Status and perspectives of Direct Dark Matter searches

Rencontres de Physique des Particules 2026

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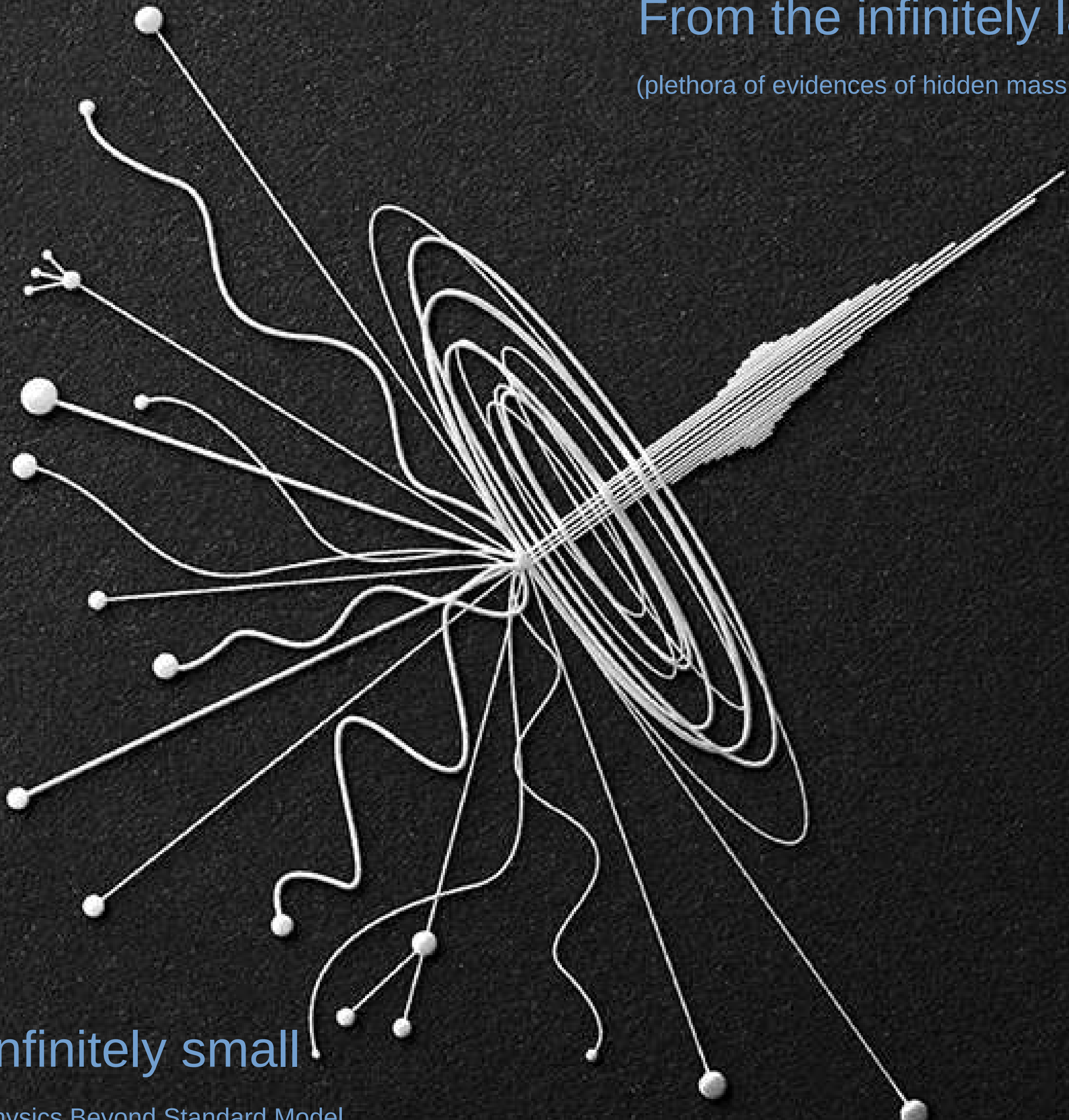
Intro

From the infinitely large . . .

(plethora of evidences of hidden mass in our Universe)



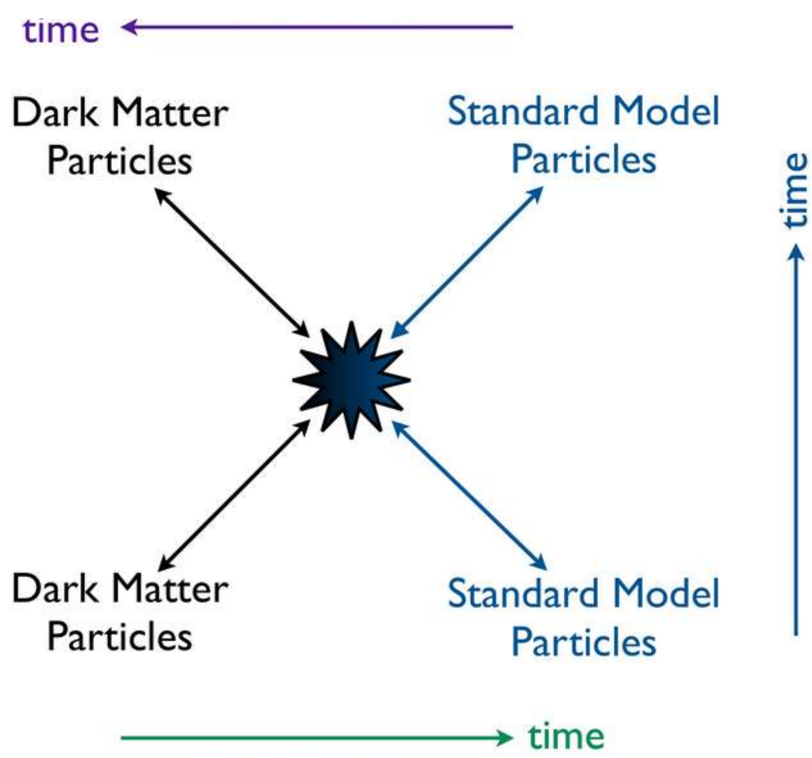
. . . to the infinitely small

(this might be a sign of Physics Beyond Standard Model of Particle Physics and/or Gravity)

Hunting Dark Matter with Particle Physics

Make ! → "Detection" with colliders : measuring missing P_T
(CMS, ATLAS @ LHC)

Each of them has their own assumptions. Possible to combine their results with some caveats



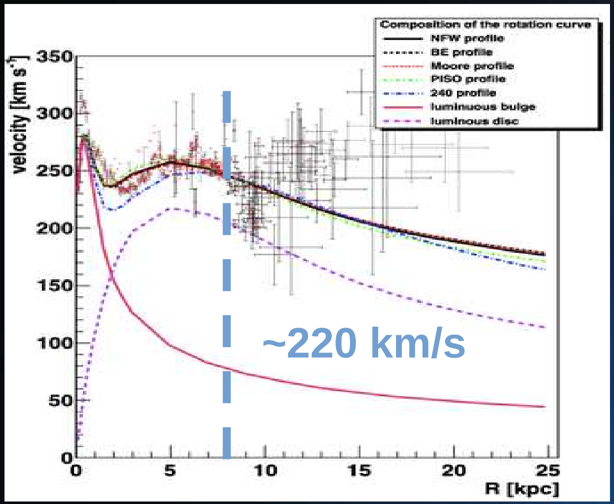
Shake ! → Direct detection of galactic DM :

on earth scattering off a detector nuclei

(Xe, Ar, Ge, NaI, Si, ...)

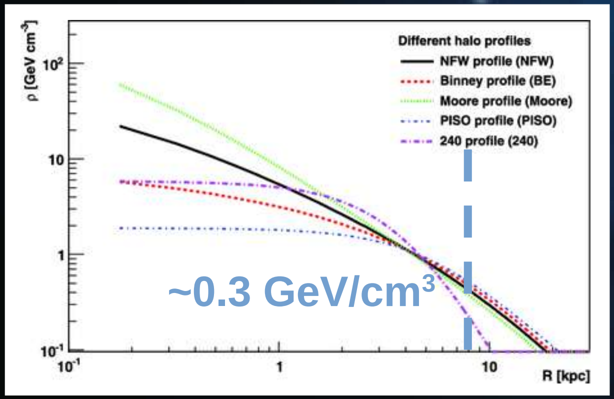
Break ! → Indirect detection of cosmic DM : annihilation
(AMS, PAMELA, CTA, IceCube, ...)

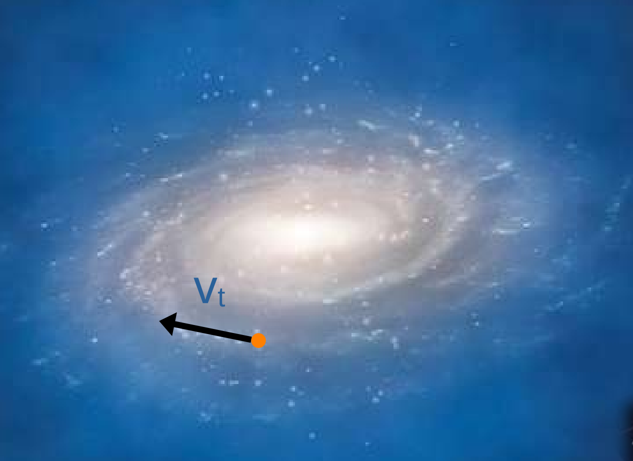
Assumptions of Direct Dark Matter search



Its velocity against us
and its density

M. Weber, W. de Boer, Astron.Astrophys.509:A25,2010

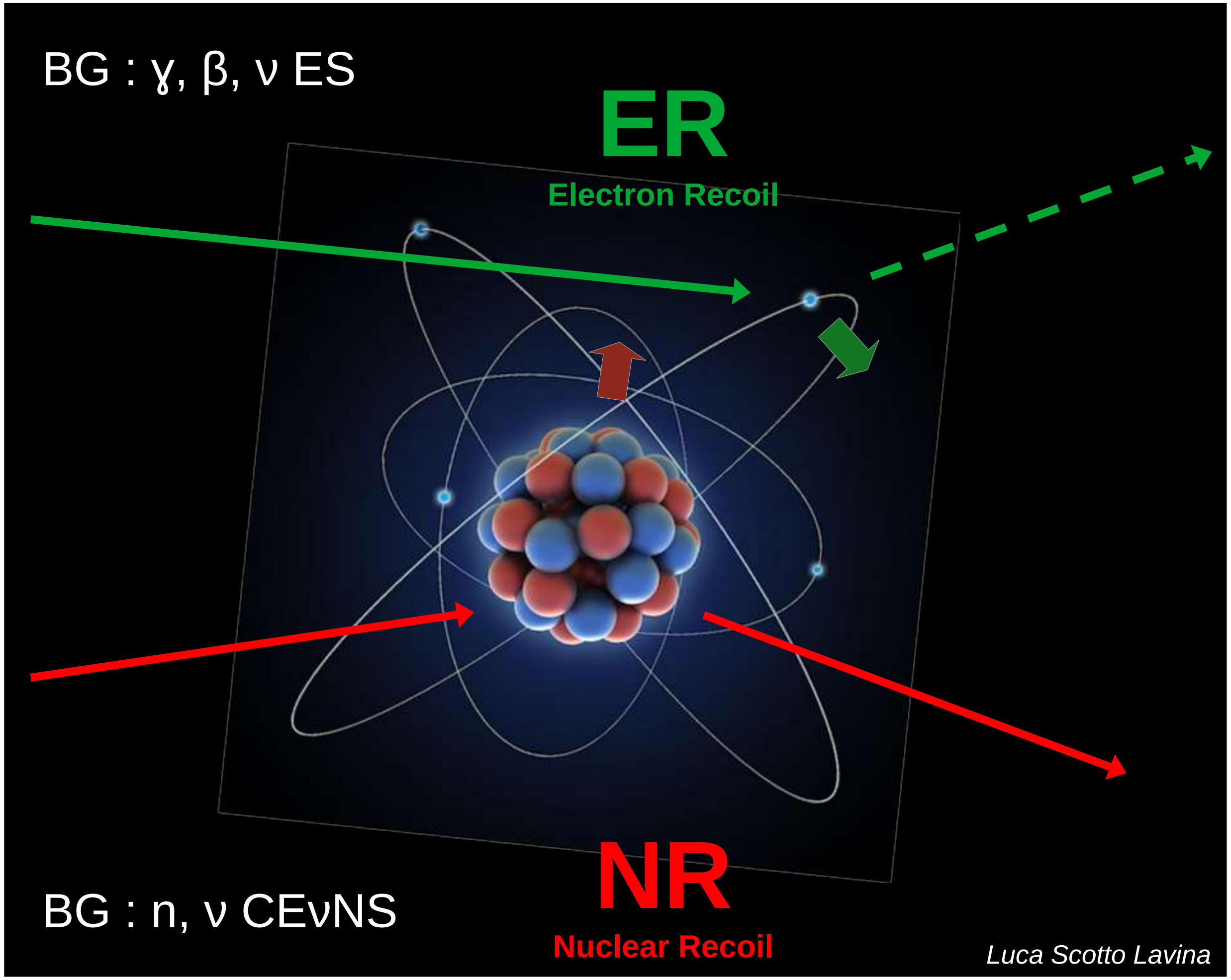




Dark
Matter
Halo

Dark Matter “wind” coming
from a well defined
direction (Cygnus
constellation)

Which target and which mechanism ?



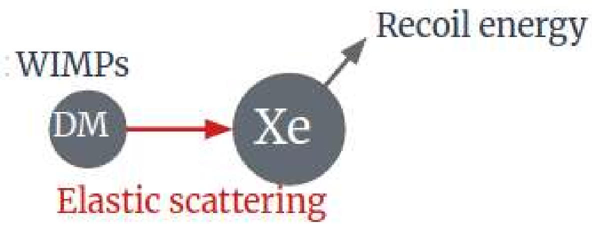
- DM-e
- ALPs
- Dark photons
- ...

- WIMPs
- MIMPs
- ...

Also :
- SD vs SI
- Elastic vs inelastic
- Light vs heavy mediator

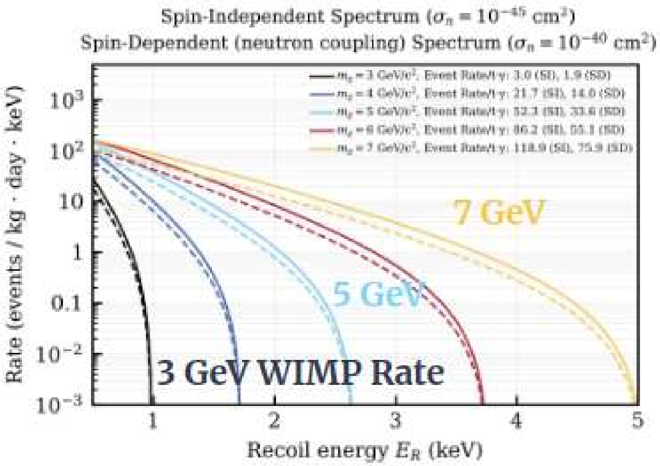
Signal Model <-> Event Rates

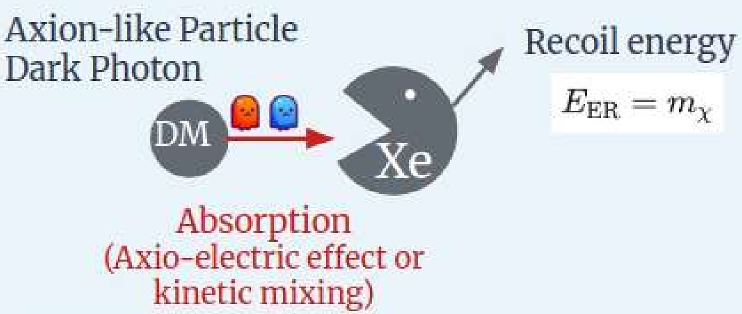
Courtesy of Y. Pan, La Thuile 2026



$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_{Xe}} \int_{v_{min}}^{v_{esc}} f(v) v \frac{d\sigma_{\chi-Xe}}{dE_R}(v)\, dv$$

DM & Xe Properties | DM Velocity | Model Dependent Cross section

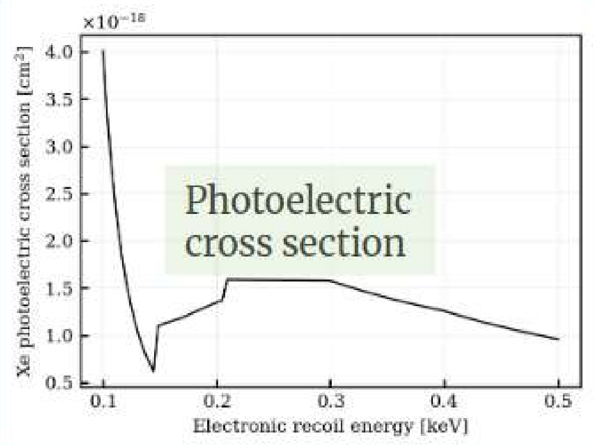


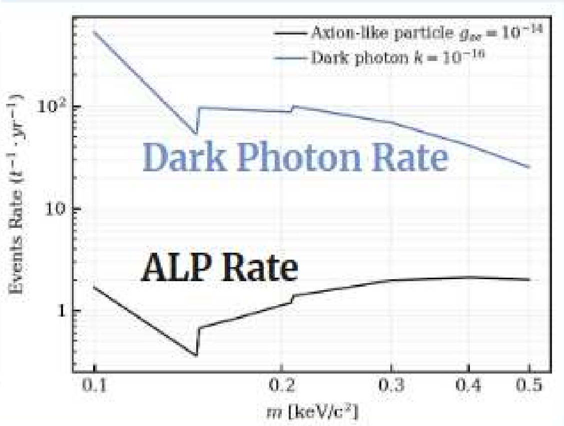


$E_{ER} = m_\chi$

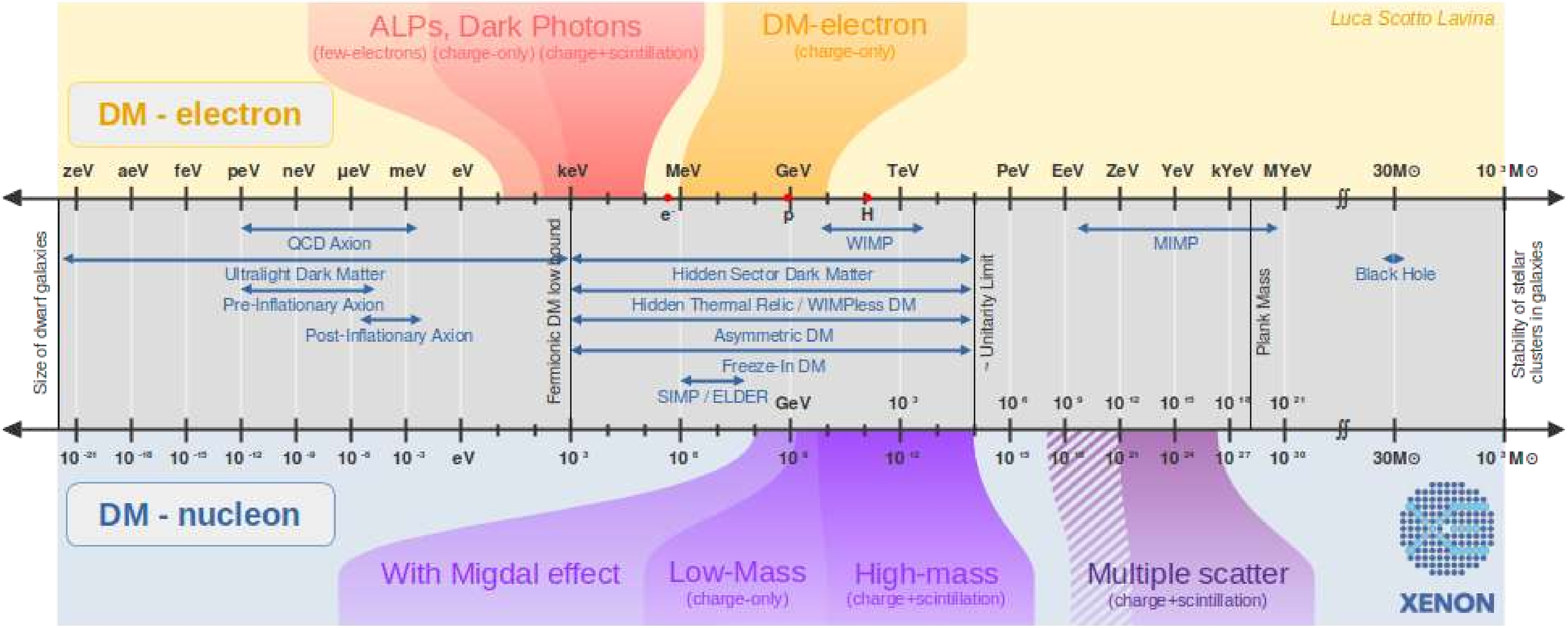
$$R_{DP} \propto \frac{\sigma_{PE}}{m_{DP}}$$

$$R_{ALP} \propto \sigma_{PE} \cdot m_{ALP}$$

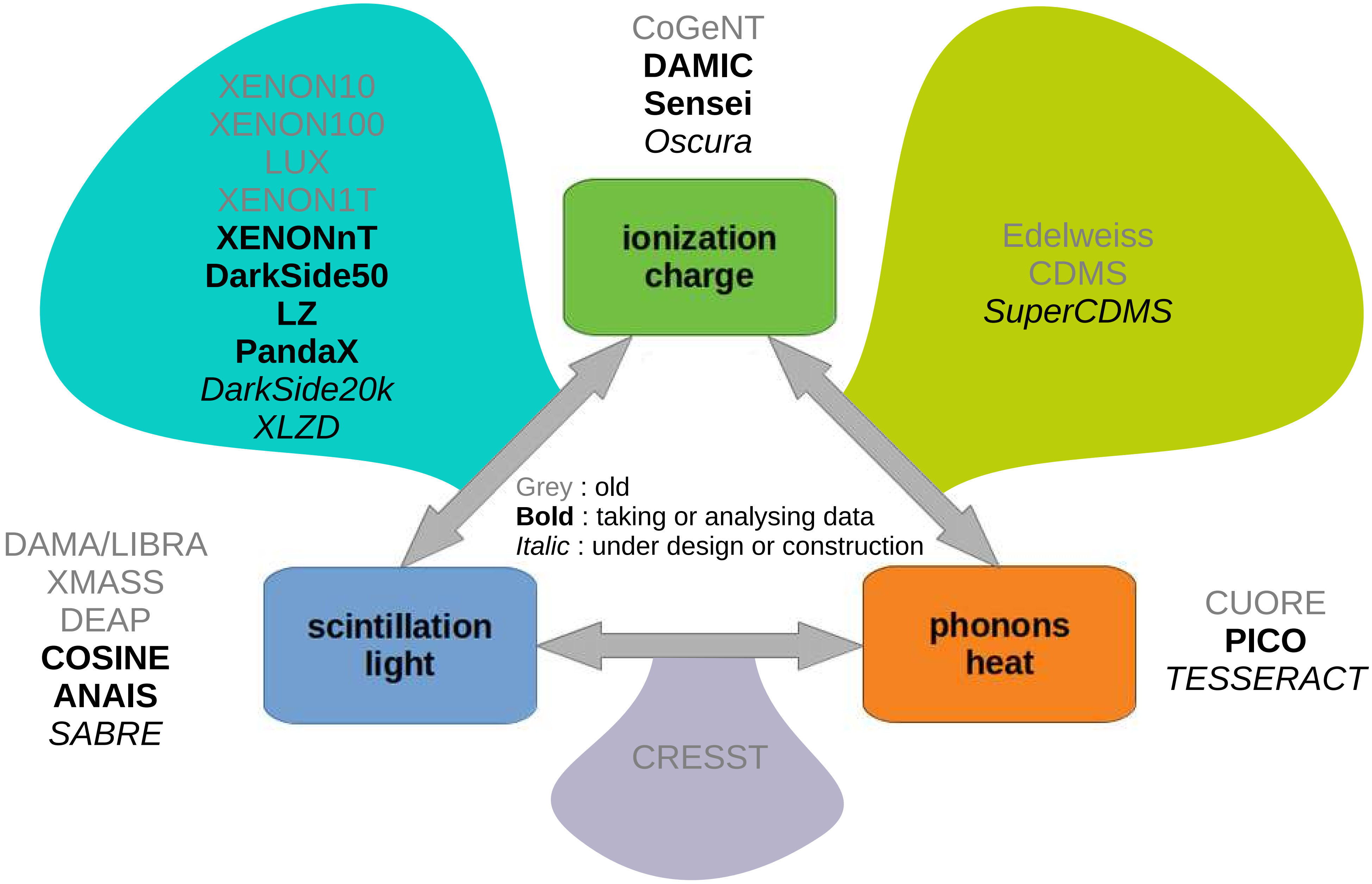




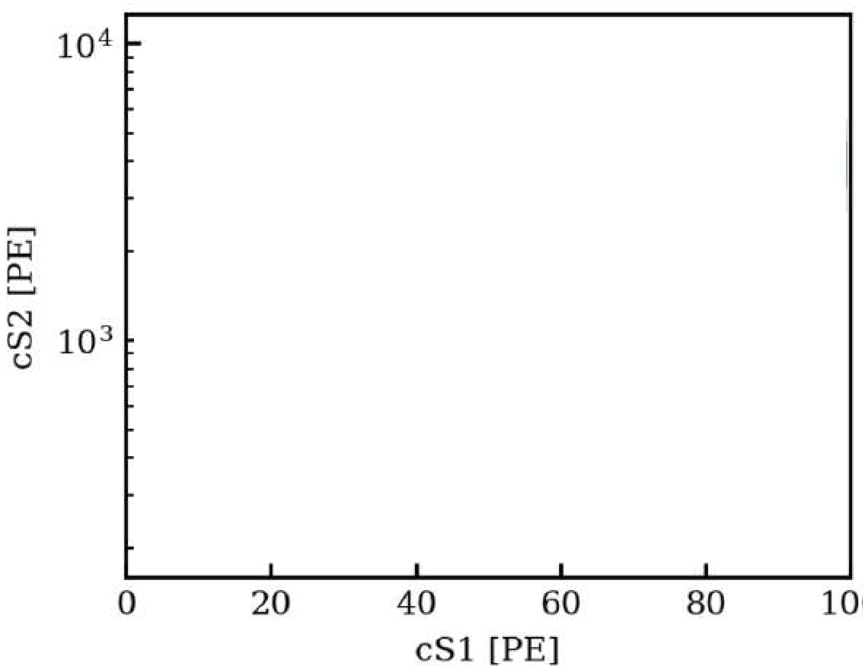
Example of scoped energy domains



Energy recoil : the observables



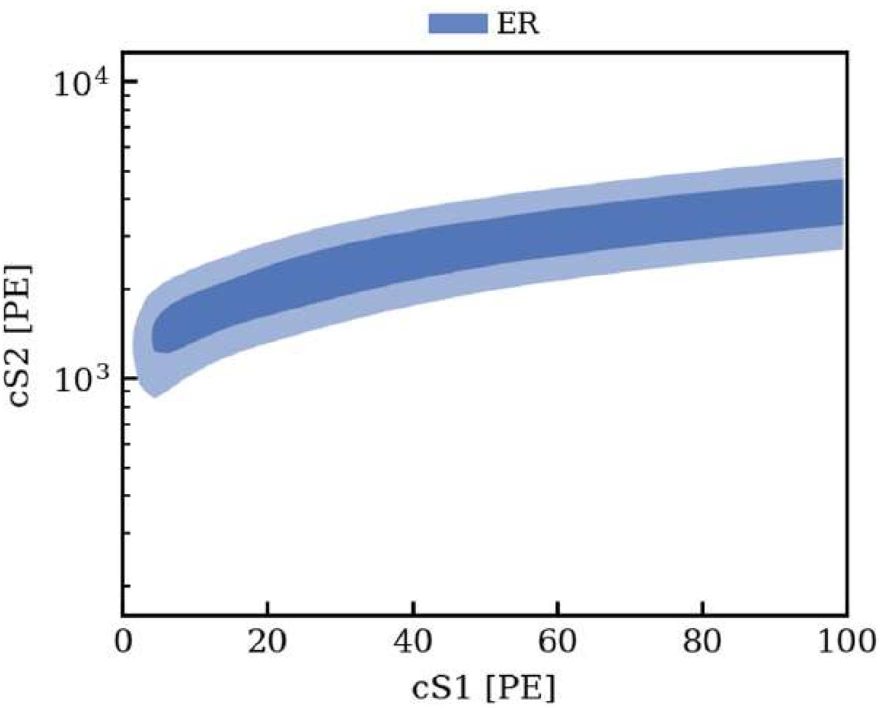
Signal and background models



Signal and background models

Electronic recoils

- Dominated by β-decay of ^{214}Pb (intrinsic to the LXe target)
- Suppressed by ER/NR discrimination



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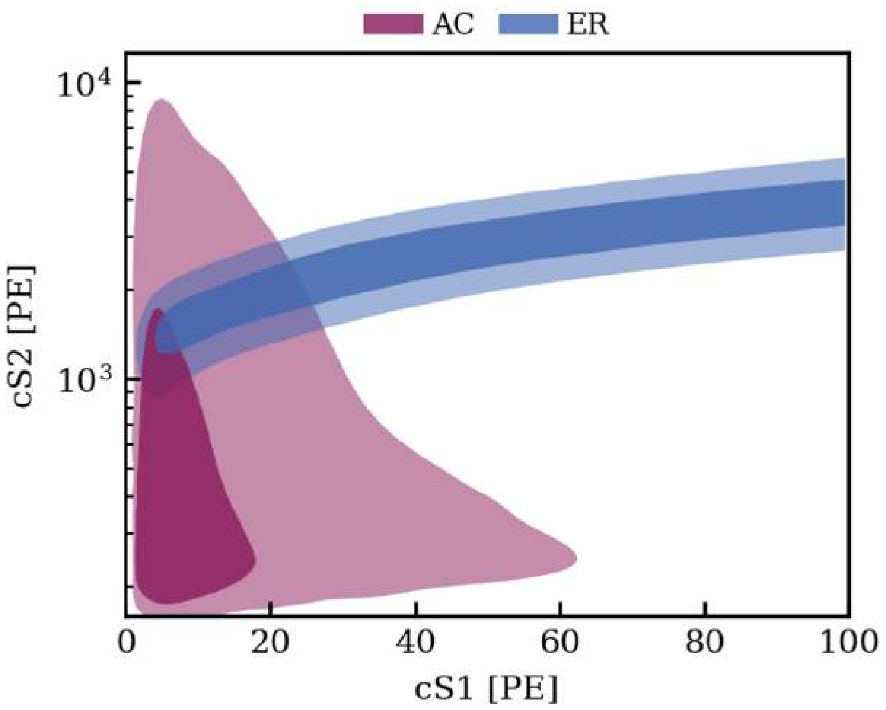
Accidental Coincidence

- Random pairing of isolated S1 & S2 signals
- Suppressed by dedicated analysis cuts



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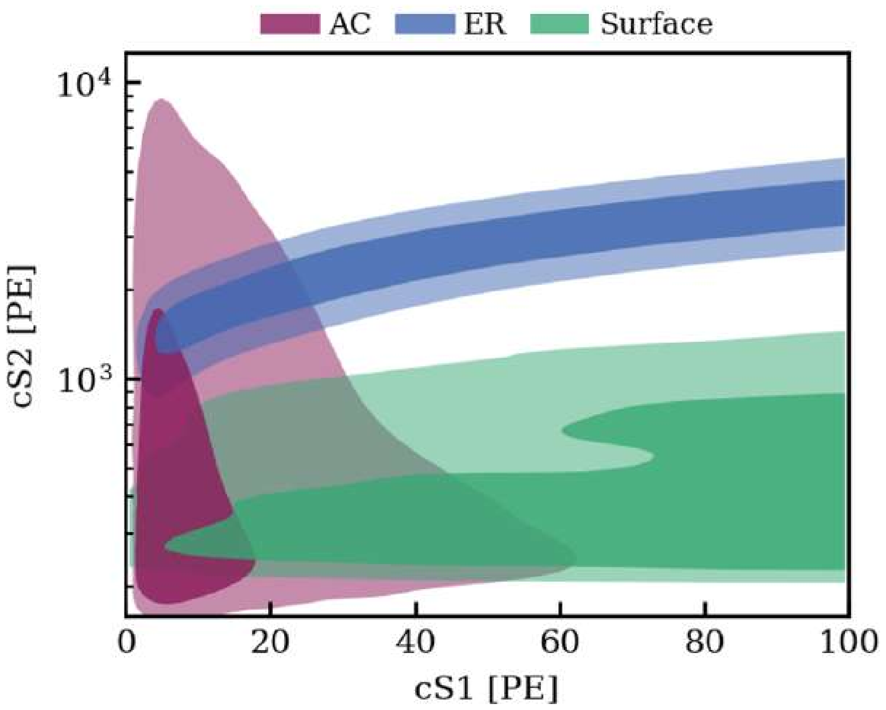
Surface

- ^{210}Pb plate-out on PTFE walls of the TPC
- Suppressed by FV.



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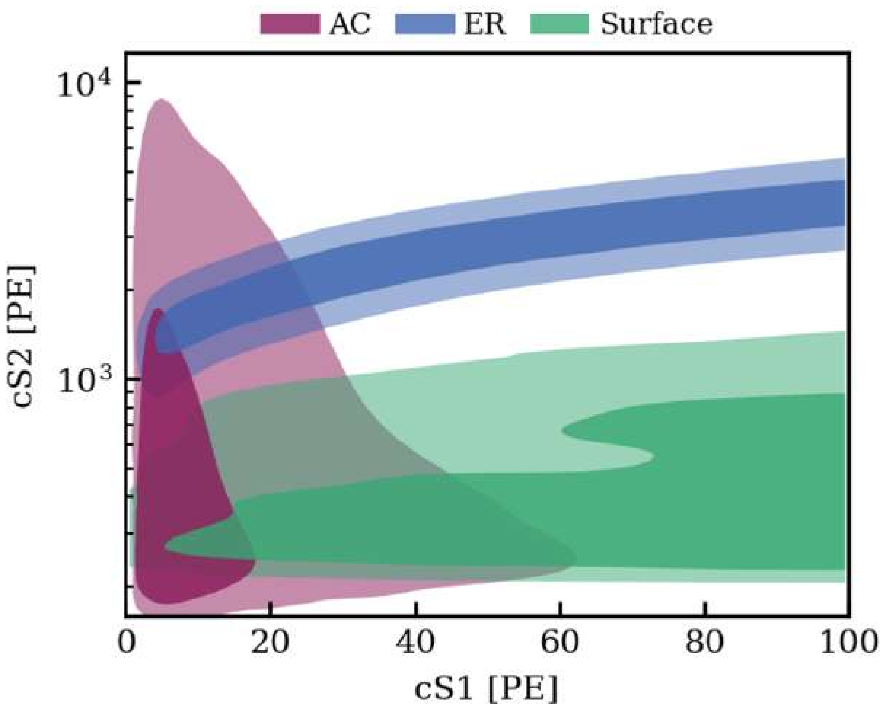
Nuclear recoils

- Radiogenic neutrons spontaneous fission & (α, n)-reactions
  - ➡ Rate prediction from NV tagging ~ 1.1 events
- Cosmogenics are negligible after μVeto
- ^{8}B CEνNS constrained by flux



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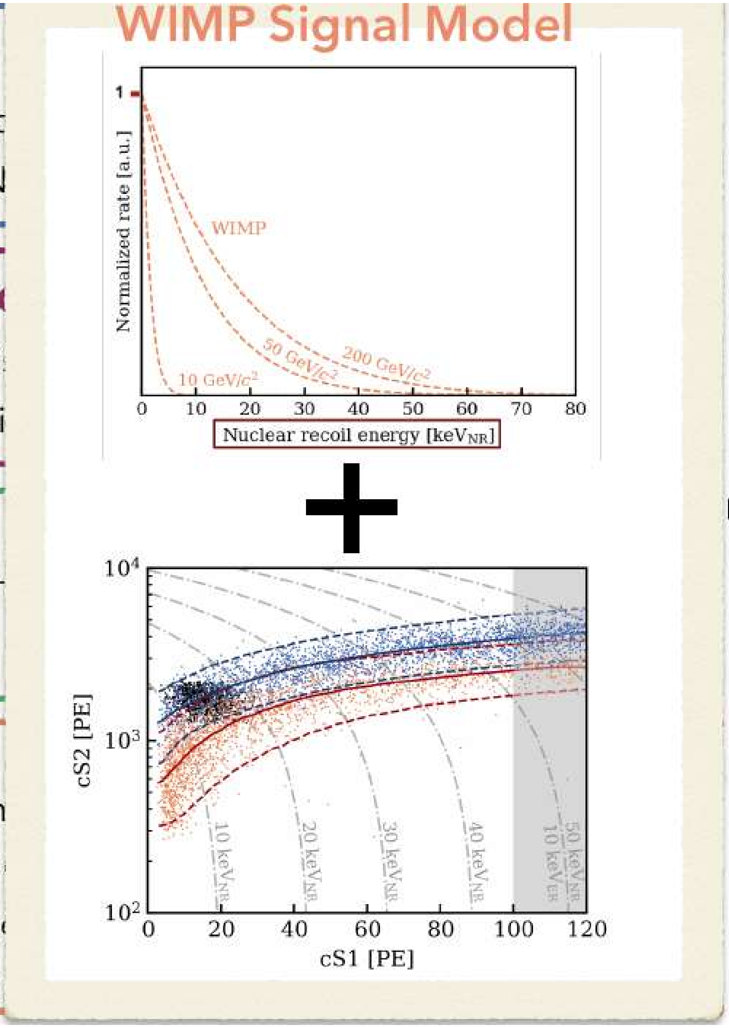

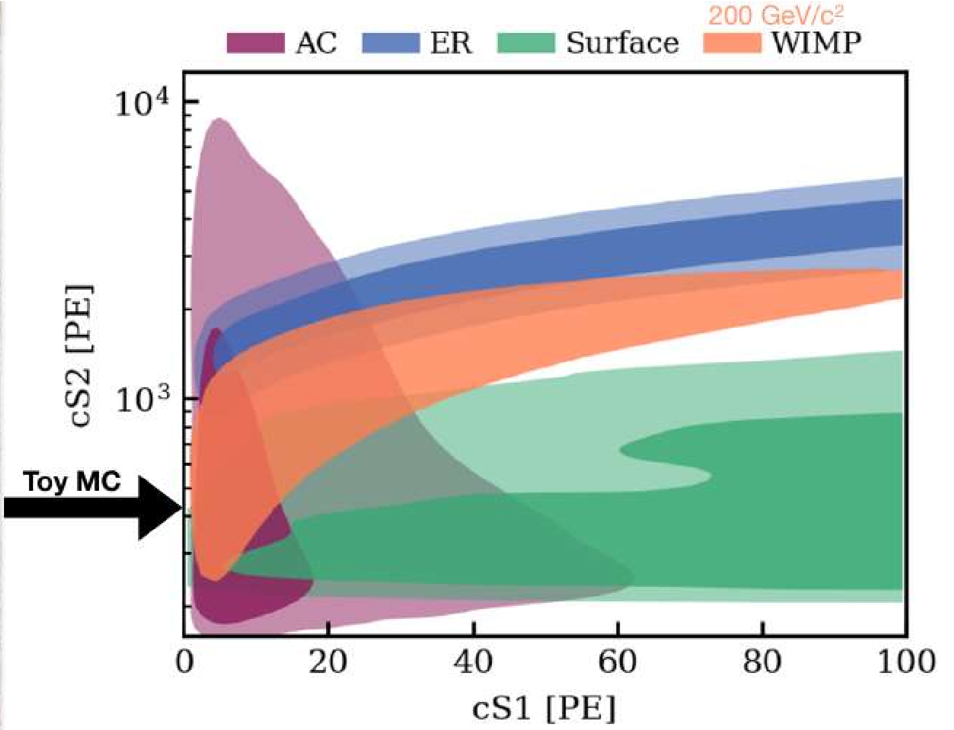

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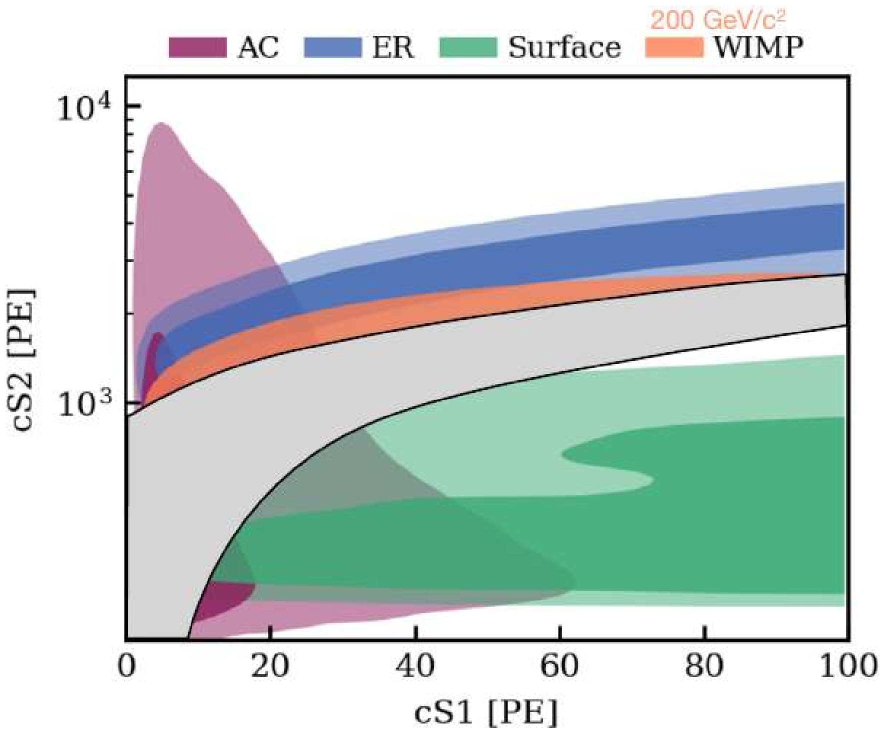
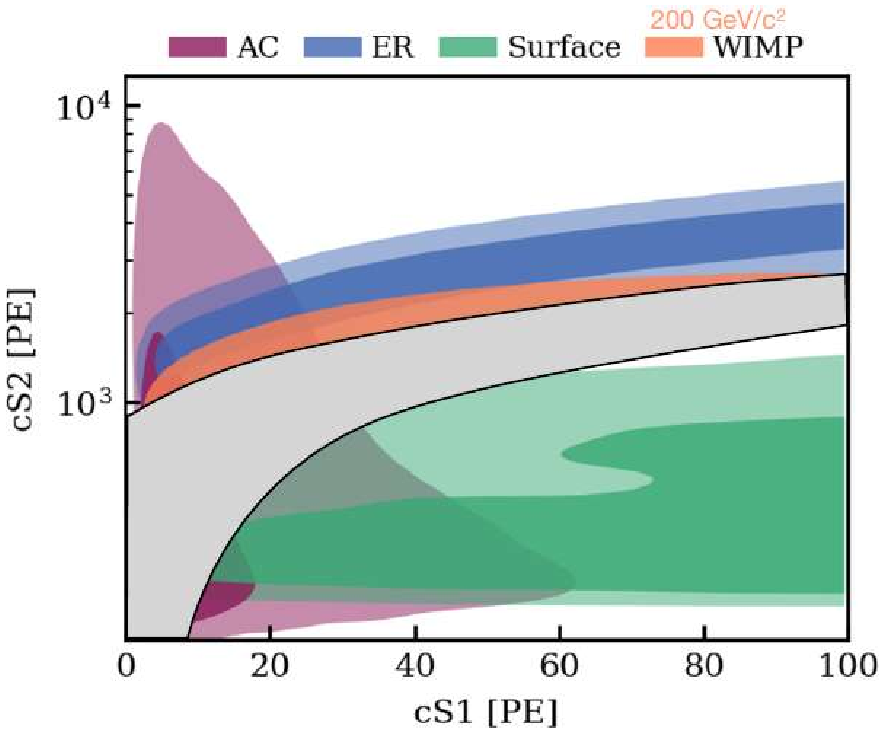


We are performing a blinded data analysis!

WIMP results

	Expectation
ER	134
Neutrons	$1.1^{+0.6}_{-0.5}$
CEvNS	0.23 ± 0.06
AC	4.3 ± 0.2
Surface	14 ± 3
Total	154
200 GeV/c² WIMP	-
Observed	-

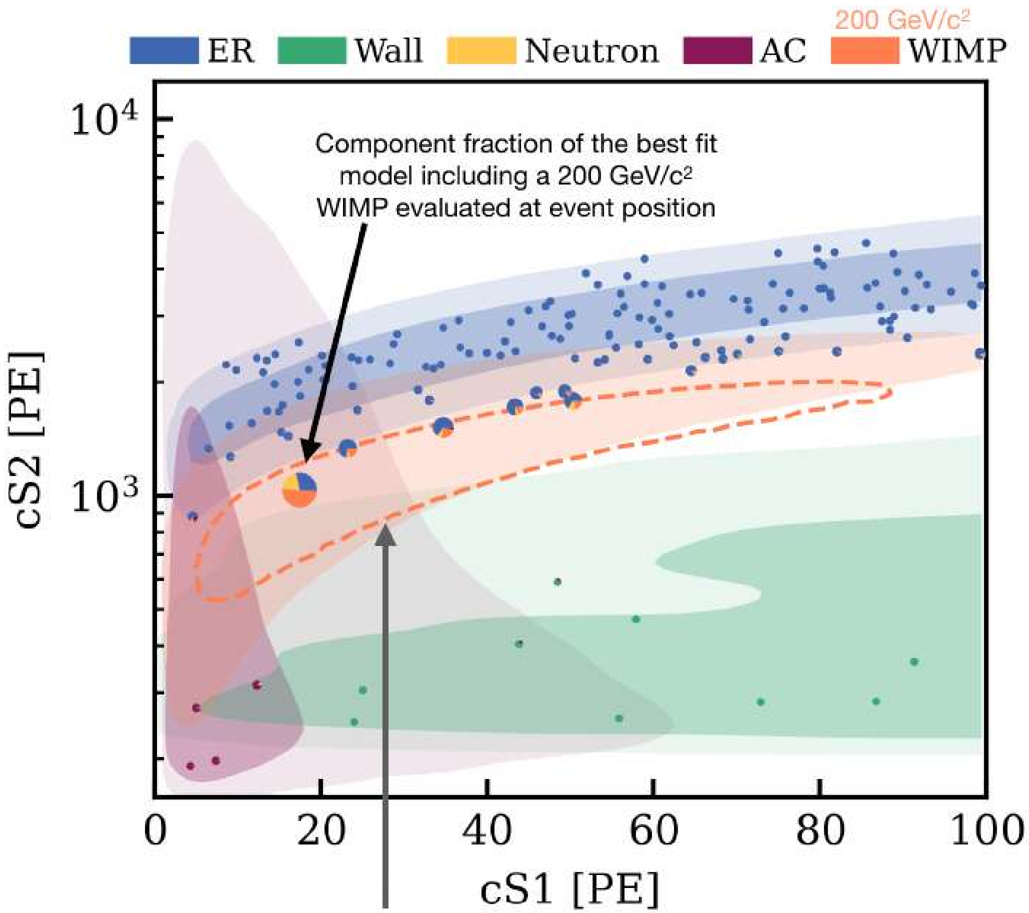


WIMP results

Unblinding

	Expectation	Best Fit
ER	134	135^{+12}_{-11}
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4
CEvNS	0.23 ± 0.06	0.23 ± 0.06
AC	4.3 ± 0.2	4.32 ± 0.15
Surface	14 ± 3	12^{+0}_{-4}
Total	154	152 ± 12
200 GeV/c² WIMP	-	2.4
Observed	-	152

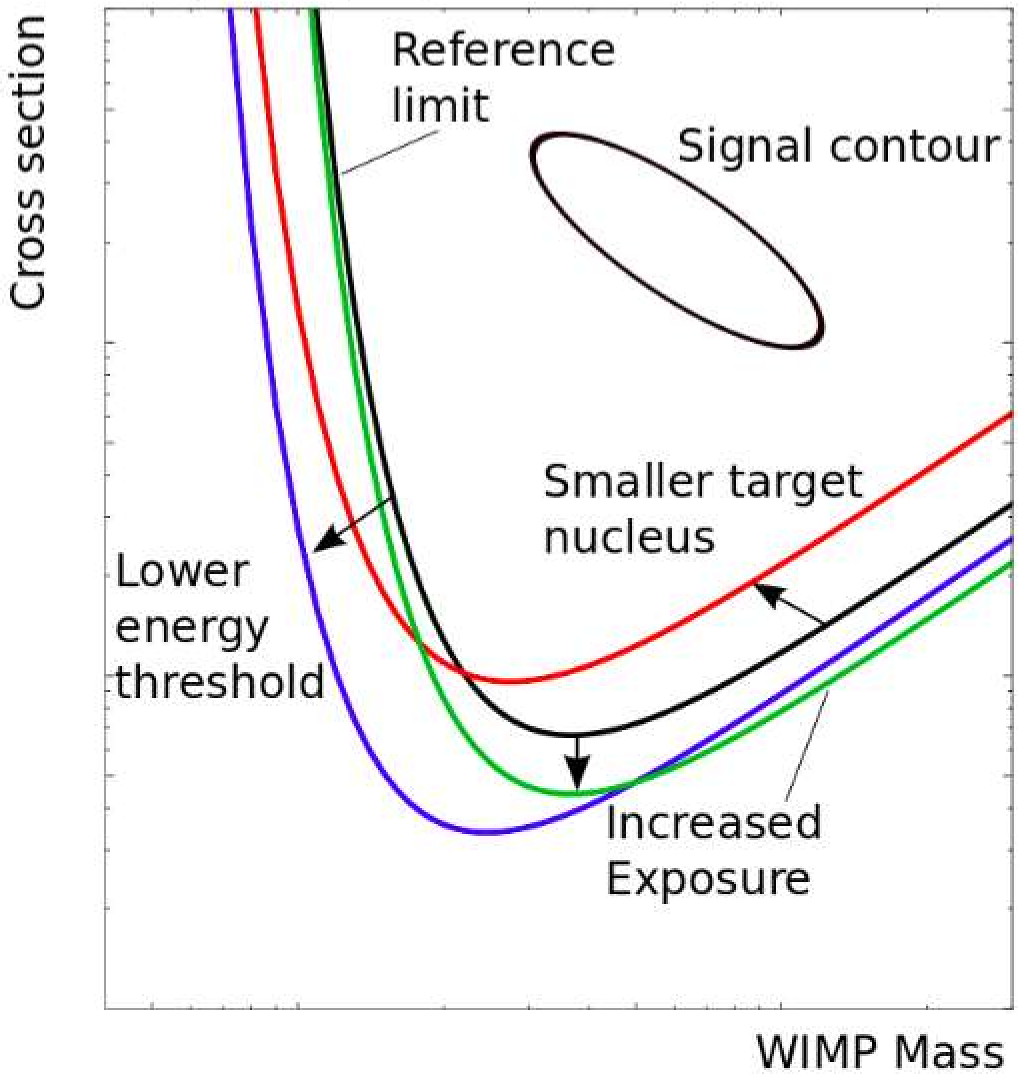
- 152 events in ROI, 16 in blinded region
- Profile log-likelihood-ratio test statistic
  - ➡ **No significant excess observed**



Signal-like region, containing 50% of a 200 GeV/c² WIMP signal with highest signal-to-noise ratio

Result of a direct detection experiment

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767



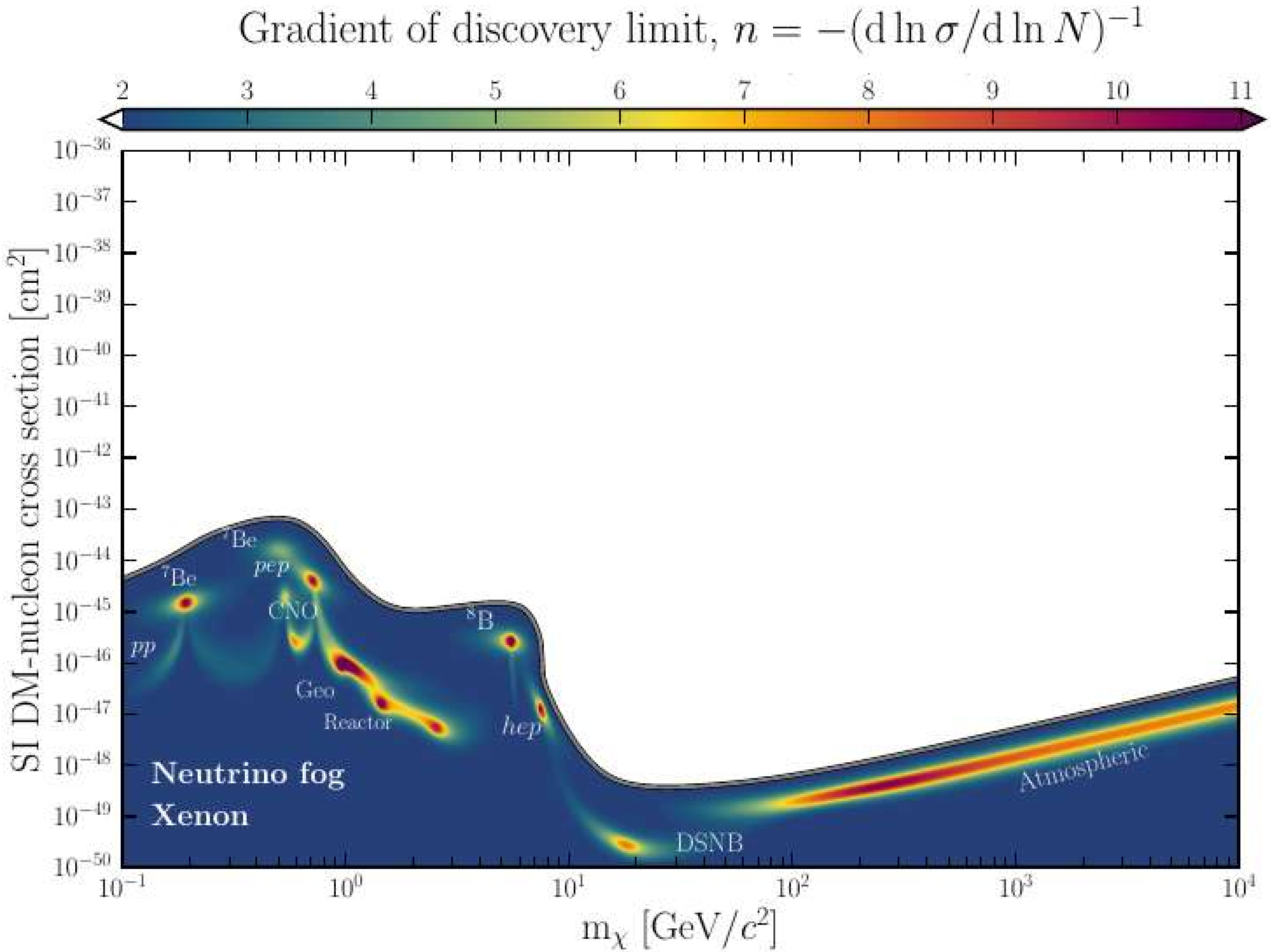
Positive signal

- Region in σ_χ versus m_χ

Zero signal

- Exclusion of a parameter region
  - Low WIMP masses: detector threshold matters
  - Minimum of the curve: depends on target nuclei
  - High WIMP masses: exposure matters = m × t

Playground and neutrino fog



The DarkPlotter

0. Load the darkplotter library

```
In [1]: # import darkplotter lib
        import darkplotter as dp
```

1. Call the Data manager constructor

the constructor automatically loads the content of the json folder where all available data are present. You can specify as well your own folder with the 'path' flag

```
In [2]: mydata = dp.DMdata(path='./json')
```

2. Select the experiment you want

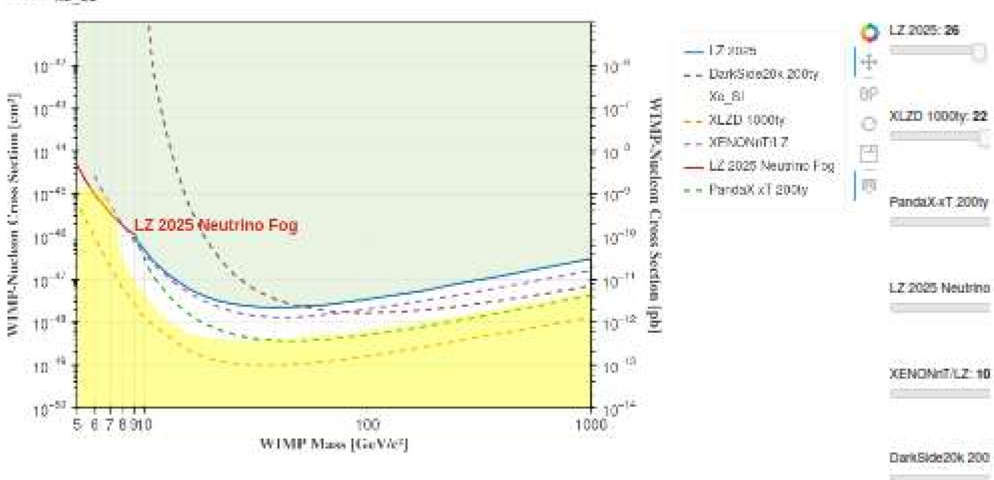
By default, all data are shown. By setting "collaboration" and "experiment" flags you can restrict the selection to specific elements

```
In [3]: import pandas as pd

        myexp = pd.concat([
            mydata.get_experiment(label=[
                "LZ 2025",
                "Xe_SI",
                "LZ 2025 Neutrino Fog",
                "XENONnT/LZ",
                "DarkSide20k 200ty",
                "PandaX-xT 200ty",
                "XLZD 1000ty"
            ])
        ])
```

4. Call the DMplotter constructor

Change the massunit by setting "massunit"

```
In [4]: myplotter = dp.DMplotter()
        myplotter.figlimits = {'xmin':5, 'xmax':1e3, 'ymin':1e-50, 'ymax':1e-41}
        myplotter.plot(myexp,massunit="GeV")

----- LZ 2025
----- XLZD 1000ty
----- PandaX-xT 200ty
----- LZ 2025 Neutrino Fog
----- XENONnT/LZ
----- DarkSide20k 200ty
----- Xe_SI
```



https://github.com/odadoun/DarkPlotter

SI-LZ-LZ8B-cbb04c5fe6f7bcc5798eb8ab18d423e4.json

{
"parameters-space": "SI",
"collaboration": "LZ",
"experiment": "LZ",
"label": "LZ 2025 Neutrino Fog",
"comment": "5.7ty SI limit",
"arxiv": "2512.08065",
"doi": "https://doi.org/10.48550/arXiv.2512.08065",
"bibtex": "@article{LZ:2025igz, author = {Akerib, D. S. and others}, collaboration = {LZ}, title = {Searches for Light Dark Matter and Evidence of Coherent Elastic Neutrino-Nucleus Scattering of Solar Neutrinos with the LUX-ZEPLIN (LZ) Experiment}, eprint = {2512.08065}, archivePrefix = {arXiv}, primaryClass = {hep-ex}, month = {12}, year = {2025}}",
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"y-units": "cm2",
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"y": [2.14e-42, 2.60e-43, 4.74e-44, 4.80e-45, 1.93e-45, 9.49e-46, 3.51e-46, 1.91e-46, 1.38e-46, 1.13e-46]
}

Deep Underground Physics

WIMPs domain (>10 GeV)

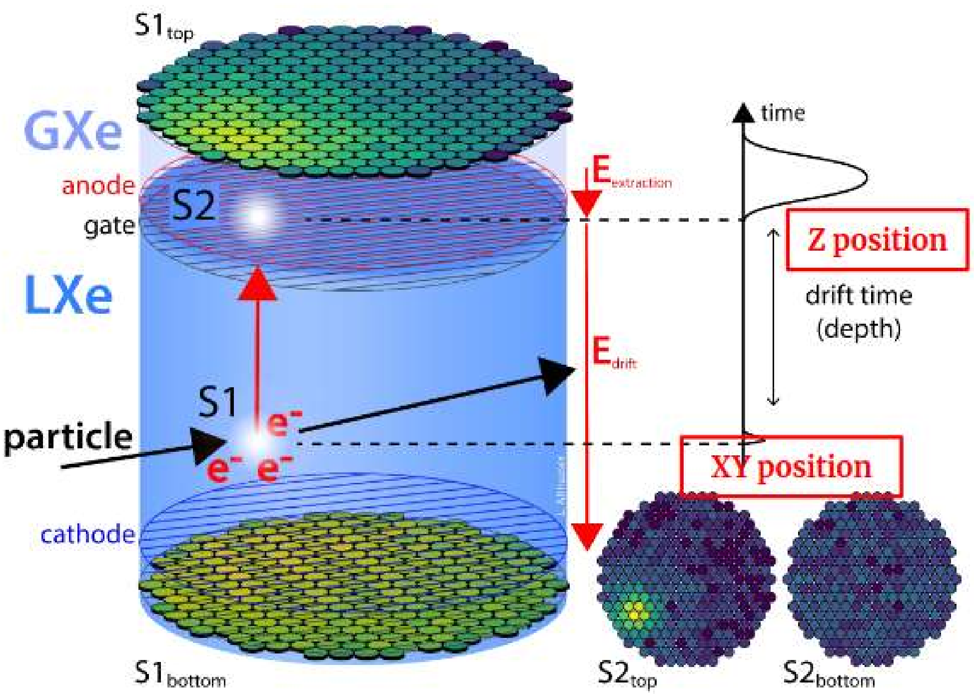
High WIMP mass : the three leading experiments

Working principle of a LXe TPC

Courtesy of Y. Pan, La Thuile 2026

XENONnT Experiment

Direct detection of dark matter



Dual phase Xe TPC (Time projection chamber)

- **S1:** Prompt scintillation light
- **S2:** Secondary scintillation light by ionized electrons

- **3D Position reconstruction:** Drift time + PMT pattern
- **Energy reconstruction:**

$$E = W\left(\frac{cS_1}{g_1} + \frac{cS_2}{g_2}\right)$$

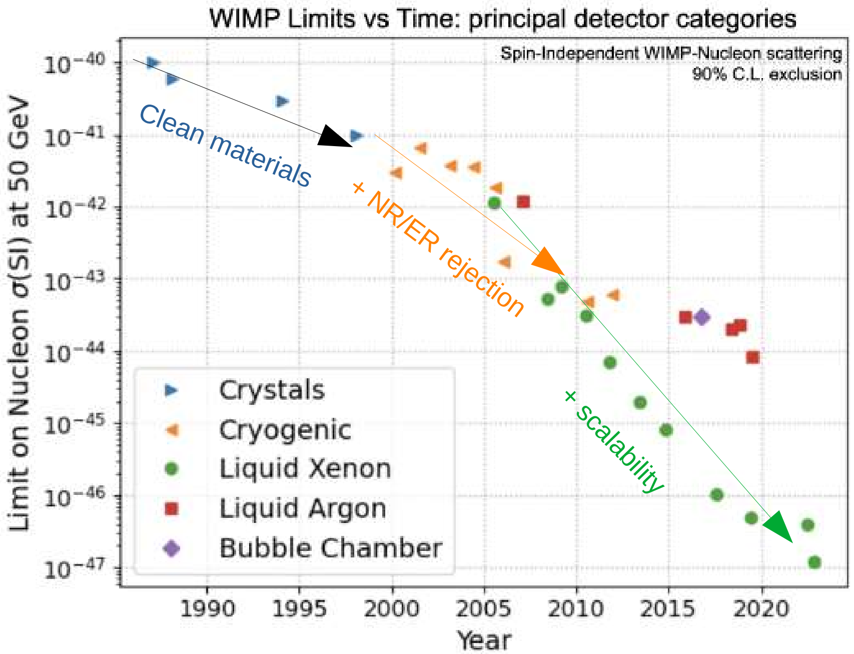
W: Average energy to produce a quanta
cS1, cS2: Corrected area of S1 and S2
g1, g2: Gain of S1 (~0.1) and S2 (~15)

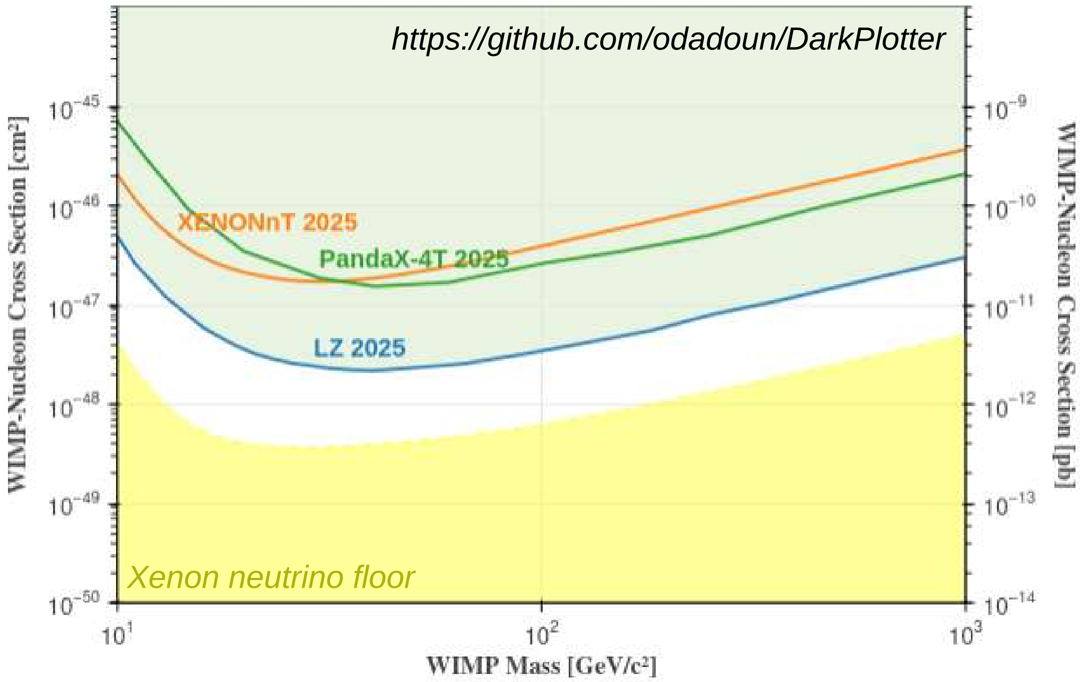
Small S1	Large S2
Low detection effciency	Strong scintillation in gas
Photon ✖100 ⇨ S1 = **10 PE** (1)	e− ✖100 ⇨ S2 = **1500 PE**

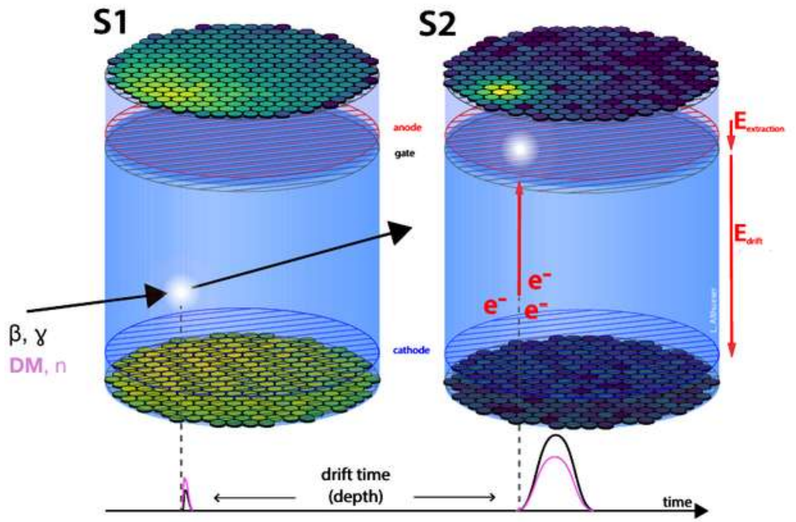
⇒ Motivation of **S2-only** analysis

(1) Detected Photoelectron [PE]

High WIMP mass (m>10 GeV) : LXe TPCs rule







- No long-lived isotopes (Xe only)
- Odd and even isotopes (Xe only) → SD
- Self-shielding
- Recoil discrimination

- S1, S2 → event energy
- S2 image → xy coordinate
- S1-S2 timing → z coord.
- S2/S1 → recoil type

State of the art of liquid xenon detectors

LZ (best limit) :
- @SURF, US
- 10t total Xe mass
- 4.2 t y exposure

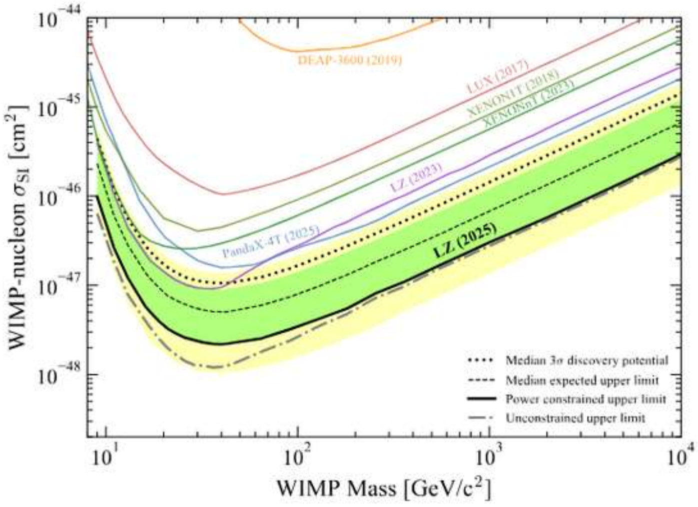
PRL 135, 011802 (2025)

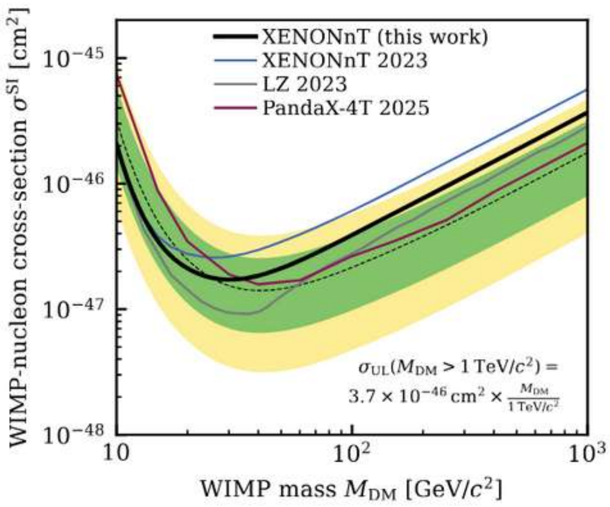
XENONnT :
- @LNGS, Italy
- 8.6t total Xe mass
- 3.1 t y exposure

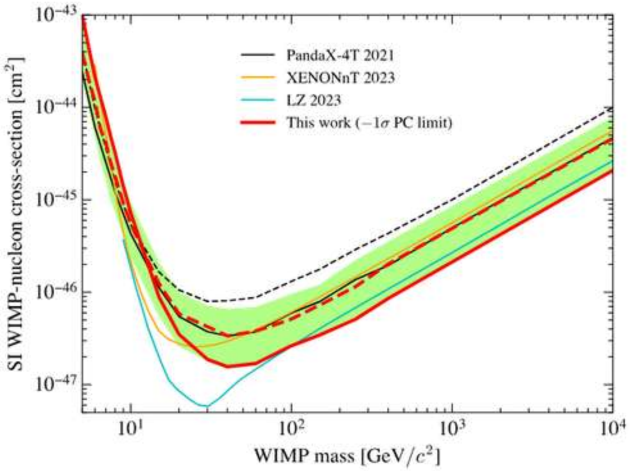
PRL 135, 221003 (2025)

PandaX-4T :
- @JinPing, China
- 6t total Xe mass
- 1.54 t y exposure

PRL 134, 011805 (2025)



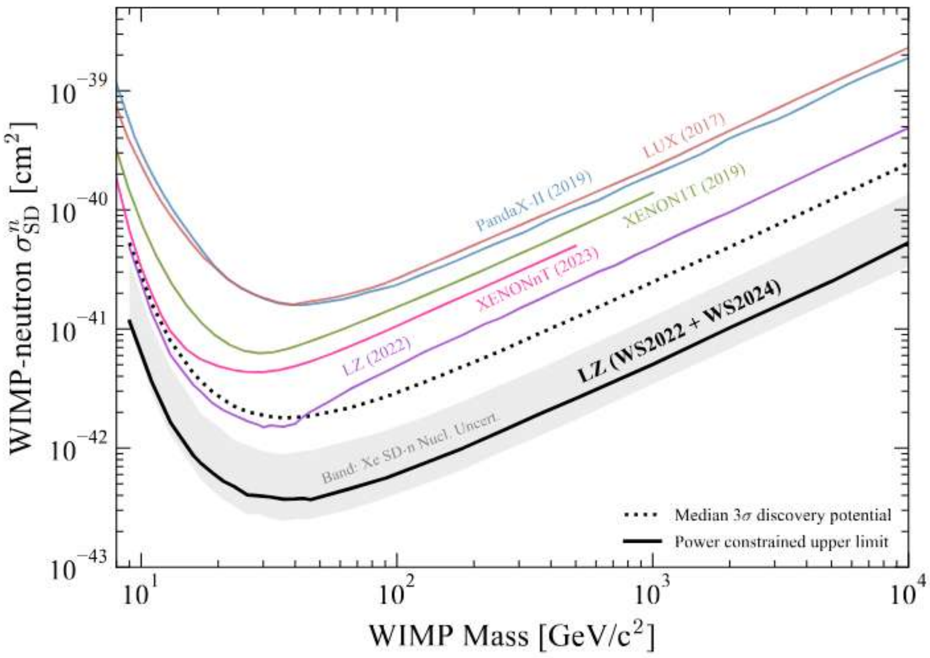




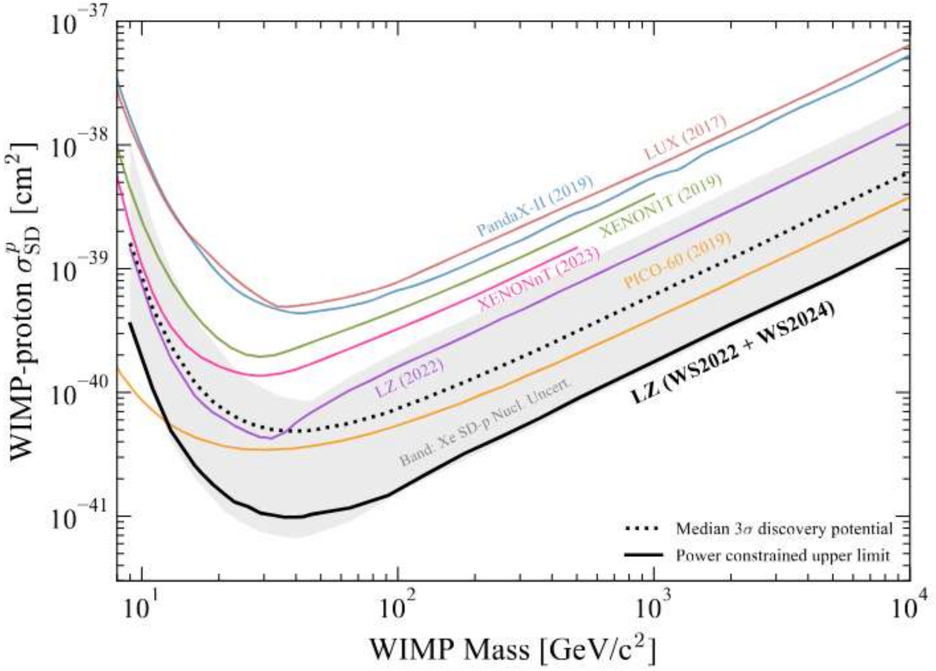
Spin Dependent interactions

LZ results (2025) :
4.2 ± 0.1 tonne-years from 280 live days

Coupling with neutron



Coupling with proton



First time LXe explored
new territory after PICO
(bubble chambers)

PRL 135, 011802 (2025), arXiv:2410.17036

WIMP-Nucleon Effective Field Theory Couplings

- Non relativistic effective field theory (NREFT)
- WIMP-nucleon interaction described by :

$$i\frac{\vec{q}}{m_N}, \quad \vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\mu}, \quad \vec{S}_\chi, \quad \vec{S}_N$$

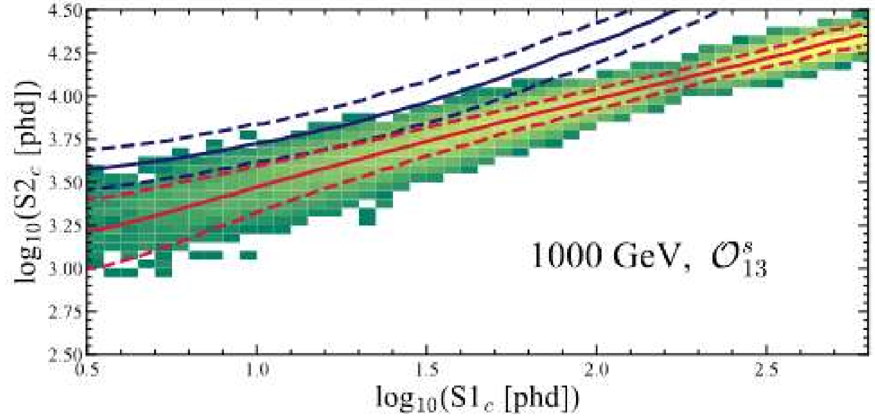
- 15 independent and dimensionless operators :

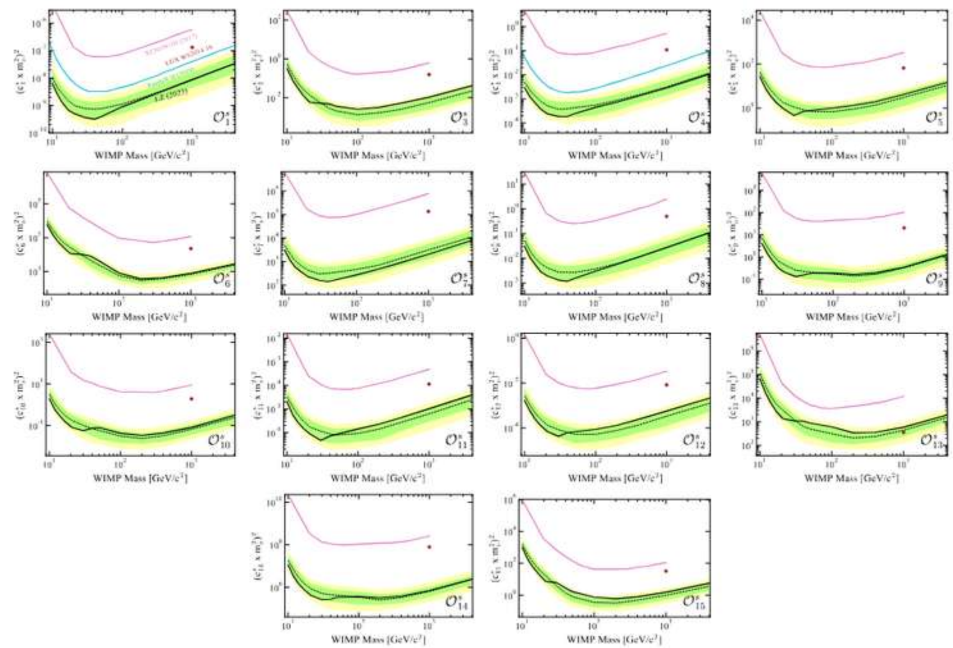
$$\begin{aligned}
&\mathcal{O}_1 = 1_\chi 1_N, \quad \mathcal{O}_2 = (v^{\perp})^2, \quad \mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}\right),\\
&\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}\right),\\
&\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right), \quad \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^{\perp},\\
&\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^{\perp}, \quad \mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right),\\
&\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}, \quad \mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N},\\
&\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}^{\perp}\right), \quad \mathcal{O}_{13} = i\left(\vec{S}_\chi \cdot \vec{v}^{\perp}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right),\\
&\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \vec{v}^{\perp}\right),\\
&\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\left(\vec{S}_N \times \vec{v}^{\perp}\right) \cdot \frac{\vec{q}}{m_N}\right).
\end{aligned}$$

- Evaluate the scattering amplitude by assuming a single operator

- Two papers :
  - XENON1T, *Phys. Rev. D 109, 112017 (2024)*
  - LZ, *Phys. Rev. D 109, 092003 (2024)*

LZ, Phys. Rev. D 109, 092003 (2024)



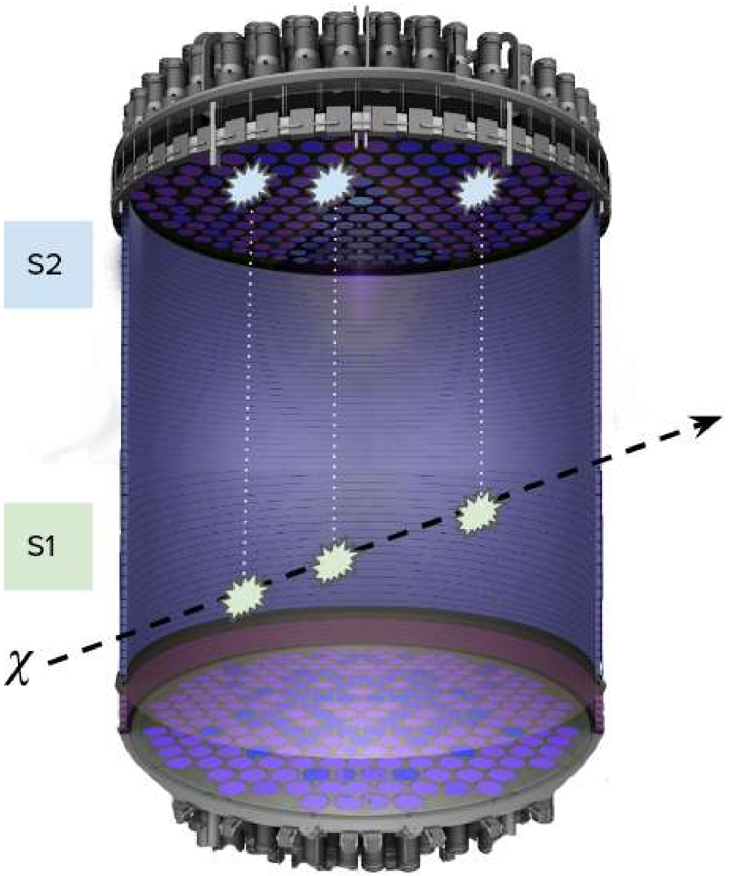


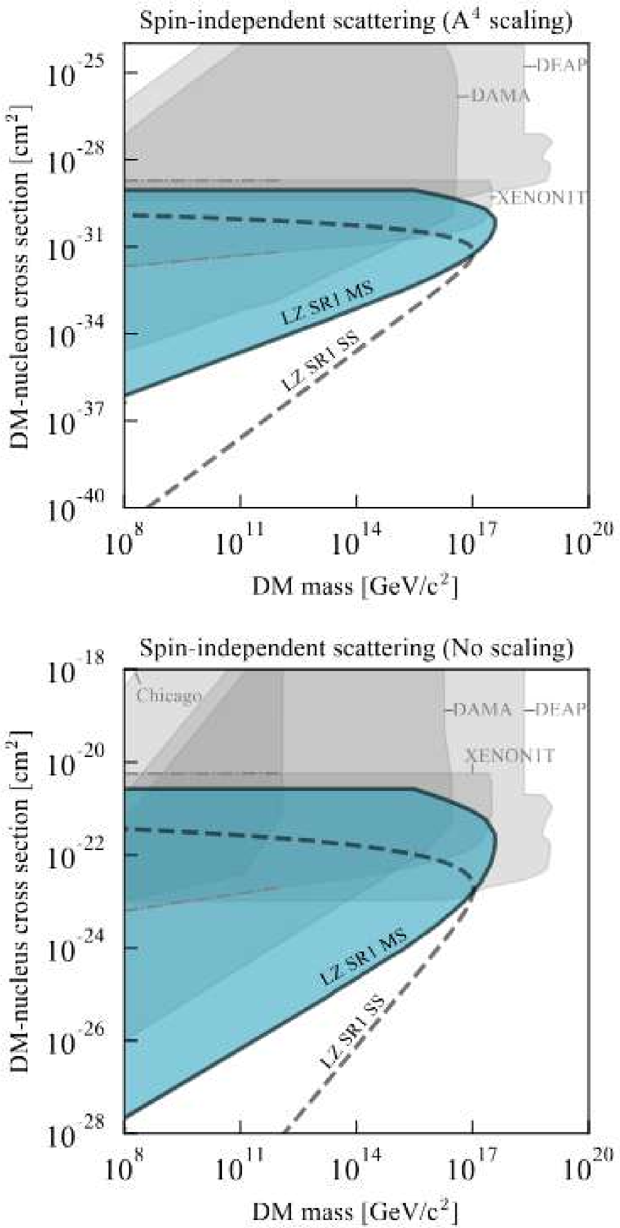
MIMPs domain

Even higher masses : MIMPs

Mass close to the Planck mass

→ Multiply-Interacting Massive Particles (MIMPs)





XENON1T : Phys. Rev. Lett. 130, 261002, arXiv:2304.10931

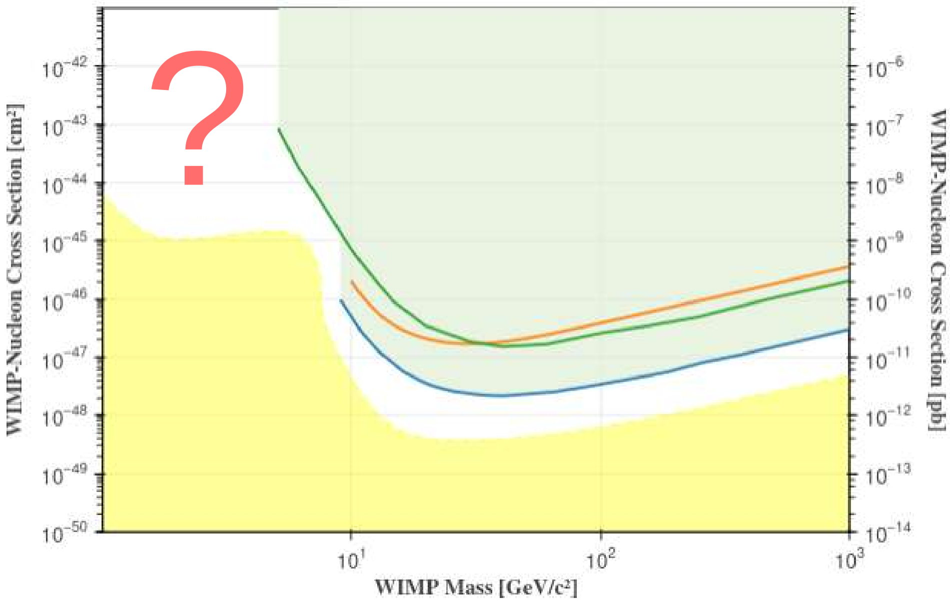
LZ : Phys. Rev. D 109, 112010, arXiv:2402.08865v1

« WIMPs » close to ^{8}B neutrino floor

(1 to 10 GeV)

Lowering the energy threshold

How an experiment, conceived to look for high WIMP masses, can lower its energy threshold and reach **low WIMP masses** ?



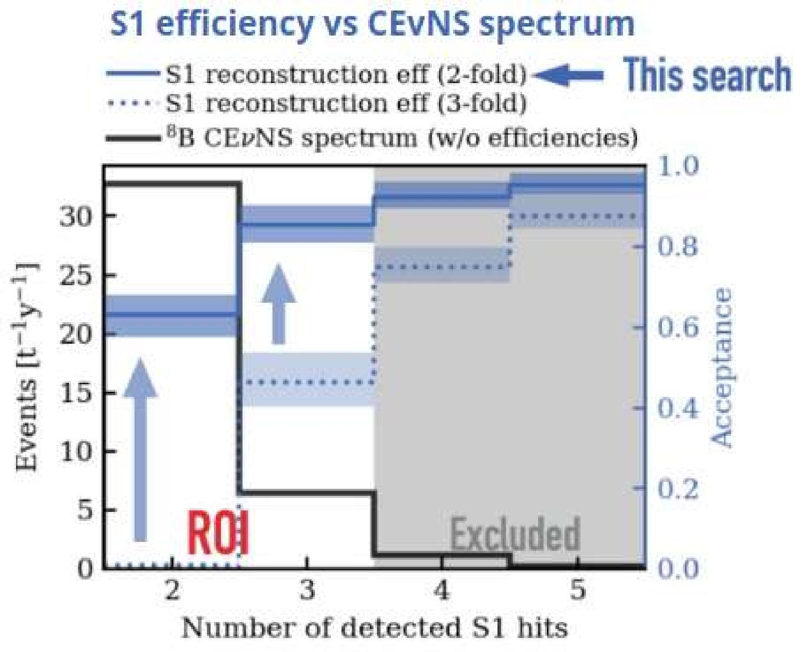
Lower the constrains on the **PMT signal hit coincidences**

Drop the S1 signal, keeping the **S2 only**

Lowering the energy threshold

Lower the constrains on the
PMT signal hit coincidences

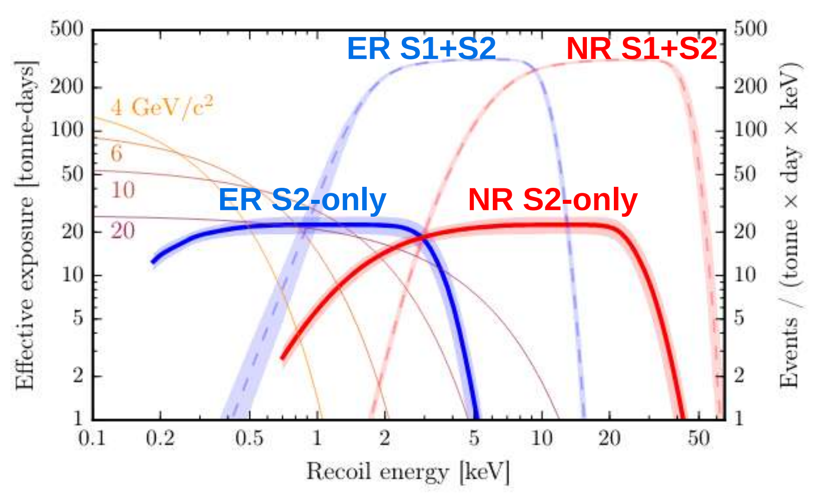
- **S1** : *requiring* at least two hits from two different PMTs within 50 ns (**2-fold PMT coincidence**)



Case of XENONnT data, S. Shi, TAUP 2025

Drop the S1 signal,
keeping the **S2 only**

- **Standard** approach (stay away from the few-electrons background)
- Dedicated analysis on the **few-electrons** range
- Focus on **1 to 3 electrons** range (highest background)

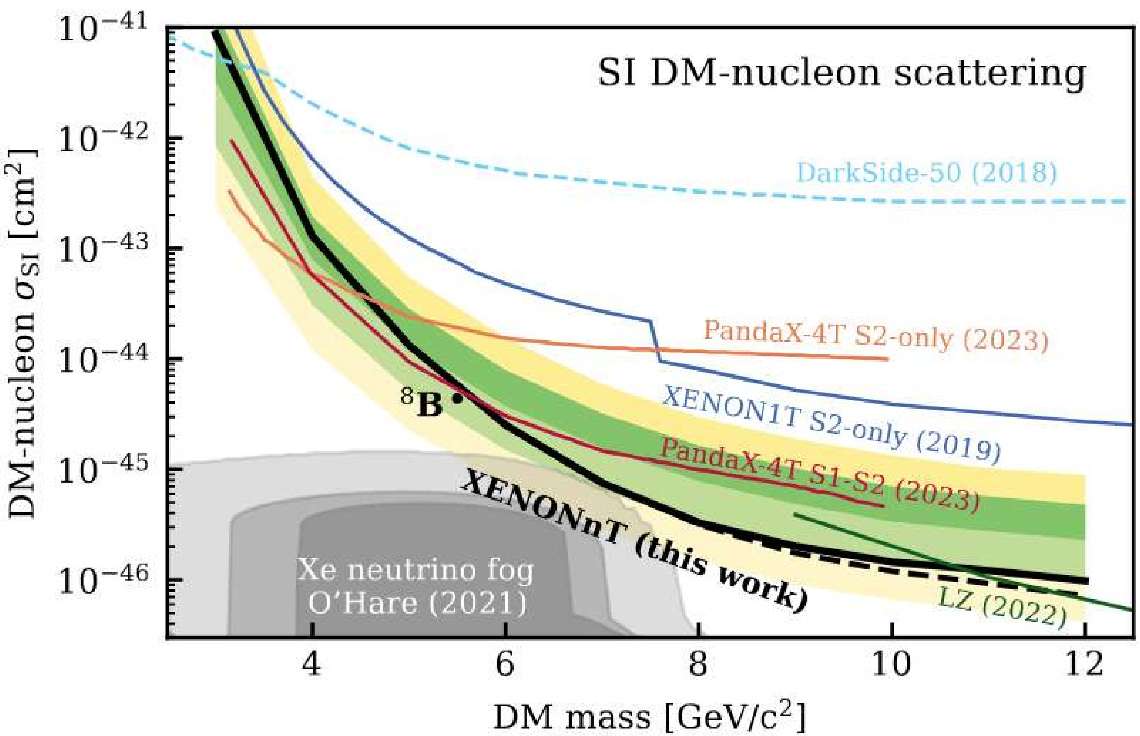


Case of XENON1T data, PRL 123, 251801

Low masses close to ^{8}B neutrinos : XENONnT

XENONnT results (2024) :
3.51 tonne-years

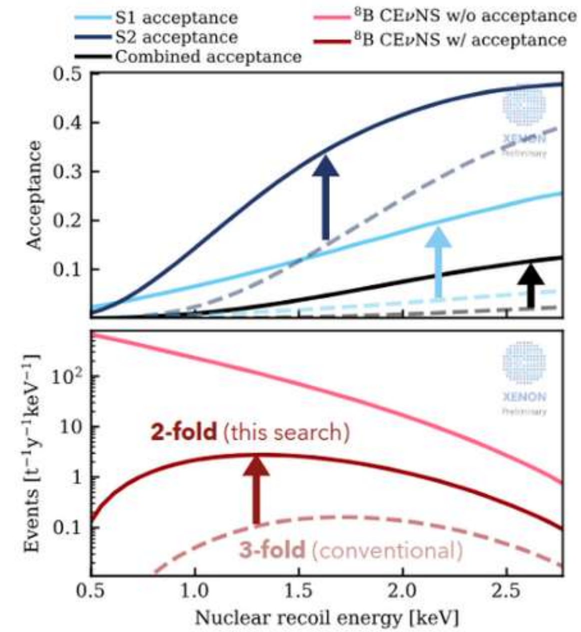
Phys. Rev. Lett. 134, 111802 (2025)

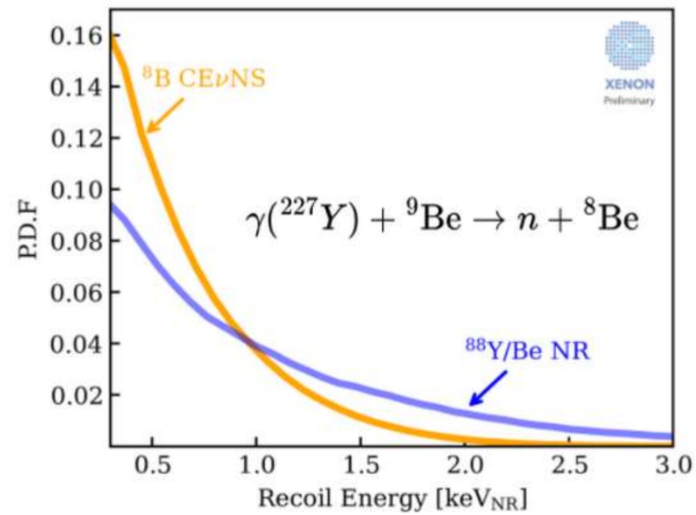


XENONnT analysis features :

- Passing from the traditional 3-fold to a 2-fold PMT **coincidence**
  - Drawback : increase of **accidental** coincidences background
- Two **BDTs** on the S1 and S2 peak
- Temporal (S2/ΔT) and spatial **correlations** with preceding events

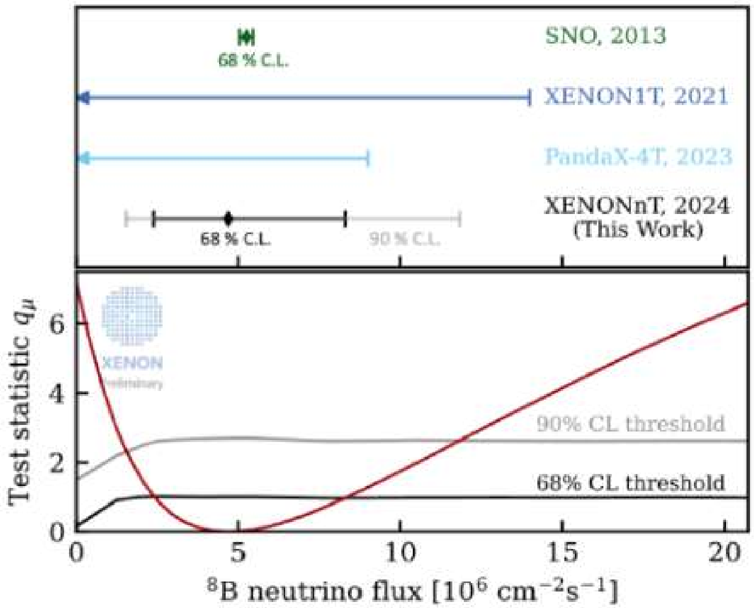
Phys.Rev.Lett. 133 (2024) 191002





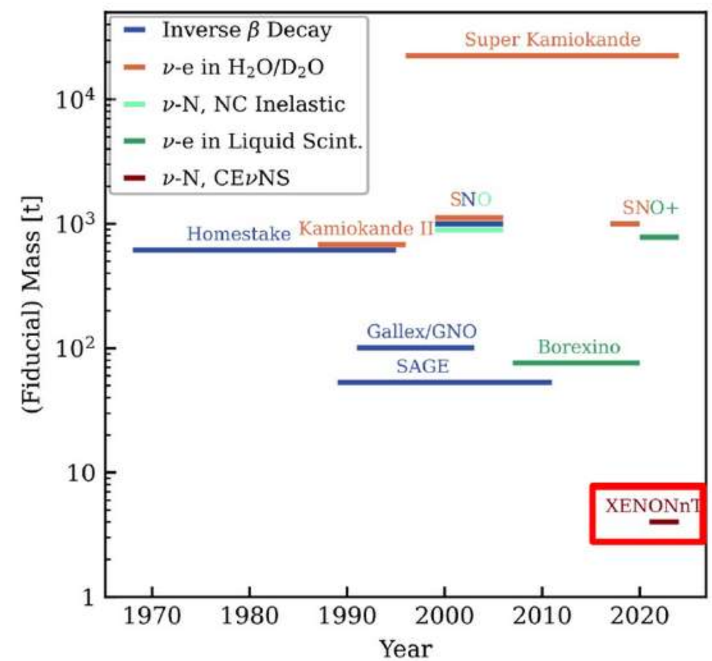
First indication of Solar ^{8}B neutrinos : XENONnT

- **^{8}B neutrino flux:** $4.6^{+3.6}_{-2.3} \times 10^6$ cm^{-2} s^{-1} at 68% C.L. no tension with literature value
- With constrain from SNO flux → Measure the **flux-weighted CEνNS cross section:** $1.1^{+0.8}_{-0.5} \times 10^{-39}$ cm^2



Phys. Rev. Lett. 133, 191002

Component	Expectation	Best-fit
AC (SR0)	7.5 ± 0.7	7.4 ± 0.7
AC (SR1)	17.8 ± 1.0	17.9 ± 1.0
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$10.7^{+3.7}_{-4.2}$
Observed	37	

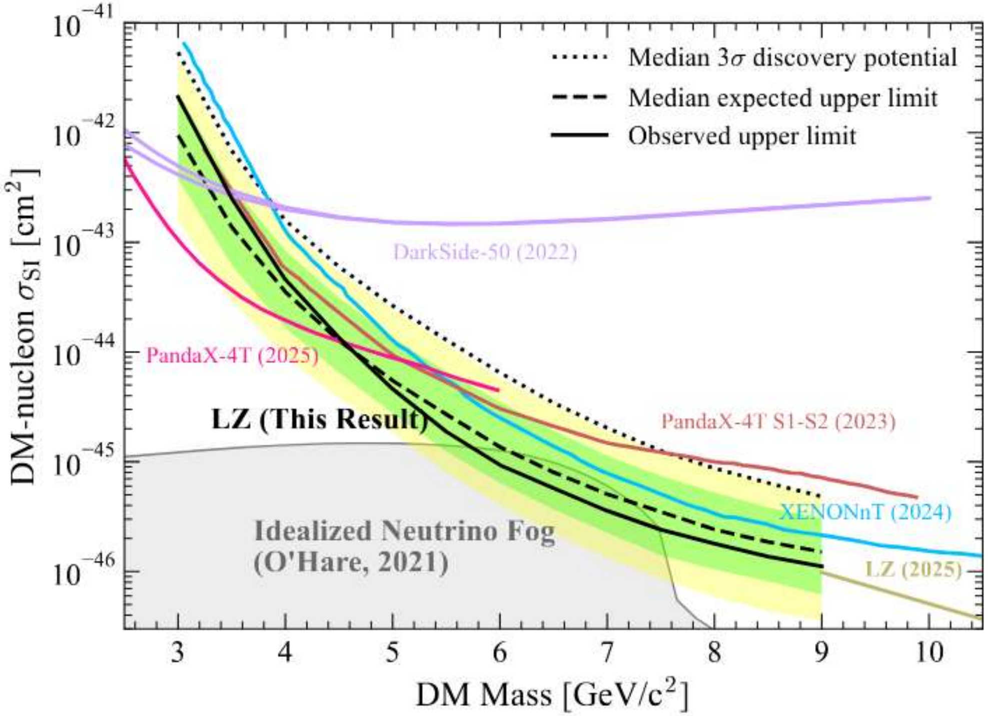


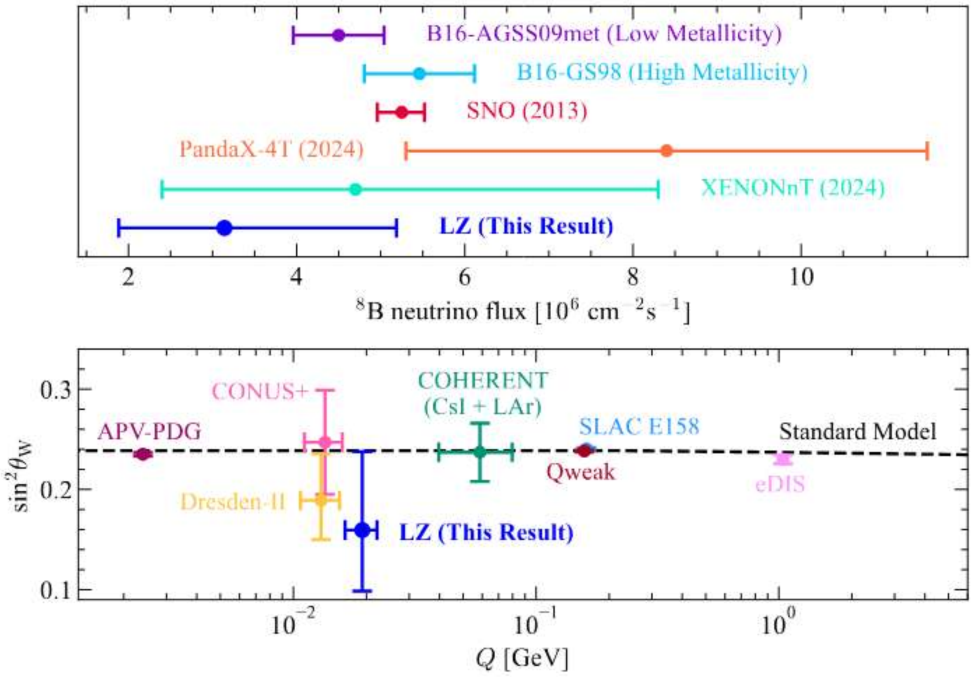
37 events found with 26 expected background events
2.73 σ discovery significance

- **FIRST** detected astrophysical ν in a **dark matter detector**
- **FIRST** measured CEνNS signal from an **astrophysical source**
- **FIRST** measured CEνNS signal on a **Xe target**

Low masses close to ^{8}B neutrinos : LZ

LZ results (2025) :
5.7 tonne-years





Statistical significances of observations of a signal consistent with ^{8}B **CEνNS** events :

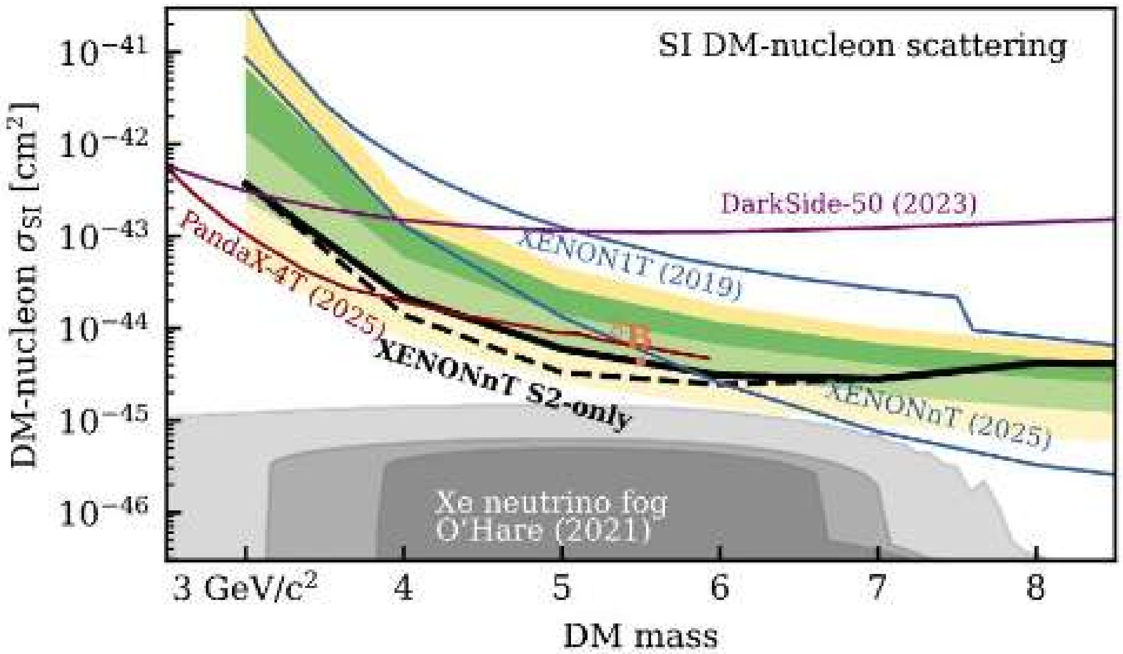
XENONnT (2024) : 2.73 **σ**
PandaX-4T (2024) : 2.64 **σ**
LZ (2025) : 4.5 **σ**

S2-only : case of XENONnT (2026)

Good agreement between the background predictions and observed events

Science run (exposure)	SR0 (1.50 t · y)		SR1 (2.44 t · y)		SR2 (3.89 t · y)	
Component	Expectation	Best fit	Expectation	Best fit	Expectation	Best fit
Cathode	480 ± 70	477^{+25}_{-24}	660 ± 70	726^{+28}_{-27}	1210 ± 90	1080 ± 30
Delayed electron	1.3 ± 0.5	1.3 ± 0.5	0.34 ± 0.07	0.34 ± 0.07	17.2 ± 2.3	17.1 ± 2.3
Accidental electron	97 ± 17	89 ± 13	108 ± 8	106 ± 8	–	
^{8}B CEνNS	21 ± 5	18^{+5}_{-4}	29 ± 7	26^{+7}_{-6}	32.3 ± 8	29^{+8}_{-6}
Total background	600 ± 80	586 ± 28	800 ± 80	858^{+30}_{-29}	1260 ± 100	1130 ± 30
Observed	583		864		1107	

Most stringent limit set on ~5 GeV light WIMPs



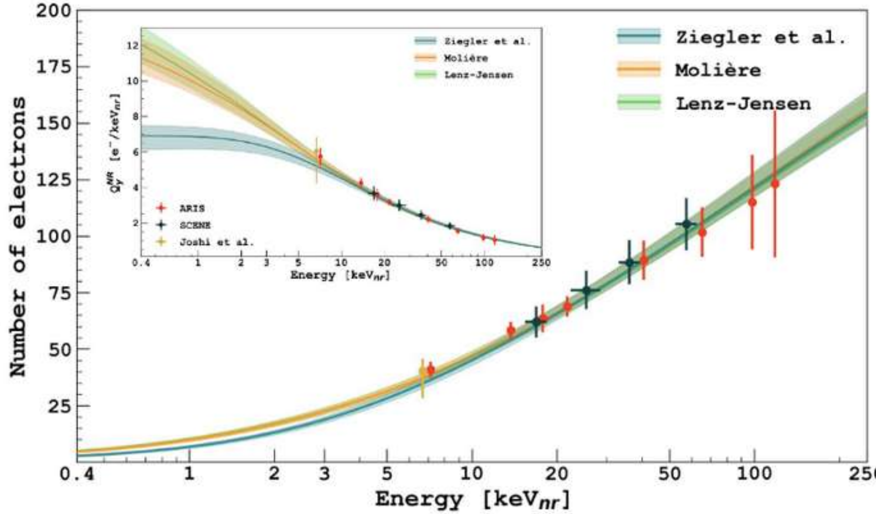
Y. Pan, La Thuile 2026, arXiv:2601.11296

Argon : change of the nuclear response

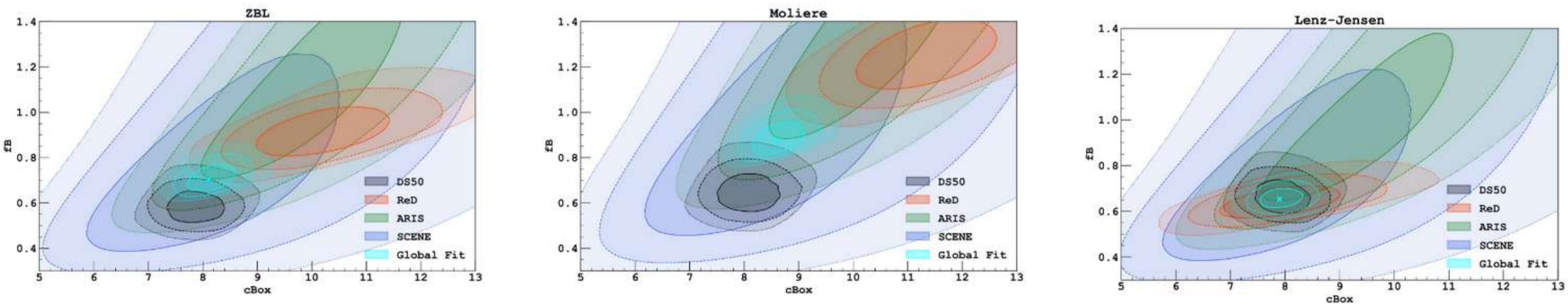
DarkSide used so far ZBL to model the response of Argon to NR :
most conservative choice

Screening Potential Models

- **ZBL** (Ziegler, Biersack, Littmark)
  - Defined from total energy difference of 2-atom system
  - Universal fit (522 potentials) → basis of SRIM
- **Molière**
  - Analytical approximation of Thomas-Fermi potential
  - Widely used in multiple scattering
- **Lenz-Jensen**
  - Modified Thomas-Fermi model with shell corrections
  - Improved accuracy at small radii

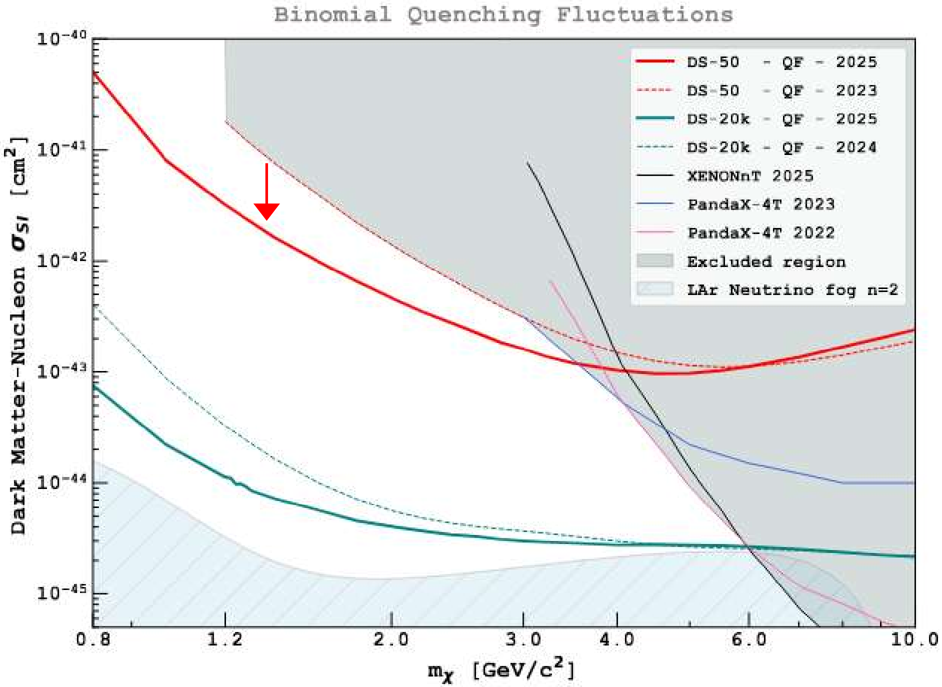


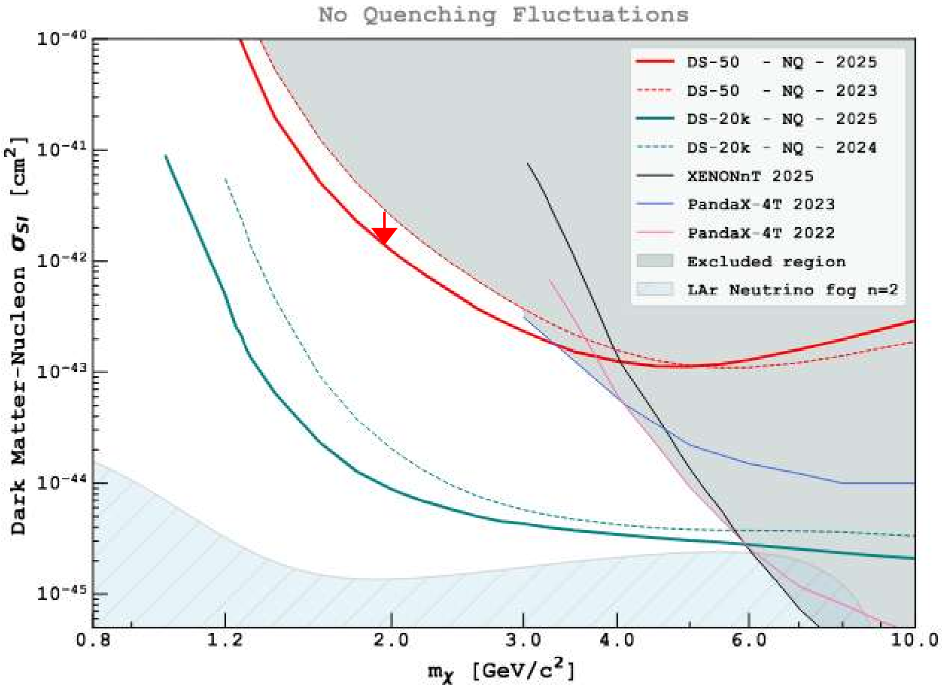
Now they moved to the Lenz-Jensen one, supported by a global fit of the independent measurements ARIS, SCENE, ReD, together with DarkSide50 data



Low masses < 3 GeV : DarkSide-50

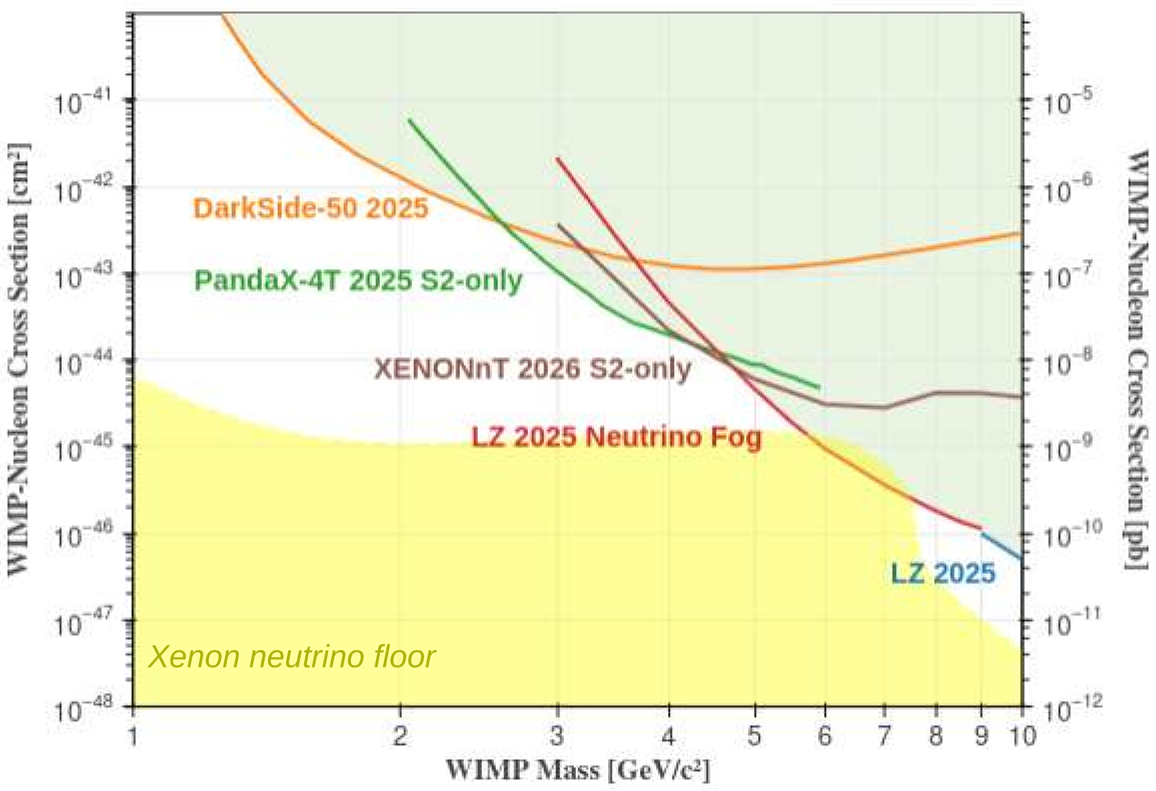
The effect is an improvement of sensitivity at low WIMP masses





Summary for WIMP masses between 1 and 10 GeV

https://github.com/odadoun/DarkPlotter



Liquid **Xenon** rules at any WIMP mass starting from ~2.5 GeV

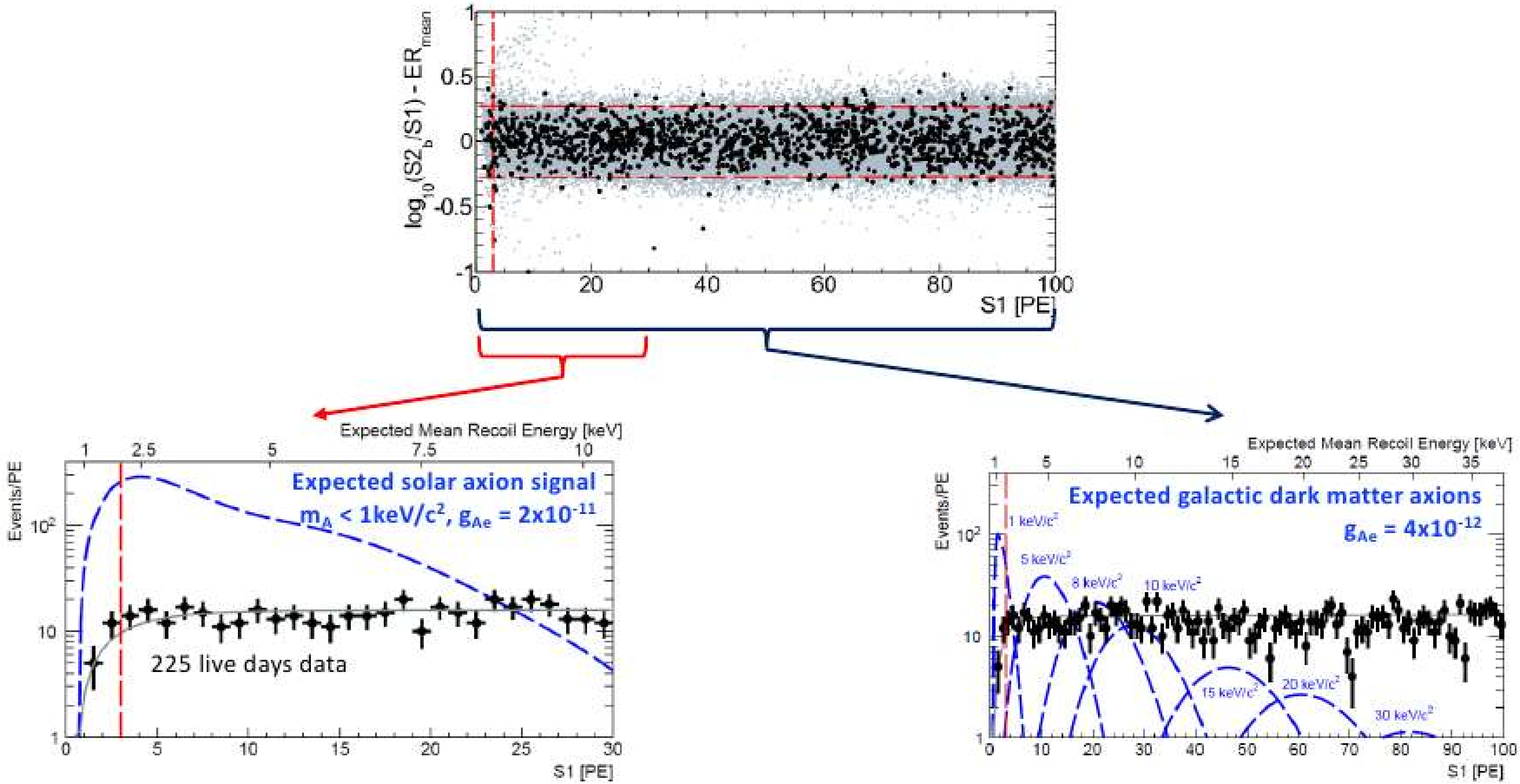
Liquid **Argon** rules below ~2.5 GeV (lighter nuclei)

Currently no other technique challenges noble liquids TPCs

sub-GeV Dark Matter

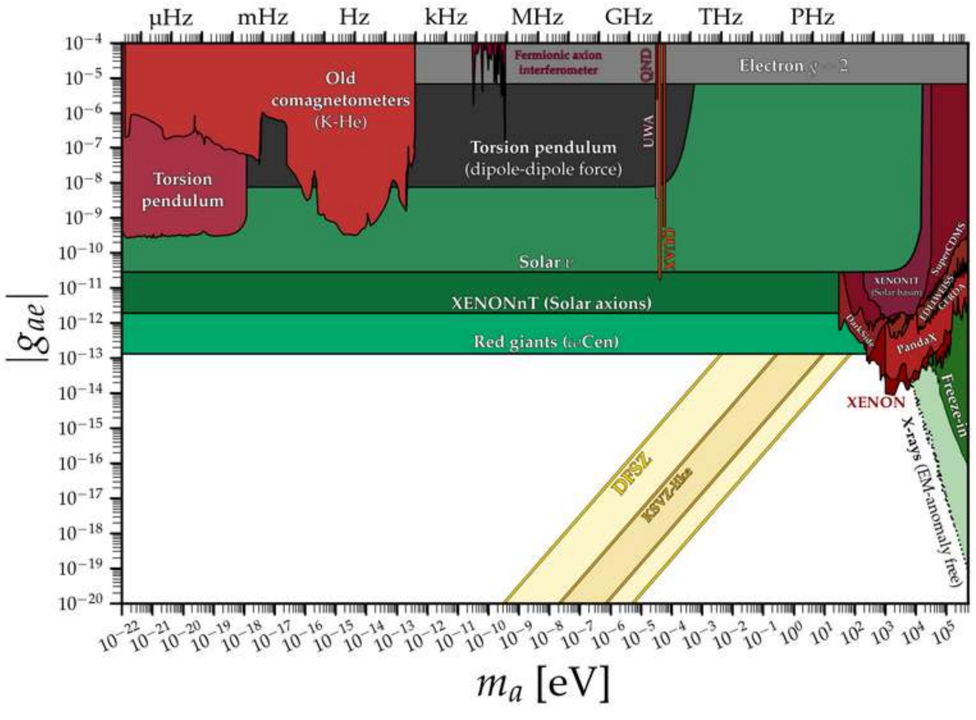
Axions search

- Origins of axion type particles: galactic dark matter and production in the Sun
- Coupling of axions and axion-like dark matter particles (ALP) to LXe target medium via axio-electric effect („absorption“ of axion and emission of electron from the atomic shell)
- Signal expected to appear in the electronic recoil band (as opposed to WIMPs)



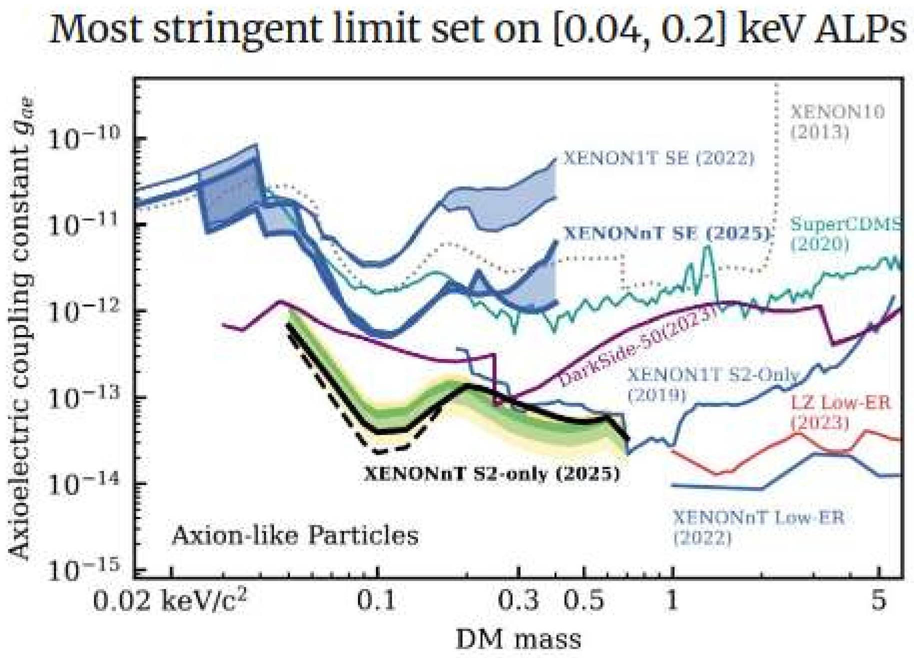
Axions search

Solar axions



Galactic ALPs

XENONnT: Y. Pan, La Thuile 2026, arXiv:2601.11296



For noble liquids, curves are a combination of several analyses :

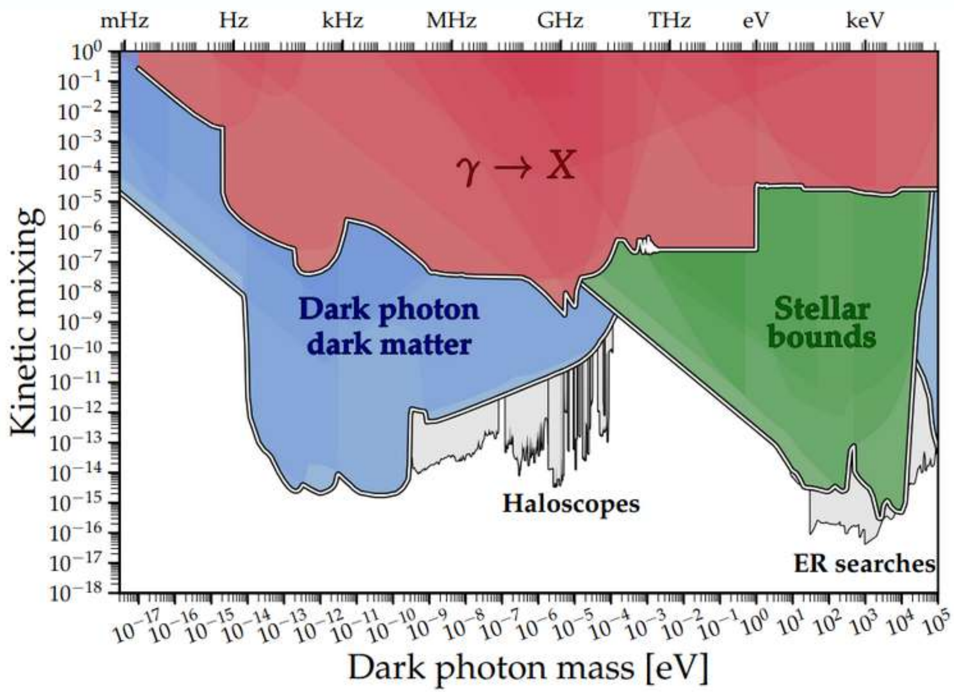
- Standard S1+S2
- S2-only analysis
- 1-to-few electron analysis

Dark Photons

- Arise from a U(1) extension of the Standard Model
- A dark electromagnetic field mixes with the SM photon
- Dark Matter searches exploit the fact that dark photons can oscillate into regular photons, producing luminous signals

"Kinetic mixing"

$$\mathcal{L} \supset -\frac{\chi}{2} F_{\mu\nu} X^{\mu\nu} \qquad (\chi \ll 1)$$



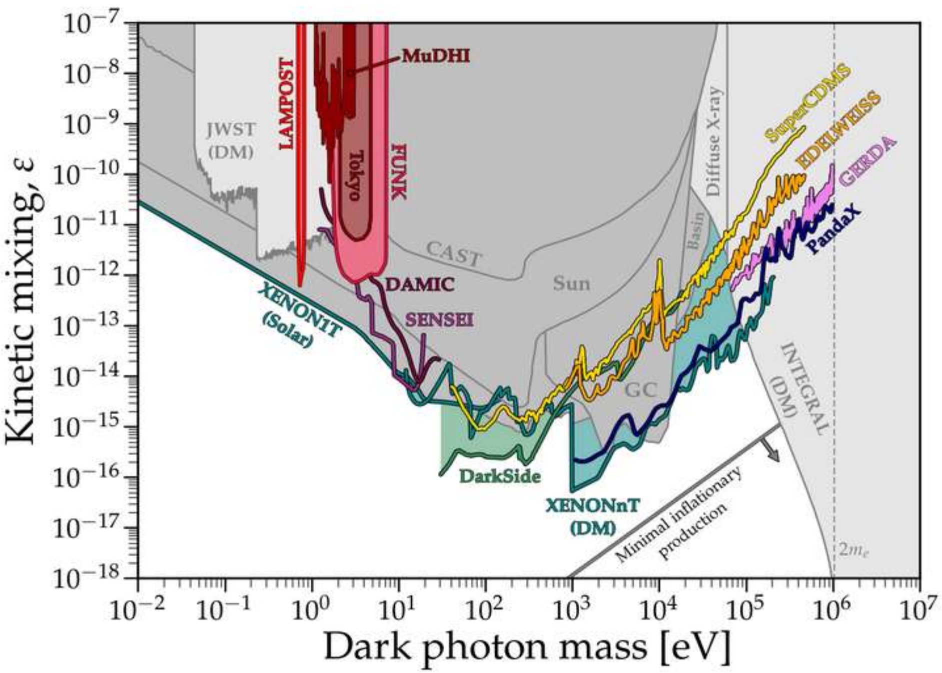
Leading results :

- **From skipper CCDs:**

DAMIC@SNOWLAB
SENSEI (2023) *arXiv:2312.13342*
SENSEI (2024) *arXiv:2410.18716*
DAMIC-M

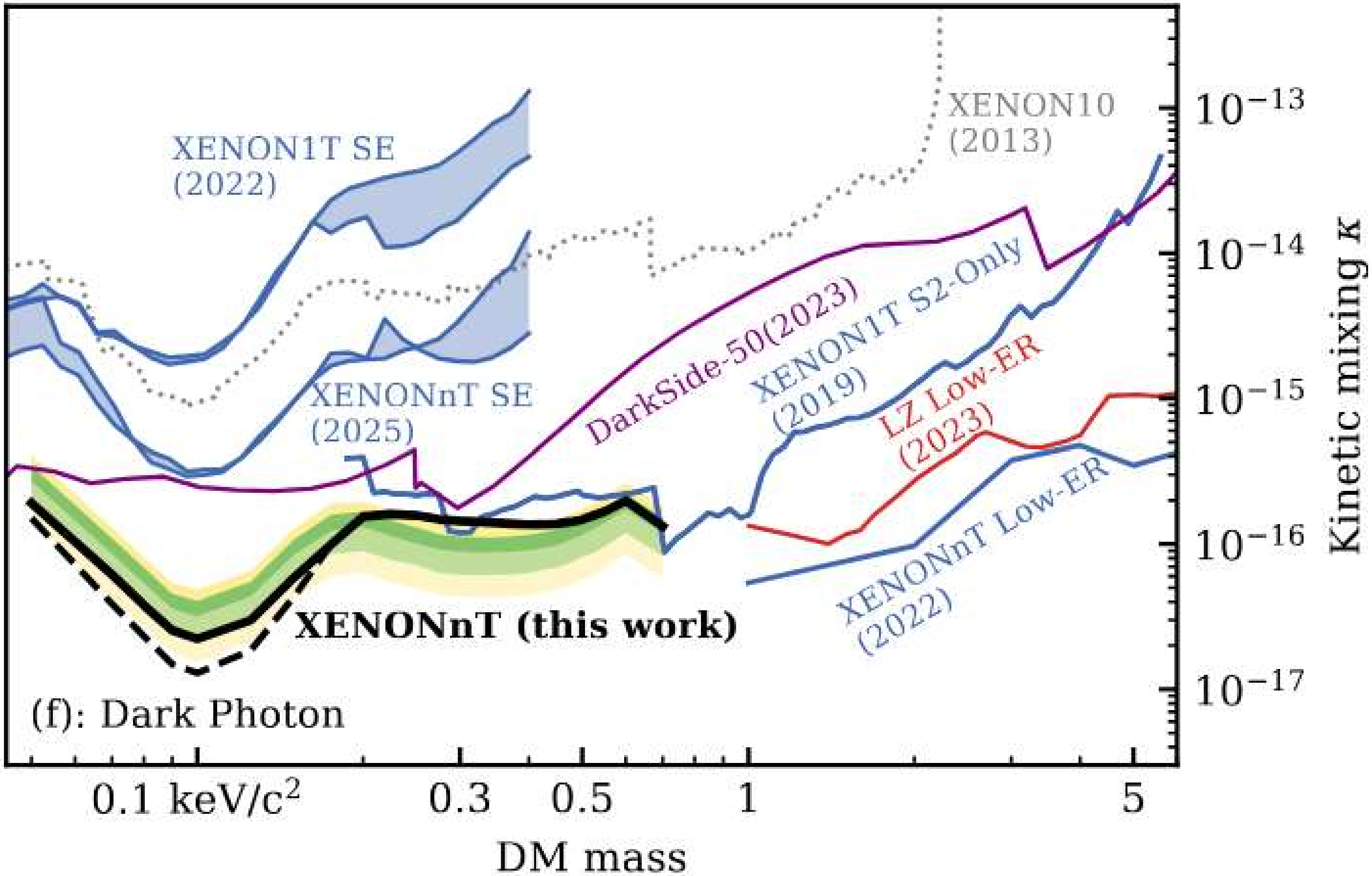
- **From noble liquids:**

DarkSide-50
XENON1T
Panda-X
XENONnT
LZ



Latest results on Dark Photons

XENONnT: Y. Pan, La Thuile 2026, arXiv:2601.11296



Light-WIMPs (sub-GeV Dark Matter)

At low masses, DM-electron scattering kinematics is more optimal than DM-nucleon scattering for experiments

Leading results :

- **From skipper CCDs:**

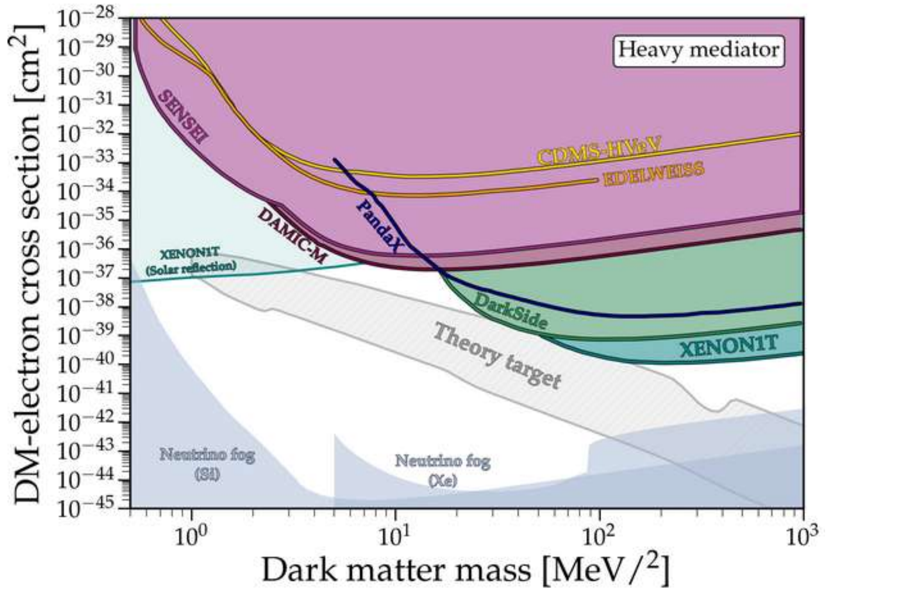
DAMIC@SNOWLAB
SENSEI (2023) *arXiv:2312.13342*
SENSEI (2024) *arXiv:2410.18716*
DAMIC-M

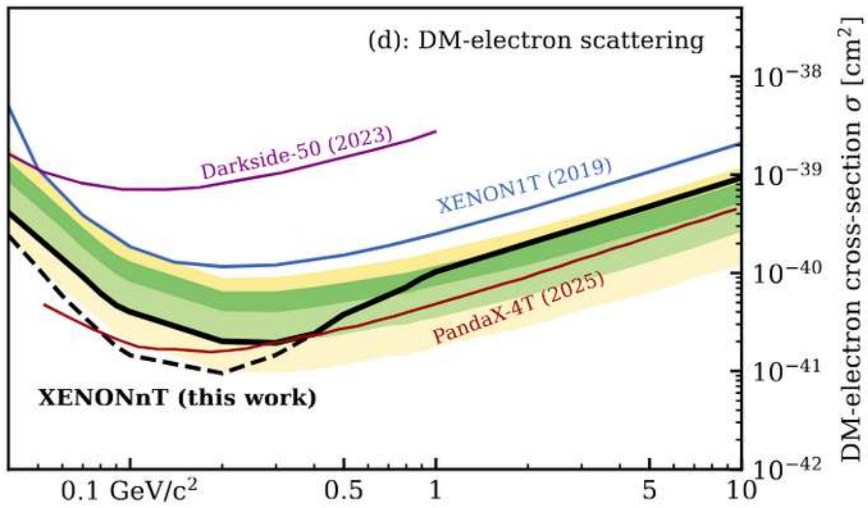
- **From noble liquids:**

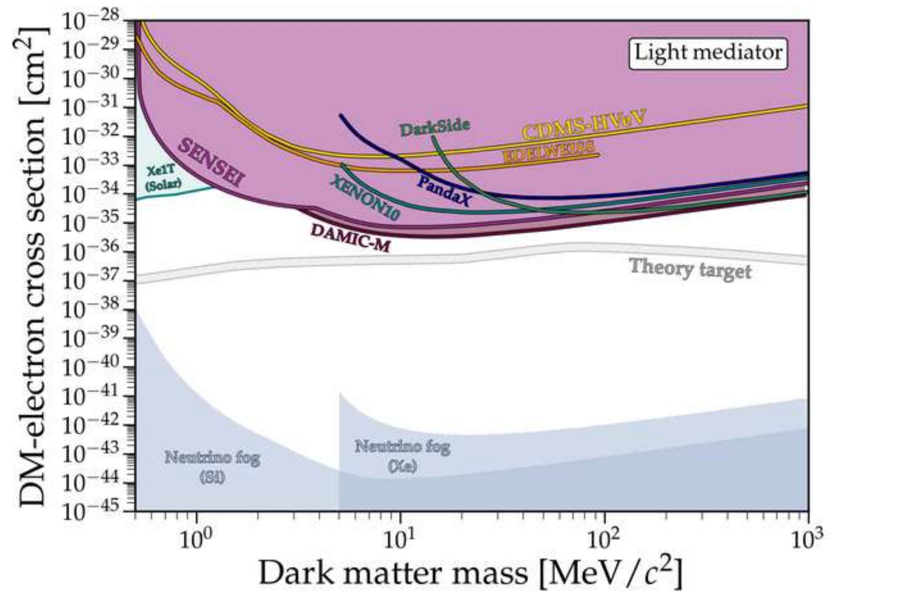
DarkSide-50
XENON1T
Panda-X
XENONnT
LZ

XENONnT: arXiv:2601.11296

PandaX-4T (2025)



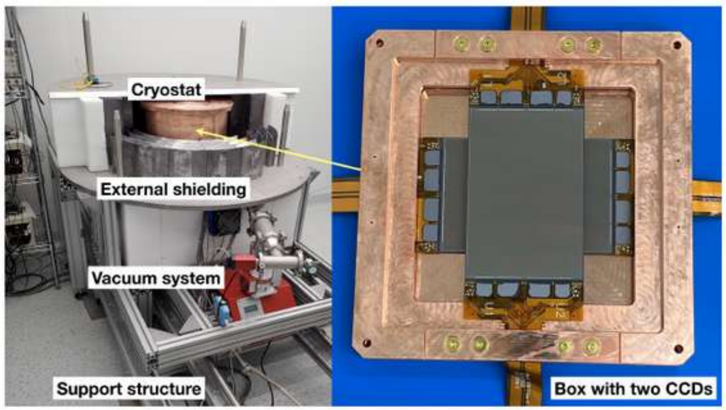




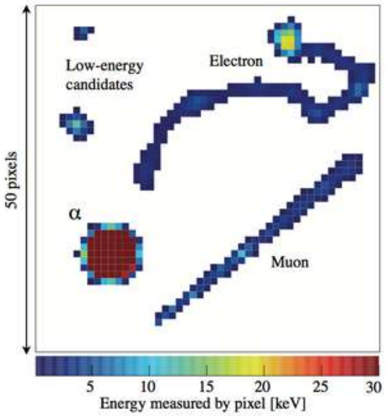
Dark Matter with Skipper-CCDs

Main idea : ultralow-noise electronics in combination with repetitive, nondestructive readout of a thick, fully depleted charge-coupled device (CCD)

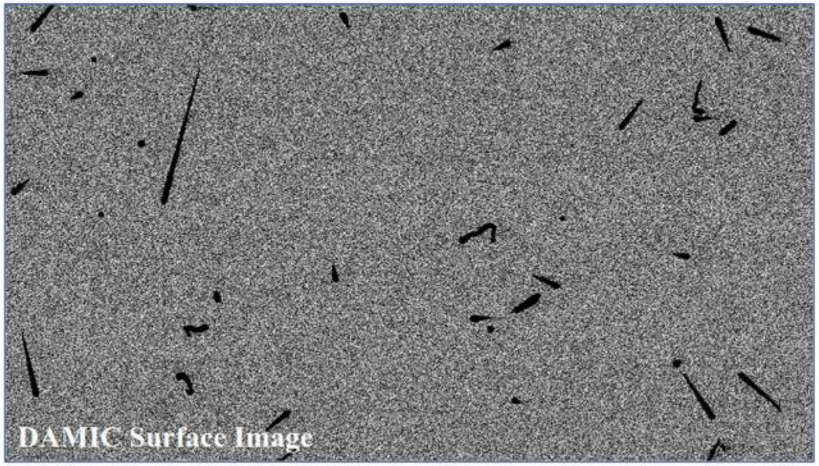
Three detectors : SENSEI, DAMIC @ SNOWLAB, DAMIC-M

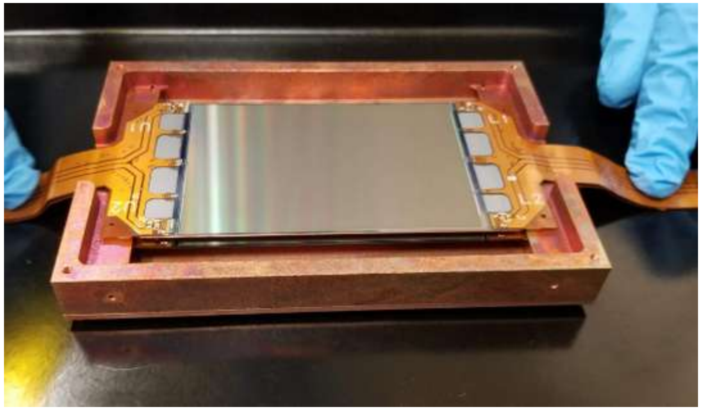


DAMIC-M

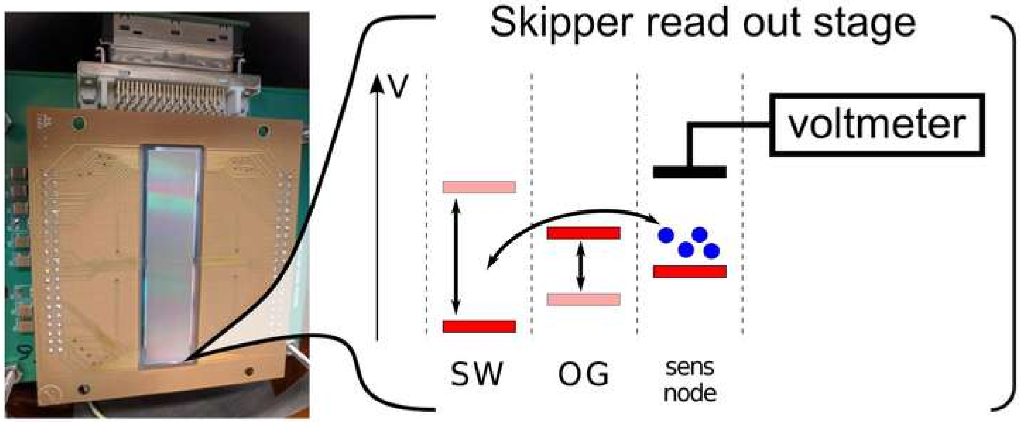


Particle ID



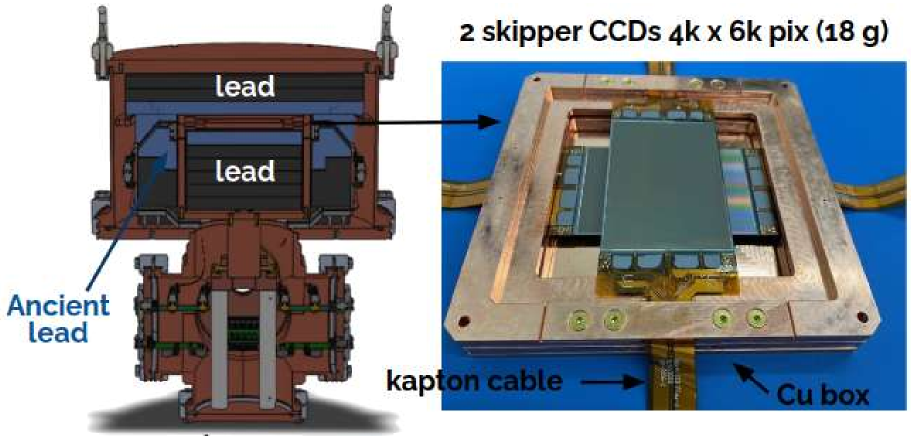


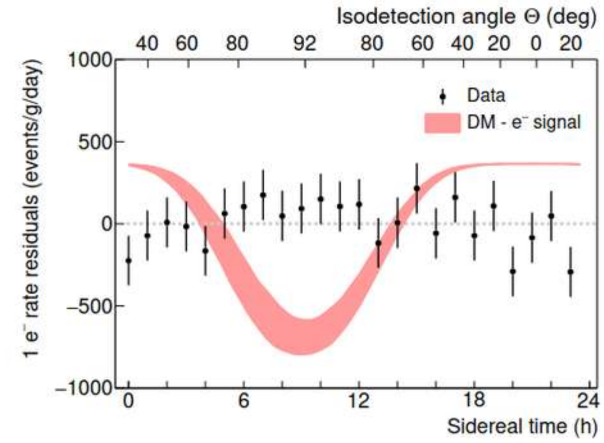
DAMIC @ SNOWLAB



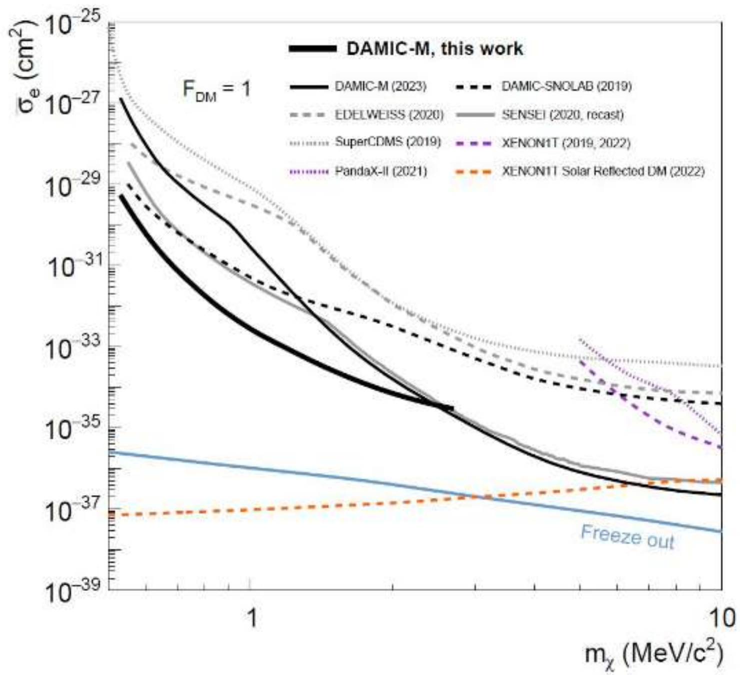
SENSEI

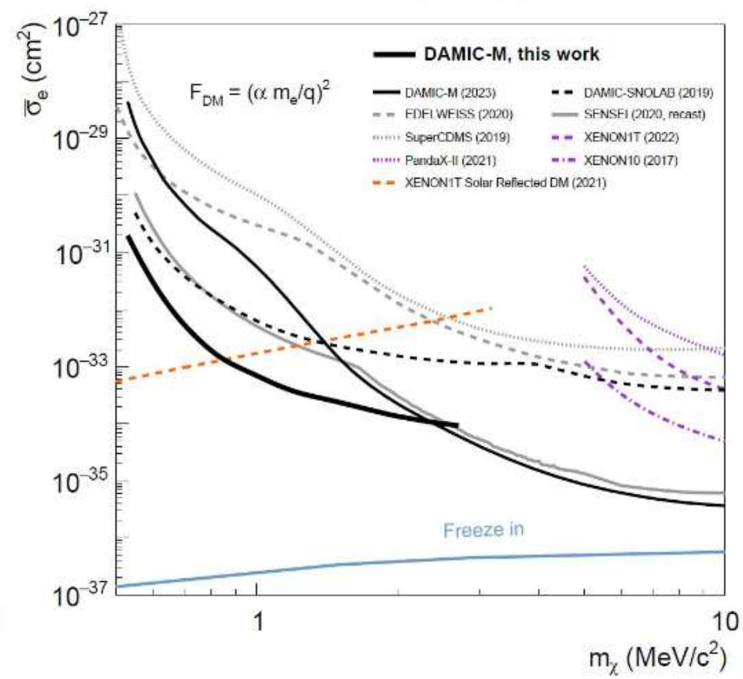
DAMIC-M Low Background Chamber
+ daily modulation analysis





Daily modulation (due to interactions in the Earth) analysis improves up to ~2 orders of magnitude their analysis with the same dataset



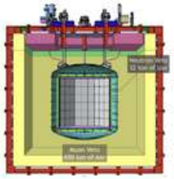


What we should expect in the future

Future at high WIMP masses

DarkSide50 :
@LNGS, Italy
50kg Ar → UAr

DarkSide20k
@LNGS, Italy
50t UAr



PandaX-4T :
@JinPing, China
6t total Xe mass

PandaX-xT :
@JinPing, China
43t total Xe mass
Approved in China

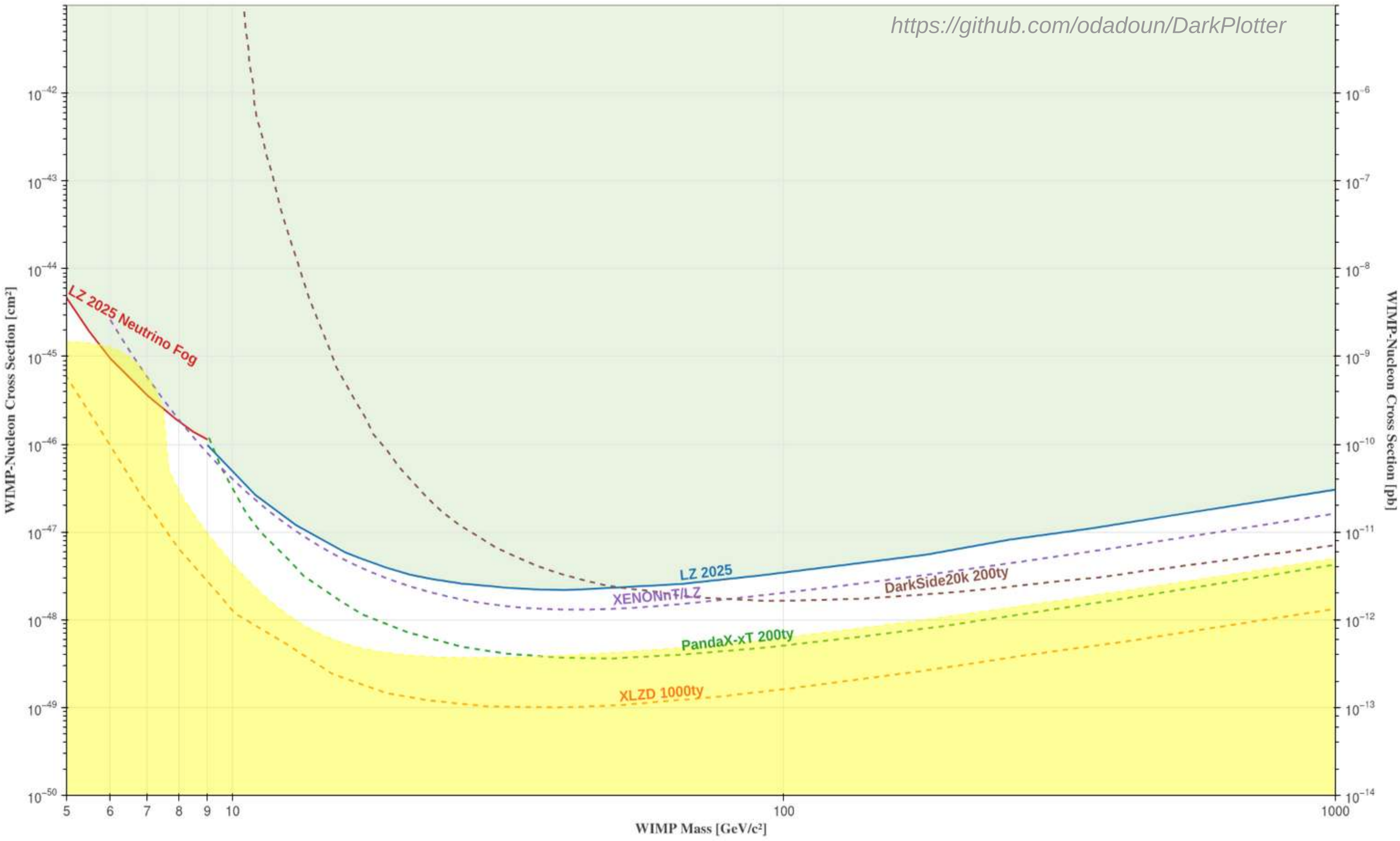
XENONnT :
@LNGS, Italy
8.6t total Xe mass

LZ :
@SURF, US
10t total Xe mass

+ DARWIN
R&D program since a decade
to build a 50t total mass

XLZD (XENON+LZ+DARWIN):
Several sites considered
80t total Xe mass (60t active)

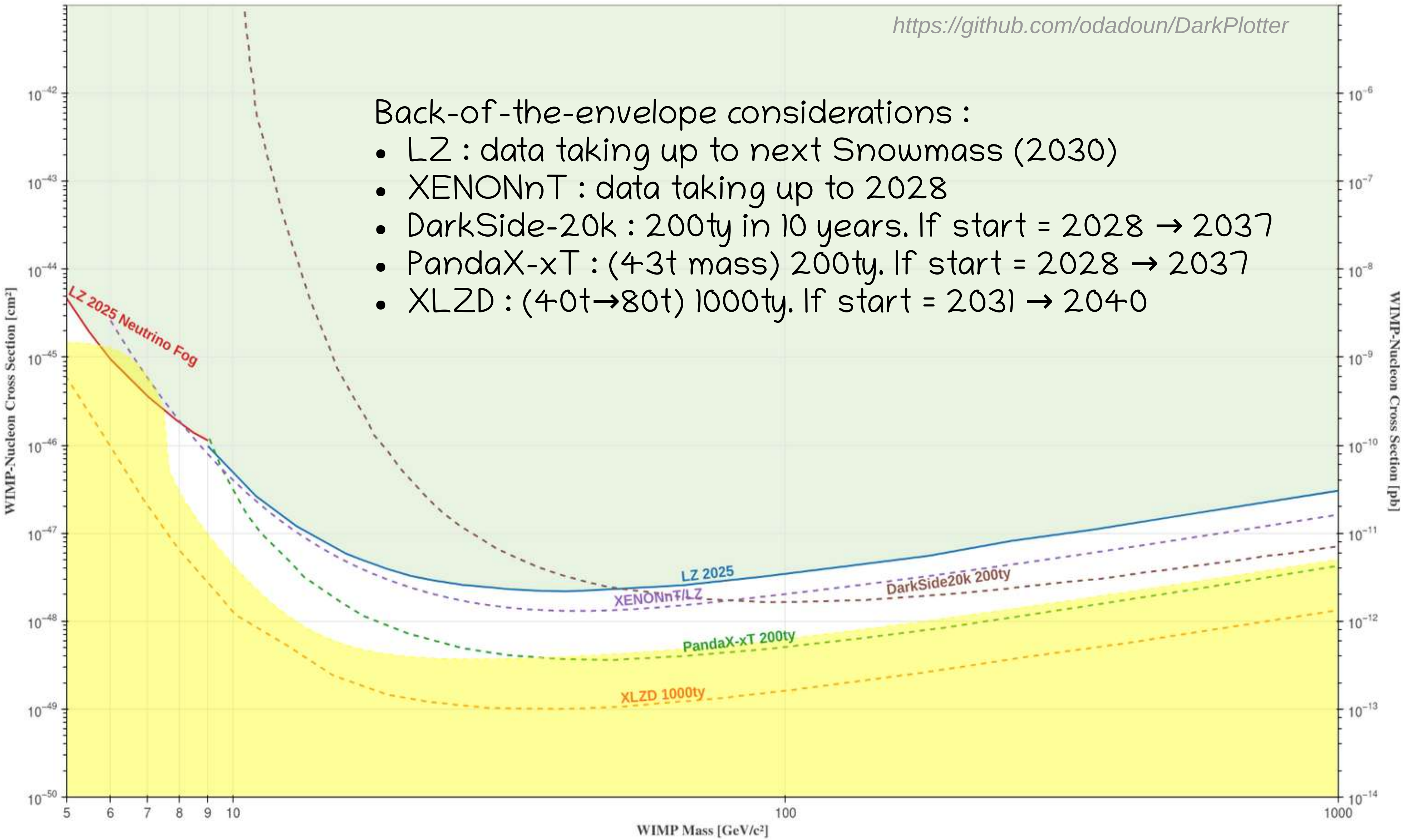
Comparison between future experiments



Timeline of future experiments

Back-of-the-envelope considerations :

- LZ : data taking up to next Snowmass (2030)
- XENONnT : data taking up to 2028
- DarkSide-20k : 200ty in 10 years. If start = 2028 → 2037
- PandaX-xT : (43t mass) 200ty. If start = 2028 → 2037
- XLZD : (40t→80t) 1000ty. If start = 2031 → 2040



Very light dark matter with phonons

- TES-based Crystal Detectors
  - TESSERACT (SPICE)
- Superfluid Helium Detectors
  - TESSERACT (HeRALD)
  - DELight (using Magnetic Micro Calorimeters)
- MKID-based Detectors
  - BULLKID
- Superconducting Qubit Sensors
  - Cosmic Quantum (CosmiQ) at FNAL
  - SQUATs

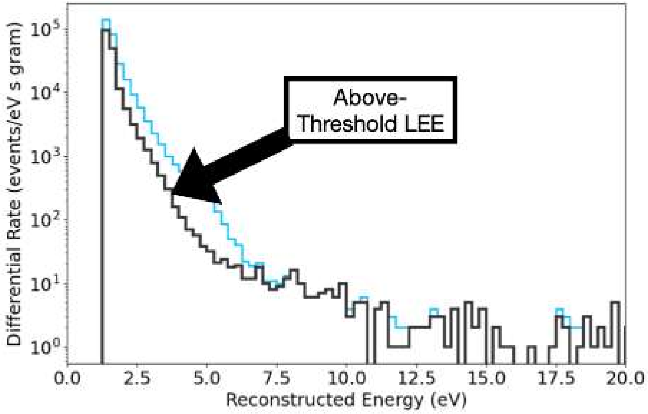
TES = Transition Edge Sensors
a superconducting “thermometer”
used in low-temperature detectors

Very light dark matter with phonons : Tesseract

Observation of a strong Low Energy Excess (LEE) of events in ALL low-threshold cryogenic experiments limiting their DM sensitivity

The LEE is both :

- the largely dominating background at the lowest energies
- limiting the phonon baseline energy resolution

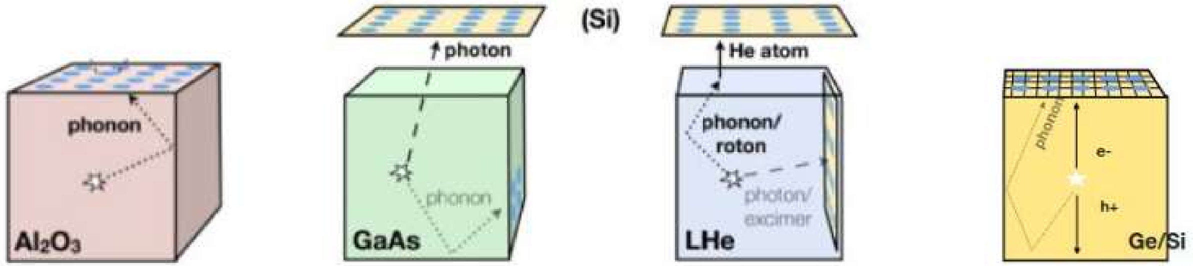


ER : 100 meV – MeV
No PID, SP

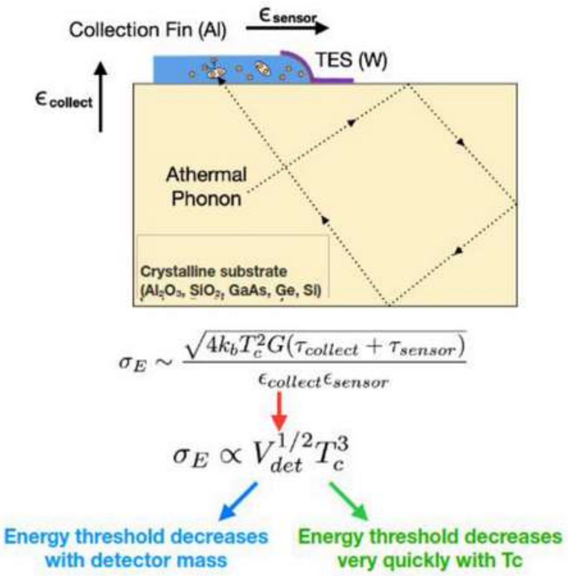
ER : eV – MeV
NR : MeV - GeV
PID : photon - phonon

NR : MeV - GeV
PID : PSD

NR : 100 MeV – 10 GeV
PID : PSD



SPICE (Al_2O_3 and GaAs) HeRALD (LHe) TES4DM (Ge/Si)



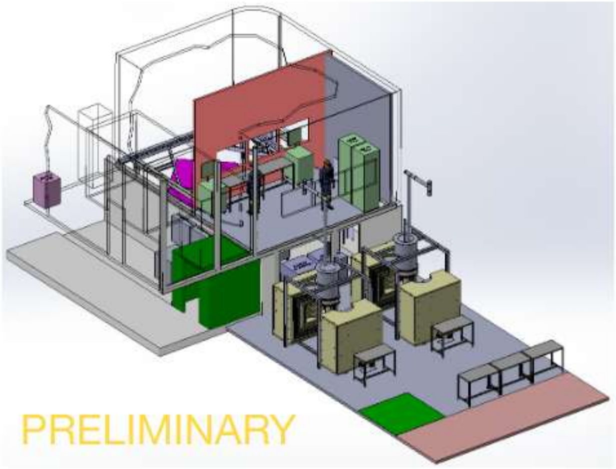
TESSERACT @ LSM : timeline

TESSERACT moved to the Project phase

Multiple target materials allow for exploration of different types of interactions and dark matter particle masses

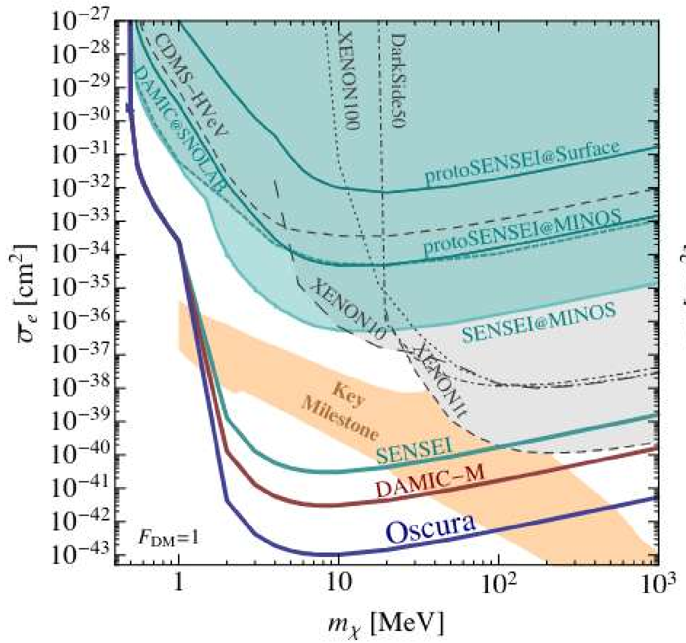
Multiple signal channels and coincidence-based background rejection to reject backgrounds, especially the LEE

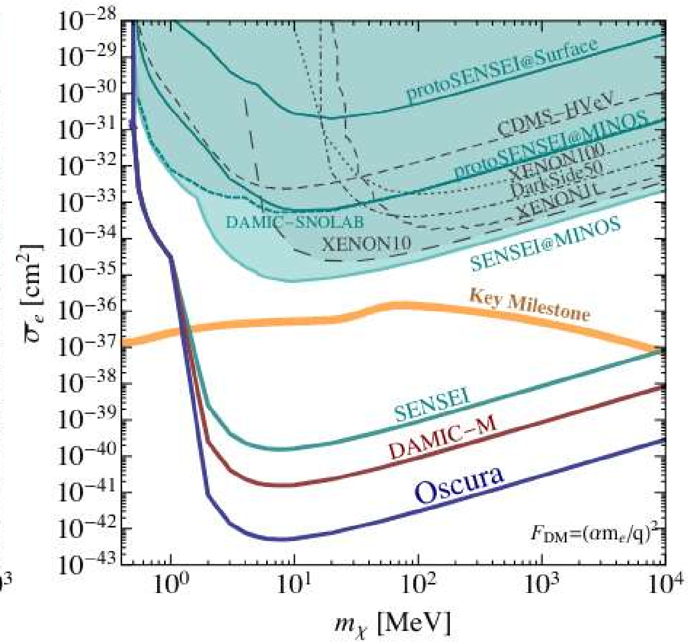
Moving to Modane in 2028 for low-background searches starting in 2029



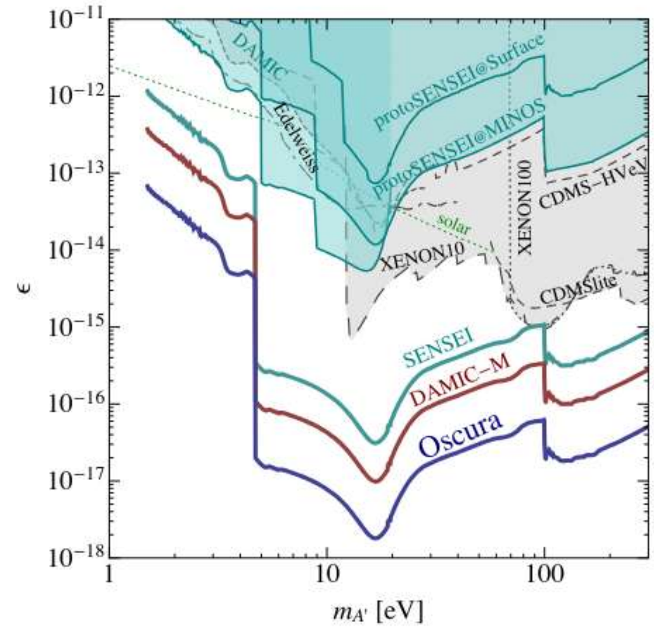
Next generation experiments : Skipper-CCDs

DM-electron scattering





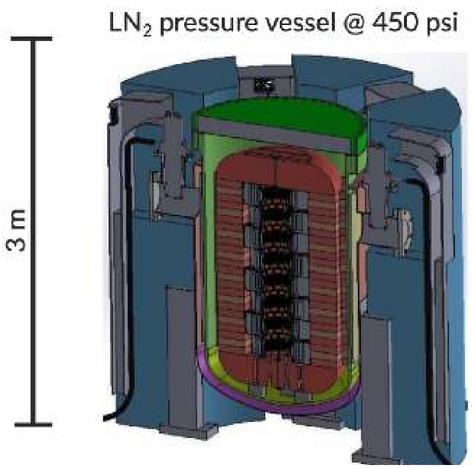
Dark photons

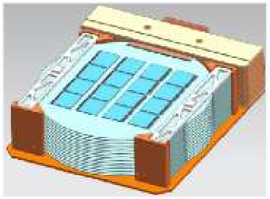


Skipper-CCD is now a well estabilished technology

To gain sensitivity it needs to

- Increase target mass
  - Silicium thickness
  - High number of devices
- Improve background





	SENSEI	DAMIC-M	Oscura
n. of CCDs	50	200	20000
mass (kg)	0.1	1	10
bkg (dru)	10	0.1	0.01
Lab	SNOLAB	LSM	SNOLAB (likely)

OSCURA merges the expertise from the two collaborations DAMIC and SENSEI

The OSCURA experiment : *arXiv:2202.10518v2*

What about sugar ?

SWEET Project :

- Hydrogen, given its light mass, is theoretically the best target for light Dark Matter search
- Organic compounds are rich of Hydrogen
- Phonon detection using sucrose crystals ($C_{12}H_{22}O_{11}$)
- Preprint : *arXiv:2510.00068*

The SWEET project: probing sugar crystals for direct dark matter searches

A. Bento[*†], F. Casadei[*], E. Cipelli[*], S. Di Lorenzo[*], F. Dominsky[*§], P. V. Guillaumon[*‡¶], D. Hauff[*], A. Langenkämper[*], M. Mancuso[*], B. Mauri[*‖], C. Moore[*], F. Petricca[*], F. Pröbst[*], M. Zanirato[*]
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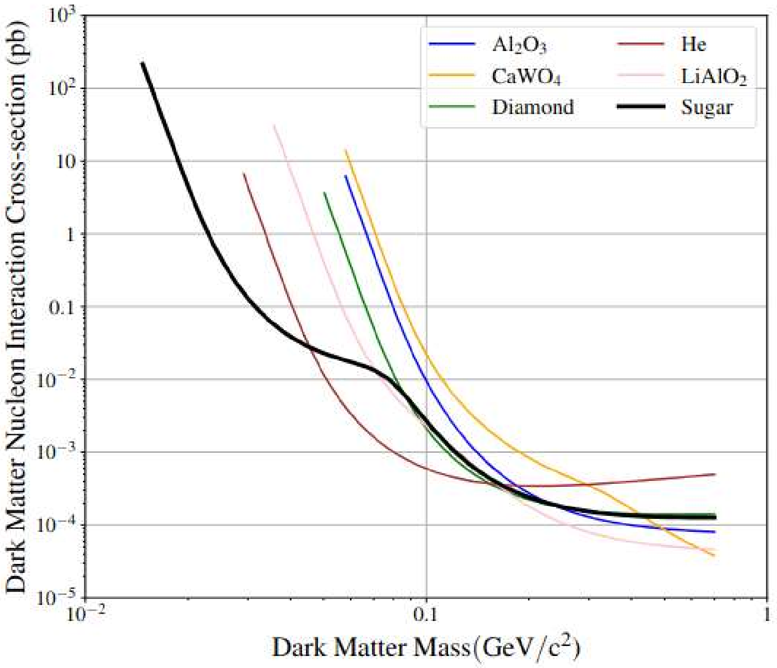


Future on Axions

Axions, coupling to the photon

Haloscopes :

- Lumped element + LC
  - m_a ~ O(10 peV - 100 eV)
  - ν ~ O(MHz)

ABRACADABRA, **DMRadio**

- Microwave cavities
  - m_a ~ O(10 μeV)
  - ν ~ O(GHz)

ADMX, HAYSTAC, CAPP, GrAHal, ORGAN, QUAX, CAST-CAPP, RADES

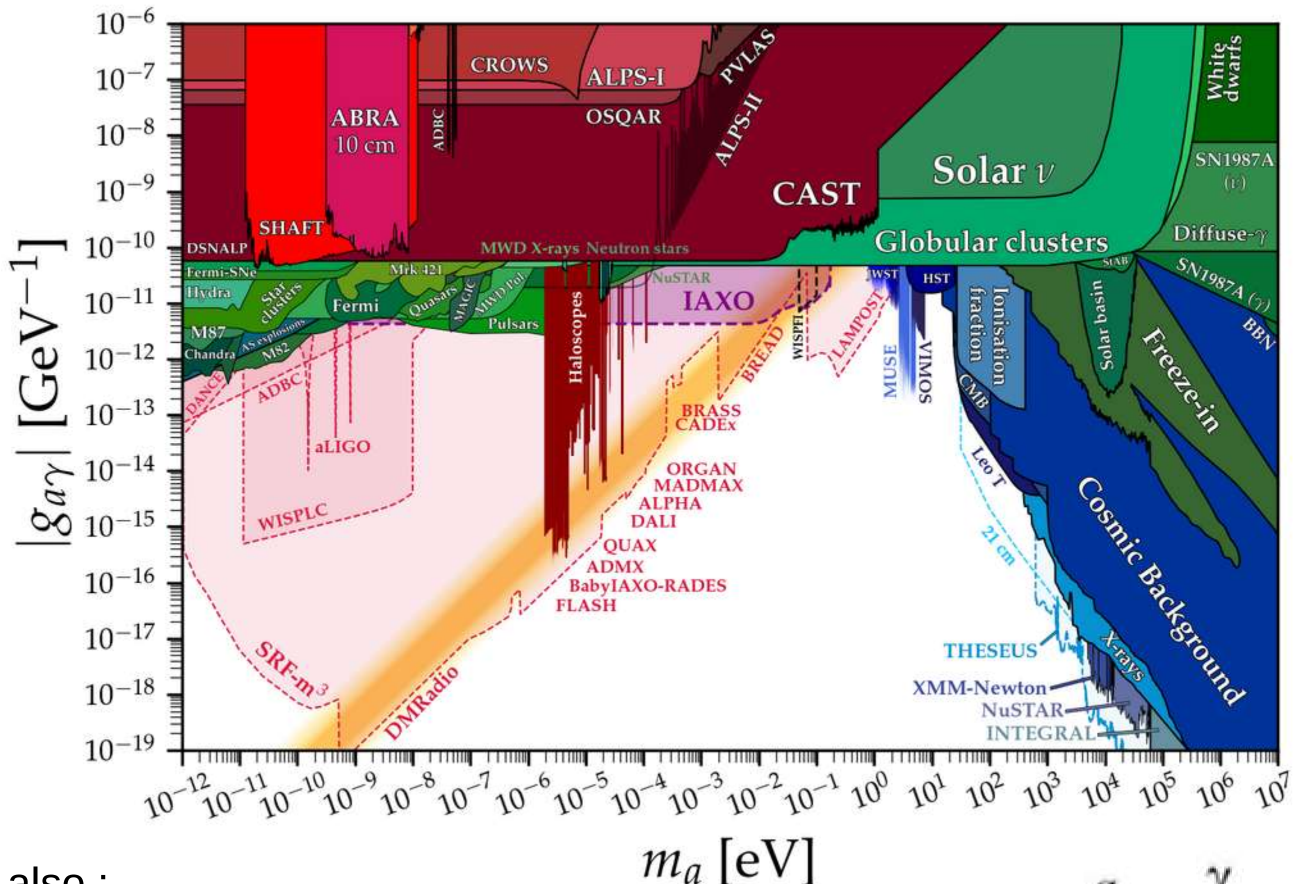
- Dielectric
  - m_a ~ O(100 μeV)
  - ν ~ O(10-100 GHz)

BREAD, BRASS, **MADMAX**

- Plasma
  - m_a O(100 μeV)
  - ν ~ O(10-100 GHz)

ALPHA

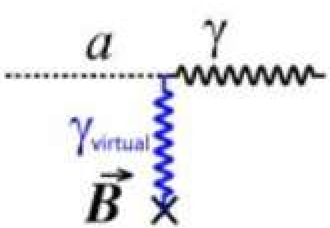
The phenomenology mostly based on the axion coupling with photons



Plot from https://cajohare.github.io/AxionLimits/

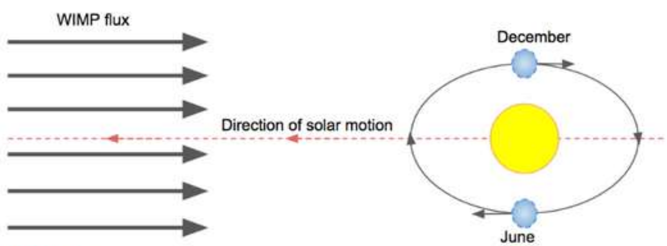
But also :

- Light-shining-through-wall (ALPS)
- Helioscopes (CAST)



Future on scoping DAMA results

Annual Modulation and DAMA experiment



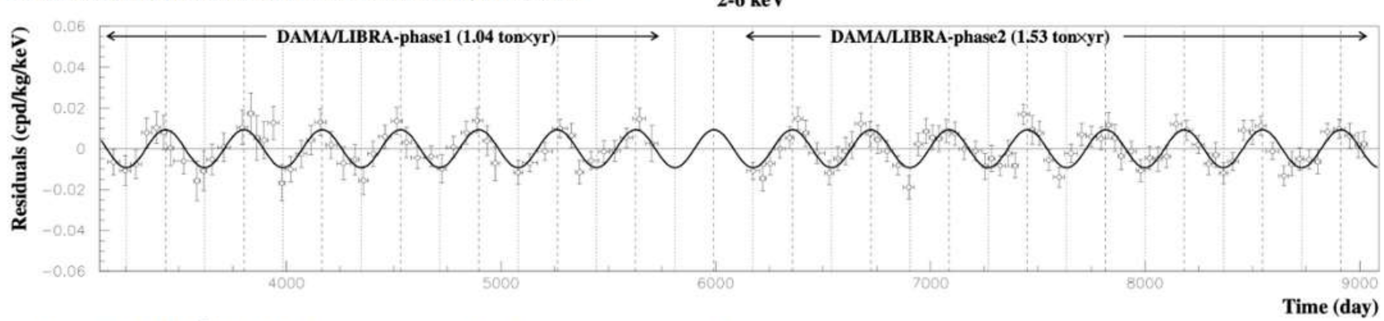
DM Rate

$$R(E) = R_0(E) + R_m(E)\cos(\omega(t - t_0))$$

Non-Modulating DM rate

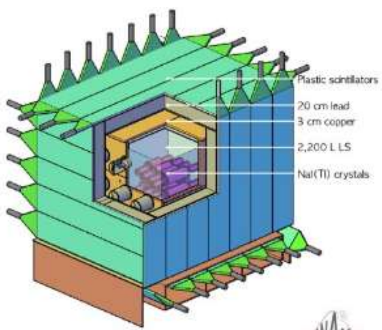
Modulating DM rate

R. Bernabei et al., Annual Modulation results from DAMA/LIBRA, 2023

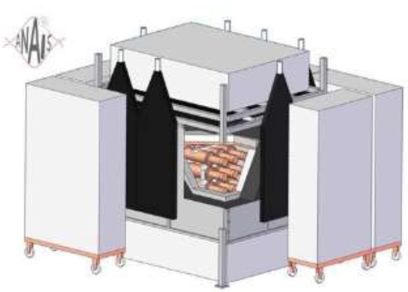


The DAMA/LIBRA Experiment has been running for 20+ years

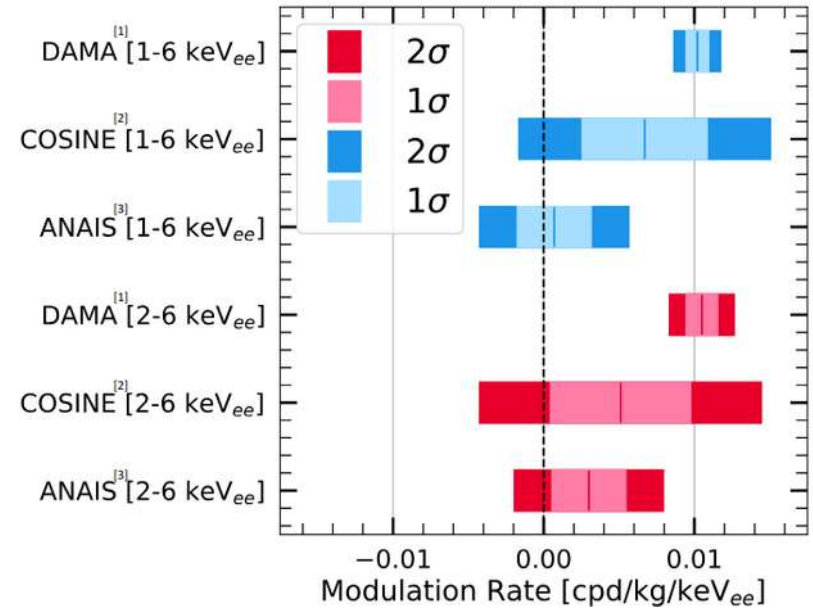
- Located at **LNGS**
- Total mass **250 kg of NaI(Tl)**
- Observed **~0.01 cpd/kg/keV** modulation in the 1-6 keV (second phase) energy range
- **12.9 σ** significance



COSINE-100
100 kg NaI(Tl)
Yang Yang National Laboratory,
South Korea



ANAIS-112
112 kg NaI(Tl)
Canfranc national laboratory,
Spain



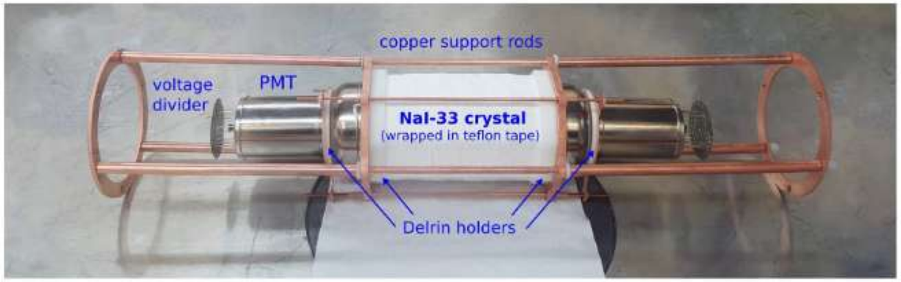
Material : courtesy of Owen Stanley, Melbourne, talk given at GDR DUPhy, Lyon

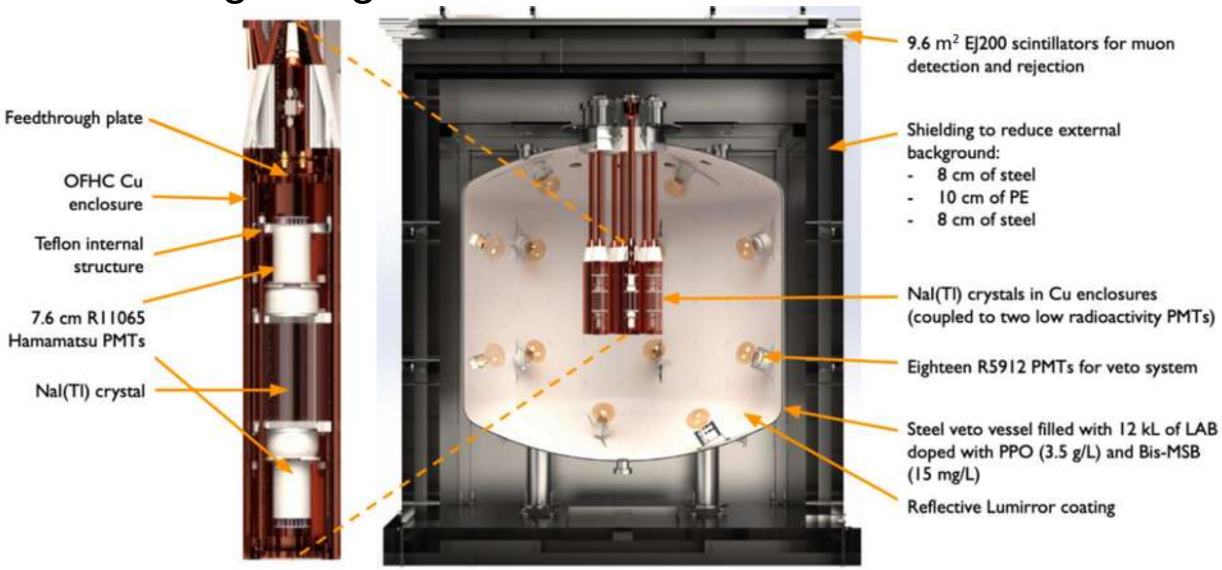
Next generation experiments : DAMA verification
(or exclusion)

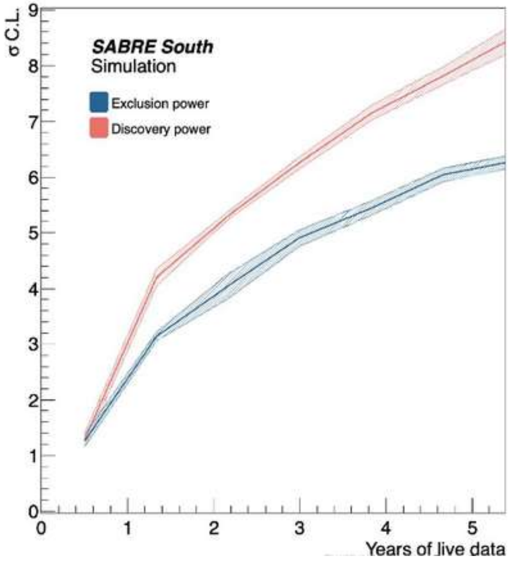
- Using same core detection technology as in DAMA (NaI)
- Two detectors in the two hemispheres :
  - SABRE-North (LNGS) same environment of DAMA
  - SABRE-South (SUPL)

Many **common** points :
  - Same crystal growth powder and crystal PMTs
  - Same DAQ and software frameworks
  - Exchange of engineering knowledge

However, **different** in :
  - Shielding design







Material : courtesy of Owen Stanley, Melbourne, talk given at GDR DUPhy, Lyon

Concluding comments

Direct Dark Matter Search is a very exciting branch of astroparticle physics

A plethora of experiments is hunting Dark Matter using any **mass range** and any **physics model** experimentally accessible

High **complementarity** of different techniques.

For WIMPs**, neutrino floor** has been already reached by xenon experiments (CEvNS @ ^{8}B)

Experiments put significant **pressure on WIMP model** but WIMPs are not yet ruled out !

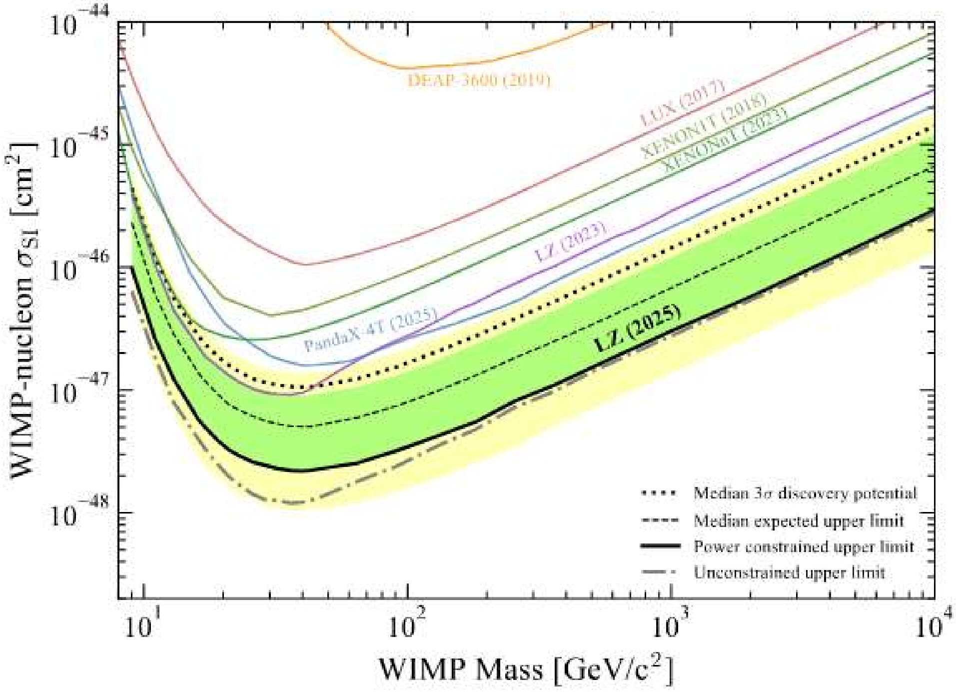
During **next decade** we will witness the final approaching to the **neutrino floor everywhere** at m > 1 GeV (discovery or end of experimentally accessible WIMP paradigm?)

We will also see the birth of novel **emerging techniques** designed specifically for alternative models (light dark matter)

Thank you

Downwards fluctuations

To **constrain large downwards fluctuations**, the limit is subjected to a power-constraint : arXiv:1105.3166



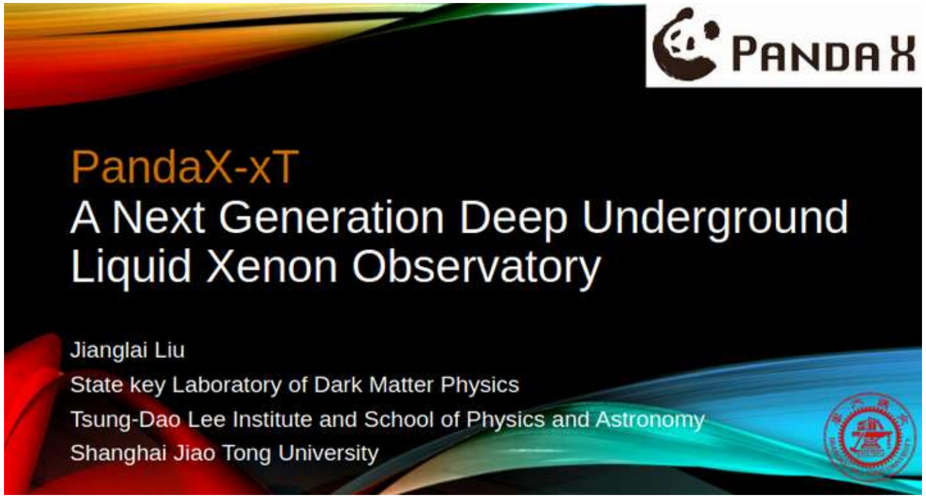
- Full curve : 90% C.L. limit with a power-constraint (-1σ) to restrict it at or above the median unconstrained upper limit
- Dot-dashed curve : no power contraint applied

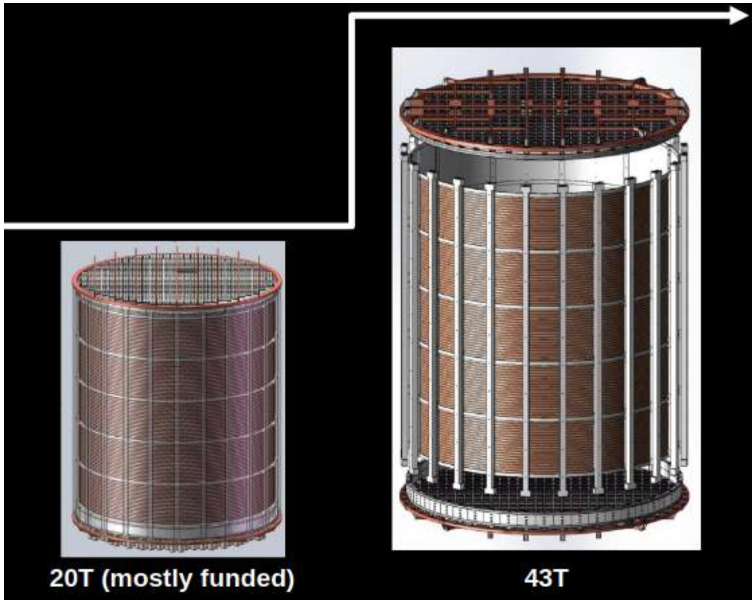
LZ results (2025) :
4.2 ± 0.1 tonne-years from 280 live days
(of which 3.3 are new with respect to 2022 results)

Source	Pre-fit Expectation	Fit Result
^{214}Pb βs	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Solar ν ER	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
Tritium+ ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe $2\nu\beta\beta$	55.6 ± 8.3	55.8 ± 8.2
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 3.6
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
Accidental coincidences	2.8 ± 0.6	2.6 ± 0.6
Atm. ν NR	0.12 ± 0.02	0.12 ± 0.02
^{8}B+hep ν NR	0.06 ± 0.01	0.06 ± 0.01
Detector neutrons	$^{a}0.0^{+0.2}$	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1203 ± 42

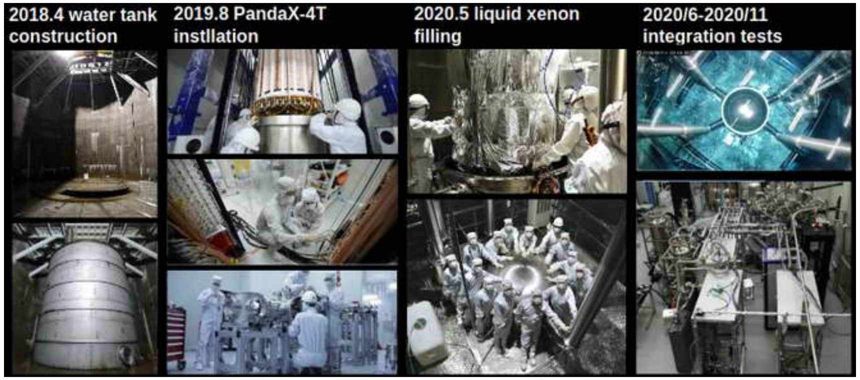
PandaX-xT

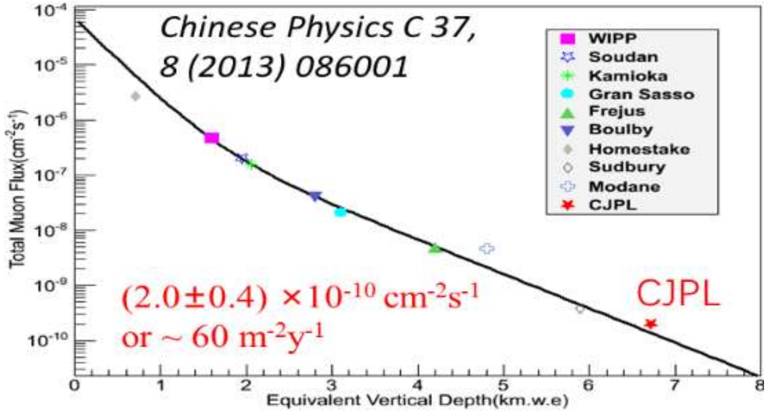
- April 2025 : First International Open Meeting for PandaX-xT
- April 2026 : Second International Open Meeting for PandaX-xT
- Including theory and phenomenology talks and a visit to Jinping Laboratory
- Staged approach : first 20T, then 43T





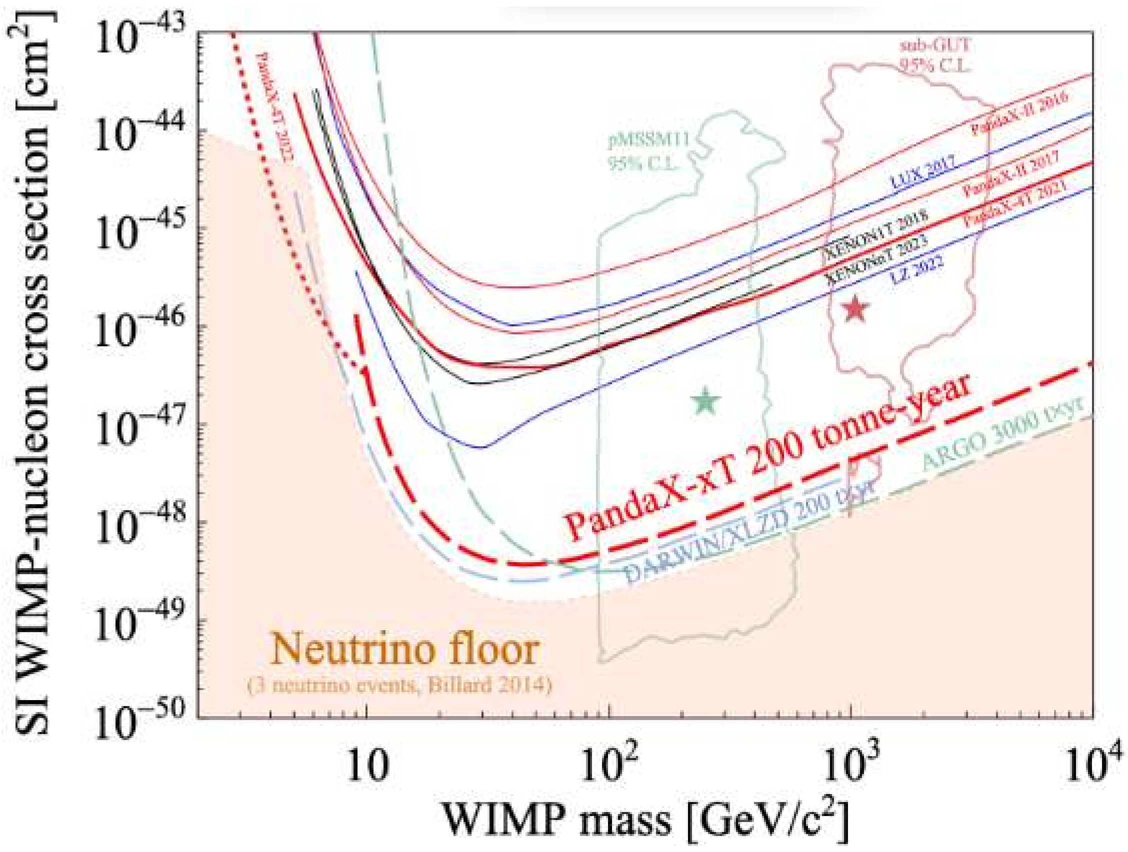
Timeline of the previous PandaX-4T

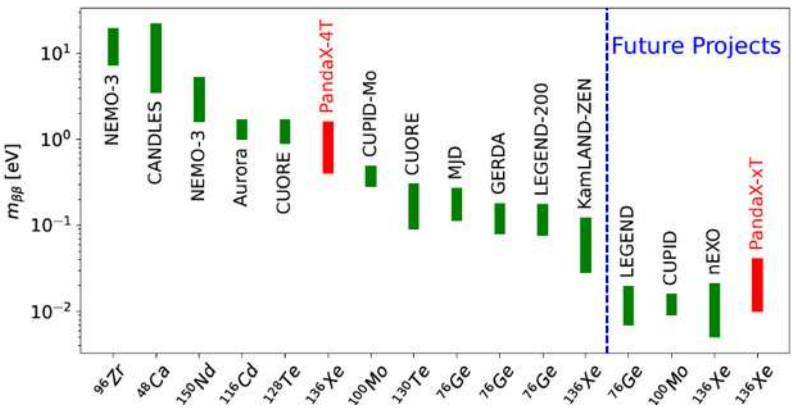


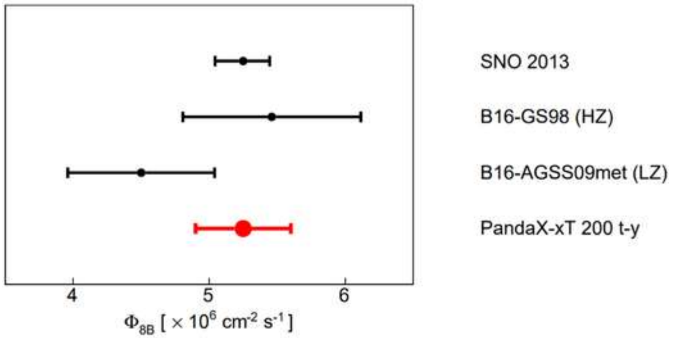


PandaX-xT : physics reach

- Results assuming 43 tonnes of fiducial mass

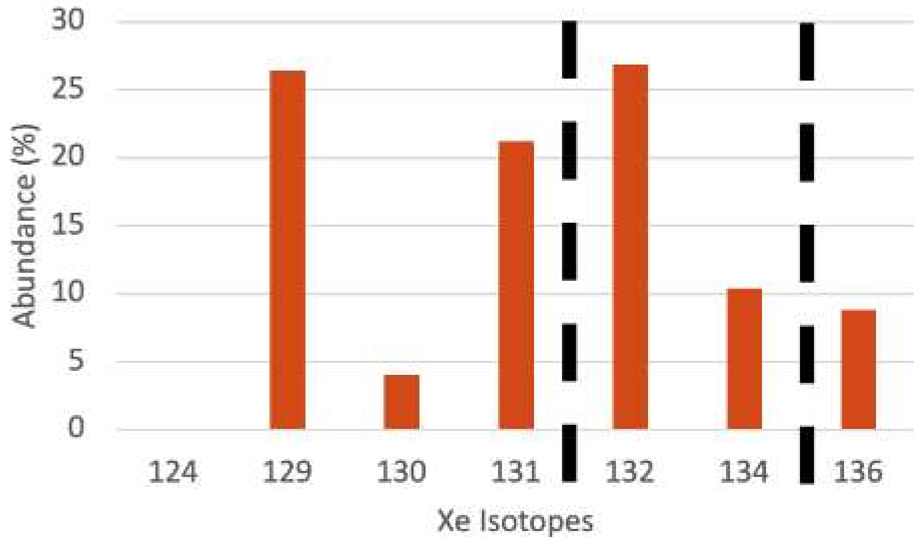


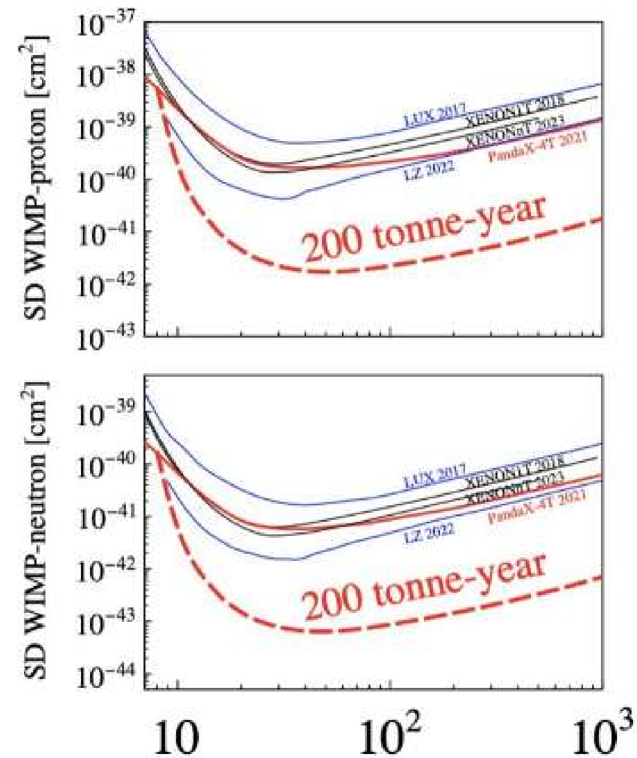


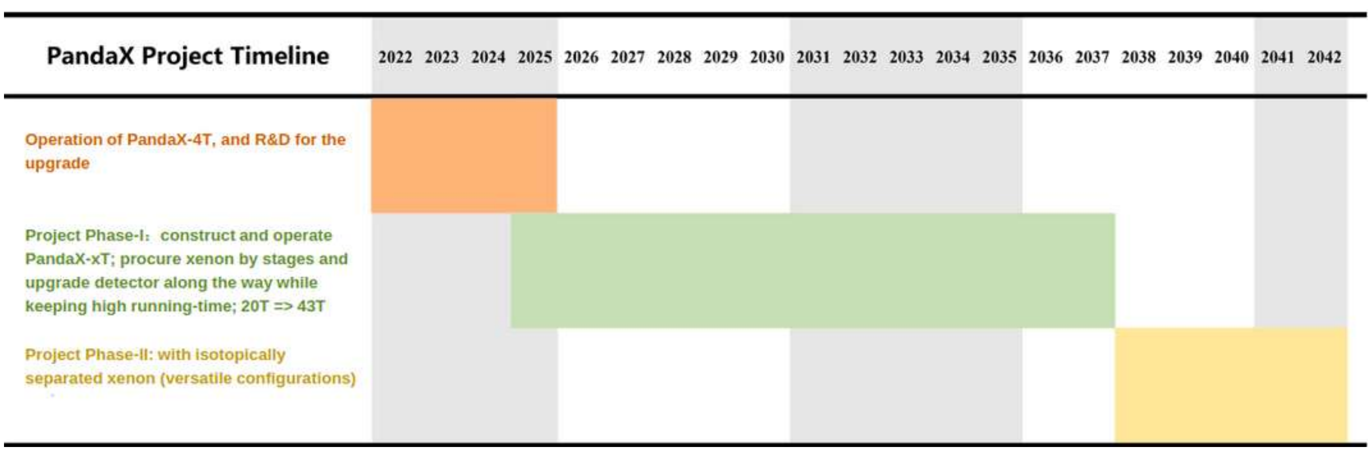


PandaX-xT : timeline and future ideas

- Timeline and future performances





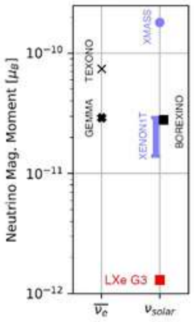


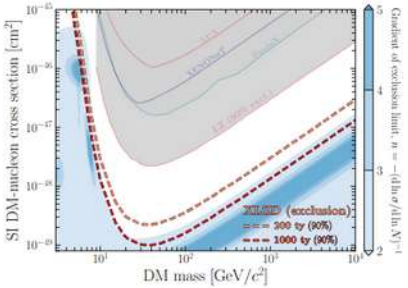
XLZD, a dark matter detector ?
No, an astroparticle observatory

XLZD is an **astroparticle observatory**, allowing not only dark matter search, but also neutrino physics and many other physics opportunities

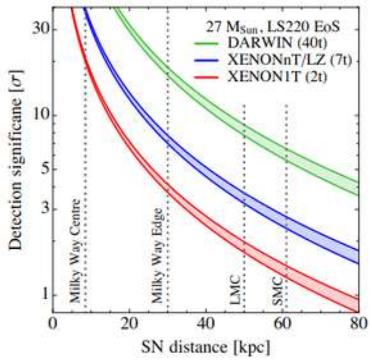
- ‘Snomass’ White paper : *J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001, arXiv:2203.02309*
- XLZD Design Book : *Eur. Phys. J. C (2025) 85: 1192, arXiv:2410.17137v1*

arXiv:2203.02309





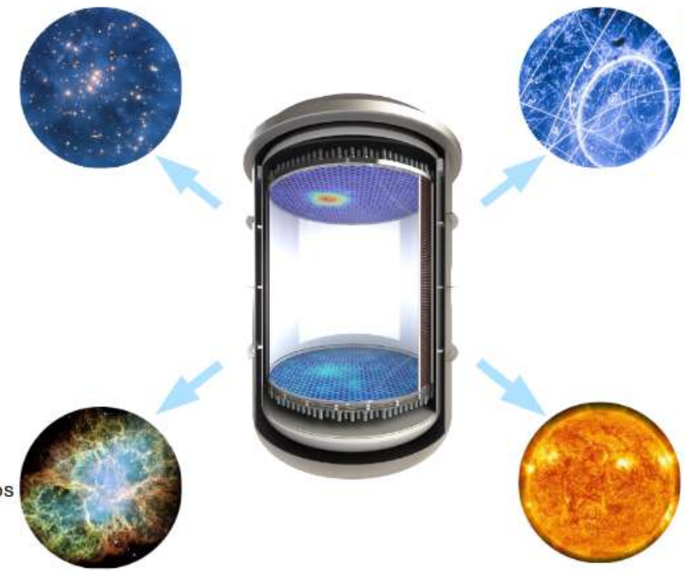
arXiv:2410.17137v1



Phys. Rev. D 94 (2016) no.10, 103009

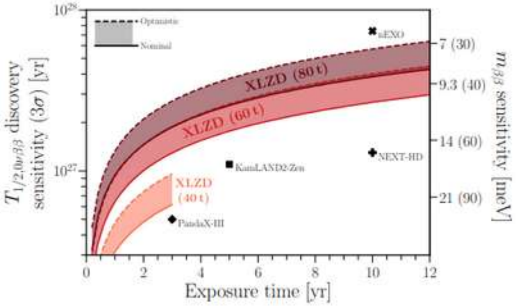
Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons

Supernovae
Early alert
Supernova neutrinos
Multi-messenger astrophysics

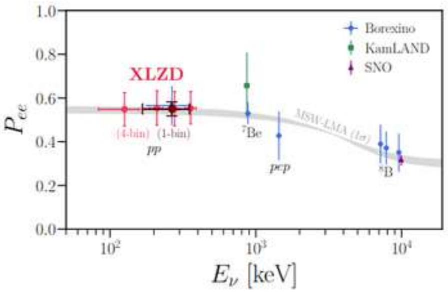


Neutrino nature
Neutrinoless double beta decay
Neutrino magnetic moment
Double electron capture

Sun
pp neutrinos
Solar metallicity
^{7}Be, ^{8}B, hep



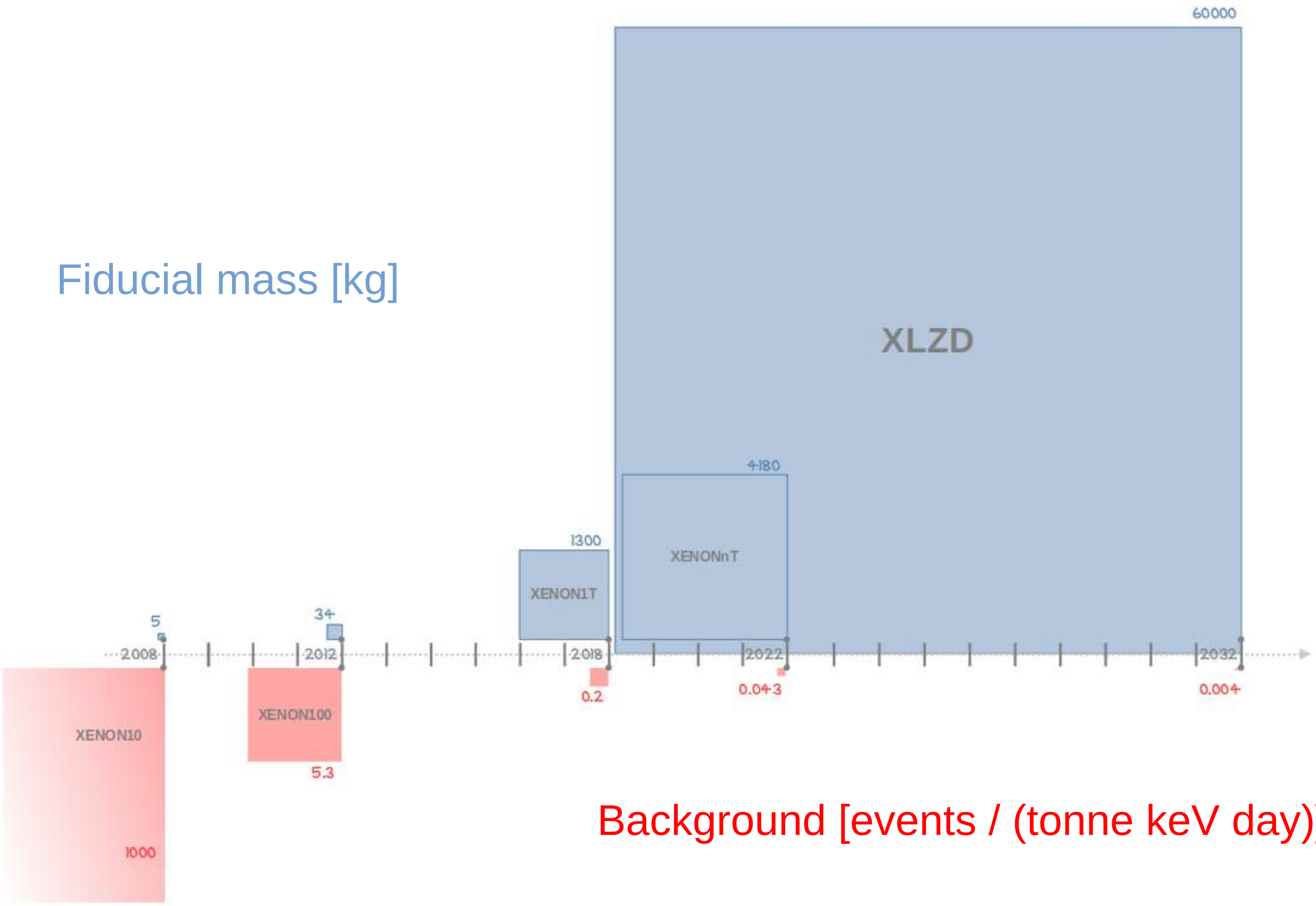
arXiv:2410.17137v1



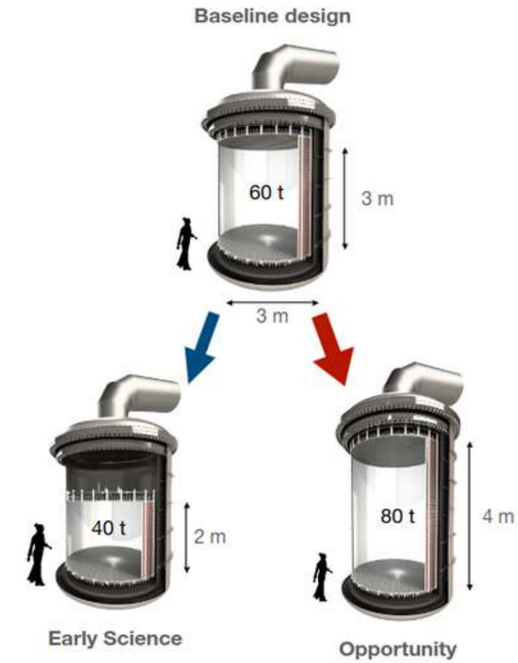
arXiv:2410.17137v1

The power of scalability

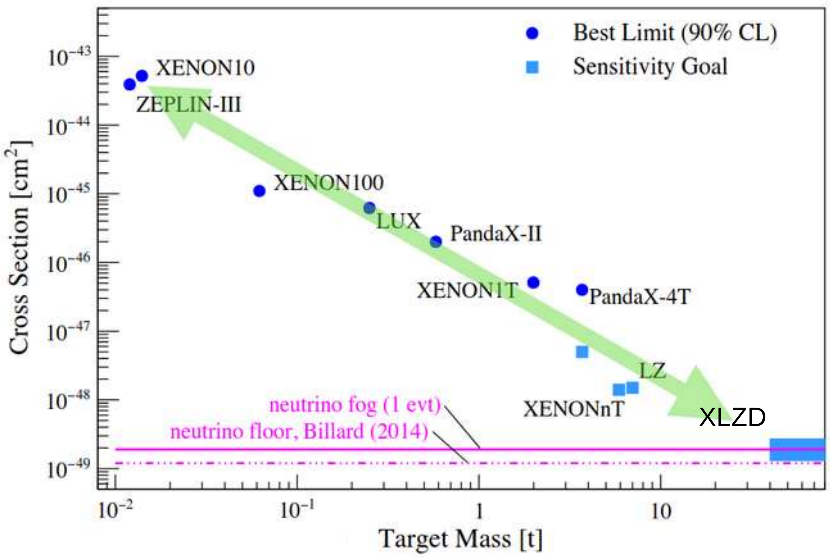
Fiducial mass [kg]



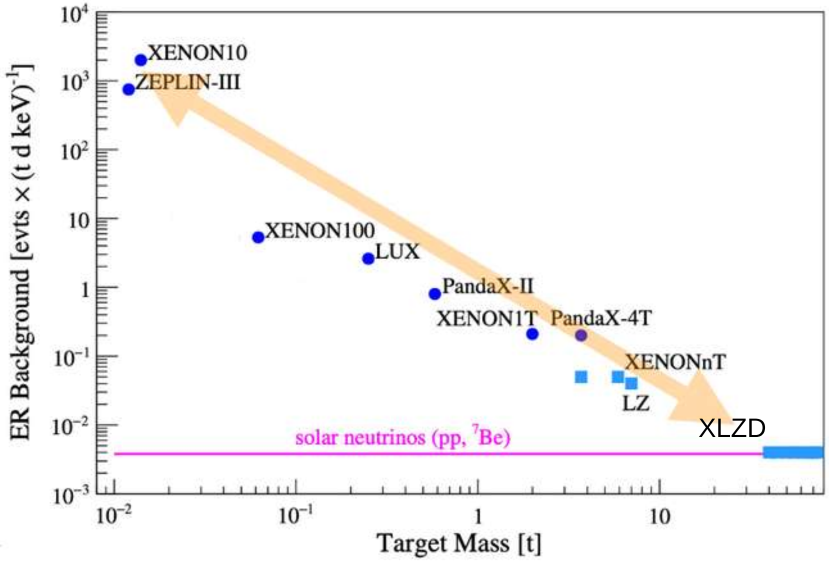
Background [events / (tonne keV day)]

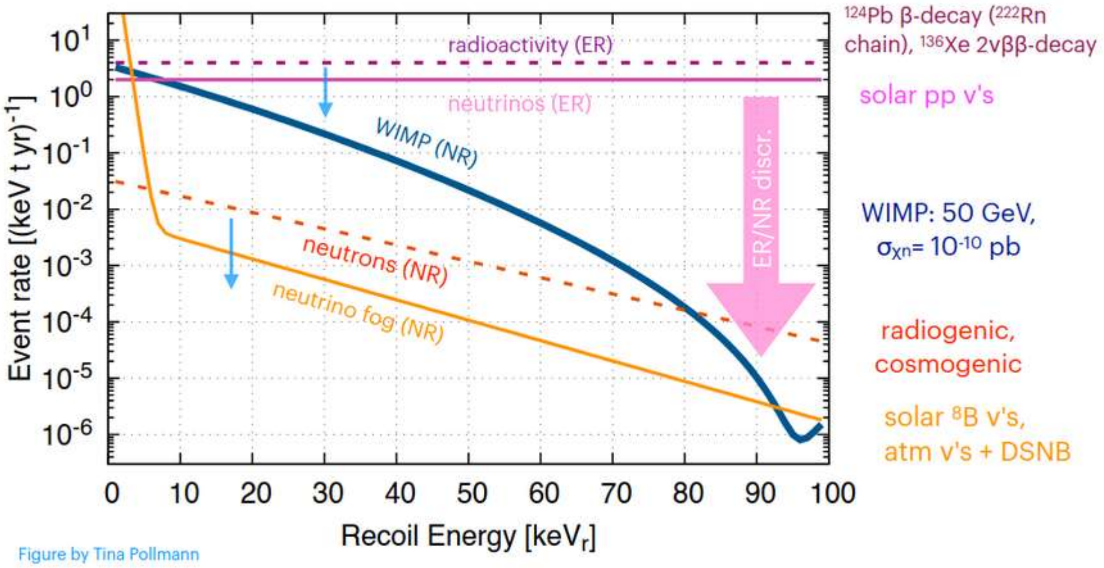


XLZD goals



Main goal : quasi “background-free” exposure of 200 t y for dark matter search
ER and NR backgrounds limited uniquely by neutrino-induced events





Size matters

New detector → new challenges

Design of electrodes: robustness (minimal sagging/deflection), maximal transparency, reduced e- emission ("hot spots")

Electric field: ensure spatial and temporal homogeneity, avoid charge-up of PTFE reflectors

High-voltage supply to cathode design, avoid high-field regions

Light sensors: reduce backgrounds and DRCs, improve PDE

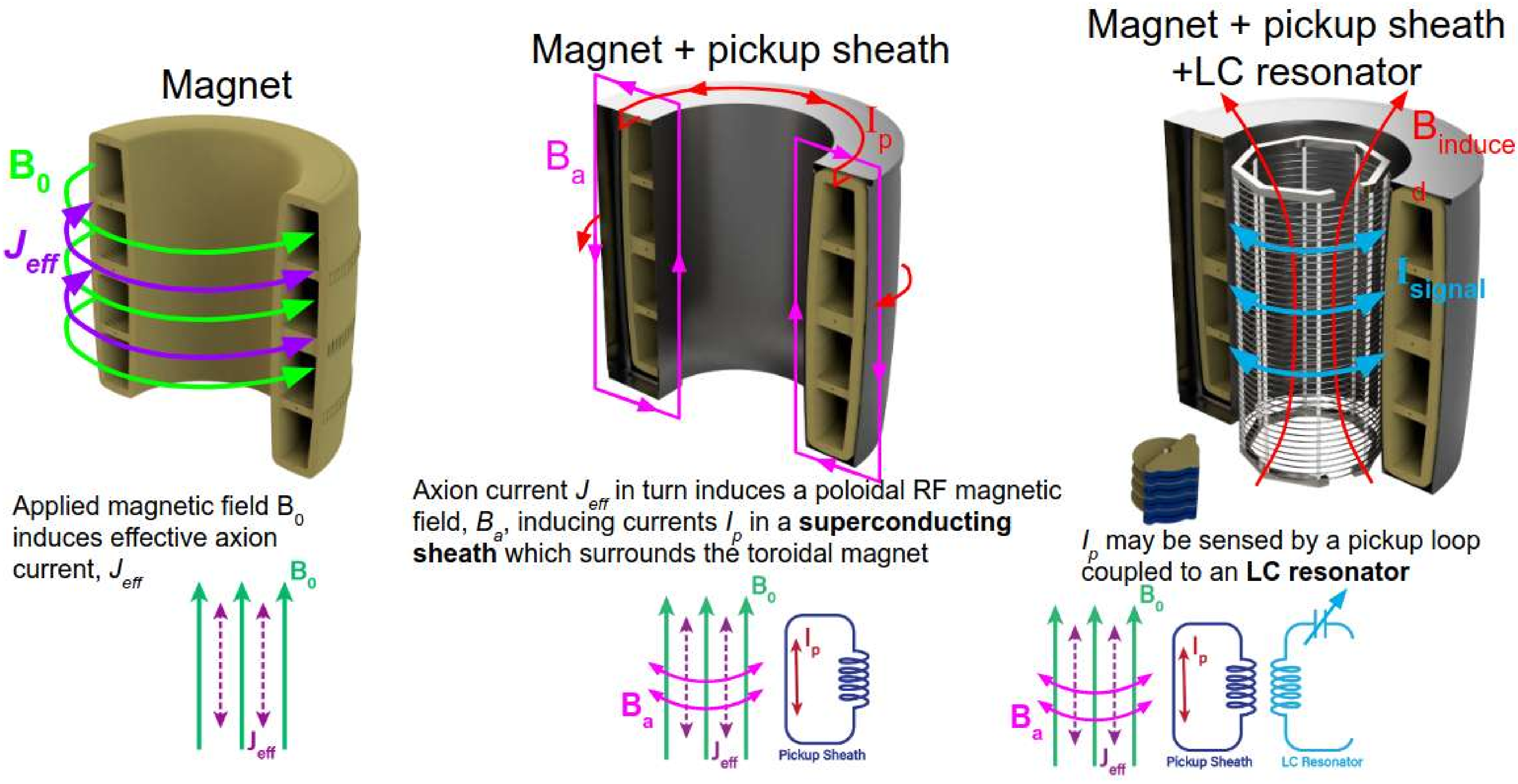
Cryogenic system and xenon **purification**

Xenon **storage and recovery** : safety and reliability

Computing : handling up to 2.4 PB / year of data

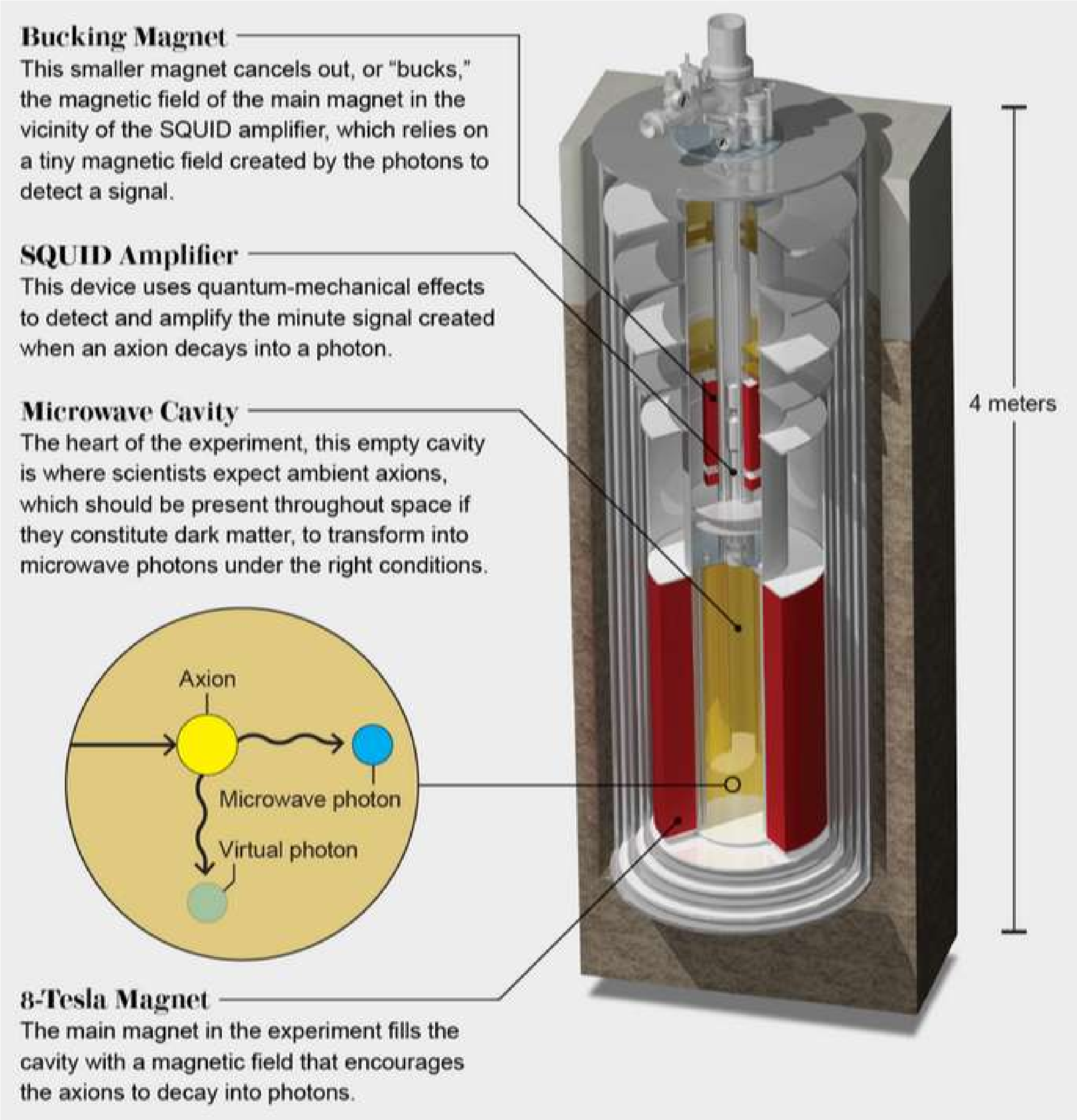
Frédéric Girard, LPNHE

Example of lumped element detection : DMRadio



Alex Droster, IDM 2024

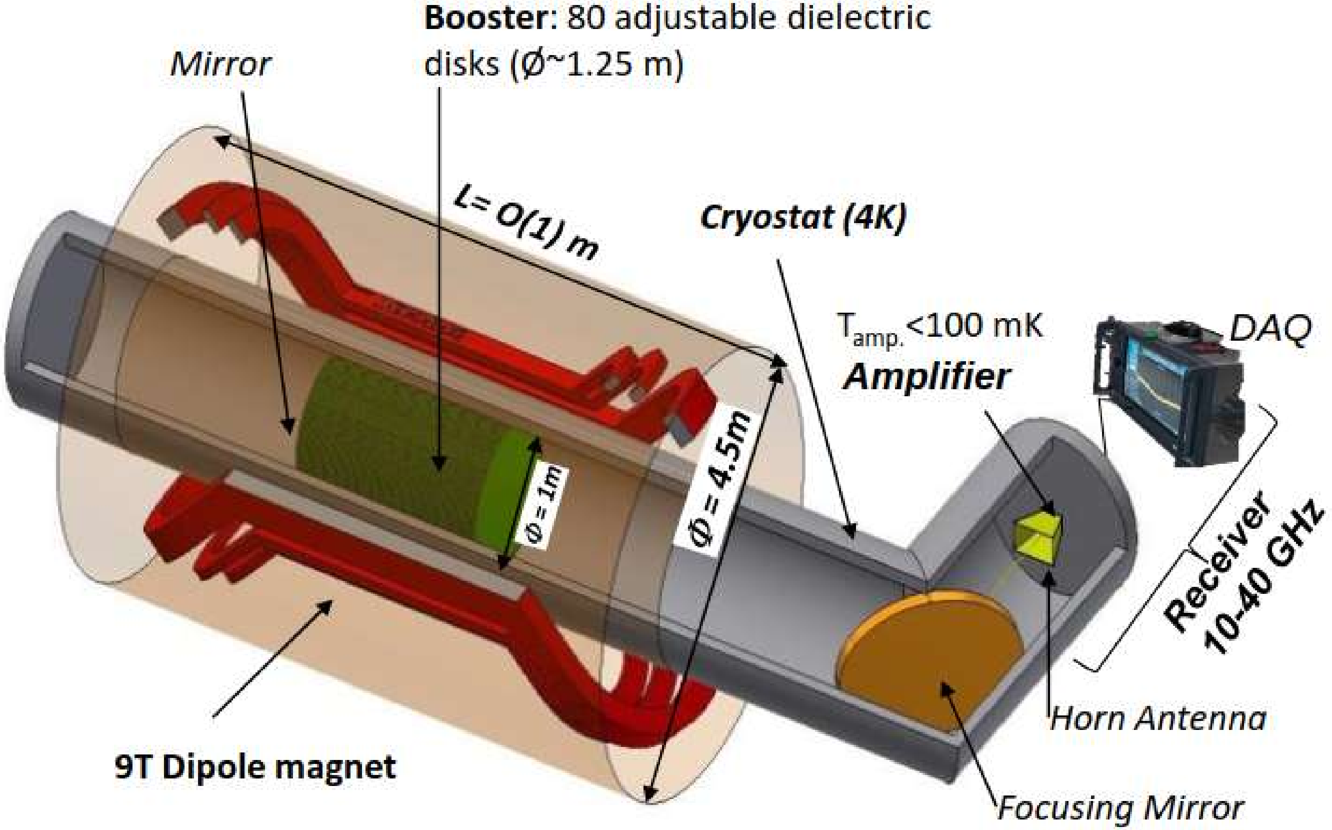
Example of cavity haloscope : ADMX



Example of dielectric haloscope : MadMax

- Constructive interference of coherent photons emitted at the disk surface + resonant enhancement (~leaky resonator cavities) : boost factor β^2 wrt mirror only
- Axion mass scan: by moving discs with piezo motors (μm precision) at 4K under 10 T

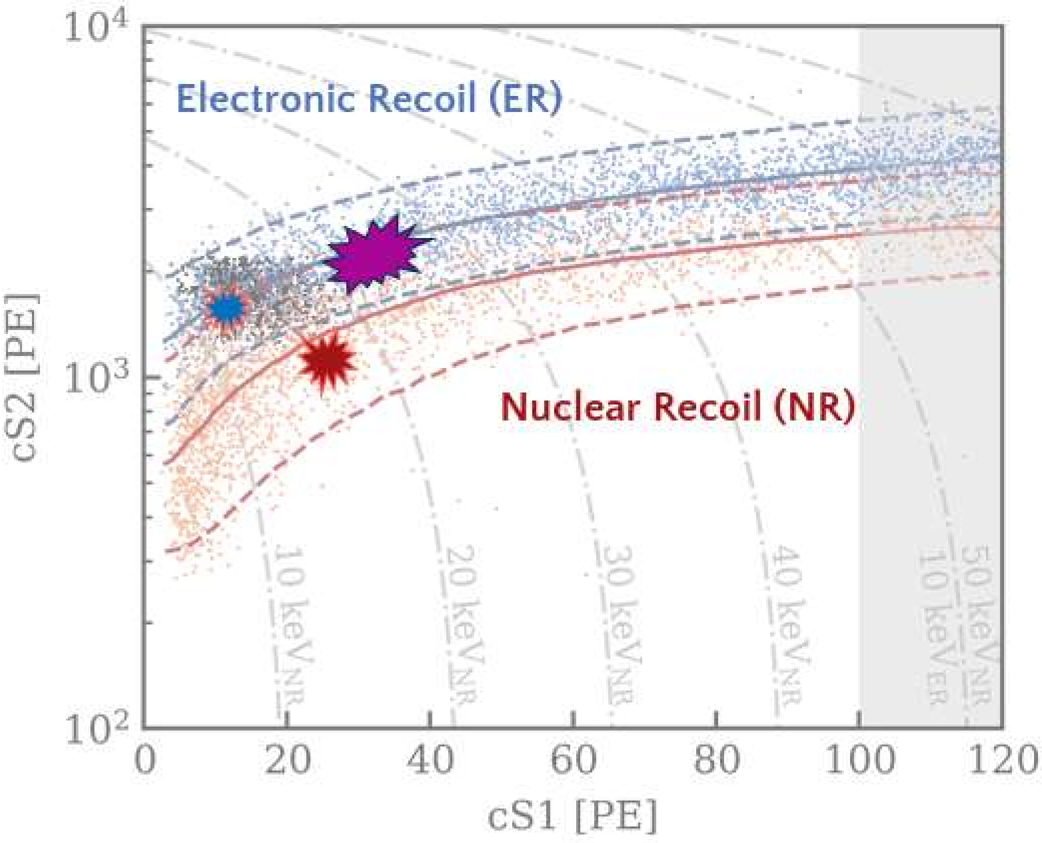
$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2 \qquad |C_{a\gamma}| = \left(\frac{|g_{a\gamma}|}{2\times 10^{-14}\ \mathrm{GeV}^{-1}}\right)\left(\frac{100\ \mu\mathrm{eV}}{m_a}\right)$$



Migdal Effect

Deposited Energy:
- **NR**
- Migdal electron
- Binding energy (X-ray + *Auger e⁻*)

ER { Migdal electron, Binding energy



First direct evidence of Migdal Effect

Nature volume 649, pages 580–583 (2026)

Article

Direct observation of the Migdal effect induced by neutron bombardment

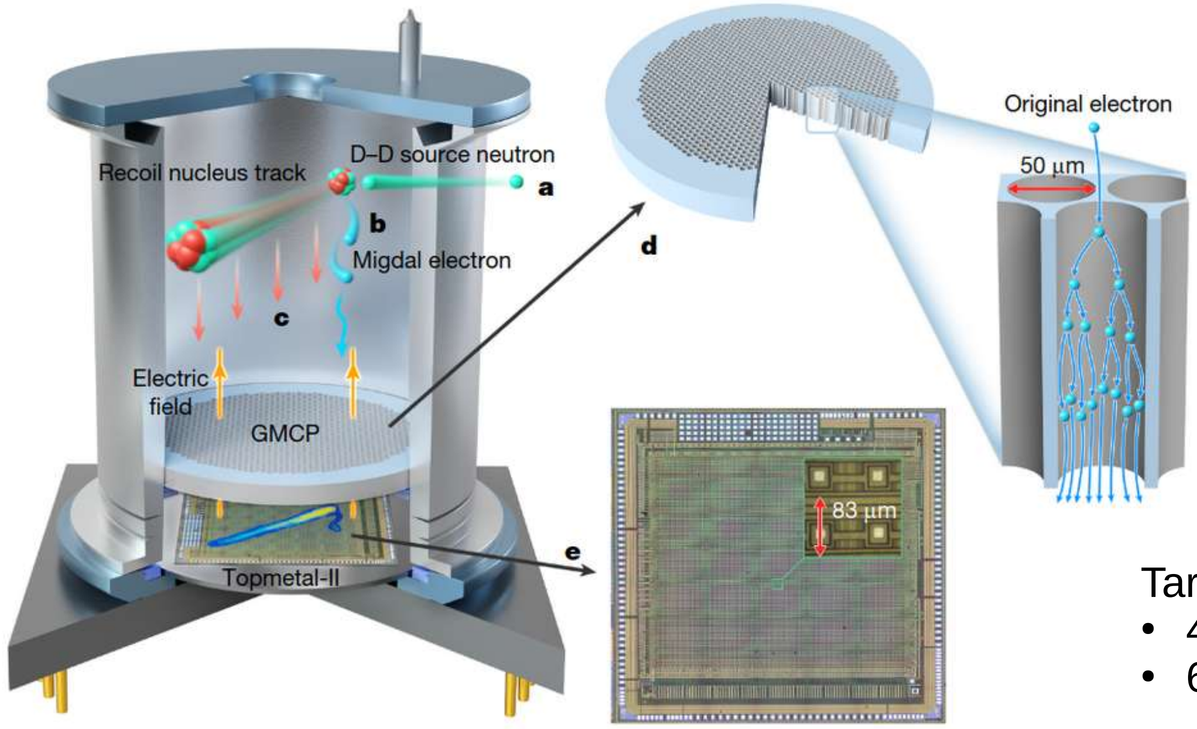
https://doi.org/10.1038/s41586-025-09918-8

Received: 4 October 2024

Accepted: 14 November 2025

Published online: 14 January 2026

Difan Yi[1,2], Qian Liu[1✉], Shi Chen[1], Chunlai Dong[3], Huanbo Feng[2], Chaosong Gao[3], Wenqian Huang[1,2], Xinmei Jing[1], Lingquan Kong[1], Jin Li[1], Peirong Li[4], Enwei Liang[2], Ruiting Ma[1], Chenguang Su[1], Liangliang Su[5], Junwei Sun[6], Dong Wang[3], Junrun Wang[4], Zheng Wei[4], Zeen Yao[4], Yunlinchen Yu[1], Yu Zhang[4], Shiqiang Zhou[3], Zhuo Zhou[3], Bin Zhu[6], Jie Zuo[1], Hongbang Liu[2✉], Xiangming Sun[3✉], Lei Wu[5✉] & Yangheng Zheng[1✉]



Target :
- 40% helium
- 60% dimethyl ether (DME, CH_3OCH_3)

First direct evidence of Migdal Effect

Phenomenon predicted more than 80 years ago but confirmed only now with a statistical significance exceeding 5σ

Relative cross-section with respect to NR cross section : $(4.9^{+2.6}_{-1.9}) \times 10^{-5}$