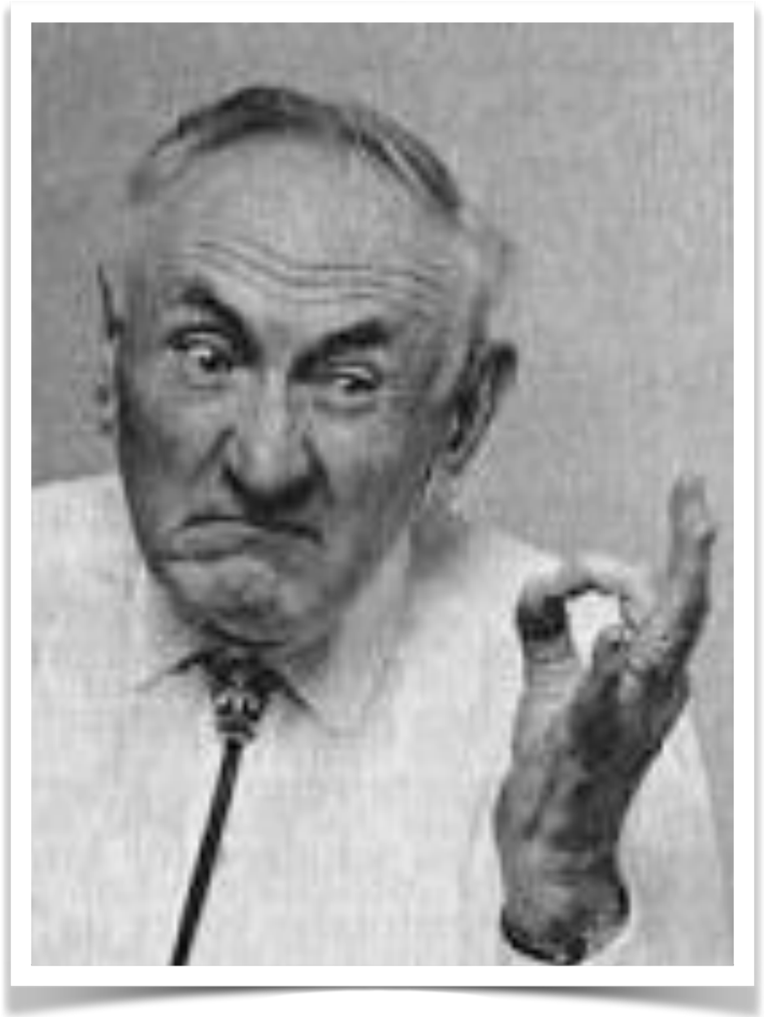
XLZD: A Next Generation Rare Event Observatory

Alexandre Lindote, 18th May 2023

LIP

Dark Matter evidence — Galaxy cluster dynamics

Fritz Zwicky (1933)



- Compared the velocity distribution of galaxies in the Coma cluster to what would be expected given the observed mass (estimated from the luminosity) — using the virial theorem
  - galaxies moved much faster than expected
  - visible matter only **0.5 %** of the total!
  - he named the invisible matter as *dunkle materie* (dark matter)

Virial theorem

$$\langle KE \rangle = -\frac{1}{2}\langle PE \rangle$$

$$\frac{1}{2}Mv^2 \nearrow \qquad \nwarrow G\frac{Mm}{R}$$

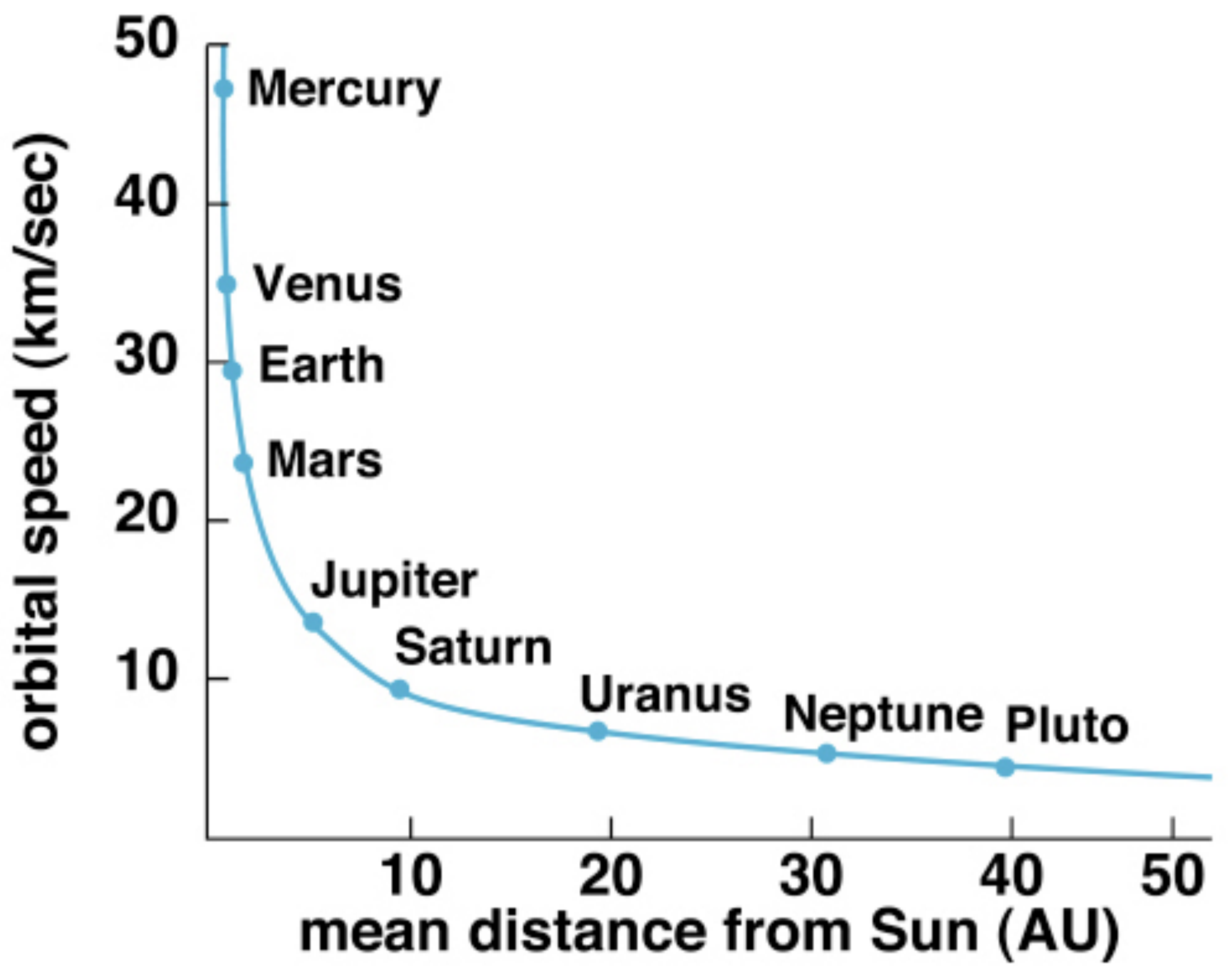
Coma cluster (image from SDSS)

Note: The existence of some form of invisible matter was not new, and had been suggested by other authors in the previous decades. See "A History of Dark Matter", by G. Bertone and D. Hooper

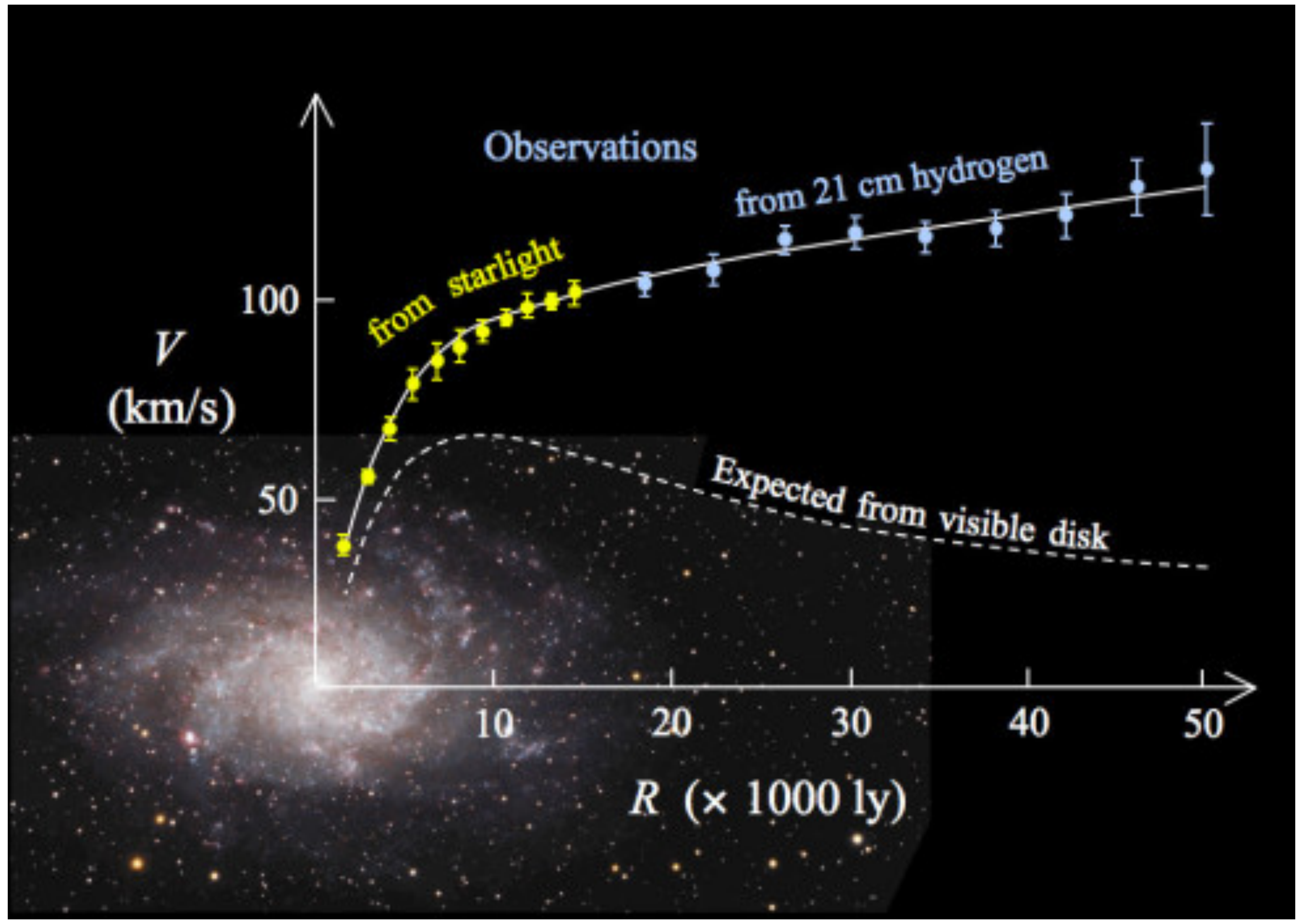
Dark Matter evidence — Galaxy rotation curves

Vera Rubin (1970s)

- During her PhD, she measured the rotation velocities of stars and dust in the outer regions of galaxies
- **She observed that stars (and dust) in the outer regions move as fast as the inner ones!**

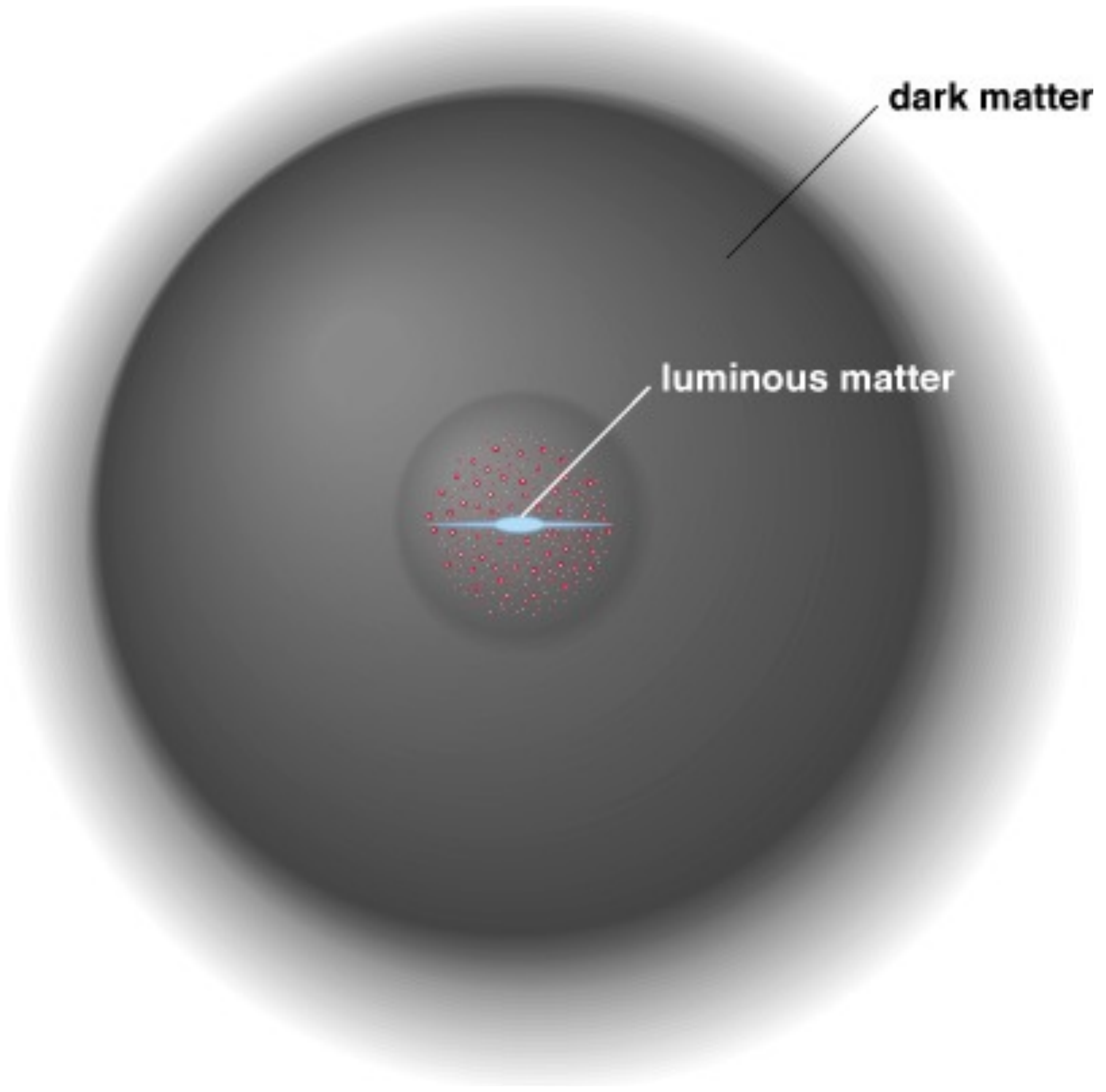


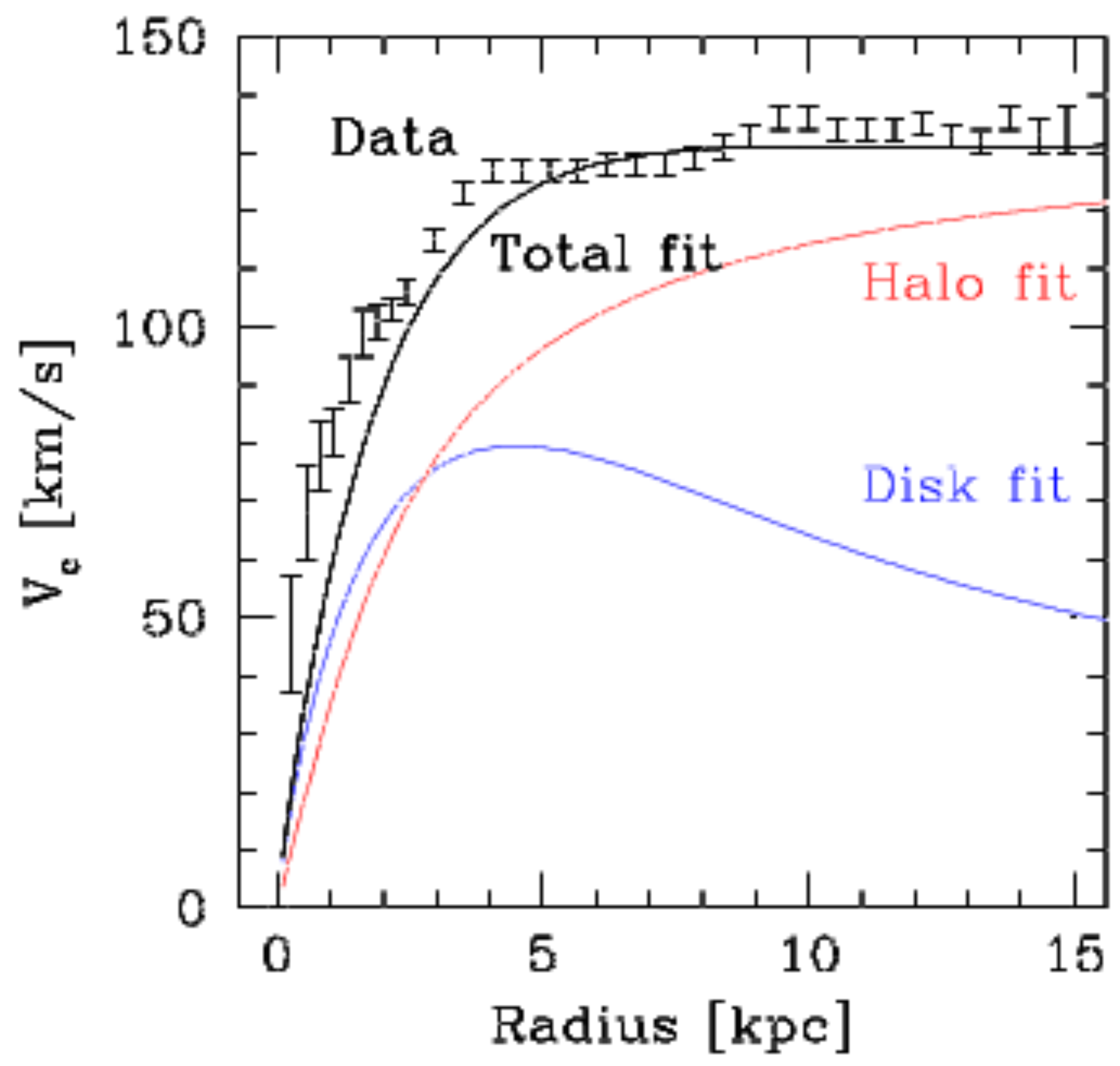
(b)



Dark Matter evidence — Galaxy rotation curves

- A non-visible mass component, which increases linearly with radius, must exist!
- Extends well beyond the luminous limits of the galaxies
- ~90% of the mass in galaxies is “dark”
- The rotation curves depend on the distribution of mass => can be used to estimate the dark matter properties

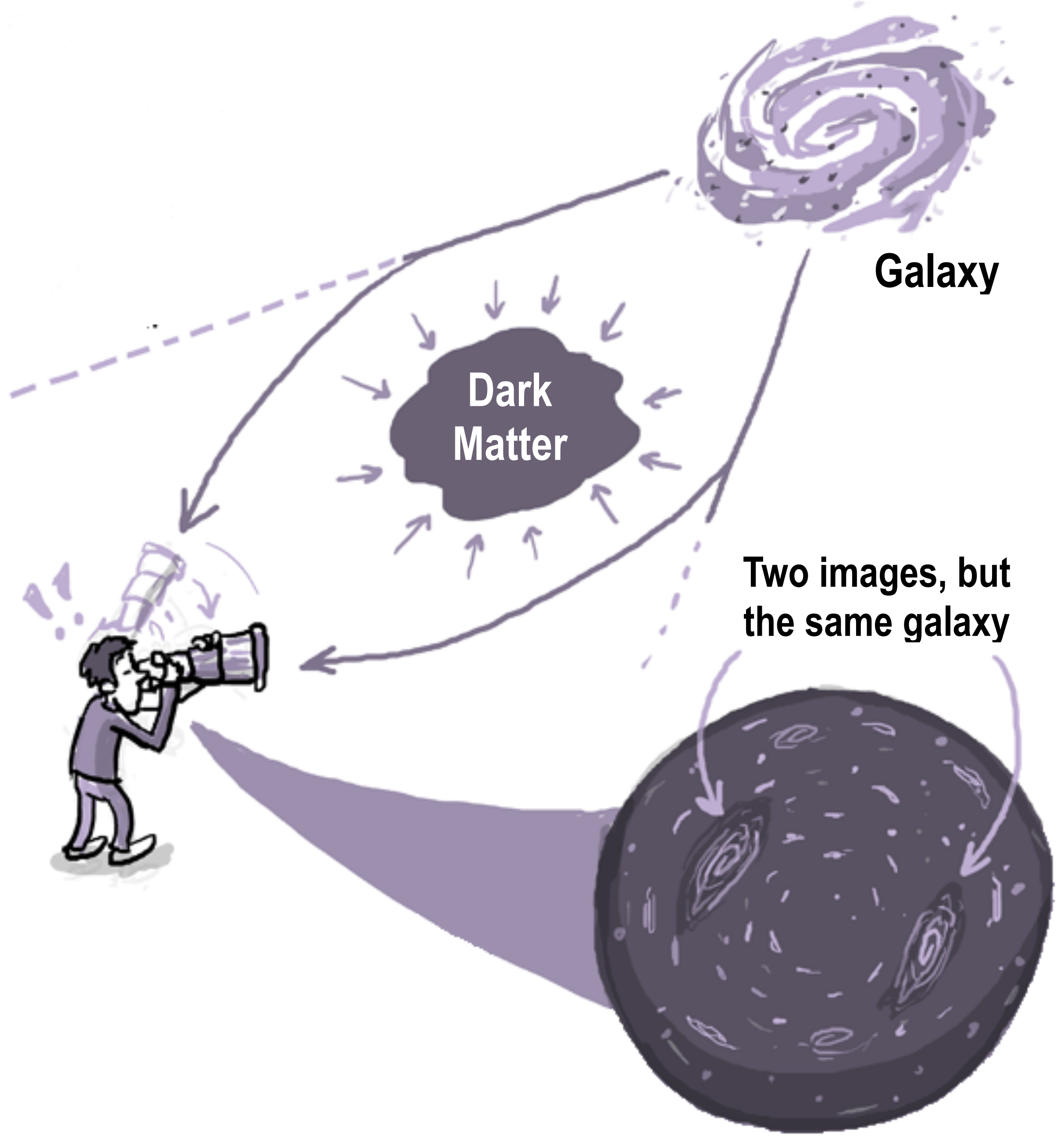




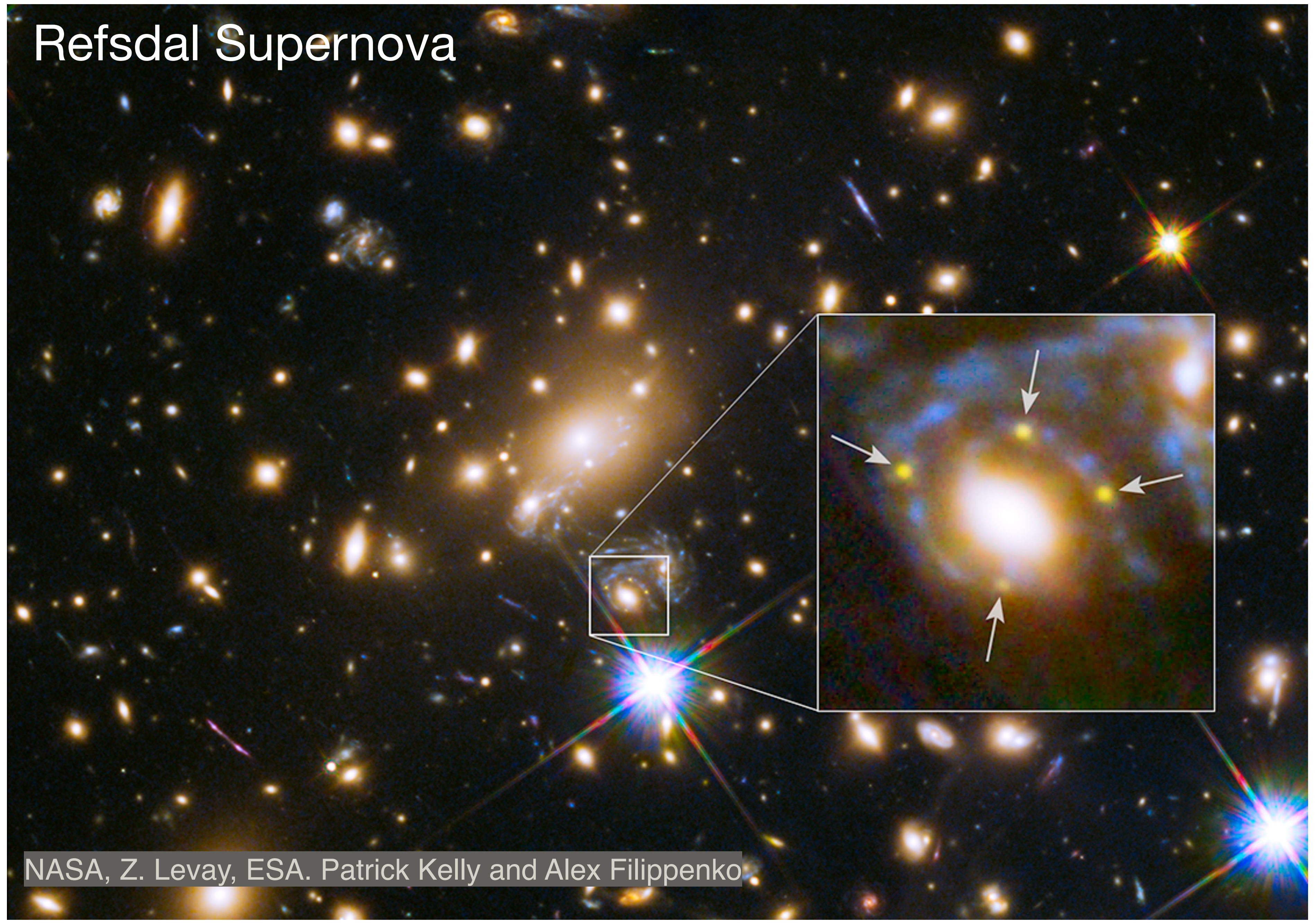
More evidence

Gravitational lensing

- General Relativity:
  - Space-time is distorted by large masses
  - The light path is deflected or distorted



- Weak lenses:
  - slight distortion of the image
- Strong lenses:
  - large distortion and multiple images



More evidence

The Bullet Cluster — the “smoking gun” of dark matter

- Shows the potential of using gravitational lensing for reconstruction of the mass distributions
- Two galaxy clusters collided
  150 million years ago
- While the gas clouds (red) interacted strongly and got distorted during the collision, the dark matter halos (blue) just passed by each other

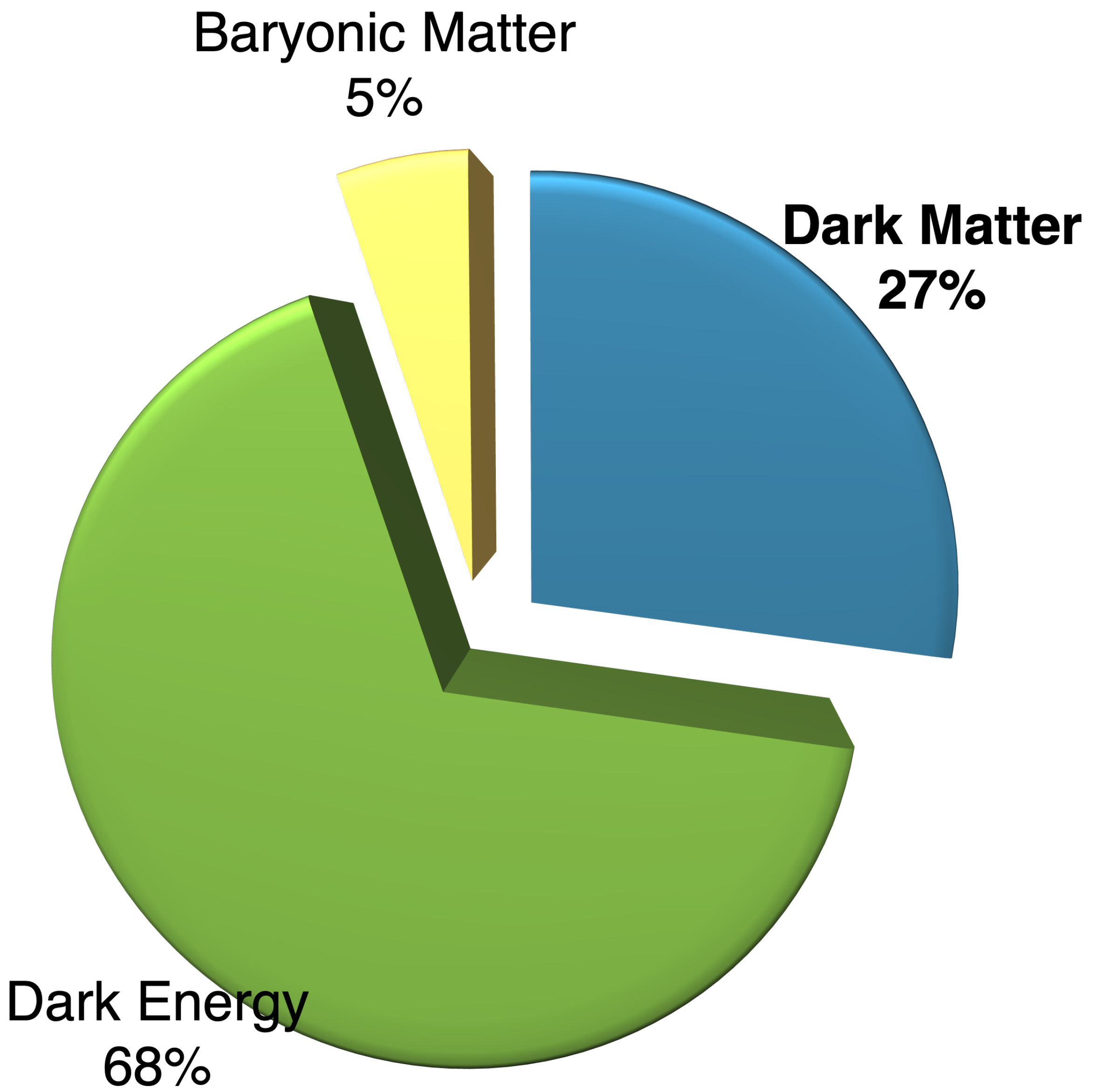
Gas distribution (red) measured using an X-ray telescope

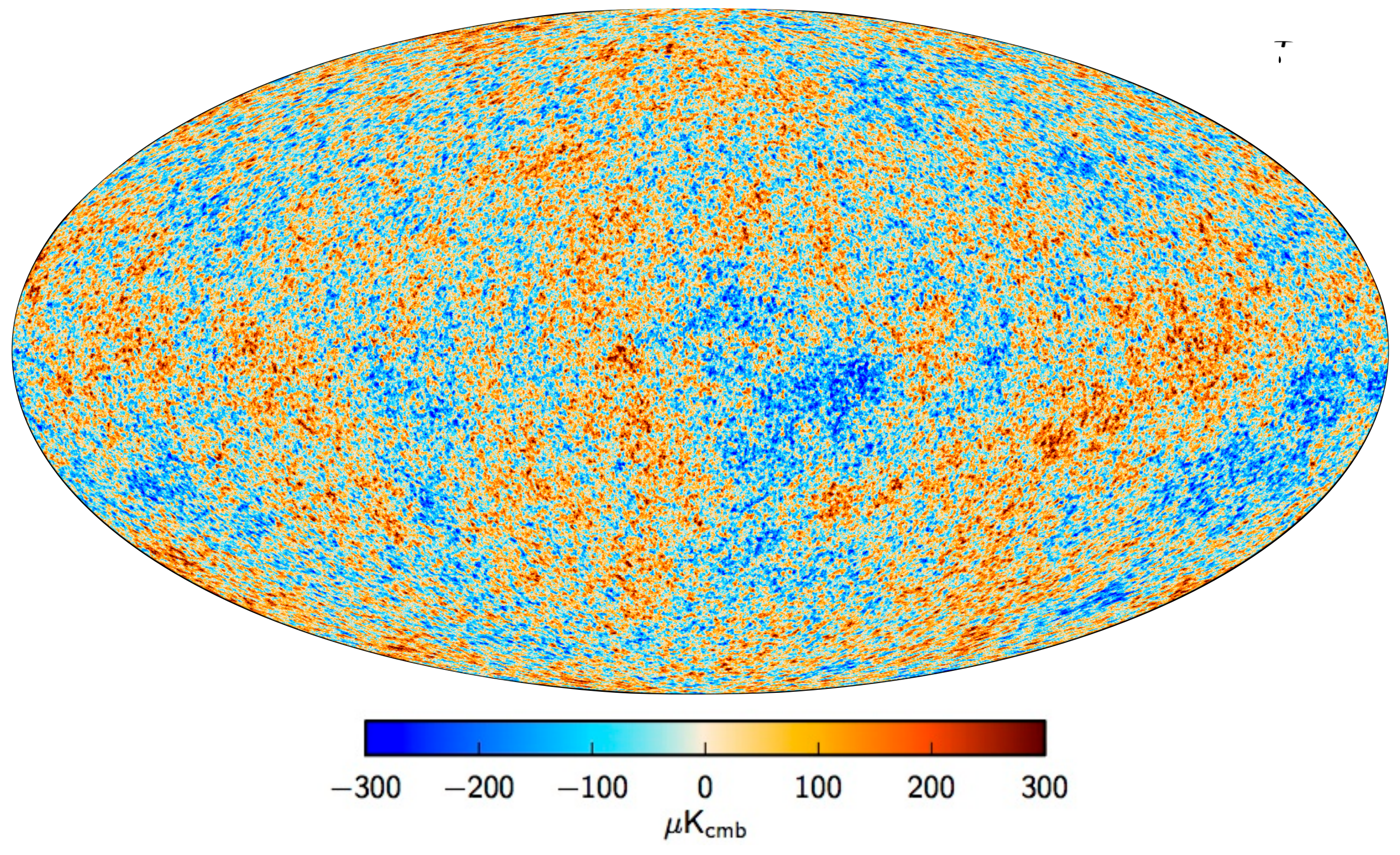
Mass distribution (blue) determined using the gravitational lens effect

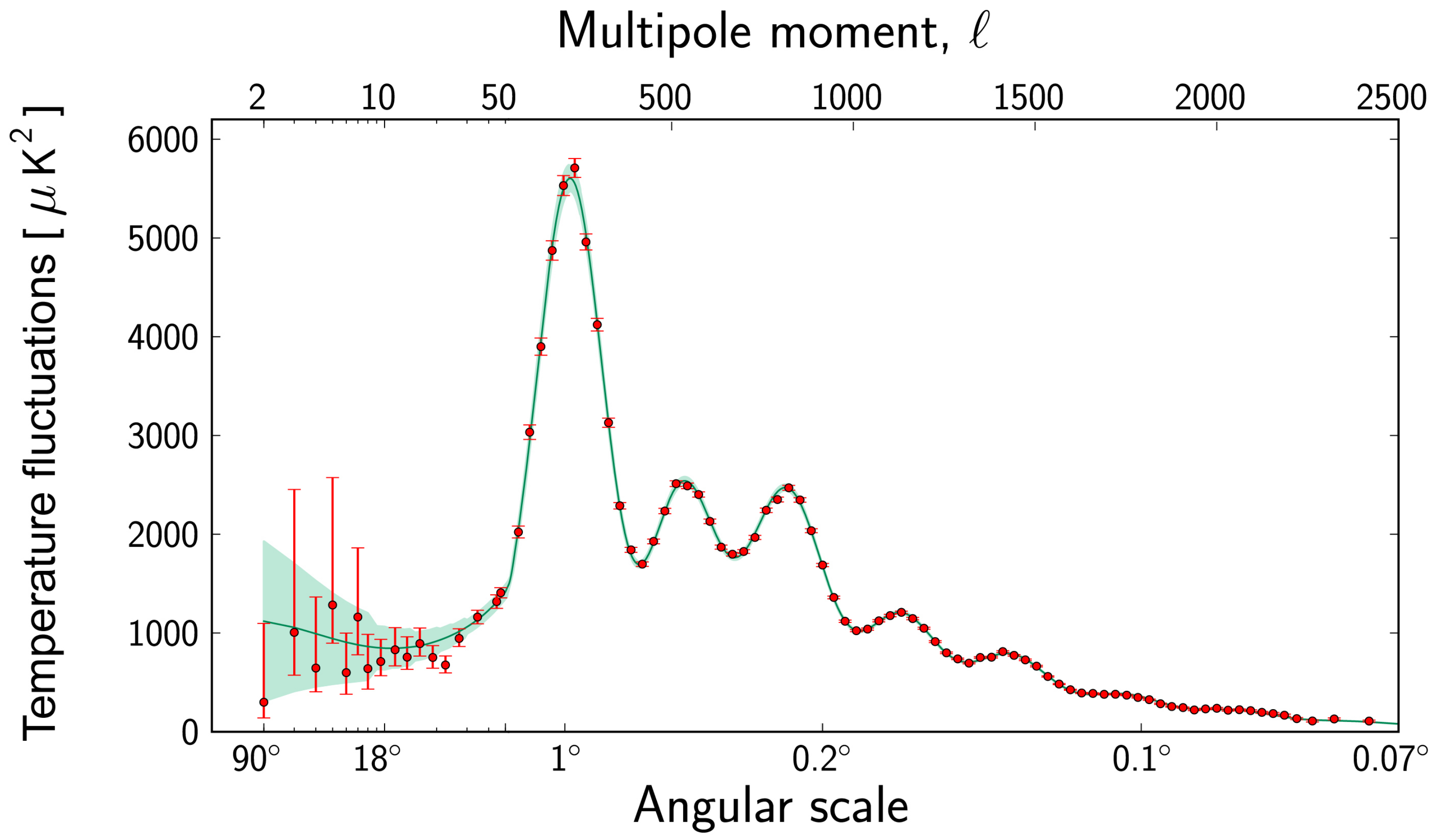
The Big Bang model

The Standard Model of Cosmology (Λ-CDM) is remarkably successful

- Initial conditions photographed at the surface of last scatters (CMB)
- Left to evolve for 13.7 Gyr under two dark 'fluids':
  – dark energy (Λ) and cold dark matter (CDM)
- To produce what we see today
  – ordinary matter (almost) does not matter…

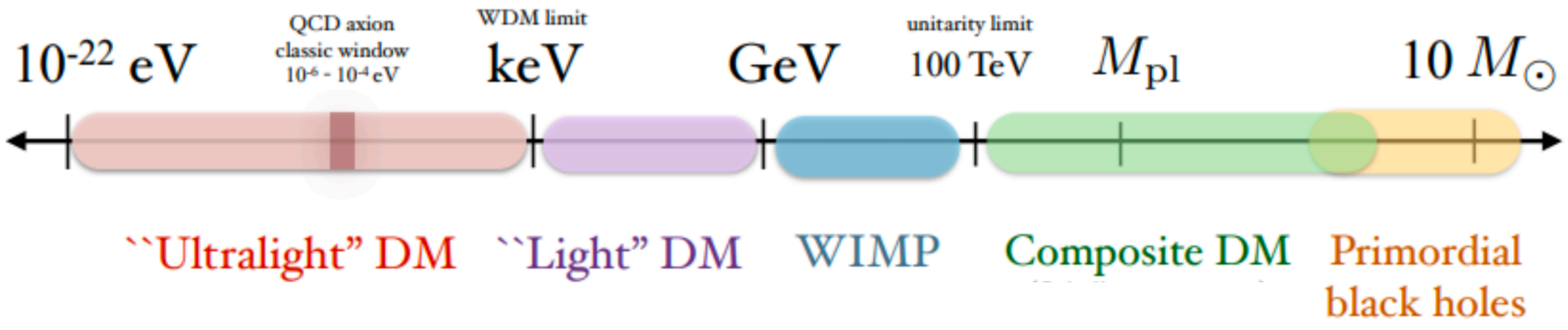






Dark Matter candidates

- Elementary particles produced in the early Universe
- They must either be stable or very long lived ($\tau \gg t_U$)
- Many candidates!



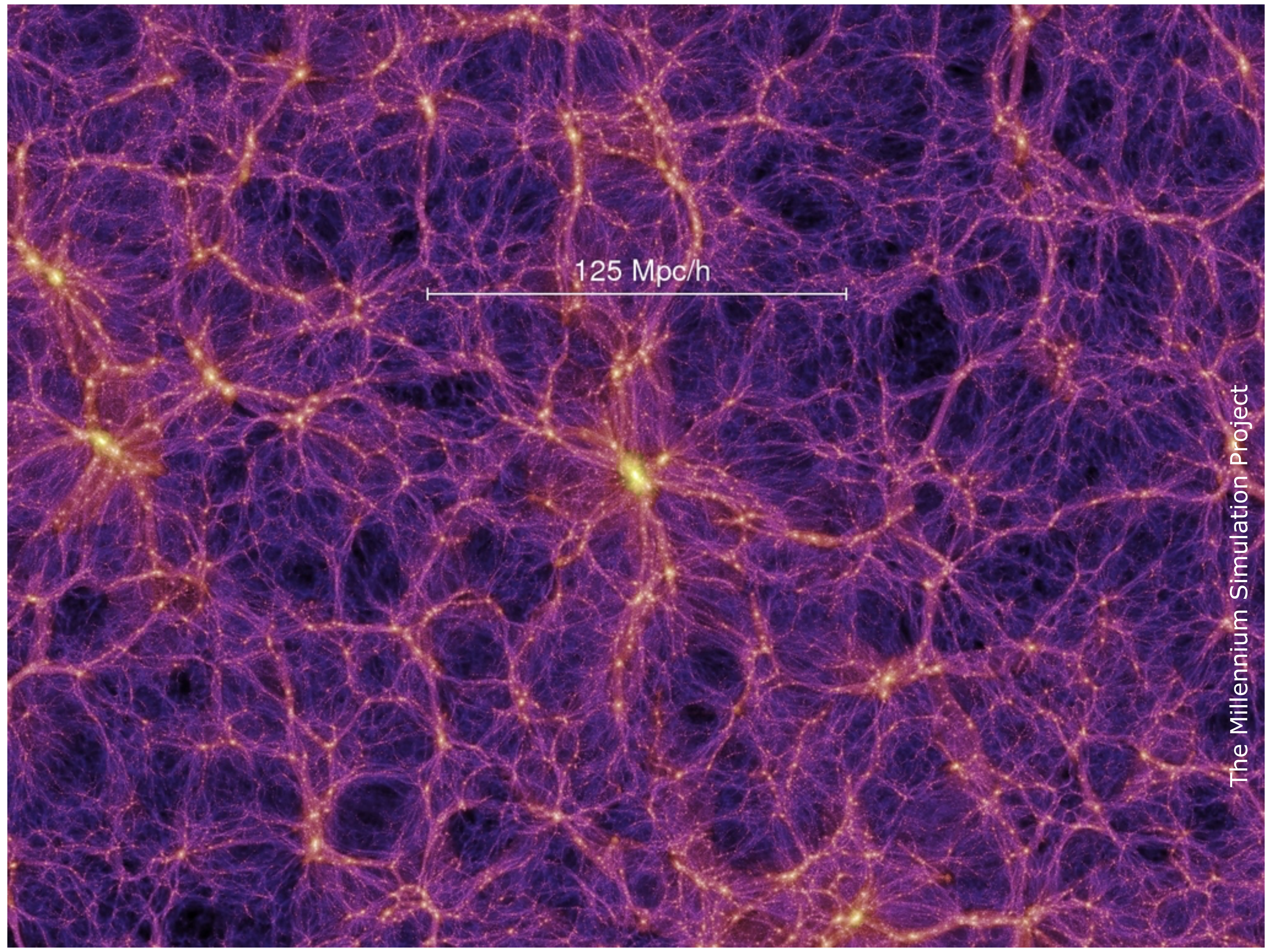
arXiv:1904.07915

- **Axions:** m ≈ 10^{-5} eV
  - light pseudo-scalar particle postulated in connection with the absence of CP violation in QCD
- **WIMPs** (Weakly Interacting Massive Particles): m ~ 1 GeV — 100 TeV
- **Superheavy dark matter:** m ~ 10^{12} - 10^{16} GeV
  - SIMPzillas, WIMPzillas, DM “nuggets", etc.

WIMPs

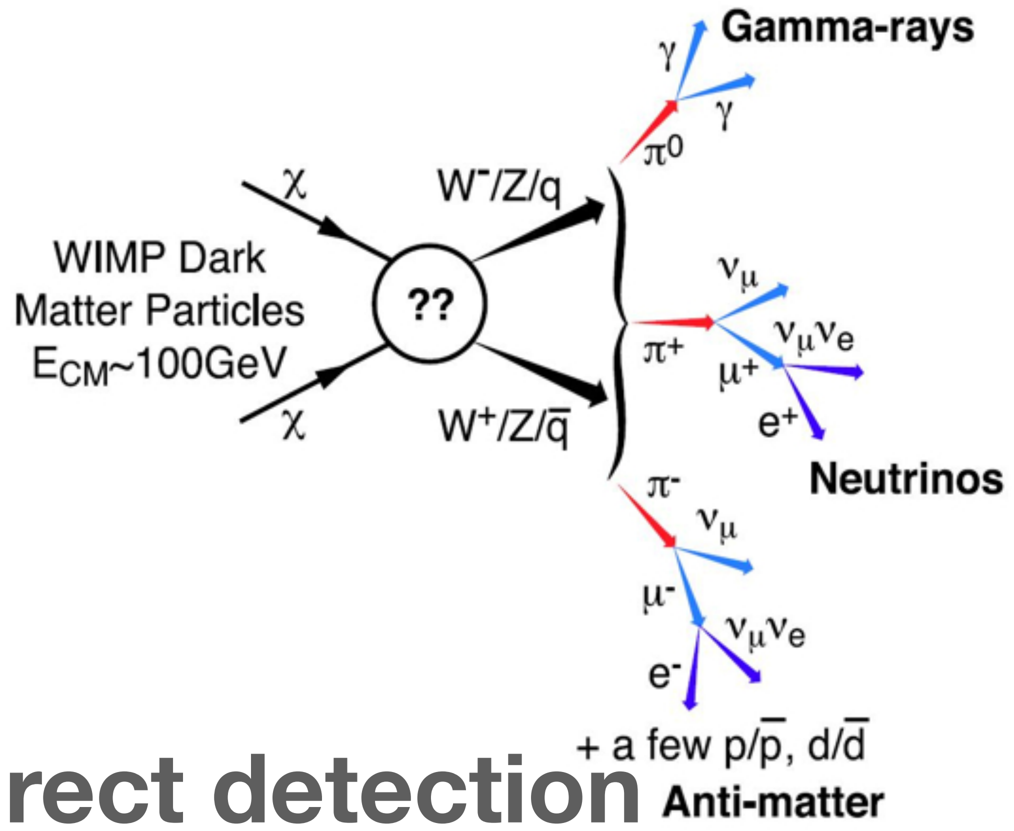
Weakly Interacting Massive Particles

- Stable heavy particles produced in the early Universe (half-life at least comparable to the age of the universe)
- Non-baryonic (no room for more baryons)
- Slow (*i.e.* non-relativistic at freeze out)
  - **Cold Dark Matter** — required for n-body simulations to match the observed structures in the Universe
- Neutral (no electromagnetic/strong interactions)
- Only feel the gravitational force and (possibly) the weak nuclear force
- Mass in the ~1 GeV — ~100 TeV range
  - Thermal production fails to explain DM abundance beyond this range
- WIMP-like candidates from **supersymmetry** (**neutralinos**), from theories with universal extra dimensions (UED) (lightest Kaluza-Klein particle), and from most other theories beyond the SM



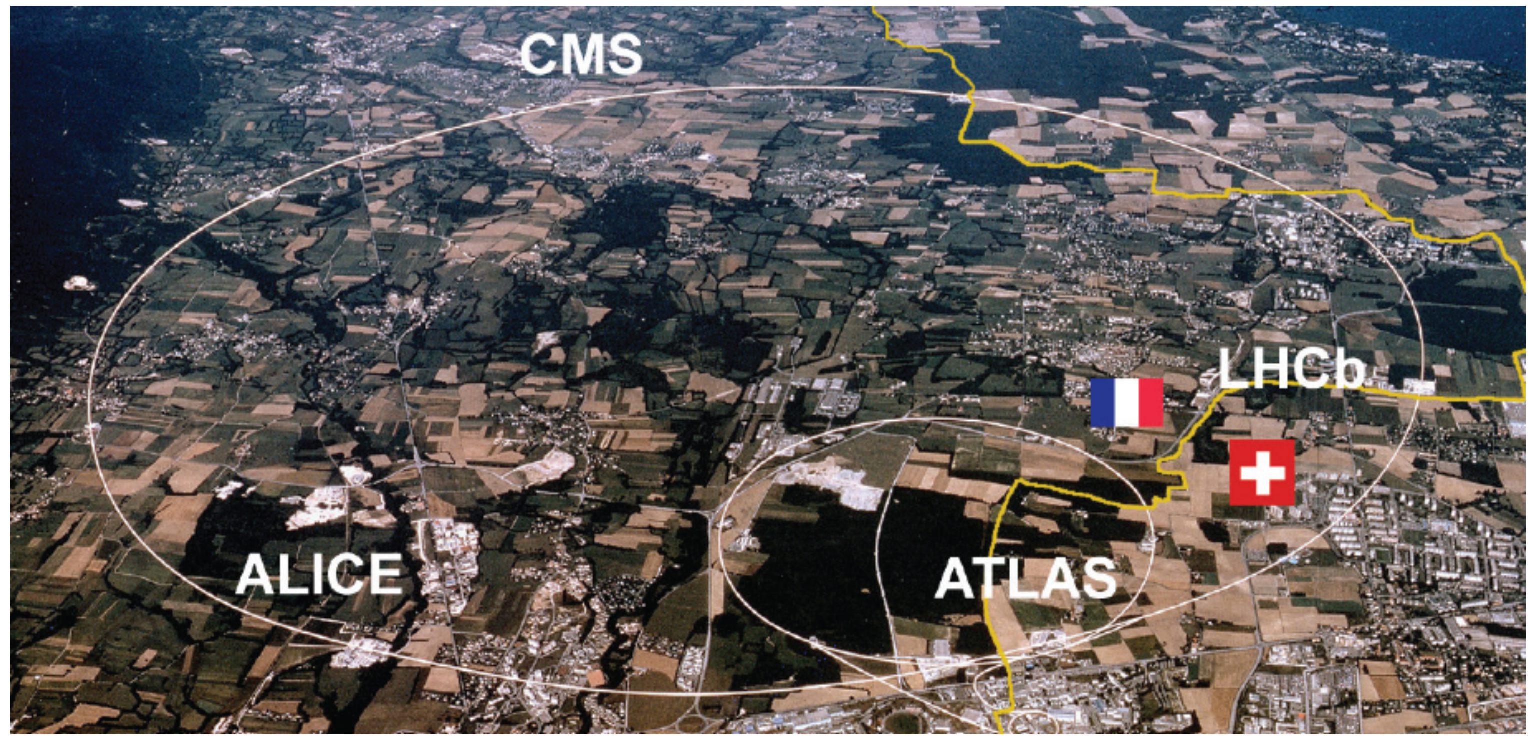
Computer simulation of large structure formation in the Universe using Cold Dark Matter

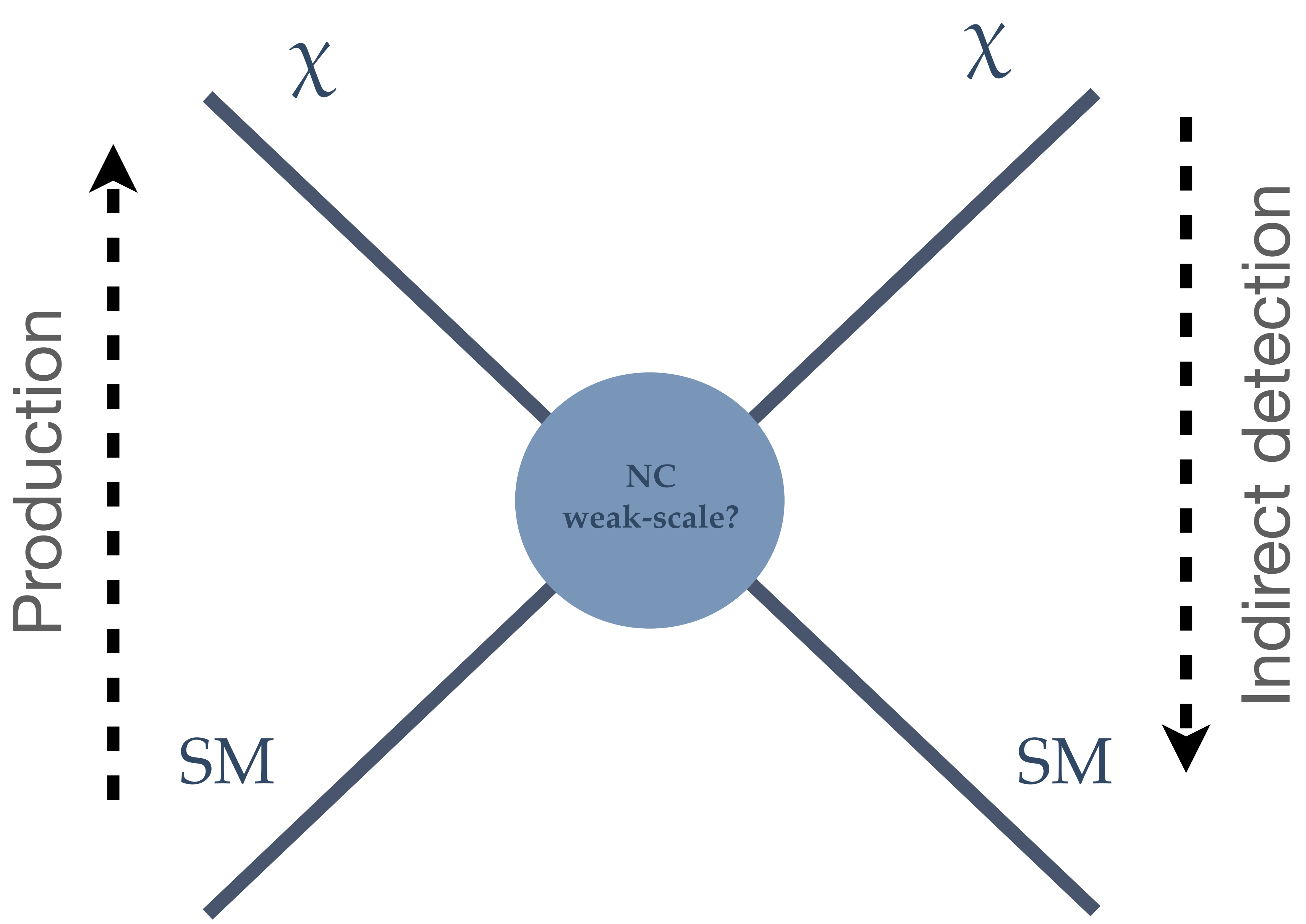
WIMP detection



Production in accelerators

- WIMPs may be produced in high-energy collisions
- They will escape detectors without interacting
- Look for missing energy in collision events

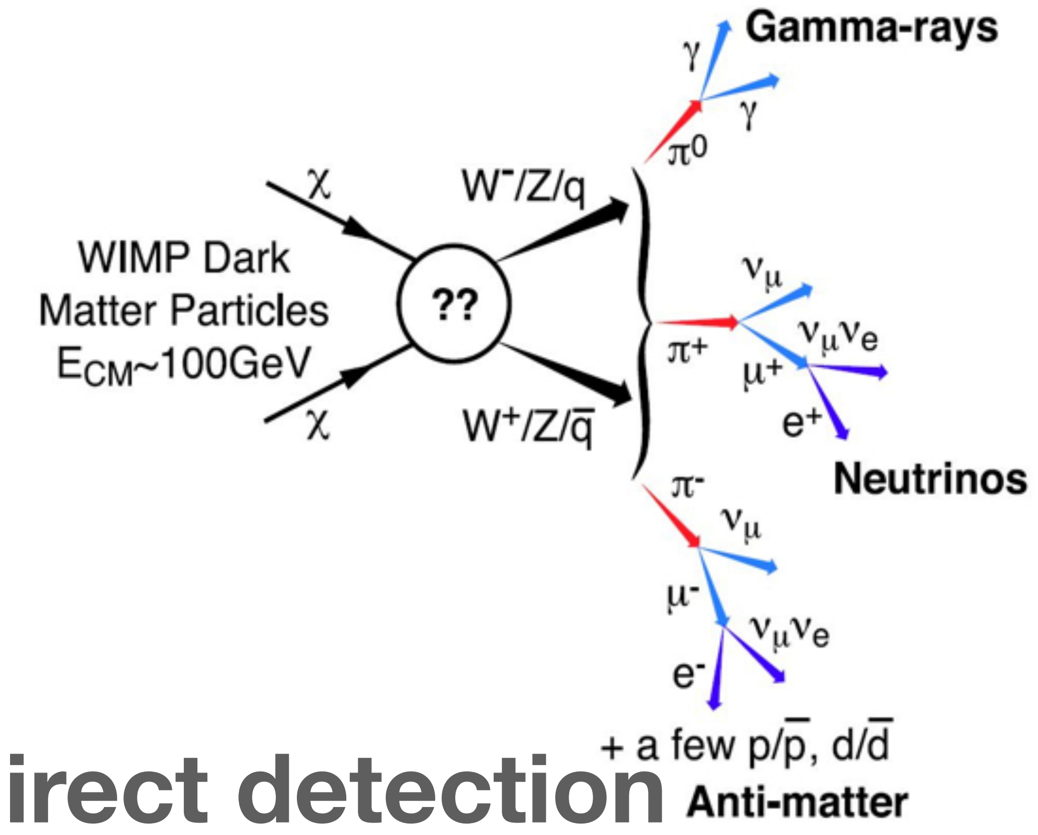




Indirect detection

- WIMPs may decay or annihilate
- Production of SM particles
- Backgrounds are very challenging (astrophysical sources)

WIMP detection



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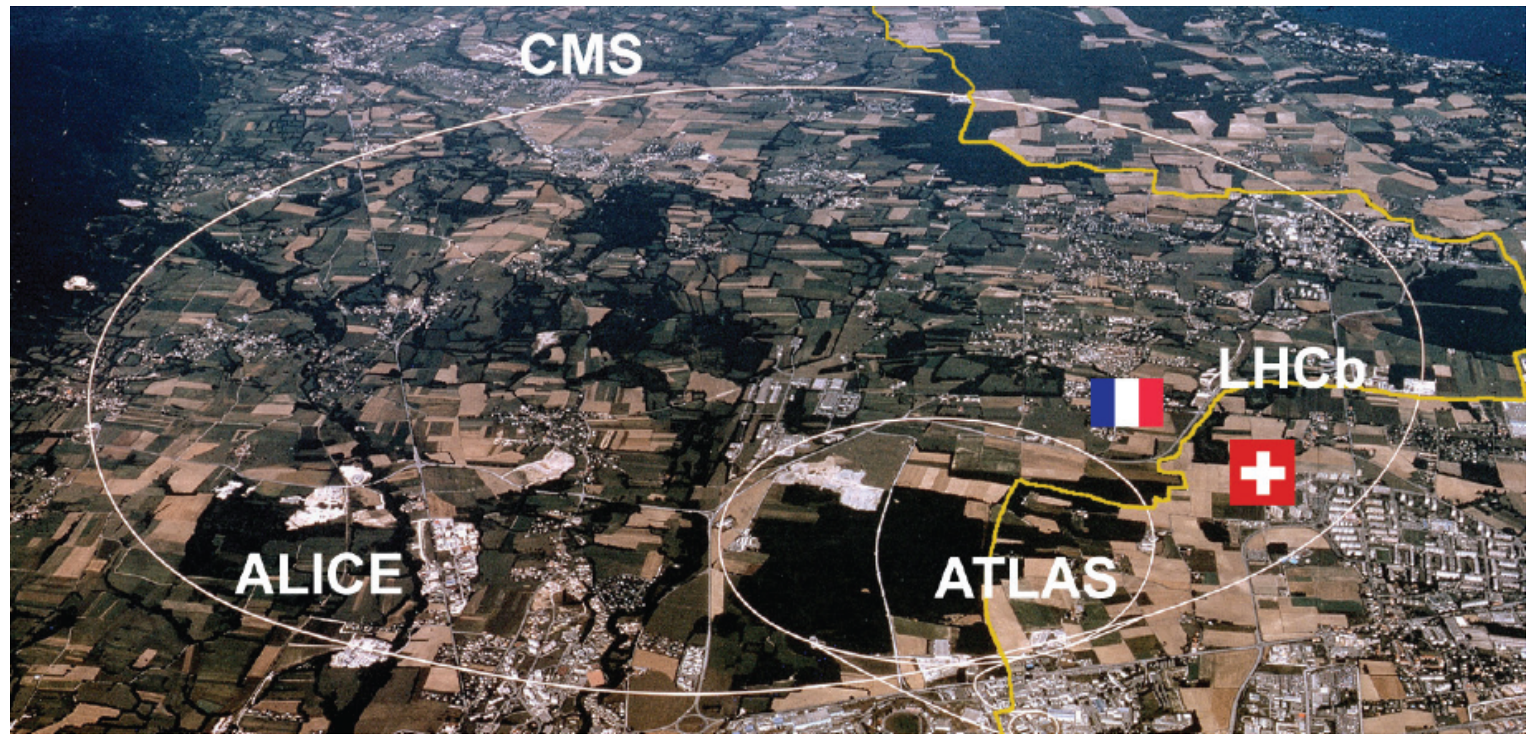

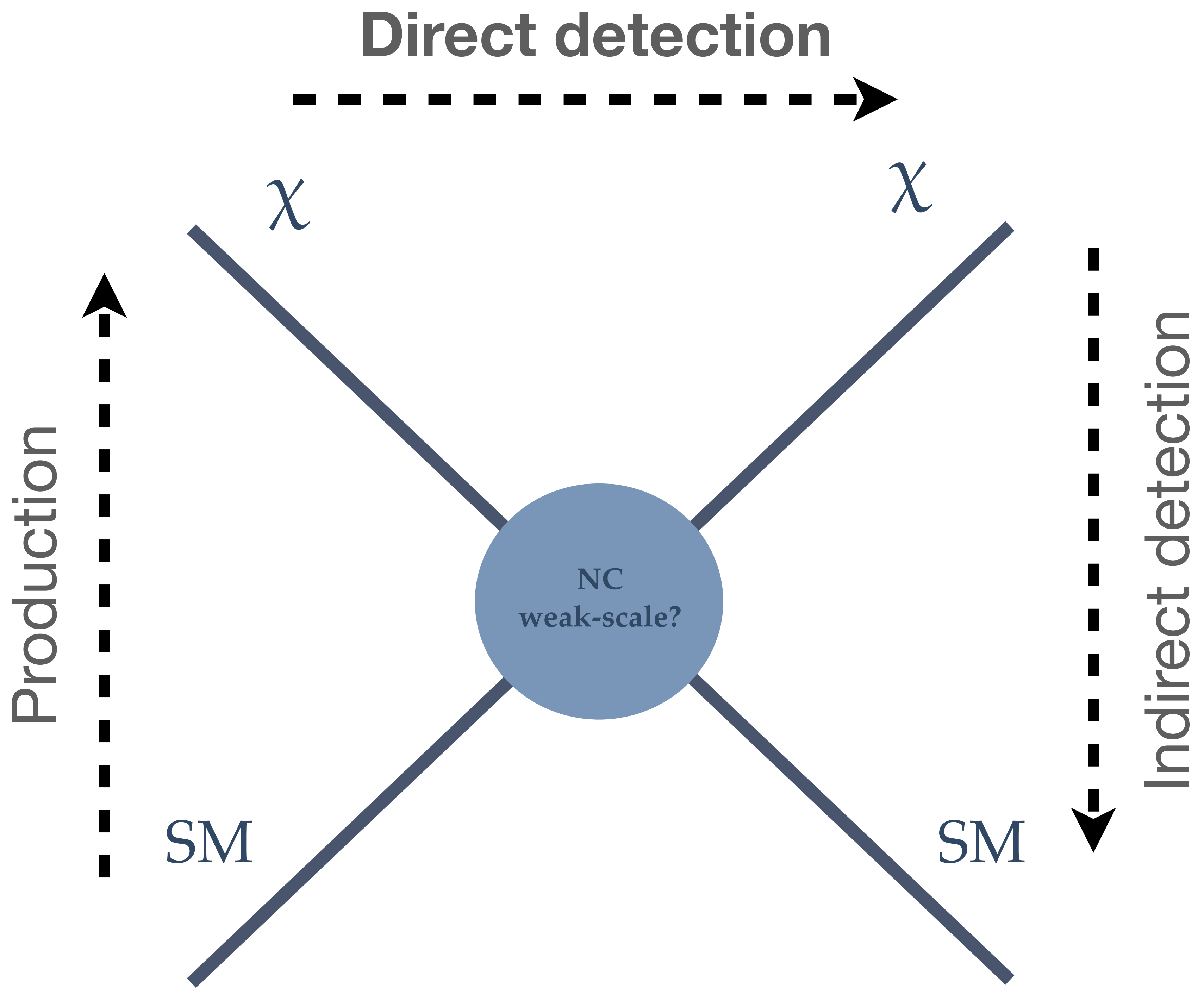

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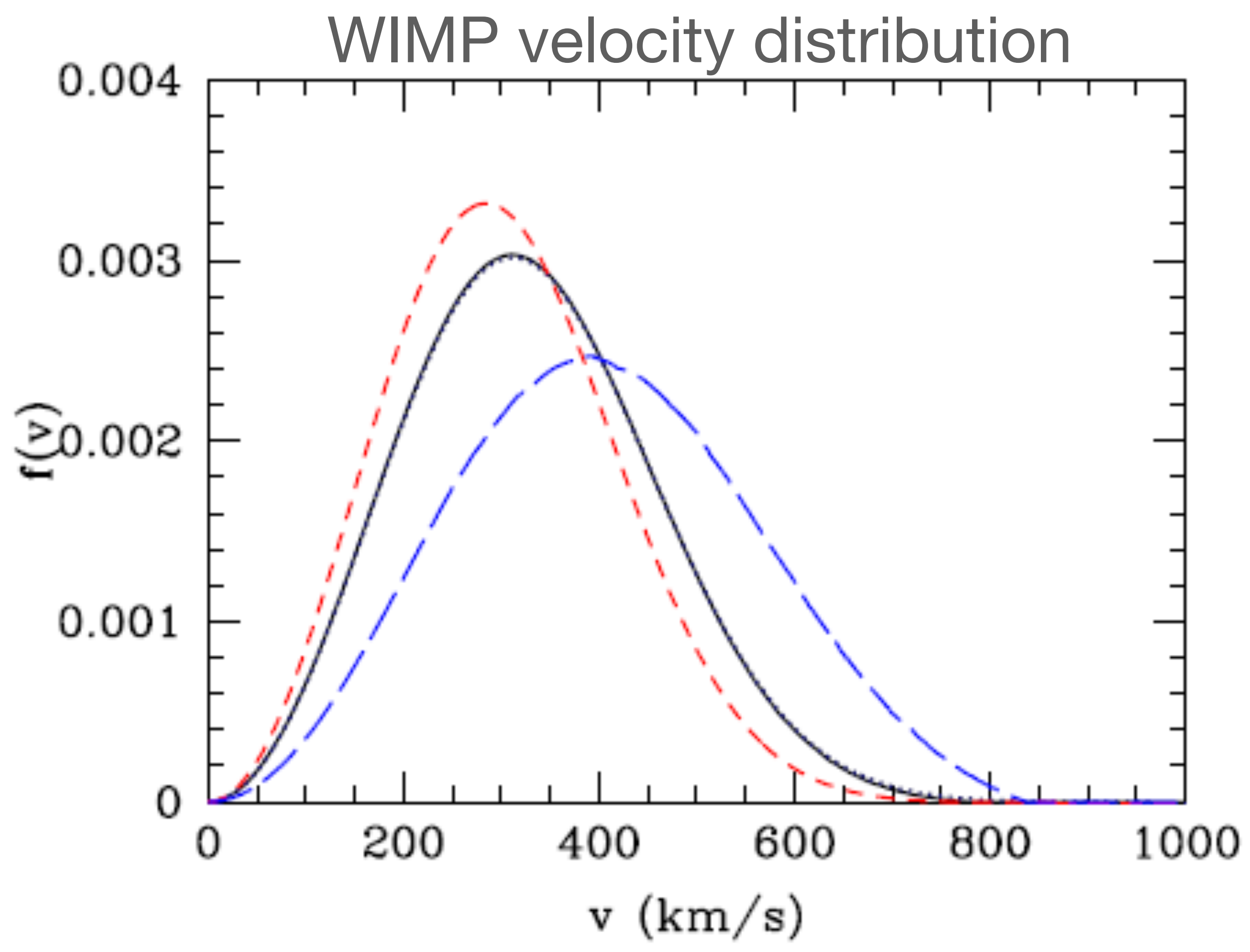
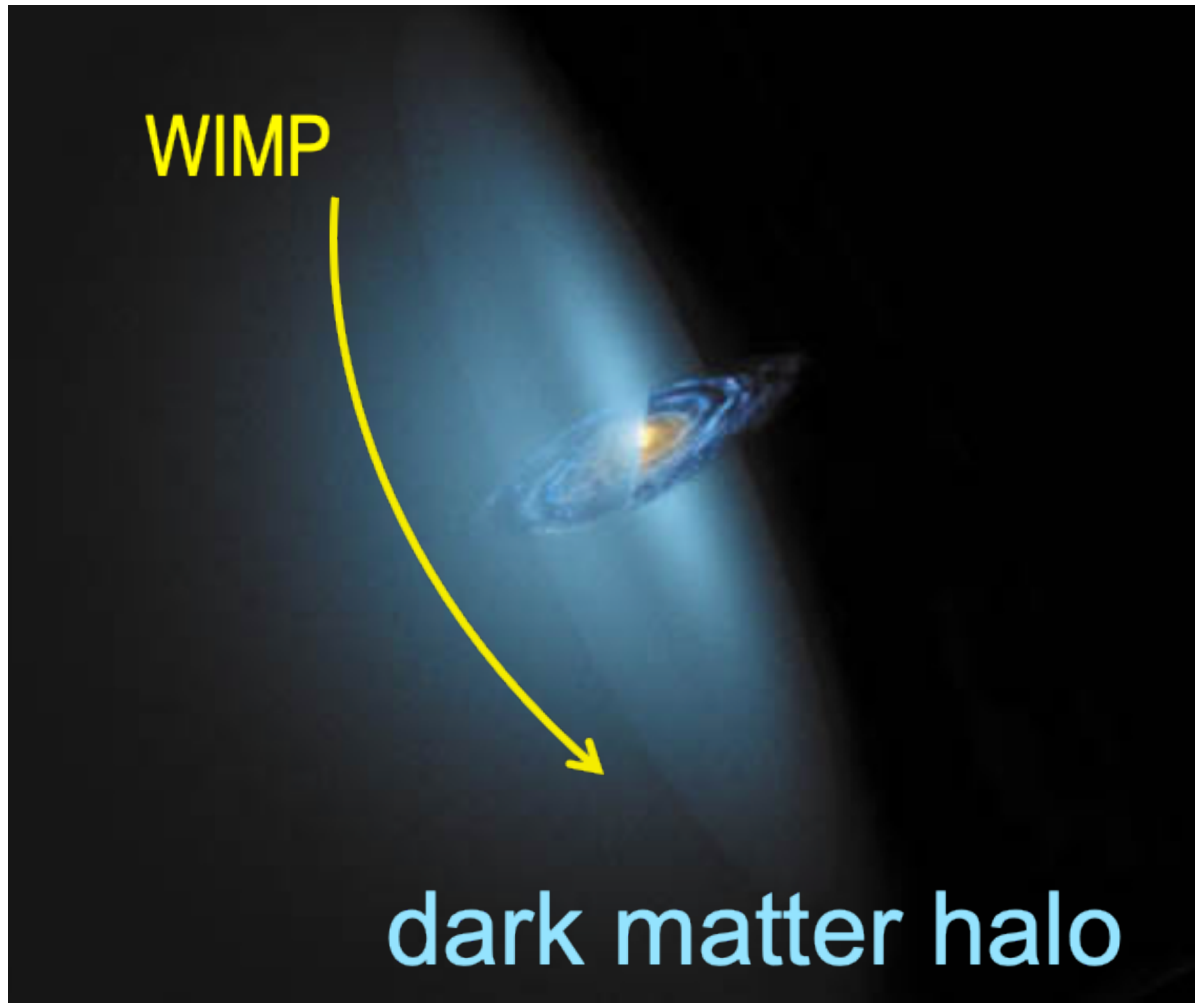
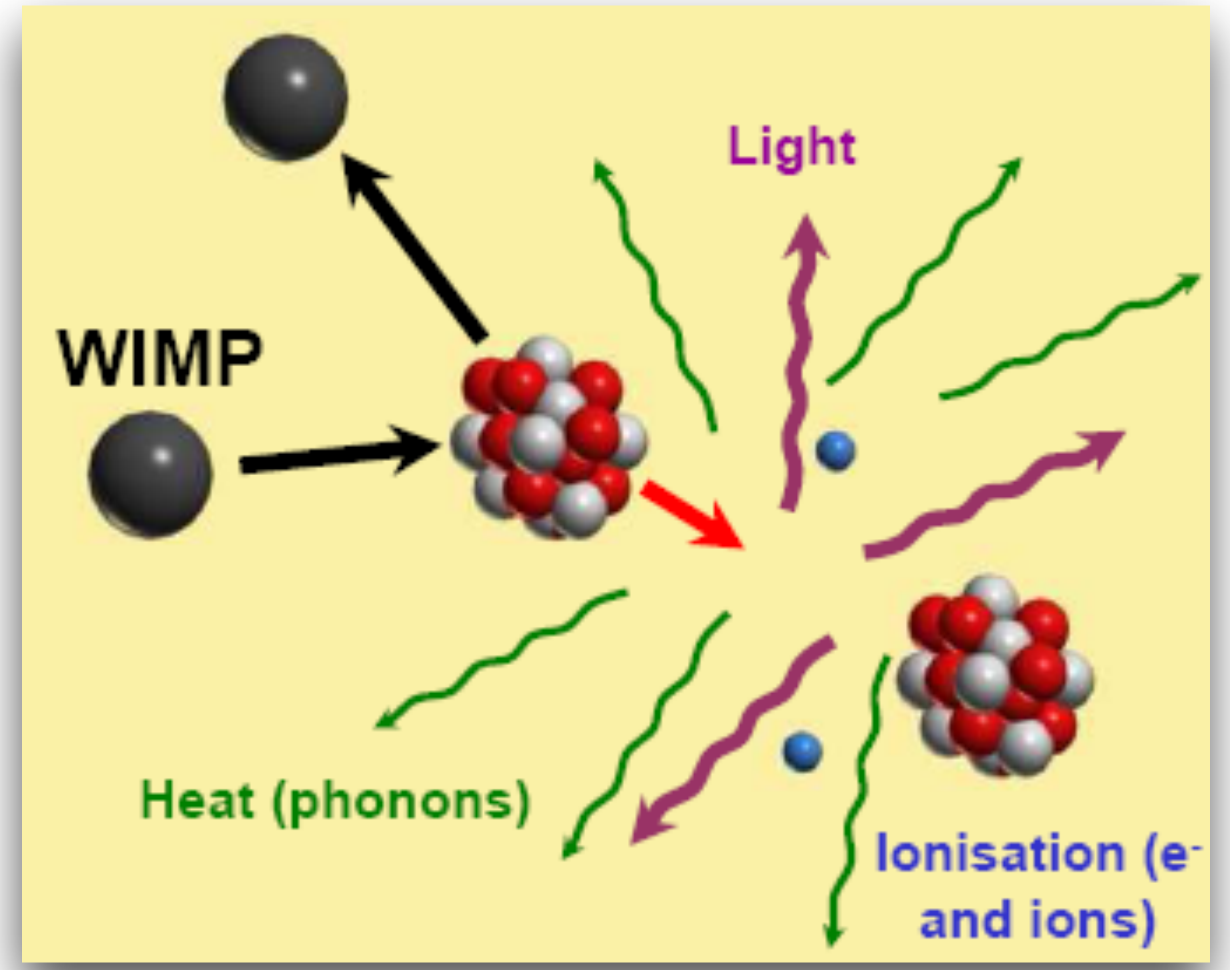
WIMP direct detection



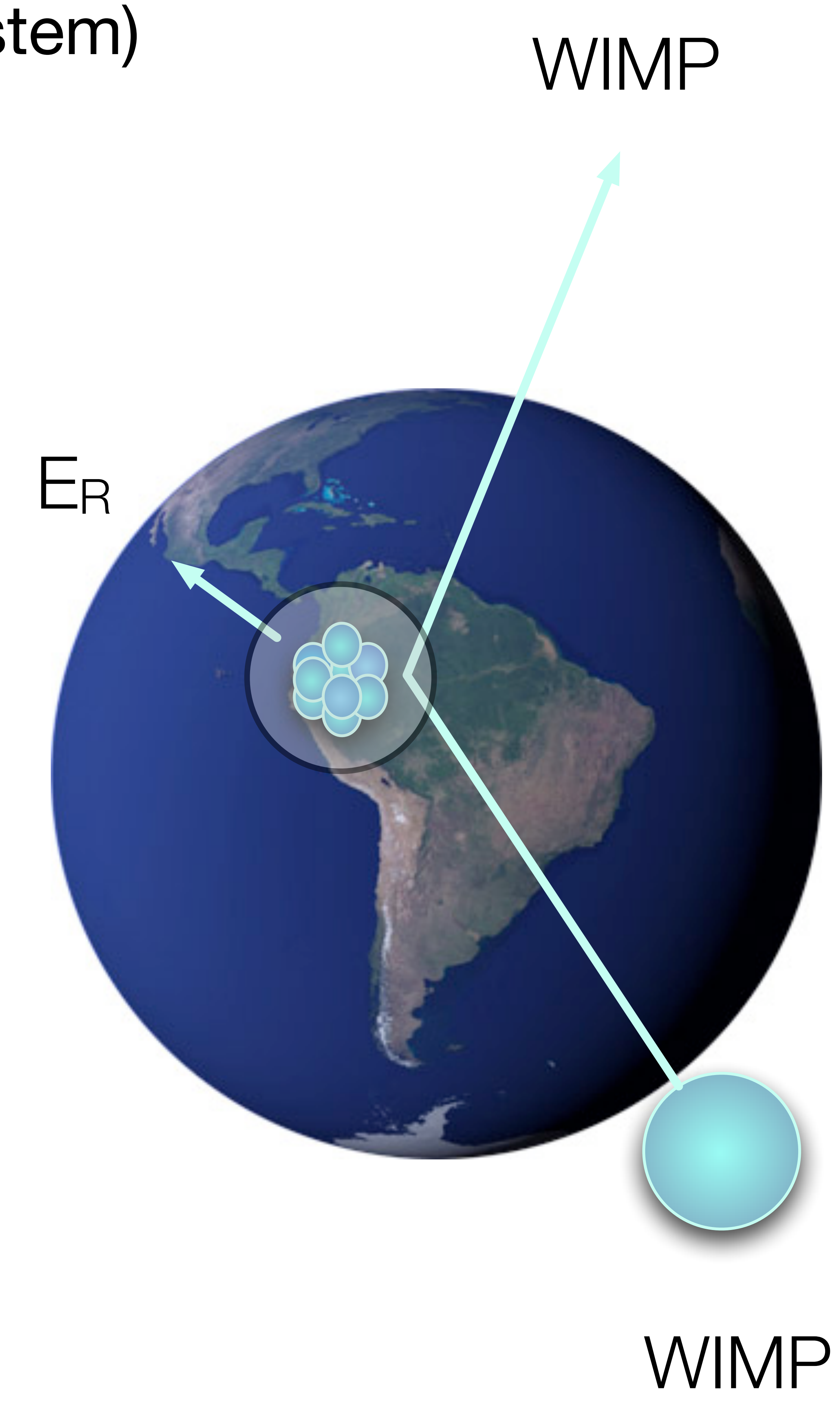


- Milky Way dark matter halo
  - Local density: ~0.3 GeV/cm^3 (Solar system)
  - WIMP wind velocity: ~220 km/s
  - Earth galactic velocity: 220 km/s
  - Flux on Earth: ~10^5 cm^{-2}s^{-1}



Interaction rate: <1 event / tonne of target material / month

$$R_0 = \frac{2}{\sqrt{\pi}} \frac{N_A}{A} \frac{\rho_{\rm DM}}{M_\chi} \sigma_0 v_0$$



Background sources

For direct detection of WIMPs

Electronic Recoils (ER):

Radiation from detector components:

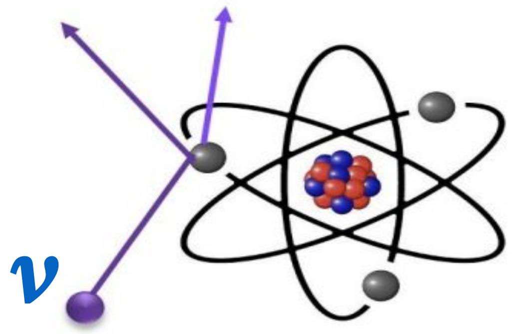
- γ from U, Th chain, K, Co
- Dissolved β: Rn-chain, Kr, Xe
- e- capture: Ar, Xe-isotopes
- Cosmogenically activated xenon

External ambient radiation:

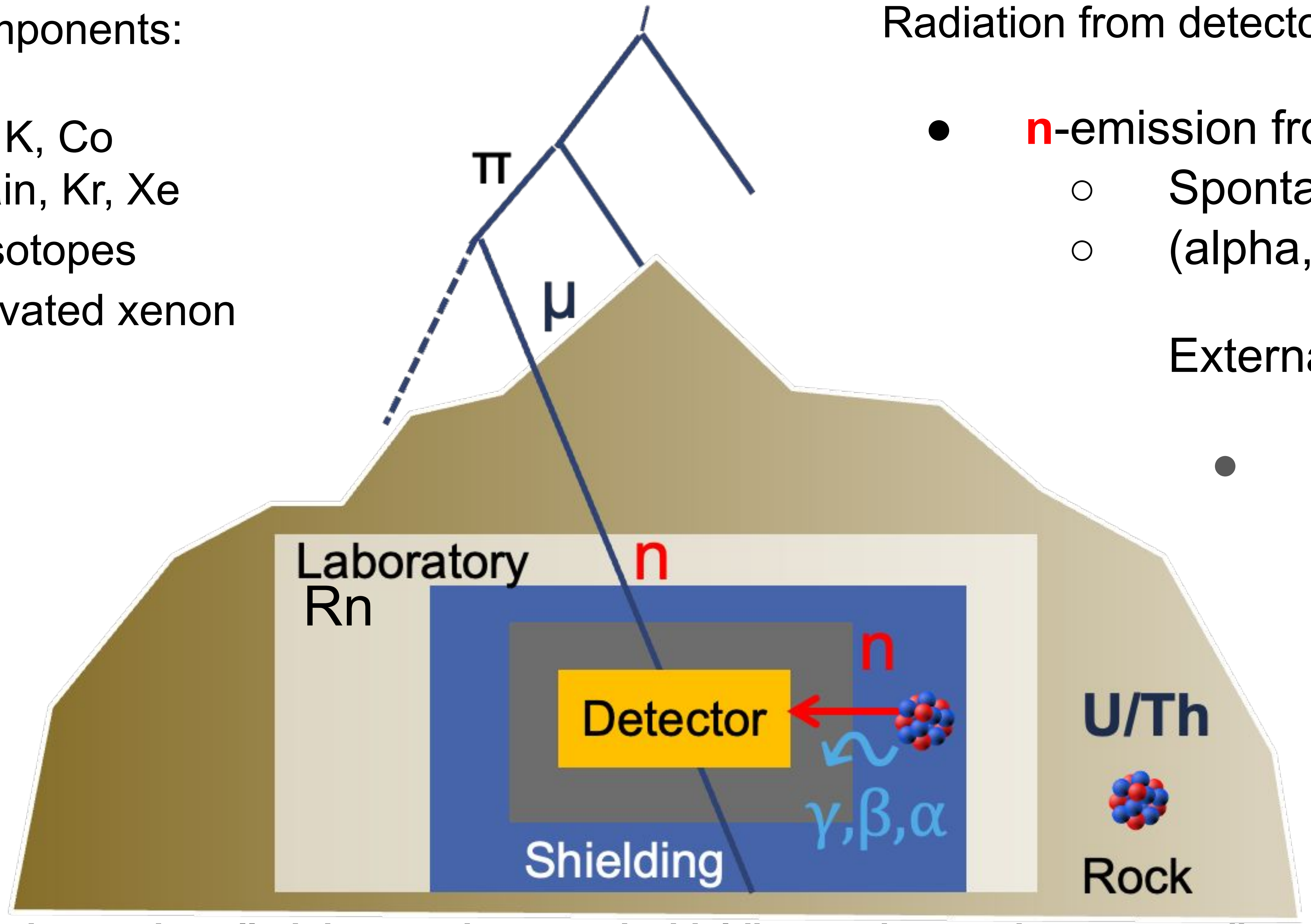
- U, Th, K, Co, Rn

Cosmogenic radiation:

- Solar ν: pp-ν
- μ



γ, β, μ, ν



Experiments installed deep underground, shielding against environment radioactivity

Nuclear recoils (NR):

Radiation from detector components:

- n-emission from U/Th:
  - Spontaneous fission
  - (alpha,n) reaction

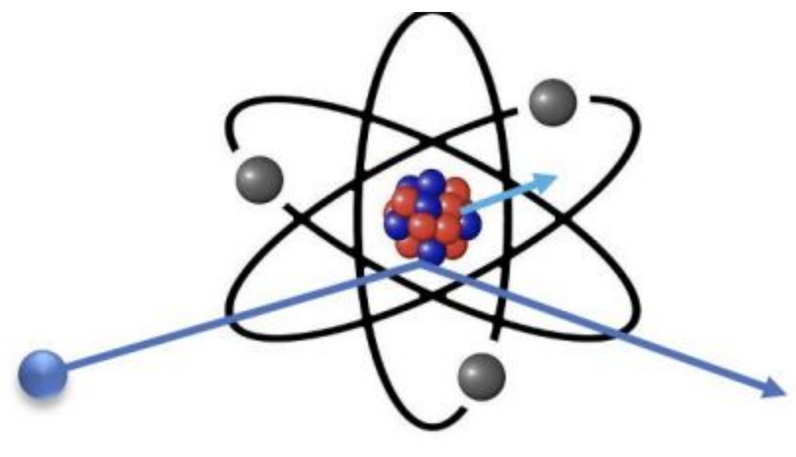
External ambient radiation:

- U/Th

Cosmogenic radiation:

- Solar ν: ^{8}B-ν
- μ-induced n

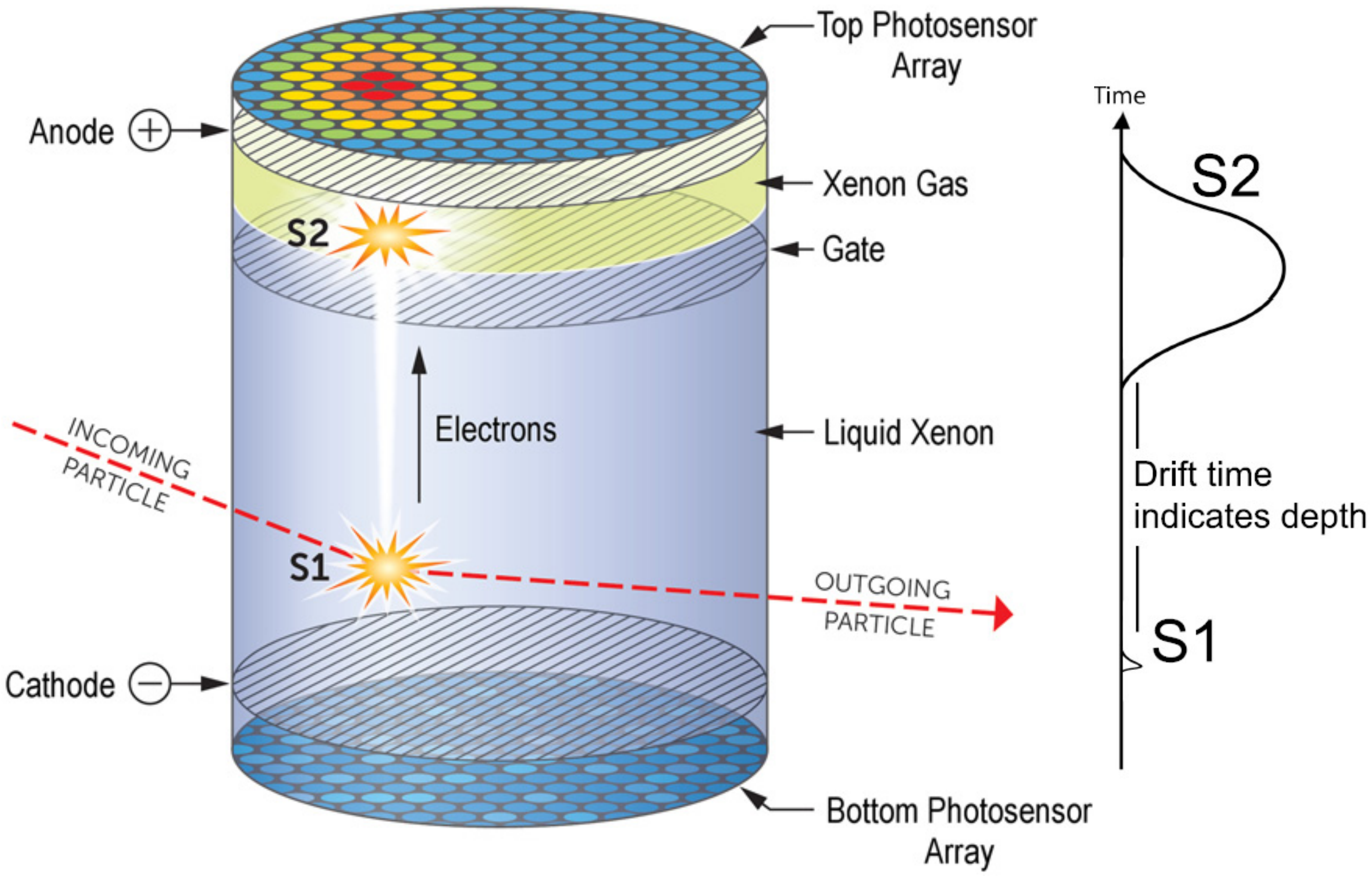
n, ν, χ



Slide by Geertje Heuermann

2-phase Xenon TPCs

Working principle



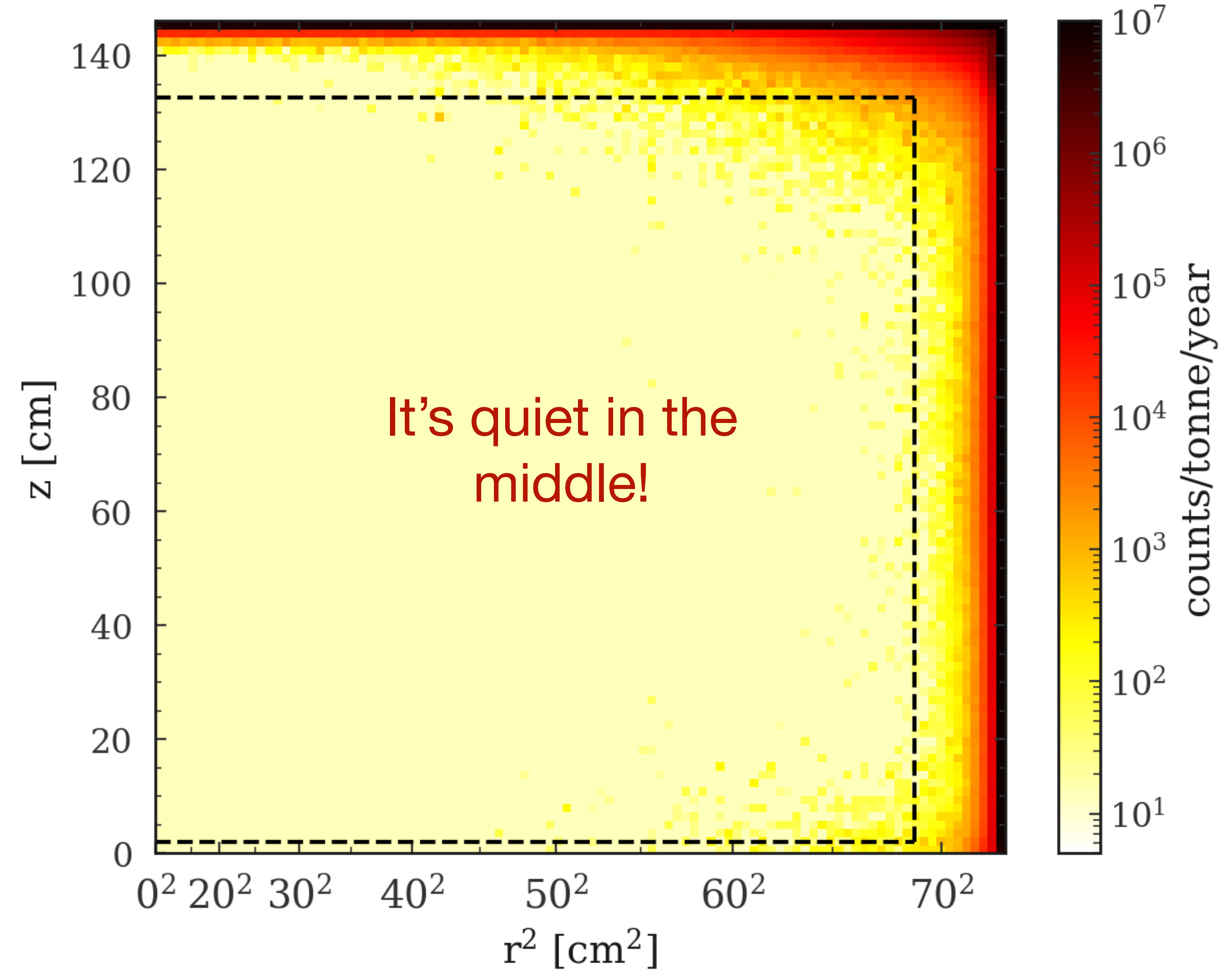
- Each particle interaction produces two signals
  - S1 - prompt scintillation light in the liquid
  - S2 - electroluminescence in the gas (much larger than S1)
- Signals are observed by one or two light sensor arrays
- From these 2 signals we get:
  - Energy of the interaction
  - 3D position reconstruction
  - Nuclear/electron recoil discrimination

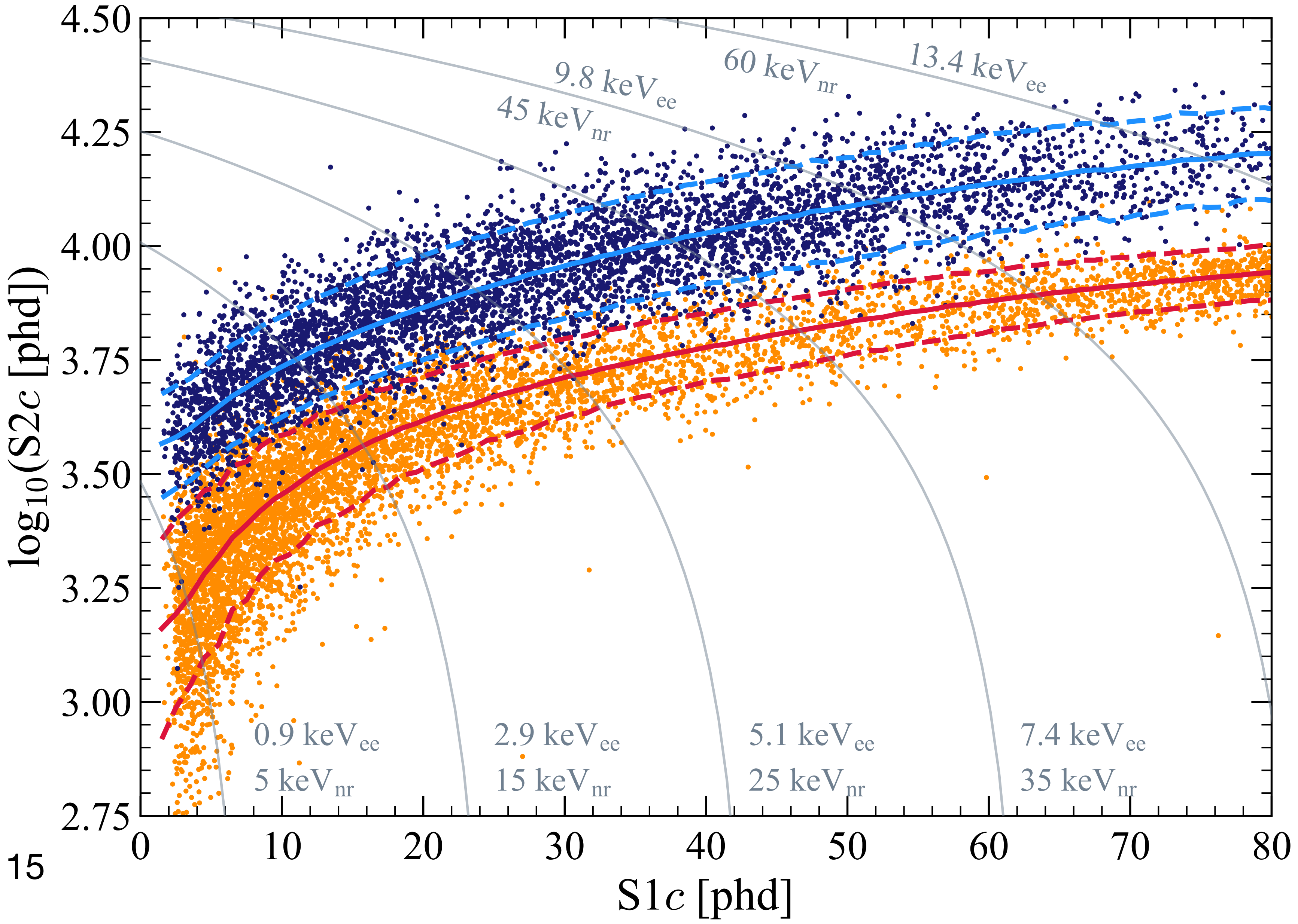
2-phase Xenon TPCs

Why use Xenon?

- High density (2.9 g/cm³)
  - **Self-shielding**
- High ionisation and scintillation yields
- Transparent to its scintillation light (175 nm)
- **Discrimination** between electron and nuclear recoils
- High atomic mass enhances WIMP-nucleus cross-section (~A^2)
- No short-lived isotopes
  - But some interesting very long-lived ones!
  - ^{124}Xe (2ν- 2EC, ECβ^+, 2β^+), $T_{1/2} > 10^{22}$ yr
  - ^{134}Xe and ^{136}Xe (2$\nu\beta\beta$), $T_{1/2} > 10^{21}$ yr

Low energy (E<100 keV) interactions of external γ-rays in a xenon TPC



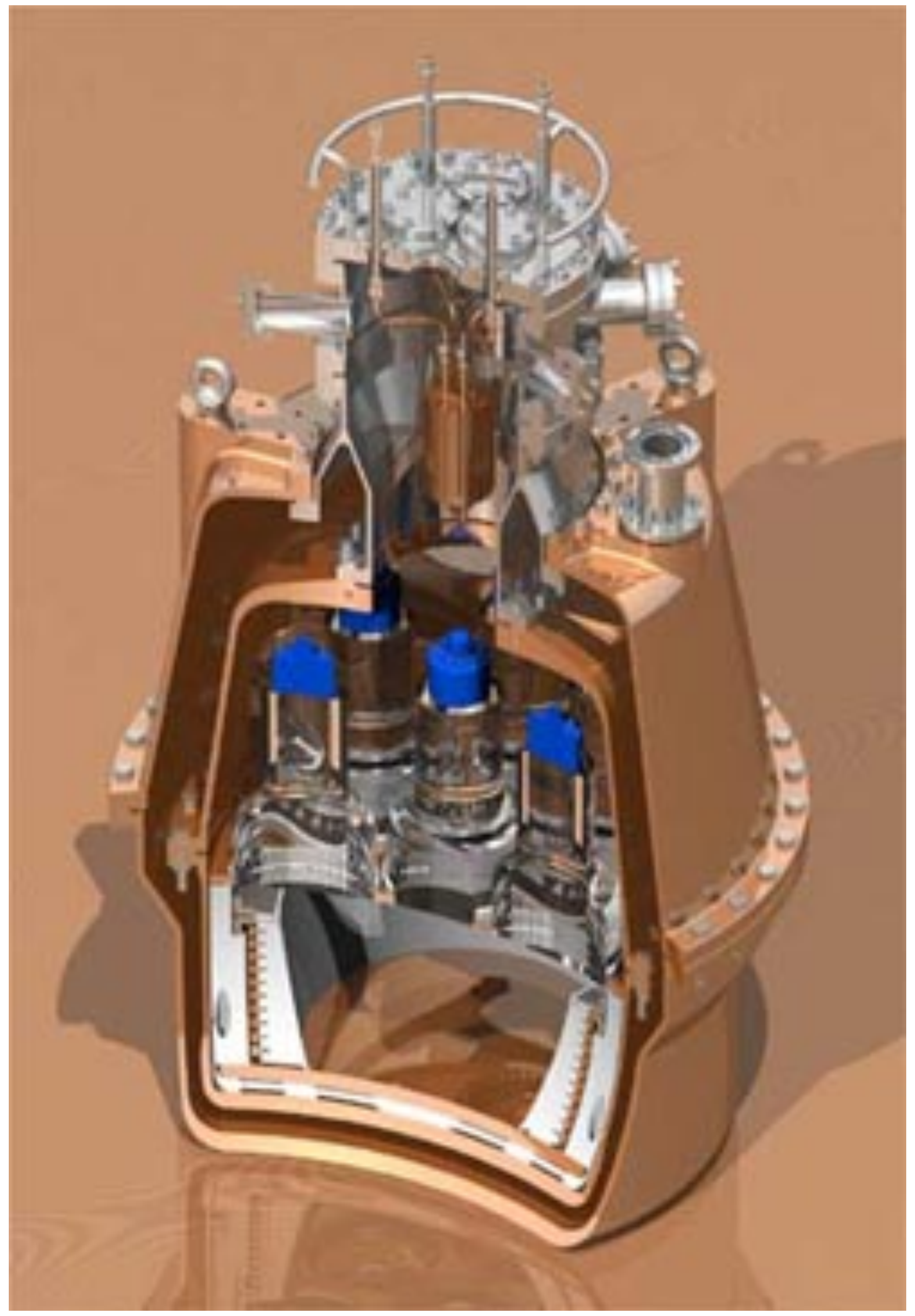


Response of a xenon TPC to:
- Electron recoils (CH_3T β decay source)
- Nuclear recoils (mono energetic neutrons)

2-phase Xenon TPCs

Scalability — same technology

16 years ago…

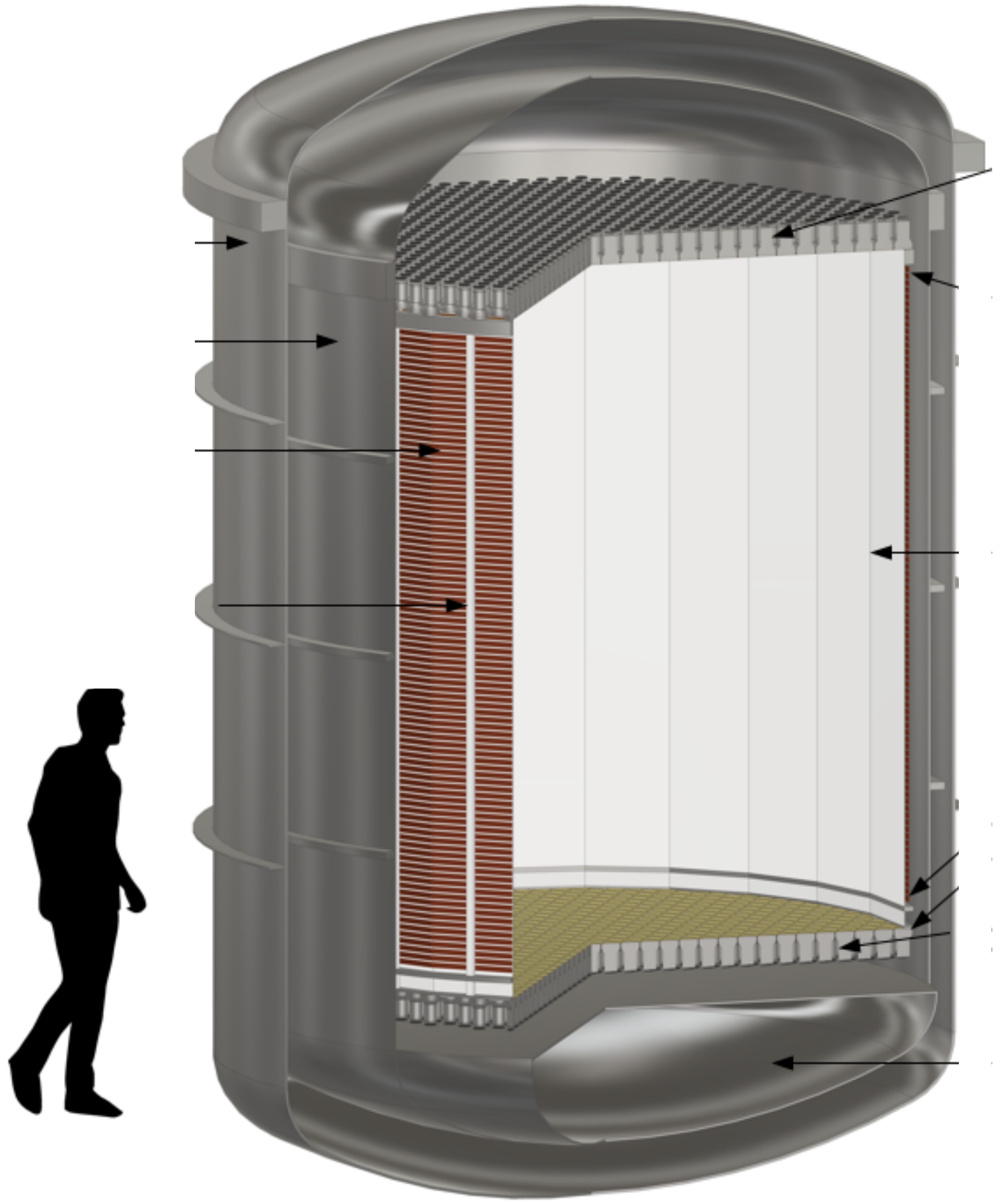


ZEPLIN-II
32 kg

Now

LUX-ZEPLIN (LZ)
10 tonnes

Future (2030 -)

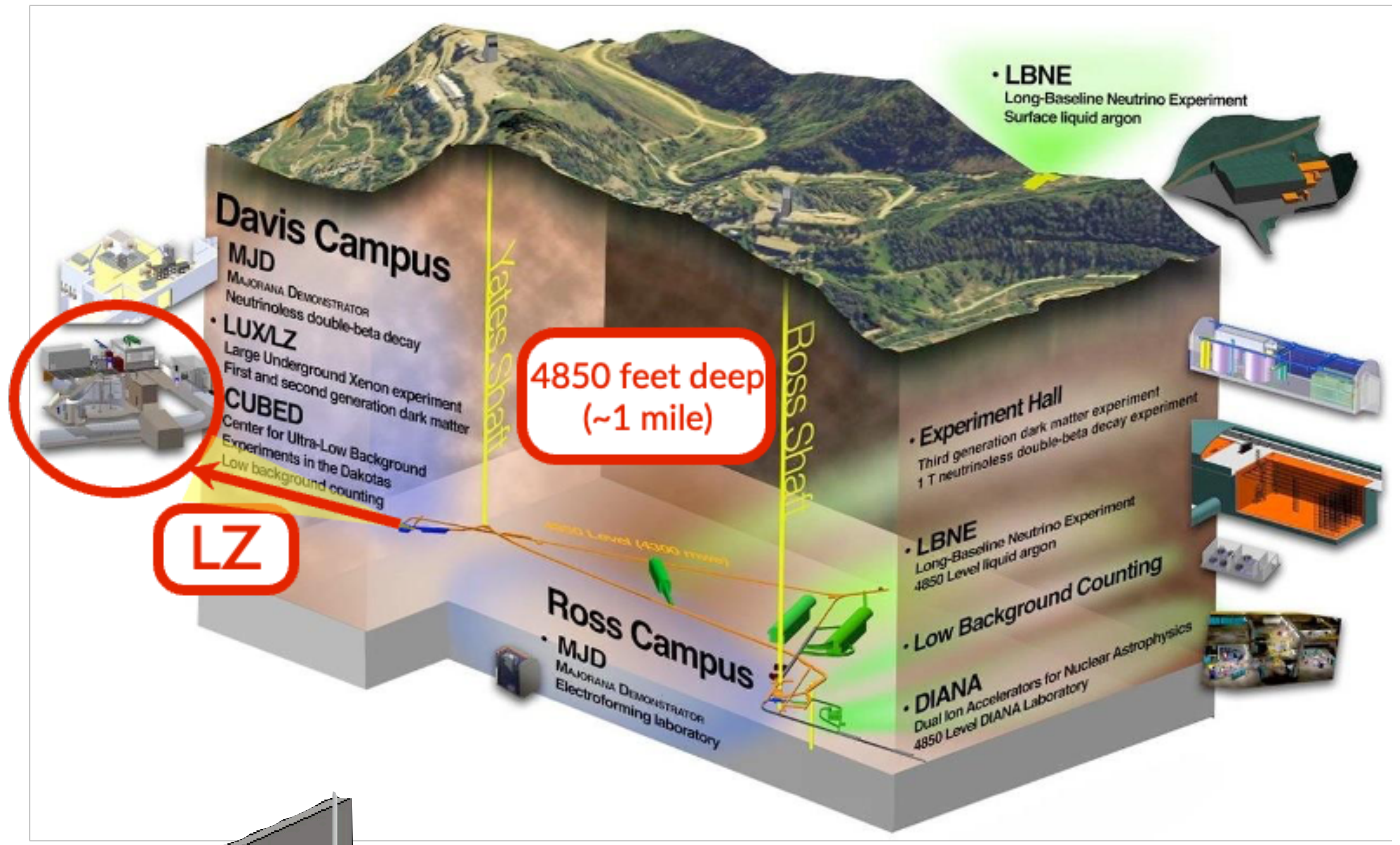


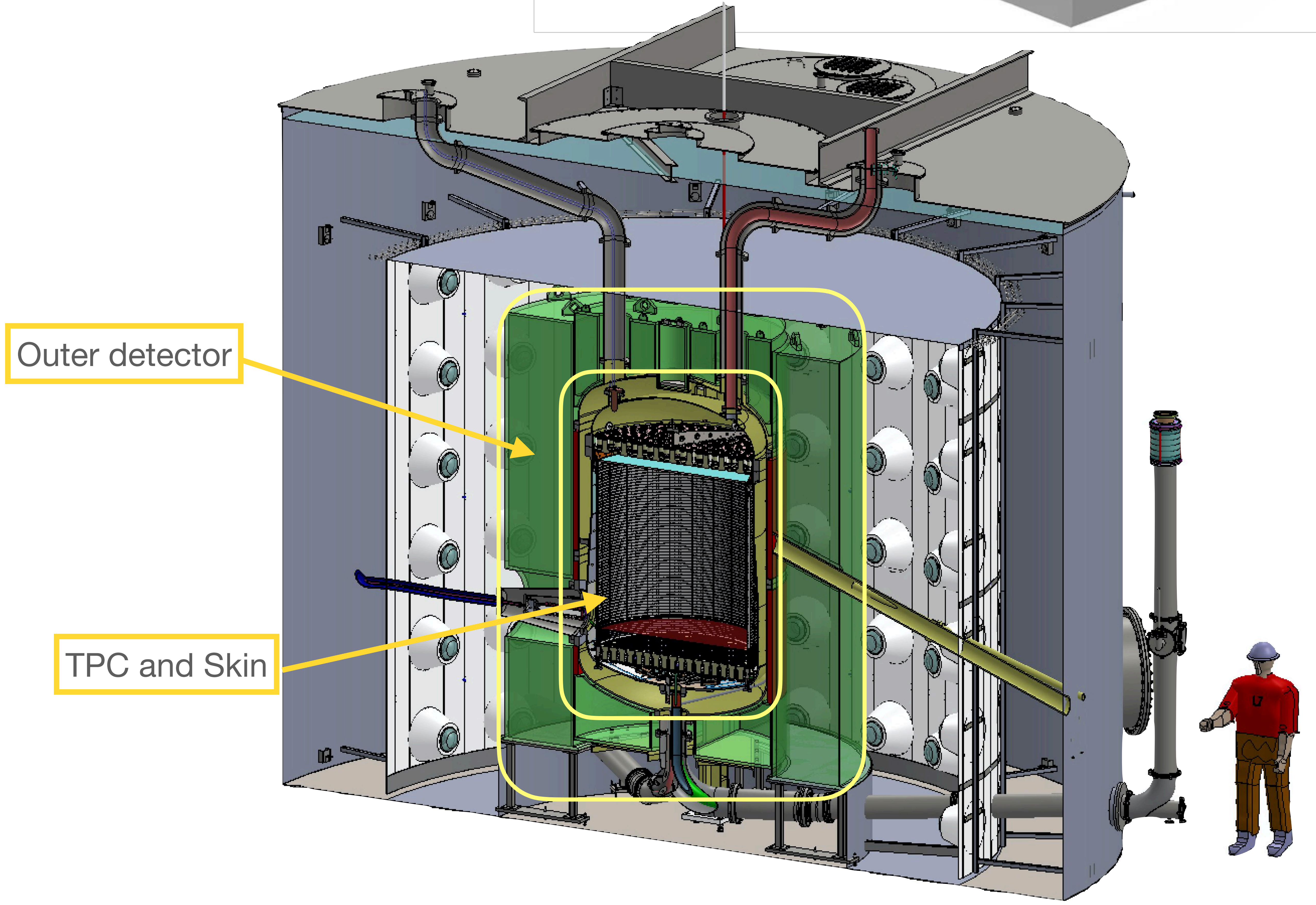
G3 detector
40-100 tons

2-phase Xenon TPCs

Current generation detectors

- **LUX-ZEPLIN**
  - 10 t of liquid xenon
    - 7 t active
  - 494 3” Hamamatsu PMTs
  - Double veto system
    - Xenon “skin”
    - Gd-loaded outer detector
  - Installed at SURF (USA)
  - Started running Dec. 2021
  - First WIMP results in Jul. 2022 (0.9 t.yr)





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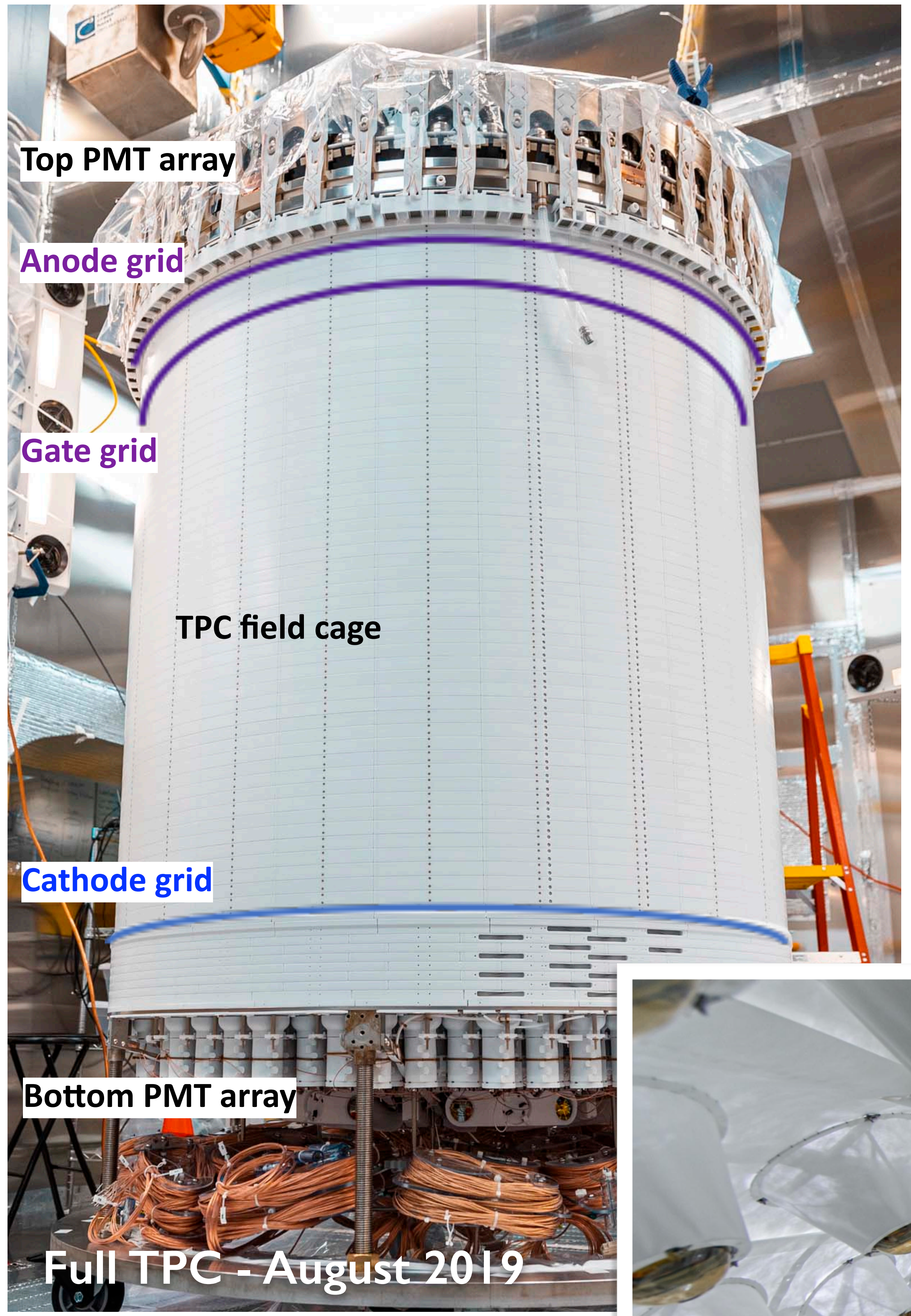

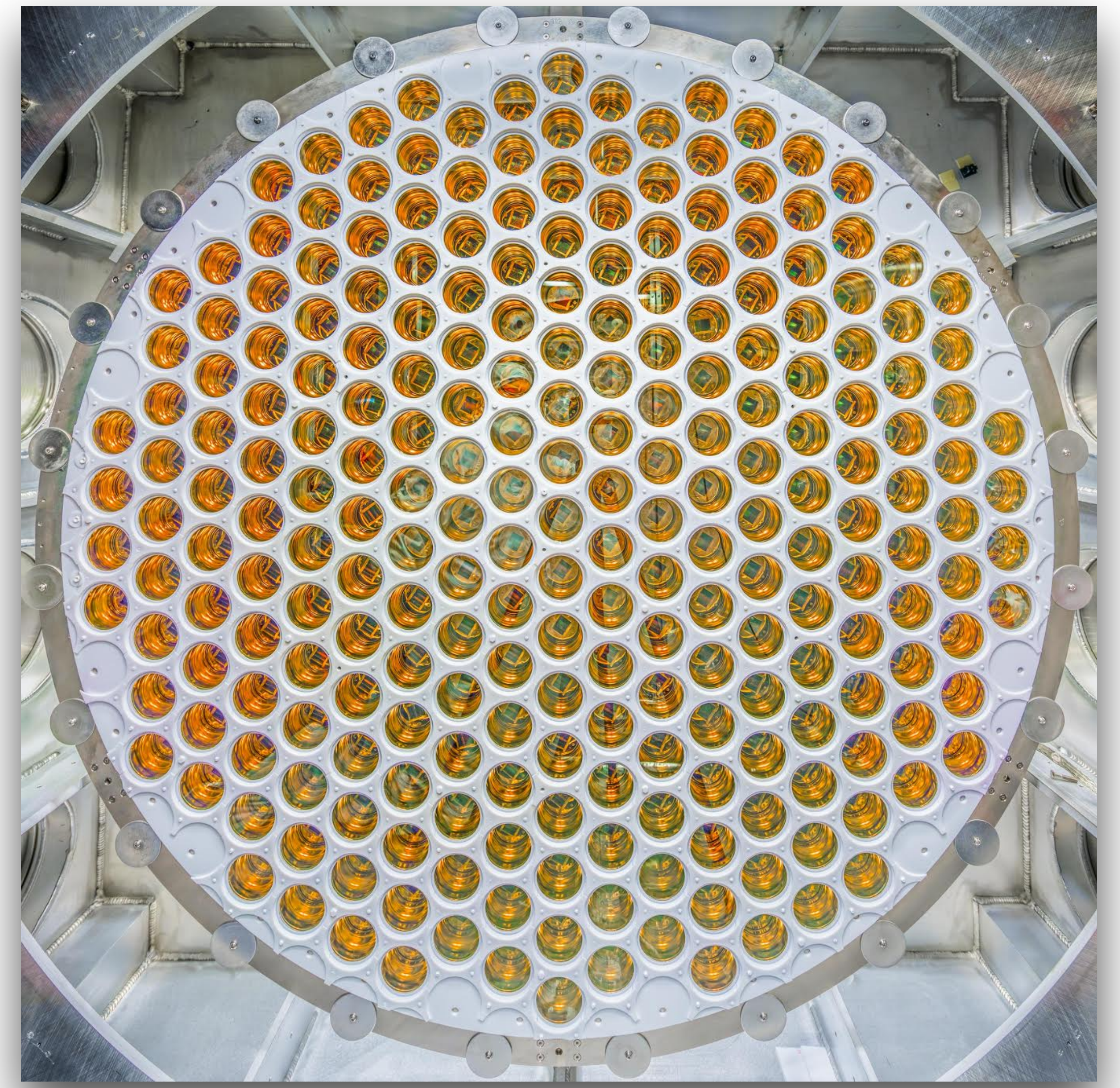

2-phase Xenon TPCs

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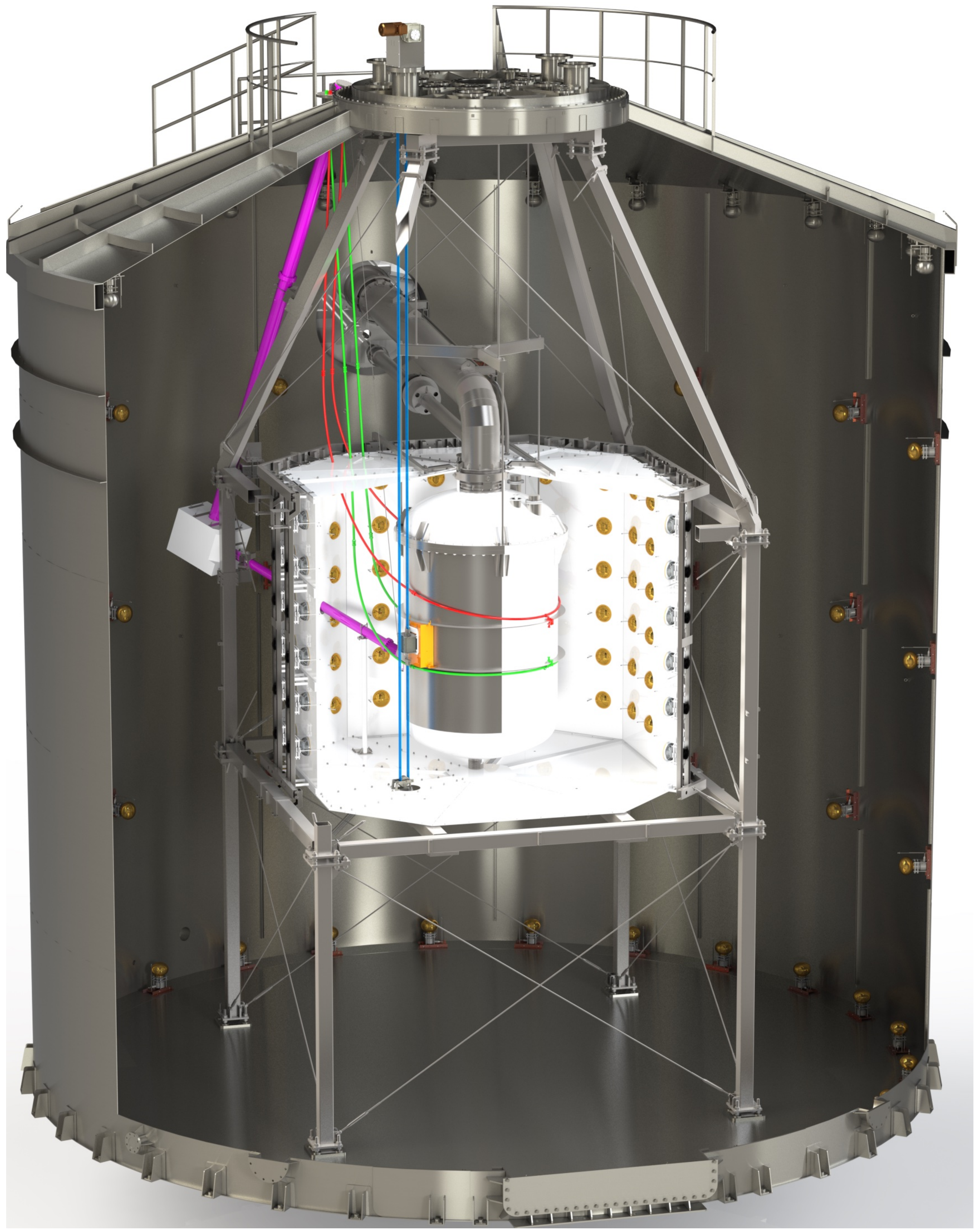
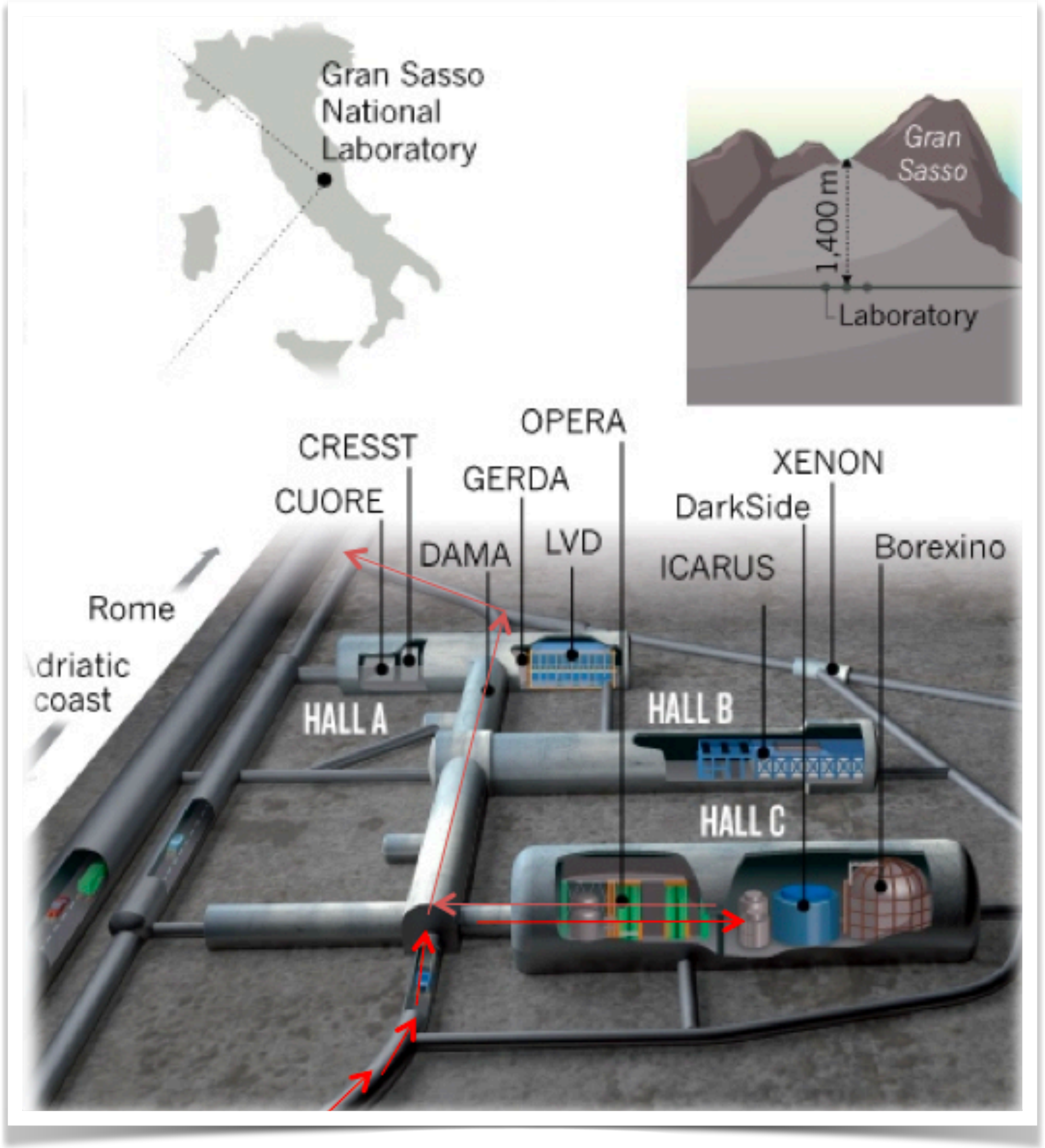


- **XENONnT**
  - 8.5 t of liquid xenon
    - 5.9 t active
  - 494 3” Hamamatsu PMTs (same model)
  - Water Cherenkov neutron veto
    - No Gd-loading yet (planned)
  - Installed in Gran Sasso (Italy)
  - Started running Jul. 2021
  - First WIMP results in Mar. 2023 (1.1 t.yr)



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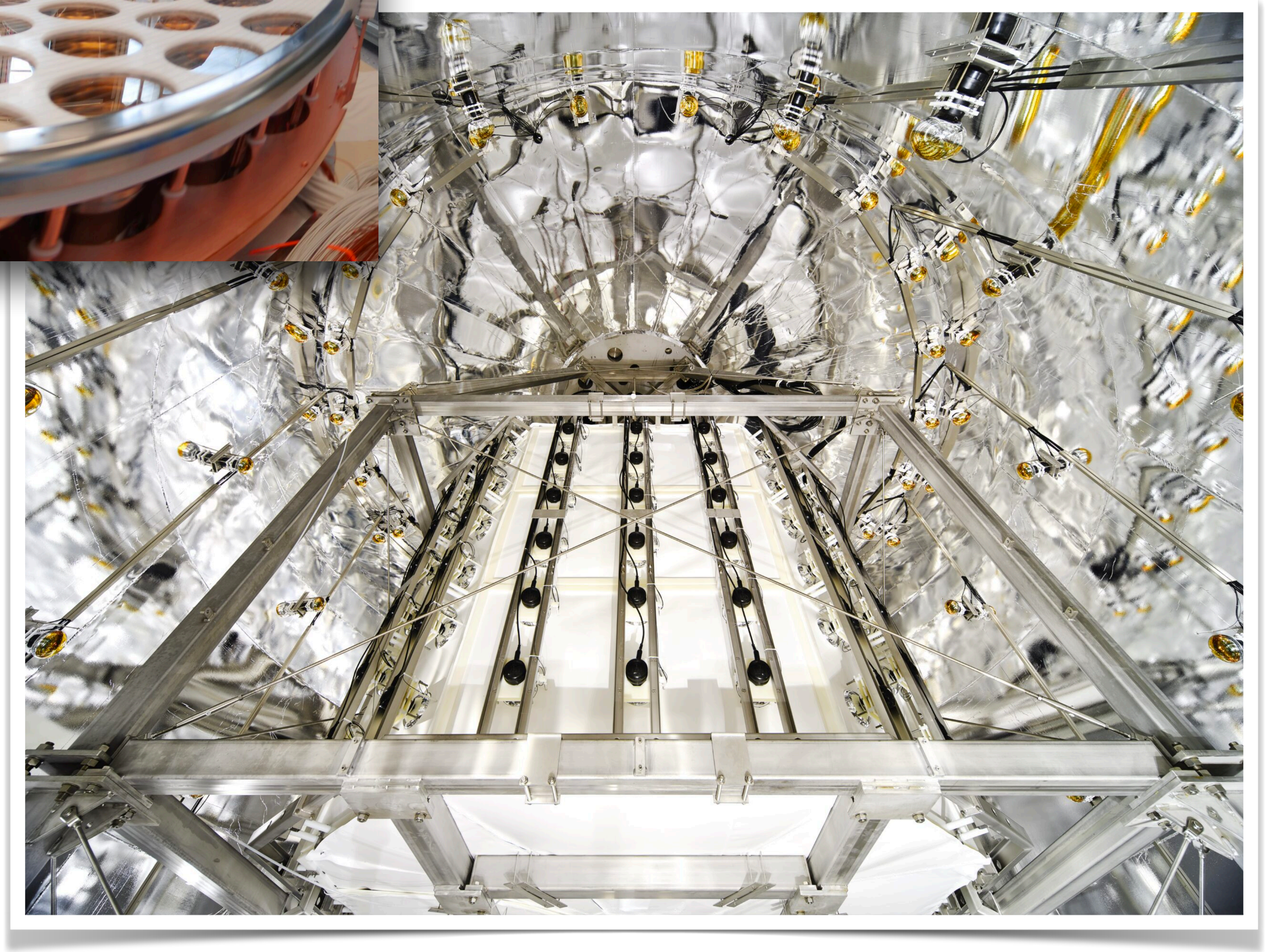

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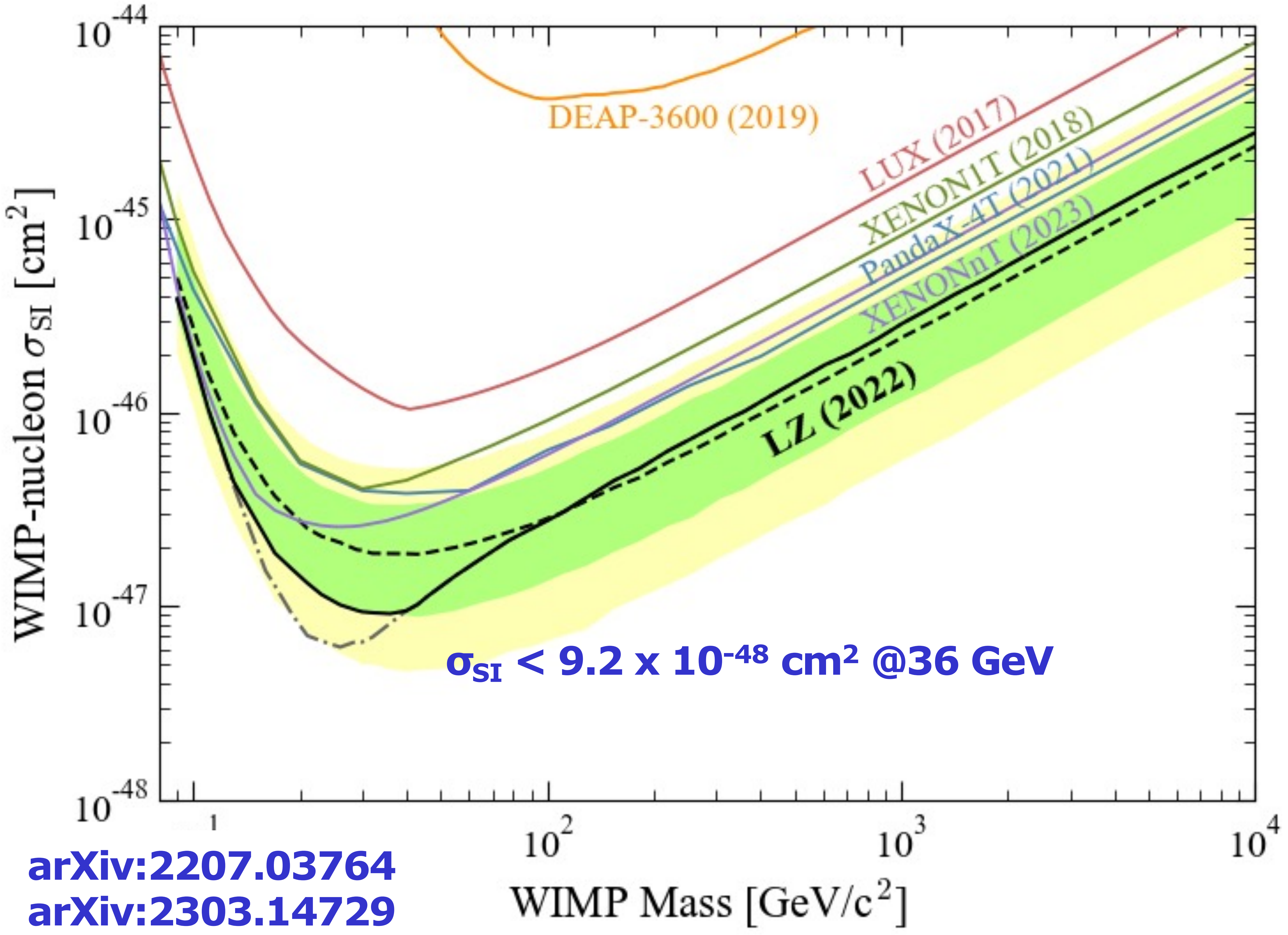
2-phase Xenon TPCs

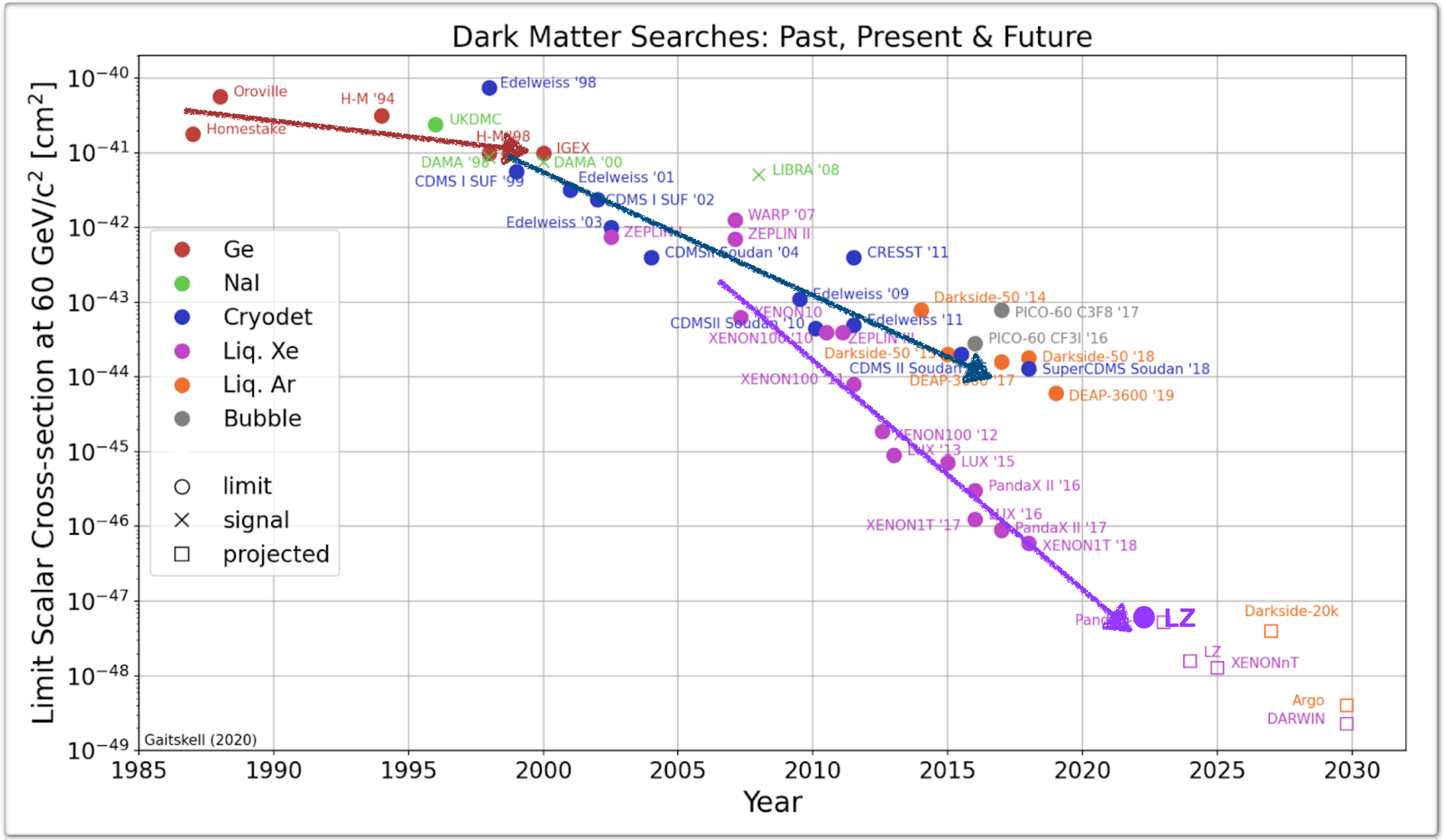
Current WIMP search limits

- LUX → LZ: more than one order of magnitude improvement just in the last 5 years
- Technology dominates WIMP search for masses >10 GeV



arXiv:2207.03764
arXiv:2303.14729

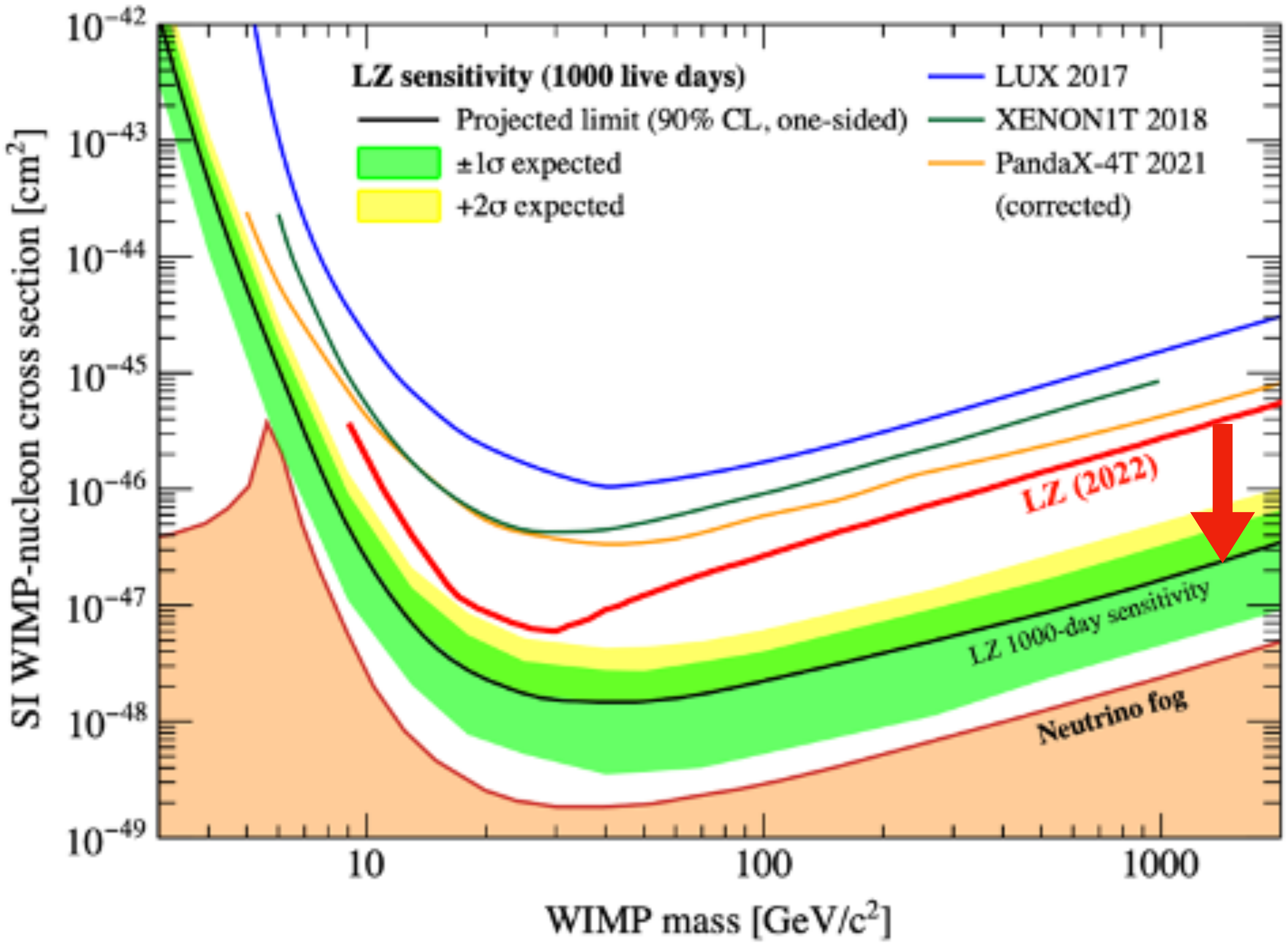
2-phase Xenon TPCs



2-phase Xenon TPCs

Projected WIMP search limits

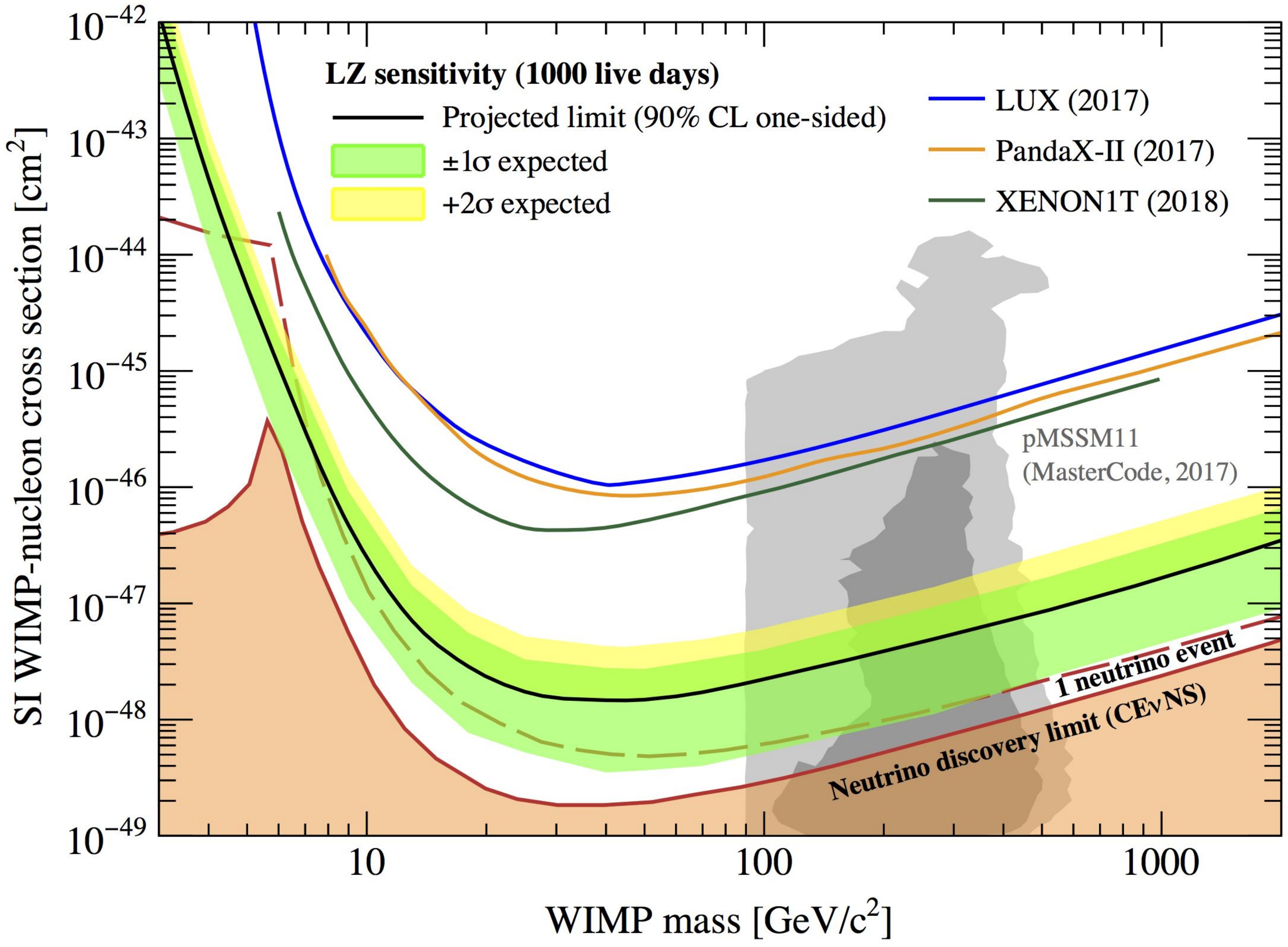
- LUX → LZ: more than one order of magnitude improvement just in the last 5 years
- Technology dominates WIMP search for masses >10 GeV
- Both detectors will continue to run until 2026-27
- Similar projected sensitivities



2-phase Xenon TPCs

Projected WIMP search limits

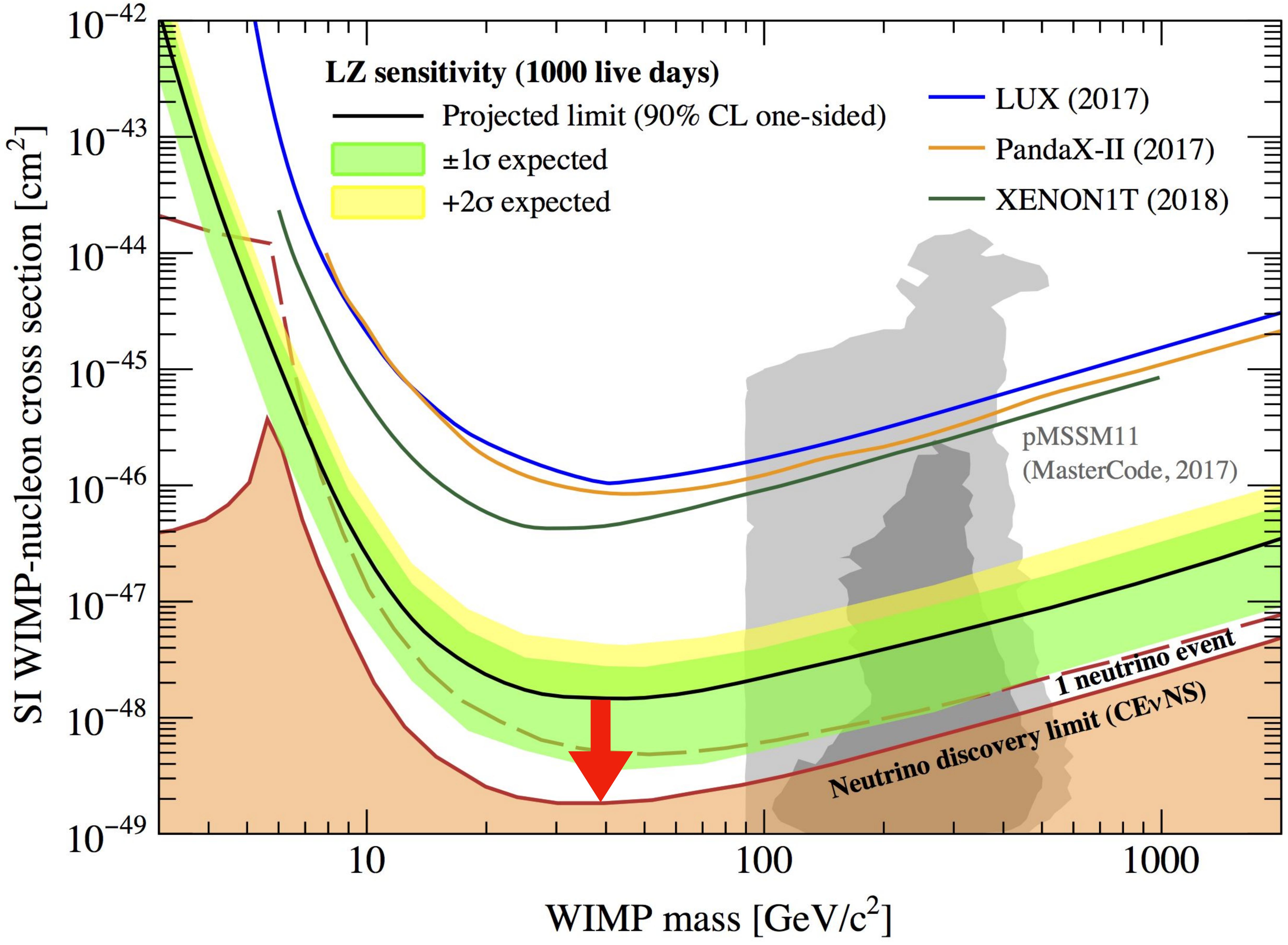
- LUX → LZ: more than one order of magnitude improvement just in the last 5 years
- Technology dominates WIMP search for masses >10 GeV
- Both detectors will continue to run until 2026-27
- Similar projected sensitivities
- Large parameter space to sweep, potential for discovery!



2-phase Xenon TPCs

The future

- Neutrino "fog" will severely hinder WIMP search
- Coherent neutrino-nucleus scattering produces indistinguishable background
- Experiments no longer "background free"
- There is still plenty of parameter space to cover before we get there
- **Need a larger detector!**



The XLZD Consortium

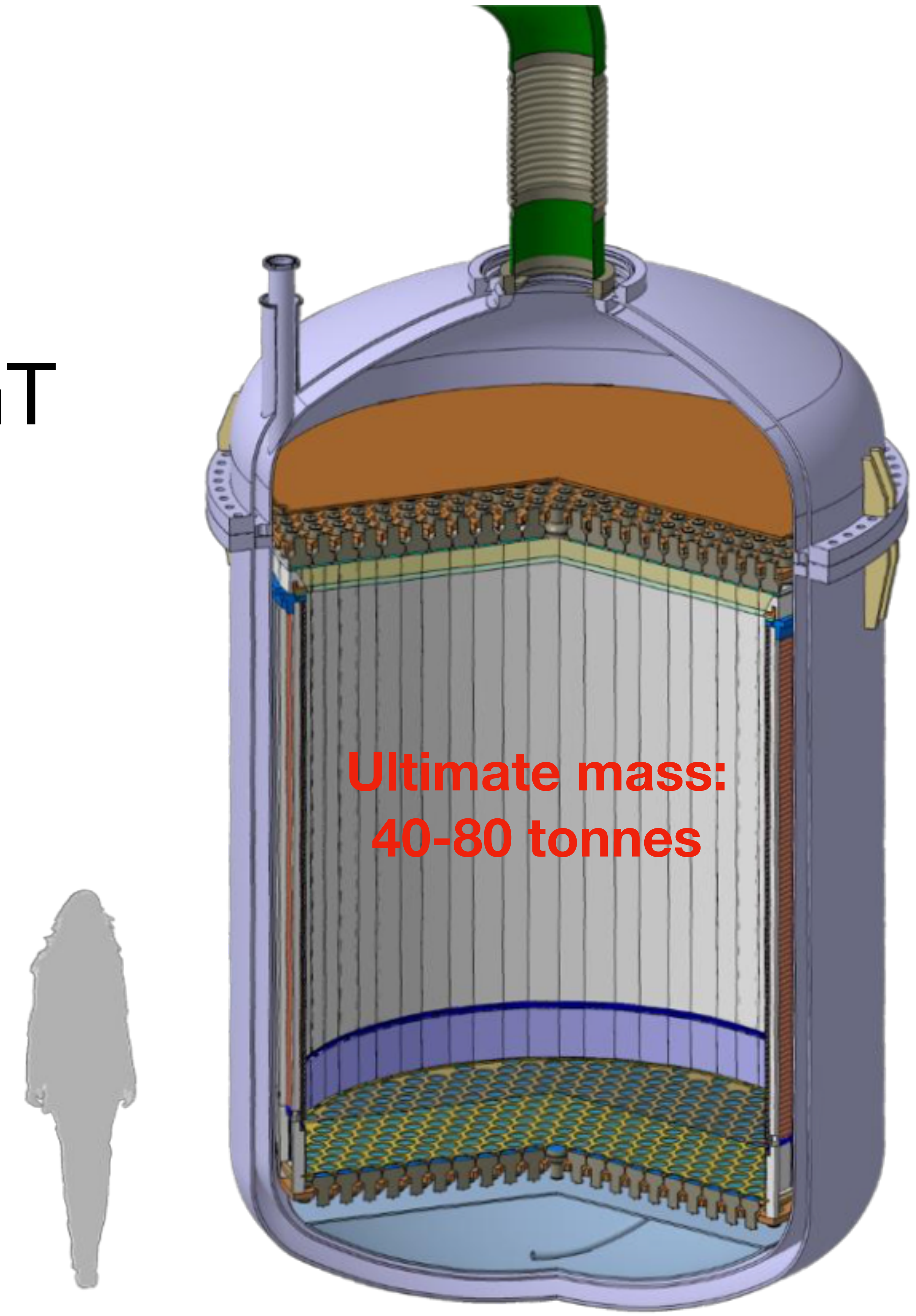
- The LXe community coming together with a common goal: build a large xenon observatory
- Consortium formed by the leading experiments in the field: LZ, XENONnT and DARWIN
- More than 350 members from more than 60 institutions

First XLZD meeting in Karlsruhe, Germany (June 2022)

- Activities:
  - Design concept development
  - Installation site discussions
  - Mixed science groups
  - Software infrastructure
  - R&D

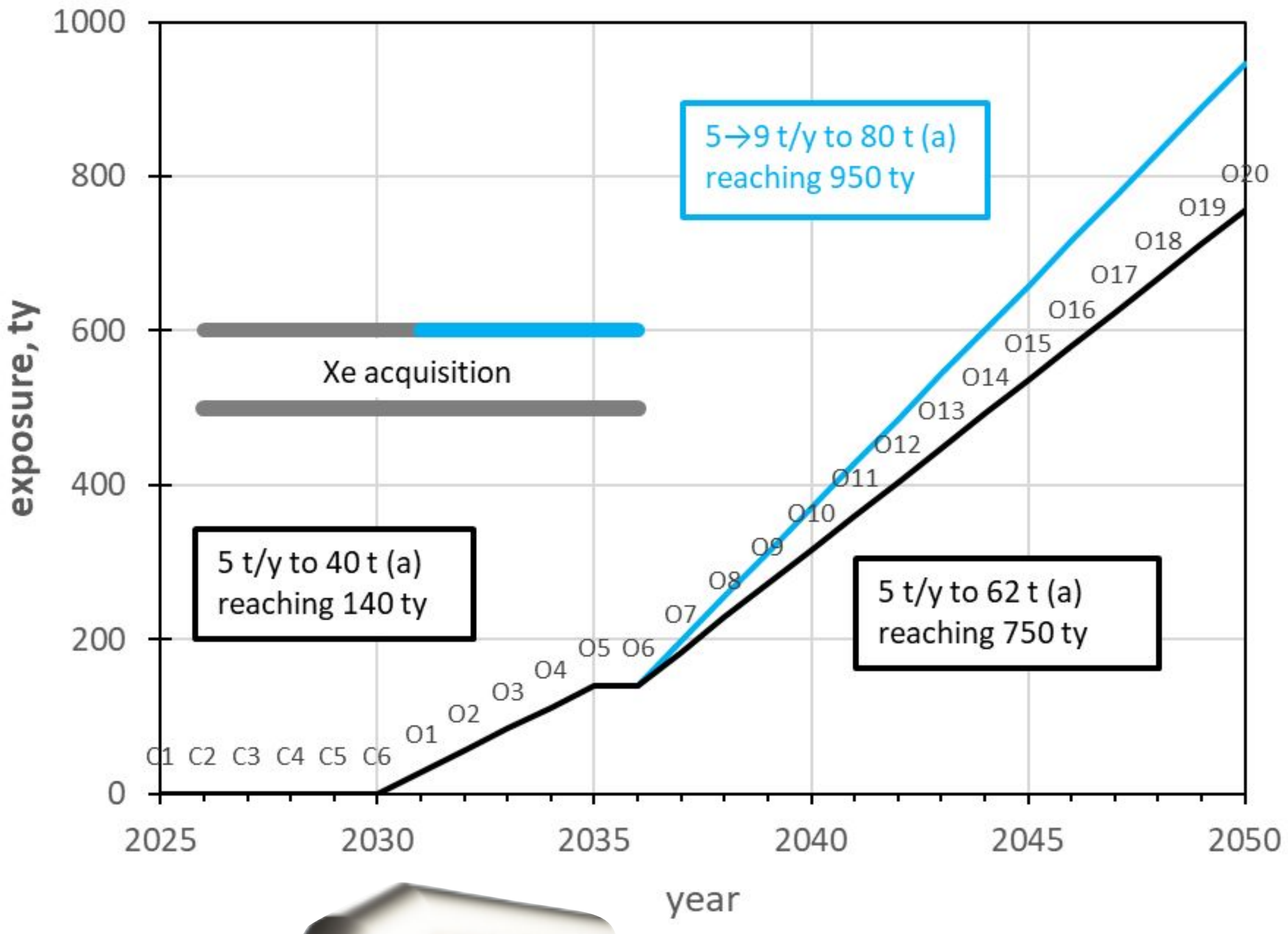
XLZD detector concept

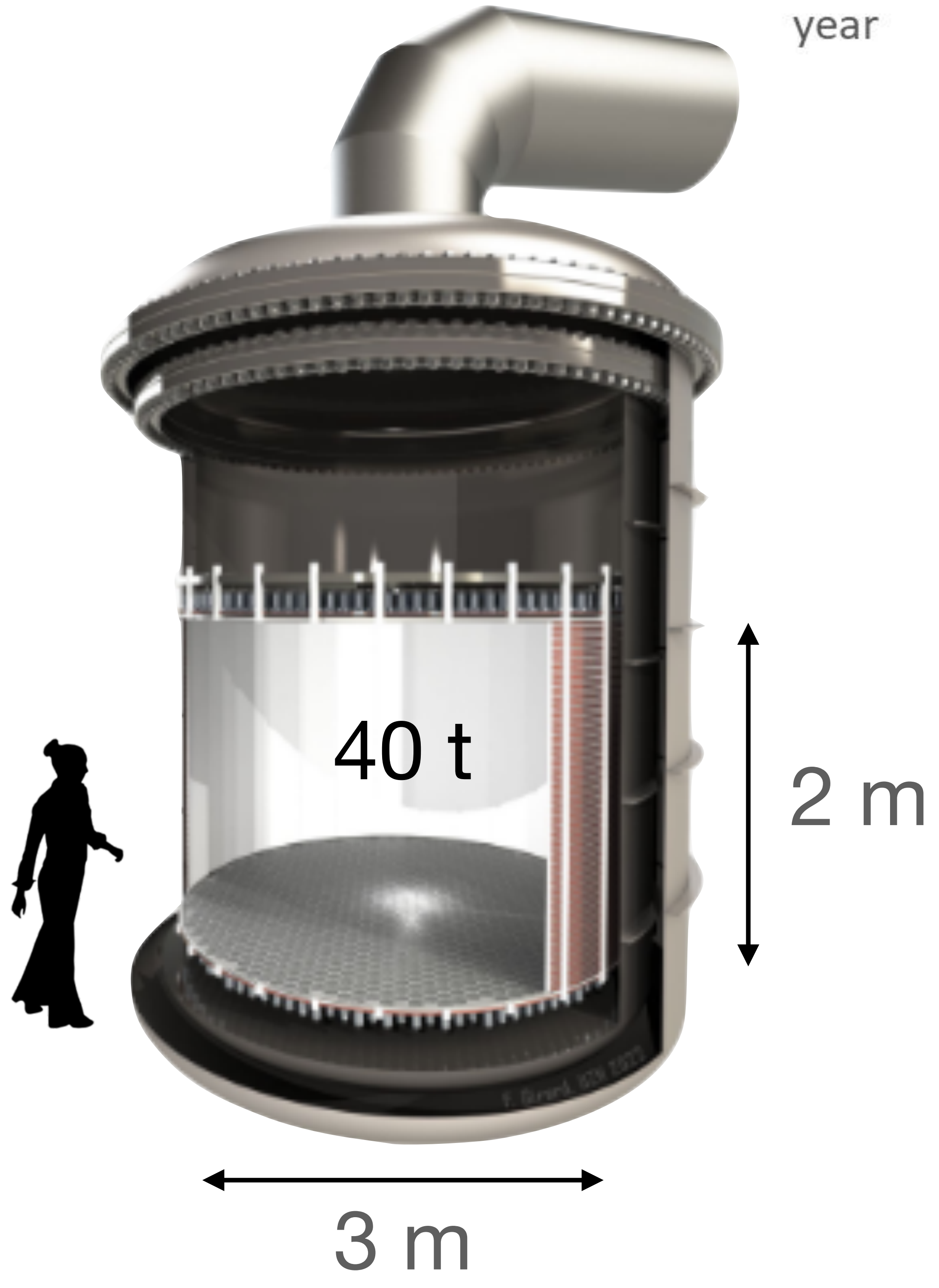
- Be the largest xenon observatory for rare events
- Search for WIMPs down to the “neutrino fog”
- Want to start science soon after LZ and XENONnT
  - Beginning of the next decade
- Be competitive with PandaX-xT
  - > 30 tonnes
- Size mostly limited by the xenon market
  - Cost and availability



XLZD detector concept

- Solution: staged approach!
  - Use 60 t diameter (~3 m) as baseline design
  - First phase, 40 t, shorter detector
    - Build infrastructure for taller detectors (cryostat, water tank, etc.)
    - Use xenon and PMTs from LZ and XENON (~50%)
    - Technical demonstration and early dark matter science result
    - 5 years run time





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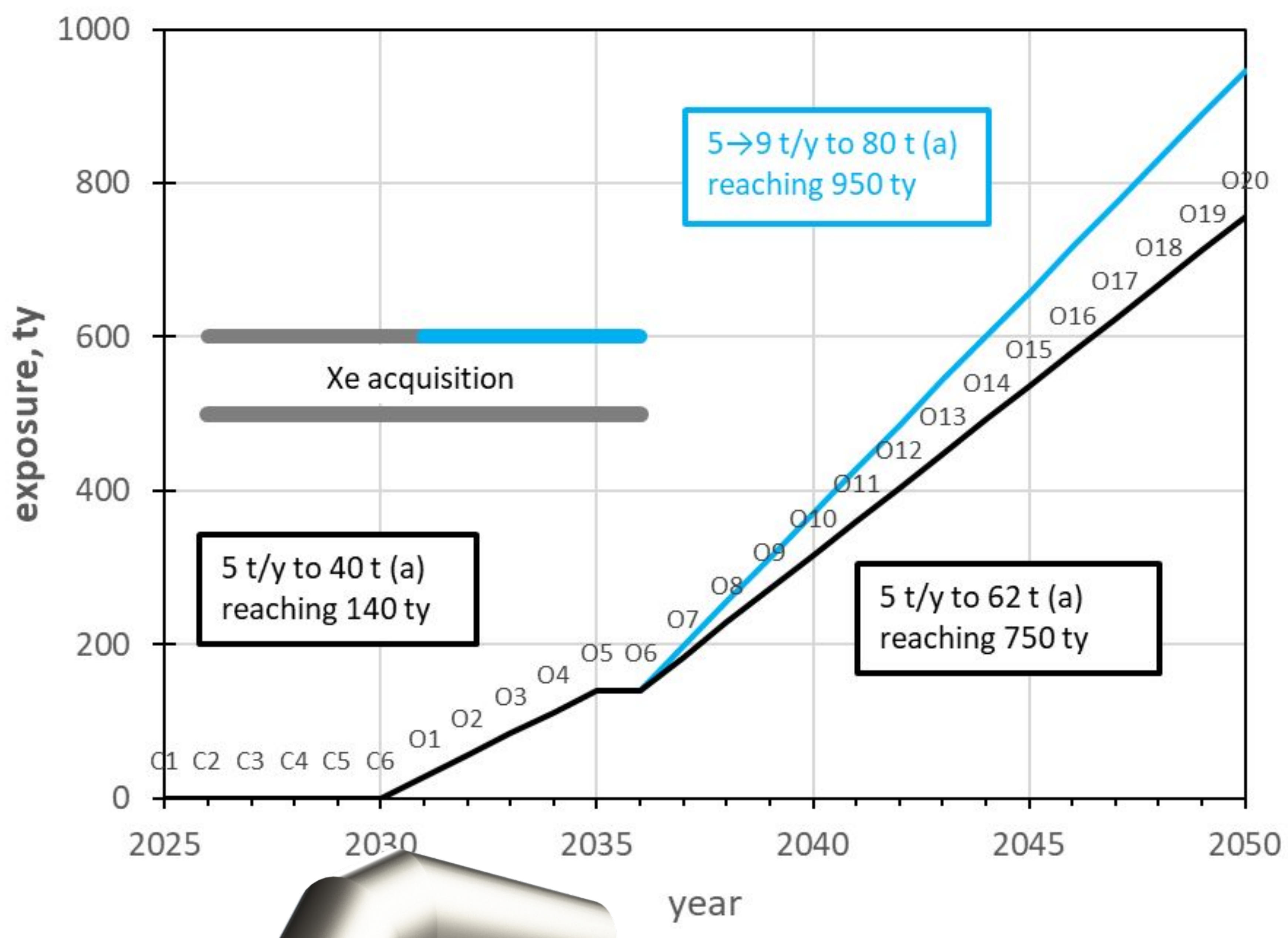
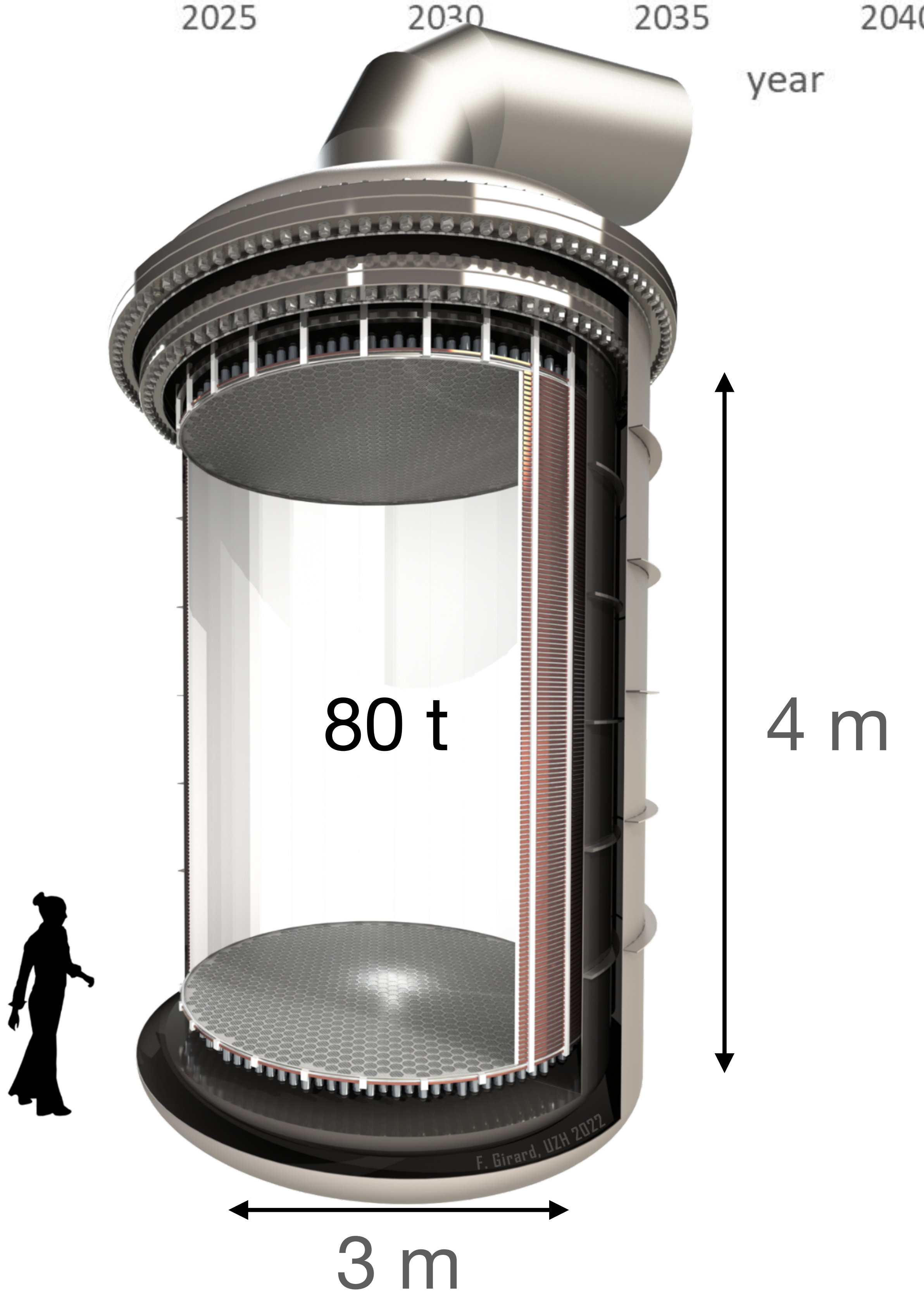


- Solution: staged approach!
  - Use 60 t diameter (~3 m) as baseline design
  - First phase, 40 t, shorter detector
  - One year upgrade interruption
  - Main science phase:
    - Nominal, 60 t, 1:1 ratio
    - Opportunity, 80 t, tall detector: full science reach



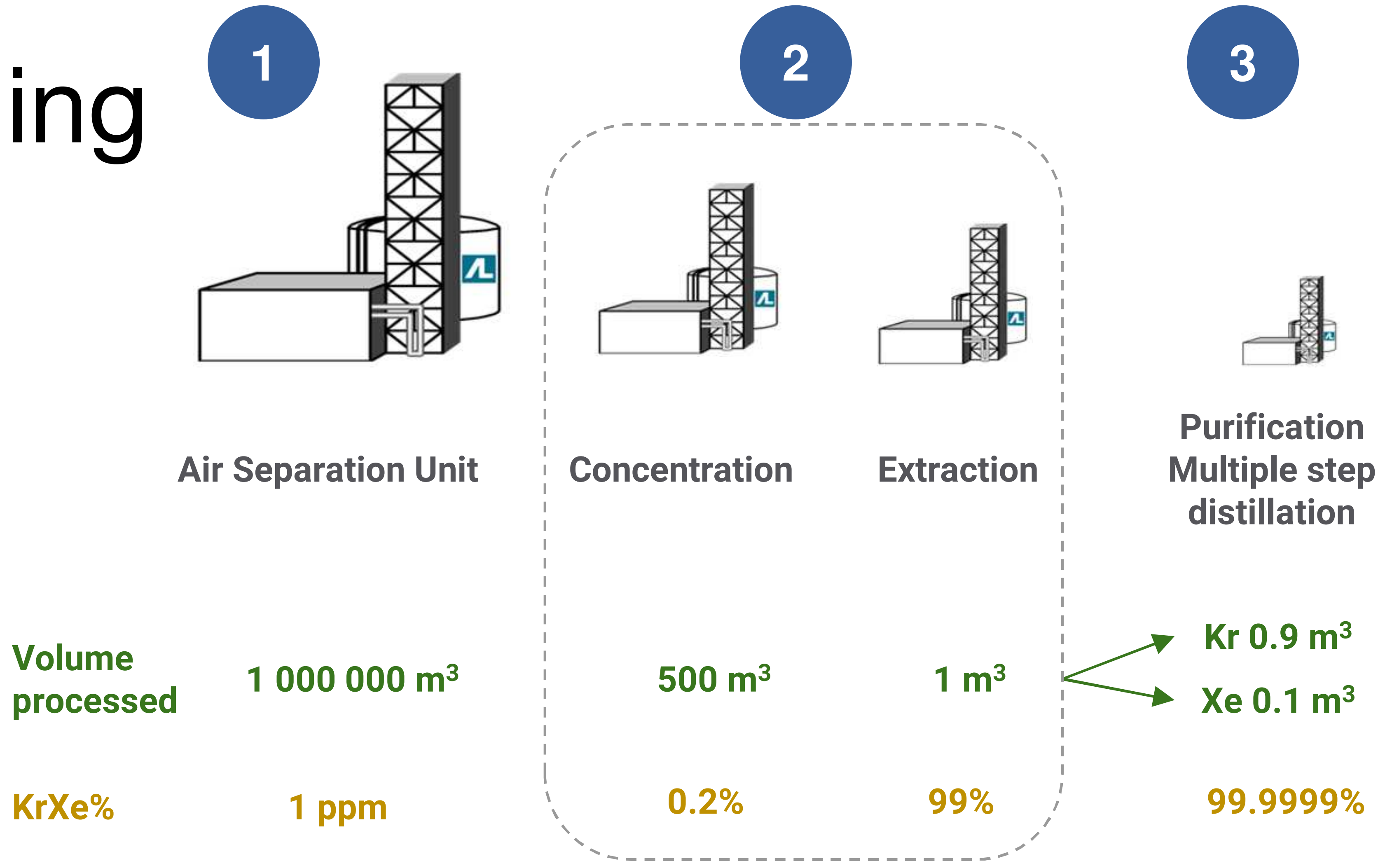
Xenon market

- Xenon is in the air in extremely small amounts
- It is a byproduct of O_2 extraction, only profitable in very large Air Separation Units
  - There are very few of these
  - Each produces ~1 t Xe/year
  - World production ~60 t/year (increasing)
- Used in electronics (increasing), space and lightning

Gaz	Abundance
N2	78,09 %
O2	20,94 %
Ar	0,93 %
CO2	350 ppm
Ne	18,2 ppm
He	5,2 ppm
Kr	1,14 ppm
H2	0,5 ppm
Xe	0,087 ppm

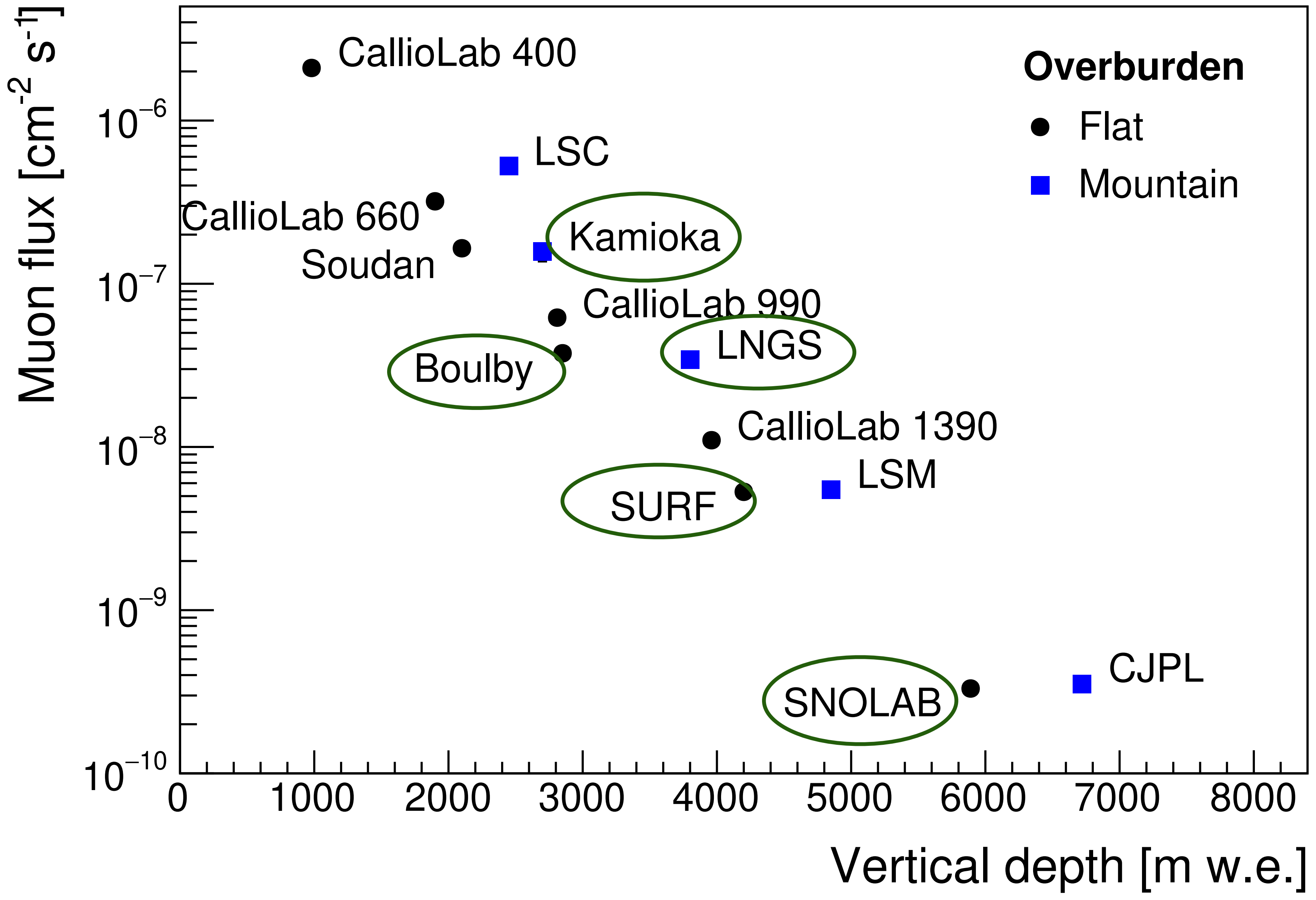
Xenon is a commodity

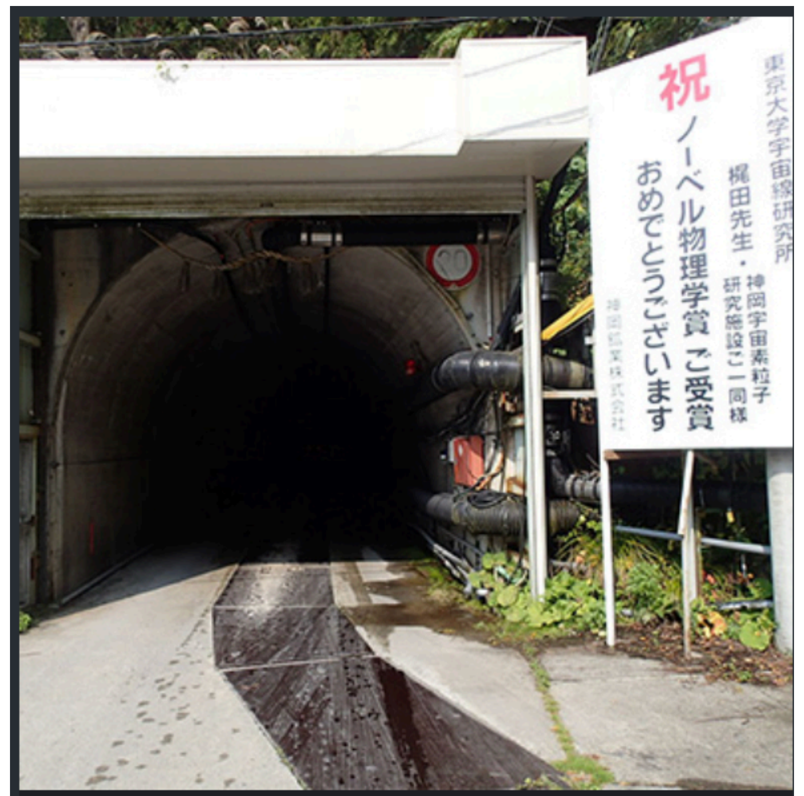
$12 - $20 /litre



Possible installation sites

- Underground deployment reduces cosmic muon flux
- XLZD will require a large cavity (~25 m) and space for clean fabrication UG
- UG access (vertical Vs horizontal) is challenging for a detector with this size
- 5 laboratories have shown interest in hosting





Kamioka

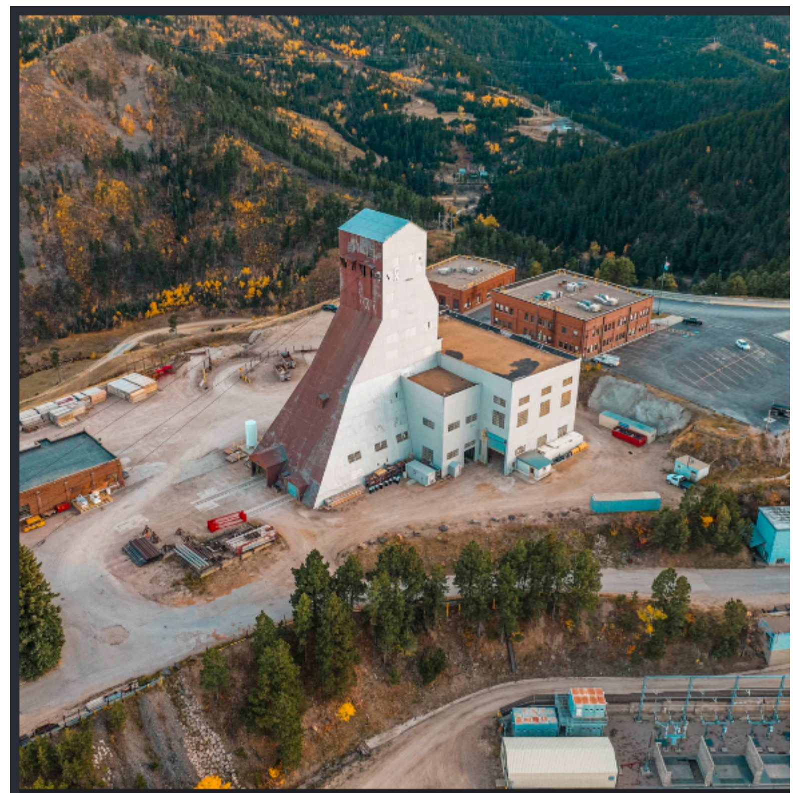
Japan

LNGS

Gran Sasso, Italy

Boulby

North Yorkshire, UK



SURF

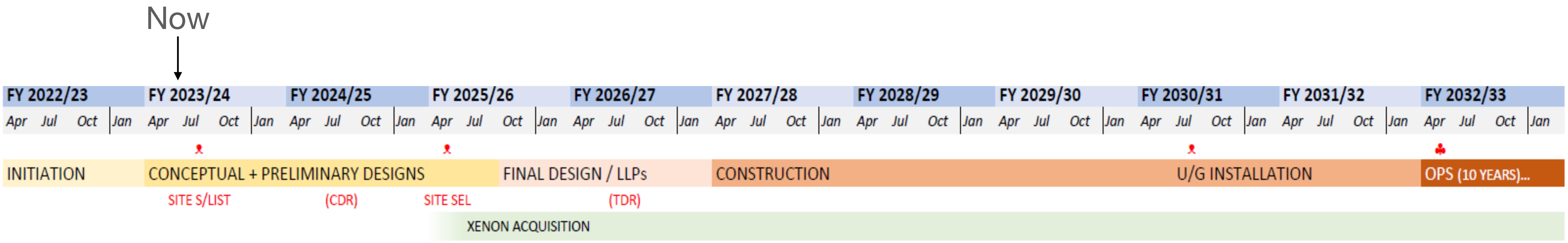
South Dakota, US

SNOLAB

Ontario, Canada

XLZD timeline

Phases: R&D (ongoing) + Pre-Construction (3y) + Construction (5y) + Operations (10+ y)

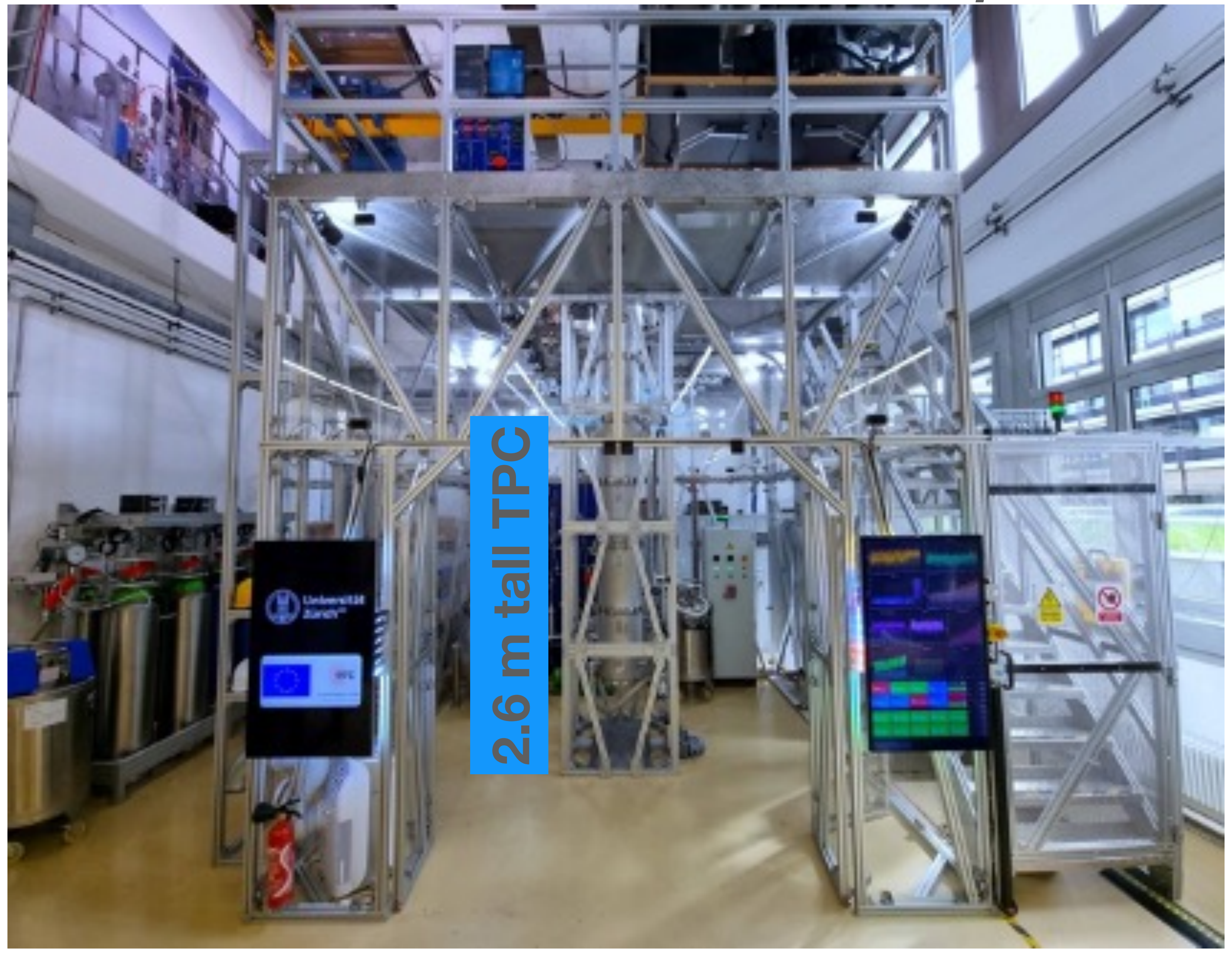


- **2023:** Agency strategies and inter-agency discussion; Site shortlisting; R&D
- **2025:** Site selection
- **2027:** Start of construction
- **2028:** First UG space for clean manufacture
- **2030:** Start of UG installation
- **2032:** Start of operations

Ongoing R&D

Large R&D setups, smaller scale in various groups

Vertical demonstrator: ***Xenoscope***

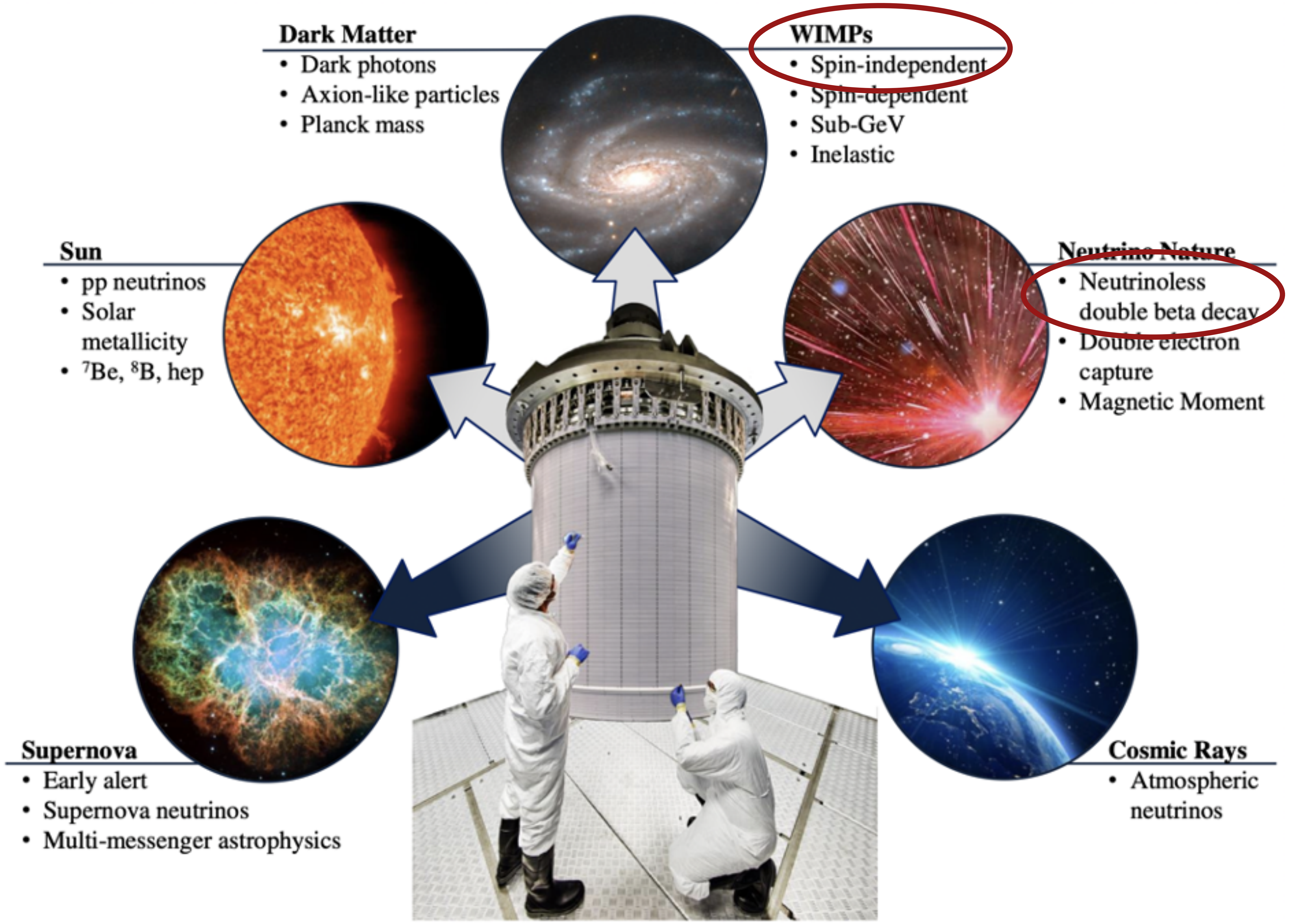


JINST 16, P08052, 2021

Horizontal demonstrator: ***Pancake***

- Alternative grid mechanics and design (need grids with 2x current diameter, limit grid impact on position reconstruction)
- Testing of HV components (need higher HV feedthroughs)
- High-flow in-line radon distillation (reduce radon levels by 10x compared to current experiments)
- Alternative readout sensors (lower radioactive contamination, better position reconstruction)
- Xenon doping with light elements (light target for low mass WIMPs, reduced electron diffusion)

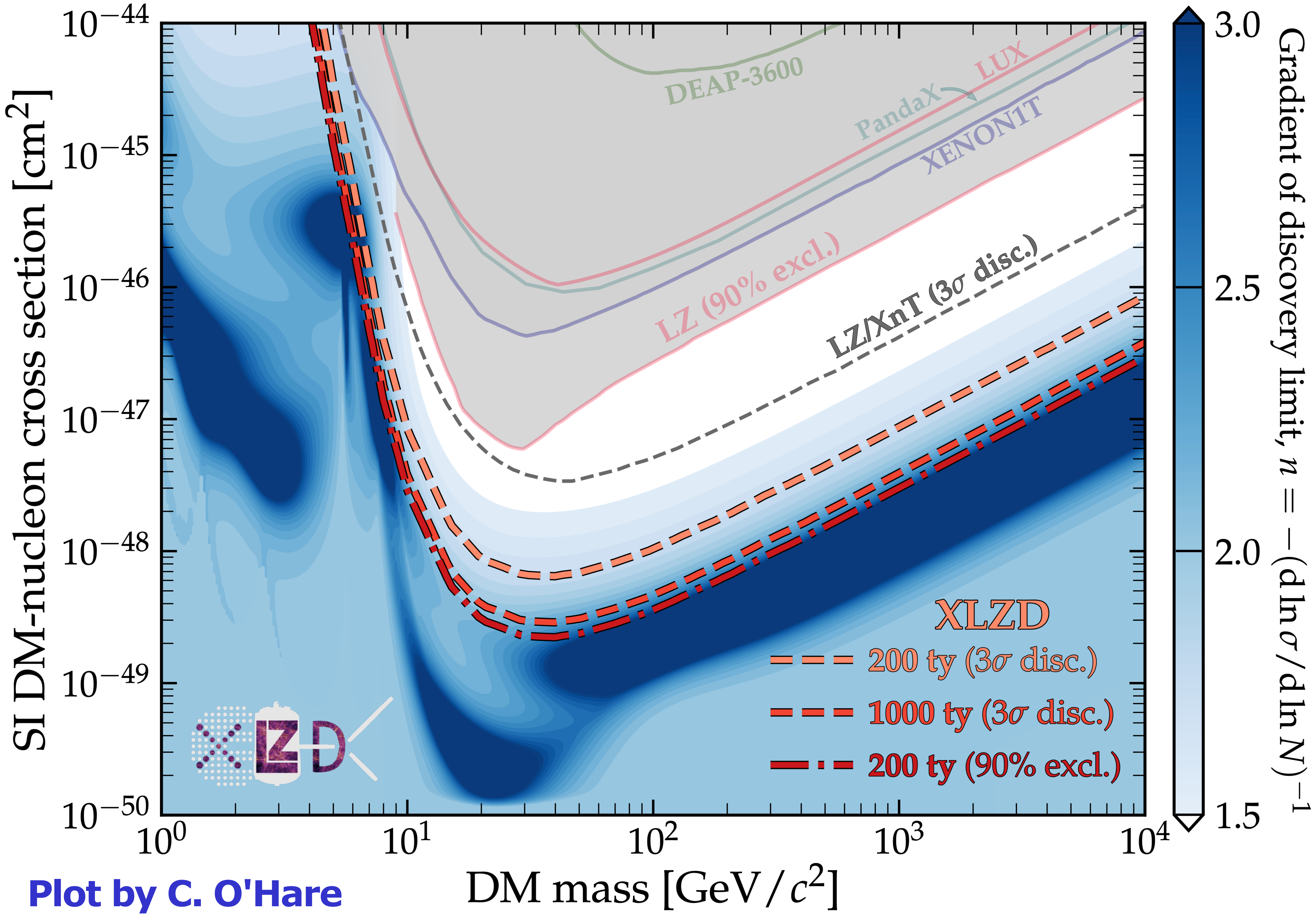
XLZD: A Rare Event Observatory



XLZD science case: [J. Phys. G 50 (2023) 013001]

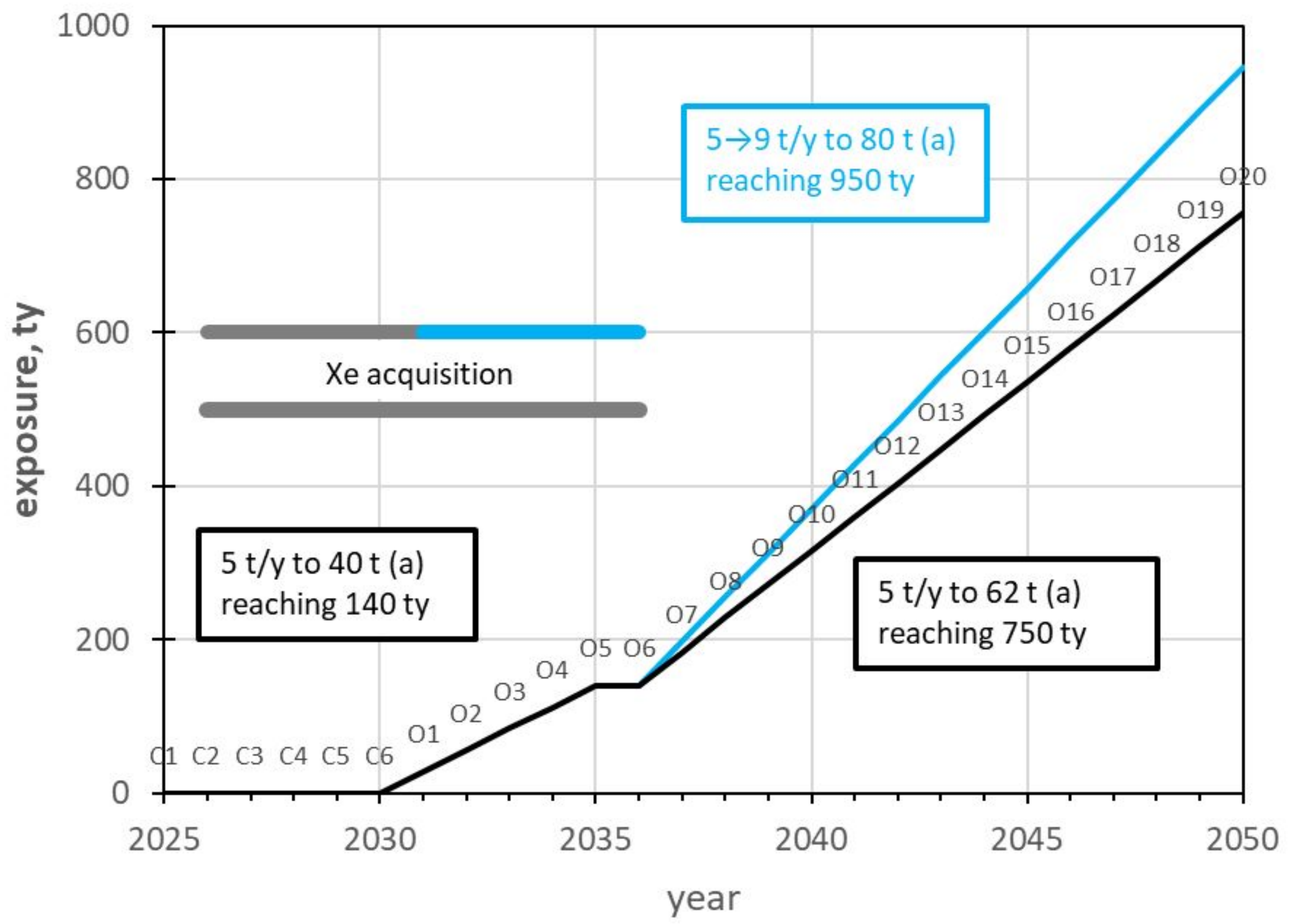
WIMP sensitivity

Spin-independent interaction



Plot by C. O'Hare

- Parameter space down to the neutrino fog can be (90% CL) excluded with 40t detector in ~6 yr
- Need 80 t and 20 yr to do a complete 3σ sweep of the parameter space
- Can rule out existence of WIMPs above the "neutrino fog"



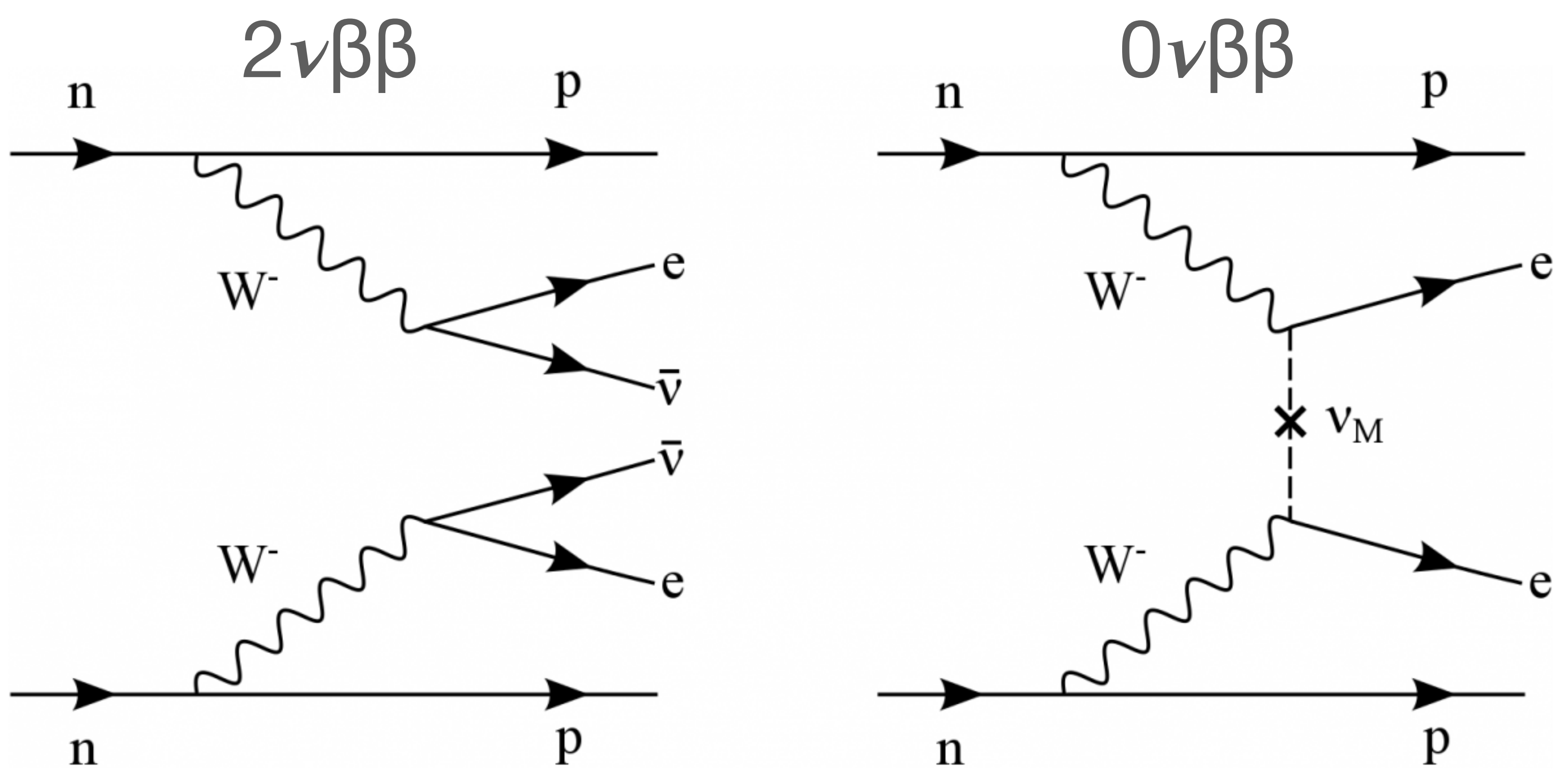
Neutrinoless Double Beta Decay

A gateway to the neutrino mass hierarchy

- Standard double beta decay: rare process, occurs when single beta decay is forbidden or highly suppressed

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

(confirmed in 14 isotopes, half-lives in the 10^{19} — 10^{21} yr range)



- Neutrinoless double beta decay

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

  - Beyond SM process
  - Violates lepton number conservation
  - Possible if neutrinos are Majorana particles
  - Never observed, half-life lower limits $T_{1/2} > 10^{24}$ yr
  - In xenon, it can occur in ^{134}Xe and in ^{136}Xe ($T_{1/2} > 10^{26}$ yr, KamLAND-Zen)

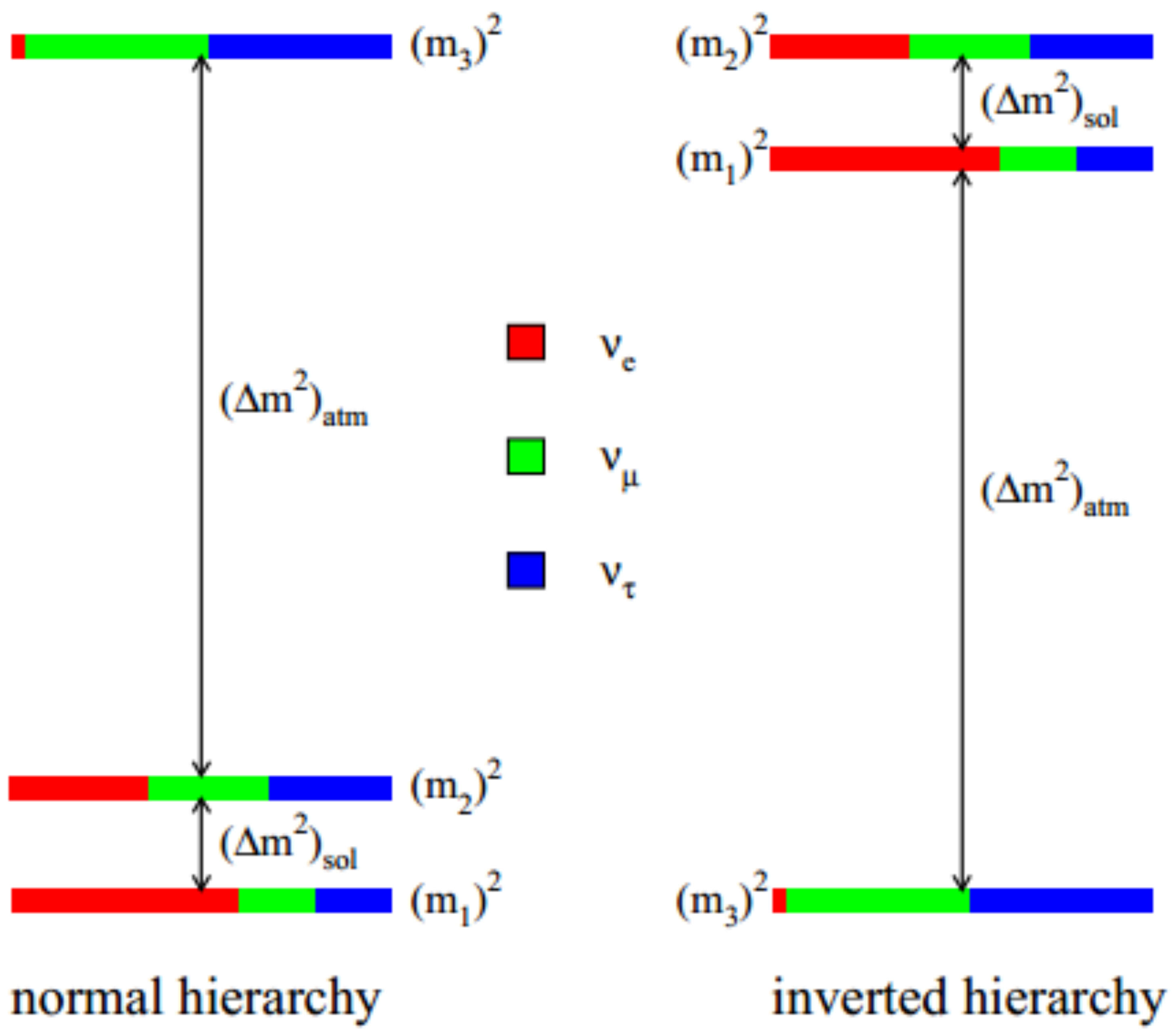
- Decay half-life is connected to the neutrino mass hierarchy by the effective Majorana mass

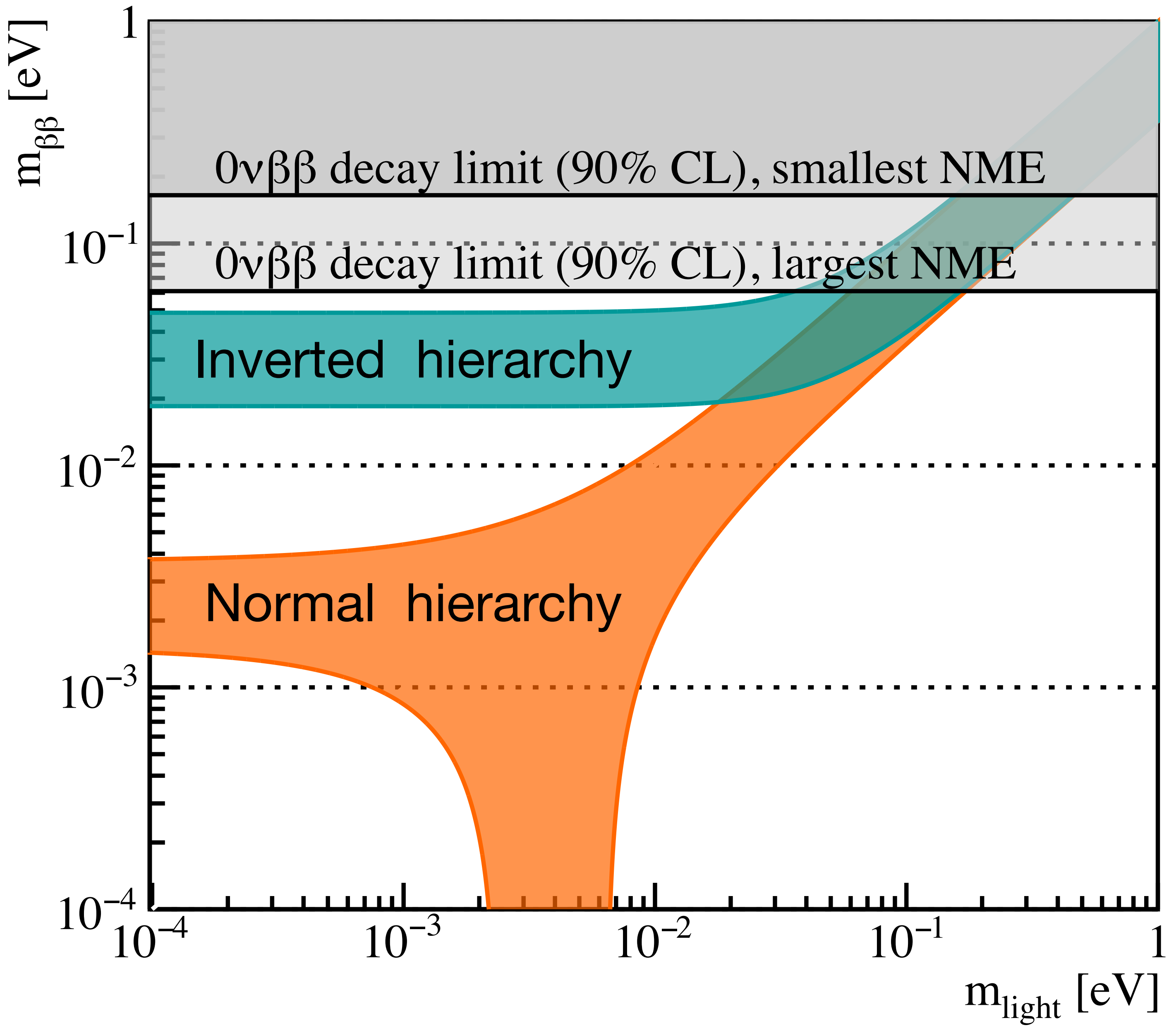
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\,\left|\mathcal{M}^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Neutrino mass hierarchies

Neutrino oscillations

- 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
- Majora mass can be used to probe the mass hierarchy

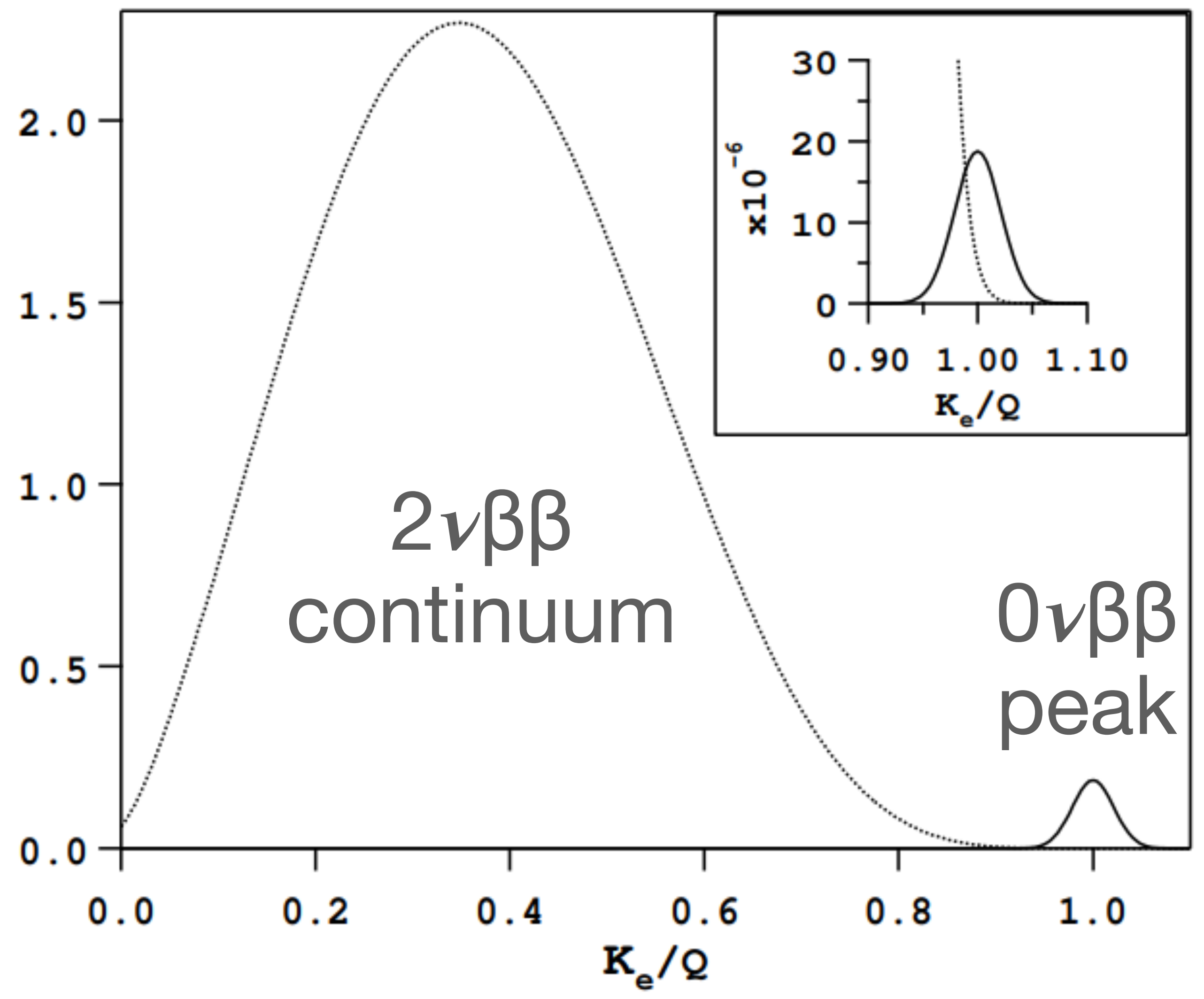




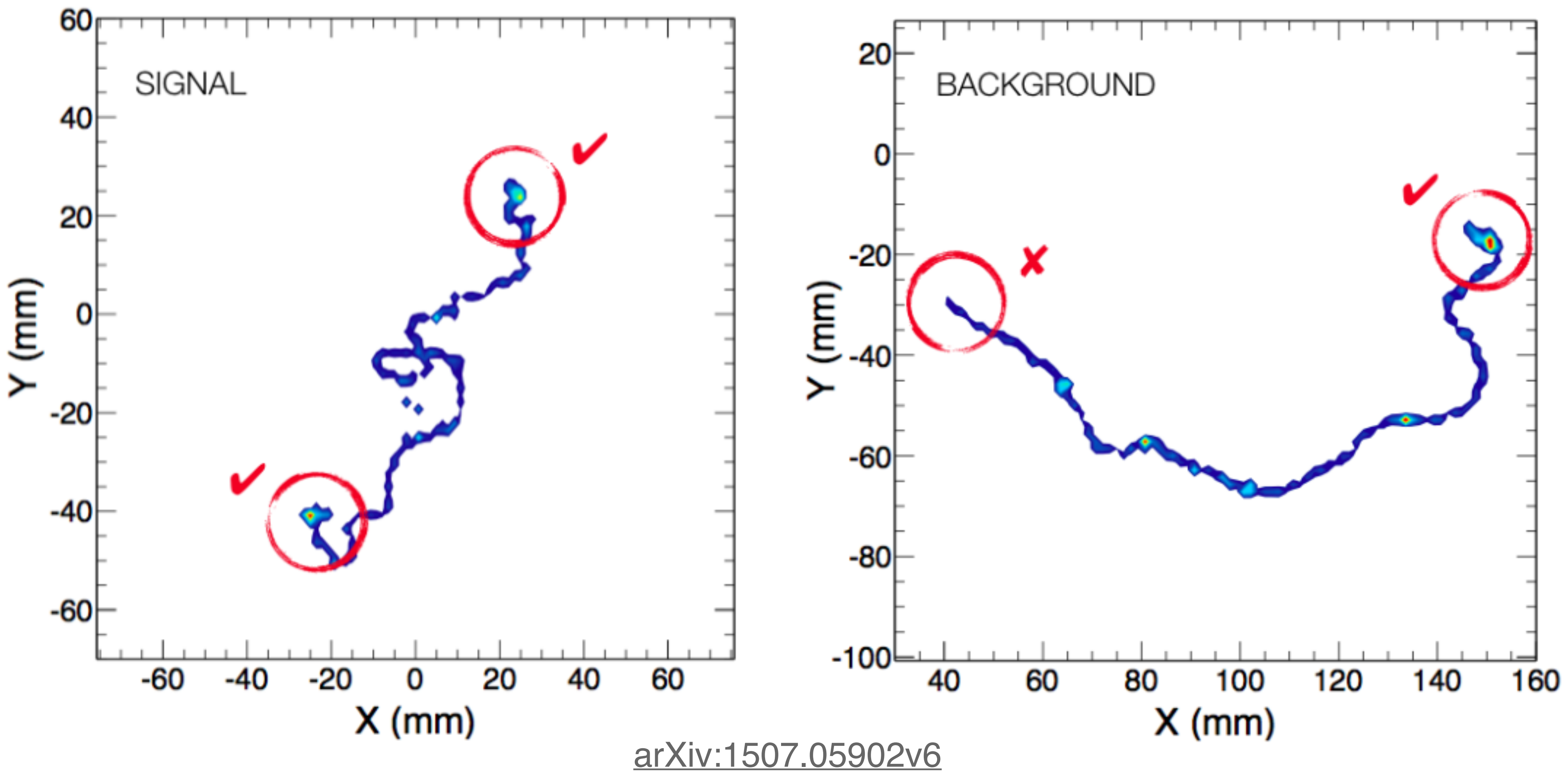
Neutrinoless Double Beta Decay

Experimental signature

- No neutrinos, so the electrons must carry the full Q-value of the decay
  - 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
  - Short range tracks (1-2 mm in LXe), challenging to reconstruct
- Main backgrounds are from
  - Single recoiling electrons with the same total energy (~3 mm tracks) (high-energy gammas, beta decays and neutrino-electron scattering)
  - Multi-site interactions of high-energy gammas that happen too close to be easily distinguished
  - Leakage from standard $2\nu\beta\beta$, due to the finite energy resolution
- Experimental requirements: large source mass, low background environment, good energy resolution, ability to discriminate background events



Event topology in Xe gas (NEXT)

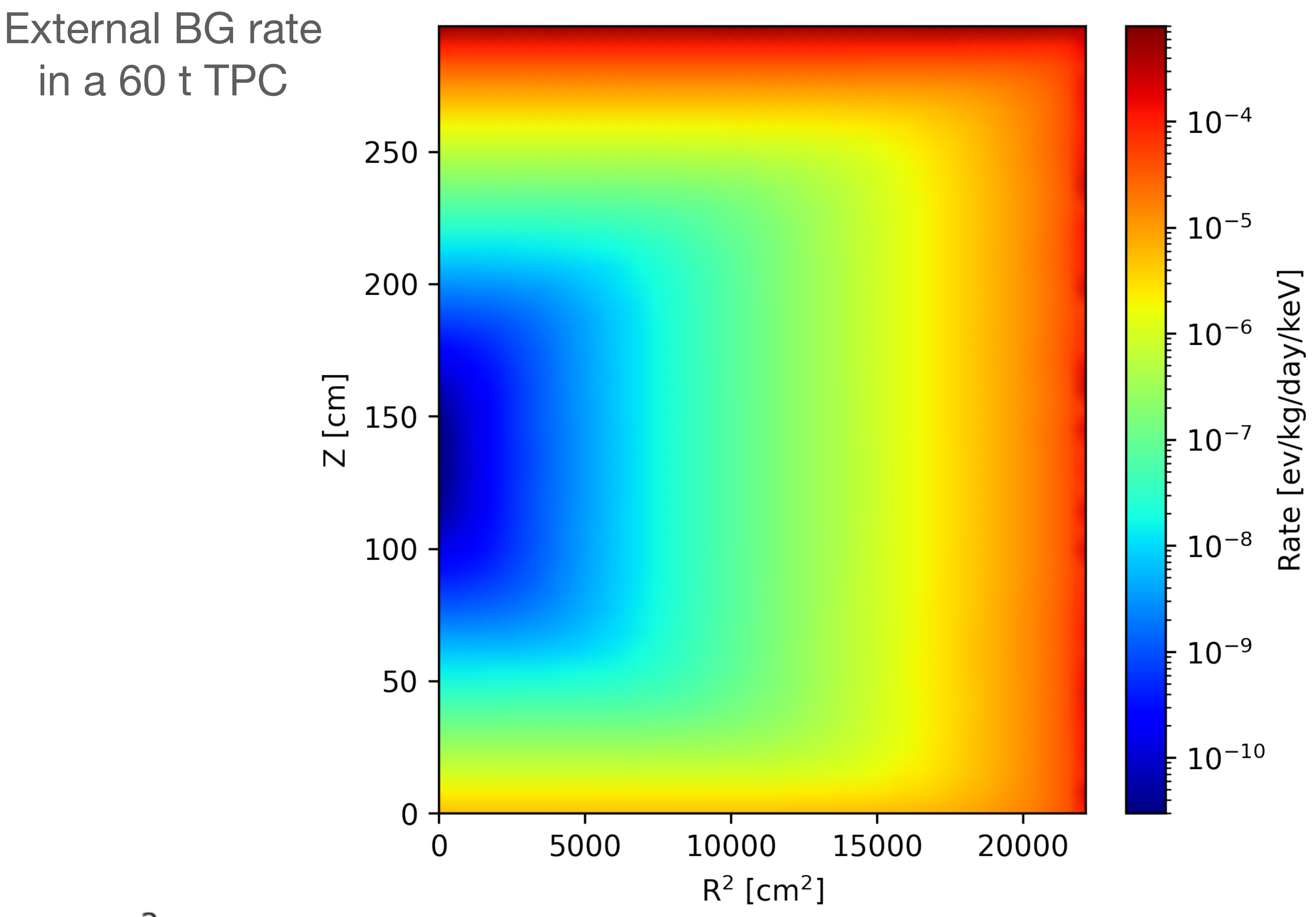


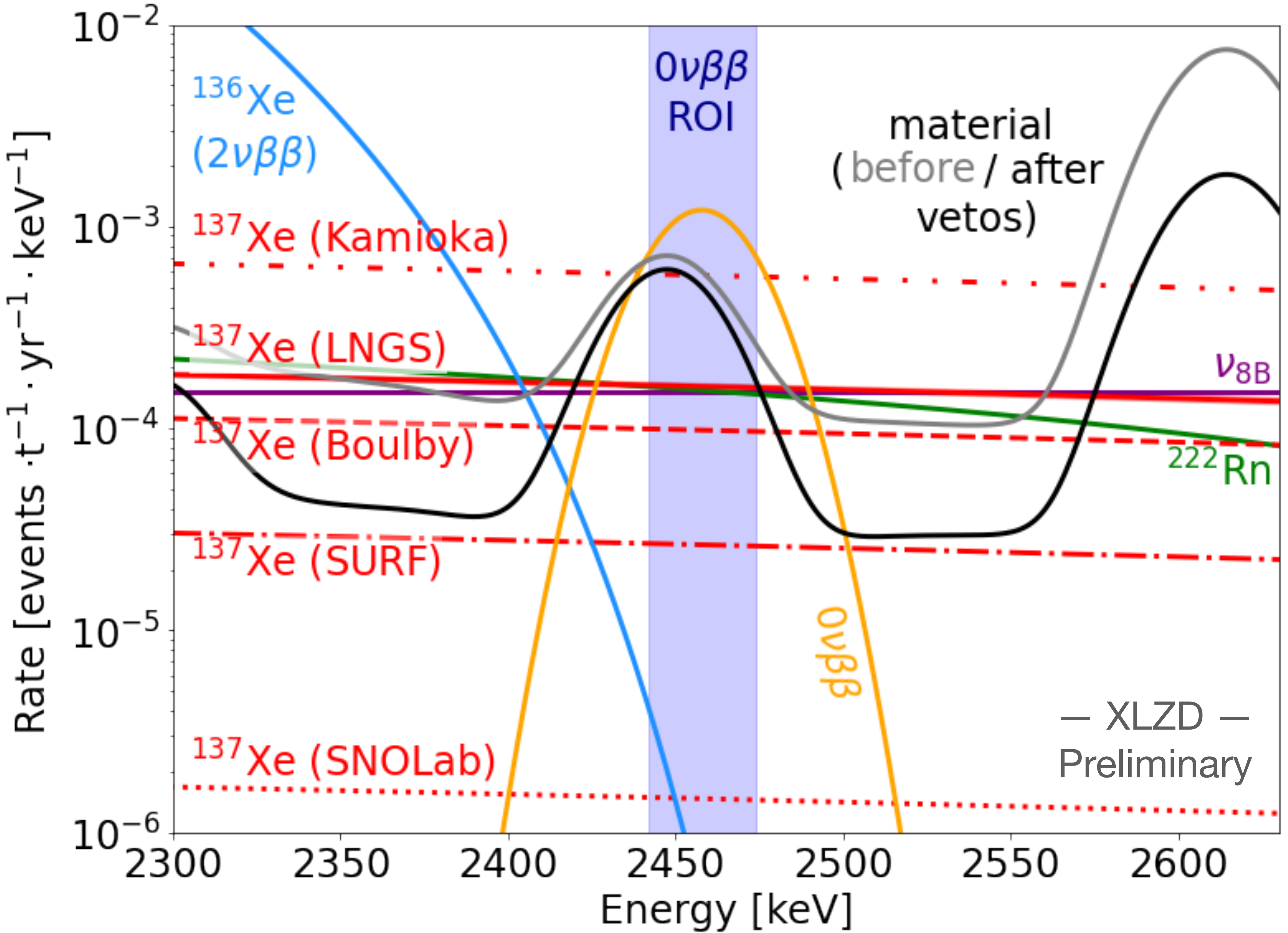
arXiv:1507.05902v6

$0\nu\beta\beta$ decay in XLZD

Main backgrounds

- ^{136}Xe $0\nu\beta\beta$ Q = 2458 keV
- External gamma-rays
  (from radioactivity in detector materials)
  - ^{214}Bi γ in the ^{238}U chain (2447 keV)
  - ^{208}Tl γ in the ^{232}Th chain (2615 keV) — highly suppressed by vetoes
  - Mostly in the outer detector regions, but highly penetrative
  - Ability to separate multiple scatters is critical
    (**<3 mm, preliminary result from LZ**)
- Internal backgrounds (uniform in the detector)
  - ^{214}Bi β from ^{222}Rn mixed in the xenon (3270 keV)
  - ^{137}Xe β (4170 keV), neutron activation of ^{136}Xe
    (mostly muon induced neutrons, depends on installation site)
  - Electron recoils from ν-e^- scattering (^{8}B), irreducible
  - $2\nu\beta\beta$ leakage is small, given the excellent energy resolution
    (**0.67% σ, measured in LZ**)

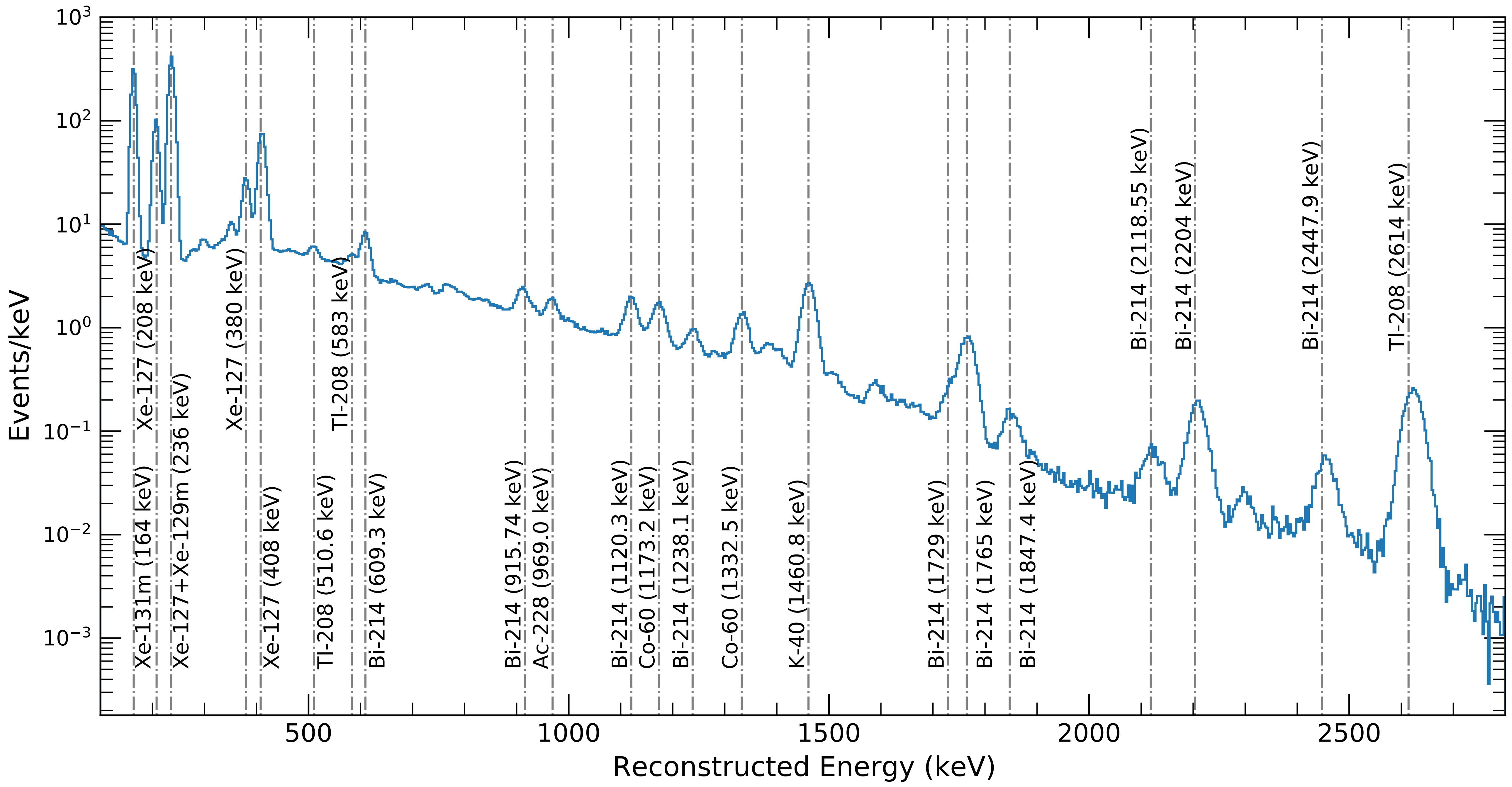


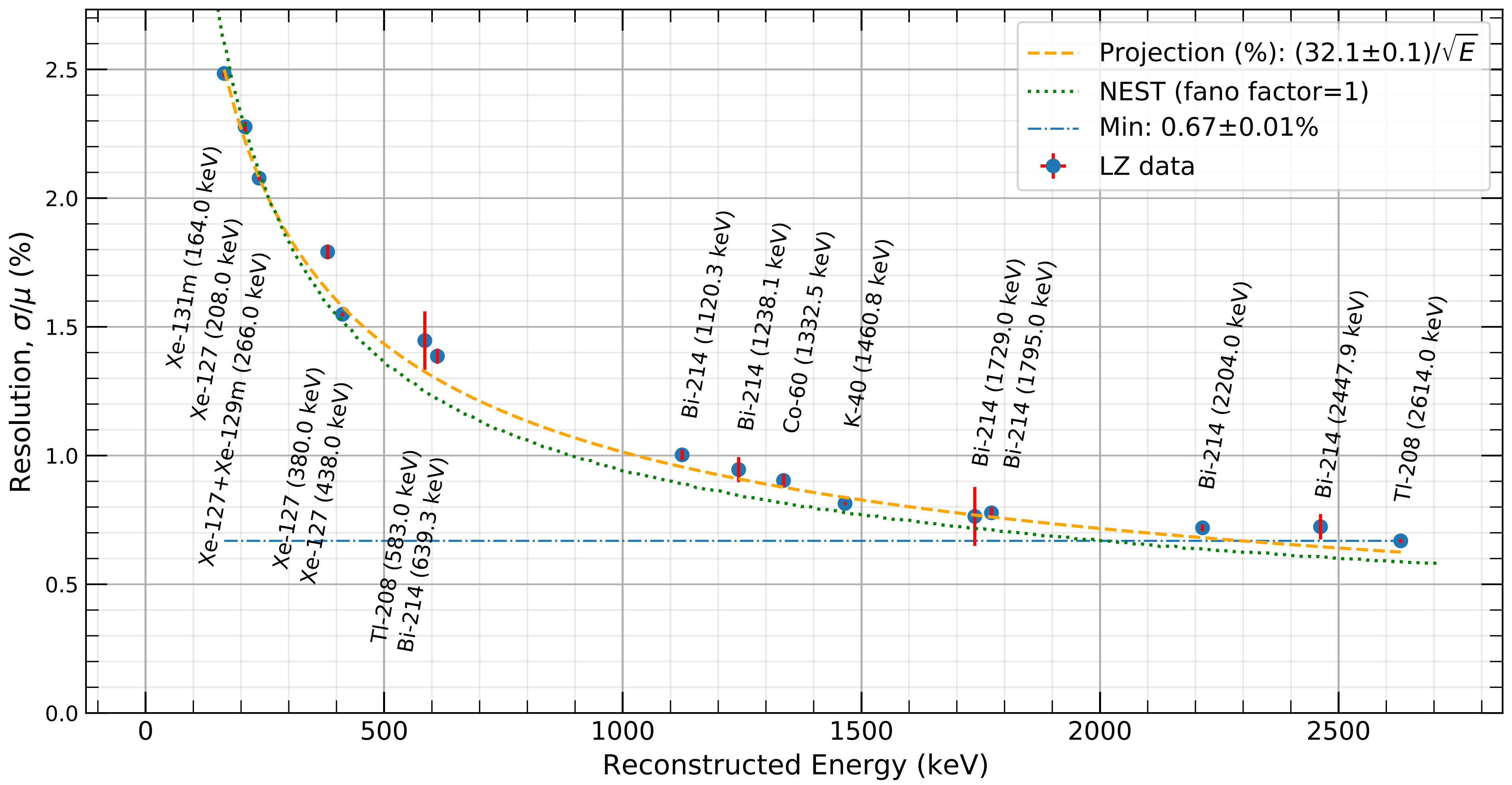


Energy resolution in Xenon TPCs

Guilherme Pereira (PhD)

- Developed detailed corrections for the S1 and S2 signals in LZ
- Based on 3D position reconstruction
- Calibrated using α-decays in the ^{222}Rn chain (uniformly distributed)
- 0.67% resolution at the ^{136}Xe Q-value → best ever in this type of detector!

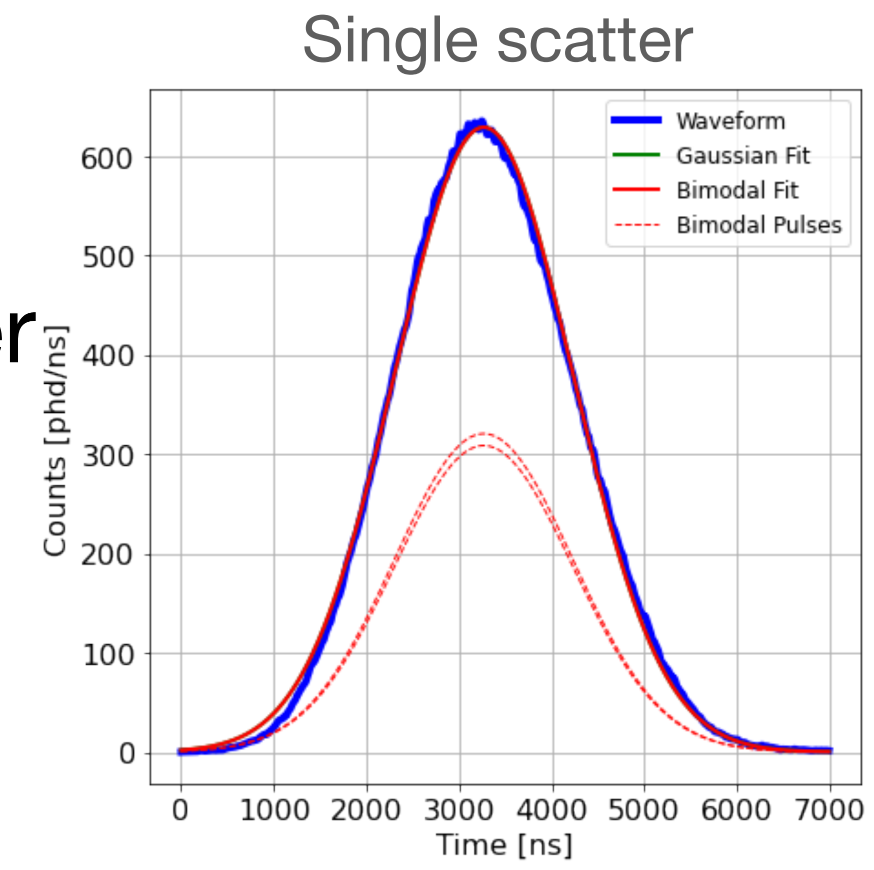




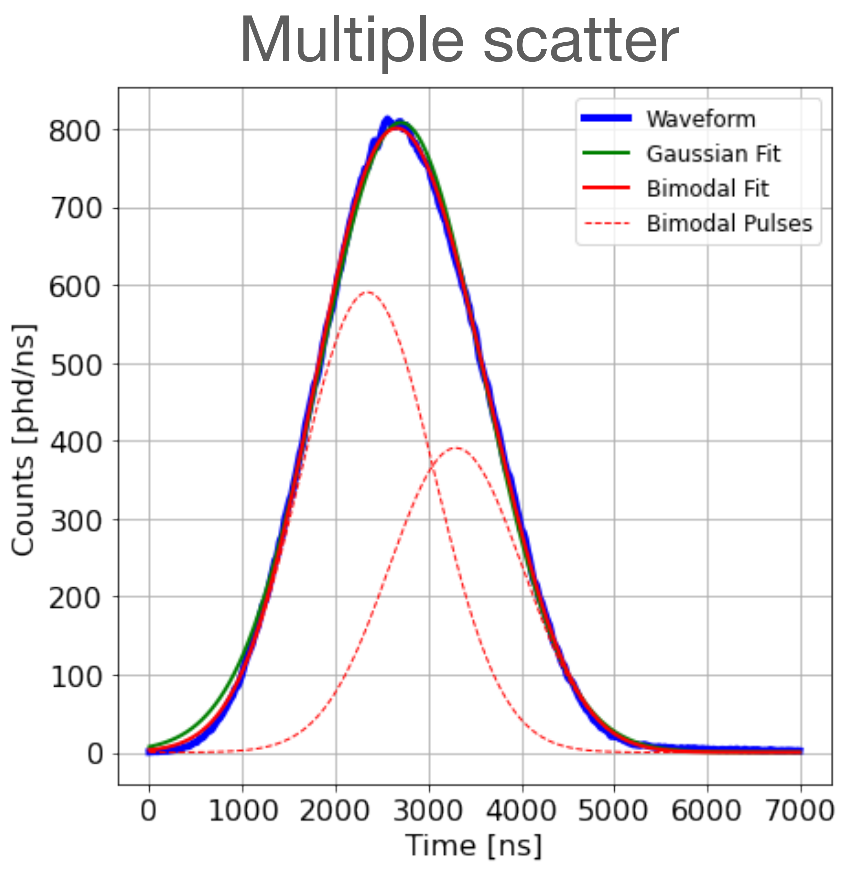
Multiple scatter discrimination in LZ

Sandro Saltão (MSc)

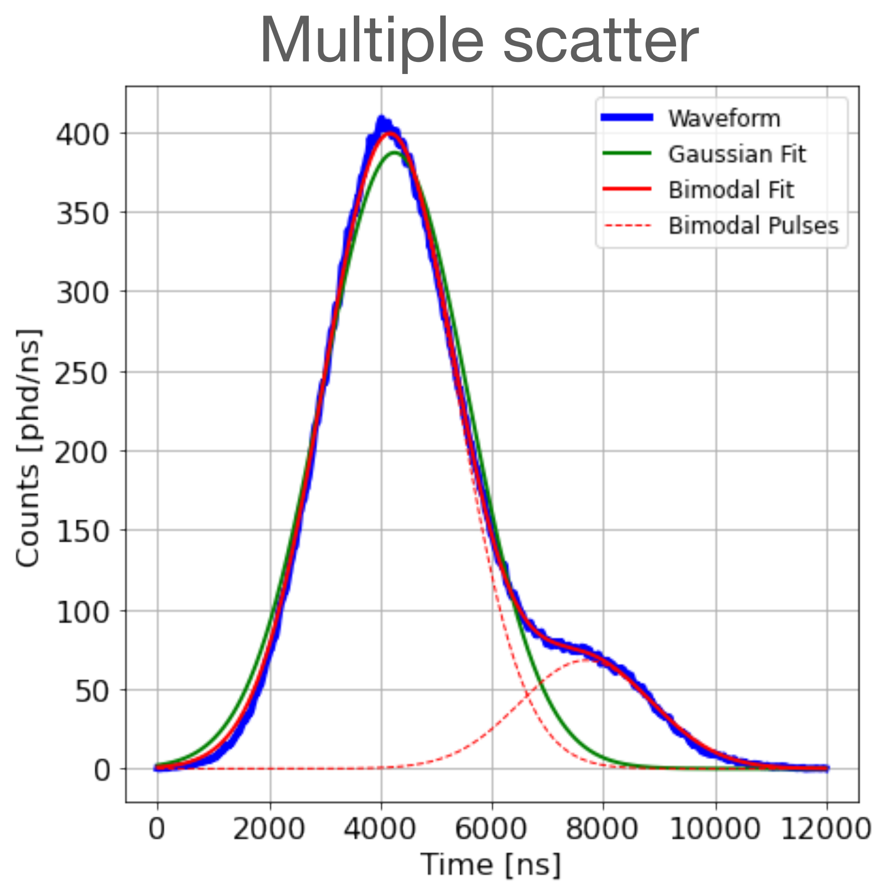
- High-energy gamma-rays are very likely to scatter multiple times in a large detector (Compton + Photoelectric)
- Multiple interactions at different heights will be reflected in the S2 pulse (shape and width)
- Fitting S2 pulses with single or double gaussians
- Preliminary tests with real LZ data: a separation of 2 mm seems possible even for interactions near the bottom of the detector
- Allows to reject >90% of the gamma background
- $0\nu\beta\beta$ signal acceptance is high (>70% at 1.5 mm)



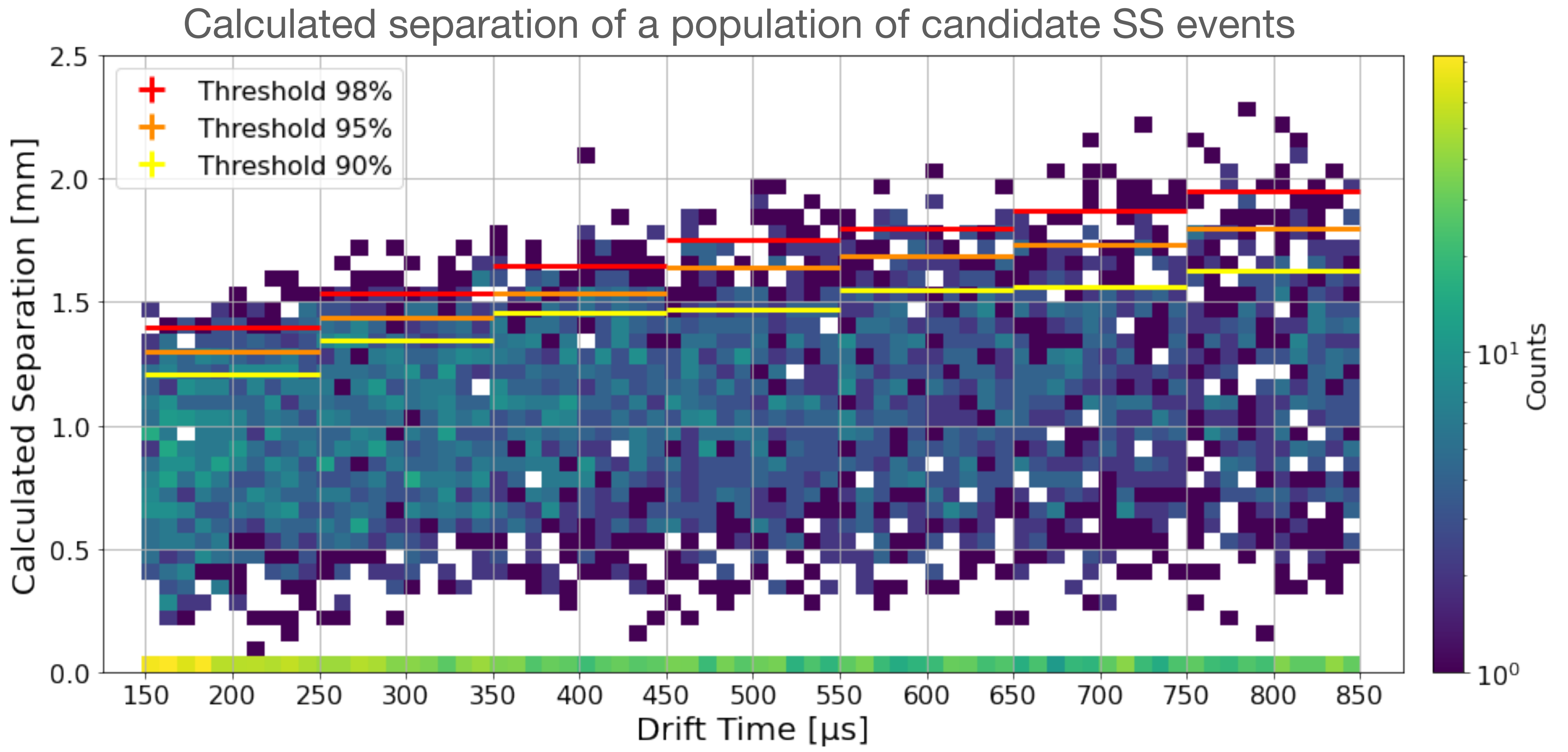
(a) Drift time = 506 μs; E = 1.260 MeV



(a) Drift time = 152 μs; E = 1.596



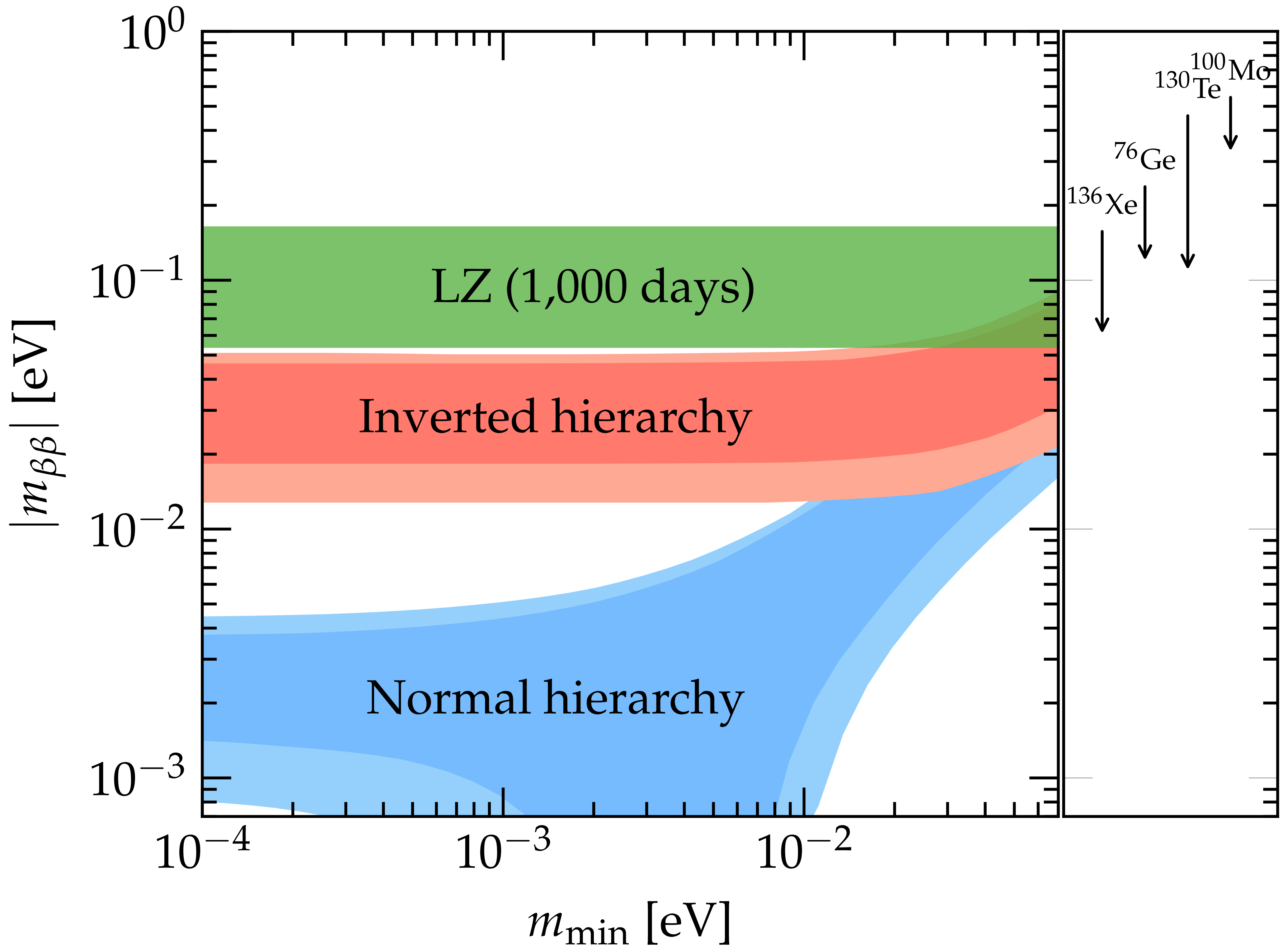
(d) Drift time = 846 μs; E = 1.168 MeV

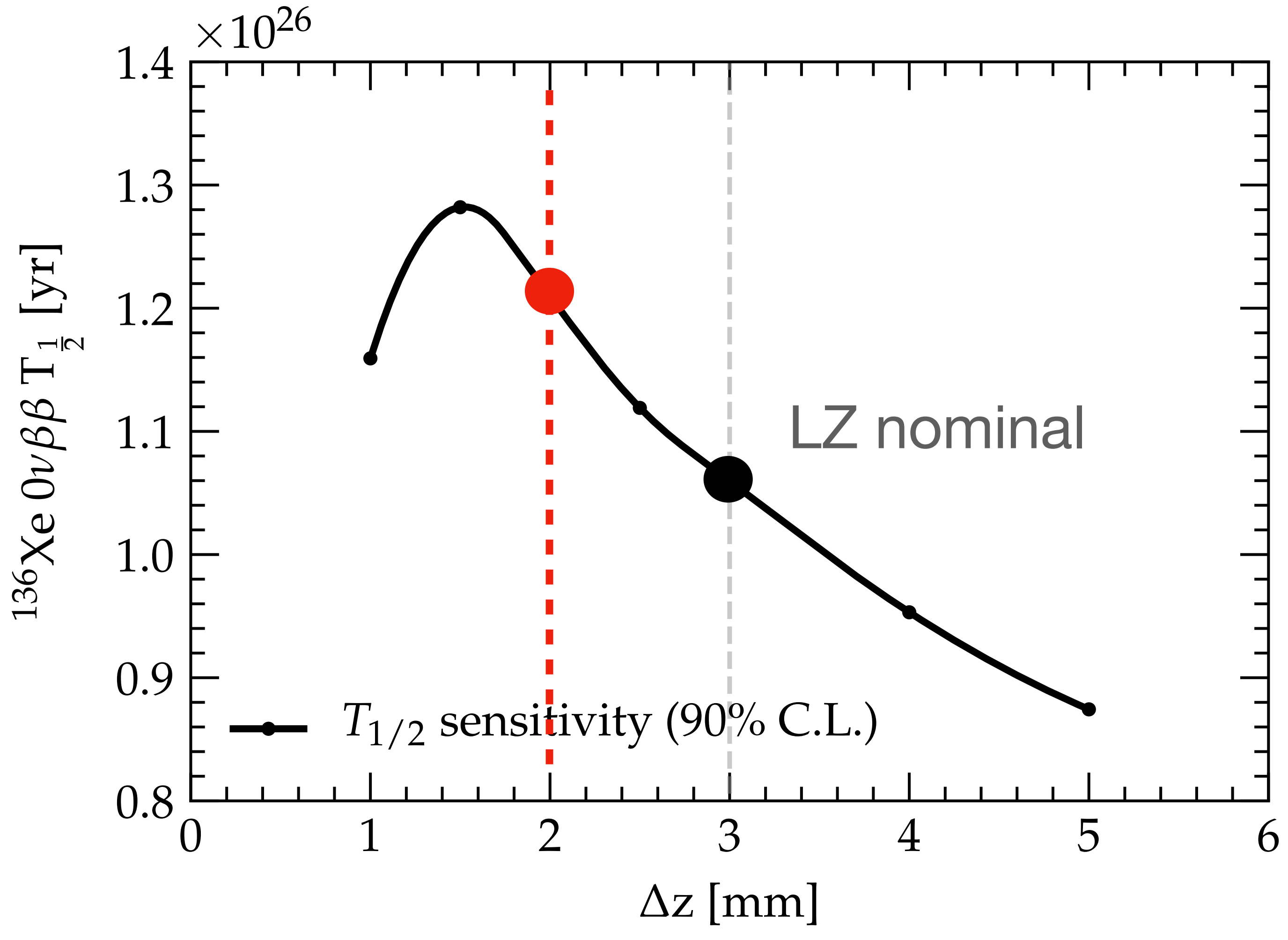


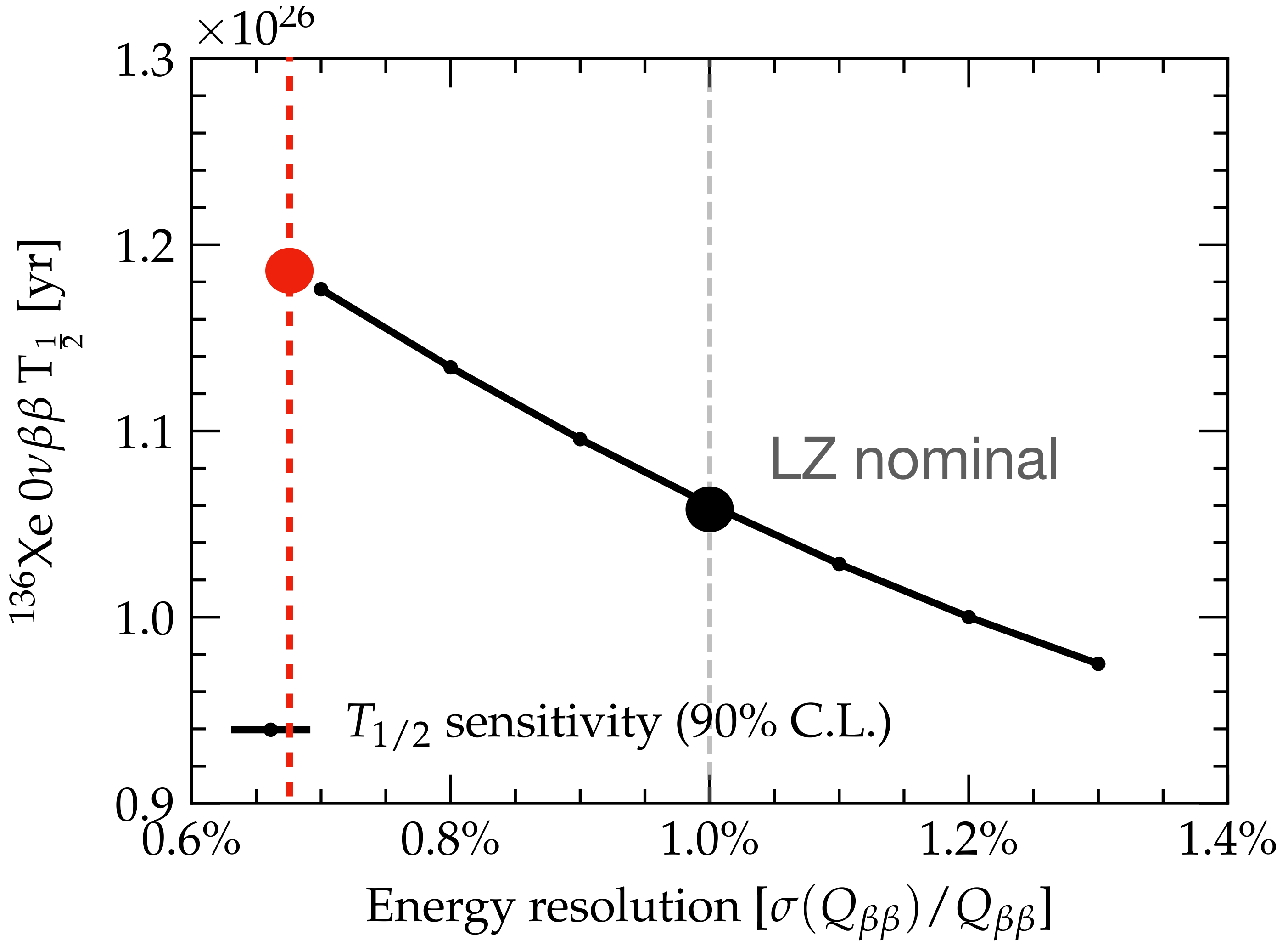
0νββ decay in LZ

Quick side note

- LZ can also search for ^{136}Xe 0νββ decay
- Expected to reach current best half-life limits with 1000 day run
- Improved energy resolution and SS/MS separation expected to improve the limit by ~10% each

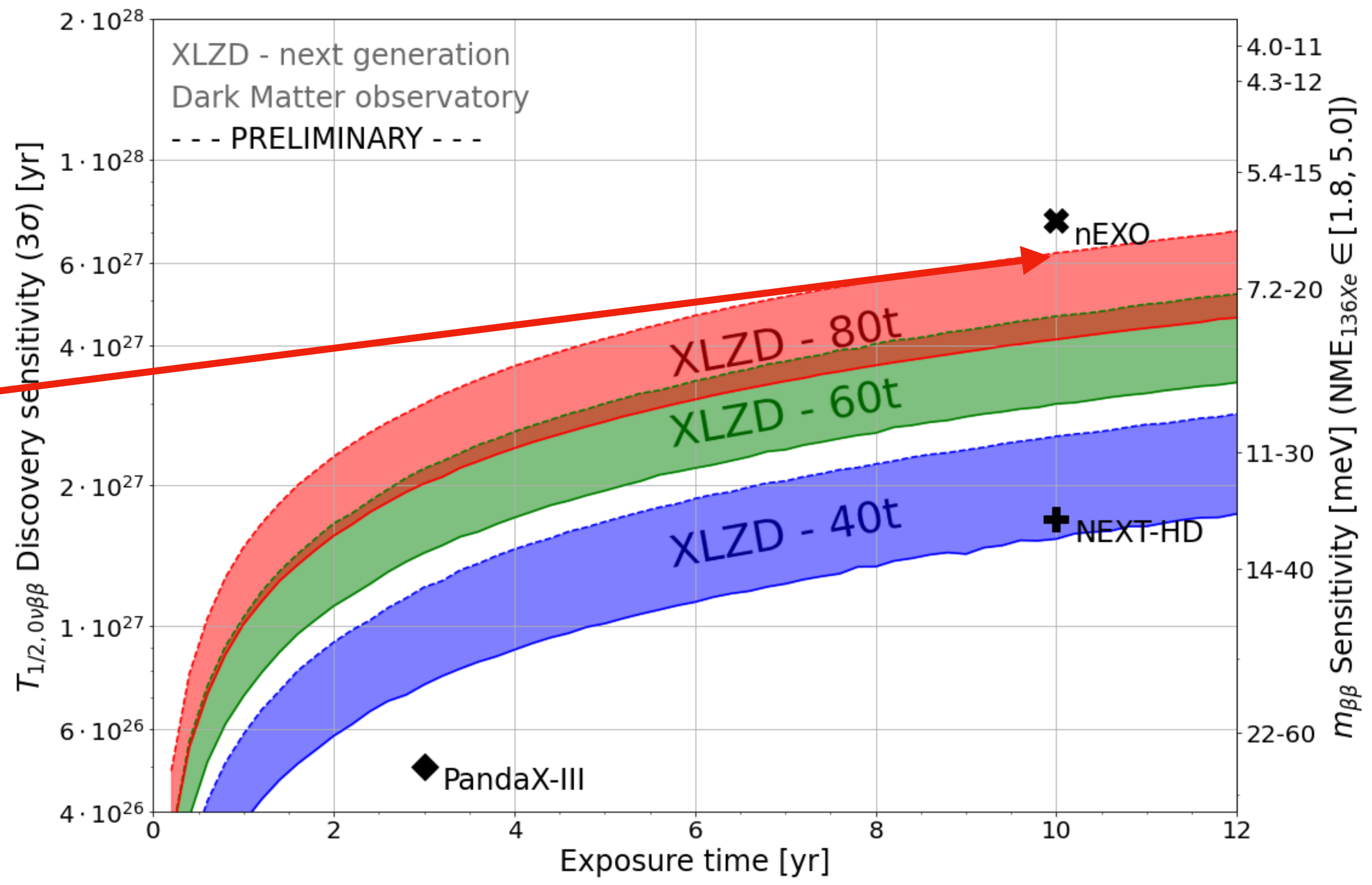


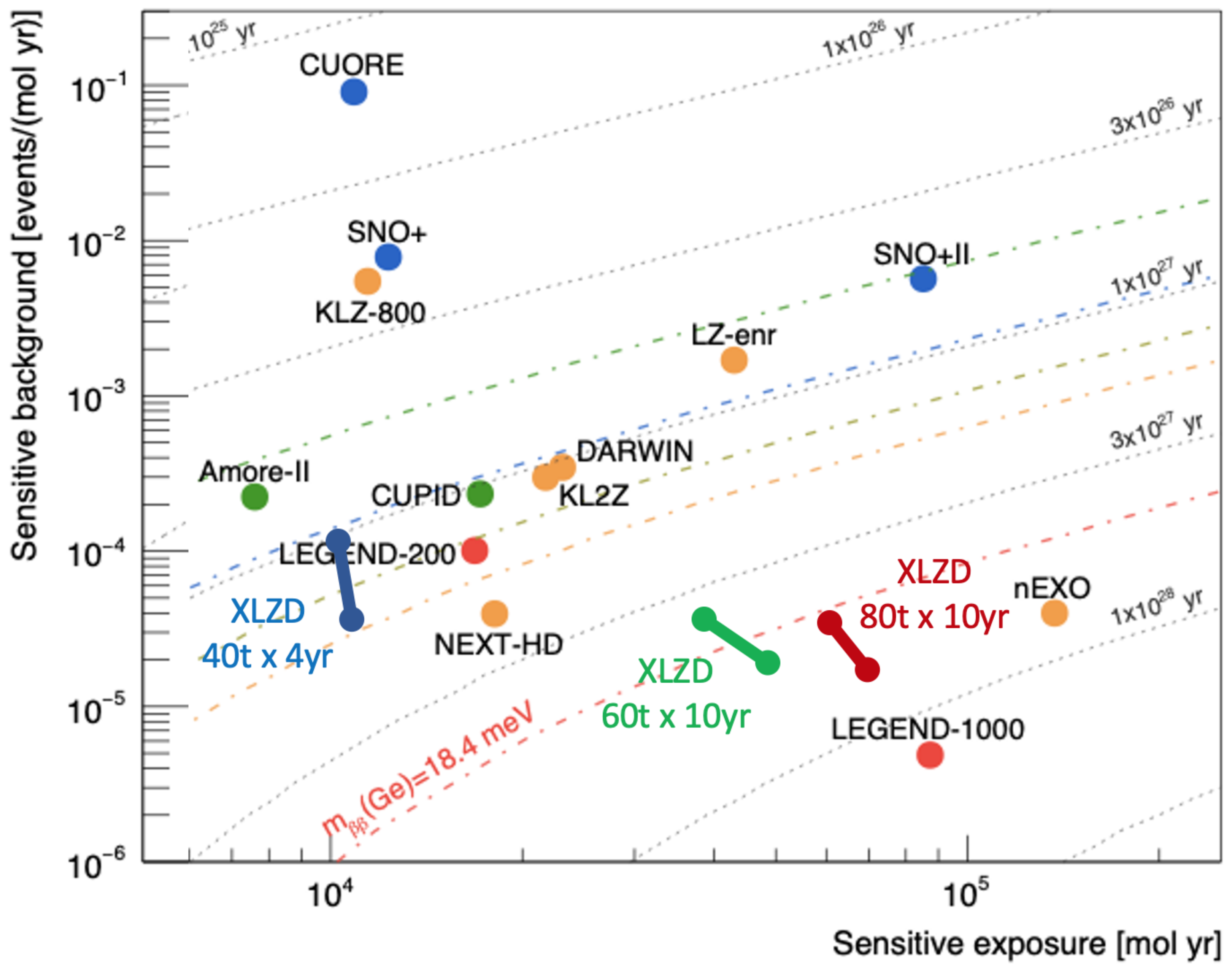




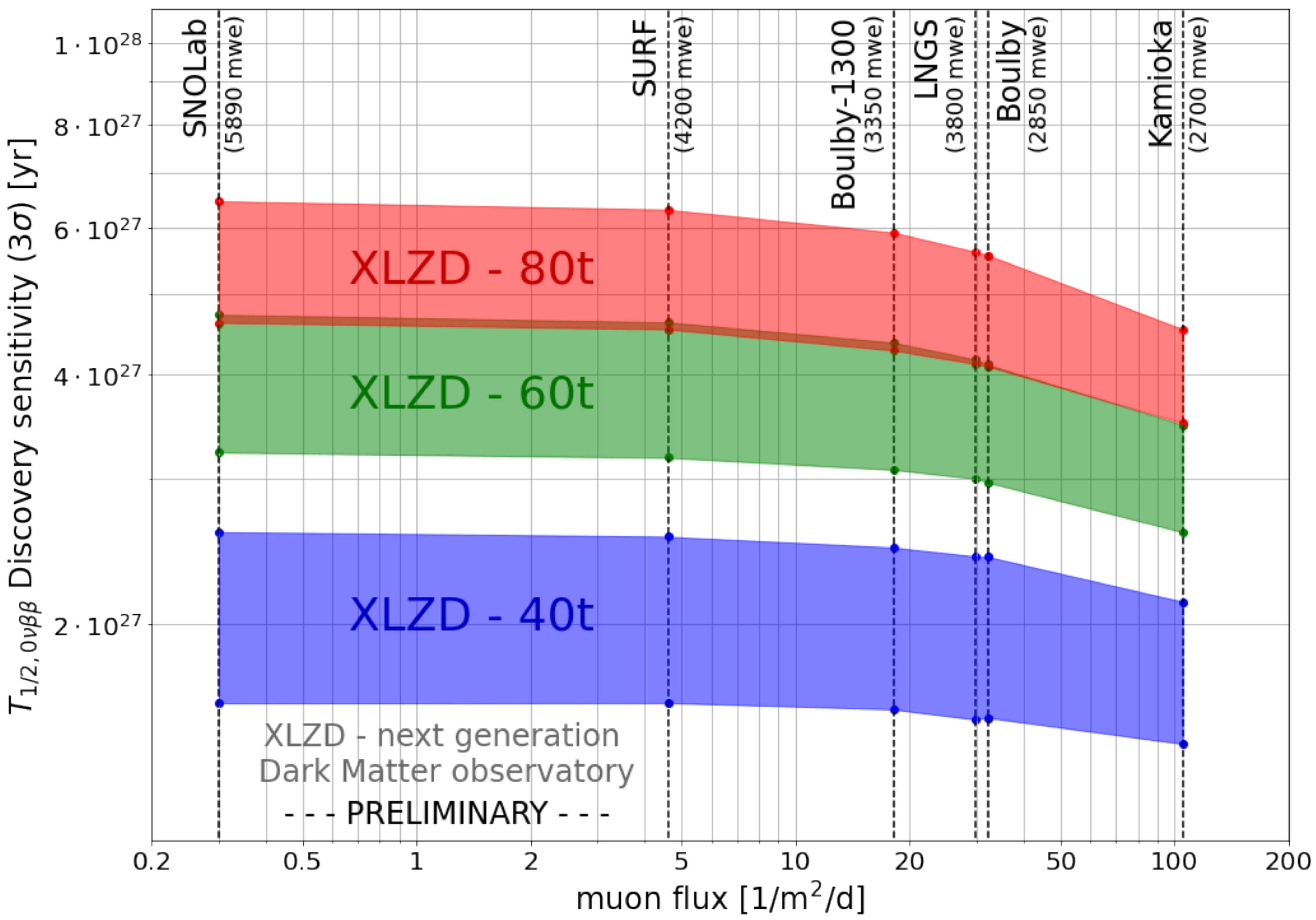
XLZD sensitivity to $0\nu\beta\beta$ decay

- 3σ discovery sensitivity: 6.4×10^{27} yr (80 t, 10 y)
- Using BG-rate based figure-of-merit and the optimal fiducial volume $$T^{0\nu}_{1/2} = \ln 2 \frac{\epsilon\, f_{\mathrm{ROI}}\, \alpha\, N_A}{1.64\, M_{\mathrm{Xe}}} \frac{\sqrt{Mt}}{\sqrt{B \Delta E}}$$
- Implementation of full PLR ongoing
- Coloured bands cover range between state-of-the-art TPC performance and backgrounds (lower) and more progressive assumptions (upper)
- Majorana mass range highly dependent on the nuclear matrix element (NME) (large variability between nuclear models)





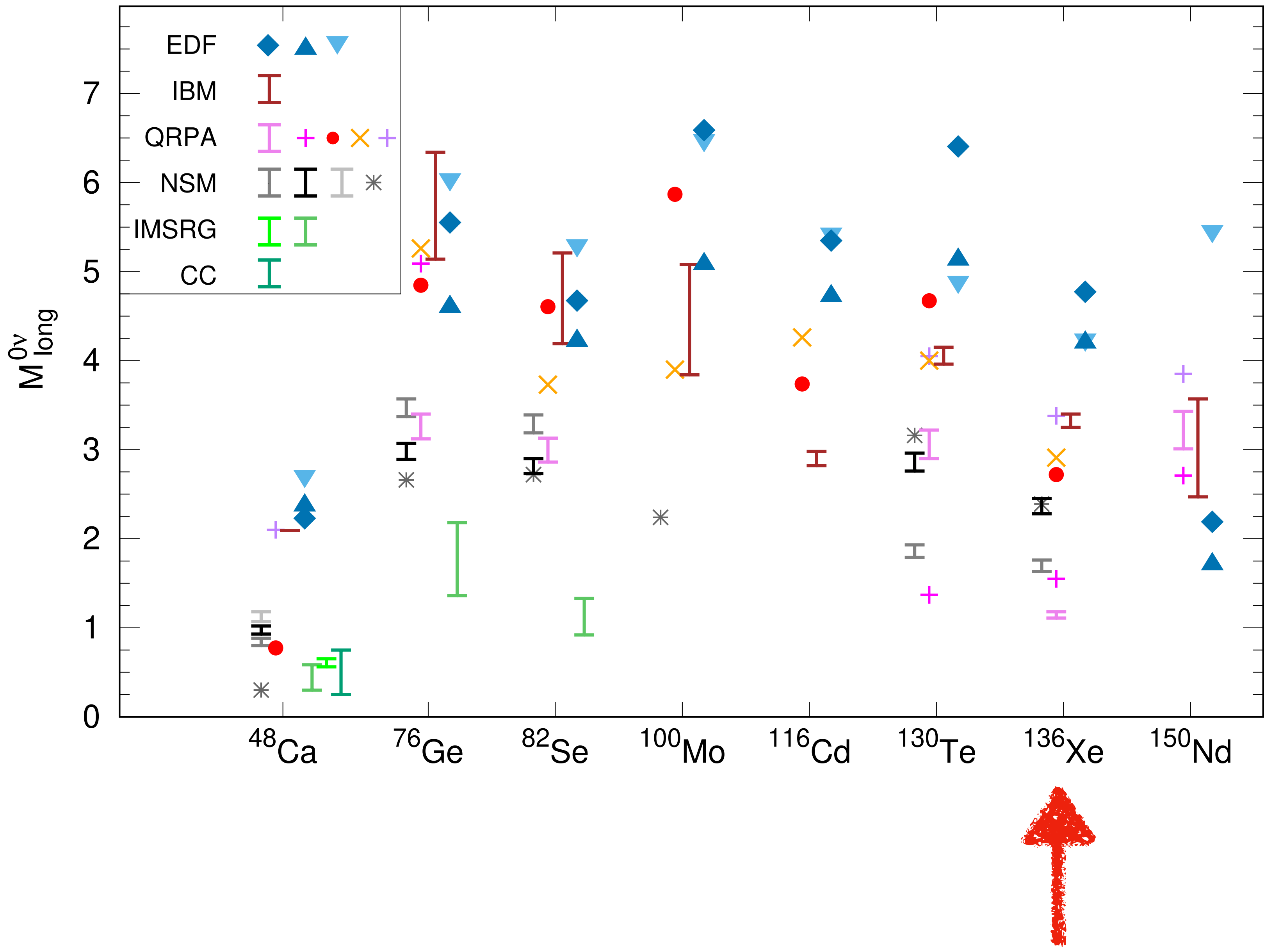
Impact of the installation site

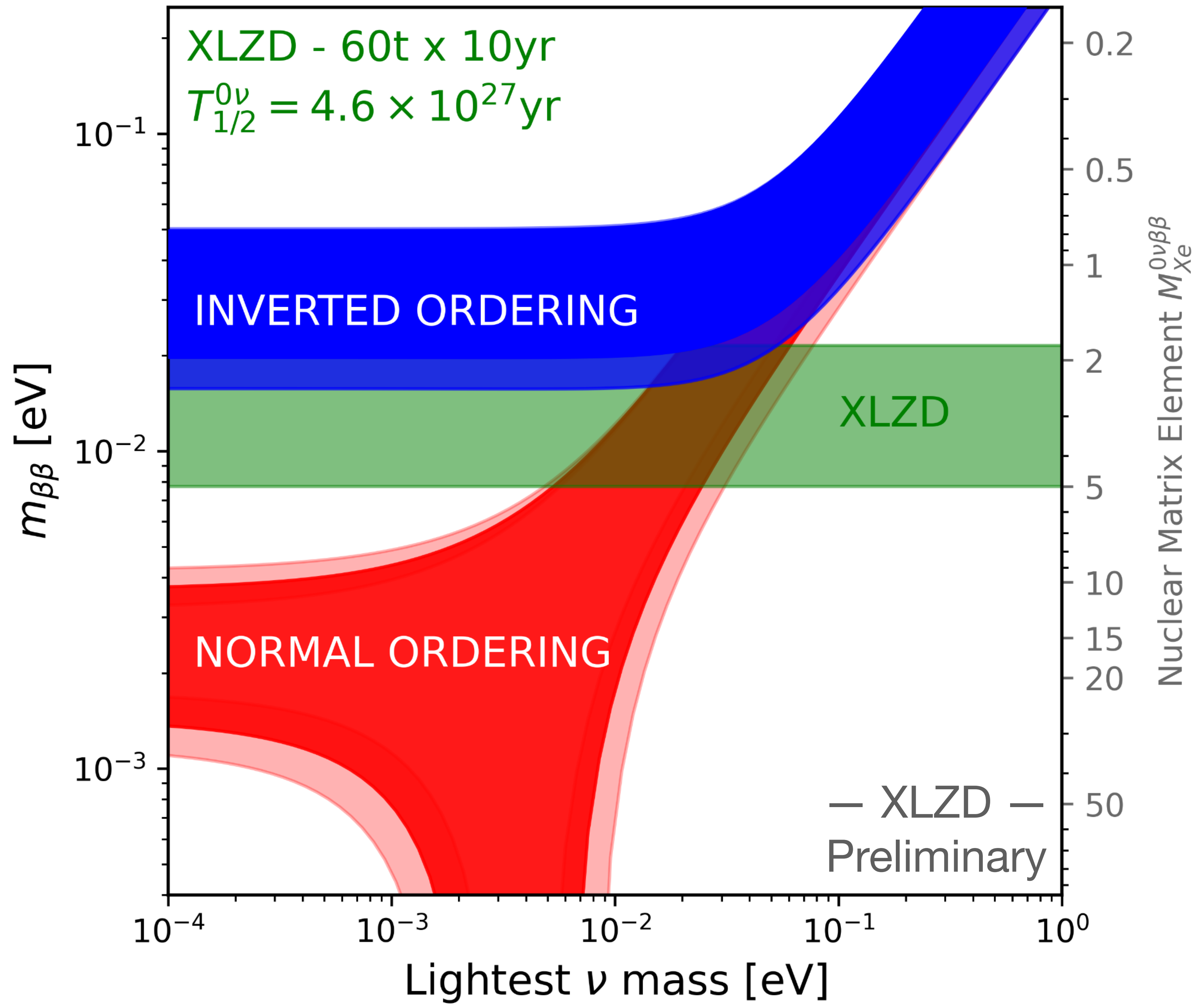


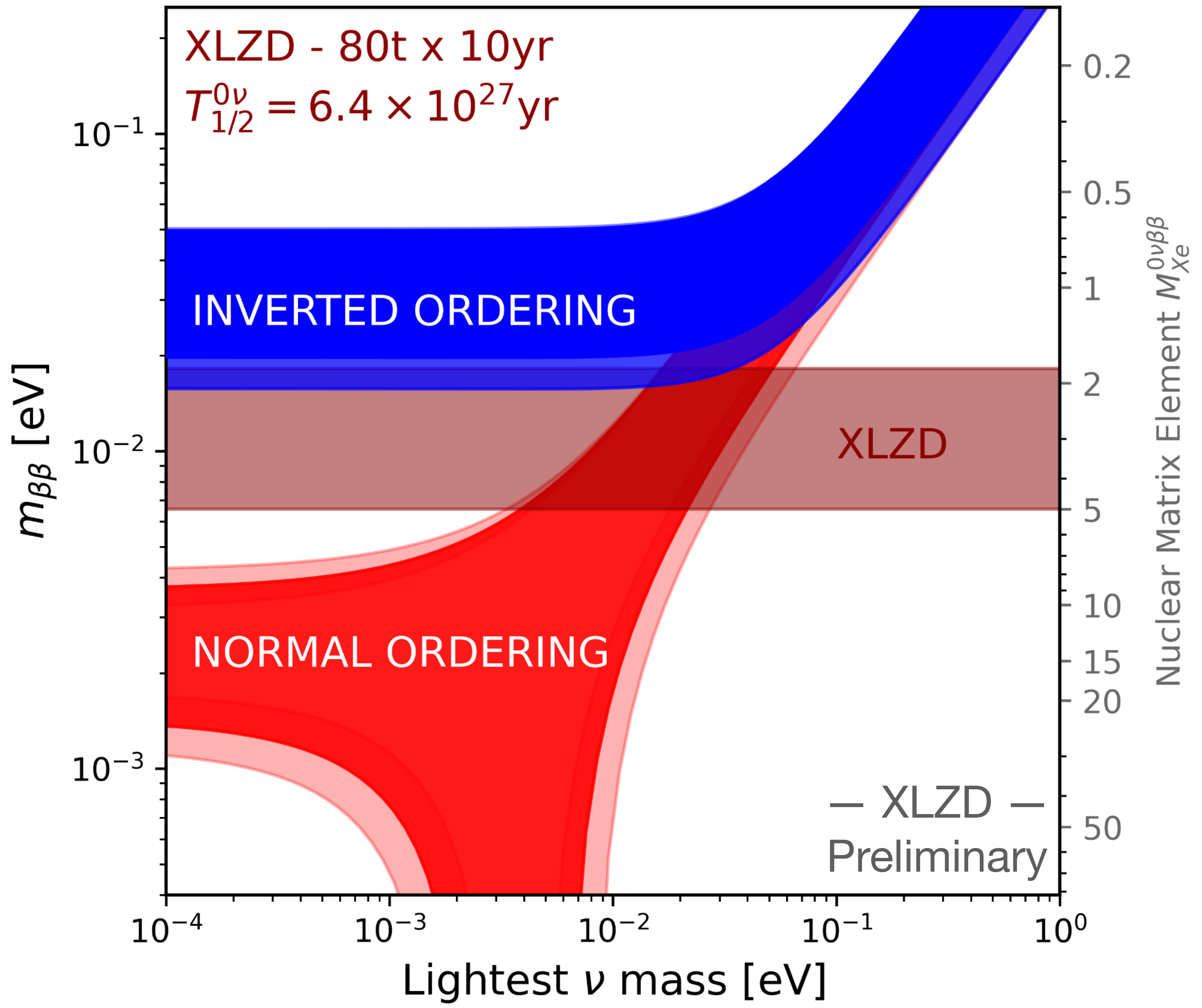
- Main variable between sites is the depth, which determines the muon flux
- Muons produce high energy neutrons that can reach the TPC and produce ^{137}Xe (beta decay)
- Impact on the sensitivity is not critical except in Kamioka
  - Gran Sasso is at the limit of ^{137}Xe being the dominant internal background
- Flux of high-energy gammas from the rock also varies between labs, but can be effectively shielded

Neutrino mass hierarchy reach

- Even in the scenario of a 60 t TPC, XLZD can mostly rule out the inverted hierarchy in 10 years
- These projections do not include the initial 5-year 40 t run, which will further increase the sensitivity reach
- Despite the uncertainties in the final detector performance and backgrounds, most of the uncertainty comes from nuclear models

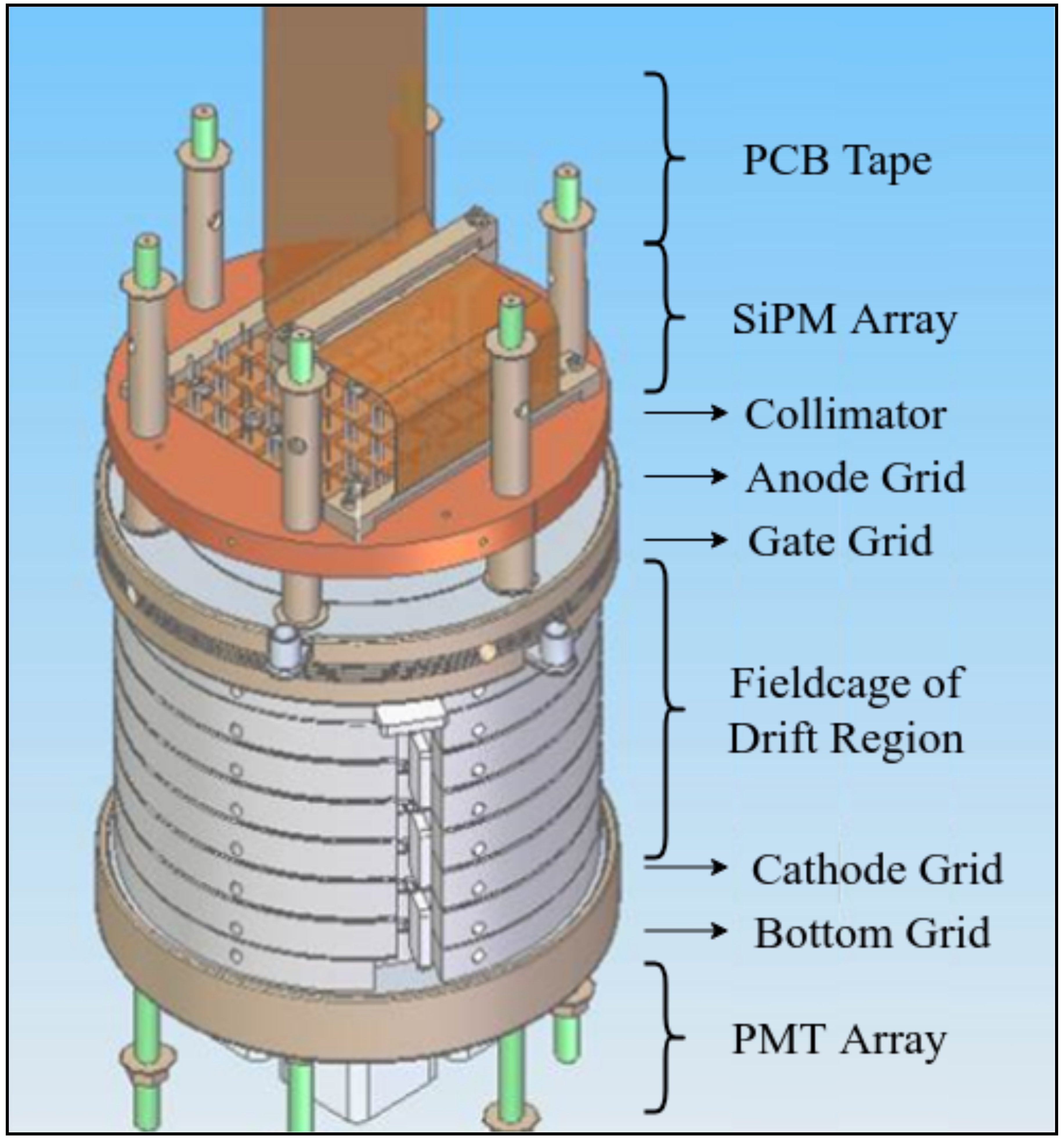






R&D for XLZD

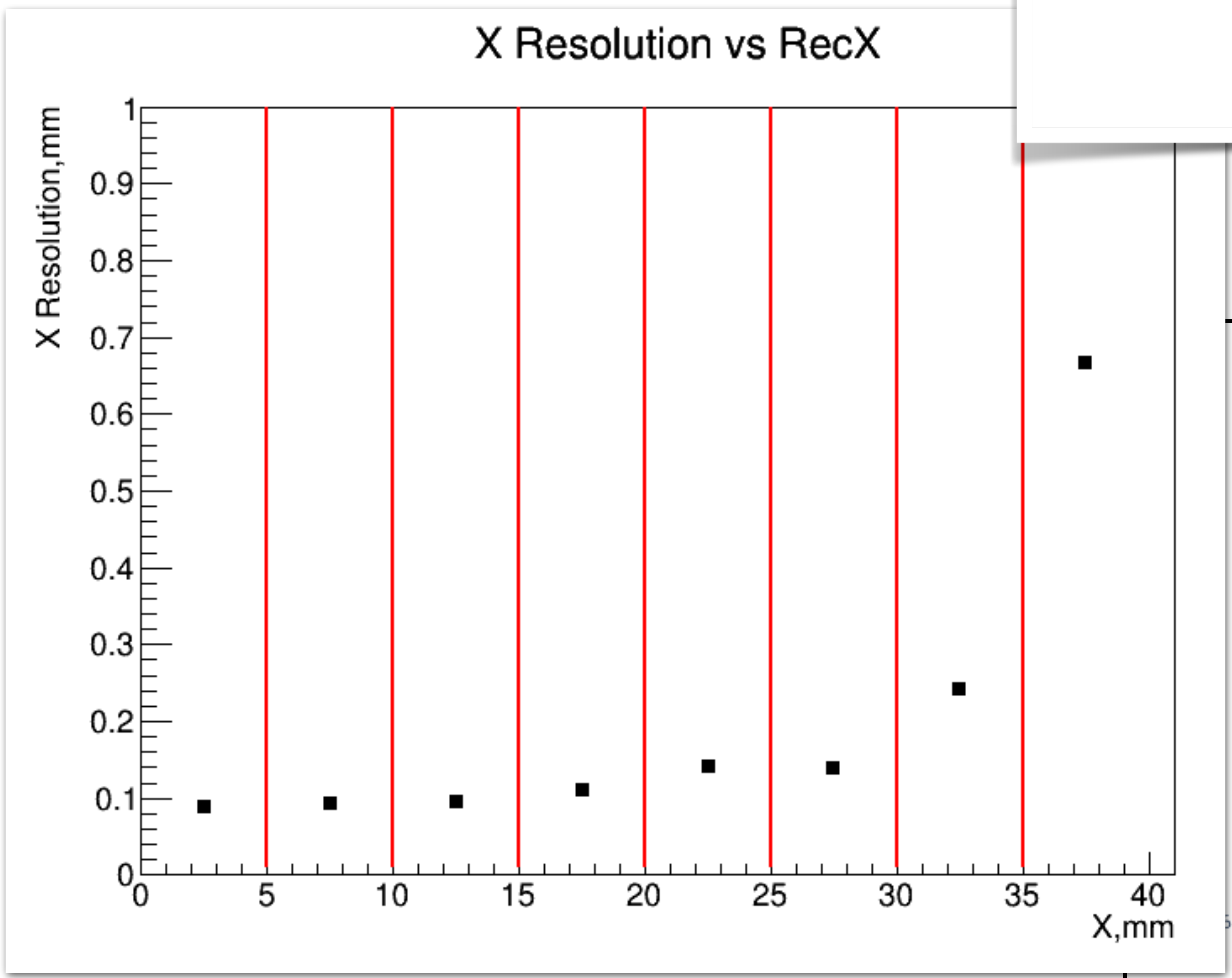
- LIP collaboration with UK groups
- Prototype chamber for various tests, all with the goal of optimising the position resolution:
  - Use of a SiPM array instead of PMTs at the top
  - Optimise electrode grids
    (geometry, wire thickness and pitch)
  - Doping with H_2 to reduce electron diffusion
    - Also improves sensitivity to low mass WIMPs
- Goal is to prove ~100 µm resolution is possible in these detectors

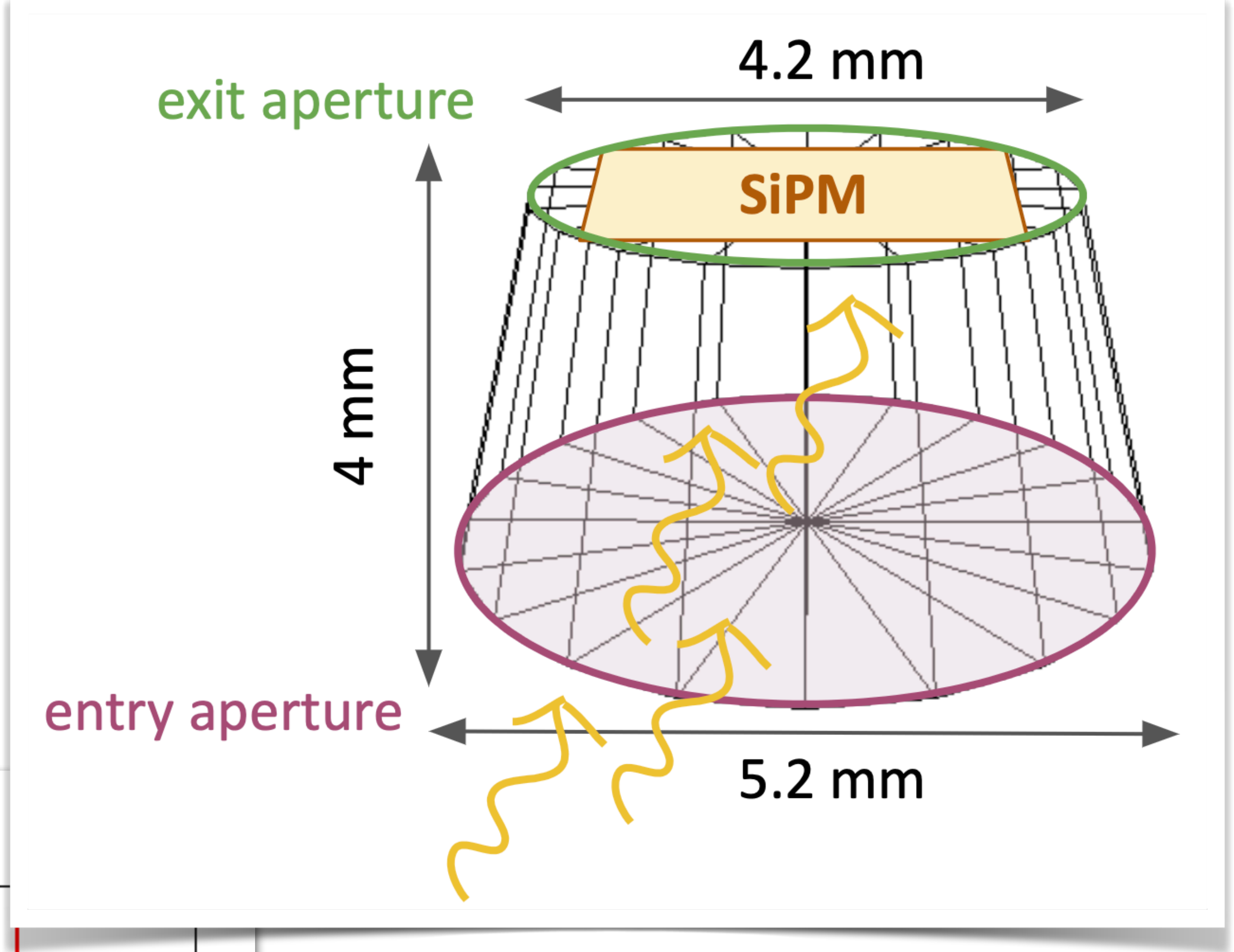


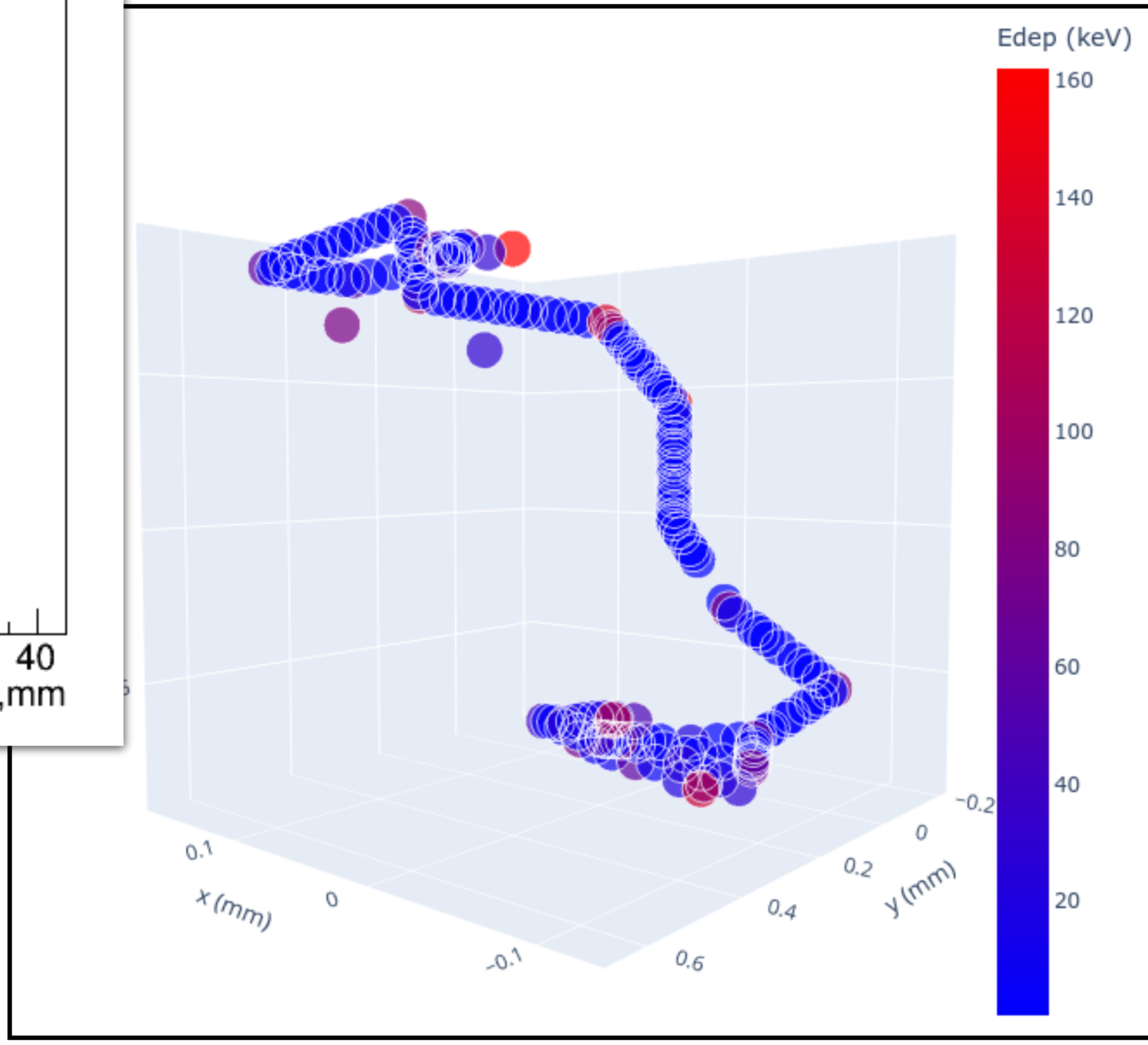
R&D for XLZD

Fátima Alcaso (MSc)

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





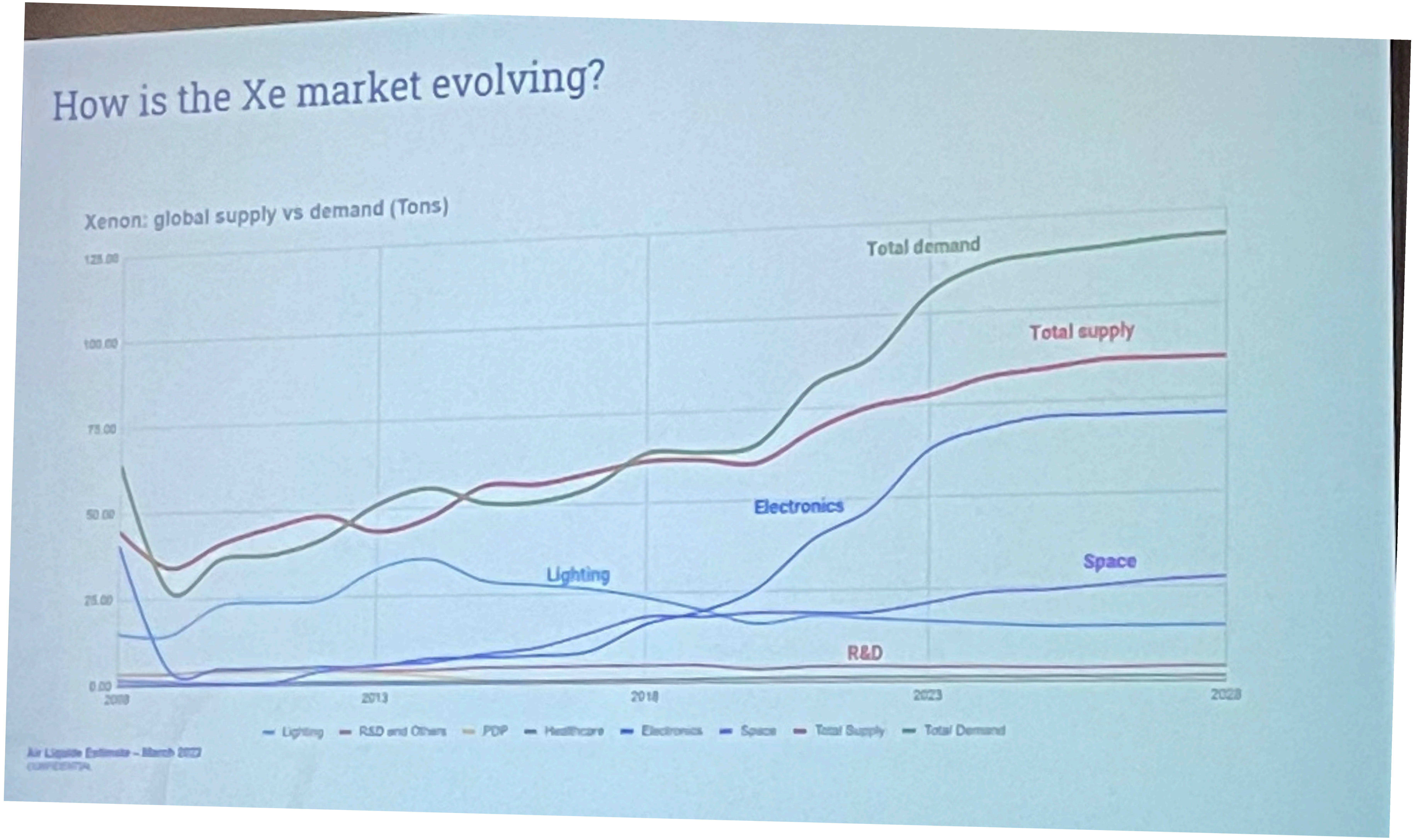


Summary

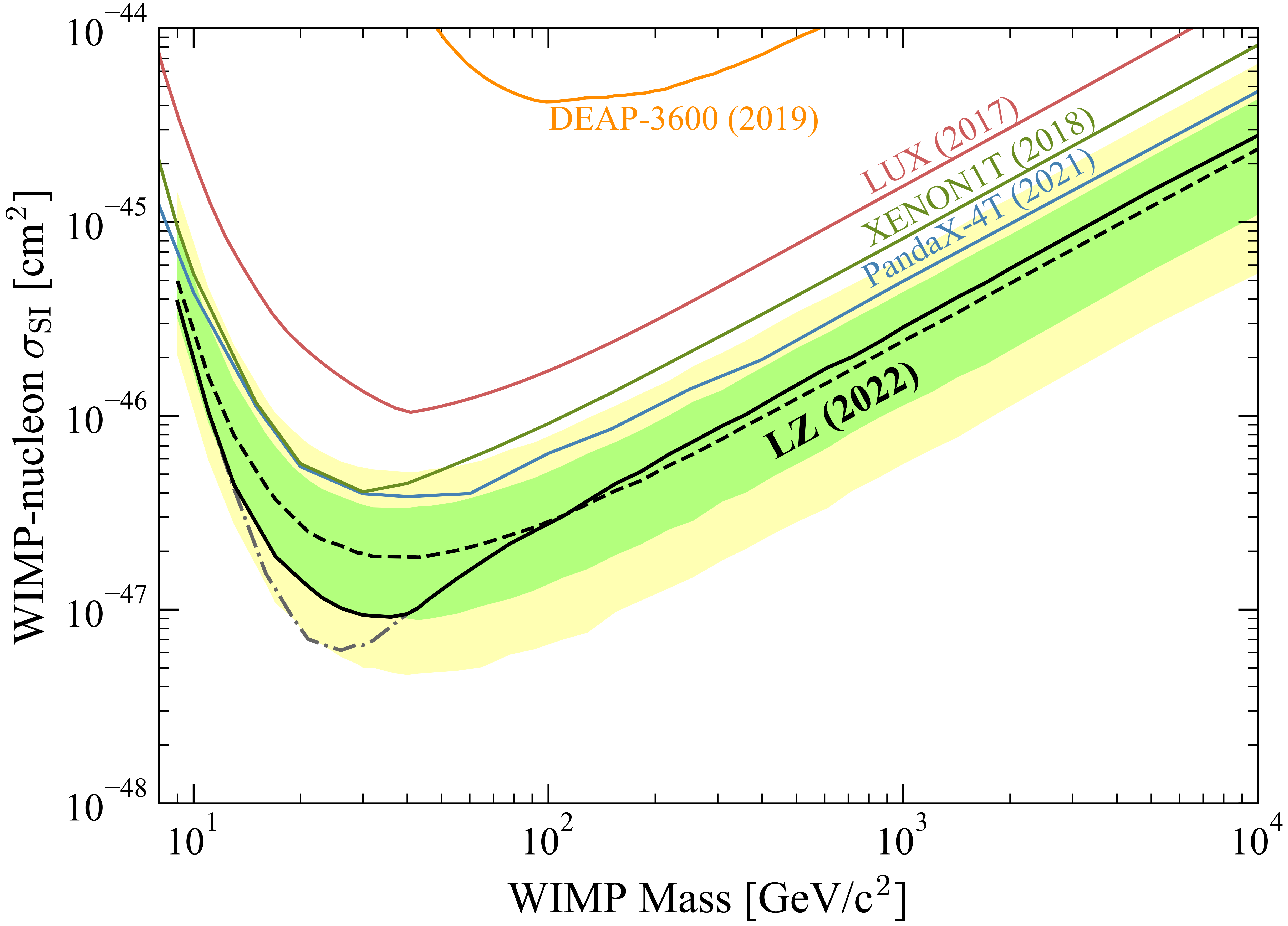
- 2-phase Xenon TPCs are the leading technology for direct WIMP search
- Technology has proven to be scalable from ~10 kg to multi-tonne detectors
- A larger detector is required to reach the neutrino fog
- LZ, XENON and DARWIN joined forces to build a 40-80 t detector: XLZD
- A large detector with extremely low background can search for other physics channels
- LIP is a founding member of XLZD
  - Active team working on ^{136}Xe $0\nu\beta\beta$ decay (3 new PhD students!)
  - R&D, background studies, simulations and design recommendations

Extras

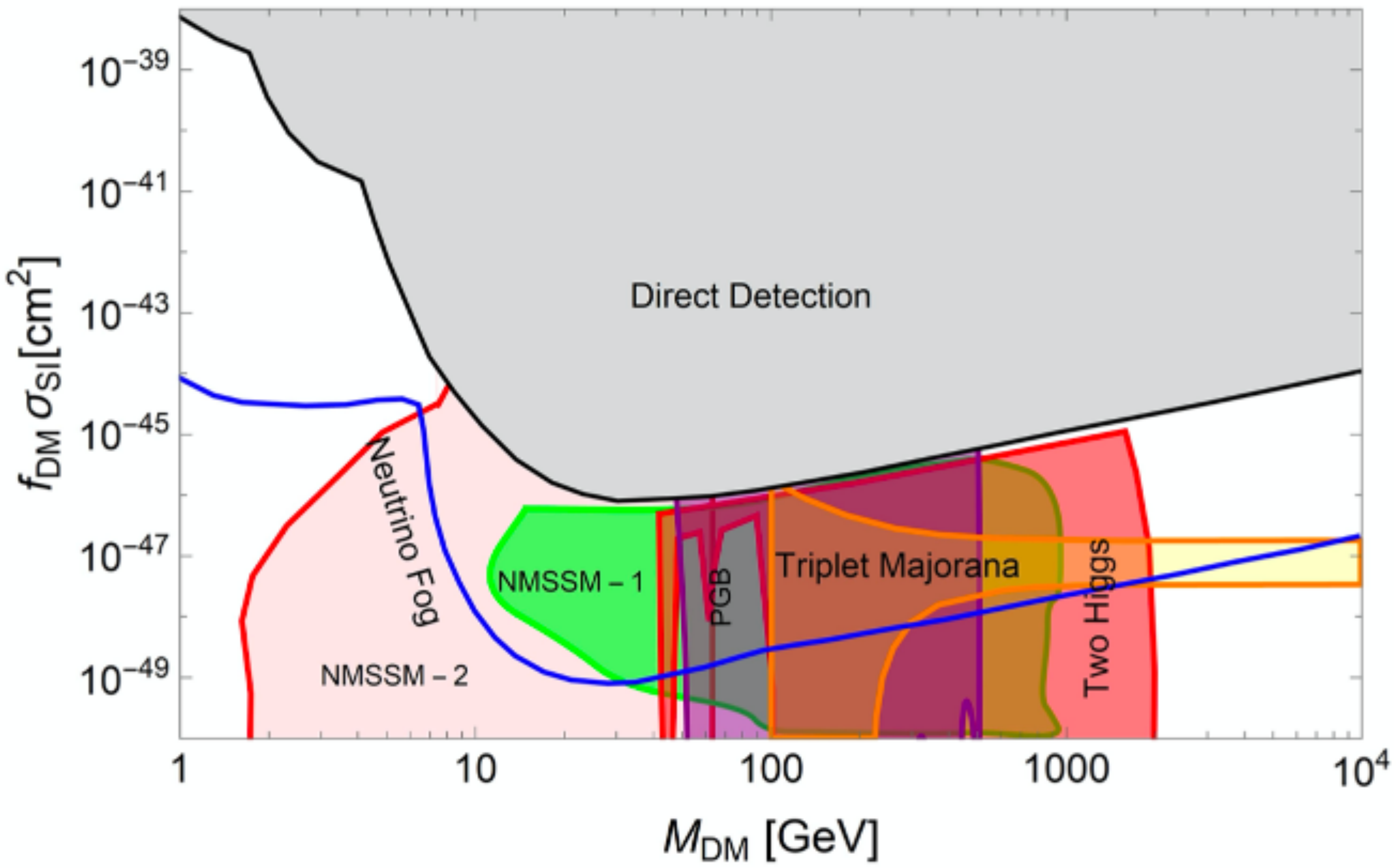
Xenon market



LUX-ZEPLIN First WIMP Results 2022



DM models



Direct Detection
Neutrino Fog
NMSSM – 1
NMSSM – 2
PGB
Triplet Majorana
Two Higgs
$f_{DM}\,\sigma_{SI}[cm^2]$
10^{-39}
10^{-41}
10^{-43}
10^{-45}
10^{-47}
10^{-49}
1
10
100
1000
10^4
M_{DM} [GeV]

Spin-dependent sensitivity