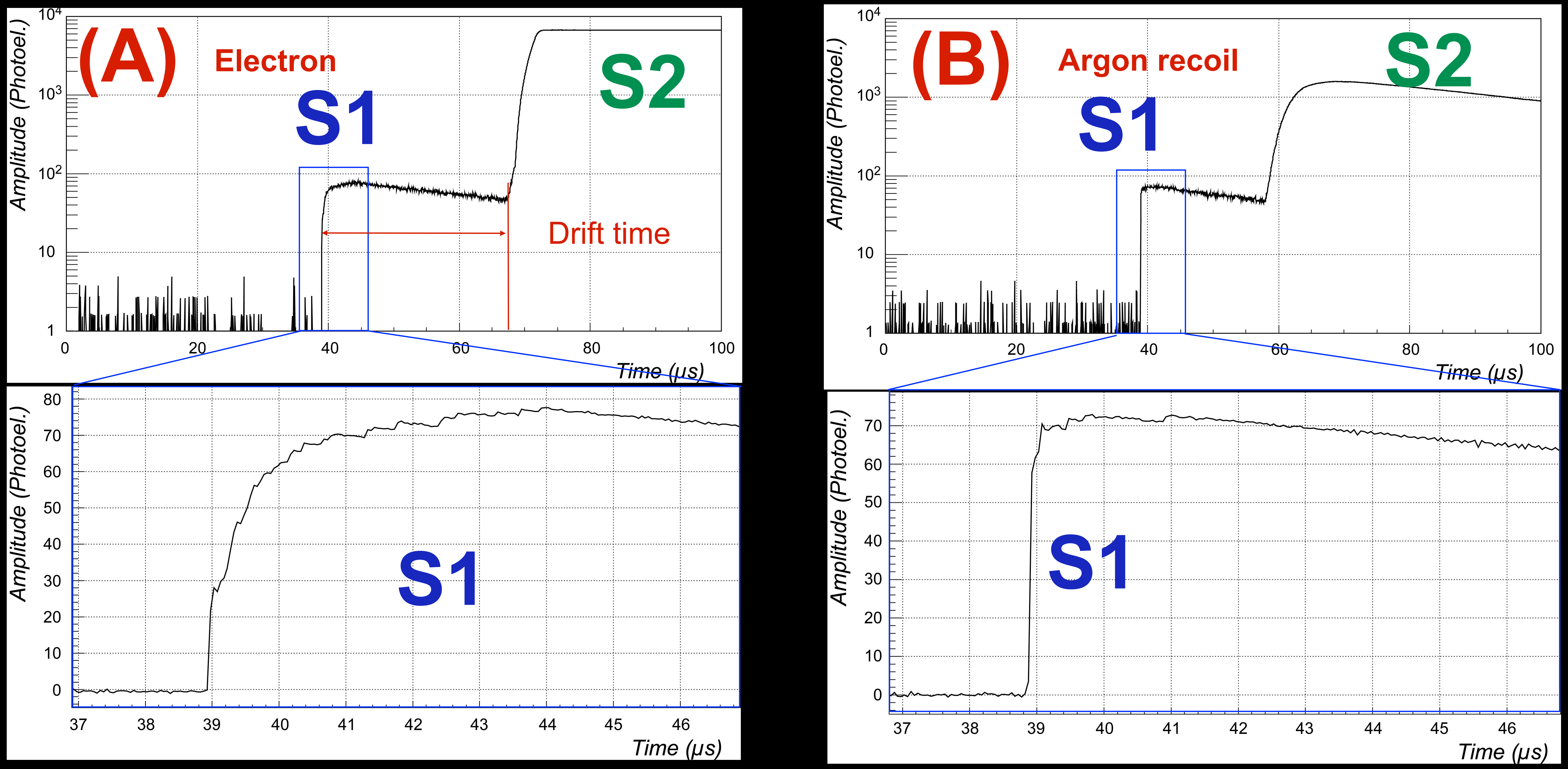
First Two Discrimination Methods

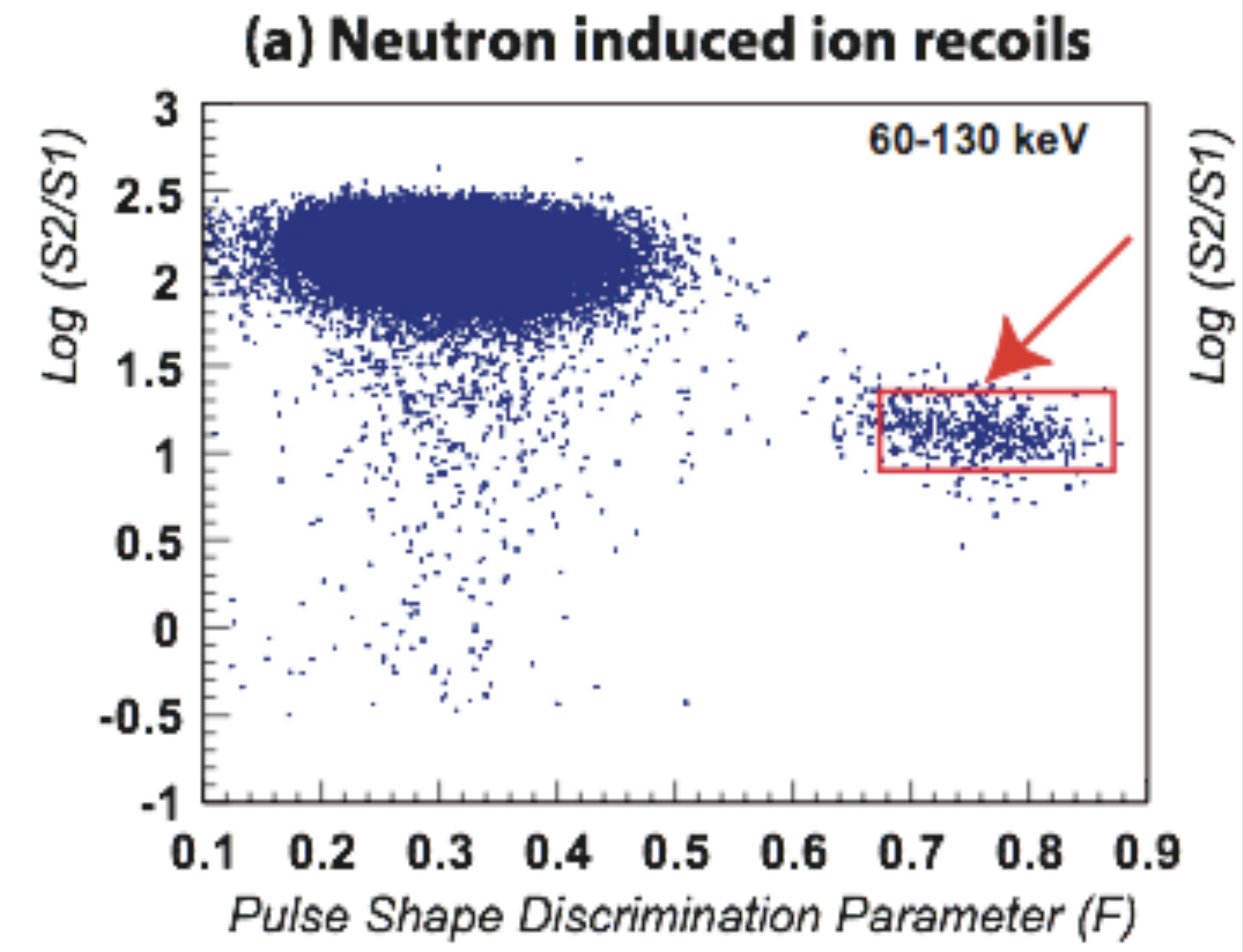


Events are characterized by:
- the ratio S2/S1 between the primary (S1) and secondary (S2)
- the rising time of the S1 signal

Minimum ionizing particles: high S2/S1 ratio (~100) and by slow S1 signal

Ar recoils: low (≤10) S2/S1 ratio and fast S1 signal

First Dark Matter Results



Selected events in the n-induced single recoils window during the WIMP search run: None

Astropart. Phys. **28**, 495 (2008)

WARP 140-kg Detector

The WARP 140-kg detector, currently under commissioning at LNGS

140 kg active target, to reach into 5×10^{-45} cm^2 and cover critical part of SUSY parameter space

Complete neutron shield!

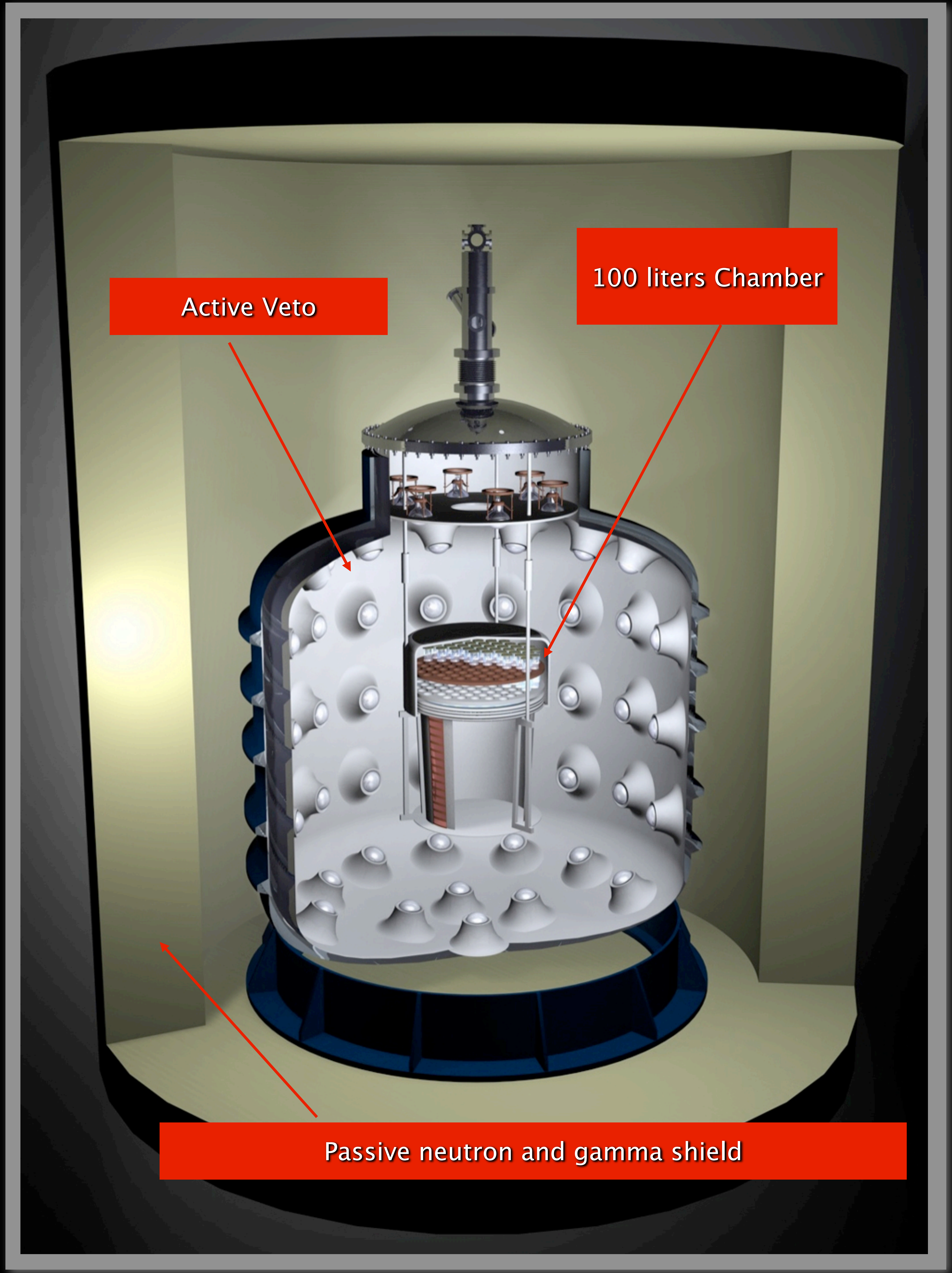
4π active neutron veto (9 tons Liquid Argon, 300 PMTs)

Active control on nuclide-recoil background, owing to unique feature (LAr active veto)

3D Event localization and definition of fiducial volume for surface background rejection

Detector designed for positive confirmation of a possible WIMP discovery

Cryostat designed to allocate a possible 1400 kg detector



Construction completed in July 2009
First run in August 2009
Obtained light yield of 1.6 ph.el./keV_{ee}
Drained in Sep 2009 to fix problem with HV cable

Restart Dec 2009

140 kg active mass
2 ph.el/keV_{ee}
55 keV_r threshold
background-free for 6 months
sensitivity 10^{-44} cm^2

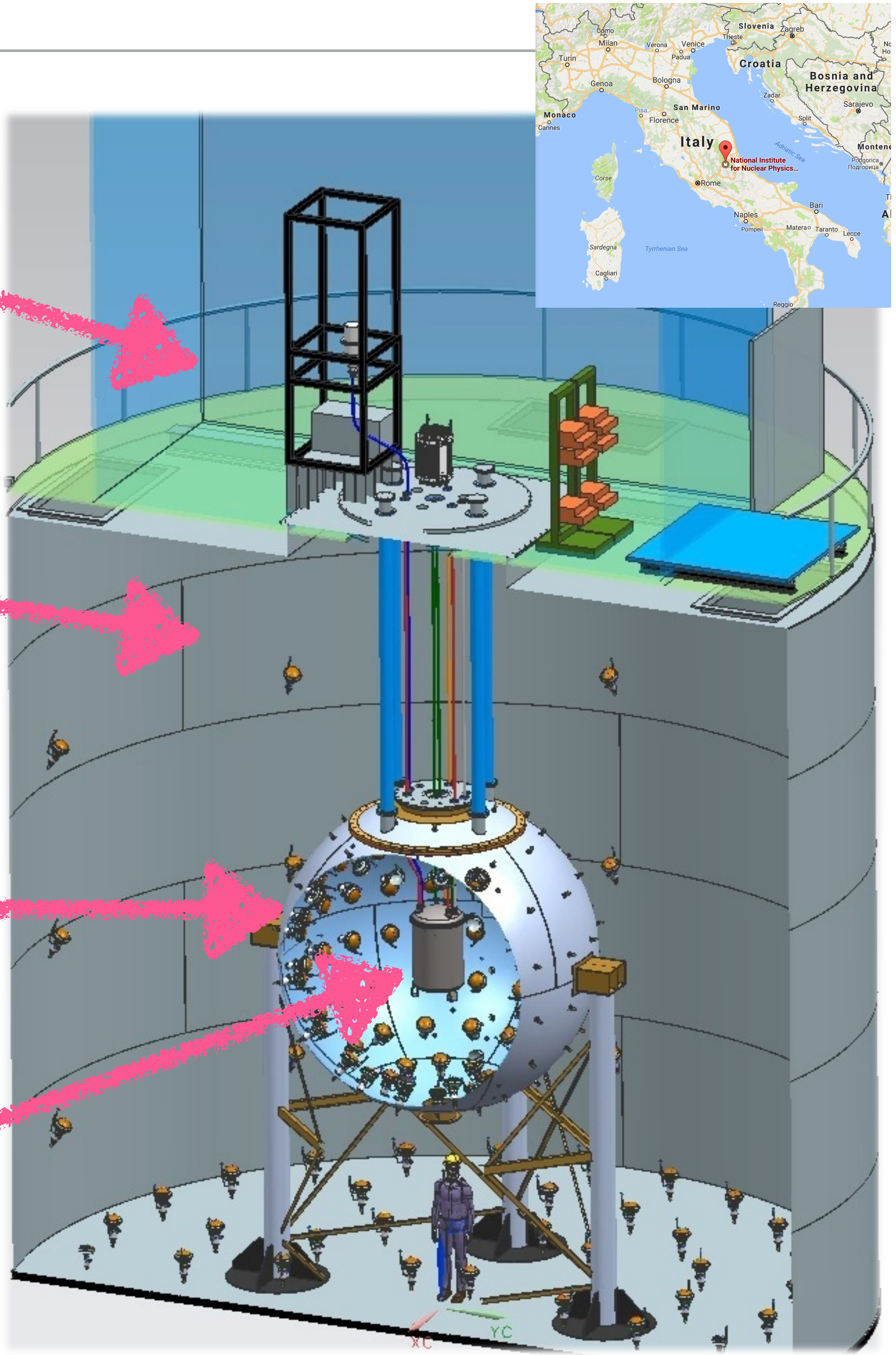
DARKSIDE-50

Radon-free (Rn levels < 5 mBq/m^3)
Assembly Clean Room

1,000-tonne Water Cherenkov
Cosmic Ray Veto

30-tonne Liquid Scintillator
Neutron and γ's Veto
Veto efficiency > 99.1%

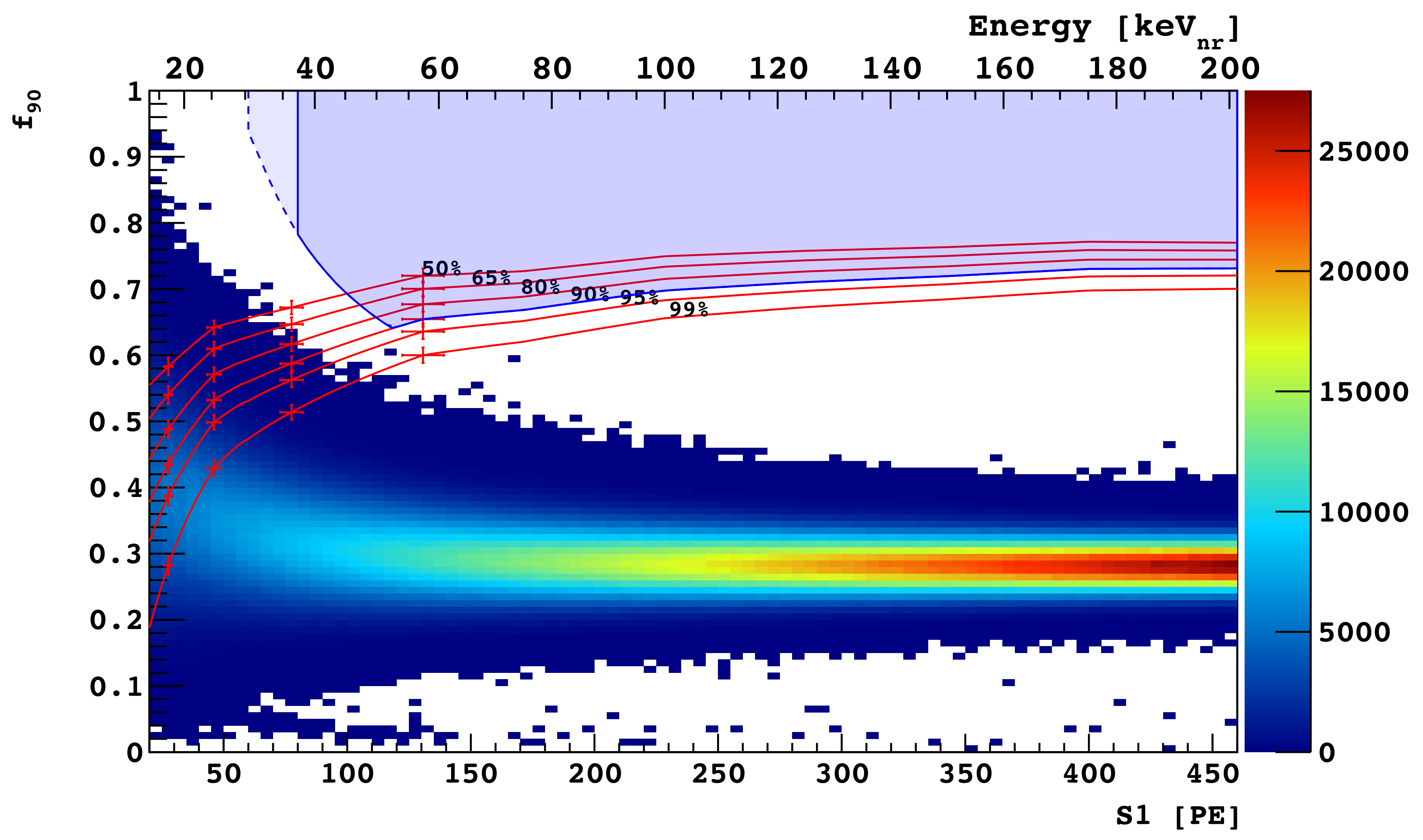
Inner detector **TPC**
filled with 150 kg of liquid
Underground Ar



DARKSIDE-50

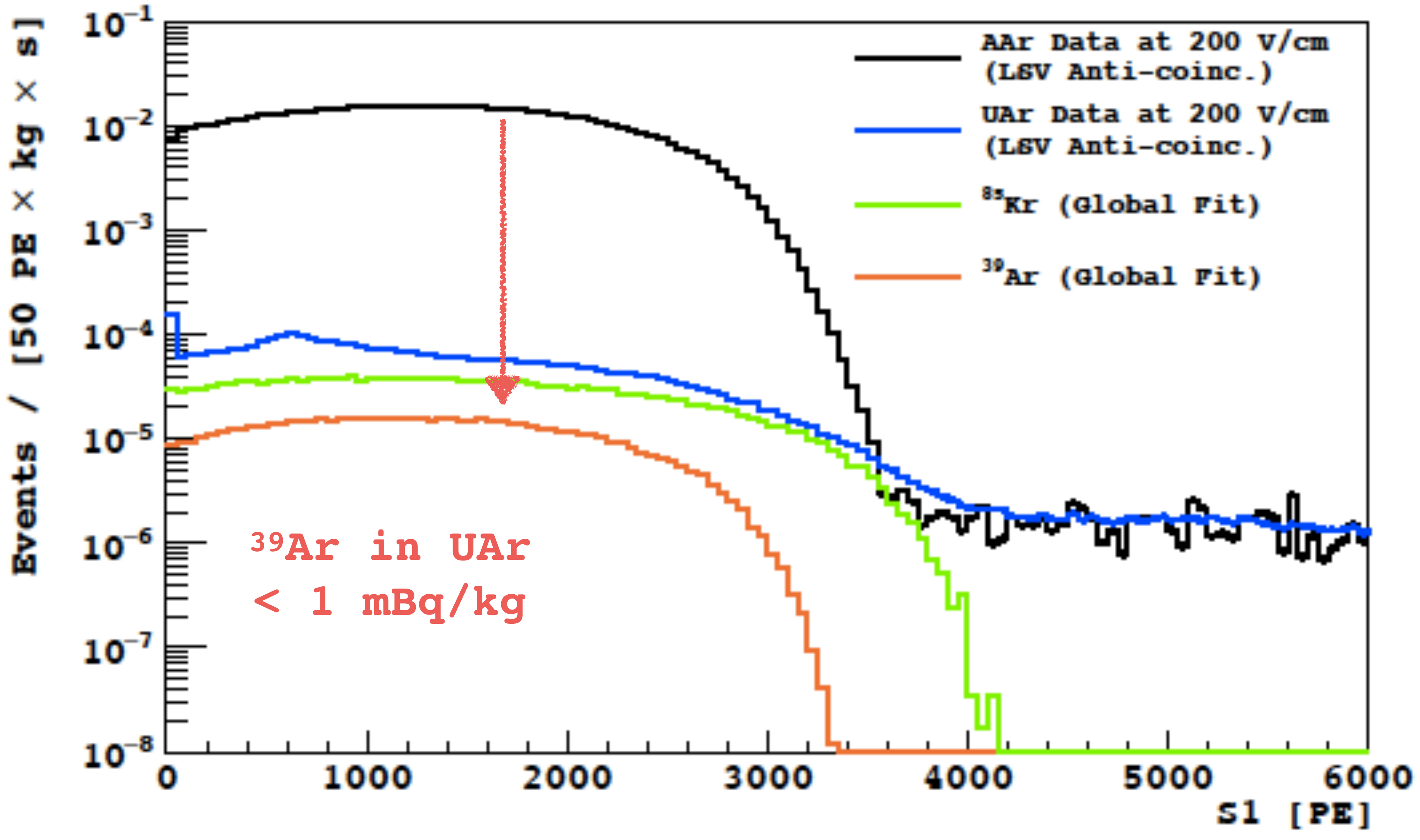
✓ ER/NR Discrimination

- PSD vs S1 for 1422 kg d atmospheric argon (AAr) exposure
- 1.5x10[7] ER events from ^{39}Ar activity in AAr and Zero NR events

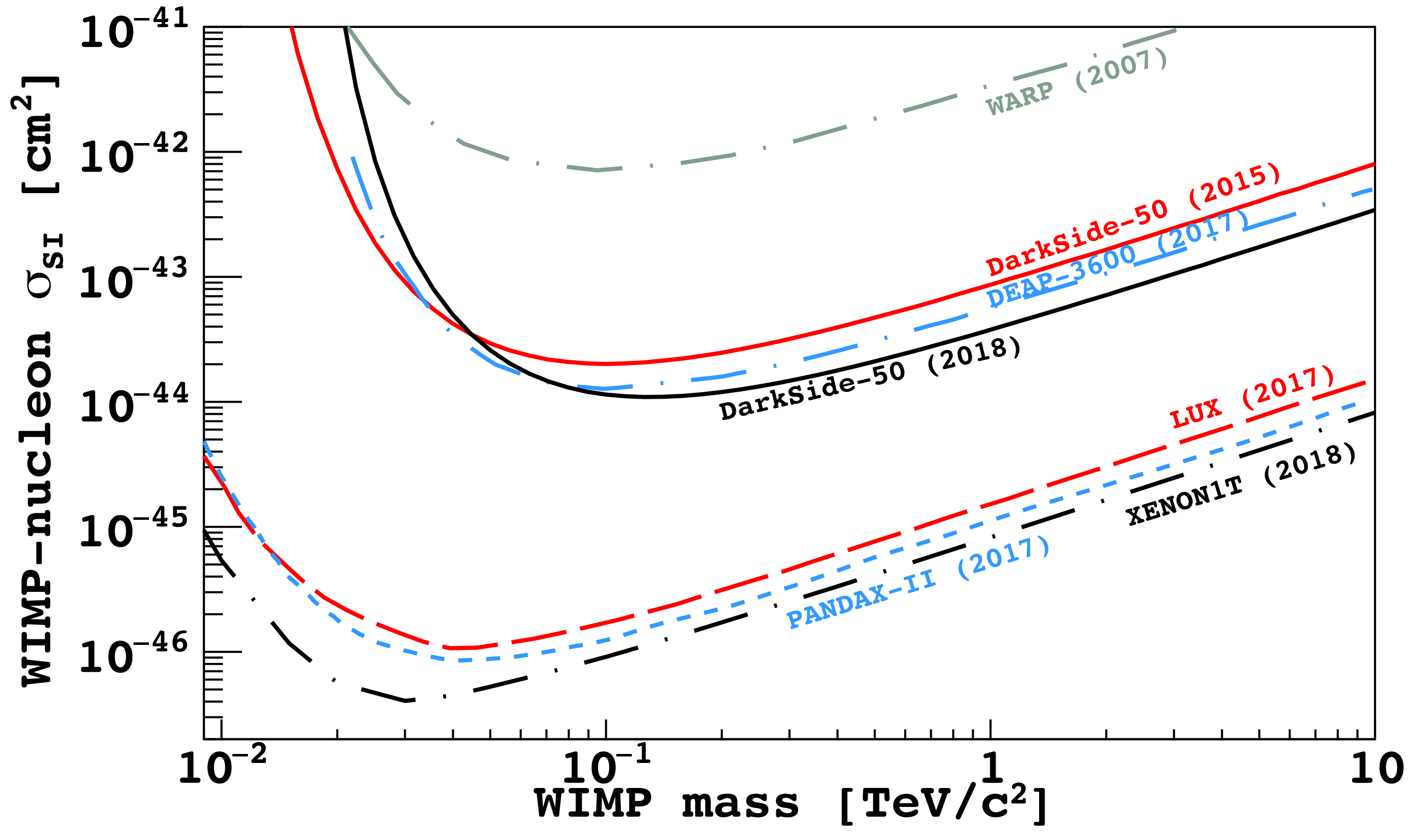


✓ Suppression: AAr Vs UAr

- ^{39}Ar production supported by cosmogenic activation via ^{40}Ar(n,2n)^{39}Ar
- Underground argon (UAr): 150 kg successfully extracted from a CO_2 well in Colorado
- ^{39}Ar depletion factor >1400

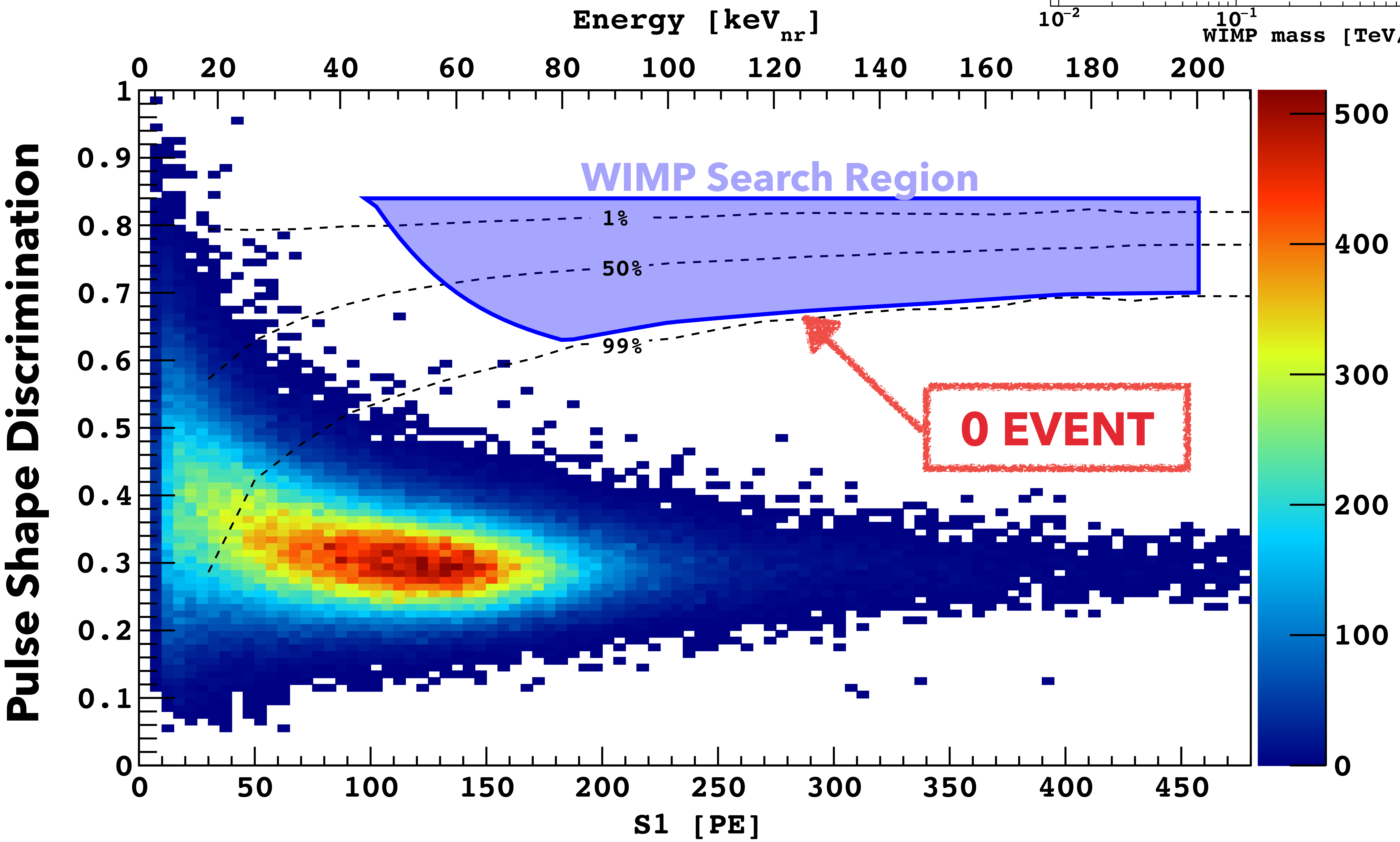


540-DAY BLIND ANALYSIS RESULT



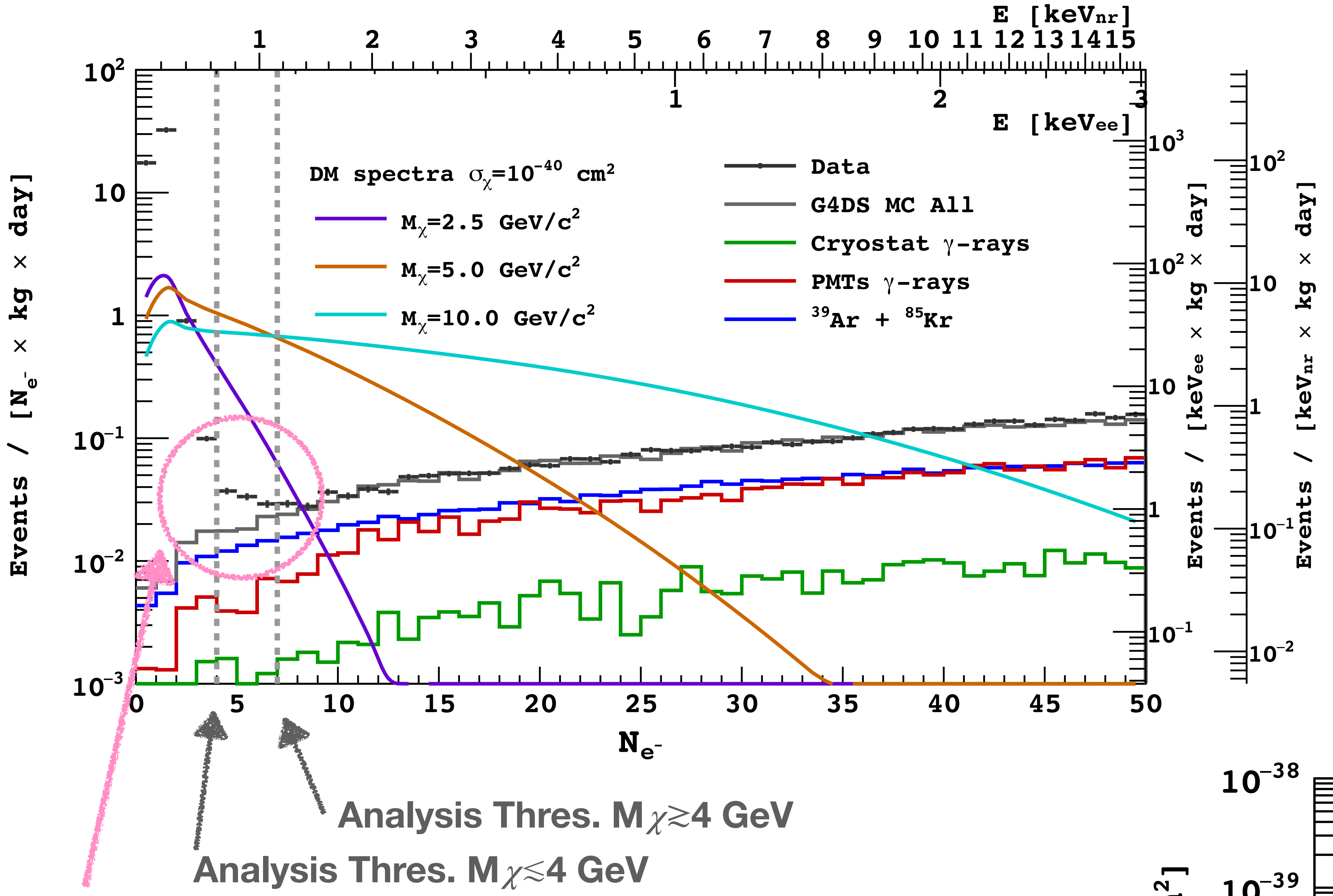
Strong Pulse Shape Discrimination!!

No BG in the Search Region



Phys. Rev. D *98* 102006 (2018)

S2-ONLY RESULT

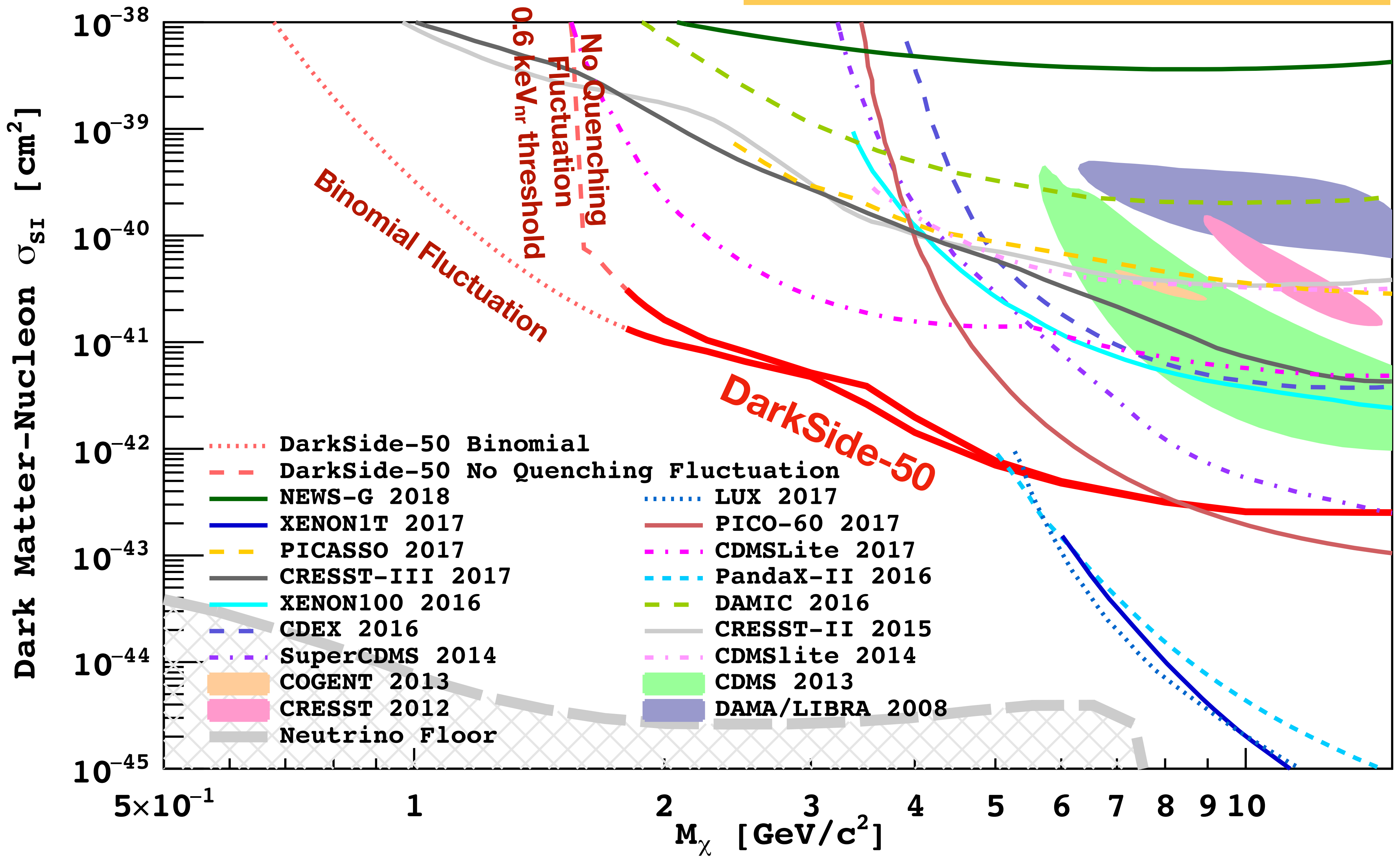


- **Excess of events**
- **Unknown source**

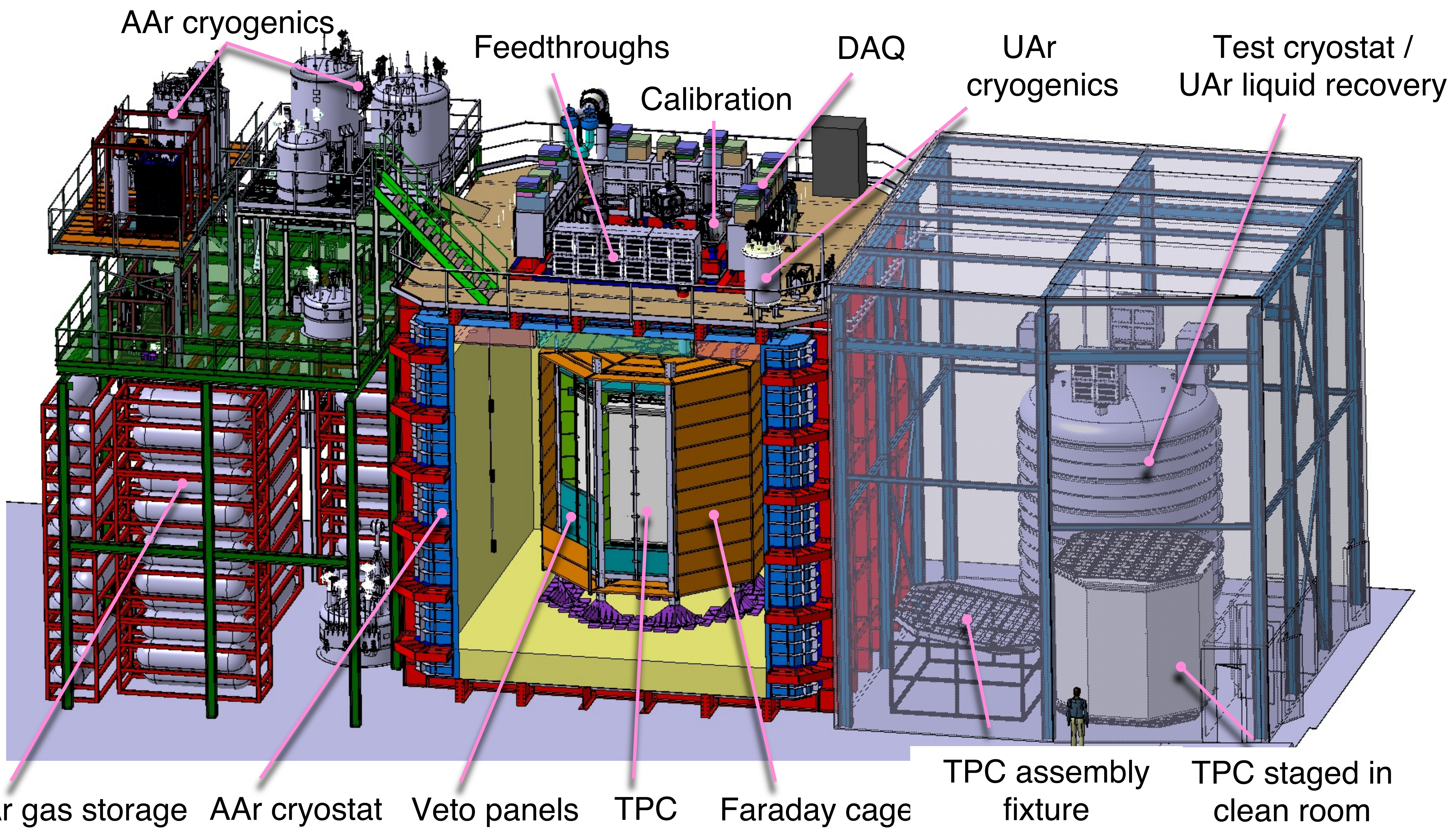
- Profile Likelihood Method is used
  - BG components are fitted at high energy and extrapolated
  - Uncertainties from both WIMP signals (NR ionization yield, single electron yields) and BG spectrum (rates, ER ionization yield) are included

- **Ionization signal** (S2): threshold <0.1 keV_{ee}/0.4 keV_{nr}
  Sensitive to low mass WIMPs
- Use Ionization (S2) Only.
  - PMTs have almost zero dark rate at 88K
  - Amplified in the gas region (~23 PE/e$^-$)
  - Sensitive to a single extracted electron
  - Radioactivity rate in the detector is remarkably low
  - No need of PSD
  - The electron yield for nuclear recoils increases at low energy
- In DS-50, we can detect down to **single electrons**

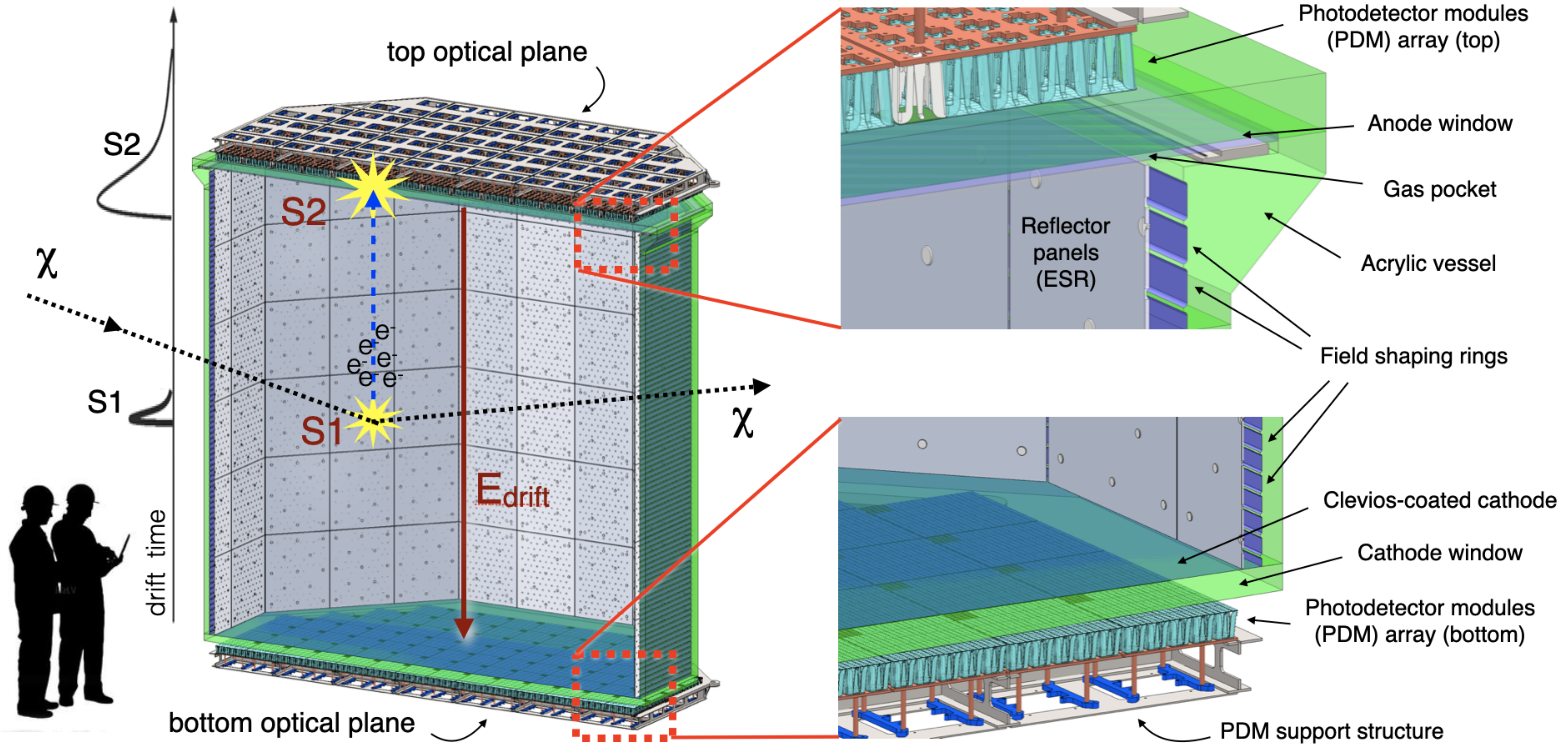
Phys. Rev. Lett. ***121*** *081307 (2018)*



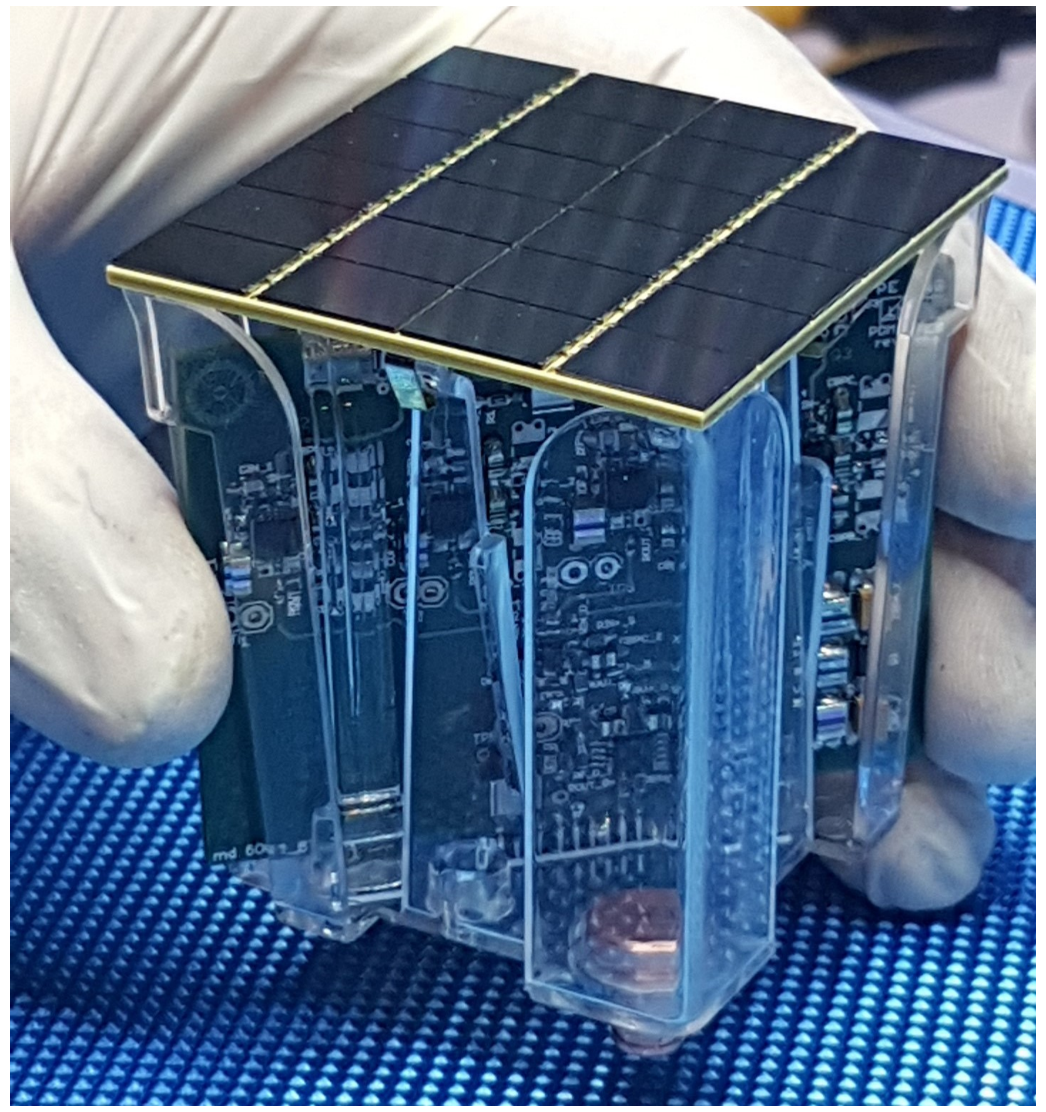
DARKSIDE-20K IN LNGS HALL-C



DARKSIDE-20K

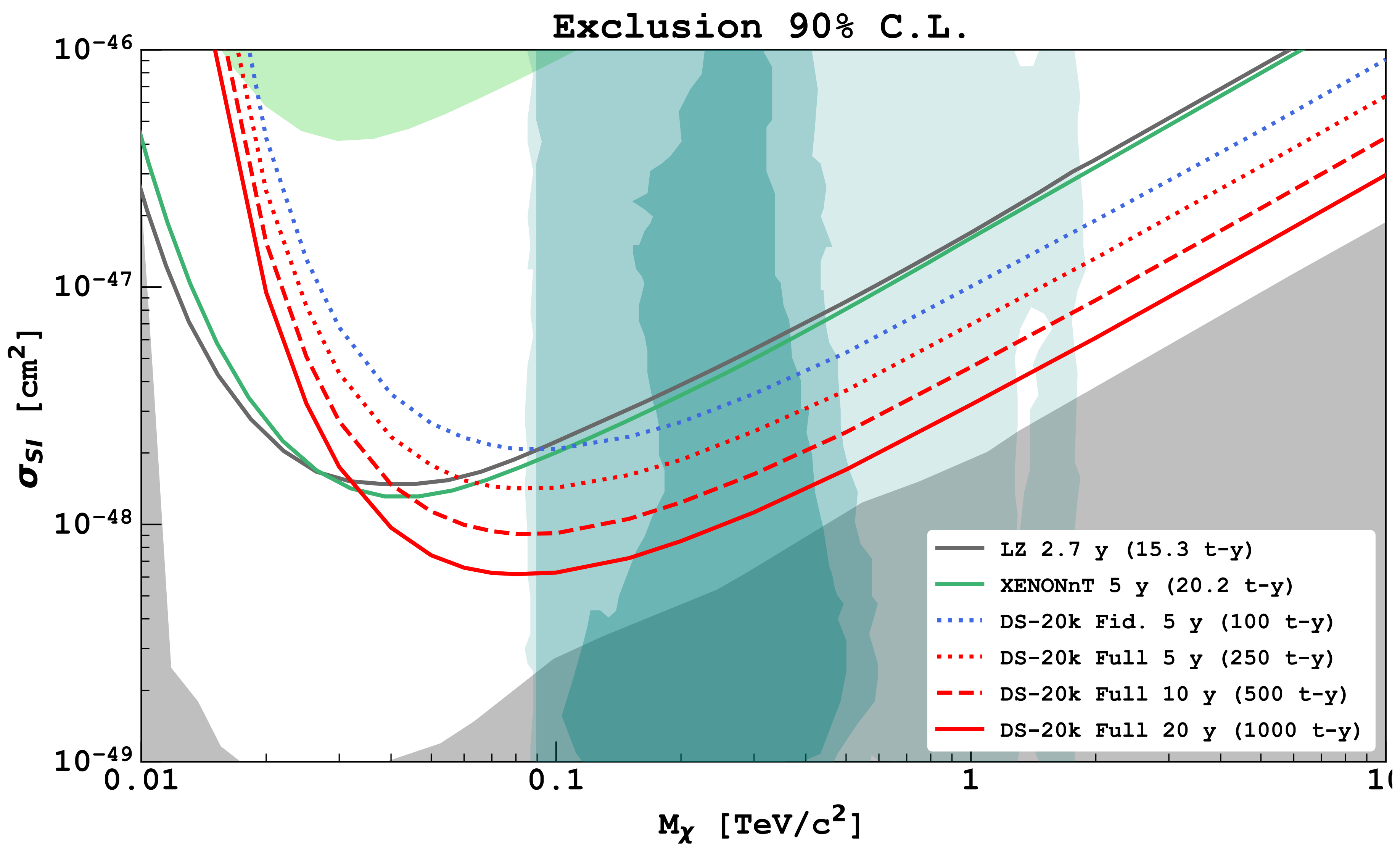


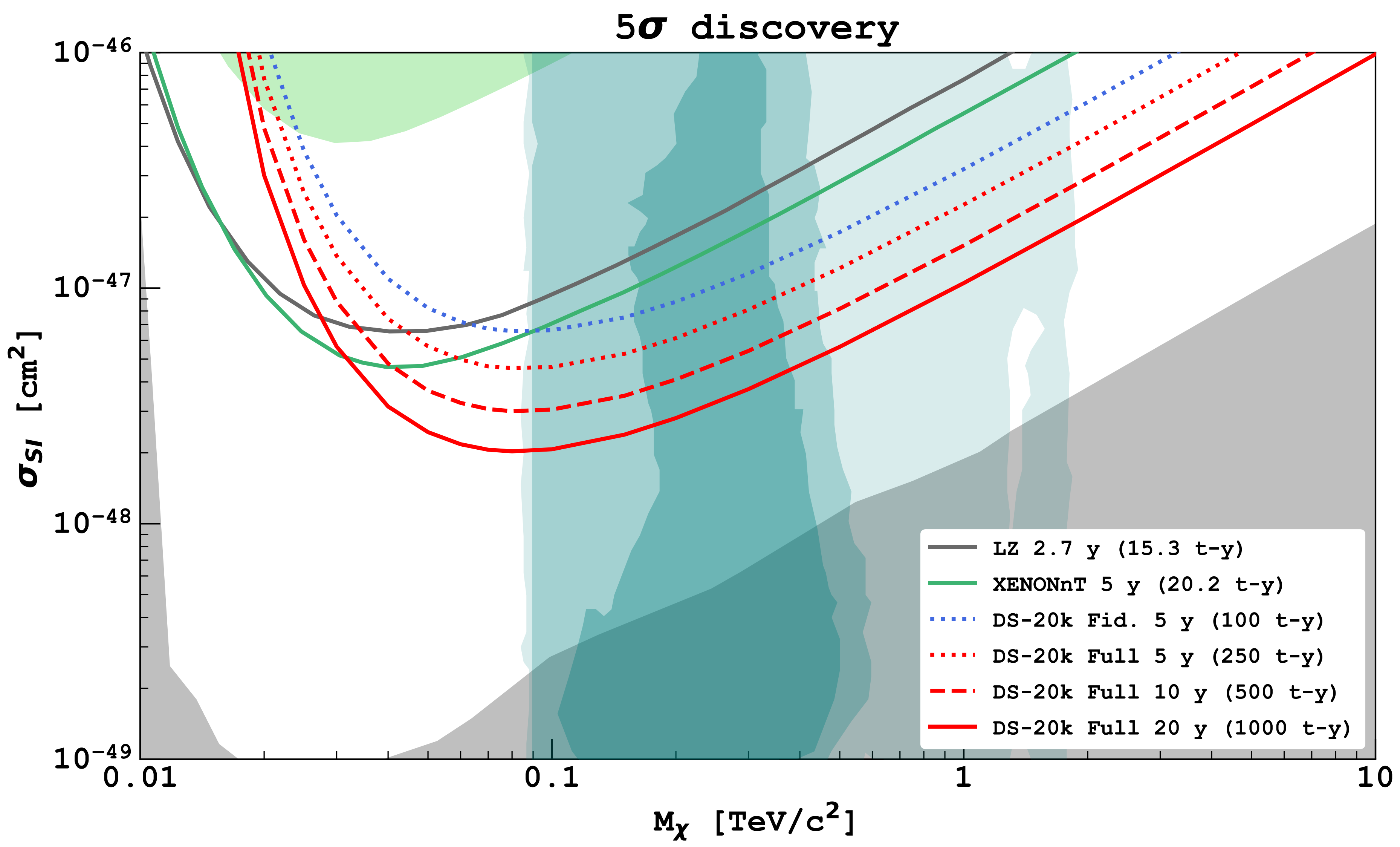
PDM



- A 20-tonnes fiducial argon detector filled with underground argon
- TPC acrylic vessel surrounded by AAr + Gd-loaded acrylic shell as a neutron veto
- 21 m2 of Cryogenic Silicon based Photo-Multipliers

EXCLUSION SENSITIVITY AND 5σ DISCOVERY POTENTIAL

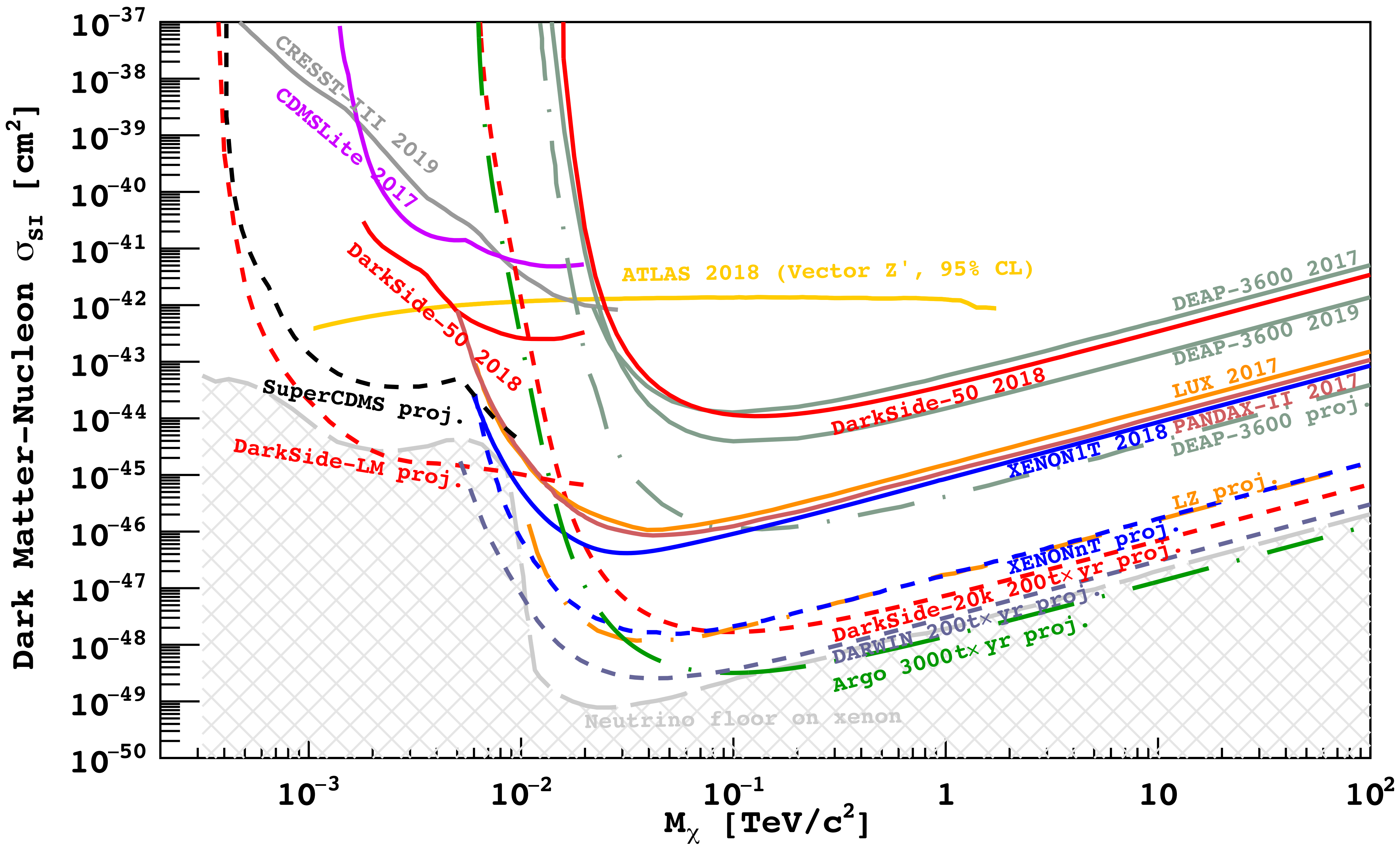




- Expect 3 events in 200 ton x year from neutrino coherent scattering
- Underground Argon target, excellent PSD, and neutron veto allow zero instrumental background

ARGO

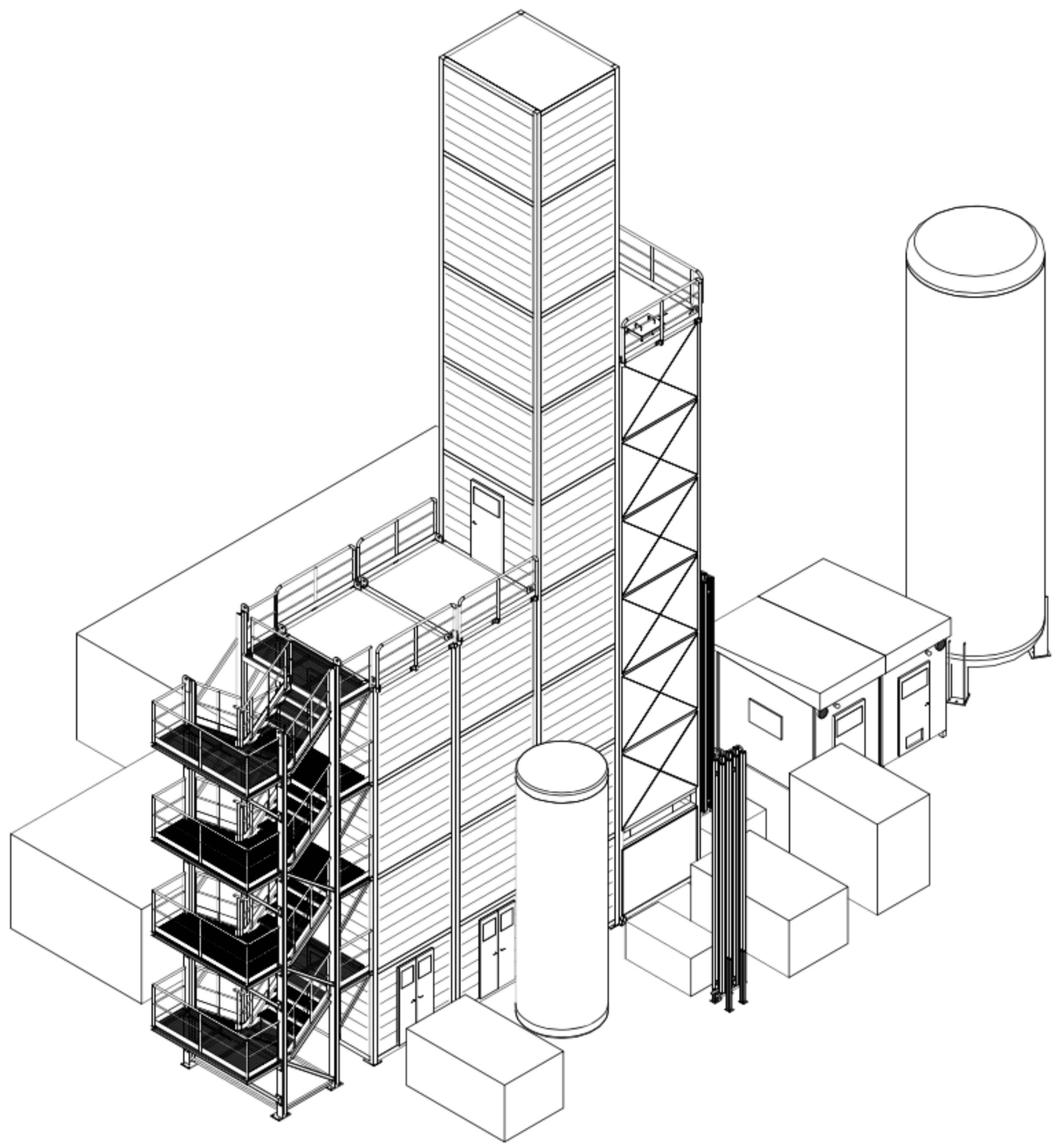
- ArDM, DS-50, DEAP-3600, and MiniCLEAN jointly formed the Global Argon Dark Matter Collaboration (GADMC)
- A 300-tonnes fiducial argon detector filled with underground argon
- 3000 tonne×year exposure to reach the neutrino floor

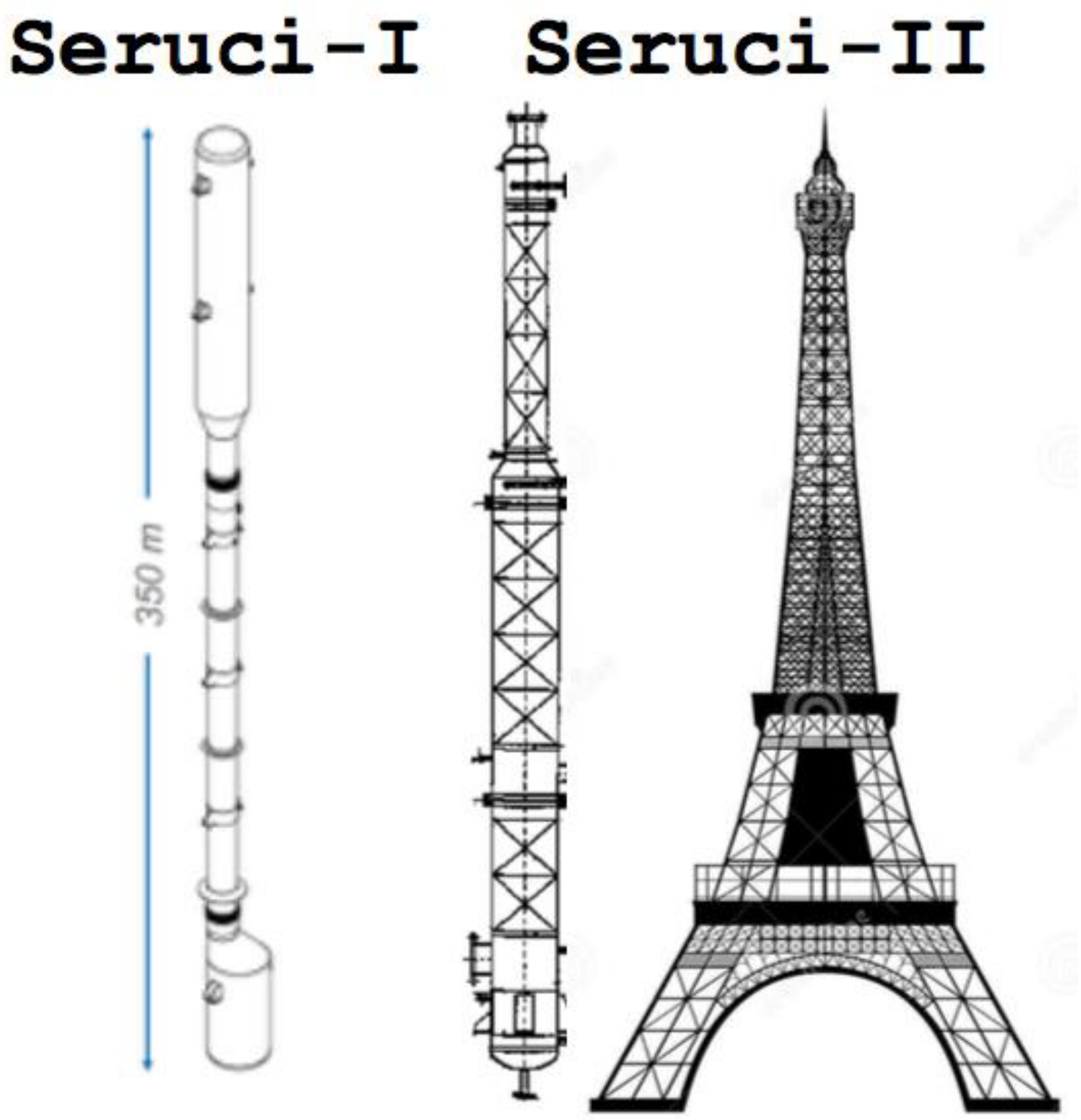


GADMC experiments cover the WIMP hypothesis from 1 GeV/c^2 to several hundreds of TeV/c^2 masses in the search for spin-independent coupling.

URANIA

- Procurement of 50 tonnes of UAr from same Colorado source as for DS-50
- Extraction of 250 kg/day, with 99.9% purity
- UAr transported to Sardinia for final chemical purification at Aria





ARIA

- Big cryogenic distillation column in Seruci, Sardinia
- Final chemical purification of the UAr
- Can process O(1 tonne/day) with 10^3 reduction of all chemical impurities
- Ultimate goal is to isotopically separate ^{39}Ar from ^{40}Ar (at the rate of 10 kg/day in Seruci-I)

The Urania project@Kinder Morgan Doe Canyon Facility, CORTEZ,CO (USA)

extraction of 65t of UAr from CO_2 deep wells, from the upper earth mantle, where cosmic rays hardly make any ^{39}Ar; nucleogenic $^{39}K(n,p)^{40}Ar$ though to be dominant

Starting from 95% CO_2 and 440ppm of UAr and aiming at 99.99% purity!

Three gas processing units followed by cryogenic distillation unit

Production rate of 330 kg/day

The Aria plant was designed to perform isotopic separation of ^{39}Ar from ^{40}Ar using a 350m cryogenic distillation column, 30cm diameter, operated in continuous mode

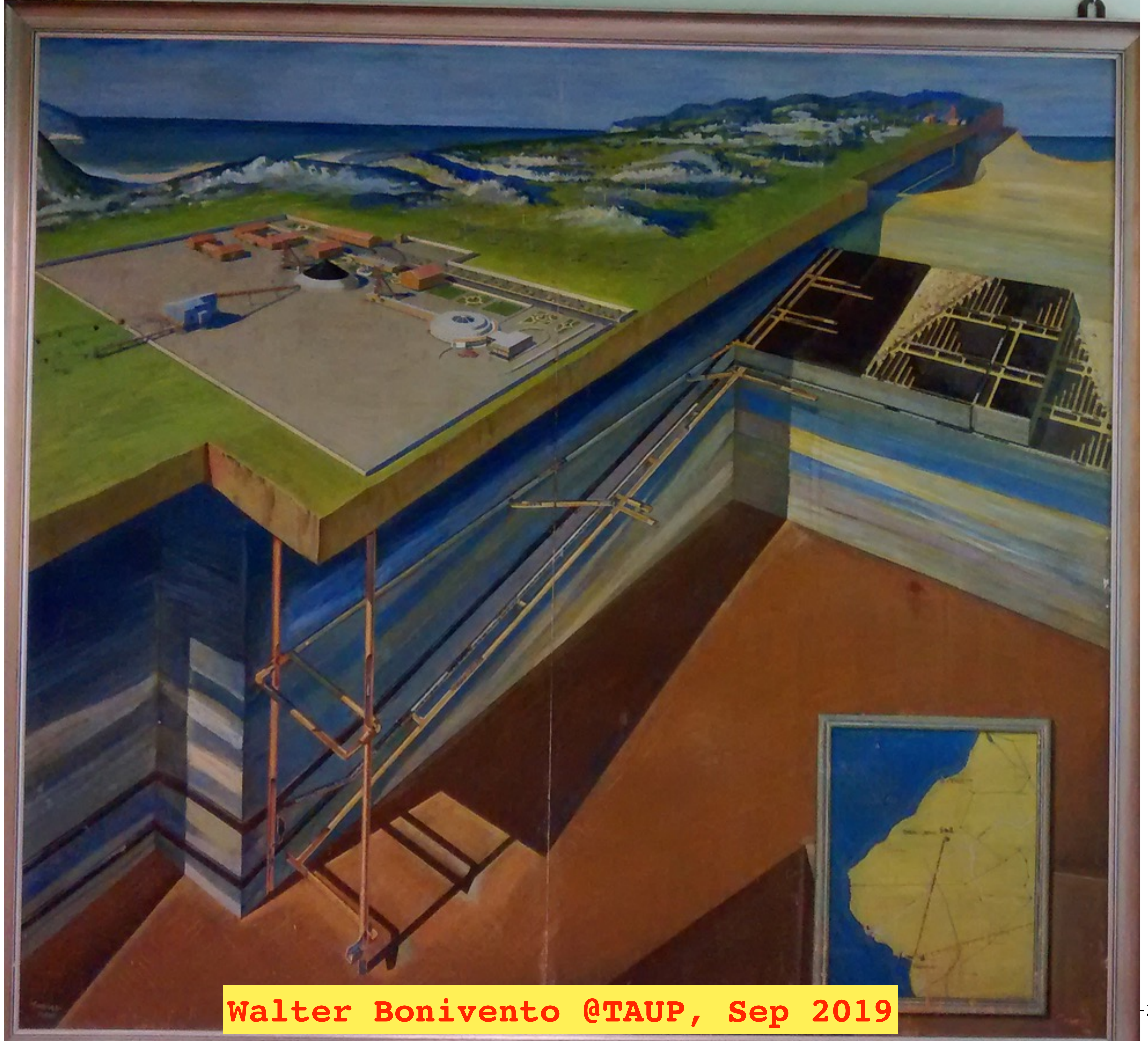
The working principle exploits the different volatility of the two isotopes

T (K)	α
84.0	1.00206
84.4	1.00154
89.2	1.00154
91.8	1.00155

with α being the vapour pressure ratio between the two isotopes

The columns can perform factor 10 suppression at 10kg/day


2000 a.c.
2000 b.c.
Walter Bonivento @TAUP, Sep 2019



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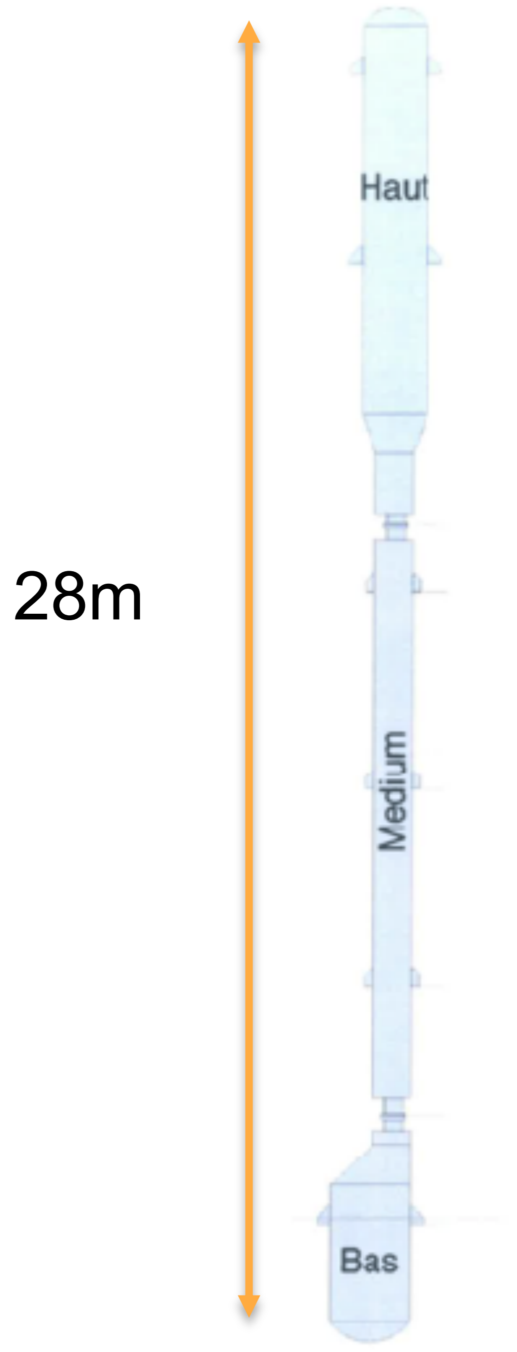
28m
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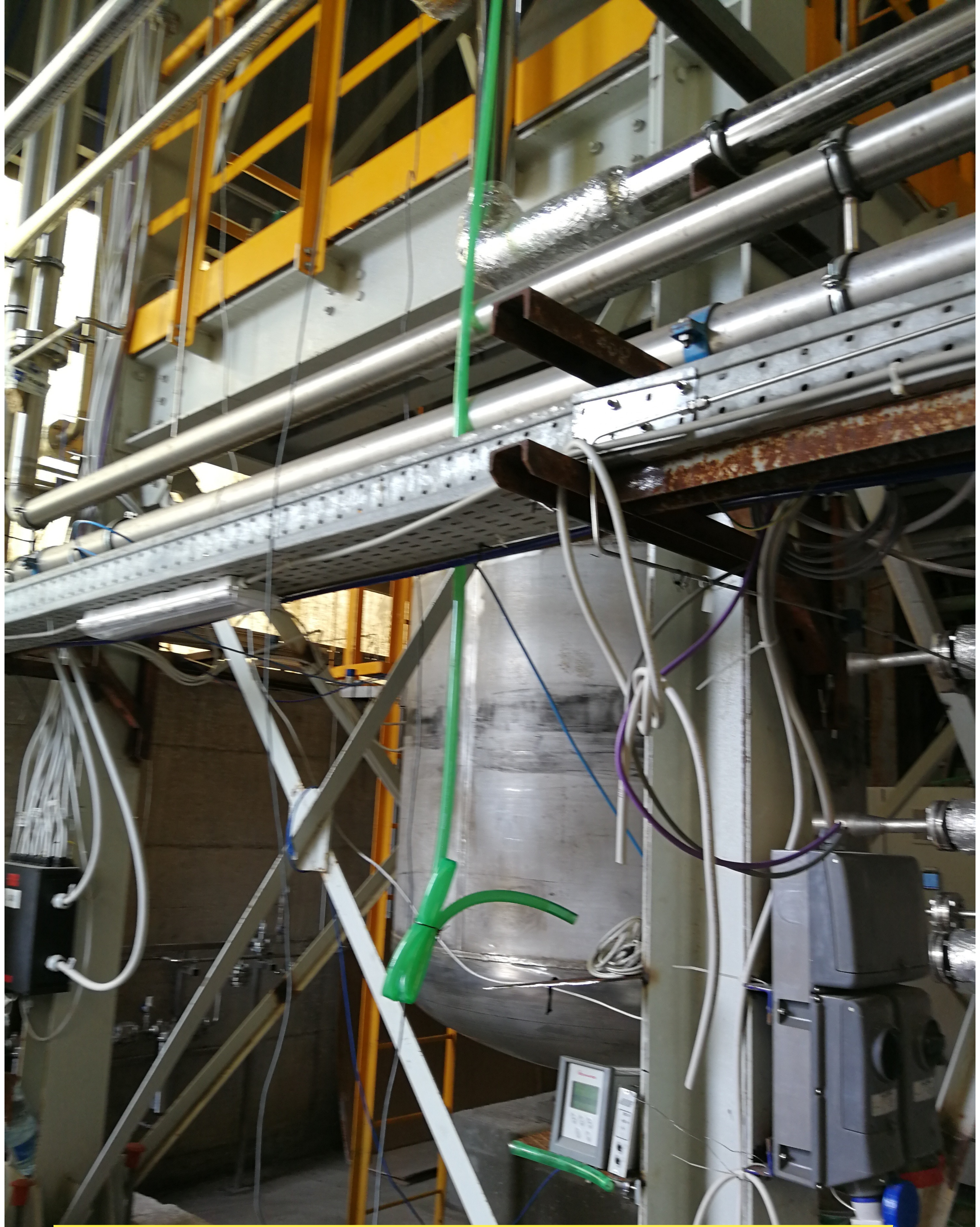
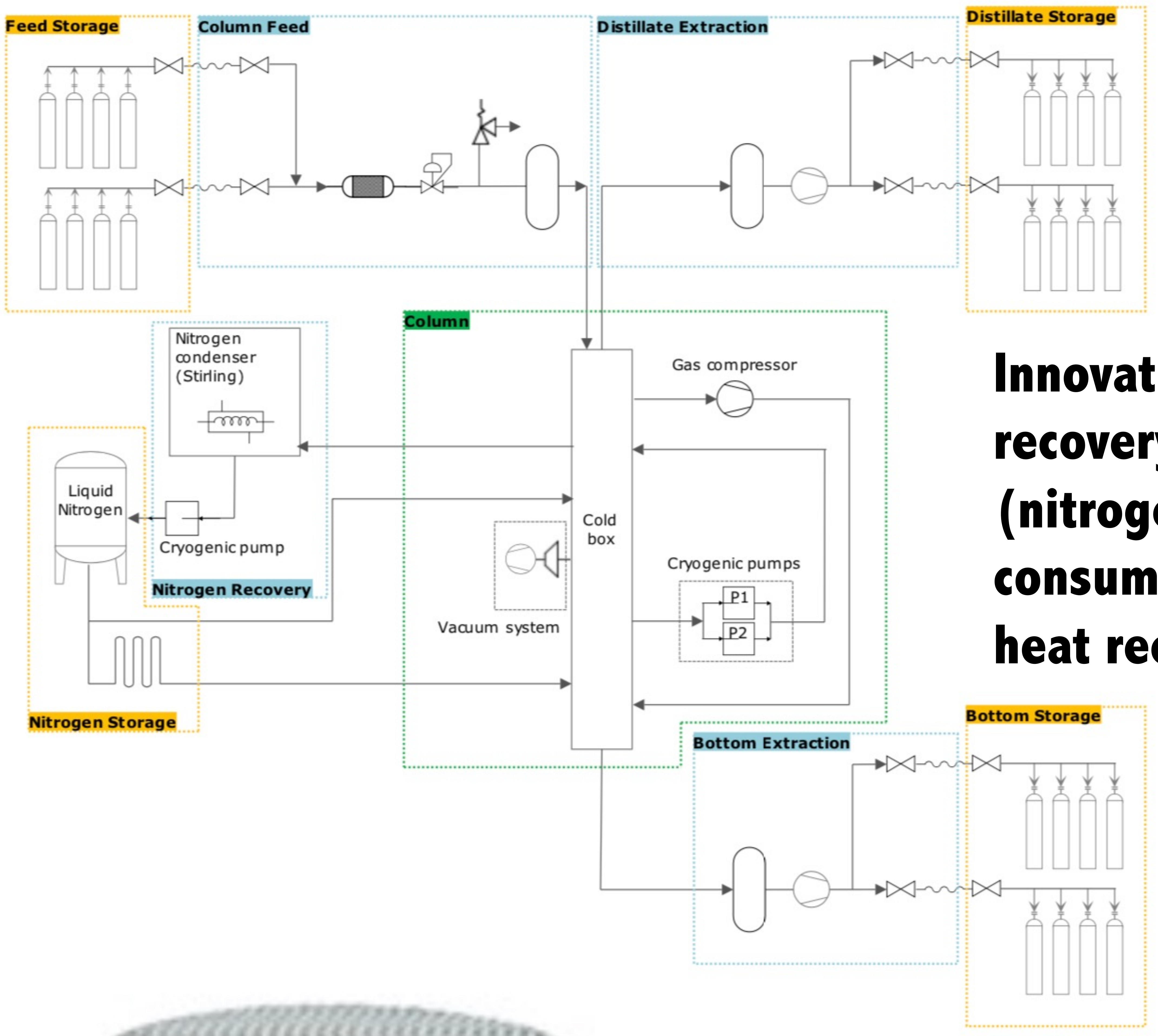
Medium
Bas



Walter Bonivento @TAUP, Sep 2019



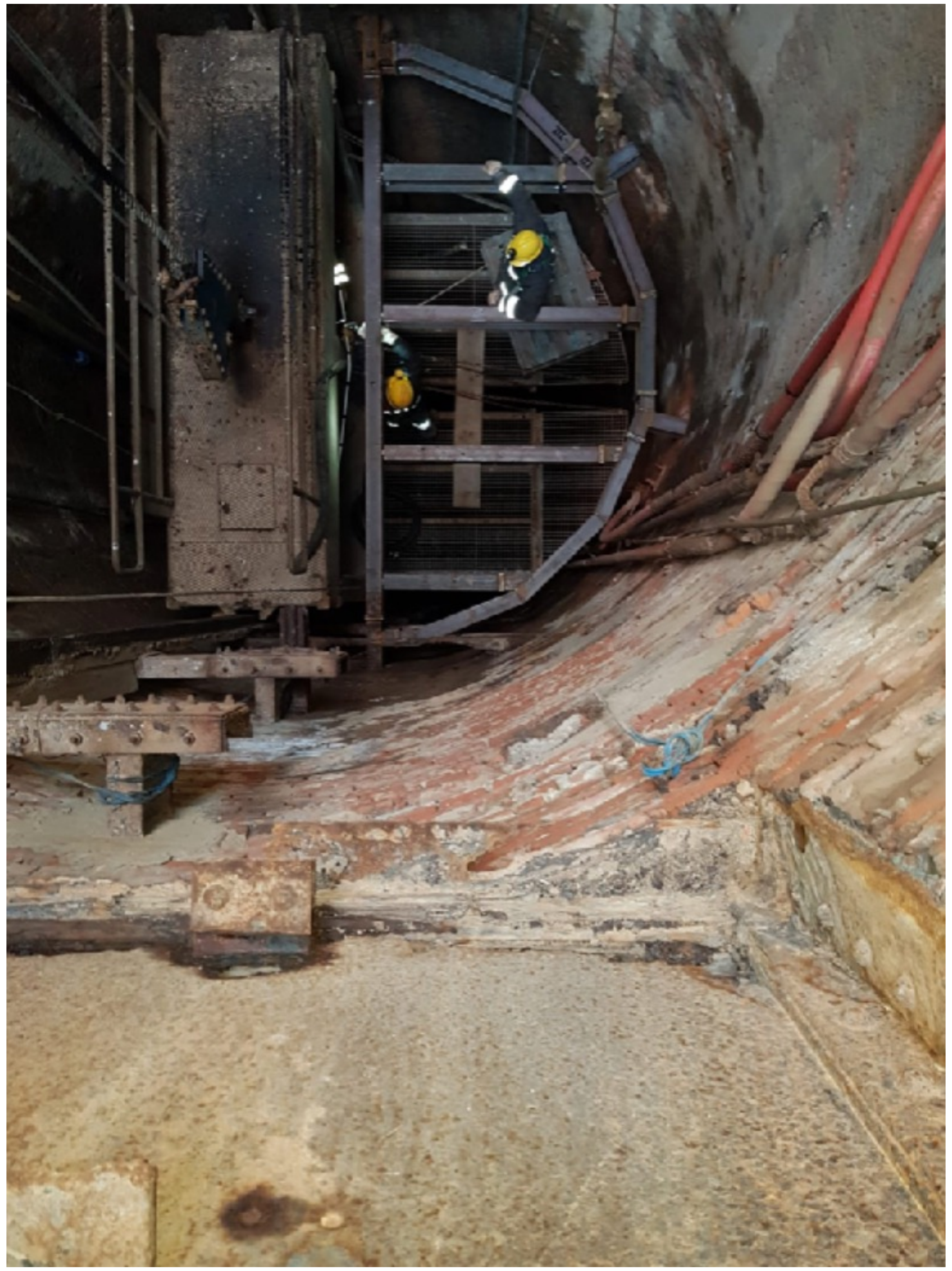
Innovative design: total recovery of the cooling liquid (nitrogen) and low power consumption due to enhanced heat recovery

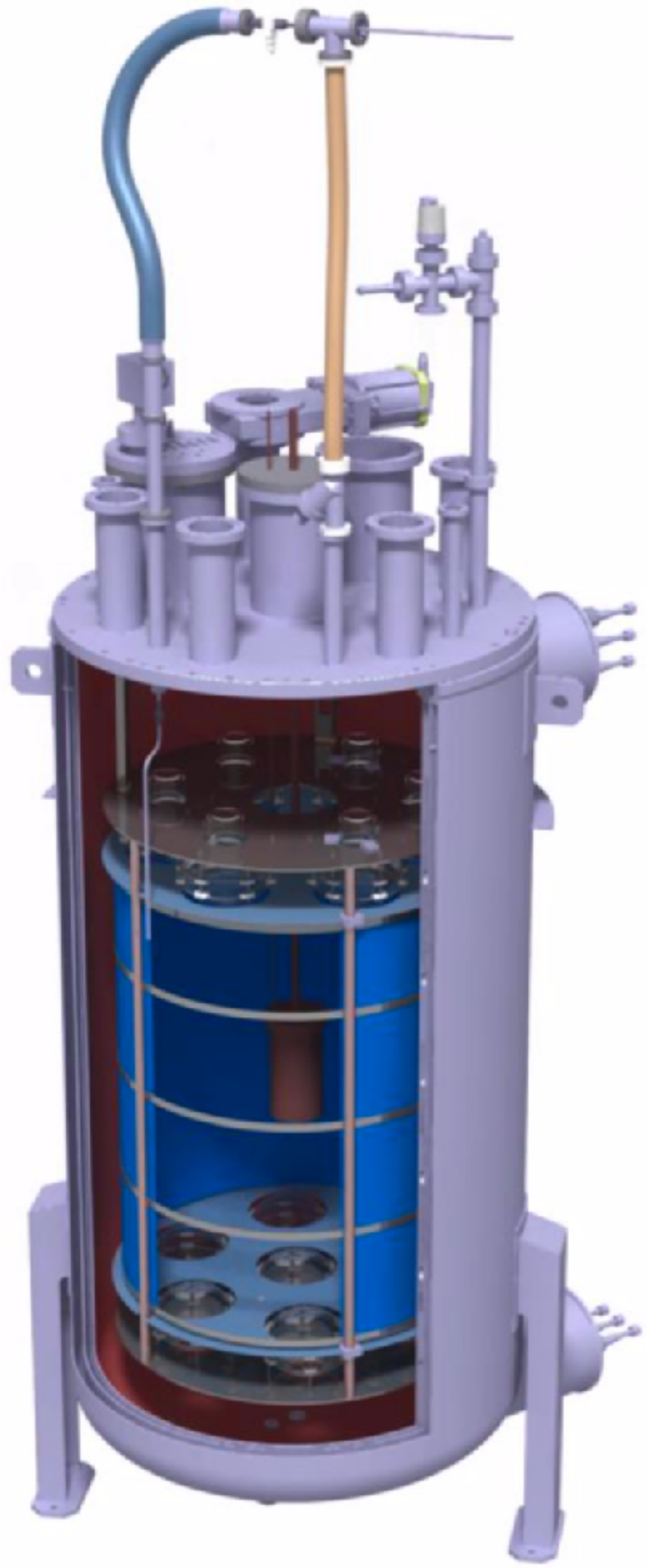
structured stainless steel

packing type called Sulzer CY

gauze

Walter Bonivento @TAUP, Sep 2019





nEXO's TPC design updates

Monolithic detector volume

- >3 ton (~10^{28} atoms) fiducial volume
- Powerful self-shielding
- Measure backgrounds directly in the same detector

Advanced scintillation readout

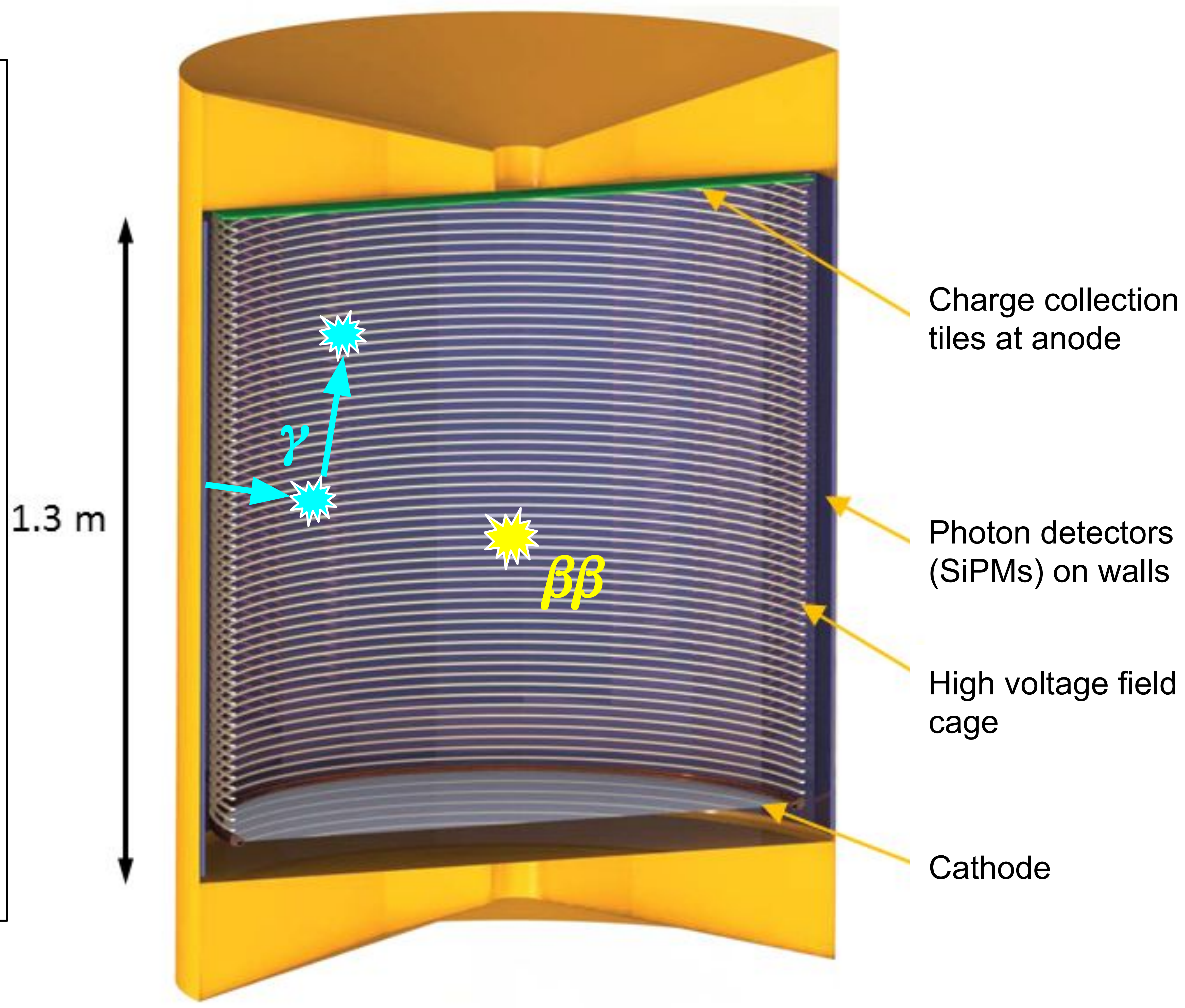
- VUV-sensitive SiPMs

Custom tiled charge readout

- Lower radioactivity, modular construction compared to wires

In-liquid-xenon, cold electronics

- Low-background ASICs for both light and charge readout



Charge readout

Gold strips on quartz substrate

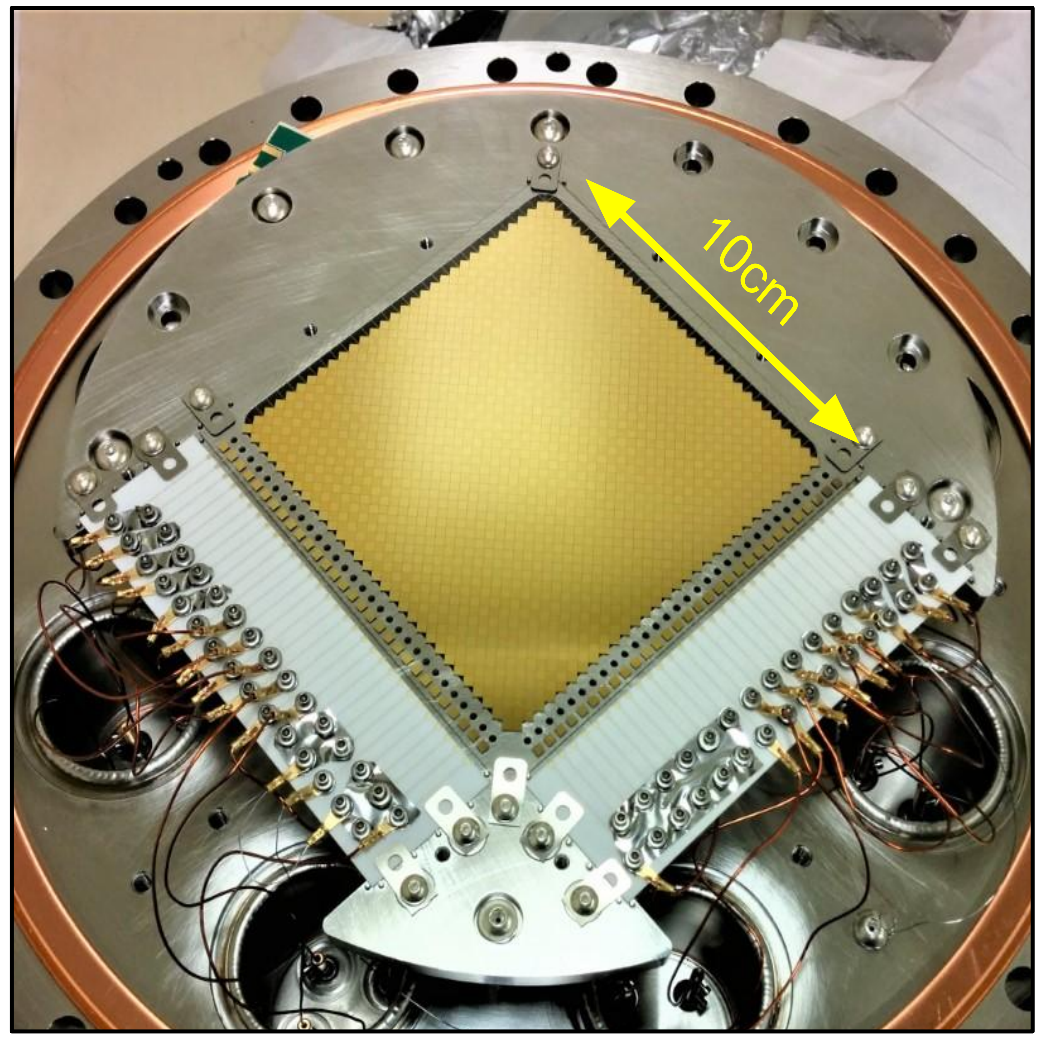
- 6mm pitch
- 3mm prototype tested: Jewell et al. *JINST* **13** (2018)

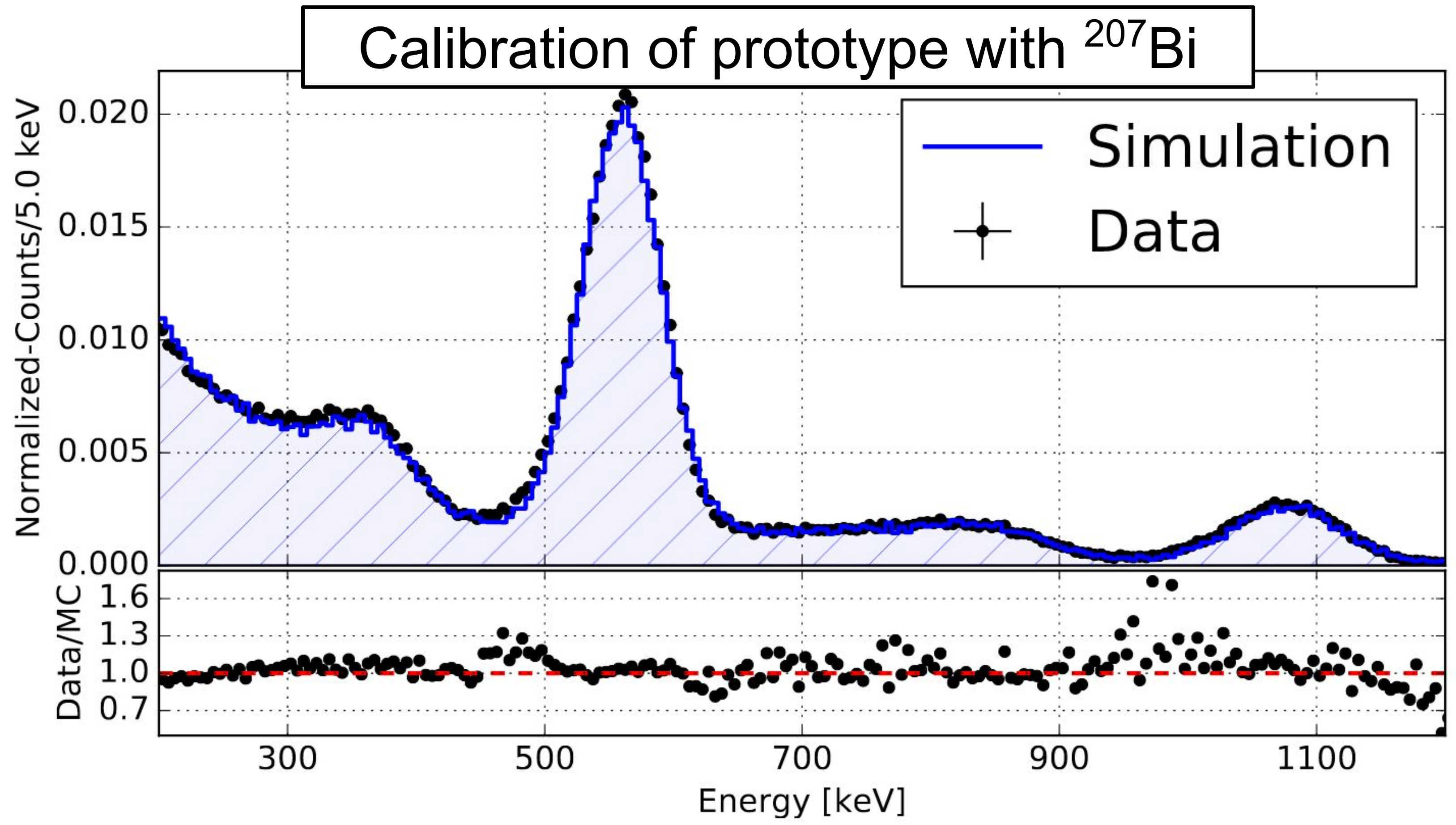
In-LXe cold electronics

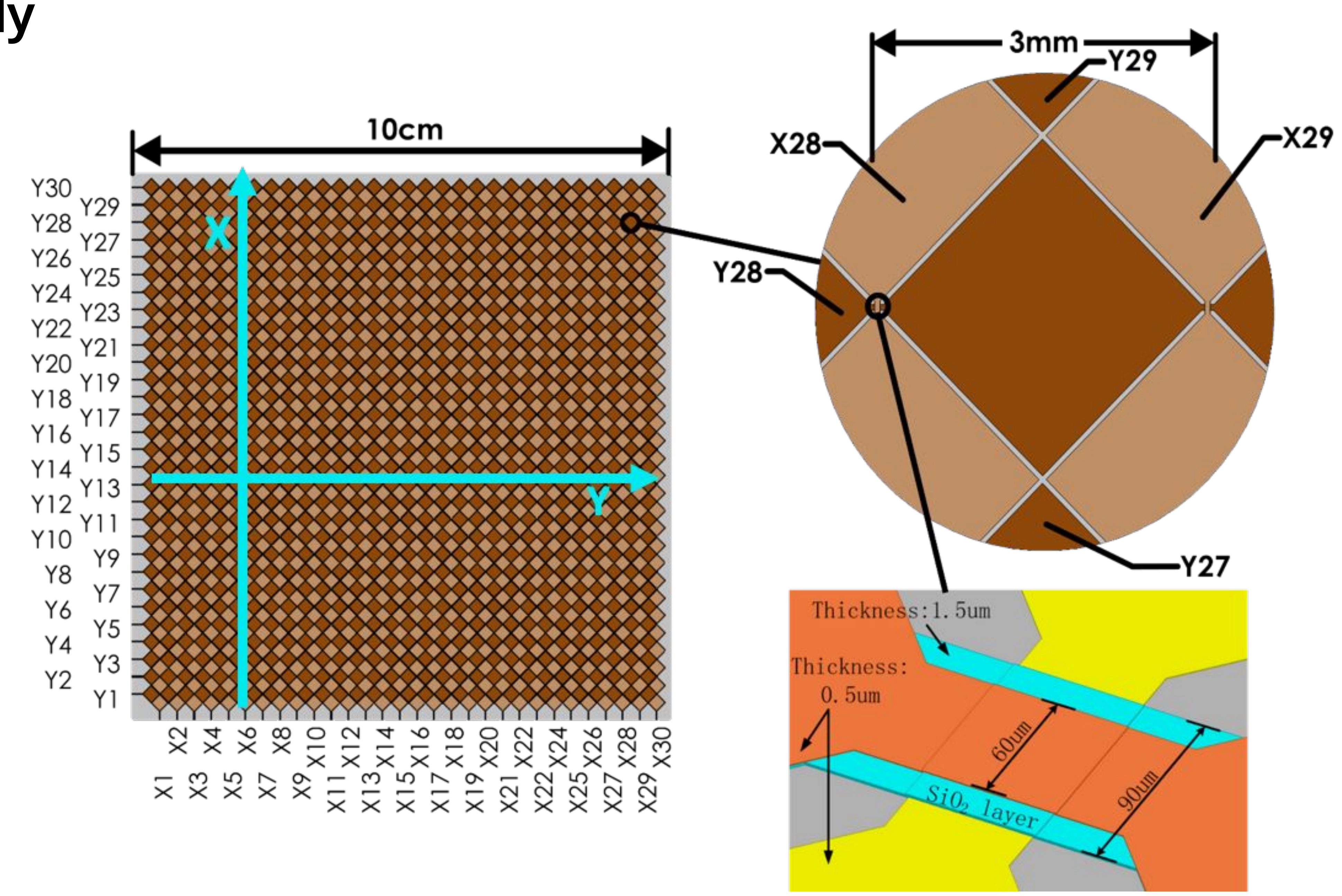
- Lower noise, smaller cable capacitance
- Stringent radioactivity & power requirements
- Custom ASICs under development

Advanced reconstruction techniques under study

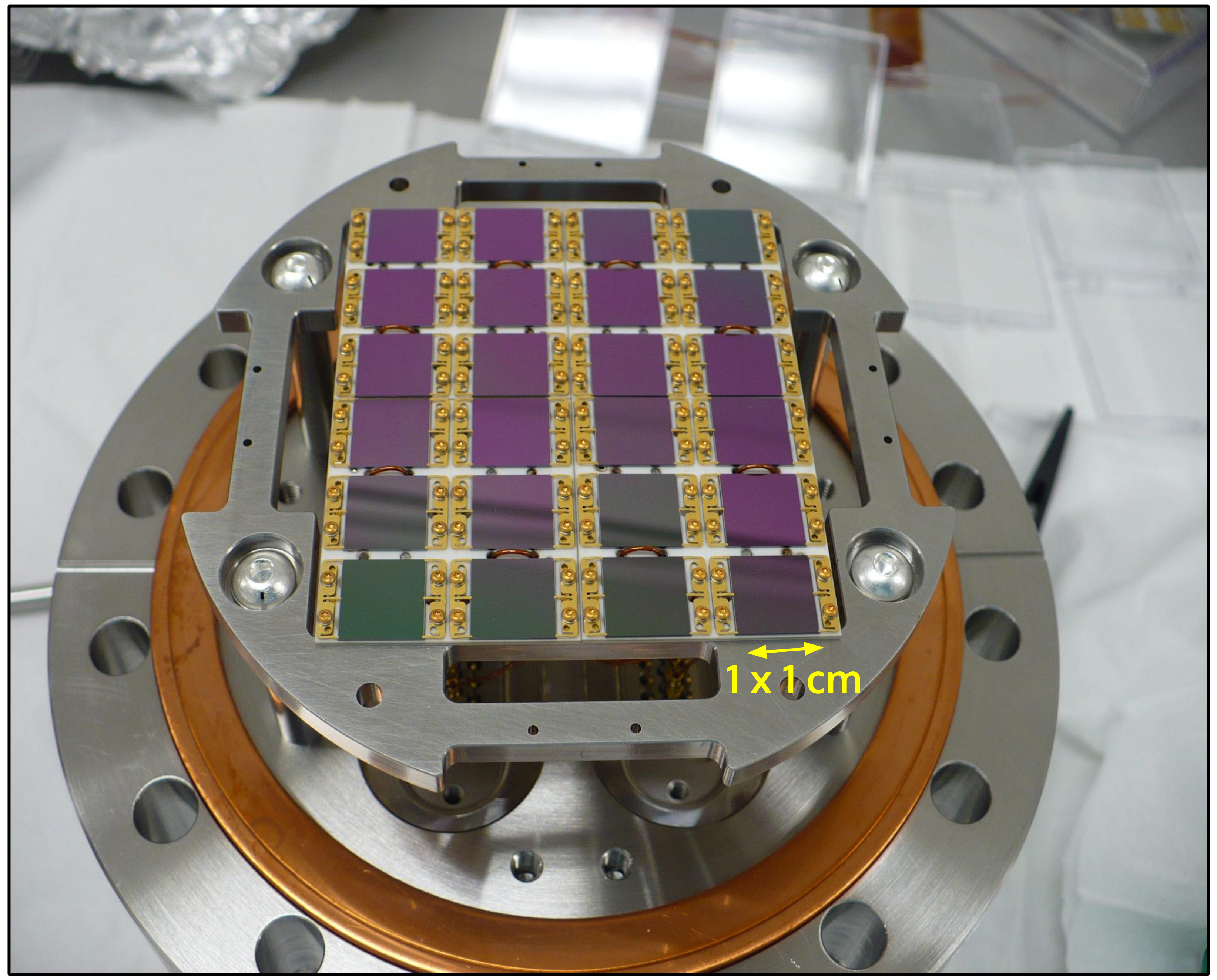
Li et al., *JINST* **14** (2019)







Scintillation readout

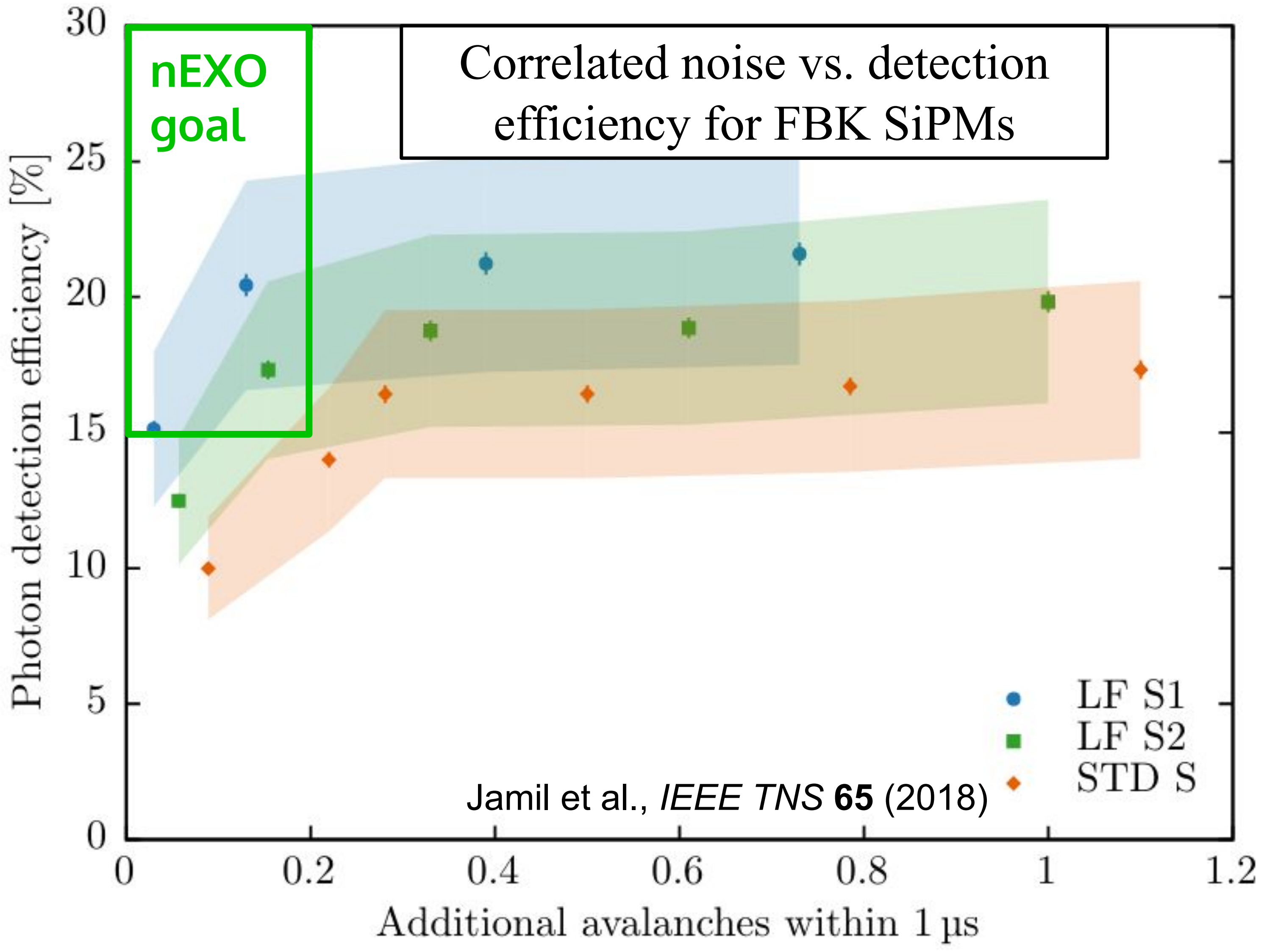


nEXO will use VUV-sensitive SiPMs for scintillation readout

- Lower noise than APDs in EXO200
- Better radiopurity than PMTs

Relatively new technology -- extensive R&D and characterization ongoing within collaboration

- Photon detection efficiency, noise properties
  - Ostrovskiy et al., *IEEE TNS* **62** (2015) arXiv:1502.07837
  - Jamil et al., *IEEE TNS* **65** (2018) arXiv:1806.02220
  - Gallina et al., *NIM A* **940** (2019) arXiv:1903.03663
- Development of in-LXe ASIC readout

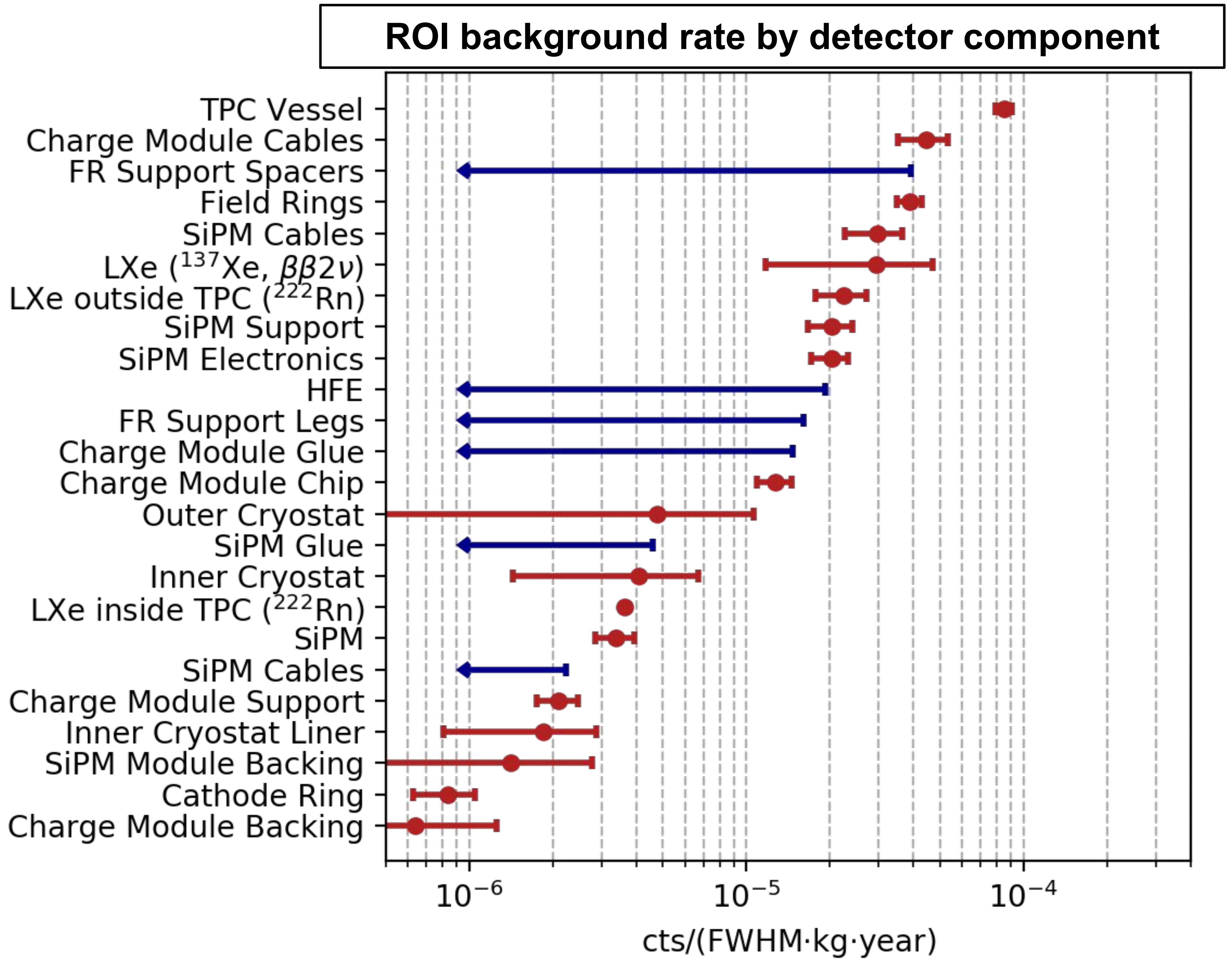


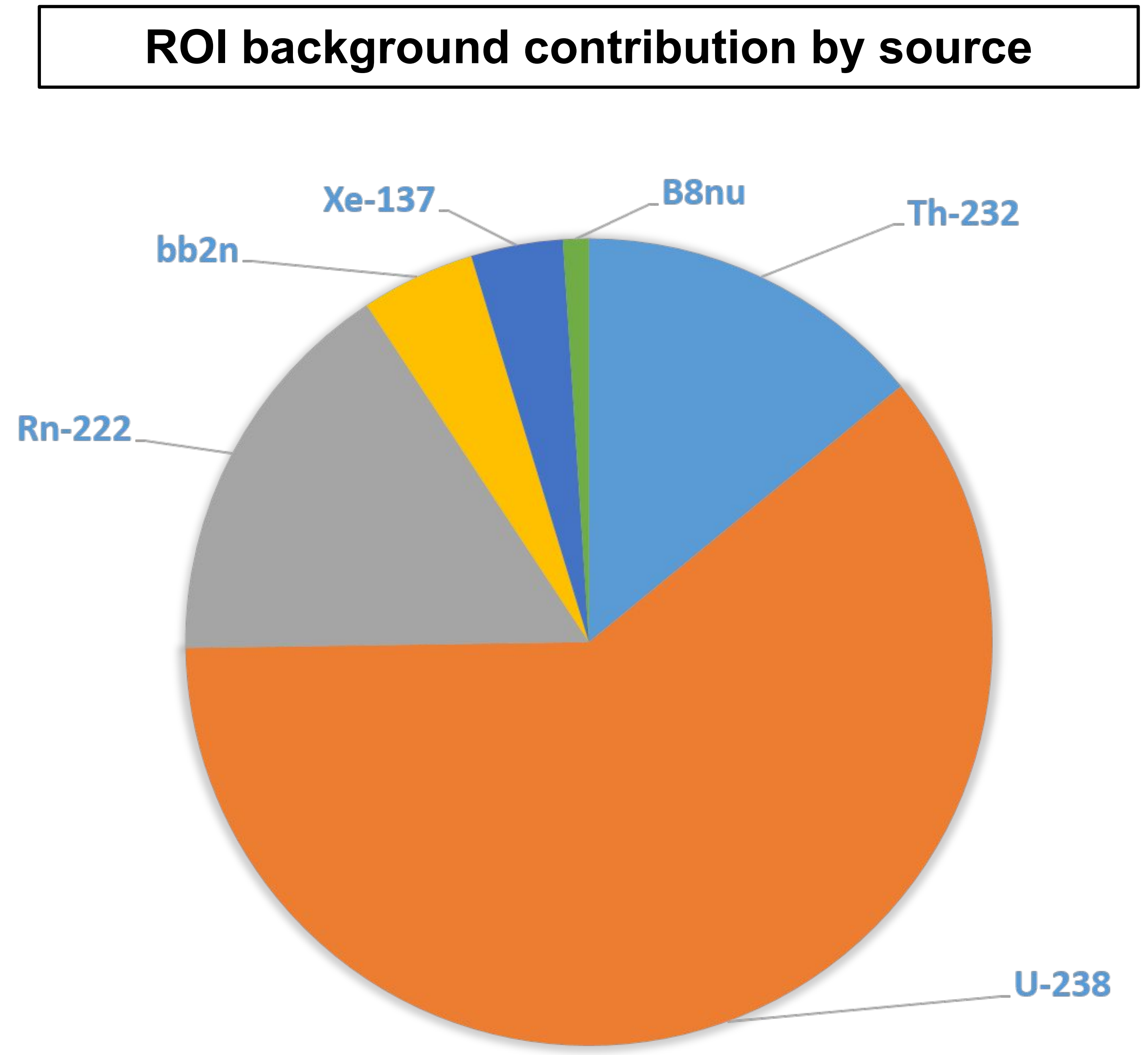
Estimating radioactive backgrounds

Extensive materials screening campaign, following success of EXO-200 (e.g. D. Leonard, *NIMA* **591** (2008))

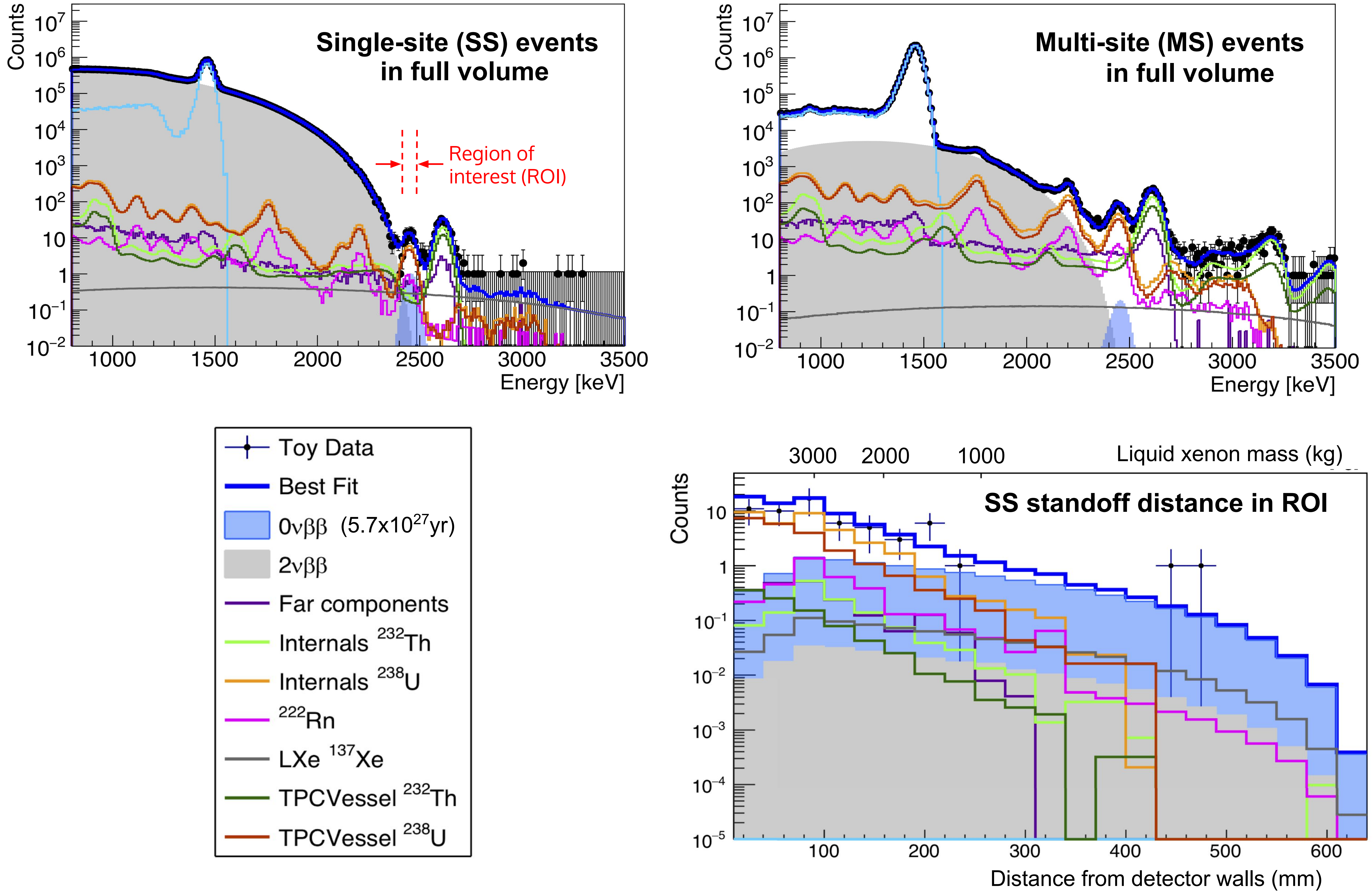
Essentially every material in existing design has been screened for radiopurity

→ nEXO background model is conservative and data-driven

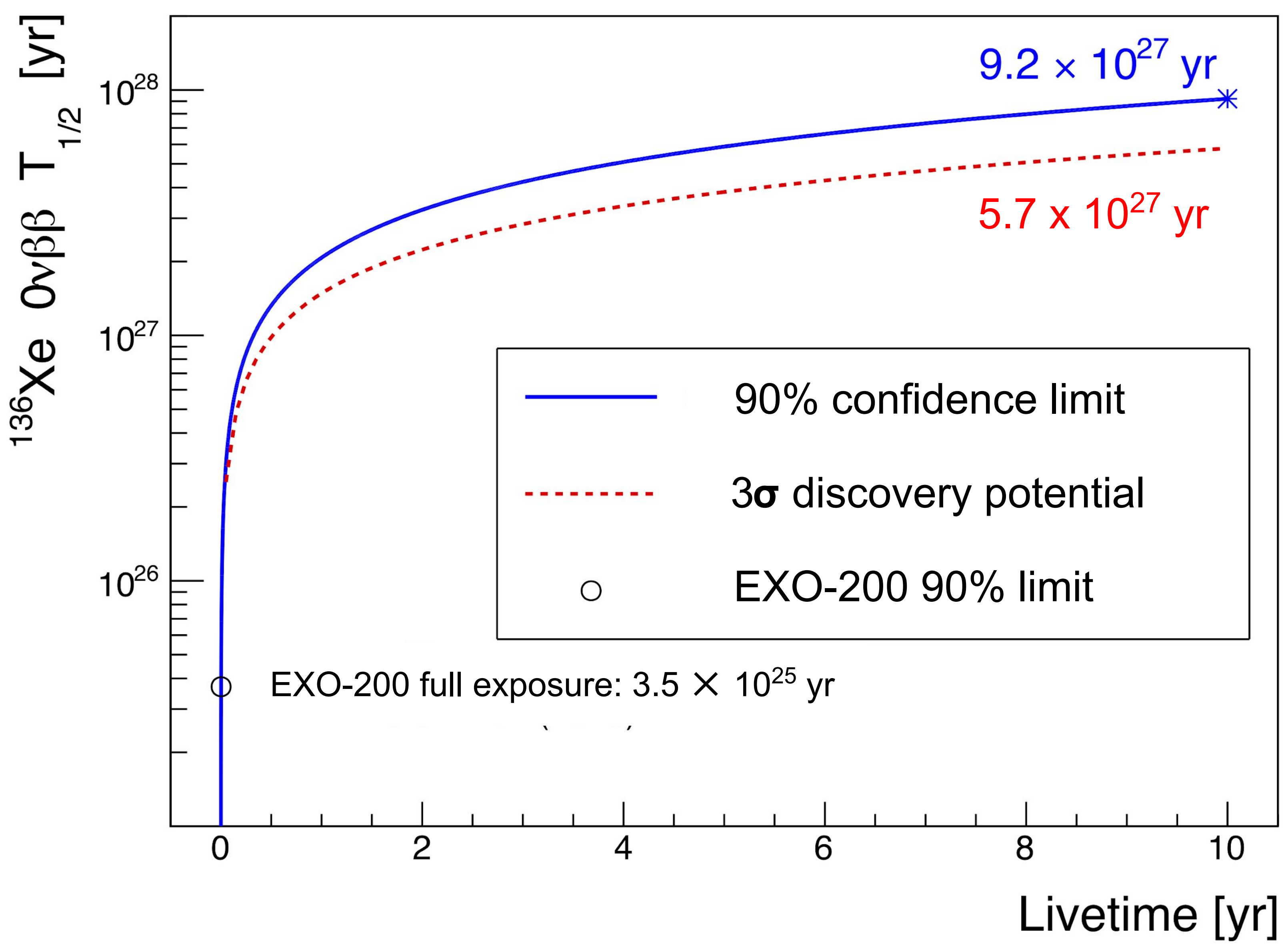


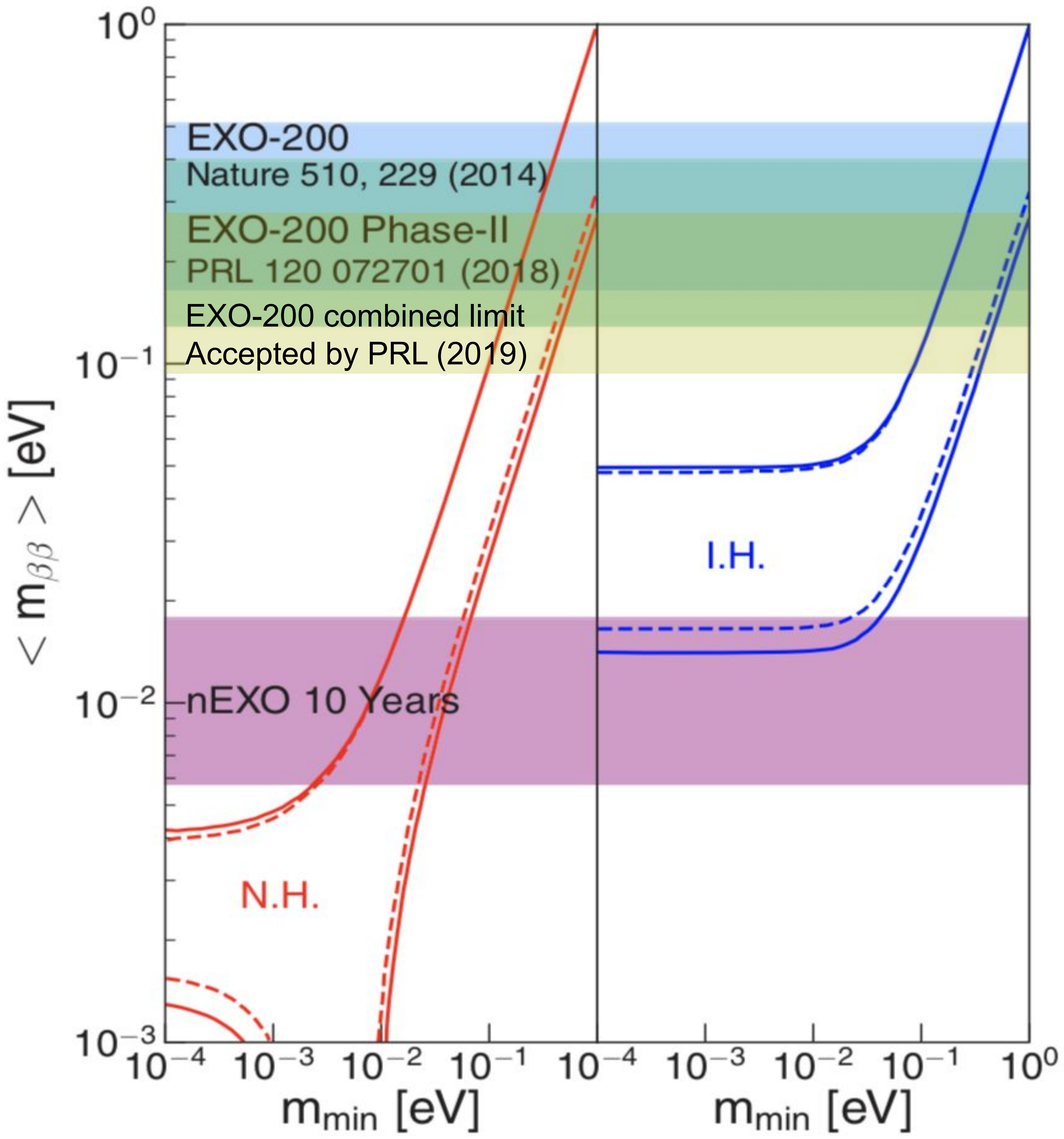


Expected performance - Geant4 simulation



Projected physics reach ca. 2018





Projected sensitivity: $T_{1/2}$ > 9.2e27 yr @ 90% CL

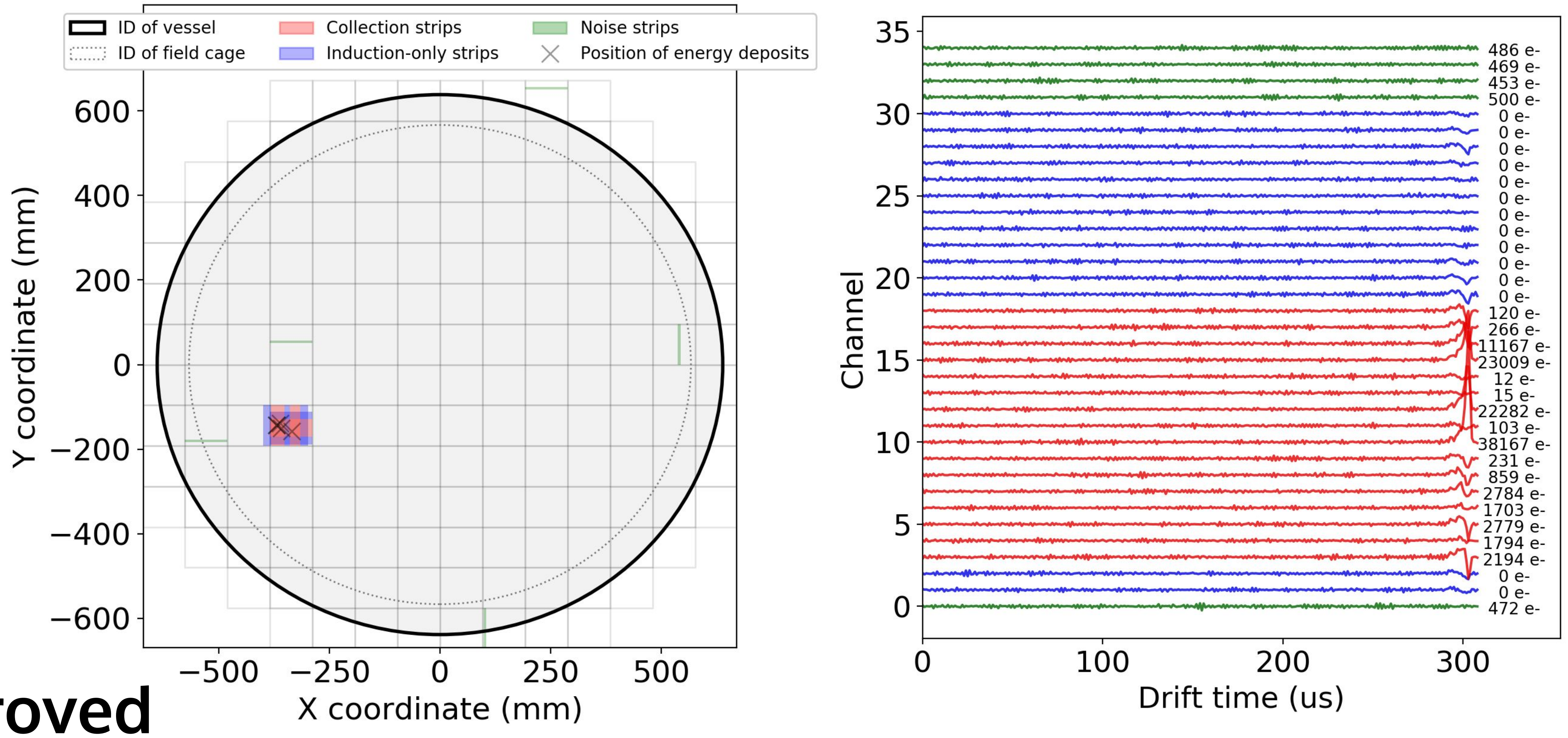
- J. Albert et al., *PRC* **97**, 2018

Recent improvements in readout simulations

Charge readout modeled end-to-end

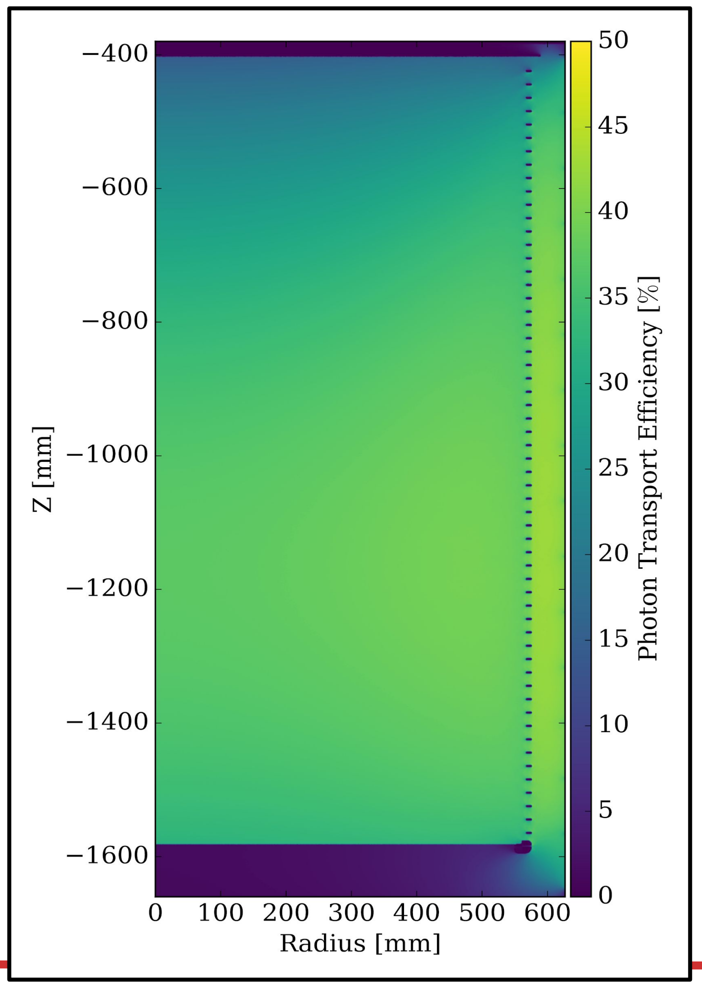
- Full noise simulation of ASIC readout and charge propagation through TPC
- Induction and noise signals generated to mimic real data
    - Z. Li et al. (NEXO) *JINST* **14** (2019)
- **Machine learning classifier likely to improve signal/bkg discrimination**

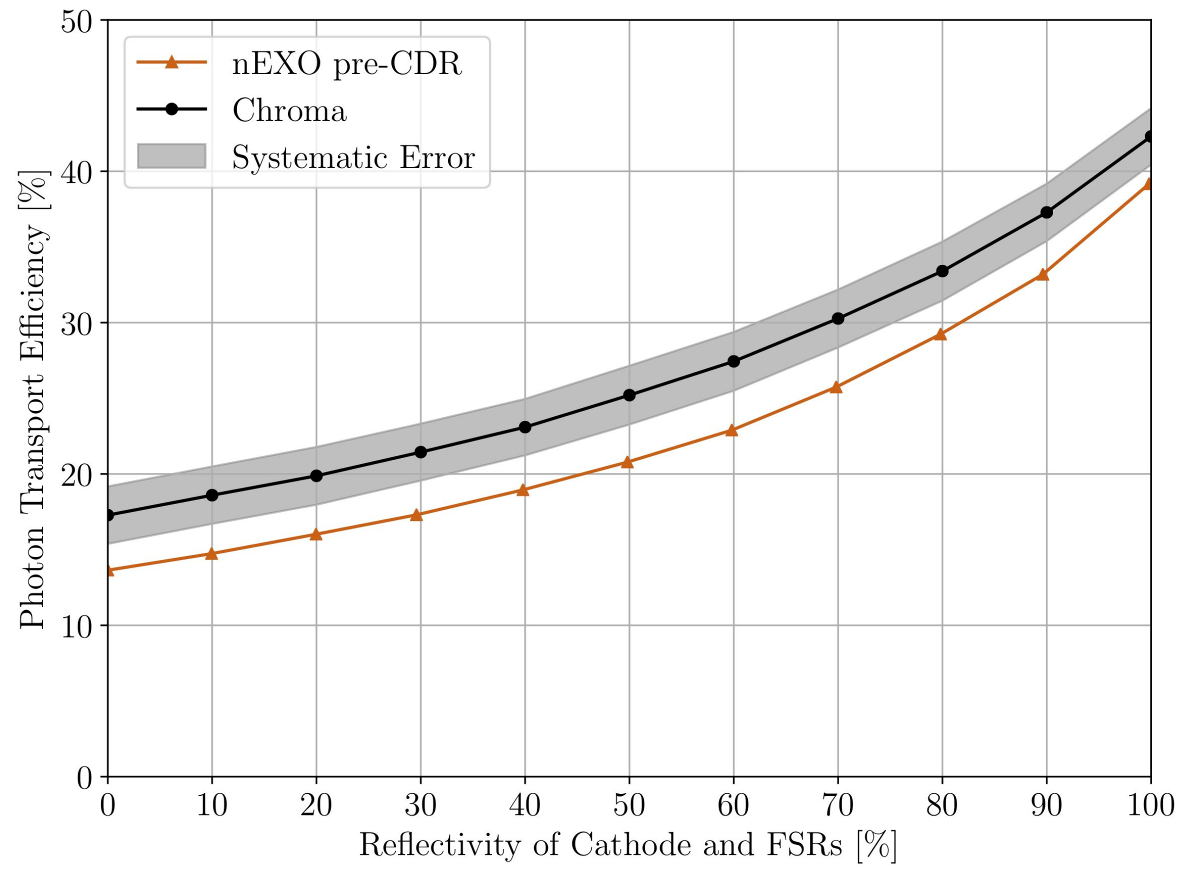
Charge reconstruction of 0nuBB event with a bremsstrahlung



Light collection modeling improved with new data and software

- High-stats, fine-grained simulation using GPU-based Chroma software
- New measurements of SiPM optical properties and performance
    - P. Nakarmi et al. (NEXO) *JINST* **15** (2020)
    - G. Gallina et al. (NEXO) *NIMA* **940** (2019)
    - A. Jamil et al. (NEXO) *IEEE TNS* **65** (2018)
    - P. Lv et al. (NEXO) *IEEE TNS* **67** (2020)
    - M. Wagenpfeil et al. (NEXO) *In preparation*
- **Improvements in projected light collection based on new data**



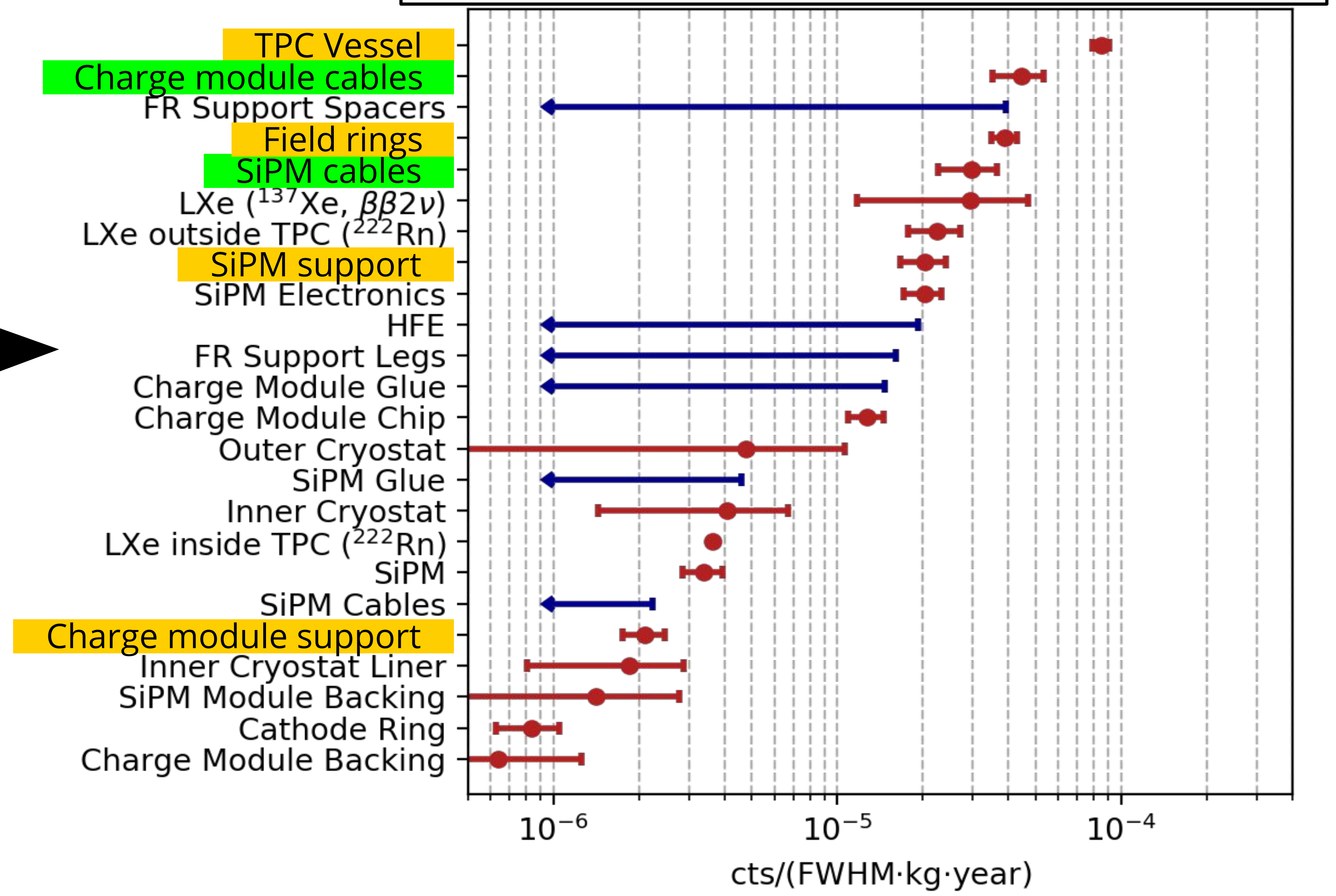


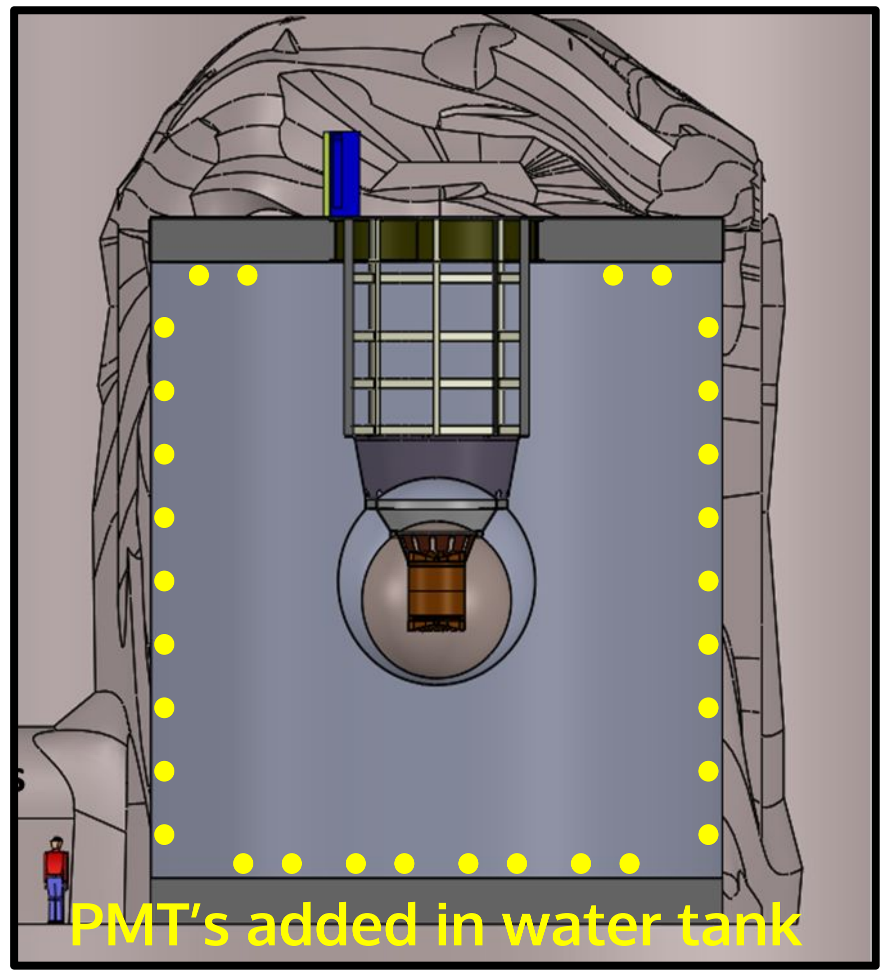
Avenues for further background reduction

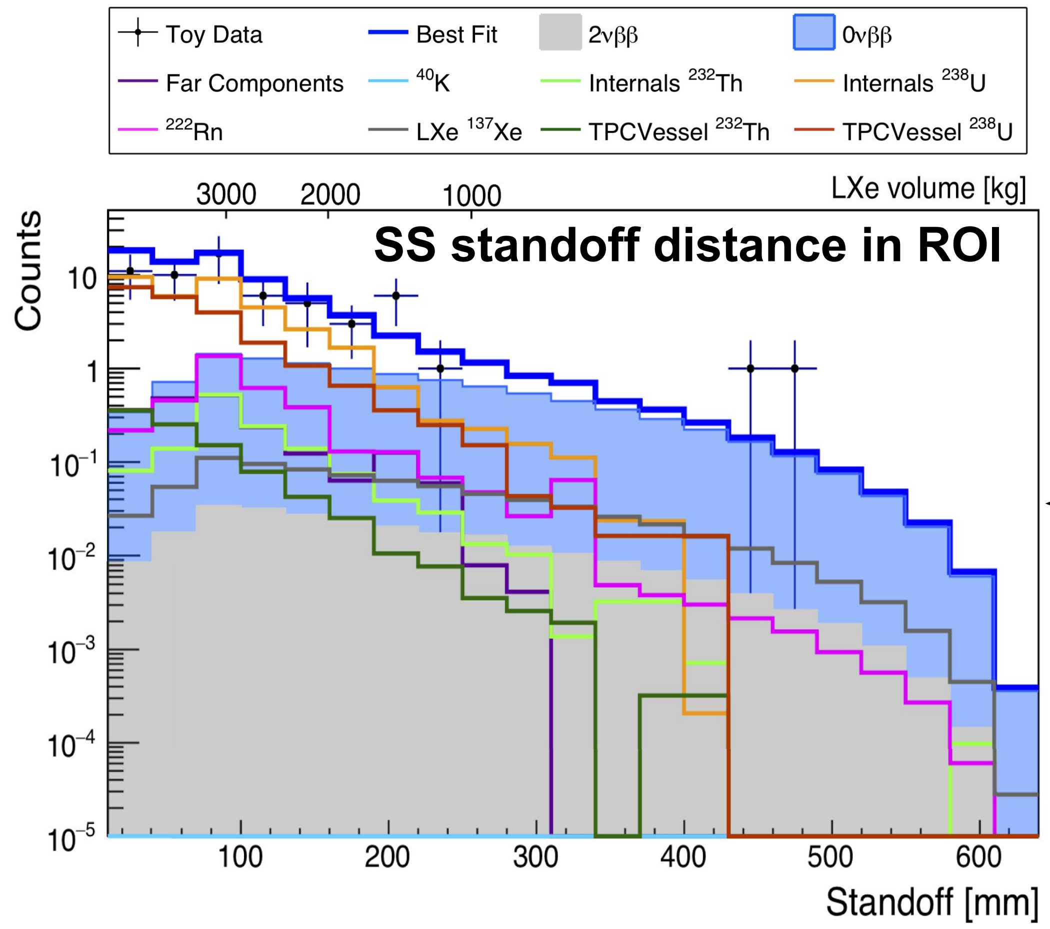
Improved construction materials

- Underground electroformed copper (pioneered by MJD) could reduce **copper radioactivity** by x20 and x4 for ^{238}U and ^{232}Th respectively
- **Better polyimide cables** identified, with x3 (x5) reduction in ^{232}Th (^{238}U) activity
- **Reduces several big contributors to gamma-ray backgrounds**

ROI background rate by detector component





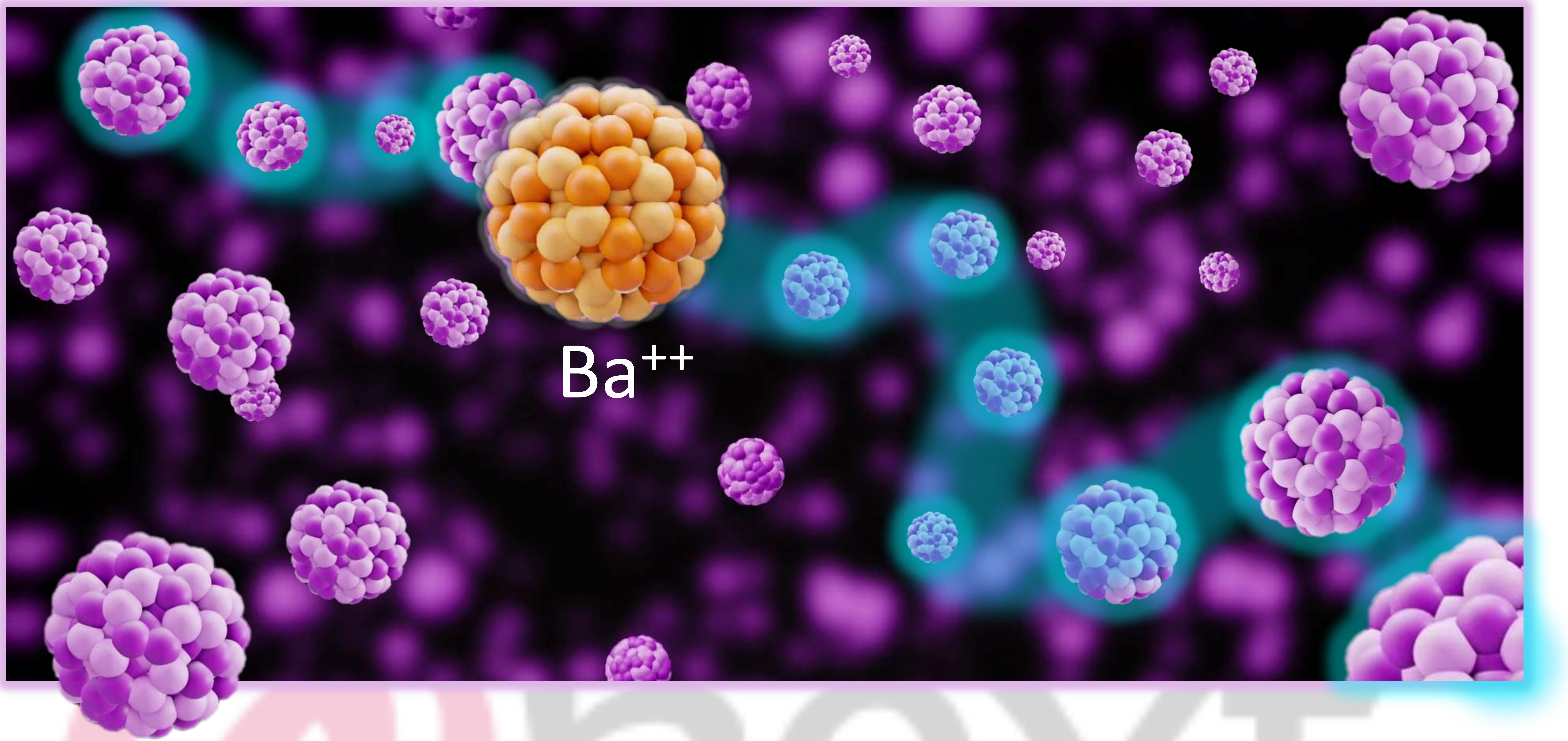


Active cosmogenic veto

- Recycled Daya Bay PMTs could instrument water shield
- Muon tagging via Cherenkov light detection
- **Reduces ^{137}Xe β-decay bkg; largest in innermost LXe**

How to confirm experimentally if neutrino is a Majorana particle?

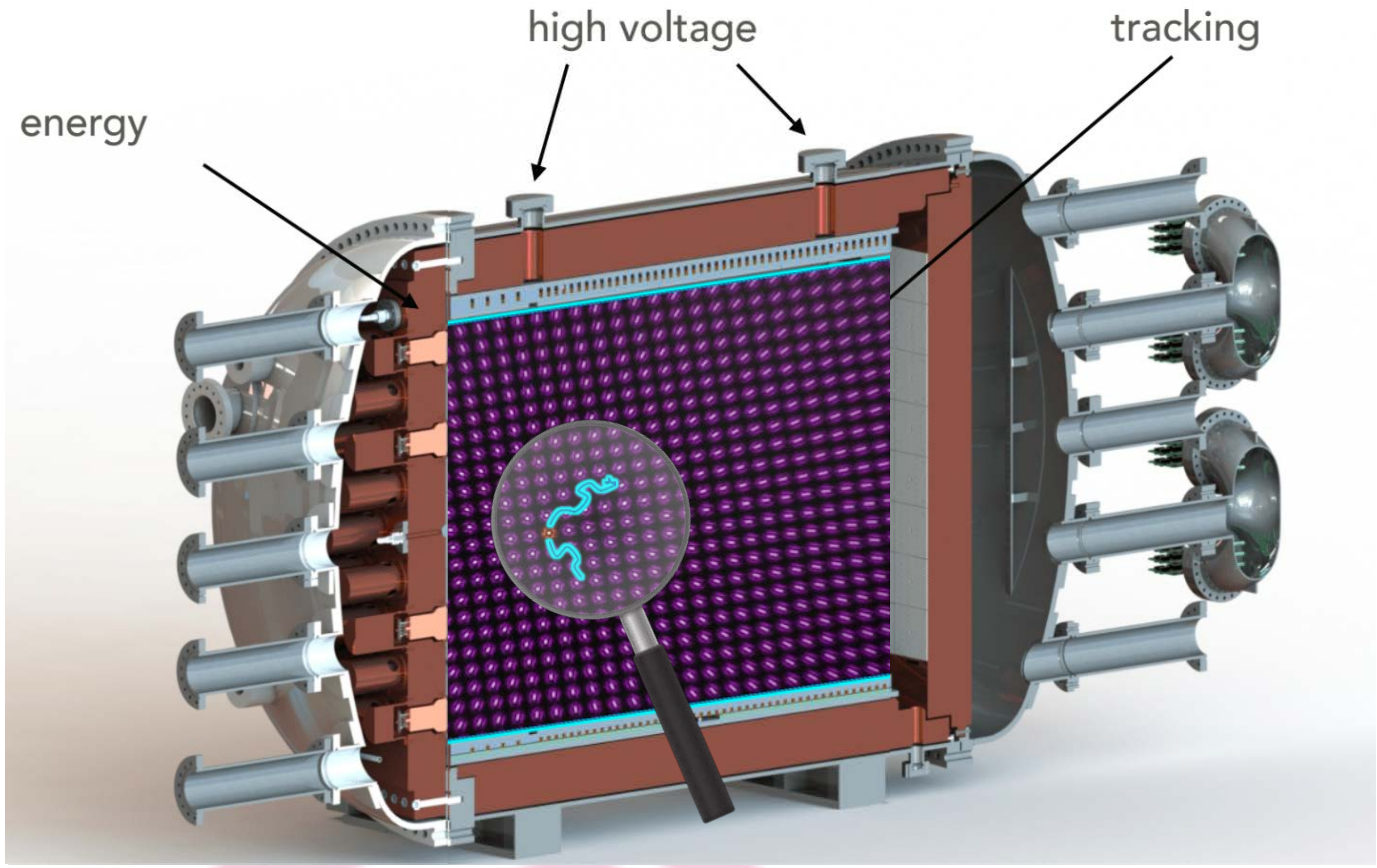
$\beta\beta0\nu$ in high-pressure ^{136}Xe gas



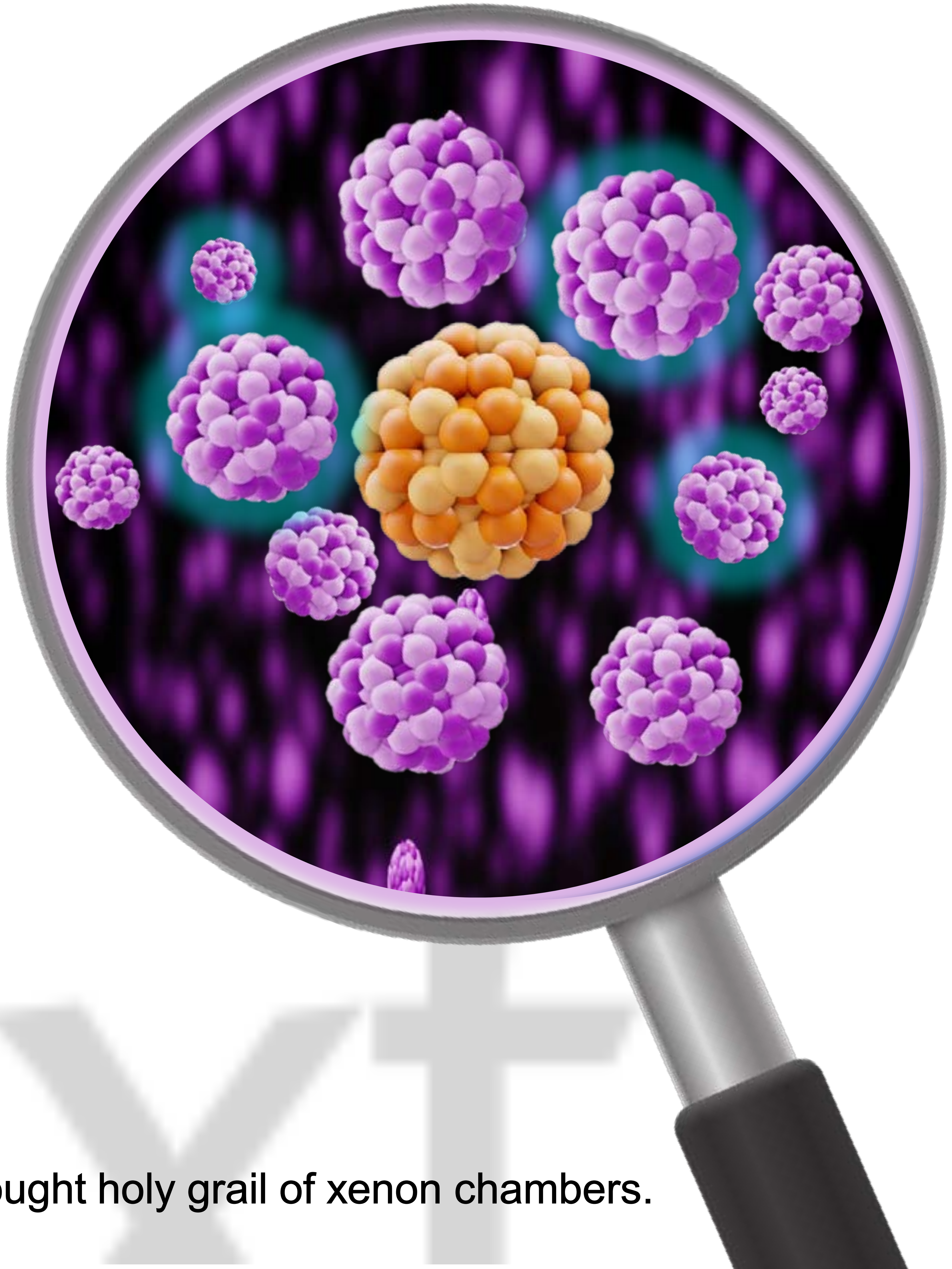
Detecting “tagging” the Ba^{++} signaling a ββ0v process has been a long sought holy grail of xenon chambers.

How to confirm experimentally if neutrino is a Majorana particle?

$\beta\beta0\nu$ in high-pressure ^{136}Xe gas



Ba^{++}

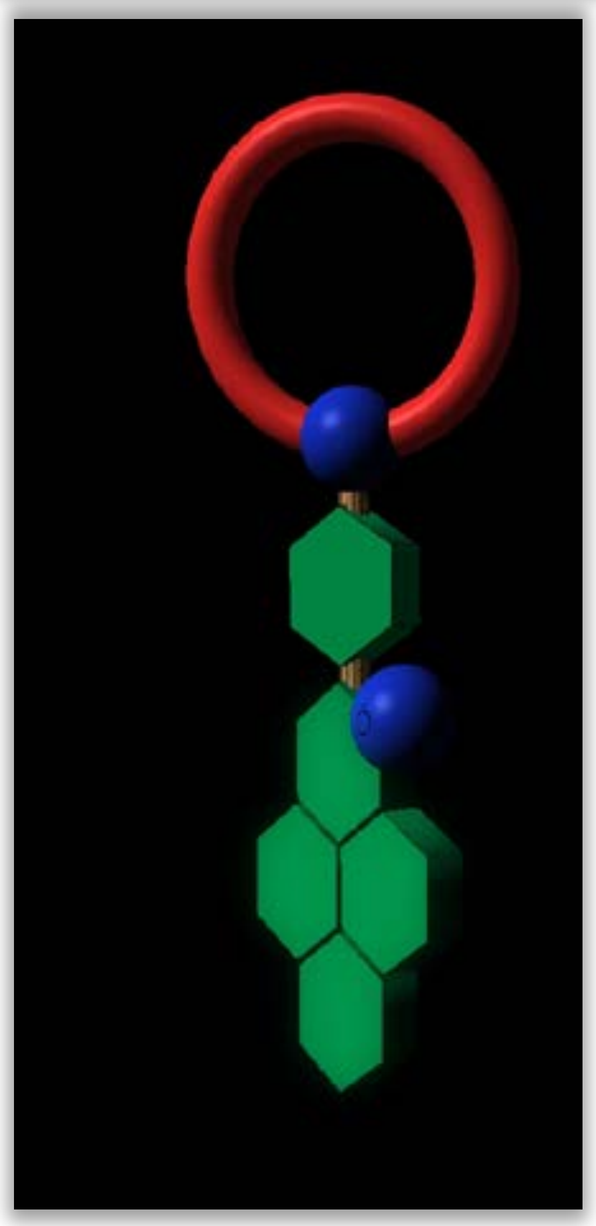


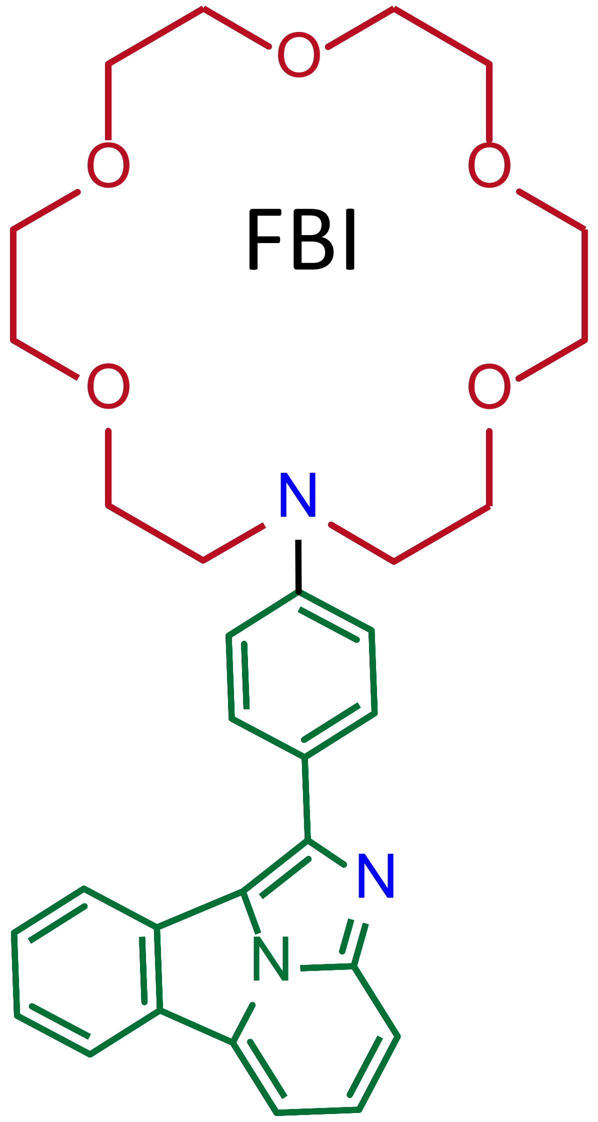
Detecting “tagging” the Ba^{++} signaling a ββ0v process has been a long sought holy grail of xenon chambers.

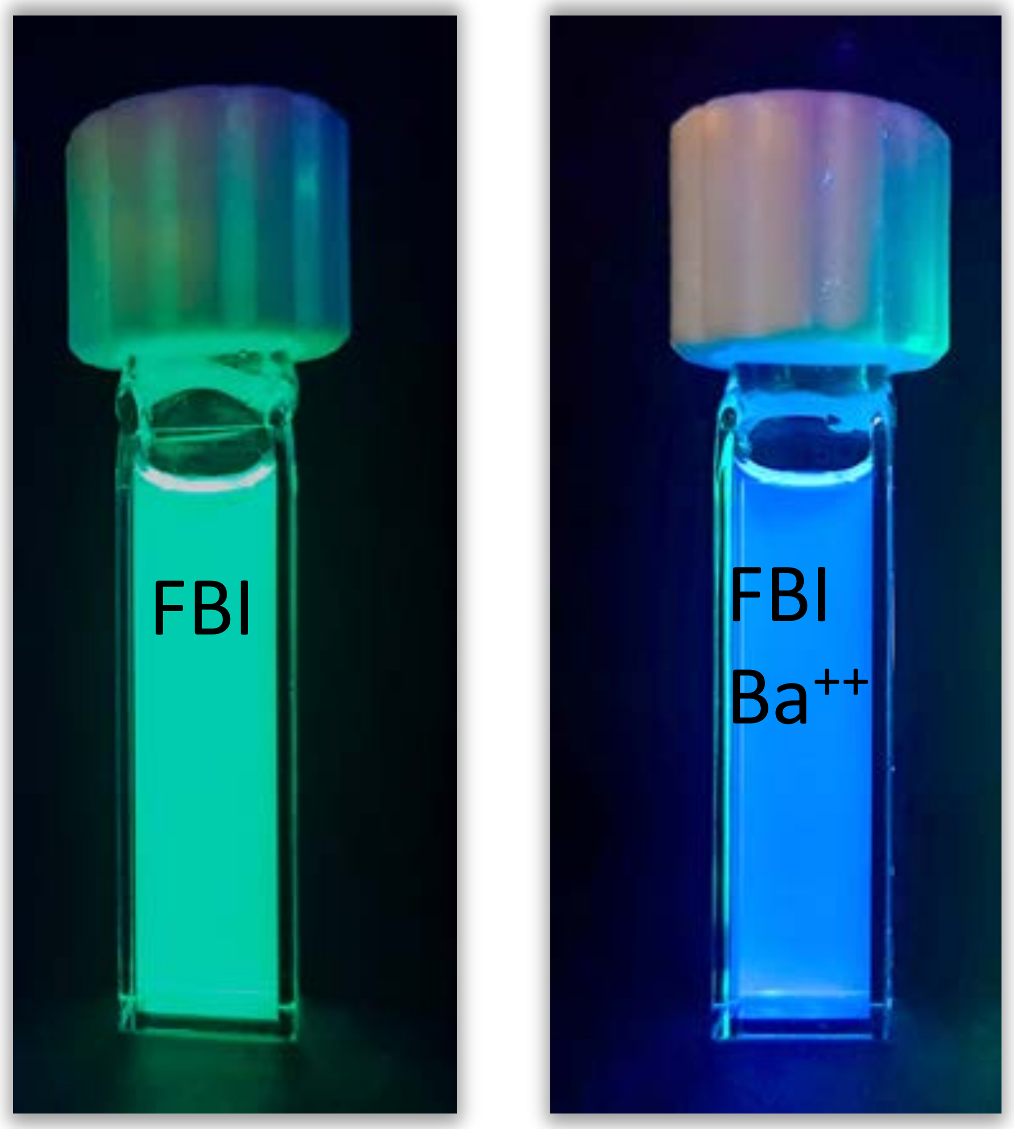
Fluorescent Bicolour Indicator

BOLD@next

Ba^{++} sensing in solution

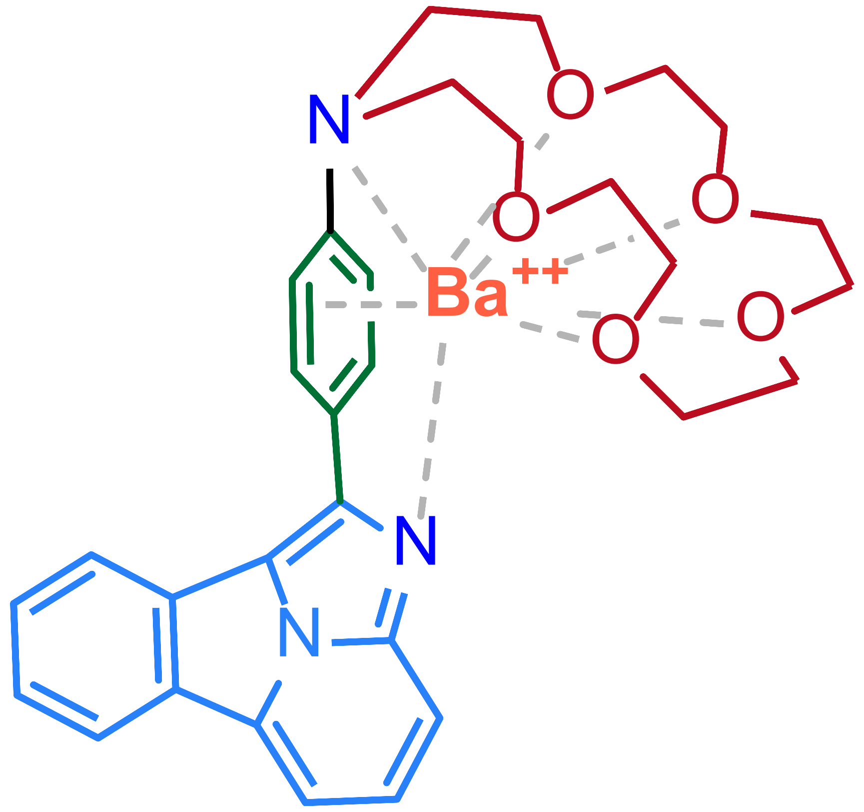


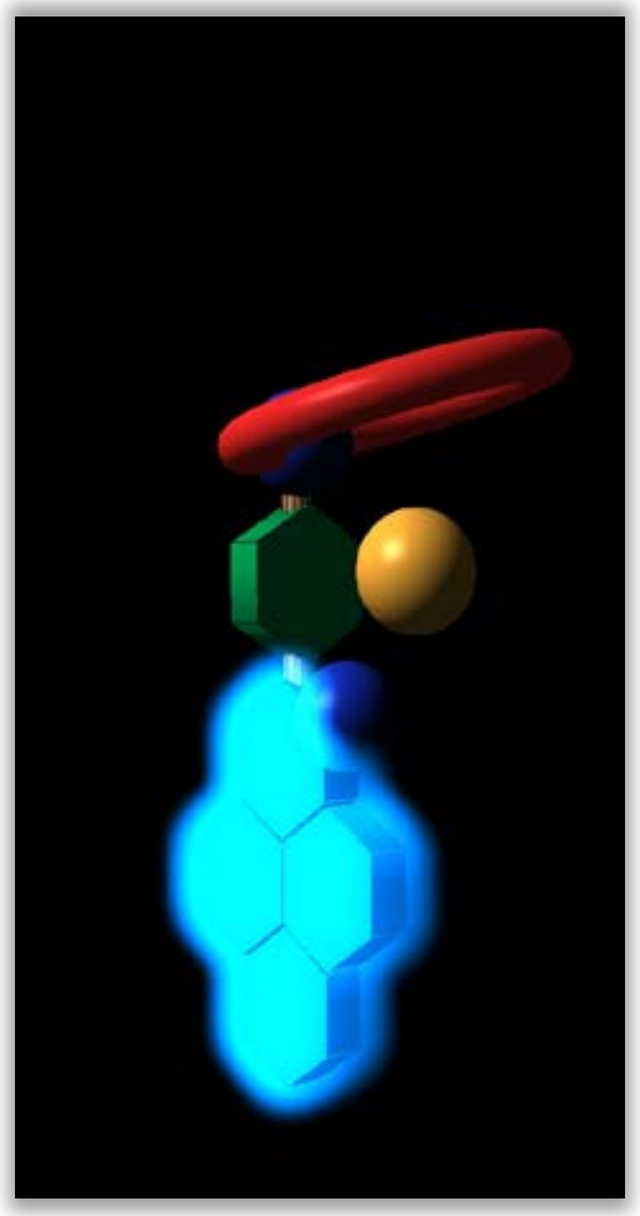


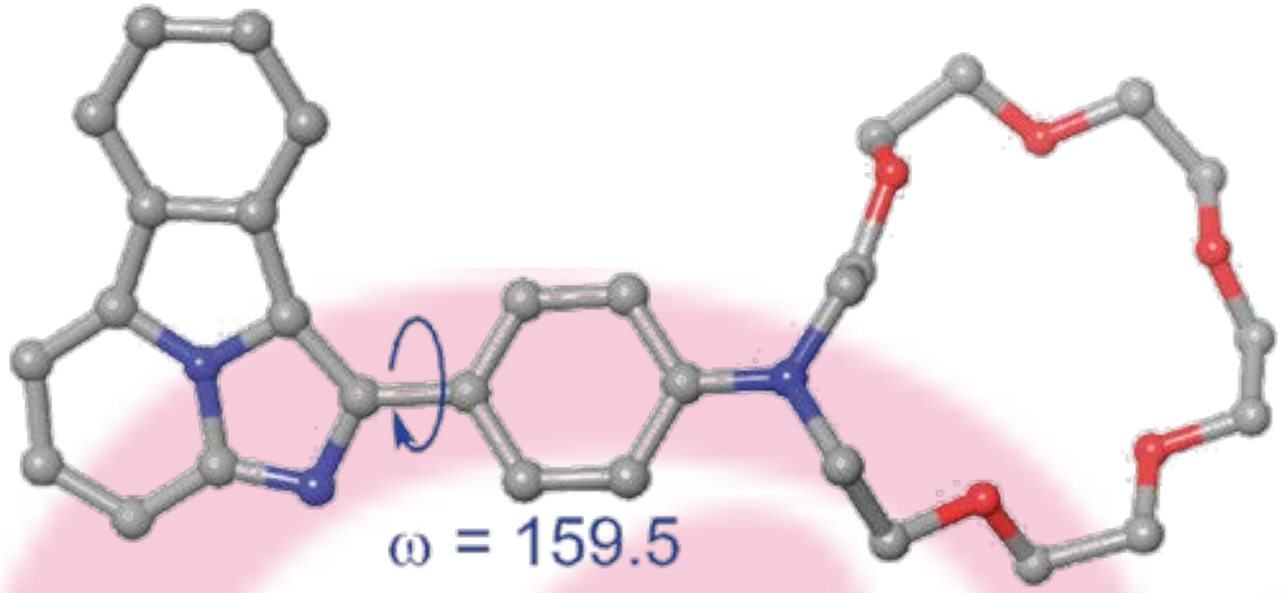


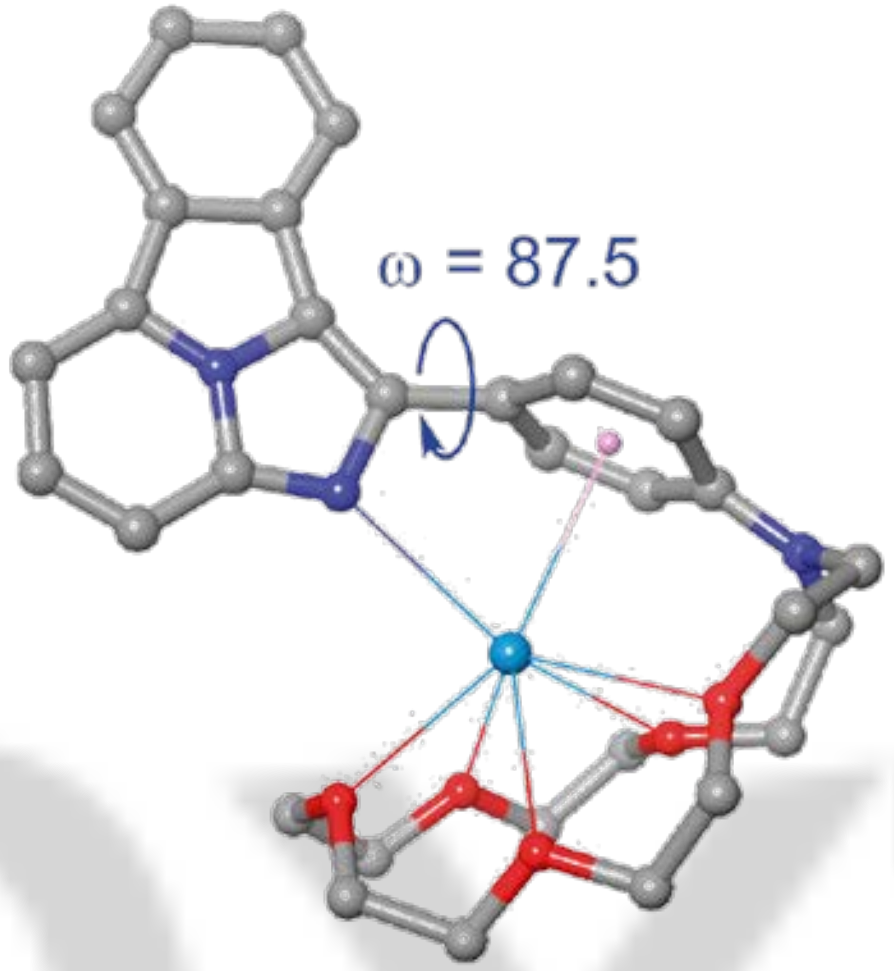
Excitation: 365 nm

FBI·Ba^{++}







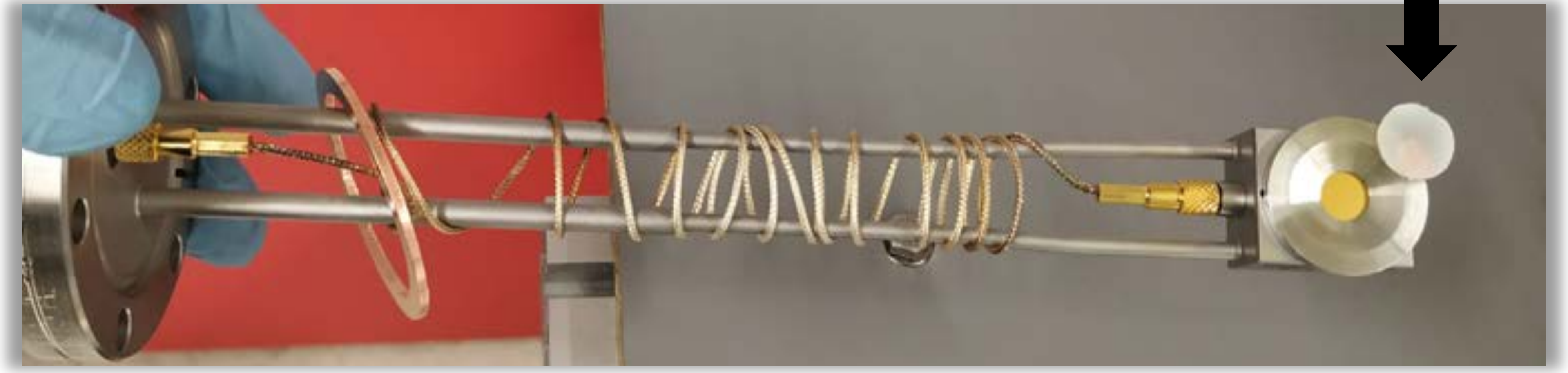


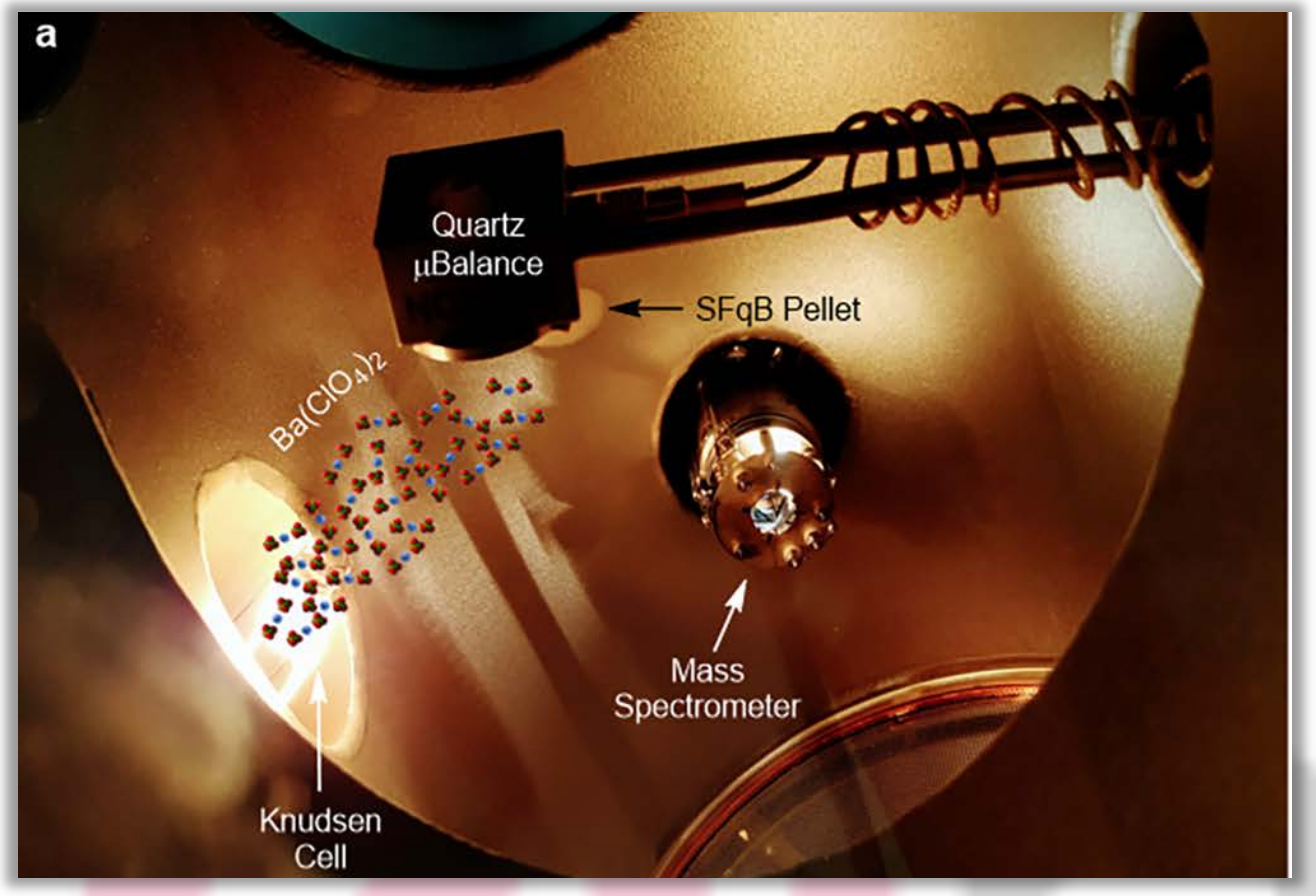
"Fluorescent bicolour sensor for low-background neutrinoless double β decay experiments", *Nature* ***2020***, *583*, 48-54.

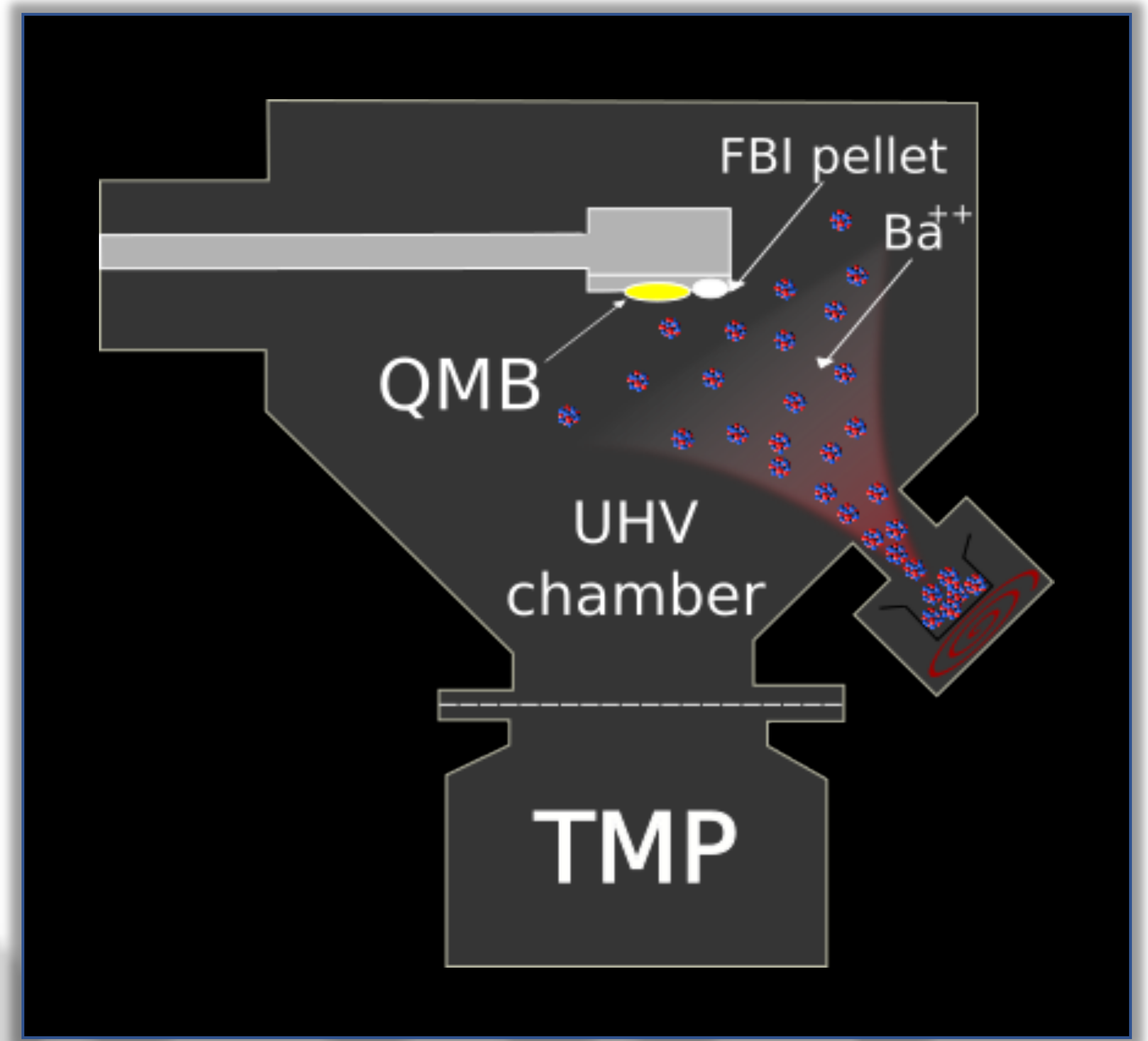
Fluorescent Bicolour Indicator

Ba^{++} sensing in high-vacuum

FBI deposited
on silica pellet



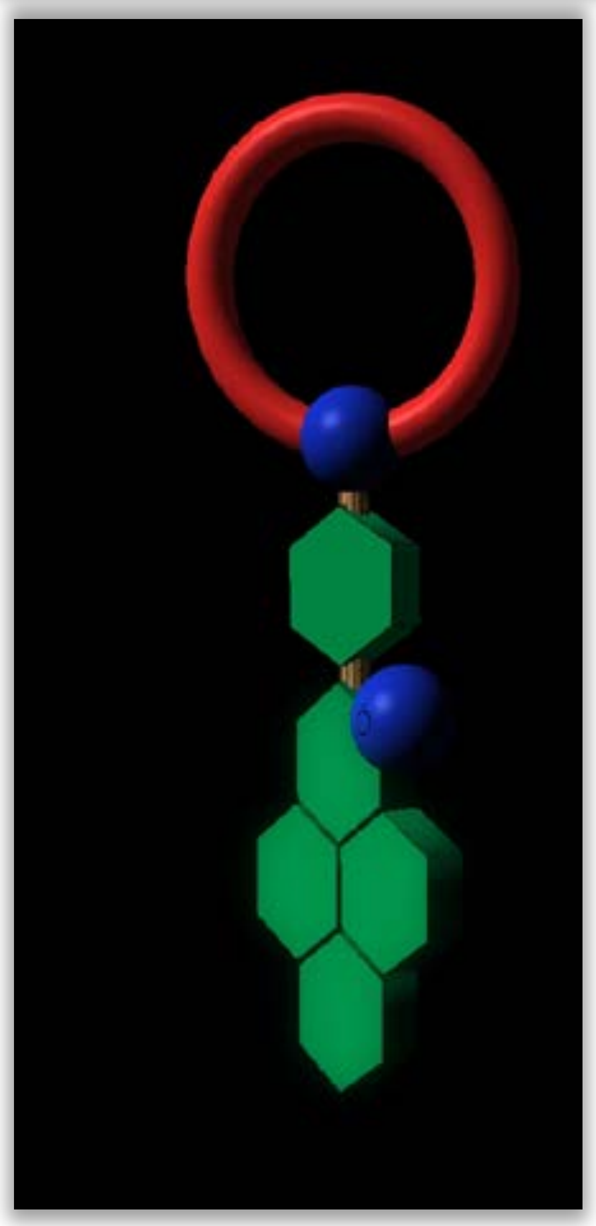




"Fluorescent bicolour sensor for low-background neutrinoless double β decay experiments", *Nature* ***2020***, *583*, 48-54.

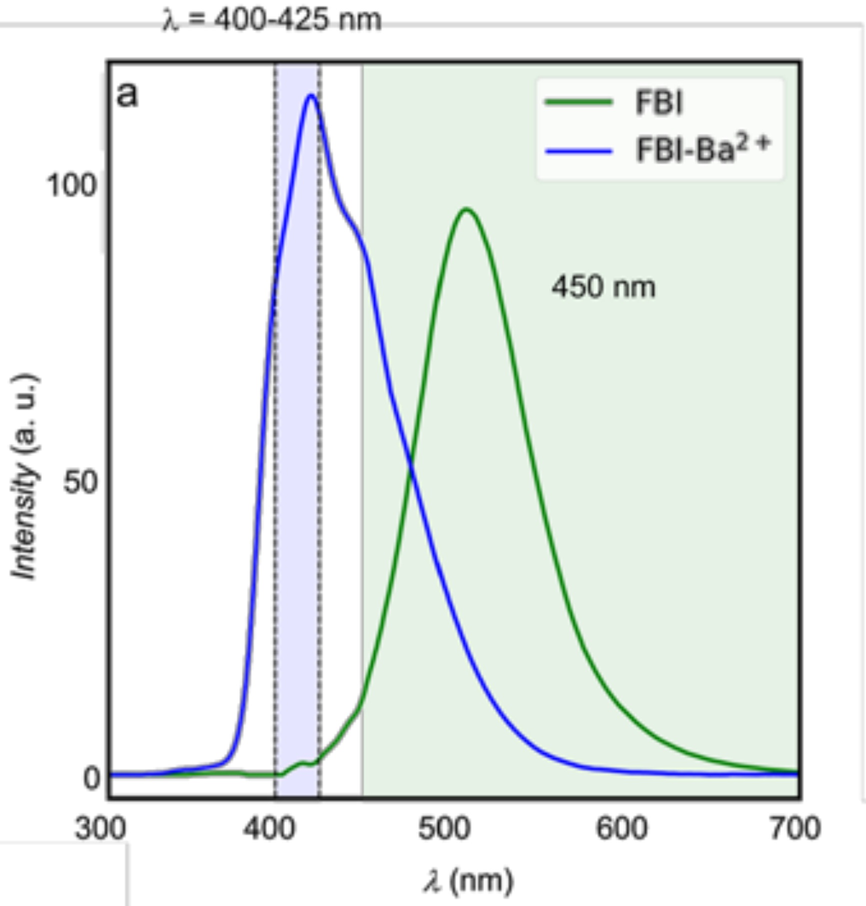
Fluorescent Bicolour Indicator

Ba^{++} sensing in high-vacuum



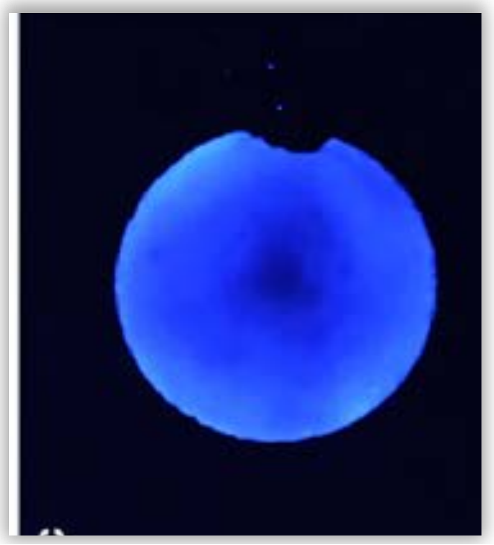
FBI

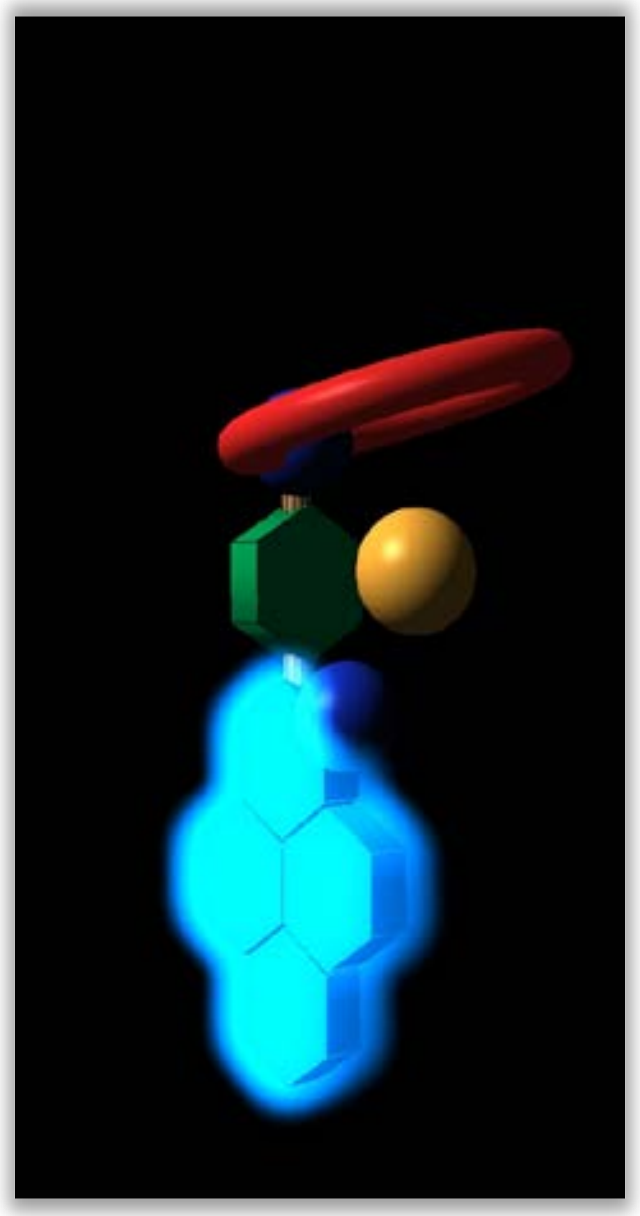
Excitation: 365 nm

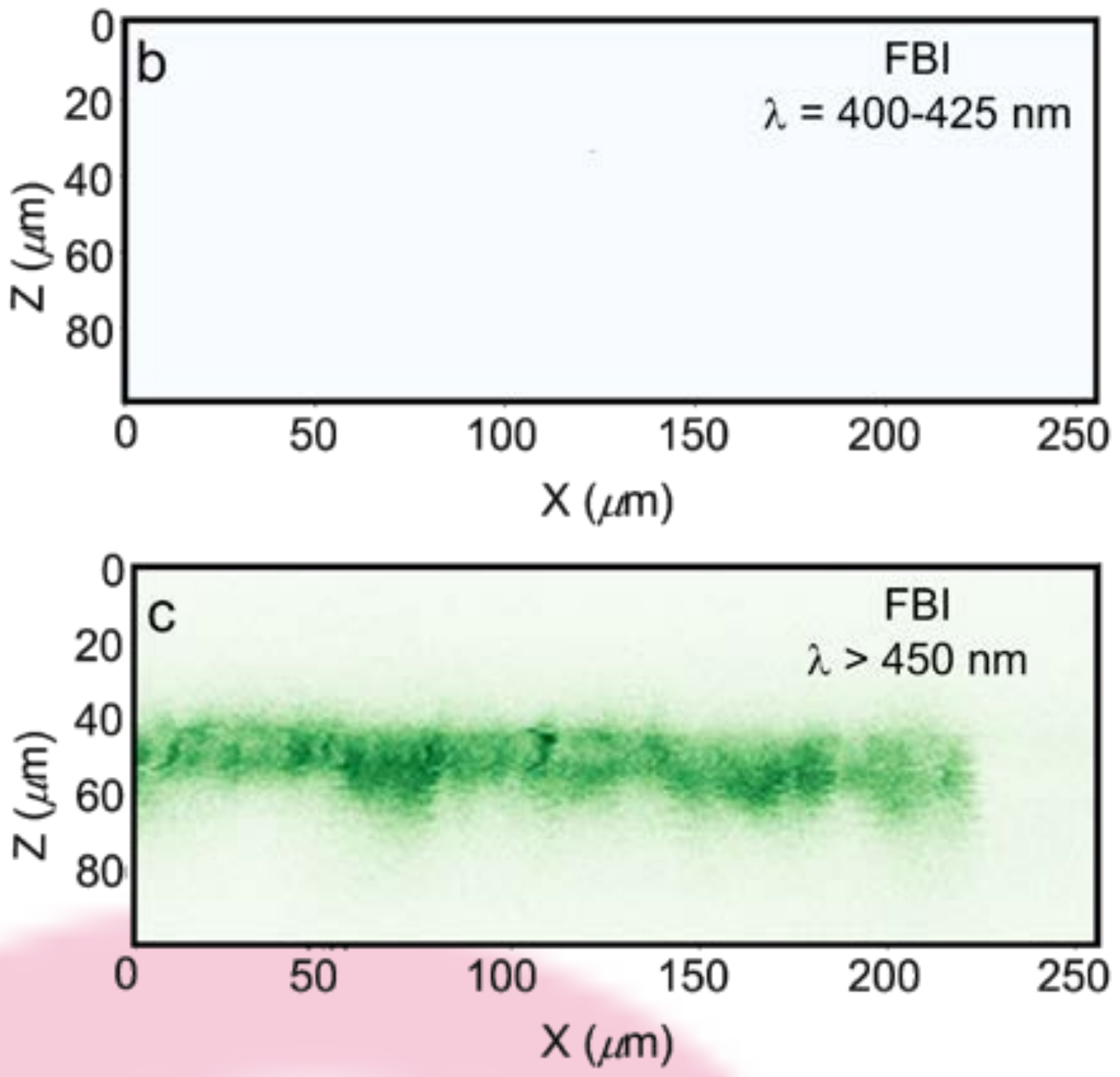


FBI·Ba^{++}

Excitation: 365 nm

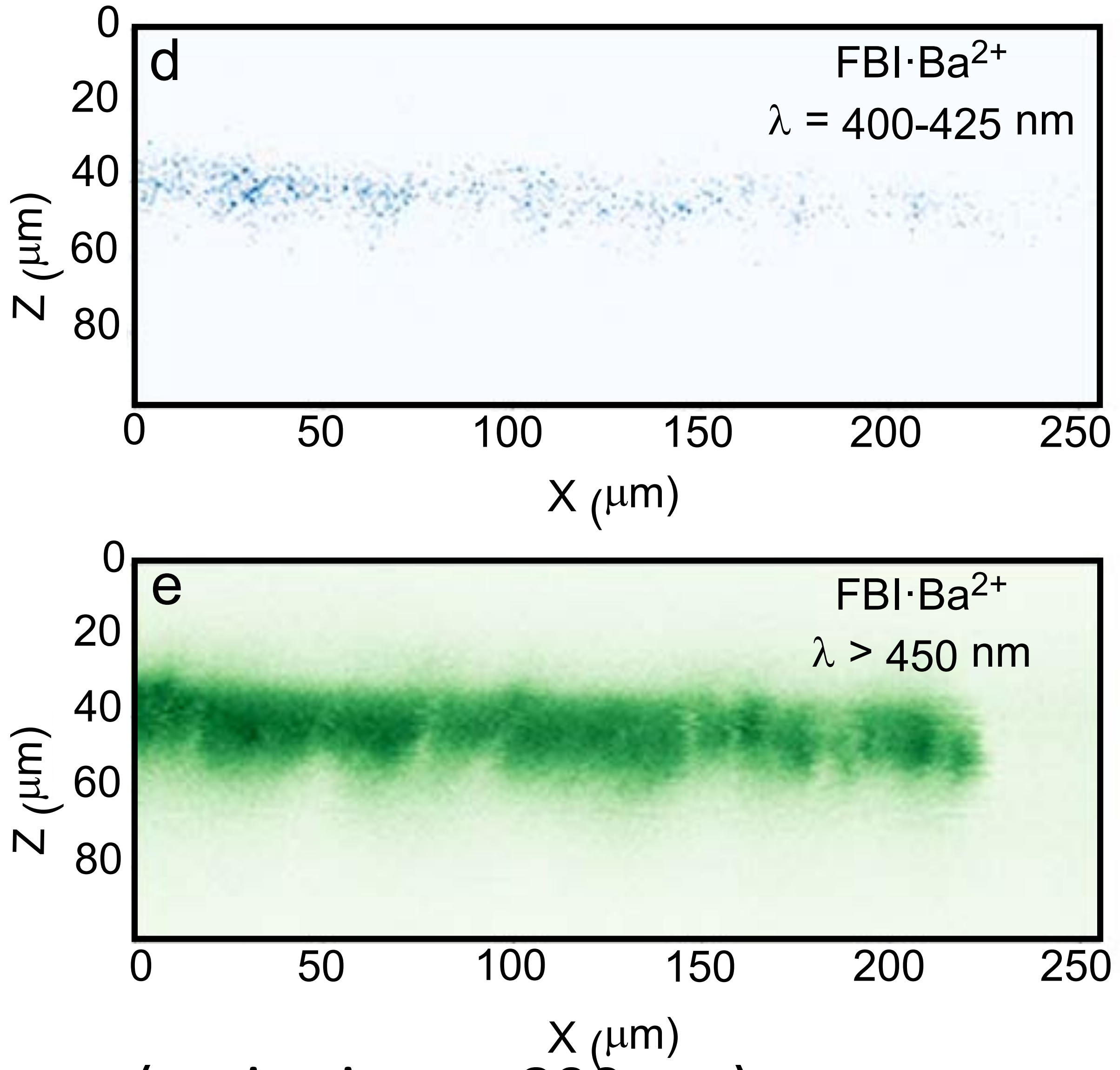






blue filter
λ = 400-425 nm

green filter
λ > 450 nm



2 Photon Absorption Microscopy (excitation at 800 nm)

DFT-computed Gibbs reaction energies

$FBI + Ba(ClO_4)_2 \longrightarrow FBI \cdot Ba(ClO_4)_2$

$\Delta G_{rx} = -90$ kcal/mol

$FBI + Ba^{++} \cdot 8Xe \longrightarrow FBI \cdot Ba^{++} + 8Xe$

$\Delta G_{rx} = -195.9$ kcal/mol

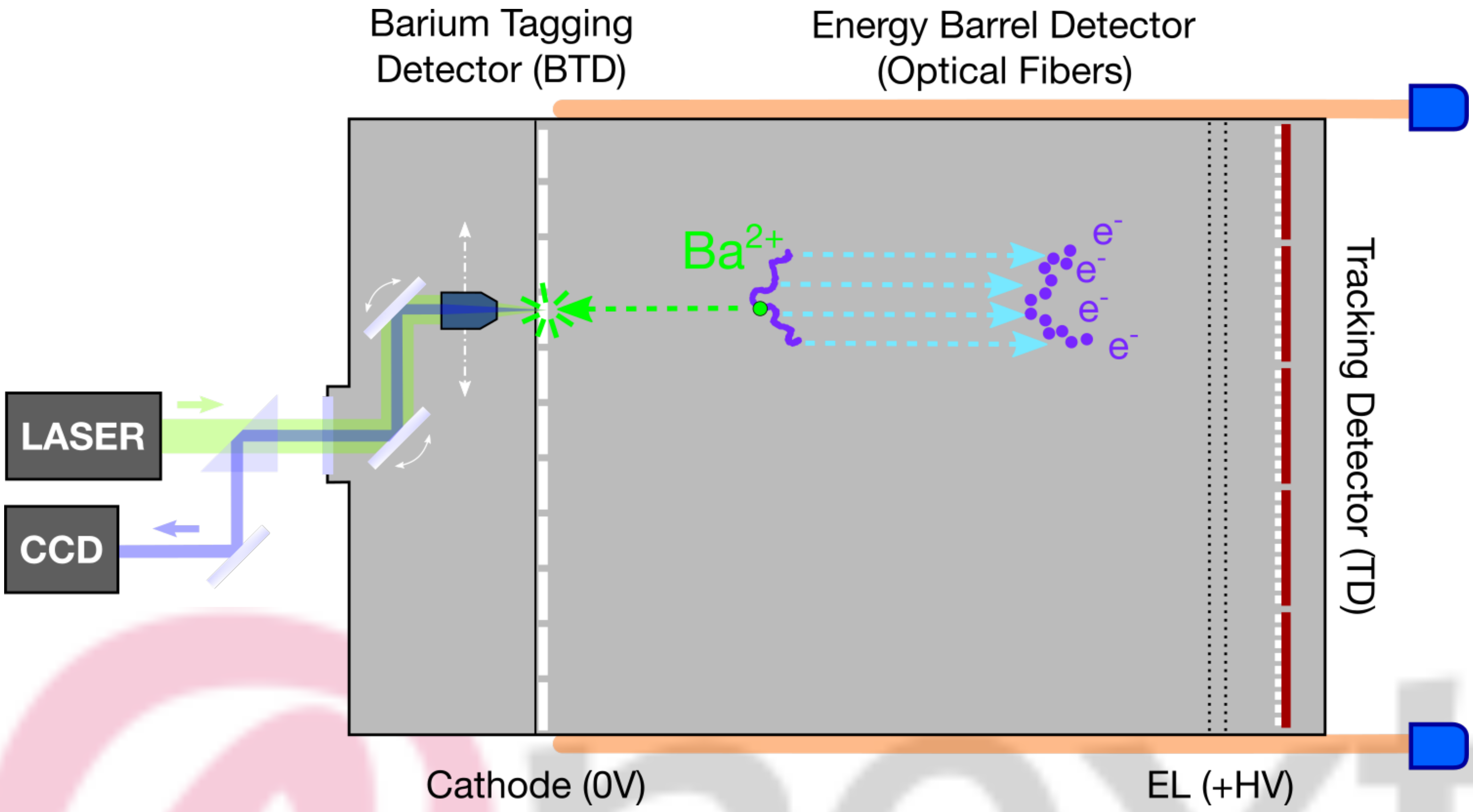
FBI sensors capture Ba^{++} in dry phase!

"Fluorescent bicolour sensor for low-background neutrinoless double β decay experiments", *Nature* ***2020***, *583*, 48-54.

Fluorescent Bicolour Indicator

What's NEXT @BOLD@next?

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



"Fluorescent bicolour sensor for low-background neutrinoless double β decay experiments", *Nature* ***2020***, *583*, 48-54.

The End