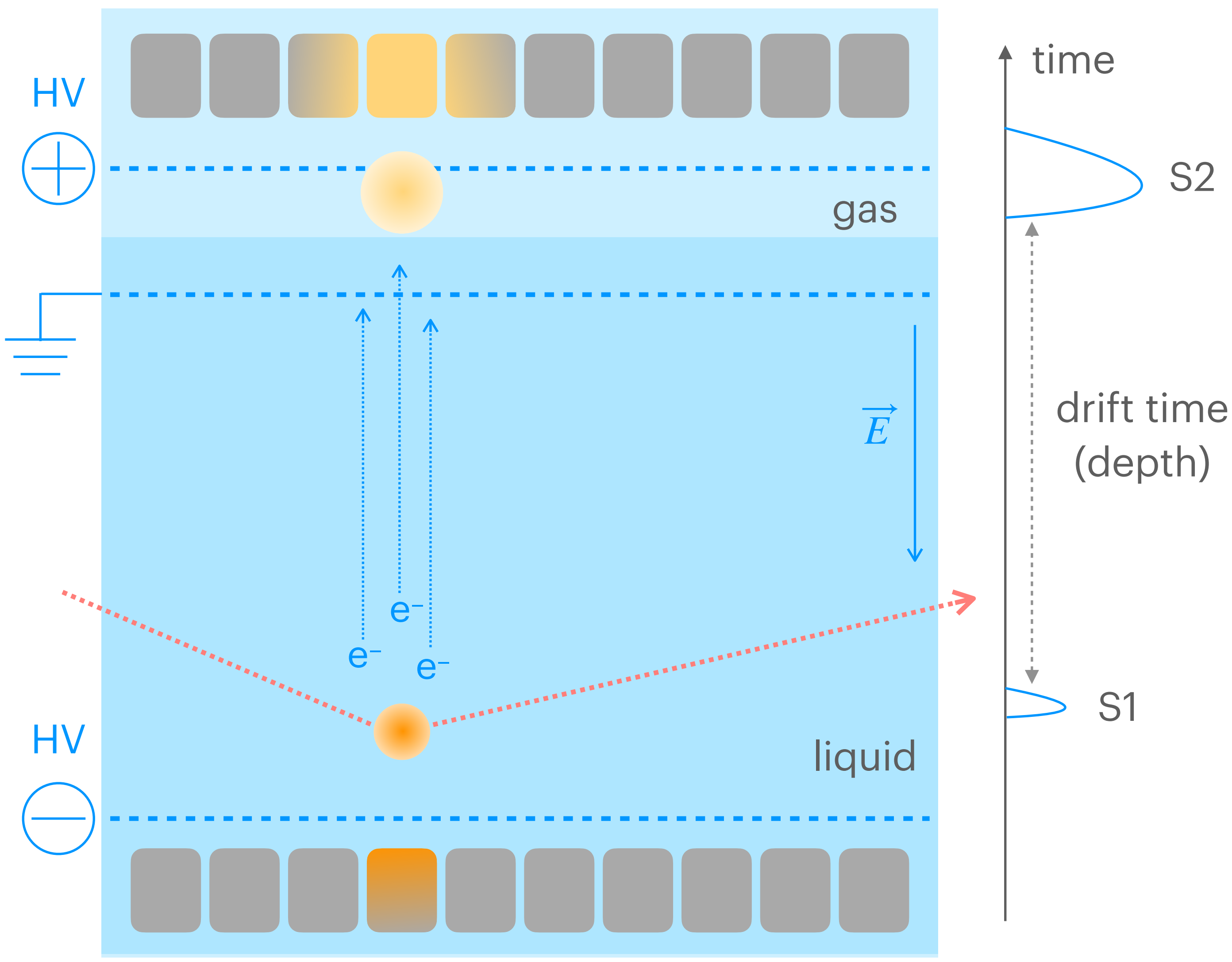
XENON AND DARWIN

LAURA BAUDIS
UNIVERSITY OF ZURICH

CHIPP ROADMAP WORKSHOP

BALSTHAL, JANUARY 18-19, 2024

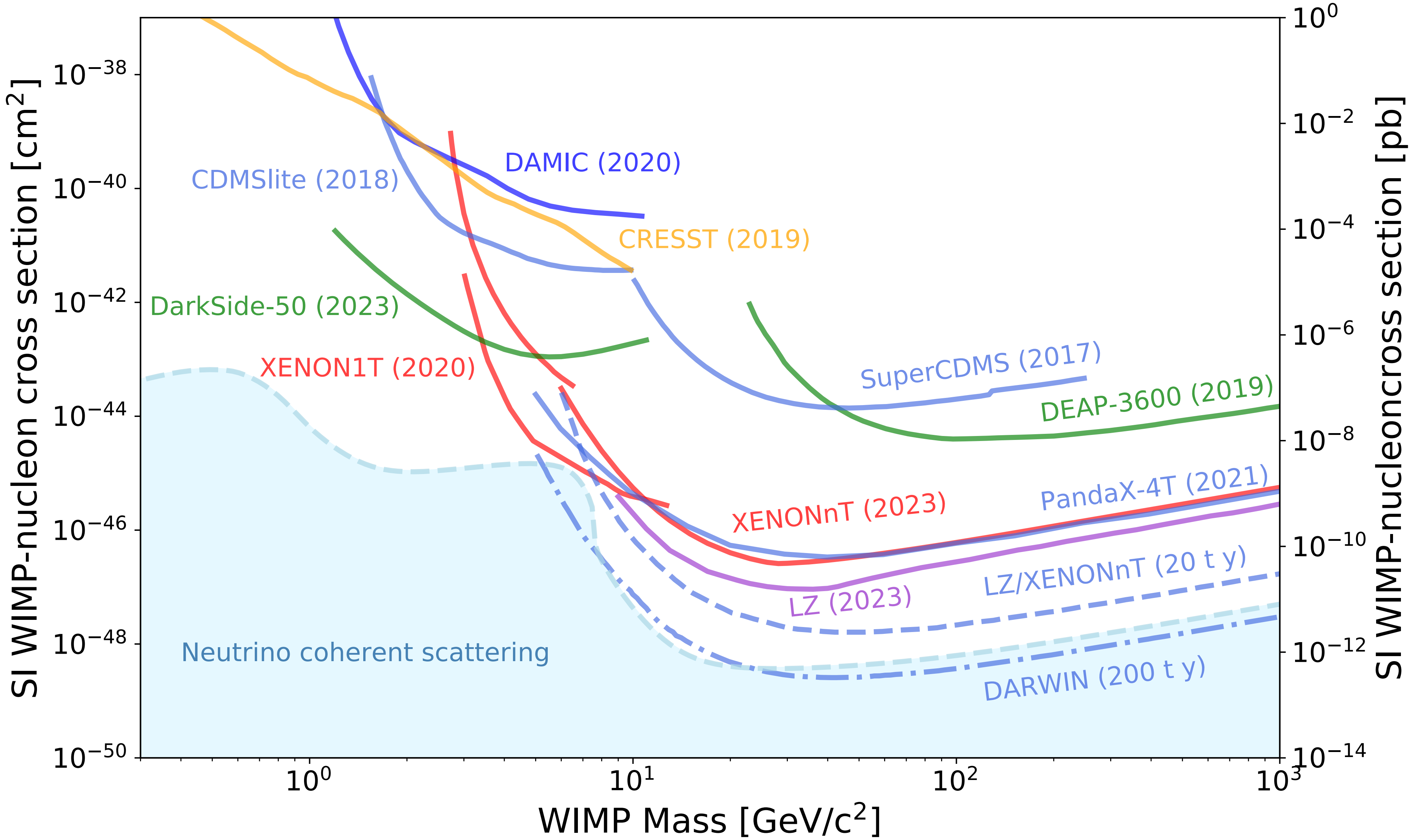
LIQUID XENON TIME PROJECTION CHAMBERS

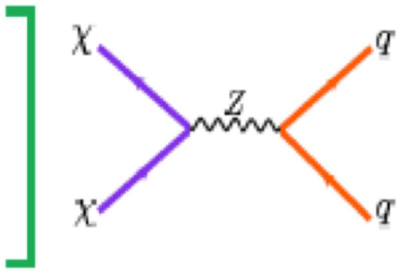


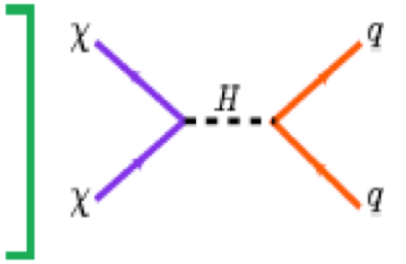
$$\lambda_{LXe} = 175 \text{ nm}$$

- Observe the small light and charge signals when a particle interacts in the dense liquid target
- 3D position reconstruction
- Good energy resolution
- Particle discrimination: ratio of charge/light

TOWARDS THE NEUTRINO FOG…



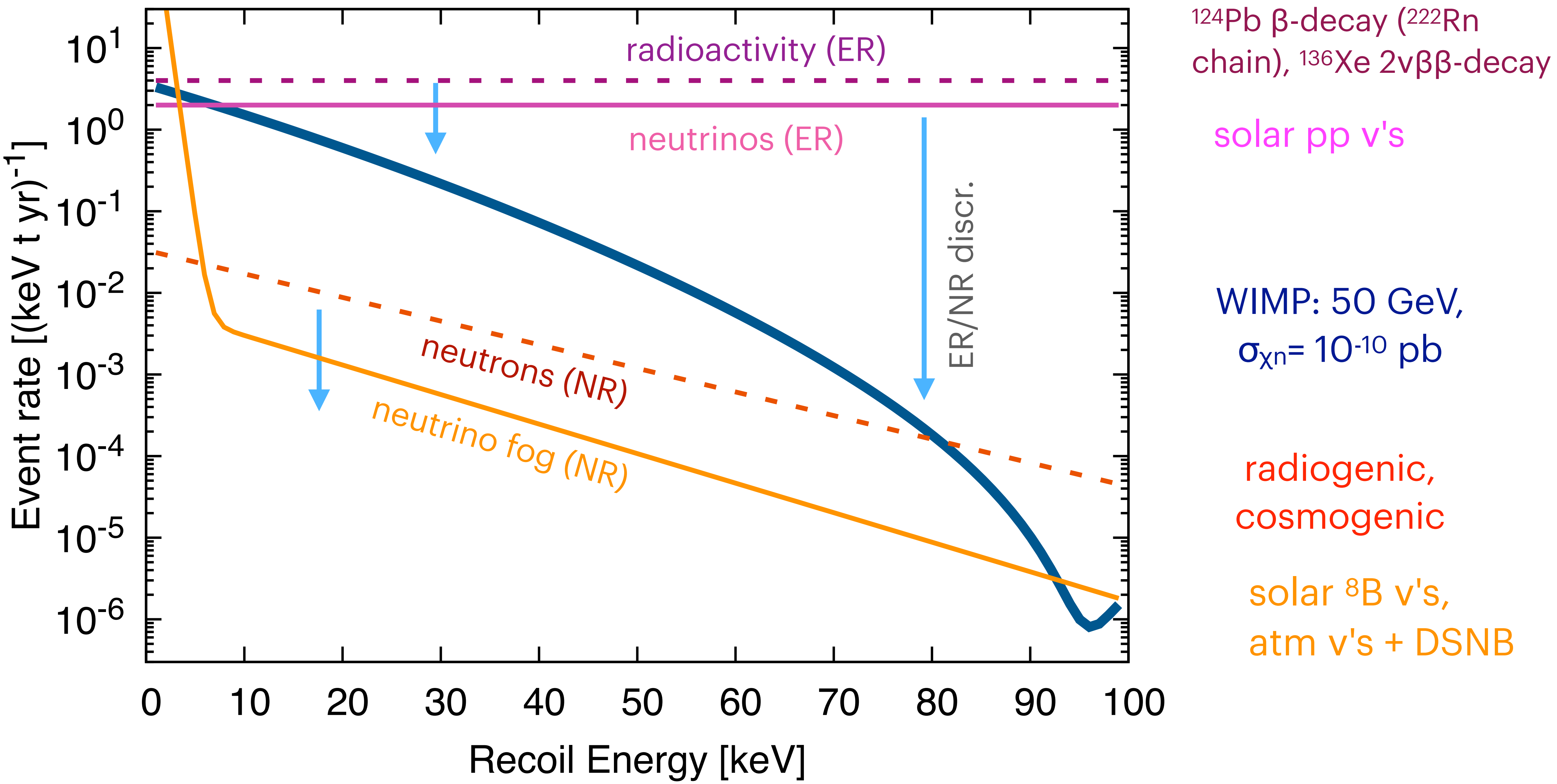




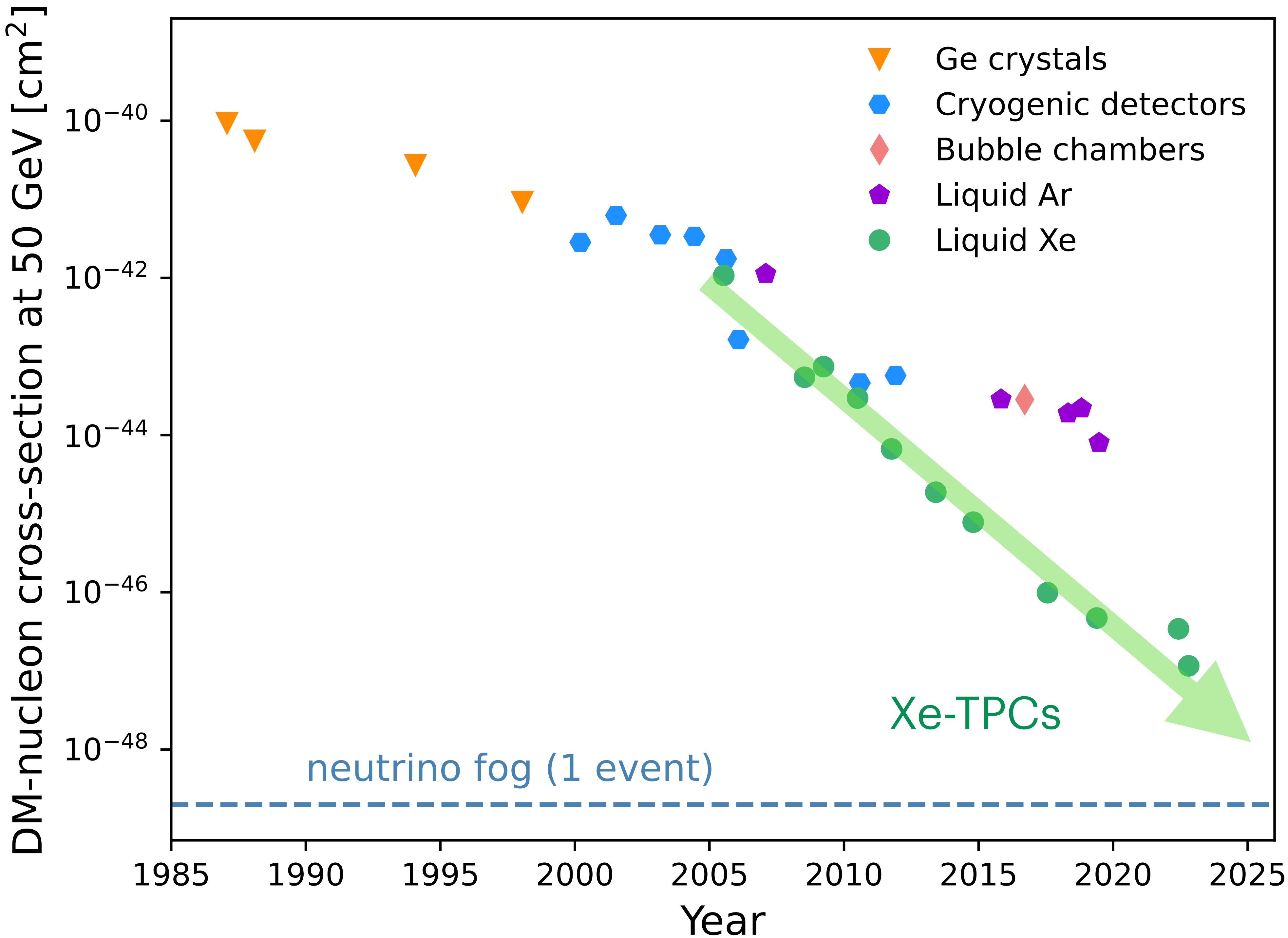
Adapted after LB and Stefano Profumo, PDG 2023

TOWARDS THE NEUTRINO FOG...

- Detectors must become **even larger, even quieter...**



WIMP CROSS SECTION LIMITS VERSUS TIME



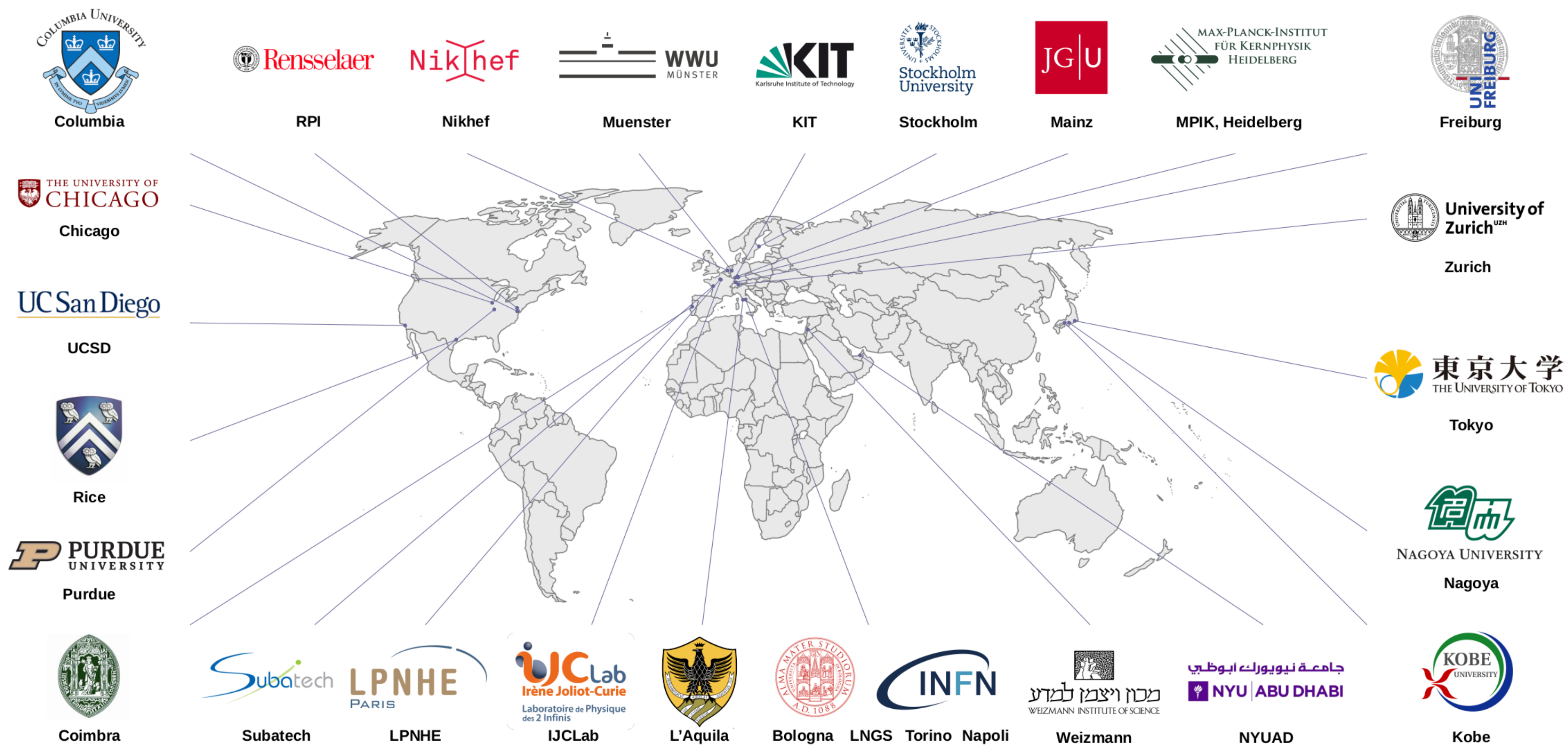
THE XENON COLLABORATION

180 scientists

27 institutions

12 countries

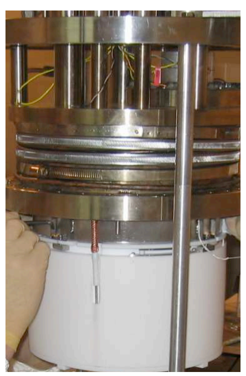
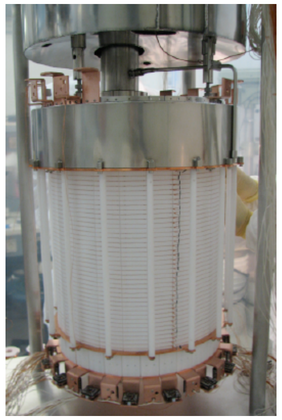
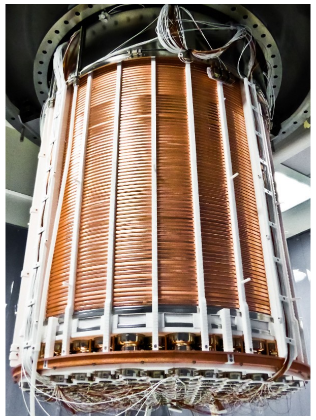
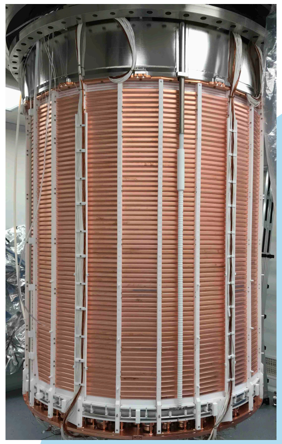
XENON




Sorbonne, Sept. 2023

THE XENON PROJECT AND BEYOND

	XENON10	XENON100	XENON1T	XENONNT	DARWIN/XLZD
	15 kg	161 kg	3.2 t	8.6 t	50 t
EX	0.8 kg y	48 kg y	1 t y	20 t y	200 t y
BI	~1	~5 x 10^{-3}	~2 x 10^{-4}	~3 x 10^{-5}	

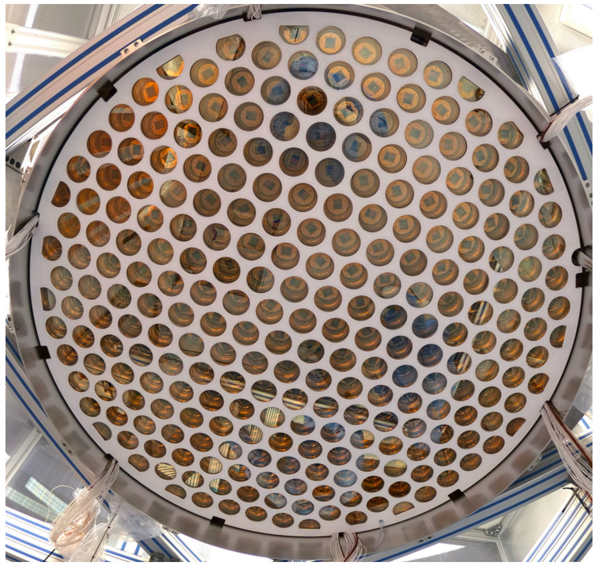
THE XENON-NT EXPERIMENT AT LNGS

UZH: TPC AND PHOTOSENSORS

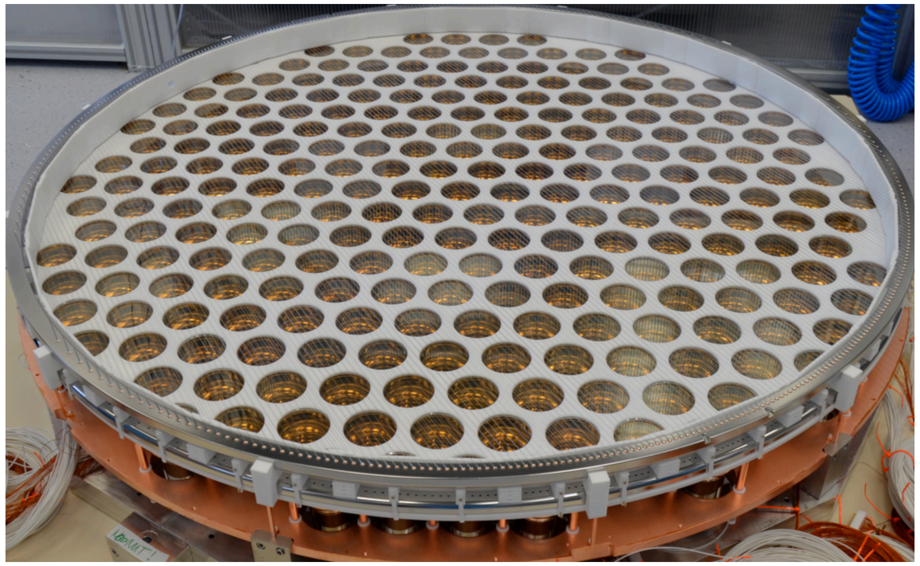
University of Zurich UZH

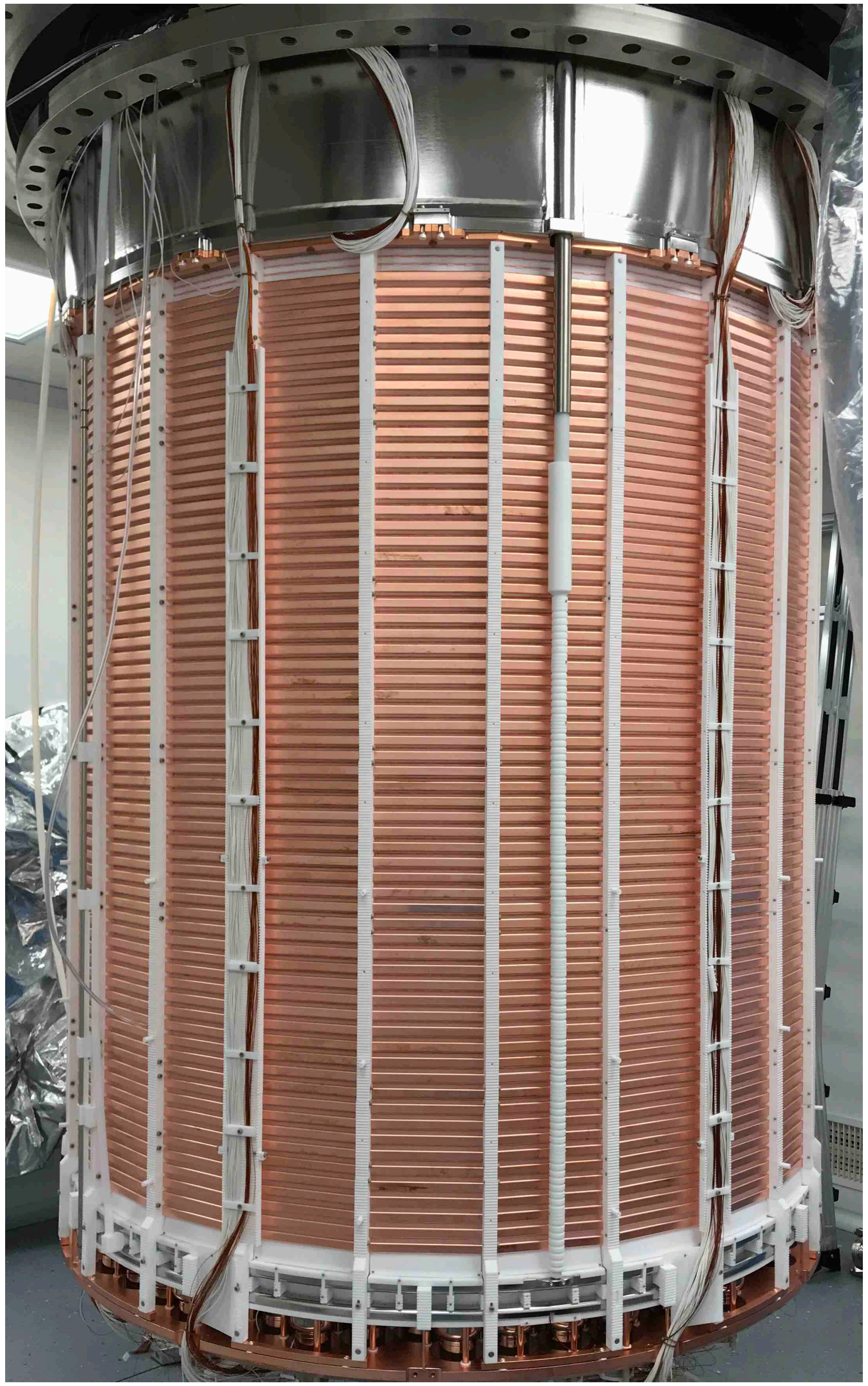
- 1.5 m tall, 1.3 m diameter, 5.9 t LXe
- 494 3-inch diameter PMTs in two hexagonal arrays at the top and bottom of the TPC
- Parallel wire electrodes, ~96% transparency
- 24-gon field cage, 64 guard rings and 72 copper field-shaping wires

253 PMTs top array



241 PMTs bottom array

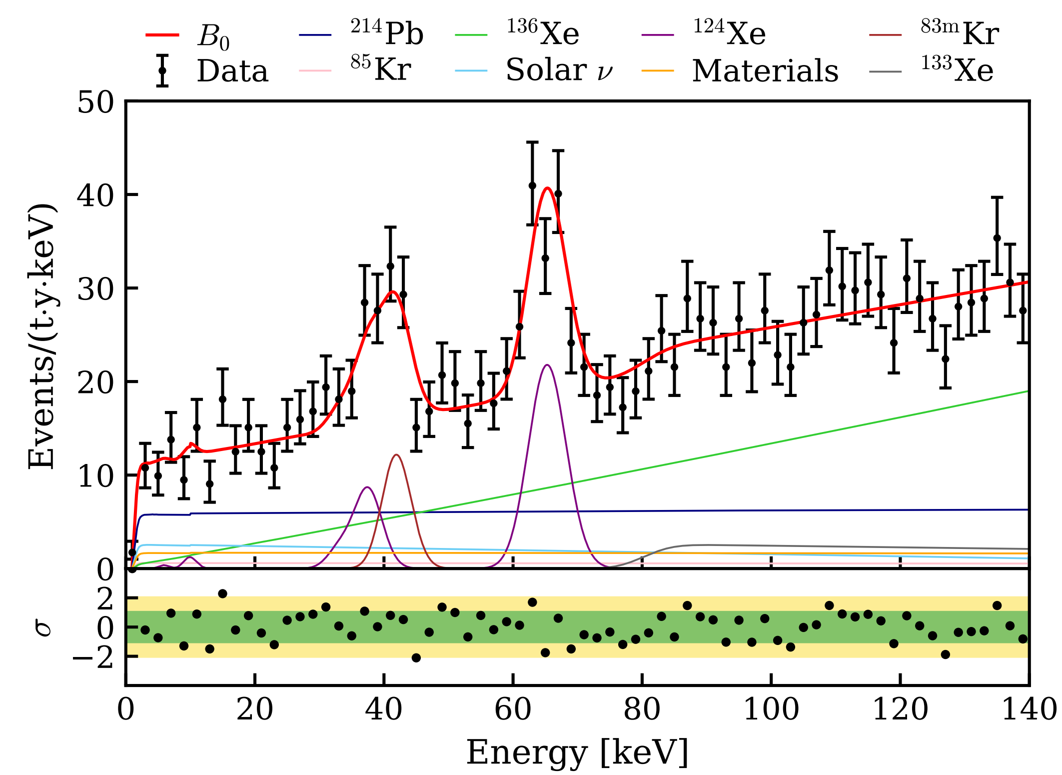


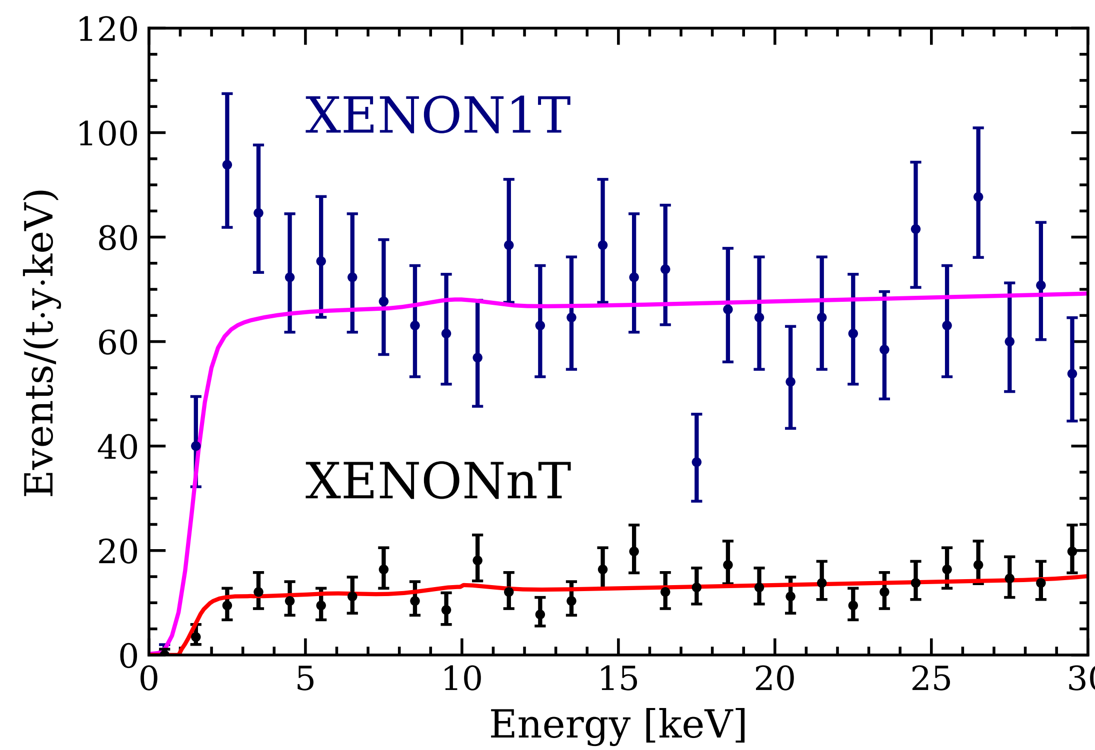


A FIRST BLIND ANALYSIS IN XENON-NT

- Total ER background < 30 keV: **15 events/(t y keV)**: ~ 0.2 x the one of XENON1T; **lowest background in the field**
- No excess observed in XENONnT

	(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

TODAY'S BACKGROUND TOMORROW'S SIGNAL?....

Rn concentration reduced for SR1

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
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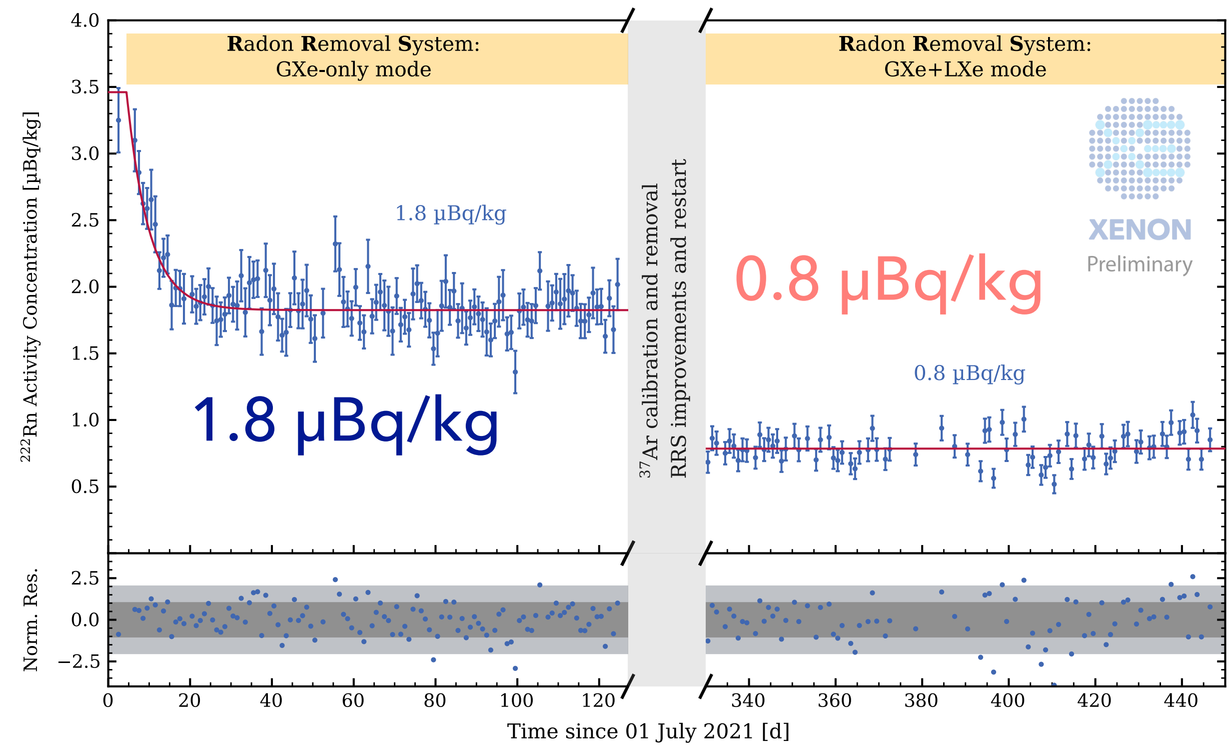
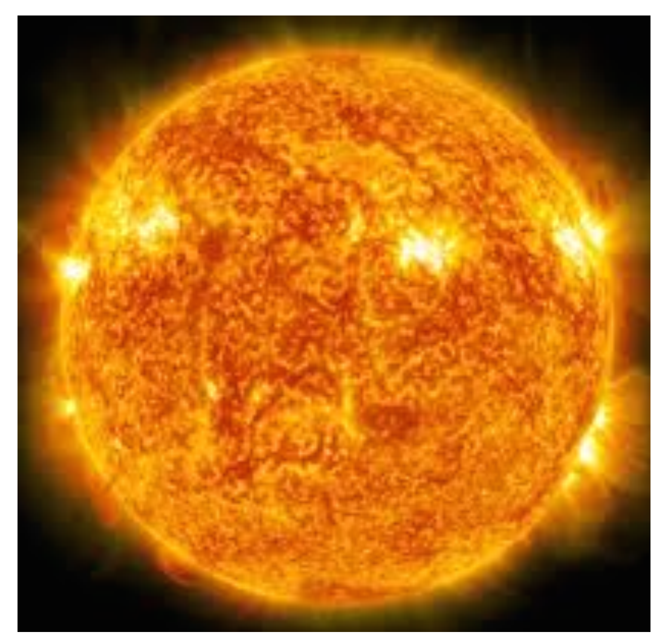
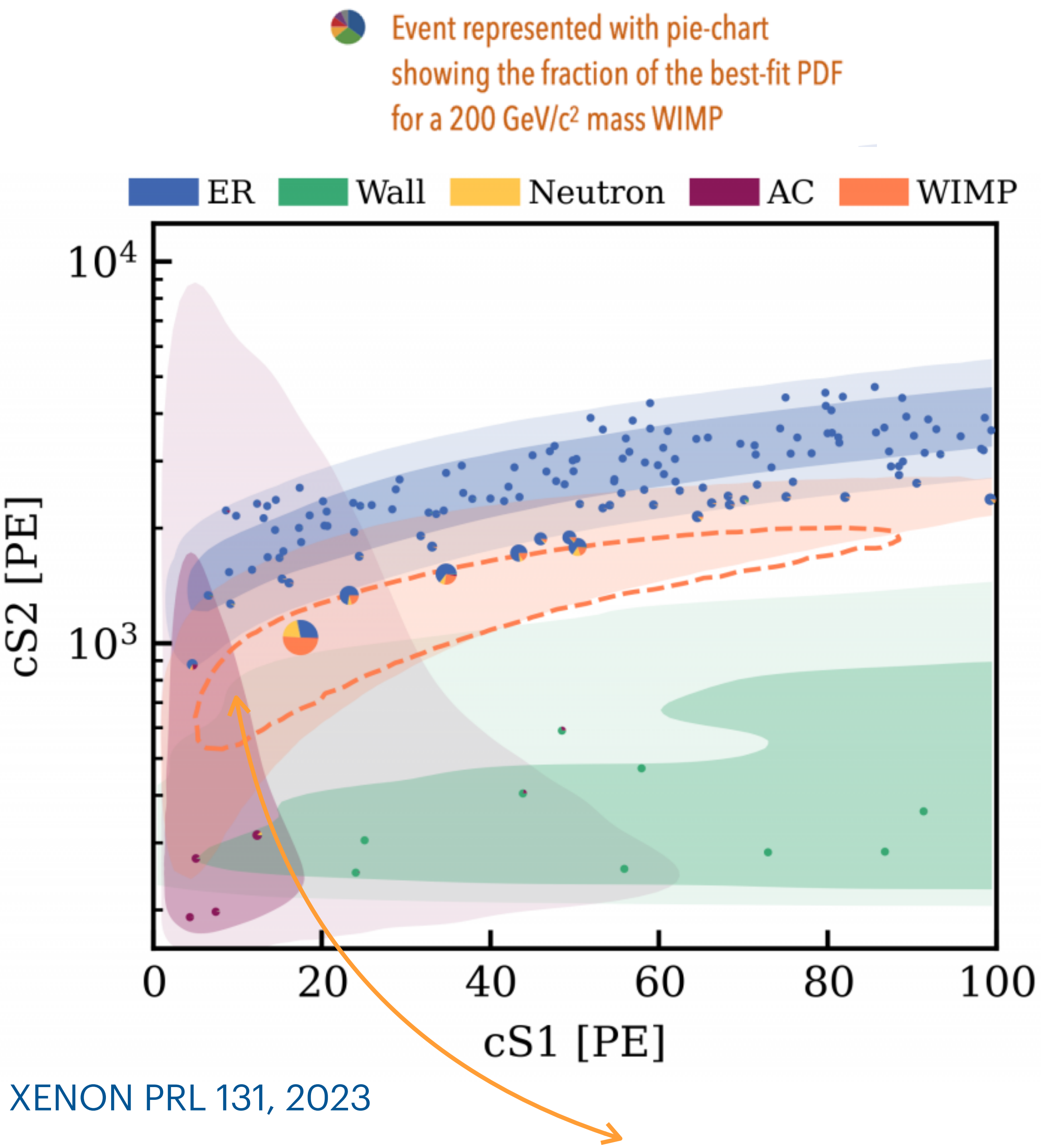


Solar neutrino flux at low energies



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

WIMP SEARCH RESULTS FROM FIRST SCIENCE RUN

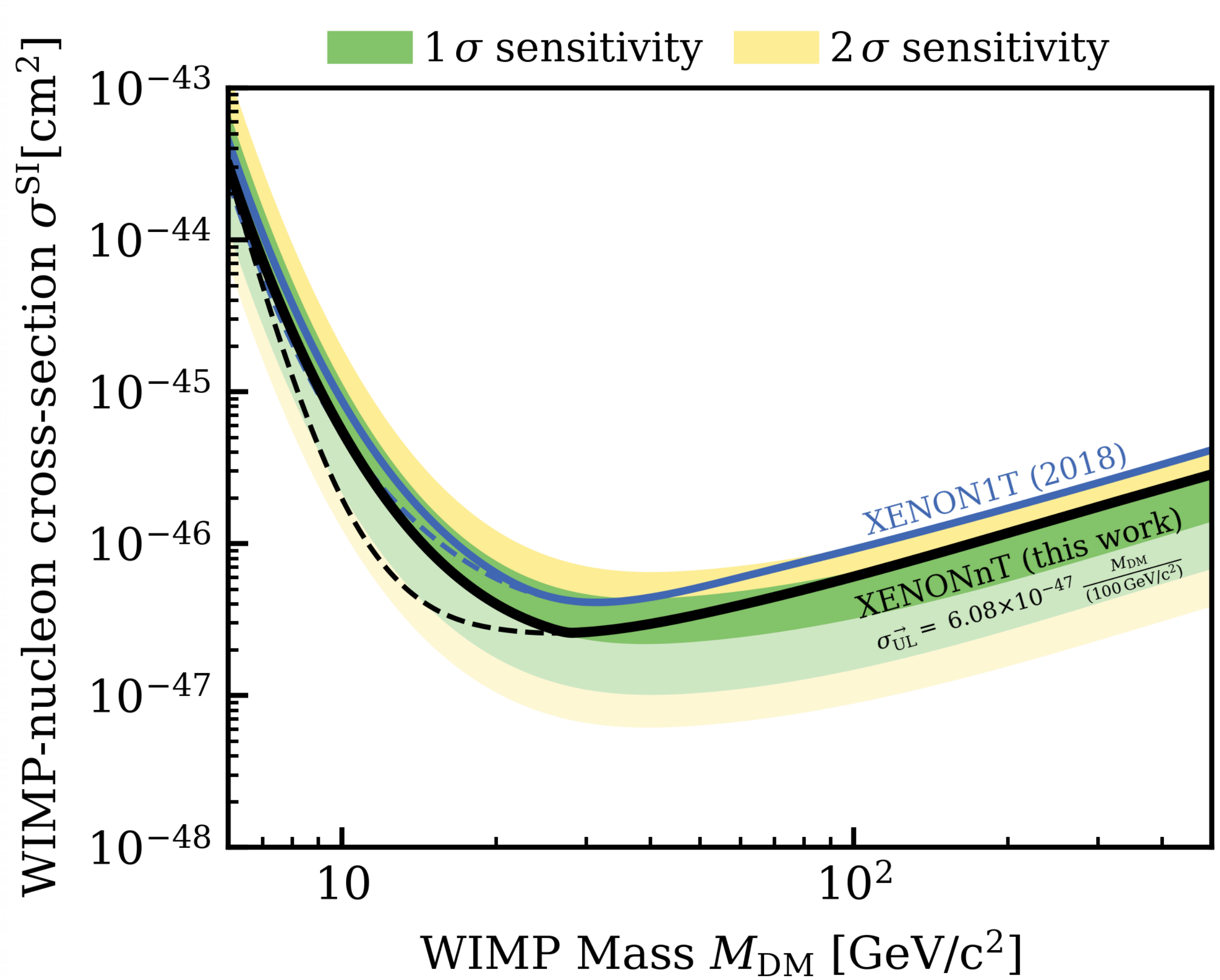


XENON PRL 131, 2023

2σ contour of 200 GeV/c² WIMP

Minimum upper limit on SI WIMP-nucleon cross sections:

2.58×10^{-47} cm² (90% C.L.) at 28 GeV/c²

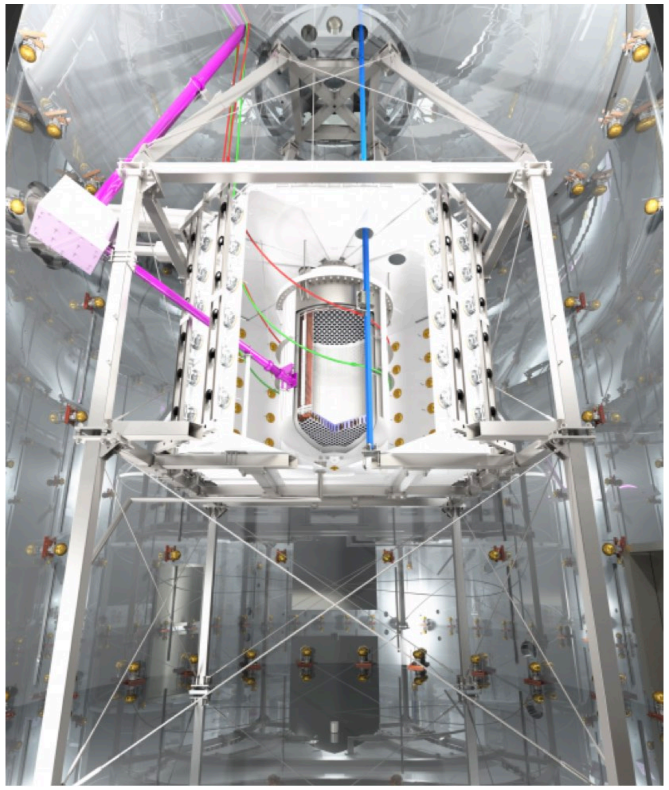


XENONnT 90% C.L. Power-Constrained Limit

(arXiv:1105.3166, arXiv:2105.00599 with 50% [median] rejection power)

XENON PHYSICS, STATUS AND PLANS

- Science Run 1: under analysis
- Science Run 2: ongoing
- Data taking until ~ 2026 to reach 20 t y



Nuclear recoils

WIMP DARK MATTER
PRL 119, 181301
PRL 121, 111302
PRL 122, 071301
PRL 122, 141301
PRL 126, 091301
PRD 103, 063028
PRL 131, 041003

LIGHT DARK MATTER
PRL 123, 241803
PRL 123, 251801

PLANCK MASS DARK MATTER
PRL 130, 261002

SOLAR ^{8}B CEvNS
PRL 126, 091301

XENONNT WILL IMPROVE UPON ALL THESE PUBLISHED RESULTS

Electronic recoils

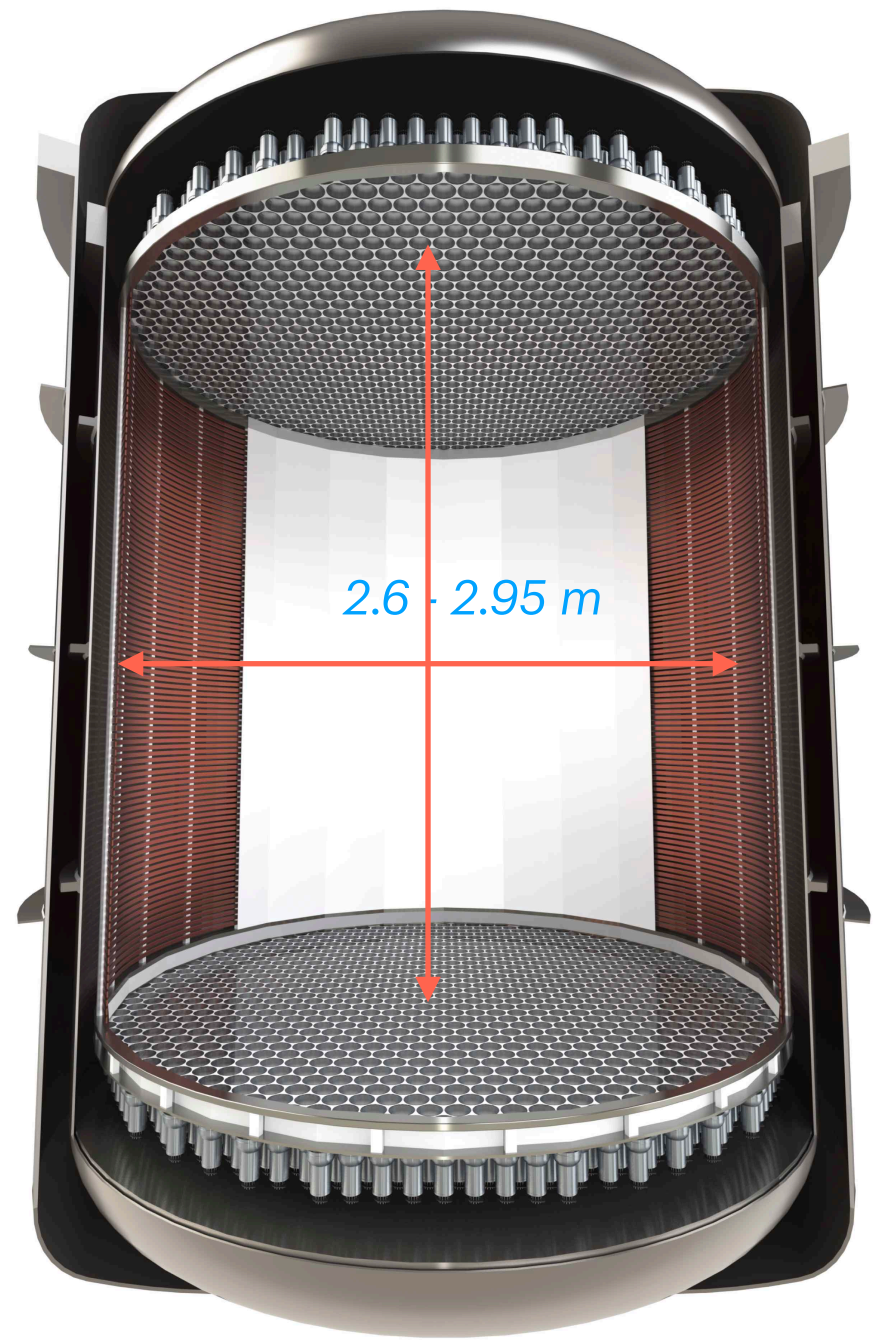
BOSONIC DARK MATTER, SOLAR AXIONS, NEUTRINO MAGNETIC MOMENT
PRD 102, 072004
PRL 129, 161805

DOUBLE ELECTRON CAPTURE
Nature 568, 532
Phys. Rev. C 106, 024328

NEUTRINOLESS DOUBLE-β DECAY
EPJ C (2020) 80:785
Phys. Rev. C 106, 024328

FUTURE: THE DARWIN PROJECT

- Total mass: 50 t LXe (40 t active target in the TPC) at LNGS
- 1900 3-inch PMTs (baseline design)
- Gd-doped water n and μ vetoes
- R&D and prototyping in progress
- XLZD: 75 t LXe (60 t active target), several labs are considered



DARWIN collaboration
JCAP 1611 (2016) 017

THE XENON-LZ-DARWIN 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

Eidgenössisches Departement für Wirtschaft, Bildung und Forschung WBF
Confederazione Svizzera
Confederaziun svizra
Staatssekretariat für Bildung, Forschung und Innovation SBFI
Forschung und Innovation

Research infrastructures ·

XENON AND DARWIN

- On the Swiss Research Infrastructures Roadmap since 2015, roadmap was updated in 2023

9. The future of dark matter detection with liquid xenon XENONnT and DARWIN

Category: Instrument
Host institution(s): University of Zurich
Main funding sources: SNSF, FLARE, ERC
Roadmap entry: 2015

Description / Development prospects
a. National level
Overview
DARk matter WImp search with Noble liquids (DARWIN) is a new observatory in astroparticle physics, with the aim of identifying the nature of dark matter, revealing the nature of neutrinos (via the search for neutrinoless double beta decay of ^{136}Xe), observing solar neutrinos via elastic neutrino-electron and coherent neutrino-nucleus scatters, as well as solar axions and axion-like particles. DARWIN will employ a time projection chamber (TPC) filled with liquid xenon (50 tons in total, 40 tons inside the TPC), viewed by arrays of VUV-sensitive photosensors to detect both light and charge signals after a particle interacts with the xenon target. The TPC and its cryostat will be surrounded by a 12 m water Cherenkov shield, to veto interactions of cosmic muons and their secondary the photosensors, as well as in material screening with a high-purity germanium facility.

DARWIN is in the R&D and design phase, supported by three ERC grants. As part of the ERC project, the UZH group is focusing on optimisation of the TPC, namely its light and charge readout. The UZH group constructed a vertical TPC prototype, Xenoscope, to demonstrate electron drift over 2.6 m (the final size of the DARWIN TPC), and is investigating new, solid-state photosensors (SiPMs) as well as novel photomultiplier tubes (PMTs), which are excellent candidates to replace the existing, 3-inch diameter PMTs.

b. International level
The DARWIN observatory will be built and operated by an international consortium of 38 groups from Europe, Asia, USA and Australia. In addition, in July 2021 the members of the DARWIN/XENON collaborations signed an MoU with the members of the LZ collaboration to form the XLZD consortium (xlzd.org) to design, construct, and operate a new, single, multi-tonne scale xenon observatory

DARWIN AND A G3 PROJECT

- Recommended in the APPEC Mid-Term Roadmap Update (2023) and in the P5 report in the US

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

APPEC Roadmap Update

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").

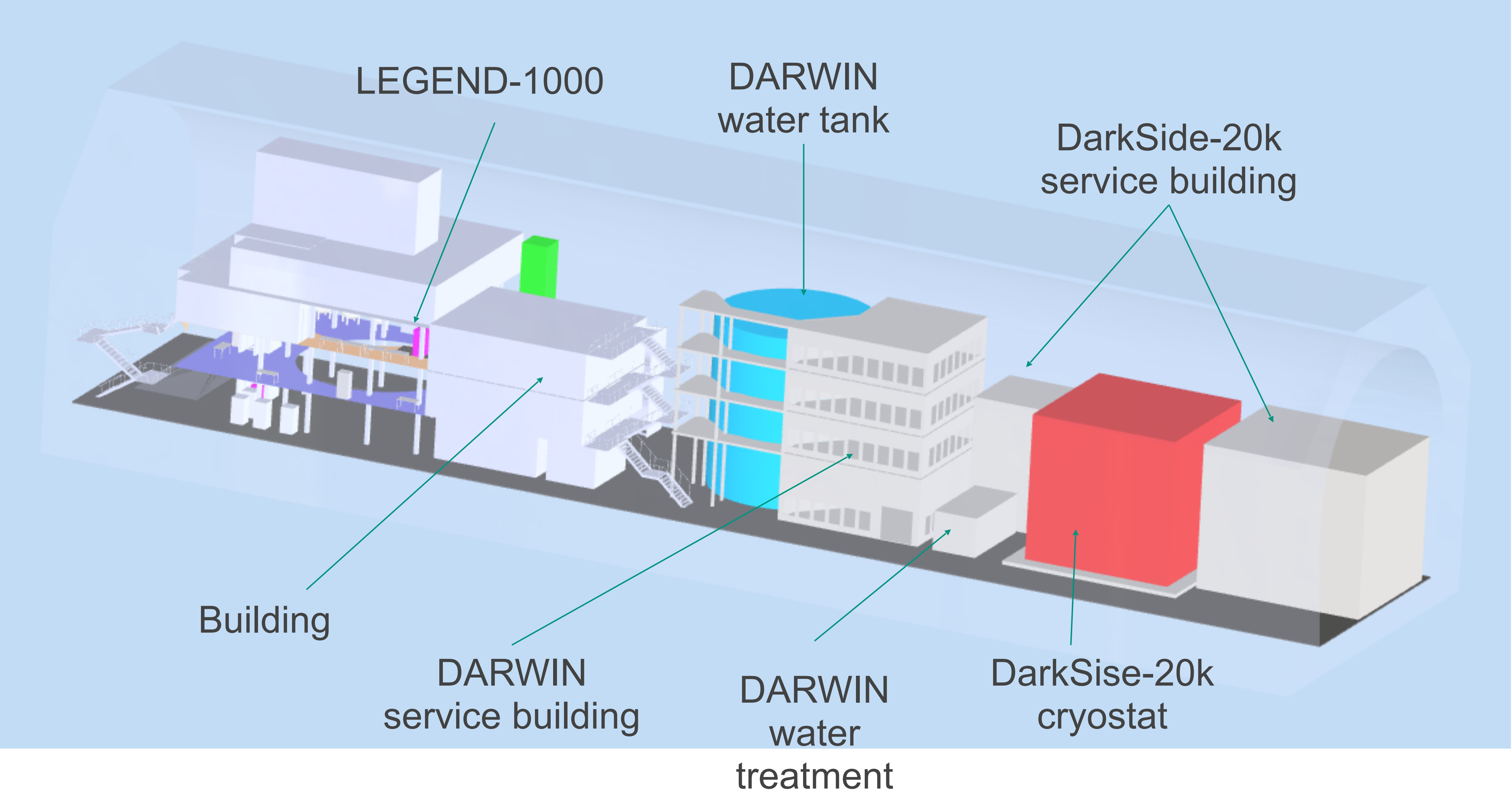
This improvement in reach would provide coverage of important benchmark WIMP models, such as most remaining potential dark matter parameter space under the constrained minimal supersymmetric extension to the Standard Model. Such a G3 experiment would also perform important measurements of solar and possibly 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.

P5 Report

DARWIN AT LNGS, HALL C

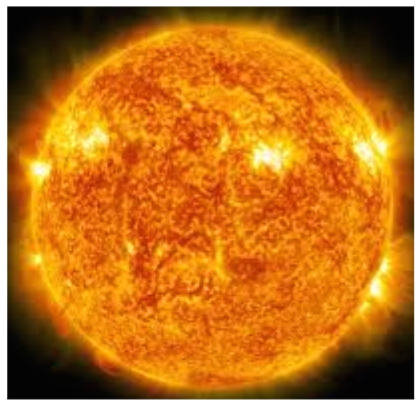
PRELIMINARY

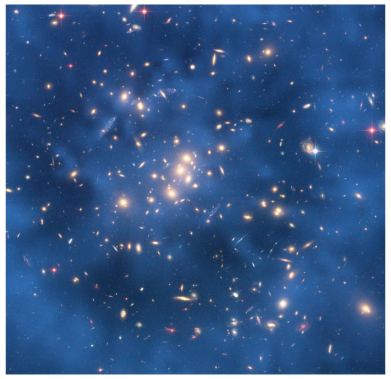


MULTI-PURPOSE OBSERVATORY FOR RARE EVENTS

Solar neutrinos (pp + ^{8}B)

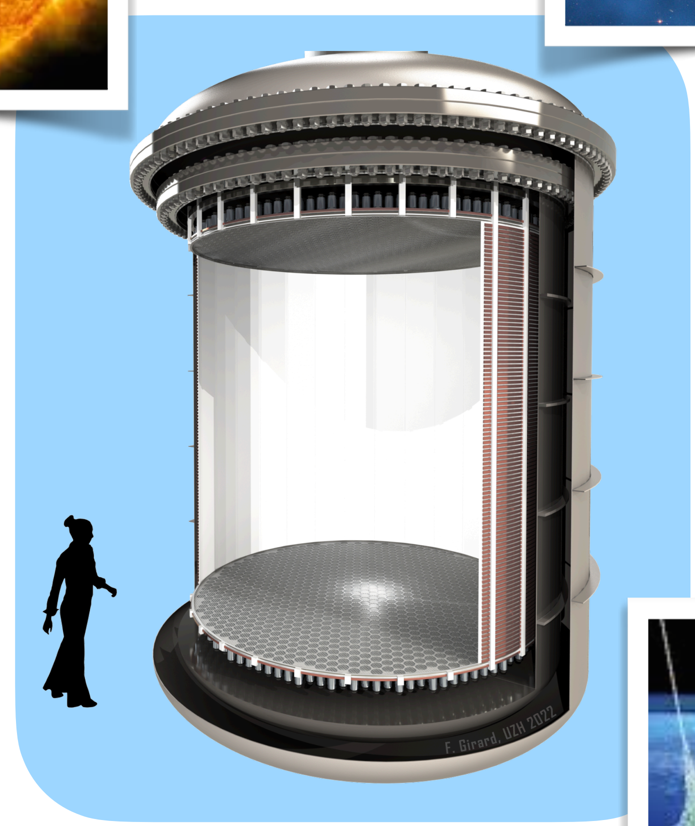
Eur. Phys. J. C 80, 12 (2020)
Phys.Rev.D 106 (2022)

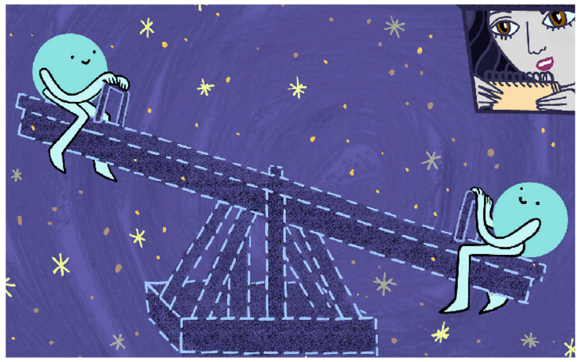




Dark matter

JCAP 10, 016 (2015)



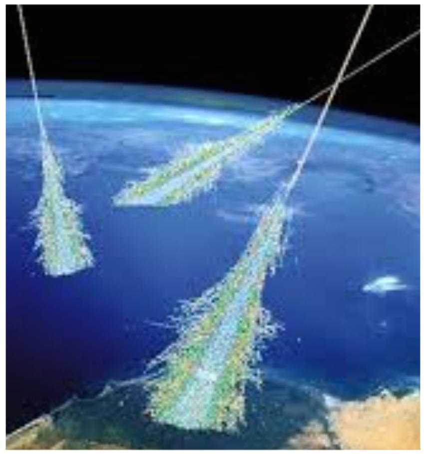


Neutrino nature

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)

LARGE-SCALE DEMONSTRATORS FOR DARWIN

- Full scale demonstrators in *z* and in *x-y*, supported by ERC grants
  - *Xenoscope*, 2.6 m tall TPC and *Pancake*, 2.6 m ø TPC in double-walled cryostats
  - Facilities available to the collaboration/consortium for R&D purposes
  - LowRad to demonstrate large-scale cryogenic distillation at Münster

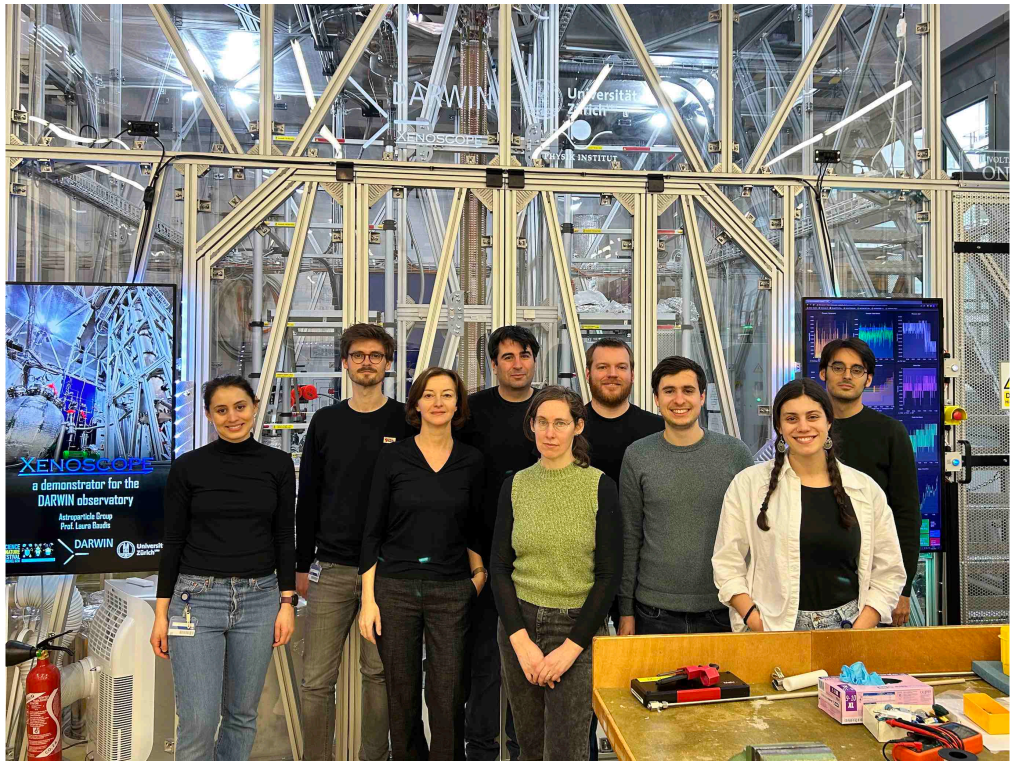
Vertical demonstrator: *Xenoscope*

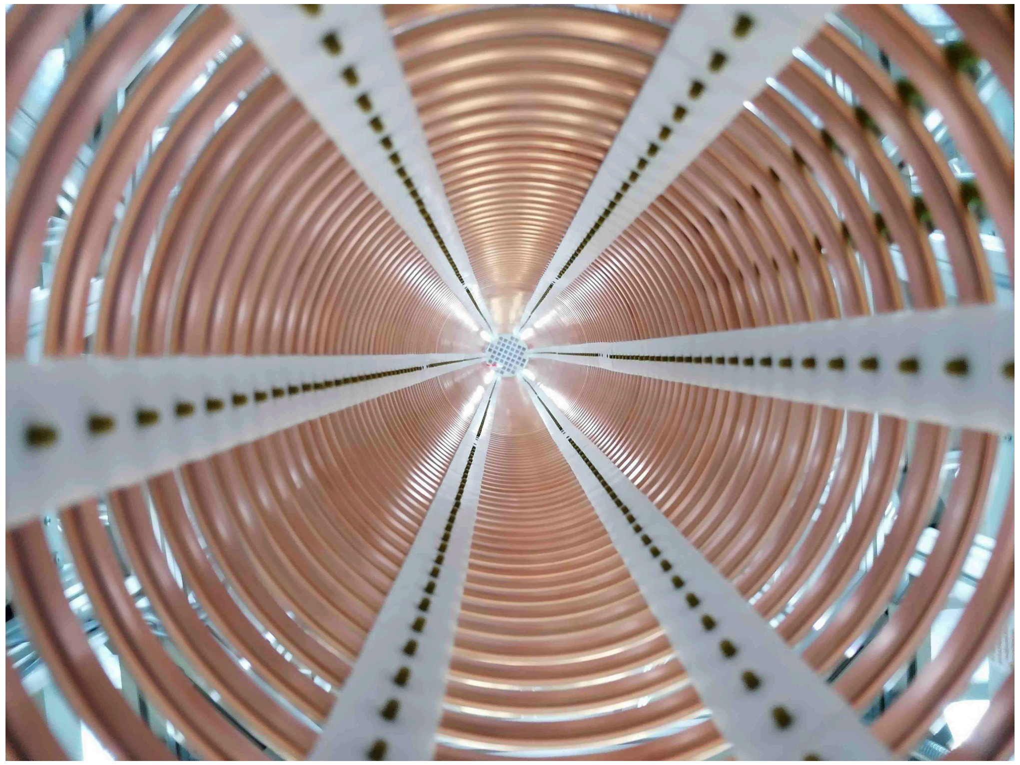
L. Baudis et al, JINST 16, P08052, 2021

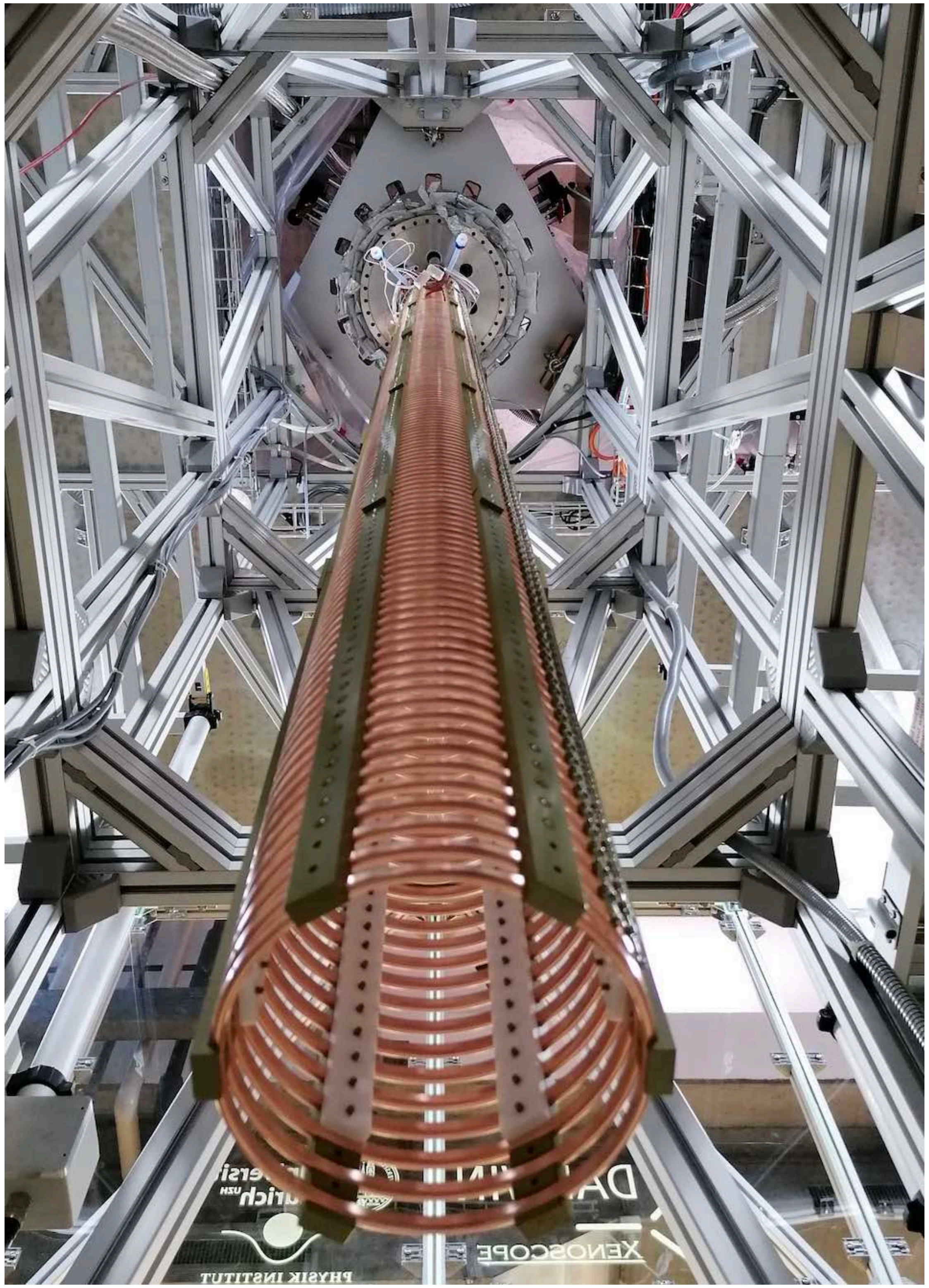
Horizontal demonstrator: *Pancake*

Test electrodes with 2.6 m Ø

XENOSCOPE: TPC INSTALLED AND LXE RUN EARLY THIS YEAR







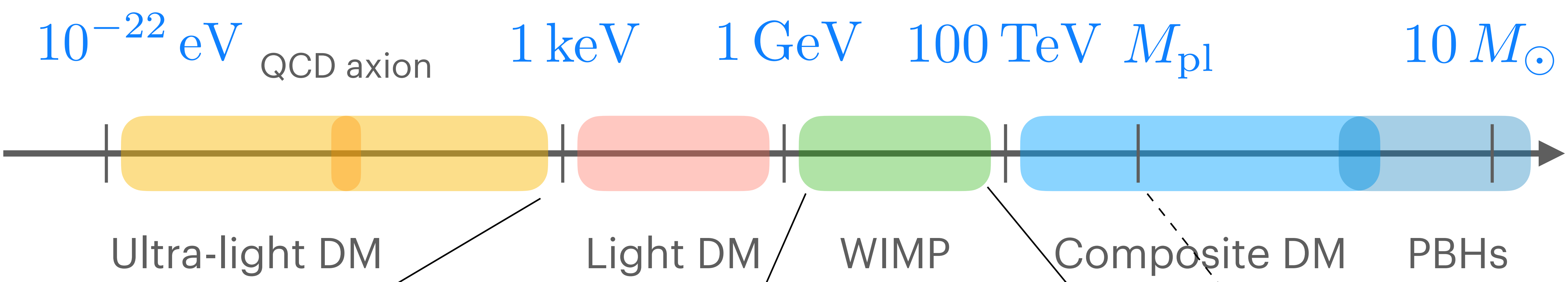
UZH MAIN RESPONSIBILITIES IN XENON AND DARWIN

- Low-background PMT development, tests and readout (co-leading XENON PMT WG)
- Design and construction of the TPC (including photosensor arrays and HV feedthrough (co-leading DARWIN detector WG)
- Prototyping the TPC in the full-scale z-dimension
- Test of new photosensors (SiPMs, 2-inch square PMTs) and their readout
- Development and prototyping of gravity-assisted LXe storage system (BoX)
- Identification of radio-pure materials with Gator (HPGe detector) (co-leading cleanliness WG)
- MC simulations and physics studies (co-leading XENON MC WG, analysis coordinator member of UZH group); LB chair of XENON SST, SP of DARWIN)

SUMMARY & OUTLOOK

- In the worldwide race to directly detect dark matter particles, liquid xenon detectors are at the forefront
- XENONnT presented first results, and continues to take data at LNGS to reach design exposure
- 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!)*

DARK MATTER CANDIDATES AND LXE-TPCS

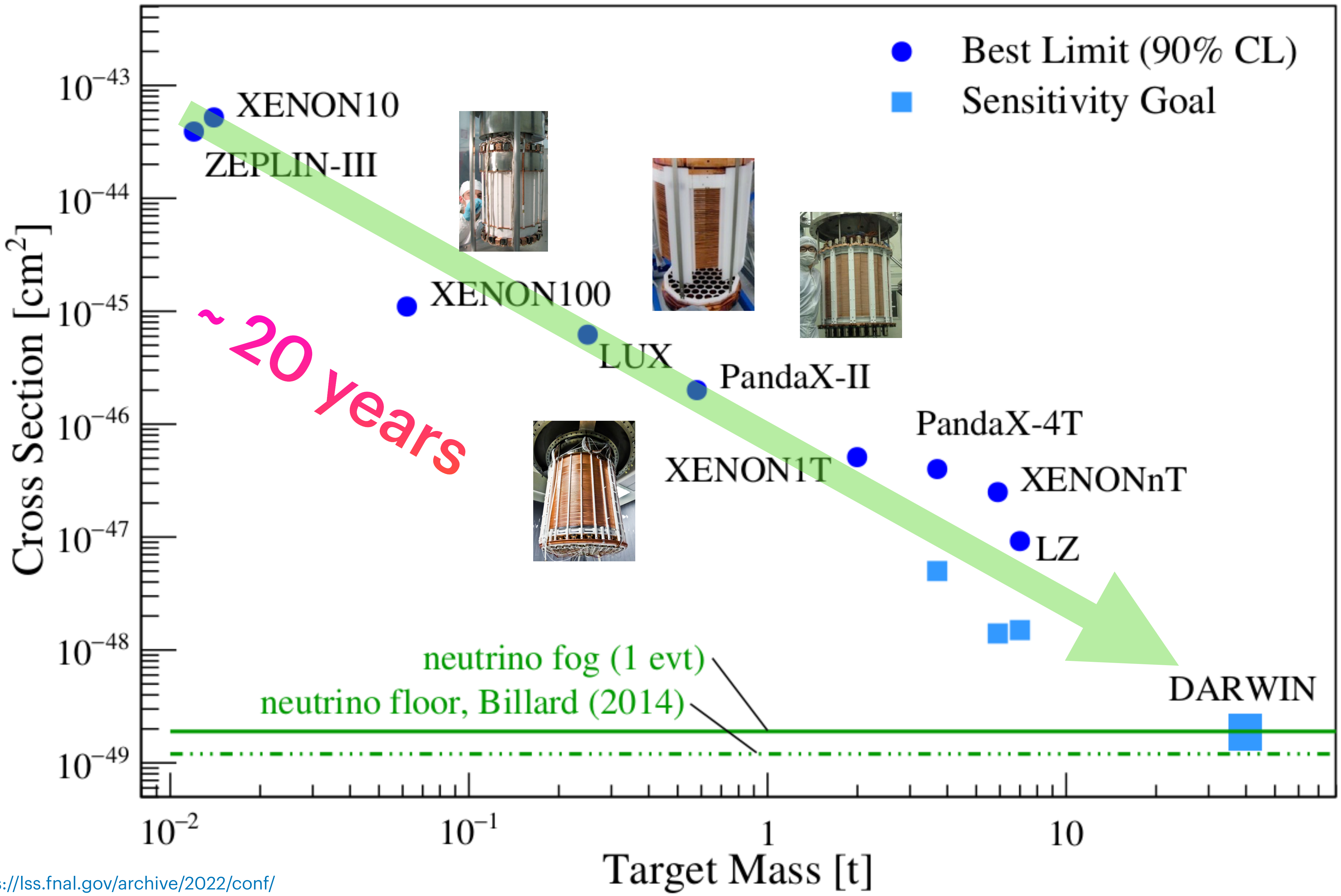


LXe TPCs:
- Migdal effect
- Scatters with e$^-$ *(interaction with SM though new mediator)*
- Absorption *(bosonic DM with direct coupling to SM particles)*

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

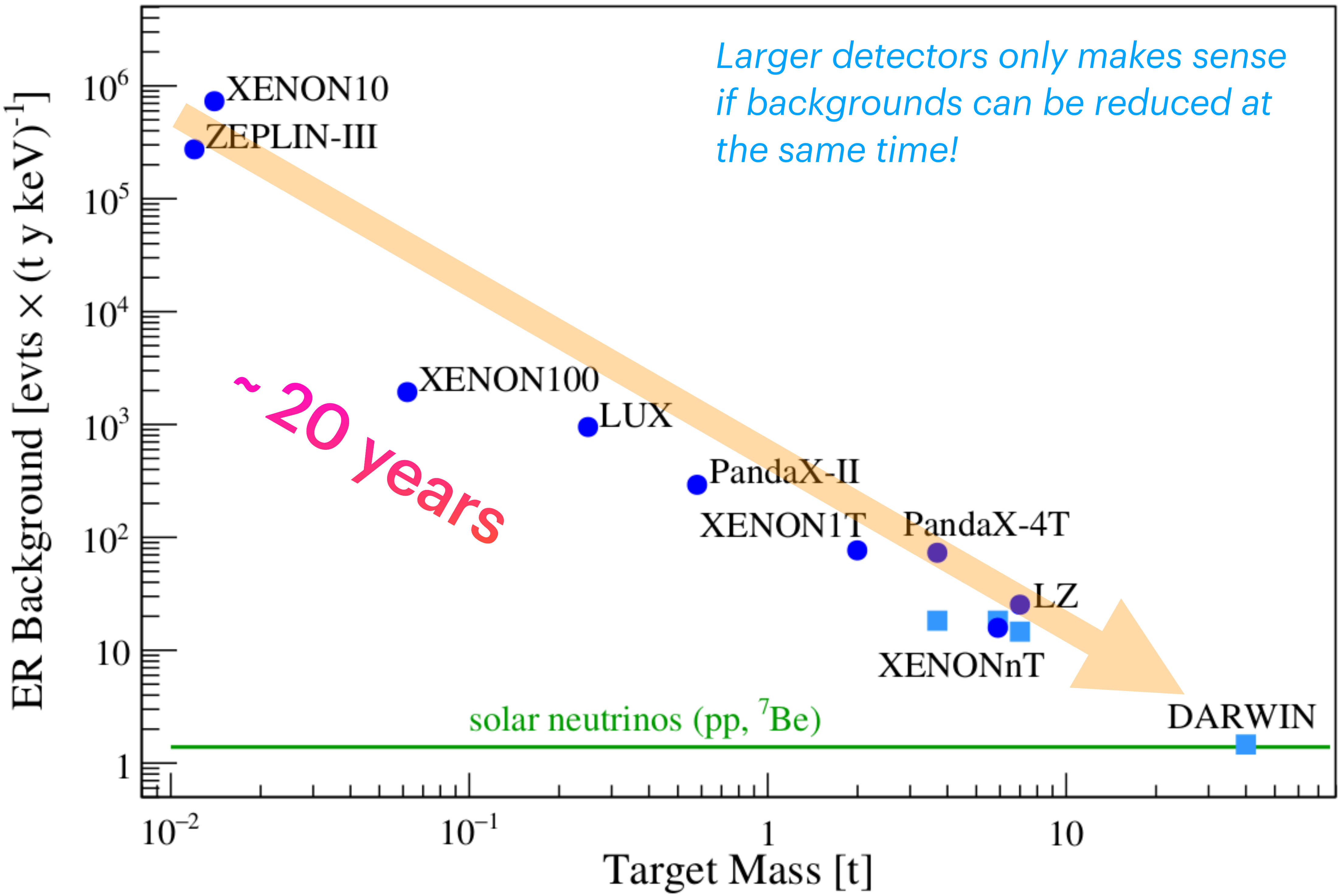
LXe TPCs:
- Multiple scatters with nuclei

CROSS SECTION LIMITS VERSUS MASS (TIME)



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

BACKGROUND RATES VERSUS MASS (TIME)

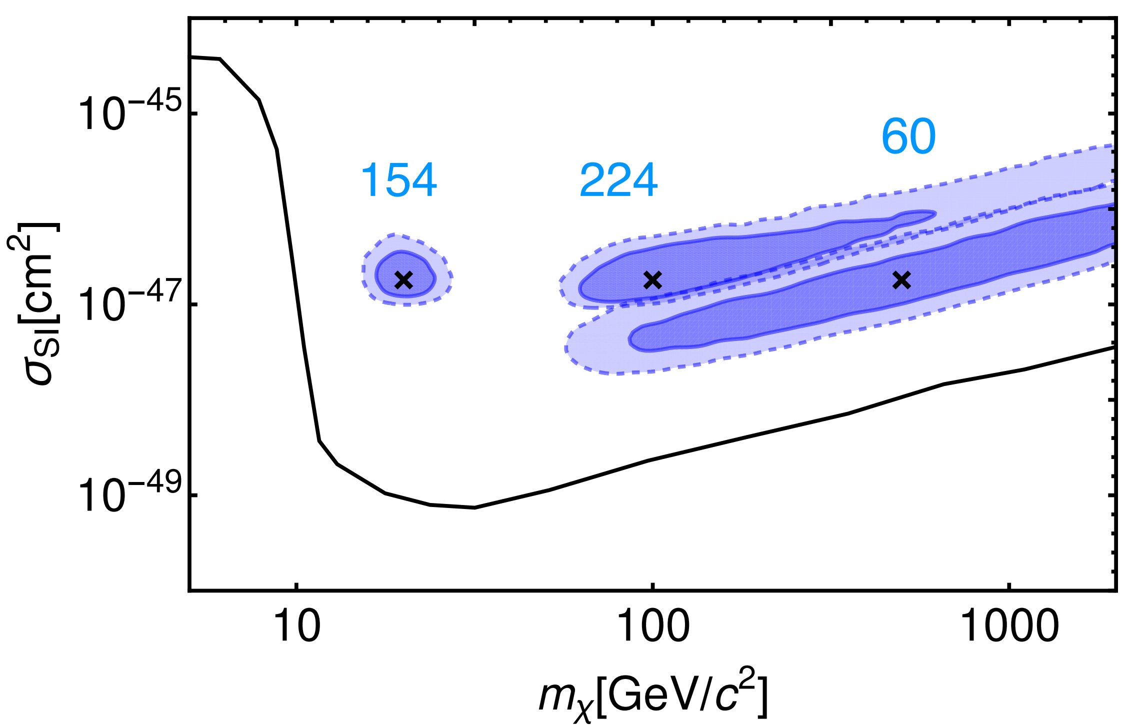


Journal of Physics G 50 (2023)

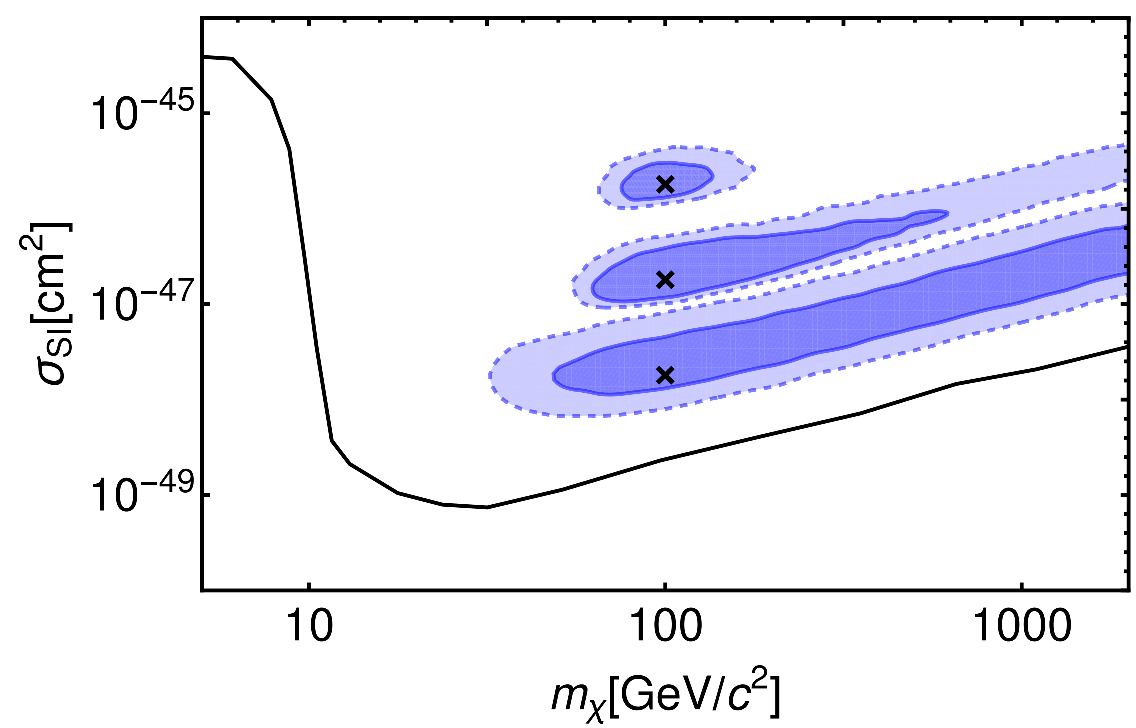
GOAL: DARK MATTER SPECTROSCOPY

- Capability of LXe detectors to reconstruct the WIMP mass and cross section for various masses - here 20, 100, 500 GeV/c² - and cross sections

Exposure: 200 t y



Exposure: 200 t y



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

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

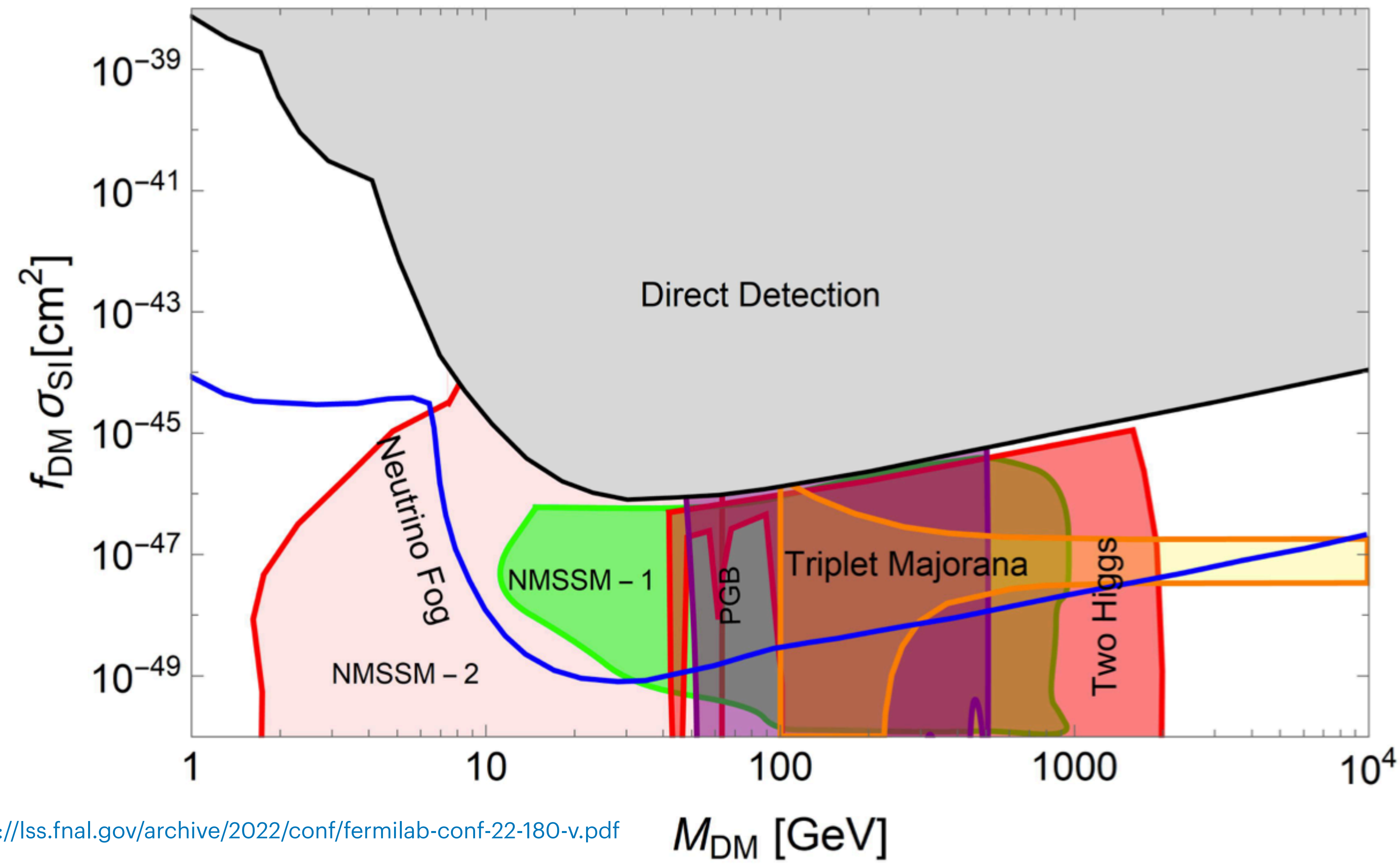
$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

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

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

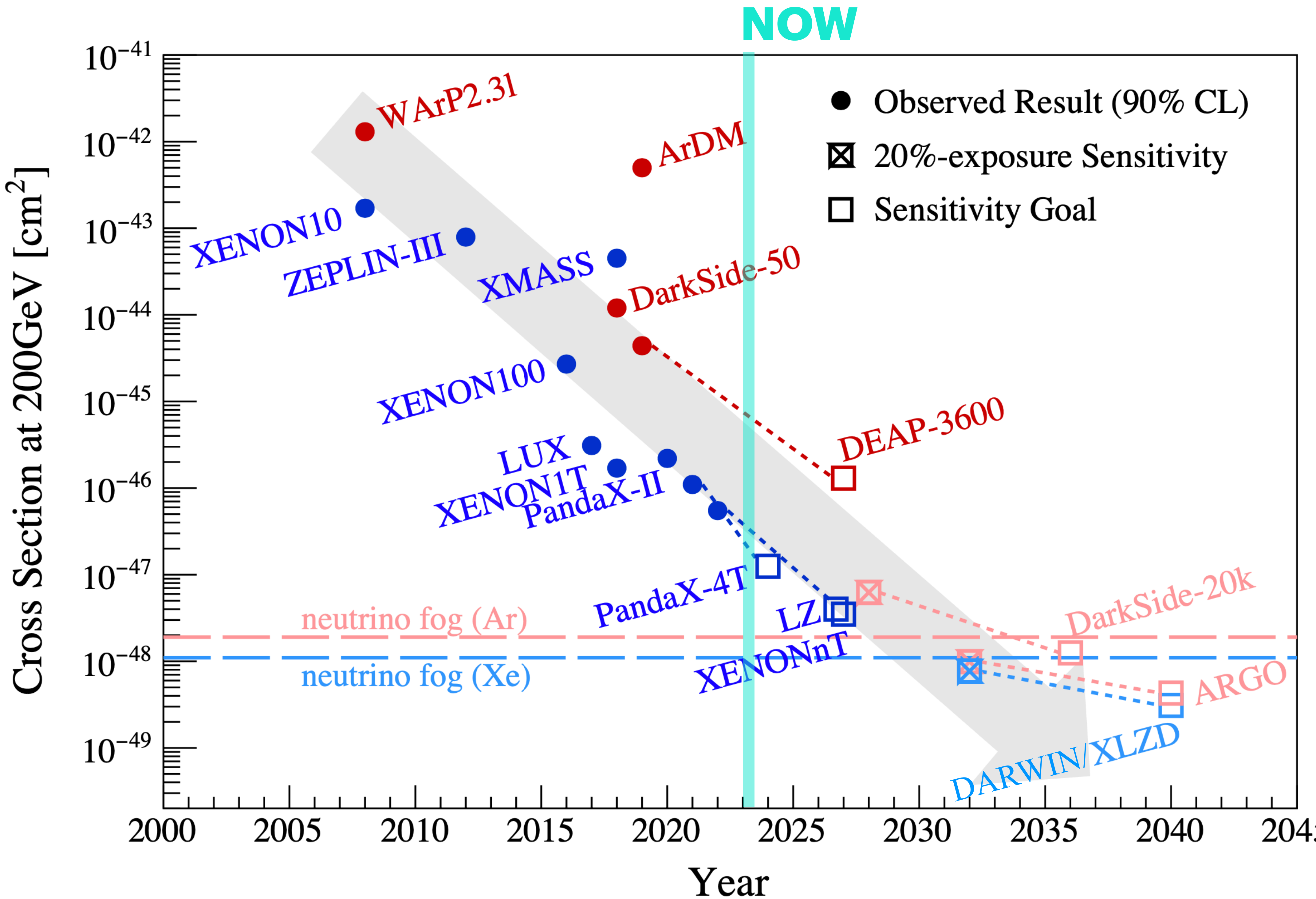
THEORY PREDICTIONS

- SI scattering cross sections for various "visible sector" models



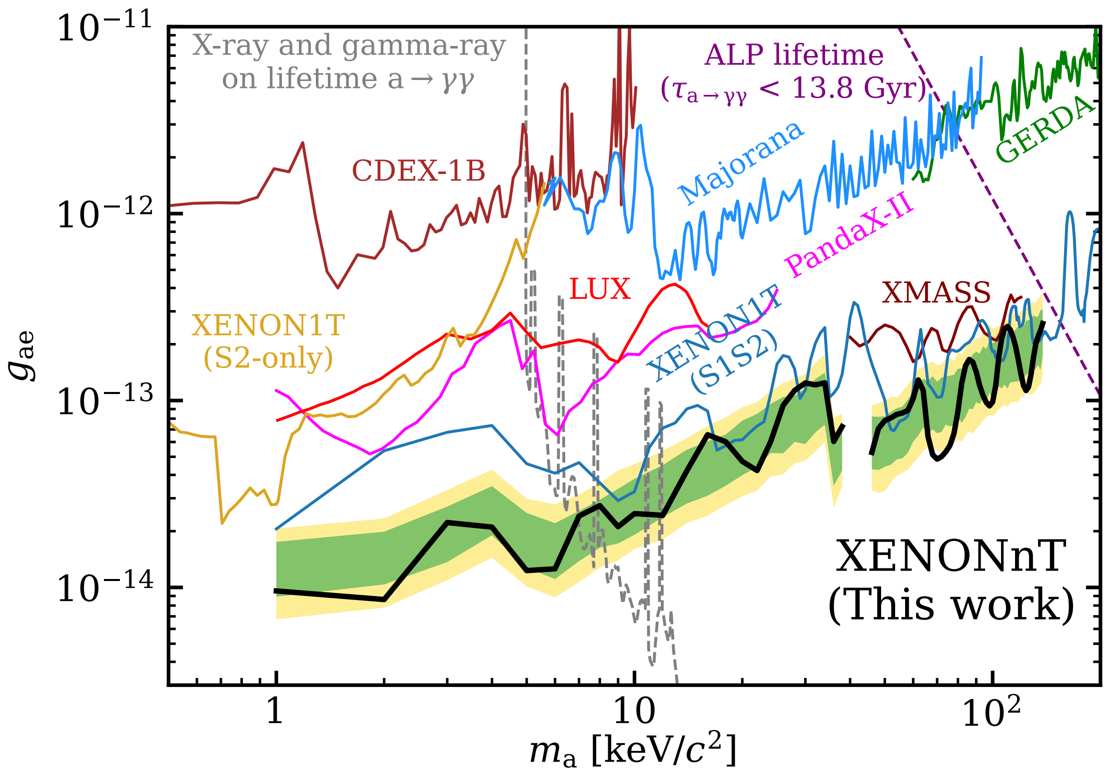
https://lss.fnal.gov/archive/2022/conf/fermilab-conf-22-180-v.pdf

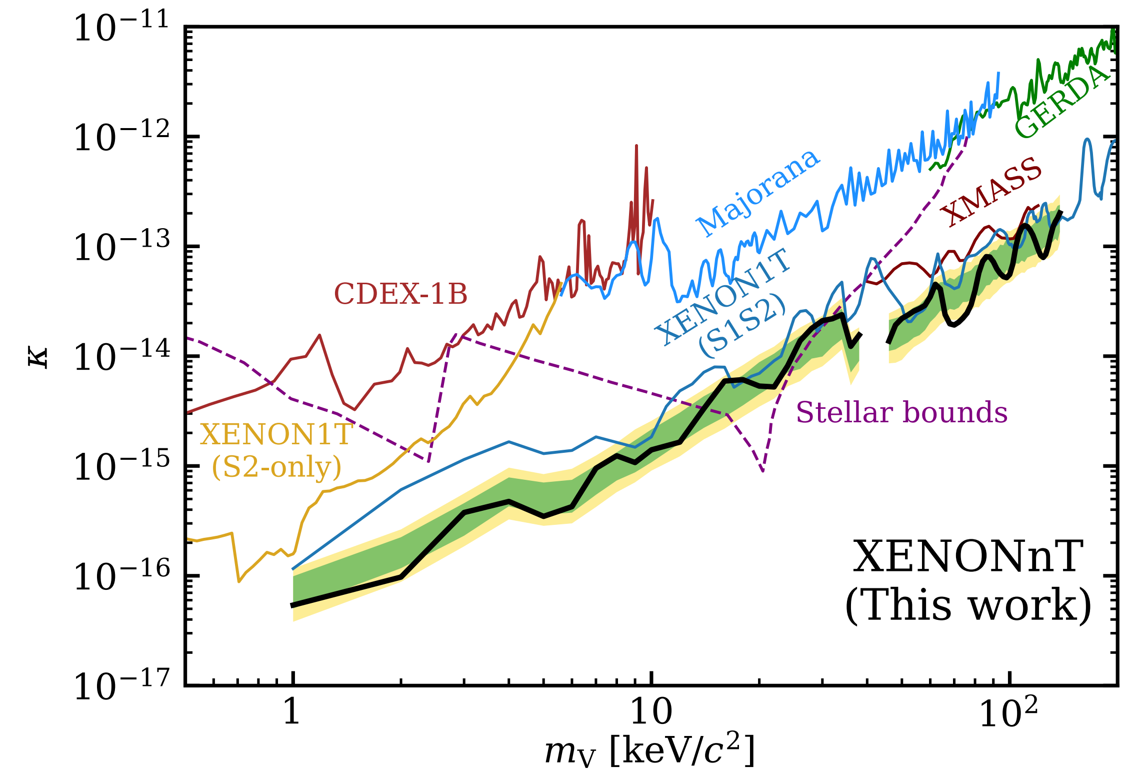
DARK MATTER CROSS SECTION VERSUS TIME



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

XENON-NT RESULTS ON BOSONIC DARK MATTER





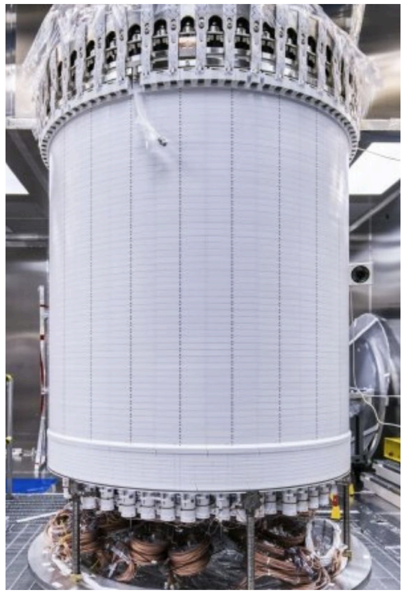
- Constrains on the couplings of galactic ALPs and dark photons:
  - competitive limits for masses in the ranges (1, 39) and (44, 140) keV/c^2
  - no limit/sensitivity between (39, 44) keV/c^2 because $^{83m}\mathrm{Kr}$ background rate is not constrained

XENON collaboration, PRL 129, 2022

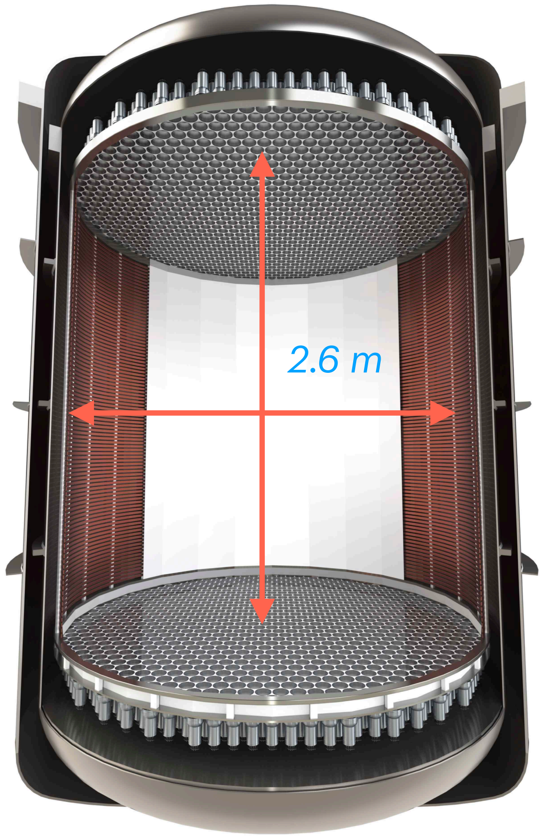
SIZE MATTERS

- LUX-ZEPLIN and XENONnT: 1.5 m e^- drift and ~ 1.5 m diameter electrodes
- **DARWIN/XLZD: 2.6 - 3.0 m ⇒ new challenges**
    - Design of electrodes: robustness (minimal sagging/ deflection), maximal transparency, reduced e^- emission
    - Electric field: ensure spatial and temporal homogeneity, avoid charge-up of PTFE reflectors
    - High-voltage supply to cathode design, avoid high-field regions
    - Liquid level control
    - Cryogenic purification (^{222}Rn and ^{85}Kr below solar pp neutrino level)
- Electron survival in LXe: > 10 ms lifetime
- Diffusion of the e^--cloud: size of S2-signals

LUX-ZEPLIN



XENONnT

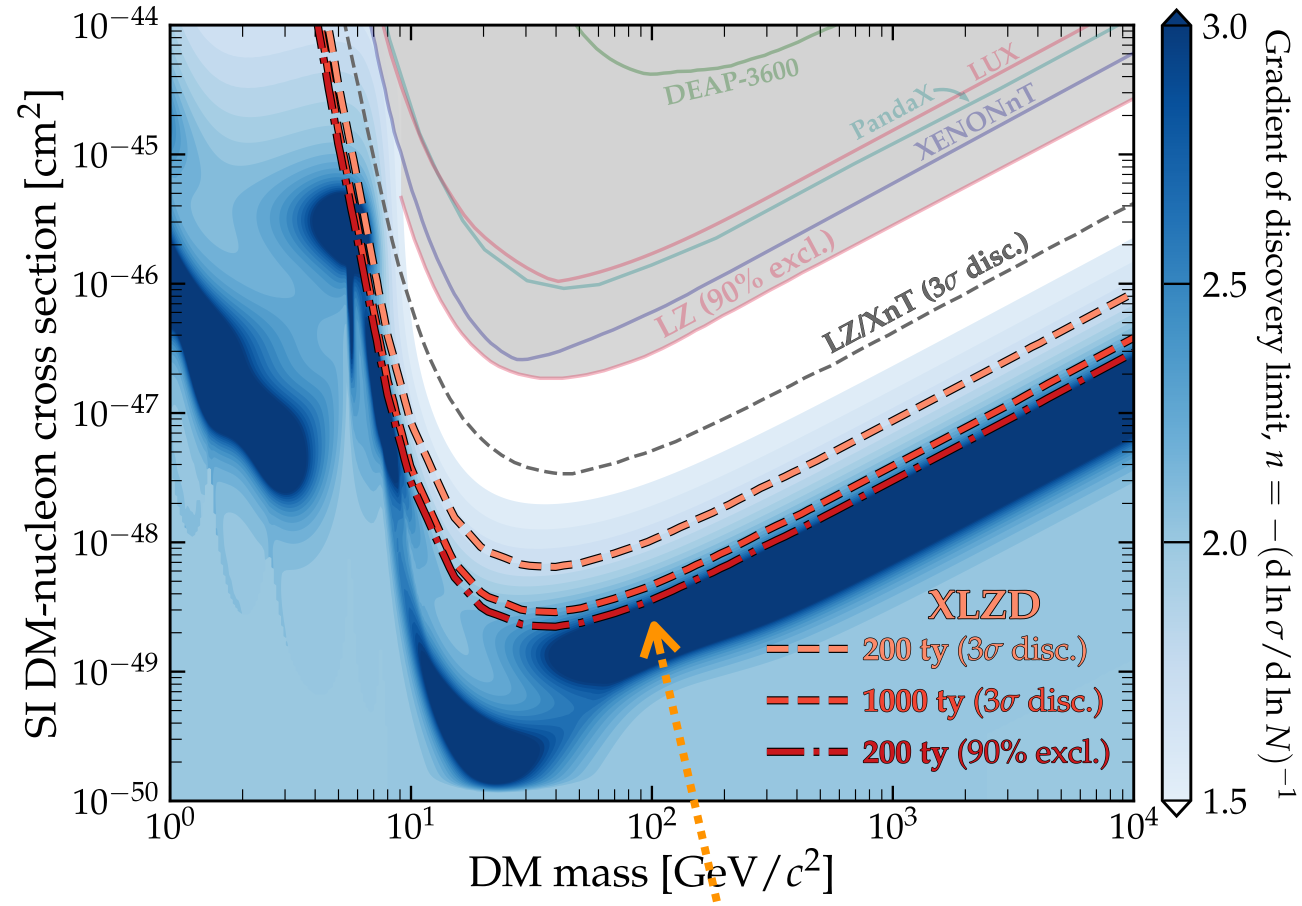


DARWIN

DARWIN/XLZD AND NEUTRINO BACKGROUNDS

- Larger LXe mass with XLZD (50 t → 75 t total)
    - 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} cm^2 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