XLZD: Ultimate WIMP Dark Matter Search

Masaki Yamashita

Kavli IPMU The University of Tokyo (WPI)

on behalf of the XLZD consortium

地下から解き明かす宇宙の歴史と物質の進化
Unraveling the History of the Universe and Matter Evolution with Underground Physics

科研費 KAKENHI

DMNet

ERAN

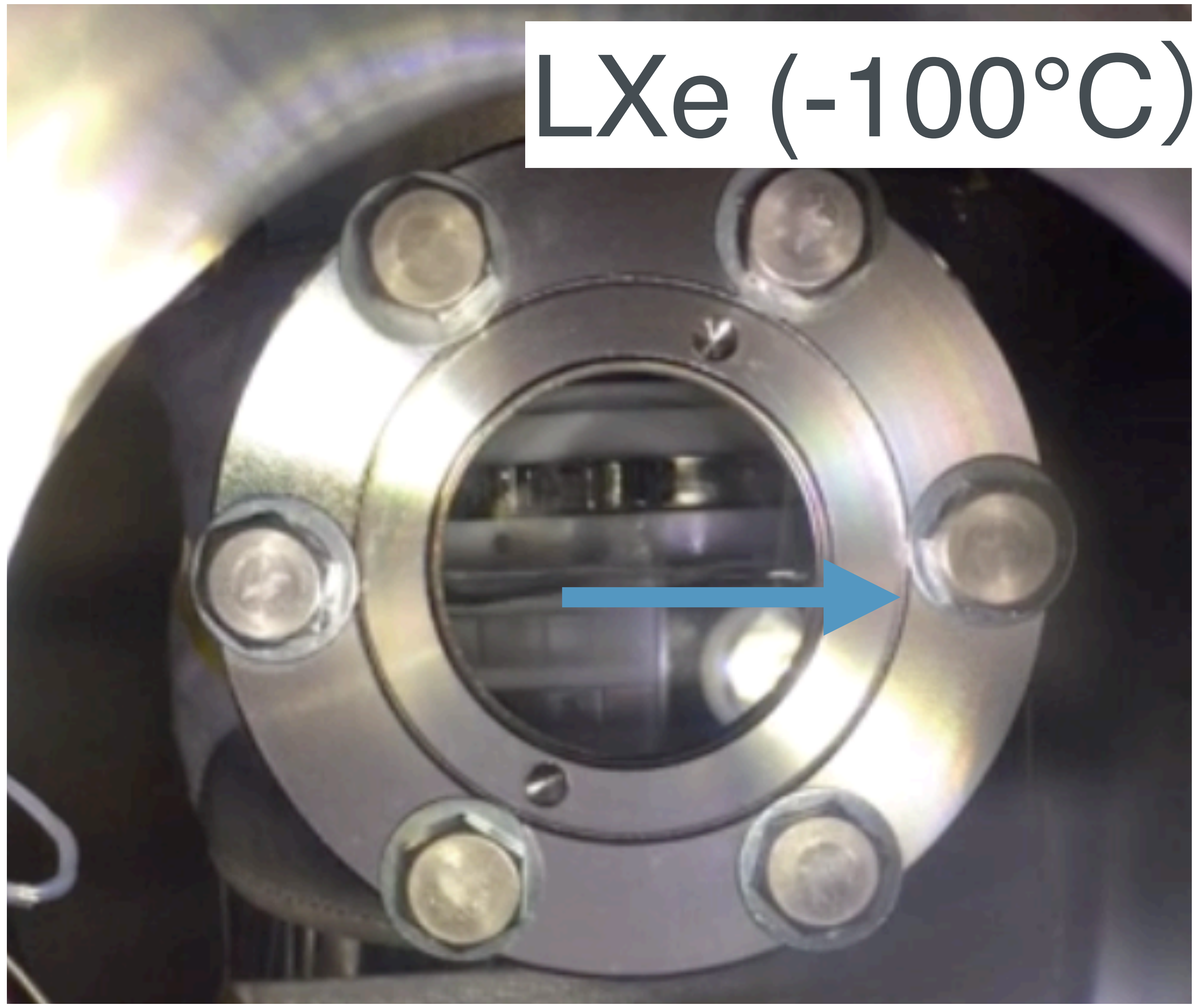
2023/12/01-03

Internal Workshop on "Double Beta Decay and Underground Science"

Liquid Xenon

	Z(A)	Boiling Point at 1 atm [K]	Density [g/cm³]	ionization [e-/keV]	scintillation [photon/keV]
Ar	18(40)	87.3	1.40	42	40
Xe	**54(131)**	**165**	**3.06**	**64**	**46**

- -100 °C (173 K)
- High-density rare gas liquid
- Hight light/charge yield



Xenon Isotopes

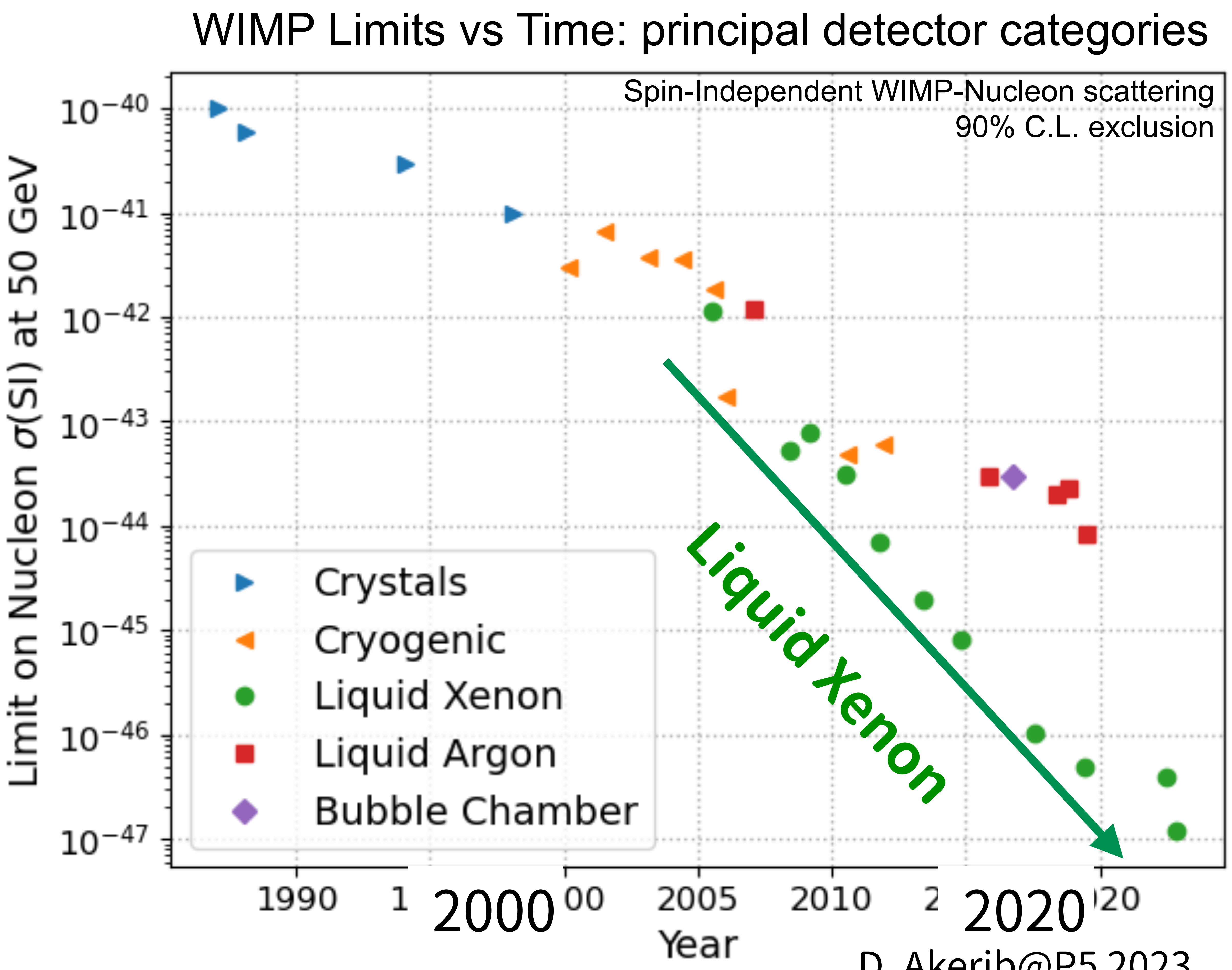
^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
0.10%	0.09%	1.92%	26.4%	4.07%	21.2%	26.9%	10.4%	8.87%

- Both spin-independent and spin-dependent WIMP DM search (half-half)
- ^{124}Xe double electron capture isotope ($T_{1/2} \sim 10^{22}$ y)
  - the longest half-life ever measured directly
- ^{136}Xe $0\nu\beta\beta$ decay
- No long-lived isotopes except ^{124}Xe and ^{136}Xe
- Enrich or depleted gases are possible.
  - e.g. Y. Suzuki arXiv:0008296

History of Direct WIMP Dark Matter Search

Liquid-gas double phase Xe Time Projection Chamber

- Scalability, large mass (tonne scale)
- Self-shielding: High Z(=54) and density (~3g/cm³)
- Easy purification in gas and liquid phase, even during science run
- Particle identification of electronic recoils and nuclear recoils
- Low energy threshold



D. Akerib@P5 2023

The XLZD Consortium

- **LZ** and **XENONnT** are operating and leading experiments
- **DARWIN**: planned after the XENON program. R&D and design studies for next-generation LXe TPC.
- Formed by
  - **XENONnT + LUX-ZEPLIN + DARWIN**

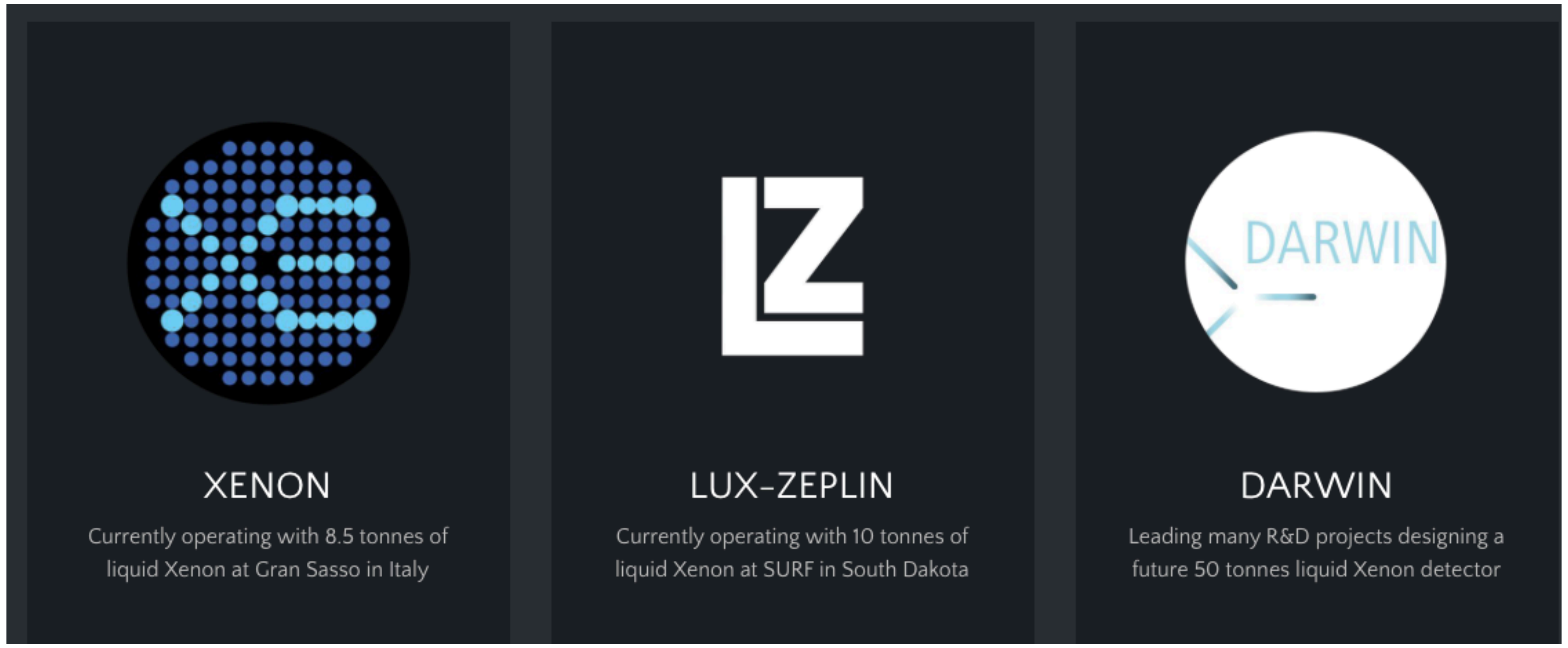
2021 XENON/DARWIN, LUX-ZEPLIN meeting
https://indico.cern.ch/event/1028794/
2021 **MOU signed**:16 countries, 104 scientists
2022 1st Summer Meeting at KIT in Germany
2023 2nd meeting at UCLA

White Paper : 2023 J. Phys. G: Nucl. Part. Phys. 50 013001

OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001 (115pp)
https://doi.org/10.1088/1361-6471/ac841a

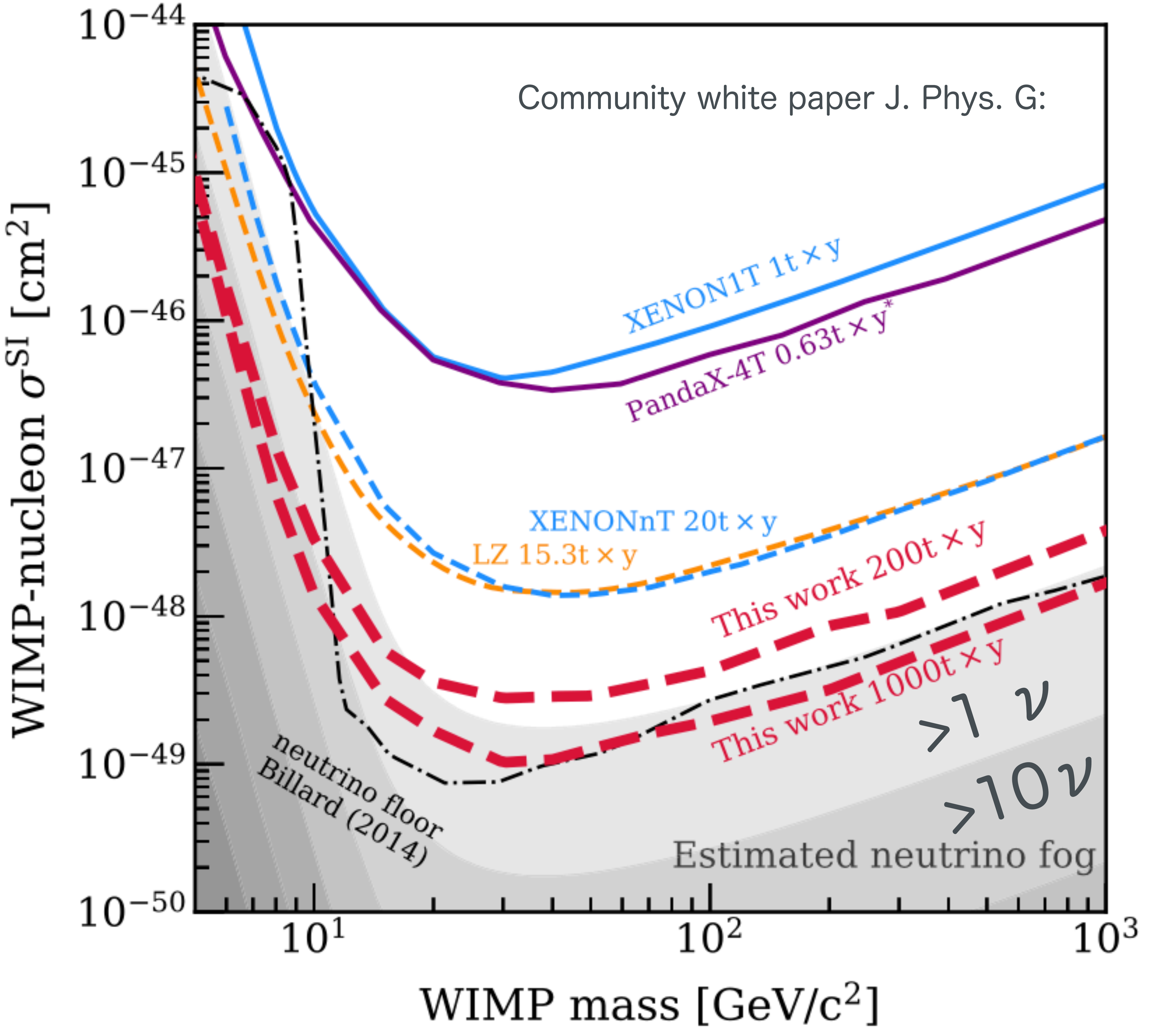
Topical Review

A next-generation liquid xenon observatory for dark matter and neutrino physics



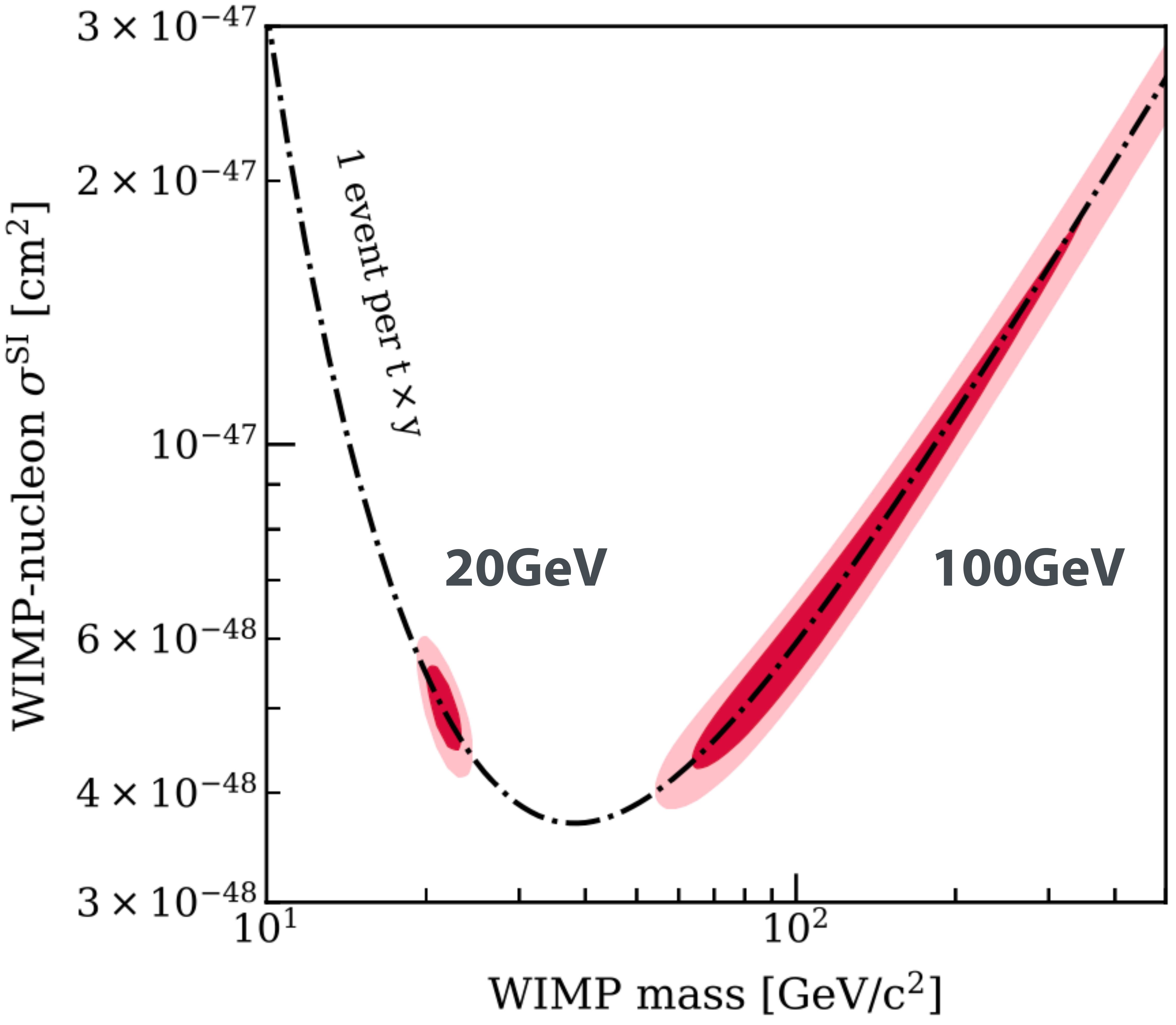
XLZD: WIMP Sensitivity

J. Phys. G 50 (2023) 013001



- **Searching for WIMPs down to the neutrino "fog"**
  - Indistinguishable background from astrophysical neutrinos
  - Limited sensitivity improvement (20% flux uncertainly)
  - Systematic uncertainty limit (1000 t·yr)
  - 90% C.L. exclusion 2.5x10^{-49} cm^2 (at 40 GeV, 200 t·yr)

Mass and Cross Section



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  - Example discovery contours
    - 1000 t X y exposure

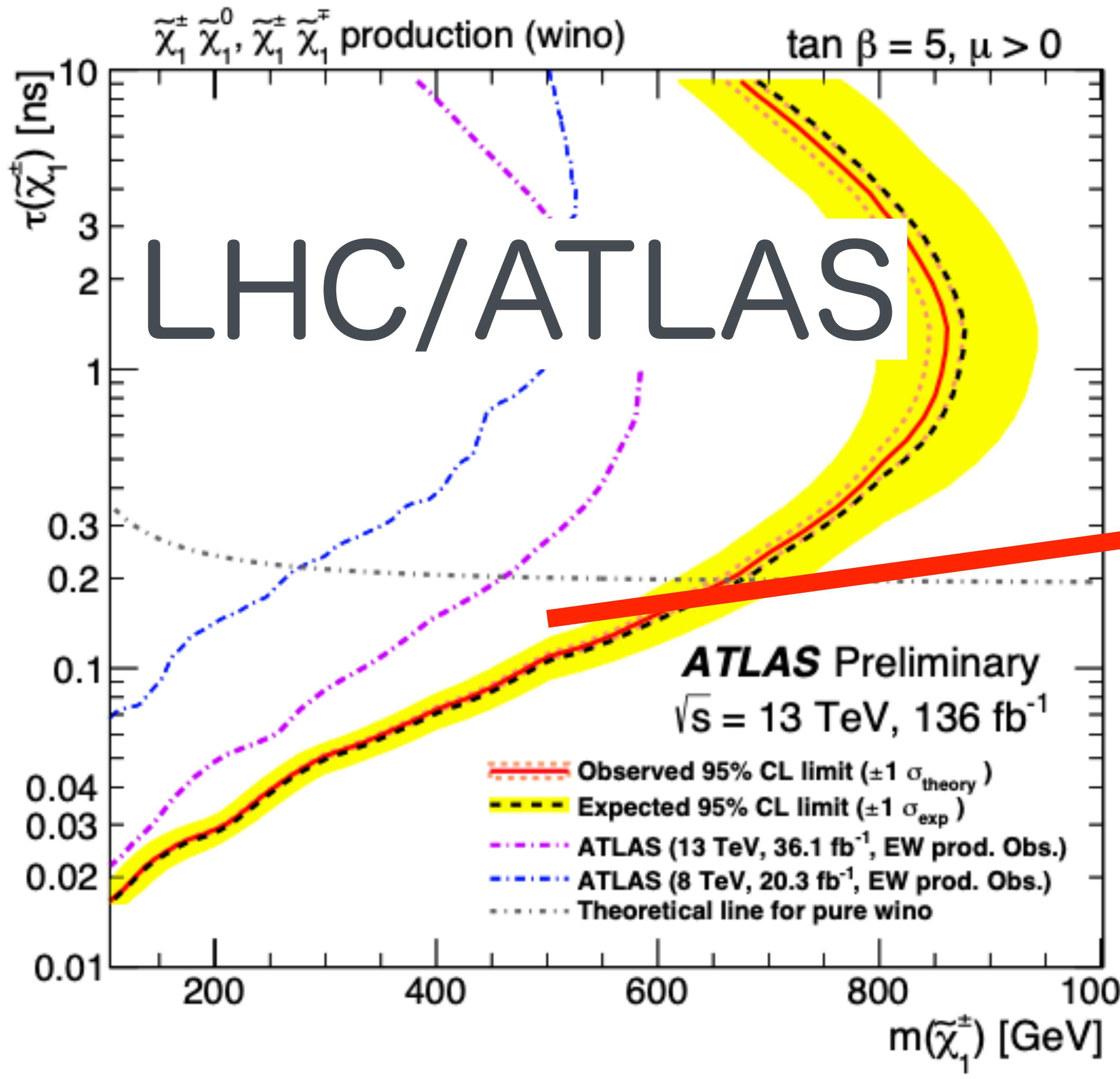
WIMP DM Search in 2020'-2030'

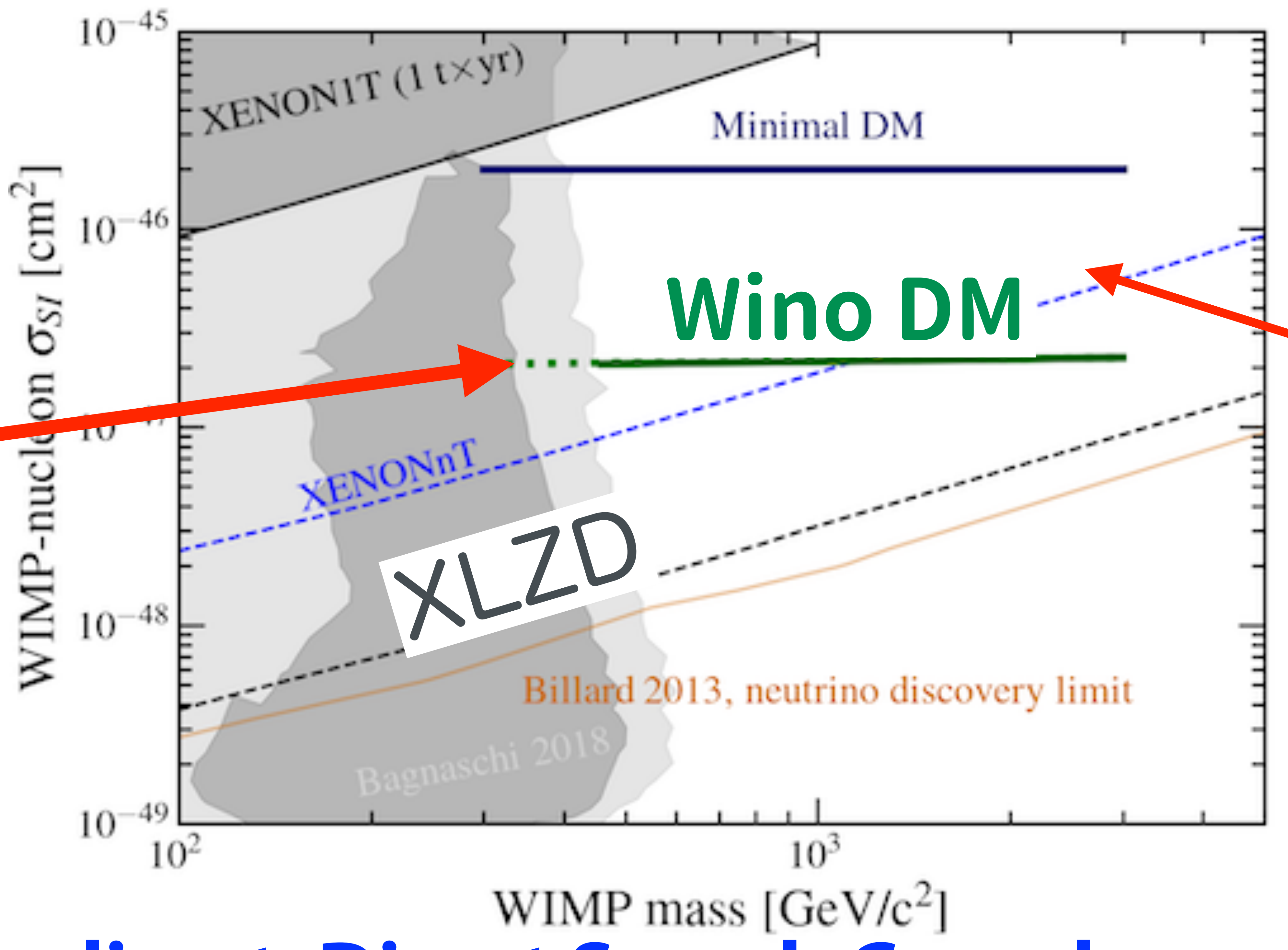
'minimal dark matter' scenario

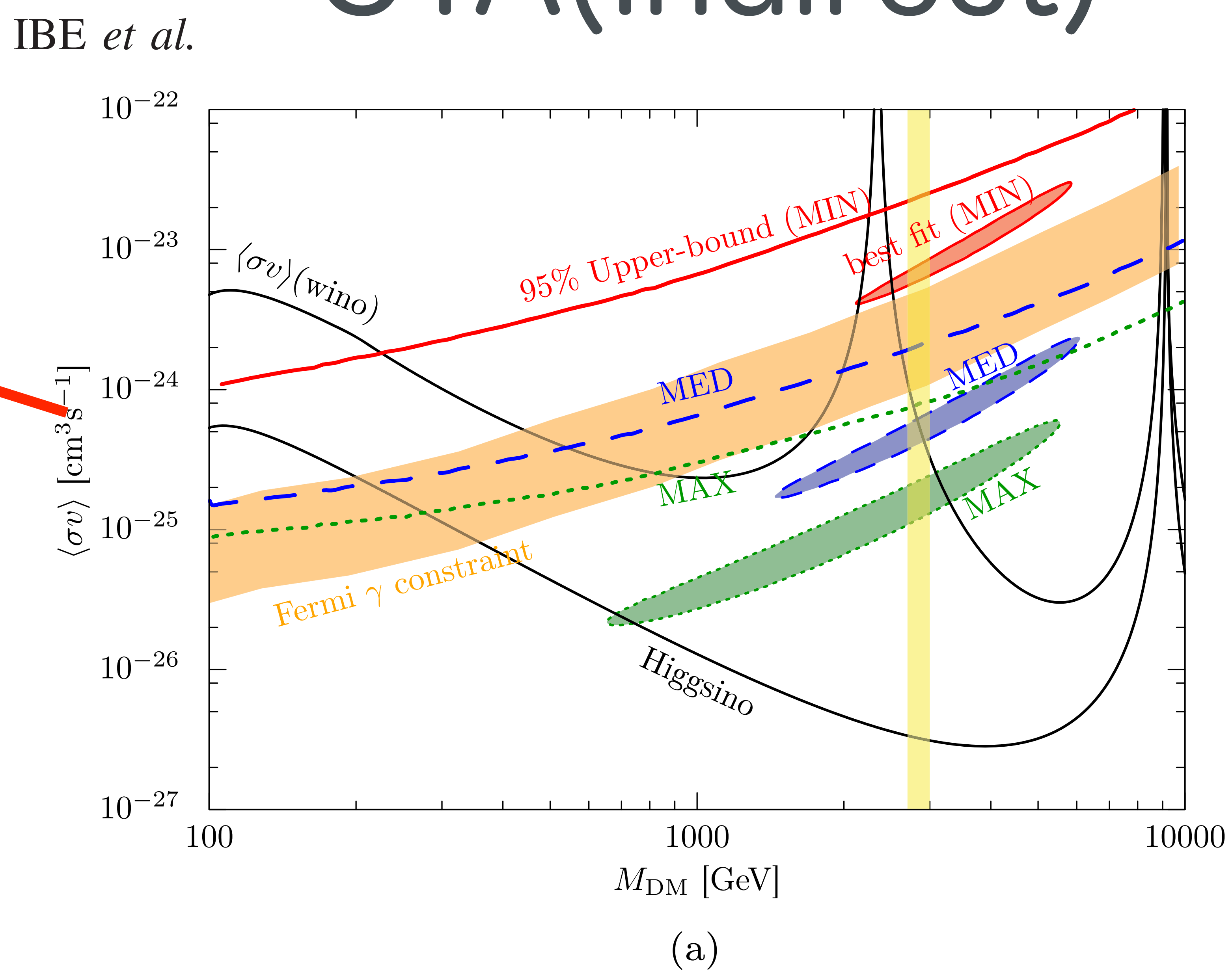
(almost) Wino DM

- the lightest member of an electroweak multiplet
- a very predictive and simple model (2×10^{-47} cm^2)

CTA(Indirect)





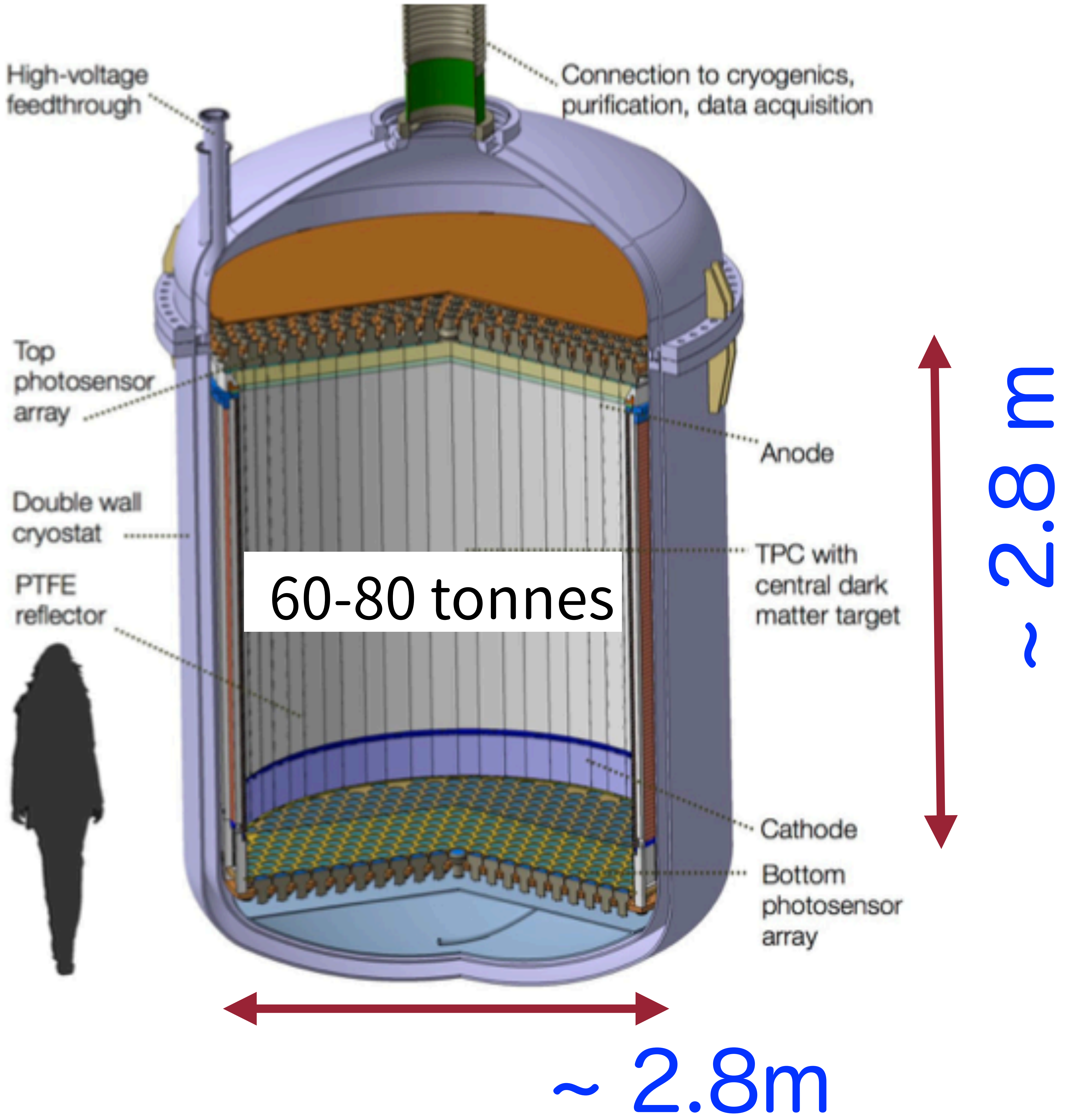


Minimal DM, almost pure Wino
-> Hisano, Ishiwata, Nagata JHEP06(2015)097

Collider, Indirect, Direct Search Complementarity

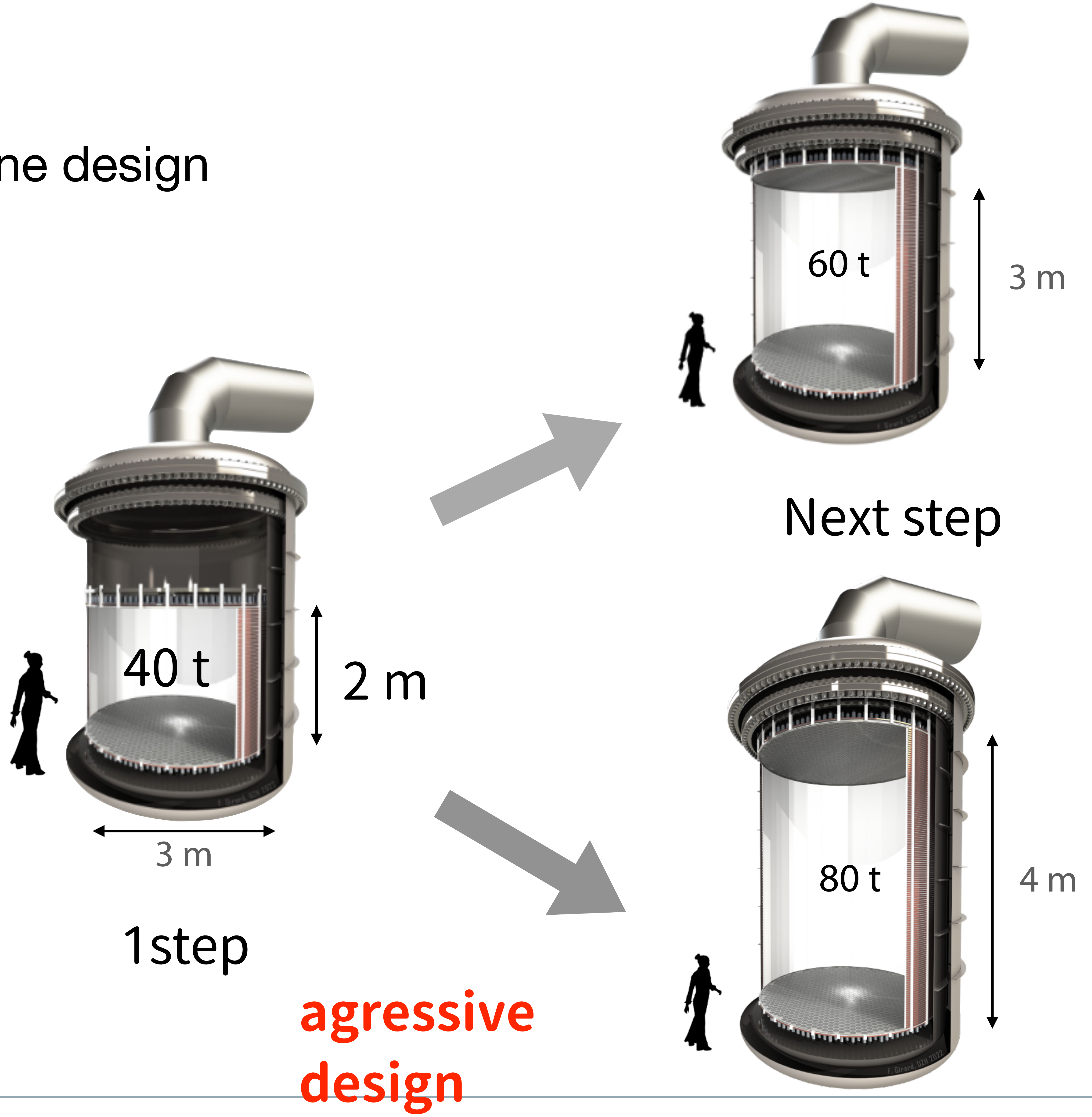
Detector: Liquid Xenon Time Projection Chamber

- **Largest xenon observatory for rare events**
  - The design is based on the mature technology of current-generation LXe TPC and will have opportunities for further optimization of the individual detector components.
  - ~ 3 m diameter and drift length
  - Target Mass: 60-80 tonnes LXe
    - limited by the xenon gas market

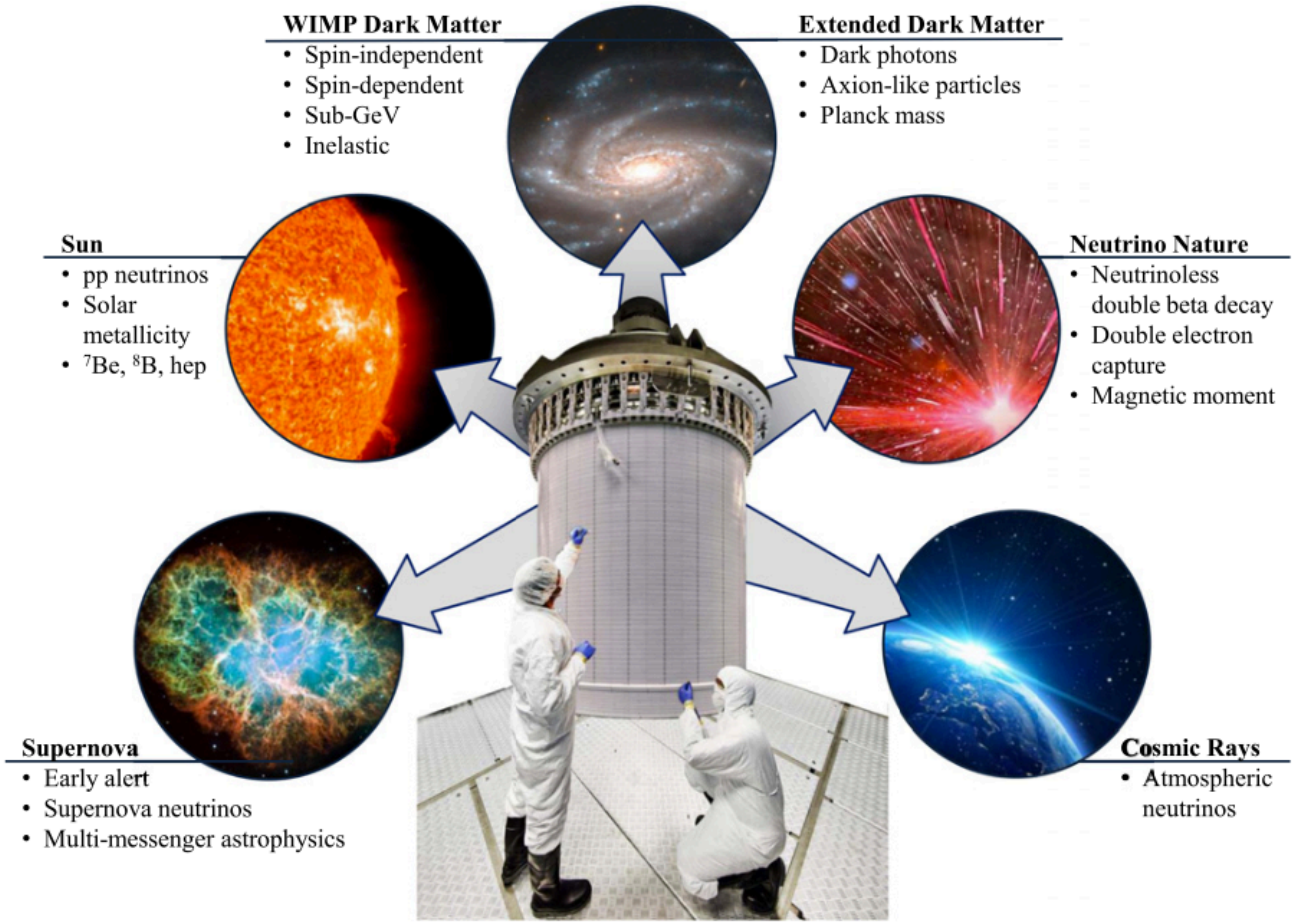


A staged approach

- Use 60 t diameter (~3 m in 1:1 ratio) as baseline design
- First phase:
  - 40 t, shallow detector
  - Build infrastructure for taller detectors (cryostat, water tank, etc.)
  - 5 years run time
  - Technical demonstration and early dark matter result
- Main phase:
  - >10 years operation
  - Full science reach
  - Ultimate size depending on xenon availability
  - **Nominal**, 60 t, 1:1 ratio
  - **Opportunity**, 80 t, tall detector



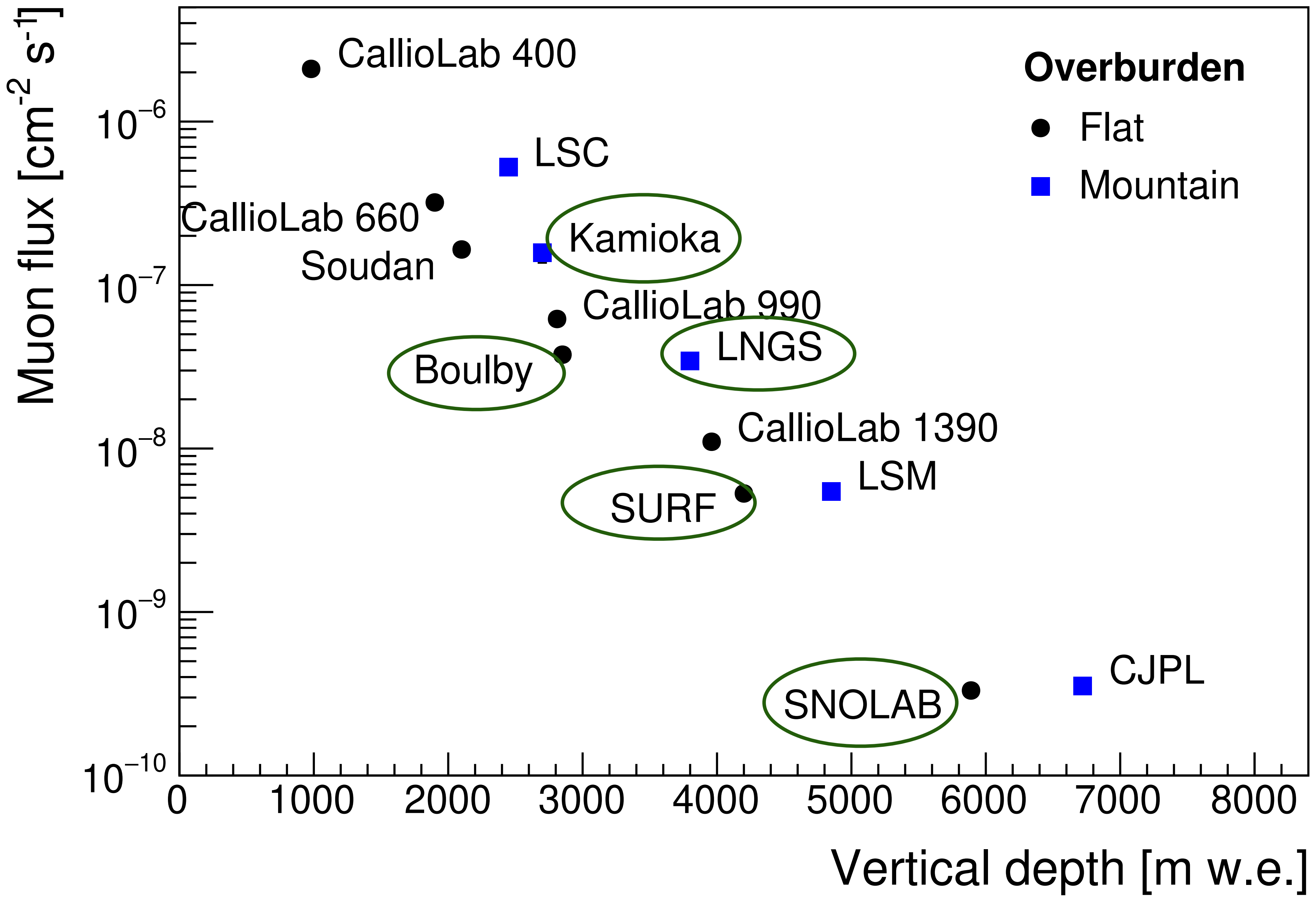
Science: Multi-purpose observatory



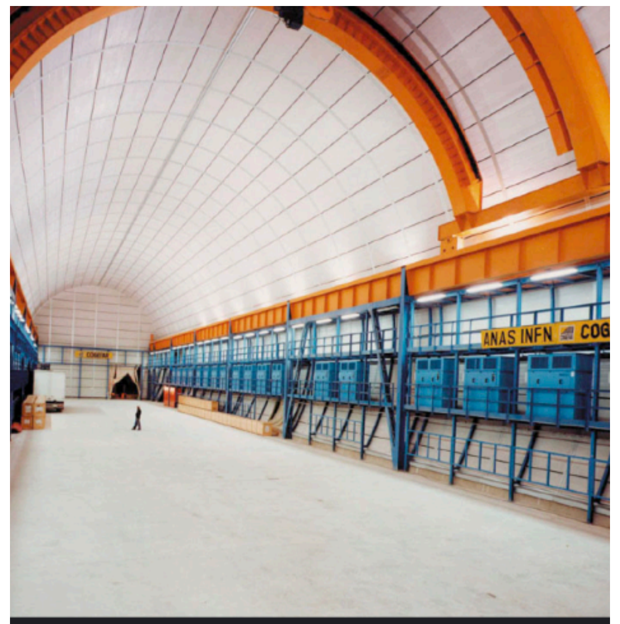
- WIMP measurement is the primary goal
- Opportunity to be competitive in $0\nu\beta\beta$
- Other DM candidates
  (Light WIMPs, Axions, ALPs, Dark Photons, etc)
- Neutrino physics
  - Solar neutrinos (model, properties)
  - Supernovae

XLZD Siting

- 5 candidate sites for hosting XLZD
  Kamioka, LNGS, Boulby, SURF, SNOLAB
- Well know laboratories
  have proven support capability for state-of-the-art experiments
- XLZD will require:
  - **Low cosmic muon flux to reach science goals**
  - **Significant staging space and UG fabrication capability**
  - **20-25 m diameter cavity: exists (LNGS, Kamioka, SNOLAB), new (Boulby, SURF**



Kamioka
Japan



LNGS
Gran Sasso, Italy

Boulby
North Yorkshire, UK

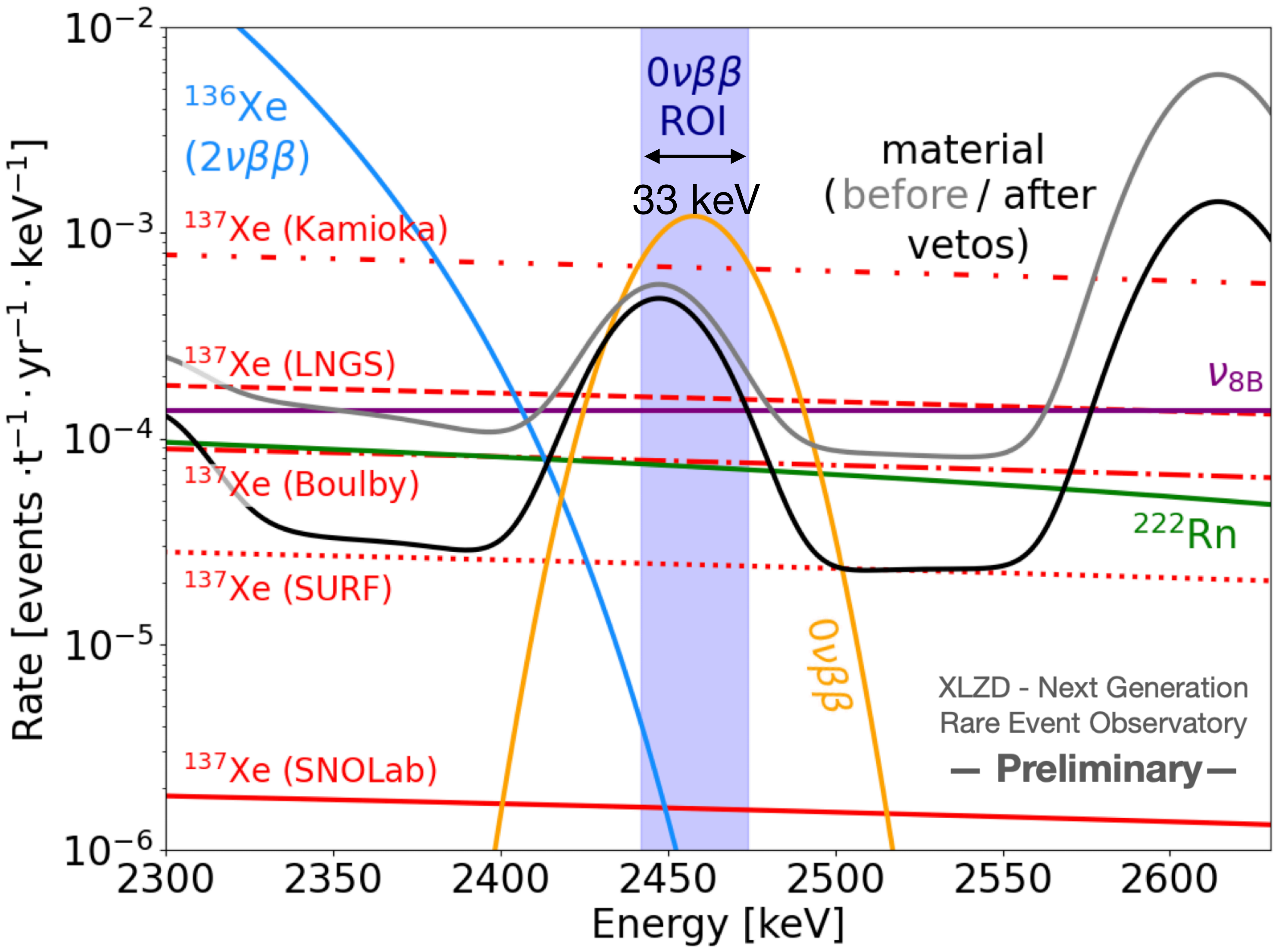
SURF
South Dakota, US

SNOLAB
Ontario, Canada

Alex Lindote@TAUP2023

XLZD: ^{136}Xe $0\nu\beta\beta$ Search

- ^{136}Xe $0\nu\beta\beta$ Q = 2458 keV
- ^{136}Xe is 8.9% of natural xenon
  - With 80 t target mass, XLZD will contain >7 t of ^{136}Xe
- Xenon TPCs have excellent resolution
  - 0.67% demonstrated in LZ, 0.8% in XENON1T



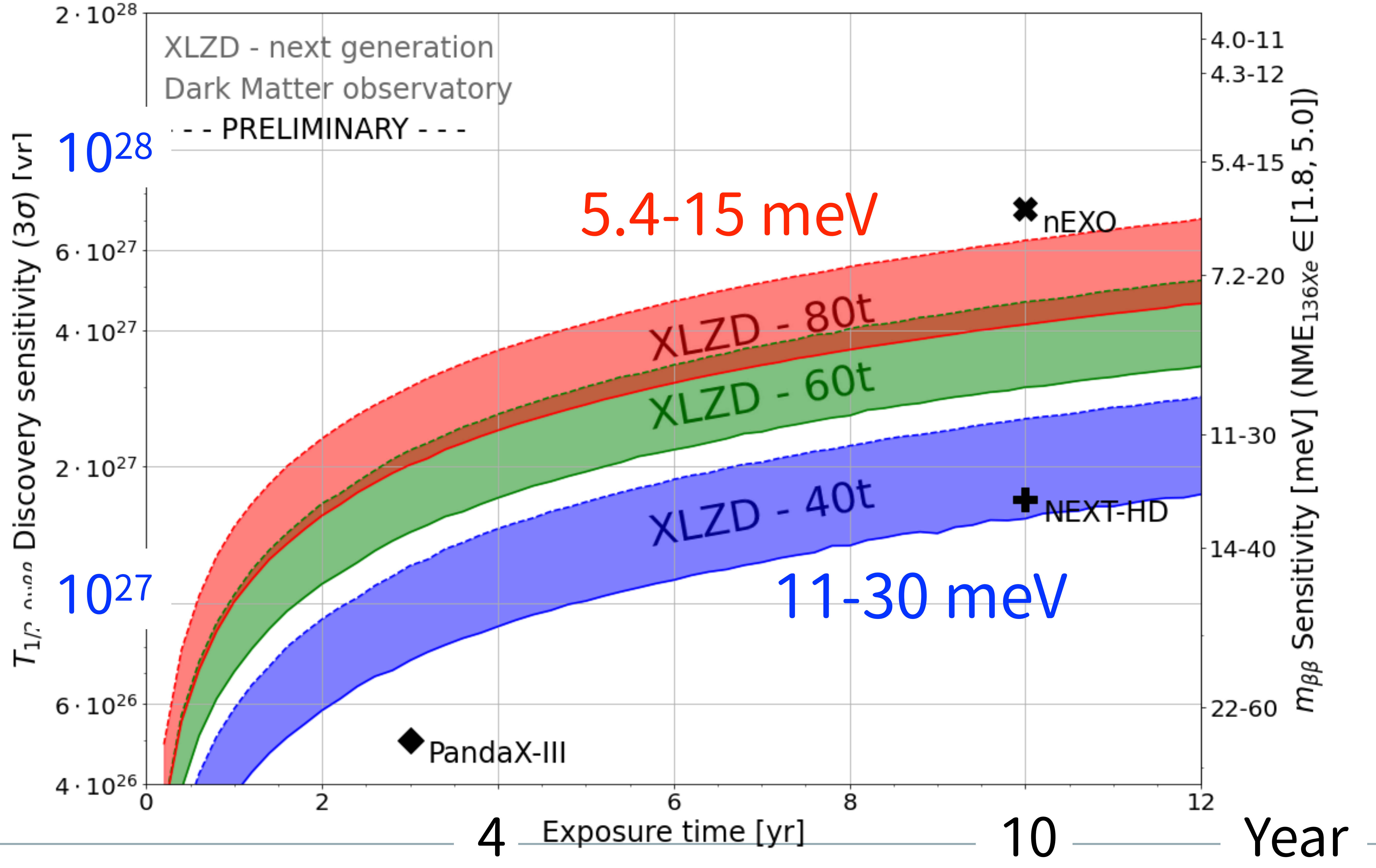
- **External gamma-ray background**
  - ^{214}Bi γ in the ^{238}U chain (2447 keV)
  - ^{208}Tl γ in the ^{232}Th chain (2615 keV) — can be highly suppressed by vetoes

- **Internal and intrinsic backgrounds**
  - ^{214}Bi β from ^{222}Rn in the xenon (Q = 3270 keV)
    - We assume 0.1 μBq/kg ^{222}Rn rate and >99.95% BiPo tagging
  - ^{137}Xe β (Q = 4170 keV), neutron activation of ^{136}Xe
    - Mostly by muon-induced neutrons, depending on the installation site
  - Electron recoils from ν-e$^-$ scattering (^{8}B), irreducible

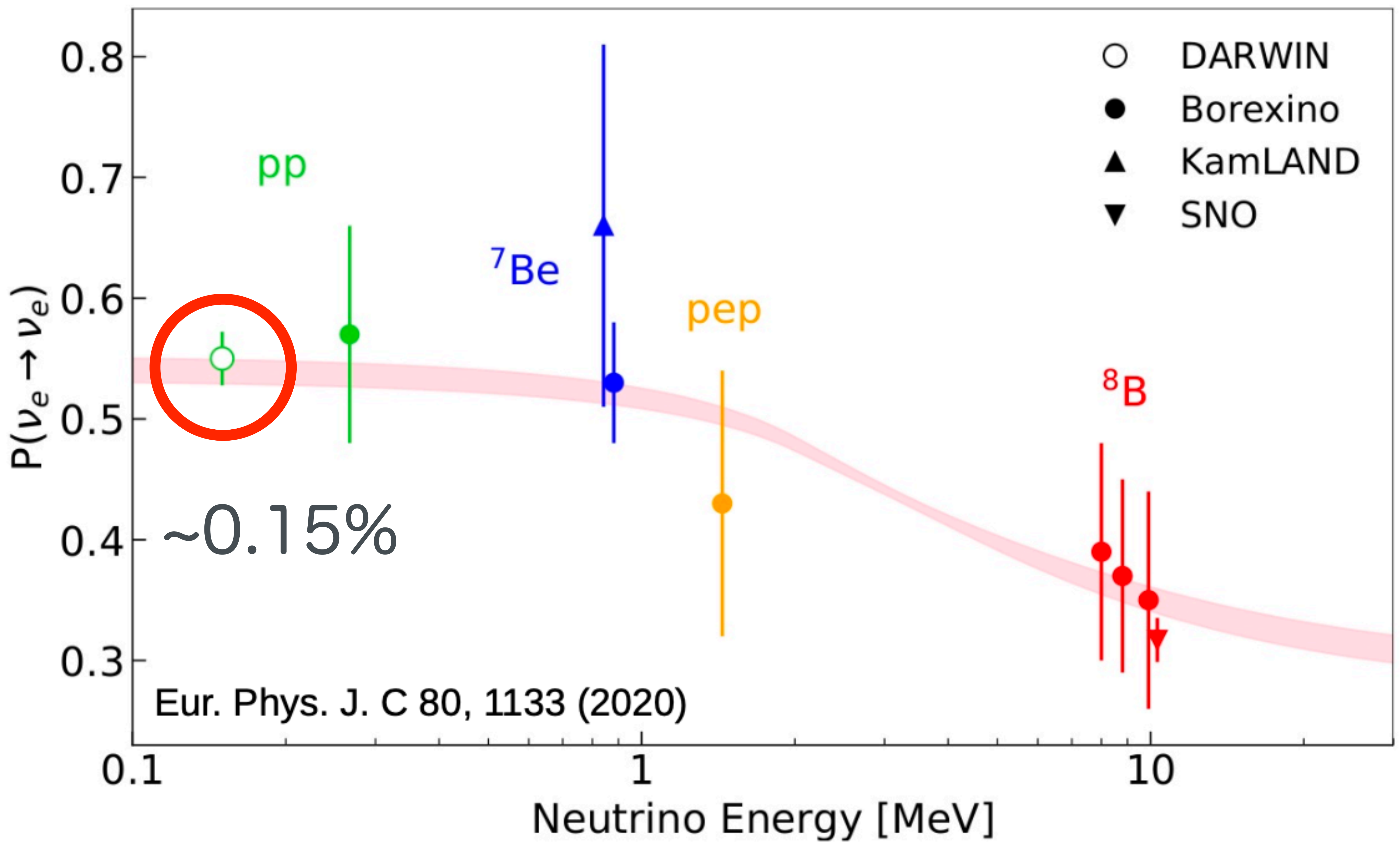
XLZD: ^{136}Xe $0\nu\beta\beta$ Search

Sensitivity Study

Bands cover the range between current TPC performance and backgrounds (lower) and more progressive assumptions (upper)



Solar Neutrino



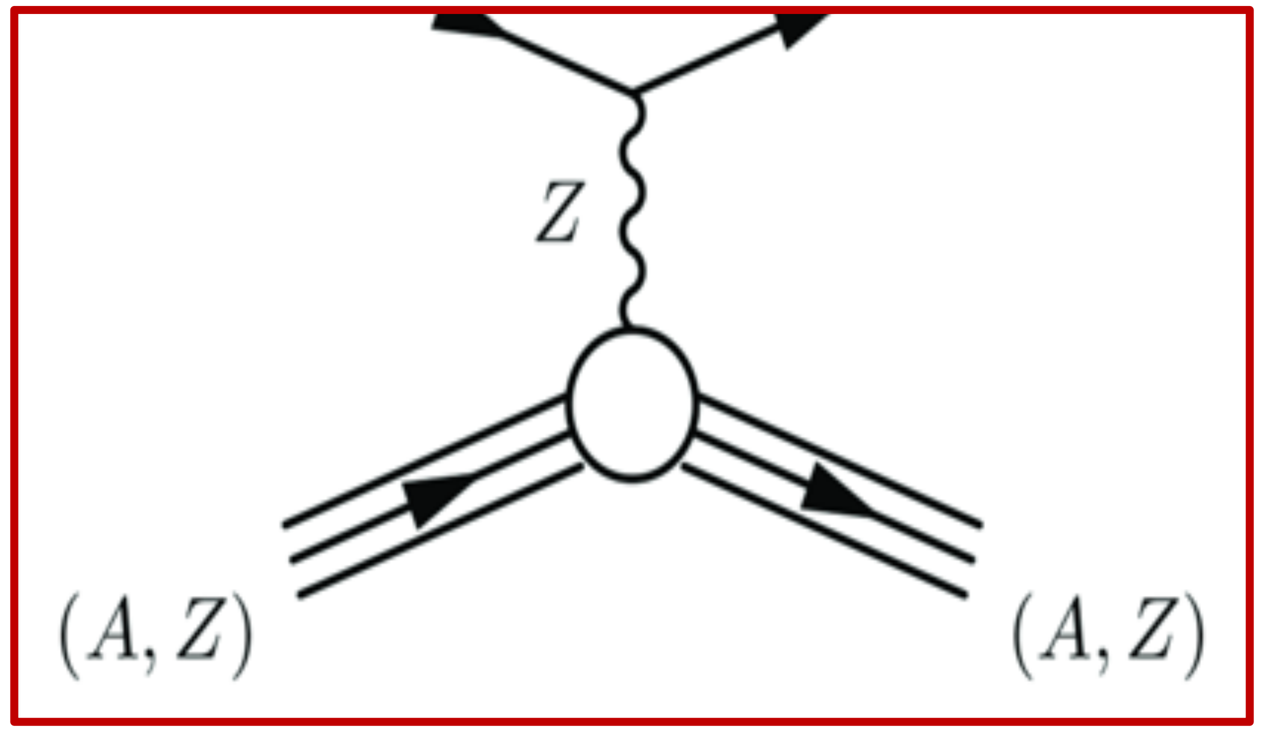
- Neutrinos (solar model, neutrino properties)
  - **High statistics pp neutrino measurement**
  - **Neutrino survival probability** at high (5-15 MeV) and very low energies
    - Test the LMA-MSW solution to neutrino oscillations
  - **Neutrino magnetic moment**

XLZD: Supernova neutrino

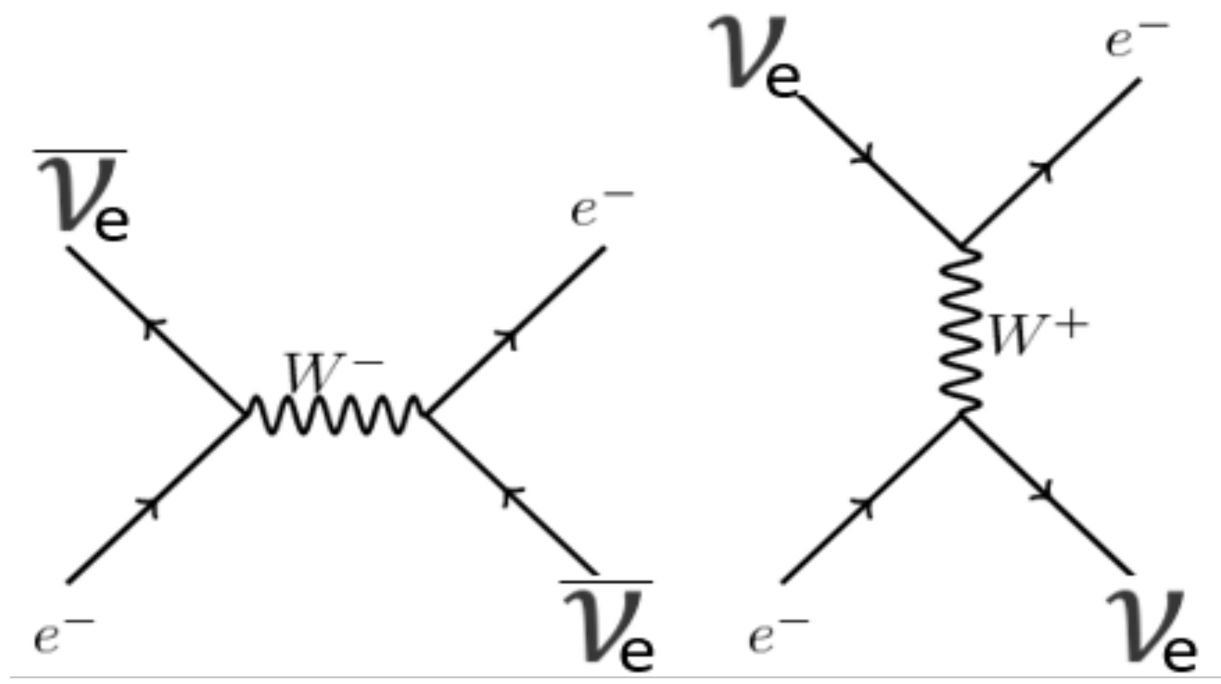
Phys.Rev.D 94 (2016) 10, 103009
Ann. Rev. Nucl. Part. Sci. 27, 167 (1977)

Kara (KIT)

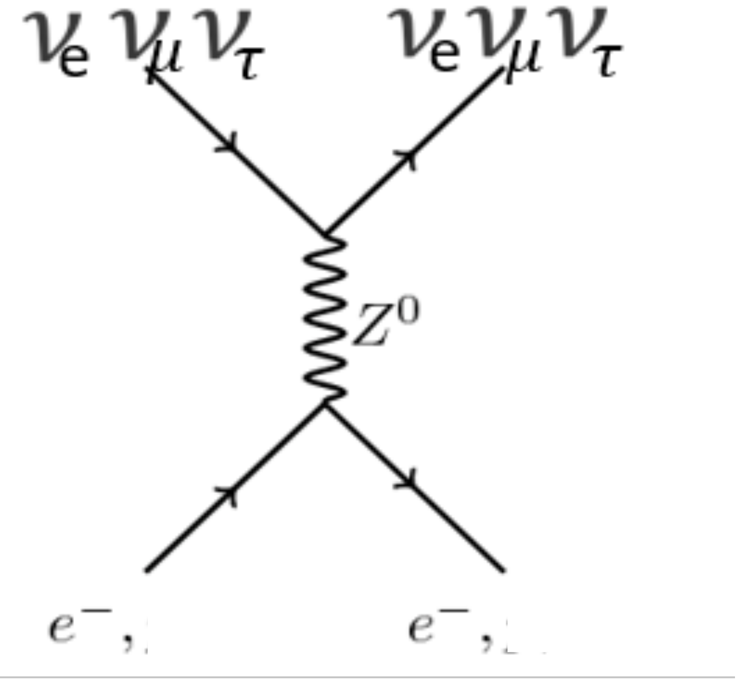
CEvNS



Charged-Current



Neutral-Current



Sub-dominant for SN neutrinos

At low energies, scattering cross-section is ***coherently*** enhanced by the square of the nucleus's neutron number

$$\frac{dR}{dE_R} = N_T \int_{E_\nu^{min}}^{E_\nu^{max}} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_R} dE_\nu$$

$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{4\pi} \left(N - Z\left(1 - 4\sin^2\theta_w\right)\right)^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

XLZD: Supernova neutrino

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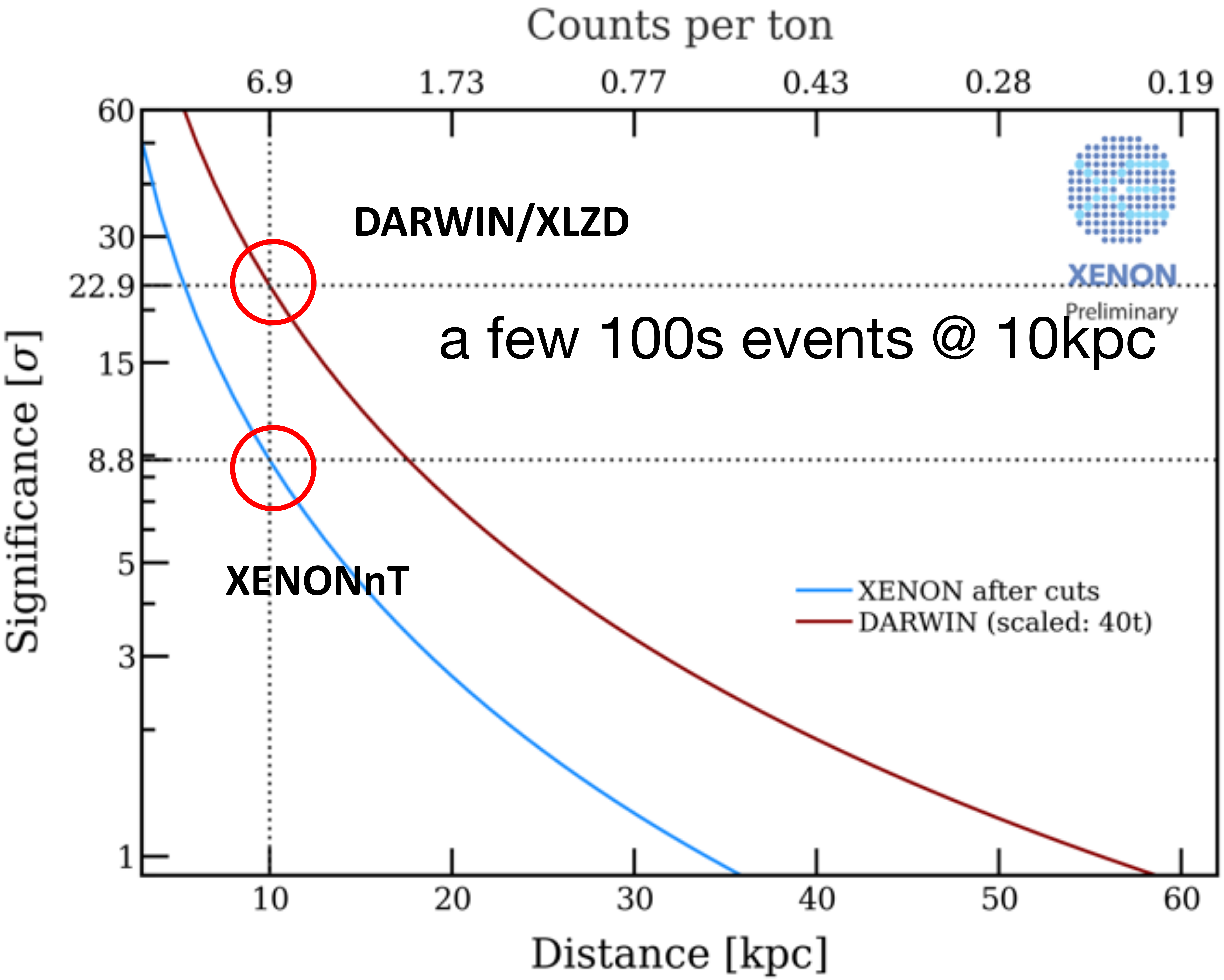
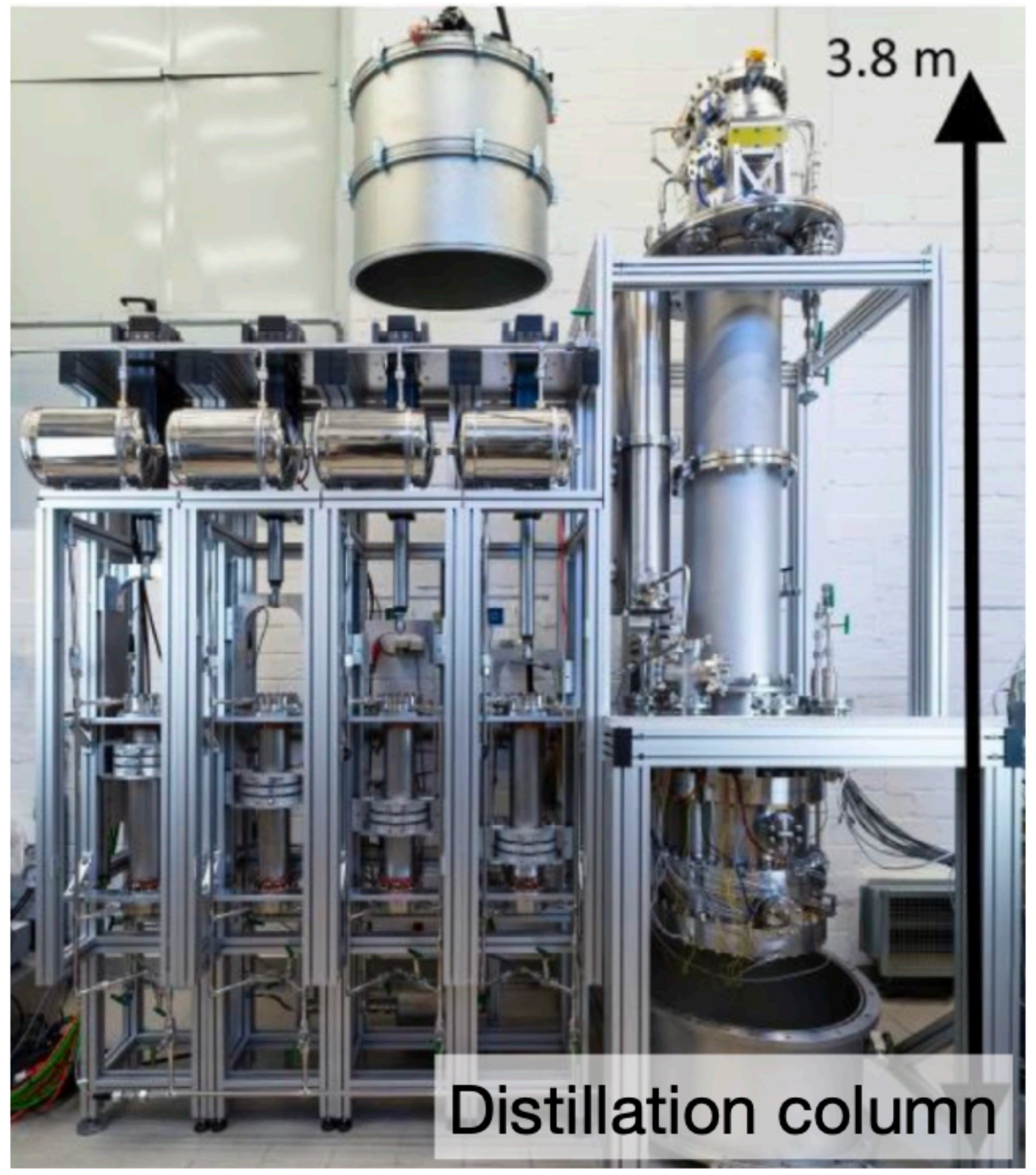


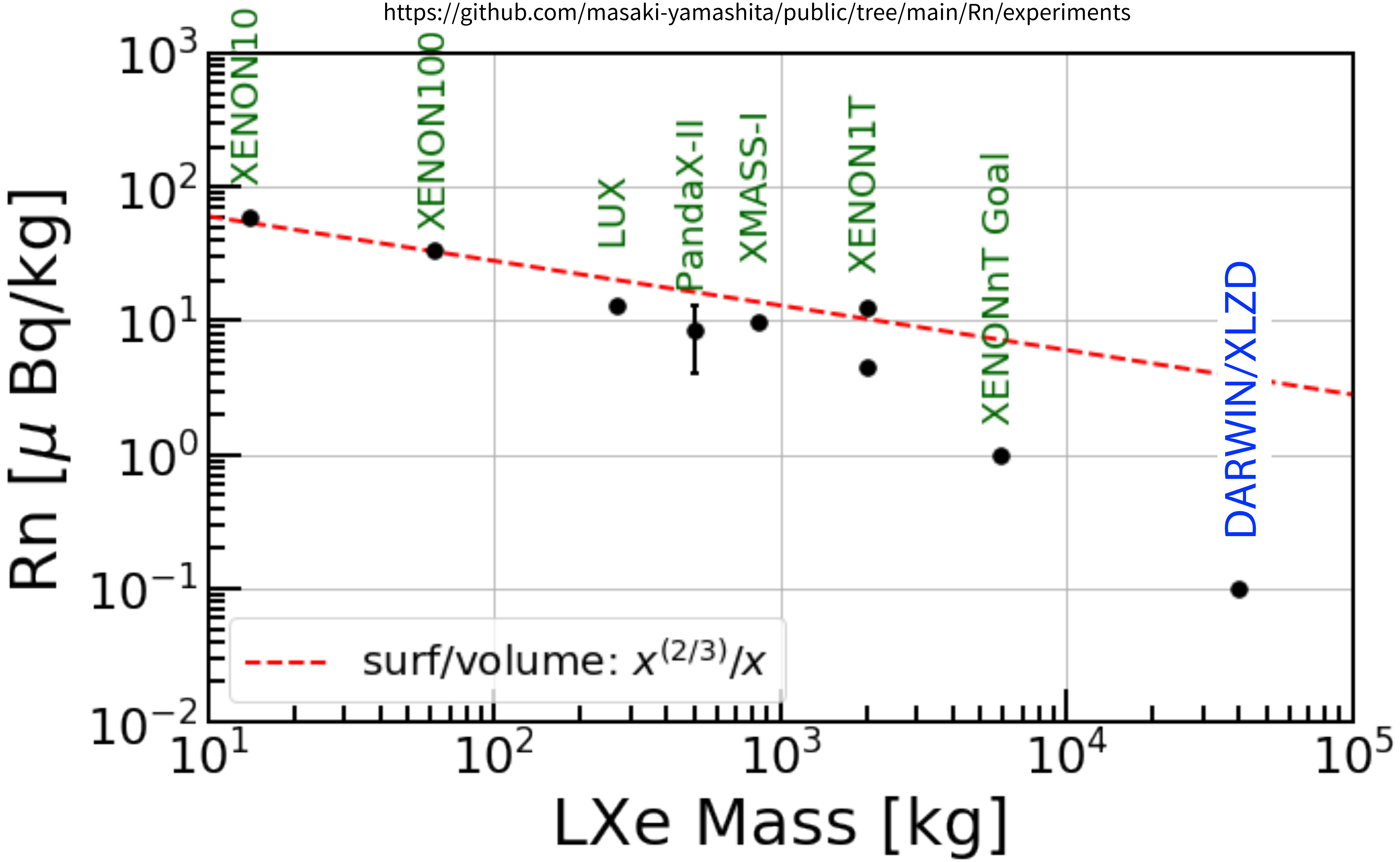
2022) 2, 107

Technology toward Ultimate detector

- Radon/Krypton distillation (XENONnT)
- 222Rn/ < 1 uBq/kg
- 85Kr < ppt



https://github.com/masaki-yamashita/public/tree/main/Rn/experiments



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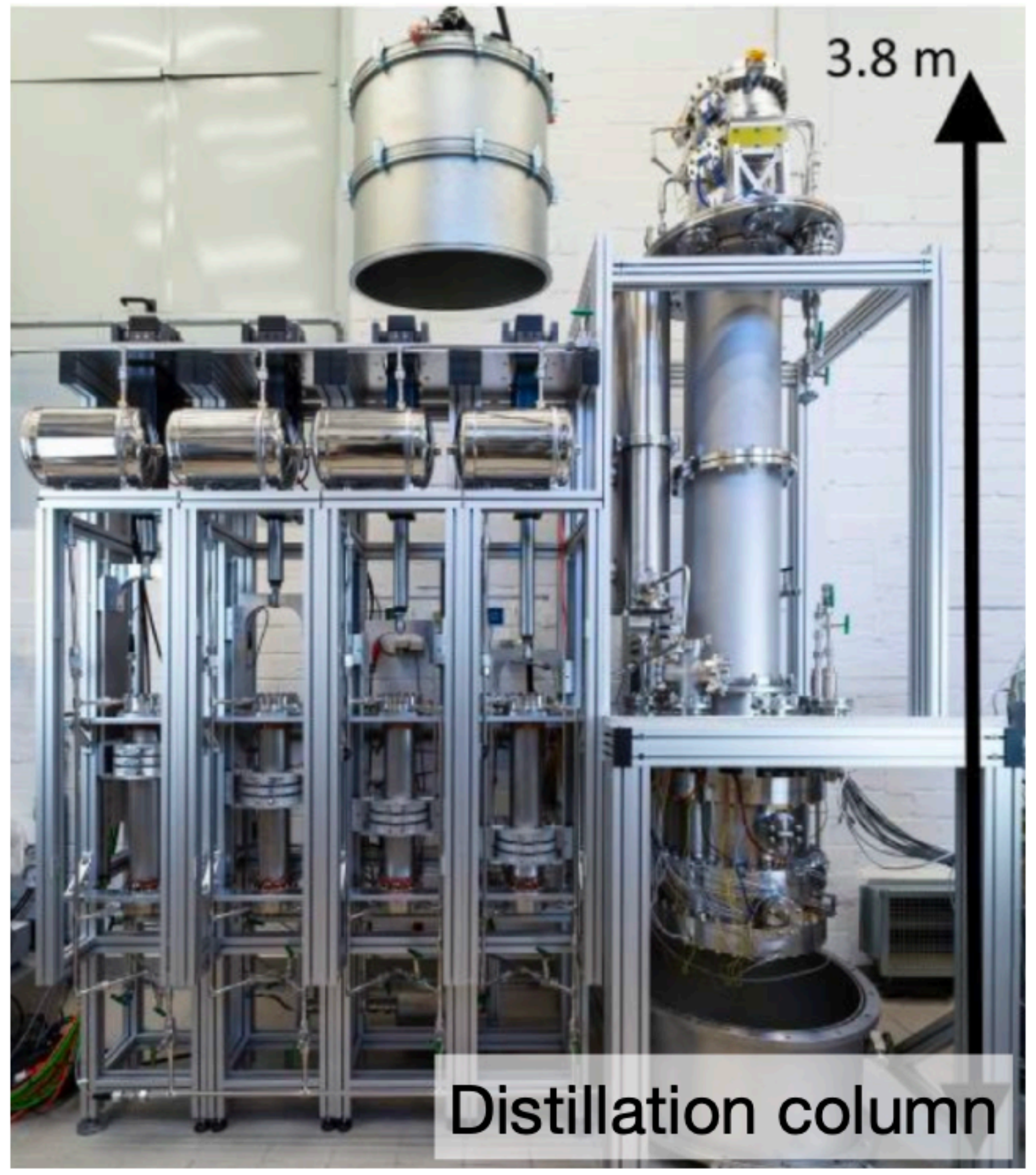
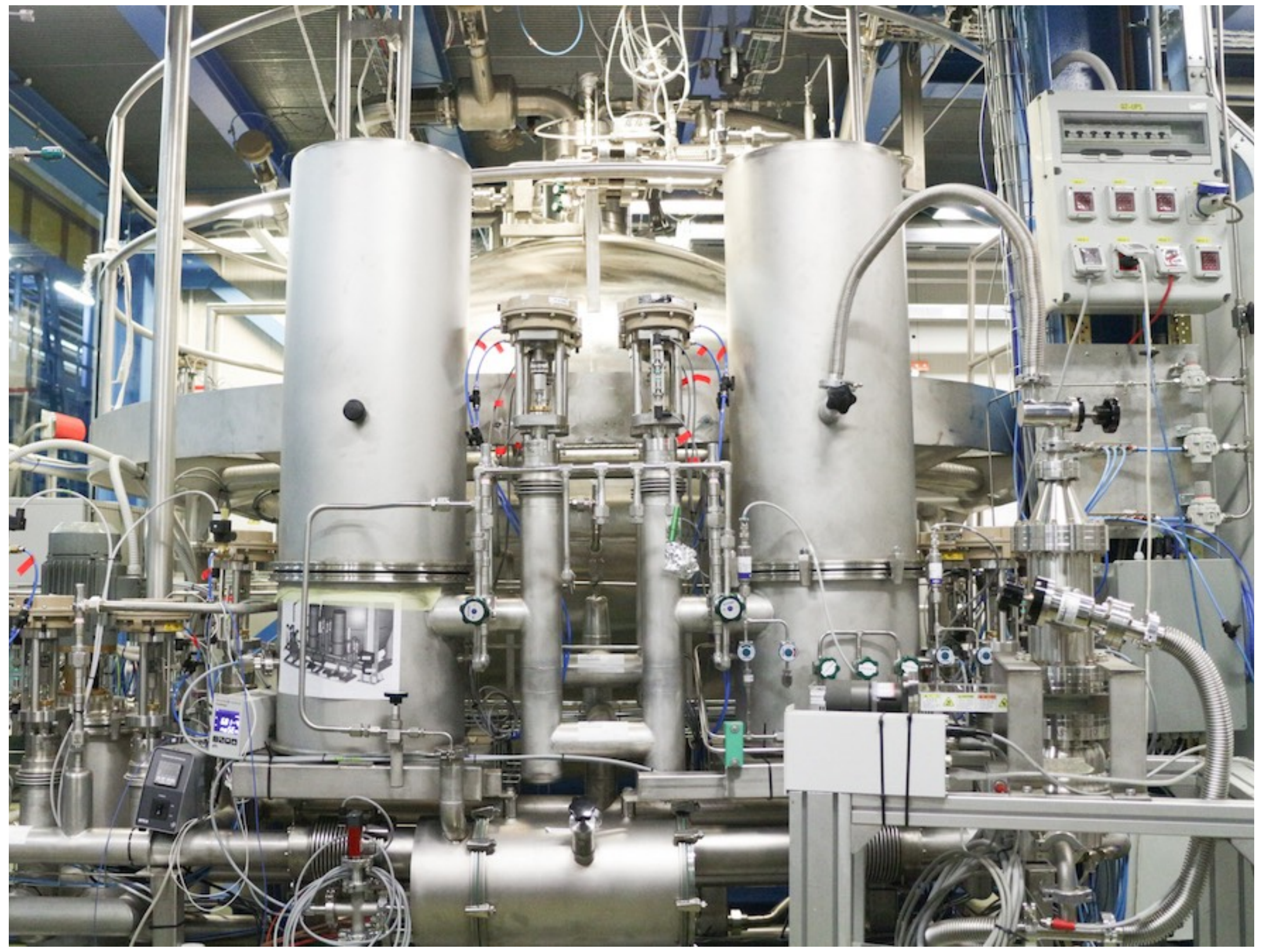
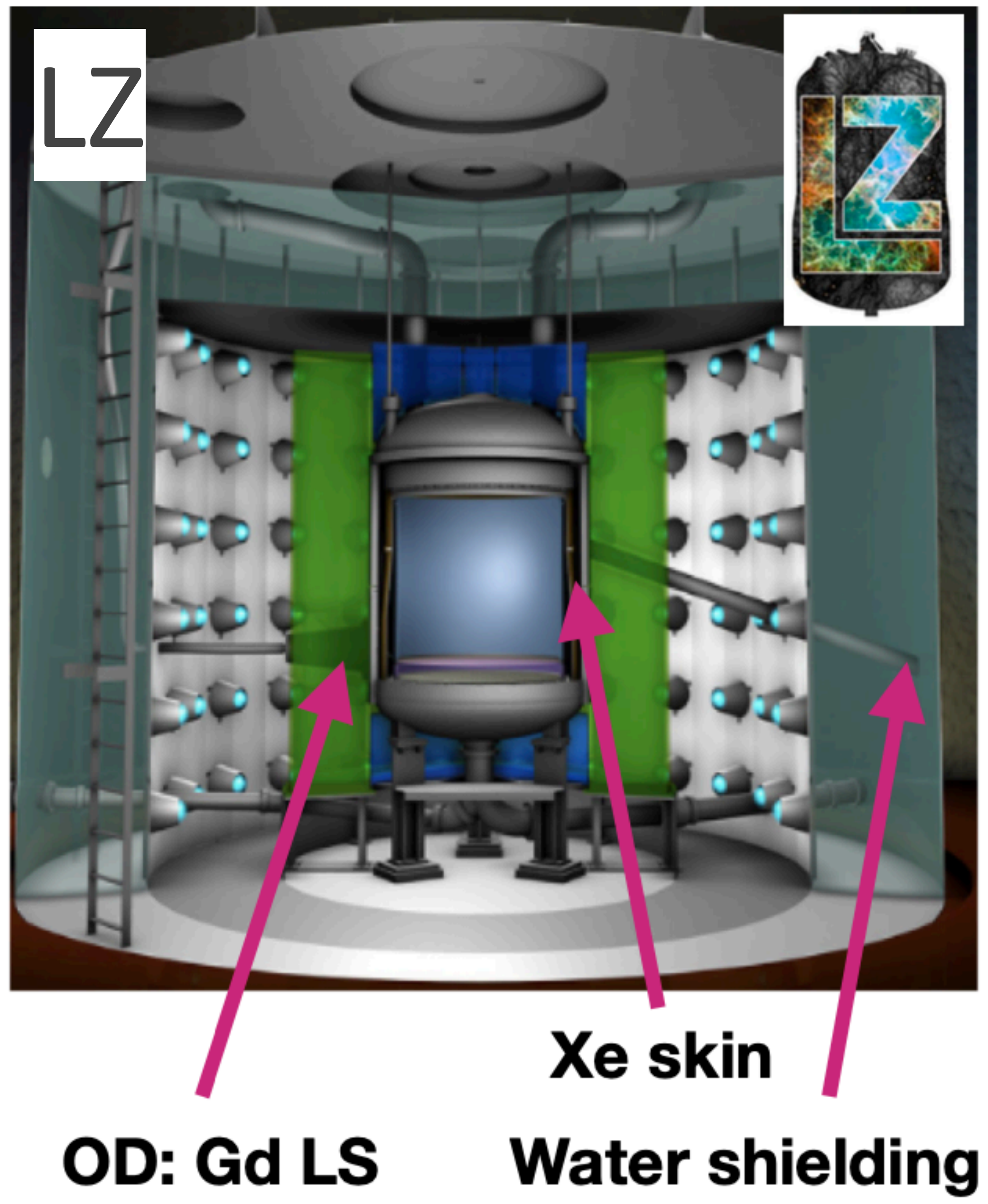
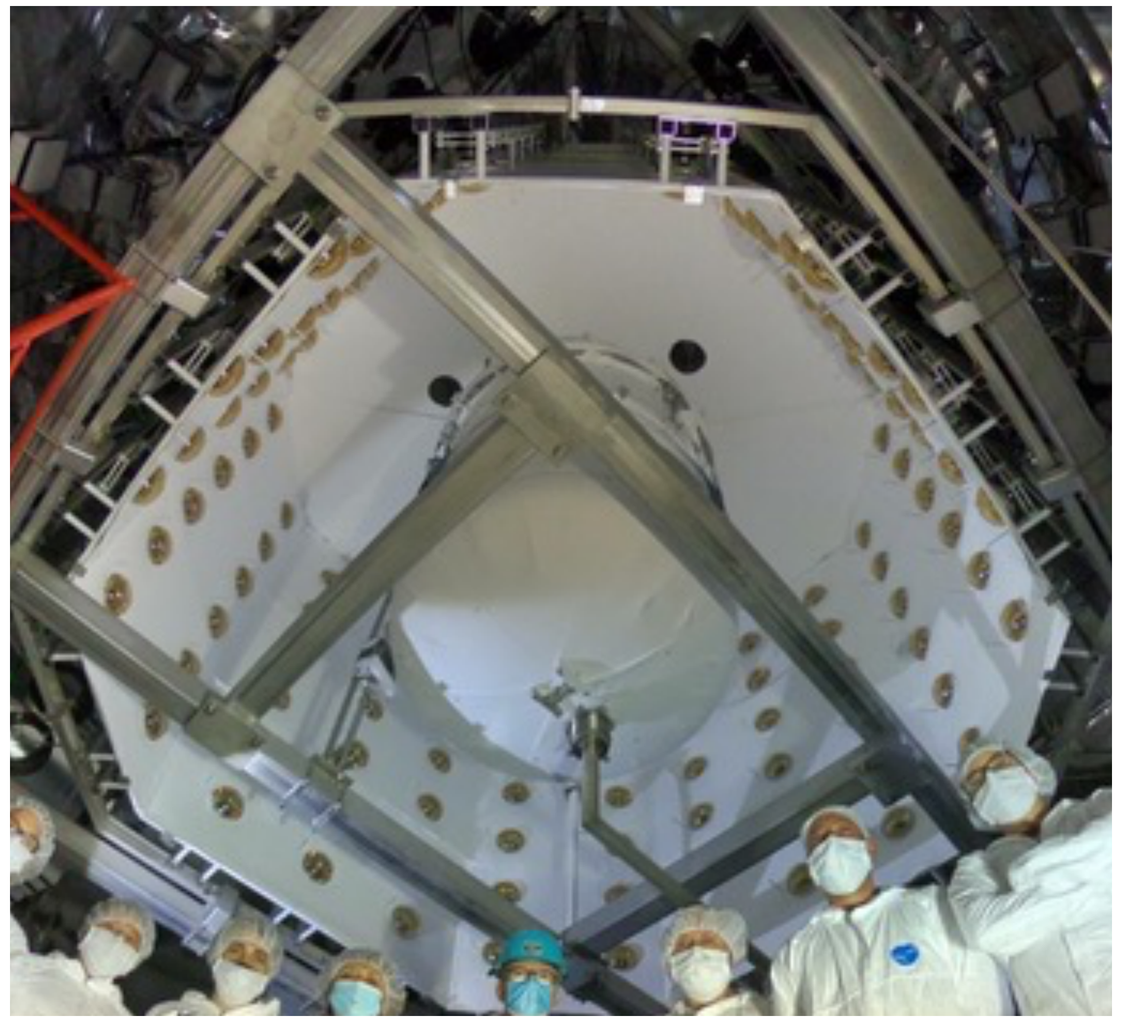


- LXePUR (XENONnT)
- Liquid phase purification
- > 15 ms electron lifetime
- => ~ 15 m drift length



- gamma Veto
- neutron Veto

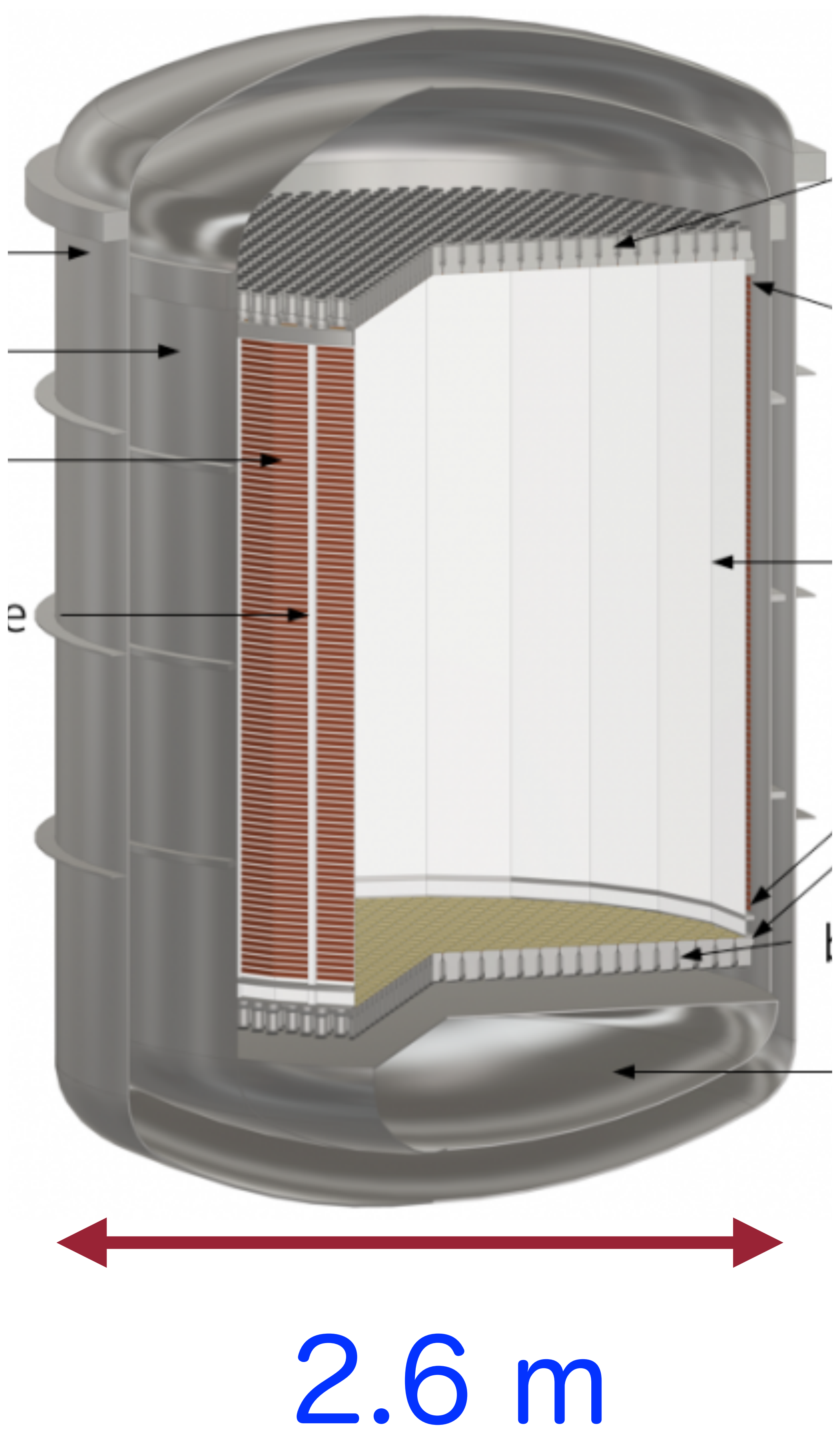


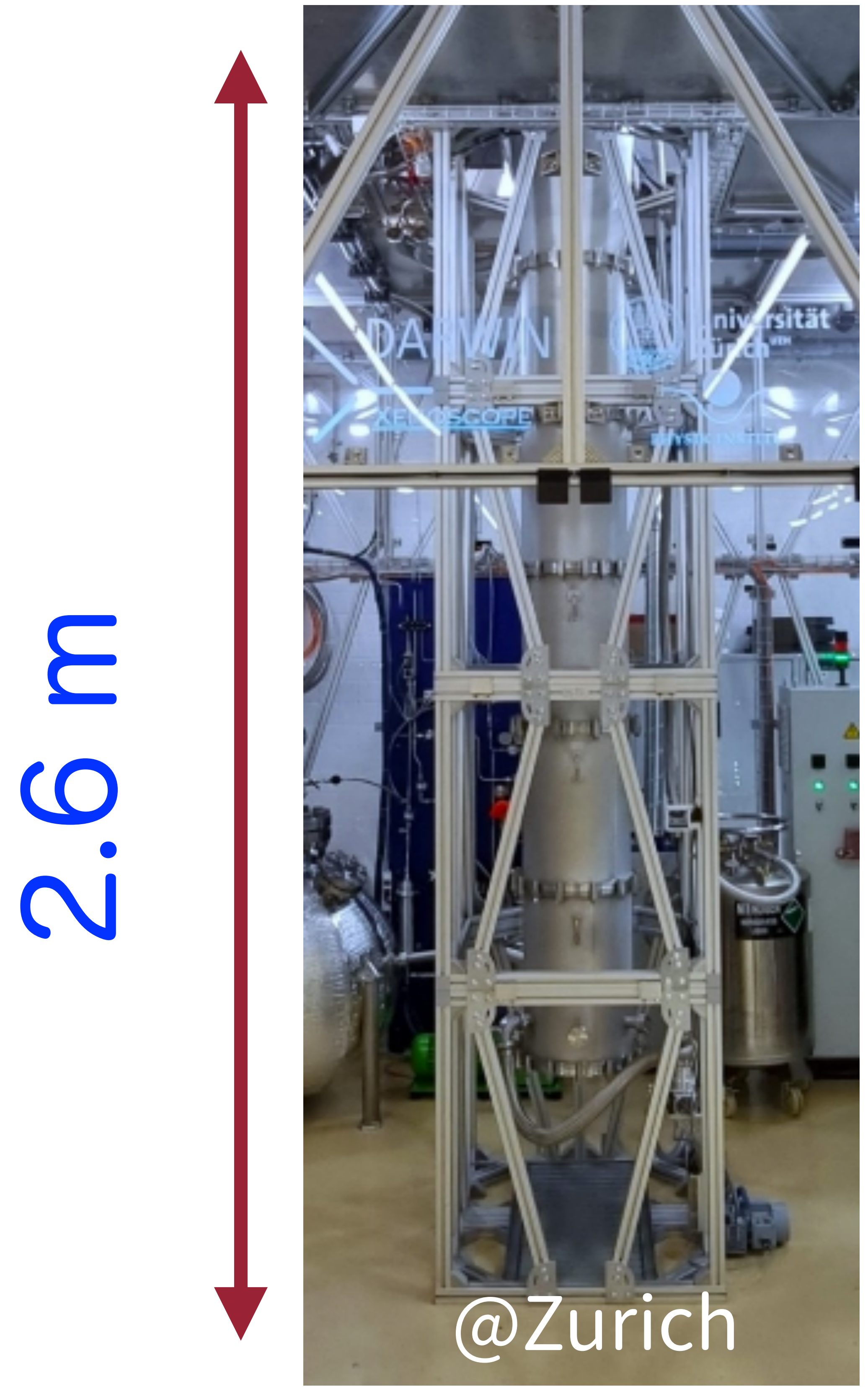


XENONnT

R&D Activities: TPC and Electrodes/HV

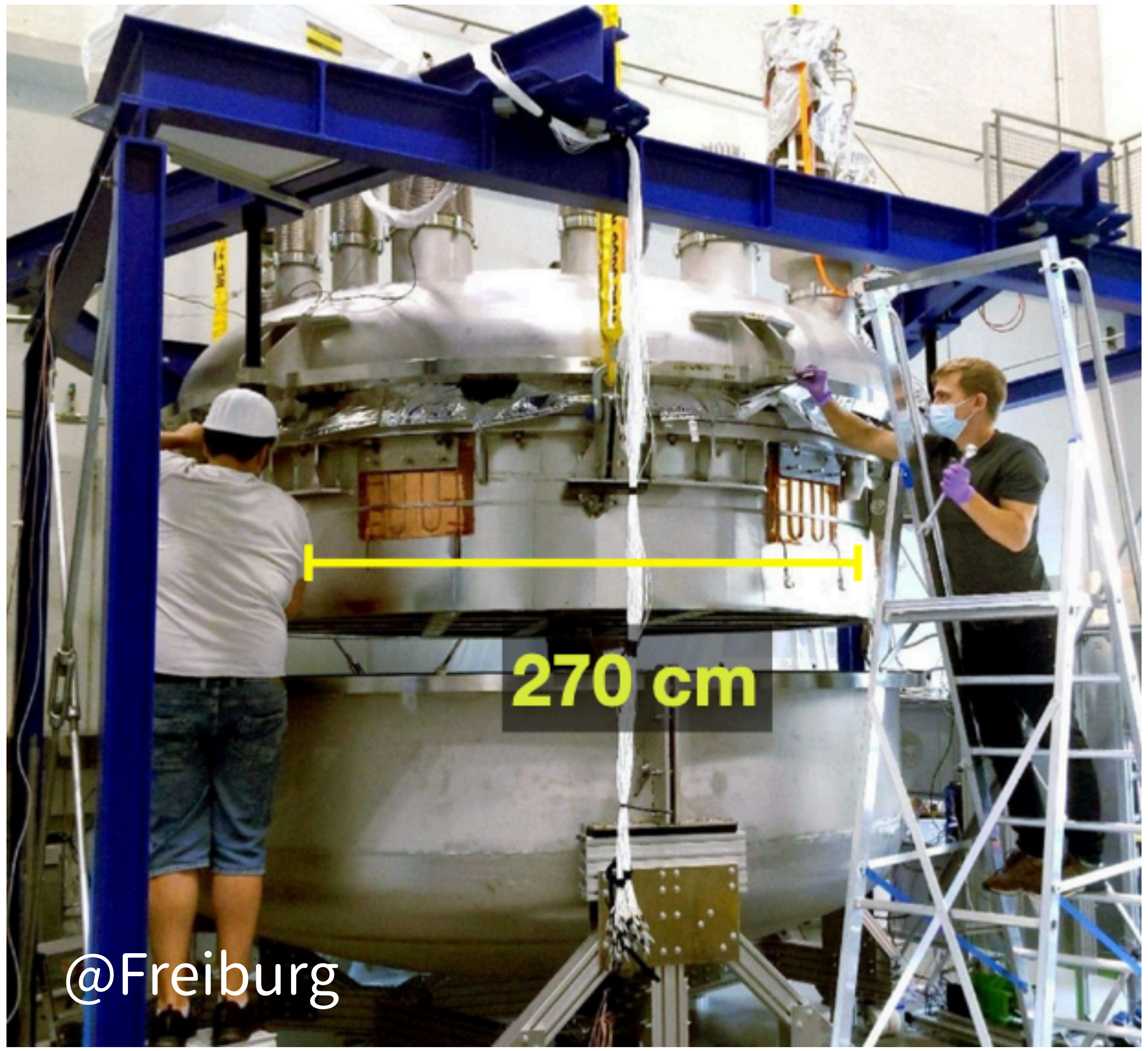
Full height and diameter test facility for DARWIN/XLZD





JINST 16 P08052(2021)

High voltage, Purity …

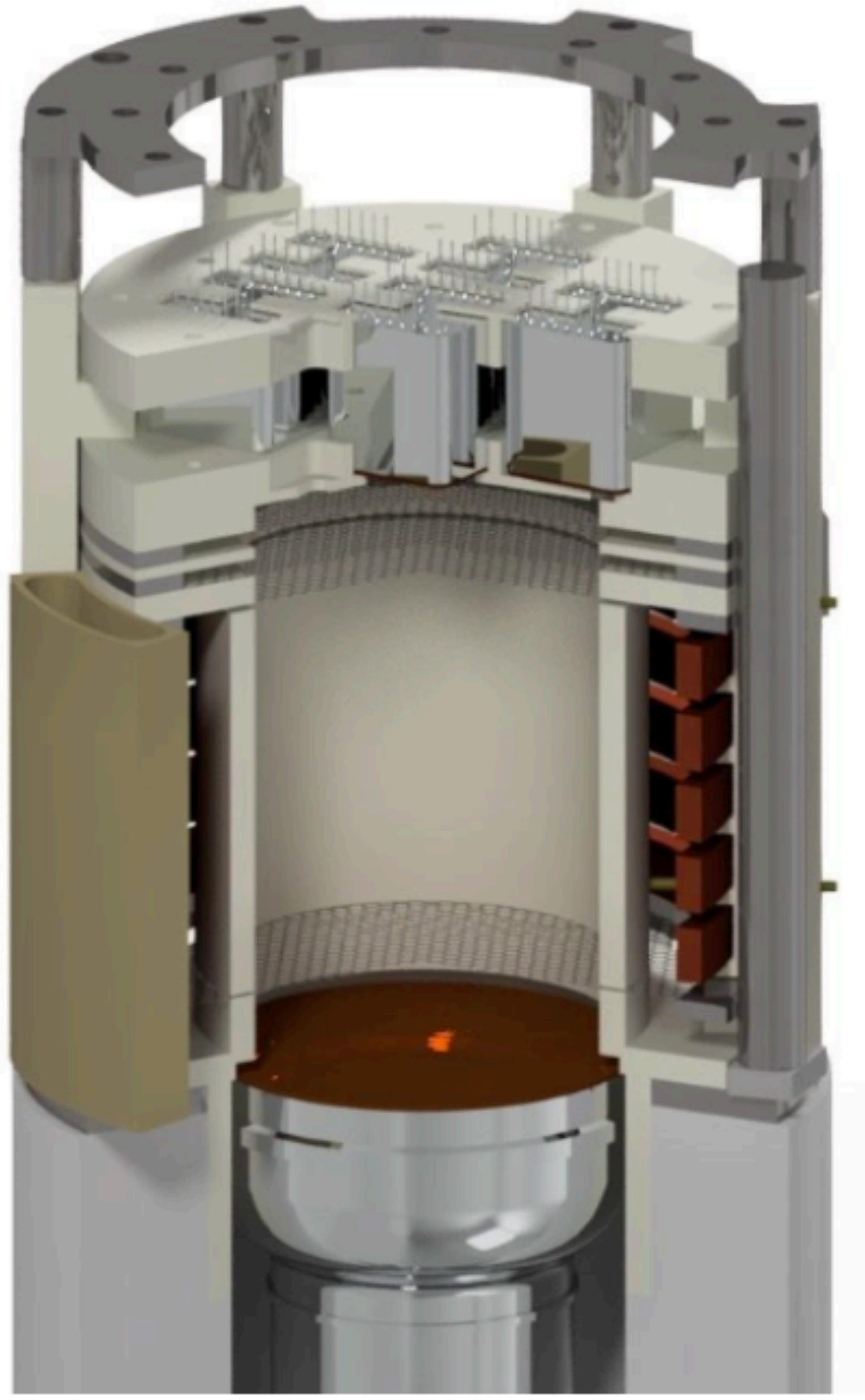


Electrode and other detector components

TPC R&D

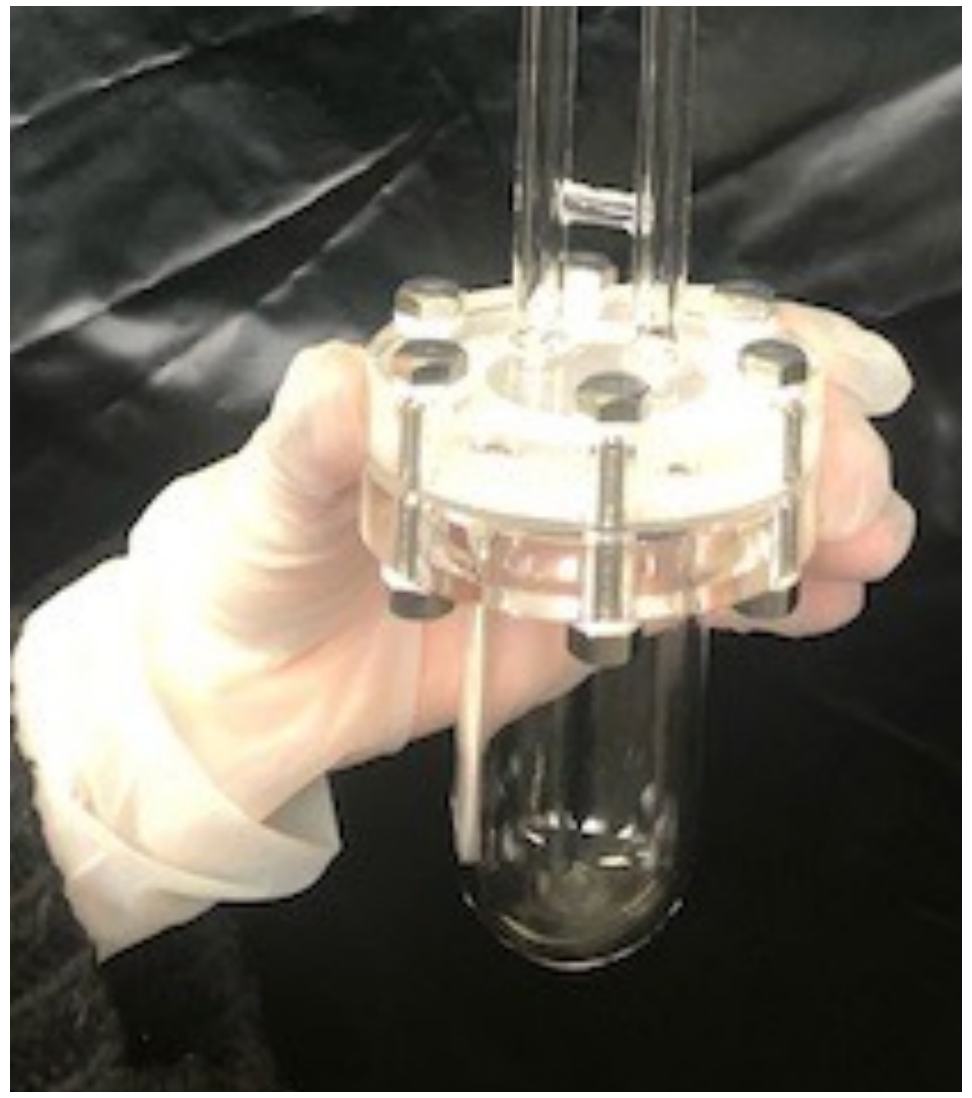
Hermetic TPC to protect Rn from outside volume

Single phase Xe TPC to avoid the liquid-gas interface control

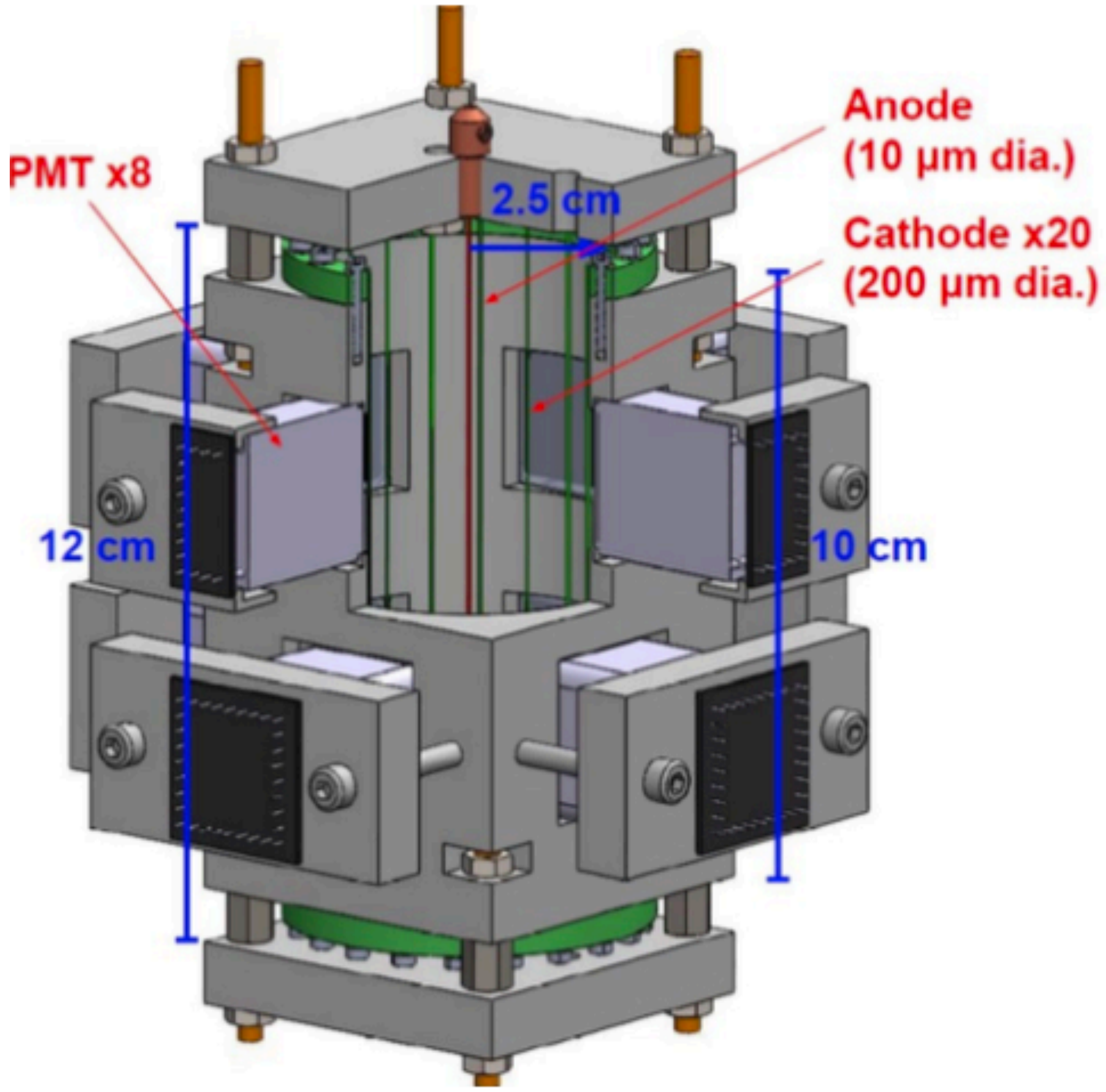


Phys. J. C 83, 9 (2023)

Quartz chamber

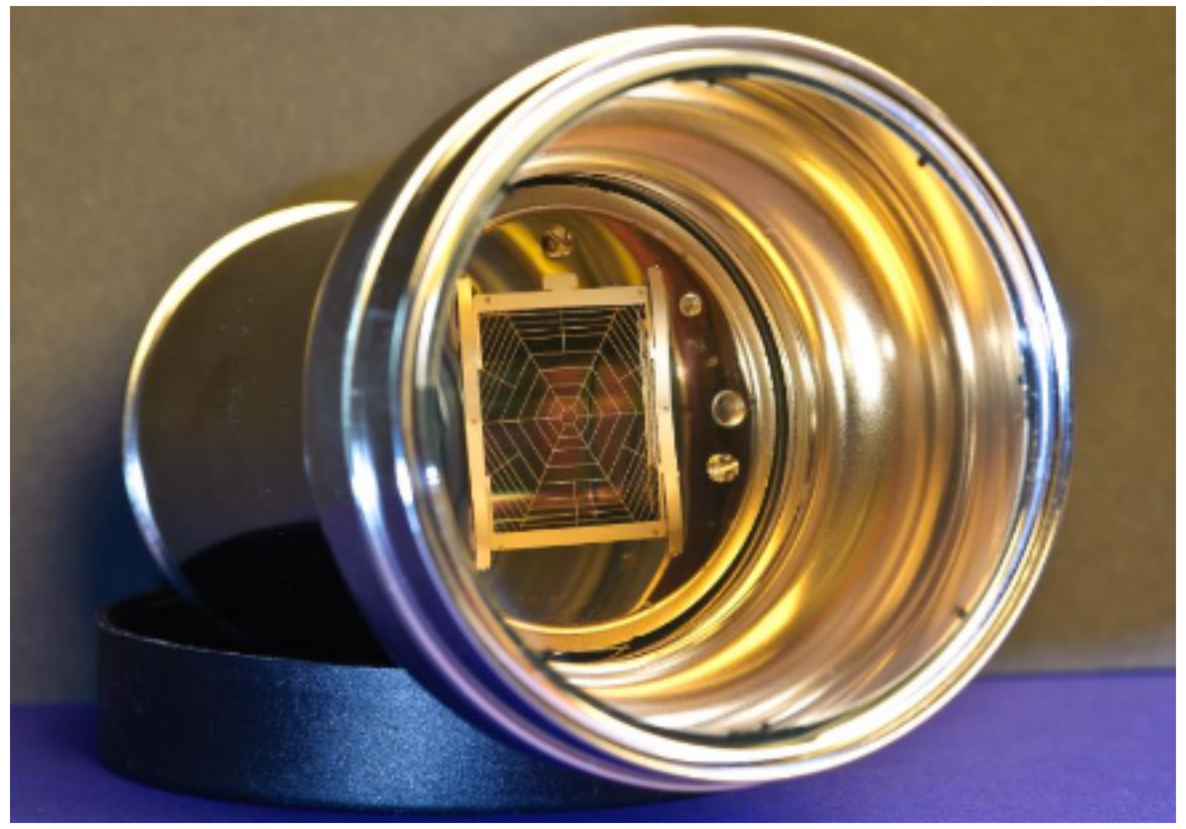


PTEP 2020 113H02



arXiv:2301.12296

DARWIN: R&D Photosensor

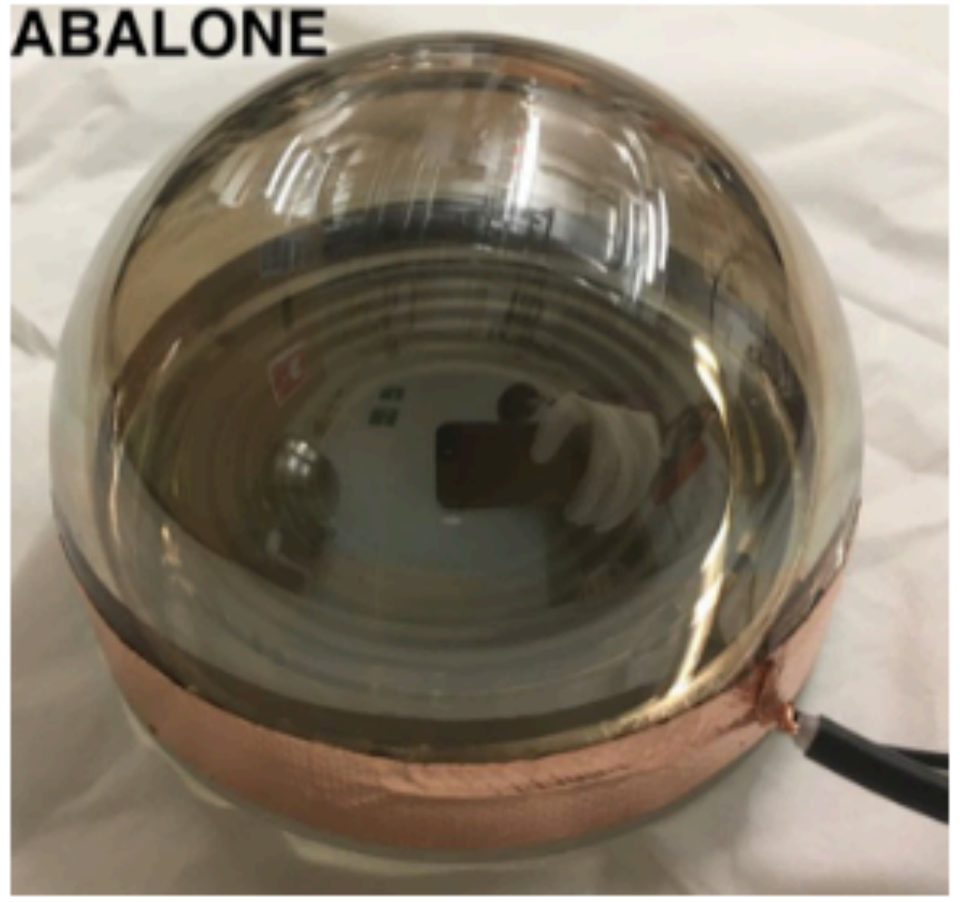


R11410 (LZ, XENONnT, PandaX)

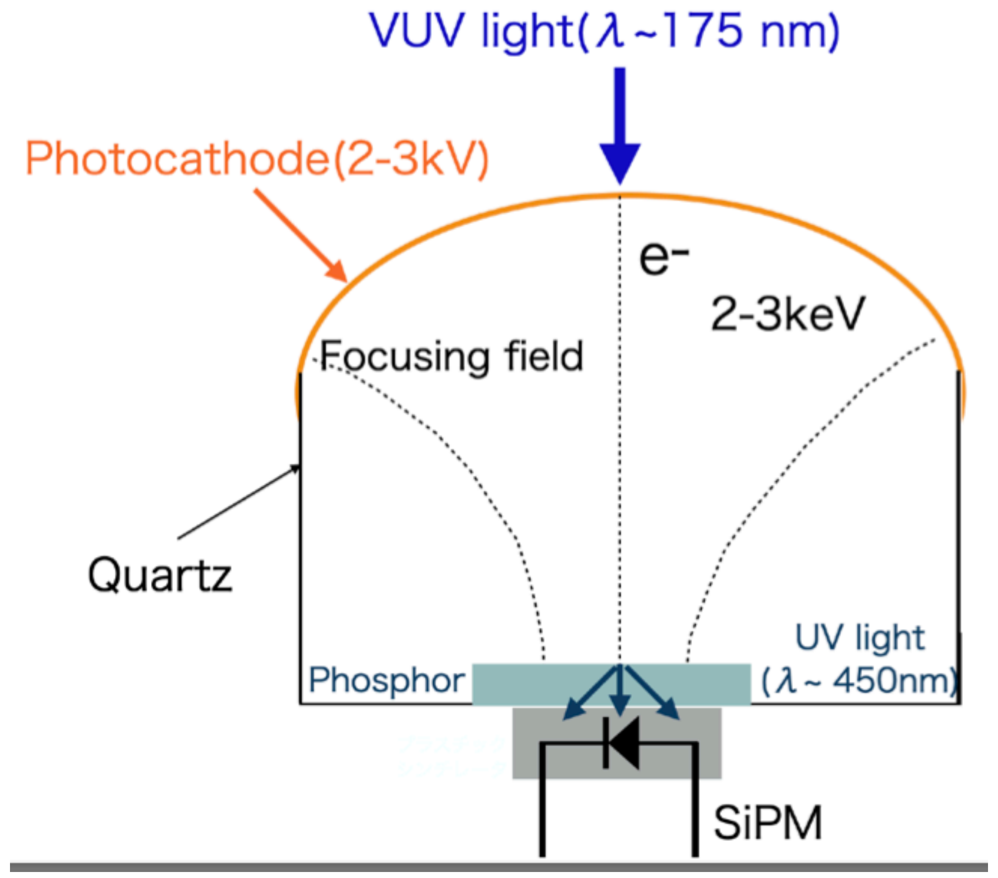
K. Abe et al. JINST 15 P09027

R13111 (XMASS)

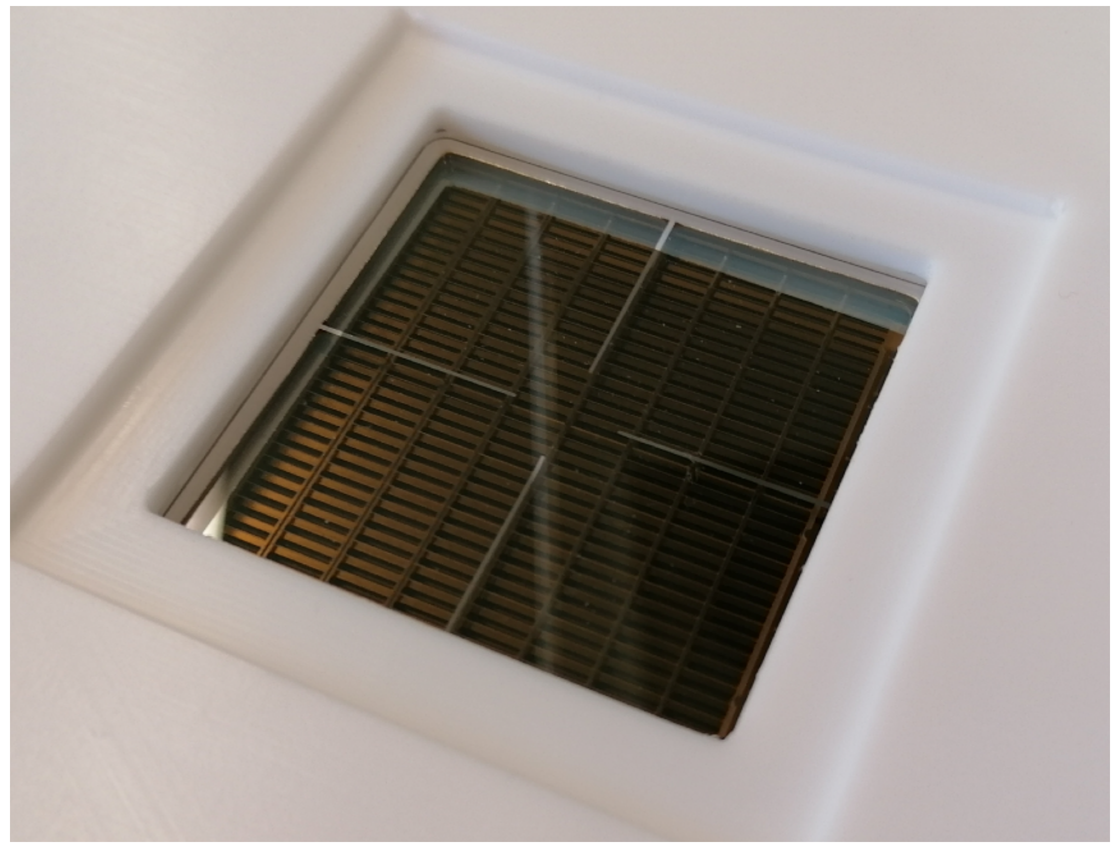
Lowest radioactivity



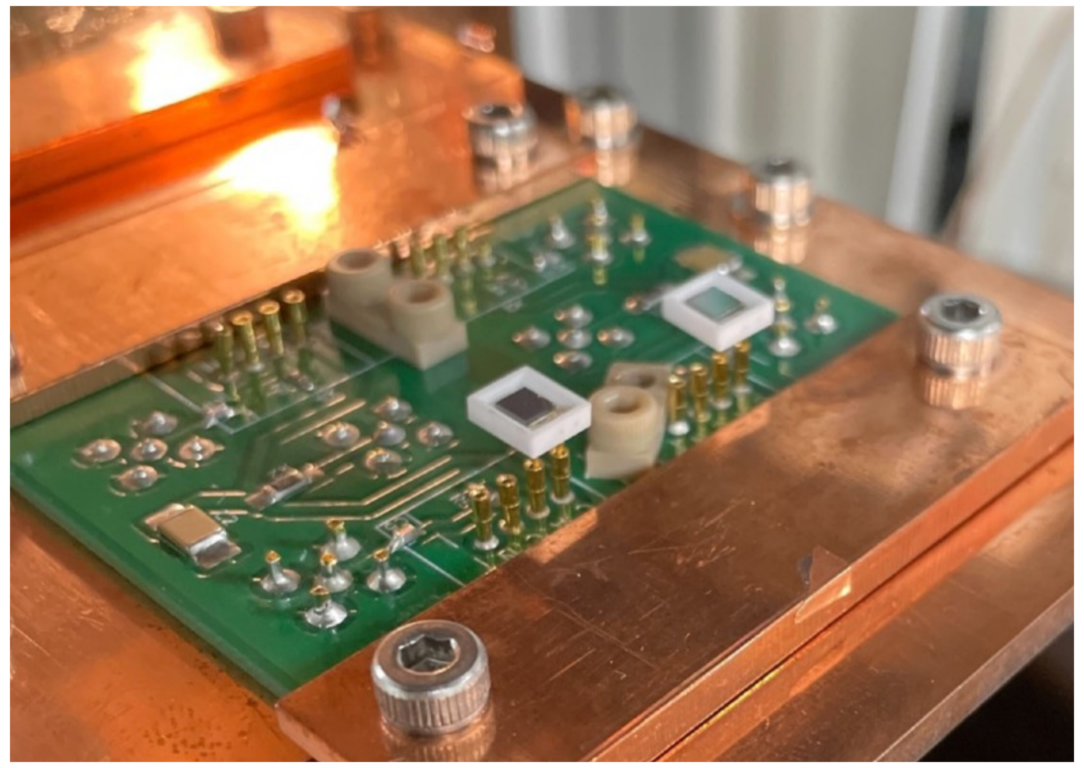
JINST **17** C01038 (2022)



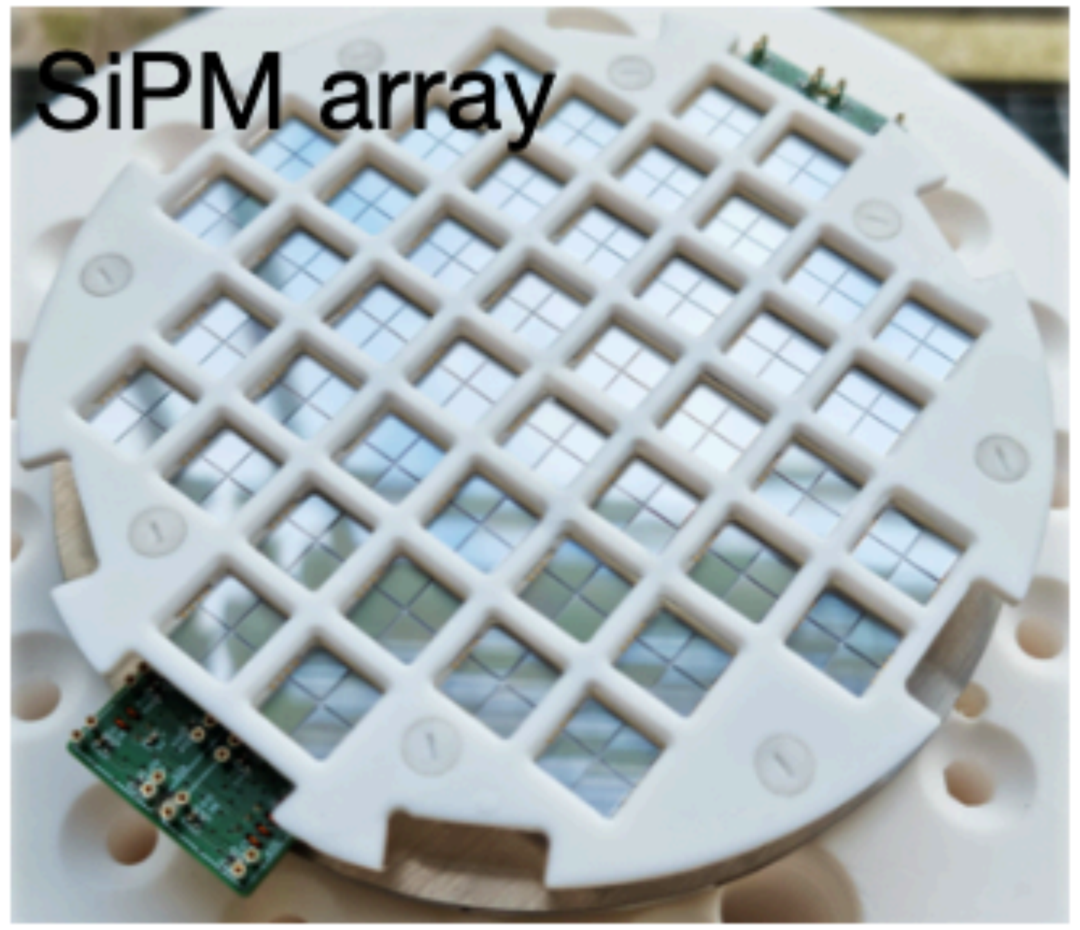
Hybrid @Nagoya



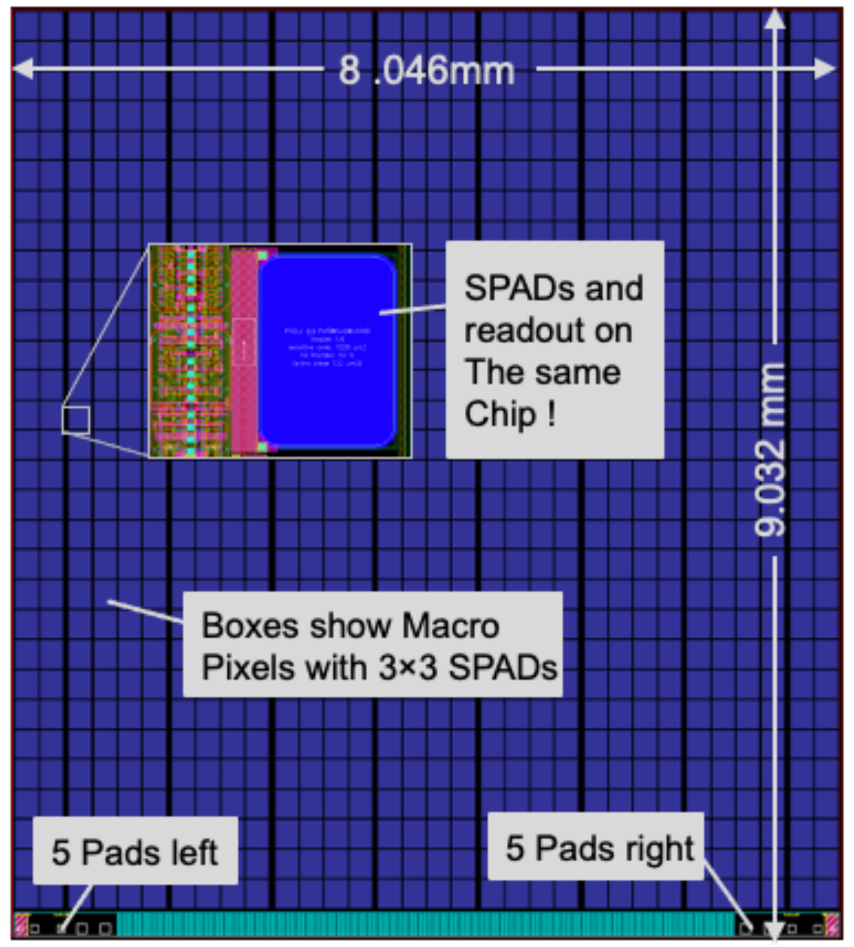
2inch square @Zurich



Low Dark Current SiPM



JINST **18** C03027 (2023)



Digital SiPM @Heidelberg

R13111 (3inch)

XMASS Collaboration
2020 *JINST* **15** P09027

(1) Stem: glass material was synthesized using low-radioactive-contamination material

(2) Photocathode: produced with 39K-enriched potassium

(3) Vacuum seal: purest grade of aluminum material

(4) Convex geometry improved the collection efficiency and TTS (~2.1 ns ↔ R11410:~9.2 ns)

μBq/PMT	^{226}Ra	^{238}U	^{228}Ra	^{40}K	^{60}Co
R13111 in 2015	$(3.8 \pm 0.7)\cdot 10^2$	$<1.6 \cdot 10^3$	$(2.9 \pm 0.6)\cdot 10^2$	$<1.4 \cdot 10^3$	$(2.2 \pm 0.5)\cdot 10^2$
R13111 in 2016	$(4.4 \pm 0.6)\cdot 10^2$	$<1.4 \cdot 10^3$	$(2.0 \pm 0.6)\cdot 10^2$	$(2.0 \pm 0.5) \cdot 10^3$	$(1.3 \pm 0.4)\cdot 10^2$
R11410-21(XENON1T) [15]	$(5.2 \pm 1.0)\cdot 10^2$	$<1.3 \cdot 10^4$	$(3.9 \pm 1.0)\cdot 10^2$	$(1.2 \pm 0.2) \cdot 10^4$	$(7.4 \pm 1.0) \cdot 10^2$
R11410-10(PandaX) [3]	$<7.2\cdot 10^2$	—	$<8.3\cdot 10^2$	$(1.5 \pm 0.8) \cdot 10^4$	$(3.4 \pm 0.4) \cdot 10^3$
R11410-10(LUX) [19]	$<4.0\cdot 10^2$	$<6.0 \cdot 10^3$	$<3.0 \cdot 10^2$	$<8.3 \cdot 10^3$	$(2.0 \pm 0.2) \cdot 10^3$

Conclusion

- **XLZD** is formed by
  - **XENONnT** + **LUX-ZEPLIN** + **DARWIN**

・XLZD will be a successor to the state-of-the-art liquid xenon dark matter detector.

・Ultimate detector for WIMP search (neutrino fog)

-Solar Neutrino

-Double Beta Decay

-SuperNova ・・・etc

・ start observation in 2030’

2010’s | 2020’s | 2030’s | 2040’

LUX/XENON1T → LZ/XENONnT → DARWIN/XLZD