Searching for $0\nu\beta\beta$ decay with a 3rd generation Dark Matter detector

Alexandre Lindote, Nov. 3rd 2022

Background and Motivation

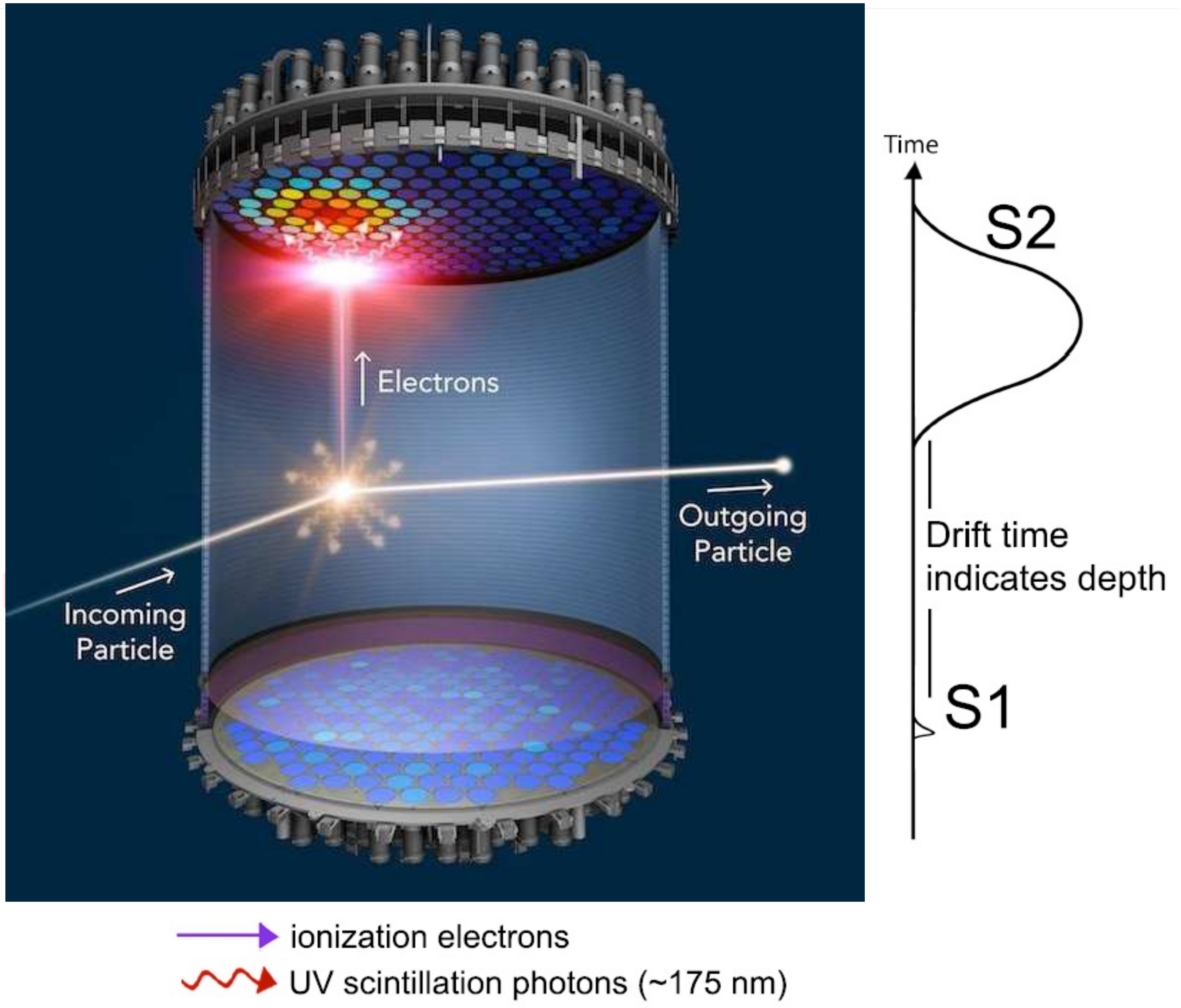
- I have started working with 2-phase xenon Time Projection Chambers (TPCs) in 2005, at the start of my PhD
- During my PhD I worked in pioneer experiments using this technology to search for dark matter in the form of WIMPs:
  - ZEPLIN-II: the first detector of this kind to be used in WIMP search
  - ZEPLIN-III: still has the best ER/NR discrimination to date
- I have since worked in LUX — leader of the WIMP search field while it was operating (2013-2017) — and more recently in LUX-ZEPLIN (LZ), the largest 2-phase xenon TPC ever built (10 t), and current most sensitive WIMP detector

Background and Motivation

- I've occupied various management positions in LUX and LZ:
  - Data processing coordinator in LUX (2015 —)
  - Coordinator of the WIMP search data analysis for the reanalysis of the FSR (2015)
  - Backgrounds assessment and simulation of LZ (2016 — 2019)
  - Joint coordinator of the high-energy electron recoil physics group of LZ (2019 —)
- Starting this last position coincided with a shift in my research focus, from WIMP search to rare and forbidden decays:
  - 2ν2EC in ^{124}Xe and ^{126}Xe [JPG47(2020)105105]
  - 2ν and **$0\nu\beta\beta$ in ^{136}Xe** and ^{134}Xe [PRC102(2020)014602, PRC104(2021)065501]

2-phase Xenon TPCs for Direct DM Search

The leading technology in the field

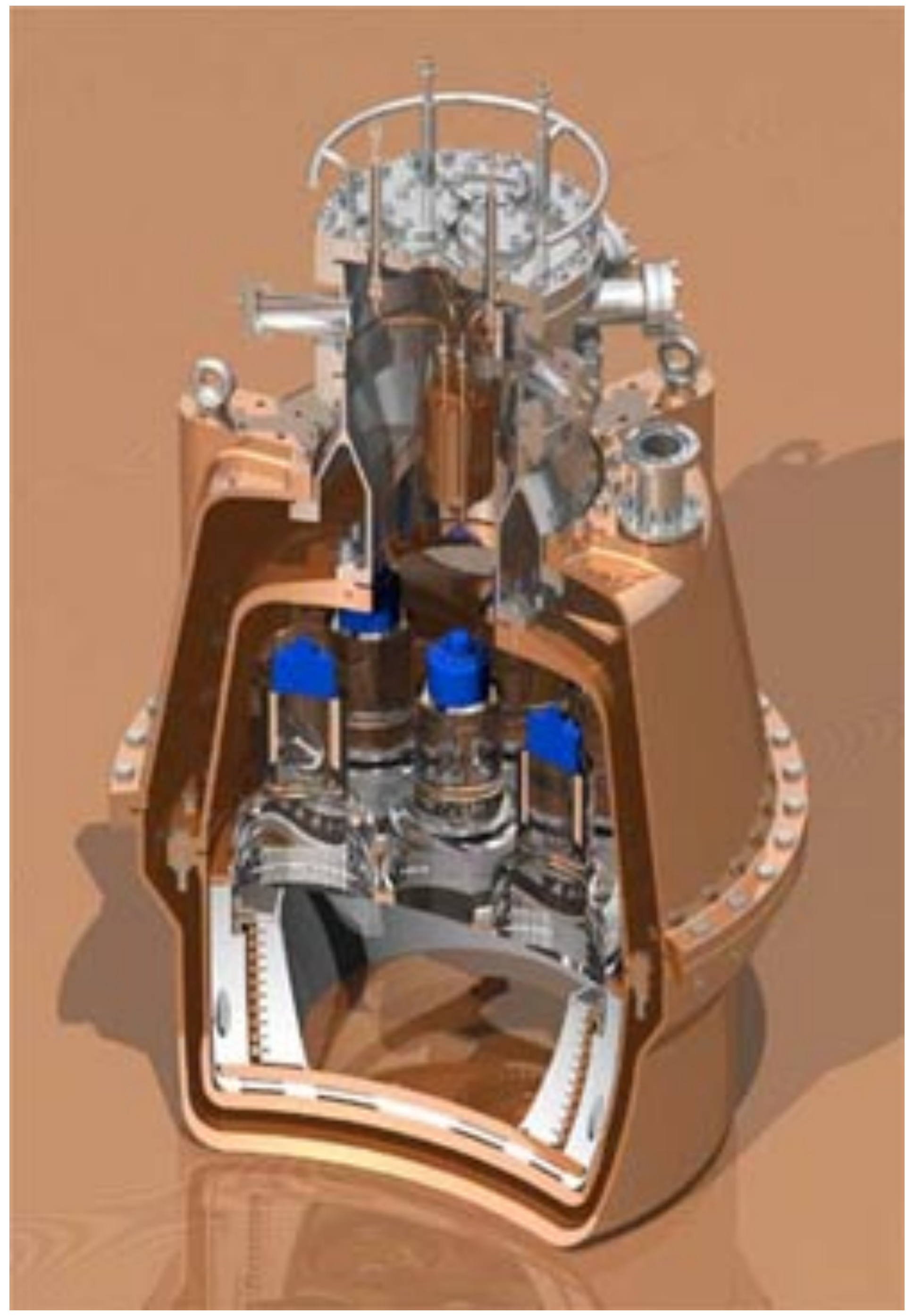


- Full event characterisation from the S1 and S2 signals (energy, position, interaction type)
- Well established and scalable technology
- Rapid evolution from detectors with ~10-100 kg of target mass (ZEPLIN/ XENON10/100) to currently running LZ/ XENONnT with ~10 t total mass
- Clear leadership of the direct DM search field for WIMPs above ~10 GeV

2-phase Xenon TPCs for Direct DM Search

Scalability

15 years ago…



ZEPLIN-II

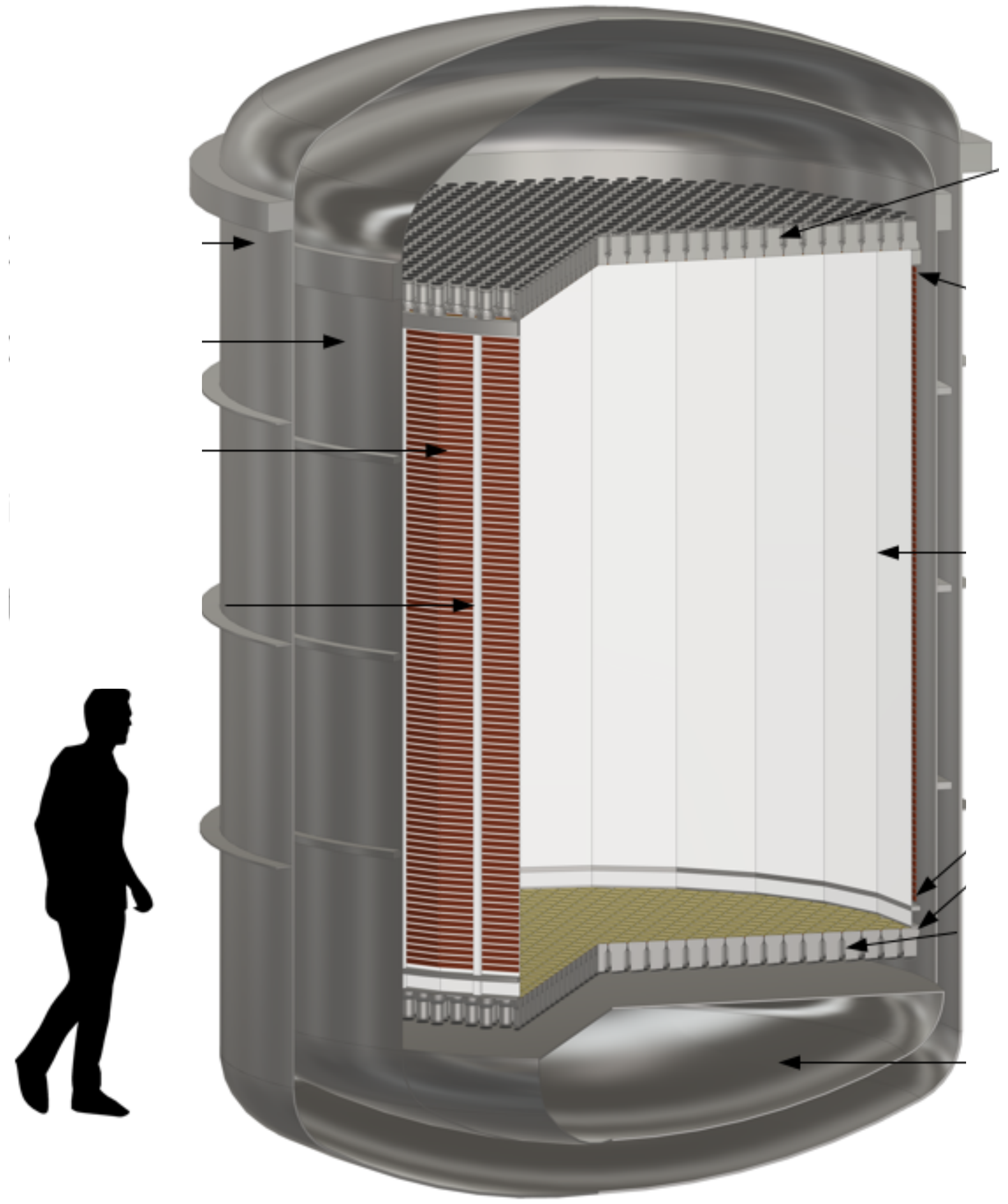
32 kg

Now

LUX-ZEPLIN (LZ)

10 tonnes

Future (2025-30)



G3 detector

50-100 tons

2-phase Xenon TPCs for Direct DM Search

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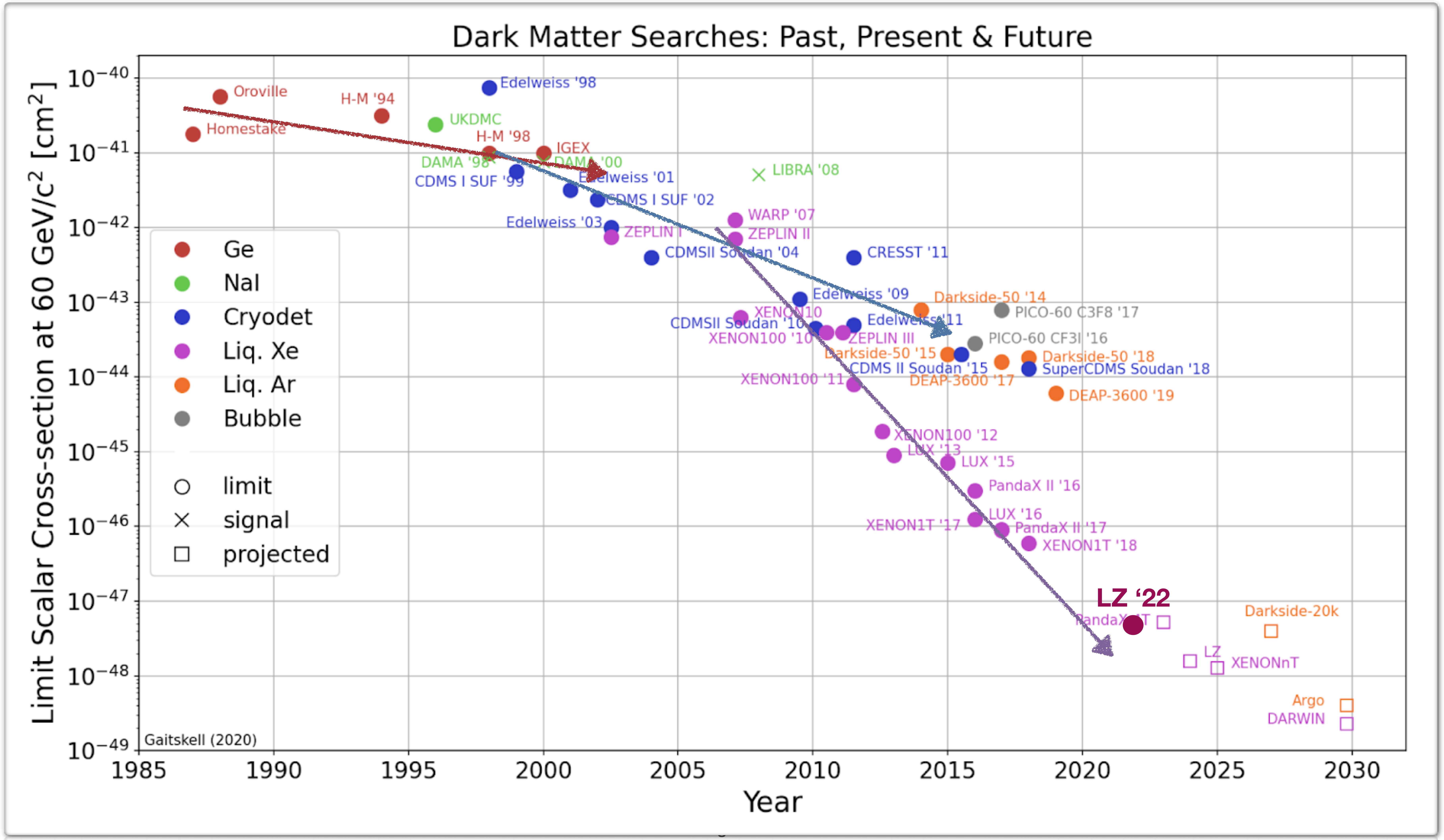
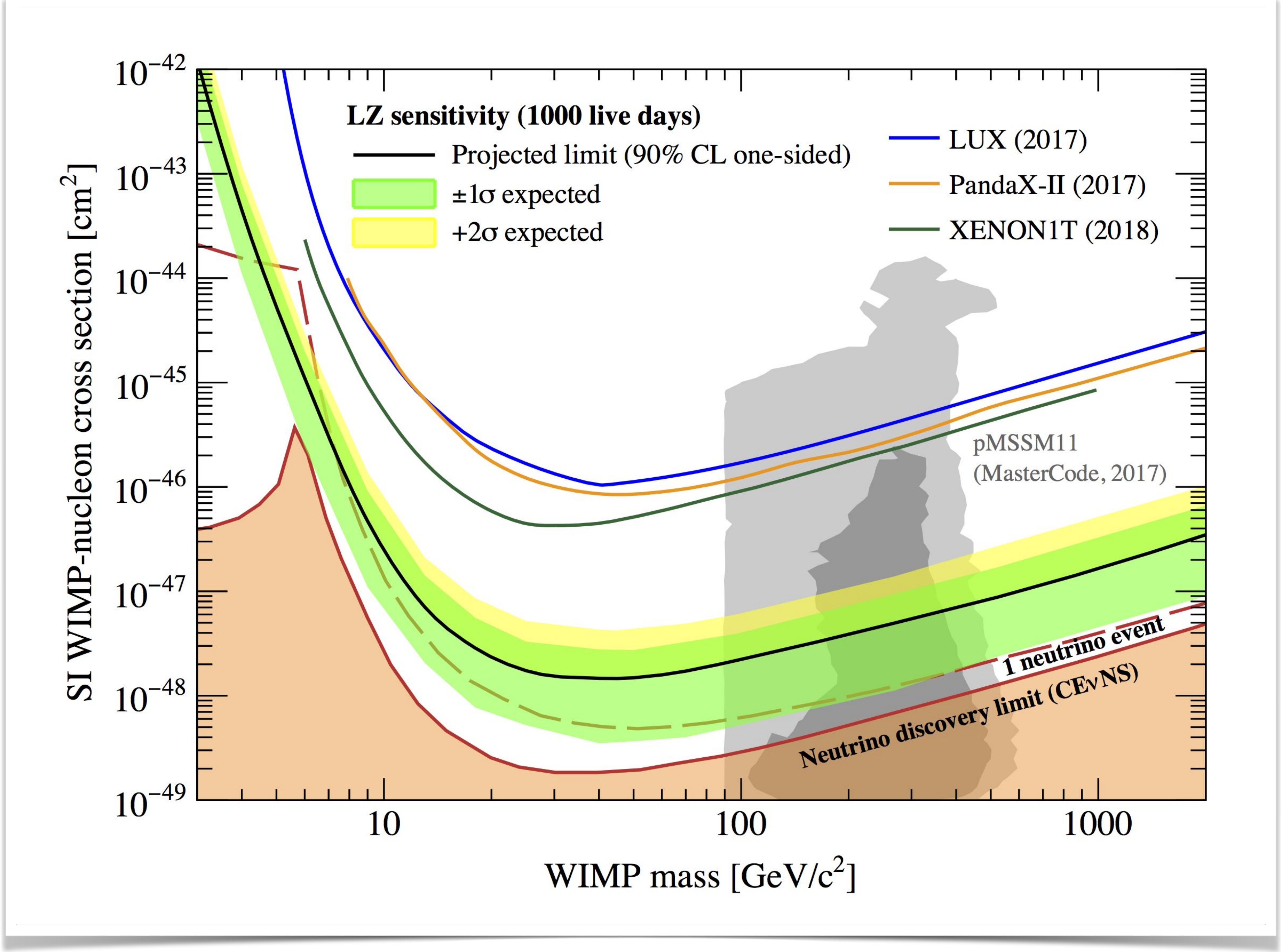


A 3rd Generation Xenon TPC

Overview

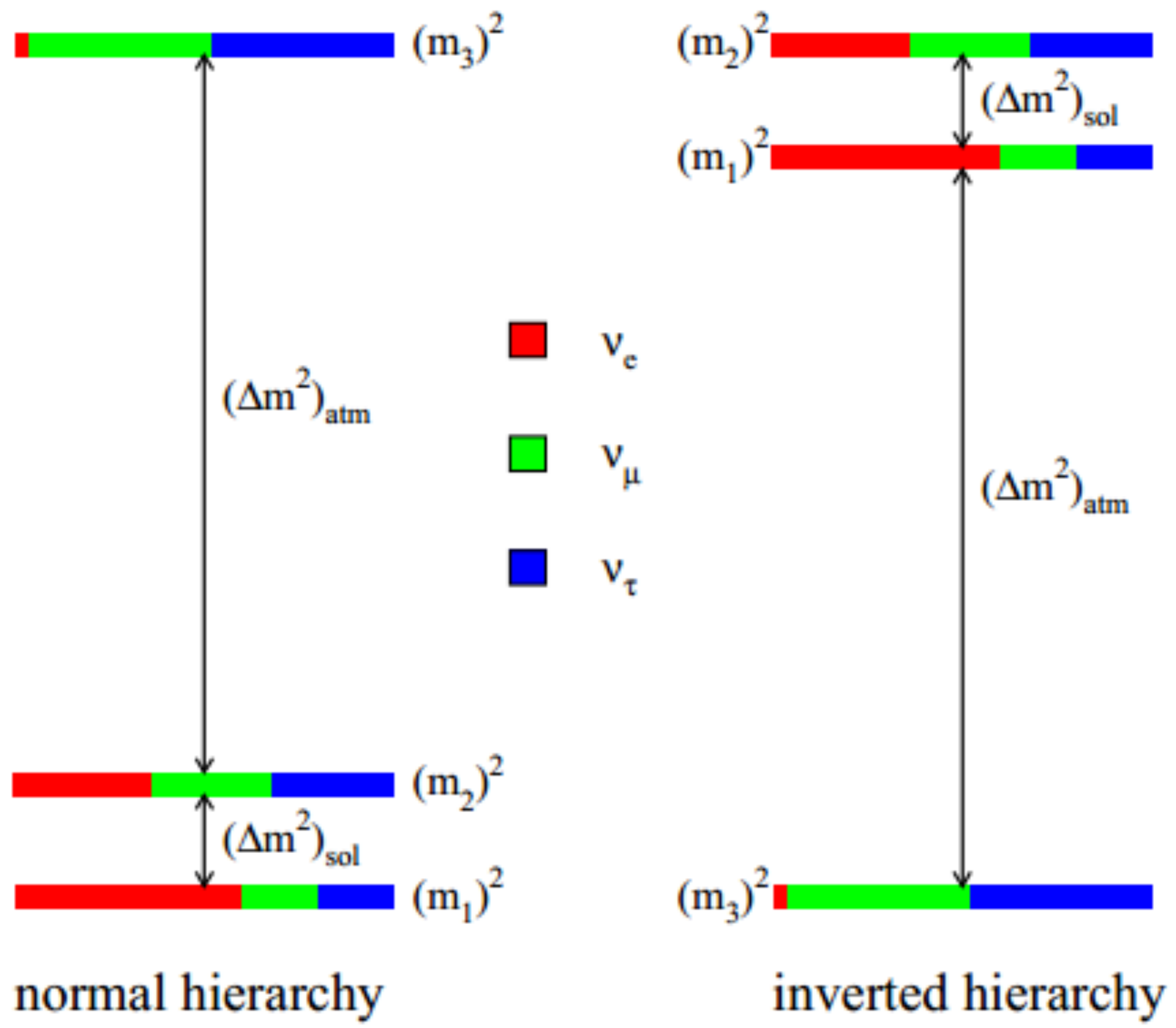
- Current generation detectors will not be able to cover the remaining parameter space down to the neutrino fog
- A larger detector is required, with a target mass between 50 and 100 tonnes.
- With such a large mass, this detector becomes competitive for other physics studies, including $0\nu\beta\beta$ decay in ^{136}Xe



Neutrino Oscillations

Neutrino mass hierarchies

- Neutrino oscillations confirmed by Super-Kamiokande and SNO
- Implies that neutrinos must have mass
- The mixing of the flavour eigenstates (ν_e, ν_μ, ν_τ) and the mass eigenstates (ν_1, ν_2, ν_3) is described by the PMNS matrix
- Oscillation measurements are only sensitive to the square of mass differences:
  - $\Delta m_{21}^2 > 0$ (solar mass difference)
  - $|\Delta m_{32}|^2 >> \Delta m_{21}^2$
  - The sign of Δm_{32} (atmospheric mass difference) is not known
  - Neutrino masses can be in **normal** or **inverted** hierarchies



Neutrinoless Double Beta Decay

A gateway to the neutrino mass hierarchy

- Standard double beta decay

$$(A, Z) \longrightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e. \qquad (2\nu\beta\beta)$$

- Neutrinoless double beta decay

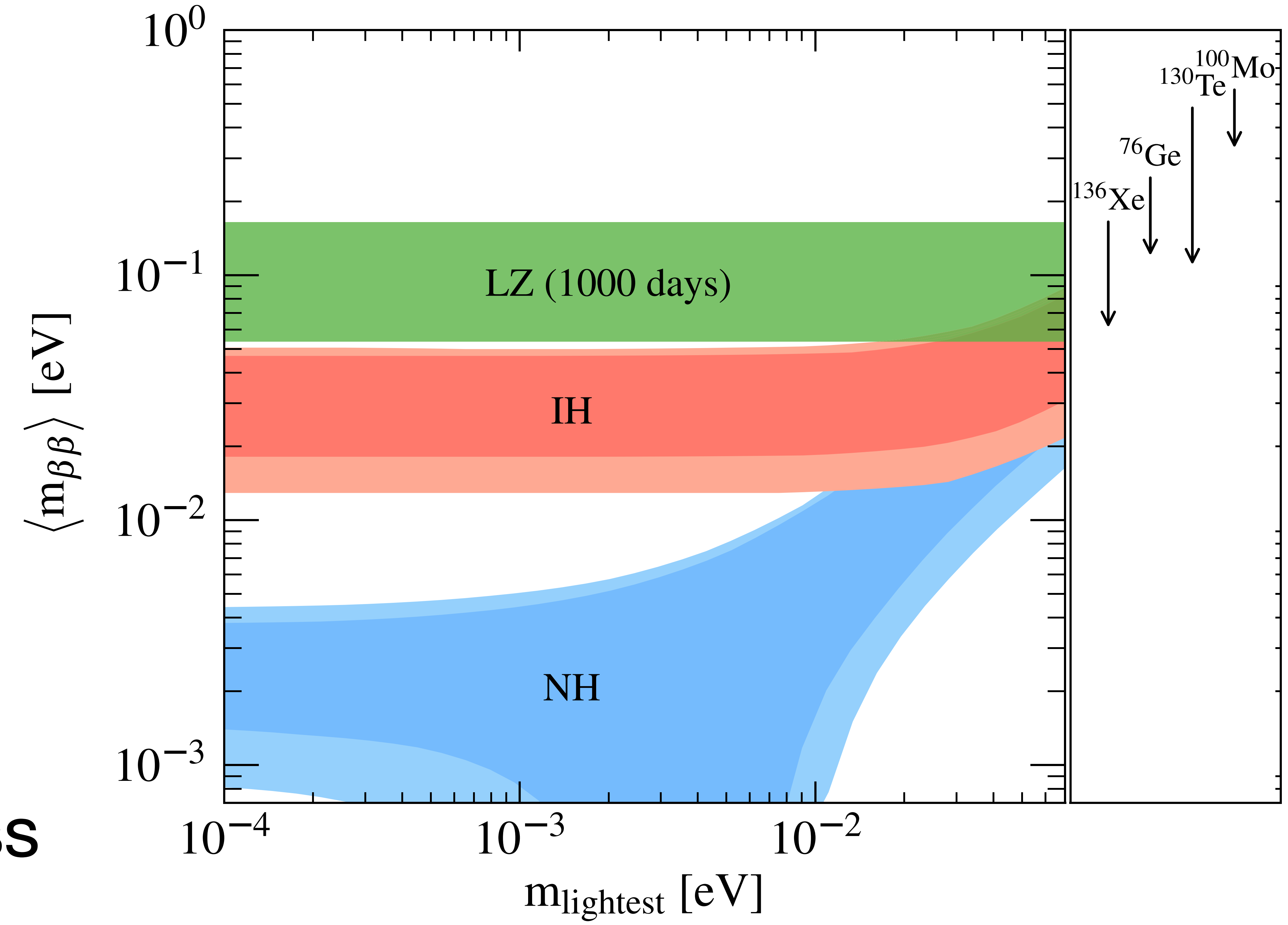
$$(A, Z) \longrightarrow (A, Z+2) + 2e^- \qquad (0\nu\beta\beta)$$

  - Violates lepton number conservation
  - Neutrino is its own antiparticle (Majorana particle)
  - Beyond SM process
  - Current half-life limits $T_{1/2} > 10^{26}$ yr

- Decay half-life is connected to the neutrino mass hierarchy by the effective Majorana mass

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\,|\mathcal{M}^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

LZ 136Xe 0νββ decay sensitivity projection

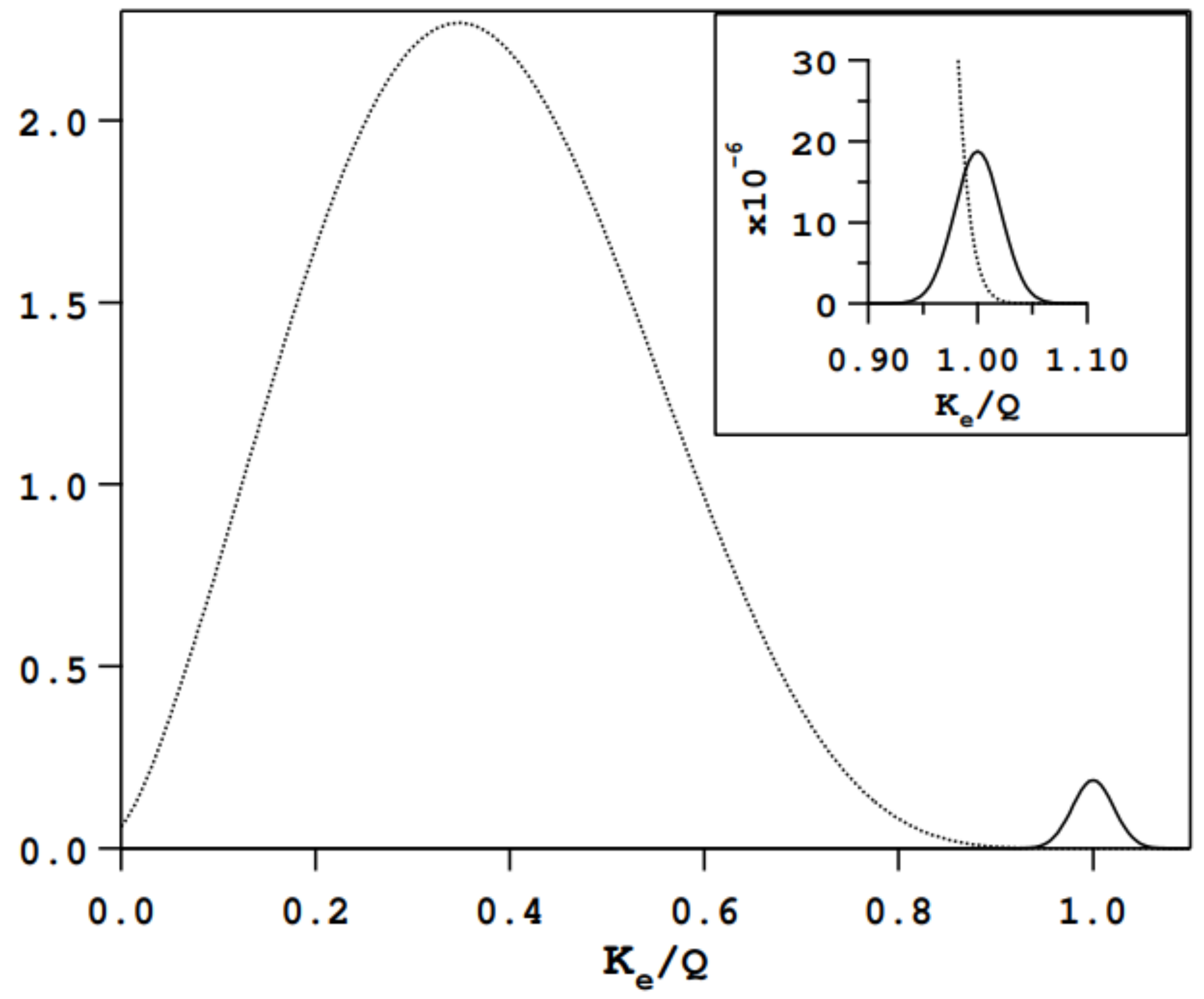


PRC102(2020)014602

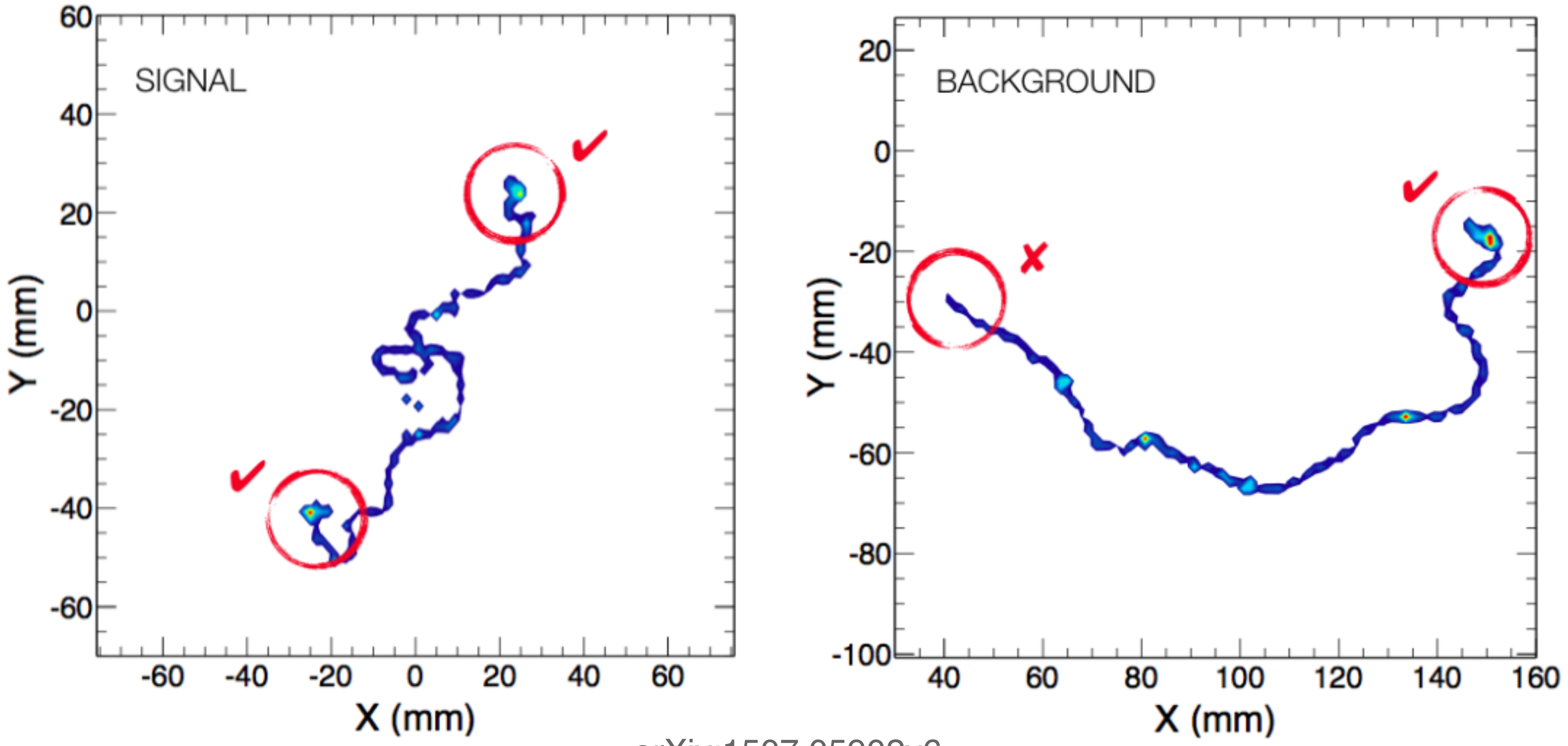
Neutrinoless Double Beta Decay

Experimental signature

- No neutrinos, so the electrons must carry the full Q-value of the decay
  - This is visible as a mono-energetic peak at the end of the $2\nu\beta\beta$ continuum
  - Electrons share the energy and are mostly back-to-back
- Main backgrounds are from
  - Single recoiling electrons with the same total energy (HE gammas, beta decays and neutrino scattering)
  - Multi-site interactions of HE gammas, too close to be easily distinguished
  - Standard $2\nu\beta\beta$
- Experimental requirements: large source mass, low background environment, good energy resolution, ability to discriminate background events



Event topology in Xe gas (NEXT)



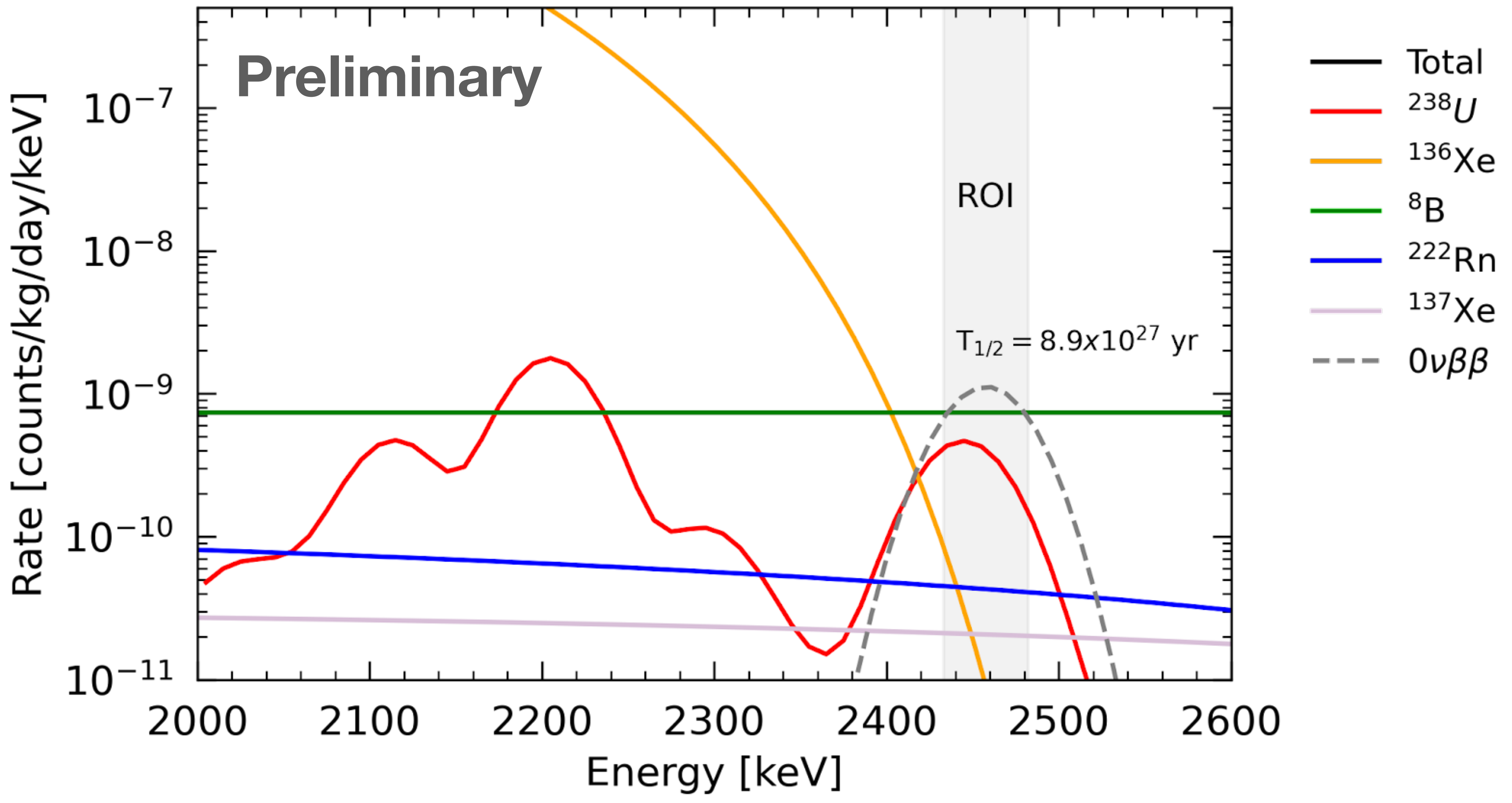
arXiv:1507.05902v6

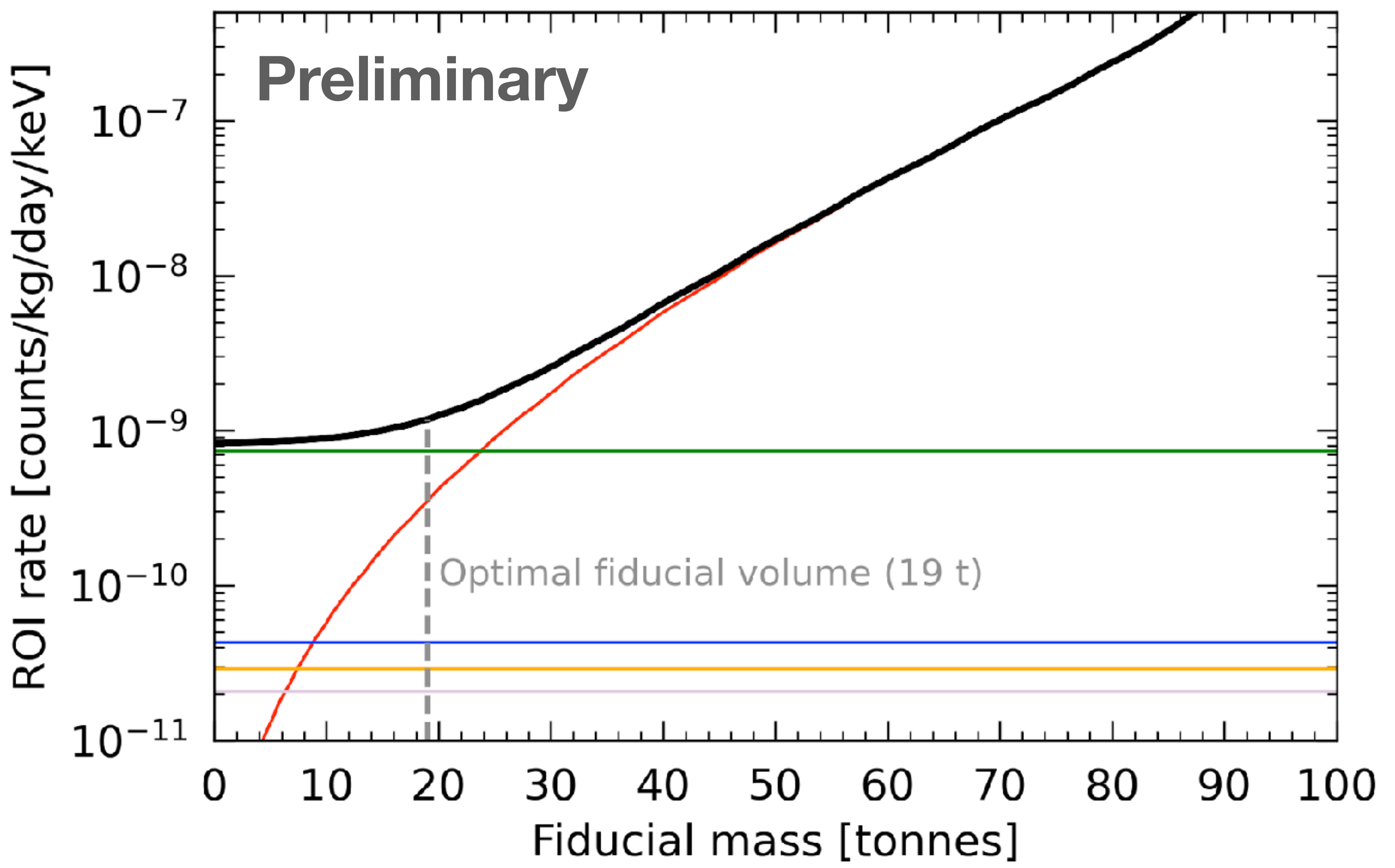
A 3rd Generation Xenon TPC

Preliminary projections for ^{136}Xe $0\nu\beta\beta$

- Preliminary study for a 75 t TPC submitted to Snowmass as a LoI (2020).
- A more complete study, covering various scenarios (total mass, radioactivity of detector materials, installation site) nearly finished.
- With such a large target mass, the effect of xenon self-shielding allows for a large fiducial volume with very low external backgrounds
- Internal backgrounds can be minimised with continuous ^{222}Rn removal and installation in a deep underground lab

100 t active mass, 10 yr exposure

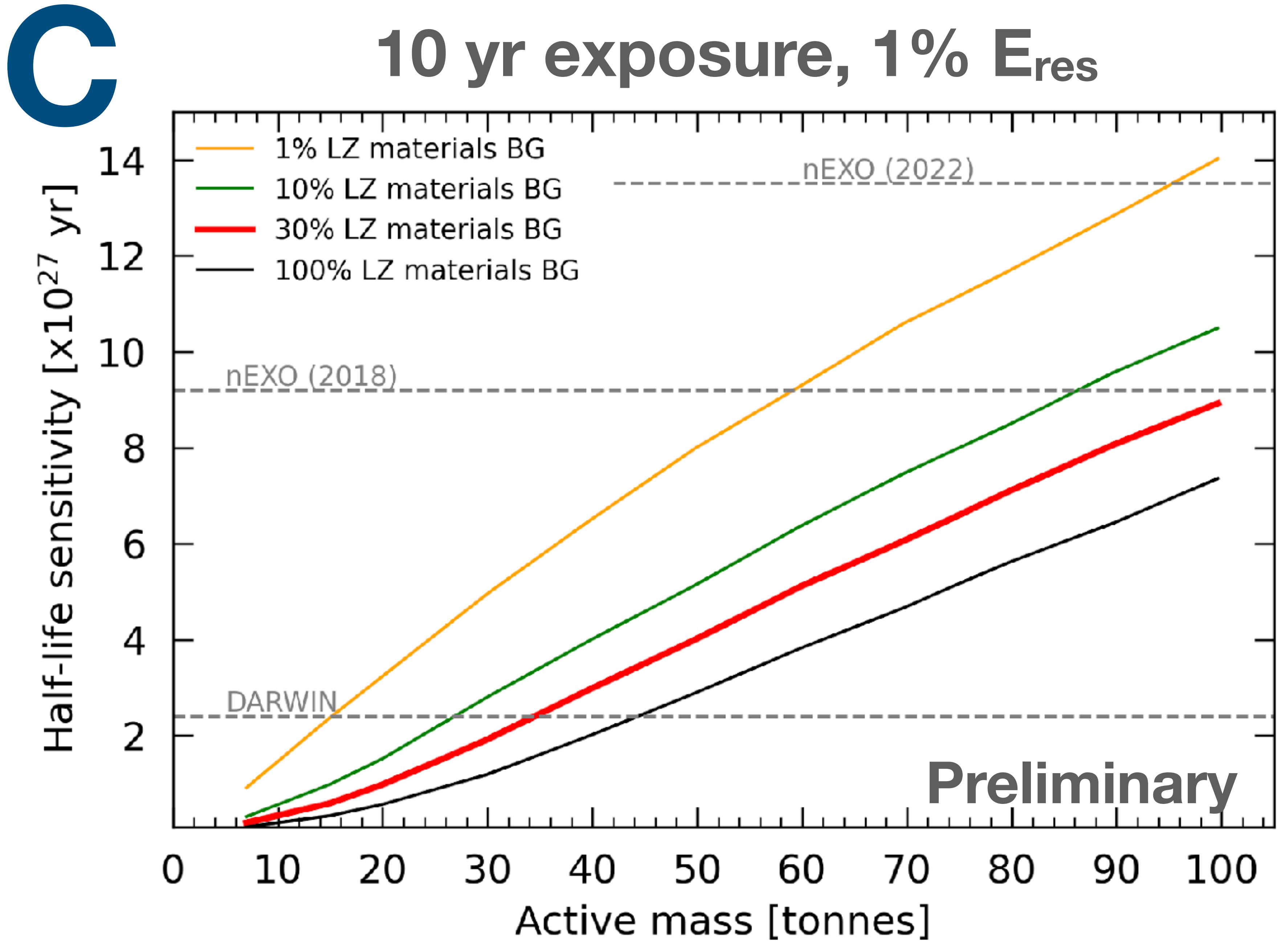


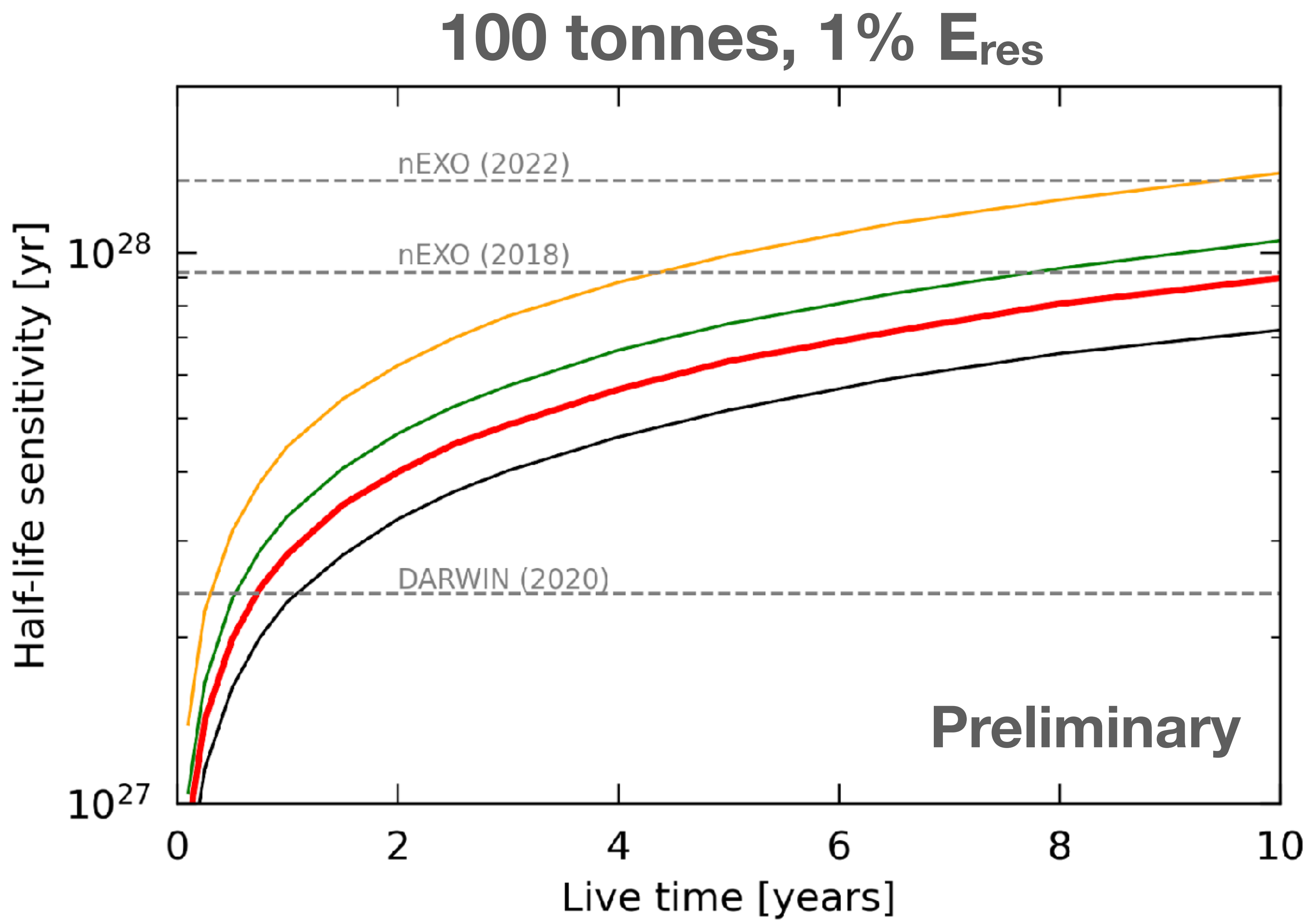


A 3rd Generation Xenon TPC

Preliminary projections for $0\nu\beta\beta$

- First results presented at Neutrino 2022, paper with full discussion by the end of the year
- A 3rd generation detector can be extremely competitive for $0\nu\beta\beta$ searches
  - Excellent energy resolution already demonstrated by LZ ($\sigma \sim 0.7\%$ @ $Q_{\beta\beta}$)
  - Has the potential to exclude the IH scenario
  - Need careful material selection and background rejection strategies:
    - SS/MS discrimination
    - Exploring the topology of the decay (electron tracks are ~mm in liquid xenon)

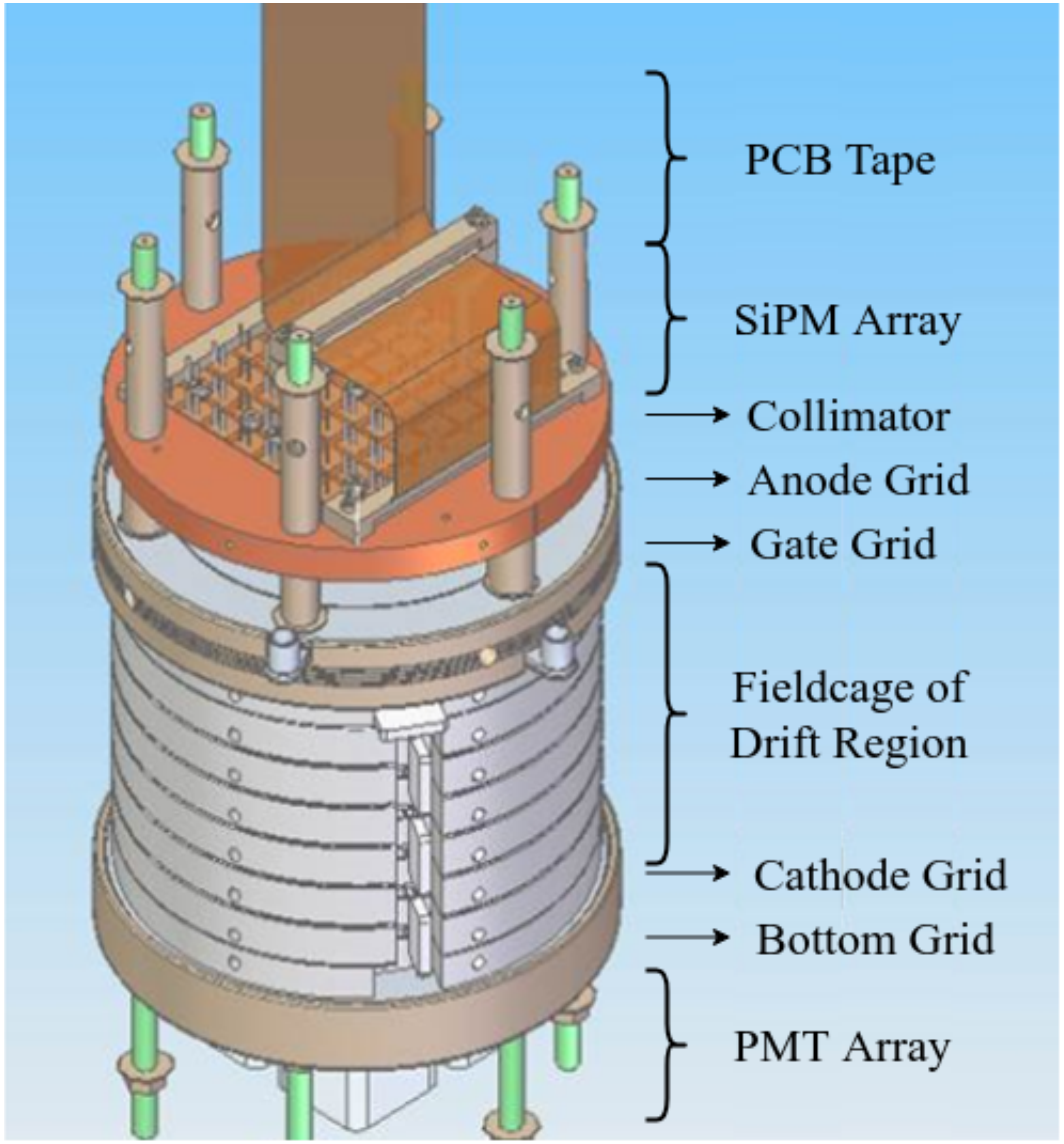




A 3rd Generation Xenon TPC

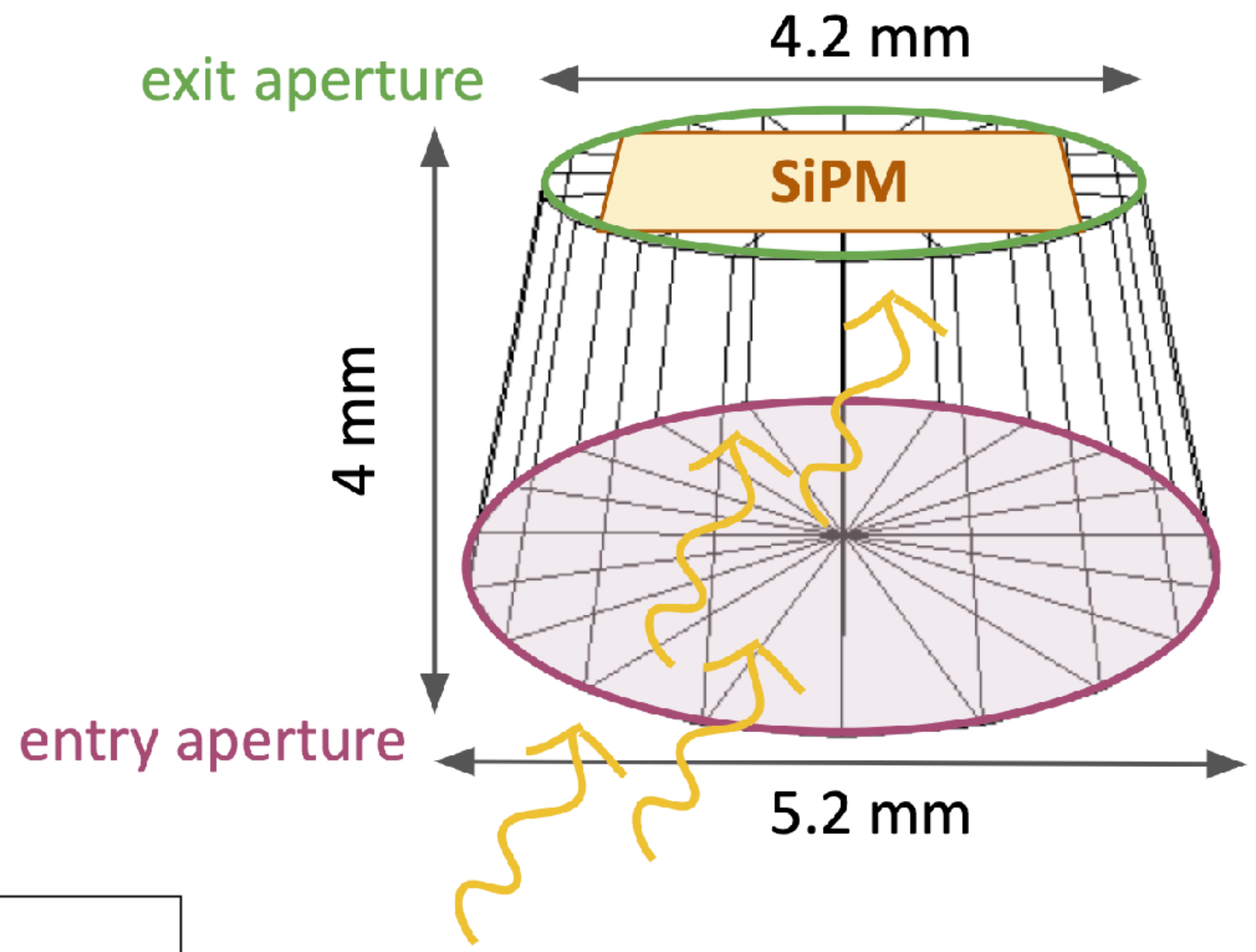
R&D

- Collaboration with UK groups, for R&D towards a G3 detector
- Prototype chamber for various tests, all with the goal of optimising the position resolution:
    - Use of a SiPM array instead of PMTs at the top
    - Optimise electrode grids (geometry, wire thickness and pitch)
    - Doping with H_2 to reduce electron diffusion
- Goal is to prove ~100 µm resolution is possible in these detectors

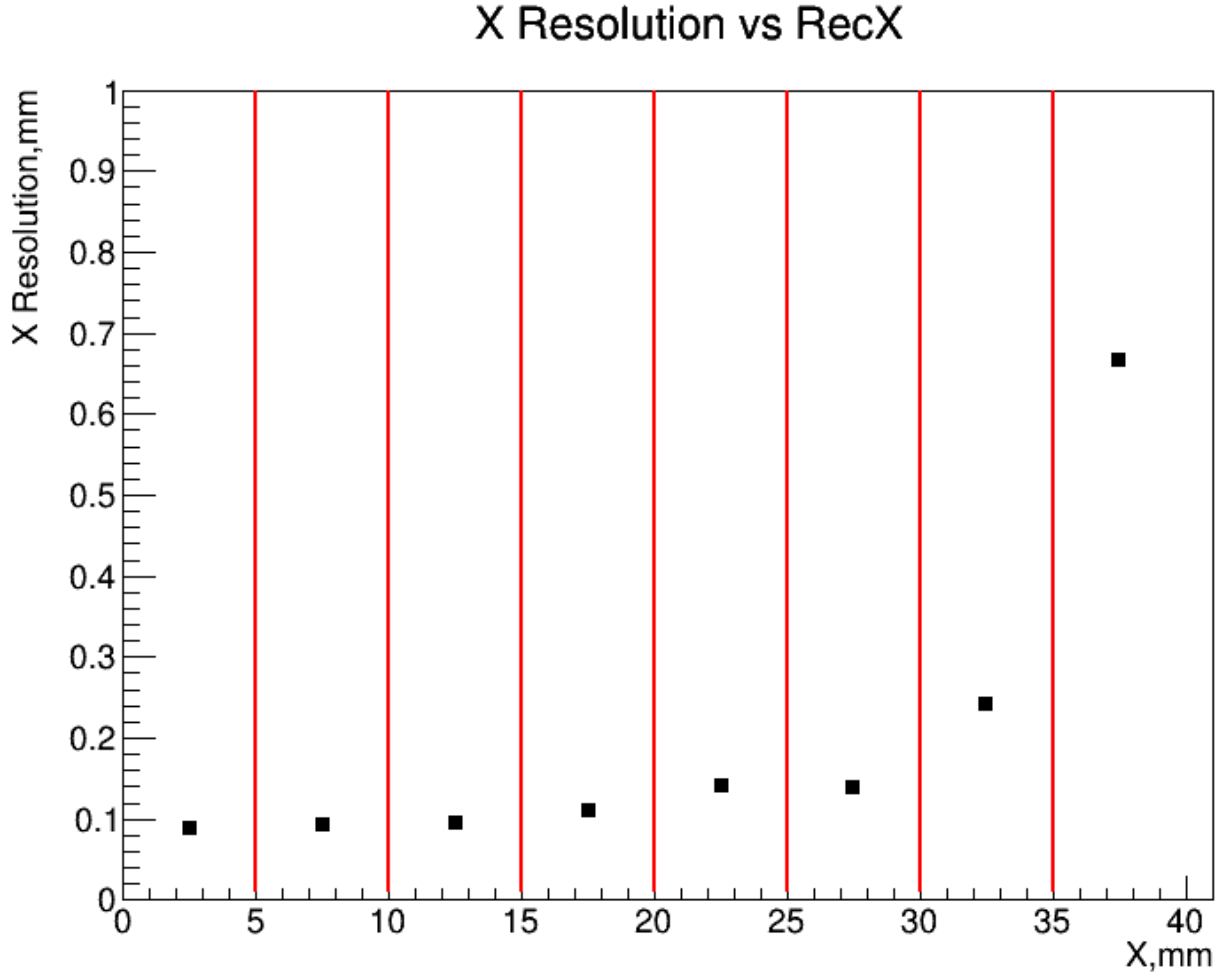


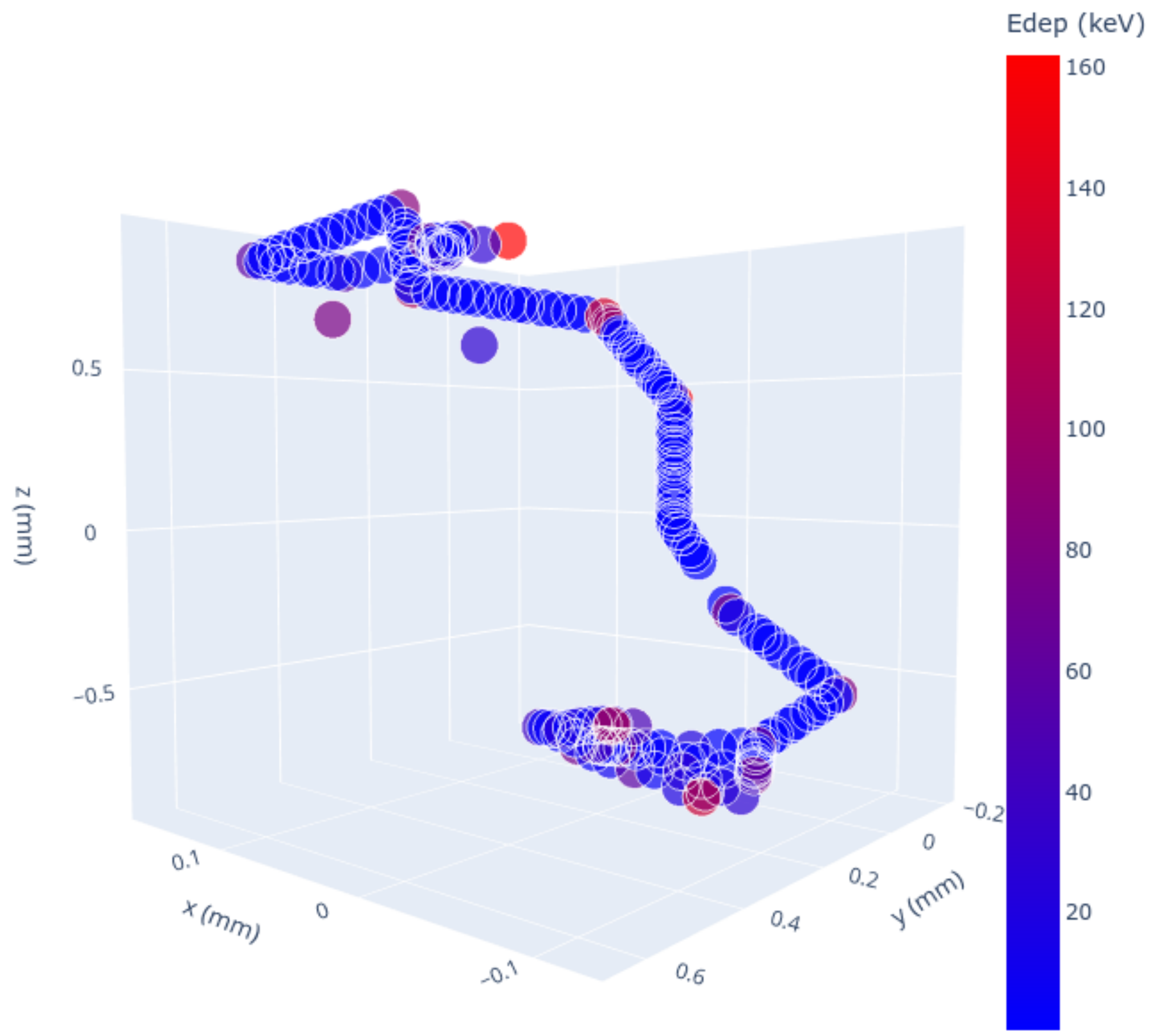
A 3rd Generation Xenon TPC

R&D



- Simulation study by F. Alcaso (master's thesis)
  - Use of a collimator mask with the SiPM array
  - Optimise collimator geometry
  - Test different grid configurations
  - Different SiPM models
  - Using simplified light emission sources
  - Still to include
    - realistic event topologies (background and $0\nu\beta\beta$)
    - Diffusion of the electron cloud
    - Focusing of the electrons by the grids





- Shows <100 μm resolution possible
  - Allows powerful discrimination between single and multiple scatters
  - Opens the possibility to reconstruct electron trajectories

A 3rd Generation Xenon TPC

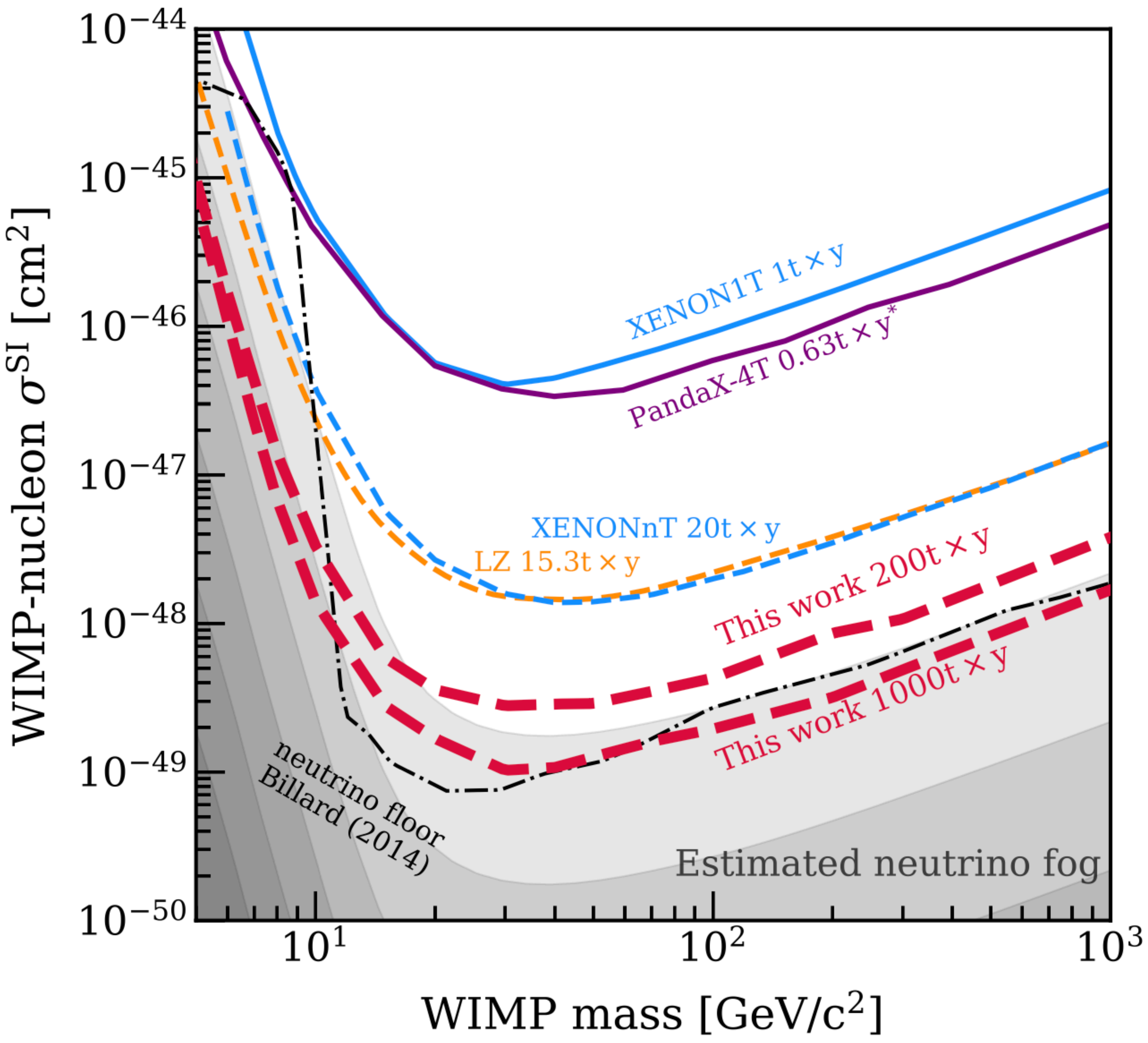
XLZD Consortium

- LZ, XENON (the leading collaborations in this field) and DARWIN have joined forces
- MoU signed in April 2021 by >150 scientists of the 3 collaborations
- Groups with people from the 3 collaborations began working together in early 2022
  - I was recently appointed as joint coordinator of the $0\nu\beta\beta$ group
- White paper on arXiv in March 2022
- First in-person meeting in June 2022

A 3rd Generation Xenon TPC

XLZD Detector

- The main goal is to develop a 2-phase xenon TPC with enough WIMP sensitivity to reach the neutrino fog
- Final detector design
  - 50 — 100 tonnes
  - Possibility of a staged construction
  - Active vetos for additional discrimination (critical to reduce the $0\nu\beta\beta$ ^{208}Tl background)
- Installation site under discussion
  - SNOLAB, SURF, LNGS, Boulby, Kamioka
  - Ease of access, available space, muon flux (depth), etc
- Many other physics channels available
  - Other DM candidates (light WIMPs, axions, dark photons, etc)
  - Rare decays (0ν and 2ν 2EC, ECβ^+ and $2\beta^+$; $2\nu\beta\beta$ and $0\nu\beta\beta$)
  - Neutrino physics



arXiv:2203.02309

Plans for the future

- The preliminary results I obtained for a G3 detector are already helping to drive the design of XLZD, but much more detailed studies will be necessary in the next couple of years
  - Detailed simulations of the backgrounds and detector response
  - Study different design alternatives and their impact on the sensitivity
  - Develop strategies to discriminate background events
- Continue the R&D studies towards an improved position resolution, with direct impact in SS/MS rejection capability and possibly reconstruction of the electron trajectories
  - Successful tests in the small UK chamber can lead to direct collaboration with European institutions of XLZD which have larger prototype chambers (Zurich, Freiburg) — opening the possibility for EU funding
- I have two master students working in $0\nu\beta\beta$, in simulations for the prototype chamber and developing SS/MS discrimination techniques. I hope to keep both for PhD.
- I plan to apply for funding in the next FCT call with an exploratory project to support the initial steps of this plan.

Summary & Conclusions

- A G3 Xe TPC experiment capable of reaching the neutrino fog is strongly supported both in the US (P5 panel) and Europe (European Strategy for Particle Physics)
- XLZD was created to pursue this effort, merging the strongest collaborations in the field
- It represents an excellent opportunity to search for physics beyond the SM, in which LIP must be involved
- XLZD can lead not only in WIMP search but also in the search for $0\nu\beta\beta$, competing with dedicated experiments while delivering a much broader physics program
- Participation in XLZD will open funding opportunities for LIP for many years, both national and European
- I've been leading the $0\nu\beta\beta$ studies for this detector and am involved in the design and installation site discussions, and have recently been nominated joint coordinator of the $0\nu\beta\beta$ group in XLZD
- I'm in a unique position to lead the LIP team in XLZD