University of Zurich[UZH]

European Research Council
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XENON

DARWIN

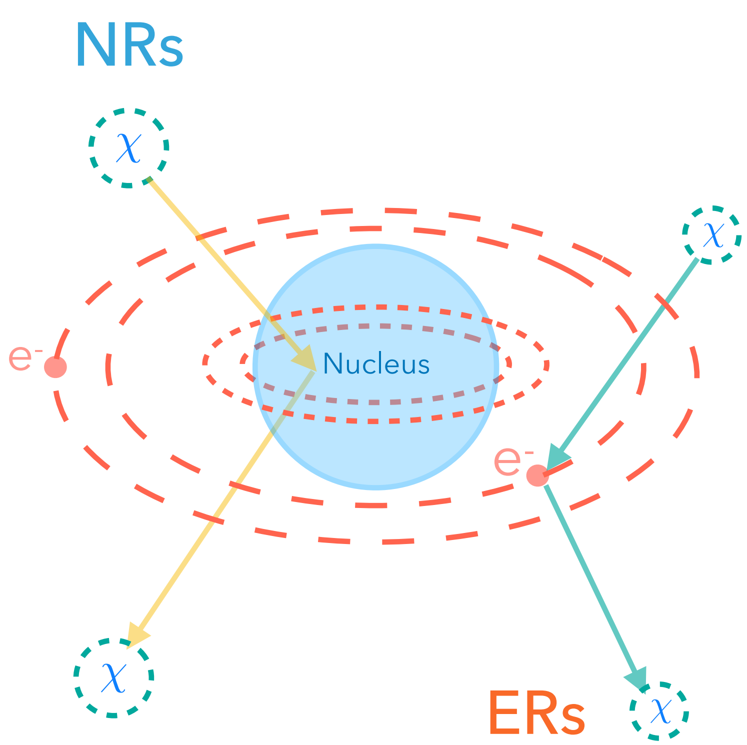
Looking into the heart of darkness: two-phase xenon time projection chambers for dark matter detection

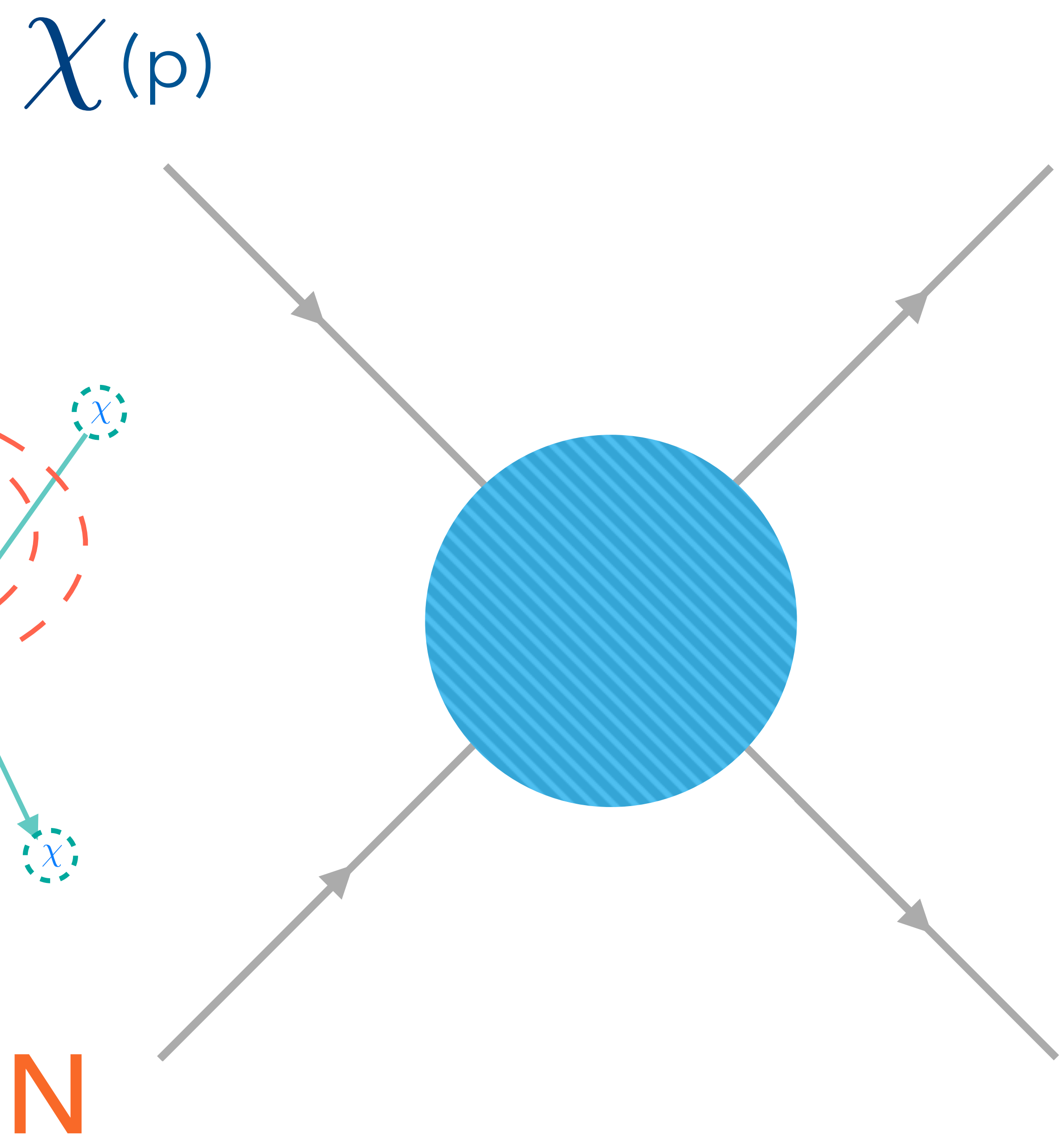
Discrete 2022, Baden-Baden

Laura Baudis, University of Zurich, November 11, 2022

Picture: eso.org

Direct dark matter detection



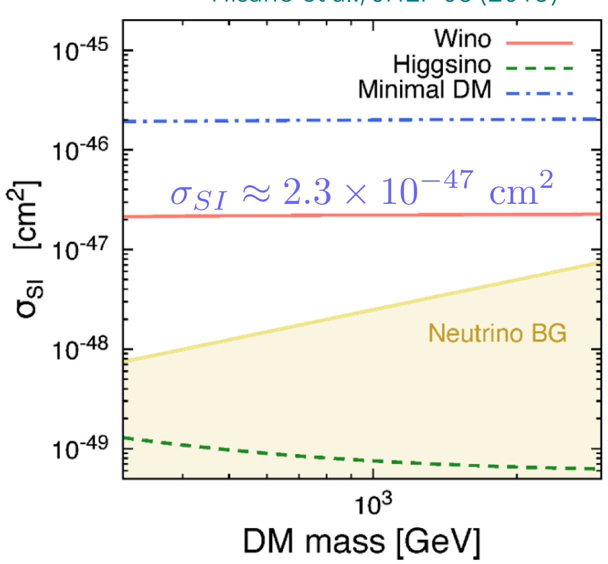


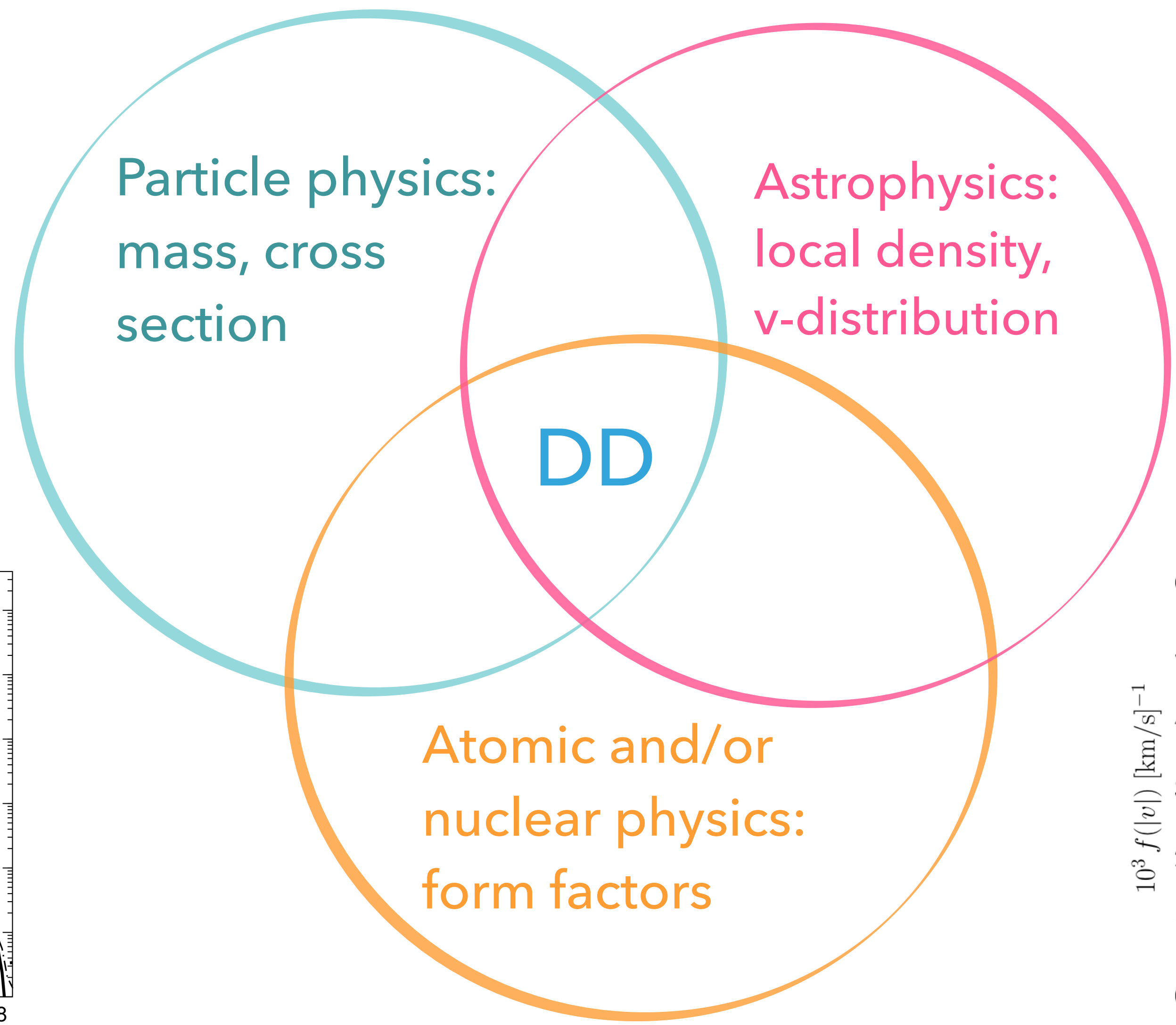
- Observe DM collisions with nuclei (NRs) or with electrons in the atomic shell (ERs)
- Look for absorption of light bosons via e.g., the axio-electric effect

Direct dark matter detection

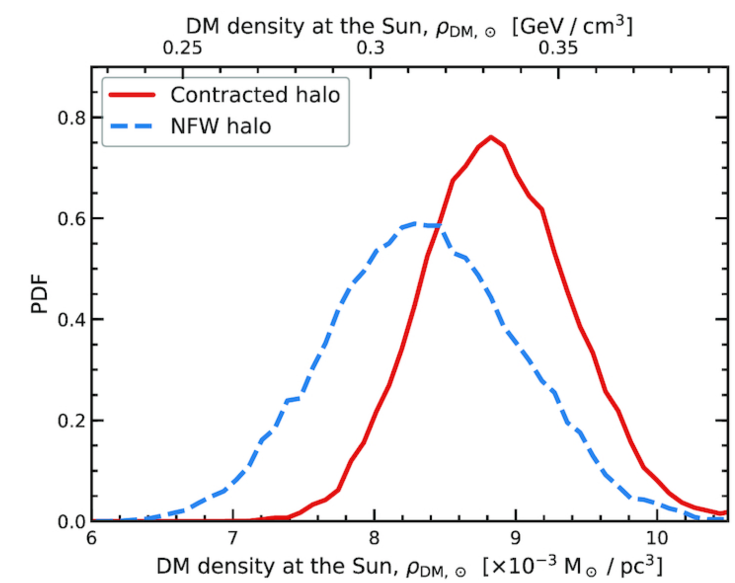
- Main physical observable: **a differential recoil spectrum;** its modelling relies on several phenomenological inputs

Hisano et al., JHEP 06 (2015)

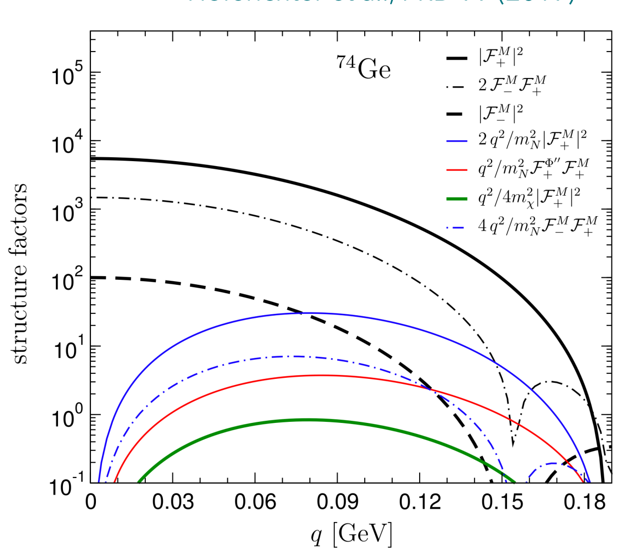




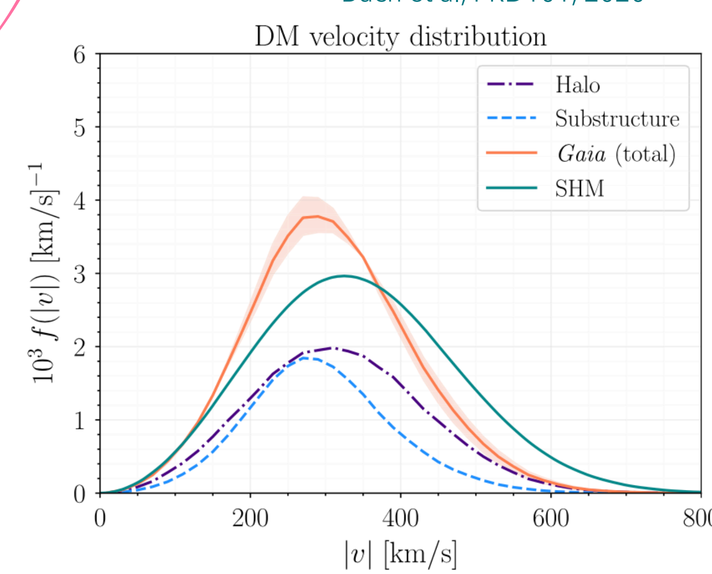
M. Cautun et al, MNRAS 2020



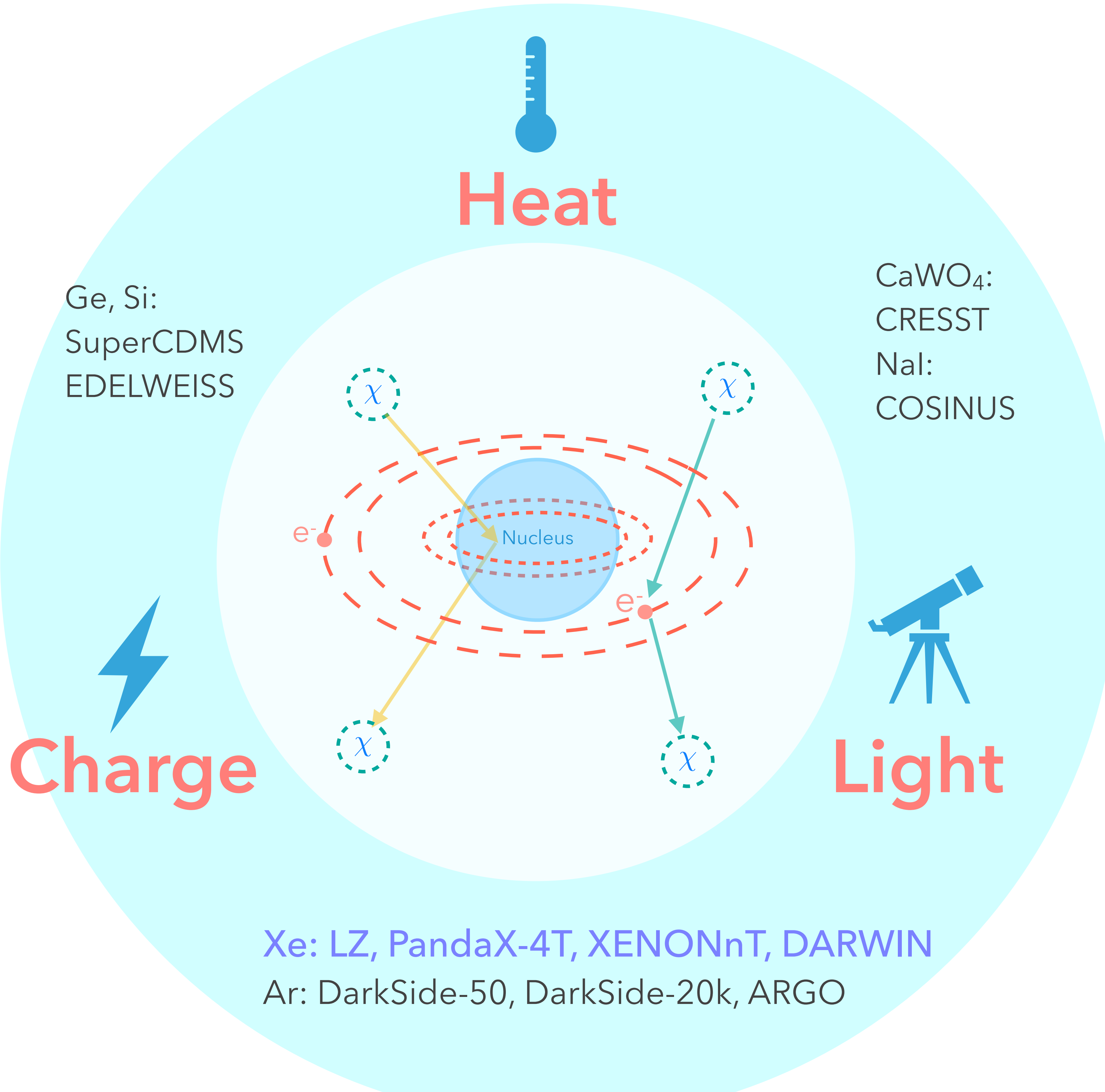
Hoferichter et al., PRD 99 (2019)



Buch et al, PRD101, 2020



Signals and experiments



Ge, Si:
SuperCDMS
EDELWEISS

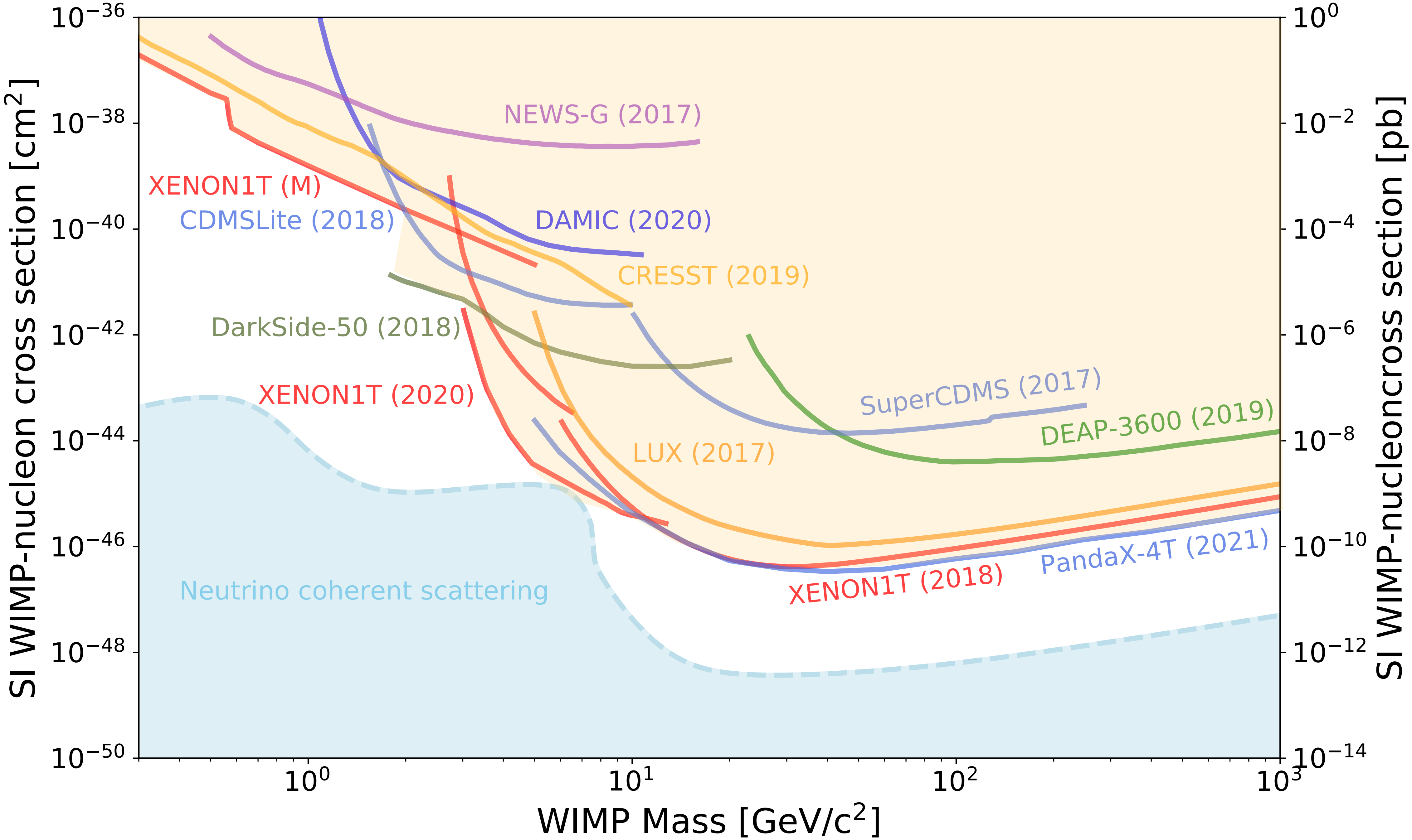
$CaWO_4$:
CRESST
NaI:
COSINUS

C_3F_8: PICO
Ge: CDEX
Si: DAMIC, SENSEI
Ar, Ne: TREX-DM
He:SF_6: CYGNUS
Ag, Br, C: NEWSdm
H, He, Ne: NEWS-G

Ar: DEAP-3600
Xe: XMASS
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE

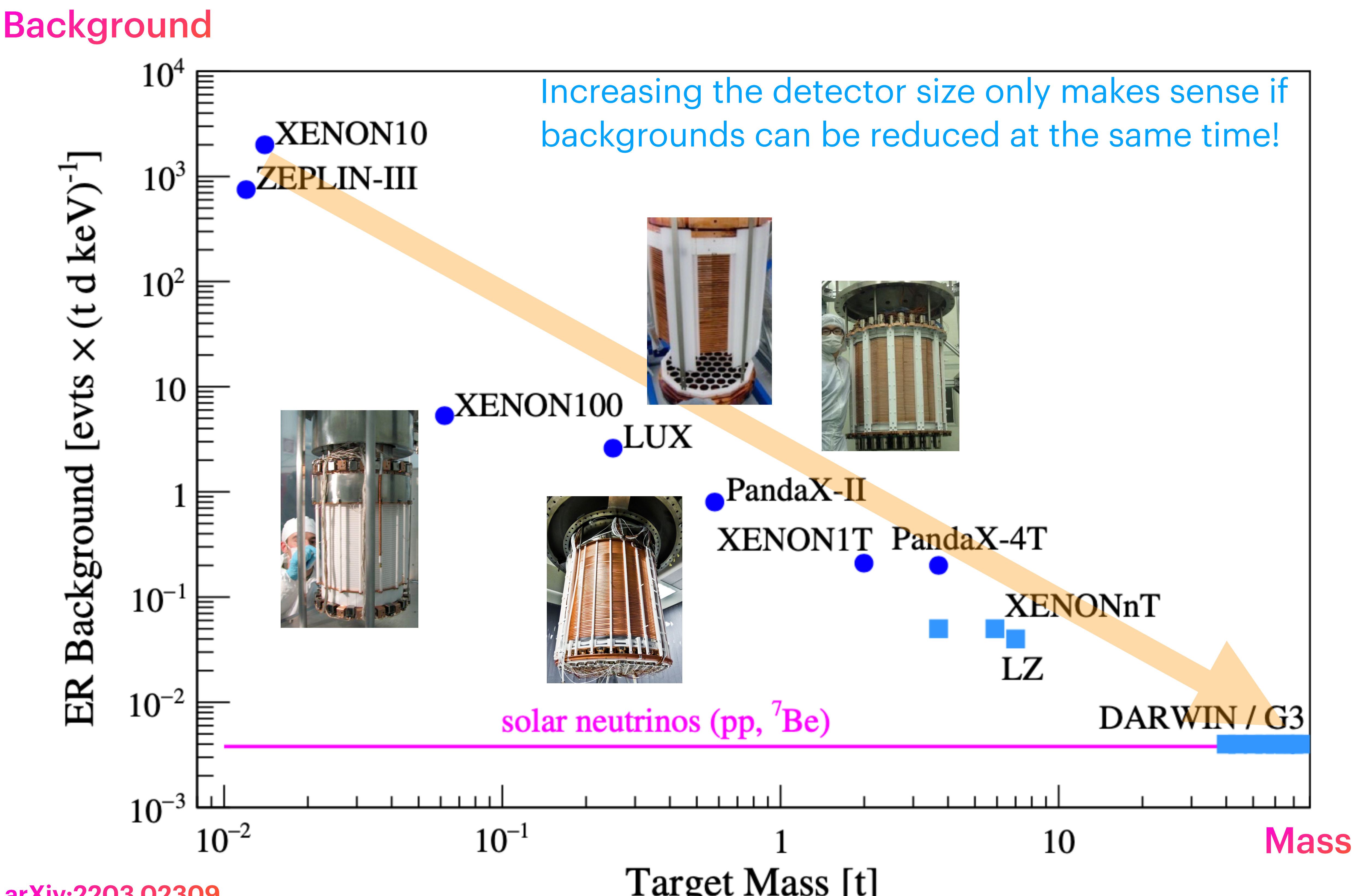
Xe: LZ, PandaX-4T, XENONnT, DARWIN
Ar: DarkSide-50, DarkSide-20k, ARGO

Direct detection landscape in early 2022



LB and Stefano Profumo, PDG 2022

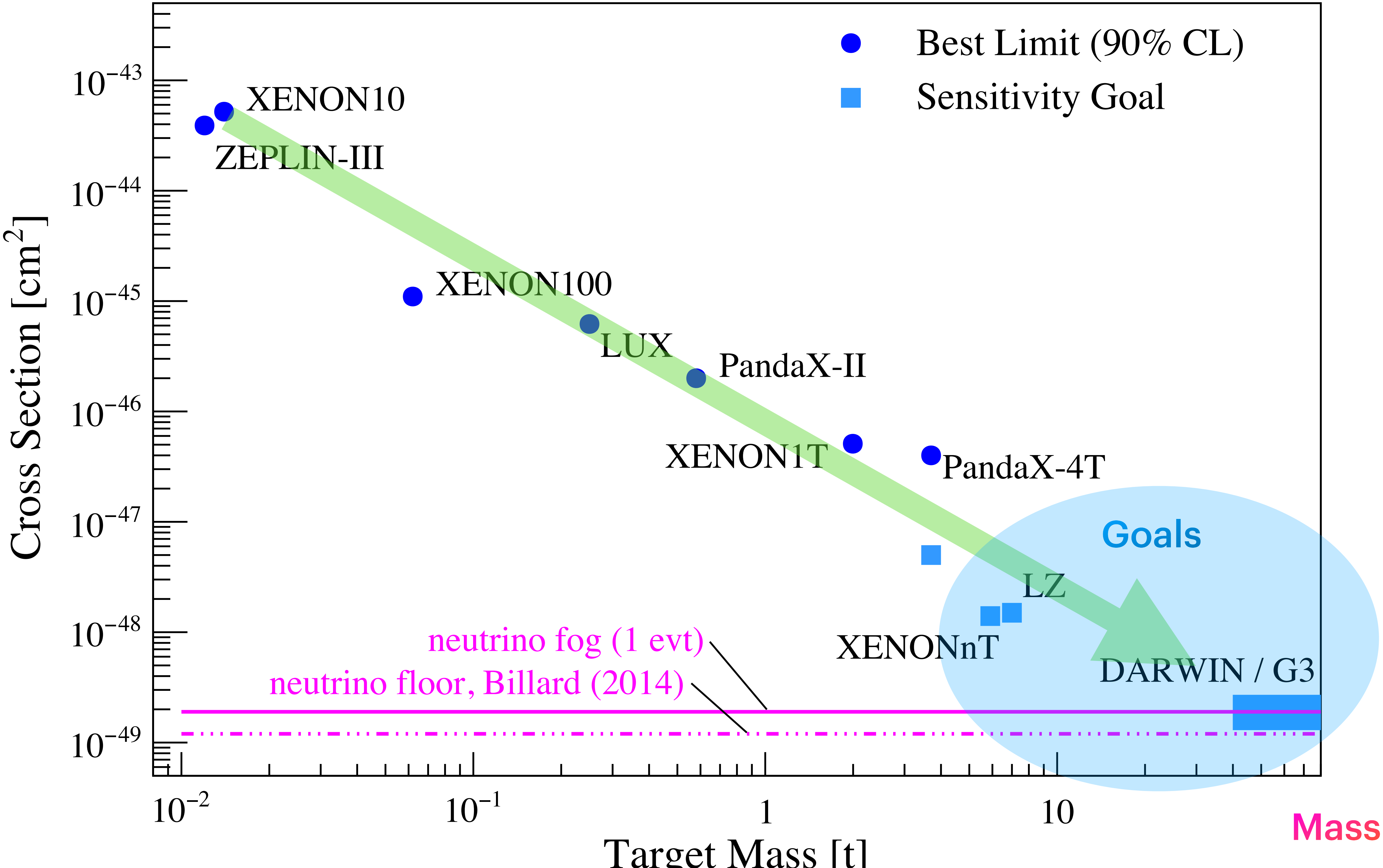
Xe TPCs: past, current & future



arXiv:2203.02309

Cross sections versus mass

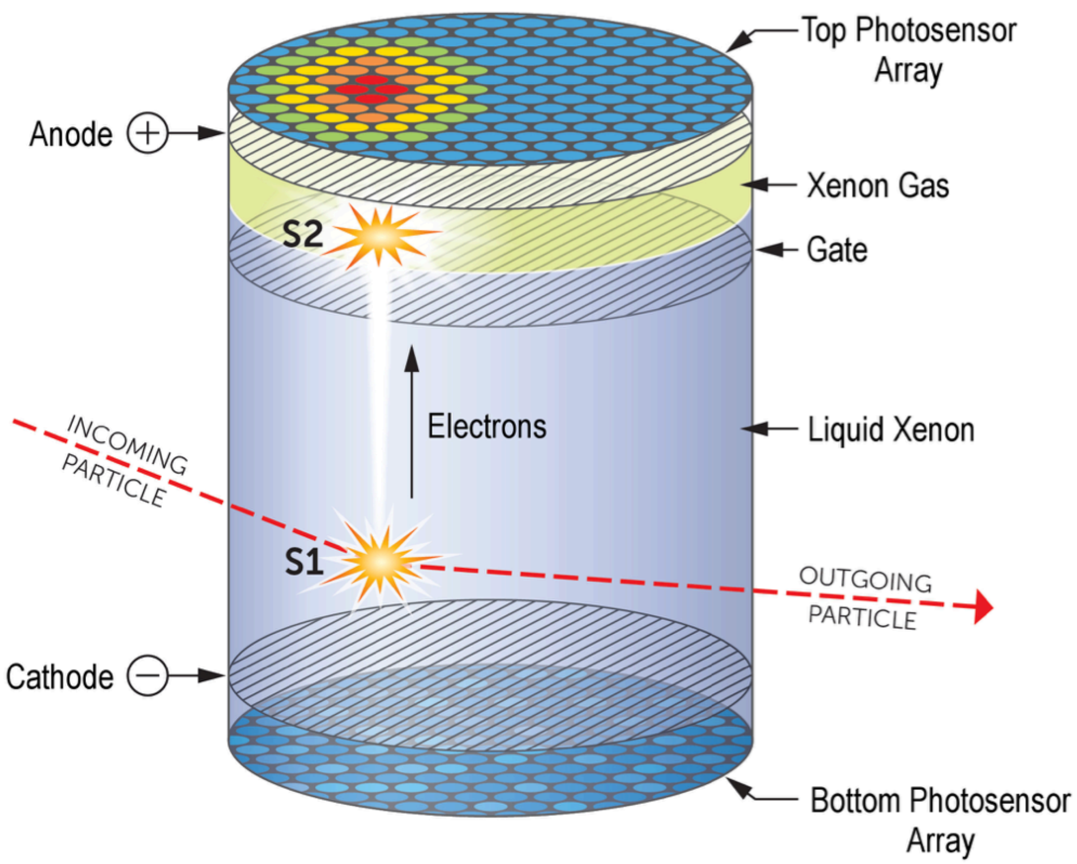
Cross section



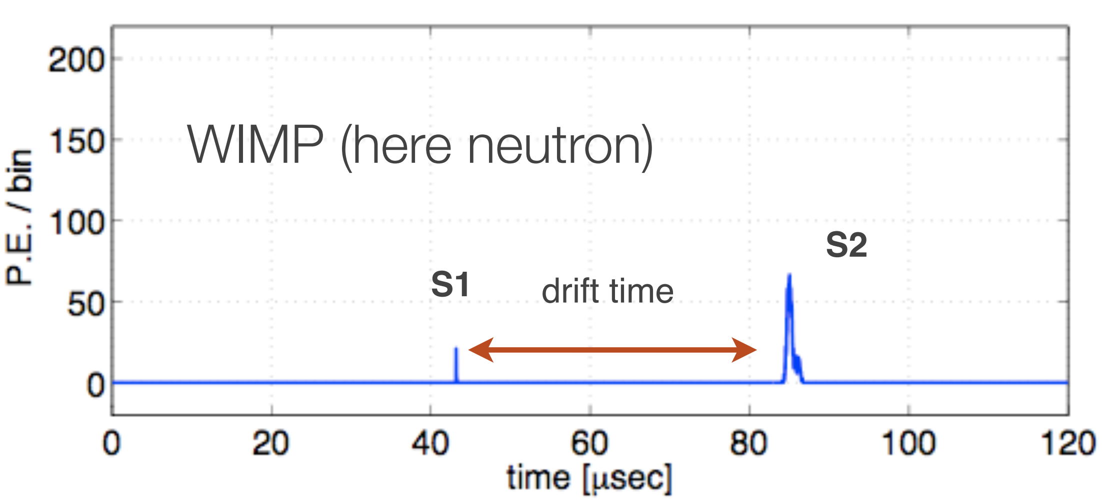
Mass

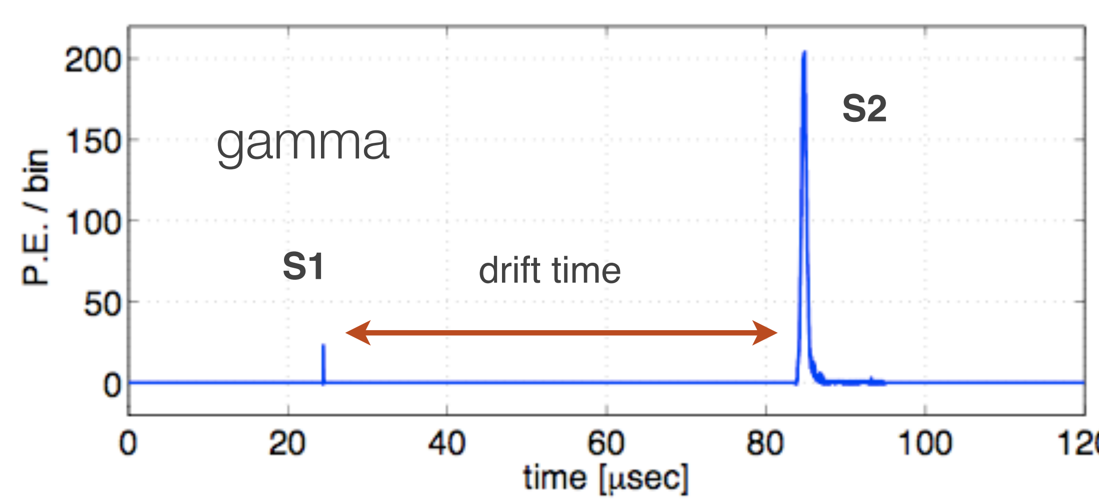
https://lss.fnal.gov/archive/2022/conf/fermilab-conf-22-180-v.pdf

Why a two-phase Xe TPC for DM?

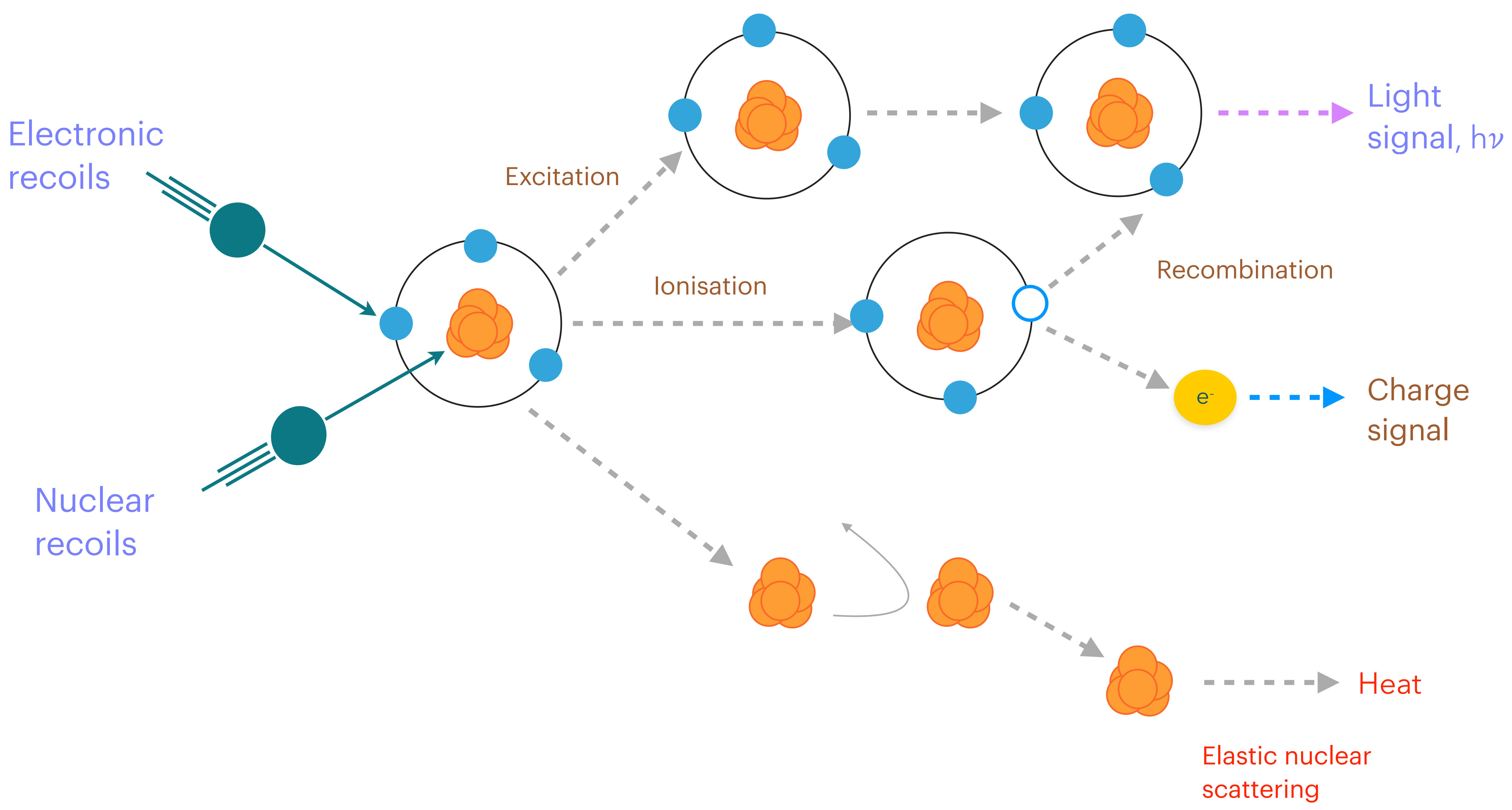


- Observe the prompt scintillation (S1) and charge (via electroluminiscence, S2) in a large volume of xenon
- Particle discrimination via the ratio of charge to light
- Good energy reconstruction (LC of S1 & S2)
- 3D position reconstruction
  - Single versus multiple scatters discrimination
  - Fiducialisation
- Lower energy threshold via "S2-only"



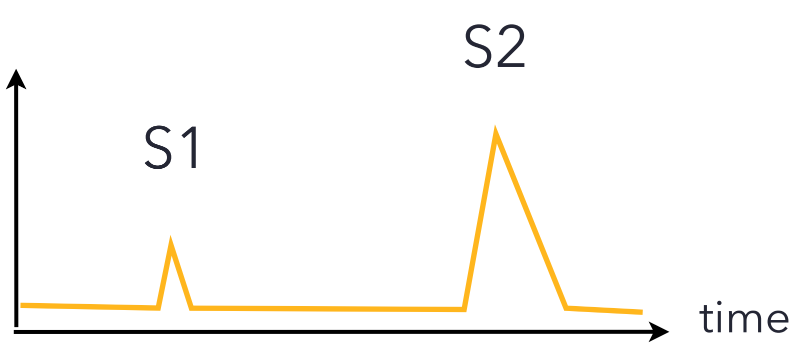


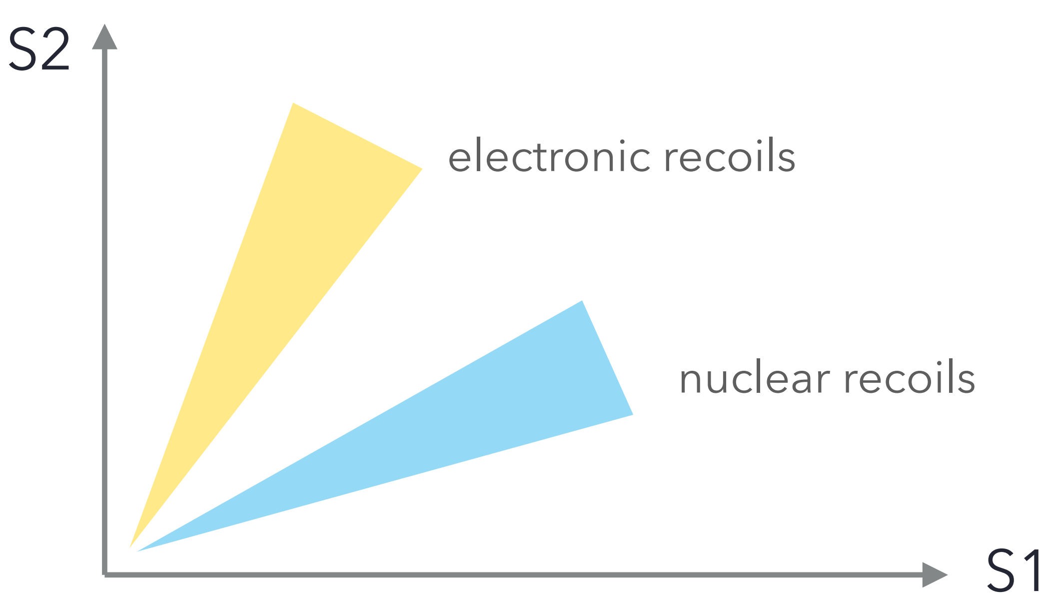
Electronic and nuclear recoils

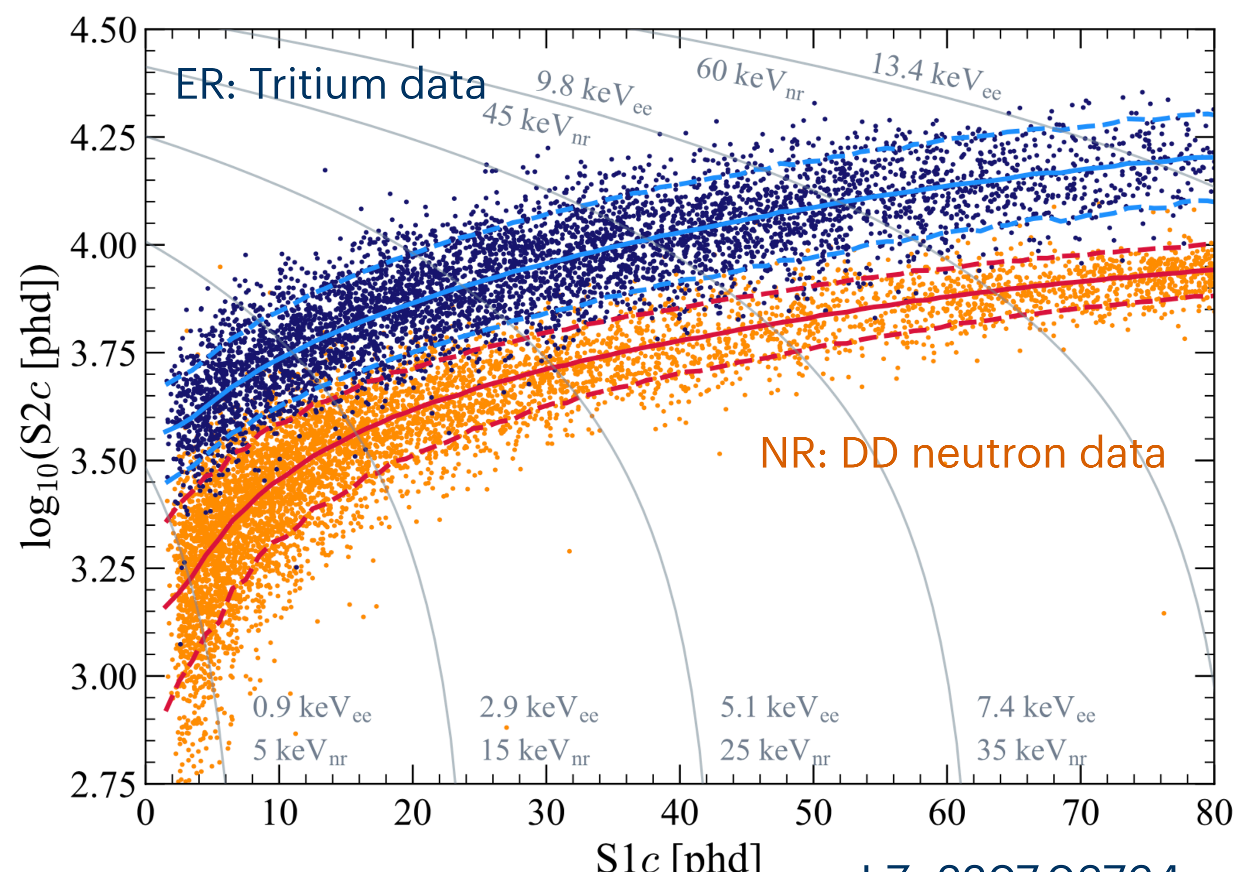


NR versus ER discrimination

- **S2 over S1 depends on the type of particle (dE/dx):** in particular, it is different for ERs versus NRs
- **ER rejection power depends on an interplay between the drift field** (that changes the mean recombination fraction $\langle r \rangle$ and the recombination fluctuations Δr; and the e⁻-ion recombination factor for ERs is more significantly affected by the field) **and total S1 light collection** (higher field means less S1 light and thus larger statistical fluctuations)
- **Typically (99.5 - 99.99)% ER rejection at ~50% NR acceptance**





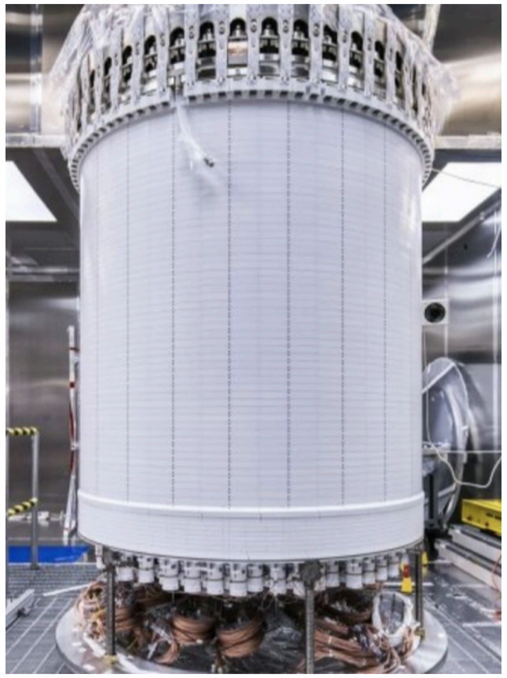


LZ: 2207.03764

Current experiments

- 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 run at SURF in 2022, XENONnT first results on ER searches, second science run ongoing at LNGS

LUX-ZEPLIN



XENONnT

PandaX-4T

The LUX-ZEPLIN experiment

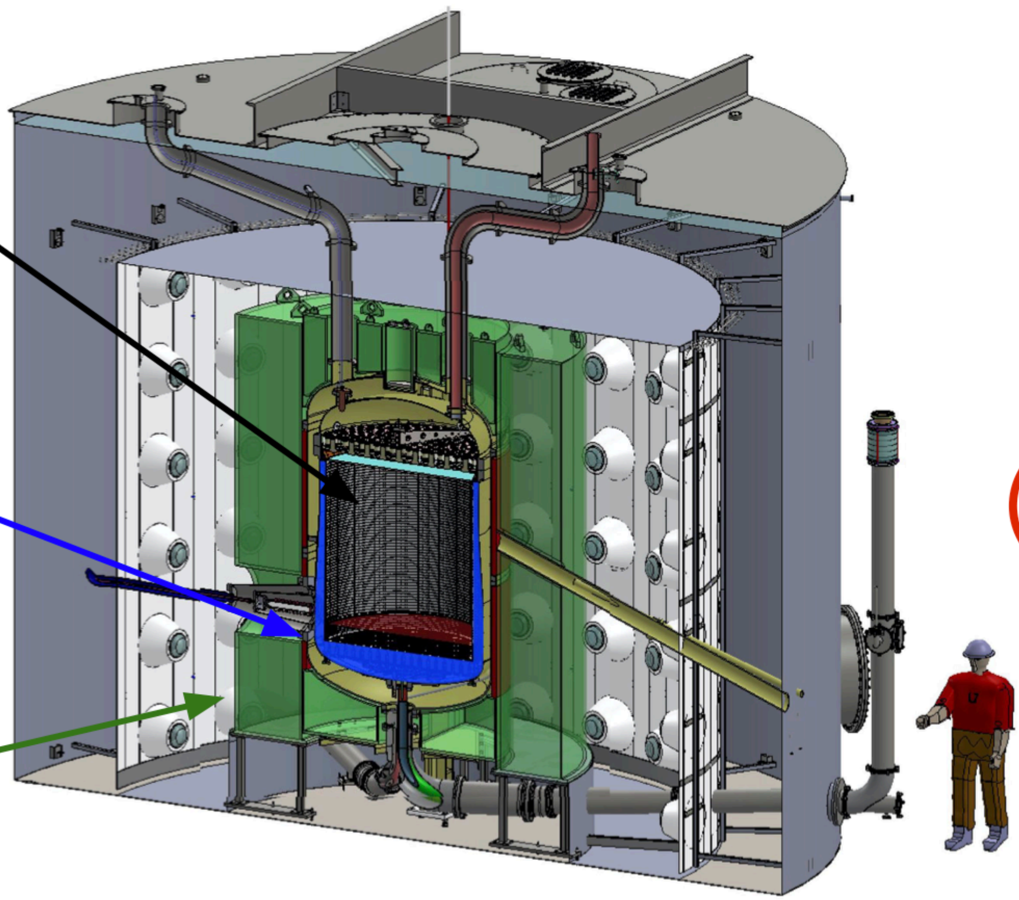
Dark matter detector

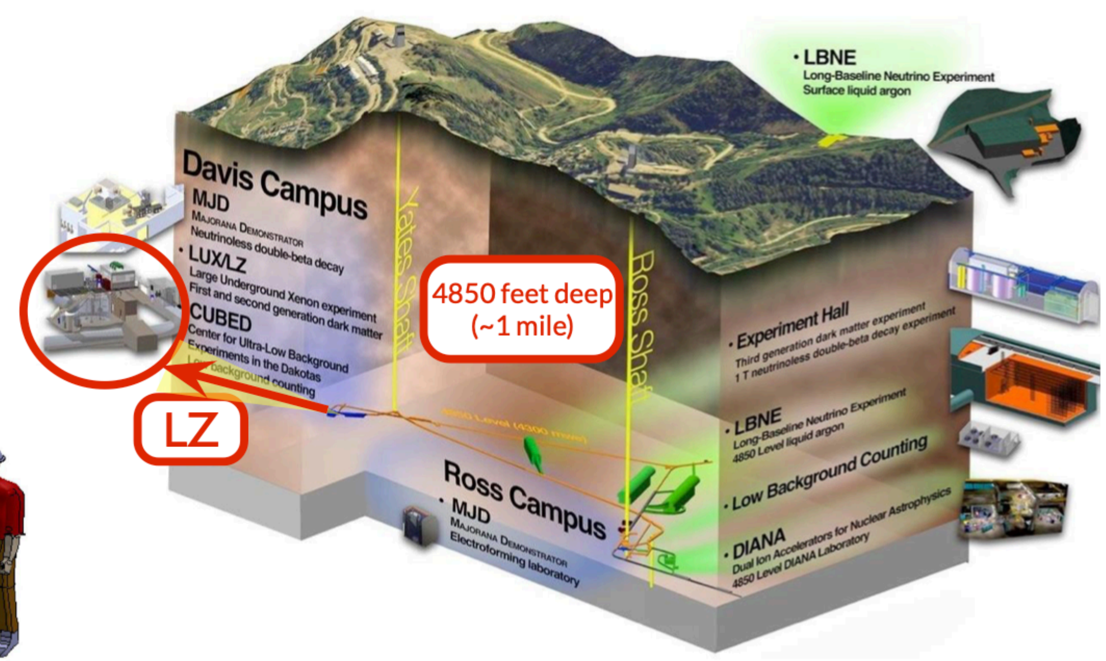
Located 4850 ft underground at
Sanford Underground Research Facility (SURF)
in South Dakota, USA

Dual-phase xenon Time
Projection Chamber
(TPC)

Liquid xenon
"Skin" detector

Gadolinium-loaded
liquid scintillator outer
detector





A. Fan

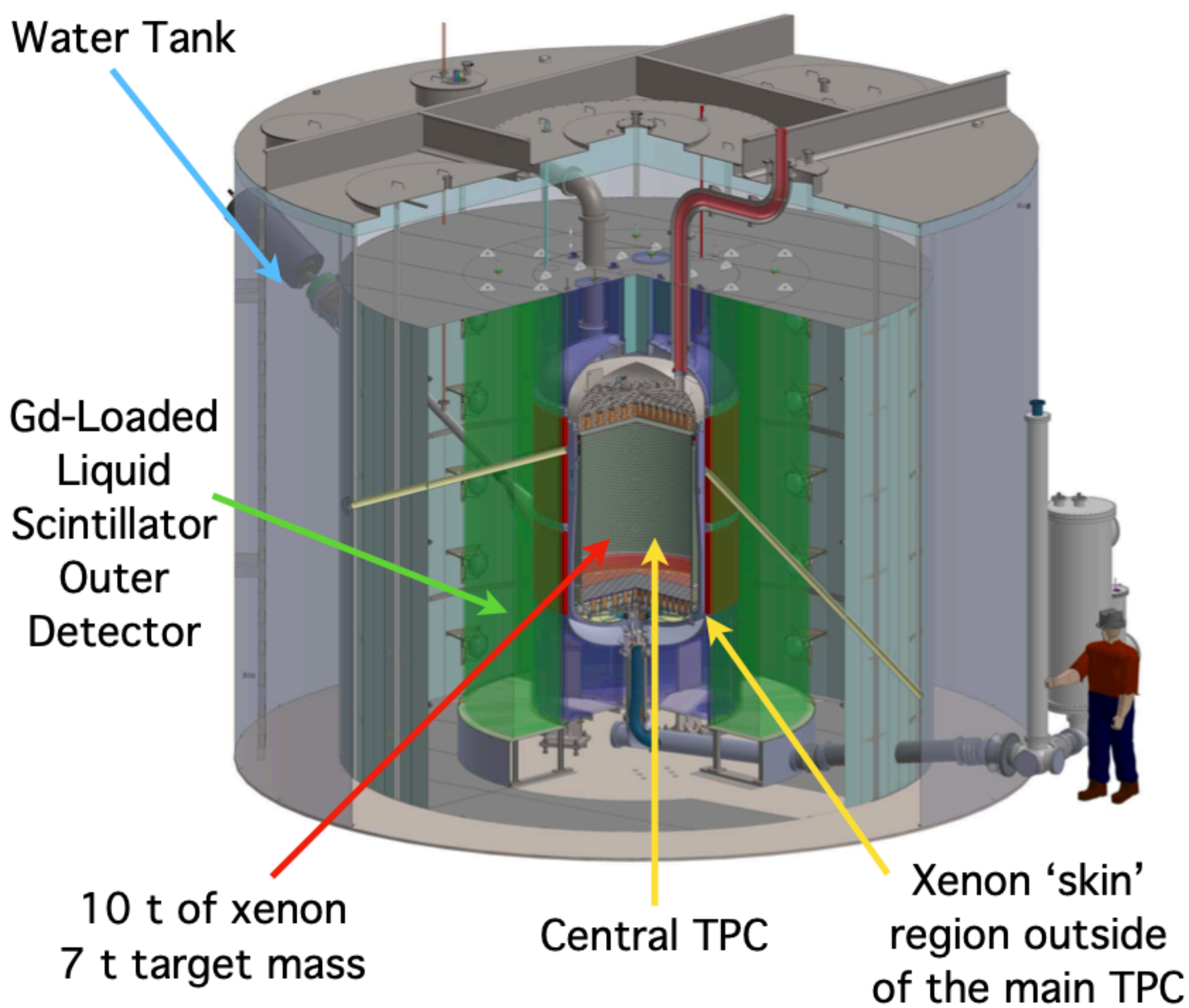
NIM A 163047 (2020)

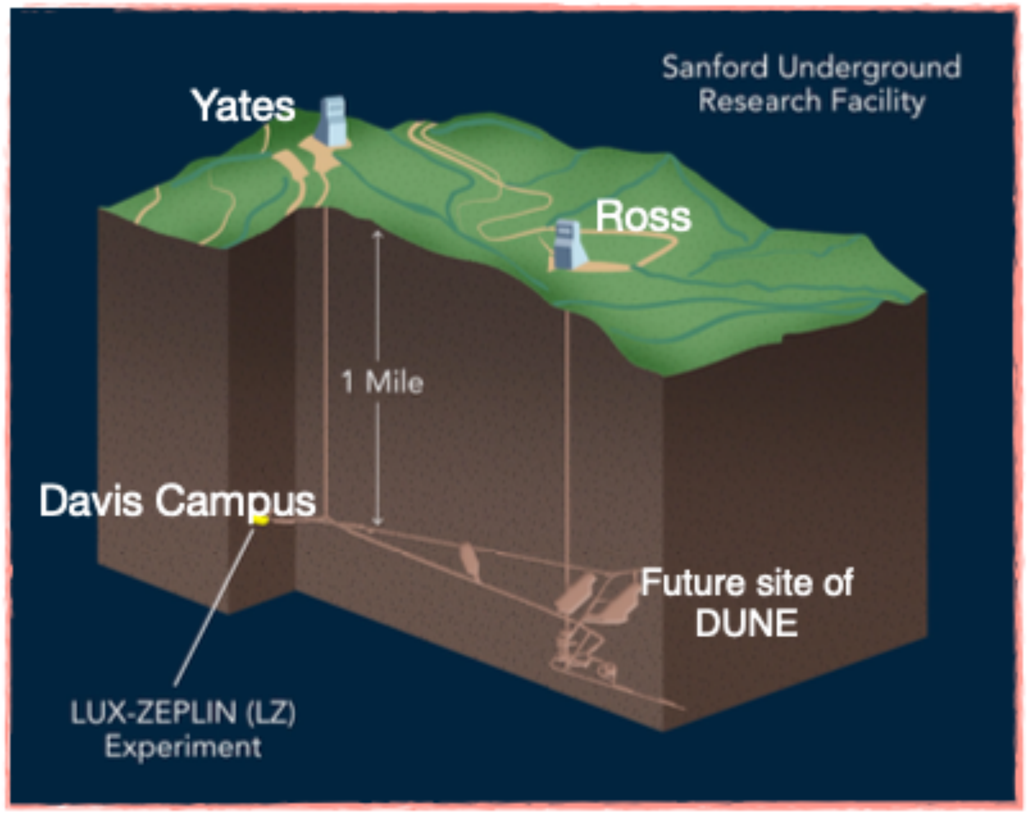
SURF: 4300 meter water equivalent

3

The LUX-ZEPLIN experiment

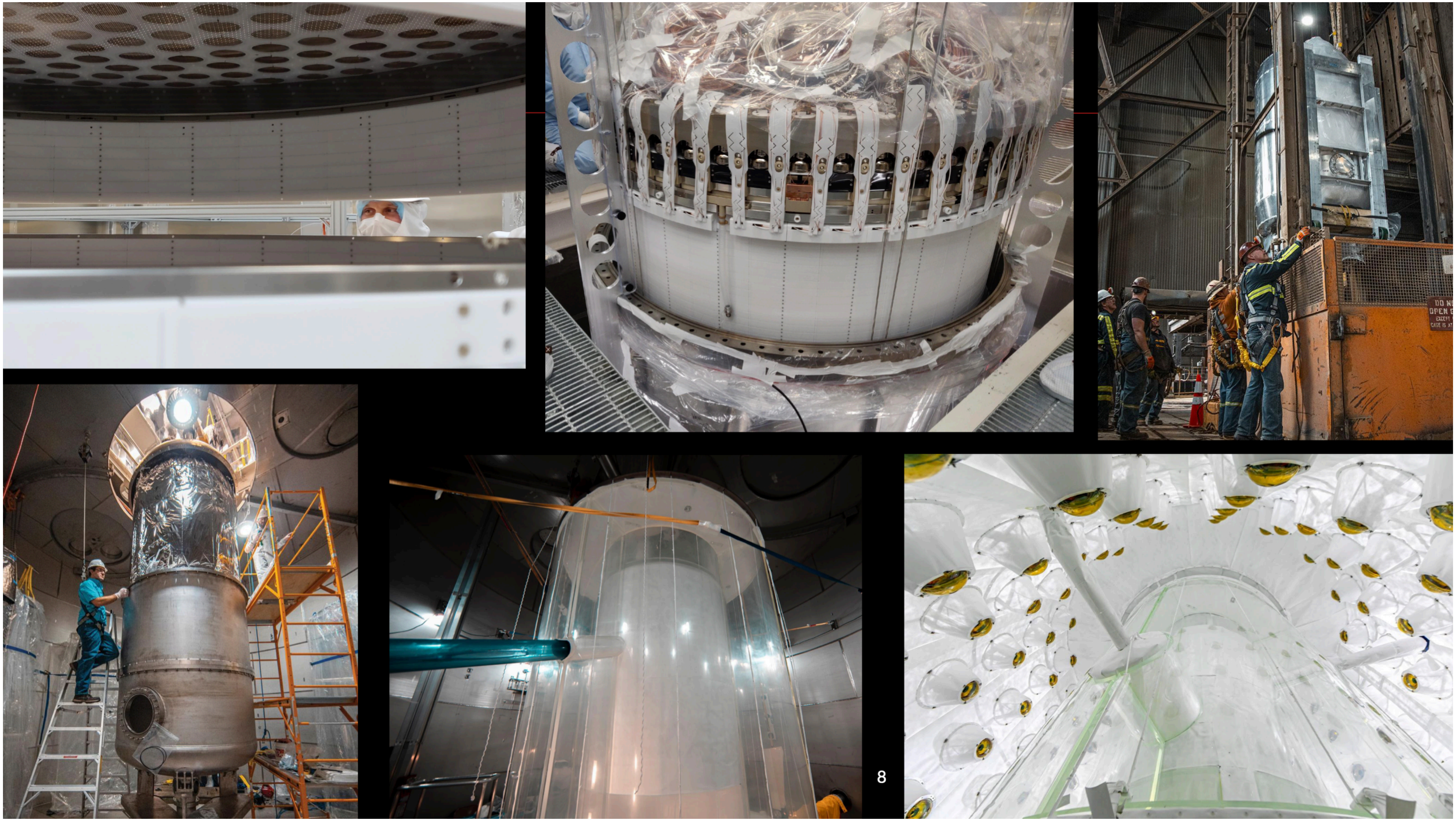
SURF: 4300 meter water equivalent





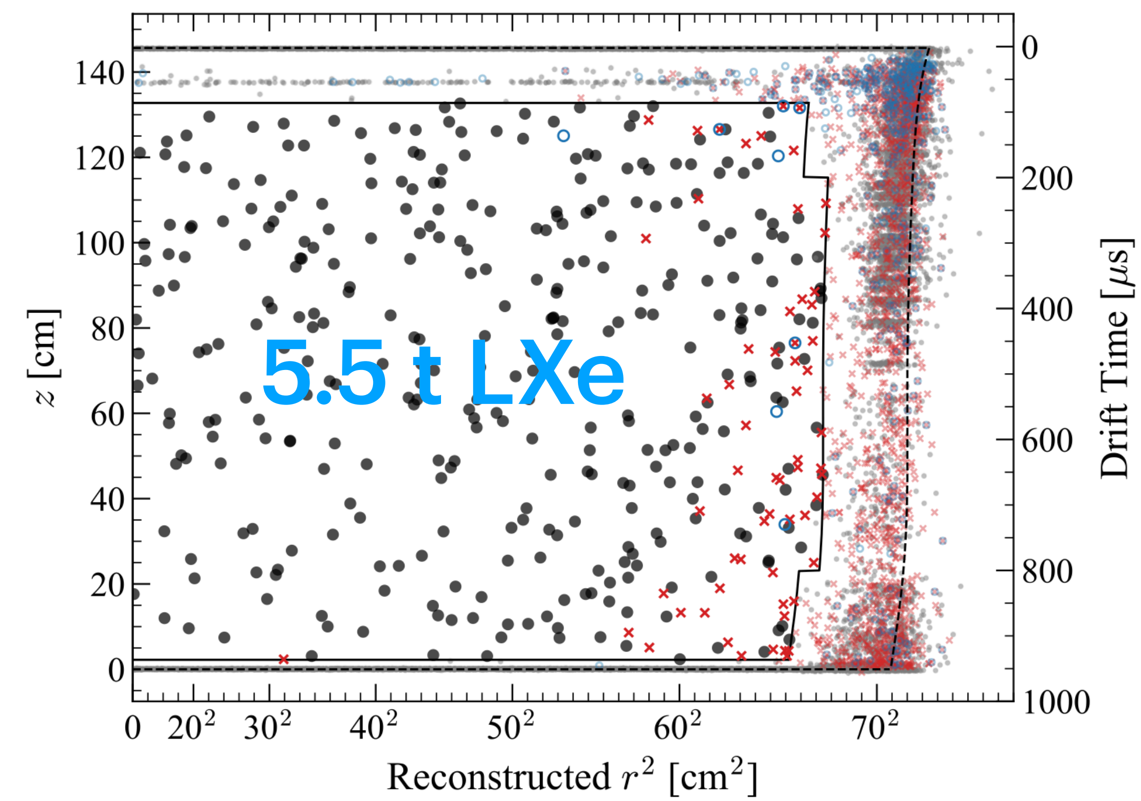
LZ collaboration, NIM-A, 2020

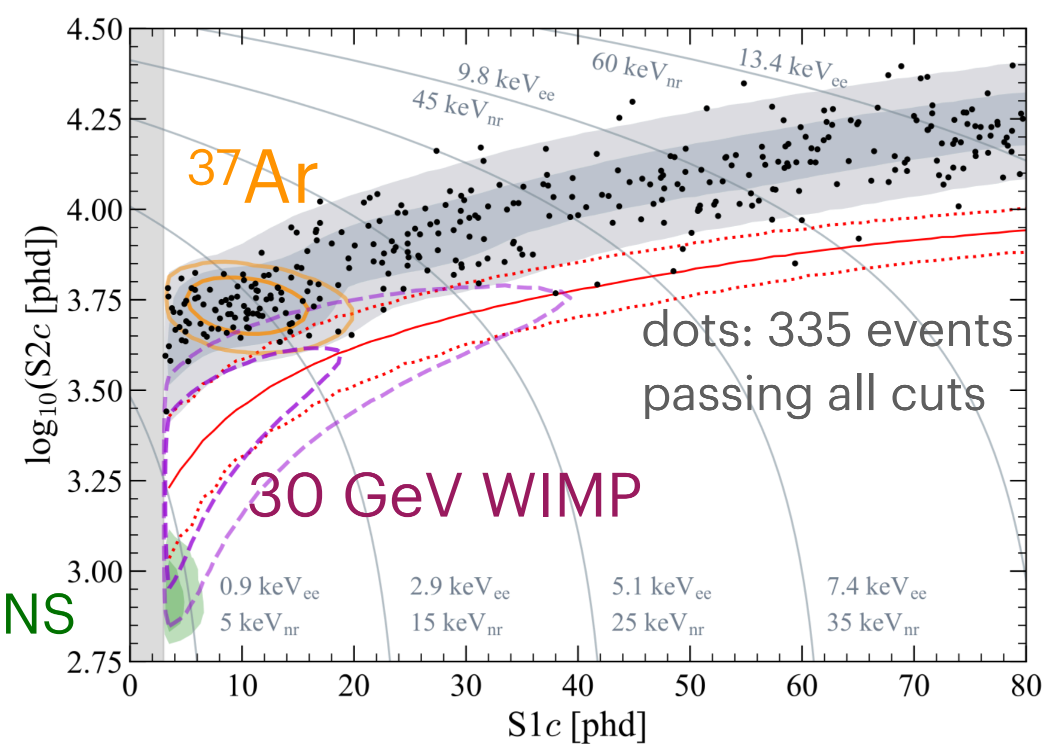
LUX-ZEPLIN at SURF



First results from LZ

- First science run: Dec 2021- May 2022, for 60 live days WIMP search
- Active LXe: 7 t, 5.5 t in fiducial volume
- ROI: S1 (3,80) phd, S2 > 600 phd (10 e$^-$)
- Backgrounds
  - Expected ERs: 276 ('naked' ^{214}Pb betas) + [0, 291] from ^{37}Ar
  - Expected NRs: 0.15
- 335 events observed in final dataset

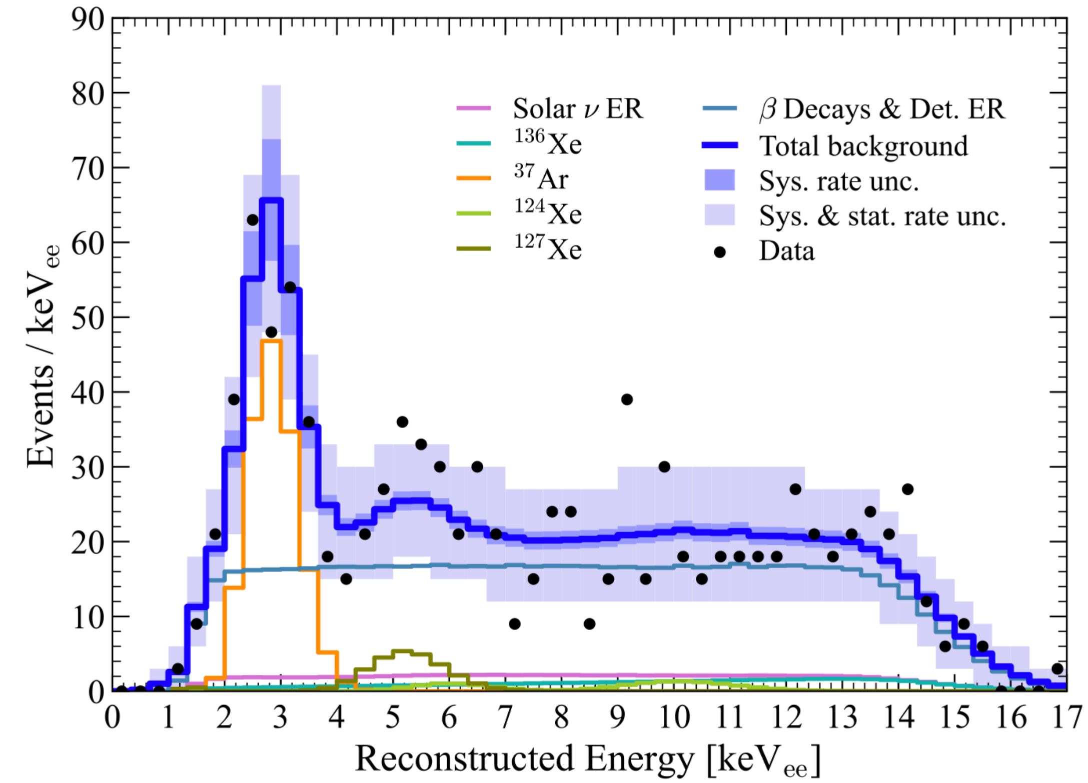




^{8}B neutrinos: CEvNS

First results from LZ

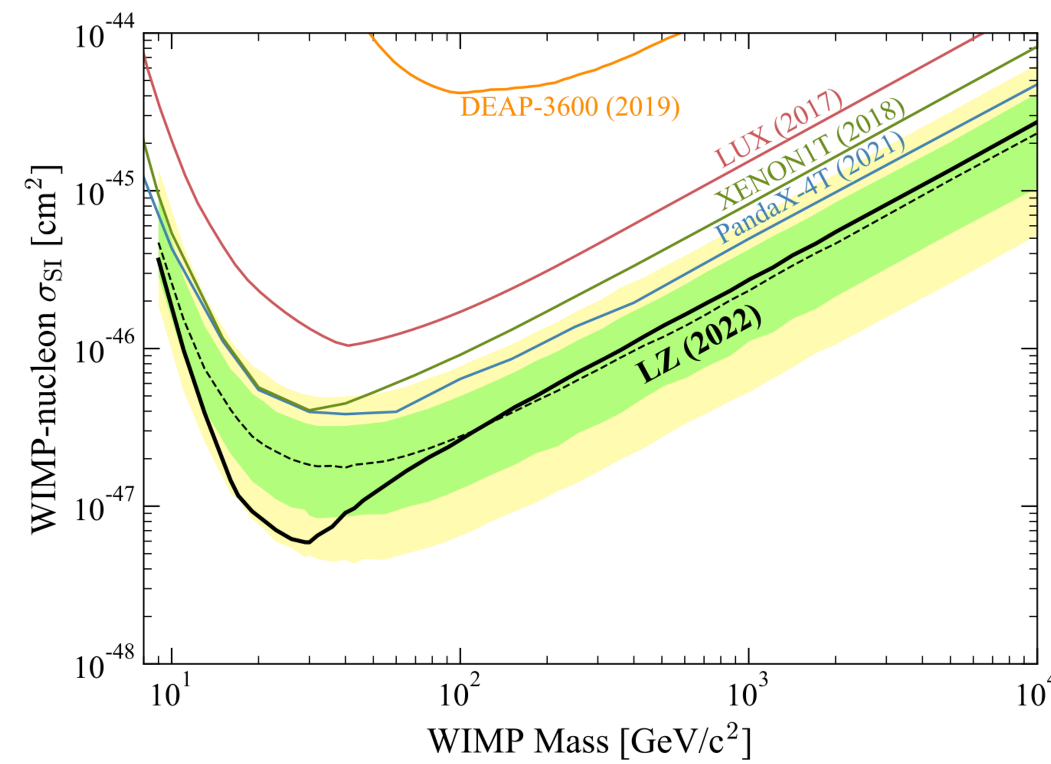
Source	Expected Events	Fit Result
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17



- Best fit: zero WIMP events at all masses

  ⇒ Upper limits on WIMP-nucleon cross section: 5.9 x 10^{-48} cm^2 at 30 GeV mass, 90% CL

- Plans: 1000 live days of data, extend the reach (S2-only, Migdal) & conduct other searches (non-WIMP dark matter, astrophysical neutrinos, rare decays)

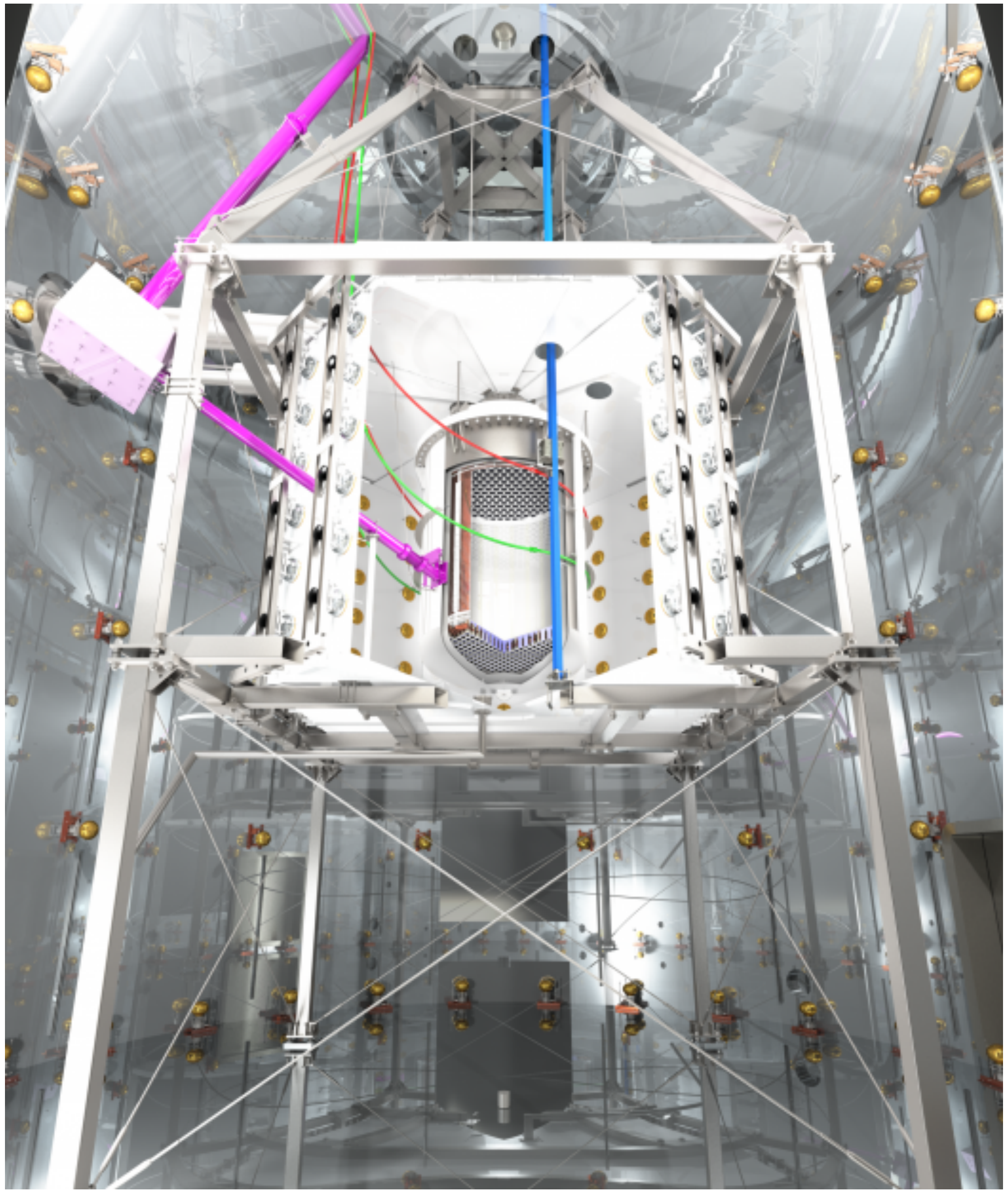


LZ collaboration, arXiv:2207.03764

The XENONnT experiment

The XENONnT experiment

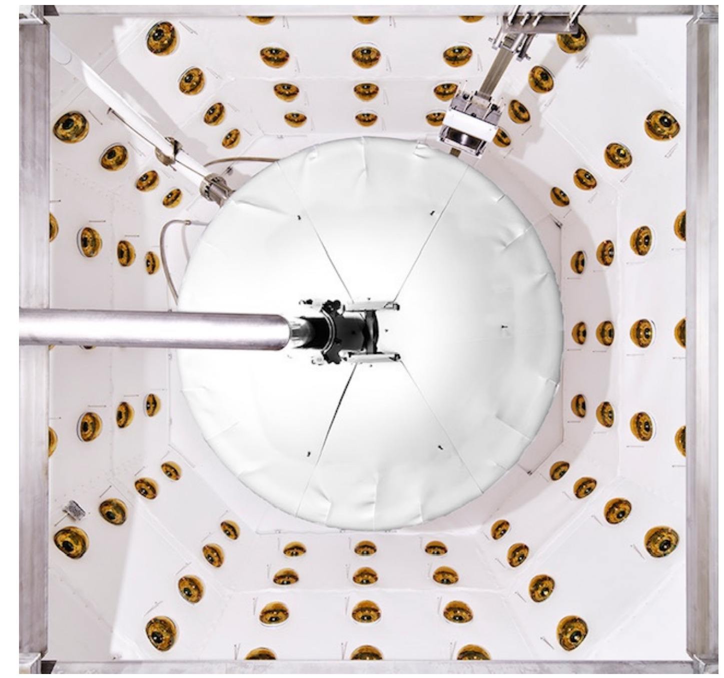
- Three nested detectors: muon & neutron vetos; TPC: 1.5 m tall, 1.3 m diameter, 494 3-inch diameter PMTs
- Total LXe mass: 8.6 t, 5.9 t in the TPC
- Liquid and gas purification systems ($\tau_e > 10\,\mathrm{ms},\ t_{\mathrm{max}} = 2.2\,\mathrm{ms}$)
- Radon and krypton distillation columns (^{nat}Kr ~ 60 ppq; ^{222}Rn: ~1.7 µBq/kg)
- First science run (SR0)
    - 97.1 live days, 4.4 t LXe in fiducial volume ⇒ 1.16 tonne years exposure

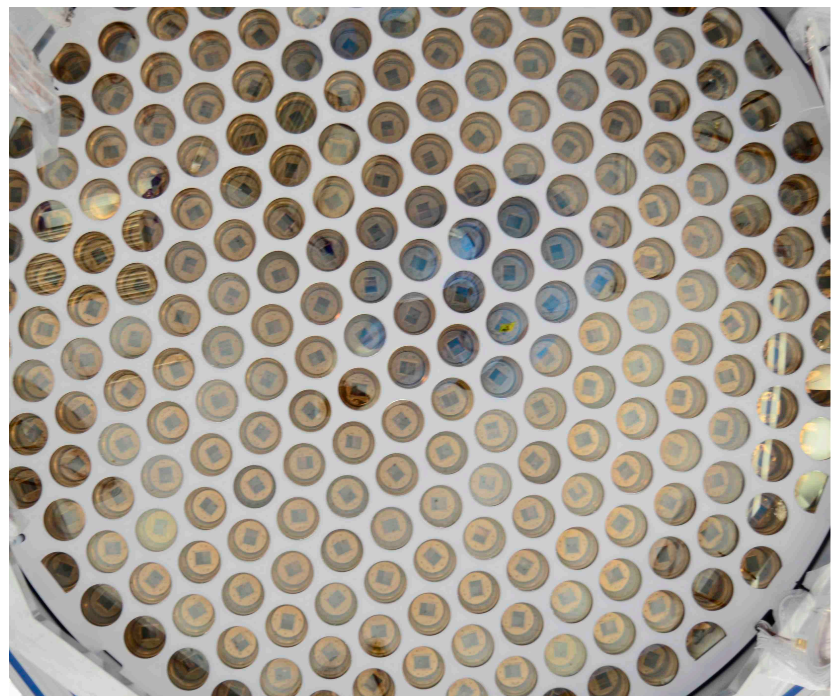


XENONnT at LNGS

TPC: 5.9 t LXe,
1.3 m Ø, 1.5 m tall

Neutron veto: 120 additional PMTs, Gd doped water



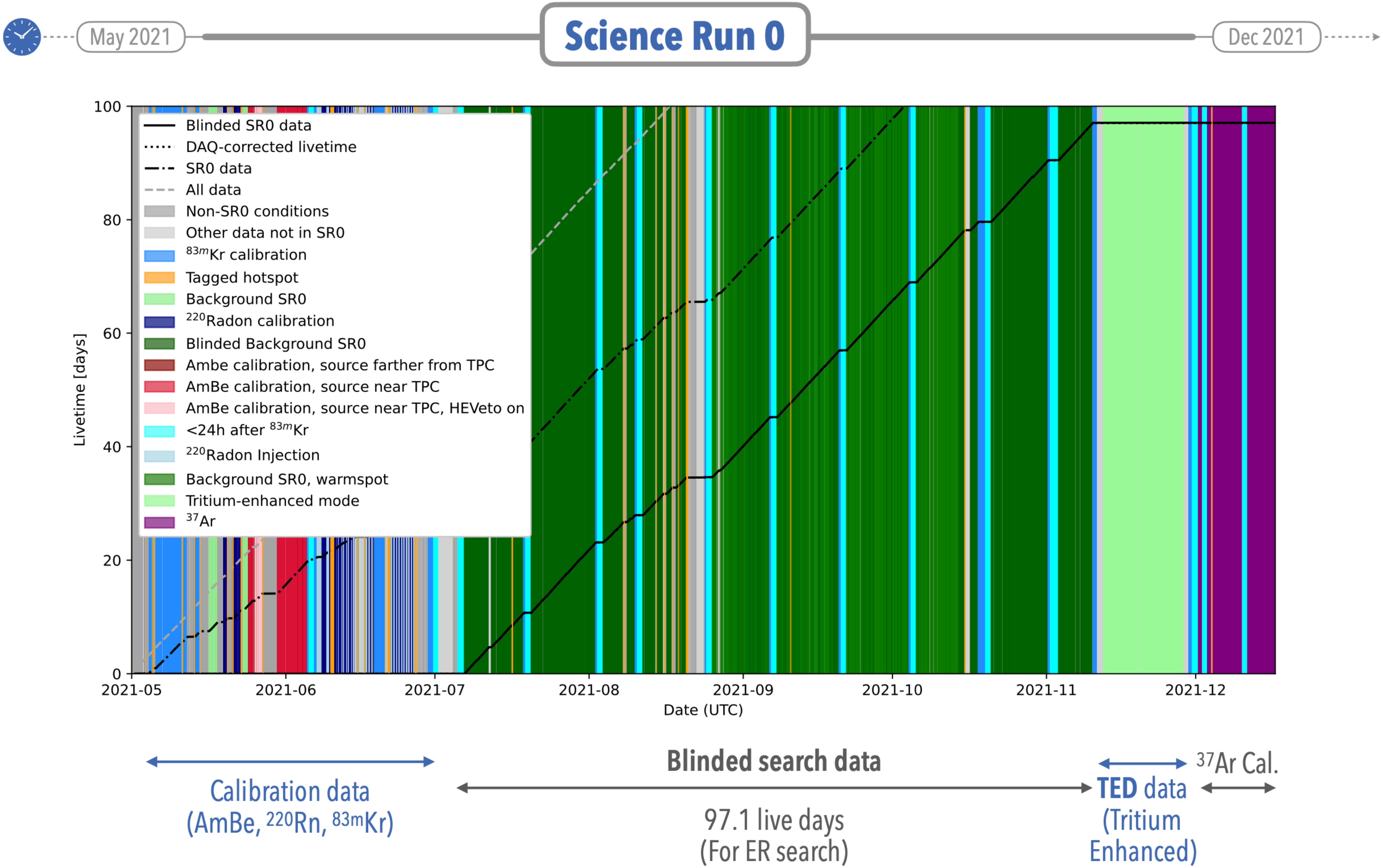


494 PMTs in total, in 2 arrays

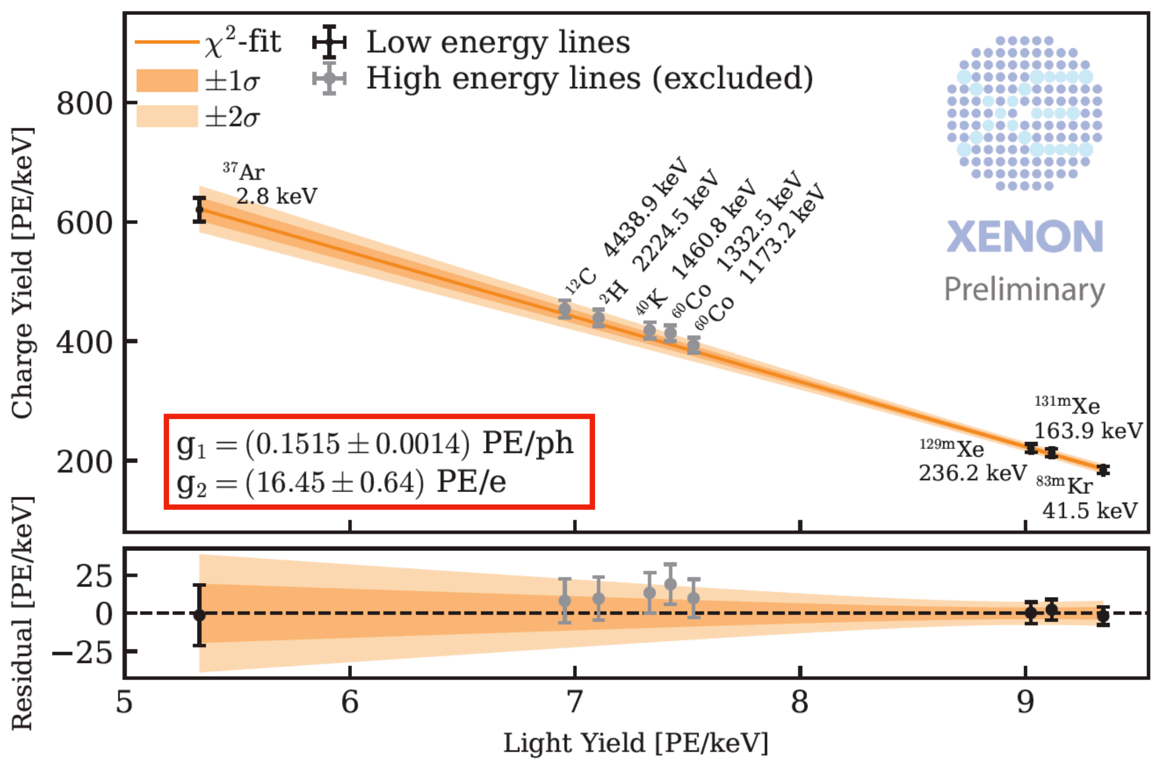
LXe purification system (5 L/min LXe, faster cleaning; 2500 slpm)

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

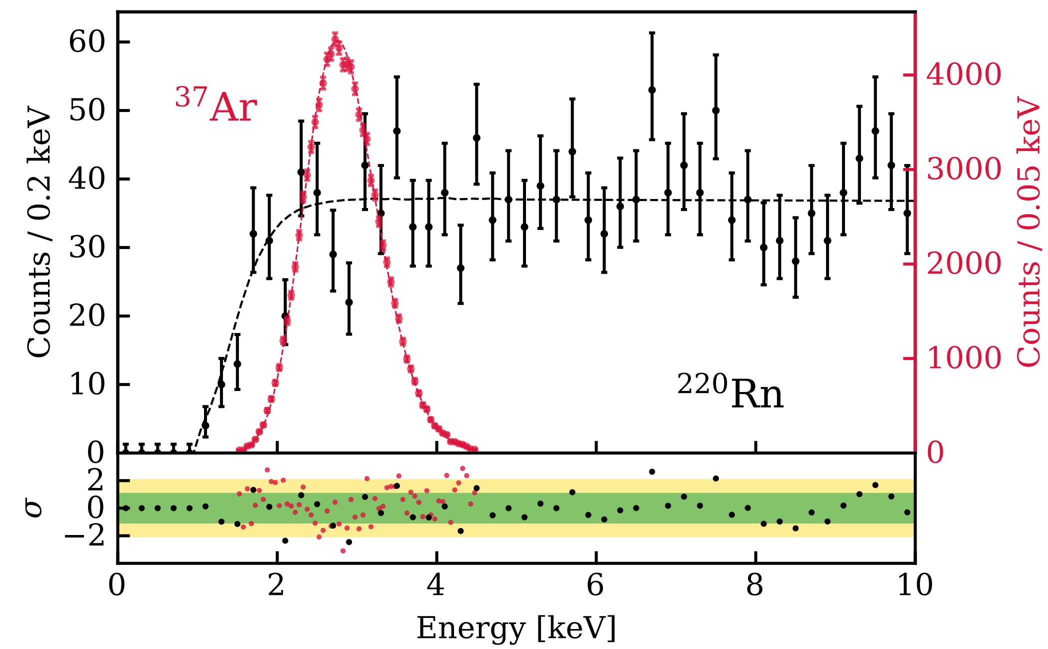
XENONnT timeline: SR0

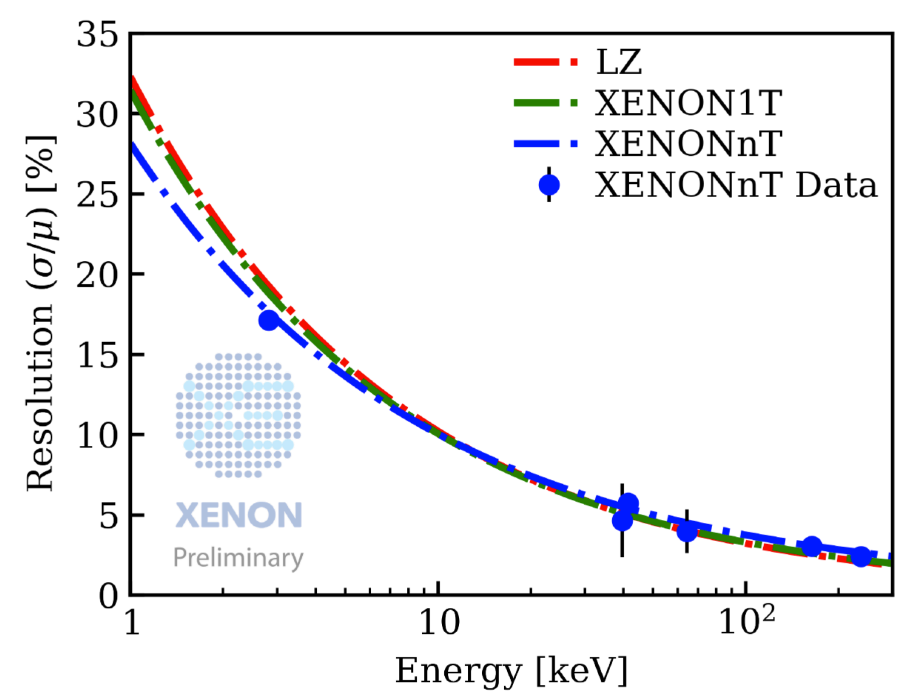


Energy response and validation



energy scale and threshold



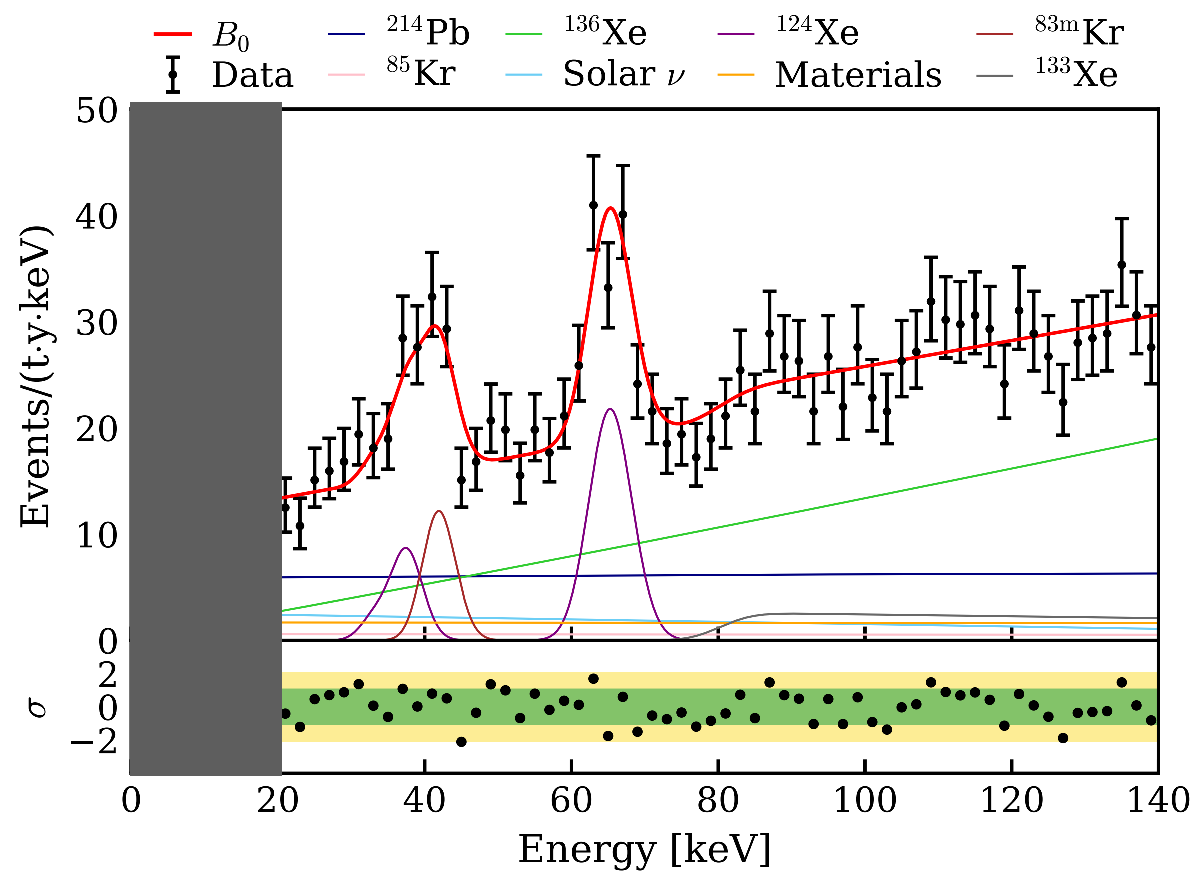


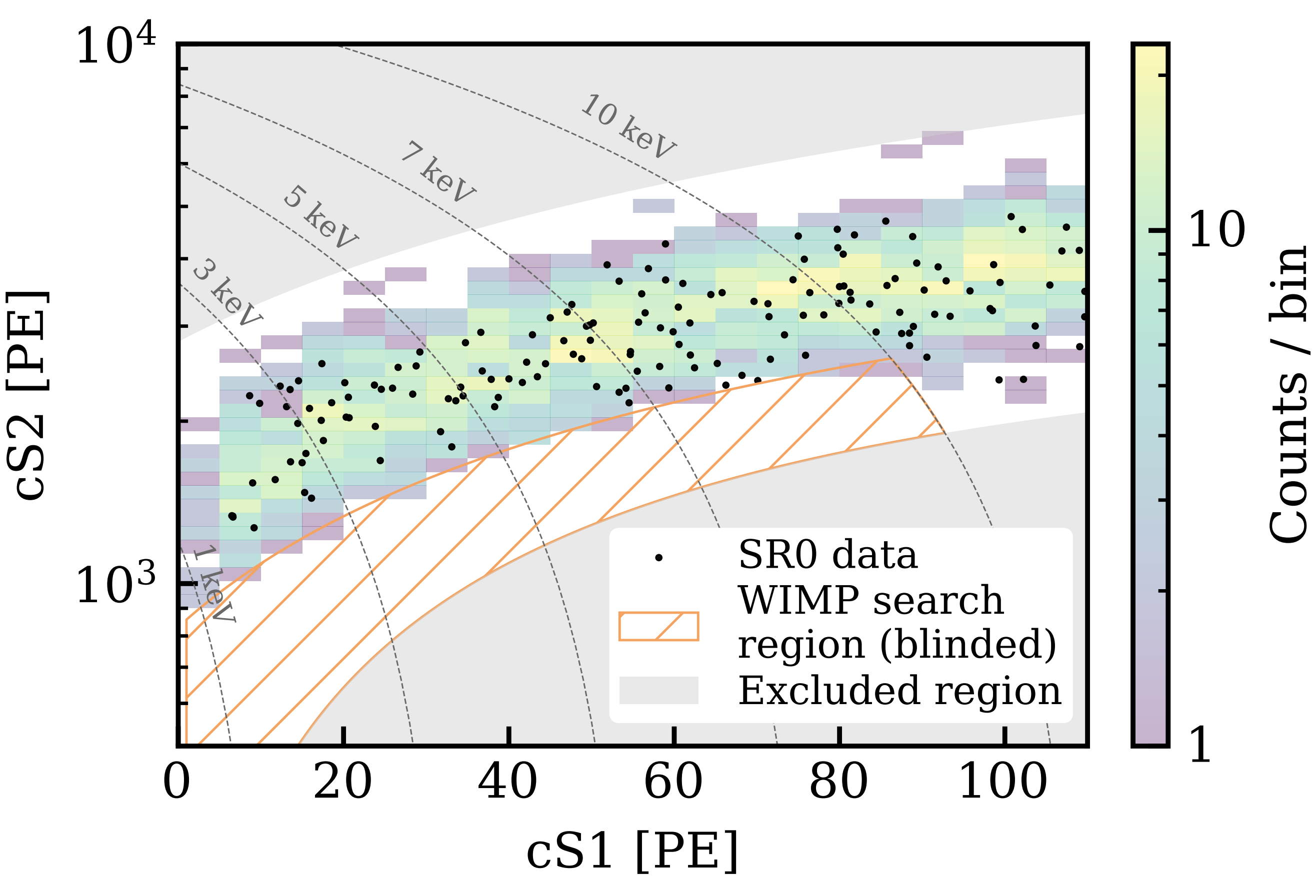
energy resolution

- Calibrations with various sources (including ^{37}Ar, ^{83m}Kr, ^{220}Rn, AmBe)
- Reconstruct energy (with g_1, g_2), validate efficiency and energy threshold with ^{37}Ar, ^{220}Rn (^{212}Pb β-decay) data

ER Backgrounds in XENONnT

- Spectral shape dominated by two double-weak decays: ^{136}Xe $2\nu\beta\beta$, ^{124}Xe 2νECEC





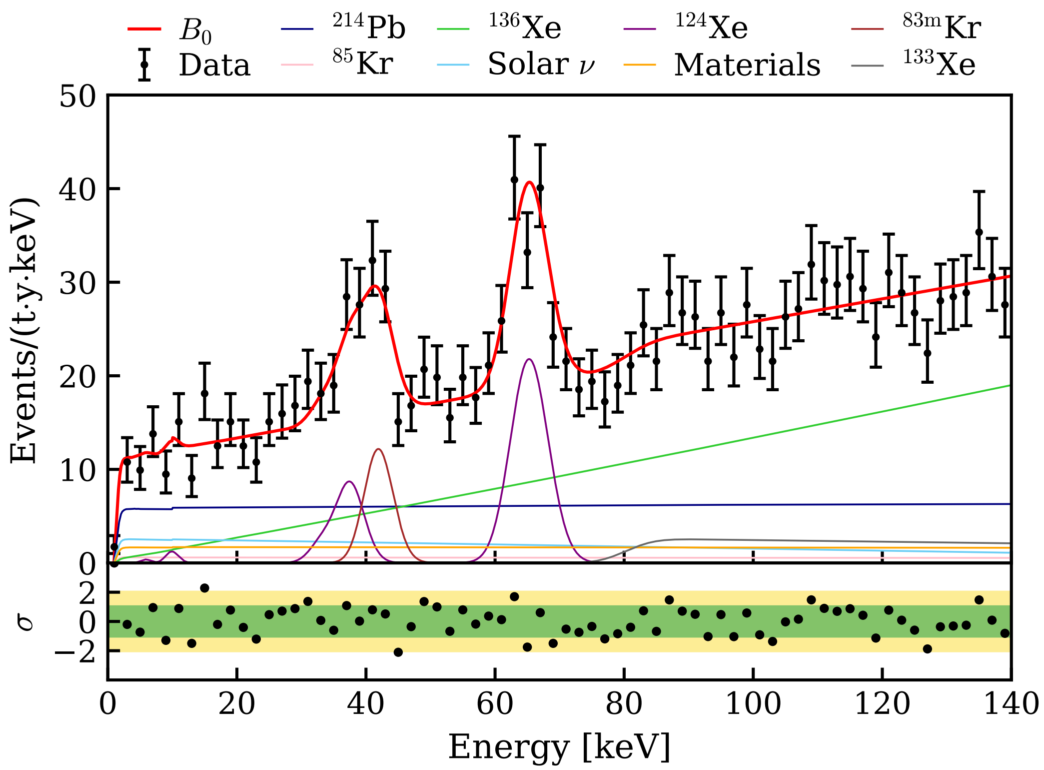
Component	Constraint	Fit
^{214}Pb	(584, 1273)	980 ± 120
^{85}Kr	90 ± 59	91 ± 58
Materials	266 ± 51	267 ± 51
^{136}Xe	1537 ± 56	1523 ± 54
Solar neutrino	297 ± 30	298 ± 29
^{124}Xe	-	256 ± 28
AC	0.70 ± 0.04	0.71 ± 0.03
^{133}Xe	-	163 ± 63
^{83m}Kr	-	80 ± 16

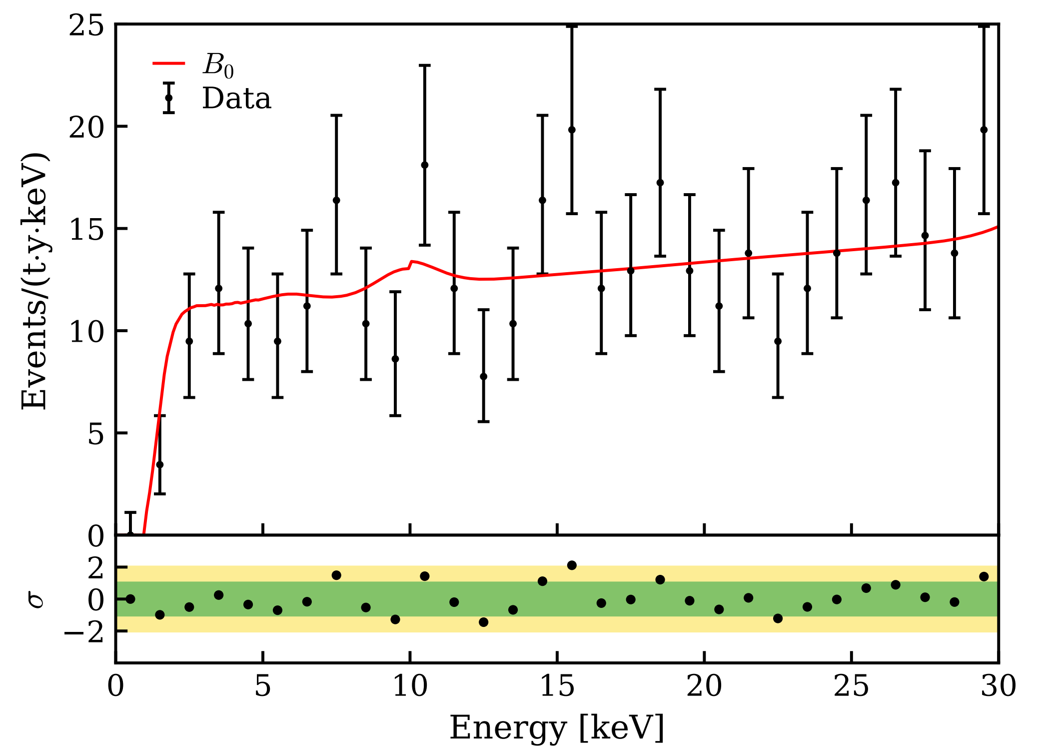
XENON collaboration, PRL 129, 2022

ER Backgrounds in XENONnT

- Best fit rate for ^{214}Pb: (1.36±0.17) μBq/kg
- Solar neutrinos: second largest background below 10 keV

	(1, 10) keV	(1, 140) keV
^{214}Pb	56 ± 7	980 ± 120
^{85}Kr	6 ± 4	90 ± 60
Materials	16 ± 3	270 ± 50
^{136}Xe	8.7 ± 0.3	1520 ± 50
Solar ν	25 ± 2	300 ± 30
^{124}Xe	2.6 ± 0.3	260 ± 30
AC	0.70 ± 0.03	0.71 ± 0.03
^{133}Xe	-	160 ± 60
^{83m}Kr	-	80 ± 16





XENON collaboration, PRL 129, 2022

ER Backgrounds in XENONnT

- Total ER background below 30 keV: (15.8±1.3) events/(t y keV): ~ 0.2 x the one of XENON1T
- Lowest background achieved in a DM detector
- No excess observed in XENONnT

	(1, 10) keV	(1, 140) keV
^{214}Pb	56 ± 7	980 ± 120
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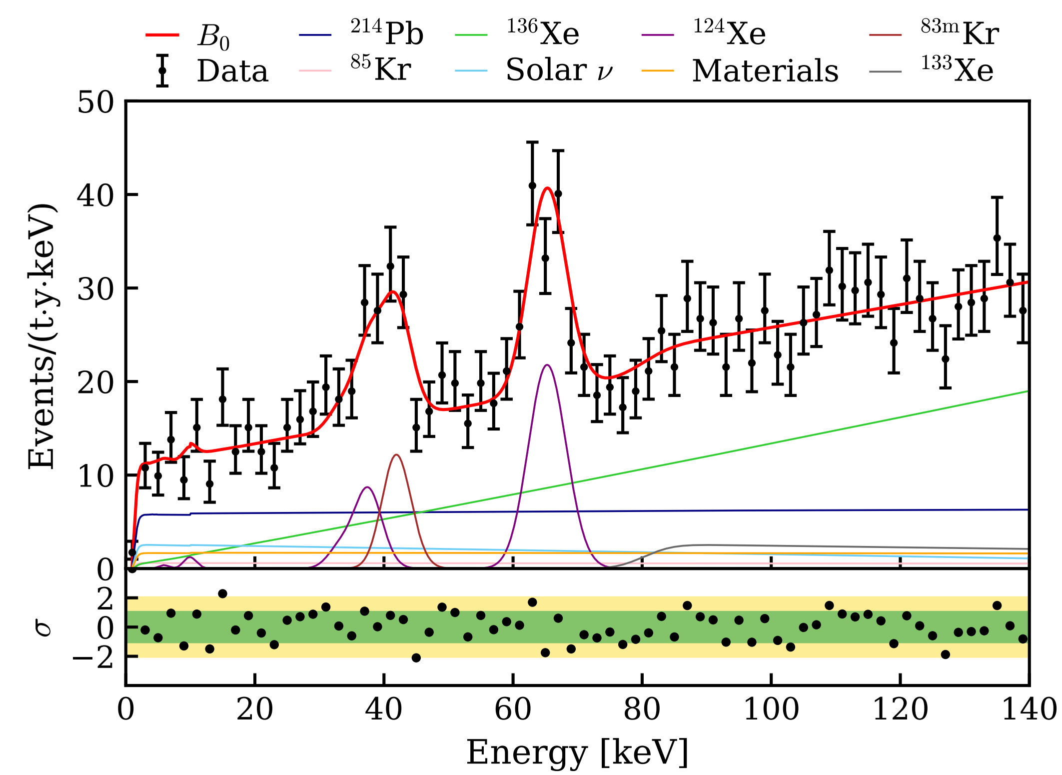

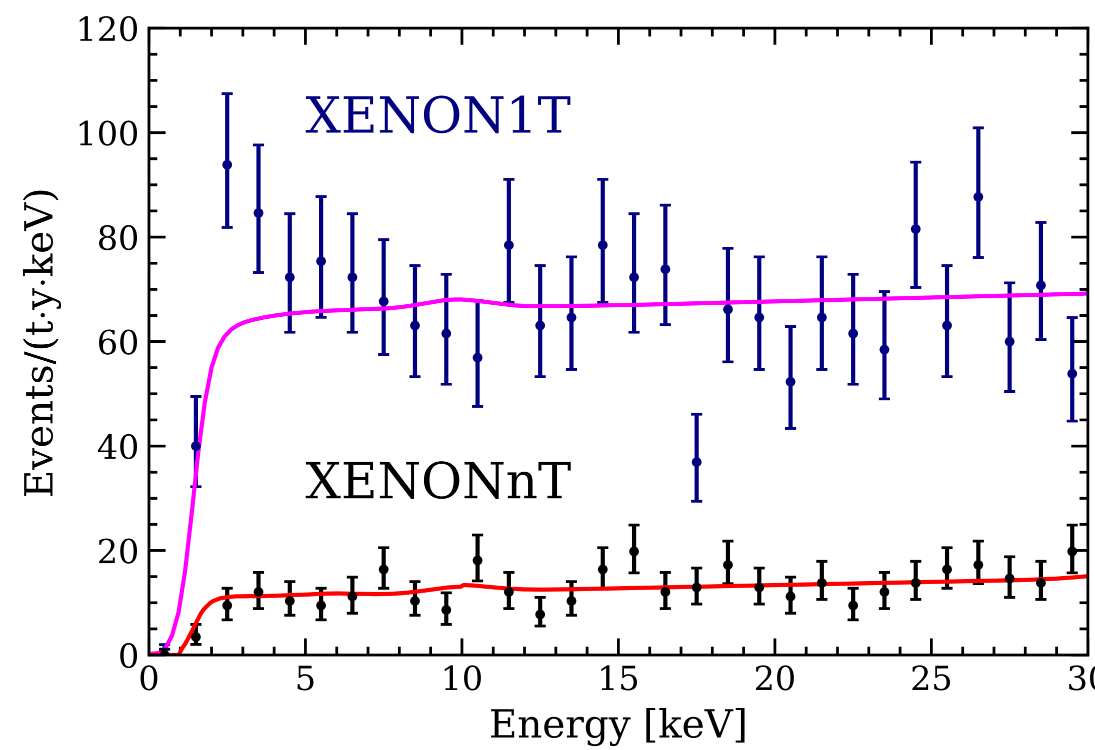

XENON collaboration, PRL 129, 2022

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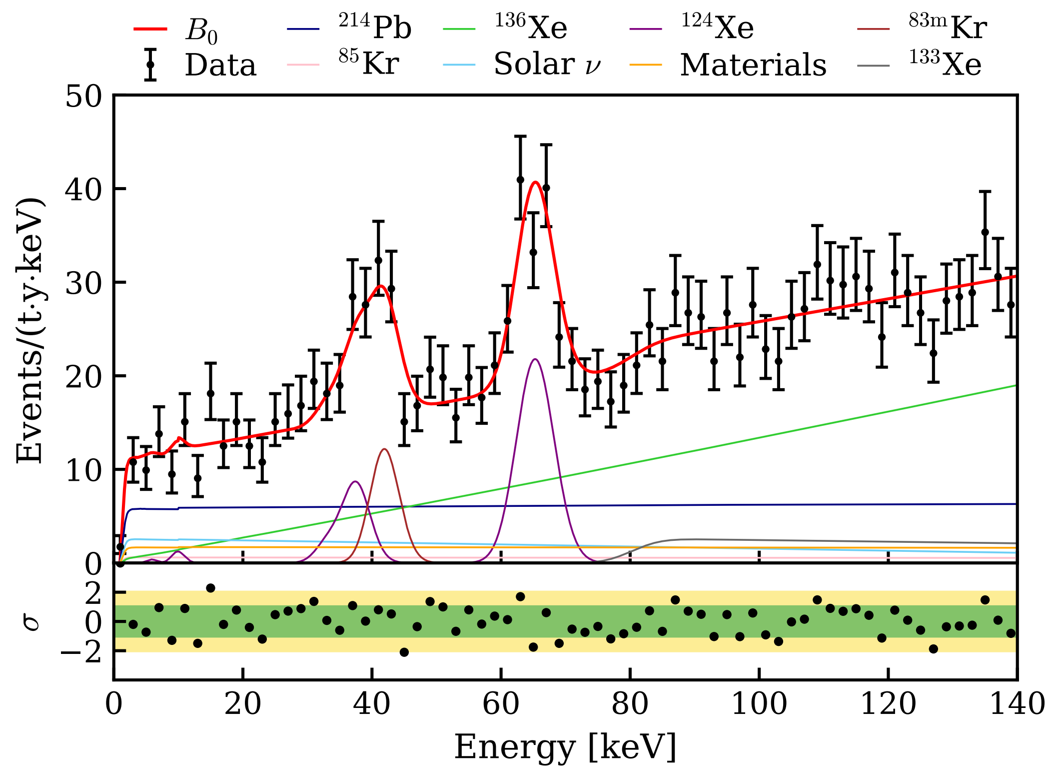
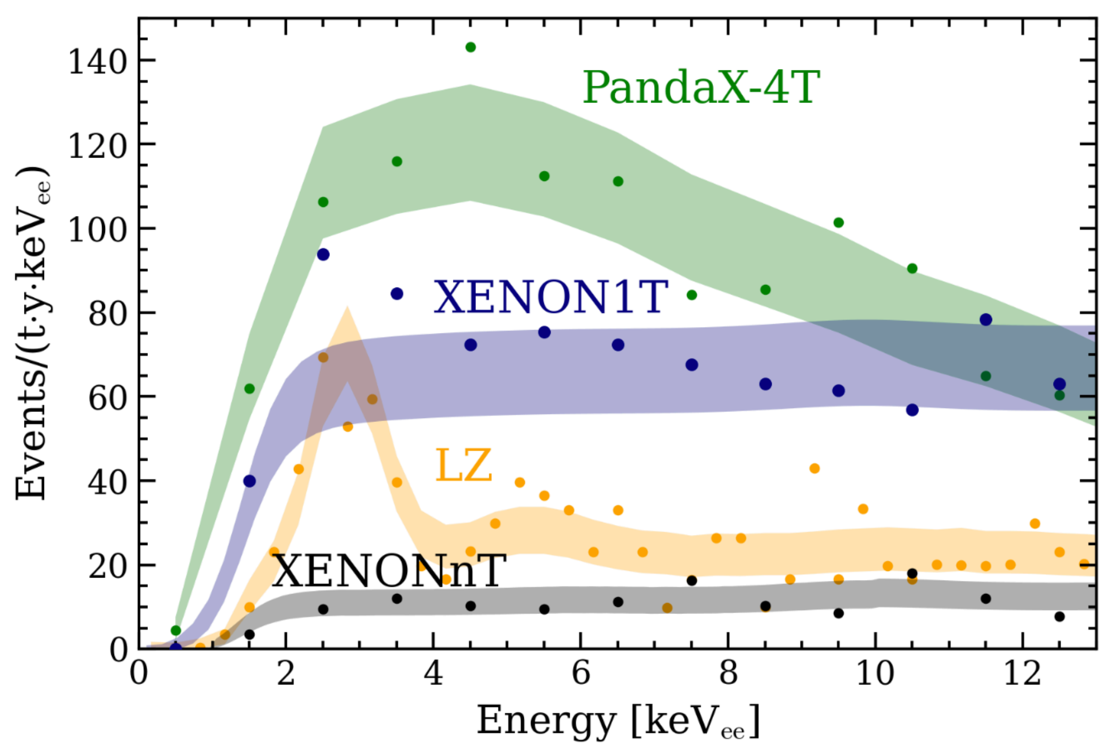
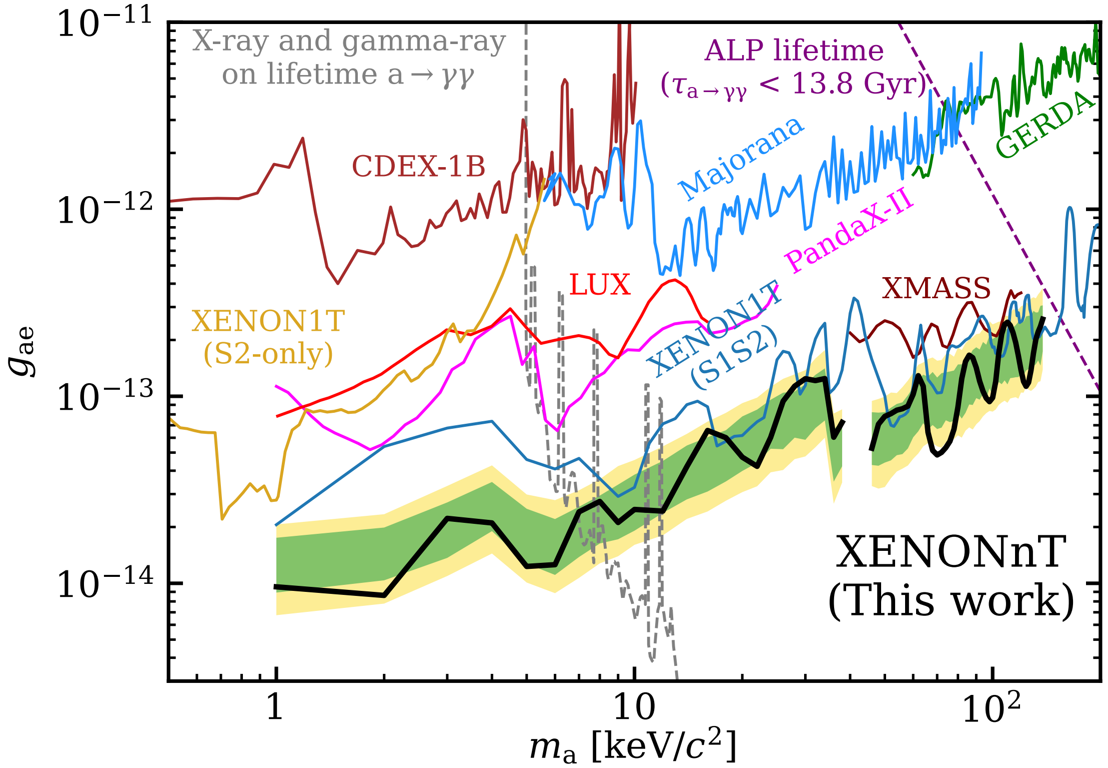
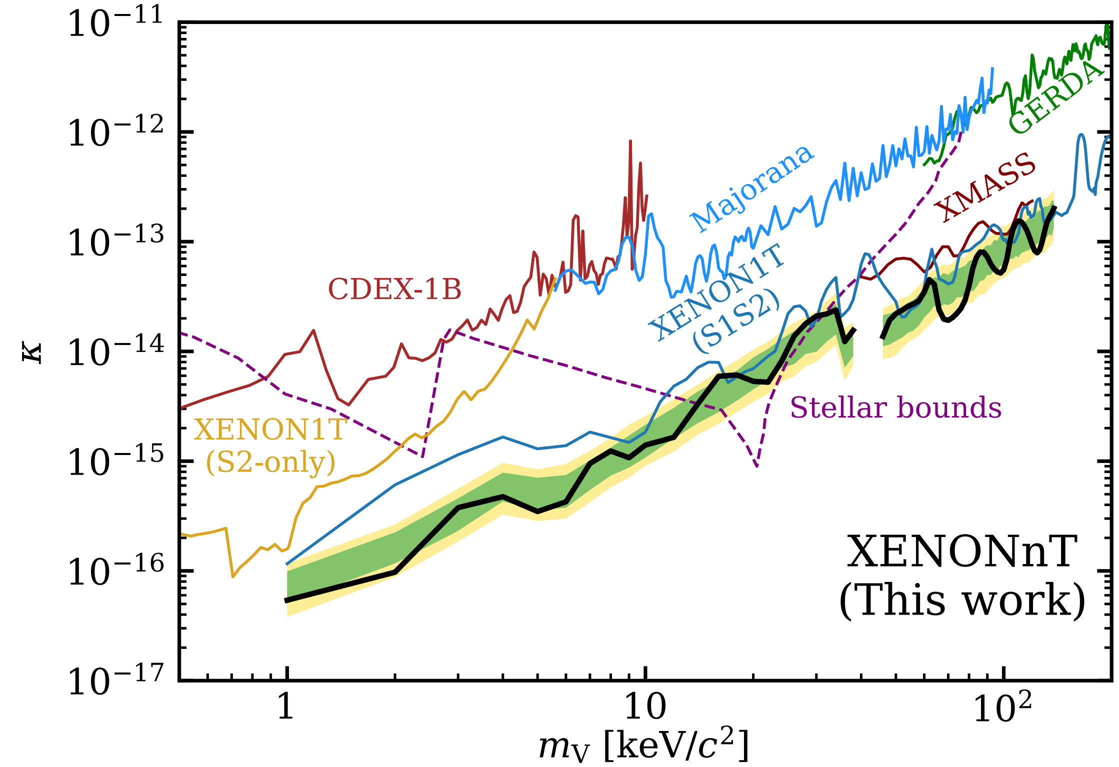




XENON collaboration, PRL 129, 2022

First results from XENONnT: bosonic dark matter

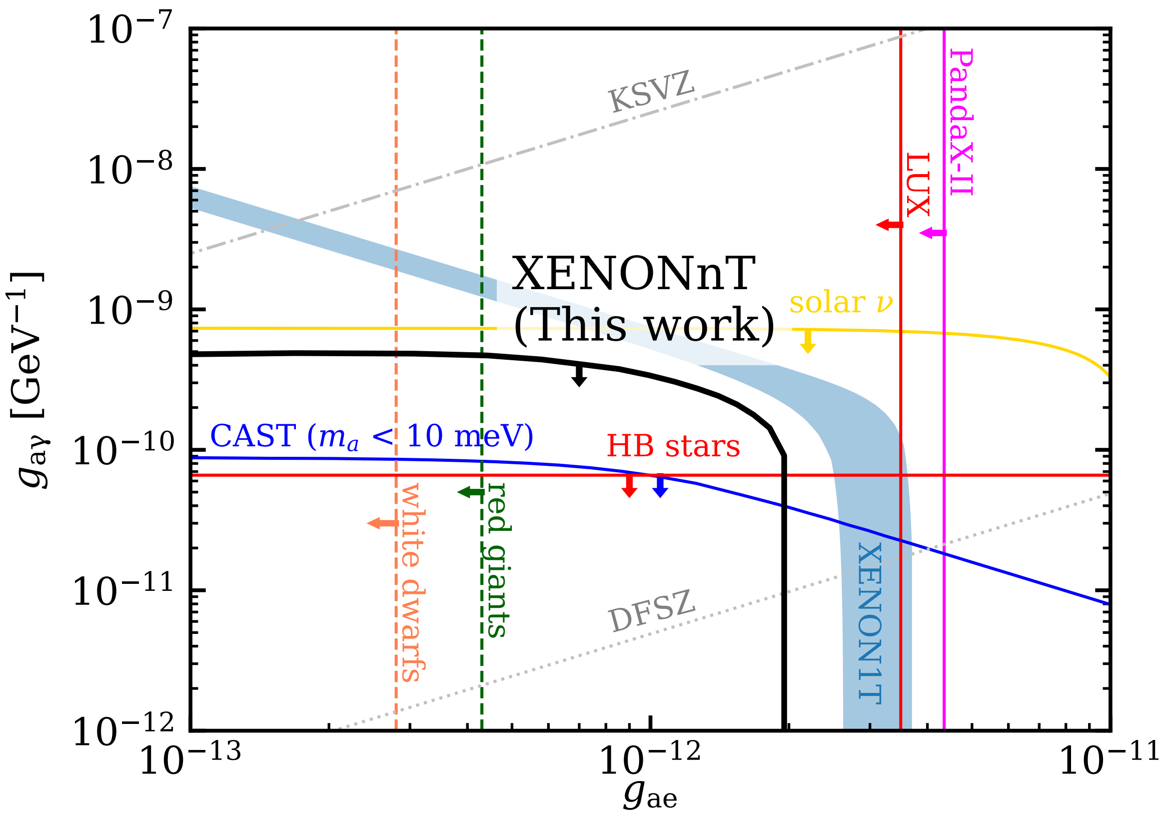


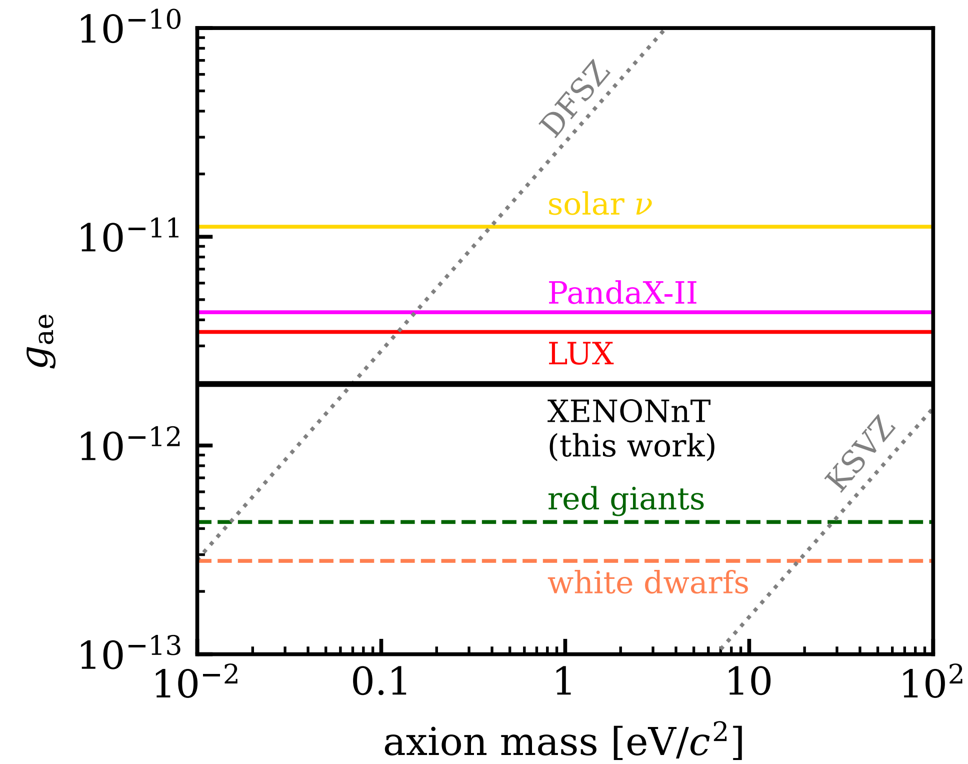


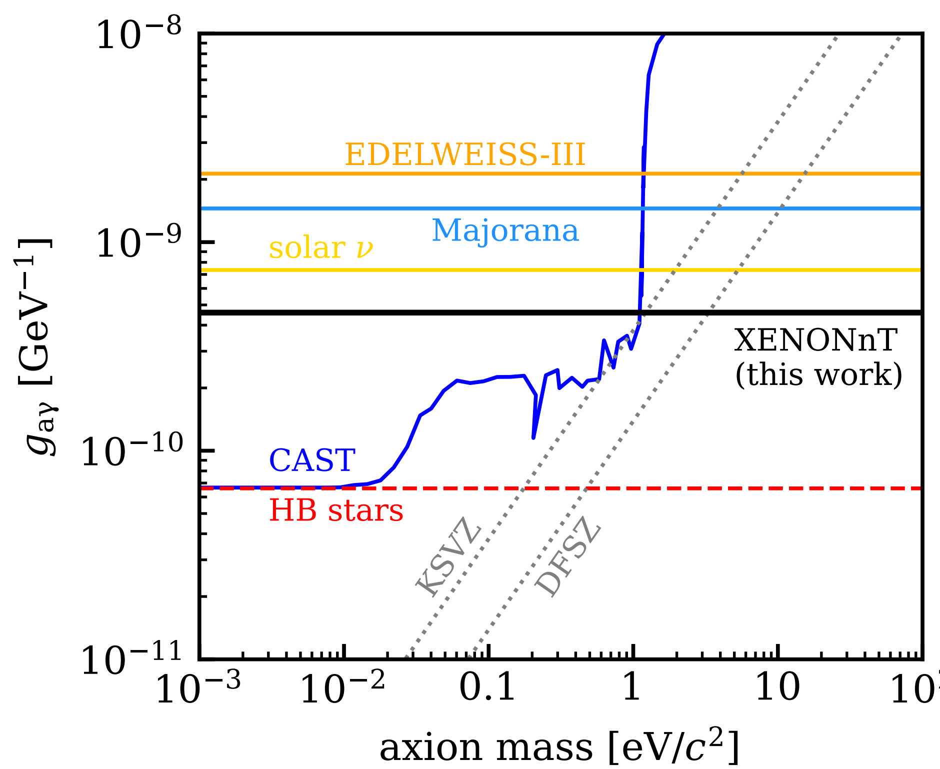
- Constrains on the couplings of galactic ALPs and dark photons:
    - competitive limits for masses in the ranges (1, 39) and (44, 140) keV/c^2
    - no limit/sensitivity between (39, 44) keV/c^2 because $^{83\mathrm{m}}\mathrm{Kr}$ background rate is not constrained

XENON collaboration, PRL 129, 2022

First results from XENONnT: solar axions



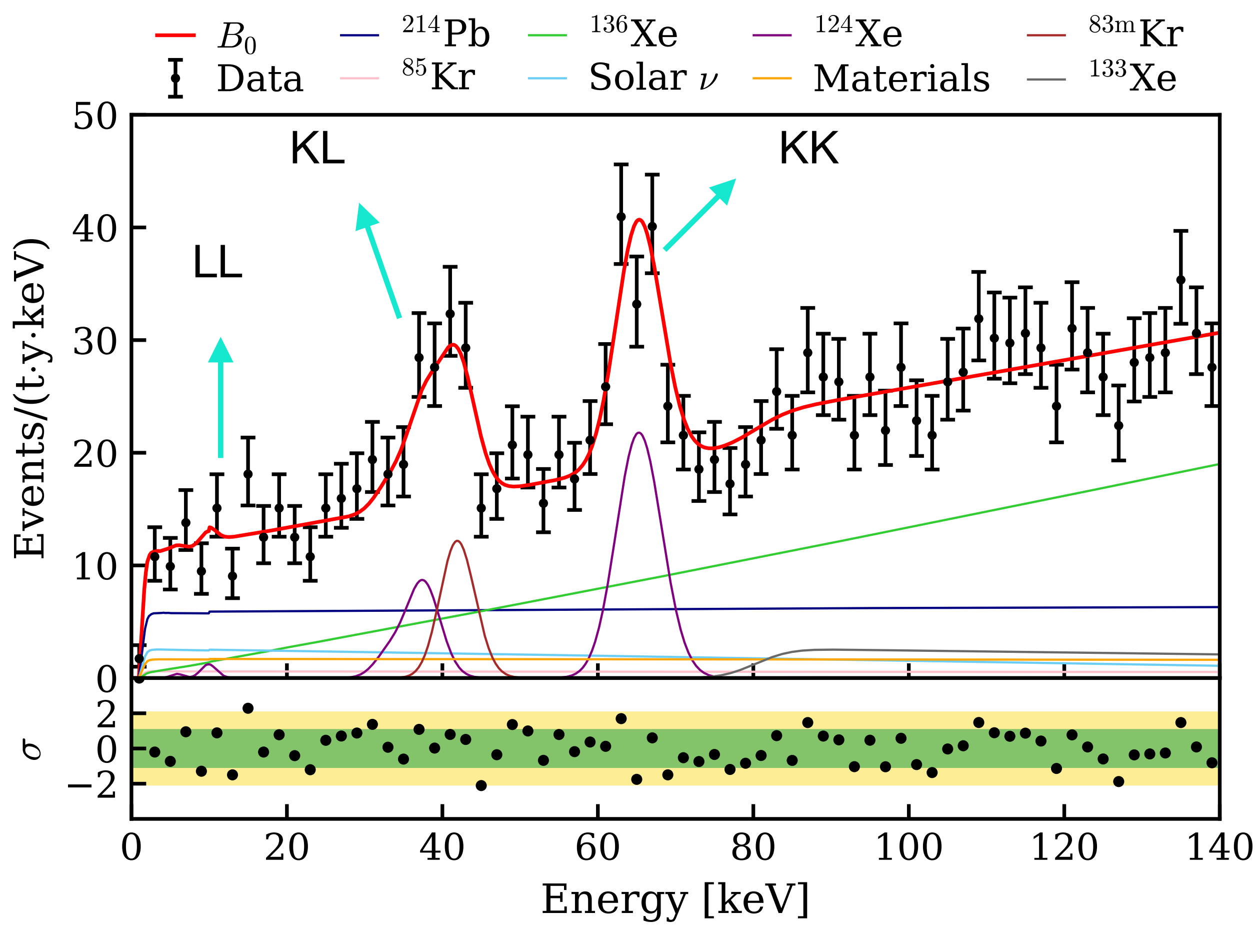


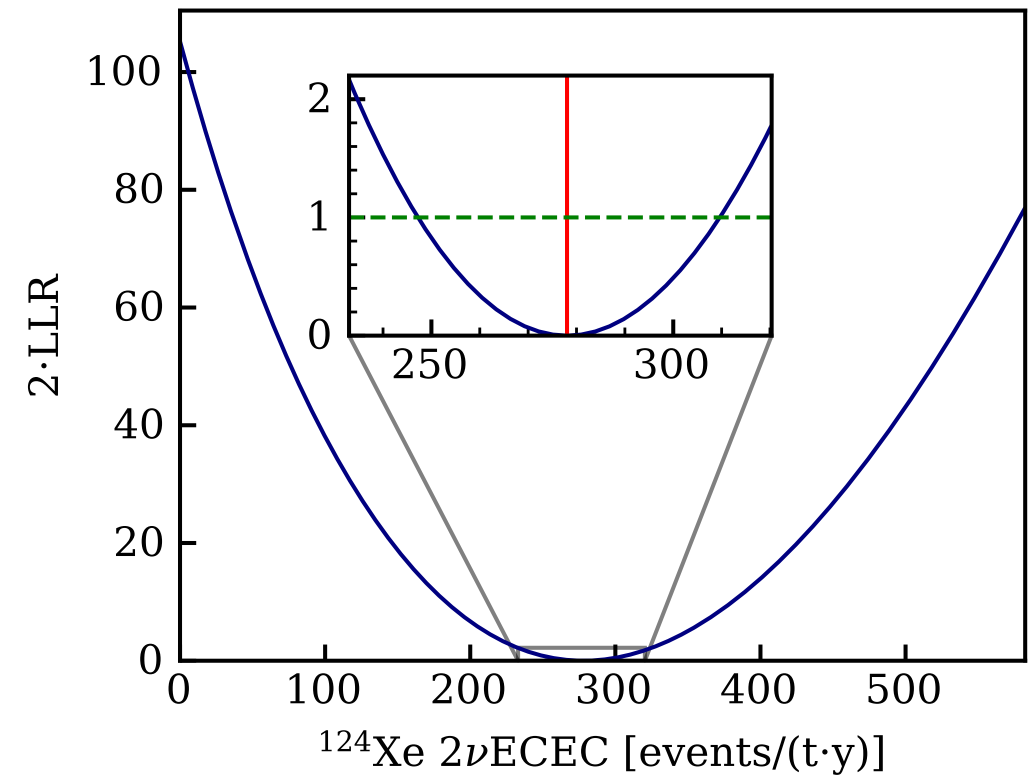


- Constrains on the couplings of solar axions:
  - statistical inference in 3D space
  - projection to 2D space of $g_{a\gamma}$ and g_{ae}

XENON collaboration, PRL 129, 2022

First results from XENONnT: ^{124}Xe



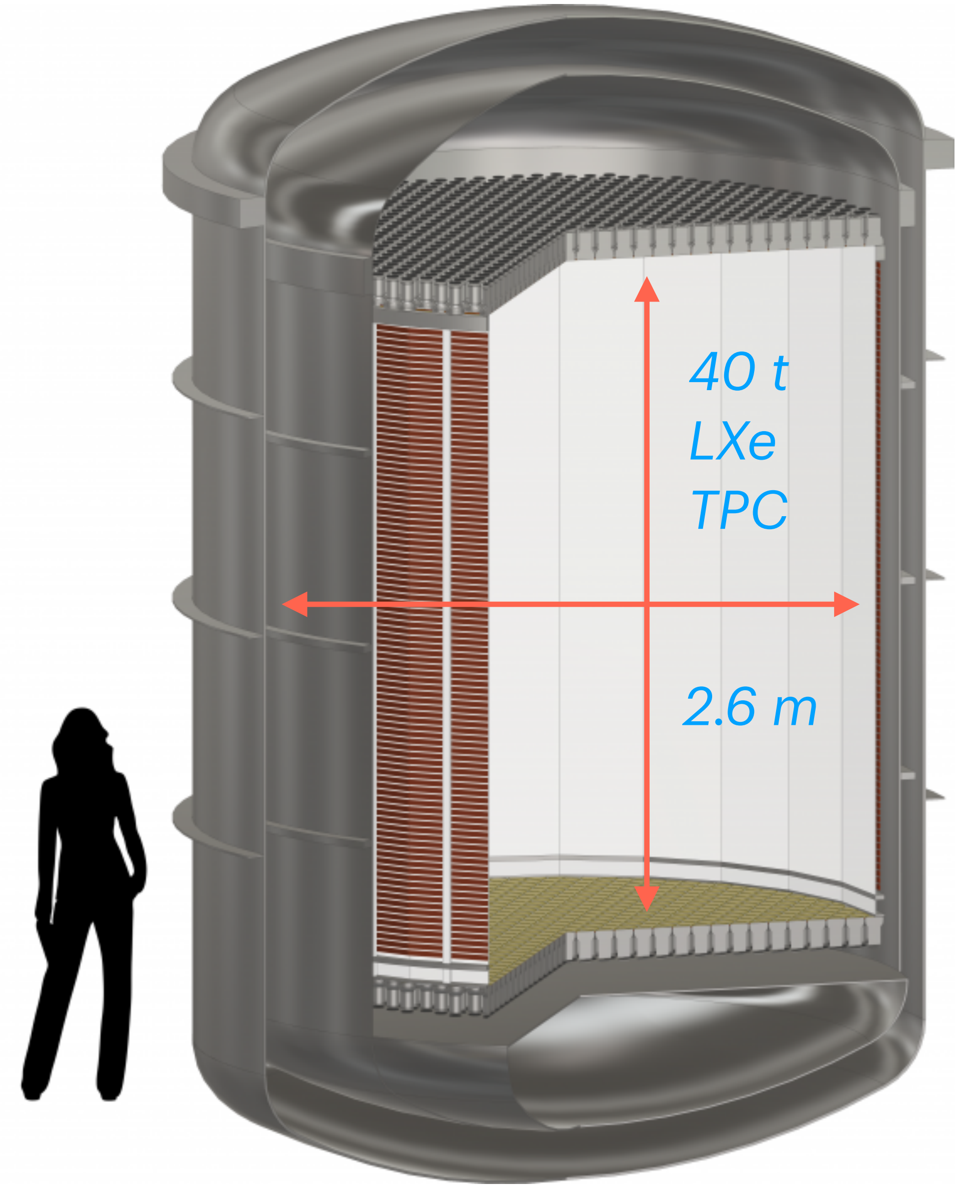


- ^{124}Xe 2vECEC rate: unconstrained in the analysis, the branching ratios are fixed
  - clear peaks in the low-energy spectrum due to the very low background rate
  - KK and KL peaks used for calibrations, LL peak starts to become visible (1% BR)
  - measured half-life $T_{1/2}^{2\nu\mathrm{ECEC}} = (1.15 \pm 0.13_{\mathrm{stat}} \pm 0.14_{\mathrm{sys}}) \times 10^{22}\,\mathrm{yr}$ with a significance of 10 $\sigma \Rightarrow$ consistent with the latest XENON1T result (PRC 106, 2022)

Future xenon TPC: DARWIN

- Two-phase TPC: 2.6 m ø and 2.6 m height
- 50 t (40 t) LXe in total (in TPC)
- Top & bottom arrays of photosensors (e.g., 1800 3-inch PMTs)
- PTFE reflectors and Cu field shaping rings
- Low-background Ti cryostat
- Gd-doped water as n- and μ-vetos

Baseline design; alternative designs and photosensors under consideration



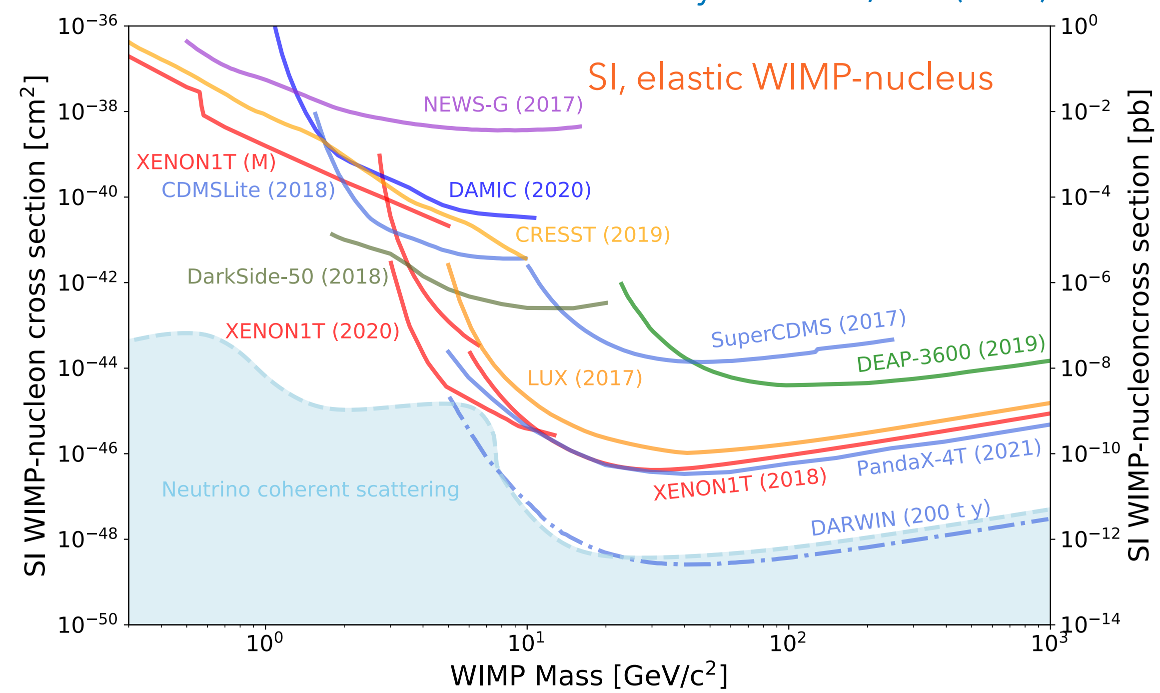
DARWIN collaboration
JCAP 1611 (2016) 017

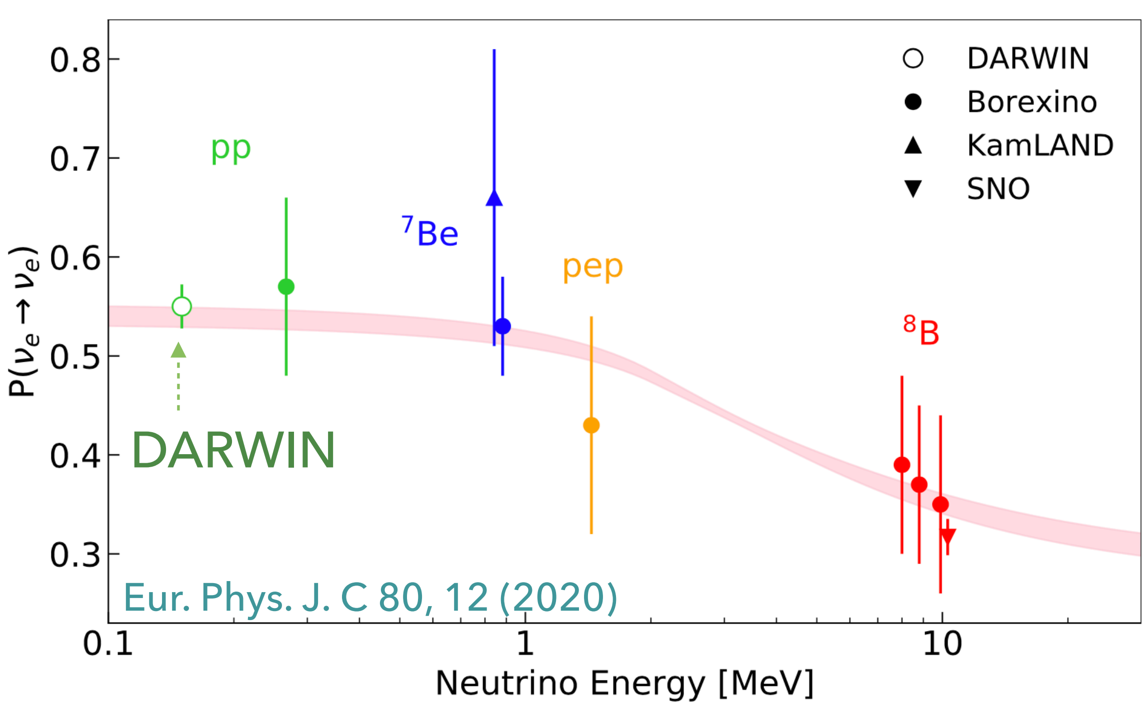
DARWIN: a multipurpose observatory for rare events

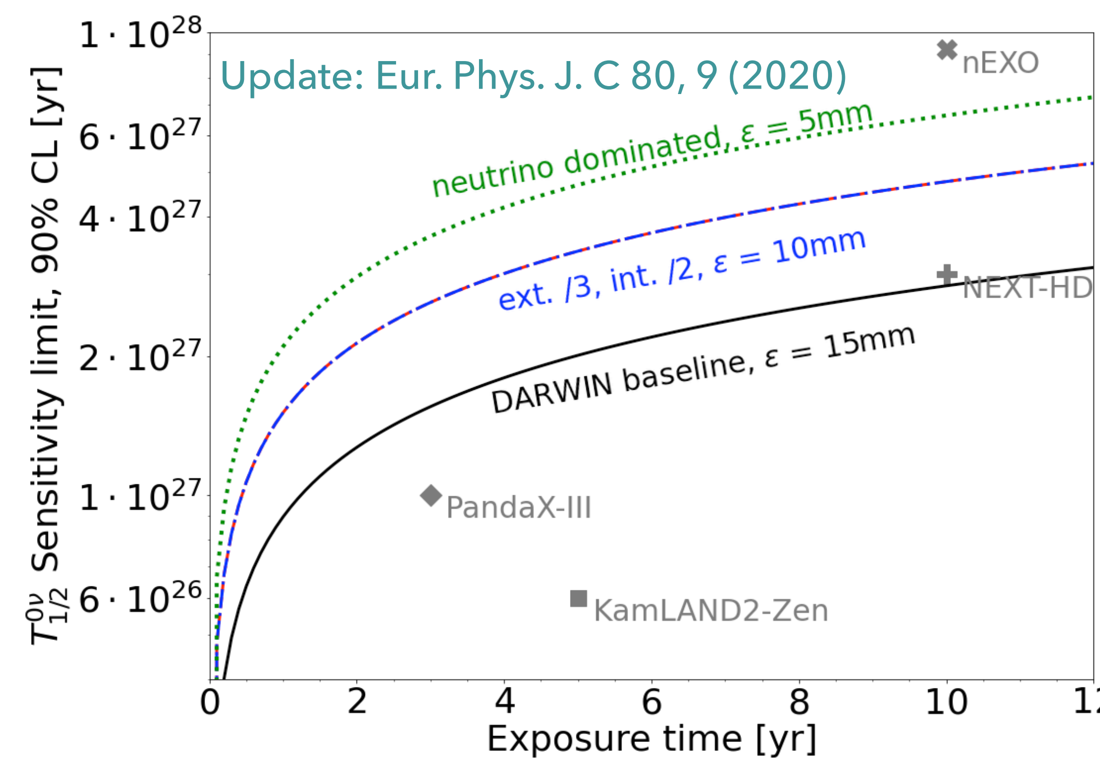
- Dark matter (WIMPs and light-DM)
- $0\nu\beta\beta$-decay of ^{136}Xe
- Low-energy solar neutrinos
- ^{8}B solar ν's via CEνNS
- Supernova neutrinos
- Solar axions; galactic ALPs, dark photons

see also arXiv:2203.02309

DARWIN study: JCAP 10, 016 (2015)



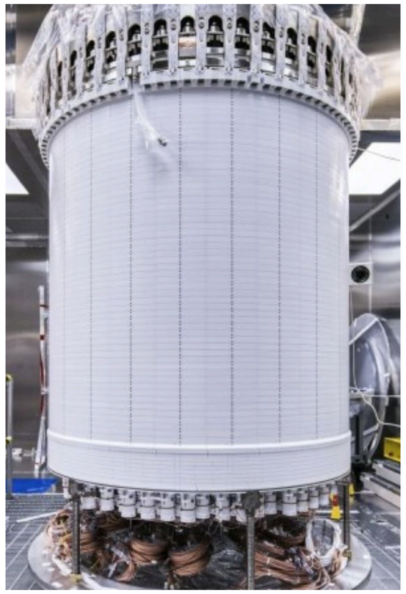




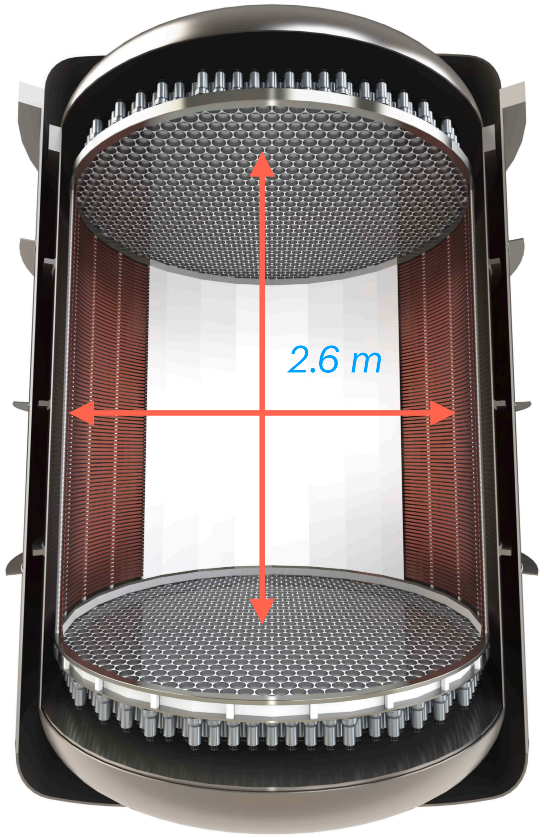
Size matters

- LUX-ZEPLIN and XENONnT: 1.5 m e^- drift and ~ 1.5 m diameter electrodes
- **DARWIN: 2.6 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
- Electron survival in LXe: > 10 ms lifetime
- Diffusion of the e^--cloud: size of S2-signals

LUX-ZEPLIN



XENONnT



DARWIN

DARWIN R&D

- Two large-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
  - Both facilities available to the collaboration for R&D purposes

Vertical demonstrator: *Xenoscope*

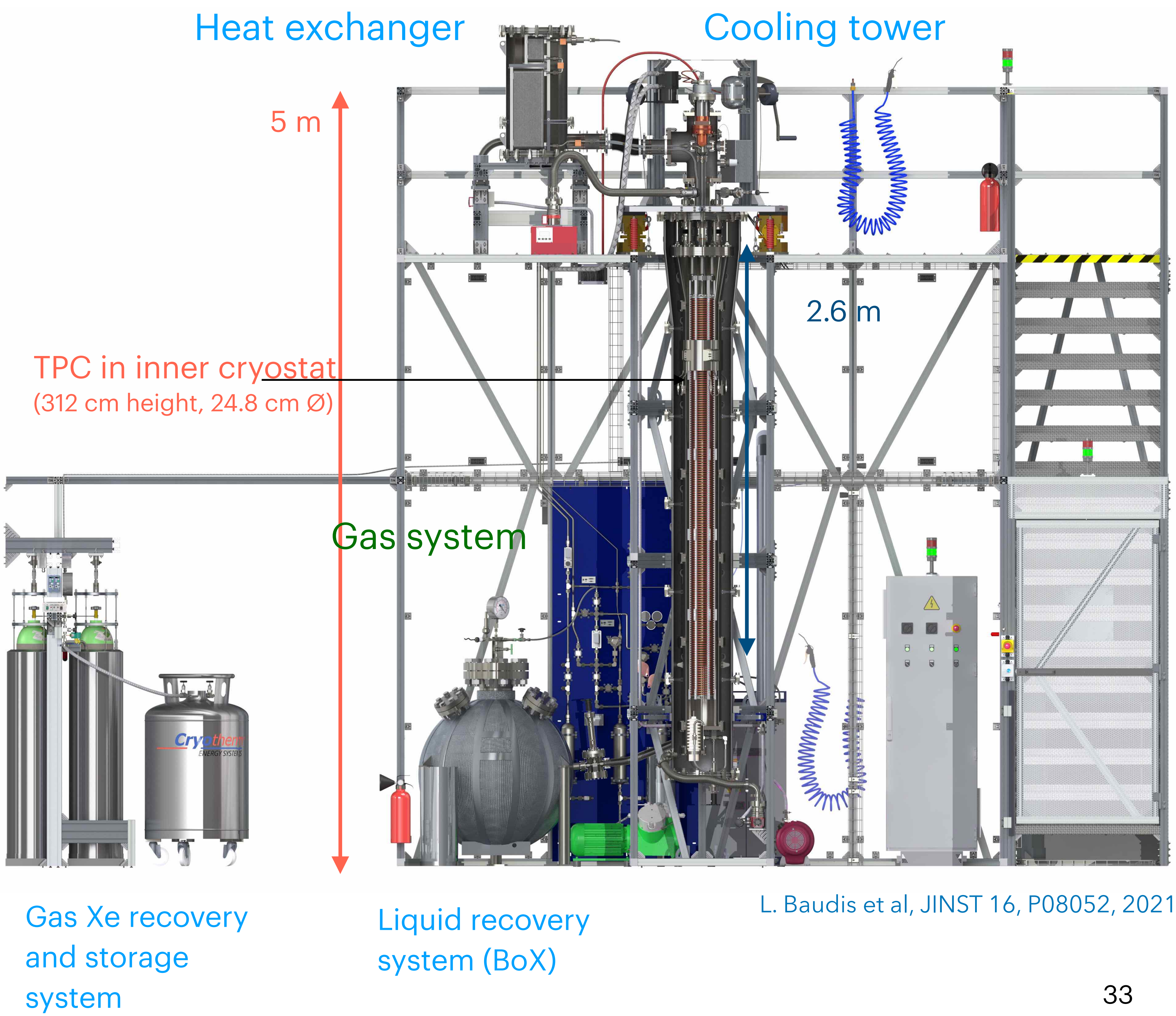
L. Baudis et al, JINST 16, P08052, 2021

Horizontal demonstrator: *Pancake*

Test electrodes with 2.6 m Ø

Xenoscope overview

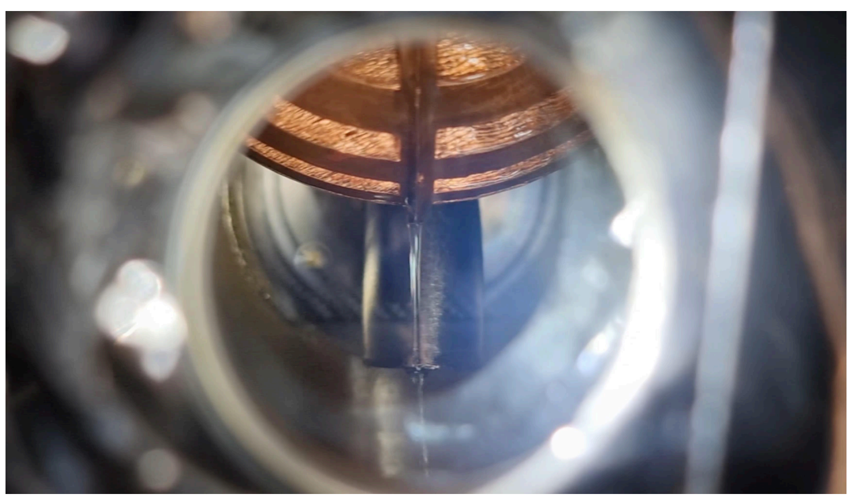
- Full-height demonstrator goals:
  - Electron drift > 2.6 m
  - Custom-made HV distribution
  - Electron cloud diffusion
  - Light attenuation measurements in LXe
  - Test of various light sensors (SiPMs, 2-inch PMTs, ...)
- Total amount of xenon:
  - ~ 400 kg

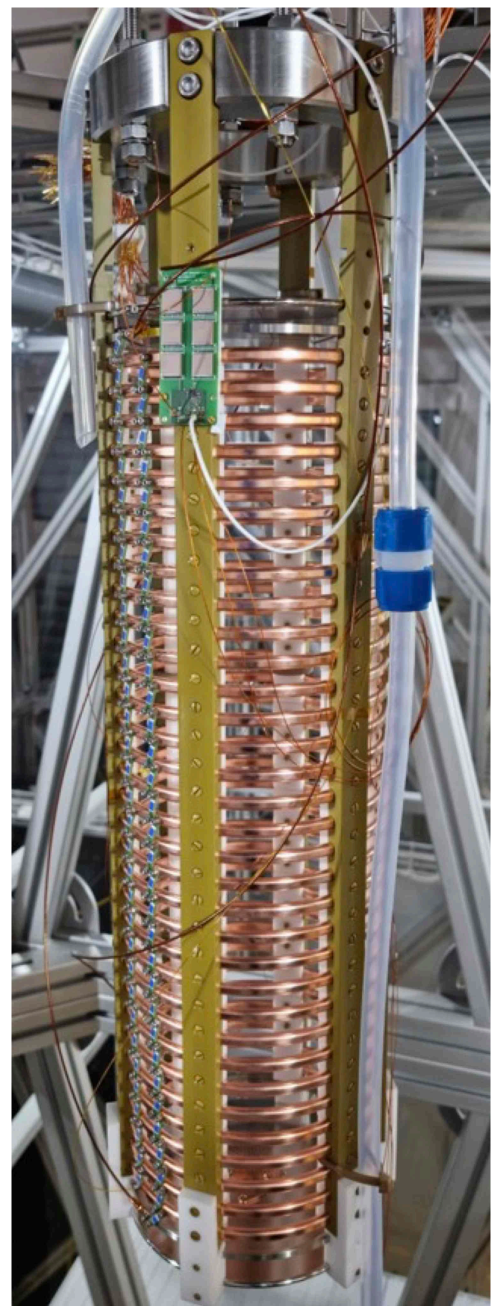


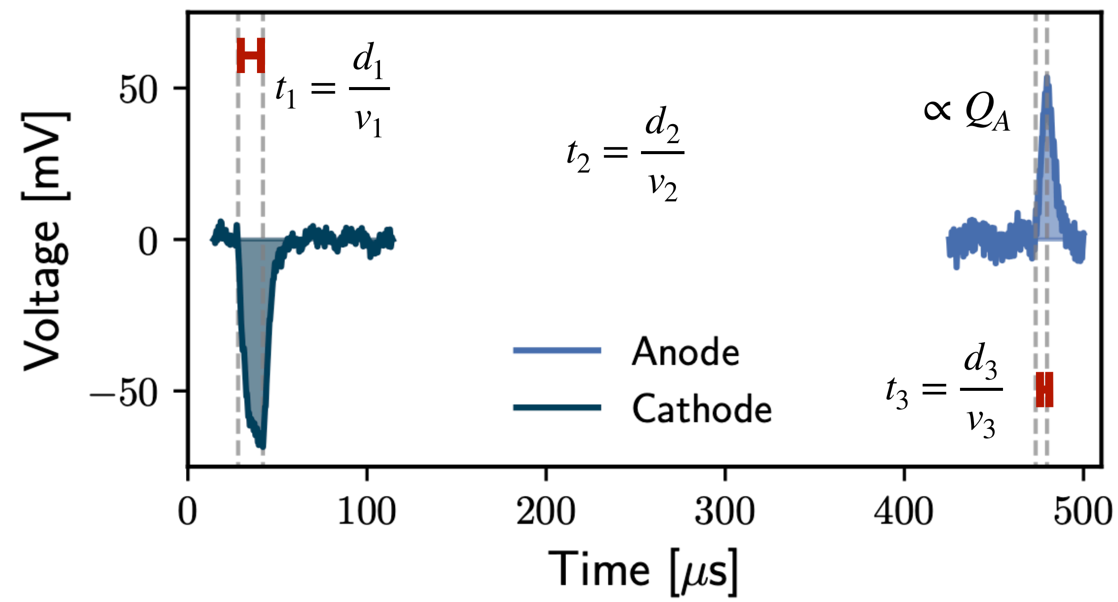
L. Baudis et al, JINST 16, P08052, 2021

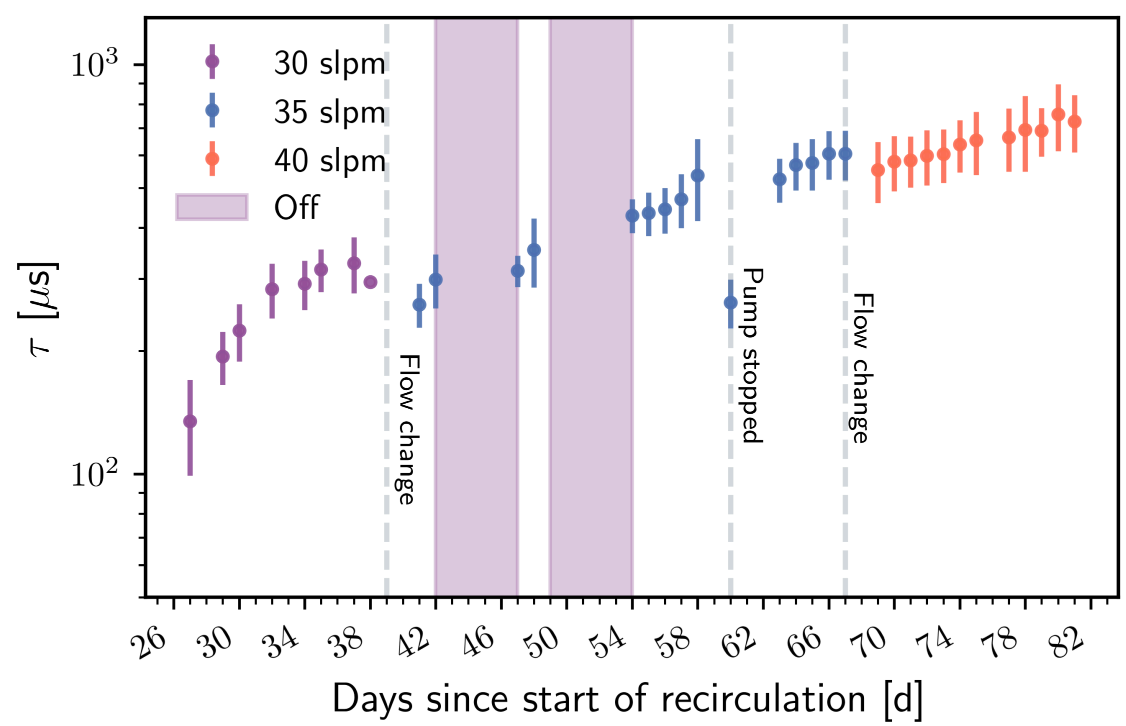
Xenoscope status

- First run with 52 cm purity monitor completed
- Run with 2.6 m TPC to start in early 2023









Future: 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
    - common summer meeting at KIT June 27-29, 2022; seven 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

DARWIN

XENON

LZ

XLZD

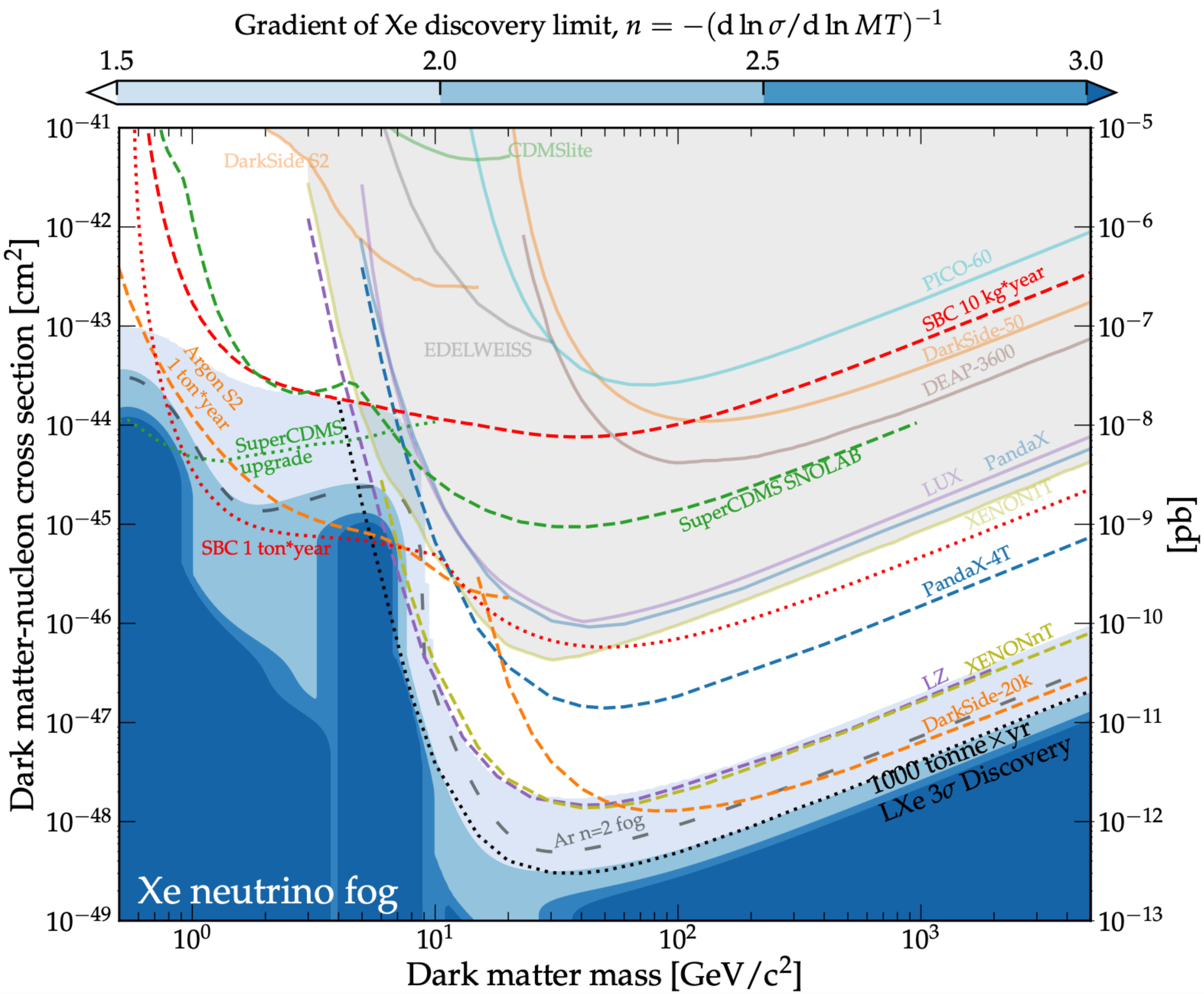
Summary and Outlook

- The nature of dark matter in our universe remains an enigma
- Direct detection experiments: tremendous progress over the past decades & covered an enormous parameter range
- In the worldwide race to directly detect dark matter particles, liquid xenon TPCs remain at the forefront
- However, no detection so far, and to probe the experimentally accessible parameter space for WIMPs, larger detector masses with lower backgrounds are needed
- Current generation of xenon TPCs presented first results this year, they continue to take data
- R&D and design of next-generation detector (DARWIN/XLZD) is ongoing
- Eventually, direct detection experiments will limited by neutrino interactions *(but also new physics opportunities & be prepared for surprises!)*

The end

Backup slides

Neutrino backgrounds



Effect of the astrophysical neutrino backgrounds: gradual, hence the "neutrino fog"

Here the neutrino fog for a xenon target: blue contour map

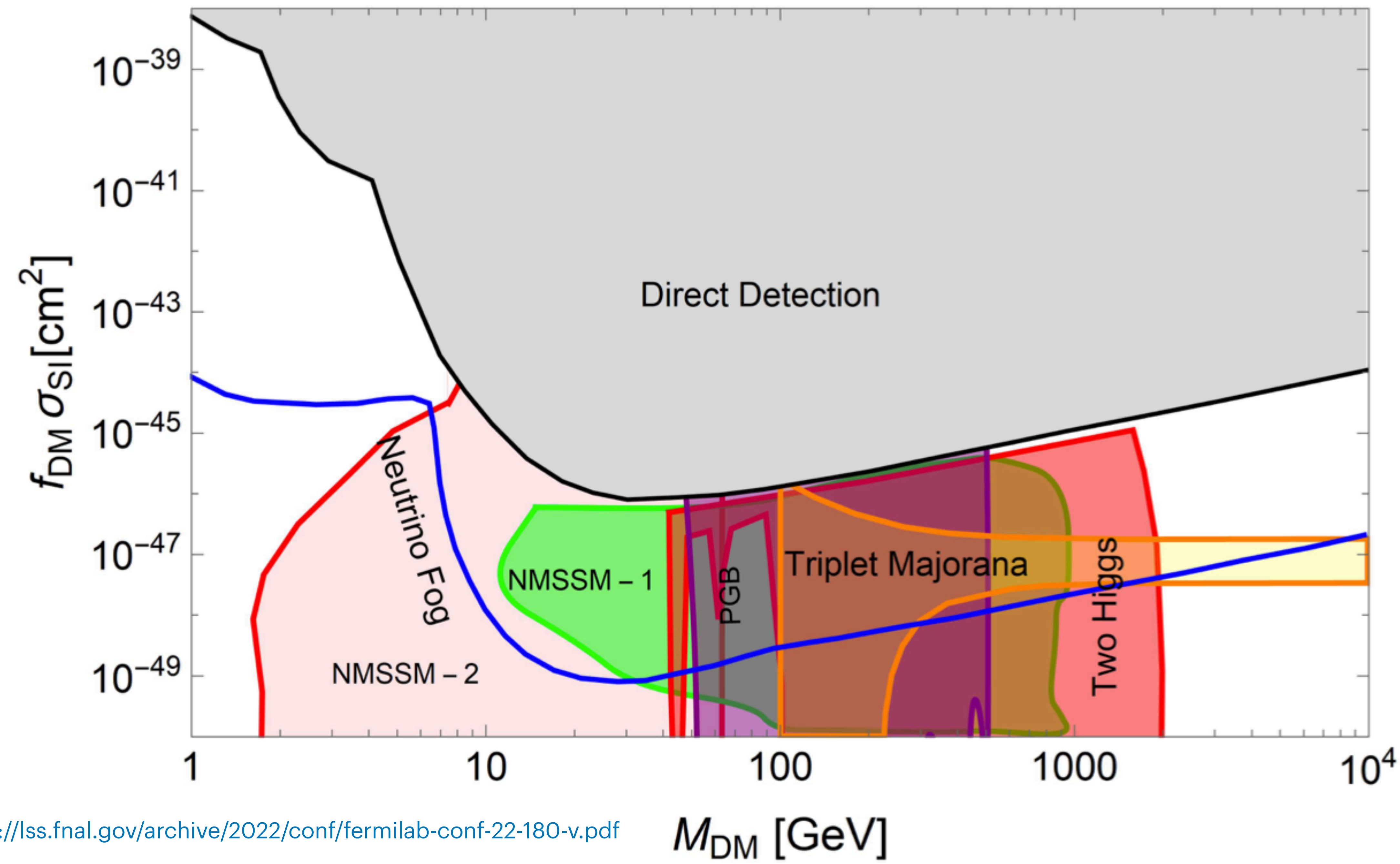
At contour n: obtaining a 10 times lower cross section sensitivity requires an increase in exposure of at least 10^n

n = gradient of a hypothetical experiment's median cross section for 3σ discovery with respect to the exposure

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

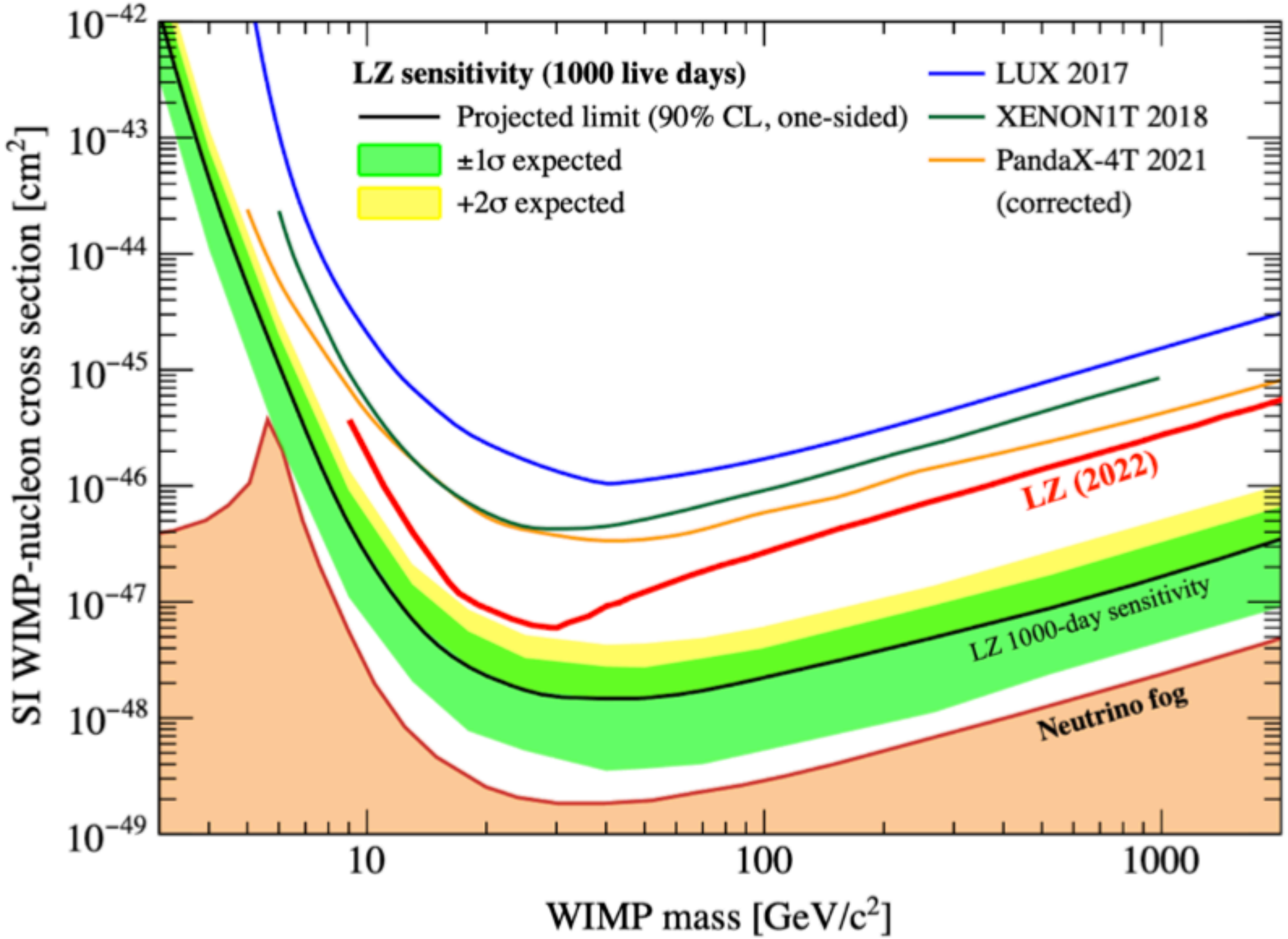
Theory predictions

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



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

LZ projected sensitivity



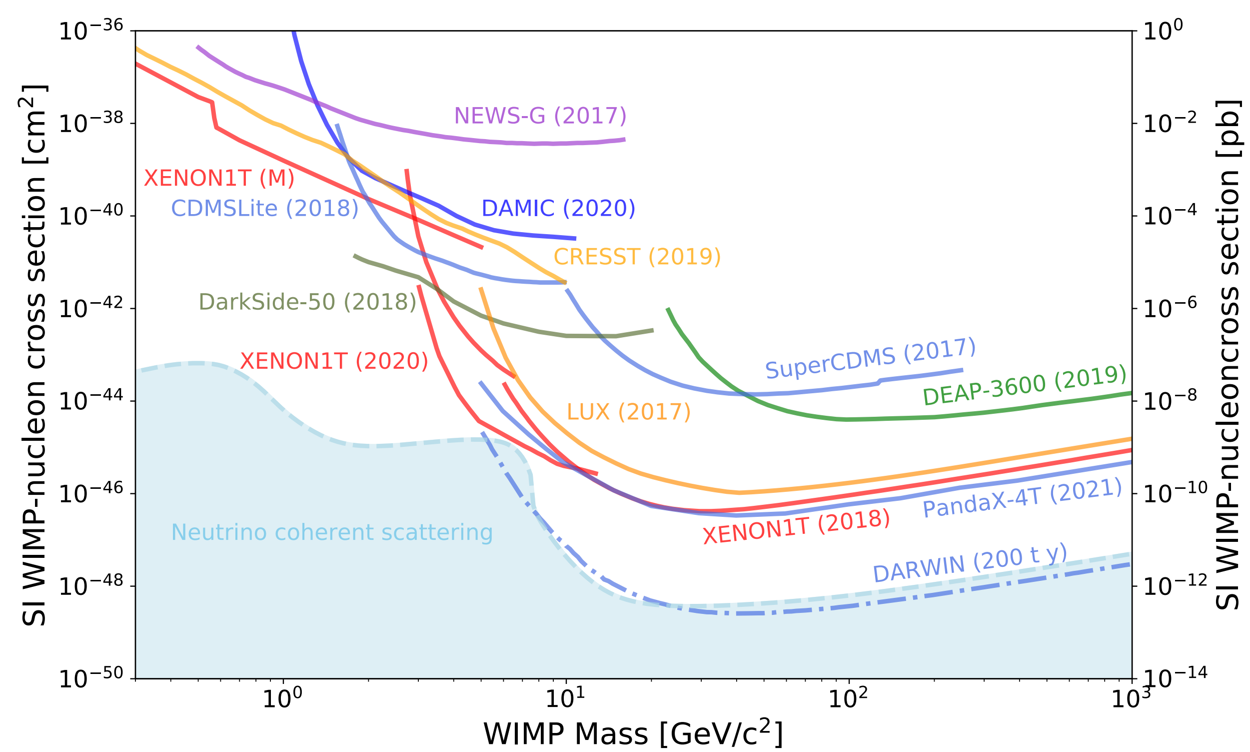
LZ collaboration, PRD101, 2020

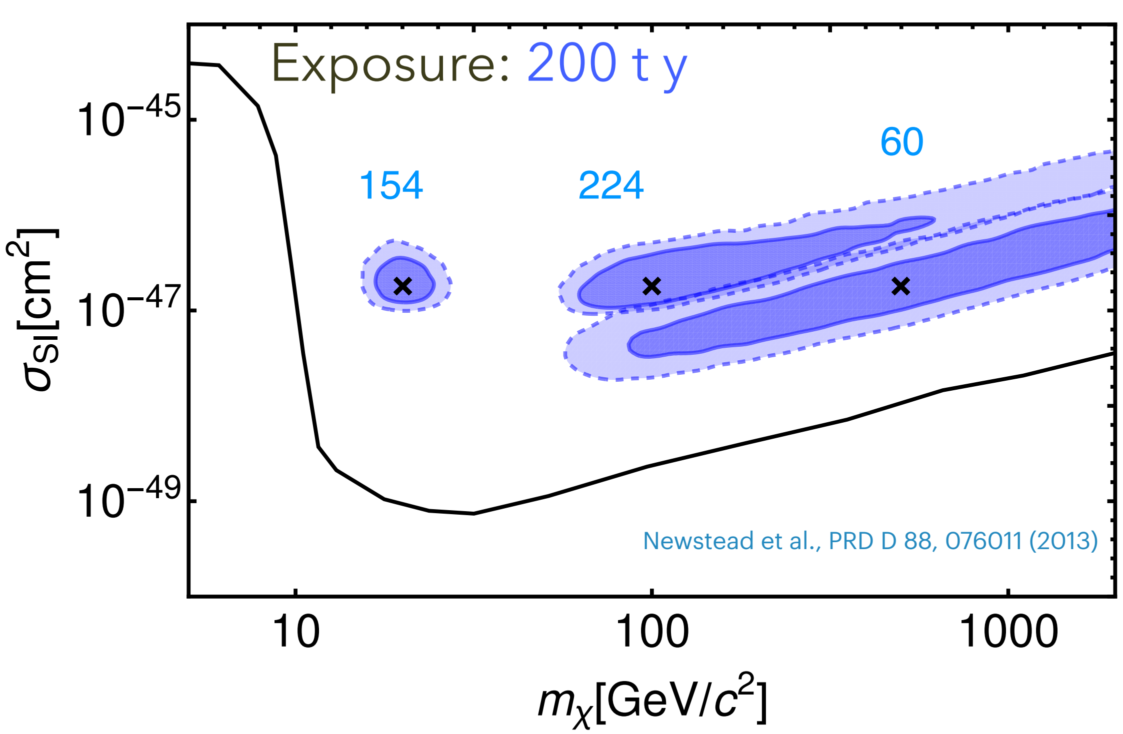
DARWIN: WIMP dark matter

- Goal: probe dark matter nucleon interactions down to the "neutrino floor"
- Sensitivity to spin-independent and spin-dependent (^{129}Xe, ^{131}Xe) interactions
- Reconstruct DM mass and cross section (for given astrophysical parameters)

DARWIN study: JCAP 10, 016 (2015)

SI, elastic WIMP-nucleus





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

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

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

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

Assumptions for DARWIN:

30 t LXe in FV

99.98% ER rejection

(at 30% NR acceptance)

Neutrinos in a DARWIN-like detector

- Study of sensitivity to atmospheric neutrinos (using NEST to model the signals)
- Below: exposure of 200 t y; need 700 t y to obtain a 5-σ detection of atmospheric neutrinos

Newstead, Lang, Strigari, arXiv: 2002.08566