Universität Münster



Direct Search for Dark Matter with Xenon Detectors

KMI2026: The 7th KMI International Symposium, Nagoya University, Nov. 9-11, 2027

Christian Weinheimer – Institute for Nuclear Physics, University of Münster, Germany

erc



Outline:

- **Search for dark matter with xenon detectors**
- **XENONnT : WIMP search and solar neutrinos**
- **The future xenon observatory XLZD and LowRad R&D**
- **Conclusions**

living.knowledge

Dark Matter candidates and direct WIMP detection



Weakly Interacting Massive Particles (WIMPs):

„The natural Cold Dark Matter candidate“

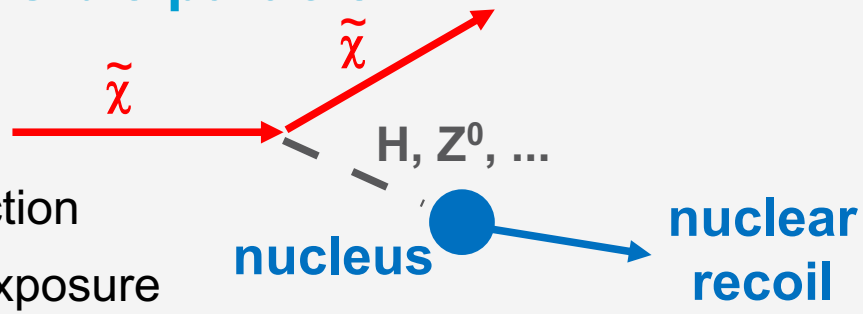
WIMPs would be naturally created with the right abundance in the early universe !

SUSY has not been detected yet, **but also many other models beyond SUSY producing WIMPs !**

Search for nuclear recoil: energy transfer to nucleus by invisible particle

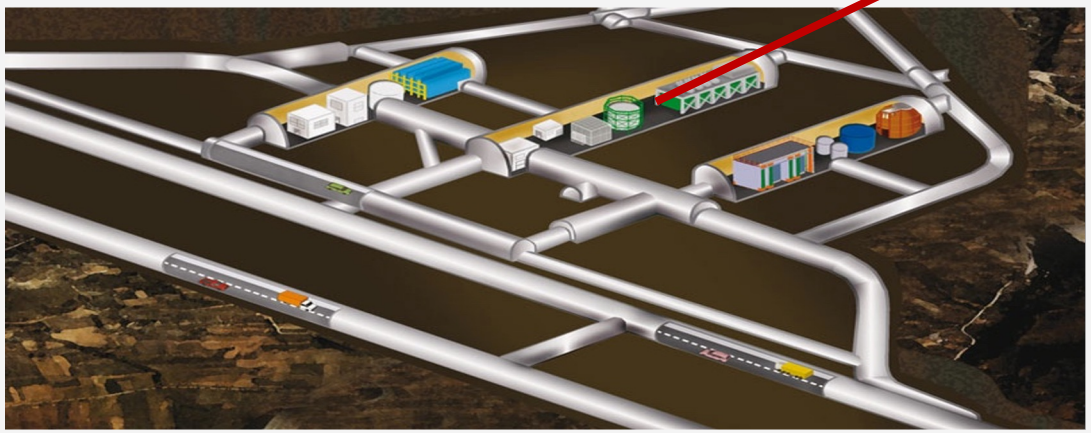
Elastic coherent scattering of the nucleus

- mediated by a spin 0 (Higgs-like) or spin 1 (Z-like) propagator
  effectively a coherent spin-independent (SI) or spin-dependent (SD) interaction
- low recoil energy & cross section requires very low background and large exposure



Direct search for dark matter
XENONnT @Laboratori Nazionali Gran Sasso (LNGS)





Laboratori Nazionali del Gran Sasso (LNGS), Italy



XENON Collaboration
~ 180 scientists
30 institutions
12 countries



Dual Phase Xenon Time Projection Chamber

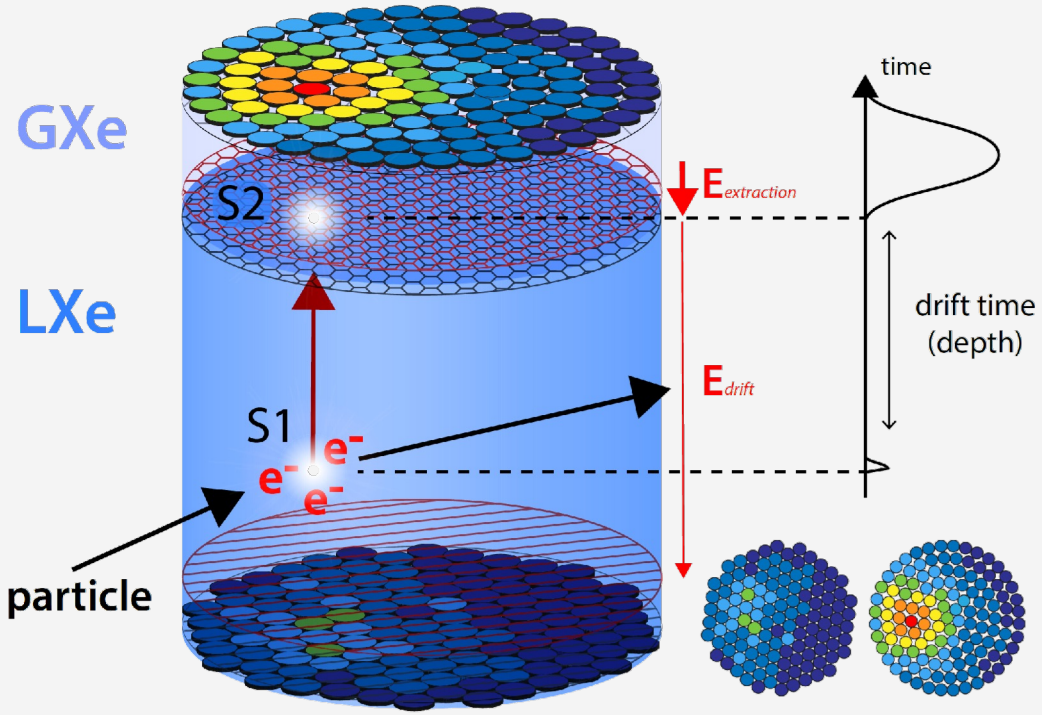
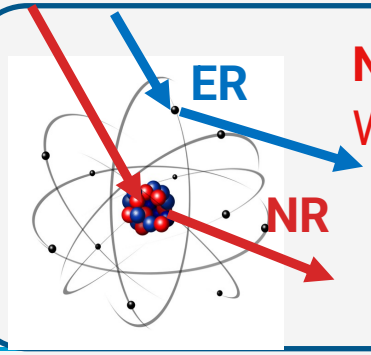


Image by L. Althüser

S1 light signal:
- prompt scintillation photons

S2 charge signal:
- secondary scintillation photons from electroluminescence in GXe due to drifted electrons

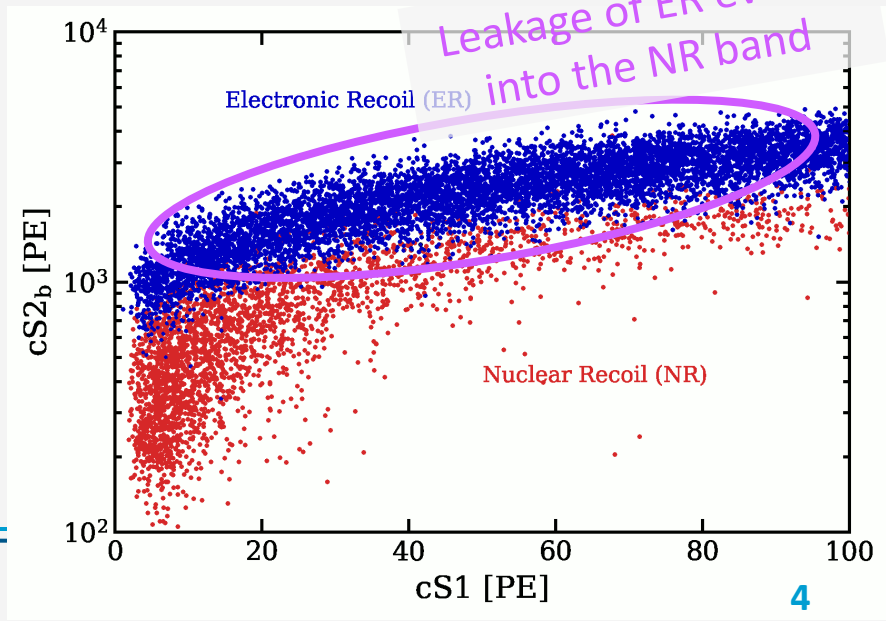
3D vertex reconstruction (-> fiducialisation):
- X,Y: S2 hit pattern
- Z: drift time S2-S1



NR (Nuclear Recoils)
WIMP signal, neutrons, CEvNs

ER (Electronic Recoils)
γ, β backgrounds

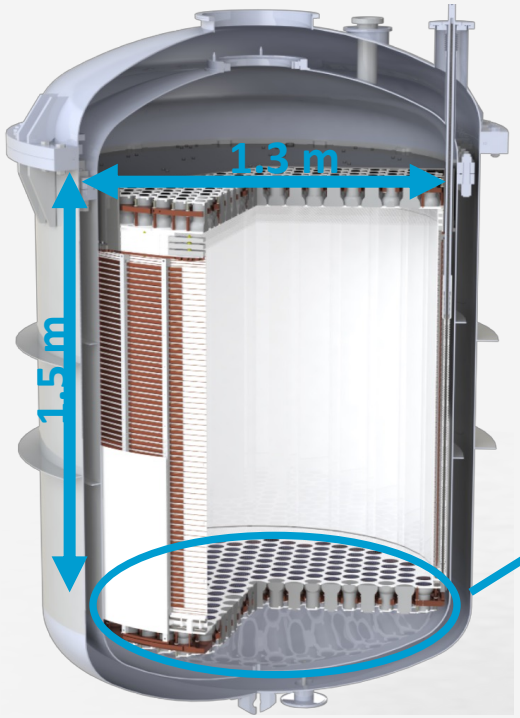
Discrimination from S2/S1
Larger for ER than NR

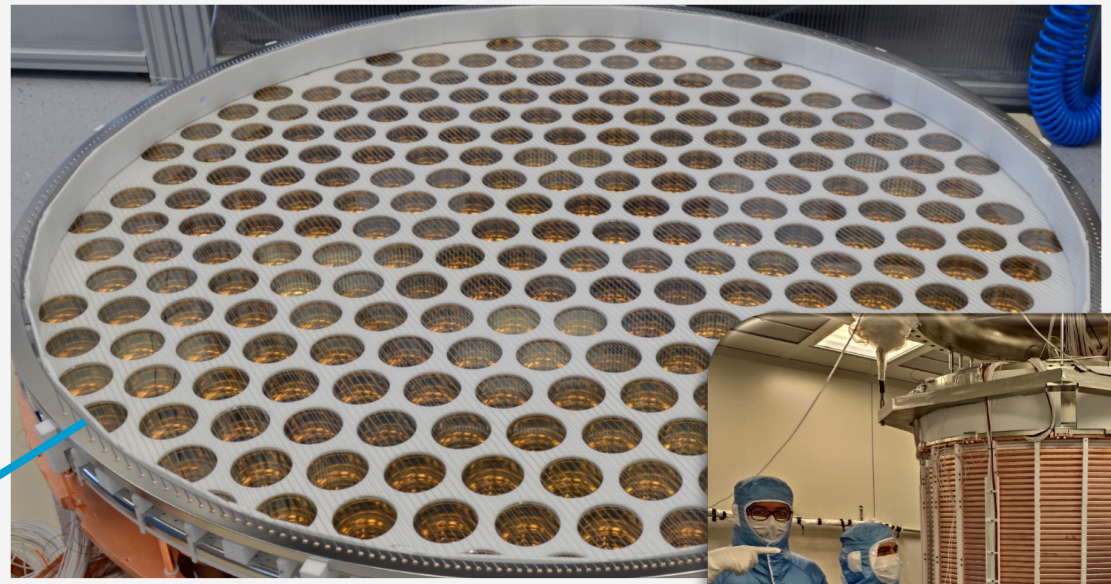


XENONnT's time projection chamber (TPC)

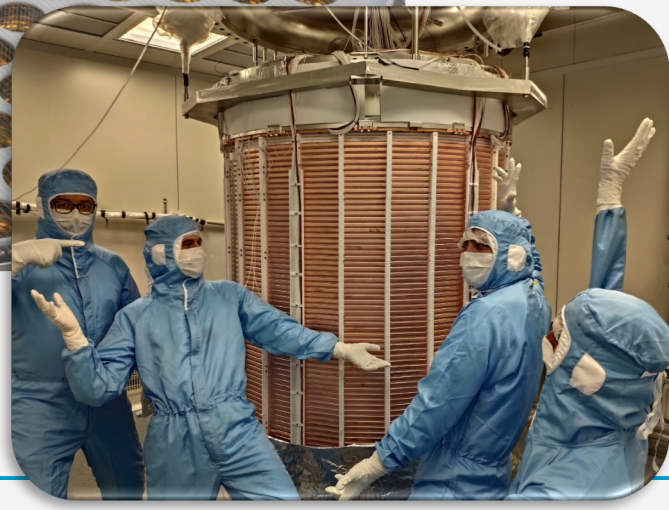


- Cylindrical PTFE walls for high reflectivity,
  all materials carefully screened and selected
- **Inside TPC: 5.9 t of liquid xenon (> 4 t fiducial volume)**
- 494 3" PMTs (R11410-21)
- 3 meshes (cathode, gate and anode) and a field cage to define electric fields



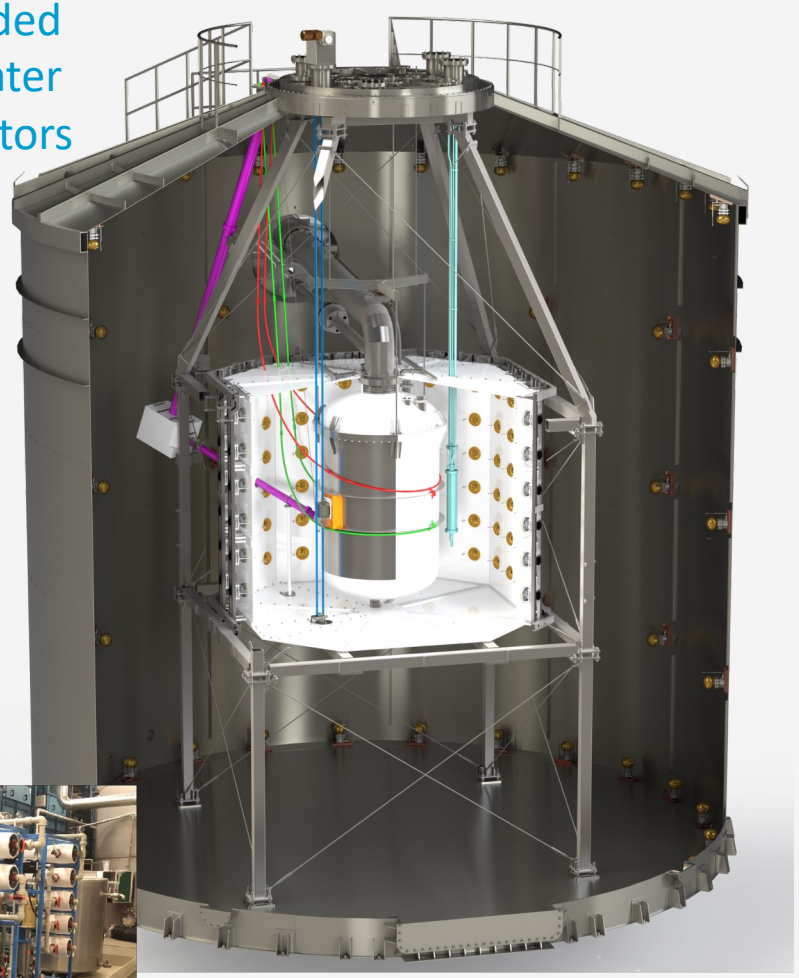






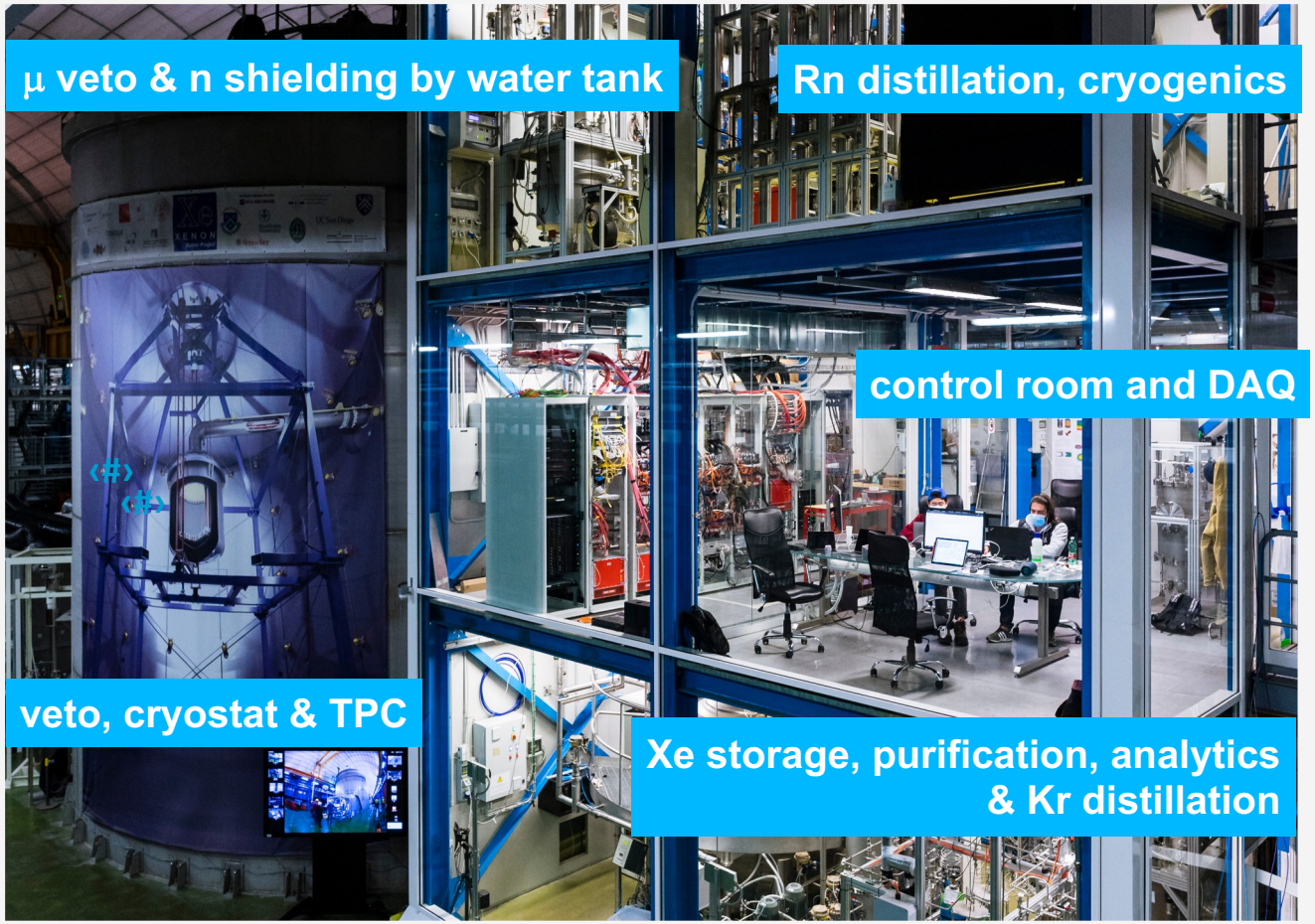
XENONnT muon & neutron veto and infrastructure

Gadolinium-loaded nested water Cherenkov detectors





Gadolinium Doping Plant

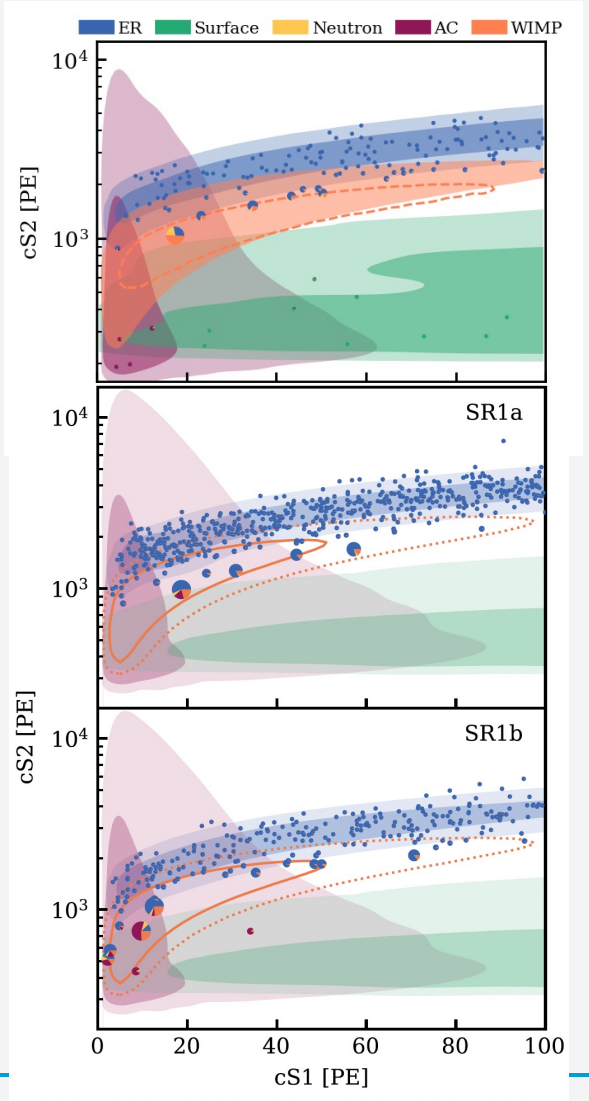


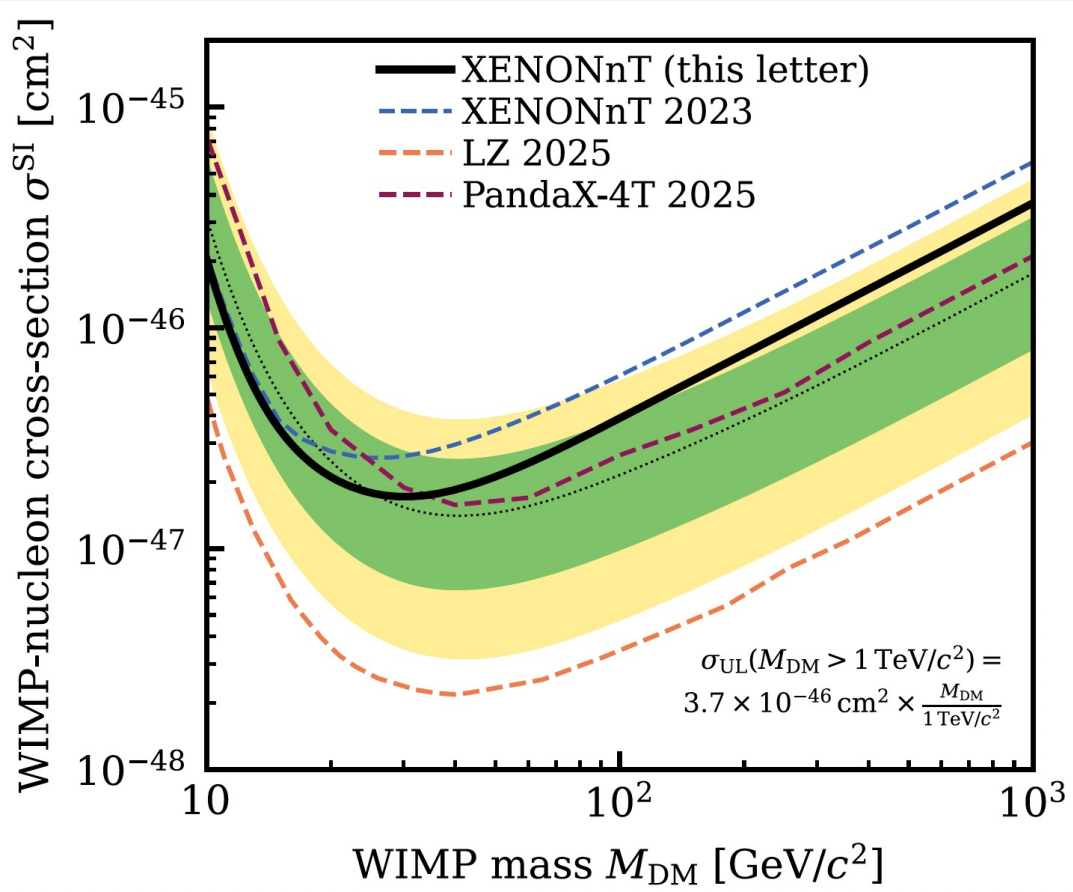
Super-Kamiokande Collab. NIM A 1027 (2022) 166248

XENON Collab., Eur. Phys. J. C 85 (2025) 695

Direct WIMP search with XENONnT: SR0+SR1

Blind analysis of SR0+SR1 science data: 3.1 tonne x years





No WIMP detected yet ☹

Currently better limits and partly higher sensitivity by LZ and PandaX-4T

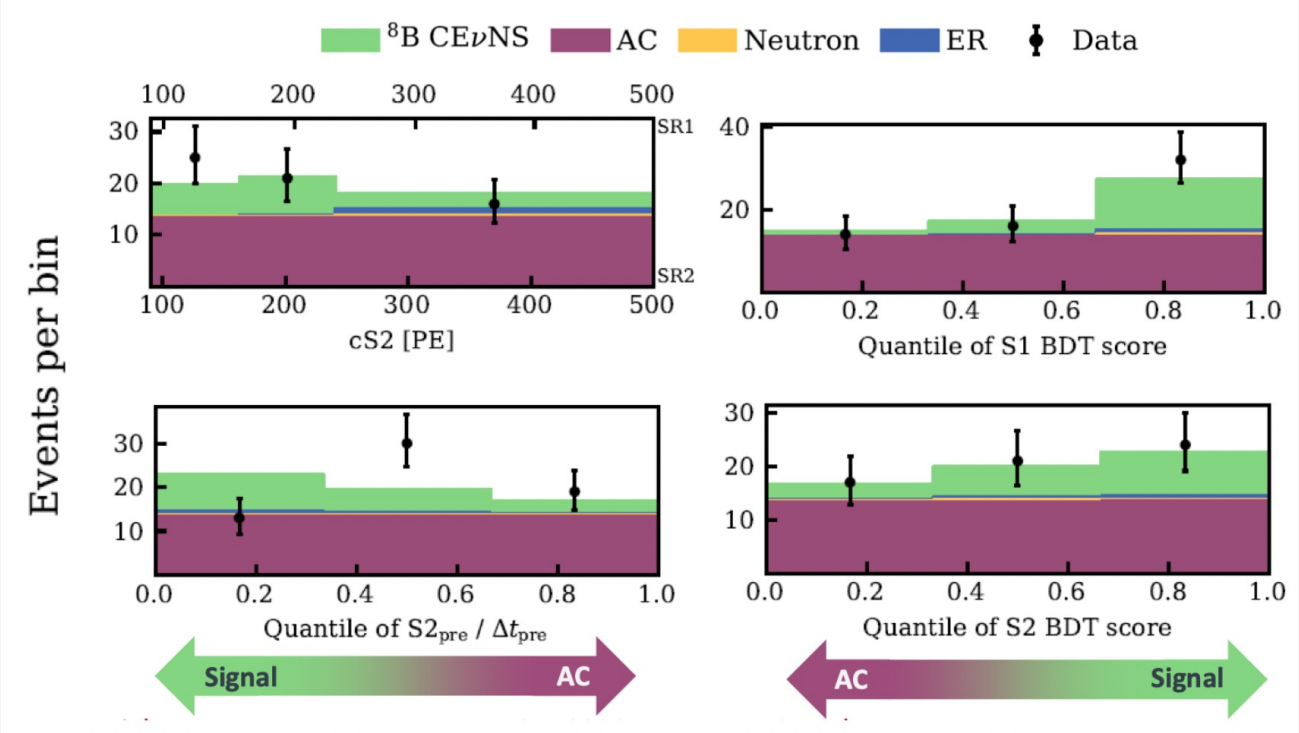
XENONnT will unblind SR2 data soon and has perfomed a detector upgrade (see later)

Phys. Rev. Lett. 135 (2025) 221003

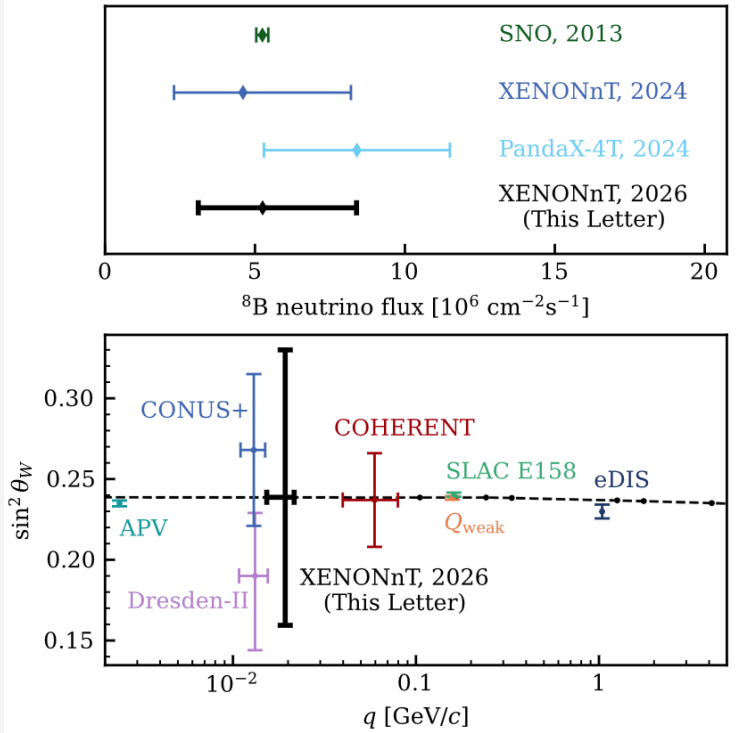
XENONnT: Solar 8B neutrinos via CEnNS SR0+SR1+SR2

very low threshold by requiring 2-fold instead of 3-fold PMT coincidences

CEνNS: $\sigma_{\mathrm{CE\nu NS}} \propto Q_W^2 \propto [N - (1 - 4sin^2 Q_W)Z^2]^2$



Phys. Rev. Lett. 137 (2026) 091807

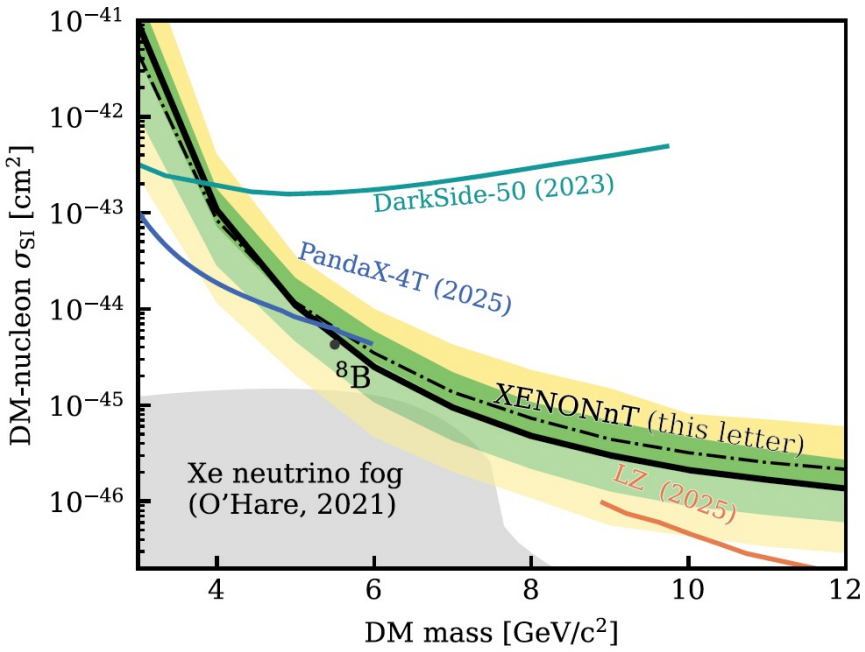


XENONnT: 3.3σ CEνNS signal

LZ: 4.5σ (August 2026), PandaX-4T: 2.6σ

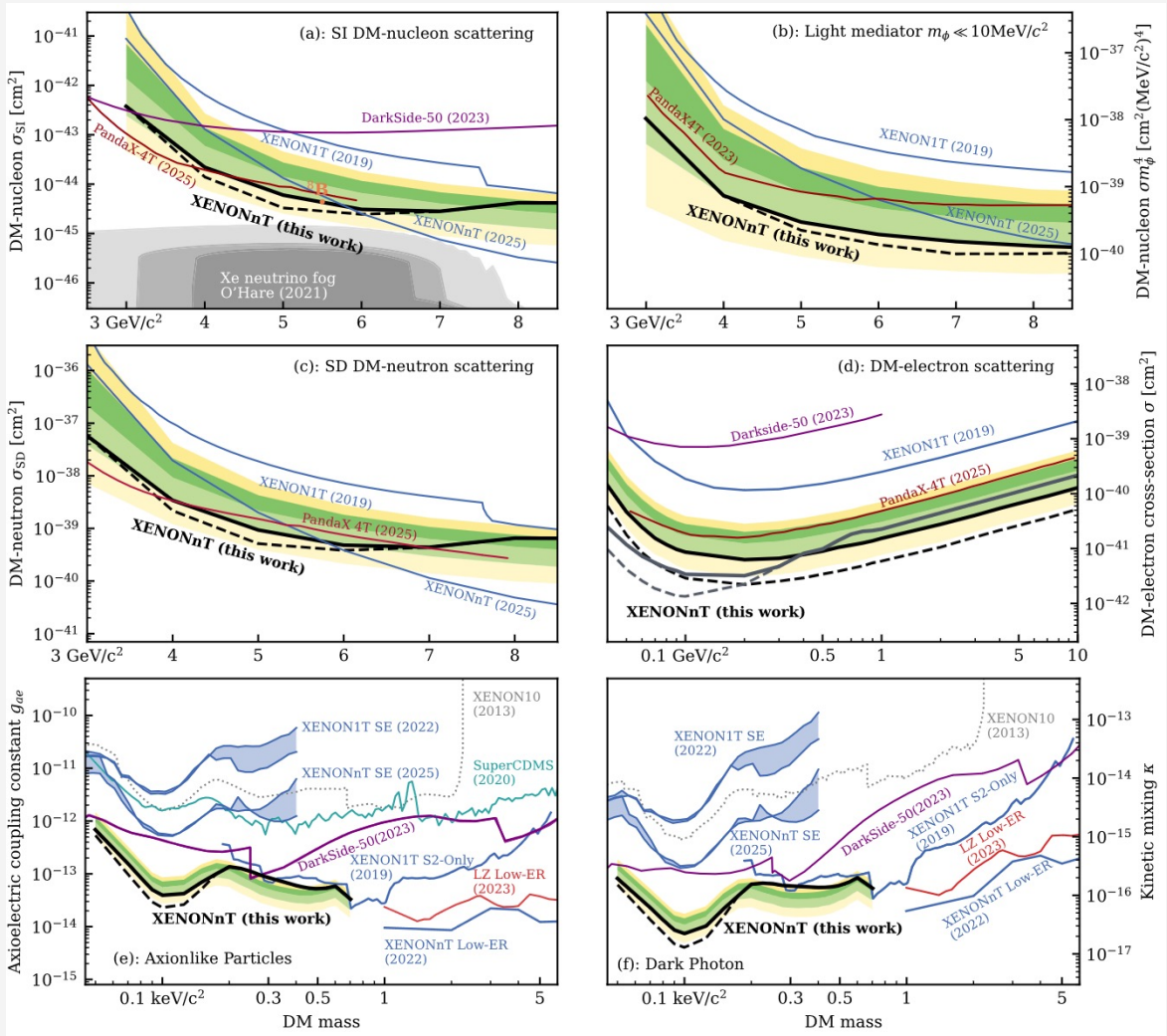
Light dark matter search with XENONnT: SR0+SR1+SR2

Using CEνNS analysis assuming ^{8}B flux from SNO



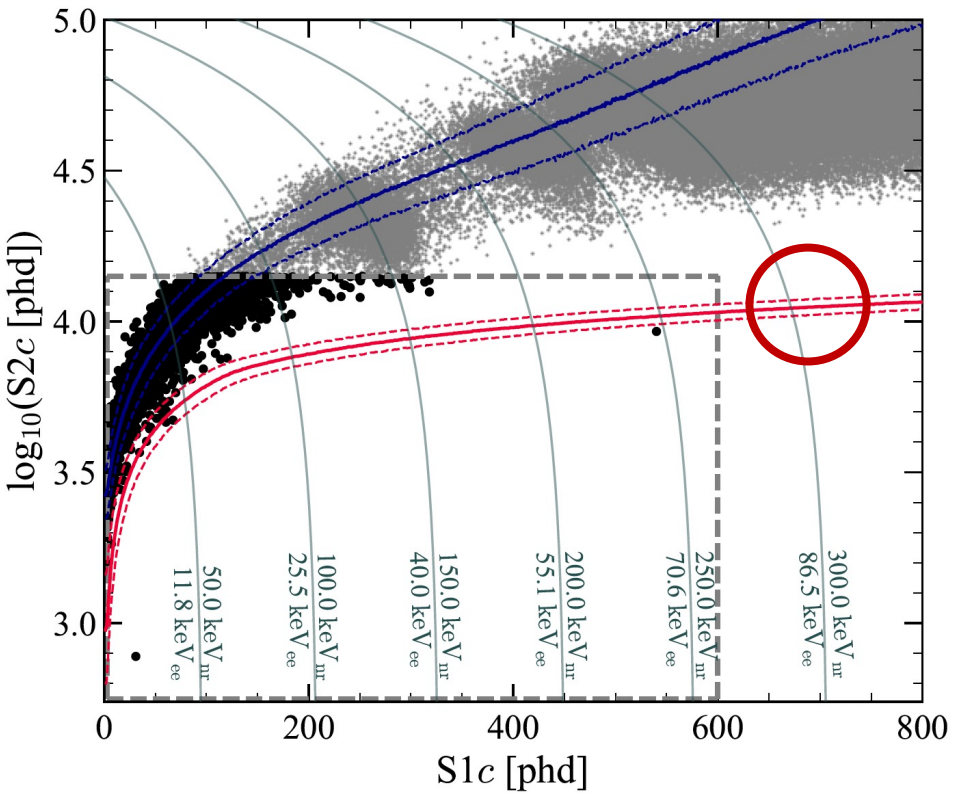
Phys. Rev. Lett. 137 (2026) 091807

Using S2-signals (charge) only



Phys. Rev. Lett. 137 (2026) 051003

High nuclear recoil event observed at LZ



arXiv:2609.02823

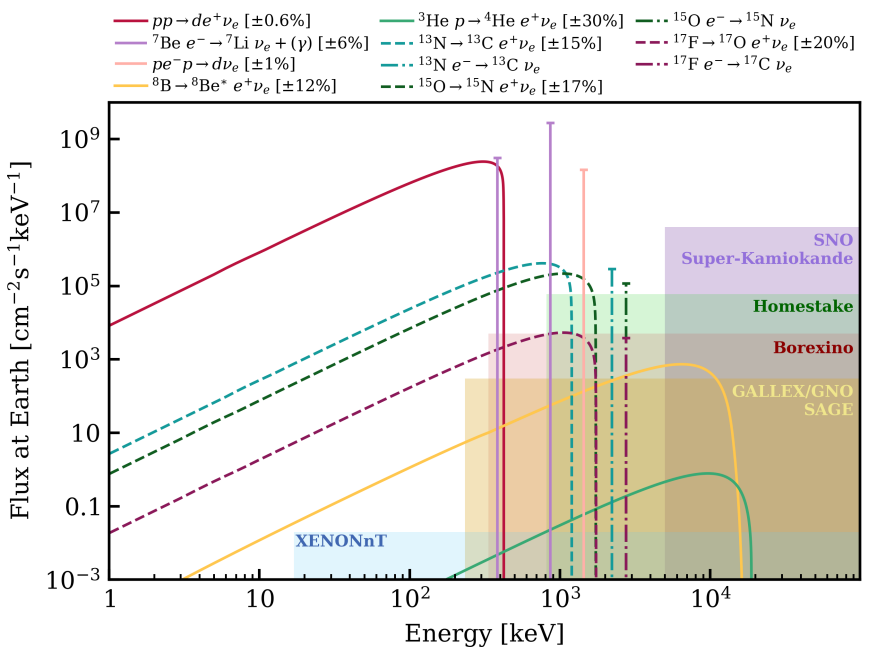
- Event is at 2.6σ tension with background only hypothesis
- $E_{nr} = 248 \pm 23$ (stat) ± 23 (sys) keV
- Data from 2.84 t · yr exposure (3 times more data by LZ recorded)

- Standard WIMP coupling would have given more events at lower nuclear recoil energies
- Explanations are possible in effective field theories (NREFT) or require other BSM physics (lots of theory papers on arXiv)
- XENONnT is performing a blinded analysis with ≈ 6 t · yr exposure
- PandaX-4T s probably doing the same ...

New kid around the blog by XENONnT:

Low energy solar neutrinos via elastic scattering: pp (and ^{7}Be) neutrinos

SR0+SR1b, possible because of XENONnT's ultralow electron recoil background & diagnostics



arXiv:2608.29450

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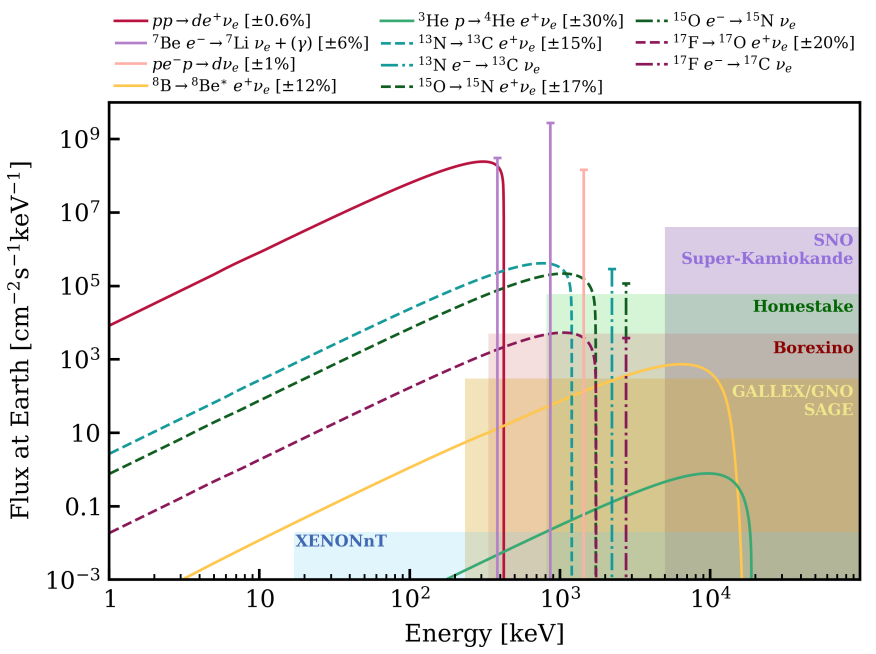
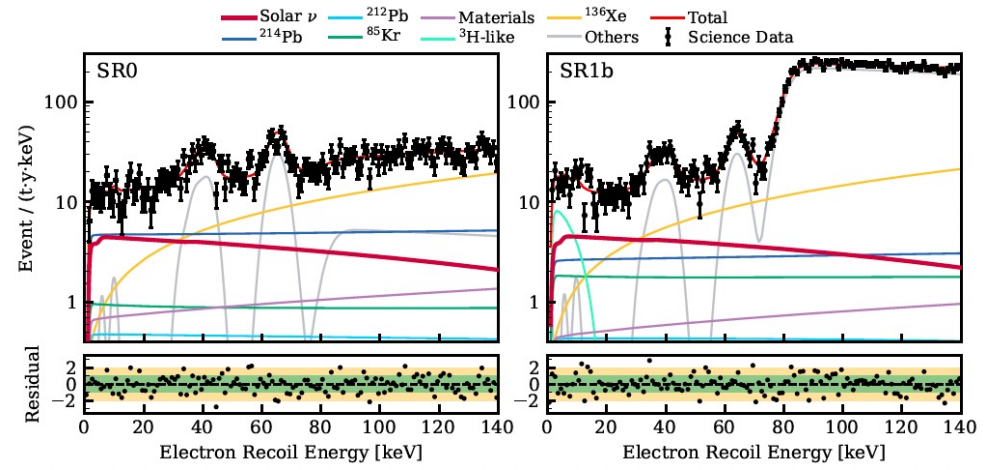
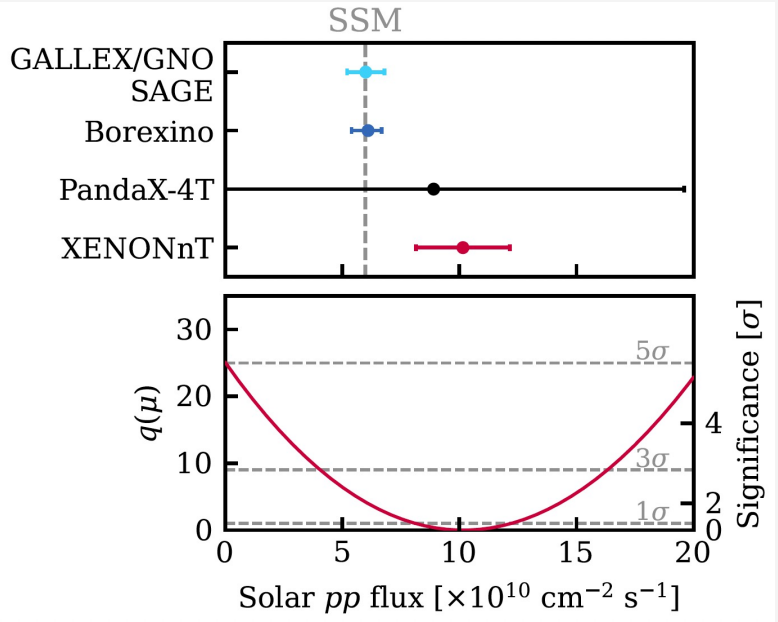




	SR0	
	Nominal	Best-fit
Solar ν	295	500 ± 70
^{124}Xe DEC	270	343 ± 22
^{214}Pb	740 ± 40	740 ± 30
^{212}Pb	68 ± 13	68 ± 12
^{85}Kr	130 ± 40	130 ± 30
Materials	160 ± 40	150 ± 30
^{3}H-like	–	–
^{136}Xe	1460 ± 50	1430 ± 40
^{133}Xe	140	310 ± 60
^{83m}Kr	free	98 ± 14
^{125}I	–	–
Accidentals	0.4 ± 0.3	0.5 ± 0.3

arXiv:2608.29450

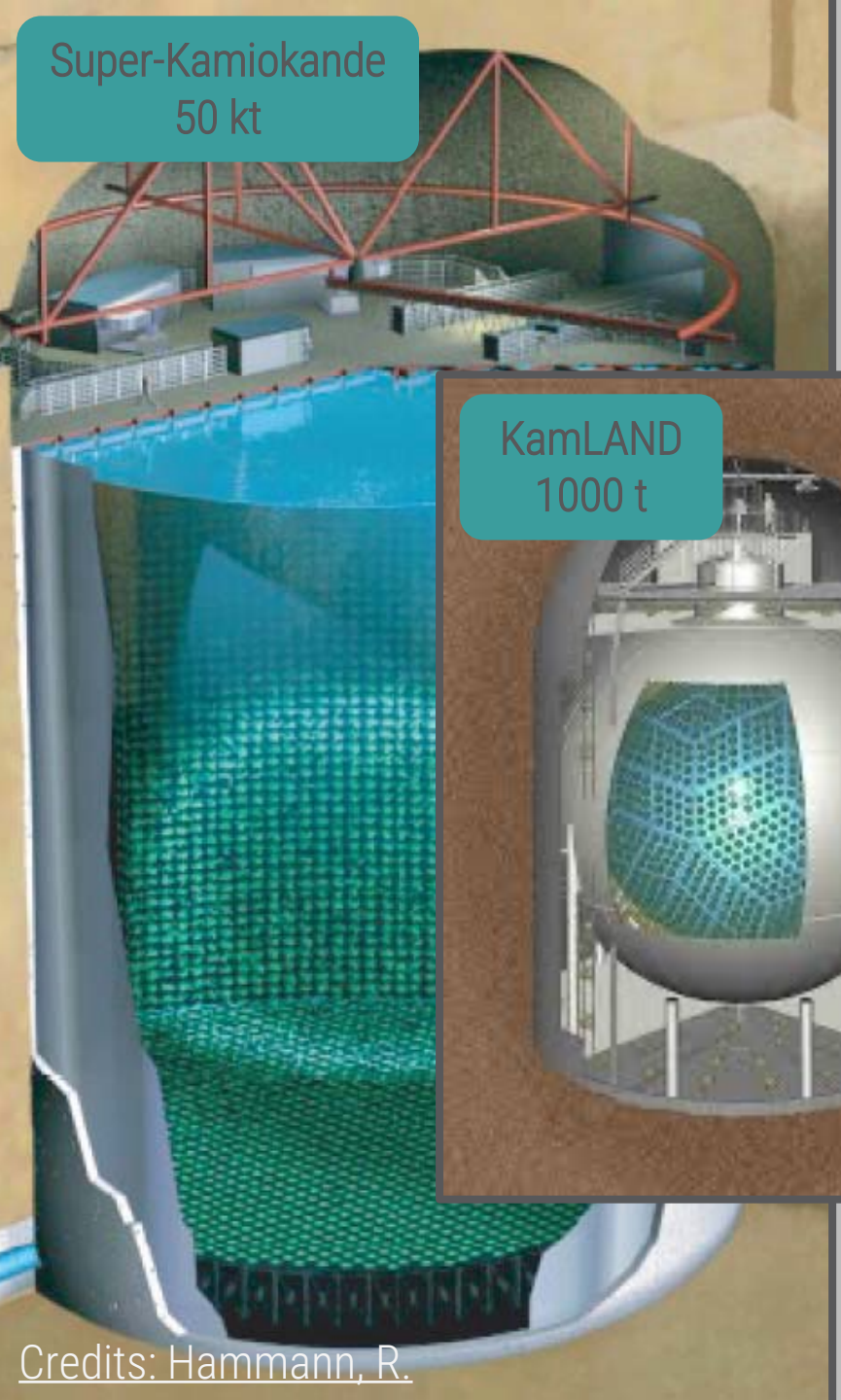
	SR1b	
	Nominal	Best-fit
Solar ν	387	660 ± 90
^{124}Xe DEC	351	445 ± 28
^{214}Pb	538 ± 24	537 ± 23
^{212}Pb	80 ± 10	80 ± 10
^{85}Kr	390 ± 170	330 ± 110
Materials	137 ± 17	136 ± 17
^{3}H-like	233	92 ± 18
^{136}Xe	1990 ± 70	1950 ± 60
^{133}Xe	15937	16740 ± 140
^{83m}Kr	free	111 ± 19
^{125}I	39	0 ± 30
Accidentals	1.3 ± 0.1	1.3 ± 0.1

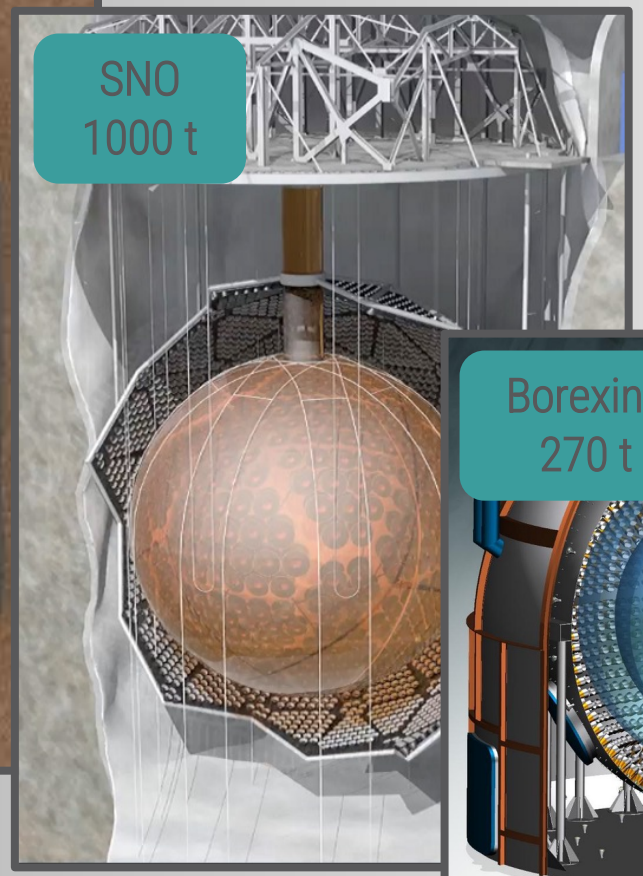


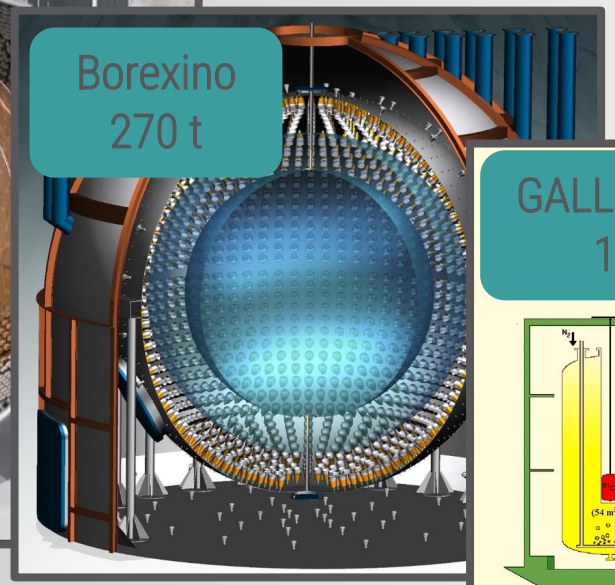
XENONnT:
First solar pp neutrino signal from a xenon detector
5σ signal

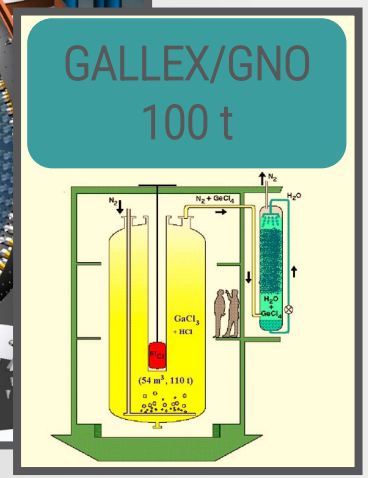
Statistically compatible with previous measurements at 1.9σ

XENONnT is the smallest solar neutrino detector!









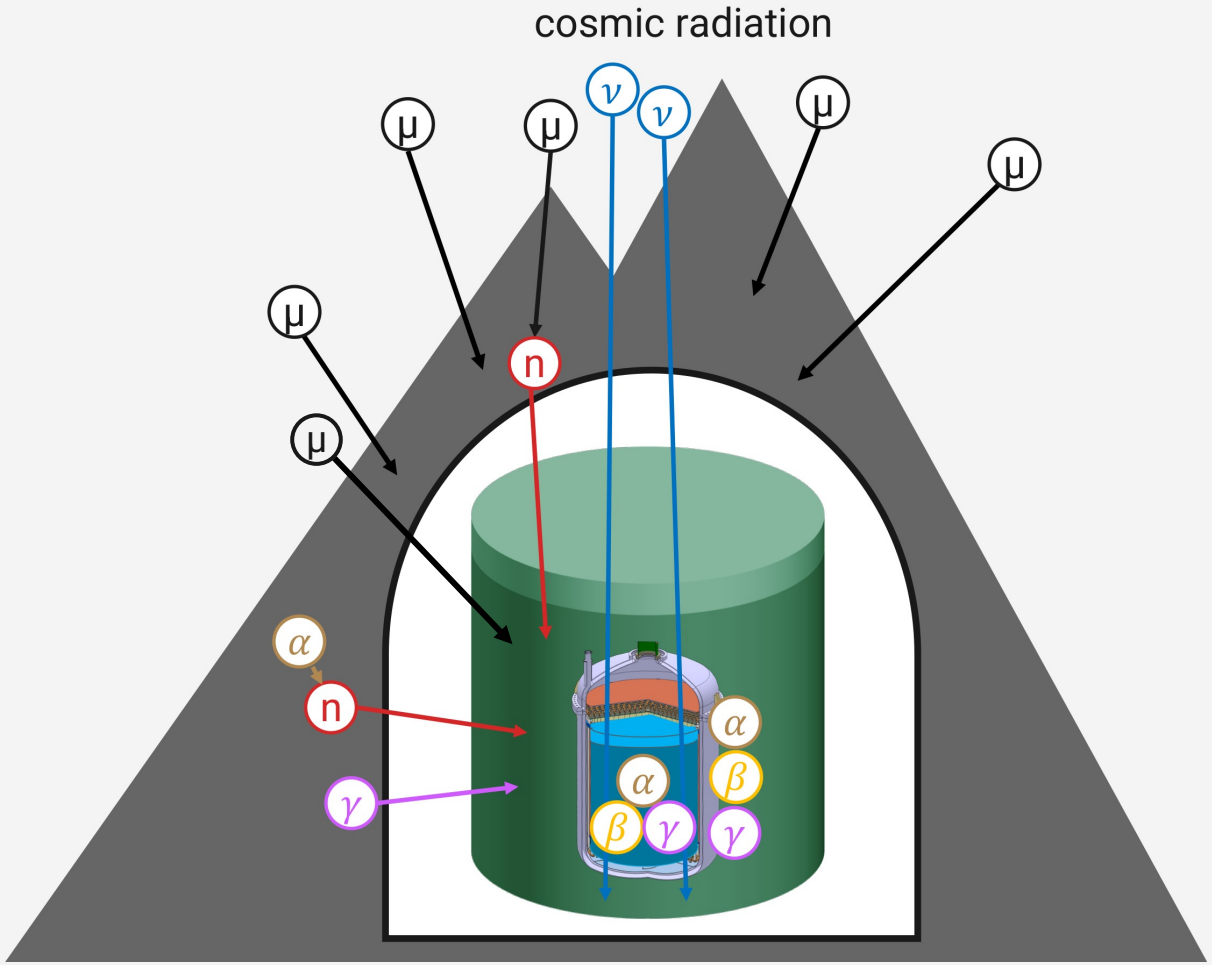


This dark matter detector is becoming an observatory ...



Credits: Hammann, R.

Limiting backgrounds in noble gas DM detectors



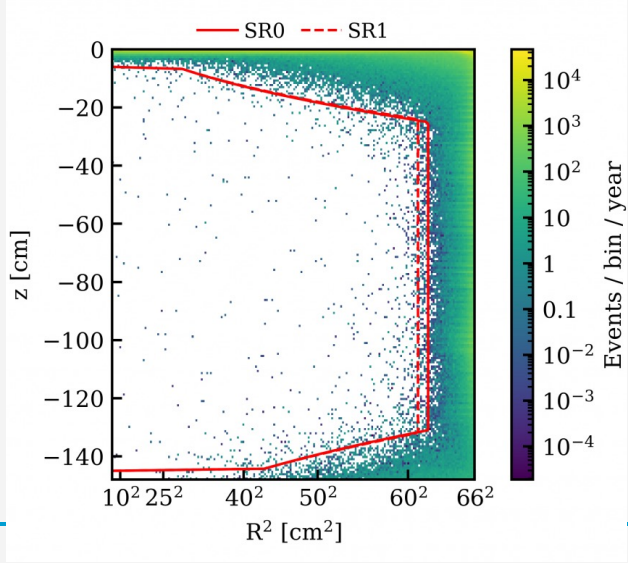
Expected dark matter scattering or 0νββ rate:

1 - 10 events per 10t and year

⇒ Profit only from larger experiments if the experiment remains background-free

Most background problems solved by

- going underground
- careful material screening & selection
- extra shieldings & vetos
- fiducialisation



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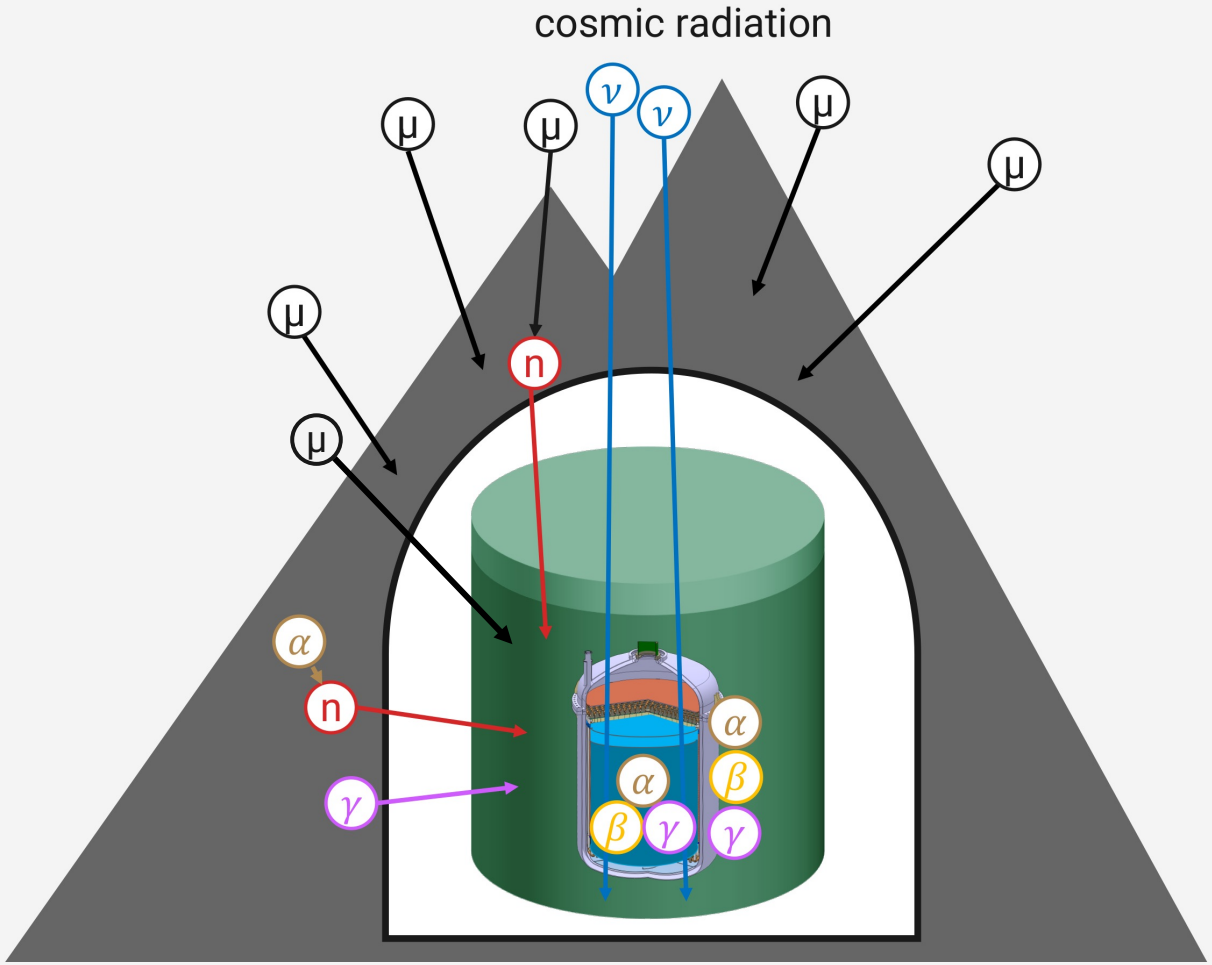

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Two remaining backgrounds:

- solar neutrinos, non-shieldable
- **intrinsic radioactive noble gases:**
  ^{85}Kr, ^{222}Rn and progenies, (^{37}Ar, ^{39}Ar, ^{136}Xe)

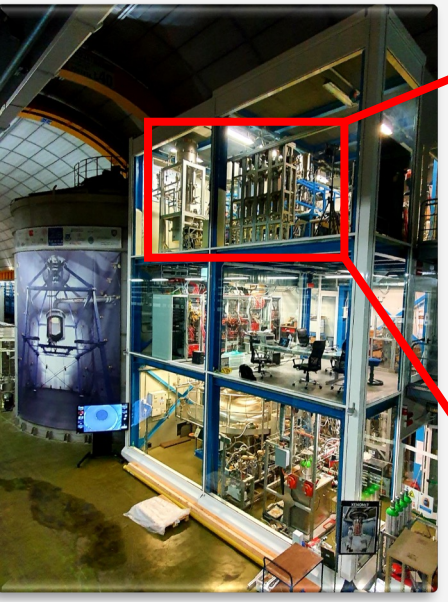
→ active Kr & Rn removal, e.g. by cryogenic distillation

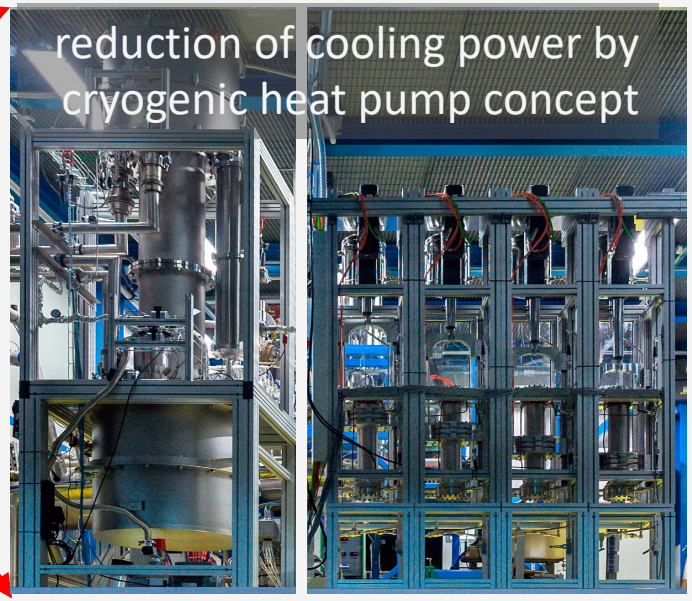
Active Radon removal at XENONnT

Cryogenic distllation system - key parameter:

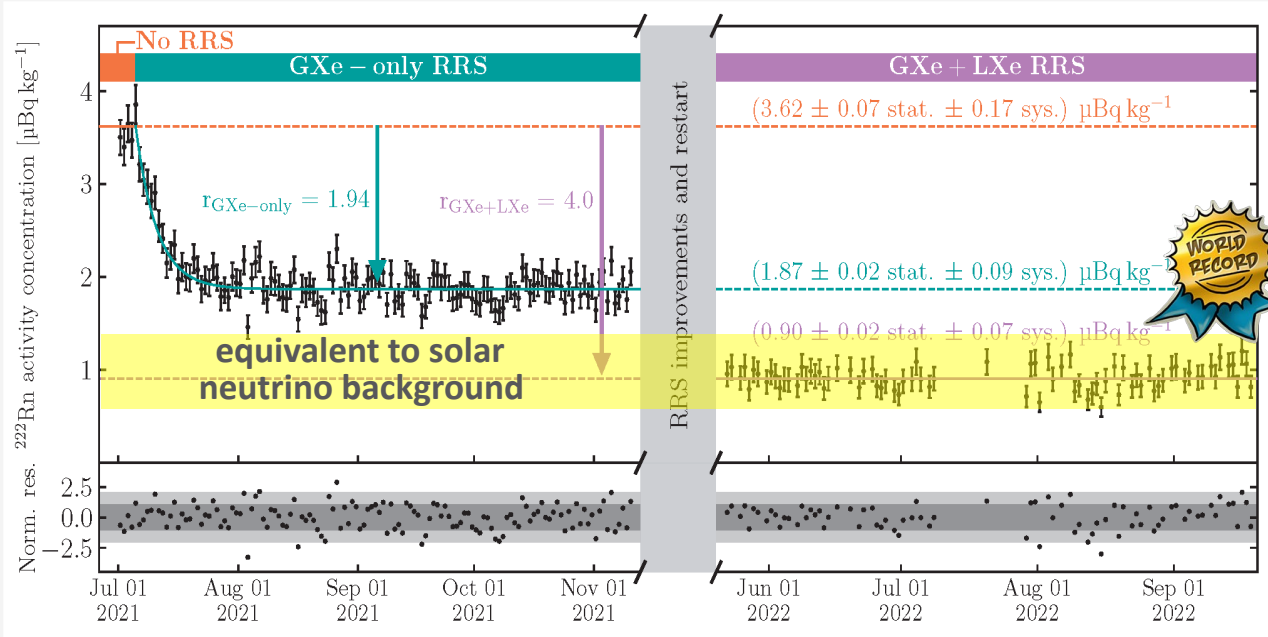
- flow of 0.4 l/min LXe = 200 SLPM ≈ 70 kg/h
- **reduction by factor of 4** for sources within detector/extern by LXe (GXe) extraction

  → **as low as solar ν-induced ER bg !**





Radon concentration at XENONnT



Proof of basic removal concept: *Eur. Phys. J C77, 358 (2017)*

Design of XENONnT system: *Eur. Phys. J. C82, 1104 (2022)*

Demonstration at XENONnT: ***Phys. Rev. X 15 (2025) 031079***
(Web of Science Core Collection)

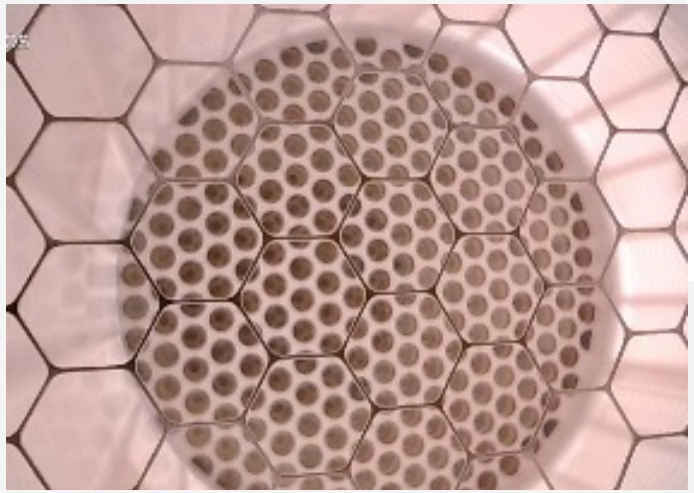
Upgrade of XENONnT Q2/2025-Q3/2026

Looking inside the TPC to observe the broken wire on the bottom screen

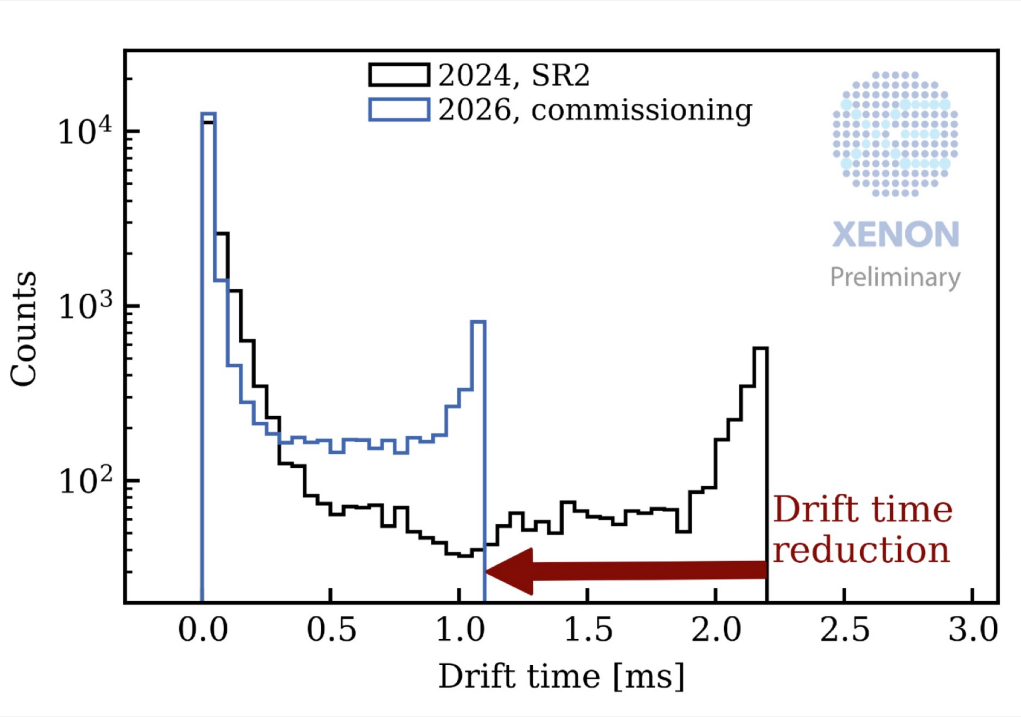




The new cathode



Looking inside to the top array through the new cathode



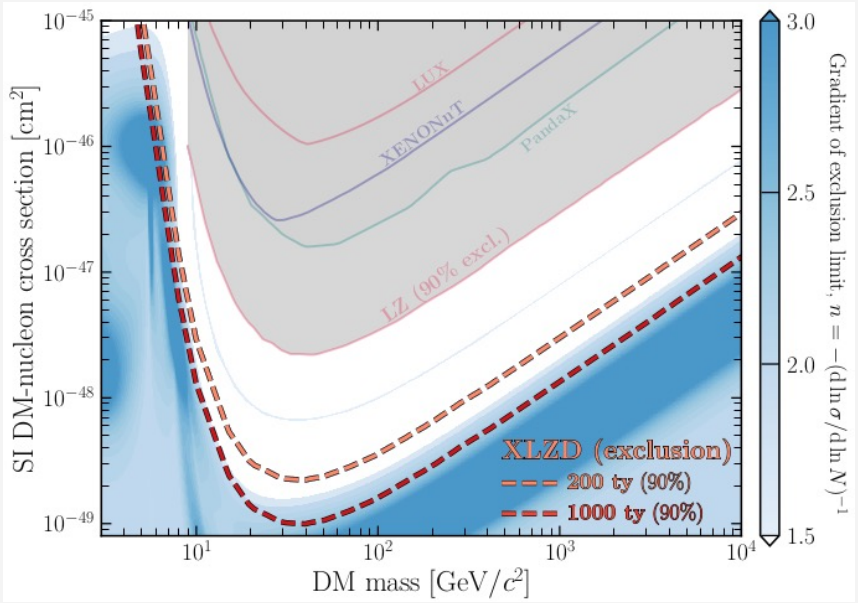
Now back to intended drift field strength ...

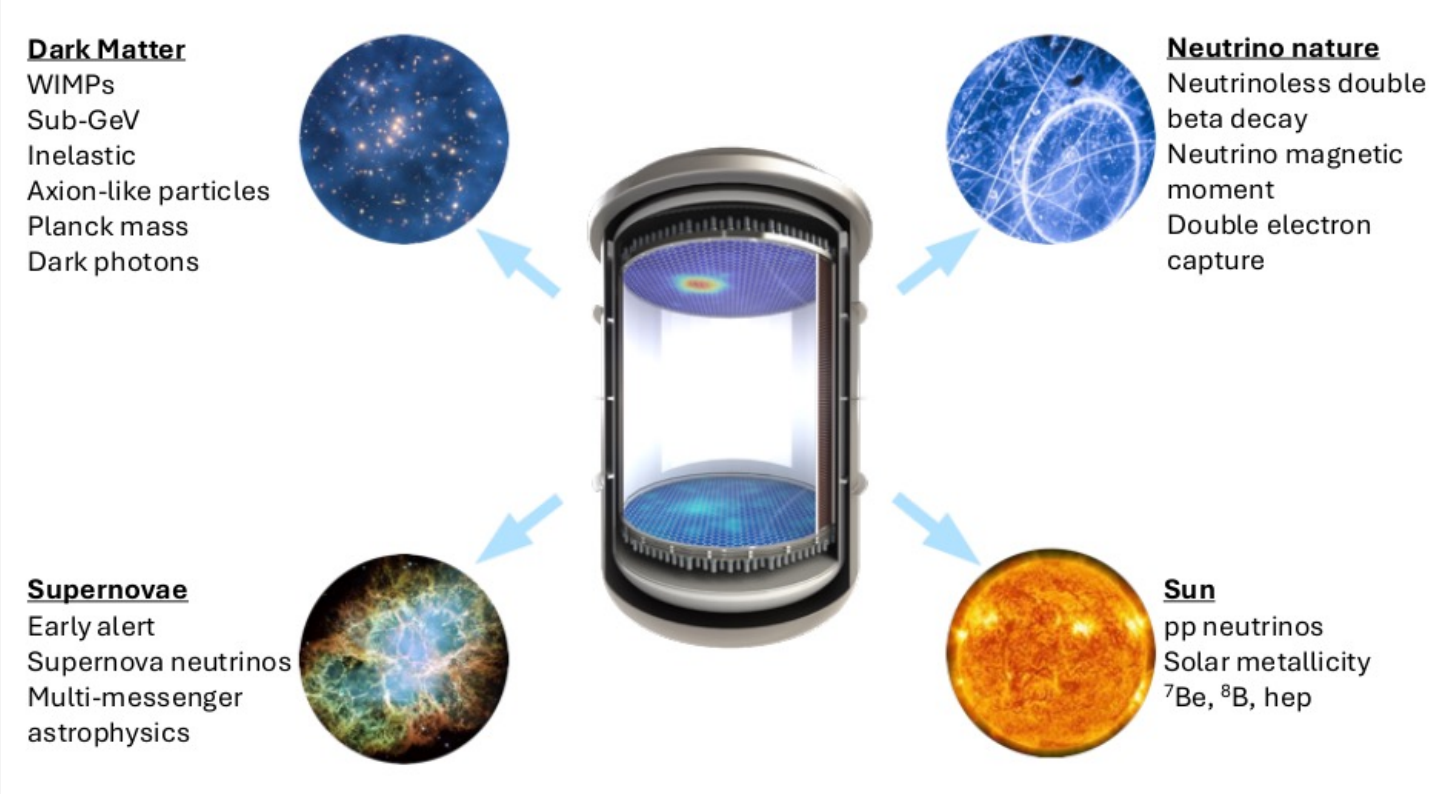
Future: XLZD (XENON-LUX-ZEPLIN-DARWIN)

A xenon-based low-background observatory for astroparticle physics

- **Broad science case: dark matter, neutrino physics, ...** → **astroparticle physics observatory**

down to the neutrino fog ...





A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics, J. Phys. G 50 (2023) 013001
XLZD Design Book: Eur. Phys. J. C 85 (2025) 1192

Low radon and low internal radioactivity
for dark matter and rare event xenon detectors
ERC Advanced Grant LowRad (PI: C. Weinheimer)

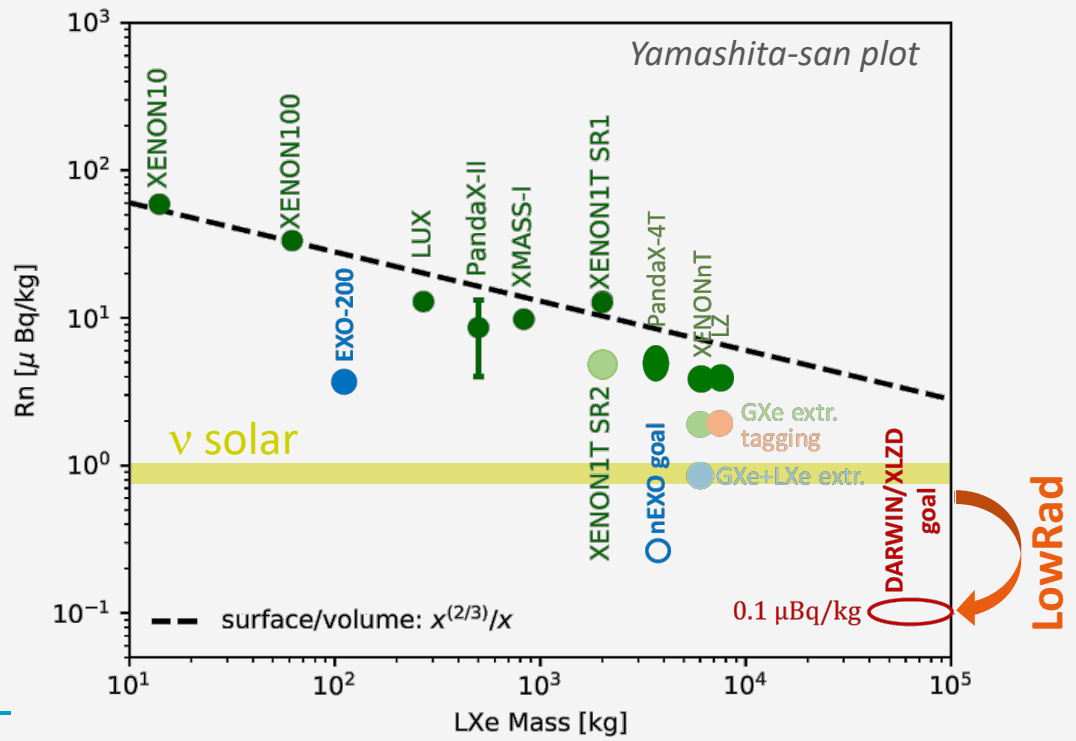
Goal: Develop and demonstrate the Kr and Rn removal technologies for the next generation
dark matter experiment XLZD with a sensitivity down to the neutrino fog (and for more channels, e.g. $0\nu\beta\beta$)

Challenges/tasks for reaching background rates by ^{85}Kr and ^{222}Rn being 10-times smaller than by ν_{solar}

- Continuous/**online nearly lossless ^{85}Kr removal** (30 ppq ^{nat}Kr)
- Another **factor 10** in **^{222}Rn reduction** (0.1 µBq/kg),
  factor 6 by cryogenic distillation
- Use fact, that cryogenic distillation enhances concentration
  on one side → **sensitive online diagnostics**
- Complete **purification* & distillation demonstrator**
  → pave the way for an **all-in-one** purification & distillation system

Goal: "less than 1 Radon atom in 160 mol of xenon"

** cooperation with Nagoya University, Columbia University, MPIK*



Radon Removal System: Demonstrator for XLZD

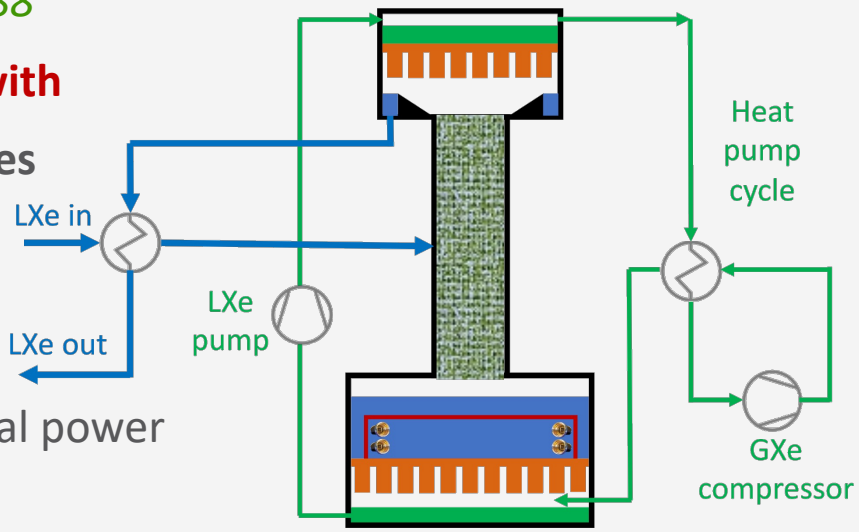
LowRad proof-of-principle of a cryogenic heat pump

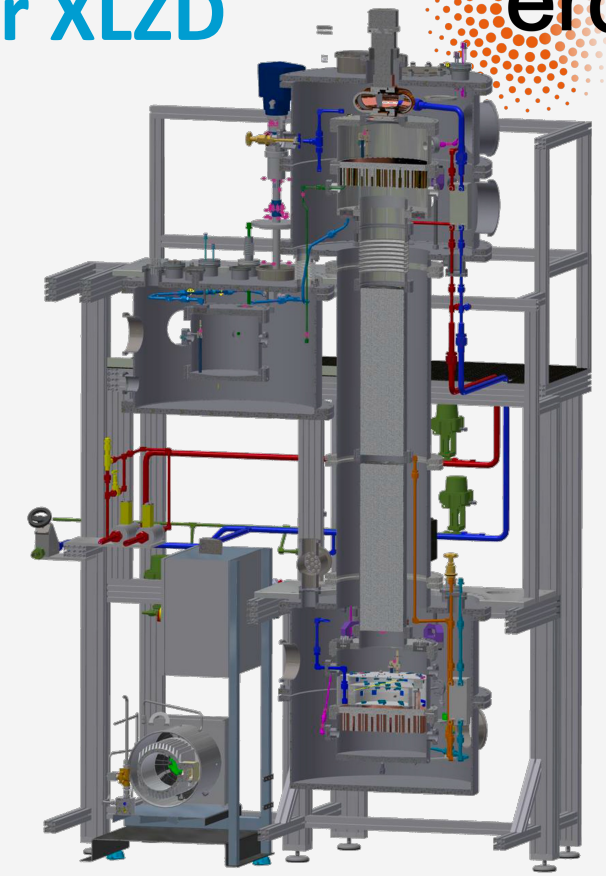
with Xe as medium: *Eur. Phys. J. C 86 (2026) 488*

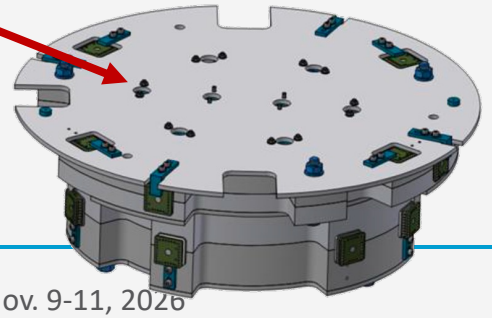
Next stage: **radon removal system demonstrator with**

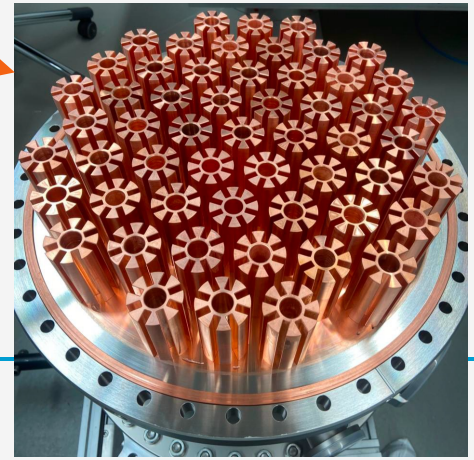
- **separate distillation and heat pump xenon cycles**
- **2nd Xe heat pump cycle, 20 times larger**
  than proof-of-principle setup:
  3 kW cooling and 3 kW heating power
  using a turbine compressor with 4 kW electrical power
  to have a more efficient compression
- **Radon-free heat exchangers**
  nominal distillation flow of 200 slpm (75kg/h)
- **a built-in radon decay detector for monitoring Rn concentration**
  in the reboiler of the distillation system

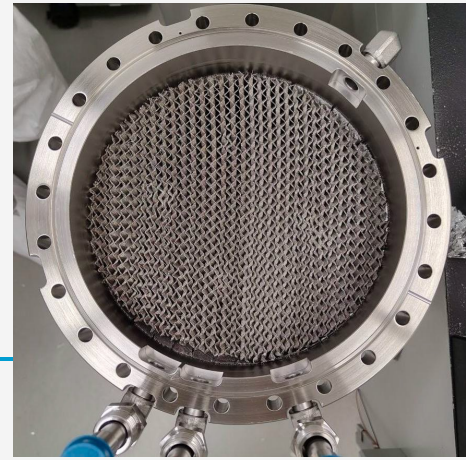
Construction has started!







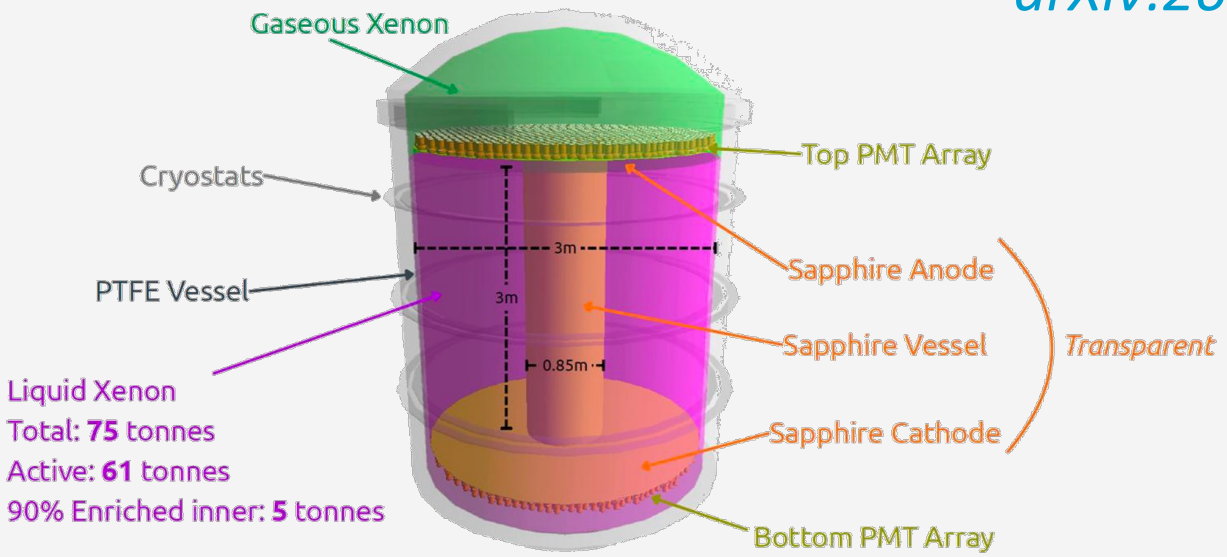


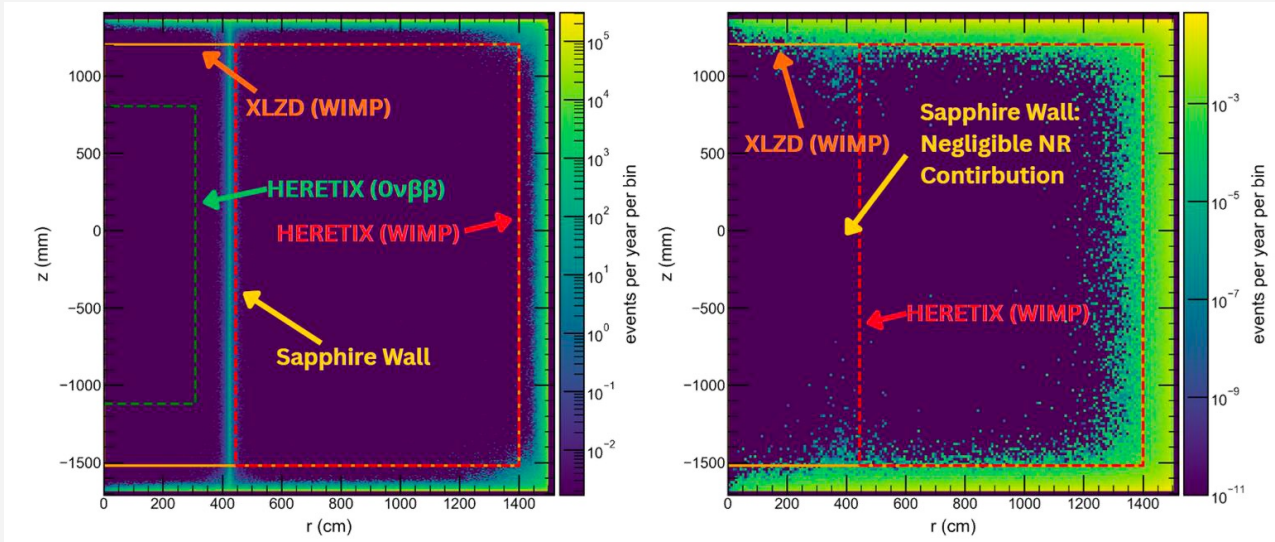


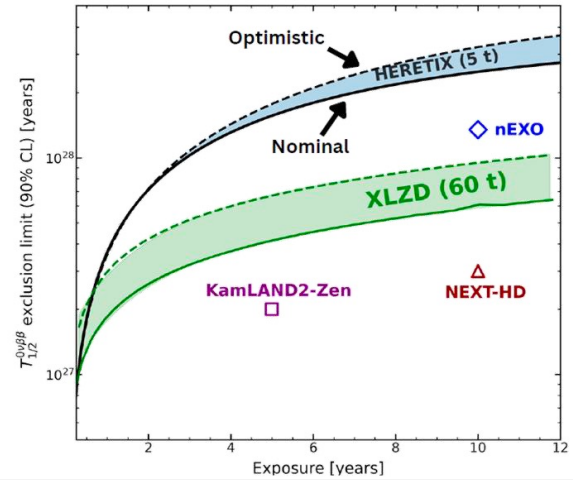
A modified version of XLZD

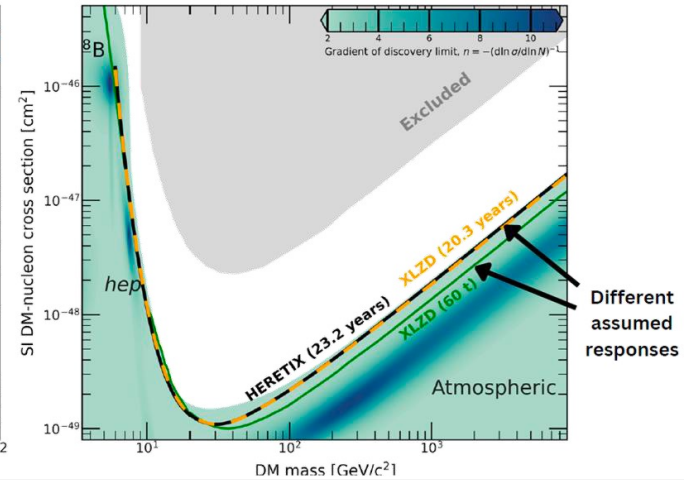
HERETIX: A Hermetic, Enriched, Rare-Event Time Projection Chamber in Xenon

arXiv:2606.26876









Basic idea:

- Two nested Xe detector volumes

- Xe enriched in 0νββ isotope ^{136}Xe is in the central (transparent?) detector shielded by the depleted Xe detector used for dark matter search

→ factor 3-5 sensitivity gain w.r.t. XLZD for 0νββ search

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Conclusions

- Xenon dual phase time projection chambers, such as LZ, Panda-4T and XENONnT
  have improved the WIMP search sensivitity dramatically for masses between a few GeV up to TeV
  no WIMP signal yet,
  but a candidate at very high nuclear recoil energies observed at LZ to be checked by other experiments
- XENONnT sees solar neutrinos now in two channels:
  coherent elastic neutrino nucleon scattering (^{8}B) and in
  elastic scattering (pp, ^{7}Be) at much lower neutrino energies (pp, 7Be)
- At the example of XENONnT it is demonstrated that these dark matter experiments
  are becoming observatories for rare and exotic event searches
- XLZD is the next generation observatory searching WIMPs down to the neutrino fog
  with a very rich neutrino and other physics topics program
- Ultralow background methods are a key for the success of XLZD, such as been developed with LowRad
- HERETIX is an idea to even improve the $0\nu\beta\beta$ sensitivity of XLZD

Thank you for your kind attention!