# Future Dark Matter Experiments with Noble Liquids

Michelle Galloway
University of Zurich

*Identification of Dark Matter*
*Technical University of Vienna*
*19 July 2022*

# WIMP direct detection landscape

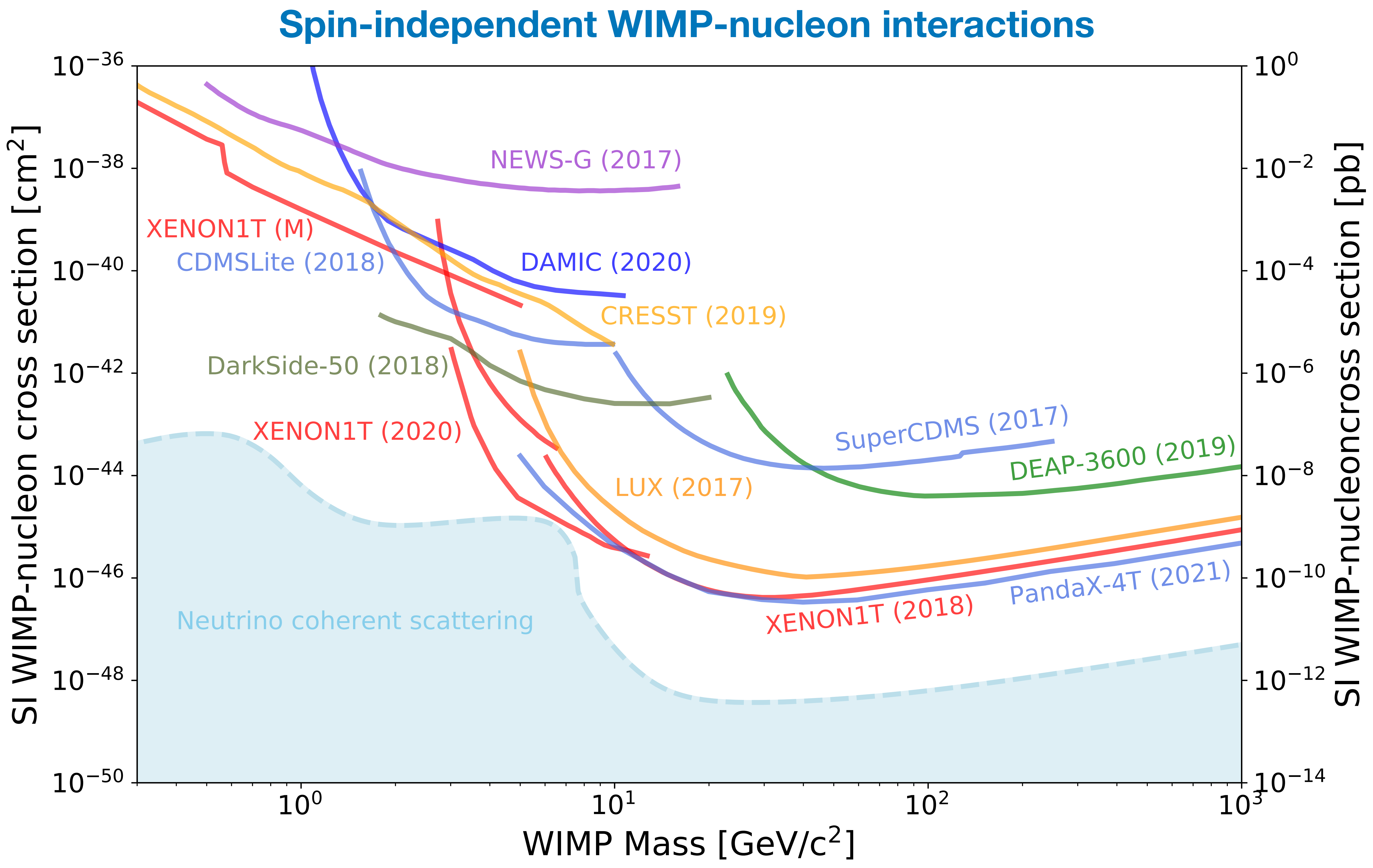


Figure adapted from P.A. Zyla et al. (Particle Data Group) (2020)

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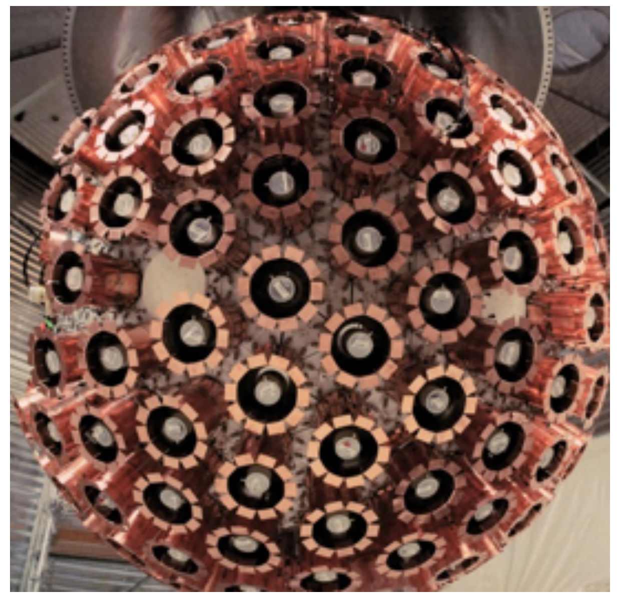
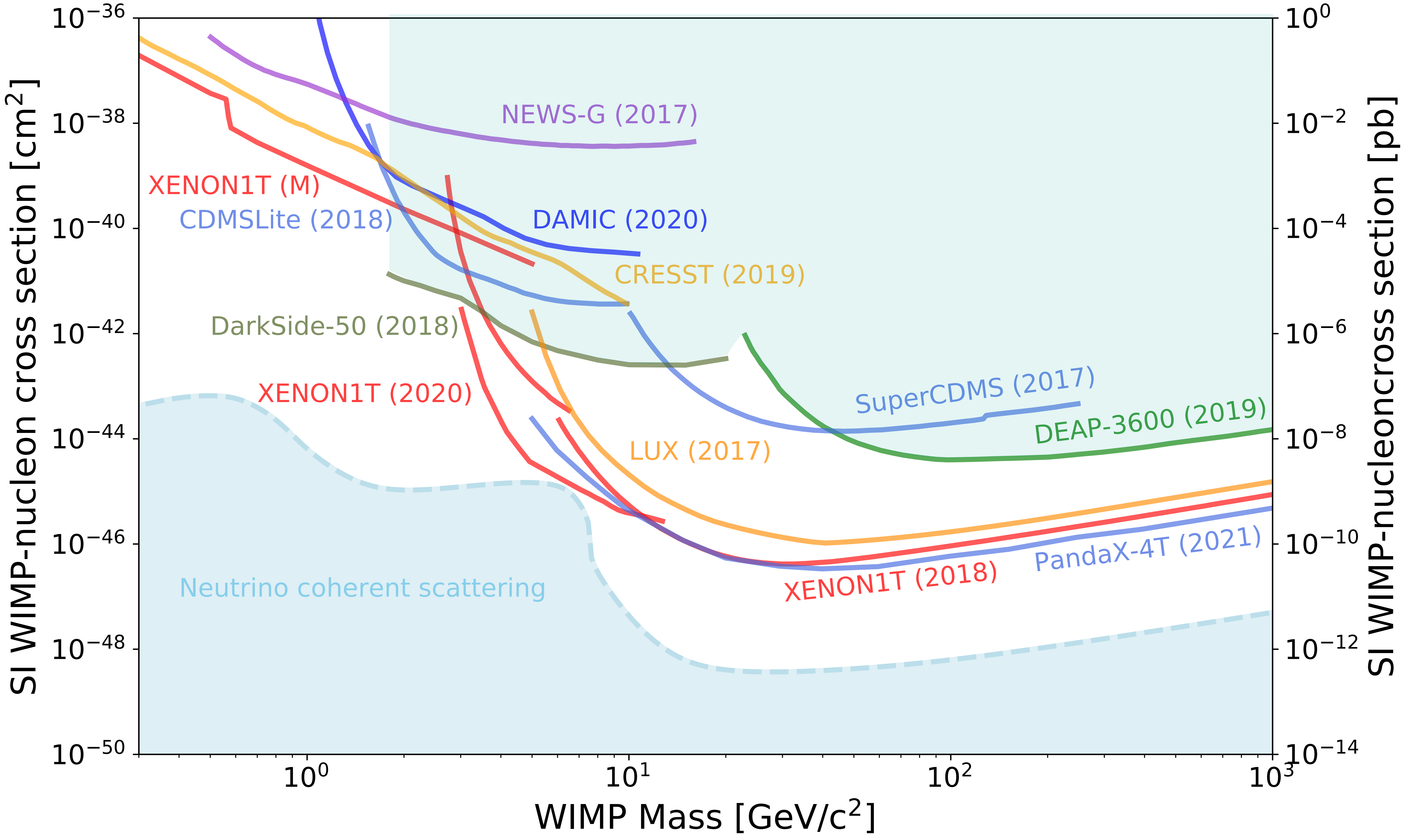


**DEAP-3600**
**3300 kg**
**SNOLAB**
**2016 - present**

**DarkSide-50**
**46 kg**
**LNGS**
**2013 - present**

**Spin-independent WIMP-nucleon interactions**

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**Liquid argon (LAr) experiments**

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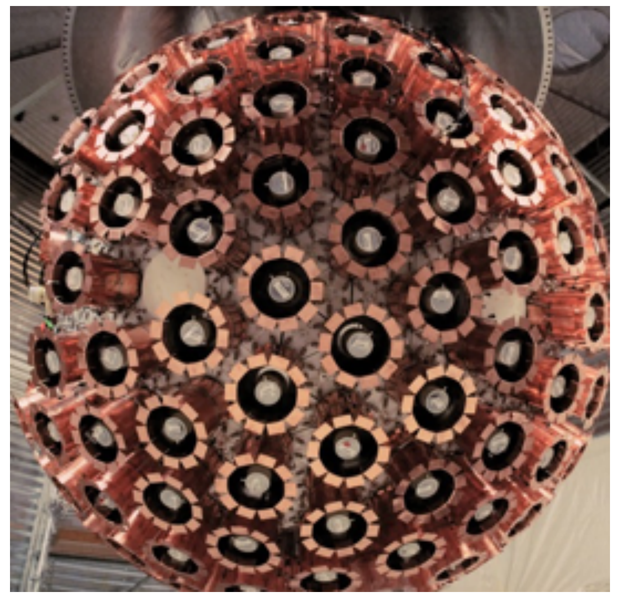

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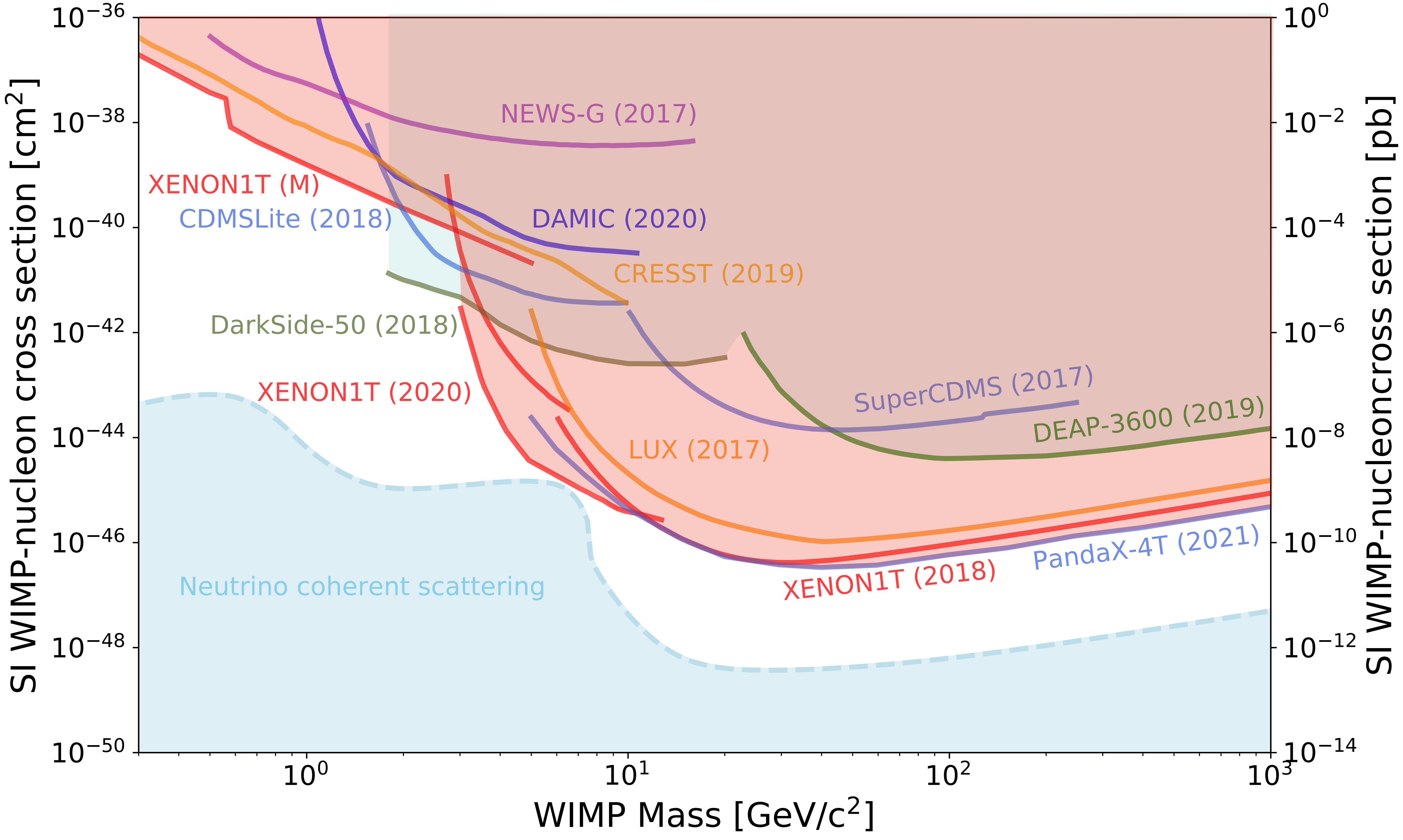
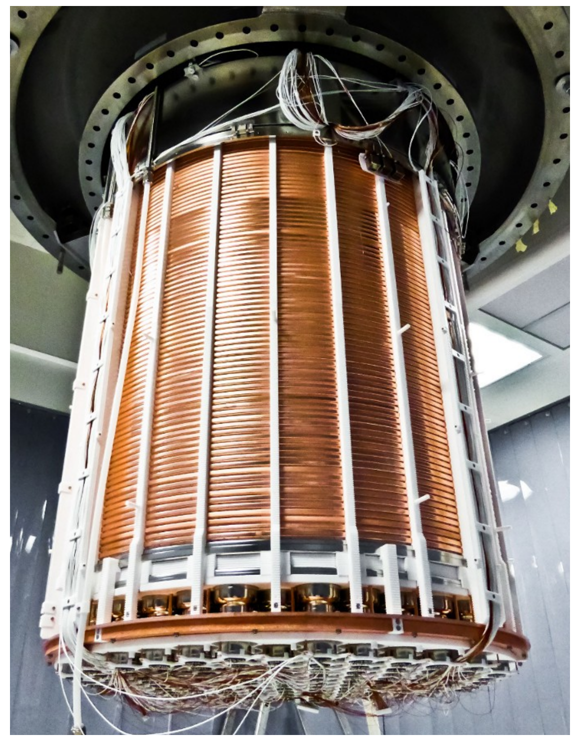



Figure adapted from P.A. Zyla et al. (Particle Data Group) (2020)

**Liquid argon (LAr) experiments**

**Liquid xenon (LXe) experiments**



**XENON1T**
**2 tonne**
**LNGS**
**2017-2019**

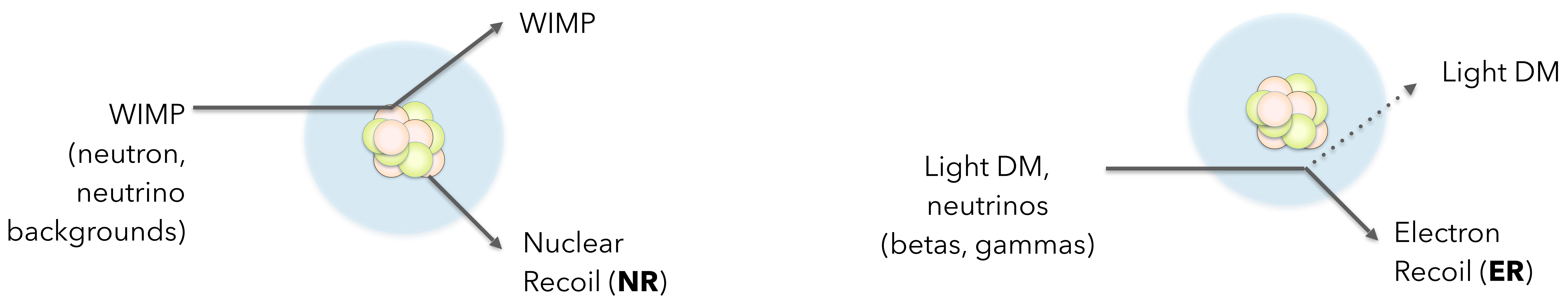
**LUX**
**250 kg**
**SURF**
**2013-2016**

**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



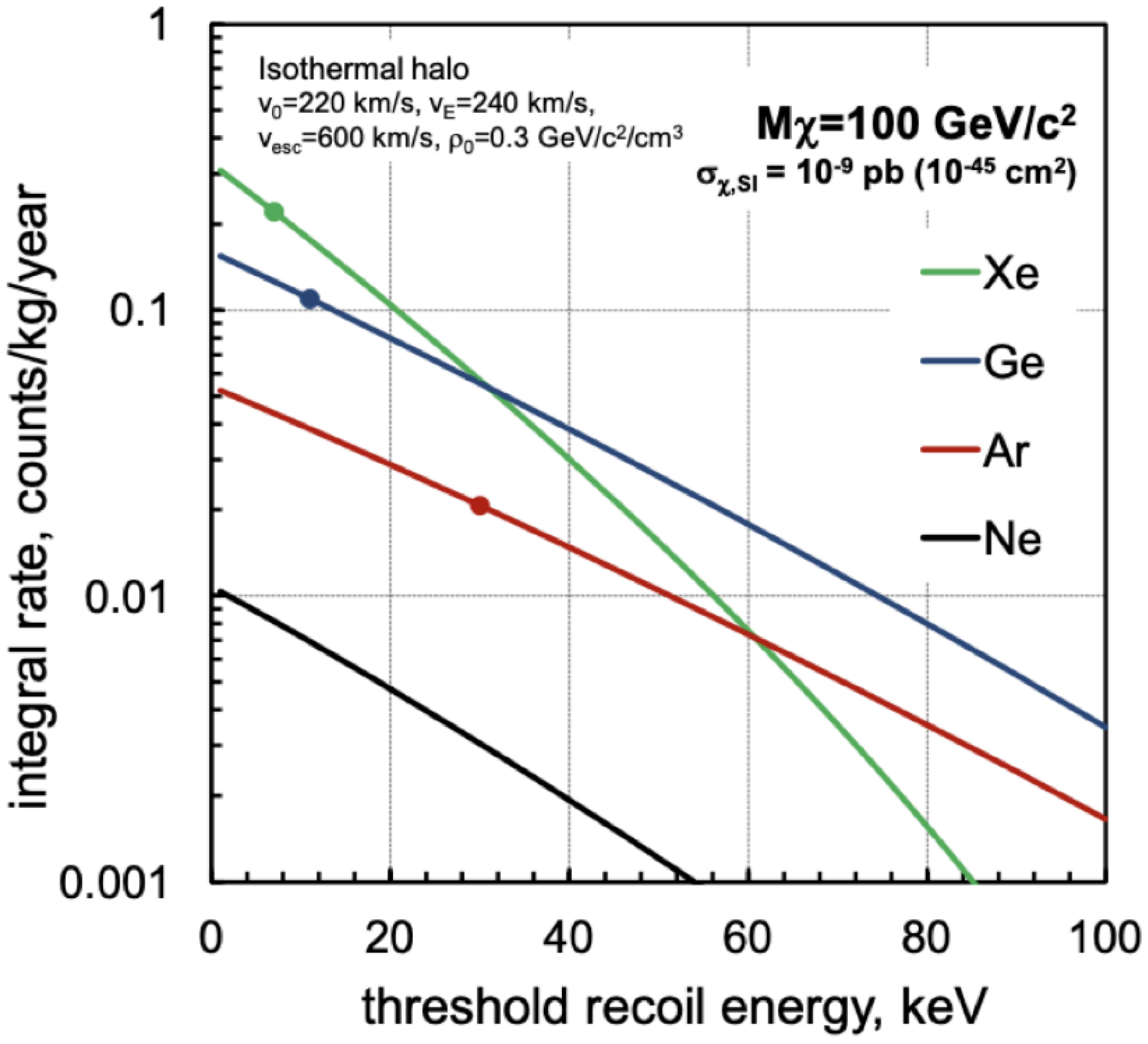
**Kinematically favors GeV to TeV DM masses**

- **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

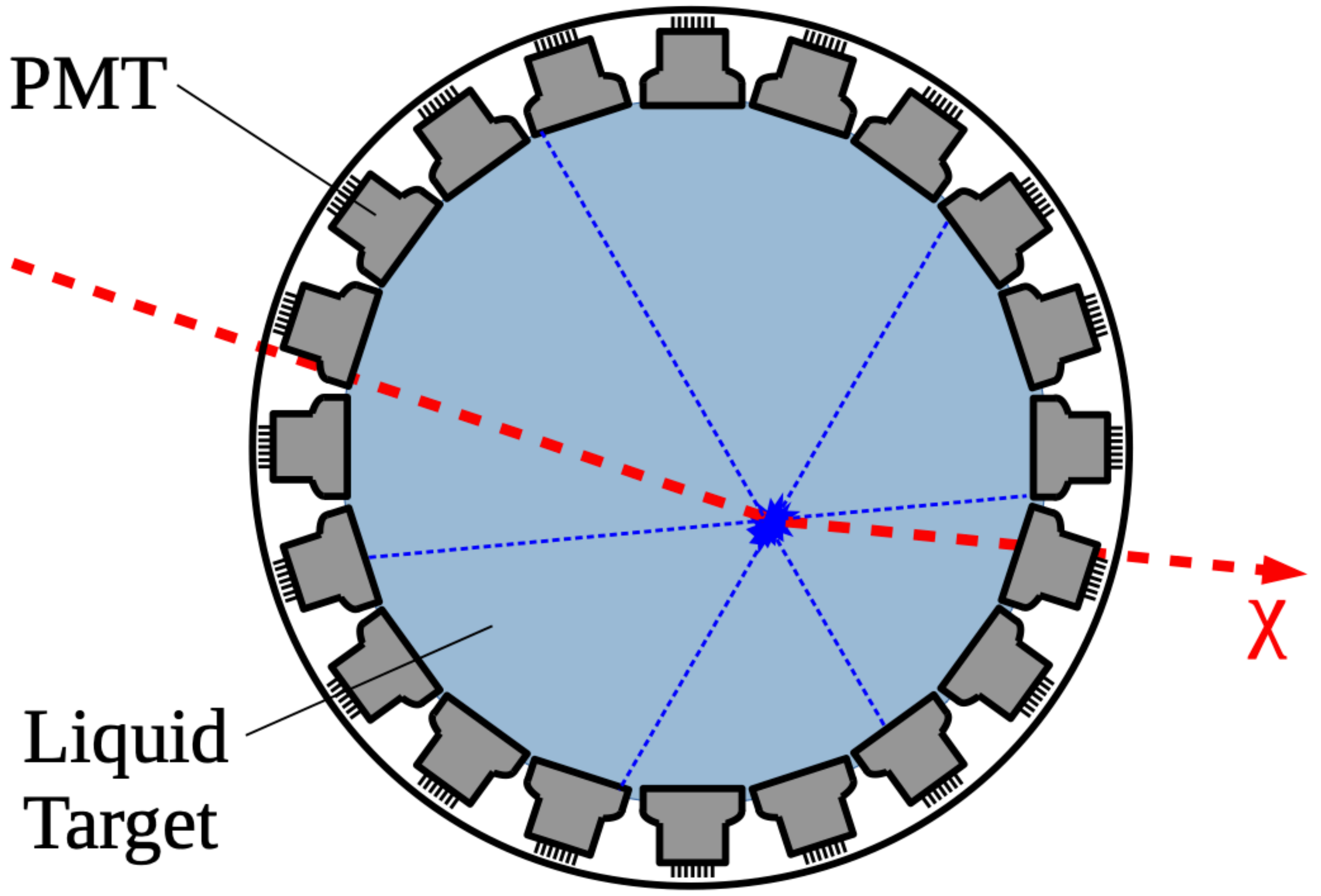



V. Chepel and H. Araujo, JINST 8(04), R04001 (2013)

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

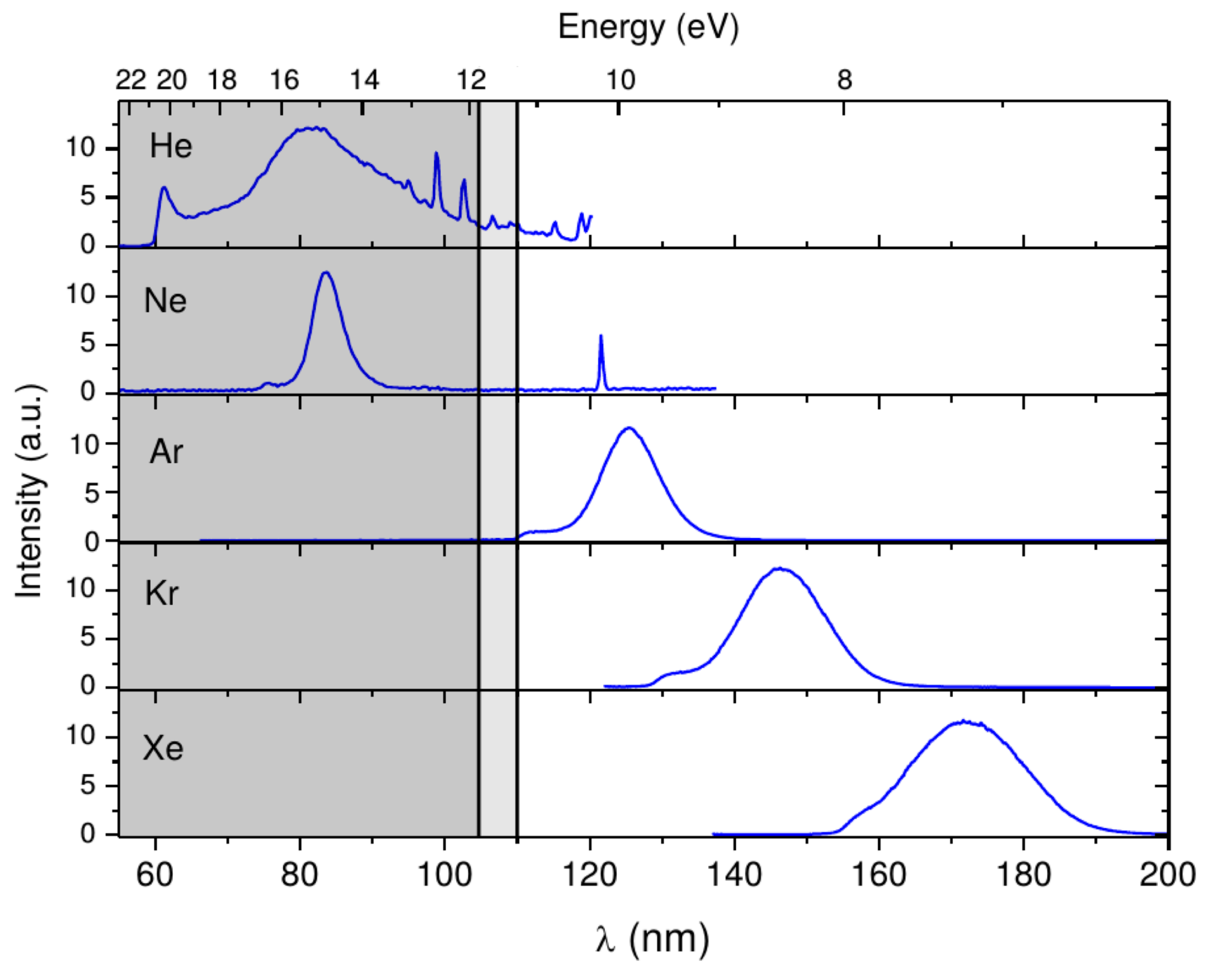
# Noble liquid detection: single phase



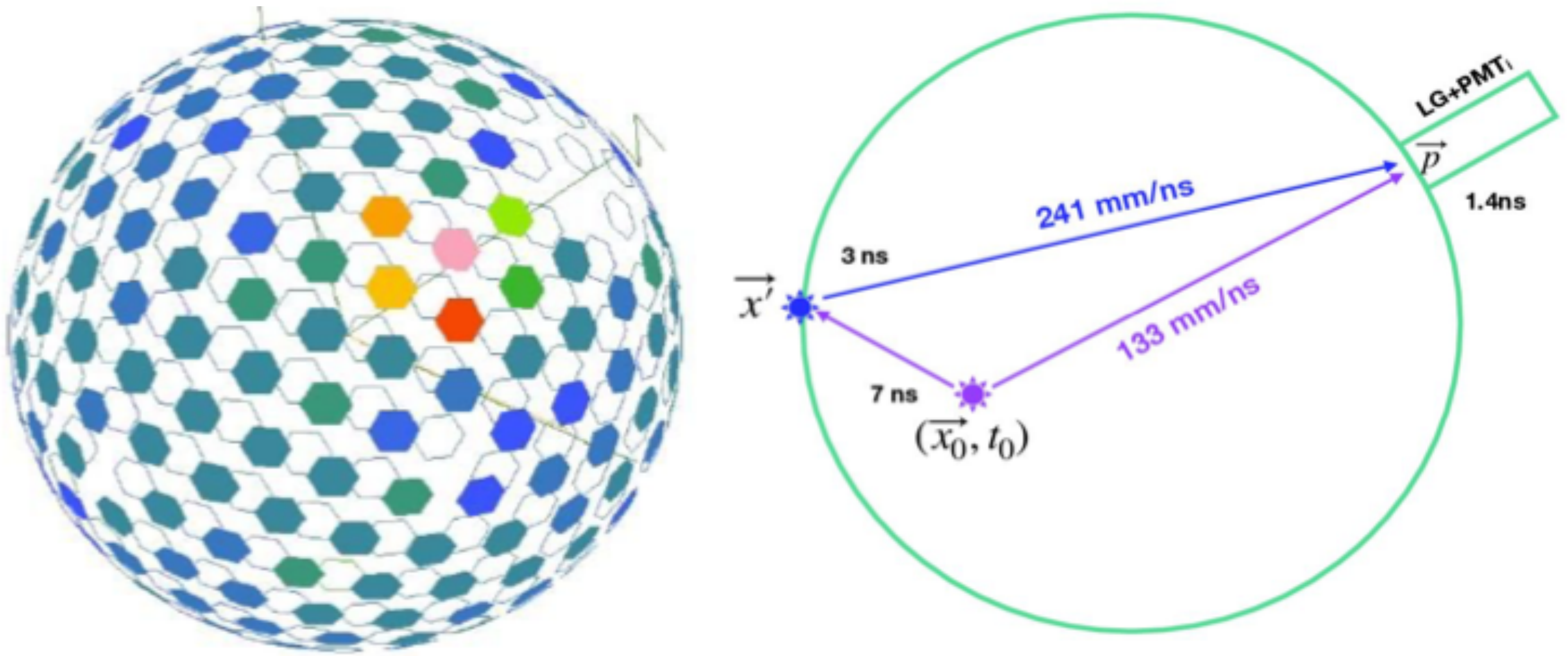



Single-phase Spherical Detector

- 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)

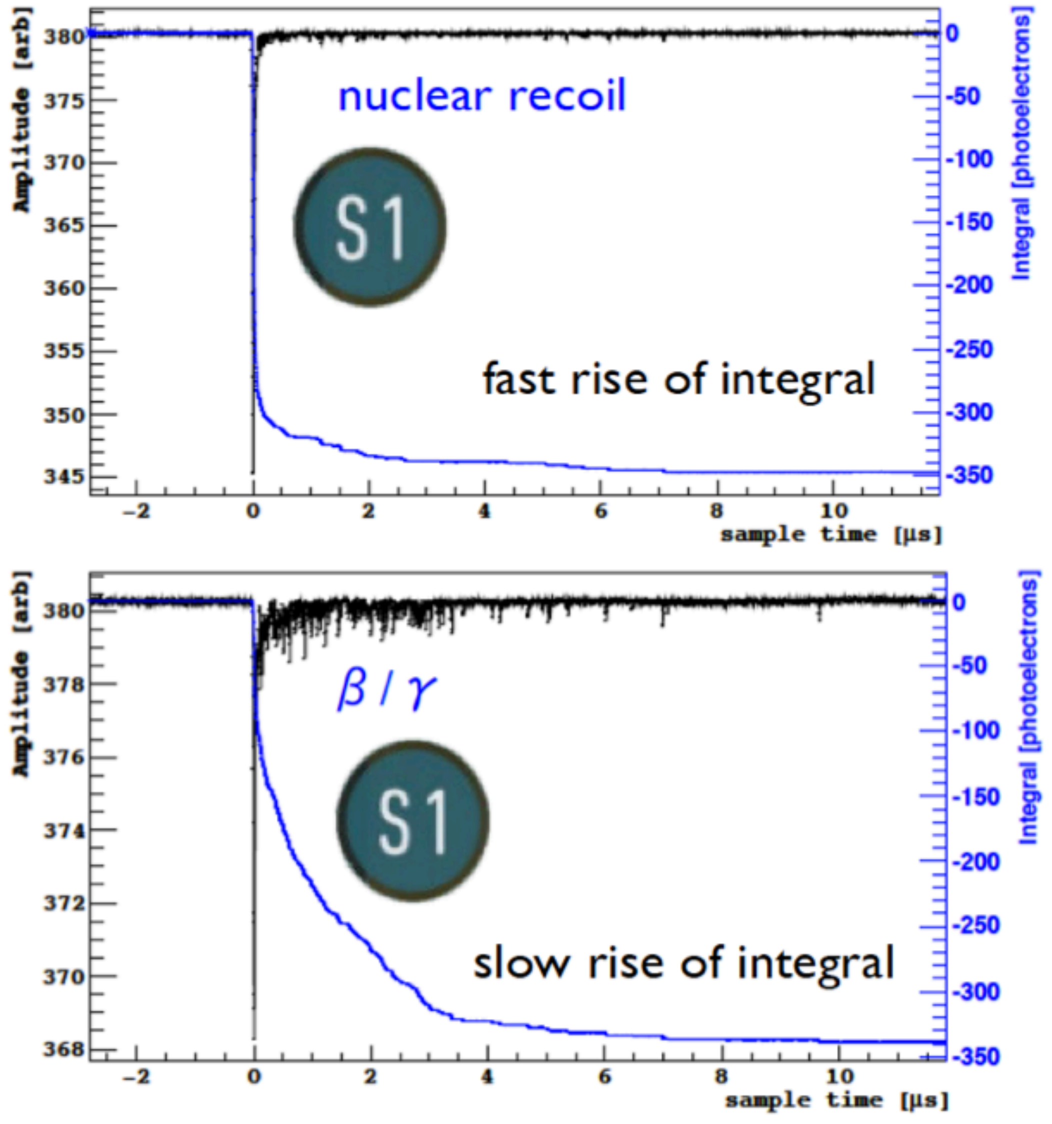



Event position reconstruction: PMT pattern and time-of-flight

**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).

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

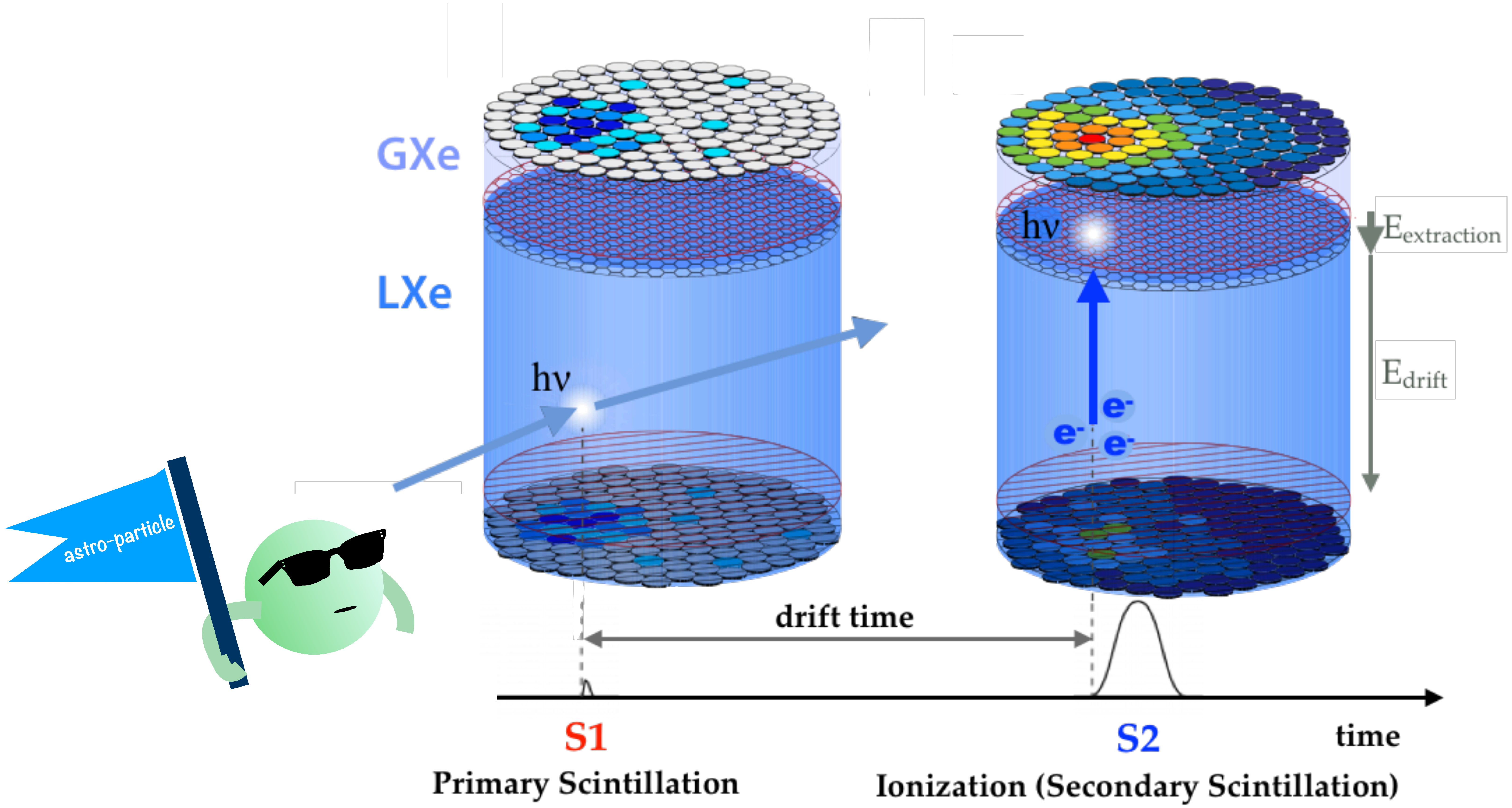


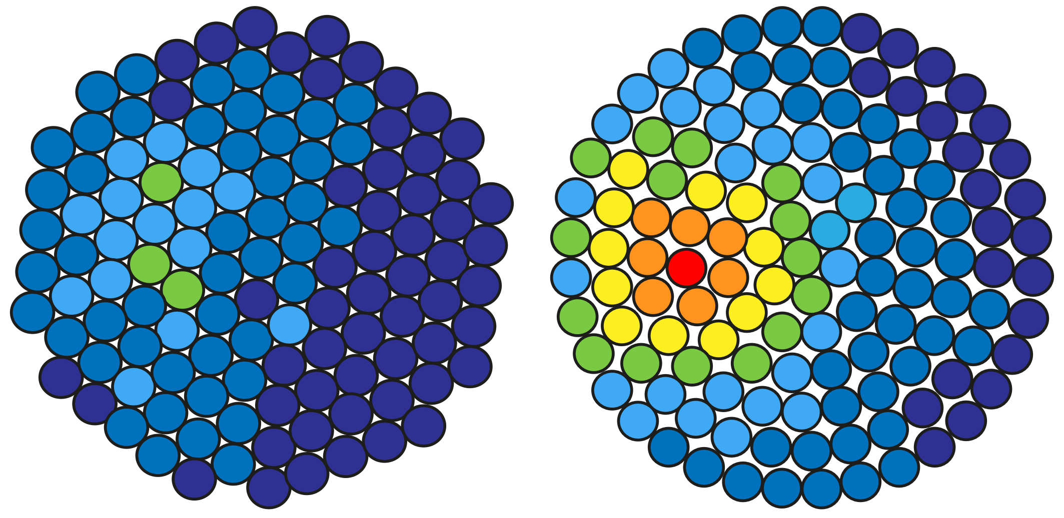
# Noble liquid detection: dual phase



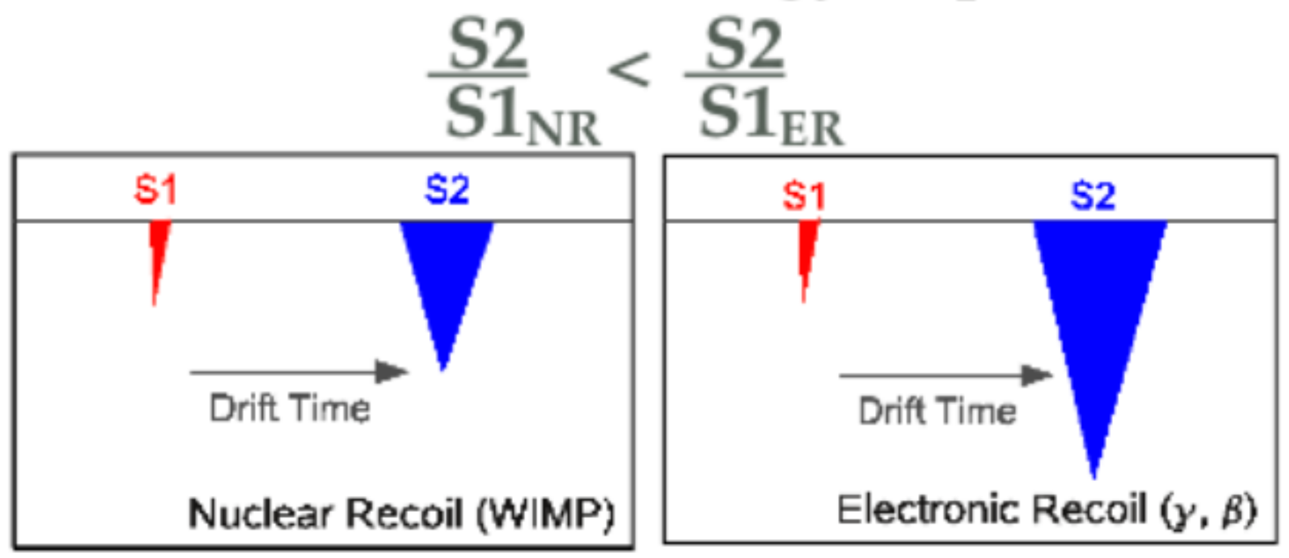
**Cryogenic xenon and argon**

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



Position reconstruction (fiducialization)

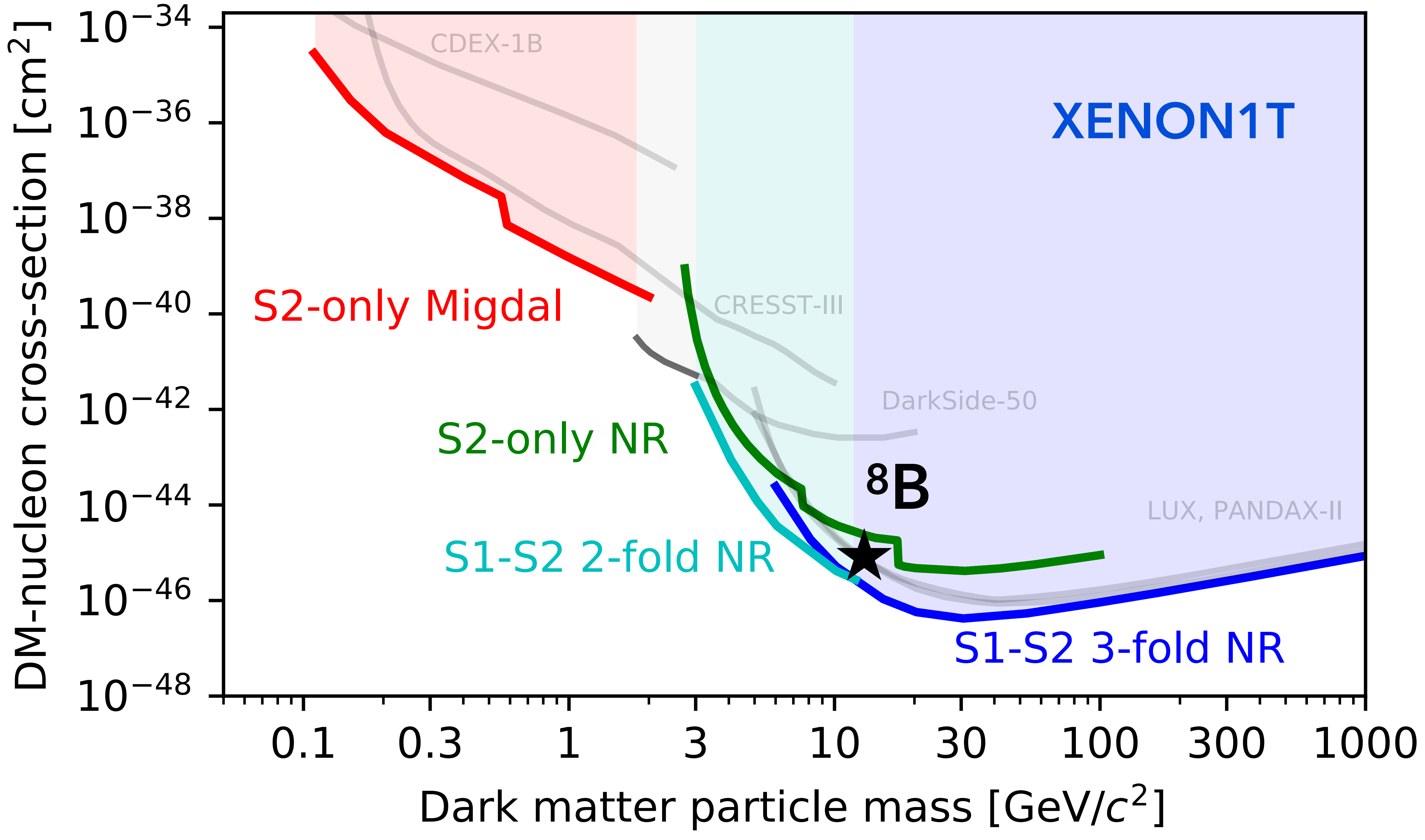



Particle discrimination

# Lowering the threshold



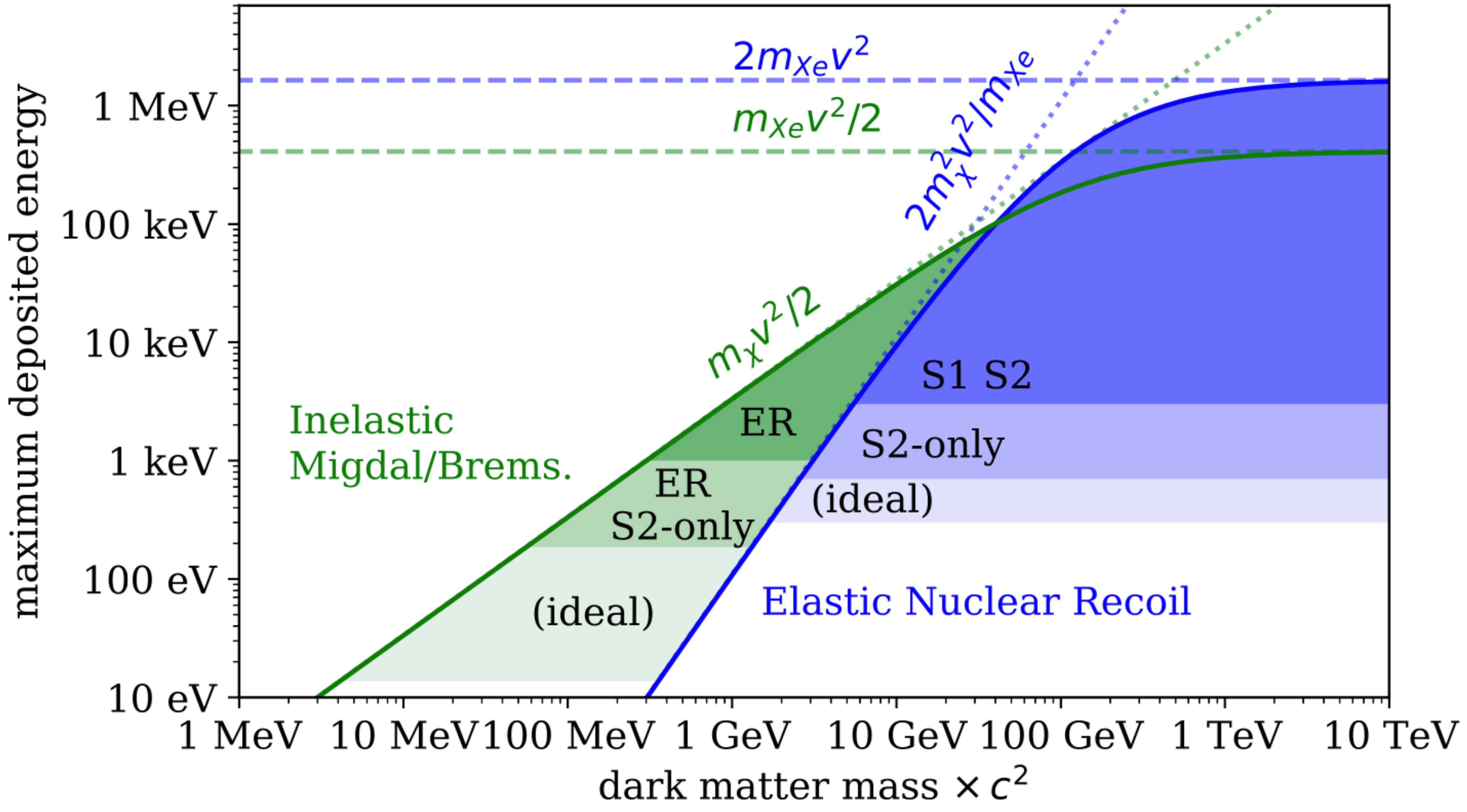
**Probing lower masses**




Phys. Rev. Lett. 126 (2021) 091301

- 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**



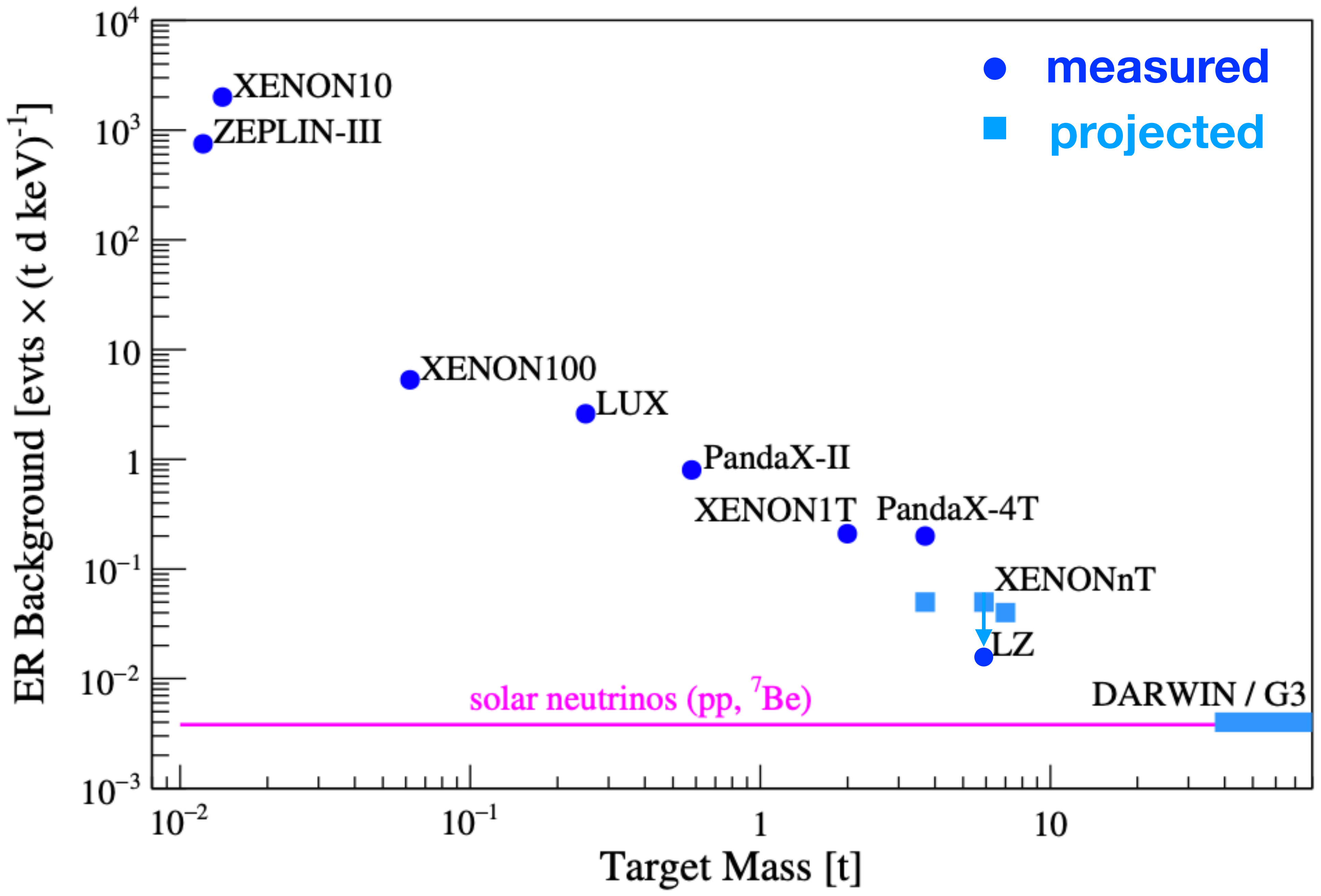

Xenon community white paper: arXiv:2203.02309 (2022)

- 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

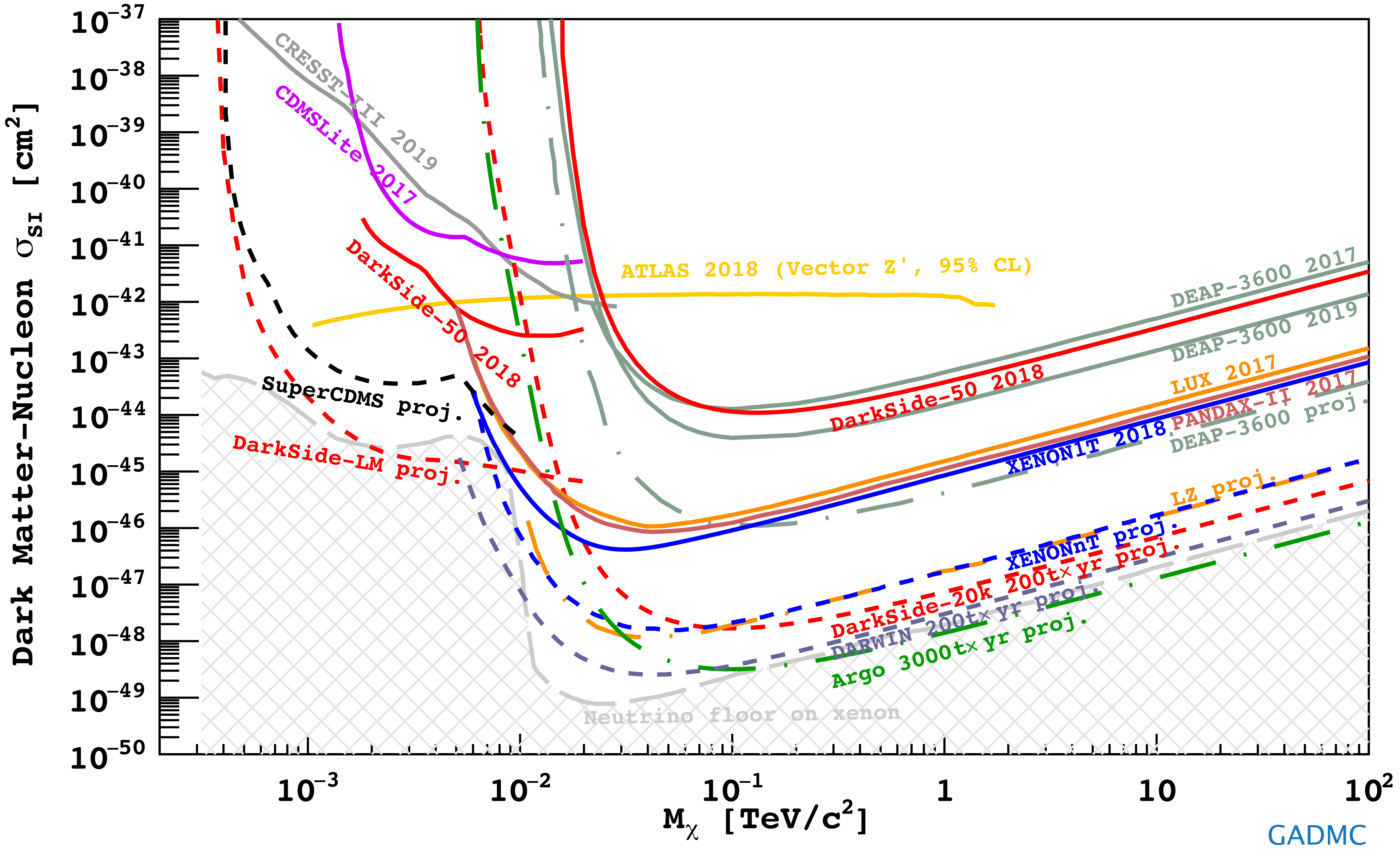
# Improving the Sensitivity






**Lower background and larger mass**

## Future experiments




**DarkSide-20K**
**DarkSide-LM**
**Argo**
*factor $10^4$*

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

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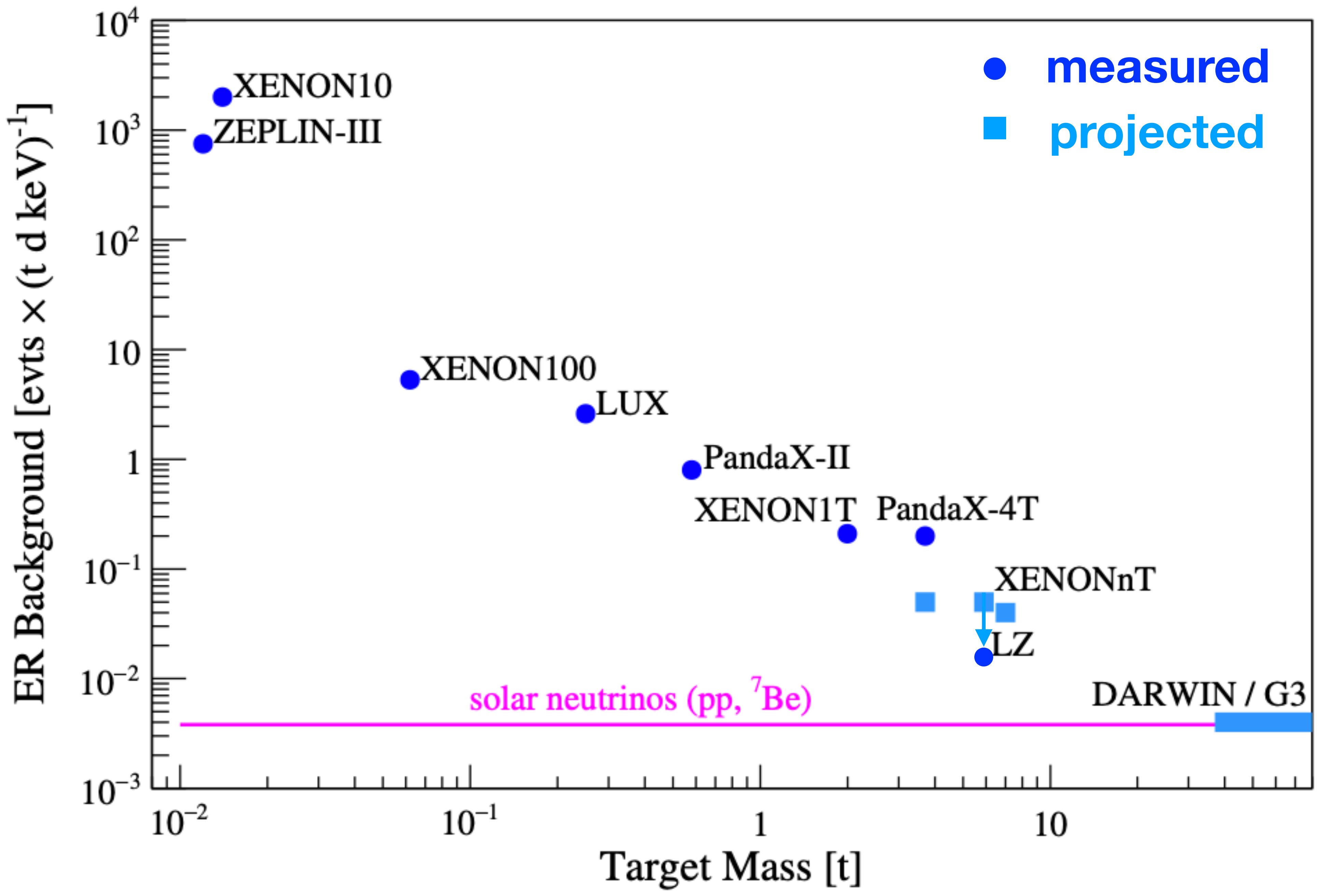
*projected sensitivity improvement in next ~10 years*

# Improving the Sensitivity



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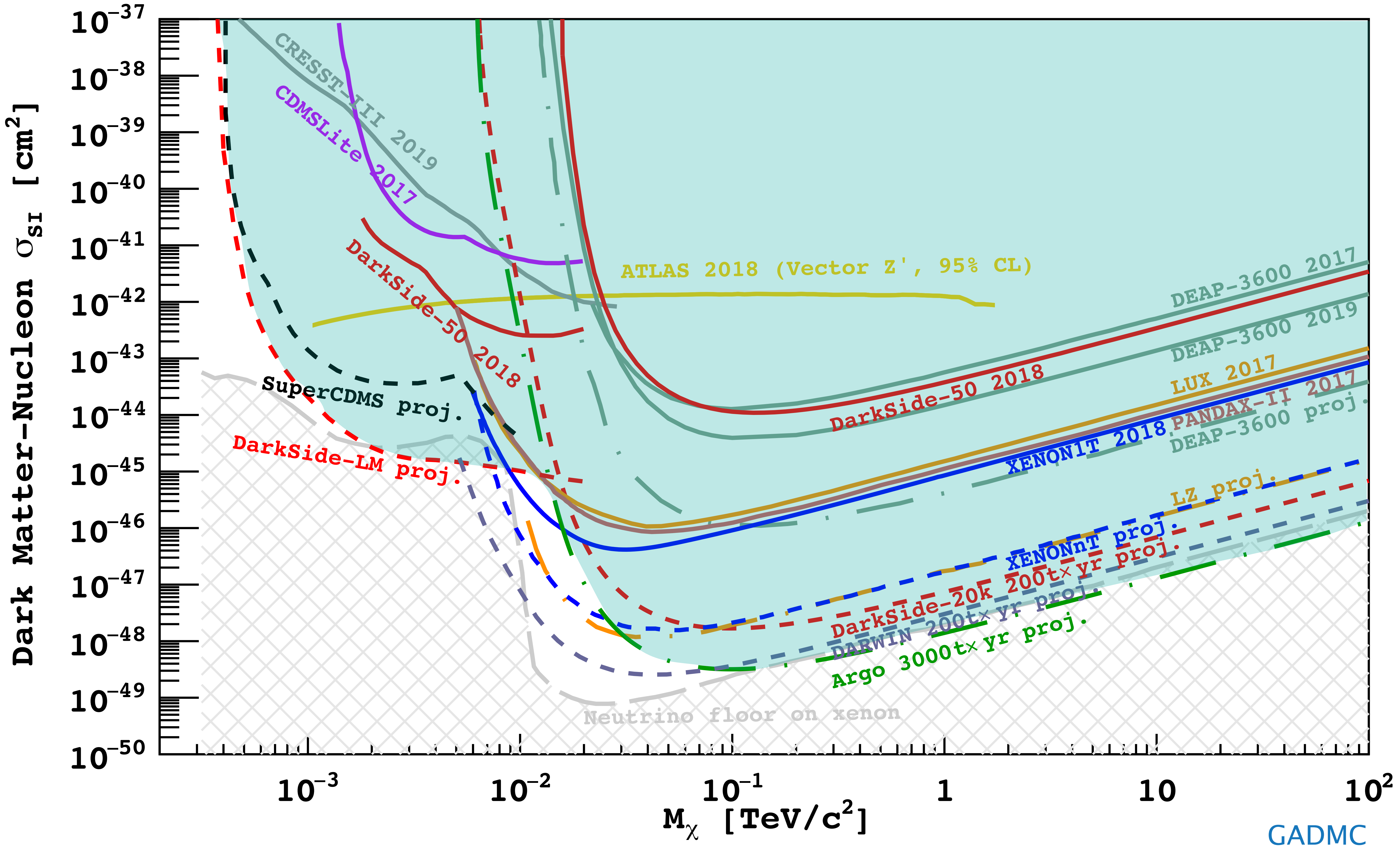


GADMC

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**DarkSide-LM**
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*factor $10^4$*

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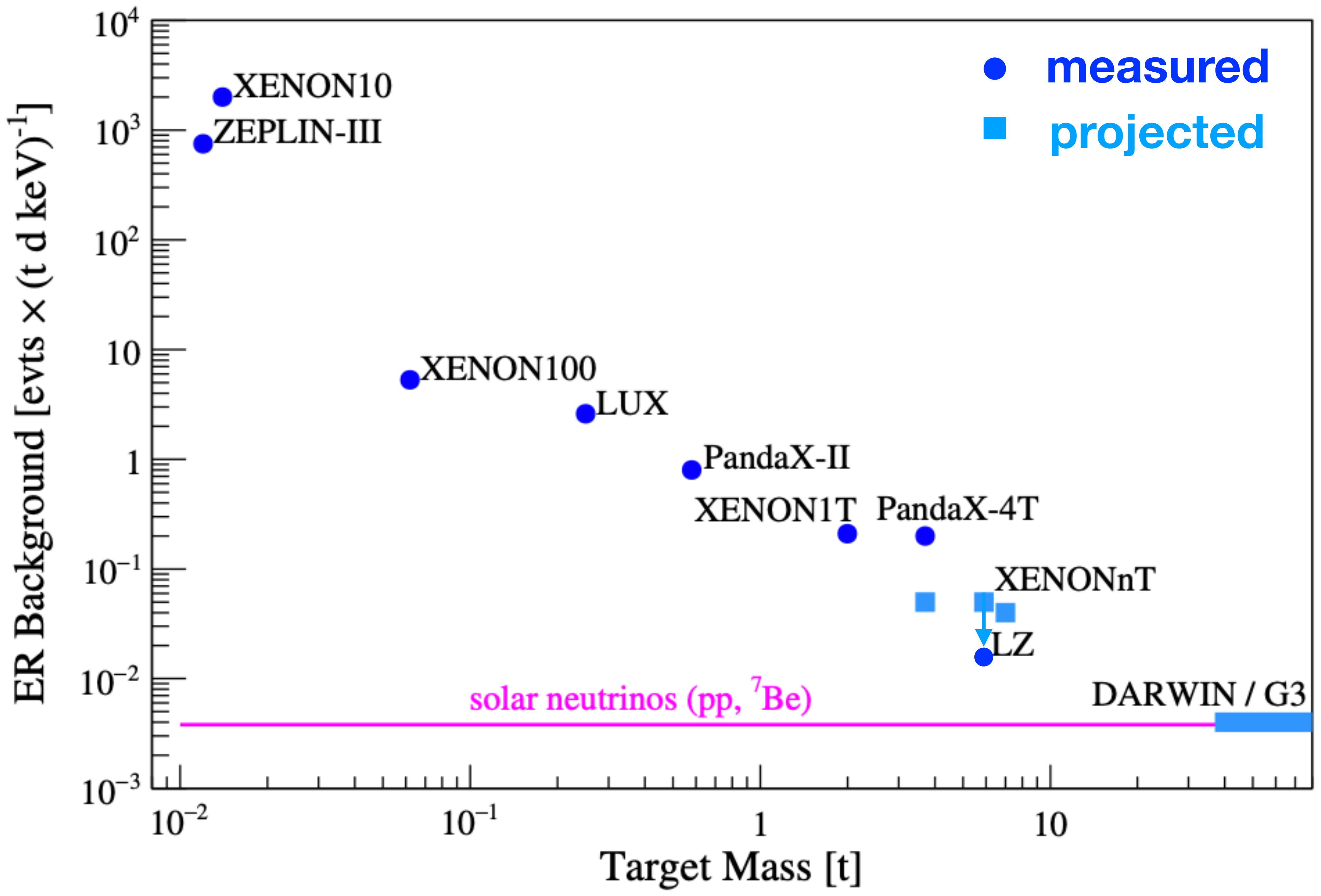


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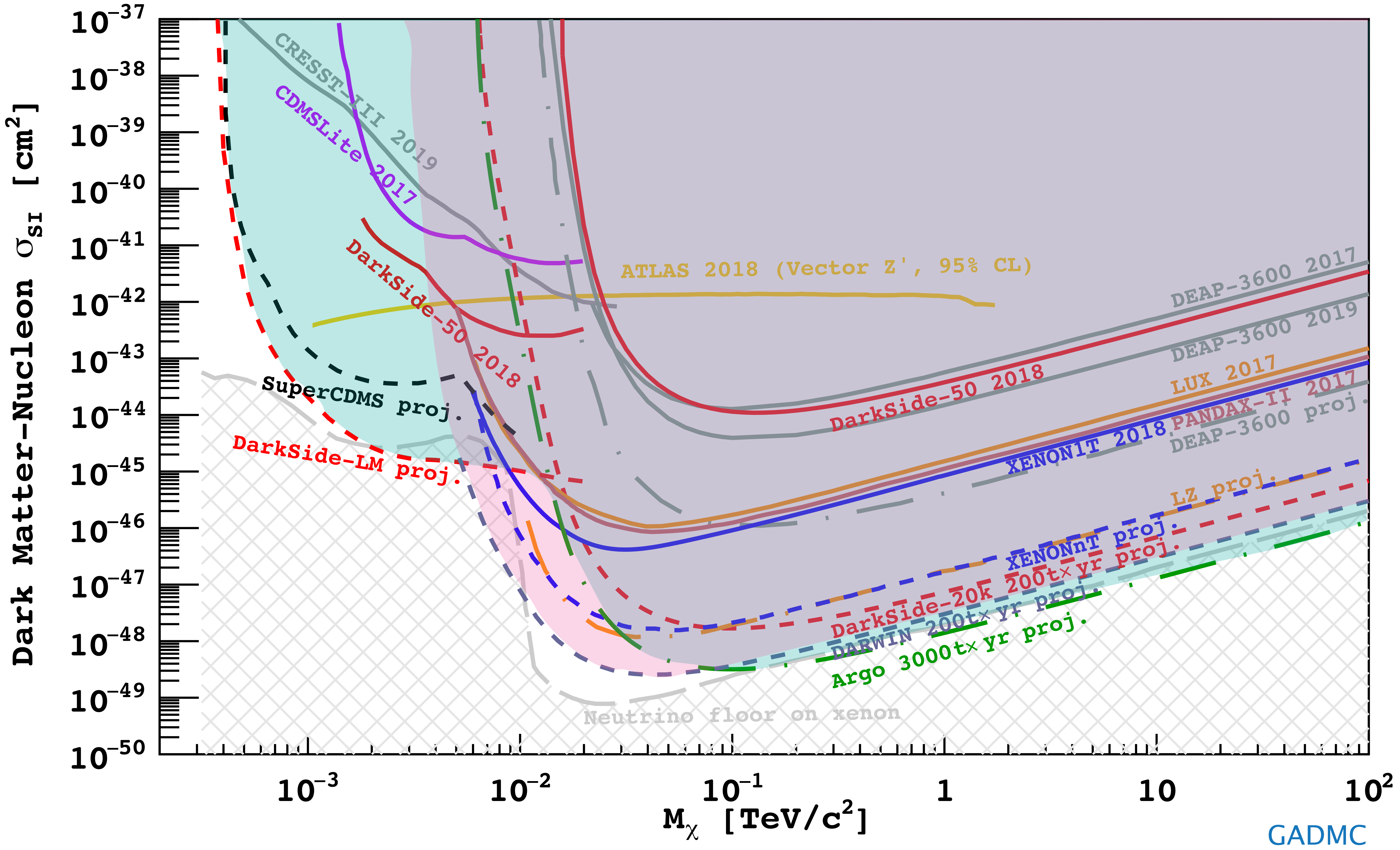


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*factor $10^4$*

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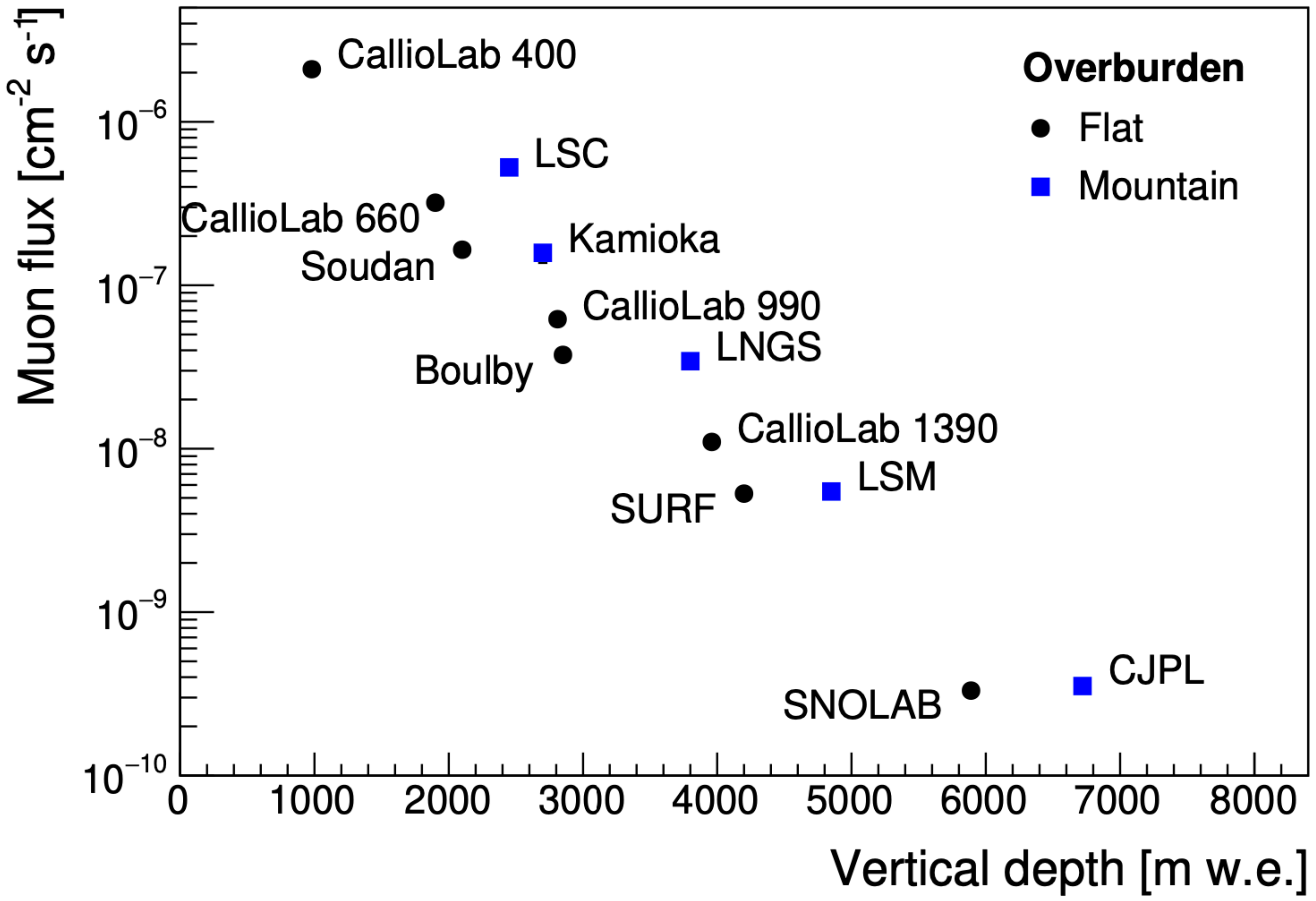
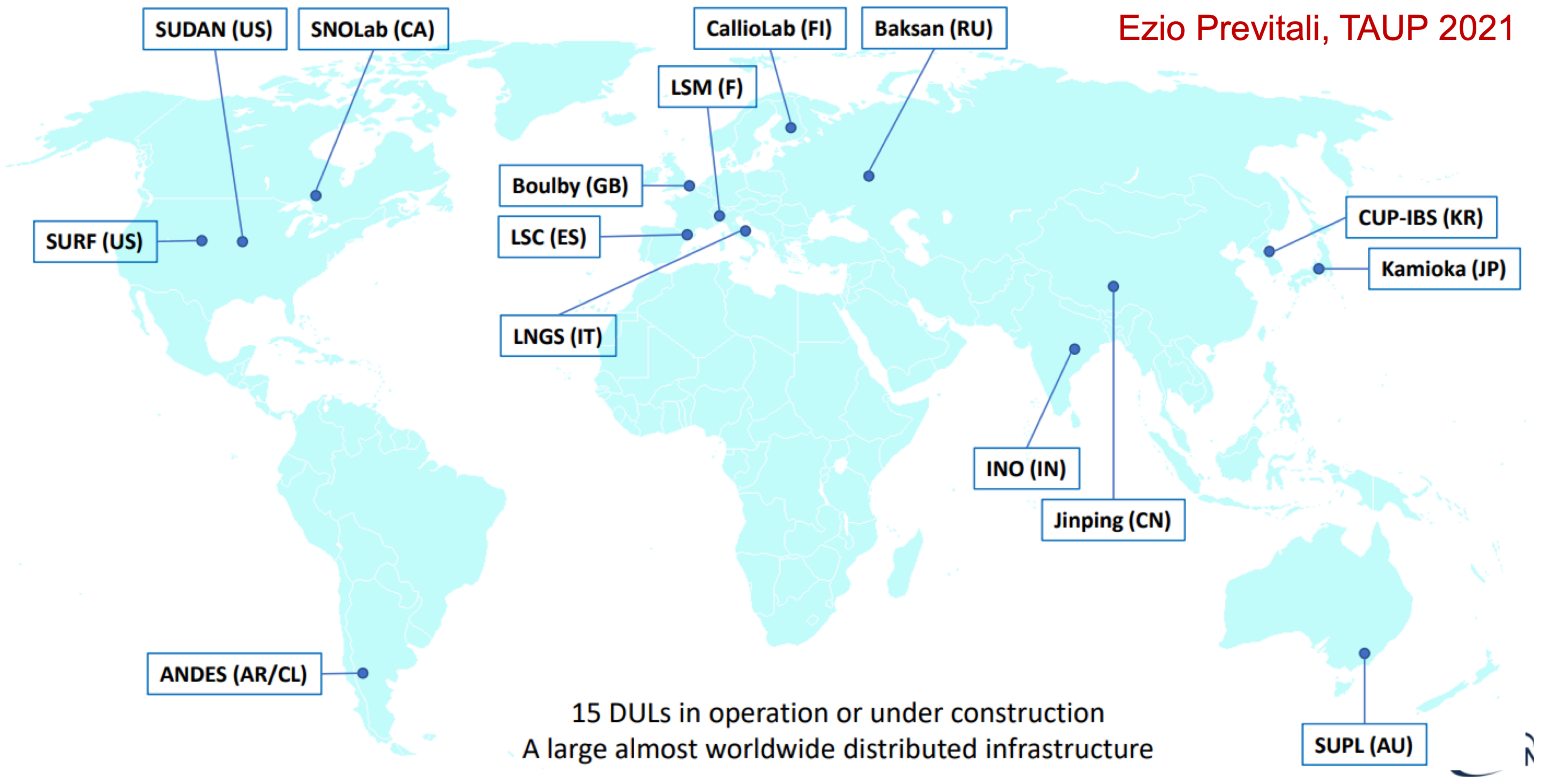
*projected sensitivity improvement in next ~10 years*

# Common Backgrounds



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



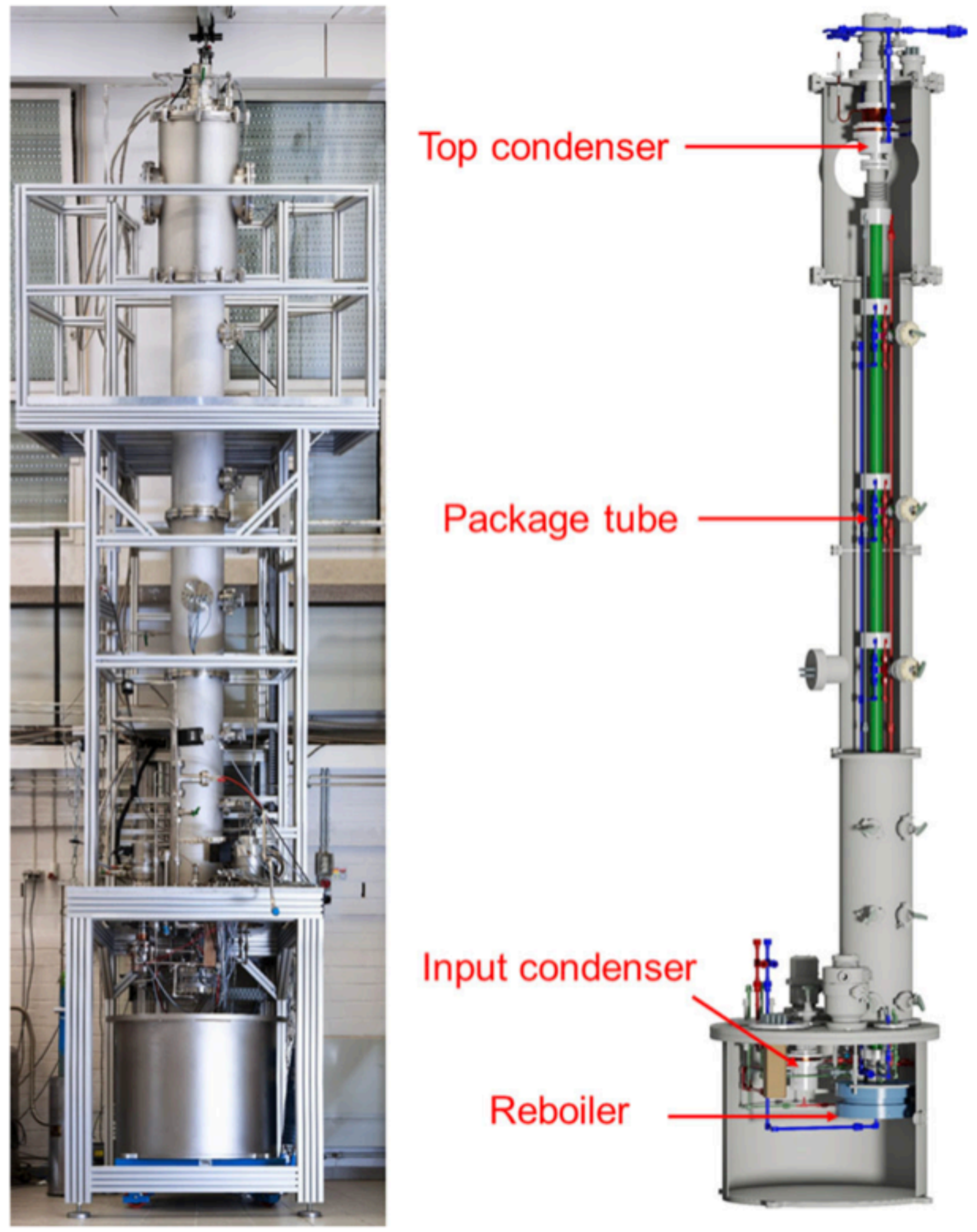




- Deep Underground Laboratories: reduce muon flux by at least $10^6$ - siting will be increasingly important given large mass/exposures
- Minimize activation of detector materials and targets (For Ar - ARGUS: planned UG storage in SNOLAB)
- Use of passive and active veto detectors (muon Cerenkov, neutron 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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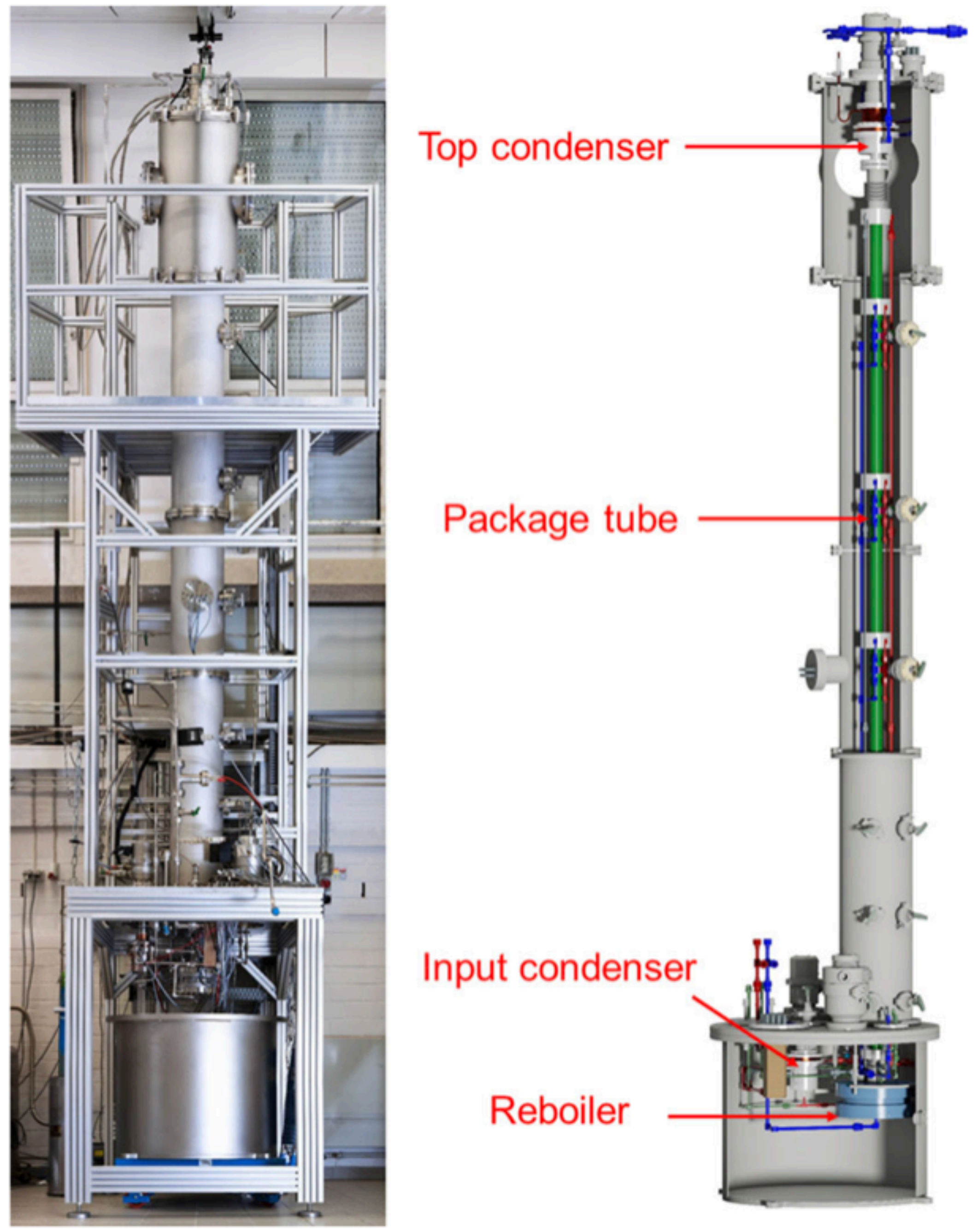
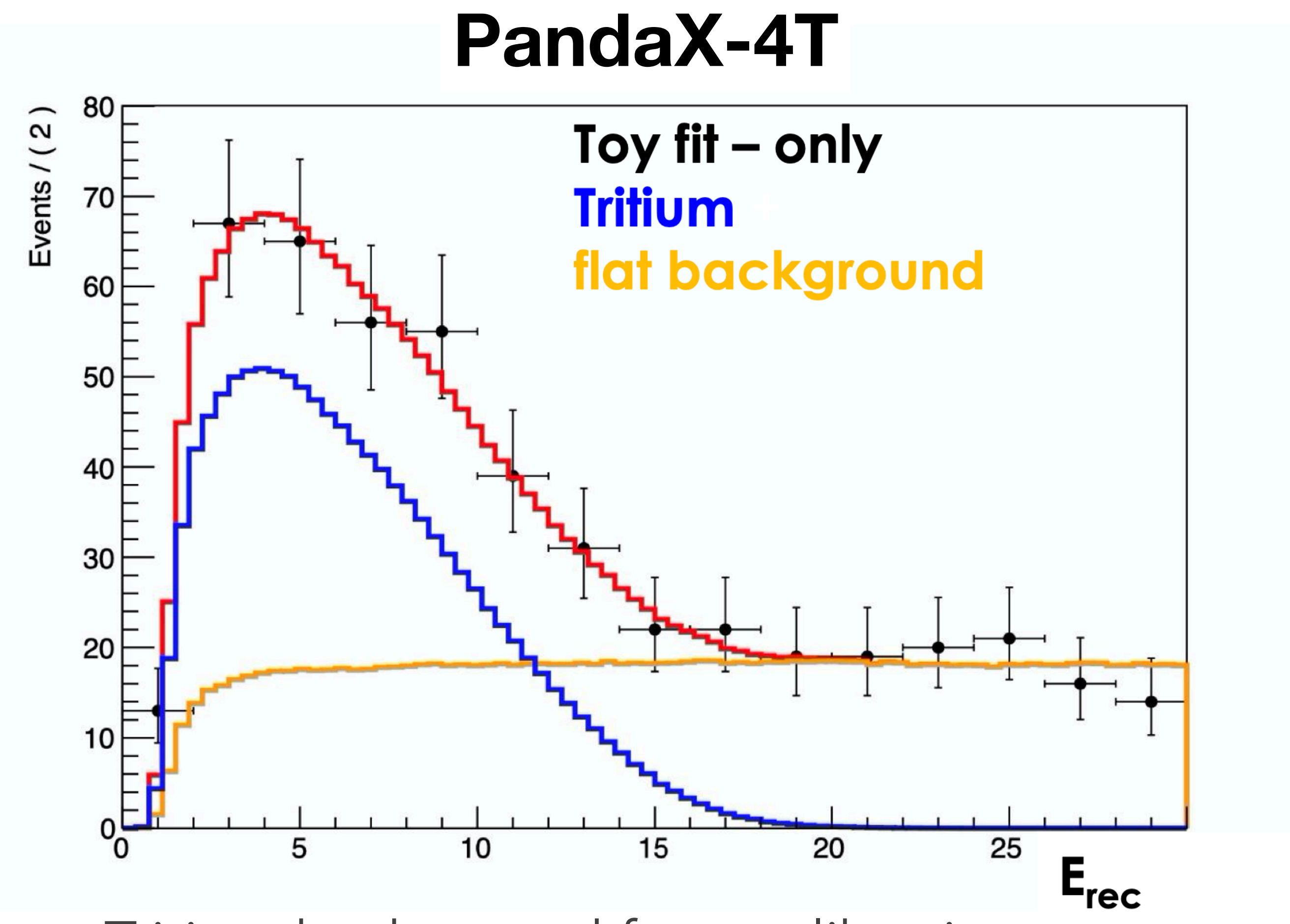


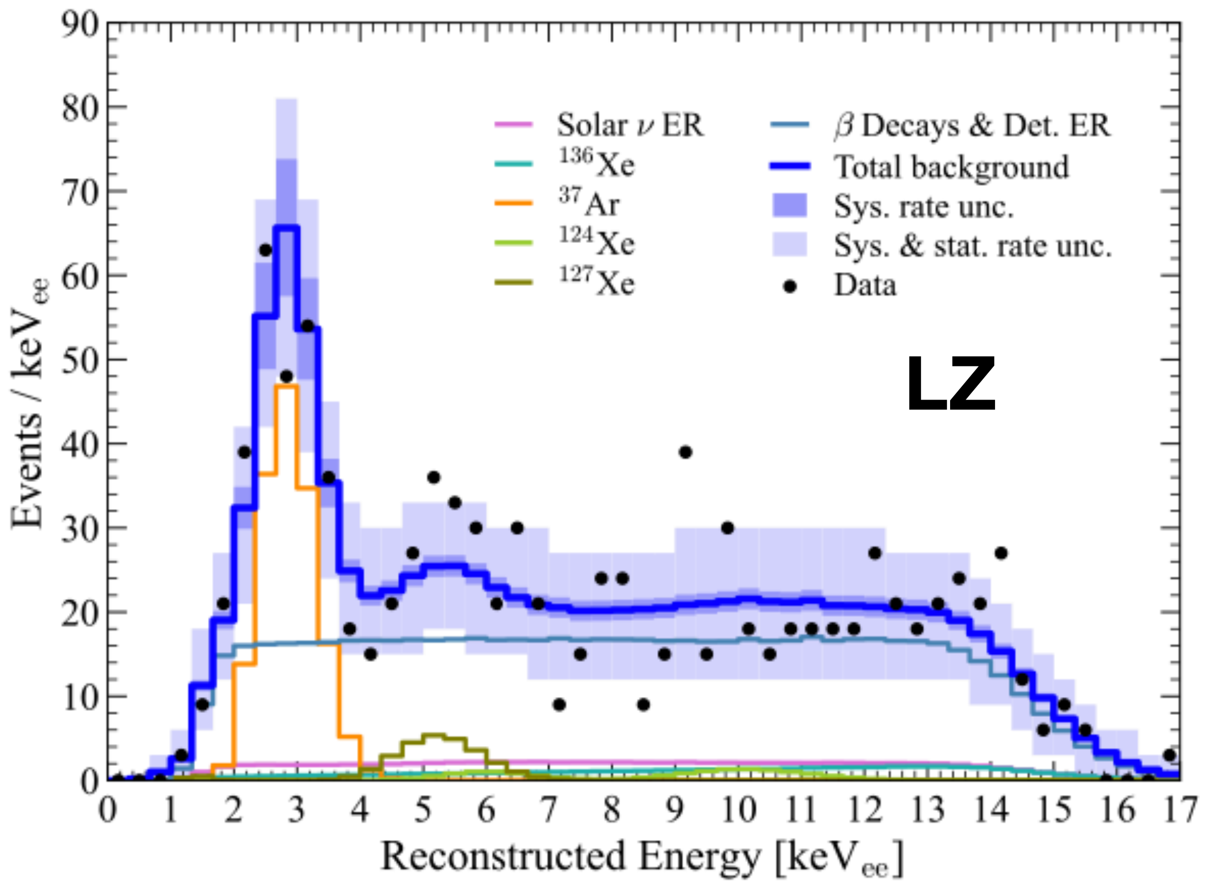

XENON distillation column

Gator low-background counting facility underground at LNGS.

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




Tritium background from calibration source




$^{37}$Ar peak at 2.8 keV in LZ due to above ground activation.

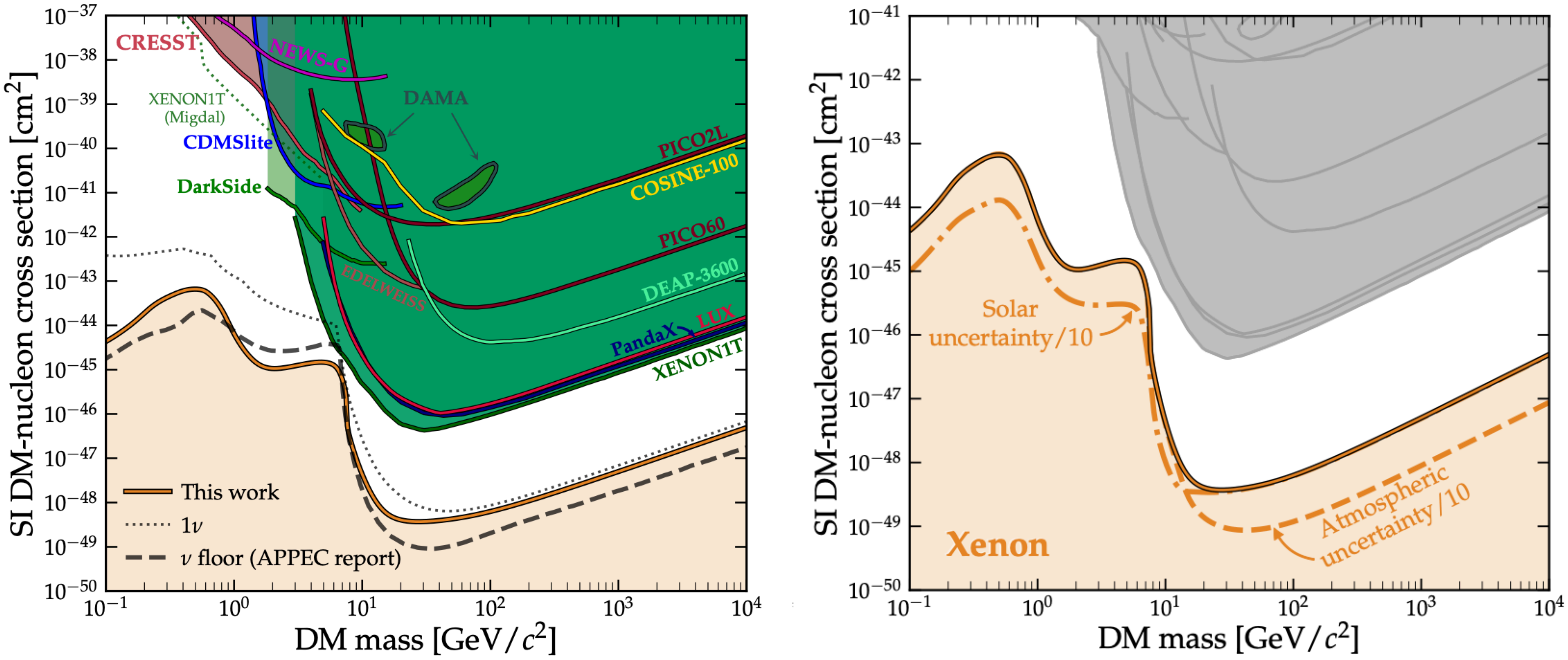
new LZ result: arxiv:2207.03764

**$^{37}$Ar 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

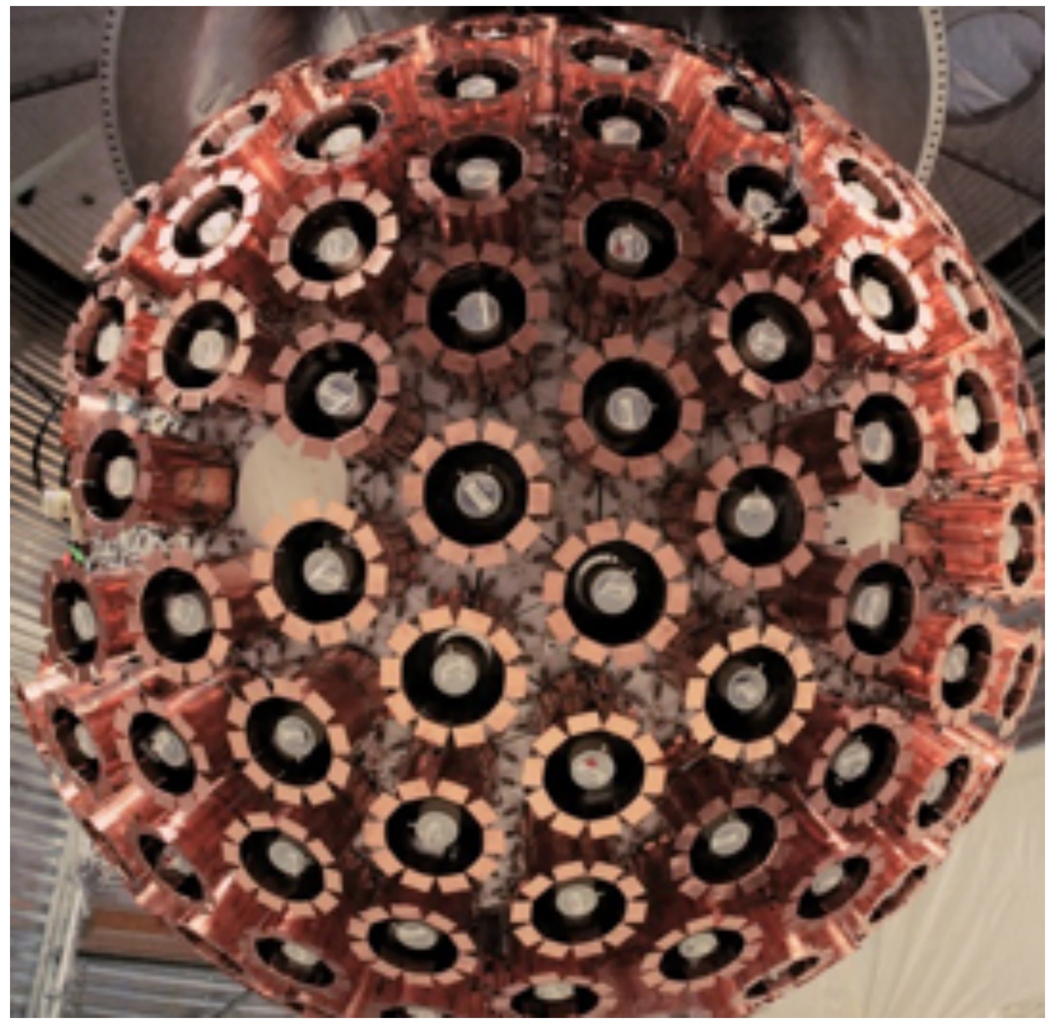


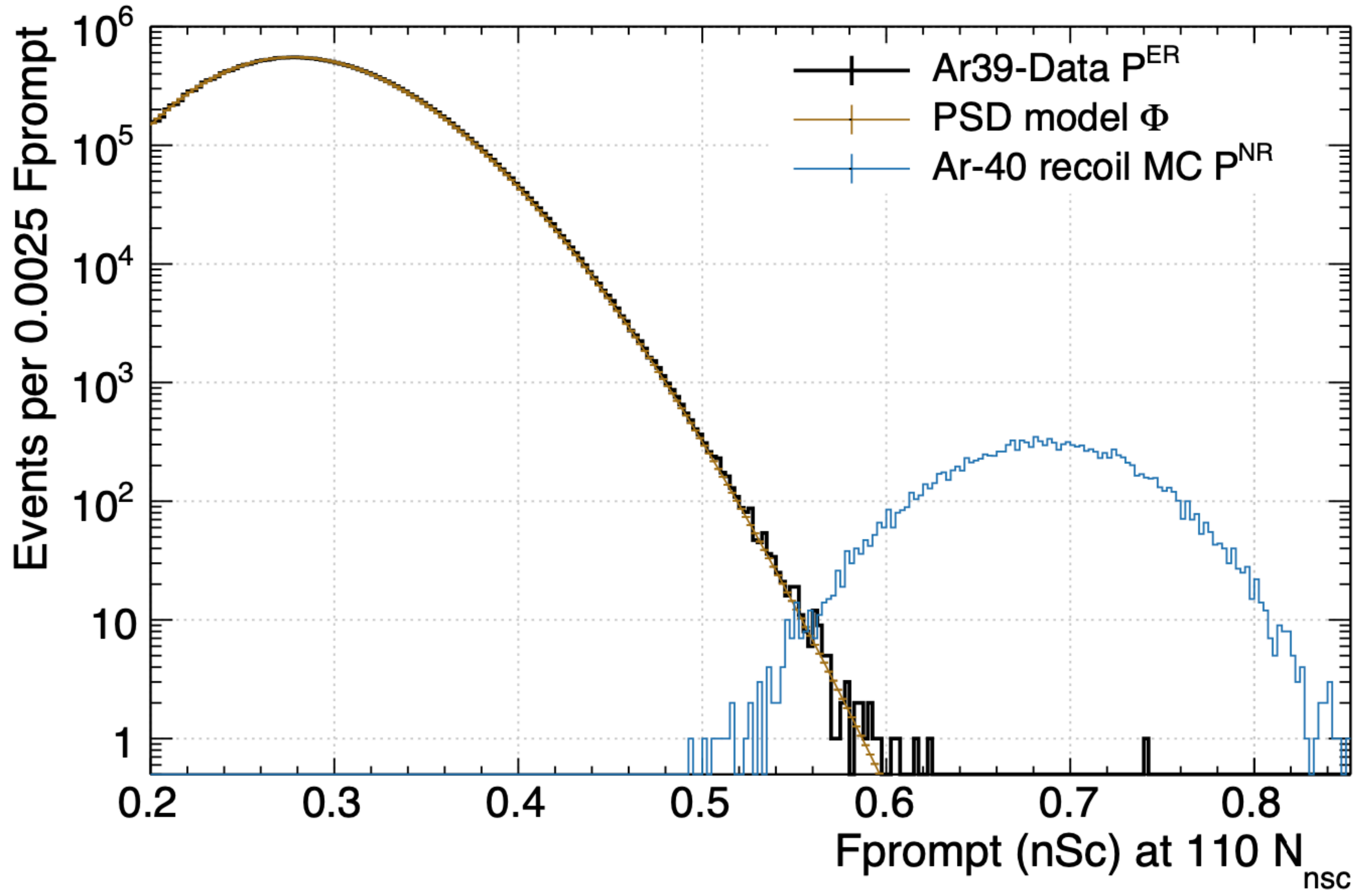

*⁸B initial detection expected ~6 GeV/c² by xenon detectors.*

O'Hare, Phys. Rev. Lett. 127 (2021) 251802

# Current LAr Experiments








**DEAP-3600**
**3300 kg**
**SNOLAB**

$$^{40}Ar(n,2n)^{39}Ar$$

$\beta^-$decay with Q-value 565 keV

**challenges: Ar39**

**strengths: pulse shape discrimination, Rn reduction**

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

See talks by Andrew Erlandson and Vicente Pseudo Forte

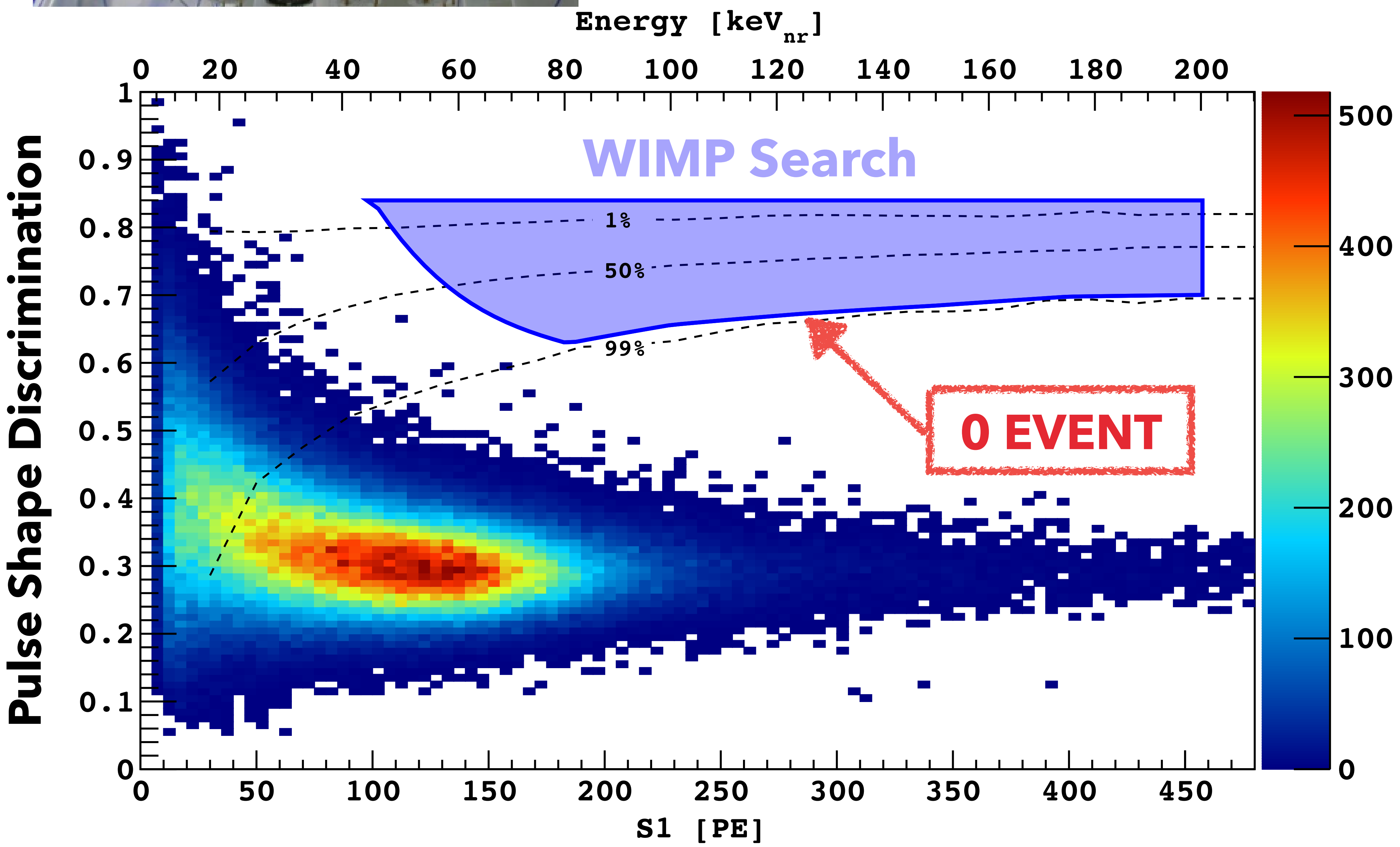
**DarkSide-50**
**46 kg**
**LNGS**

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**

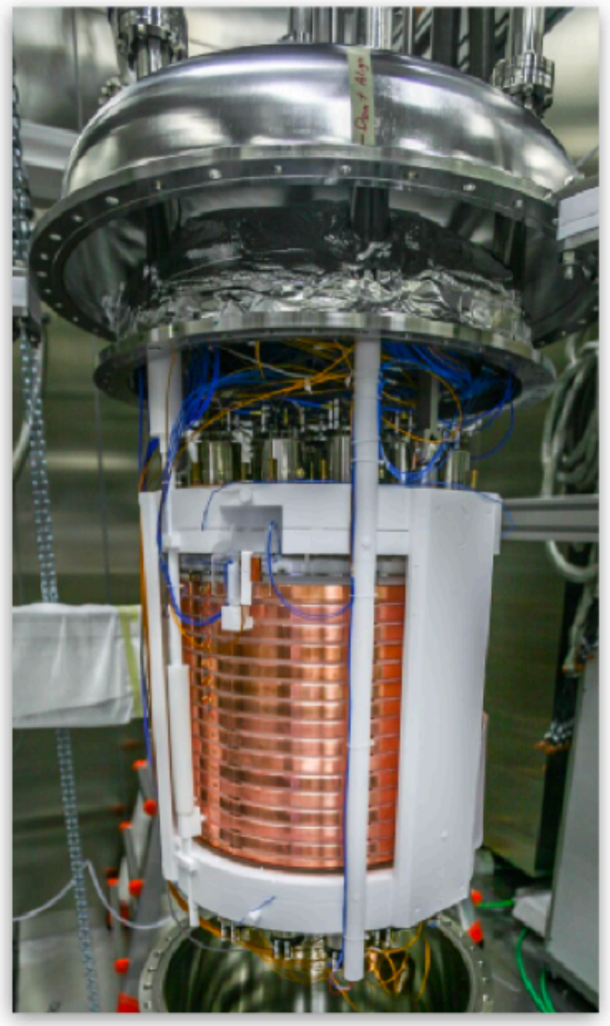


# Towards the Future

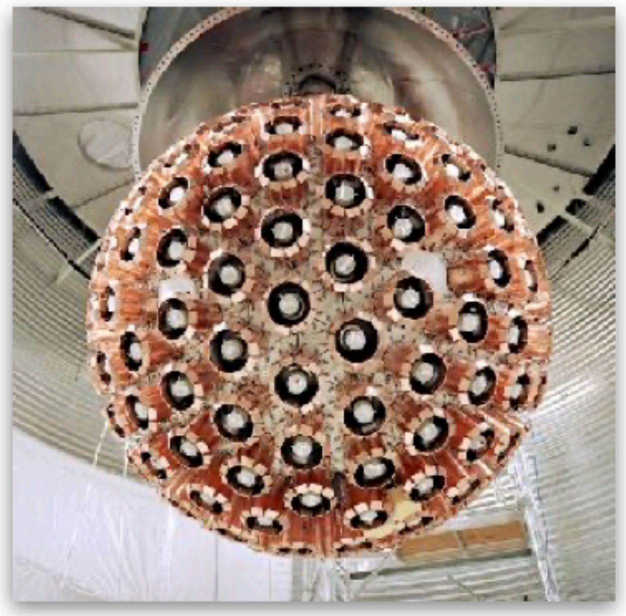


see talk by Thomas Nathan Thorpe

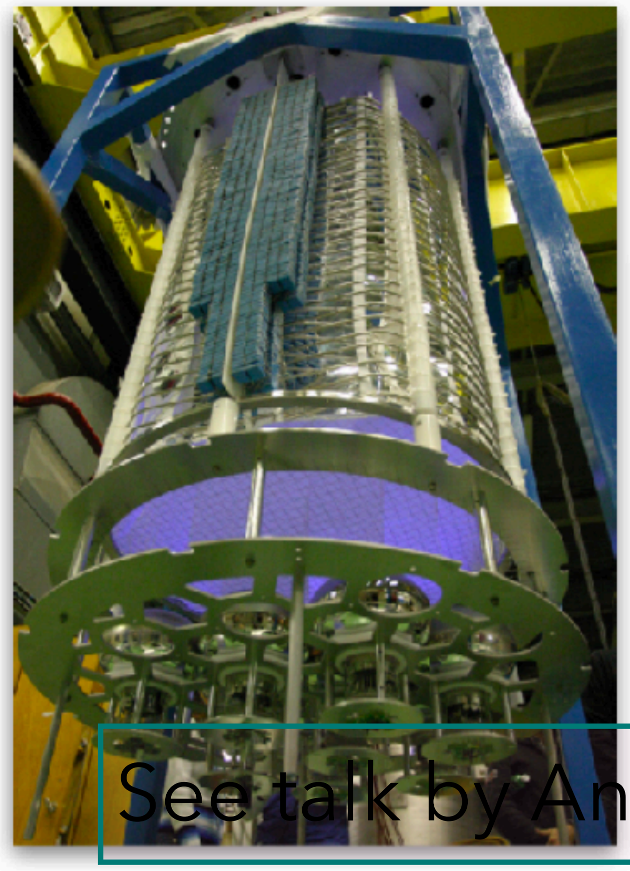
**DarkSide-50**



**DEAP-3600**



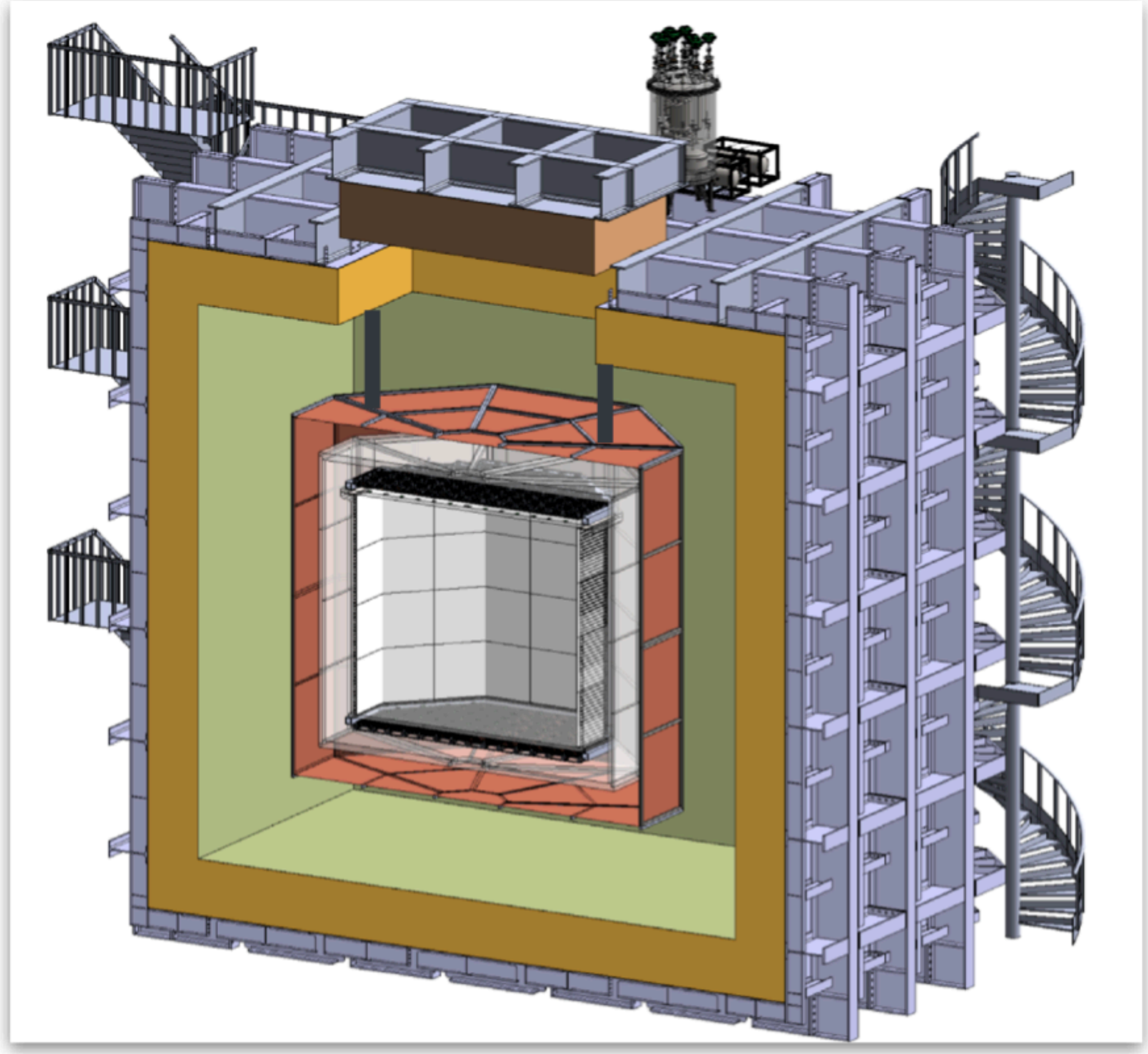
**ArDM**



**MiniCLEAN**

See talk by Andrew Erlandson

## DarkSide-20k



from 2022 at LNGS

50t underground argon dual-phase TPC
in 700t atmospheric argon cryostat
→ sensitivity $1.2\times10^{-47}$ cm$^2$ at WIMP mass of 1TeV/c$^2$
(with 100 tonne year exposure with a 20t fiducial mass)

## GADMC: Global Argon Dark Matter Collaboration

**ARGO**

~300t TPC

from 2029
at Snolab

- Multi-national collaboration >500 scientisits 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

slide courtesy Alex Kish

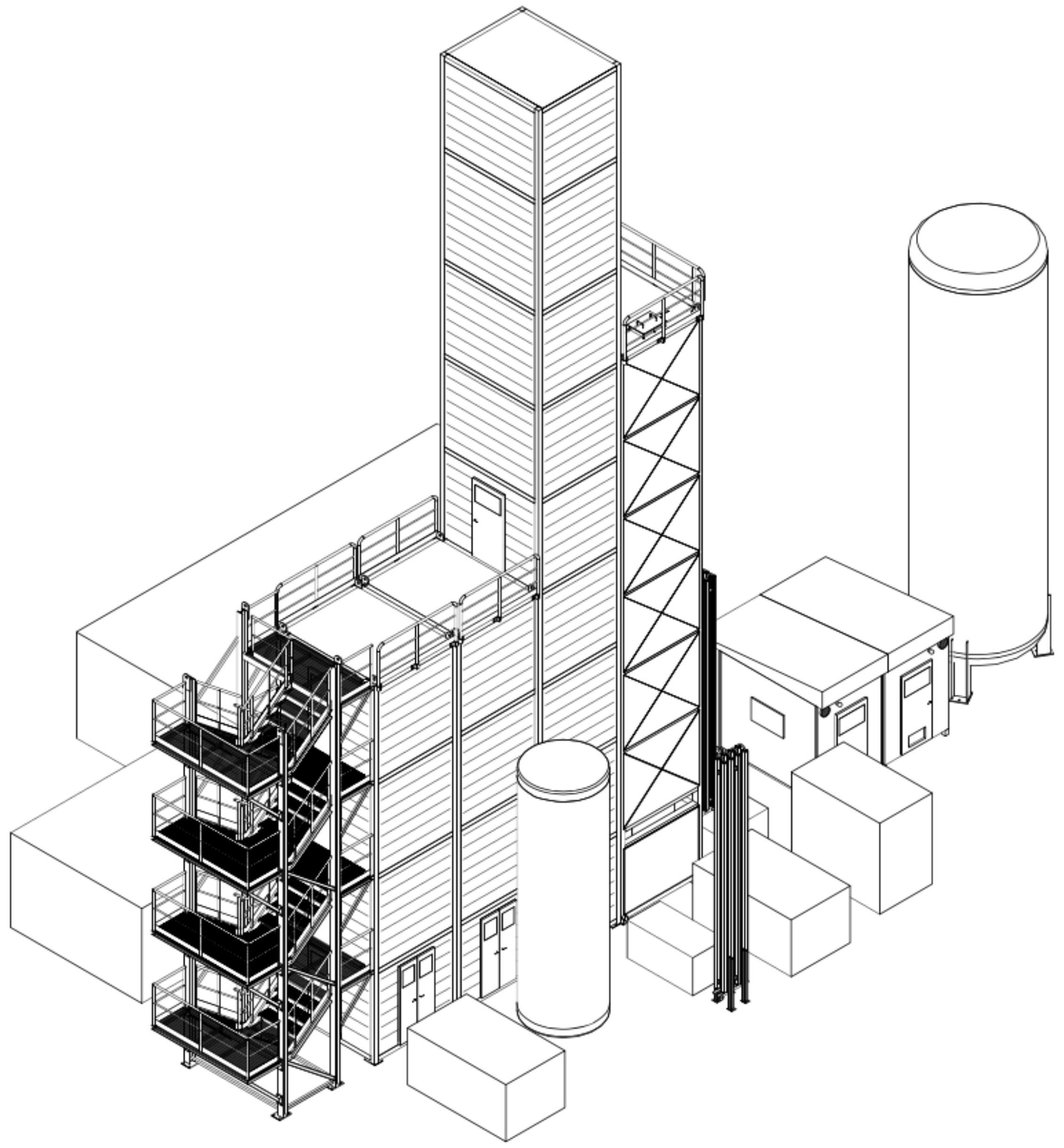
# Argon sourcing and purification



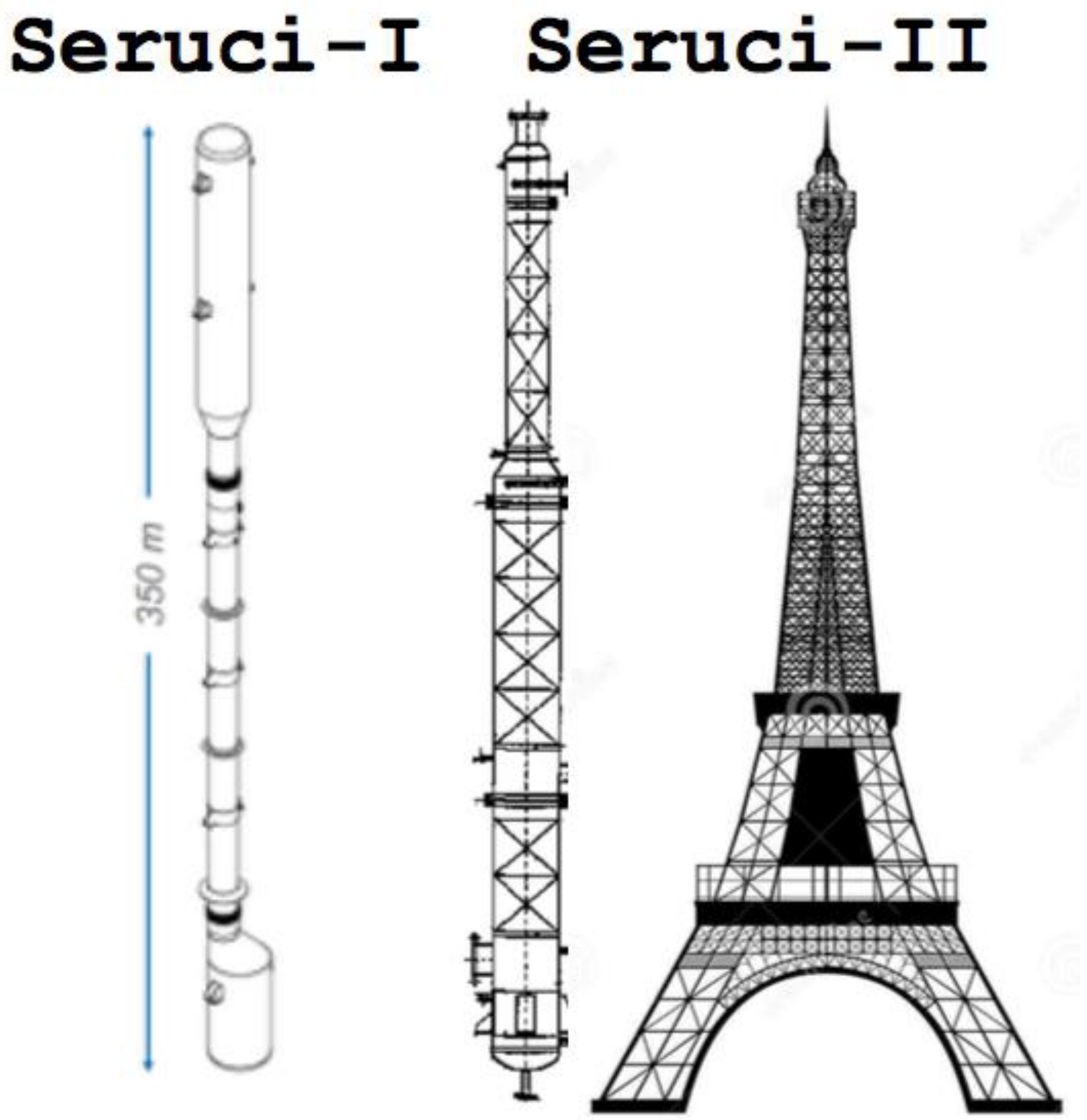
LOW RADIOACTIVITY ARGON

## 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

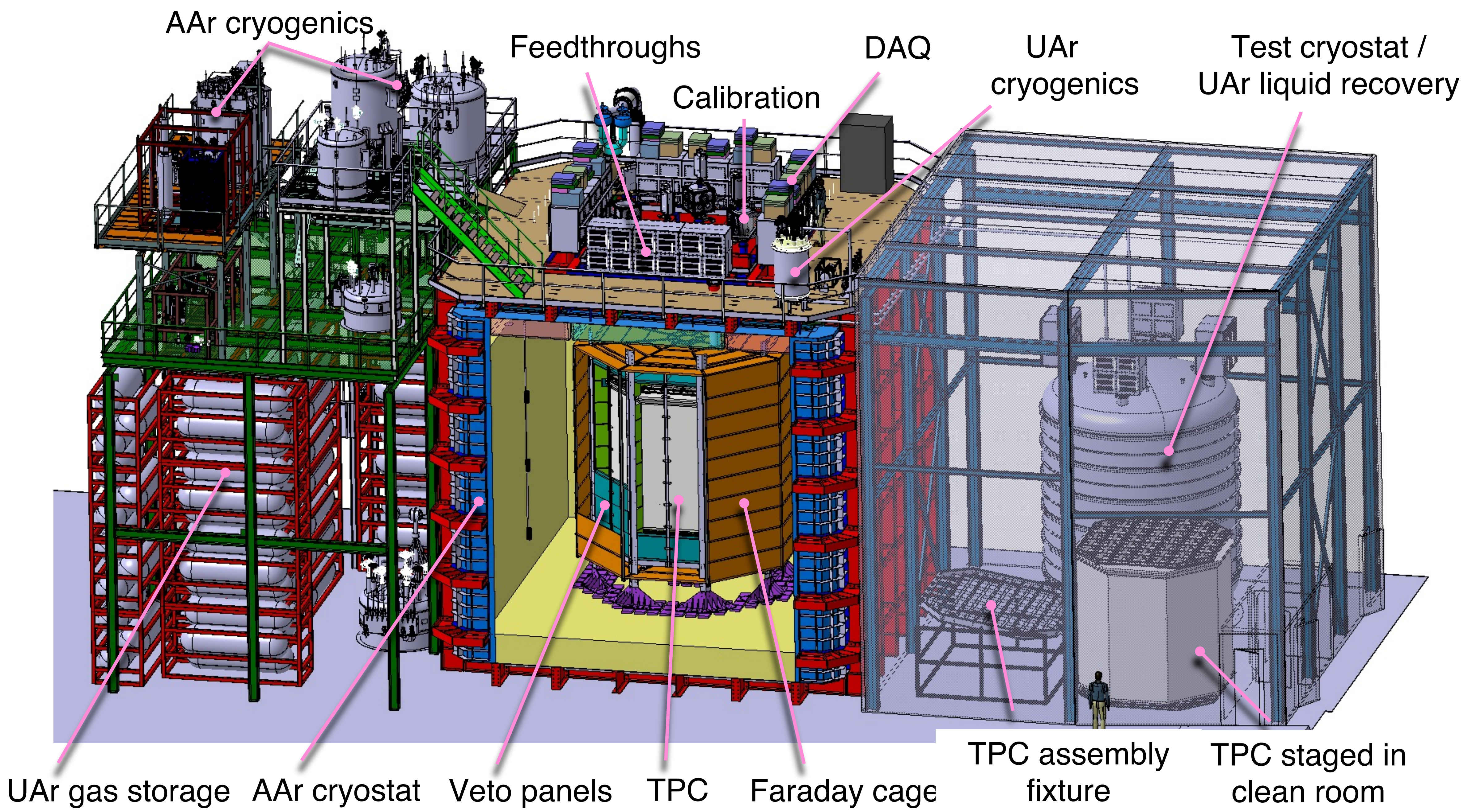


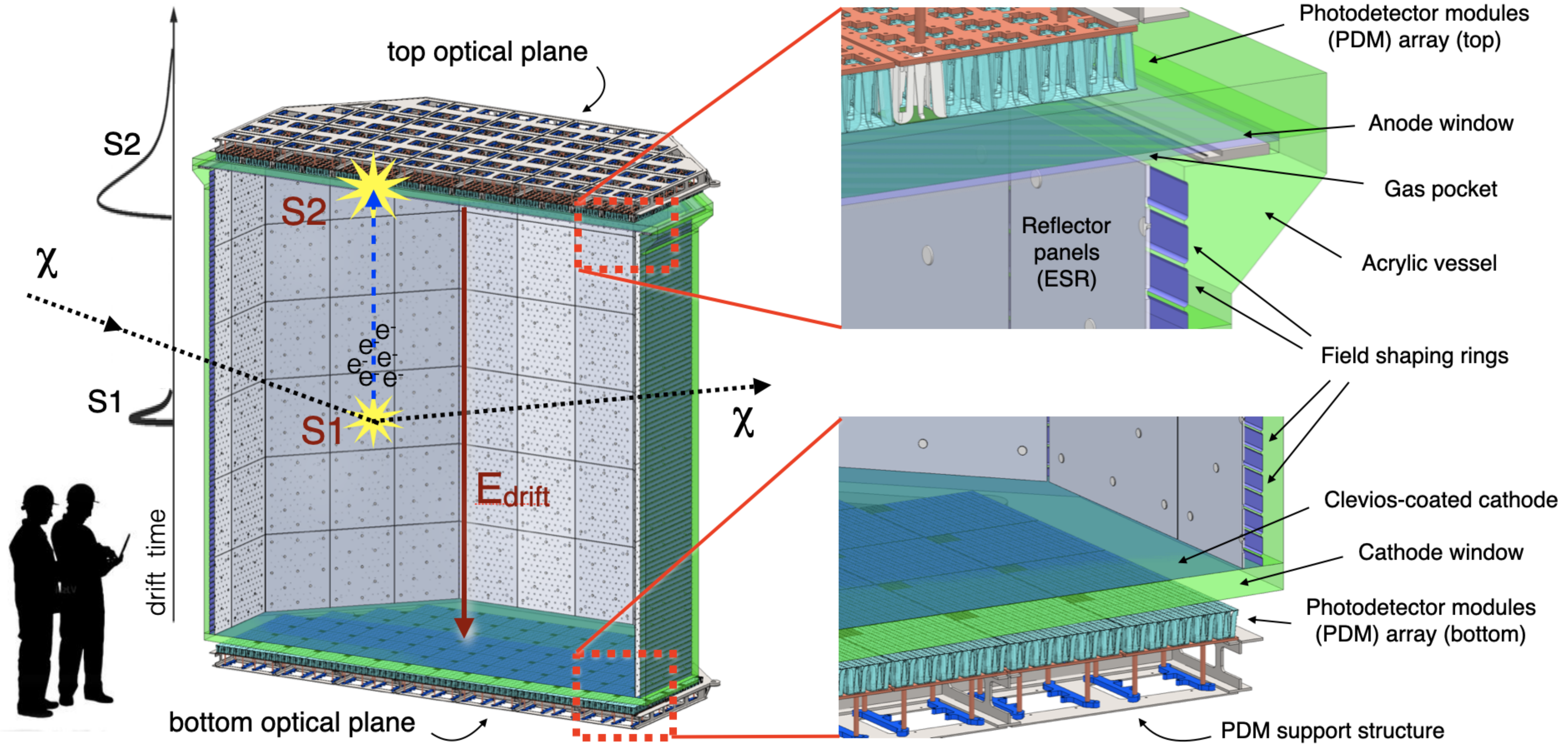

- 350-m tall cryogenic distillation column in Seruci, Sardinia
- Final chemical purification of the UAr
- Can process O(1 tonne/day) with $10^3$ reduction of all chemical impurities
- Ultimate goal is to isotopically separate $^{39}Ar$ from $^{40}Ar$ (at the rate of 10 kg/day in Seruci-I)
- goal to reduce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

# DarkSide-20K



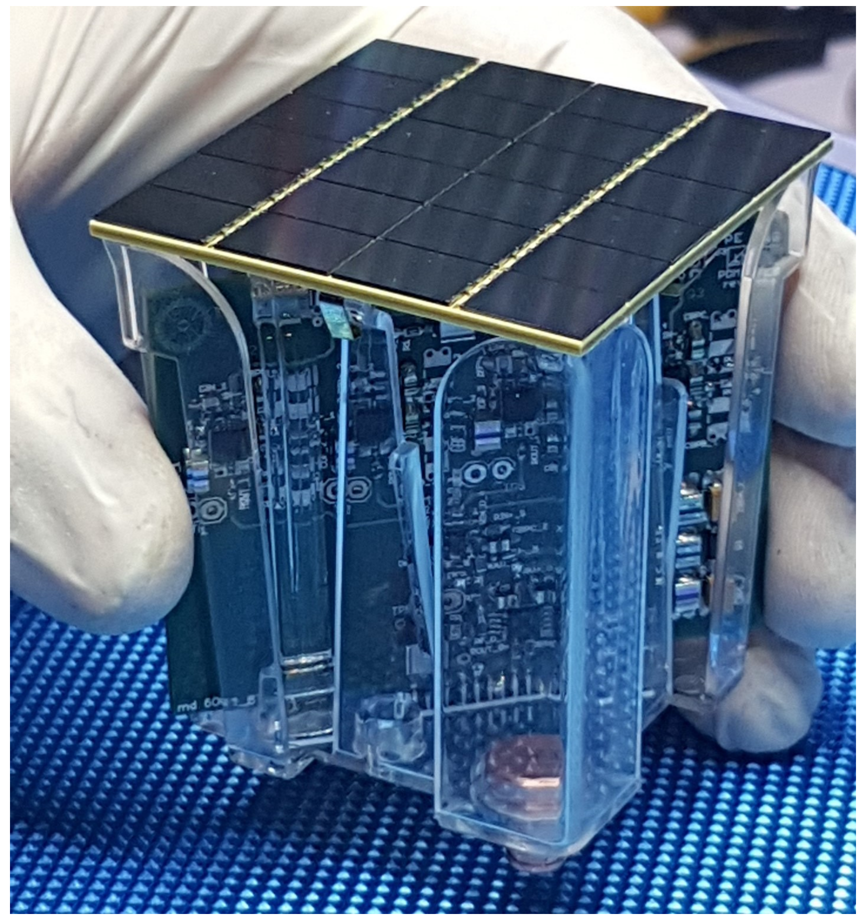
FUTURE DETECTOR




## 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 m$^2$ of Cryogenic Silicon based Photomultipliers (5x5 cm$^2$ tile); TPC lined with wavelength shifter

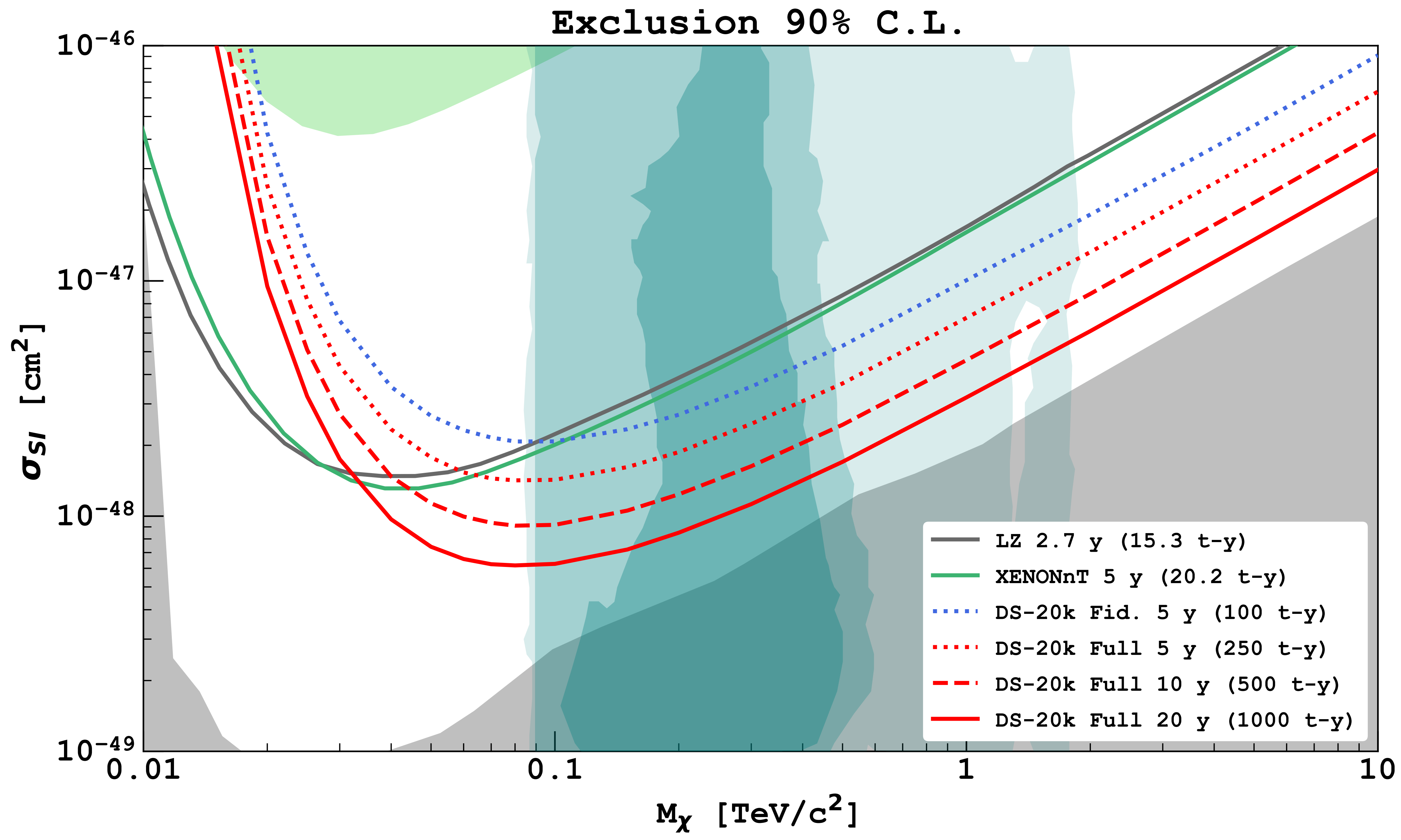


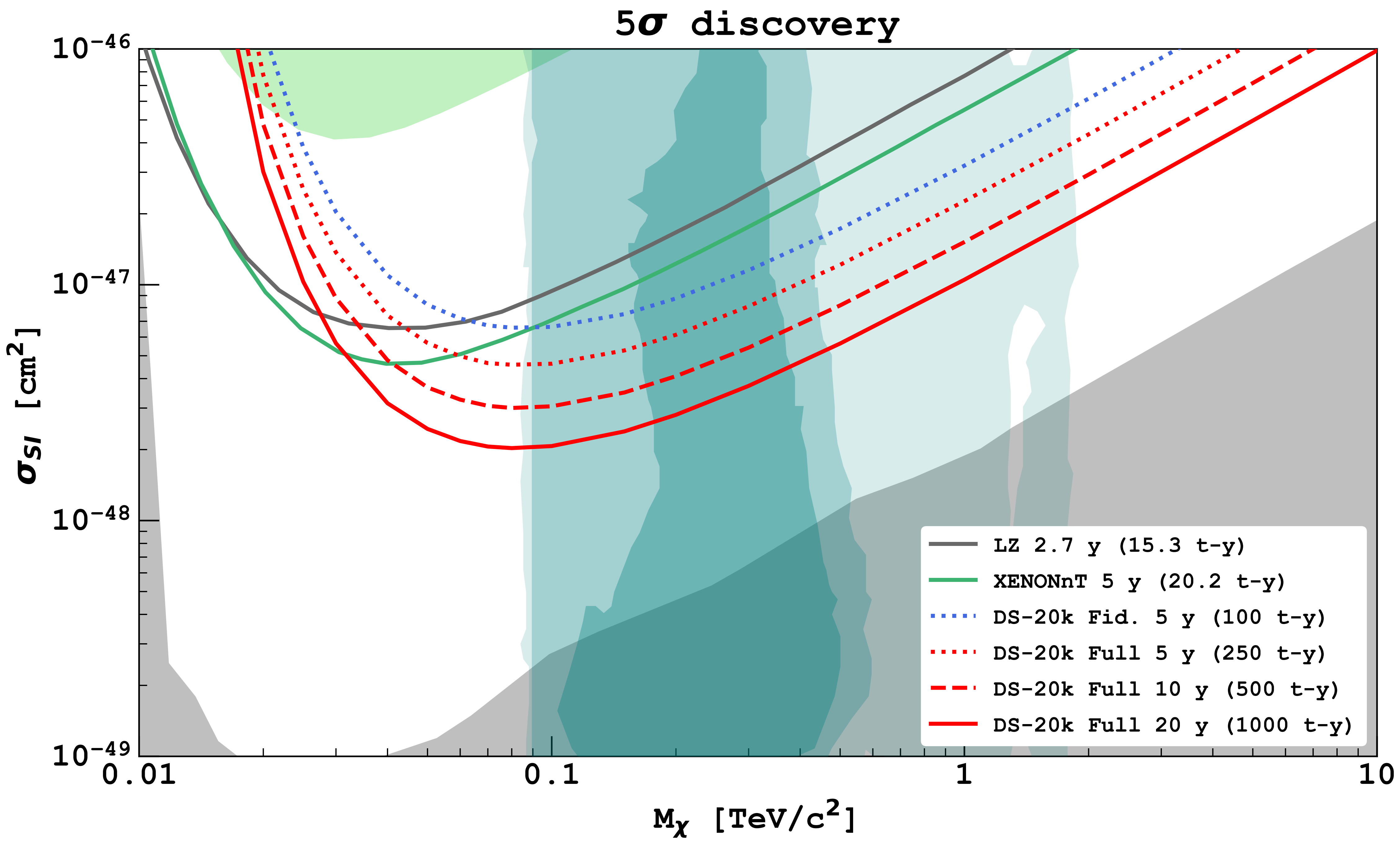
# Projected Sensitivity DS-20K



PHYSICS POTENTIAL

## EXCLUSION SENSITIVITY AND 5σ DISCOVERY POTENTIAL



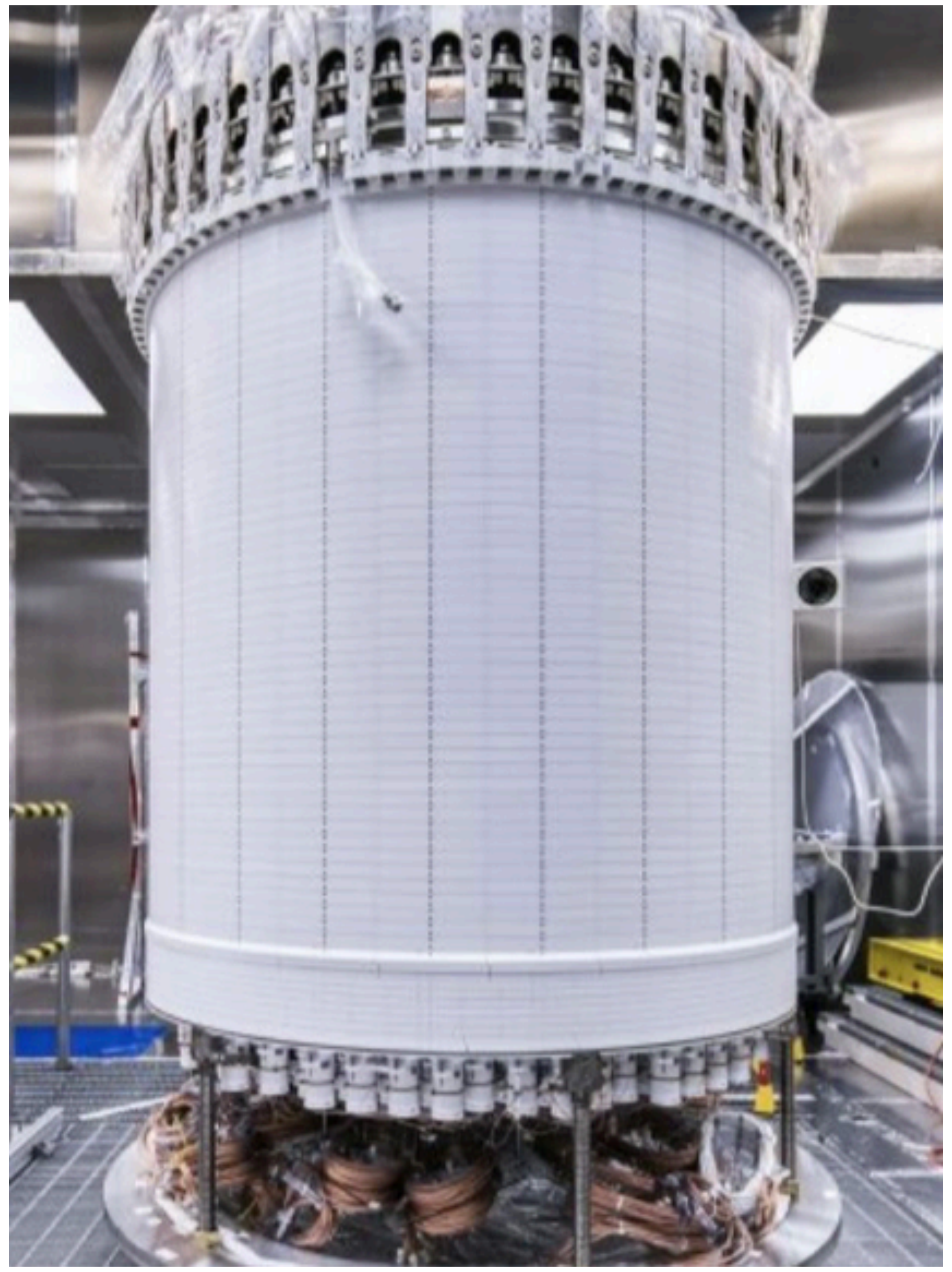




- Expect 3 events in 200 ton x year from neutrino coherent scattering ; neutrons same background condition as in DS-50 (<0.1 background events in full exposure)
- Underground Argon target, excellent PSD, and neutron veto allow zero instrumental background

# 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 5.9x$10^{-48}$ (90%CL)

see talk by Alden Fan

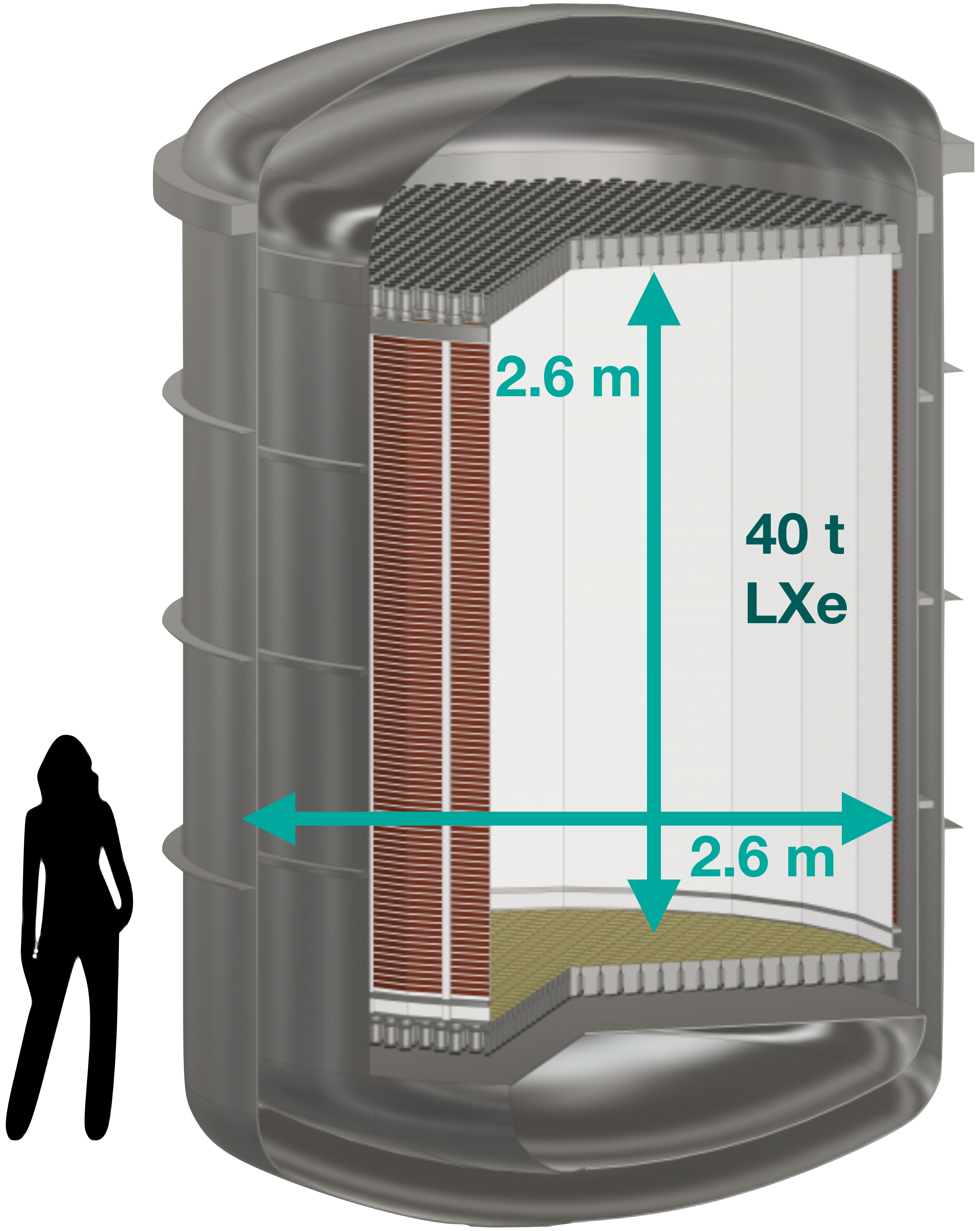
**XENONnT at LNGS**
**5.9 t target LXe**
**first results coming soon**

see status talk by Knut  Morå
also Daniel Wenz (nveto)

**xenon future:** **PandaX-30T** **DARWIN/G3 40-80 tonne detector**

# Future LXe experiments: DARWIN

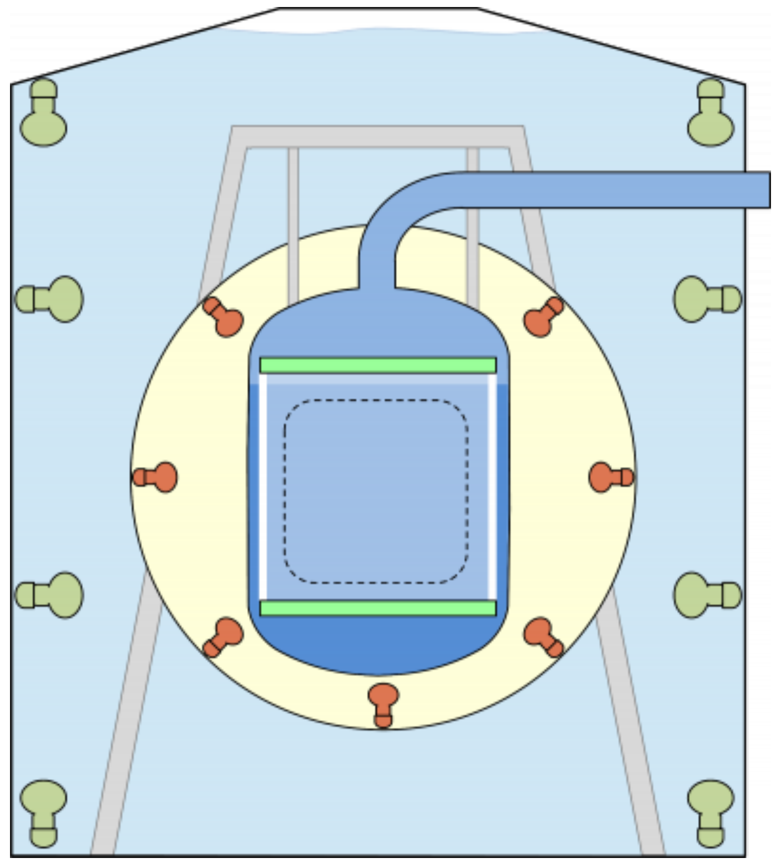





**DARk matter WImp search with liquid xenoN**

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



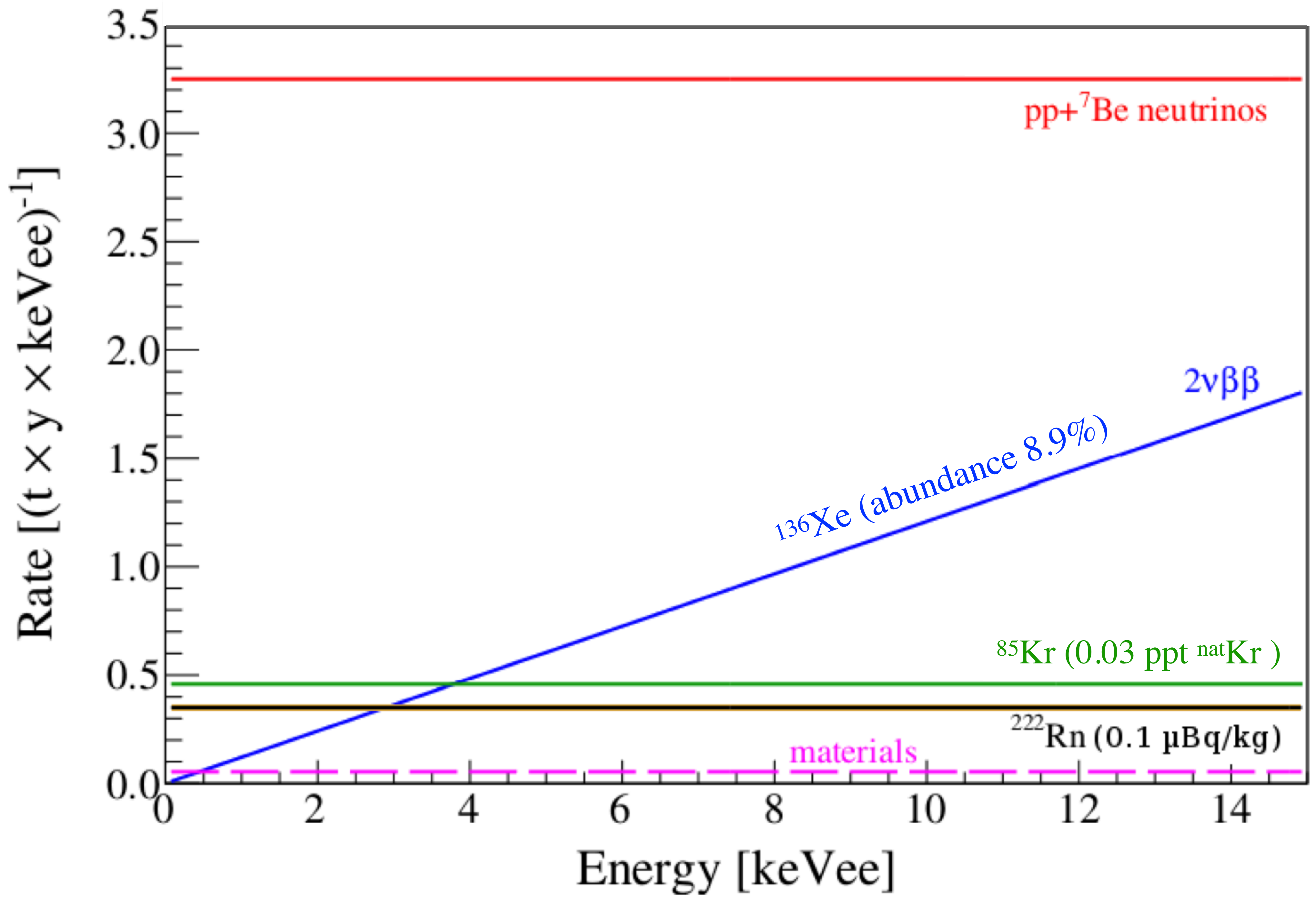
*plus an active R&D program at many institutes*

see talk by Klaus Eitel

# DARWIN



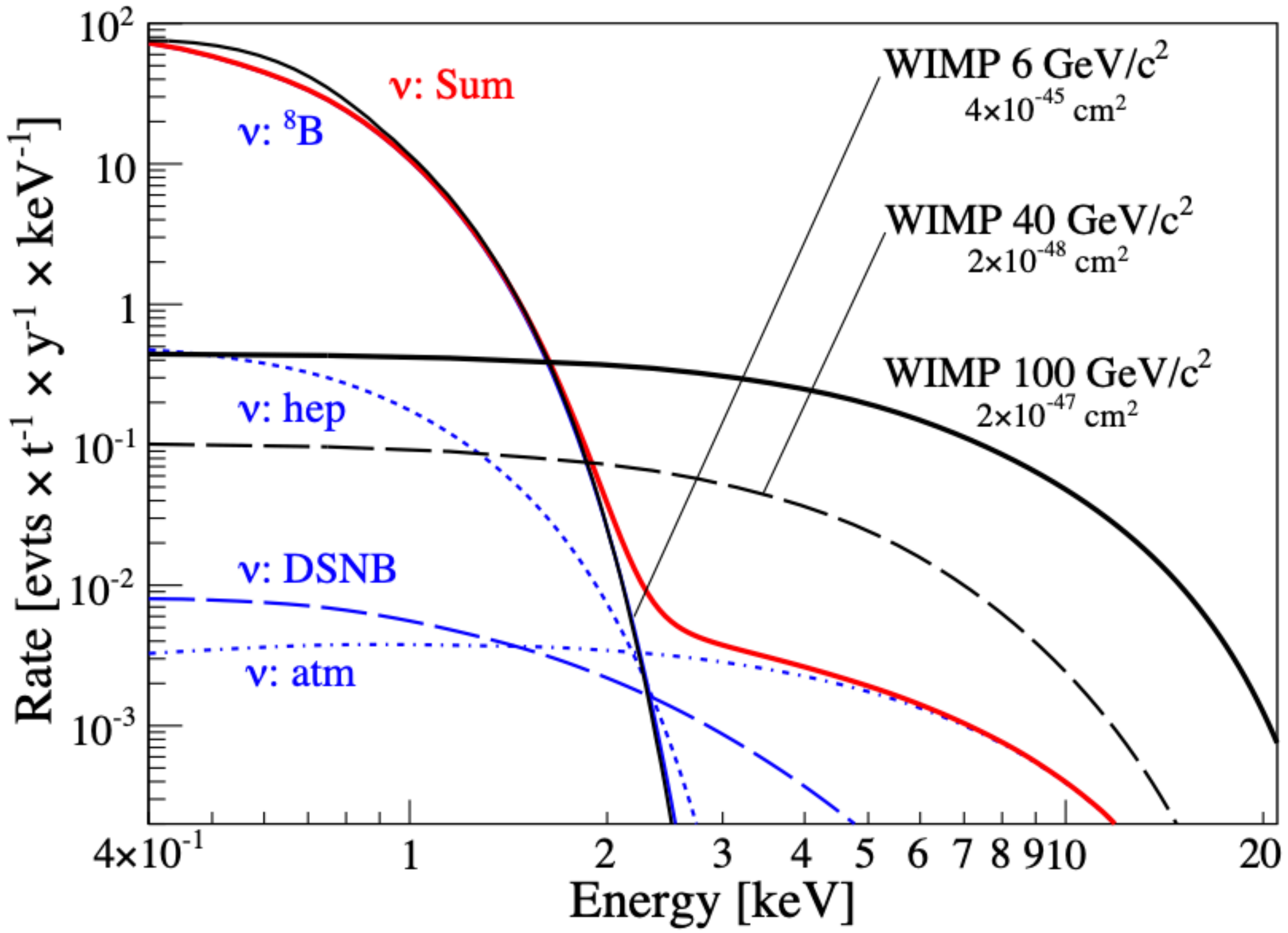
## Electronic recoil (ER) background




- 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

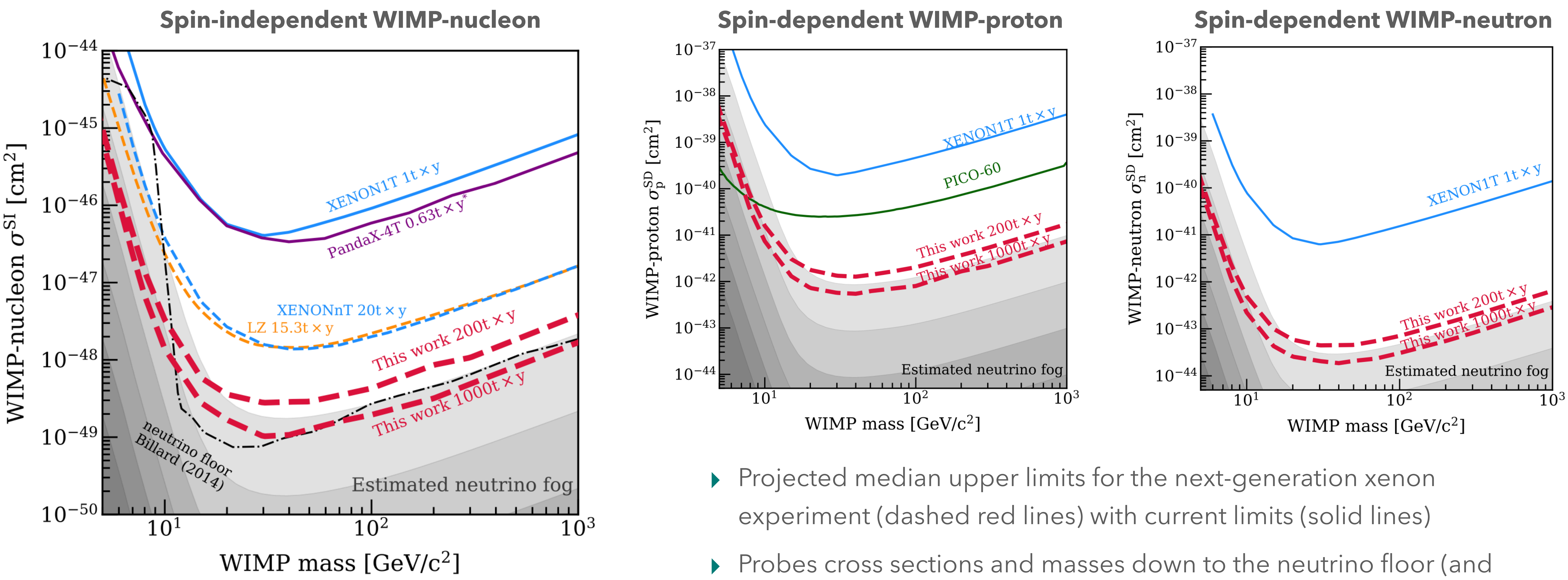



- NR background dominated by coherent elastic neutrino-nucleus scattering (**CEνNS**)
- Radiogenic neutrons: ~2 events/ 200 t yr (**materials**)
- **muon-induced neutrons**: ~0.4 events/ 200 t yr (12 m diameter water tank at LNGS)

DARWIN Collaboration, JCAP 1611 (2016) 017

# DARWIN/G3 Science Reach





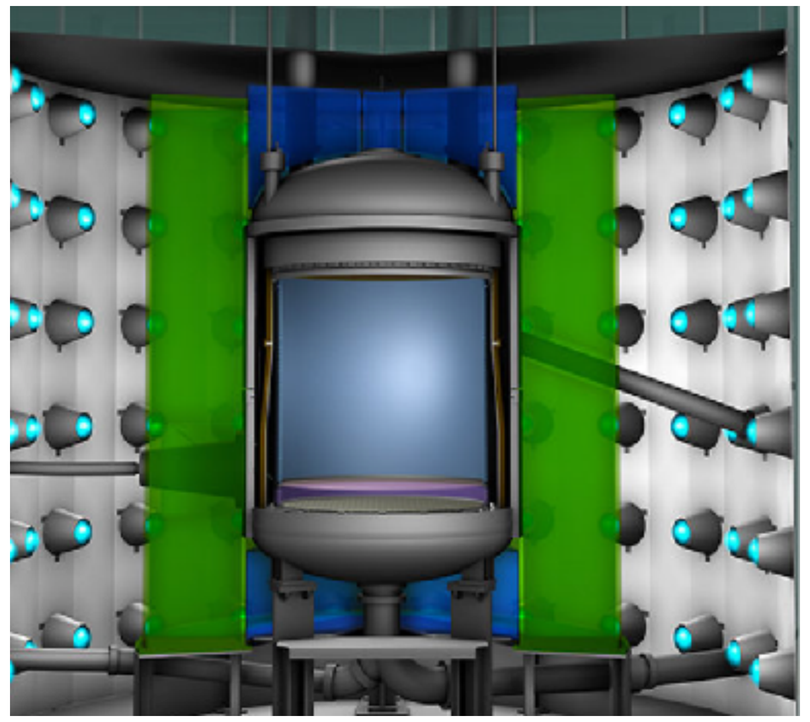

- Projected median upper limits for the next-generation xenon experiment (dashed red lines) with current limits (solid lines)
- Probes cross sections and masses down to the neutrino floor (and into the neutrino fog)
- Grey bands indicate >1, 10, 100, etc. expected neutrino events in the 50% signal-like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

Xenon community white paper: arXiv:2203.02309 (2022)

# 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**

XENON DARWIN LZ

Data taking 2027/28

- **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**

4 Mar 2022

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. Angevaare,[18] V.C. Antochi,[19] D. Antón Martin,[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. Cabrita,[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]

Xenon community white paper: arXiv:2203.02309 (2022)

**Dark Matter**

WIMPs (sub-GeV - TeV scale)

ALPs/dark photons (keV scale)

**Supernova Neutrinos**
Early alert
Multi-messenger

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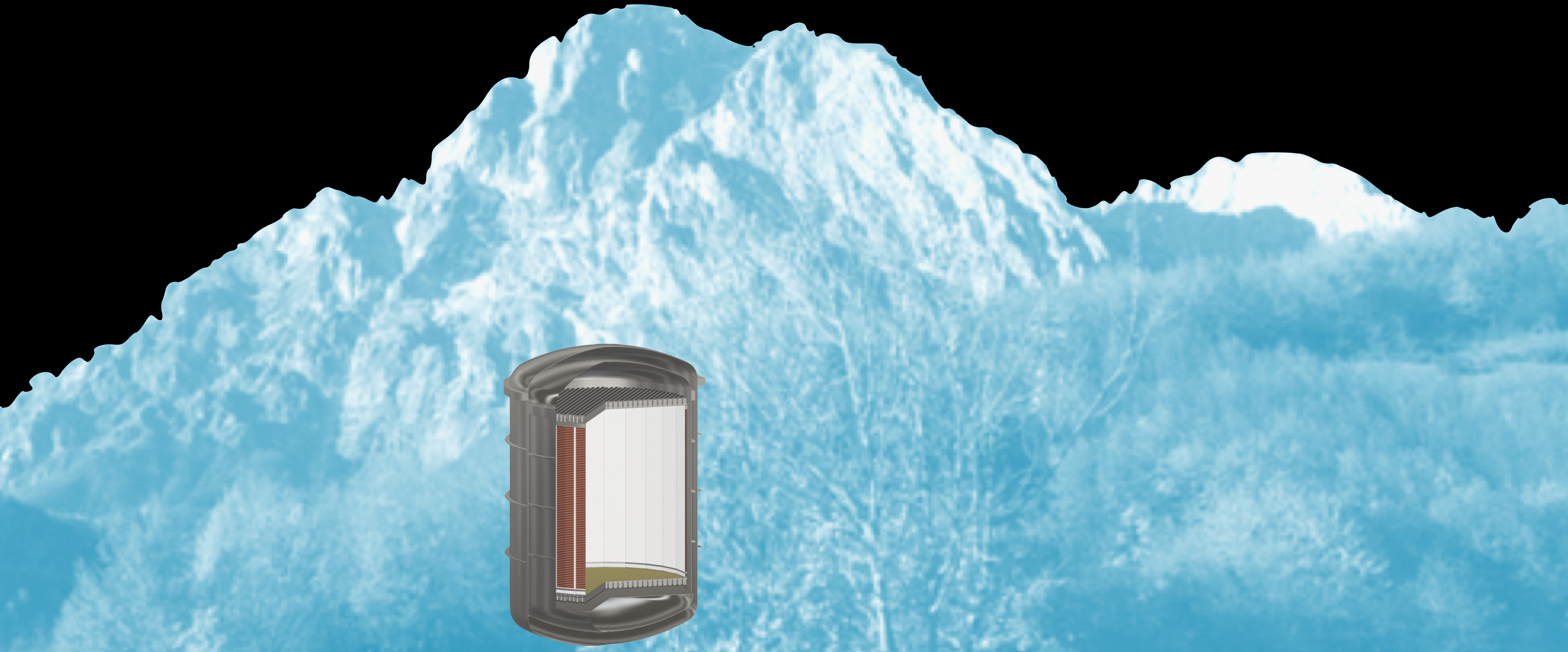

**Supernova Neutrinos**
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**Solar Neutrinos**
pp neutrino flux, $\sin^2\theta_w$
**Solar Axions**

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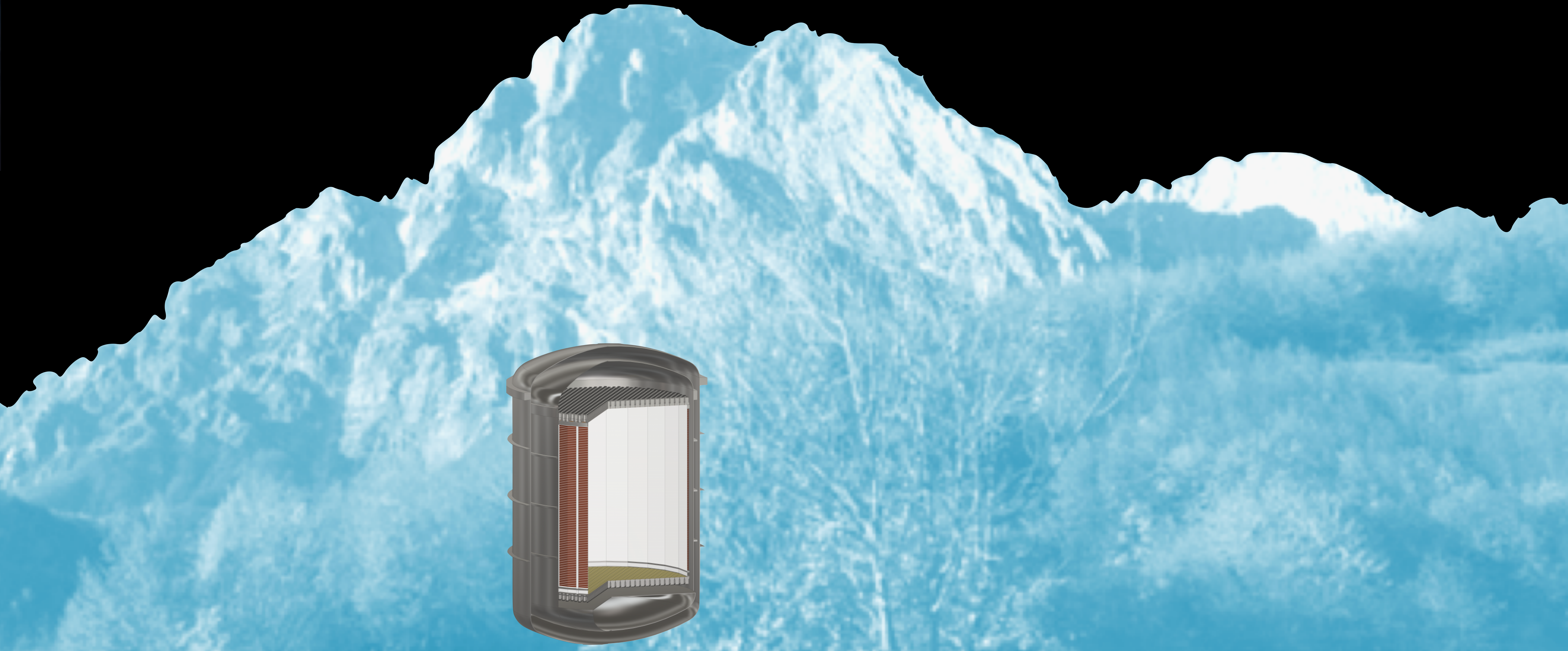

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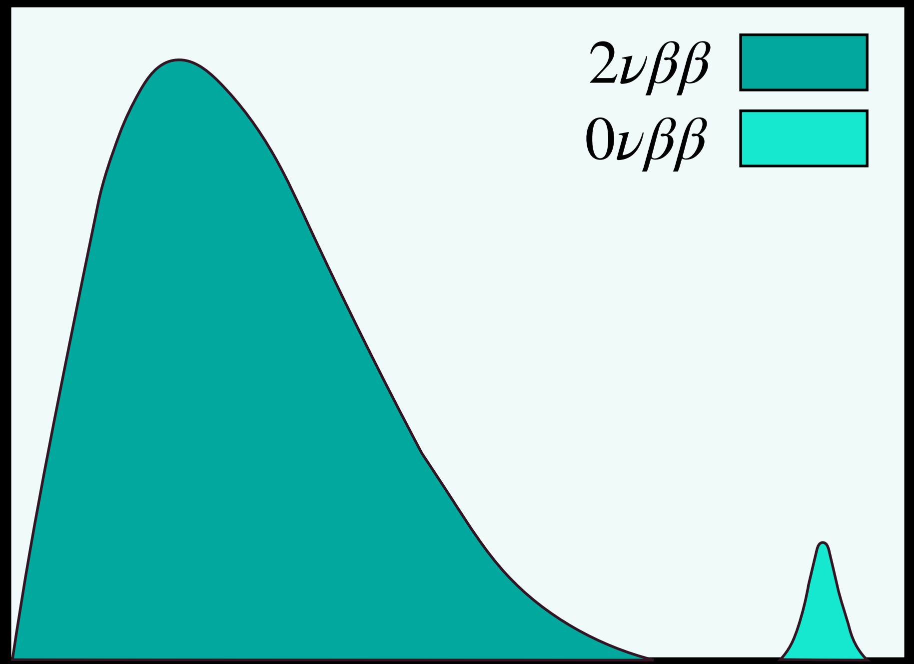
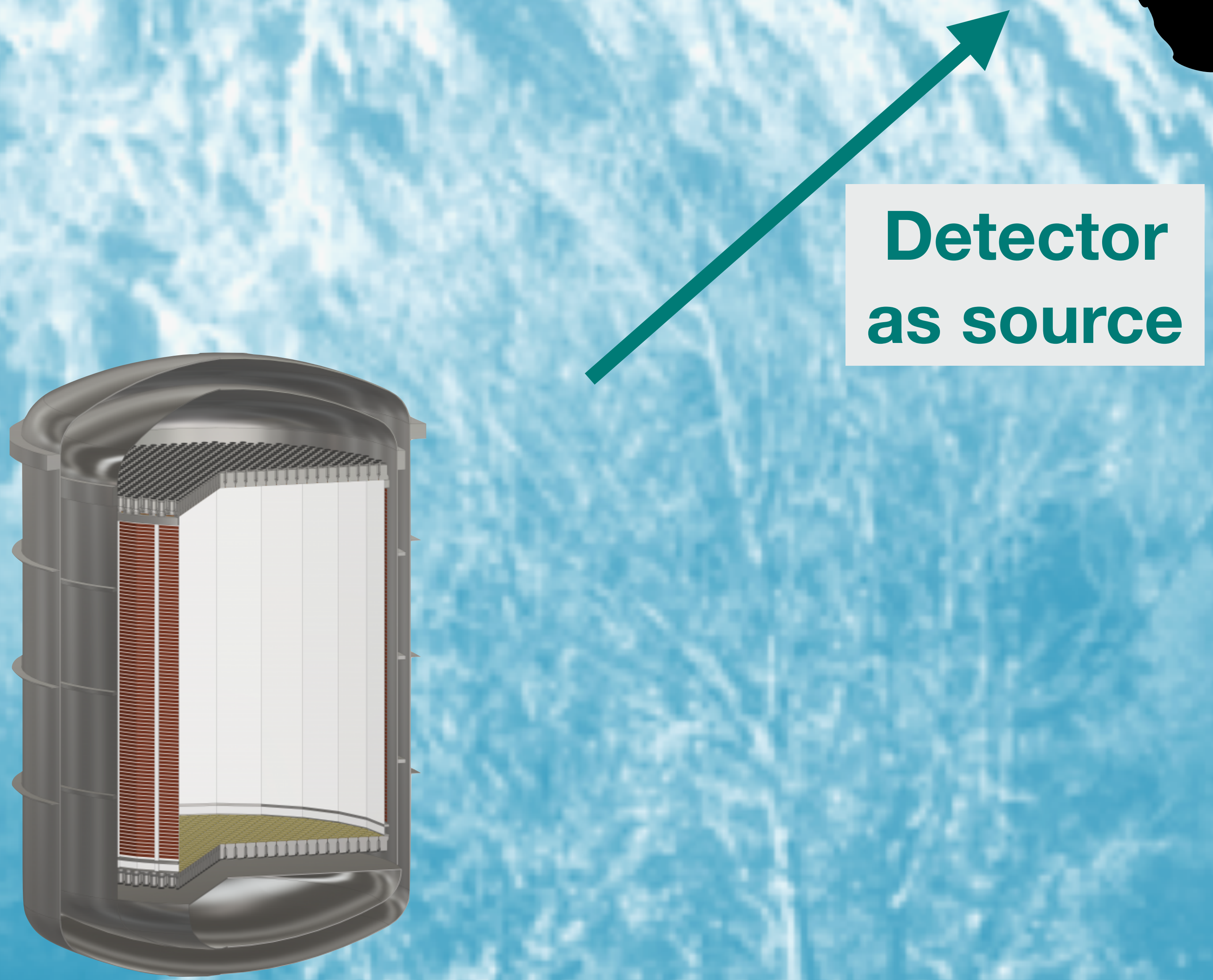
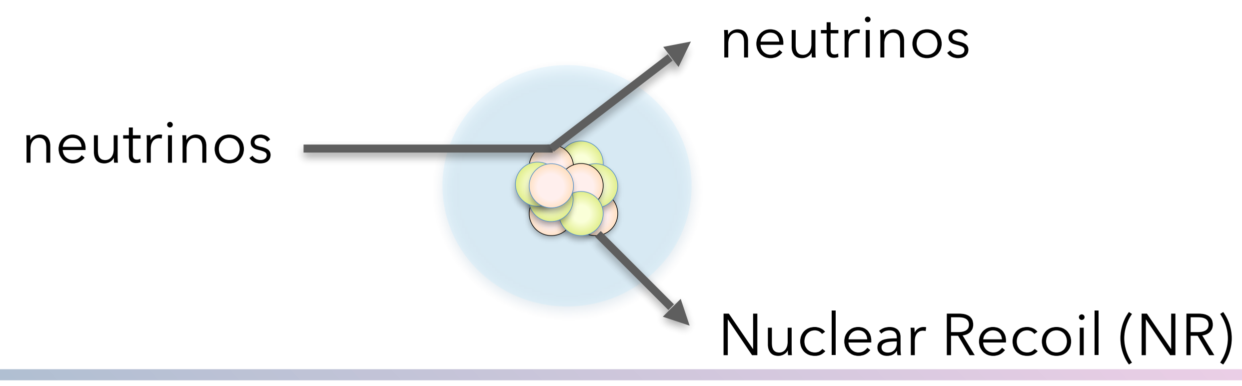
**Fundamental Physics**
Neutrinoless double beta decay of $^{136}Xe$
Rare decays



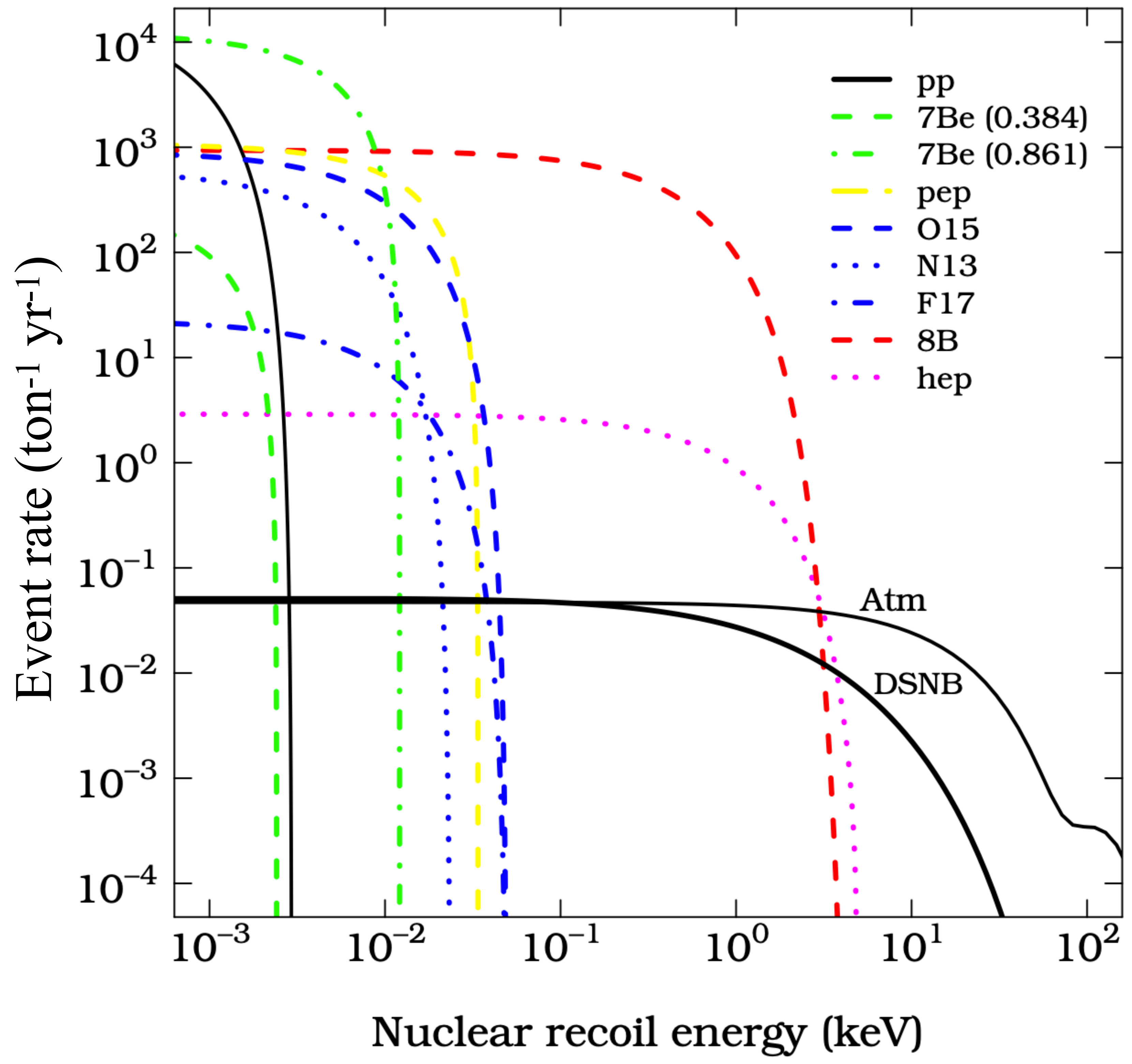



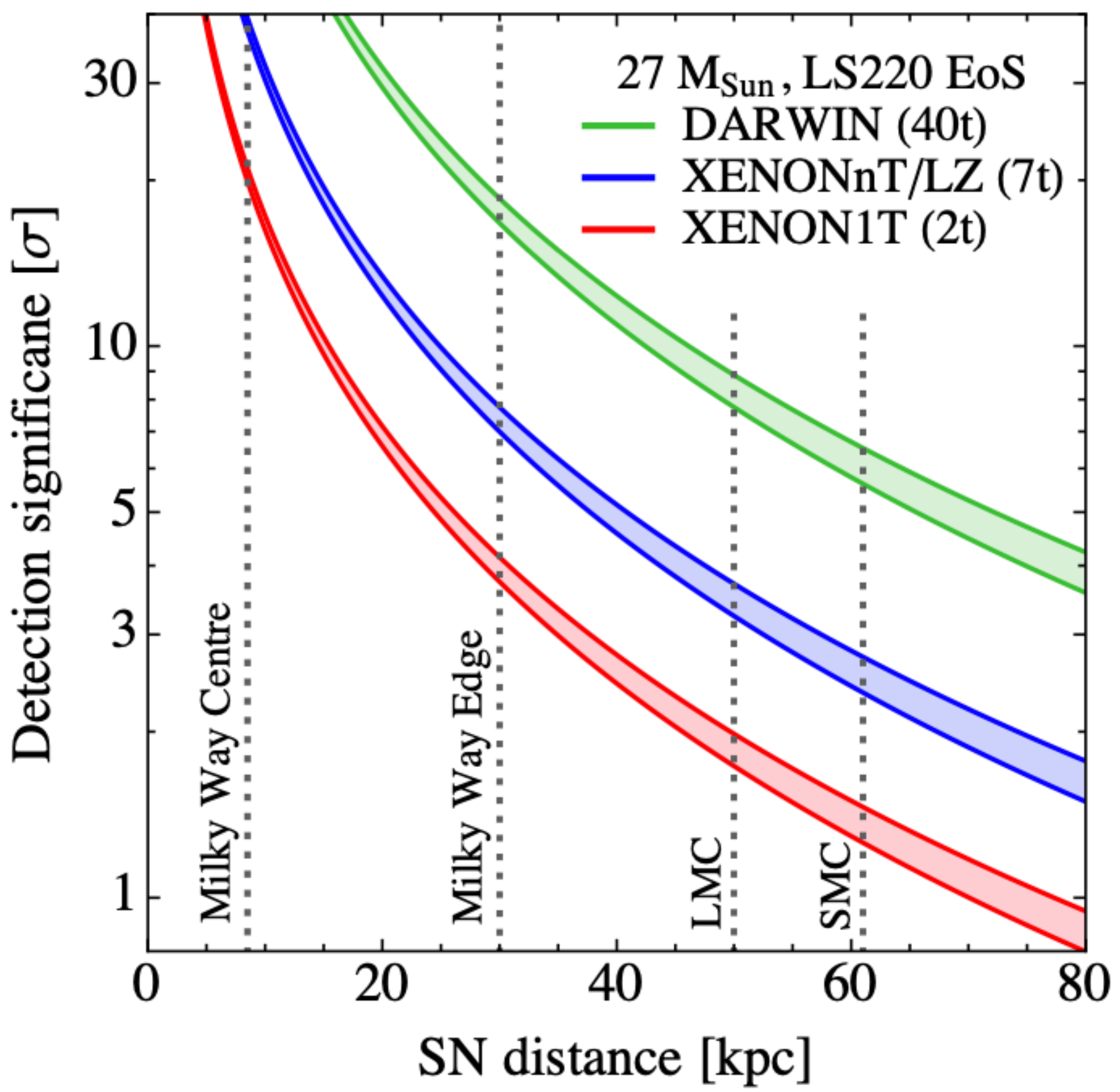
# Solar and Supernova neutrinos






**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

Xenon community white paper: arXiv:2203.02309 (2022)

R. Lang et al, PRD 94, 103009)

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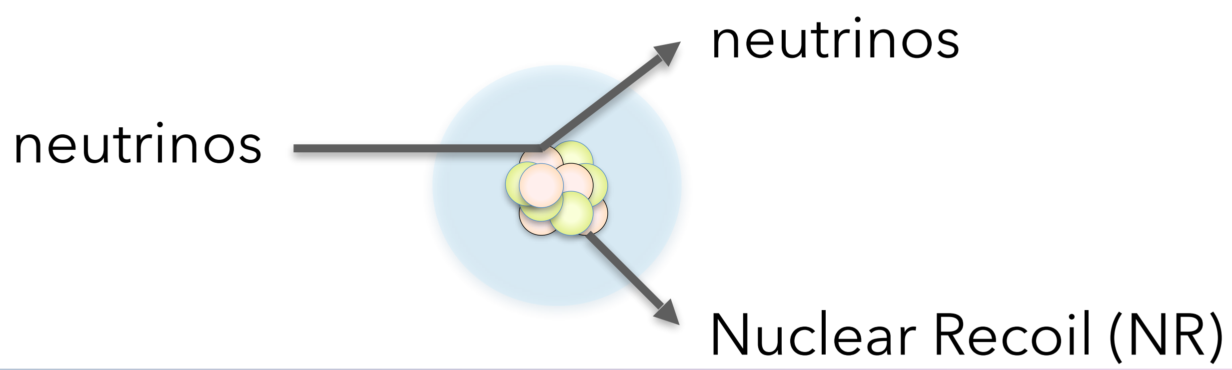




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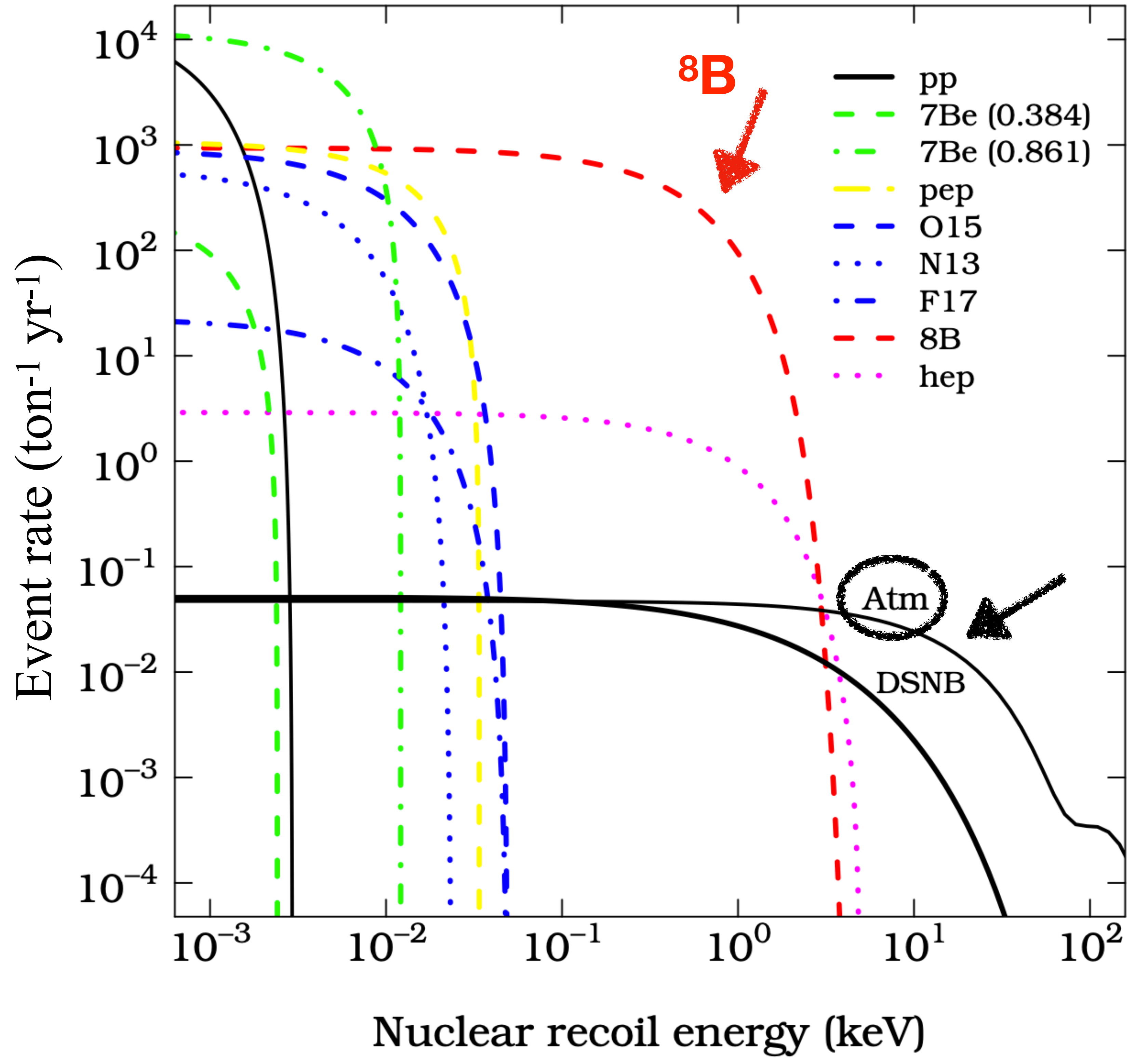


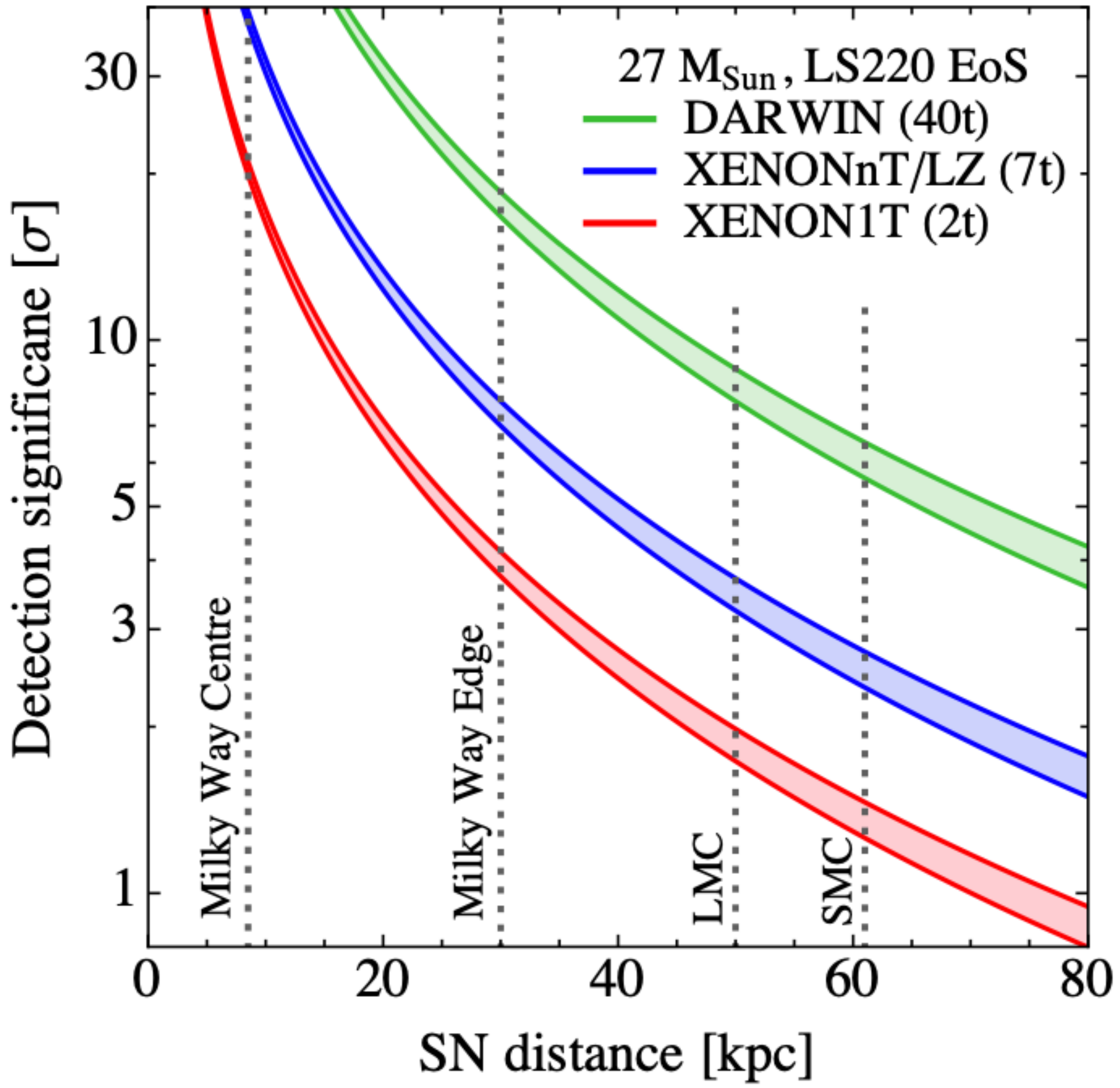


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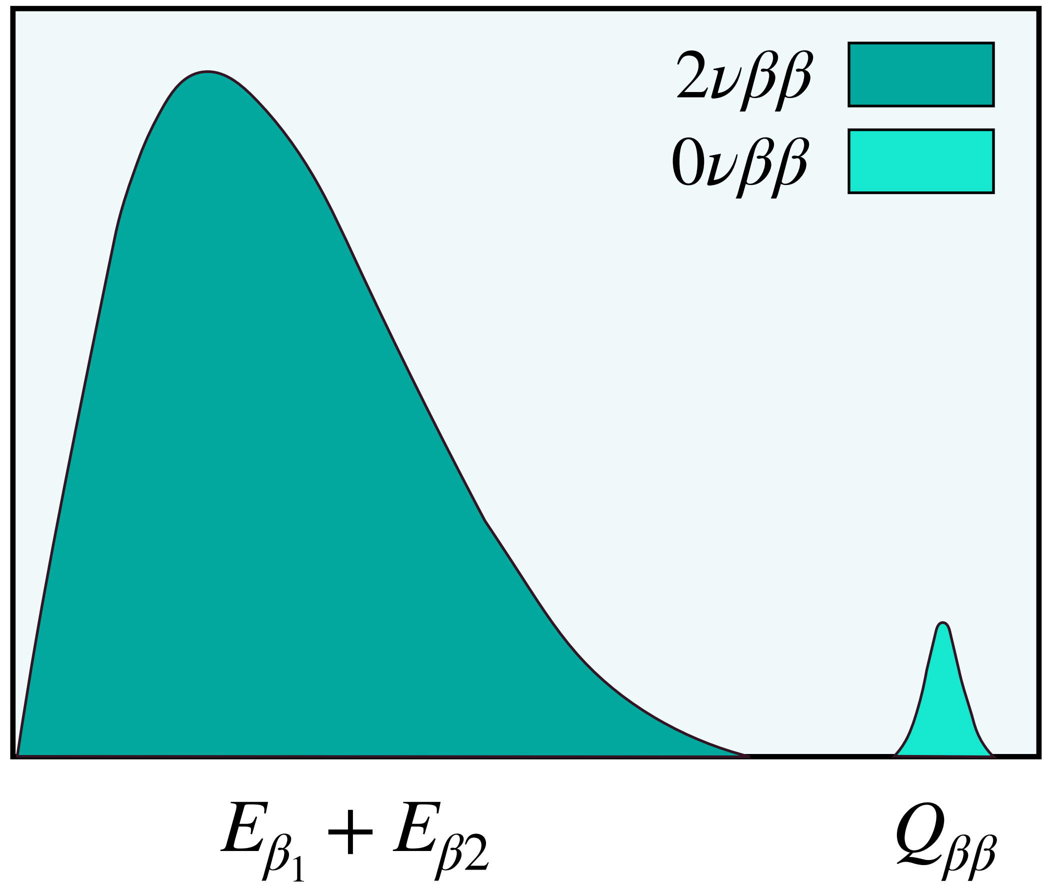
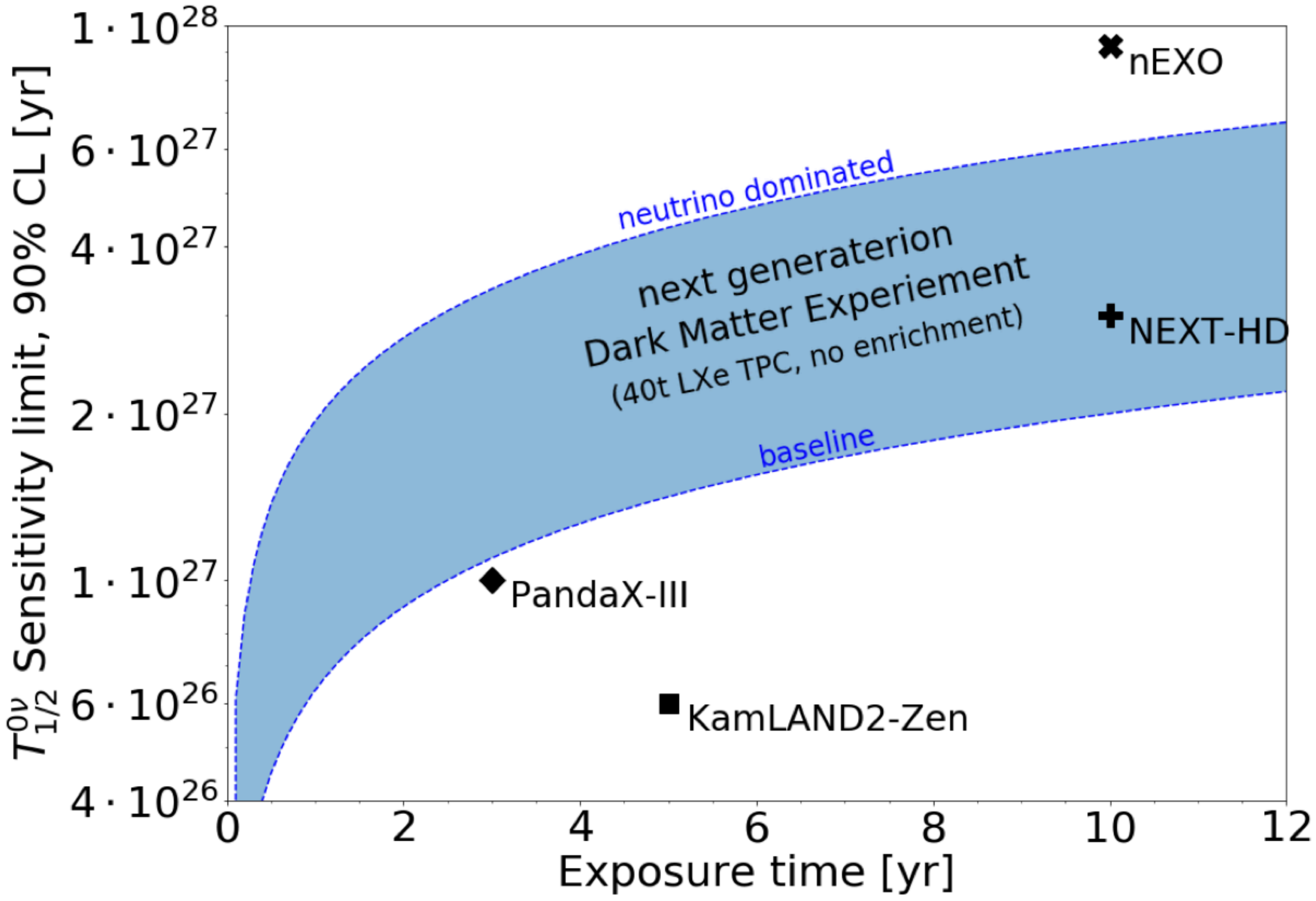



- Test of lepton number conservation
- Majorana neutrino nature

- $^{136}Xe$ 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




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

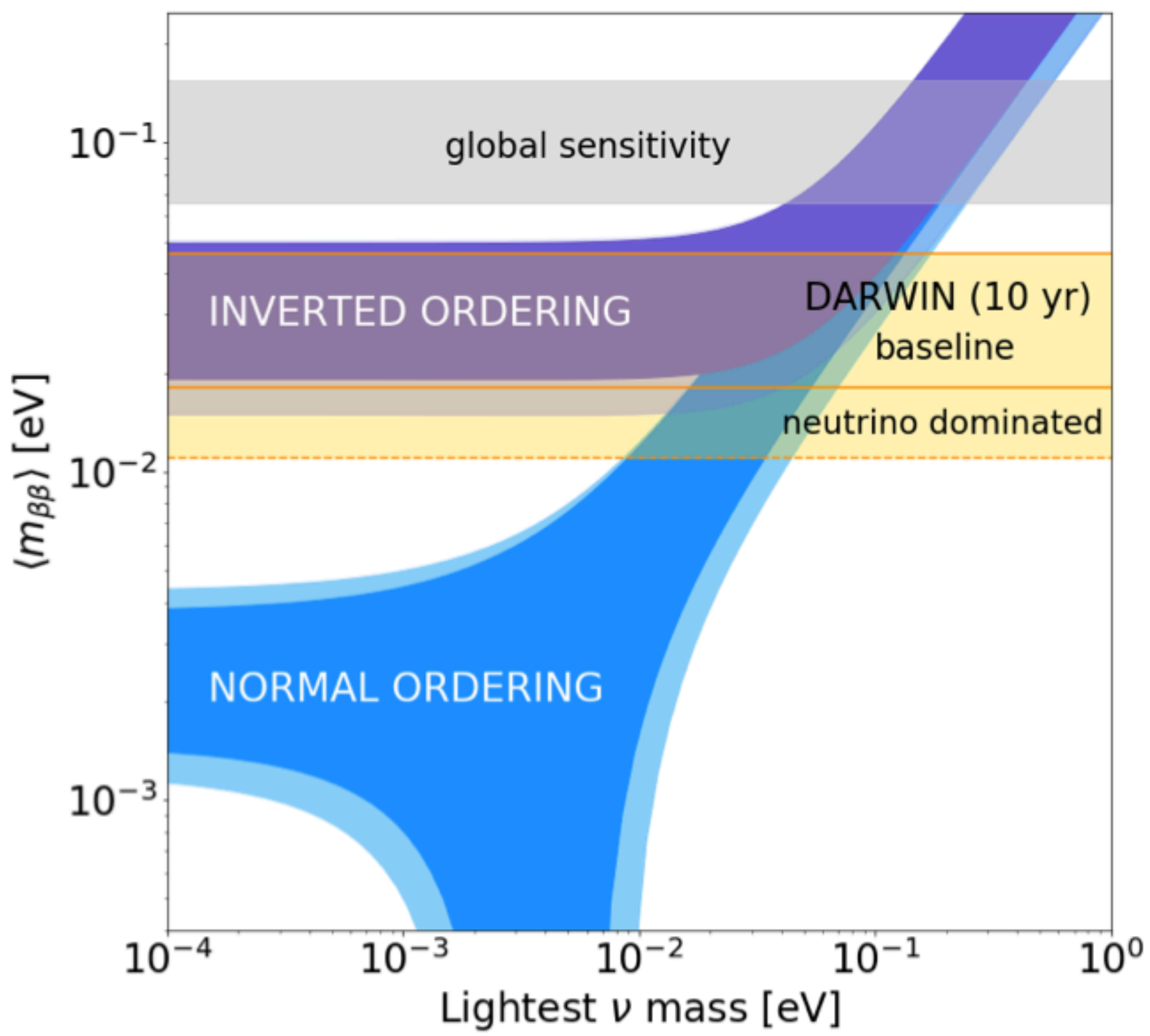
Projected sensitivity

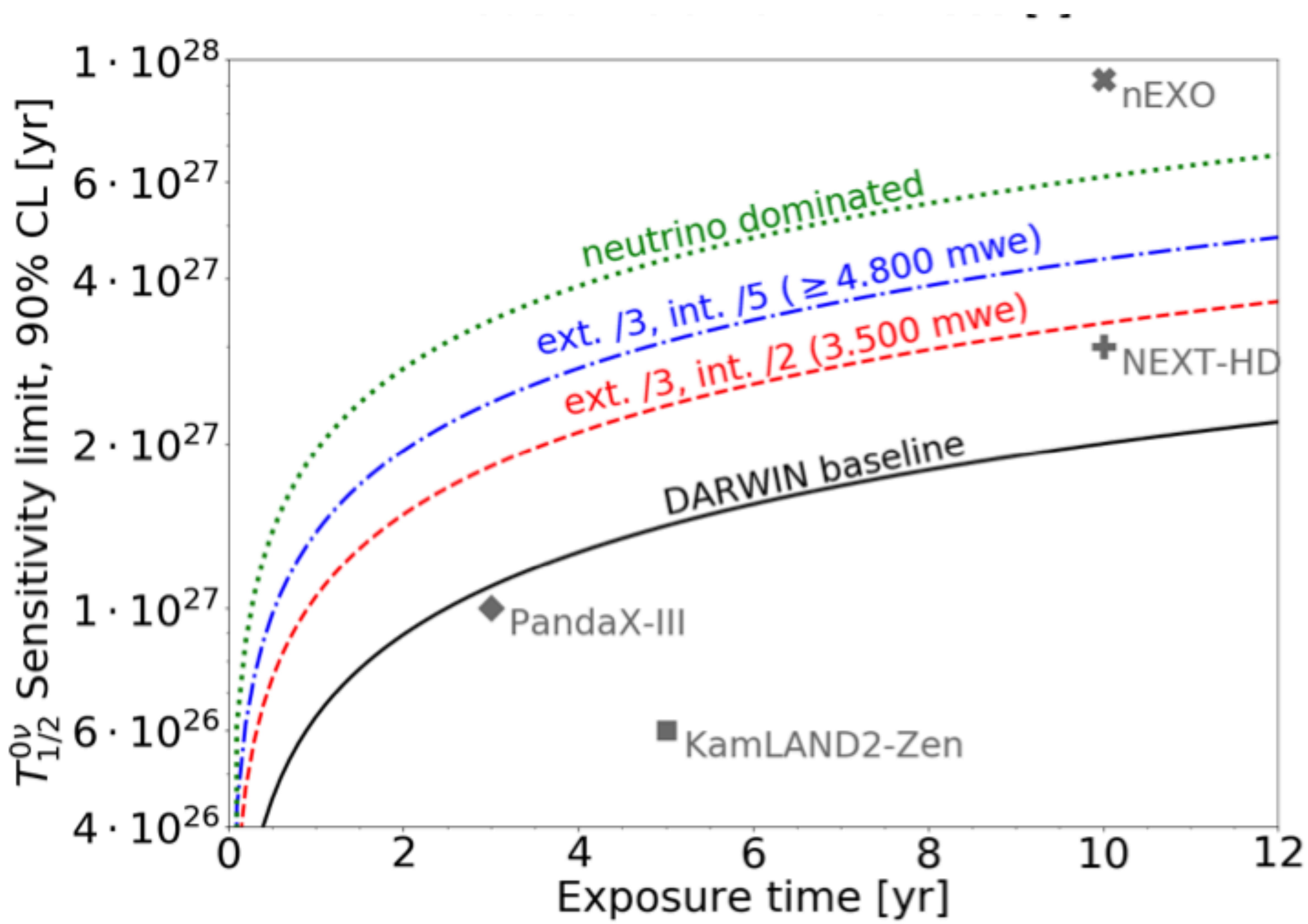
$T_{1/2} = 2.4 \times 10^{27}$ yrs in 50 t yr

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

# DARWIN/G3 Science Reach





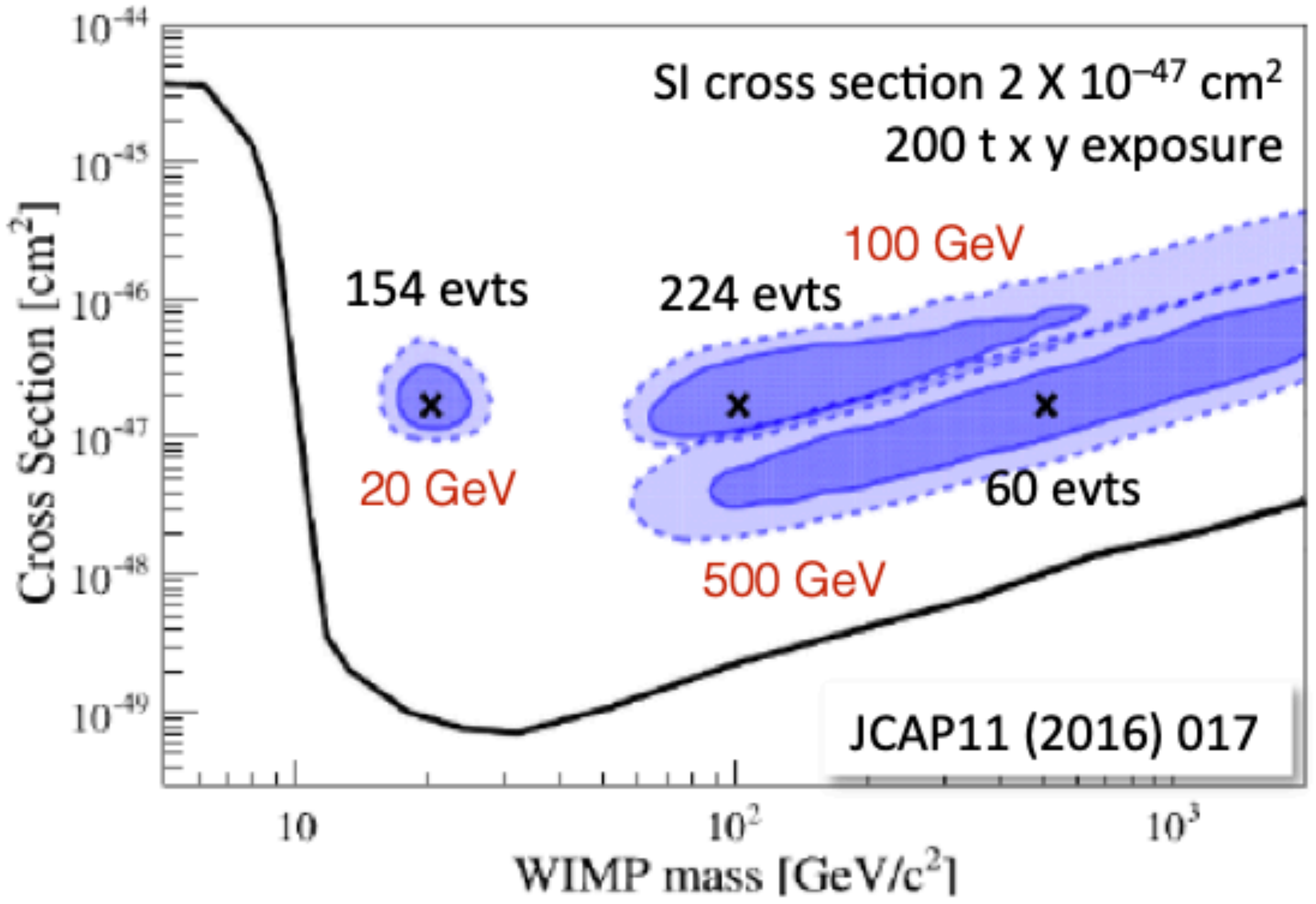

- Probe the neutrino mass heirarchy
- Background rate assumption 0.2 events/(t yr); dominated by materials (fiducial volume dependent), plus cosmogenic $^{137}Xe$ (site dependent), intrinsic $^{222}Rn$, and $^{8}B$ solar neutrinos.
- Active area of R&D aimed at reducing $0\nu\beta\beta$ backgrounds.

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

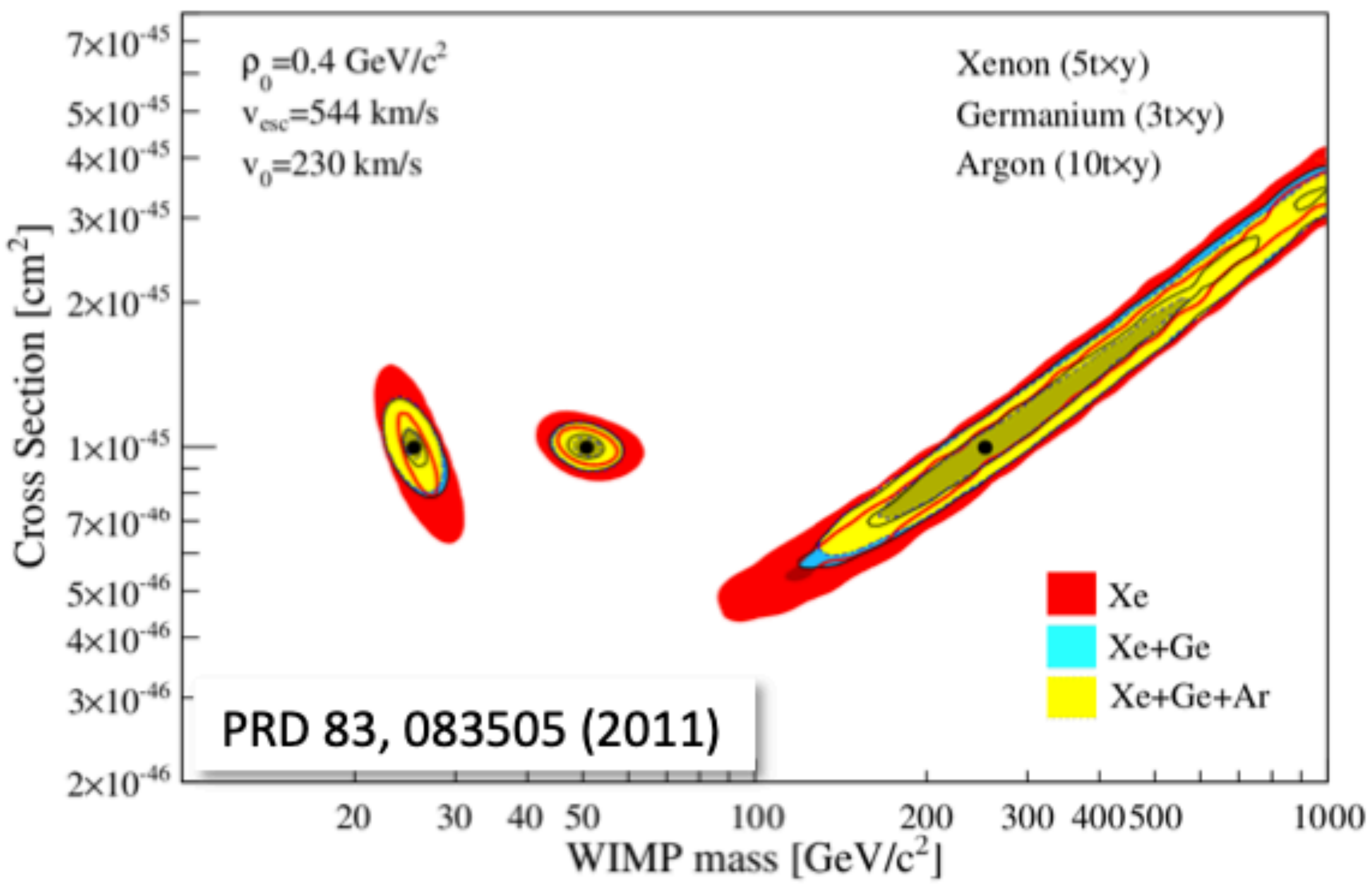
# Complementarity



## WIMP properties




## Target complementarity



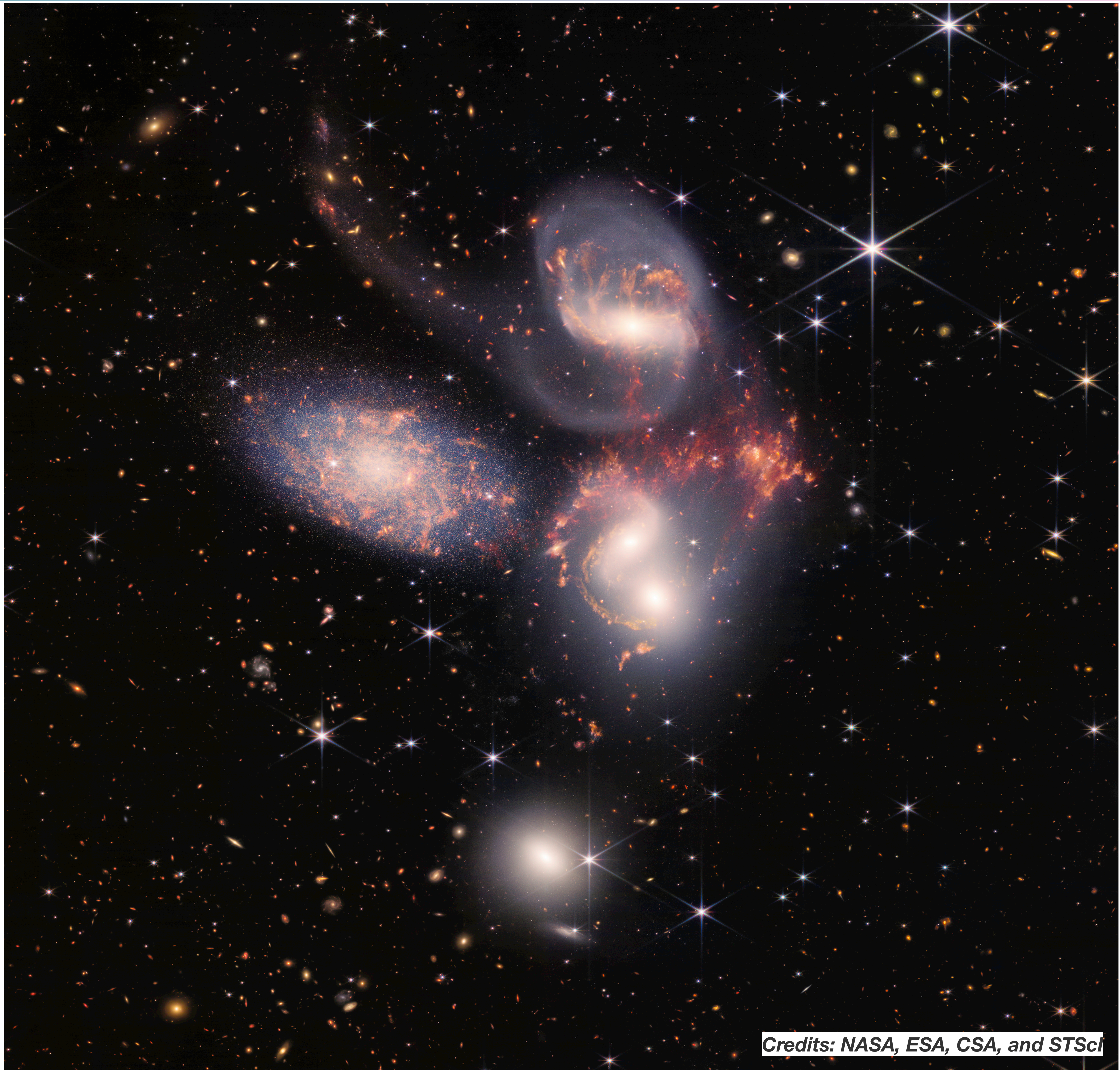

- Number of events needed to reconstruct WIMP mass and SI scattering cross section
- 1 and 2-sigma credibility regions for 20, 100, 500 GeV WIMP masses; marginalized over uncertainties in astrophysical parameters
- Can constrain up to a few 100 GeV
- Parameter reconstruction improves when considering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

# Summary



- Xenon and argon noble liquid detectors 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.

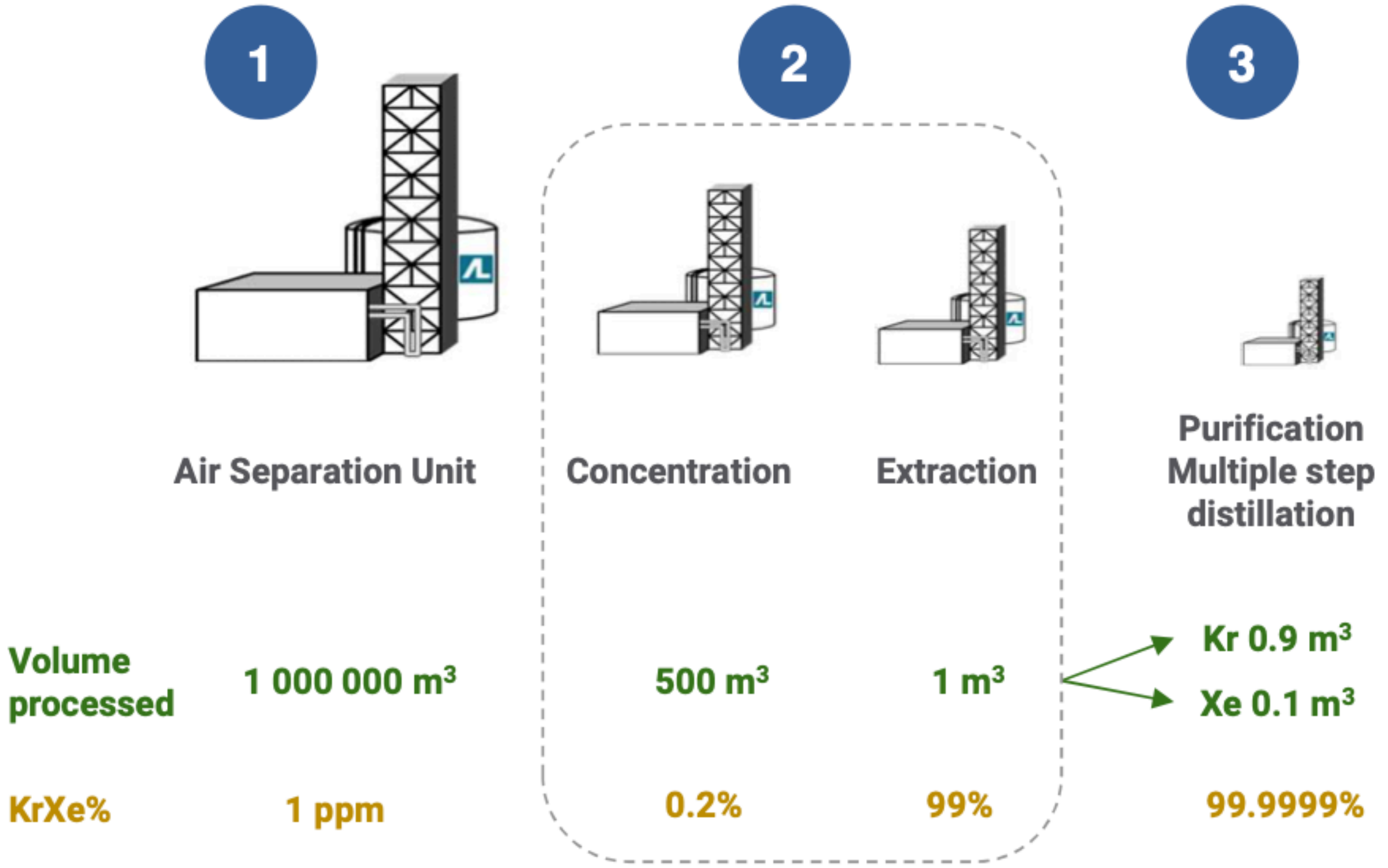
Thank you for your attention!



# 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.**

Reference: Air Liquide, Gaffet, XeSAT 2022