



University of
Zurich^{UZH}

Future Dark Matter Experiments with Noble Liquids

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University of Zurich

Identification of Dark Matter
Technical University of Vienna
19 July 2022

WIMP direct detection landscape

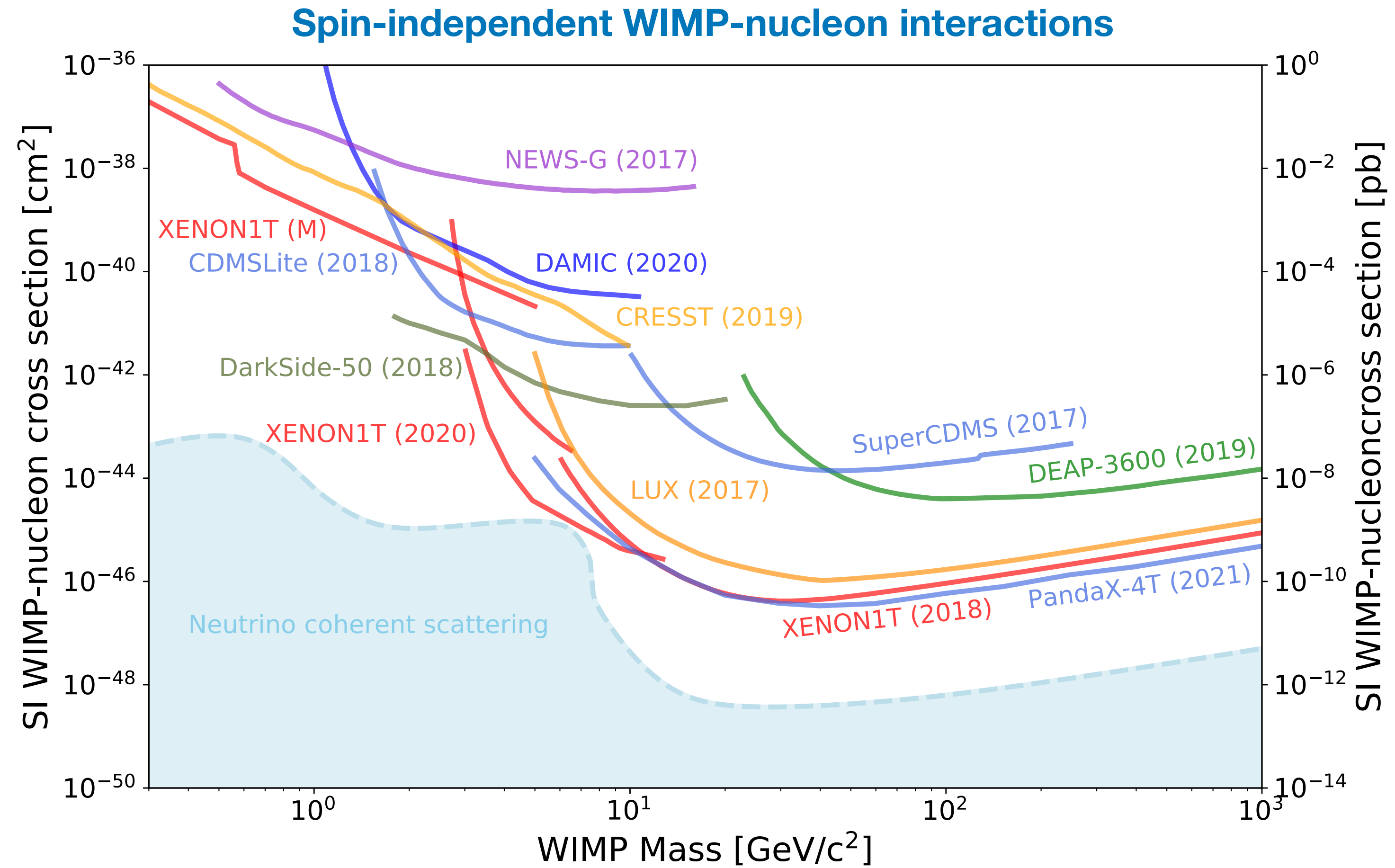


Figure adapted from P.A. Zyla et al. (Particle Data Group) (2020)

WIMP direct detection landscape

Spin-independent WIMP-nucleon interactions

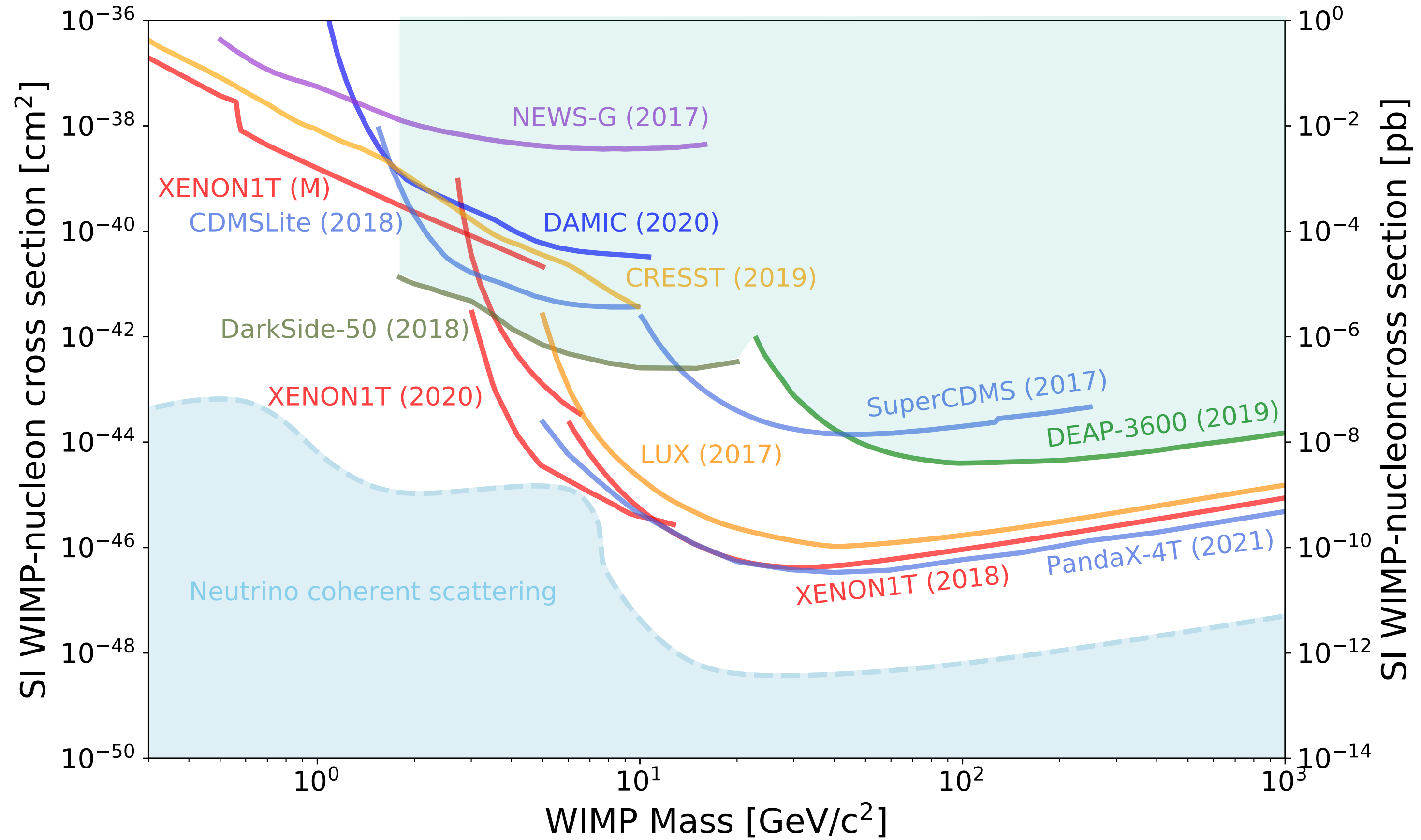


Figure adapted from P.A. Zyla et al. (Particle Data Group) (2020)

Liquid argon (LAr) experiments



DEAP-3600
3300 kg
SNOLAB
2016 - present



DarkSide-50
46 kg
LNGS
2013 - present

WIMP direct detection landscape

Spin-independent WIMP-nucleon interactions

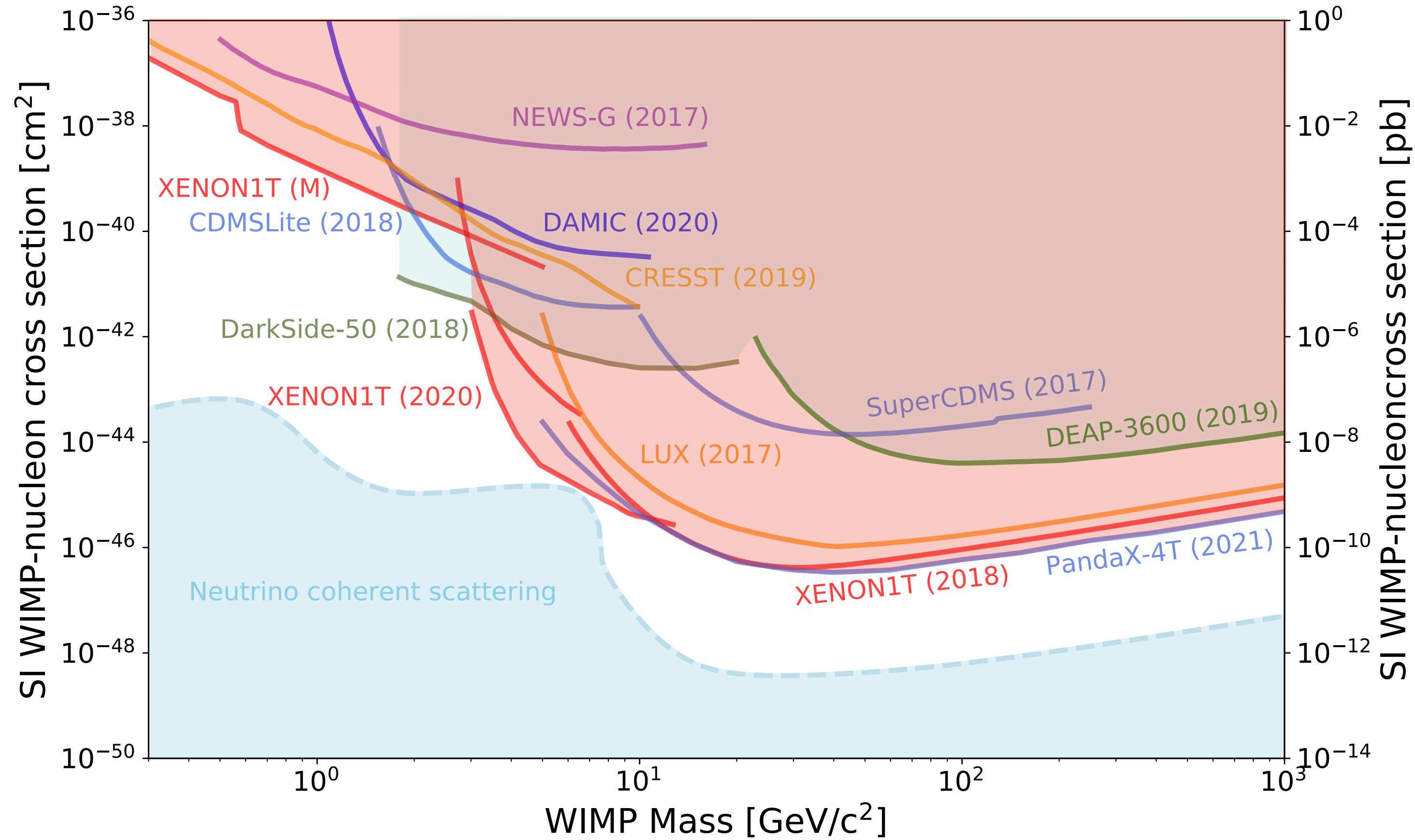


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Liquid argon (LAr) experiments

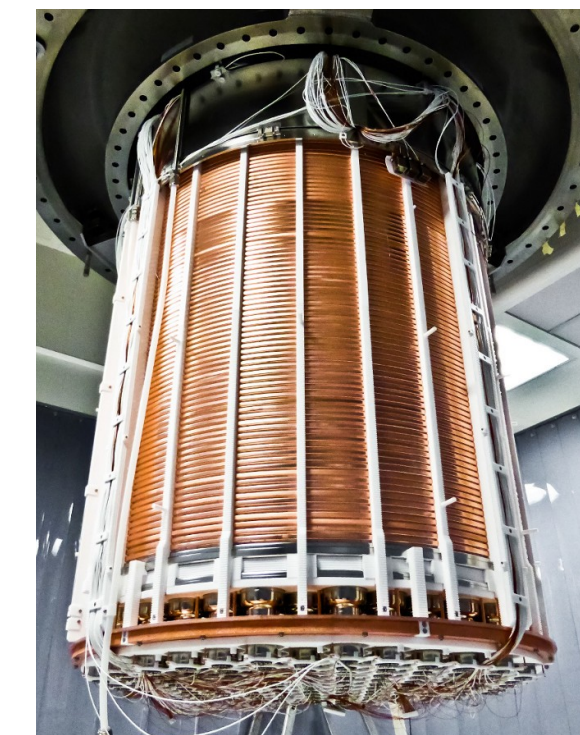
Liquid xenon (LXe) experiments



DEAP-3600
3300 kg
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DarkSide-50
46 kg
LNGS
2013 - present



XENON1T
2 tonne
LNGS
2017-2019



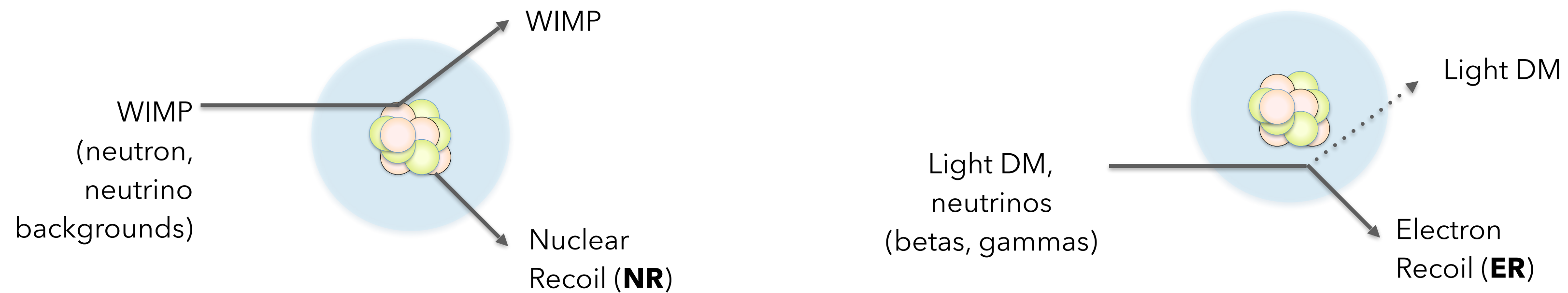
LUX
250 kg
SURF
2013-2016



PandaX-4T
400 kg
CJPL
2021 - present

The General Strategy

Search for interactions between Standard Model particles and dark matter from the Milky Way halo.



Readout the prompt scintillation signal (S1) and/or the ionization signal (S2) produced from the interaction.

Use veto detectors, fiducialization, single-scatter requirement, and particle identification (PID) techniques for background discrimination.

Build increasingly larger, cleaner and more radiopure detectors. Make clever analysis choices, also to expand the search range.

Noble liquids: Xe and Ar

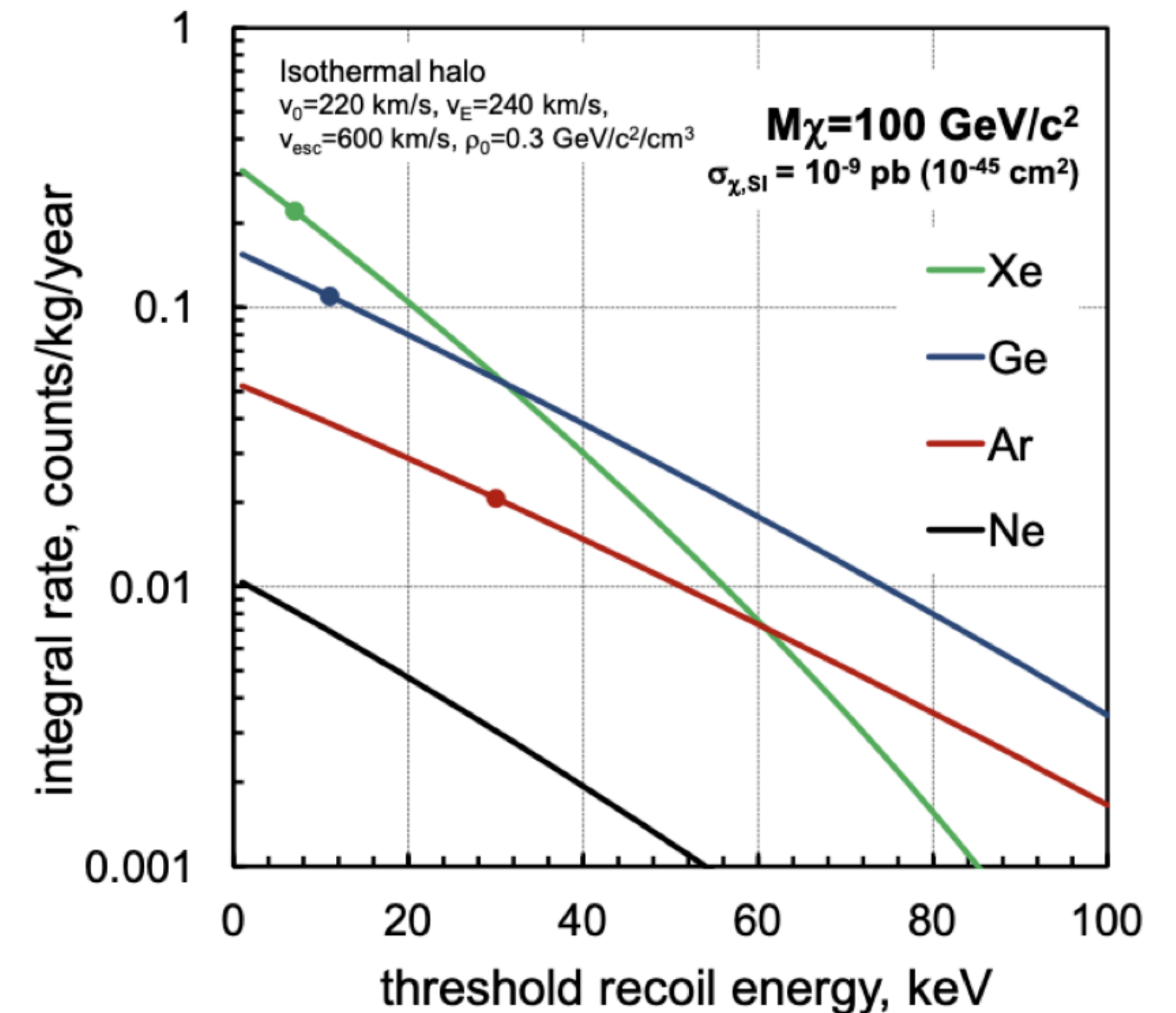
Kinematically favors GeV to TeV DM masses

- ▶ **Scalability** to large (multi-ton) detector masses
- ▶ Manageable cryogenics: 170 K (LXe), 87 K (LAr)
- ▶ **Purification** in stages or continuously (both for radiopurity and electronegative impurities)
- ▶ High scintillation yield and transparent to its own light
- ▶ Can be easily ionized
- ▶ High atomic number and high density (particularly LXe) gives stopping power, self-shielding.
- ▶ Intrinsic radioactivity: Xe has long-lived ^{136}Xe and ^{124}Xe ; ^{85}Kr can be removed.
- ▶ Ar has cosmogenically produced ^{39}Ar , but a clear path forward.
- ▶ Ar hints for directionality? (area of R&D)

Nobles towards lower DM masses

for helium detectors, see talks by Dan McKinsey and Belina von Krosigk

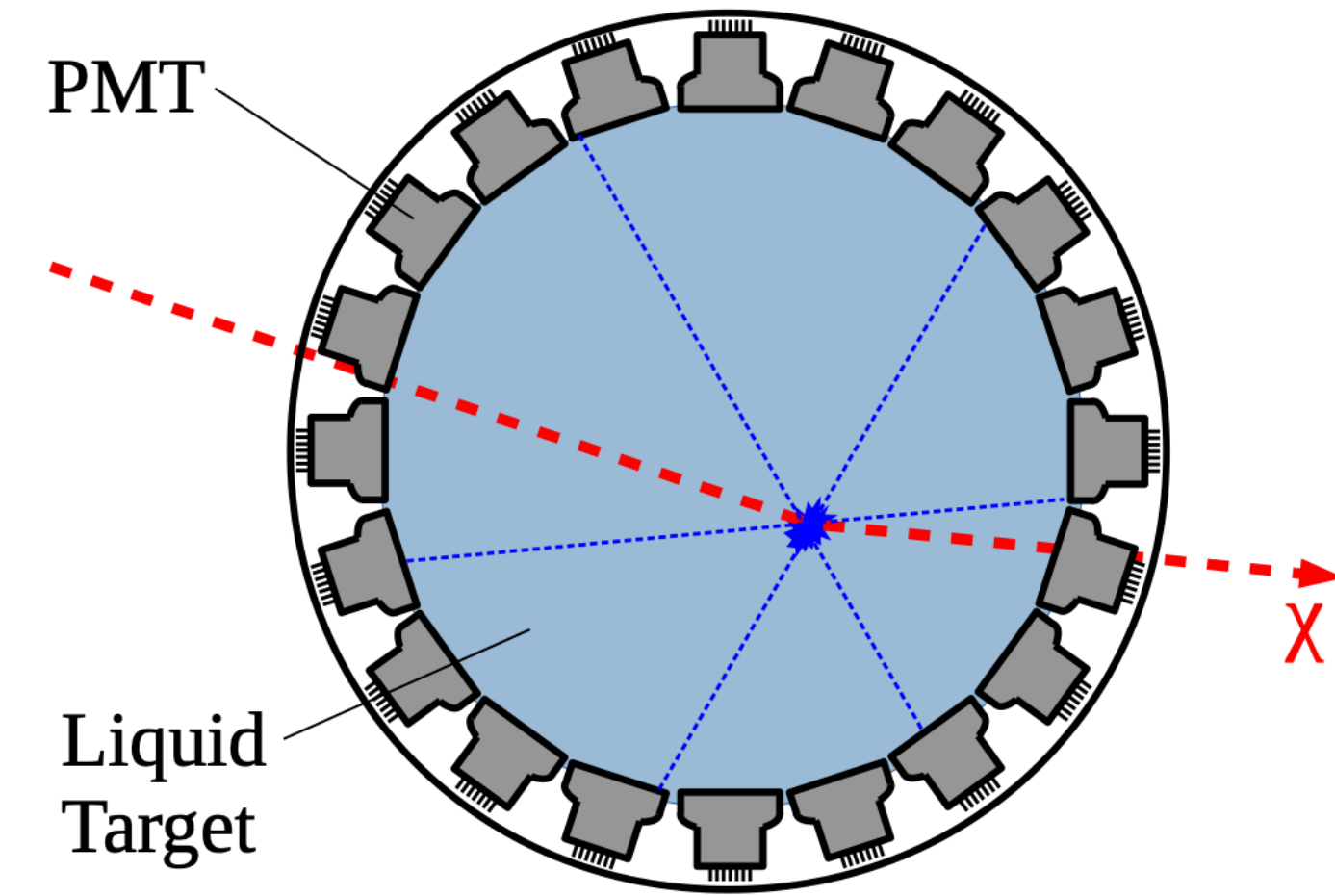
for argon scintillating bubble chambers see talk by Ben Broerman



V. Chepel and H. Araujo, JINST 8(04), R04001 (2013)

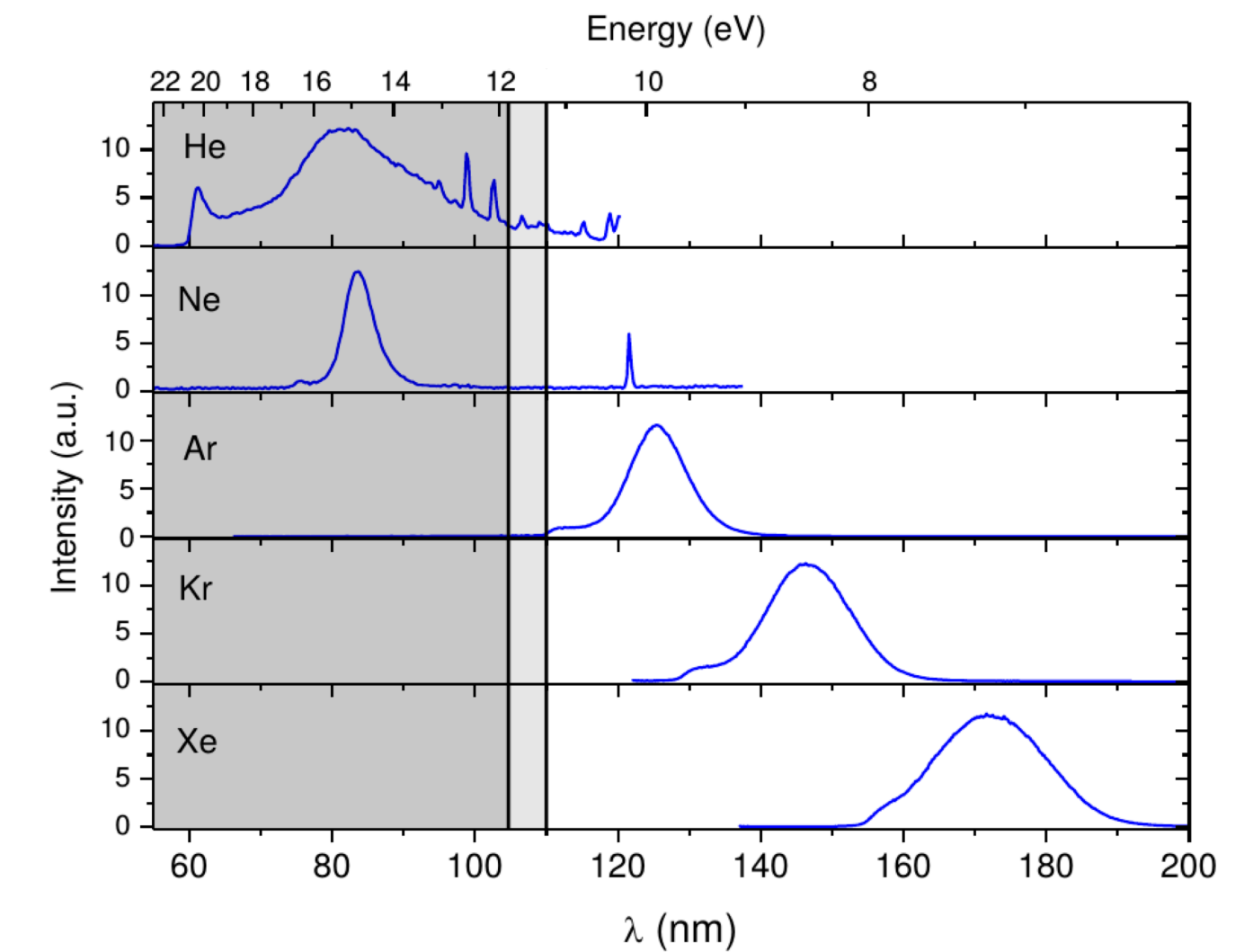
- ▶ cross section scales as A^2
- ▶ Xe has also spin-dependent isotopes ($A \sim 131$)

Noble liquid detection: single phase



Single-phase Spherical Detector

- ▶ Liquid noble target surrounded by photosensors
- ▶ Detection of primary scintillation signal only (LAr **128 nm** requires wavelength shifter)
- ▶ Event position reconstructed by PMT pattern and time-of-flight
- ▶ NR/ER discrimination can be achieved through pulse shape for argon

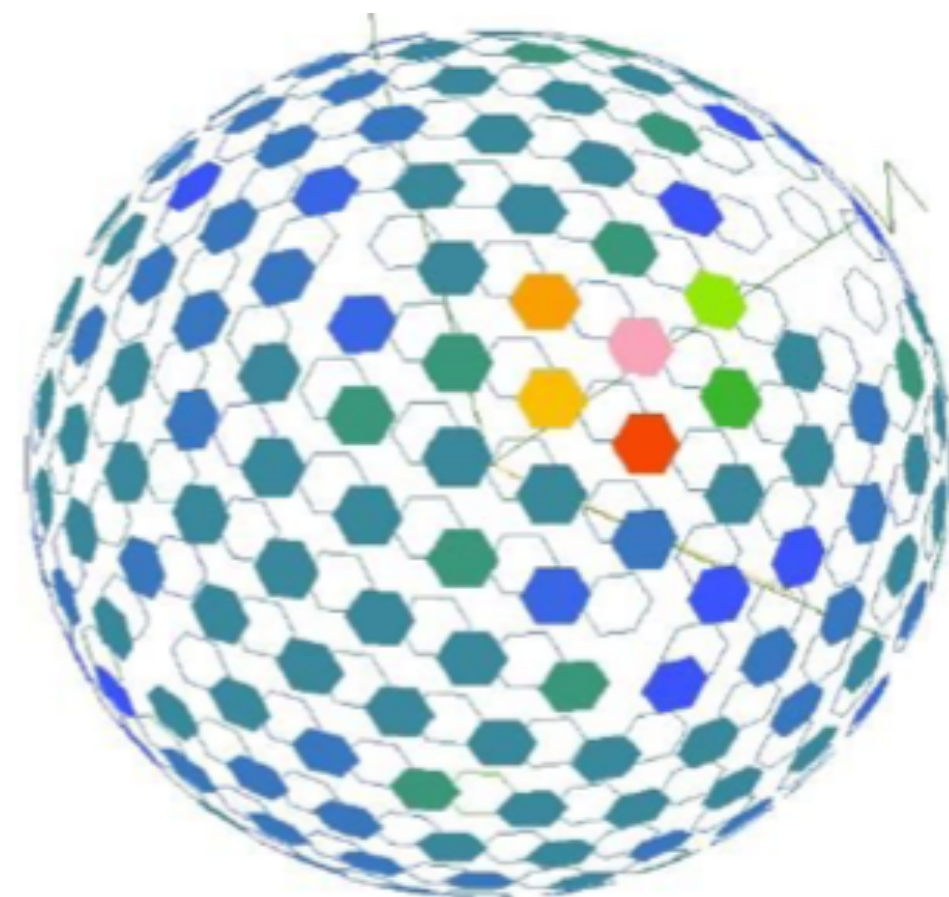


A. Ulrich; Dissertation A. Neumeier, TUM (2014)

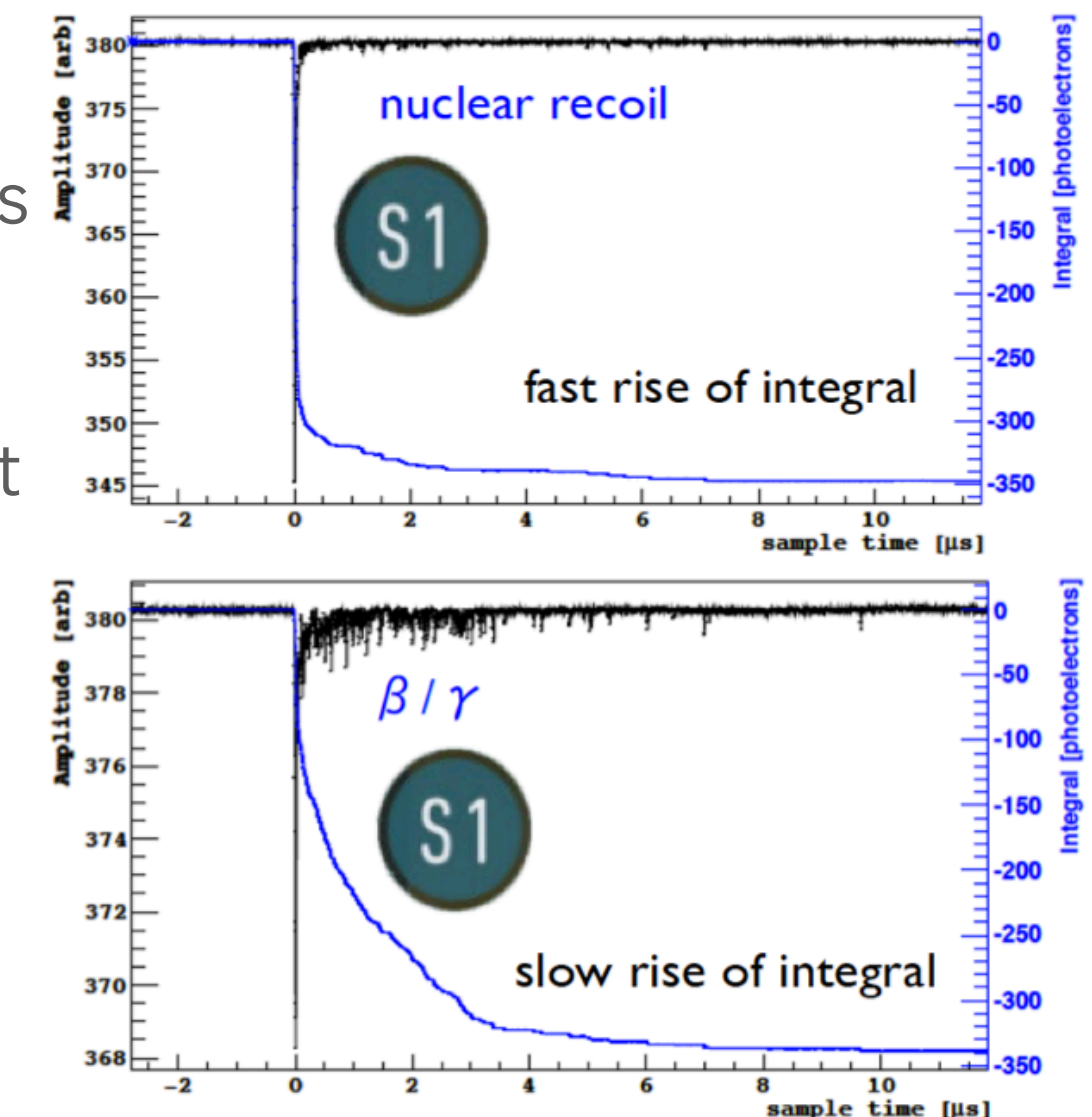
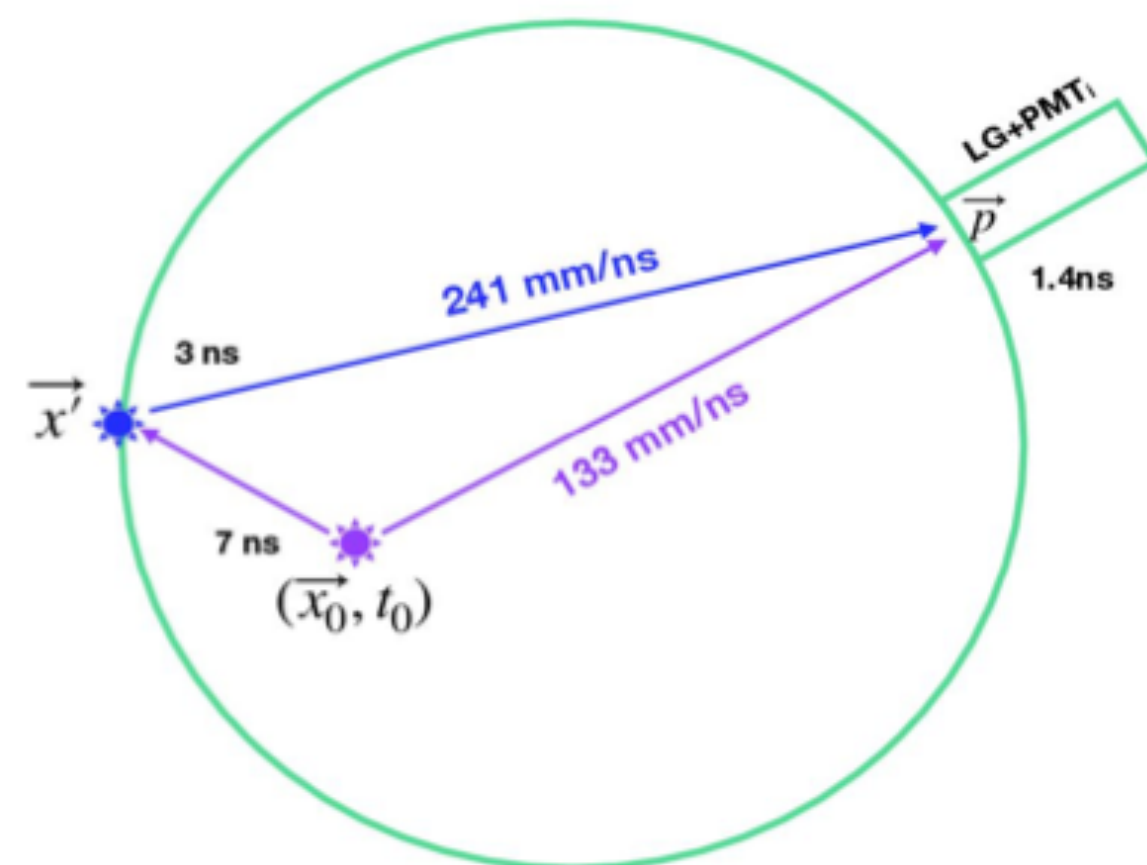
Argon:

- ▶ **ERs**: higher fraction of triplet states (**7ns**) than NRs (singlet **1.6 us**).
- ▶ The resulting signals have different shapes
- ▶ PSD technique (f₉₀ fraction of signal in the first 90ns).

$$f_{90} = \frac{\text{S1 light in first 90ns}}{\text{total S1 light}}$$



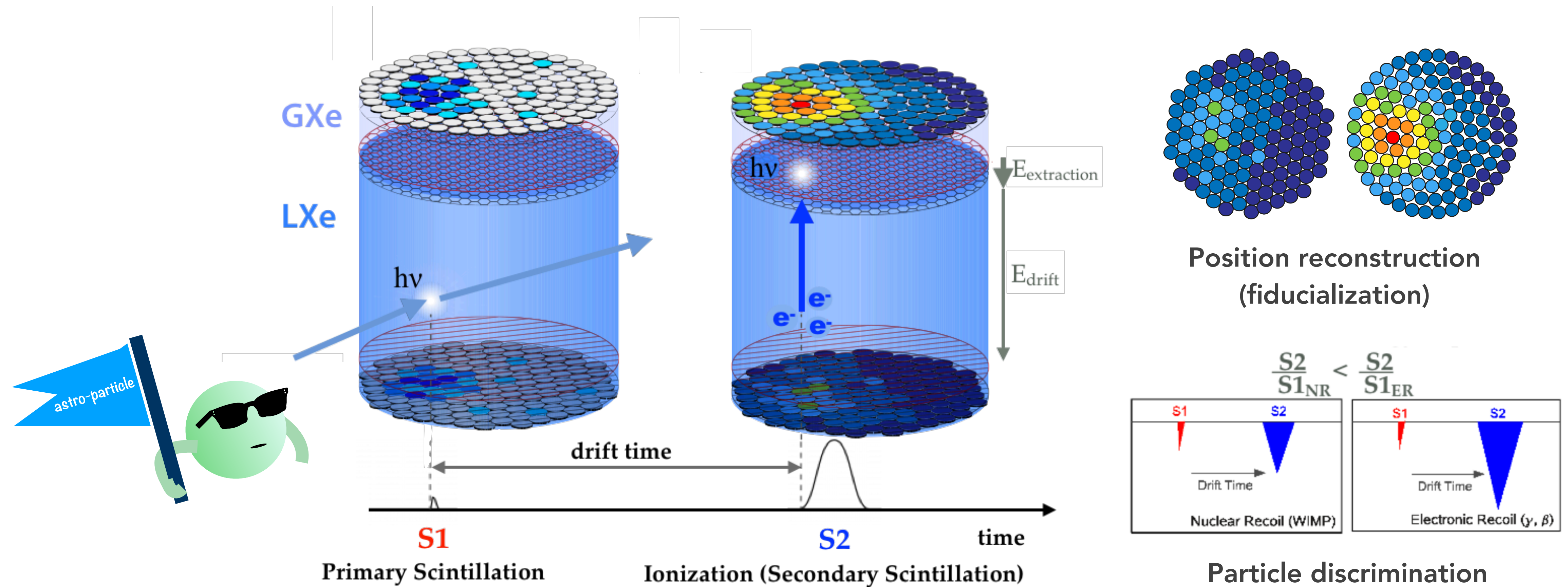
Event position reconstruction: PMT pattern and time-of-flight



Noble liquid detection: dual phase

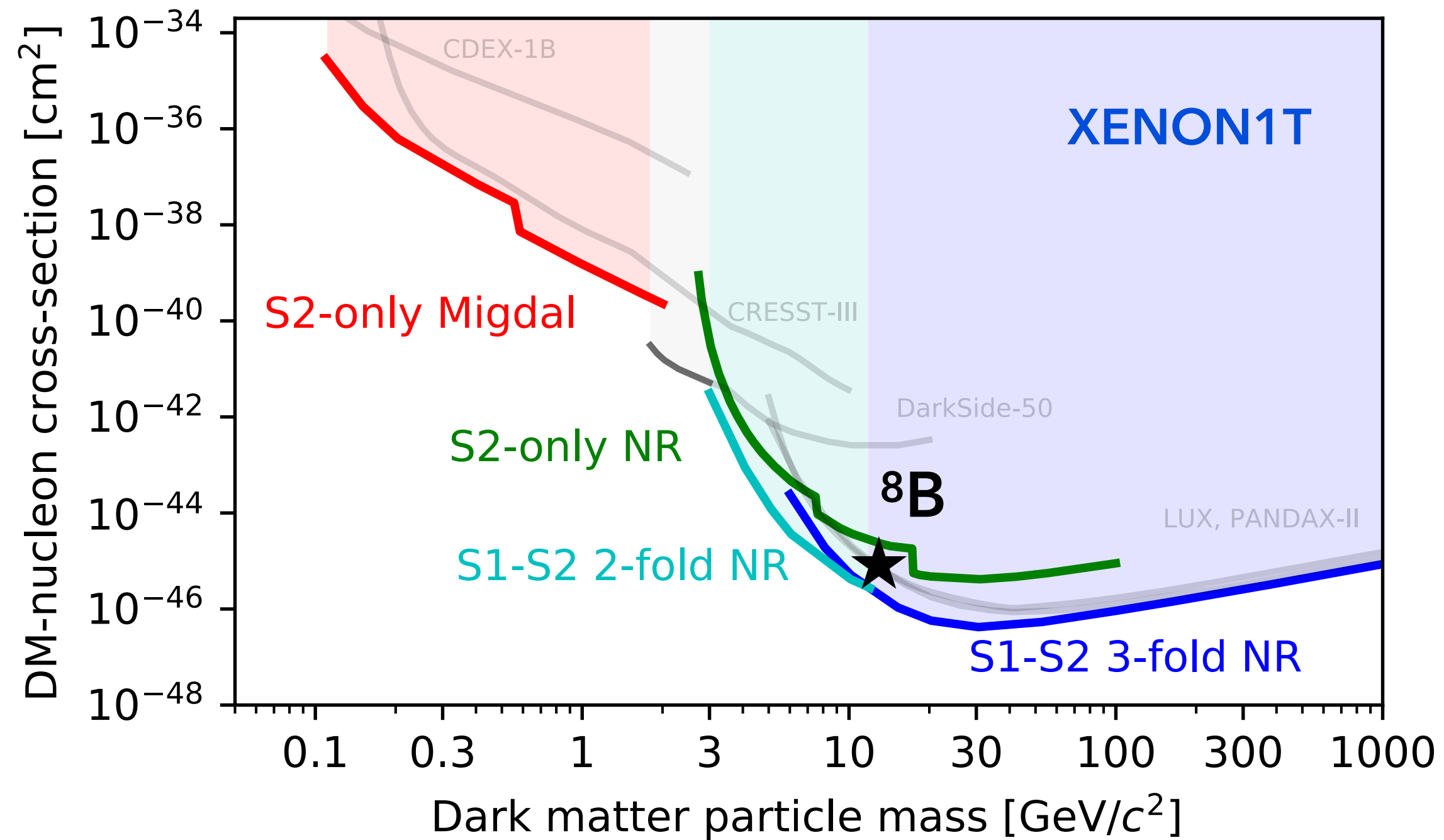
Cryogenic xenon and argon

applied fields to drift charges, photosensors arrays to collect light signals



Lowering the threshold

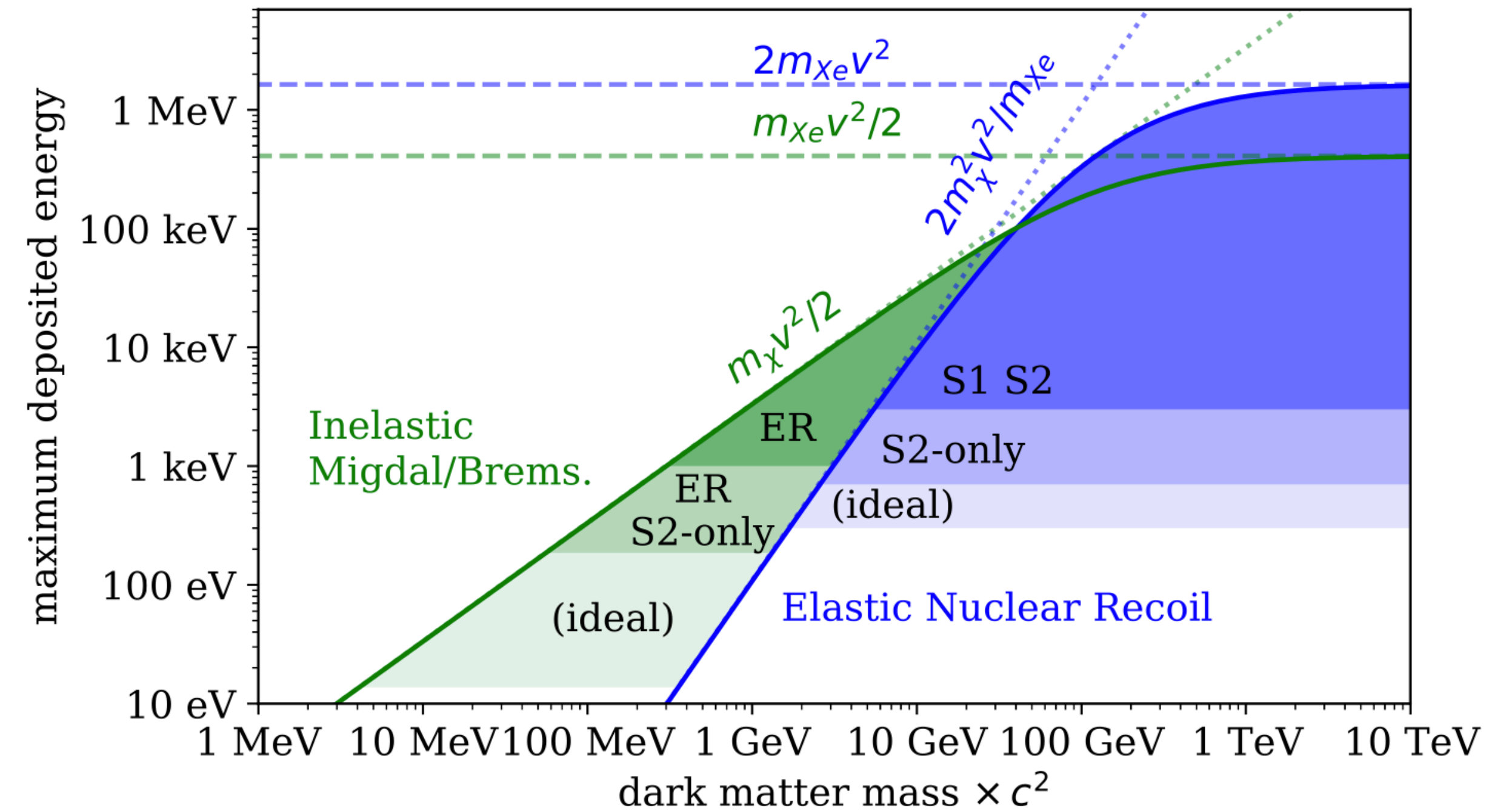
Probing lower masses



[Phys. Rev. Lett. 126 \(2021\) 091301](https://arxiv.org/abs/2105.08204)

- ▶ Threshold dominated by 3-fold PMT coincidence (XENON) - lower it to 2
- ▶ Drop the S1: ionization (S2)-only - limit setting
- ▶ Look for the Migdal effect

Interaction kinematics in xenon

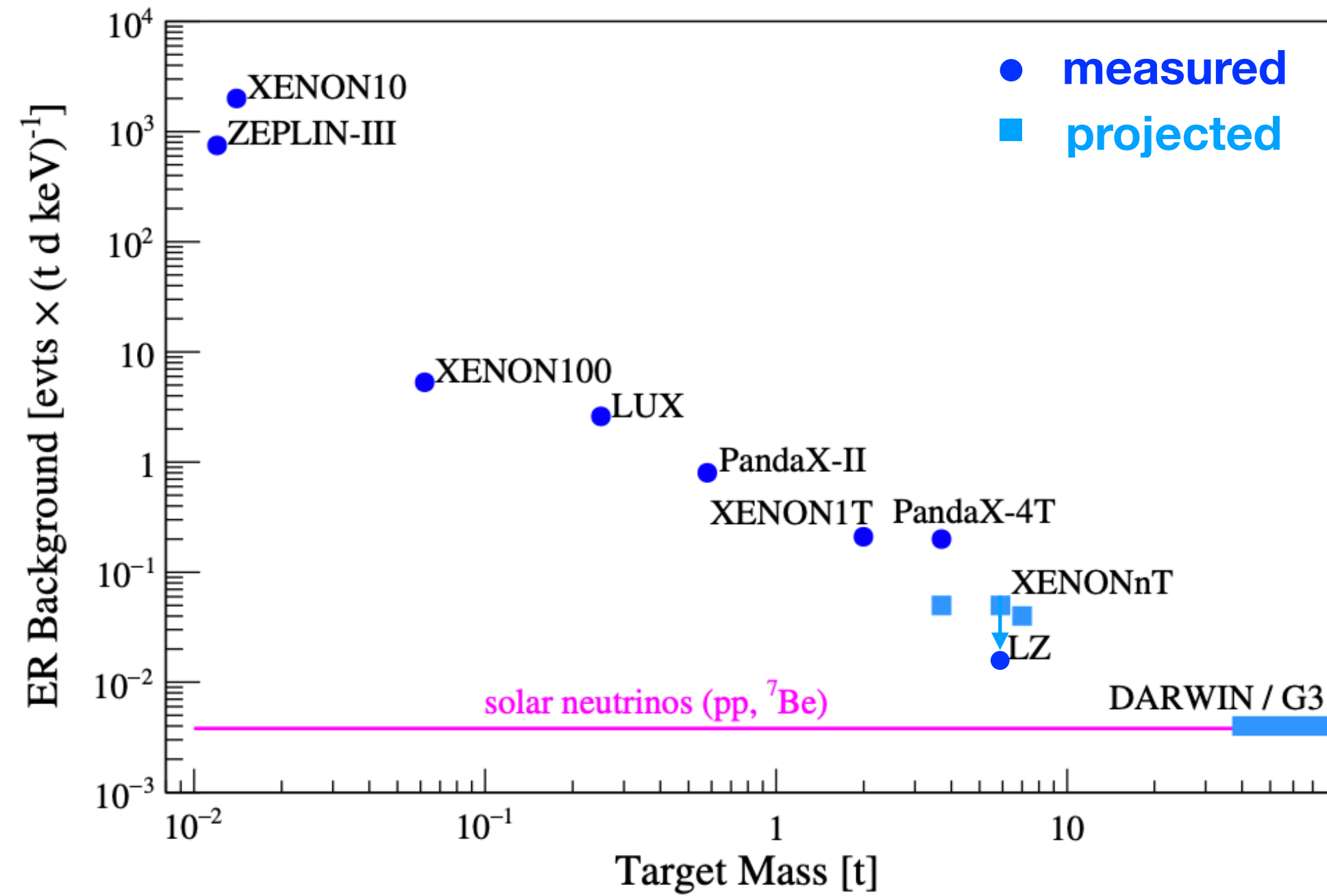


Xenon community white paper: [arXiv:2203.02309 \(2022\)](https://arxiv.org/abs/2203.02309)

- ▶ ER S1/S2 channels rely on good backgrounds models
- ▶ ER: particle scatters or can be absorbed (axioelectric effect)

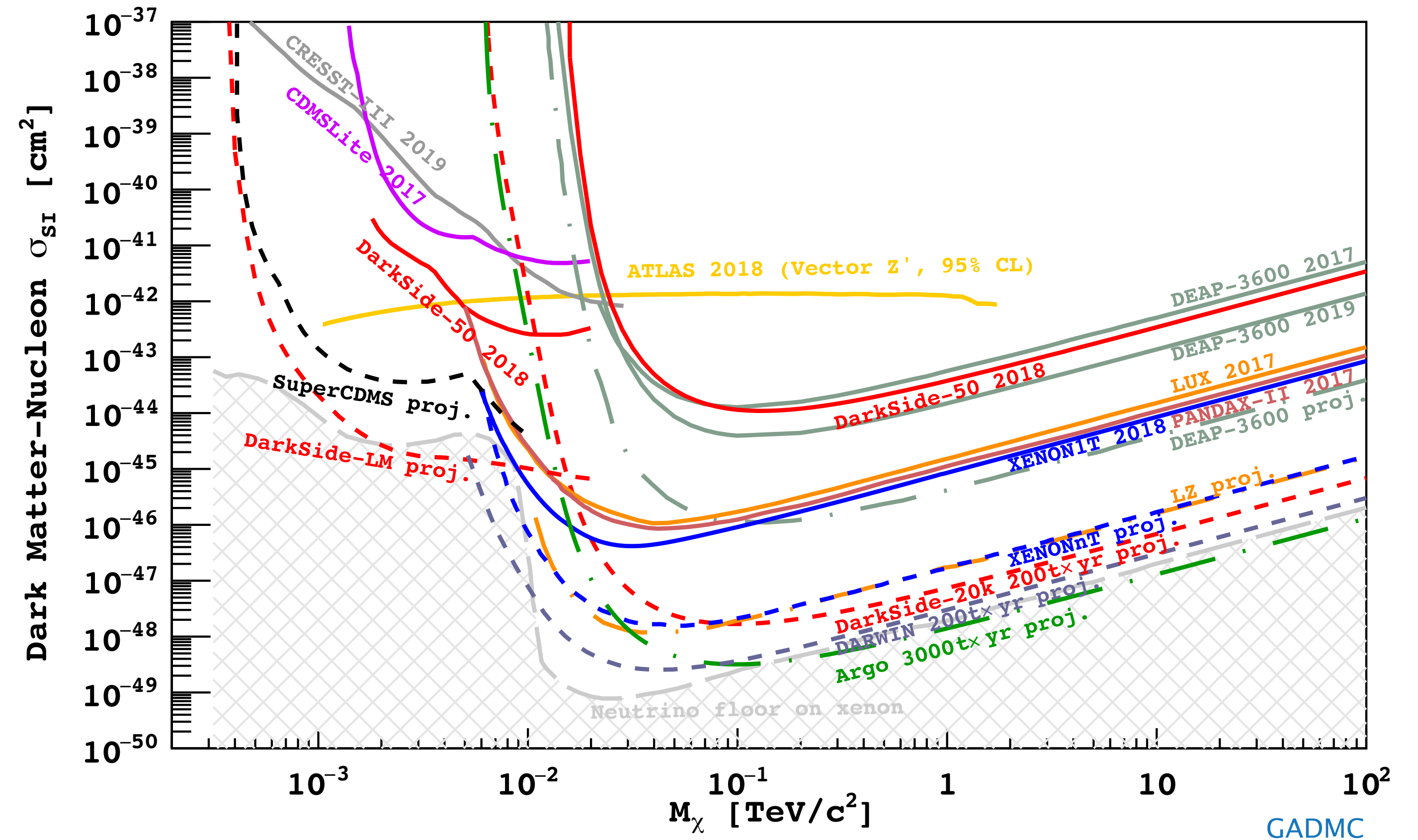
Migdal effect -see talk by Henrique Araujo

Improving the Sensitivity



Lower background and larger mass

Future experiments



DarkSide-20K
DarkSide-LM
Argo

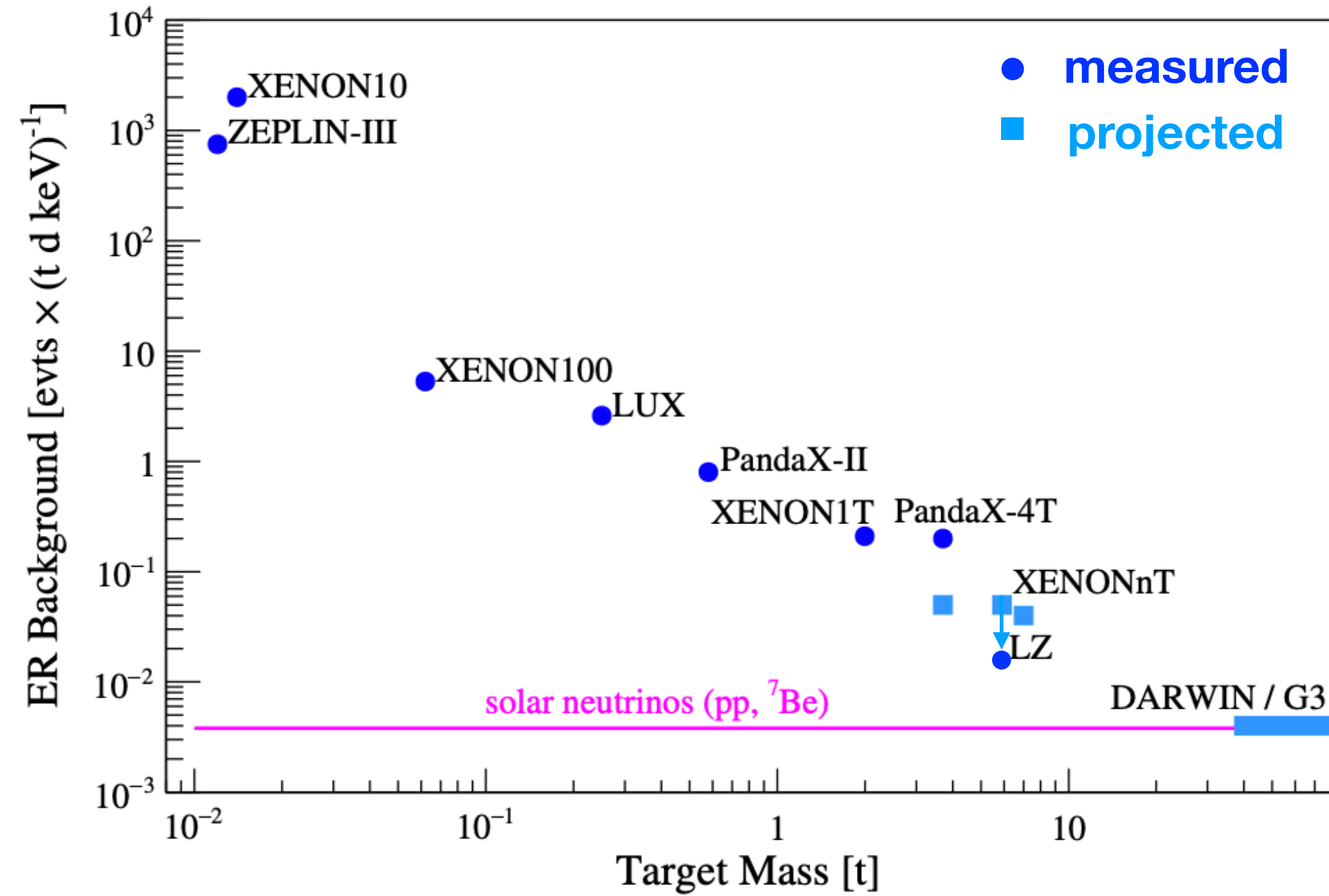
PandaX-30T (not shown)
DARWIN/G3
factor 10

factor 10⁴

projected sensitivity improvement in next ~10 years

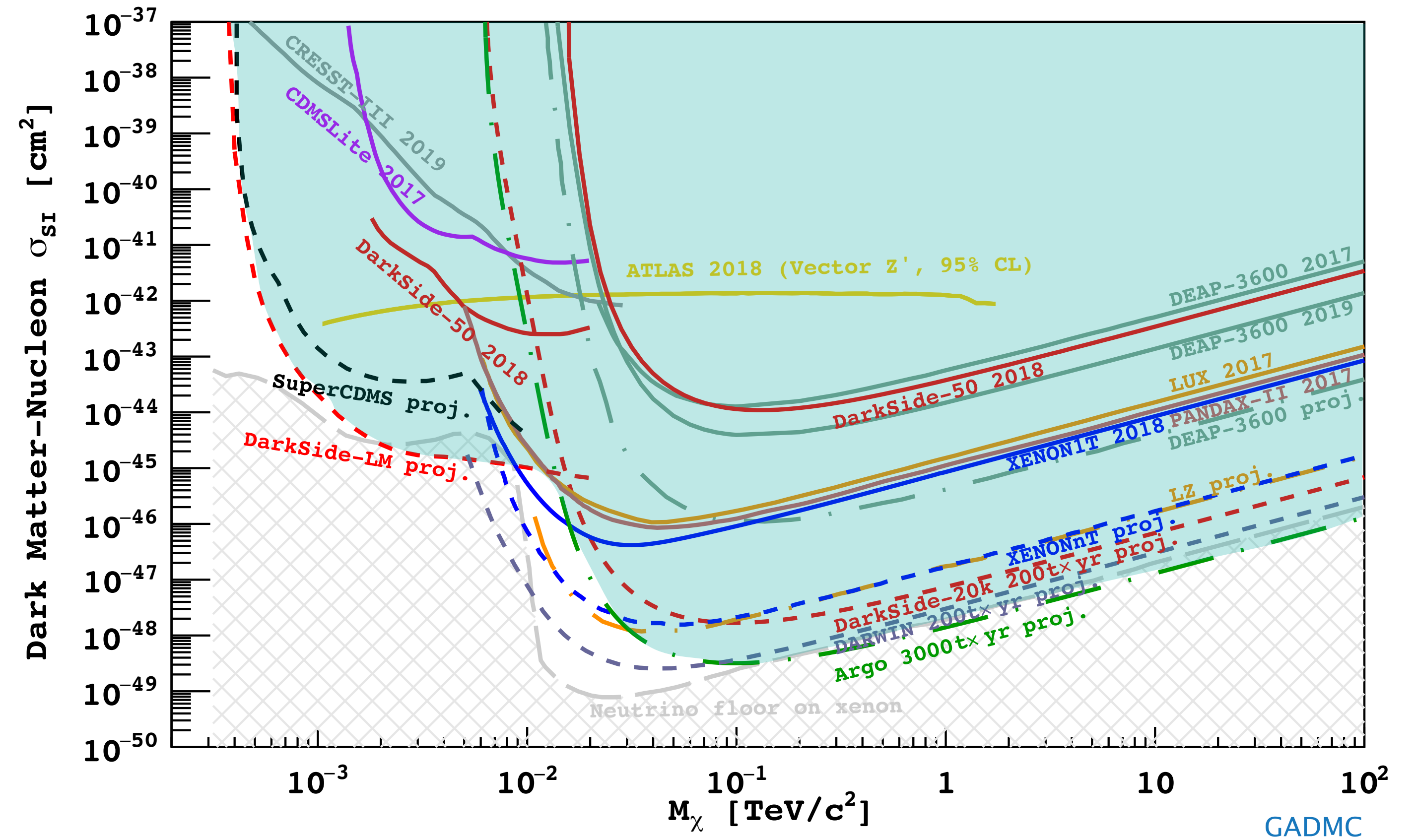
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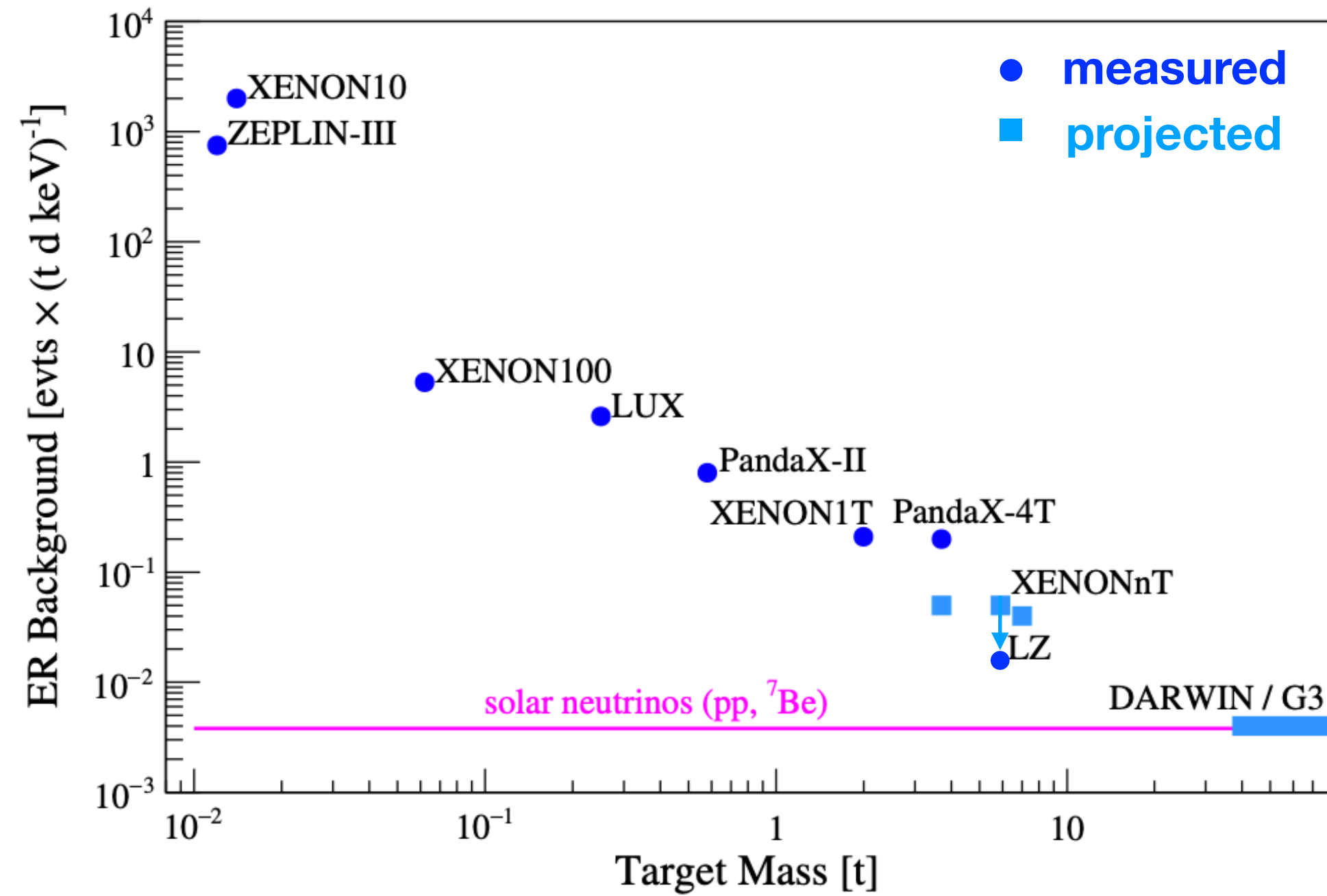
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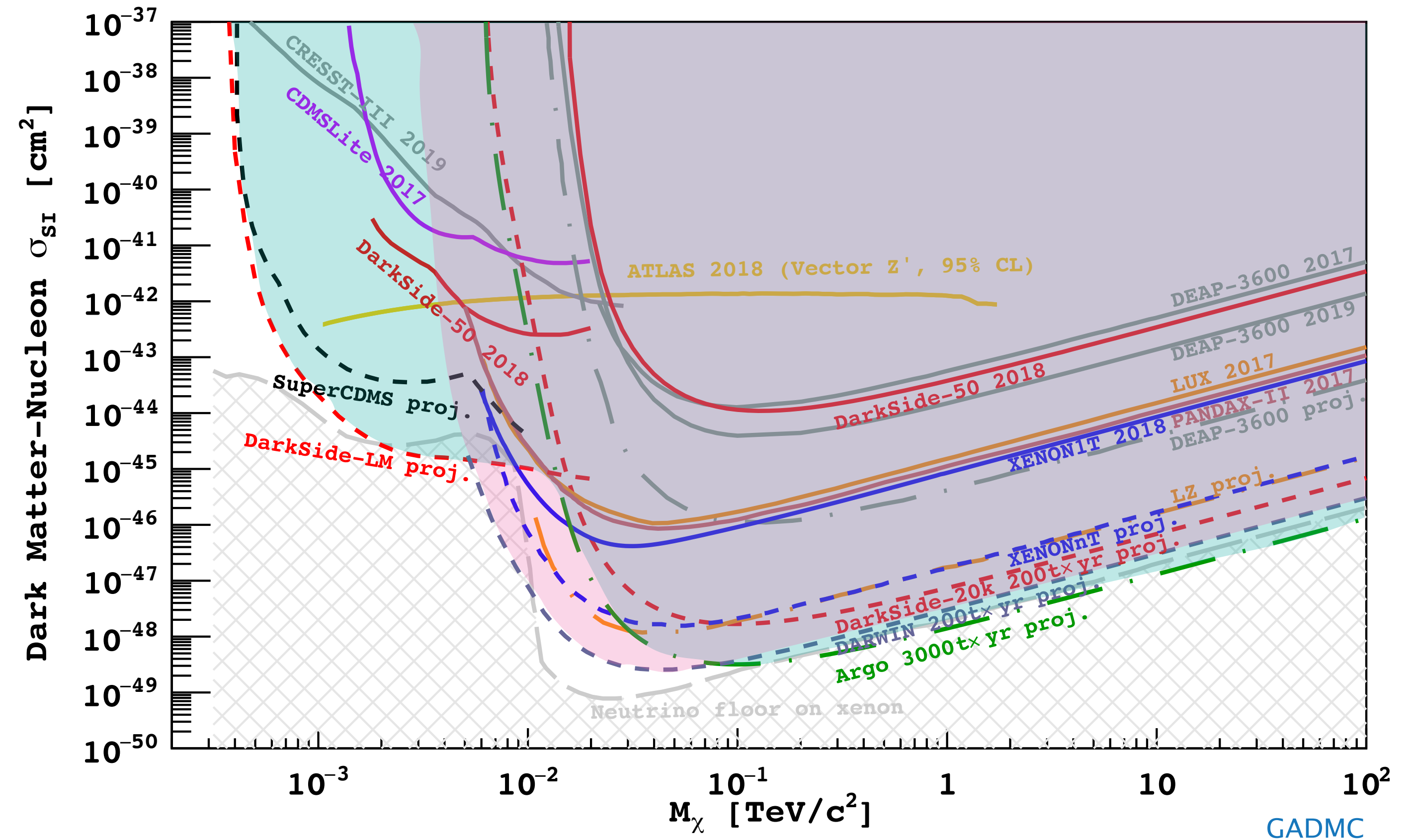
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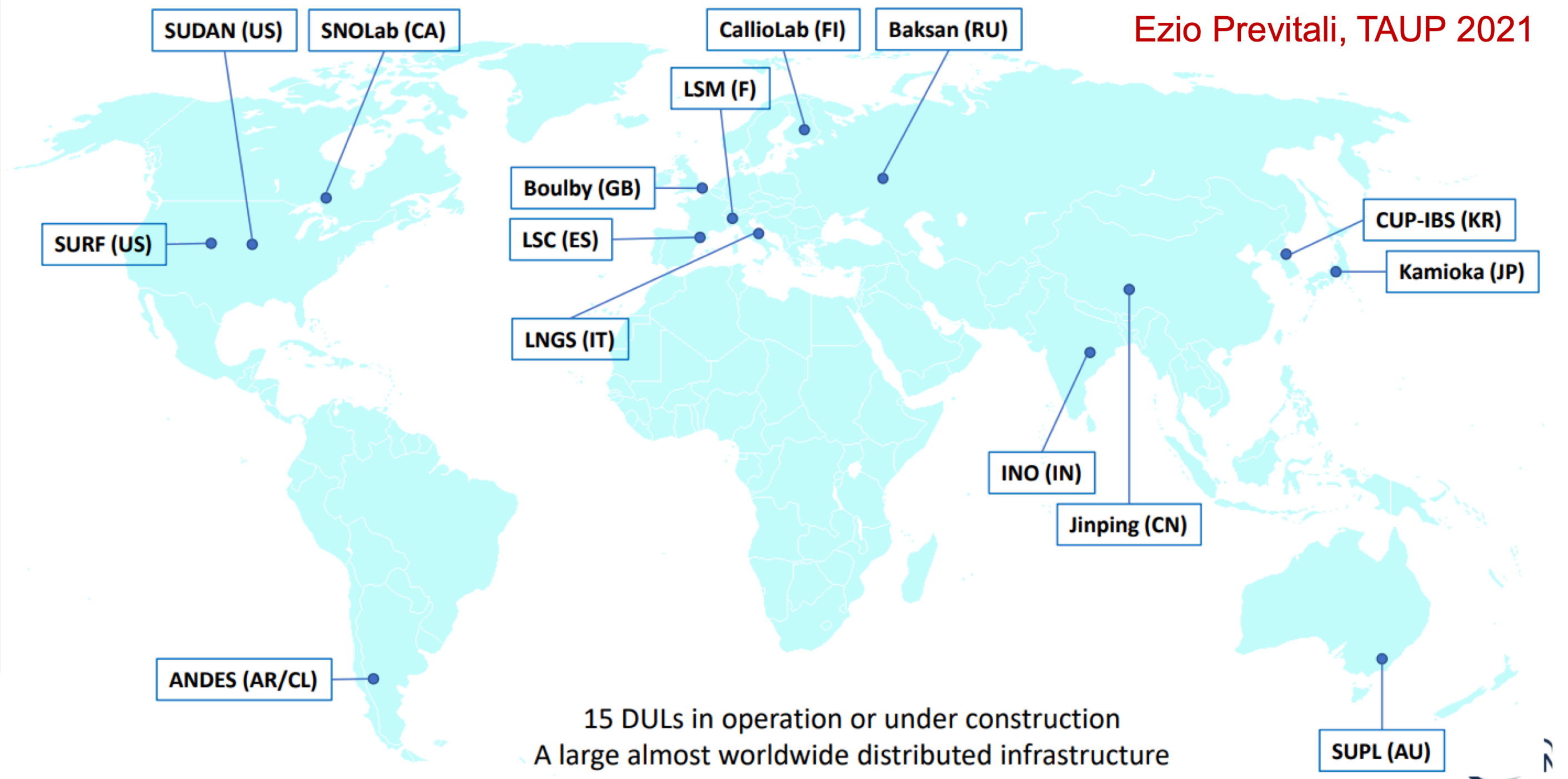
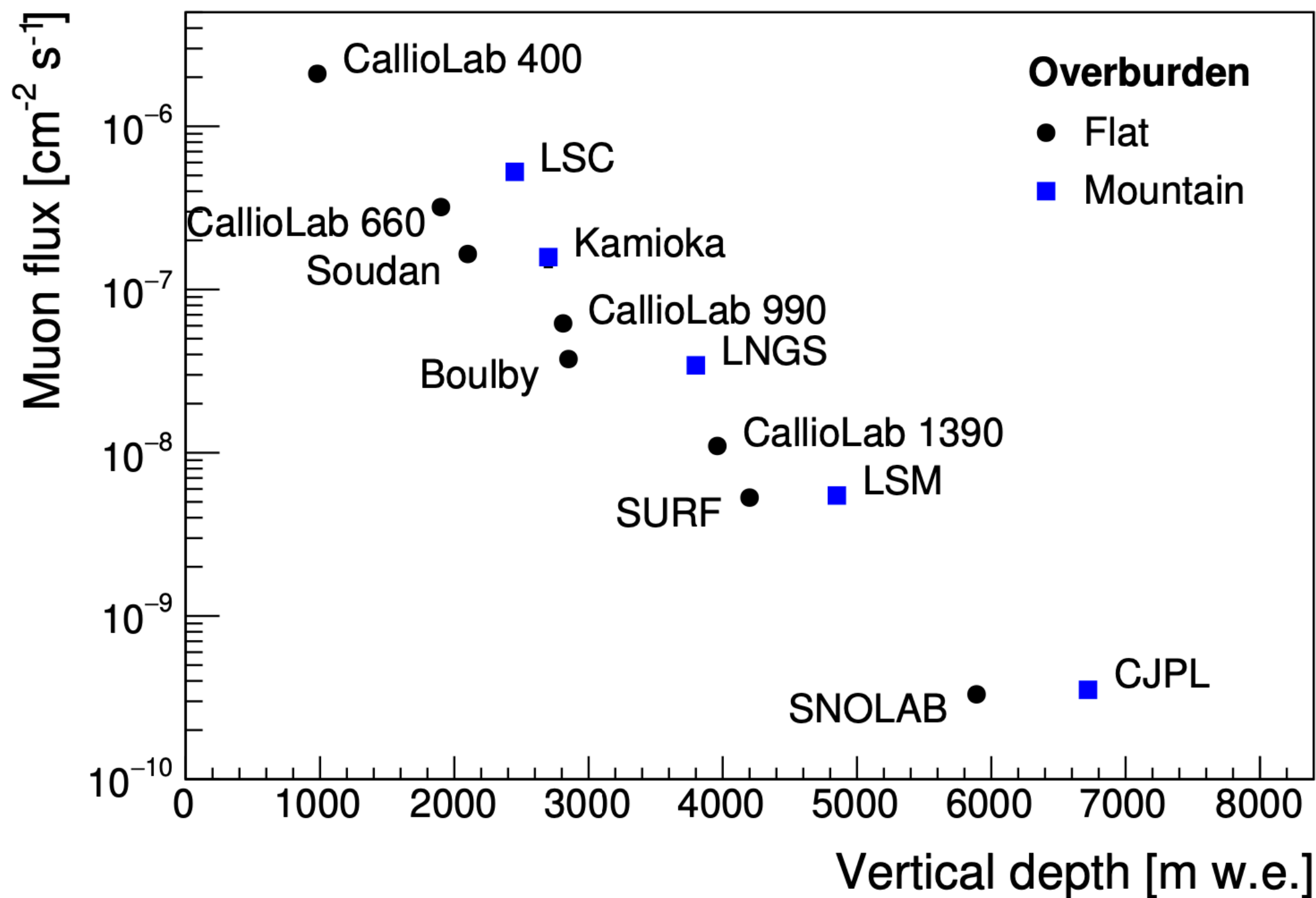
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Common Backgrounds

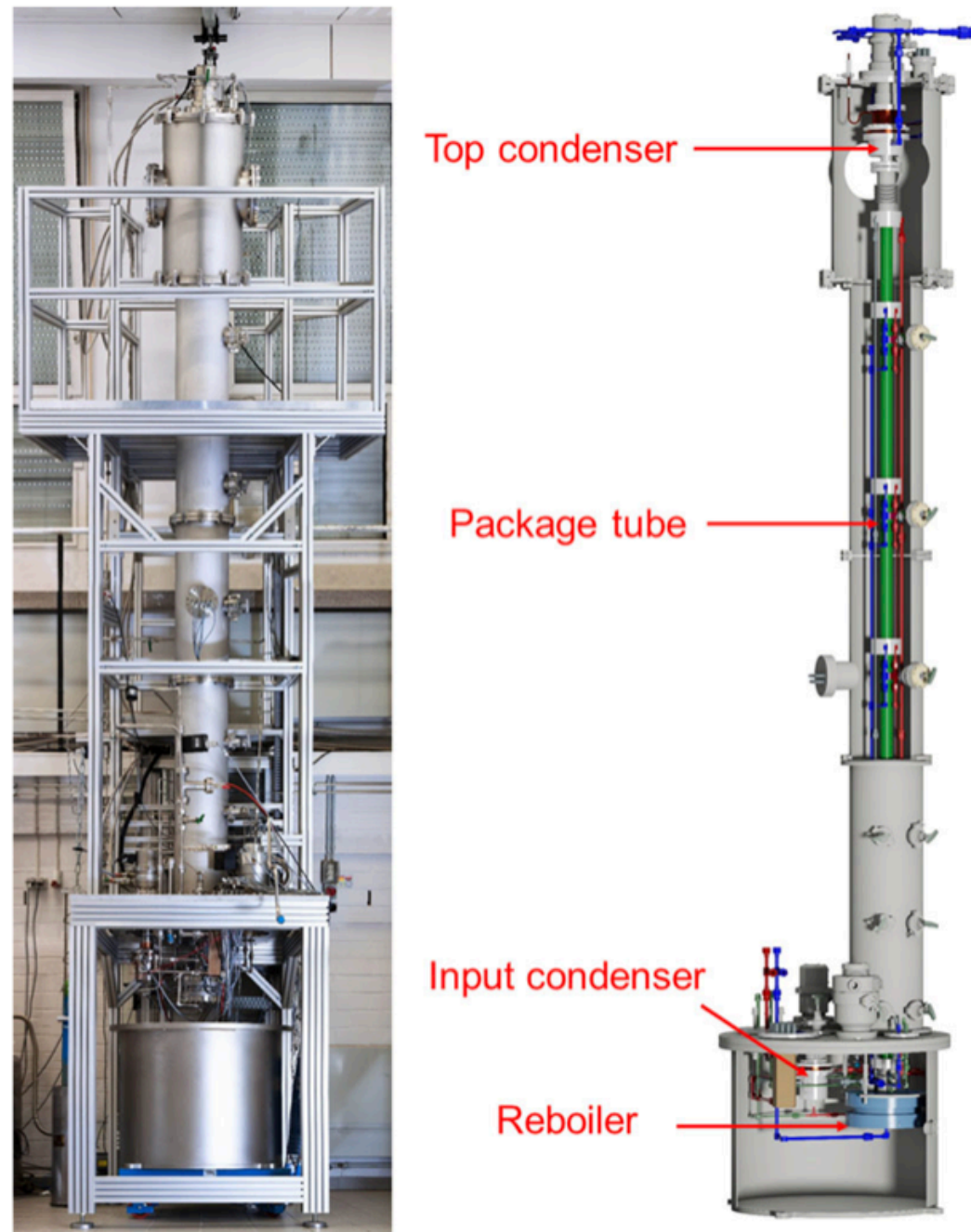
Mitigate cosmogenics and environmental backgrounds (muons and muon-induced neutrons, radiogenic neutrons, radon)



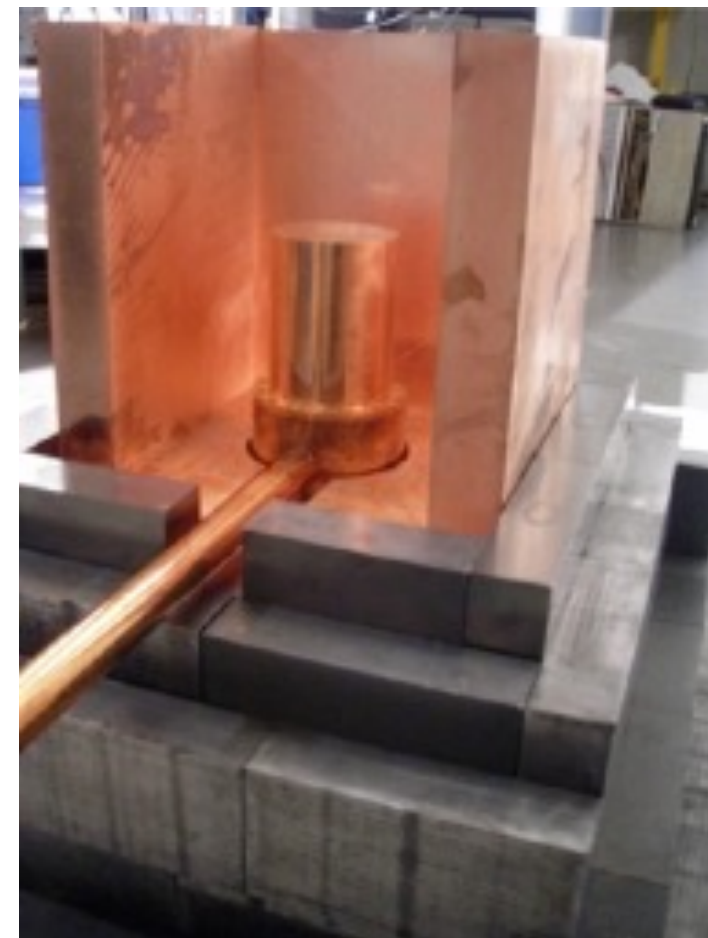
- ▶ Deep Underground Laboratories: reduce muon flux by at least 10^6 - siting will be increasingly important given large mass/exposures
- ▶ Minimize activation of detector materials and targets (For Ar - ARGUS: planned UG storage in SNOLAB)
- ▶ Use of passive and active veto detectors (muon Cerenkov, neutron capture on Gd)
- ▶ other activation backgrounds (mitigate, use clever vetos without too much deadtime)

Backgrounds

- ▶ Environmental (intrinsic) **radon** (filters, pure materials or surface treatments, distillation columns)
- ▶ **materials** (germanium spectroscopy, mass spectrometry, Rn-emanation measurements)
- ▶ **Detector backgrounds**: accidental coincidences, spurious emission (2-phase)



XENON distillation column

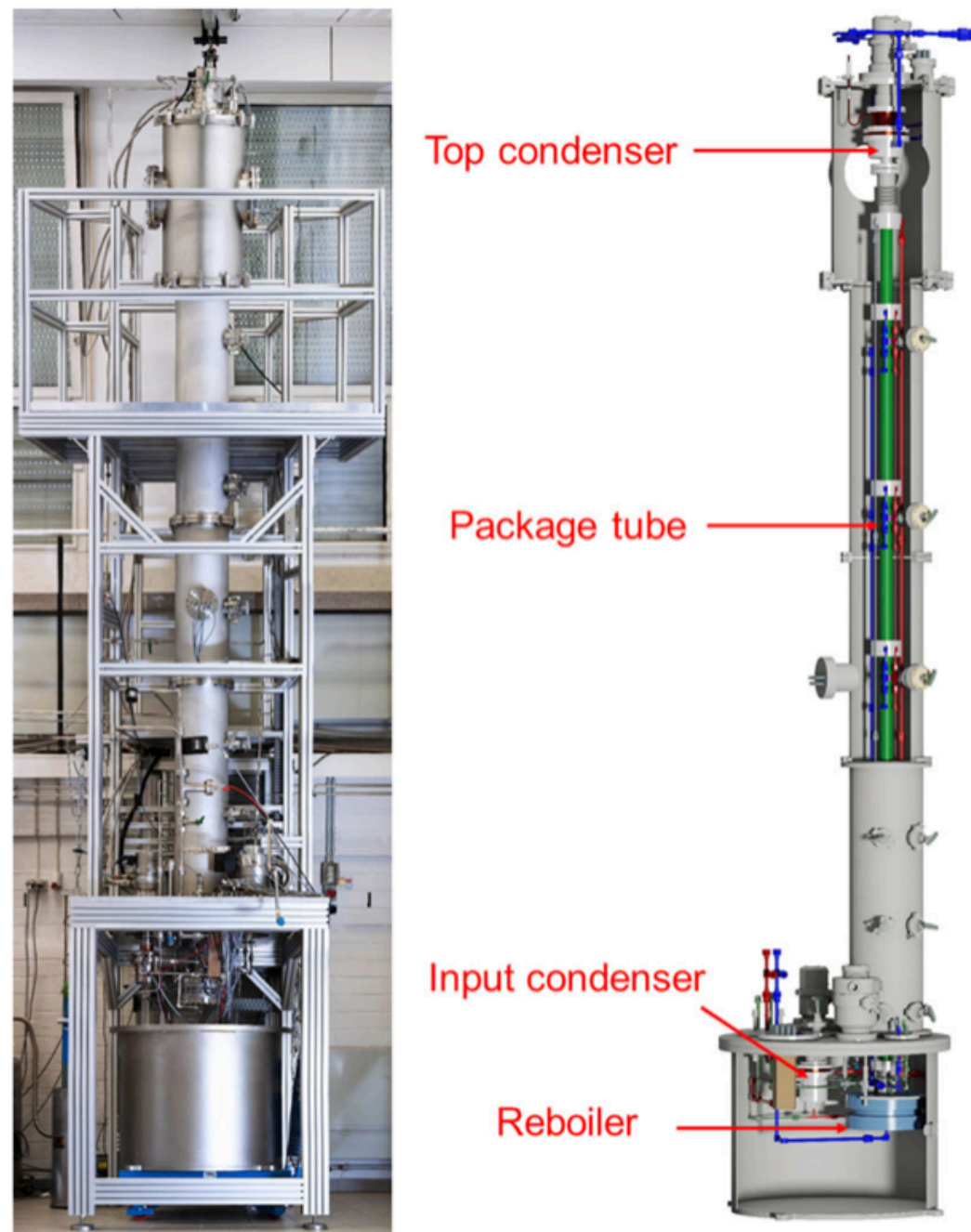


Gator low-background counting facility underground at LNGS.

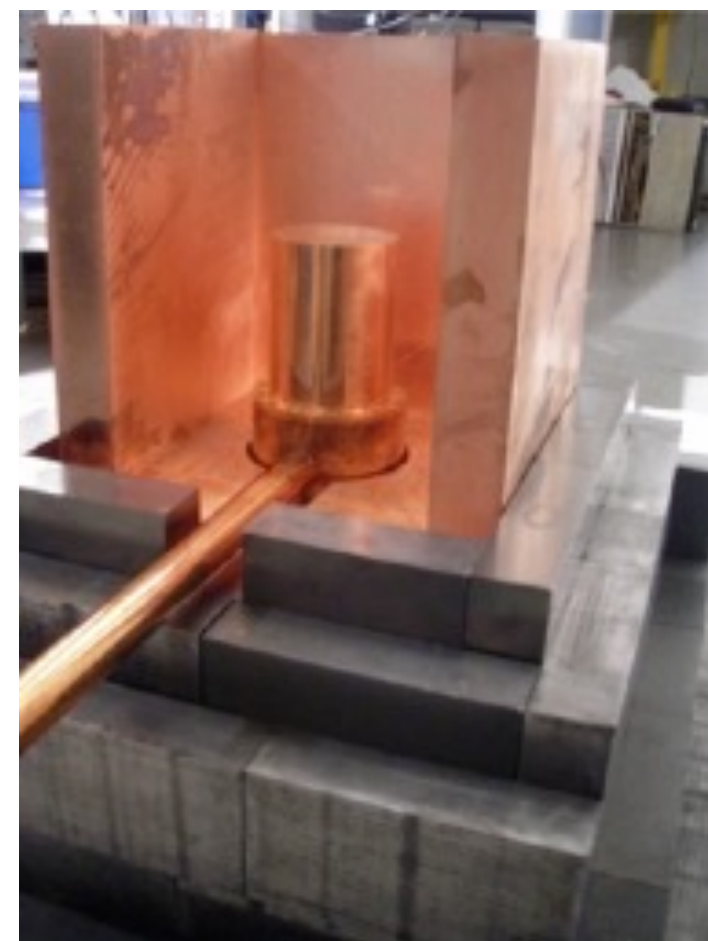
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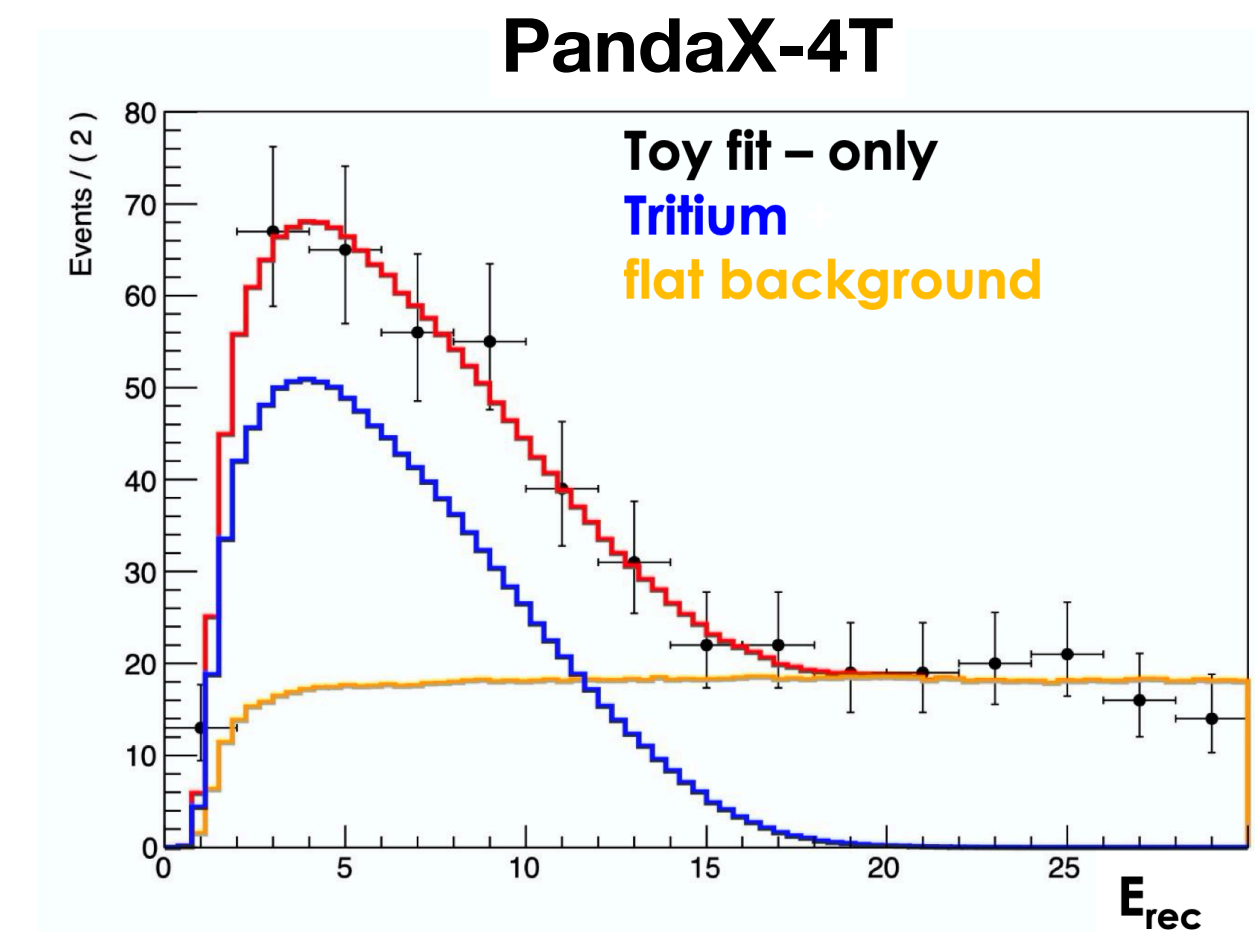
Also can have different backgrounds among same detector type. Example: xenon



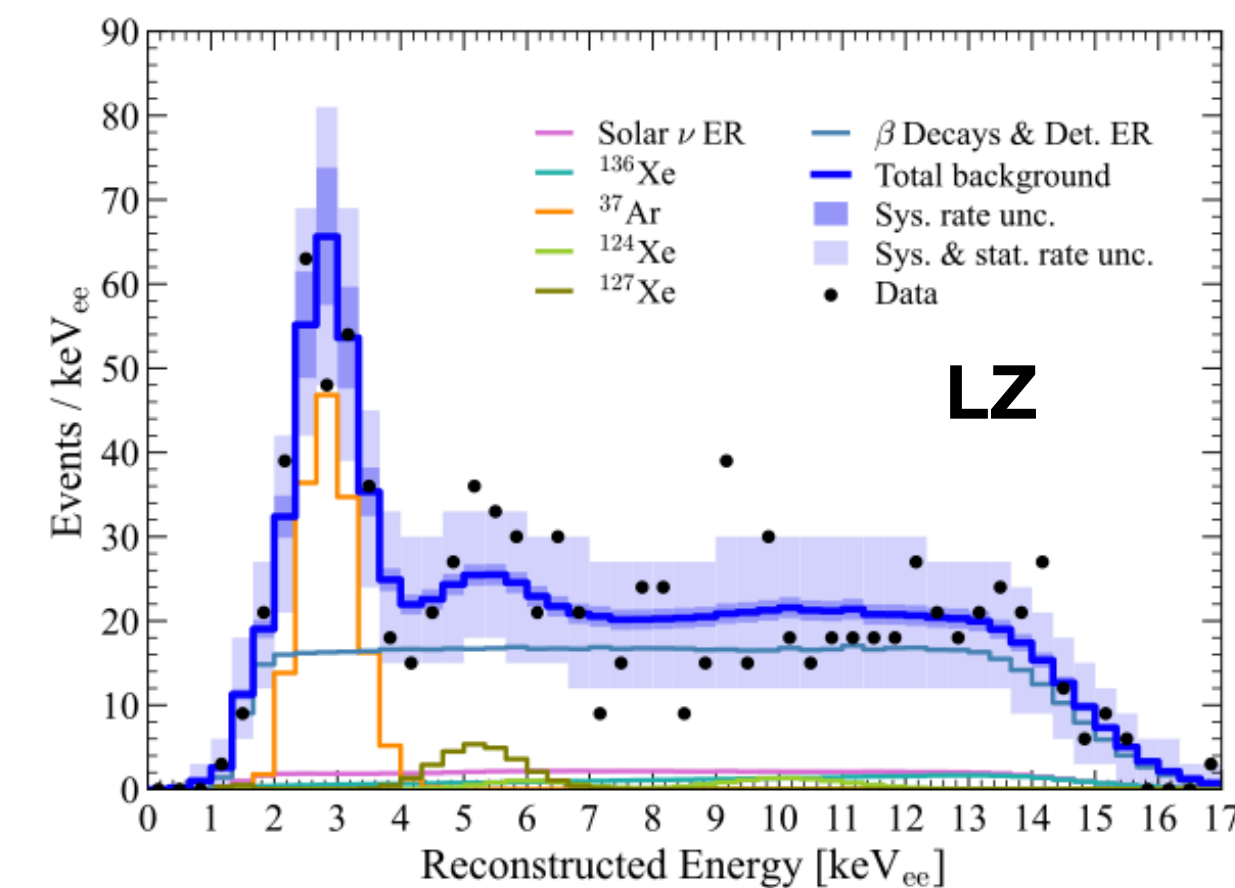
XENON distillation column



Gator low-background counting facility underground at LNGS.



Tritium background from calibration source



³⁷Ar peak at 2.8 keV in LZ due to above ground activation.

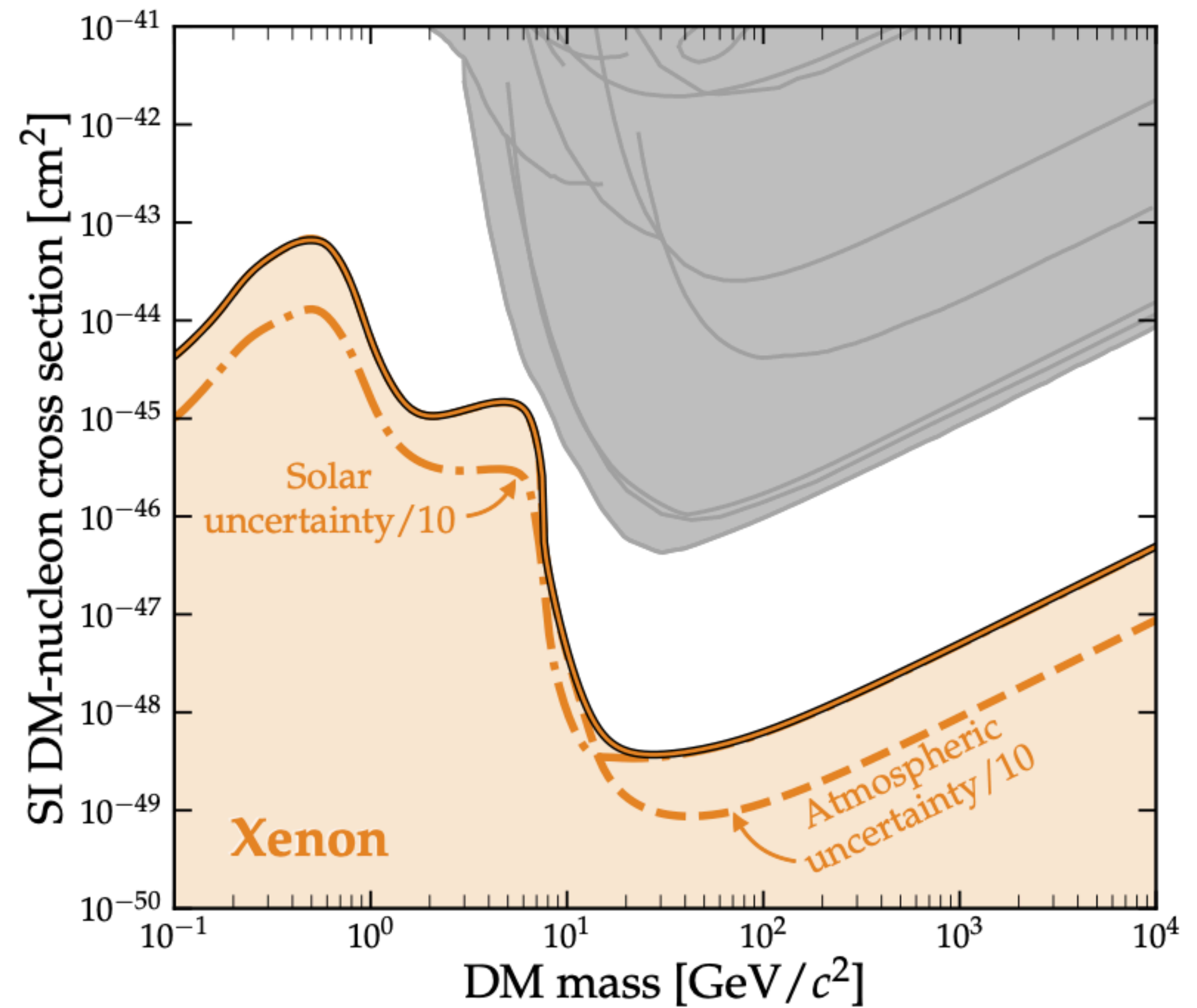
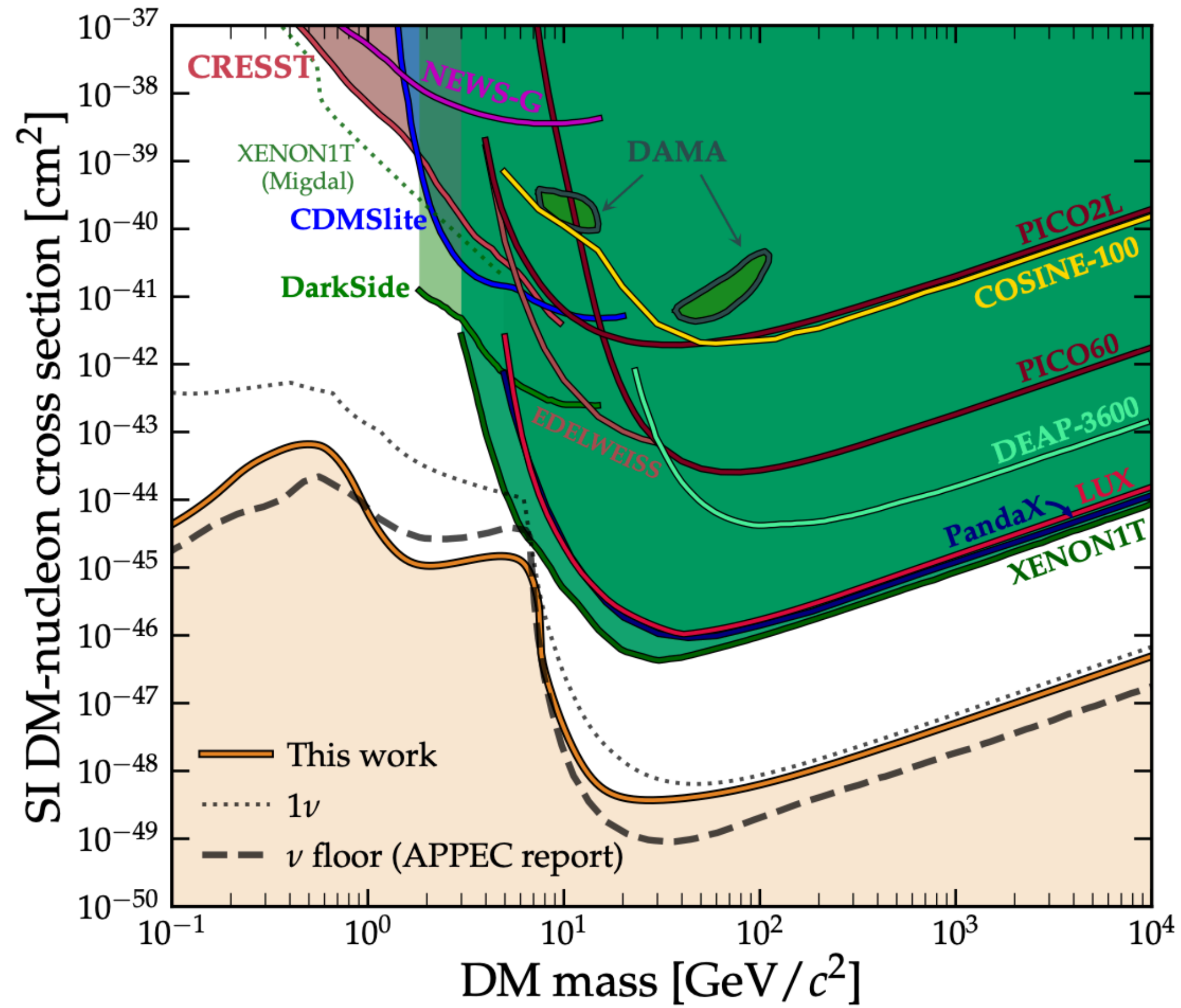
new LZ result: arxiv:2207.03764

³⁷Ar excluded as reason for XENON1T excess due to distillation, UG storage, peak at 2.3 keV, etc.

Common Backgrounds

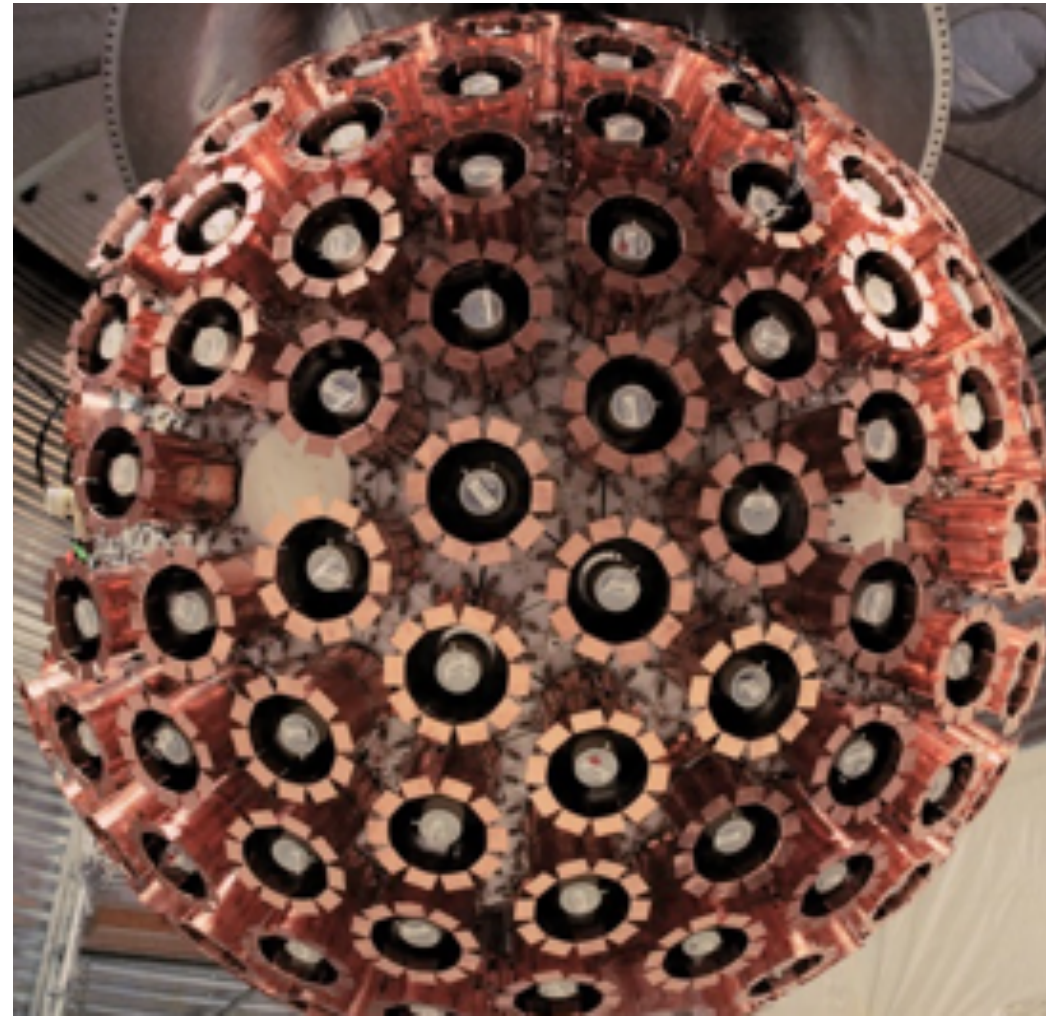
Fog on the horizon

See talk by O'Hare



^8B initial detection expected $\sim 6 \text{ GeV}/c^2$ by xenon detectors.

Current LAr Experiments

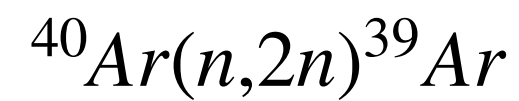
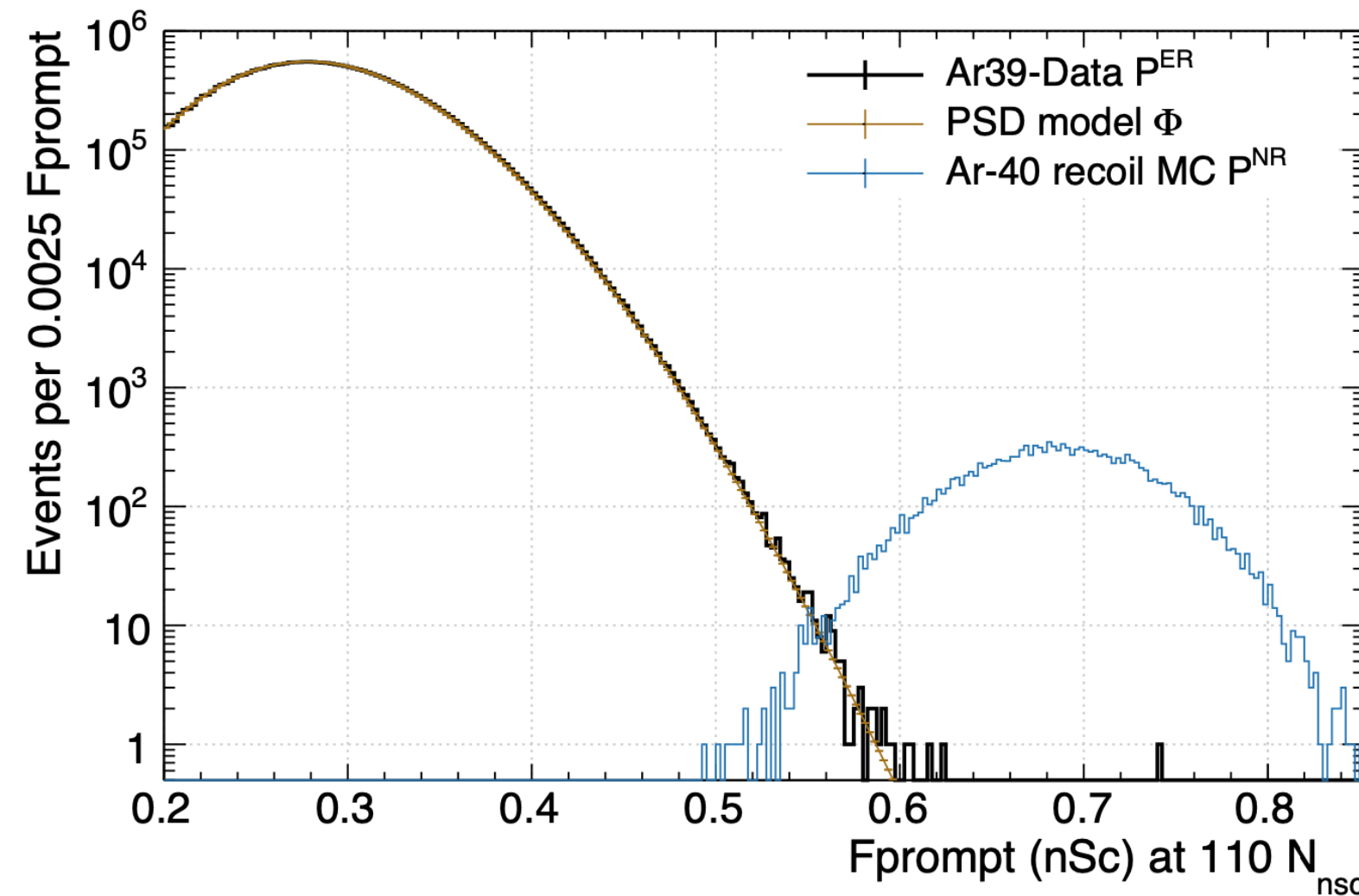


DEAP-3600
3300 kg
SNOLAB

challenges: Ar39

strengths: pulse shape discrimination, Rn reduction

See talks by Andrew Erlandson and Vicente Pseudo Forte



β^- decay with Q-value 565 keV

- ▶ achieved ER rejection power 10^{-9}
- ▶ still need to keep ^{39}Ar low to prevent leakage



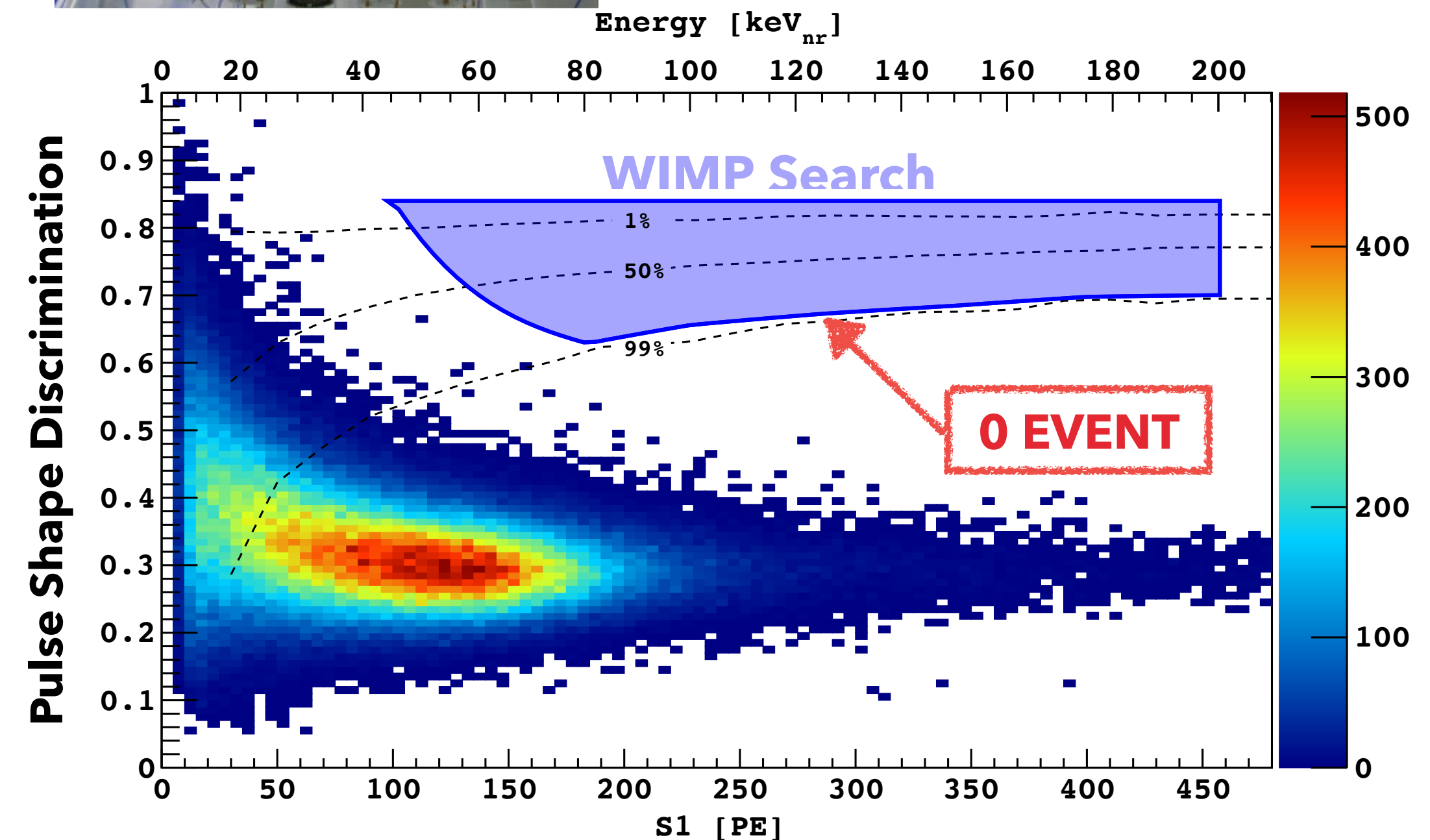
DarkSide-50
46 kg
LNGS

See talk by
 Masato
 Kimura

argon from underground wells (Urania) -> factor 1400 reduction in ^{39}Ar .

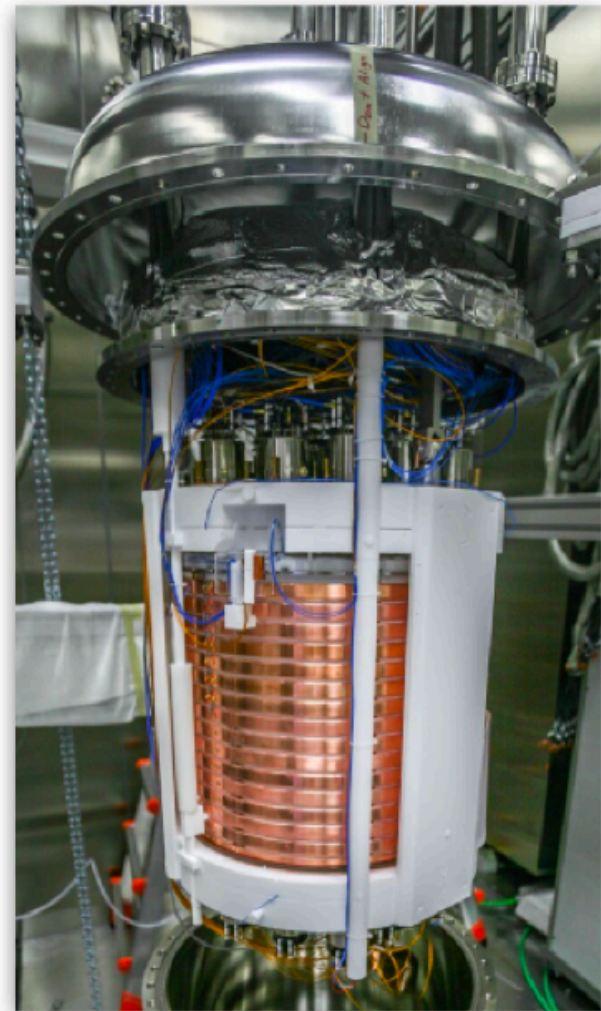
540-DAY BLIND ANALYSIS RESULT

No BG in the Search Region

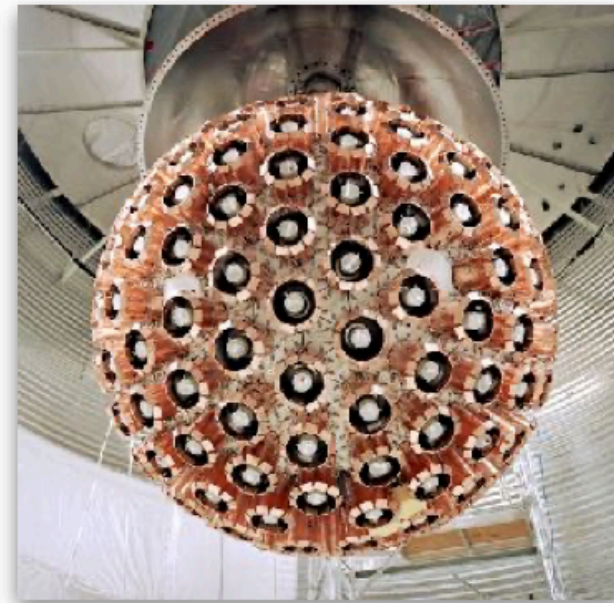


see talk by Thomas Nathan Thorpe

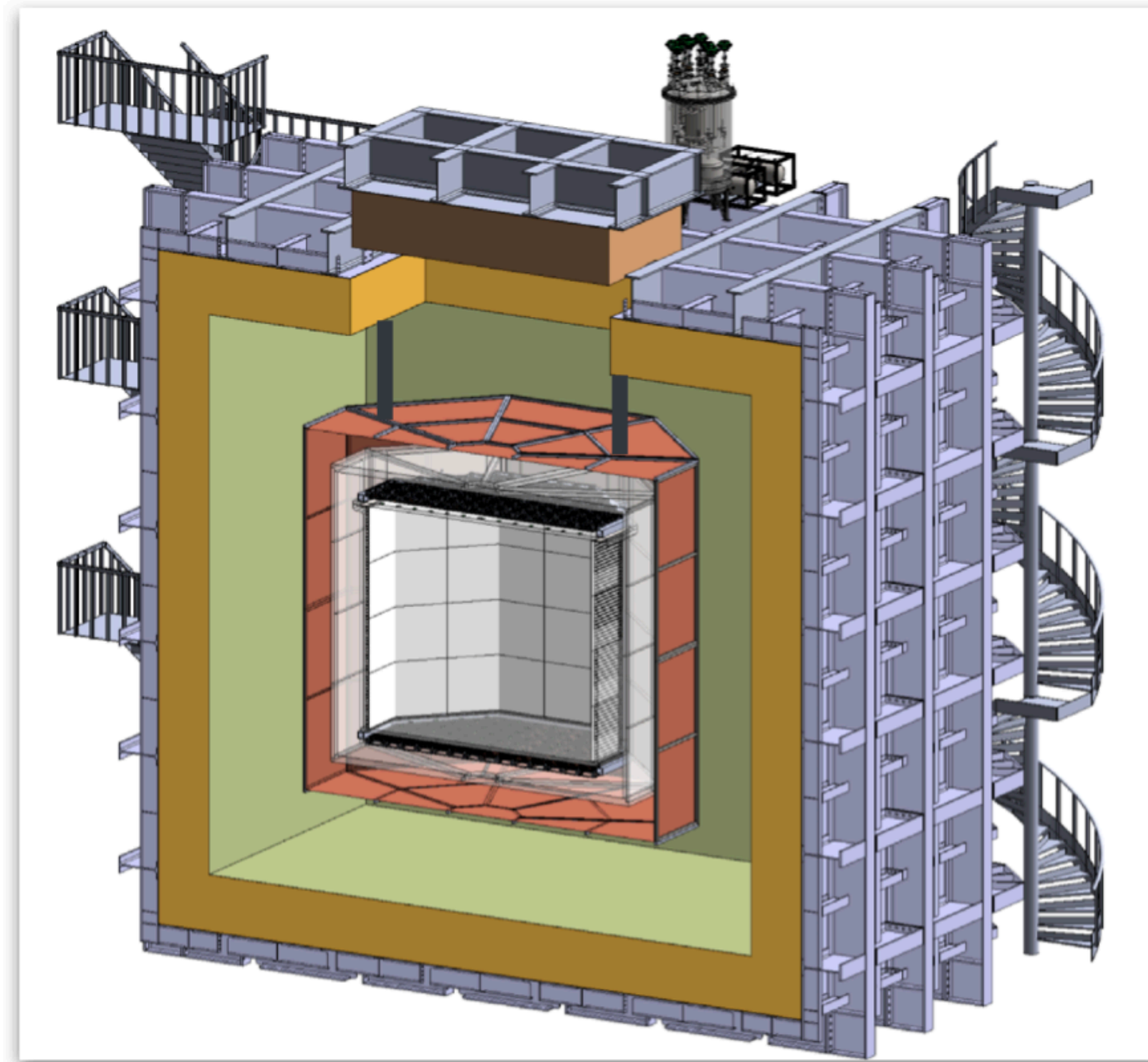
DarkSide-50



DEAP-3600



DarkSide-20k



from 2022 at LNGS

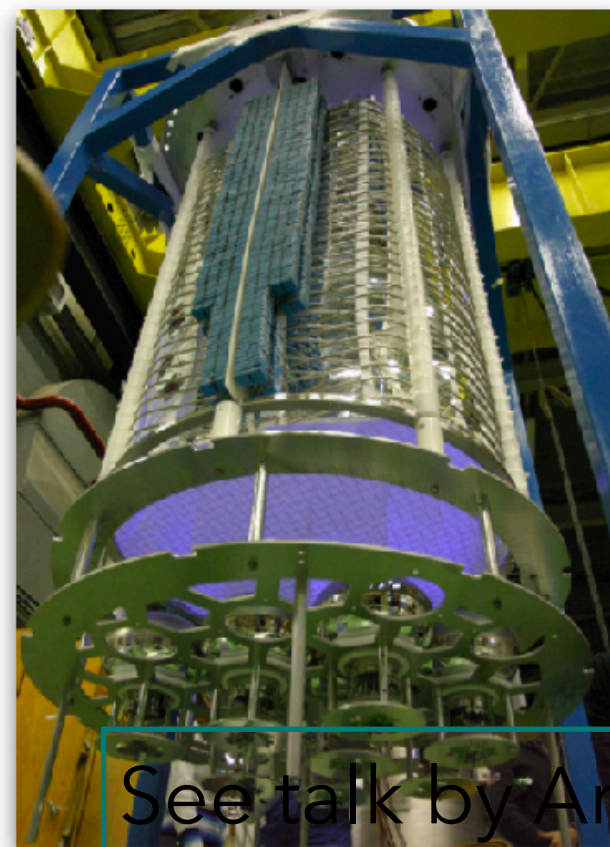
GADMC: Global Argon Dark Matter Collaboration

ARGO
~300t TPC

from 2029
at Snolab

- ▶ Multi-national collaboration >500 scientists from >80 institutions
- ▶ Joint, complementary expertise of several argon dark matter experiments
- ▶ Synergies with CERN (Protodune)
- ▶ Also will have a specific detector for low mass DM

ArDM



MiniCLEAN



See talk by Andrew Erlandson

50t underground argon dual-phase TPC
in 700t atmospheric argon cryostat

→ sensitivity $1.2 \times 10^{-47} \text{ cm}^2$ at WIMP mass of $1 \text{ TeV}/c^2$
(with 100 tonne year exposure with a 20t fiducial mass)

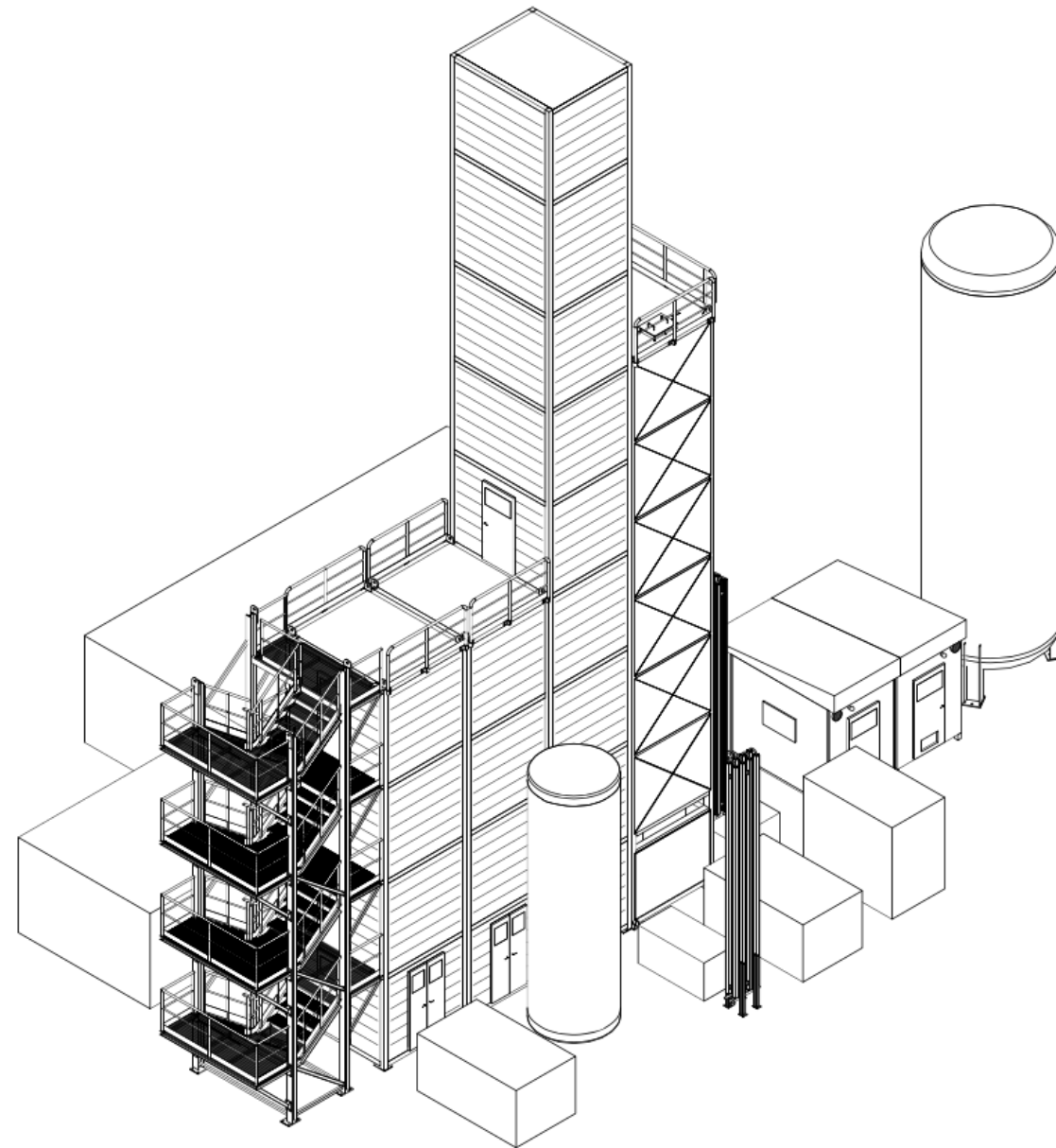
slide courtesy Alex Kish

Argon sourcing and purification

LOW RADIOACTIVITY ARGON

URANIA

- ▶ Procurement of 50 tonnes of Underground Argon (UAr) from same Colorado source as for DS-50
- ▶ Extraction of 250 kg/day, with 99.9% purity
- ▶ UAr transported to Sardinia for final chemical purification at Aria

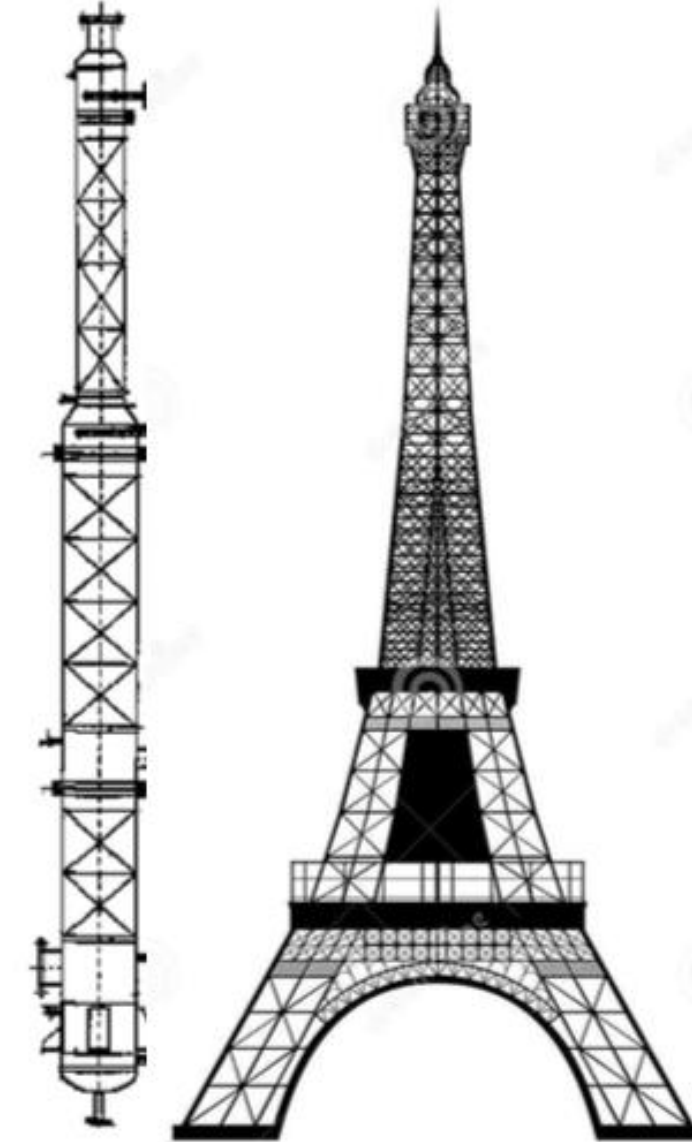


ARIA

Seruci-I

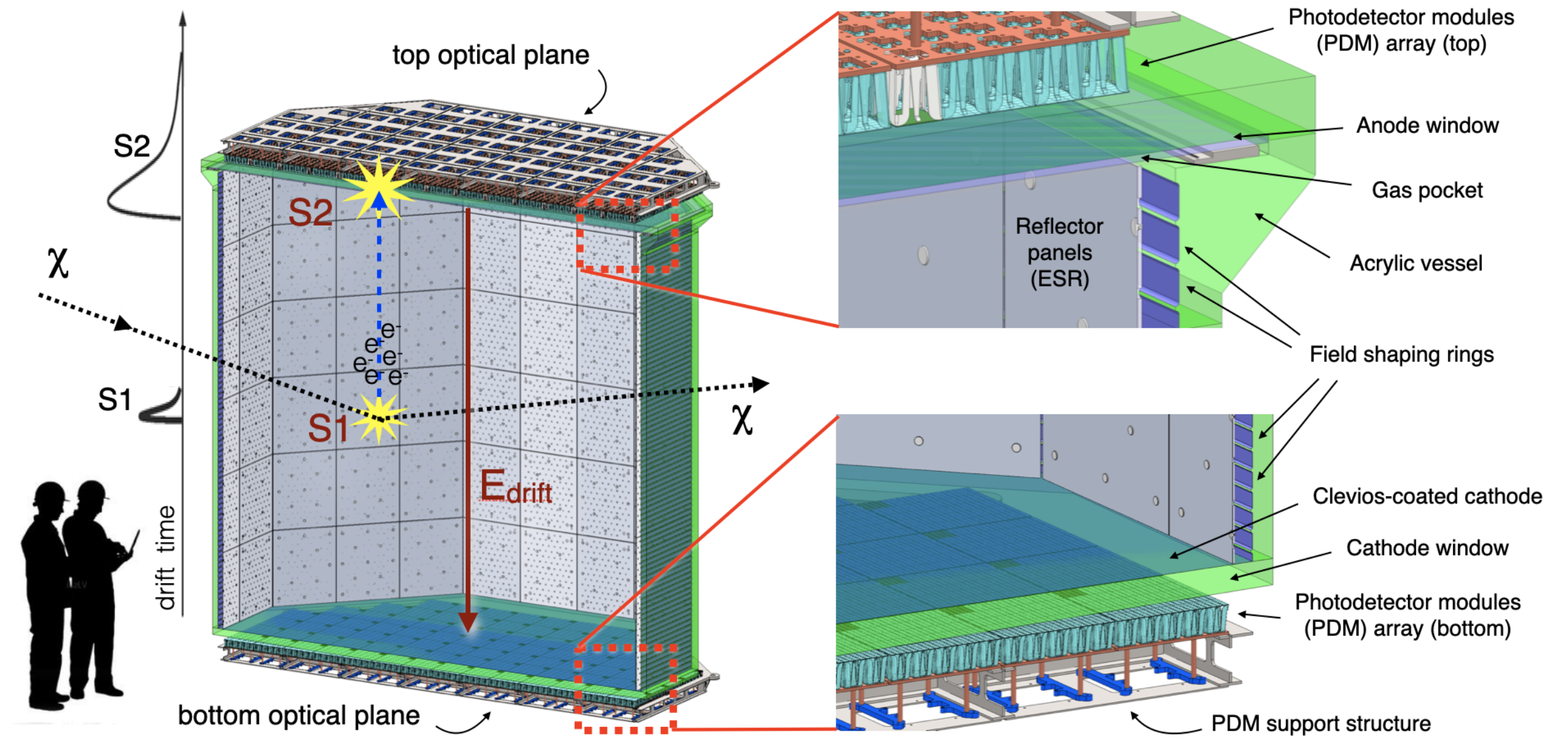
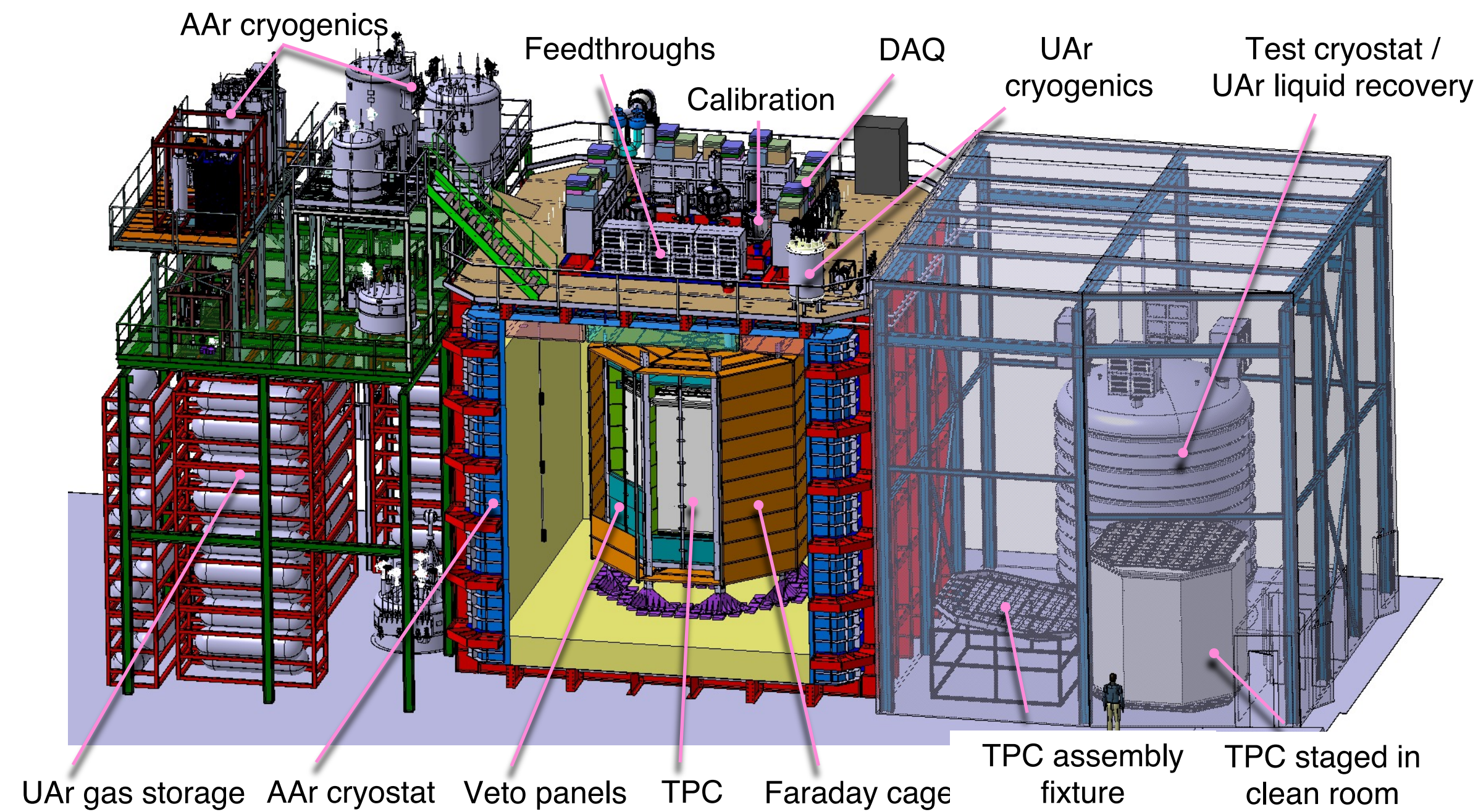


Seruci-II



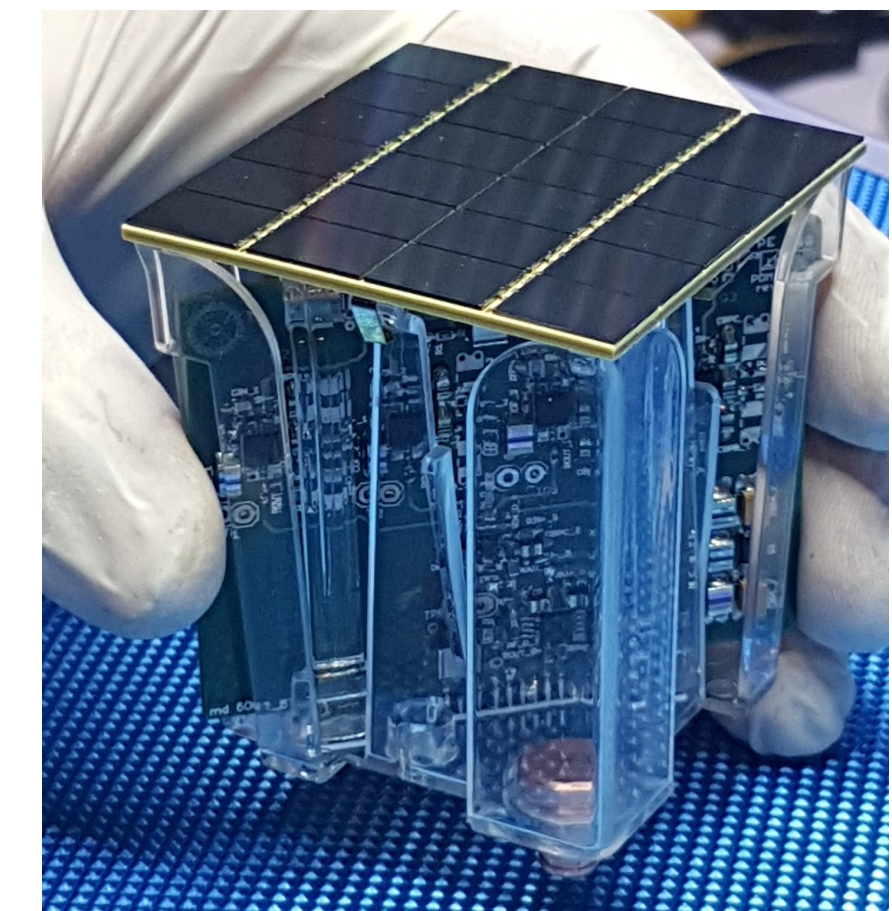
- ▶ 350-m tall cryogenic distillation column in Seruci, Sardinia
- ▶ Final chemical purification of the UAr
- ▶ Can process $O(1 \text{ tonne/day})$ with 10^3 reduction of all chemical impurities
- ▶ Ultimate goal is to isotopically separate ^{39}Ar from ^{40}Ar (at the rate of 10 kg/day in Seruci-I)
- ▶ goal to reduce factor of 10 isotope fraction per pass; can make multiple passes.

FUTURE DETECTOR



LNGS HALL-C

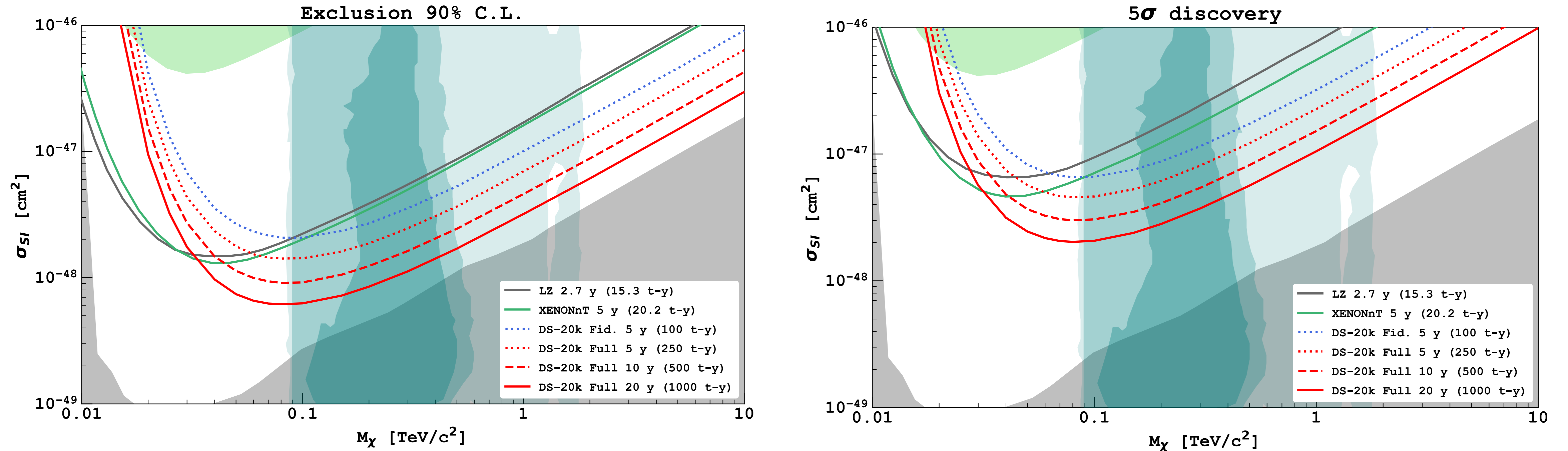
- ▶ A 20-tonnes fiducial argon detector filled with underground argon
- ▶ TPC acrylic vessel surrounded by Atmospheric Argon (AAr) + Gd-loaded acrylic shell as a neutron veto
- ▶ 21 m² of Cryogenic Silicon based Photomultipliers (5x5 cm² tile); TPC lined with wavelength shifter



Projected Sensitivity DS-20K

PHYSICS POTENTIAL

EXCLUSION SENSITIVITY AND 5σ DISCOVERY POTENTIAL

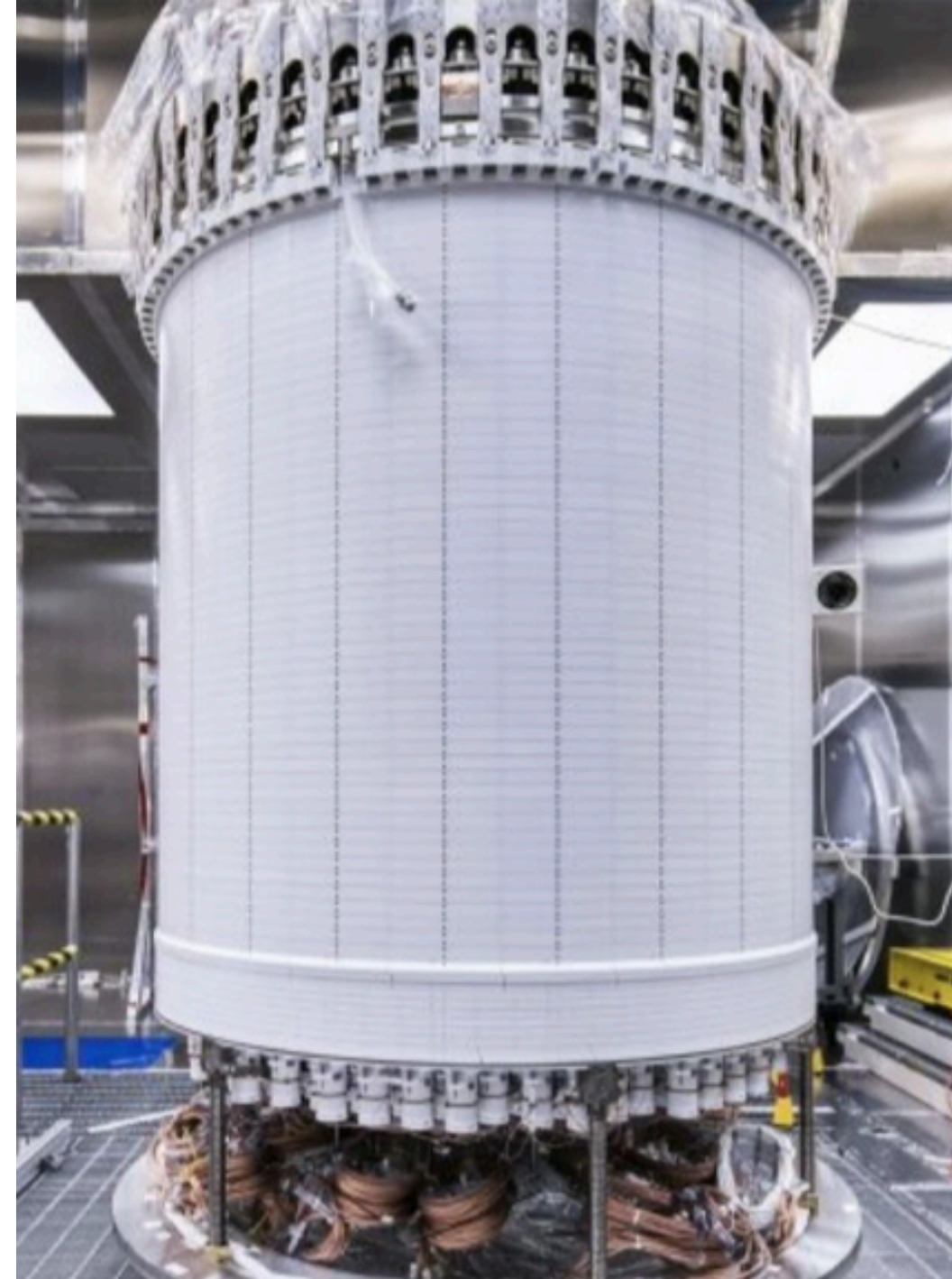


- ▶ Expect 3 events in 200 ton x year from neutrino coherent scattering ; neutrons same background condition as in DS-50 (<0.1 background events in full exposure)
- ▶ Underground Argon target, excellent PSD, and neutron veto allow zero instrumental background

Current LXe Experiments



400 kg
first results PRL



Lux-Zeplin at SURF
first results arxiv:2207.03764
5.9 t fiducial mass
at GeV/c^2 excluding above 5.9×10^{-48} (90%CL)

see talk by Alden Fan



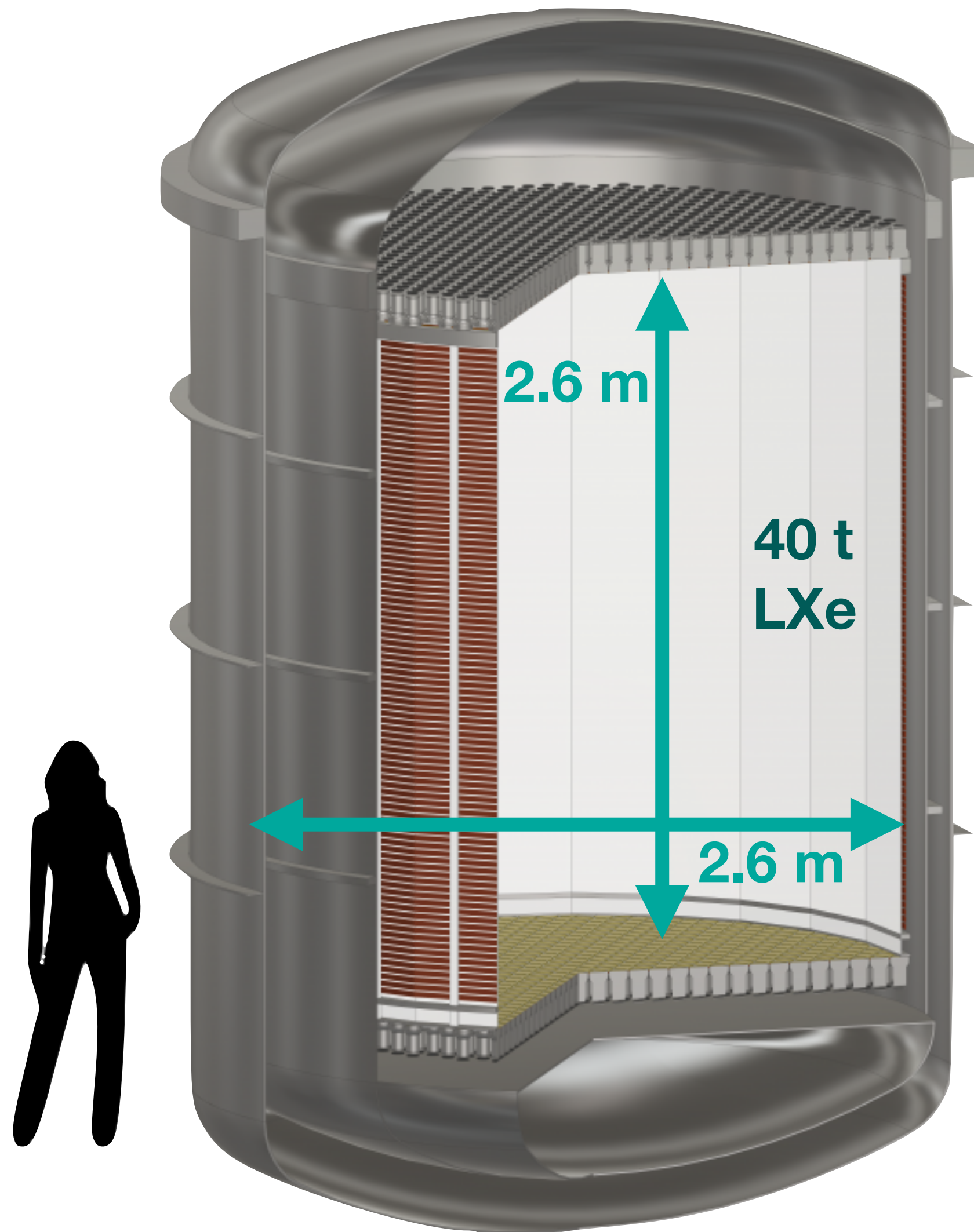
XENONnT at LNGS
5.9 t target LXe

first results coming soon
see status talk by Knut
also Daniel Wenz (nveto)

xenon future: PandaX-30T

DARWIN/G3 40-80 tonne detector

Future LXe experiments: DARWIN

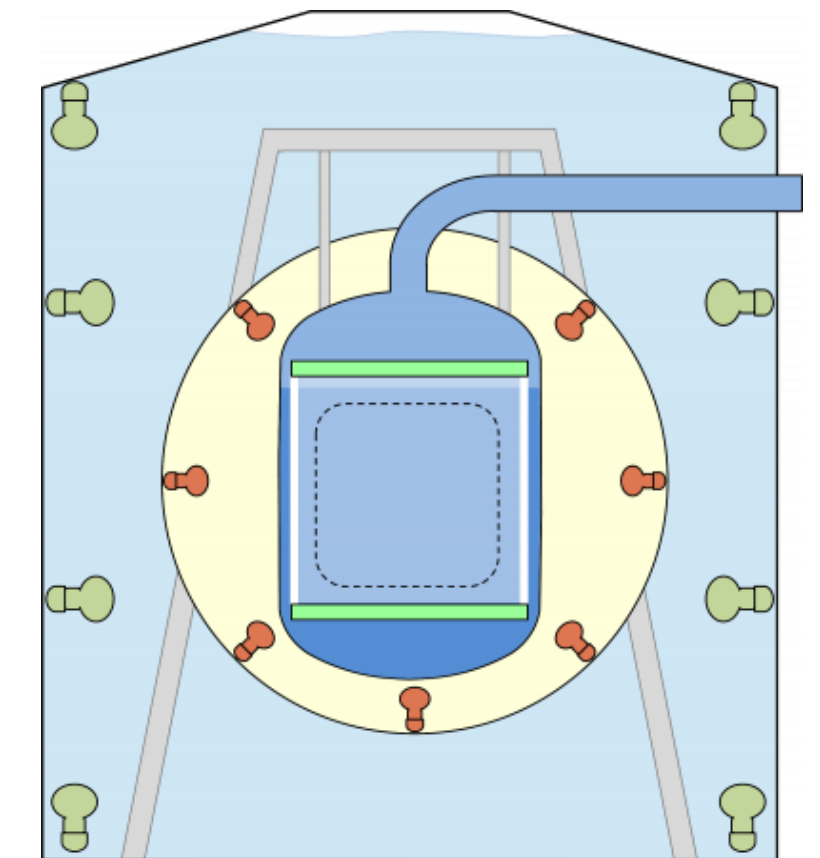


DARk matter WImp search with liquid xenON

Baseline design

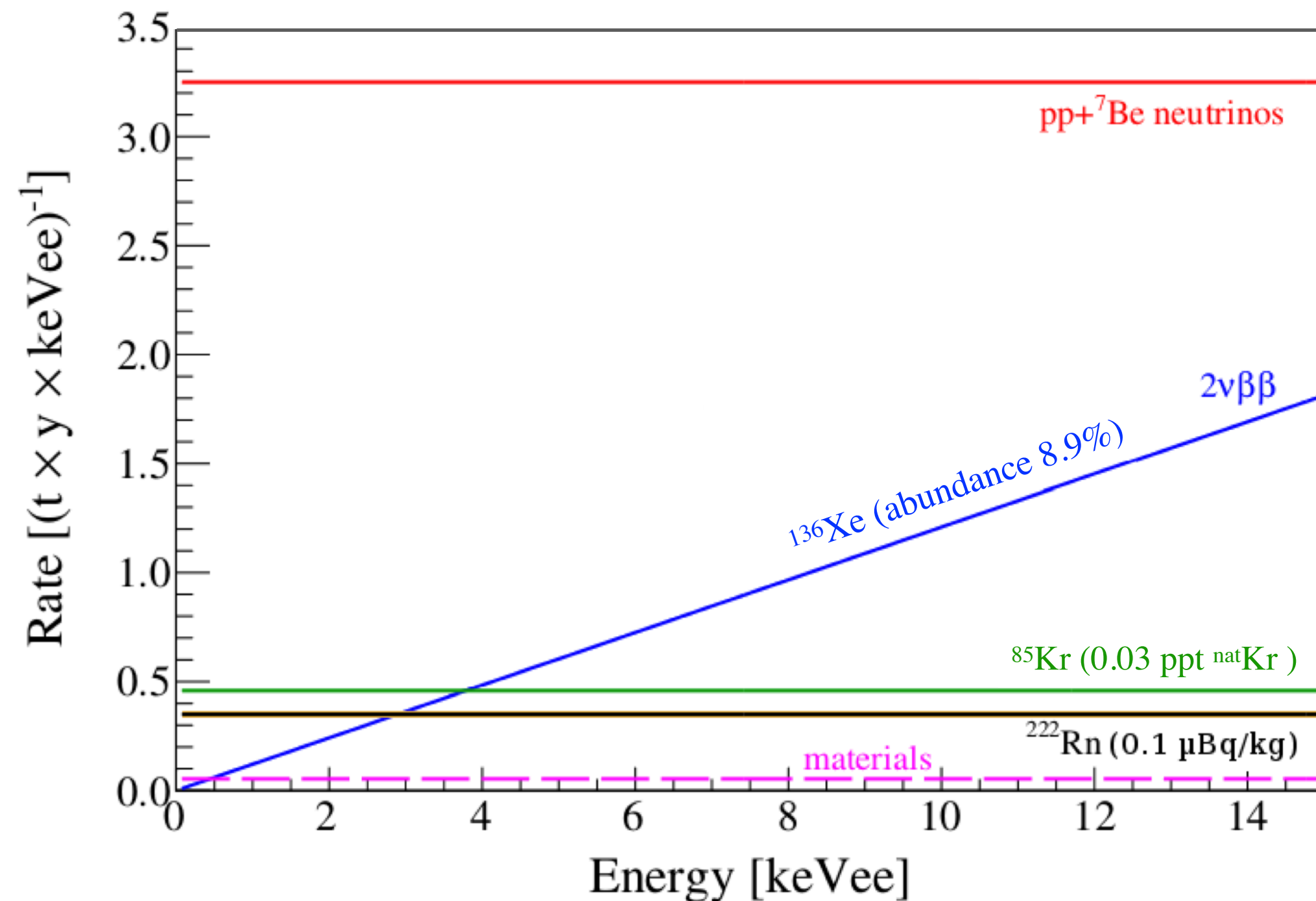
- ▶ Two-phase LXe/GXe TPC; aspect ratio 1
- ▶ **50 t total** LXe (40 t target)
- ▶ Top and bottom photosensors (~1800 3" XENON PMTs)
- ▶ PTFE reflectors and Cu field-shaping rings
- ▶ In-situ purification plus krypton and radon distillation (background mitigation)
- ▶ Veto detectors: water Cerenkov for muons with Gd doping for neutrons

plus an active R&D program at many institutes



see talk by Klaus Eitel

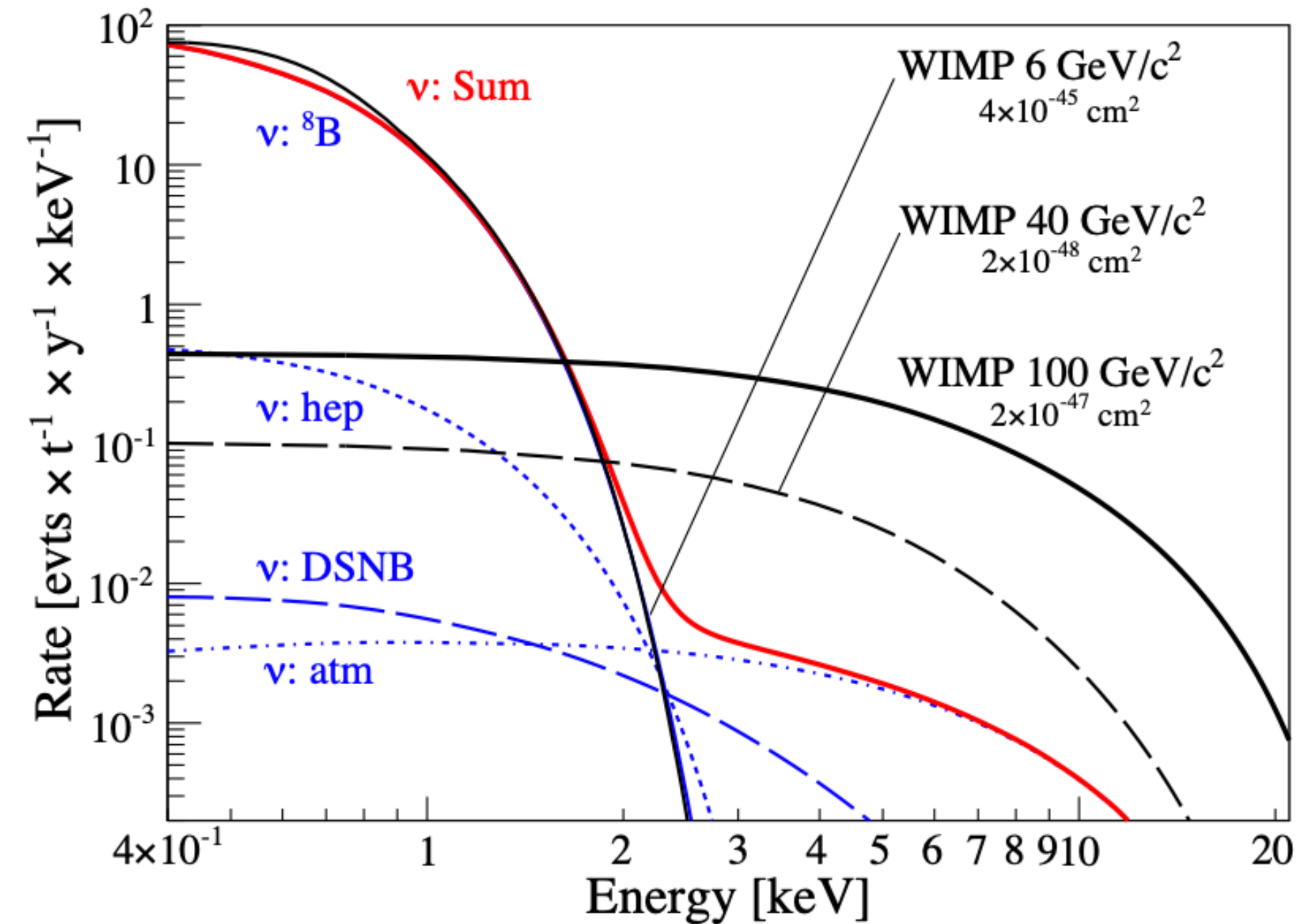
Electronic recoil (ER) background



- ▶ Intrinsic goal: ~one order of magnitude lower ^{222}Rn , ^{85}Kr than currently achieved by XENON
- ▶ Expected **neutrino**-dominated ER background

Figure updated from Schumann et al., JCAP 1510 (2015) 016

Nuclear recoil (NR) background

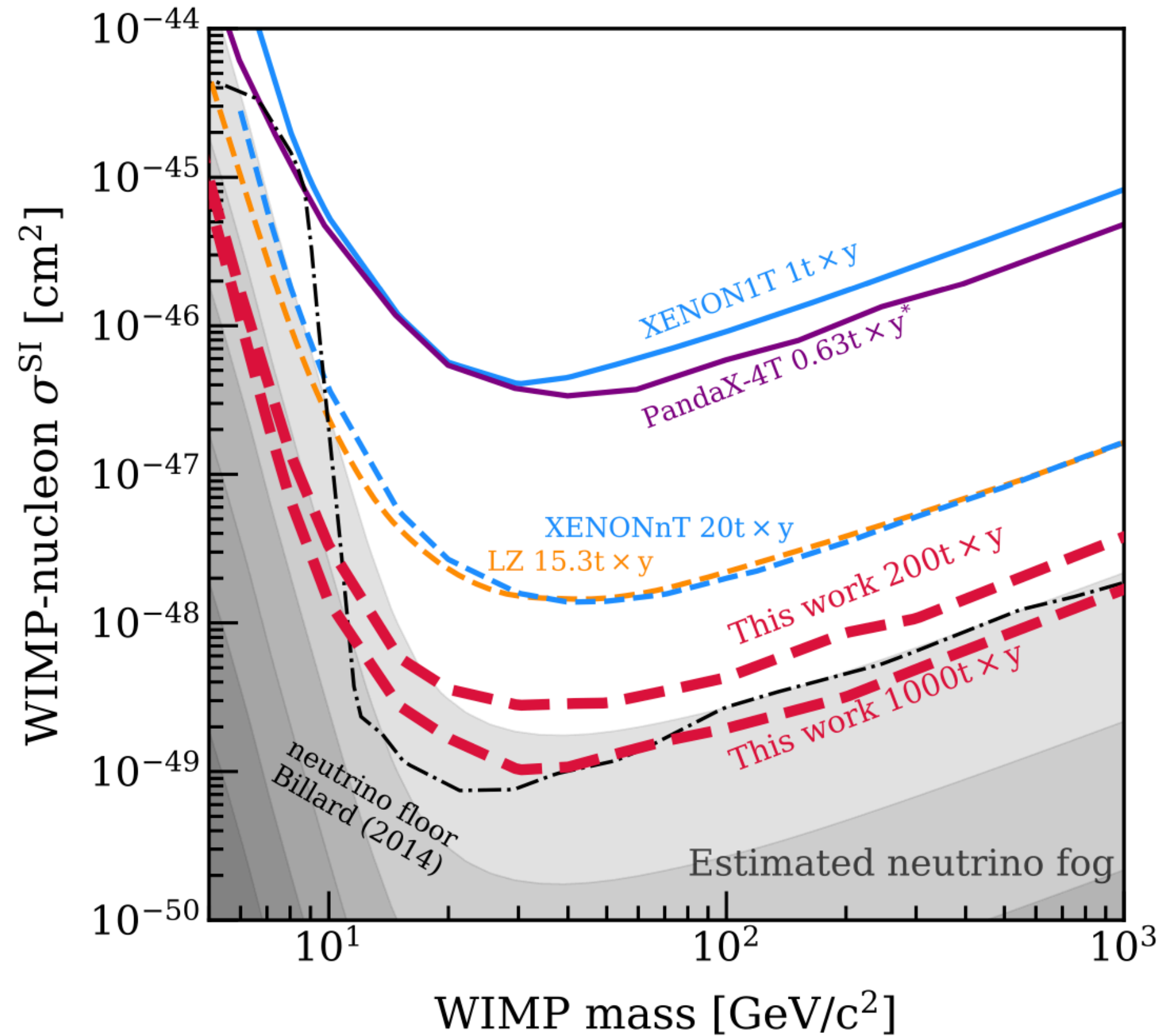


- ▶ NR background dominated by coherent elastic neutrino-nucleus scattering (**CEνNS**)
- ▶ Radiogenic neutrons: ~2 events/ 200 t yr (**materials**)
- ▶ **muon-induced neutrons**: ~0.4 events/ 200 t yr (12 m diameter water tank at LNGS)

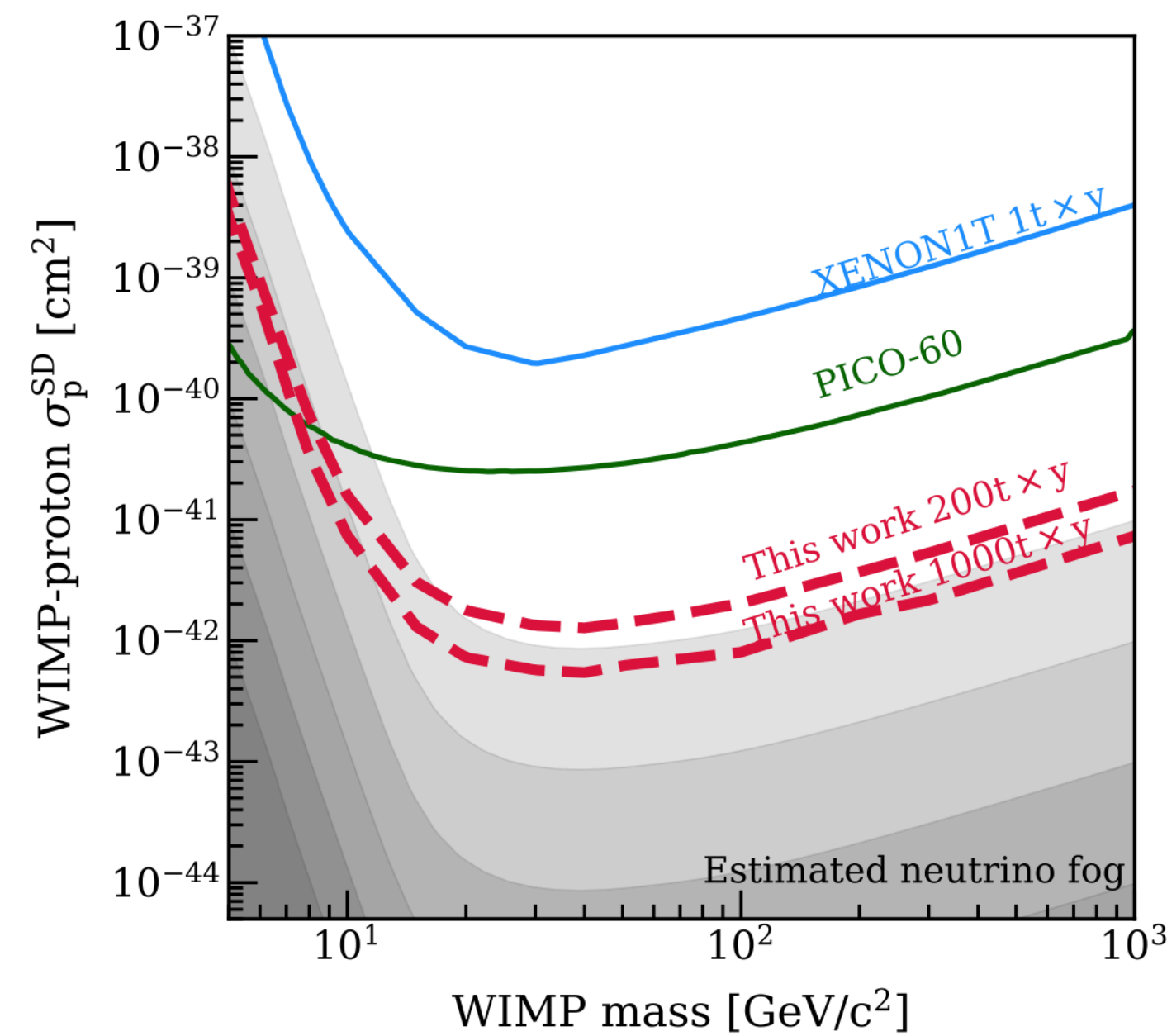
DARWIN Collaboration, JCAP 1611 (2016) 017

DARWIN/G3 Science Reach

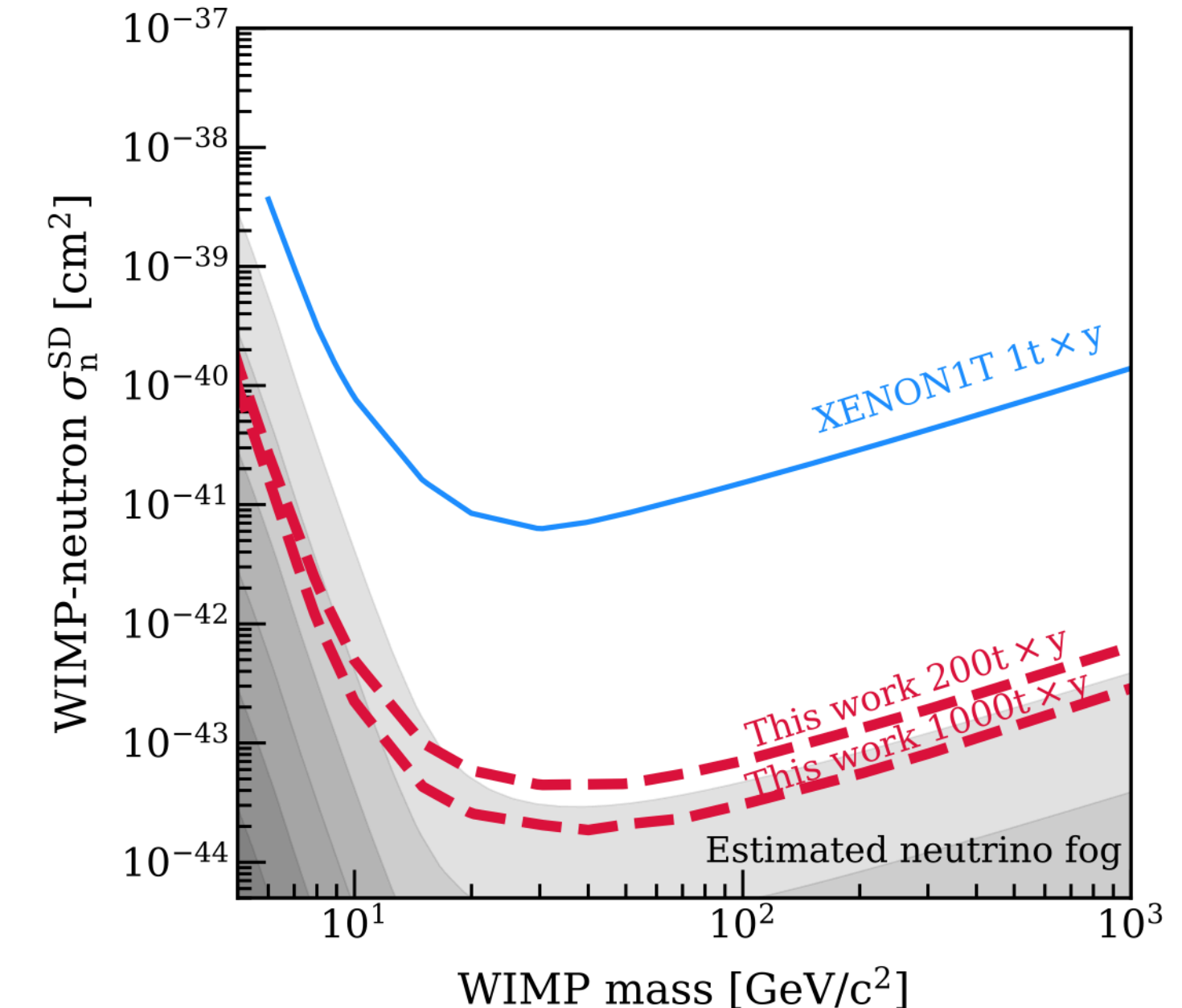
Spin-independent WIMP-nucleon



Spin-dependent WIMP-proton



Spin-dependent WIMP-neutron



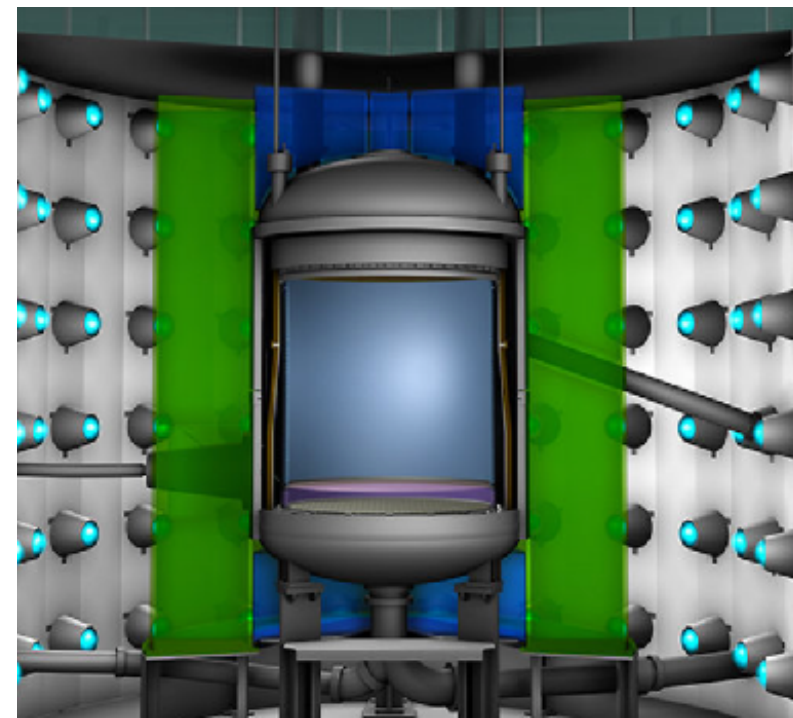
- ▶ Projected median upper limits for the next-generation xenon experiment (dashed red lines) with current limits (solid lines)
- ▶ Probes cross sections and masses down to the neutrino floor (and into the neutrino fog)
- ▶ Grey bands indicate >1, 10, 100, etc. expected neutrino events in the 50% signal-like region

XLZD Consortium (Xenon Lux Zeplin DARWIN)

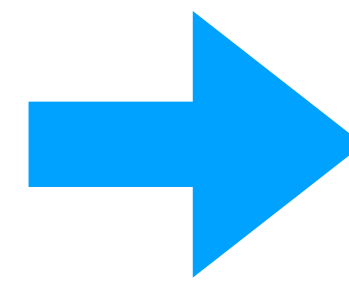
Current generation



XENONnT: 8.6 t LXe
Data taking 2021

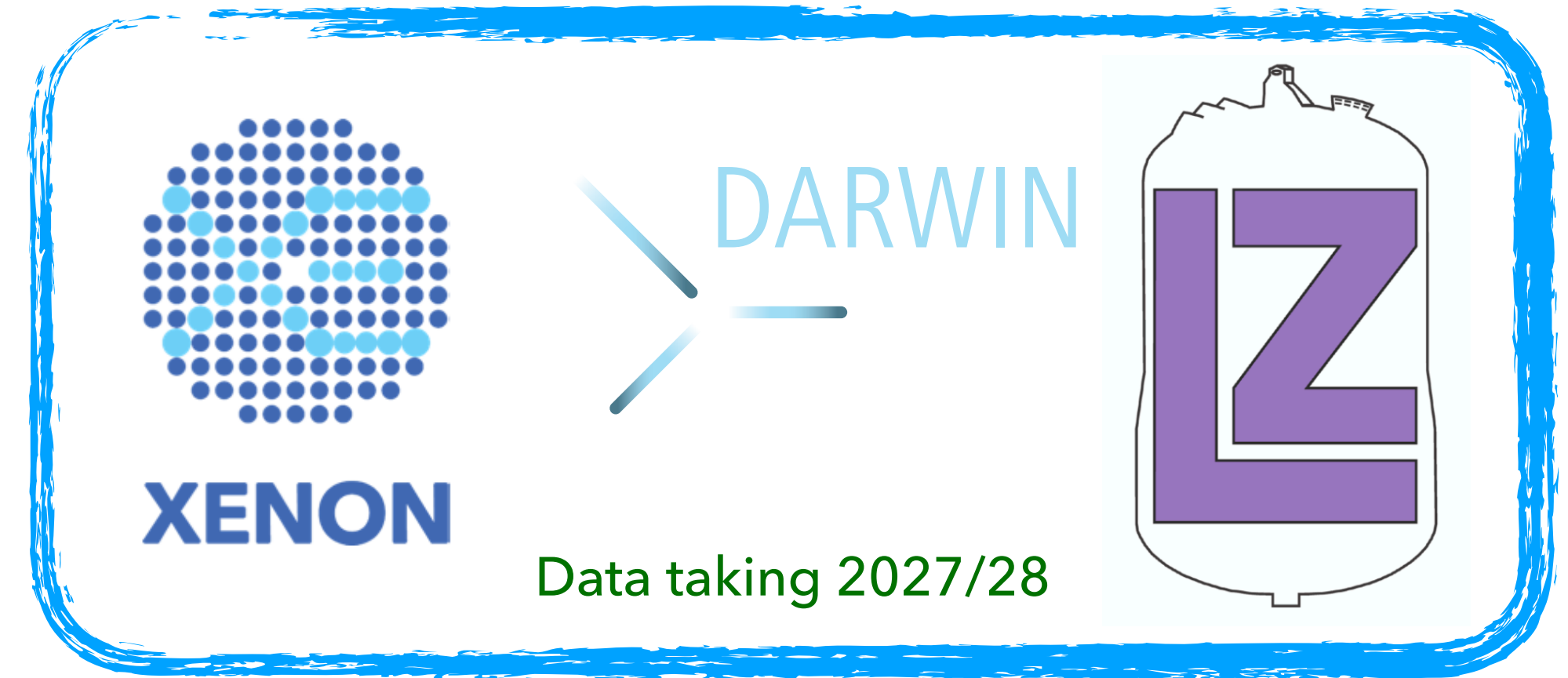


LUX-ZEPLIN (LZ): 10 t LXe
Data taking 2021



<https://xlzd.org>

Merger of leading collaborations for a future DARWIN/G3 xenon-based experiment



- ▶ **Memorandum of Understanding** signed July 6, 2021 by 106 research group leaders from 16 countries
- ▶ International collaboration with complementary areas of expertise
- ▶ First joint meeting April 2021 online; second meeting June 2022 hosted by Karlsruhe Institute of Technology
- ▶ **Community whitepaper** with combined science goals, background considerations, priorities - posted March 2022.

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

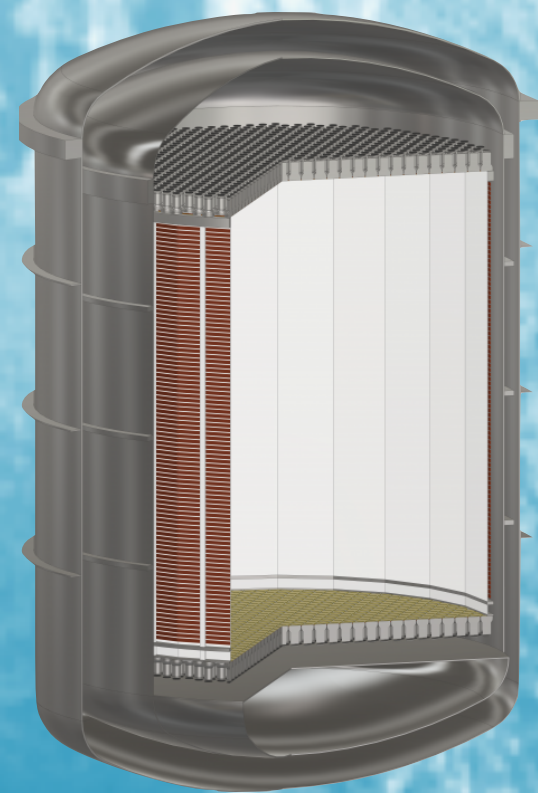
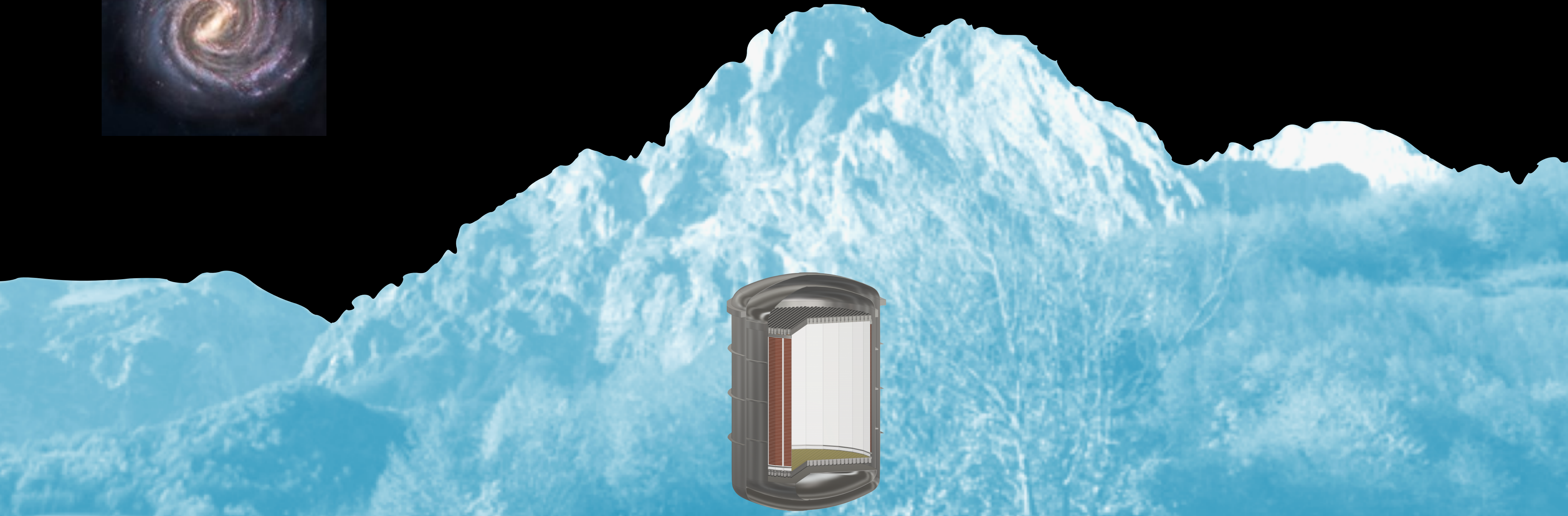
J. Aalbers,^{1,2} K. Abe,^{3,4} V. Aerne,⁵ F. Agostini,⁶ S. Ahmed Maouloud,⁷ D.S. Akerib,^{1,2} D.Yu. Akimov,⁸ J. Akshat,⁹ A.K. Al Musalhi,¹⁰ F. Alder,¹¹ S.K. Alsum,¹² L. Althueser,¹³ C.S. Amarasinghe,¹⁴ F.D. Amaro,¹⁵ A. Ames,^{1,2} T.J. Anderson,^{1,2} B. Andrieu,⁷ N. Angelides,¹⁶ E. Angelino,¹⁷ J. Angevaere,¹⁸ V.C. Antochi,¹⁹ D. Antón Martín,²⁰ B. Antunovic,^{21,22} E. Aprile,²³ H.M. Araújo,¹⁶ J.E. Armstrong,²⁴ F. Arneodo,²⁵ M. Arthurs,¹⁴ P. Asadi,²⁶ S. Baek,²⁷ X. Bai,²⁸ D. Bajpai,²⁹ A. Baker,¹⁶ J. Balajthy,³⁰ S. Balashov,³¹ M. Balzer,³² A. Bandyopadhyay,³³ J. Bang,³⁴ E. Barberio,³⁵ J.W. Bargemann,³⁶ L. Baudis,⁵ D. Bauer,¹⁶ D. Baur,³⁷ A. Baxter,³⁸ A.L. Baxter,⁹ M. Bazyk,³⁹ K. Beattie,⁴⁰ J. Behrens,⁴¹ N.F. Bell,³⁵ L. Bellagamba,⁶ P. Beltrame,⁴² M. Benabderrahmane,²⁵ E.P. Bernard,^{43,40} G.F. Bertone,¹⁸ P. Bhattacharjee,⁴⁴ A. Bhatti,²⁴ A. Biekert,^{43,40} T.P. Biesiadzinski,^{1,2} A.R. Binau,⁹ R. Biondi,⁴⁵ Y. Biondi,⁵ H.J. Birch,¹⁴ F. Bishara,⁴⁶ A. Bismark,⁵ C. Blanco,^{47,19} G.M. Blockinger,⁴⁸ E. Bodnia,³⁶ C. Boehm,⁴⁹ A.I. Bolozdynya,⁸ P.D. Bolton,¹¹ S. Bottaro,^{50,51} C. Bourgeois,⁵² B. Boxer,³⁰ P. Brás,⁵³ A. Breskin,⁵⁴ P.A. Breur,¹⁸ C.A.J. Brew,³¹ J. Brod,⁵⁵ E. Brookes,¹⁸ A. Brown,³⁷ E. Brown,⁵⁶ S. Bruenner,¹⁸ G. Bruno,³⁹ R. Budnik,⁵⁴ T.K. Bui,⁴ S. Burdin,³⁸ S. Buse,⁵ J.K. Busenitz,²⁹ D. Buttazzo,⁵¹ M. Buuck,^{1,2} A. Buzulutskov,^{57,58} R. Cabrera,⁵³ C. Cai,⁵⁹ D. Cai,³⁹ C. Capelli,⁵ J.M.R. Cardoso,¹⁵ M.C. Carmona-Benitez,⁶⁰ M. Cascella,¹¹ R. Catena,⁶¹ S. Chakraborty,⁶² C. Chan,³⁴ S. Chang,⁶³ A. Chauvin,⁶⁴ A. Chawla,⁶⁵ H. Chen,⁴⁰ V. Chepel,⁵³ N.I. Chott,²⁸ D. Cichon,⁶⁶ A. Cimental Chavez,⁵ B. Cimmino,⁶⁷ M. Clark,⁹ R.T. Co,⁶⁸ A.P. Colijn,¹⁸ J. Conrad,¹⁹ M.V. Converse,⁶⁹ M. Costa,^{50,51} A. Cottle,^{10,70} G. Cox,⁶⁰ O. Creaner,⁷¹ J.J. Cuenca Garcia,⁴¹ J.P. Cussonneau,³⁹ J.E. Cutter,³⁰ C.E. Dahl,^{72,70} V. D'Andrea,⁷³ A. David,¹¹ M.P. Decowski,¹⁸ J.B. Dent,⁷⁴

4 Mar 2022



Dark Matter

- WIMPs (sub-GeV - TeV scale)
- ALPs/dark photons (keV scale)



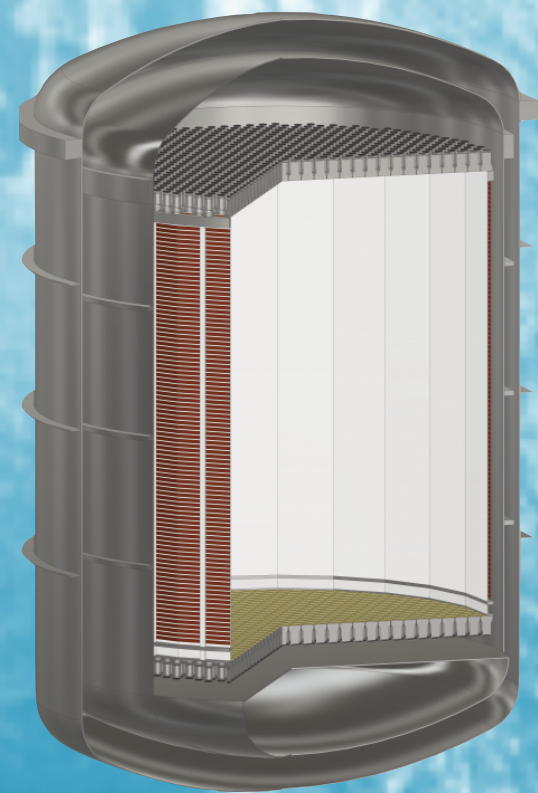
Supernova Neutrinos

Early alert
Multi-messenger



Dark Matter

WIMPs (sub-GeV - TeV scale)
ALPs/dark photons (keV scale)



Supernova Neutrinos

Early alert
Multi-messenger



Solar Neutrinos

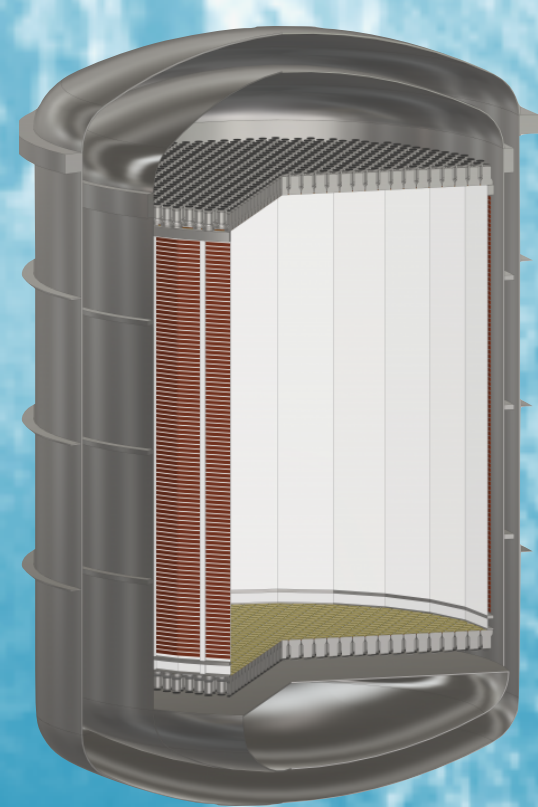
pp neutrino flux, $\sin^2\theta_w$

Solar Axions



Dark Matter

WIMPs (sub-GeV - TeV scale)
ALPs/dark photons (keV scale)



Supernova Neutrinos

Early alert
Multi-messenger



Solar Neutrinos

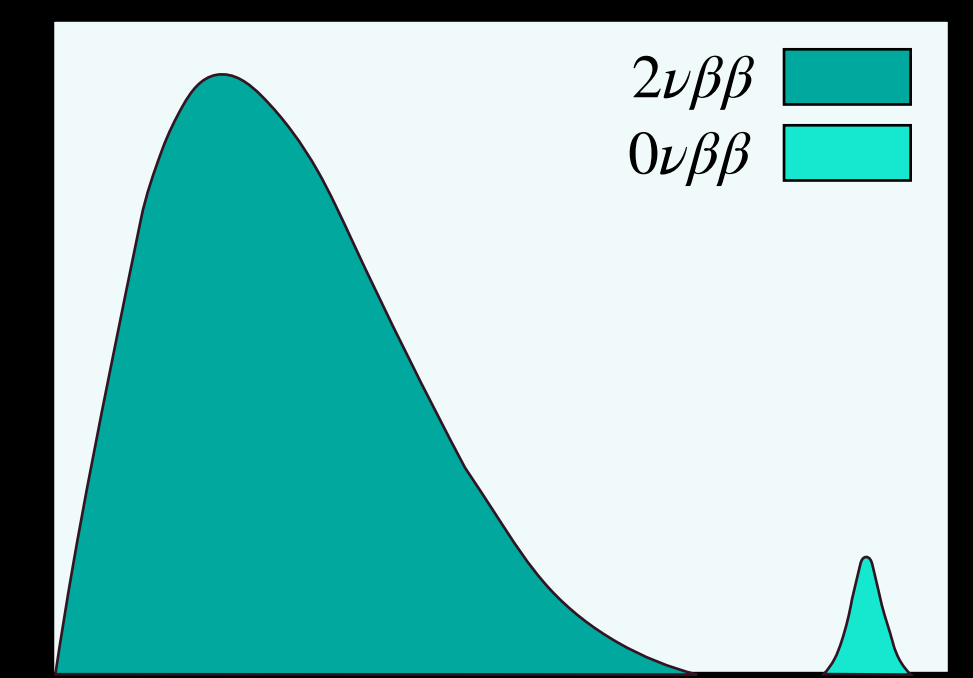
pp neutrino flux, $\sin^2\theta_w$

Solar Axions



Fundamental Physics

Neutrinoless double beta decay of ^{136}Xe
Rare decays

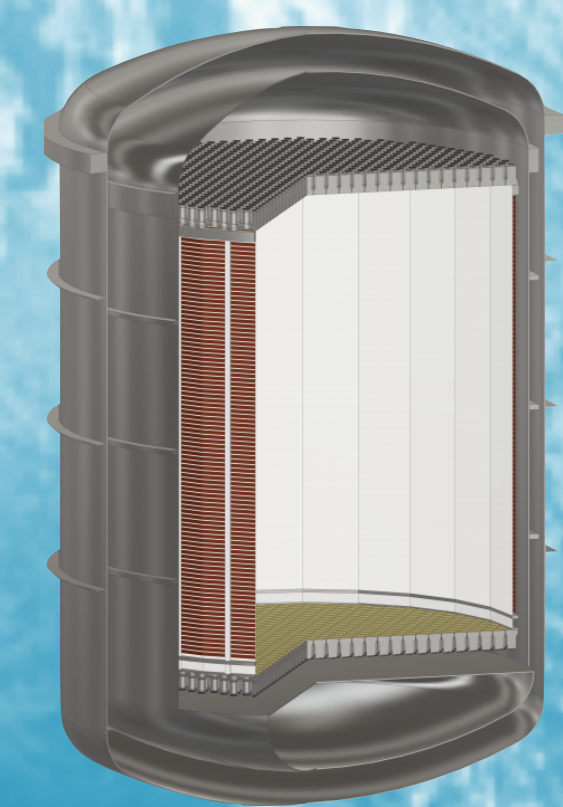


Dark Matter

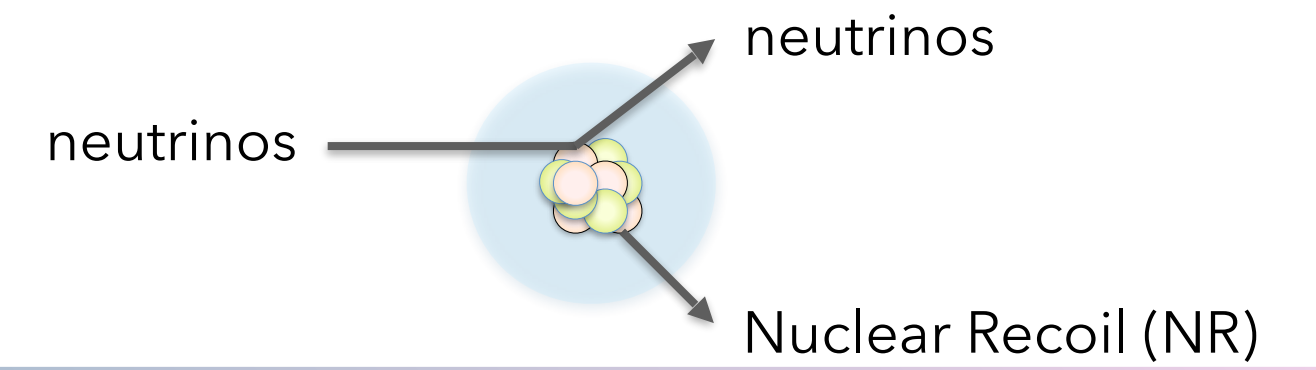
WIMPs (sub-GeV - TeV scale)
ALPs/dark photons (keV scale)



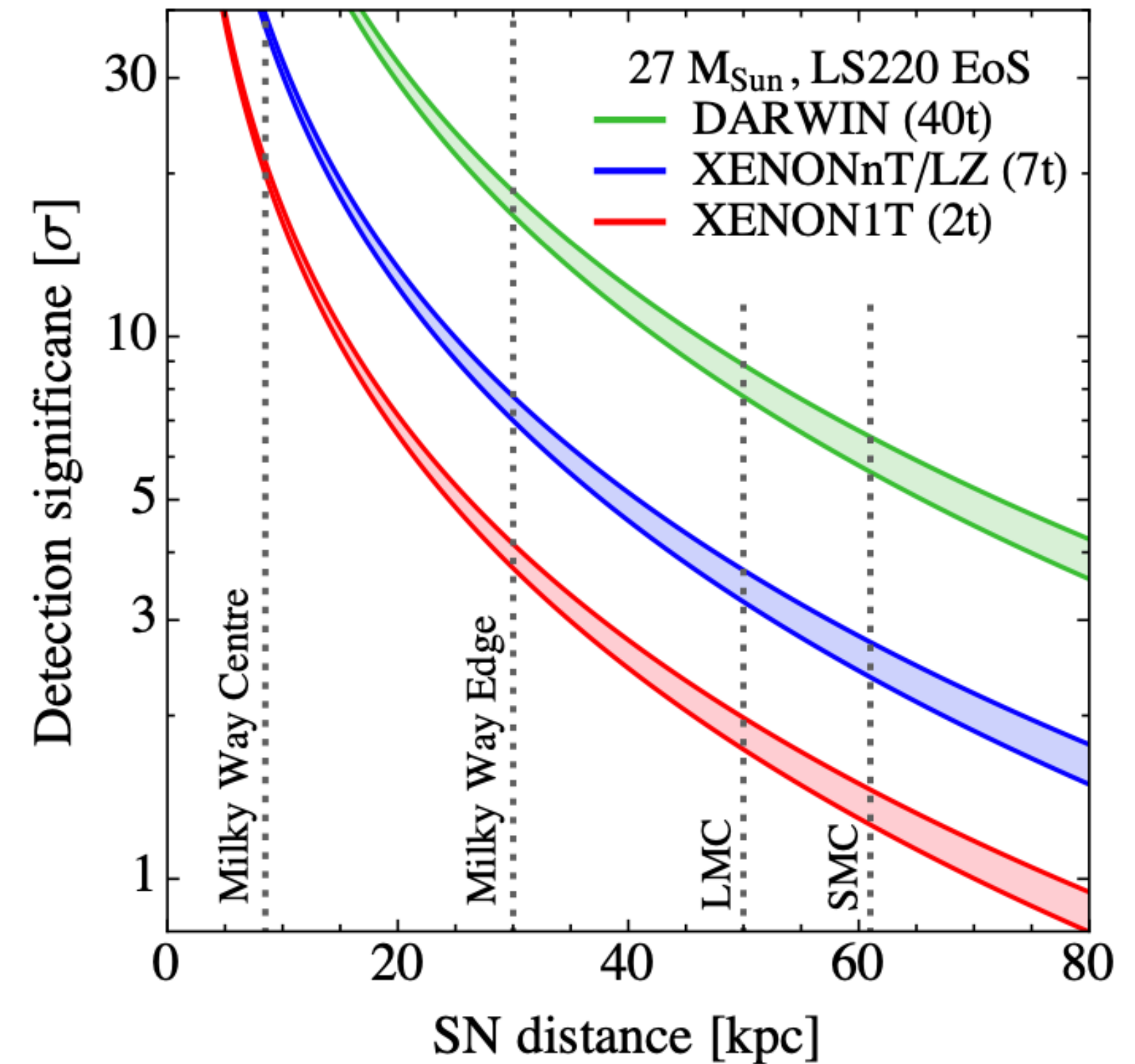
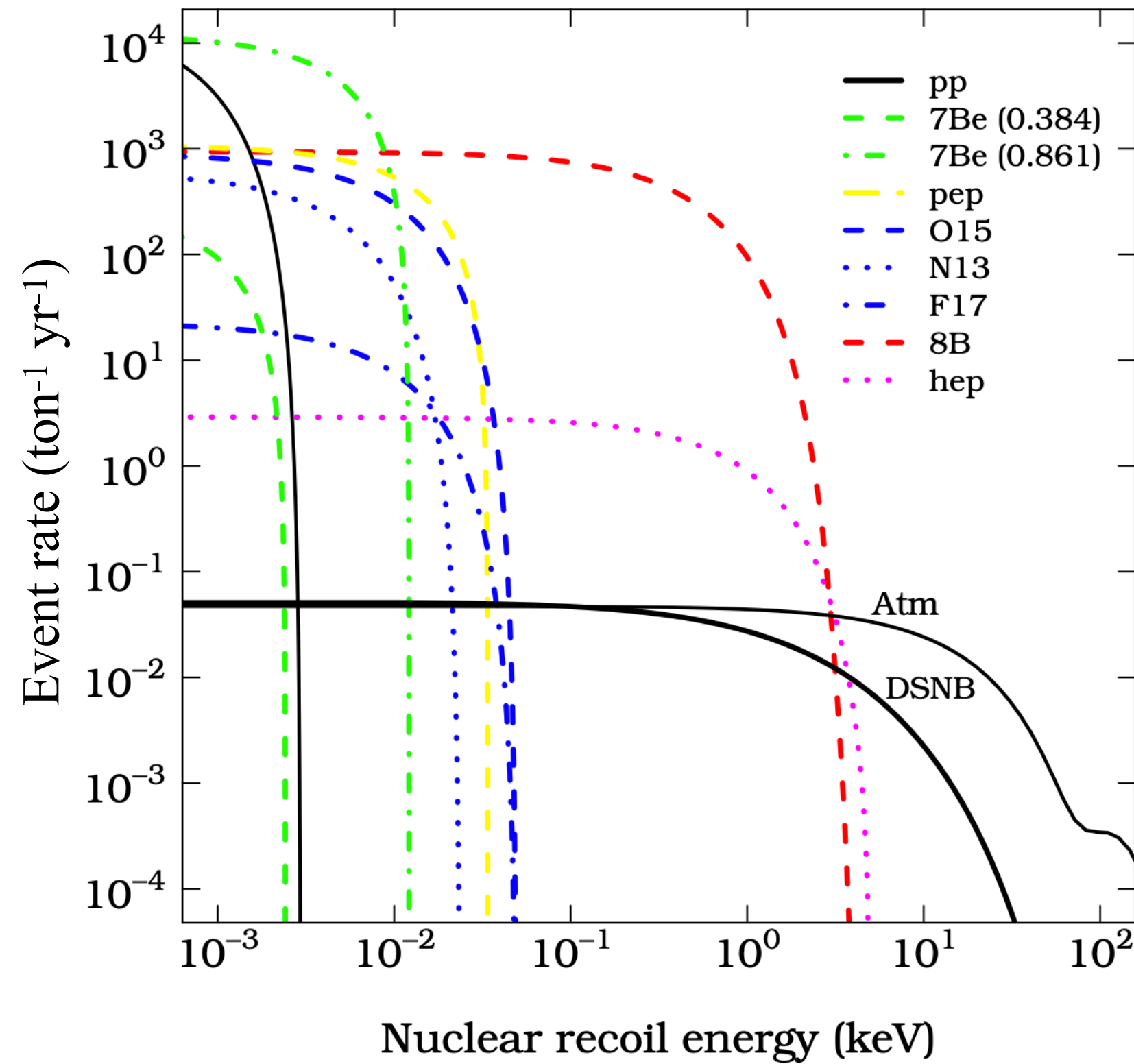
Detector
as source



Solar and Supernova neutrinos



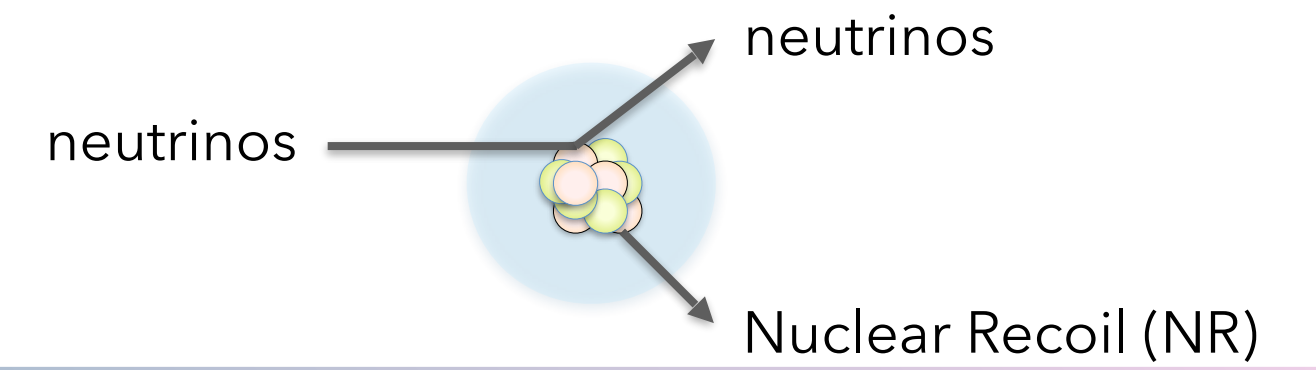
Coherent elastic neutrino-nucleus scattering ($CE\nu NS$)



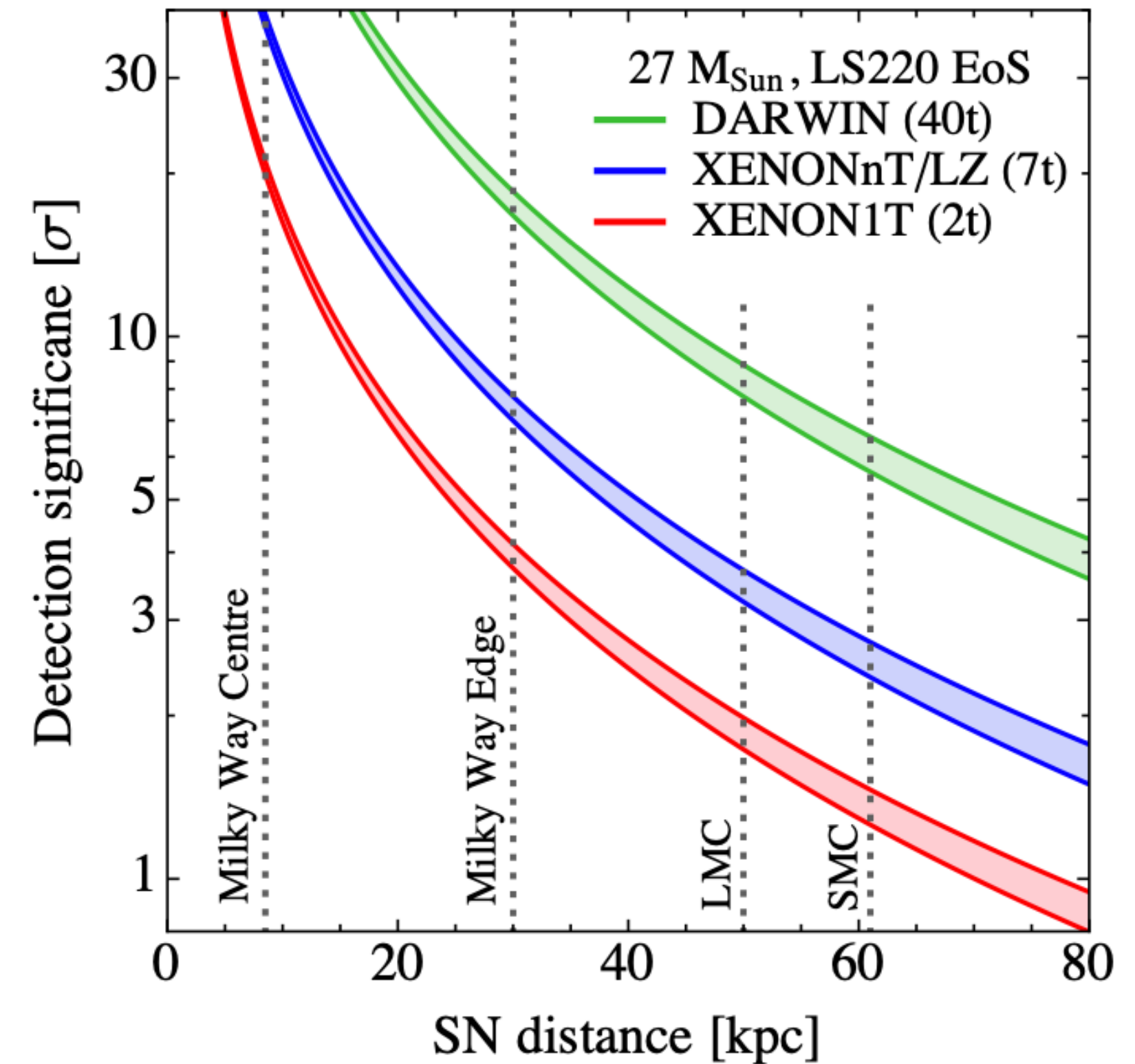
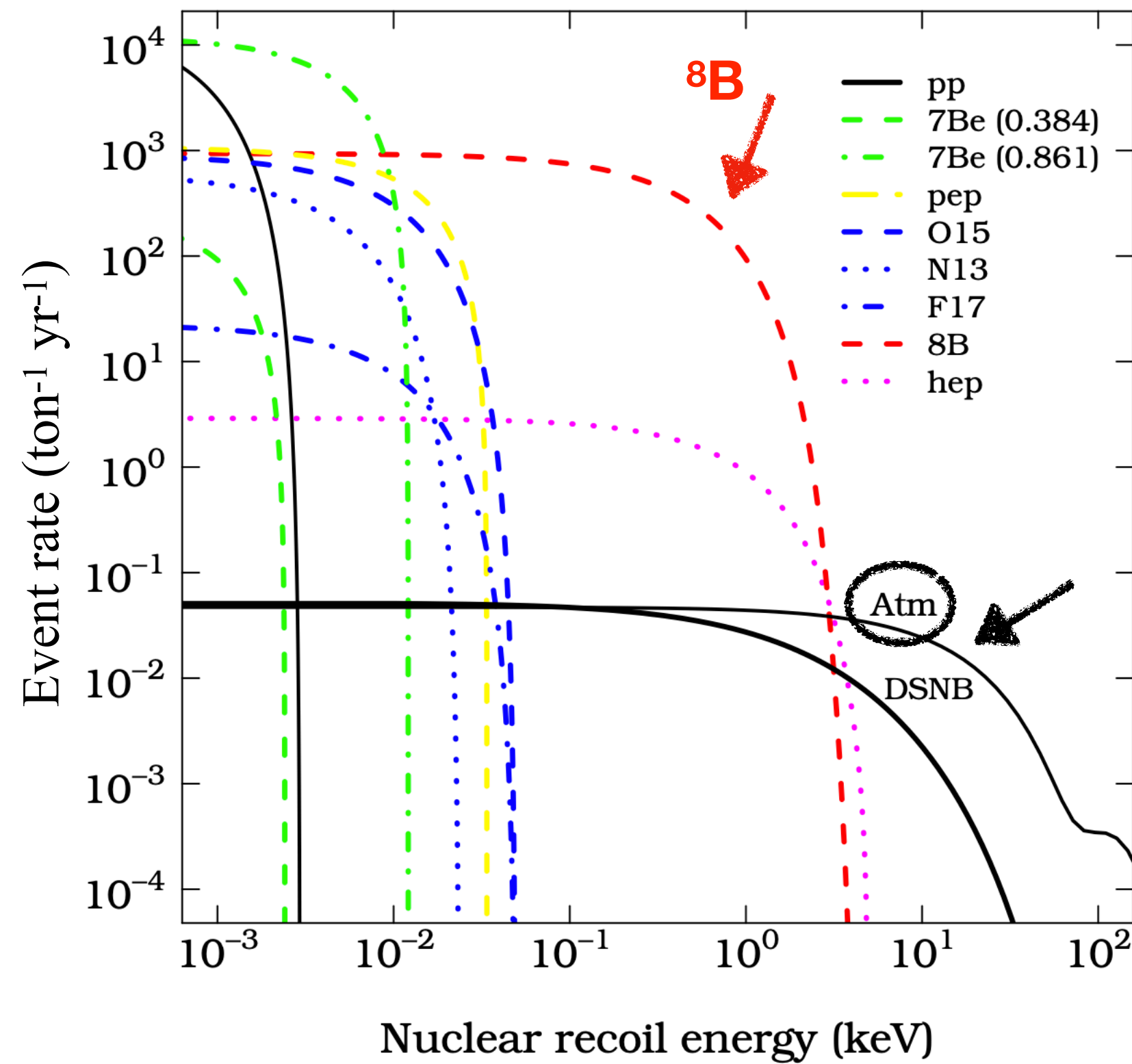
- ▶ Detect solar and atmospheric neutrinos via $CE\nu NS$ interactions

- ▶ Flavour-insensitive detection of supernovae neutrinos
- ▶ Participation in SNEWS network

Solar and Supernova neutrinos



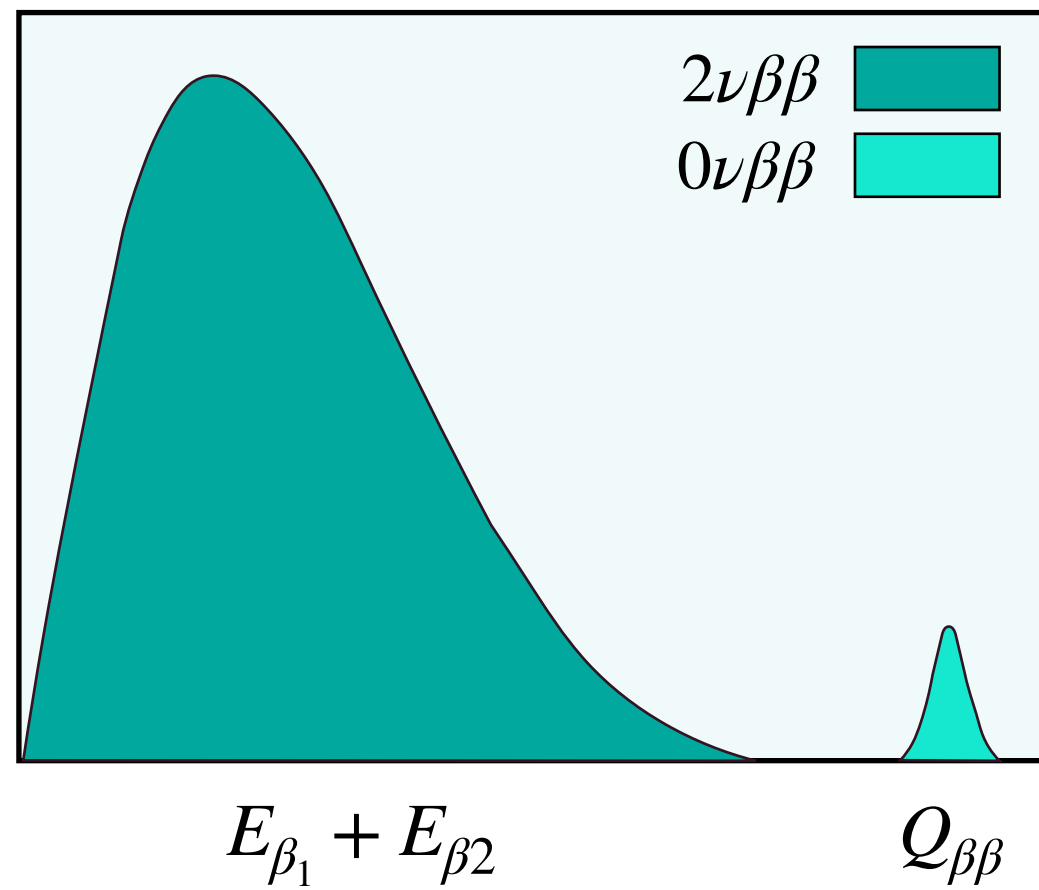
Coherent elastic neutrino-nucleus scattering ($\text{CE}\nu\text{NS}$)



- ▶ Detect solar and atmospheric neutrinos via $\text{CE}\nu\text{NS}$ interactions

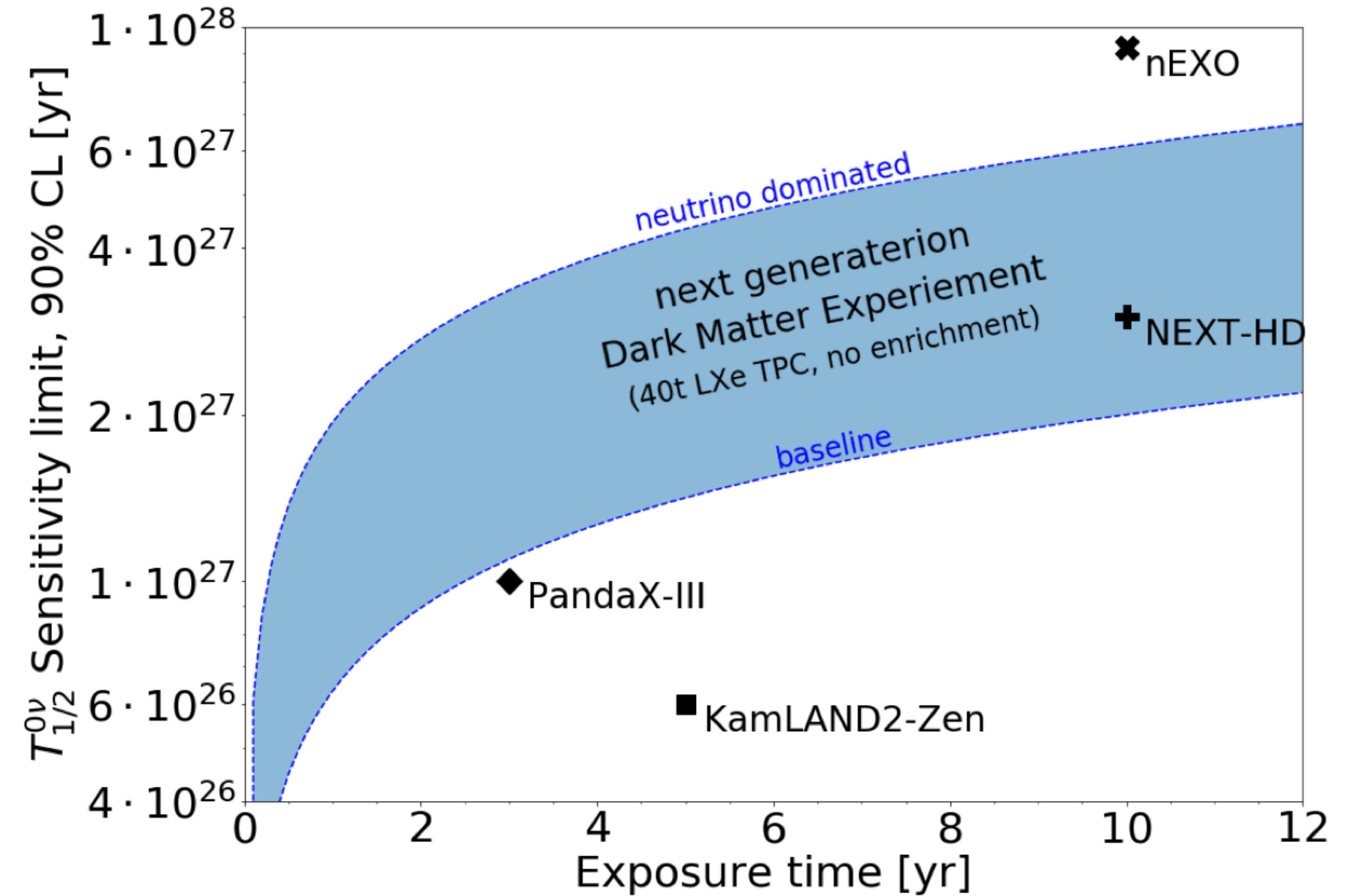
- ▶ Flavour-insensitive detection of supernovae neutrinos
- ▶ Participation in SNEWS network

DARWIN/G3 Science Reach



- Test of lepton number conservation
- Majorana neutrino nature

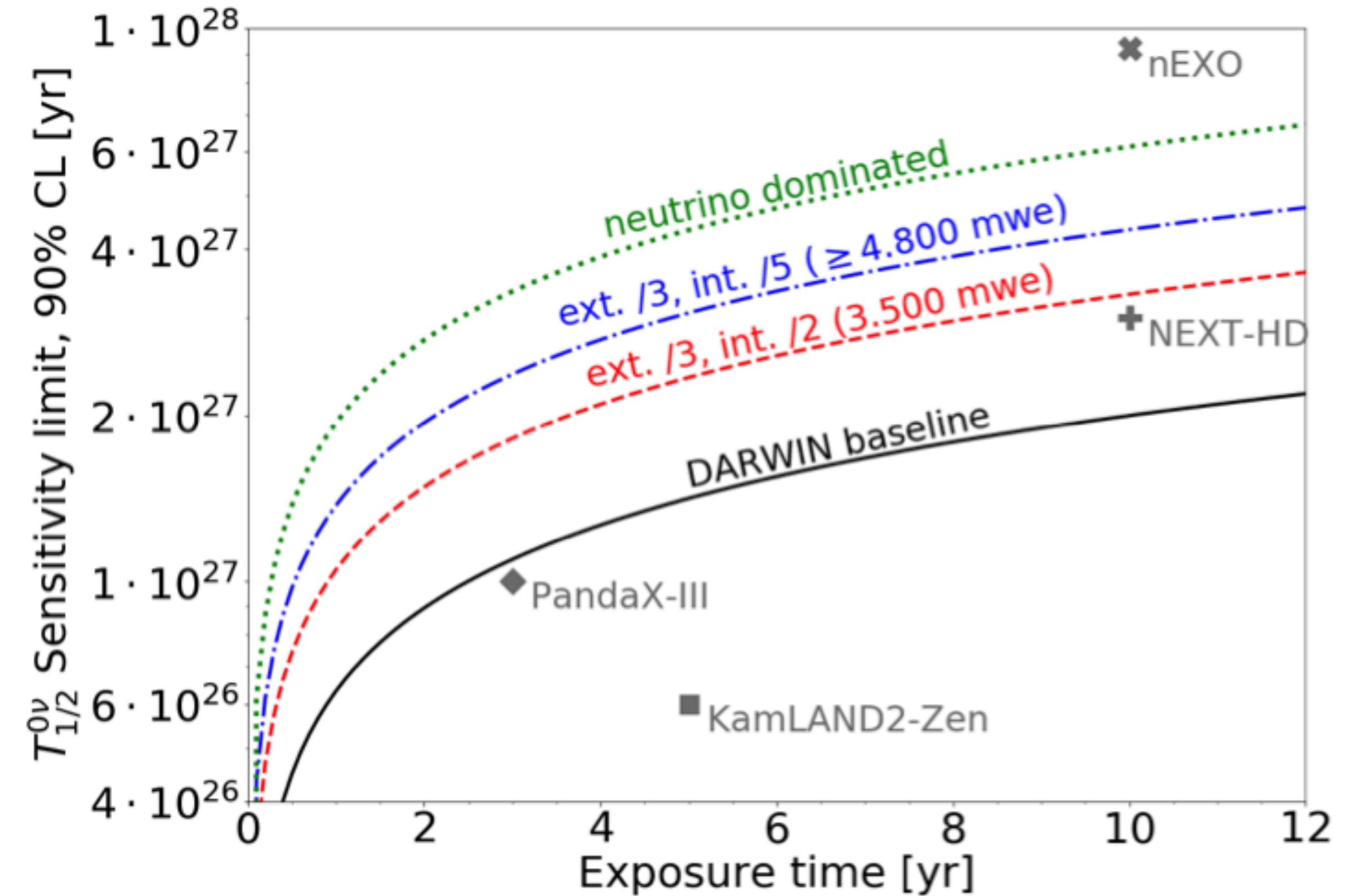
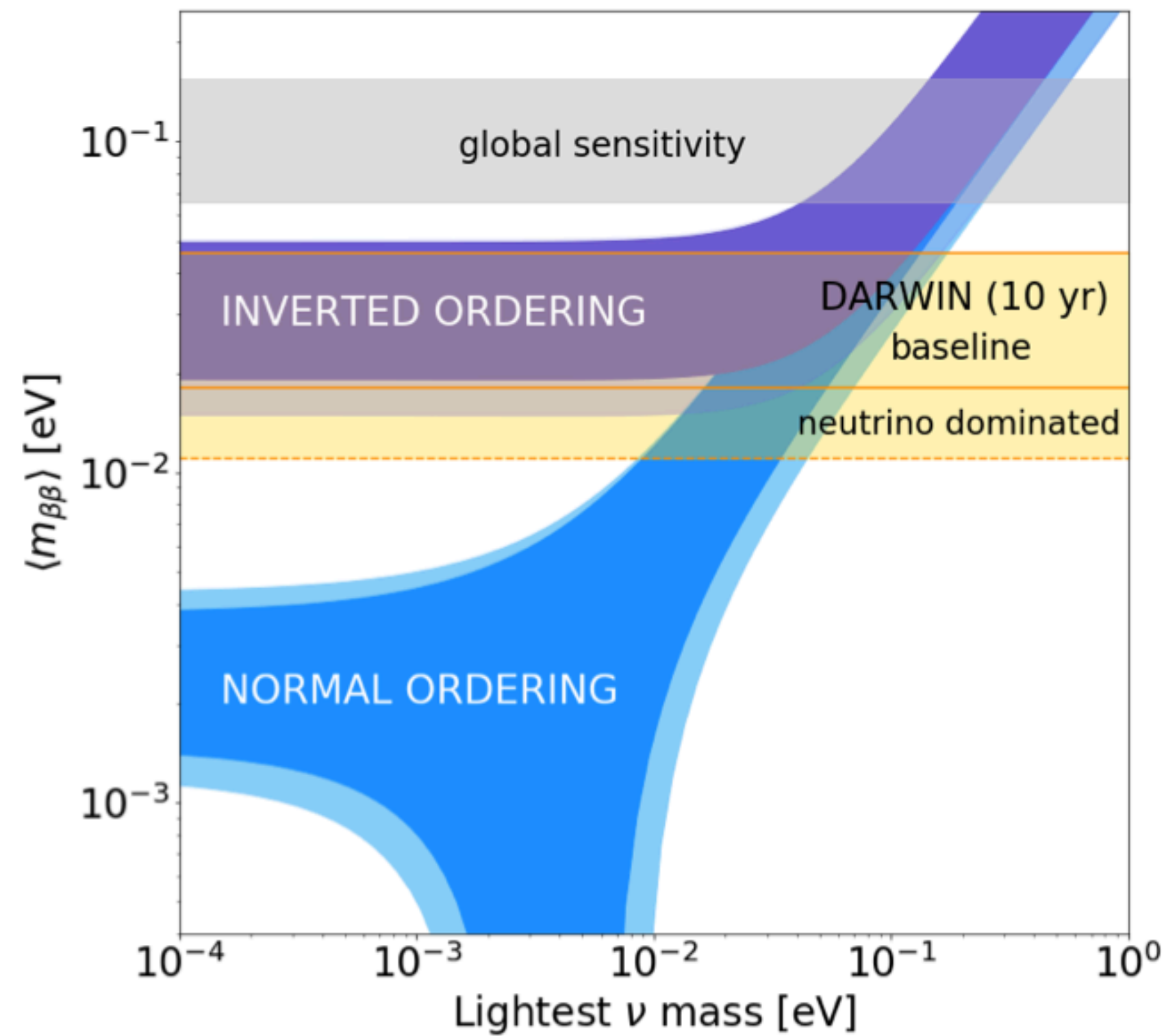
- ▶ ^{136}Xe is a neutrinoless double beta decay candidate (8.9% natural abundance ~ 3.6 t in 40 t DARWIN)
- ▶ $Q_{\beta\beta}$ peak at 2.458 MeV with 0.8% energy resolution (XENON, EPJ C 80 (2020) 8).
- ▶ Half-life measurement (constraint); can also probe the mass hierarchy



$$T_{1/2}^{0\nu} \propto \sqrt{\frac{Mt}{B}}$$

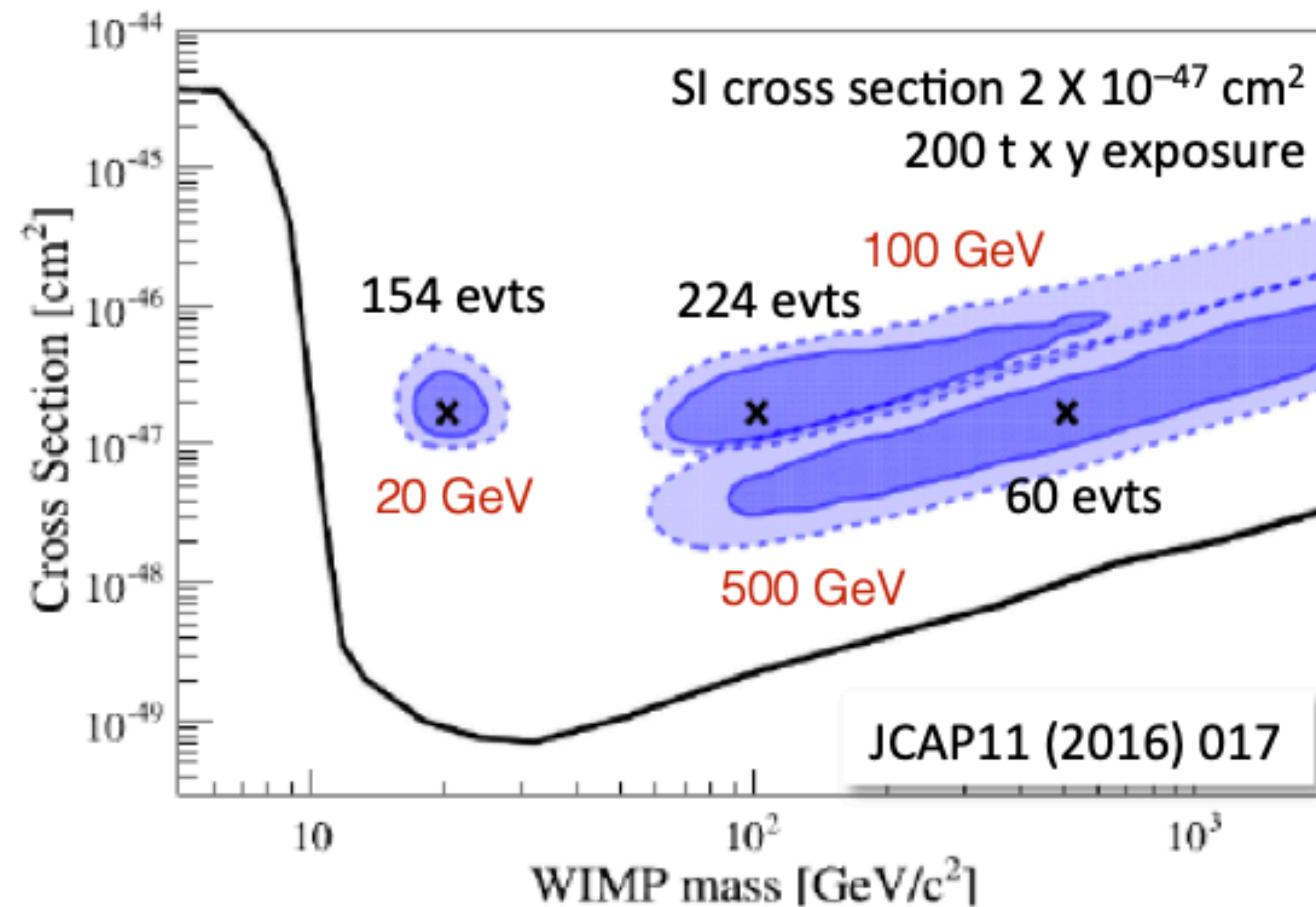
Projected sensitivity
 $T_{1/2} = 2.4 \times 10^{27}$ yrs in 50 t yr

DARWIN/G3 Science Reach

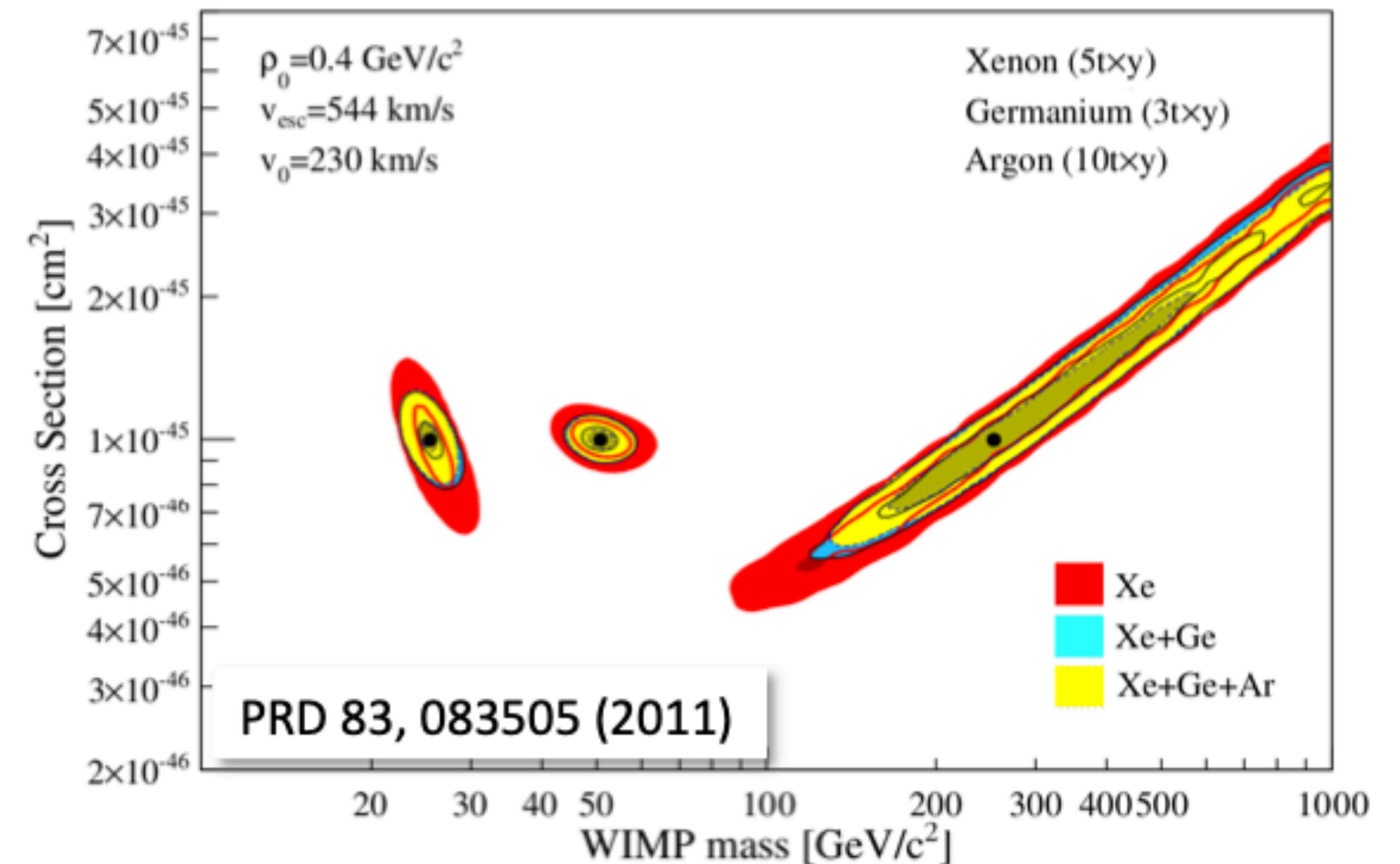


- ▶ Probe the neutrino mass hierarchy
- ▶ Background rate assumption 0.2 events/(t yr); dominated by materials (fiducial volume dependent), plus cosmogenic ^{137}Xe (site dependent), intrinsic ^{222}Rn , and ^8B solar neutrinos.
- ▶ Active area of R&D aimed at reducing $0\nu\beta\beta$ backgrounds.

WIMP properties



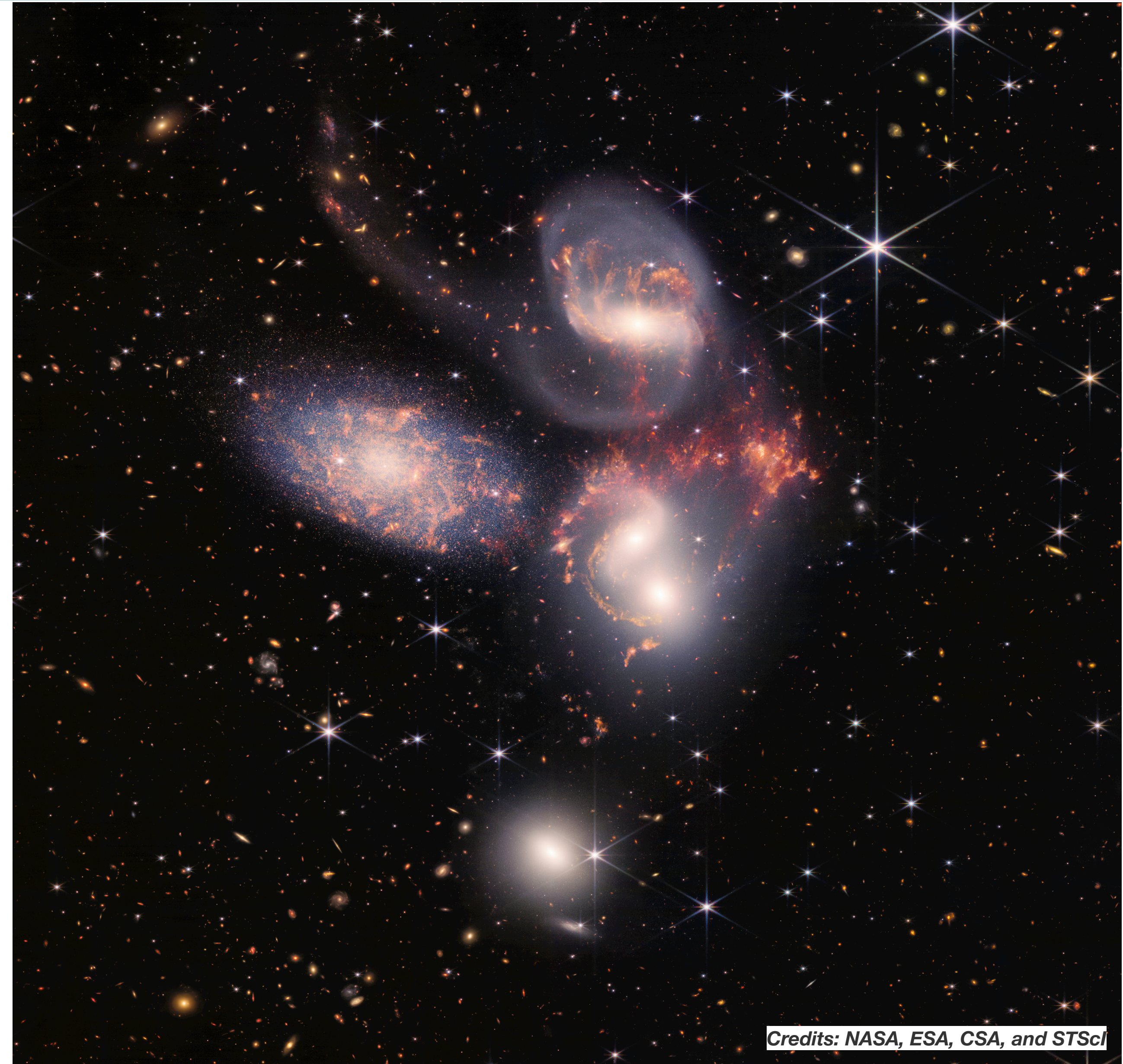
Target complementarity



- ▶ Number of events needed to reconstruct WIMP mass and SI scattering cross section
- ▶ 1 and 2-sigma credibility regions for 20, 100, 500 GeV WIMP masses; marginalized over uncertainties in astrophysical parameters
- ▶ Can constrain up to a few 100 GeV
- ▶ Parameter reconstruction improves when considering detections in other targets.

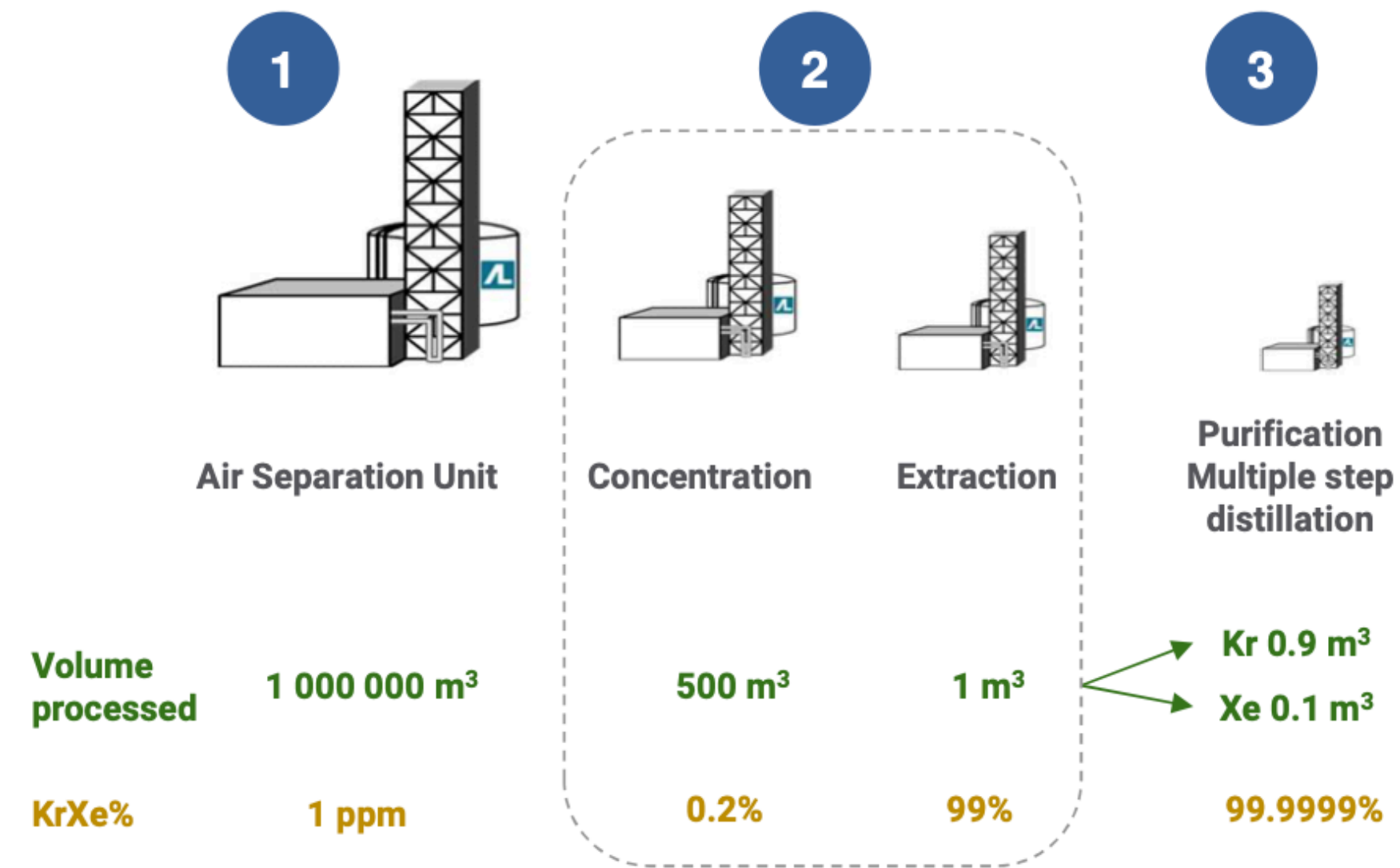
- Xenon and argon noble liquid detectors have lead standard WIMP searches in the GeV-TeV WIMP masses, extending further into the sub-GeV and below range.
- A new generation of multi-ton scale detectors are now taking science data, already with first results.
- The next generation argon (underway) and xenon (R&D phase) are to come online within this decade.
- Experiments driven by standard WIMP searches, have reached exceedingly low backgrounds, thus opening new detection channels.
- New technologies as well as synergies and collaboration will allow to search for WIMPs down to into the neutrino fog.

Thank you for your attention!



XENON availability

- ▶ Xenon abundance **0.087 ppm** in the Earth's atmosphere
- ▶ Extraction from air requires multiple steps
- ▶ Electronics demand expected to continue until 2030
- ▶ Space demand is booming (recent developments + private investment)
- ▶ Long-term supply may be affected by geopolitical crises



Key facts:

- Only very large air separation units (ASUs) can justify extraction of Kr and Xe
- Even large ASUs can only produce a small amount of Kr and Xe
- Increasing Kr/Xe capacity requires investments in very large ASUs which are Kr/Xe ready

⇒ **Production of Kr and Xe is managed globally in order to maximize reliability of supply**

> **Such demand provoked a shortage situation that is meant to continue over the next few years despite the different investments made by industrial players.**

Solar neutrinos

