University of Zurich[UZH]

XENON

DARWIN

DARWIN/XLZD: a future xenon observatory for dark matter and other rare interactions

Nobel Symposium on Dark Matter

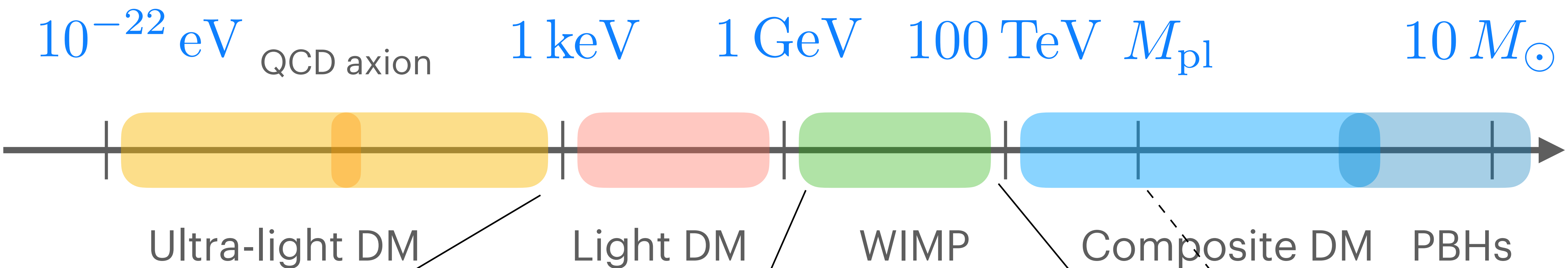
Laura Baudis, University of Zurich

August 25, 2023

European Research Council

Established by the European Commission

Dark matter mass parameter space

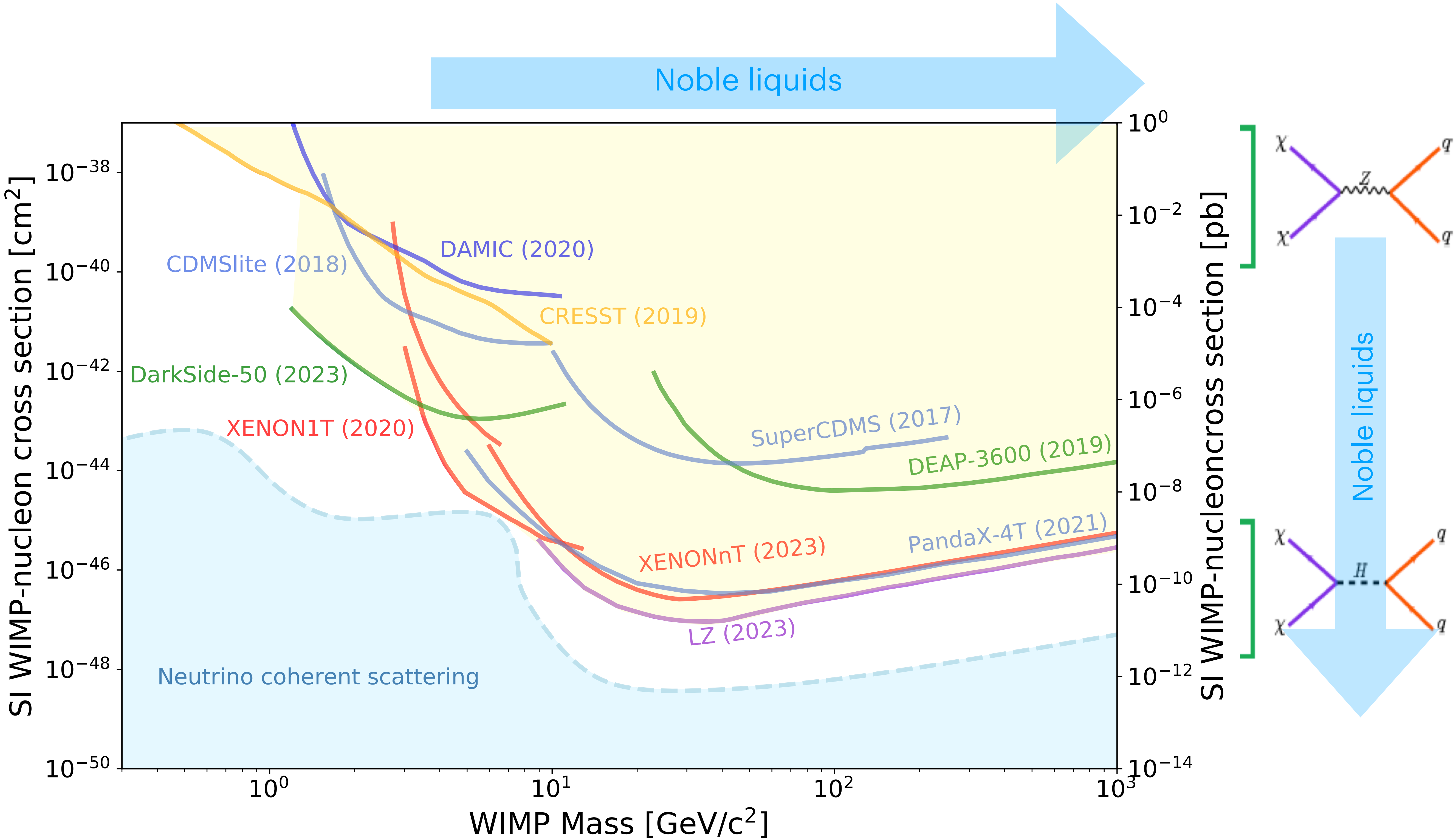


Noble liquids:
- Migdal effect
- Scatters with e⁻ *(interaction with SM though new mediator)*
- Absorption *(bosonic DM with direct coupling to SM particles)*

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

Noble liquids:
- Multiple scatters with nuclei

Direct detection landscape in 2023



LB and Stefano Profumo, PDG 2023

A brief reminder that Nature does not relinquish her secrets easily...
...and that an experiment worth doing has rarely been done before
- we are literally mapping out new territory

Liquid xenon detectors

- 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)

Limits for a 50 GeV WIMP

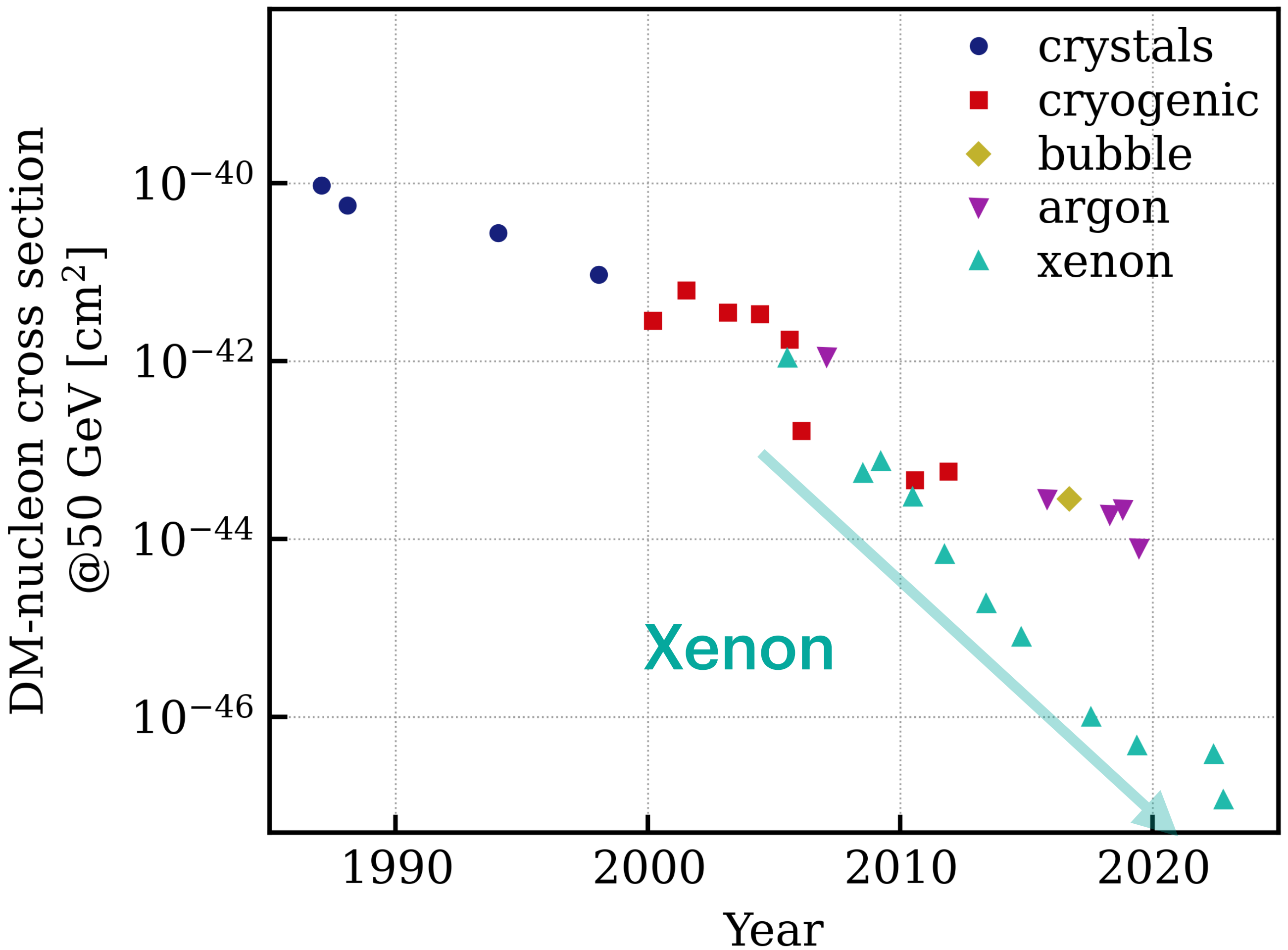
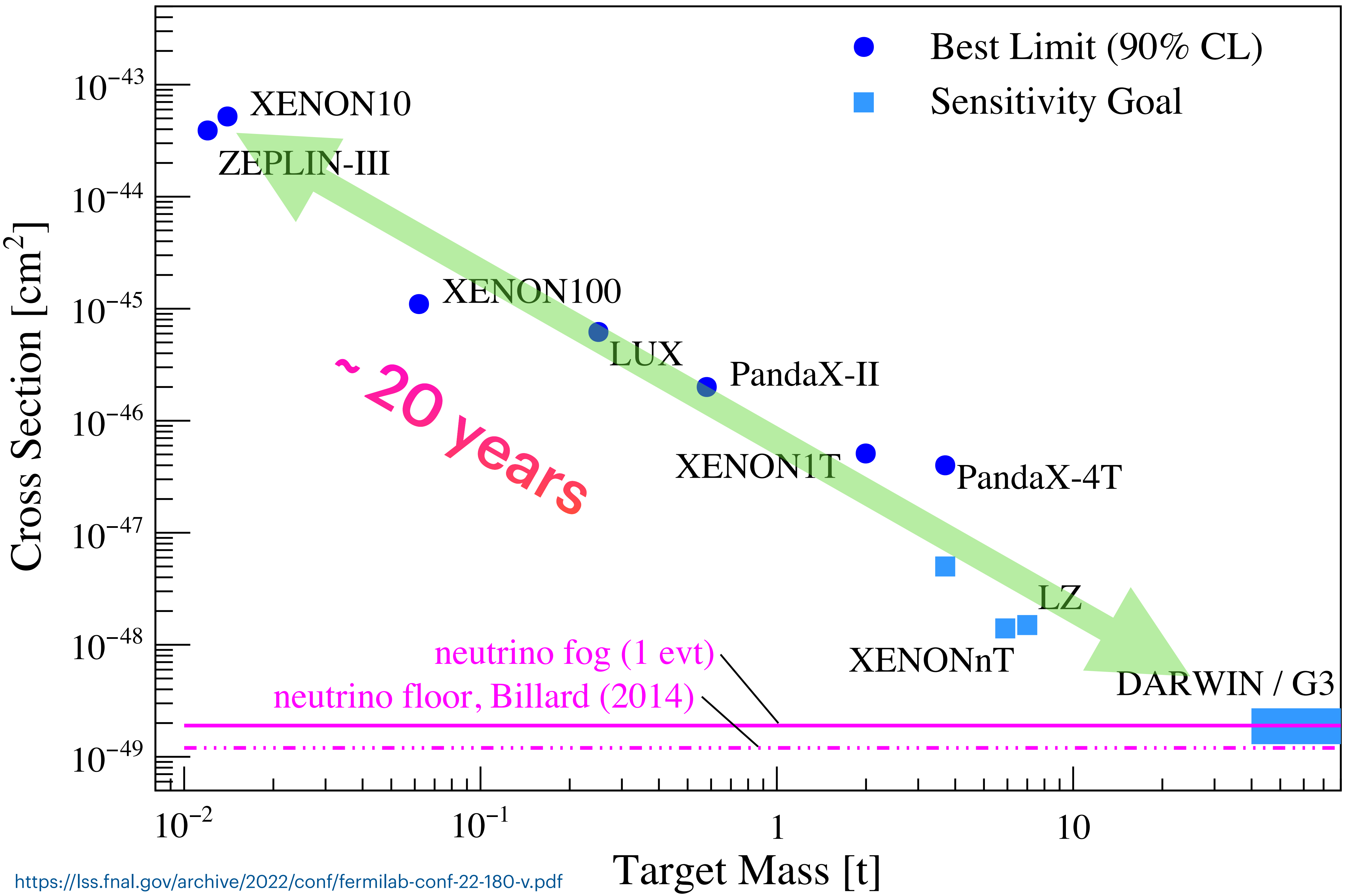


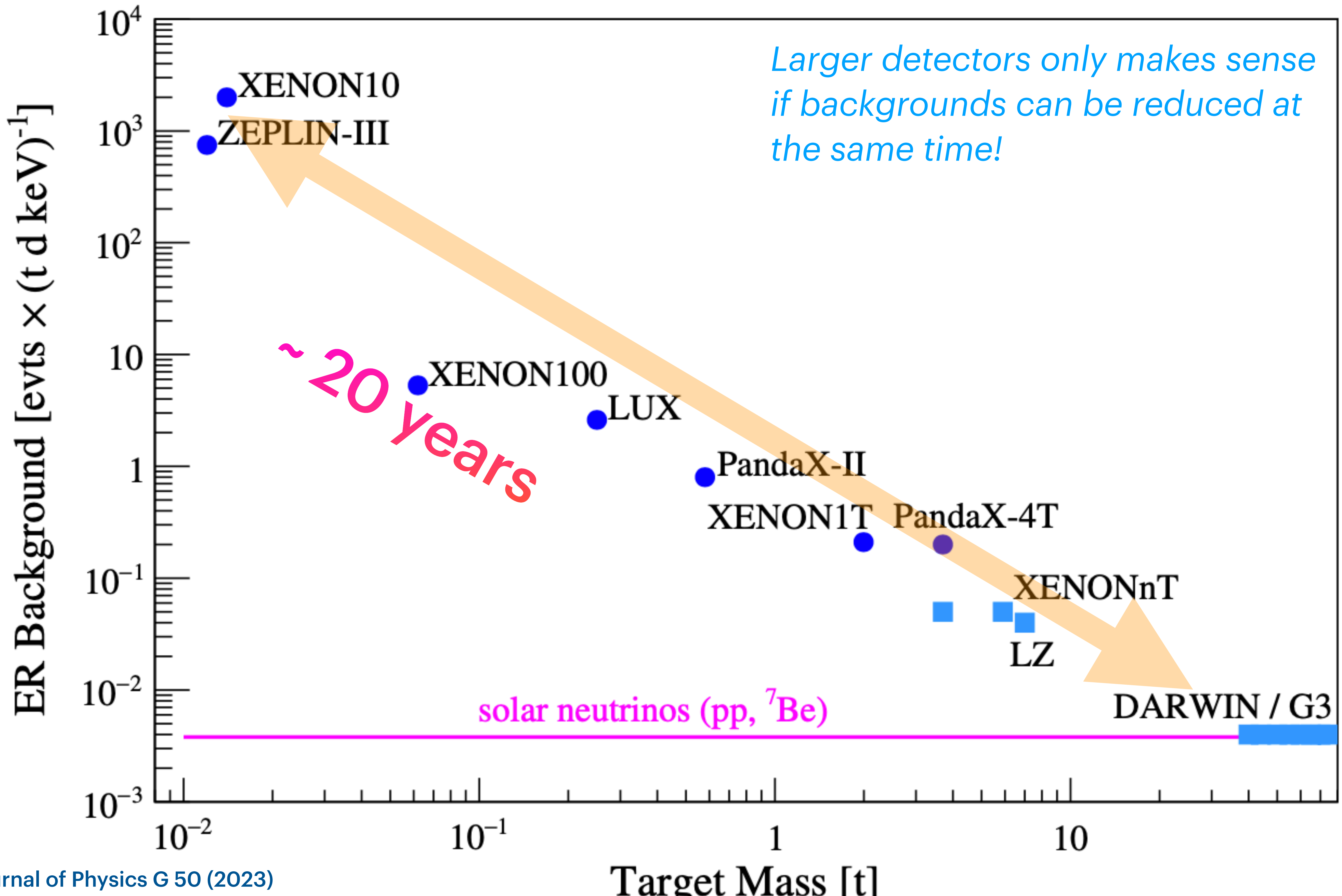
Figure after Tom Shutt, SLAC

Cross section versus mass



https://lss.fnal.gov/archive/2022/conf/fermilab-conf-22-180-v.pdf

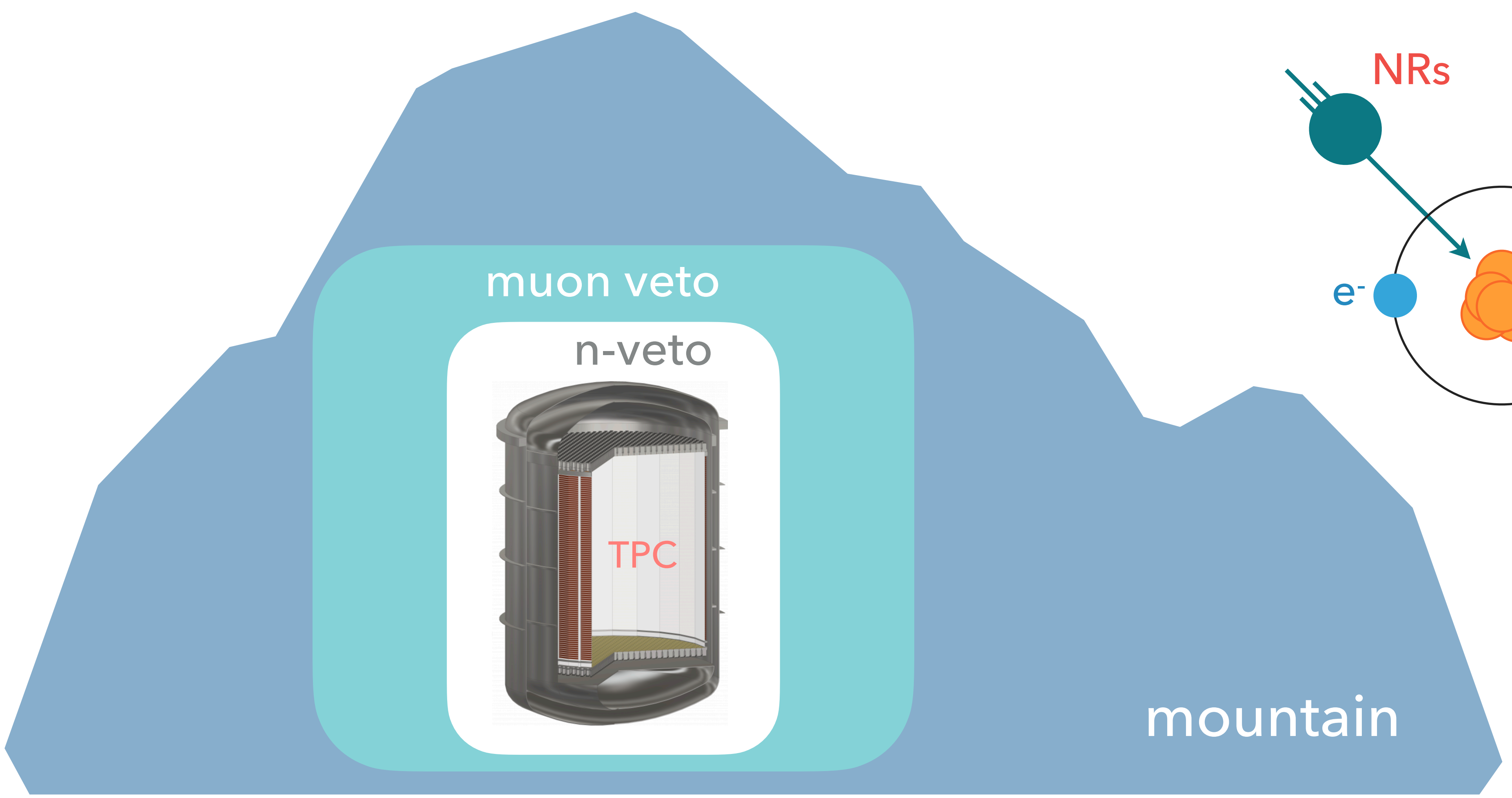
Backgrounds versus mass

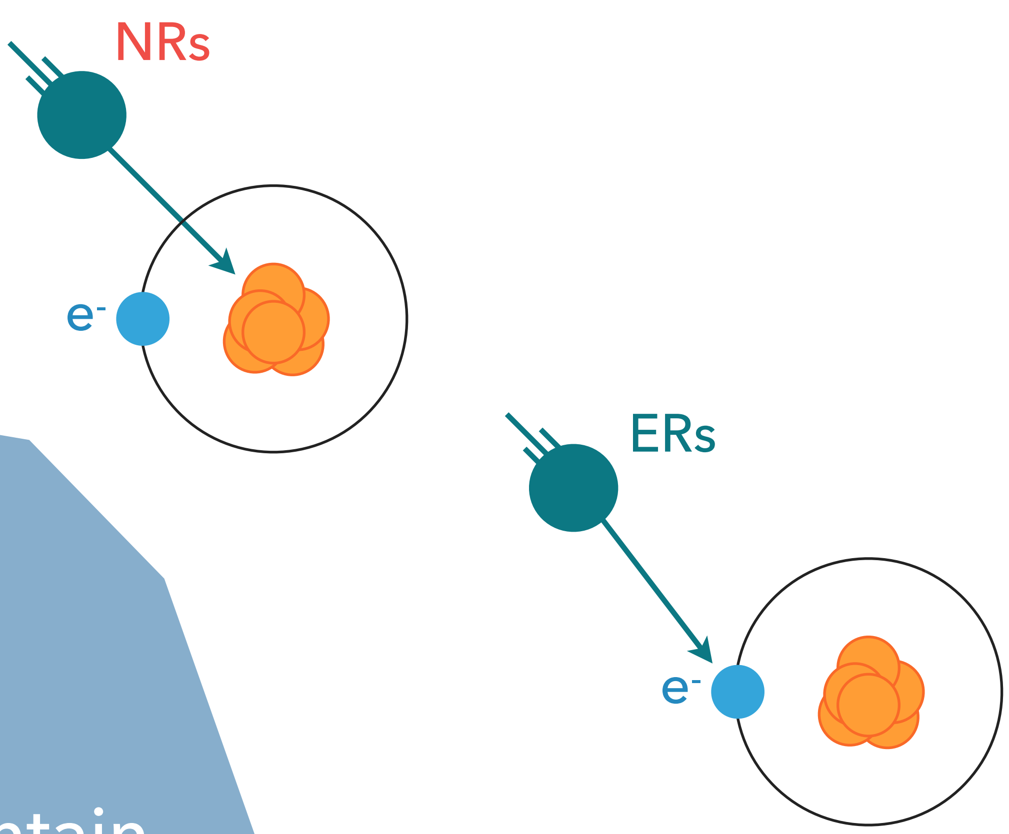


Journal of Physics G 50 (2023)

Background goals and sources

- Main goal: quasi "background-free" exposure of **200 t y** for dark matter search
- ER and NR backgrounds: to be limited by *neutrino-induced* events
  - NRs: cosmogenic, radiogenic neutrons & neutrinos
  - ERs: intrinsic (^{222}Rn, ^{85}Kr, ^{136}Xe, ^{124}Xe), materials & neutrinos





Towards the neutrino fog

- In summary: detectors must become **even larger, even quieter…**

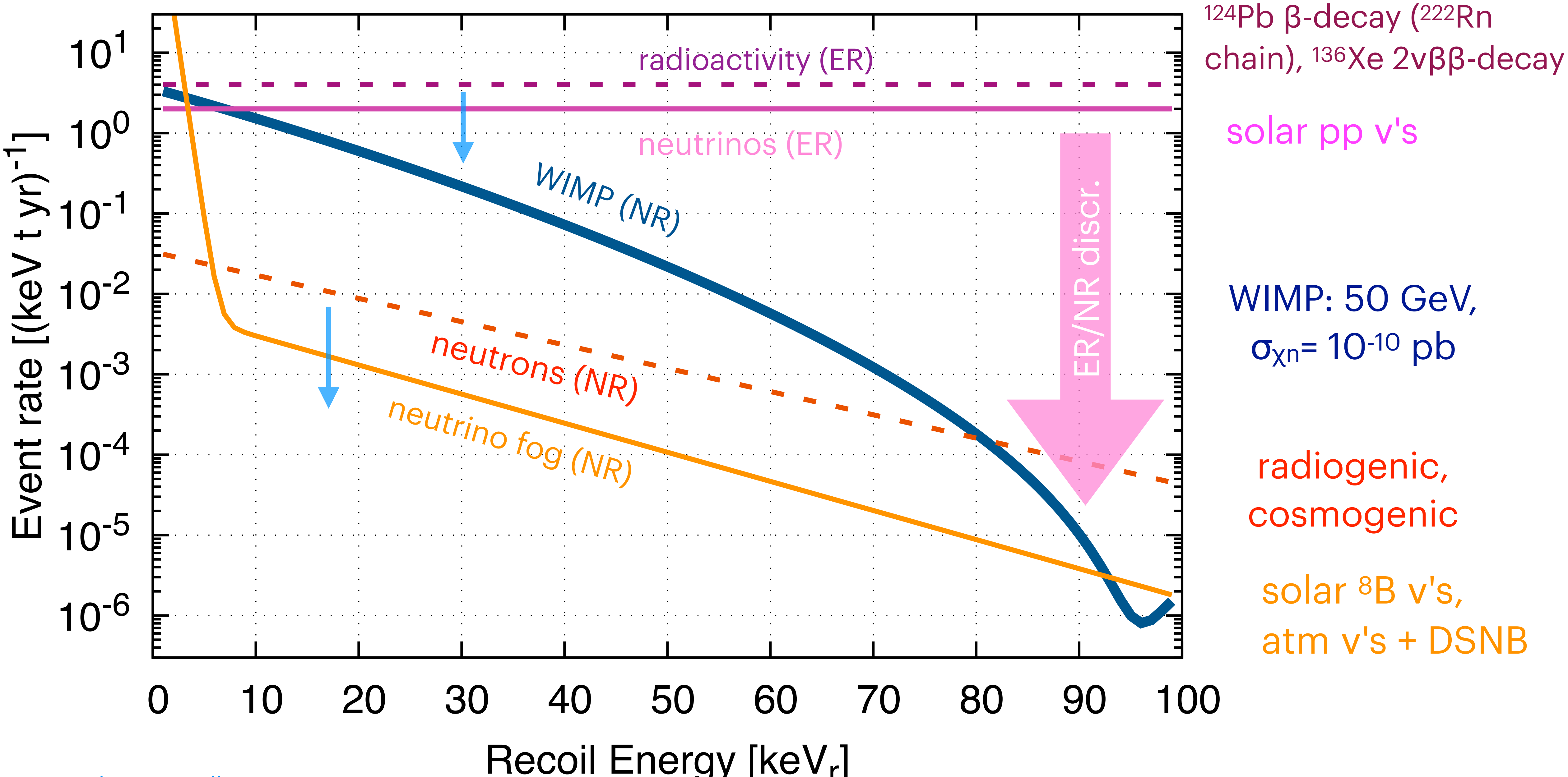
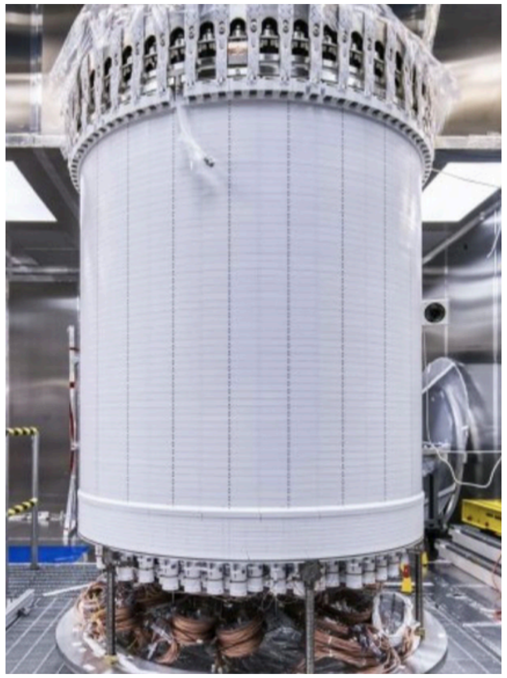


Figure by Tina Pollmann

Current liquid xenon detectors

- LZ at SURF, PandaX-4T at JinPing, XENONnT at LNGS
- Detector scales: 10 t (LZ), 6 t (PandaX-4T) and 8.6 t LXe (XENONnT) in total xenon mass
    - 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
- Status: PandaX-4T first result in 2021 from commissioning run, LZ first results from 2022 run, XENONnT first results from SR0 in 2021/22

LUX-ZEPLIN

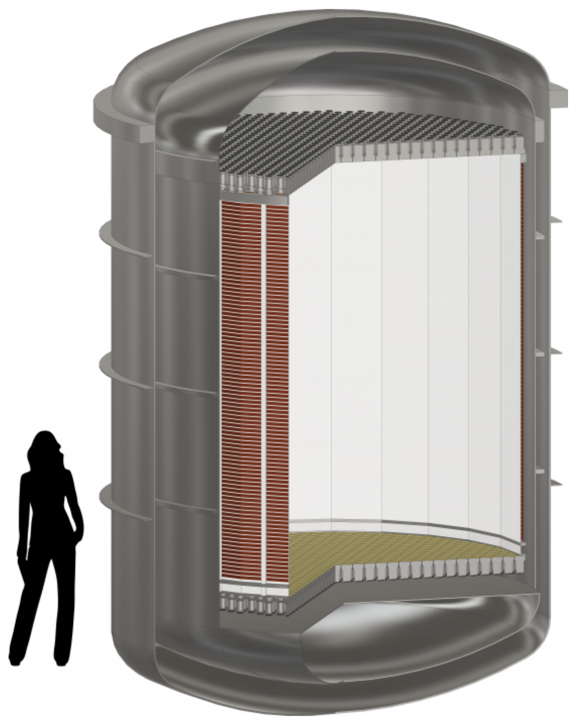


XENONnT

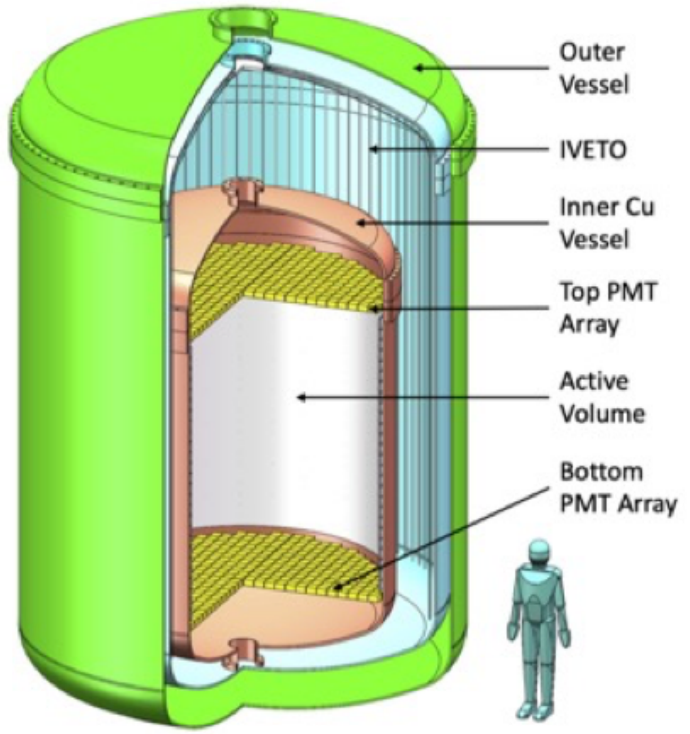
PandaX-4T

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
- PandaX-xT at CJPL
  - >30 t active volume at CJPL; 2 arrays of 2-inch $\times$ 2-inch flat panel PMTs; Cu inner vessel, active shield between inner and outer cryostat

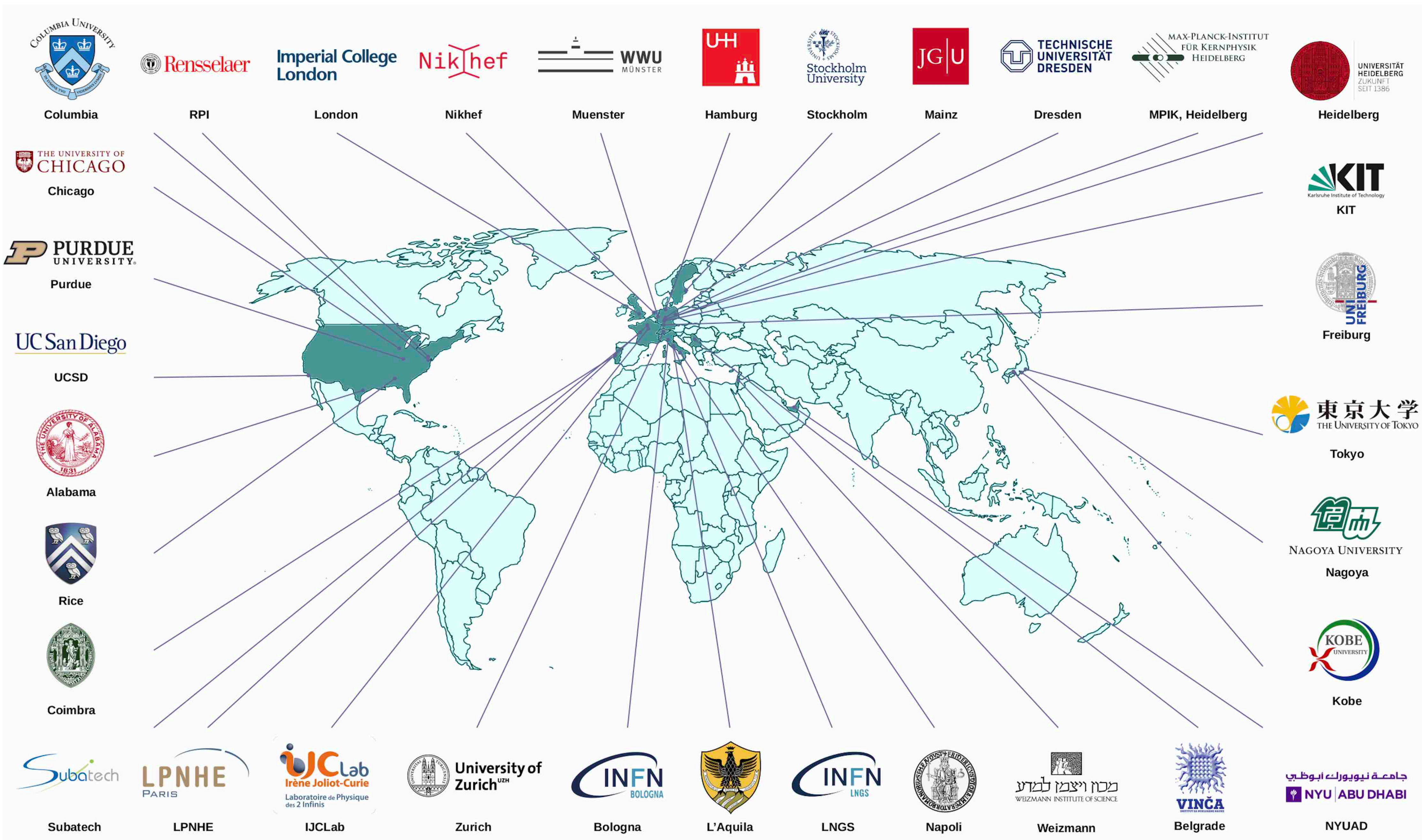


DARWIN collaboration
JCAP 1611 (2016) 017



DARWIN Collaboration

- 200 members from 35 institutions in Europe, USA, Asia, Australia



The XLZD Consortium

- Merger of DARWIN/XENON and LUX-ZEPLIN collaborations to build and operate next-generation liquid xenon detector
  - new, stronger international collaboration with demonstrated experience in xenon time projection chambers
- Paving the way now
  - First joint, successful DARWIN/XENON & LZ workshop, April 26-27 2021 https://indico.cern.ch/event/1028794/
  - MoU signed July 6, 2021 by 104 research group leaders from 16 countries
  - Summer meeting at KIT June 2022; spring meeting at UCLA April 2023; several working groups in place to study science, detector, Xe procurement, R&D etc
  - XLZD consortium (xlzd.org) to design and build a common multi-ton xenon experiment

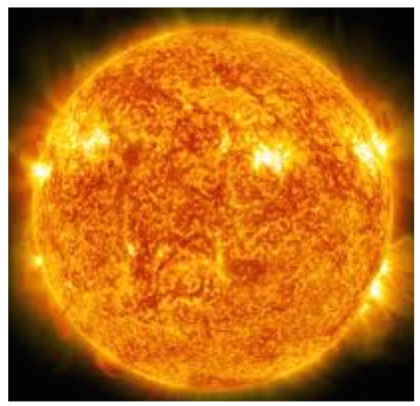
UCLA, spring 2023

KIT, summer 2022

Science goals

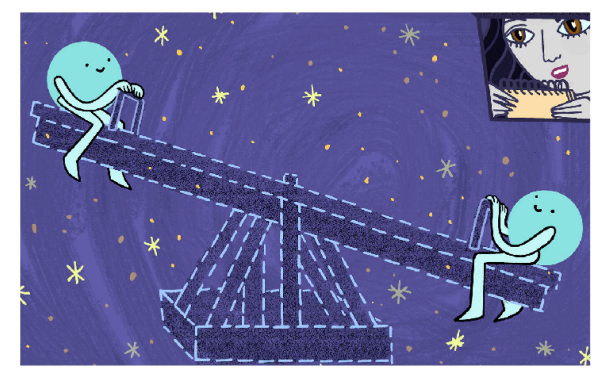
Solar neutrinos ($pp + {}^8B$)

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



Dark matter

JCAP 10, 016 (2015)

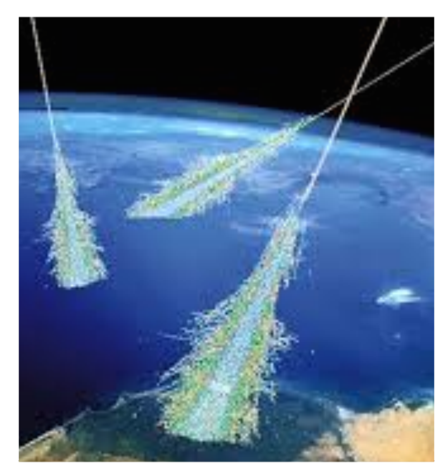


Neutrino nature

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

Supernova neutrinos

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



Atmospheric neutrinos

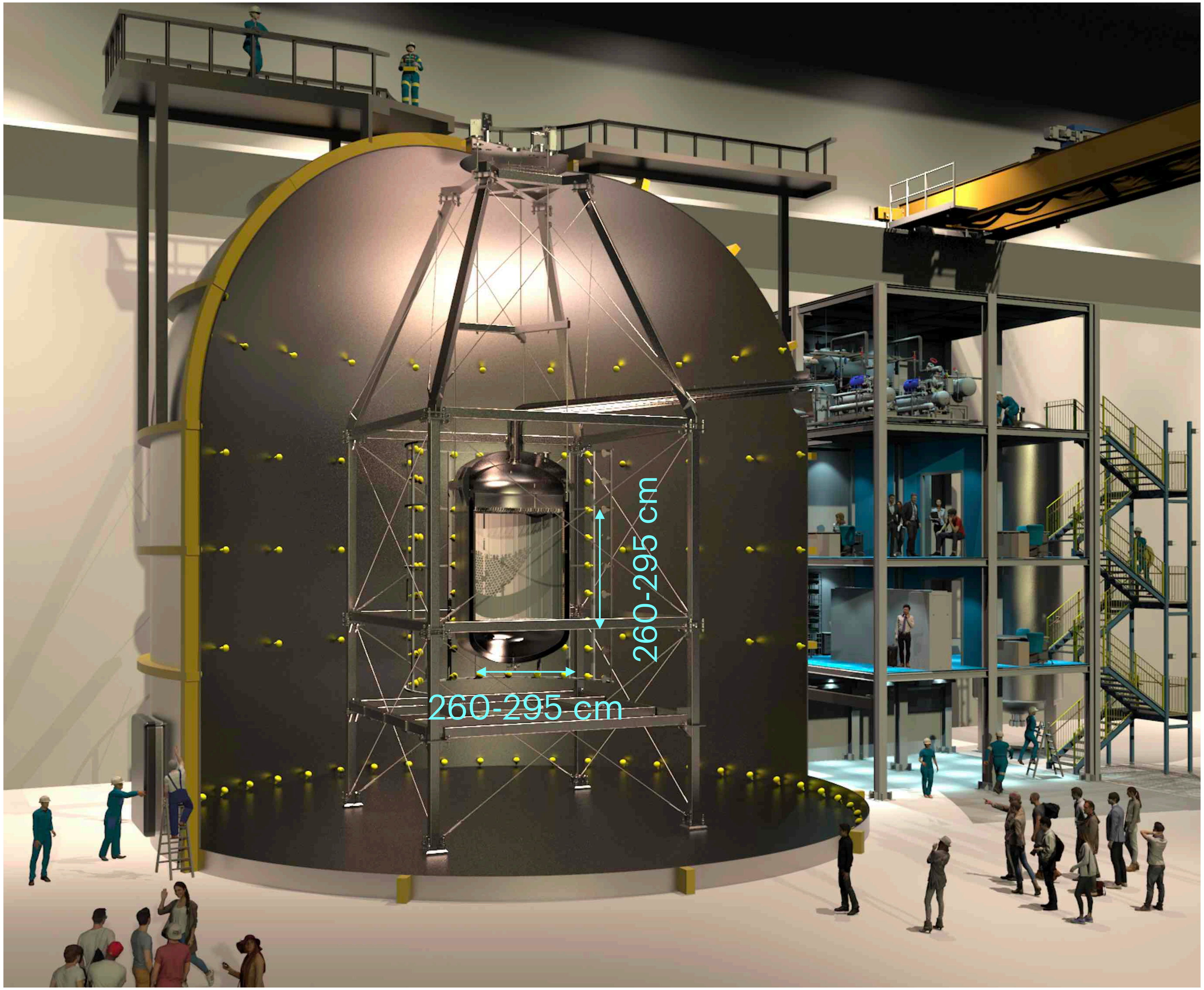
PRD 104 (2021)

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

Size matters

- LZ & XENONnT:

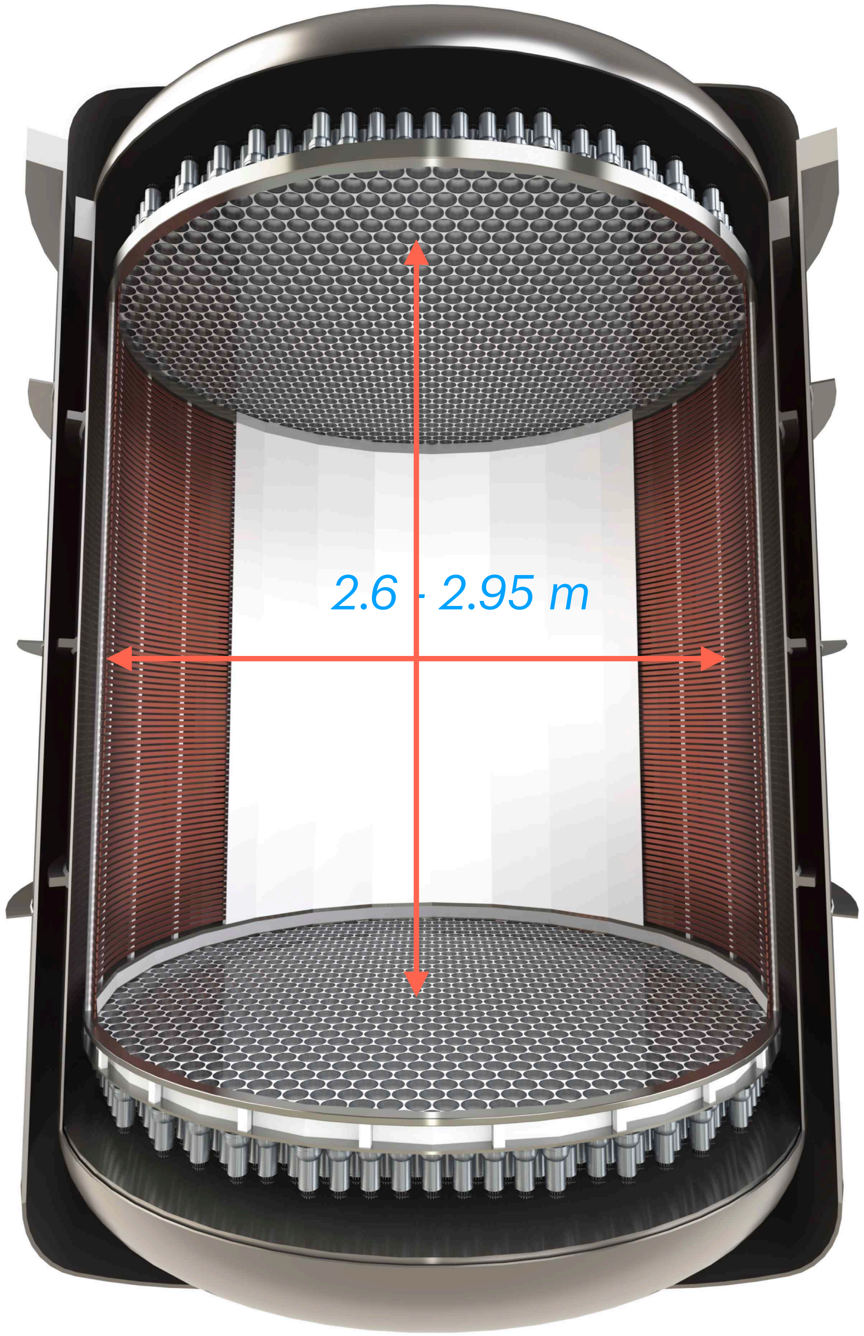
~ 1.5 m e^- drift,
~ 1.5 m Ø electrodes



Size matters

- New detector ⇒ new challenges

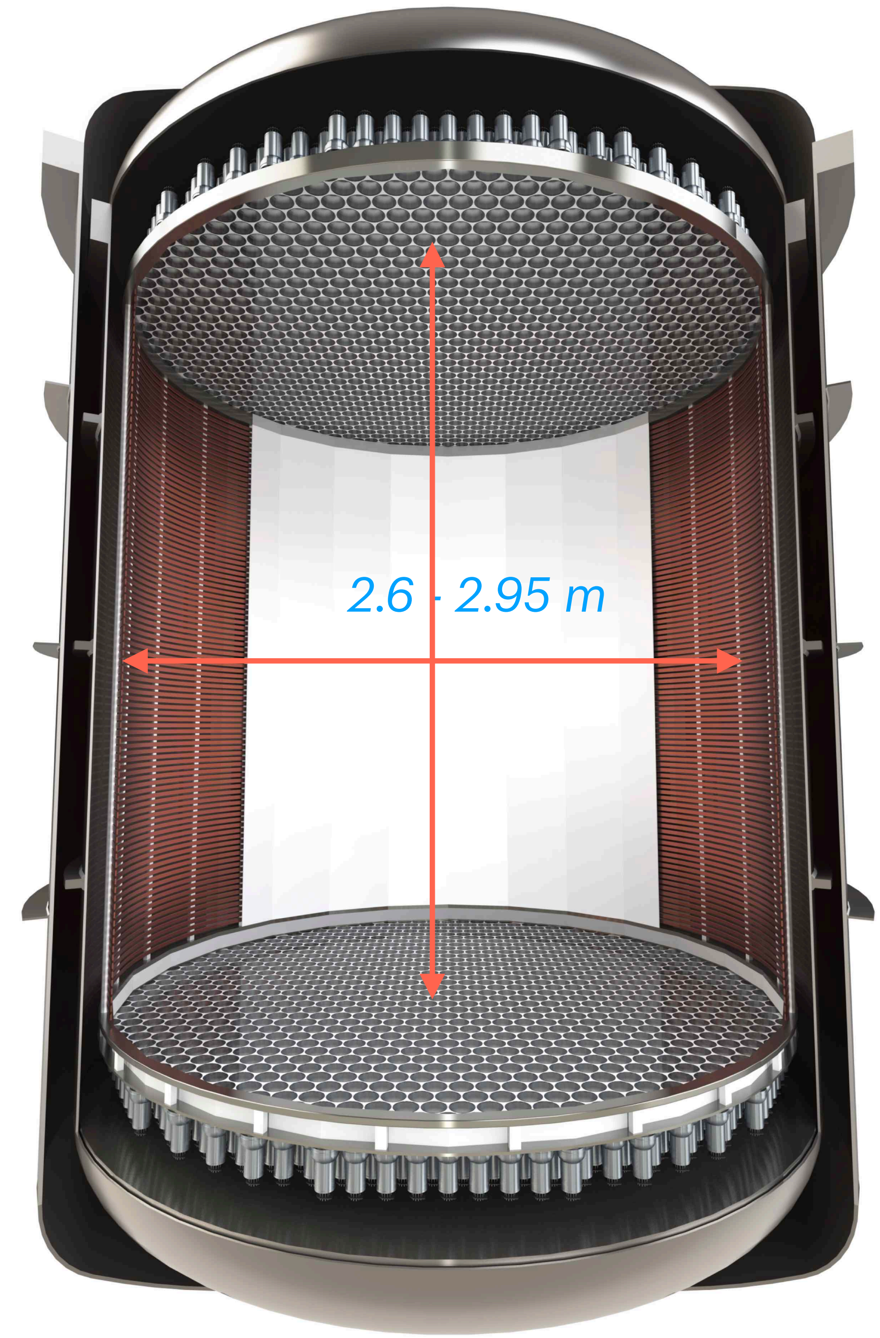
1 m XENON1T



DARWIN/XLZD

Size matters

- **New detector ⇒ new challenges**
  - Design of electrodes: robustness (minimal sagging/deflection), maximal transparency, reduced e^- emission ("hot spots")
  - Electric field: ensure spatial and temporal homogeneity, avoid charge-up of PTFE reflectors
  - High-voltage supply to cathode design, avoid high-field regions
  - Light sensors: reduce backgrounds and DRCs, improve PDE
  - Cryogenic system and xenon purification
- Electron survival in LXe: > 10 ms lifetime
- Diffusion of the e--cloud: size of S2-signals



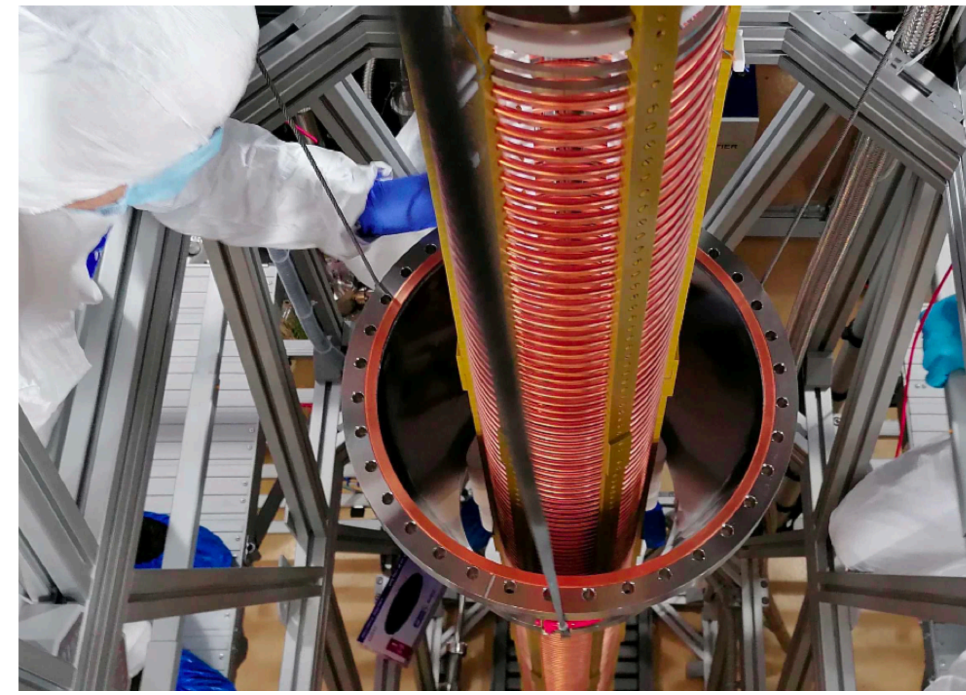
DARWIN/XLZD

R&D: detector design

- Demonstrate e^--drift over >2.5 m, measure e^- cloud diffusion for different drift fields
- Design high-voltage feed-throughs: deliver 50 kV or more to the cathode
- Build/test electrodes with > 2.5 m diameter: wire, mesh/woven, micro-pattern
- Optimise light collection efficiency in the TPC
- Cryostat design: stability; reduce the amount of material and hence gamma and neutron emitters close to the TPC

Pancake & Xenoscope available as test platforms to the collaboration

Xenoscope, JINST 16, P08052, 2021, EPJ-C 83, 2023

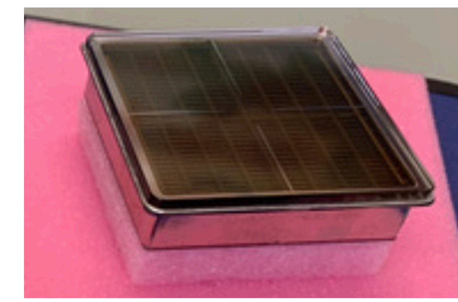


Pancake, Test electrodes with 2.6 m Ø

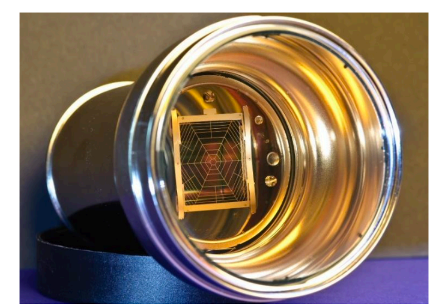
R&D: light and charge

- **Photomultipliers:** established technology, low DCR (~0.02 Hz/mm^2), high QE (mean around 34%, up to > 40% at 175 nm)
  - issues: lower radioactivity required, long-term stability in cryogenic liquids (AP rates due to vacuum leaks) & light emission
- **SiPM arrays:** lower radioactivity/area, lower voltage; main issue → dark count rate (too high by ~ factor 10-100 in LXe)
  - low-field SiPMs (reduce band-to-band tunnelling), digital SiPMs

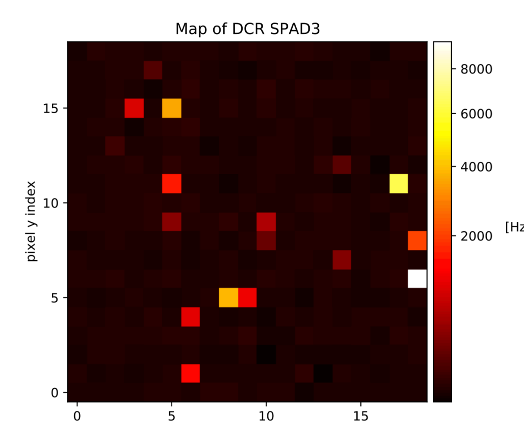
3'' (R1311 low-rad PMT by XMASS), JINST 15, 2020



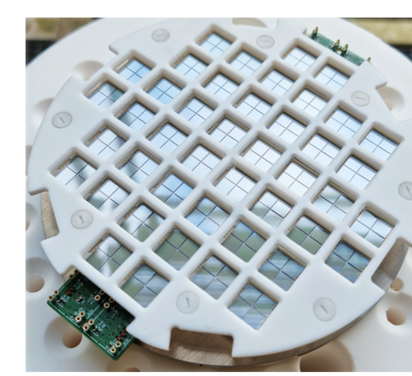
2''x 2'' flat panel PMT (R12699)



Baseline: R11410, 3''; R&D for lower radioactivity (refined metal) stems in progress



Digital SiPM

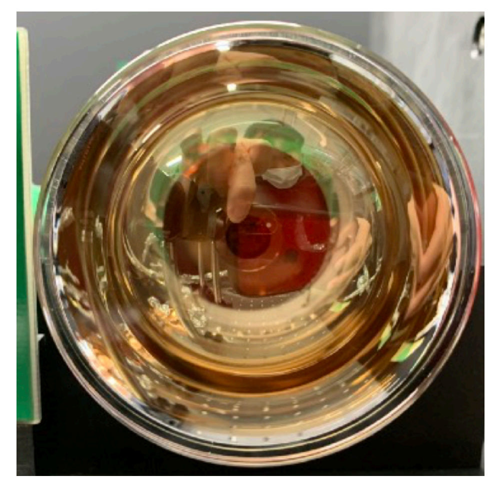


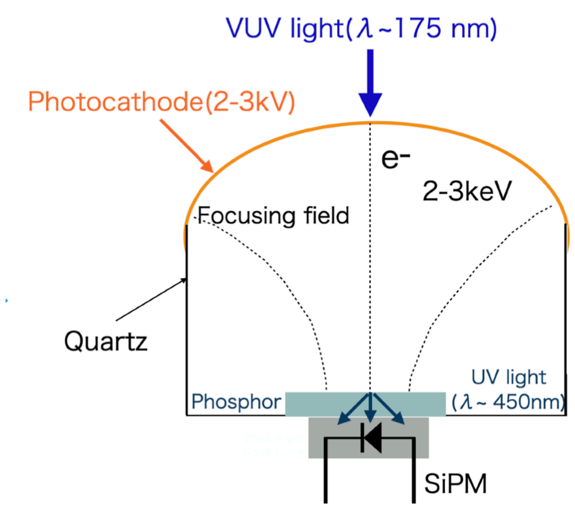
SiPM array, Xenoscope

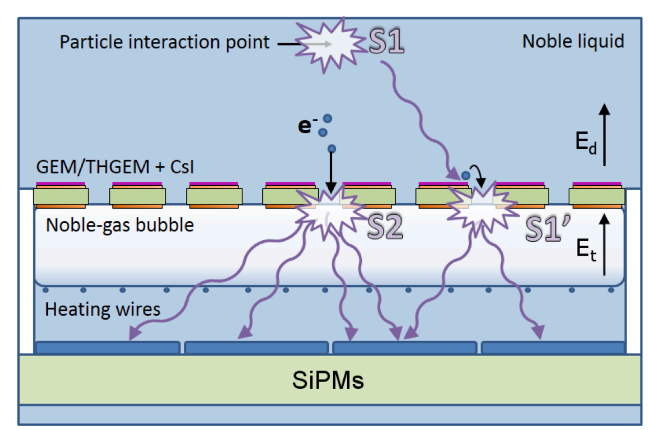
R&D: light and charge

- Hybrid sensors
    - SiPM + Quartz + photocathode: reduced radioactivity compared to PMTs
    - lower DCR compared to SiPM arrays (photosensitive area difference)
- Cryogenic low-noise, low-radioactivity, low heat dissipation readout
- **Bubble-assisted Liquid Hole Multipliers**: local vapour bubble underneath GEM-like perforated electrode in LXe

Hybrid photosensor with SiPM: ABALONE; NIM A 954 (2020)



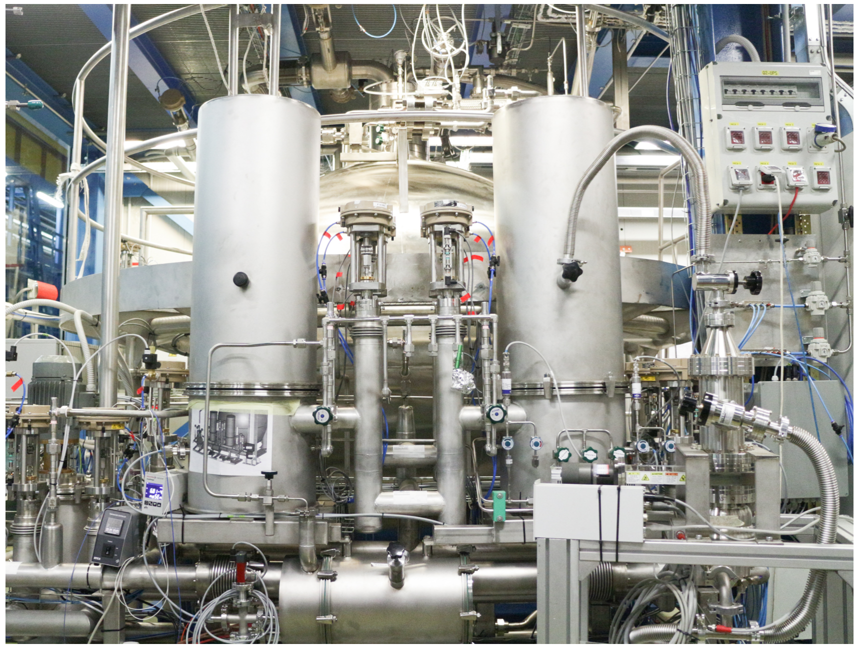




Hybrid photosensor with SiPM: Hamamatsu with Nagoya group

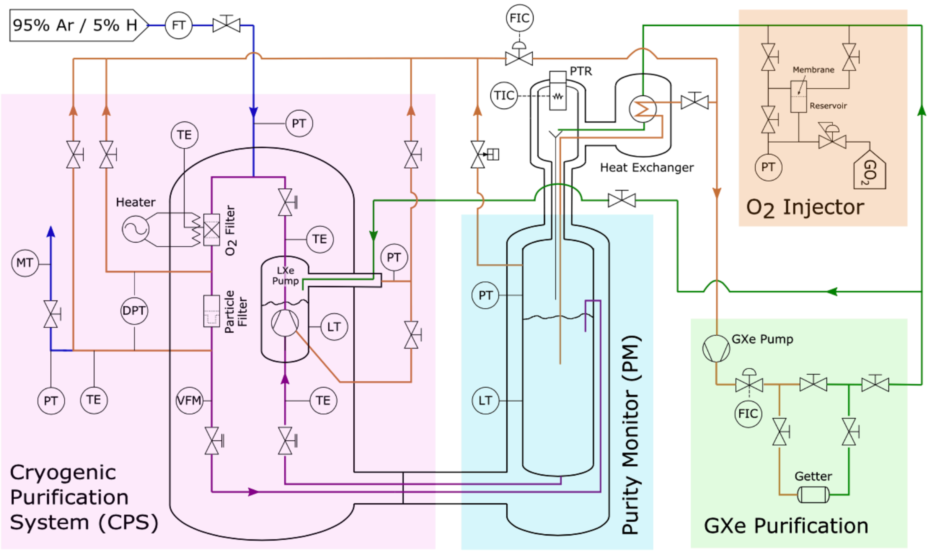
R&D: liquid target

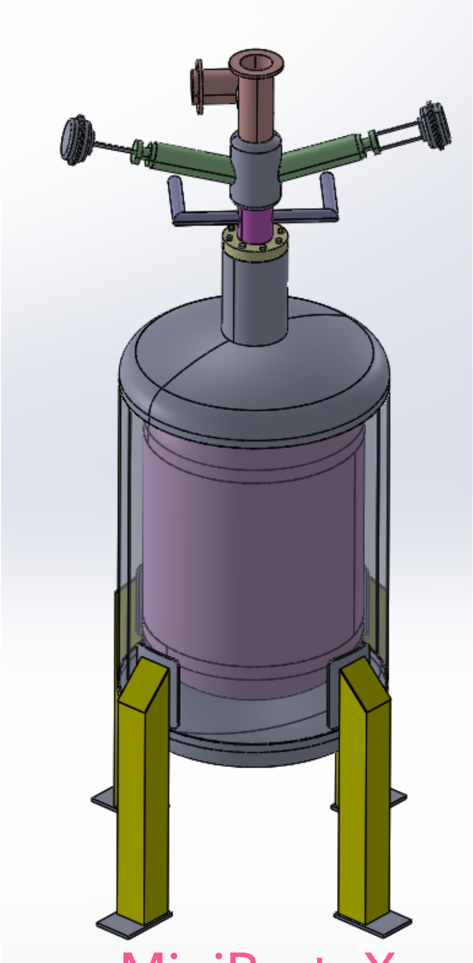
- Fast purification in liquid phase for large e^{-} lifetime; radon-free filters
- Gravity-assisted recuperation and large-scale storage systems



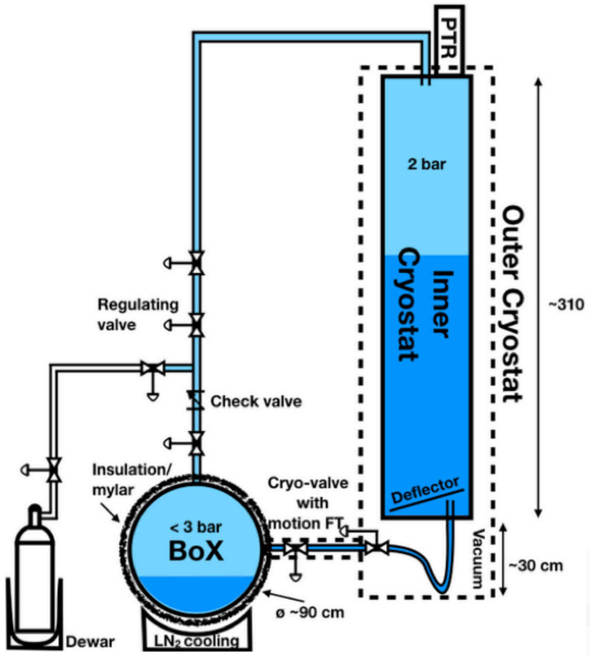
LXe purification system (5 L/min LXe, faster cleaning; 2500 slpm) for XENONnT

G. Plante et al., EPJ-C 82 (2022), Xeclipse





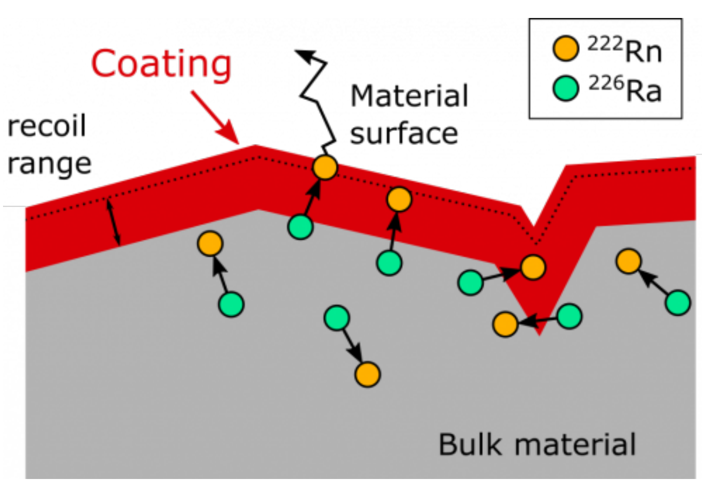
MiniRestoX

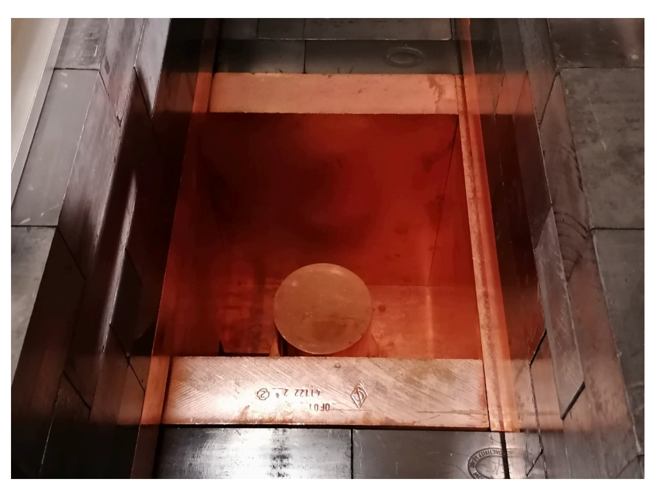


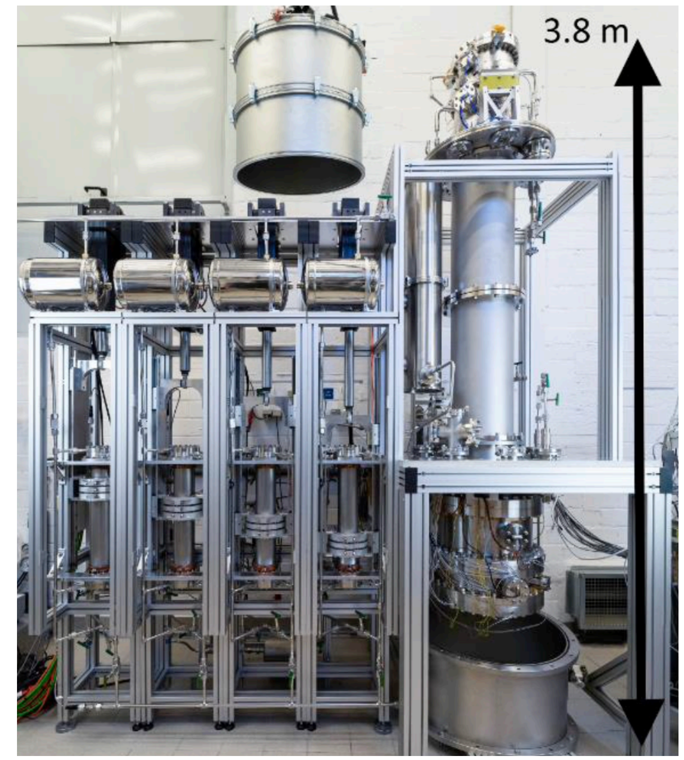
Gravity assisted Xe recuperation and storage system (Ball of Xenon, BoX) for Xenoscope

R&D: background control

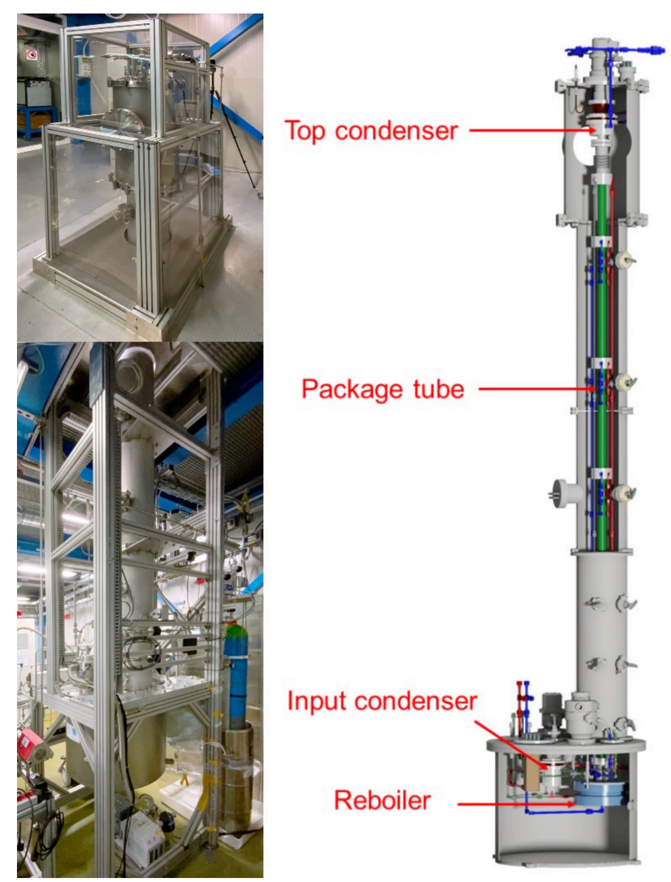
- ^{222}Rn distillation column (goal is 0.1 μBq/kg, background below ER from pp solar neutrinos; DEAP-3600 reached 0.15 μBq/kg in LAr)
- "Radon-free" circulation pumps
- Coating techniques to avoid radon emanation (electrochemical deposition of Cu best results)
- ^{85}Kr distillation (^{nat}Kr goal: 0.1 ppt, achieved < 0.026 ppt)
- Radio-pure materials with low Rn-emanation





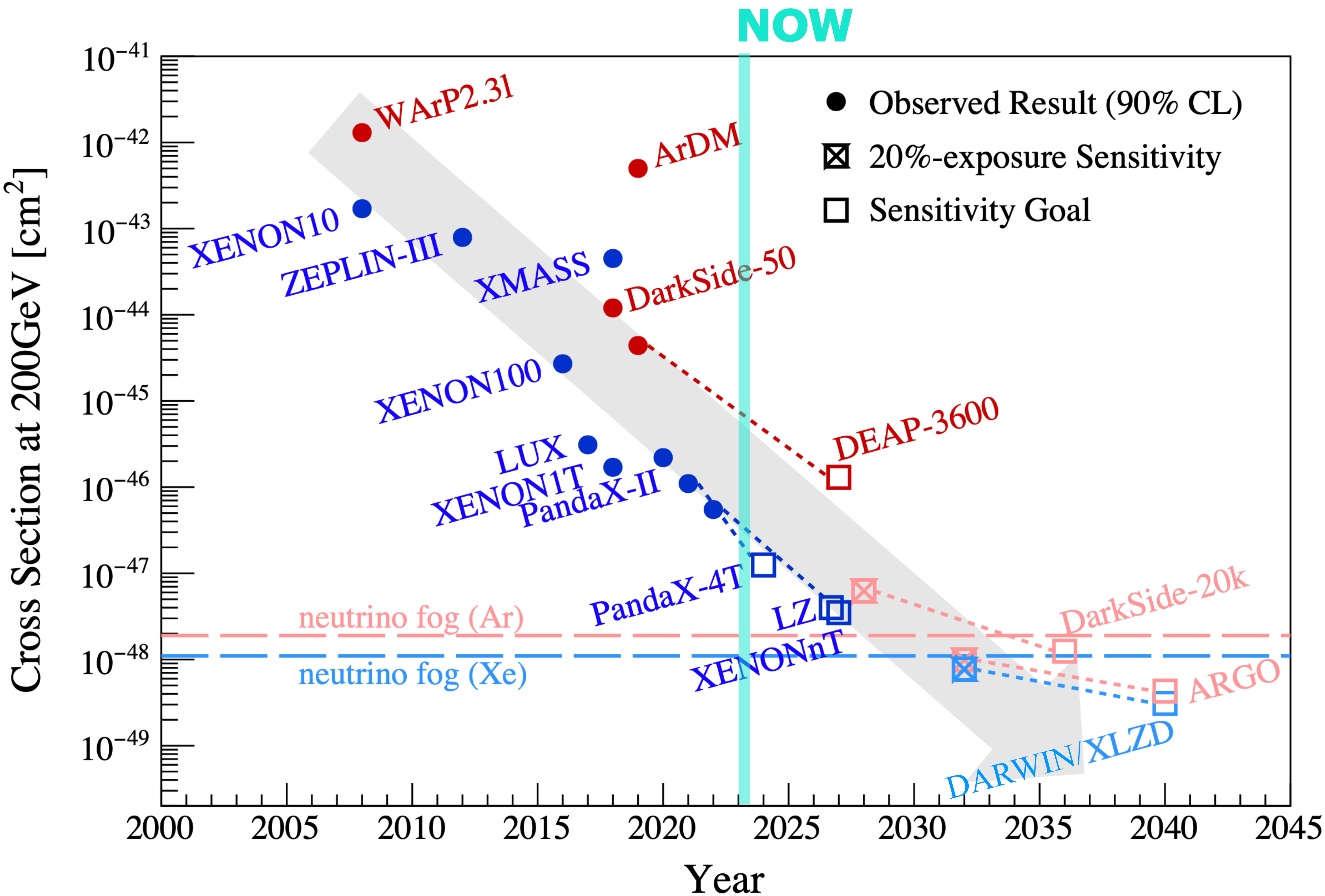


Rn distillation column for XENONnT (reduce ^{222}Rn - hence also ^{214}Bi - from pipes, cables, cryogenic system)



Kr distillation column for XENONnT, EPJ-C 77, 2017

DM cross section versus time



Snowmass, Topical Group on Particle Dark Matter Report, arXiv: 2209.07426

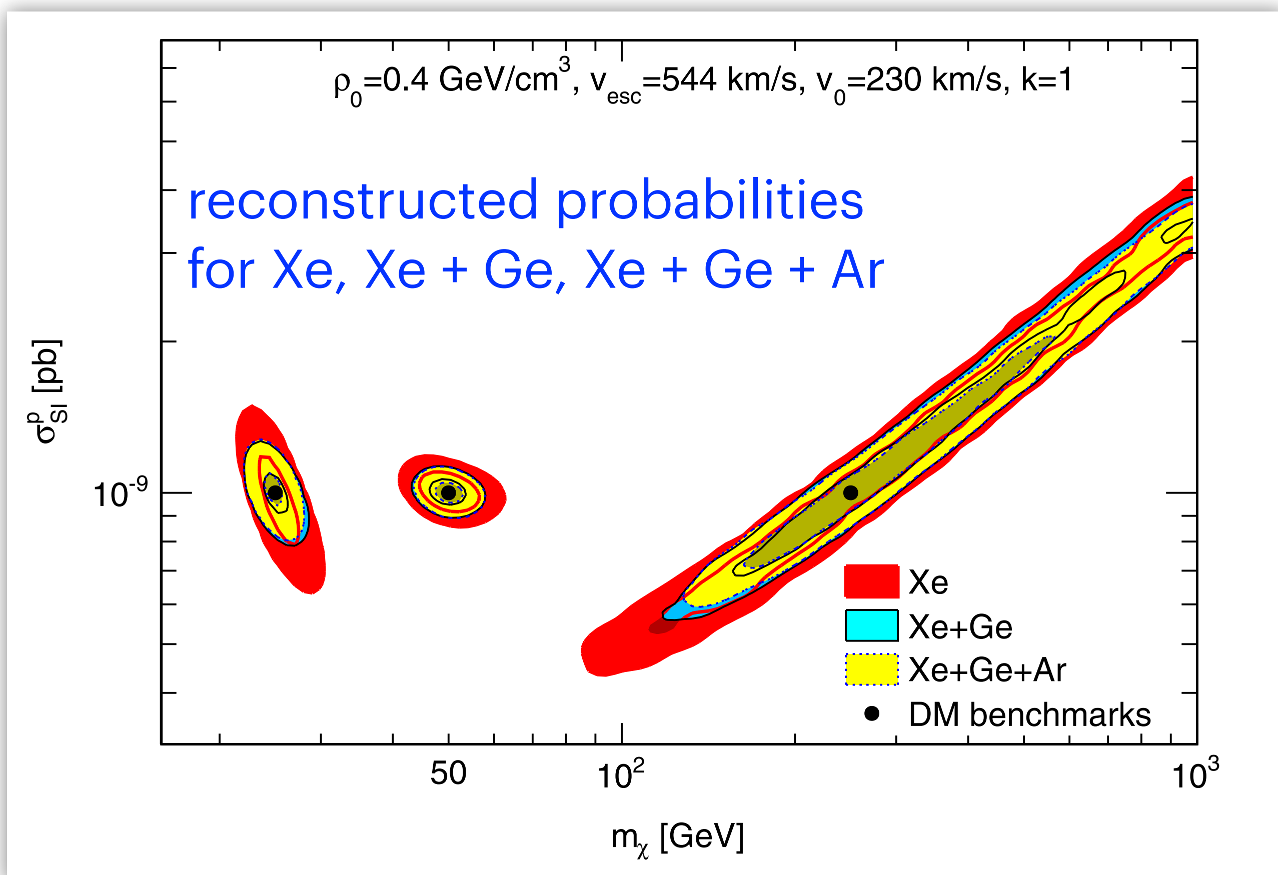
WIMP spectroscopy

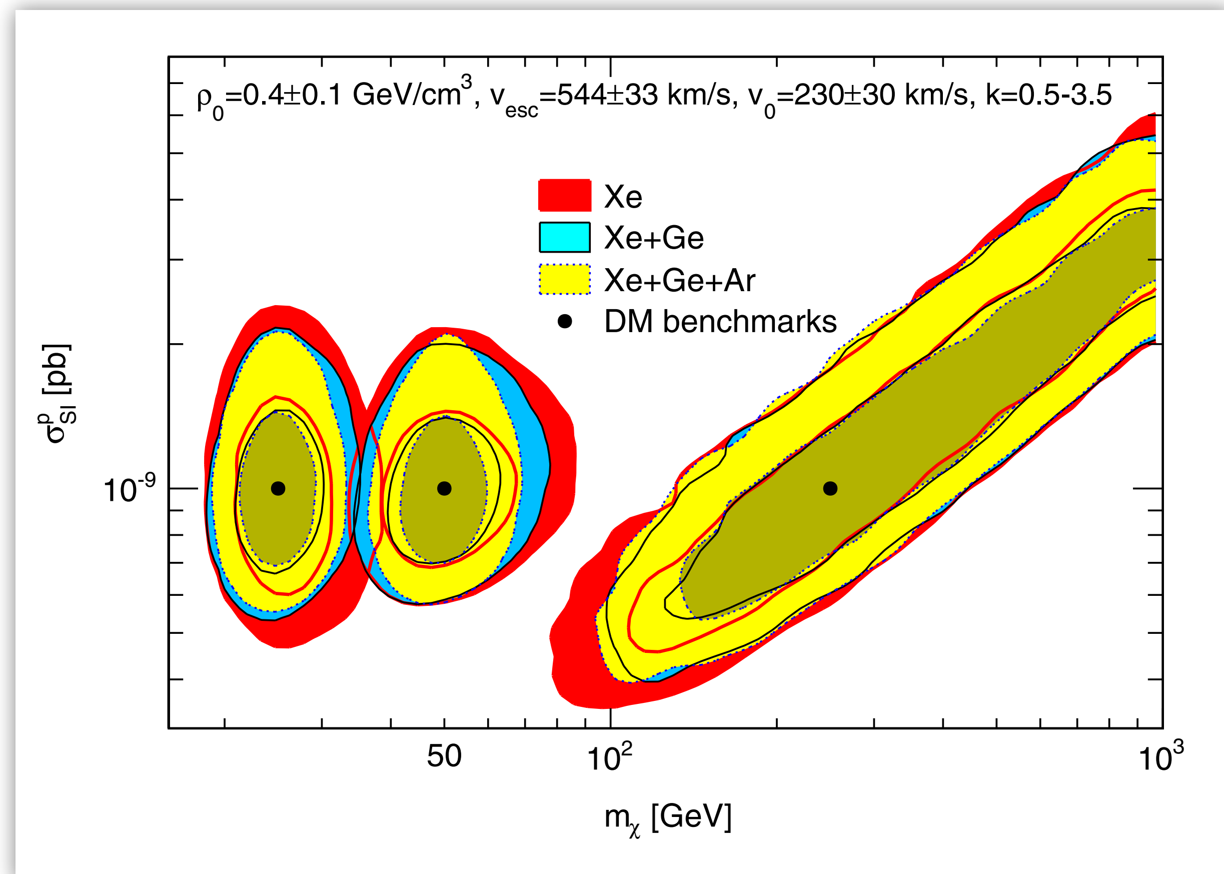
- Different DM targets are sensitive to different directions in the m_χ- σ_{SI} plane

Xe: 2.0 t x yr, E_{th} =10 keV_{nr}
Ge: 2.2 t x yr, E_{th} =10 keV_{nr}
Ar: 6.4 t x yr, E_{th} = 30 keV_{nr}

fixed galactic model

including galactic uncertainties

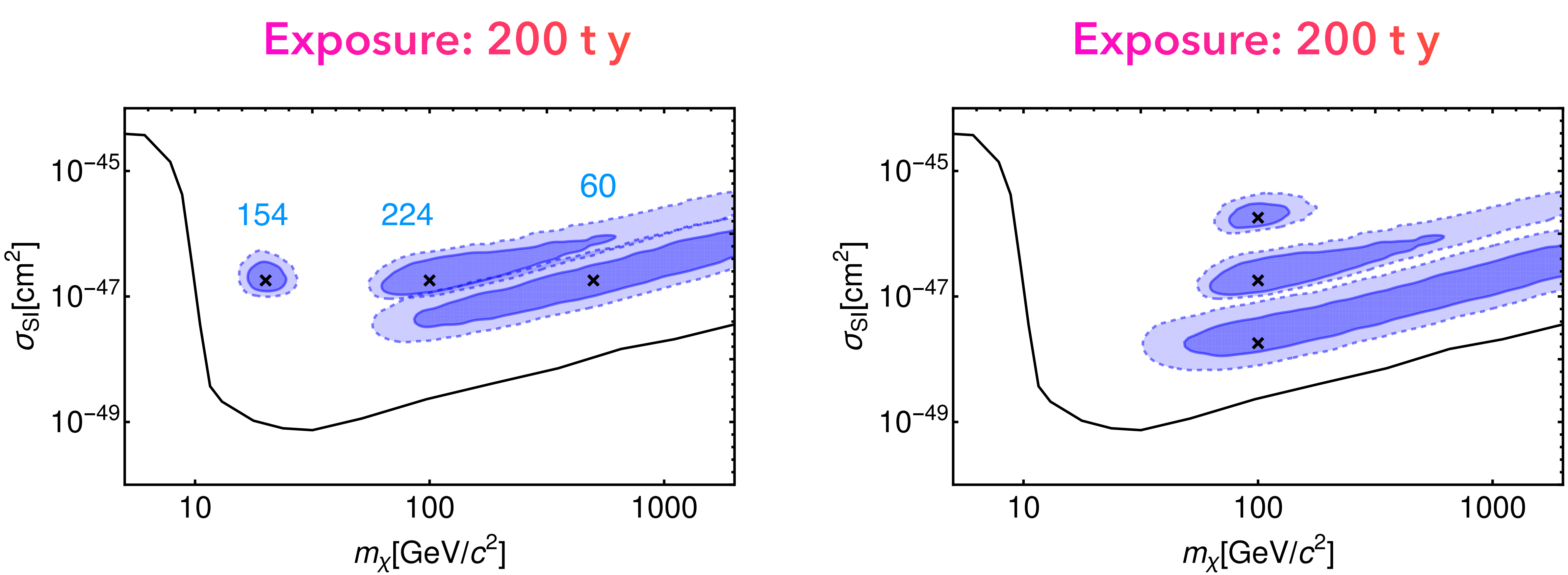




Pato, Baudis, Bertone, Ruiz de Austri, Strigari, Trotta: Phys. Rev. D 83, 2011

WIMP spectroscopy

- Capability in LXe alone 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: $v_{esc} = 544 \pm 40\,\mathrm{km/s}$

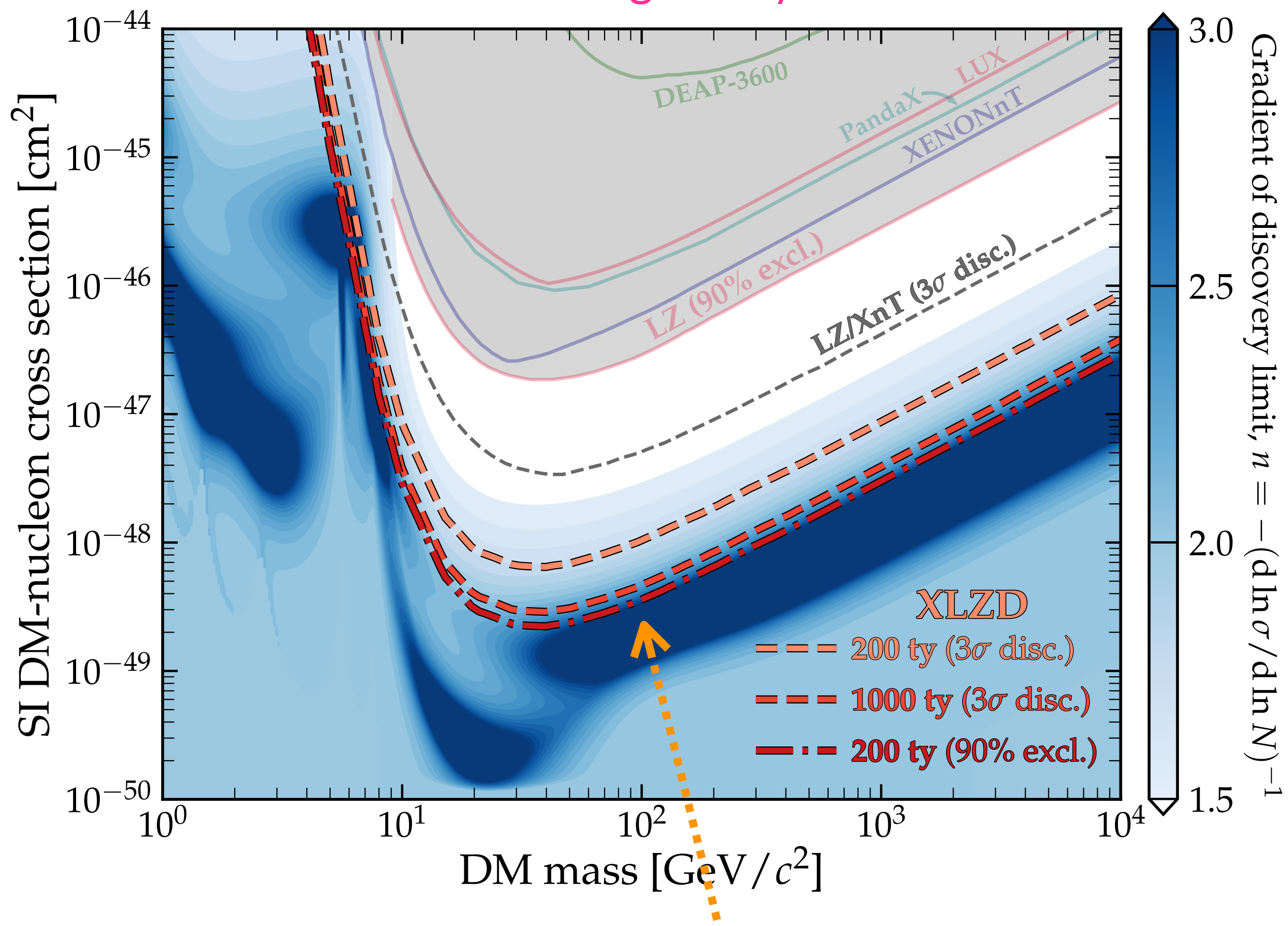
$v_0 = 220 \pm 20\,\mathrm{km/s}$

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

Definitive search for medium to high-mass WIMPs

- Larger LXe mass with XLZD
  - reaches sooner the systematic limit of the neutrino fog (~ 1000 tonnes × years exposure)
  - allows for 3-σ discovery at SI cross section of 3 × 10^{-49} cm² at 40 GeV mass
- Detector design: combine best of LZ and XENONnT

Figure by Ciaran O'Hare



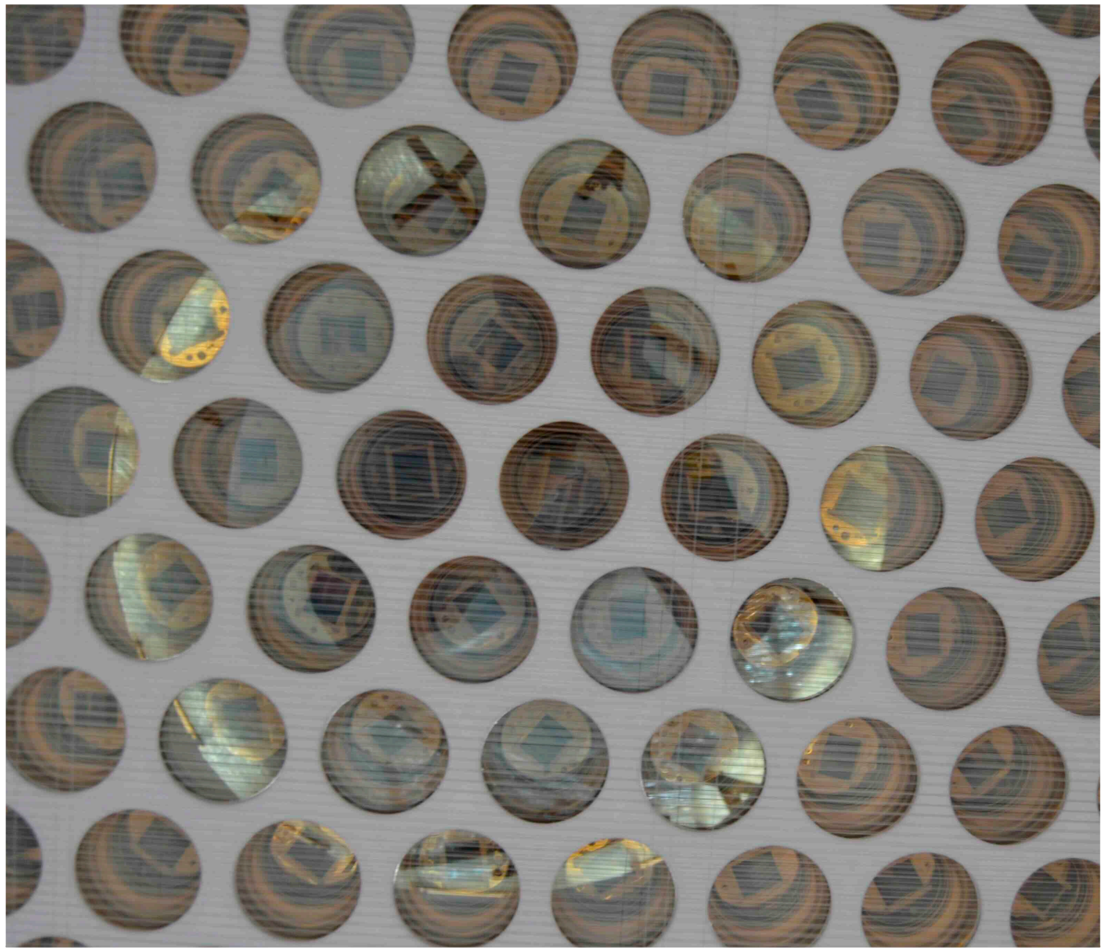
Systematic limit imposed by CEvES from atmospheric neutrinos

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

Summary and Outlook

- The nature of dark matter in our universe remains an enigma
- In the worldwide race to directly detect dark matter particles, liquid xenon detectors are at the forefront
- Current generation of detectors presented first results, and they continue to take data to reach design exposures
- DARWIN has been leading the efforts towards a next-generation LXe detector
- XLZD: merger of expert teams and international planning is underway
- Design book in progress (risks defined and tractable); potential for DM discovery
- Eventually, will limited by neutrino interactions *(but also many new physics opportunities & be prepared for surprises!)*


"There's always
something to look at
if you open your eyes."
– The Doctor



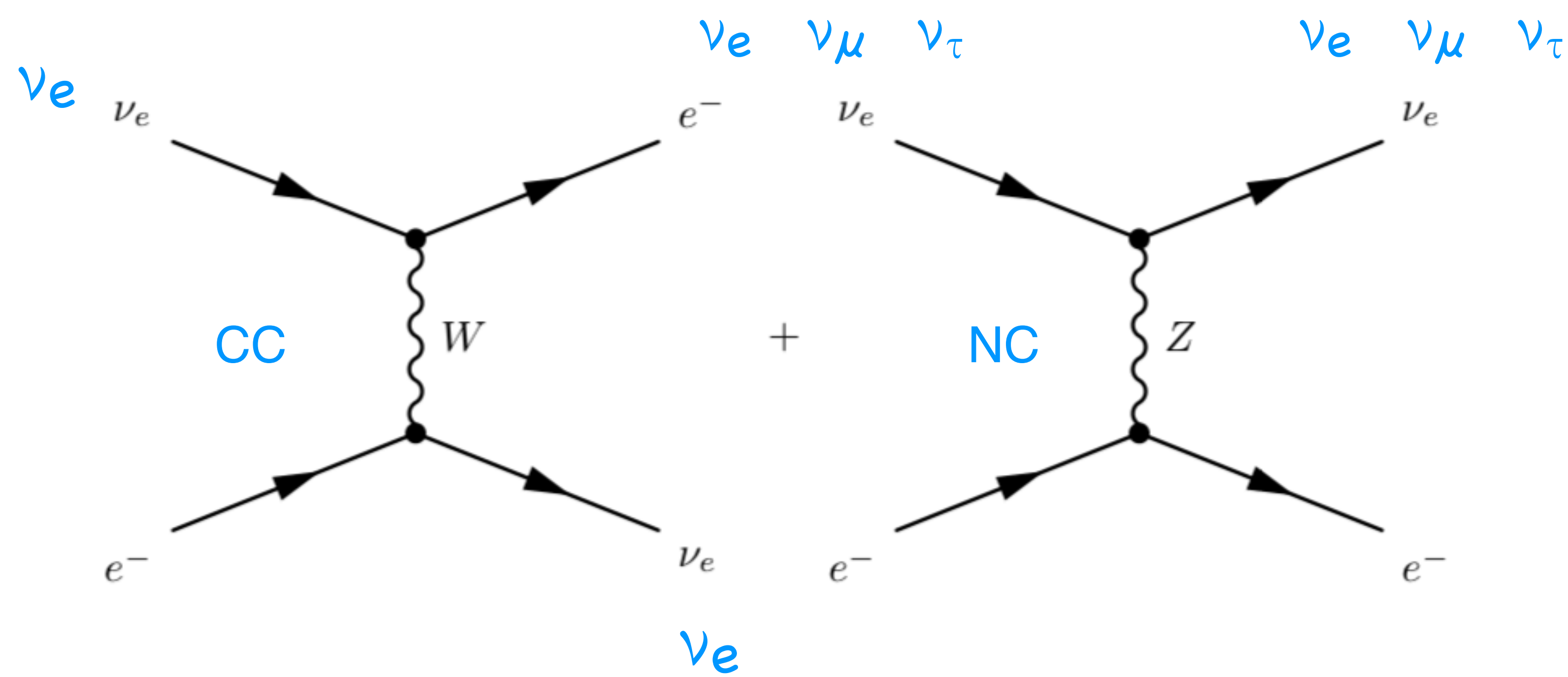
The end

Backup slides

Low-energy solar neutrinos

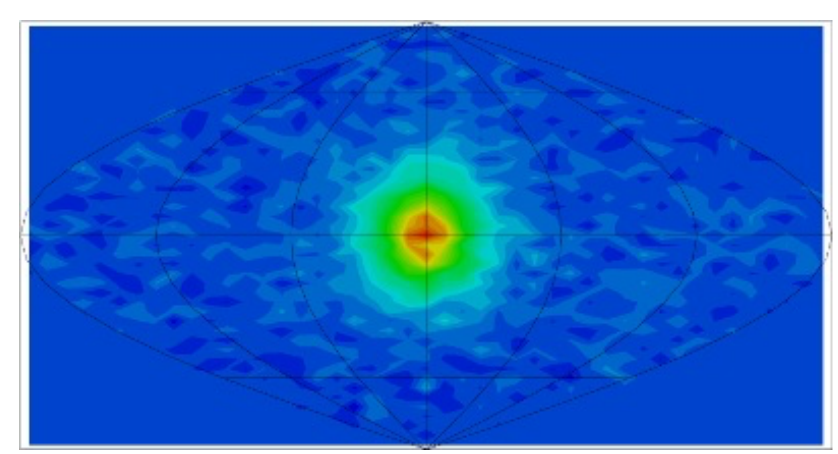
Elastic neutrino-electron scattering

$$\nu_x + e^- \to \nu_x + e^-$$



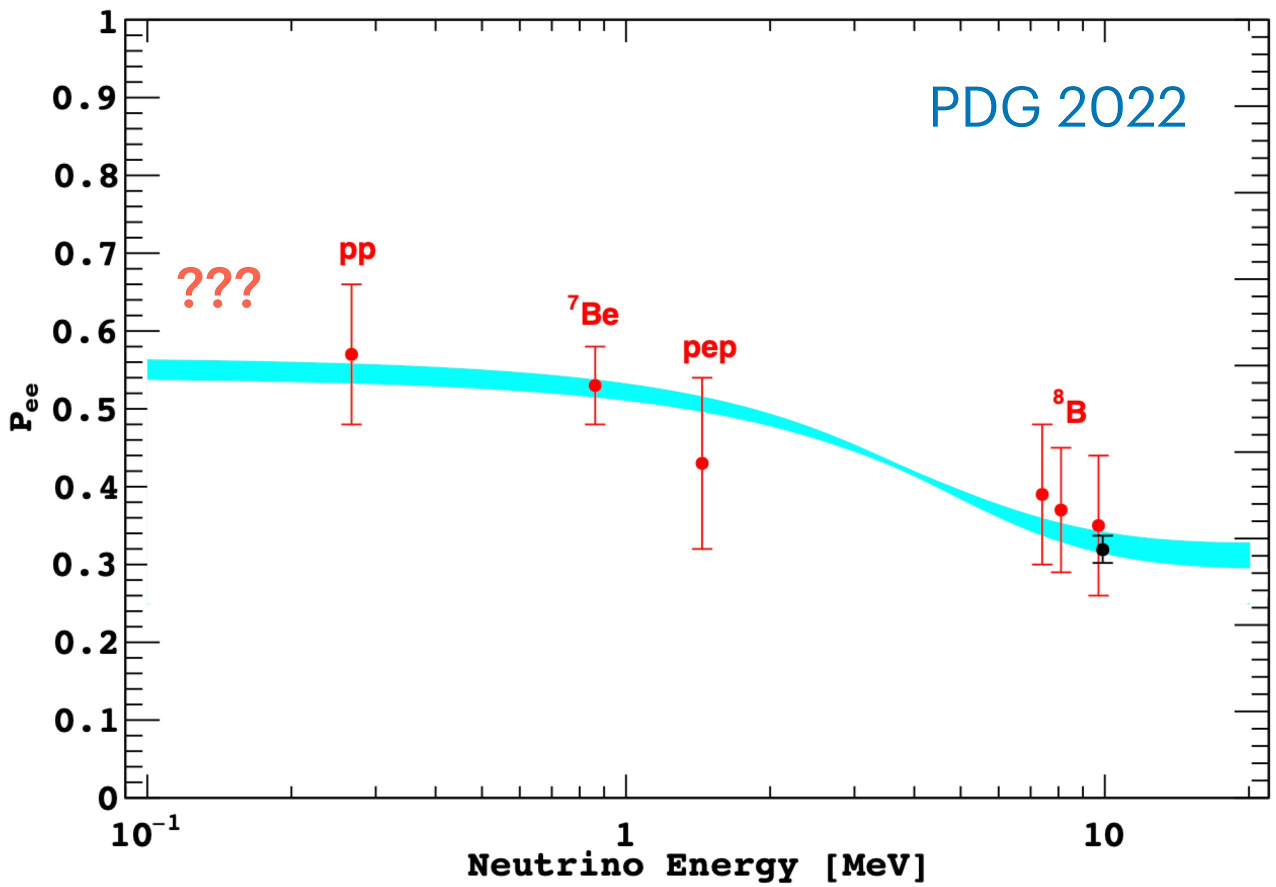
- ν_e interactions: CC & NC
- ν_μ and ν_τ interactions: only via NC

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

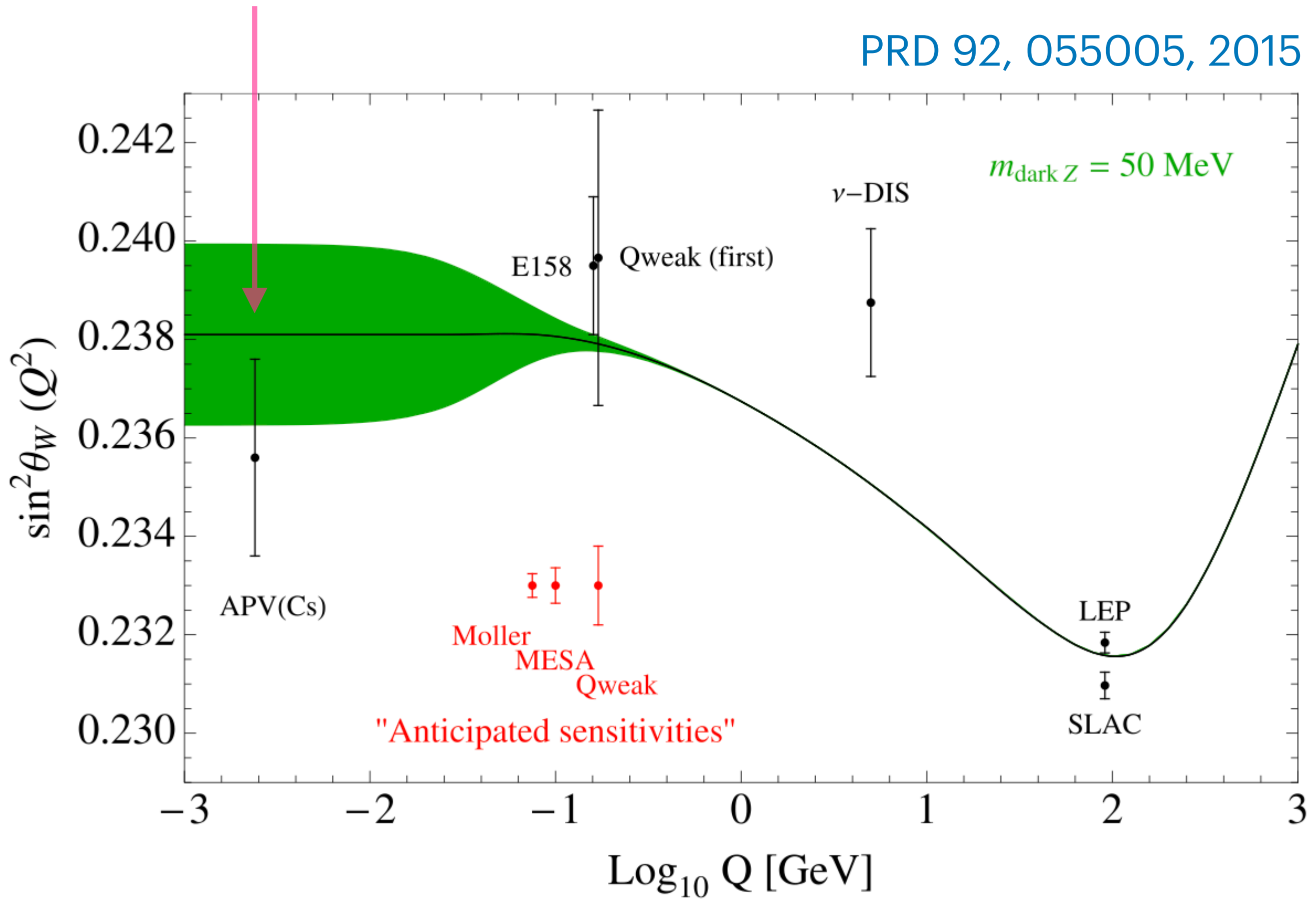


Low-energy solar neutrinos

Survival probability P_{ee}



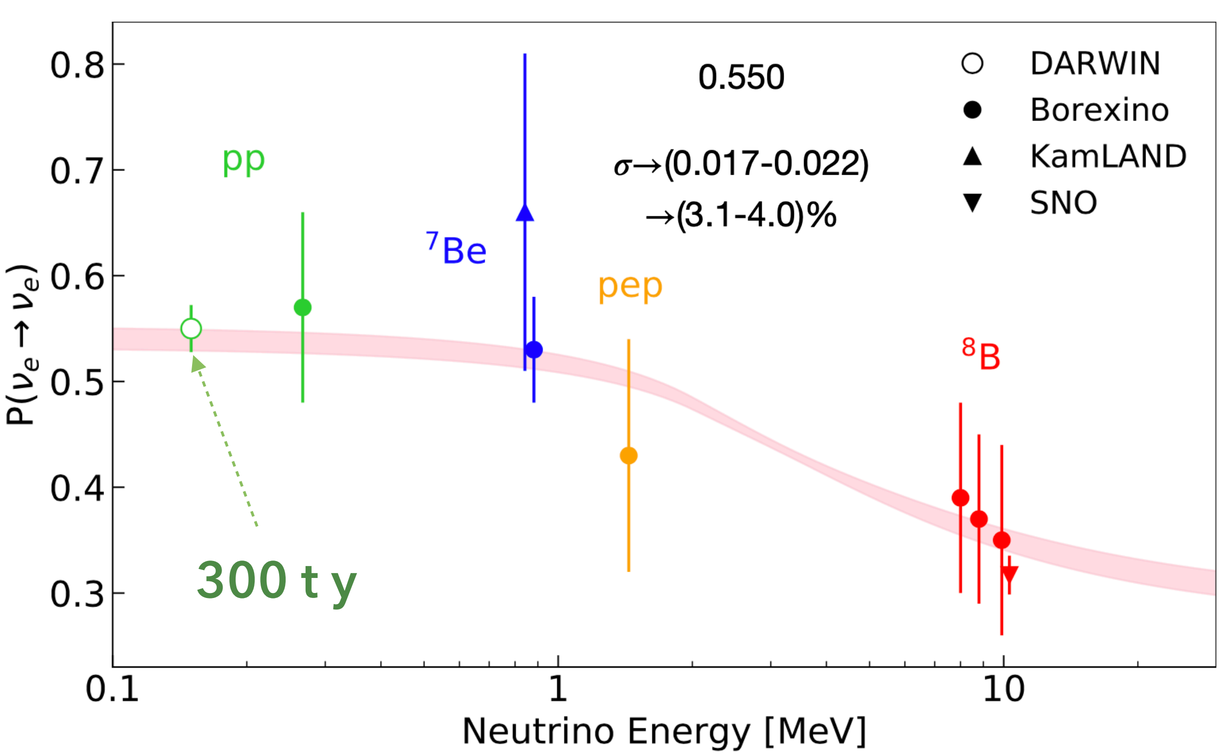
2.4 MeV



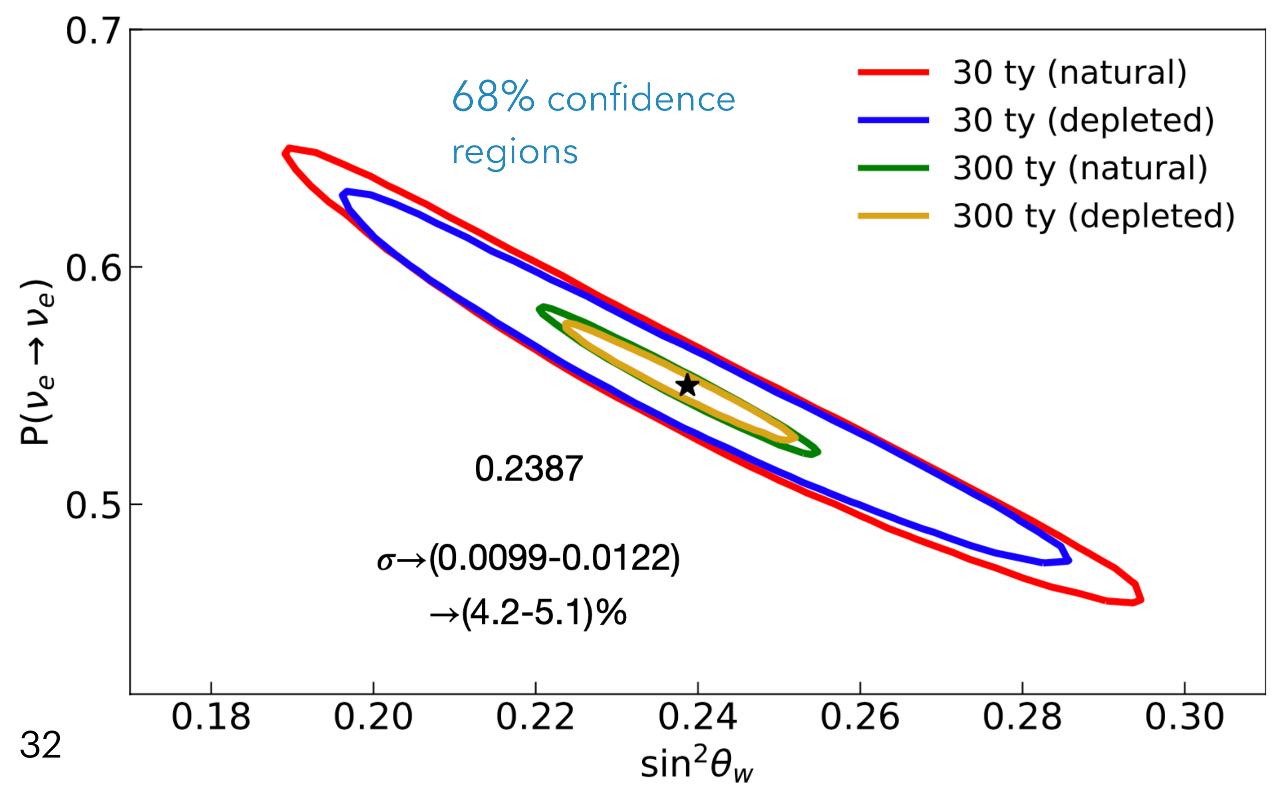
- What is the ν_e survival probability (P_{ee}) below 200 keV?
- What is the value of the weak mixing angle ($\sin^2\theta_w$) at low energies?

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

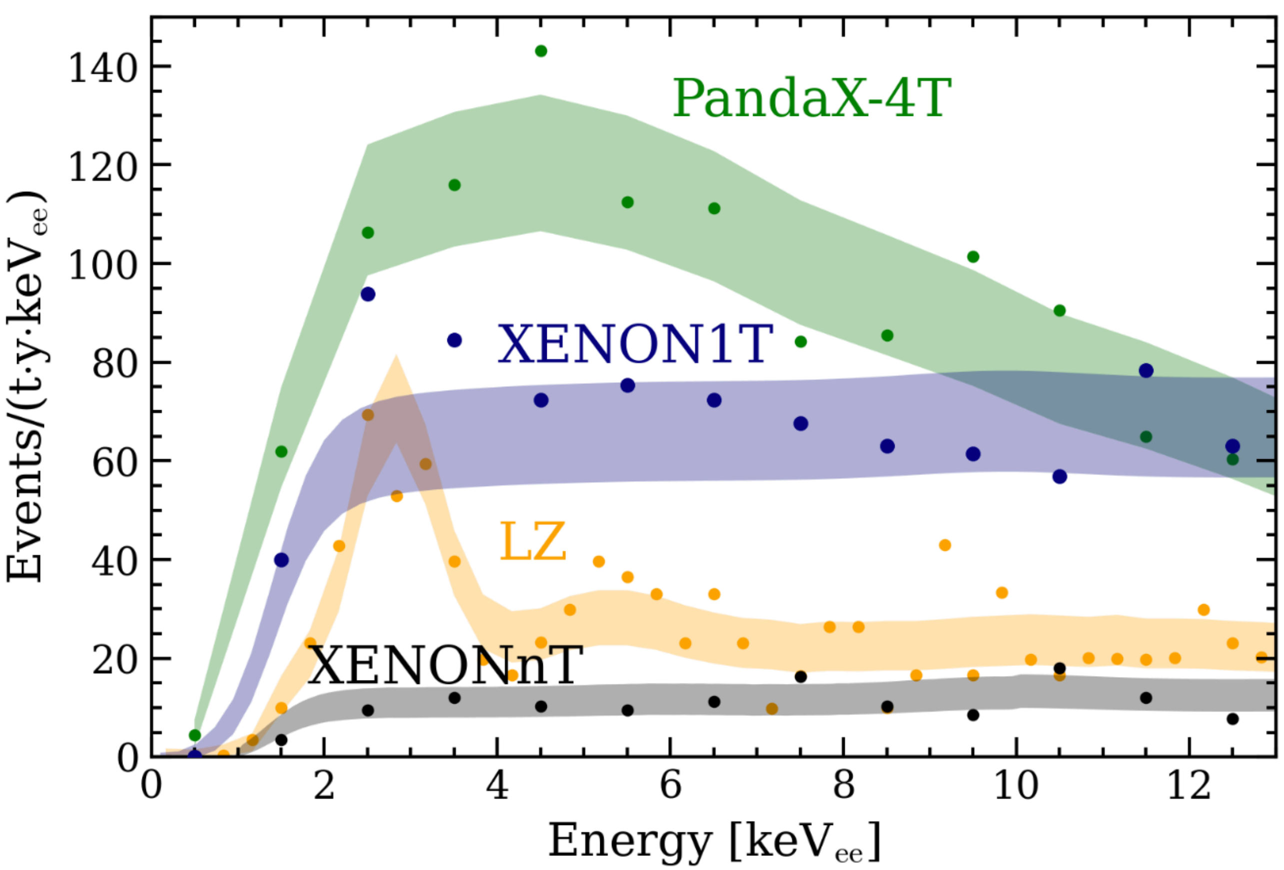


DARWIN collaboration, EPJ-C 80 12 (2020)

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

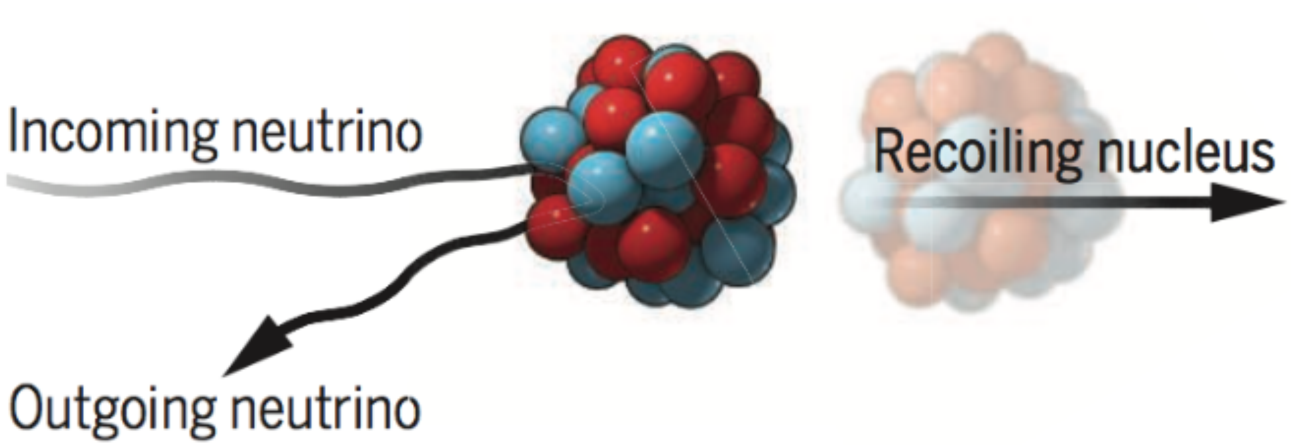
	(1,10) keV	(1, 140) keV
^{214}Pb	56±7	980±120
^{85}Kr	6±4	90±60
Materials	16±3	270±50
Solar ν	**25±2**	300±30
^{124}Xe	2.6±0.3	260±30
^{136}Xe	8.7±0.3	1520±50
AC	0.7±0.03	0.7±0.03



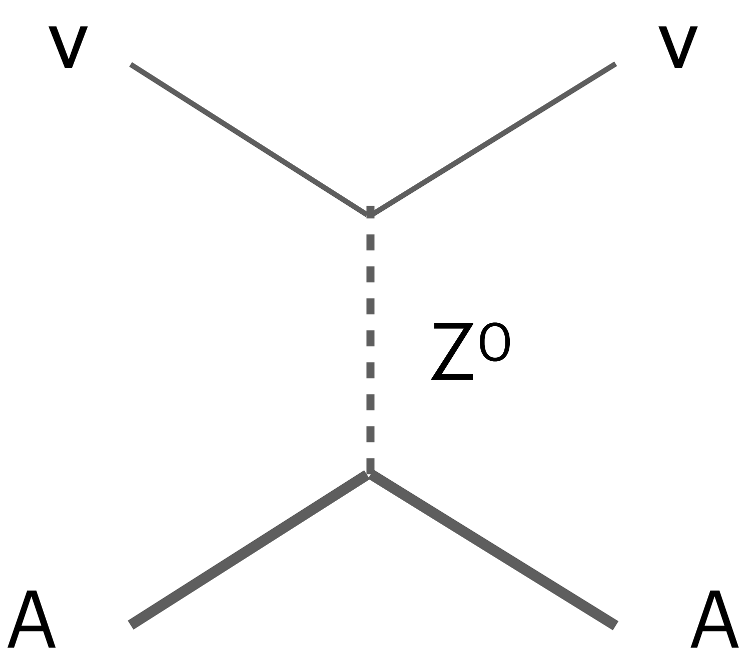
XENON collaboration, PRL 129, 2022

CEvNS in DARWIN/XLZD

$$\nu + A \to \nu + A$$



- 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



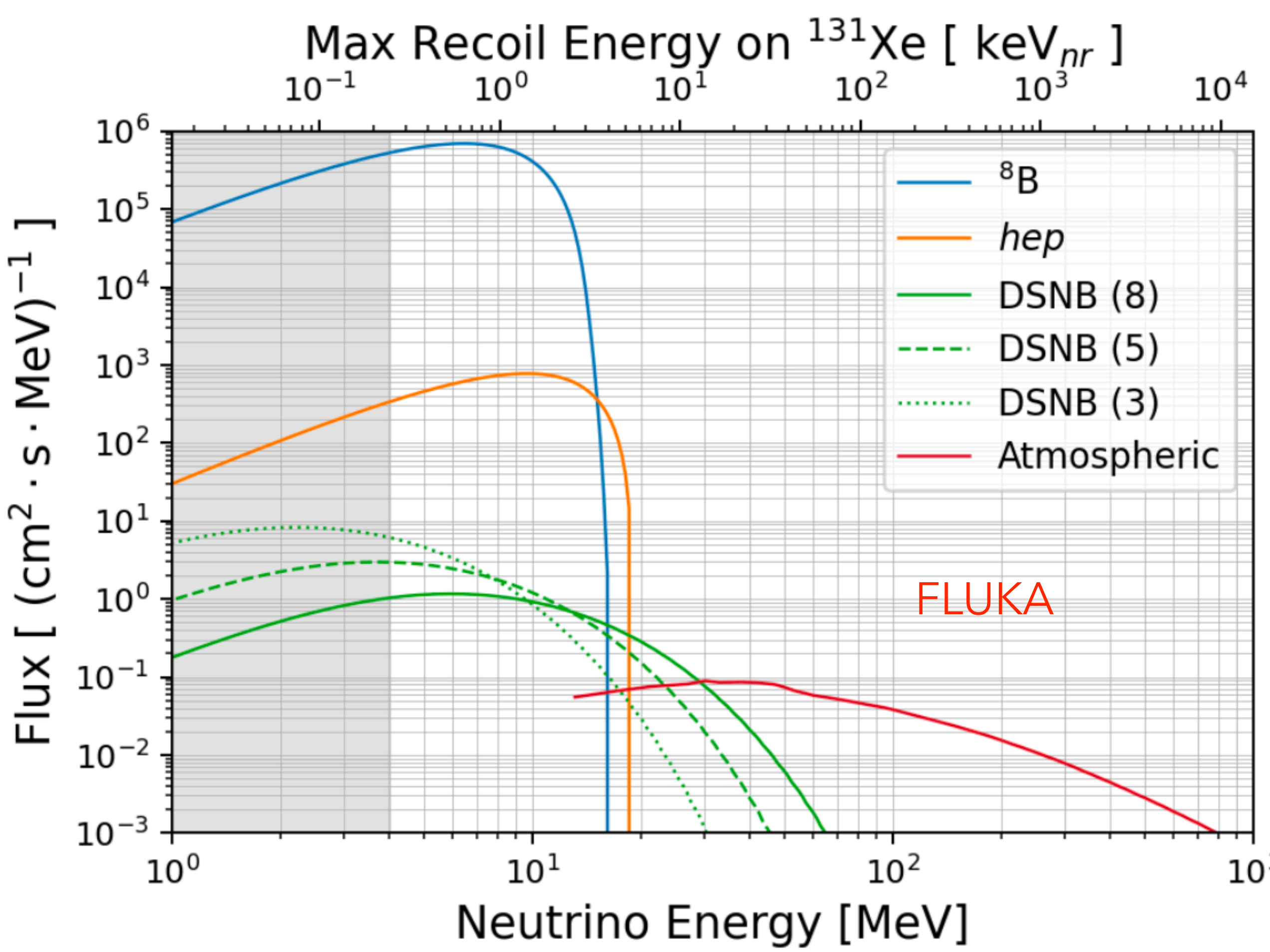
Nucleon wavefunctions in the target nucleus in phase with each other at low momentum transfer

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

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

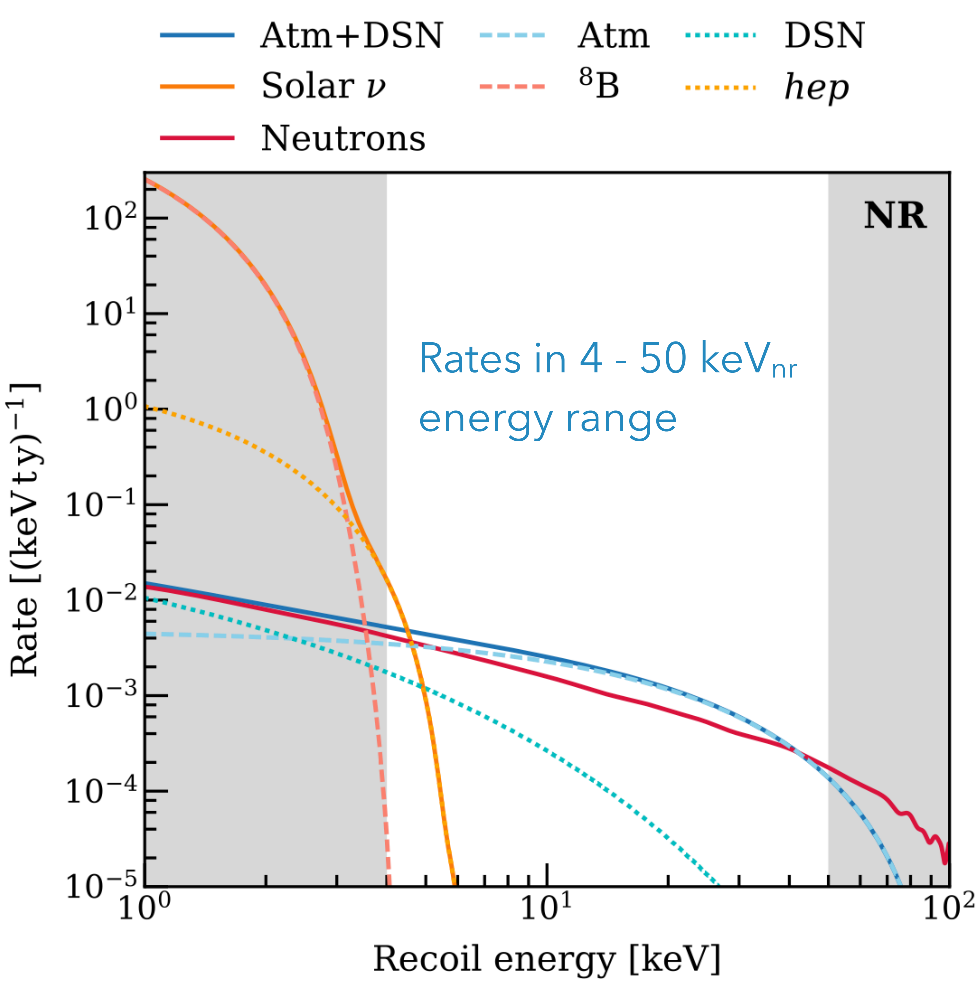
form factor F = 1 full coherence

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

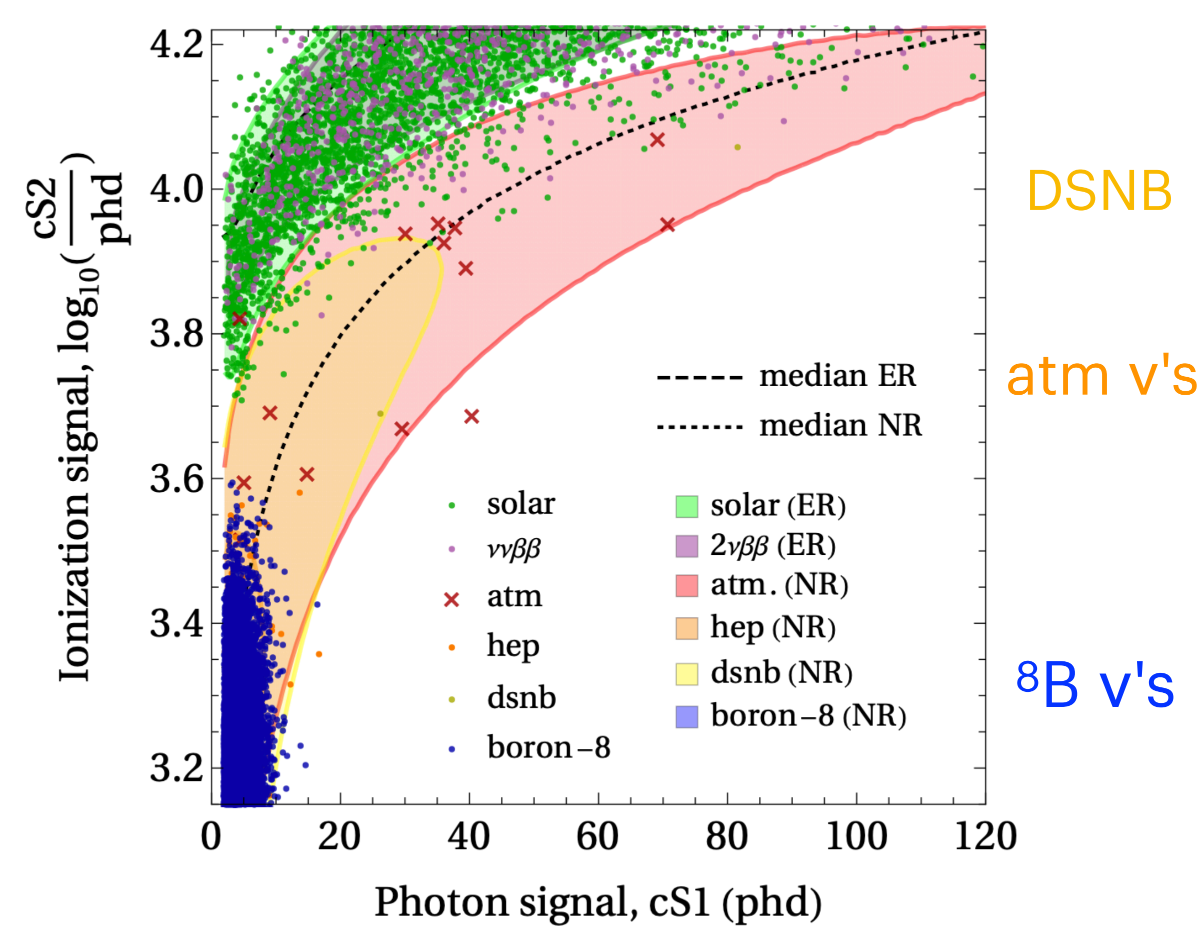
CEvNS with ^{8}B neutrinos

- ~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

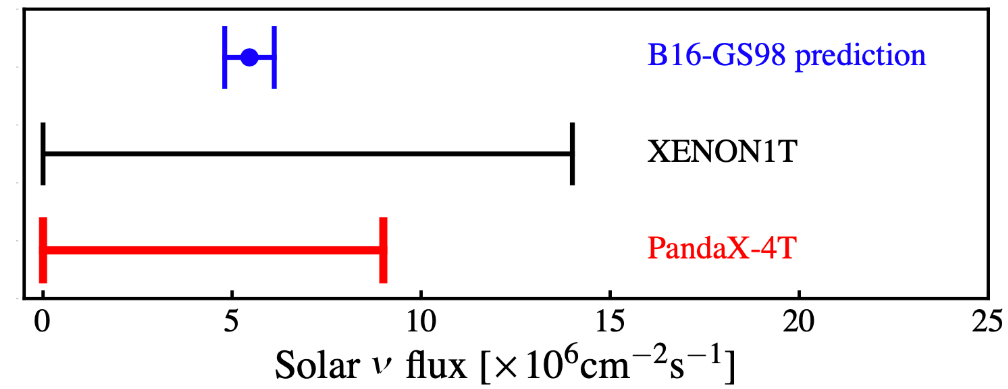


Newstead, Lang, Strigari, PRD 104, 2021

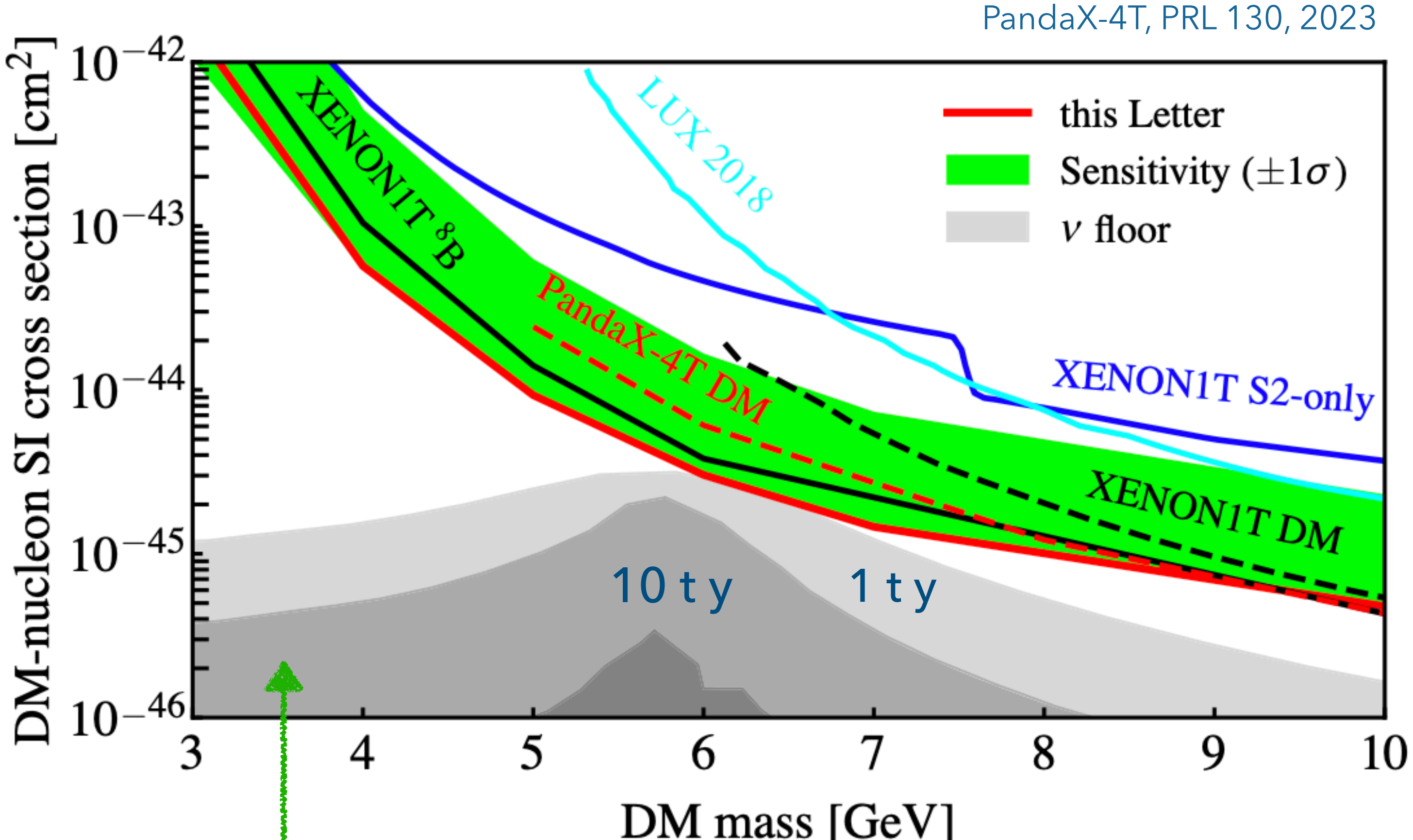
Existing ^{8}B ν constraints

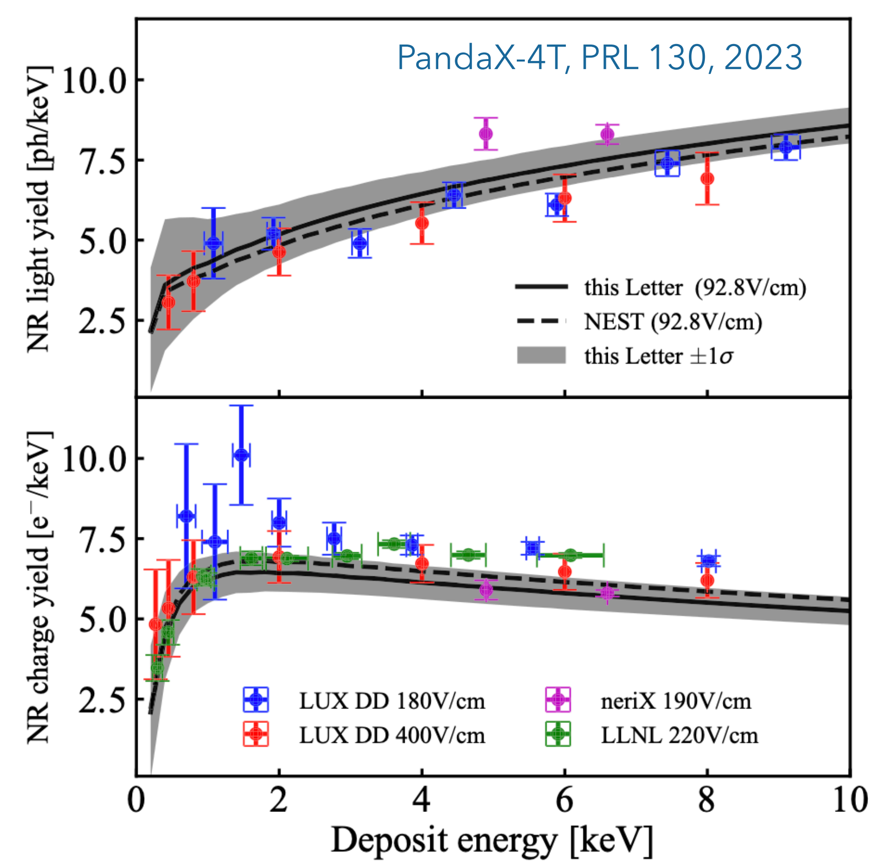
- XENON1T, PandaX-4T
- Searches ongoing in LZ, PandaX-4T, XENONnT

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



PandaX-4T, PRL 130, 2023



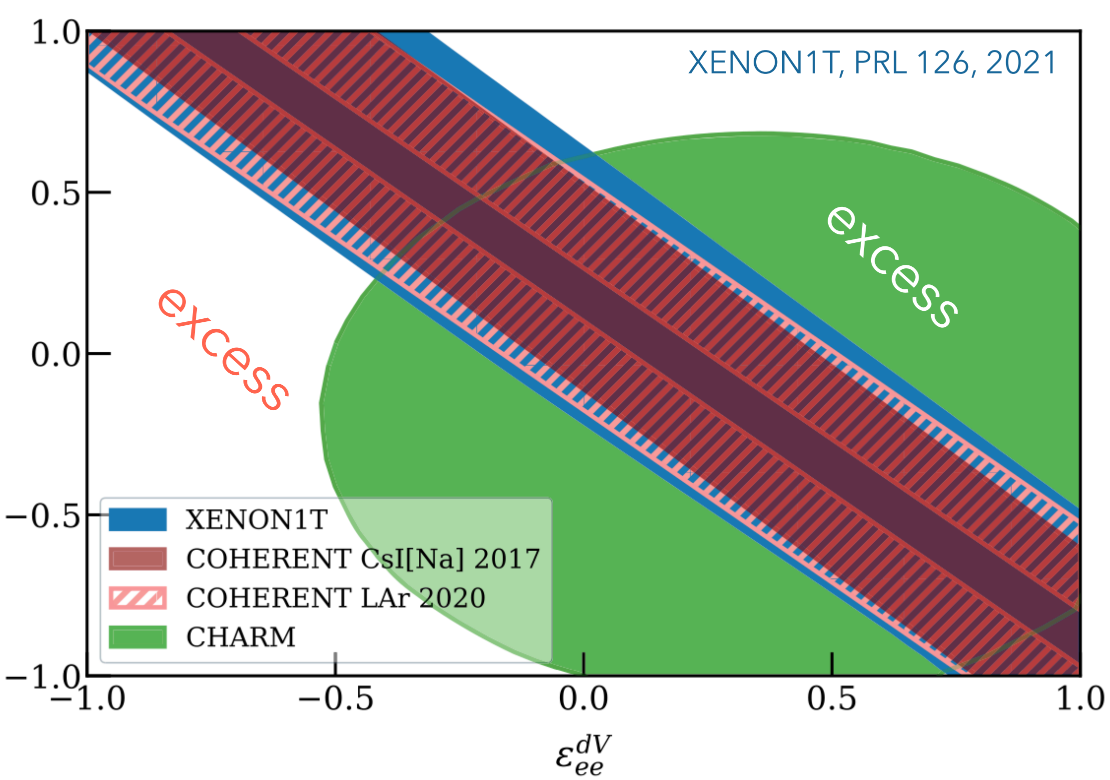


ν-floor: probability for an ideal xenon detector to see < 3-σ DM signal

Non-standard ν interactions

- New physics specific to ν-nucleon interactions poorly constrained
- In general: *model-independent parametrisation* of non-standard contributions to ν-q interaction cross sections (with vector and axial-vector couplings)
- Presence of NSI results in enhancement or suppression of CEνNS rate

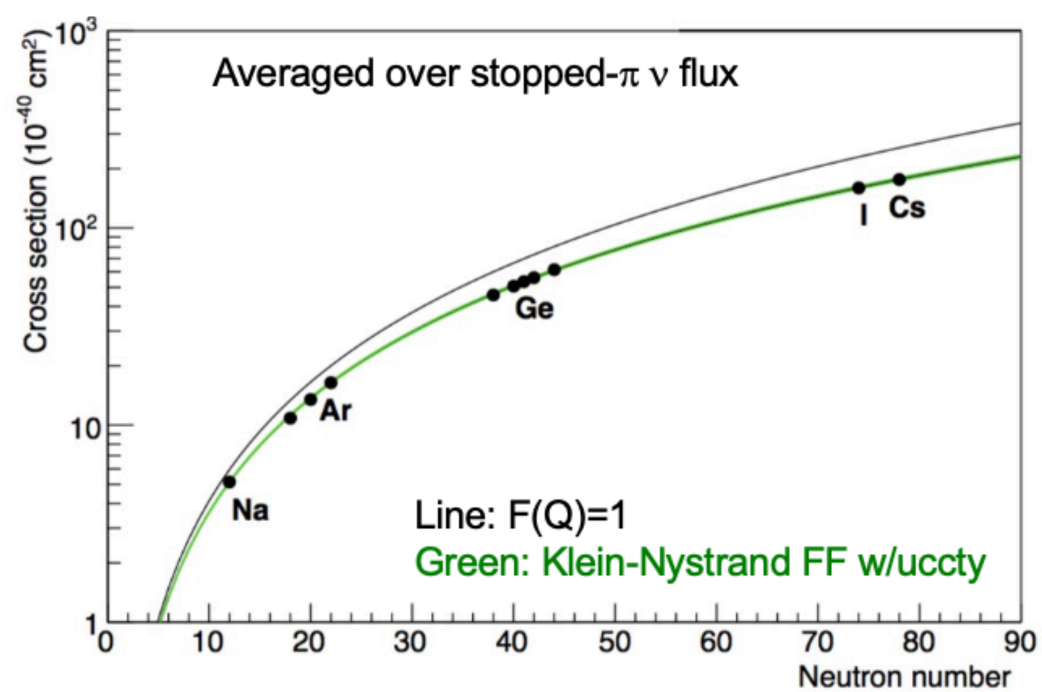
Ratio wrt SM



New ν_e-u quark interaction

New ν_e-d quark interaction

If we see additional or fewer CEνNS than expected in DARWIN/XLZD: could be BSM physics!



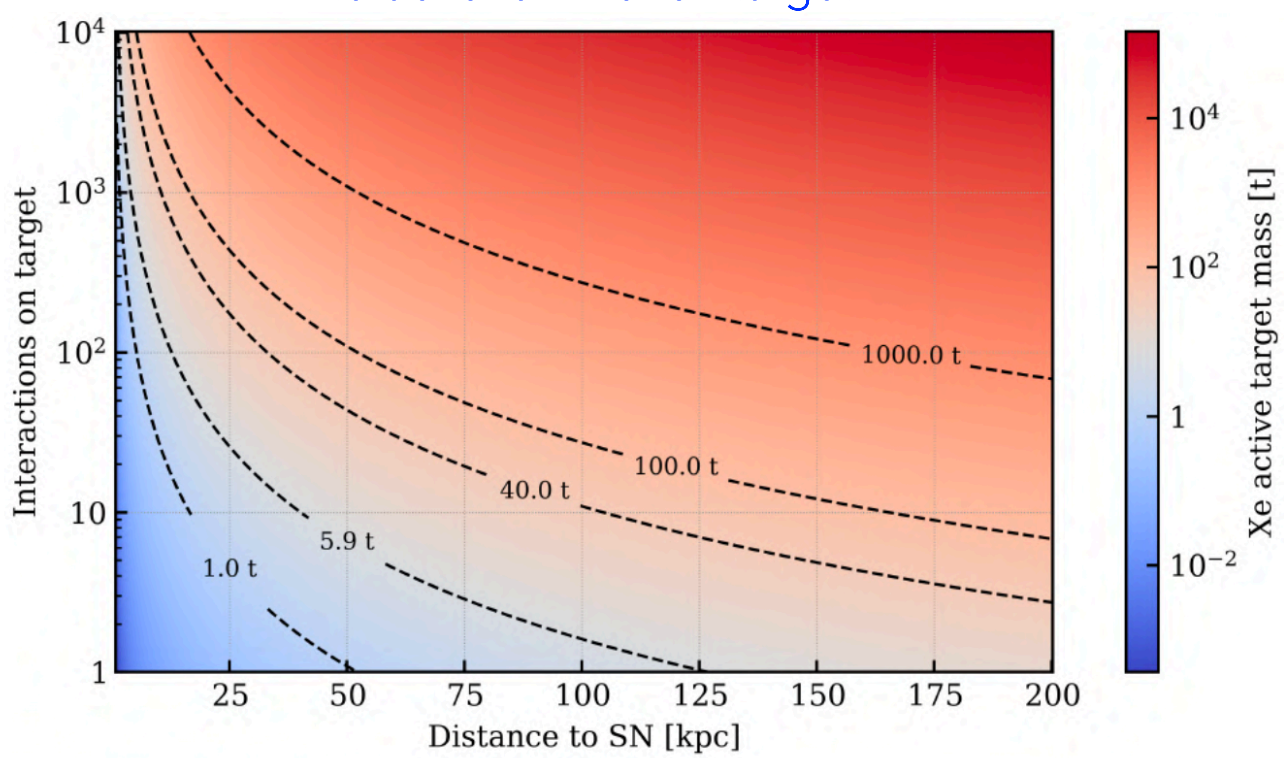
N^2 prediction

At different energies & different systematics than COHERENT

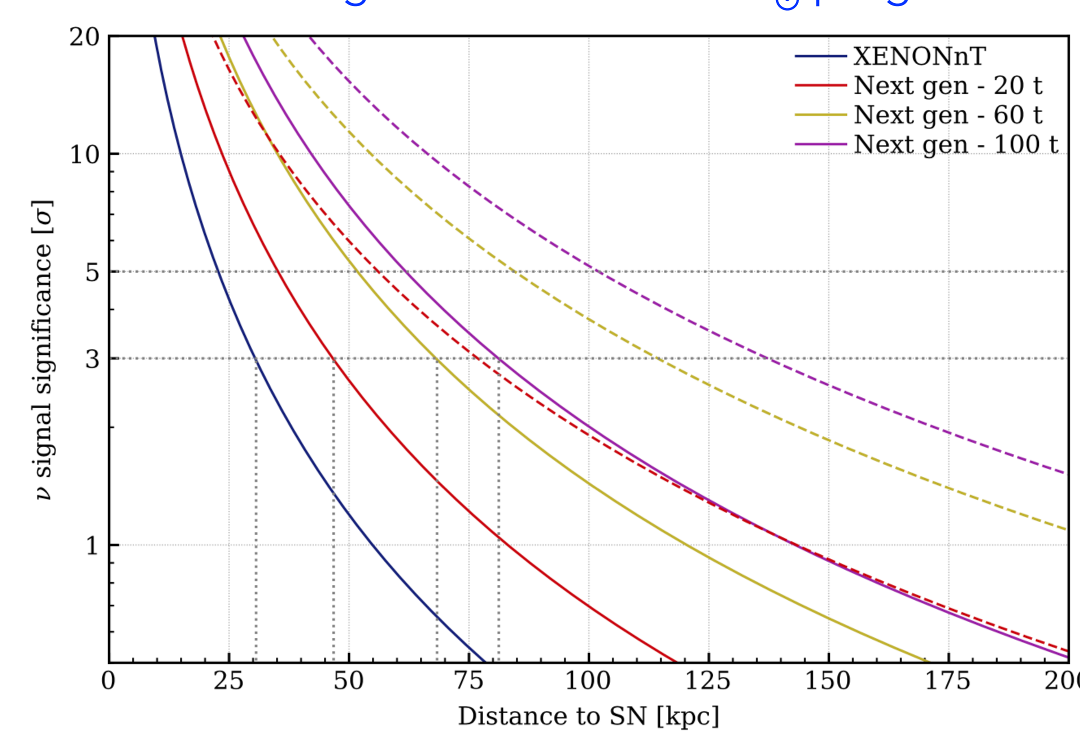
CEvNS with SN neutrinos

- Collapse of a star: ~99% of gravitational binding energy of proto-neutron star goes into ν's of all flavours, ~ 10s of MeV ν energies
- DARWIN/XLZD: sensitivity to all neutrino flavours
  - few events/tonne expected for SN at 10 kpc
  - 700 events (in 40 t) from SN with 27 $M_\odot$ at 10 kpc

Interactions in xenon target



Detection significance for a 27 $M_\odot$ progenitor



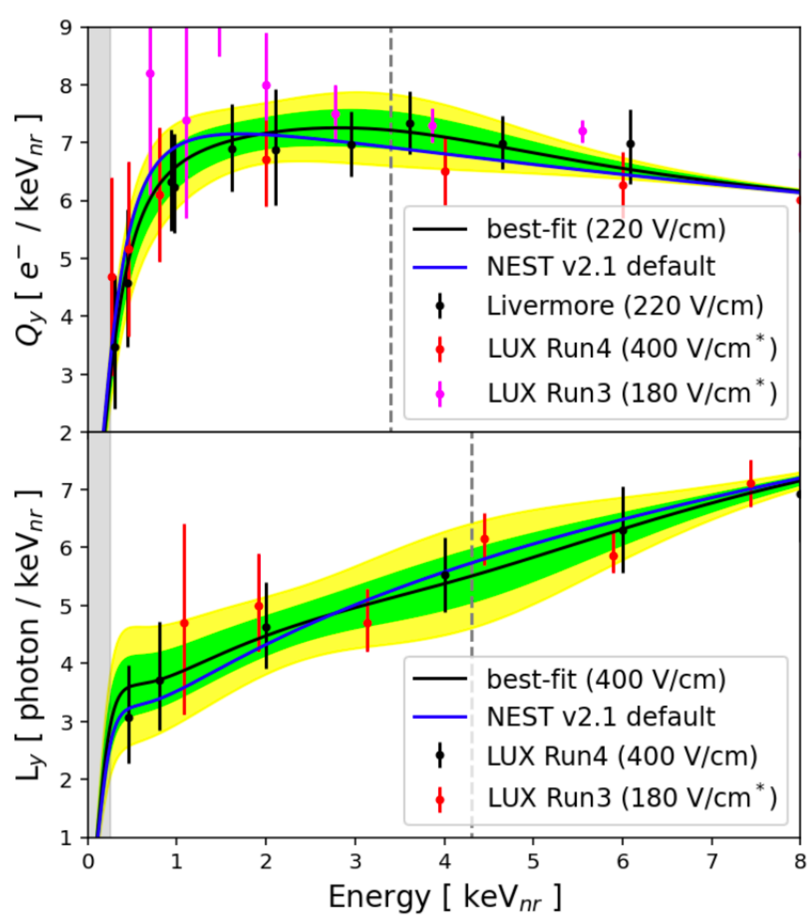
Plots by Ricardo Peres

Some challenges

- 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) in place for DARWIN/XLZD

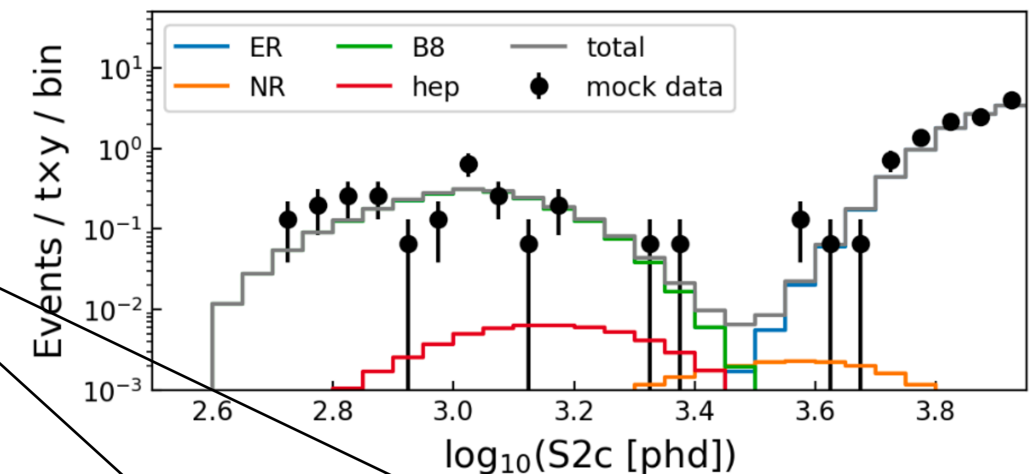
Charge yield

Light yield



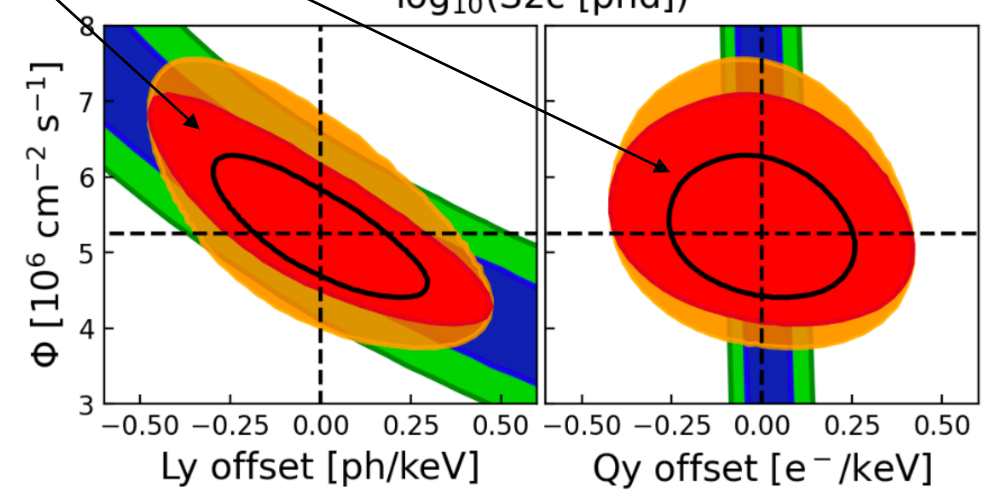
50 t y with Q_y, L_y uncertainties reduced by 1/2

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

Accidental coincidences

- Contribution from ACs to the background at low energies could 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

Study for DARWIN/XLZD by Tina Pollmann