Next Generation Direct Dark Matter Search with LXe (B01)

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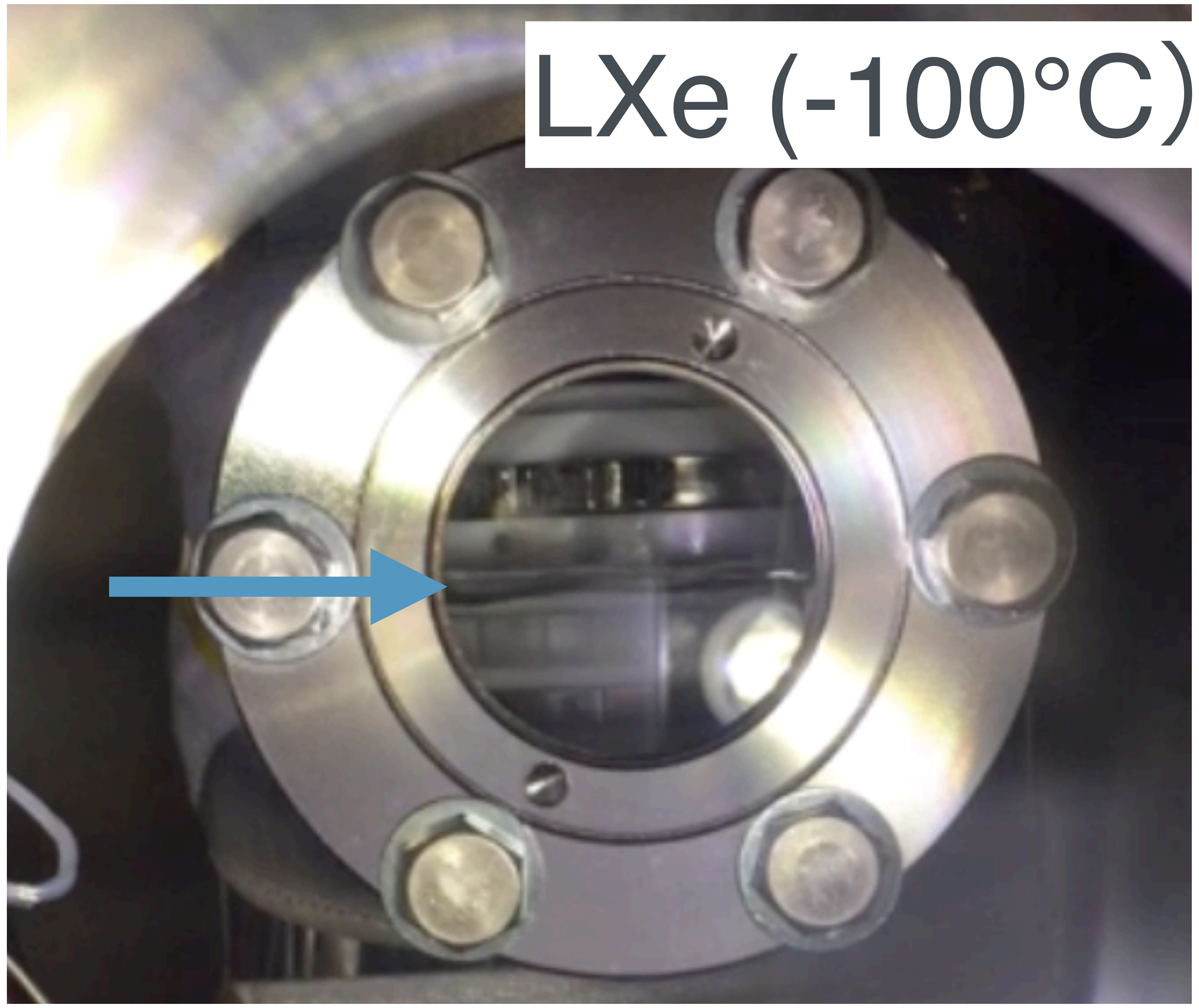
地下から解き明かす宇宙の歴史と物質の進化
Unraveling the History of the Universe and Matter Evolution with Underground Physics

2024/March/04-06
UGAP2024@Tohoku University

Liquid Xenon

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

- High-Z for good self-shielding
- High-density rare gas liquid
- -100 °C (173 K)
- 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%

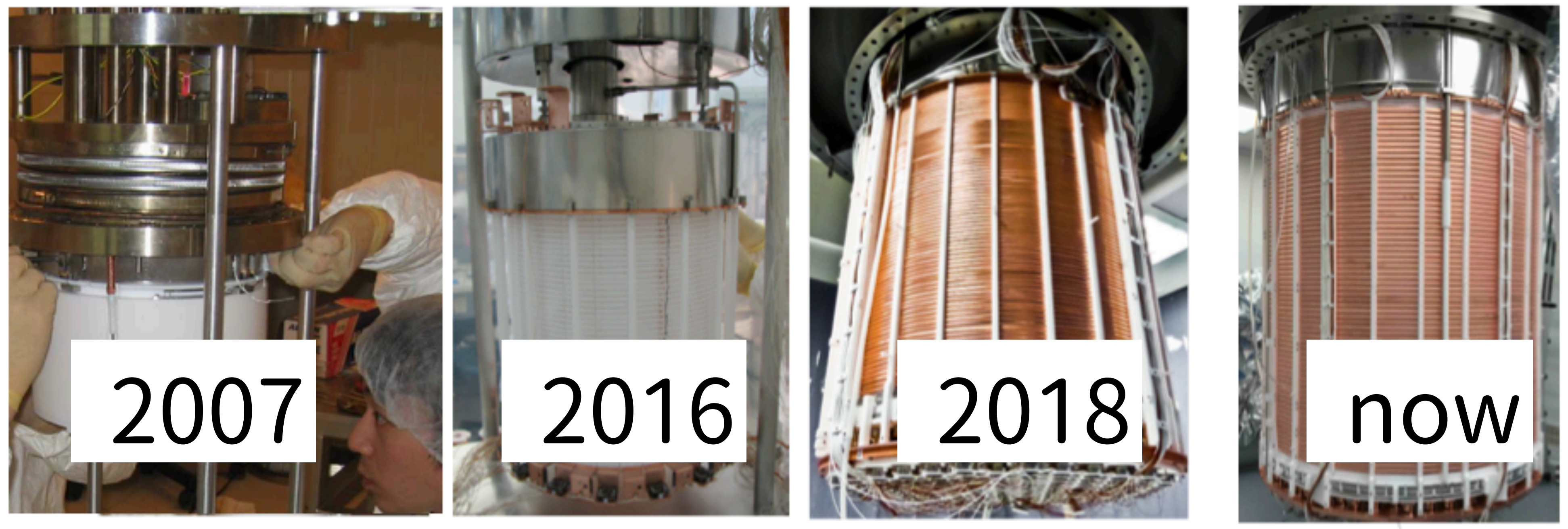
- half-half: even and odd isotopes
  - Both spin-independent and spin-dependent WIMP DM search
- No long-lived isotopes except ^{124}Xe and ^{136}Xe
  - ^{124}Xe double electron capture isotope ($T_{1/2} \sim 10^{22}$ y)
    - the longest half-life ever measured directly (XENON1T)
- ^{136}Xe $0\nu\beta\beta$ decay
- Enrich or depleted gases are possible.
  - e.g. Y. Suzuki arXiv:0008296

History of Direct WIMP Dark Matter Search

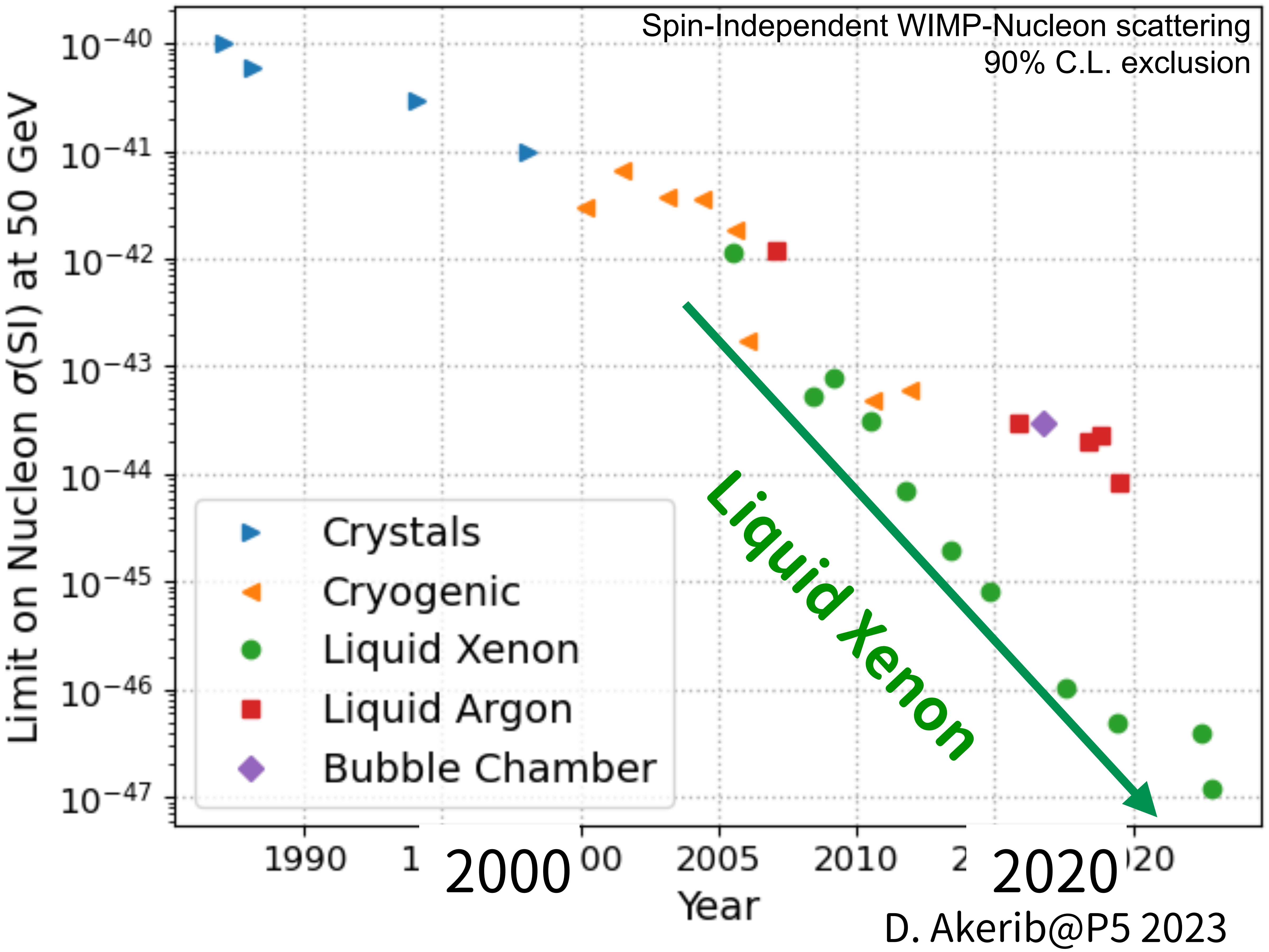
Liquid-gas double phase Xe Time Projection Chamber

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

XENON10 XENON100 XENON1T XENONnT



WIMP Limits vs Time: principal detector categories



D. Akerib@P5 2023

The XLZD Consortium

- **To realize an ultimate liquid xenon experiment**
- Forming **XLZD :**
  - XENONnT + LUX-ZEPLIN + DARWIN
- **LZ** and **XENONnT** are operating and leading experiments
- **DARWIN**: planned after the XENON program.

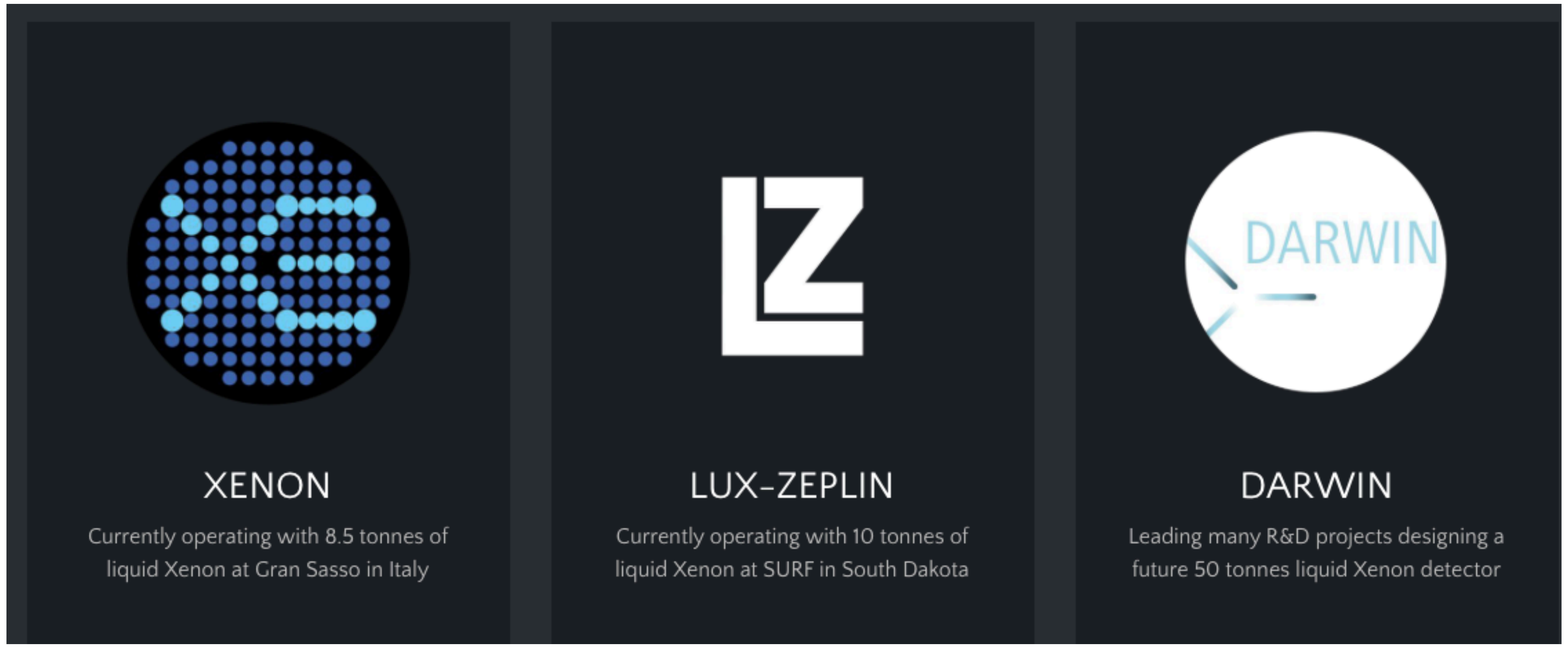
2021 XENON/DARWIN, LUX-ZEPLIN meeting
https://indico.cern.ch/event/1028794/
2021 **MOU signed**:16 countries, 104 scientists
2022 1st Summer Meeting at KIT in Germany
2023 2nd meeting at UCLA

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

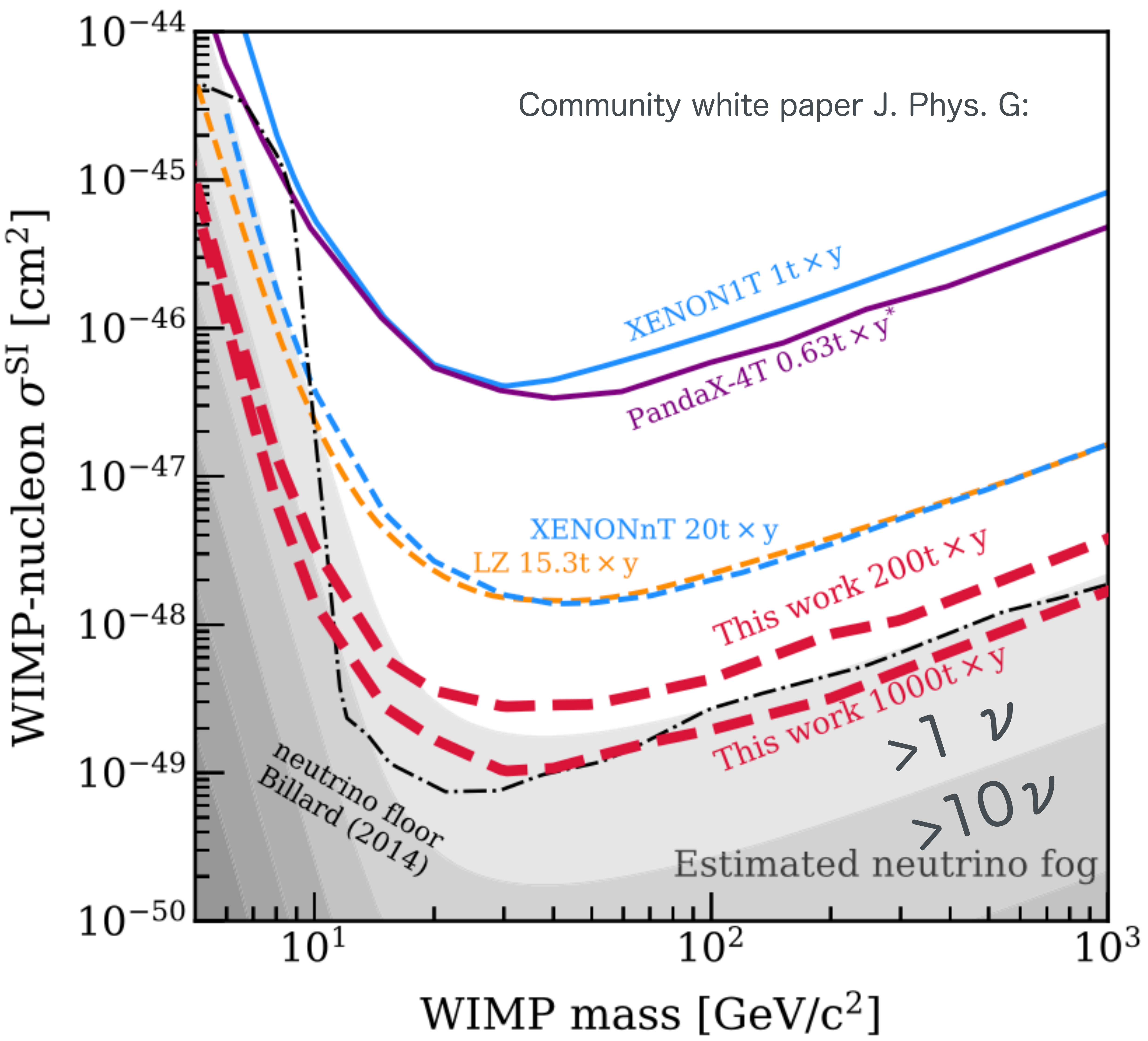
Topical Review

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



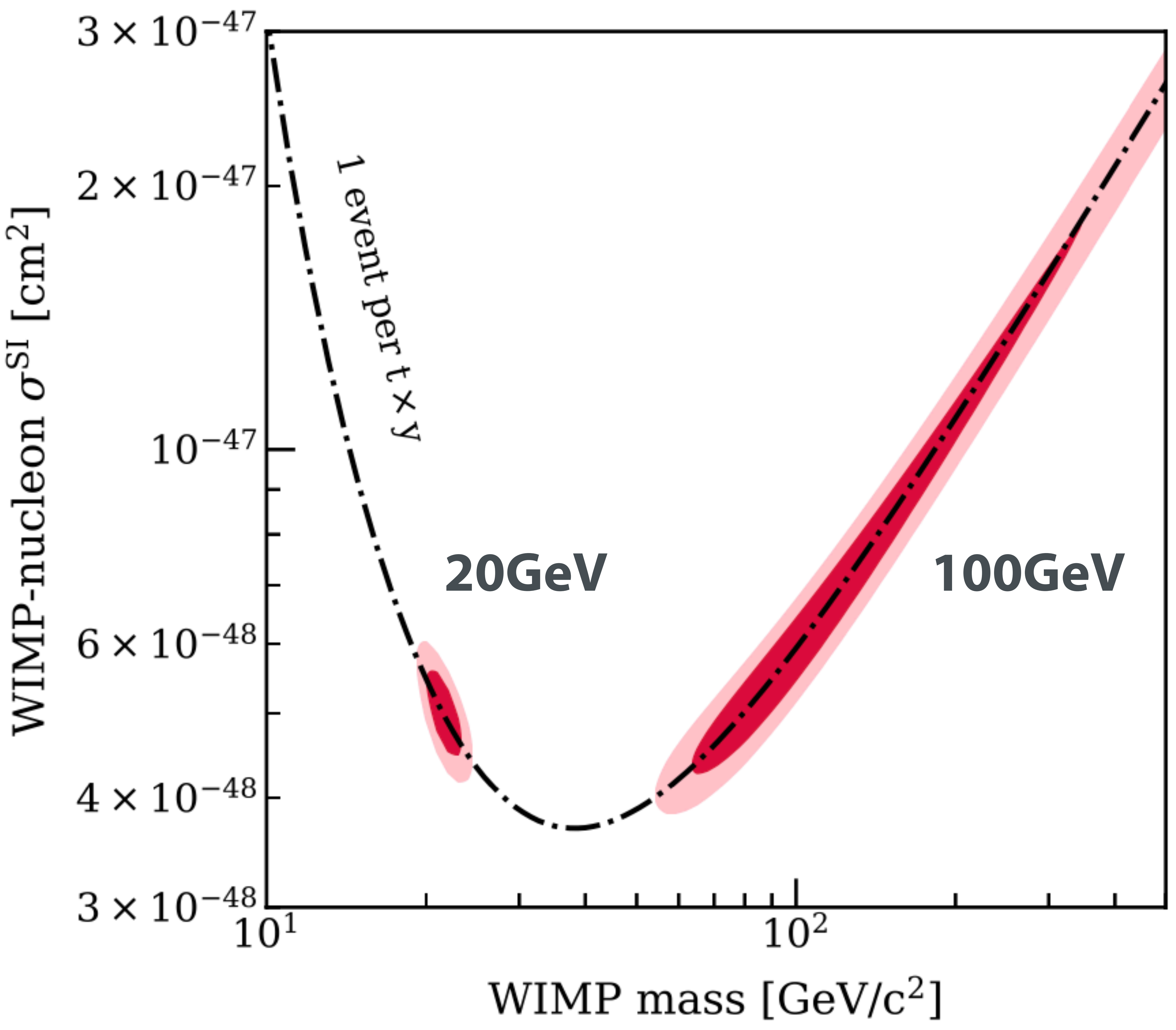
XLZD: WIMP Sensitivity

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 2.5×10^{-49} cm^2 (at 40 GeV, 200 t·yr)

Mass and Cross Section



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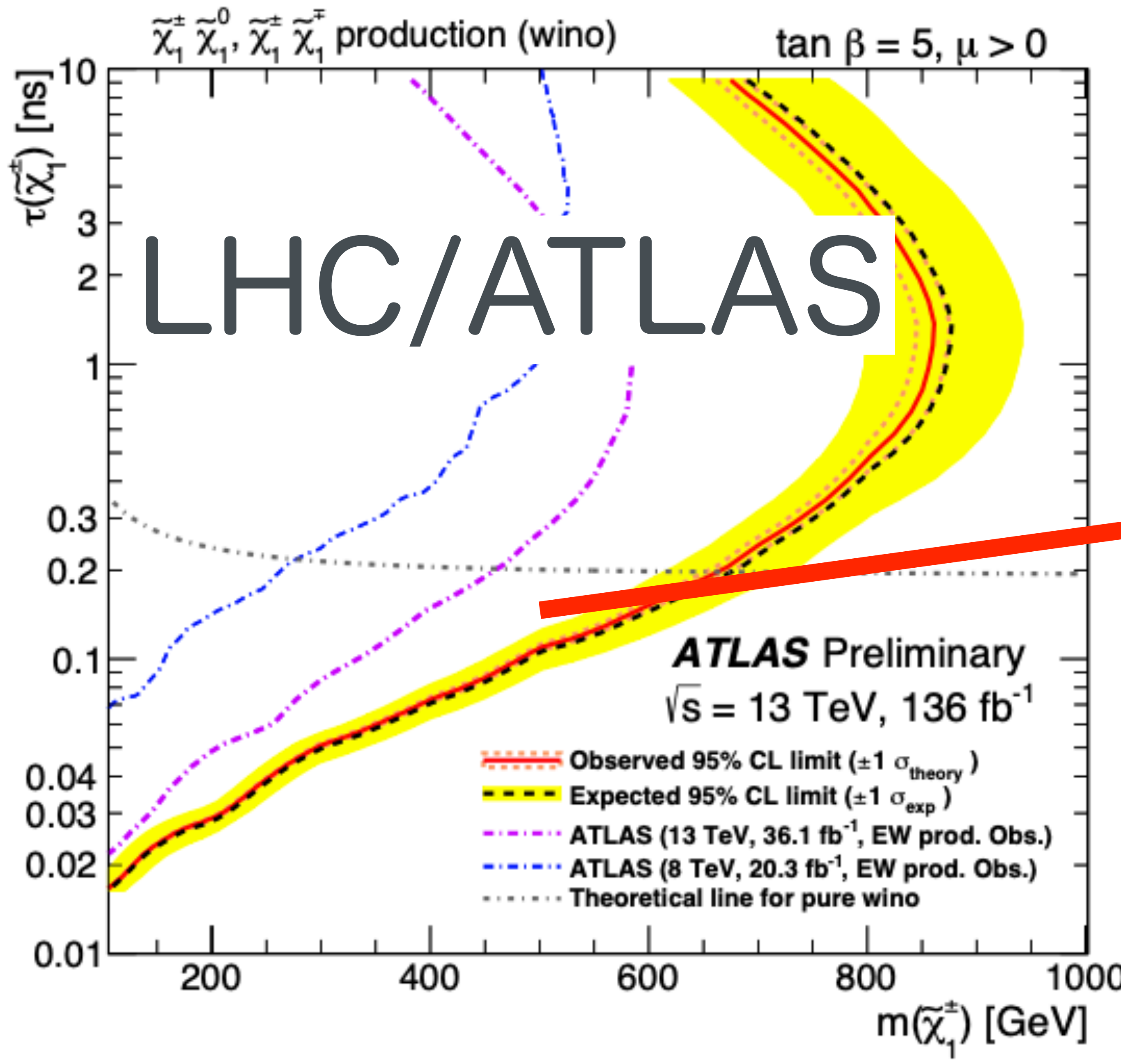
  - Example discovery contours (DM Mass + Cross Section)
    - 1000 t X y exposure

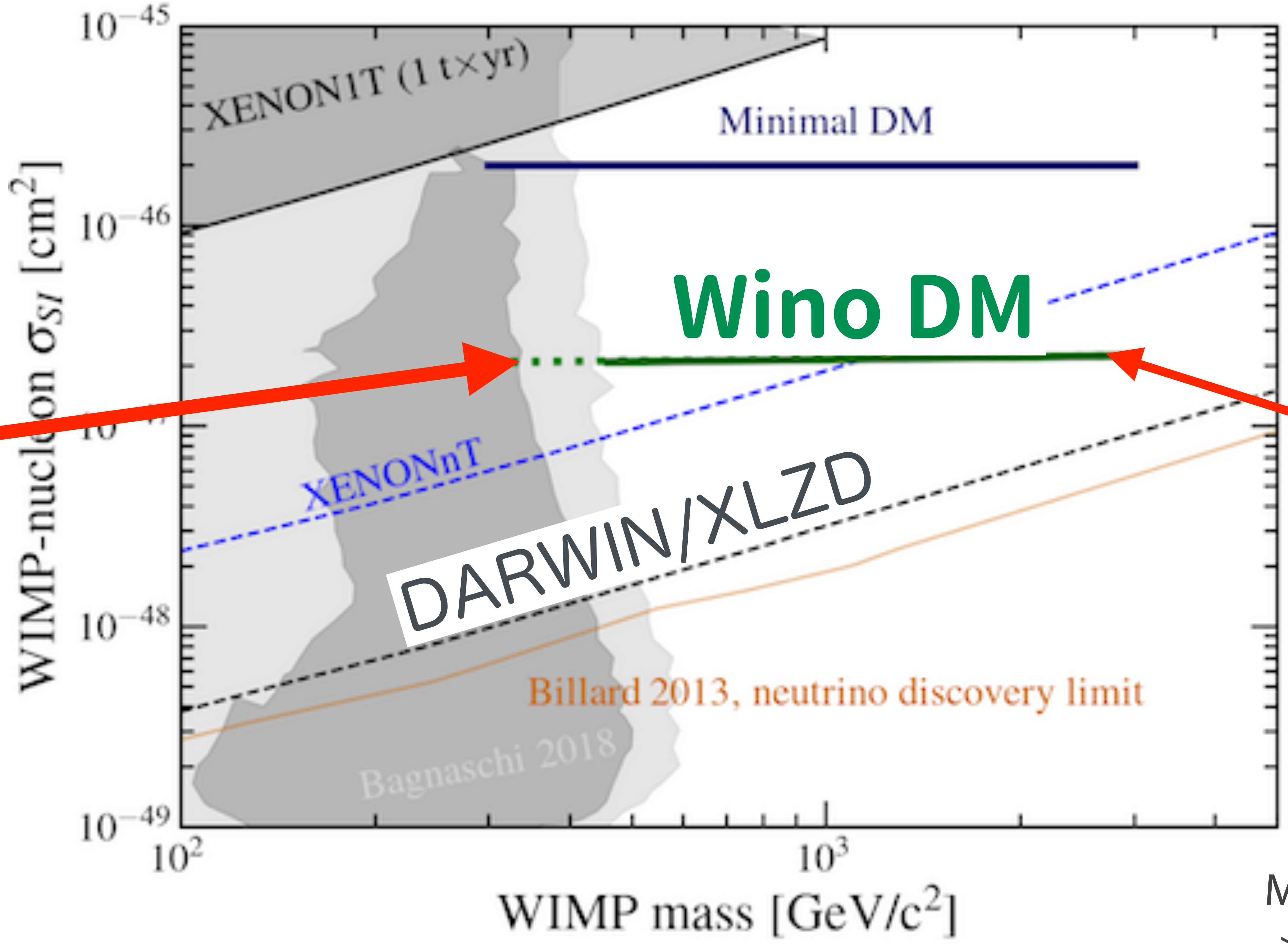
WIMP DM Search in 2020′-2030′

‘minimal dark matter’ scenario

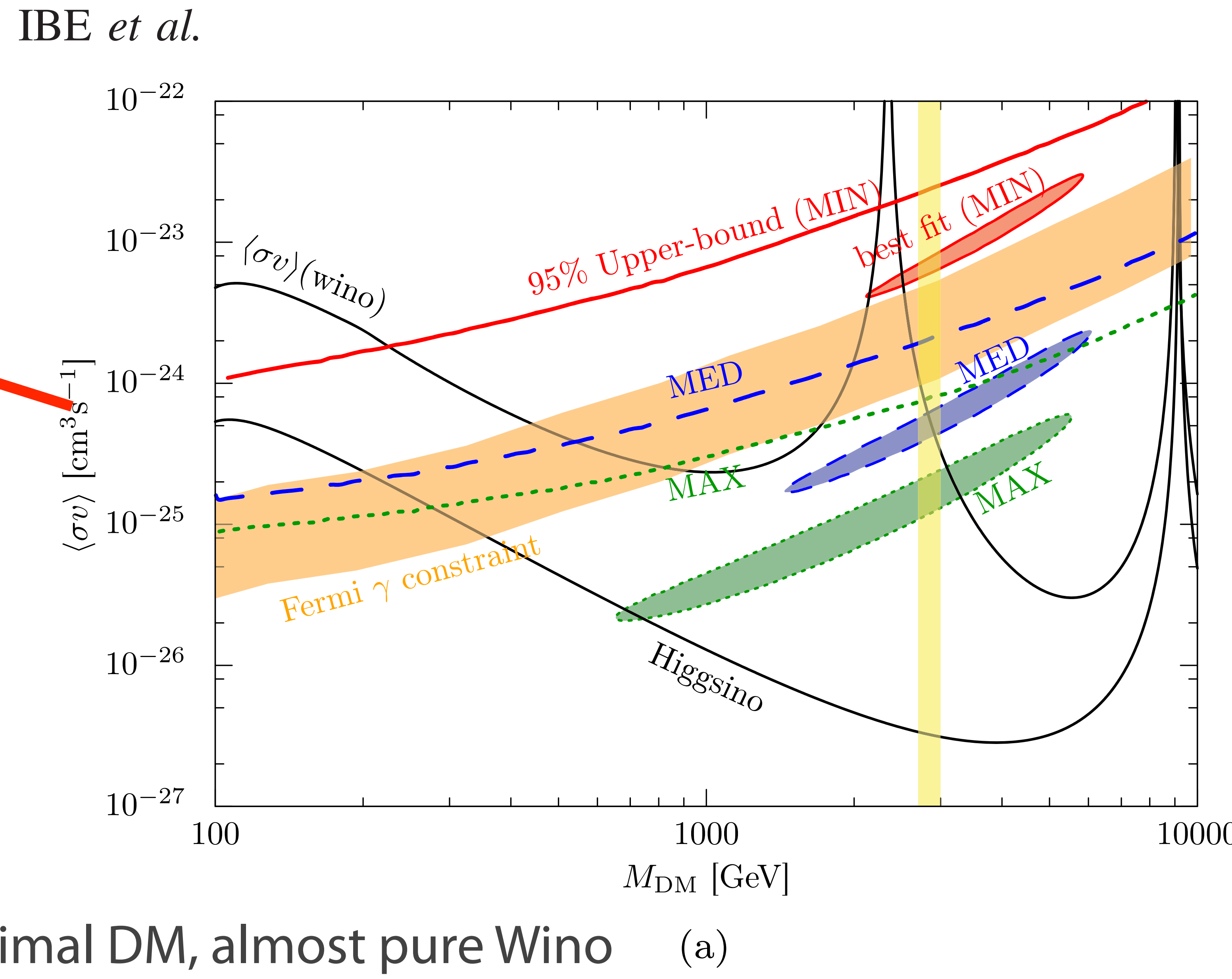
(almost) Wino DM

- WIMP interacting with the SM particles via the SM weak interaction.
- a very predictive and simple model (2×10^{-47} cm^2)





CTA(Indirect)

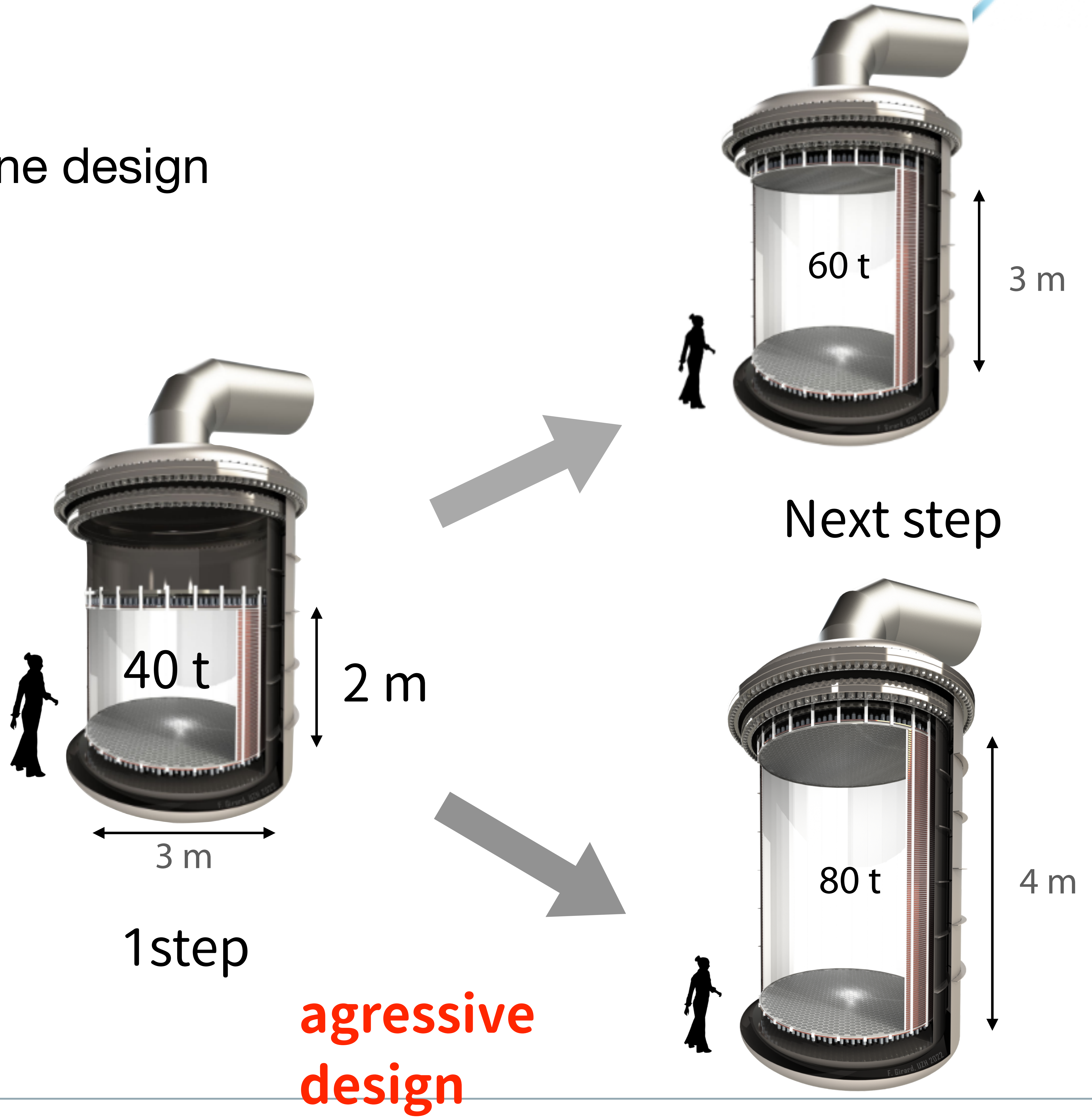


Minimal DM, almost pure Wino
-> Hisano, Ishiwata, Nagata JHEP06(2015)097

Collider, Indirect, Direct Search Complementarity

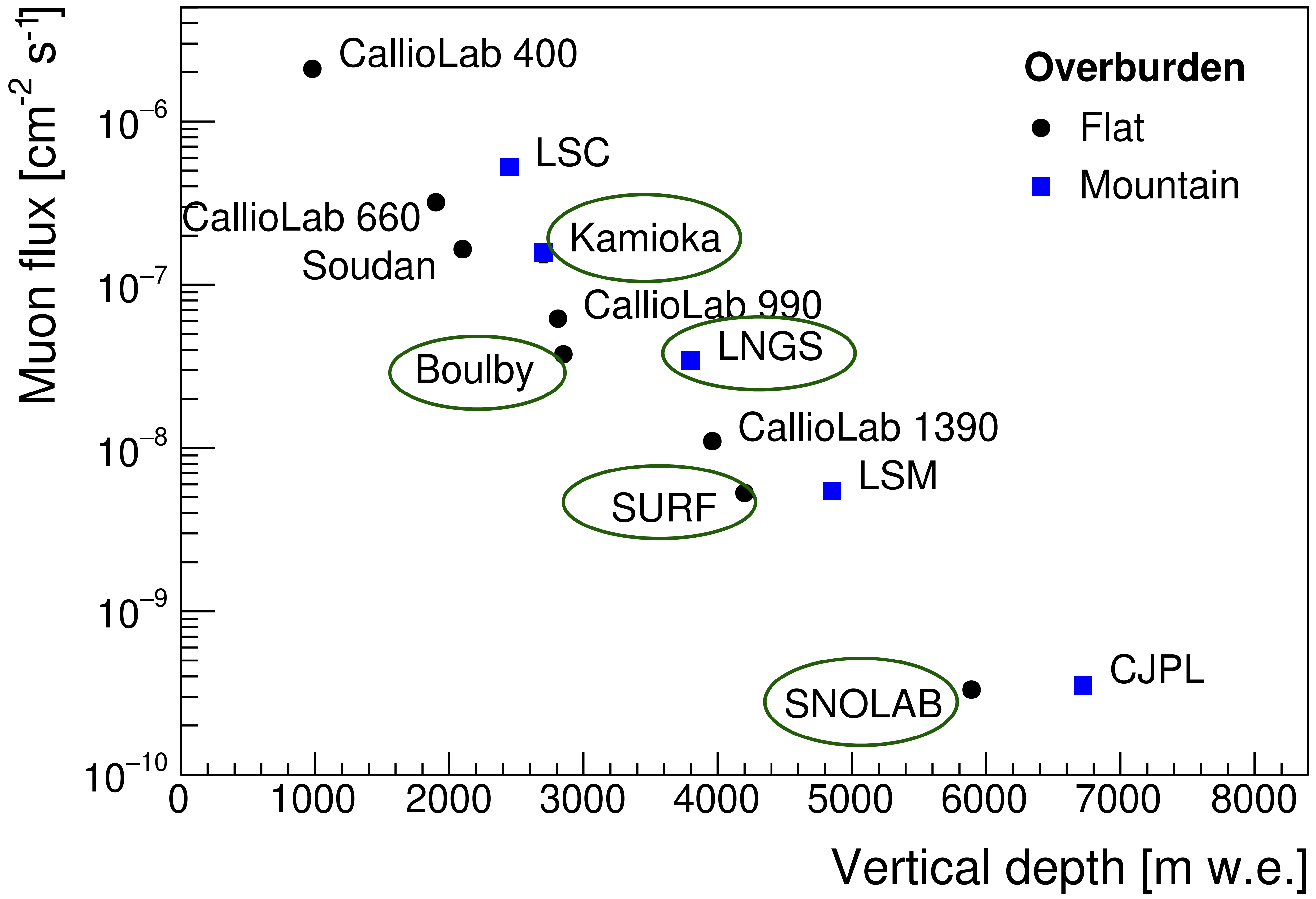
A staged approach

- 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



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

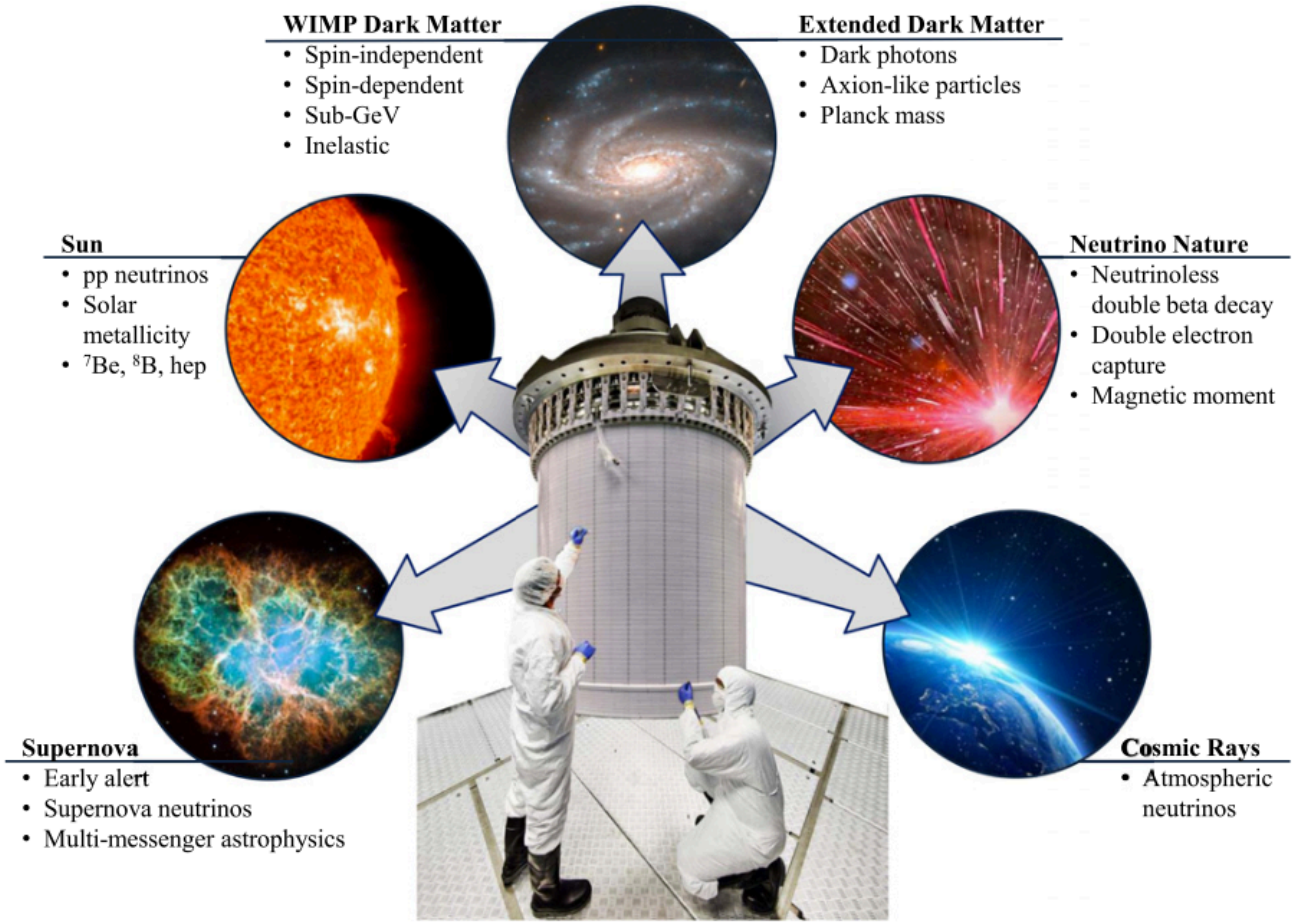

LNGS
Gran Sasso, Italy


Boulby
North Yorkshire, UK


SURF
South Dakota, US


SNOLAB
Ontario, Canada

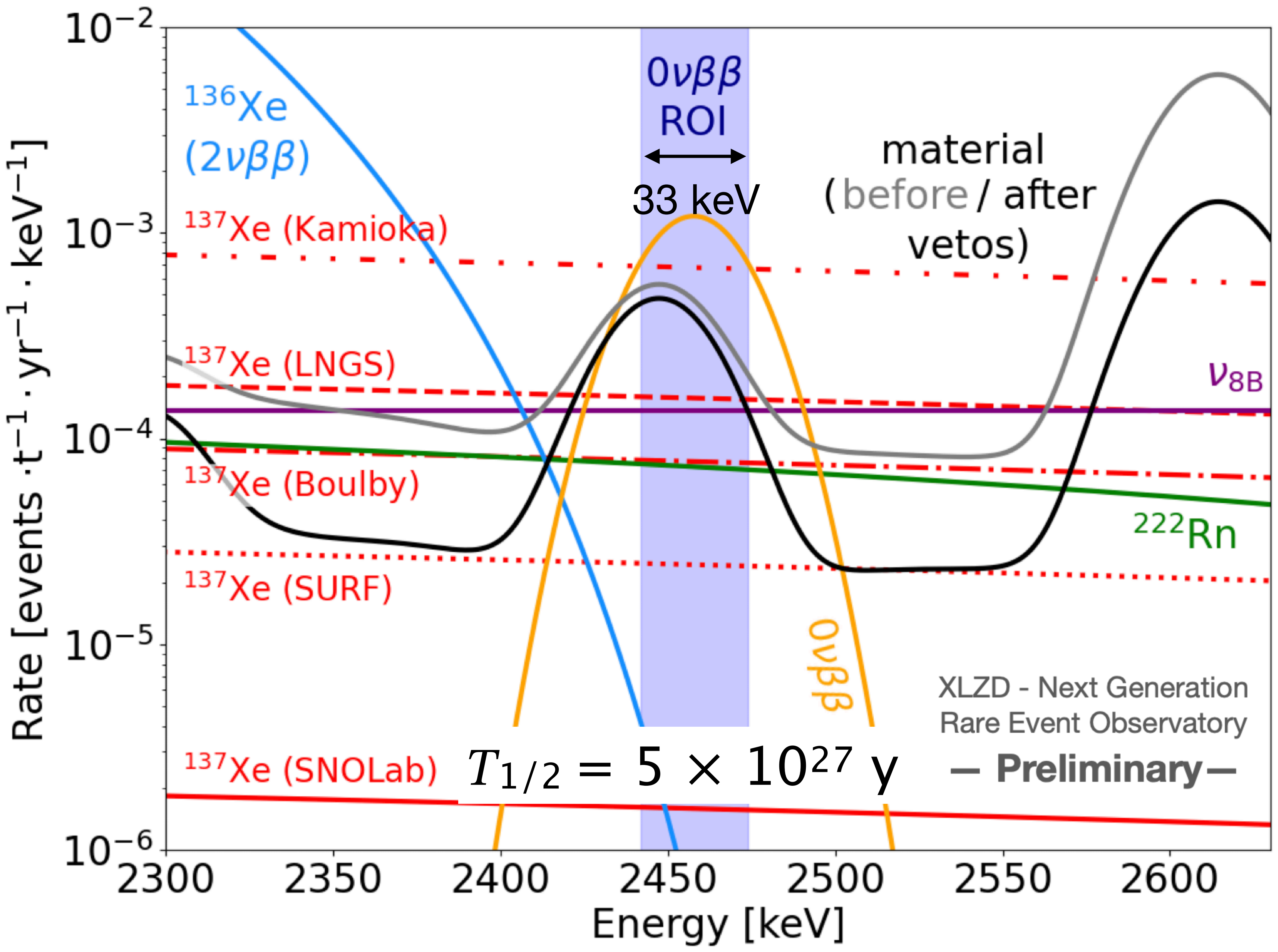
Science: Multi-purpose observatory



- 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: ^{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 (σ)

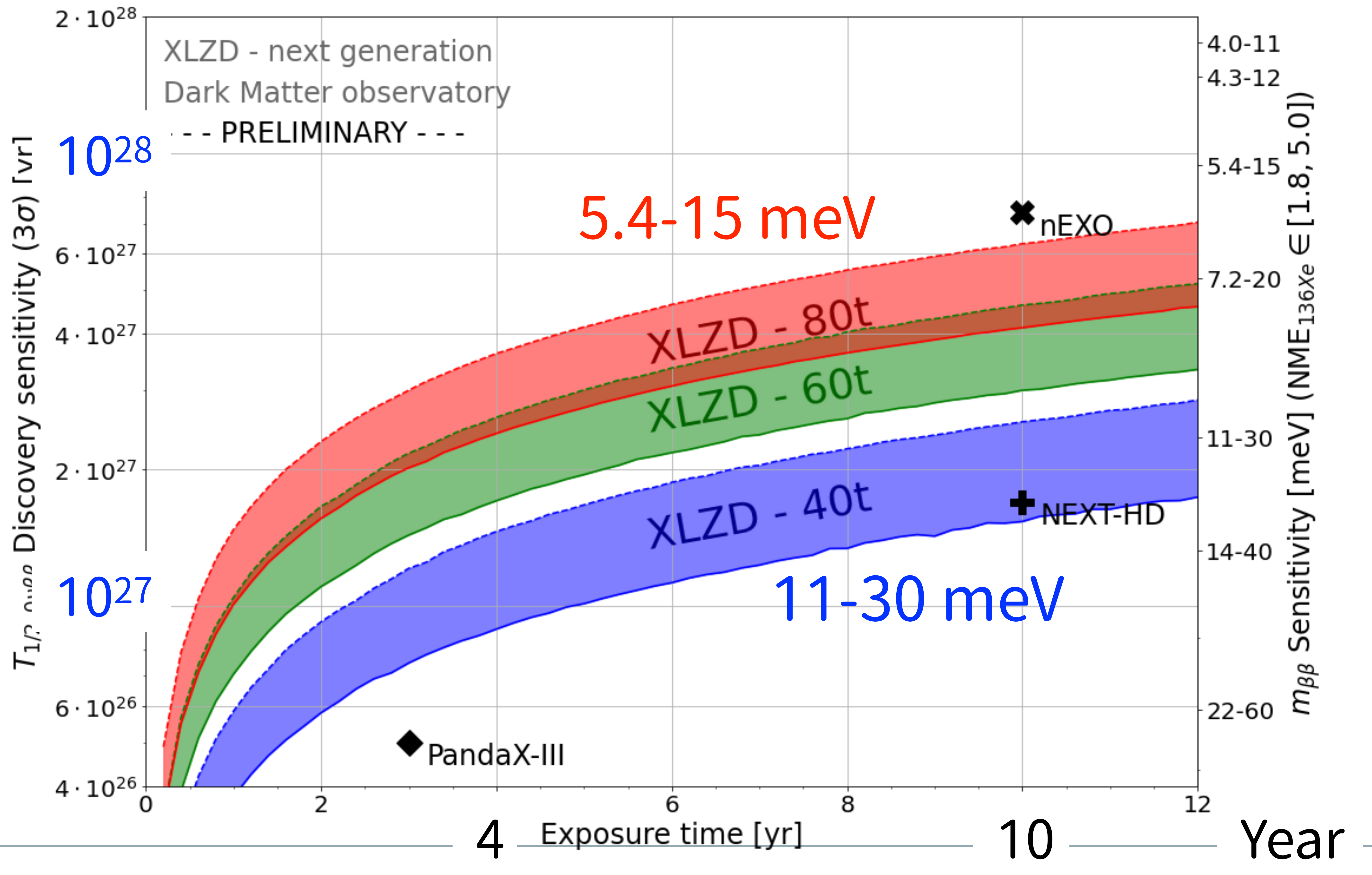


- **External gamma-ray background**
  - ^{214}Bi γ in the ^{238}U chain (2447 keV)
  - ^{208}Tl γ in the ^{232}Th chain (2615 keV) — can be highly suppressed by vetoes
- **Internal and intrinsic backgrounds**
  - ^{214}Bi β from ^{222}Rn in the xenon (Q = 3270 keV)
    - We assume 0.1 μBq/kg ^{222}Rn 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

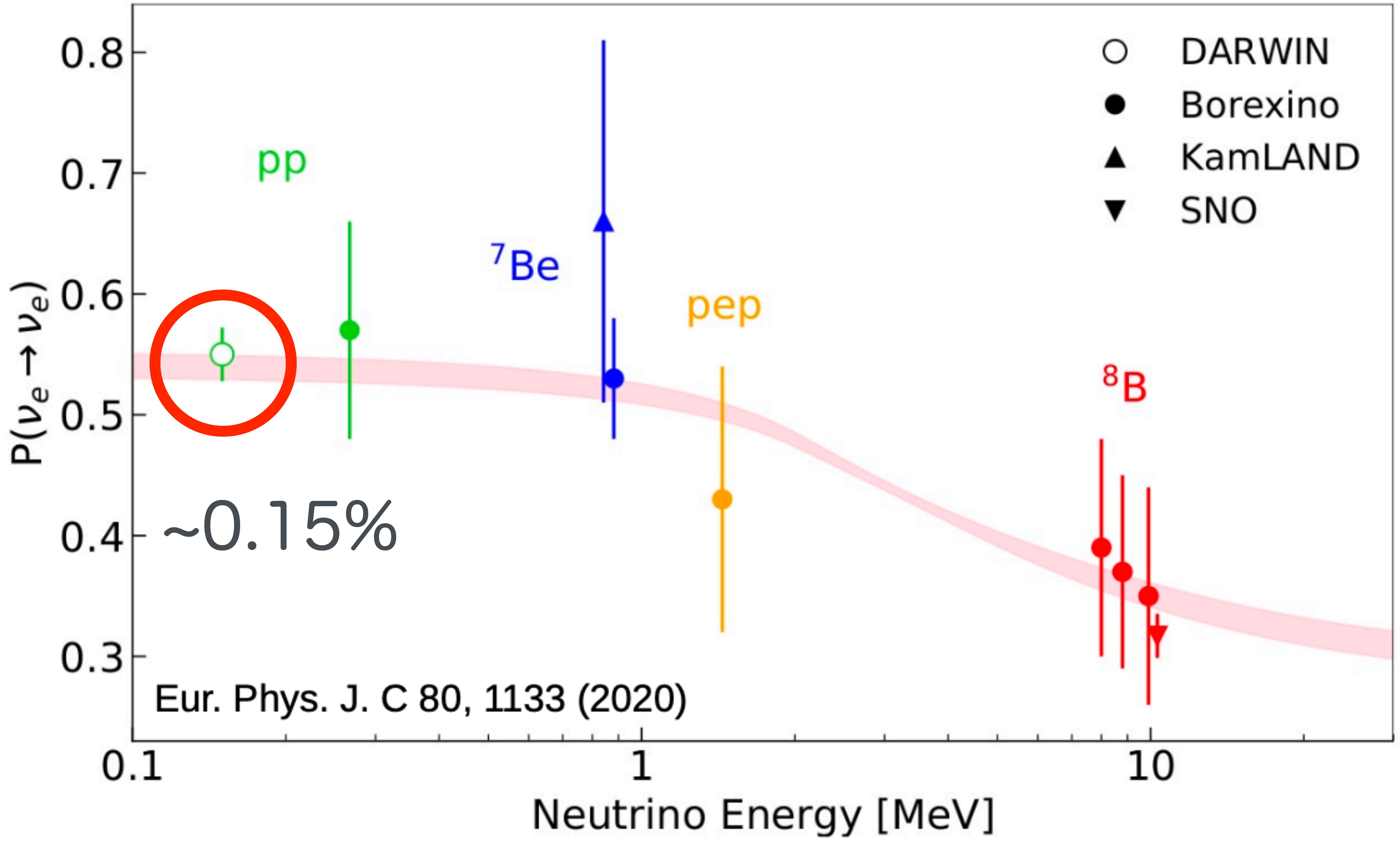
XLZD: ^{136}Xe $0\nu\beta\beta$ Search

Sensitivity Study

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



Solar Neutrino



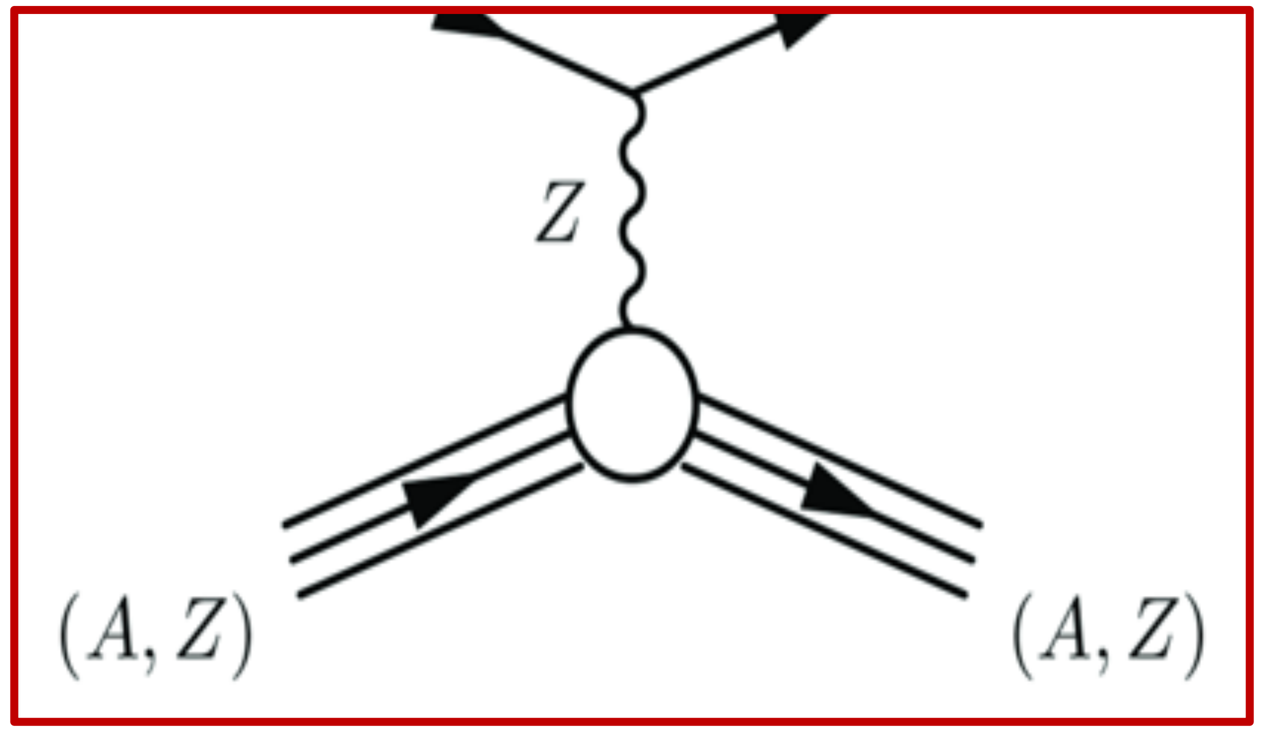
- Neutrinos (solar model, neutrino properties)
  - **High statistics pp neutrino measurement**
  - **Neutrino survival probability** at high (5-15 MeV) and very low energies
  - **Neutrino magnetic moment**

XLZD: Supernova neutrino

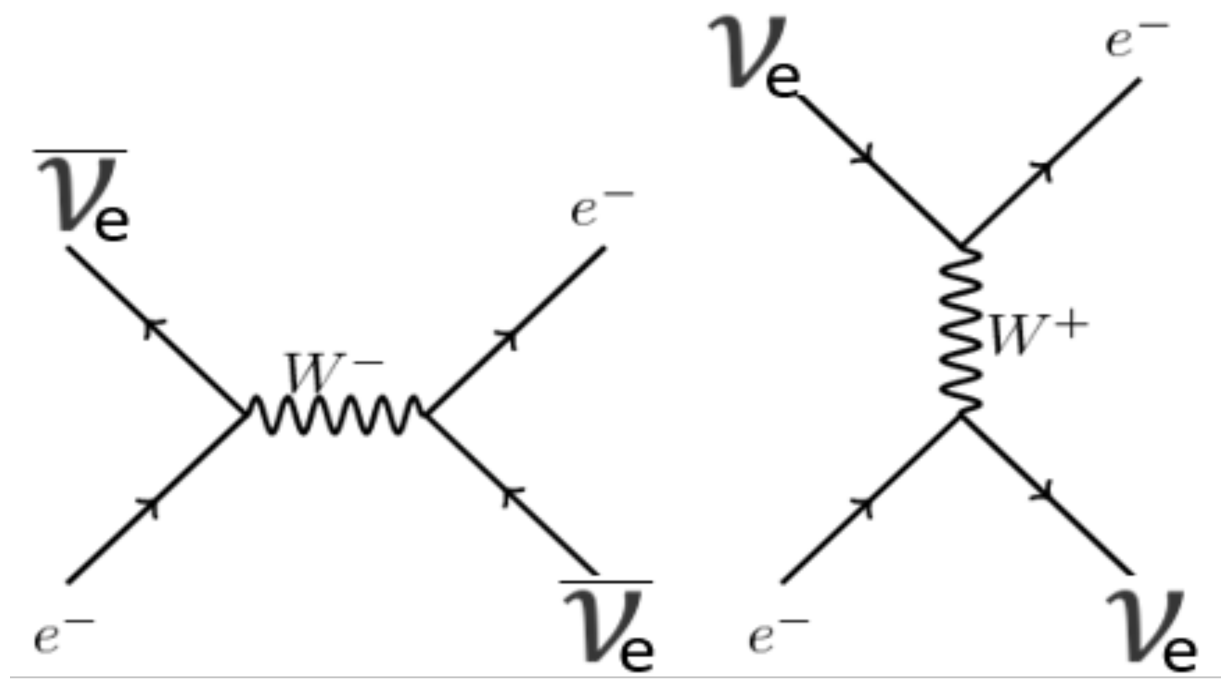
Phys.Rev.D 94 (2016) 10, 103009
Ann. Rev. Nucl. Part. Sci. 27, 167 (1977)

Kara (KIT)

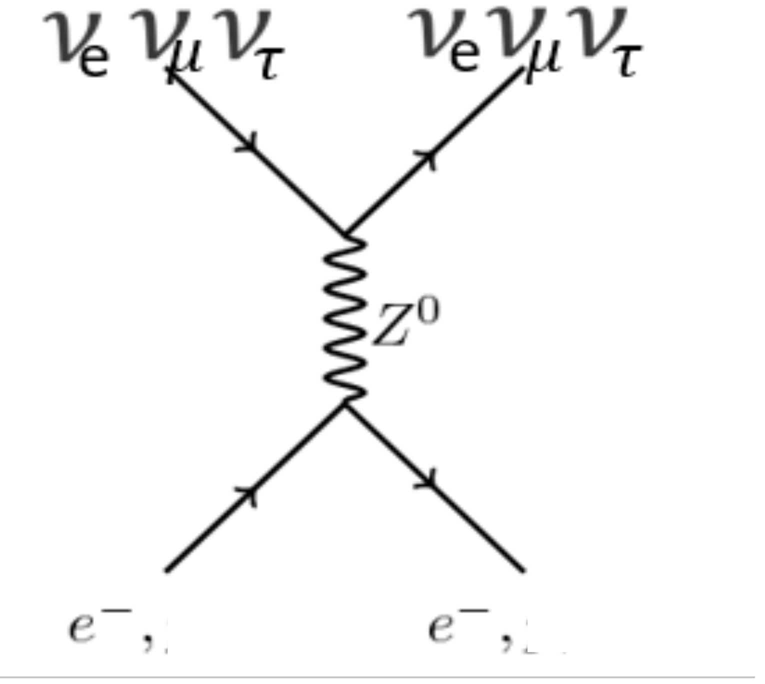
CEvNS



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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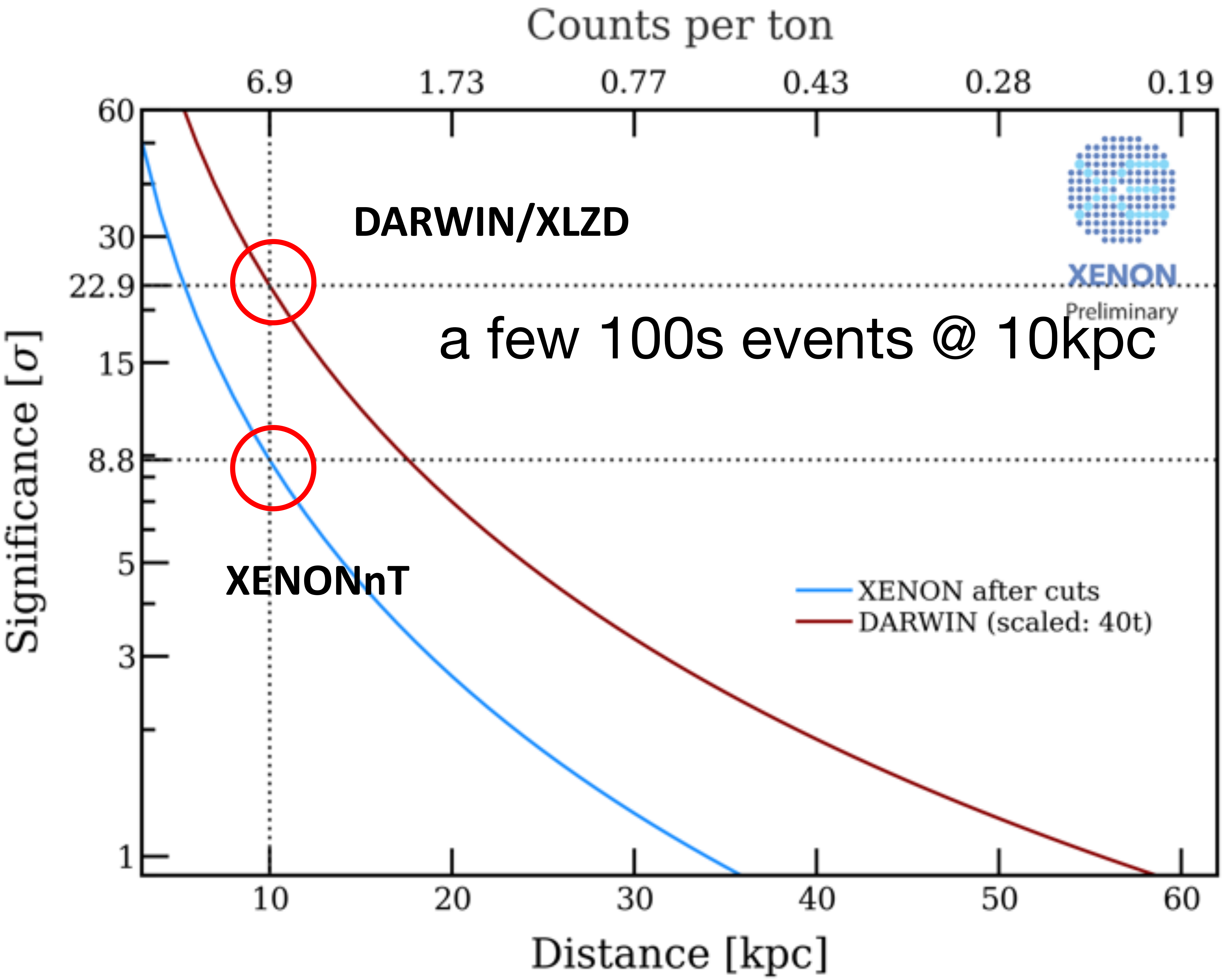
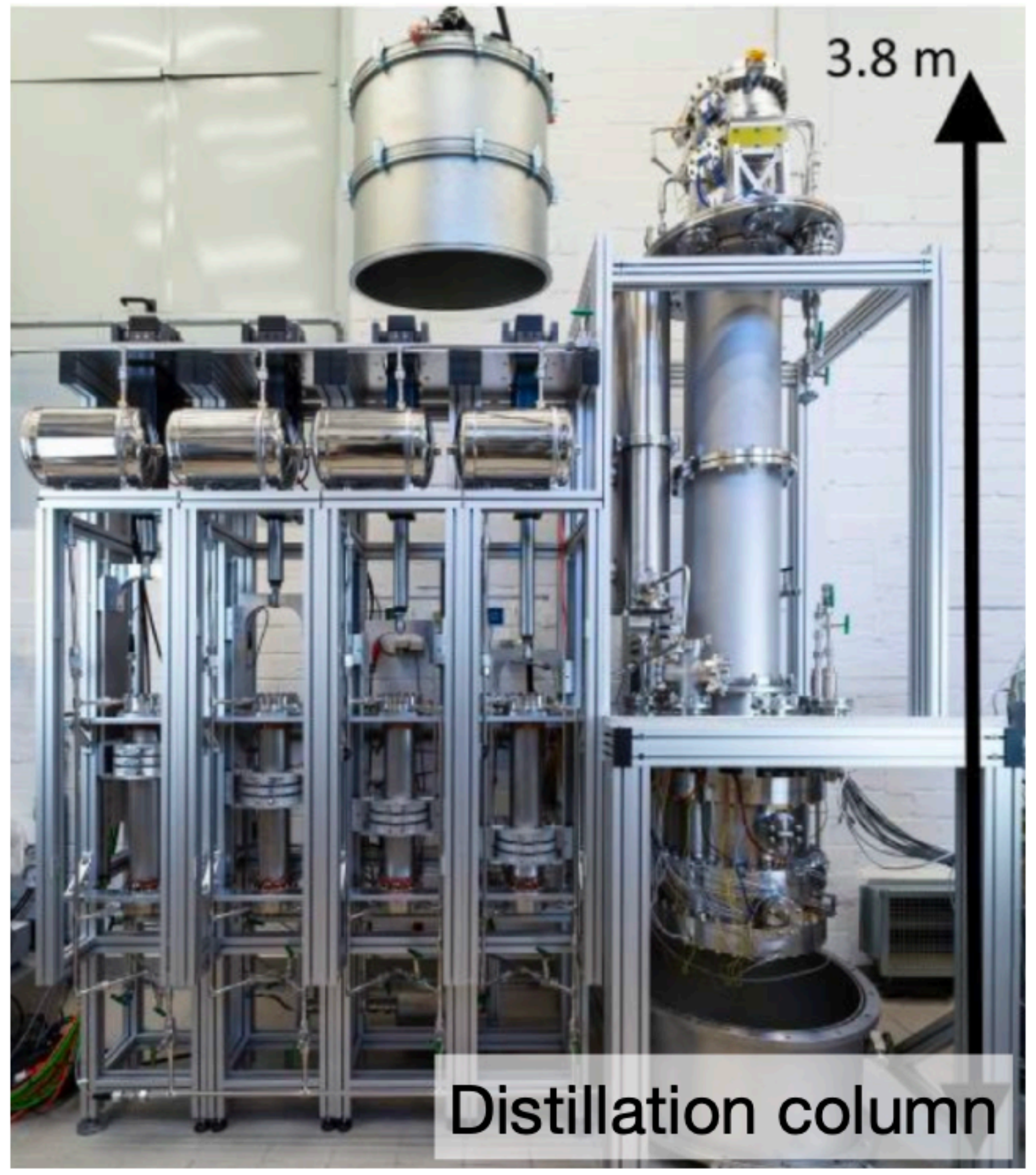
Ann. Rev. Nucl. Part. Sci. 27, 167 (1977)



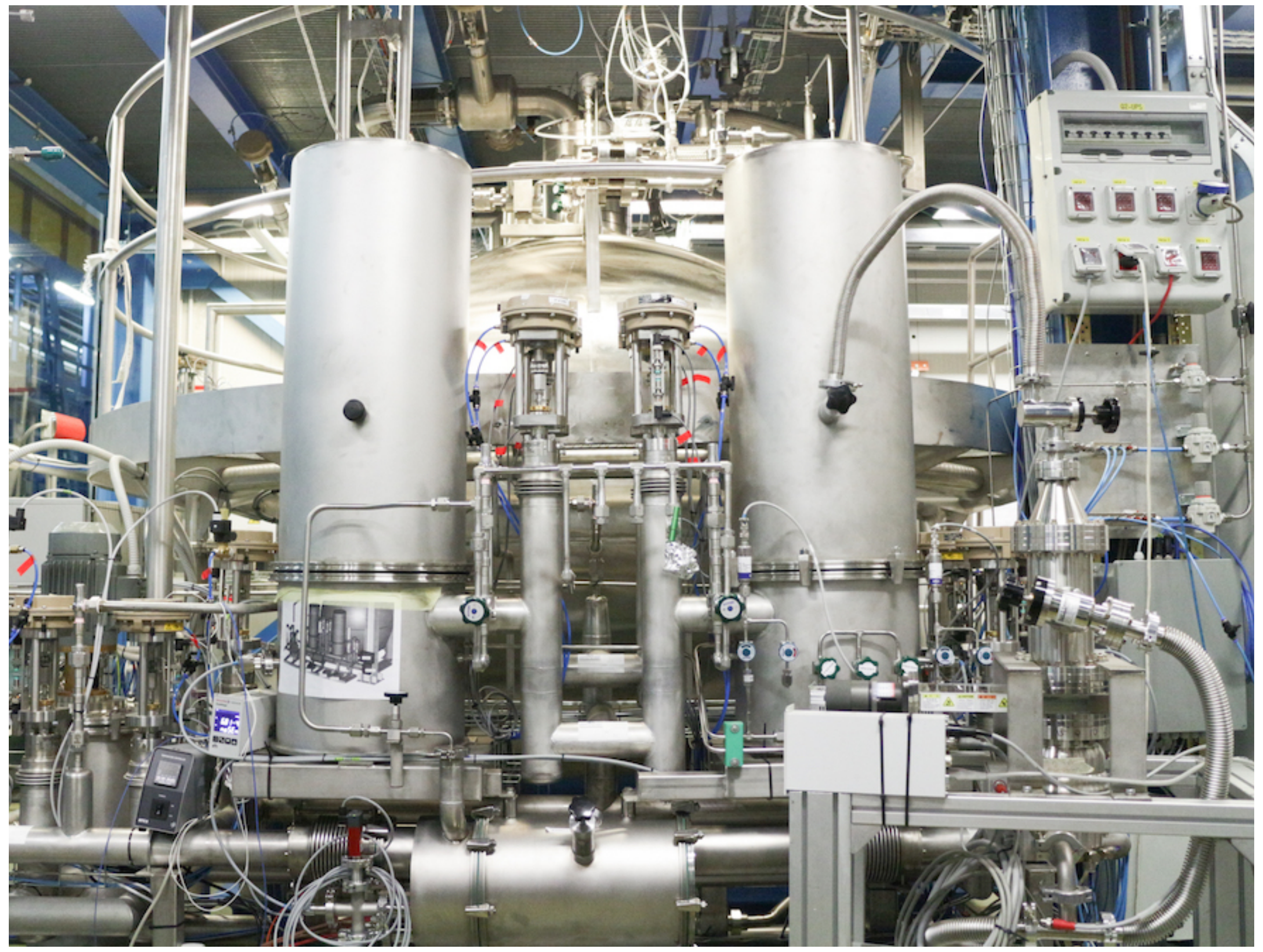
2022) 2, 107

Technology toward Ultimate detector

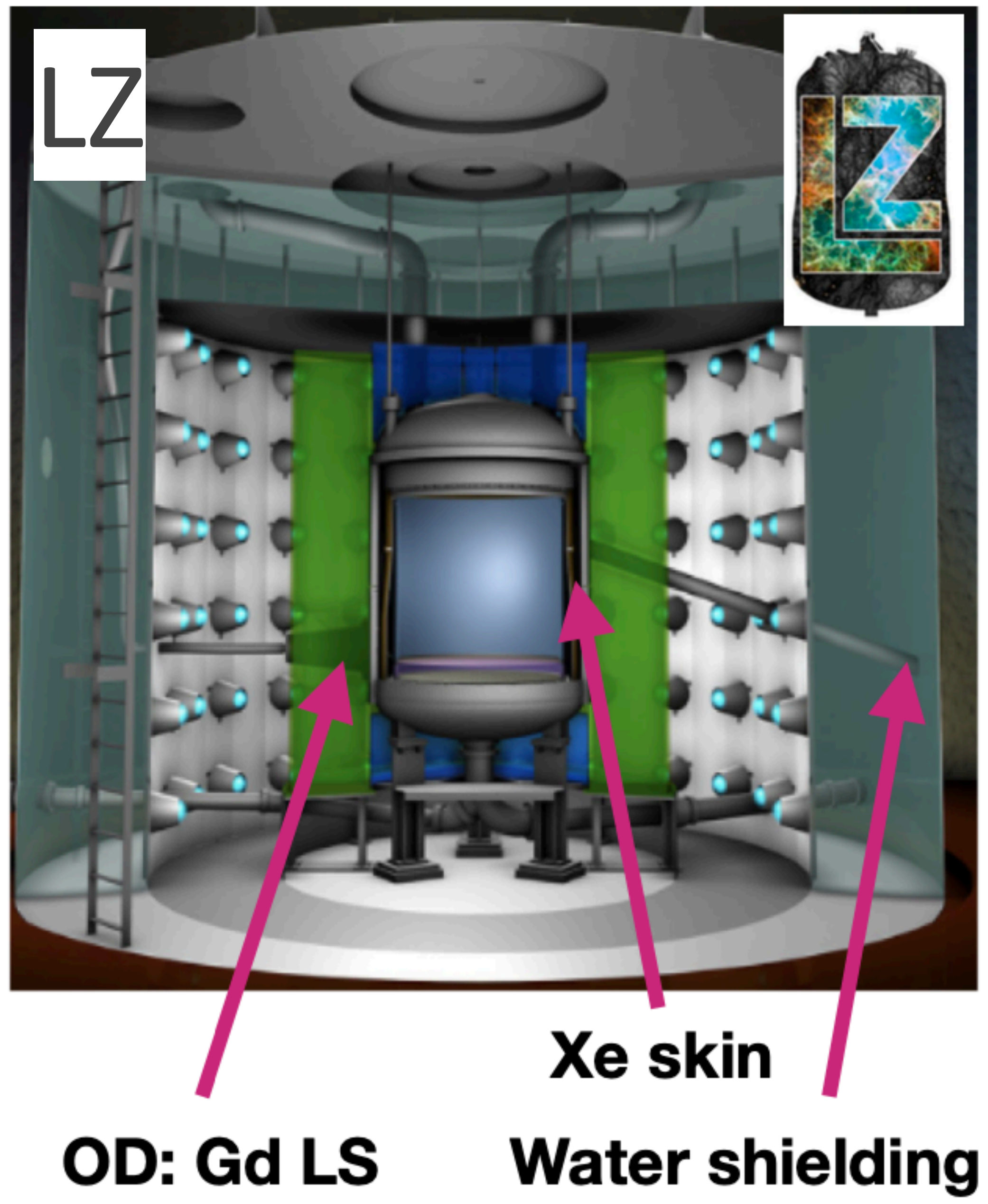
- Radon/Krypton distillation (XENONnT)
- 222Rn/ < 1 uBq/kg
- 85Kr < ppt

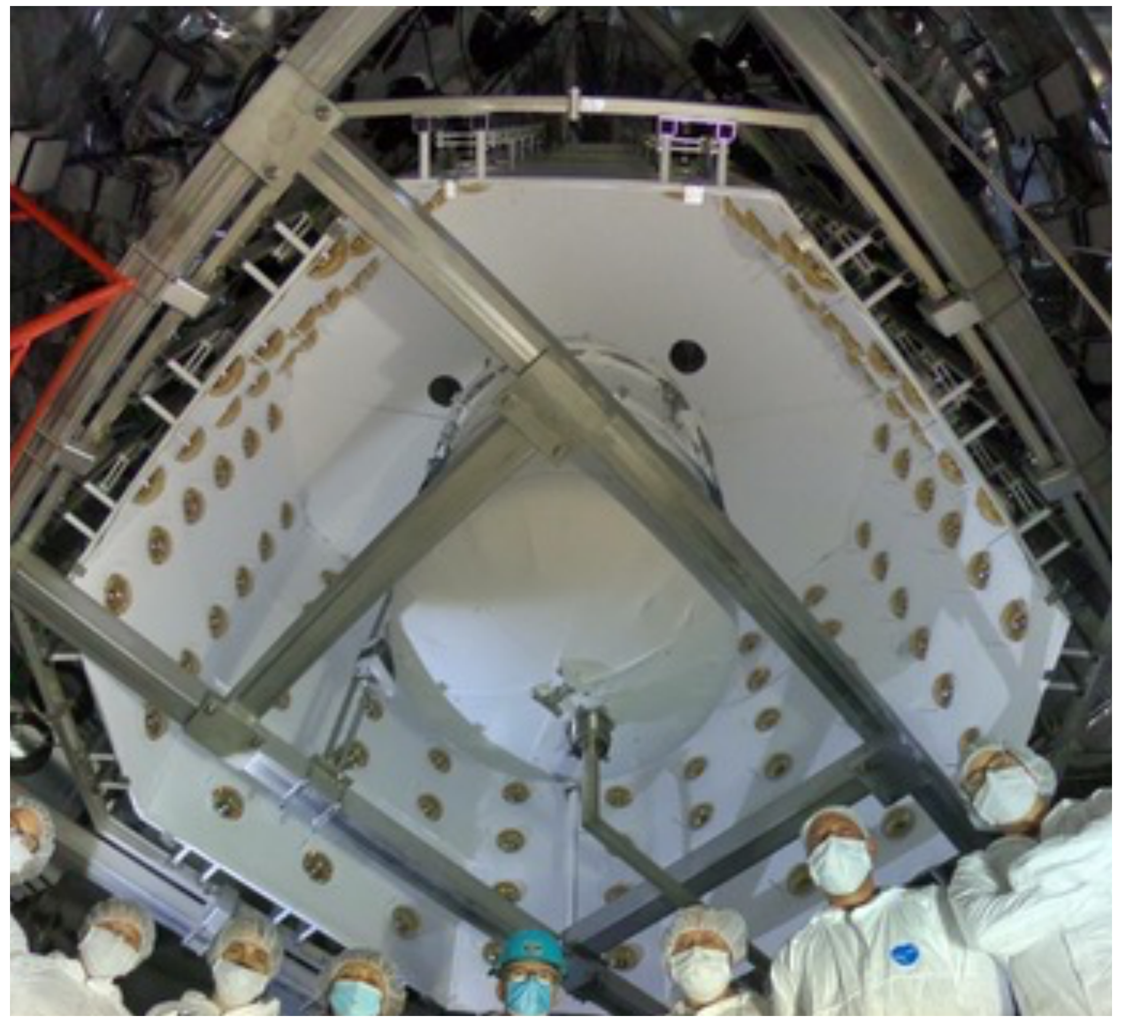


- LXePUR (XENONnT)
- Liquid phase purification
- > 15 ms electron lifetime
  - =>   ~ 15 m drift length



- gamma Veto
- neutron Veto

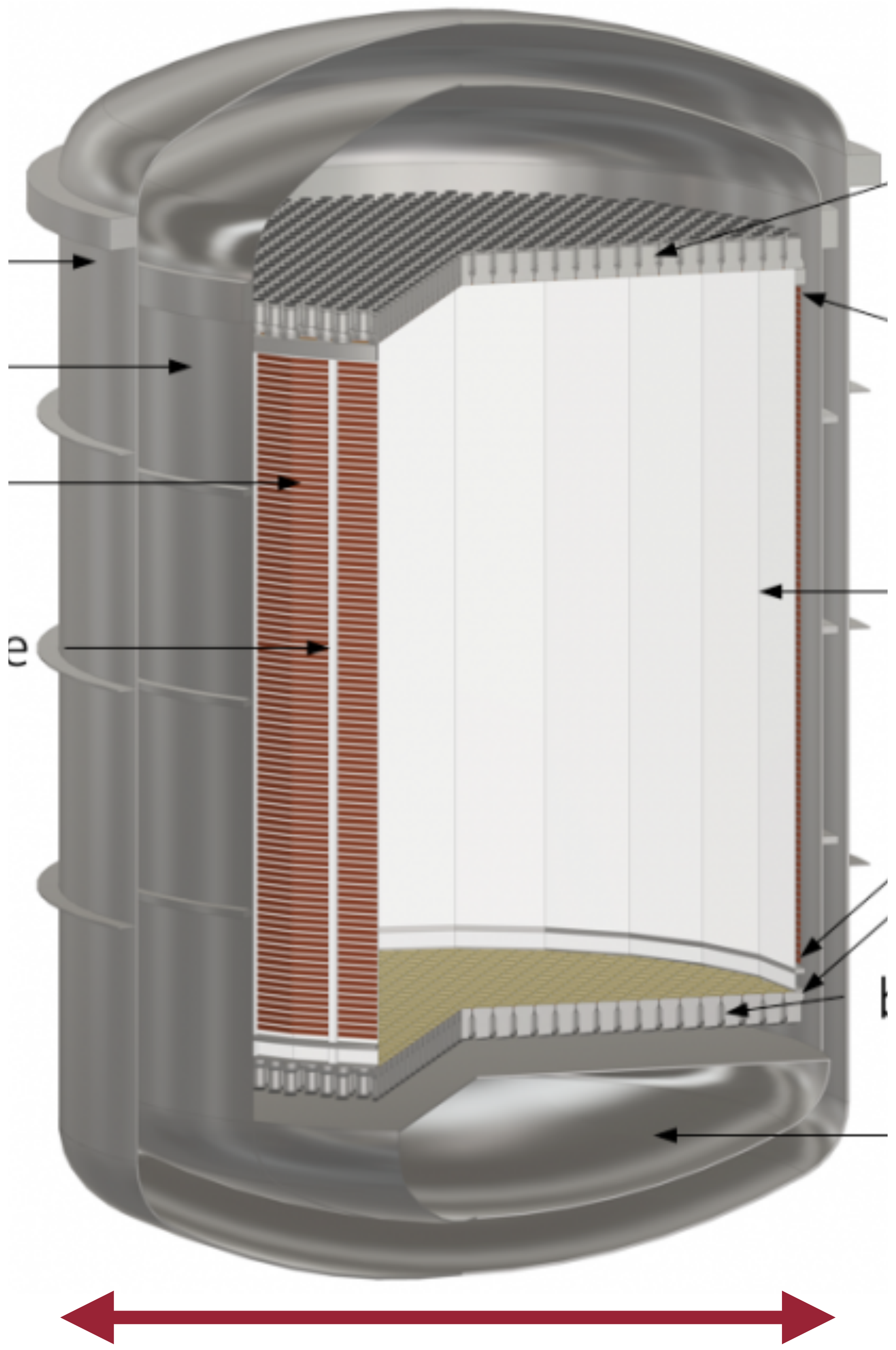




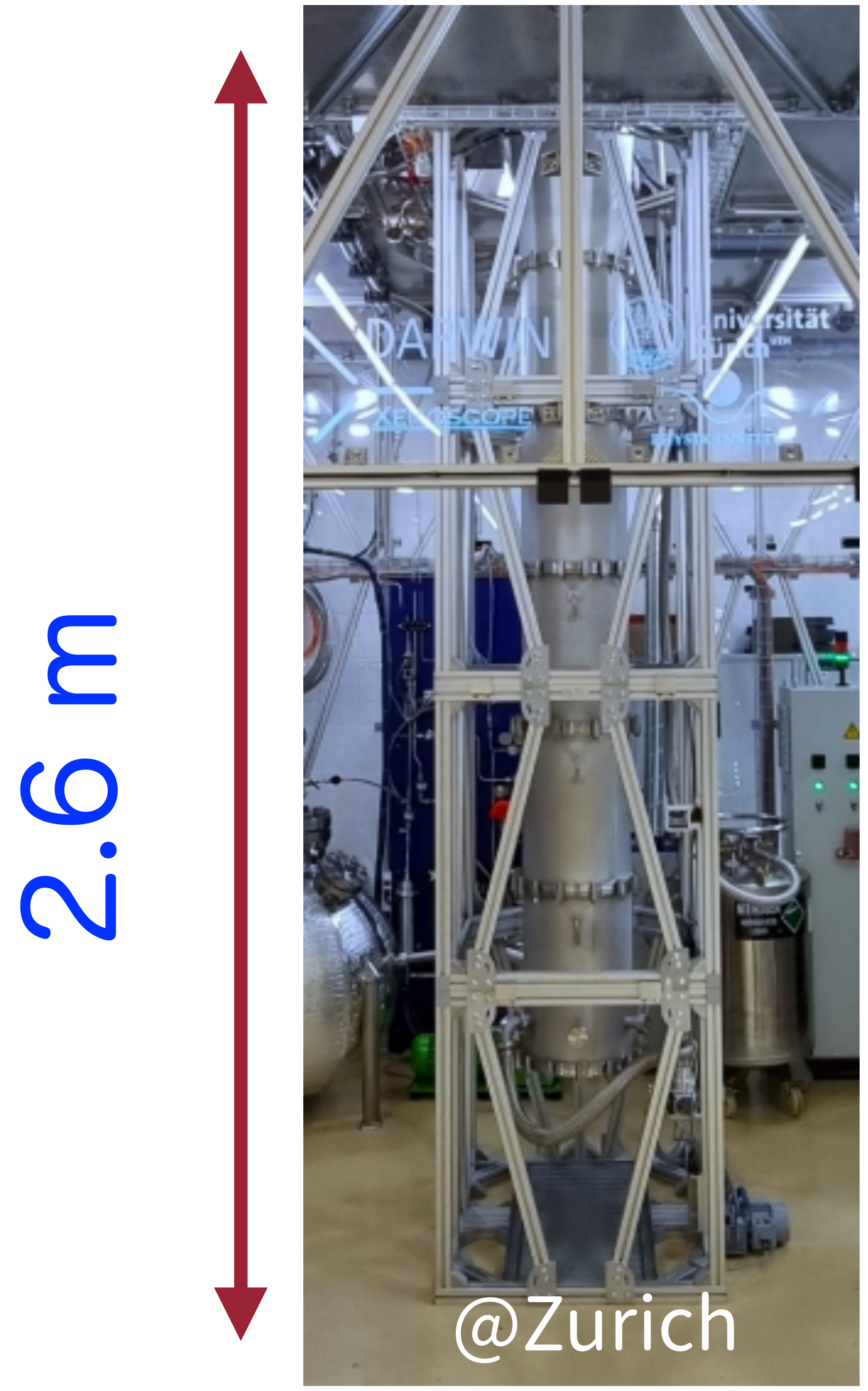
XENONnT

R&D Activities: TPC and Electrodes/HV

Full height and diameter test facility for DARWIN/XLZD

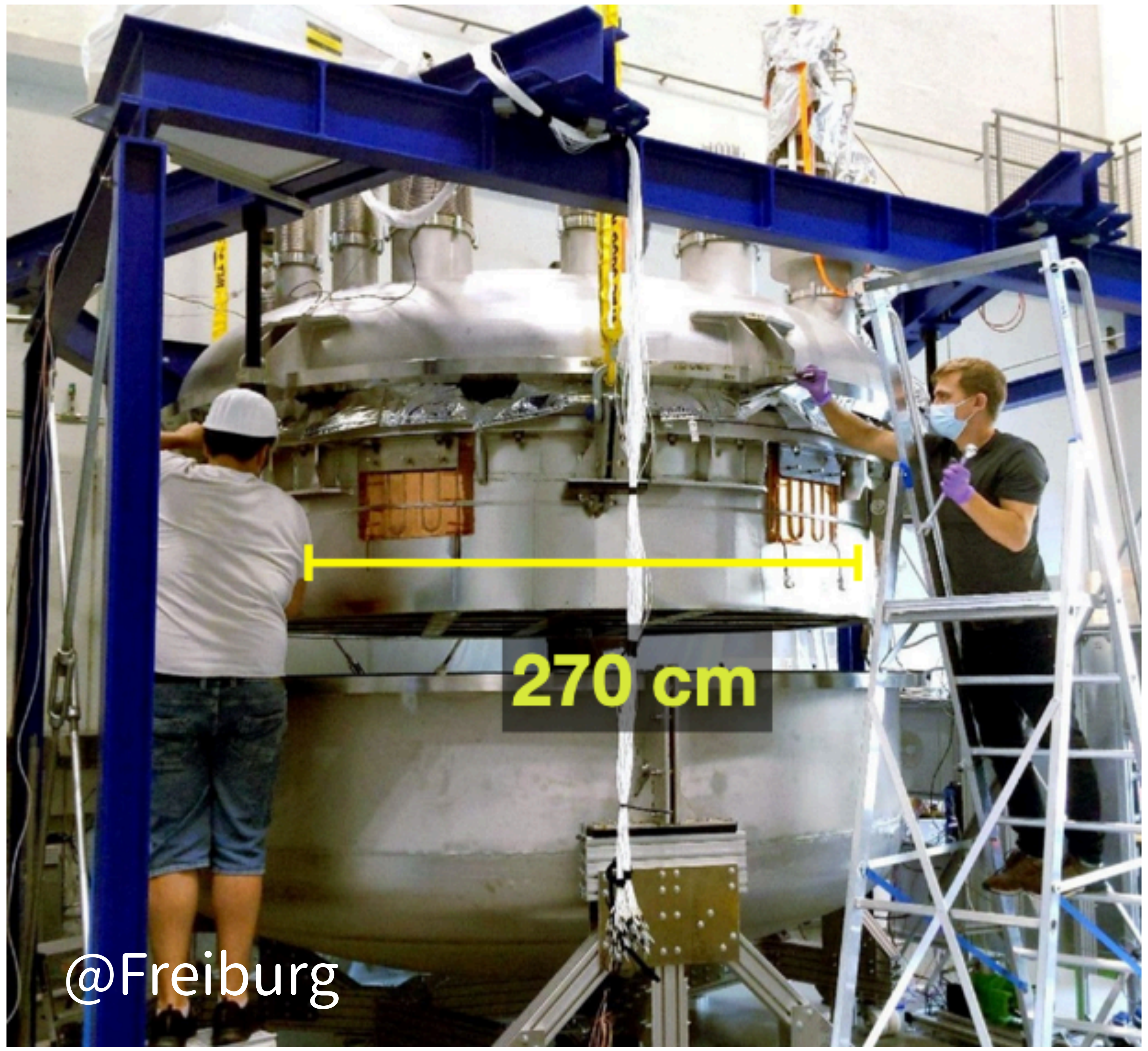


2.6 m



JINST 16 P08052(2021)

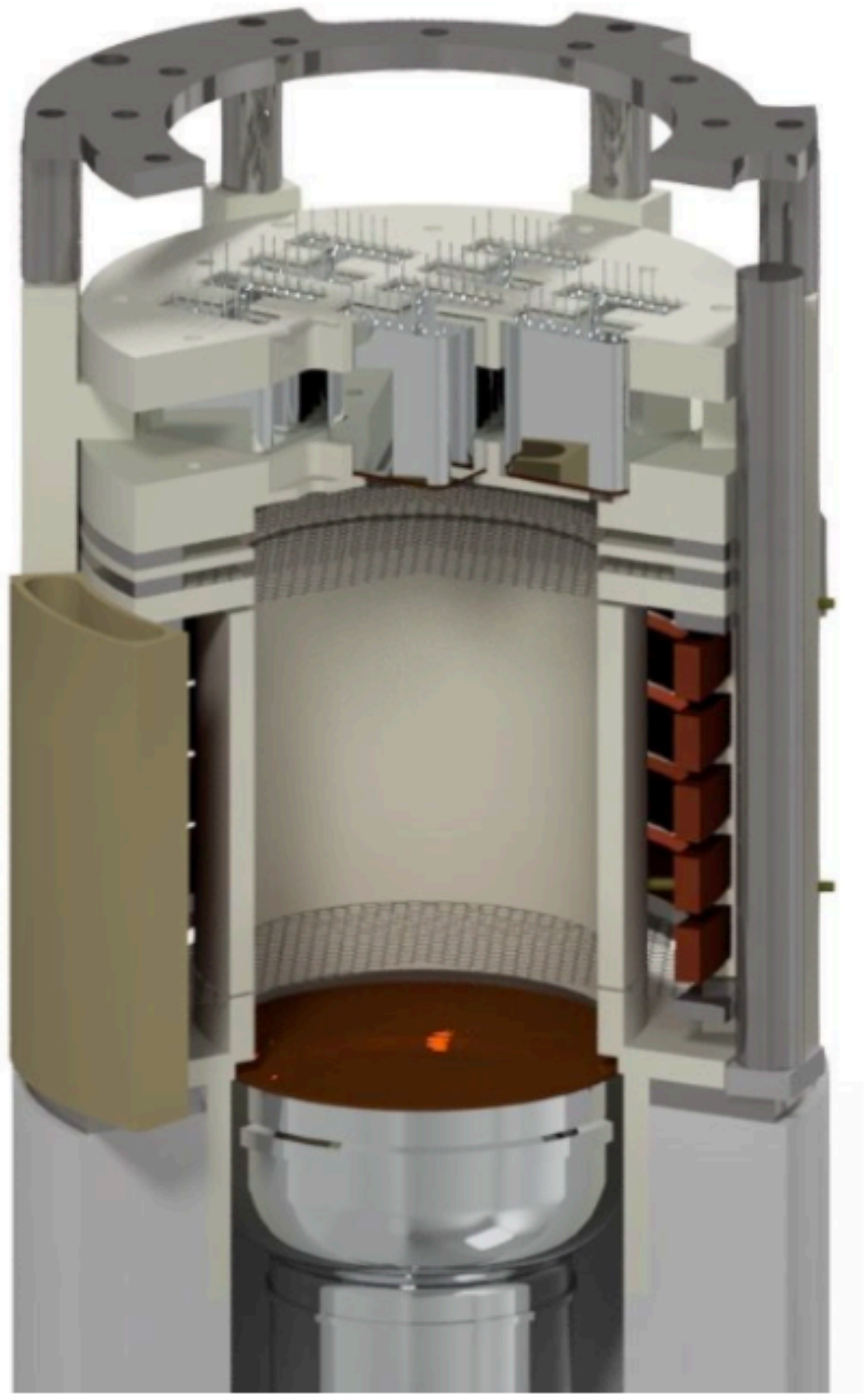
High voltage, Purity … s



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

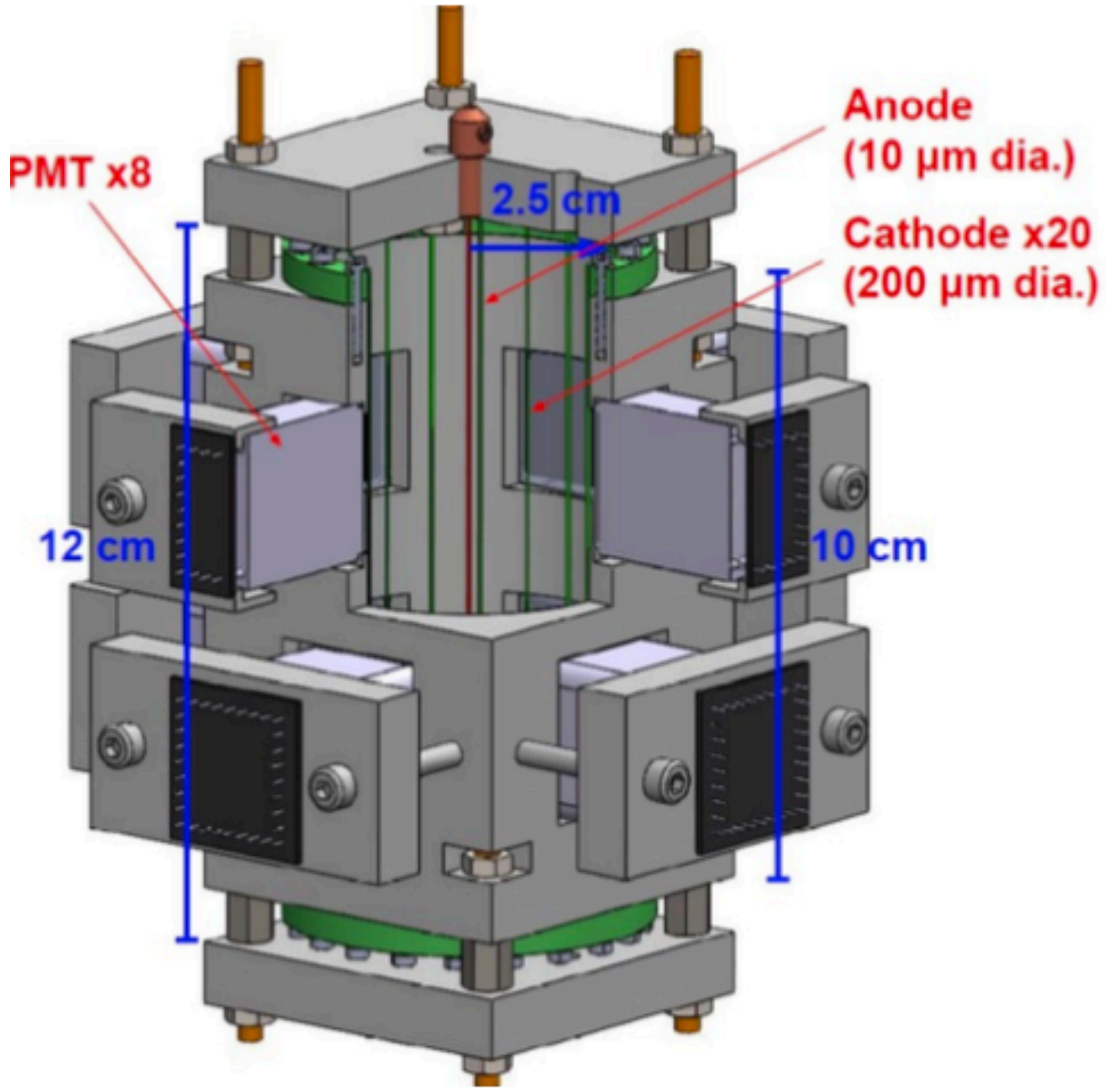


Phys. J. C 83, 9 (2023)

Quartz chamber

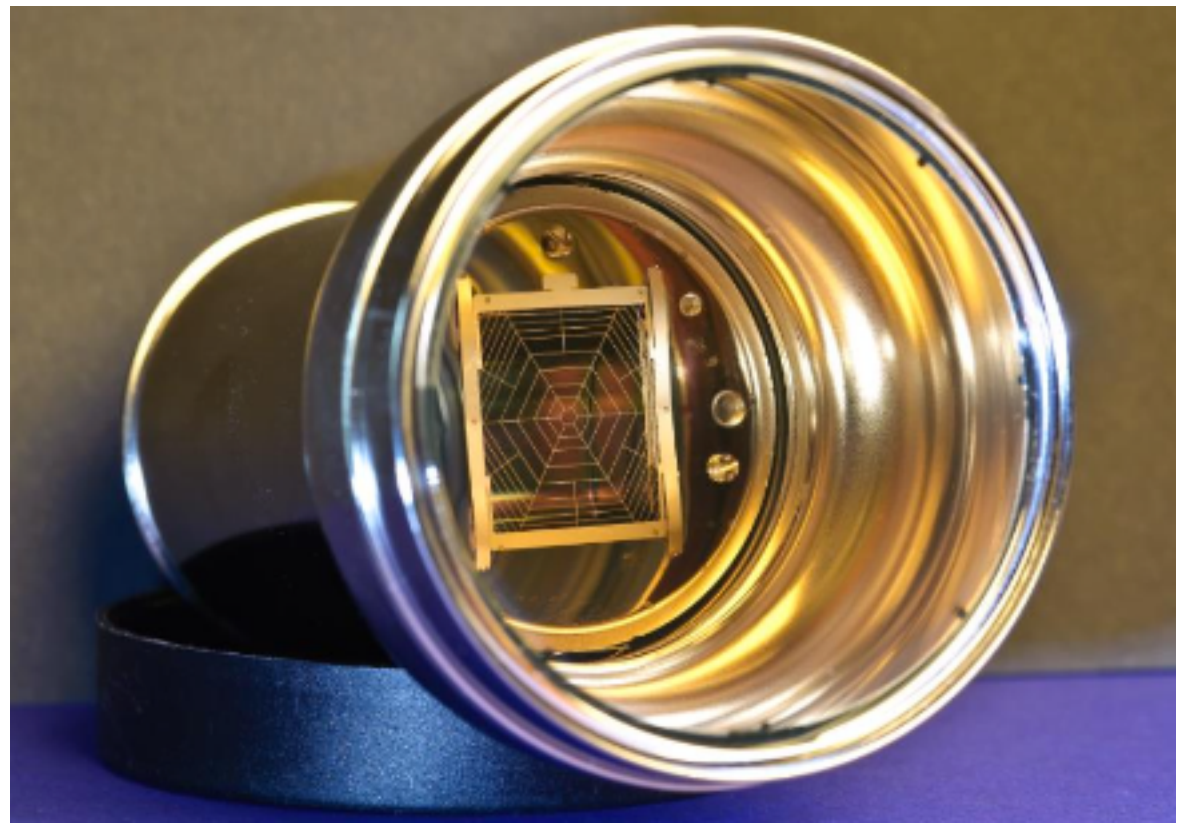
@Nagoya

PTEP 2020 113H02
@Kamioka



arXiv:2301.12296

DARWIN: R&D Photosensor

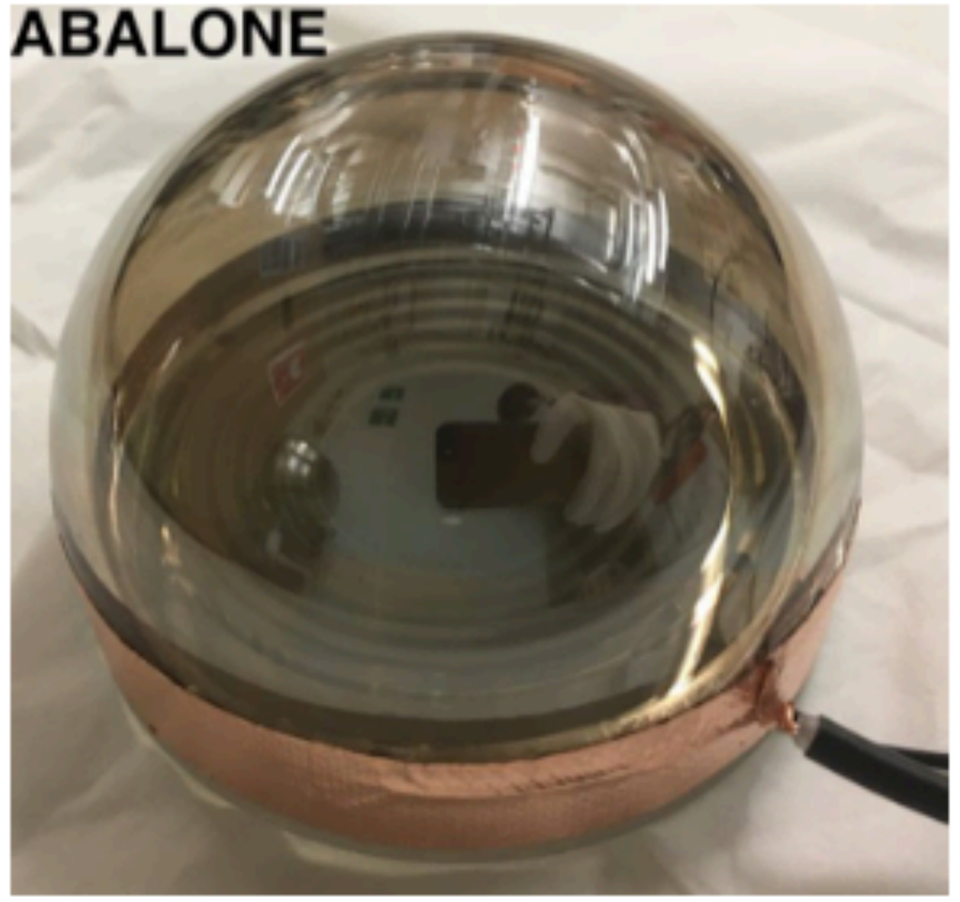


R11410 (LZ, XENONnT, PandaX)

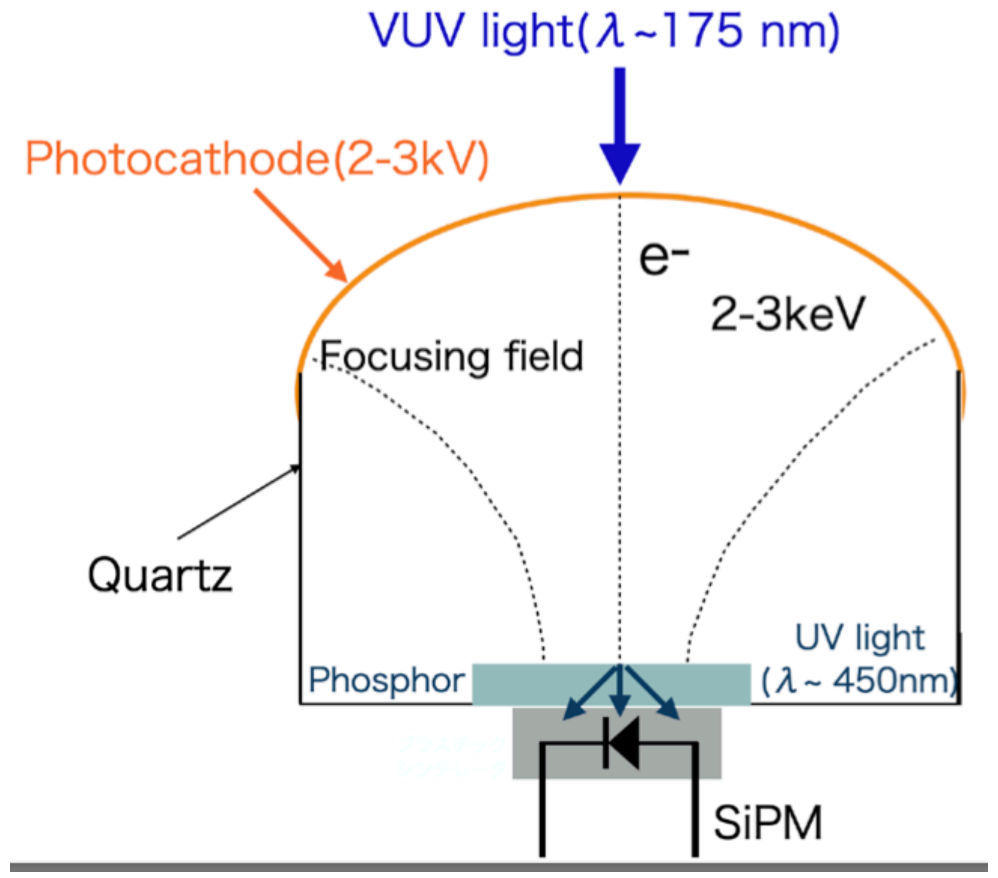
K. Abe et al. JINST 15 P09027

R13111 (XMASS)

Lowest radioactivity



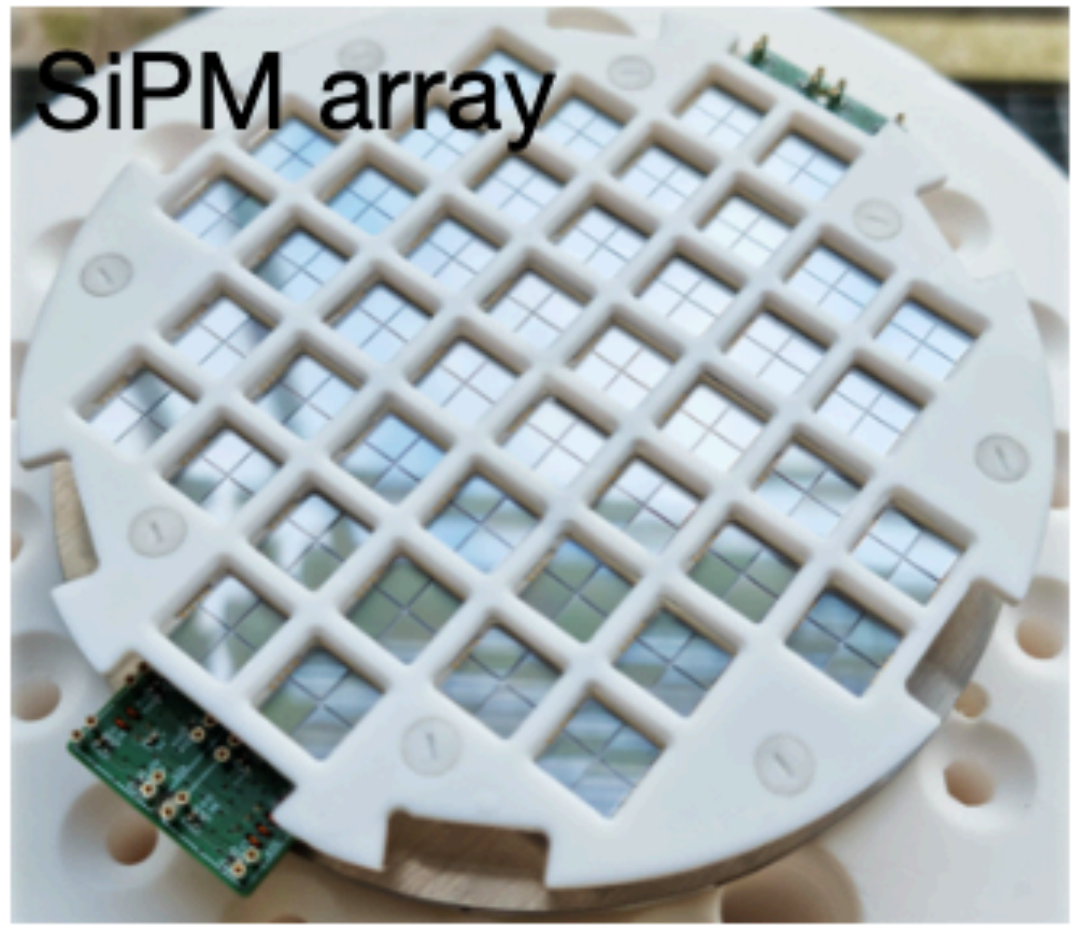
JINST 17 C01038 (2022)



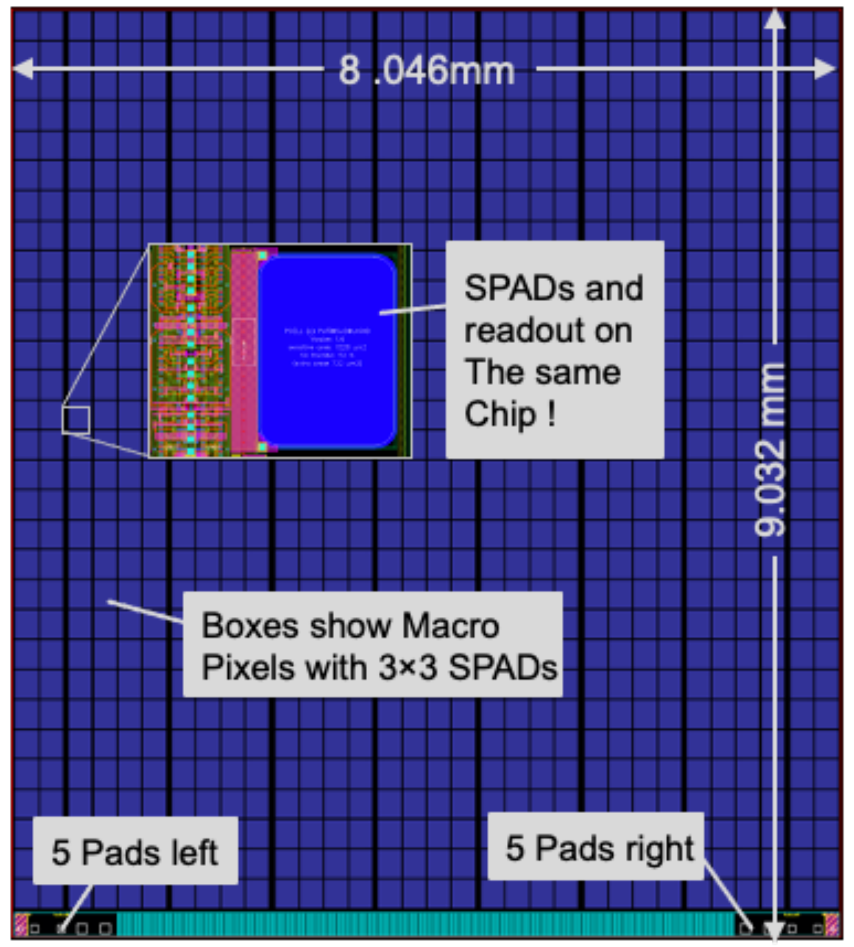
Hybrid @Nagoya

2inch square @Zurich

Low Dark Current SiPM



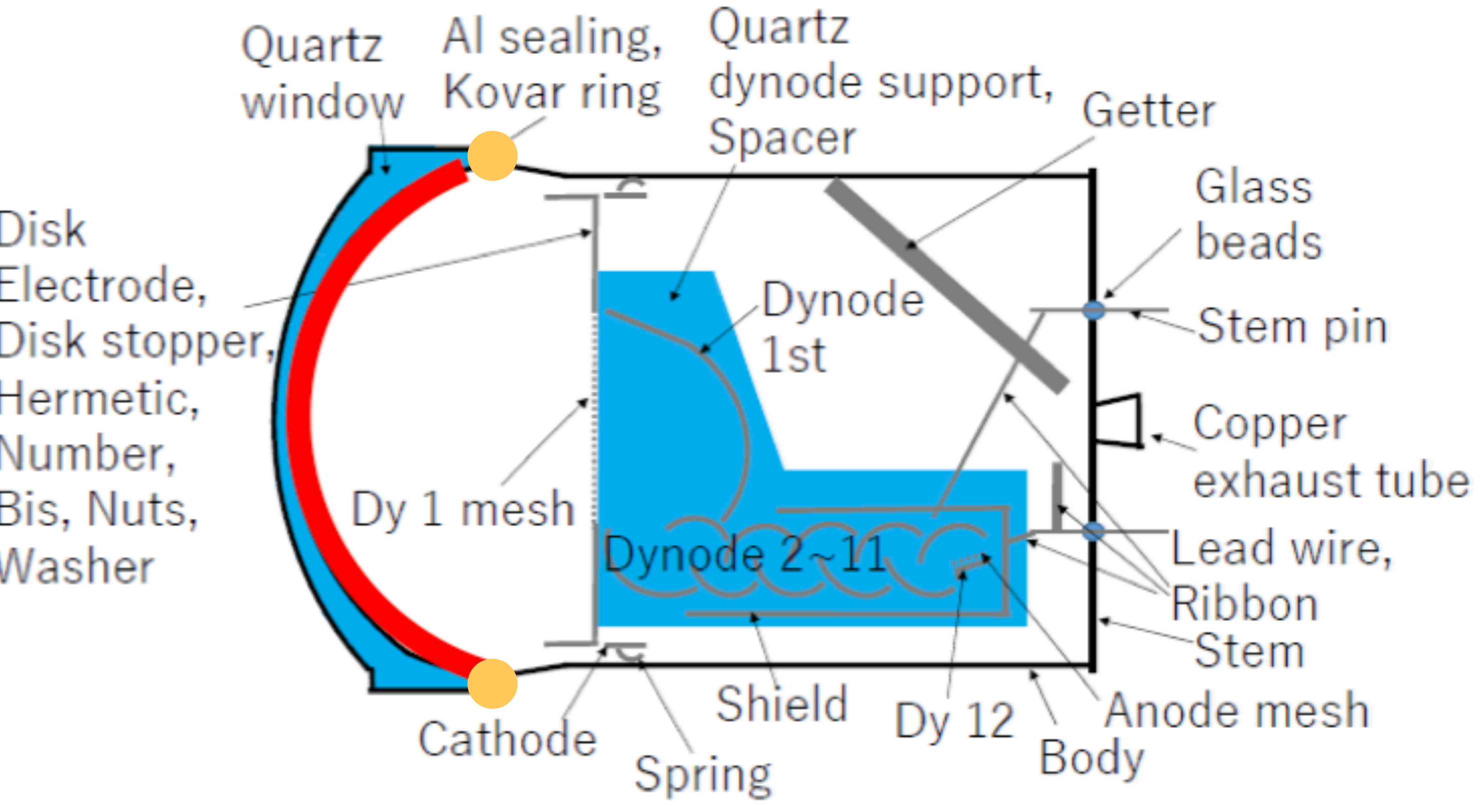
JINST 18 C03027 (2023)



Digital SiPM @Heidelberg

R13111 (3inch)

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

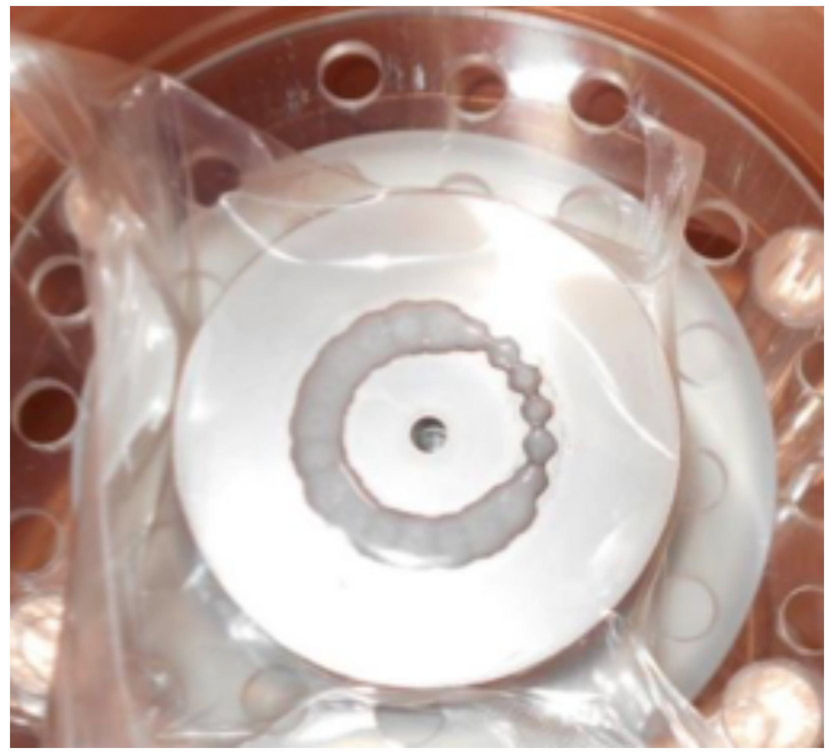


(1) Photocathode: produced with 39K-enriched potassium

(2) Vacuum seal: purest grade of aluminum material

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

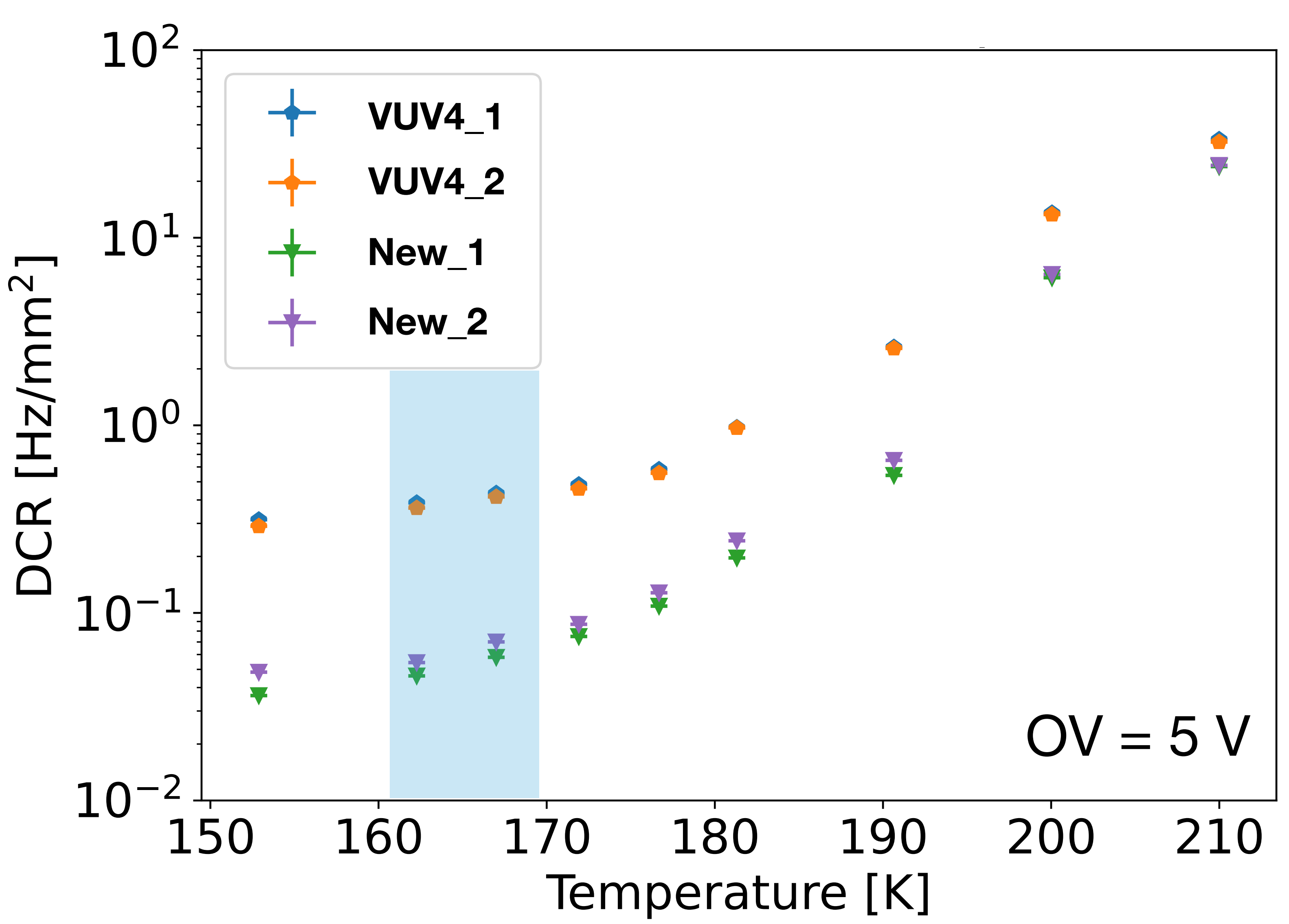
(4) Convex geometry improved the collection efficiency and TTS (~2.1 ns ↔ R11410:~9.2 ns)

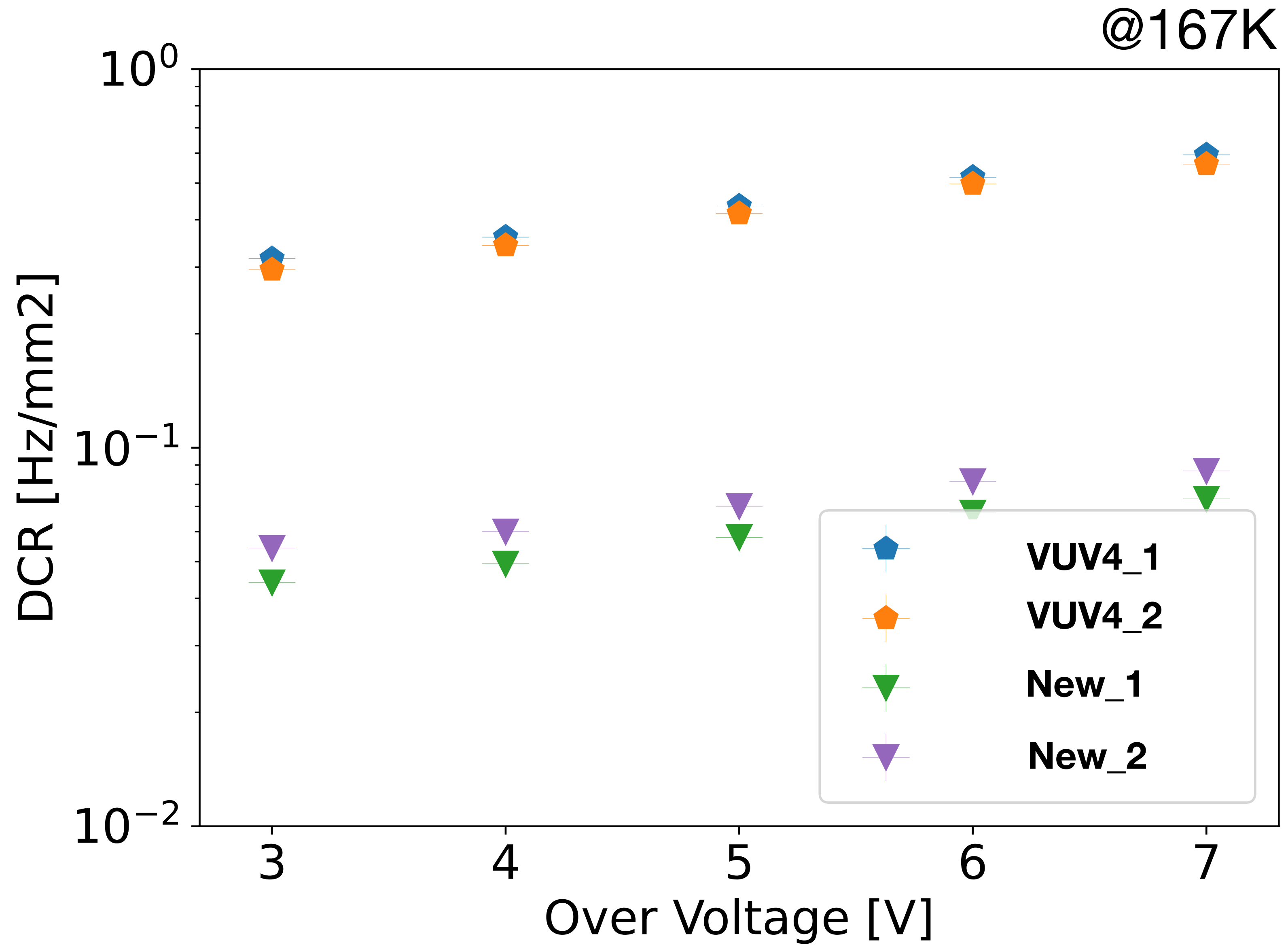


μBq/PMT	^{226}Ra	^{238}U	^{228}Ra	^{40}K	^{60}Co
R13111 in 2015	$(3.8 \pm 0.7) \cdot 10^2$	$<1.6 \cdot 10^3$	$(2.9 \pm 0.6) \cdot 10^2$	$<1.4 \cdot 10^3$	$(2.2 \pm 0.5) \cdot 10^2$
R13111 in 2016	$(4.4 \pm 0.6) \cdot 10^2$	$<1.4 \cdot 10^3$	$(2.0 \pm 0.6) \cdot 10^2$	$(2.0 \pm 0.5) \cdot 10^3$	$(1.3 \pm 0.4) \cdot 10^2$
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]	$<4.0 \cdot 10^2$	$<6.0 \cdot 10^3$	$<3.0 \cdot 10^2$	$<8.3 \cdot 10^3$	$(2.0 \pm 0.2) \cdot 10^3$

Dark Count Rate: 50um pixel

Kazama@Nagoya workshop 2024 11





	DCR [Hz/mm^2]	Reduction w.r.t. VUV4
New-1 (50um)	0.049 – 0.073	13 - 16%
New-2 (50um)	0.060 – 0.087	15 - 20 %

- Dark count rate (DCR) at high temperature(200-210K) was measured with random trigger because of its large DCR

- DCR at low temperature was measured using self-trigger with the threshold of 0.5 pe pulse height.

- **Reached DCR of O(0.01) Hz/mm2 for 50um pixel size**

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'

> ·**US P5**:
>
> ·An ultimate Generation 3 (G3) dark matter direct detection experiment reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).
>
> · **Europe APPEC:**
>
> · at least one next- generation xenon (order 50 tons) and one argon (order 300 tons) detector,
>
> ·**Japan 'Future Academic Initiative (未来の学術構想)'**:
>
> The DARWIN/XLZD proposal was accepted by the Science Council of Japan.