



Noble liquid observatories for dark matter and astrophysical neutrinos

Ning Zhou (in place of Jianglai Liu)

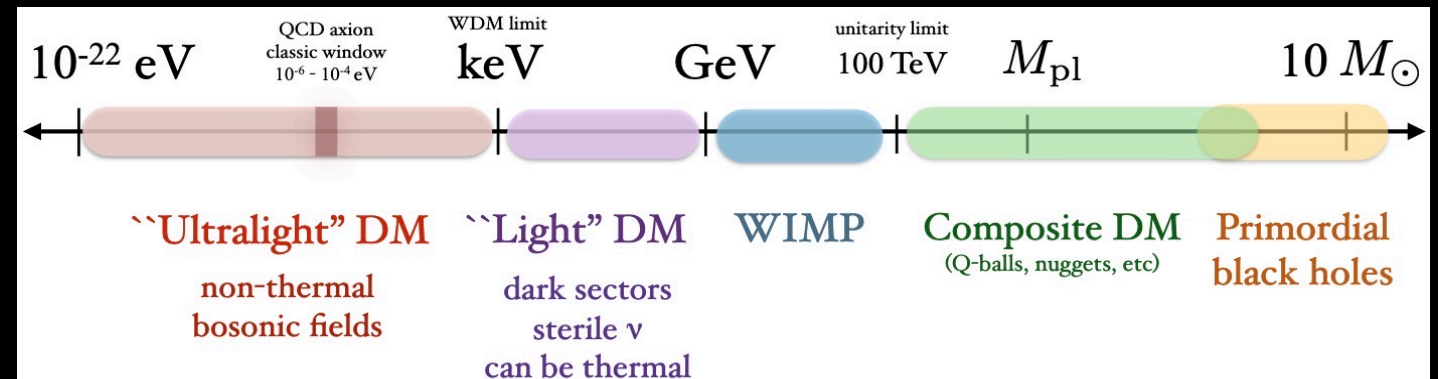
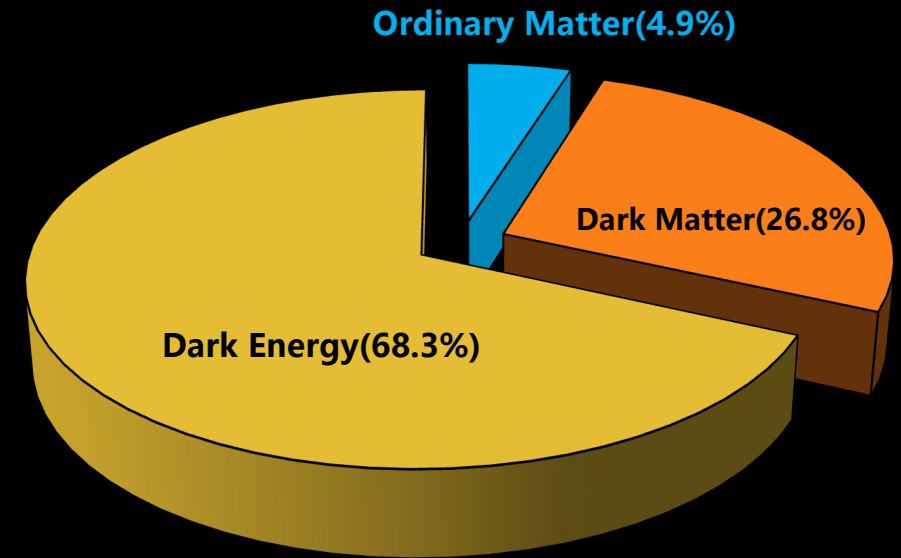
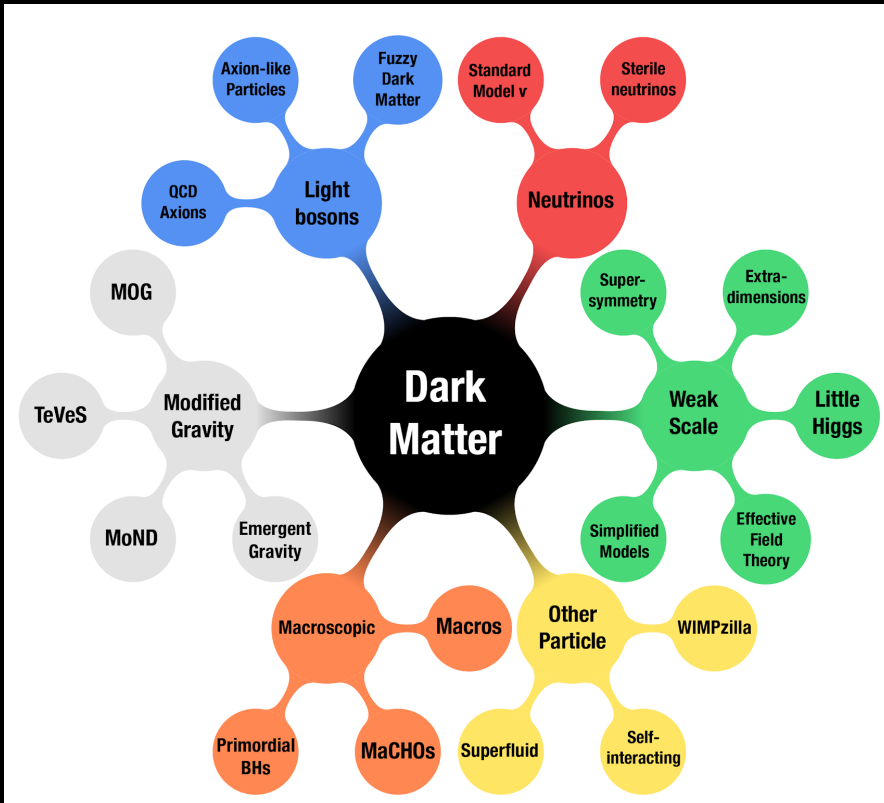
Shanghai Jiao Tong University

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.

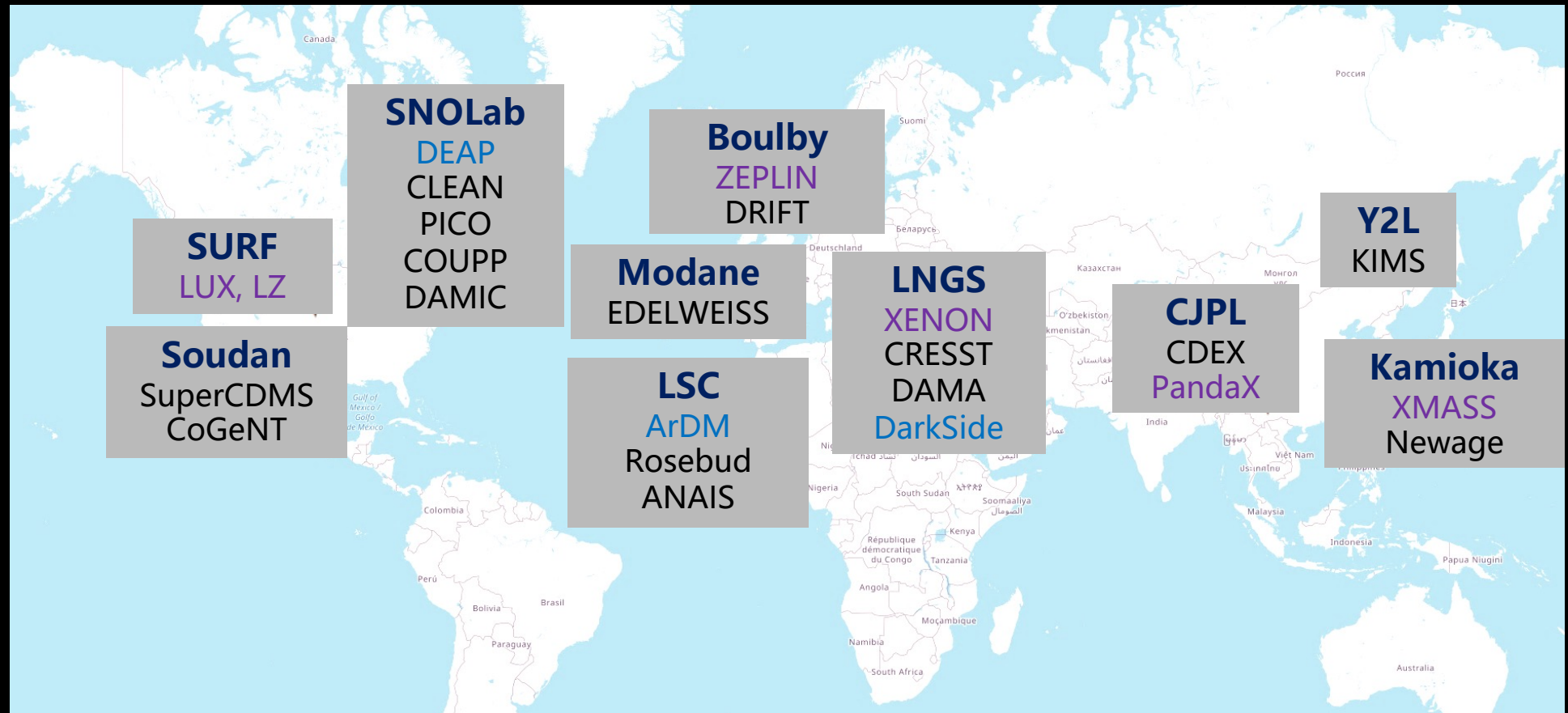
Dark Matter

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



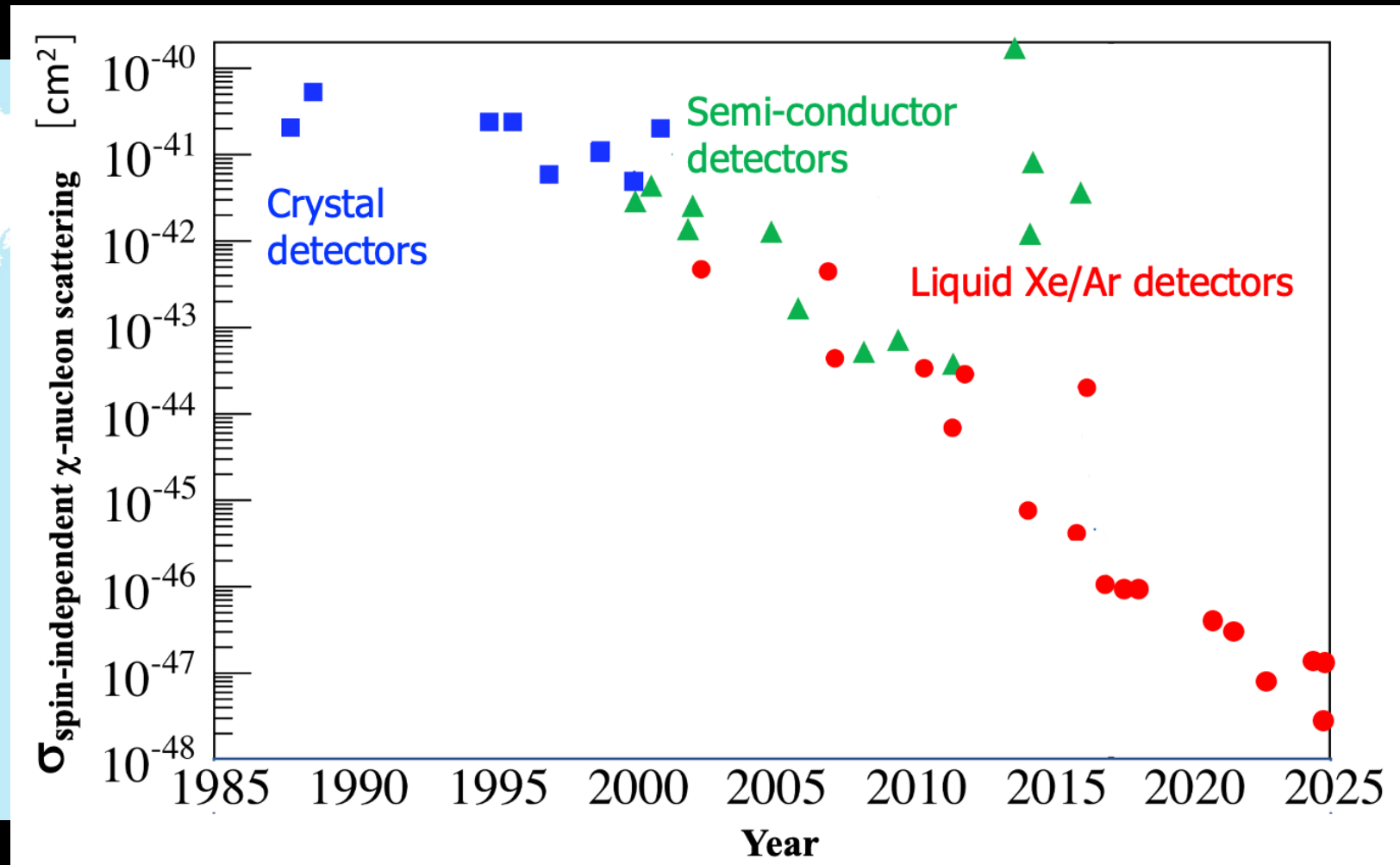
Underground Laboratories

- World-wide efforts at underground laboratories

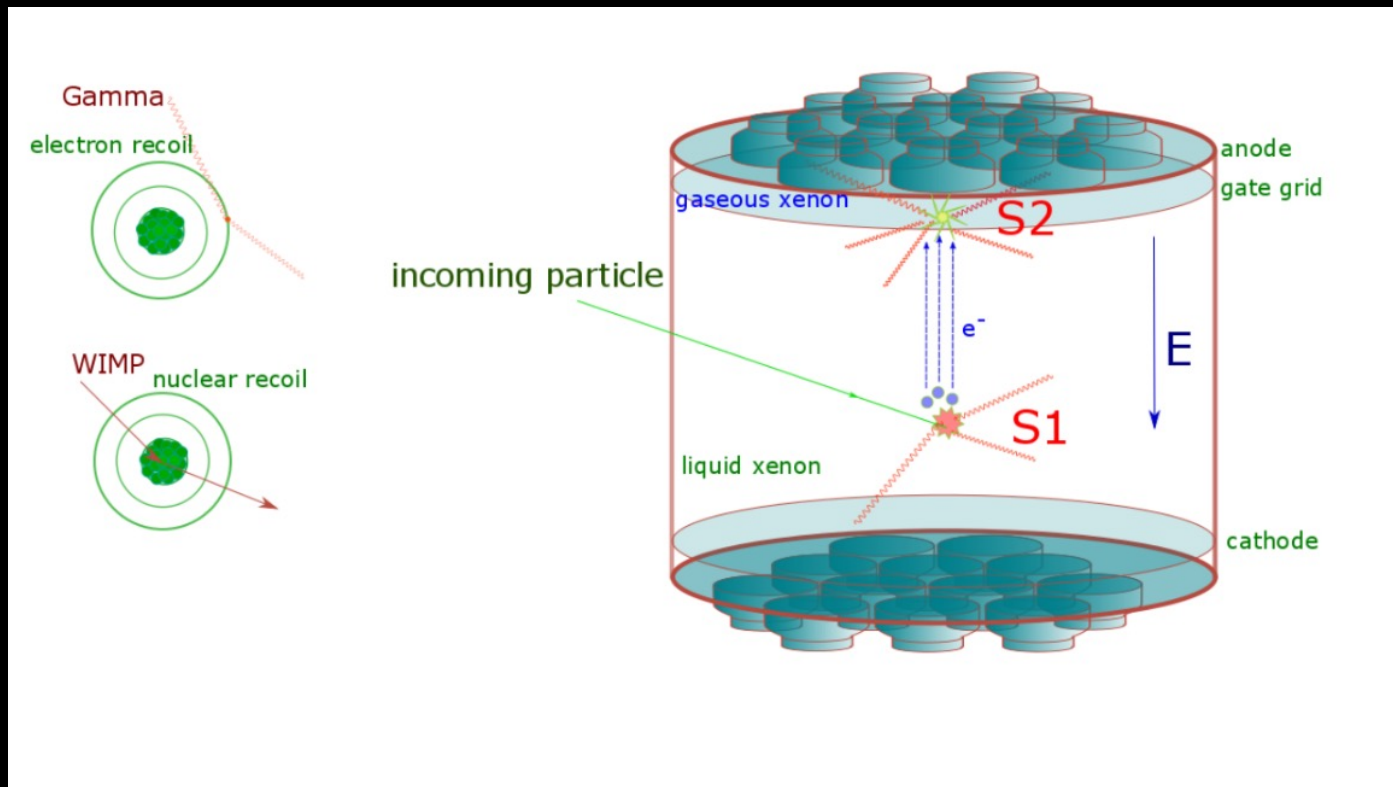


Underground Laboratories

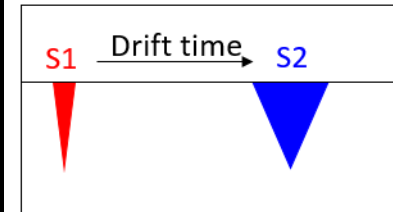
- World-wide efforts at underground laboratories



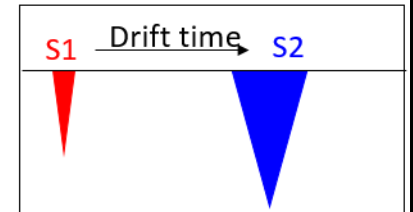
Nobel-liquid dual-phase time projection chamber



Dark matter: nuclear recoil (NR)

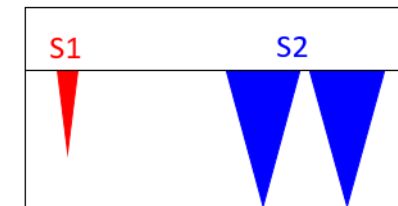


γ background: electron recoil (ER)



$$(S2/S1)_{NR} \ll (S2/S1)_{ER}$$

Multi-site scattering background (ER or NR)



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

Global Ar Collaboration

C. Galbiati, UCLA-DM 2025

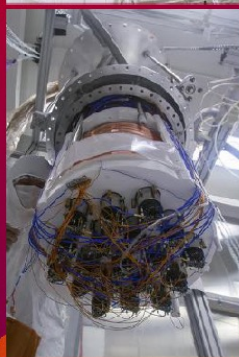
Since 2017

The Global Argon Dark Matter Collaboration (GADMC)

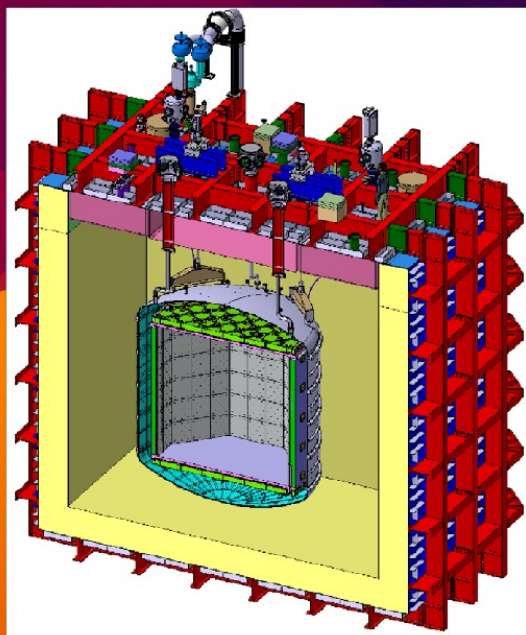
GADMC unified in a single Collaboration more than 400 scientists interested in DM searches with argon to explore heavy (and light) dark matter to the neutrino floor and beyond



DEAP-3600



DarkSide-50



DarkSide-20k => ARGO

MiniCLEAN



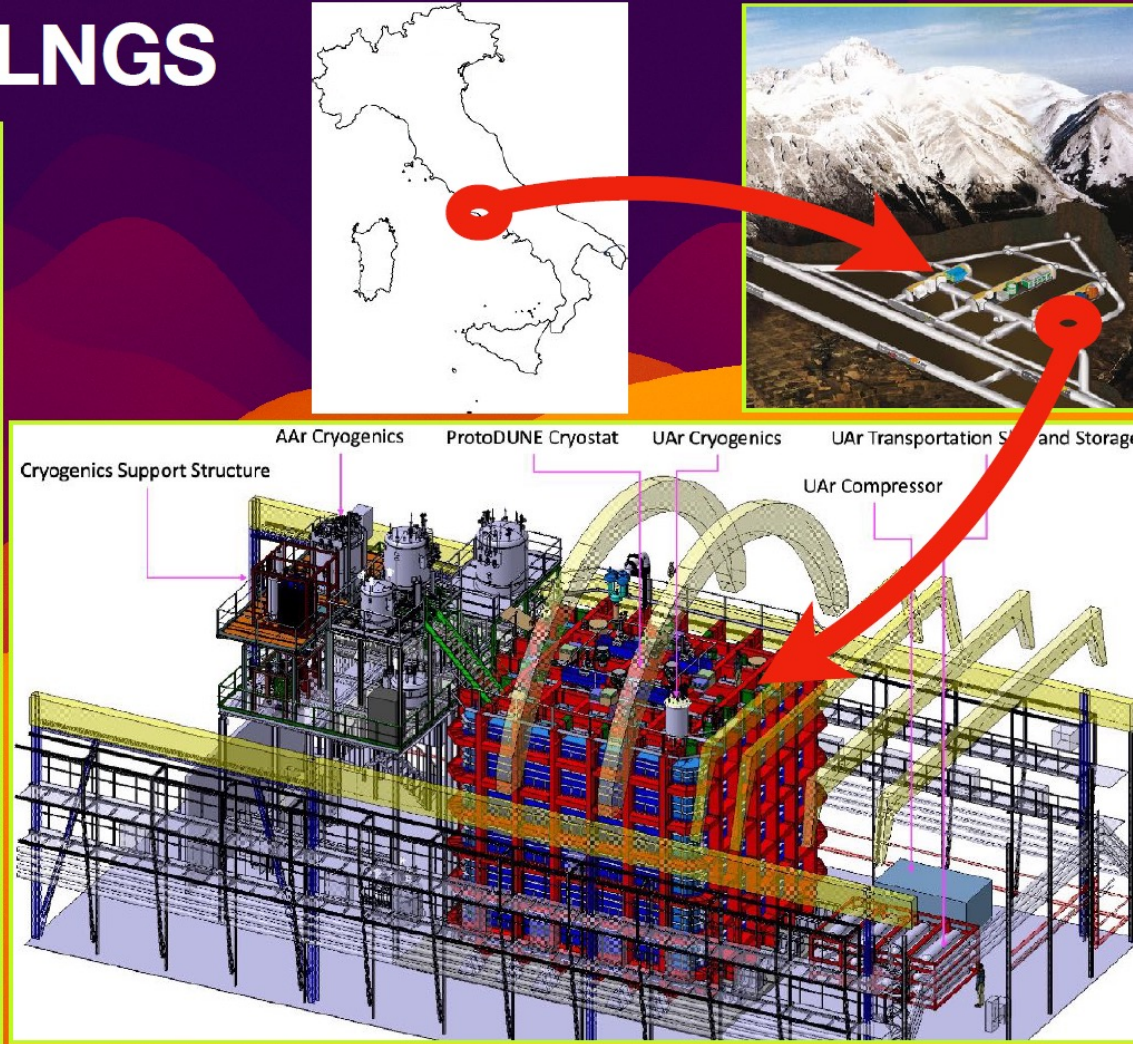
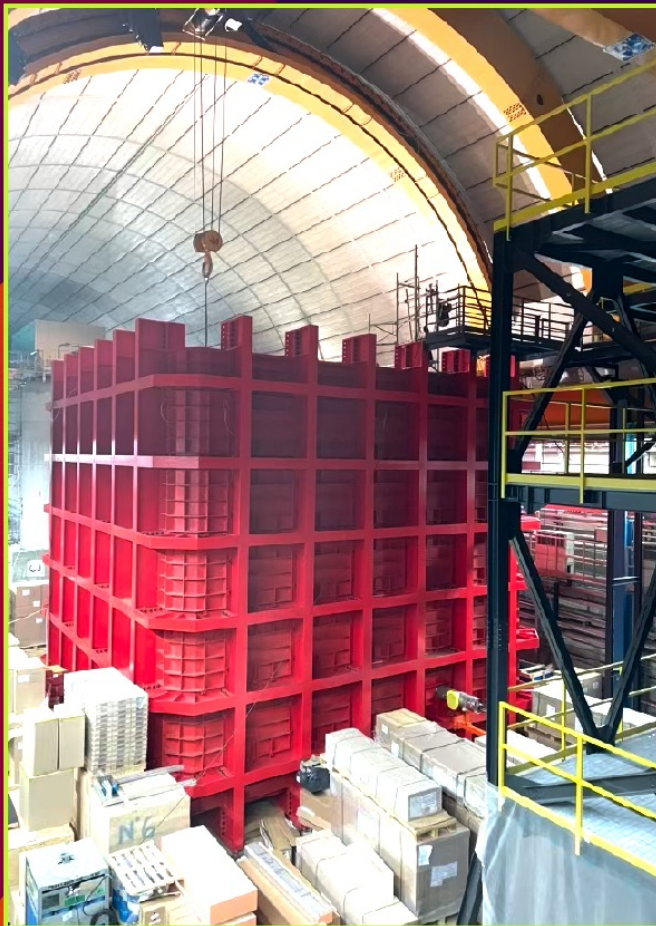
ARDM



Progress of DS-20K @ LNGS

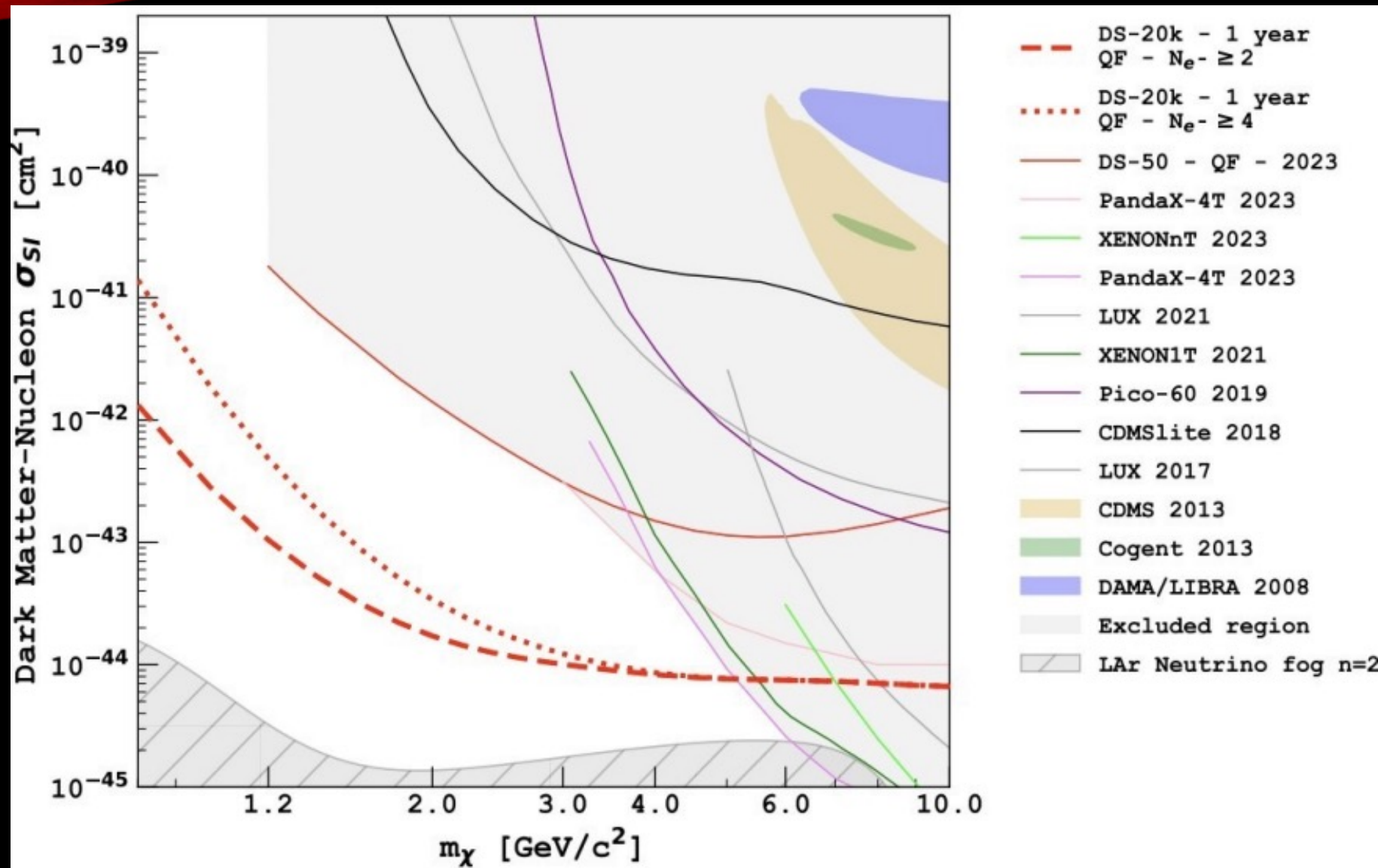
C. Galbiati, UCLA-DM 2025

DarkSide-20k at LNGS



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)!

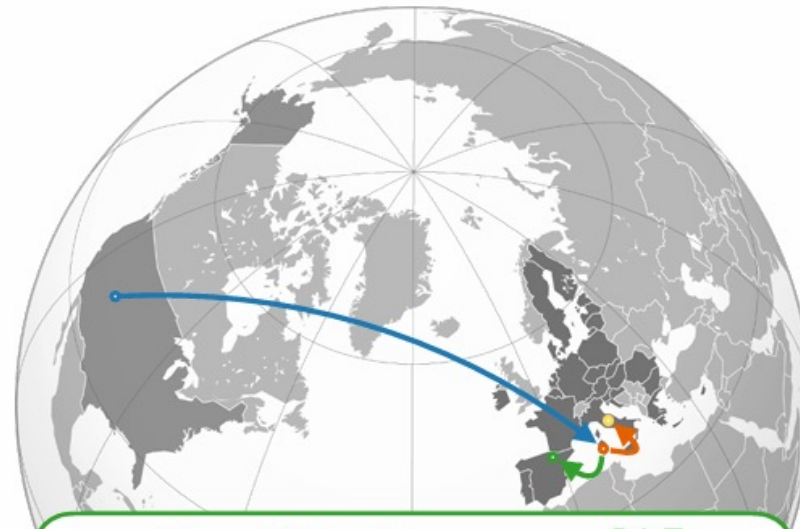
- C. Galbiati, UCLA-DM 2025



Production

URANIA Site
Cortez, CO, US

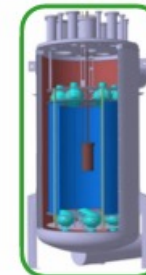
- Industrial-scale extraction plant
- Extraction rate of (250 – 330) kg/day
- Production capability of ≈ 120 t over two years for Darkside
- UAr purity of 99.99 %



Qualification

DArT
Canfranc, Spain

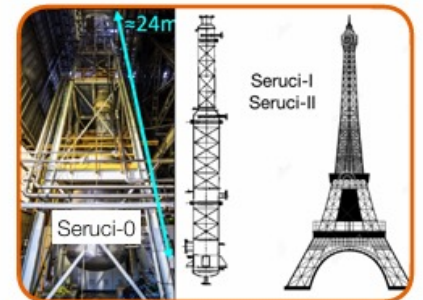
- Single-phase detector to measure ^{39}Ar depletion factor
- Sensitive to ^{39}Ar down to a reduction factor of 1400 with 7% accuracy
<https://doi.org/10.1088/1748-0221/15/02/P02024>
- DArT soon to be installed inside ArDM



Purification

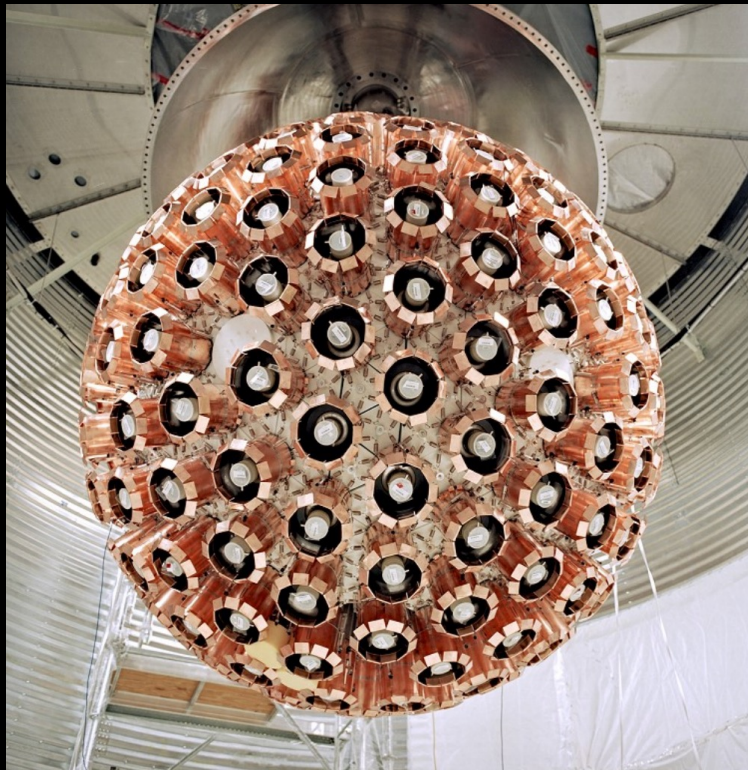
ARIA Site
Sardinia, Italy

- Seruci-0 demonstrator tested
- 350 m long cryogenic distillation column
- $\mathcal{O}(1 \text{ tonne/day})$ purification throughput
- Resulting UAr purity of 99.999 %
<https://doi.org/10.1140/epjc/s10052-021-09121-9>
<https://arxiv.org/abs/2301.09639>



DEAP3600 upgrade

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



DEAP-3600: Completed Hardware Upgrades Installation at SNOLAB (March 2020 to December 2024)

Started commissioning for cooldown Feb 2025; summer 2025 data collection;
New configuration targets background-free exposure with LAr (mitigates degraded α 's)

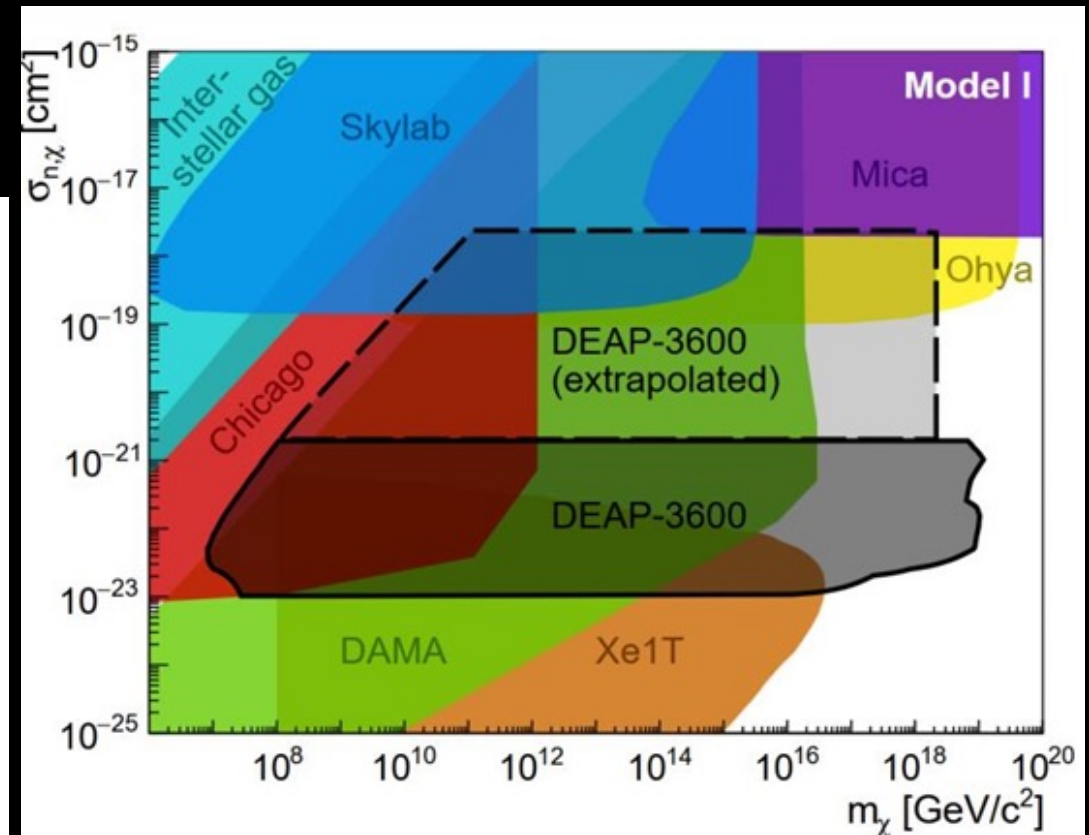
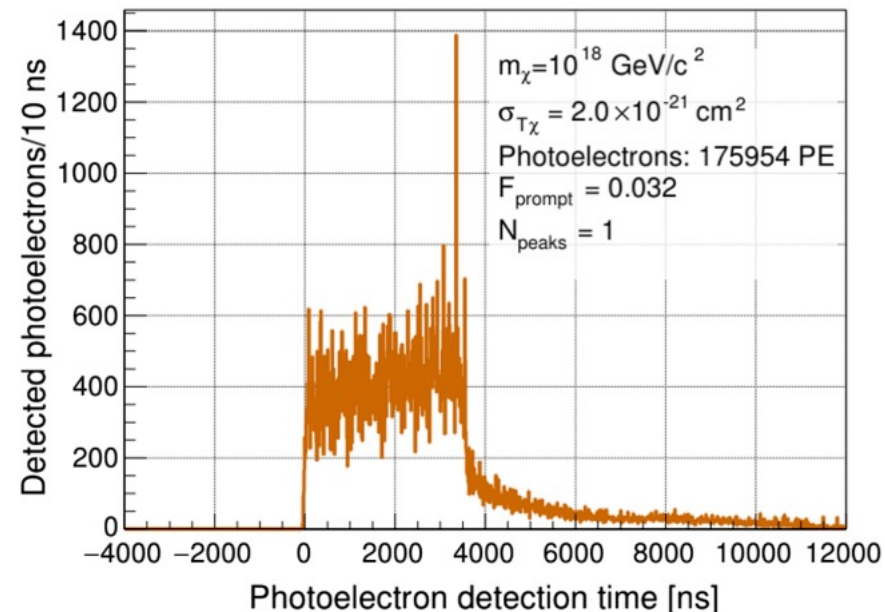
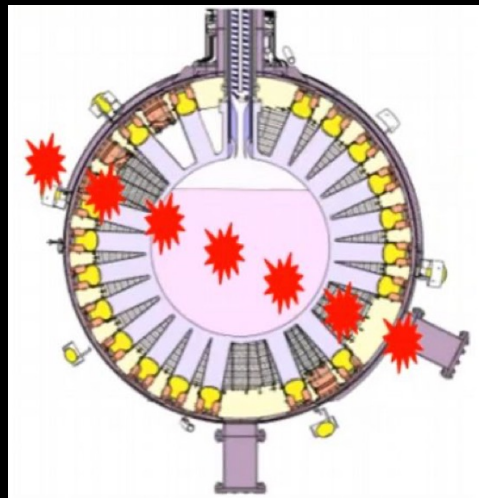


More in talk from
S. Westerdale

Very heavy (Planck-scale) DM

Signature: multi-scattering and straight track

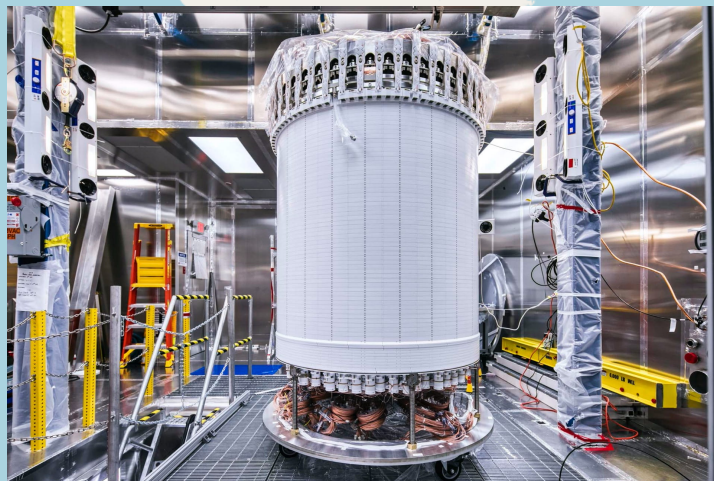
PRL 128, 011801 (2022)



Unique advantage of large monolithic noble liquid DM detector See talk by M. Olszewski 11

Liquid xenon experiments

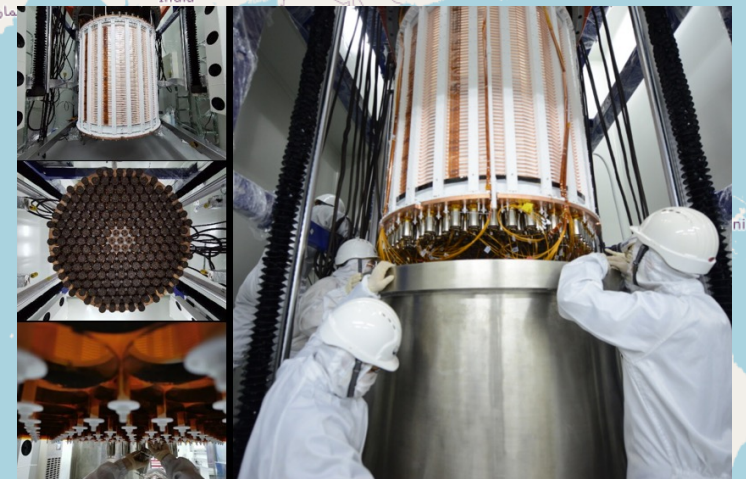
Sanford Lab, LZ, 7 ton



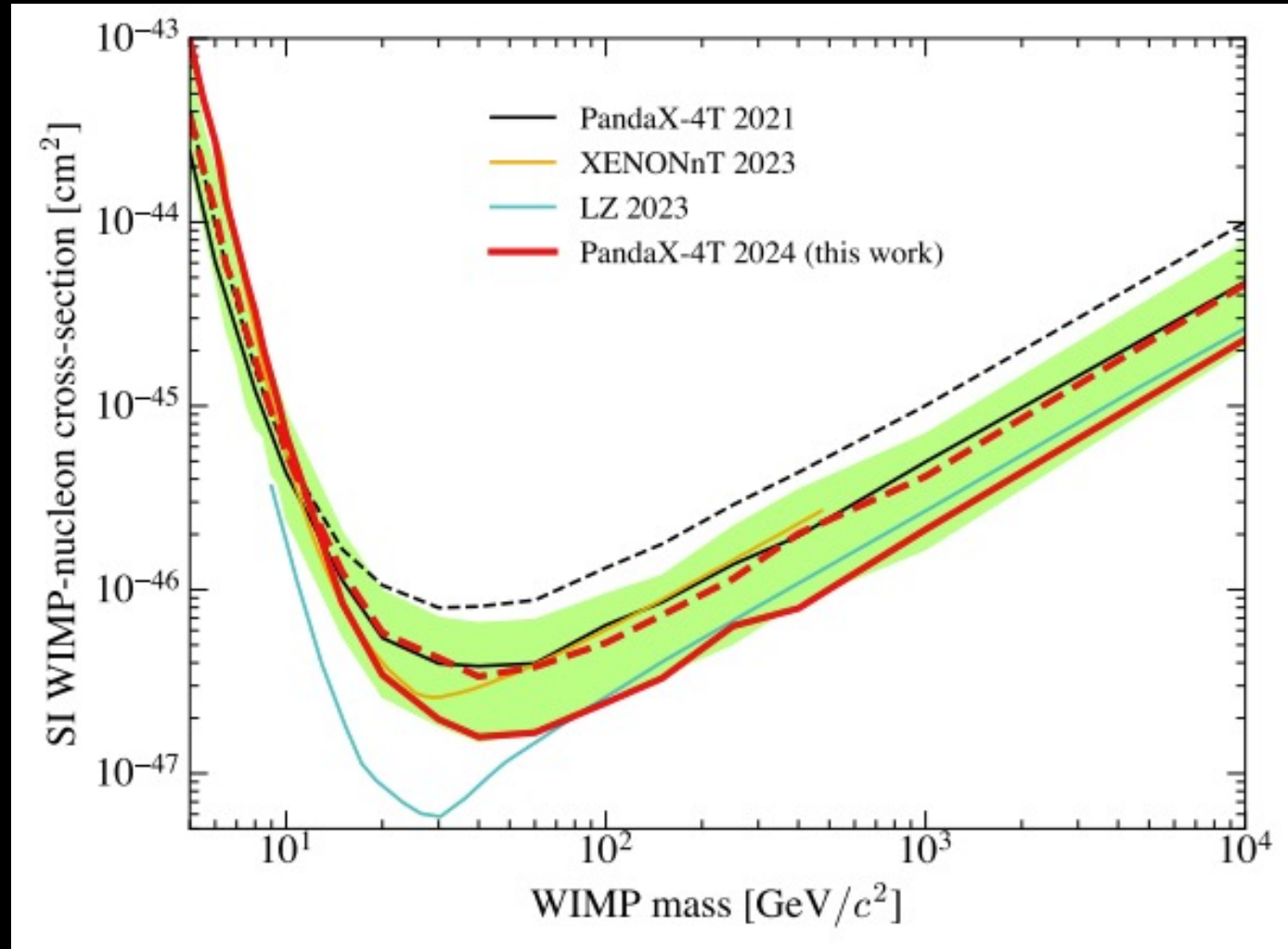
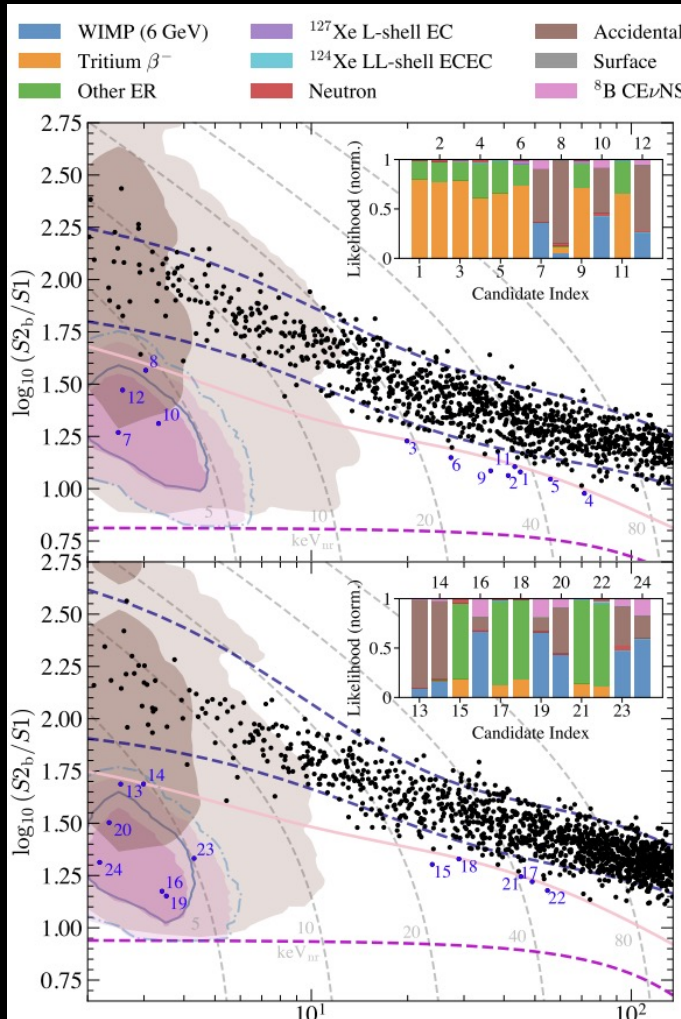
LNGS, XENONnT, 6.5 ton



CJPL, PandaX-4T, 3.7 ton

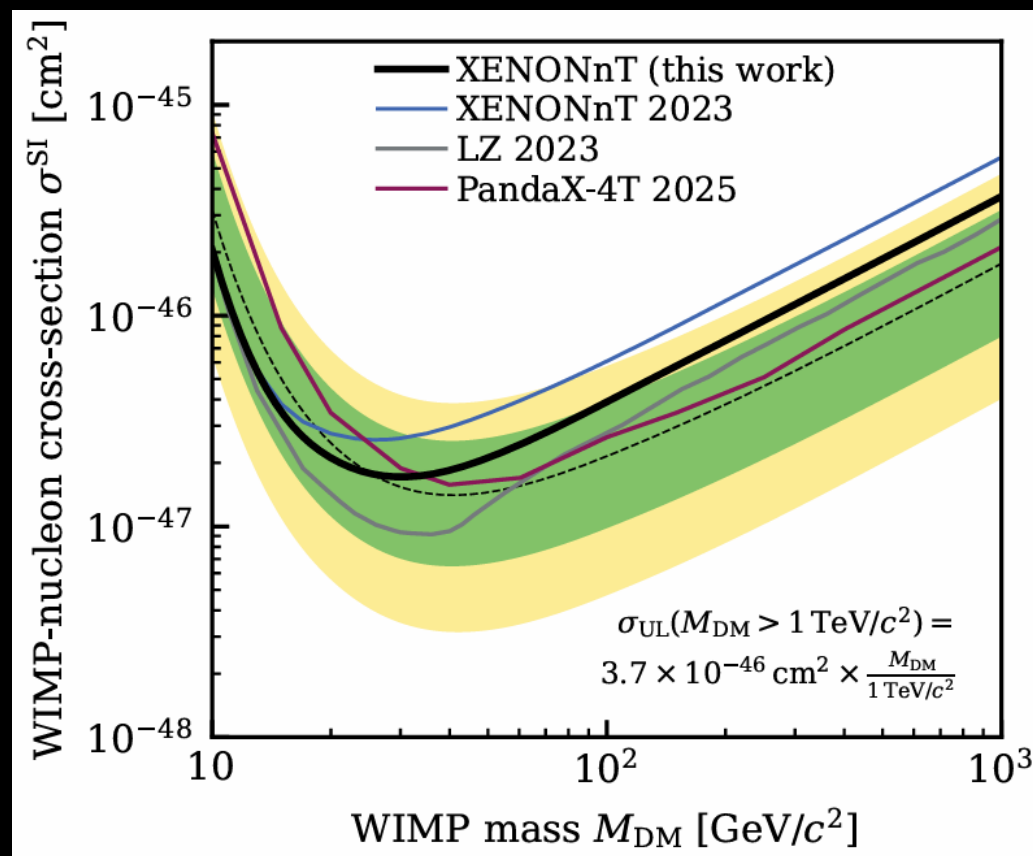
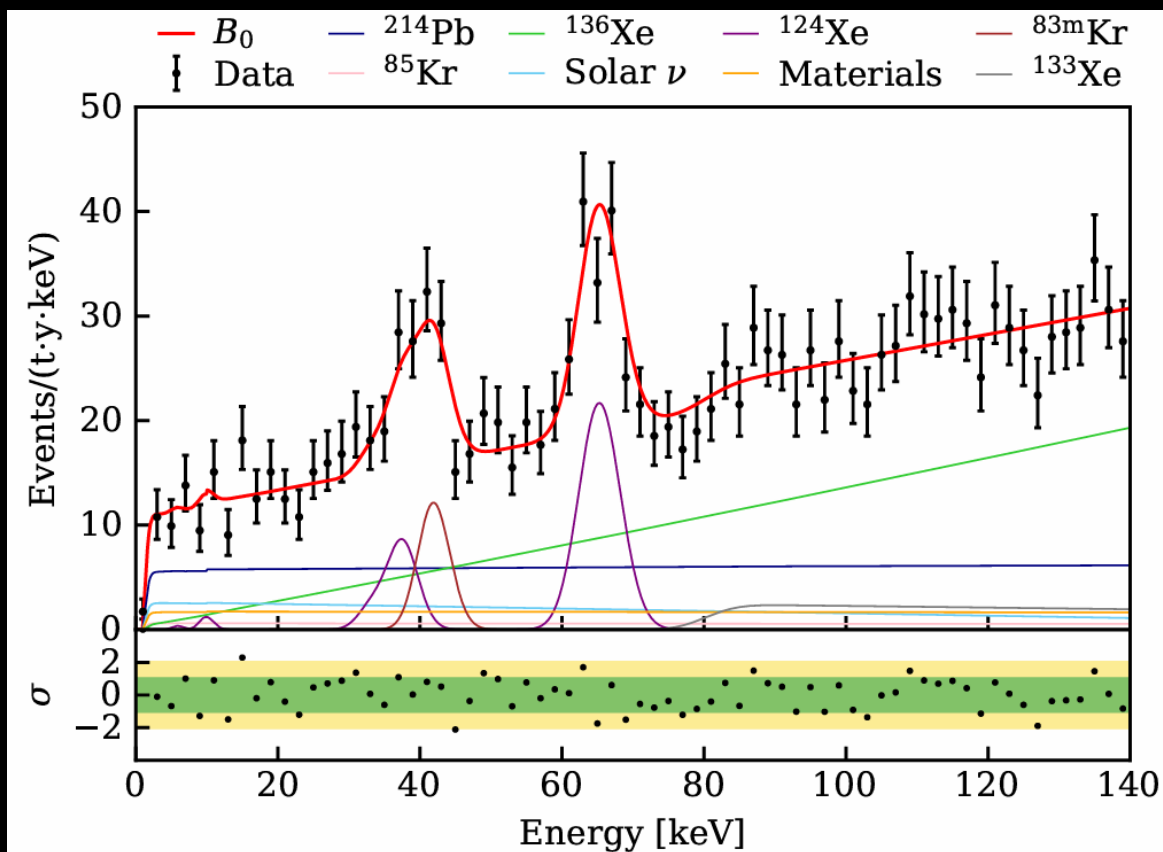


PandaX-4T, 1.5 tonne*year blinded analysis, Run0+1



PRL 134, 011805 (2025), arXiv:2408.00664

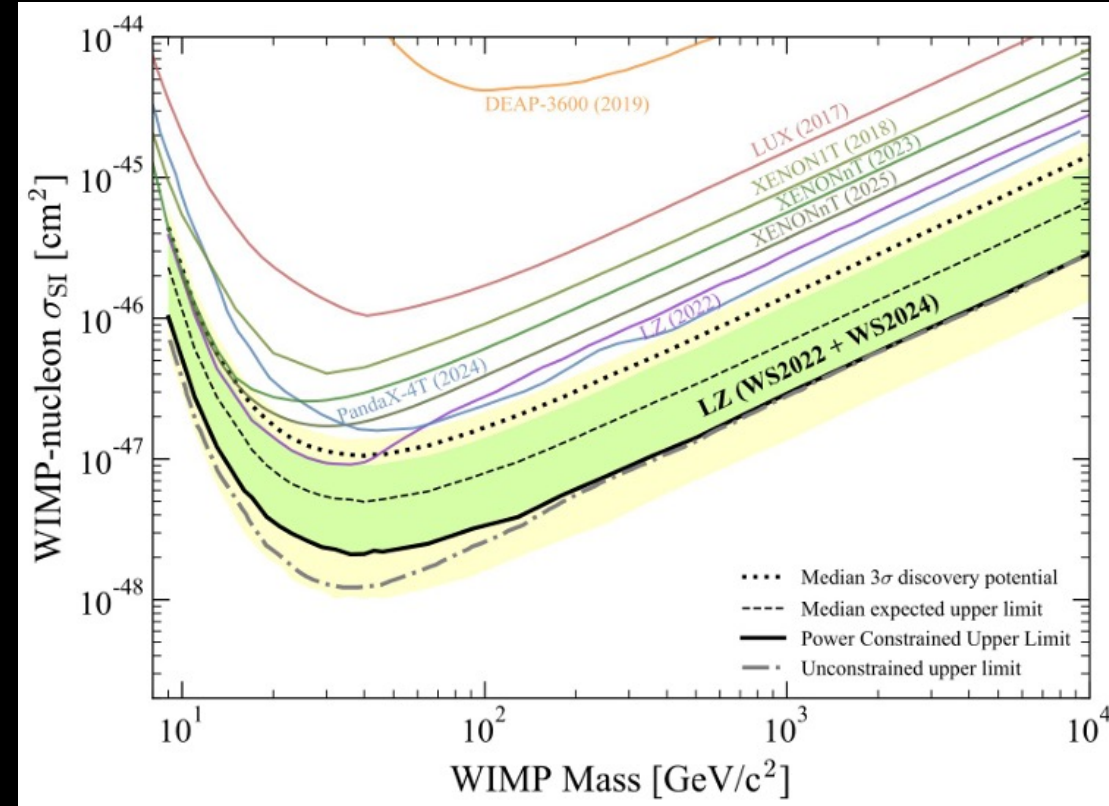
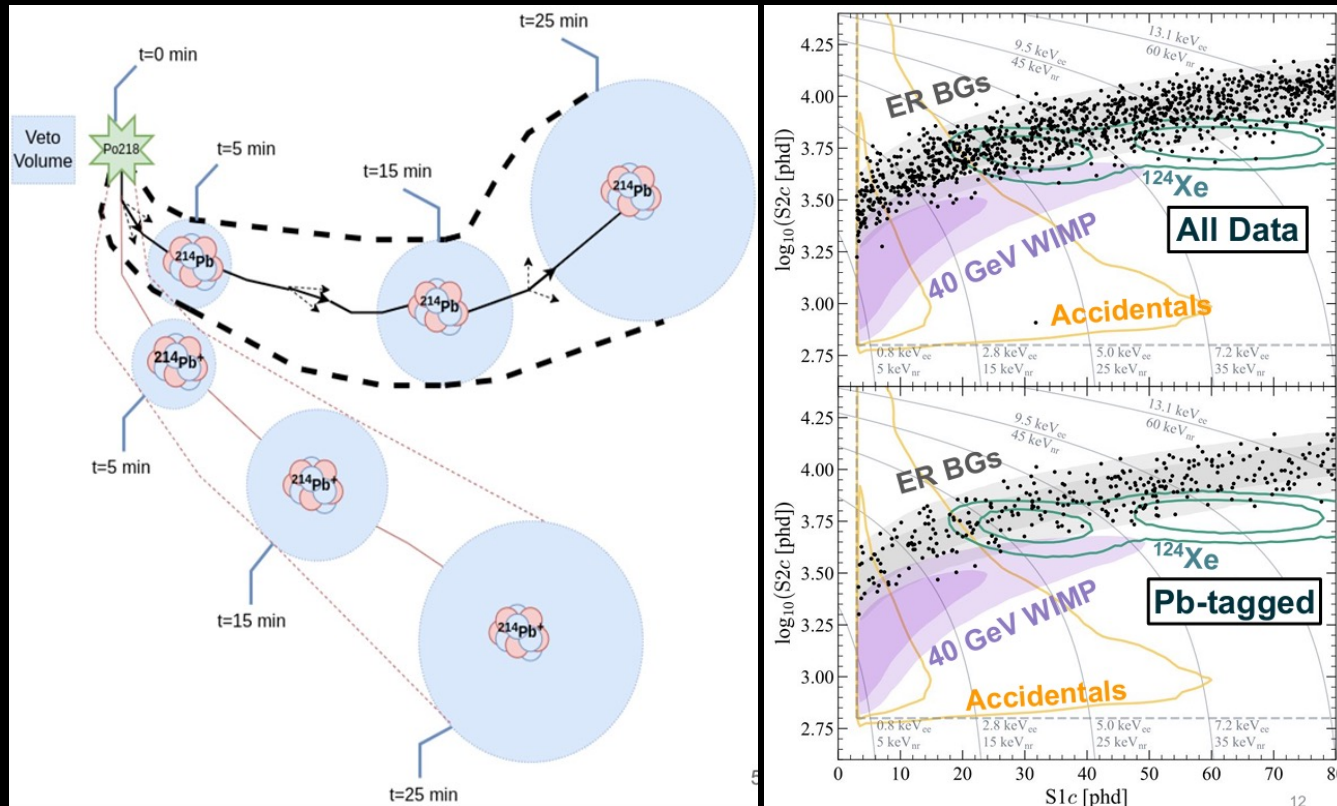
XENONnT: 3.1 tonne*year



- Record-low ER background: *PRL* 129, 161805 (2022), *arXiv:2207.11330*
- Rn distillation removal: $<1 \mu\text{Bq/kg}$, *2502.04209*

New result: *2502.18005*, 3.1 tonne*year
See Maxime Pierre's talk

LZ 4.2 tonne*year

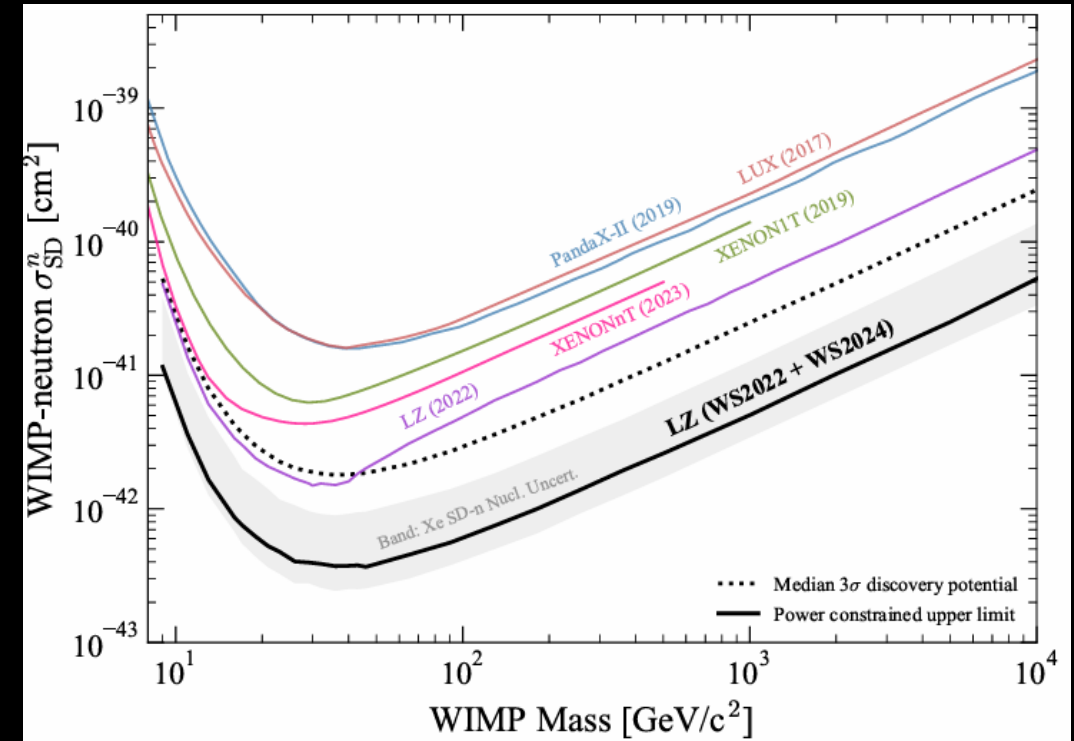
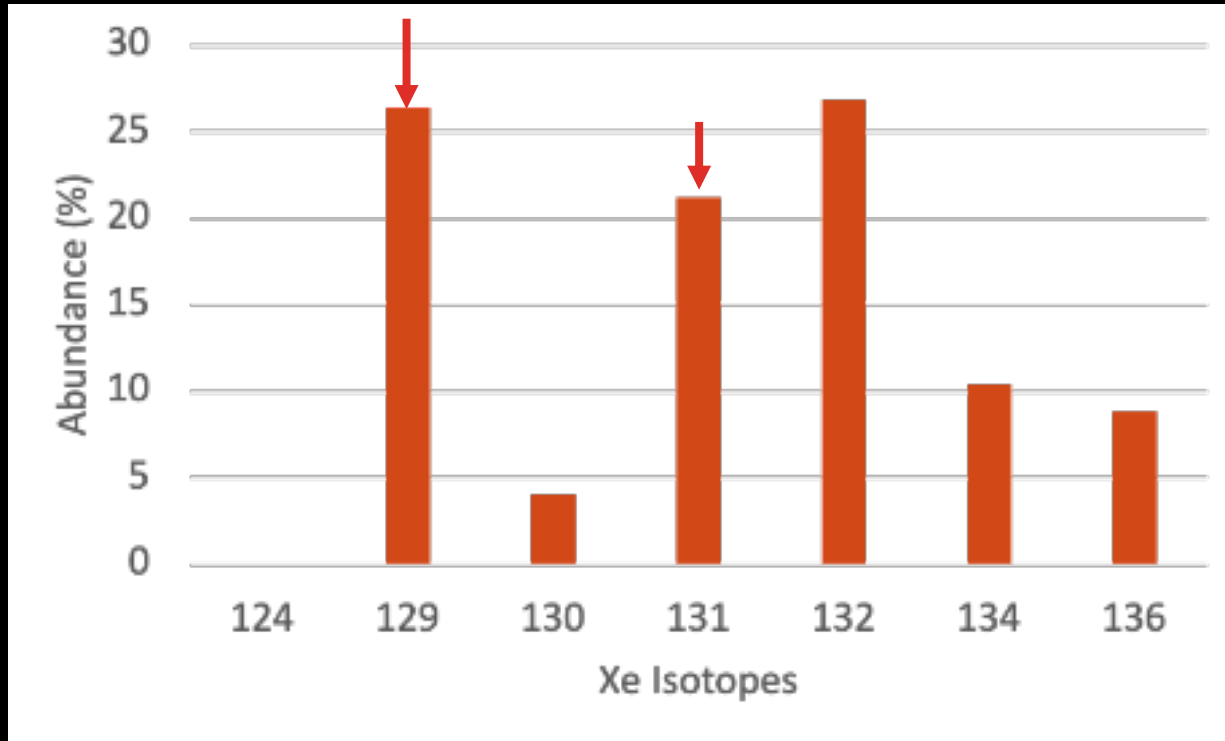


- Tag radon daughter ^{214}Pb via ^{218}Po - ^{214}Pb ($t_{1/2} = 27$ min)
- Untagged Rn rate: 1.8 $\mu\text{Bq/kg}$

- Latest results: [arXiv:2410.17036](https://arxiv.org/abs/2410.17036), *PRL* **135**, 011802 (2025)
- Leading DM exclusion

See talk by Amy Cottle

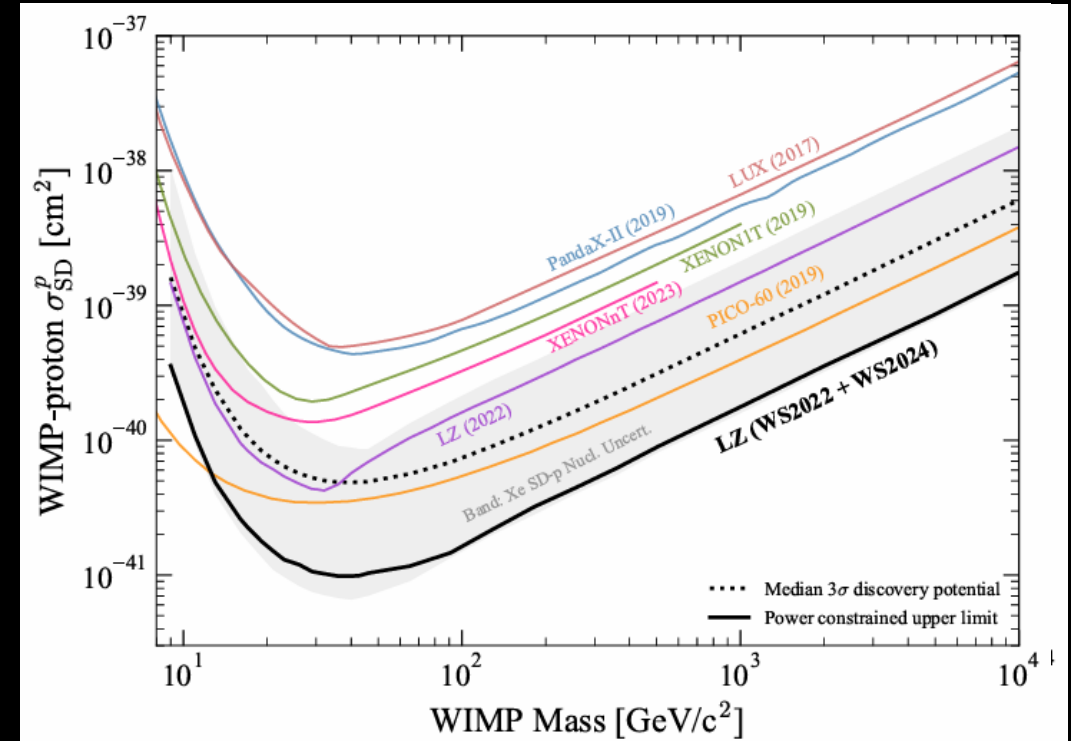
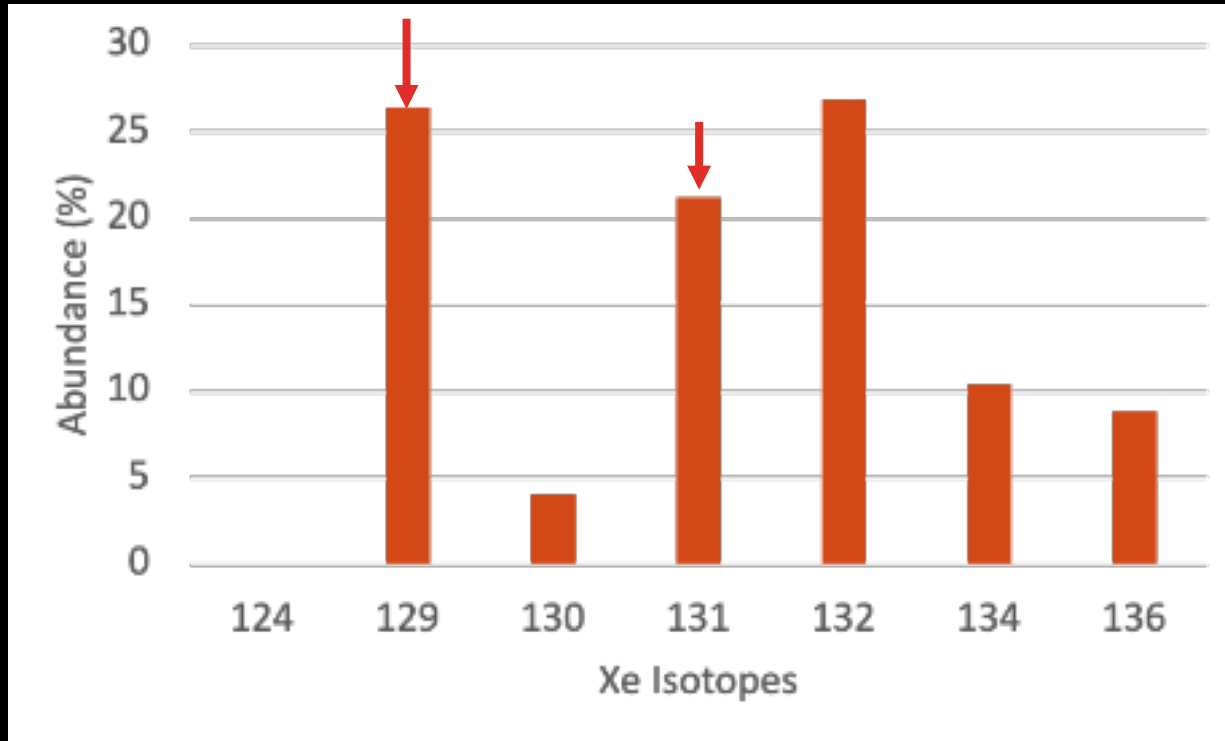
Spin-dependent interactions



LZ 4.2 tonne*year, [arXiv:2410.17036](https://arxiv.org/abs/2410.17036),
PRL 135, 011802 (2025)

See talk by Amy Cottle

Spin-dependent interactions



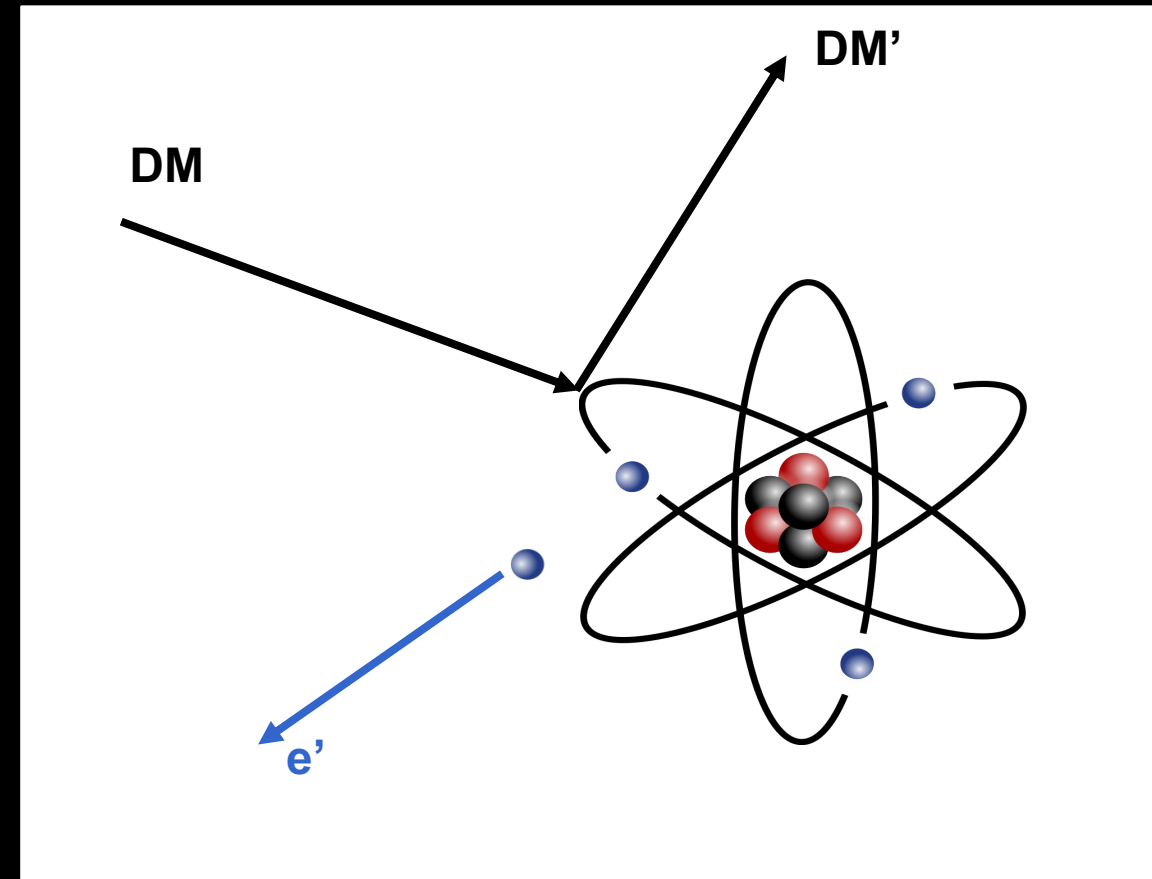
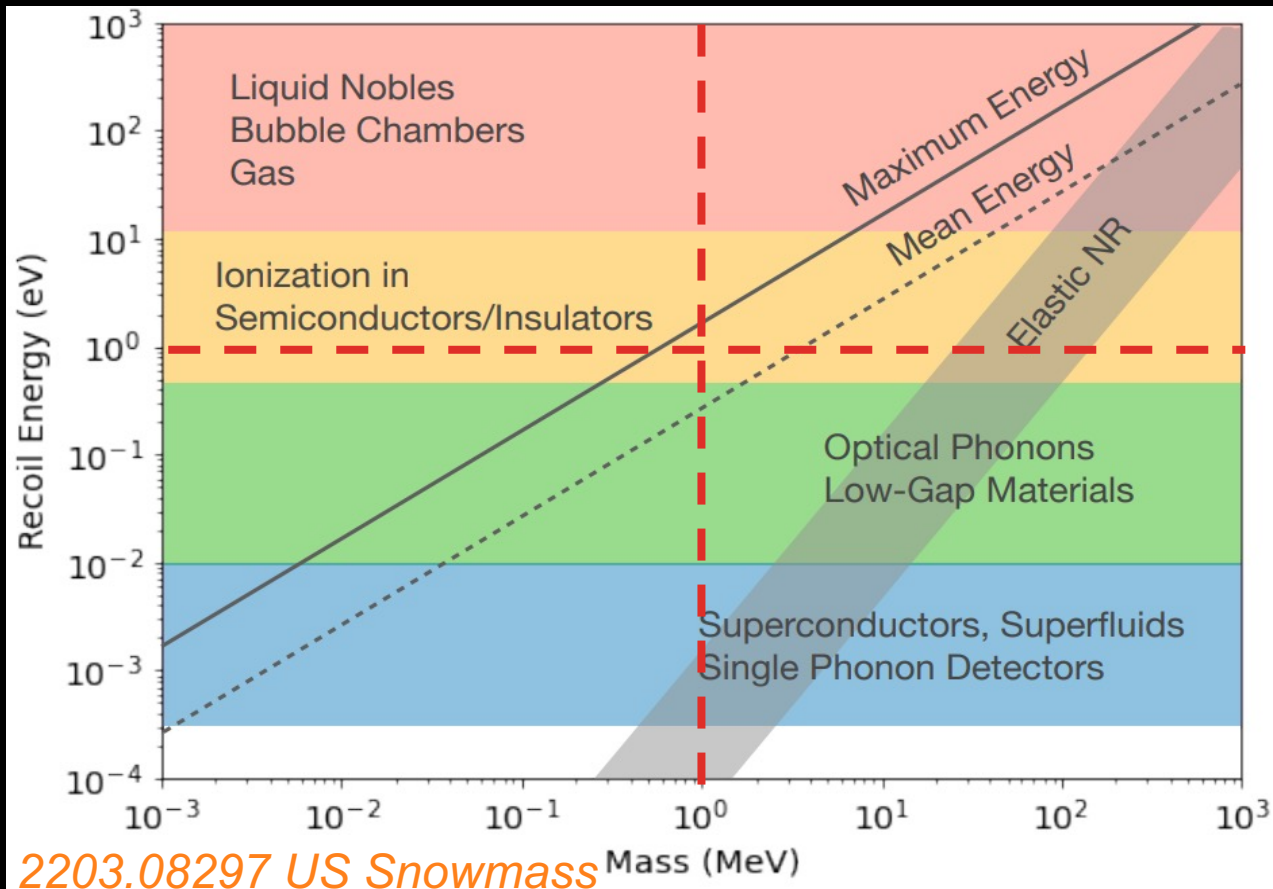
LZ 4.2 tonne*year, [arXiv:2410.17036](https://arxiv.org/abs/2410.17036),
PRL 135, 011802 (2025)

See talk by Amy Cottle

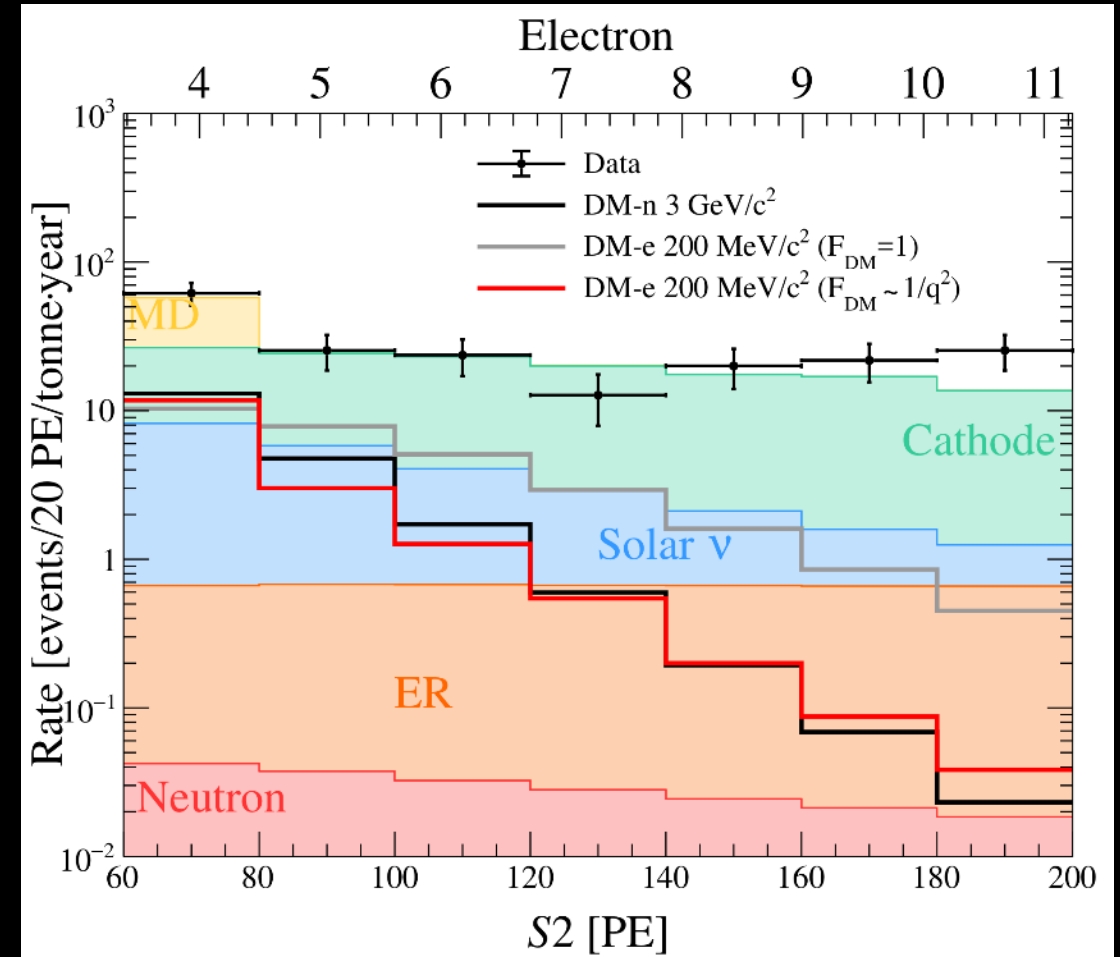
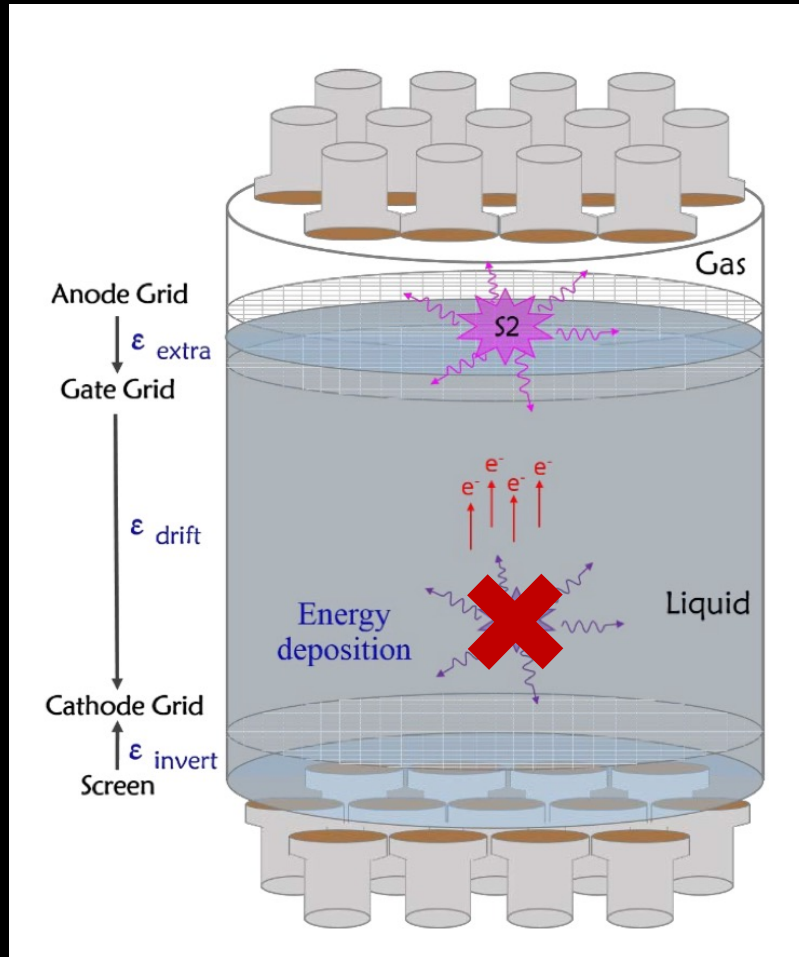
Low mass DM detection techniques with Noble Gas: example 1

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

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

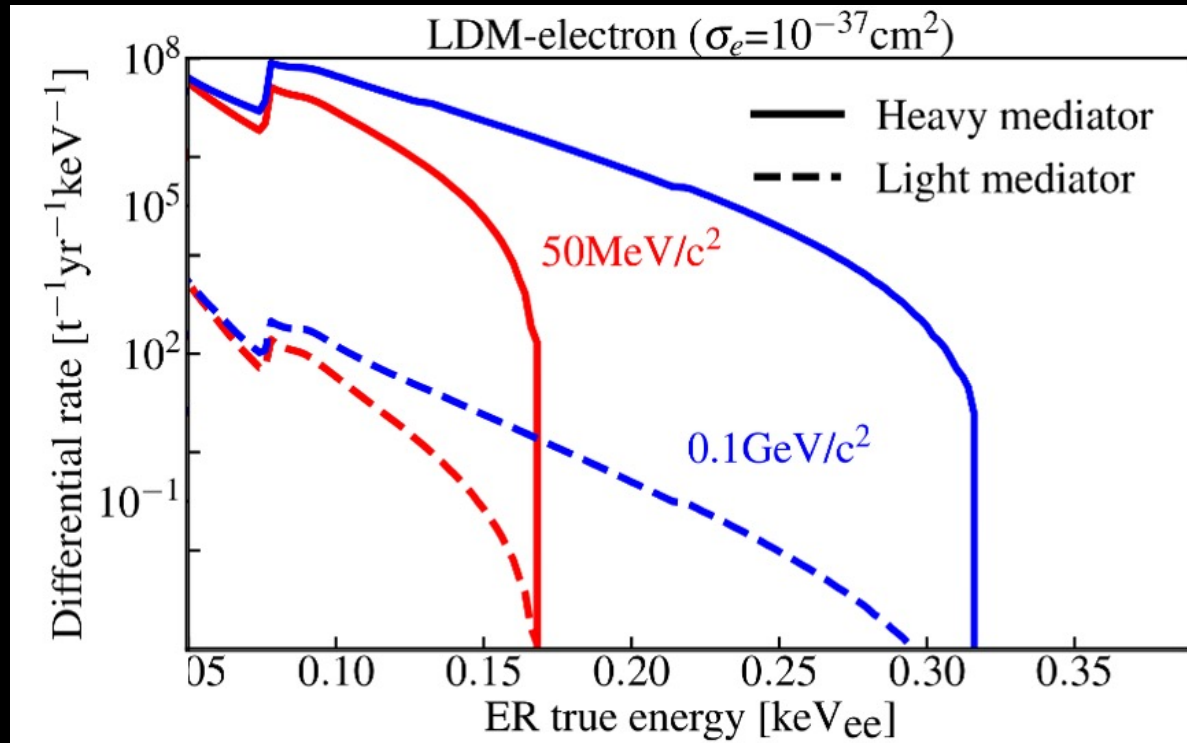


Accessing light DM: S2-only



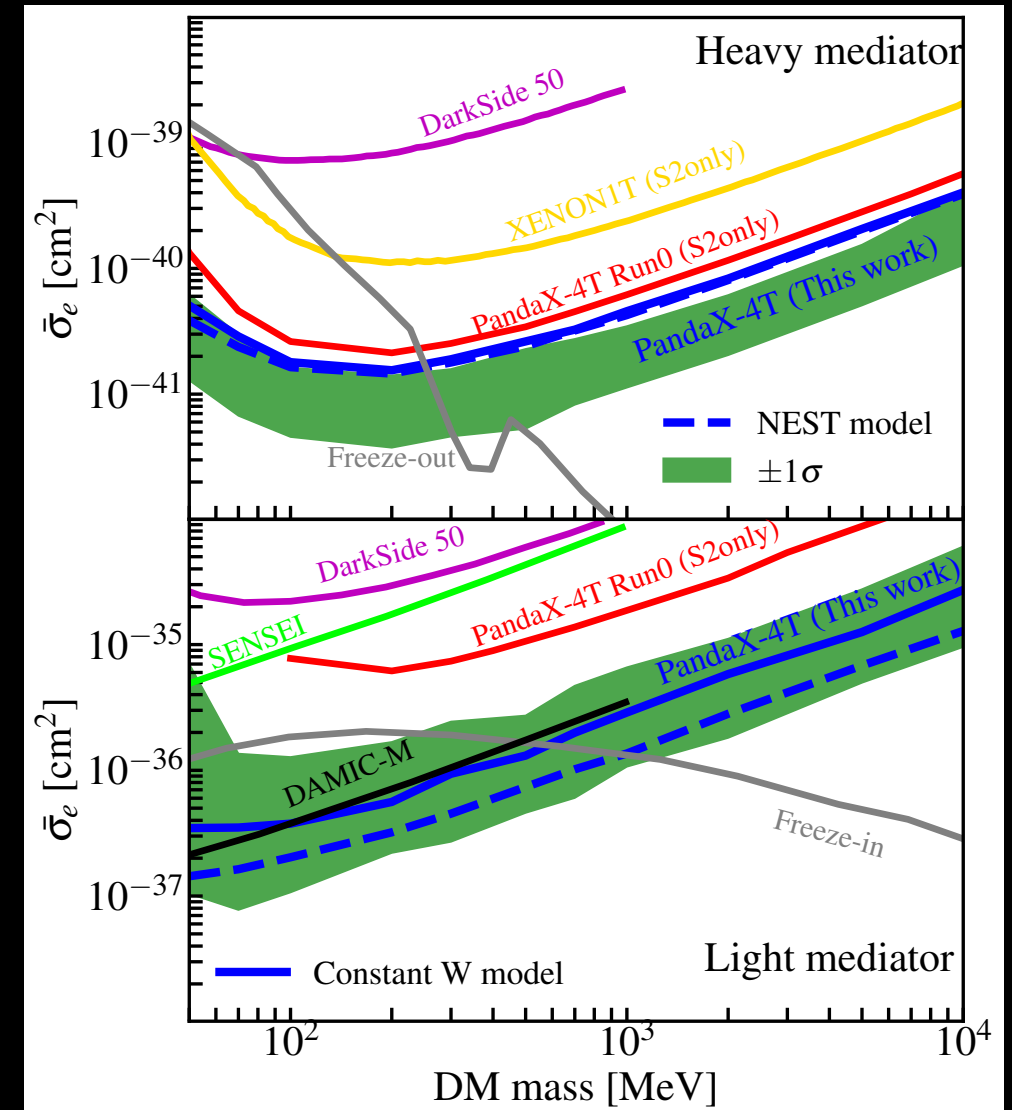
PandaX-4T, PRL 130, 261001 (2023)

Tight limits on light DM



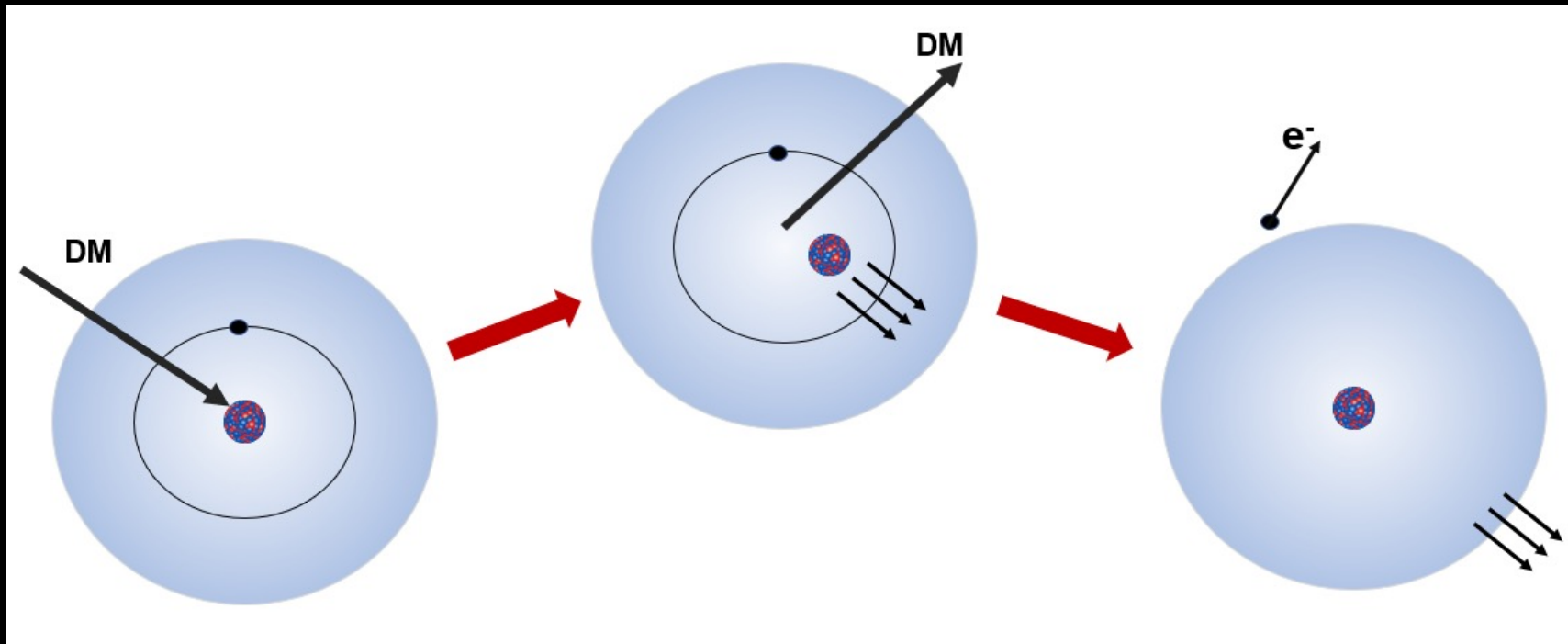
[arXiv:2507.11930](https://arxiv.org/abs/2507.11930)

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



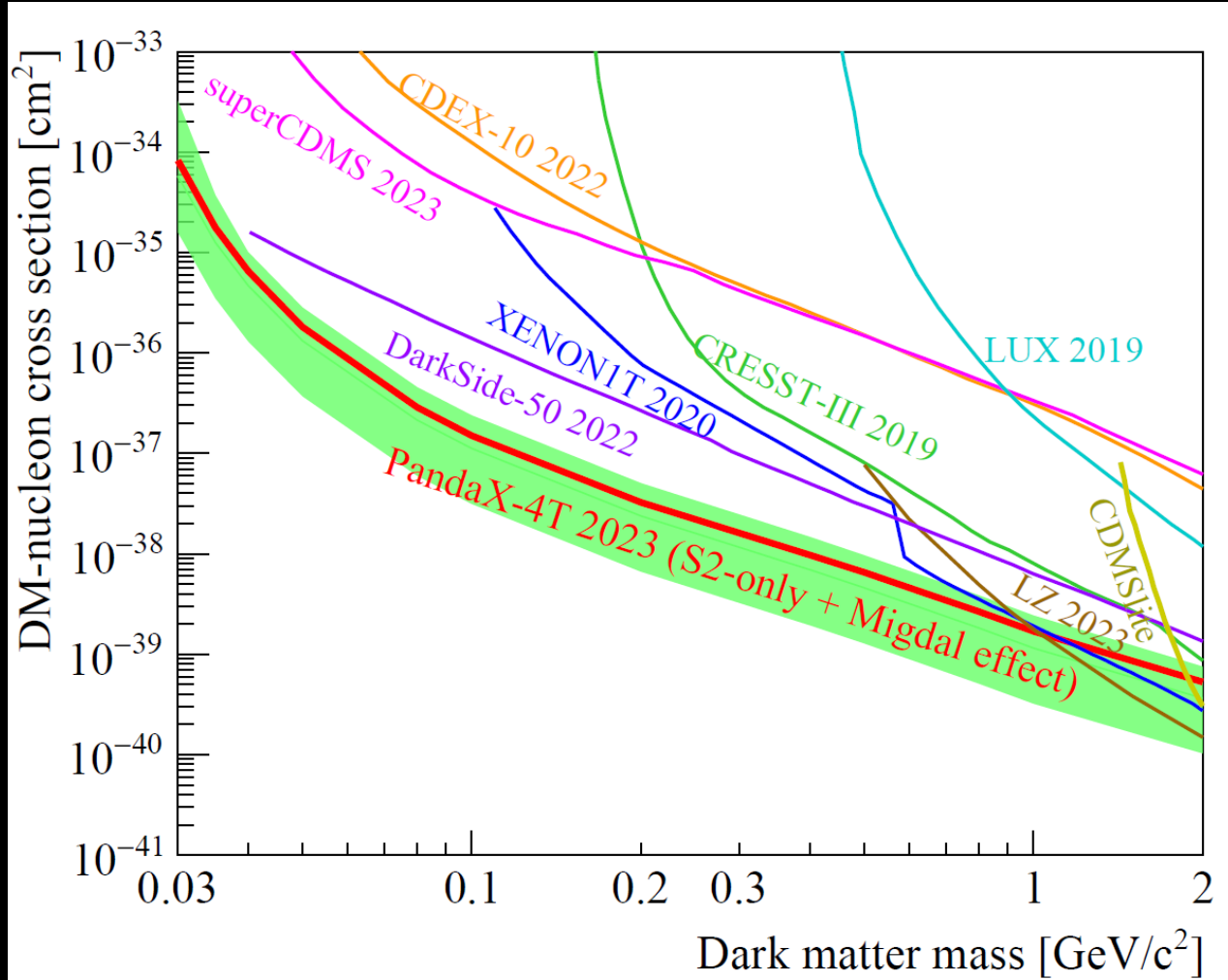
Low mass DM detection techniques with Noble Gas: example 2

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 Migdal-induced ionization probability are closely related, *Essig, Pradler, Sholapurkar, and Yu, PRL 124, 021801 (2020)*

S2-only + Migdal



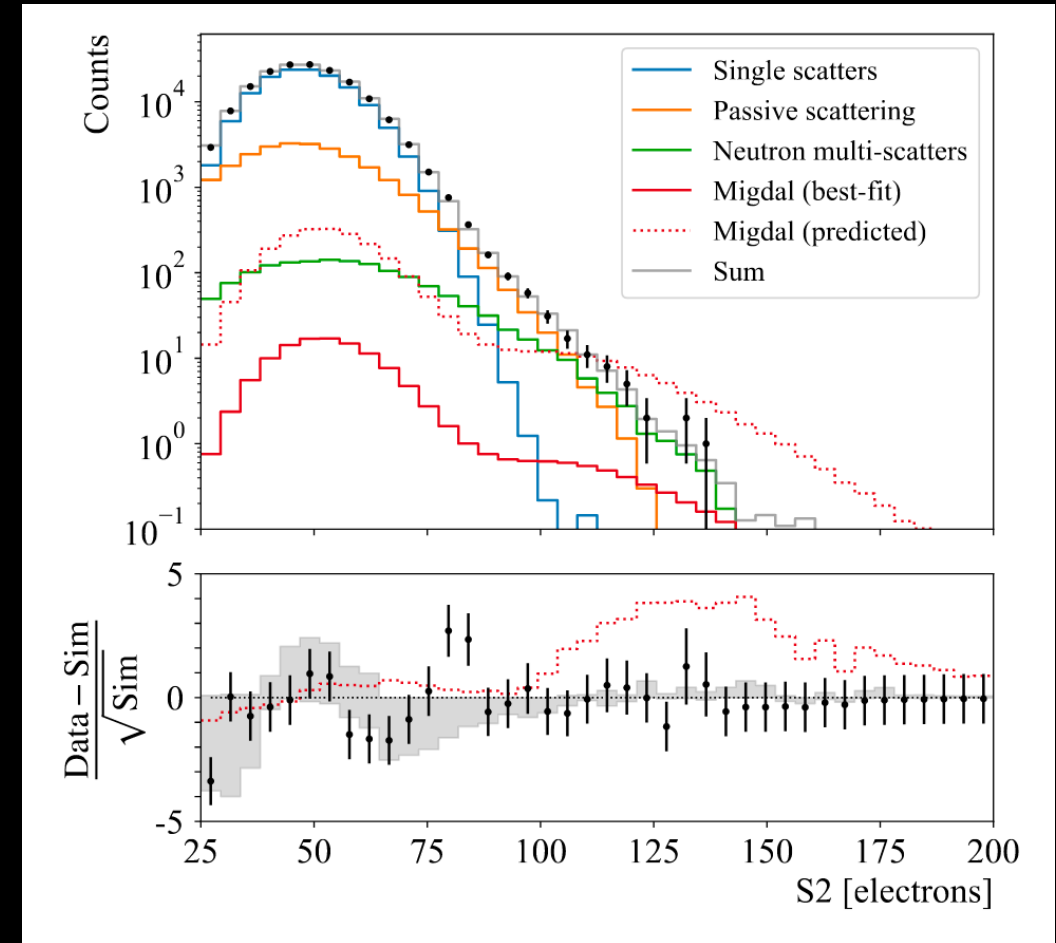
Migdal effect now widely used in light DM searches

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

Grain-of-salt: seeing Migdal?

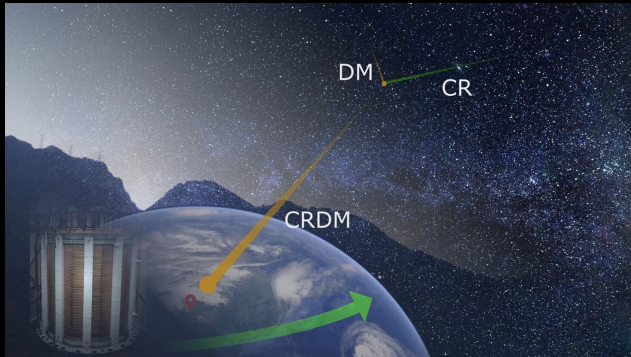
Many experimental efforts (with neutron beam)

- 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*

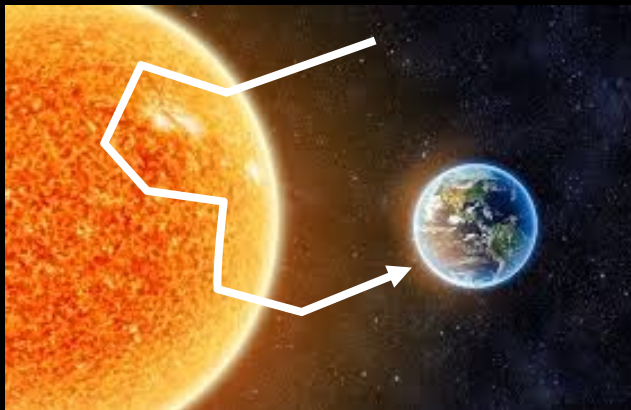


Low mass DM detection techniques with Noble Gas: example 3

“Boosting” by energetic nucleus or electrons

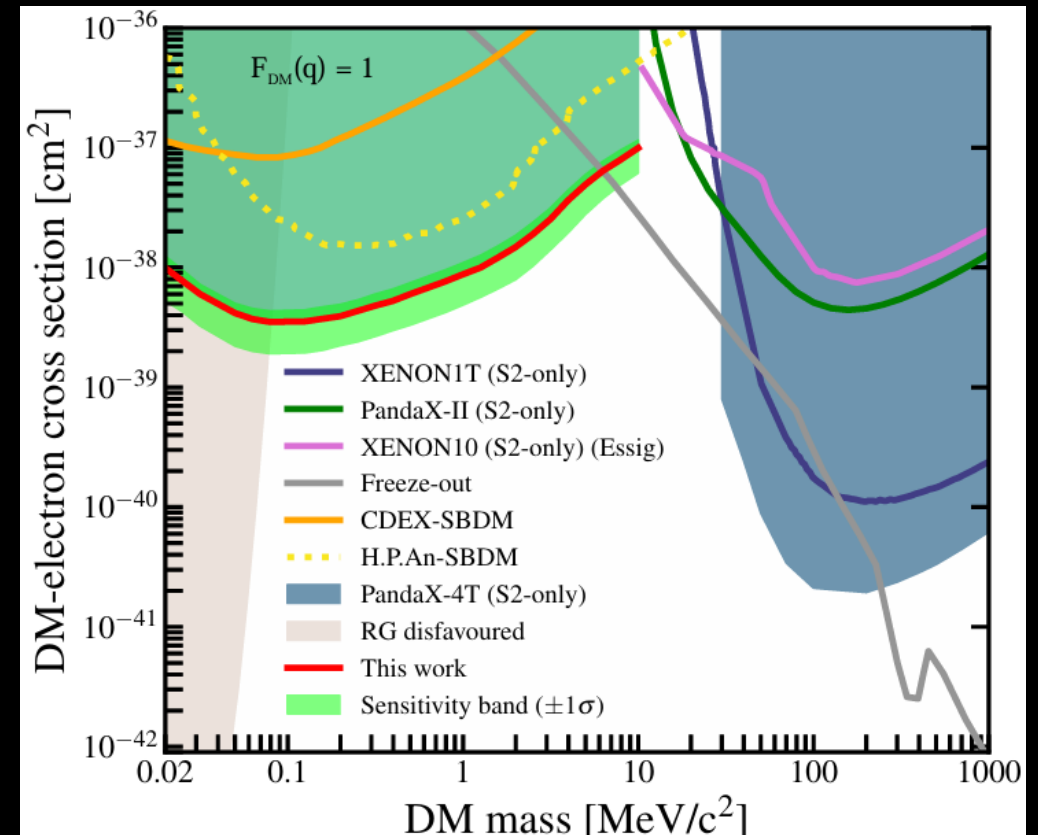


Bringmann and Pospelov,
PRL 122, 171801 (2019)



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

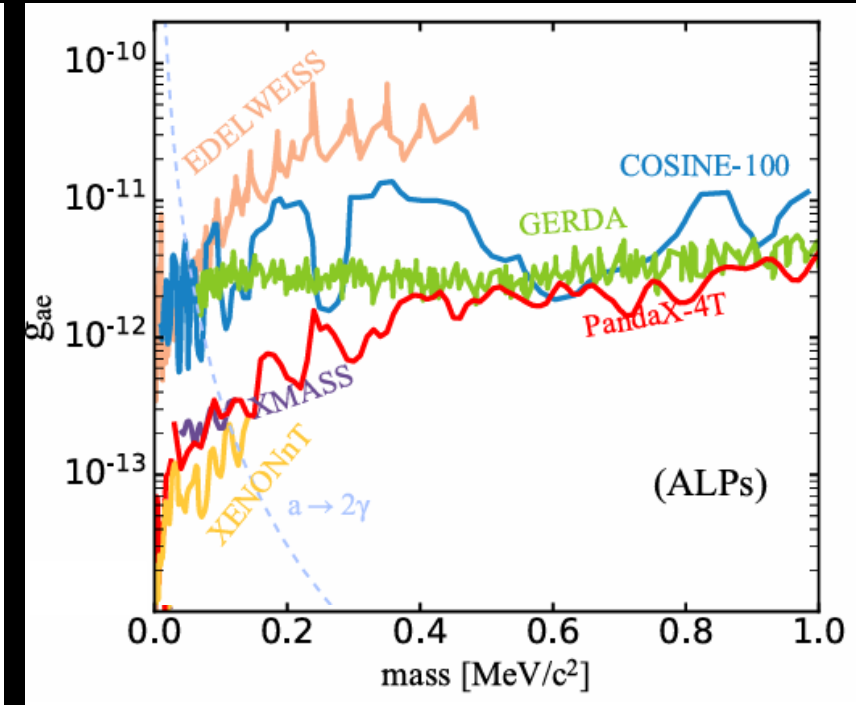
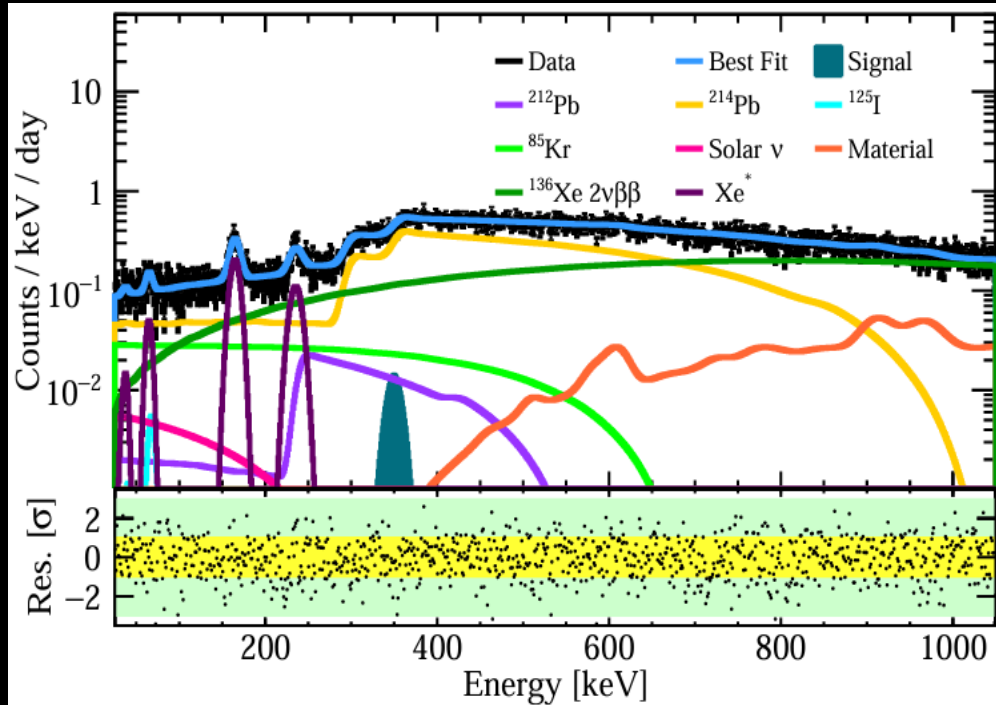
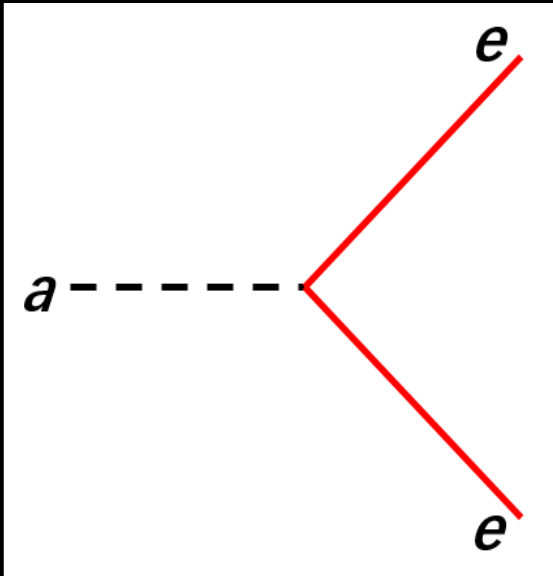
PRL 134, 161003 (2025), 2412.19970



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

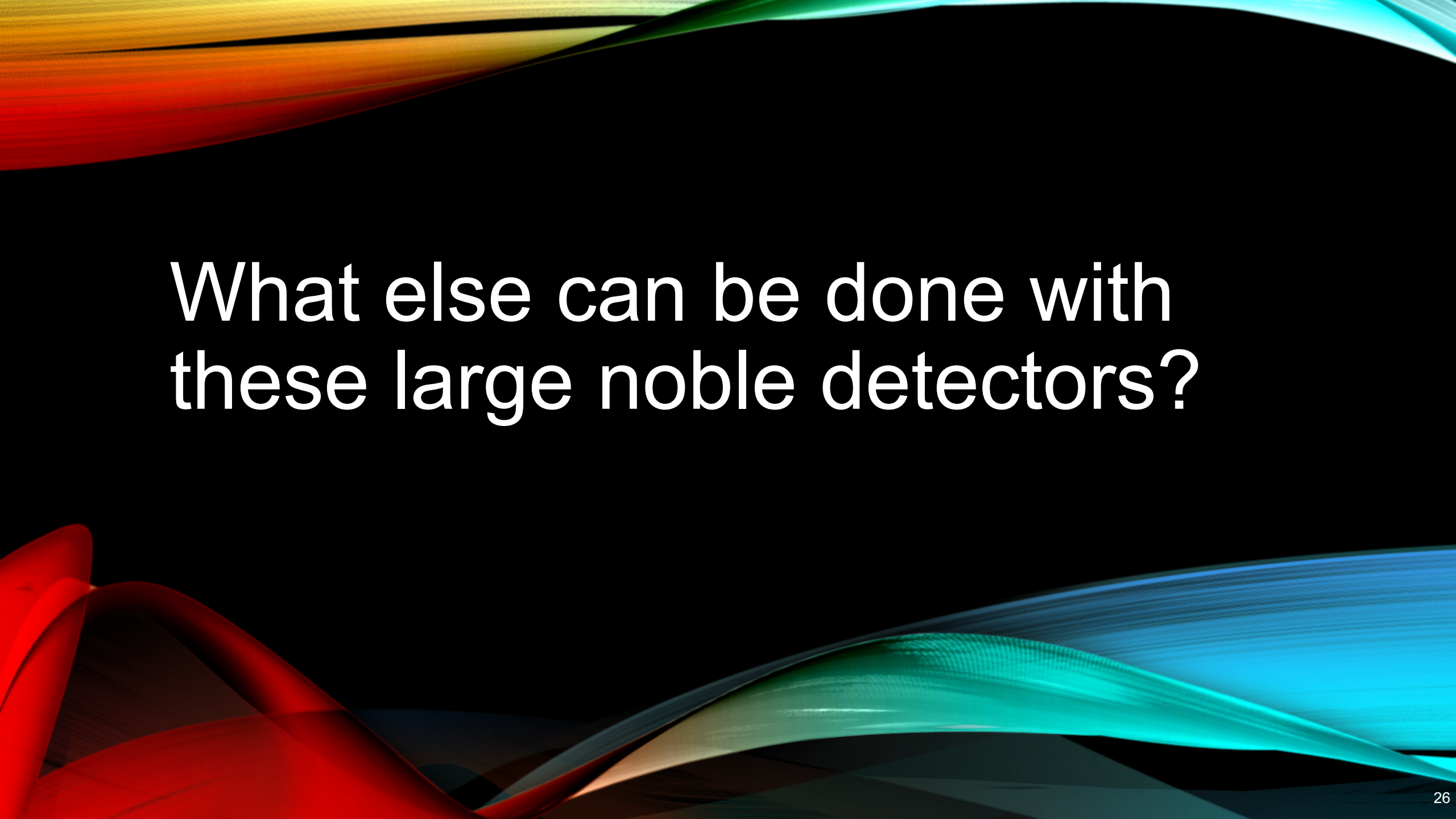
Low mass DM detection techniques with Noble Gas: example 4

Axion-like particle absorption by atomic electron



PandaX-4T, *PRL* 134, 071004 (2025), [arXiv:2409.00773](https://arxiv.org/abs/2409.00773)

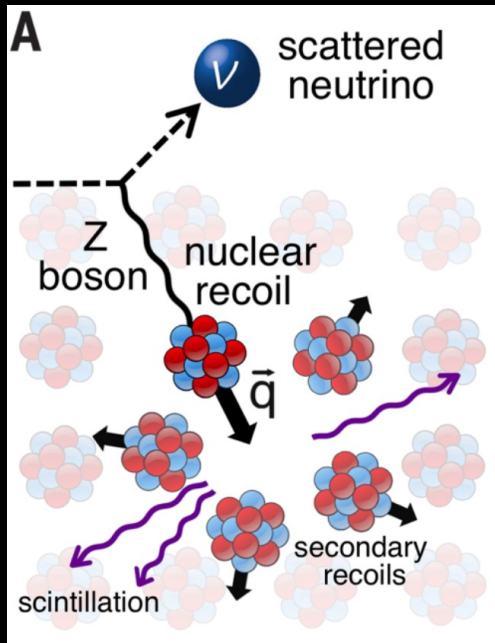
See talks by Tao Li (PandaX) and Yongheng Xu (LZ)



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

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ABSTRACT

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ 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 $\nu + A \rightarrow \nu + A^*$ 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.

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

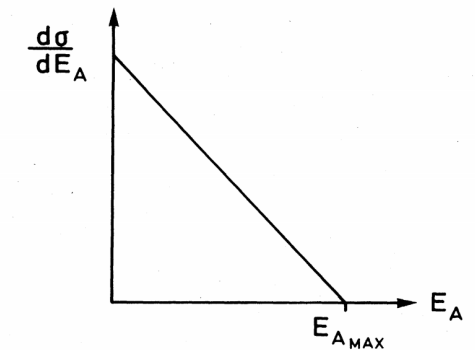


FIG. 1. Recoil-energy spectrum of the struck nucleus A in elastic neutrino scattering.

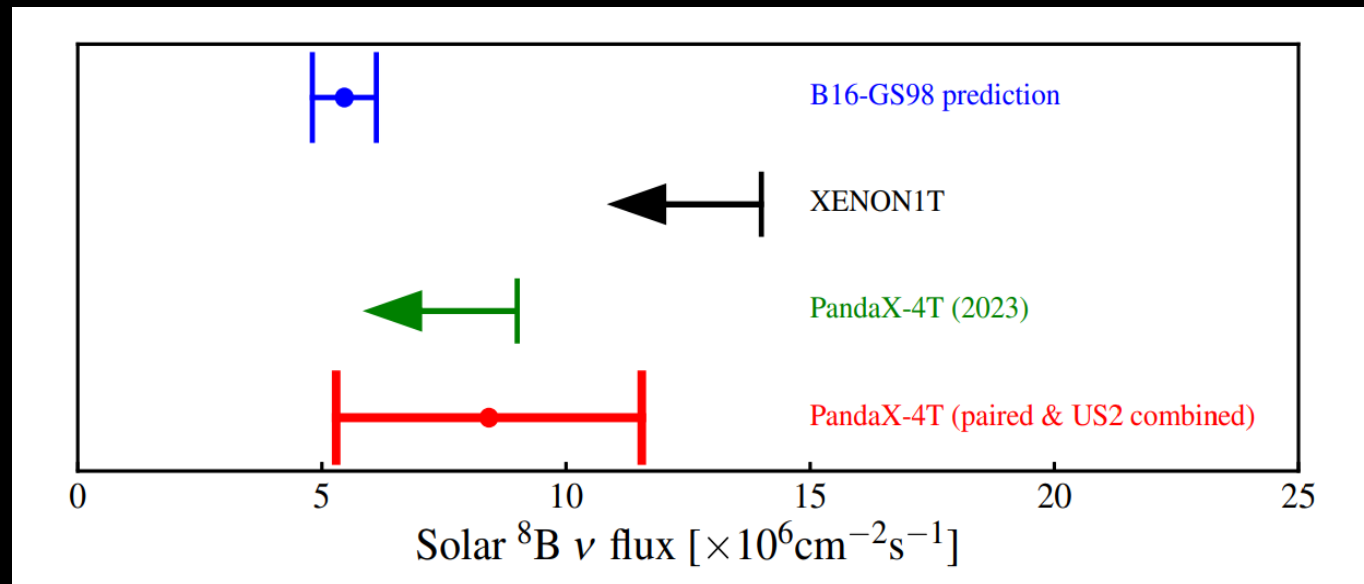
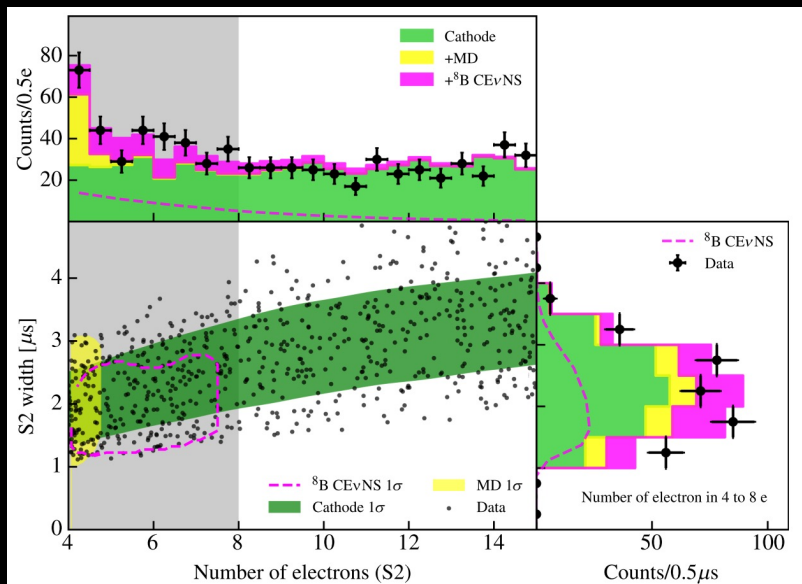
$$\bar{E}_A = \frac{2}{3A} (E/1 \text{ MeV})^2 \text{ keV}$$

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

Solar B8 neutrinos!

- PandaX-4T uses S2-only data ($\sim 1 \text{ ton} \times \text{year}$)
 - 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



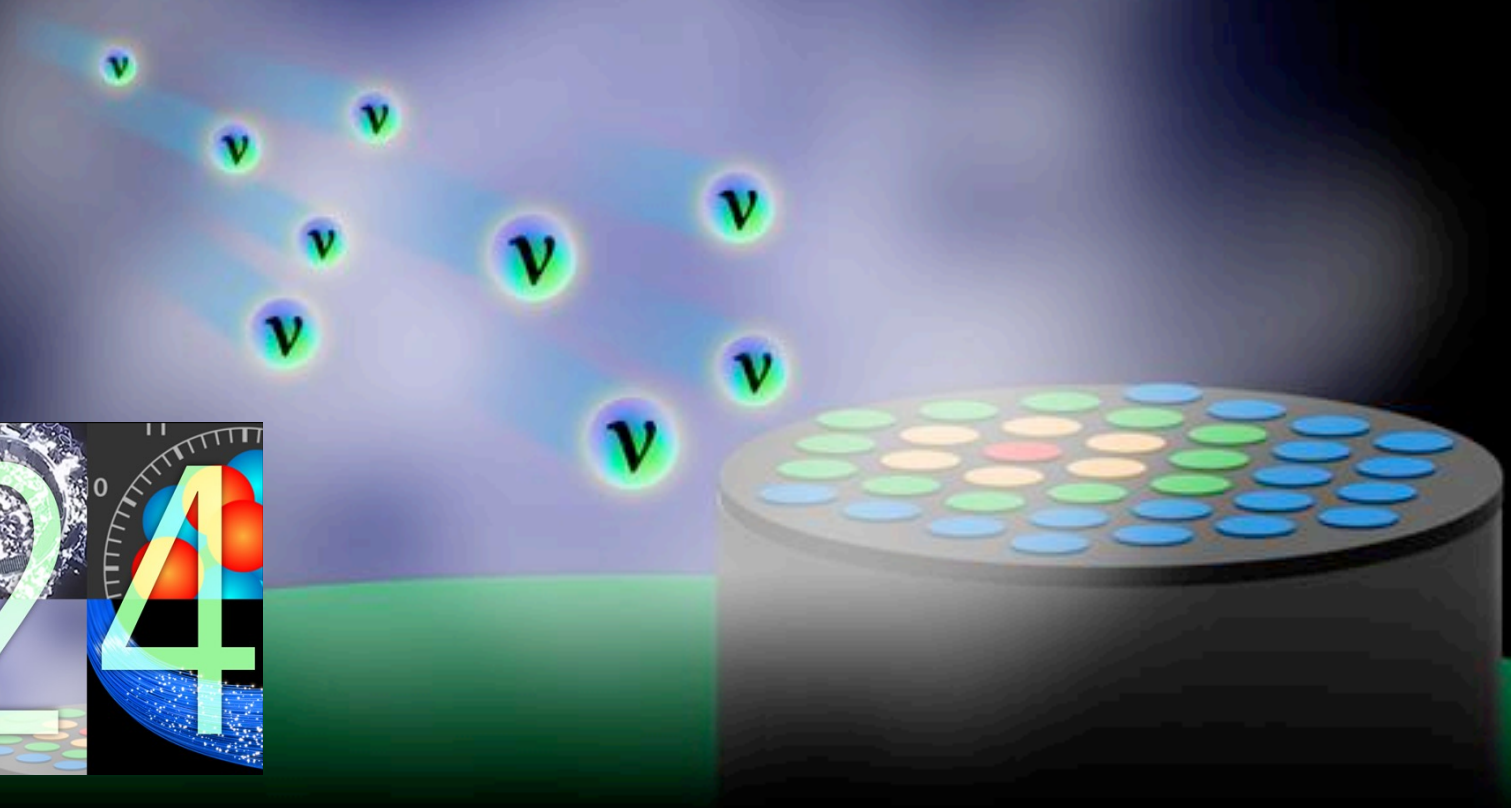
Solar B8 neutrinos!

- PandaX 4T uses S2 only data (~1 ton/year)



Physics Magazine highlights of the year 2024

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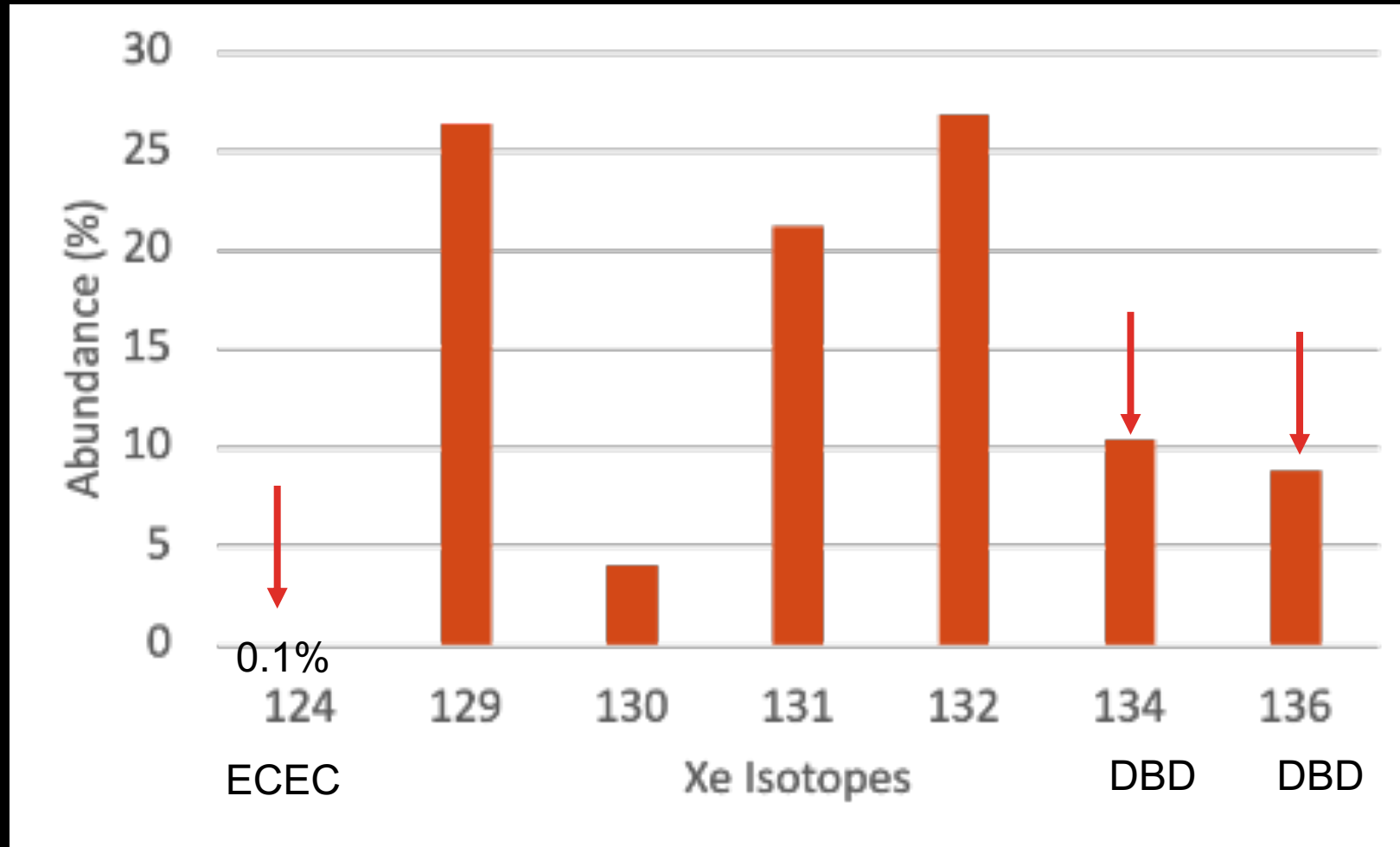
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Nt talk



Number of electrons (S2)

Counts/0.5 μ s

Natural xenon multiple double weak decay targets



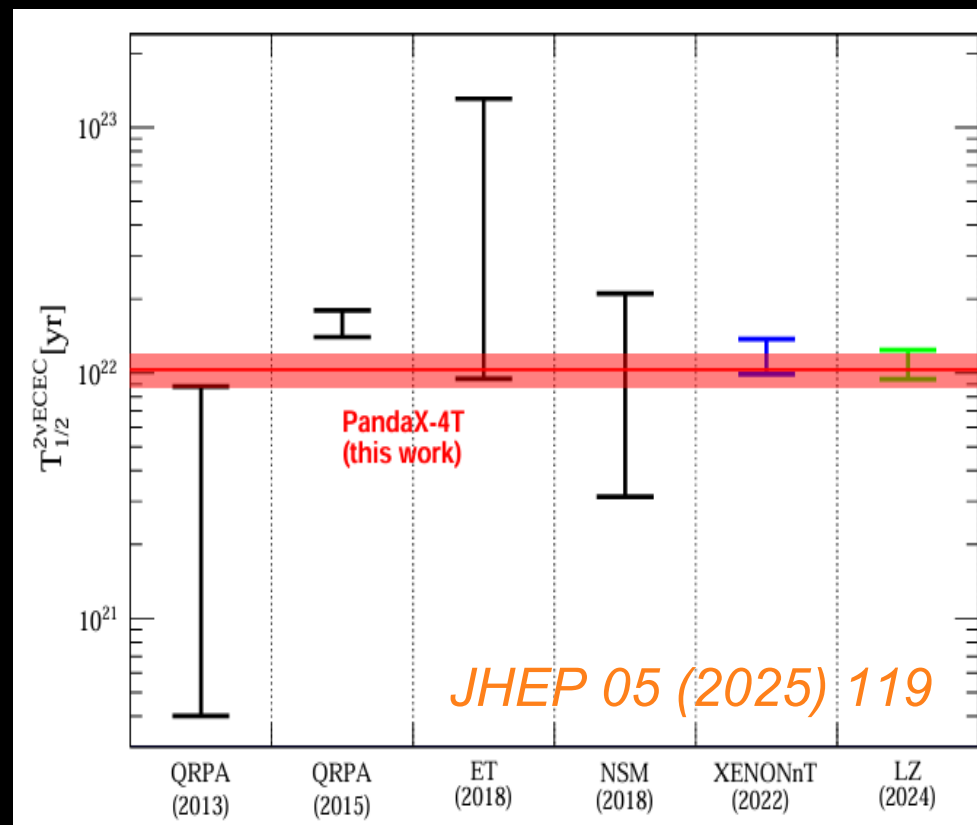
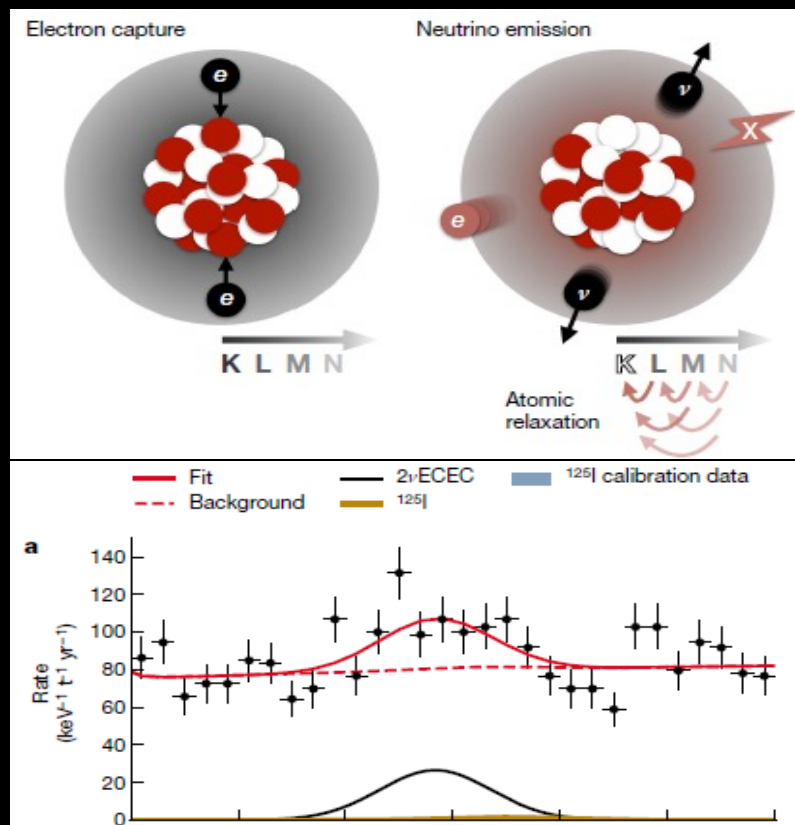
Challenges: background, energy resolution, MS event selections etc

^{124}Xe ECEC

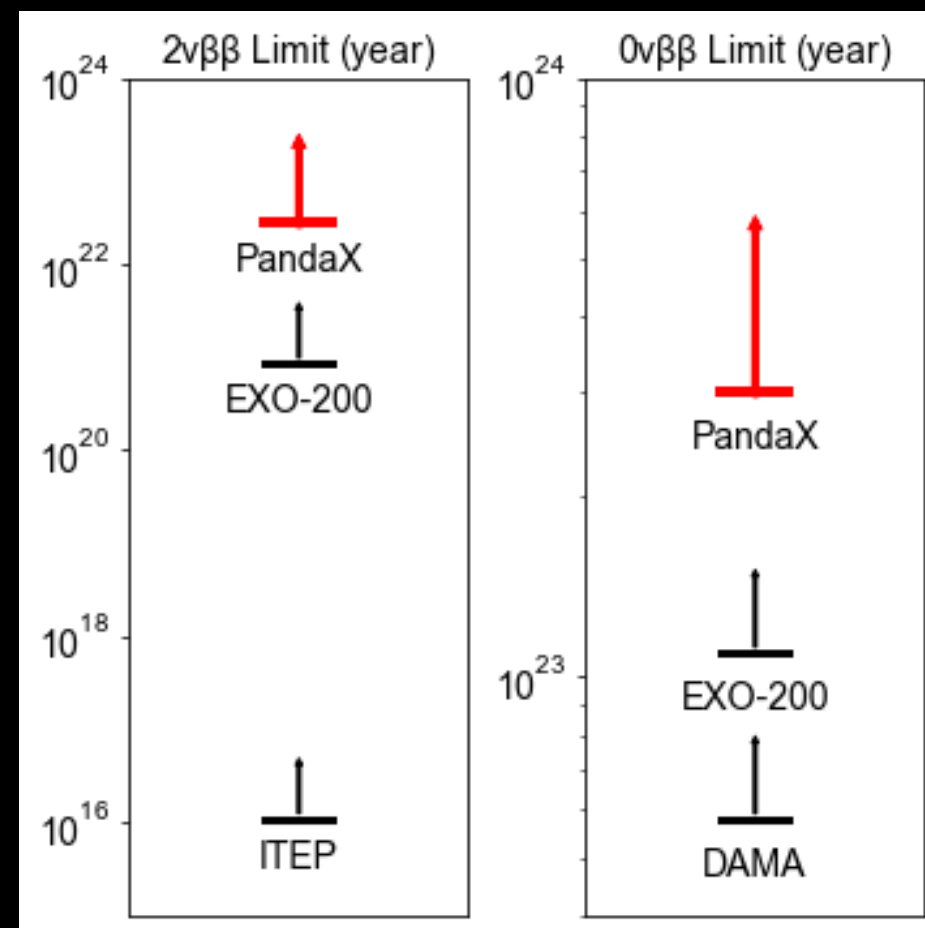
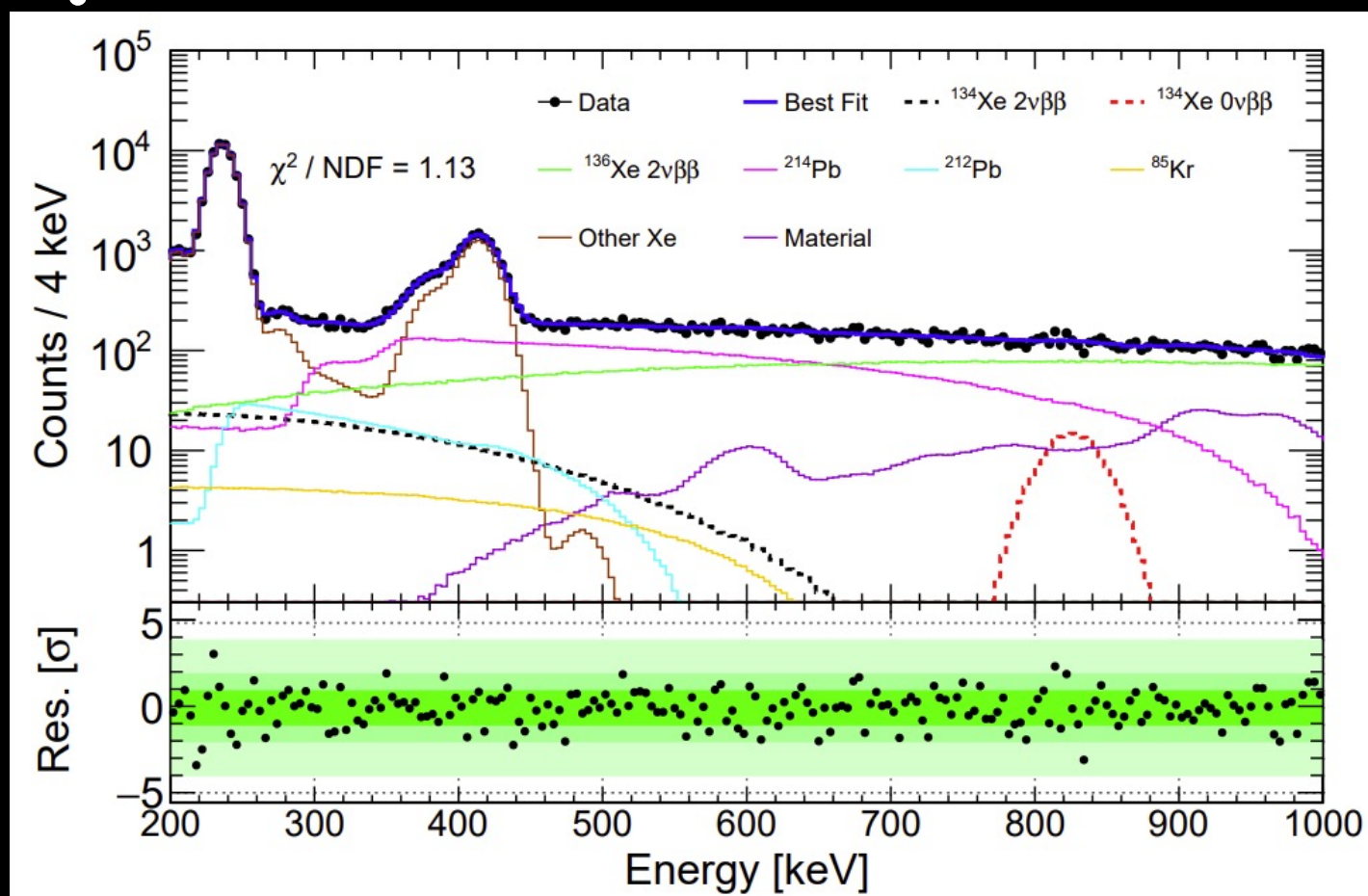
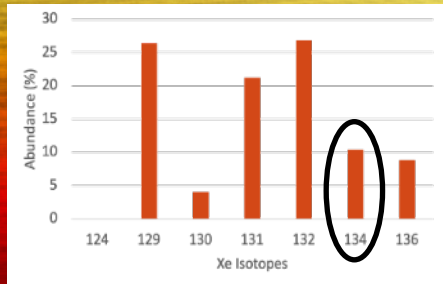
First observed by XENON-1T 2019

Nature 568, 532 (2019)

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



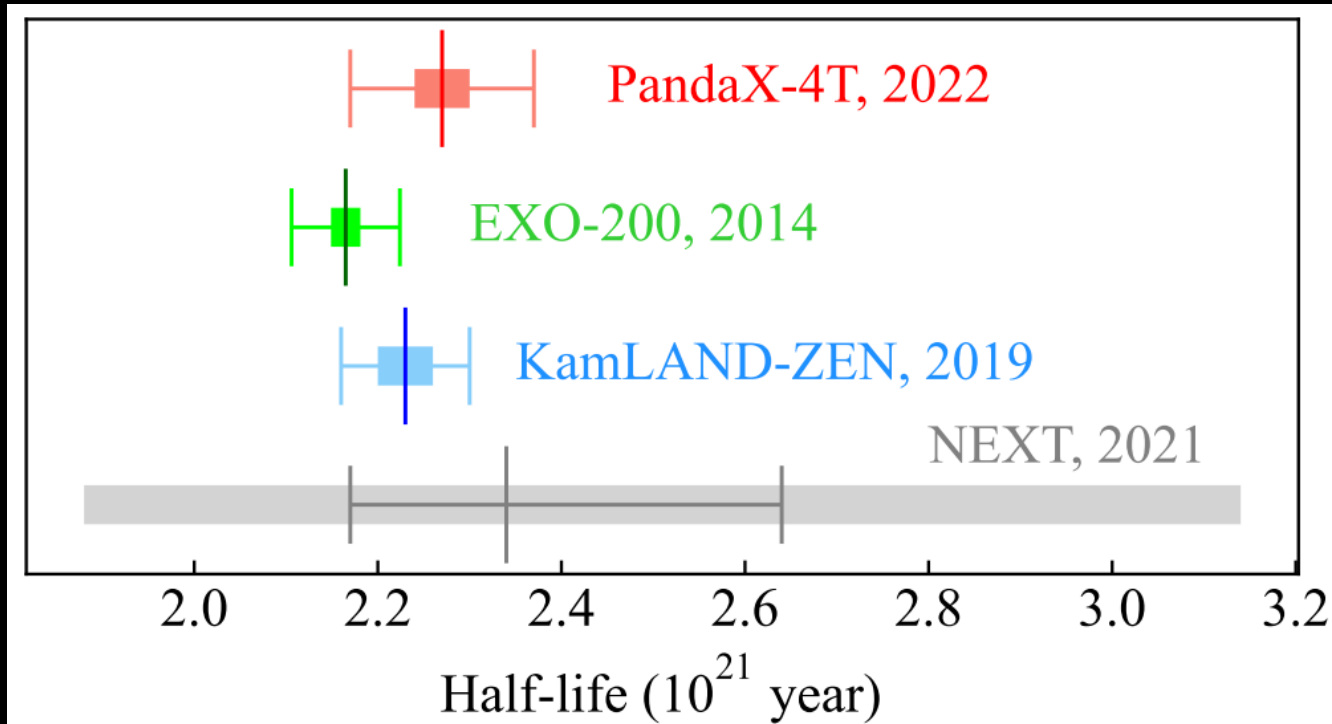
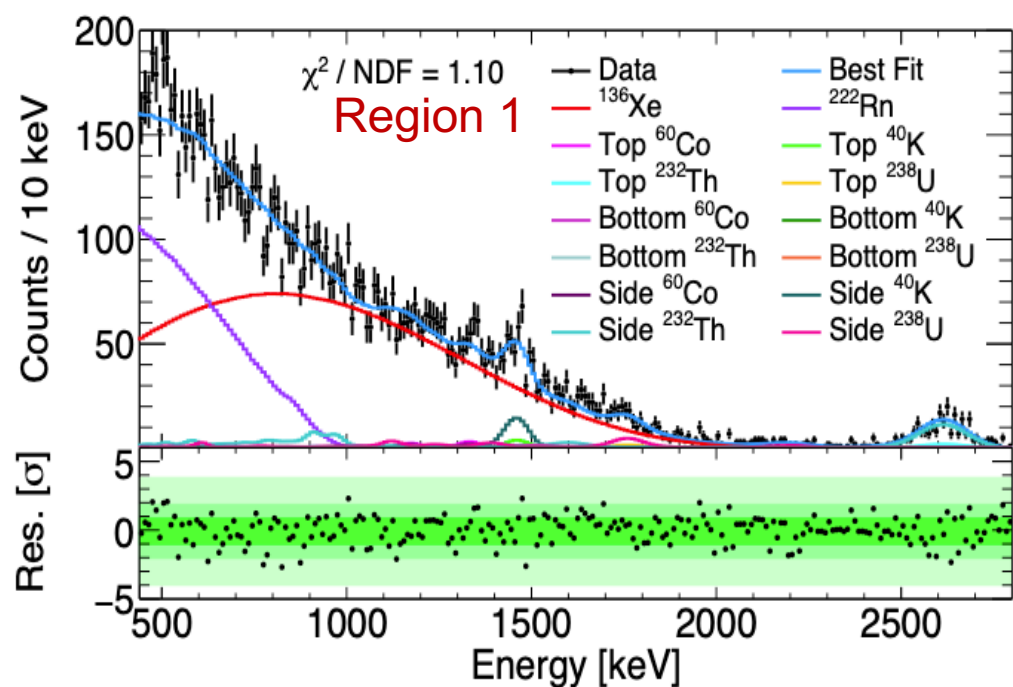
^{134}Xe : a unique blessing



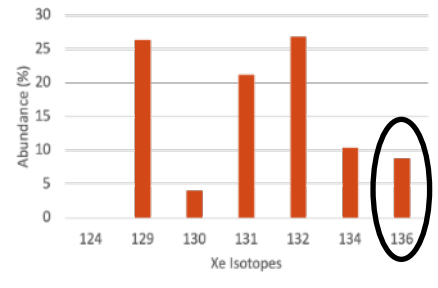
PandaX-4T, *PRL* 132, 152502 (2024)



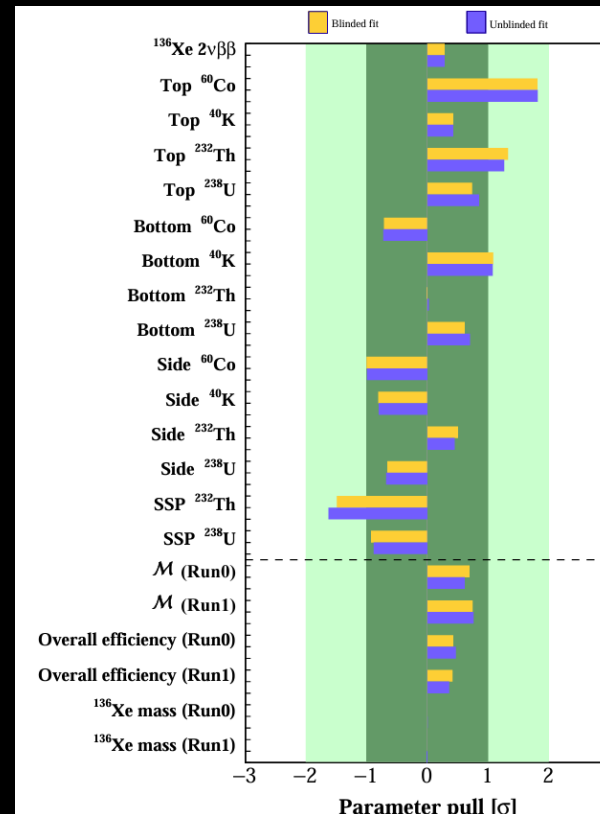
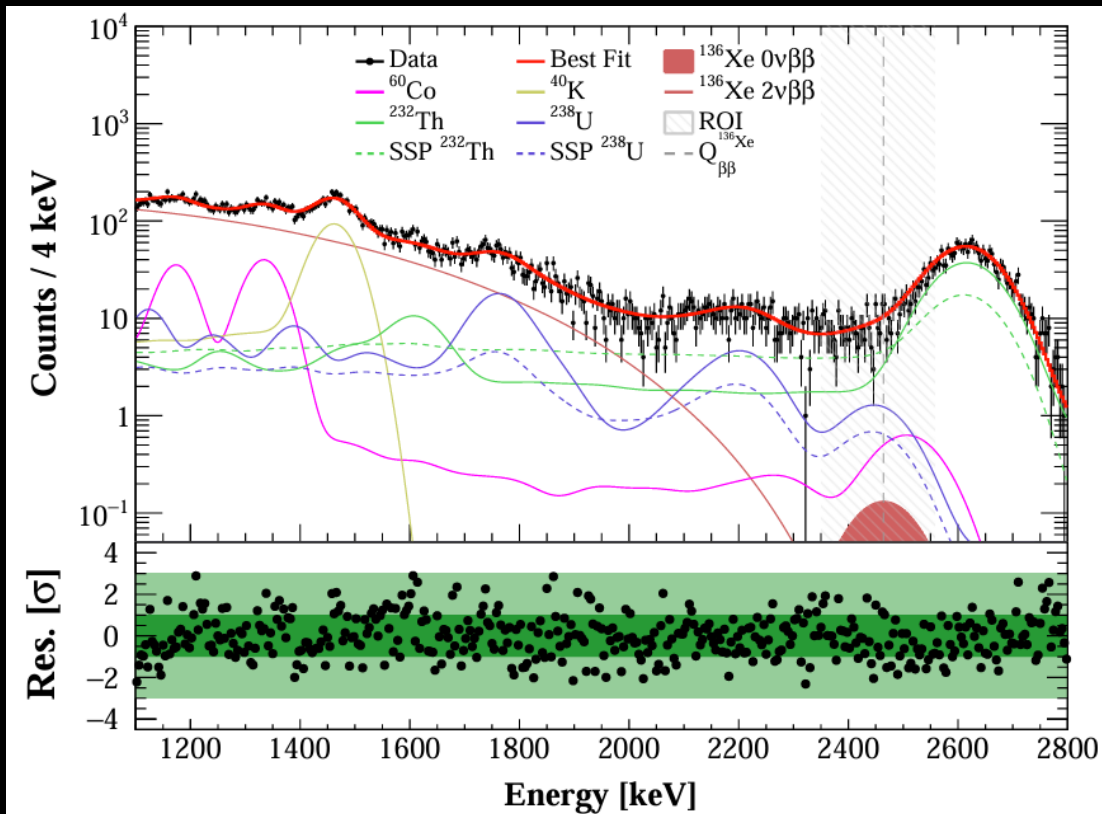
Precise measurement of ^{136}Xe 2vDBD



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



PandaX Search for ^{136}Xe $0\nu\text{DBD}$



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

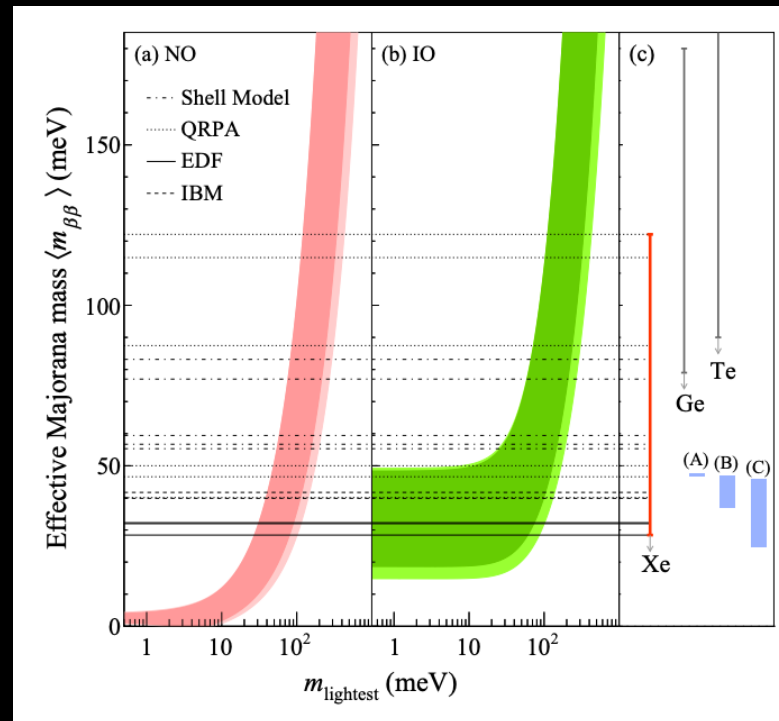
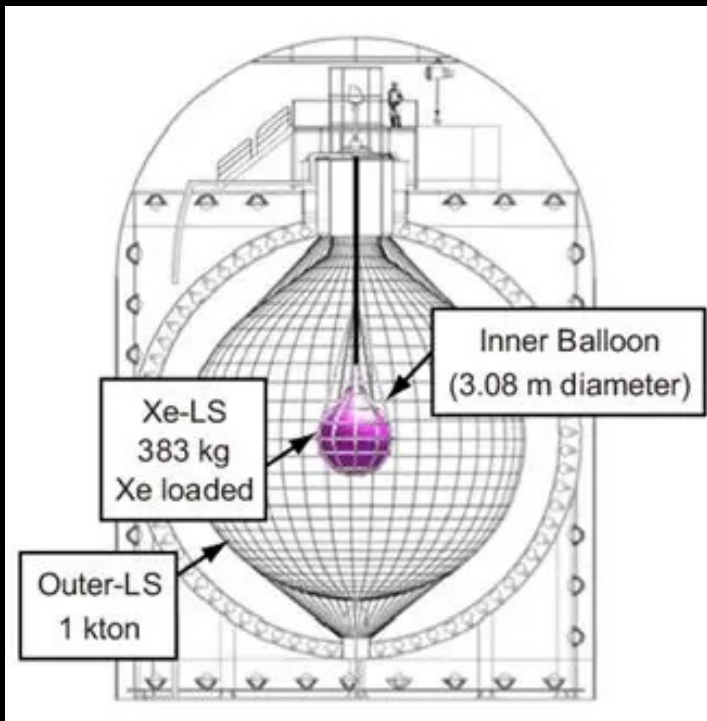
Lifetime
 $> 2.1 \times 10^{24}$ year
 $m_{\beta\beta} < 0.6-1.4$ eV

Median sensitivity
 2.7×10^{24} year

See talk by S. Zhang

Enriched ^{136}Xe Observatories

- KamLAND-Zen, EXO, NEXT: mainly focus on $0\nu\beta\beta$
- Exploring solar neutrino, dark matter etc



Lifetime $> 3.8 \times 10^{26}$ 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

C. Galbiati, UCLA-DM 2025

ARGO: Key Elements of Conceptual Design

UAr Mass:

- total 400 tonnes;
- fiducial 300 tonnes.

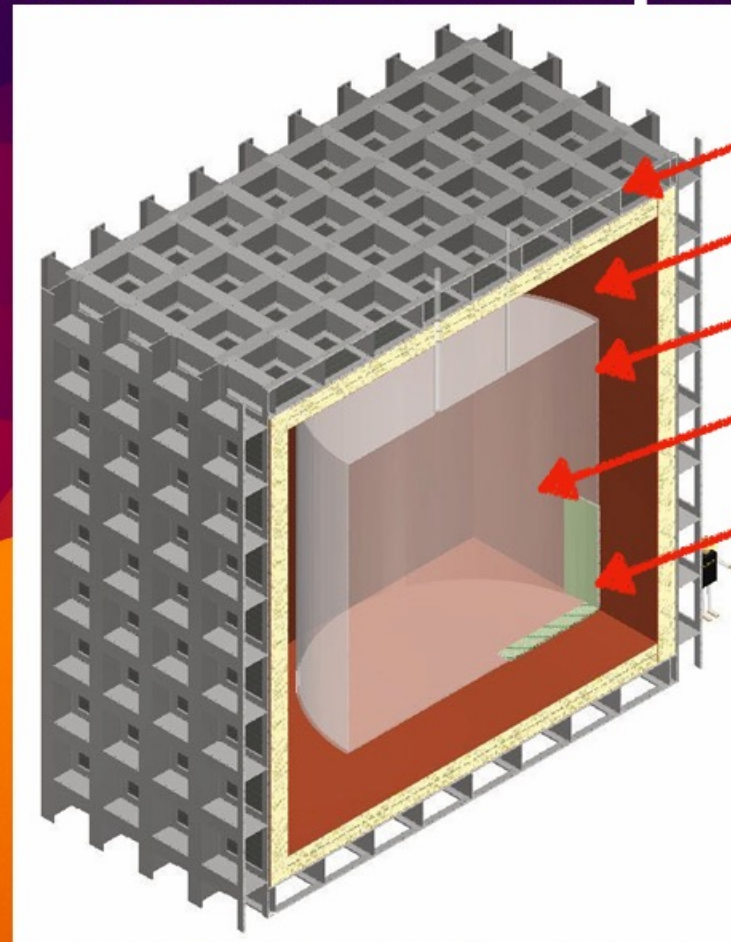
SiPMs assemblies are arranged as pixelated photodetectors.

Preferred site: SNOLAB Cube Hall
(current DEAP location);
Second site: SURF.

Currently considering both single-phase and TPC designs.

Completing background budget estimates along with conceptual design.

Submitted proposal in Canada for prototyping facility at SNOLAB.



Outer cryostat

Liquid argon buffer

Ultrapure acrylic vessel
(7m diameter and height)

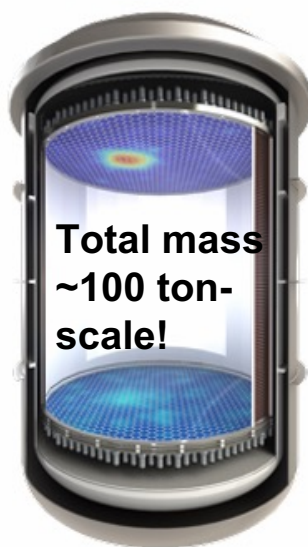
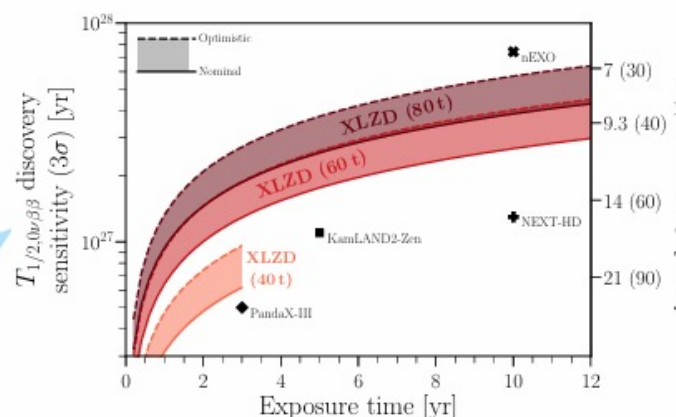
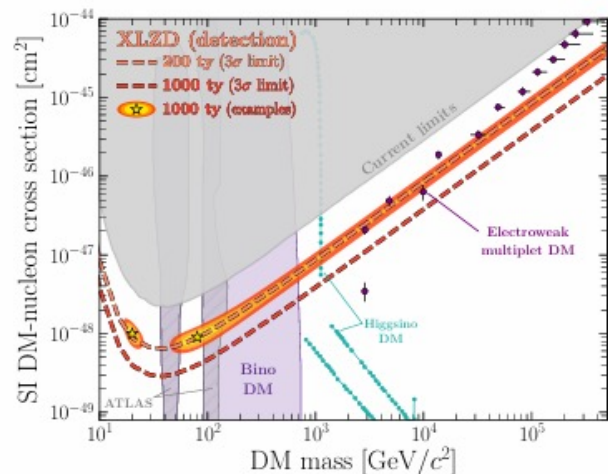
400 tonnes low-radioactivity
argon within acrylic vessel

250 m² photodetectors
covering full acrylic vessel
surface

Next Generation Xe

Dan Akerib, UCLA-DM-2025

A Liquid Xenon Observatory with a broad science program



Supernovae

Early alert
Supernova neutrinos
Multi-messenger
astrophysics



Sun

pp neutrinos
Solar metallicity
 ^7Be , ^8B , hep



Unprecedented reach for
low-energy rare processes

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

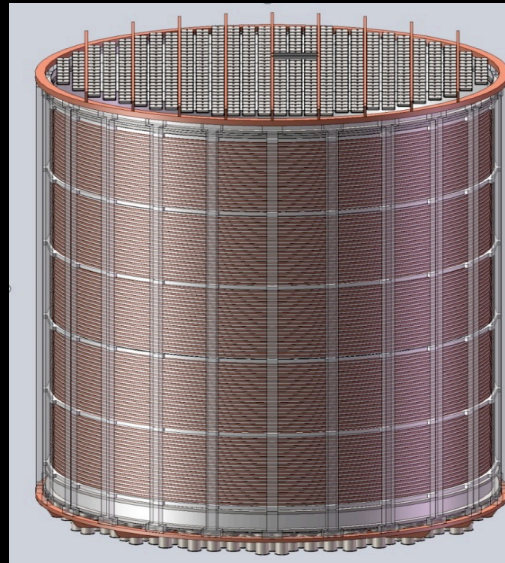
Next Generation Xe

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

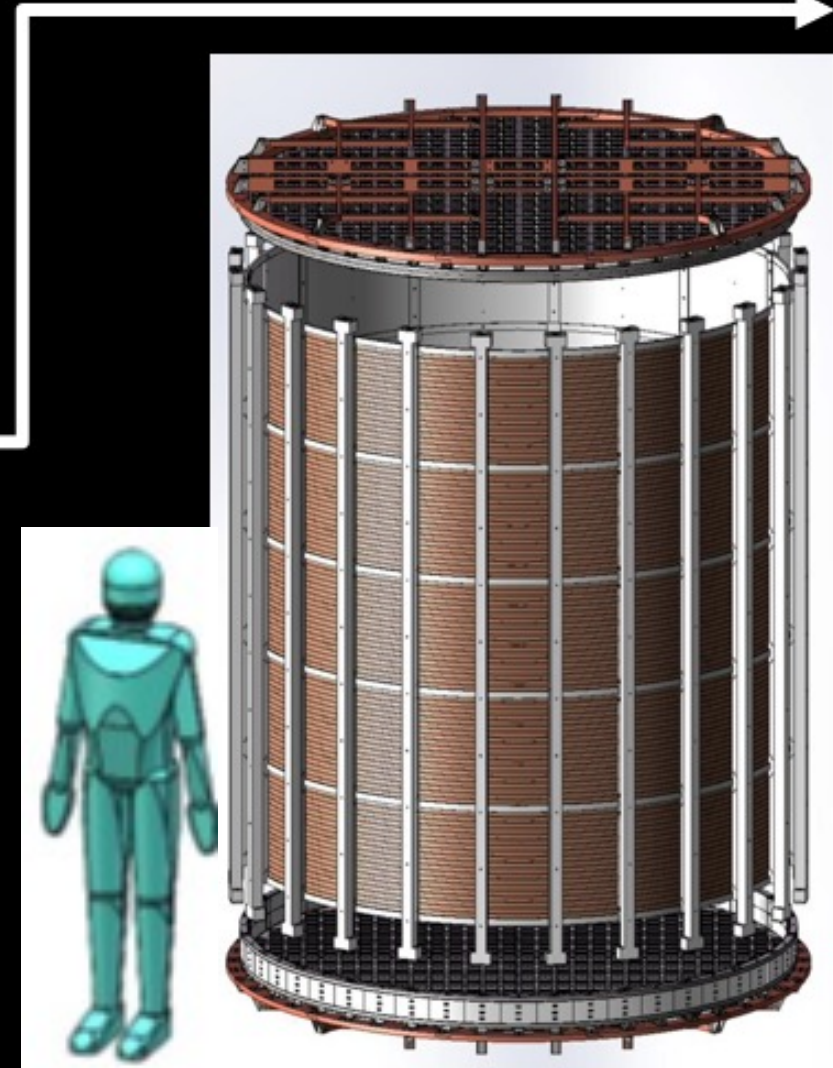
PandaX-4T



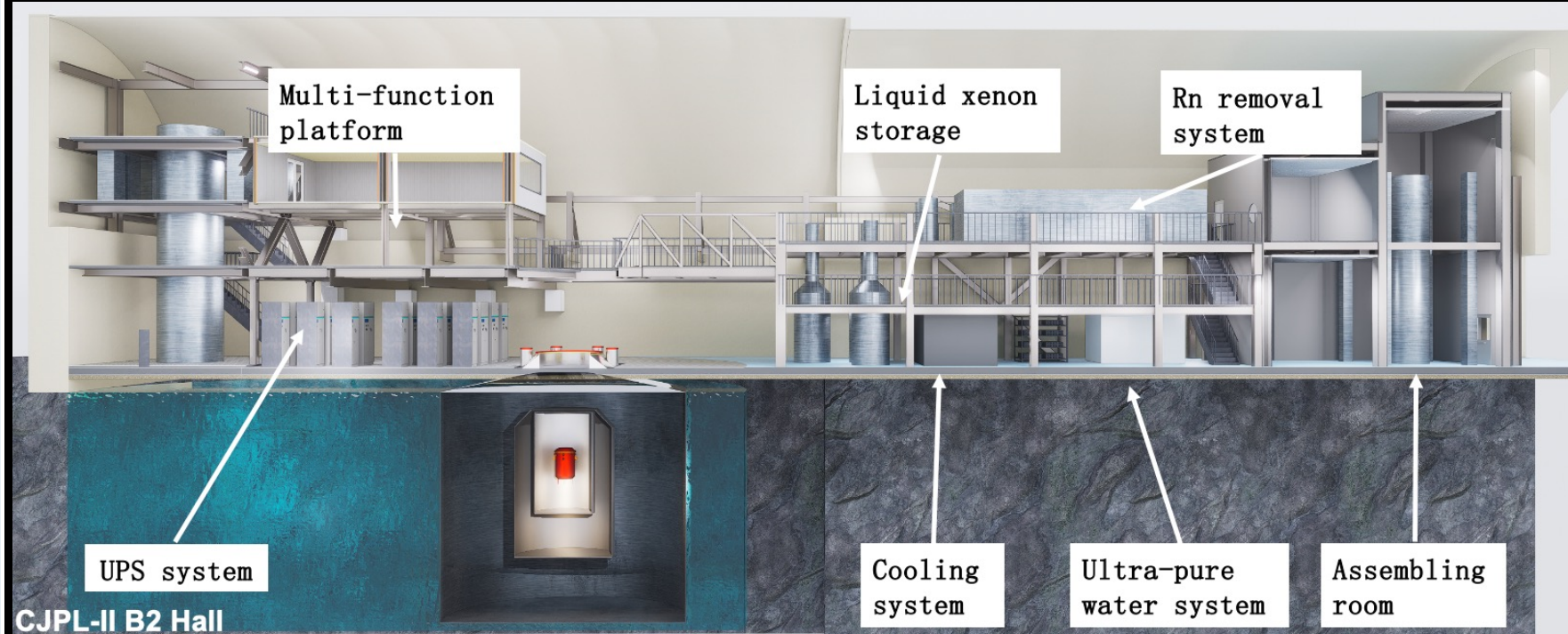
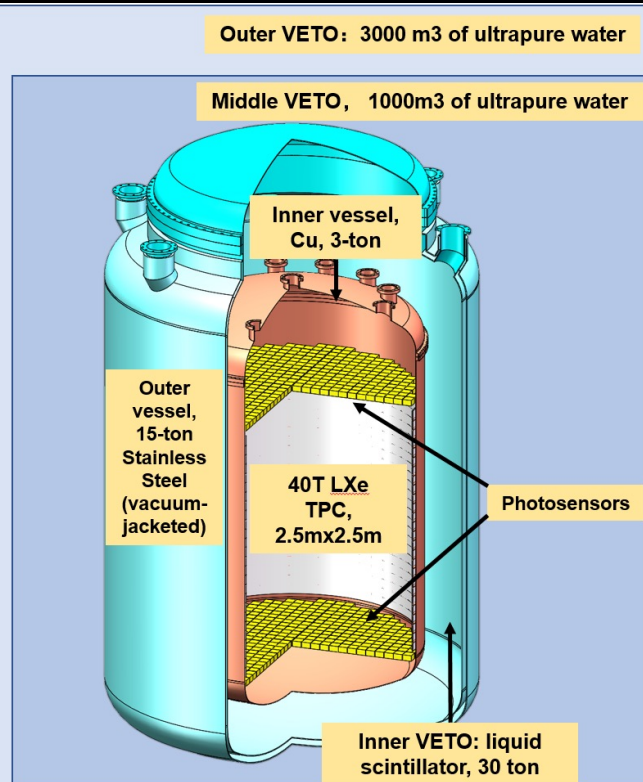
PandaX-20T (2027, mostly funded)



PandaX-40T

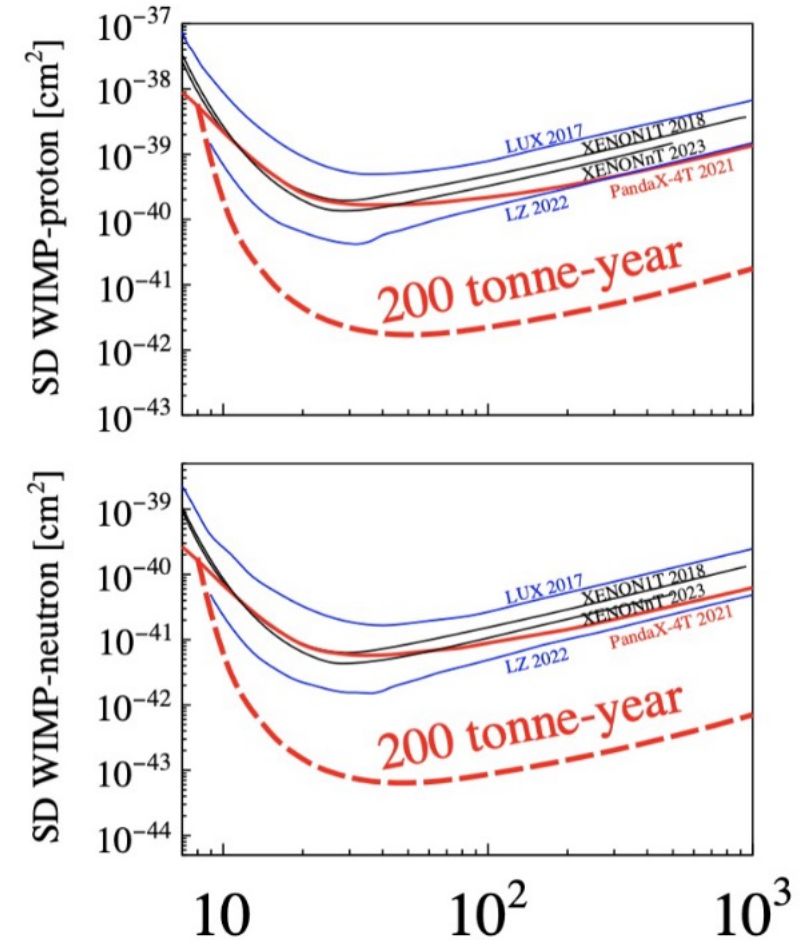
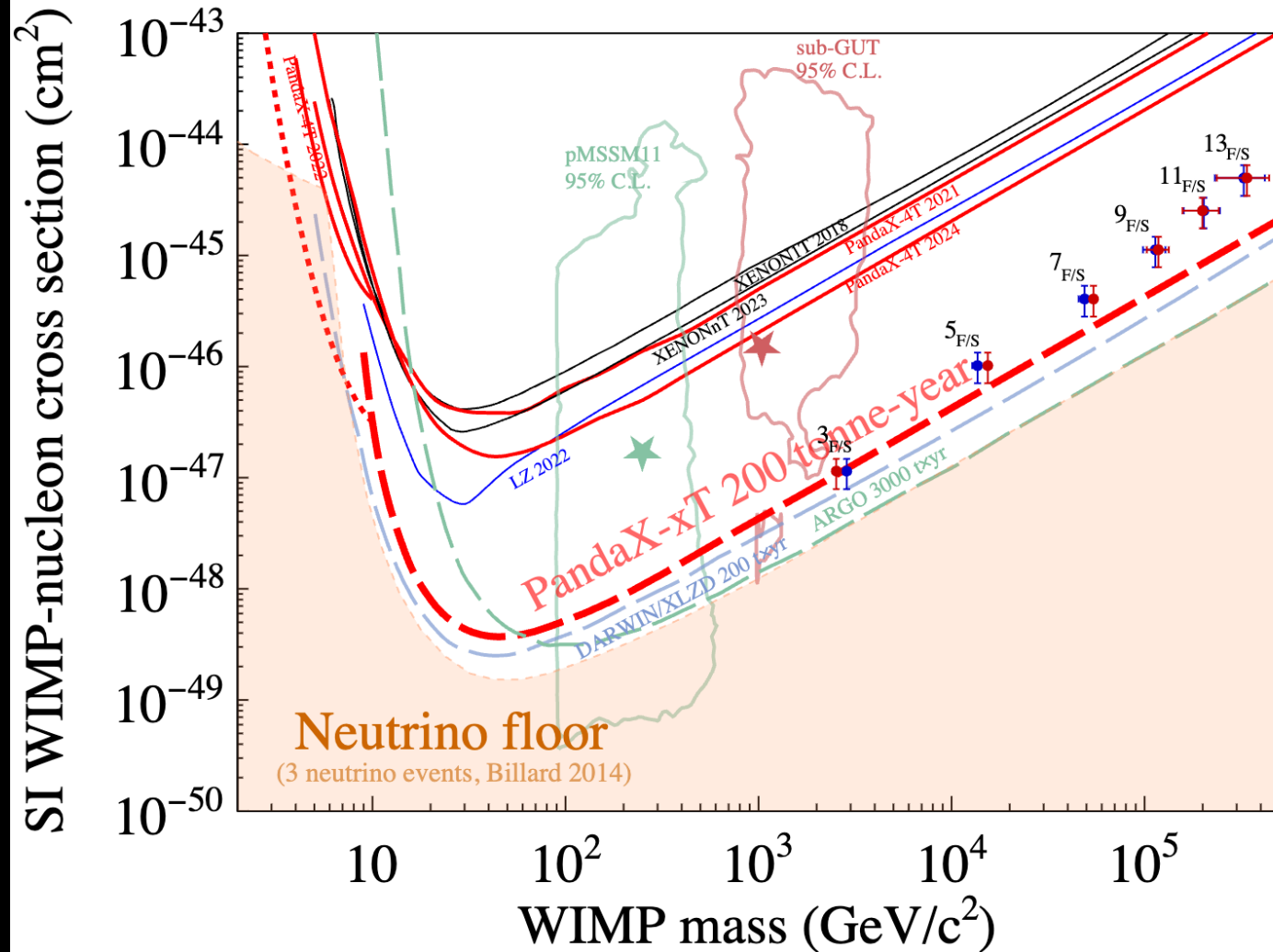


PandaX-20/40T @ CJPL

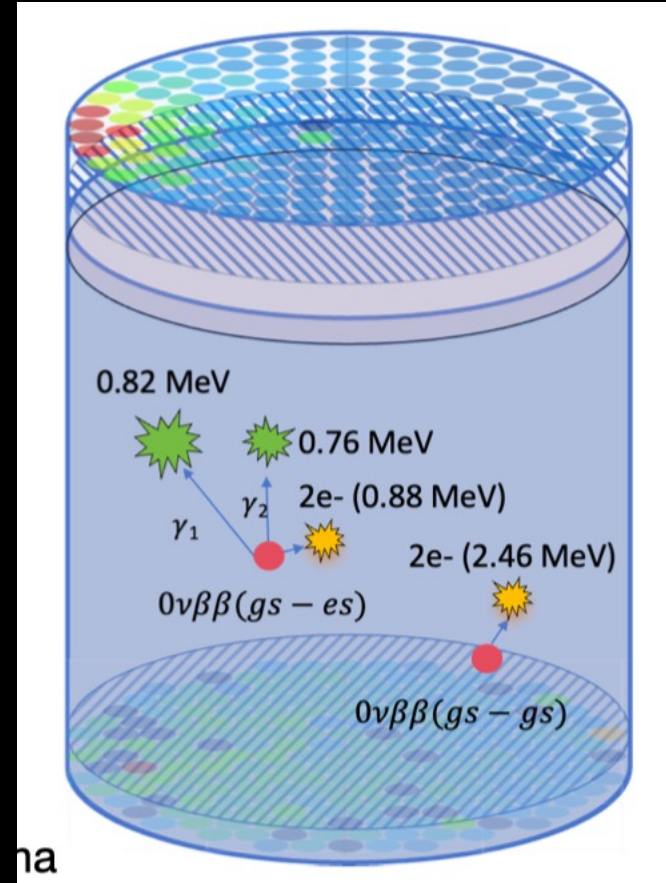
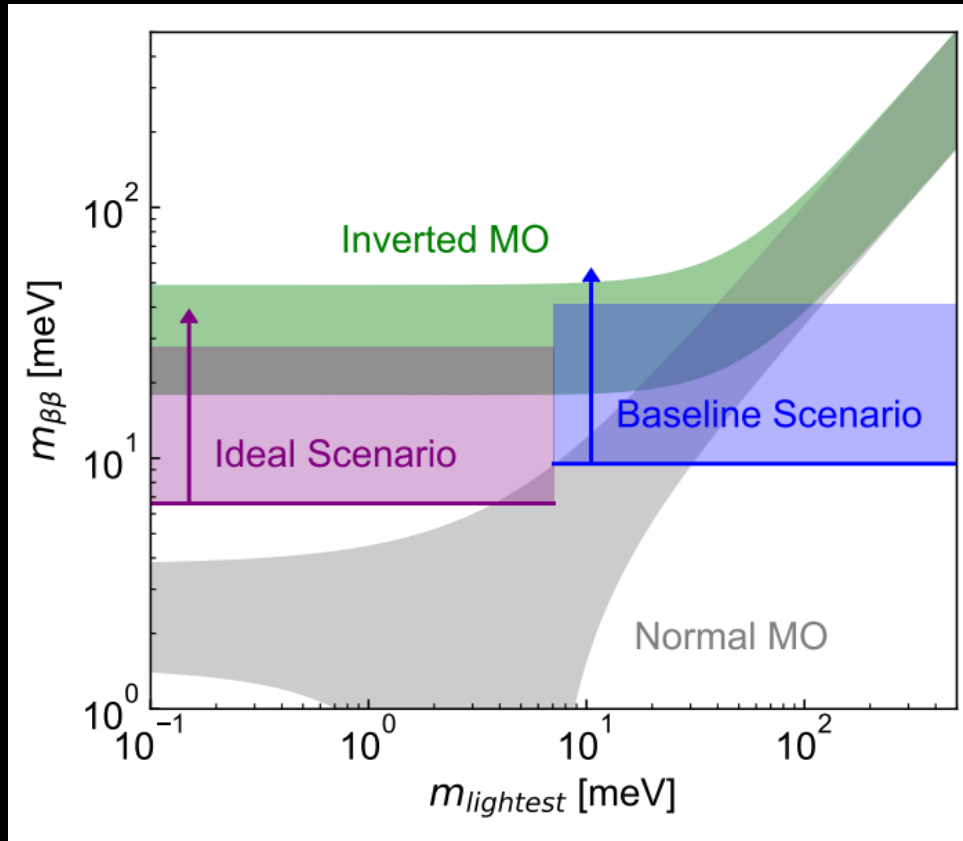


See talk by Juntaing Huang on PandaX veto detector development

DM Potential (PandaX-40T)



0νDBD potential (PandaX-40T)

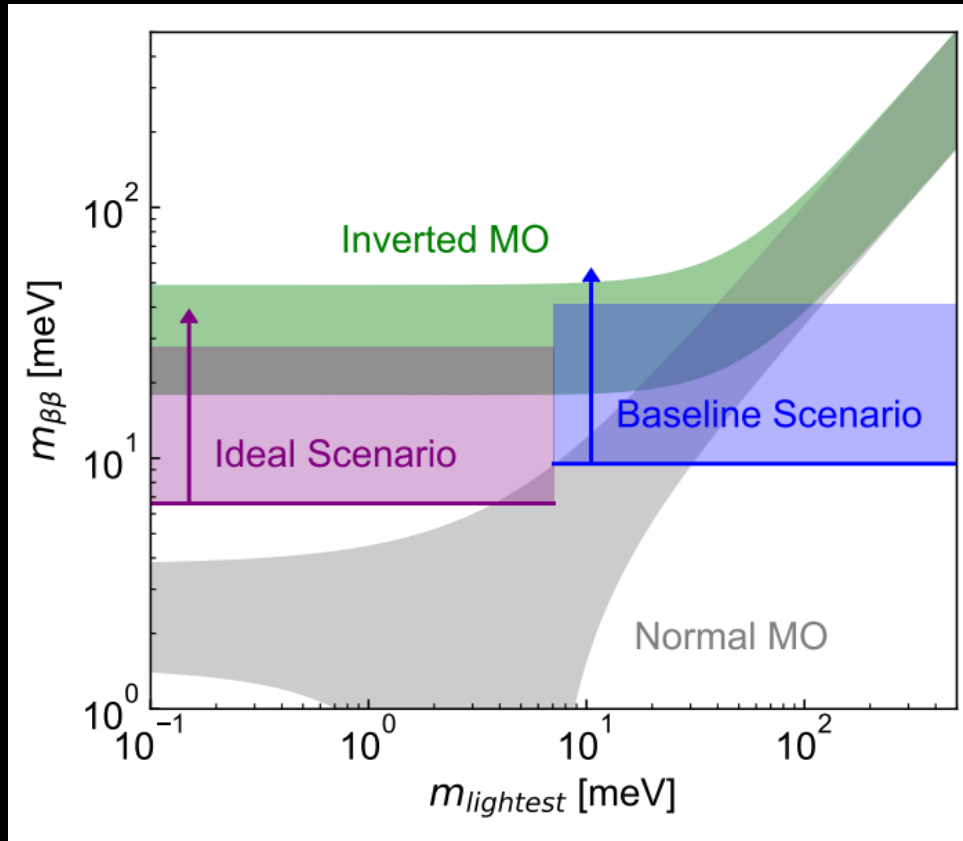


Sci. China Phys. Mech. Astron. 68, 221011 (2025)

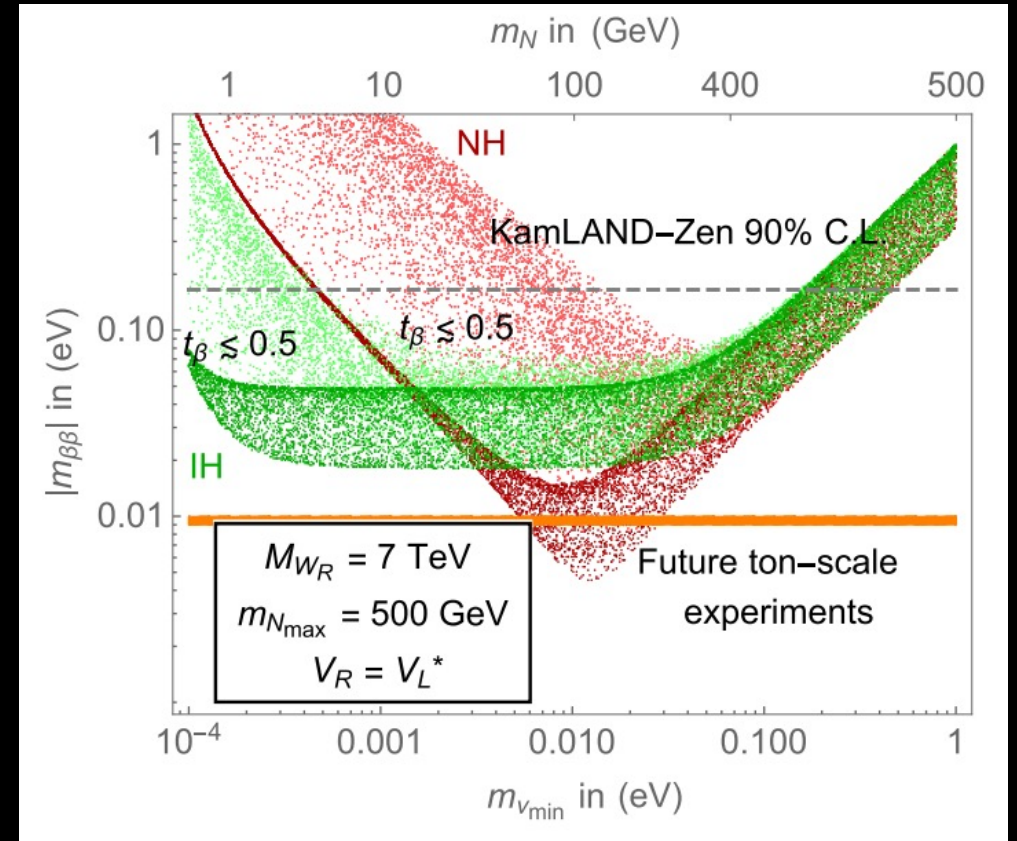
arXiv:[2508.17413](https://arxiv.org/abs/2508.17413)

Further sensitivity could be gained by combining multiple $0\nu\beta\beta$ transitions, see Ke Han, session 3B

0νDBD potential (PandaX-40T)

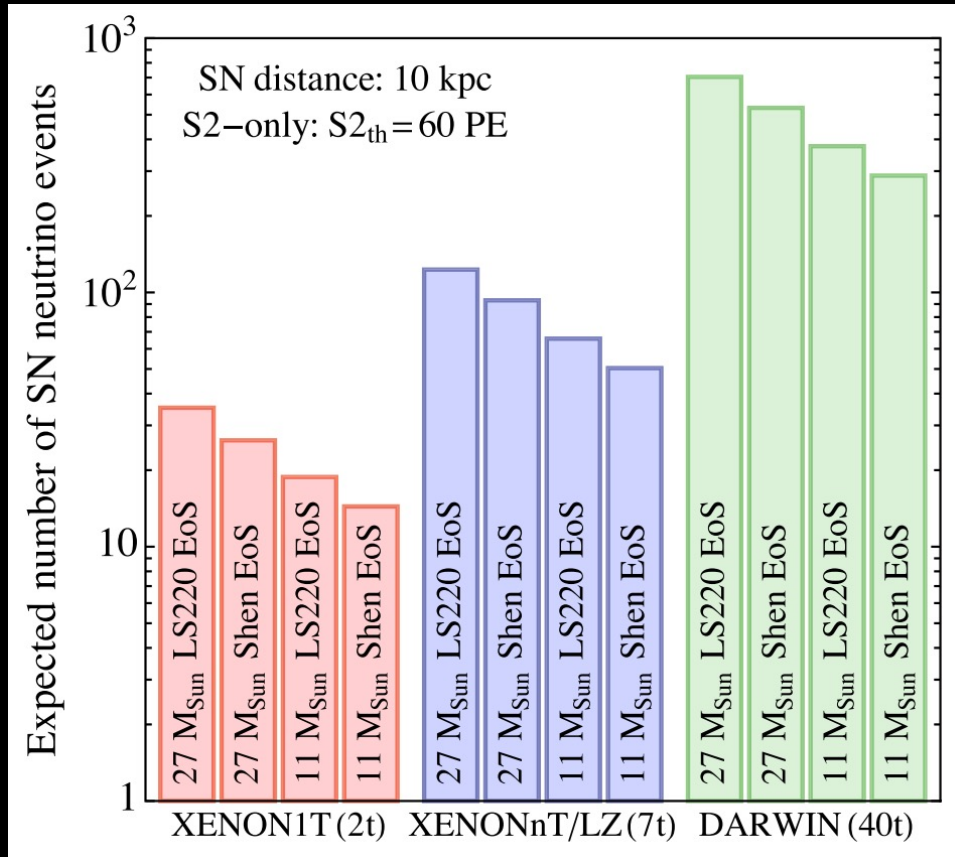


Sci. China Phys. Mech. Astron. 68, 221011 (2025)



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

Scientific potentials (SNEWS)



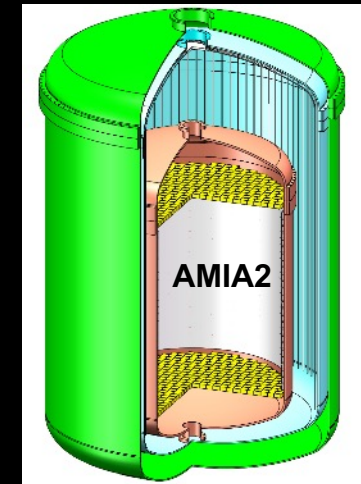
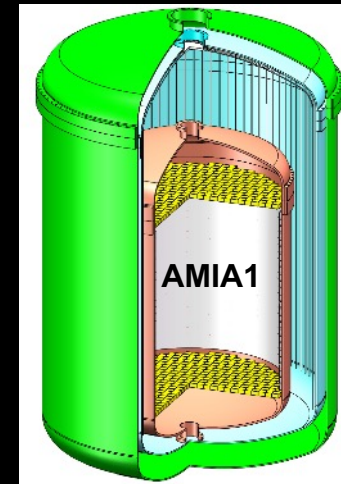
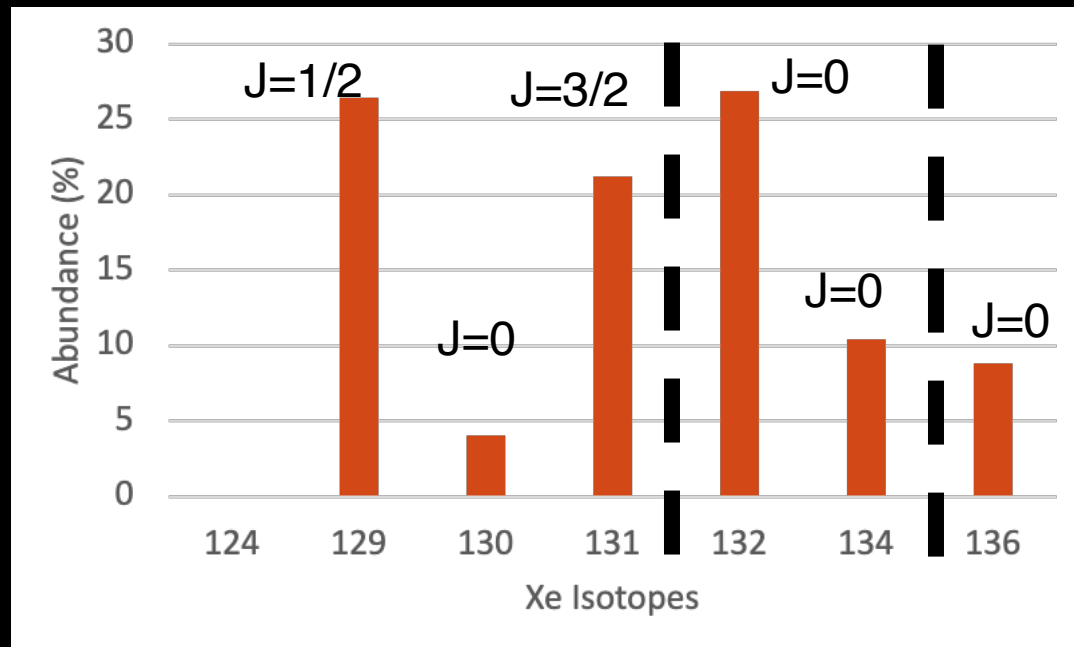
R.F. Lang, C. McCabe, S. Reichard, M. Selvi, I. Tamborra, PRD 94, 103009 (2016)

Now S2-only become a standard!



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*)



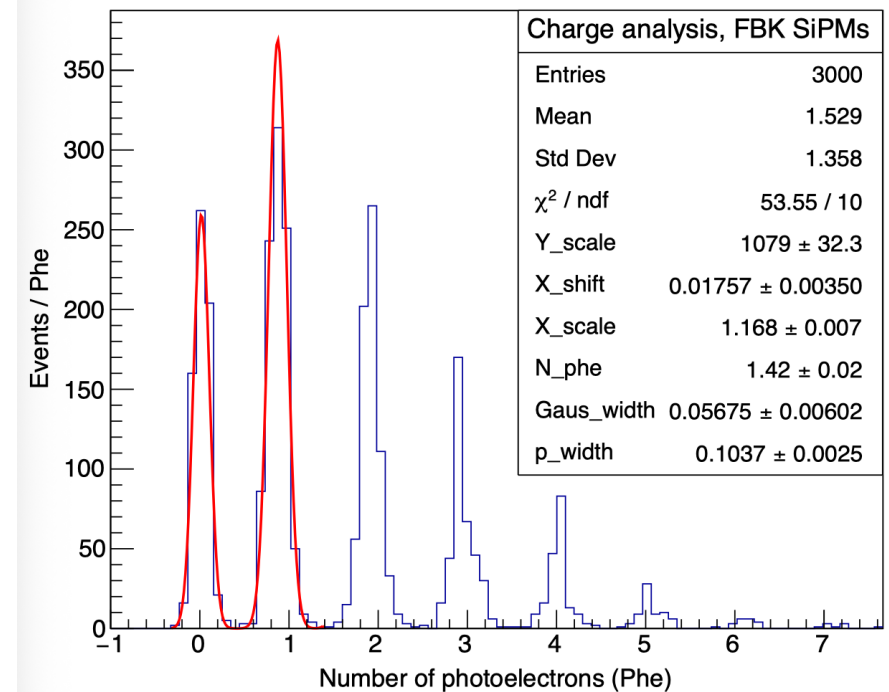
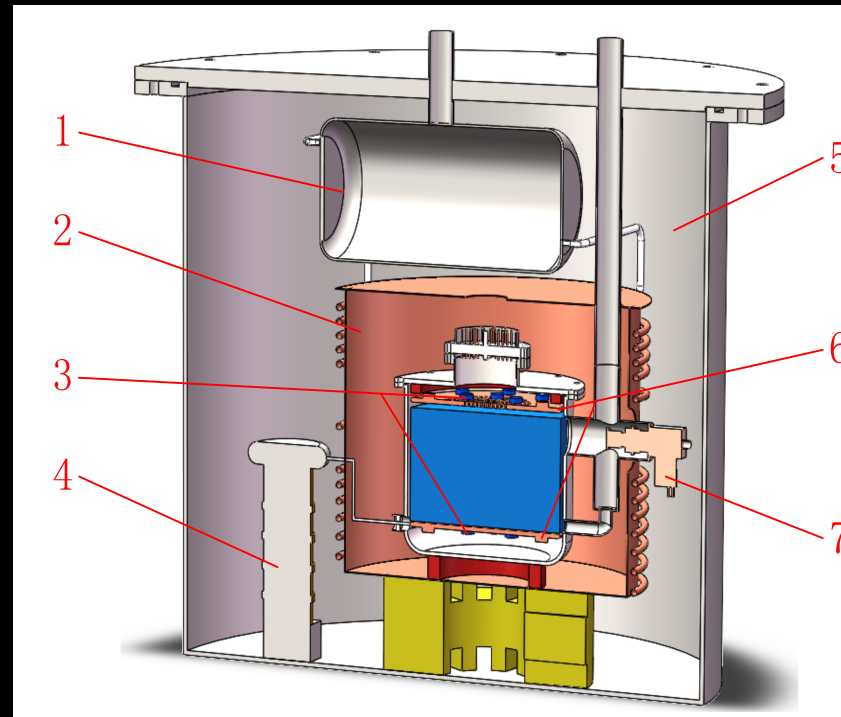
Discovery smoking gun !

Helium

- ALETHEIA: lower threshold, no radioactive isotope



See talk from Junhui Liao



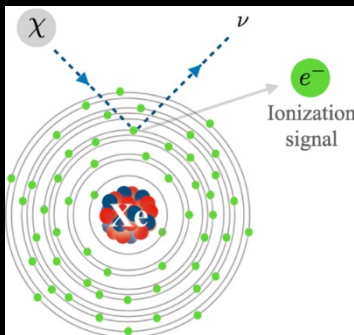
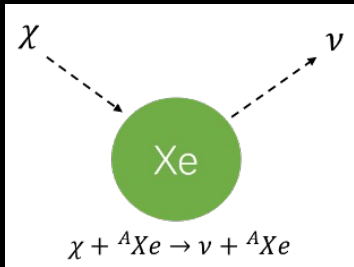
Summary

- **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!

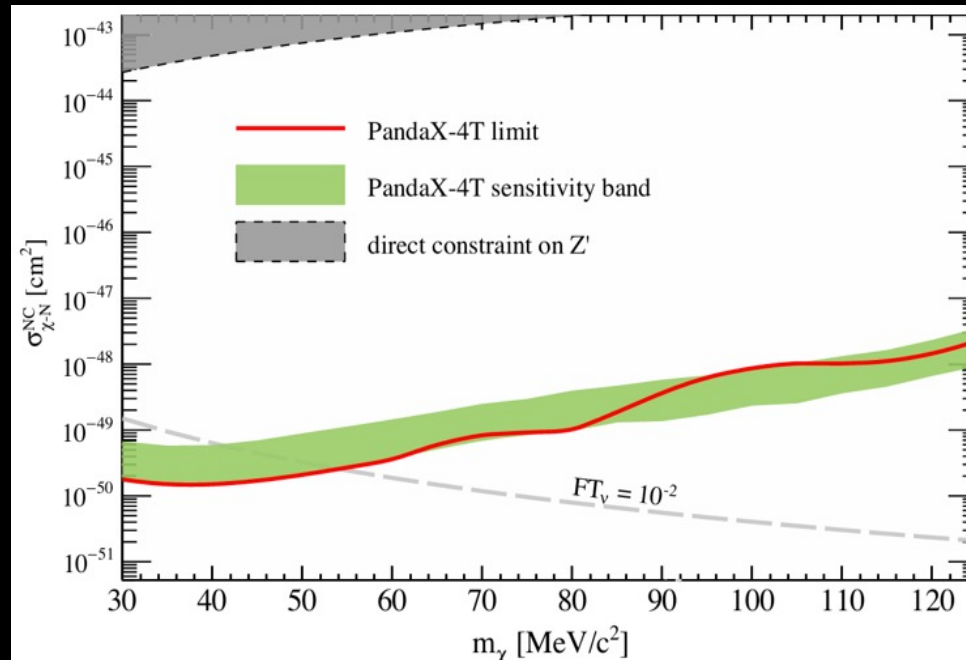
Backup

Low mass DM detection techniques with Noble Gas: example 3

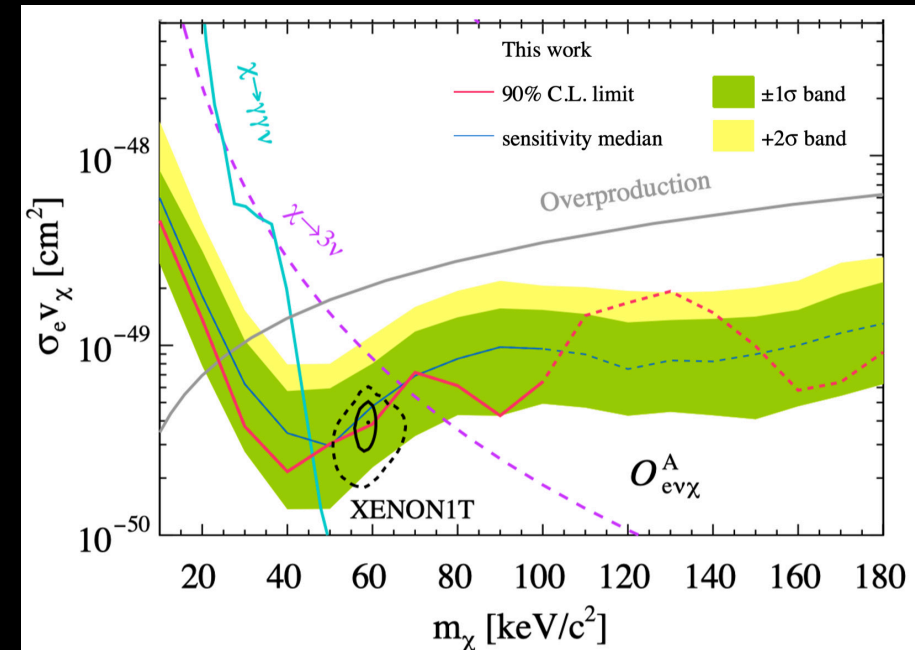
Dark matter absorption on nucleus or electron



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

