XLZD:
A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

Identification of Dark Matter 2024
L'Aquila

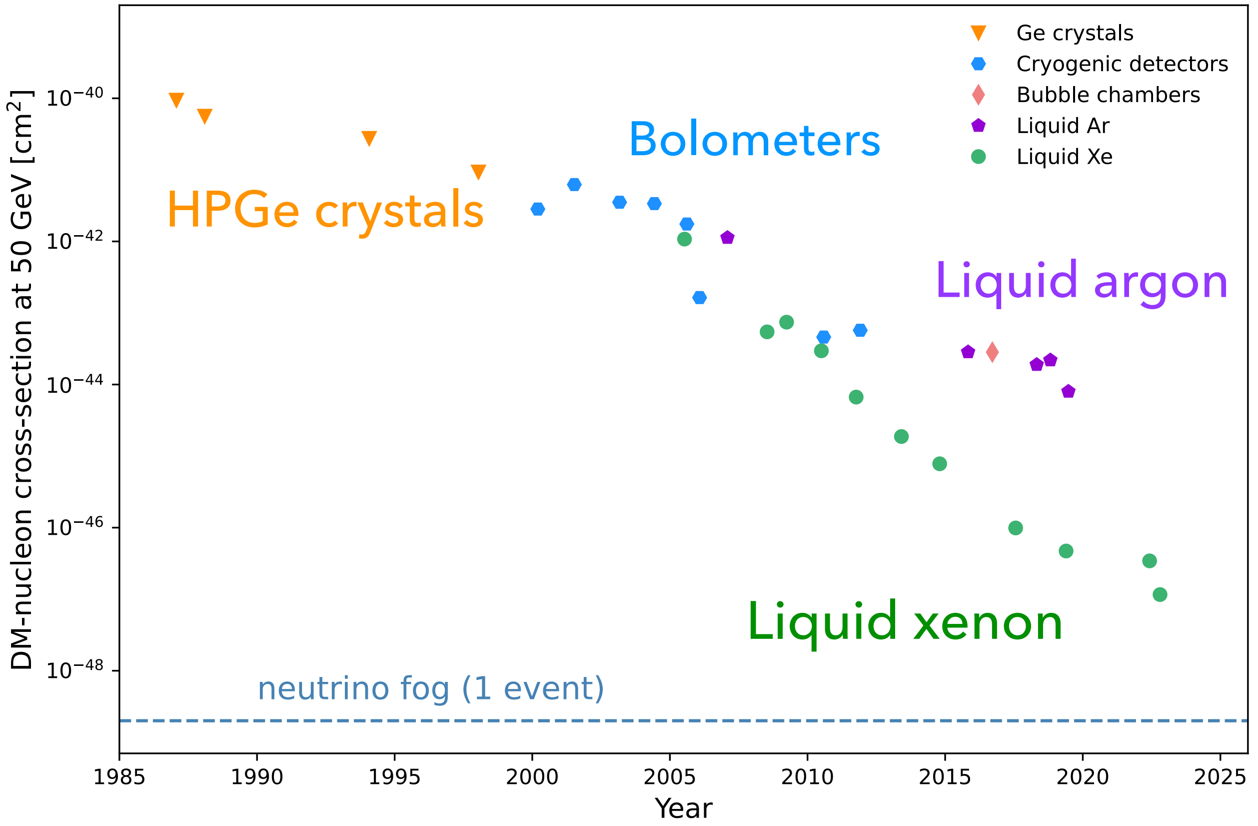
Laura Baudis
on behalf of the XLZD consortium

University of Zurich
July 11, 2024

Liquid xenon detectors

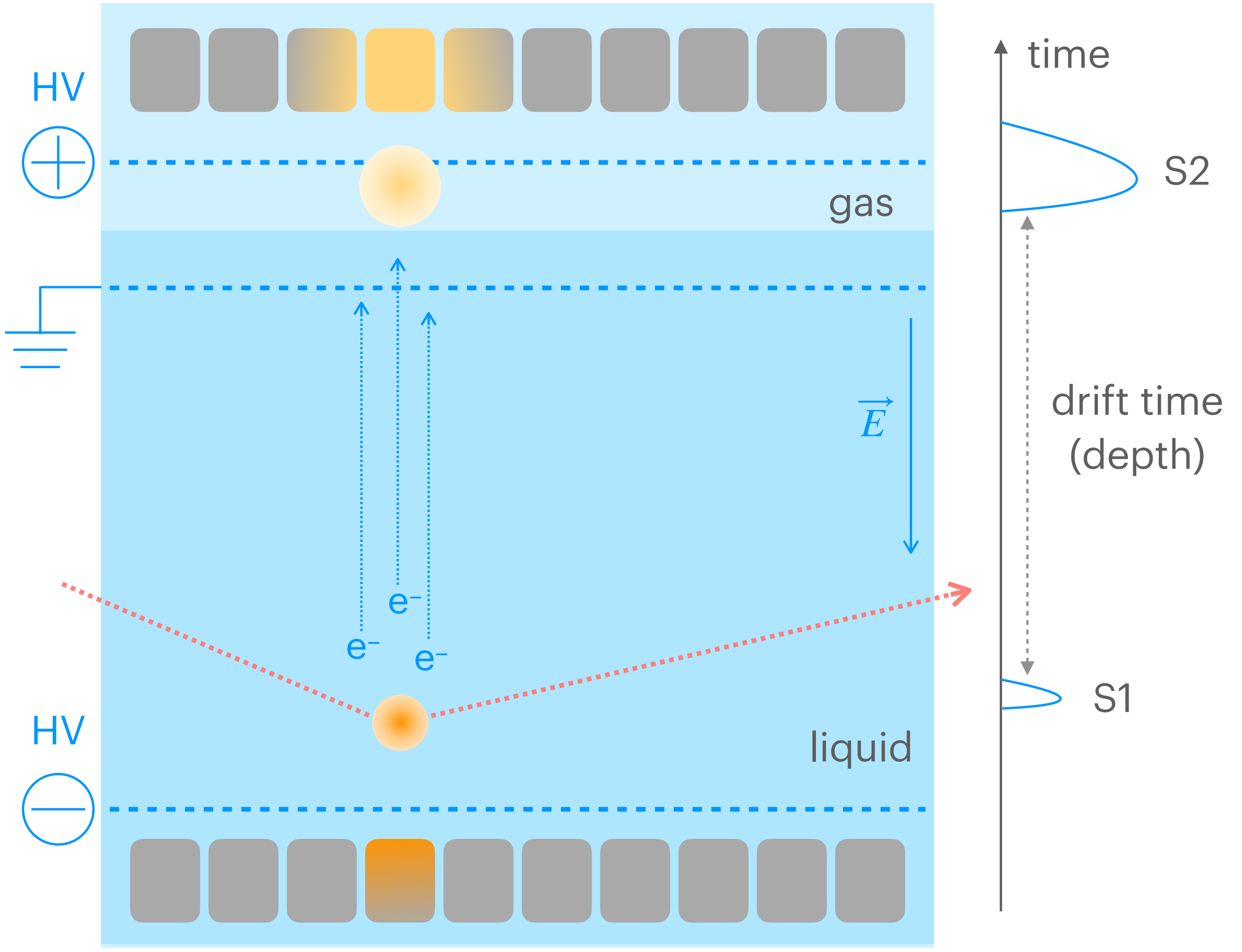
- Leading sensitivity at intermediate/high DM masses since ~2007
- Advantages
  - scalable ⇒ large target masses
  - readily purified ⇒ ultra-low backgrounds
  - high density ⇒ self-shielding
- SI and SD (^{129}Xe, ^{131}Xe) interactions
- Many other science opportunities (second order weak decays of ^{124}Xe, ^{126}Xe, ^{134}Xe, ^{136}Xe; solar and supernova neutrinos)

Upper limits for a 50 GeV WIMP



Two-phase xenon TPCs

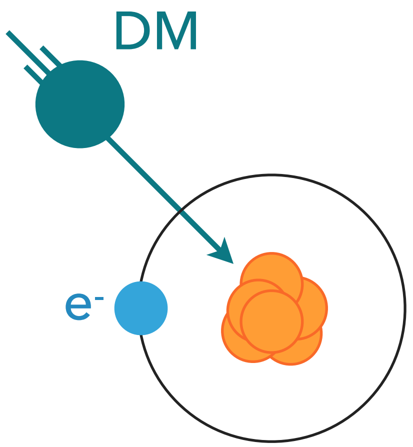
5D detectors: (x,y,z,E,t)

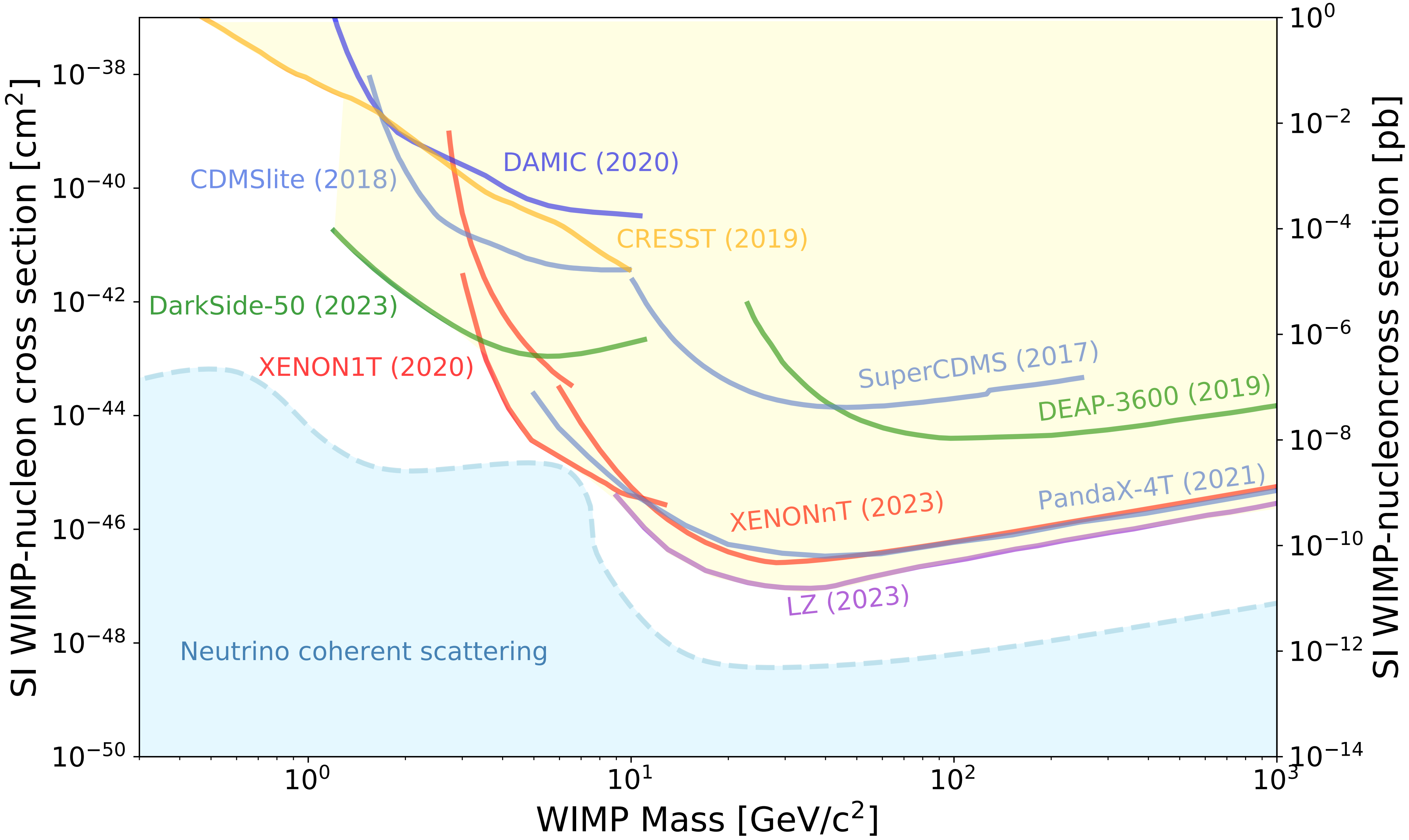


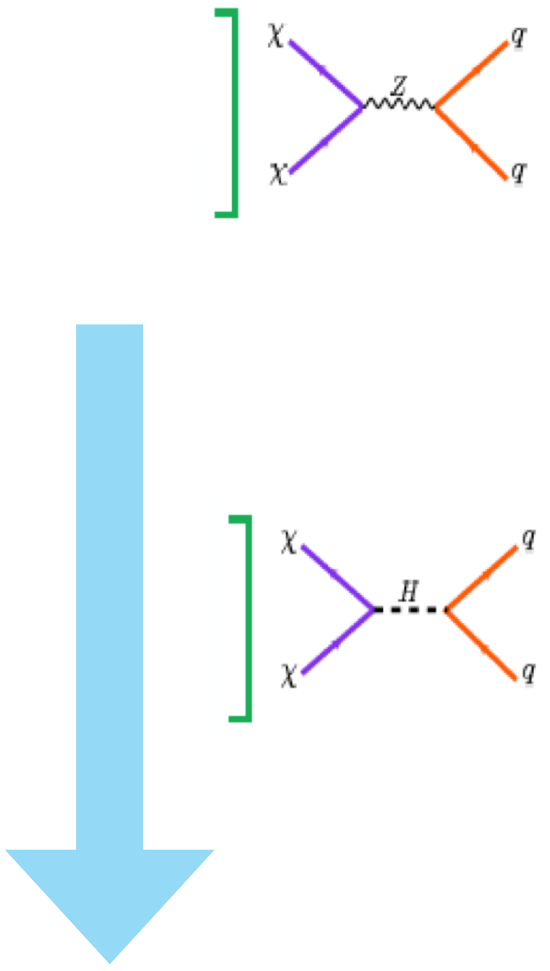
$$\lambda_{LXe} = 175 \text{ nm}$$

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

Towards the neutrino fog





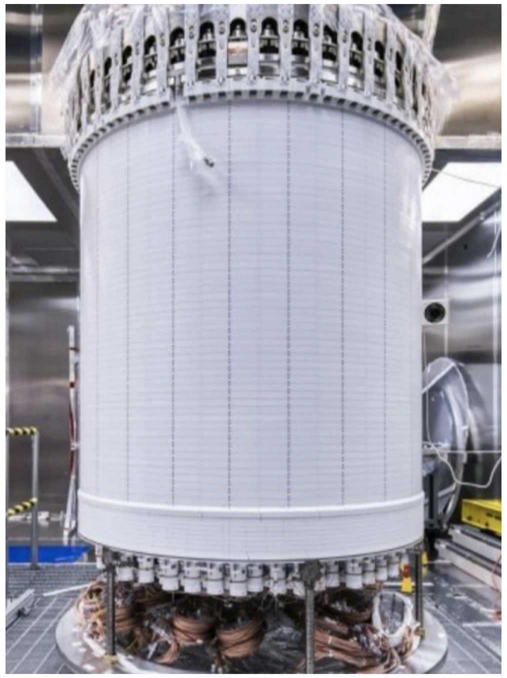


LB and Stefano Profumo, PDG 2024

See talks by Q. Lin, K. Liu, H. Schulze, I. Olcina, M.E. Monzani

Ongoing LXe experiments

LUX-ZEPLIN



SURF, 7 t

XENONnT

LNGS, 5.9 t

PandaX-4T

JinPing, 3.7 t

- TPCs with 2 arrays of 3-inch ø PMTs
- Kr & Rn removal techniques (to mitigate ^{85}Kr and ^{222}Rn backgrounds)
- Ultra-pure water shields, neutron & muon vetos

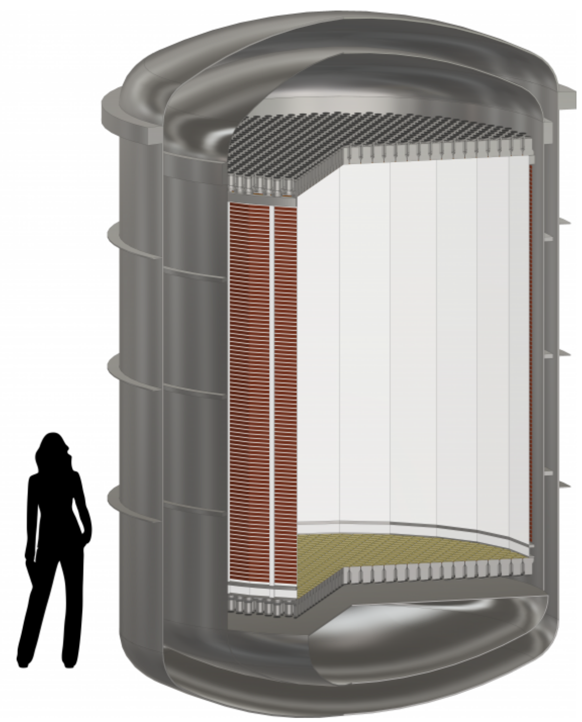
See talks by A. Usón, M. Selvi

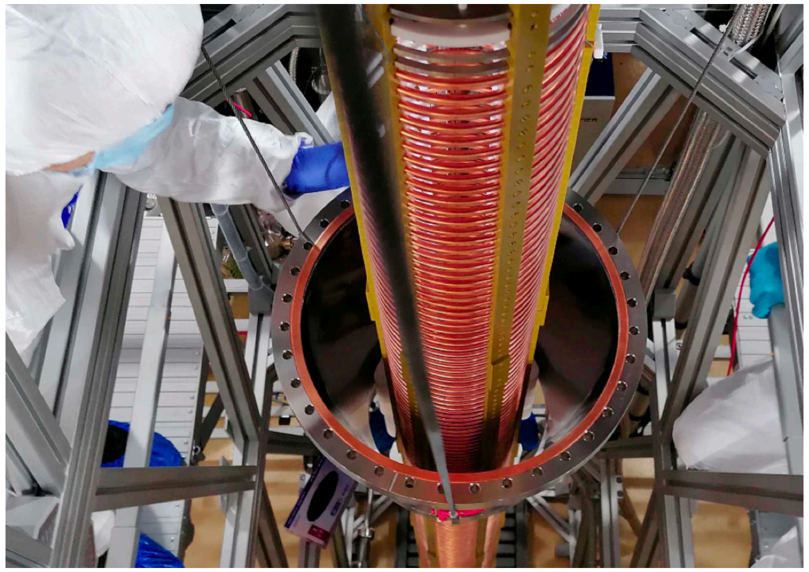
DARWIN R&D

Next talk by Chiara Capelli

- R&D for next-generation liquid xenon detector
- Several large-scale demonstrators in operation (3 ERCs)
- Photosensors, TPC design, large-scale purification, etc

DARWIN collaboration
JCAP 1611 (2016) 017





Xenoscope at UZH

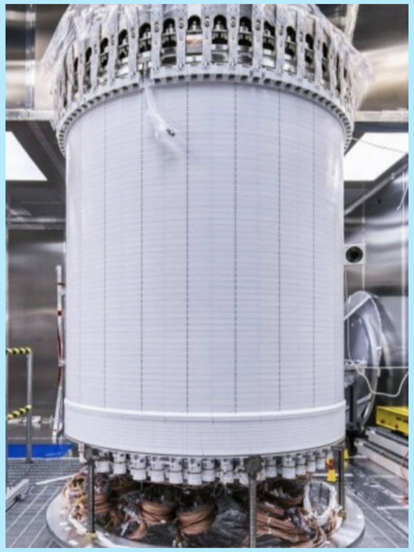
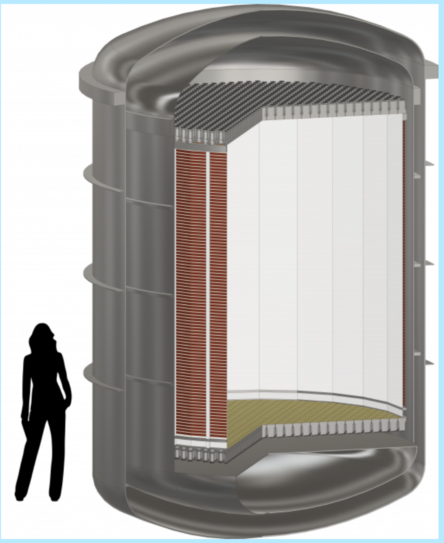
LB et al., JINST 16, 2021, EPJ-C 83, 2023

Pancake in Freiburg

A. Brown at al., JINST 19, 2024

XLZD

XENON-LUX-ZEPLIN-DARWIN

- 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
- June 2022: meeting at KIT, April 2023: meeting at UCLA, April 2024: meeting at RAL
- SteCo and WGs in place, regular meetings; design book in preparation

XLZD

XENON-LUX-ZEPLIN-DARWIN

KIT, summer 2022

UCLA, spring 2023

RAL, spring 2024

XLZD

XENON-LUX-ZEPLIN-DARWIN

LNGS, yesterday

XLZD: endorsement

XENON-LUX-ZEPLIN-DARWIN

- APPEC Mid-Term Roadmap
- Helmholtz Roadmap
- P5 report
- UKRI infrastructure funds allocated for design study
- Several national roadmaps in Europe

APPEC report

RECOMMENDATIONS:

APPEC strongly supports the European leadership role in Dark Matter direct detection, underpinned by the pioneering LNGS programme, to realise at least one next-generation xenon (order 50 tons) and one argon (order 300 tons) detector, respectively, of which at least one should be situated in Europe. APPEC strongly encourages detector R&D to reach down to the neutrino floor on the shortest possible time scale for WIMP searches for the widest possible mass range.

View of the external structure of XENON nT, experiment devoted to direct search of dark matter, which constitutes 85% of the matter in the Universe. Beside the tank, containing the sensitive part of the detector, it is visible the three levels building which hosts the apparatus necessary for the functioning of the detector.
© Fabrizio Ursini / LNGS-INFN

P5 report

4.1.4 – Major Initiative: G3, the Ultimate WIMP Dark Matter Search

The next phase of the search for WIMP dark matter requires experiments capable of reaching roughly order-of-magnitude weaker interaction strengths than current experiments. A large Generation-3 (G3) WIMP dark matter search would build on the most successful designs of the current G2 experiments, providing sensitivity to dark matter-Standard Model interactions that are small enough that neutrinos become an irreducible background (the "neutrino fog").

This improvement in reach would provide coverage of important benchmark WIMP models, such as most remaining potential dark matter parameter space under the constrained minimal supersymmetric extension to the Standard Model. Such a G3 experiment would also perform important measurements of solar and possibly supernova neutrinos. A G3 direct detection experiment would be the ultimate WIMP search within the current approach; moving past the reach of the G3 experiment and deeper into the neutrino fog would require significant changes in method and technology.

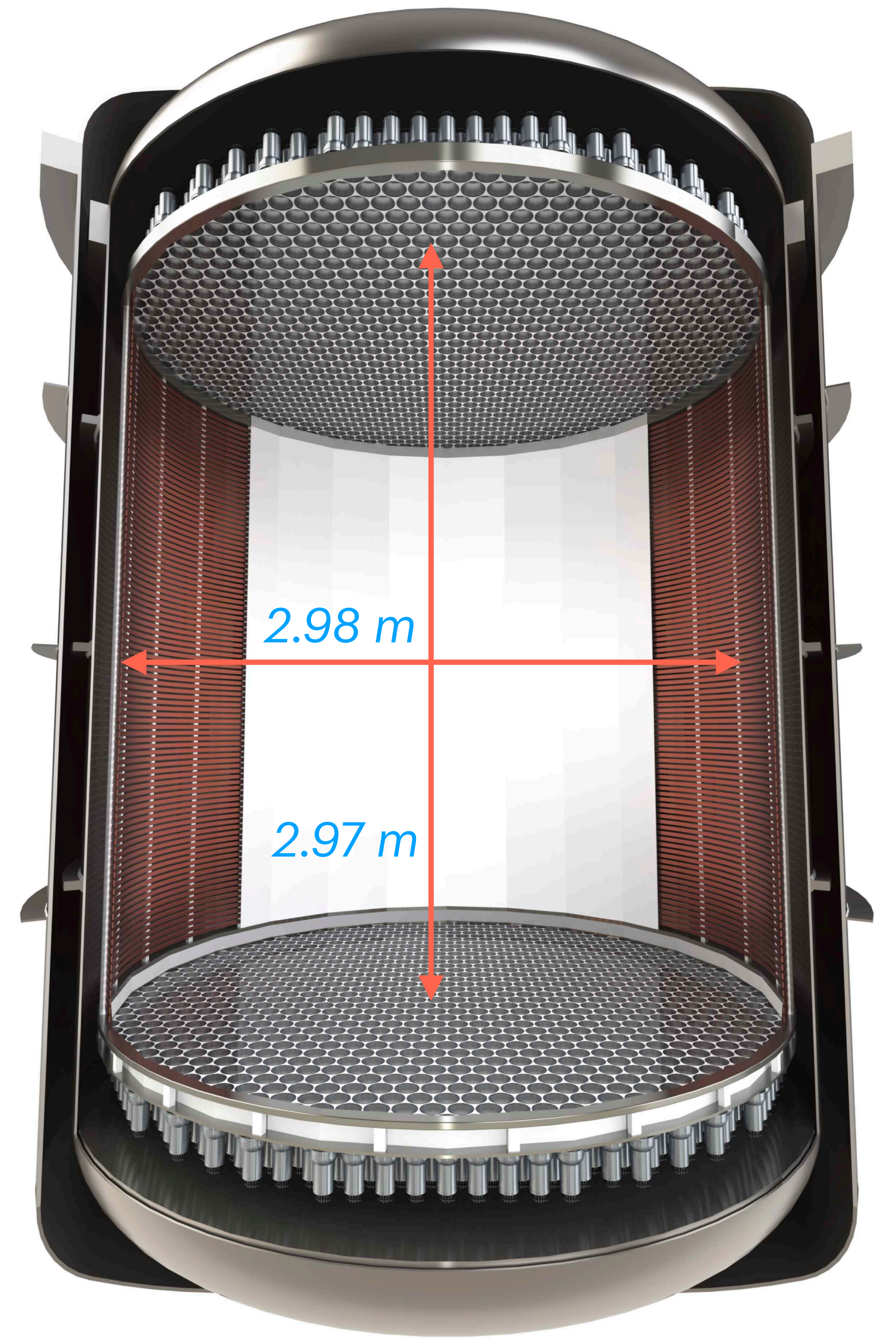
Although supporting more than one G3 experiment would be beneficial, expected costs are high enough, especially compared to the costs of the portfolio of smaller dark matter projects, that funding two does not appear feasible. Our recommendation supports one G3 experiment, preferably sited on US soil to help maintain US leadership (Recommendation 2d). Investment in the expansion of SURF, taking advantage of the DUNE excavation infrastructure and potential private funding, would enable such siting. Continued support by both DOE and NSF is needed to maximize the science and US leadership. A second, complementary G3 experiment would maximize the discovery potential and would teach us more about dark matter if one of the G2 experiments has promising results.

XLZD nominal design

Design book in preparation

- Nominal plan: 60 t LXe in TPC (78 t total), early science with 40 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

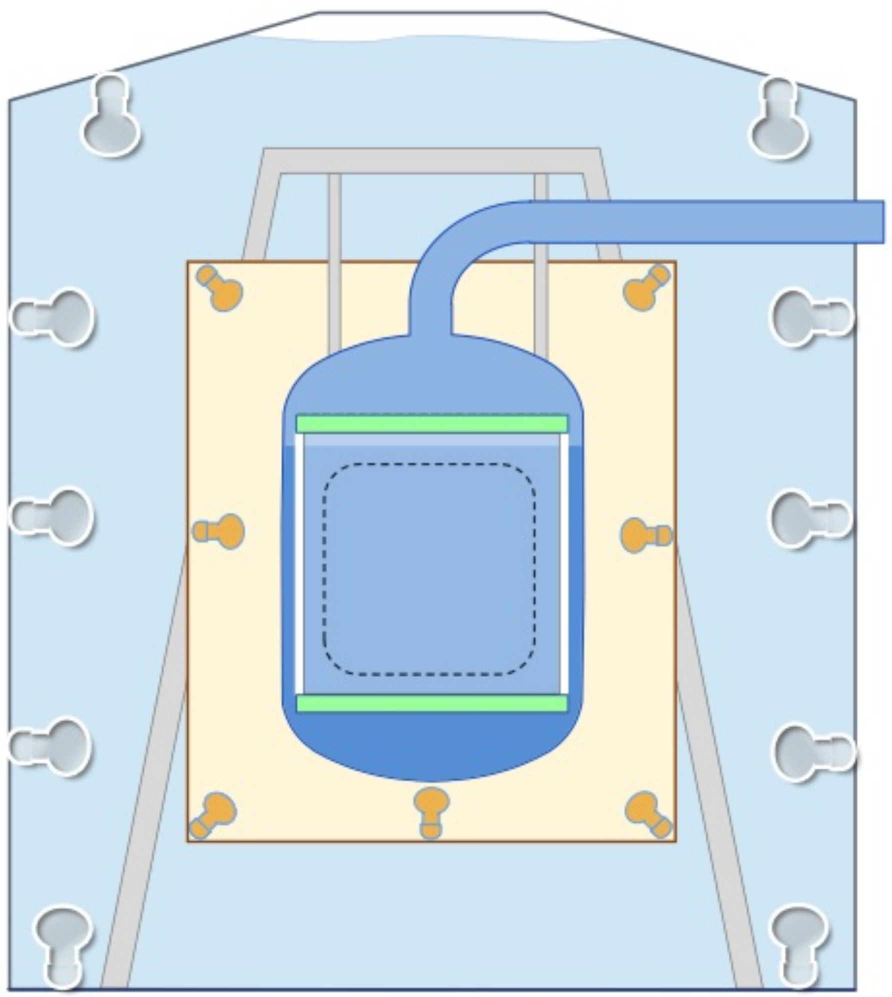


*80 t LXe in TPC final size if market is favourable

XLZD baseline design

Design book in preparation

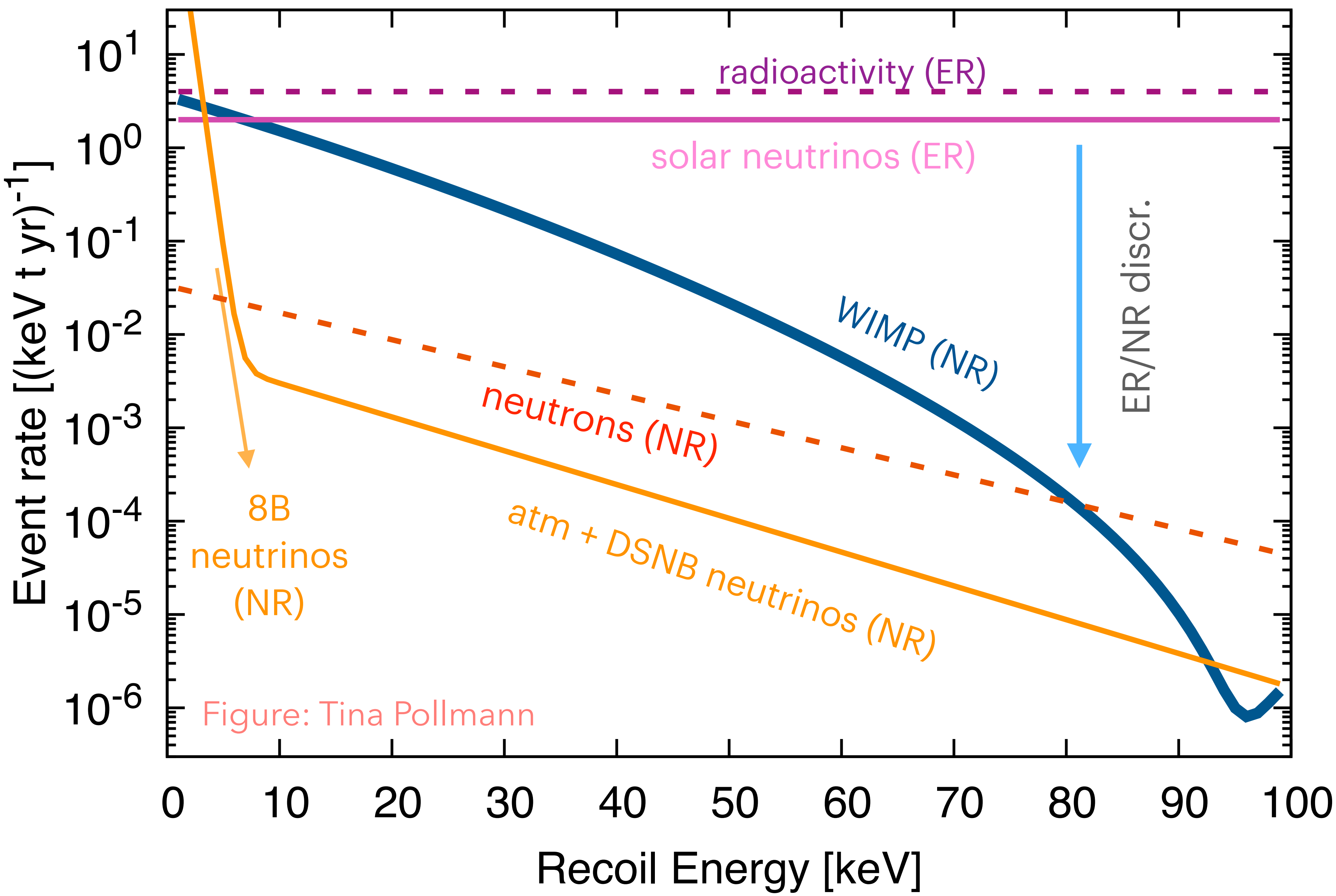
- Neutron and muon vetoes
- Underground site: several options are being considered (LNGS, Boulby extension, SURF, SNOLAB)
- Large-scale underground demonstrator planned



XLZD n and μ shields, schematic view

Background goals

- ER and NR regions: dominated by cosmic neutrinos



materials, intrinsic etc

v-e scattering: solar v's

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

radiogenic, cosmogenic

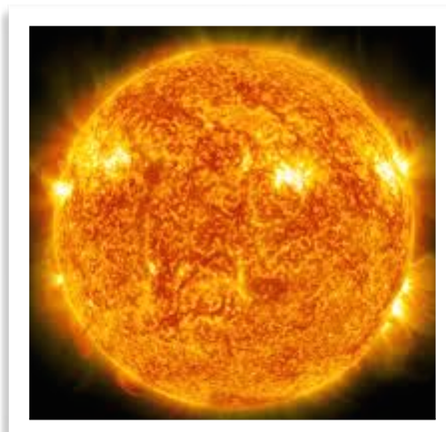
CEvNS: solar v's, atm v's + DSNB

Science goals

Physics case for a large liquid xenon detector: JoPG and arXiv:2203.02309 (600 authors)

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

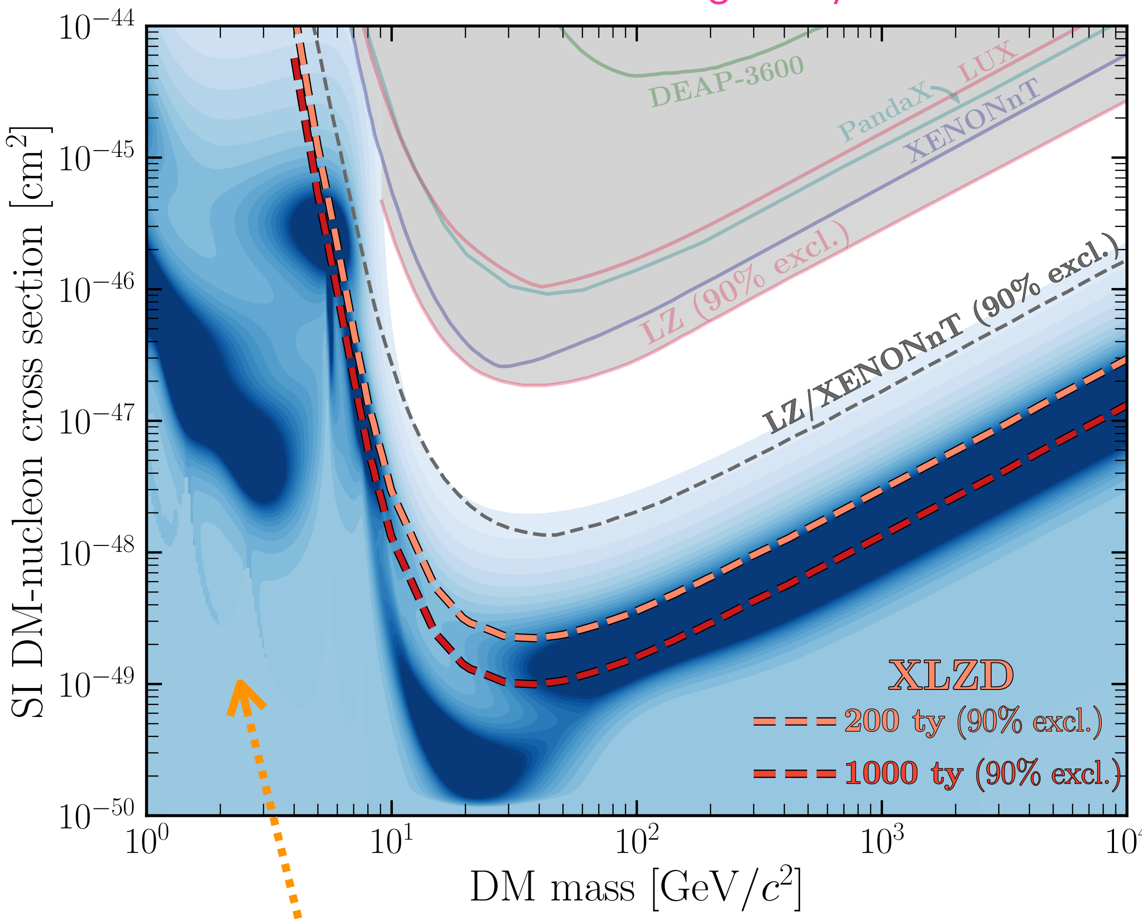
Eur. Phys. J. C 80, 9 (2020)

WIMPs

- Definite search for medium to high WIMP masses
  - **reach the systematic limit of the neutrino fog** (~ 1000 tonnes × years exposure)
  - 3-σ discovery at SI cross section of 3×10^{-49} cm² at 40 GeV mass

Projected SI upper limits for 200 t y and 1000 t y exposures

Figure by Ciaran O'Hare



Systematic limit imposed by CEvNS from atmospheric neutrinos

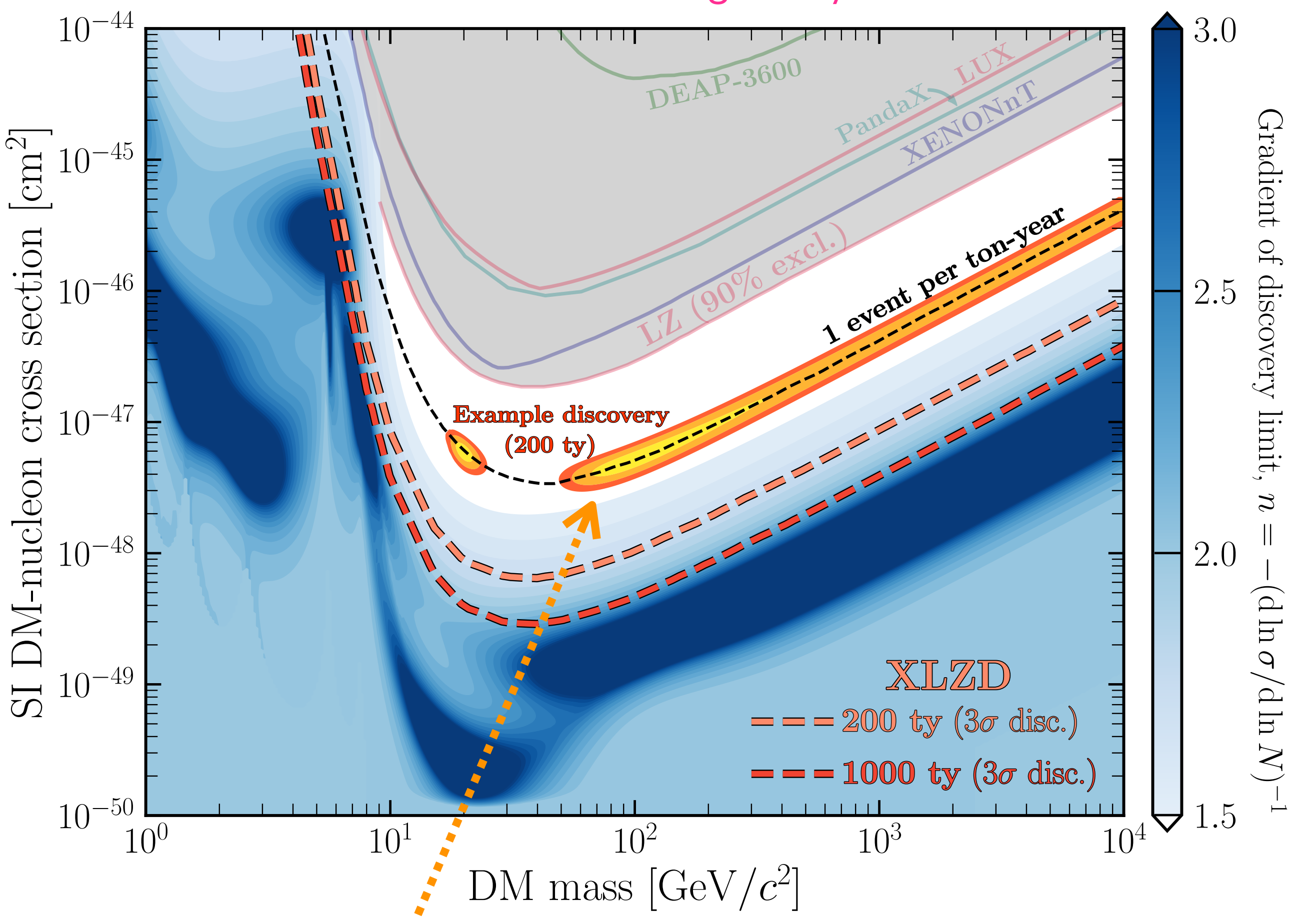
At contour n: obtaining a 10 times lower cross section sensitivity requires an **increase in exposure of at least 10^n**

WIMPs

- Definite search for medium to high WIMP masses
  - reach the systematic limit of the neutrino fog (~ 1000 tonnes × years exposure)
  - **3-σ discovery at SI cross section of 3 × 10^{-49} cm² at 40 GeV mass**

Median discovery potential 200 t y and 1000 t y exposures

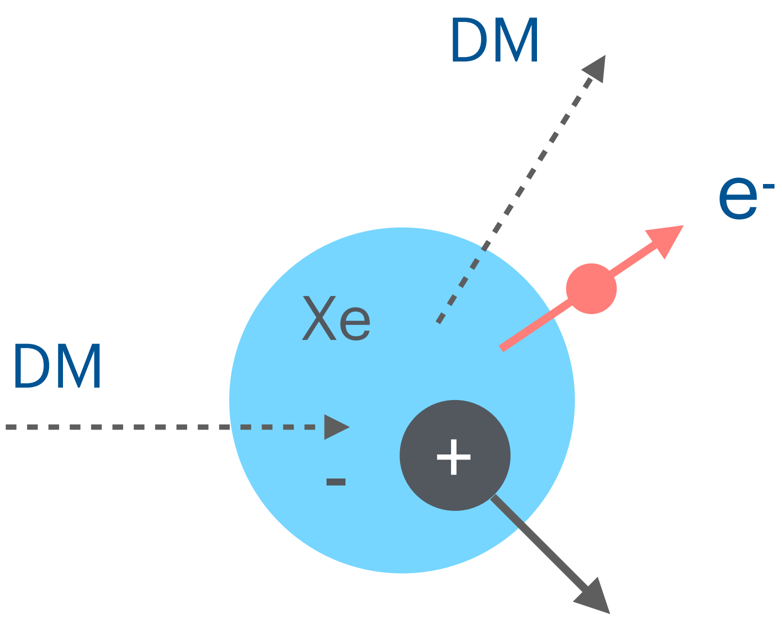
Figure by Ciaran O'Hare



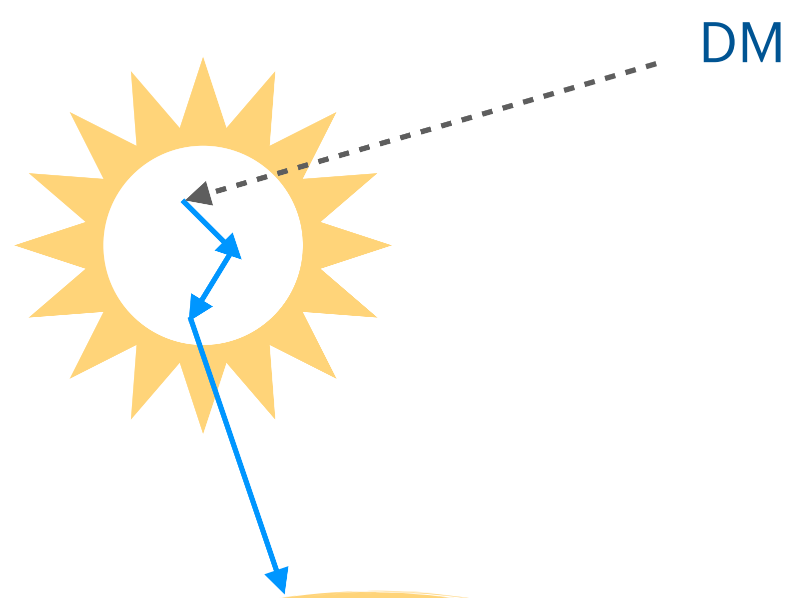
Confidence intervals for 200 t x y (1-, 2-, 3-σ: yellow, orange, red)

Dashed line: ≡ 1 event per t-y

Light dark matter searches

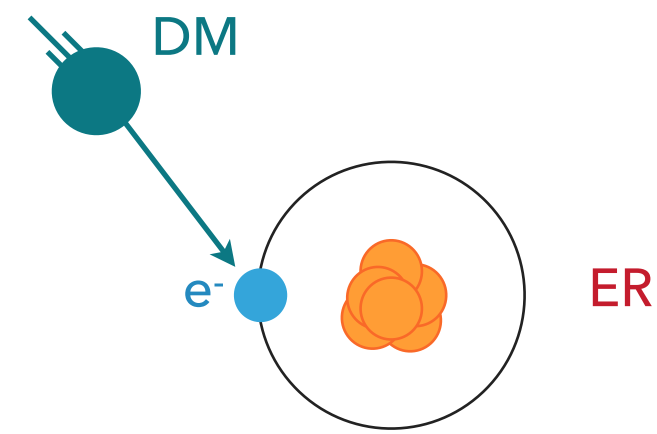


Migdal effect: NR signal with ER character

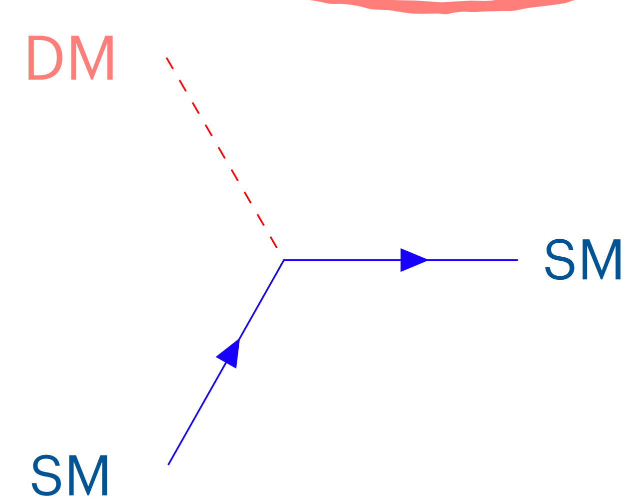


Use the Sun for a velocity boost

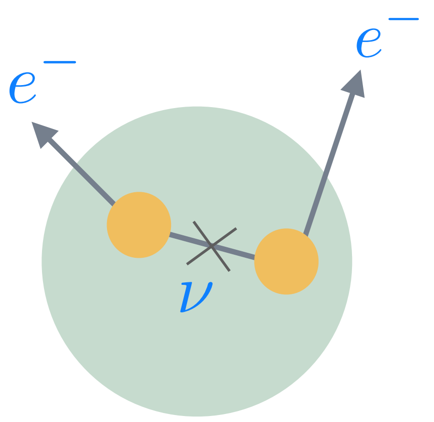
Ionisation-only searches



DM-e- scattering
DM absorption

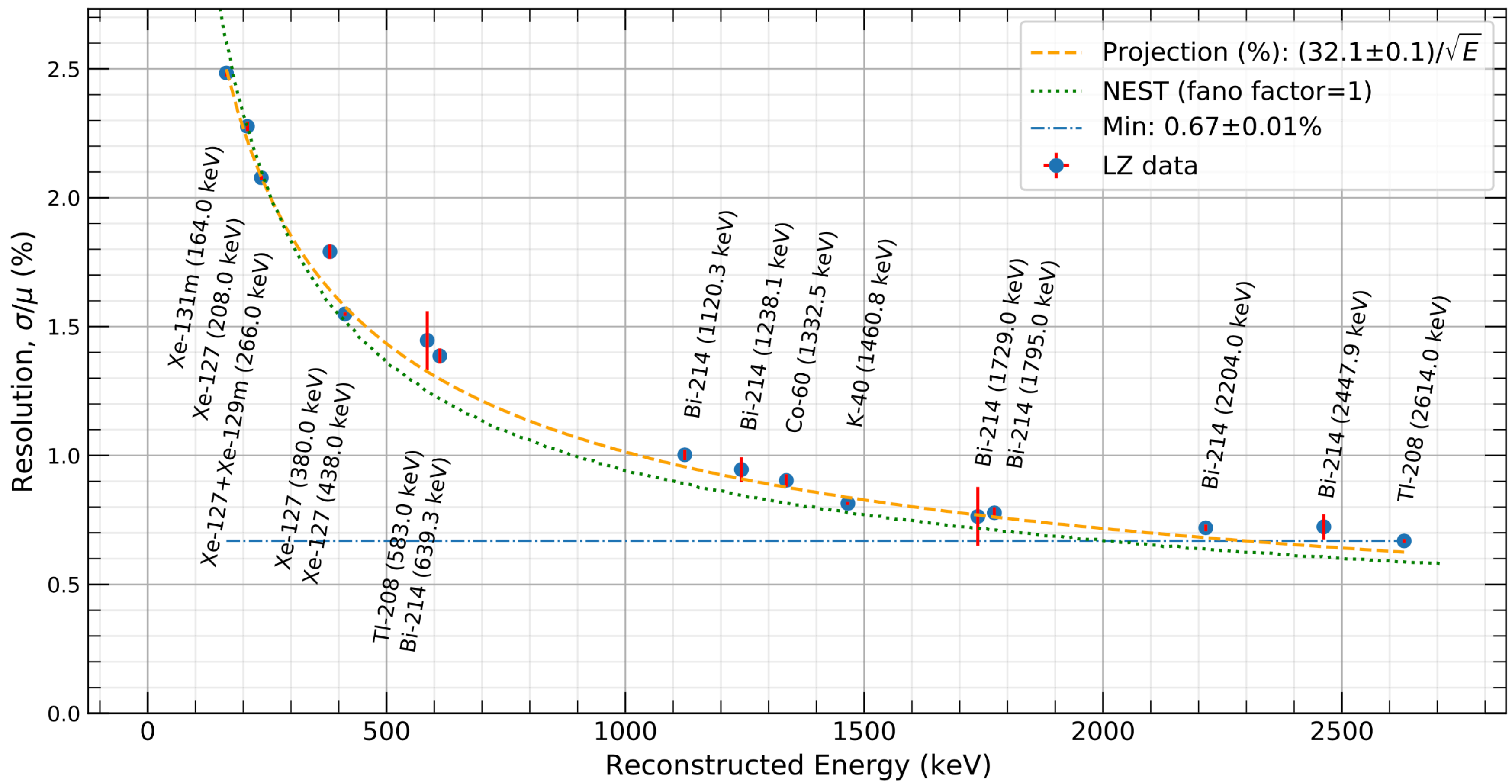


0νββ decay of ^{136}Xe

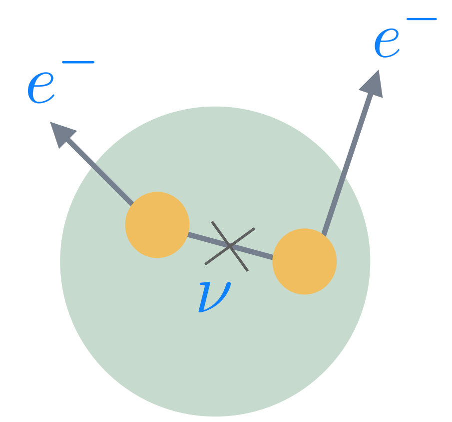


- **^{136}Xe:** present at **8.9%** abundance in ^{nat}Xe
- Energy resolution of large two-phase Xe TPCs at $Q_{\beta\beta}$: **< 1% (σ/E)**

LUX-ZEPLIN, JINST 18, 2023

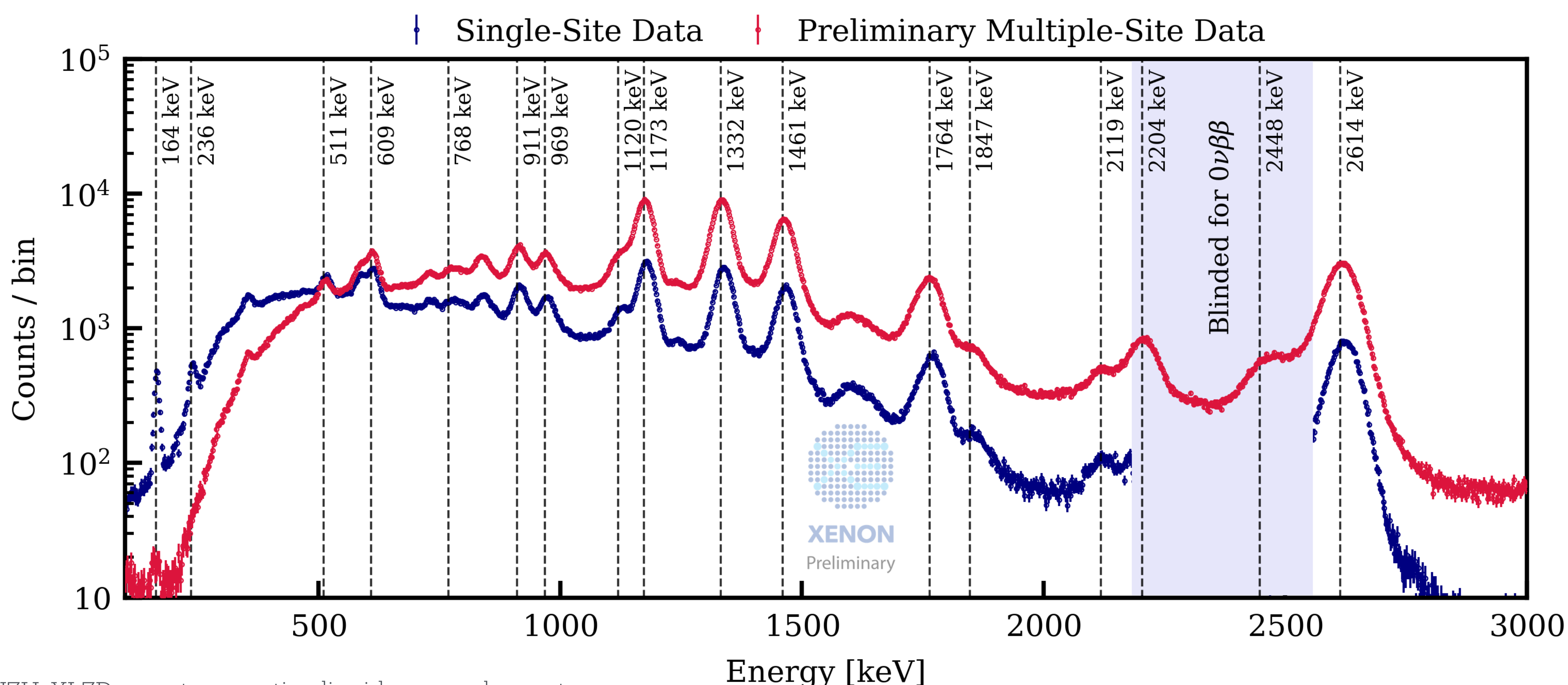


0νββ decay of ^{136}Xe

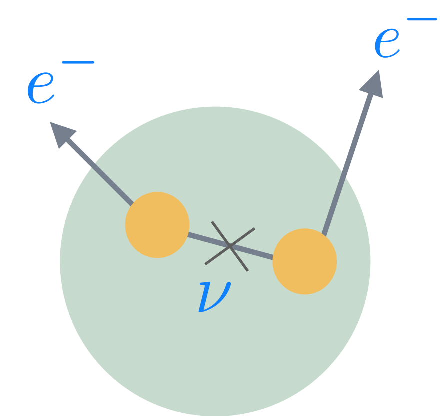


- Ongoing searches in **LZ and XENONnT**
- LZ sensitivity: $T_{1/2}$ ~ 1.1 x 10^{26} y, Phys.Rev.C 102 (2020) 1

XENONnT, preliminary; ^{136}Xe 0νββ region blinded



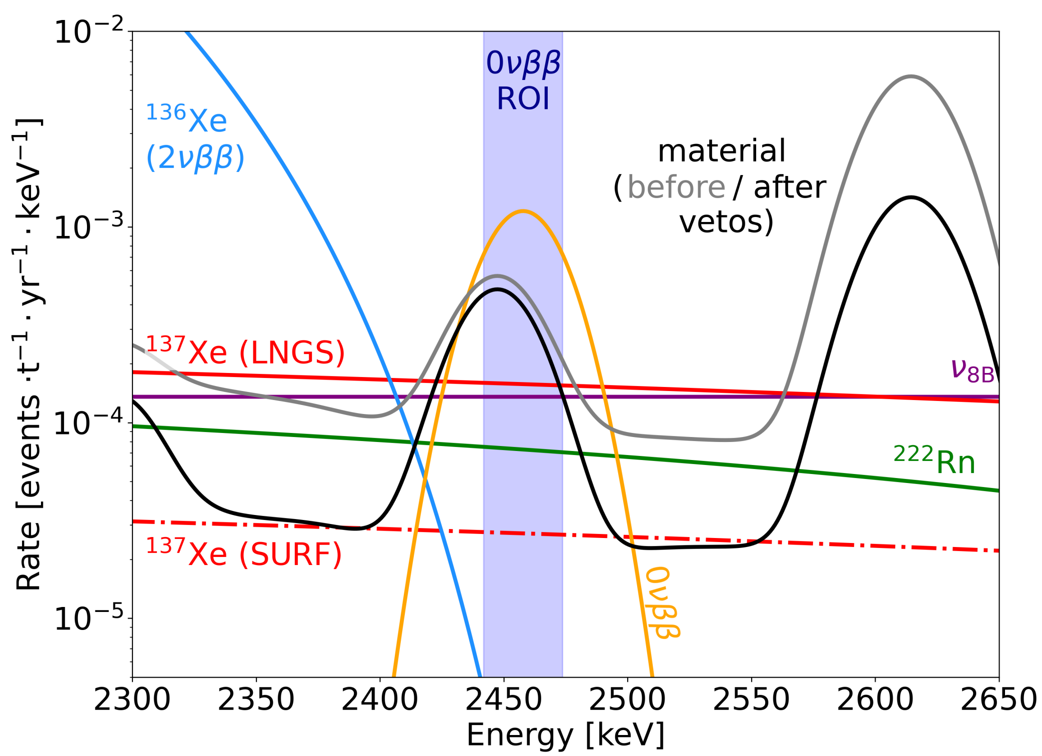
$0\nu\beta\beta$ decay of ^{136}Xe



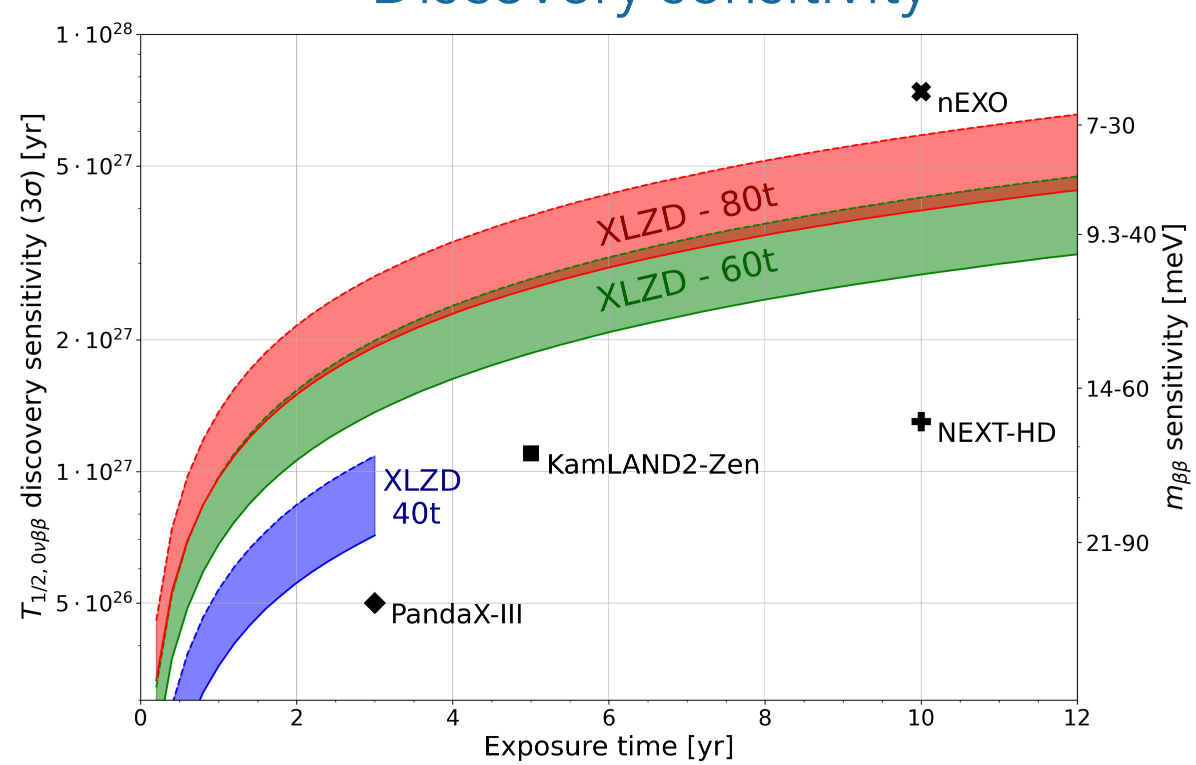
- **XLZD:** competitive sensitivity to dedicated experiments
- Assumptions: 0.1 μBq/kg ^{222}Rn, materials radiopurity already identified

XLZD preliminary

Signal: $T_{1/2}^{0\nu\beta\beta} = 5 \times 10^{27}$ y



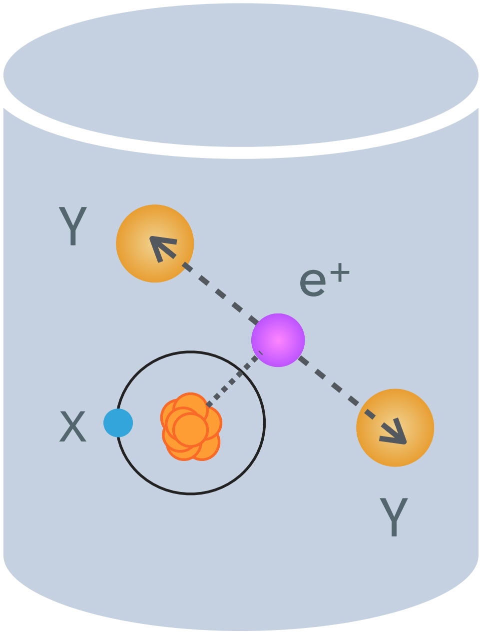
Discovery sensitivity



DARWIN study: EPJ-C 80, 2020

Other 2nd order weak decays

- **^{124}Xe, ^{126}Xe, ^{134}Xe**
- Some with **interesting topologies** 0ν/2νECβ⁺, 0ν/2νβ⁺β⁺
- Can also probe SM/nuclear physics

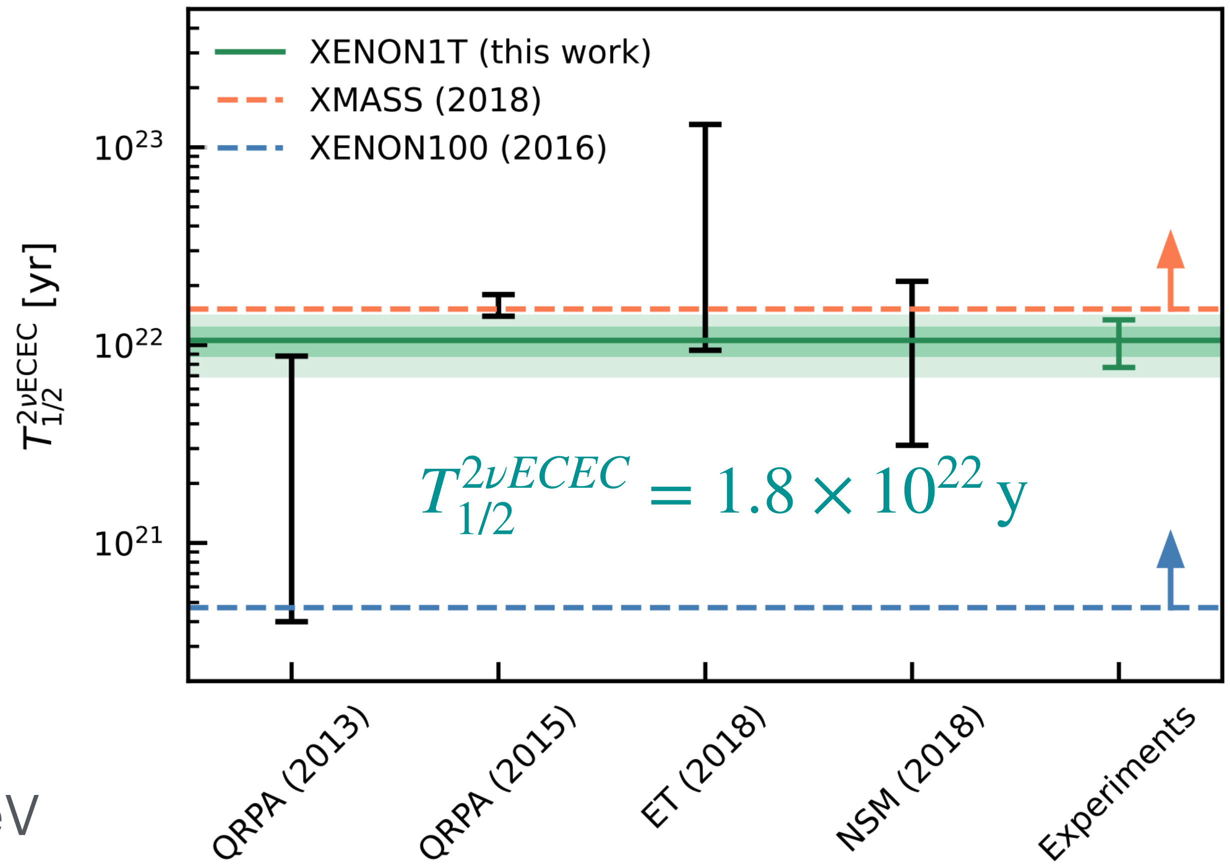


$$^{124}\mathrm{Xe} + e^- \rightarrow ^{124}\mathrm{Te} + e^+ + X_K$$

1.8 MeV 31.8 keV

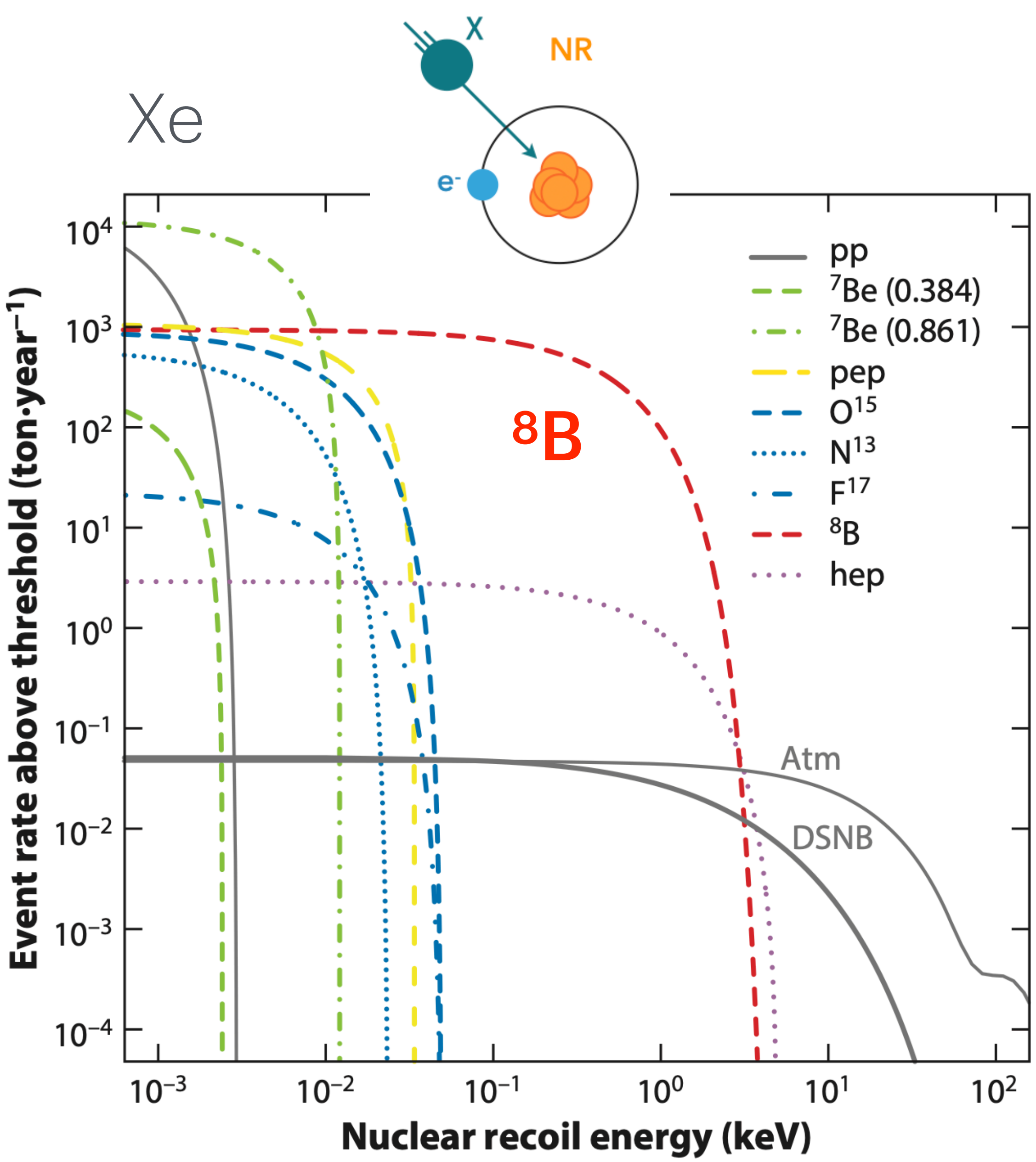
Q (^{124}Xe) = (2856.73 ± 0.12) keV

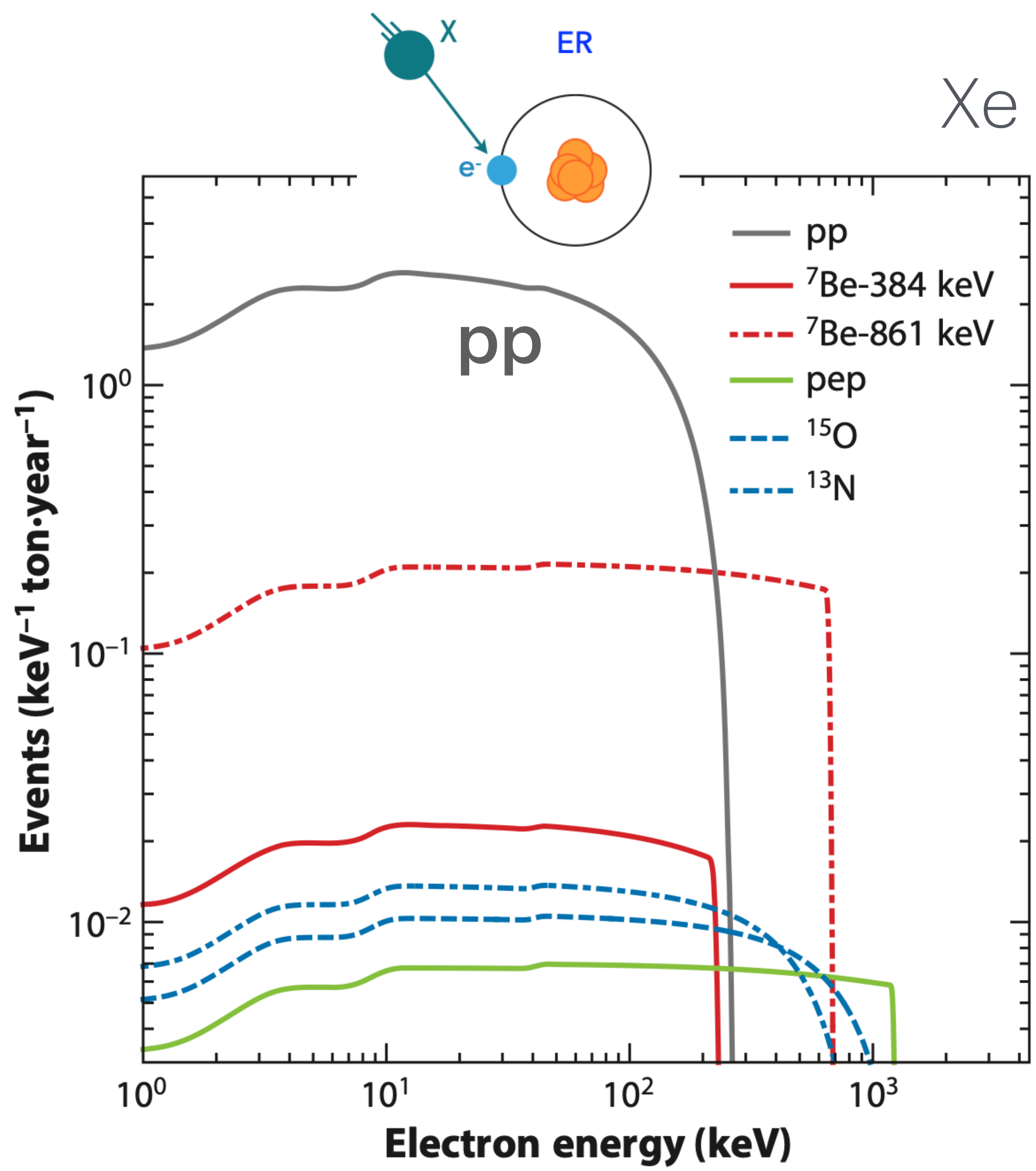
XENON, Nature 568, 2019 , PRC 106, 2022



Solar neutrino signals

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

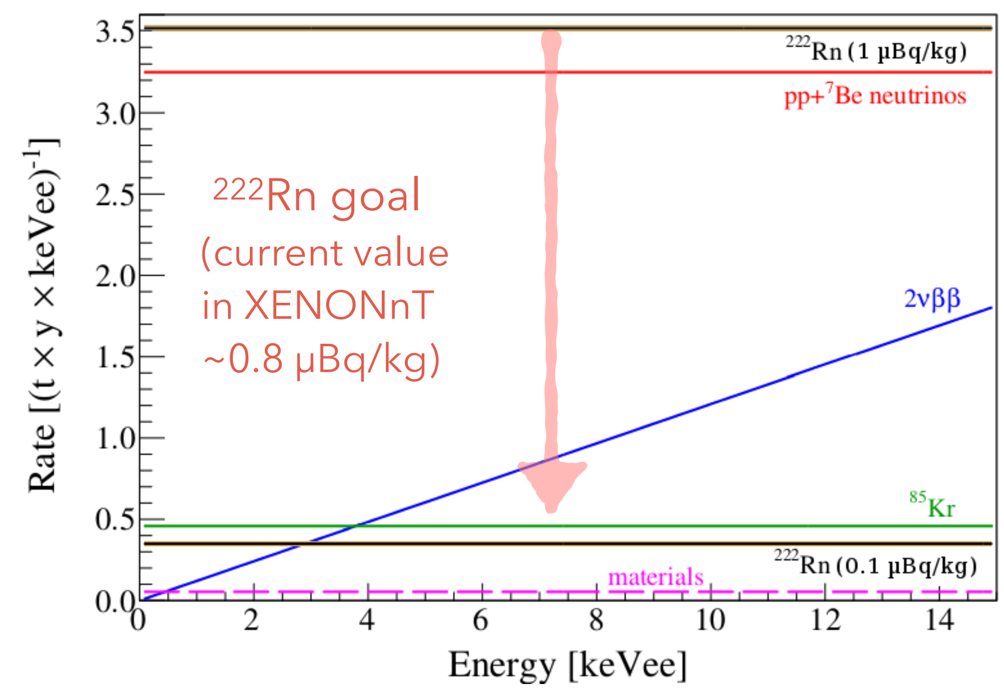




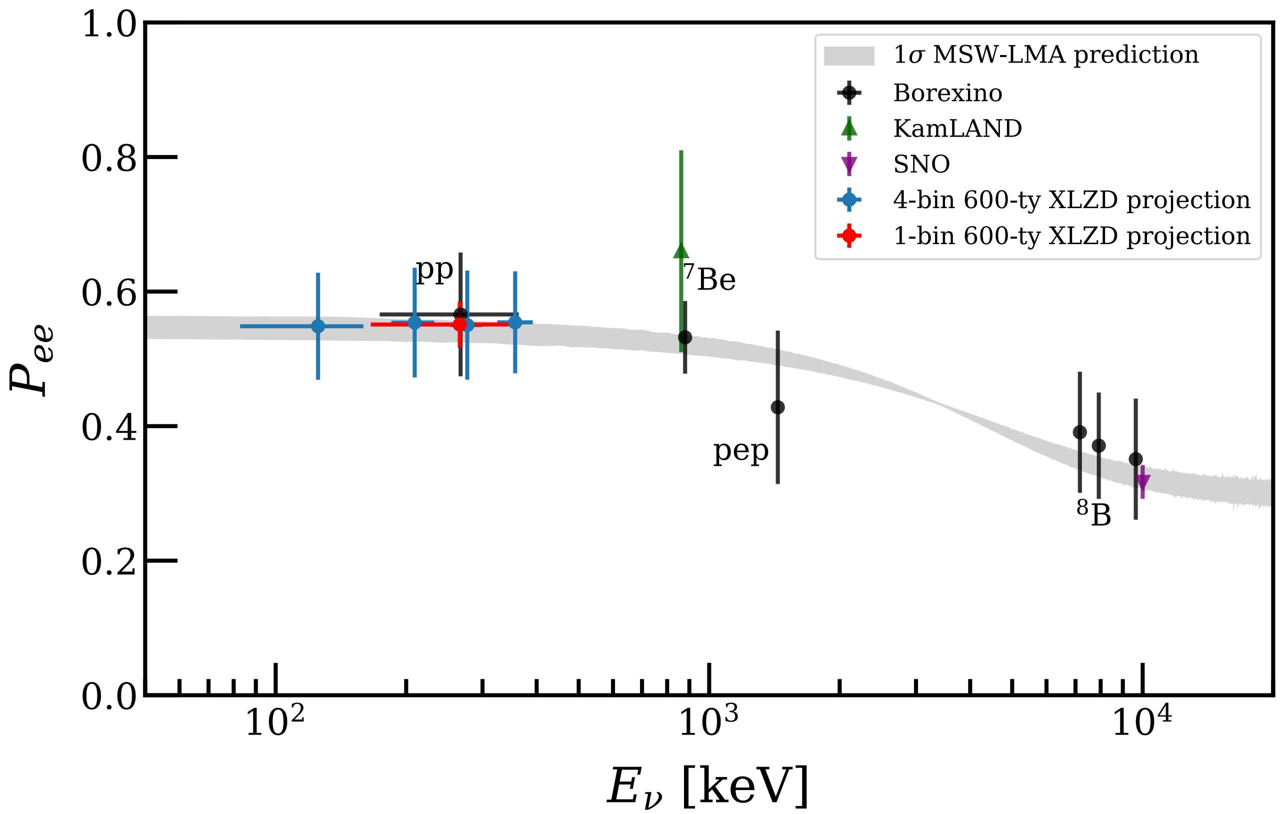
B. Dutta, E. Strigari, Annu. Rev. Nucl. Part. Sci. 2019

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)

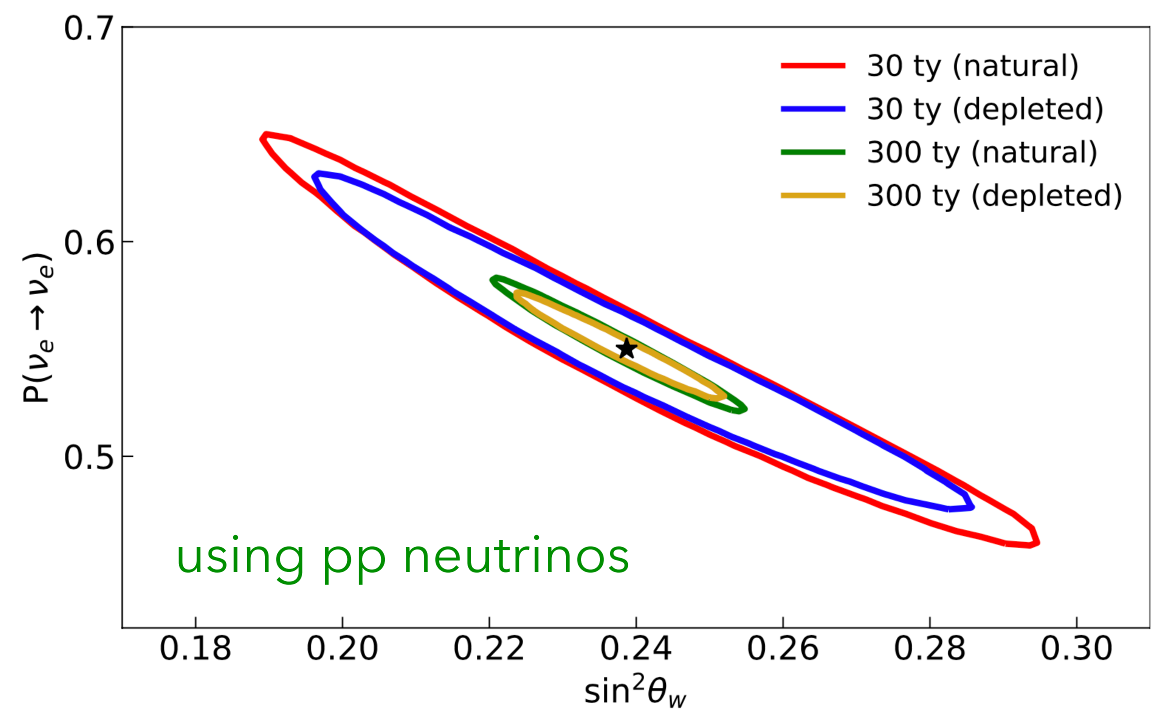


XLZD preliminary

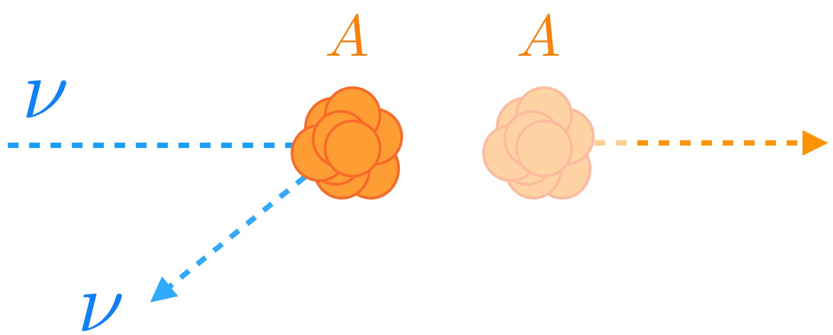


600 t y exposure, 1 and 4 energy bins

DARWIN collaboration, EPJ-C 80 12 (2020)

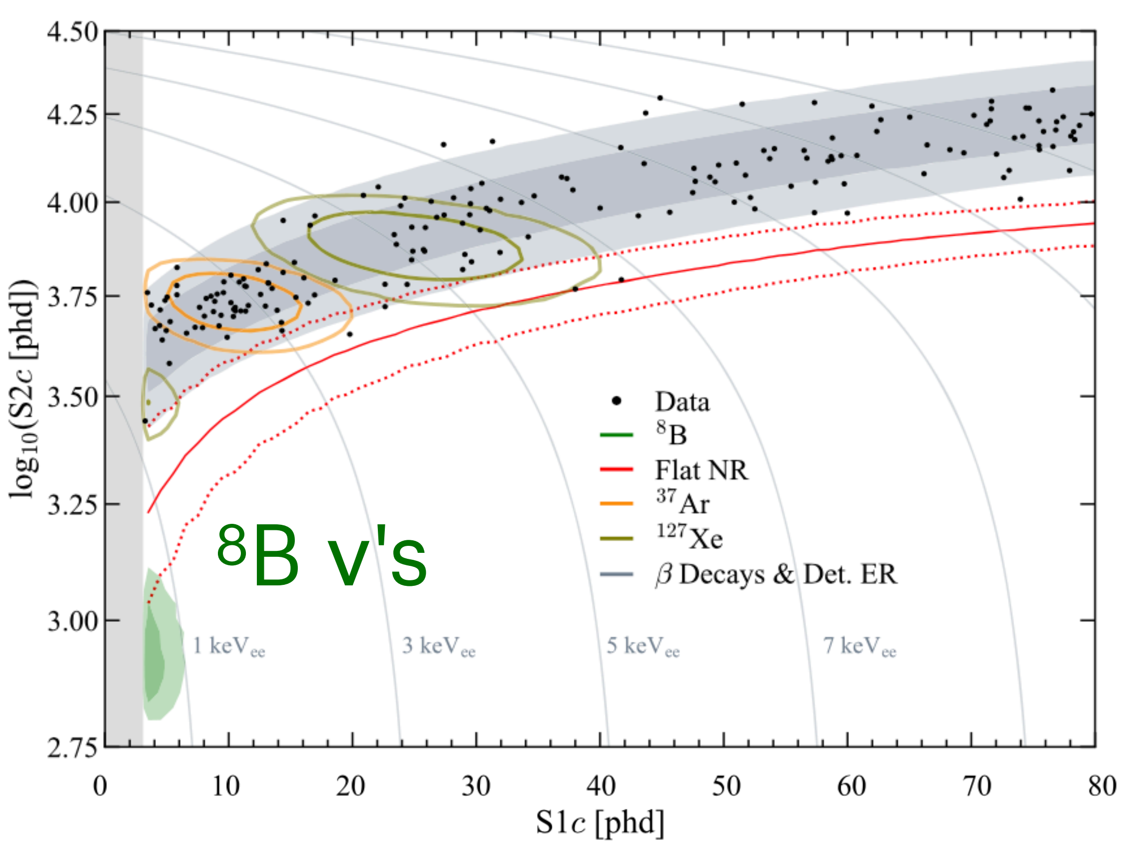


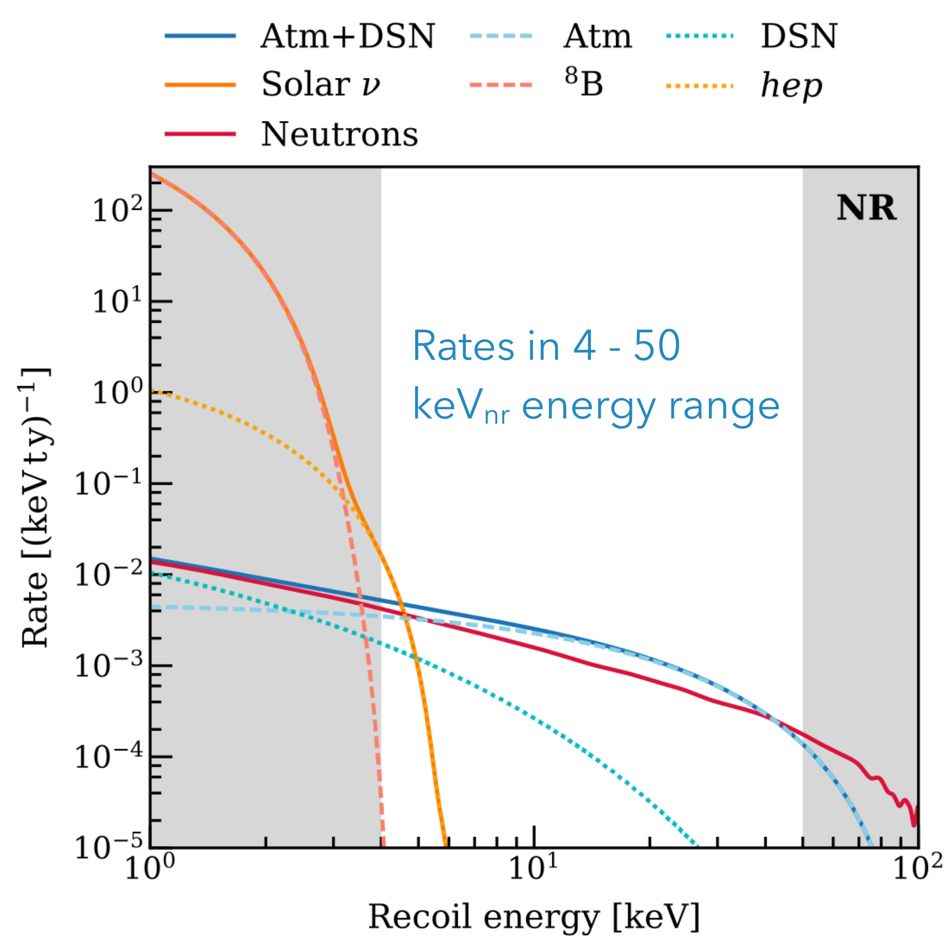
Solar ν-nucleus scattering



- Main goal: observe ^{8}B neutrinos via CEvNS
- In LXe: ~99% of events expected < 4 keV NR energy
- Expect: 10^4 events/(200 t y) for 2-fold S1 and 5 n_e S2*

LZ, PRD 108, 2023

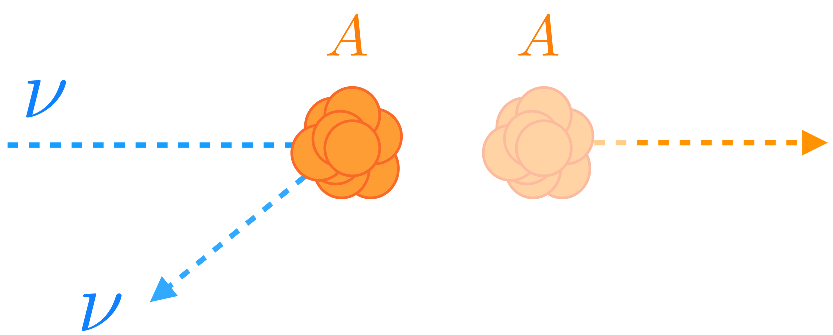




XENON collaboration, JCAP11(2020)031

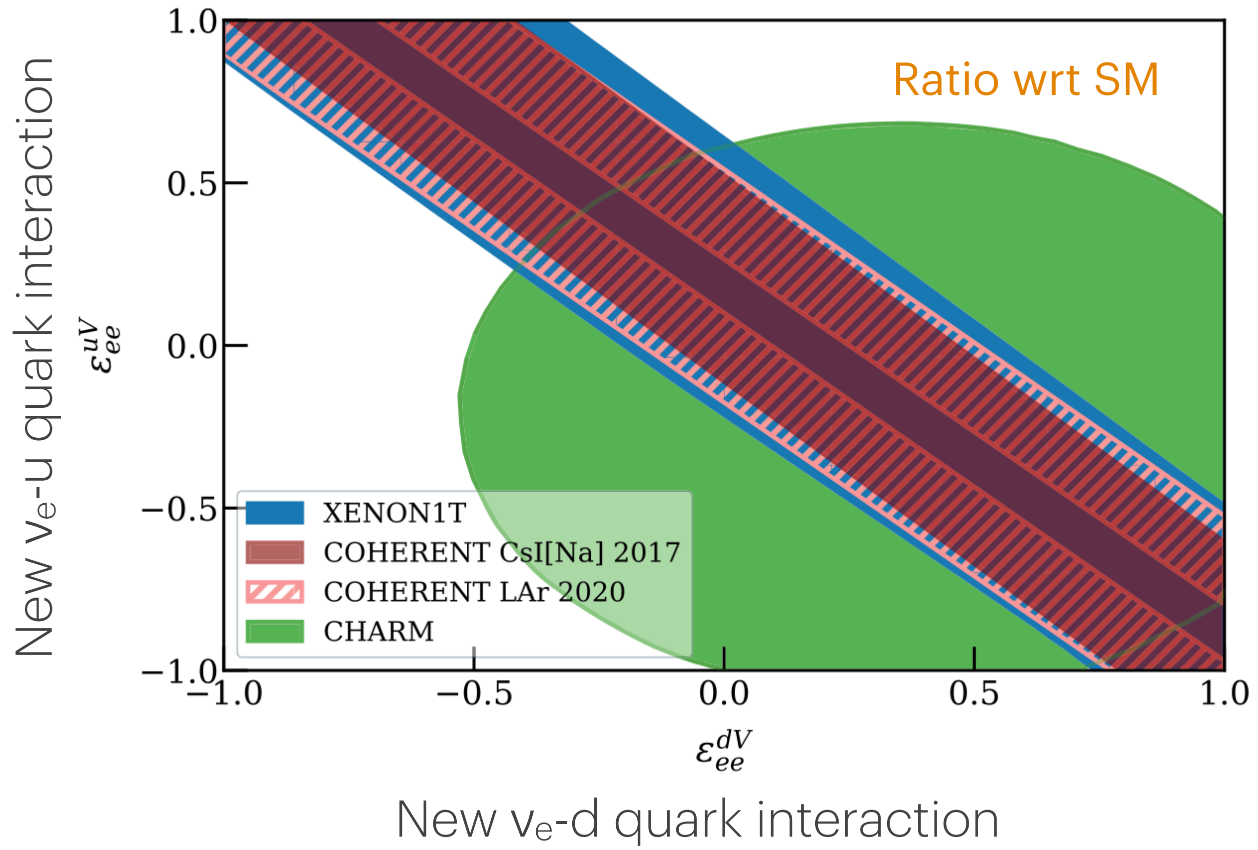
*e.g., X. Xiang et al., PRD 108, 2023

Solar ν-nucleus scattering

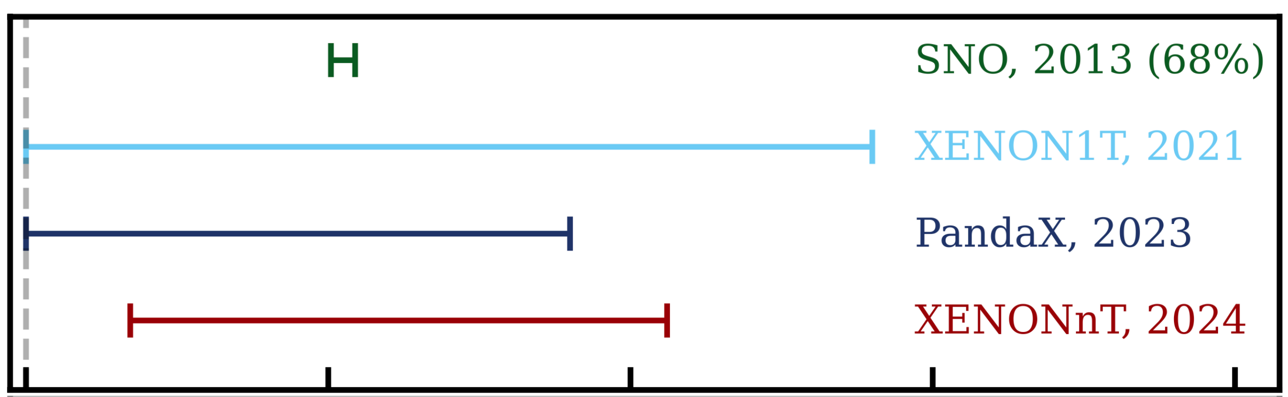


- Main goal: observe ^{8}B neutrinos via CEvNS
- Look for non-standard interactions

XENON1T, PRL 126, 2021

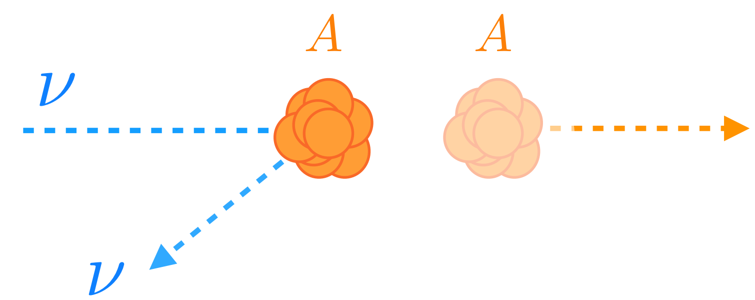


Talk by Fei Gao yesterday



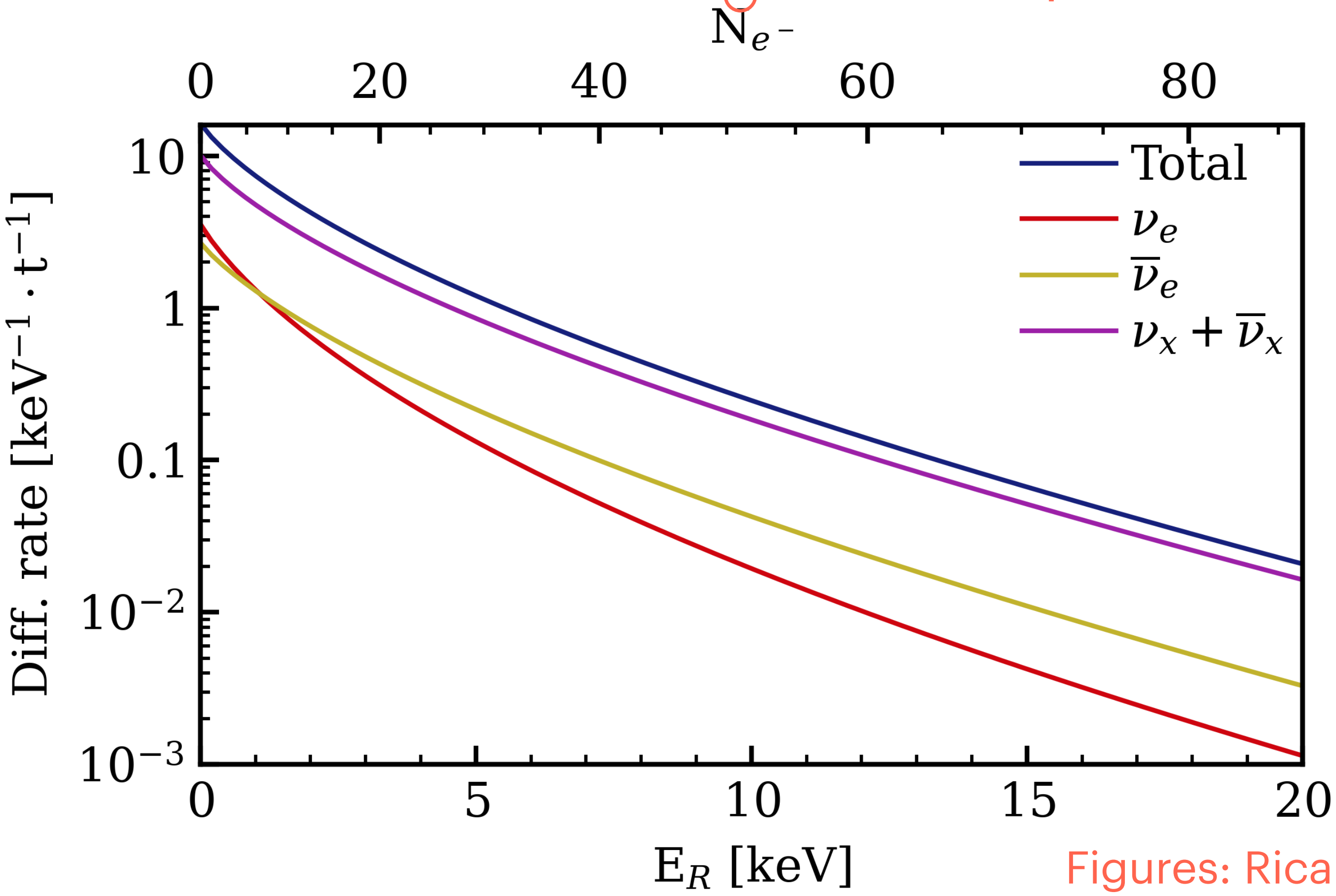
^{8}B flux constraints from SNO, XENON1T, PandaX-4T (2023) and XENONnT

SN ν-nucleus scattering

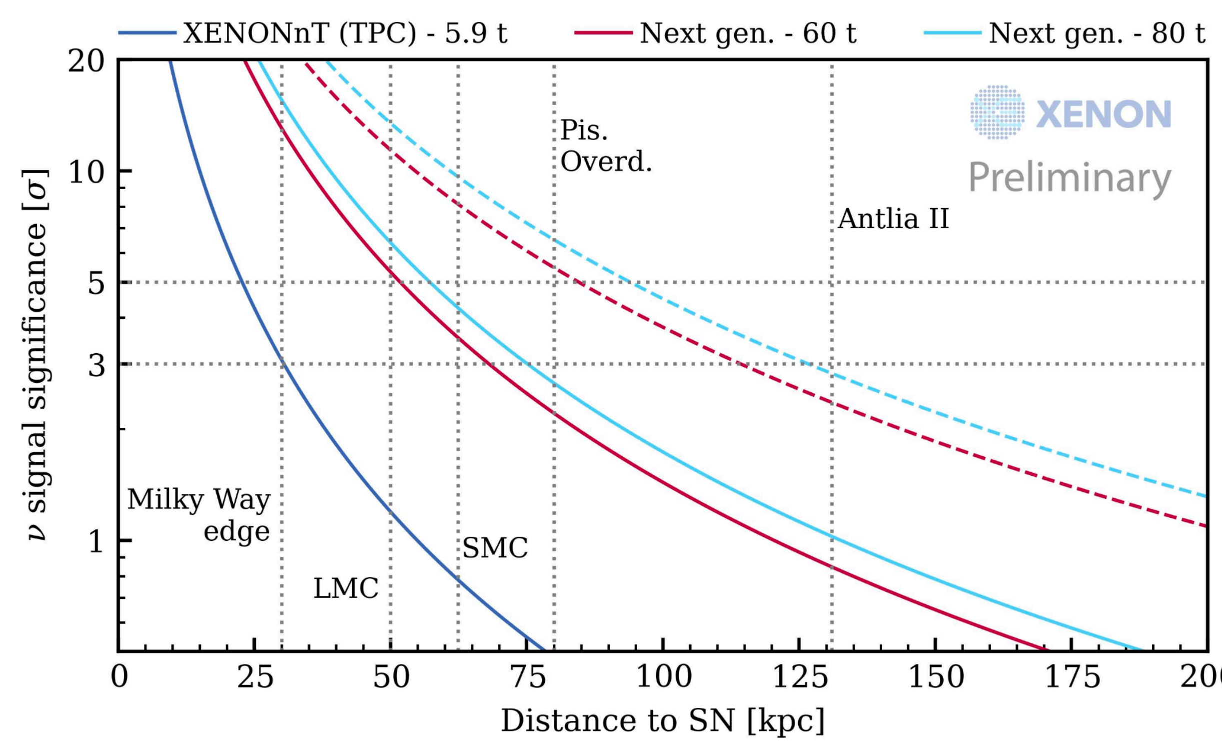


- Sensitivity to all ν flavours: few events/ton expected from SN at ~10 kpc
- Main challenge: low energies, understand few-e⁻ backgrounds
- **XLZD:** sensitivity beyond SMC; part of SNEWS2.0

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



XENONnT/LZ and XLZD



Figures: Ricardo Peres, UZH

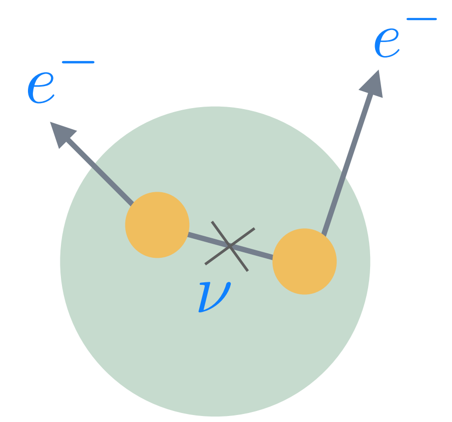
Conclusions & Outlook

- Liquid xenon detectors: at the forefront of direct DM searches
- LZ and XENONnT: continue to take data towards design exposures
- 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
- Test WIMP paradigm into the neutrino fog (& other DM candidates)
- Search for 0νββ-decay in ^{136}Xe, address inverted ordering scenario
- Observe solar and SN neutrino, other second order weak decays

Thank you

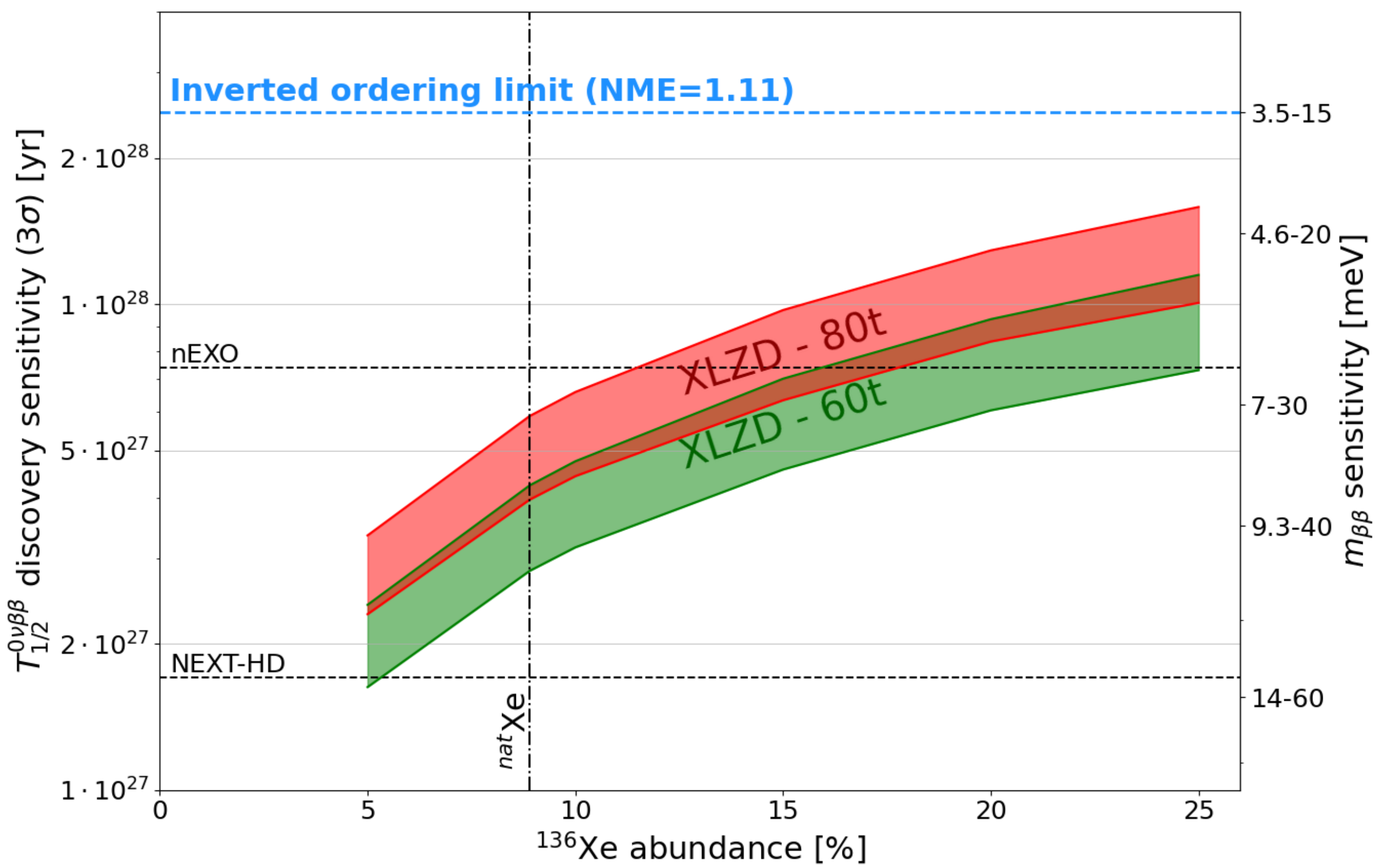
Additional material

$0\nu\beta\beta$ decay of ^{136}Xe



- Competitive sensitivity to dedicated experiments
- Assumptions: 0.1 μBq/kg ^{222}Rn, materials radiopurity already identified

XLZD preliminary



Discovery sensitivity as a function of ^{136}Xe abundance

The XLZD @ Boulby programme

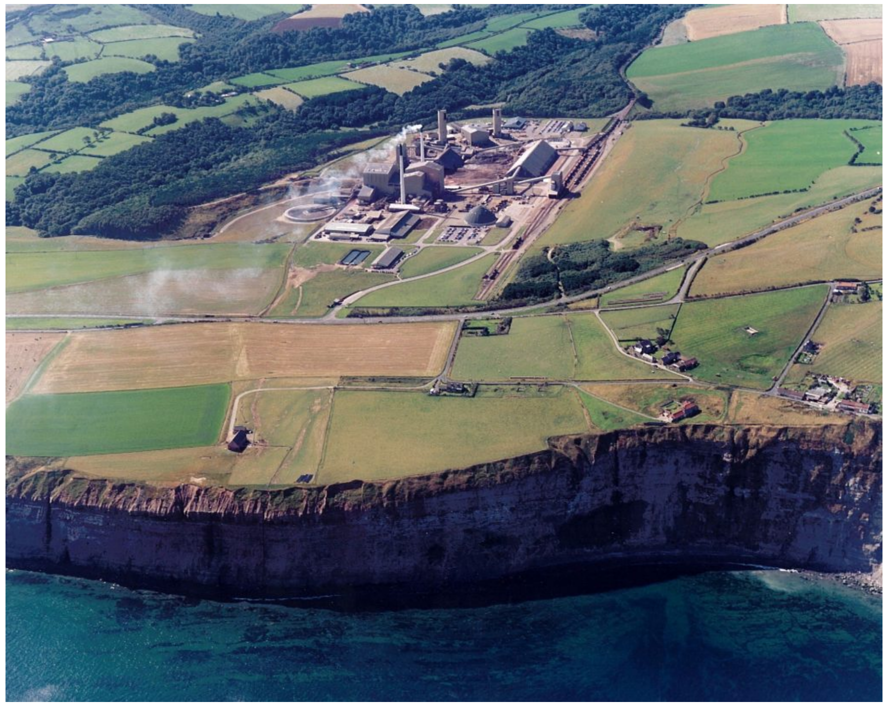
UK team proposing to host XLZD in a major new underground laboratory at Boulby.

Nominal infrastructure plan entails a Stage 1 facility at 1,100 m depth by 2028 (XLZD manufacture) and a larger Stage 2 facility at 1,300 m depth by 2030 (XLZD installation).

XLZD@Boulby Pre-Construction project just approved (£8.7M) by UKRI Infrastructure Fund

i) **Develop the Conceptual Design of the UK scope by 2025**, including determination that the selected options meet the needs and definition of the outline costing for the Full Project. Key outputs include a Conceptual Design Report and Review, draft procurement plans for hardware systems, and delivery plans for non-hardware packages.

ii) **To develop the Preliminary Design of the UK scope by 2027,** to define the baseline scope, cost and schedule, including procurement plans for the main hardware deliverables, and associated development of a Business Case for the Full Project. Key outputs include a Technical Design Report and Review, final procurement plans and delivery plans.



UK pre-construction project

WP1 Xenon Acquisition: Prepare UK xenon acquisition (inc. advanced procurement), design of storage & feed equipment.

WP2 Outer Detector: Design and prototyping of Gd-WBLS system (~1 ktonne) with BUTTON, BNL and other international partners, including optical and mechanical designs of inner and outer volumes, design of fluid handling and purification systems and hazard analysis, PMT readout structures, front-end electronics and OD calibration. Gd-W option with international partners.

WP3 Cryostat: Design of nested pressure vessels made from radiopure material aiming at fabrication underground, including material/supplier identification and plans for manufacture/procurement, test/certification, transportation and installation.

WP4 Xenon Detector Elements: Mechanical, optical and electrostatic designs and prototyping of field-cage and Skin Detector surrounding LXe-TPC meeting the most demanding radioactivity and cleanliness requirements.

WP5 Data Centre & On-Site Computing: design of data pipeline and data centre with international partners; coordination of computing needed for the design phase (simulations, data challenges, data management) and software infrastructure.

WP6 Clean Manufacture: Design and prototyping of radioassay and cleanliness systems and processes, and of the clean manufacture systems and equipment that will compose the Stage 1 Manufacturing Facility at Boulby. Extensive radioassay campaign for selection of critical materials; background simulations.

WP7 Engineering and Skills: Provision of required engineering effort for design coordination (Lead Eng; Integration Eng; Safety Eng; CAD Designer); design of Stage 1 facility specialist outfitting for XLZD; development of apprenticeship scheme.

WP8 Environmental Sustainability: delivery plan for an experiment sustainable in operations; carbon modelling and accounting, development of digital twin, training for green computing and lab operations, design of heat recovery from data centre. Substantial work being led by Boulby Development Project in this area already.

DOE-HEP response to P5

Recommendation 1

- As the highest priority independent of the budget scenarios, **complete construction projects and support operations of ongoing experiments and research** to enable maximum science. We reaffirm the previous P5 called out these major existing projects:
  - **HL-LHC ATLAS, CMS, and Accelerator Upgrade Project**
  - The first phase of **DUNE and PIP-II**
  - The Vera C. Rubin Observatory to carry out the **Legacy Survey of Space and Time (LSST)**
- In addition, we recommend continued support for the following ongoing experiments at the medium scale including completion of construction, operations and research on:
  - NOvA, SBN, and T2K
    - elucidate the mysteries of neutrinos
  - DarkSide-20k, LZ, SuperCDMS, and XENONnT
    - determine the nature of dark matter
  - DESI
    - understand what drives cosmic evolution
  - Belle II, LHCb, and Mu2e
    - pursue quantum imprints of new phenomena

M. Procario, HEP DOE office, May 13, 2024

DOE-HEP response to P5

Recommendation 2

In priority order

- Construct a portfolio of new major projects
  - **CMB-S4,** which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals.
  - **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam (**ACE-MIRT**), a **third far detector**, and an **upgraded near-detector complex** as the definitive long-baseline neutrino oscillation experiment of its kind.
  - An **off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of **FCC-ee and ILC meet our scientific requirements**. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics.
  - An **ultimate Generation 3 (G3) dark matter** direct detection experiment reaching the neutrino fog, in coordination with international partners and **preferably sited in the US**.
  - **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool.

M. Procario, HEP DOE office, May 13, 2024

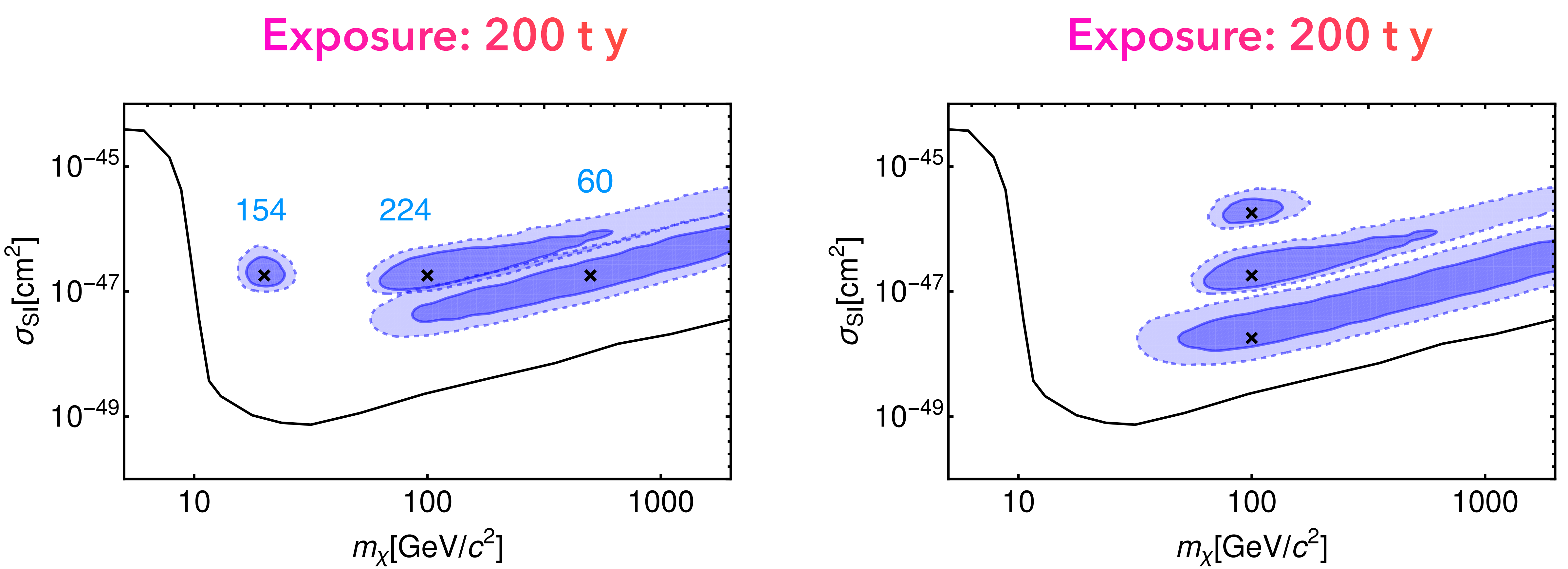
DOE-HEP response to P5

G3 Dark Matter

- From P5 Recommendation 2, Priority 4 out of 5 :
  - An **ultimate Generation 3 (G3) dark matter** direct detection experiment reaching the neutrino fog, in coordination with international partners and **preferably sited in the US**.
- DOE response and actions:
  - At the present time, based on the Snowmass Community Summer Study, there have been two proposals for G3 Dark Matter detectors : XLZD and ARGO
  - P5 recommended a **domestic site for the experiment in the higher funding scenario** and an international site in the lower funding scenario.
  - Start with site independent R&D as we understand the funding that will be available.
    - Engage with partners who are interested in hosting.
  - DOE will entertain proposals by U.S. groups for pre-project R&D.

WIMPs

- Capability to reconstruct the WIMP mass and cross section for various masses - here 20, 100, 500 GeV/c^2 - and cross sections



Newstead et al., PRD D 88, 076011 (2013)

1 and 2 sigma credible regions after marginalising the posterior probability distribution over:

$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

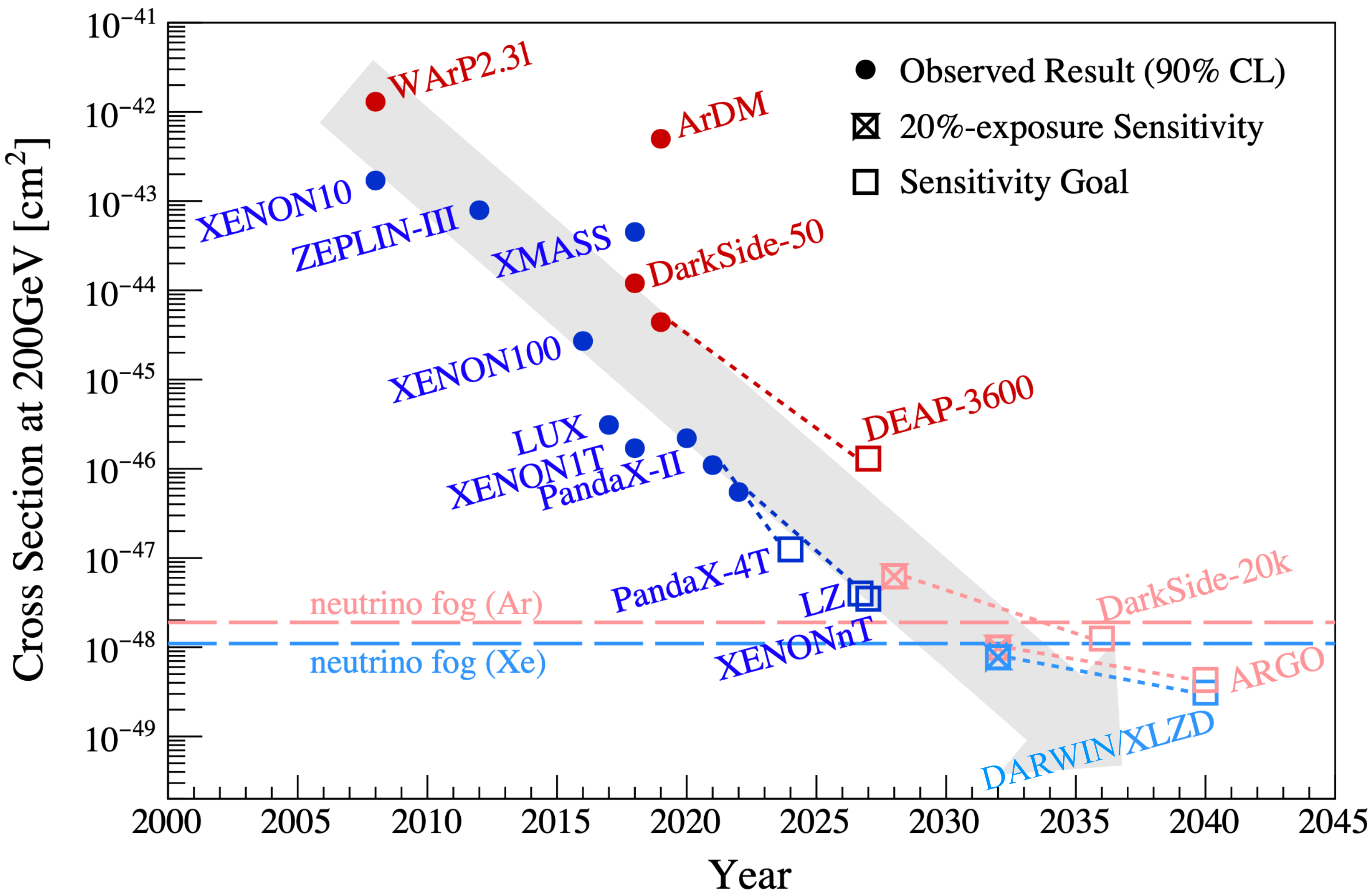
$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

36

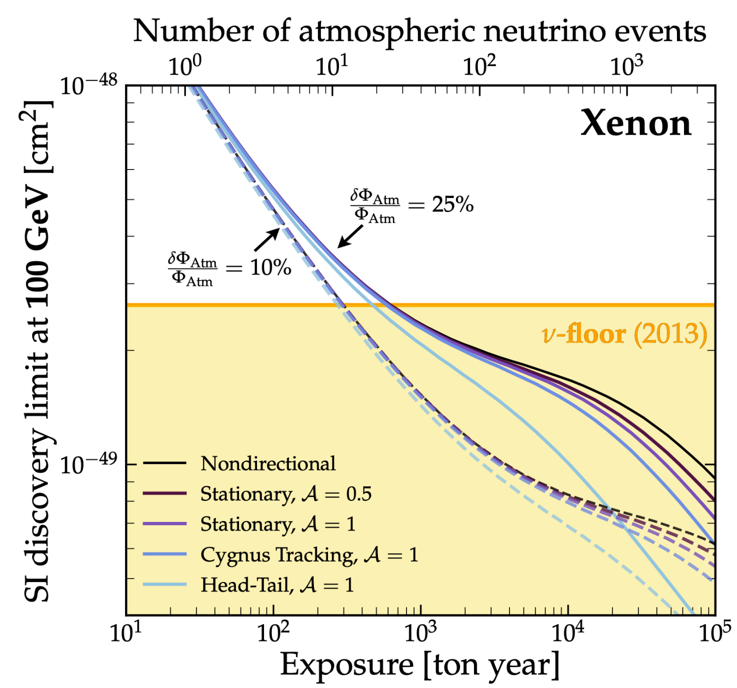
Approaching the neutrino fog

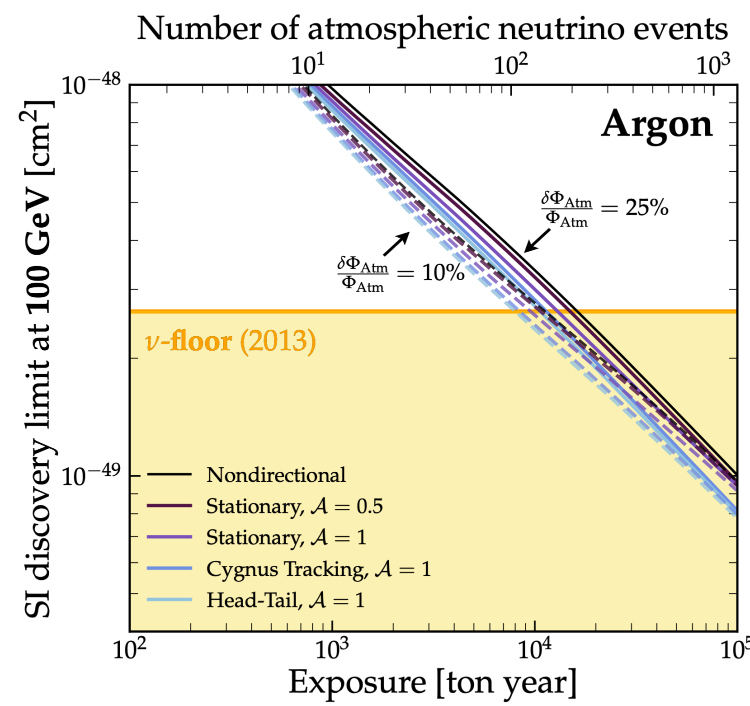
- Current & future noble liquid experiments



Snowmass, Topical Group on Particle Dark Matter Report, 2209.07426:
"A critical feature of the neutrino fog is that it will move to lower cross section if uncertainties in the neutrino fluxes are reduced, opening up new space for continuing searches."

100 GeV WIMP discovery limits

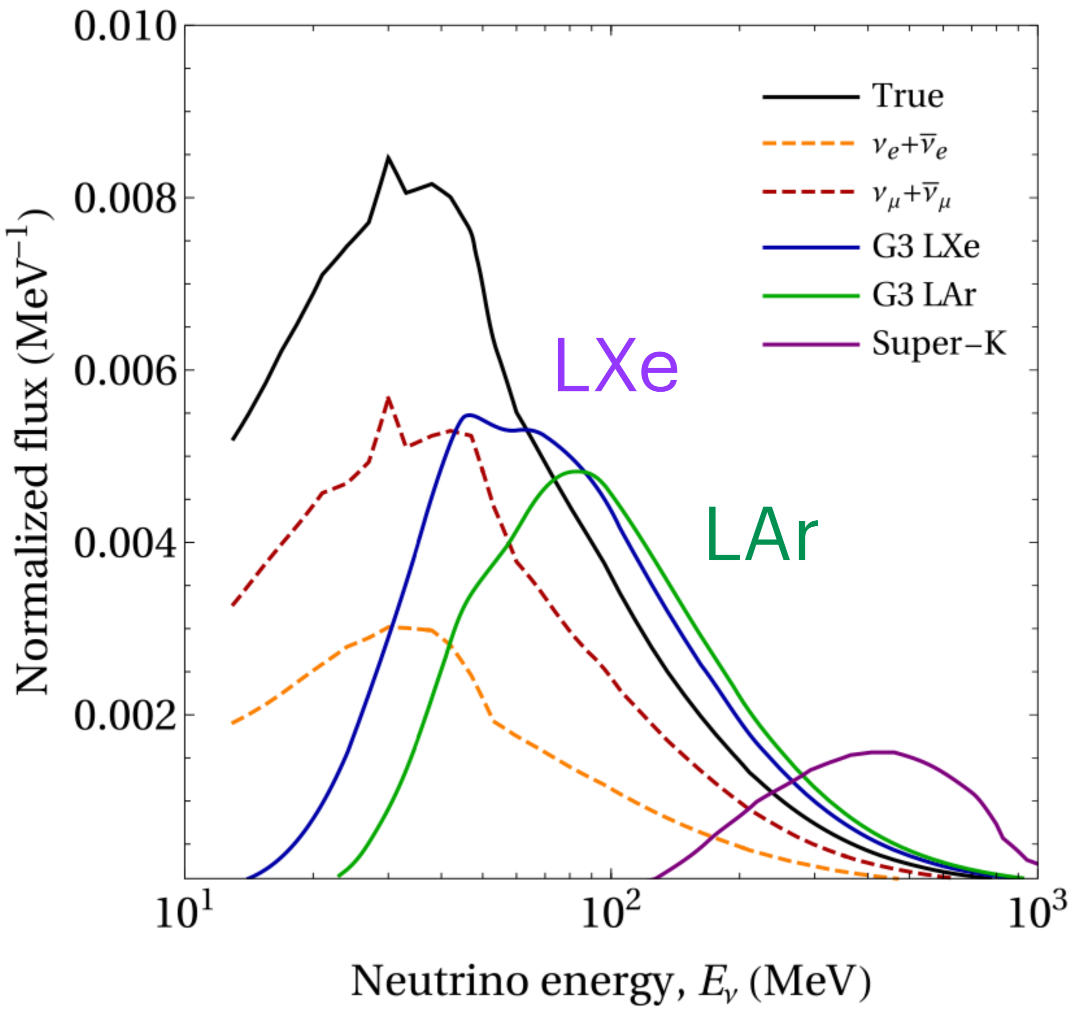


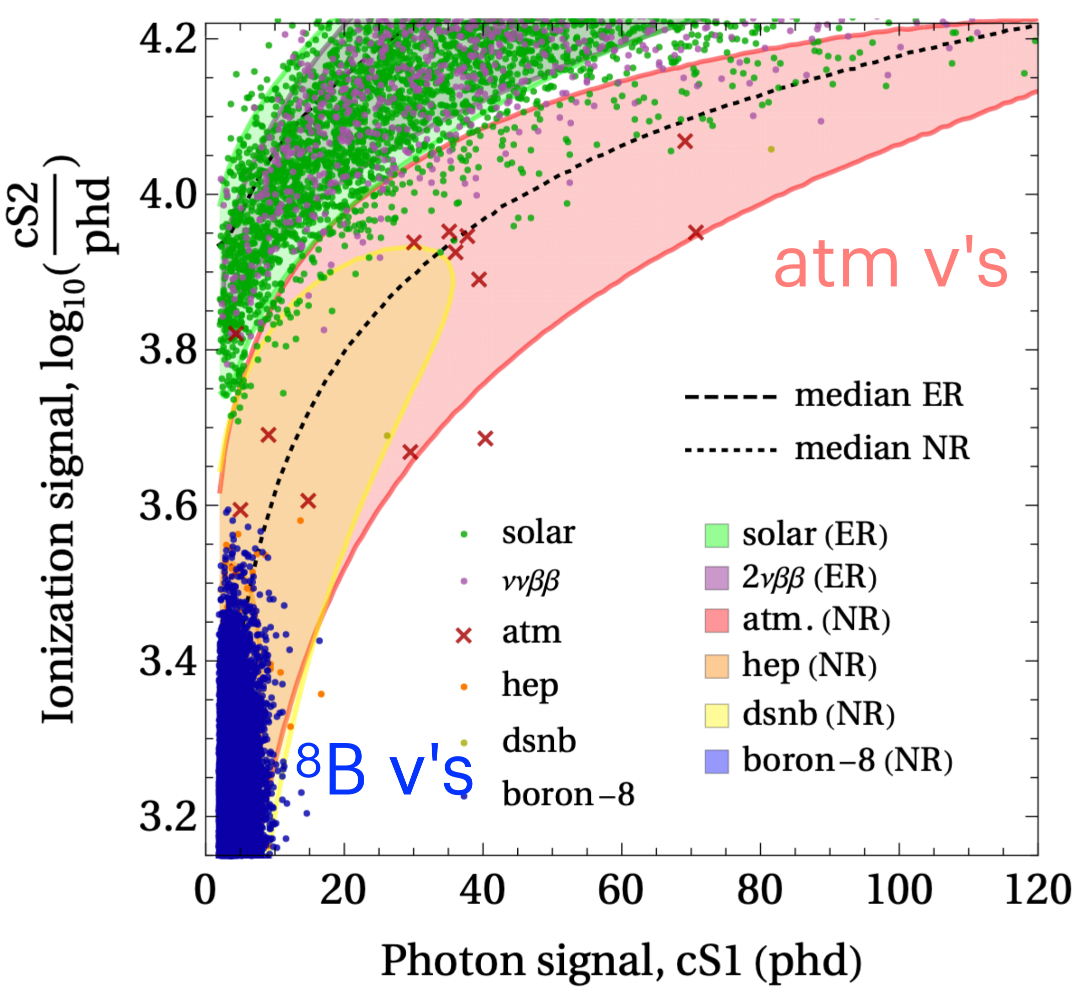


C. O'Hare, PRD 102, 2020

Atmospheric neutrinos

- In general, exposures > few 100 t y are needed for 5-σ detection



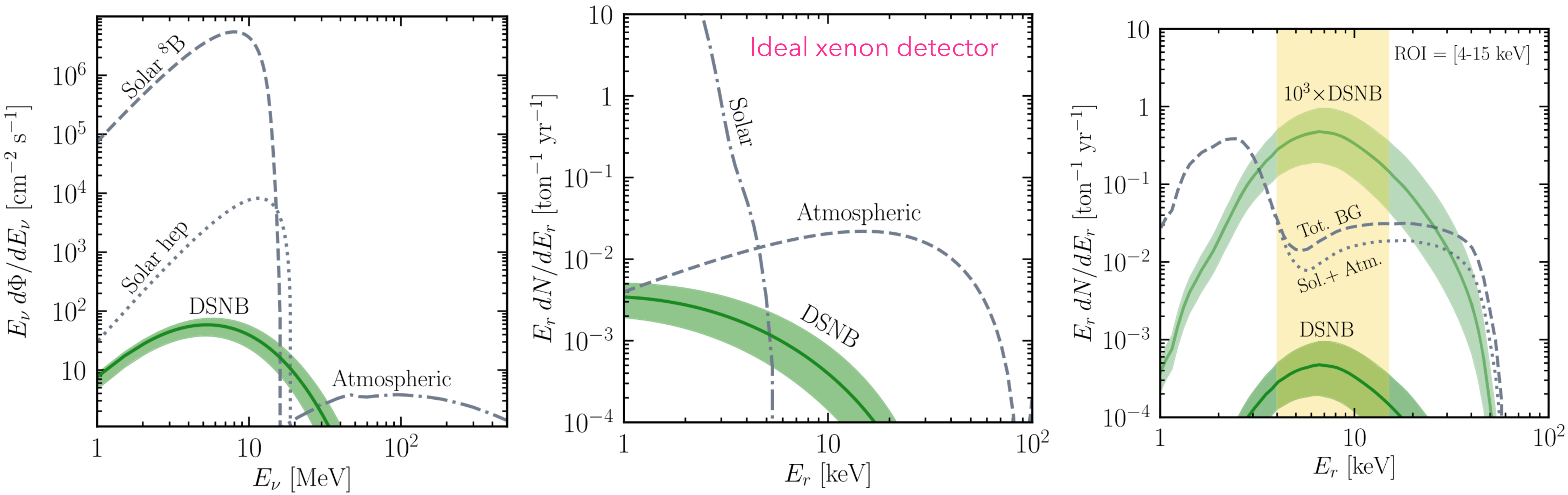


Newstead, Lang, Strigari, PRD 104, 2021

DSNB with CEvNS

- Understanding of core-collapse SN depends on probing DSNB with all flavours
- So far, only upper limits in ν_e and $\bar{\nu}_e$ flux by SNO and SuperK (19 $cm^{-2}s^{-1}$, 2.7 $cm^{-2}s^{-1}$), limits on in $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ fluxes much weaker (per flavour, ~10^3 $cm^{-2}s^{-1}$), XLZD could probe these down to ~ 10 $cm^{-2}s^{-1}$ or better, depending on fiducial mass

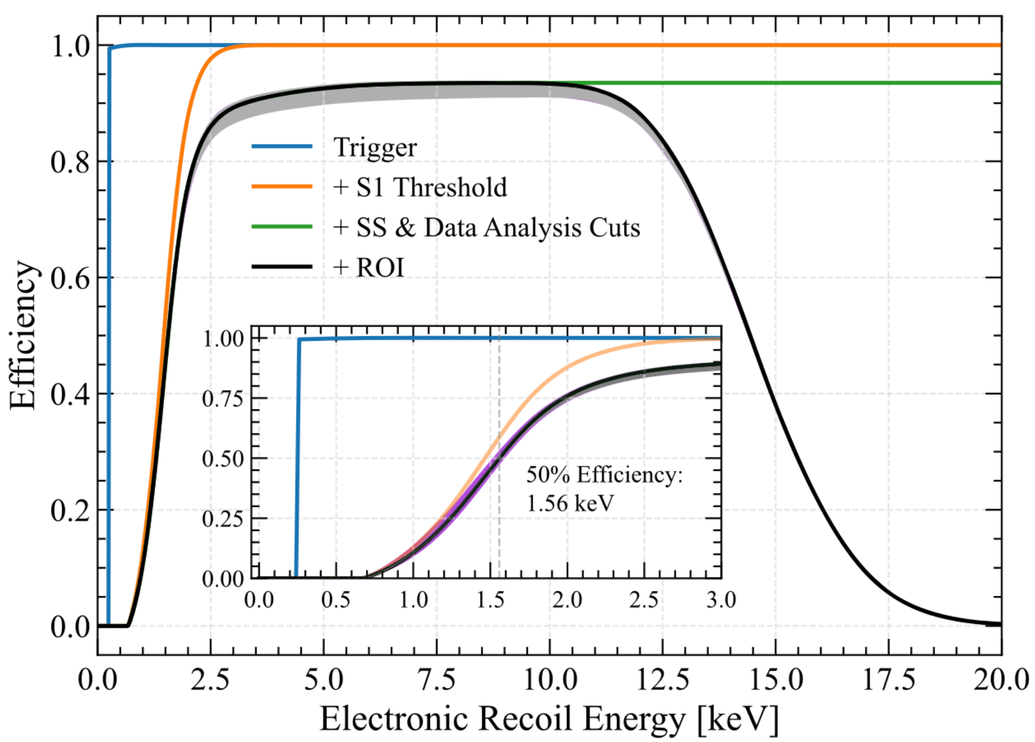
Suliga, Beacom, Tambora, PRD 105, 2022



Energy thresholds in Xe TPCs

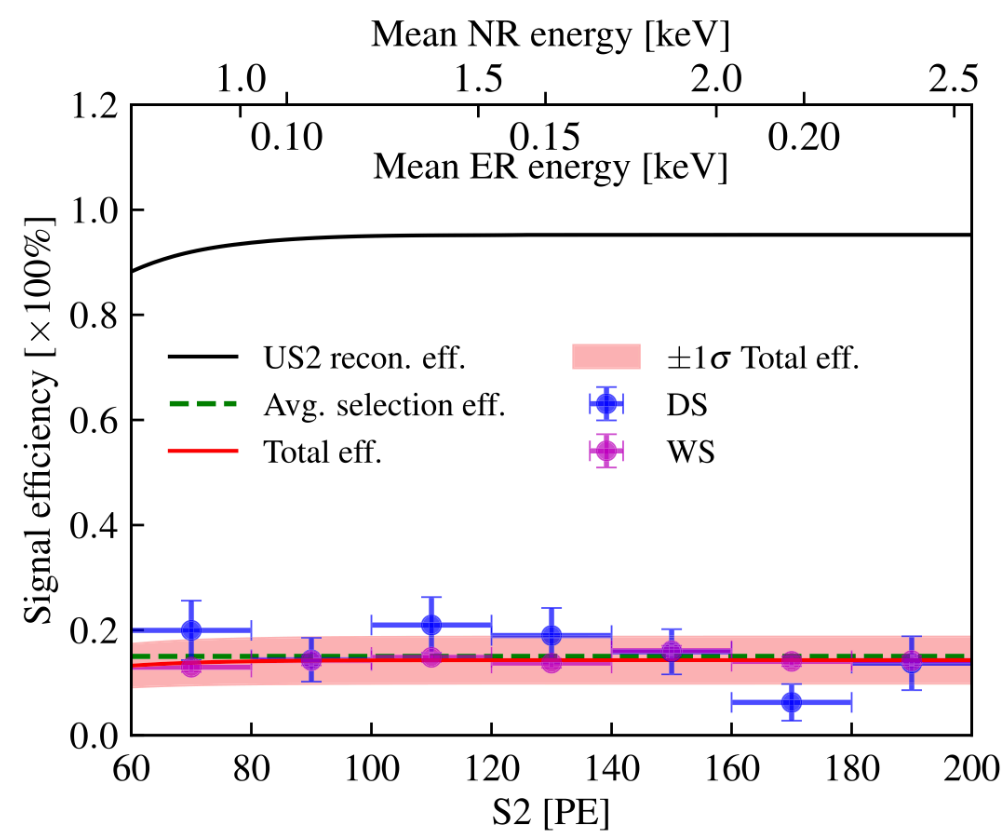
- S1 + S2: ~ 1 keV with 3-fold coincidence (ER) (hits in ≥ 3 PMTs within ~50-100 ns); lower threshold (< 1 keV) with 2-fold coincidence (with lower signal efficiency)
- S2-only: ~ 0.2 keV, with 5 e⁻ - 100 e⁻ detected (probe ER and NR interactions), down to W-value, with 1 e⁻ - 5 e⁻ signal (mostly probe 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

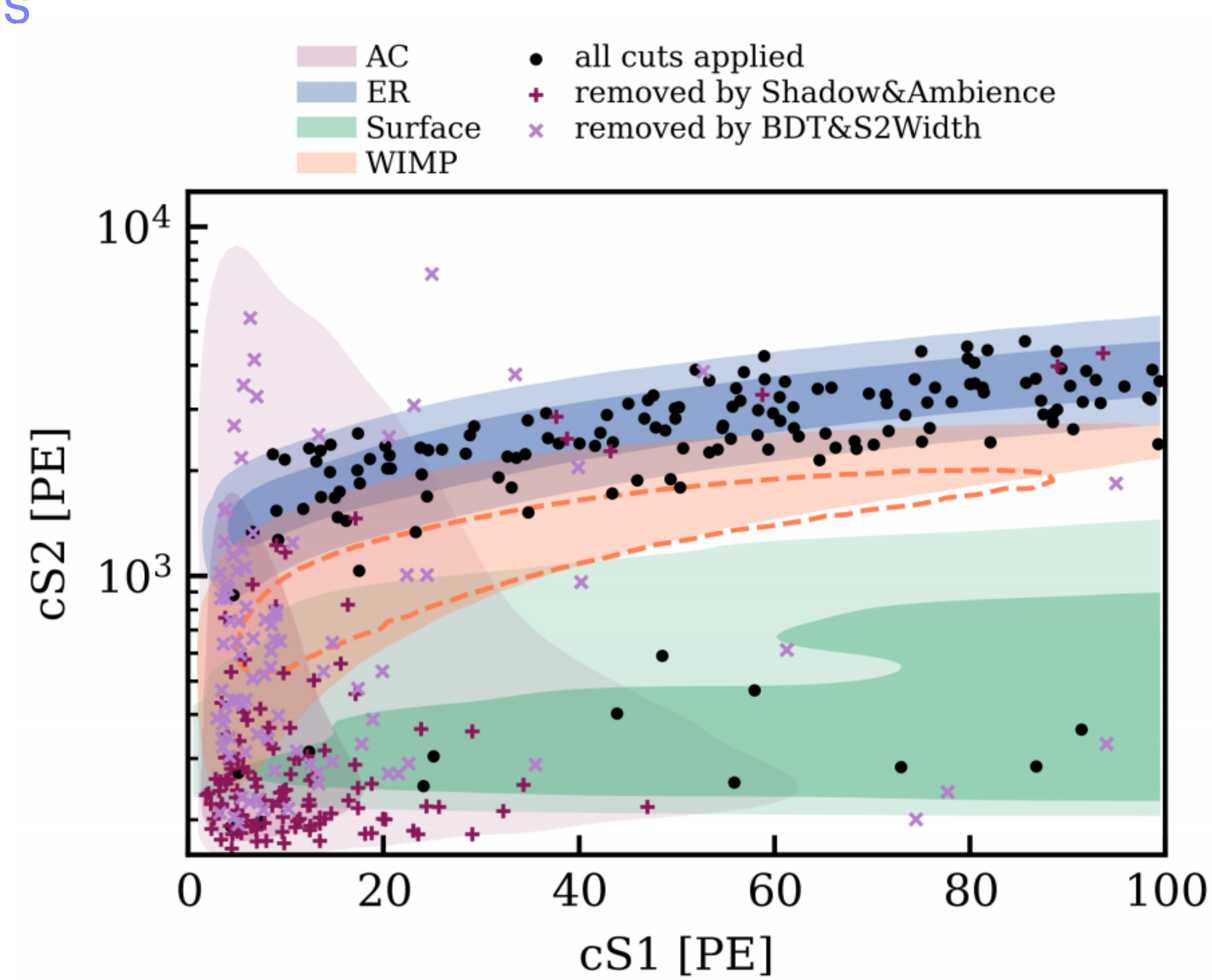
PandaX-4T, PRL 130, 2023



AC backgrounds in TPCs

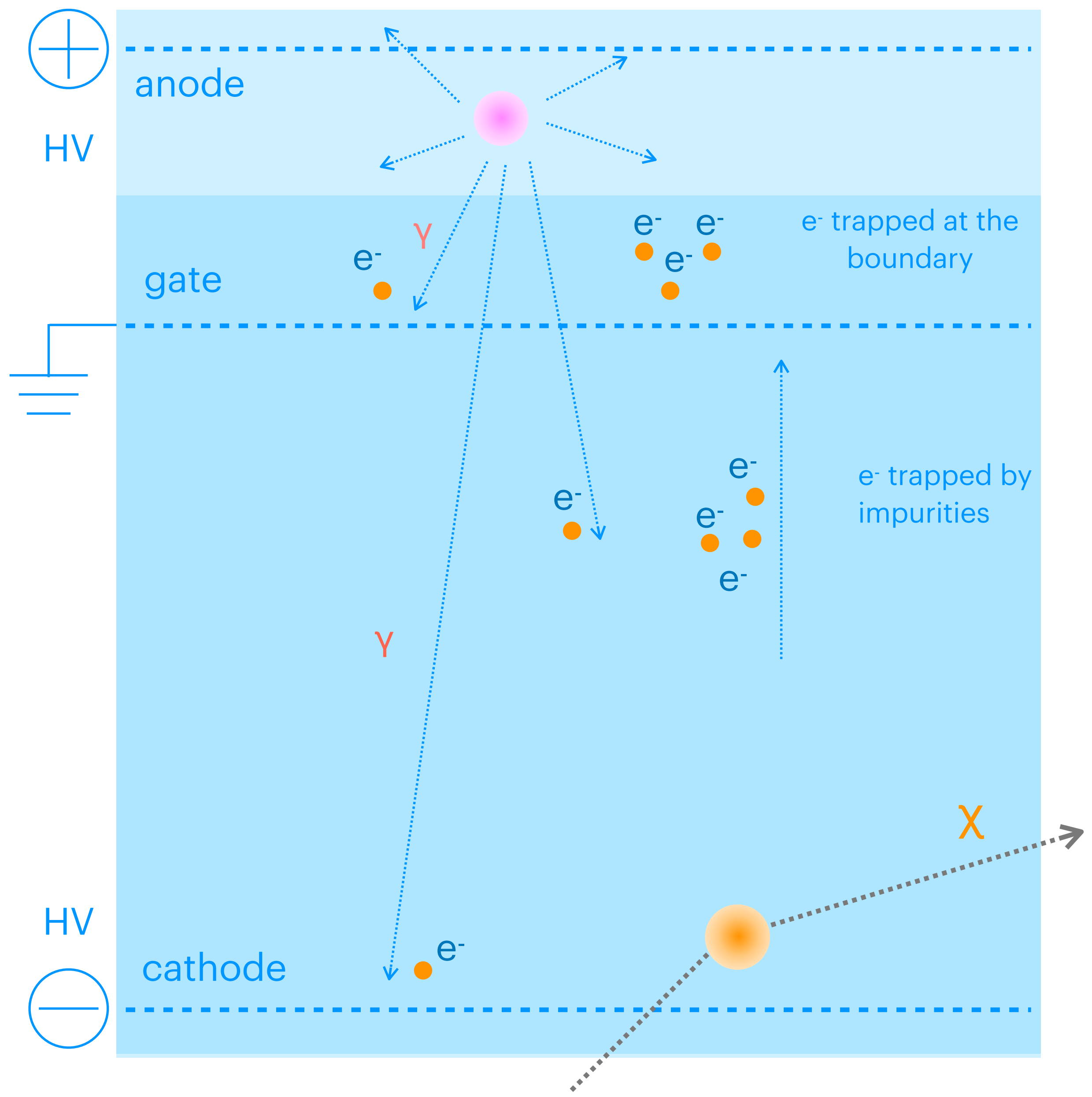
- Combinatorial background at low energies can be significant
- Main sources for isolated S1 and isolated S2 signals
  - Primary scintillation (S1s)
    - Dark counts (pile-up) ∝ nr. channels
    - Charge-insensitive regions
    - Delayed photons
  - Electroluminiscence (S2s)
    - Bulk xenon S2-only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

Example from XENONnT



Ionisation only backgrounds

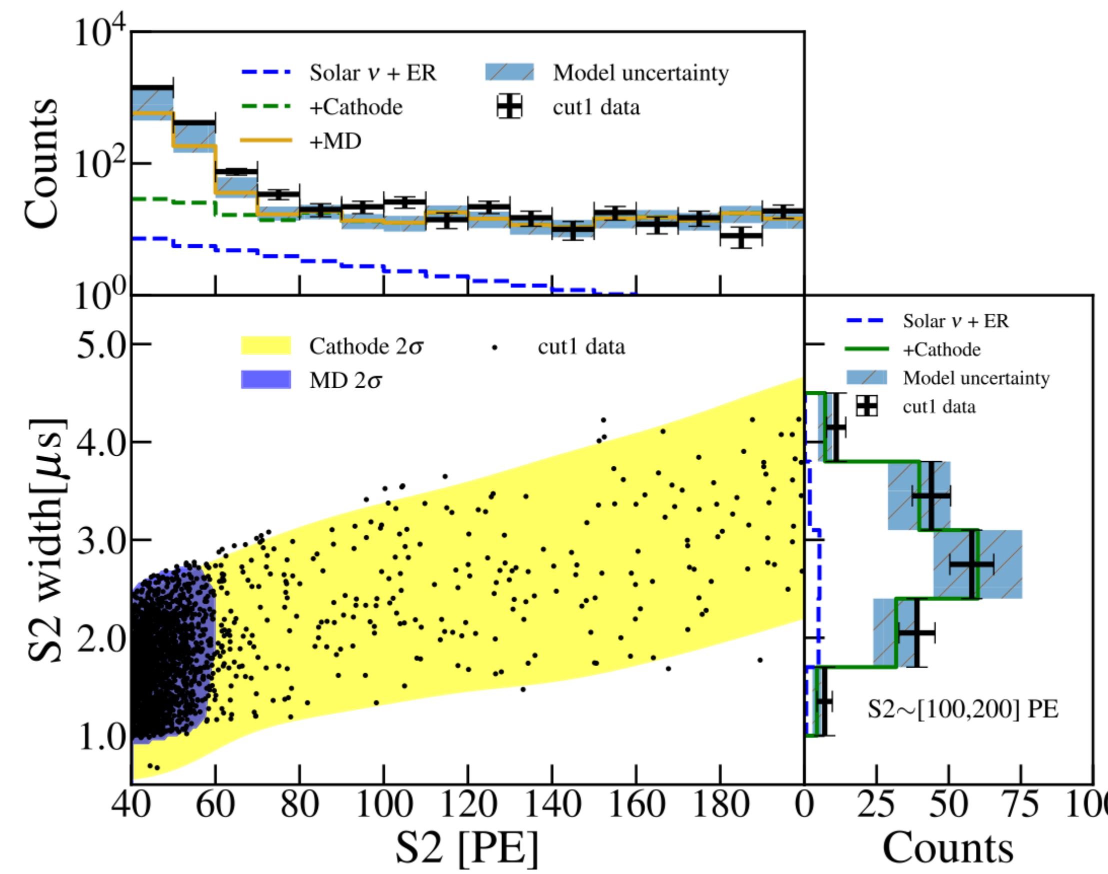
- Radioactivity
- Solar neutrinos
- Instrumental
  - Spurious emission of single and few electrons from the cathode
  - Delayed e- after large S2 signals: trapped e- at the liquid/gas interface; e- emitted from impurities, etc
- Important to understand & mitigate origin, develop background models



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