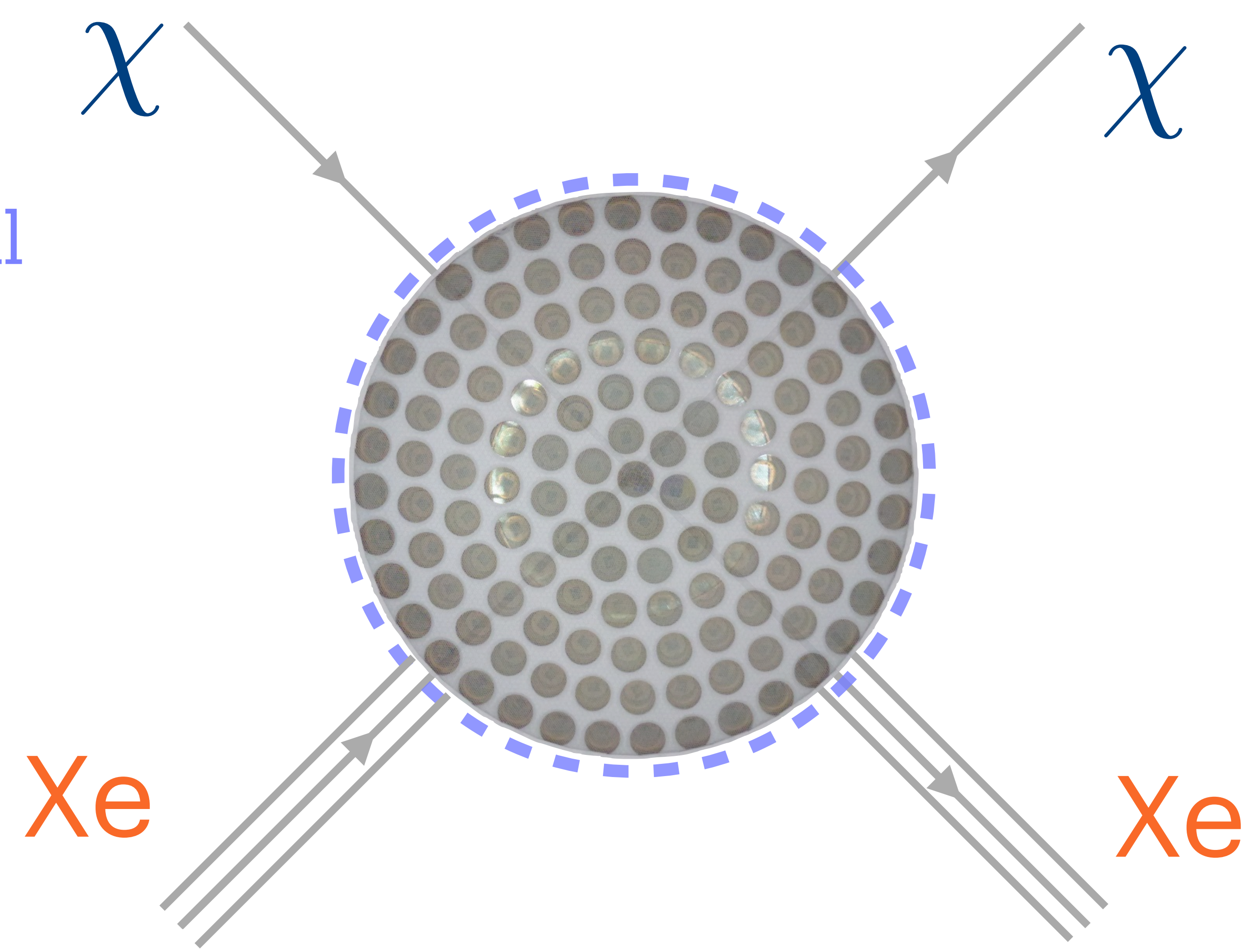
Universität Zürich[UZH]

Probing Dark Matter with Liquid Xenon Detectors

PLANCK25: The 27th International Conference from the Planck Scale to the Electroweak Scale



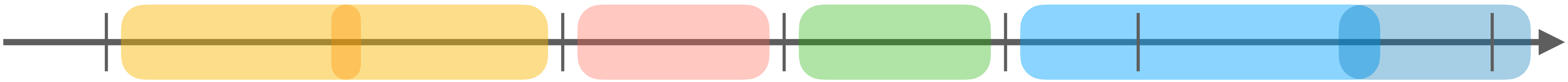
Laura Baudis
University of Zurich

May 28, 2025

What is the Dark Matter?

How does it interact?

$10^{-22}\,\mathrm{eV}$ QCD axion $1\,\mathrm{keV}$ $1\,\mathrm{GeV}$ $100\,\mathrm{TeV}$ M_{pl} $10\,M_{\odot}$



Ultra-light DM

bosonic fields

Light DM

dark sector

WIMP

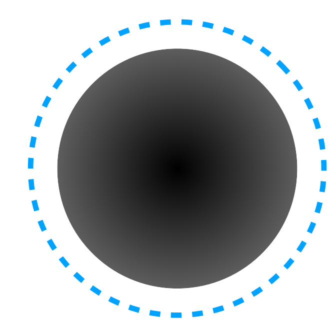
Composite DM

Q-balls, dark atoms, dark mesons etc

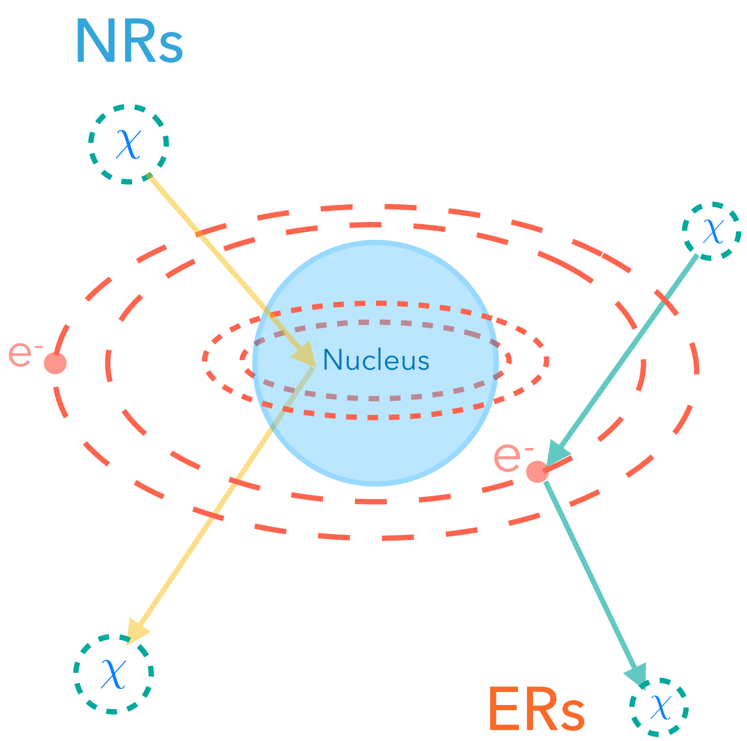
PBHs

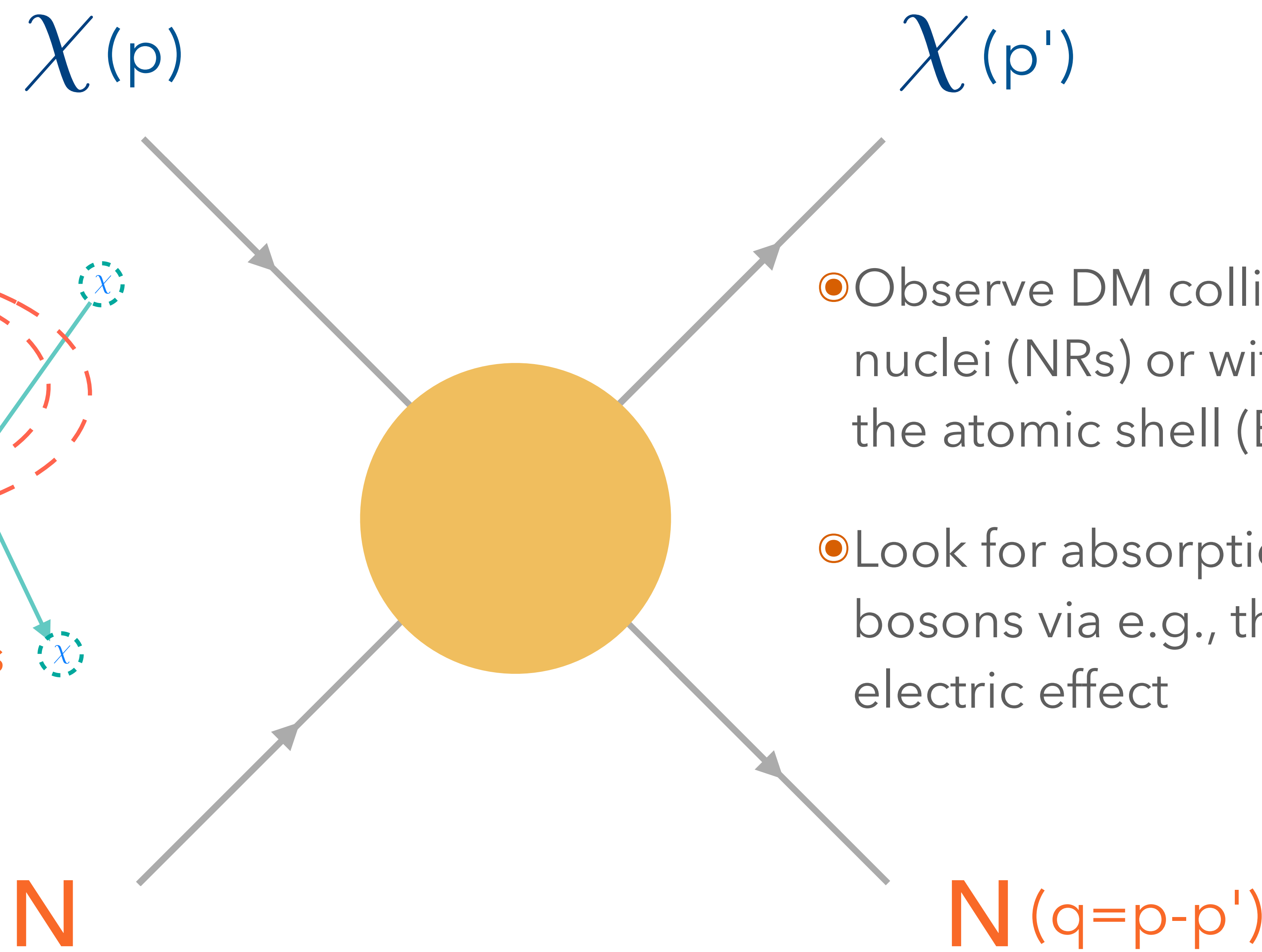
Structures on the scale of dwarf galaxies can form: $\lambda = \dfrac{2\pi}{mv} \sim \mathrm{kpc}$

Weak scale dark matter (still alive)



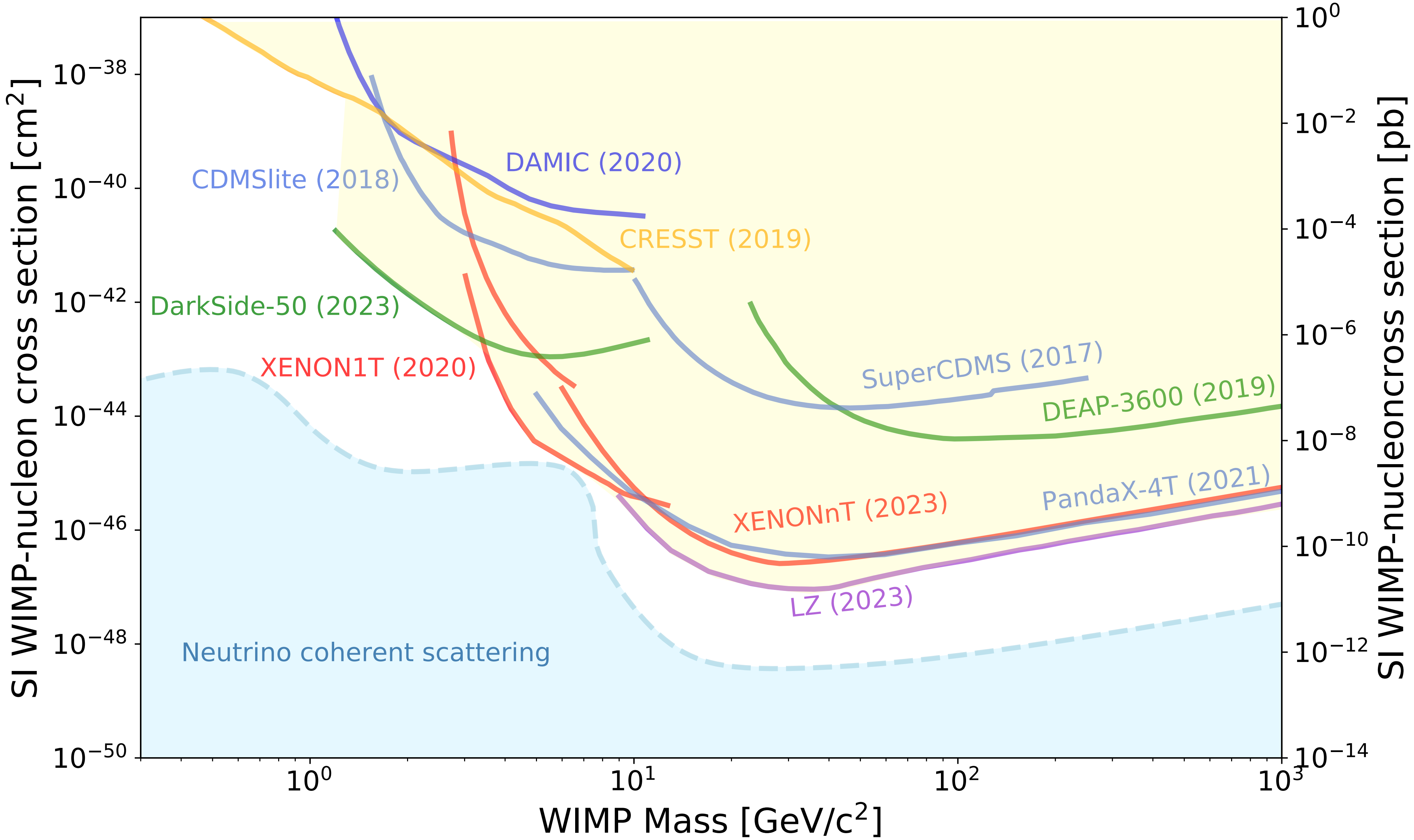
Direct Dark Matter Detection

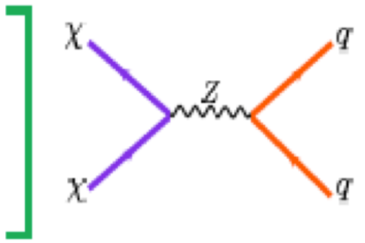


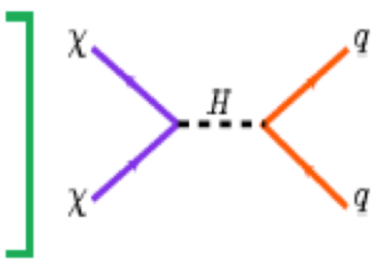


- Observe DM collisions with nuclei (NRs) or with electrons in the atomic shell (ERs)
- Look for absorption of light bosons via e.g., the axio-electric effect

Towards the Neutrino Fog





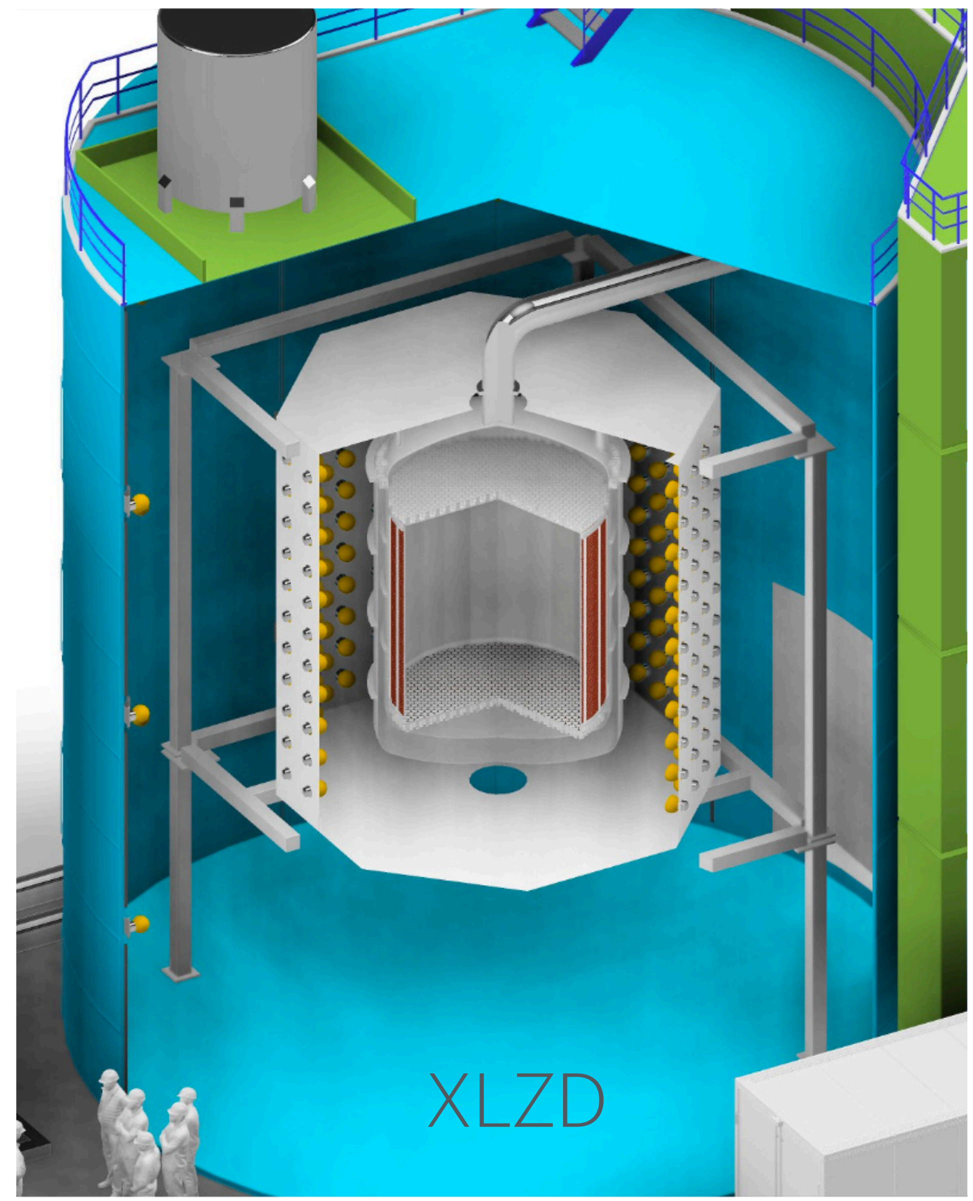


LB and Stefano Profumo, PDG 2024

Why Liquid Xenon Detectors?

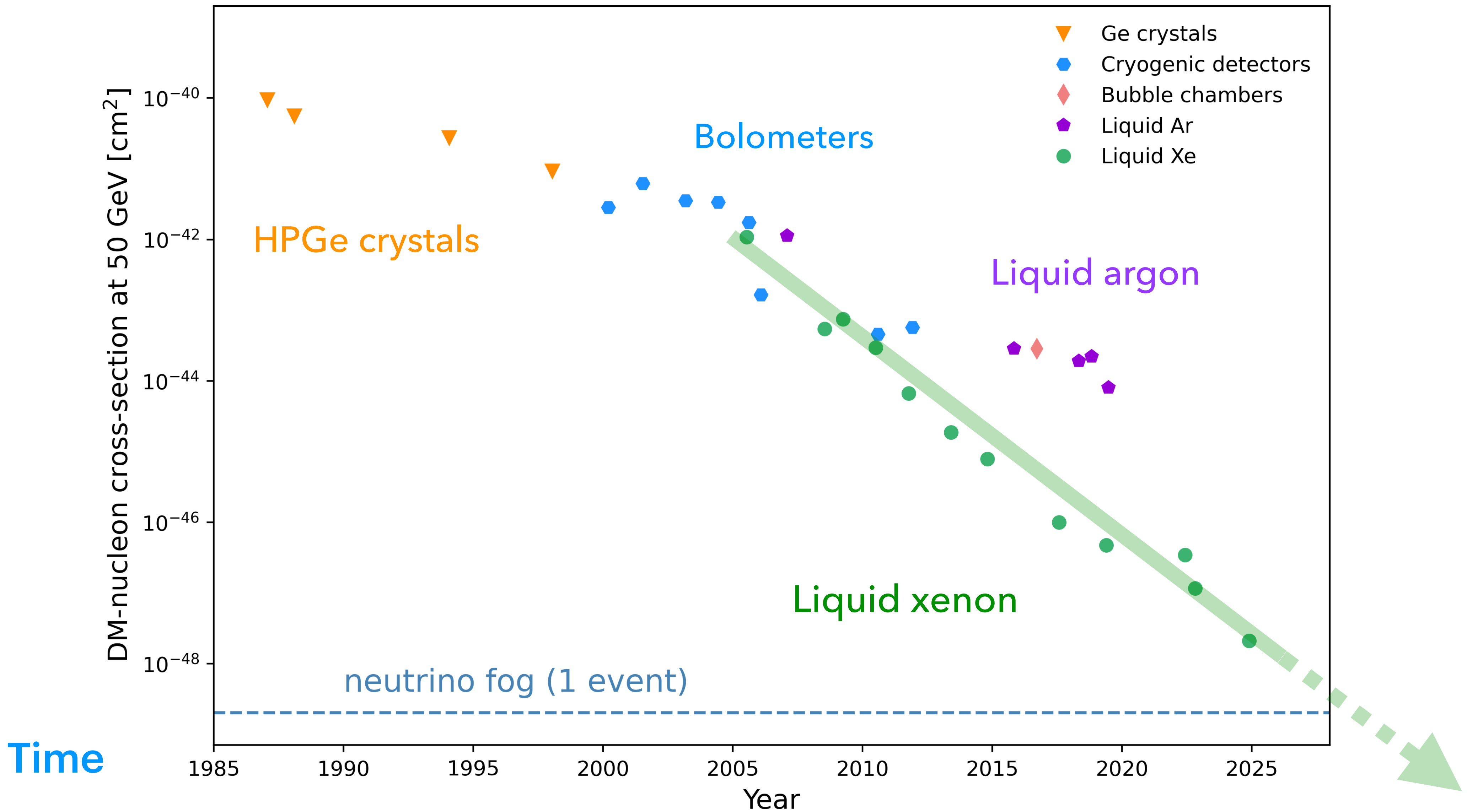
- Leading WIMP sensitivity since ~2007

- Scalable ⇒ large target masses
- Readily purified ⇒ ultra-low backgrounds
- High density ⇒ self-shielding
- SI and SD (^{129}Xe, ^{131}Xe) interactions
- Other science opportunities
  - second order weak decays:
    - ^{124}Xe, ^{126}Xe, ^{134}Xe, ^{136}Xe
  - solar and supernova neutrinos



Why Liquid Xenon Detectors?

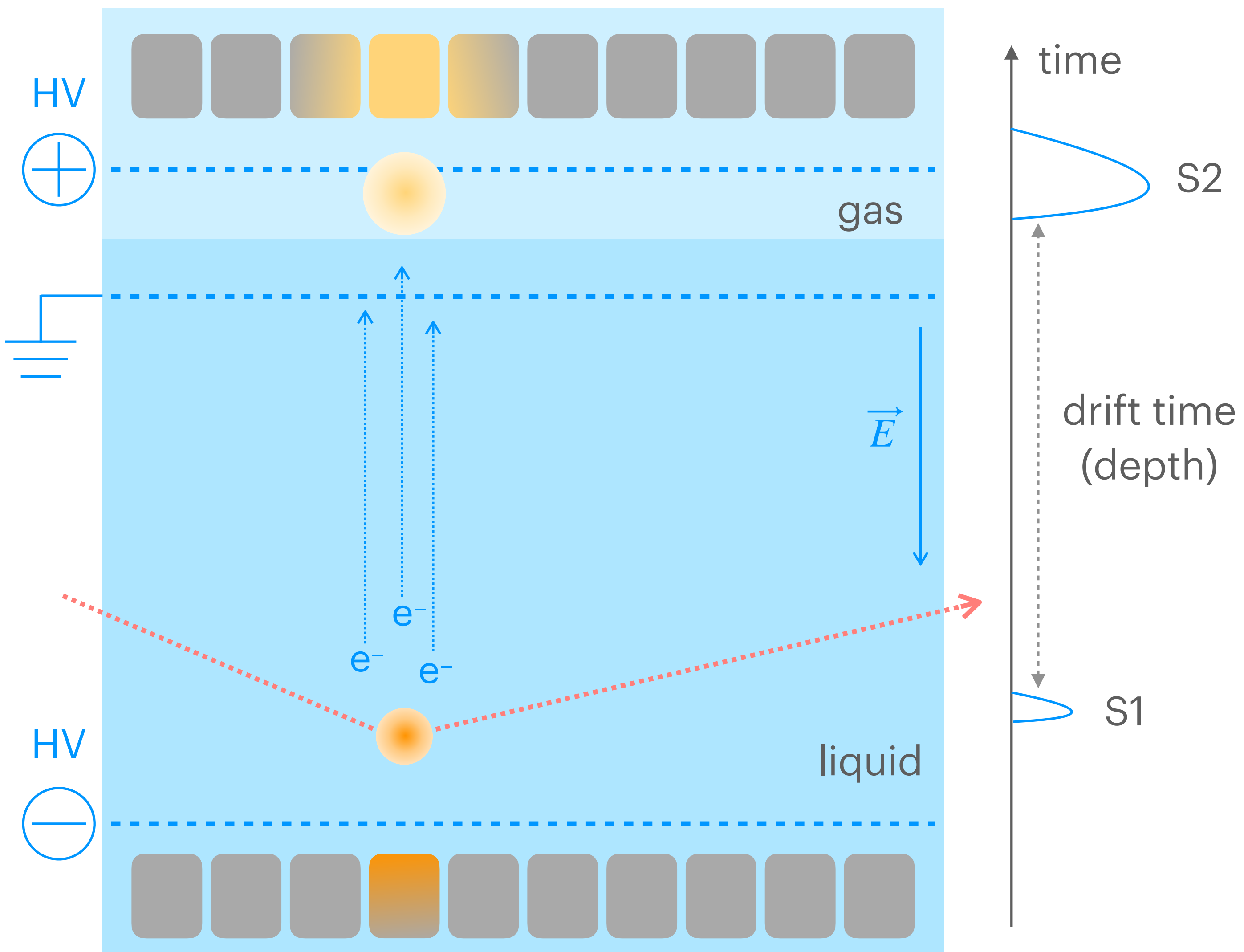
- Leading WIMP sensitivity since ~2007



Upper limits on the DM-nucleon cross section for a 50 GeV WIMP

Two-phase Xenon TPCs

5D detectors: *(x,y,z,E,t)*

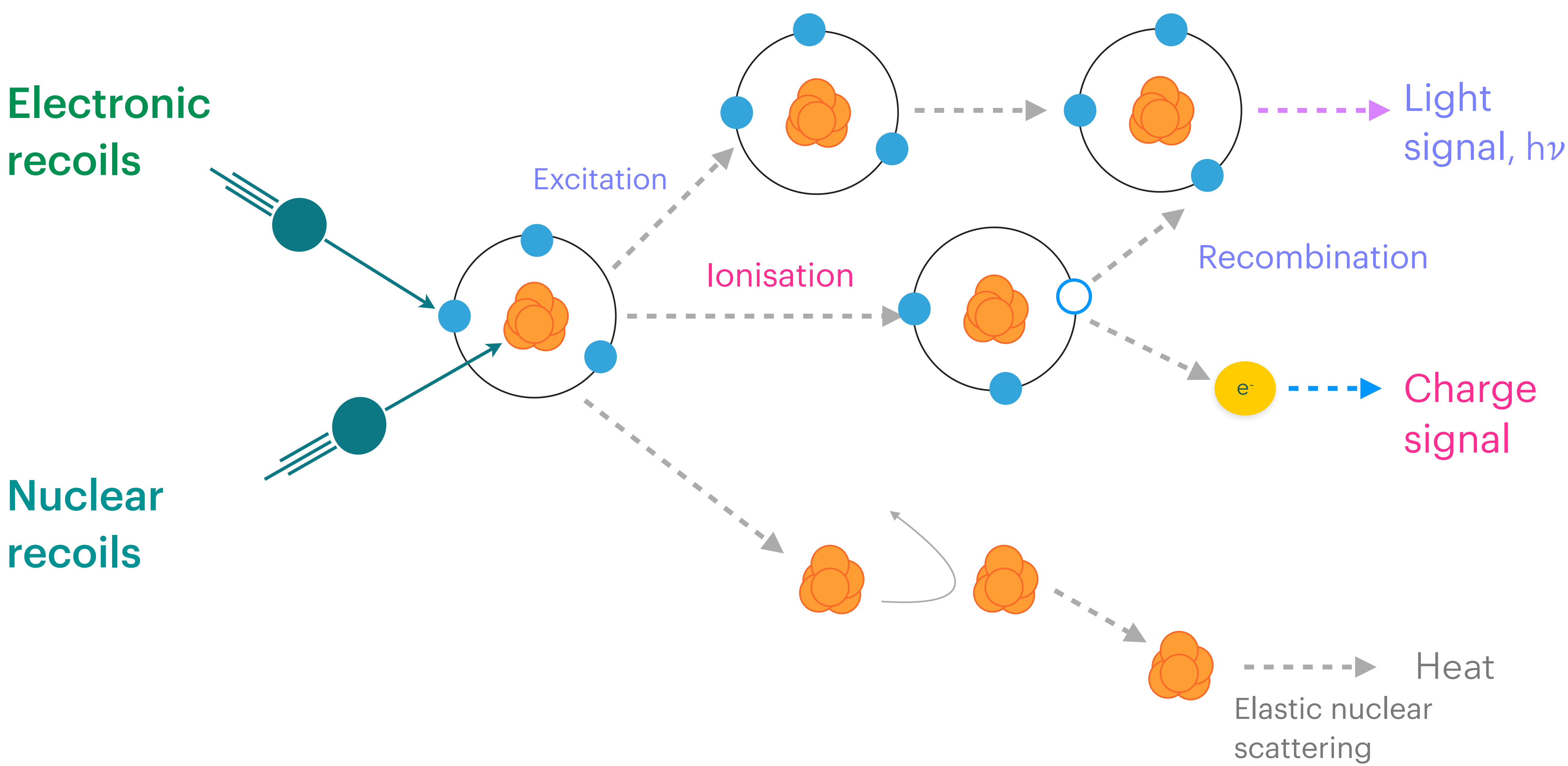


$$\lambda_{LXe} = 175 \text{ nm}$$

- Observe light (S1) and charge signals (S2) when particles interacts in the dense liquid
- 3D position reconstruction
- Energy reconstruction
- Particle discrimination: ratio of charge/light (ERs vs. NRs)

LB, Phil. Trans. R. Soc. A382 (2023), 0083

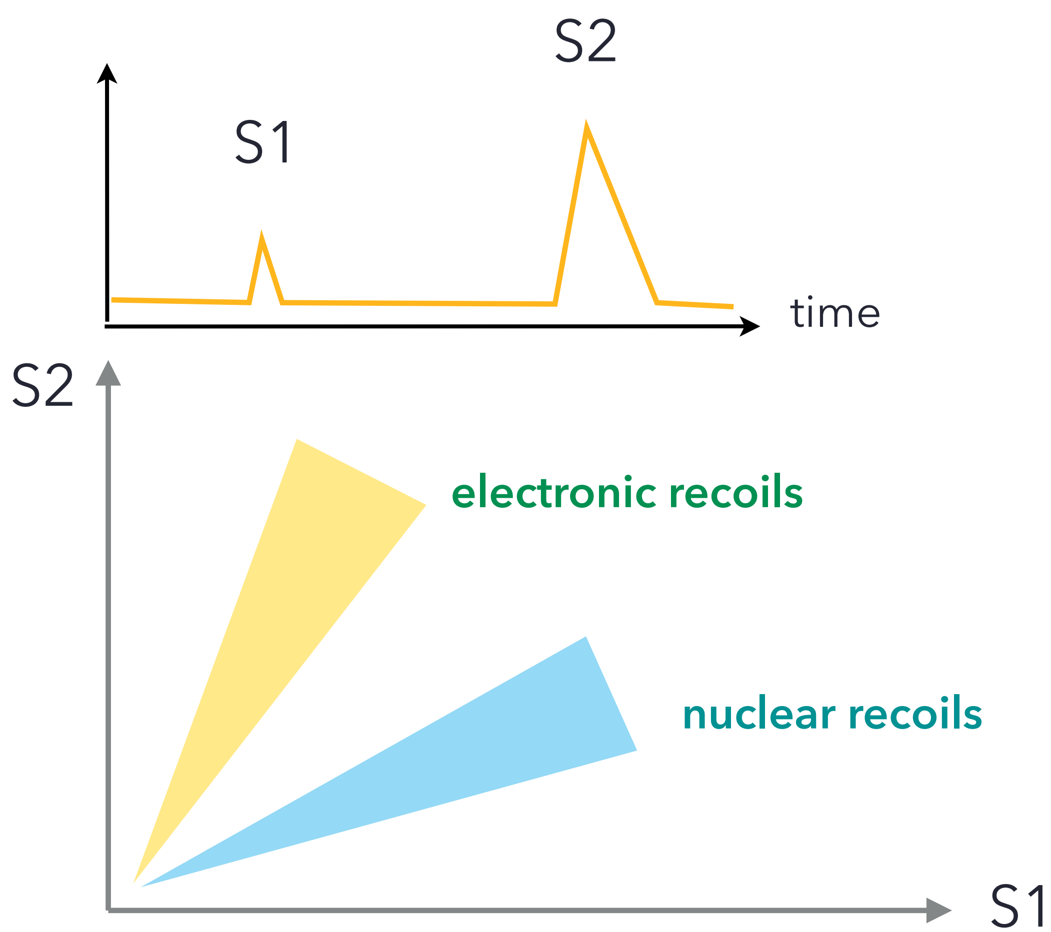
Electronic and Nuclear Recoils



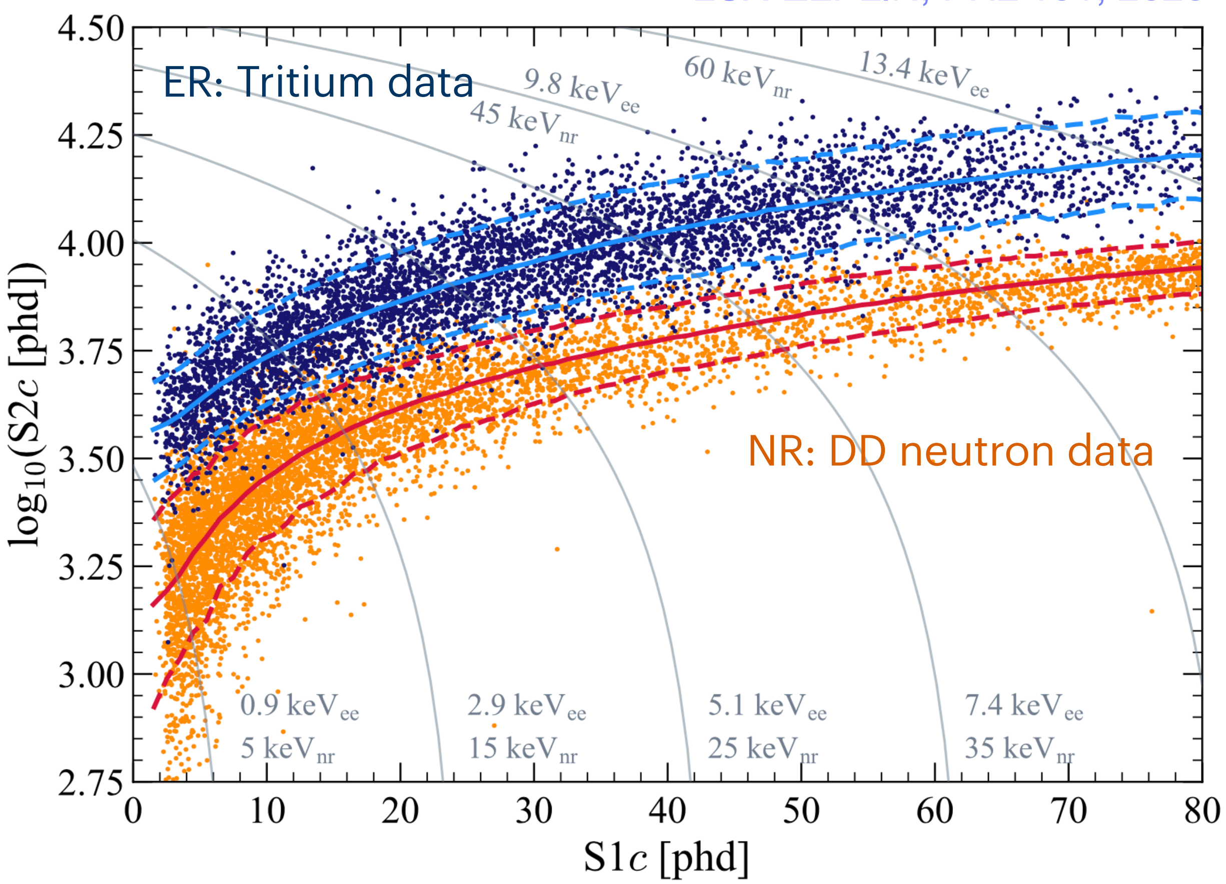
LB, Phil. Trans. R. Soc. A382 (2023), 0083

Particle Discrimination

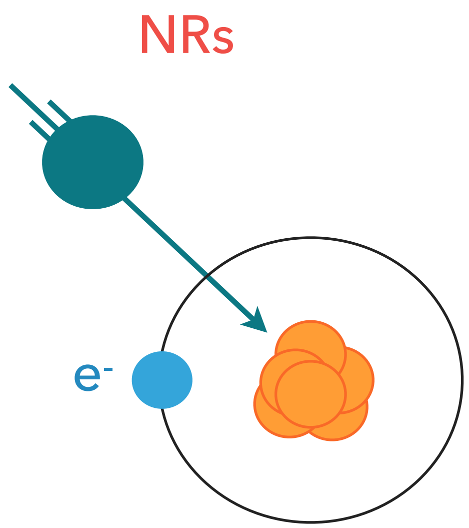
- S1-S2-ratio: type of particle (dE/dx), different for ERs and NRs
- Discrimination power: interplay between **drift field** and **total S1 light collection**
- Typically: (99.5 - 99.99)% ER rejection at ~50% NR acceptance

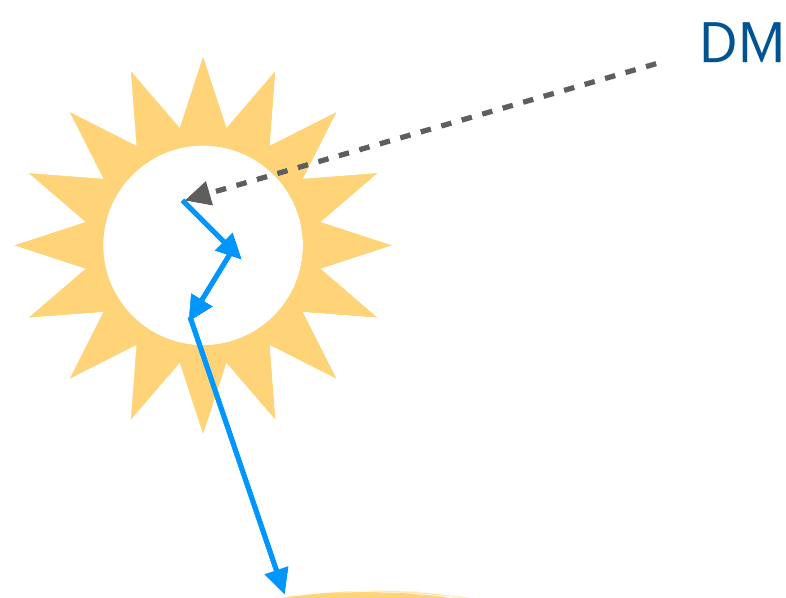


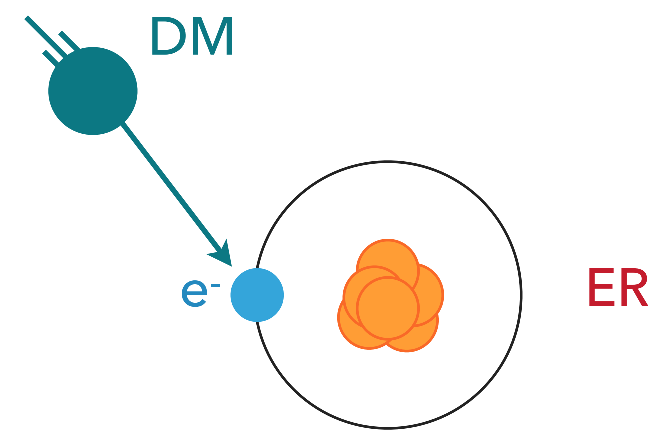
LUX-ZEPLIN, PRL 131, 2023

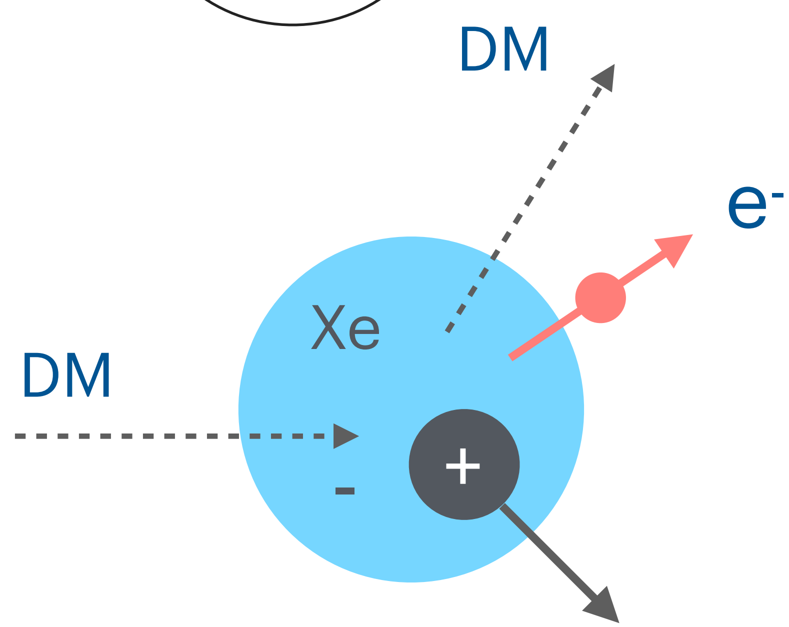


LXe Dark Matter Searches







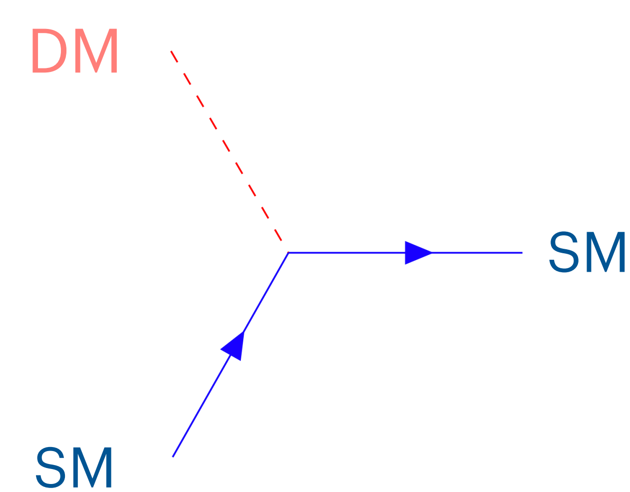


Use the Sun for a velocity boost

DM-e- scattering
DM absorption

Migdal effect: NR signal with ER character

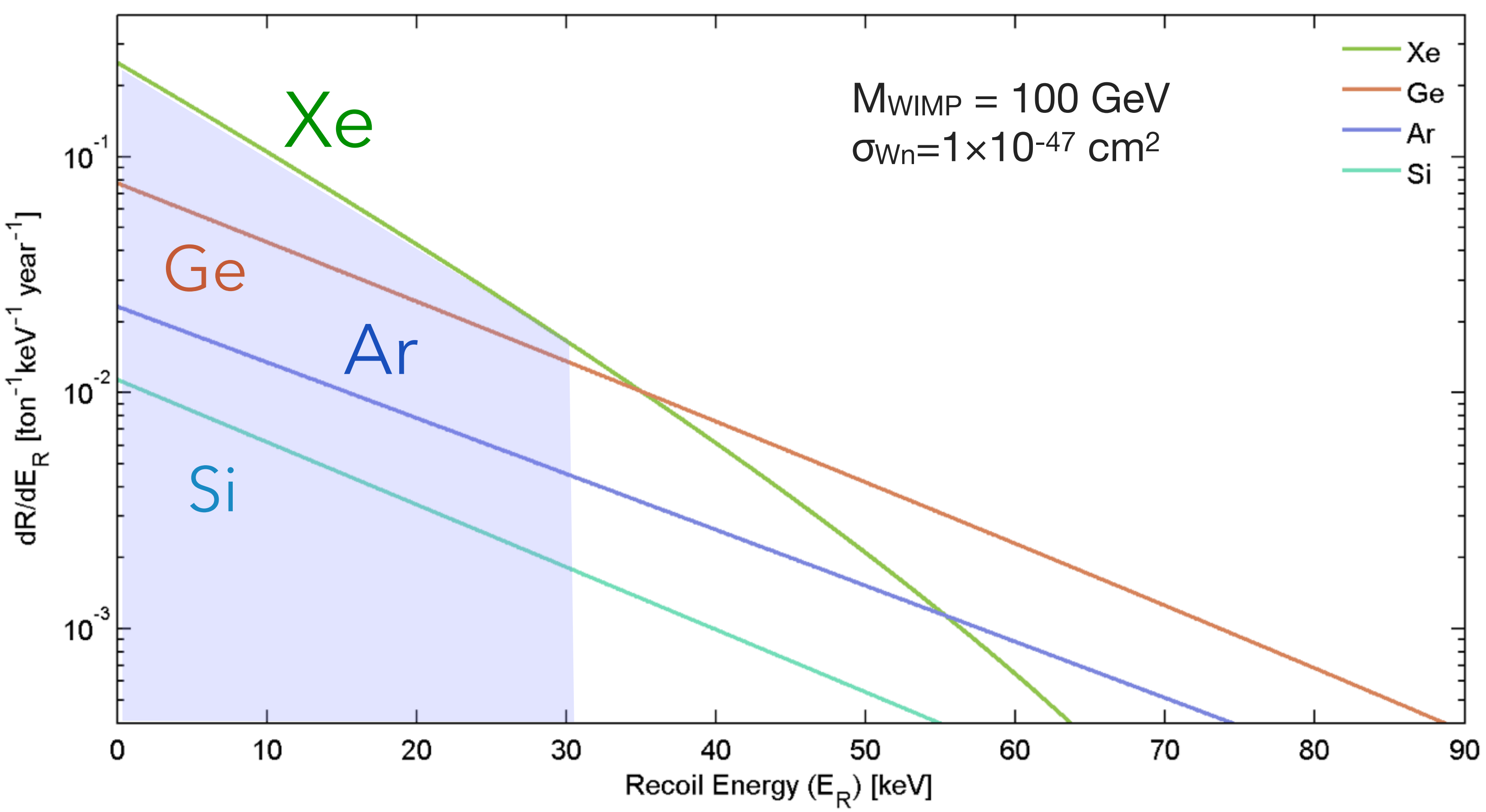
Ionisation-only searches



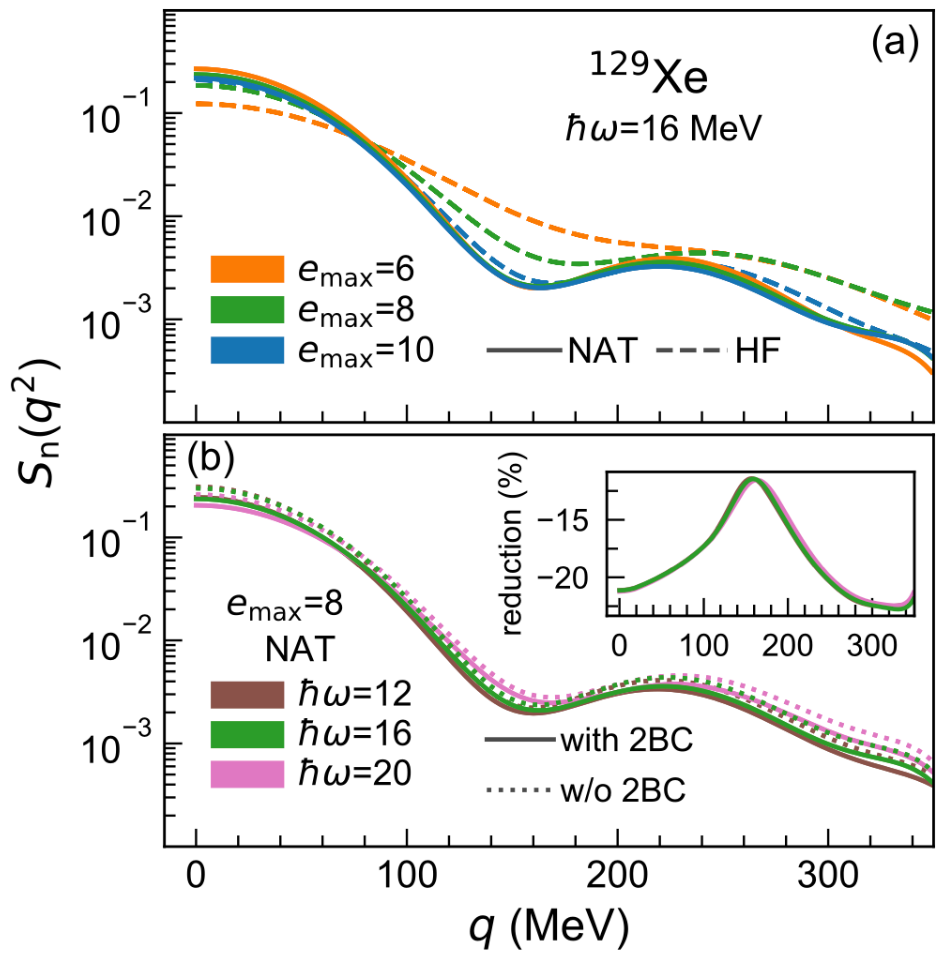
Interaction Rates: DM-Nucleus

$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

Spin-independent



Spin-dependent

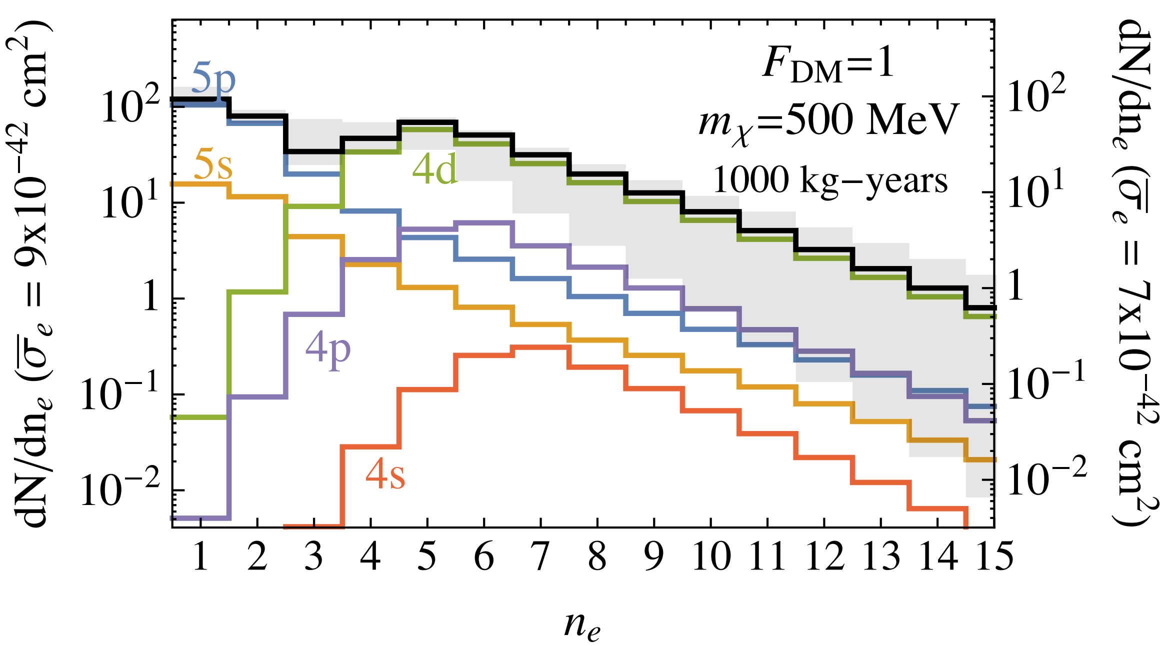


B.S. Hu et al, PRL 128, 2022

Interaction Rates: DM-Electron

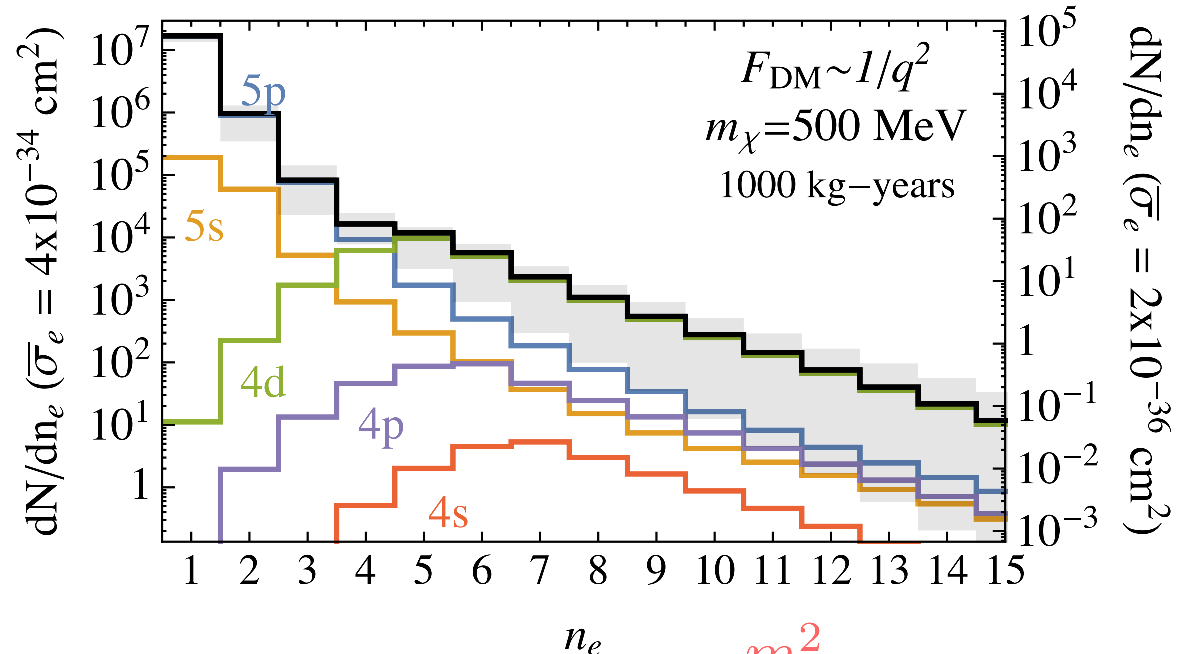
$$\frac{dR_{ion}}{d\ln E_R} = \frac{6.2}{A}\left(\frac{\rho_0}{0.4\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{\sigma_e}{10^{-40}\mathrm{cm}^2}\right)\left(\frac{10\,\mathrm{MeV}}{m_{\mathrm{DM}}}\right)\times\frac{d\langle\sigma_{ion}v\rangle/d\ln E_R}{10^{-3}\sigma_e}\,\frac{\mathrm{events}}{\mathrm{kg\,d}}$$

Number of events for a 1-tonne-year exposure in LXe (500 MeV DM)



$F_{DM} = 1$

Heavy dark photon A' mediator



$F_{DM} = \alpha^2 \frac{m_e^2}{q^2}$

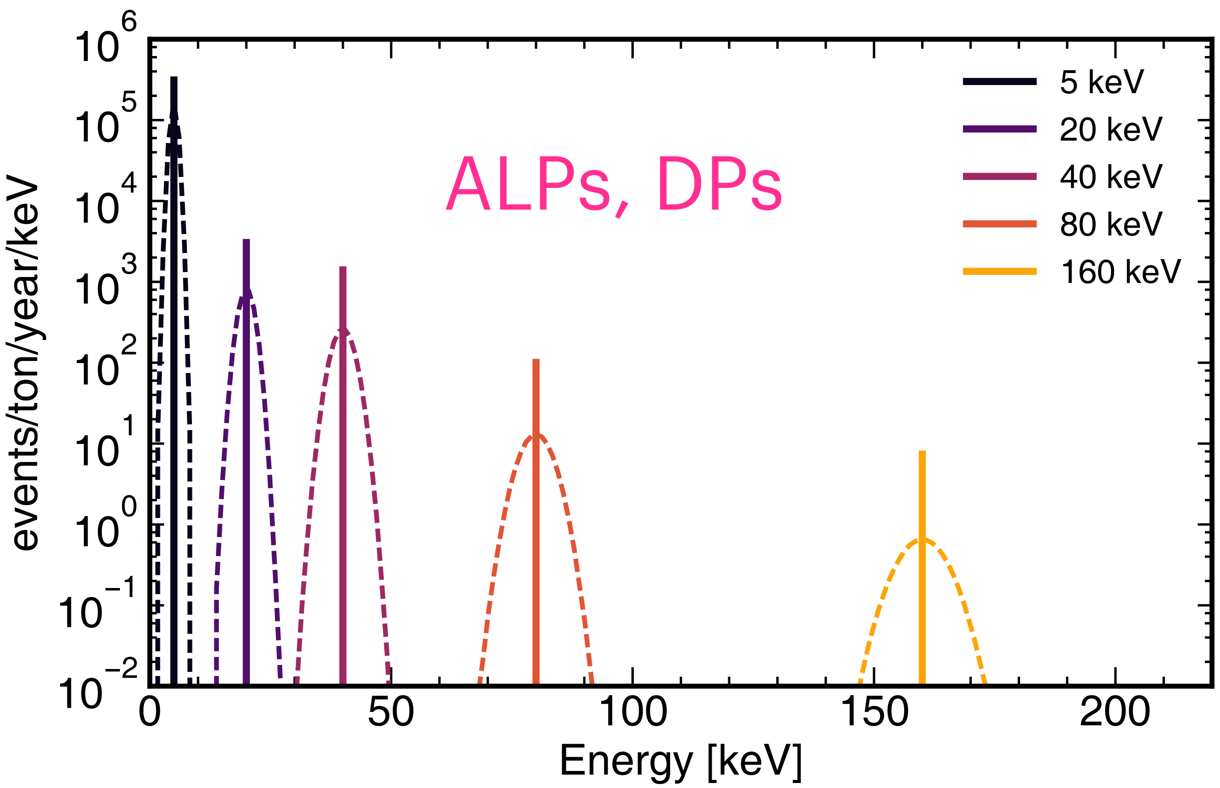
Ultra-light dark photon A' mediator

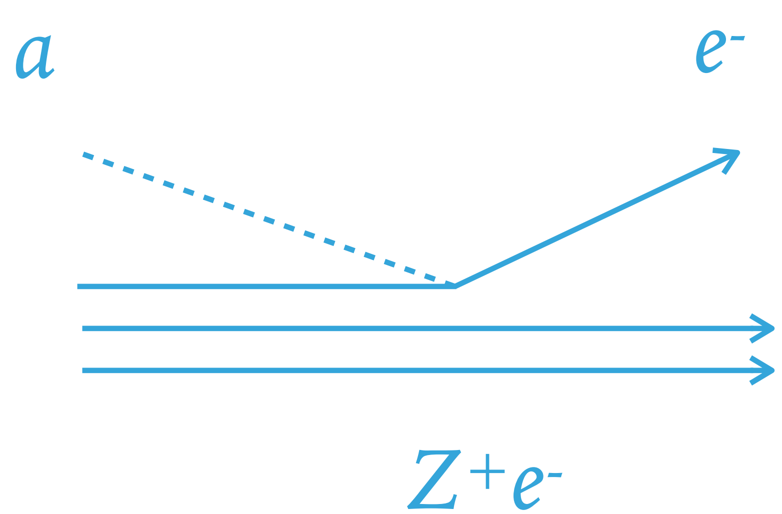
Essig, Volanski, Yu, PRD 96, 2017

Interaction Rates: DM Absorption

- **Absorption of bosonic DM** (keV-scale) ⇒ peak-like signatures
- **Rates:** ~ φ x σ ~ ρ x v/m x σ (here for ρ = 0.3 GeV/cm³)

$$R \simeq \frac{1.5 \times 10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\mathrm{keV}}\right) \left(\frac{\sigma_{pe}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

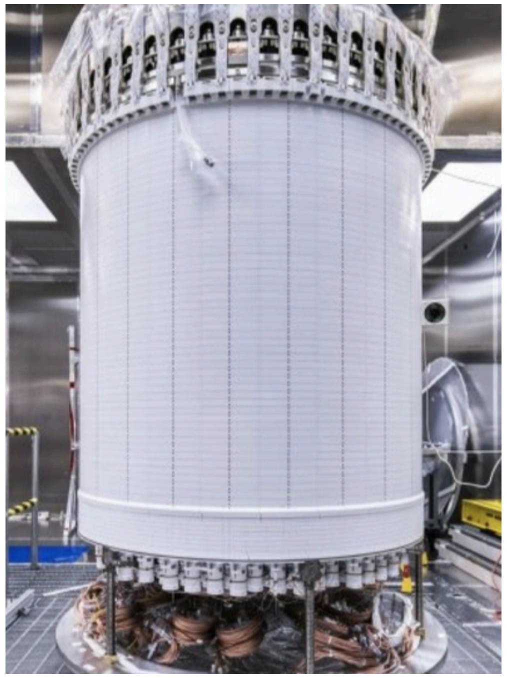




Pospelov, Ritz, Voloshin, PRD 78, 2008; An, Pospelov, Pradler, Ritz, PLB747, 2015

Ongoing Experiments

LUX-ZEPLIN



SURF: 7 (10) t

XENONnT

LNGS: 5.9 (8.6) t

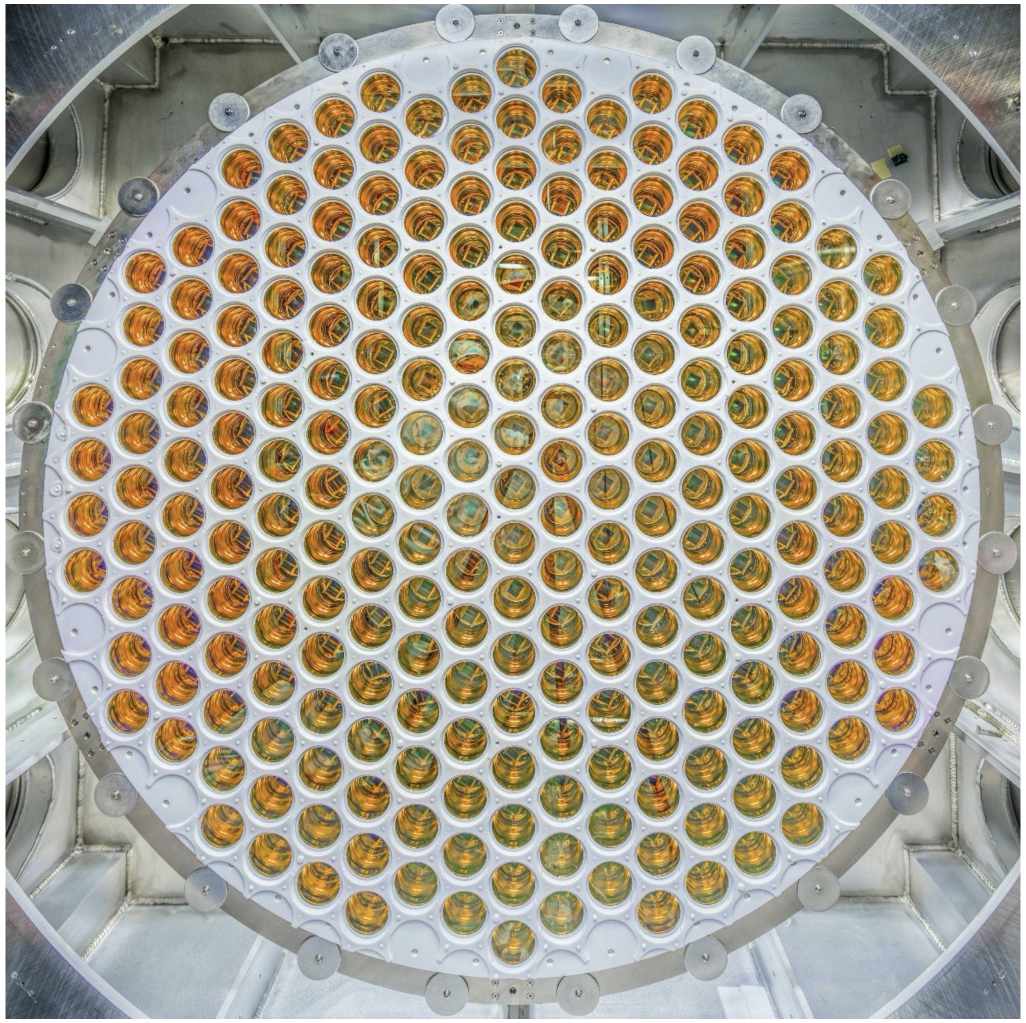
PandaX-4T

JinPing: 3.7 (5.6) t

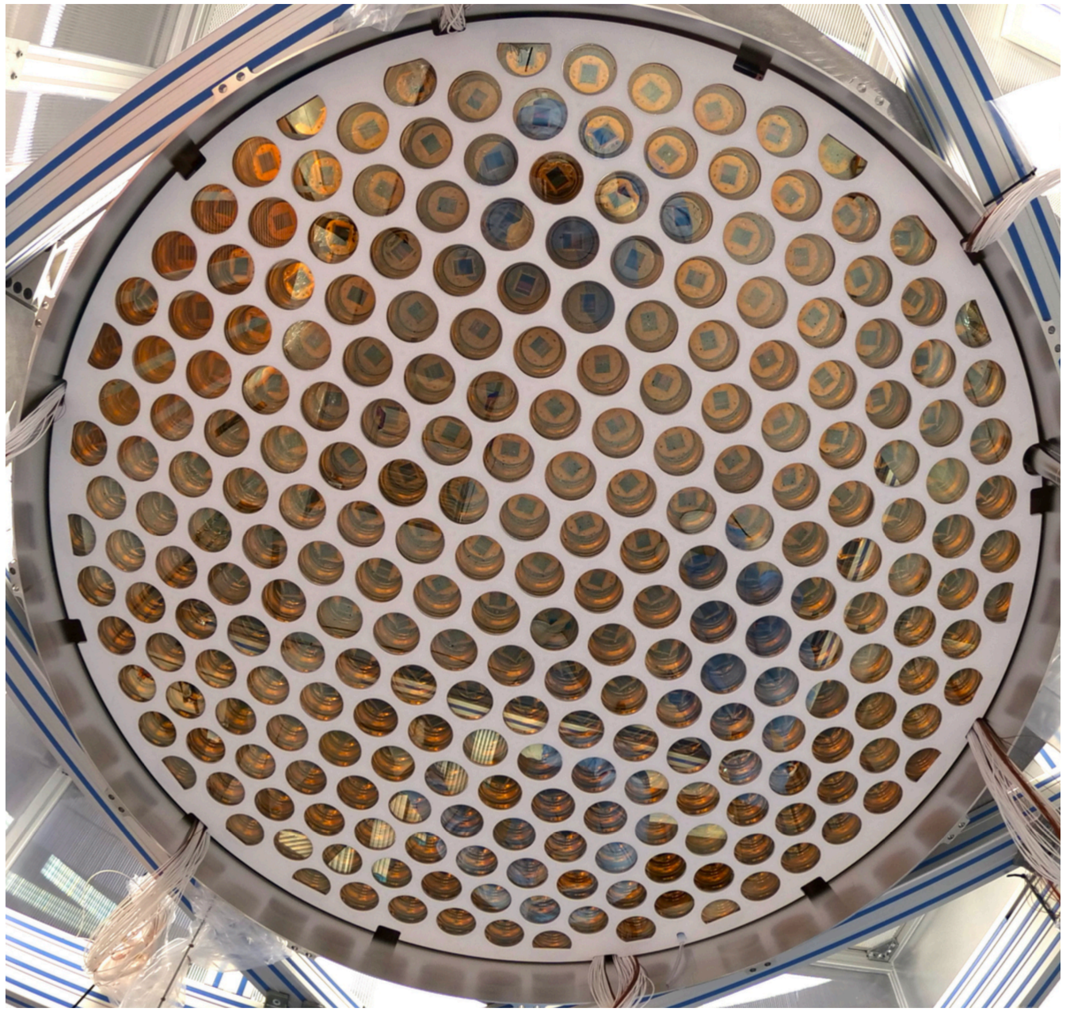
- **Two-phase TPCs:** 2 arrays of 3-inch ø low-radioactivity PMTs
- **Kr & Rn removal techniques:** mitigate ^{85}Kr and ^{222}Rn backgrounds
- **Ultra-pure water shields:** neutron & muon vetos

Detector Eyes for VUV-light

LUX-ZEPLIN top PMT array



XENONnT top PMT array

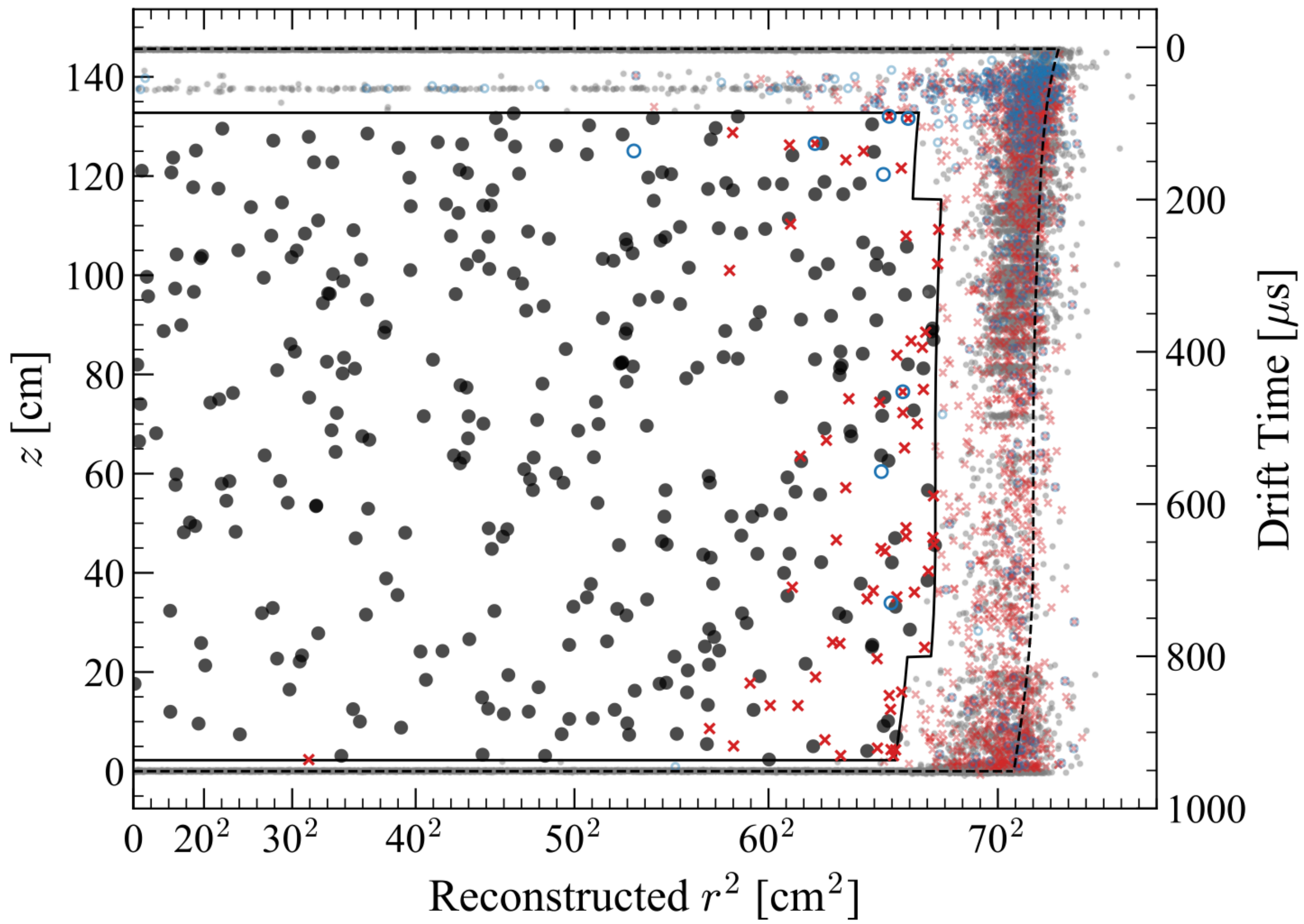


V.C. Antochi et al., JINST 16 (2021) 08, P08033

LUX-ZEPLIN and XENONnT

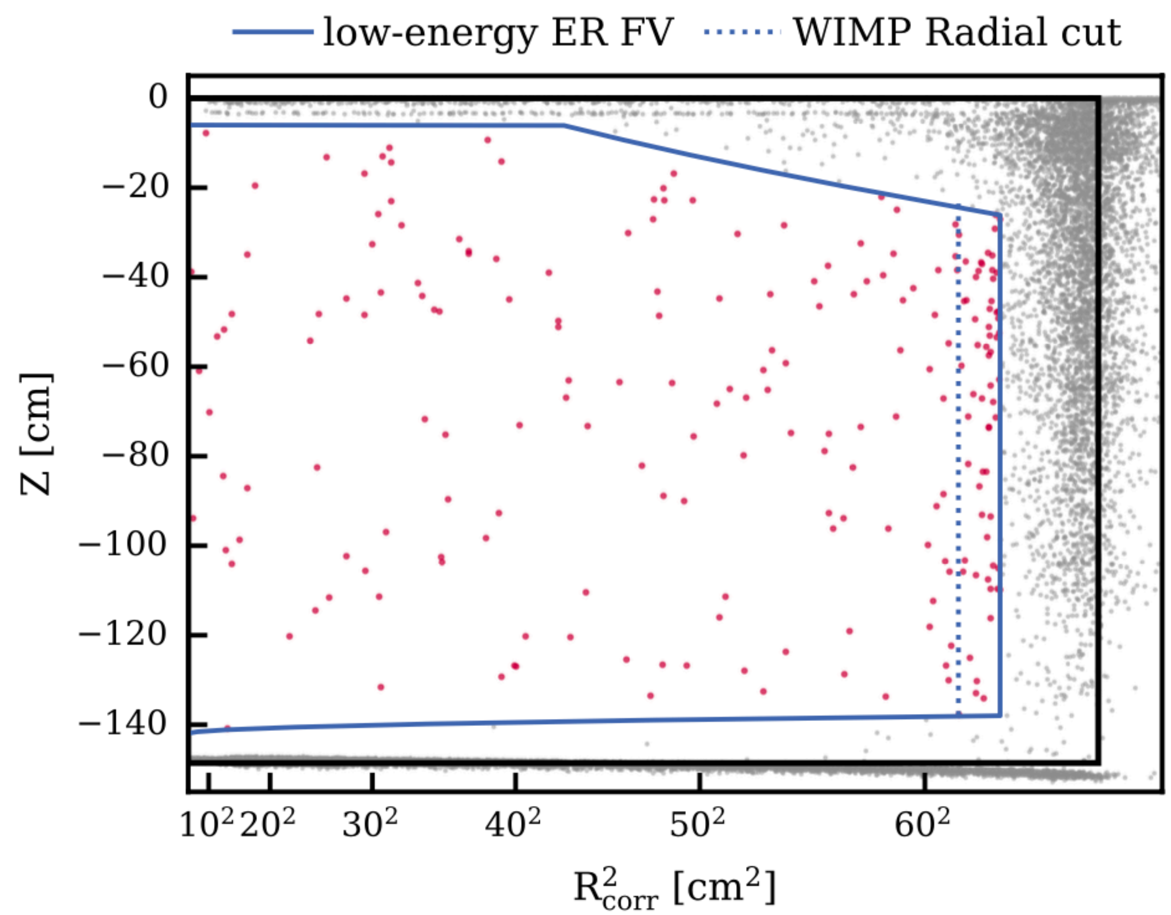
- Spatial distribution of events in the TPCs

LUX-ZEPLIN



LZ, PRL 131, 2023

XENONnT

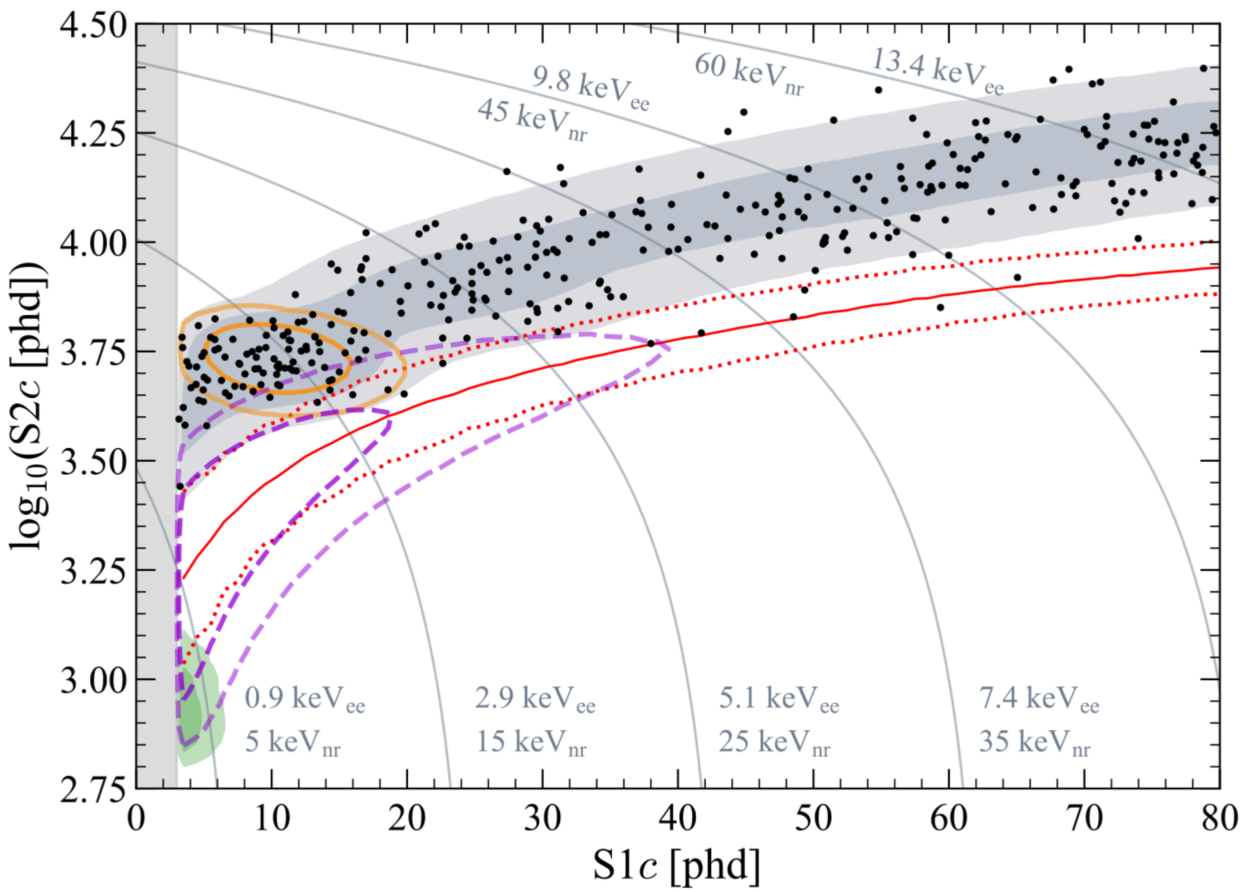


XENONnT, PRD 111, 2025

LUX-ZEPLIN and XENONnT

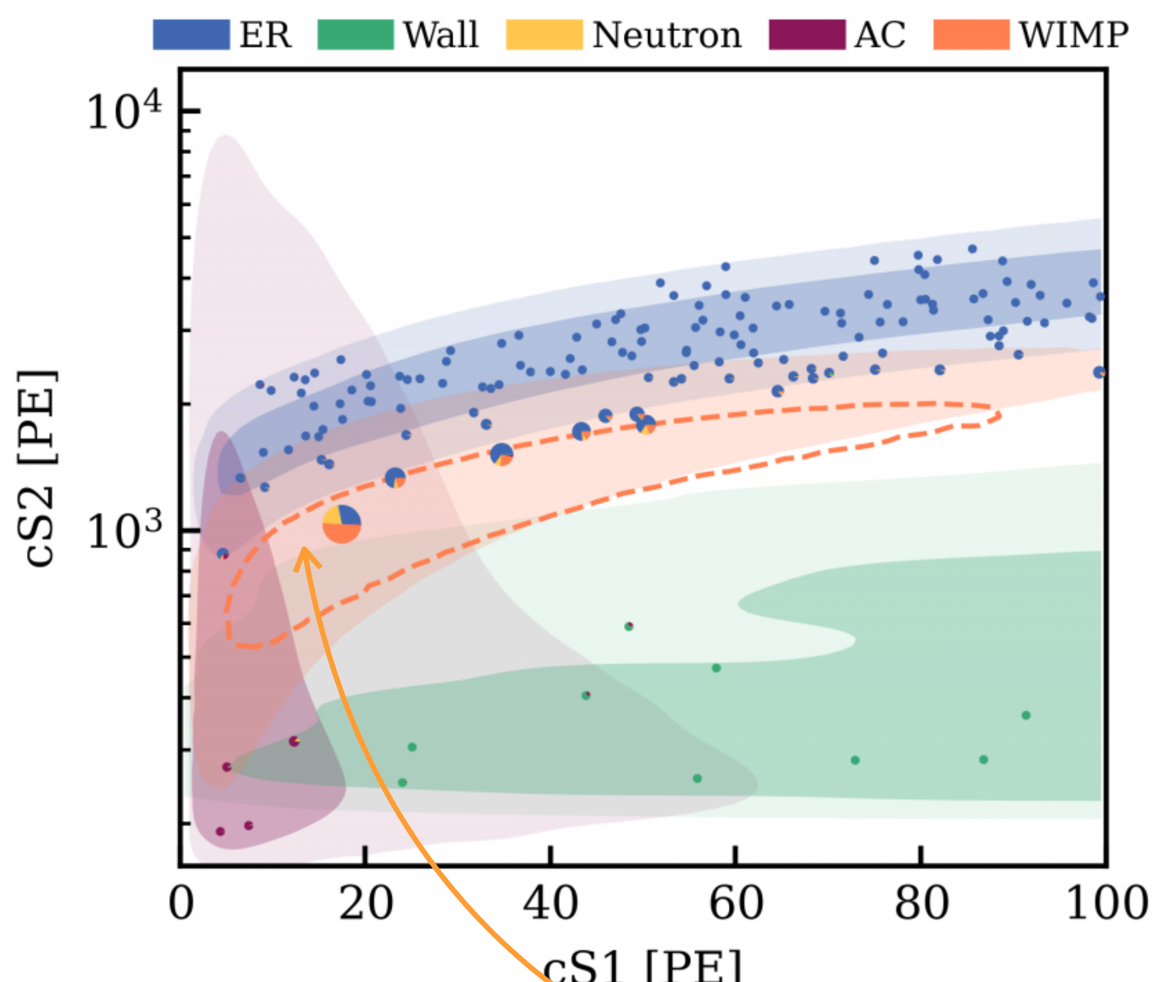
- Distribution of events in S2 versus S1 space in the TPC

LUX-ZEPLIN



LZ, PRL 131, 2023

XENONnT

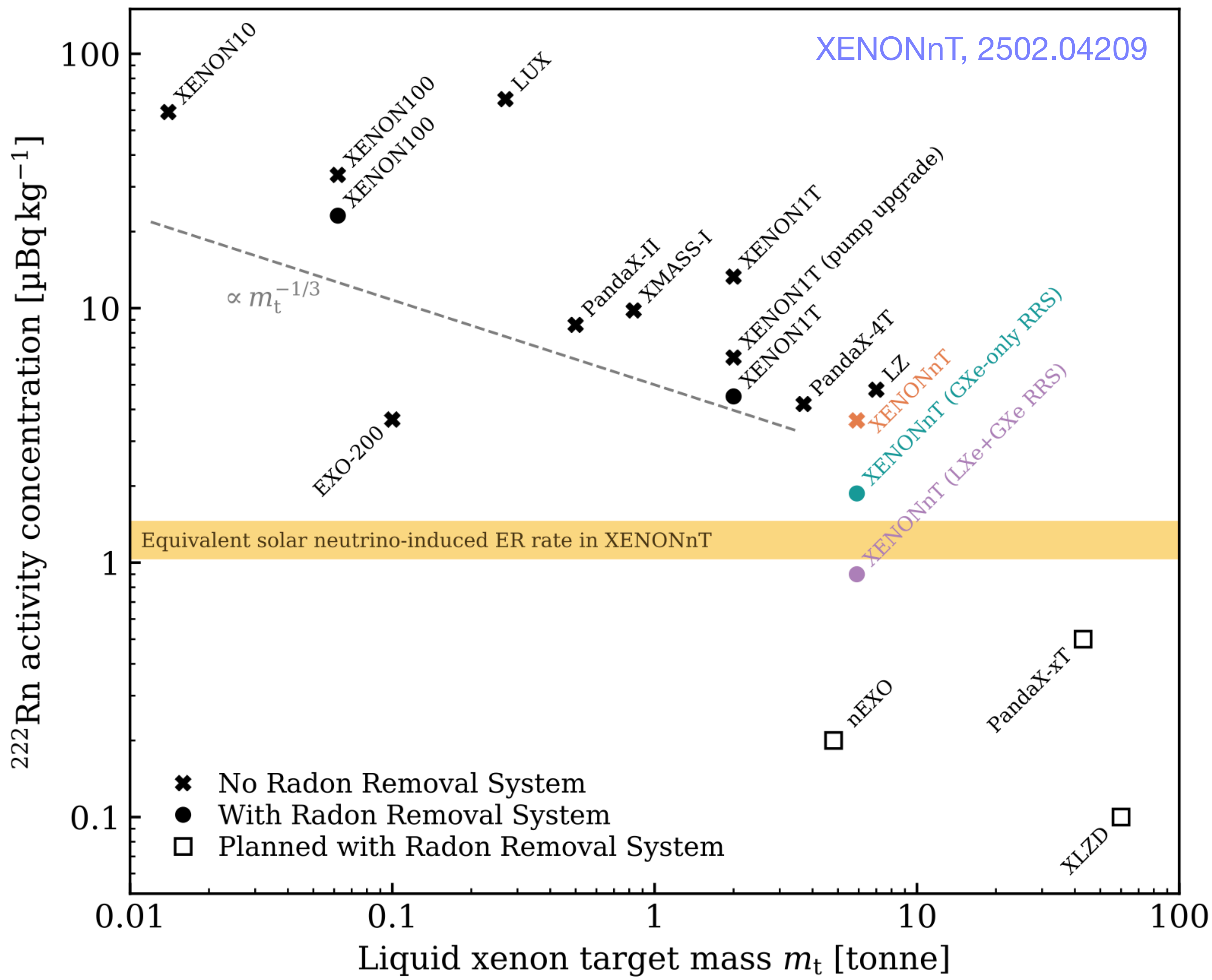


XENON PRL 131, 2023

2σ contour of 200 GeV/c² WIMP

Backgrounds

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

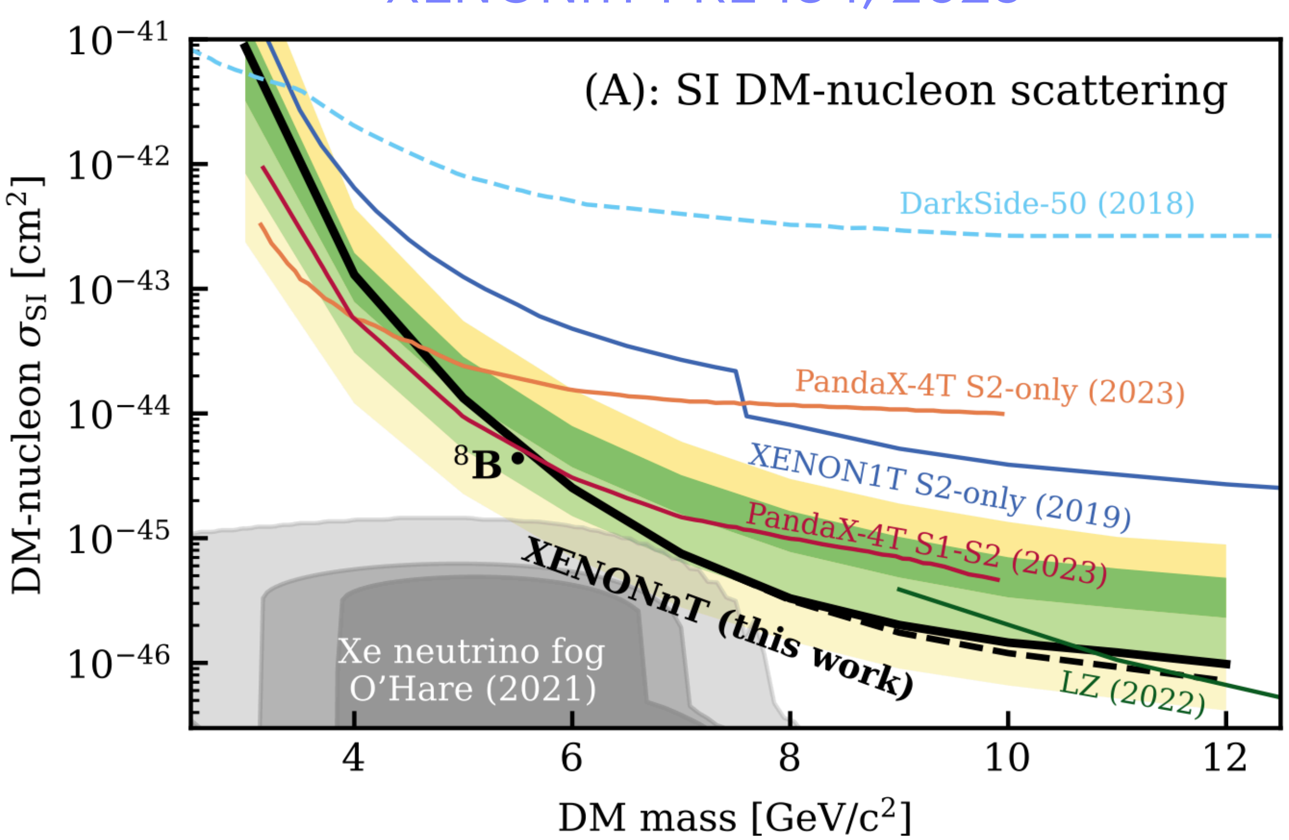


Solar pp-ν equivalent rate

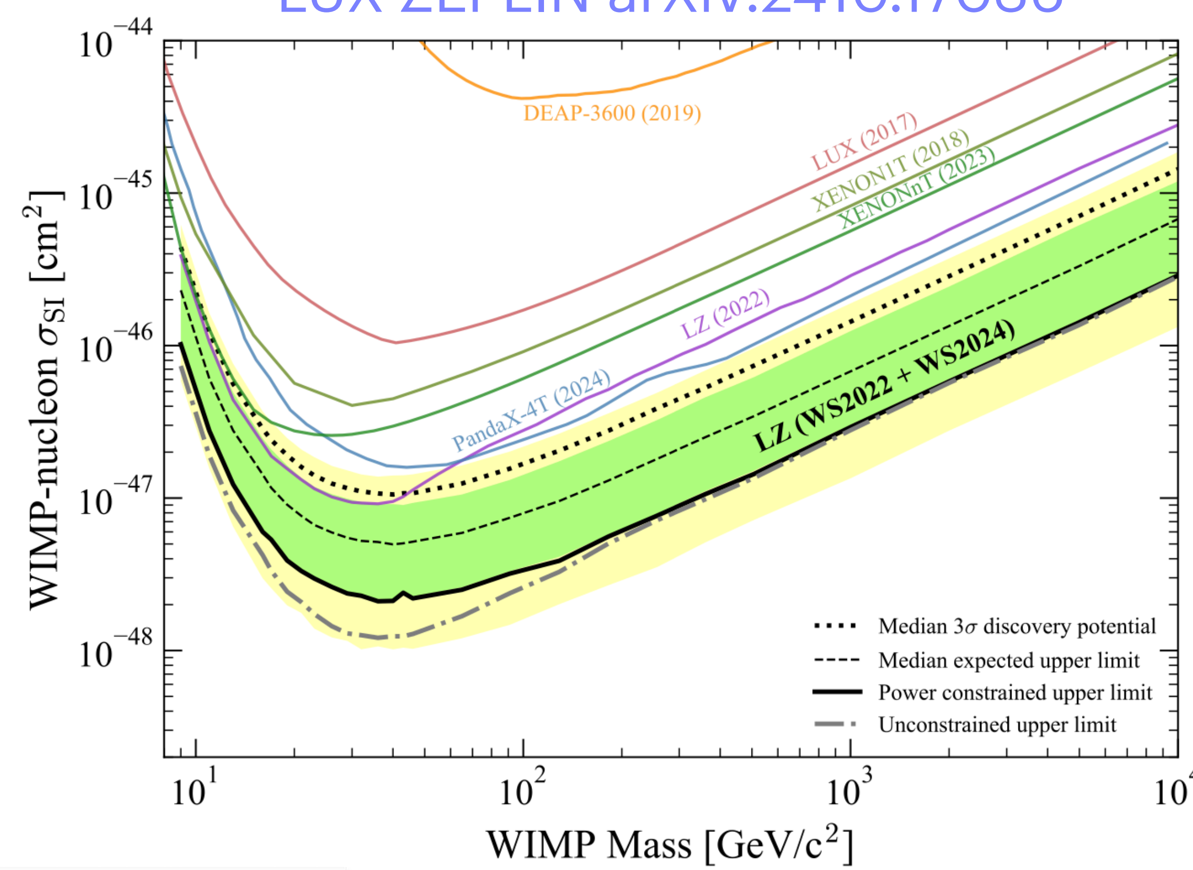
Recent Results: DM-Nucleus

- DM mass range: ~ 3 GeV - 10 TeV

XENONnT PRL 134, 2025



LUX-ZEPLIN arXiv:2410.17036



EDITORS' SUGGESTION | OPEN ACCESS

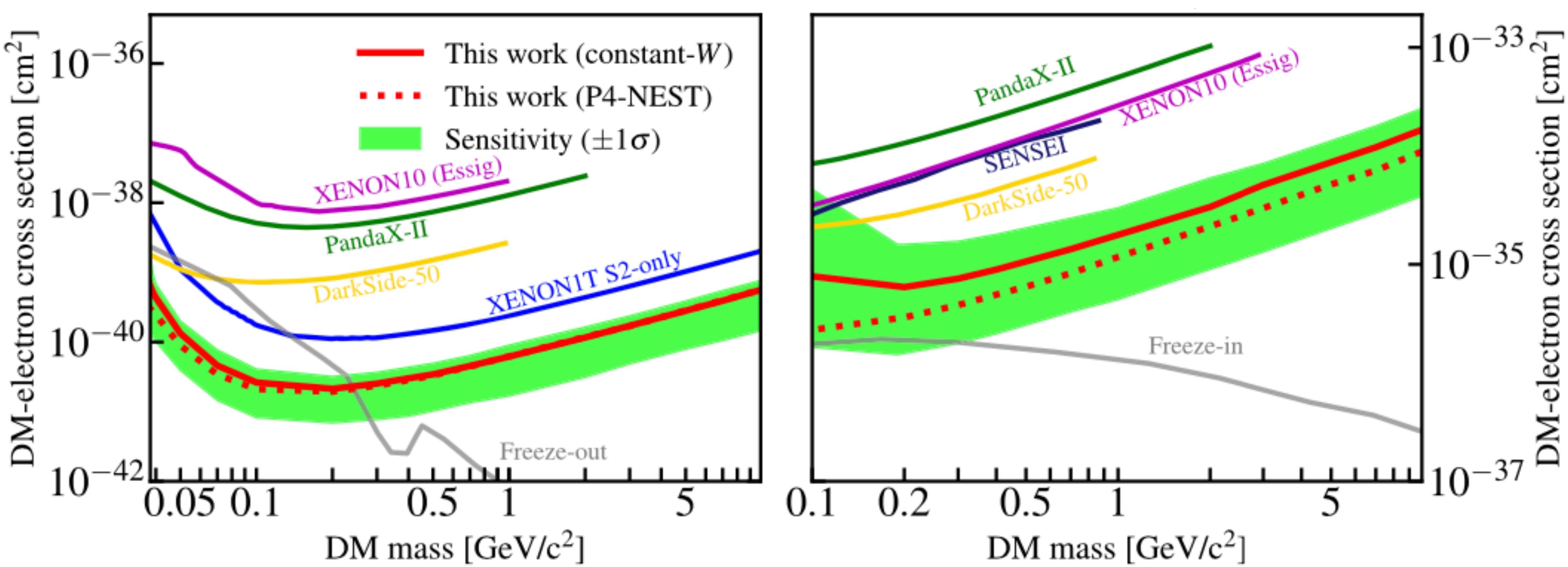
First Search for Light Dark Matter in the Neutrino Fog with XENONnT

Recent Results: DM-Electron

- DM mass range: ~ 50 MeV - 10 GeV

PandaX-4T, PRL 130, 2023

$F_{DM} = 1$ $F_{DM} = 1/q^2$



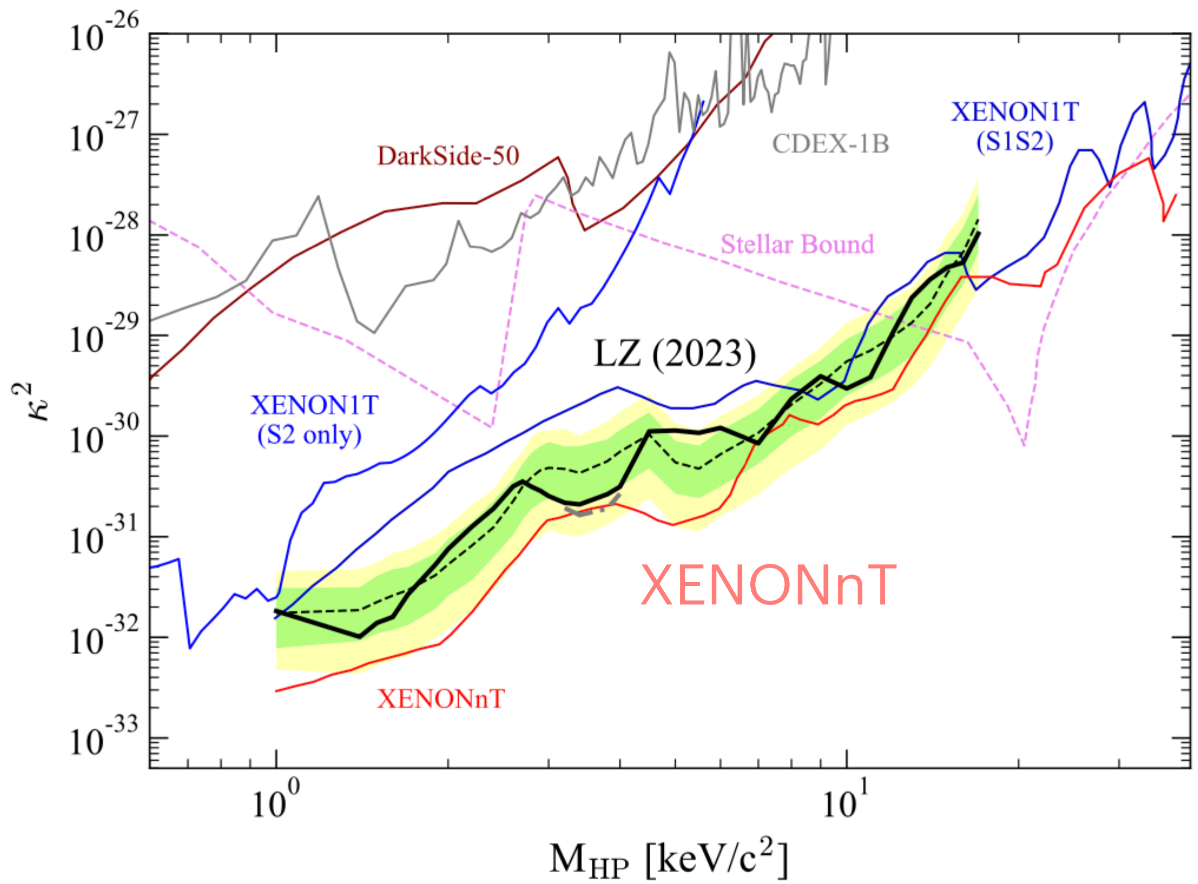
Heavy dark photon A′ mediator

Ultra-light dark photon A′ mediator

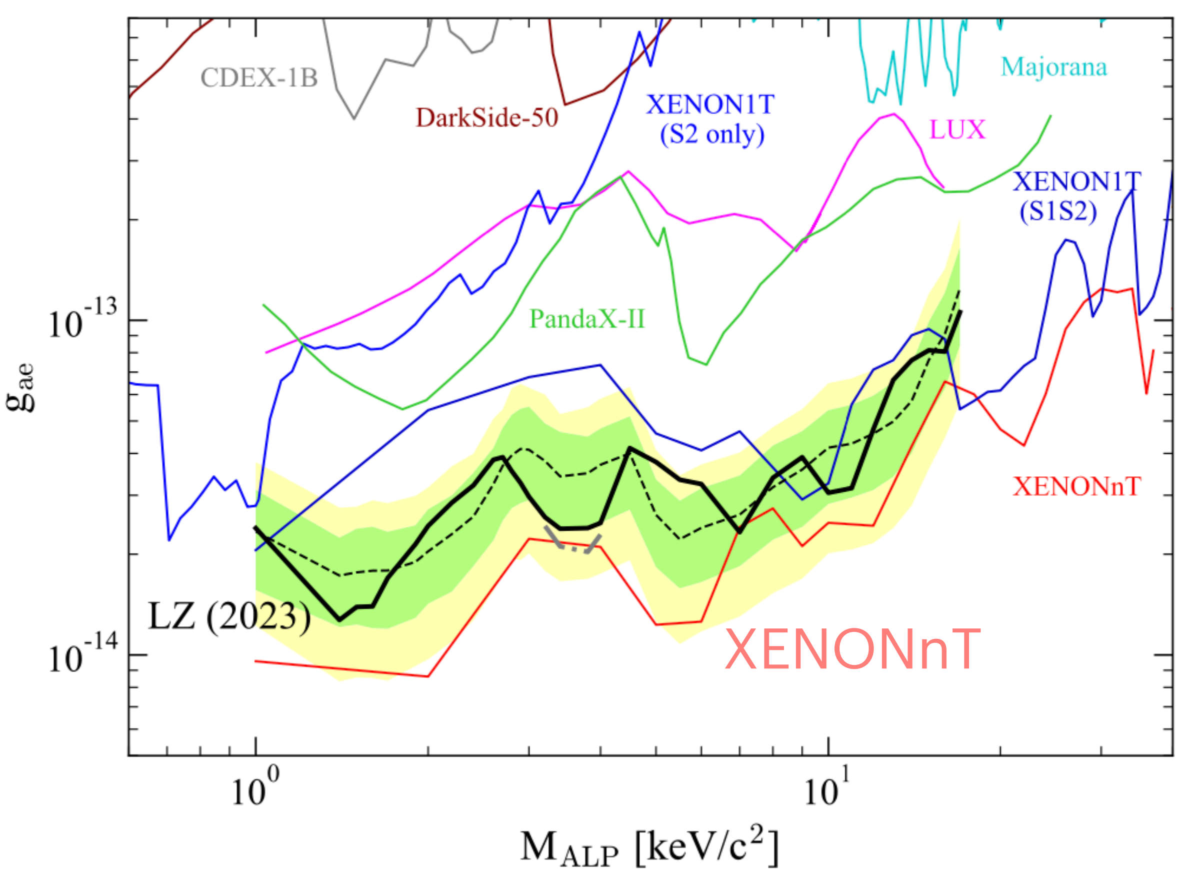
Recent Results: DM Absorption

- DM mass range: ~ 0.5 keV - 100 keV

Dark photons



Axion like particles

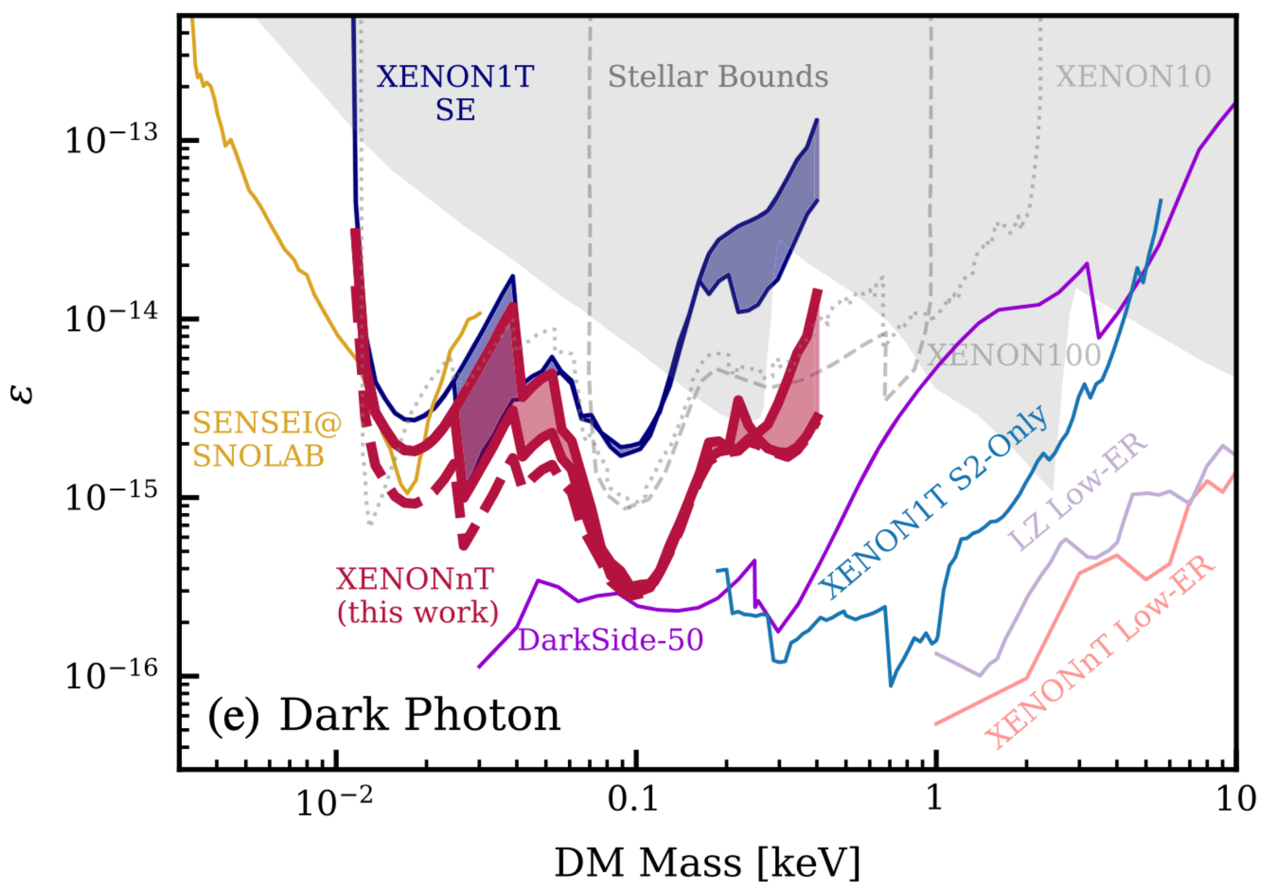


XENONnT, PRL 129, 2022; LZ, PRD 108, 2023

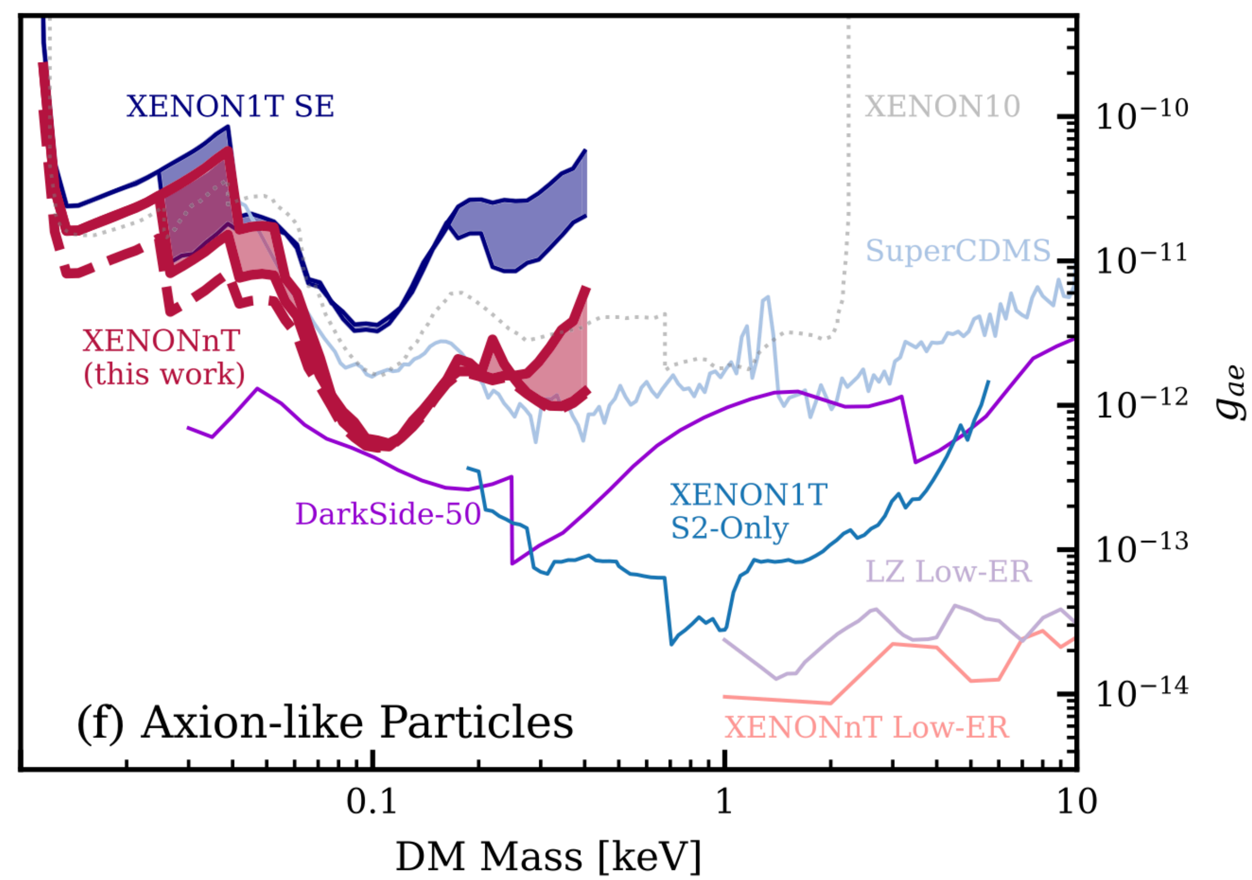
Recent Results: DM Absorption

- DM mass range: ~ 0.01 keV - 10 keV

Dark photons



Axion like particles

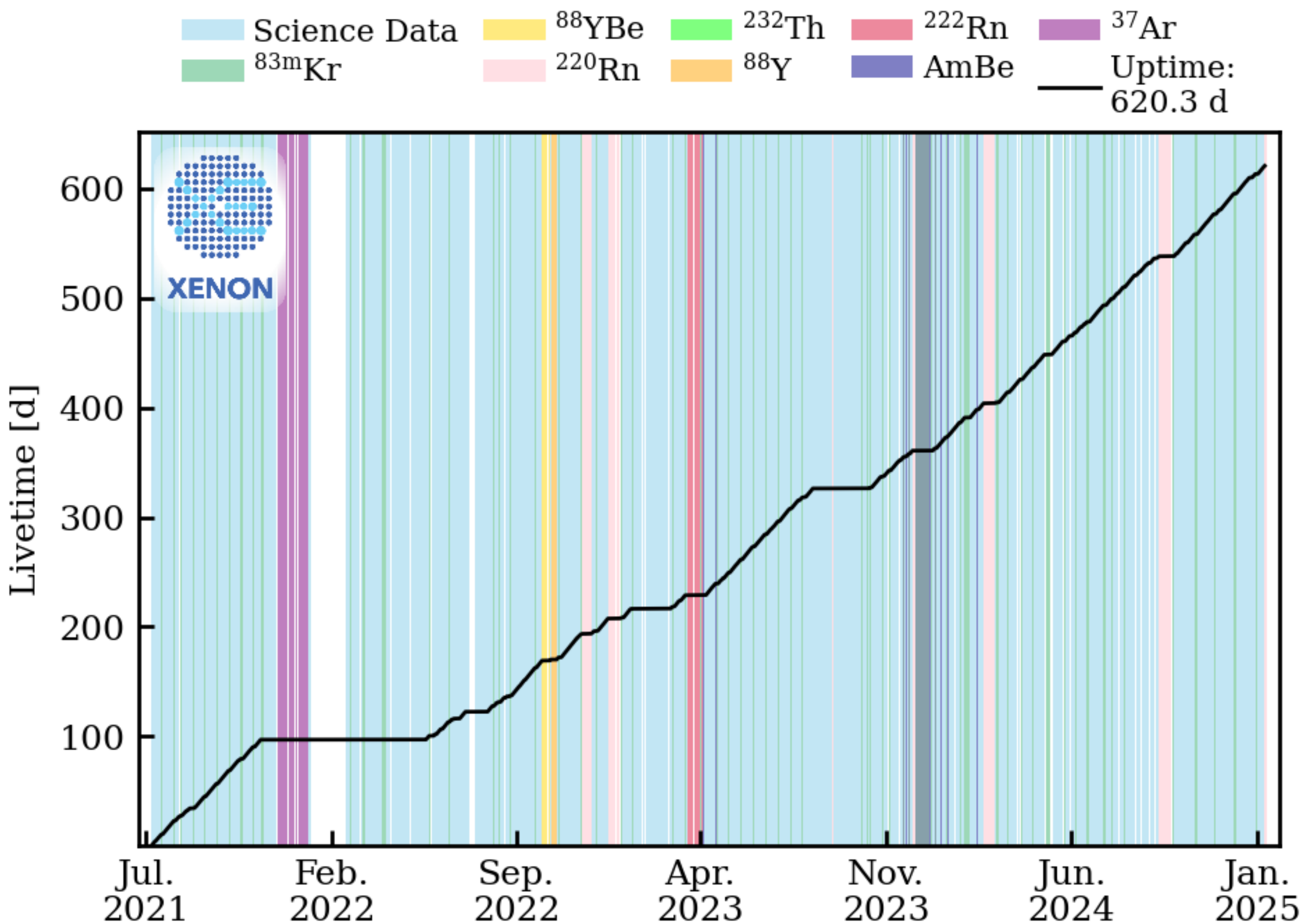


XENONnT, PRL 134, 2025

XENONnT at LNGS

XENONnT at LNGS

- Several science runs (SR0, SR1, SR2), analyses ongoing



XENONnT at LNGS

- Several science runs (SR0, SR1, SR2), analyses ongoing: examples

✳pp and ^{7}Be solar neutrinos
✳bosonic DM
✳solar axions

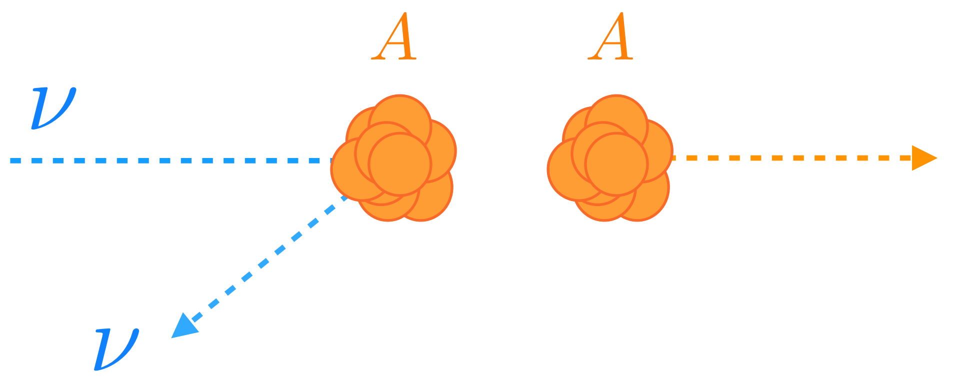
✳ββ-decay ^{136}Xe ($Q_{\beta\beta}$ = 2.46 MeV)
✳DEC, ECβ^{+}-decay ^{124}Xe (Q_{DEC} = 2.86 MeV)

✳^{8}B solar neutrinos
✳WIMP DM (SI, SD)

✳inelastic DM
✳EFT DM models

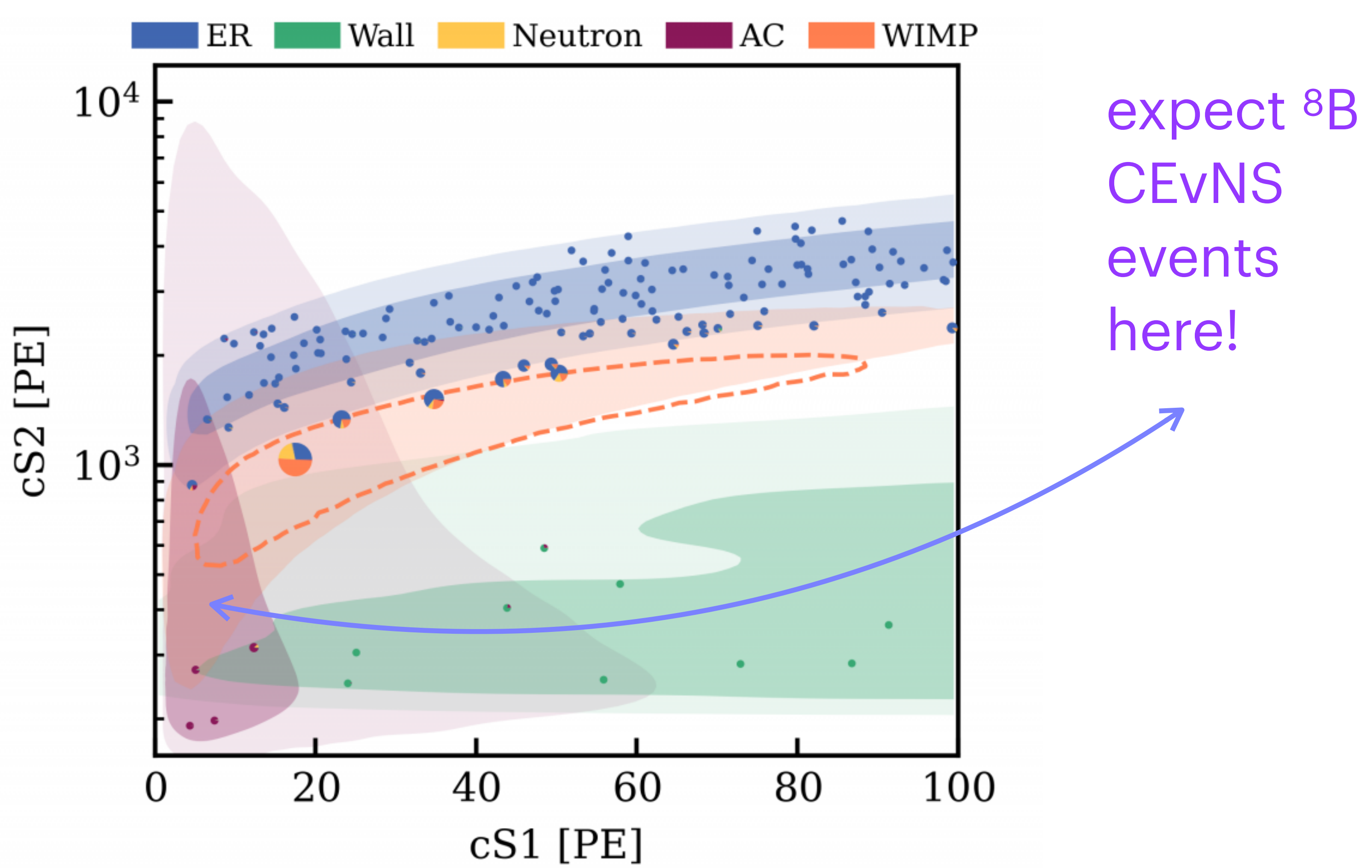
Solar Neutrinos: ν-Nucleus Scattering

- Observed ^{8}B neutrinos via CEvNS
- In LXe: ~99% of events < 4 keV NR energy
- Expect: ~ 10^4 events/(200 t y)



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

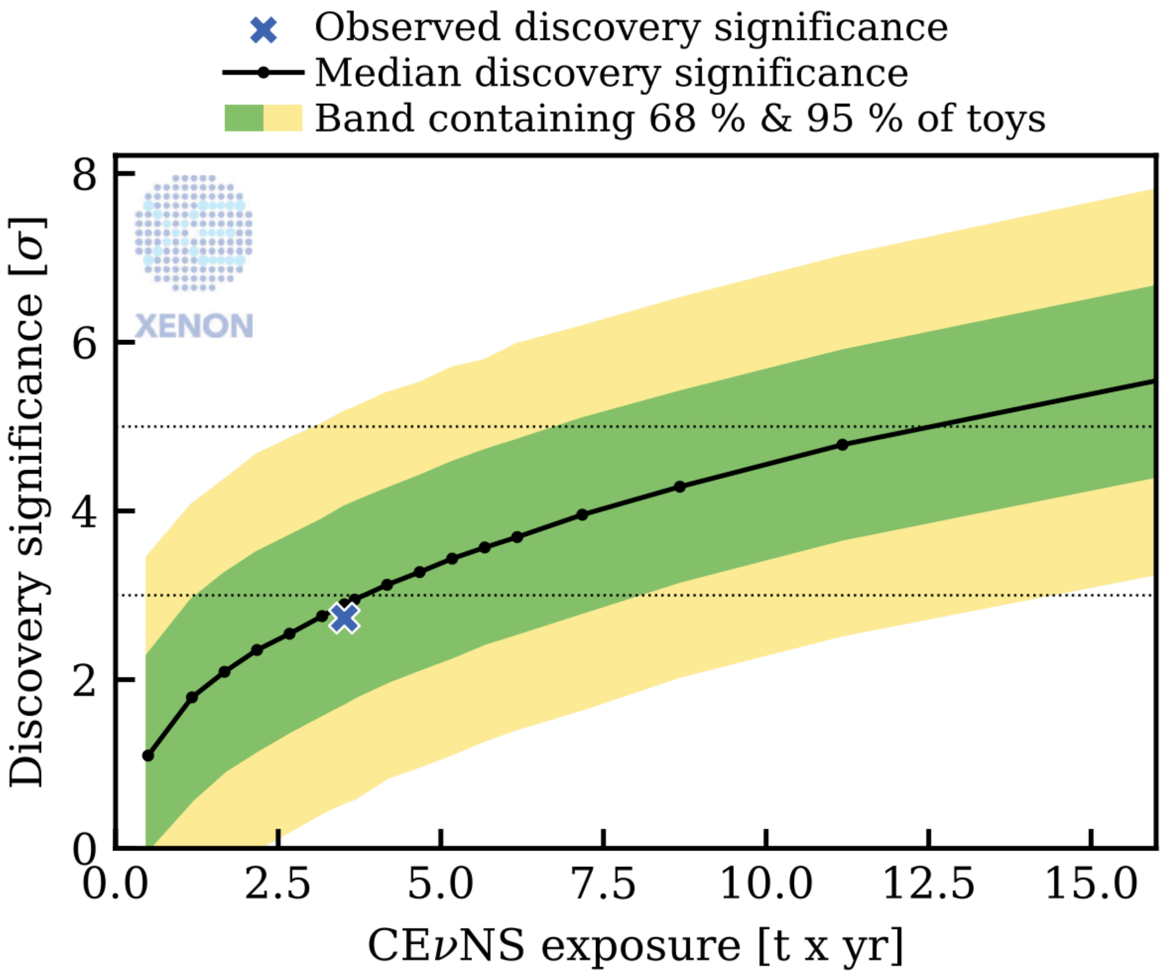
XENON, PRL 131, 2023

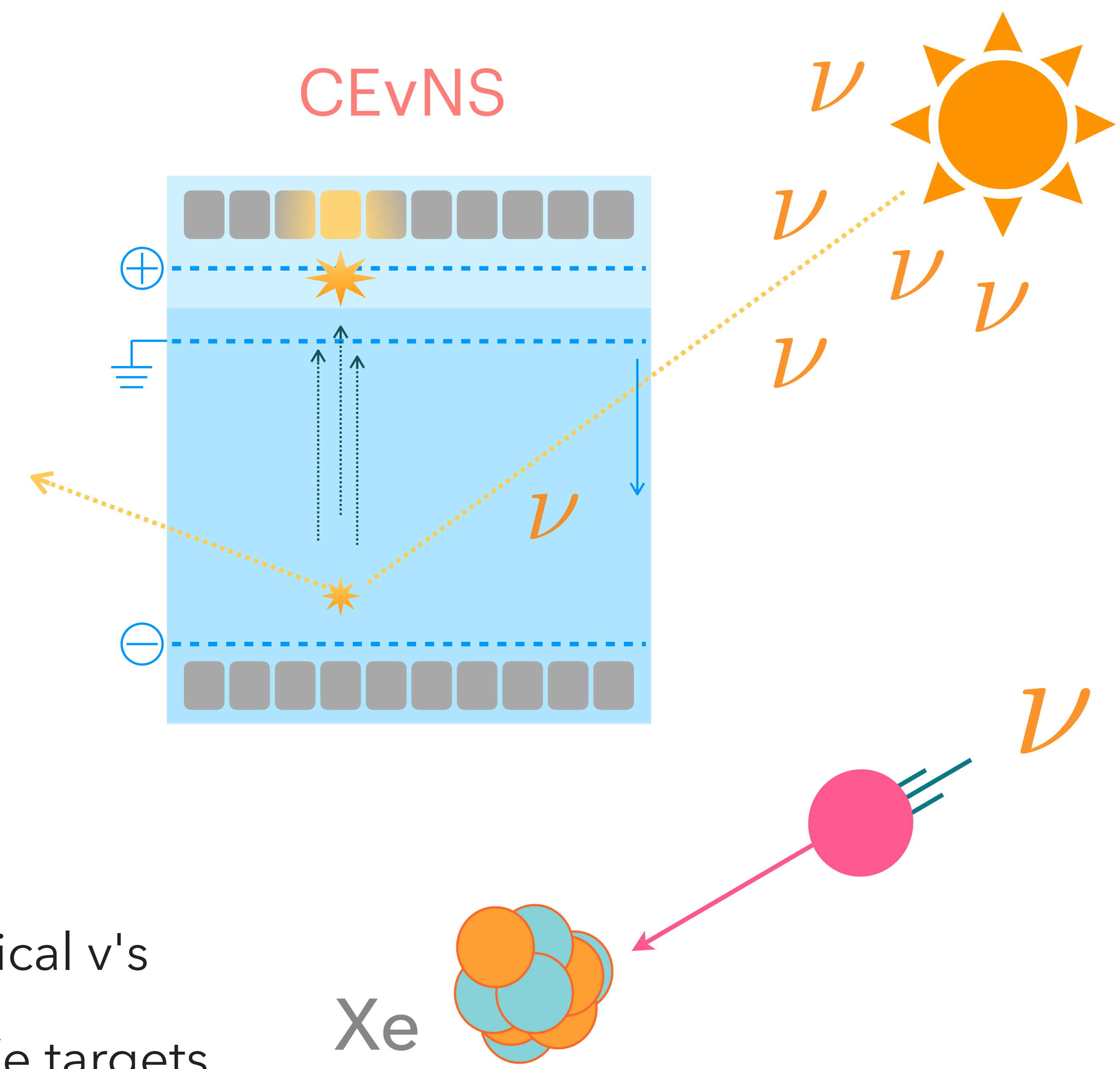


✳ Complementary measurements to experiments using CC reactions

✳ "Flavour democratic" (C. Lunardi, Neutrino-2024)

Solar Neutrinos: ν-Nucleus Scattering





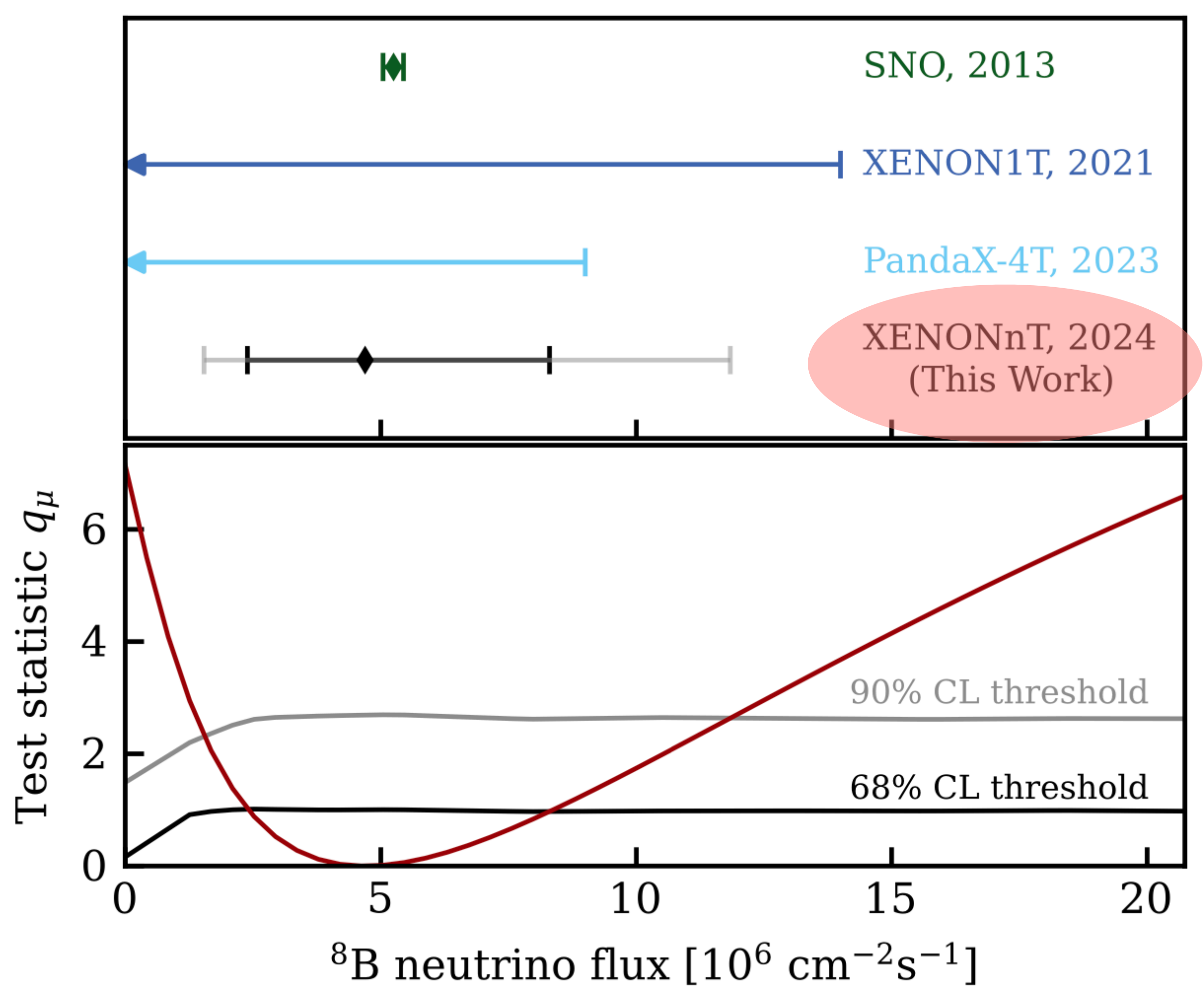
- **First** detection of elastic NRs from astrophysical ν's
- **First** measurement of CEvNS process with Xe targets
- **First** step into the "neutrino fog" by a DM experiment

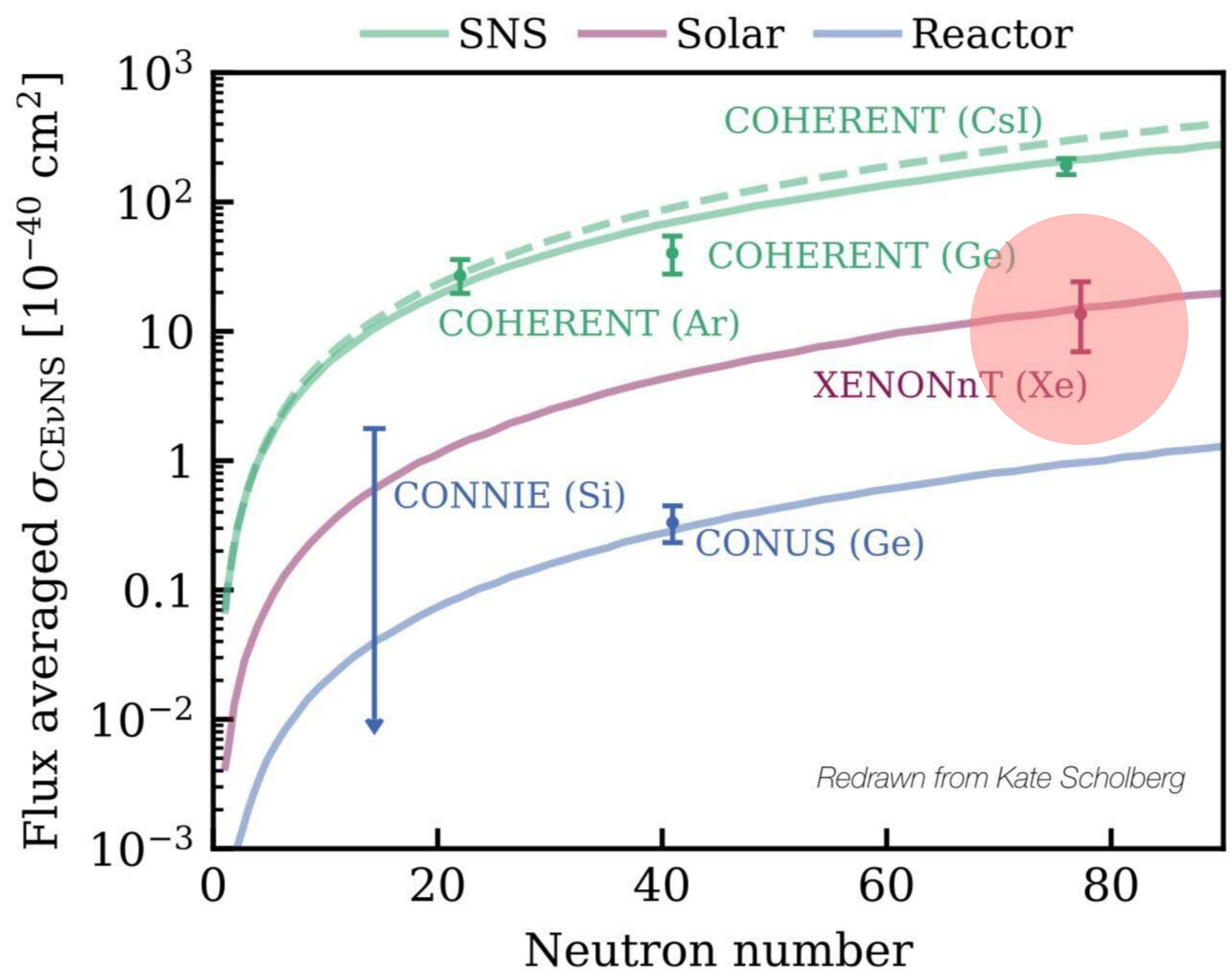
XENONnT: PRL 123, 2024

Solar Neutrinos: ν-Nucleus Scattering

- Measured ^{8}B flux: (4.7 + 3.6 - 2.6) x 10^6 cm^{-2}s^{-1}
- 5-σ discovery and precision measurement in reach with XENONnT data

XENONnT: PRL 123, 2024





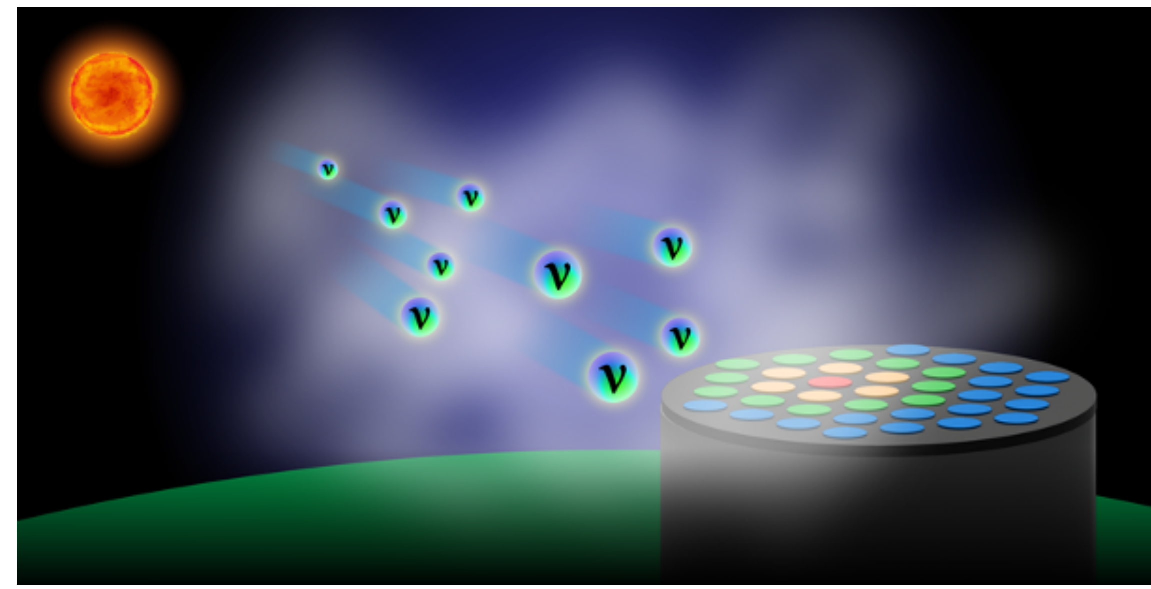
Solar Neutrinos: ν-Nucleus Scattering

Highlights of the Year

December 16, 2024 • *Physics* 17, 181

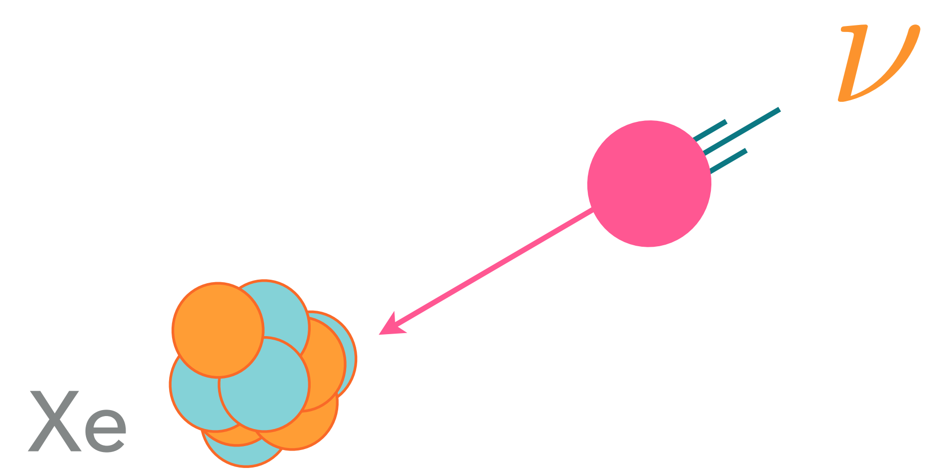
***Physics Magazine* Editors pick their favorite stories from 2024.**

APS/Alan Stonebraker



Neutrino Fog Rolling into Sight

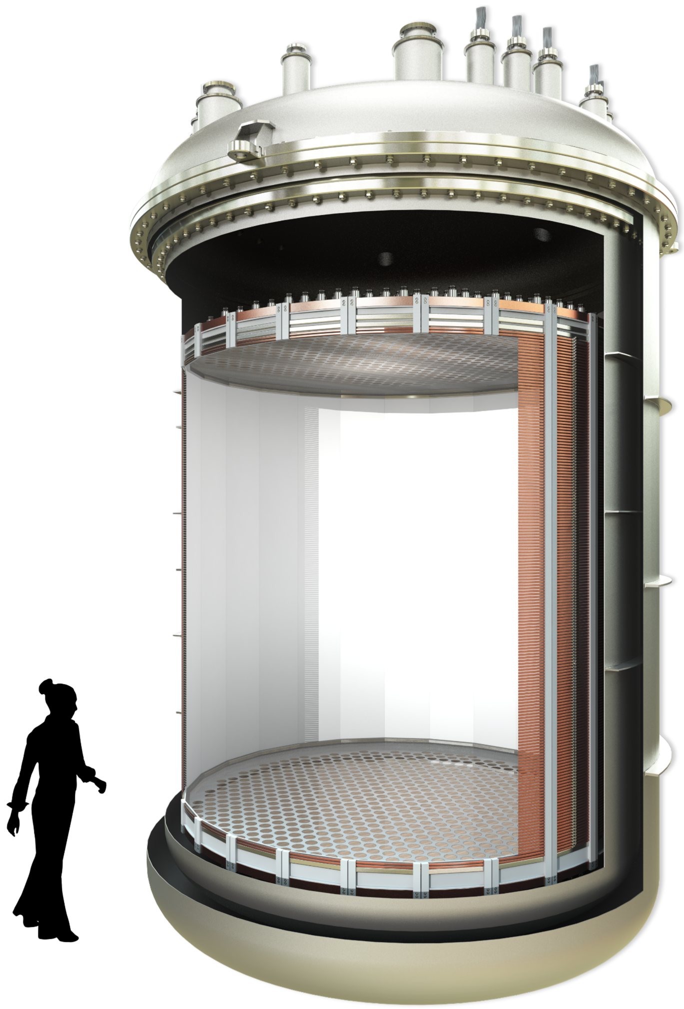
After years of null results, dark matter searches might finally have a real signal to contend with. Alas, the signal doesn't come from dark matter particles but from a stream of neutrinos produced by nuclear reactions in the Sun (see **Research News: First Glimpses of the Neutrino Fog**). In 2024, the PandaX and XENON collaborations independently reported that their detectors have likely started to see this "neutrino fog." Whereas in the long run the neutrino fog could pose a threat to dark matter searches, researchers agree that its impact won't be felt until next-generation experiments kick off in a decade or so. What's more, dark matter experiments could be turned into multipurpose detectors for probing various aspects of neutrino physics.



XENONnT: PRL 123, 2024

Future Liquid Xenon TPCs

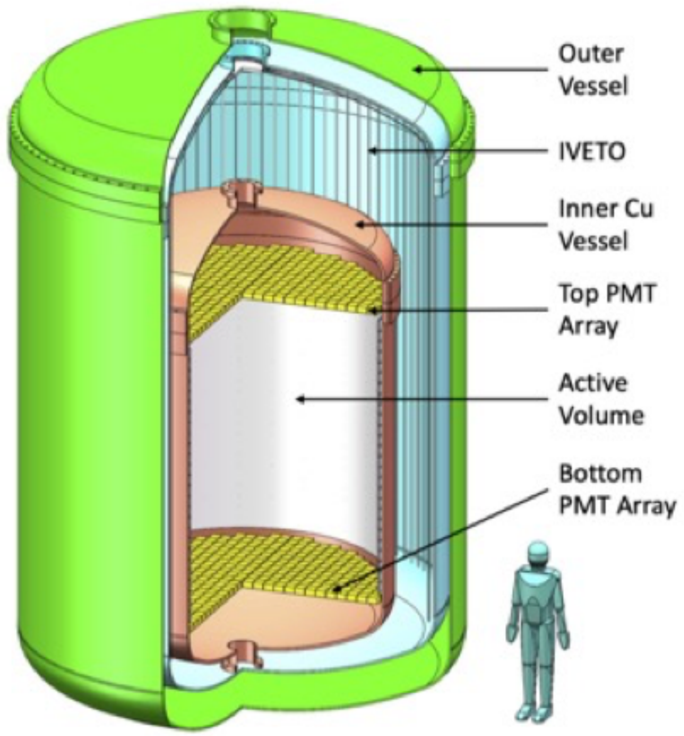
XLZD (XENON-LZ-DARWIN)



78 t LXe (60 t active target)

2 arrays of 3-inch PMTs

PandaX-xT

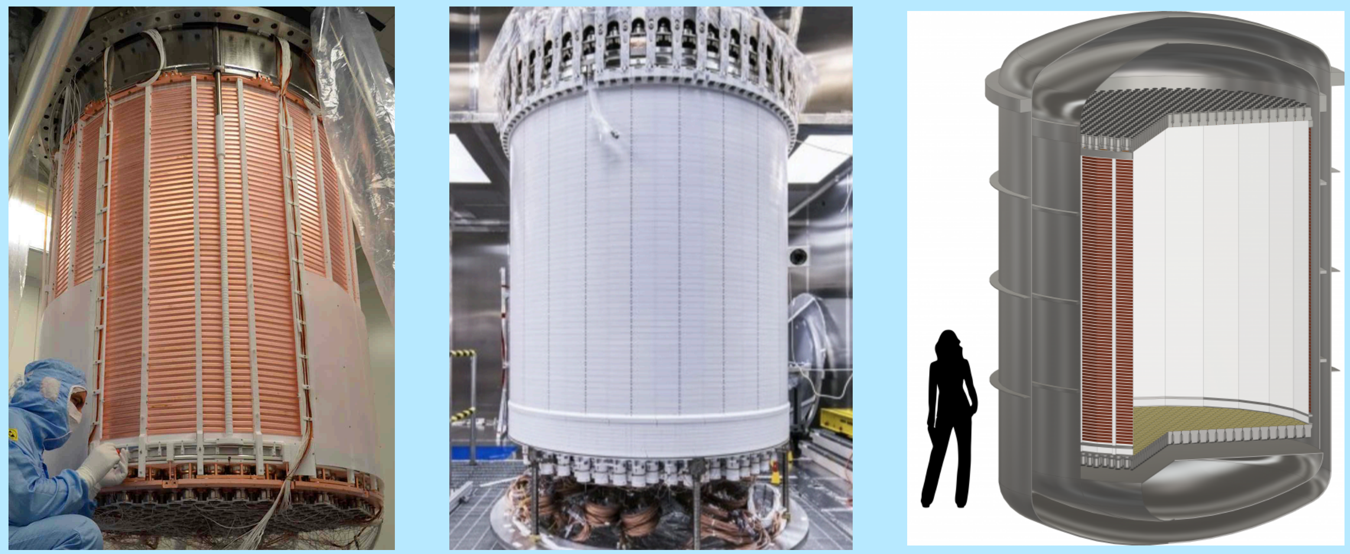


47 t LXe (43 t active target)

2 arrays of 2-inch PMTs

XLZD

XENON-LUX-ZEPLIN-DARWIN



DARWIN collaboration
JCAP 1611 (2016) 017

- New collaboration to build & operate next-generation detector
- Demonstrated experience in large-scale LXe TPCs
- July 2021: MoU signed by 104 research group leaders from 16 countries
- Several meetings (KIT, UCLA, RAL); since fall 2024 full collaboration
- Executive committee and WGs in place. Design Book here: 2410.17137

XLZD

XENON-LUX-ZEPLIN-DARWIN

KIT, summer 2022

UCLA, spring 2023

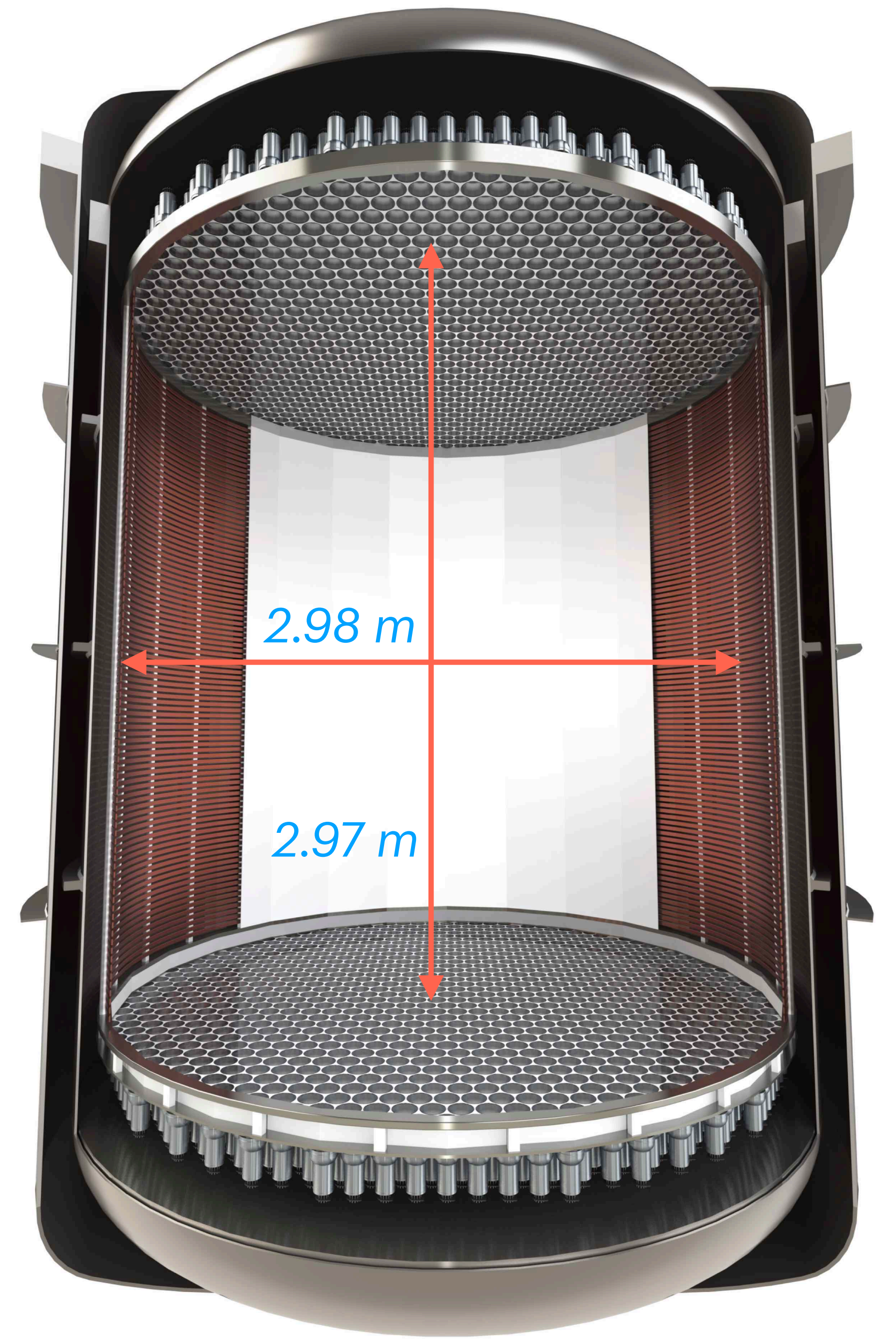
RAL, spring 2024

Next: LNGS, July 2025

XLZD Nominal Design

- **TPC: 60 t LXe** (78 t total), early science with 45 t LXe
- **Two arrays** of 3-inch PMTs, 1182/array
- 2.97 m e^- drift, 2.98 m diameter
- **Drift field**: 240-290 V/cm
- Extraction field: 6-8 kV/cm
- **Double-walled Ti cryostat**, 7 cm LXe "skin" detector around the TPC

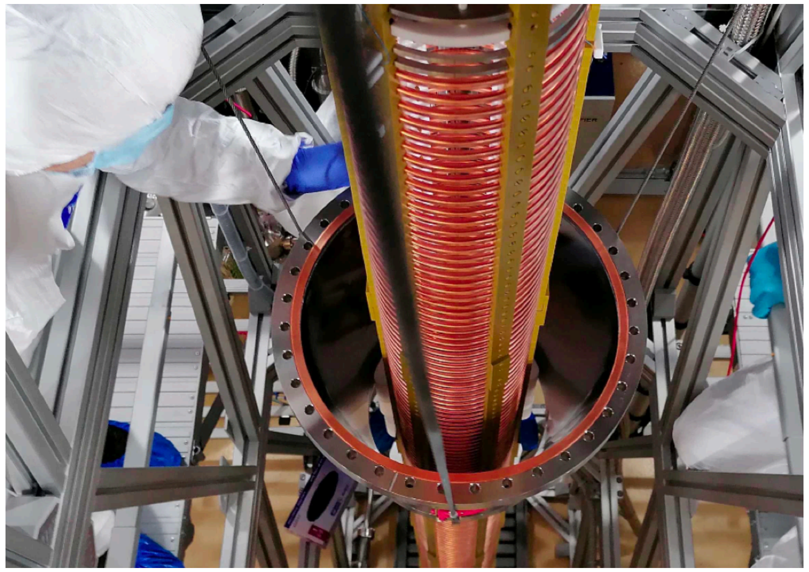
XLZD TPC



XLZD collaboration
Design Book, arXiv: 2410.17137

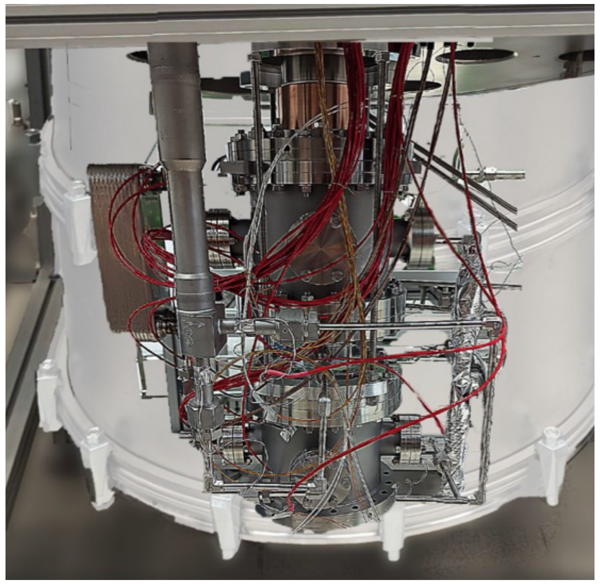
DARWIN R&D

- R&D for next-generation liquid xenon detector since ~2010
- Several large-scale demonstrators: Xenoscope, Pancake, LowRad (3 ERCs)
- Photosensors, TPC design, large-scale purification, etc



Xenoscope at UZH
LB et al., JINST 16, 2021, EPJ-C 83, 2023, JINST 20, 2025

Pancake in Freiburg
A. Brown at al., JINST 19, 2024

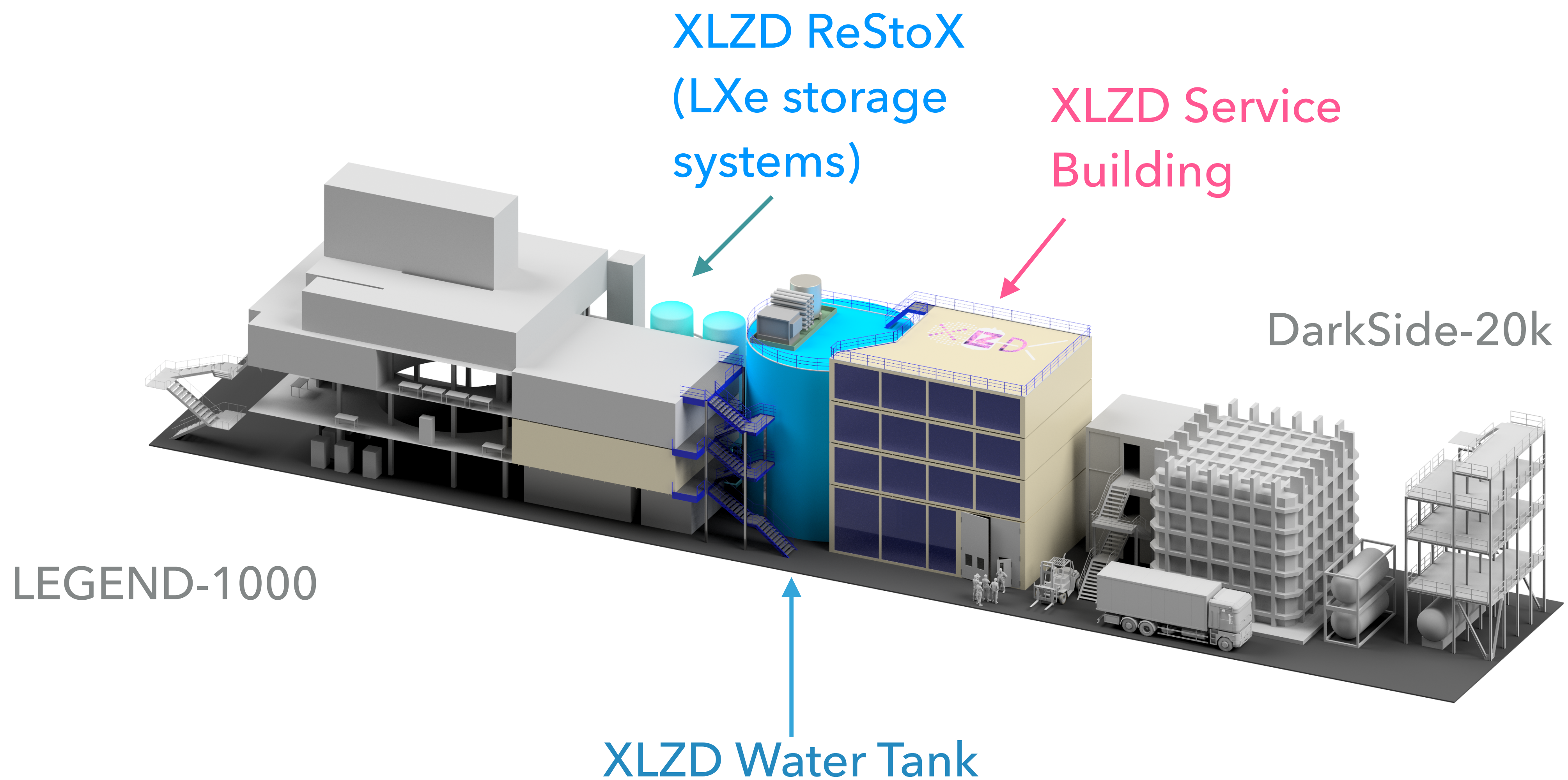


LowRad in Münster
C. Weinheimer et al.

"1 Rn atom in 100 moles of Xe"

XLZD Underground Sites

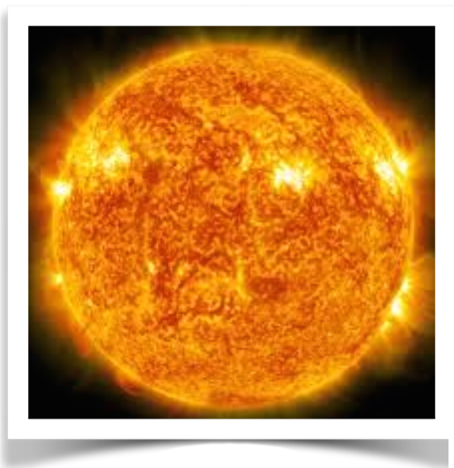
- Four experimental sites are being considered within XLZD: LNGS, a new lab at Boulby (UK), SURF (USA), SNOLAB (Canada)
- Example: the LNGS option in Hall-C of the underground lab (between LEGEND-1000 and DarkSide-50k)



XLZD Science Goals

Solar neutrinos (pp + ^{8}B)

Eur. Phys. J. C 80, 12 (2020)
Phys.Rev.D 106 (2022)



Dark matter

JCAP 10, 016 (2015)

Supernova neutrinos

PRD 94, 103009 (2016)
Phys.Rev.D 105 (2022)

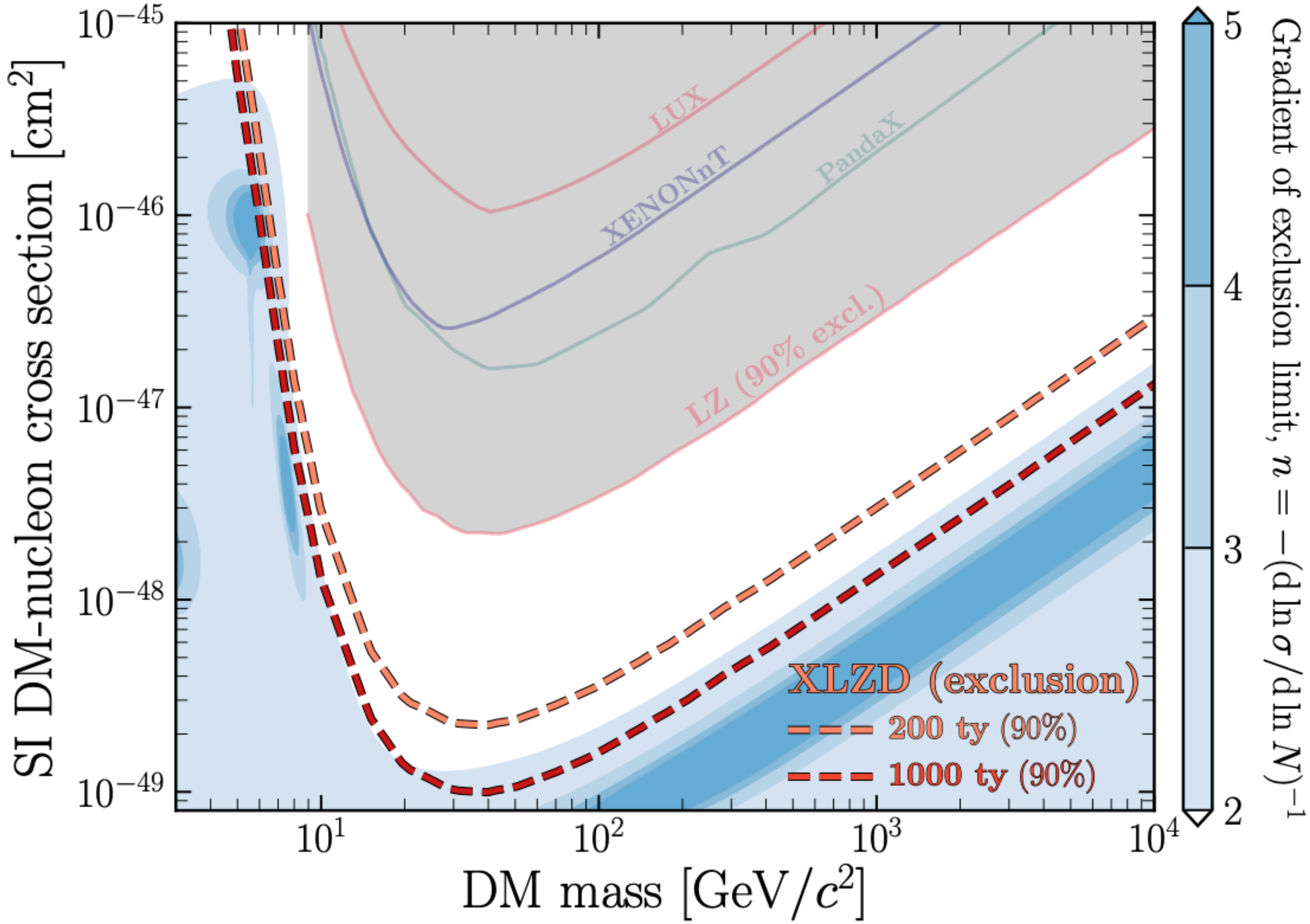
Neutrino nature

Eur. Phys. J. C 80, 9 (2020) ; Journal of Physics G 52 (2025)

LB, Nucl. Phys. B 1003 (2024)

Physics case for a large liquid xenon detector: *J.Phys.G* 50 (2023) 1 (600 authors)

XLZD Dark Matter: Exclusion



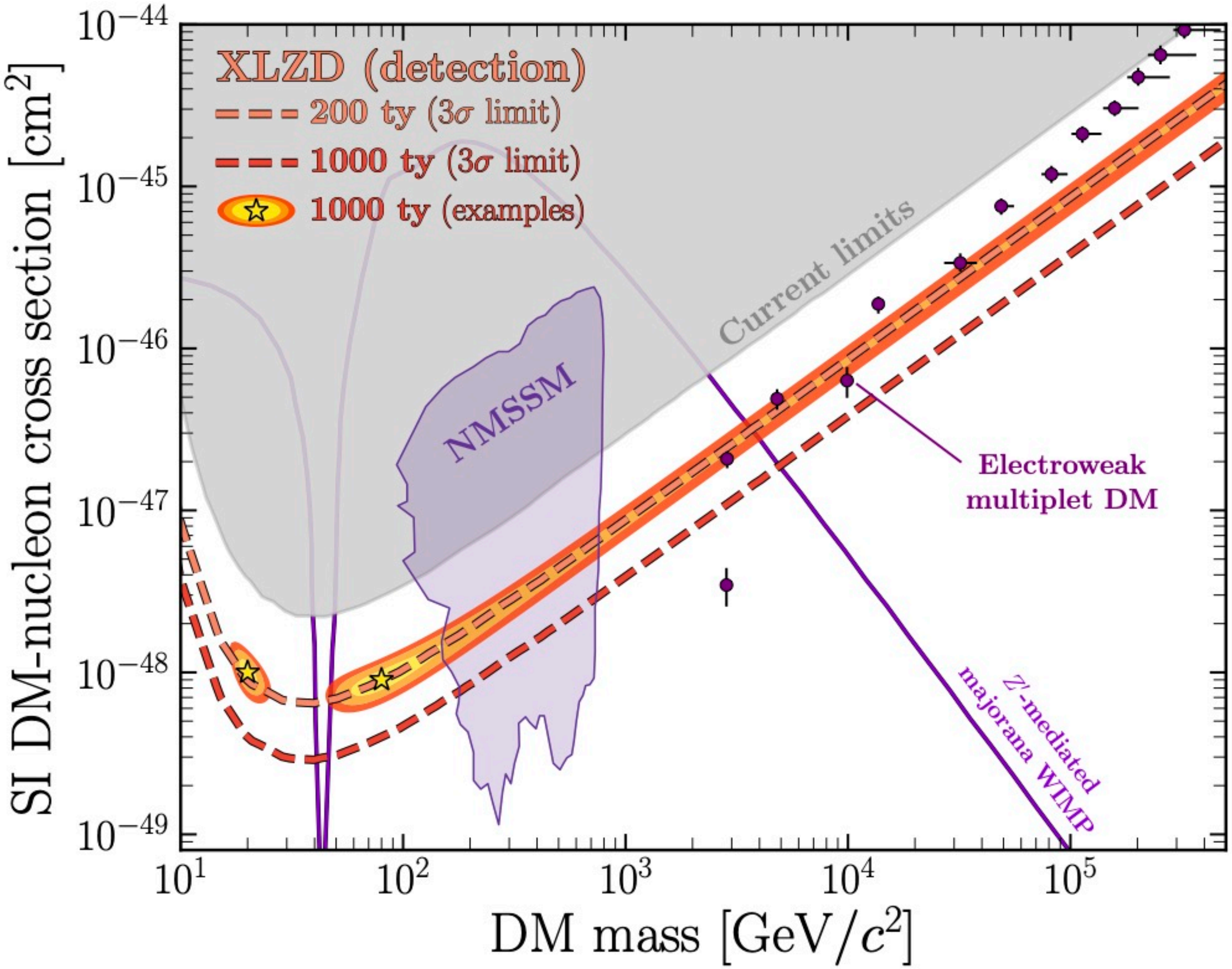
XLZD collaboration
Design Book
arXiv: 2410.17137

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,... events are expected in the WIMP ROI)

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

XLZD Dark Matter: Detection



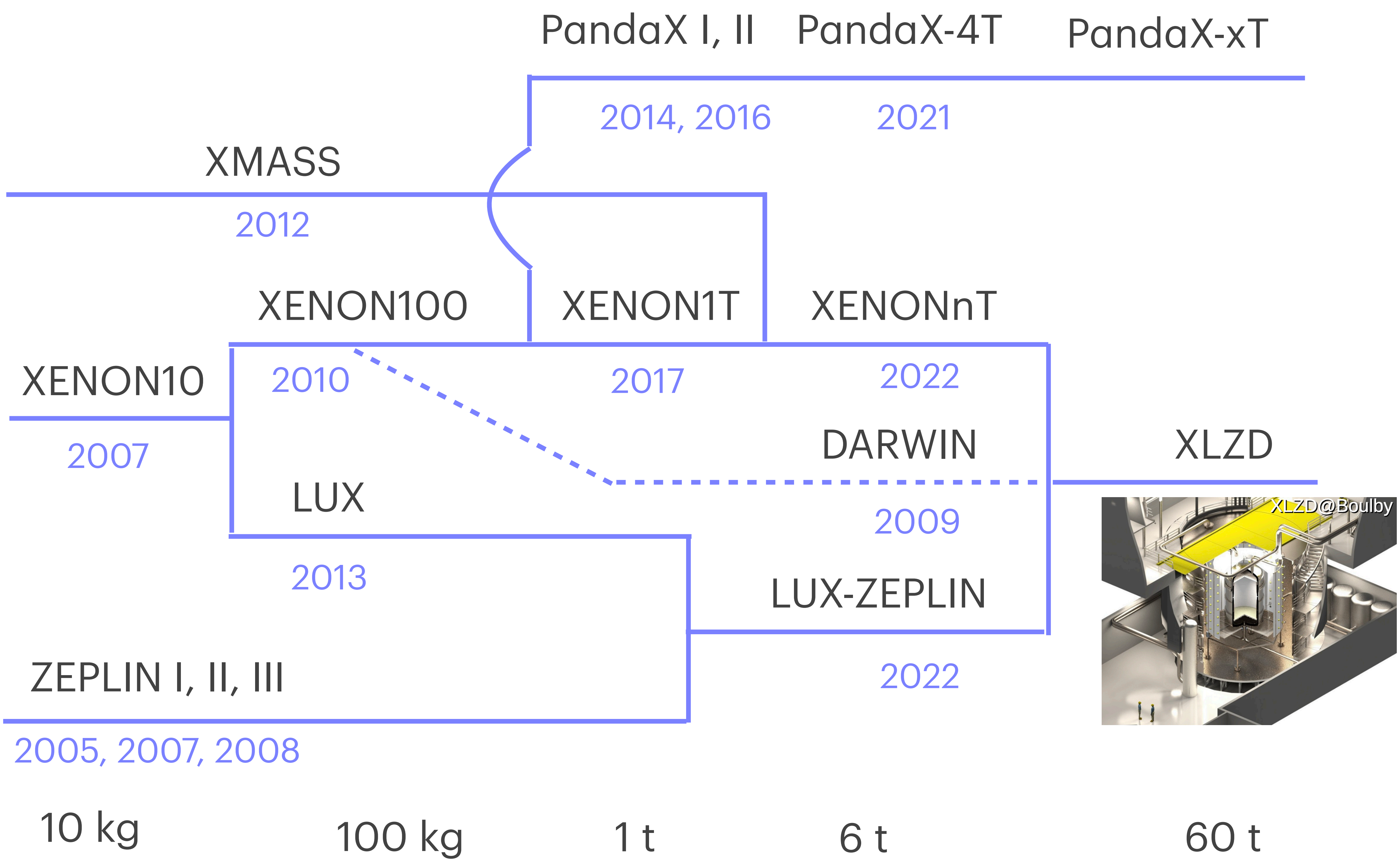
XLZD collaboration
Design Book
arXiv: 2410.17137

Evidence contours for 20 GeV and 80 GeV WIMPs

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

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

The Xenon Family Tree



Indicative timelines; year of first results

Thirteen DM detectors in 20 years!

Conclusions & Outlook

- Liquid xenon detectors: at the forefront of direct DM searches
- LZ, PandaX, XENONnT: many new results in 2025; additional data towards design exposures and sensitivities
- DARWIN: leading the R&D efforts towards next-generation detectors
- XLZD (XENON-LZ-DARWIN): new international collaboration to build and operate a ≥ 60 tonne scale LXe TPC; PandaX-xT: upgrade to 20 t, then will construct 50 tonne scale detector
- Main goal: test WIMP paradigm into the neutrino fog (& many other DM candidates)
- Neutrino physics: search for $0\nu\beta\beta$-decay in ^{136}Xe, address inverted ordering scenario, observe solar and SN neutrino, other second order weak decays

PLANCK33: A new particle?

PDG particle data group

- Mass =?
- J = ?
- $\tau > ?$
- $\sigma(\chi + \bar{\chi} \rightarrow SM + SM) = ?$
- $\sigma(\chi + SM \rightarrow \chi + SM) = ?$
- ...

Thank you

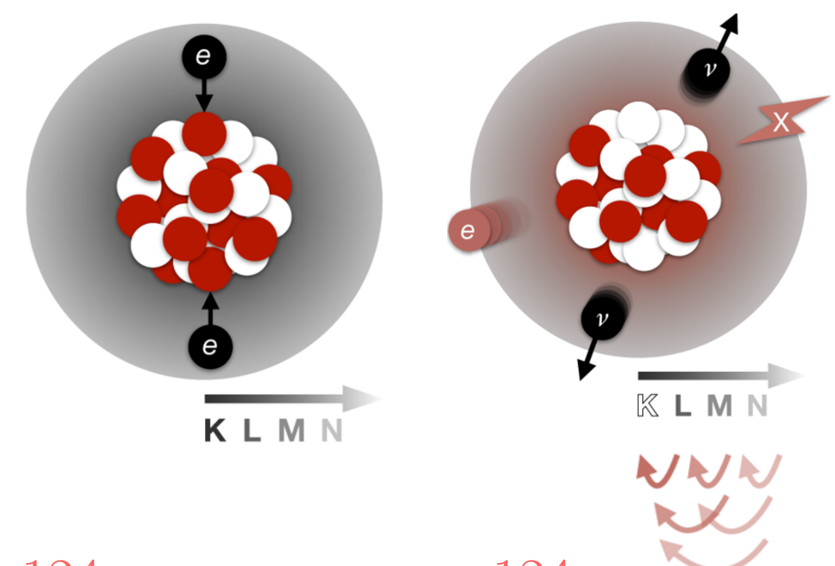
Additional material

Second Order Weak Decays

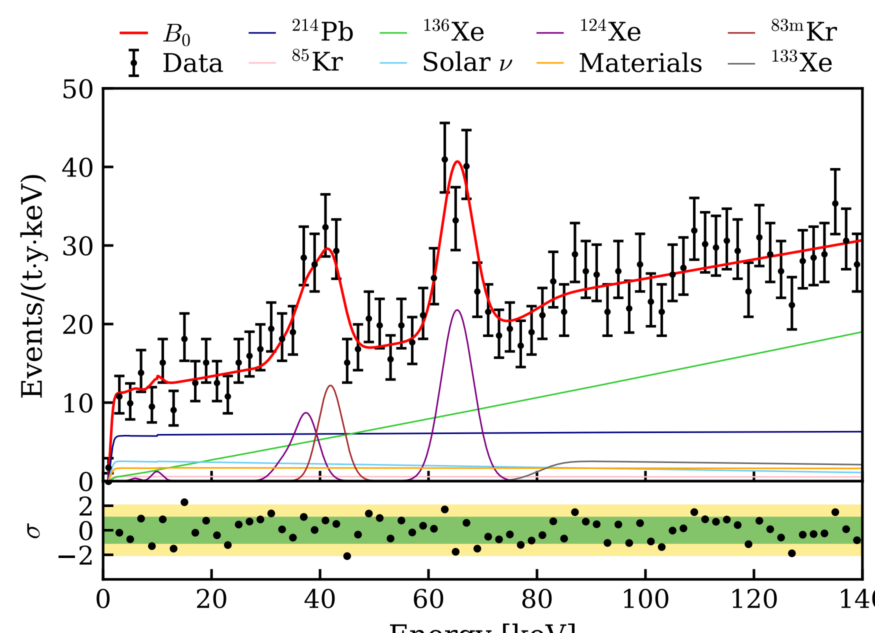
XENON, Nature 568, 2019

Double electron capture

$$T_{1/2} = (1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}\ \text{y}$$



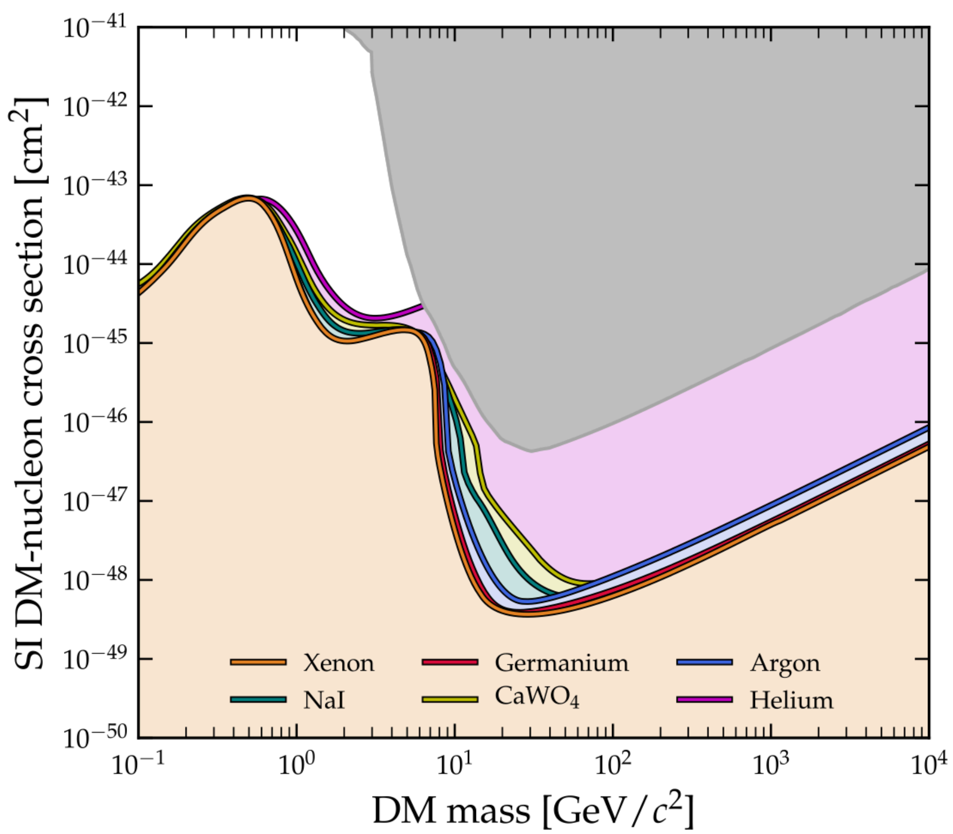
$$^{124}\text{Xe} + 2\text{e}^- \rightarrow {}^{124}\text{Te} + 2\nu_e$$



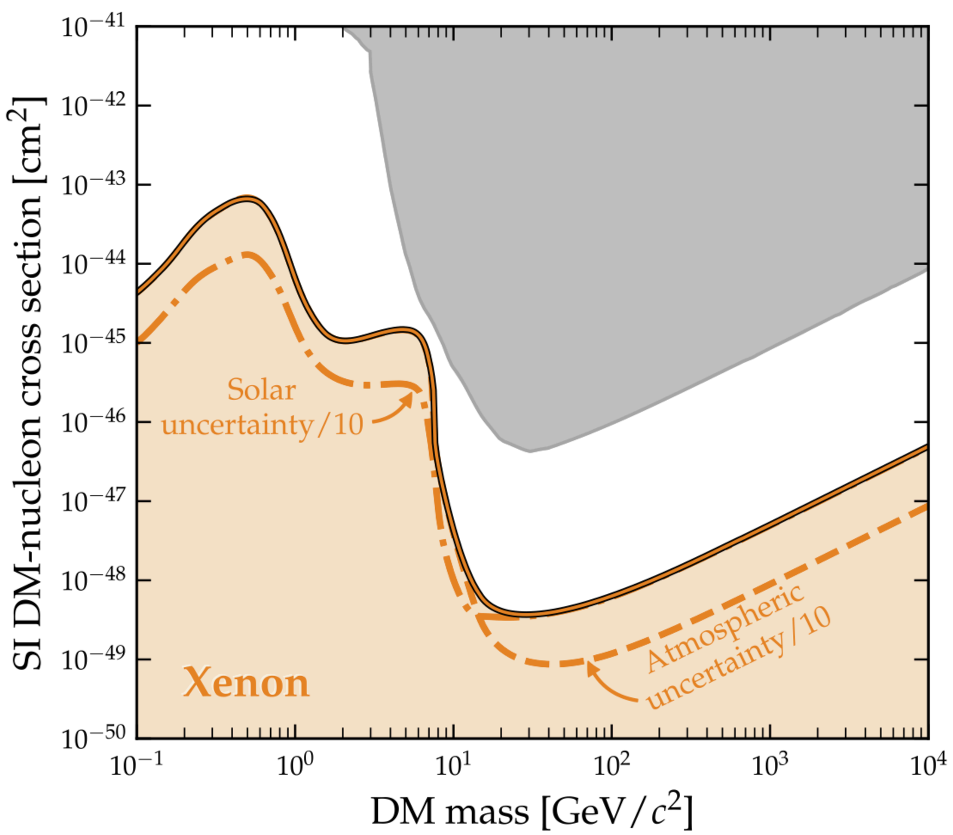
Approaching the Neutrino Fog

- 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

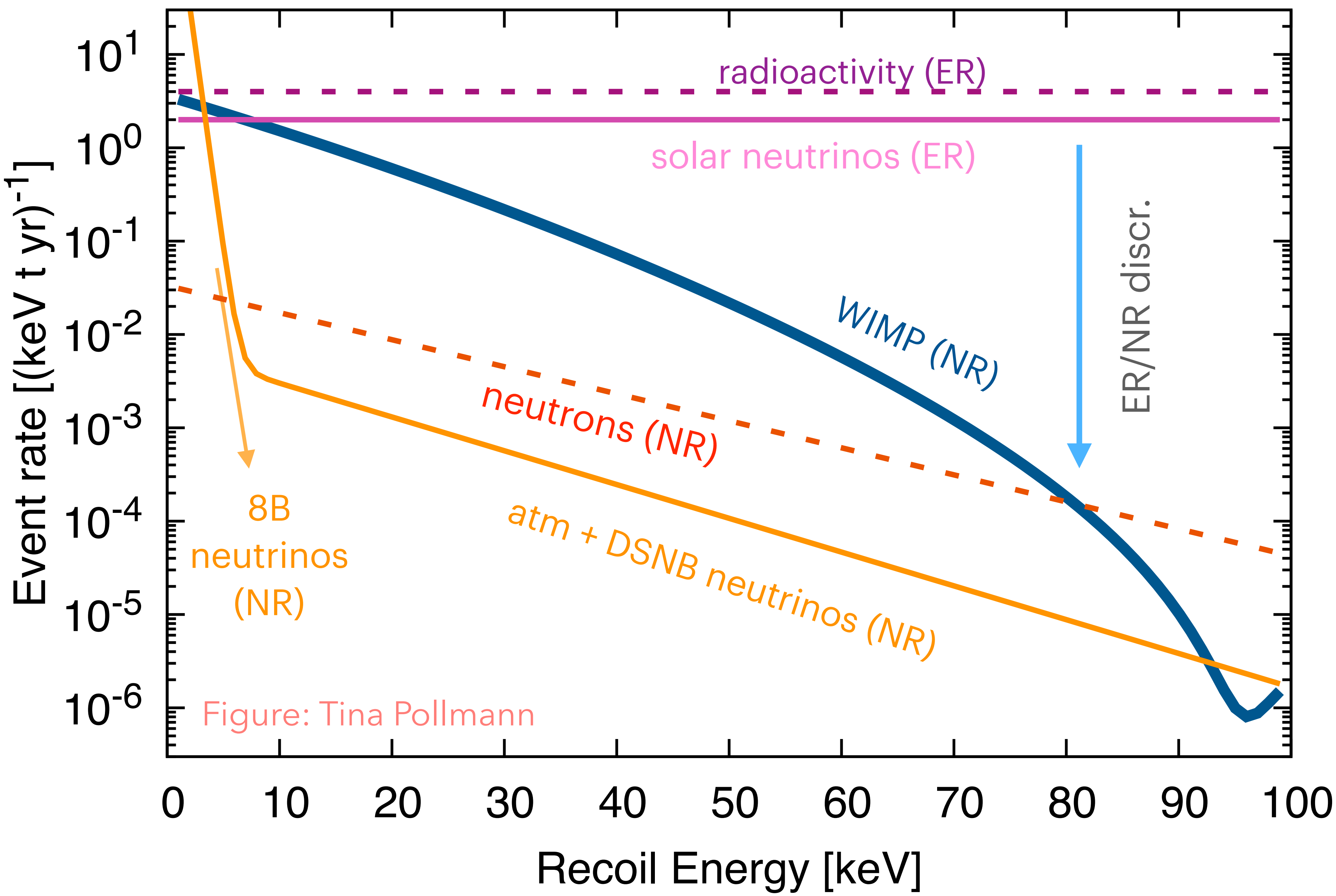


C. O'Hare, PRL 127, 2021

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

Background Goals

- ER and NR regions: dominated by cosmic neutrinos



materials, intrinsic etc

ν-e scattering:
solar ν's

WIMP: 50 GeV,
$\sigma_{\chi n}$= 10^{-10} pb

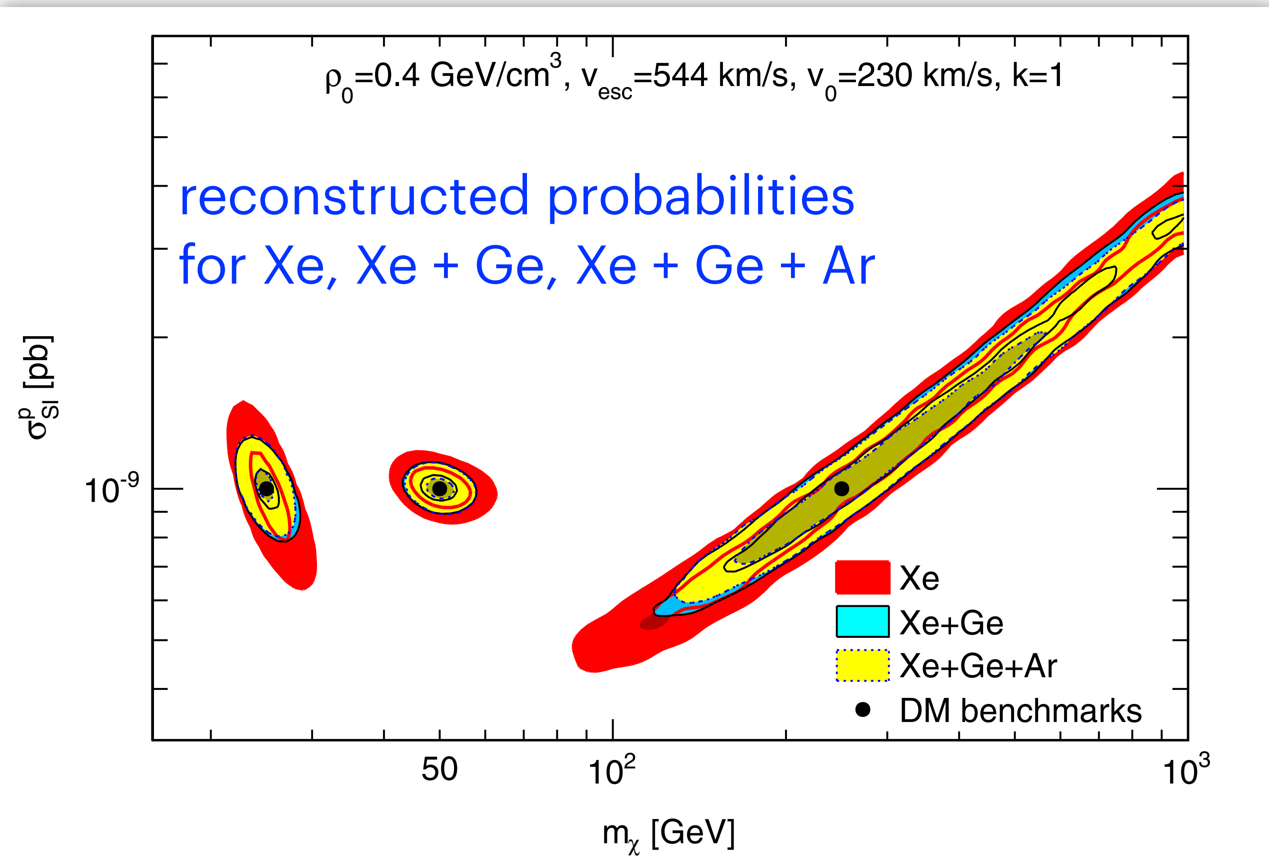
radiogenic,
cosmogenic

CEvNS: solar ν's,
atm ν's + DSNB

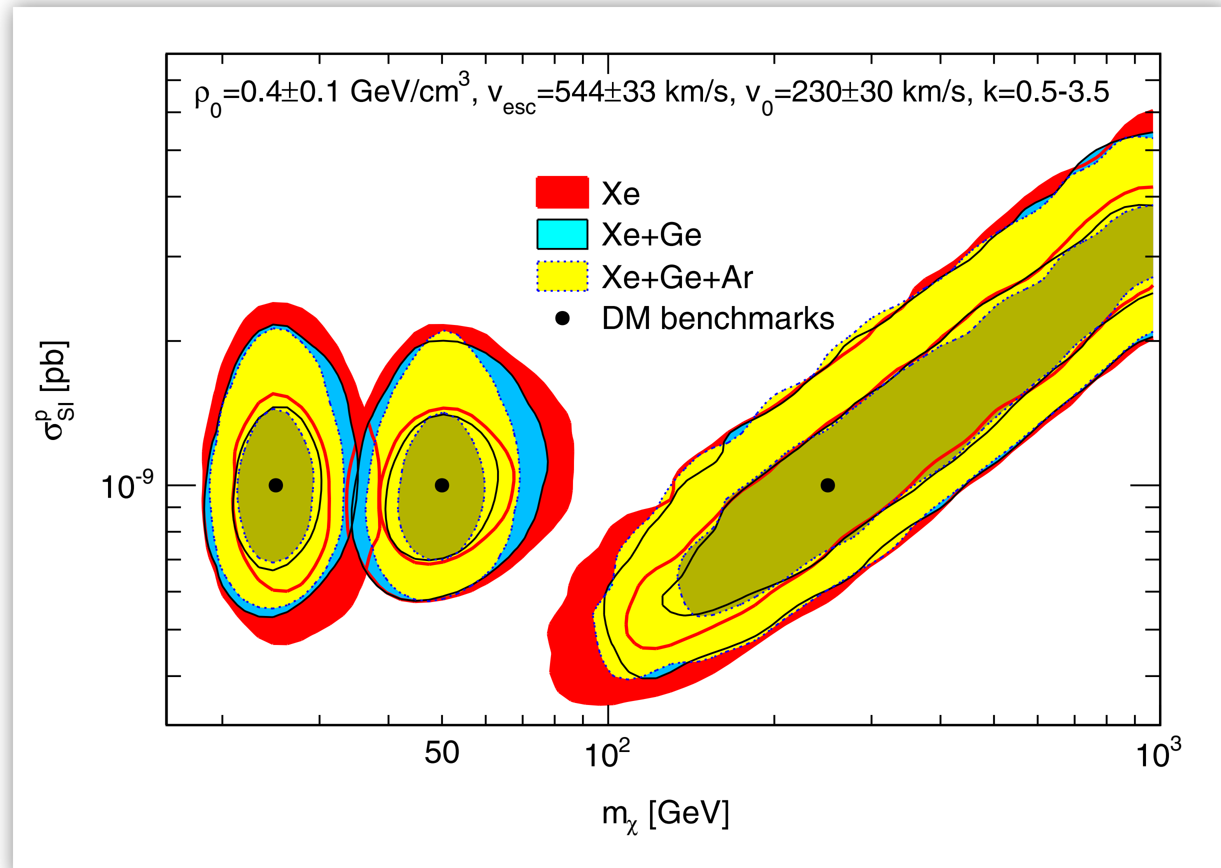
Dark Matter Spectroscopy

- 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

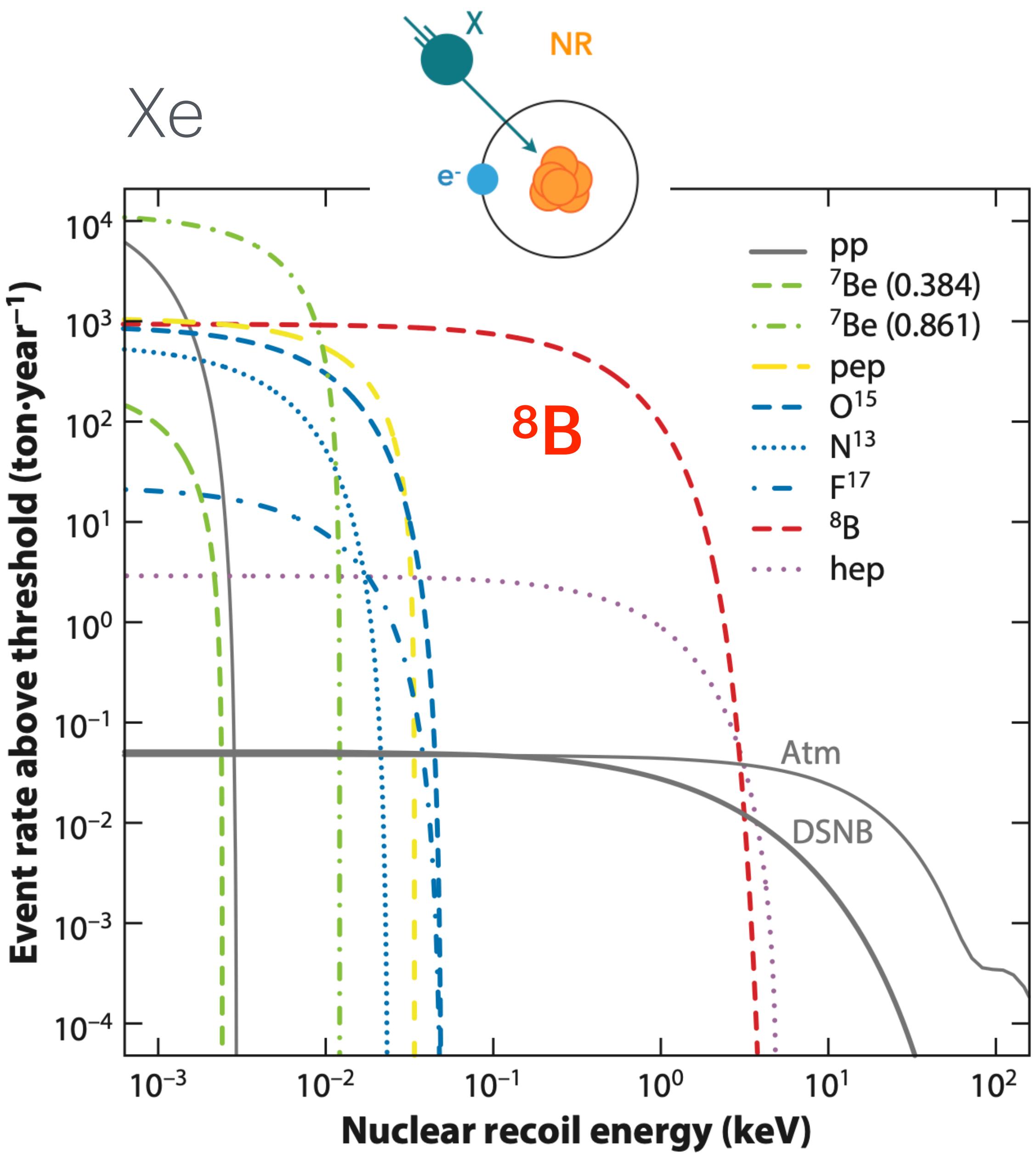


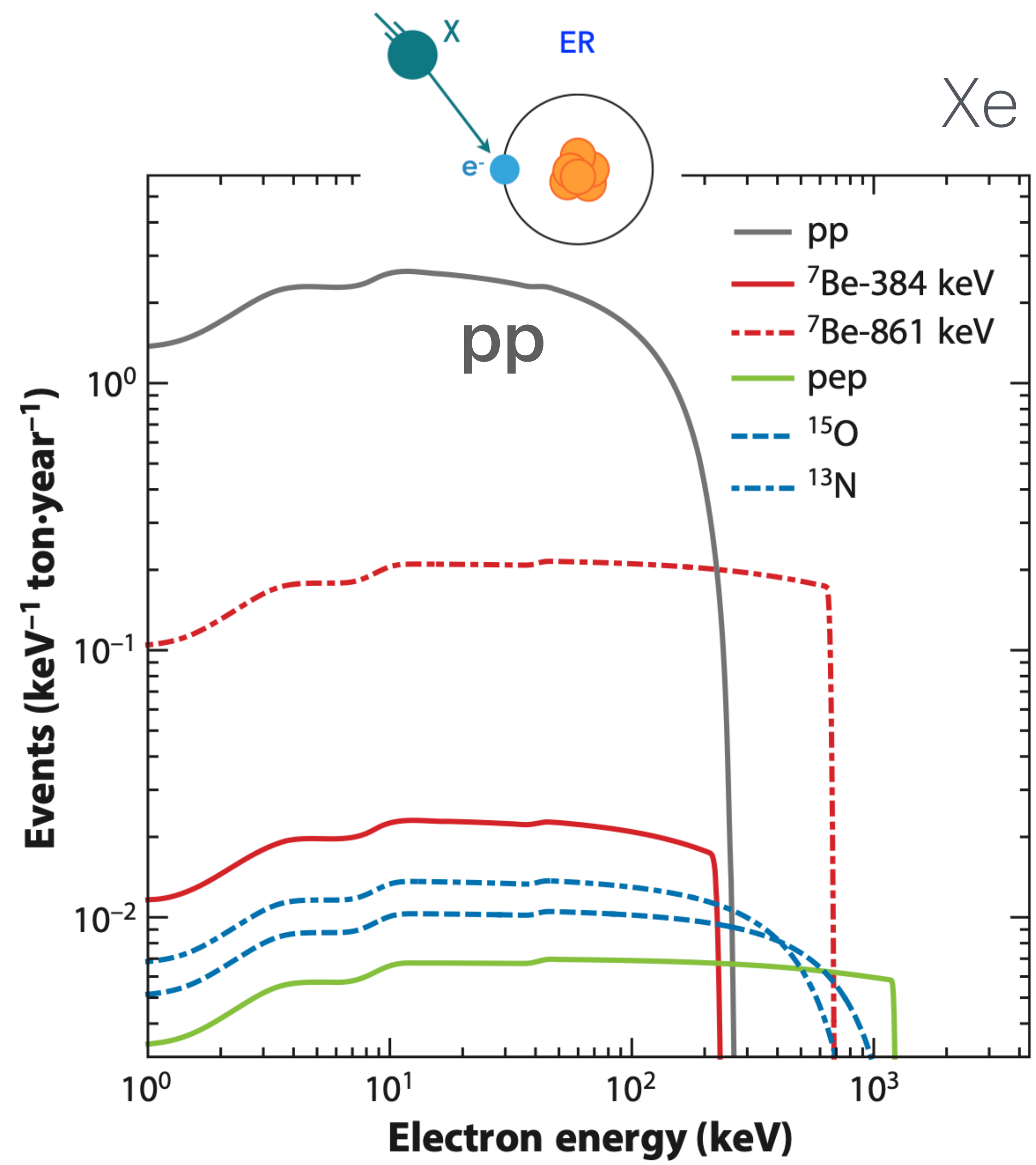
Xenon + Germanium + Argon

Pato, Baudis, Bertone, Ruiz de Austri, Strigari, Trotta: Phys. Rev. D 83, 2011

Solar Neutrino Signals

- Neutrino signals: NRs (CEvNS), ERs (all other reactions)



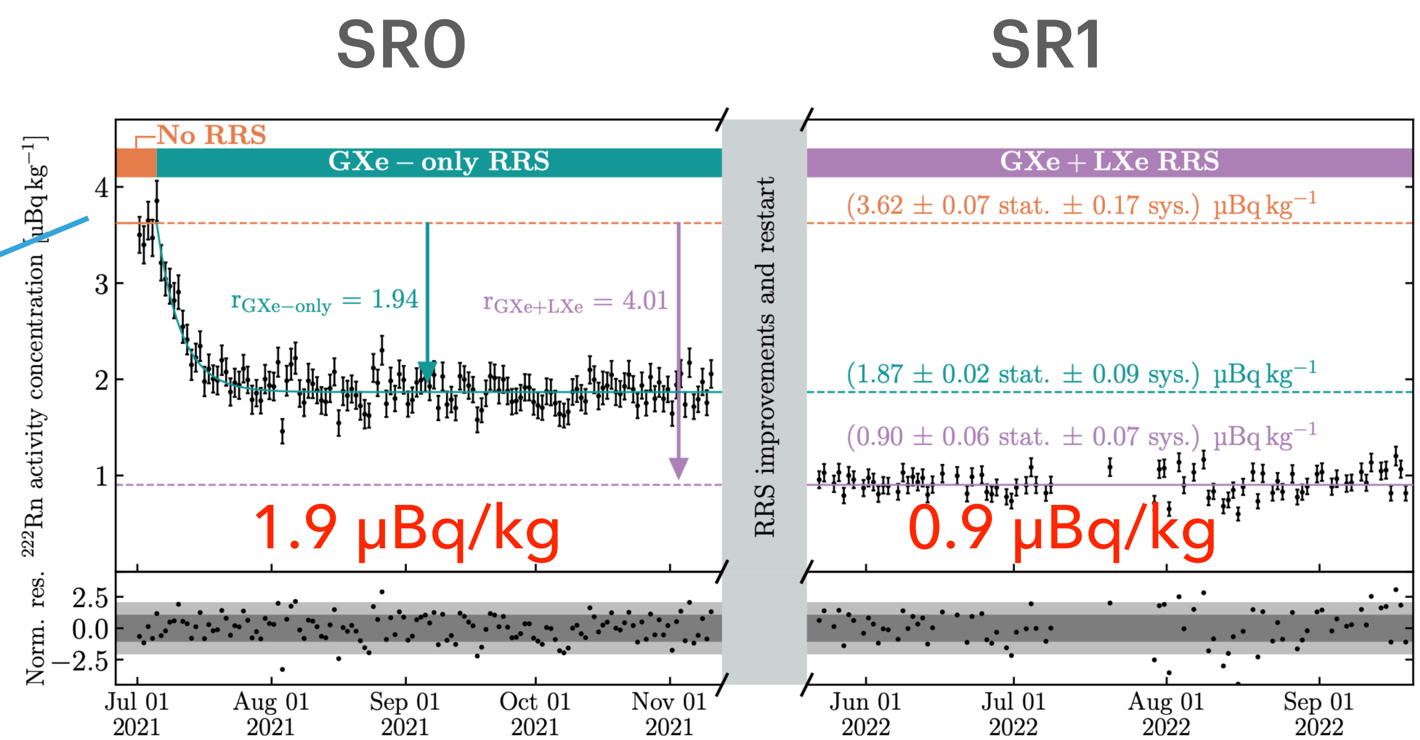


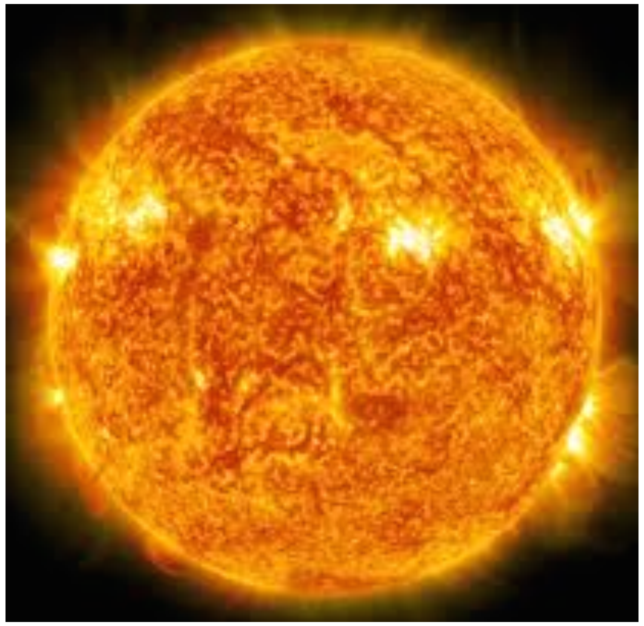
B. Dutta, E. Strigari, Annu. Rev. Nucl. Part. Sci. 2019

Solar Neutrinos: ν-e Scattering

ER events in SR0

Component	(1,10) keV
^{214}Pb (^{222}Rn)	**56±7**
^{85}Kr	6±4
Materials	16±3
Solar ν	**25±2**
^{124}Xe	2.6±0.3
^{136}Xe	8.7±0.3
AC	0.7±0.03





ν-e scattering

Solar neutrino flux at low energies (pp and ^7Be)

Some History...

- CEvNS-based detectors were proposed as "neutrino observatories" in the mid eighties (1984, Drukier and Stodolsky)
- These detectors were then proposed to detect "some possible candidates for dark matter" (1985, Goodman and Witten)
- Forty year later: dark matter detectors observed solar neutrinos via CEvNS for the first time* (2024, XENONnT and PandaX-4T)

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Phys. Rev. D **30**, 2295 – Published 1 December 1984

ABSTRACT

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10-10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

Received 21 November 1984

DOI: https://doi.org/10.1103/PhysRevD.30.2295

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

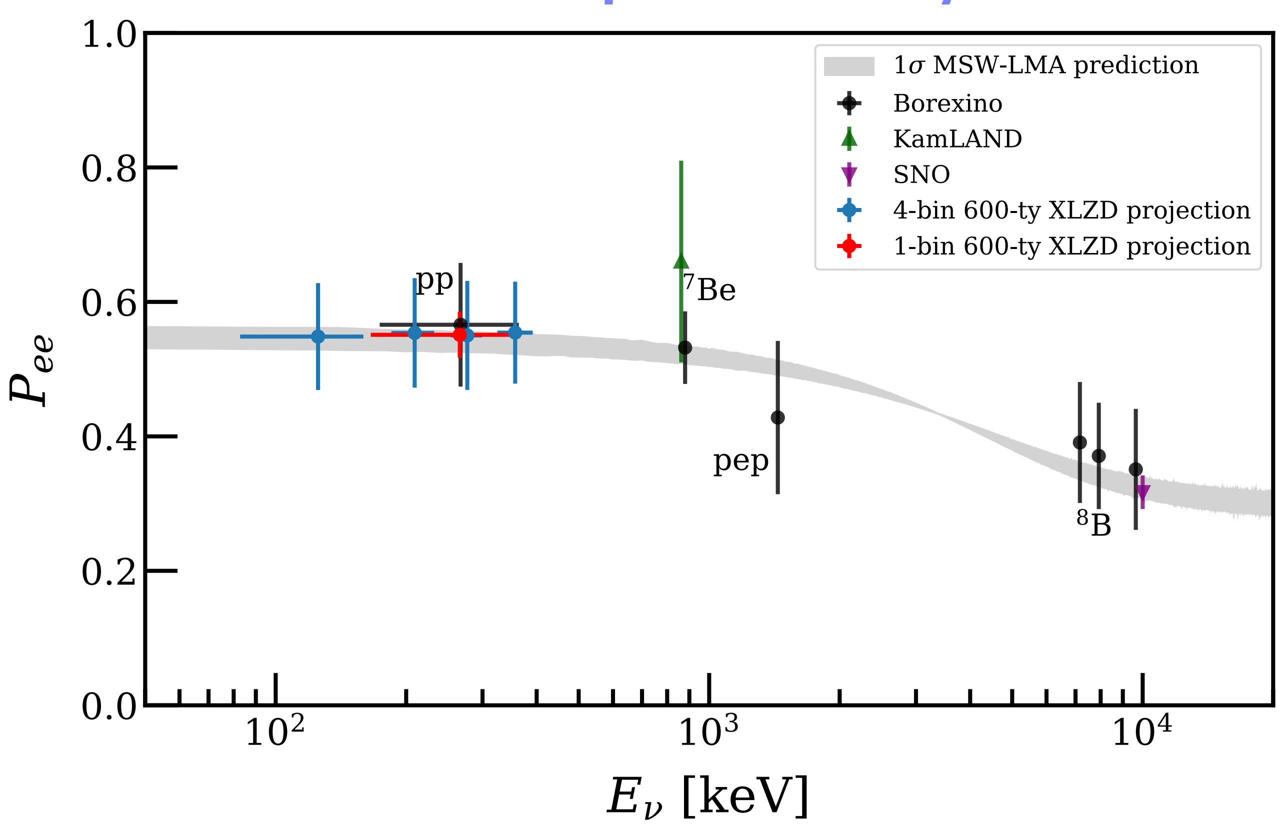
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

*not with superconducting grains, but with large liquid Xe detectors

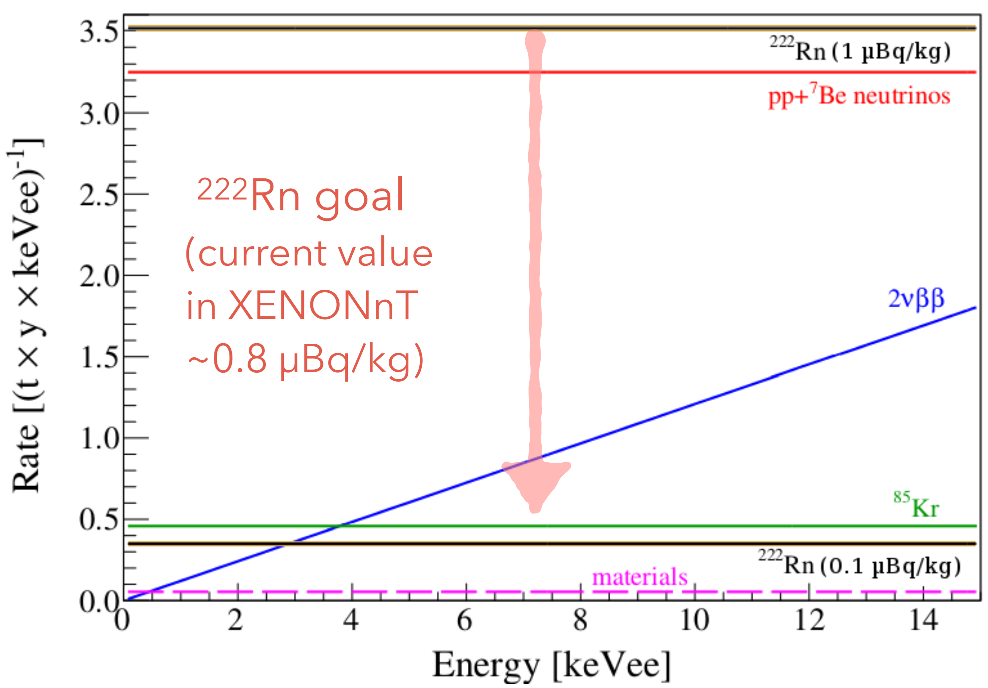
Solar ν-Electron Scattering

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

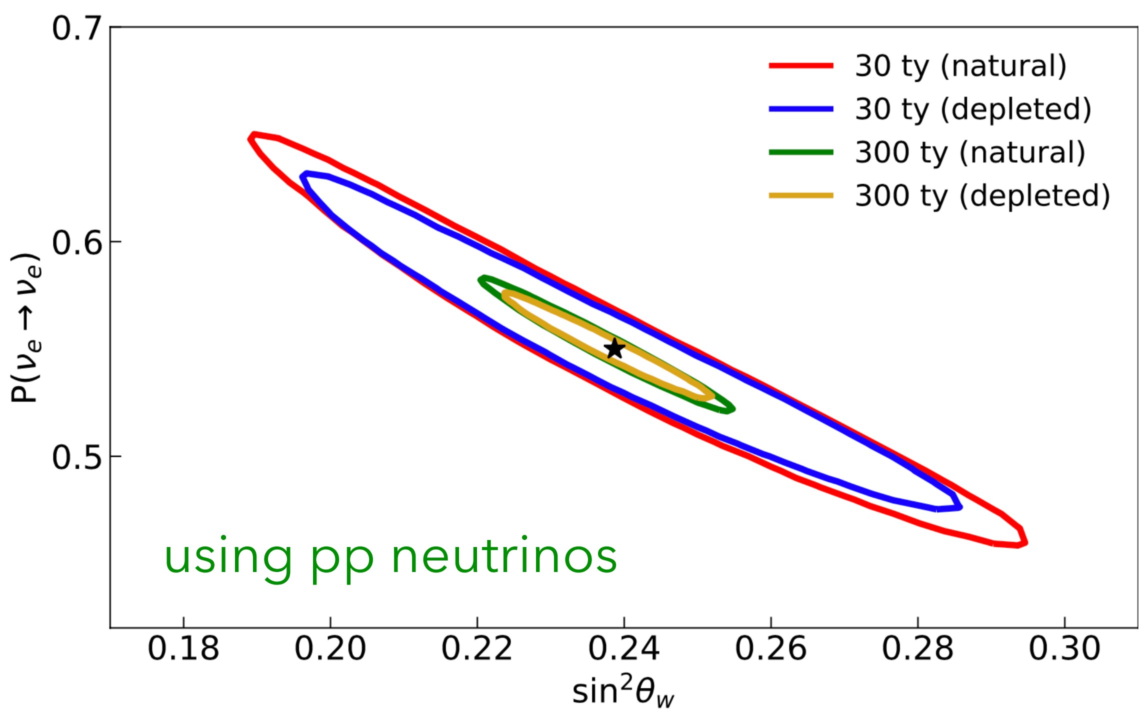
XLZD preliminary



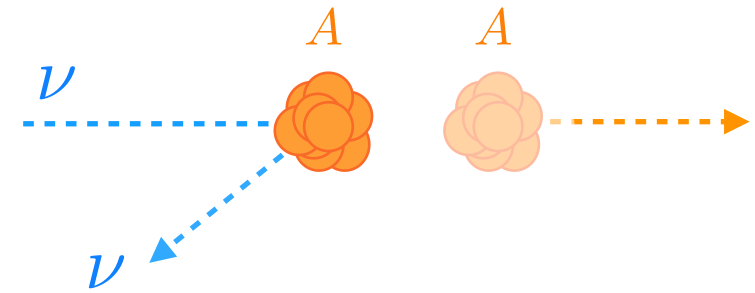
600 t y exposure, 1 and 4 energy bins



DARWIN collaboration, EPJ-C 80 12 (2020)

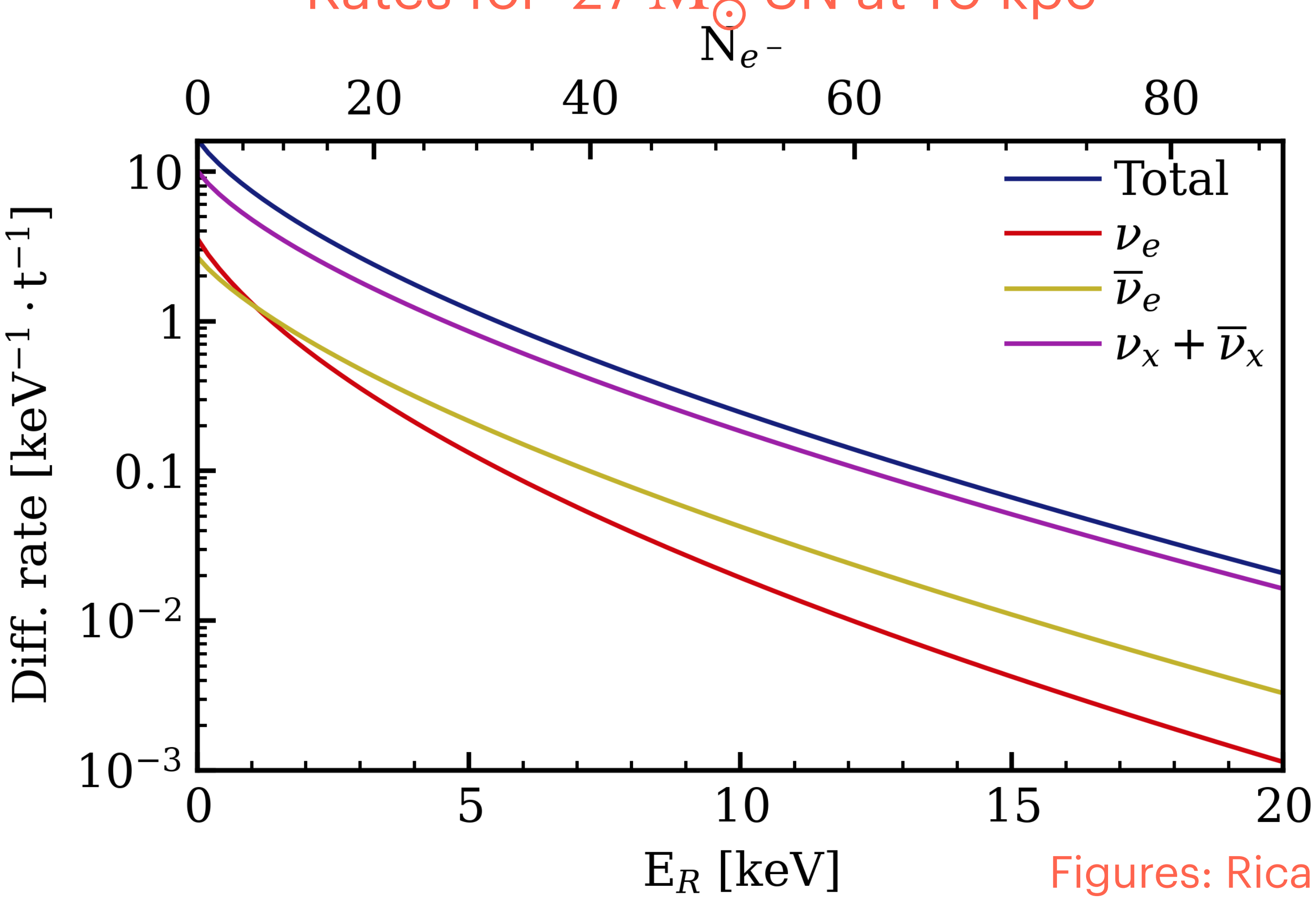


SN ν-Nucleus Scattering

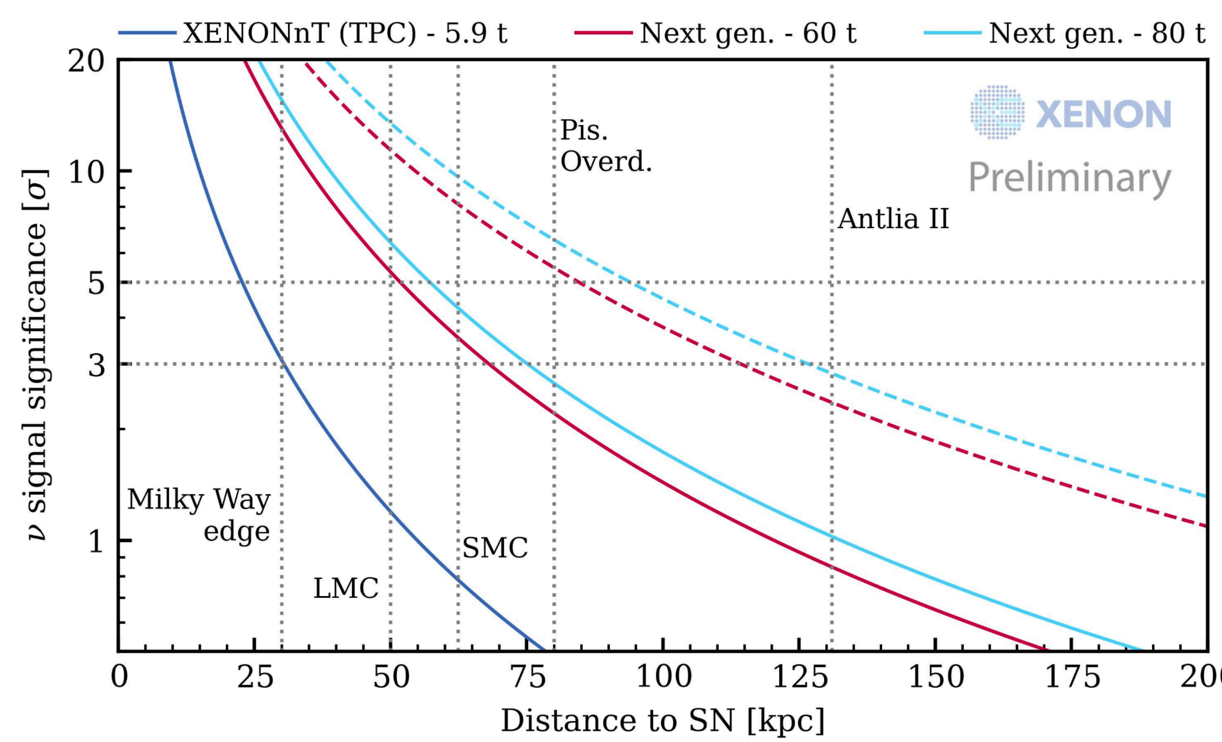


- Sensitivity to all ν flavours: few events/ton expected from SN at ~10 kpc
- Main challenge: low energies, understand few-e⁻ backgrounds
- **XLZD:** sensitivity beyond SMC; part of SNEWS2.0

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



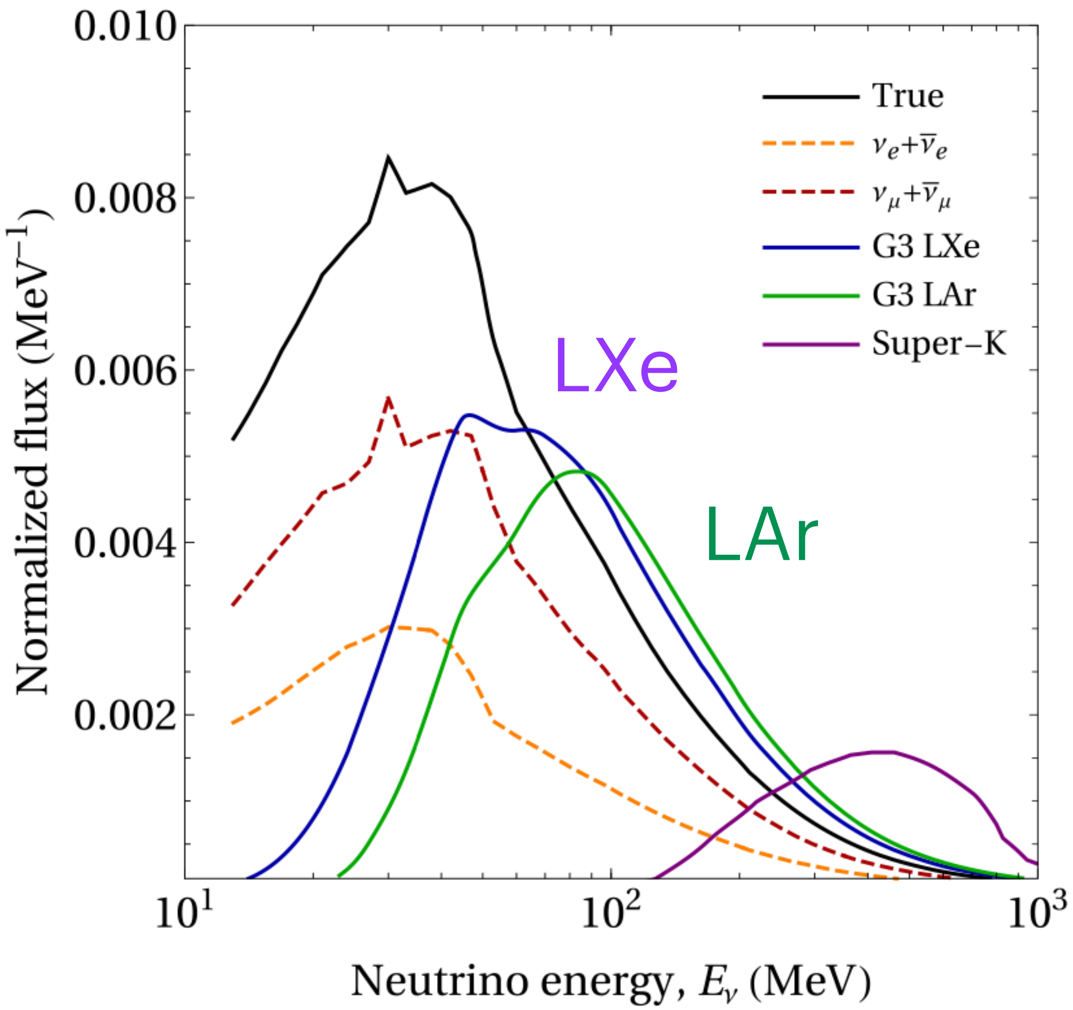
XENONnT/LZ and XLZD

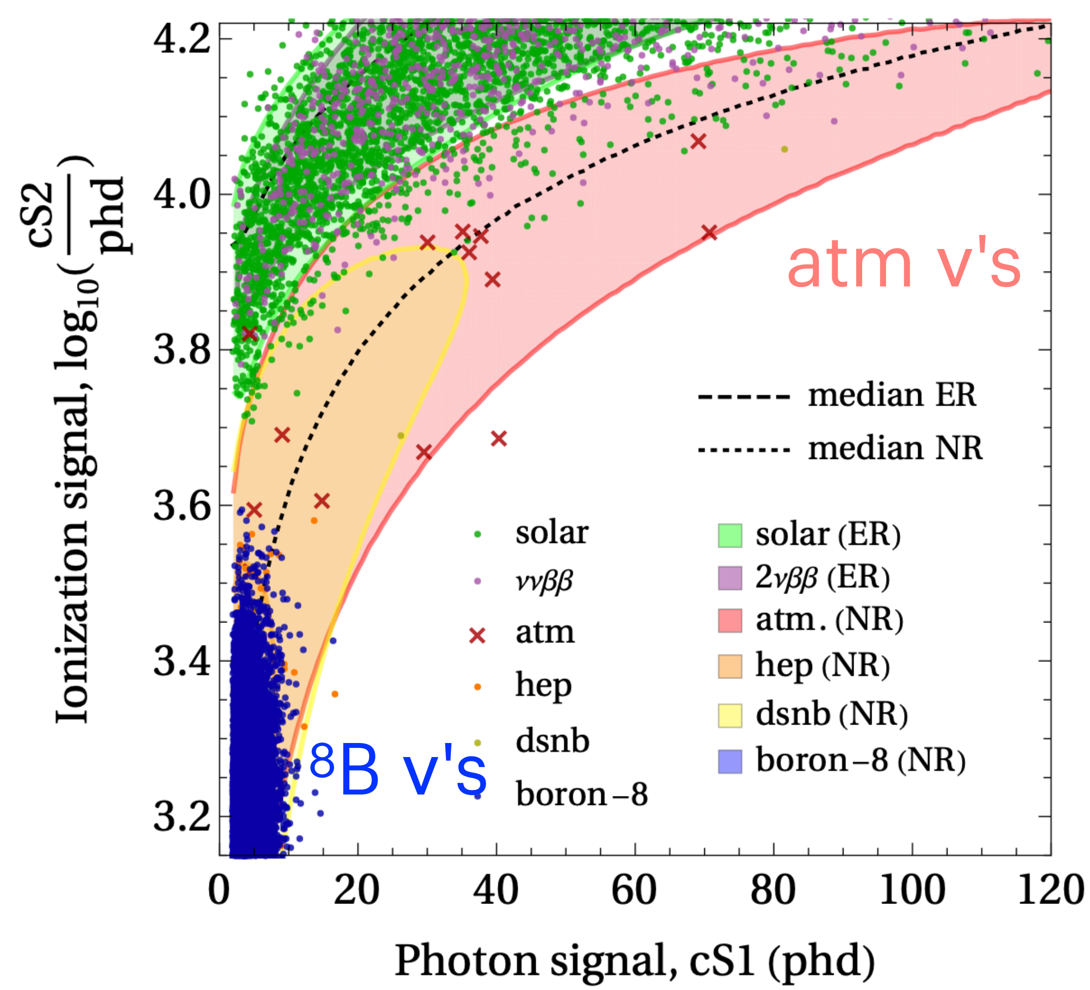


Figures: Ricardo Peres, UZH

Atmospheric Neutrinos

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



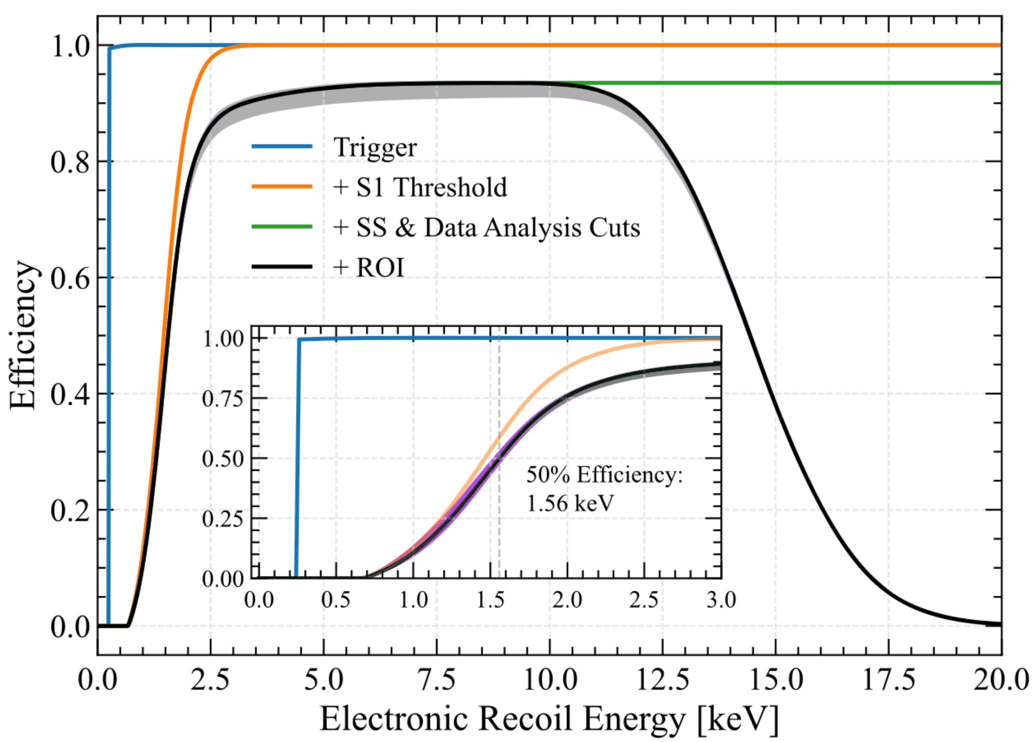


Newstead, Lang, Strigari, PRD 104, 2021

Energy Thresholds in Xe TPCs

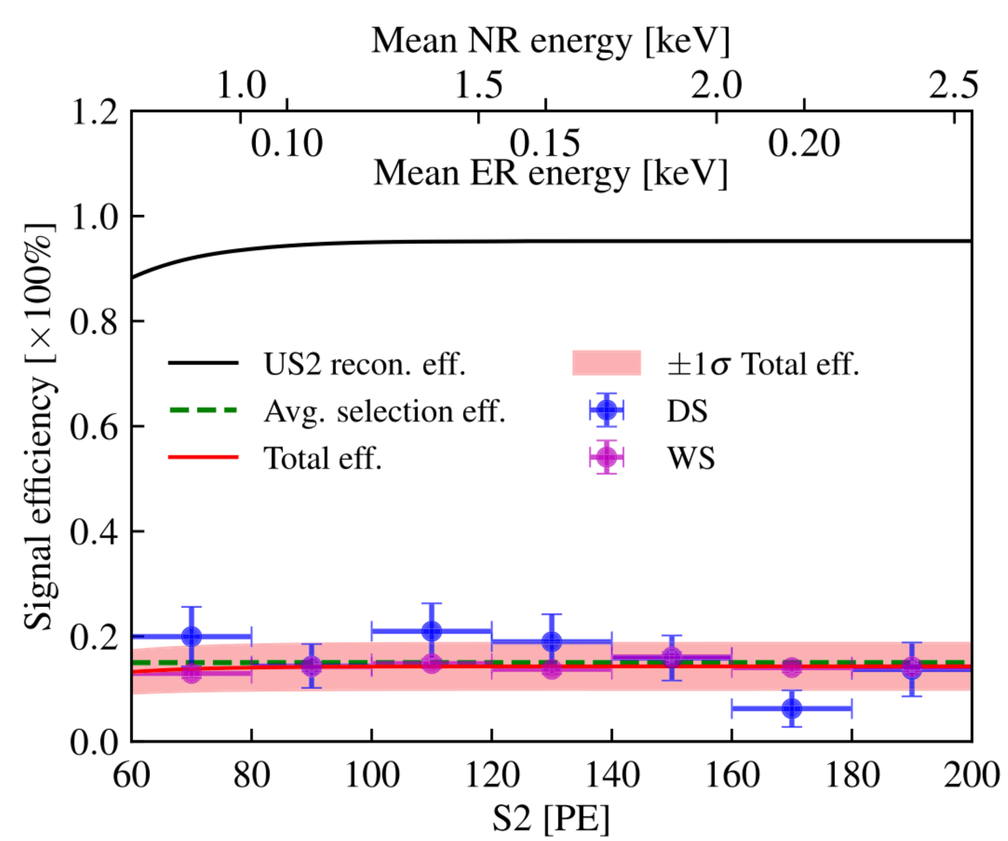
- S1 + S2: ~ 1 keV with 3-fold coincidence (ER) (hits in ≥ 3 PMTs within ~50-100 ns); lower threshold (< 1 keV) with 2-fold coincidence (with lower signal efficiency)
- S2-only: ~ 0.2 keV, with 5 e$^-$ - 100 e$^-$ detected (probe ER and NR interactions), down to W-value, with 1 e$^-$ - 5 e$^-$ signal (mostly probe ER interactions due to large uncertainty in quenching factor for NRs at lowest energies)

LZ, PRD 108, 2023



At least 3 PMTs see a signal, summed signal > 3 phd

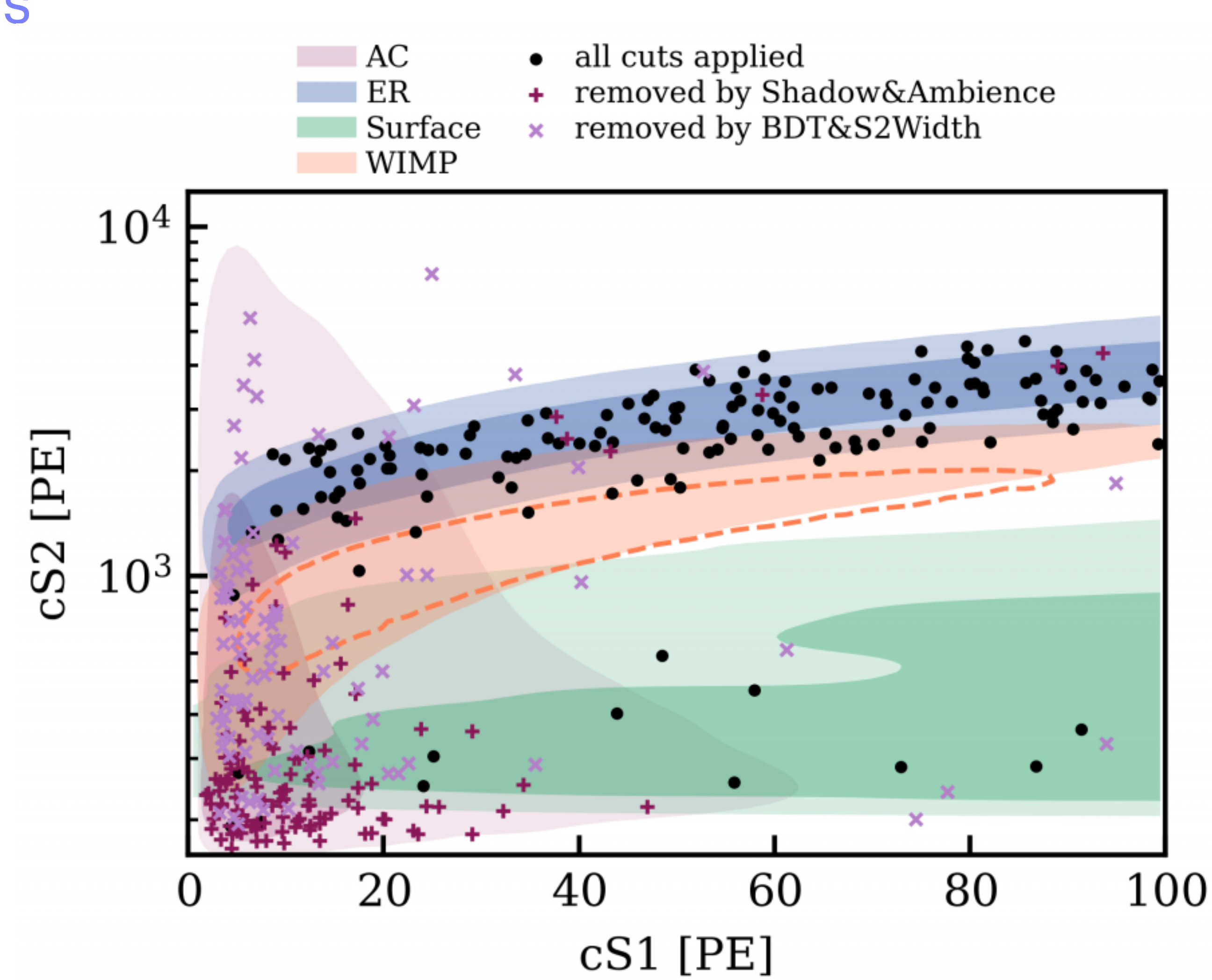
PandaX-4T, PRL 130, 2023



AC Backgrounds in TPCs

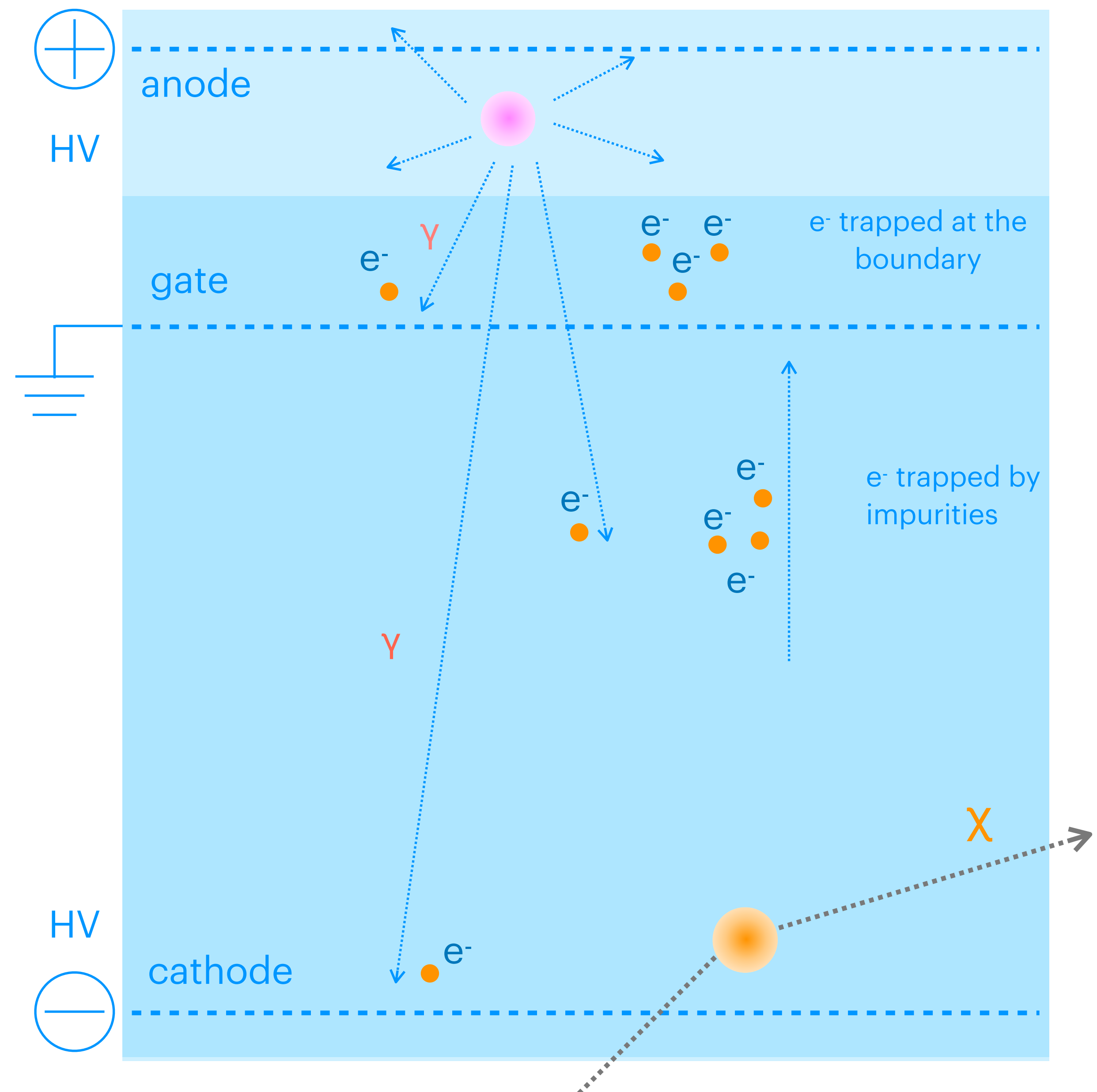
- Combinatorial background at low energies can be significant
- Main sources for isolated S1 and isolated S2 signals
  - Primary scintillation (S1s)
    - Dark counts (pile-up) ∝ nr. channels
    - Charge-insensitive regions
    - Delayed photons
  - Electroluminiscence (S2s)
    - Bulk xenon S2-only events
    - Delayed electrons
    - Electrode events

Example from XENONnT



Ionisation Only Backgrounds

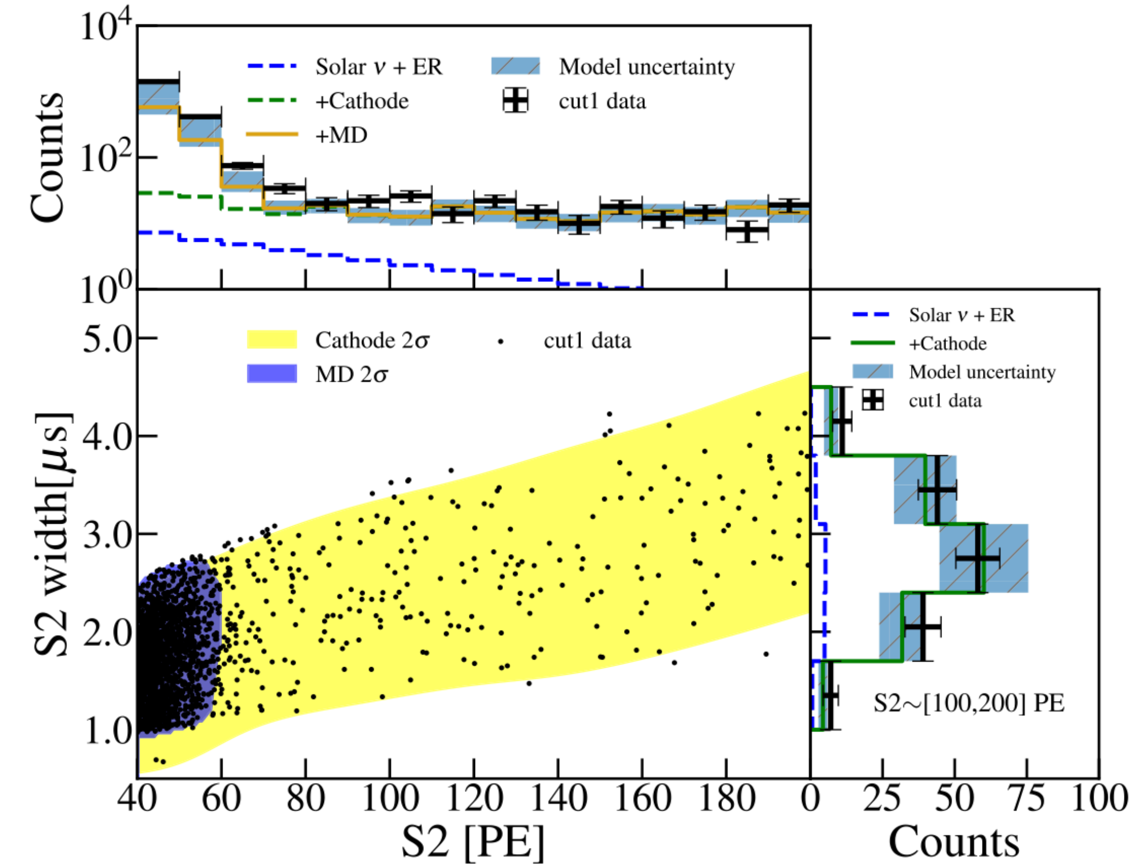
- Radioactivity
- Solar neutrinos
- Instrumental
  - Spurious emission of single and few electrons from the cathode
  - Delayed e- after large S2 signals: trapped e- at the liquid/gas interface; e- emitted from impurities, etc
- Important to understand & mitigate origin, develop background models



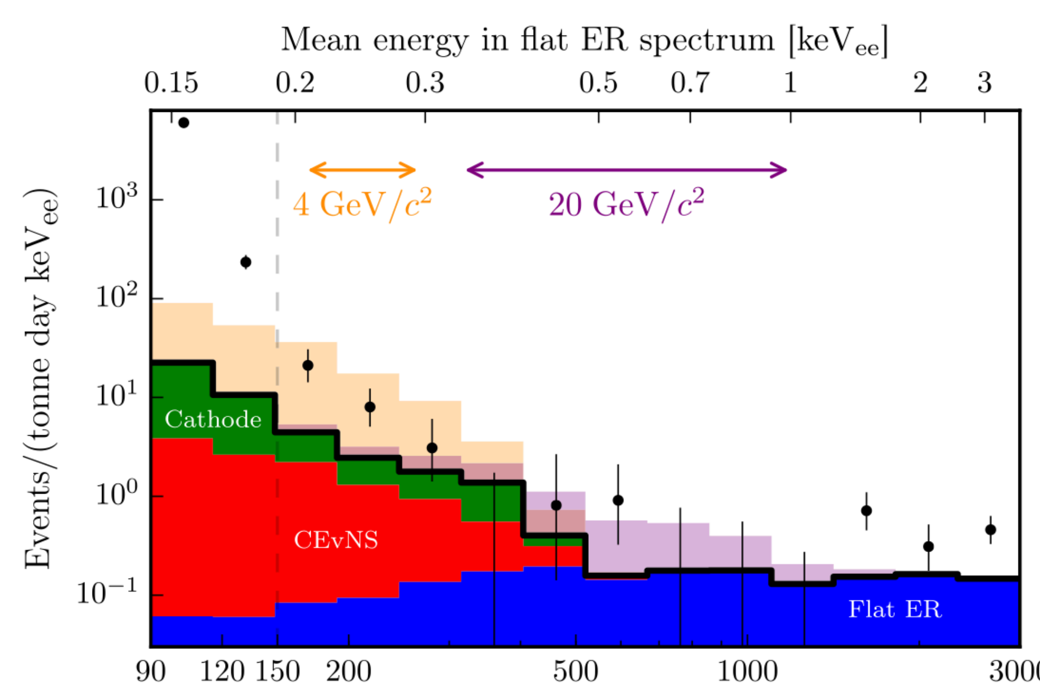
Ionisation Only Backgrounds

- Radioactivity
- Solar neutrinos
- Instrumental
  - Spurious emission of single and few electrons from the cathode
  - Delayed e⁻ after large S2 signals: trapped e⁻ at the liquid/gas interface; e⁻ emitted from impurities, etc
- Important to understand & mitigate origin, develop background models

PandaX-4T, PRL 130, 2023

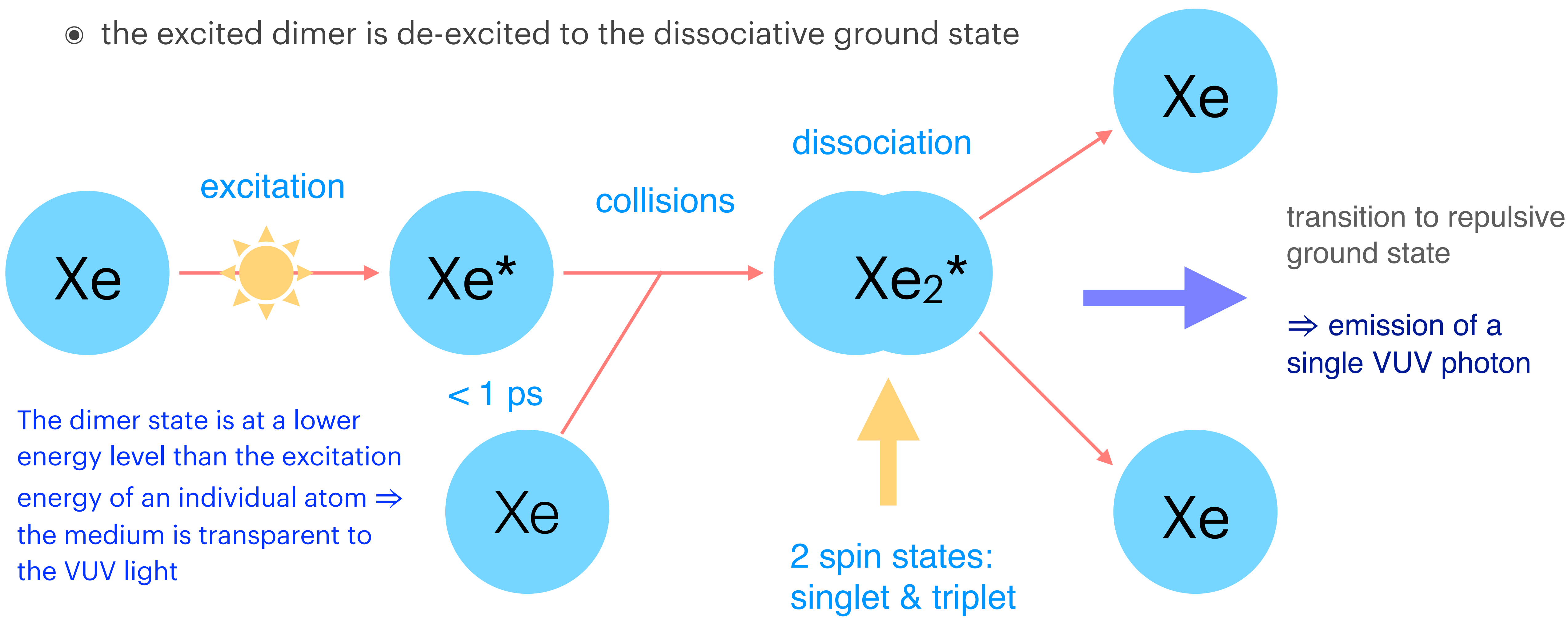


XENON1T, PRL 123, 2019



Scintillation in Liquid Xenon

- Two distinct processes; in the first process:
  - excited atoms Xe* (excitons) and ions Xe^+, both produced by ionising radiation
  - direct excitation: less than 1 ps after the excitation, the excited atom (exciton, Xe*) forms a bound state with a stable atom (Xe): *a bound dimer state, called excimer*
  - the excited dimer is de-excited to the dissociative ground state



★ The dimer state is at a lower energy level than the excitation energy of an individual atom ⇒ the medium is transparent to the VUV light

★ the two spin states refer to the combined spin state of the electron and the angular momentum due to the molecular orbit