Noble liquid observatories for dark matter and astrophysical neutrinos

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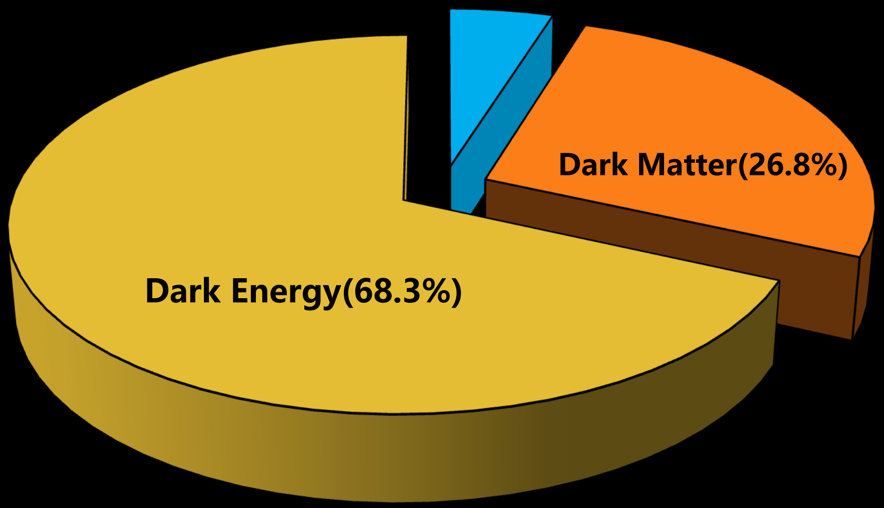
Shanghai Jiao Tong University

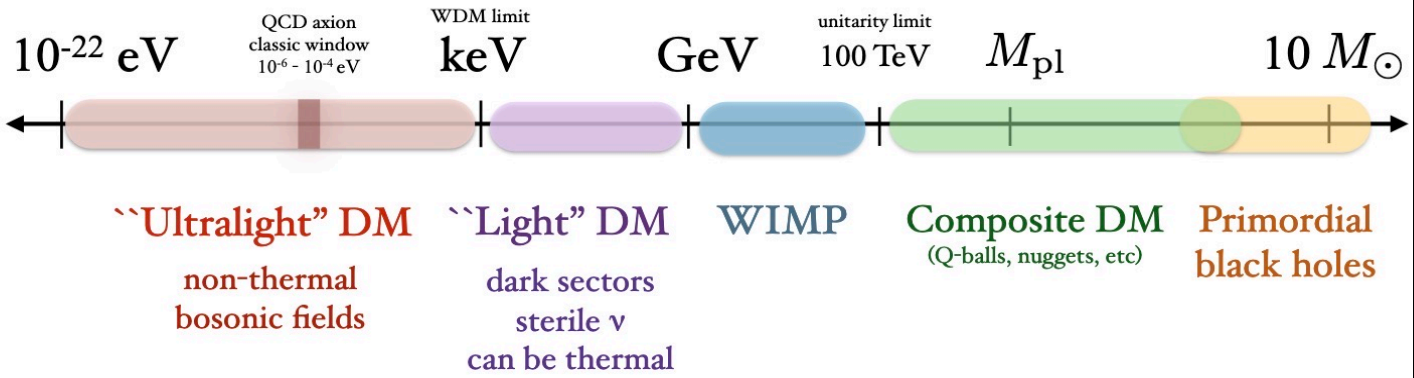
2025-08-26

Disclaimer: This is a large community with a lot progress. I had to make personal choices on what's covered here. Many info are from public talks. You will also hear many updates from this conference.

Dark Matter

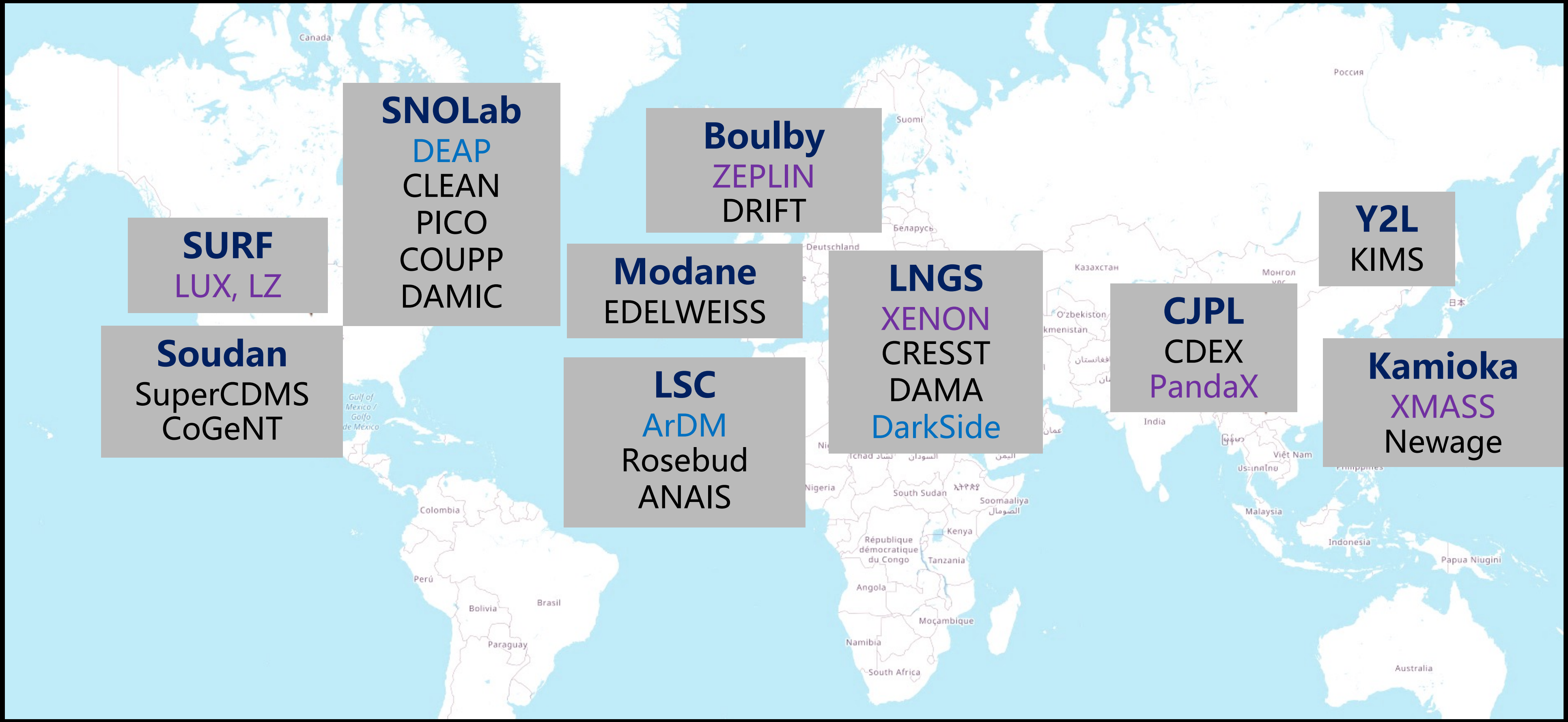
- Mysterious element in the universe
- Little knowledge of its nature





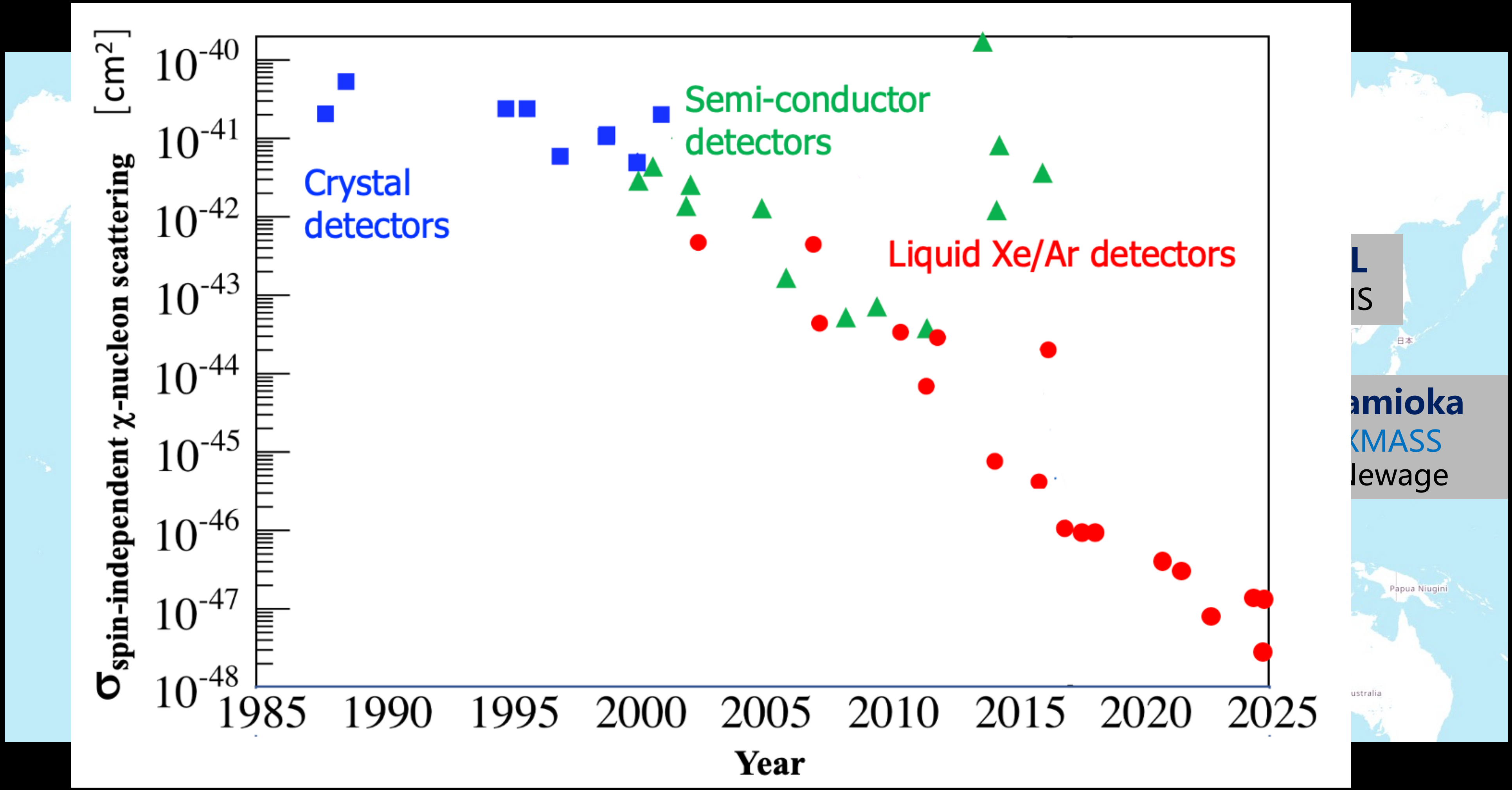
Underground Laboratories

- World-wide efforts at underground laboratories

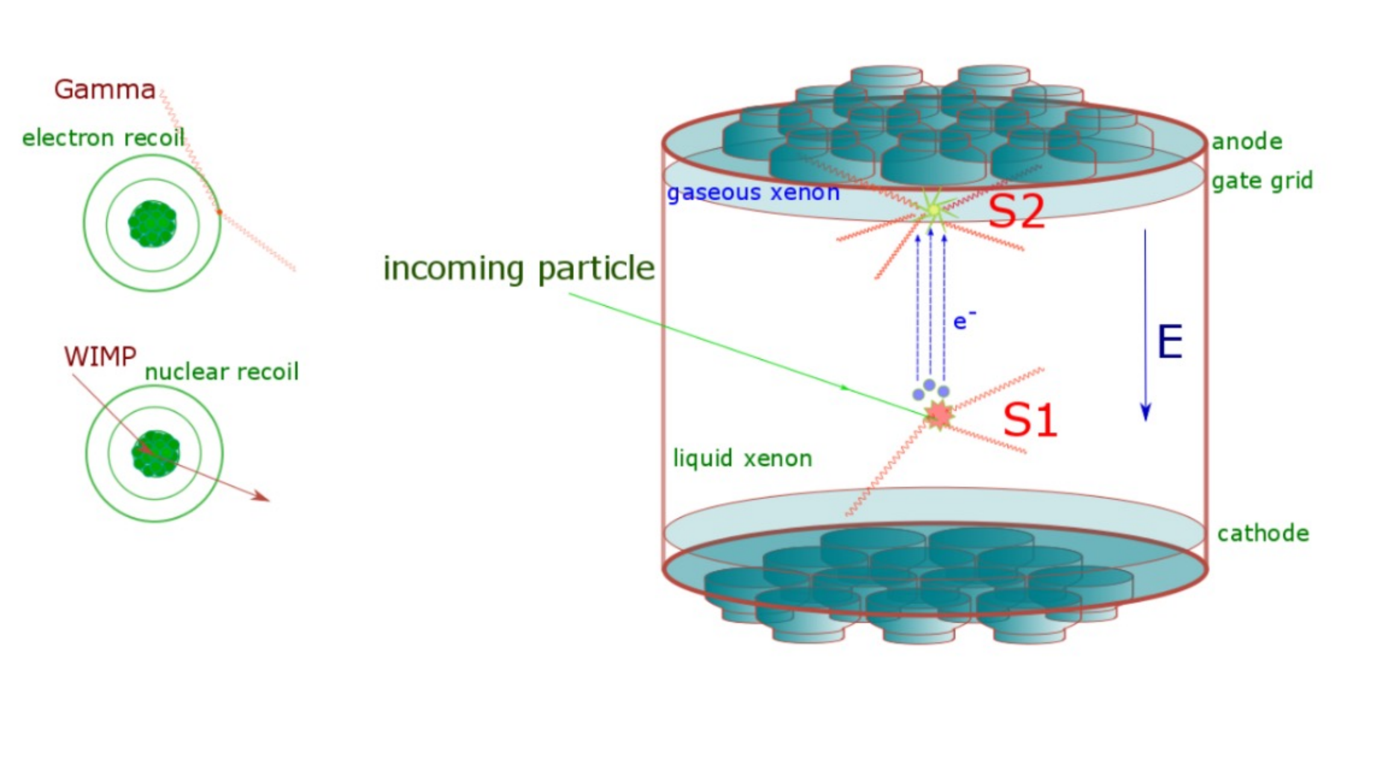


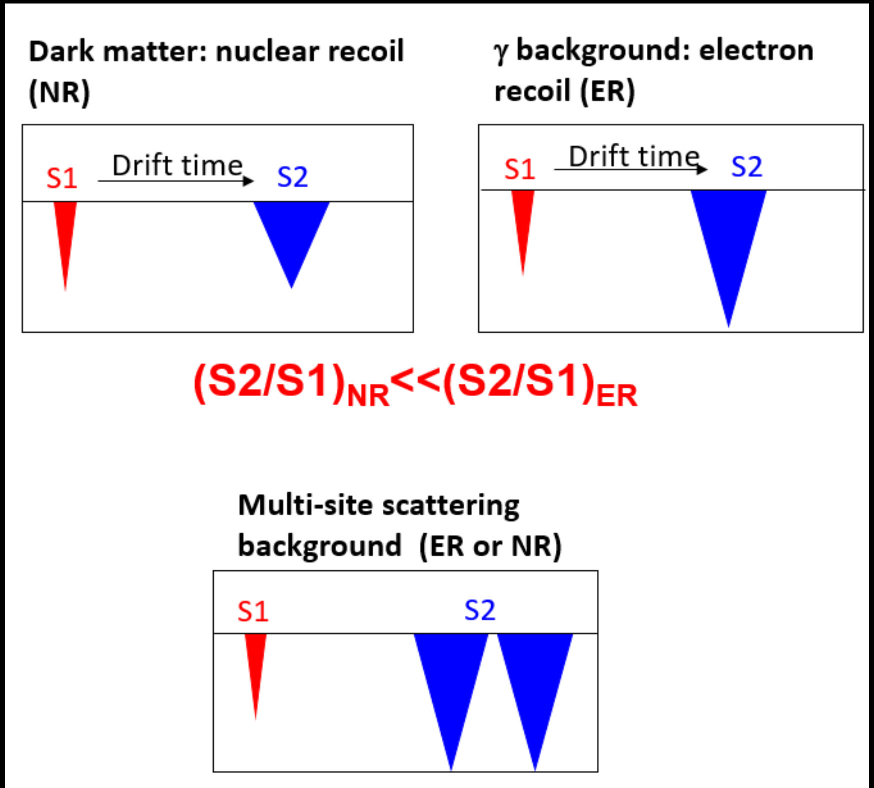
Underground Laboratories

- World-wide efforts at underground laboratories



Nobel-liquid dual-phase time projection chamber





In the case of Ar, significant pulse-shape discrimination ability to differentiate ER/NR

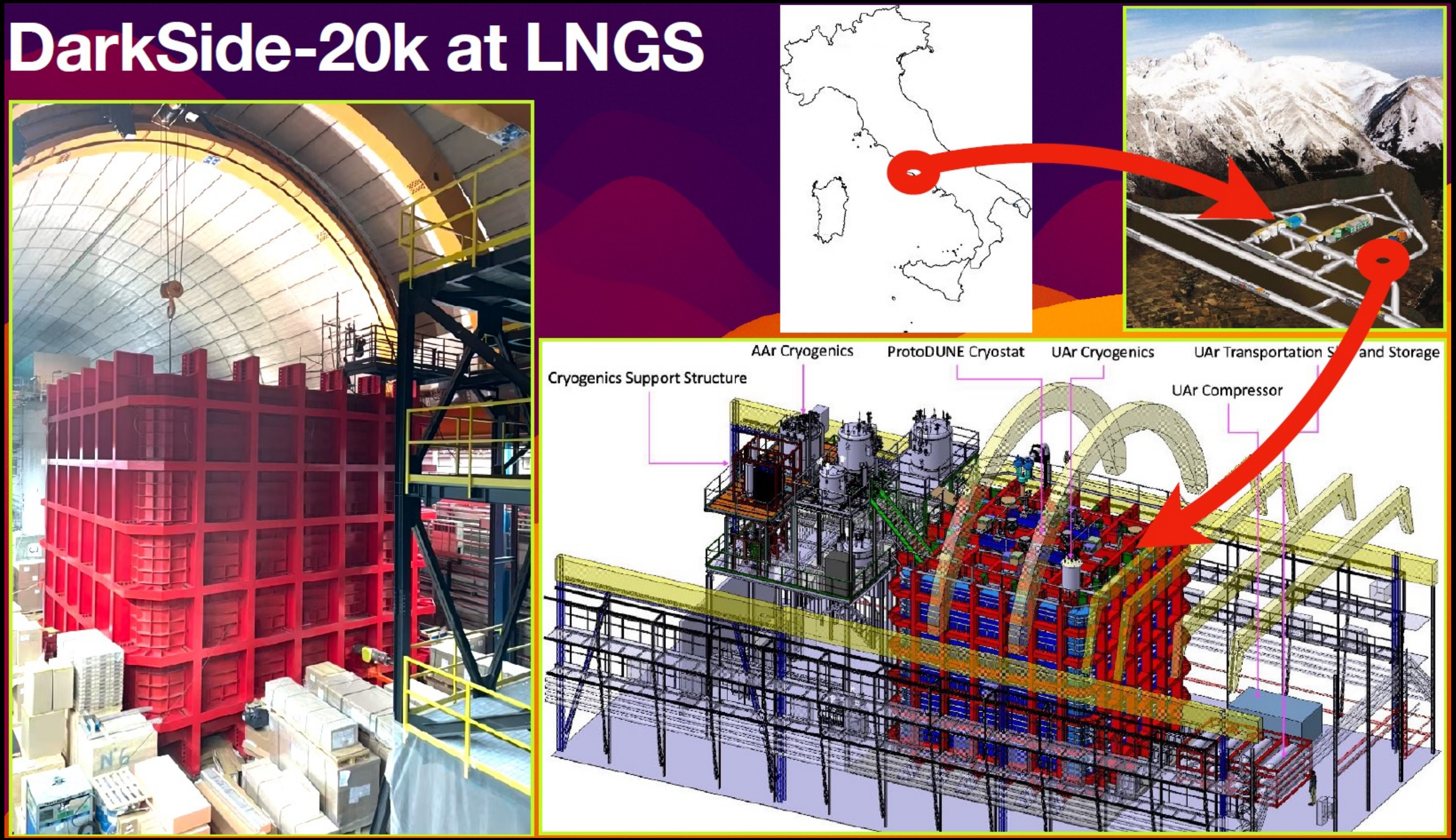
Global Ar Collaboration

C. Galbiati, UCLA-DM 2025

DarkSide-20k => ARGO

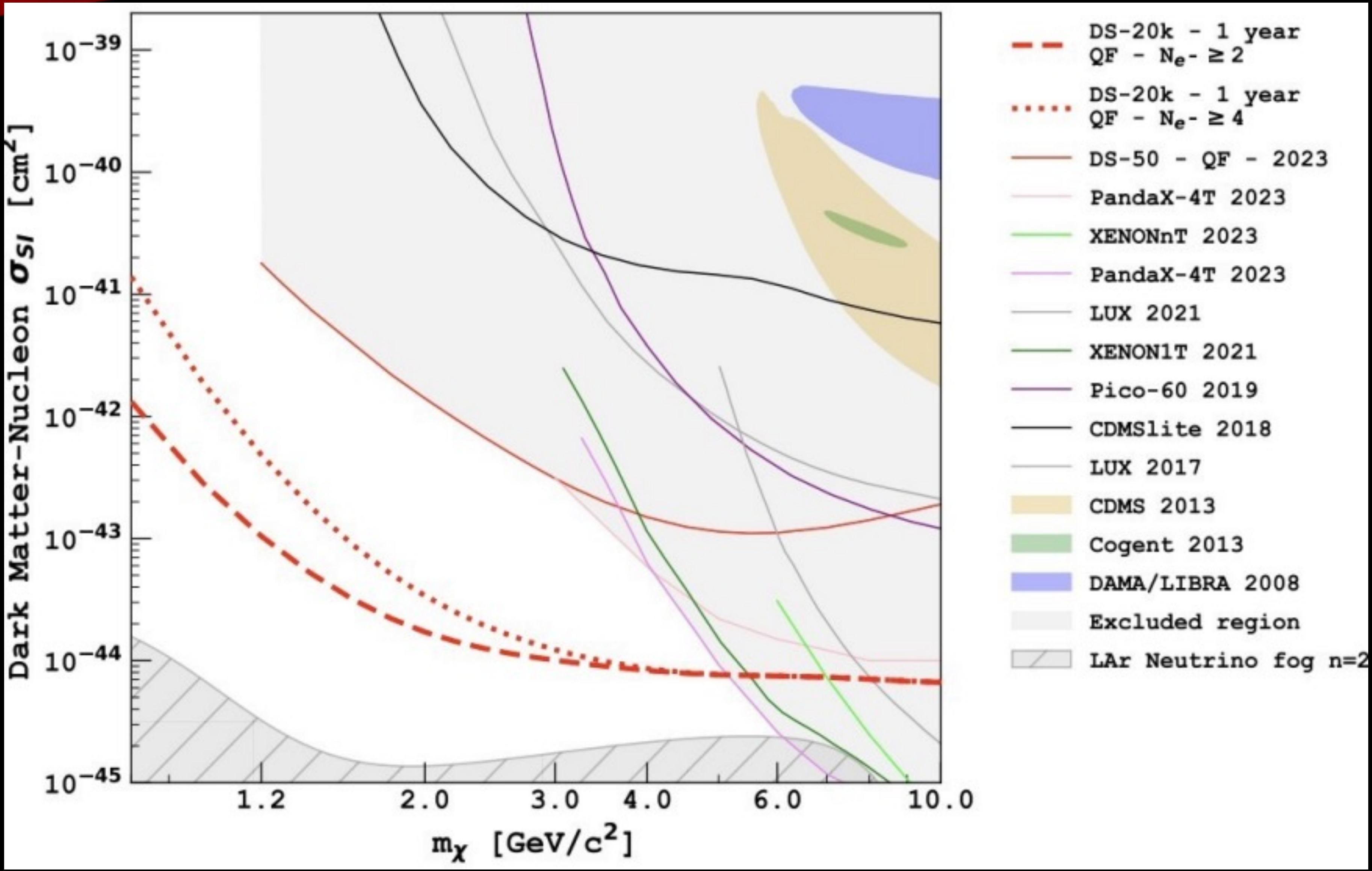
Progress of DS-20K @ LNGS

C. Galbiati, UCLA-DM 2025



More in talks from W. Bonivento, M. Wada, A. Jamil

Progress of DS-20K @ LNGS

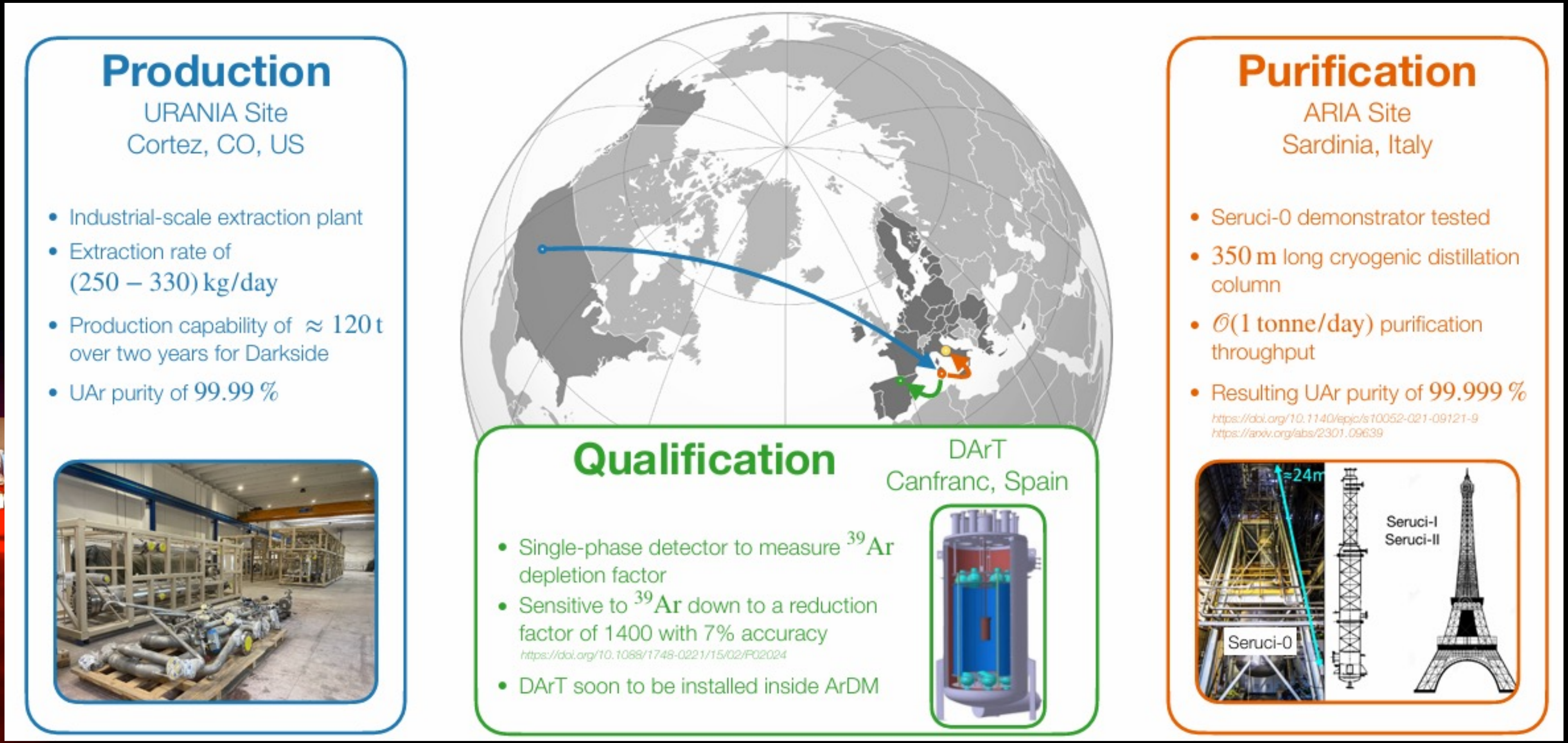


More in talks from W. Bonivento, M. Wada, A. Jamil

See the talk from L. Pandola

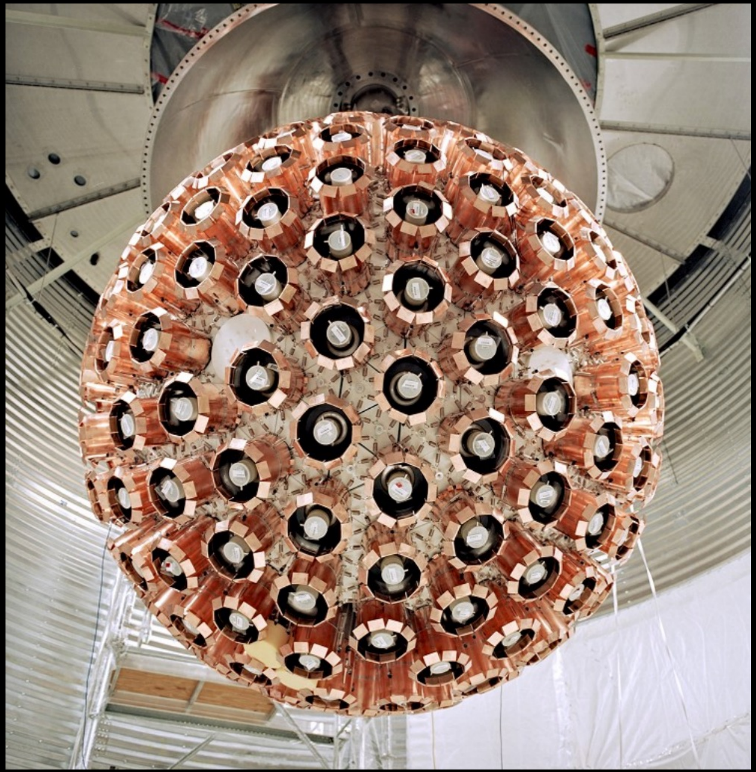
Underground Ar (suppress ^{39}Ar)!

- C. Galbiati, UCLA-DM 2025



DEAP3600 upgrade

Upgrade on the Neck and Dust removal system, Theo Hugues, UCLA-DM 2025
Pictures from C. Galbiati, UCLA-DM 2025

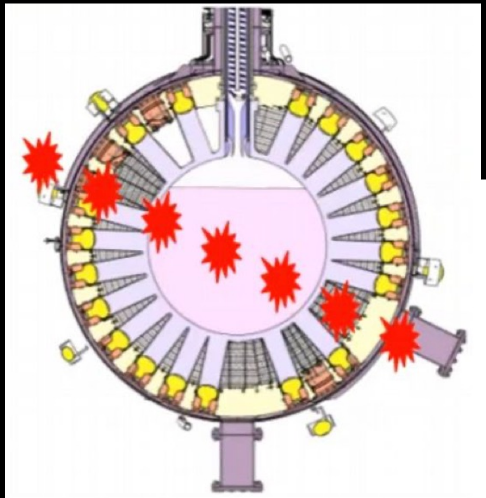


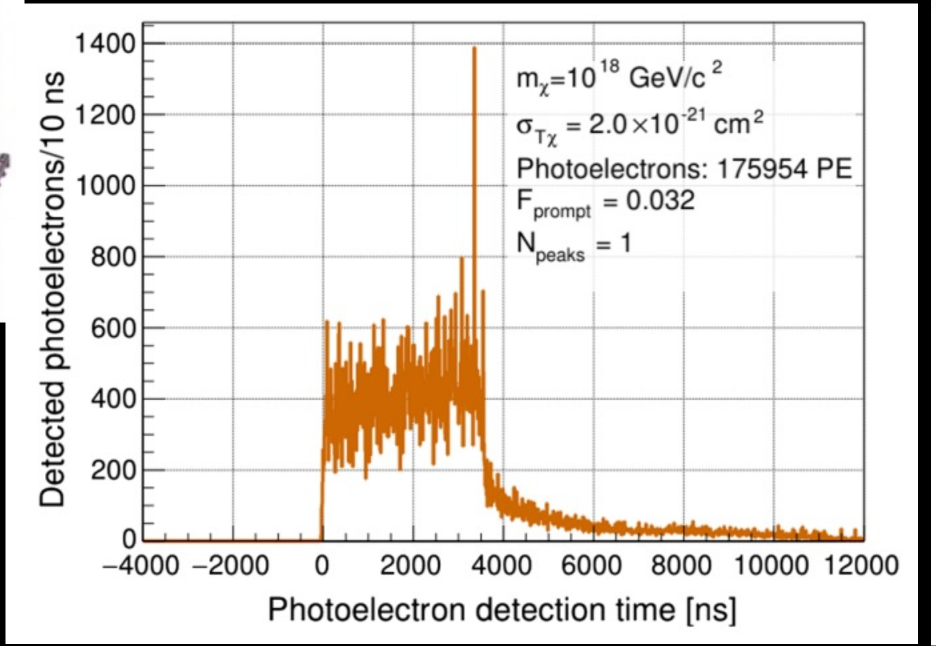
More in talk from
S. Westerdale

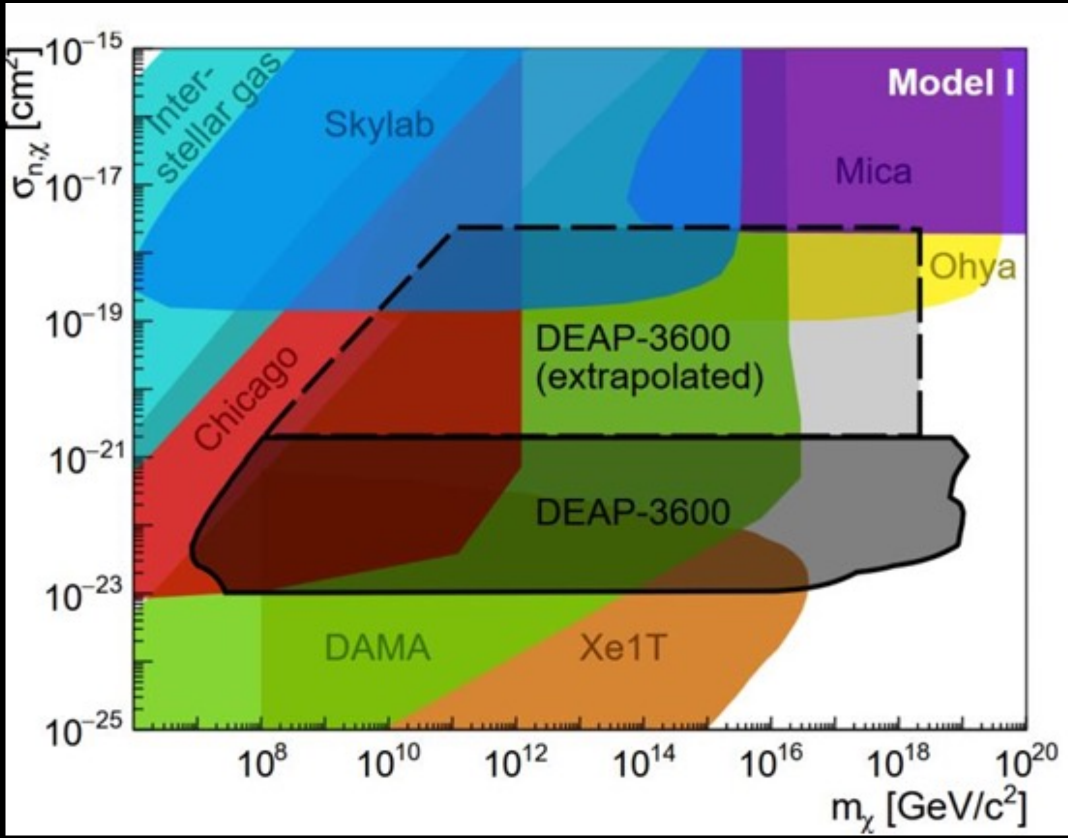
Very heavy (Planck-scale) DM

Signature: multi-scattering and straight track

PRL 128, 011801 (2022)

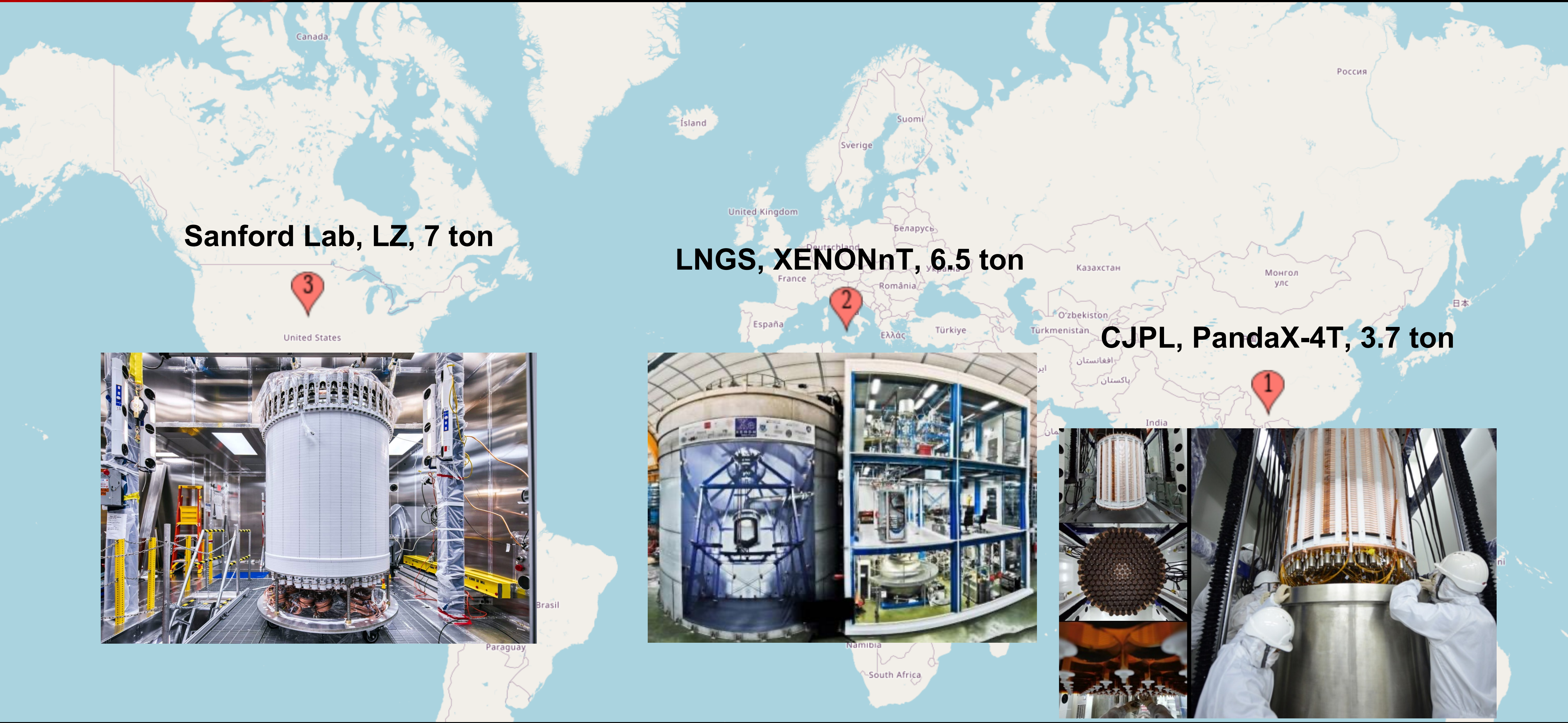






Unique advantage of large monolithic noble liquid DM detector   See talk by M. Olszewski

Liquid xenon experiments



PandaX-4T, 1.5 tonne*year blinded analysis，Run0+1

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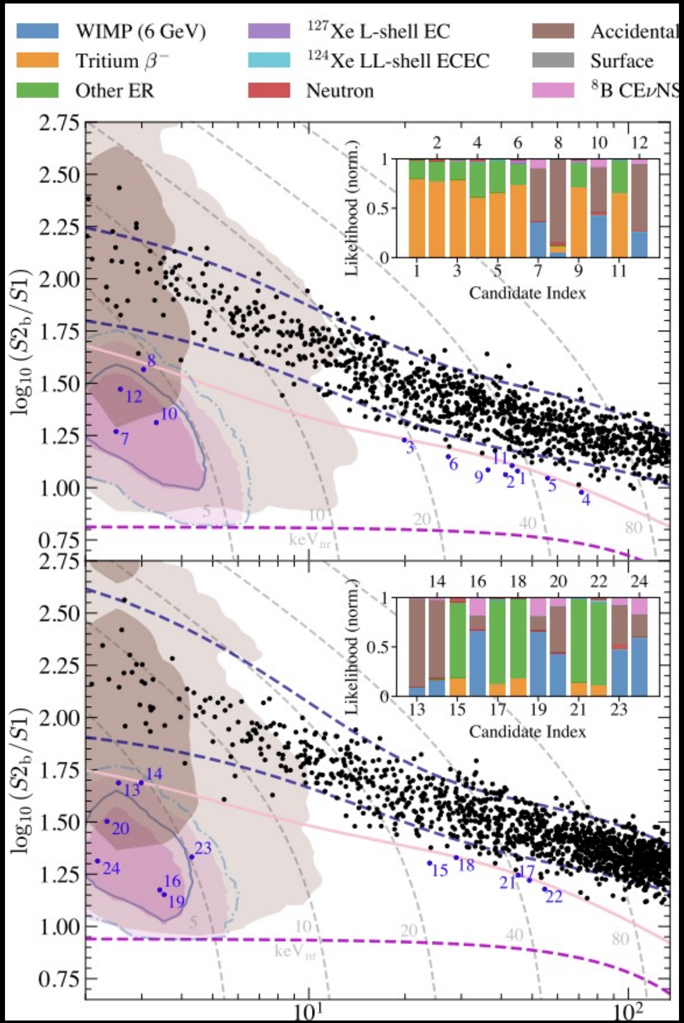
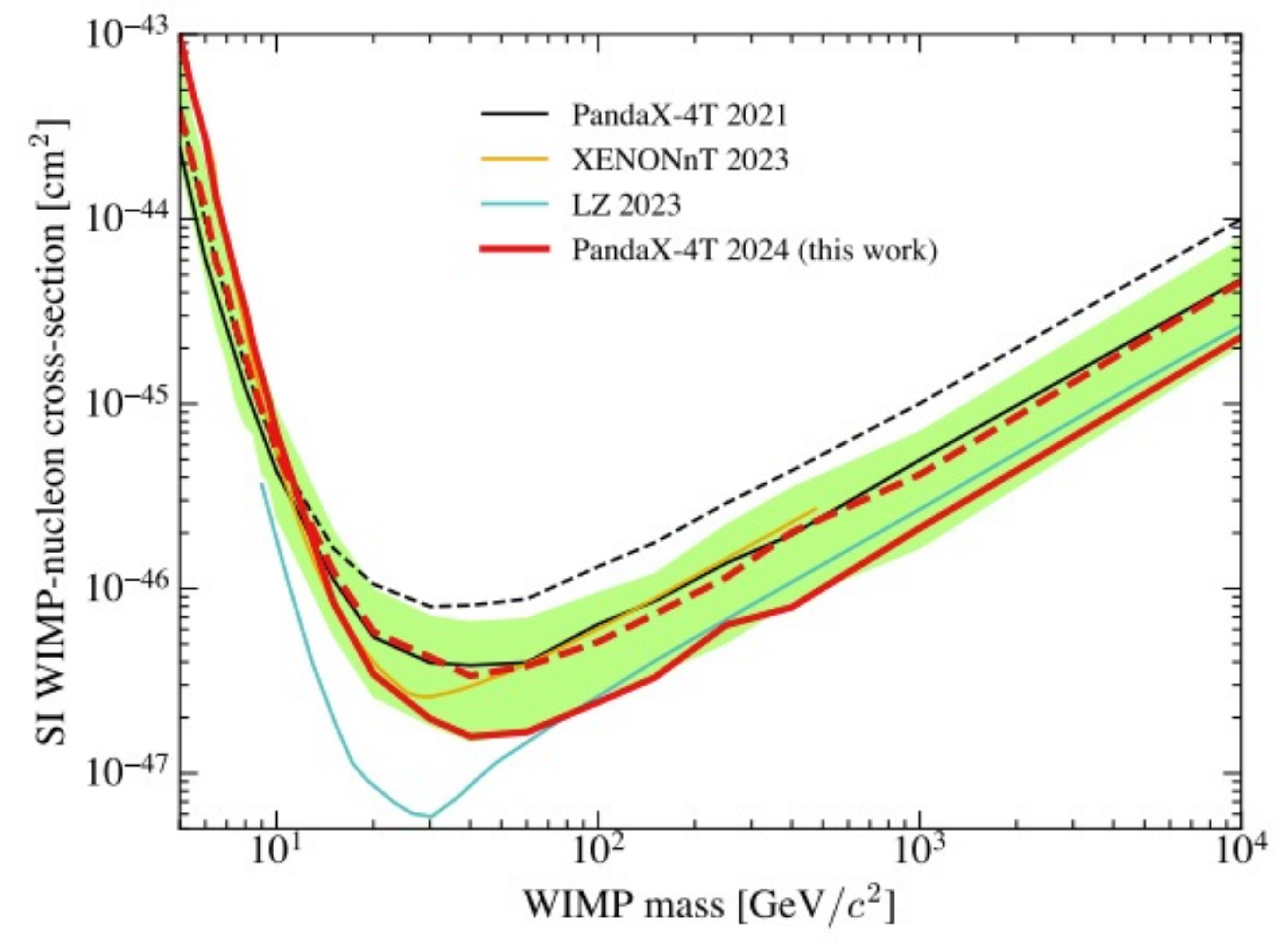
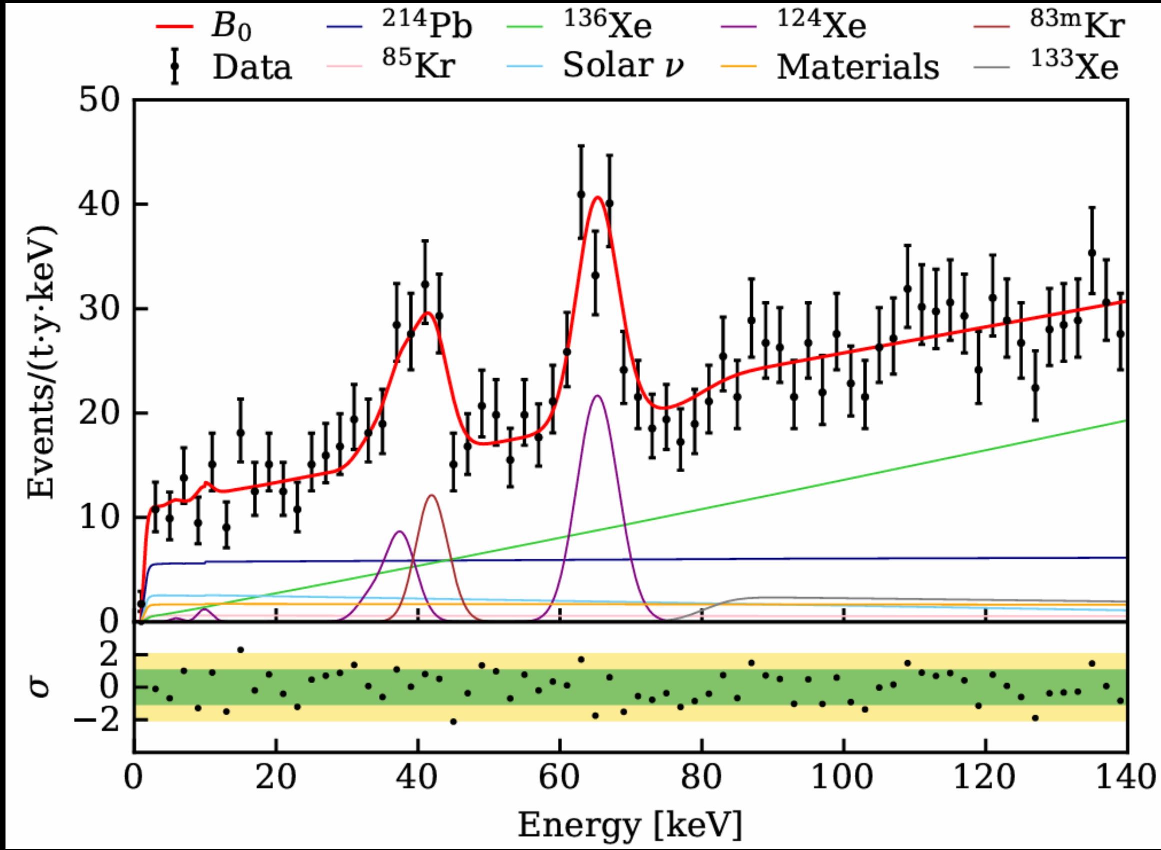
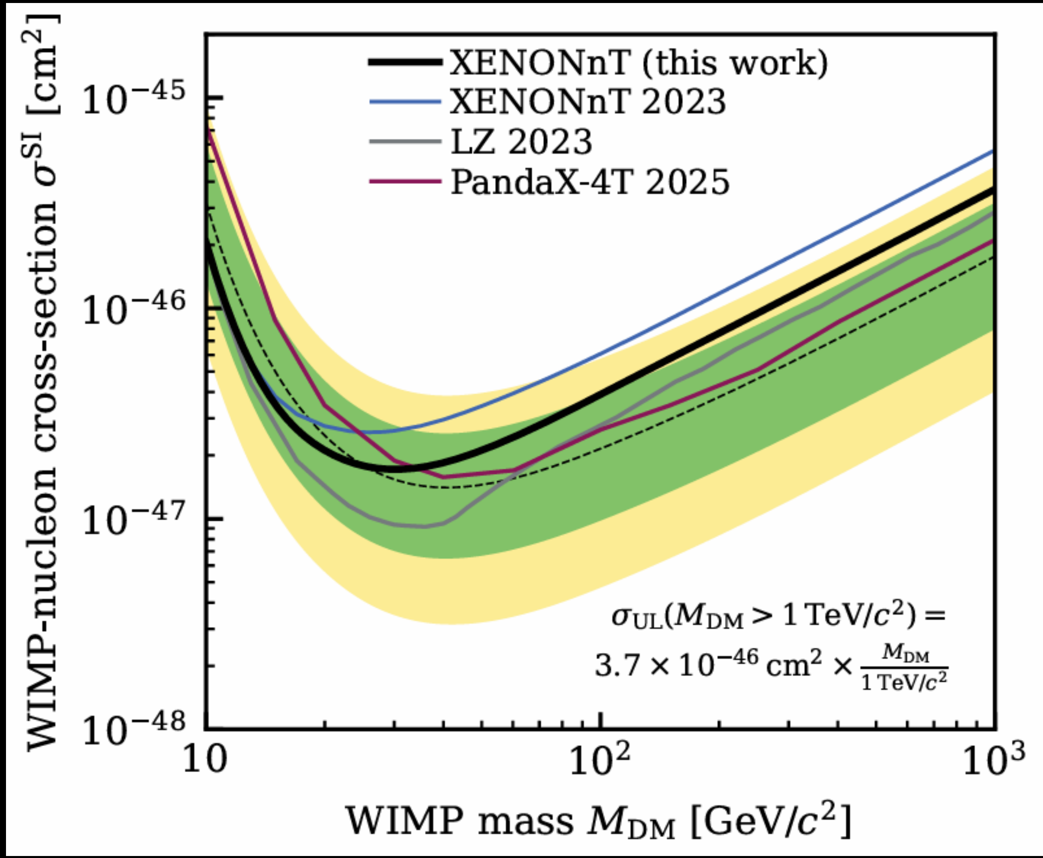




PRL 134, 011805 (2025), arXiv:2408.00664

XENONnT: 3.1 tonne*year



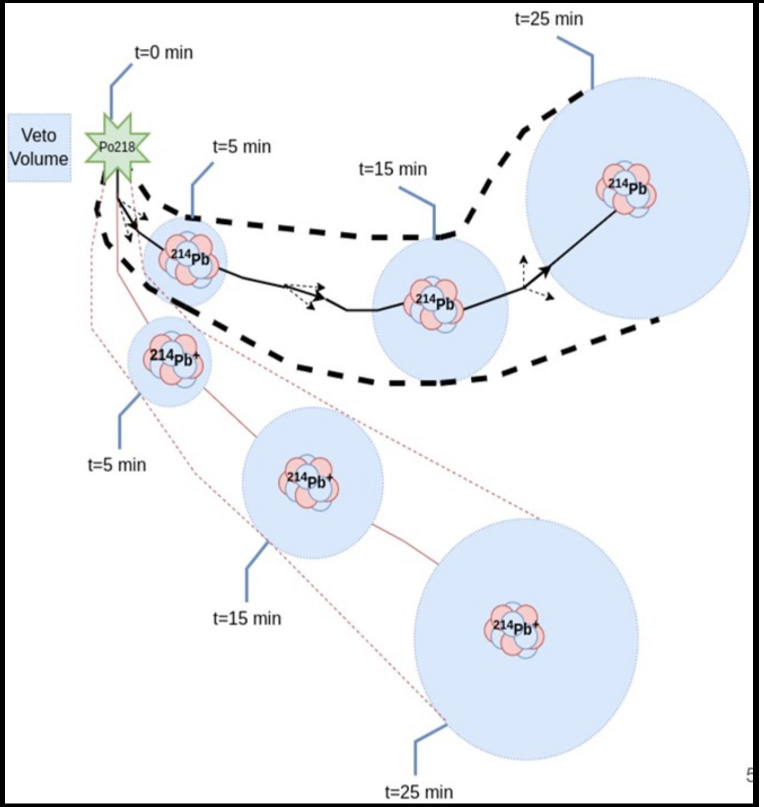


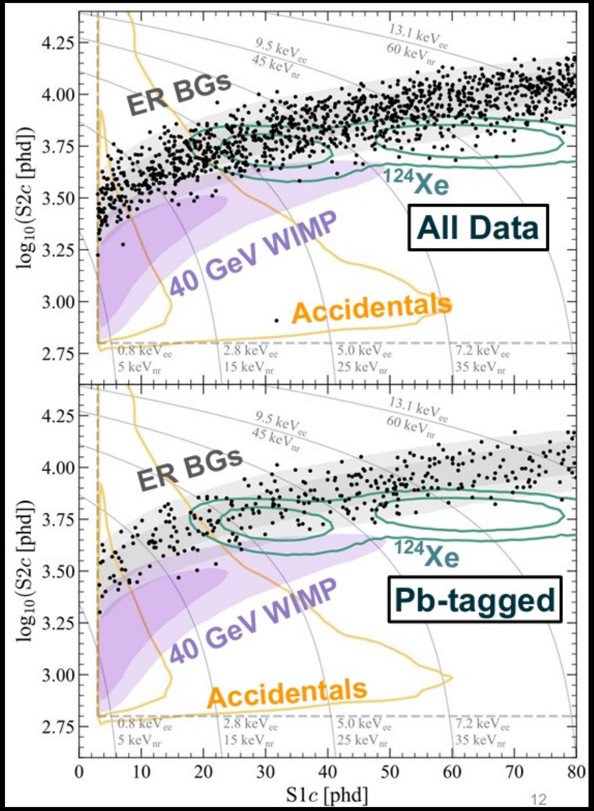
- Record-low ER background: *PRL 129, 161805 (2022), arXiv:2207.11330*
- Rn distillation removal: <1 μBq/kg, *2502.04209*

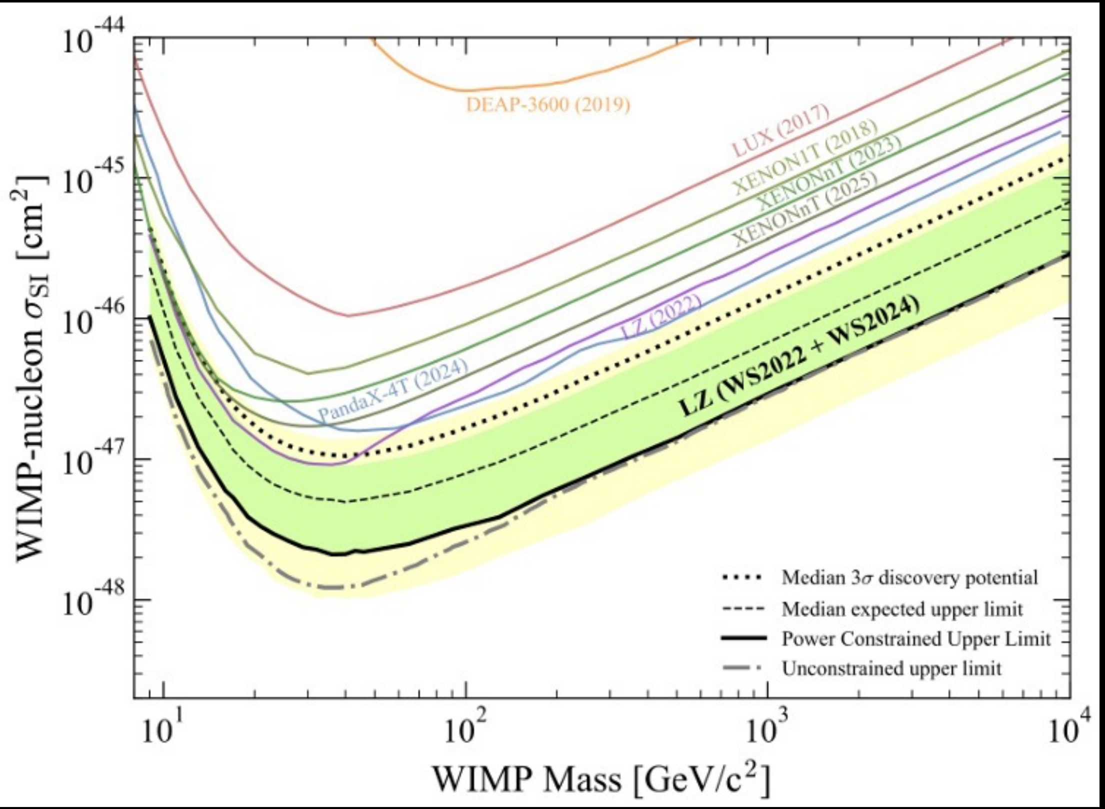
New result: *2502.18005*, 3.1 tonne*year

See Maxime Pierre's talk

LZ 4.2 tonne*year







- Tag radon daughter ^{214}Pb via ^{218}Po-^{214}Pb ($t_{1/2}$ = 27 min)
- Untagged Rn rate: 1.8 μBq/kg

- Latest results: *arXiv:2410.17036, PRL 135, 011802 (2025)*
- Leading DM exclusion

See talk by Amy Cottle

Spin-dependent interactions

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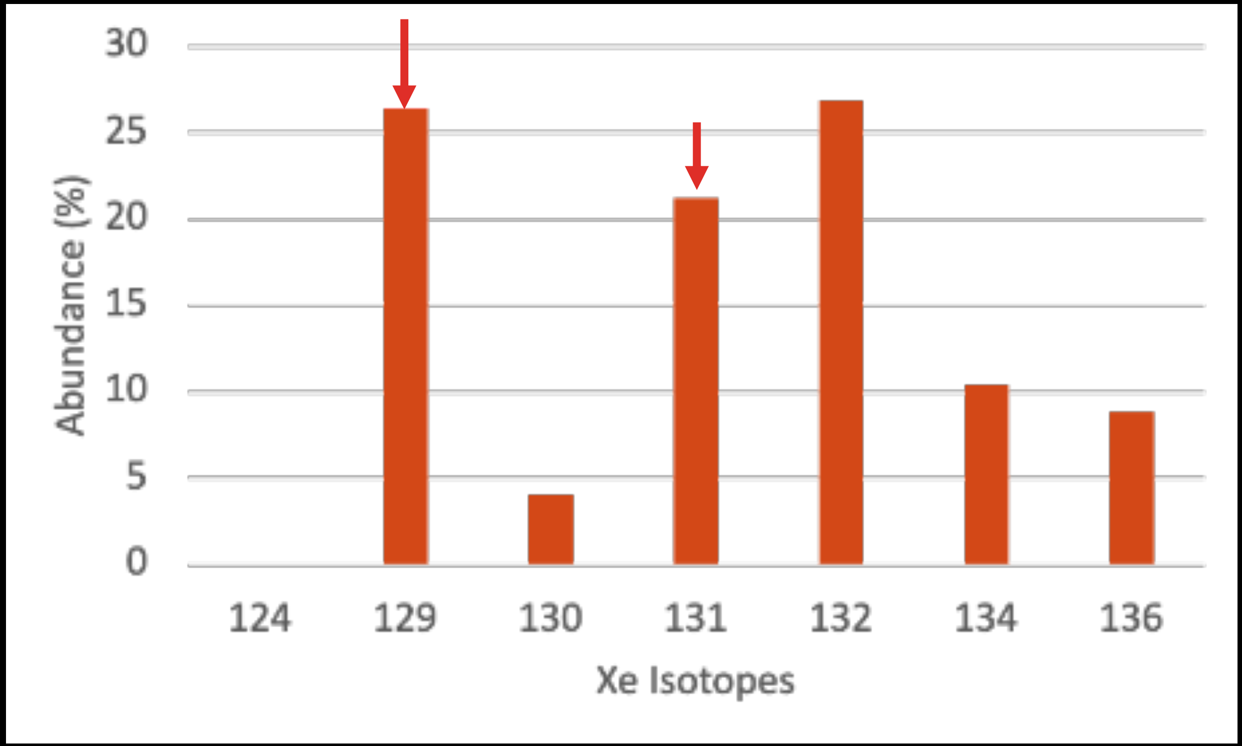

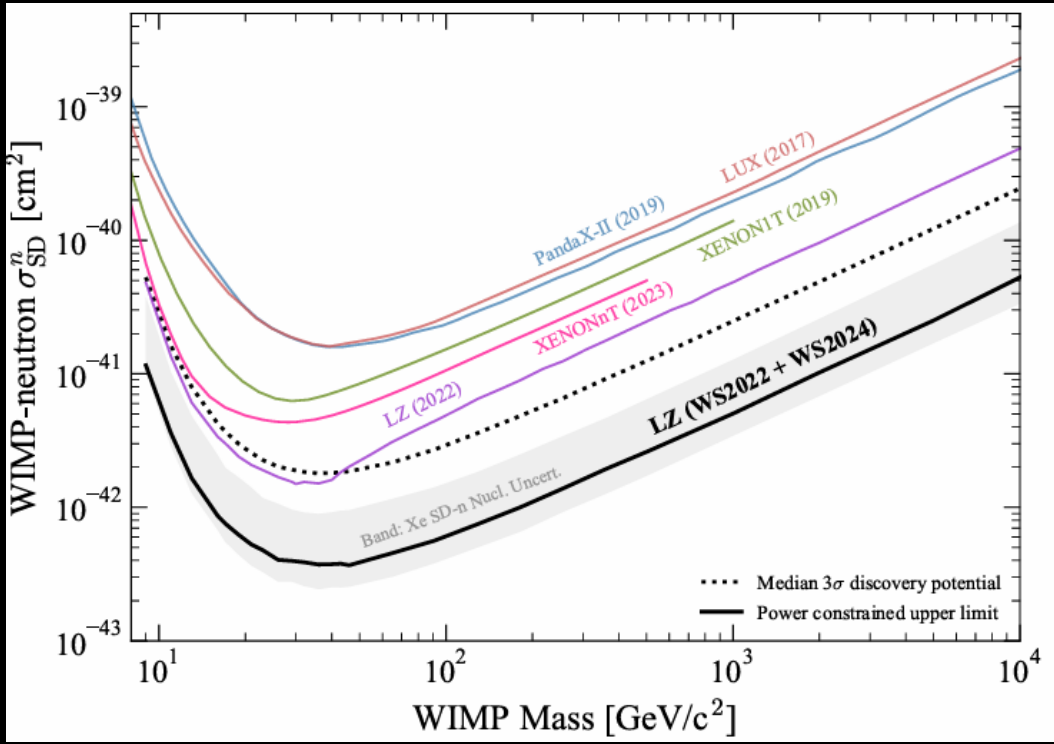

LZ 4.2 tonne*year, *arXiv:2410.17036, PRL 135, 011802 (2025)*

See talk by Amy Cottle

Spin-dependent interactions

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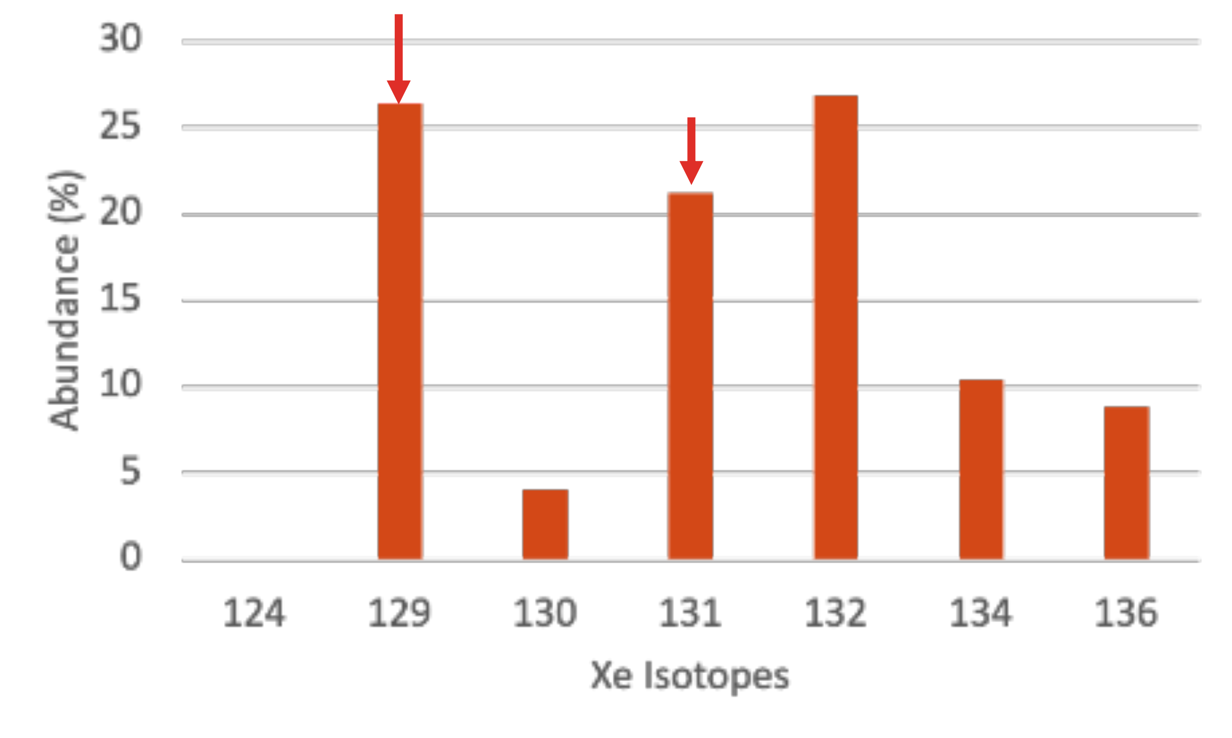
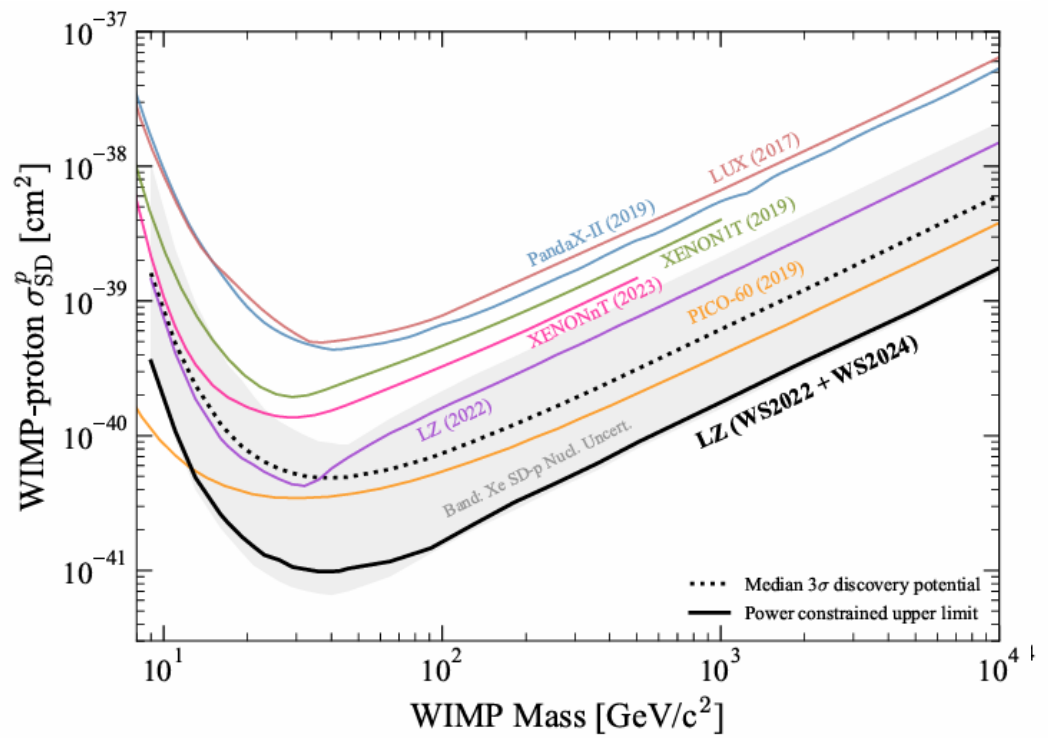




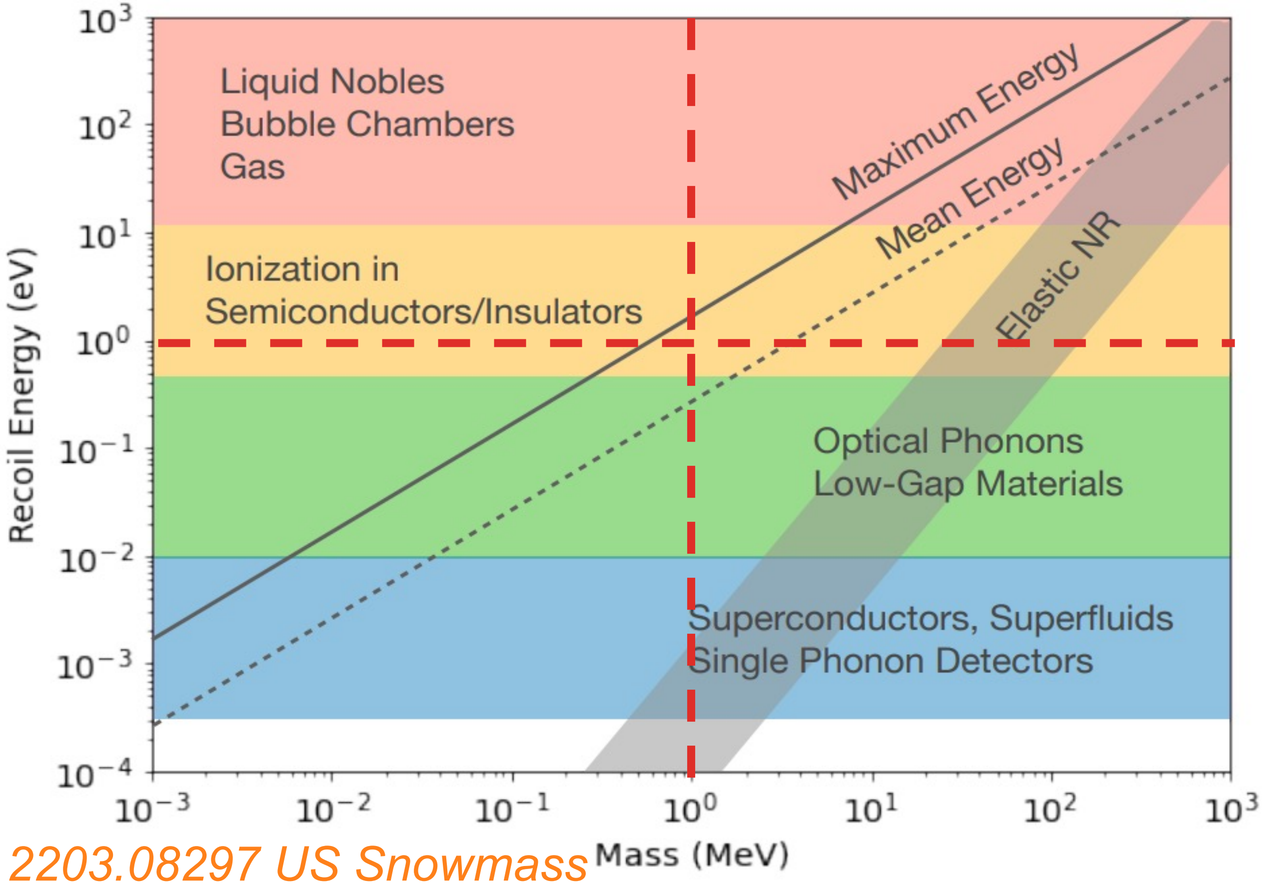
LZ 4.2 tonne*year, *arXiv:2410.17036, PRL 135, 011802 (2025)*

See talk by Amy Cottle

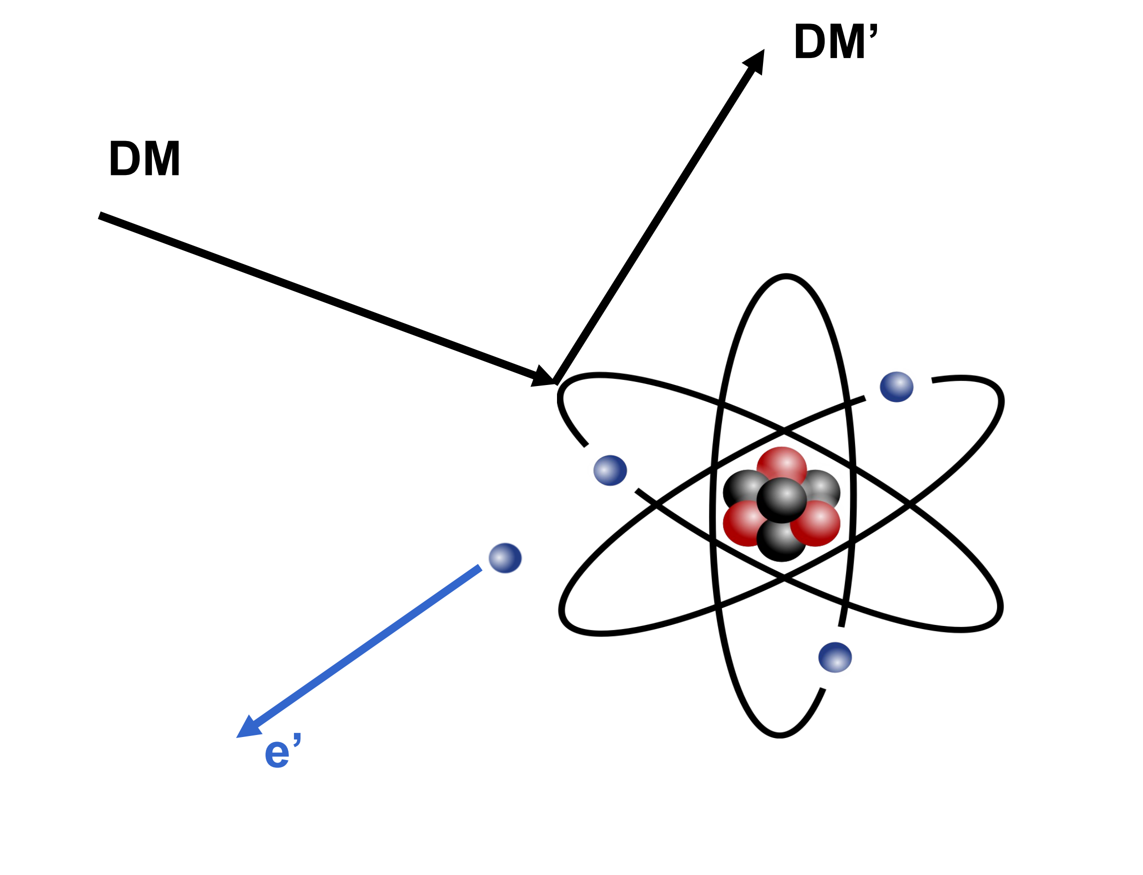
Low mass DM detection techniques with Noble Gas: example 1

Electron as target (atomic inelastic scattering) => full DM KE-binding.

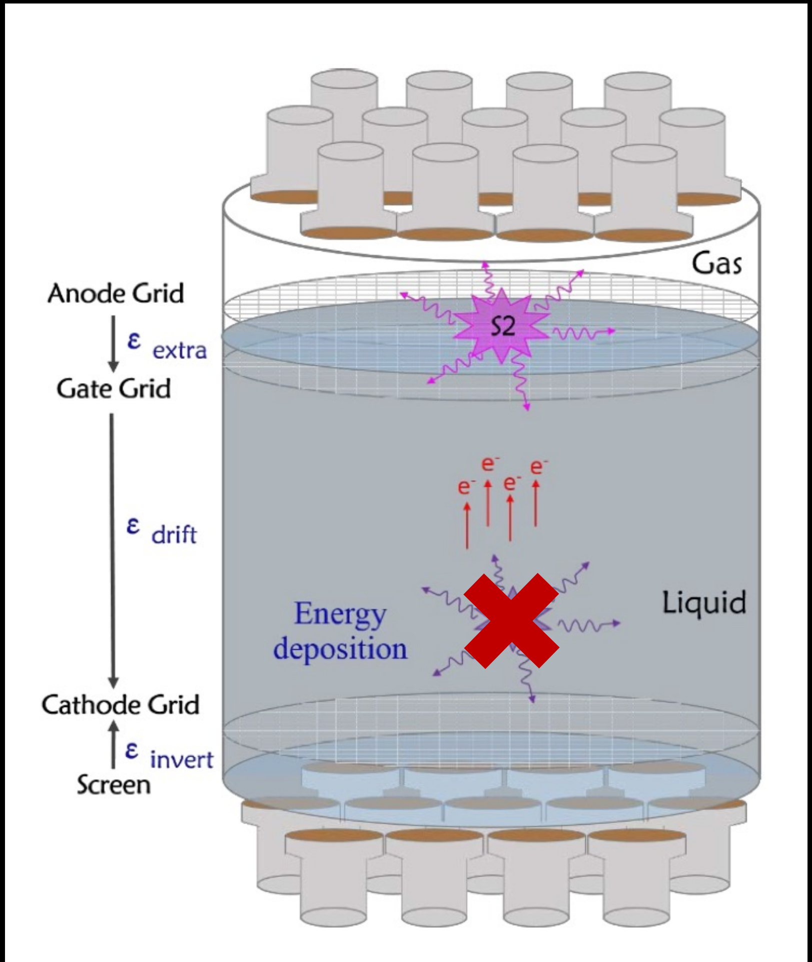
Essig, Mardon, Volansky, PRD 85, 076007 (2012)

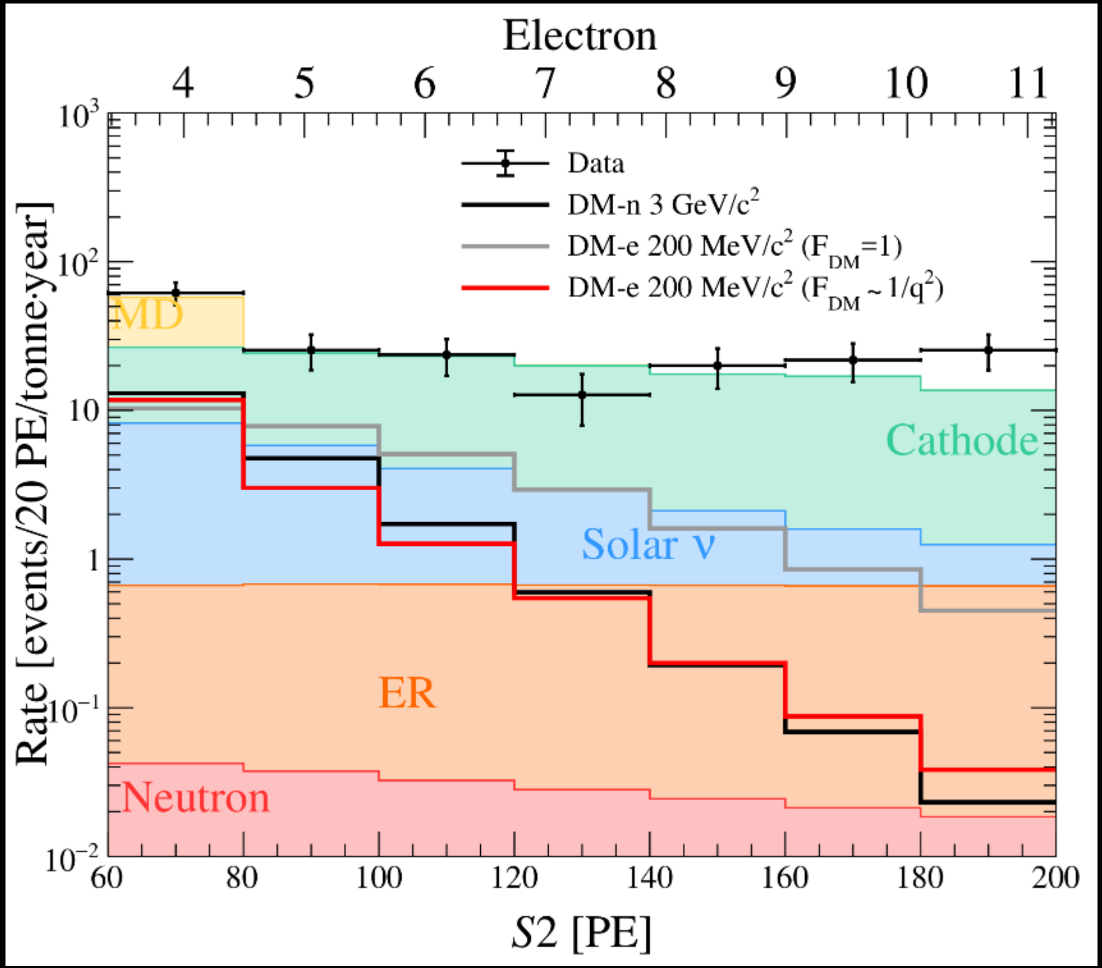


2203.08297 US Snowmass



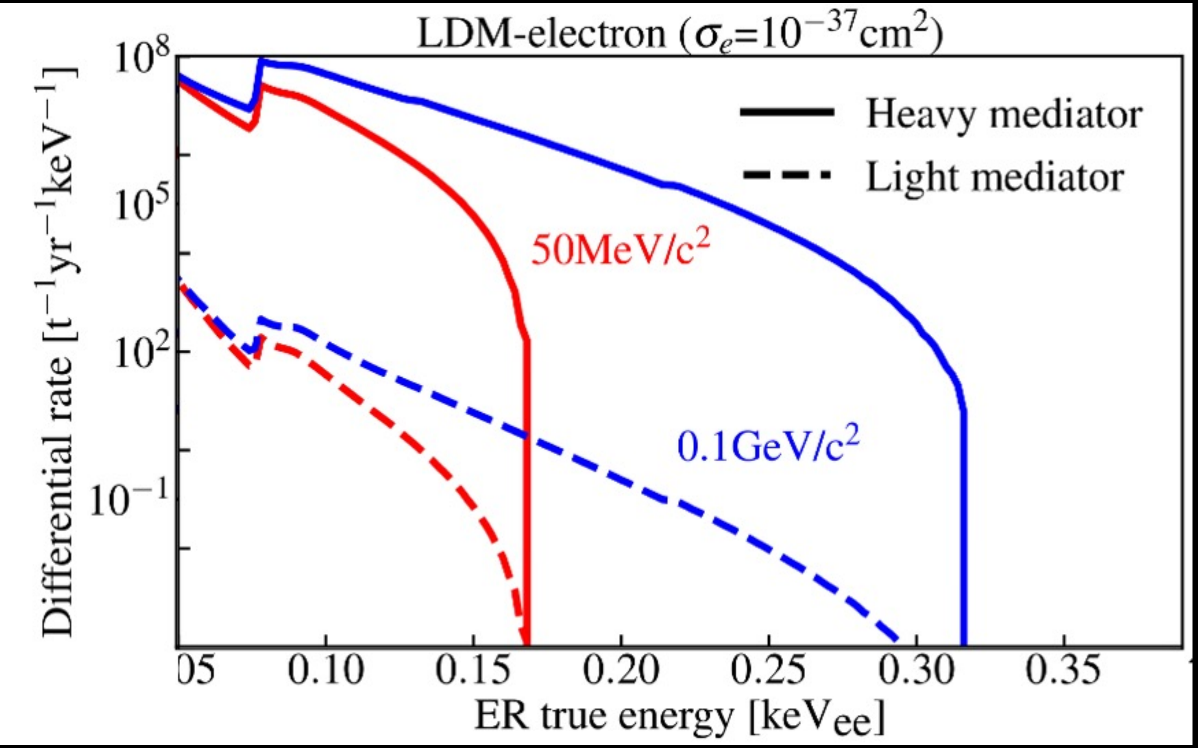
Accessing light DM: S2-only

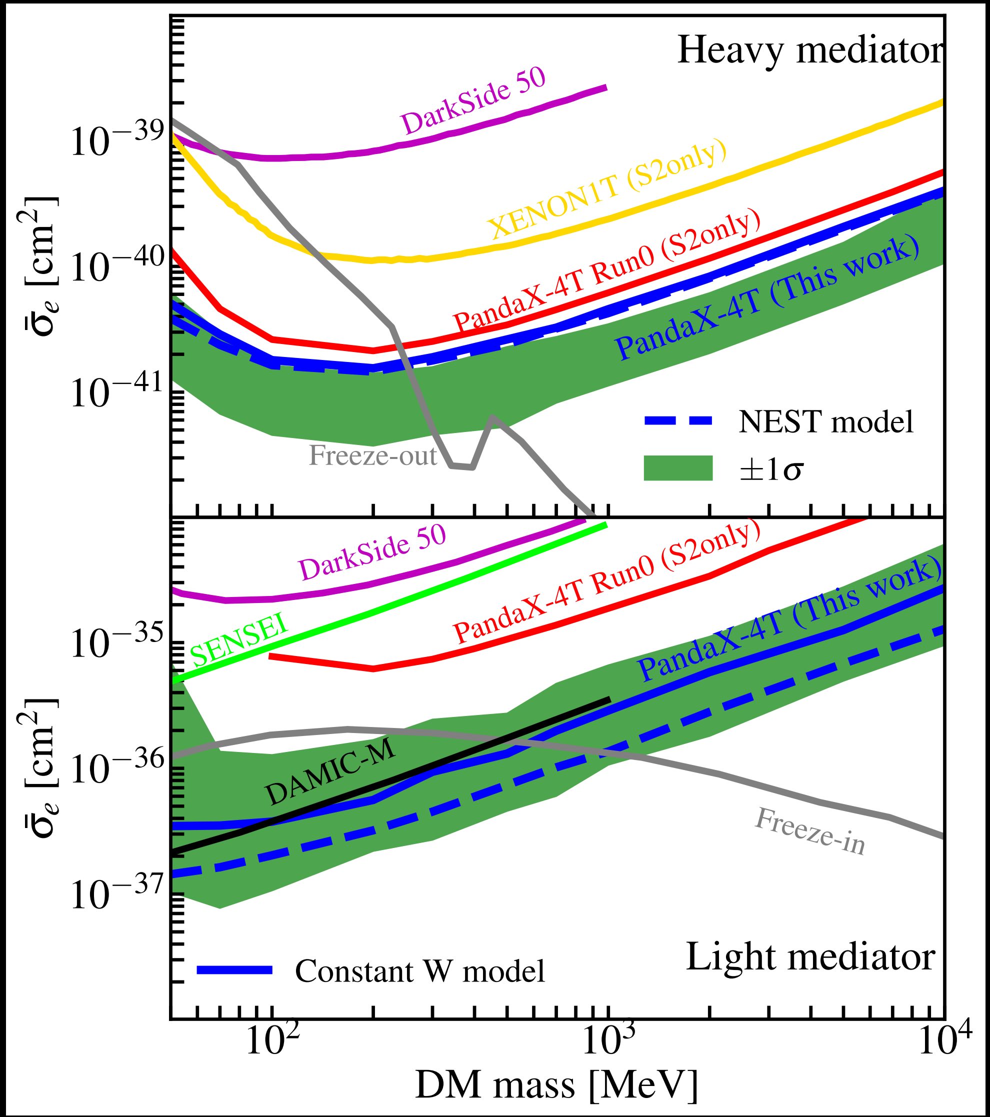




PandaX-4T, PRL 130, 261001 (2023)

Tight limits on light DM



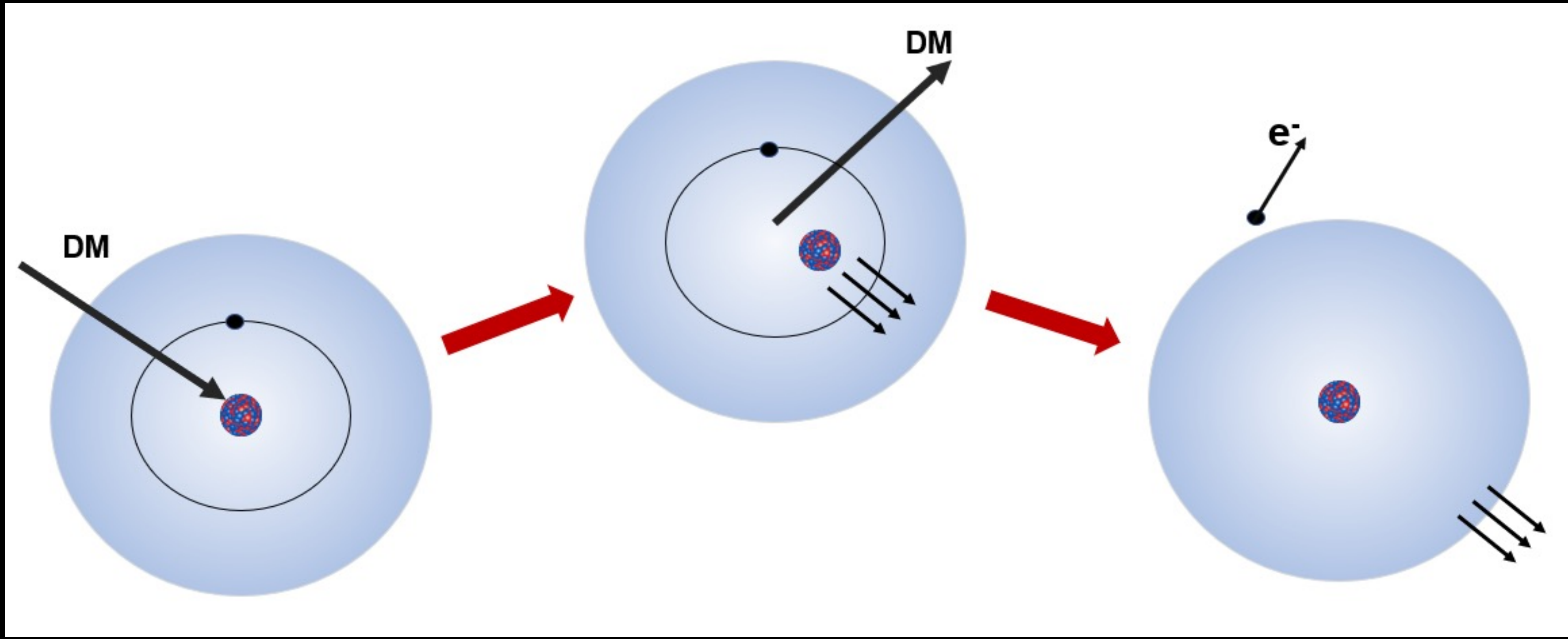


arXiv:2507.11930

See talks from Minzhen Zhang, Shuaijie Li (PandaX), Shenyang Shi (XENON)

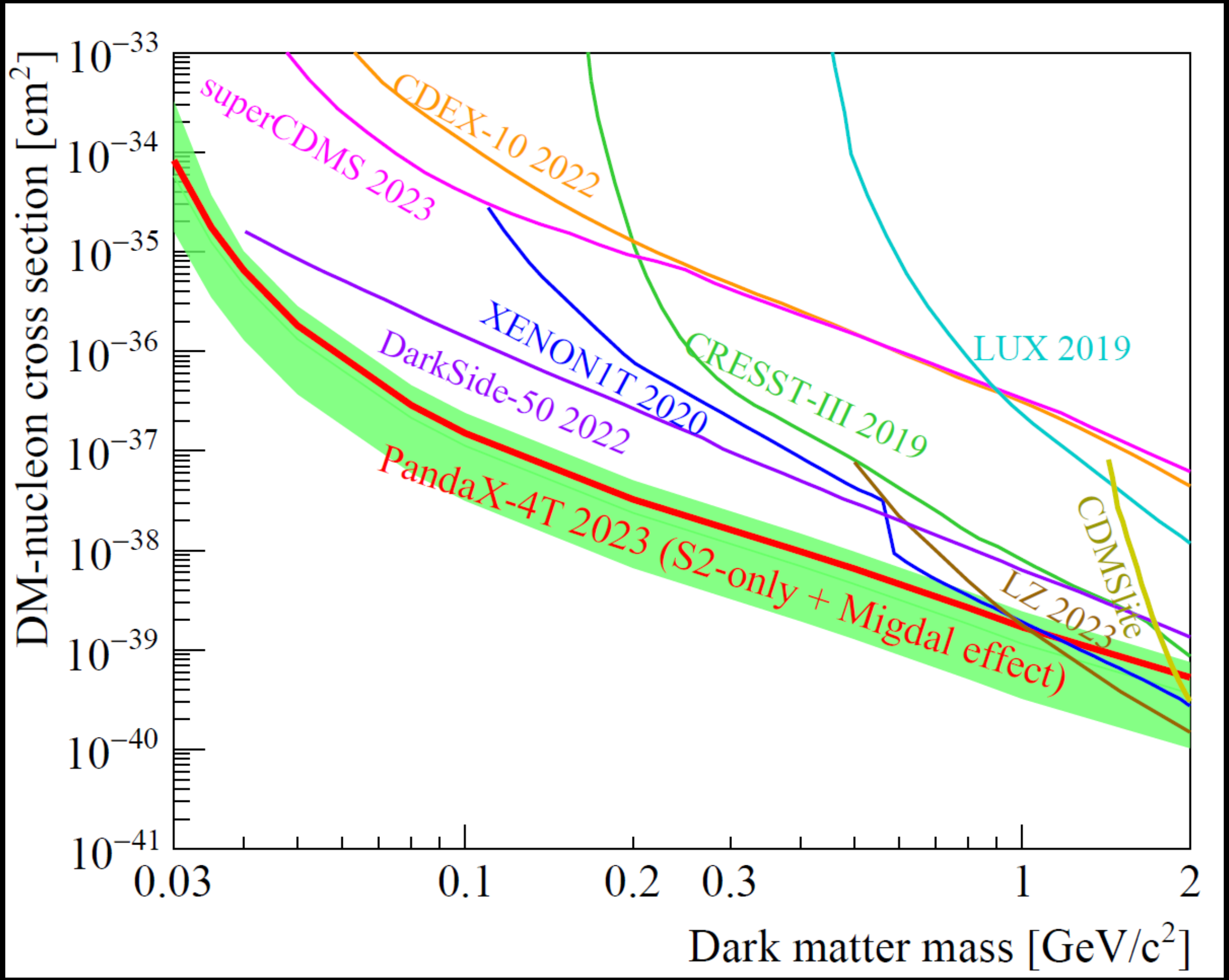
Low mass DM detection techniques with Noble Gas: example 2

Migdal effect associated with NR



- Reformulated: *Ibe et al., JHEP 2018, 194 (2018); Dolan et al., PRL 121, 101801 (2018)*
- Direct DM-e ionization and Midgal-induced ionization probability are closely related, *Essig, Pradler, Sholapurkar, and Yu, PRL 124, 021801 (2020)*

S2-only + Migdal



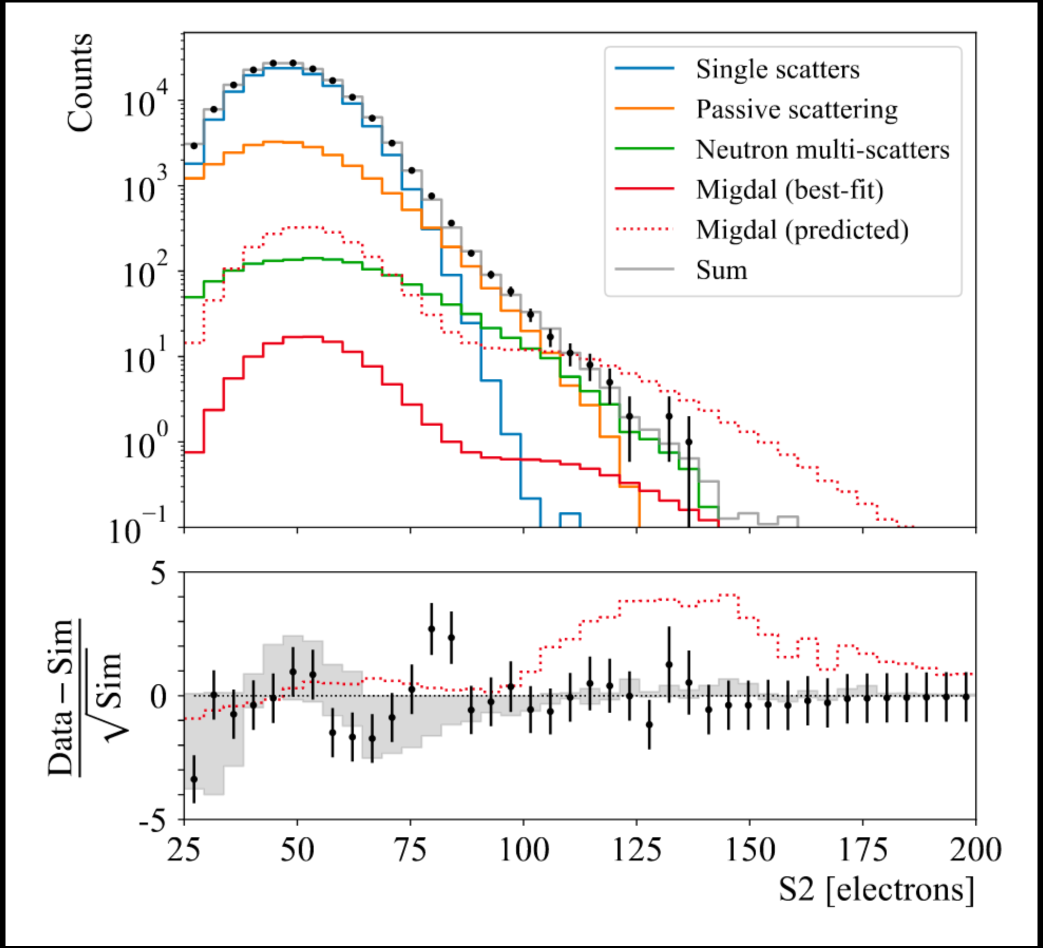
Migdal effect now widely used in light DM searches

E.g. *PRL 130, 261001 (2023), 2212.10067*

Grain-of-salt: seeing Migdal?

Many experimental efforts (with neutron beam)

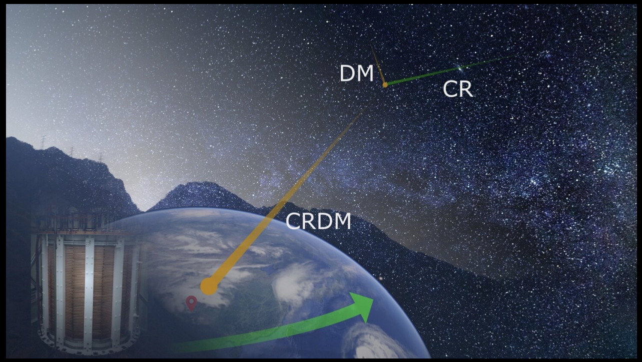
- Gas TPC
  - MIGDAL experiment: *Astropart.Phys. 151,102853(2023), arXiv:2207.08284*
  - *PTEP, Vol 2021, 1, 013C01*
- Semi-conductor: *PRD 107, 4, L041303 (2024), arXiv:2210.04917*
- Liquid xenon: *PRD 109, L051101 (2024), arXiv: 2307.12952*



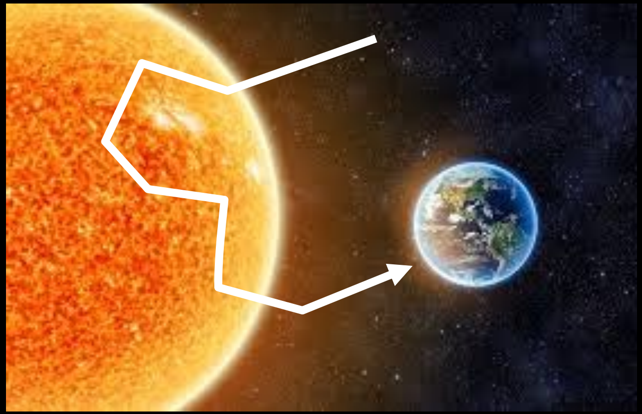
Low mass DM detection techniques with Noble Gas: example 3

"Boosting" by energetic nucleus or electrons

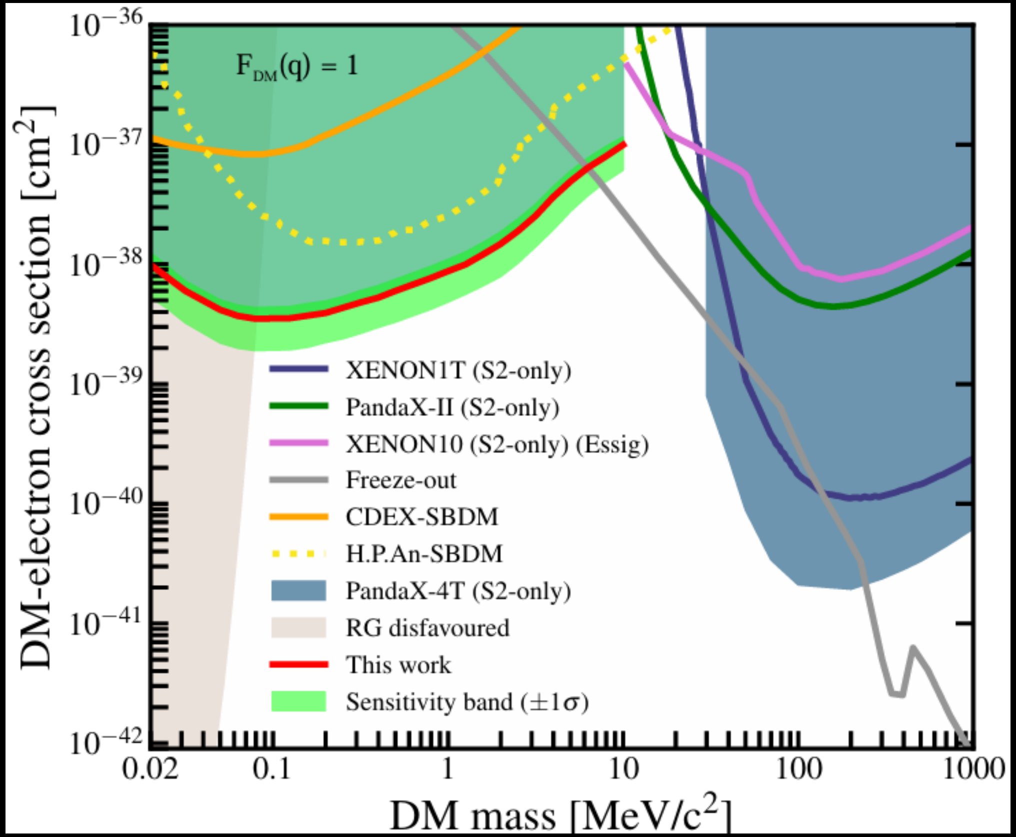
PRL 134, 161003 (2025), 2412.19970



Bringmann and Pospelov, PRL 122, 171801 (2019)



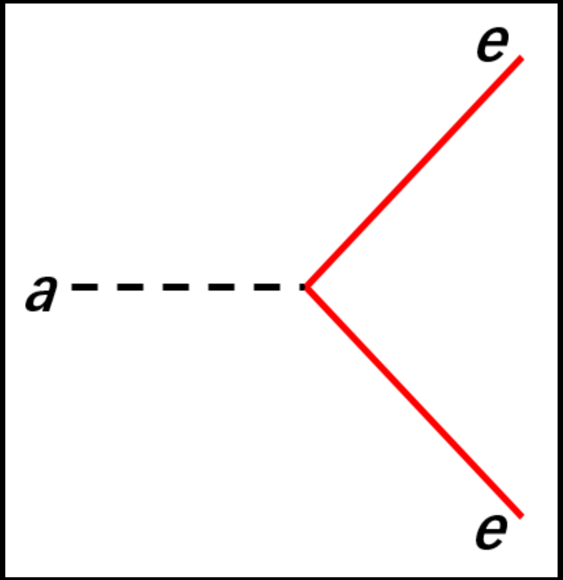
An, Pospelov, Pradler, Ritz PRL 120, 141801 (2018)

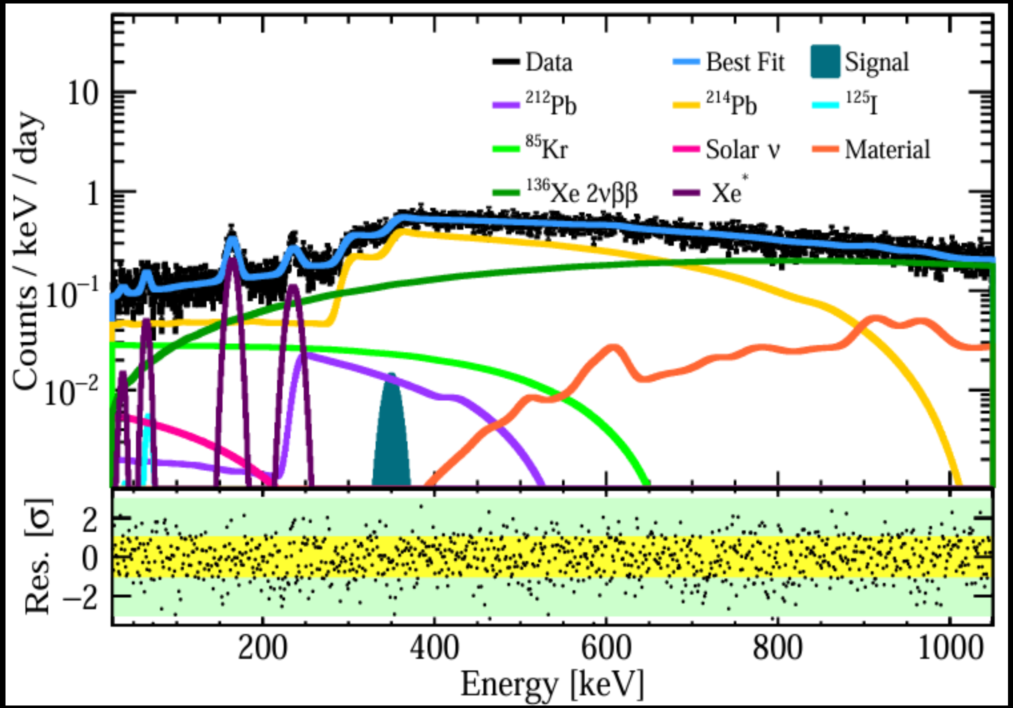


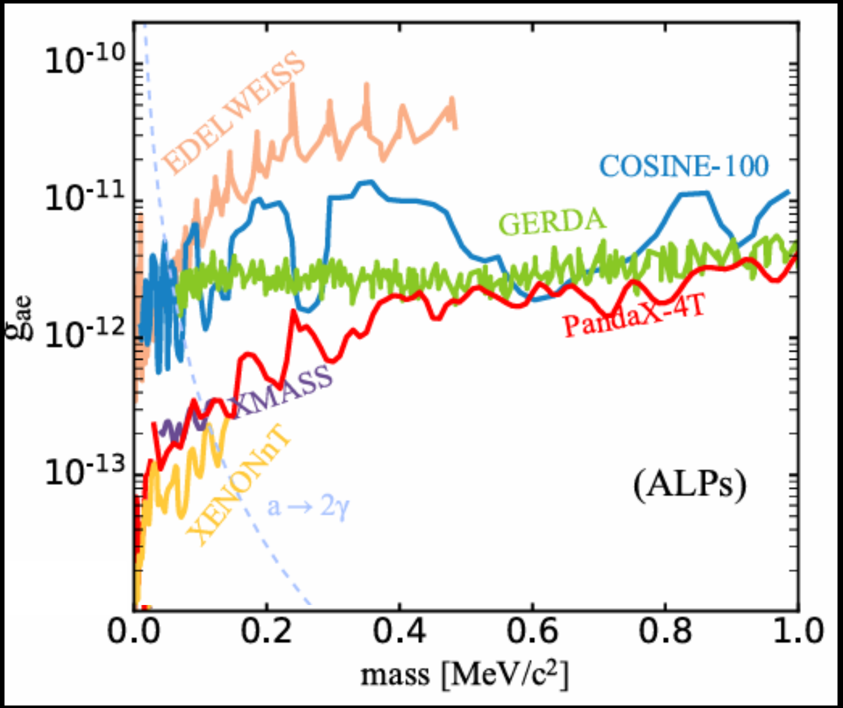
See talks by Xiaopeng Zhou(PandaX) and Yongheng Xu (LZ)

Low mass DM detection techniques with Noble Gas: example 4

Axion-like particle absorption by atomic electron







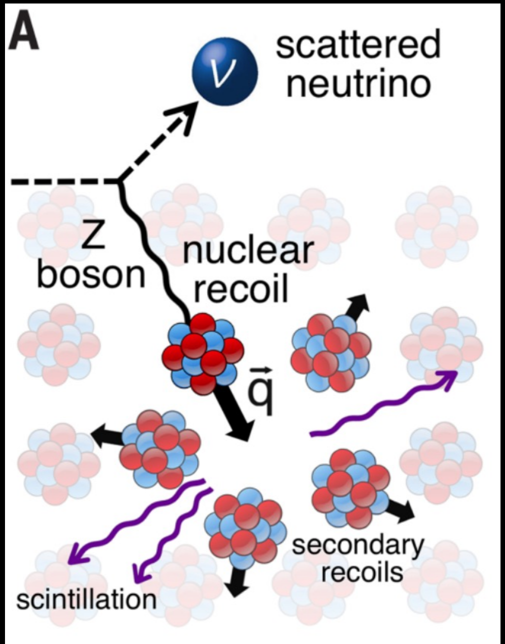
PandaX-4T, *PRL 134, 071004 (2025), arXiv:2409.00773*

See talks by Tao Li (PandaX) and Yongheng Xu (LZ)

What else can be done with these large noble detectors?

Coherent Neutrino-Nucleus Scattering

- **Quantum mechanics: 200 MeV ~ 1 fm**
- **So MeV neutrino cannot resolve individual atomic nucleus**



Coherent effects of a weak neutral current

Daniel Z. Freedman

Phys. Rev. D **9**, 1389 – Published 1 March 1974

Article | References | Citing Articles (412) | PDF | Export Citation

ABSTRACT

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

$$\sigma = \frac{G^2}{16\pi} N^2 \Delta_{max}{}^2 = \frac{G^2 N^2}{4\pi} E^2 .$$

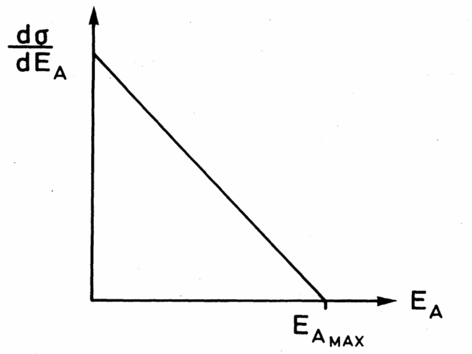


FIG. 1. Recoil-energy spectrum of the struck nucleus A in elastic neutrino scattering.

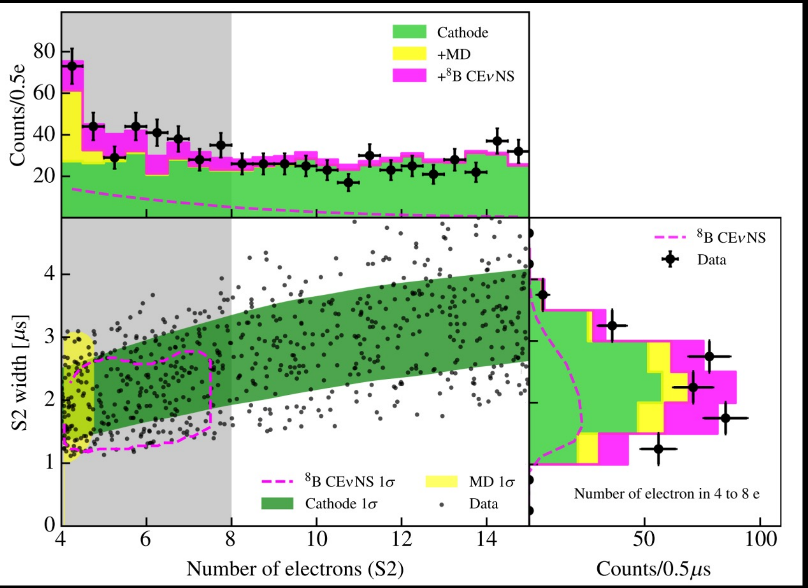
$$\bar{E}_A = \frac{2}{3A} (E/1\ \text{MeV})^2\ \text{keV}$$

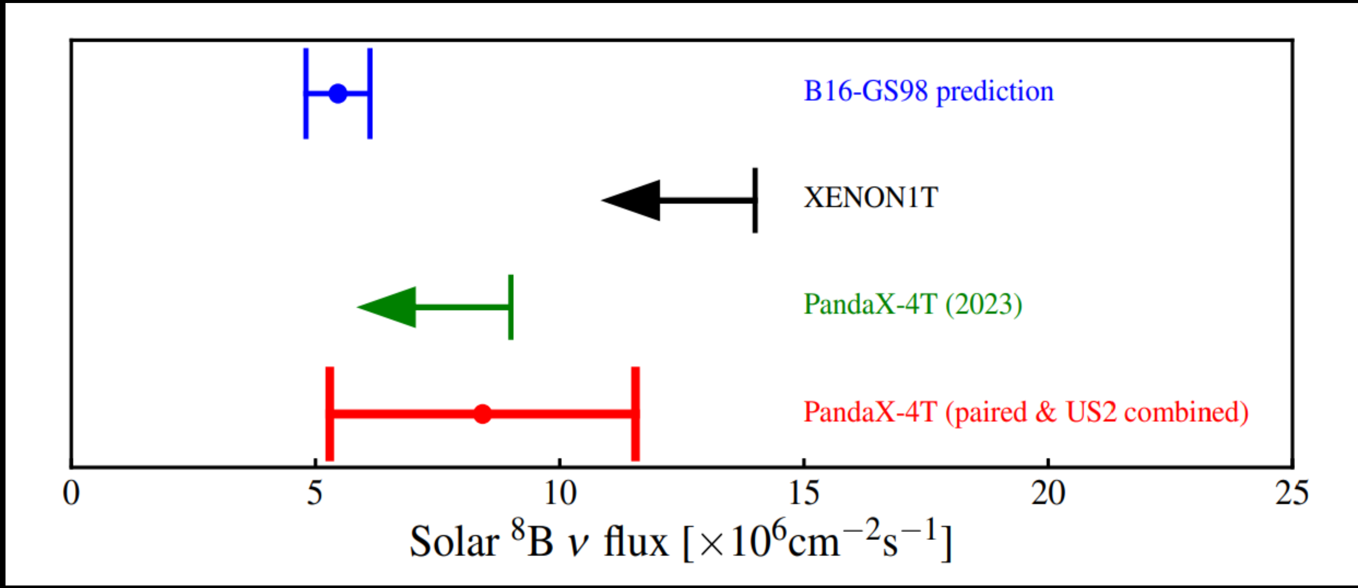
The experimental idea that motivated DM direct detection 40 some years ago!

Solar B8 neutrinos!

- PandaX-4T uses S2-only data (~1 ton×year)
  - Best-fit B8 events: 75±28 (S2 only) and 3.5±1.3 (S1-S2 paired)
  - Reject background-only hypothesis with significance of 2.64σ
  - *PRL 133, 191001 (2024),* Editors' Suggestion
- XENONnT results in same issue of *PRL (191002),* similar significance

See more in Kexin Liu XENONnT talk





Solar B8 neutrinos!

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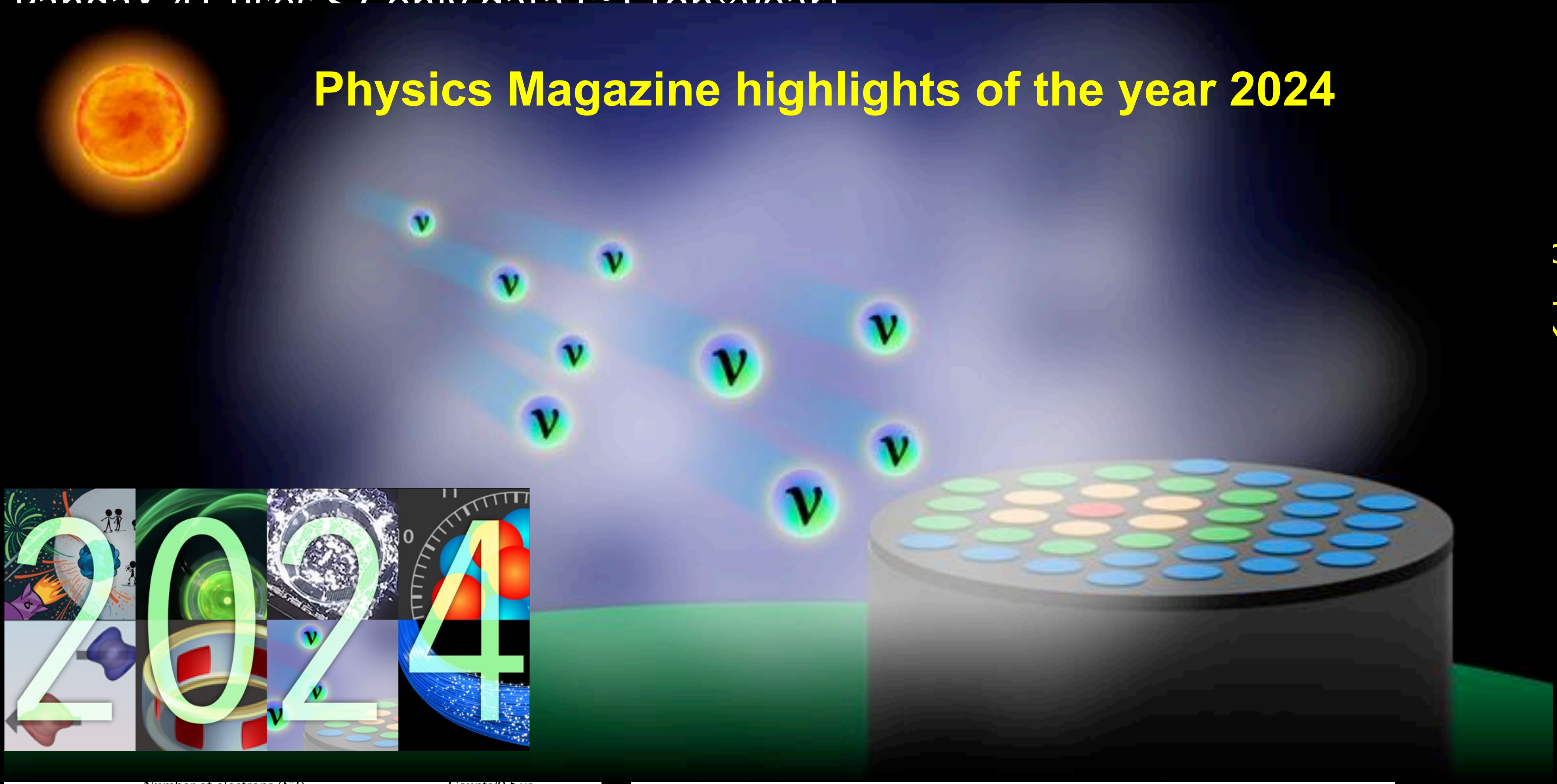
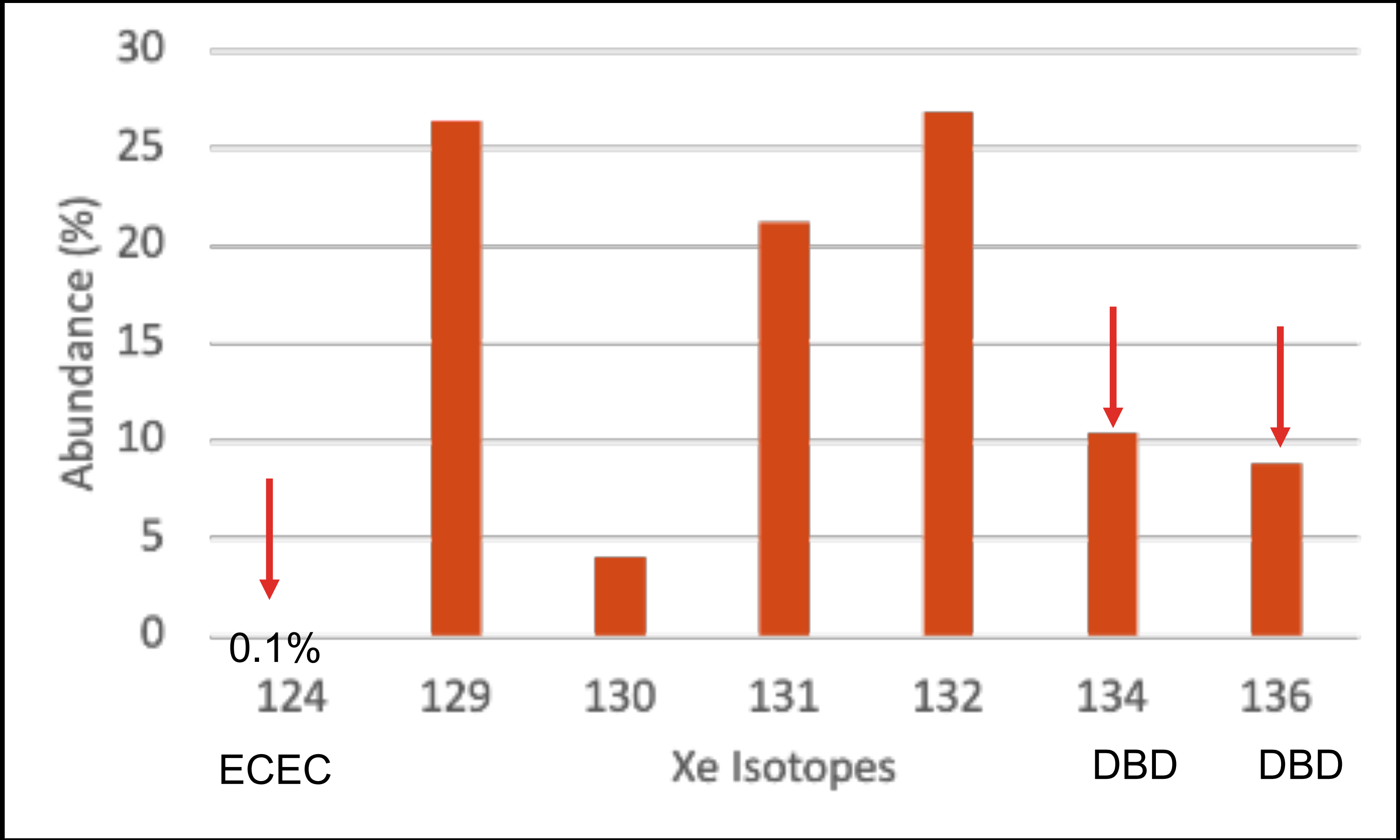


ore in
Liu
XnT talk

Number of electrons (S2)
Counts/0.5μs

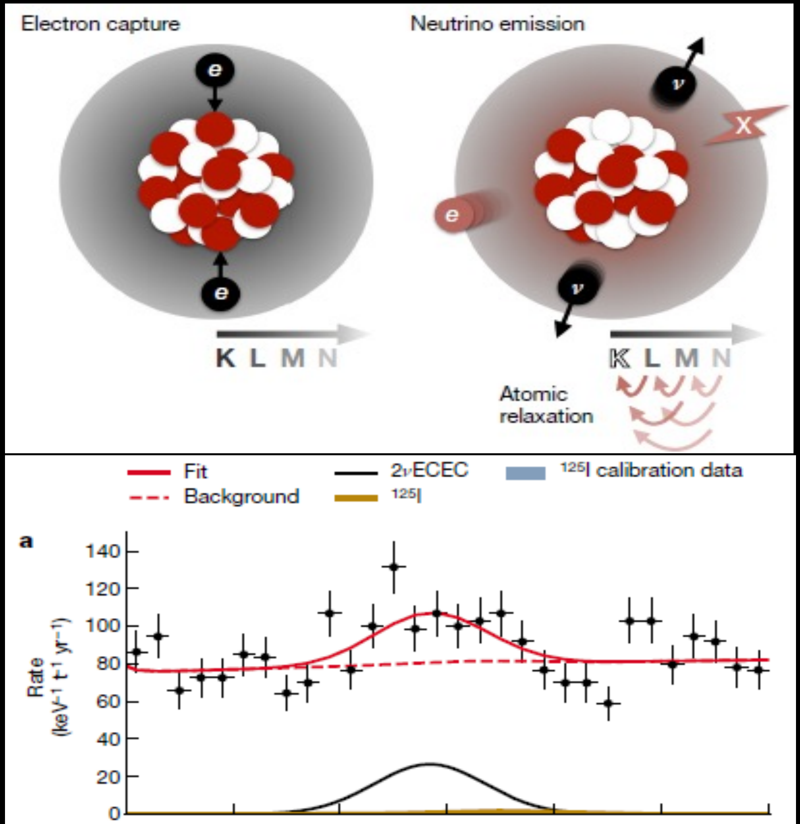
Natural xenon
multiple double weak decay targets



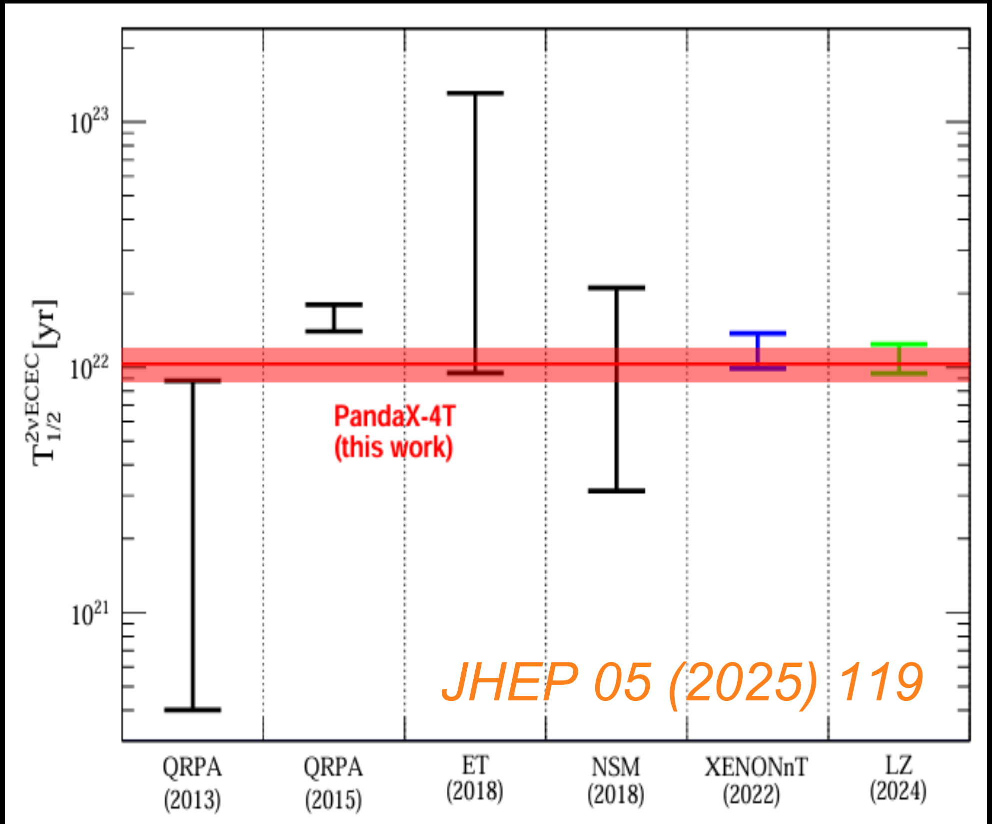
Challenges: background, energy resolution, MS event selections etc

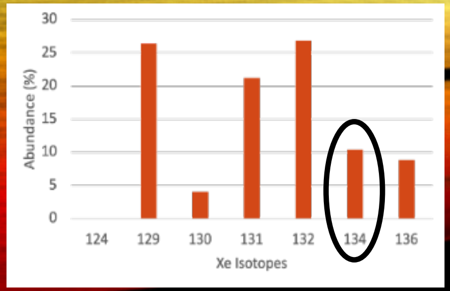
^{124}Xe ECEC

First observed by XENON-1T 2019
Nature 568, 532 (2019)

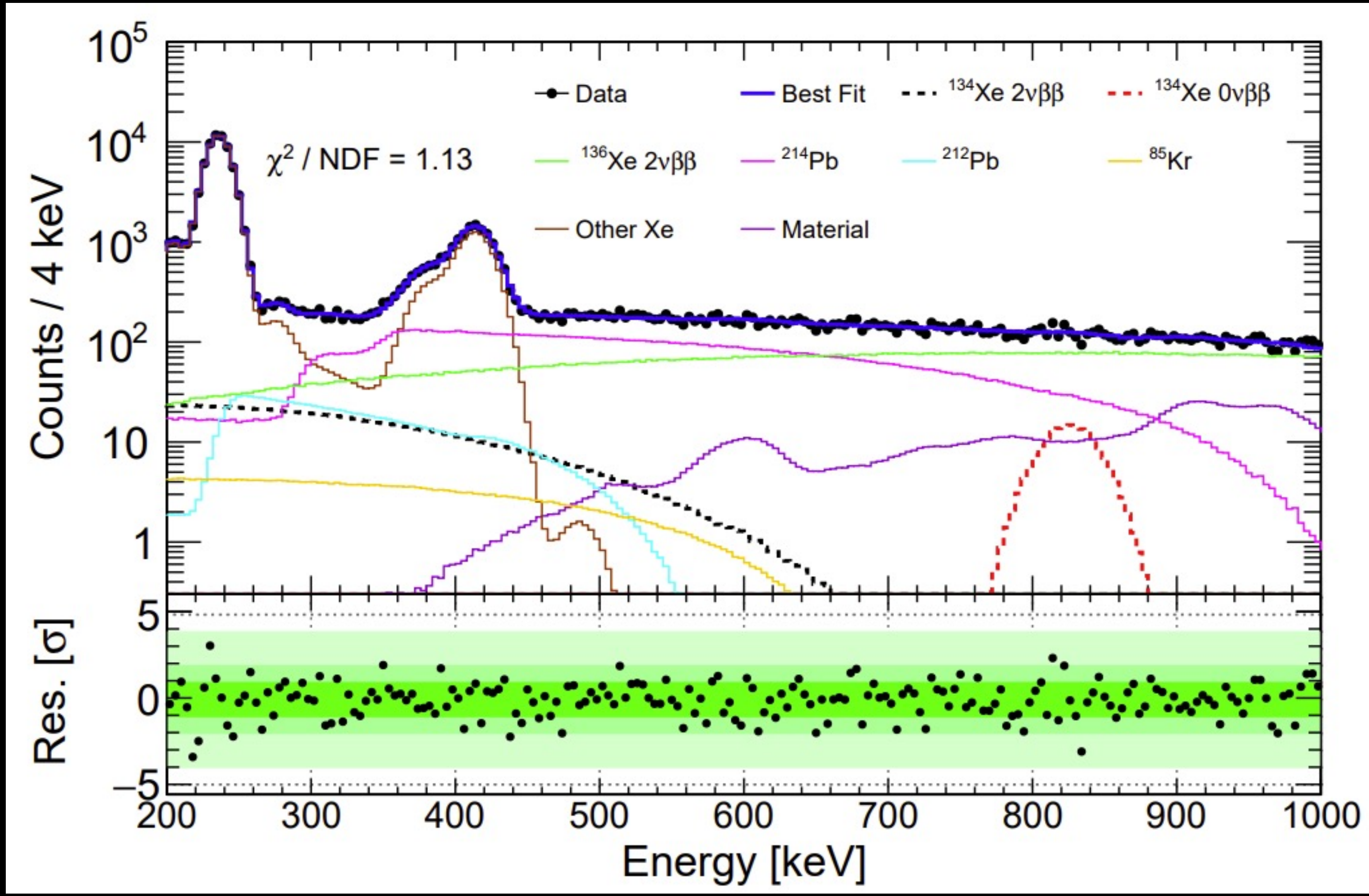


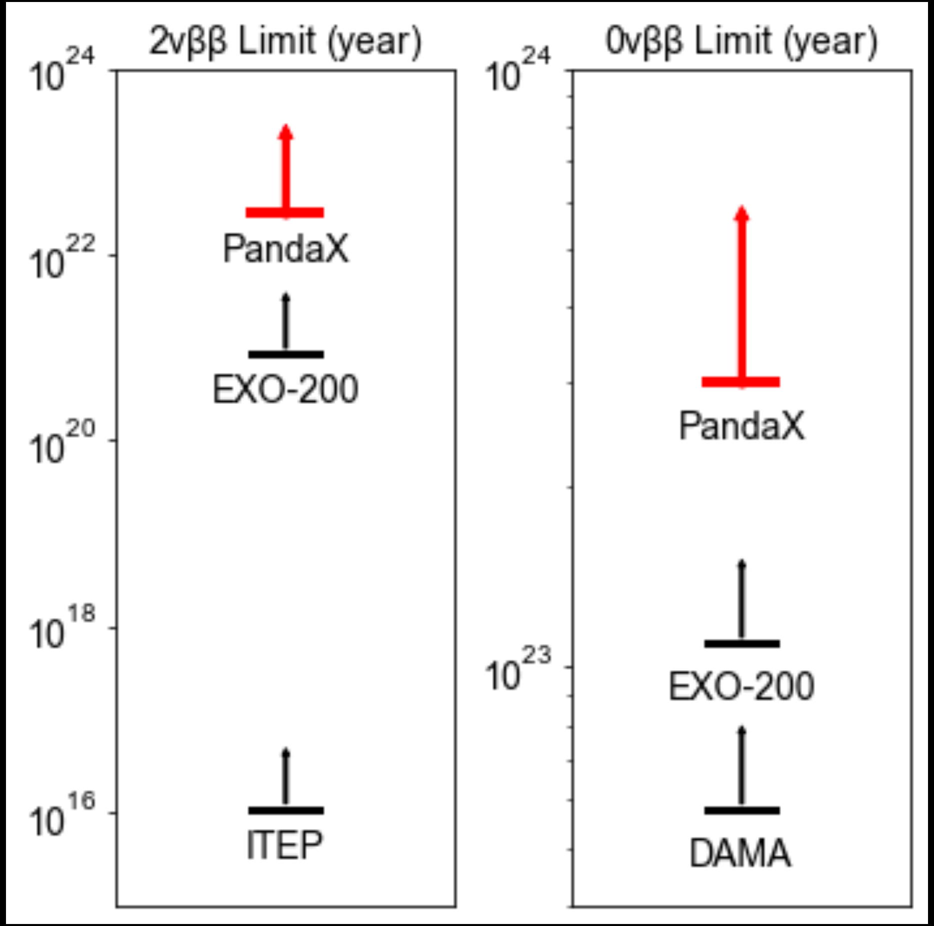
Now ECEC lifetime accurately measured by XENONnT, LZ, and PandaX-4T



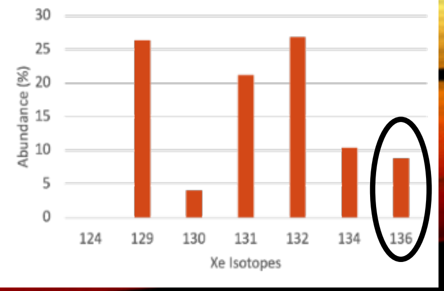


^{134}Xe: a unique blessing

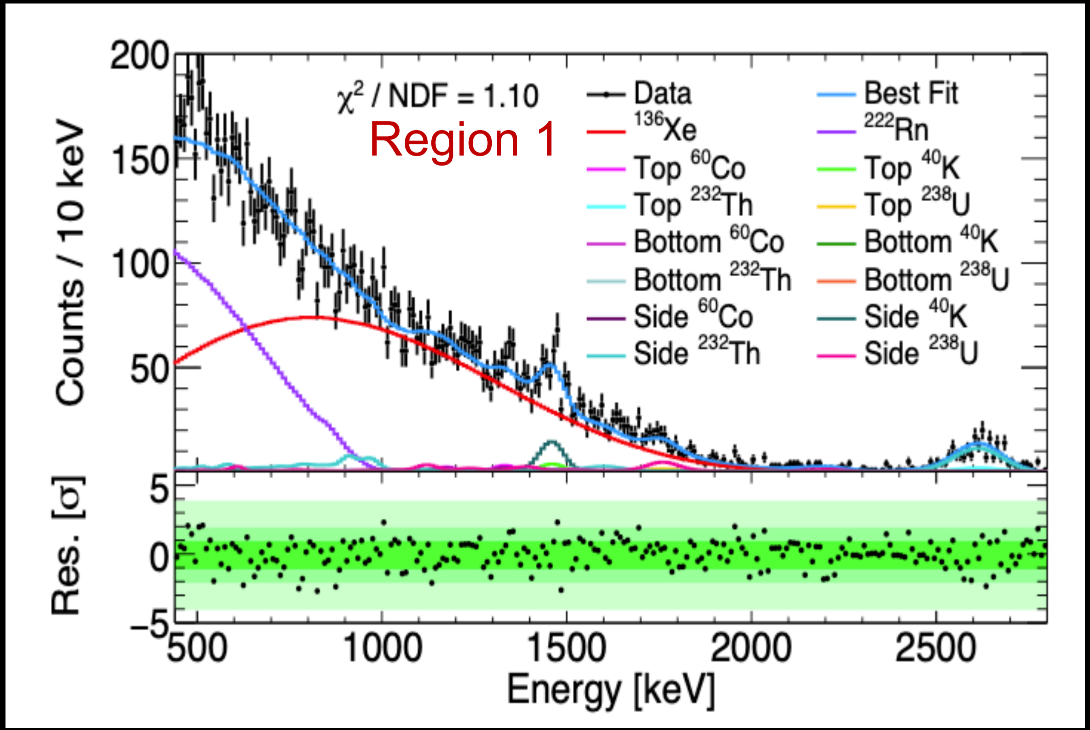


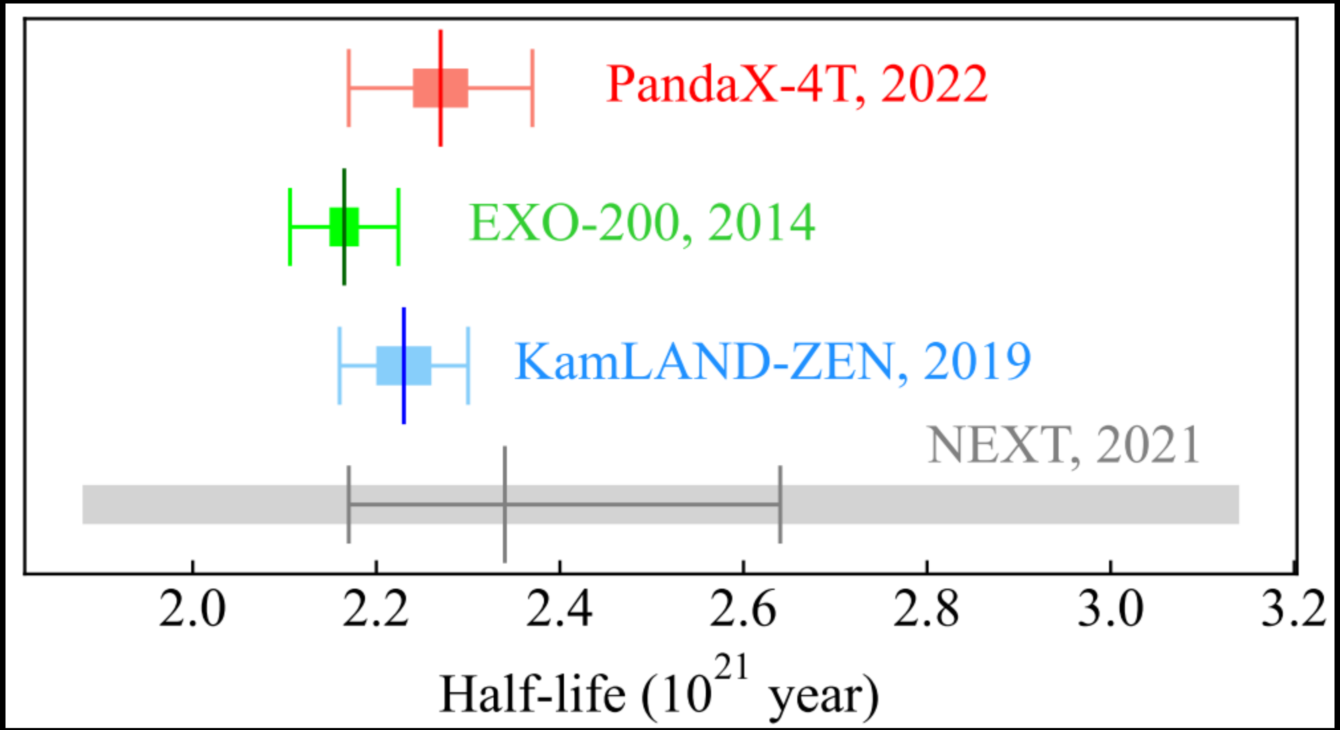


PandaX-4T, *PRL 132, 152502 (2024)*

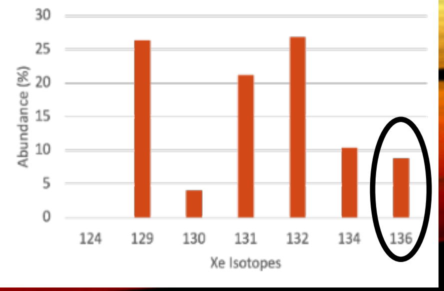


Precise measurement of ^{136}Xe 2vDBD





- PandaX-4T ^{136}Xe 2vDBD half-life 2.27 ± 0.03(stat.) ± 0.10(syst.) × 10^{21} y
- FV: 0.65 ton of natural xenon
- *Research vol 2022, 9798721, arXiv:2205.12809*



PandaX Search for ^{136}Xe 0vDBD

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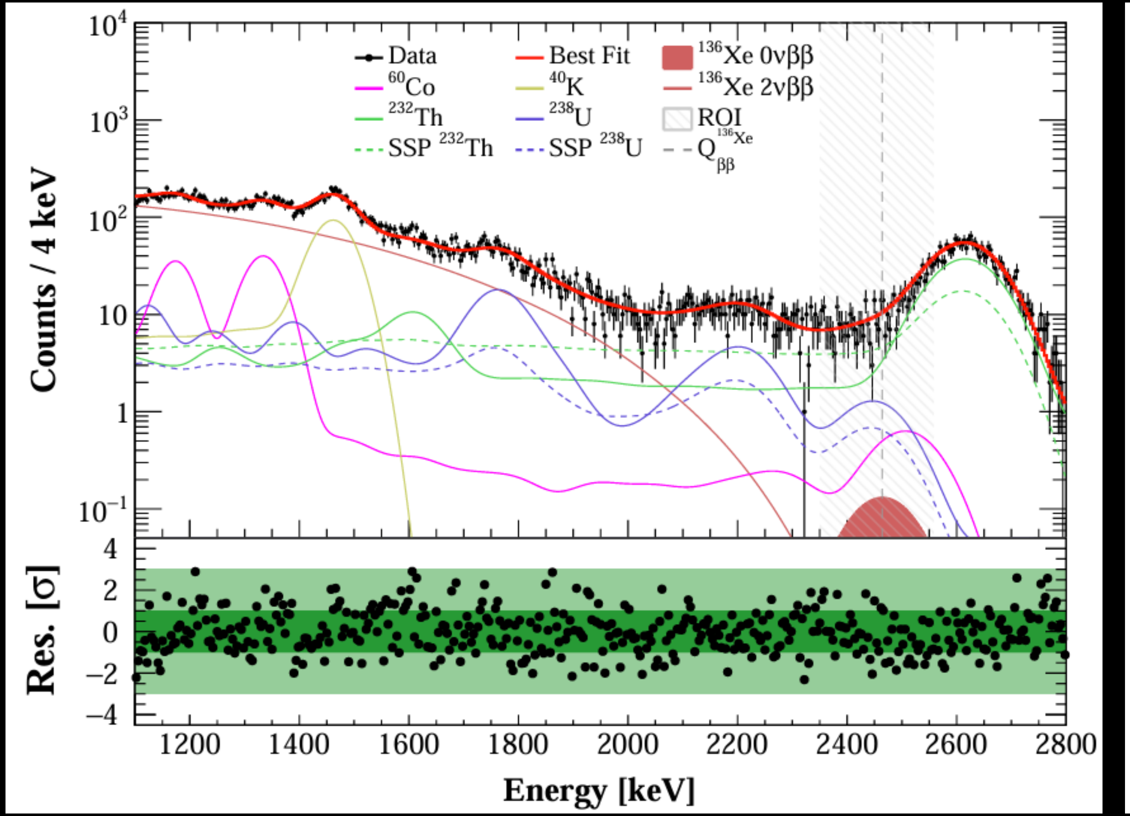
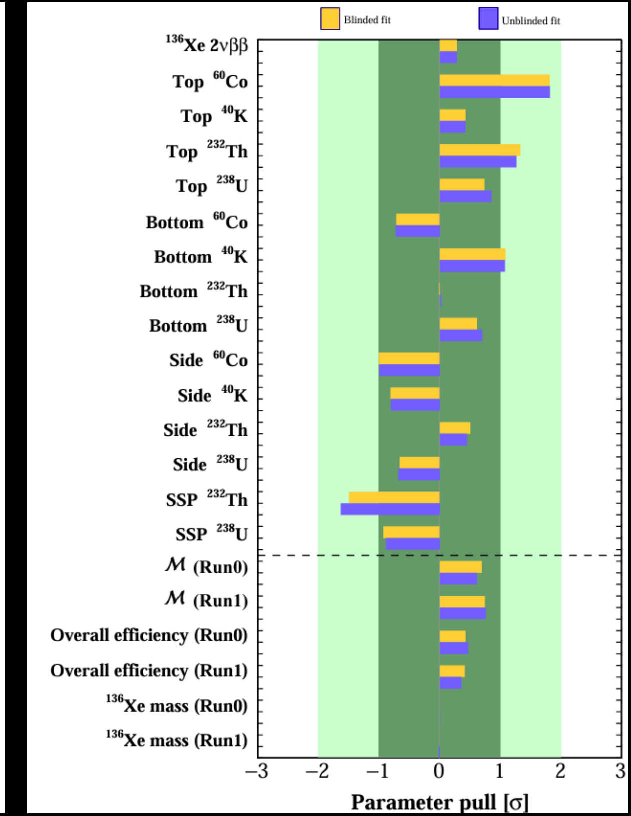




Science Bulletin Vol. 70,11 (2025)
arXiv:2412.13979

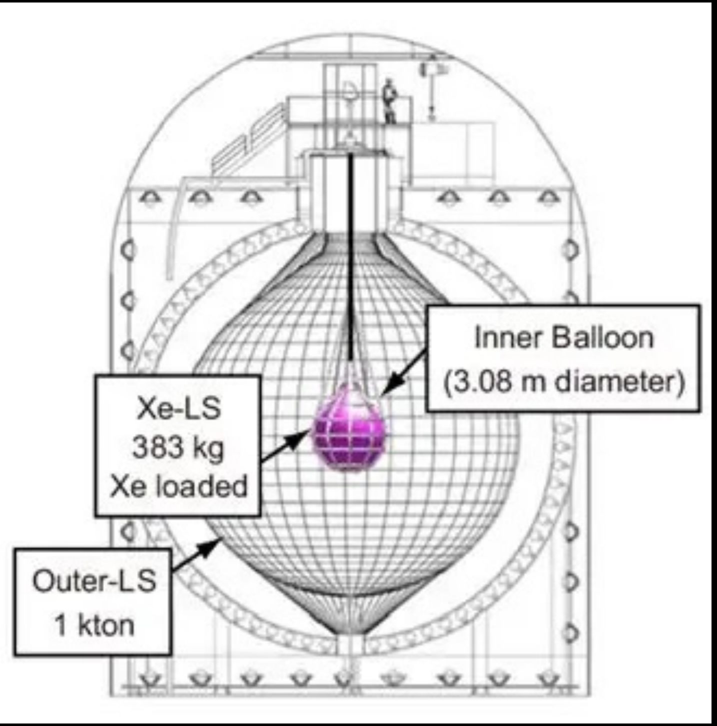
Lifetime
$> 2.1\times10^{24}$year
$m_{\beta\beta}$<0.6-1.4 eV

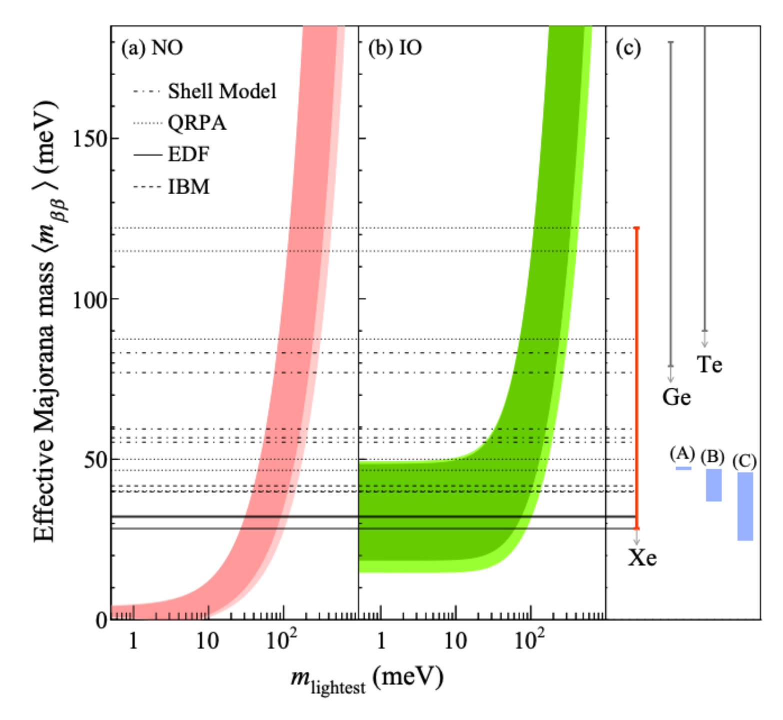
Median sensitivity
2.7×10^{24}year

See talk by S. Zhang

Enriched ^{136}Xe Observatories

- KamLAND-Zen, EXO, NEXT: mainly focus on 0vbb
- Exploring solar neutrino, dark matter etc



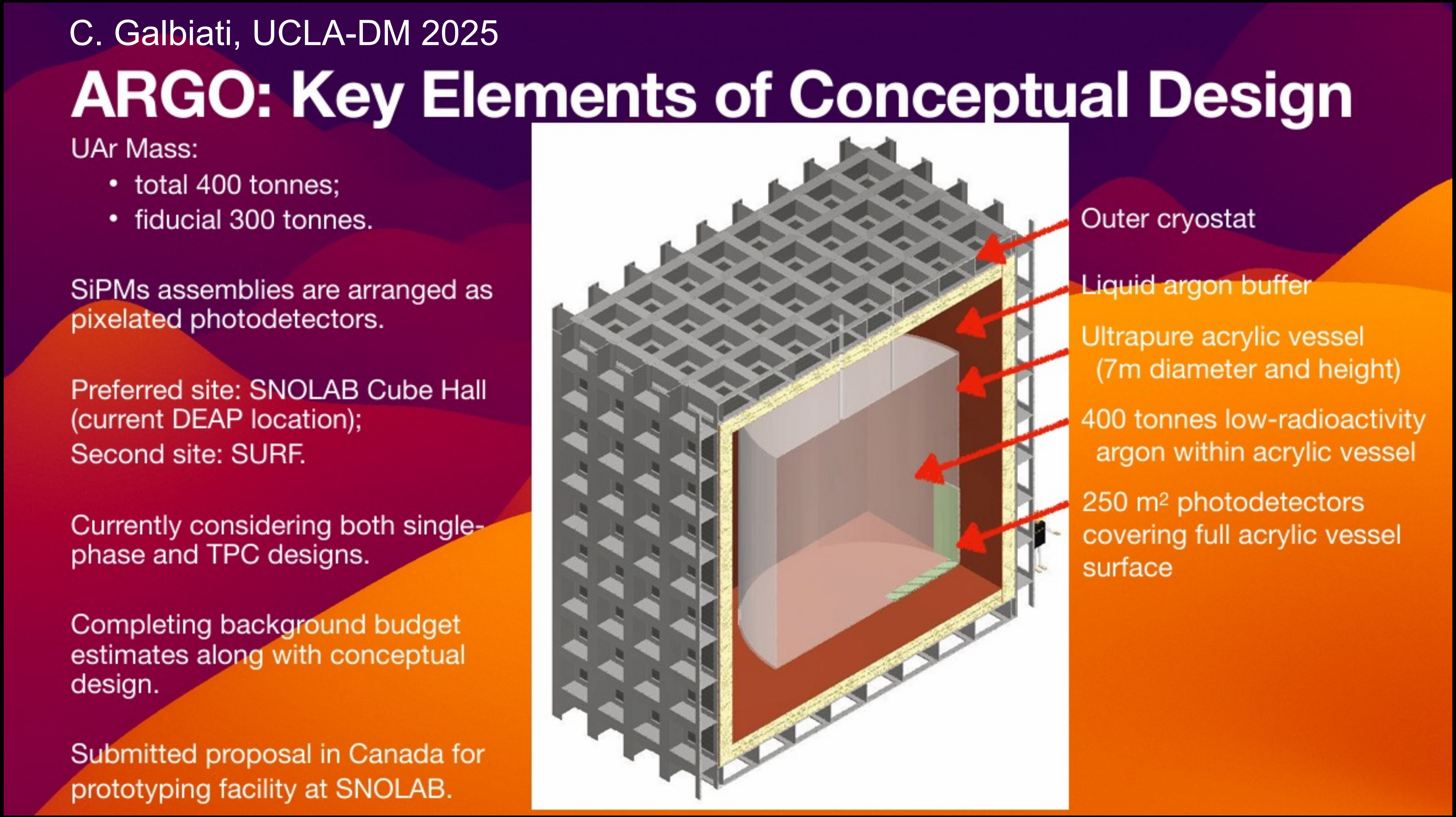


arXiv:2406.11438

Lifetime $> 3.8\times10^{26}$year
$m_{\beta\beta}$ < 28 - 122 meV

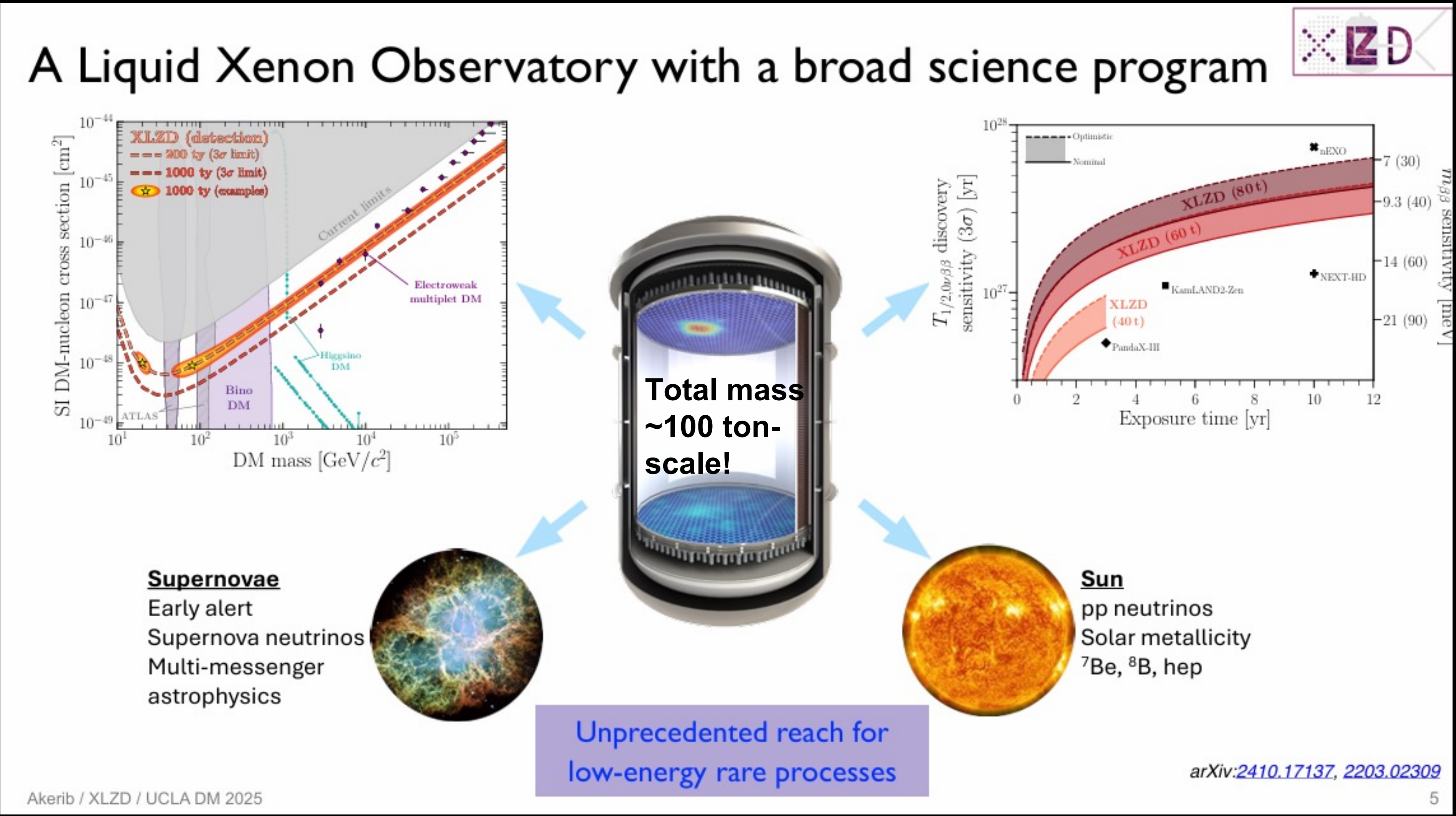
See talks from Kelly Weerman (KamLand),Glenn Richardson (nEXO), Gaosong Li, Thomas Brunner (EXO-200), Samuele Torelli (NEXT)

Next Generation Ar

- 

Next Generation Xe

Dan Akerib, UCLA-DM-2025



XENONnT, LUX-ZEPLIN, DARWIN
Consortium formed 2021
Collaboration formed 2024

Rich physics, rich team experience

Possible sites in Europe and North America

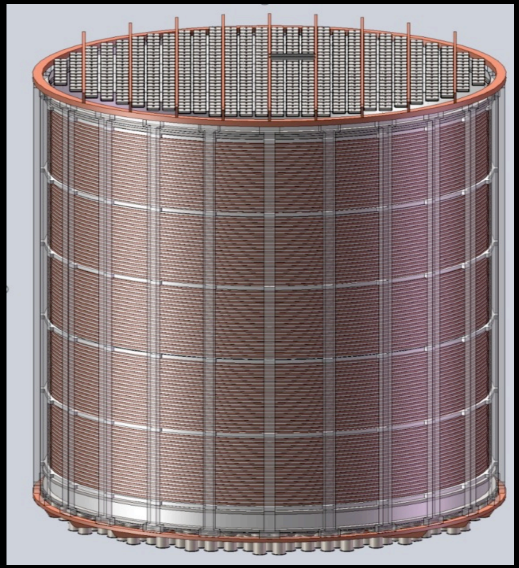
See talks from
M. Yamashita and K.D. Mora

Next Generation Xe

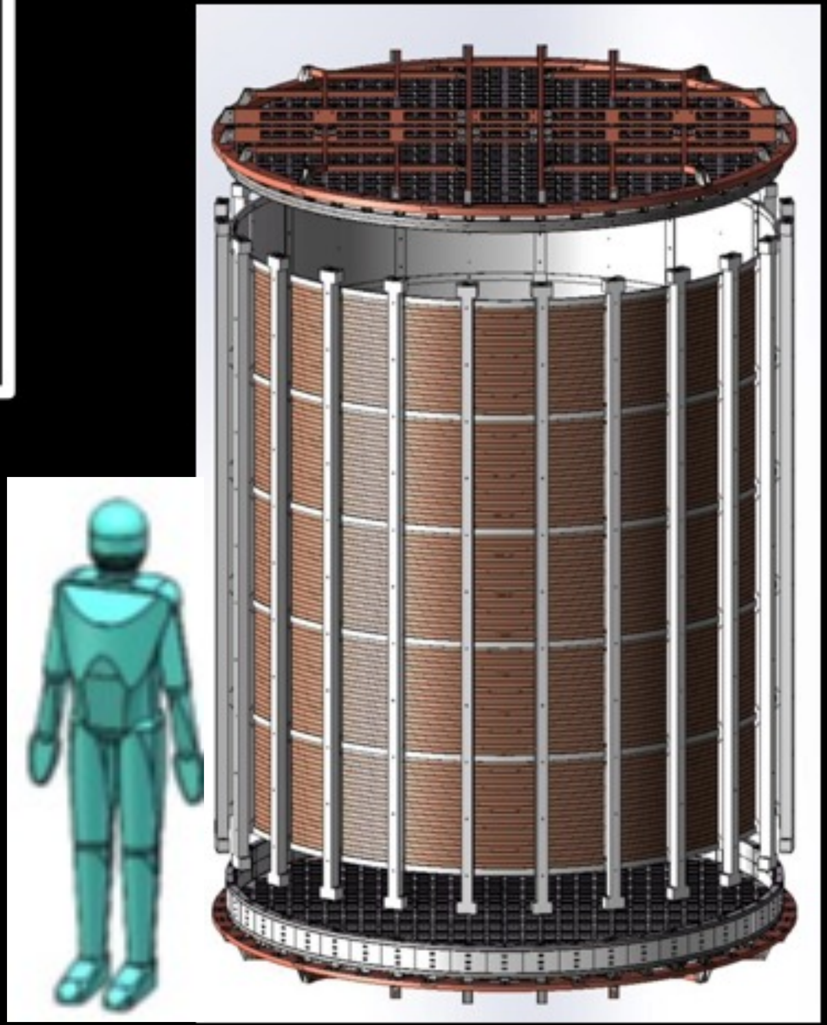
PandaX-xT: step-wise strategy to a 40-ton-scale LXe observatory at CJPL

PandaX-4T

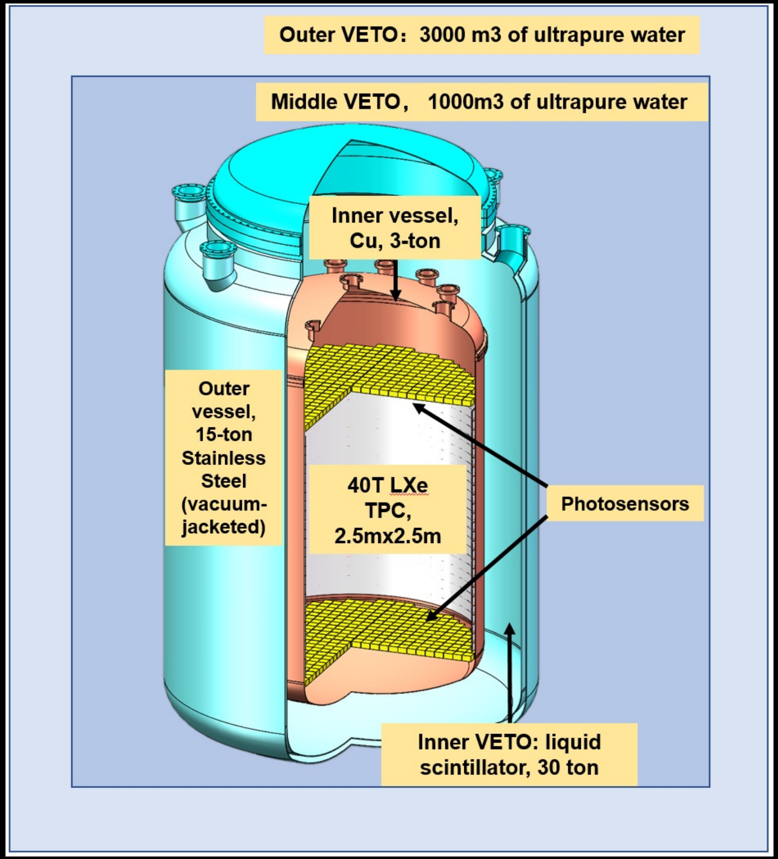
PandaX-20T (2027, mostly funded)

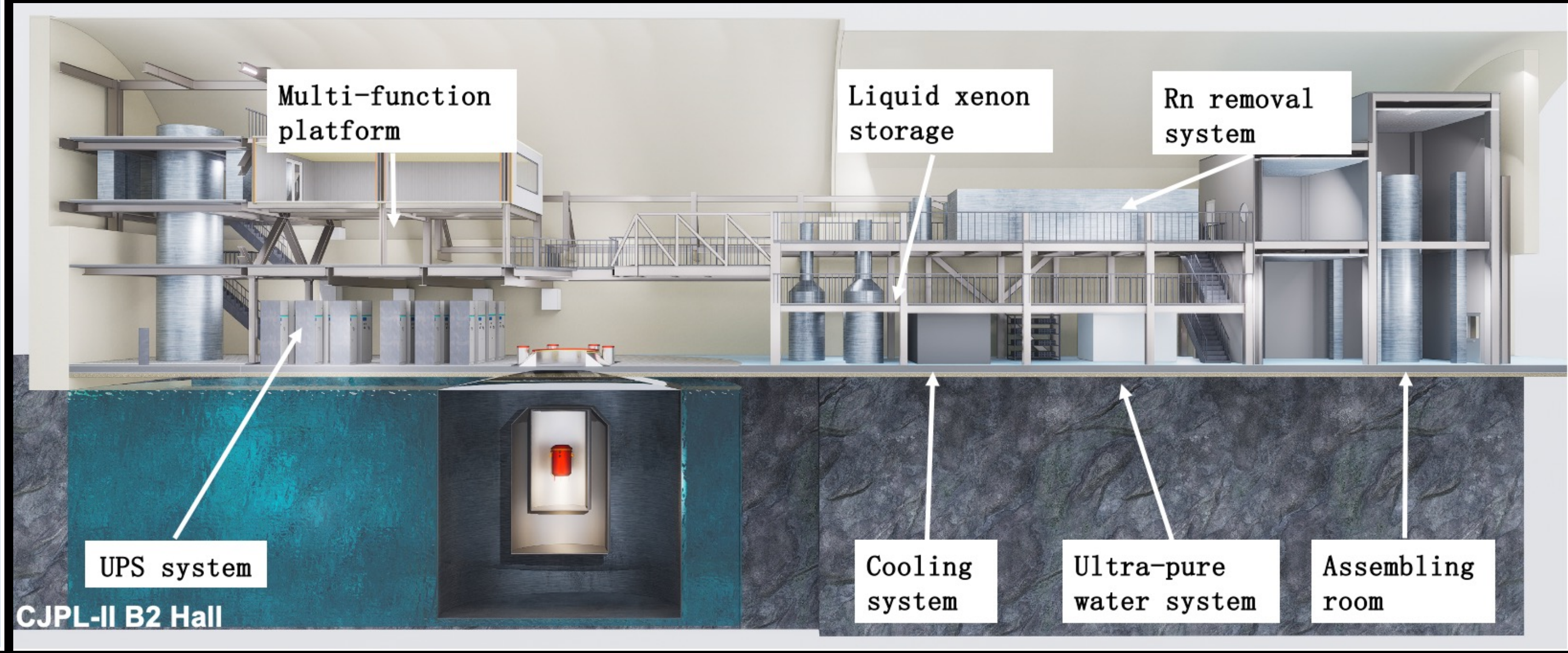


PandaX-40T



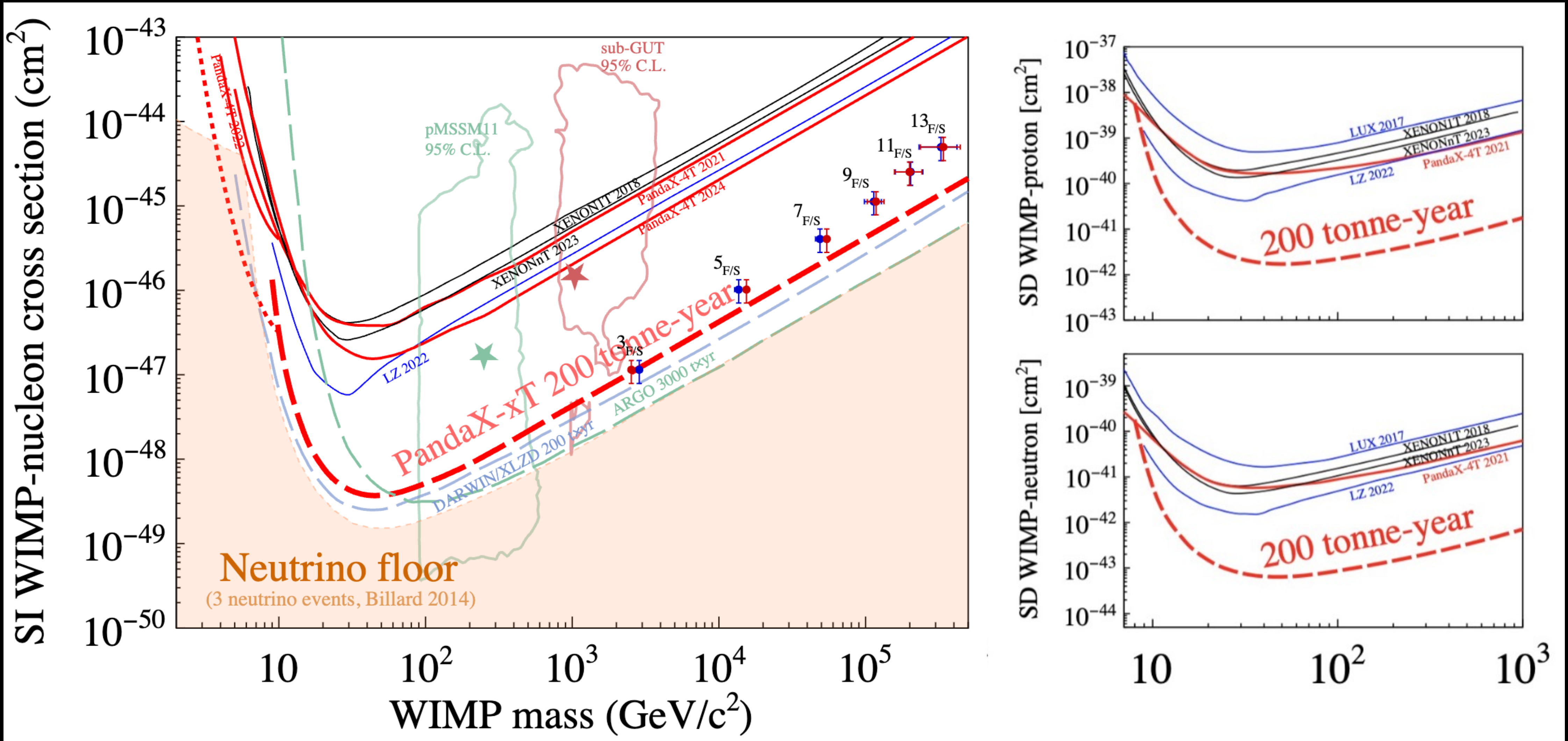
PandaX-20/40T @ CJPL





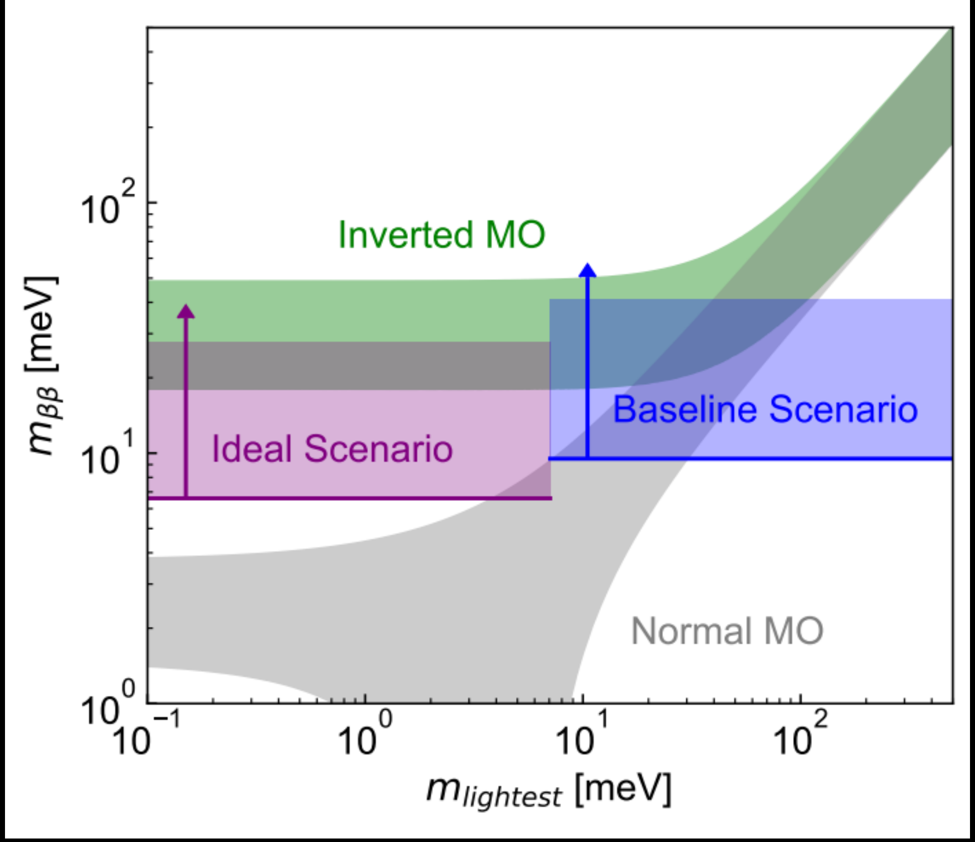
See talk by Junting Huang on PandaX veto detector development

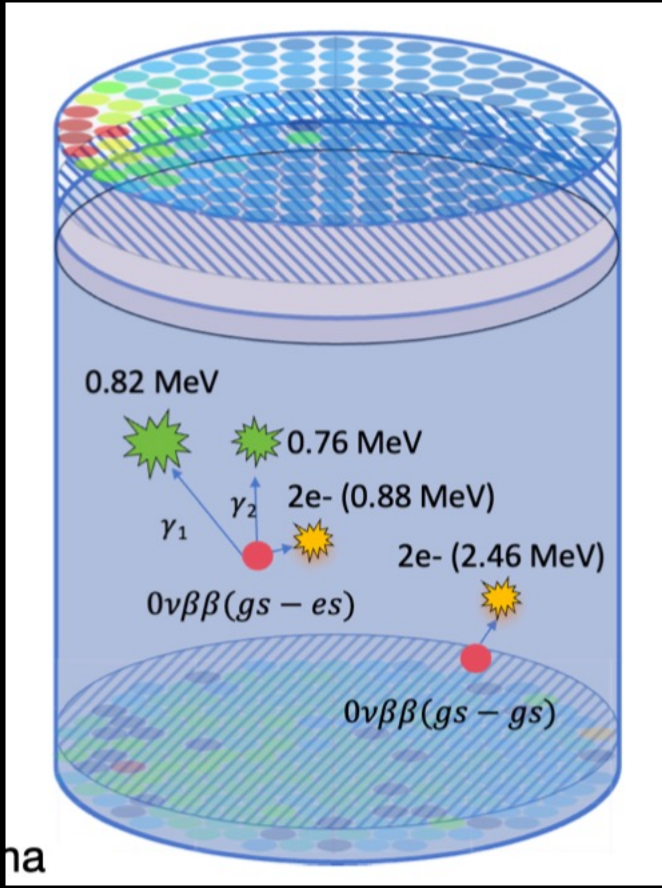
DM Potential (PandaX-40T)



Sci. China Phys. Mech. Astron. 68, 221011 (2025) arXiv:2402.03596

0vDBD potential (PandaX-40T)



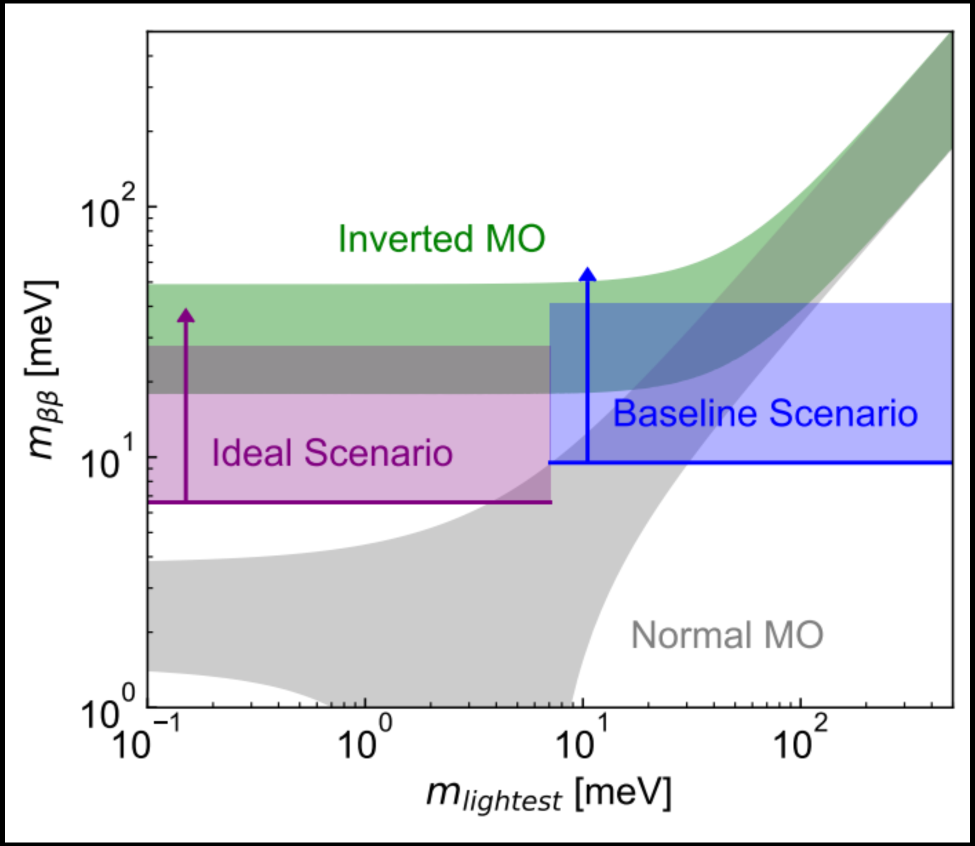


Sci. China Phys. Mech. Astron. 68, 221011 (2025)

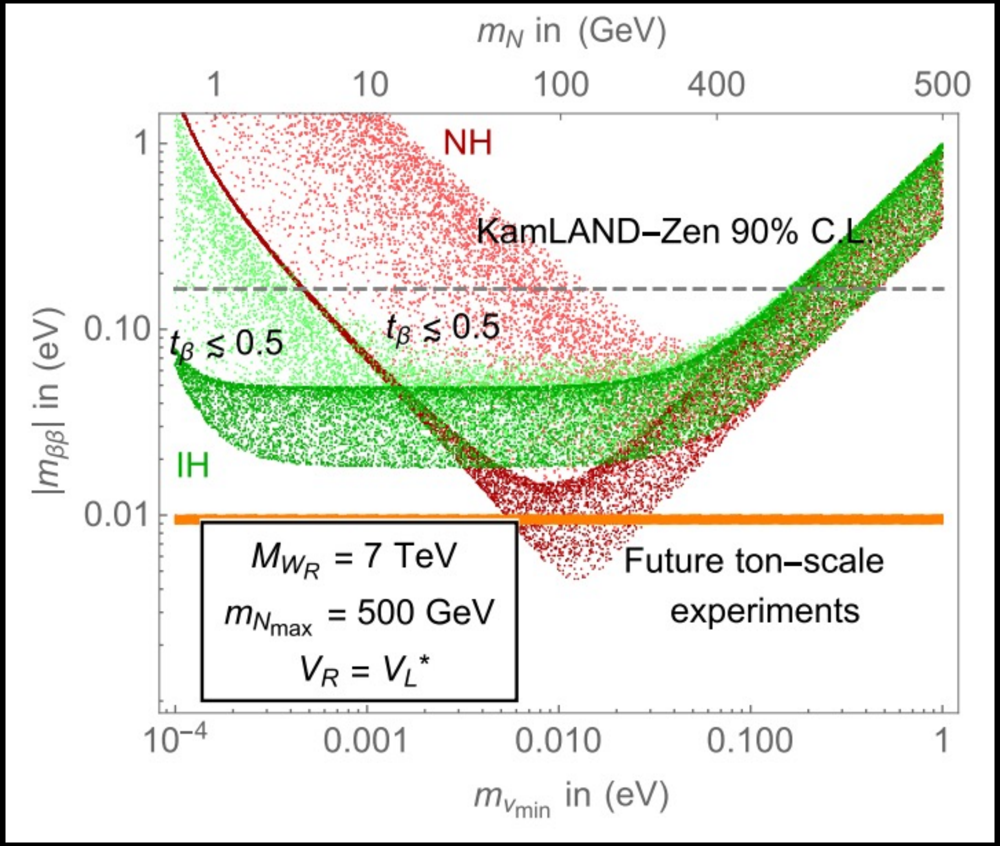
arXiv:2508.17413

Further sensitivity could be gained by combining multiple 0νββ transitions, see Ke Han, session 3B

0vDBD potential (PandaX-40T)

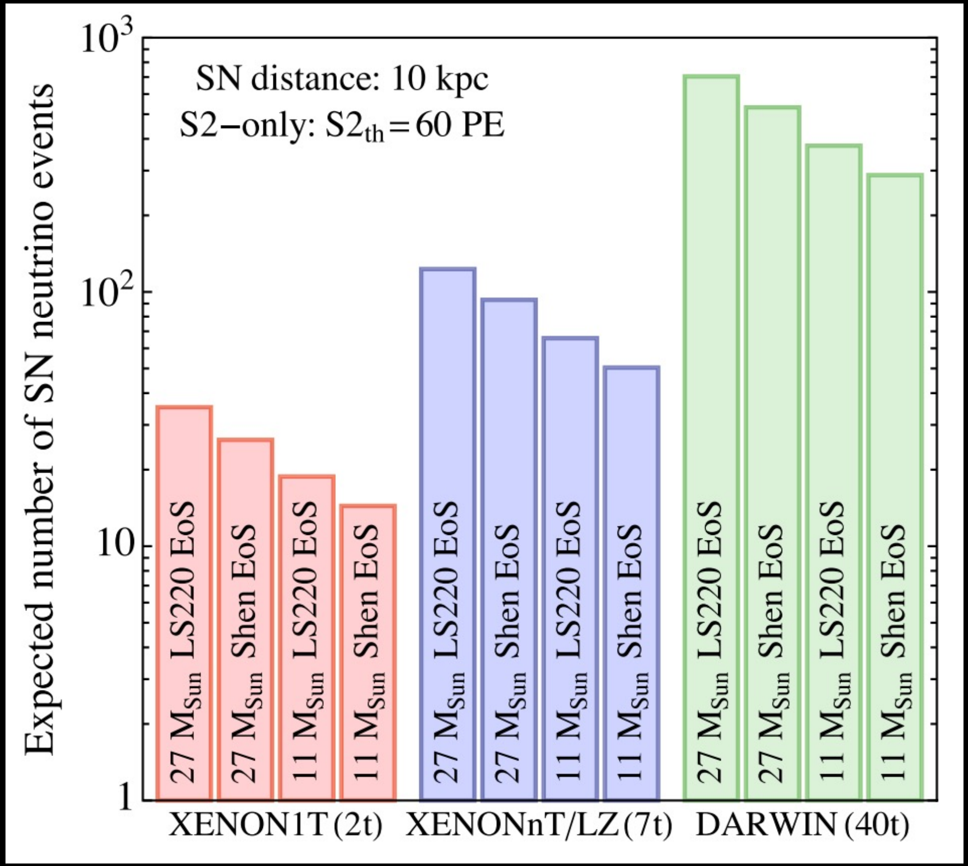


Sci. China Phys. Mech. Astron. 68, 221011 (2025)



E.g. TeV L-R model scenario
Li, Ramsey-Musolf, Vasquez, PRL 126, 151801 (2021)

Scientific potentials (SNEWS)



R.F. Lang, C. McCabe, S. Reichard, M. Selvi, I. Tamborra, PRD 94, 103009 (2016)

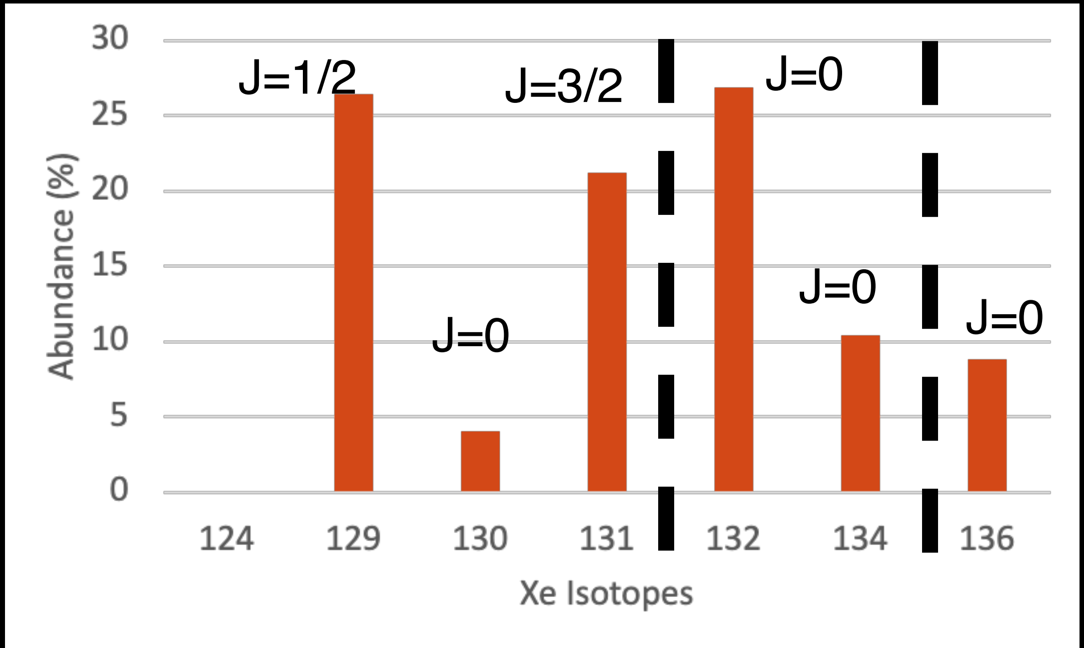
Now S2-only become a standard!

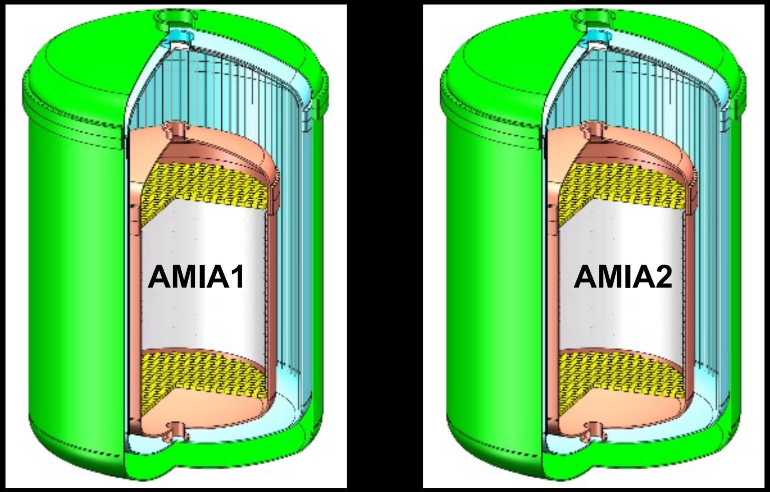
SNEWS

SUPERNOVA EARLY WARNING SYSTEM

Further future development

Xenon with artificially modified isotopic abundance (AMIA), either via a split of odd and even nuclei, or further enrichment of ^{136}Xe, to improve sensitivity to spin-dependence of DM-nucleon interactions and NLDBD (*Y. Suzuki，arXiv:hep-ph/0008296, 2000*)



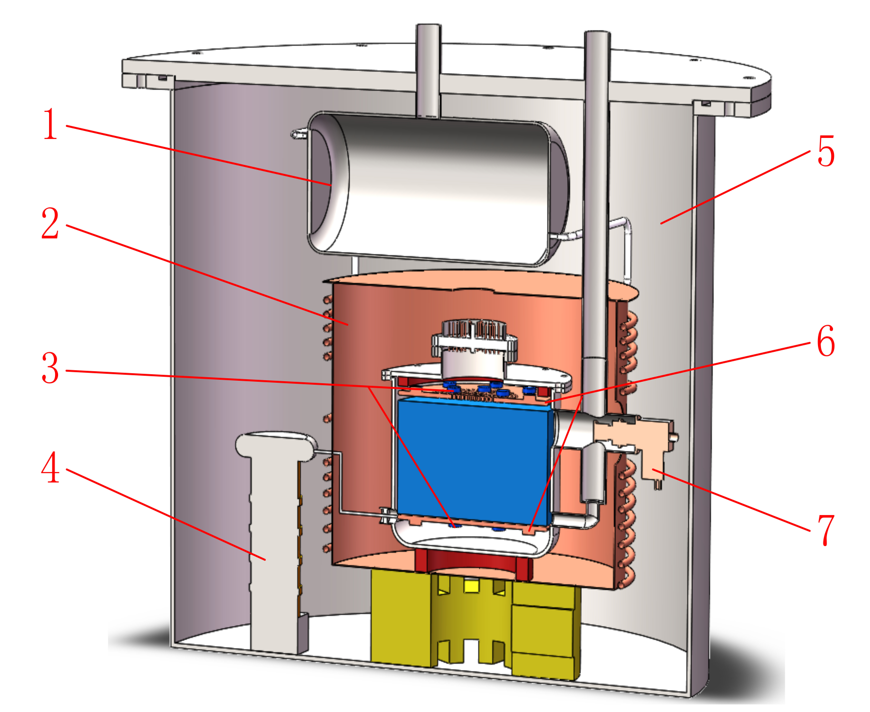


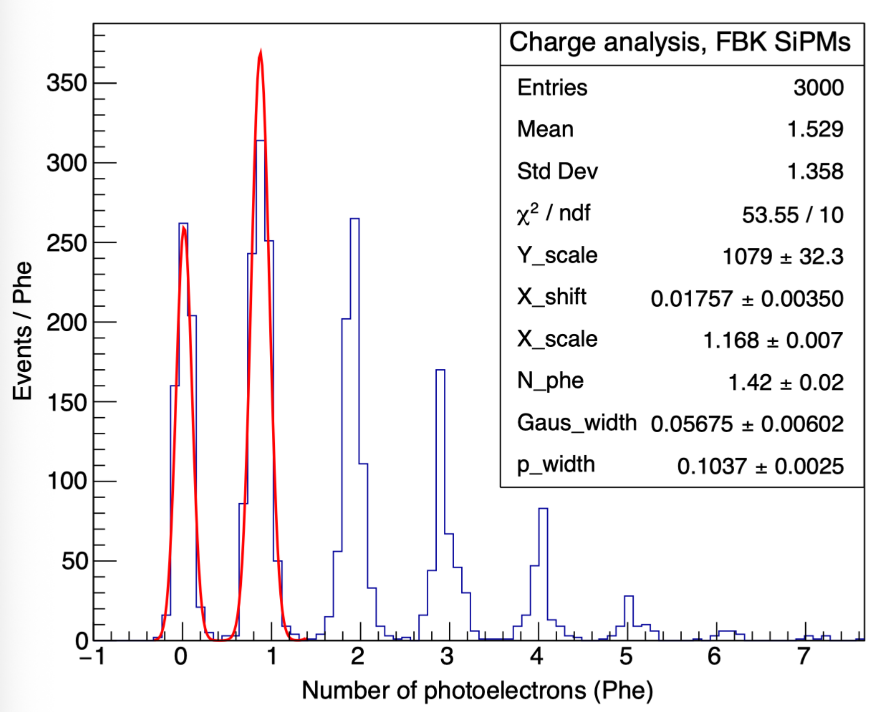
Discovery smoking gun！

Helium

- **ALETHEIA: lower threshold, no radioactive isotope**

See talk from Junhui Liao





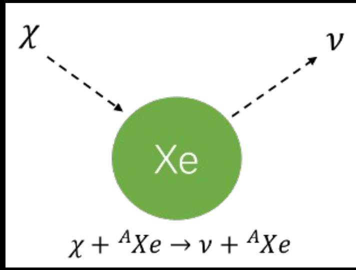
Summary

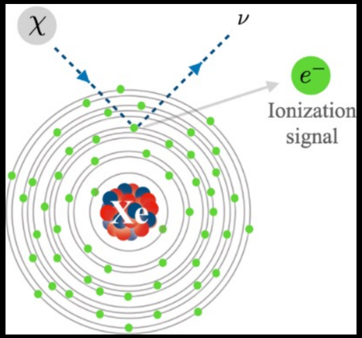
- **DM direct detections with noble liquid: huge experimental processes**
  - Significant WIMP parameters covered
  - Xe detectors reached “solar neutrino fog”
  - Many non-WIMP model spaces are being explored
- **Large noble liquid detectors very rich physics potentials (DM+neutrinos)**
  - Hopefully they do not take too long to build!

Backup

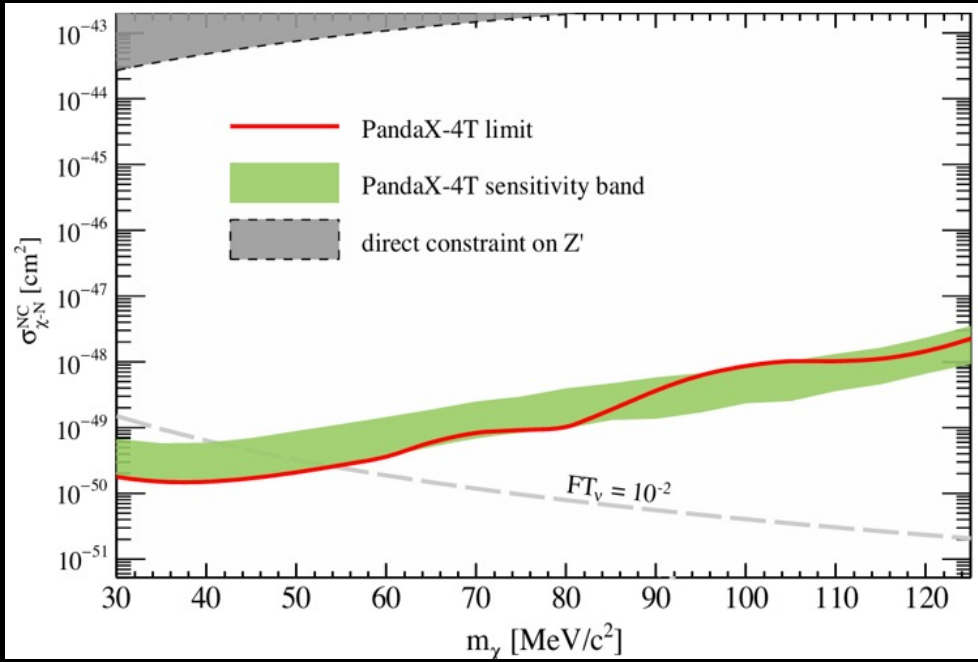
Low mass DM detection techniques with Noble Gas: example 3

Dark matter absorption on nucleus or electron

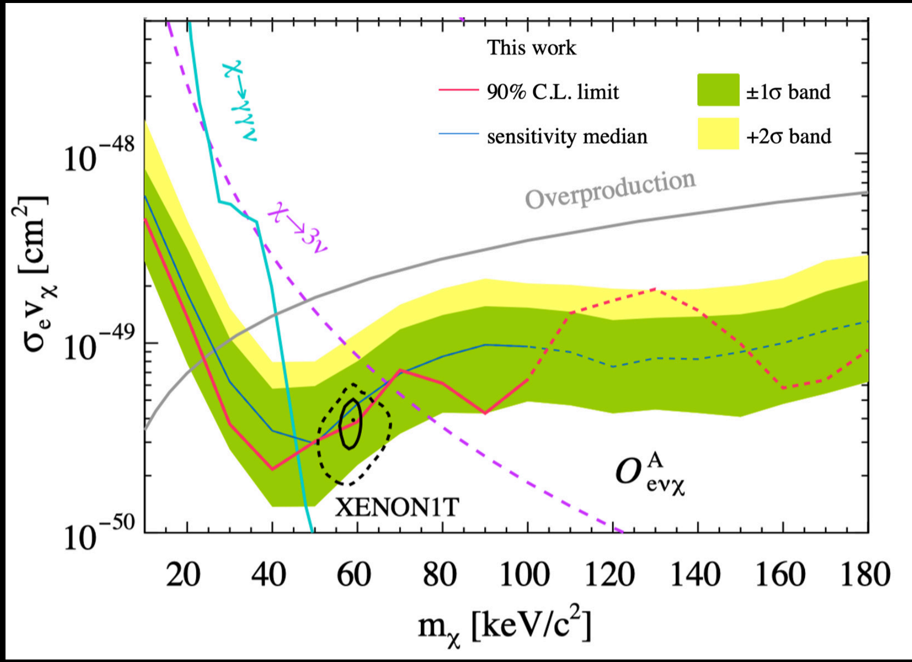




PRL 129, 161803 (2022)



PRL 129, 161804 (2022)



J. Dror, G. Elor, R. McGehee, *PRL 124, 181301 (2020)*
J. Dror, G. Elor, R. McGehee, T.-T. Yu, *PRD 103, 035001 (2021)*
S.-F. Ge, X.-G. He, X.-D. Ma, J. Sheng, *JHEP 05 (2022) 191*

Xe134

	^{134}Xe mass	^{136}Xe abundance	Analysis threshold	Live Time
PandaX-4T	68.7 kg	8.9%	200 keV	94.9 days
EXO-200	18.1 kg	81%	470 keV	600 days