



University of
Zurich^{UZH}

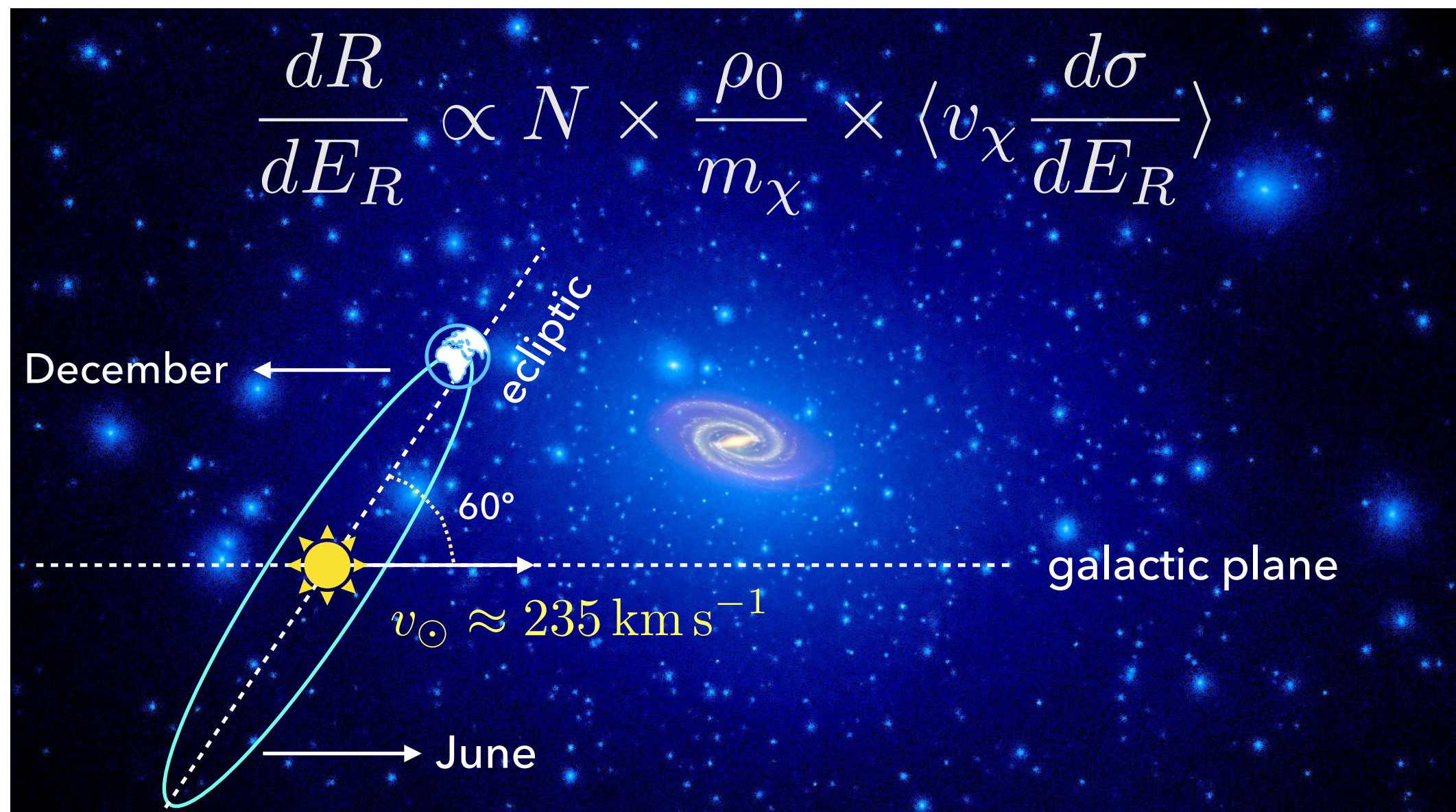
Direct dark matter searches: overview

Laura Baudis
University of Zurich
Wandering in the dark

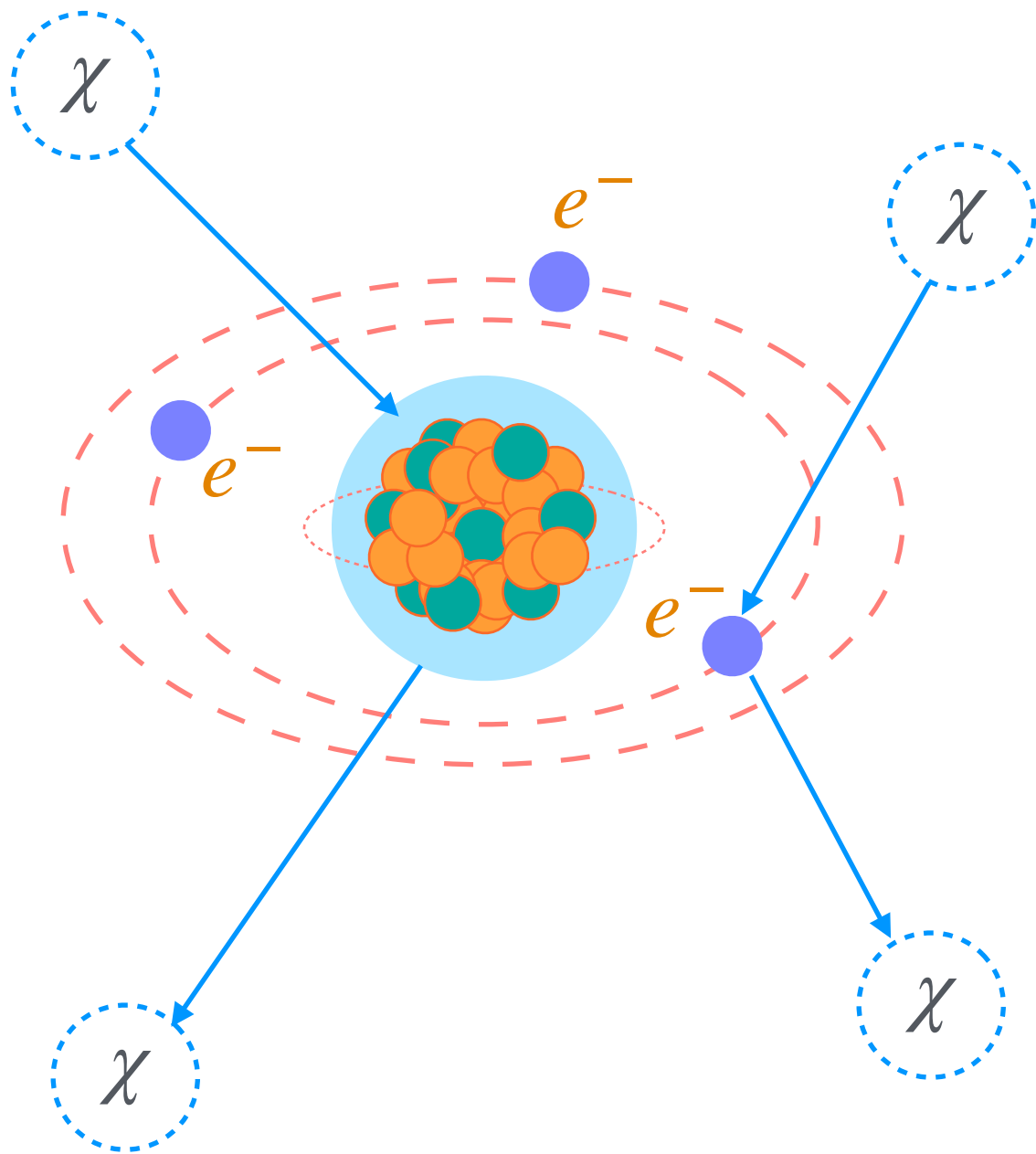


Direct dark matter detection

- Search for interactions of a new particle from the Big Bang which we haven't yet detected in the lab

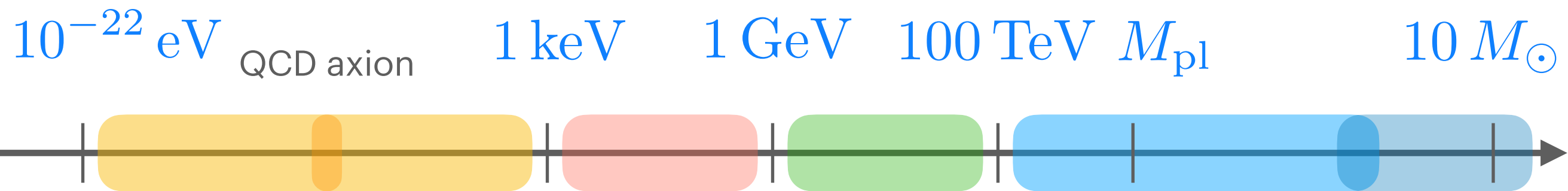


Direct dark matter detection



- Elastic (or inelastic) DM collisions with atomic nuclei (NRs)
- Inelastic DM collisions with electrons in the atomic shell (ERs)
- Absorption of light bosons via
 - axio-electric effect (ALPs)
 - kinetic mixing (dark photons)

Direct dark matter detection



See talks by
M. Fairbairn,
M. Bauer

Absorption

DM

SM

SM

DM

SM

DM

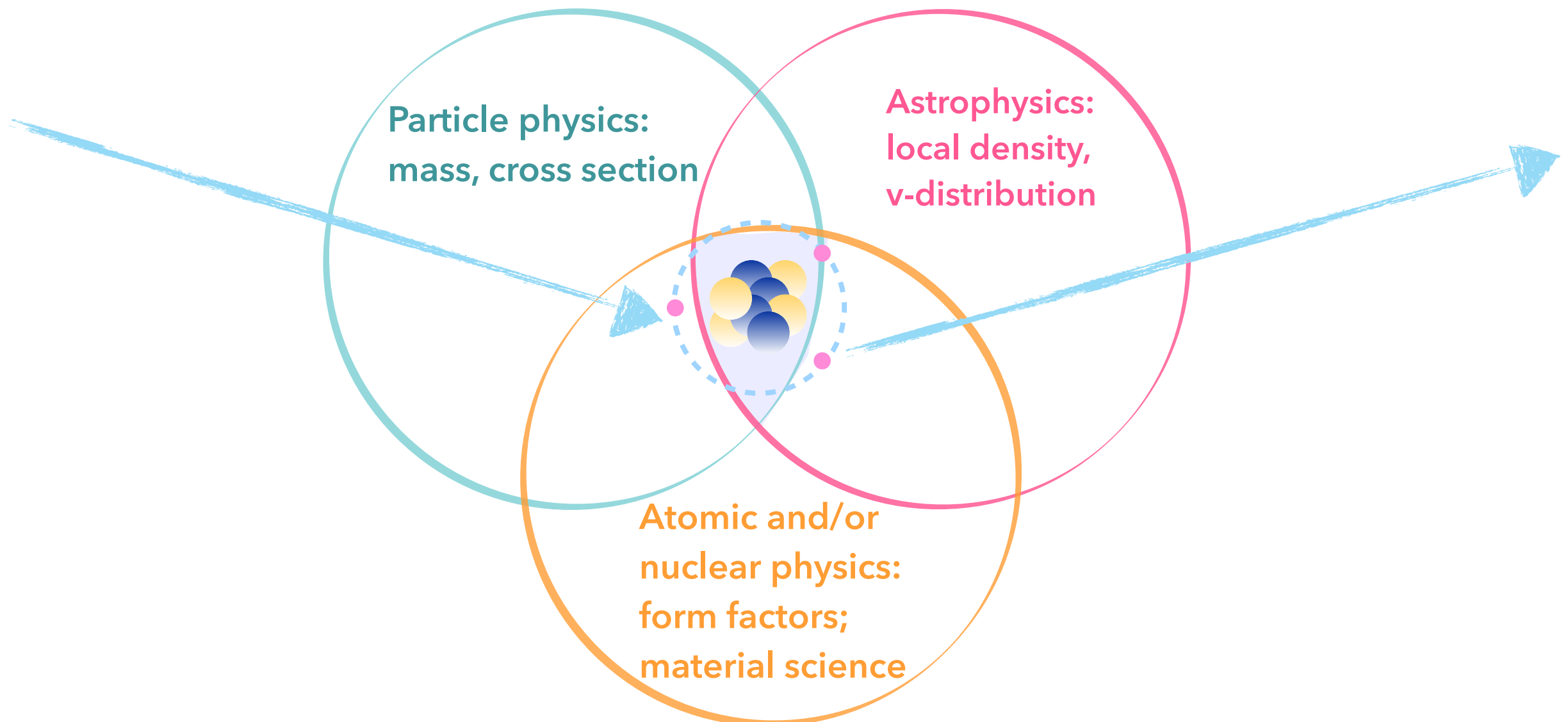
SM

mediator

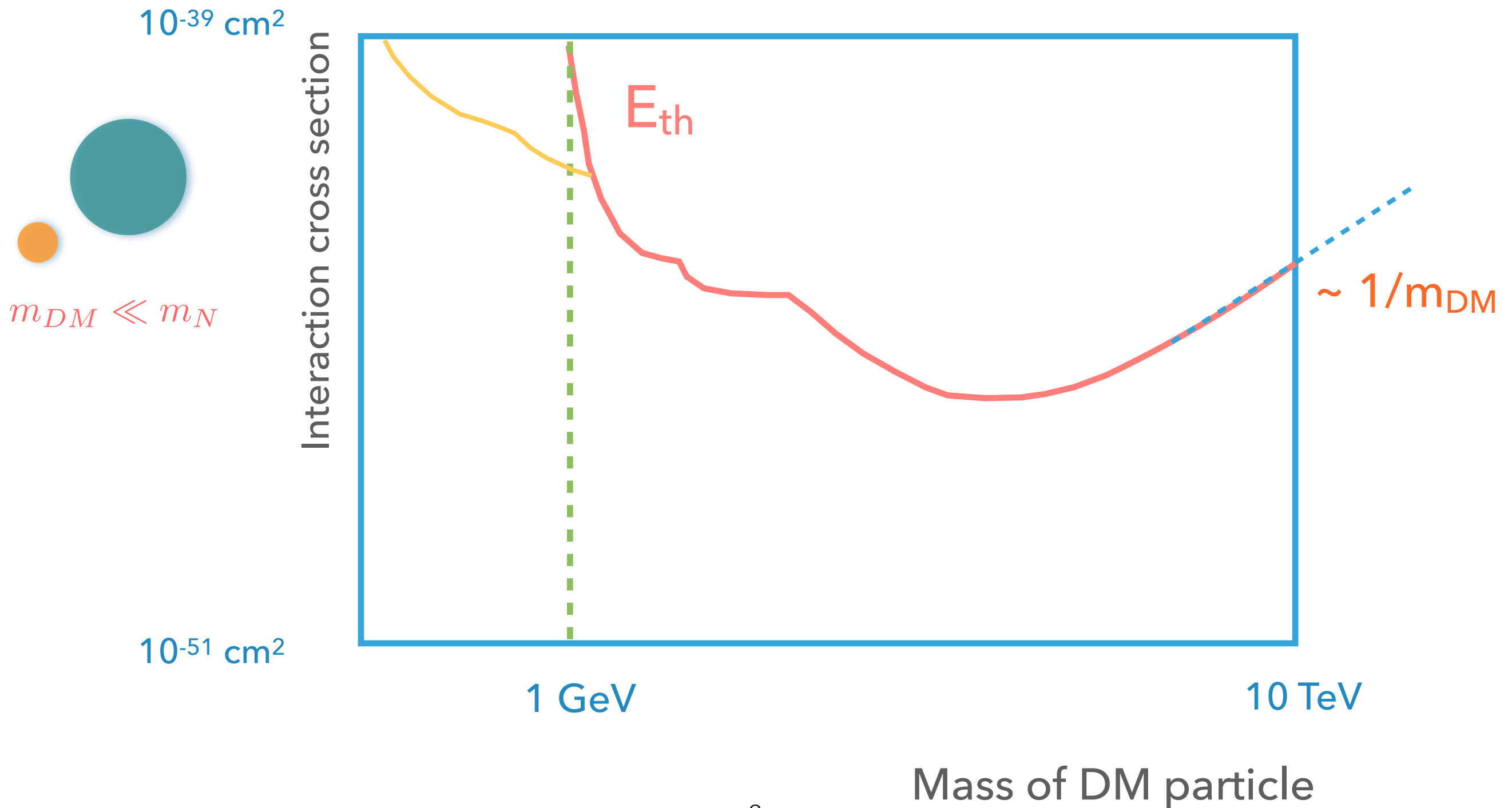
Scattering

Direct dark matter detection

- Inputs from several fields required to predict expected event rates

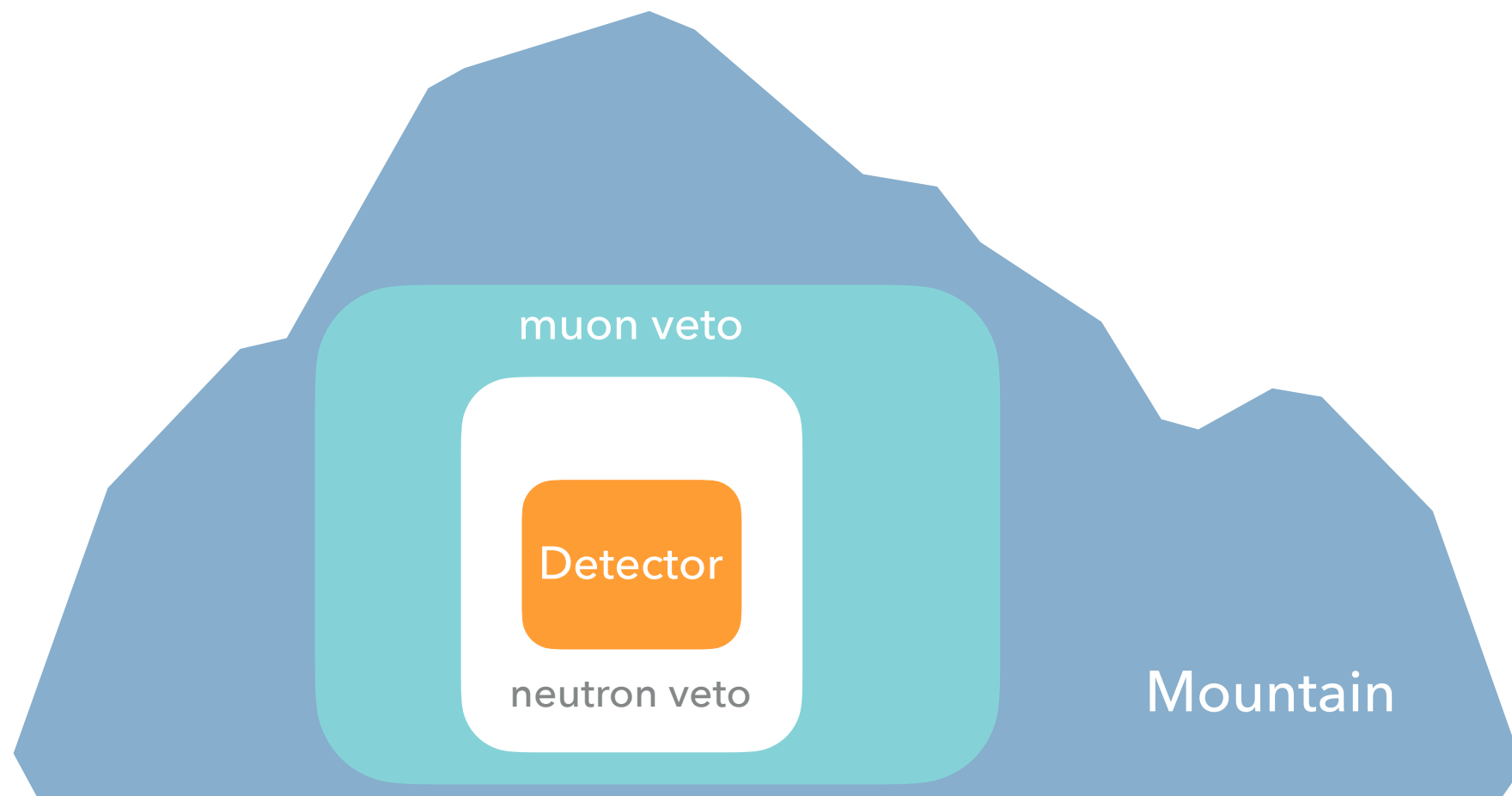


Interaction cross section versus mass



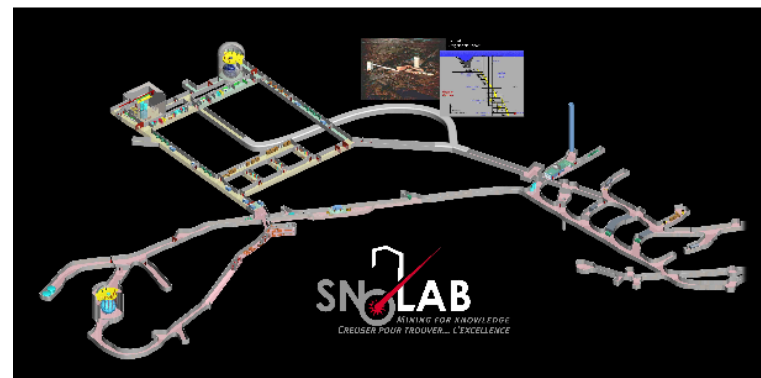
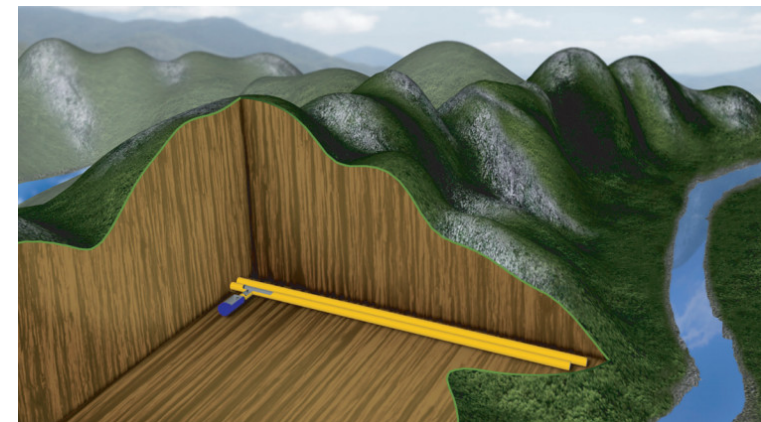
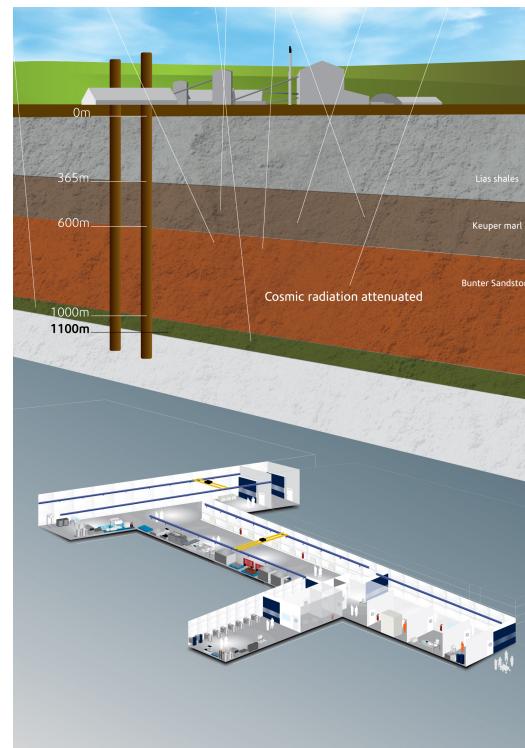
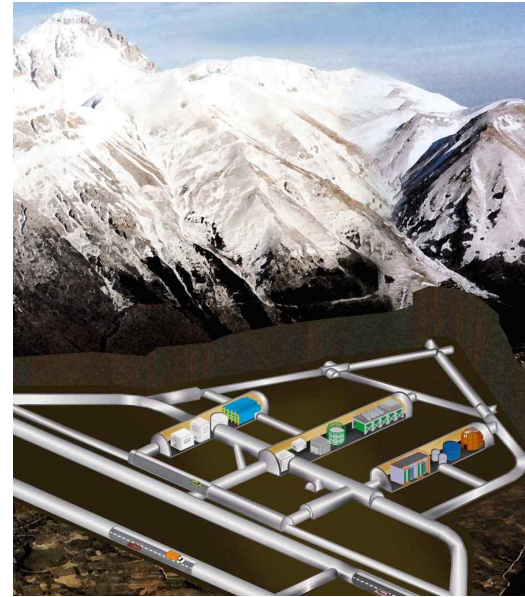
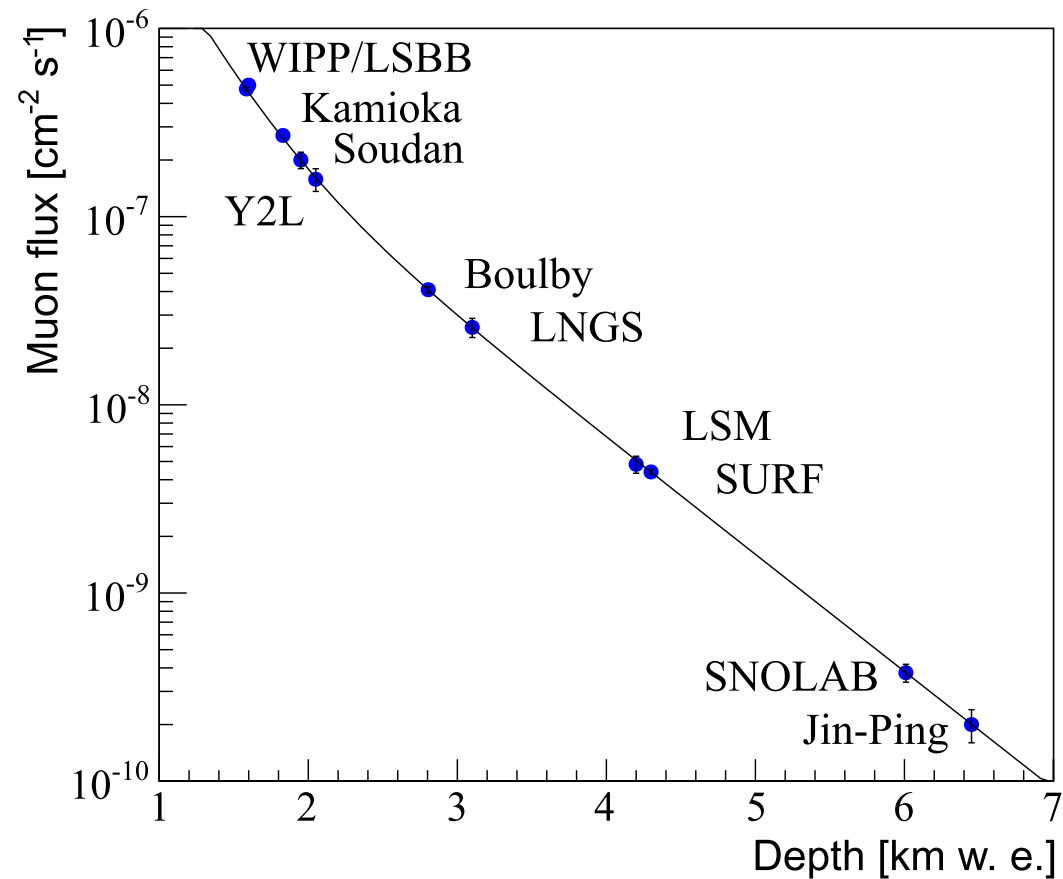
Main experimental challenges

- To observe a signal which is:
 - very small → low recoil energies $\sim \text{eV}$ to keV (perhaps $\sim \text{meV}$)
 - very rare → $< 1 \text{ event}/(\text{kg y})$ at low masses and $< 1 \text{ event}/(\text{t y})$ at high masses
 - hidden in backgrounds → deep underground & low-radioactivity materials



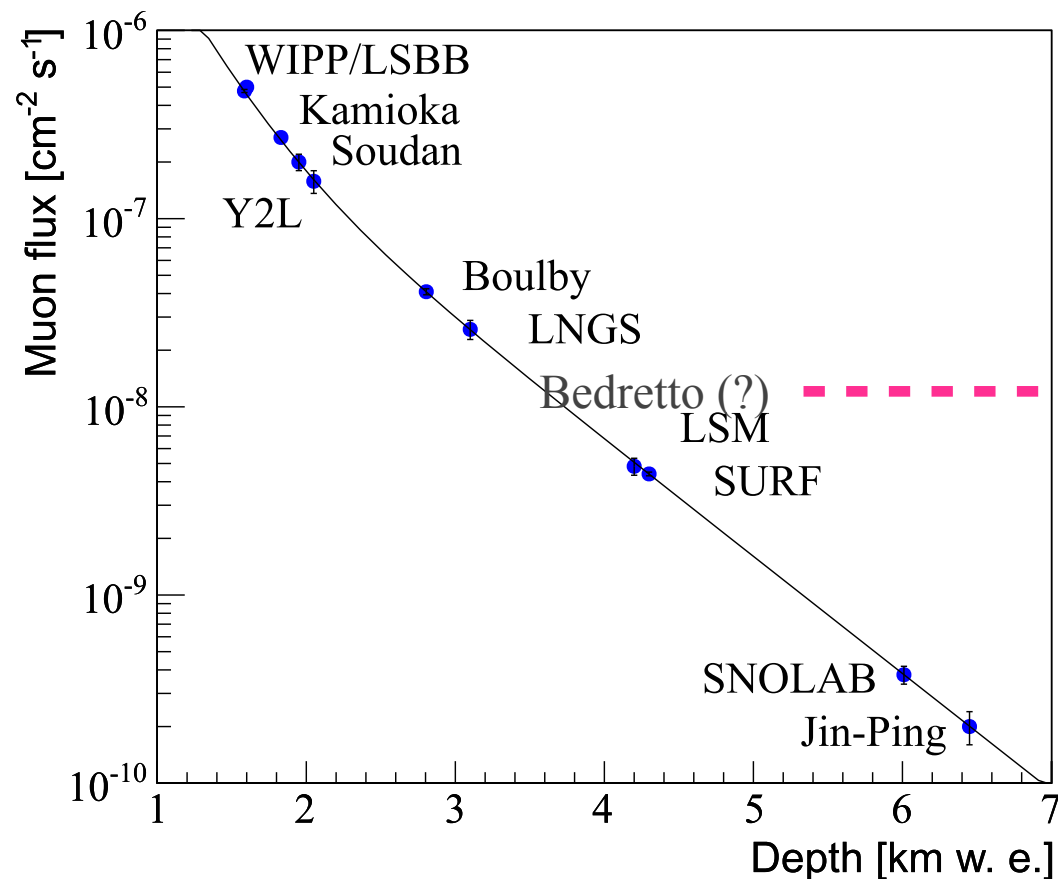
Backgrounds

- Cosmic rays, radioactivity
 - Deep underground, large shields
 - Ultimate: neutrinos



Backgrounds

- Cosmic rays, radioactivity
 - Deep underground, large shields
 - Ultimate: neutrinos

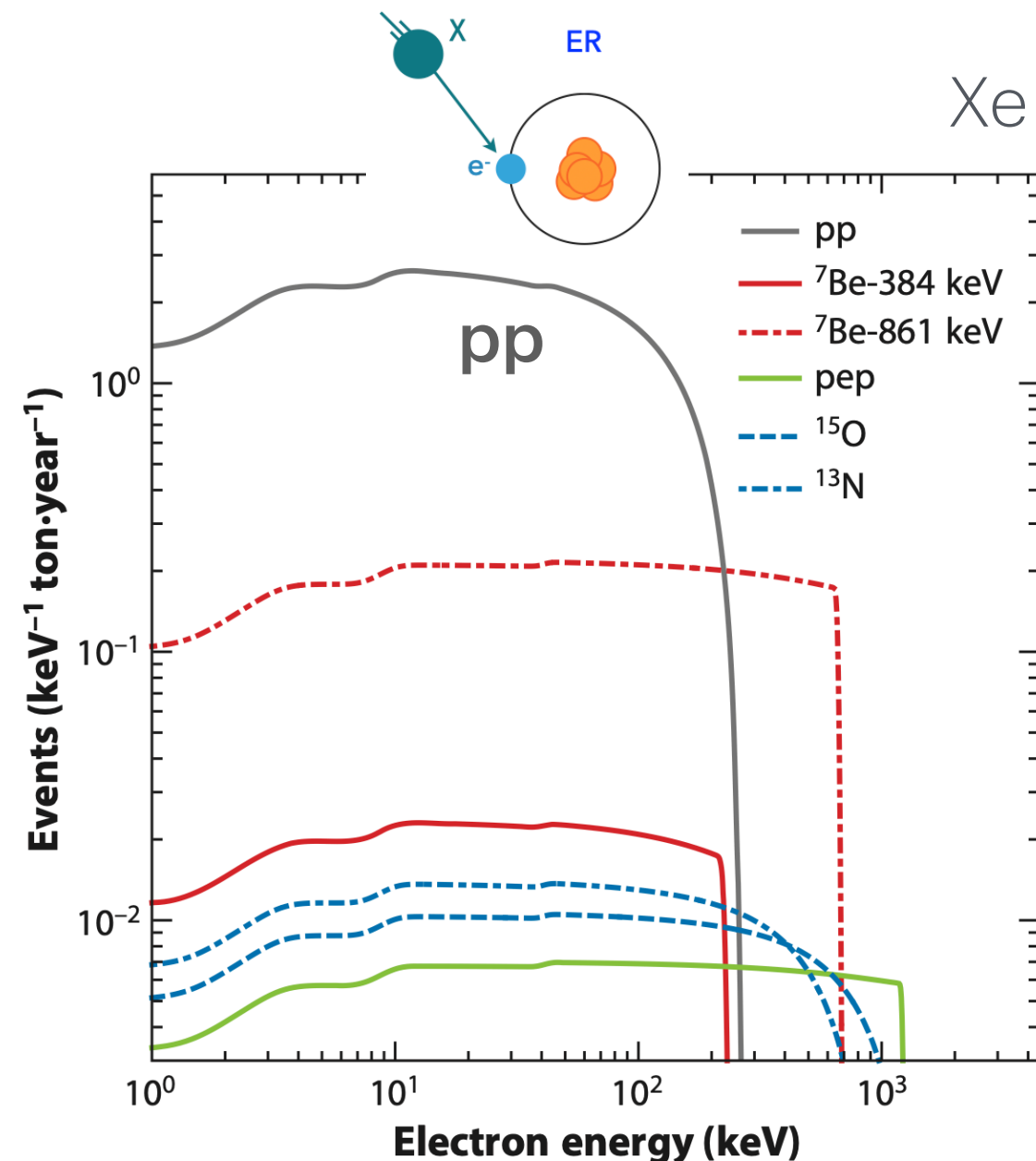
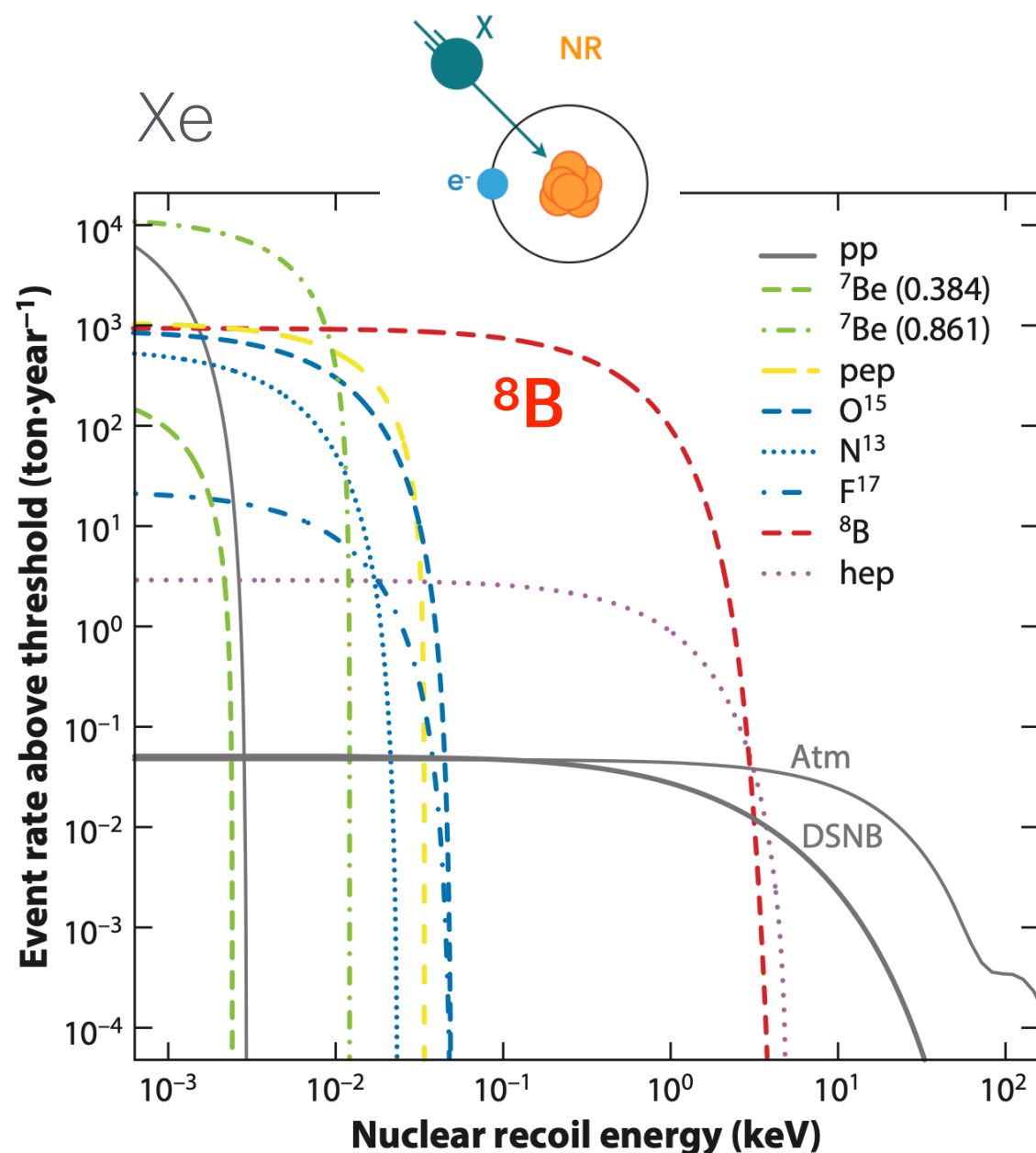


New kid
on the
block?

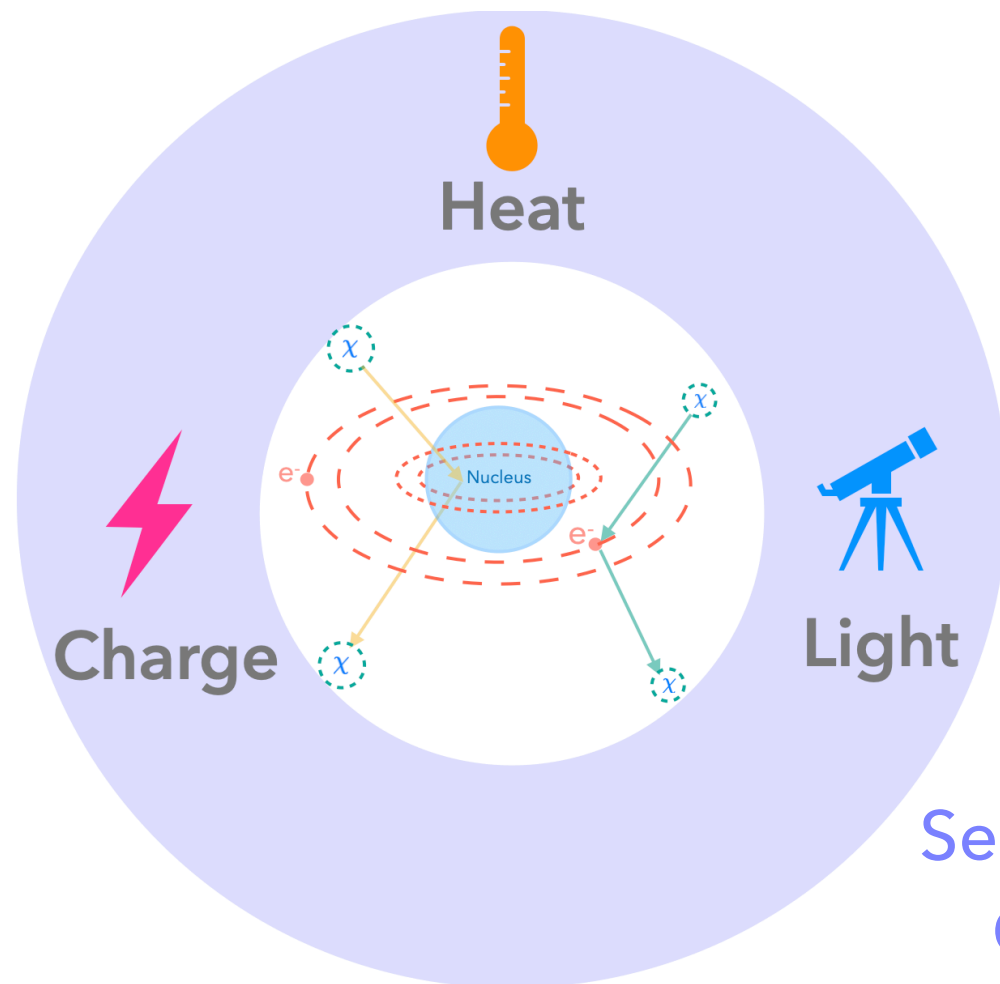


Neutrino signals/backgrounds

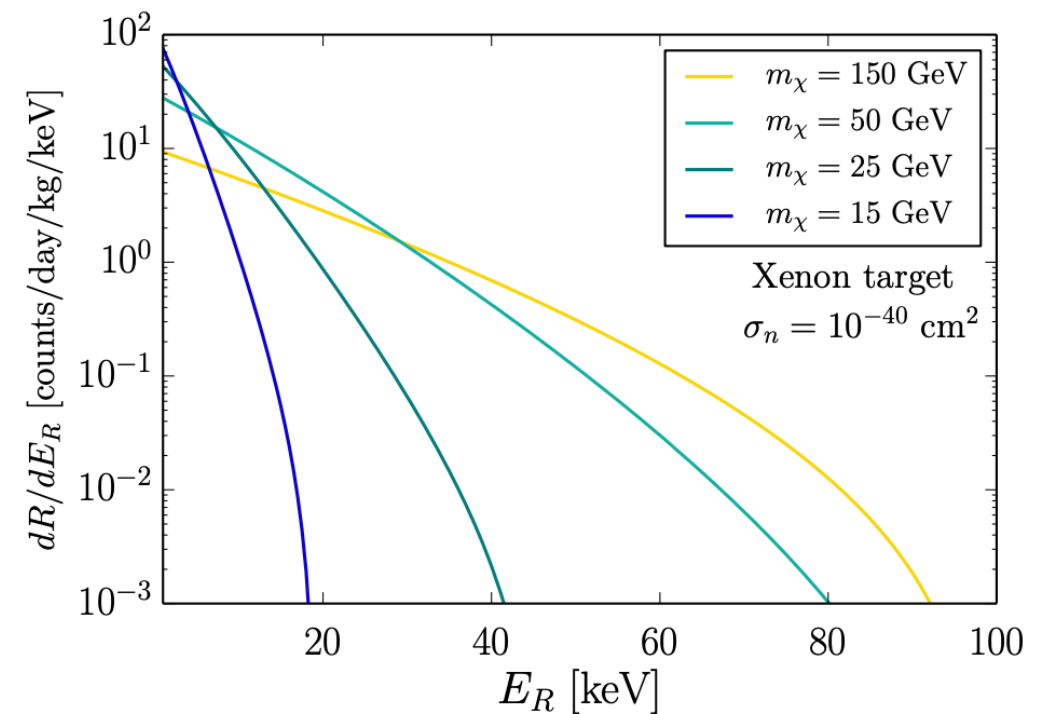
- NRs (CEvNS) and ERs (all other reactions)



Experiments and signatures

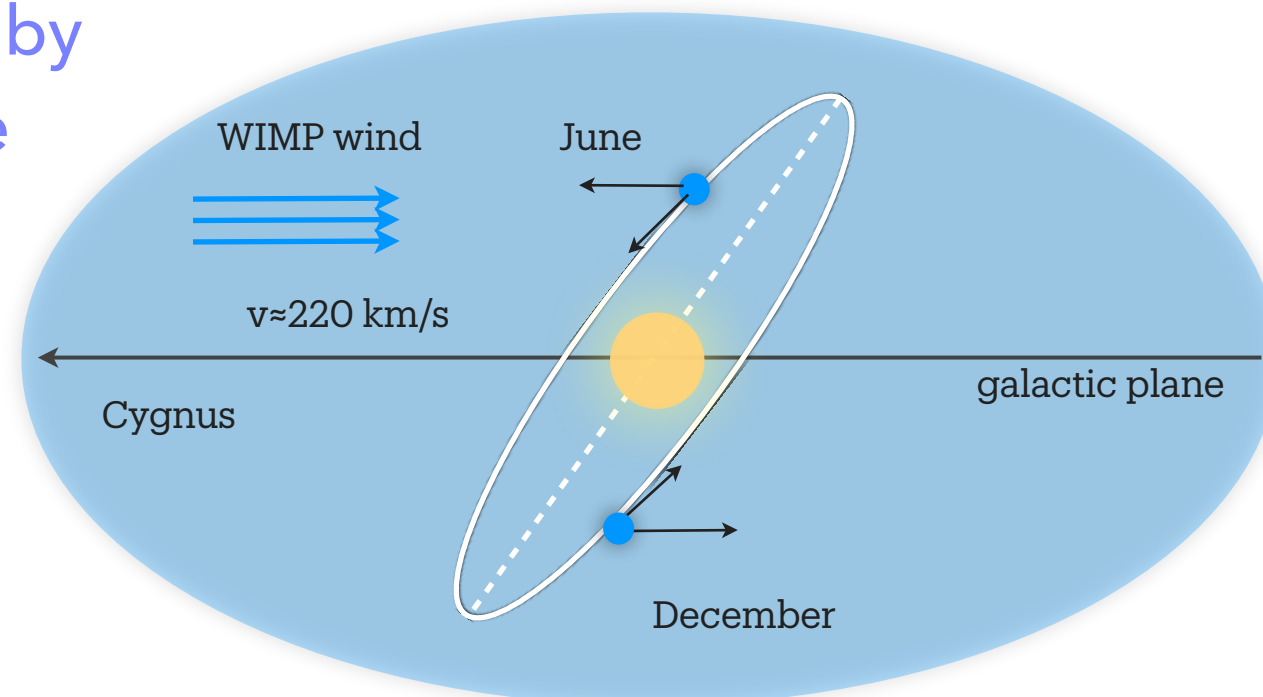


See also talk by
C. McCabe



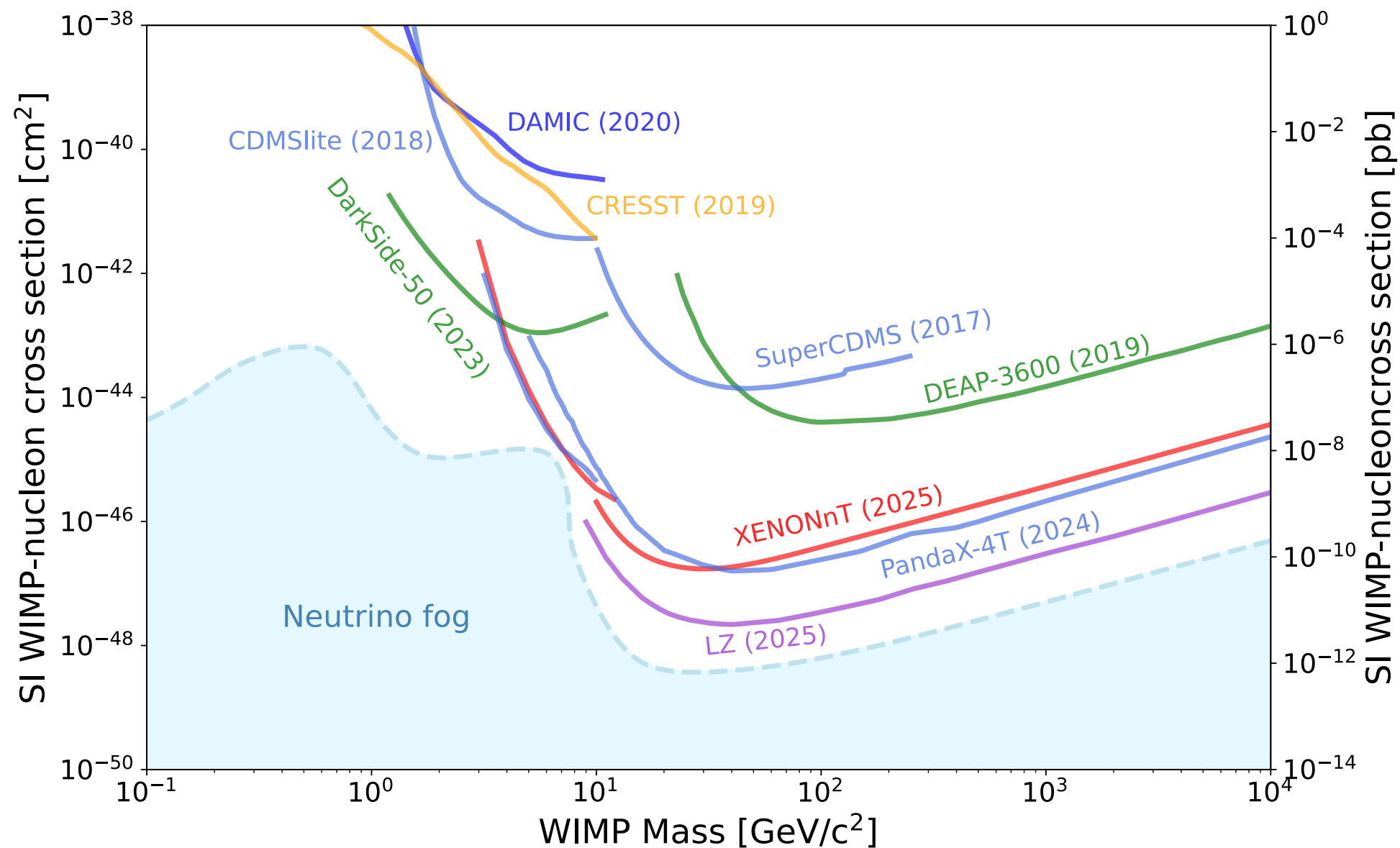
Signatures

- DM particle mass
- Target material
- Time and direction



Towards the neutrino fog

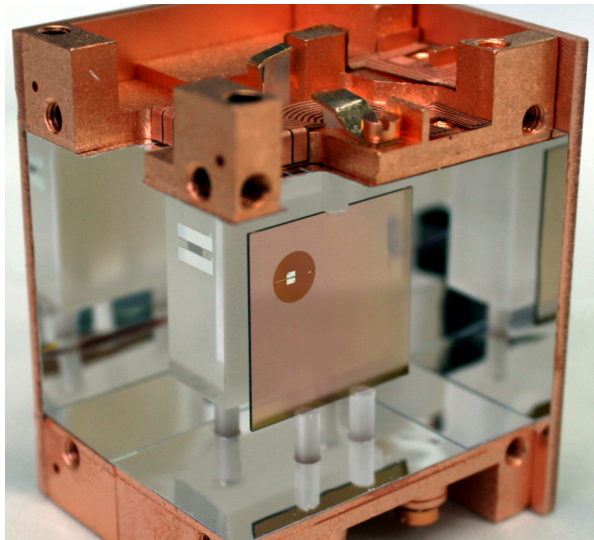
Decrease energy
thresholds



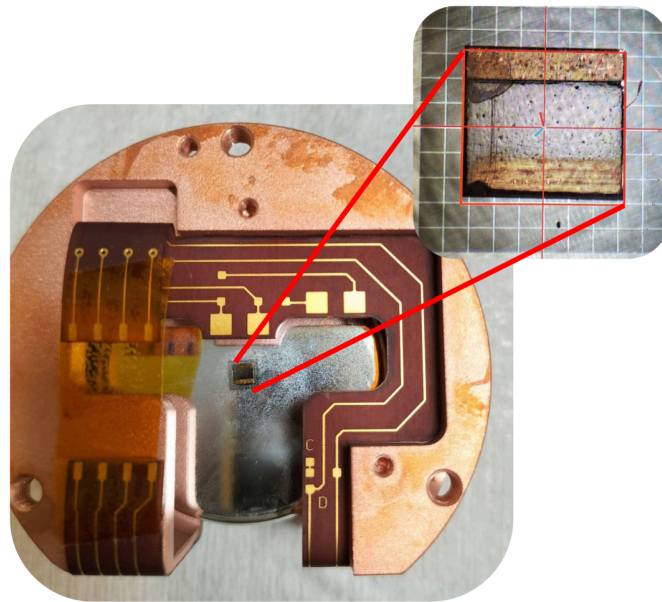
Increase
target
mass:
noble
liquids

LB and S. Profumo, PDG 2025

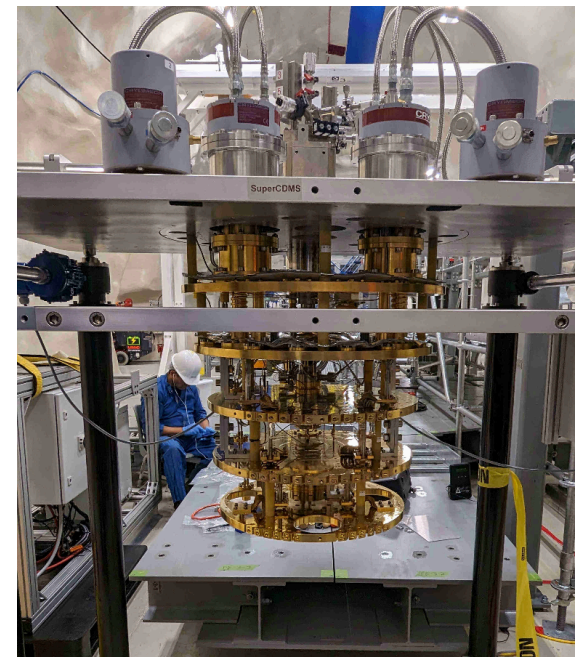
Cryogenic experiments



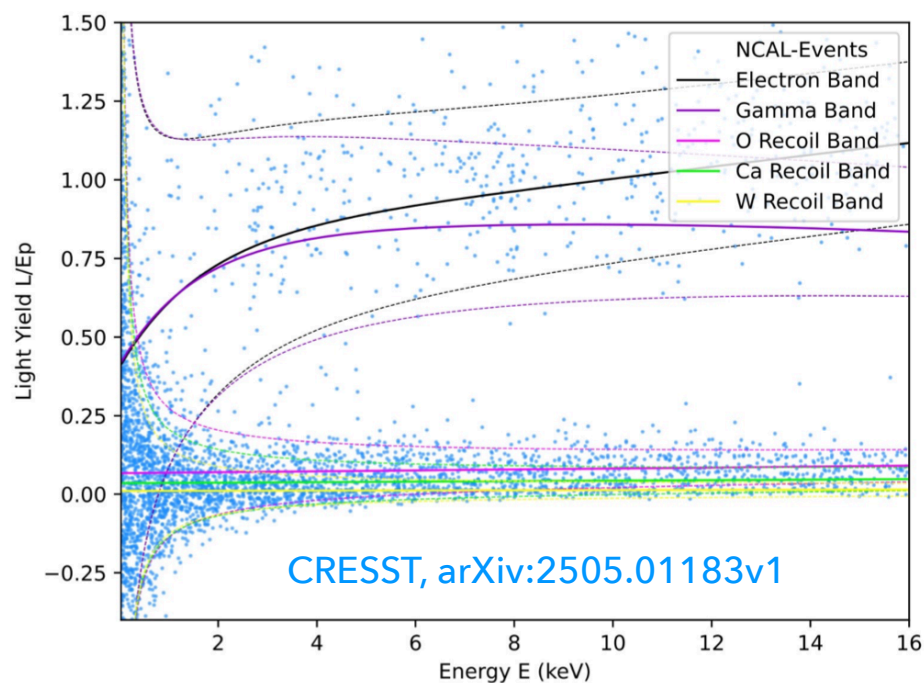
CRESST (Al_2O_3 , CaWO_4 , Si, LiAlO_2)



CRYOSEL (Ge)



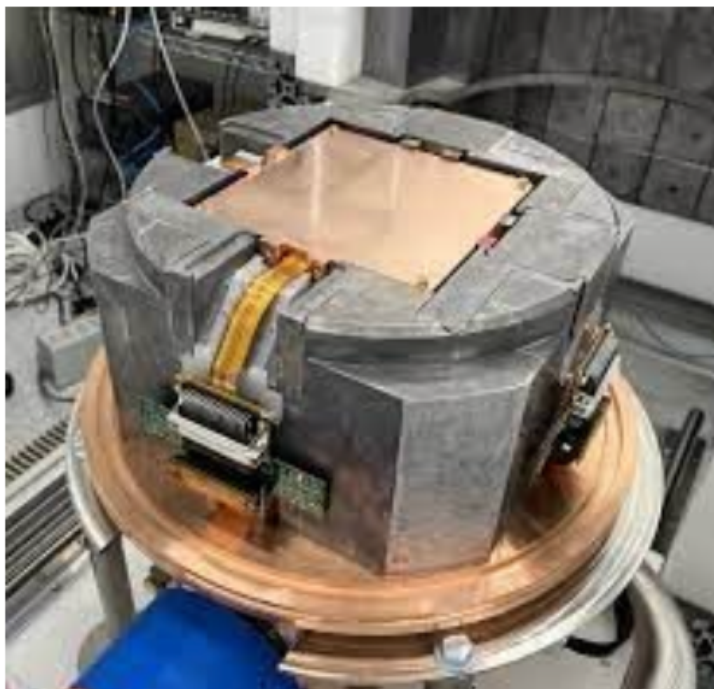
Super-CDMS (Ge, Si)



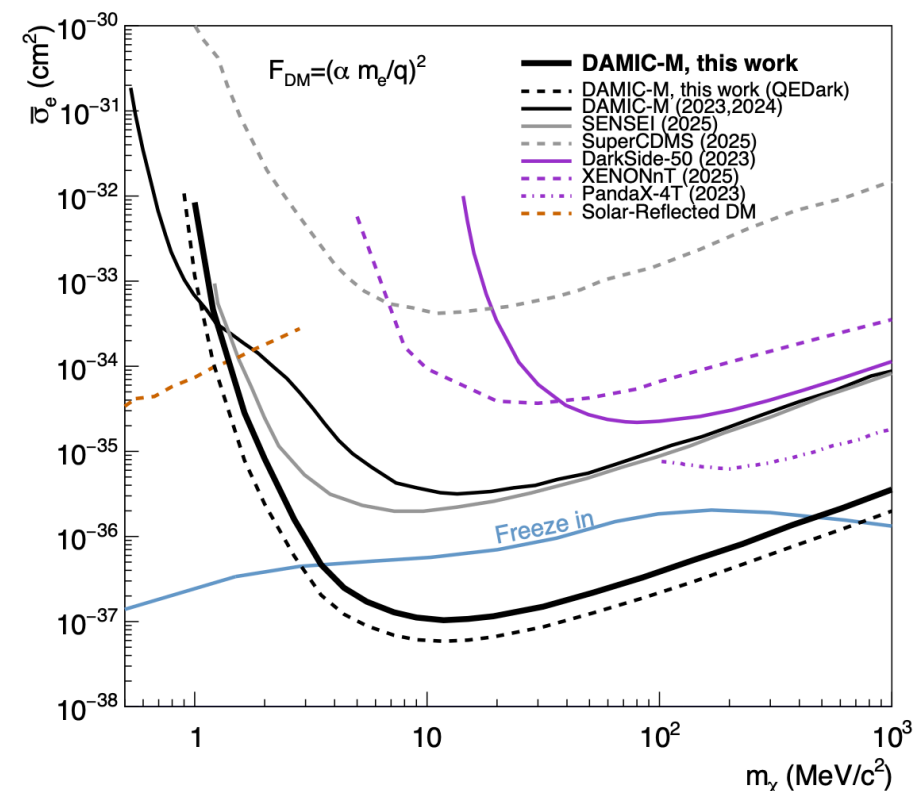
- Sub-keV (< 100 eV) energy thresholds
- Phonons and/or ionisation/light $\Rightarrow$ background discrimination
- Optimised to probe sub-GeV DM
- All see low-energy excess (LEE)

CCDs: SENSEI and DAMIC

- Low ionisation energy, low noise, and particle tracks for background reduction
 $\Rightarrow \sim \text{eV}$ energy thresholds and particle ID
- SENSEI at SNOLAB, DAMIC-M at Modane**; DAMIC-M prototype: 1.3 kg-d exposure at Modane, probes freeze-in scenario
- OSCURA**: next-gen detector 10 kg active, construction planned for SNOLAB



DAMIC-M,
DM-electron
PRL 135, 2025



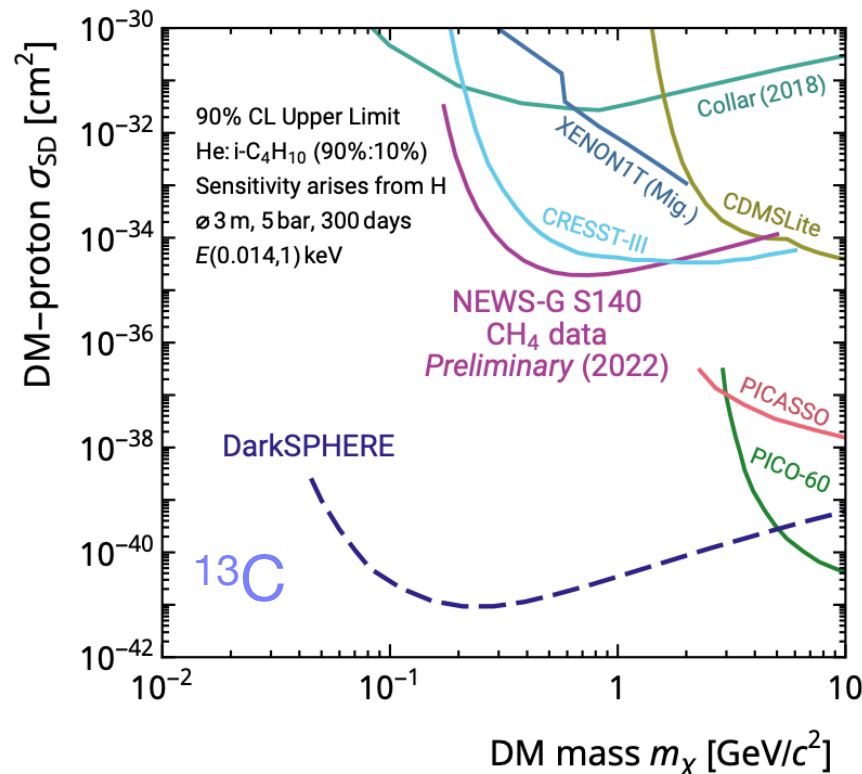
Here for
ultra-
light
mediator

$$F_{\text{DM}} \sim 1/q^2$$

Spherical proportional counters

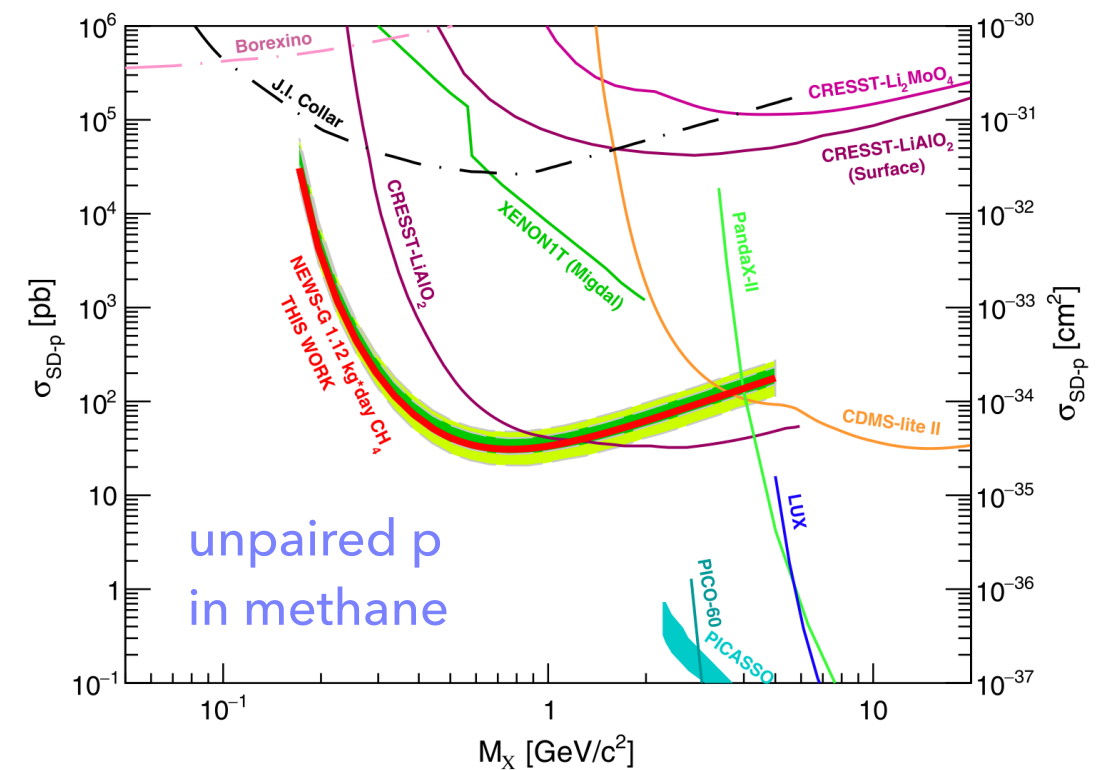
- **NEWS-G**: light targets (H, He, Ne), pulse shape discrimination against surface events, low energy threshold (very low capacitance)
- **S140 (140 cm $\varnothing$ Cu sphere)**: 10 d physics data at Modane, then shipped to SNOLAB, taking data
- DarkSPHERE (**3 m $\varnothing$ Cu sphere**) in preparation for Boulby

Talks by
G. Rogers,
P. Walters



DarkSHPERE SD projections: arXiv:2301.05183

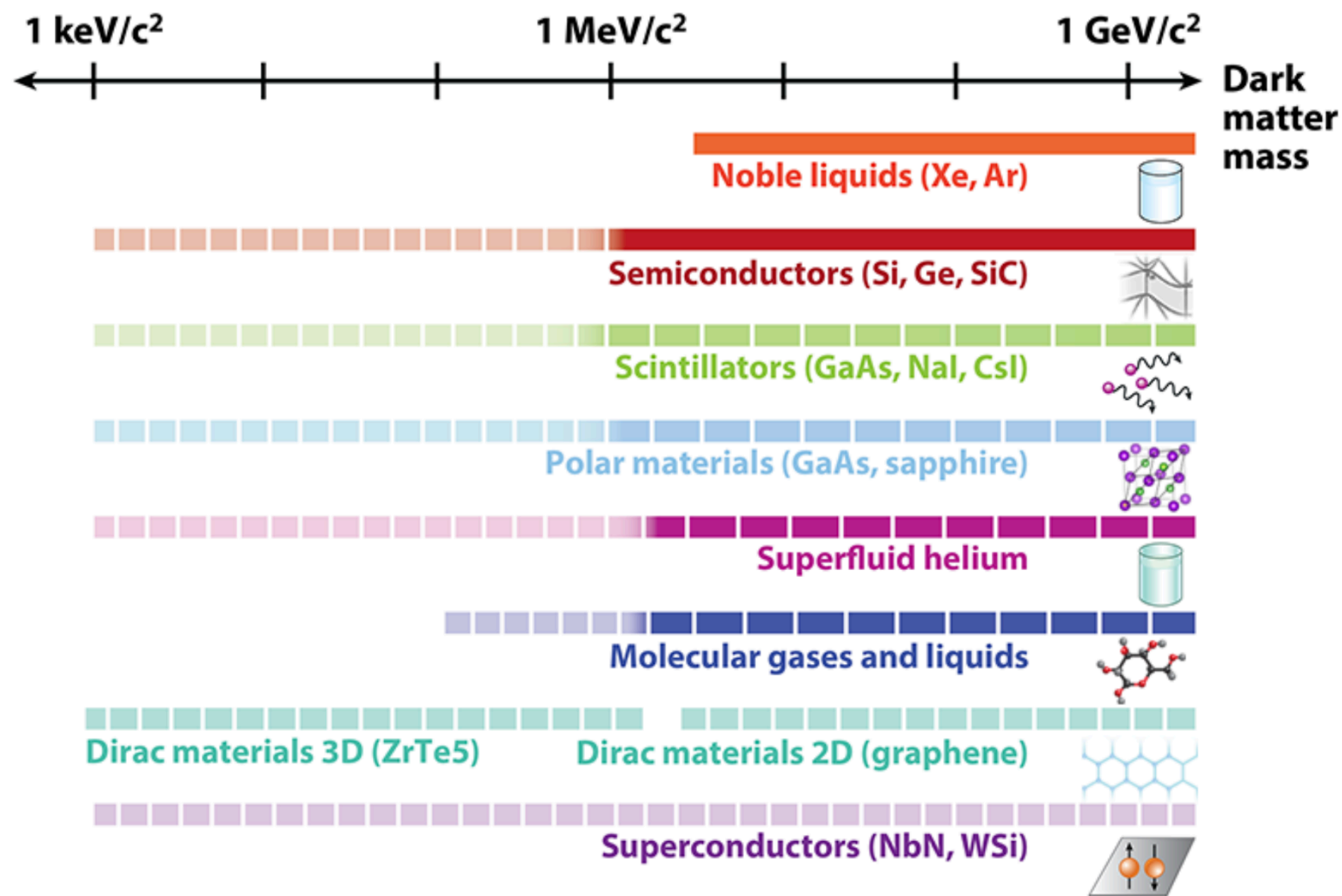
SD limits: PRL 134, 2025



S140 at Modane in its shield

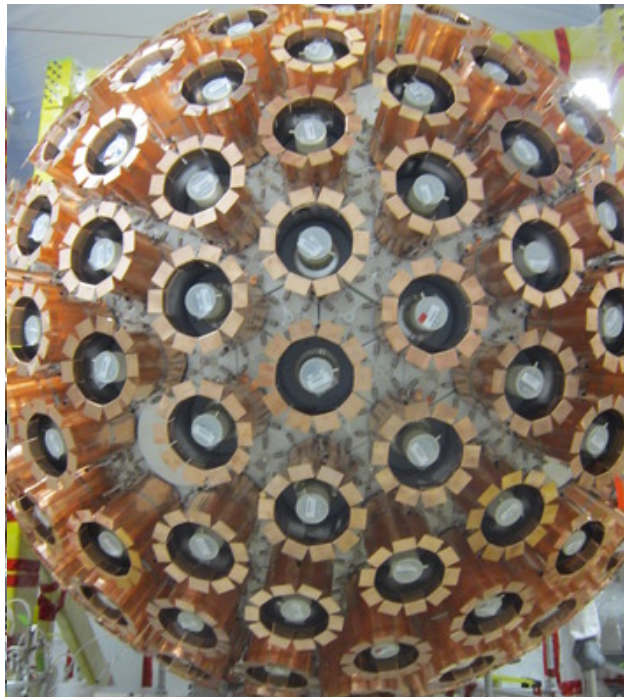
Light DM: existing technologies + many new ideas

See talk by Ashlea Kemp



- Reach energy thresholds at the **eV-scale** (R&D towards meV-scale)
- Exposure less relevant, best constraints for **kg-d or less**
- Particle **discrimination** in general not feasible
- **Low energy excess**: seen by many experiments (not related to particle interactions)

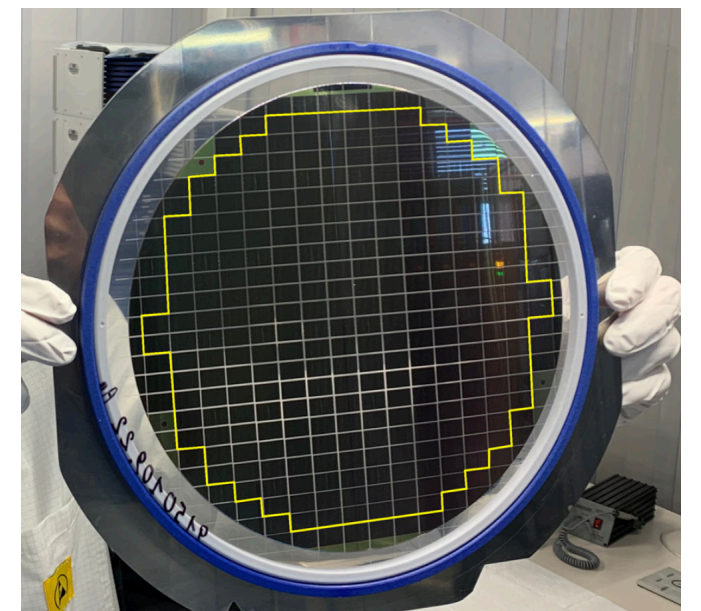
Noble liquids: LAr



DEAP-3600 at SNOLAB



DarkSide-20K at LNGS (Hall C)

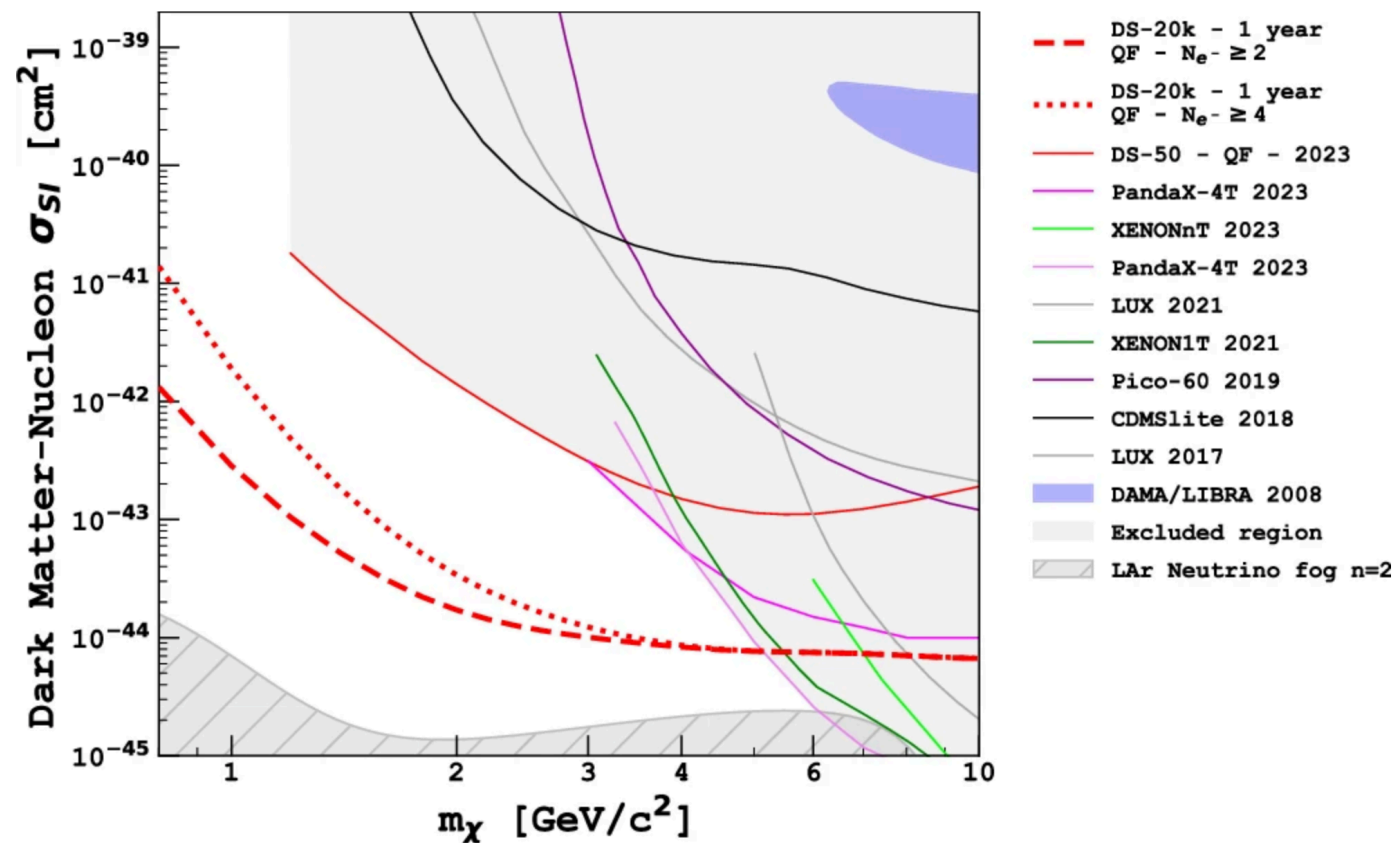


- **DEAP**: detector upgrades finalised, new DM search run in 2025
- **DarkSide-20k**: 50 t underground LAr in TPC with 21 m² cryogenic SiPM arrays
- **PDU**s: DCR < 0.01 Hz/mm² at 77 K, PDE: ~45%, ASIC
- **Under construction**: in Hall C at LNGS

DS collaboration, EPJ-C 85, 2025

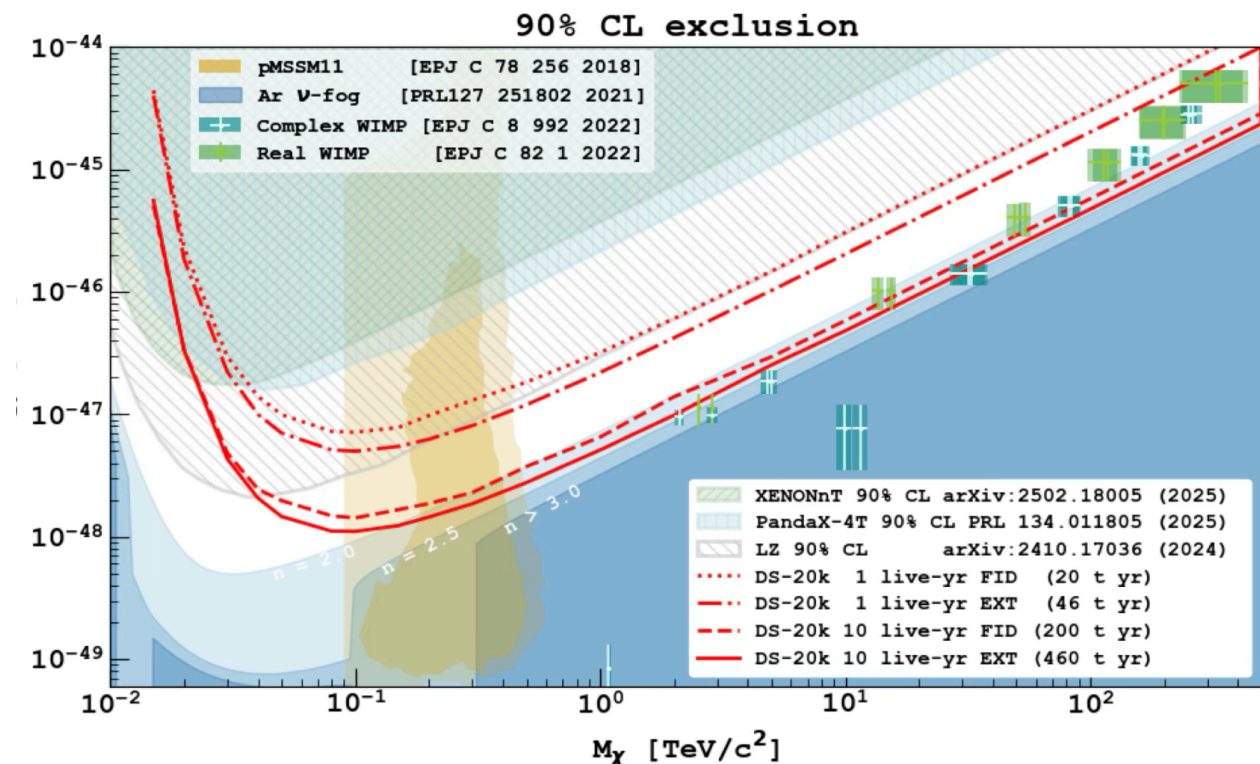
Noble liquids: LAr

Low mass sensitivity



DS collaboration, [Communications Physics 7, 2024](#)

High mass sensitivity

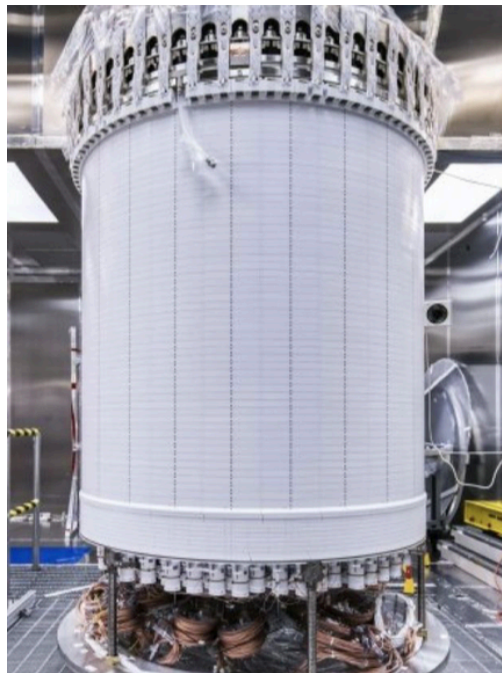


Solid line: 460 t years exposure

- DarkSide-20k: first detector filling: 2027, first data taking in 2028
- Argo: 400 t (300 t fiducial) LAr in single or two-phase, proposed for SNOLAB CubeHall

Noble liquids: LXe

LZ: talks by I.
Darlington, S.
Dave



LUX-ZEPLIN at SURF



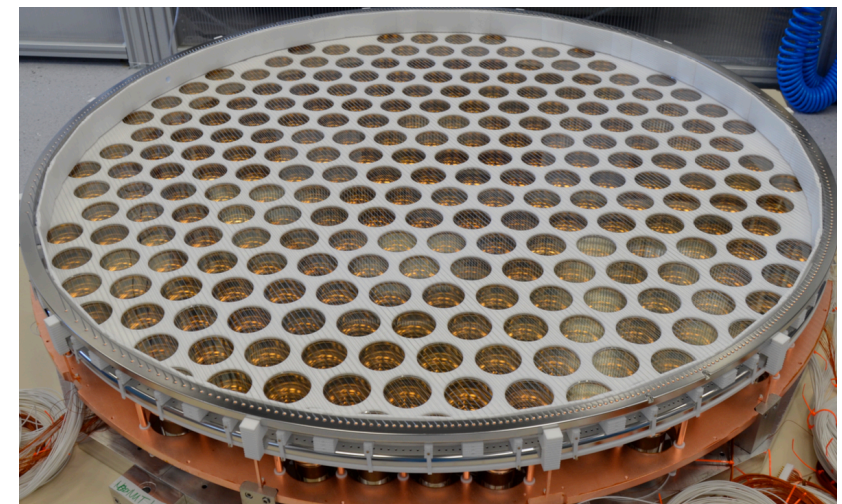
XENONnT at LNGS



PandaX-4T at JingPing

- Existing experiments:

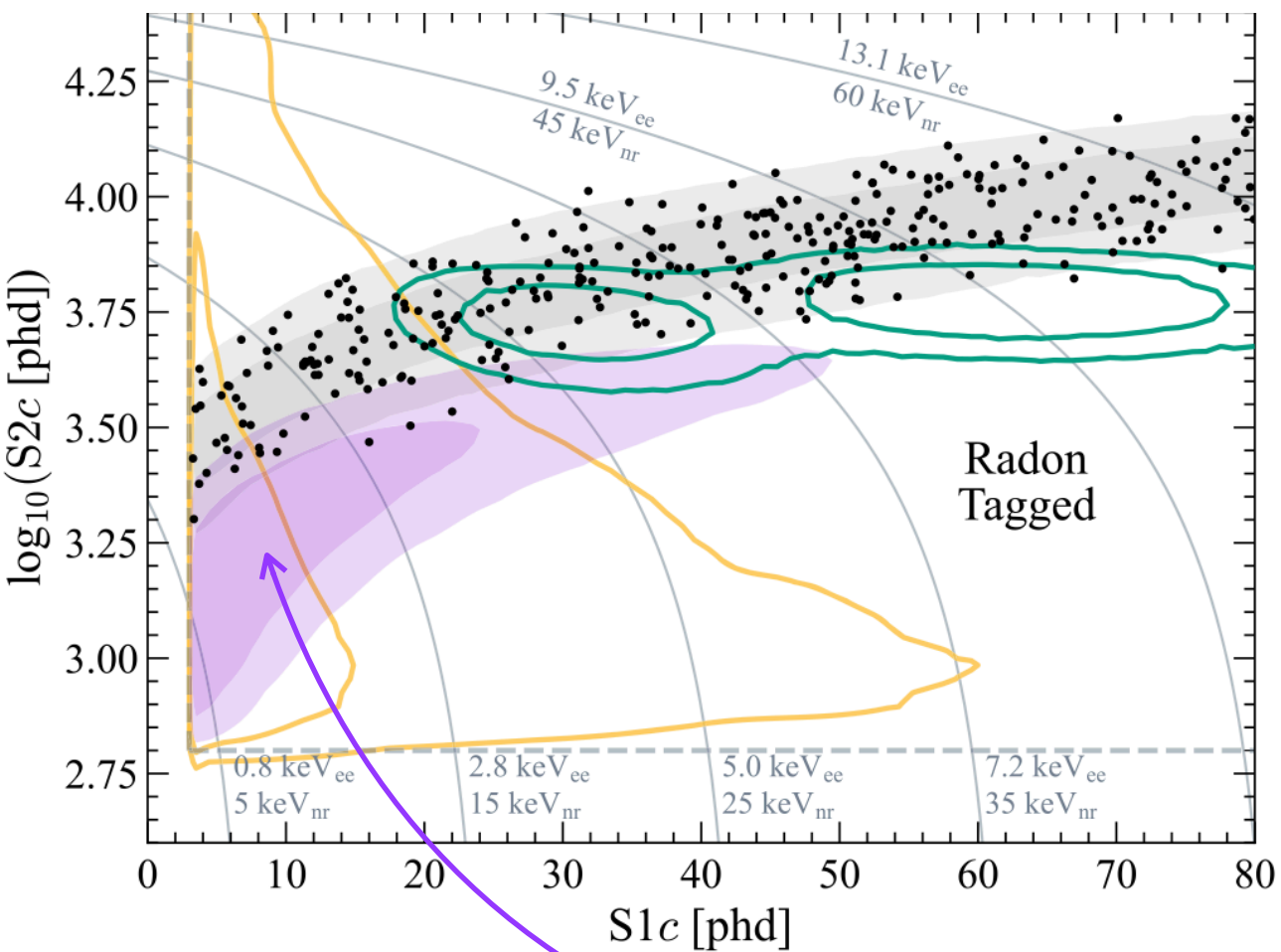
- ▶ TPCs with 2 arrays of 3-inch PMTs
- ▶ Kr and Rn removal techniques
- ▶ Ultra-pure water shields, n & μ vetos



LXe: Recent results

- Distribution of events in $S2$ versus $S1$ space in the TPC

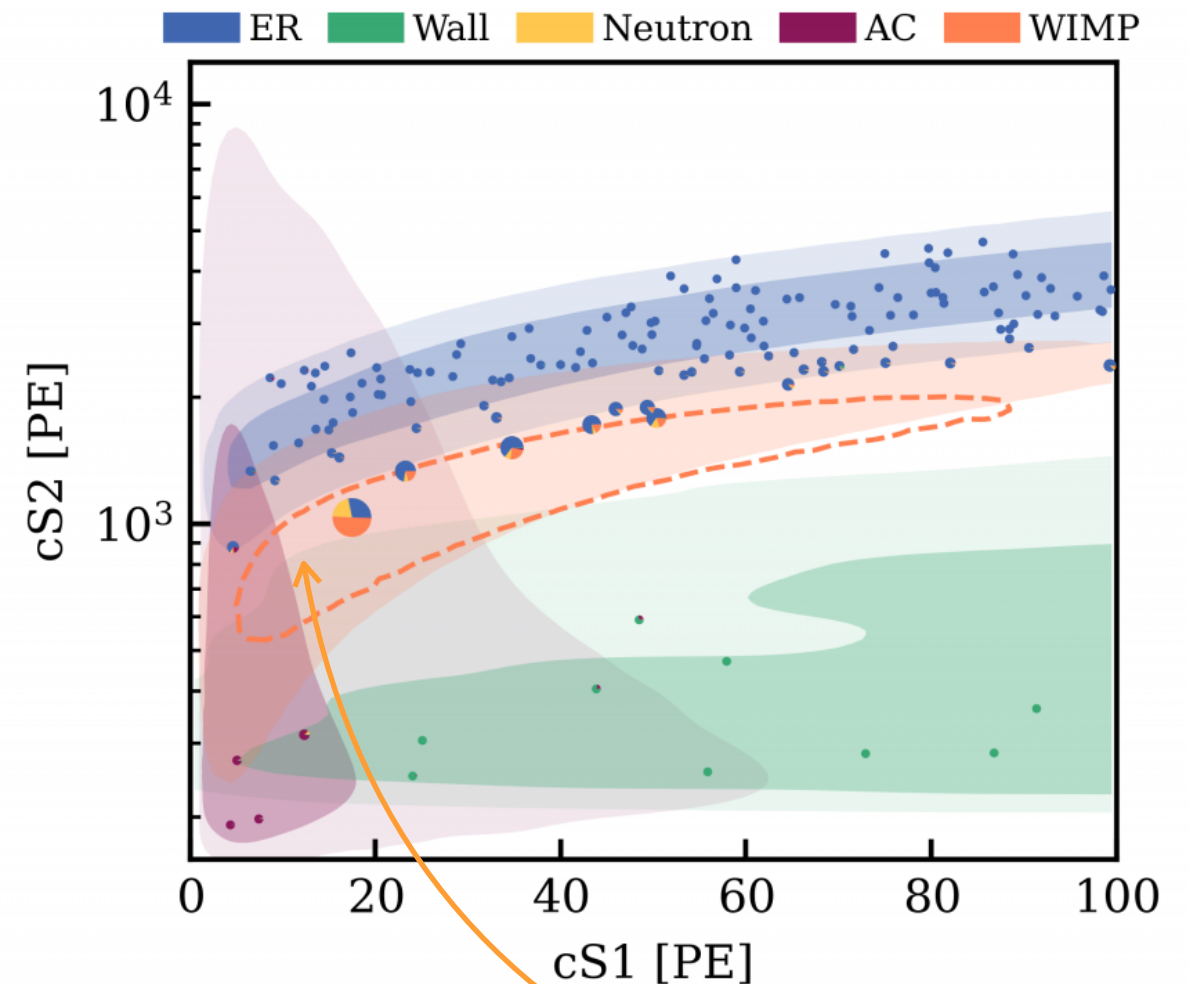
LUX-ZEPLIN



LZ, PRL 135, 2025

2σ contour $40 \text{ GeV}/c^2$ WIMP

XENONnT



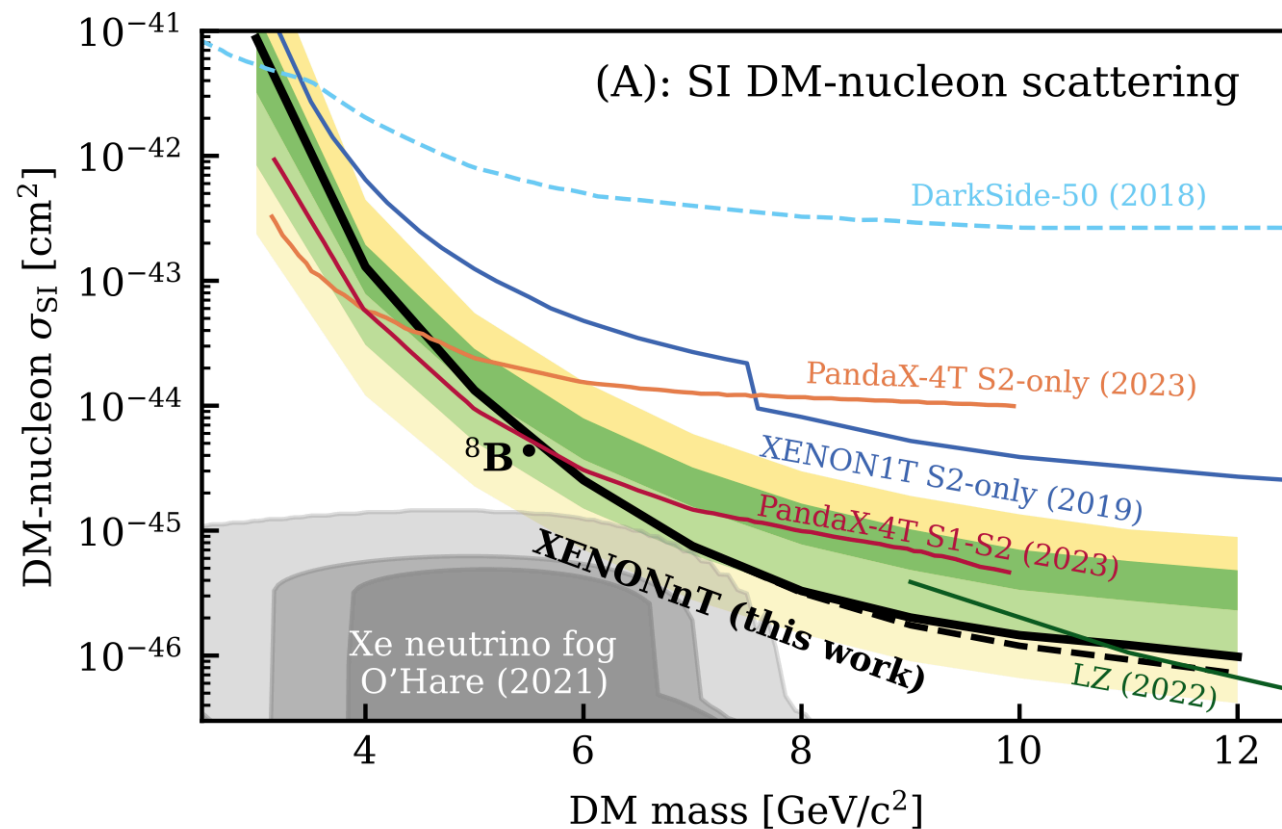
XENON PRL 131, 2023

2σ contour $200 \text{ GeV}/c^2$ WIMP

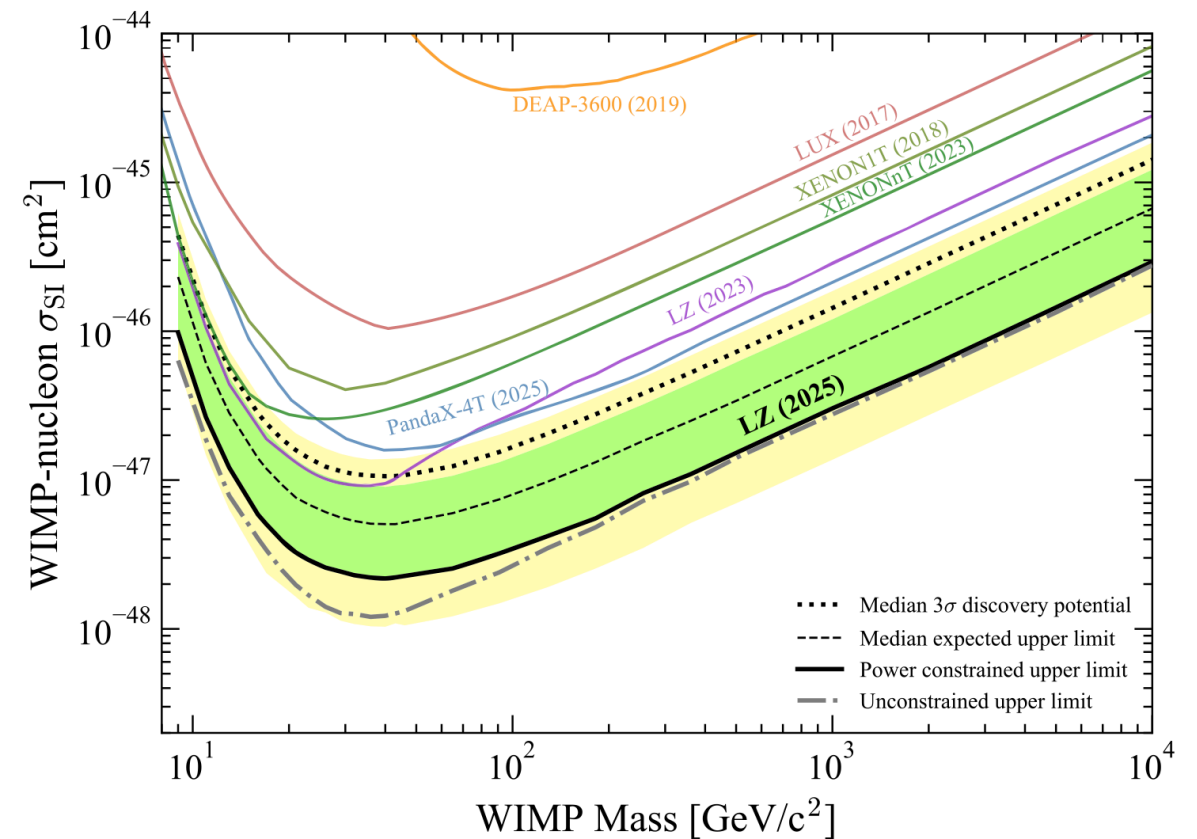
Recent results: DM-Nucleus

- DM mass range: ~ **3 GeV - 10 TeV**

XENONnT PRL 134, 2025



LUX-ZEPLIN PRL 135, 2025



EDITORS' SUGGESTION | OPEN ACCESS

First Search for Light Dark Matter in the Neutrino Fog with XENONnT

FEATURED IN PHYSICS | EDITORS' SUGGESTION | OPEN ACCESS

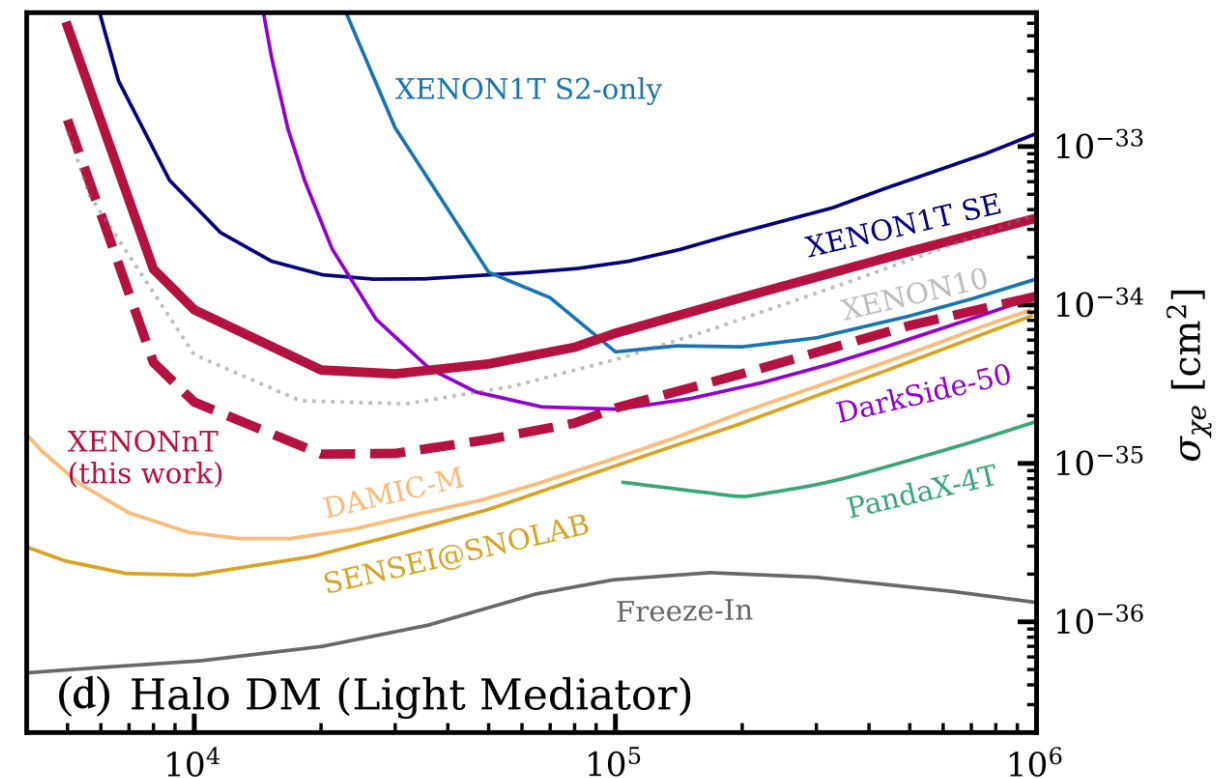
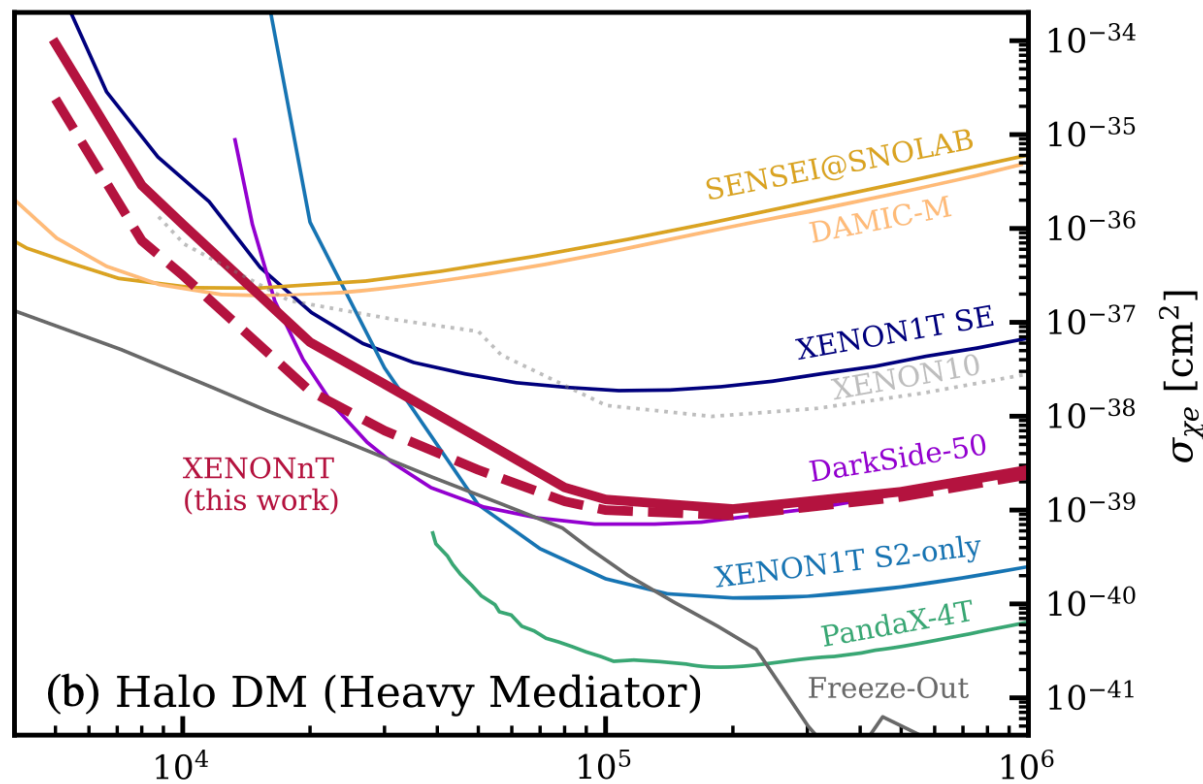
Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment

Recent results: DM-Electron

- DM mass range: ~ **5 MeV - 1 GeV**

$$F_{DM} = 1$$

$$F_{DM} \propto \frac{1}{q^2}$$



PandaX-4T, PRL 130, 2023, XENONnT, PRL 134, 2025

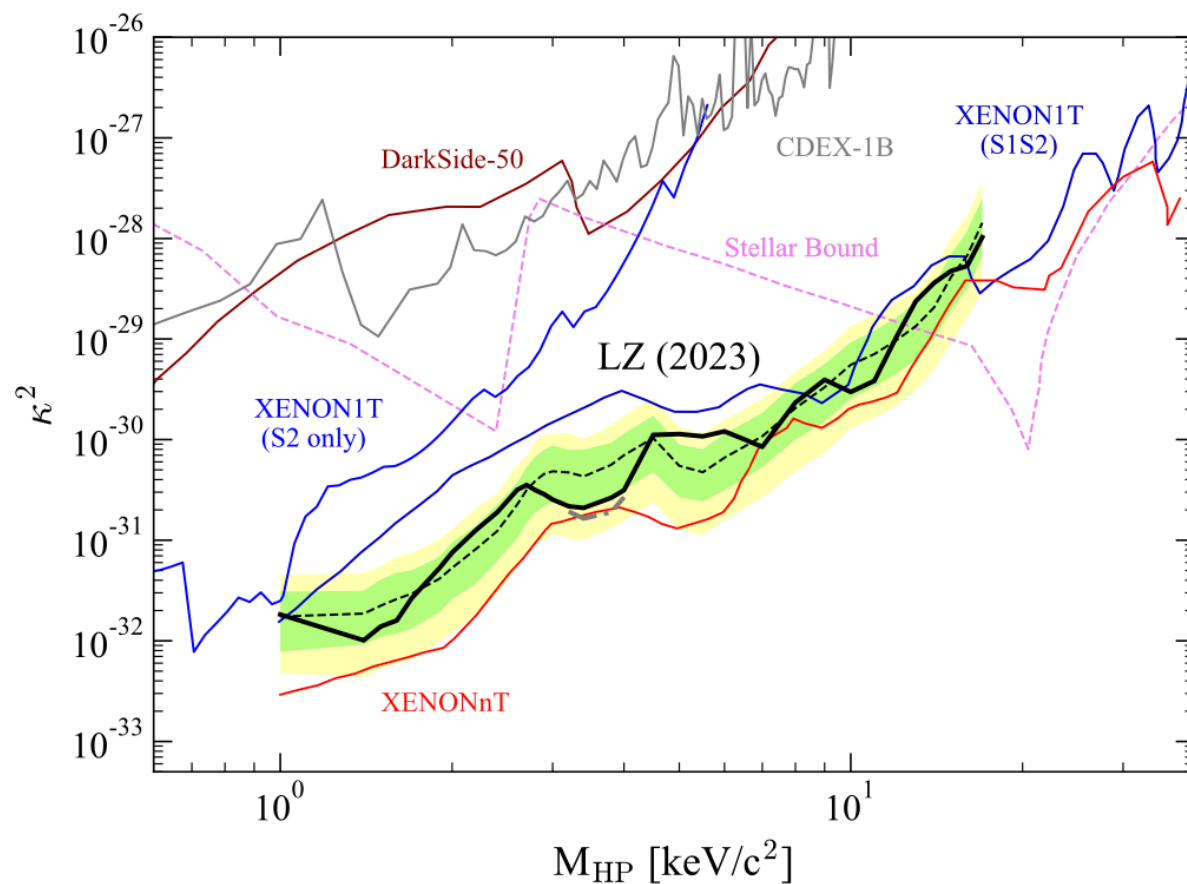
Heavy dark photon A' mediator

Ultra-light dark photon A' mediator

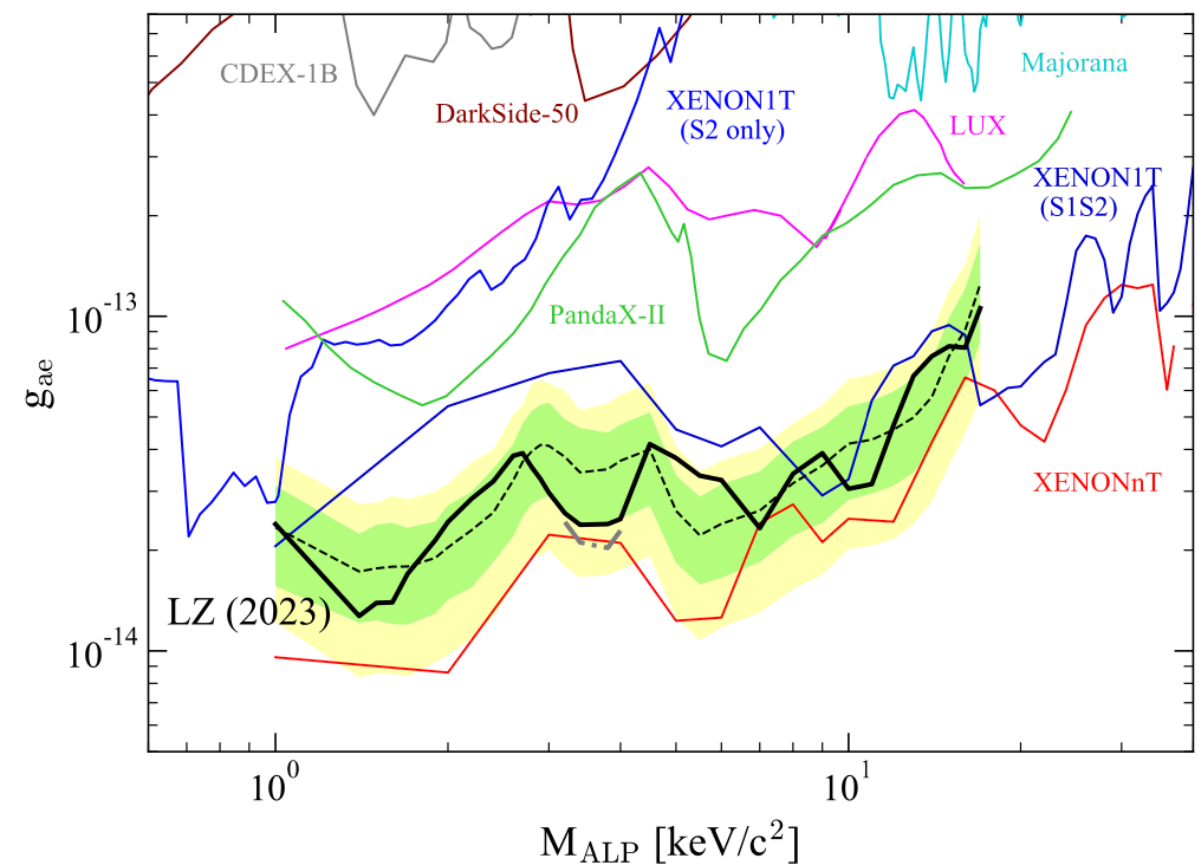
Recent results: DM Absorption

- DM mass range: ~ **0.5 keV - 100 keV**

Dark photons



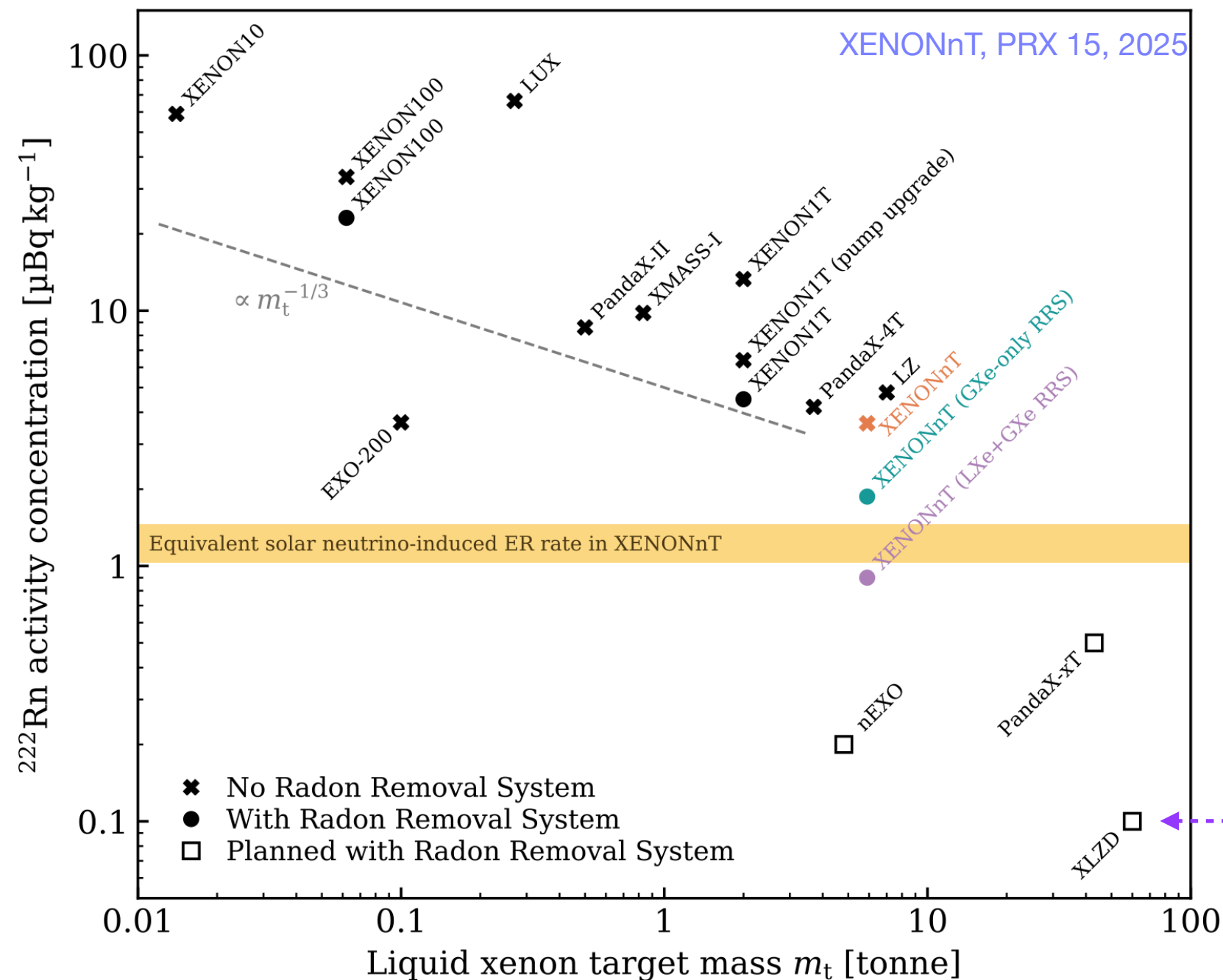
Axion like particles



XENONnT: PRL 129, 2022; LZ: PRD 108, 2023

Backgrounds

- Dominated by **electronic recoils from ^{222}Rn decays** in the LXe



**Solar pp- ν
equivalent rate**

Goal for XLZD

Other searches with LXe detectors

- *pp and ${}^7\text{Be}$ solar neutrinos

- *solar axions

- * $\beta\beta$ -decay ${}^{136}\text{Xe}$ ($Q_{\beta\beta} = 2.46 \text{ MeV}$)

- *DEC, $\text{EC}\beta^+$ -decay ${}^{124}\text{Xe}$ ($Q_{\text{DEC}} = 2.86 \text{ MeV}$)

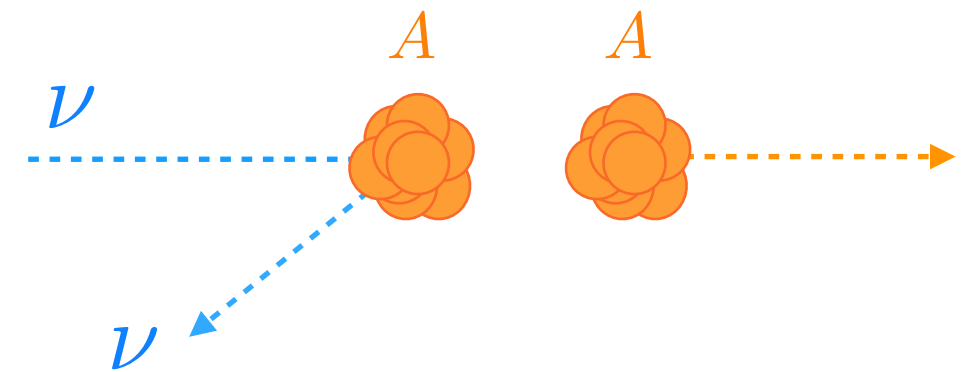
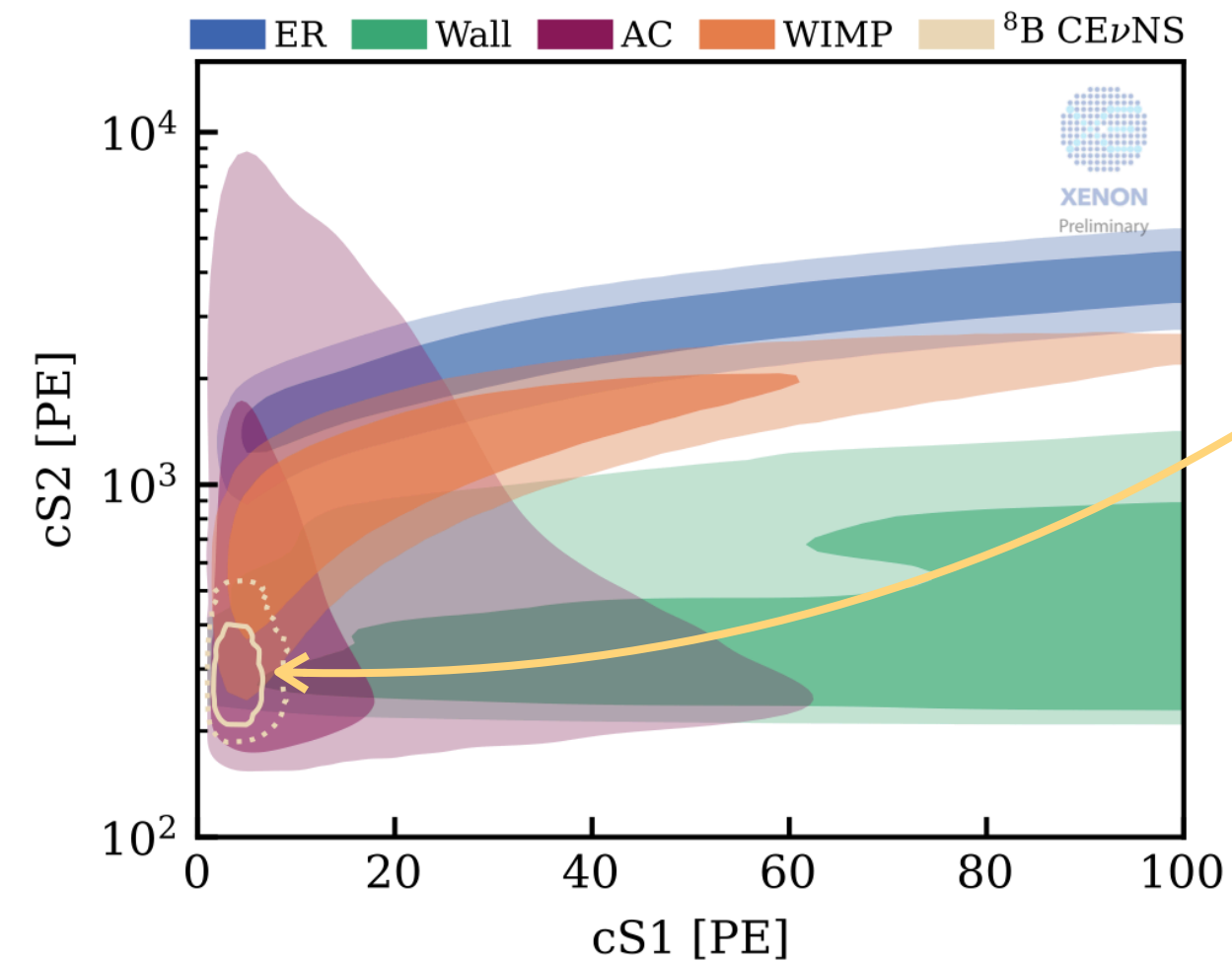
- * ${}^8\text{B}$ solar neutrinos

- *SN neutrinos

- *inelastic DM

- *EFT DM models

Solar neutrinos: ν -Nucleus Scattering

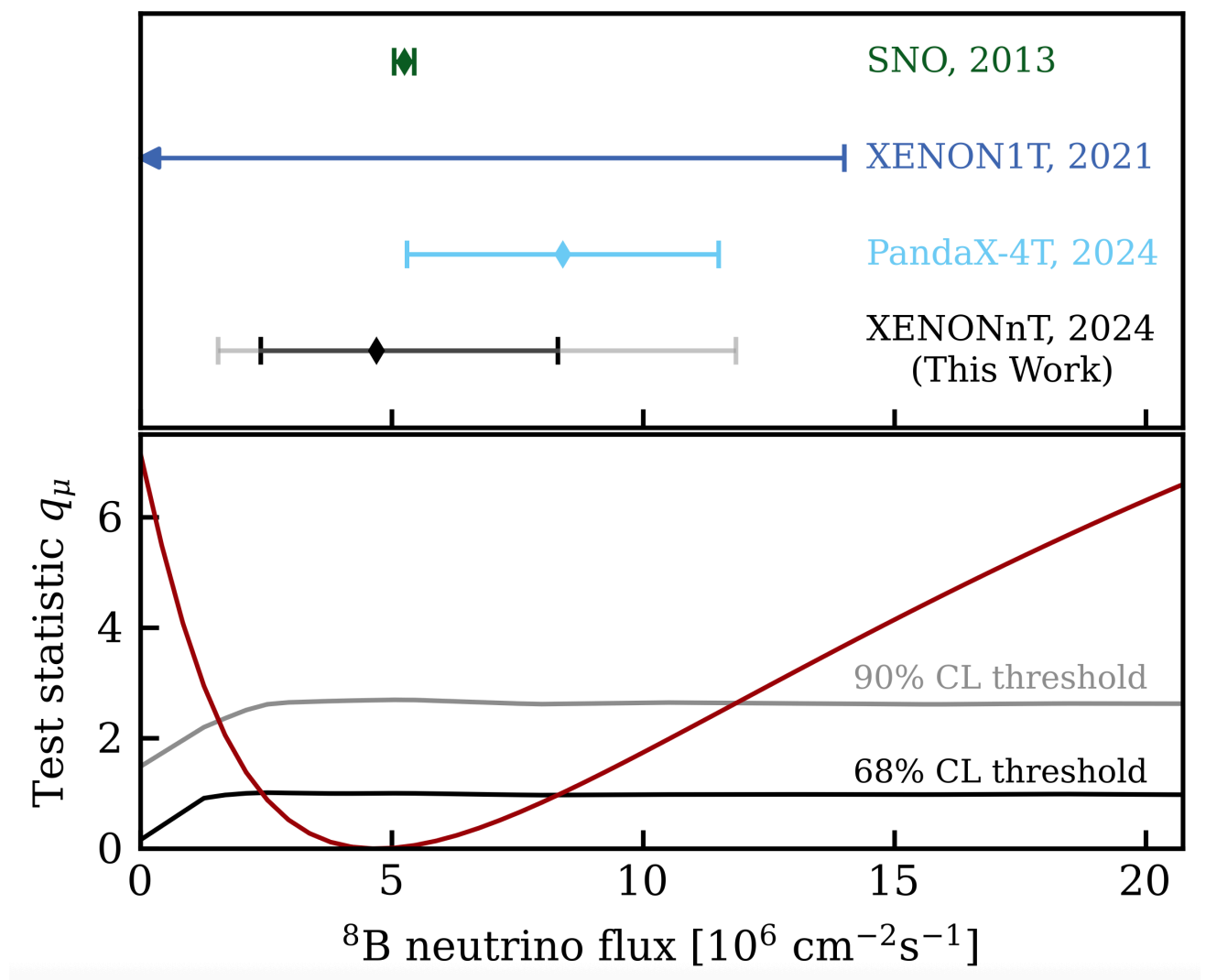
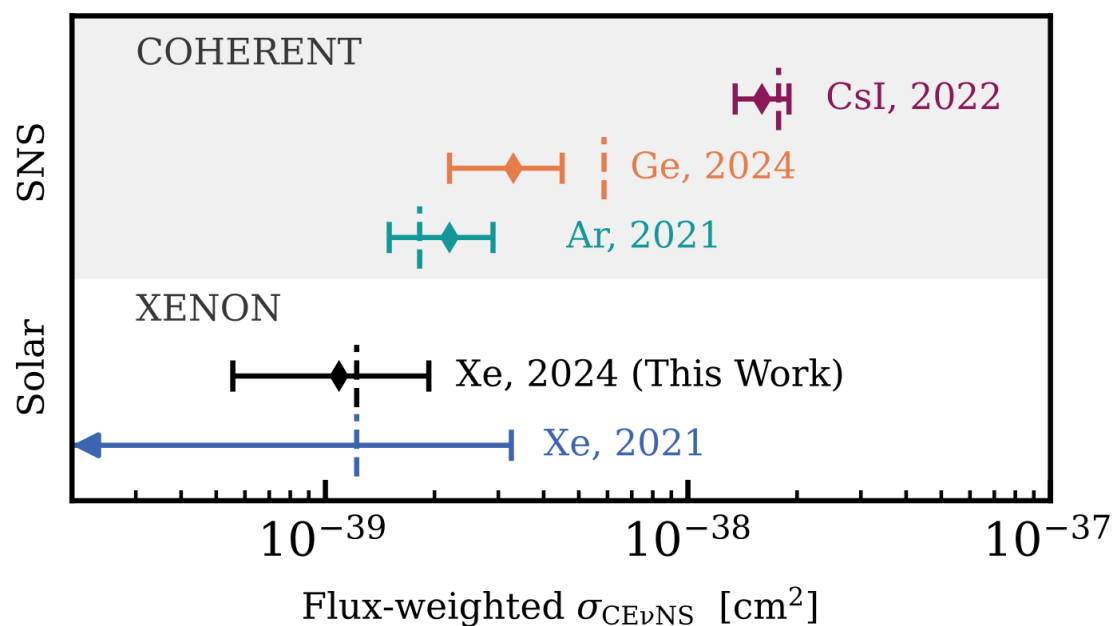


$$\nu_x + A \rightarrow \nu_x + A$$

- * Complementary measurements to experiments using CC reactions
- * "Flavour democratic" (C. Lunardi, Neutrino-2024)

Solar neutrinos: ν -Nucleus Scattering

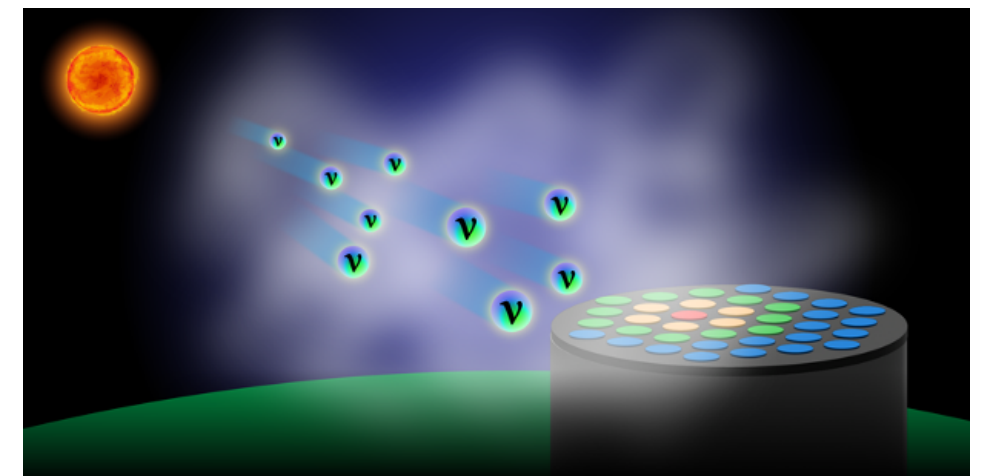
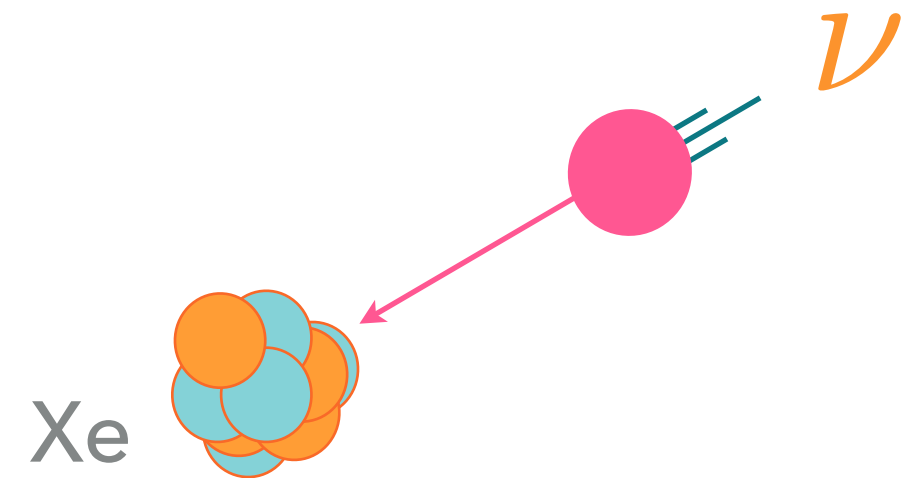
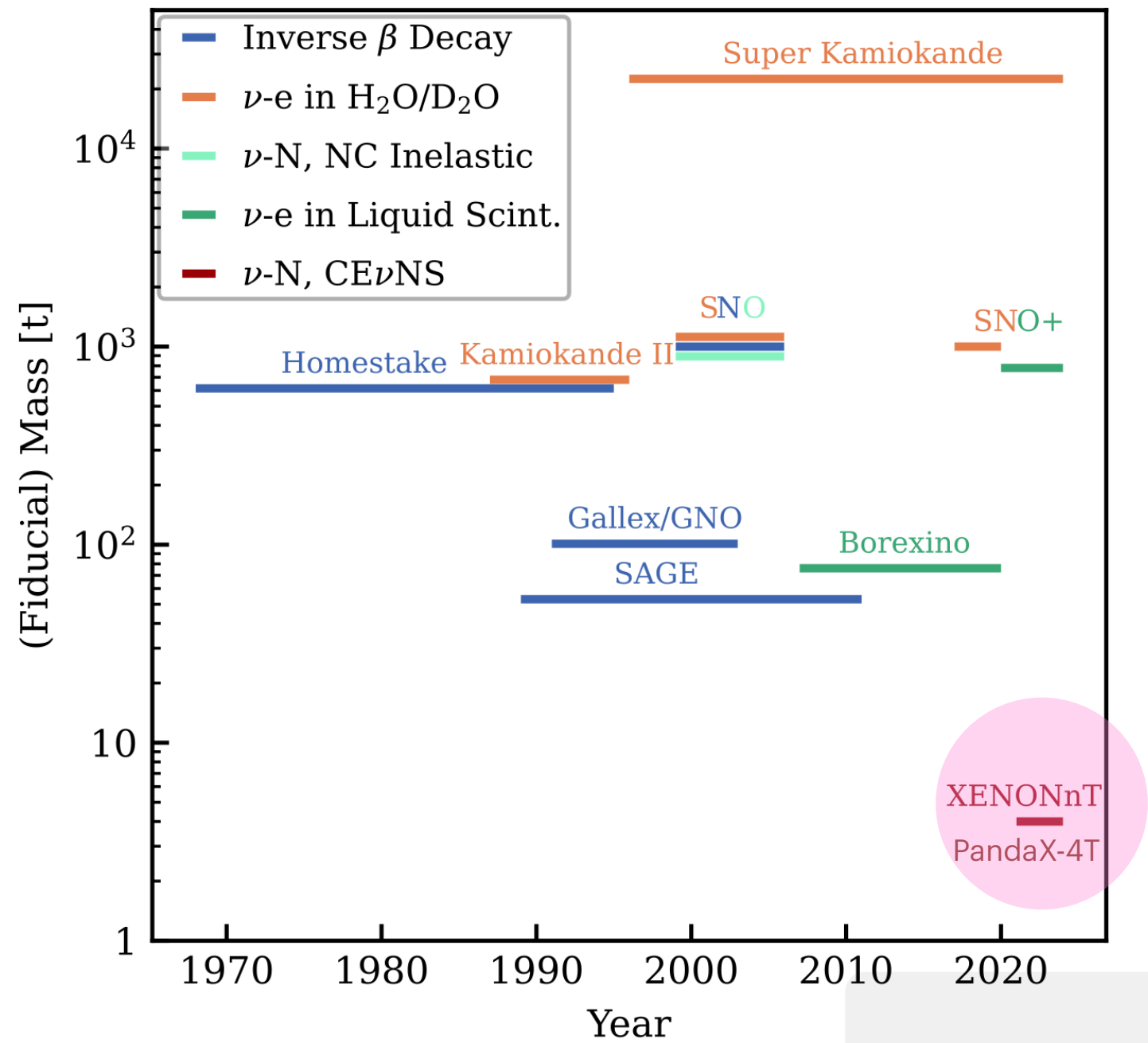
- First detection of elastic NRs from astrophysical ν 's
- First measurement of CEvNS process with Xe targets
- First step into the “neutrino fog” by DM experiments



XENONnT: PRL 123, 2024

PandaX-4T: PRL 123, 2024

Very small solar ν detectors



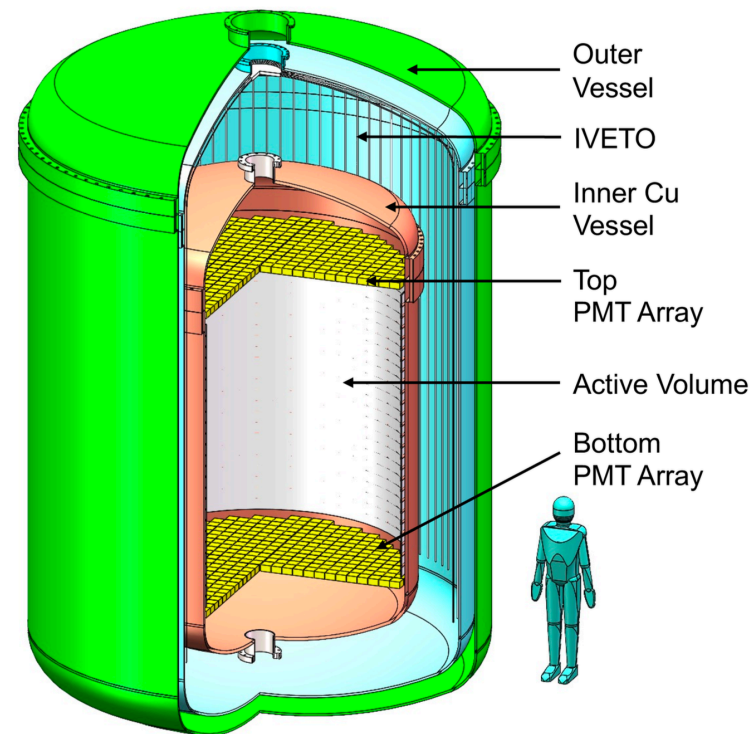
Future LXe experiments

XLZD (XENON-
LZ-DARWIN)

PandaX-20T
PandaX-40T

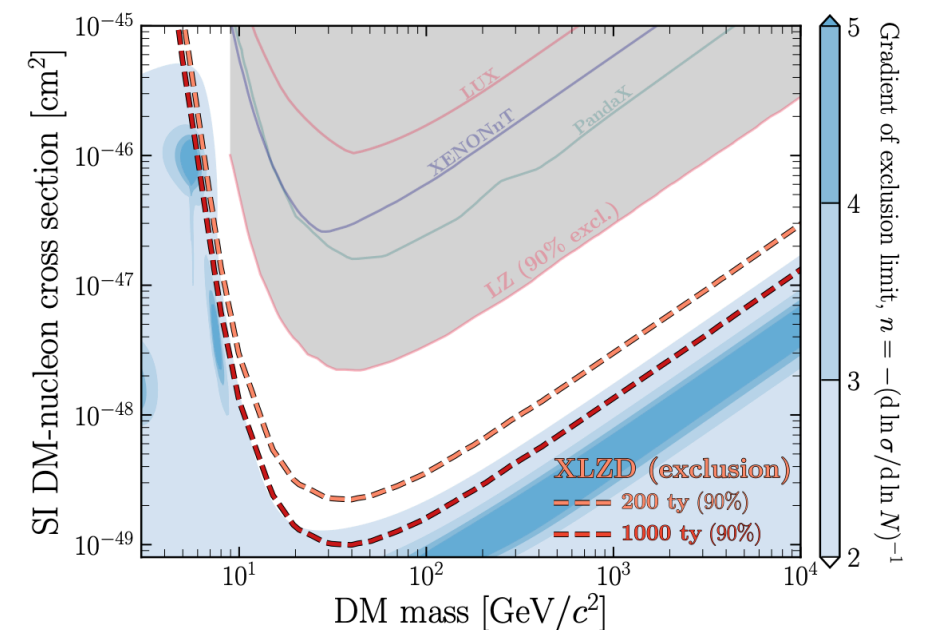
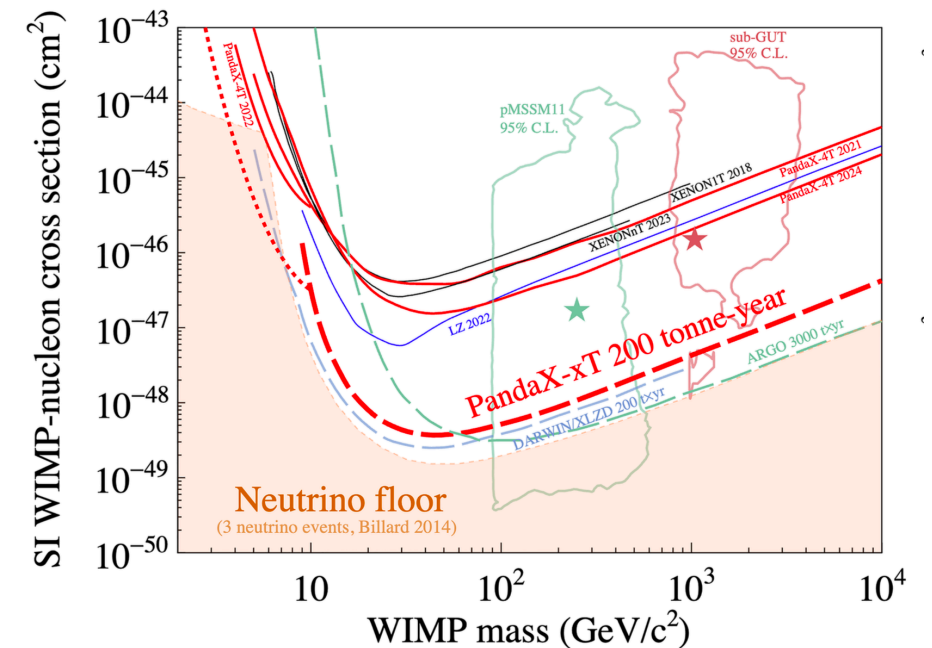


78 t LXe (60 t
active target)



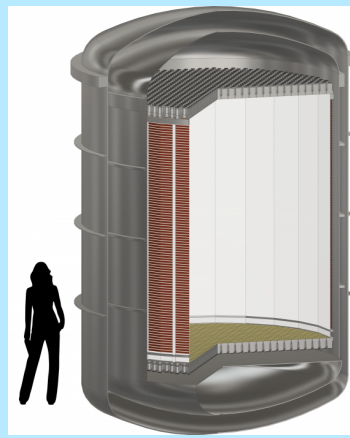
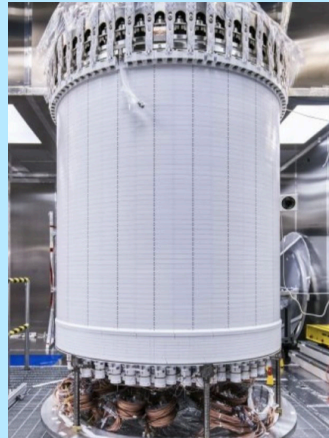
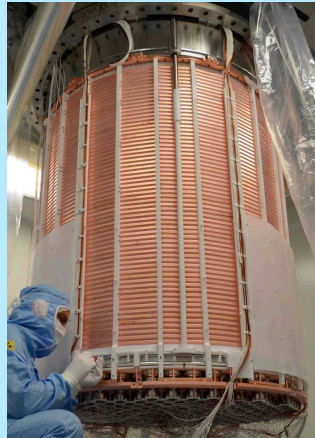
20 t and 40 t LXe in
total; 20 t in 2027,
mostly funded

PandaX-xT: SCPMN 68, 2025



XLZD, arXiv: 2410.17137

XLZD



~450 members

79 institutions

17 countries

xlzd.org

Talks by H. Araujo, R.
Matheson, H. Zhang

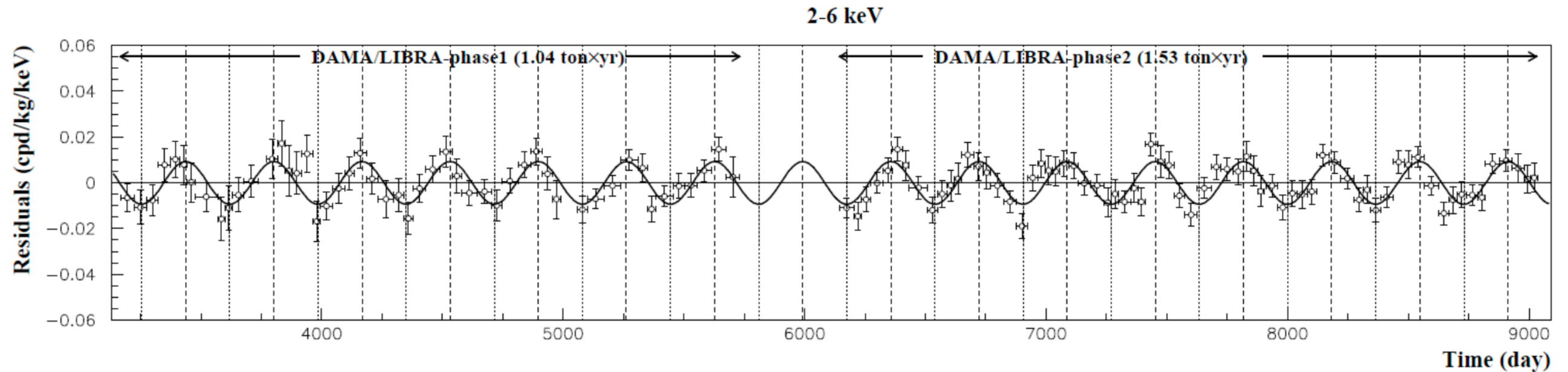


Collaboration meeting at
LNGS, July 2025

☉ Design Book: [2410.17137](https://arxiv.org/abs/2410.17137) (accepted in EPJ-C)

Nal experiments

> 13 σ stat significance, R. Bernabei et al., Nucl. Phys. At. Energy 22 (2021) 329-342

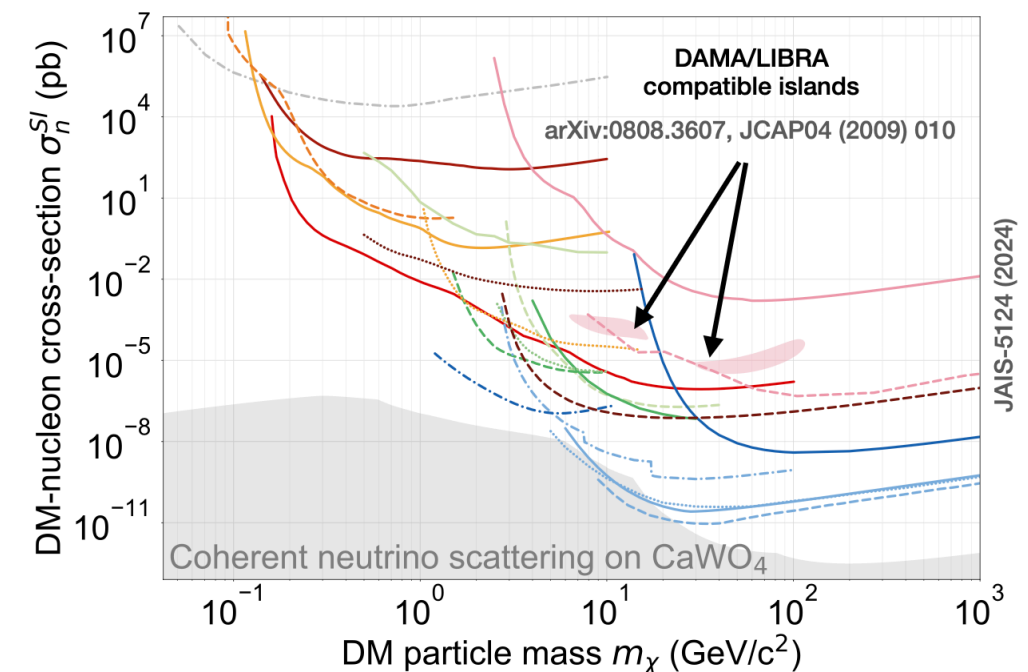


- Test DAMA/LIBRA annual modulation signal with NaI(Tl)
- **No evidence for annual modulation** from ANAIS-112 (6 y of data, 626 kg y, ongoing) and COSINE-100 (6 y of data, $E_{th}=0.7$ keV, concluded in March 2023)
- **Combined ANAIS and COSINE analysis:** arXiv:2503.19559
- **In construction:** COSINUS, SABRE and COSINE-200

ANAIS: PRL 135, 2025, COSINE-100: 2501.13665

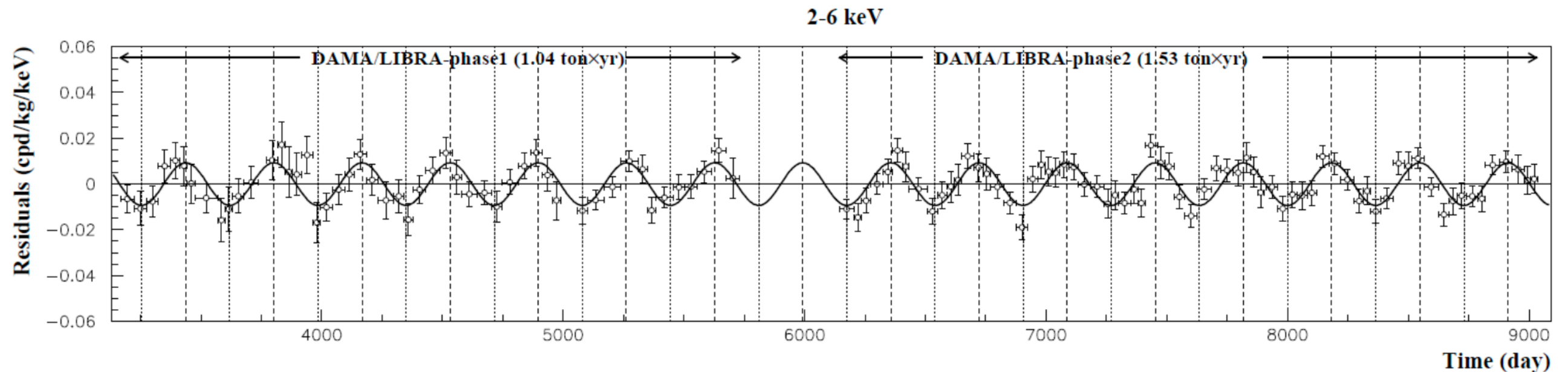
Combined analysis: PRL 135, 2025, 12

P. Schreiner, Santander June 2025



Nal experiments

> 13 σ stat significance, R. Bernabei et al., Nucl. Phys. At. Energy 22 (2021) 329-342

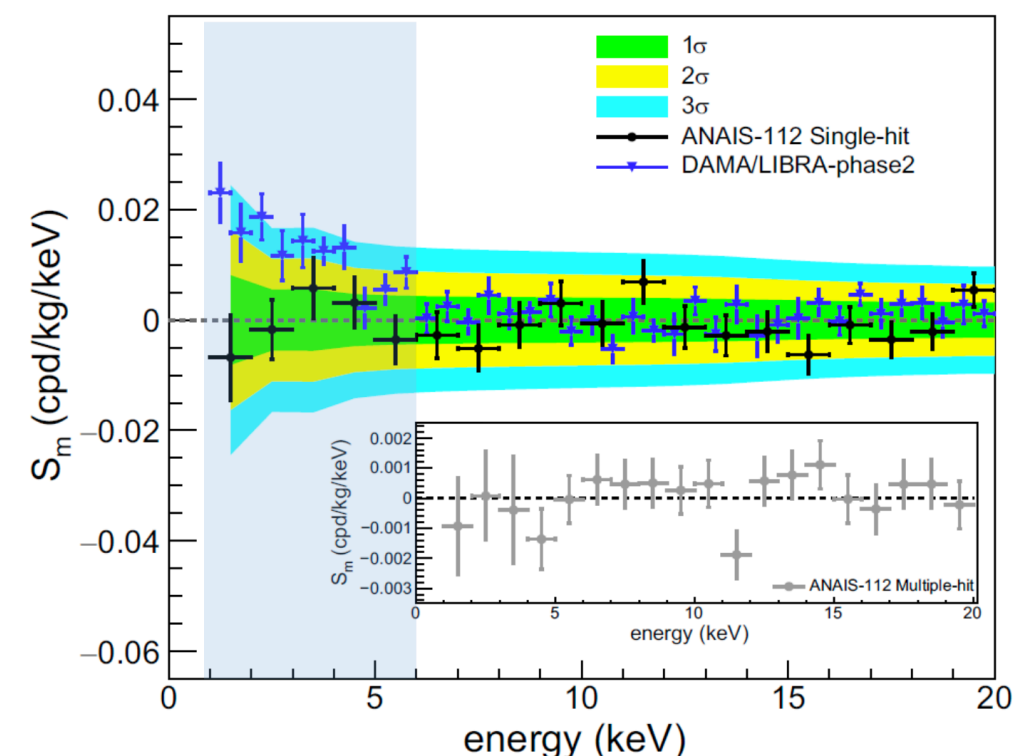


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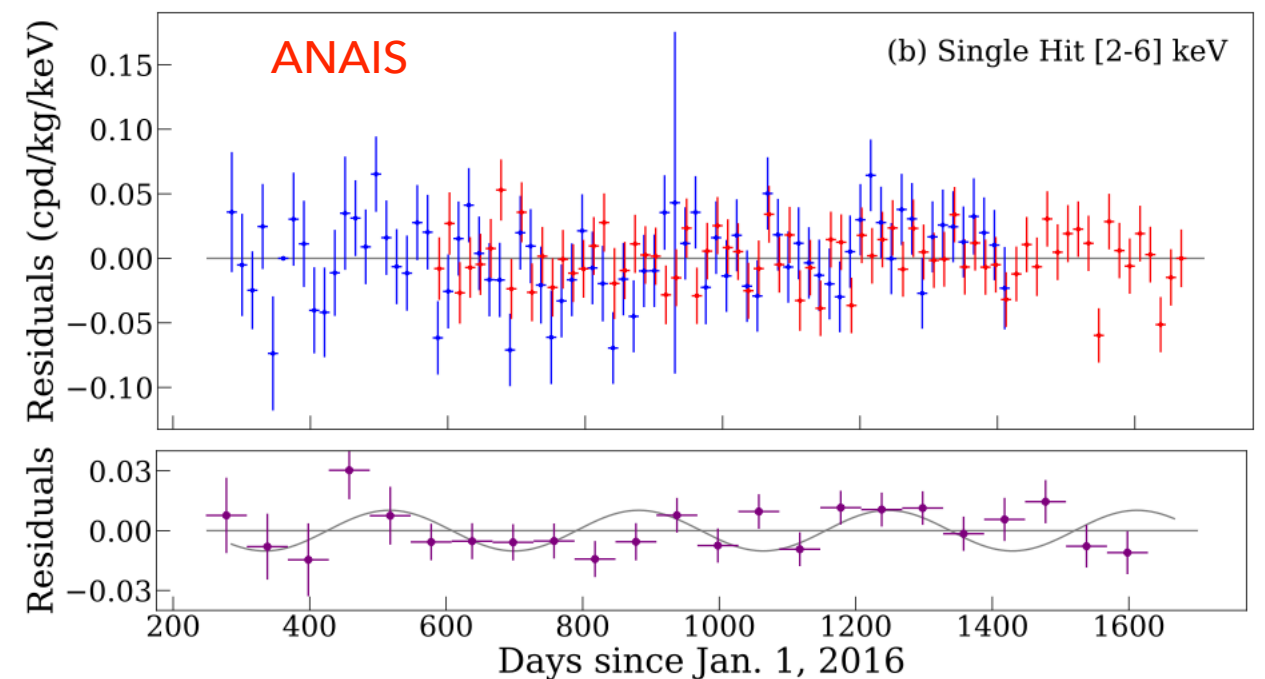
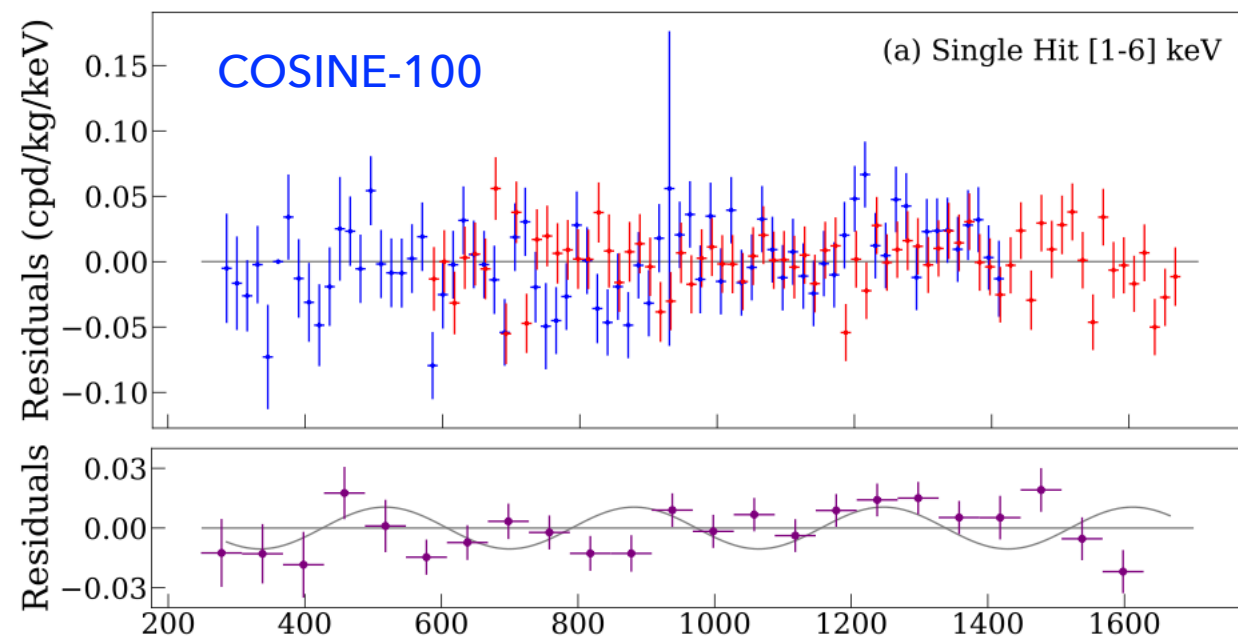
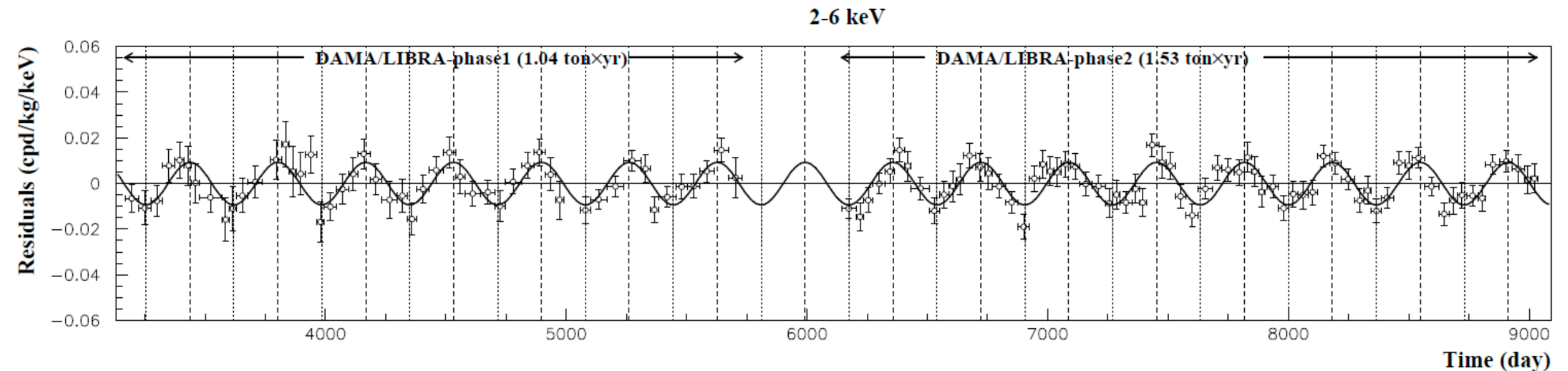
Combined analysis: PRL 135, 2025, 12

ANAIS: PRL 125, 2025



Nal experiments

> 13 σ stat significance, R. Bernabei et al., Nucl. Phys. At. Energy 22 (2021) 329-342

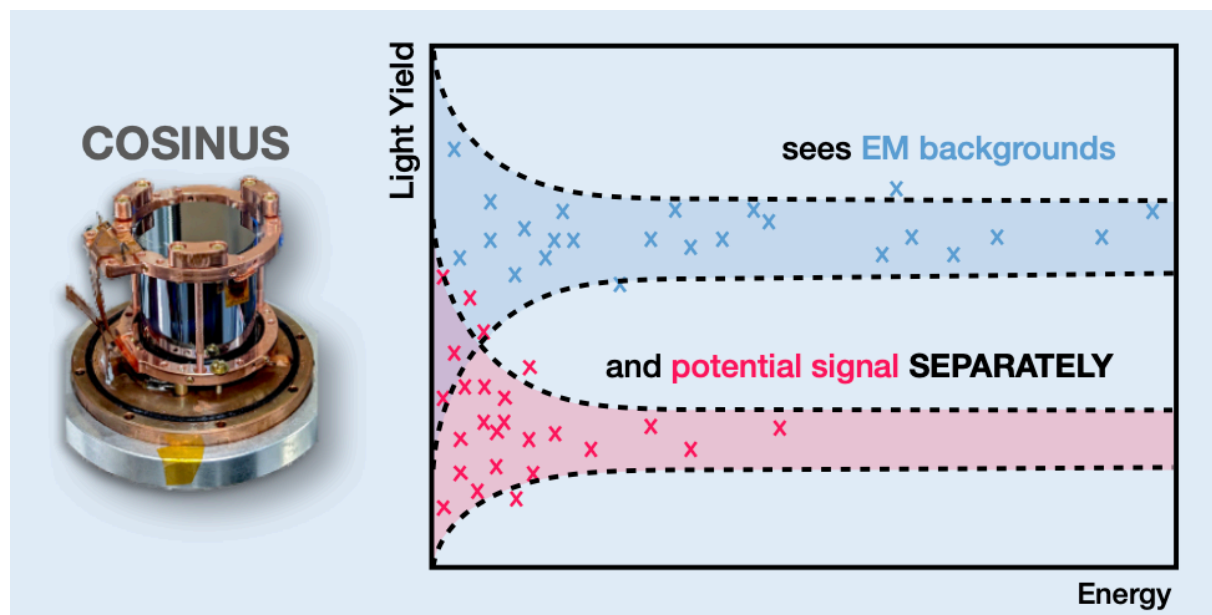
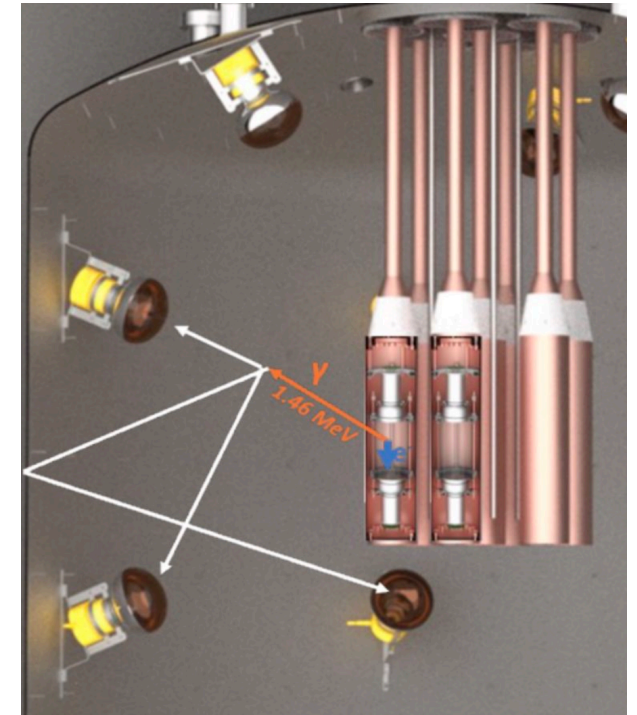


Combined analysis: PRL 135, 2025, 12

Nal experiments

- **SABRE** at LNGS & SUPL: ultra-pure NaI powder; active shield; finish installation end of 2027 & 2025, reach 5σ in two years
- **COSINE-200** at Yemilab: in-house crystal growing, improved light yields; 0.2 dru backgrounds; move to Yemilab in progress
- **COSINUS** at LNGS: detects also phonons in un-doped NaI (apart from scintillation) at few mK, for active background rejection; first data expected by end of 2025

SABRE South at SUPL



COSINUS at LNGS

Nal experiments

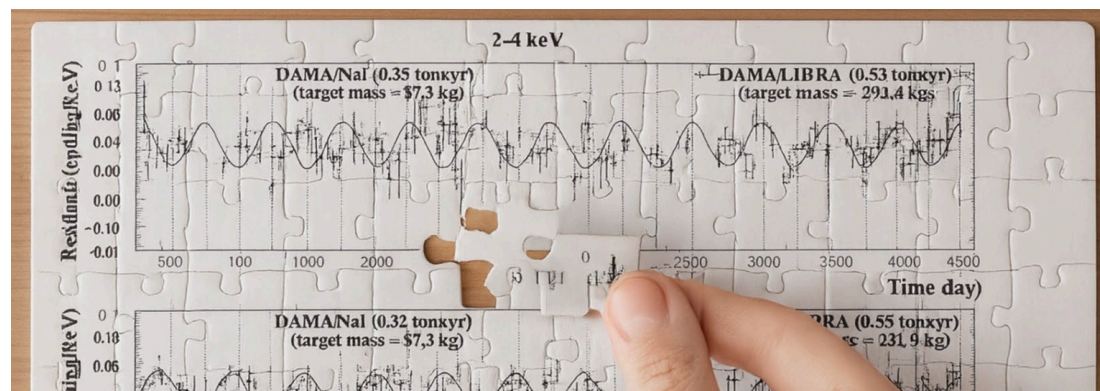
- **SABRE** at LNGS & SUPL: ultra-pure NaI powder; active shield; finish installation end of 2027 & 2025, reach 5σ in two years
- **COSINE-200** at Yemilab: in-house crystal growing, improved light yields; 0.2 dru backgrounds; move to Yemilab in progress
- **COSINUS** at LNGS: detects also phonons in un-doped NaI (apart from scintillation) at few mK, for active background rejection; first data expected by end of 2025

In addition:

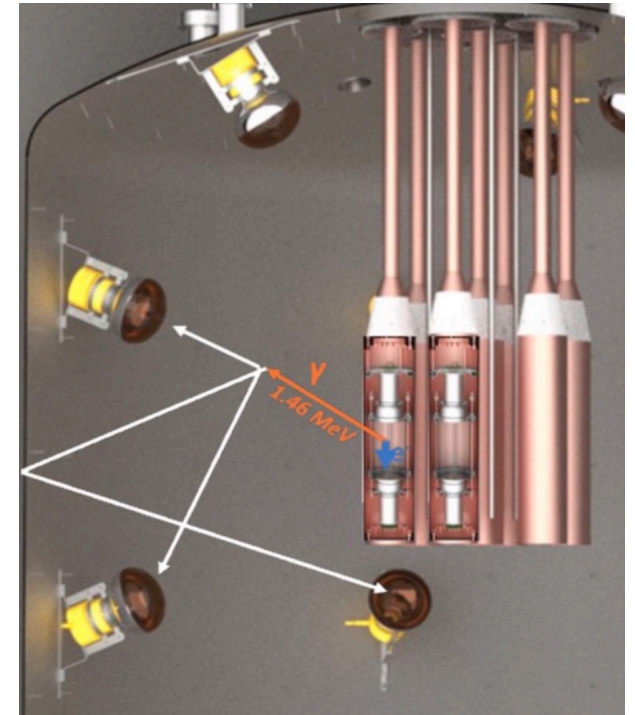
Maria Martinez, TAUP2025

expression of intent to INFN-LNGS to merge know-how, experience, and equipment among ANAIS, COSINE, and SABRE collaborations for operating DAMA/LIBRA detectors:

- Direct search for modulation in same/different setup
- Independent measurement of DAMA/LIBRA NR quenching factors

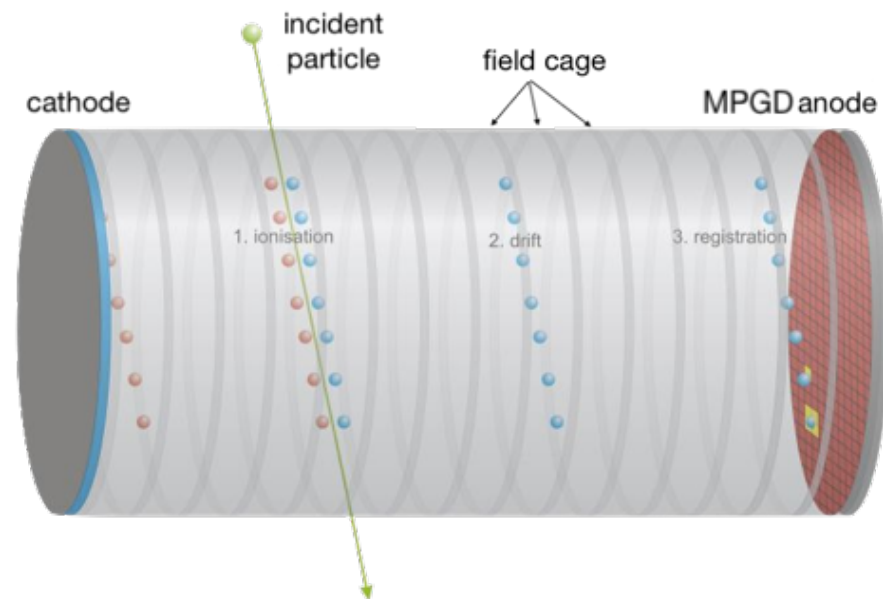


SABRE South at SUPL

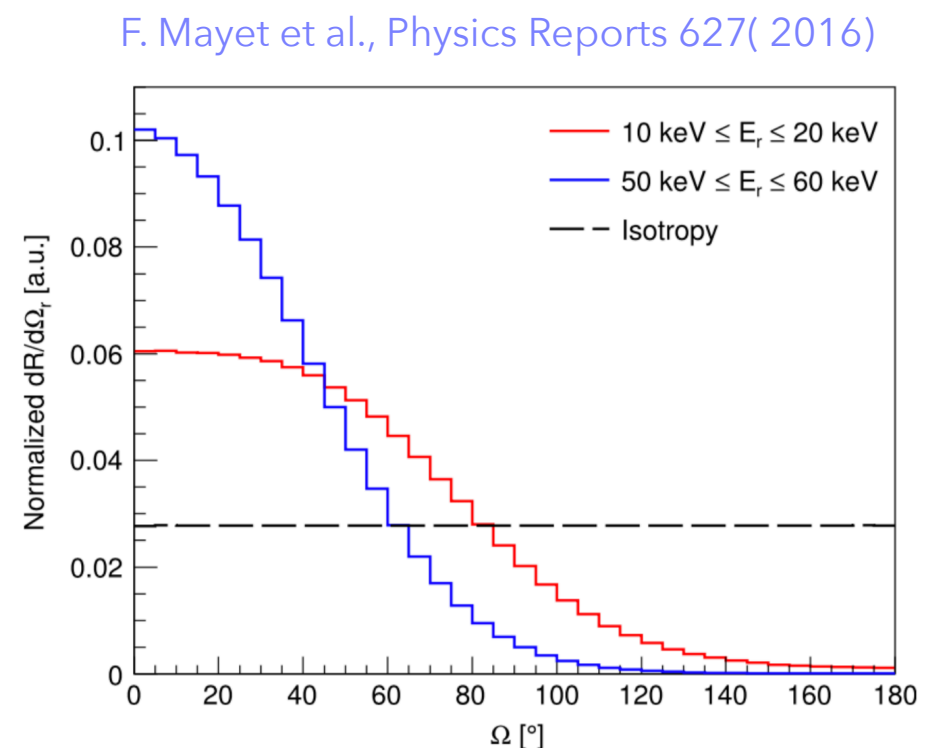
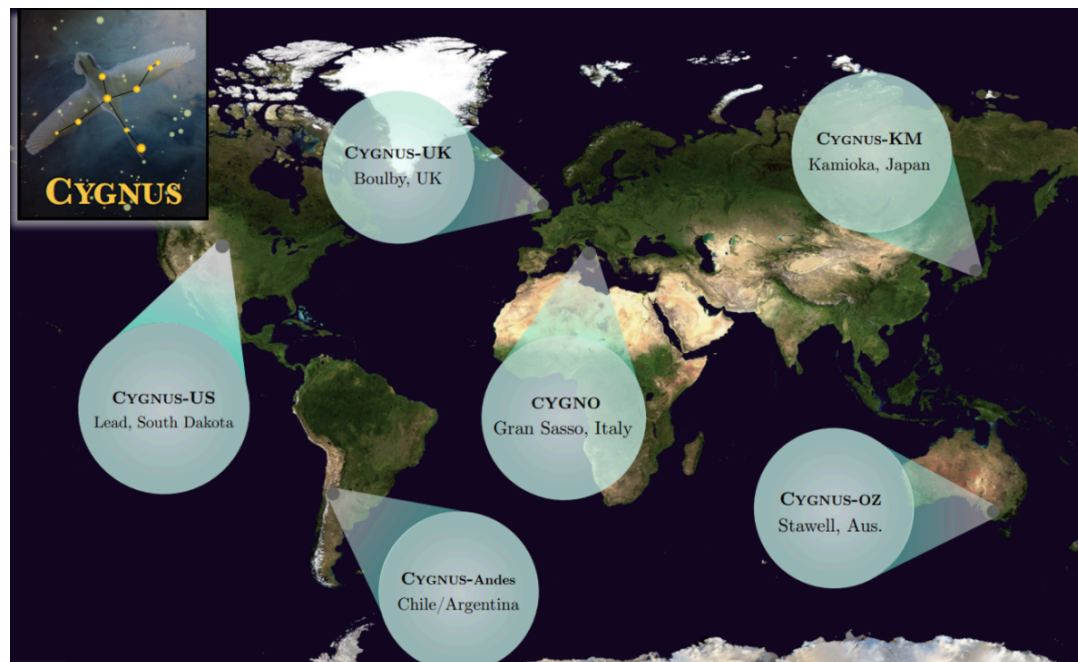


COSINUS at LNGS

Directional detectors

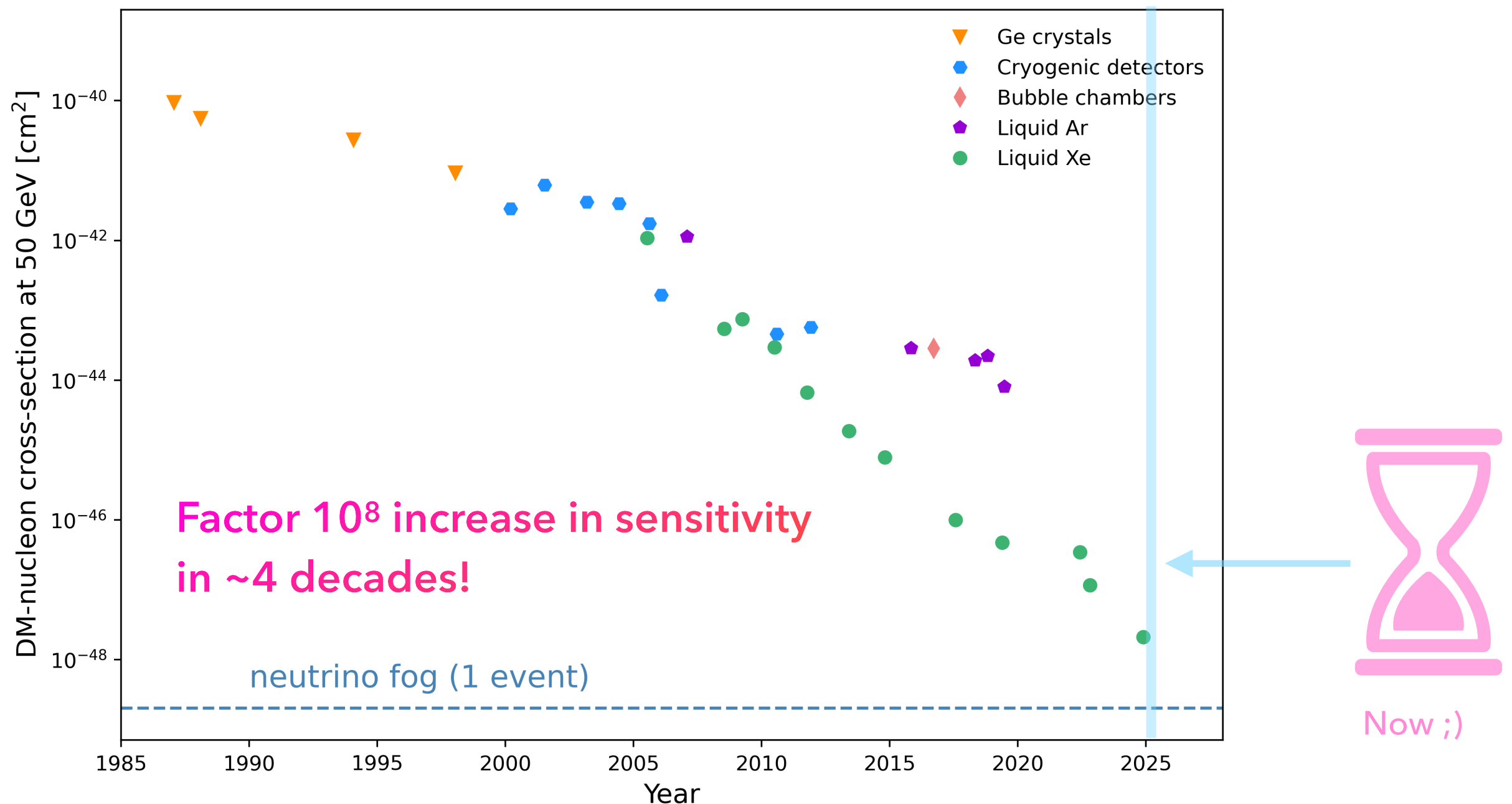


- **Gaseous TPCs** to measure the recoil direction correlated to galactic motion towards Cygnus
- **Challenge:** good angular resolution & head vs. tails at low recoil energies
- **Cygnus:** coordinates efforts for global 1000 m³ (He-CF₄) TPCs with ~ 1 keV threshold



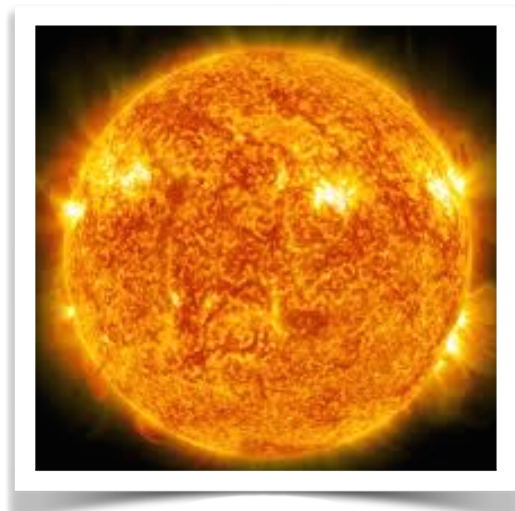
SI cross section vs time

- Constraints on SI cross section (50 GeV DM) over the past 40 years



New tools, new discoveries

Solar
neutrinos
(pp + ^8B)

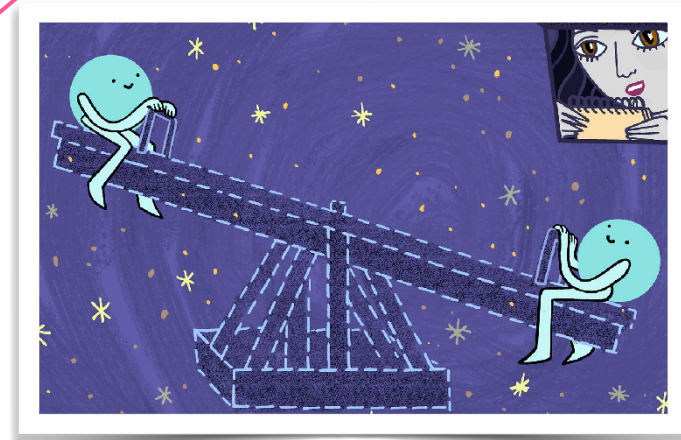
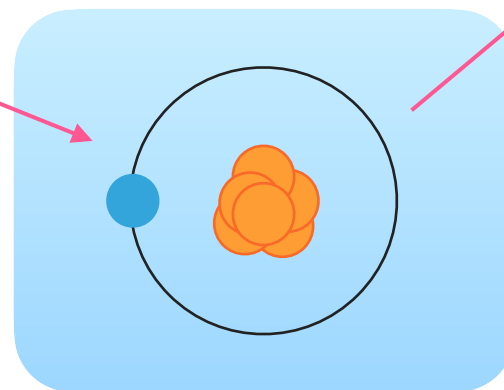


Dark matter



X

X



Neutrino
nature

Supernova
neutrinos



Atmospheric
neutrinos



Summary & Outlook

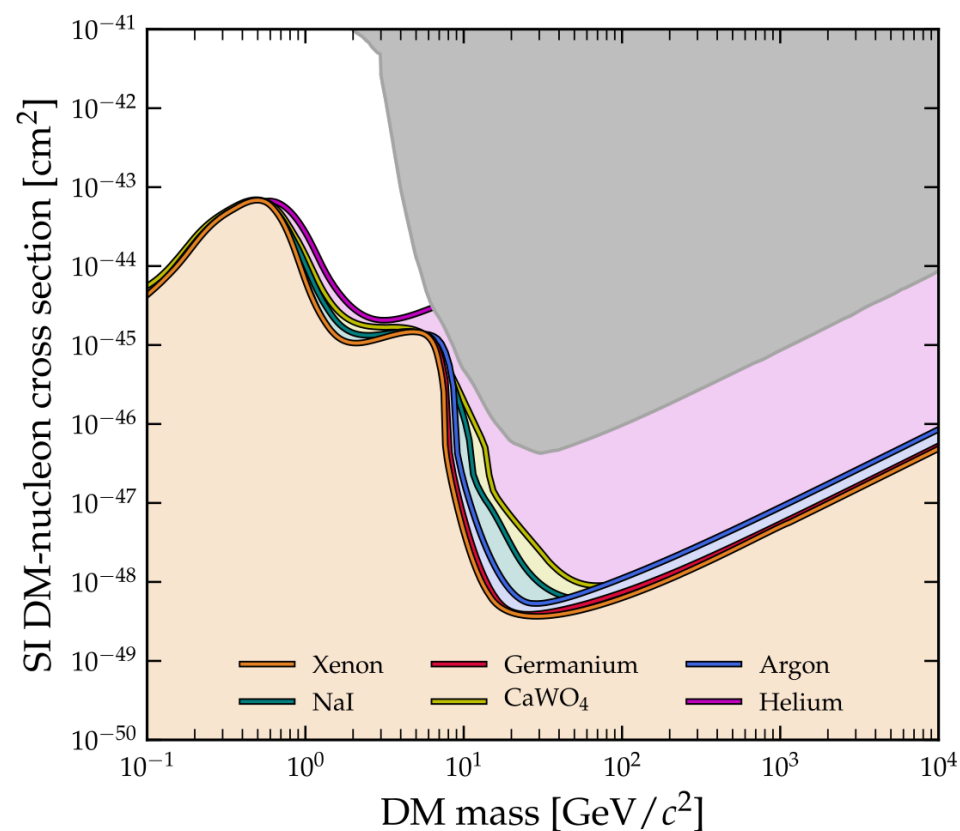
- ◉ **DD experiments:** many different technologies, covering a large range in DM masses & cross sections
- ◉ **Challenges:** reduce energy thresholds further (with existing & new technologies), reduce & understand backgrounds, increase target masses
- ◉ **Goals:** discover a new, dark species; explore the parameter space until astrophysical neutrinos will dominate event rates
- ◉ **Explore a variety of DM candidates** and break new grounds in neutrino physics, solar axions, etc
- ◉ **Must always be prepared for a discovery & for the unexpected ;-)**

Extra material

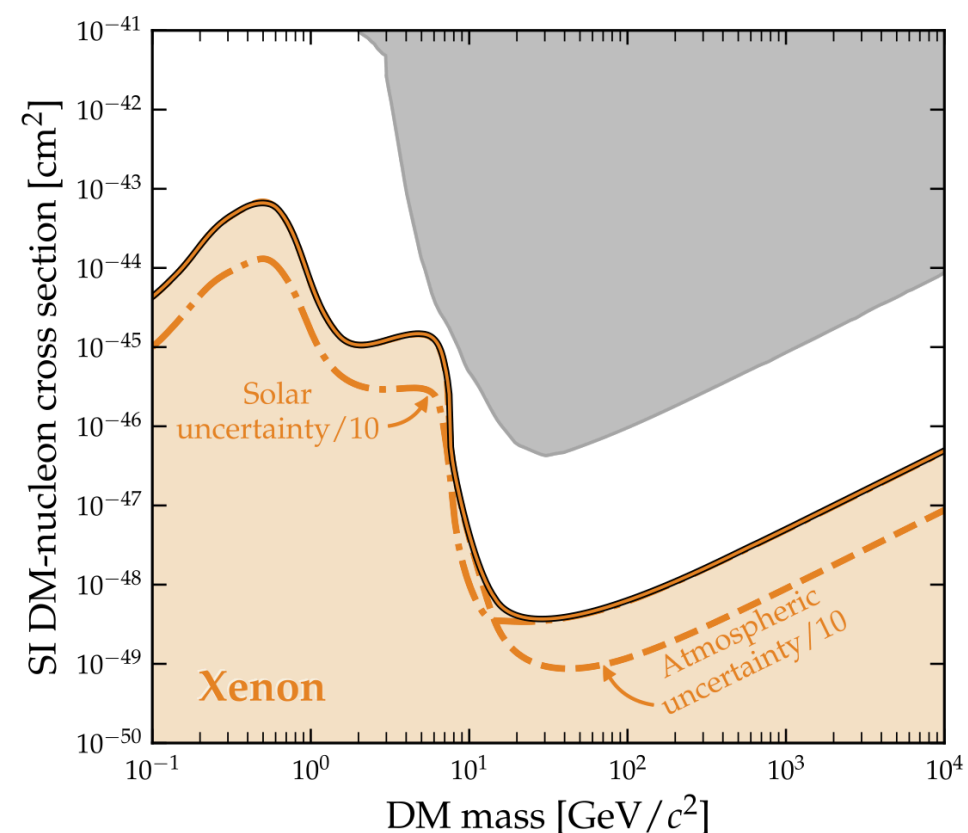
Approaching the Neutrino Fog

- Here shown for nuclear recoils (ν floor as boundary to " ν fog")
- Region where experiments leave the Poissonian regime*

The "fog" for different targets



Effect of ν fluxes uncertainties



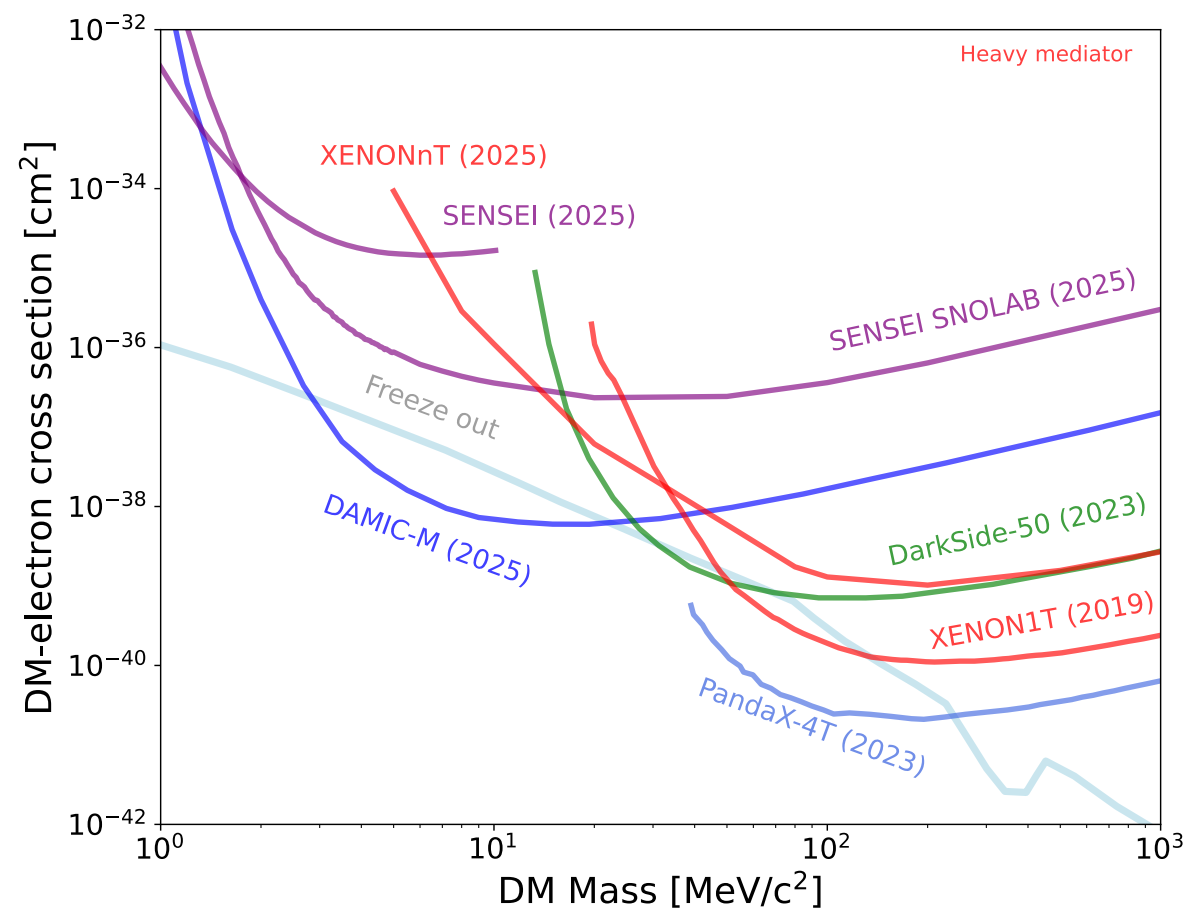
C. O'Hare, PRL 127, 2021

* σ where the DM discovery limit scales as $\sim (Mt)^{-1/n}$

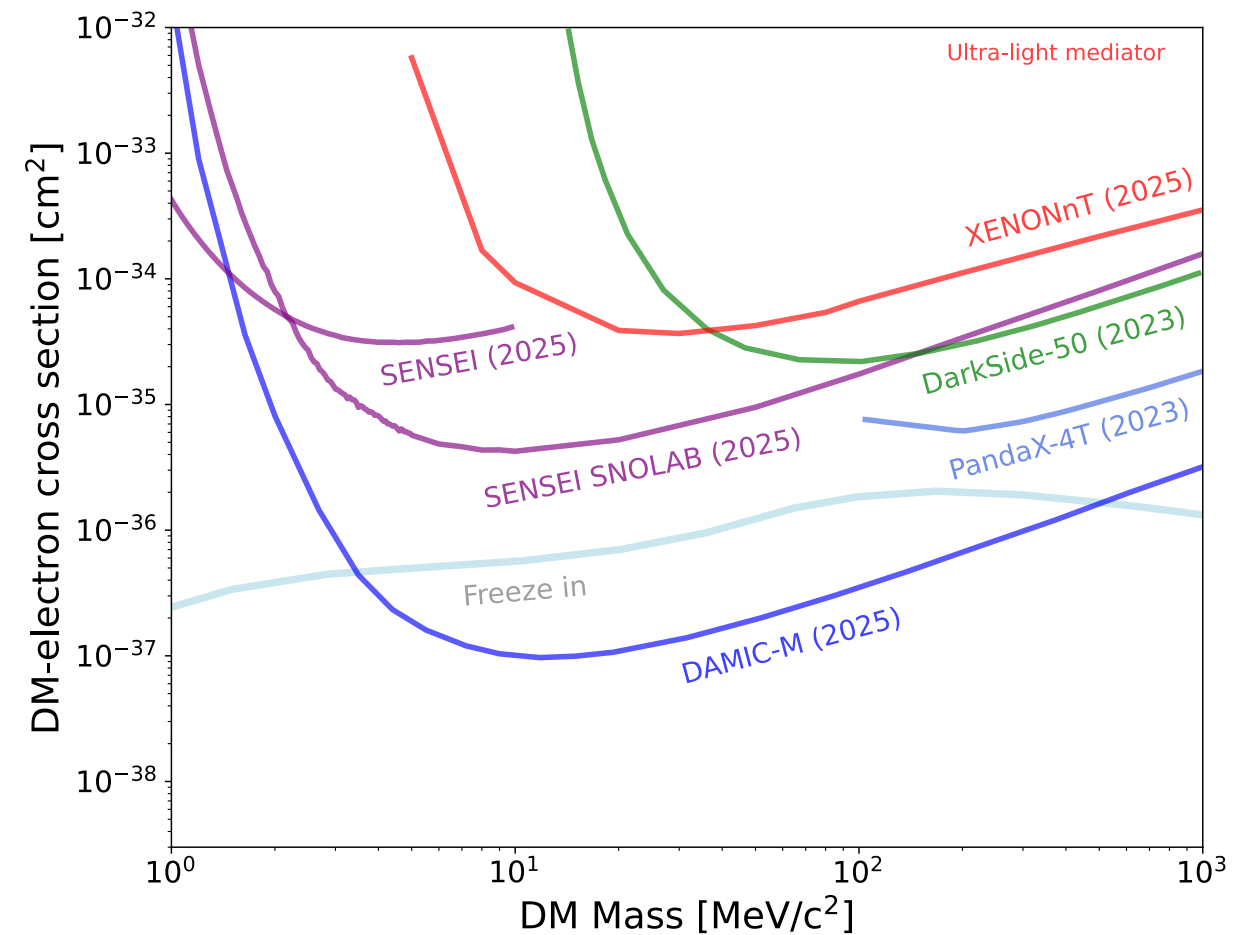
DM-electron scattering

- Overview of recent results

Heavy mediator



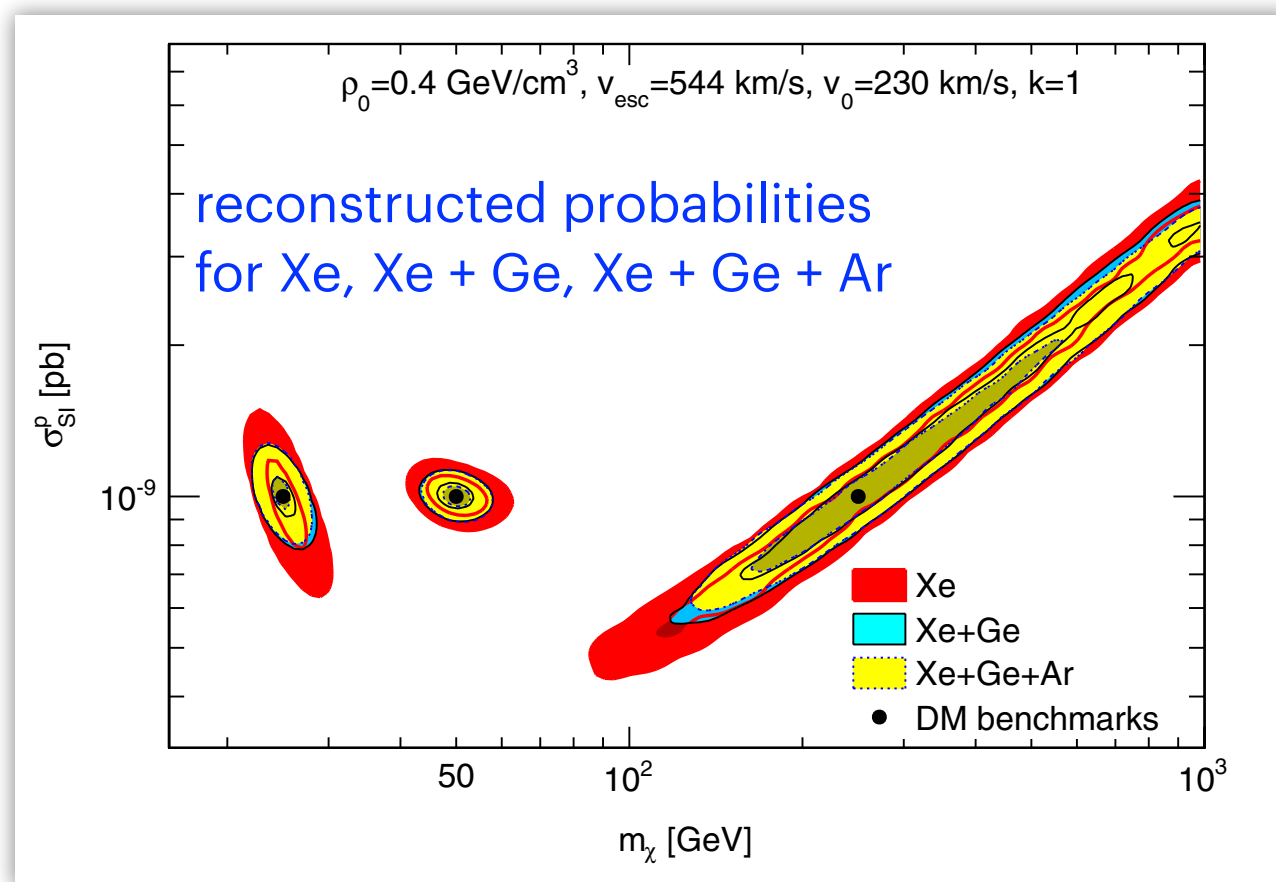
Ultralight mediator



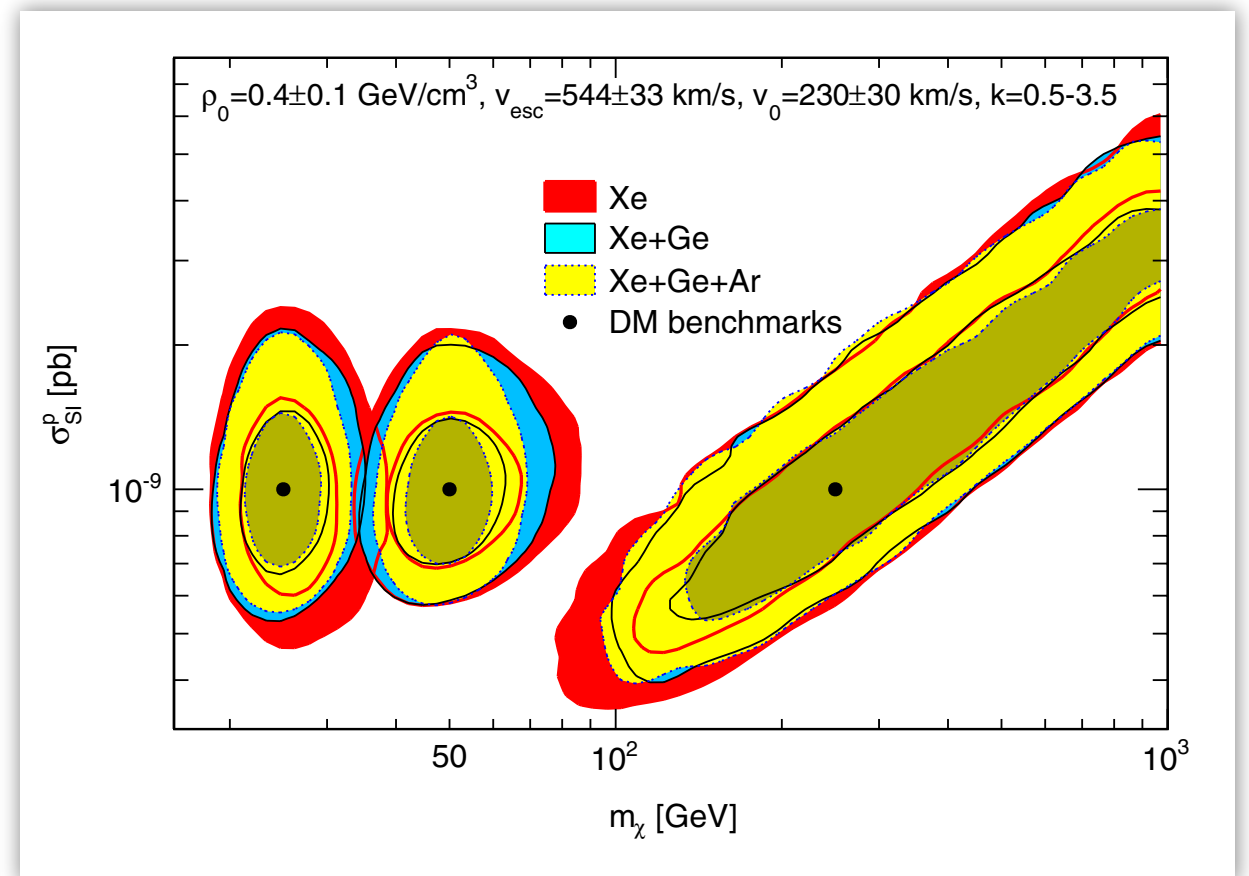
Dark Matter Spectroscopy

- Capability to reconstruct the DM mass and cross section for various masses - here 25, 50, 250 GeV/c^2 - and cross sections

fixed galactic model

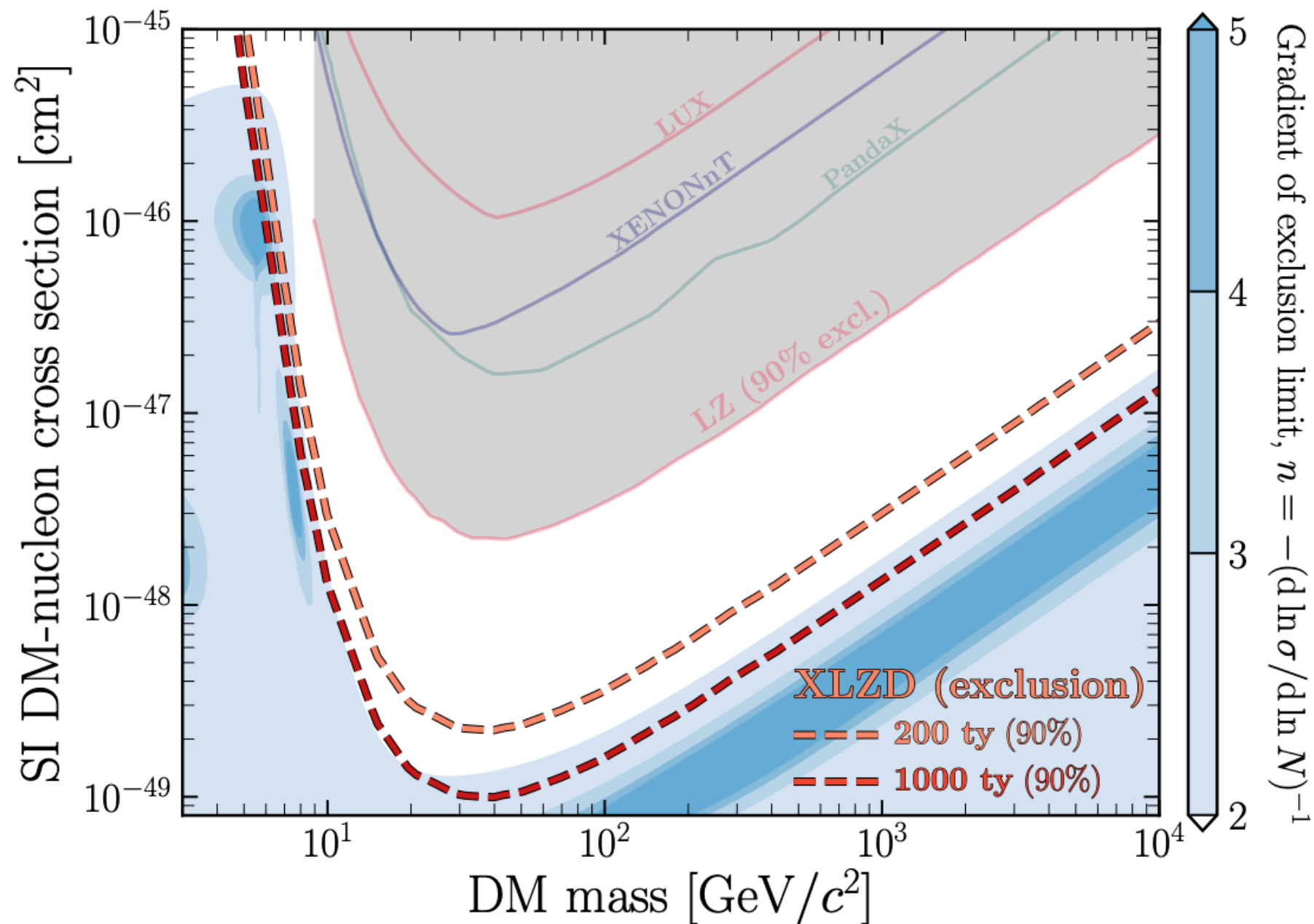


including galactic uncertainties



Xenon + Germanium + Argon

XLZD Dark Matter: Exclusion



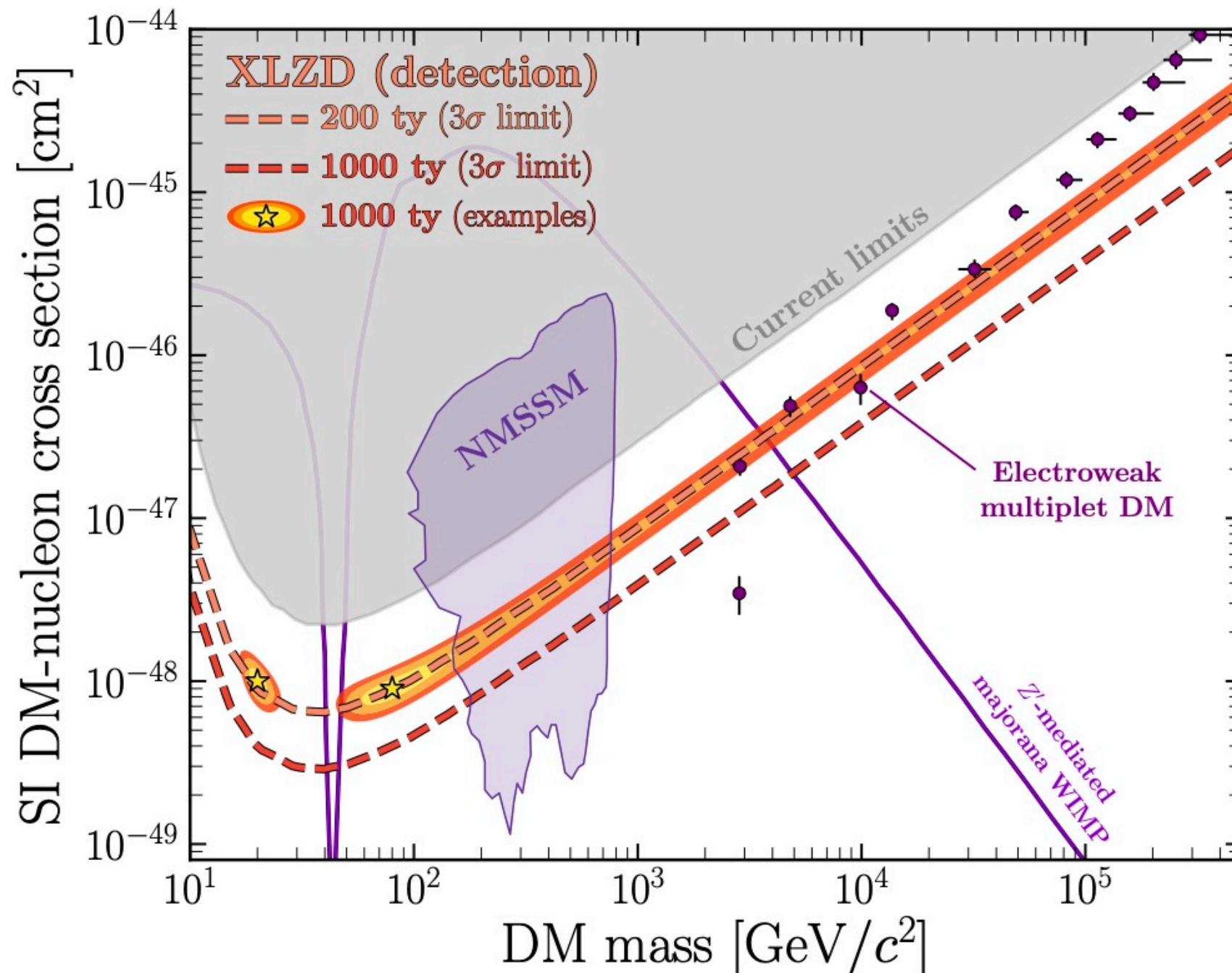
XLZD collaboration
Design Book
arXiv: 2410.17137

Systematic limit
imposed by
CEvES from
atmospheric
neutrinos

Exposure of **1000 t y** needed to dive into the atmospheric neutrino fog (where $> 1, 10, 100, \dots$ events are expected in the WIMP ROI)

At contour n : a $10 \times$ lower XS sensitivity requires an increase in exposure of at least 10^n

XLZD Dark Matter: Detection



XLZD collaboration
Design Book
arXiv: 2410.17137

Evidence
contours for
20 GeV and
80 GeV
WIMPs

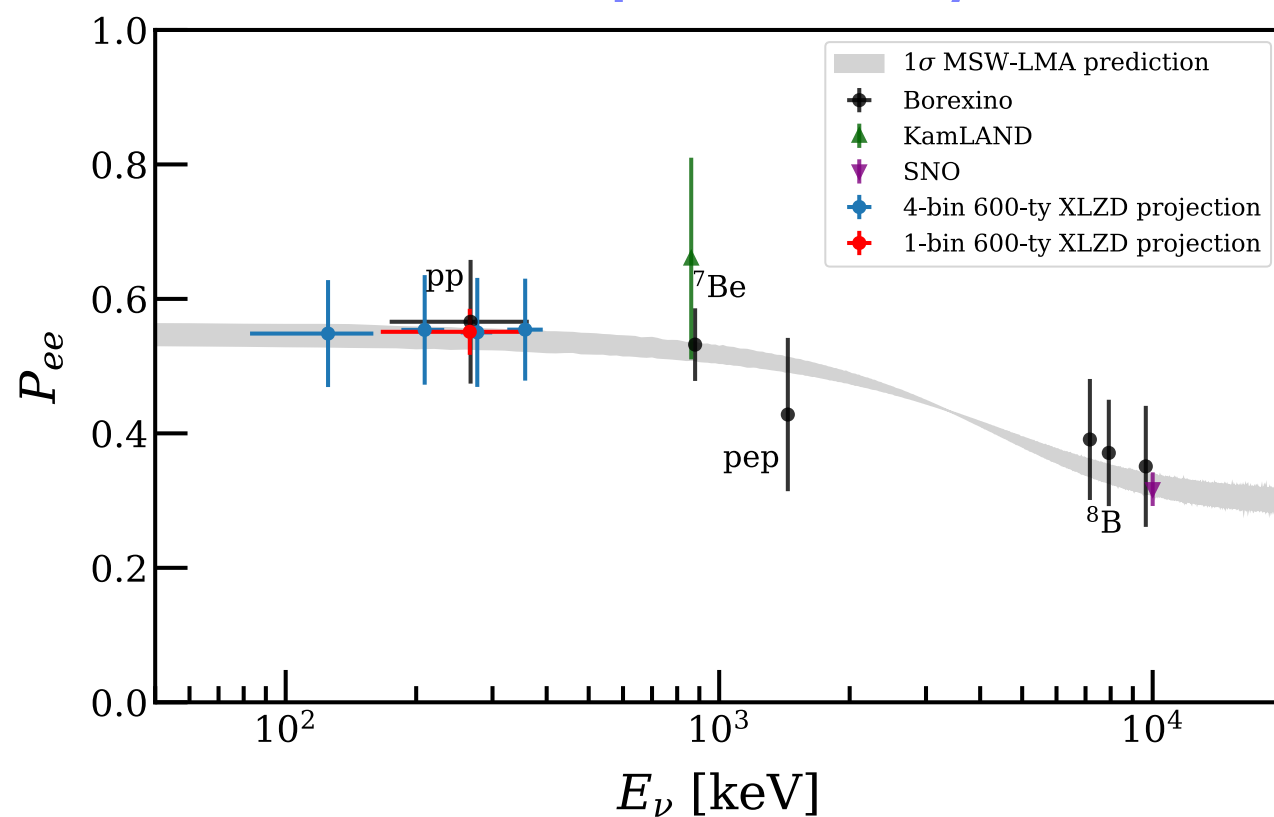
Theory:
EW multiplet, S. Bottaro
et al., EPJ-C 82, 2022 ,
Single complex EW n -plet
with non-zero
hypercharge added to SM

Exposure of 1000 t y: 1-, 2- and 3-sigma (yellow, orange, red) Cls

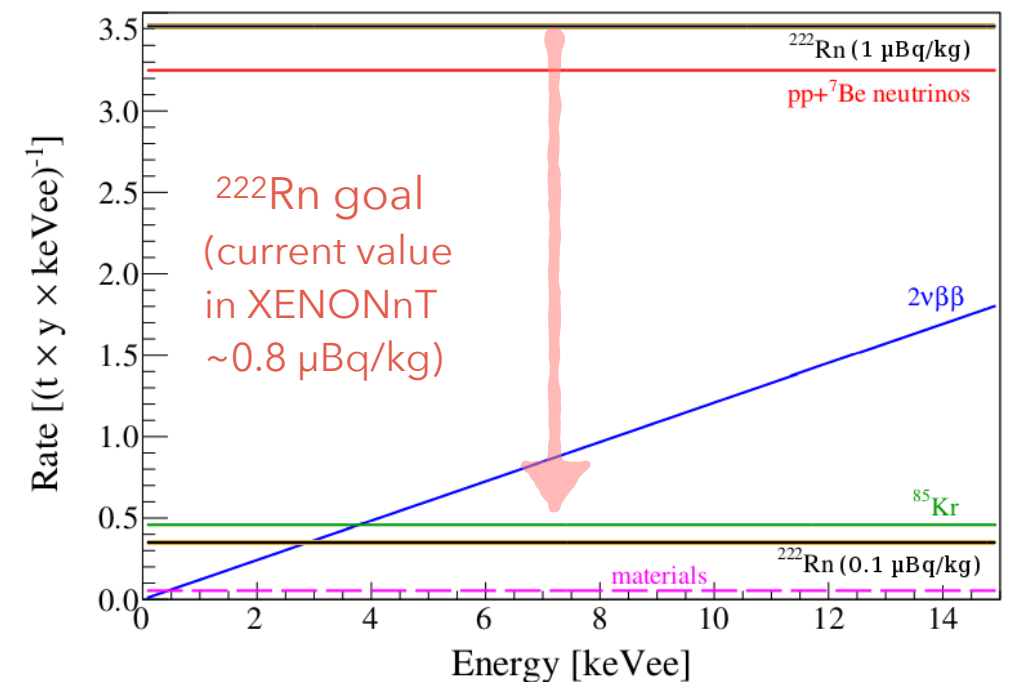
Solar ν -Electron Scattering

- Main challenge:** reduce ^{222}Rn (^{214}Pb β -decay) background to x 10 below the pp rate (0.1 $\mu\text{Bq/kg}$)

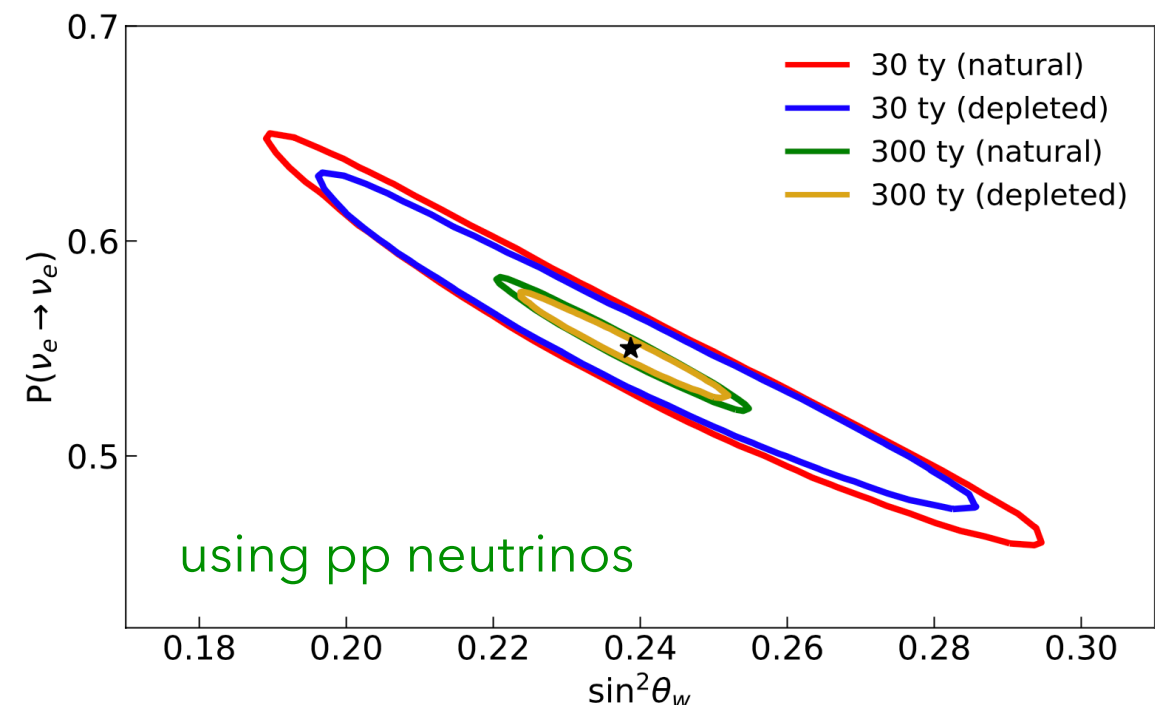
XLZD preliminary



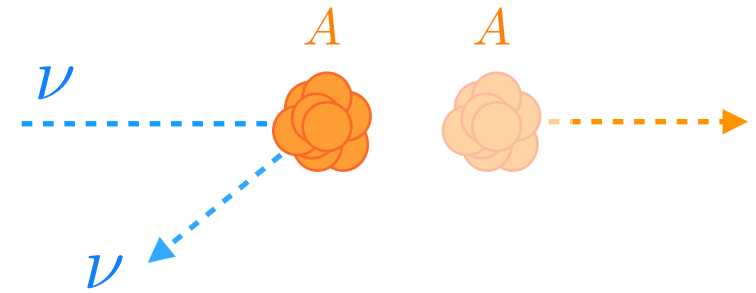
600 t y exposure, 1 and 4 energy bins



DARWIN collaboration, EPJ-C 80 12 (2020)

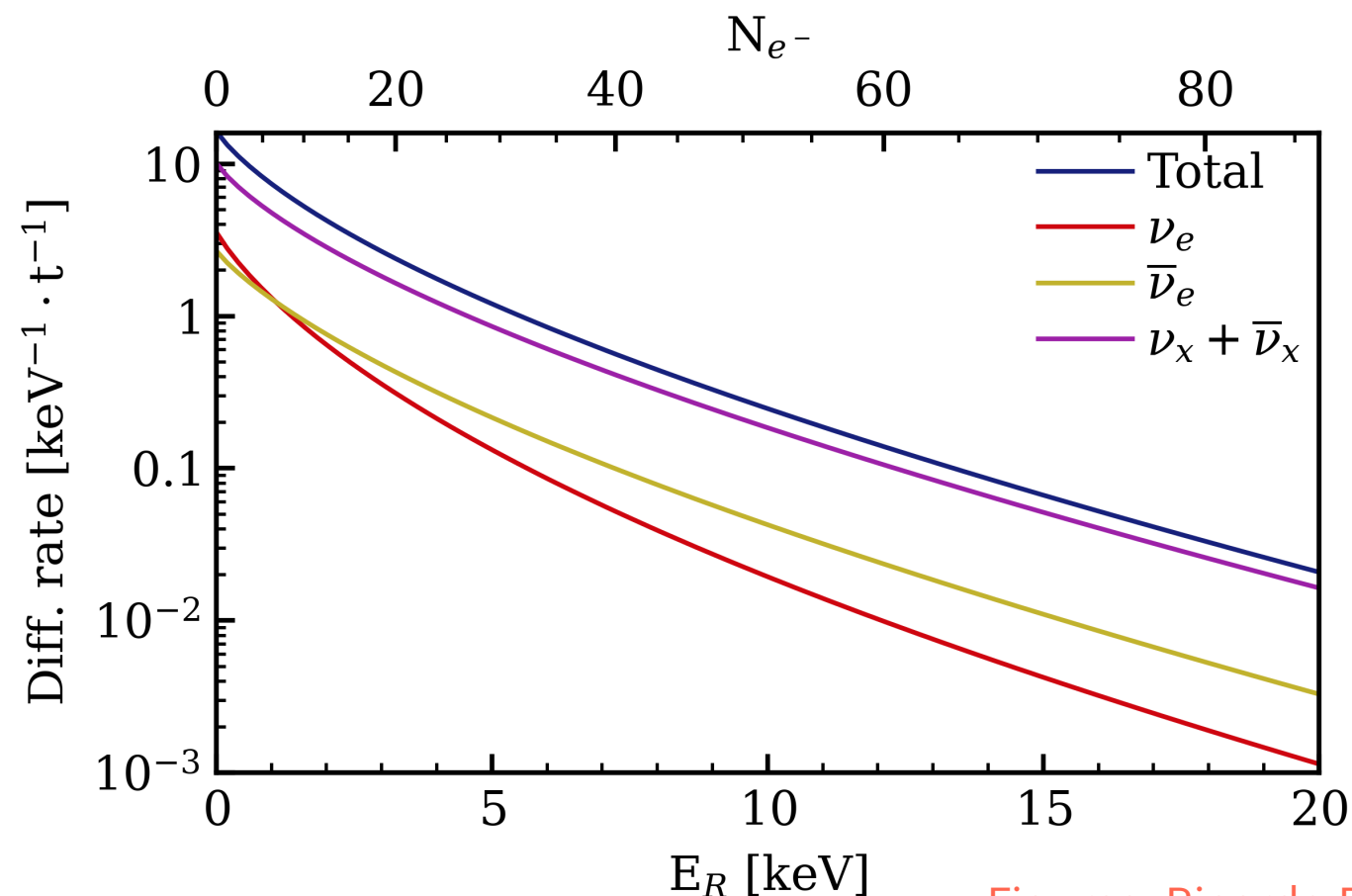


SN ν -Nucleus Scattering

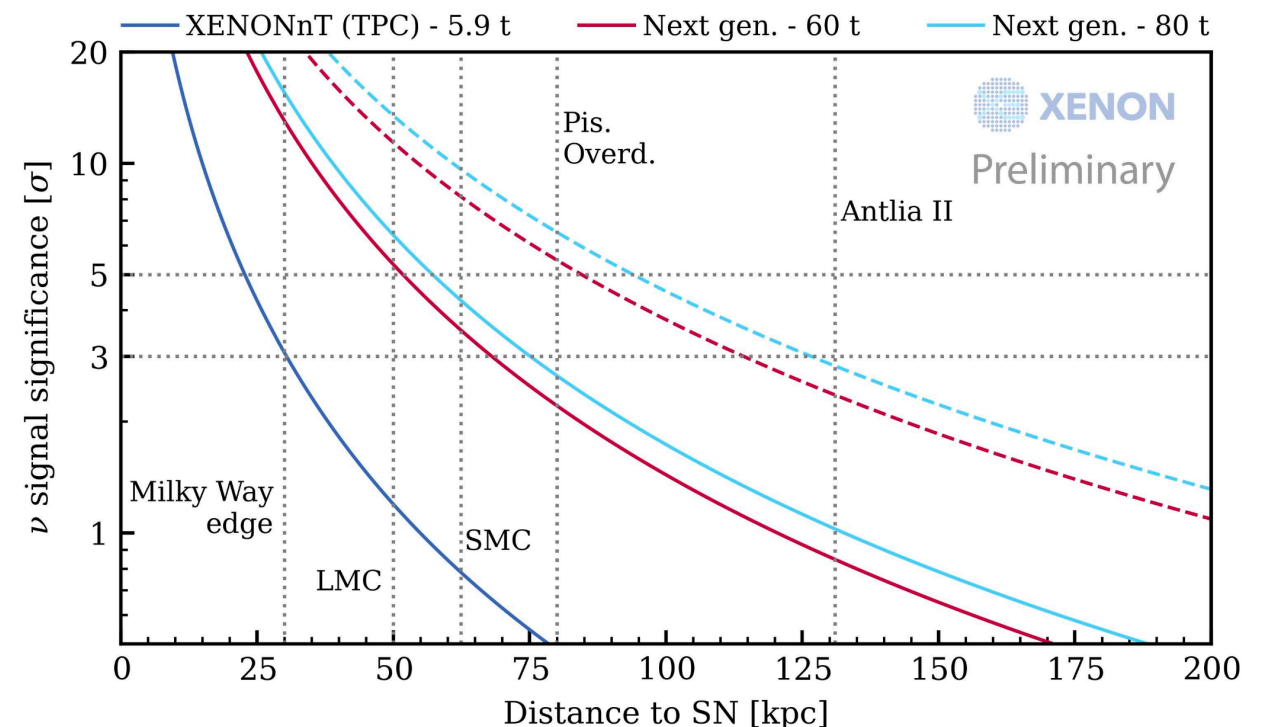


- Sensitivity to all ν flavours: **few events/ton** expected from SN at ~ 10 kpc
- **Main challenge:** low energies, understand few-e⁻ backgrounds
- **XLZD:** sensitivity beyond SMC; part of SNEWS2.0

Rates for $27 M_{\odot}$ SN at 10 kpc



XENONnT/LZ and XLZD



Figures: Ricardo Peres, UZH/Imperial

Atmospheric Neutrinos

- In general, exposures $>$ few 1000 t y are needed for 5- σ detection

