Feb 4th, 2026

The extreme Universe viewed in very-high-energy gamma rays 2025

Dark Matter (WIMP) Direct Searches

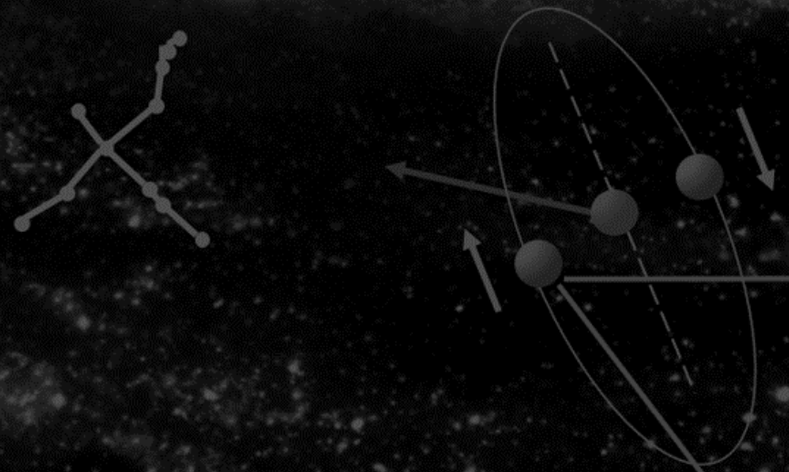
Kentaro Miuchi

(Kobe University)

- WIMPs
- Direct Searches
- Future
- Summary

科研費 KAKENHI

WIMPs



- WIMPs
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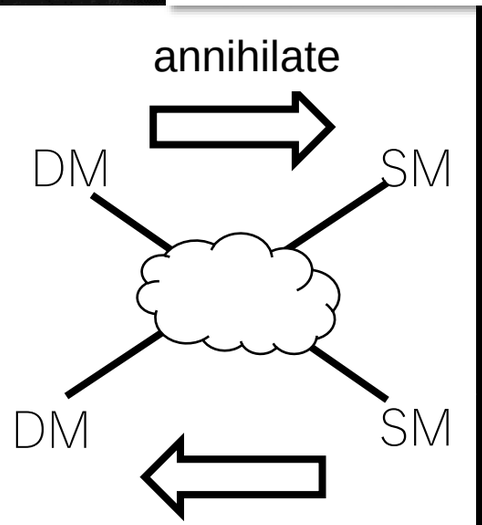
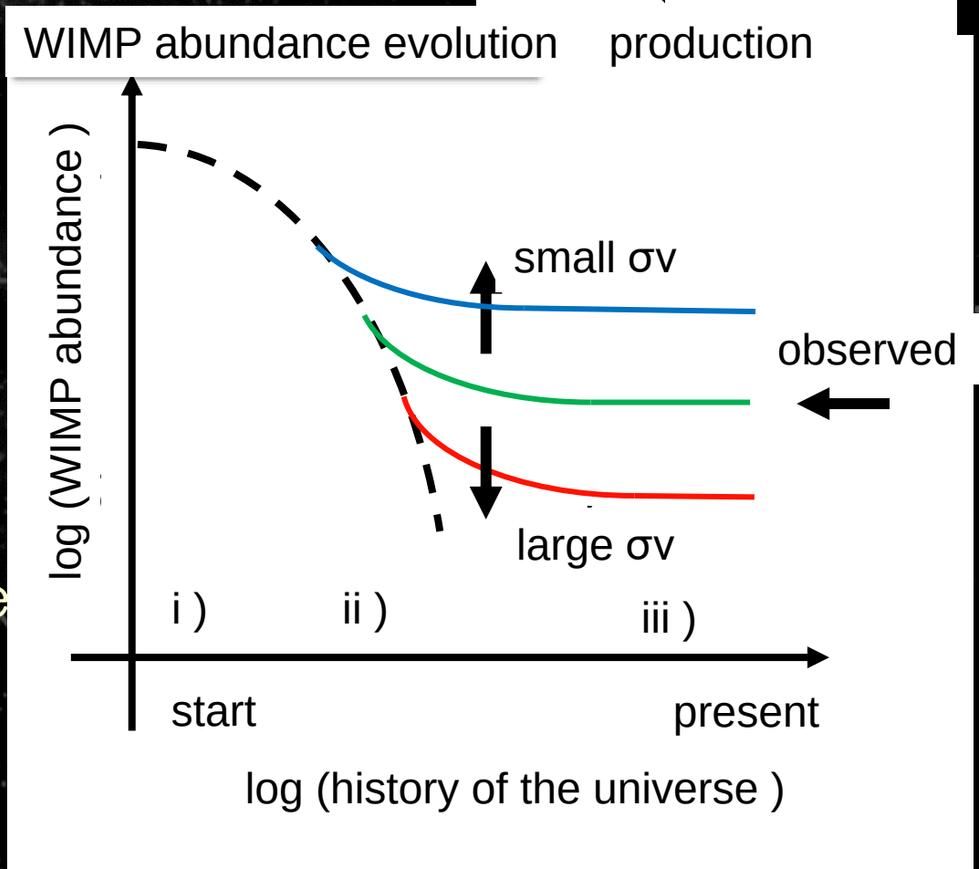
- WIMPs
  - “good” candidates would solve other problems
    - AXION (CP problem in QCD)
    - Primordial black hole (BHs are there!)
    - WIMPs (Weakly Interacting Massive Particles)

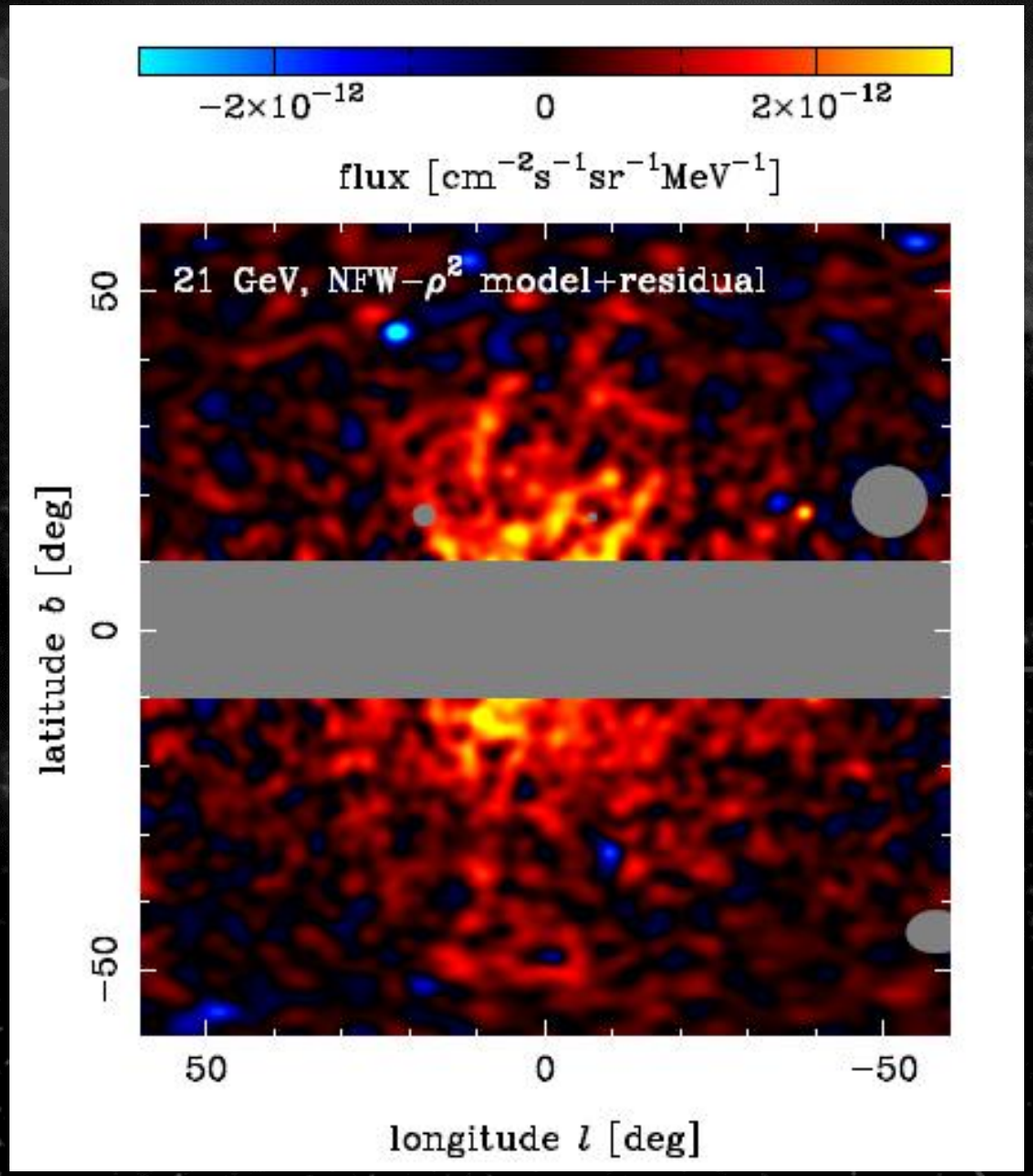


- WIMPs
  - Produced in the early universe
  - Annihilate
    rate ∝ cross section × velocity
  - Freeze out at some point
    abundance is fixed

  - σ～weak scale explains present abundance
    ⇒WIMP miracle !

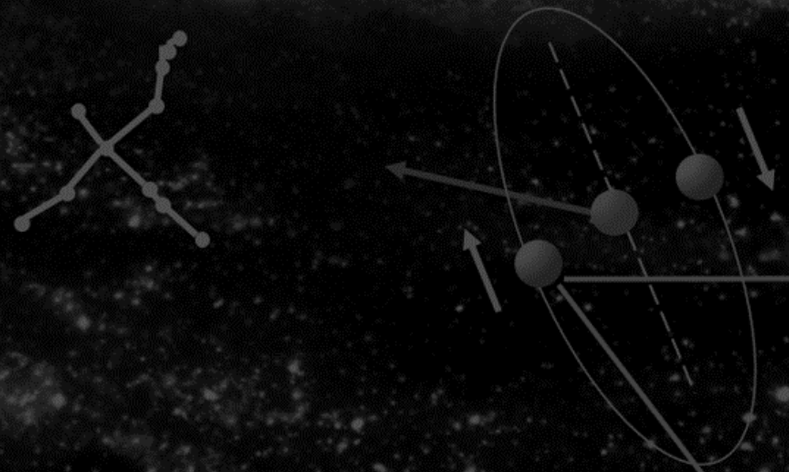


- 20 GeV halo gamma-rays can be 500 GeV WIMPs...



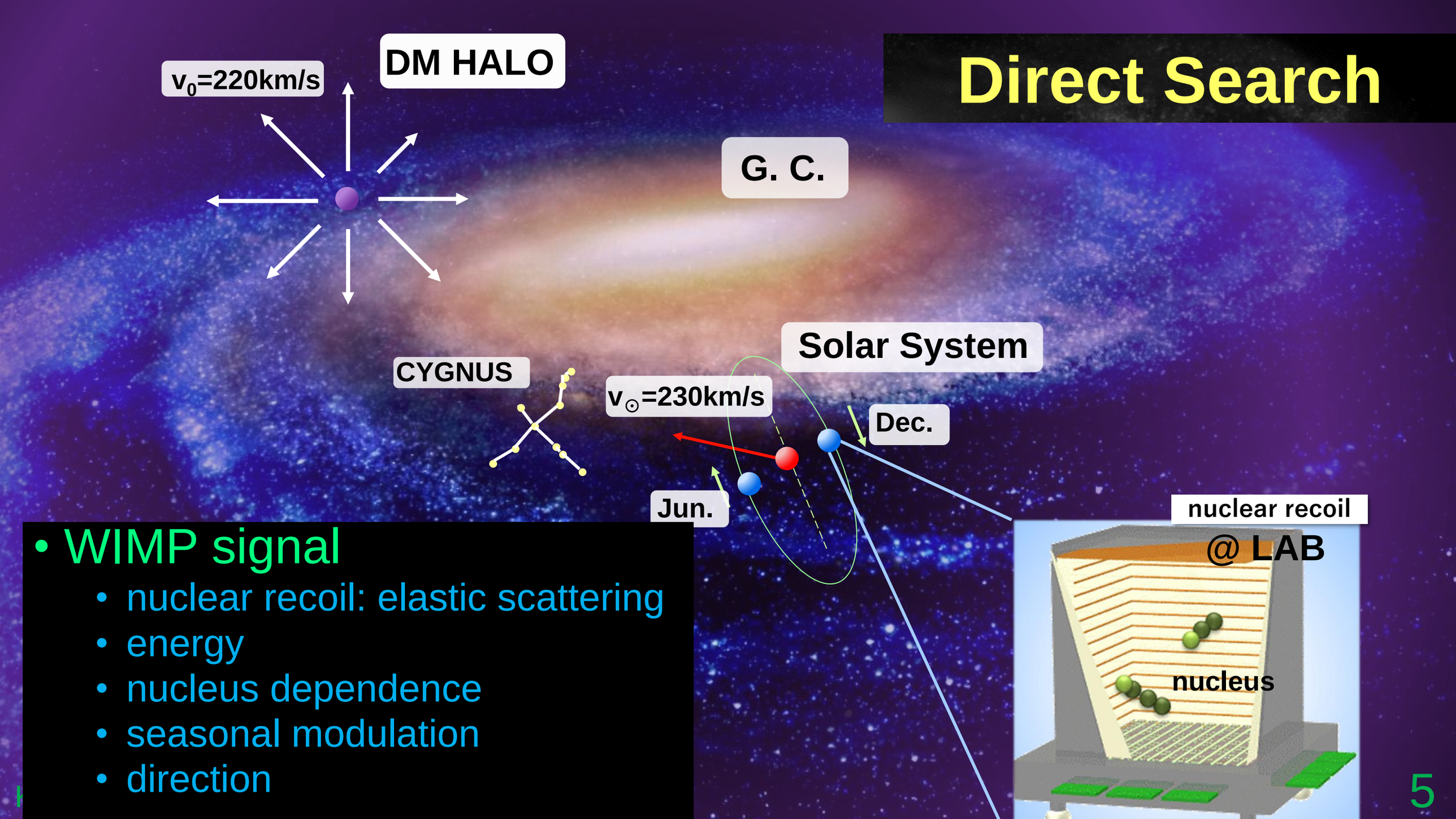
JCAP11(2025)080

Direct Searches

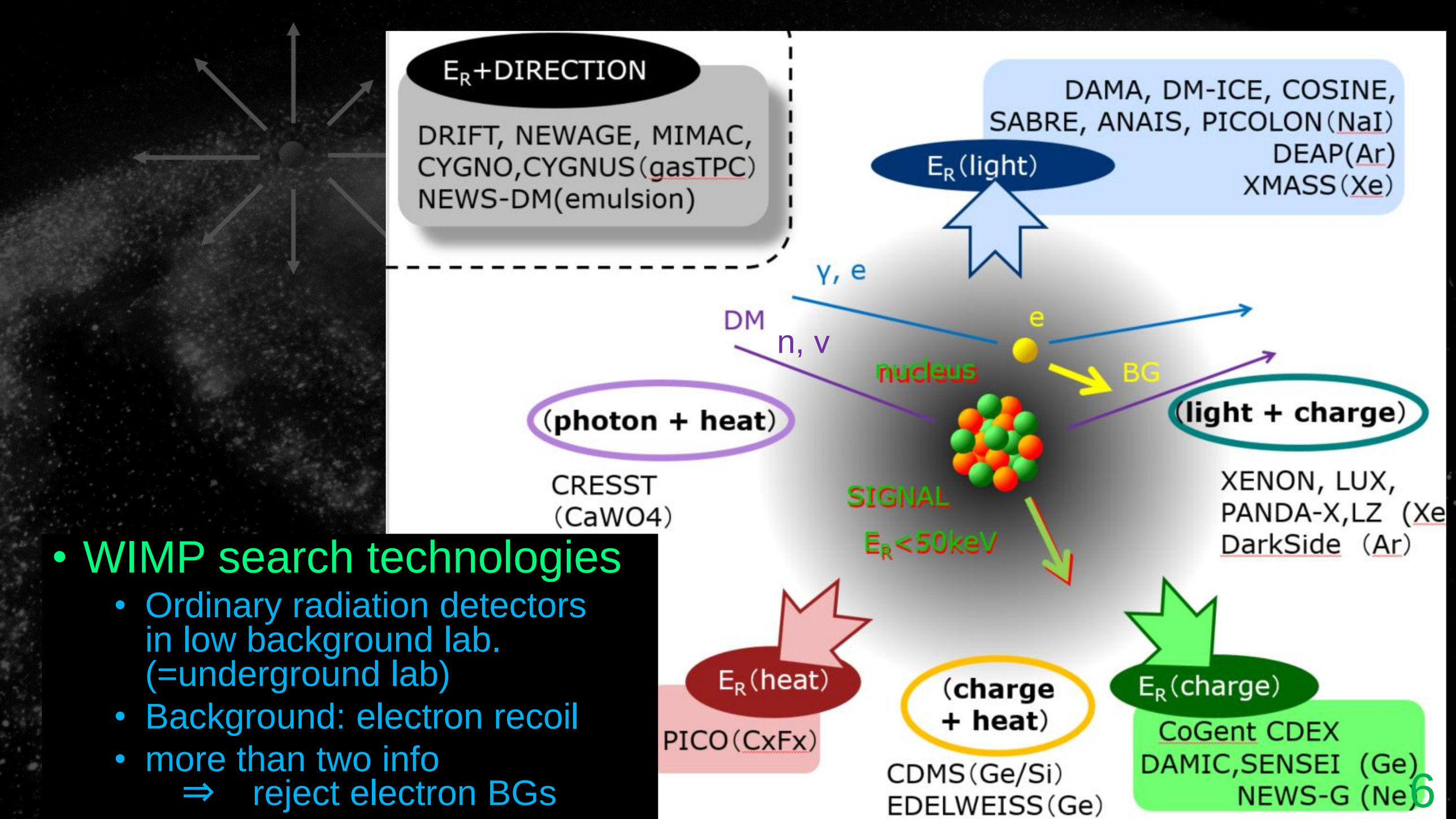


- WIMPs
- Direct Searches
- Future
- Summary

Direct Search

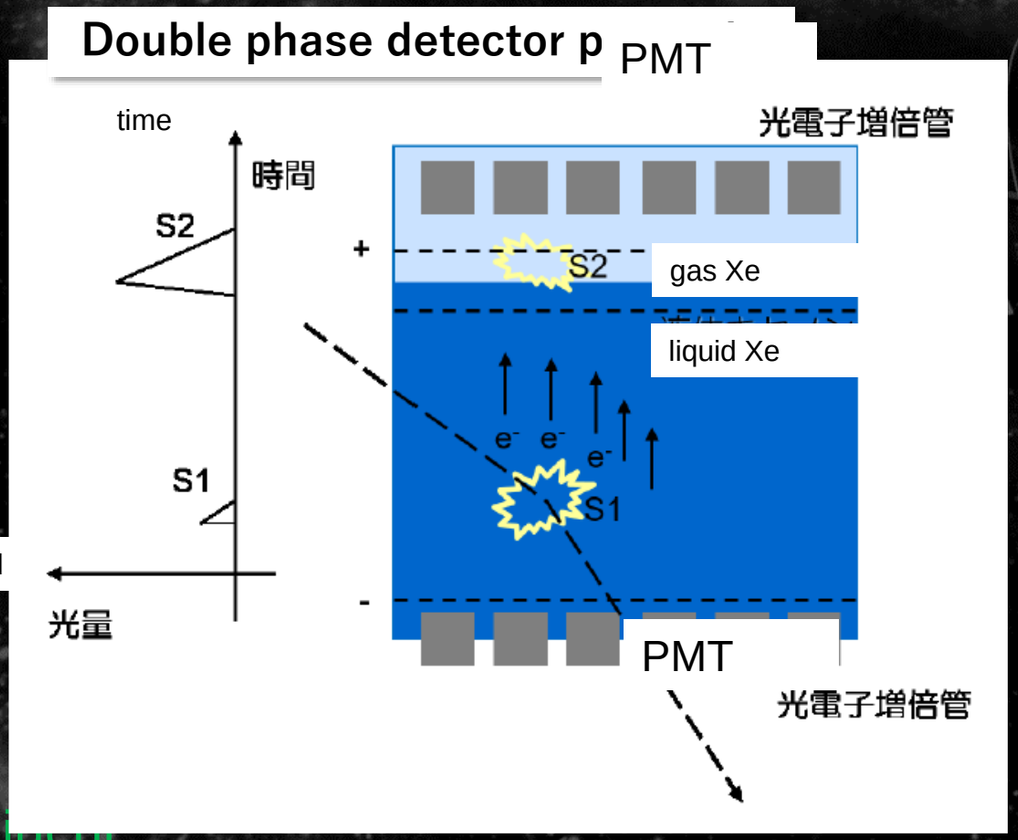


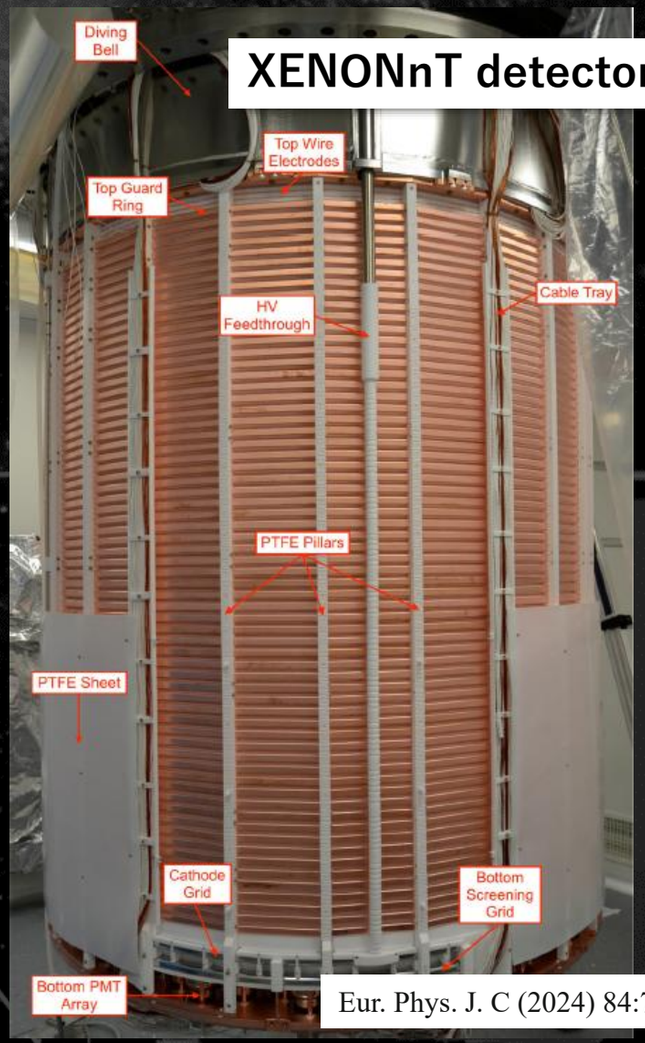
- WIMP signal
  - nuclear recoil: elastic scattering
  - energy
  - nucleus dependence
  - seasonal modulation
  - direction



- WIMP search technologies
  - Ordinary radiation detectors in low background lab. (=underground lab)
  - Background: electron recoil
  - more than two info
    ⇒ reject electron BGs

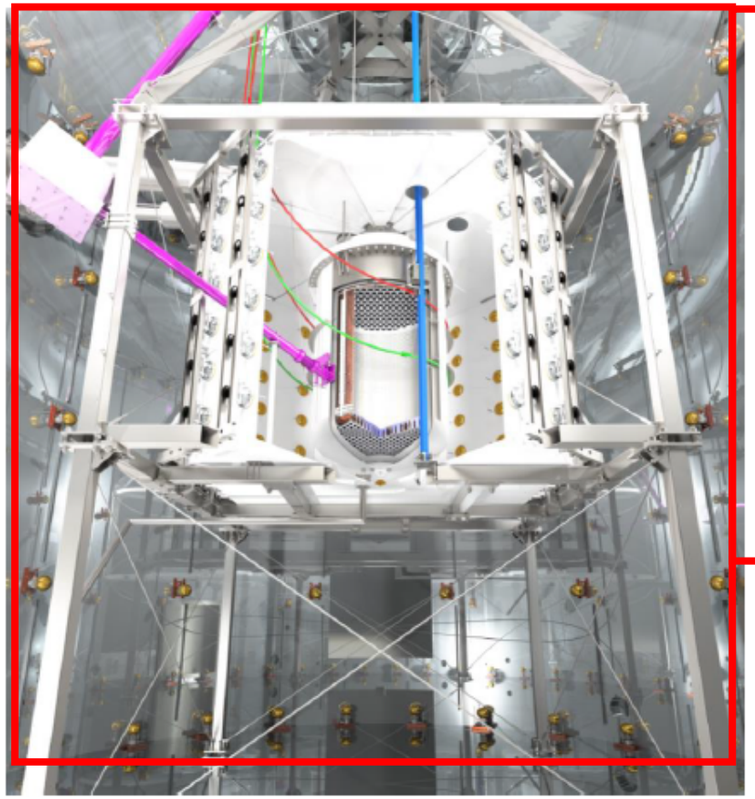
- Liquid Xe/Ar：double-phase (liquid+gas)
  - XENONnT, L/Z, PandaX(Xe) , DARKSIDE(Ar)
  - Several ton
  - z position can be known
  - Electron background can be discriminated





Eur. Phys. J. C (2024) 84:784

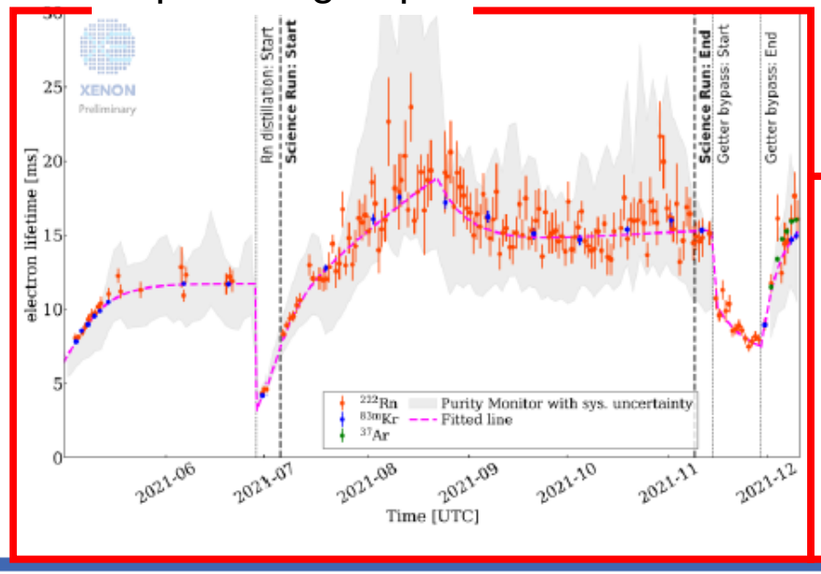
From XENON1T to XENONnT: main upgrades



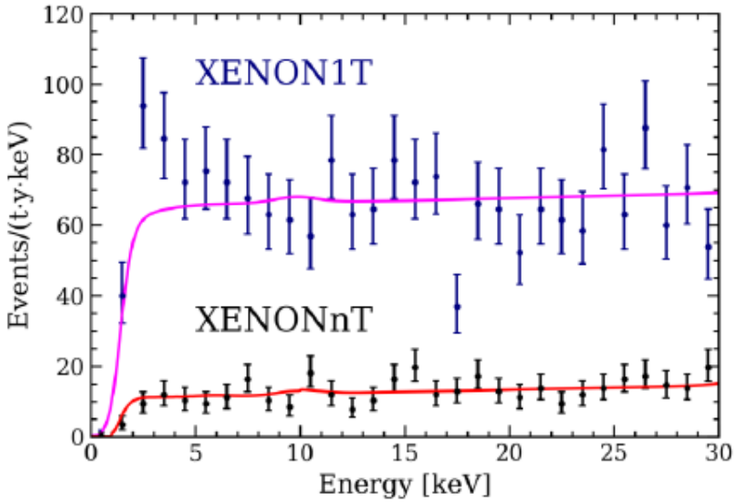
Neutron veto
Built inside existing muon veto
120 PMTs observe
2.2 MeV n-capture gamma
(53 ± 3)% tagging efficiency
(250 μs window) with life time loss of 1.6%
Gd will improve efficiency to 87% (150 μs window)

Triggerless DAQ
All signals of photoelectron size or bigger saved
Improves low-energy sensitivity
2212.11032

Japanese group

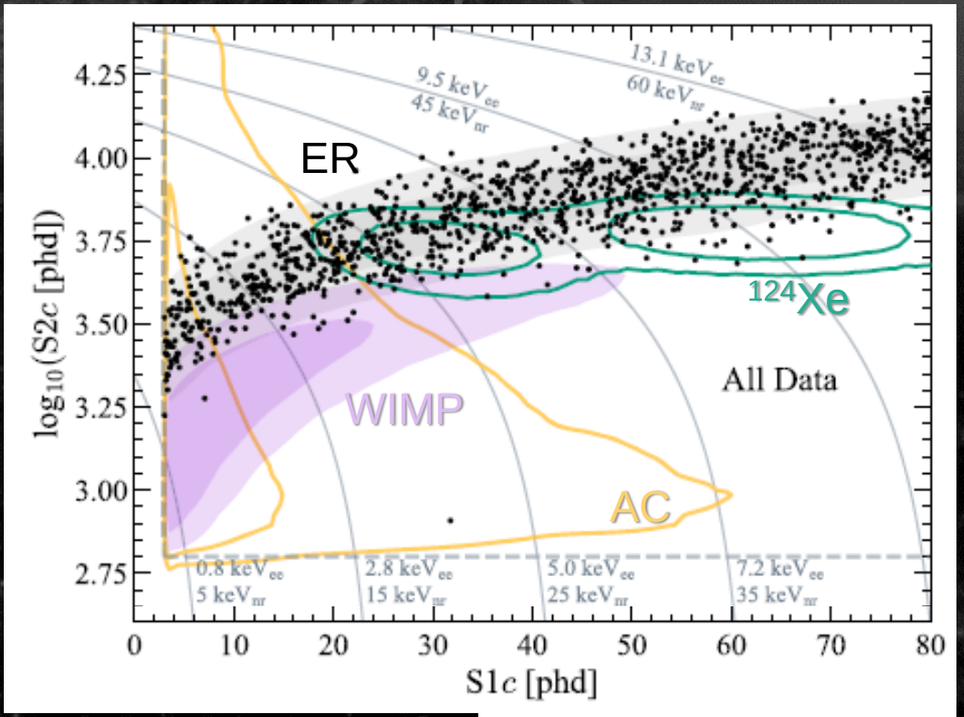


Radon distillation column
Continuous radon removal
Activity 1.8 μBq/kg for these results
See poster H. Schulze Eißing (PDM1-3)
EPJC 82, 1104 (2022), 2205.11492

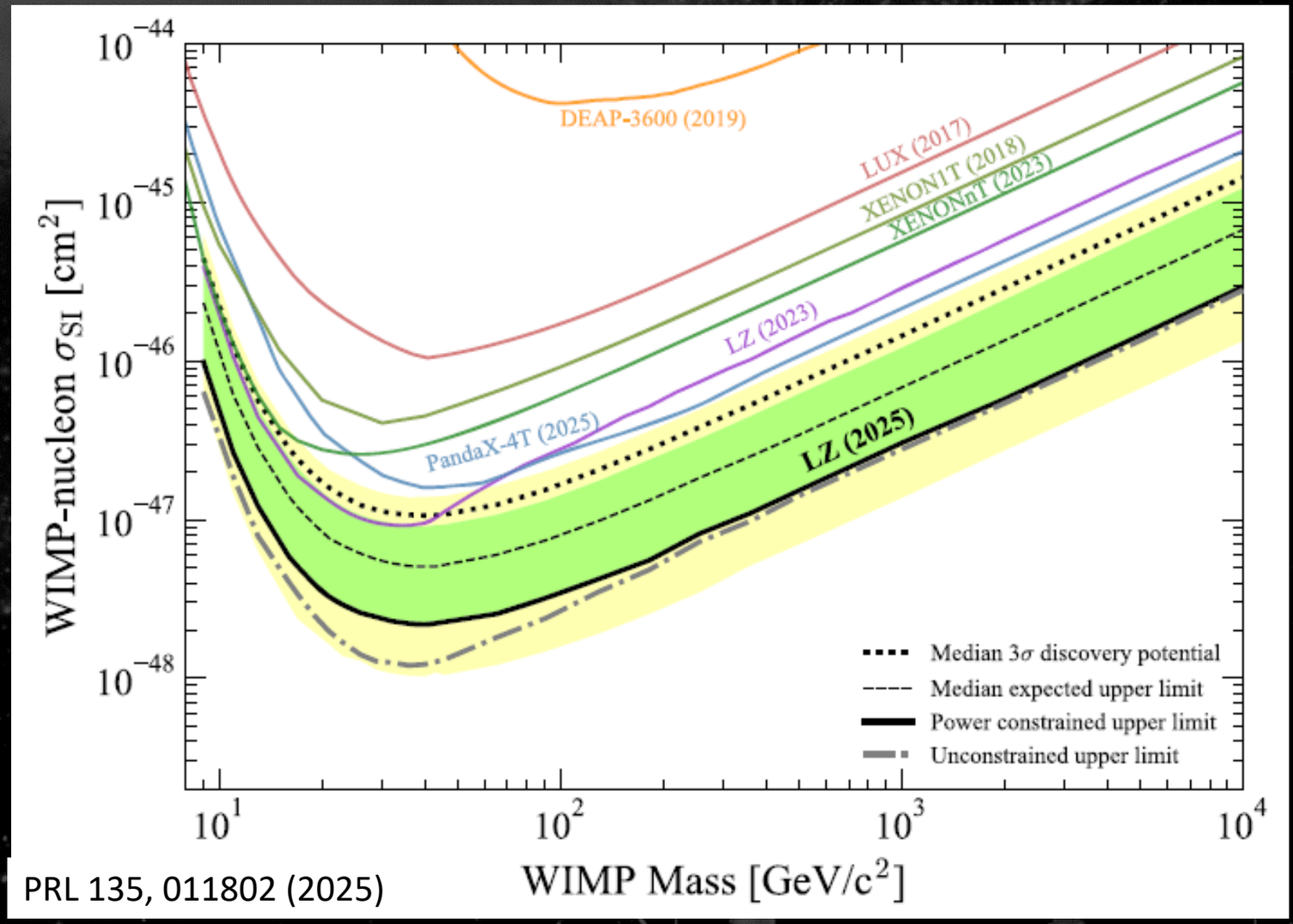


Liquid xenon purification
Clean 2 l liquid Xe per minute
(full 8.5 t in 18 hours)
Lifetime > 15 ms achieved
See poster M. Kobayashi (PDM1-2)
EPJC 82, 860 (2022), 2205.07336

- Leading results (LZ 2025)
  - 4.2 Tonne-Years (280 live days)
  - 2.2×10^{-48} cm^2 @ 40GeV



PRL 135, 011802 (2025)



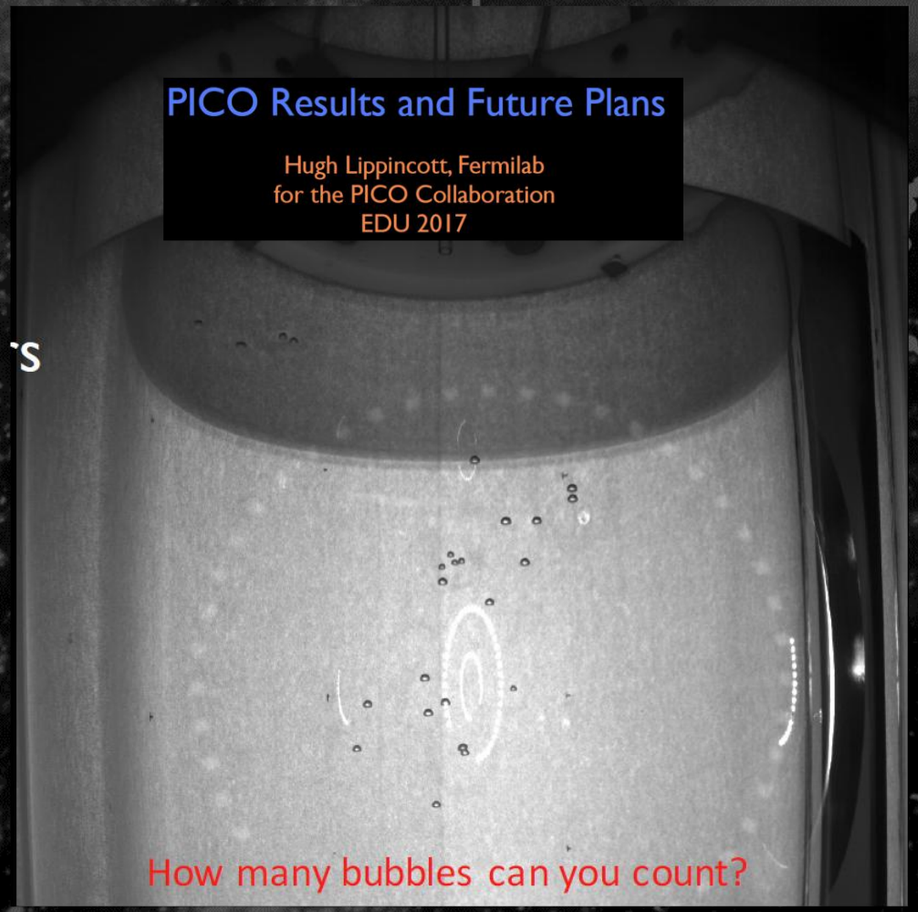
PRL 135, 011802 (2025)

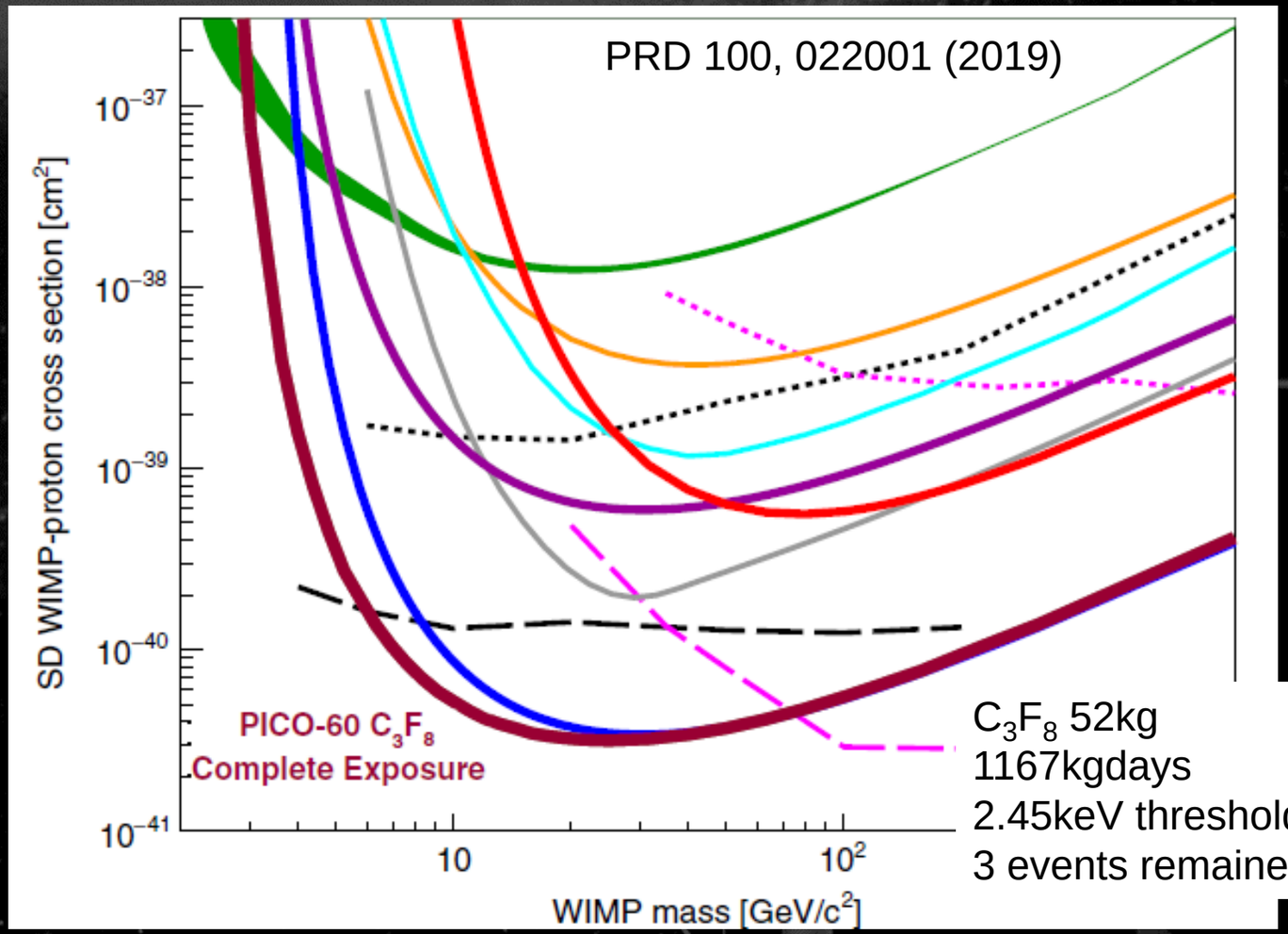
ER: electric recoil
^{124}Xe: 2v double electron capture of ^{124}Xe
AC: accidental coincidence

• Bubble chamber (w/ fluorine)

• PICO

- Superheated chamber
- Threshold-type detector
- good SD (spin-dependent) sensitivity





C_3F_8 52kg
1167kgdays
2.45keV threshold
3 events remained

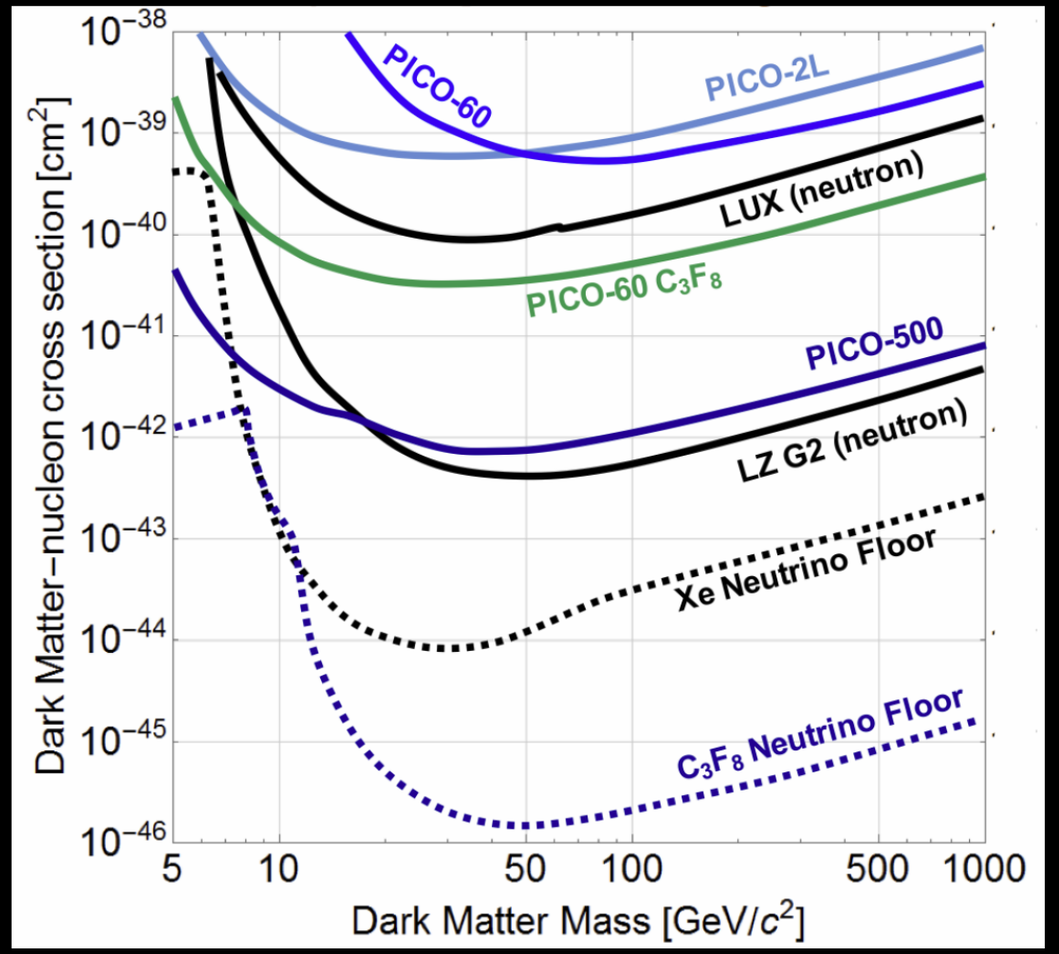
- Fluorine advantage
  - SD search
  - different "Neutrino floor" from xenon

PICO Results and Future Plans

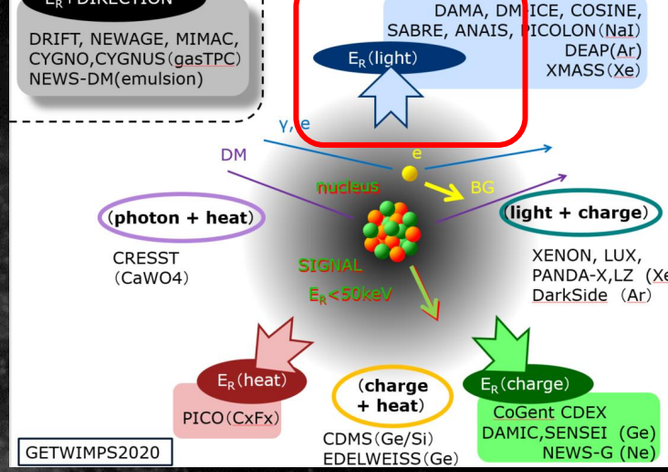
Hugh Lippincott, Fermilab
for the PICO Collaboration
EDU 2017

Isotope	J	Abundance(%)	$\mu_{\rm mag}$	$\lambda^2 J(J+1)$	unpaired nucleon
^{1}H	1/2	100	2.793	0.750	proton
^{7}Li	3/2	92.5	3.256	0.244	proton
^{11}B	3/2	80.1	2.689	0.112	proton
^{15}N	1/2	0.4	−0.283	0.087	proton
^{19}F	1/2	100	2.629	0.647	proton
^{23}Na	3/2	100	2.218	0.041	proton
^{127}I	5/2	100	2.813	0.007	proton
^{133}Cs	7/2	100	2.582	0.052	proton
^{3}He	1/2	1.0×10^{-4}	−2.128	0.928	neutron
^{17}O	5/2	0.0	−1.890	0.342	neutron
^{29}Si	1/2	4.7	−0.555	0.063	neutron
^{73}Ge	9/2	7.8	−0.879	0.065	neutron
^{129}Xe	1/2	26.4	−0.778	0.124	neutron
^{131}Xe	3/2	21.2	0.692	0.055	neutron
^{183}W	1/2	14.3	0.118	0.003	neutron

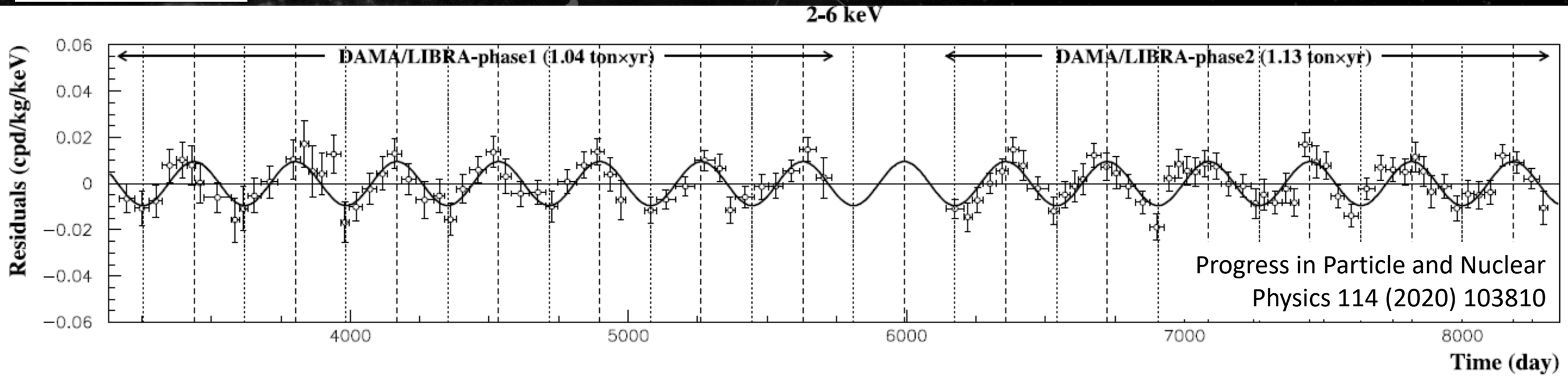
Scaling to PICO-500



- DAMA (NaI)
  - 250kg NaI scintillators
  - Annual modulation reported：1998～
  - Latest 2.17 ton year 12.9 σ
  - SOMETHING is detected



DAMA/LIBRA



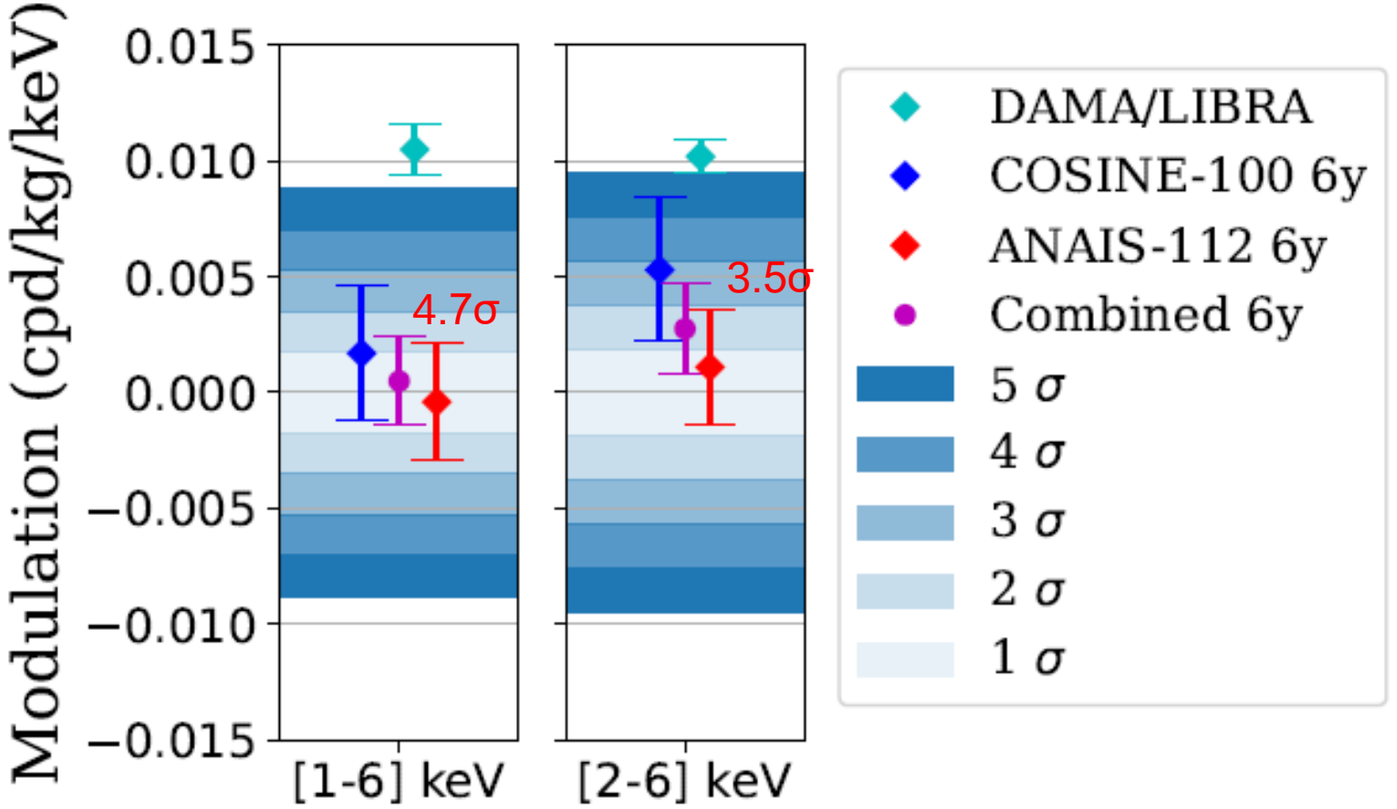
No BG explains this modulation

No natural DM model explains, either…

Kentaro Miuchi

- Other NaI detectors
  - COSINE(106kg)+ ANAIS (112kg)
    - 6 years' annual modulation measurements
    - inconsistent with DAMA result (4.7σ)
  - SABRE
    - North and South
  - PICOLON
    - Pure crystal

Phys. Rev. Lett. **135**, 121002 (2025)



- MIGDAL effect
  - Low mass search with “MIGDAL effect”
  - Ordinary nuclear recoil : ionization along the track
  - Low energy recoil : ionization efficiency is low ⇒ difficult to detect
  - Very rare case electrons are emitted

PRL123, 241803 (2019)

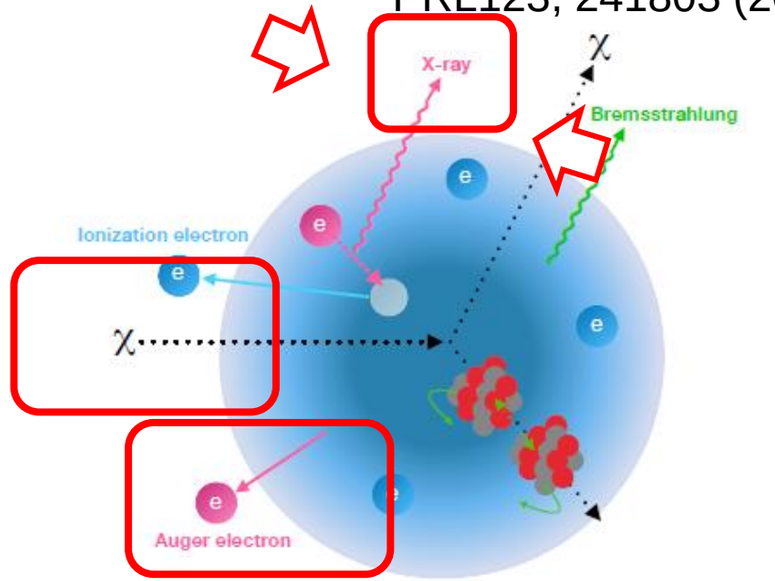
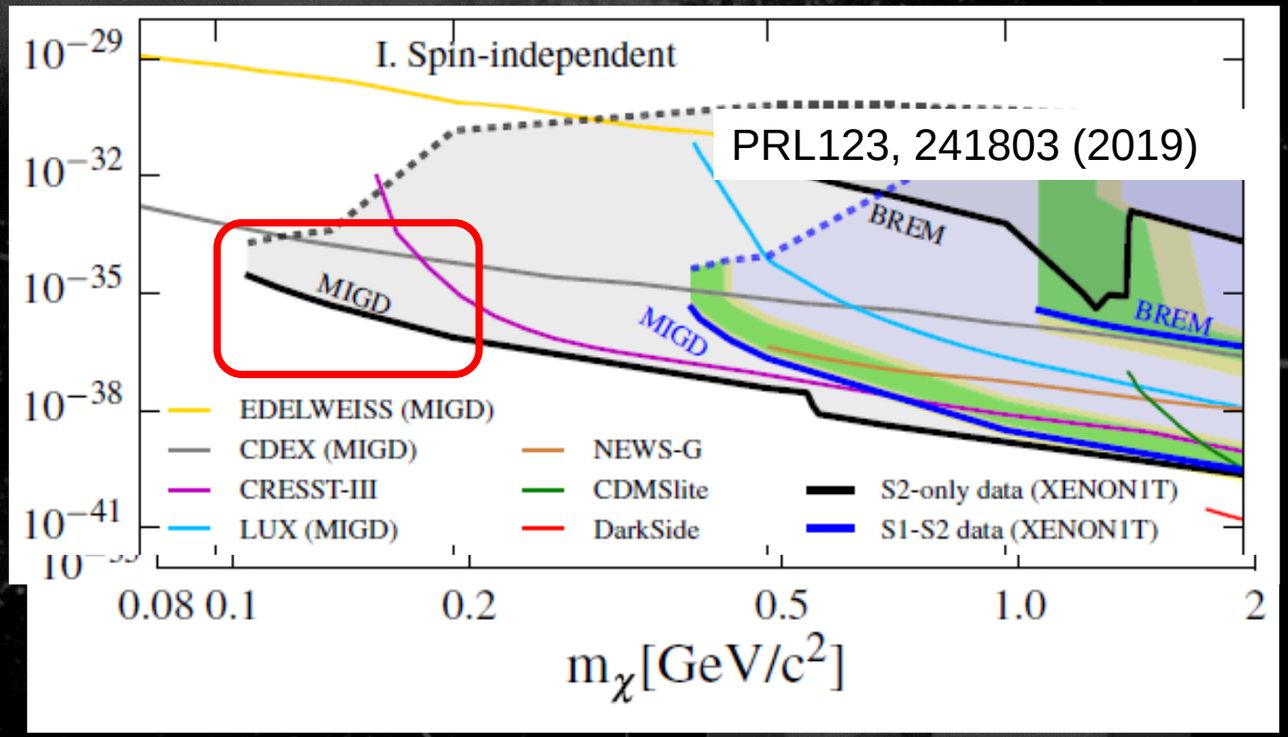
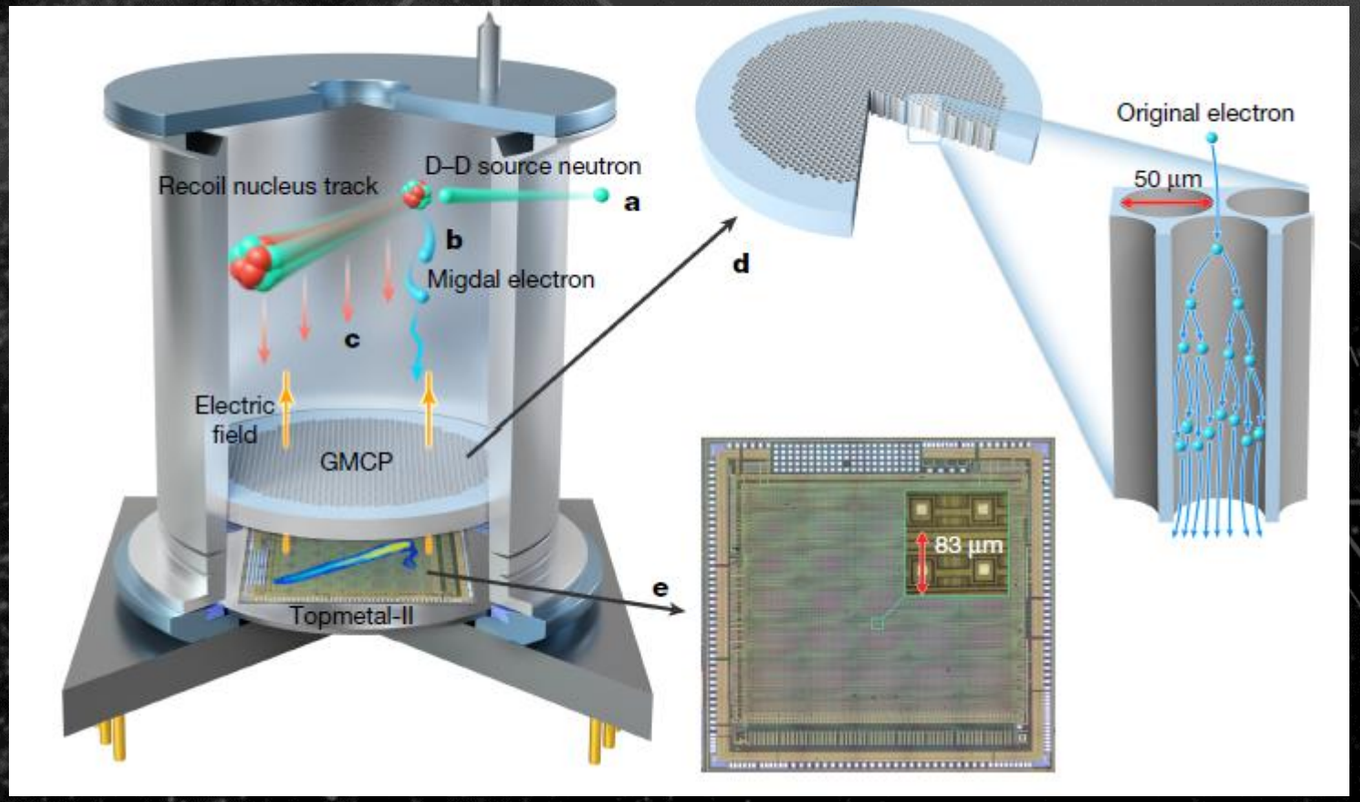


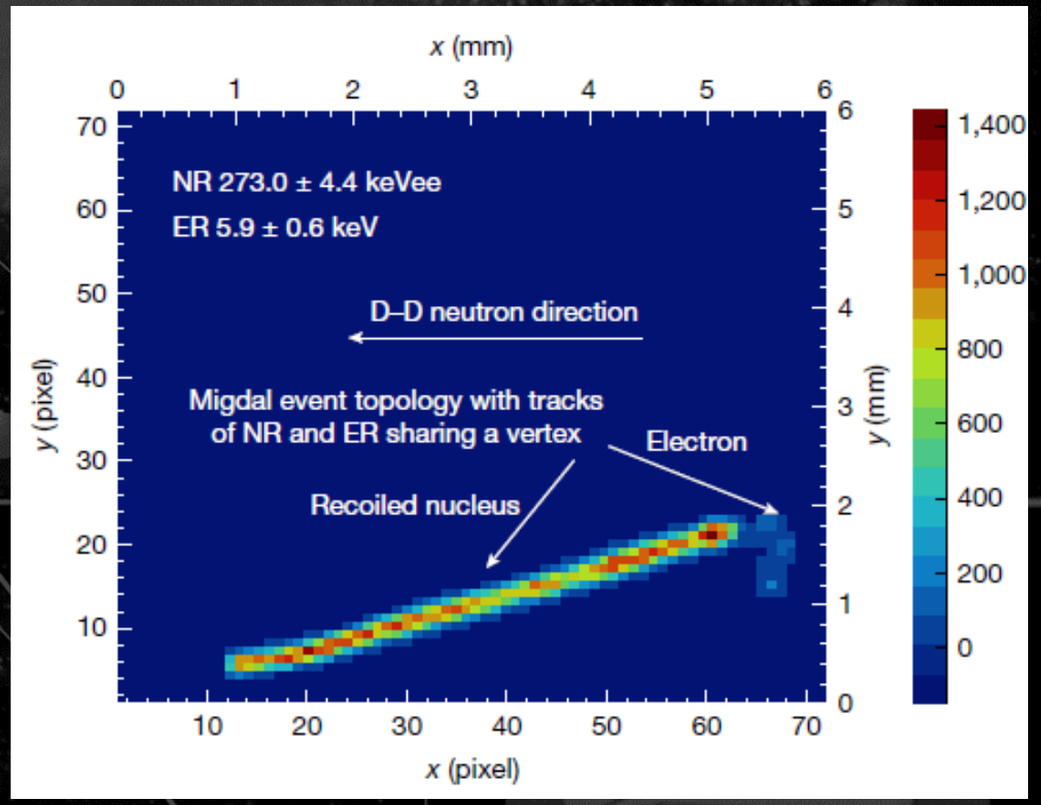
FIG. 1. Illustration of the ER signal production from BREM (green) and Migdal processes (pink) after elastic scattering between DM (χ) and a xenon nucleus.



- MIGDAL effect itself were yet to be confirmed experimentally.

- First observation of the MIGDAL effect
  - $> 5\sigma$ observation
  - $He+C_3HOCH_3$



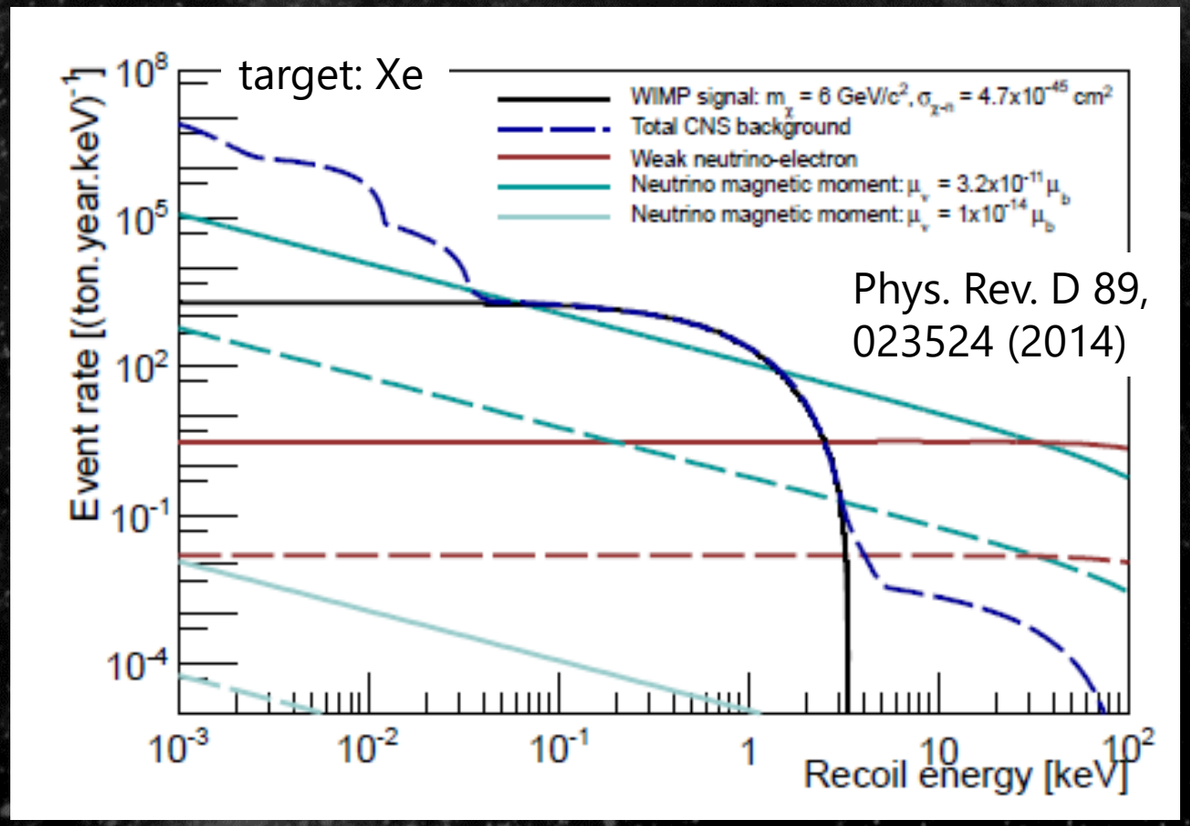


580 | Nature | Vol 649 | 15 January 2026

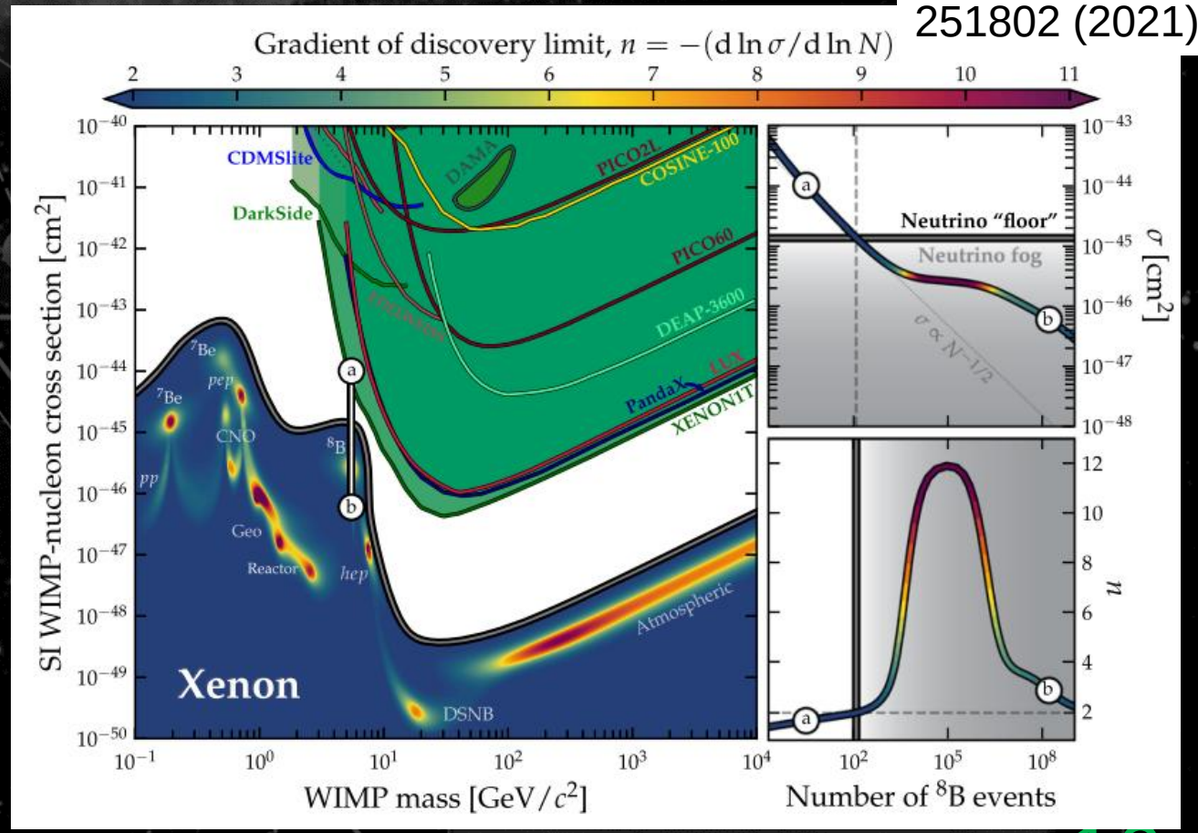
- MIGDAL effect happens
- Xe, Ar observations are awaited

• Going into the FOG: CEvNS

- Irreducible background:
  Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
- e. g. ^{8}B solar neutrino looks like 6 GeV WIMPs
- "Neutrino FOG"



PRL127, 251802 (2021)



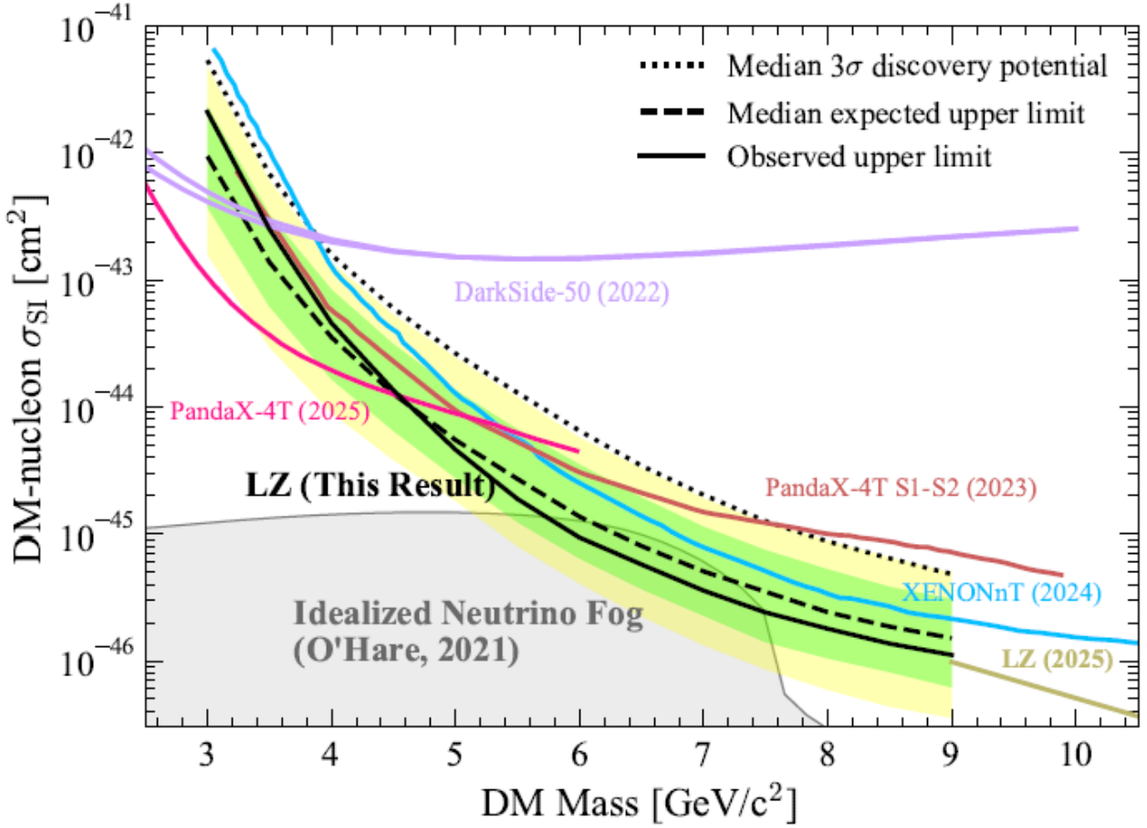
- Start observing the FOG
  - 2.64 σ (PANDA-X, 2024)
  - 2.73 σ (XENONnT, 2024)
  - 4.5σ (LZ, 2025)

133, 191001 (2024)

133, 191002 (2024)

arXiv:2512.08065

arXiv:2512.08065



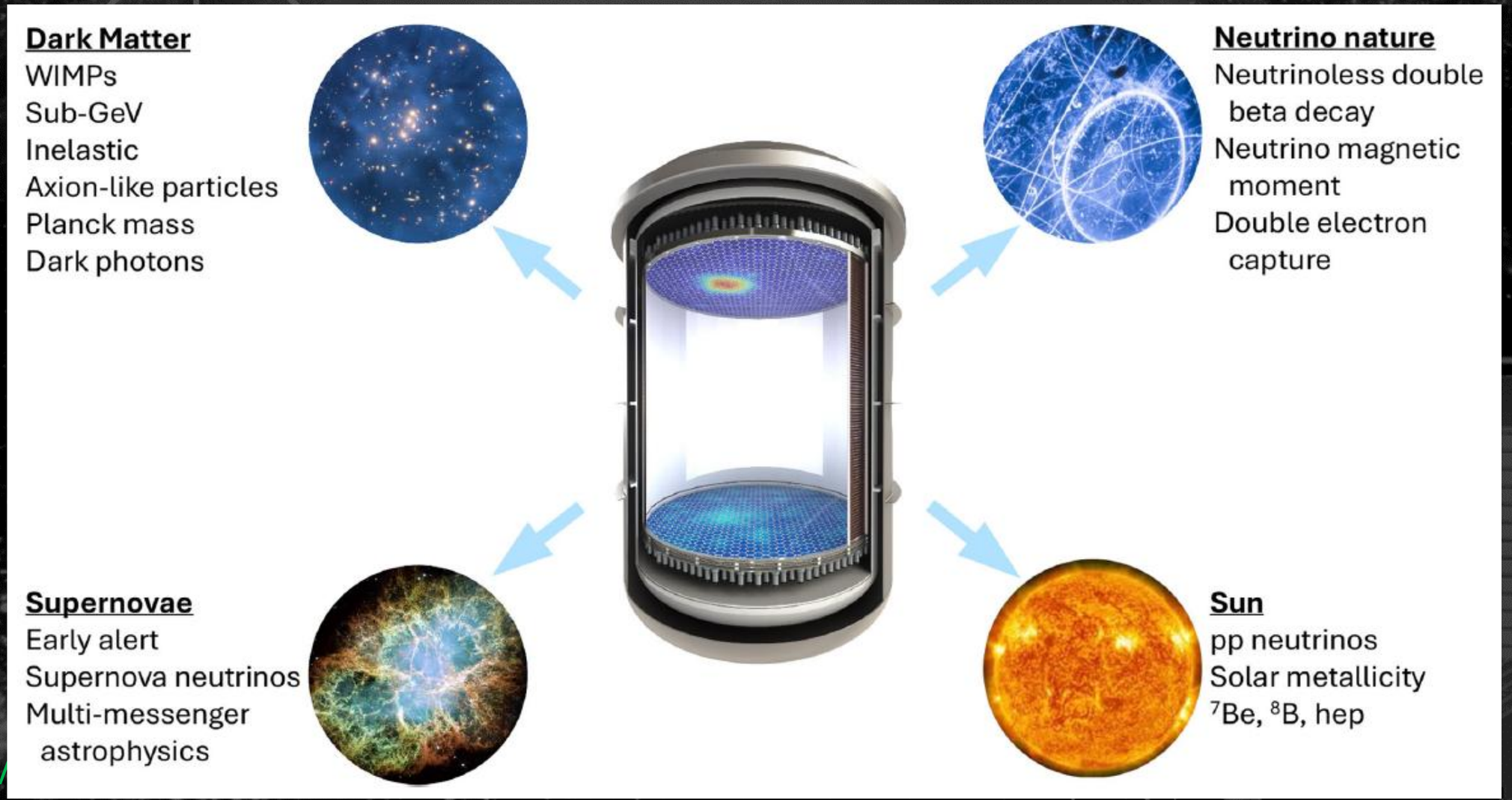
- and exploring in the FOG
  - XENONnT: PRL 134, 111802 (2025)
  - LZ: 2512.08065

Direct Searches: Future

- WIMPs
- Direct Searches
- Future
- Summary

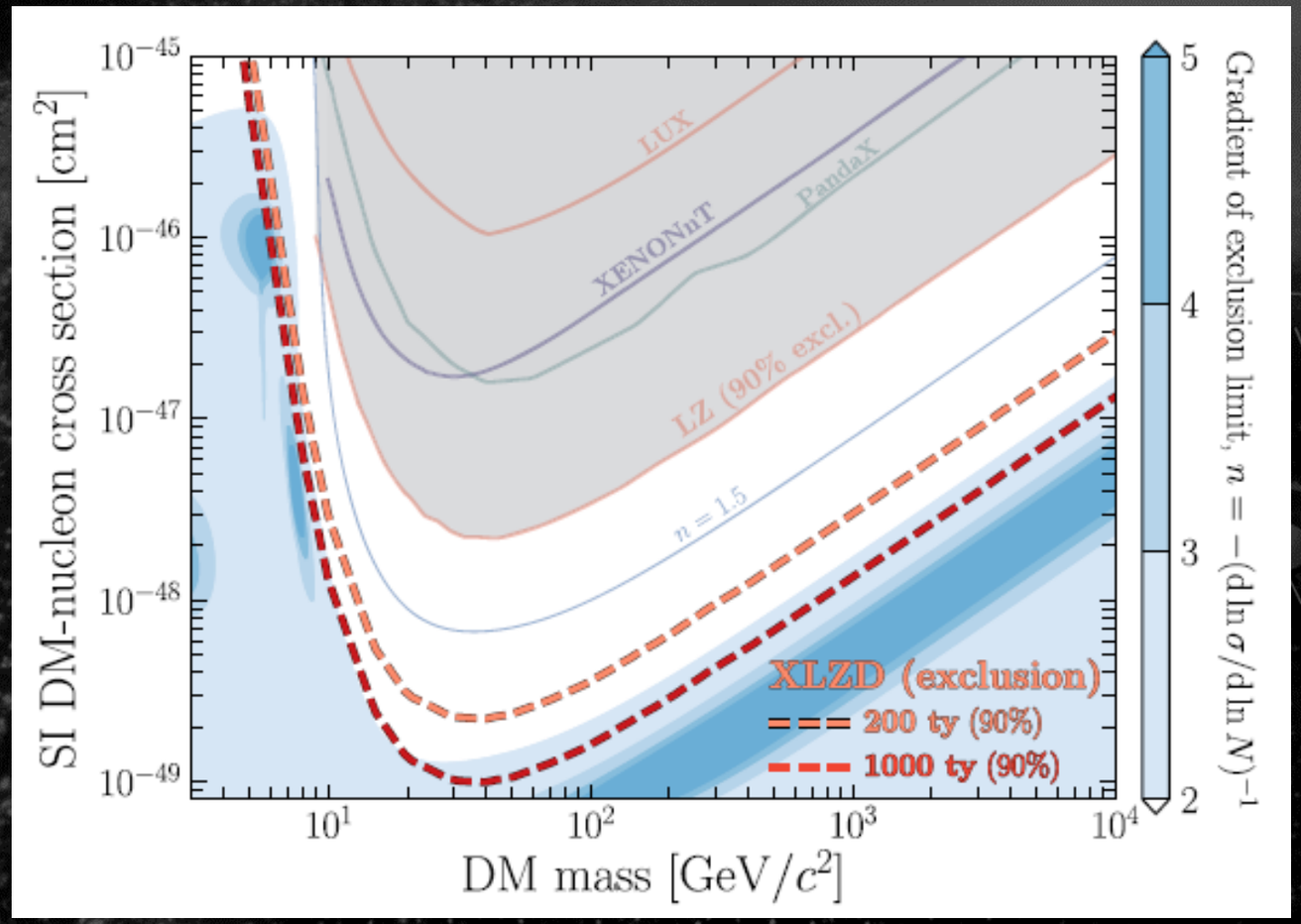
- XLZD (=XENON+LZ+DARWIN)
  - 60-80 tonne Liquid xenon
  - multi-purpose observatory

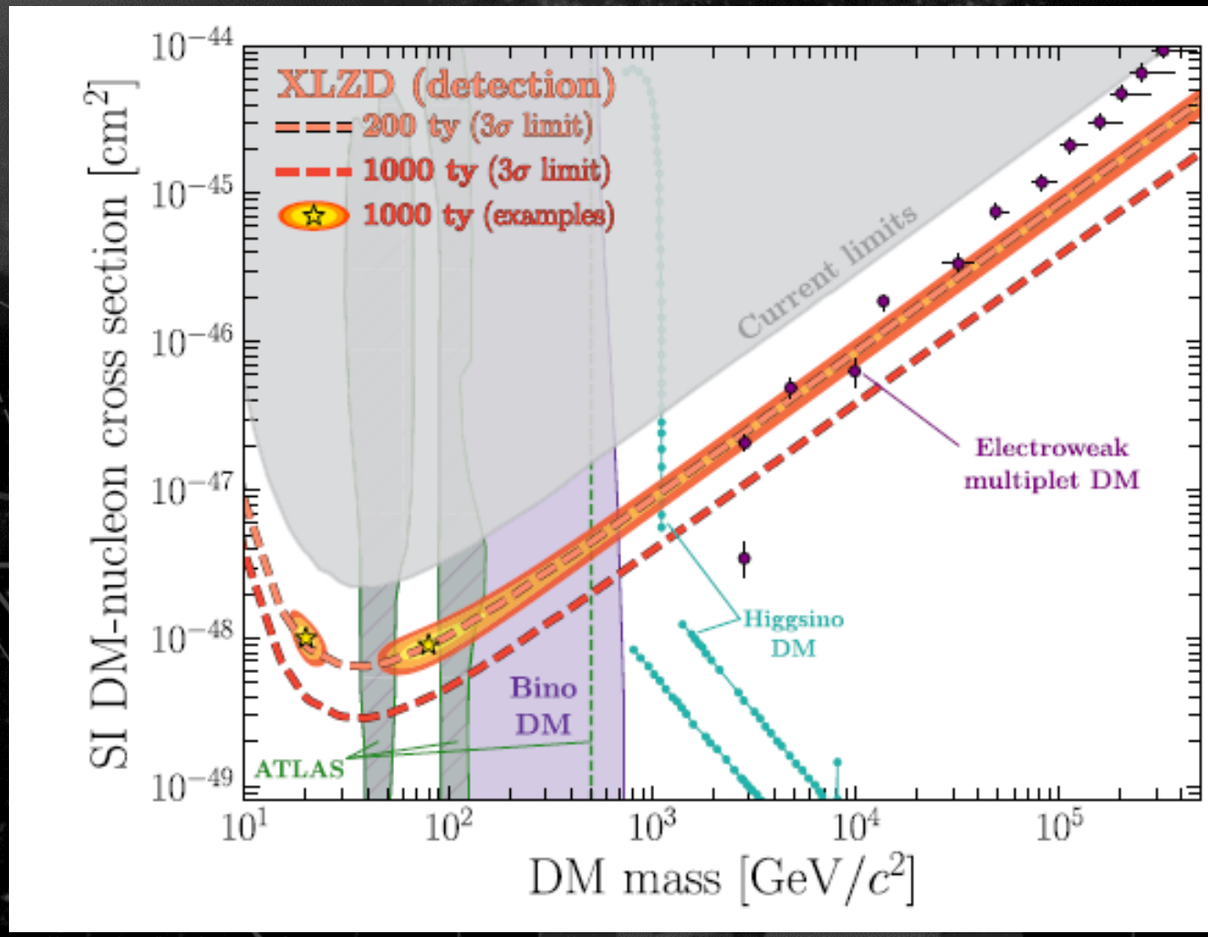
Eur. Phys. J. C (2025) 85:1192



- XLZD towards the neutrino fog

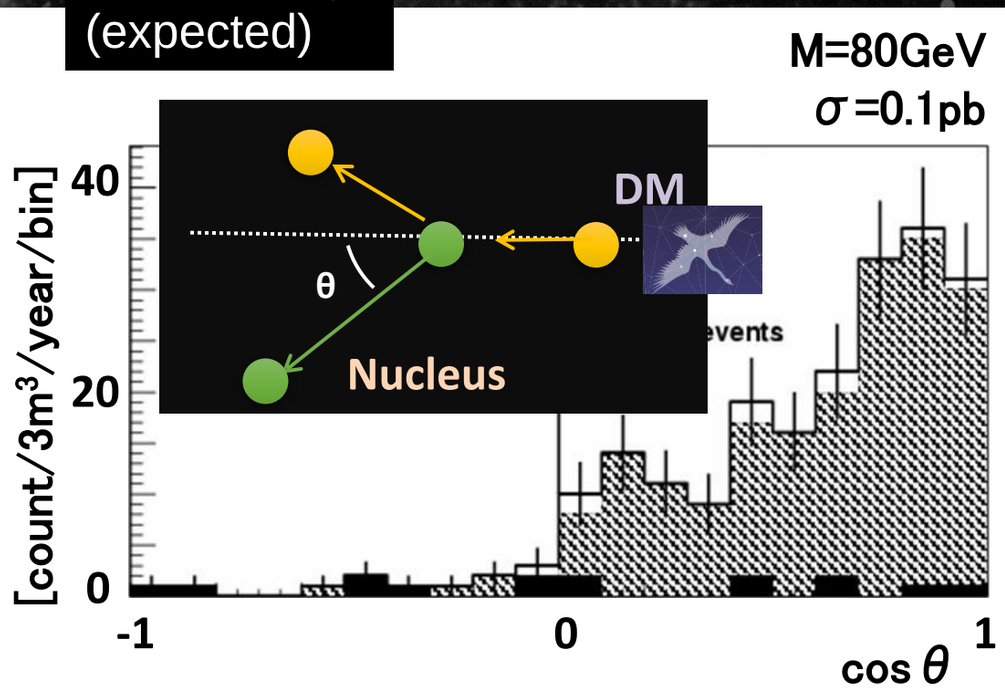
Eur. Phys. J. C (2025) 85:1192





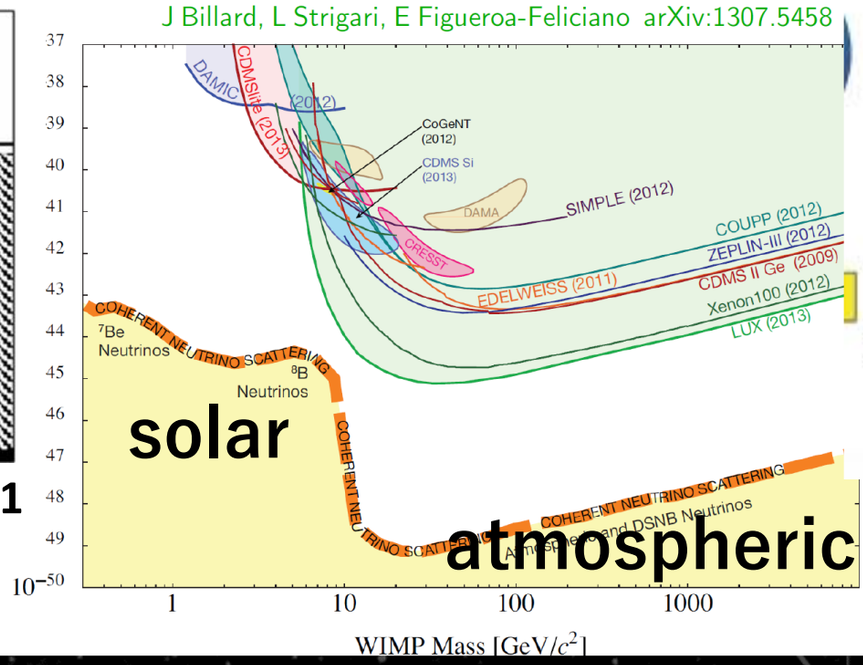
- Directional detection
  - Clear Discovery
    even with the neutrino BG
    + study the nature of DM after discovery

directionality (expected)

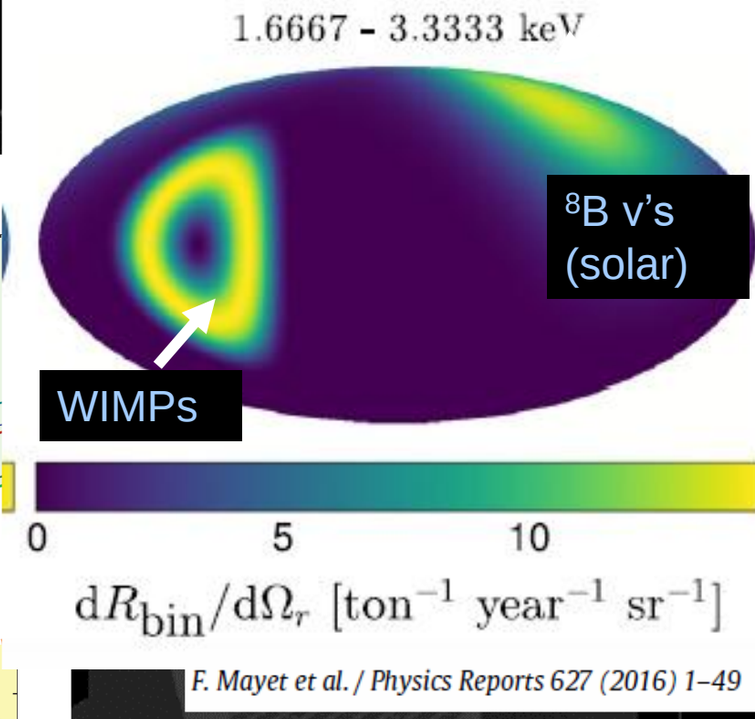


Physics Letters B 578 (2004) 241–246

neutrino floor



w/ neutrino BG (expected)



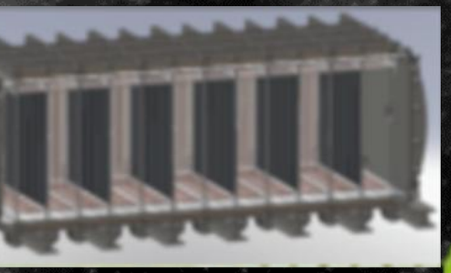
F. Mayet et al. / Physics Reports 627 (2016) 1–49

- CYGNUS: worldwide directional network

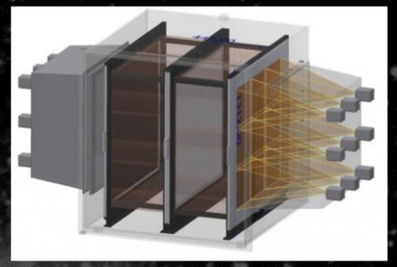
2020 J. Phys.: Conf. Ser. 1468 012044

CYGNUS-10
Boulby, UK
10m^3 He:SF_6
GEM + wire readout

NEWAGE/CYGNUS-KM
Kamioka, Japan
SF6 / CF4
Strip readout

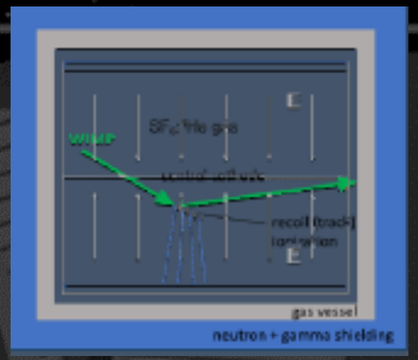


CYGNO-Initium
Gran Sasso, Italy
He CF_4 (SF_6)
sCMOS+PMT readout



CYGNUS-OZ
Stawell, Australia
R&D leading to 1 m^3
Long-term plan 10 m^3

CYGNUS-HD10
SURF, USA
He:CF_4:C_4H_{10}
Strip readout



multi-site observatory

CYGNUS 2026

9th edition of the international CYGNUS Workshop on Directional Recoil Detection

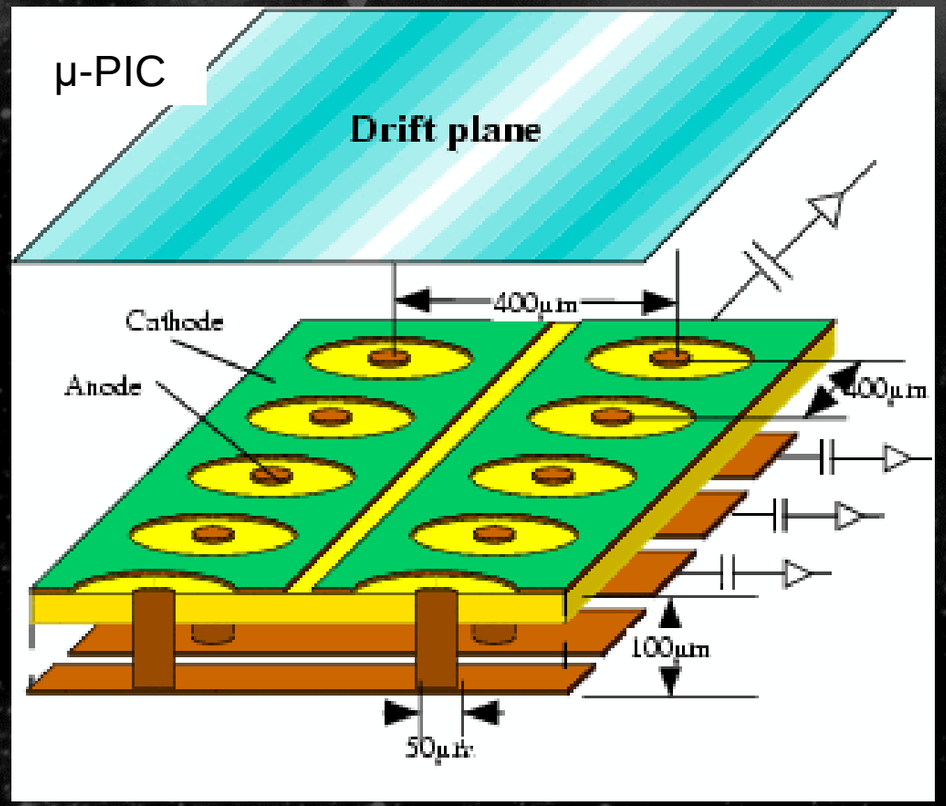
Kobe University (Japan)

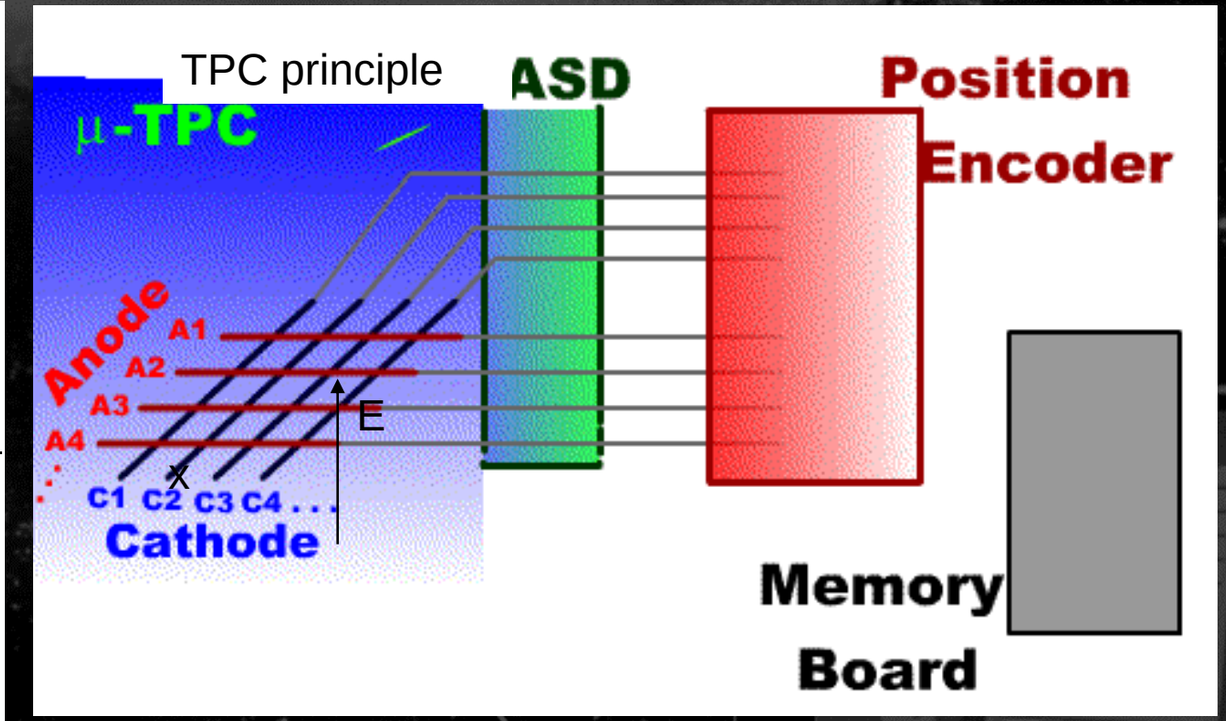
2026 Feb. 23-25

https://indico.global/event/15704/overview

- Technology: Gaseous Time Projection Chamber
  - 2-dimensional image: Micro Patterned Gaseous Detector (MPGD)
  - timing information: 3rd dimension
  - realtime 3-dimensional tracking

MPGD:
GEM, micromegas, μ-PIC

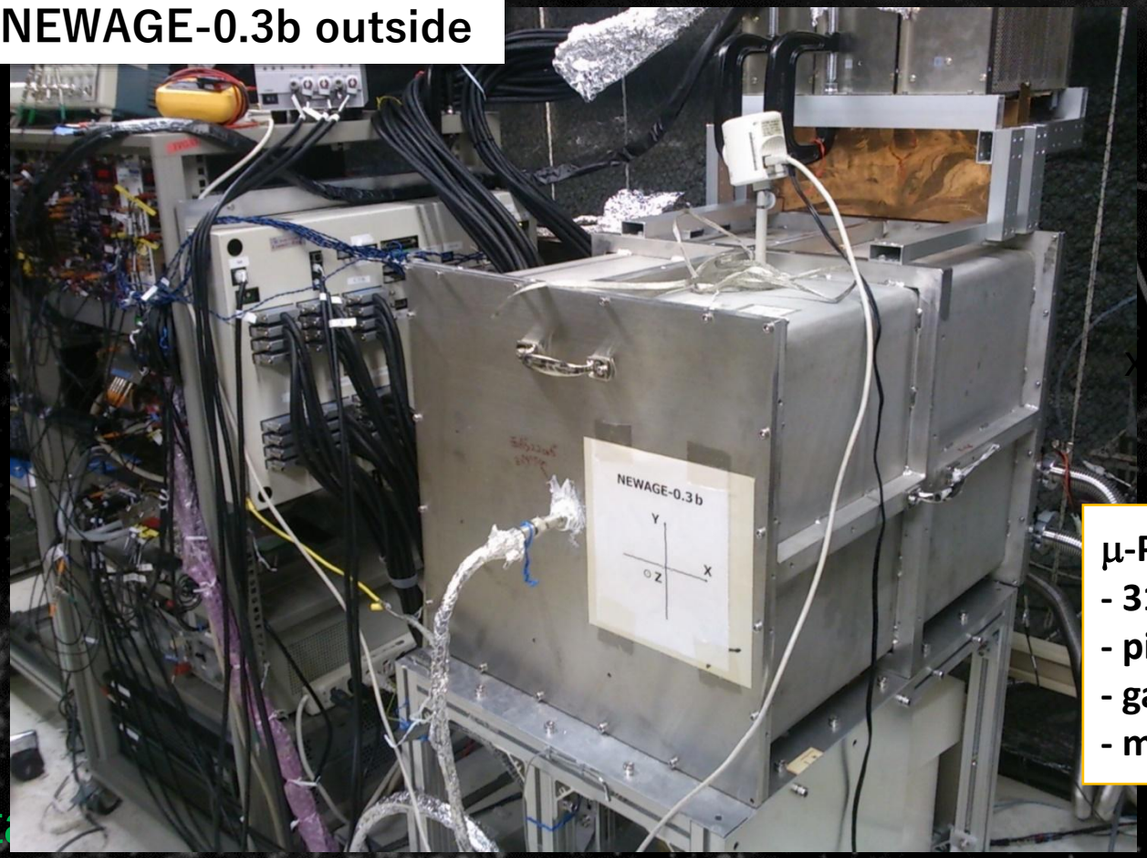




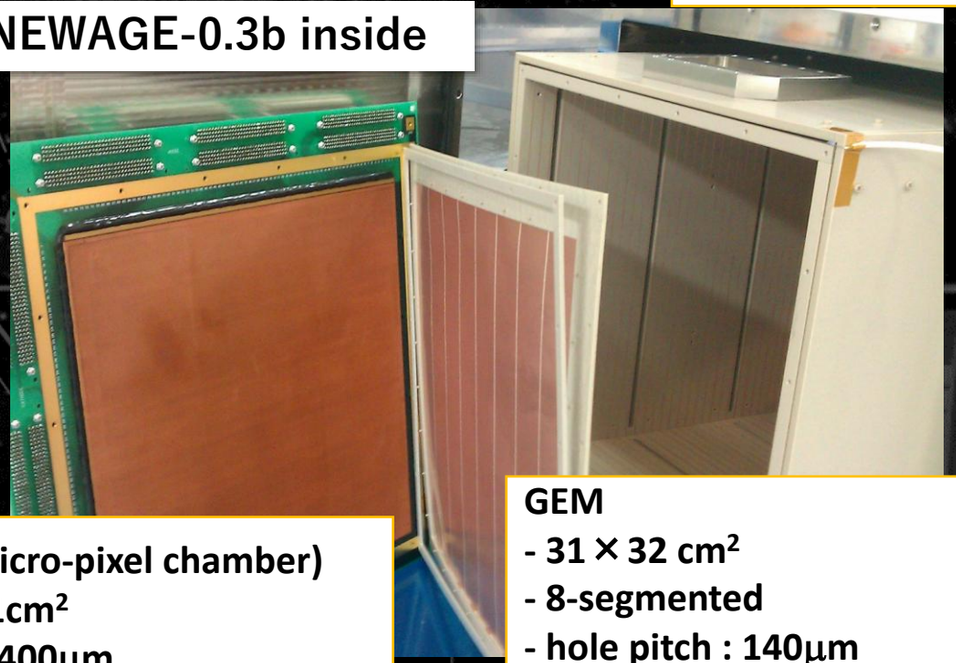
- drawback: small mass O(kg) / m^3

- Detector: NEWAGE-0.3b”
  - Detection Volume: $31 \times 31 \times 41 cm^3$
  - ～1500ch readout system
  - Gas: CF_4 at 0.1atm (50keVee threshold)
  - Gas circulation system with cooled charcoal
-

NEWAGE-0.3b outside



NEWAGE-0.3b inside



Field cage
Drift length: 41cm
PEEK + copper wires

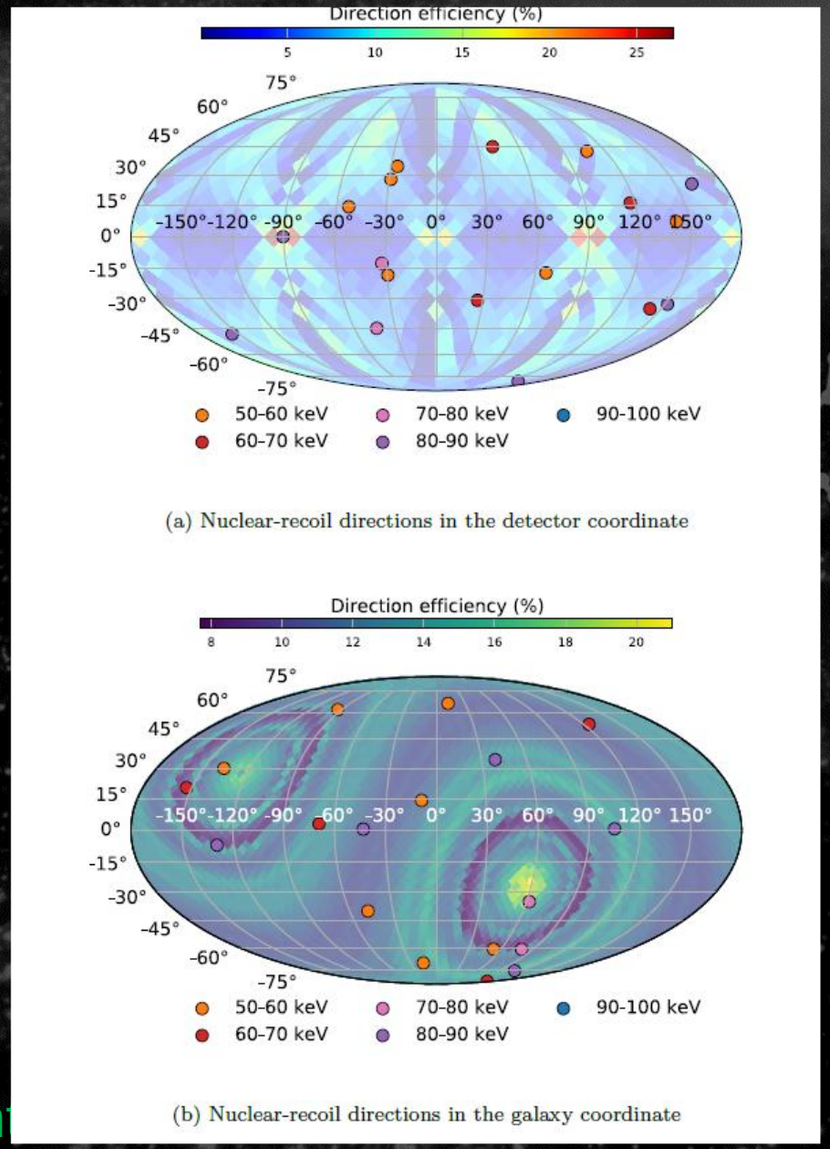
μ-PIC(Micro-pixel chamber)
- 31 × 31cm²
- pitch : 400μm
- gain : ~1000
- made by DNP, Japan

GEM
- 31 × 32 cm²
- 8-segmented
- hole pitch : 140μm
- hole diameter: 70μm
- insulator : LCP 100μm
- gain : ~5
- made by Scienergy, Japan

- NEWAGE latest results

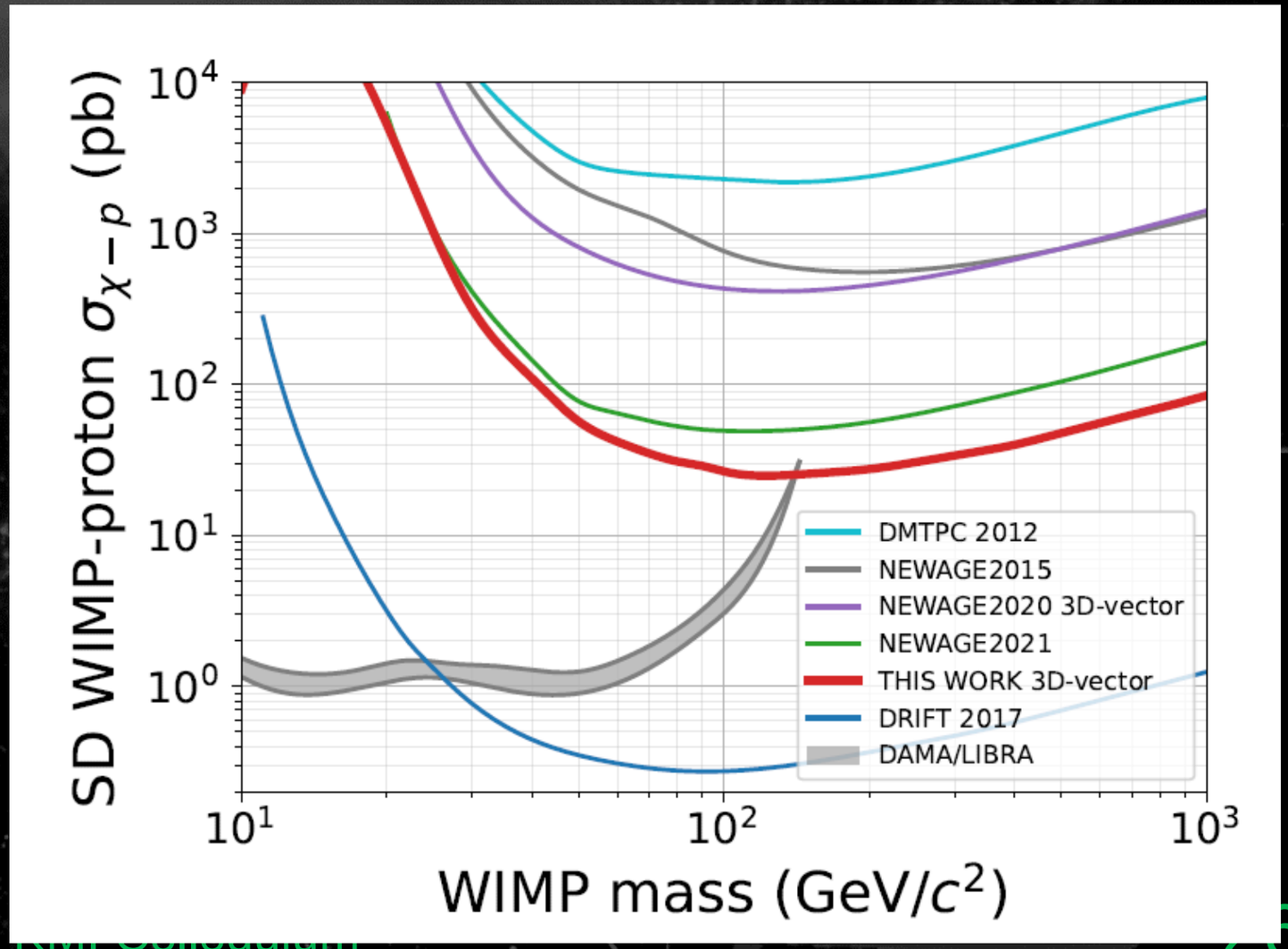
PTEP(2023)ptad120

  - 318 days measurement @ Kamioka



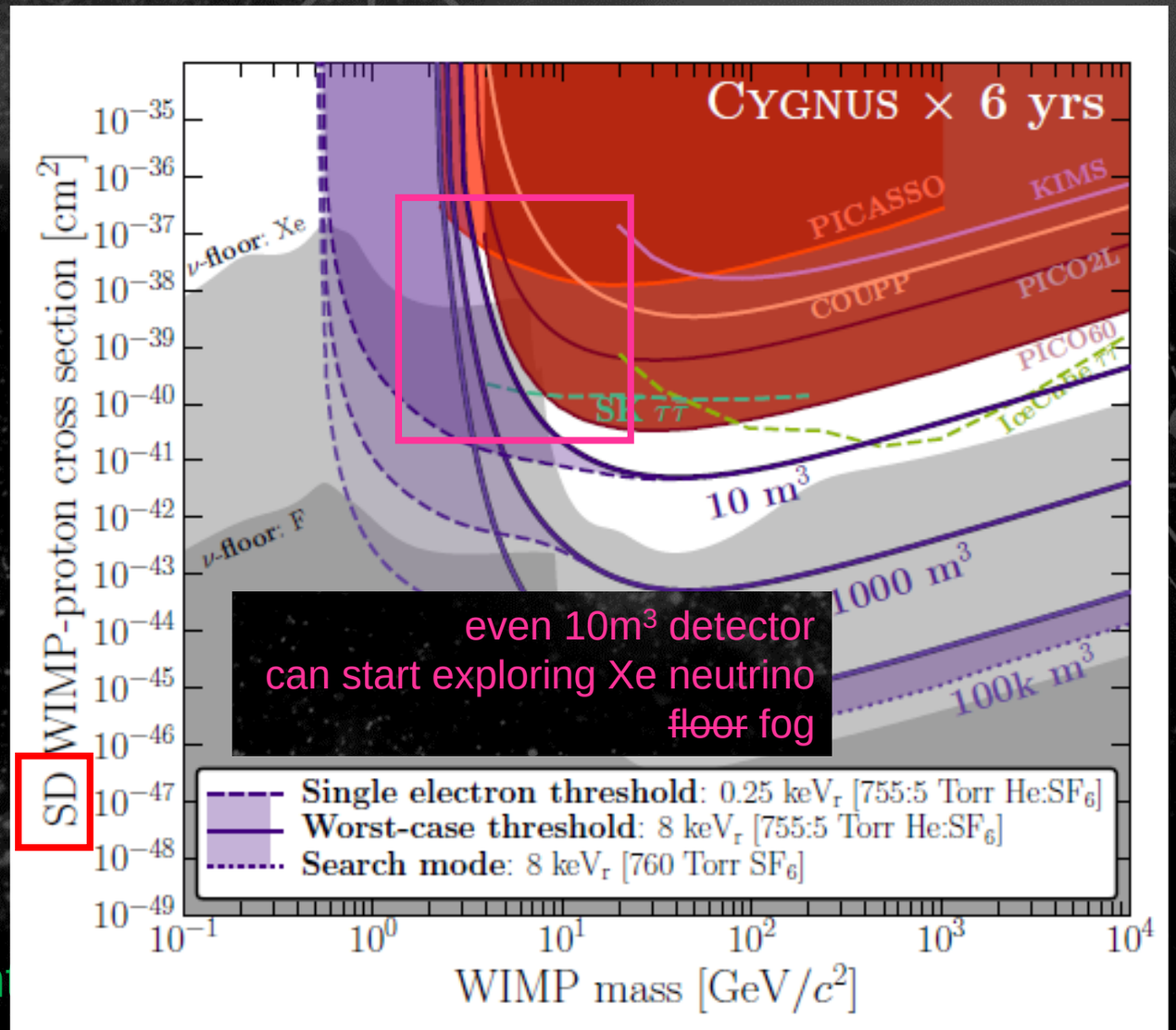
(a) Nuclear-recoil directions in the detector coordinate

(b) Nuclear-recoil directions in the galaxy coordinate

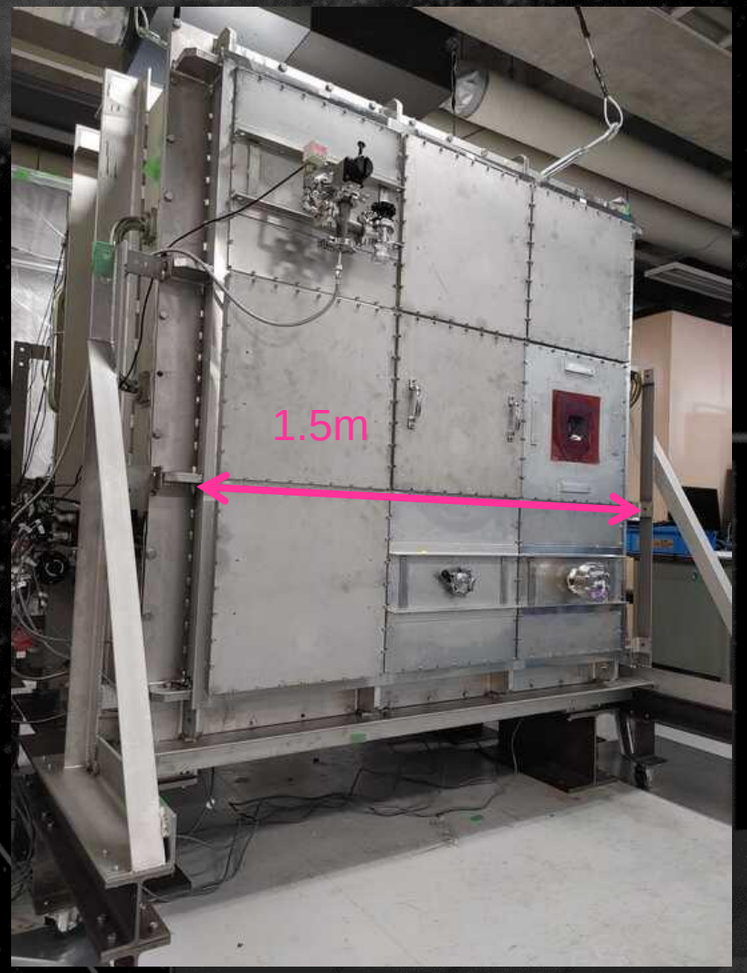


- CYGNUS: physics reaches
  - Realistic simulation (strip readout)

arXiv 2008.12587

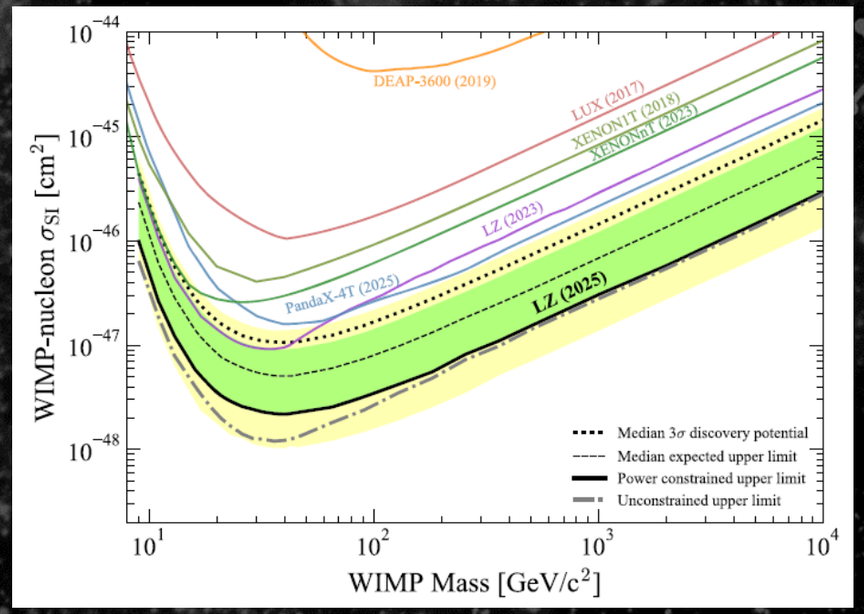


first “CYGNUS” chamber @Kobe

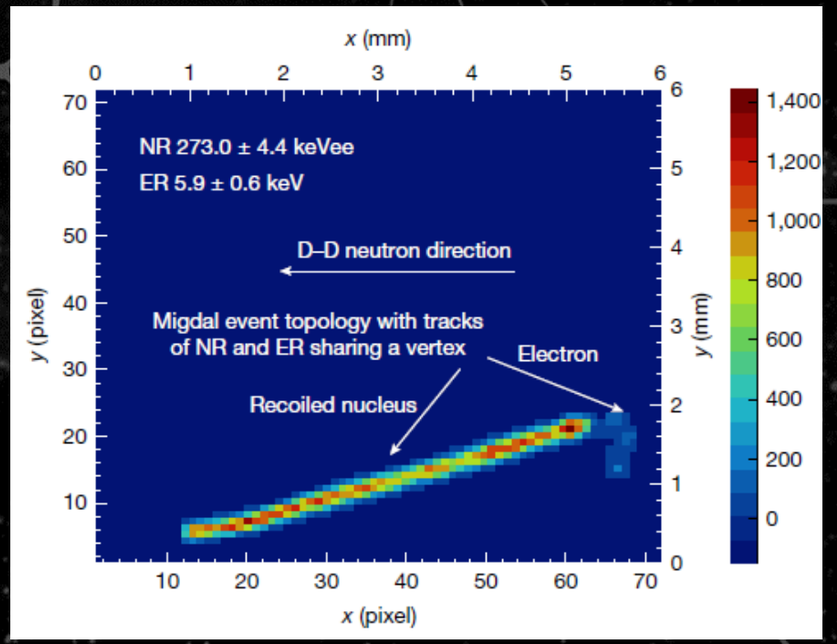


SUMMARY

- Liq. Xe (SI), Fluorine (SD)
- CEvNS, Migdal
- Future: large scale, directional



PRL 135, 011802 (2025)



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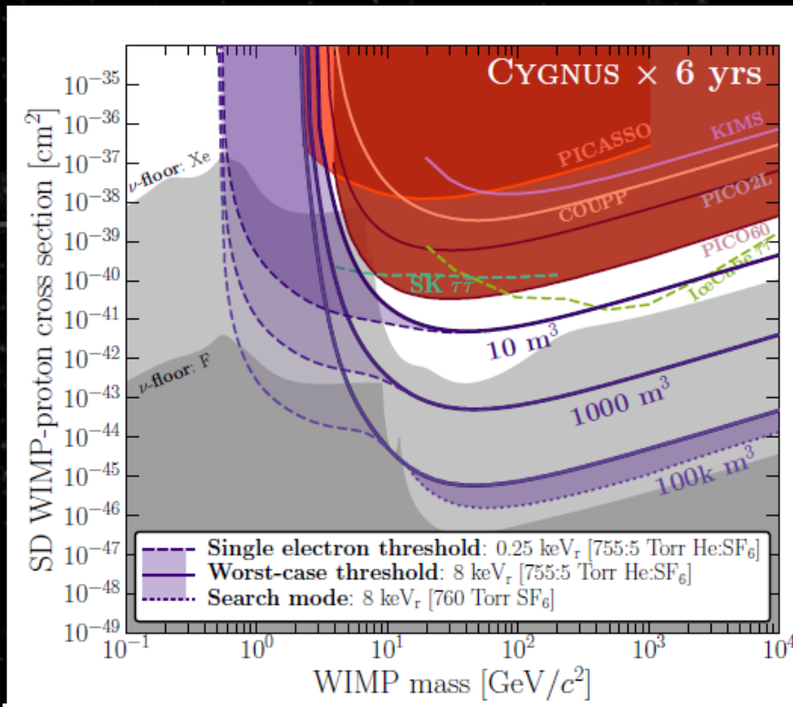

arXiv 2008.12587


Thank you