University of Zurich[UZH]

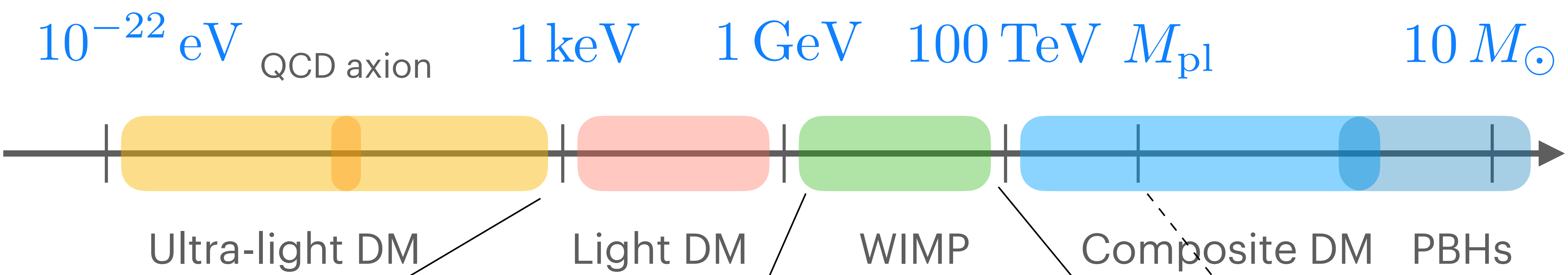
Light DM searches with Xenon TPCs and Qrocodile

ALPS 2024, an ALpine Particle Physics Symposium

Laura Baudis, University of Zurich

April 4, 2024

Dark matter mass parameter space

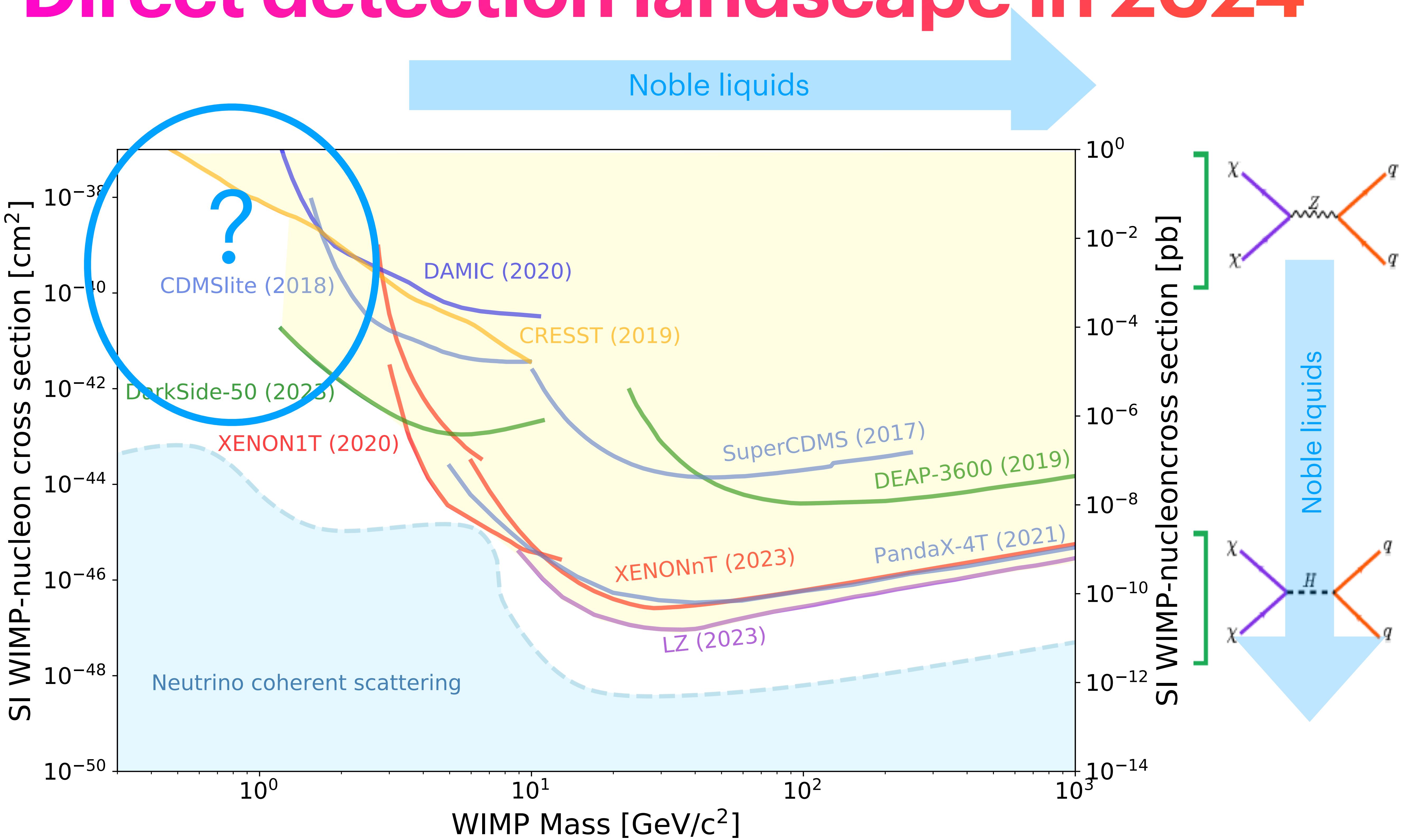


Noble liquids:
- Multiple scatters with nuclei

Noble liquids:
- Migdal effect
- Scatters with e⁻ *(interaction with SM though new mediator)*
- Absorption *(bosonic DM with direct coupling to SM particles)*

Noble liquids:
- Scatters with nuclei *(interactions with SM through, e.g., Higgs or new mediator)*
- Coherent enhancement across the nucleus for elastic scattering

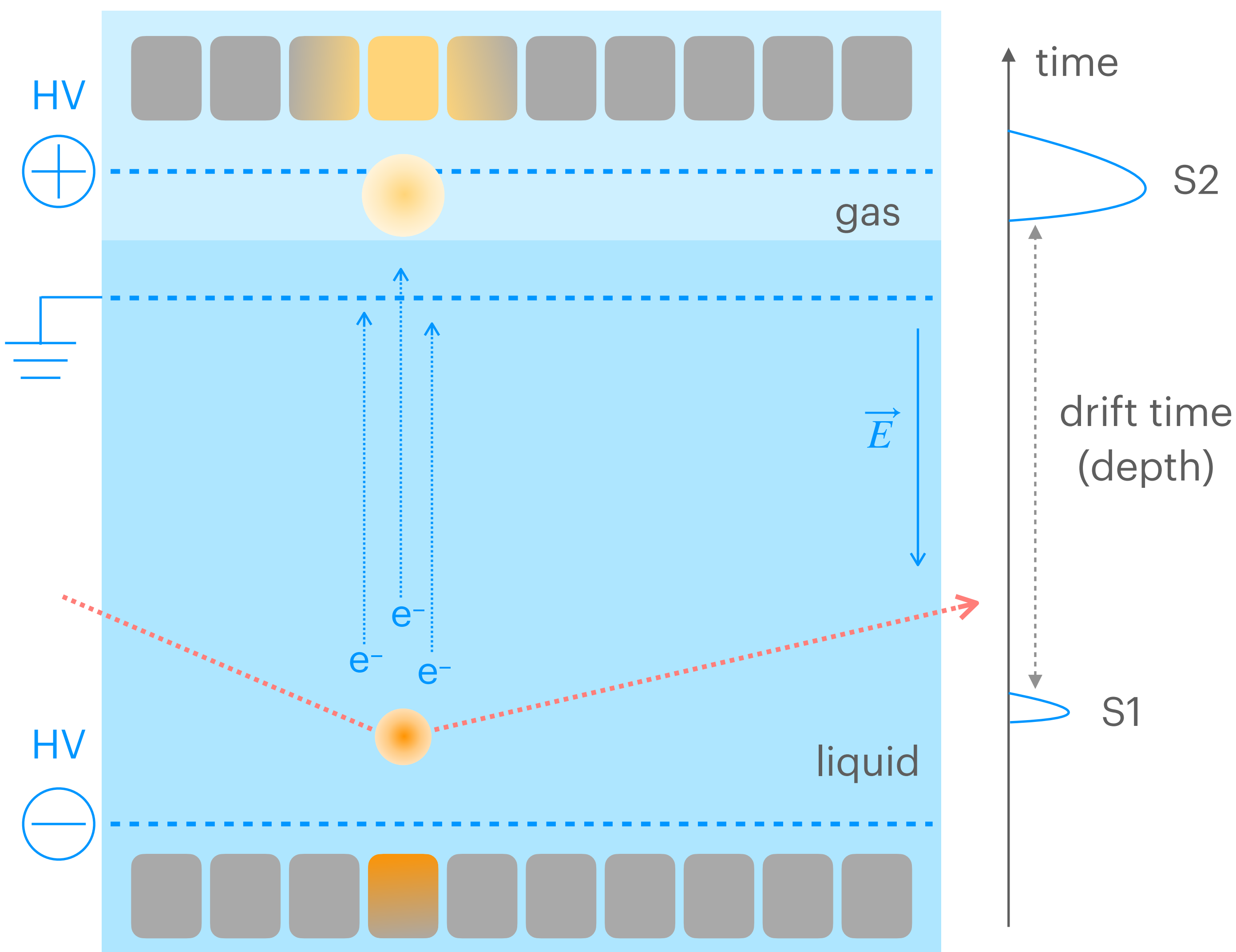
Direct detection landscape in 2024



LB and Stefano Profumo, PDG 2023

Liquid xenon TPCs

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



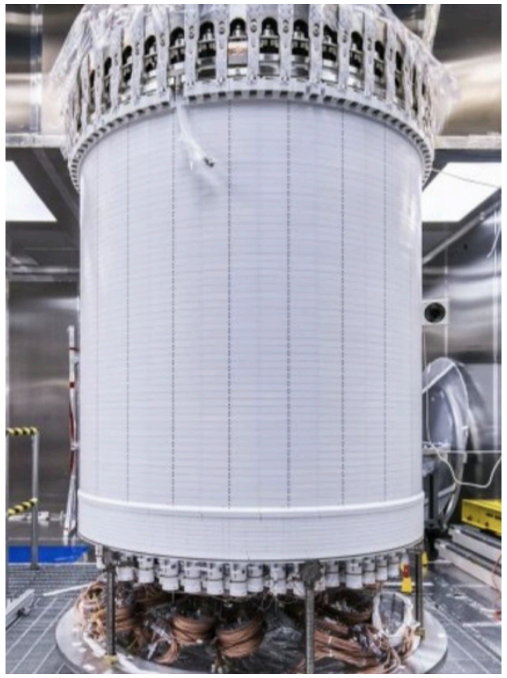
$$\lambda_{LXe} = 175 \text{ nm}$$

- Observe light (S1, primary scintillation) and charge signals (S2, secondary scintillation) when a particle interacts in the dense liquid target
- 3D position reconstruction
- Energy reconstruction
- Particle discrimination: ratio of charge/light (ERs vs. NRs)

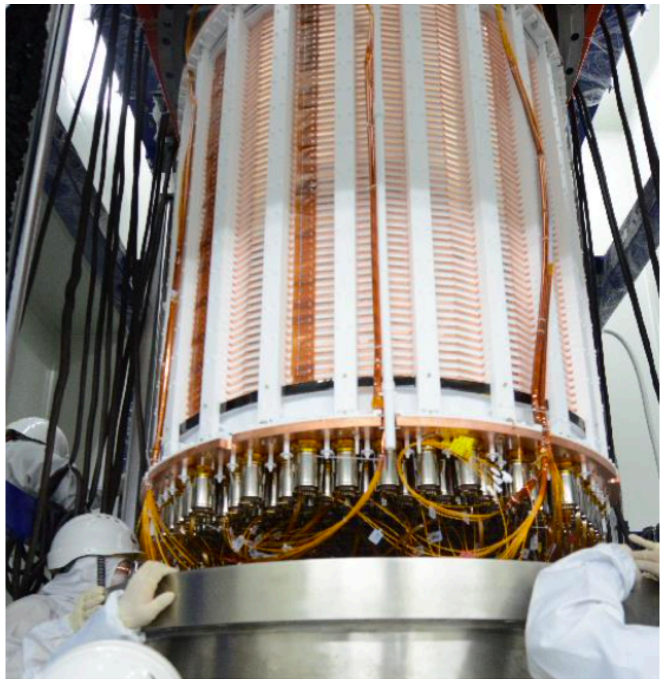
Ongoing experiments

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

LUX-ZEPLIN at SURF
10 t LXe total
494 PMTs
First results in 2022



PandaX-4T at JINPING
6.0 t LXe in total
368 PMTs
First results in 2021

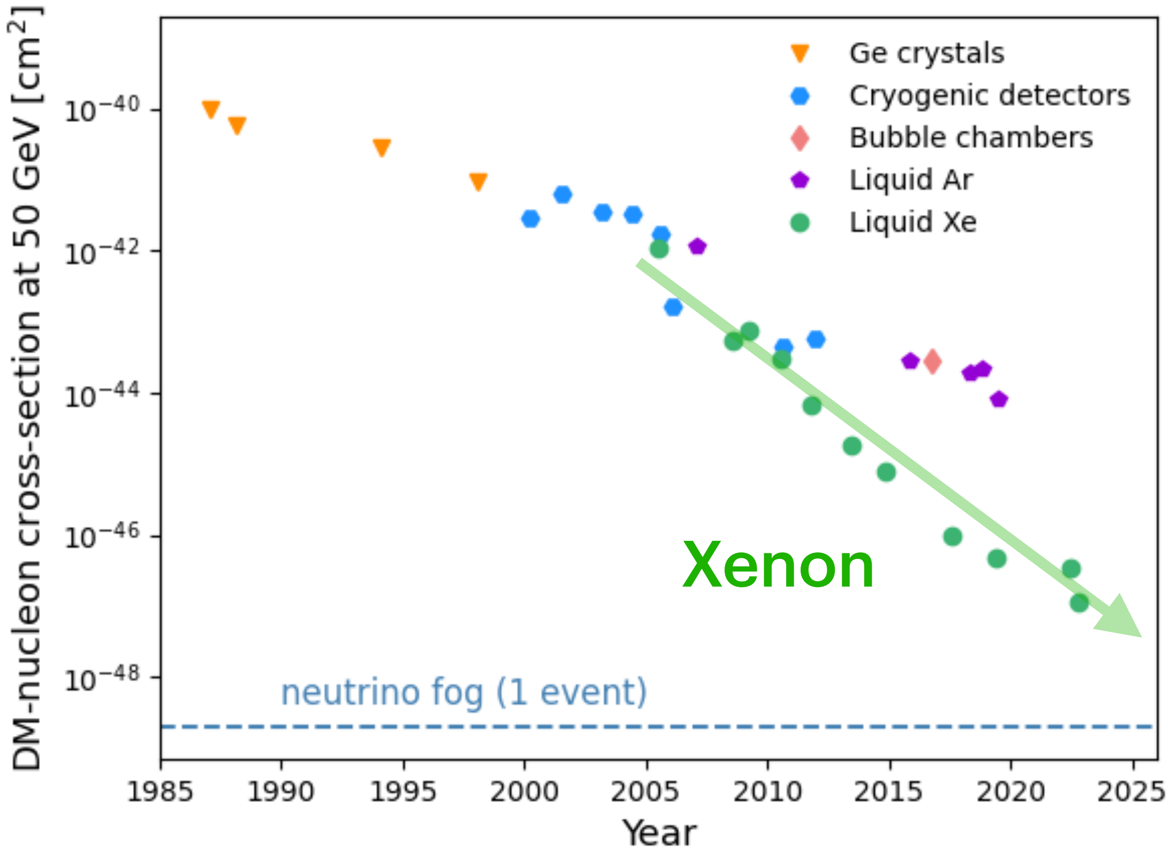


XENONnT at LNGS
8.6 t LXe total
494 PMTS
First results in 2022/23

WIMP sensitivity

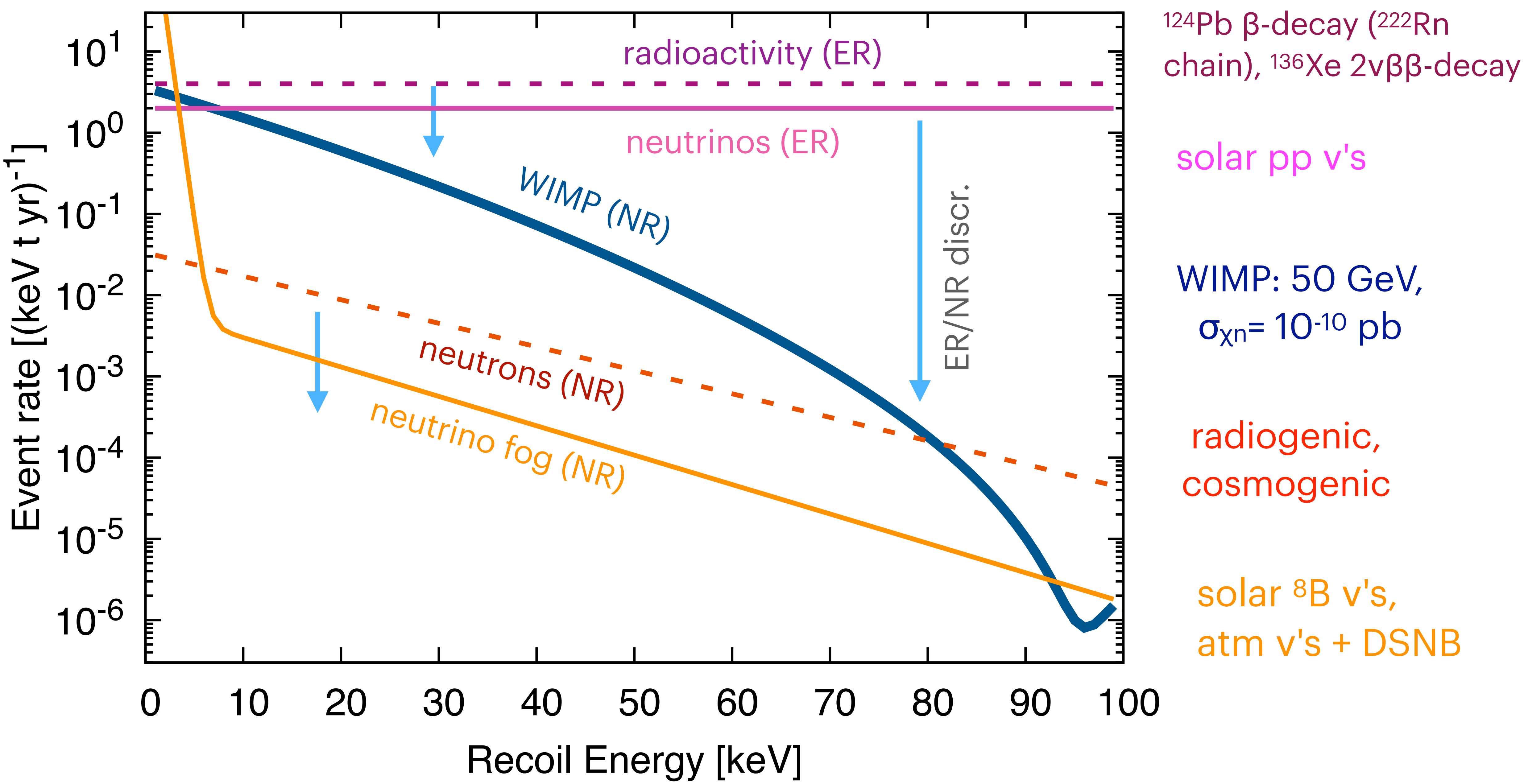
- Leading sensitivity at intermediate/high DM masses since ~2007
- Liquid xenon detectors
  - scalable ⇒ large target masses
  - readily purified ⇒ ultra-low backgrounds
  - high density ⇒ self-shielding
- SI and SD (^{129}Xe, ^{131}Xe) interactions
- Many other science opportunities: second order weak decays of ^{124}Xe, ^{136}Xe; solar and SN neutrinos, etc

Limits for a 50 GeV WIMP

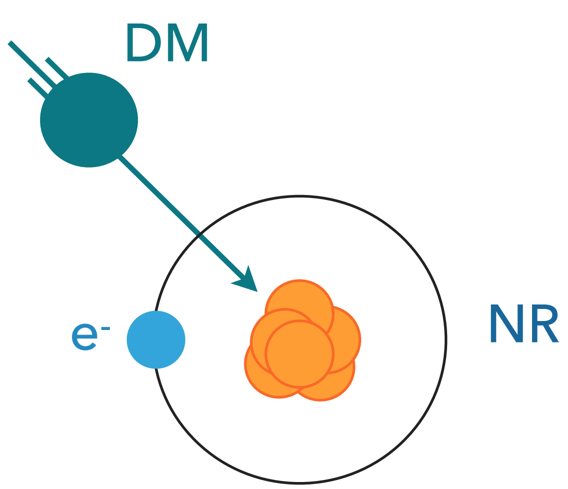


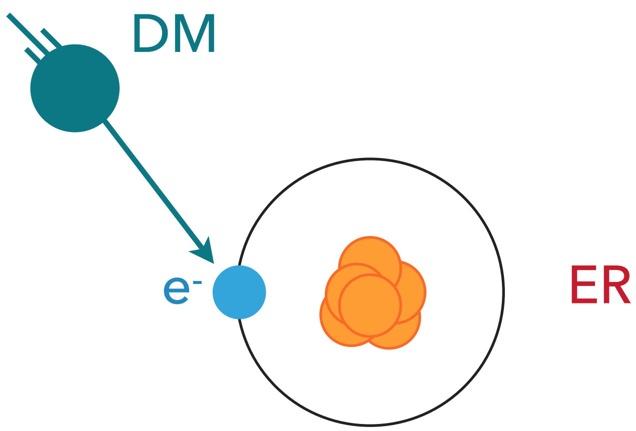
Backgrounds

- Overview: main ER and NR backgrounds



Light dark matter searches





Use the Sun* for a velocity boost

Migdal effect: NR signal with ER character

DM-e⁻ scattering
DM absorption

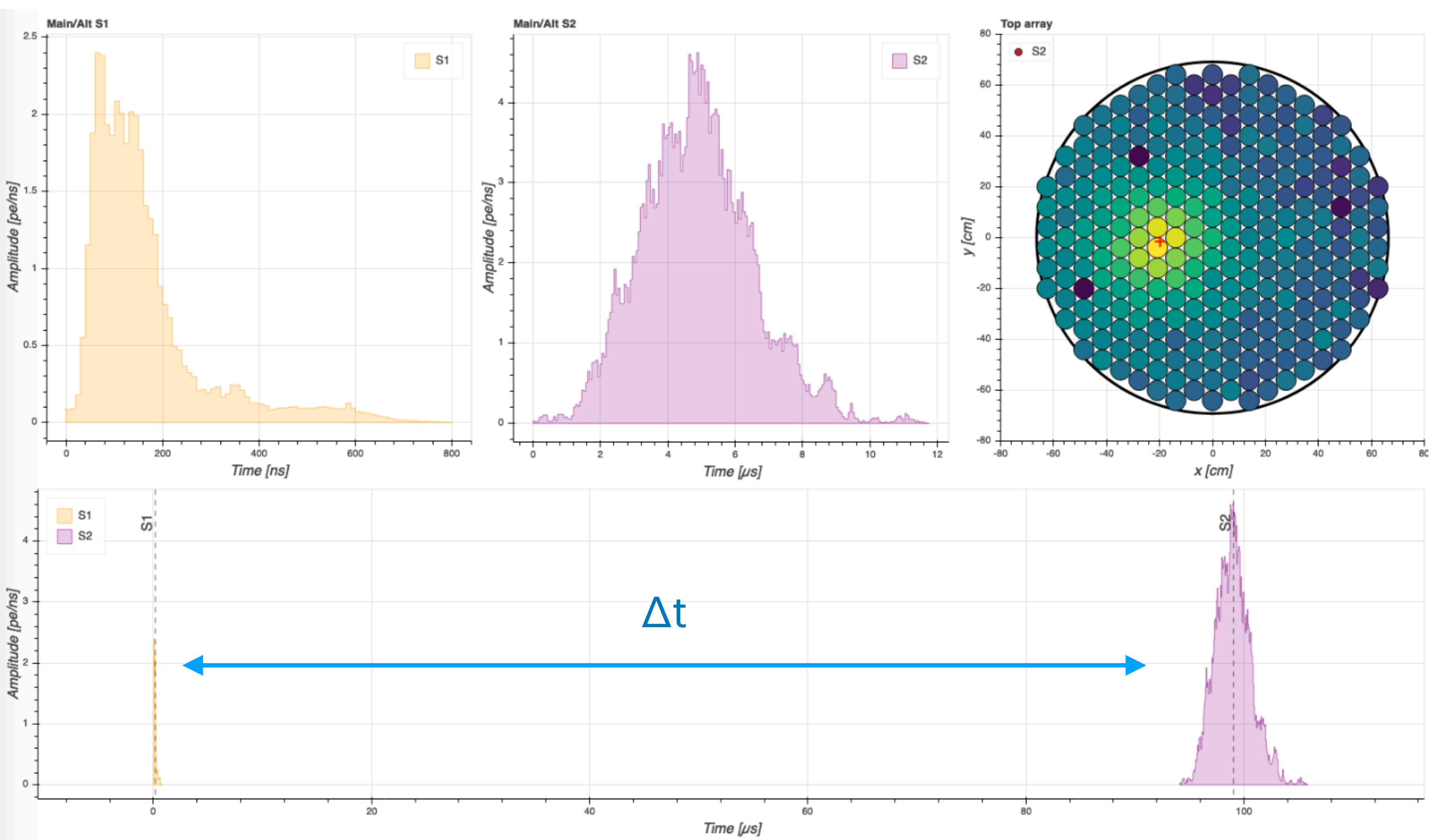
Ionisation-only searches

*or CRs, or the DSNB, see talk by Maxim Pospelov

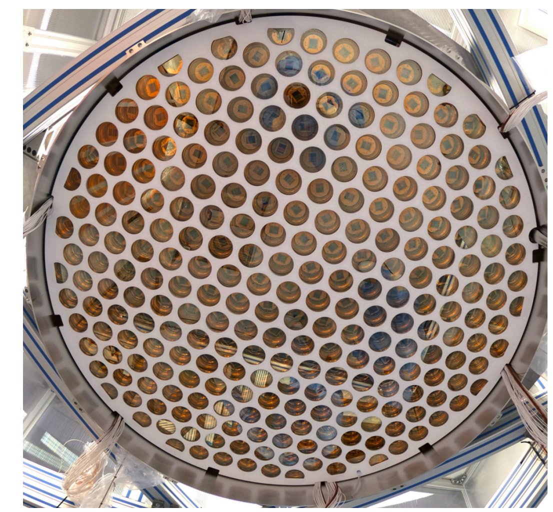
Signal example

- S1 + S2 signals from an ^{83m}Kr calibration event in XENONnT

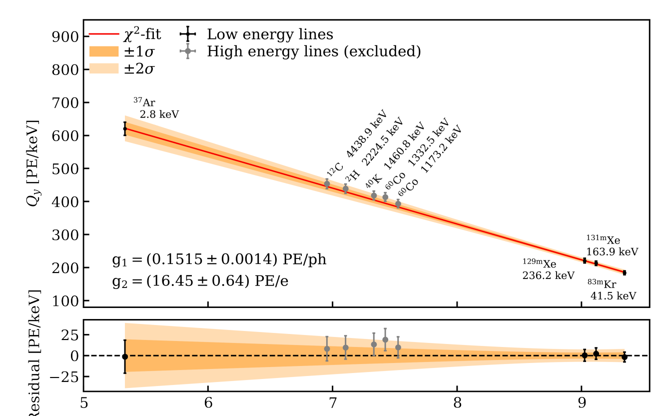
S1 S2



S1 S2



Maximum e⁻ drift time: 2.3 ms
Electron lifetime τ_e: > 10 ms

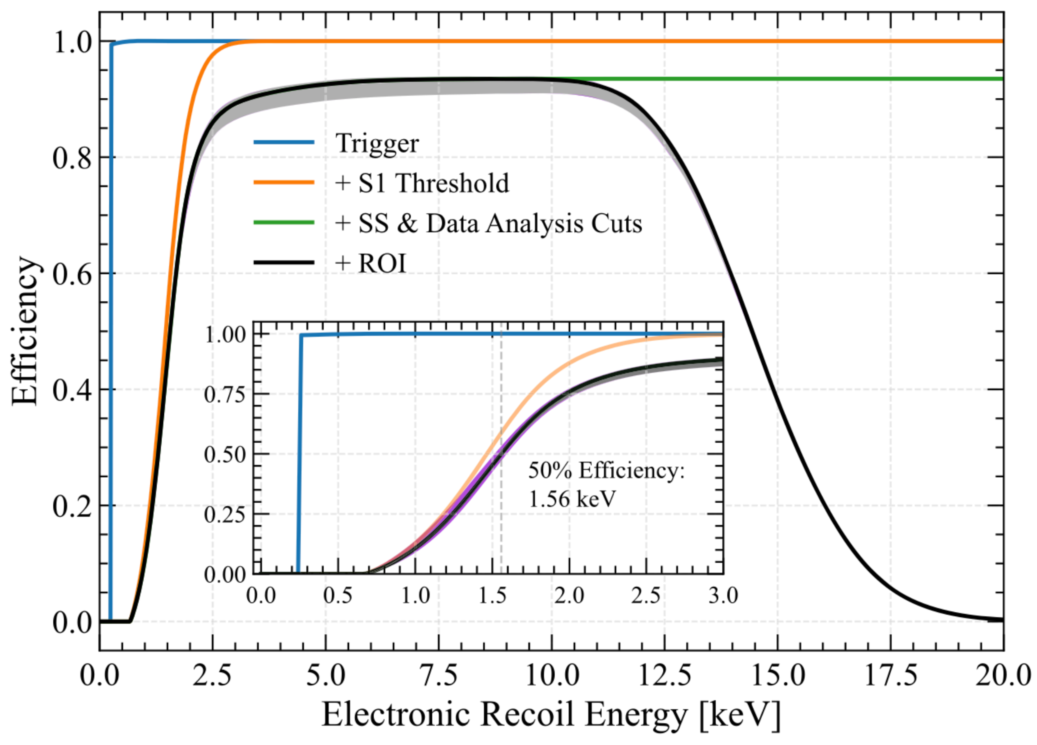


XENONnT arXiv:2402.10466

Energy thresholds

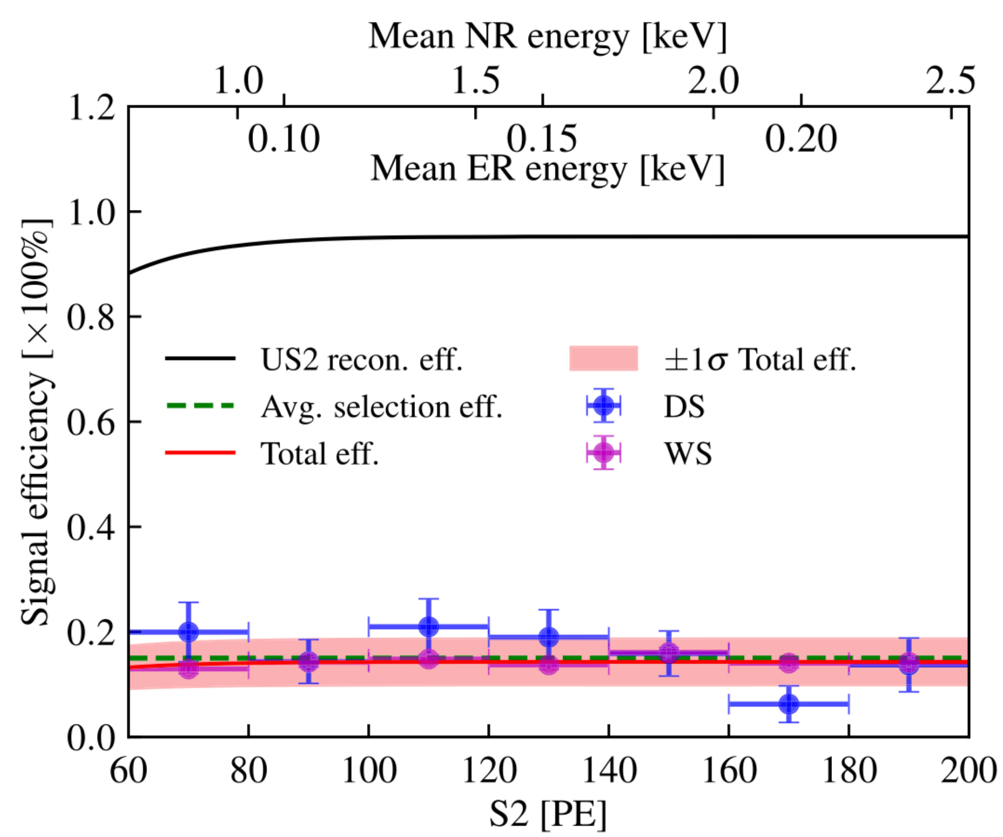
- **S1 + S2 searches:** typically ~ 1 keV with 3-fold coincidence (ER) (hits in at least 3 PMTs within, e.g., ~50-100 ns); lower threshold (< 1 keV) with 2-fold coincidence possible (with lower signal efficiency)
- **S2-only searches:** down to ~ 0.2 keV, with 5 e^- – 100 e^- detected (probe ER and NR interactions), down to W-value, with 1 e^- – 5 e^- signal (mostly probe ER DM models 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

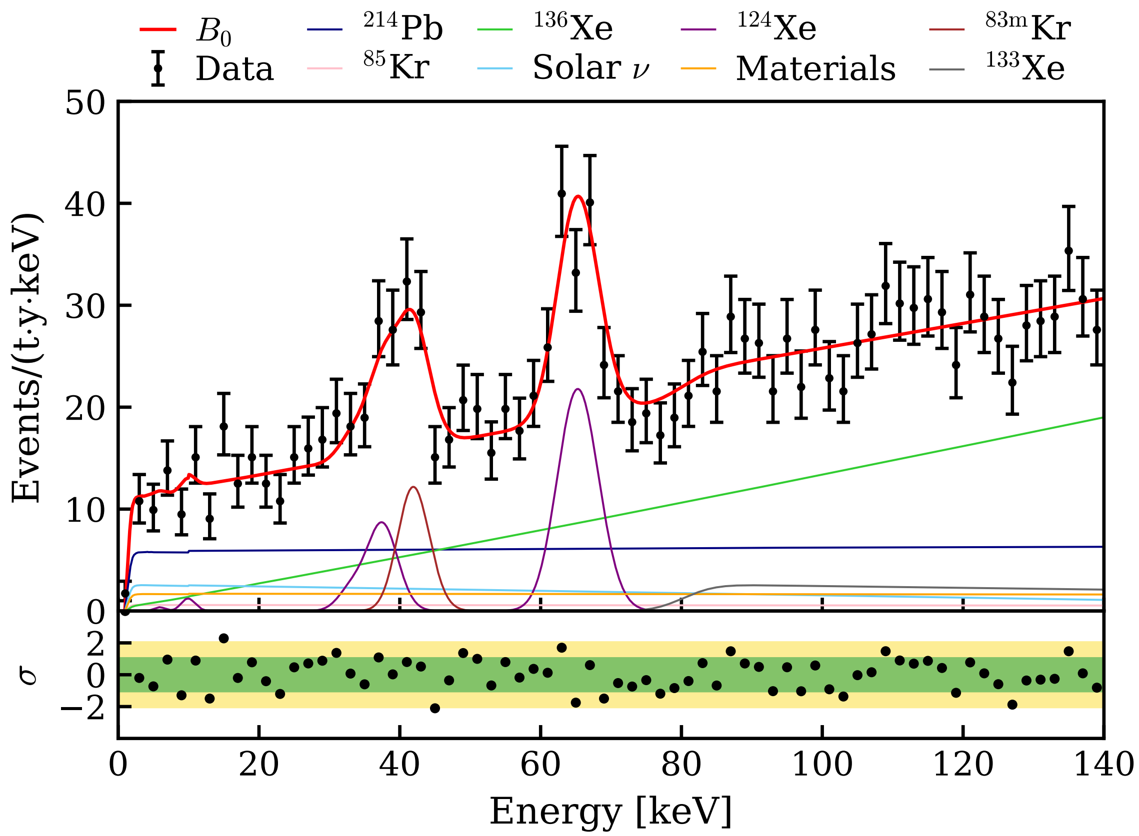
PandaX-4T, PRL 130, 2023



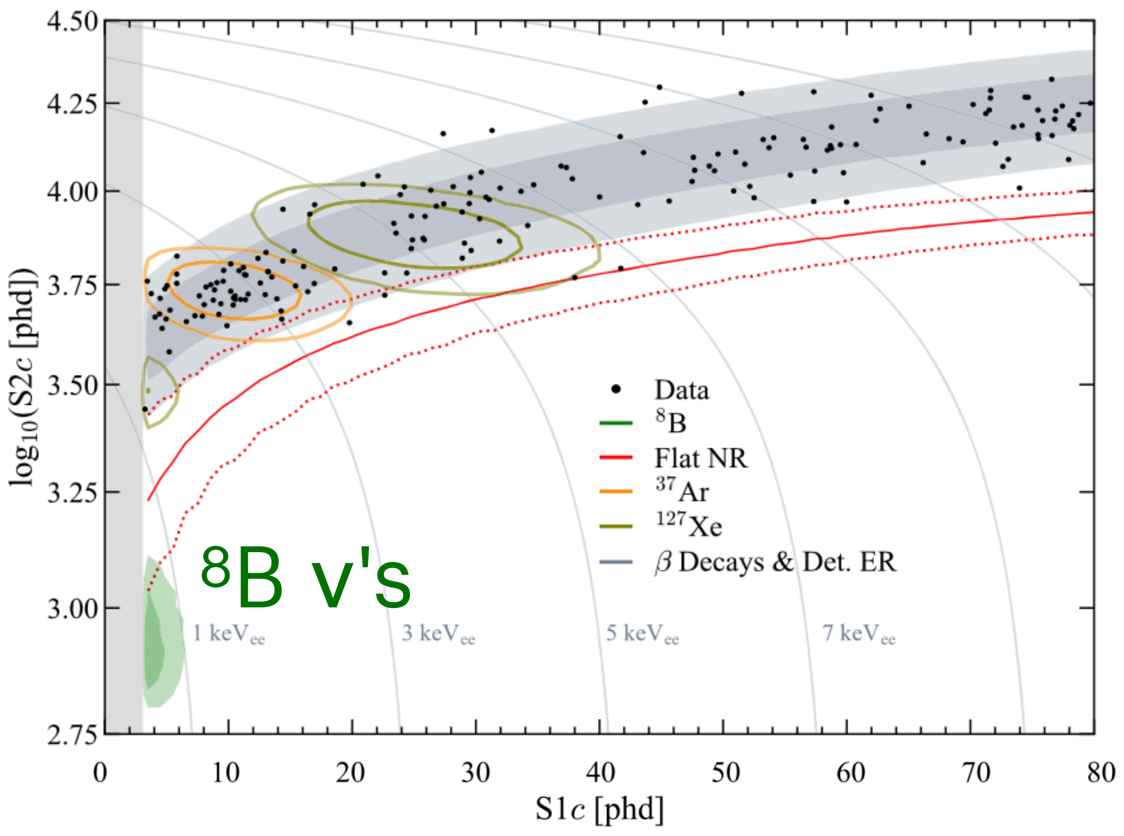
ER+NR Backgrounds

- ER: ^{214}Pb β-decays, ^{124}Xe DEC, ^{85}Kr β-decays, ^{136}Xe ββ-decays
- NR: ^{8}B ν's
- At lowest energies: combinatorial (AC) background becomes important

XENONnT, PRL 129, 2022



LZ, PRD 108, 2023

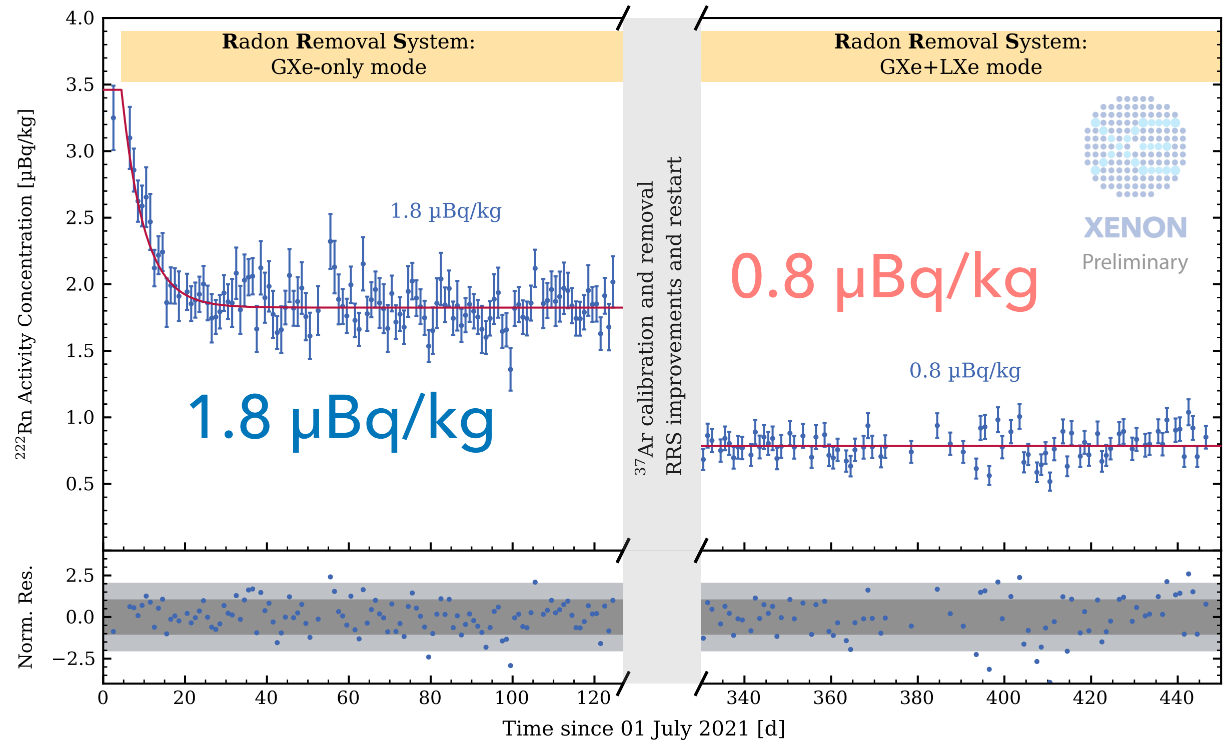


Side remark

- Today's background, tomorrow's signal...

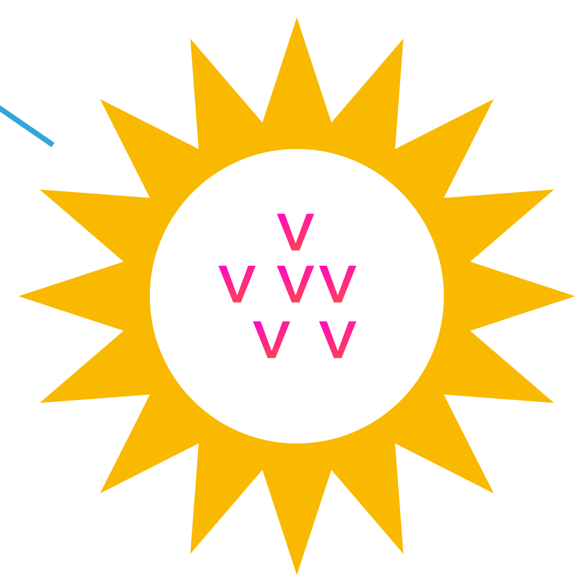
Component	(1,10) keV
^{214}Pb	**56±7**
^{85}Kr	6±4
Materials	16±3
Solar ν	**25±2**
^{124}Xe	2.6±0.3
^{136}Xe	8.7±0.3
AC	0.7±0.03

XENONnT: ^{222}Rn concentration reduced for SR1, compared to SR0



Solar ν flux at low energies:

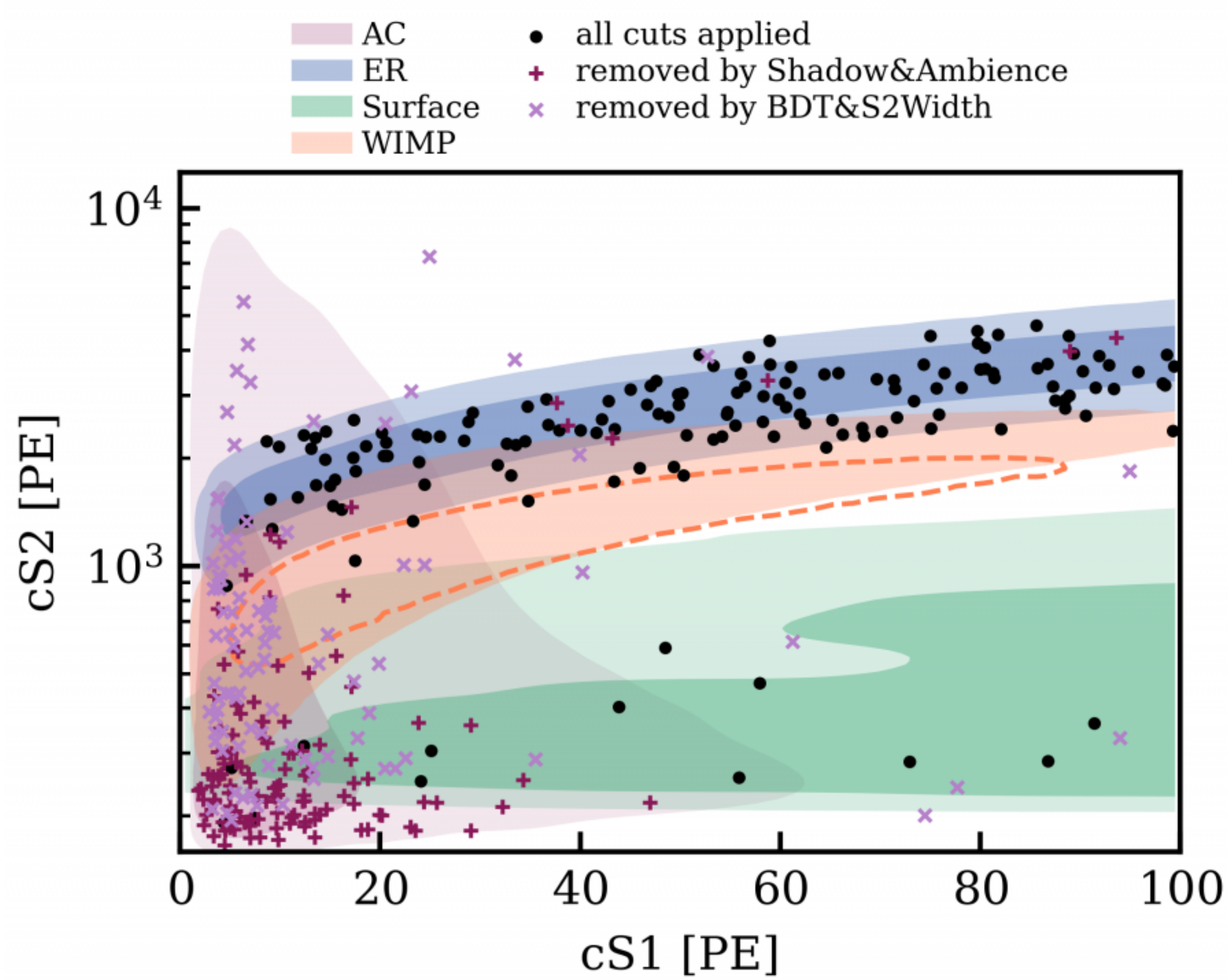
$$\frac{dR}{dT} = N_e \int \frac{d\Phi}{dE_\nu} \left(P_{ee} \frac{d\sigma_e}{dT} + (1 - P_{ee}) \frac{d\sigma_{\nu,\tau}}{dT} \right) dE_\nu$$



AC backgrounds

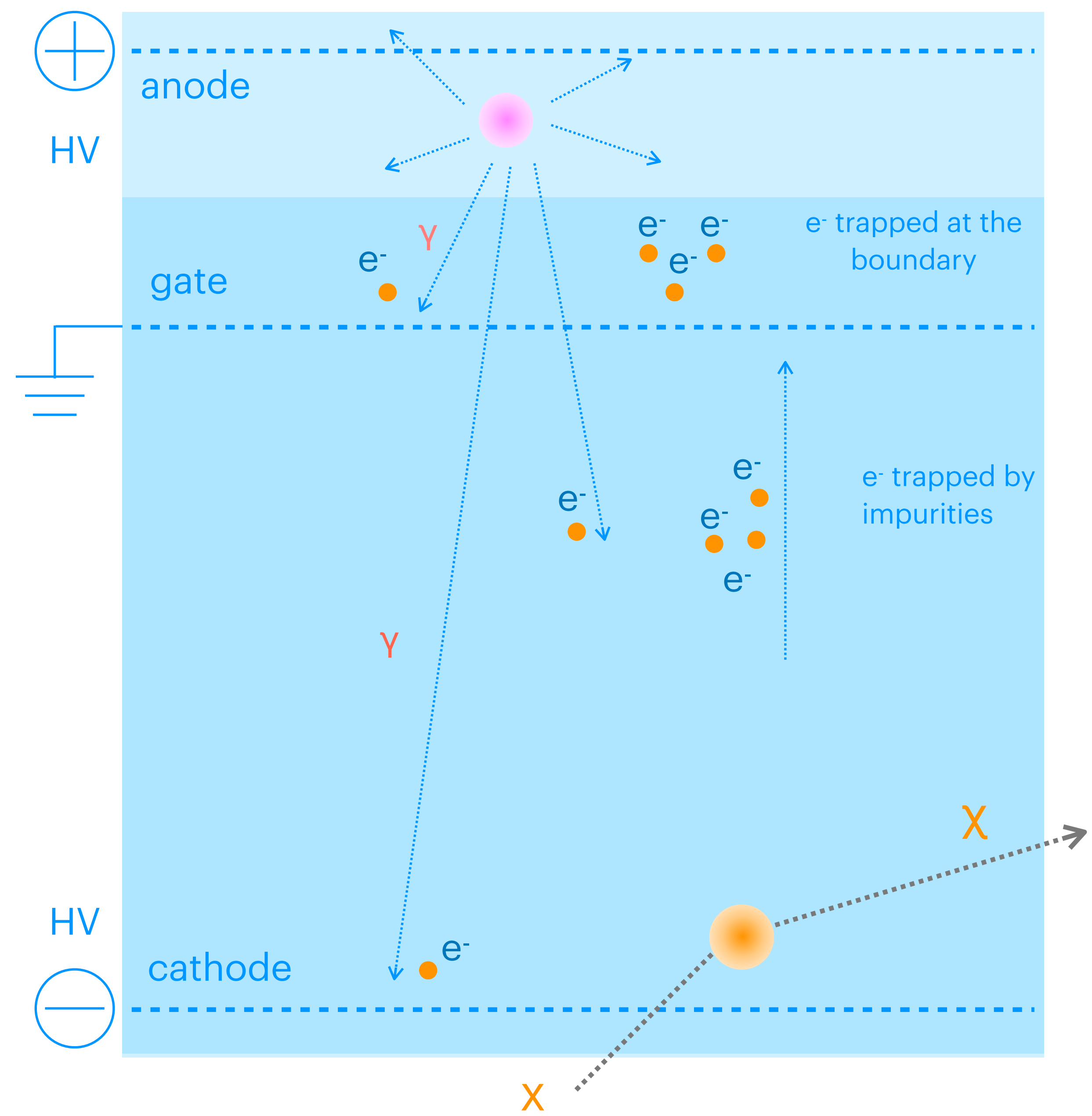
- Combinatorial background at low energies can be significant
- Main sources for isolated S1 and isolated S2 signals
  - Primary scintillation (S1s)
    - Dark counts (pile-up) ∝ nr. channels
    - Charge-insensitive regions
    - Delayed photons
  - Electroluminiscence (S2s)
    - Bulk xenon S2-only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



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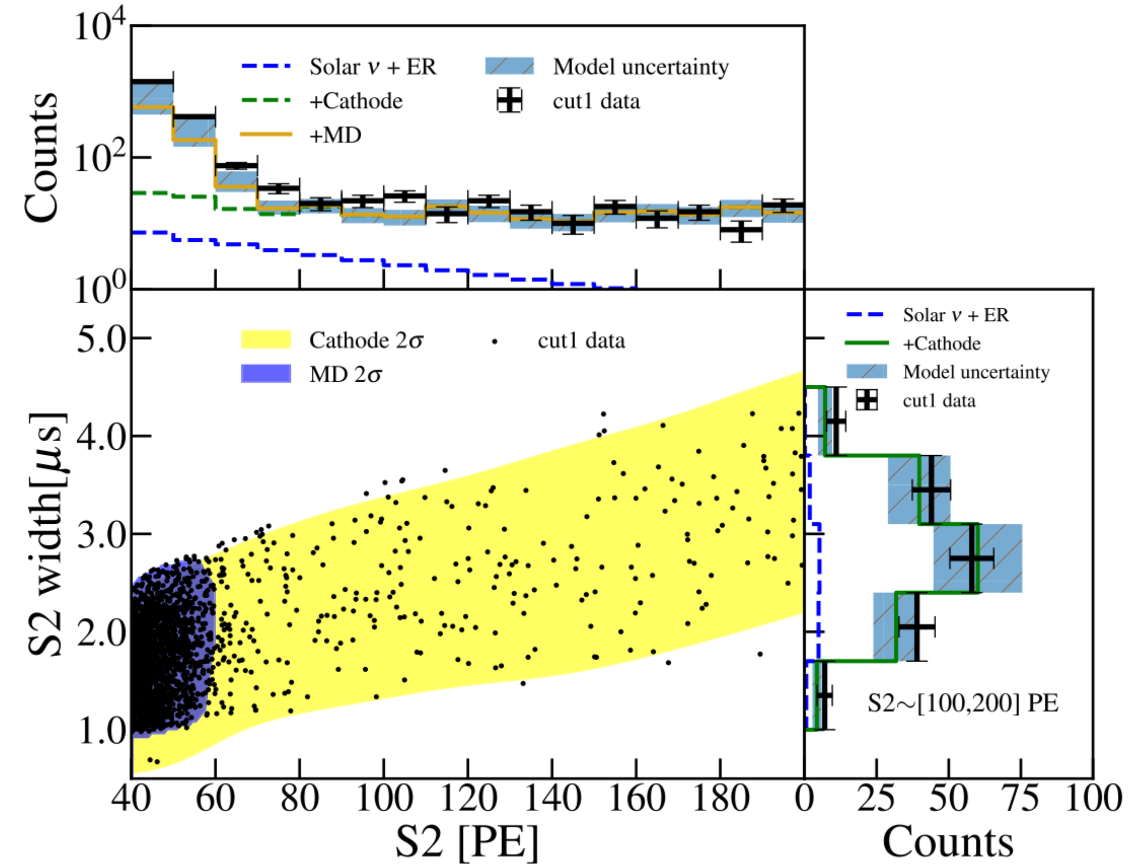
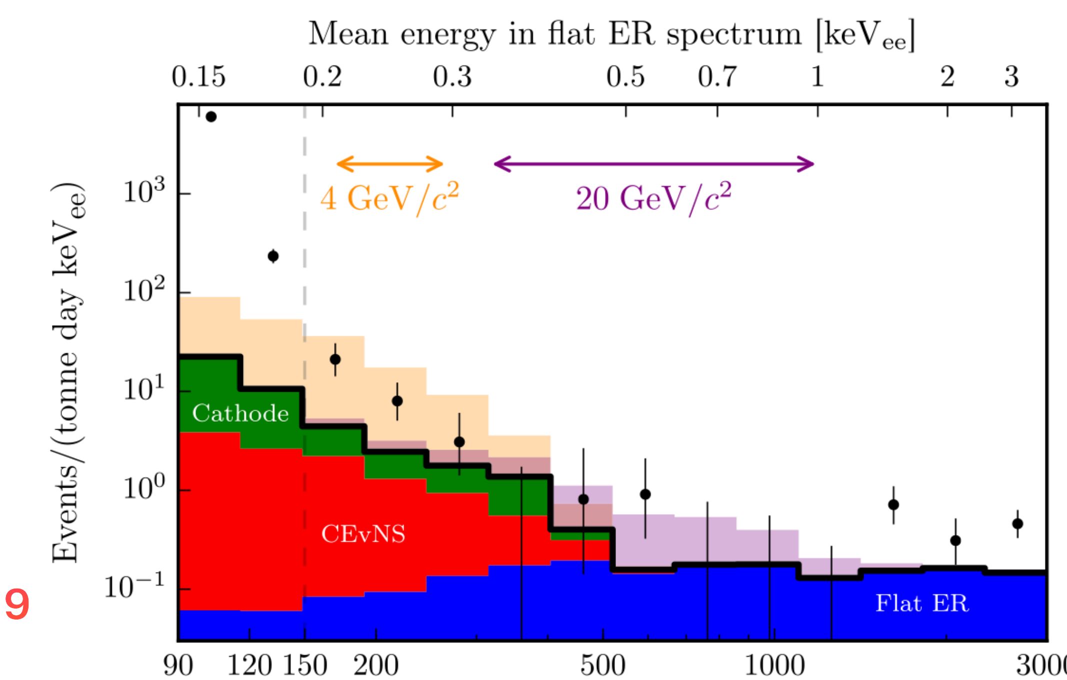
PandaX-4T, PRL 130, 2023

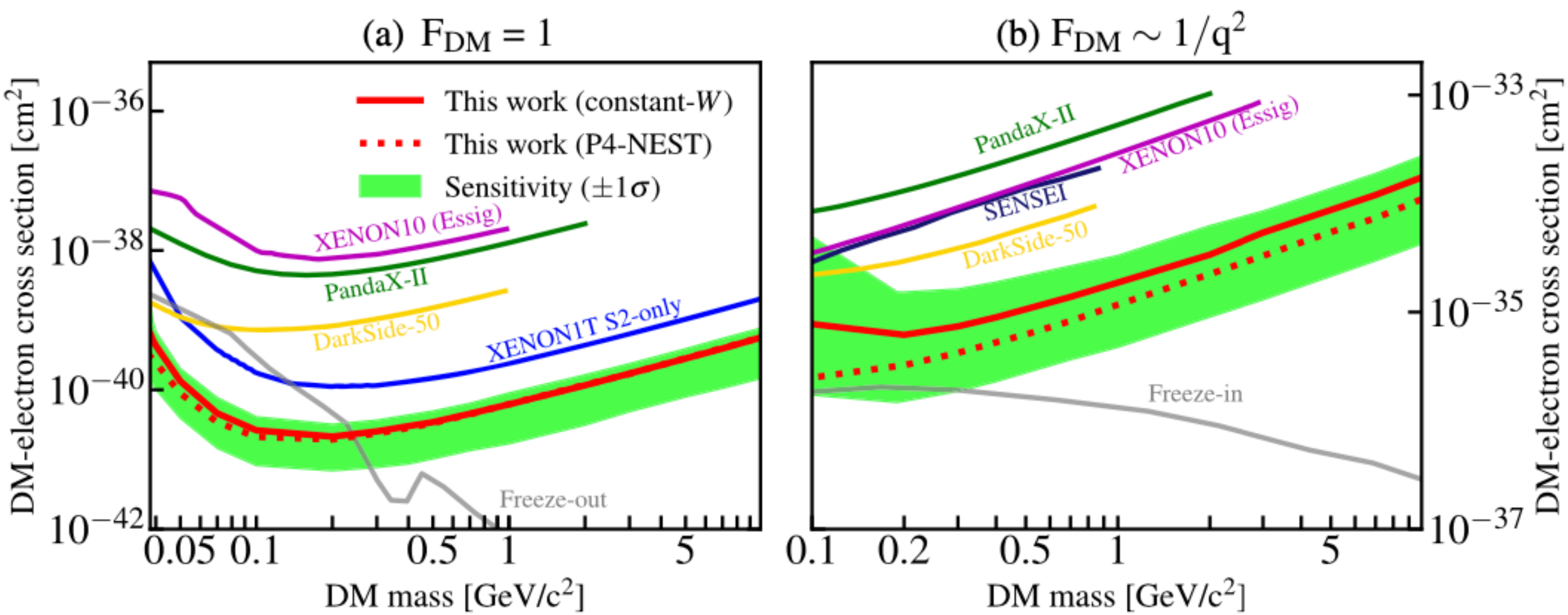




XENON1T, PRL 123, 2019

Ionisation-only results

- Constraints on dark matter electrons interactions
- XENON1T: 22 t d exposure, DM particle masses > 30 MeV
- PandaX-4T: 0.55 t y exposure, DM mass range from ~ 40 MeV to 10 GeV

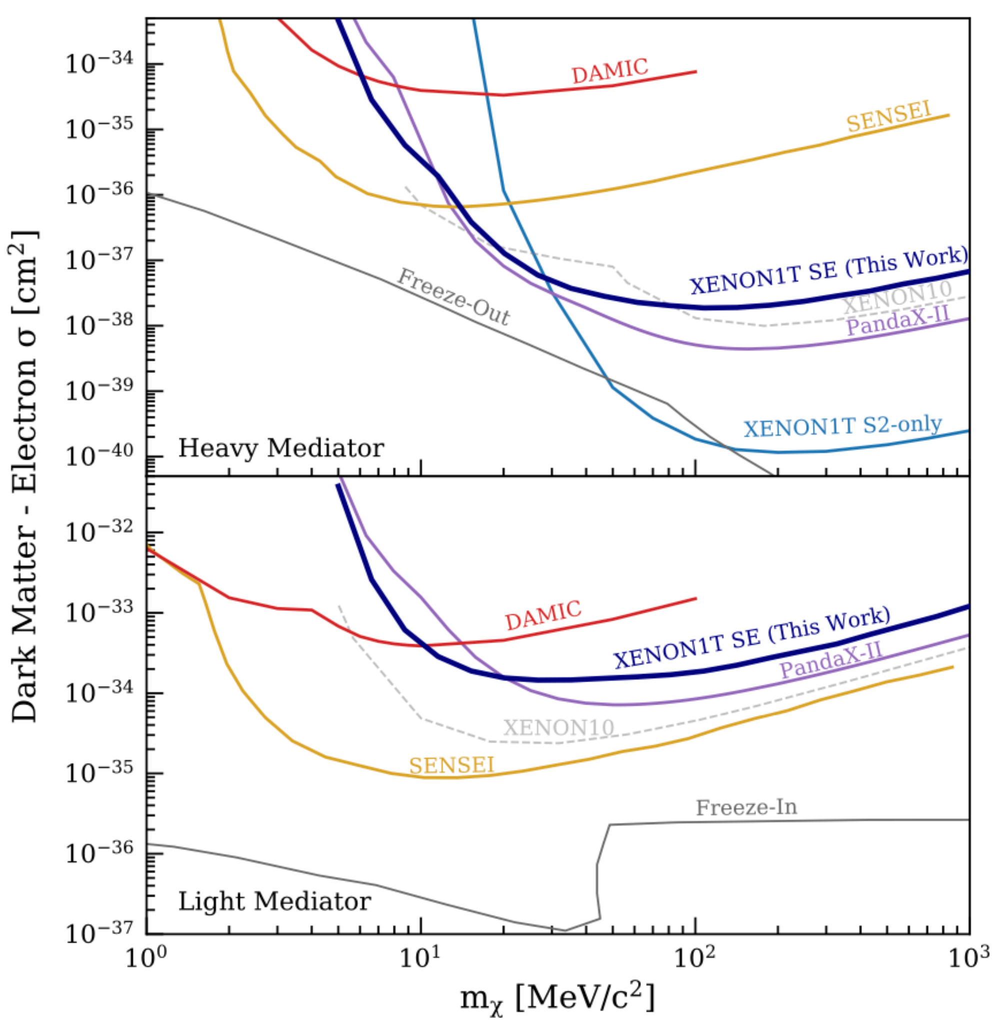


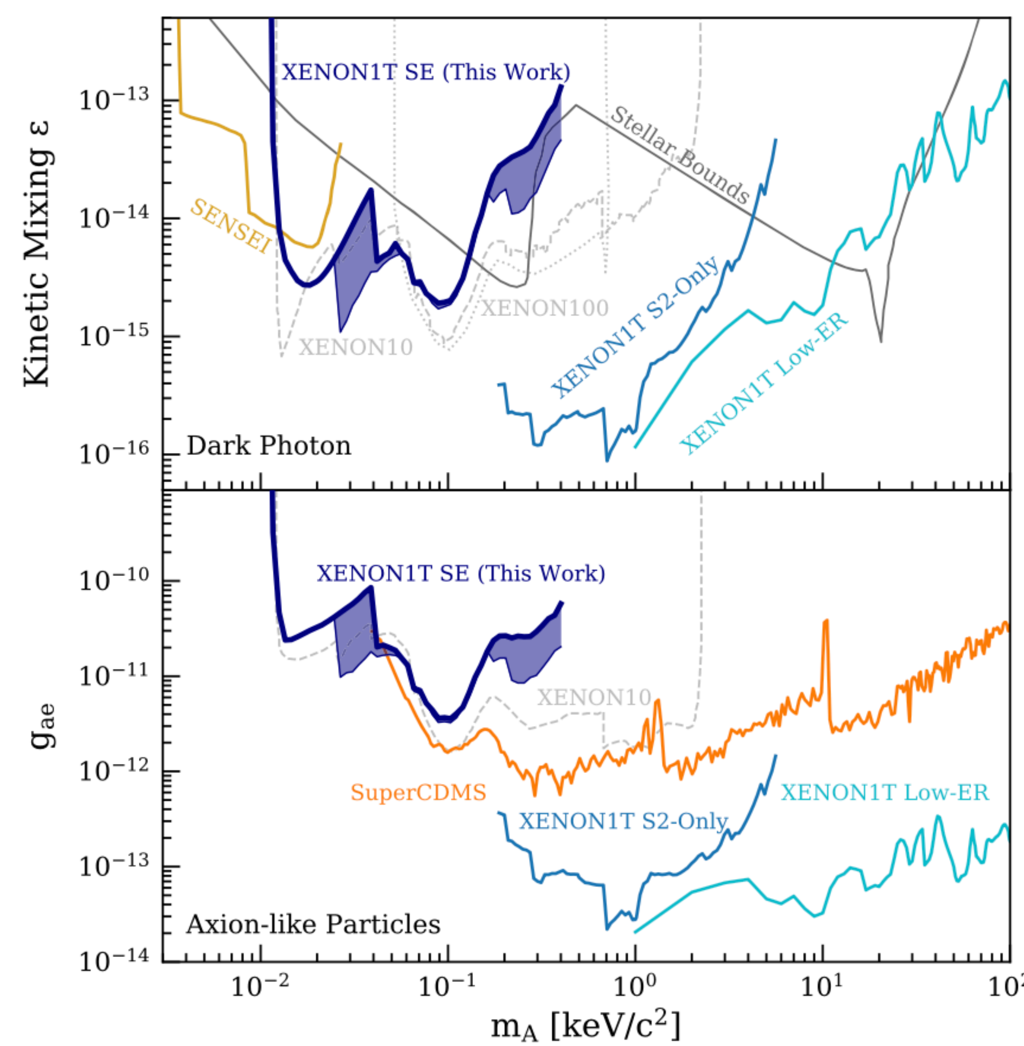
PandaX-4T, PRL 130, 2023

XENON1T, PRL 123, 2019

Ionisation-only results

- XENON1T: extended analysis down to single electrons (1 - 5 e-)
- Showed that delayed e- are correlated in time & space with HE events and can be vetoed (background rate of < 30 events/(kg d) after cuts)

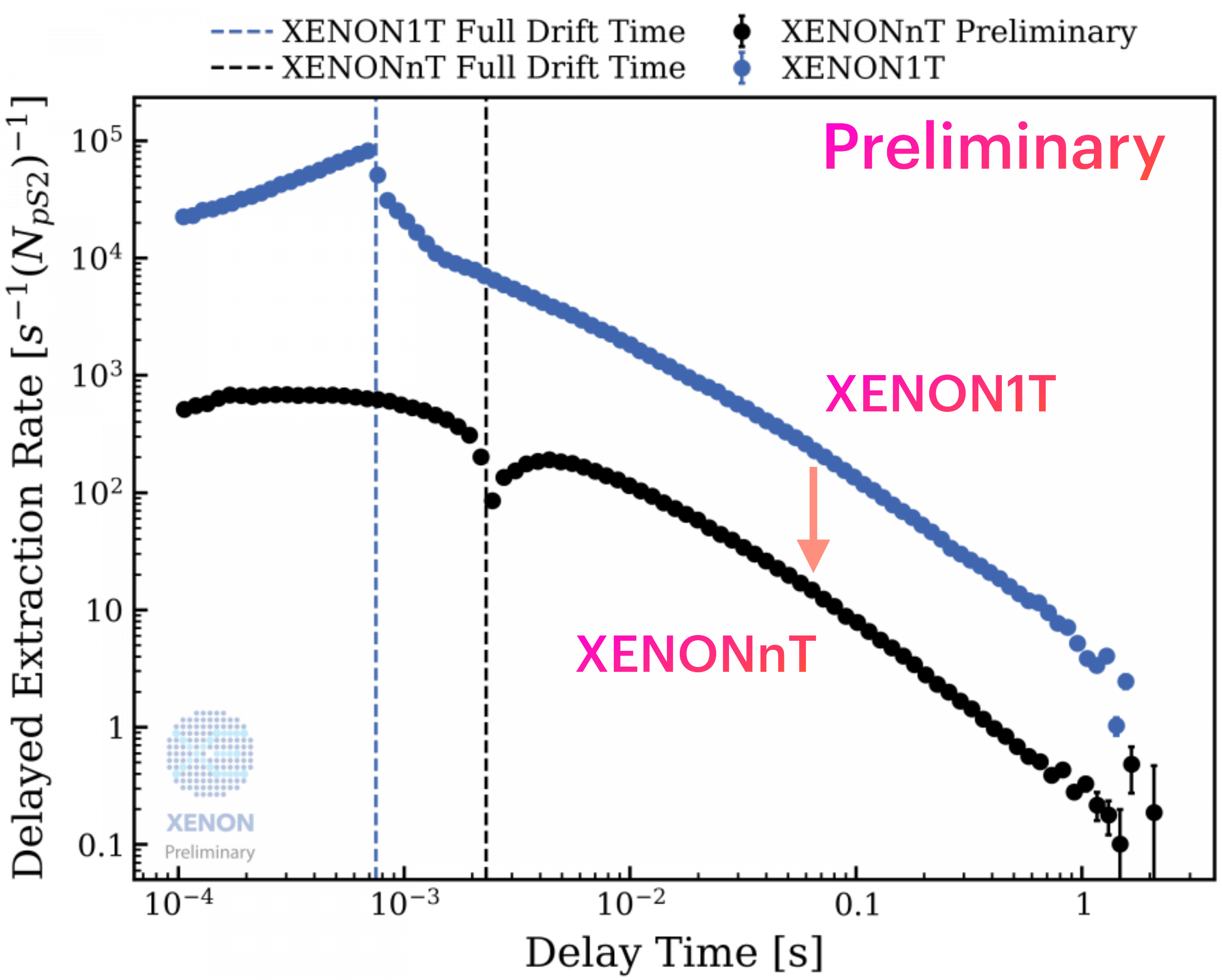




XENON1T, PRL 106, 2022

Ionisation-only results

- XENONnT: 3 x larger active target, 10 x lower overall delayed electron rate compared to XENON1T



- Single-electron delay rate as a function of delay time from the preceding S2
- In general: longer drift times ⇒ higher delayed emission rate
- XENONnT: higher LXe purity (lower concentration of electronegative impurities) & lower concentration of ^{222}Rn ⇒lower S2 rates

XENON1T, PRD 106, 2022

Ionisation-only results

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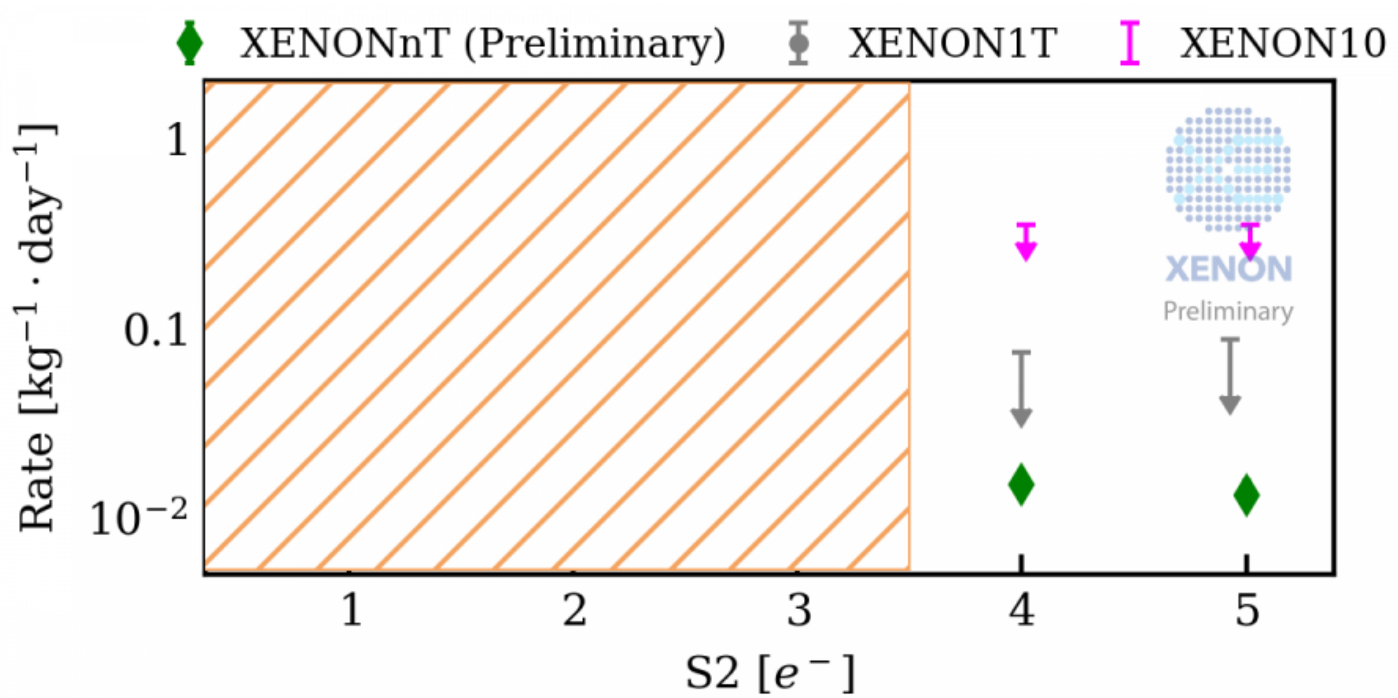


XENONnT preliminary

- XENONnT science data: still blinded
- Rates shown here: based on a calibration run after first science run (SR0)

ER: DM absorption

- ALPs and dark photons: absorption results in peak at boson mass
- Rates $\propto \phi \times \sigma = \rho \times \frac{v}{m} \times \sigma$ (here below for ρ = 0.3 GeV/cm³)

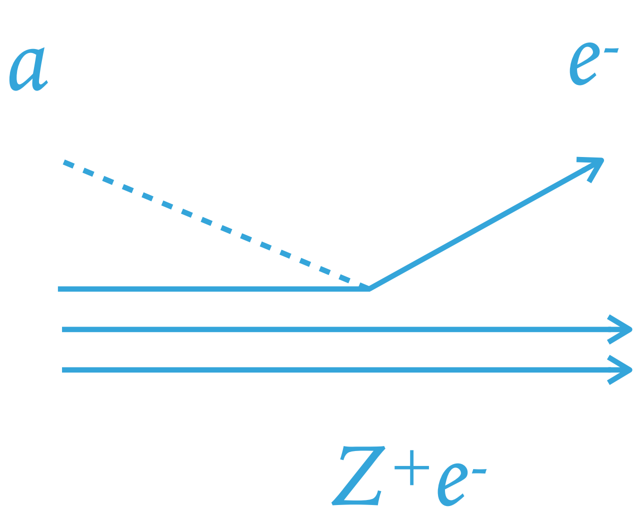
$$R \simeq \frac{1.5 \times 10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\mathrm{keV}}\right) \left(\frac{\sigma_{pe}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

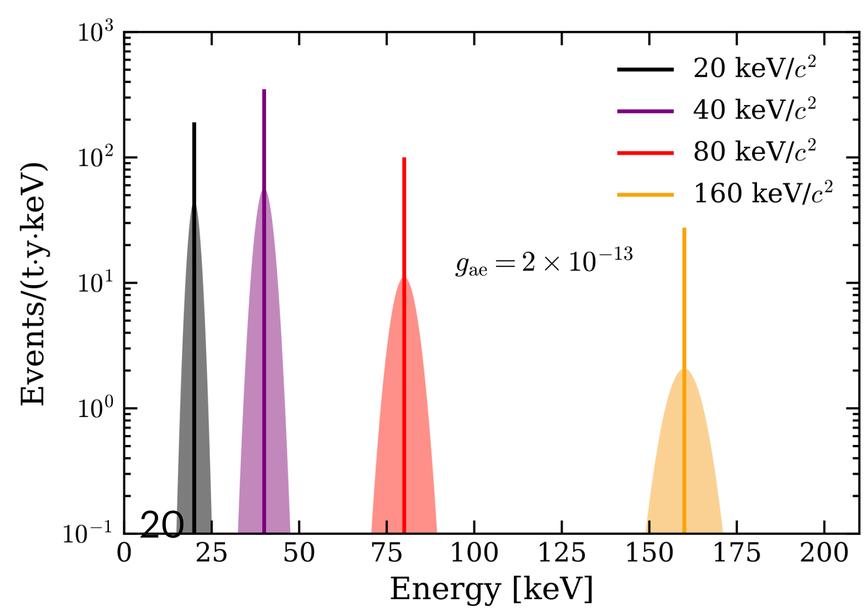
$$R \simeq \frac{4.7 \times 10^{23}}{A} \kappa^2 \left(\frac{\mathrm{keV}}{m_V}\right) \left(\frac{\sigma_{pe}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

$$\sigma_v \simeq \frac{\sigma_{pe}}{\beta} \kappa^2$$

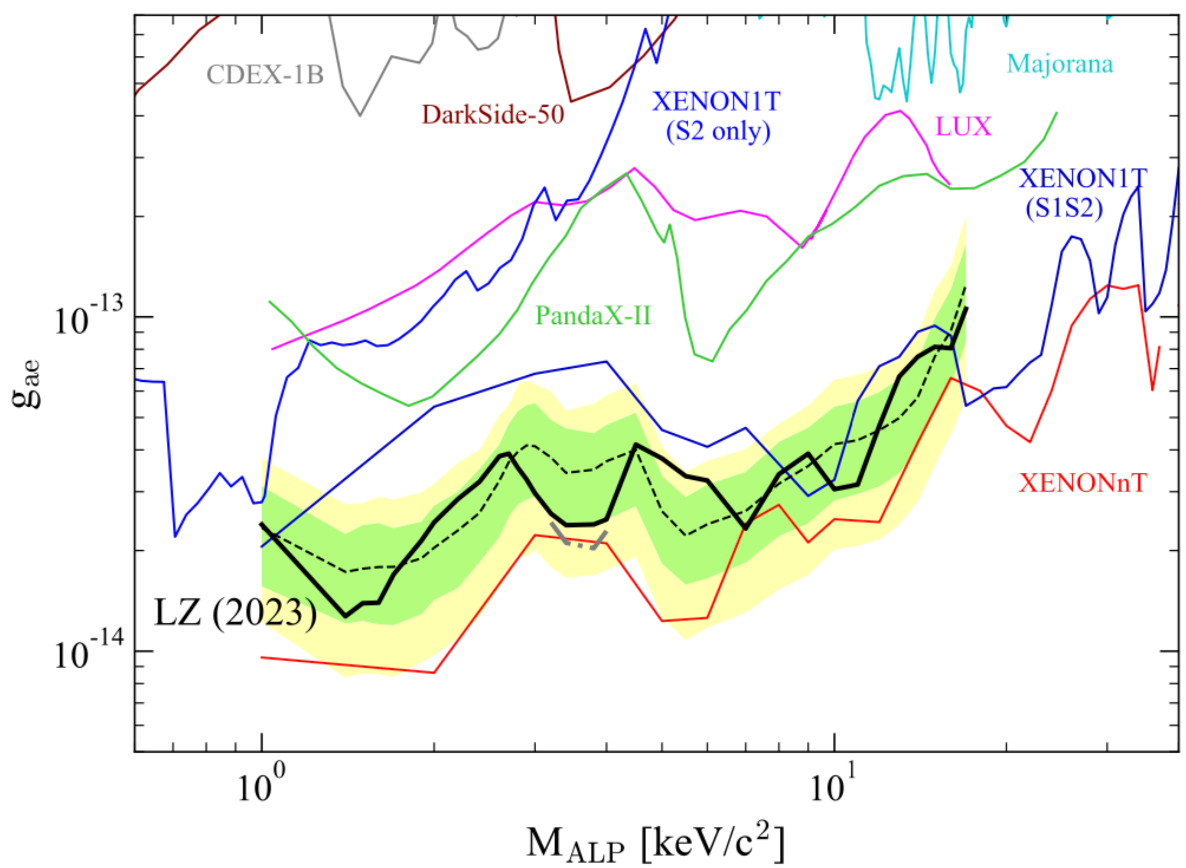
strength of kinetic mixing between photon and dark photon

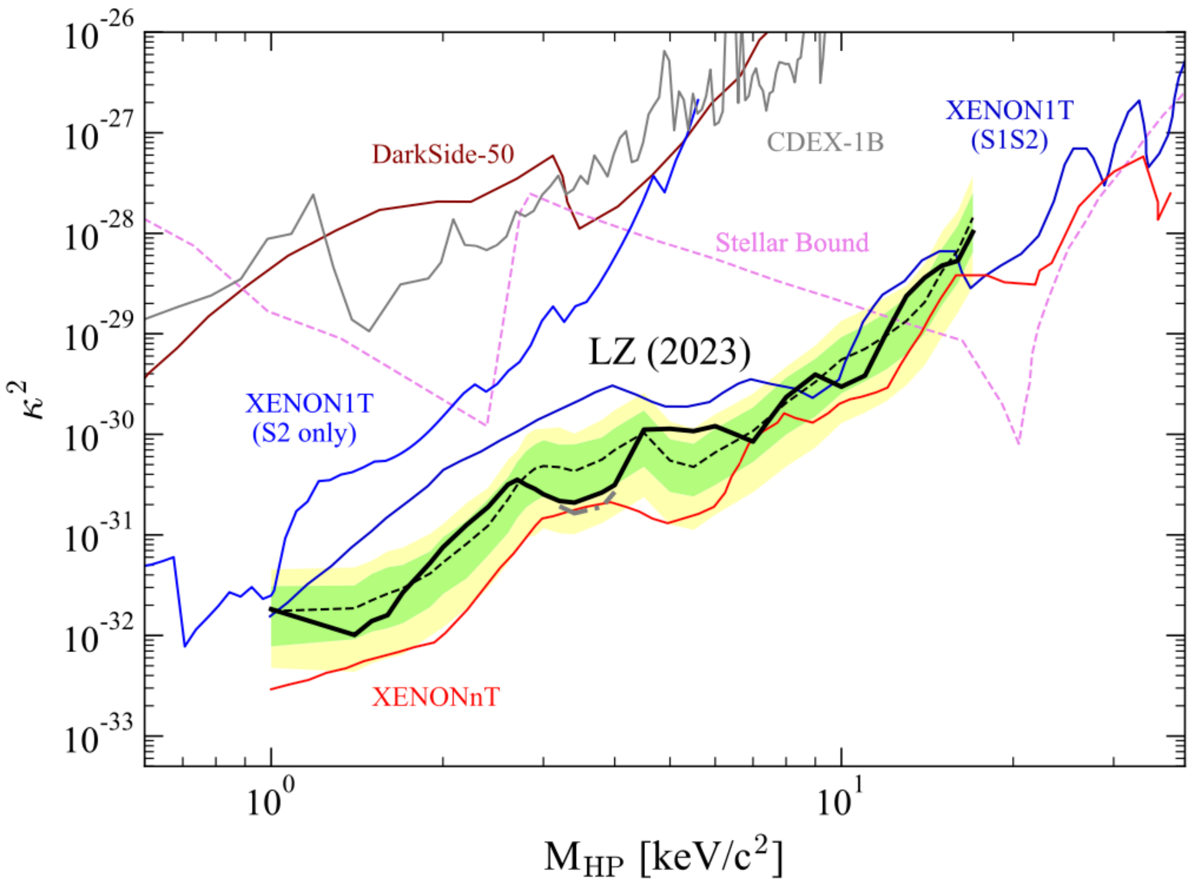




An, Pospelov, Pradler, Ritz PLB 747, 2015

ER: DM absorption





- Constrains on the couplings of galactic ALPs and dark photons:
  - LZ, XENONnT: competitive upper limits for masses in the range ~ 1 - 140 keV

XENONnT, PRL 129, 2022

LZ, PRD 108, 2023

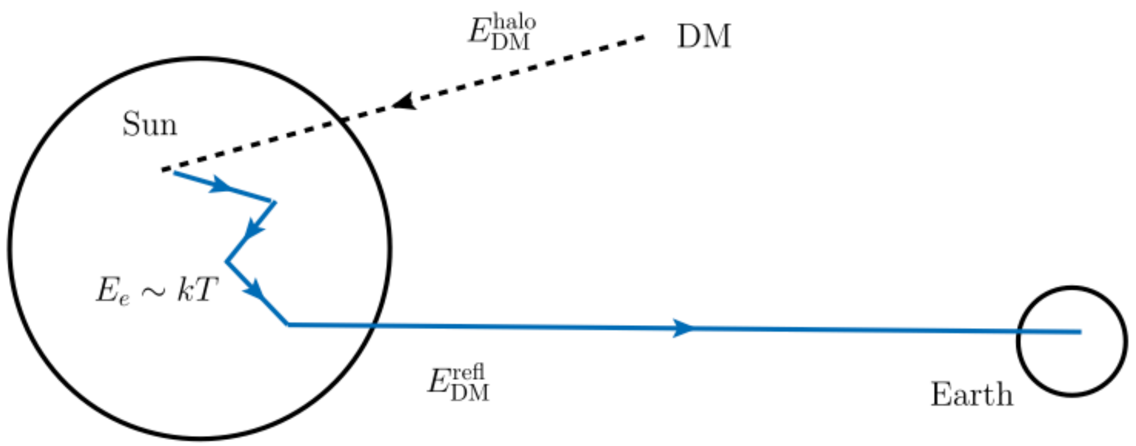
Solar reflected dark matter

- If DM particles interact with nuclei or e⁻, they will also interact with the p and e⁻ in the Sun

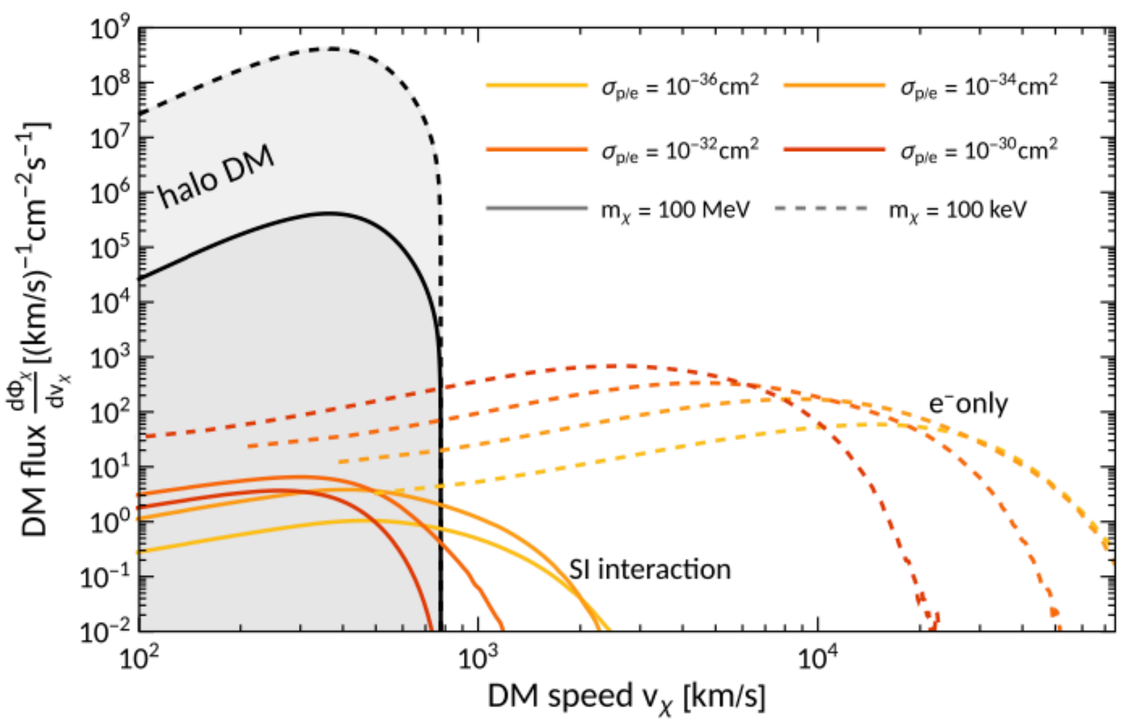
  ⇒Up-scattering of DM particles in the Sun

- Smaller flux, but faster particles
- Allows LXe experiments to probe LDM
- Flux can be computed with, e.g., DaMaSCUS-SUN public code* (T. Emken)

*https://github.com/temken/DaMaSCUS-SUN?tab=readme-ov-file



H. An, H. Nie, M. Pospelov, J. Pradler, A. Ritz, PRD 104, 2021

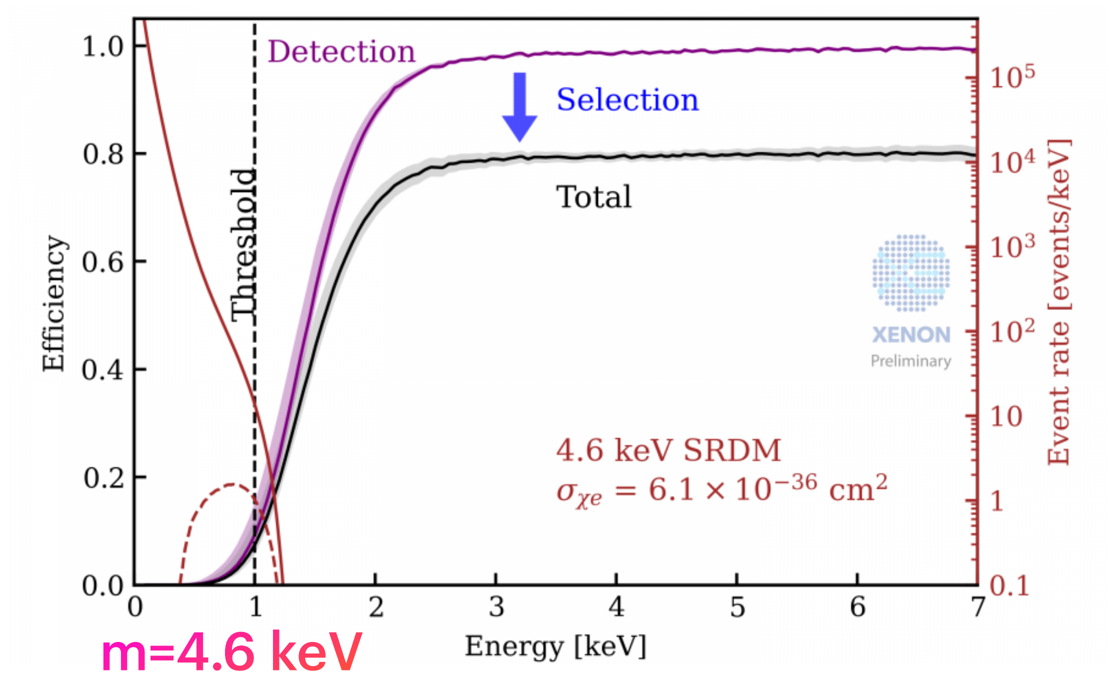


T. Emken, PRD 105, 2022

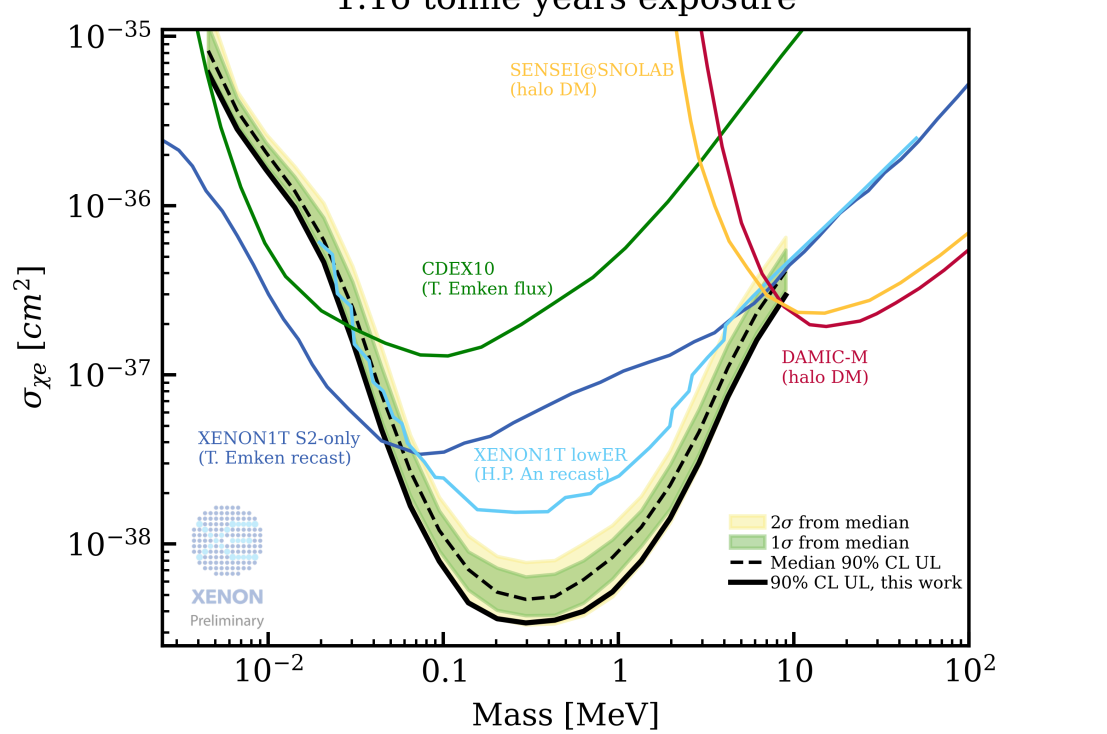
SRDM in XENONnT

Preliminary

- Compute expected ER spectrum via MC simulations (DaMaSCUS-SUN code)
- Apply energy resolution and detection efficiency
- Event selection criteria (reject multiple scatters, events far away from ER band, coincident with neutron veto, etc)
- Unbinned loglikelihood analysis: 1-140 keV energy range, full background model (SR0)
- XENON1T → XENONnT: 2✕ exposure, 5 ✕ lower ER background rate
- DM mass range probed: **4.6 keV - 9 MeV**



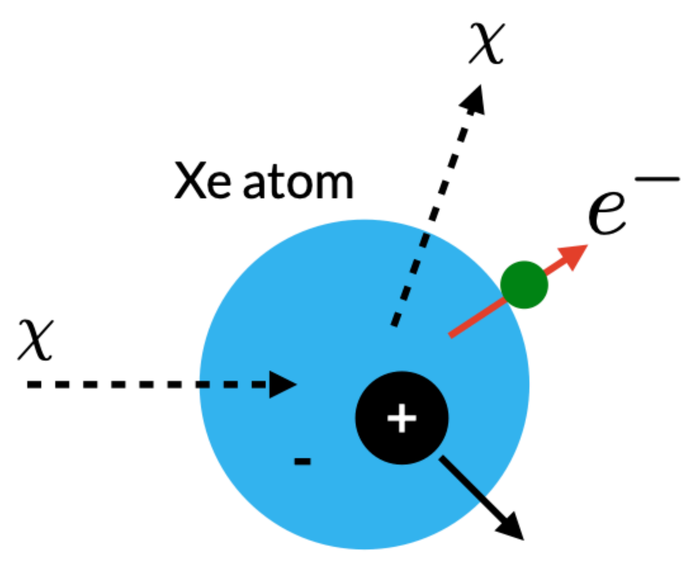
m=4.6 keV

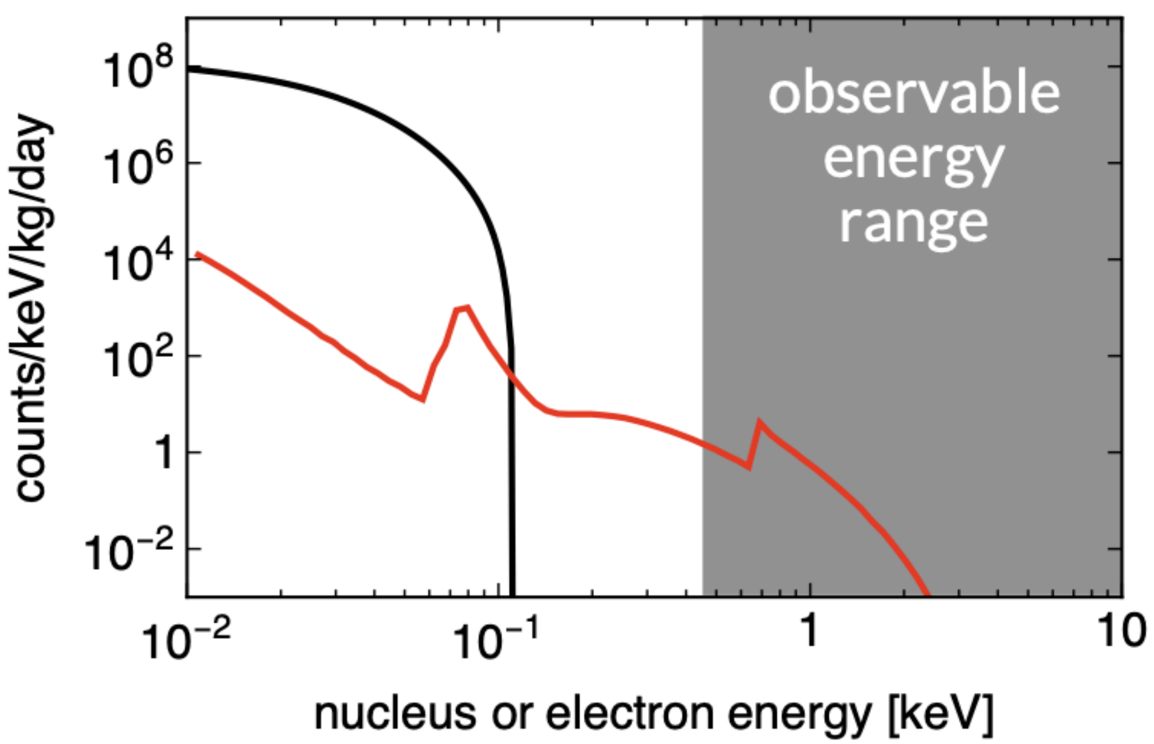


XENON collaboration, preliminary

Migdal effect

- Perturbations of the nucleus induce electronic transitions*
- Low-energy NRs could be observed as ERs
- Effect not yet conclusively observed experimentally (several efforts ongoing, in light atoms C, F and in heavier Ar, Xe)
- But used to set constraints on LDM





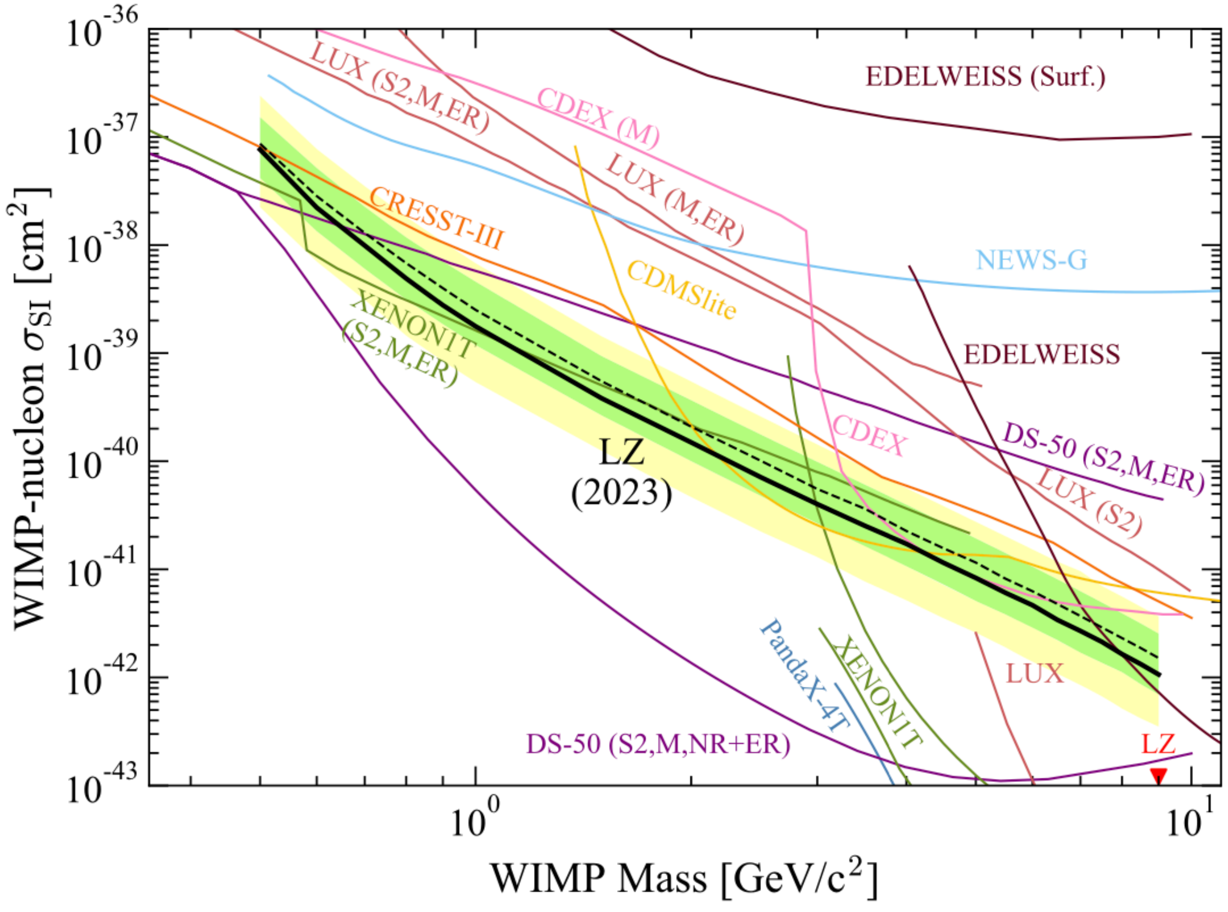
M. Ibe, W. Nakano, Y. Shoji. K. Suzuki, JHEP 03, 2018
P. Cox, M. Dolan, C. McCabe, H. Quiney. PRD 107, 2023

C. McCabe, Padova, Sept 2023

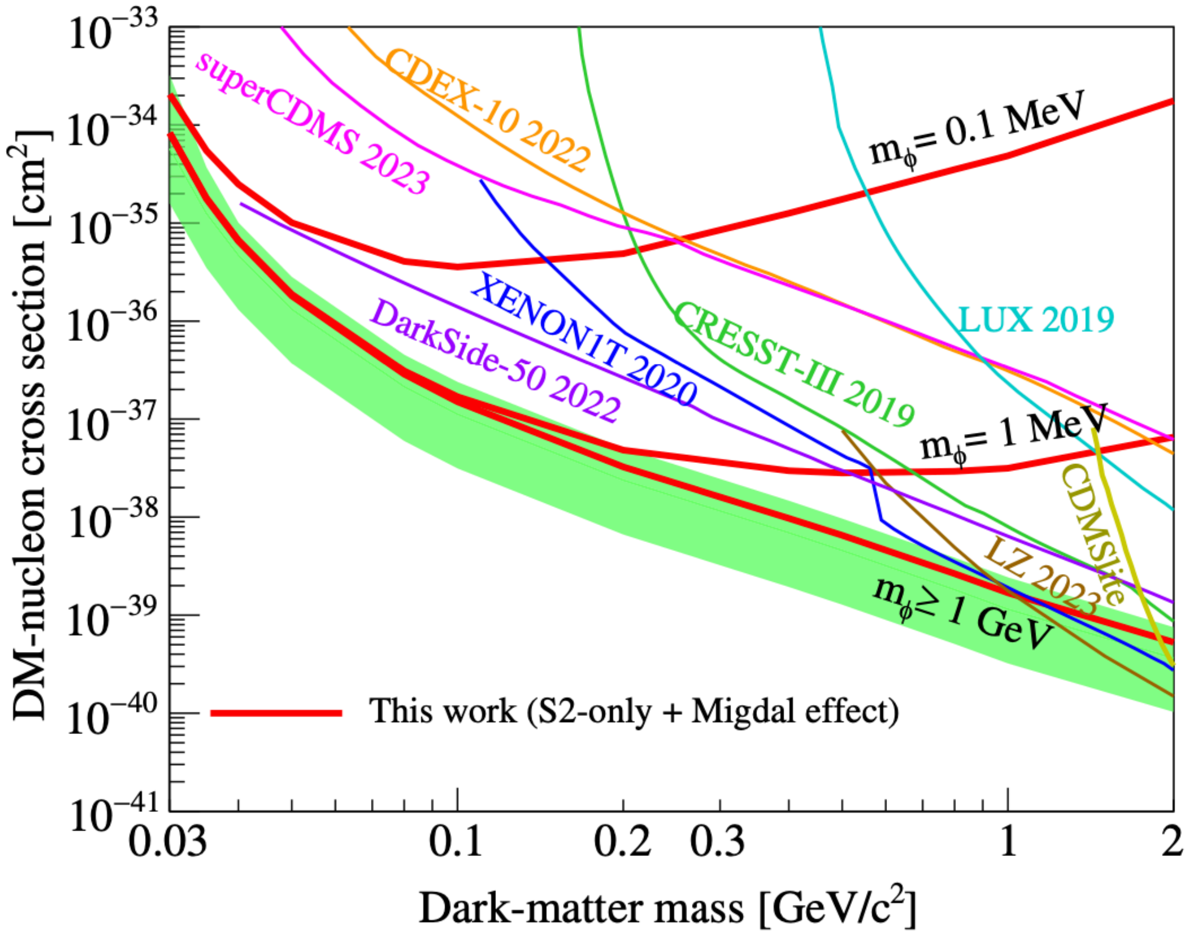
*DM particle collides with a Xe atom: abrupt momentum change of the nucleus with respect to the e- => excitation or ionisation

NR: Migdal effect

- Results on WIMP-nucleon interactions



S1 and S2, LZ, PRD 108, 2023



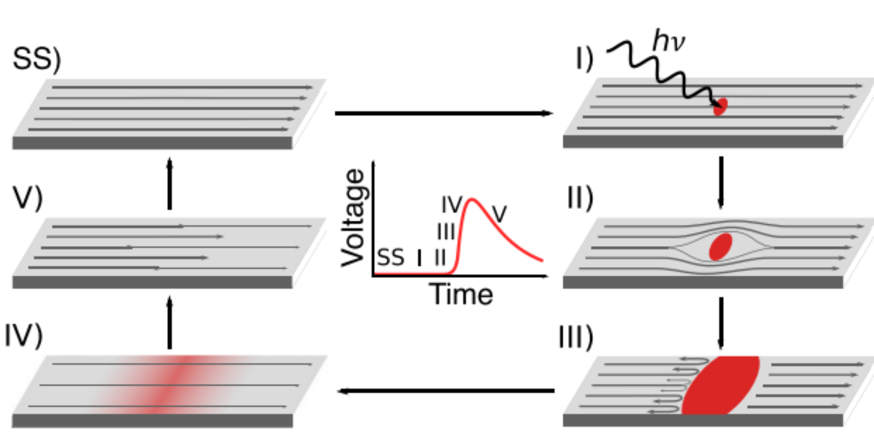
S2 only, PandaX-4T, PRL 131, 2023
(light and heavy mediators)

Qrocodile

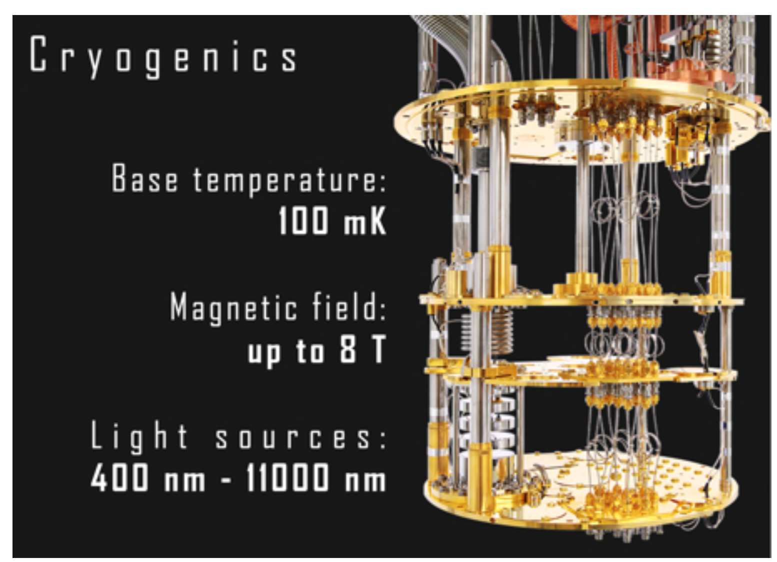
QROCODILE

Quantum sensoR cryOgeniC search fOr Dark matter In Light mass rangE

- **Newly formed collaboration:**
  - condensed matter/astroparticle experiment/quantum sensing/particle theory
- **Goal:** use SC nanowires as both target and sensor for sub-GeV DM particles (scatters on electron and absorption)



Appl. Phys. Lett. 118, 190502 (2021)



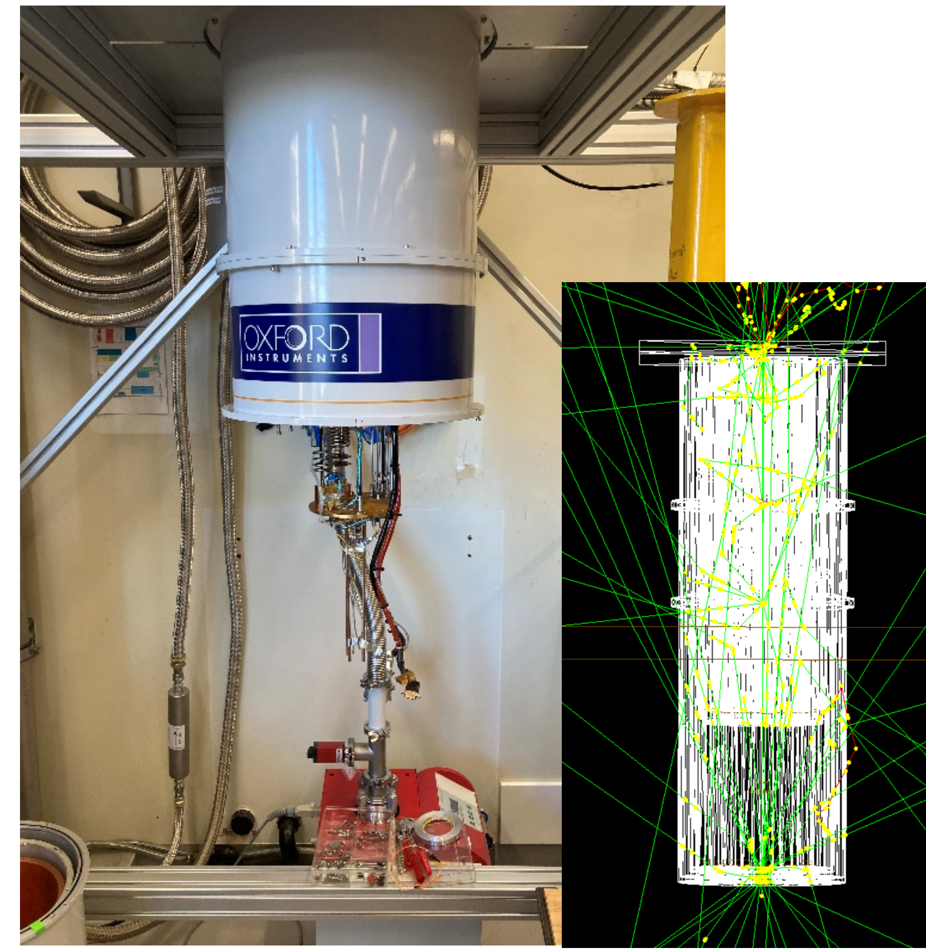
Universität Zürich UZH

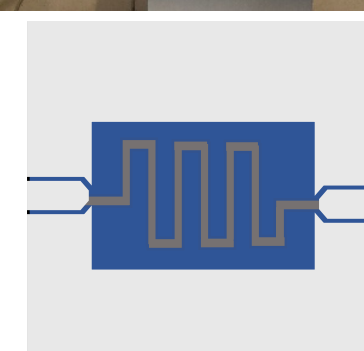
Massachusetts Institute of Technology

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

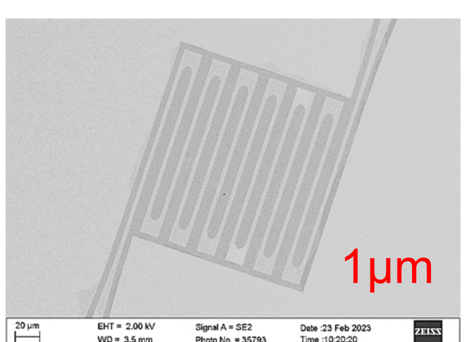
QROCODILE

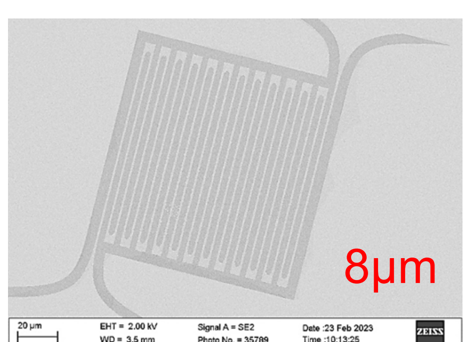
- **Location:** at UZH, in the future possibly underground (LNGS, Modane,?...)
- **UZH groups** (LB, I. Charaev, T. Neupert, A. Schilling)
  - sensor development, production, testing
  - background characterisation, MC simulations, material radio-assay with Gator at LNGS
  - condensed matter theory
- **MIT:** B. Lehmann, **Jerusalem:** Y. Hochberg
  - particle physics theory: DM interaction rates, based on the dielectric response of the target

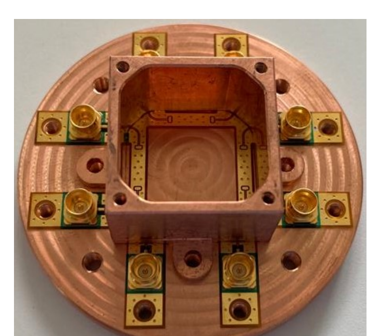




Patterned WSi nanowires with e- beam lithography and reactive ion etching





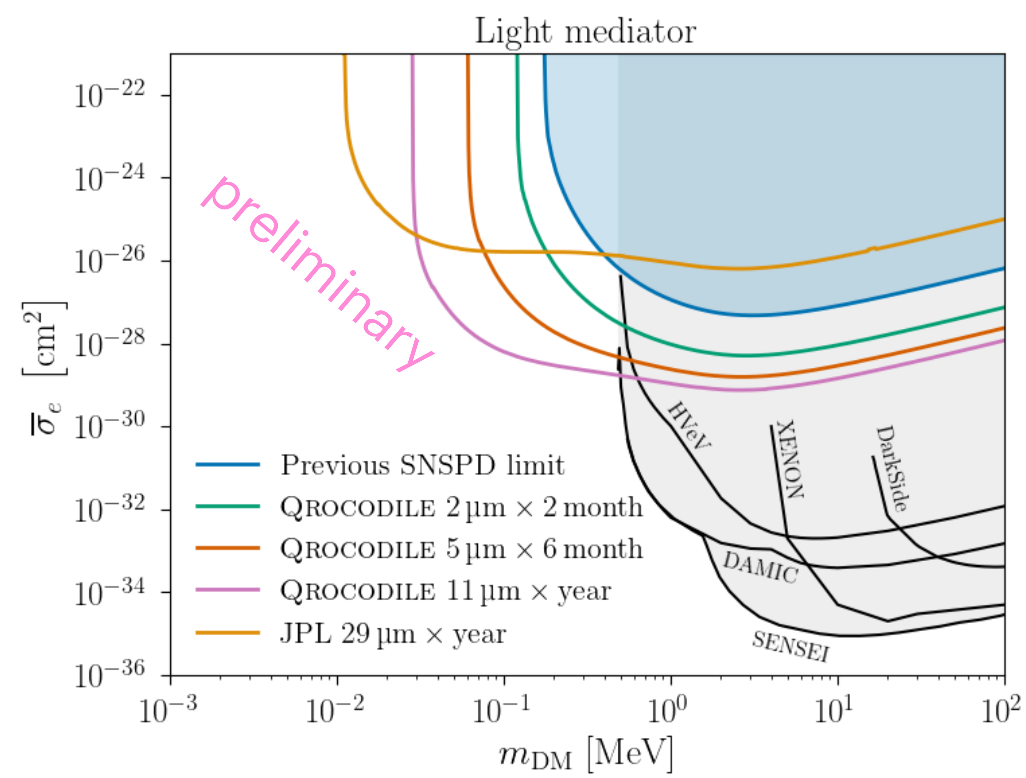


QROCODILE

- **Presently**
  - running at surface, 400 × 400 μm^2 active area, 98% detection efficiency at 1.55 μm (0.8 eV)
  - 15 counts in ~ 16 d
  - test impact of radioactive sources
  - probe the energy threshold (with lasers at 5 μm and 11 μm)

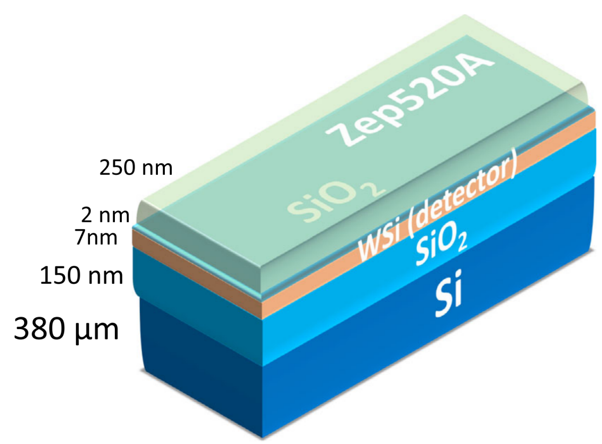
- **Plans**
  - scale-up the SNSPDs detector mass with areas ~ cm^2 and beyond
  - extend the energy threshold to the fundamental limit
  - understand and reduce backgrounds

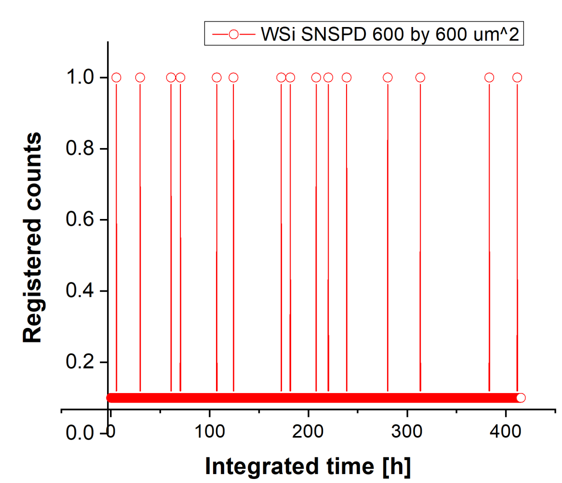
DM-electron scattering



Projections: 0.73 eV (1.6 μm), 0.5 eV (2 μm) thresholds

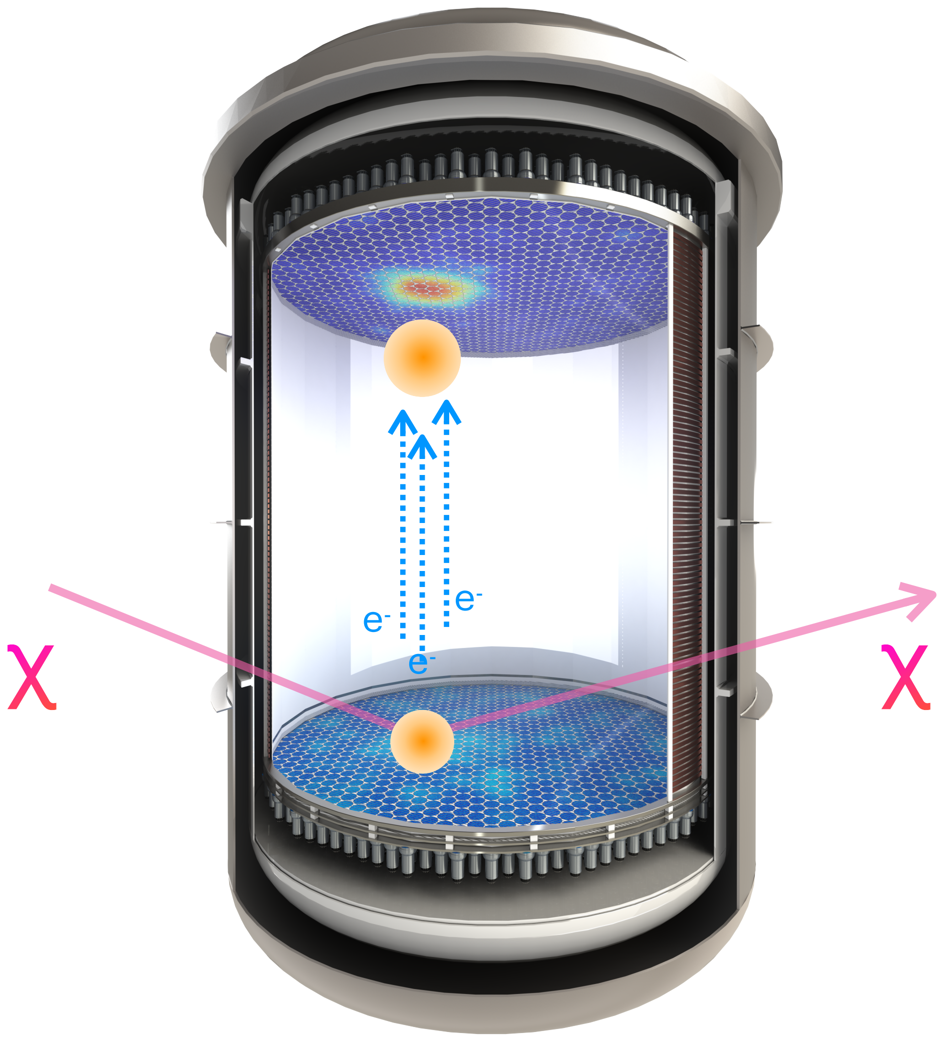
Previous: Y. Hochberg et al., PRD 106, 2022

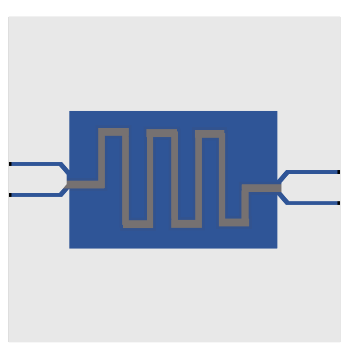




Events: pulses with amplitude ~1 mV, few ns long, for absorbed energies 0.1 meV - 10 eV.

Conclusions





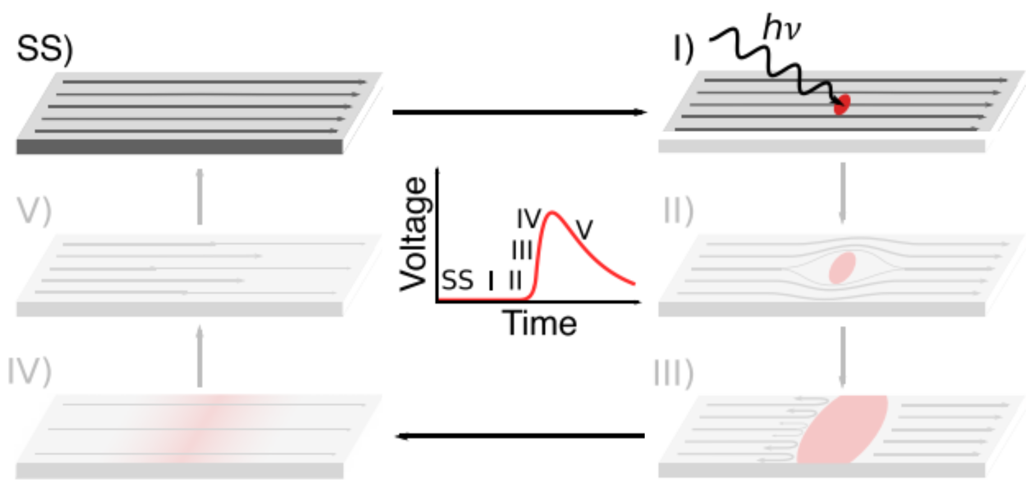
- LXe detectors: primarily developed to search for medium to heavy (few GeV - 100 TeV) DM particles
- Due to very low background levels & charge amplification via proportional scintillation ⇒ sensitivity to various light DM particles
- Current generation of two-phase TPCs: still taking data, while several analyses of past science runs in progress
- Qrocodile: new project to use single-photon detectors (SC nanowires) as target and sensors for sub-GeV dark matter

The end

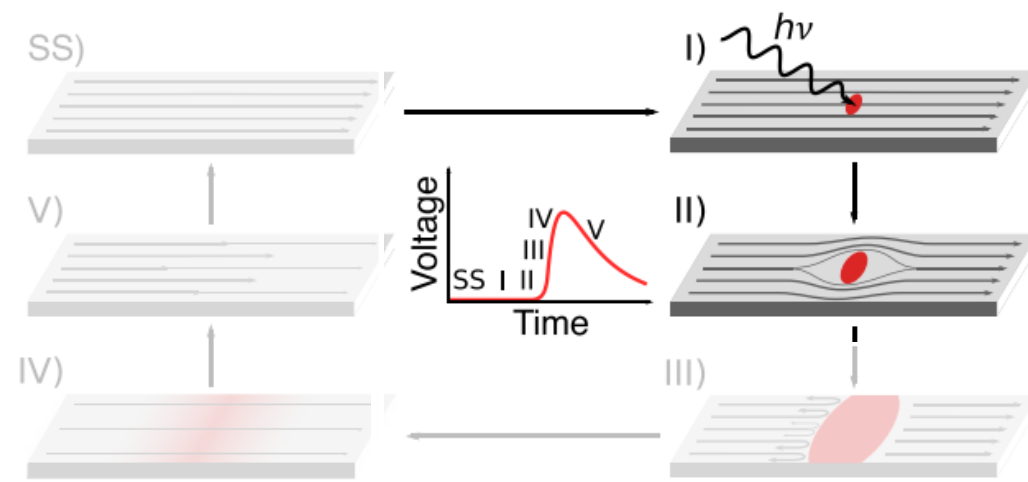
Extra slides

SNSPDs

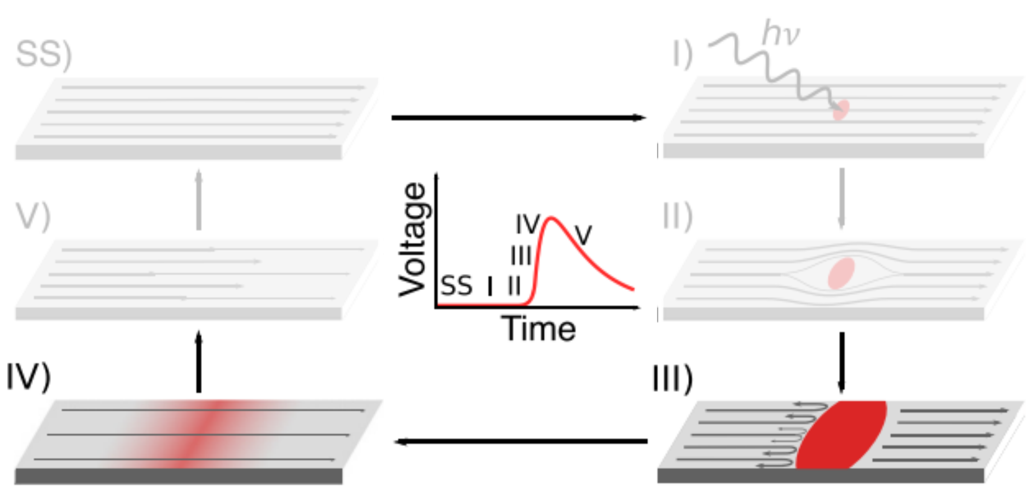
1) SC nanowire maintained < T_C, current biased < I_C



2) Incoming photon get absorbed and leads to a quasiparticle cloud, or hotspot

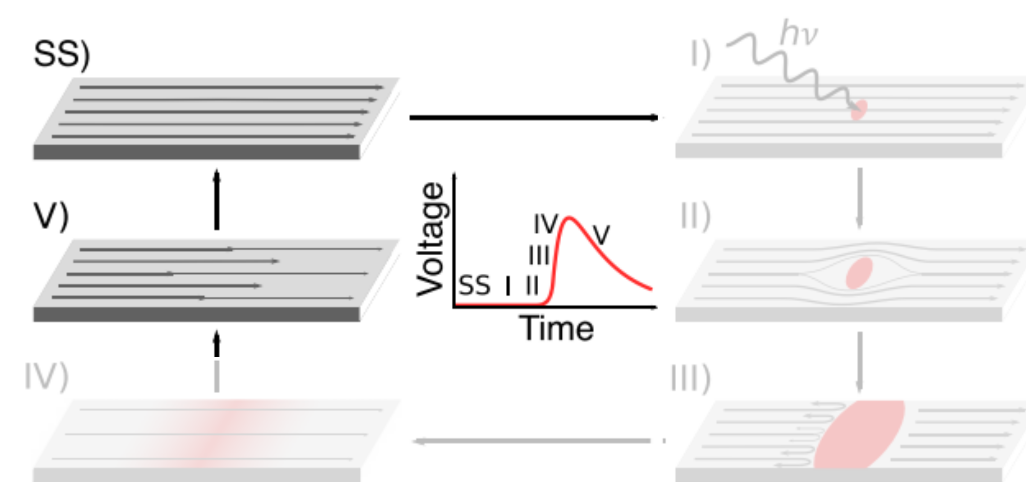


3) The local current density around the hotspot increases, exceeding the SC state, leading to a resistive barrier



4) The increasing resistance leads to a redirection of the bias current from the nanowire to the electronic readout

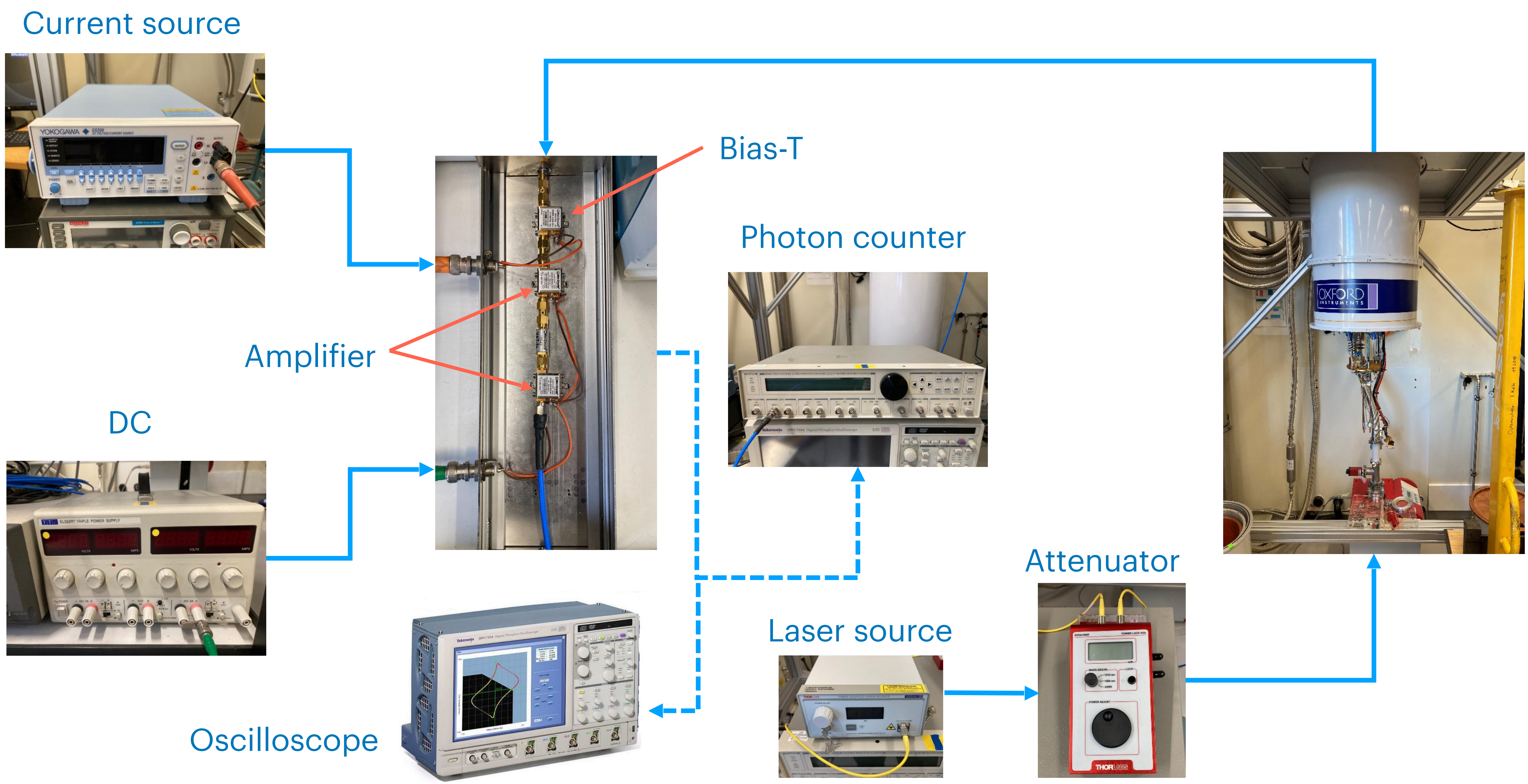
5) Once the temperature around the resistive area cooled down to a certain value, SC is restored



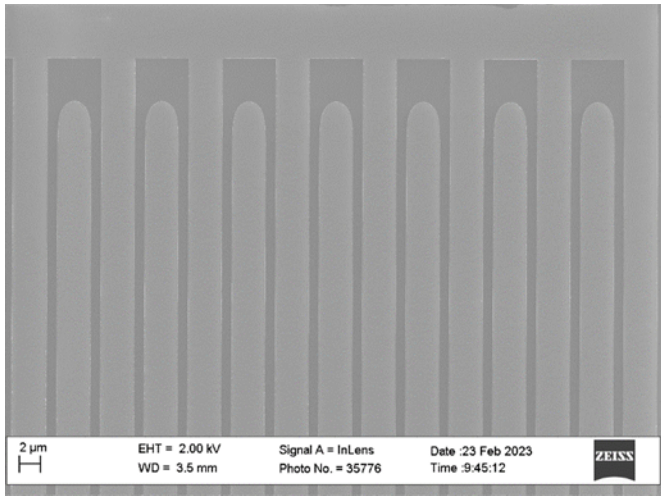
6) The bias current through the nanowire returns to I)

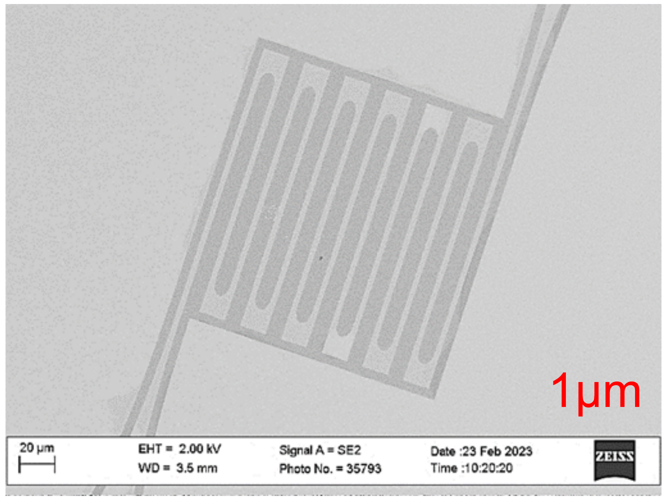
Applied Phys. Lett. 118, 2021

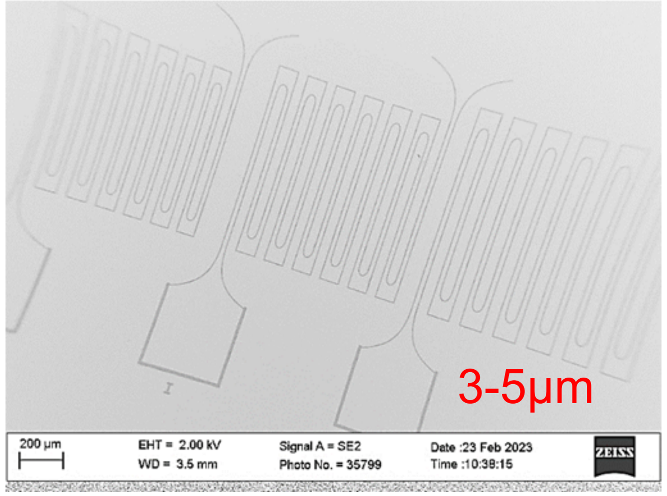
Qrocodile setup

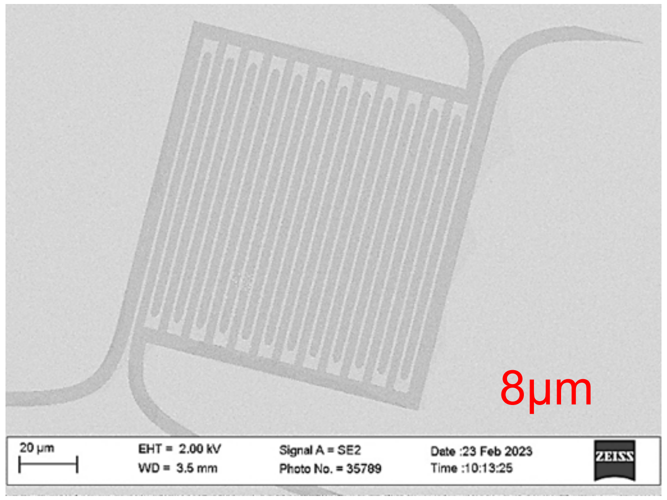


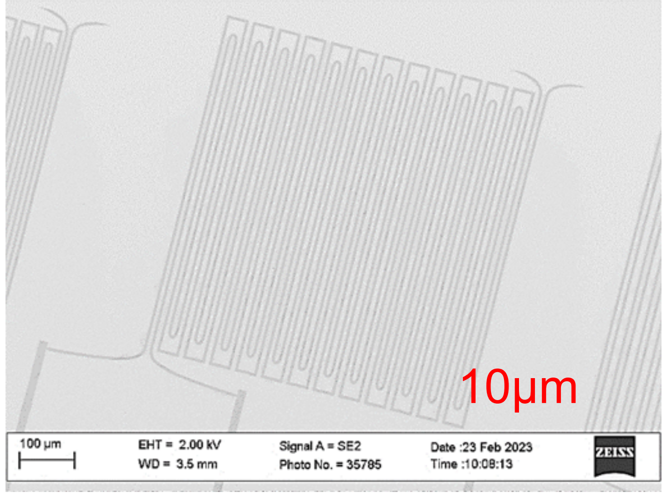
Qrocodile SEM images

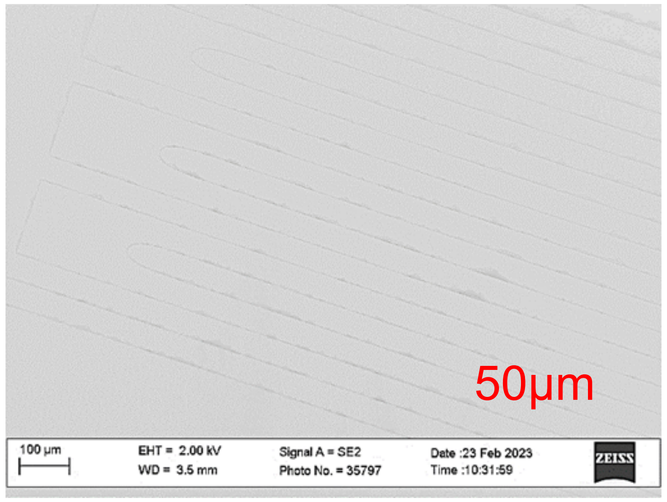










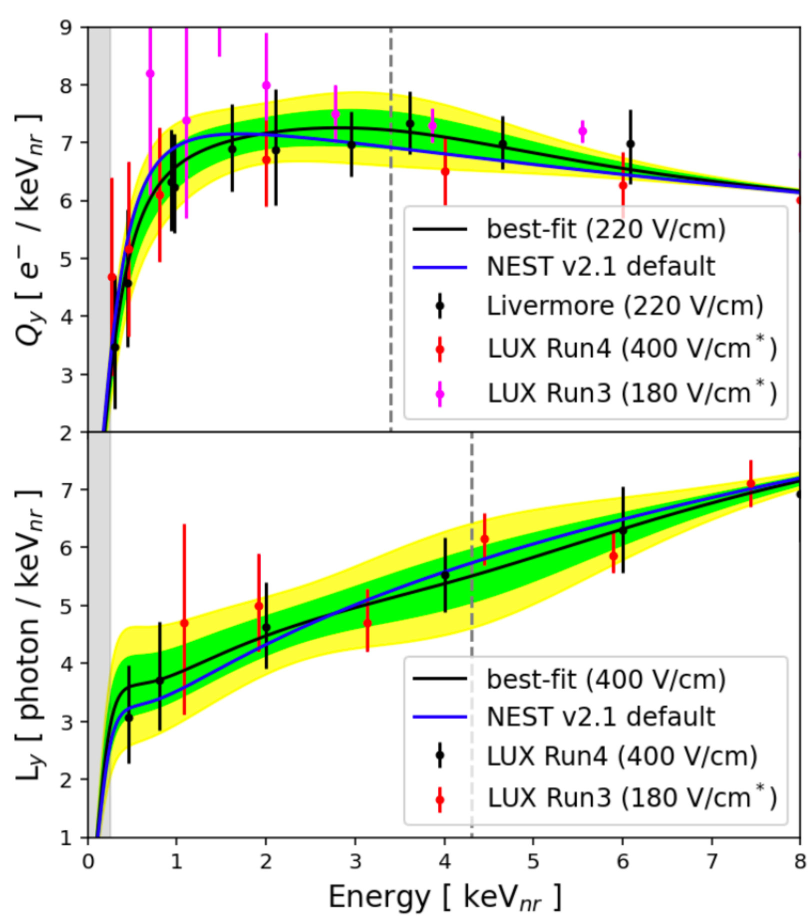


Challenges at low NR energies

- Light and charge yields at lowest energies & their uncertainties: dominate systematics (especially in constraining NSI); in situ and special calibrations needed
- Accidental coincidence rate (due to isolated S1 and isolated S2 signals; R&D programme and modelling (semi-empirical code) for next-generation experiments

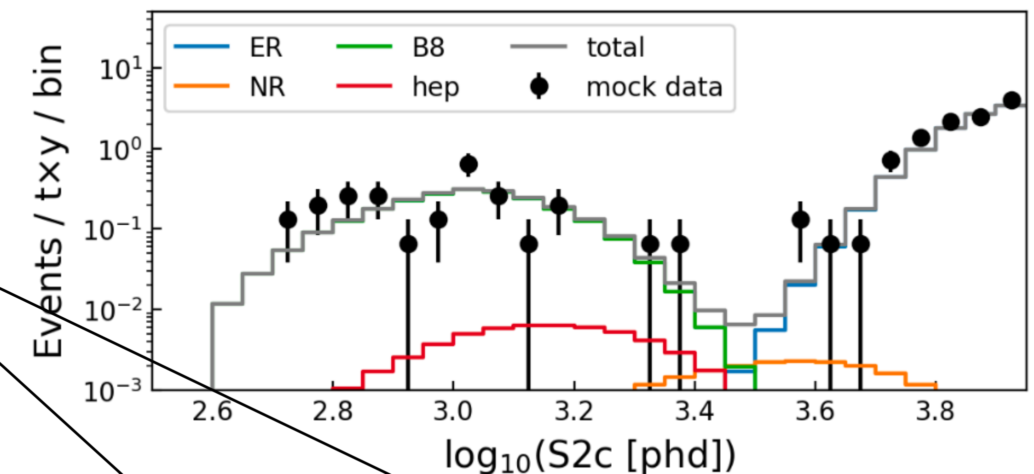
Charge yield

Light yield



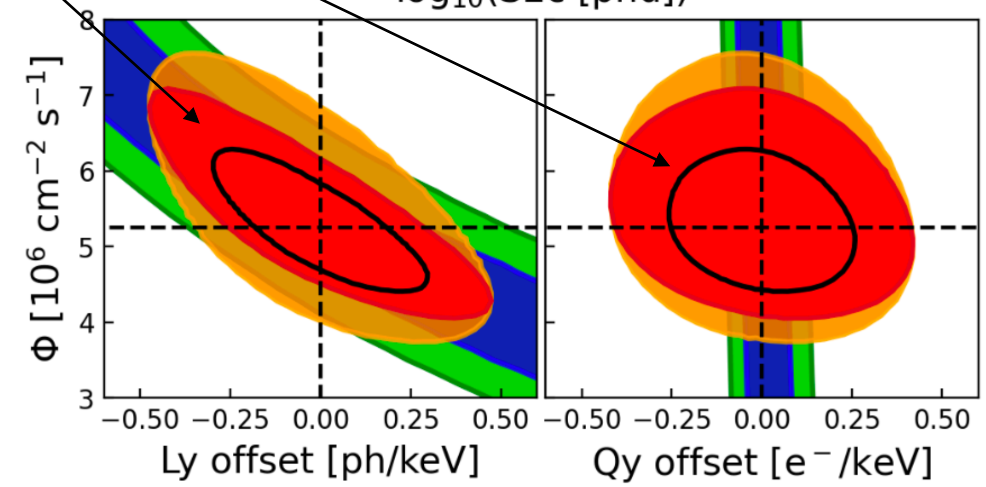
50 t y with Q_y, L_y uncertainties reduced by 1/2

Mock data for 15.3 t y exposure



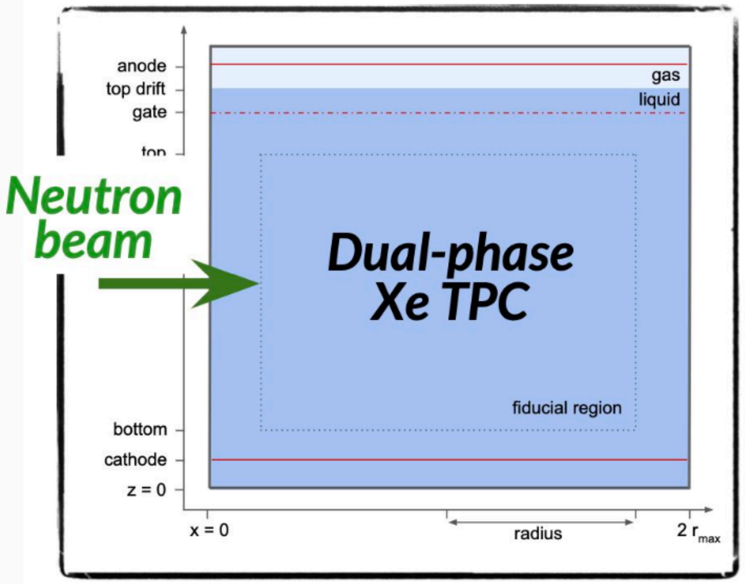
Bands: no constraints on Q_y, Ly

Contours: Qy, LY constrained to calib data

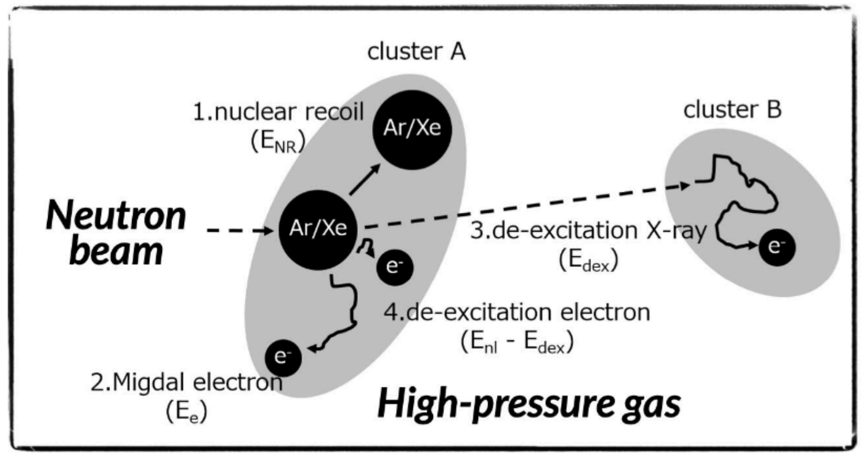


X. Xiang et al., 2304.06142

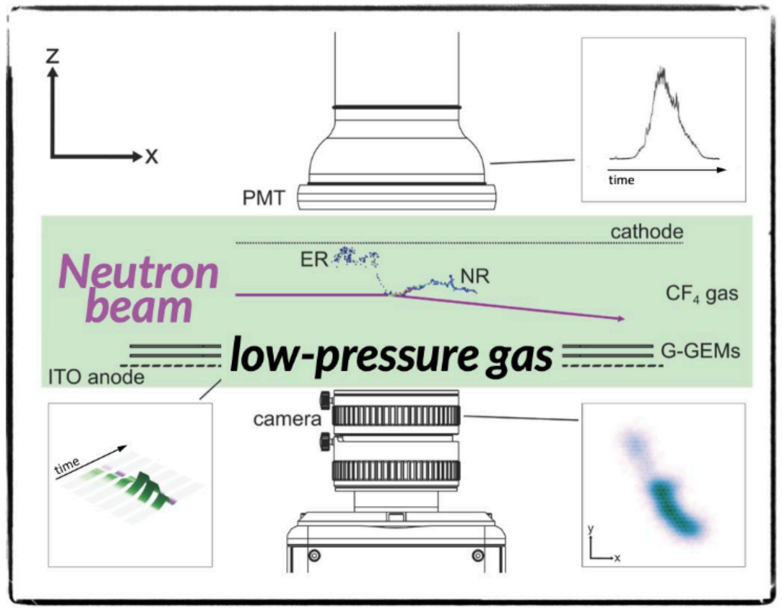
Midgal effect searches



1. Dense medium.
2. NR+EL transitions in close proximity.
3. Signal from enhanced S1 and S2 due to X-rays from L and M shells.
4. Experiment at LLNL with fast neutrons from DT generator.
5. LZ experiment at SURF with fast neutrons from DD generator.



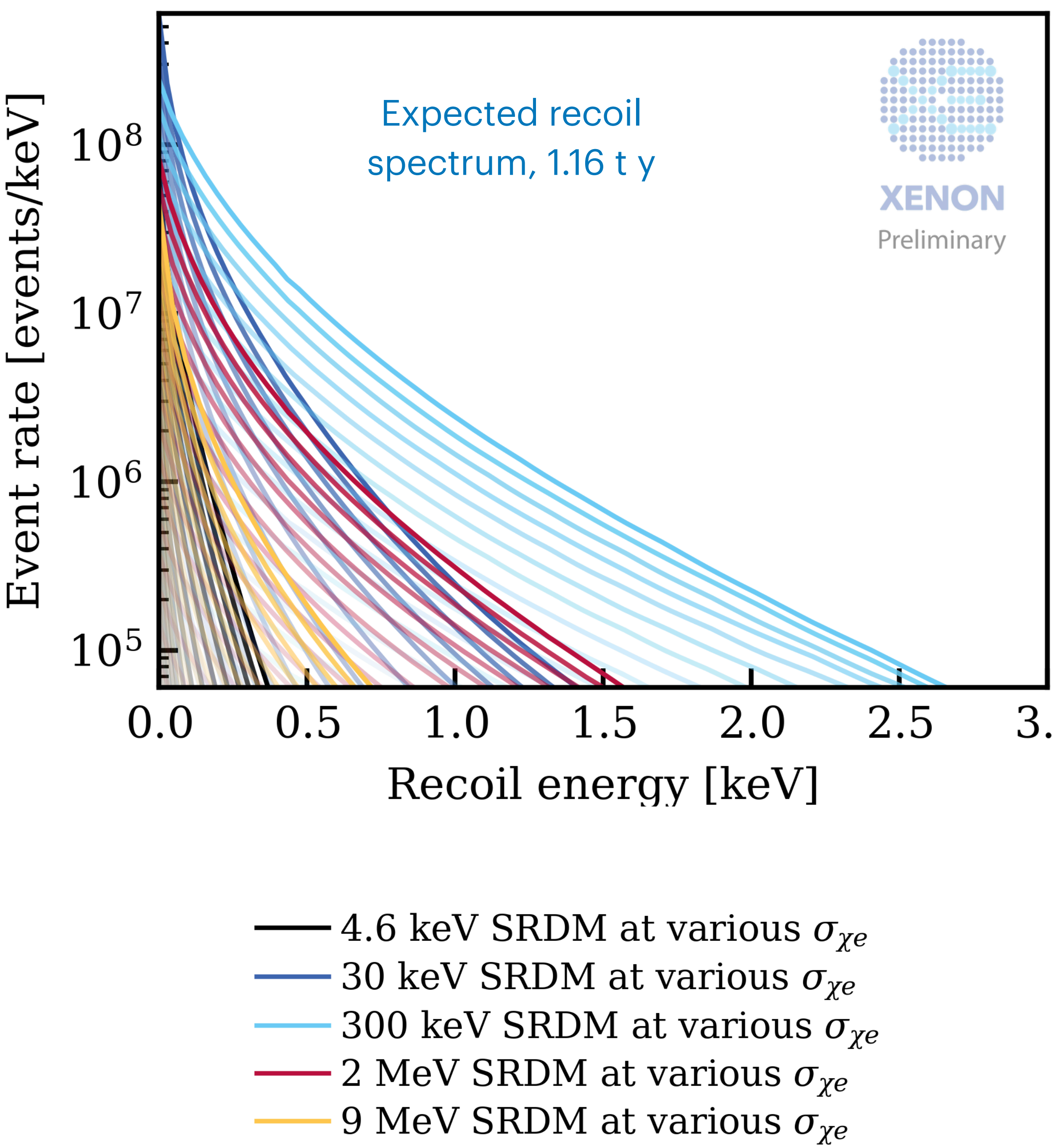
1. High pressure Ar (1 bar) and Xe (5 bar).
2. Looking for two-cluster signals from NR+Migdal electron (cluster A). and characteristic X-ray (cluster B).
3. Experiment at in Tsukuba with 565 keV neutrons from $^7Li(p, n)^7Be$ reaction at an irradiation facility at the National Institute of Advanced Industrial Science and Technology (AIST), Japan.

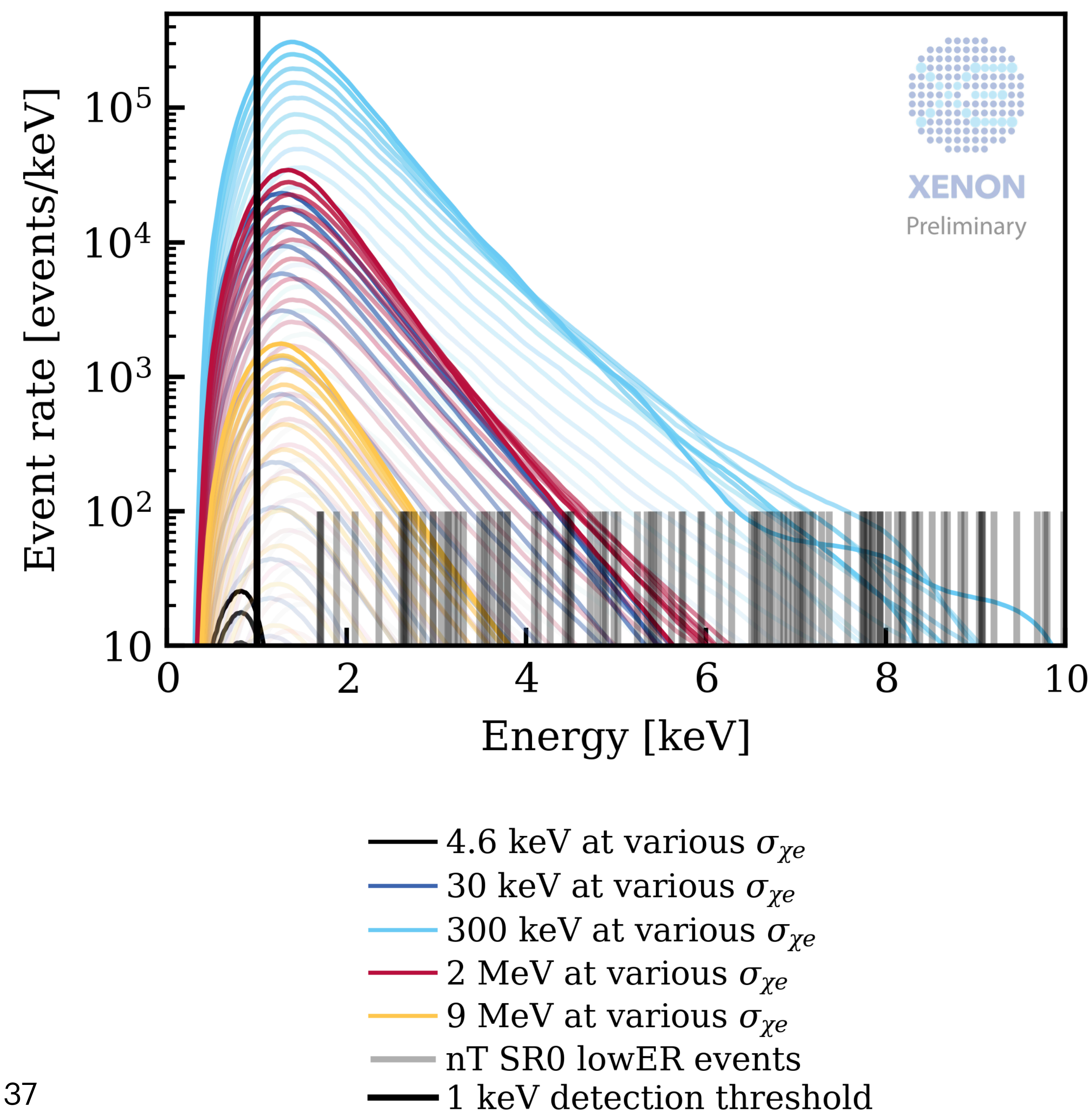


1. Low pressure operation at 66 mbar.
2. Enough mass as a target for fast neutrons from DD/DT neutron generators.
3. NR and electrons tracks with 5 keV threshold long enough for optical detection to provide direction and dE/dx information.
4. Experiment at ISIS/NILE (UK).

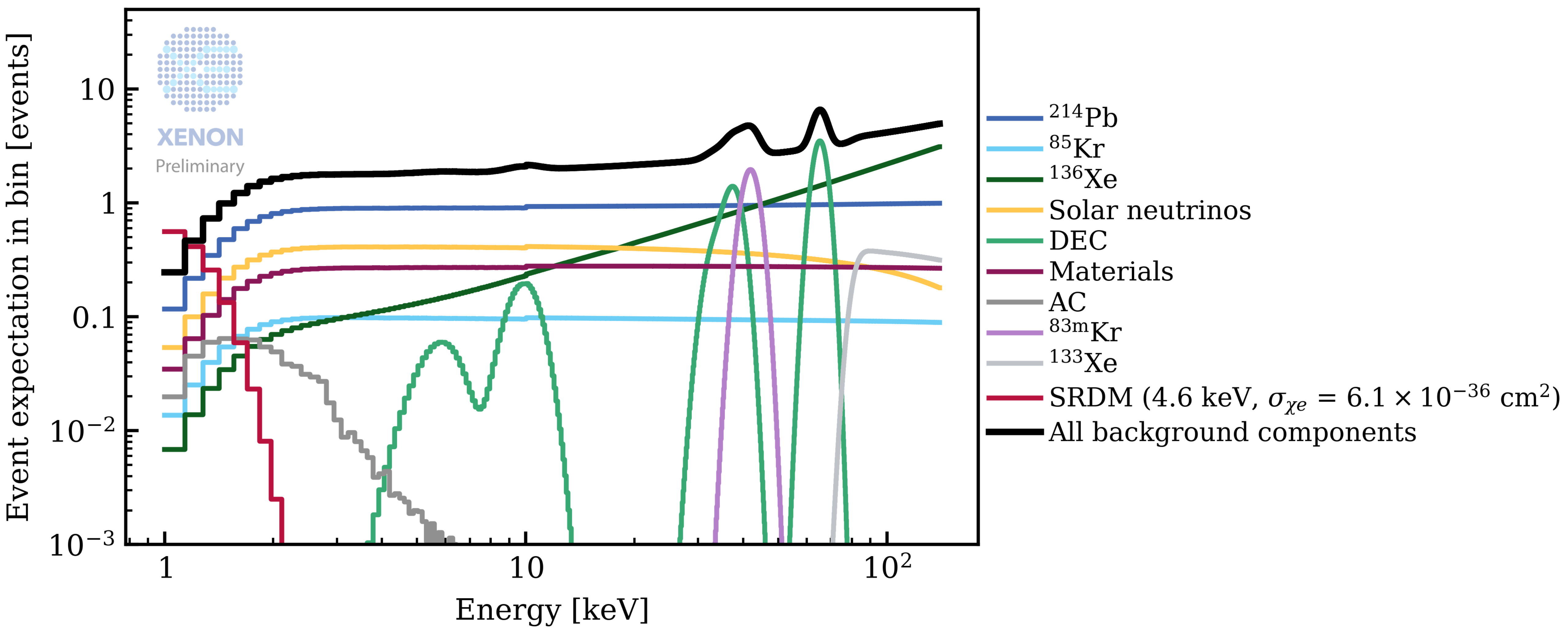
SRDM in XENONnT

XENON collaboration, preliminary





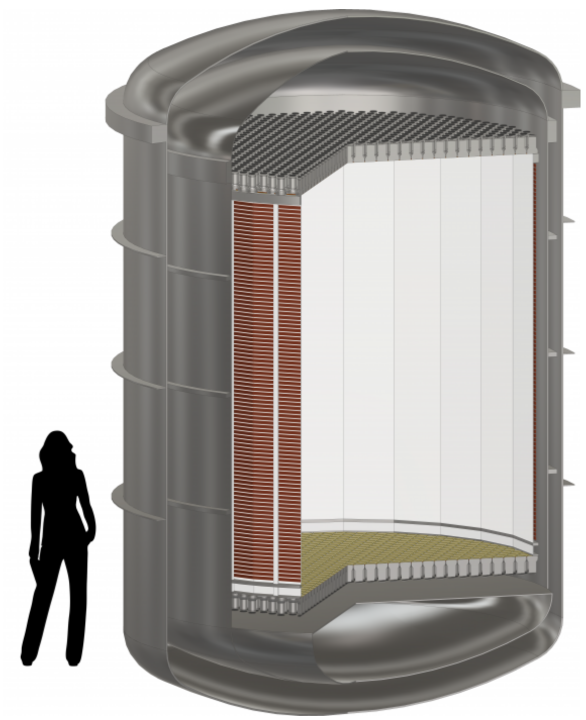
SRDM in XENONnT



XENON collaboration, preliminary

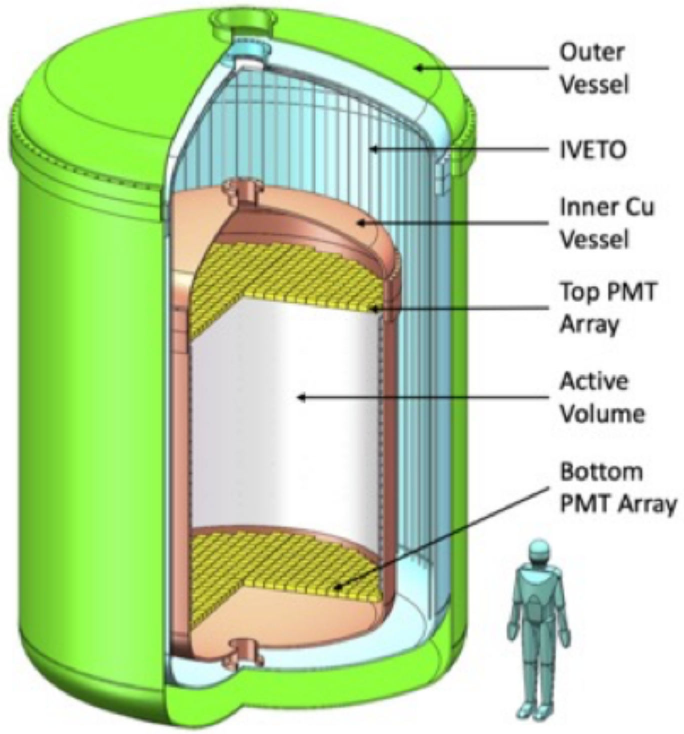
Future liquid xenon detectors

- **DARWIN/XLZD**
  - DARWIN: 50 t LXe (40 t active target) at LNGS; Gd-doped water n- and μ- vetoes
  - XLZD: 75 t LXe (60 t active target), several labs are considered



DARWIN collaboration JCAP 1611 (2016) 017

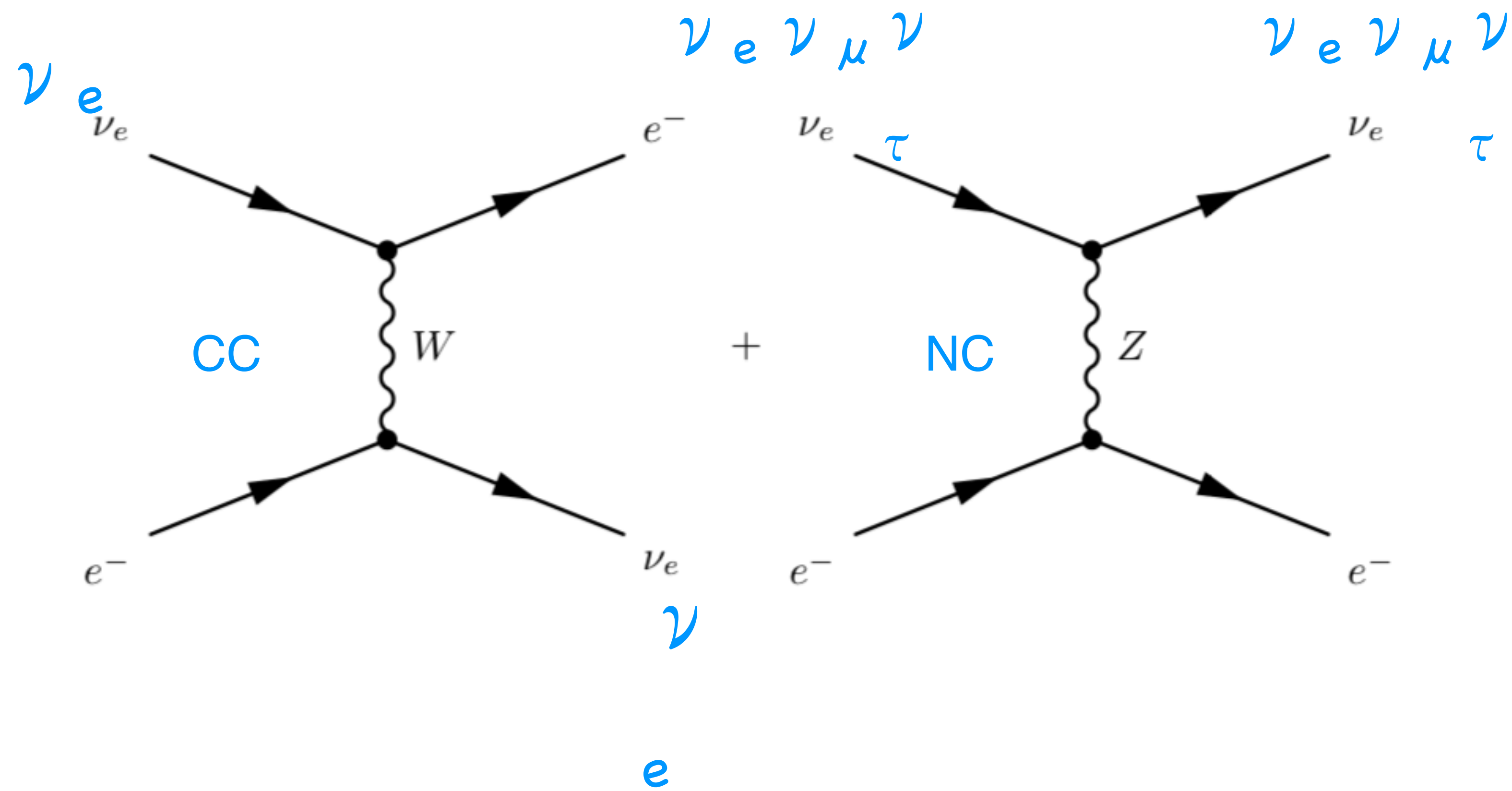
- **PandaX-xT at CJPL**
  - 43 t active volume (47 t total) at CJPL; 2 arrays of 2-inch × 2-inch flat panel PMTs; Cu inner vessel, active shield between inner and outer cryostat



Low-energy solar neutrinos

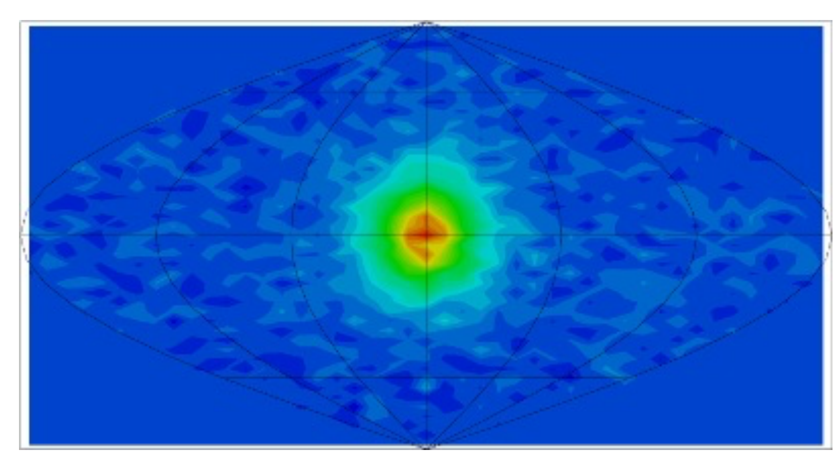
Elastic neutrino-electron scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$



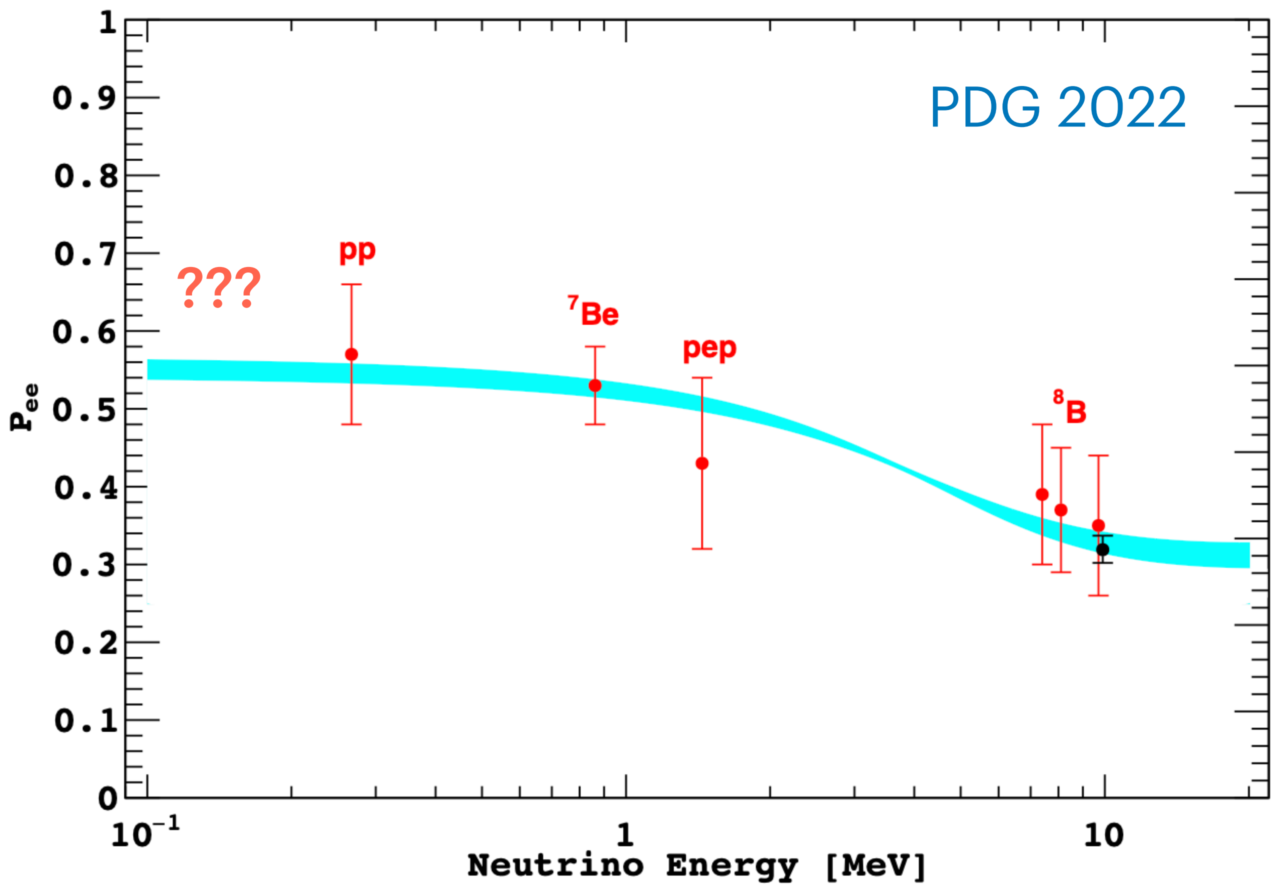
- ν_e interactions: CC & NC
- ν_μ and ν_τ interactions: only via NC

($\sigma_{tot} \approx 10^{-43}$ cm^2, solar ν have low energies and the CC reactions involving ν_μ and ν_τ are kinematically not allowed)



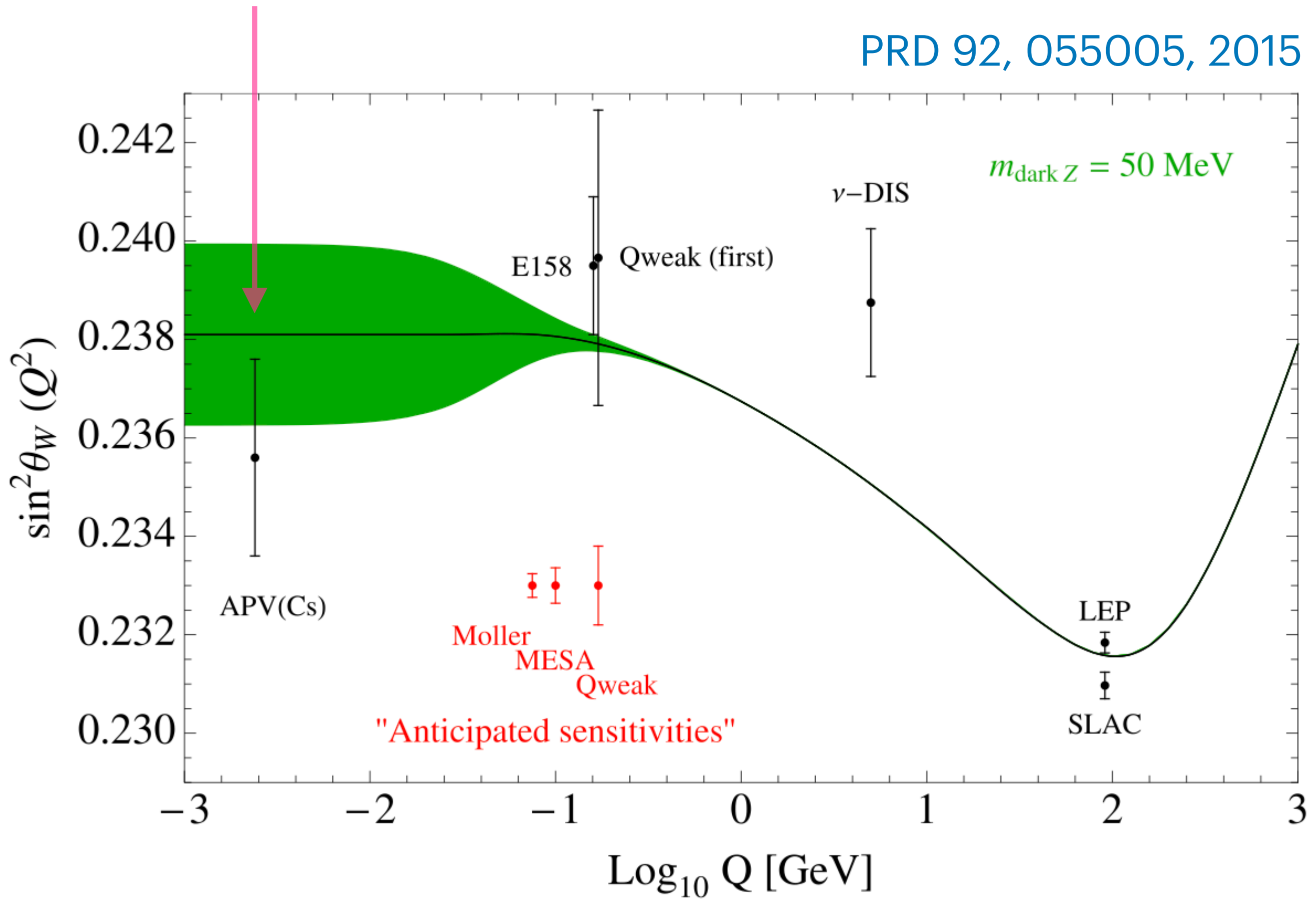
Low-energy solar neutrinos

Survival probability P_{ee}



2.4 MeV

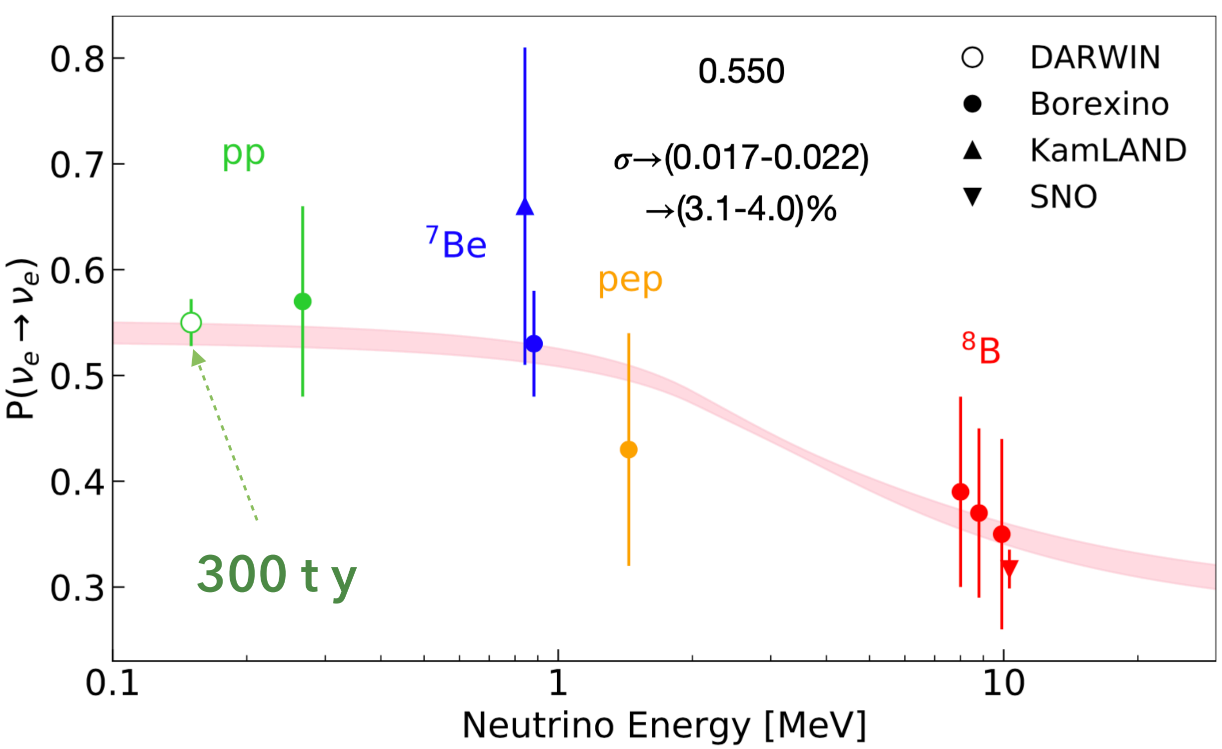
PRD 92, 055005, 2015



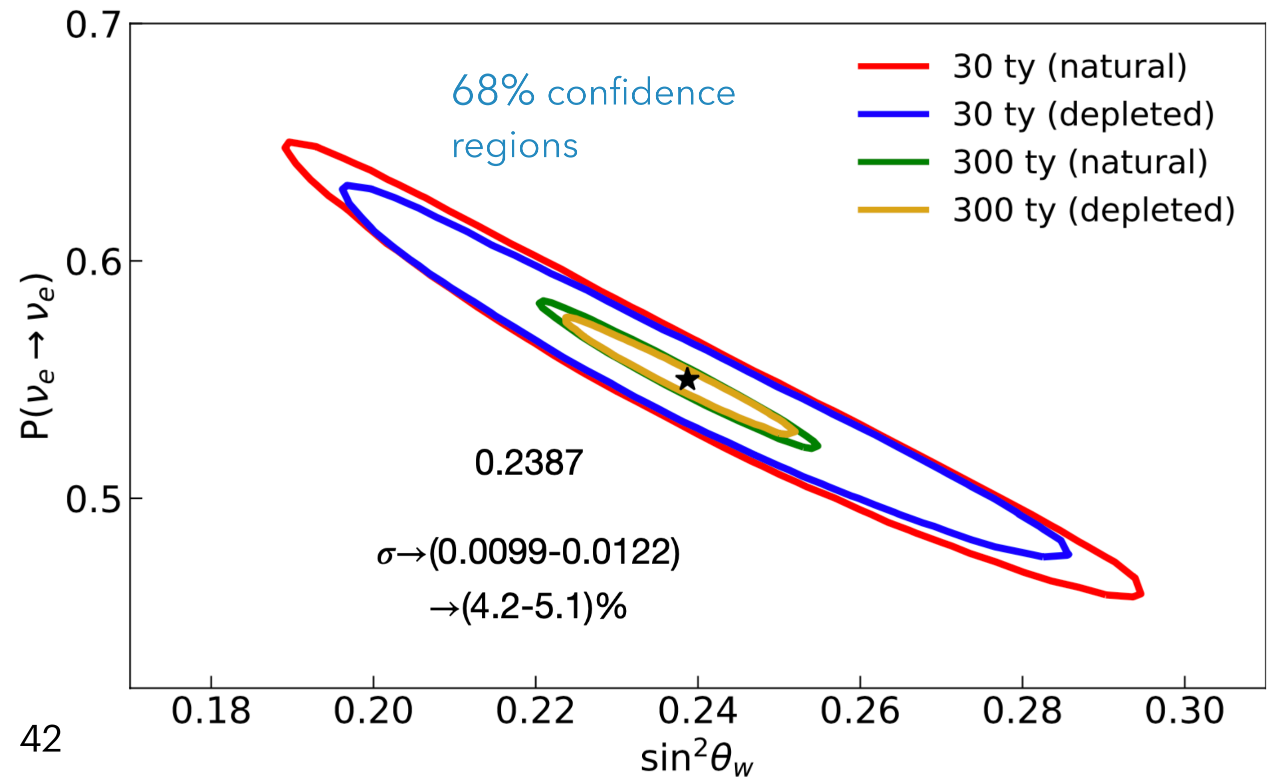
- What is the ν_e survival probability (P_{ee}) below 200 keV?
- What is the value of the weak mixing angle ($\sin^2\theta_w$) at low energies?

Low-energy solar neutrinos

- Rates: 365 events/(t y) from pp ν and 140 events/(t y) from ^{7}Be ν; ^{13}N: 6.5/(t y), ^{15}O: 7.1/(t y)
- **pp-flux: 0.15% statistical precision with 300 t y exposure** (sub-percent after 10 t y)
- ν_e survival probability & weak mixing angle < 300 keV
  - P_{ee}: ~4% relative uncertainty; $\sin^2\theta_W$: ~5% relative uncertainty



using pp neutrinos

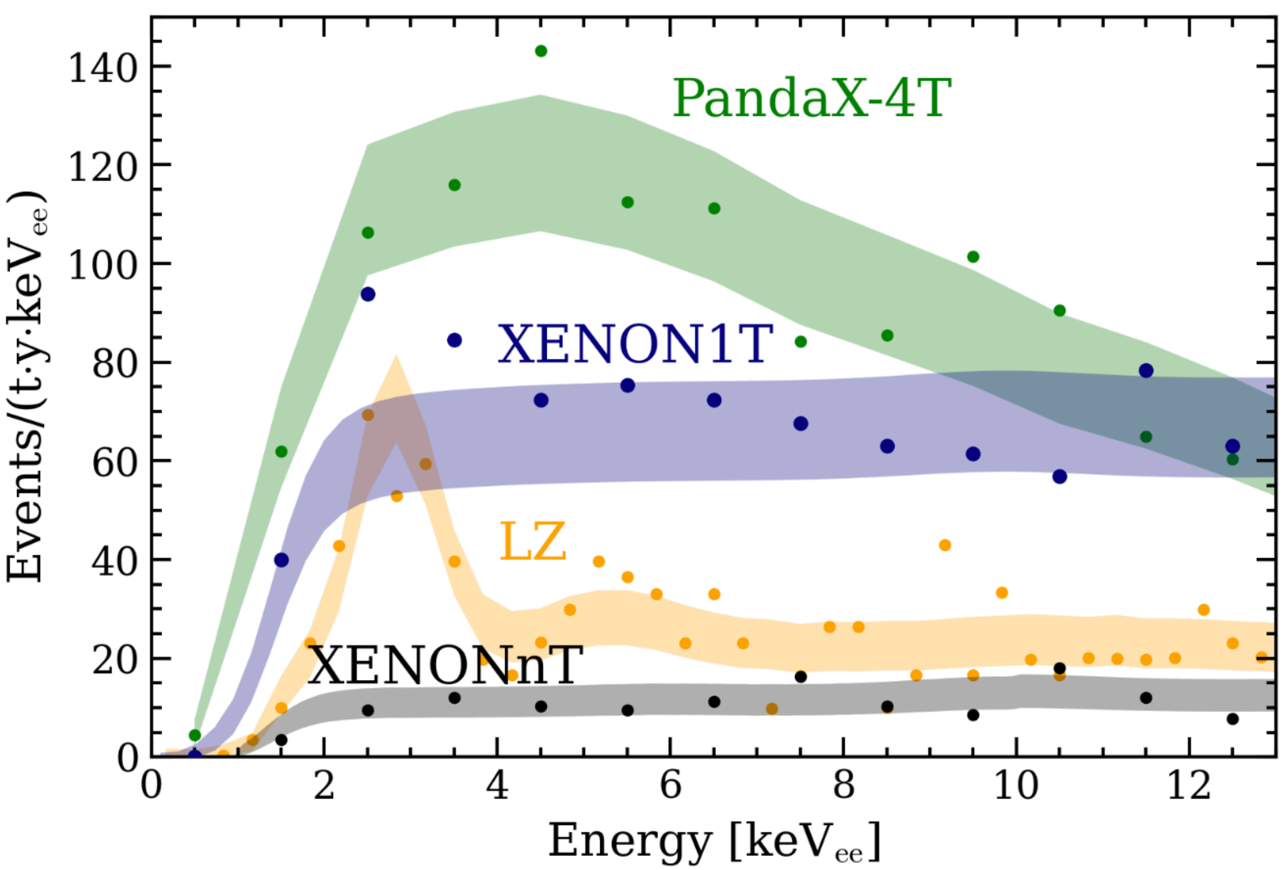


DARWIN collaboration, EPJ-C 80 12 (2020)

Where are we now?

- In XENONnT, SR0 ER background below 30 keV
  - (15.8±1.3) events/(t y keV) (0.2 x the one of XENON1T)
  - Solar ν: ~1/2 of the dominant (^{222}Rn) background in SR0

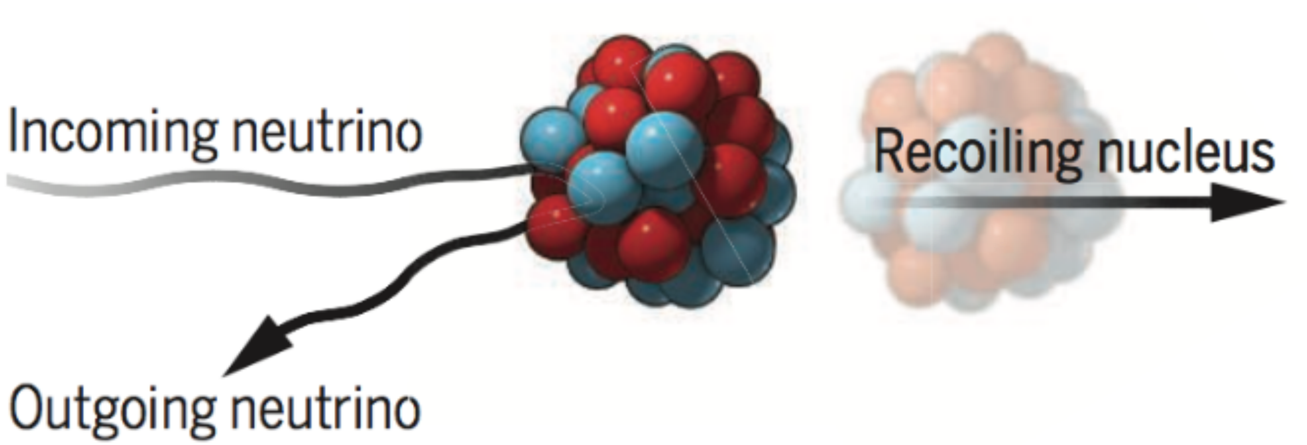
	(1,10) keV	(1, 140) keV
^{214}Pb	56±7	980±120
^{85}Kr	6±4	90±60
Materials	16±3	270±50
Solar ν	**25±2**	300±30
^{124}Xe	2.6±0.3	260±30
^{136}Xe	8.7±0.3	1520±50
AC	0.7±0.03	0.7±0.03



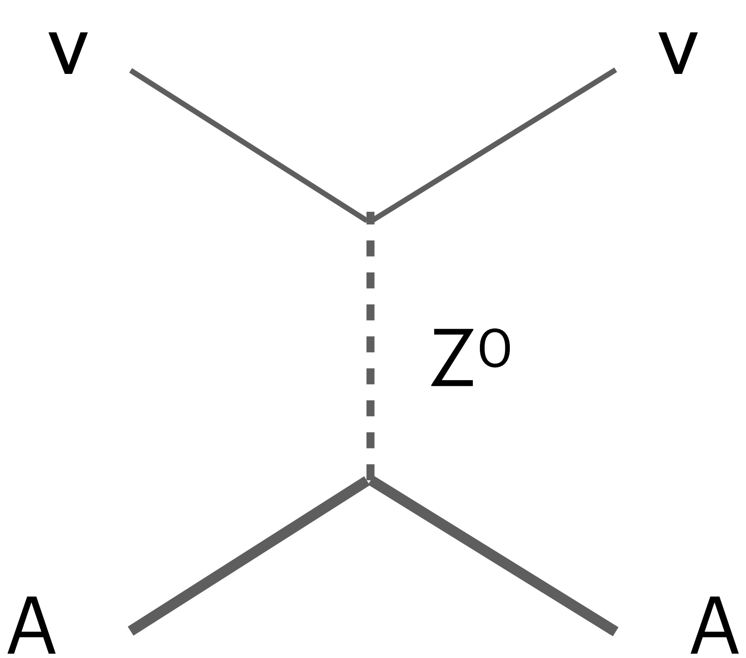
XENON collaboration, PRL 129, 2022

CEvNS in DARWIN/XLZD

$$\nu + A \rightarrow \nu + A$$



- A neutrino hits a nucleus via Z-exchange
- The nucleus recoils as a whole
- The process is coherent up to neutrino energies of ~50 MeV



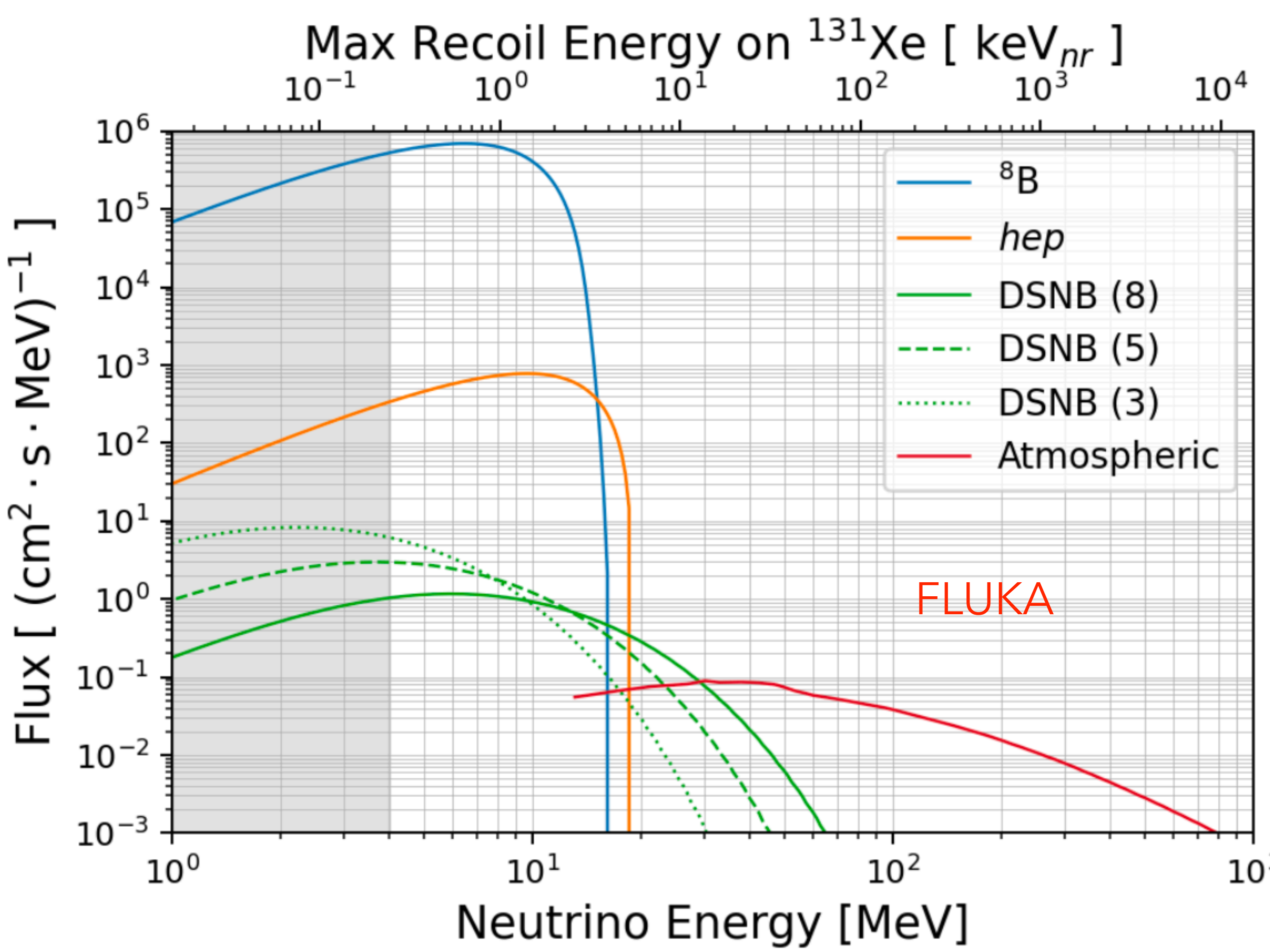
Nucleon wavefunctions in the target nucleus in phase with each other at low momentum transfer

Image: J. Link *Science* Perspectives

CEvNS in DARWIN/XLZD

- **Sources**: solar ^{8}B and hep ν's; core-collapse SN; DSNB and atmospheric ν's

$$T_{\max} \propto \frac{2E_\nu^2}{M}$$



X. Xiang et al., 2304.06142

$$\sin^2\theta_W = 0.231$$

$$Q_W = (1 - 4\sin^2\theta_W)\,Z - N$$

weak nuclear charge

kinematics

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2 - \frac{MT}{E_\nu^2}\right)$$

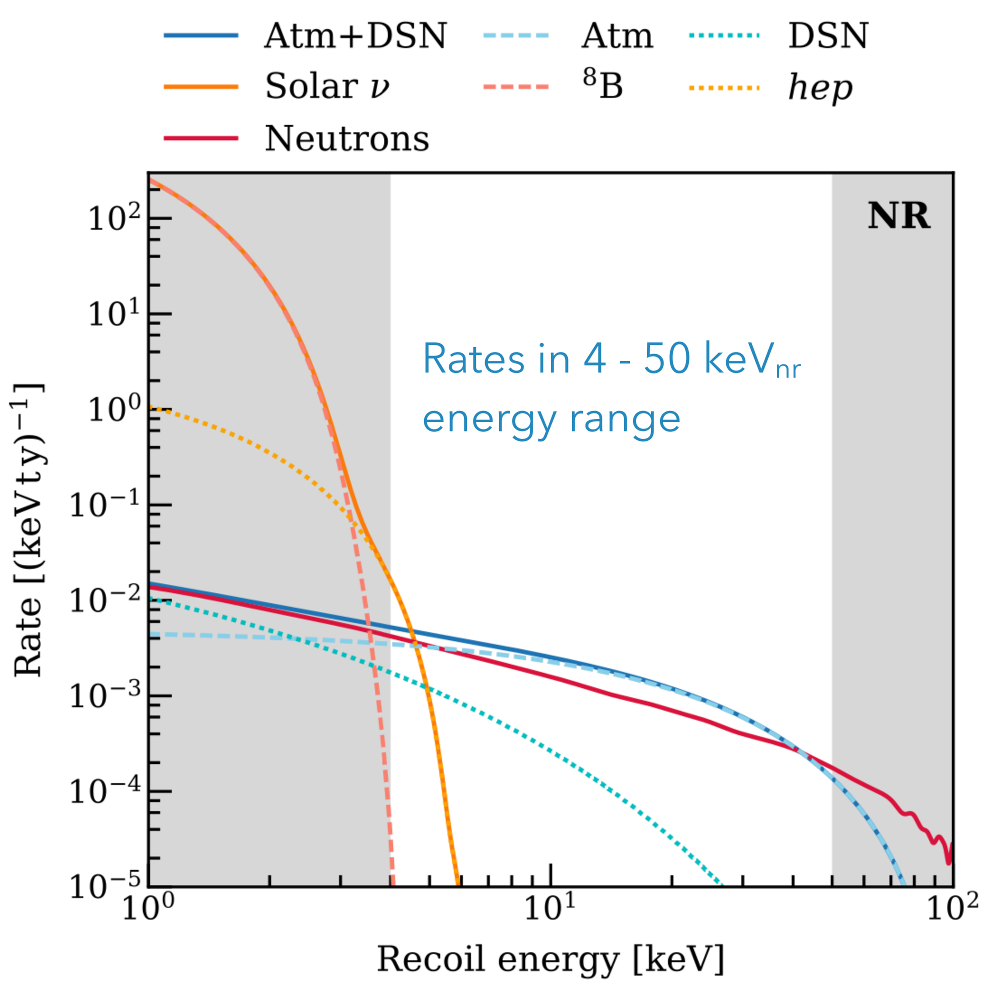
form factor F = 1 full coherence

$$\Rightarrow \frac{d\sigma}{dT} \propto N^2$$

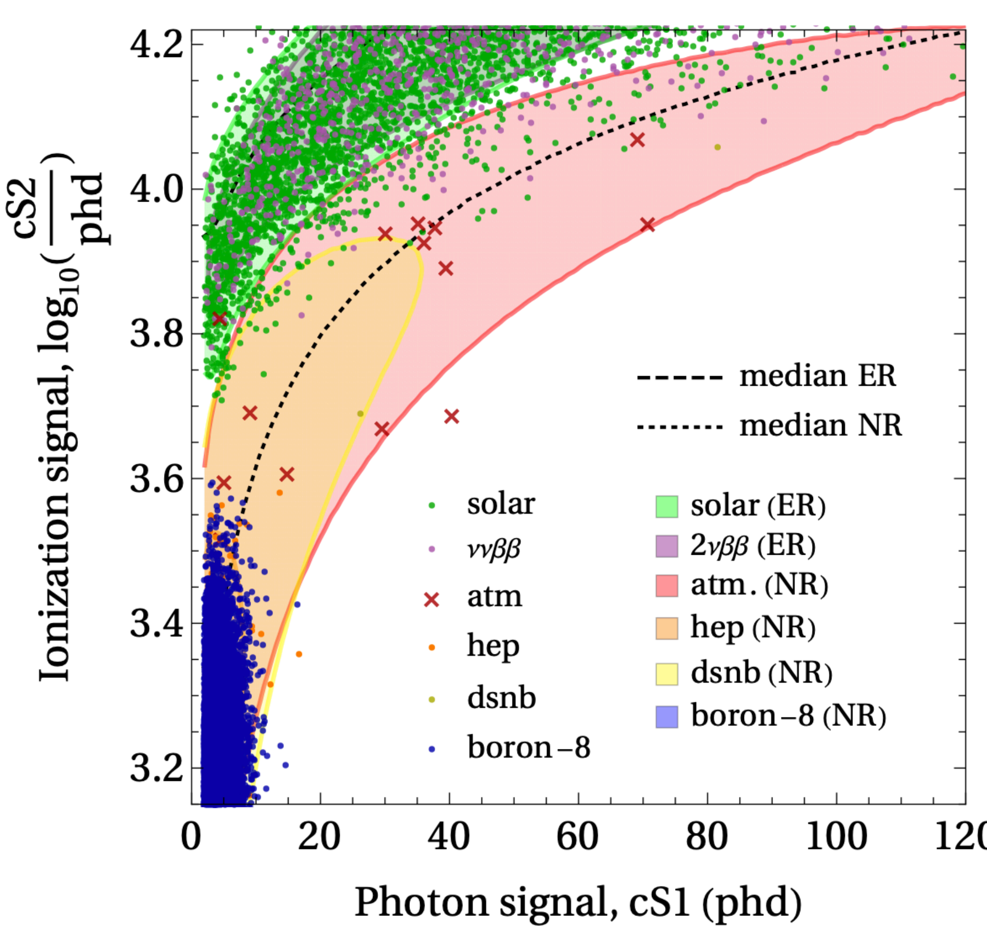
CEvNS with ^{8}B neutrinos

- ~99% of CEvENS-induced events expected < 3 keV_{nr}
- ~ 10^4 events/(200t y) for 2-fold S1 and 5 n_e S2 (see X. Xiang et al., 2304.06142)

XENON collaboration, JCAP11(2020)031



Signal for 200 t x y exposure

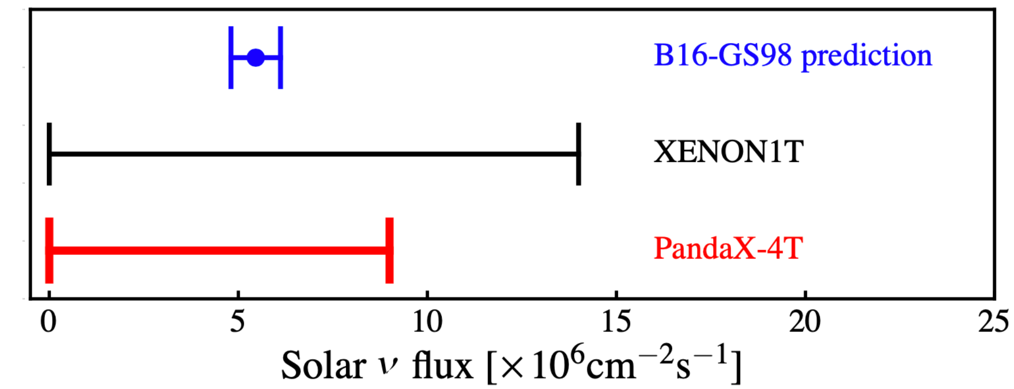


Newstead, Lang, Strigari, PRD 104, 2021

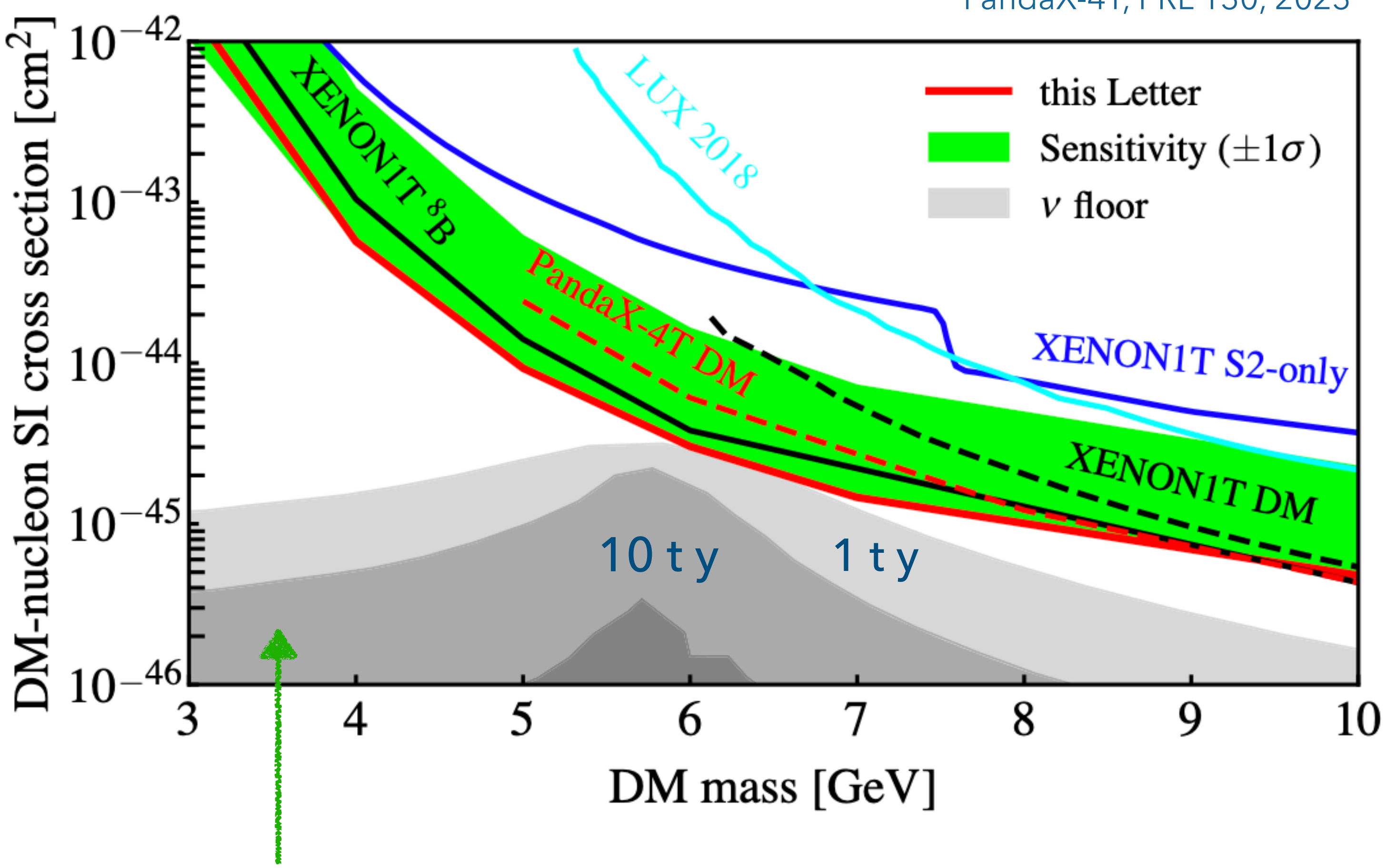
Existing ^{8}B ν constraints

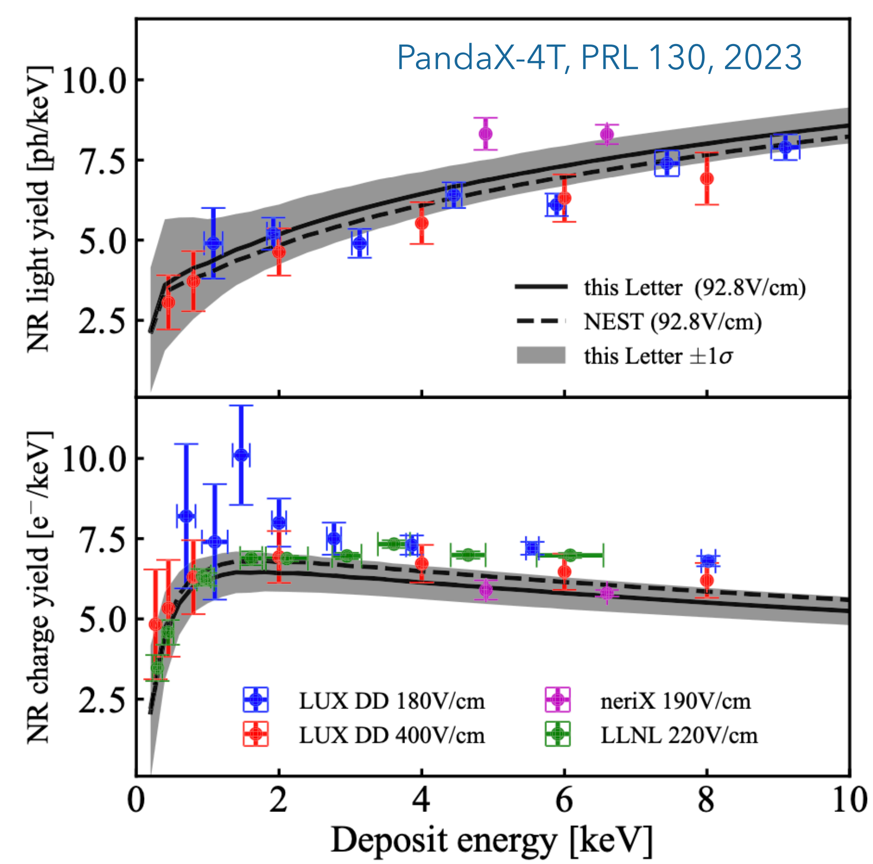
- XENON1T, PandaX-4T
- Searches ongoing in LZ, PandaX-4T, XENONnT

^{8}B flux prediction and constraints from XENON1T and PandaX-4T



PandaX-4T, PRL 130, 2023





ν-floor: probability for an ideal xenon detector to see < 3-σ DM signal