Nikhef DM Group:
XENON1T, XENONnT, DARWIN

KamLAND-Zen and next talk: XAMS, Modulations

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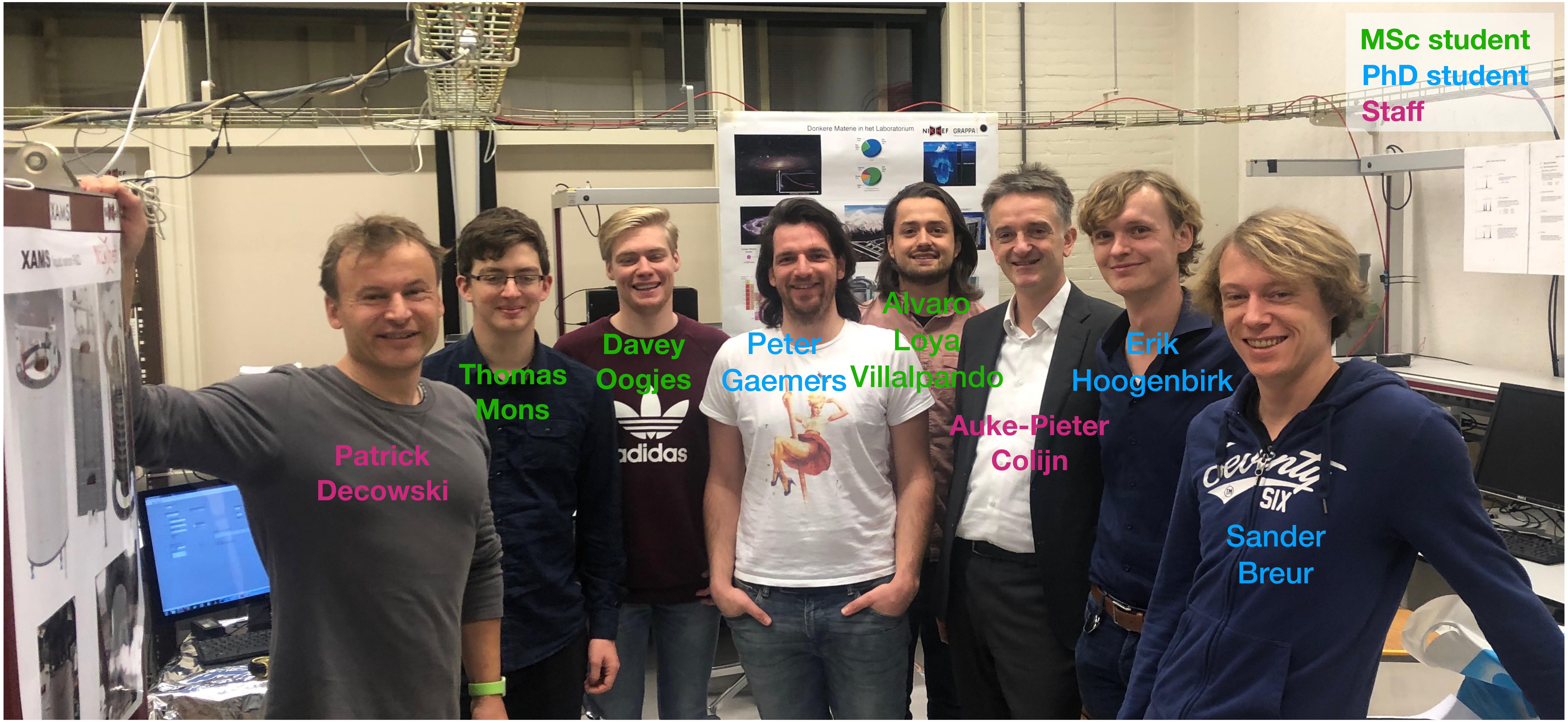
GRavitation AstroParticle Physics Amsterdam

Nikhef

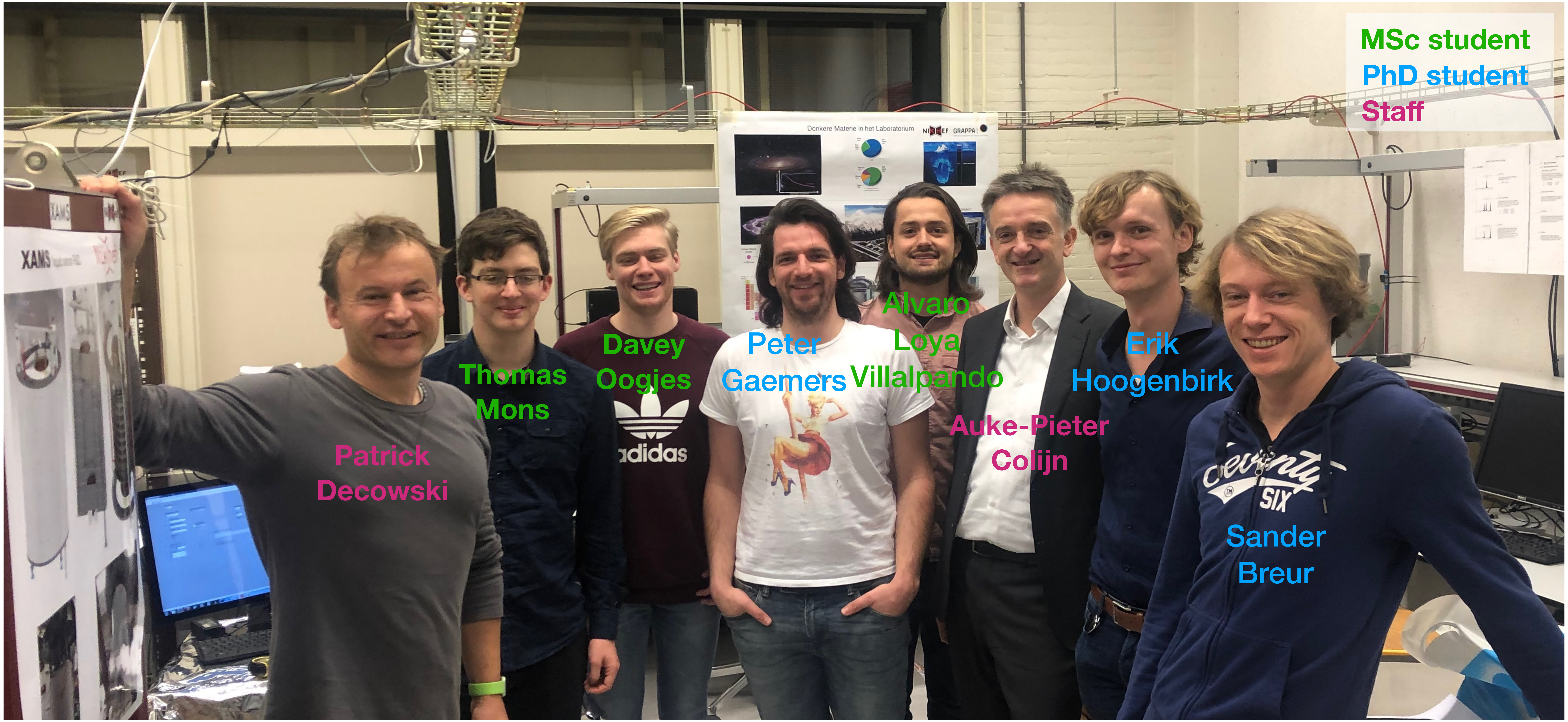
The DM Group



Not pictured: Bouke Jisse Jung

Left group: Andrew Brown (Postdoc), Jelle Aalbers (PhD), Frank Linde
New in group: Peter Gaemers (PhD), Joran Aangevare (PhD)

The DM Group



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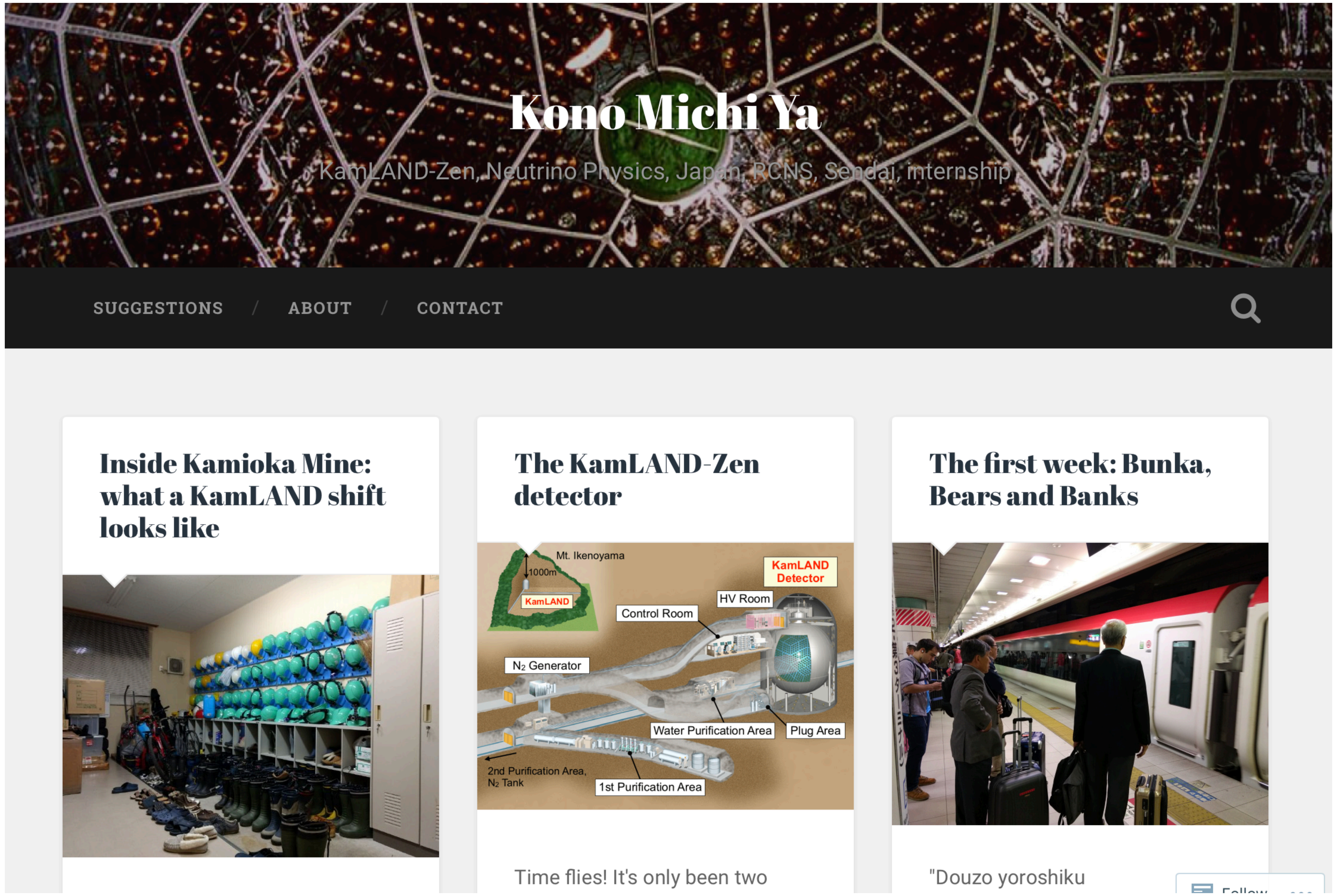
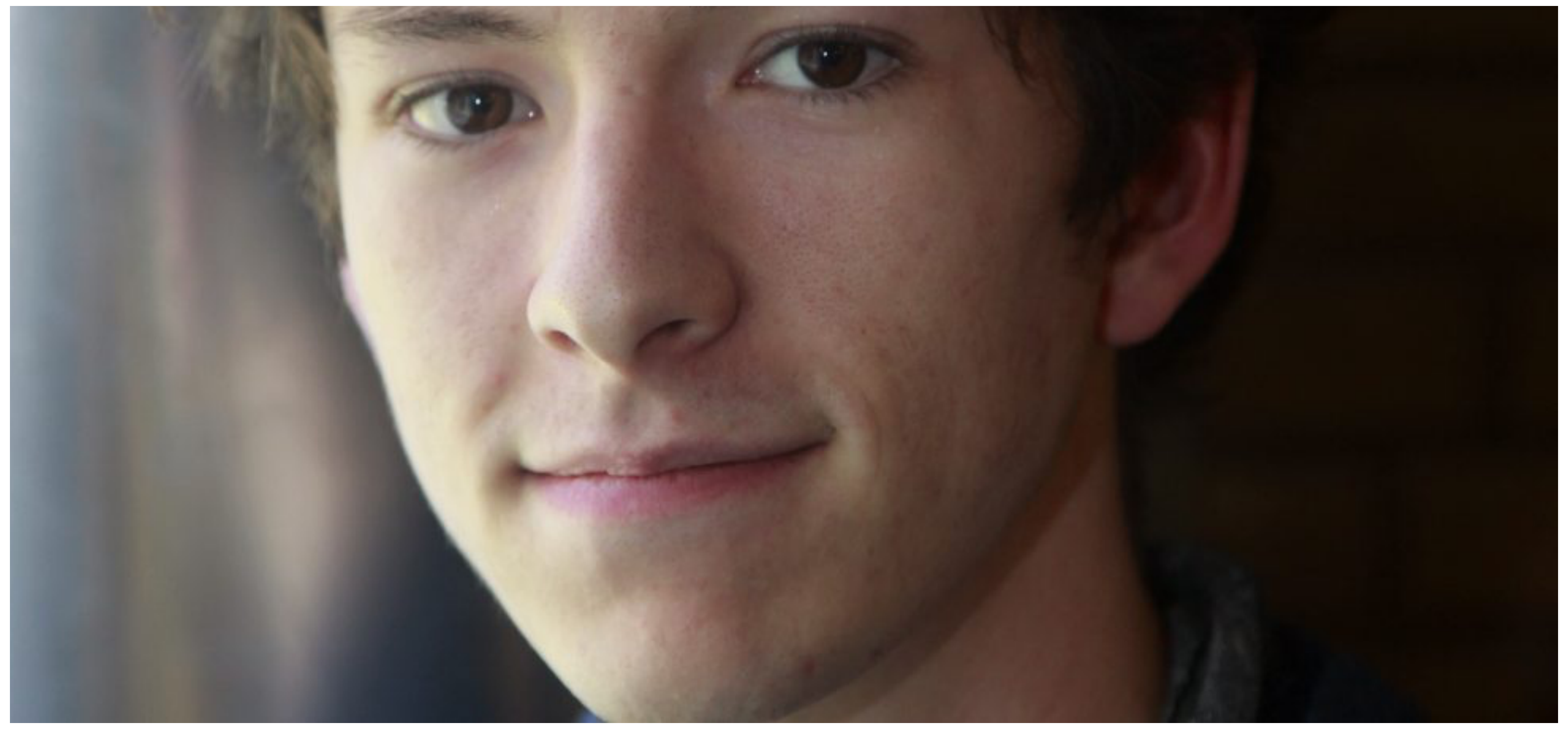
[Failed in "Expert and Newcomer's View": all people at DARWIN meeting]

Our man in Sendai: KamLAND-Zen 800

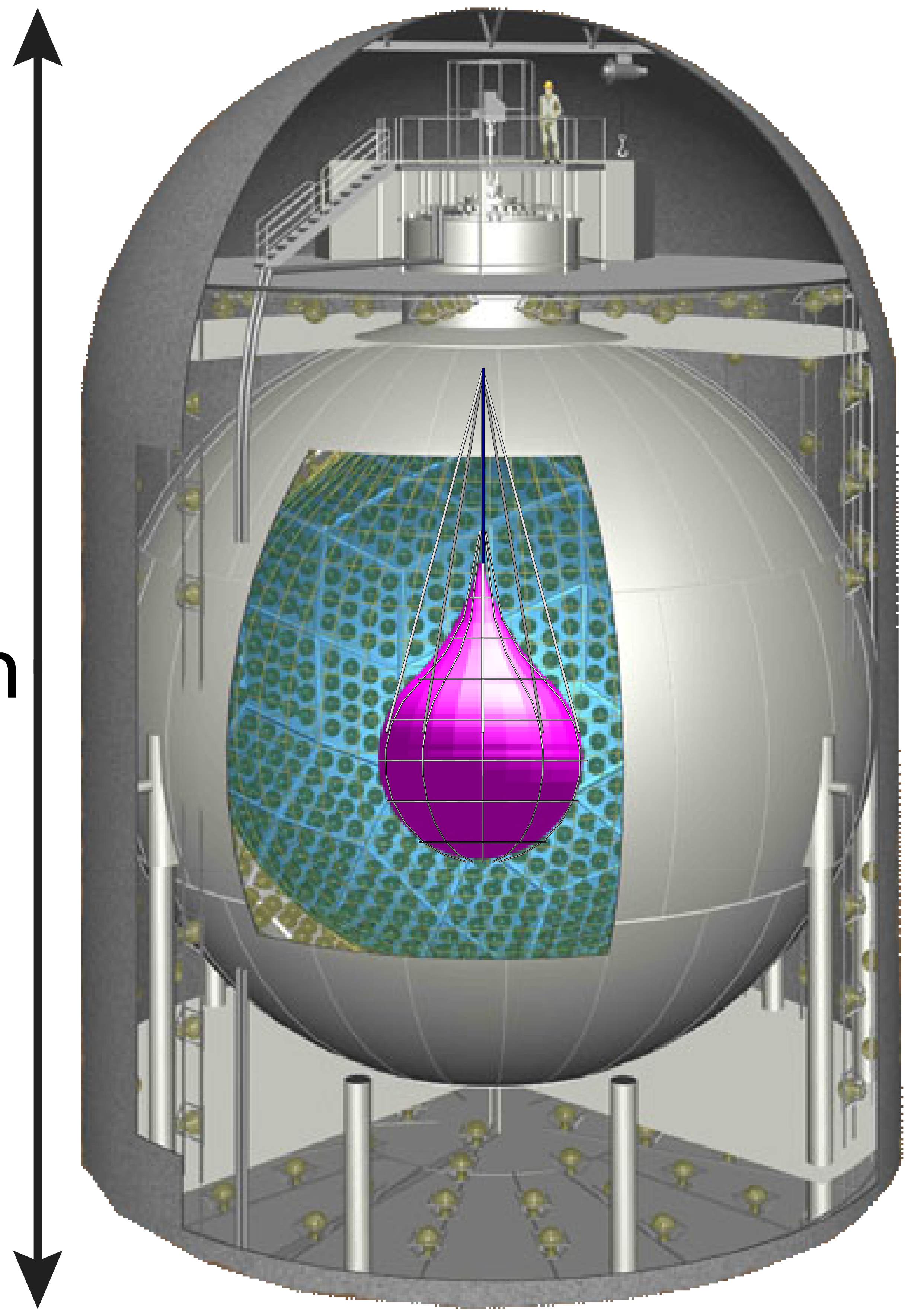
Blog: https://kono-michi-ya.com



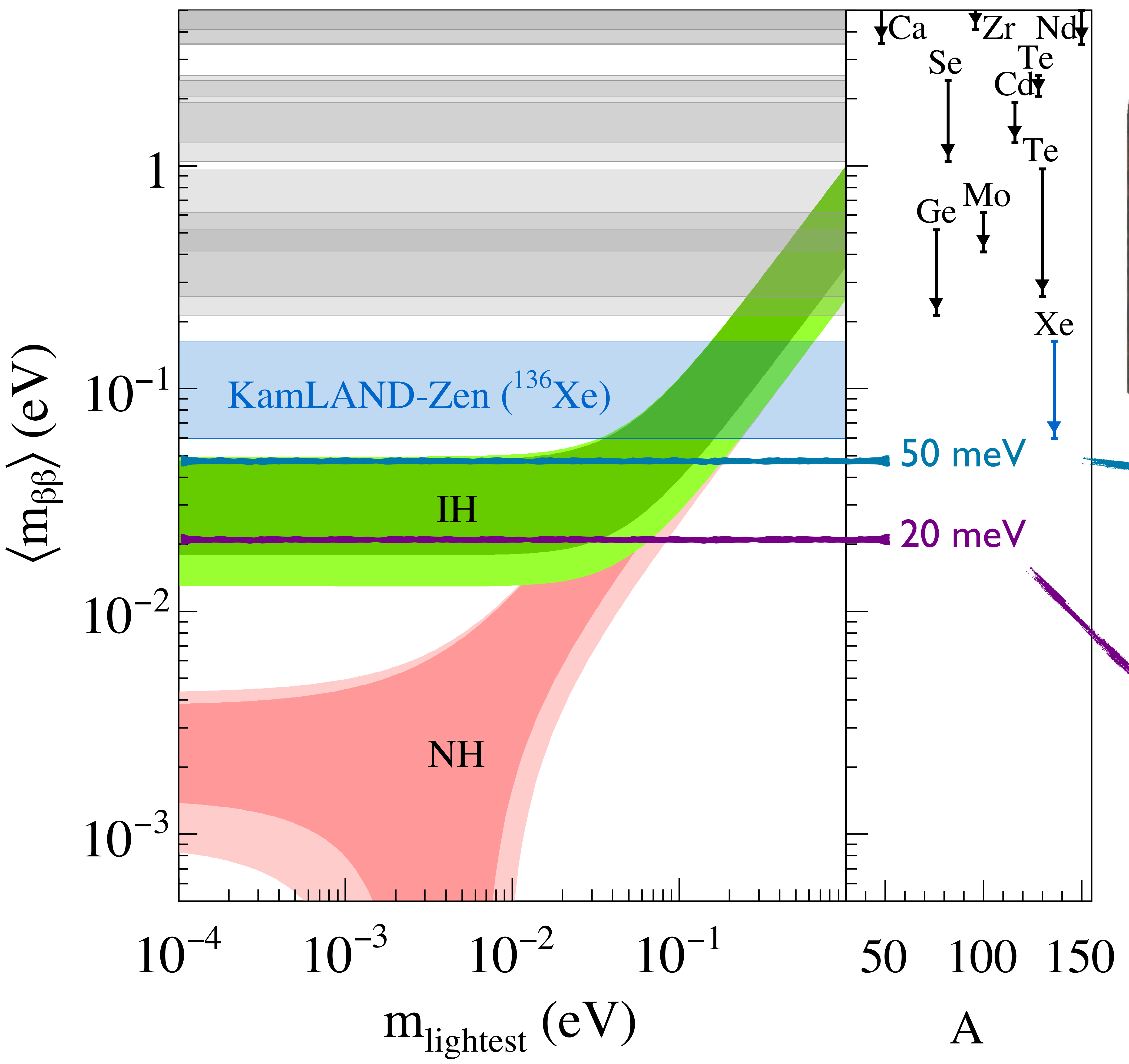


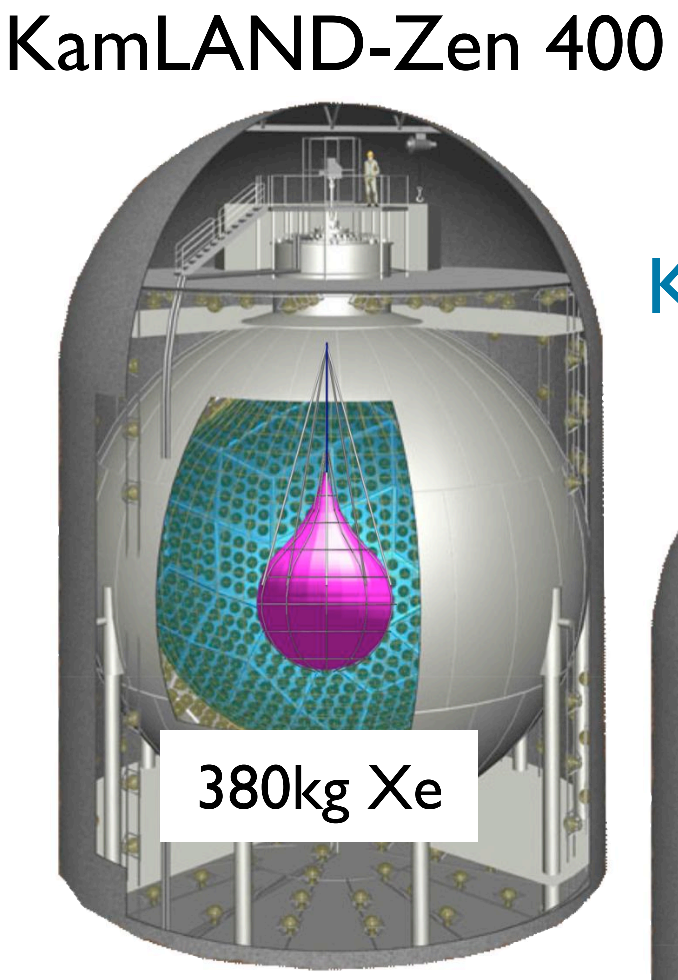
Bouke Jisse Jung (MSc student)
Volkert van der Willigen Grant

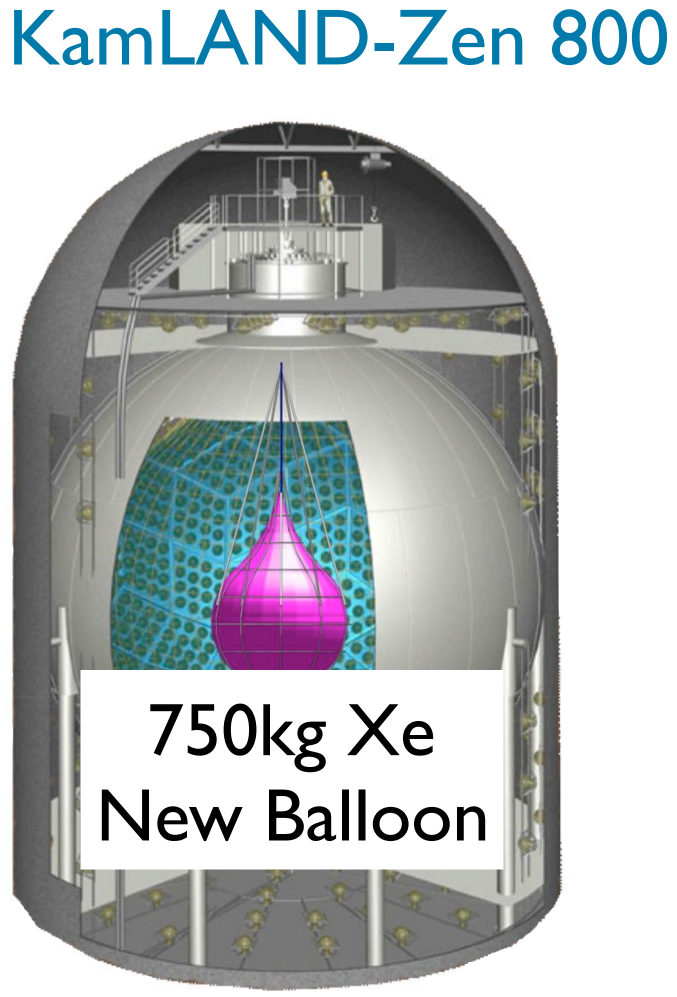
Another Xe Experiment: KamLAND-Zen 800

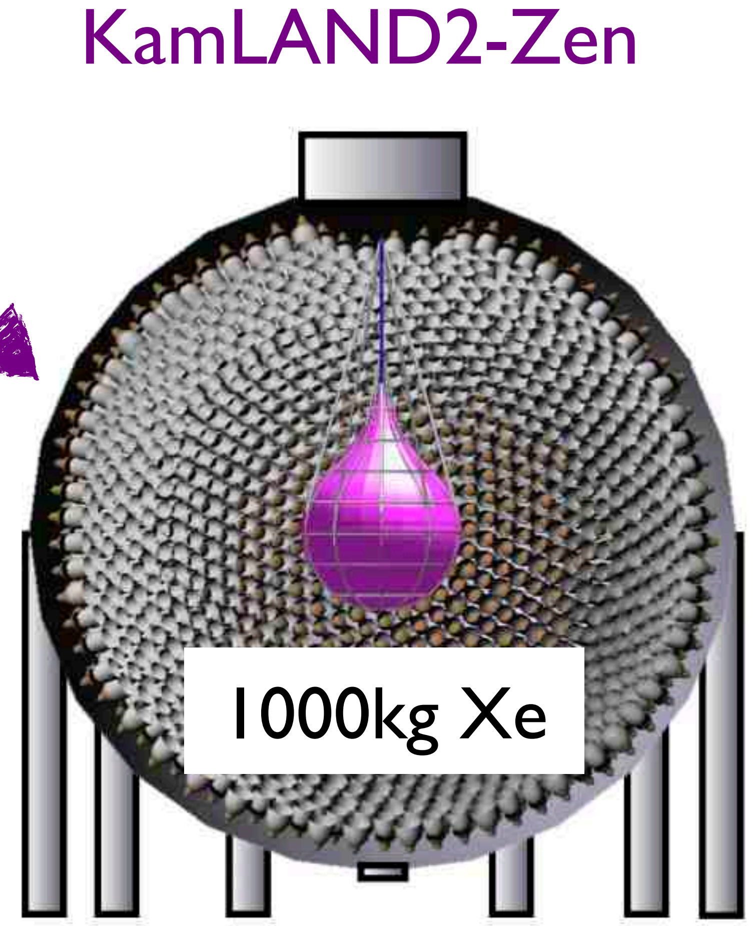


20m







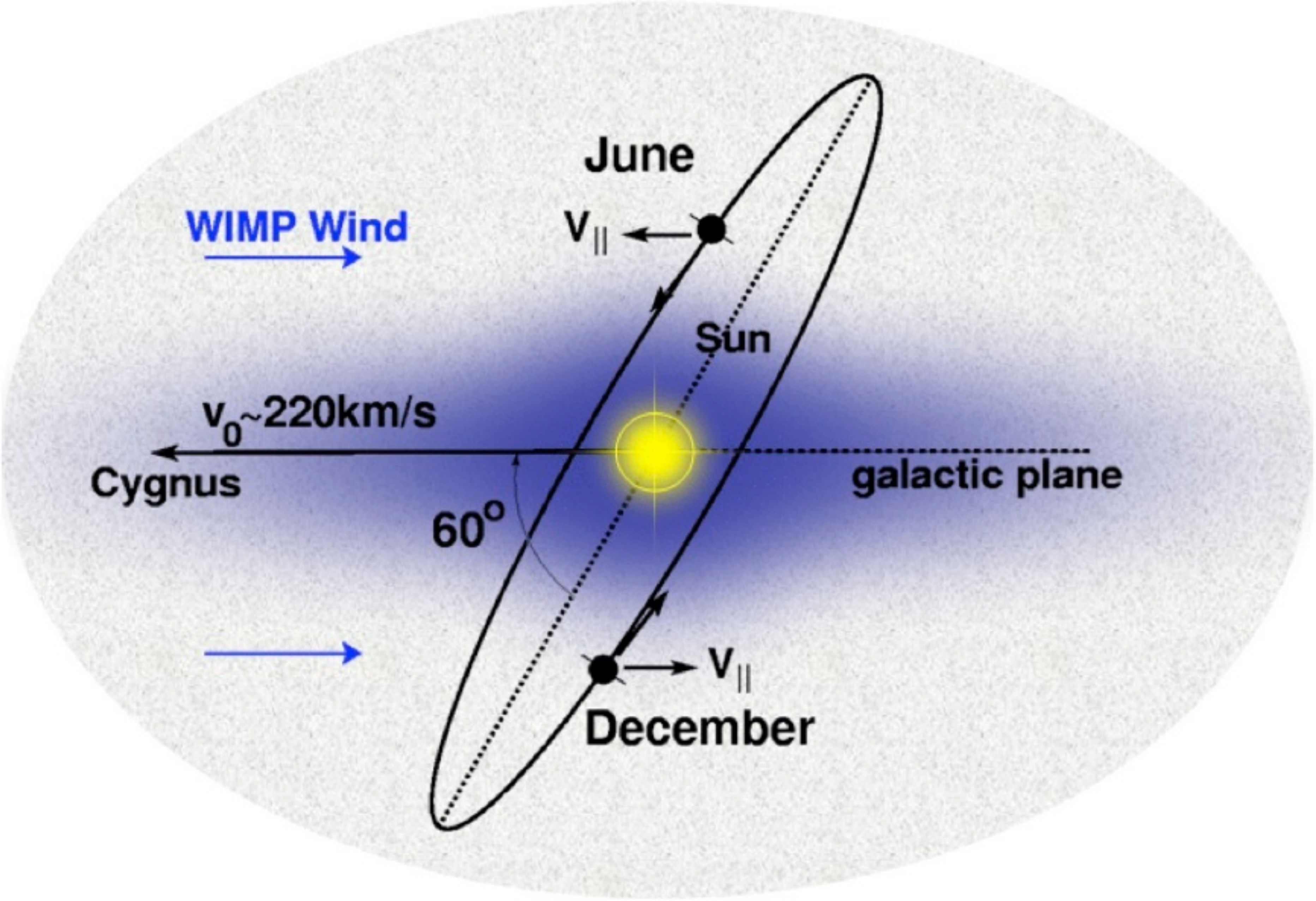


750kg ^{136}Xe: Looking for Majorana Neutrinos


Ch2 22/05 11:42
Normal


Ch2 22/05 11:42
Normal
New Balloon: ~4m radius

Use annual modulation: DM claim



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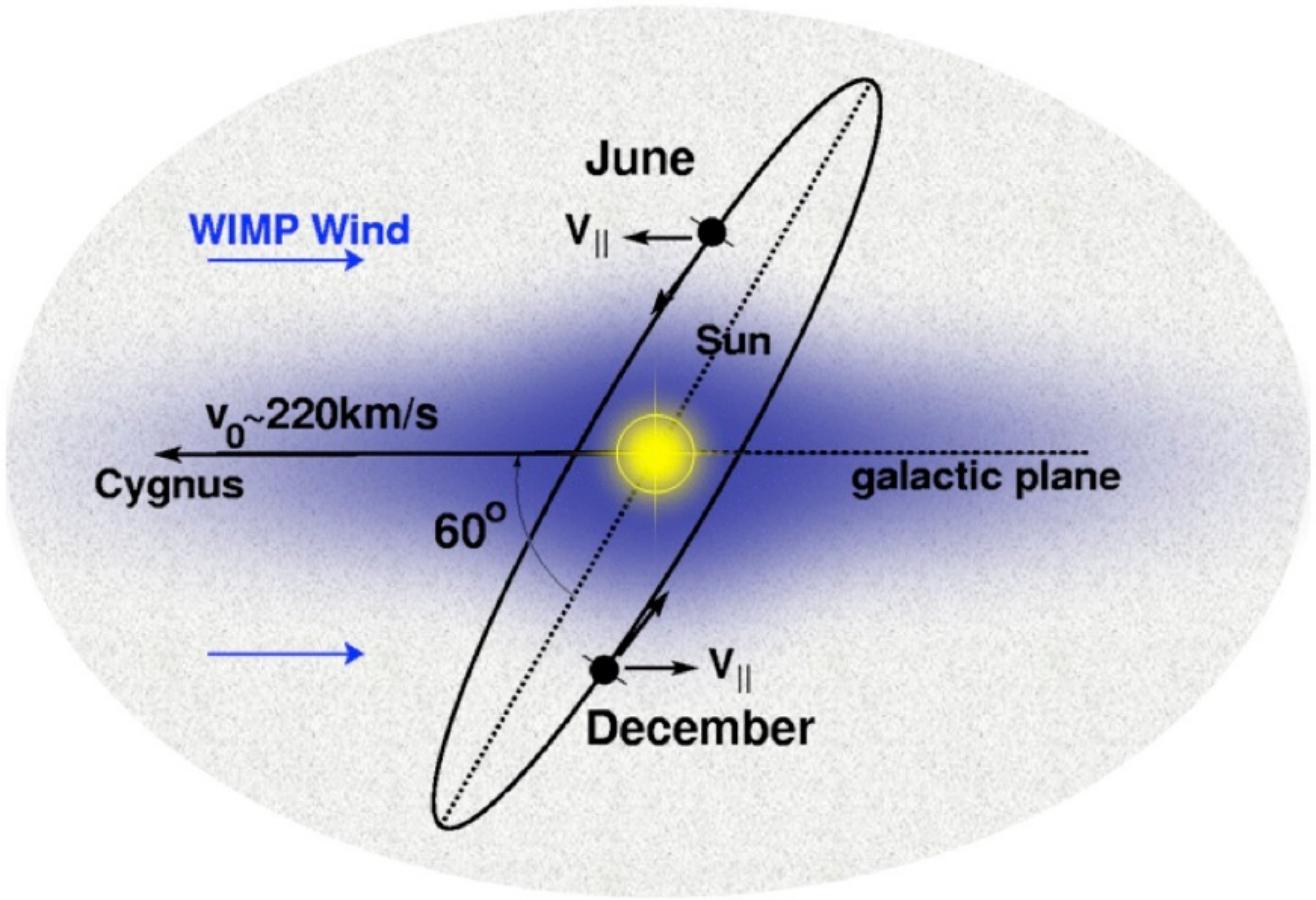
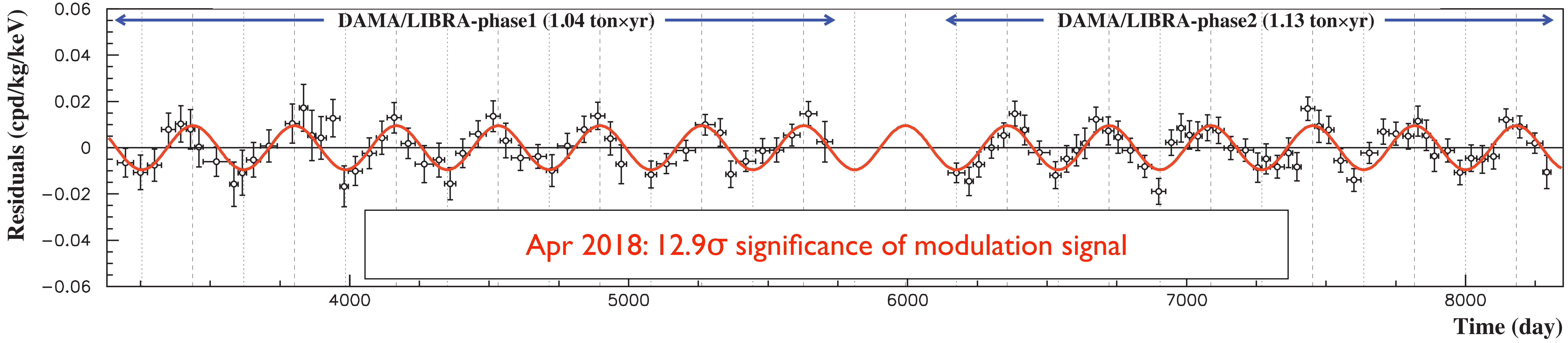
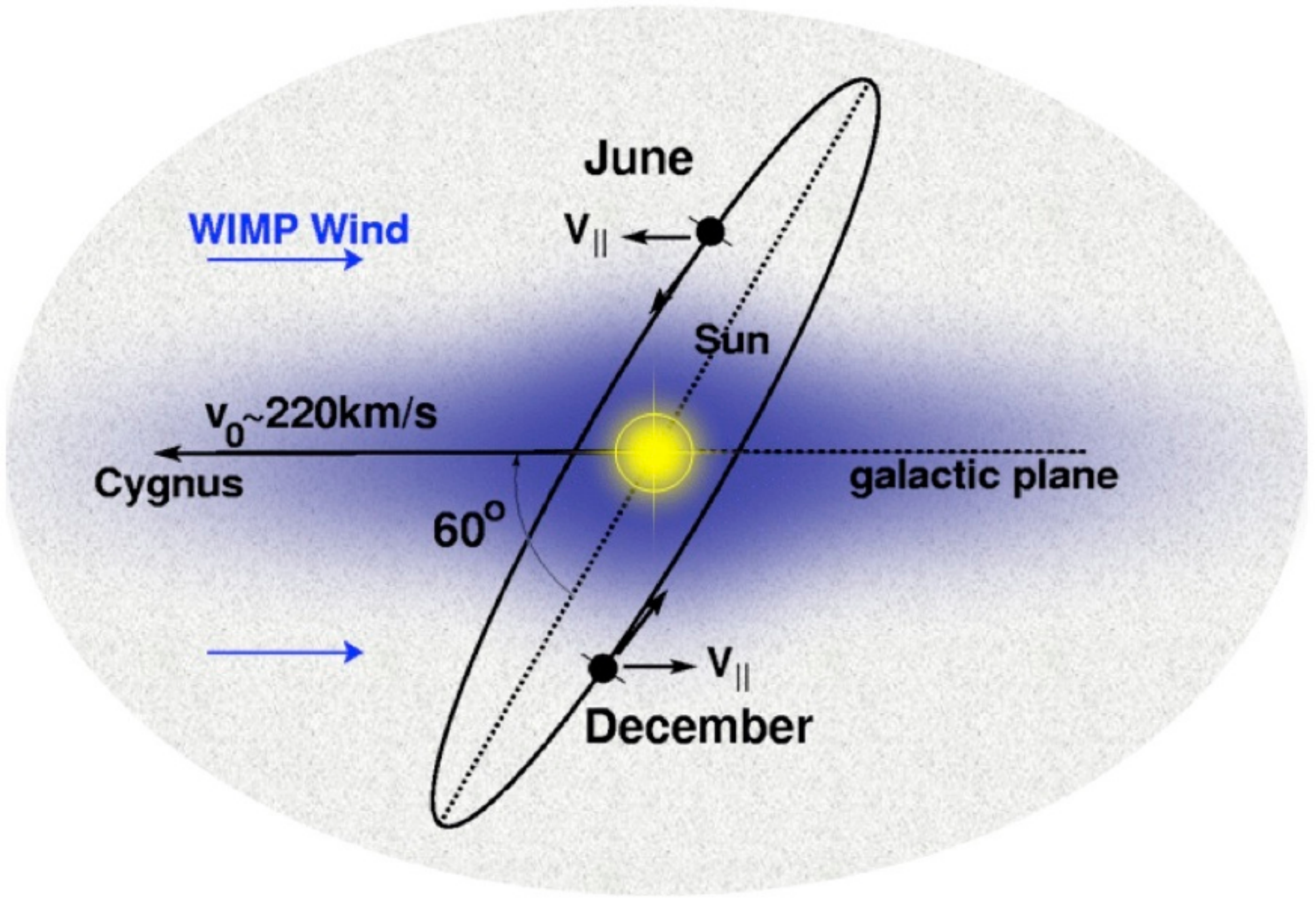


Modulation present in 2-6 keV, absent above 6 keV

arXiv:1805.10486



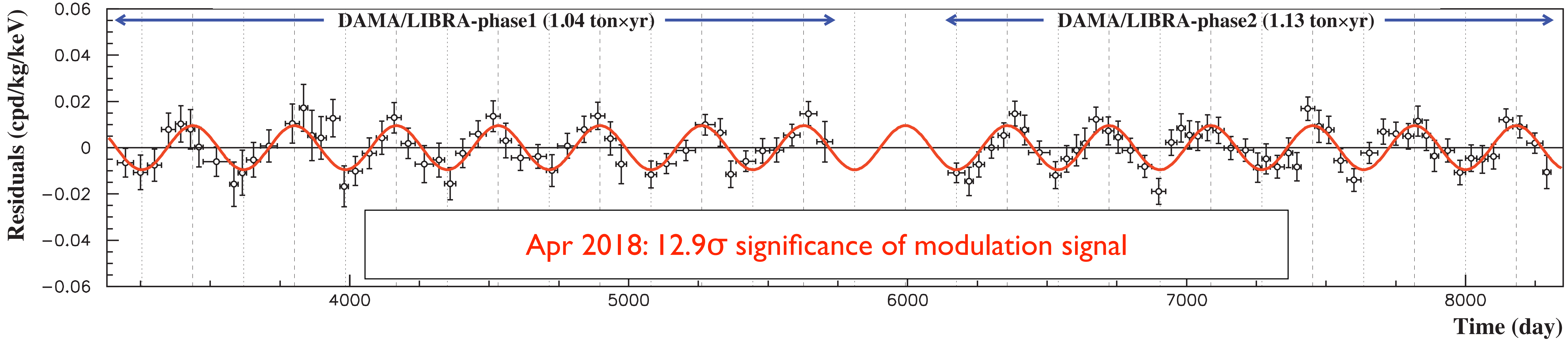
Use annual modulation: DM claim



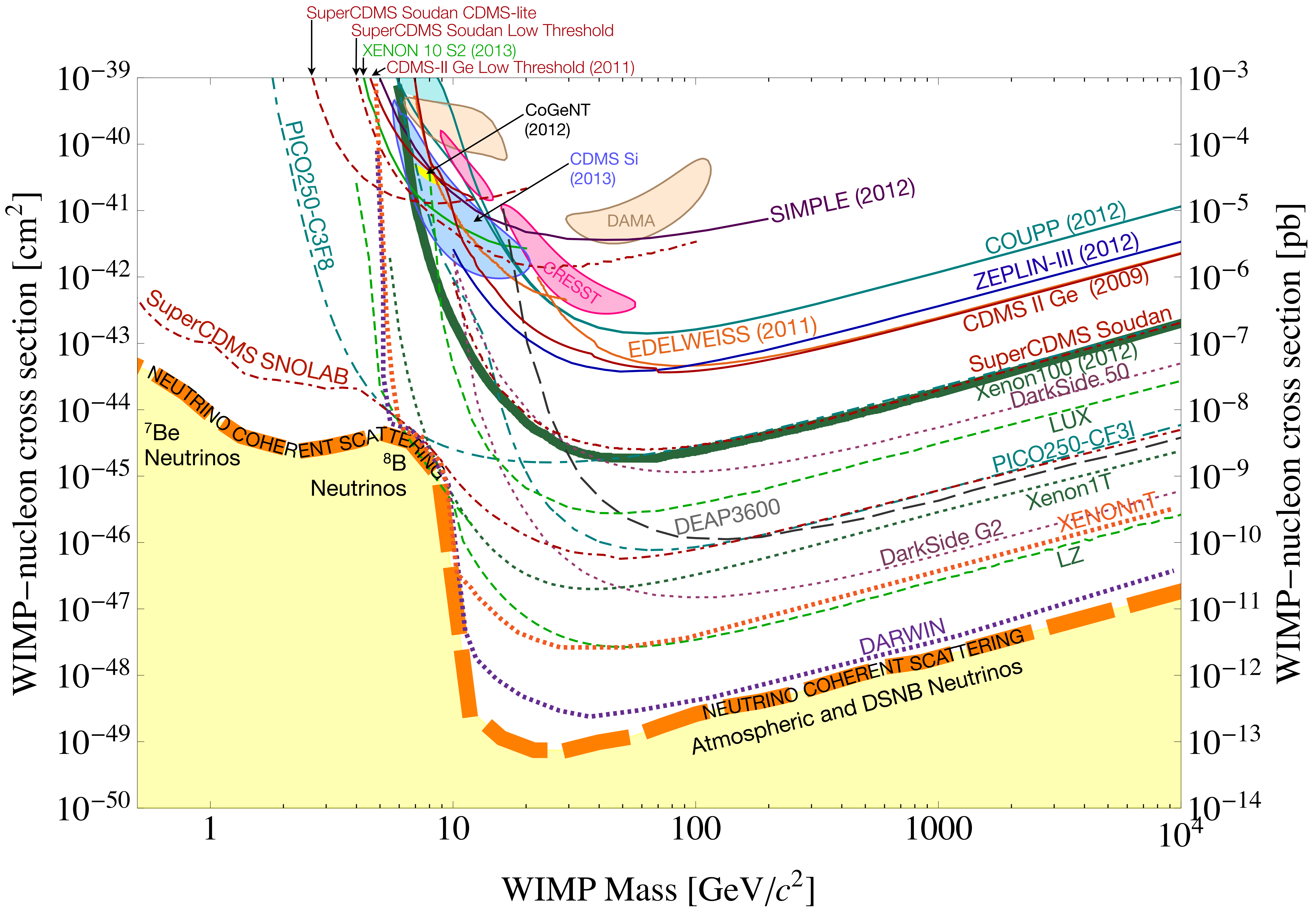
- DAMA claim in NaI
- Several DM experiments investigating:
  - COSINE-100, SABRE, ANAIS, …
  - Manufacturing of Low BG crystals achieved
  - Southern hemisphere

Modulation present in 2-6 keV, absent above 6 keV

arXiv:1805.10486



Projections in 2013



Adapted from SNOWMASS Report arXiv:1310.8327

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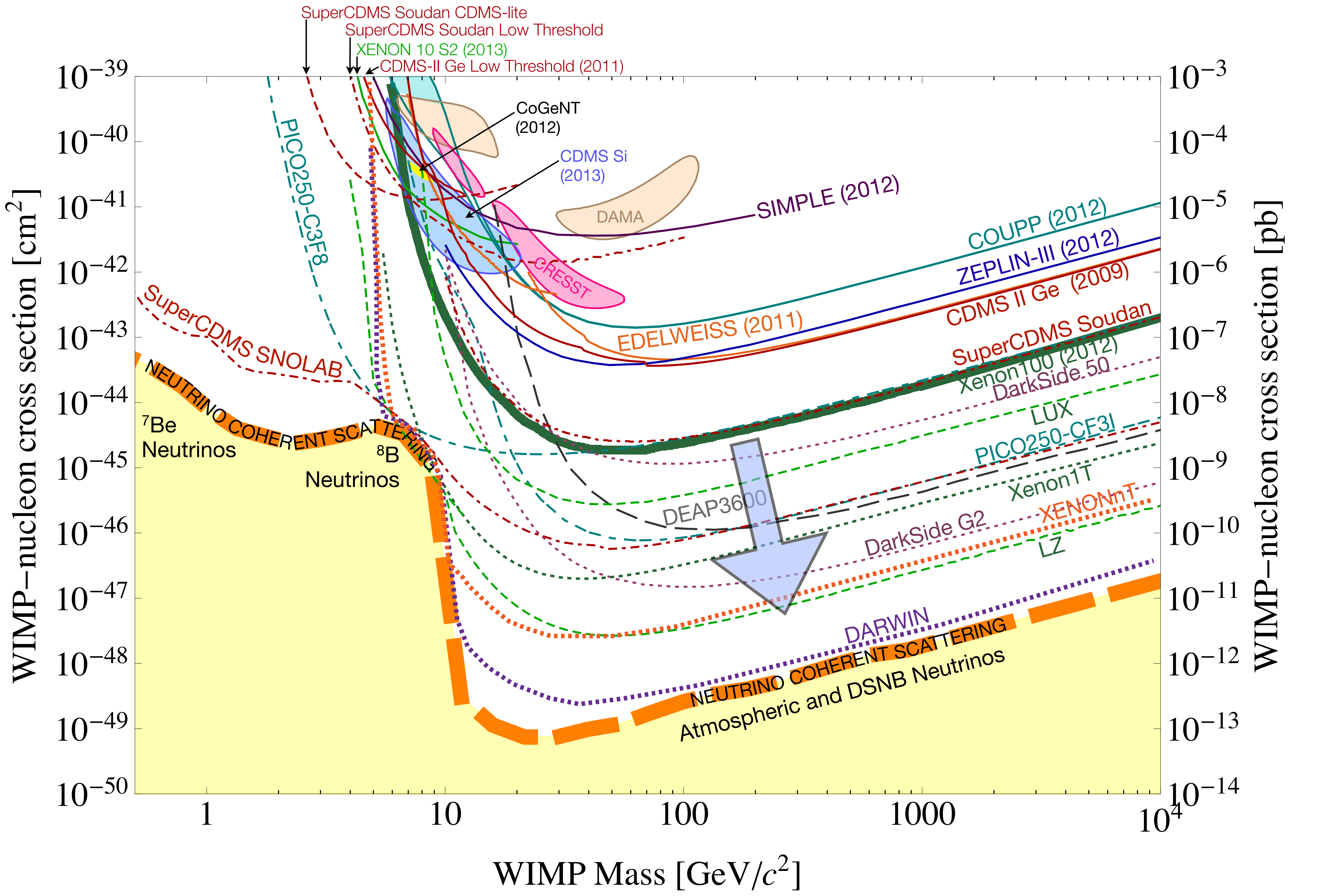
Projections in 2013



Adapted from SNOWMASS Report arXiv:1310.8327

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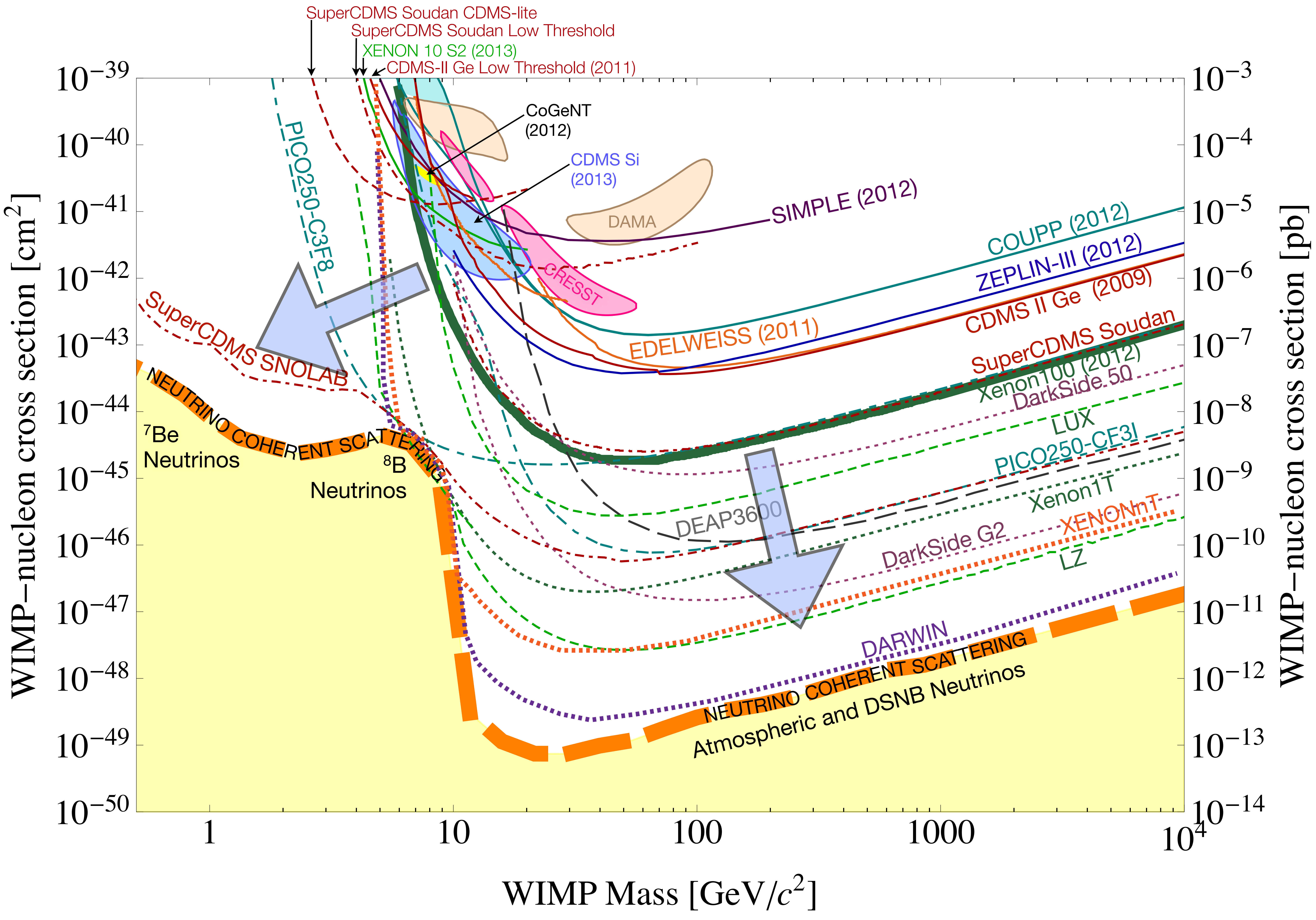
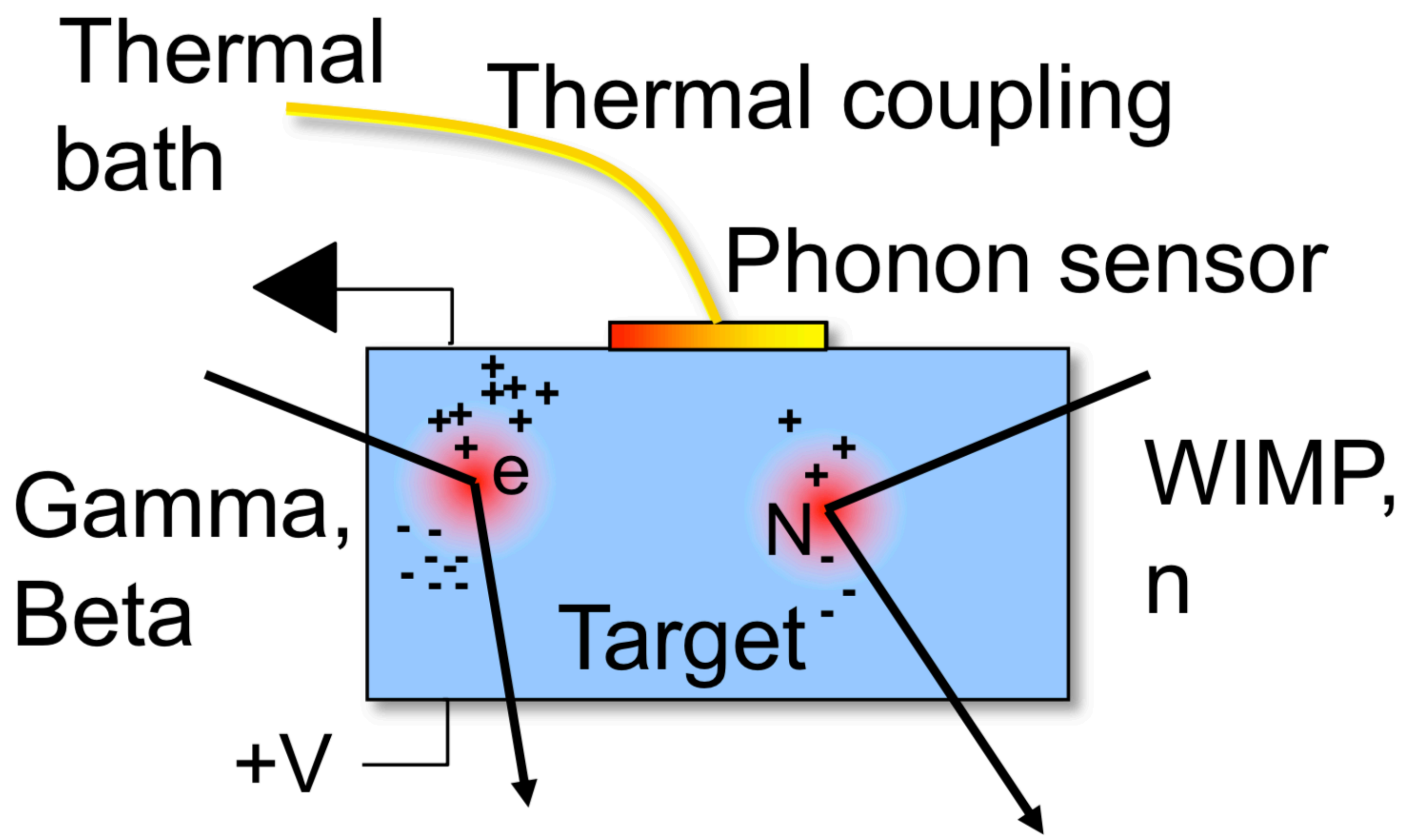
Projections in 2013



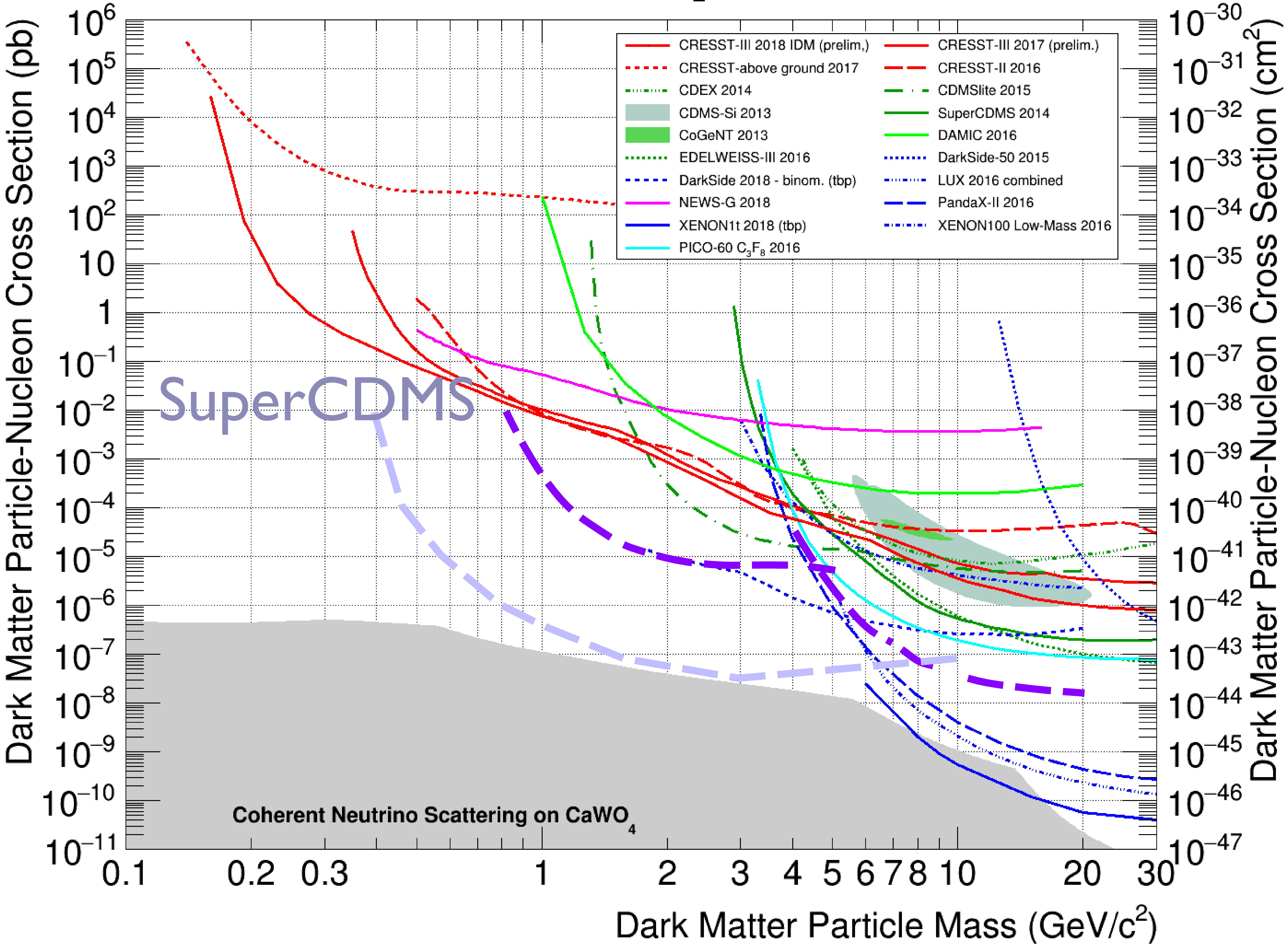
Adapted from SNOWMASS Report arXiv:1310.8327

Solid State Cryogenic Detectors

- Cryogenic detectors @ 10s of mK temperatures
  - Low energy threshold (100 - 1keV)
  - Excellent energy resolution (<1%)
  - Differentiate NR from ER on Event-by-Event basis
  - Readout: TES and NTD-Ge bolometers
  - CRESST, SuperCDMS, EDELWEISS



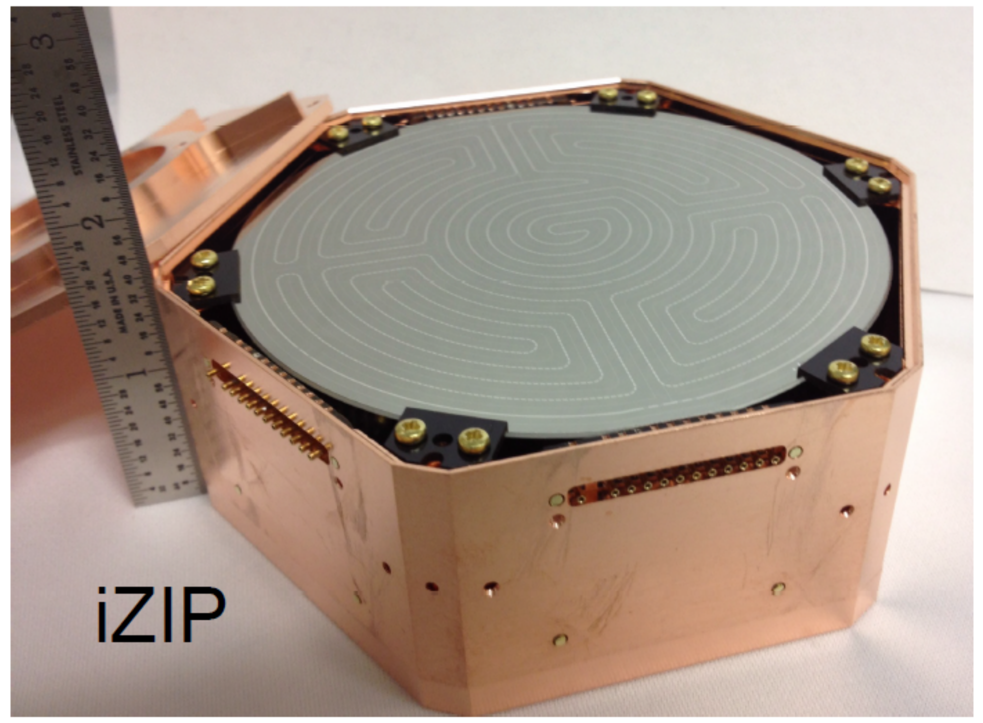
SuperCDMS@SNOLAB



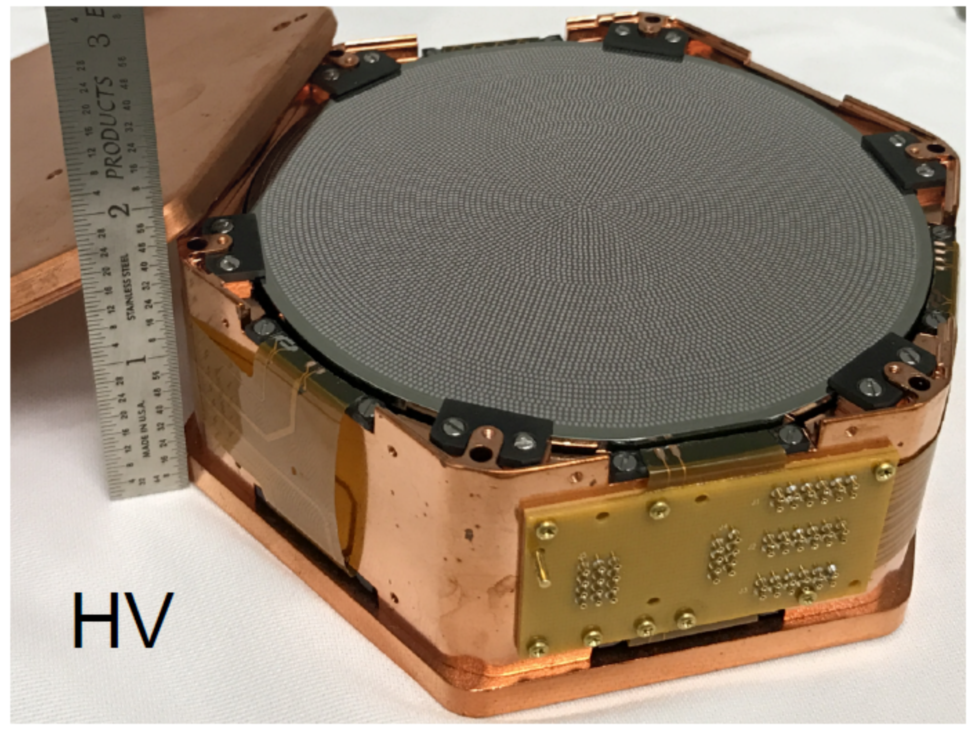
Use Ge and Si crystals

ionization & phonons

iZIP: better BG rejection



HV: lower E threshold

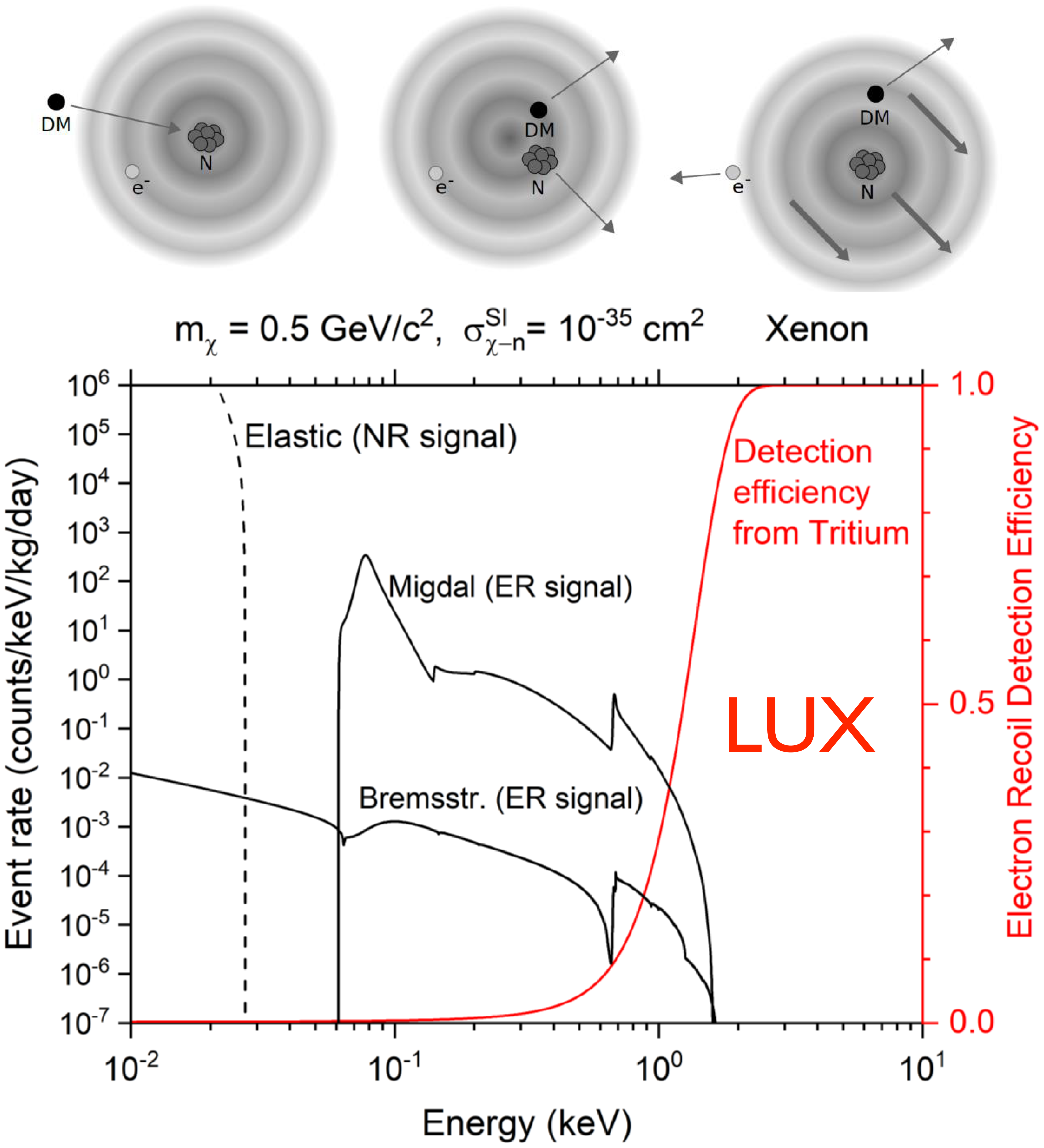


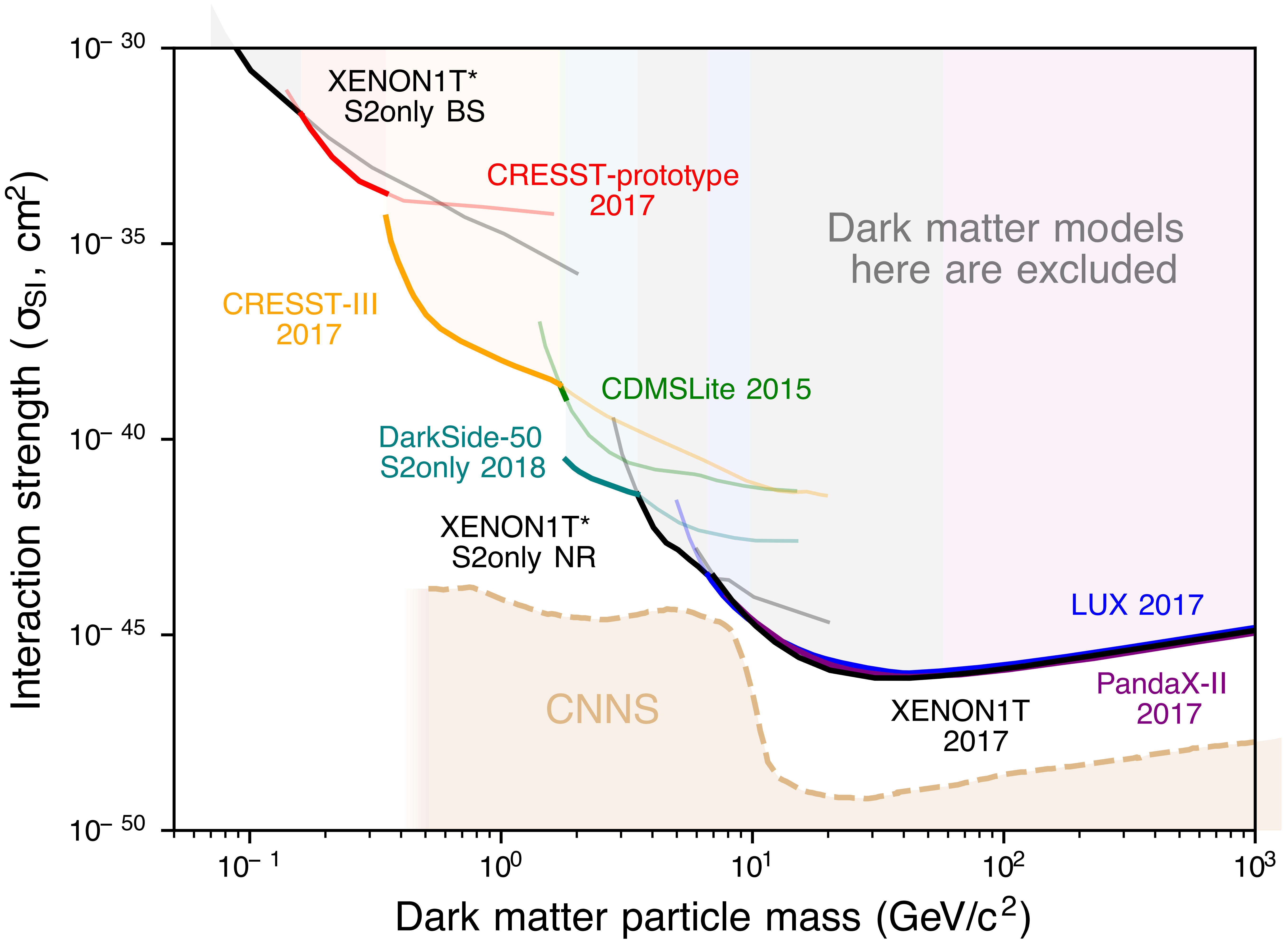
- Use Neganov-Luke, better E-resolution
- Relatively short exposure due to cosmic BG activation

Searching for Sub-GeV WIMPs

Thesis Jelle Aalbers

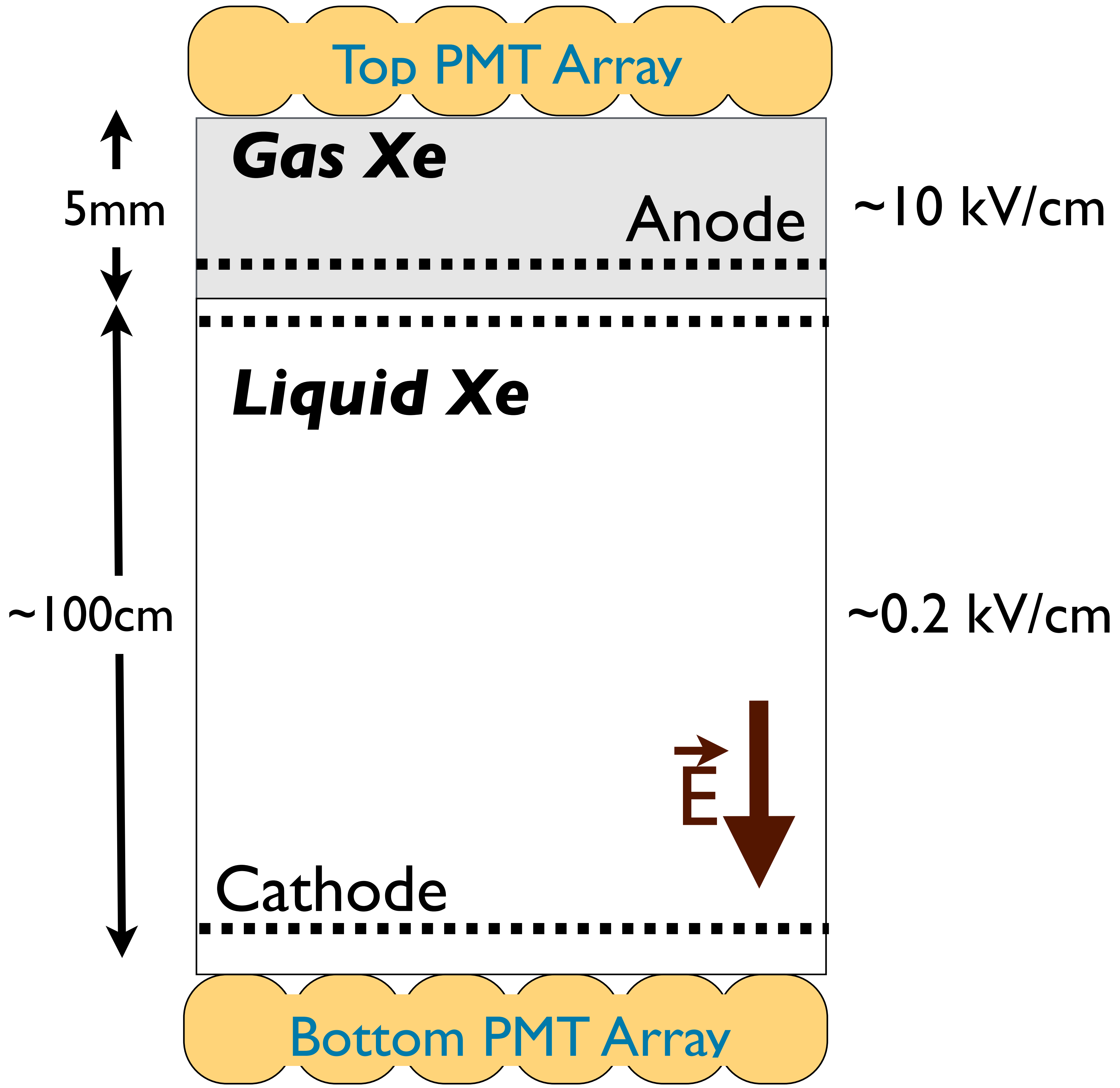
"Migdal"-effect, "S2-only" analysis





Drive to be sensitive to sub-GeV mass DM

Dual-Phase Xe TPC

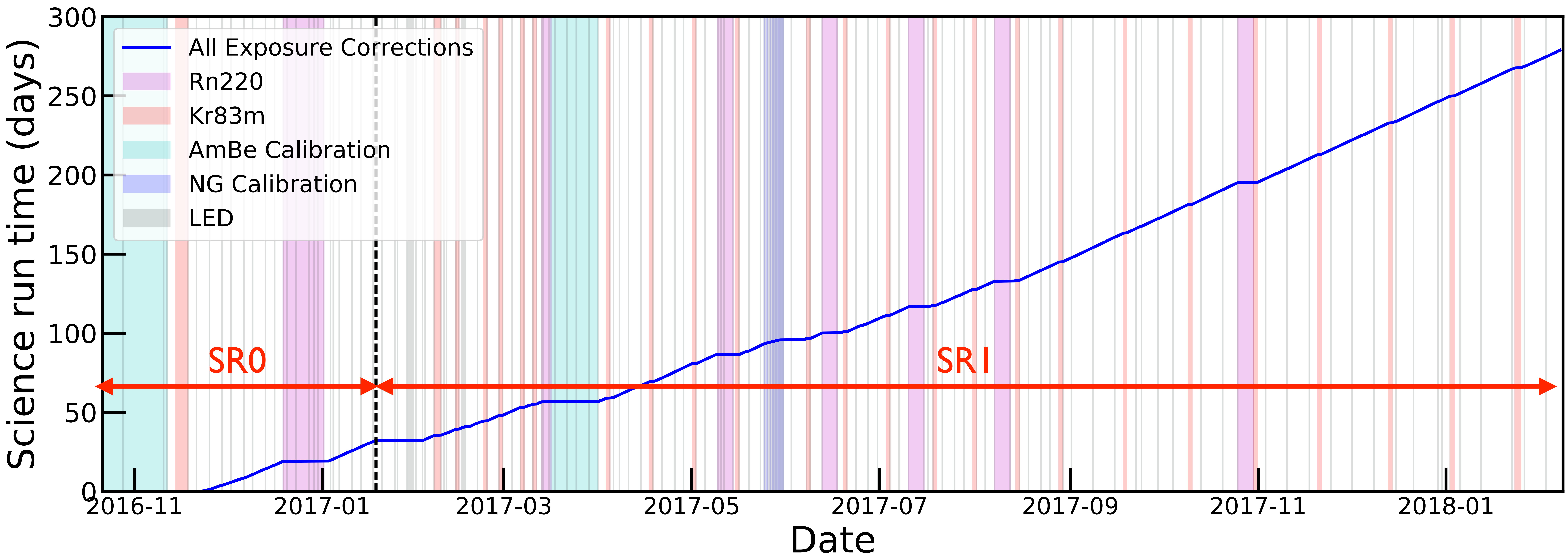


XENON1T: 3.2 tons of liquid xenon


Xe
XENON
Matter Project
XENON1
enlightening the


TPC assembly during Fall 2015

Exposure

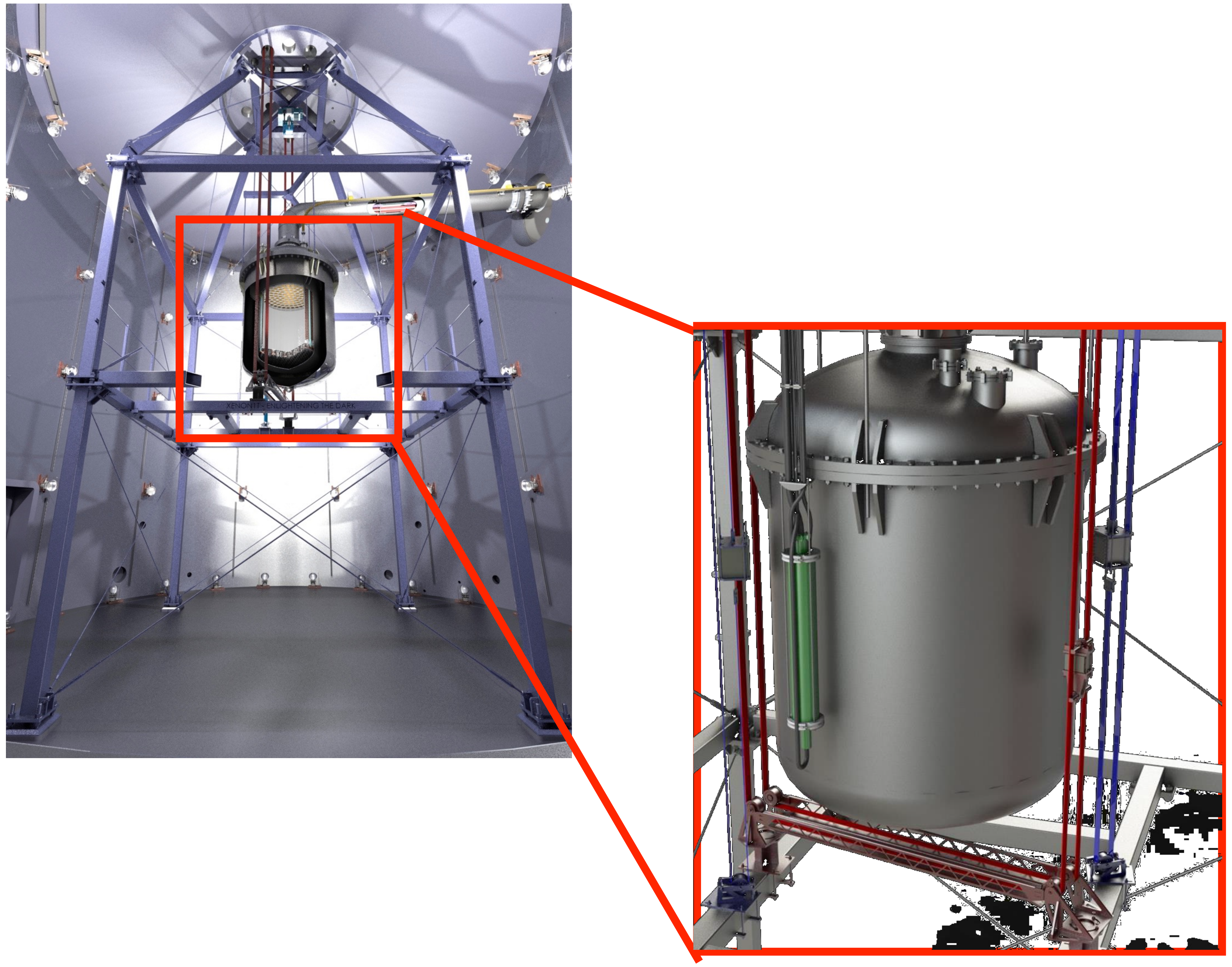


- Detector ran smoothly - DAQ efficiency ~99%
- Two Science Runs: 32 days and 247 days
- About 1 ton-year of exposure accumulated in 1.3 ton fid. volume

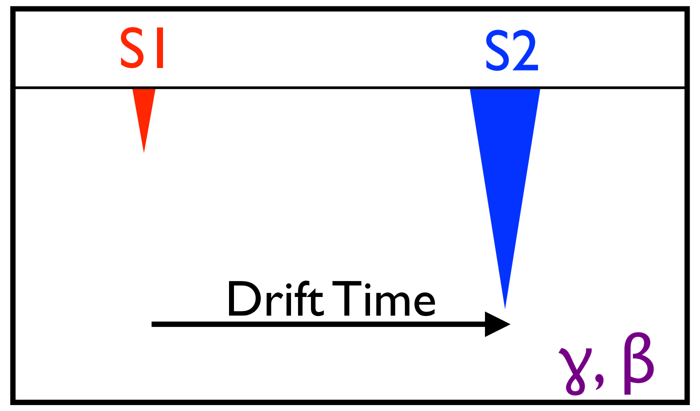
Calibration Systems

Thesis
Erik Hogenbirk

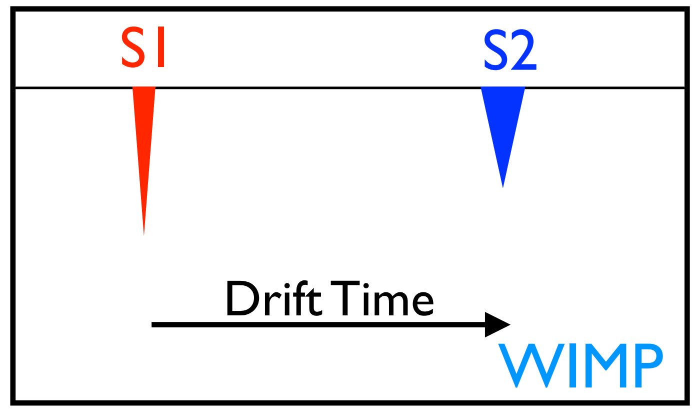
- Variety of calibration sources:
  - "Internal" sources: ^{83m}Kr, ^{220}Rn
  - External sources: ^{241}AmBe, neutron generator
  - Materials: ^{60}Co, ^{129m}Xe, ^{131m}Xe



Improved calibration statistics

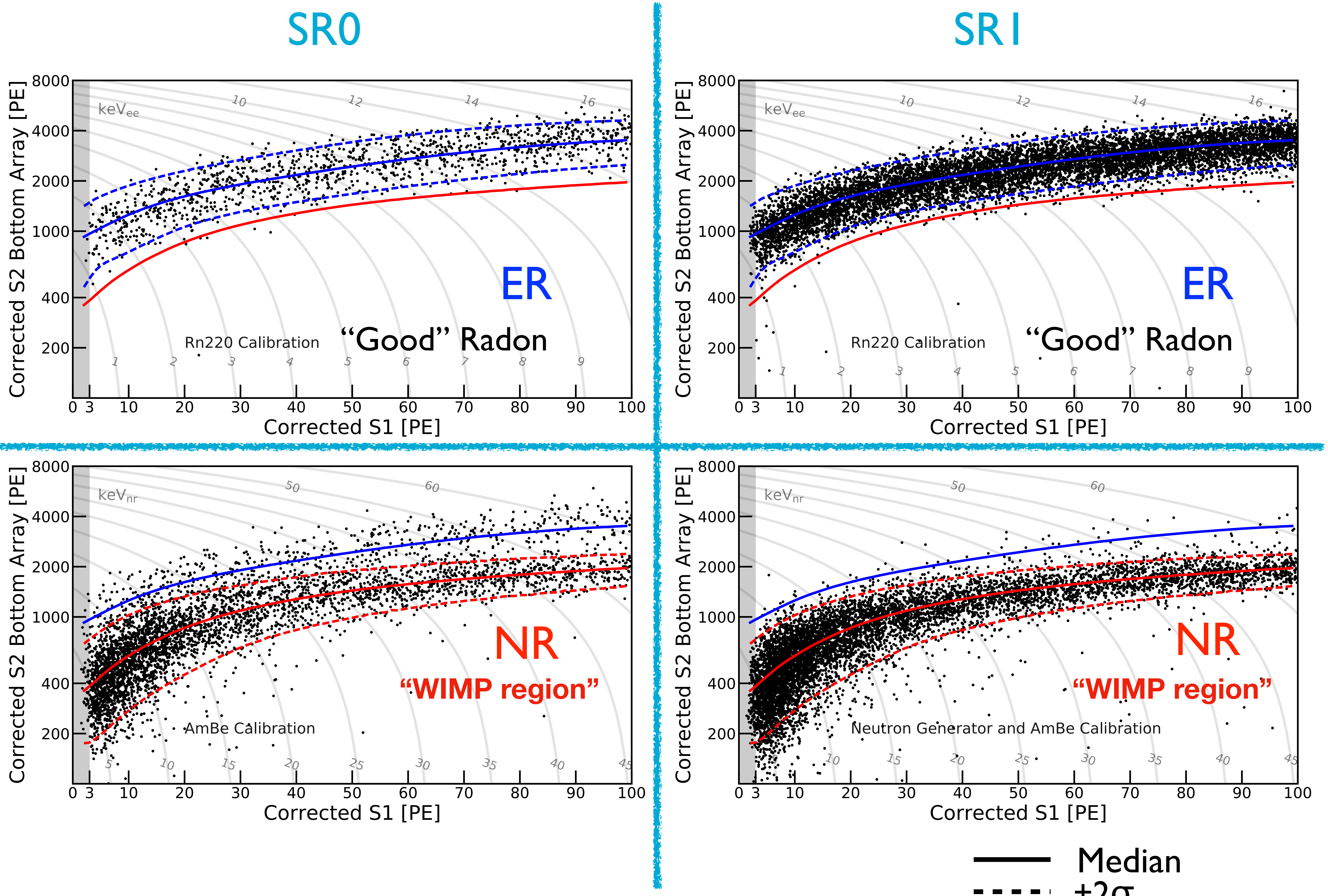


Background: Electron recoil



Signal: Nuclear recoil

$$\frac{S2}{S1}_{\gamma,\beta} > \frac{S2}{S1}_{\mathrm{WIMP}}$$



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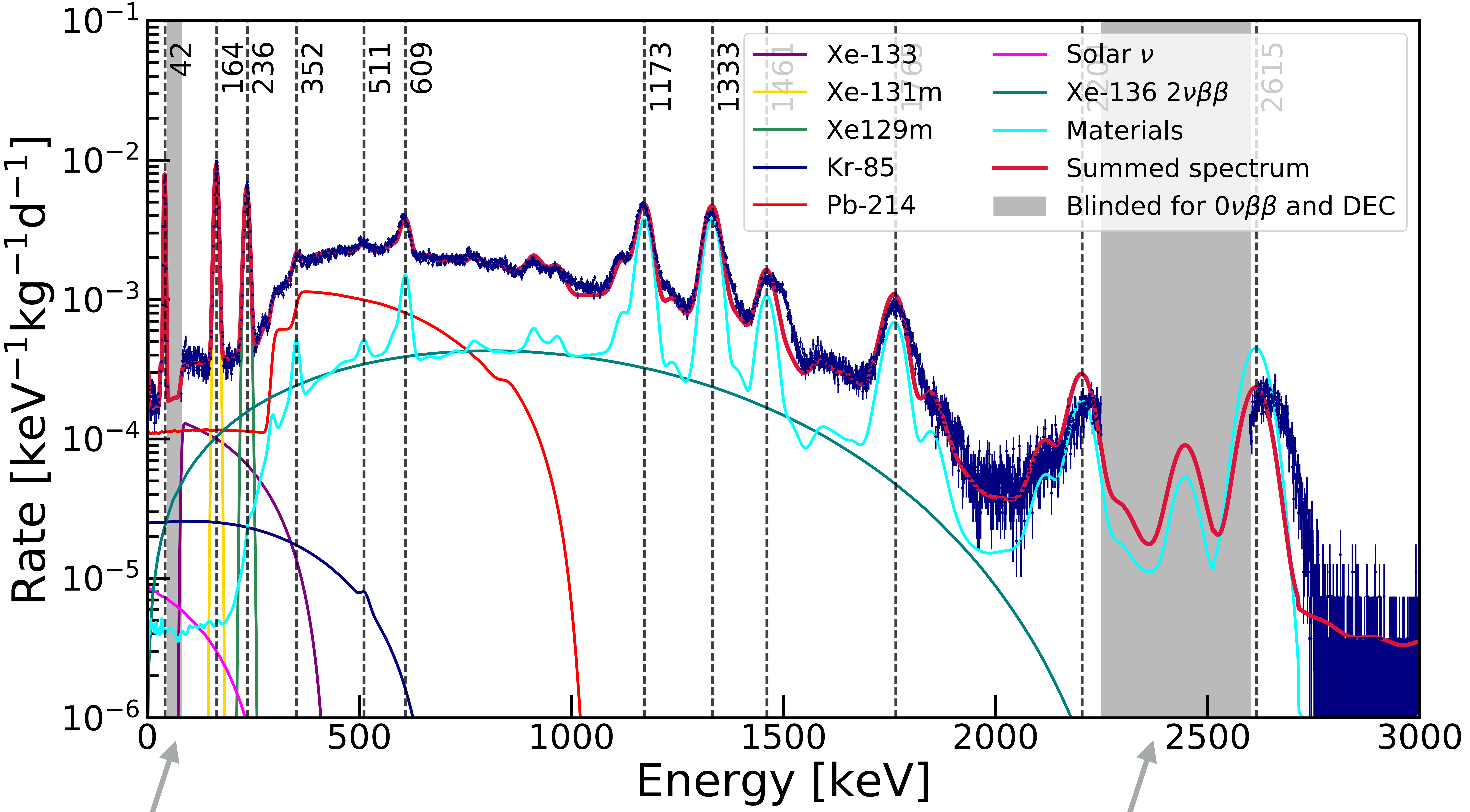
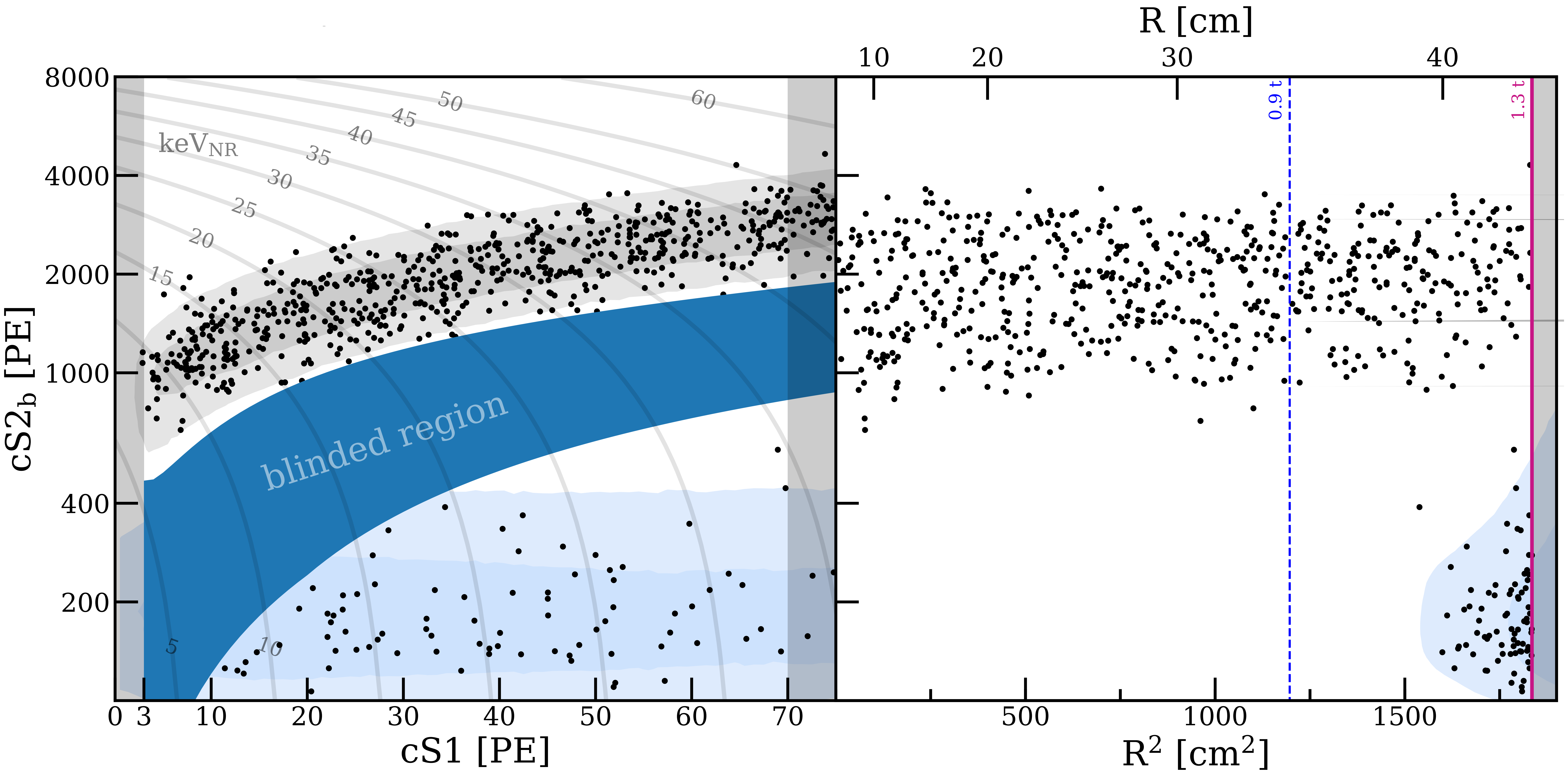
Wide range energy reconstruction



2 E.C. in ^{124}Xe

0ν2β in ^{136}Xe

WIMP Search Region



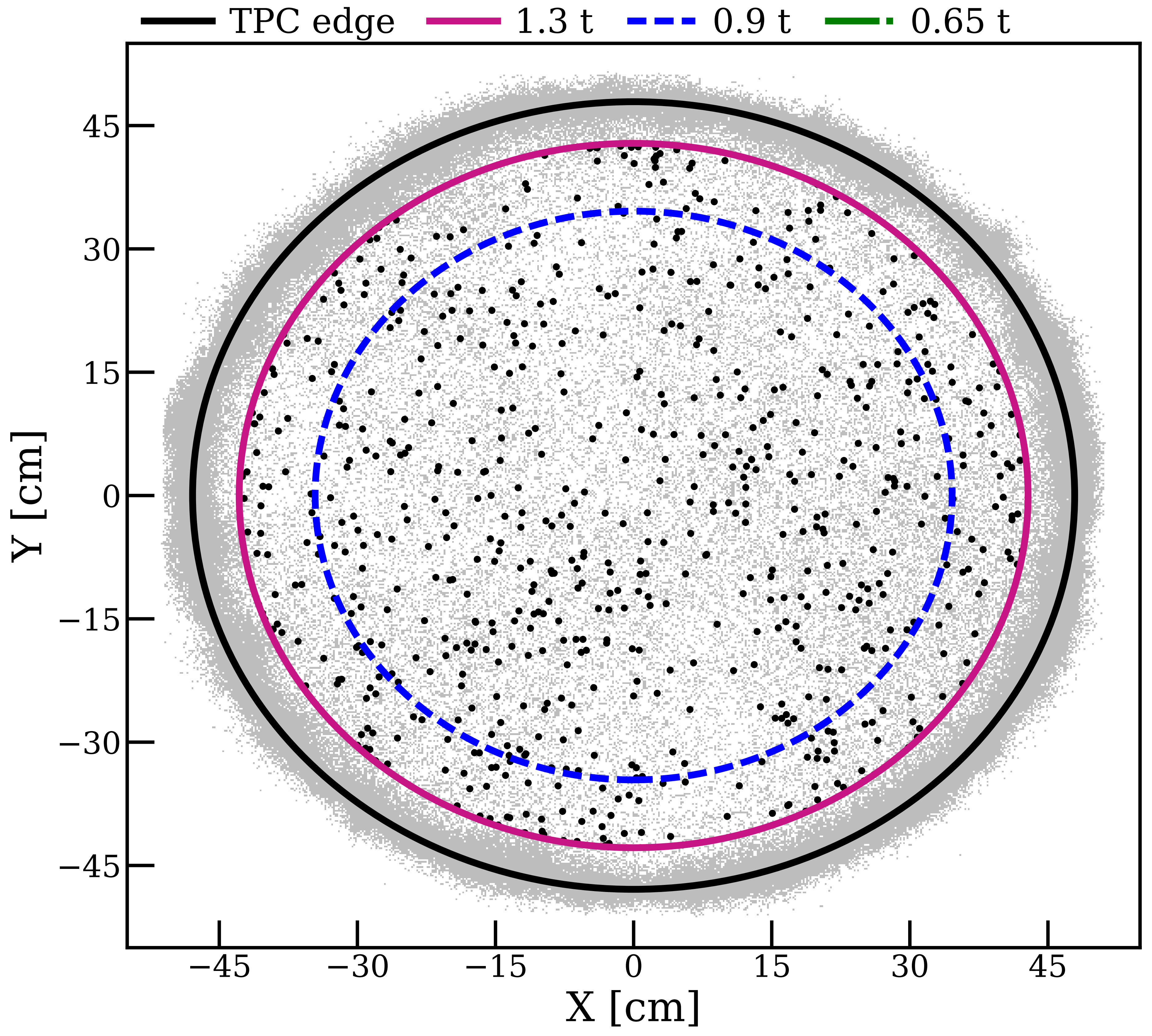
ROI: 3PE < S1 < 70PE

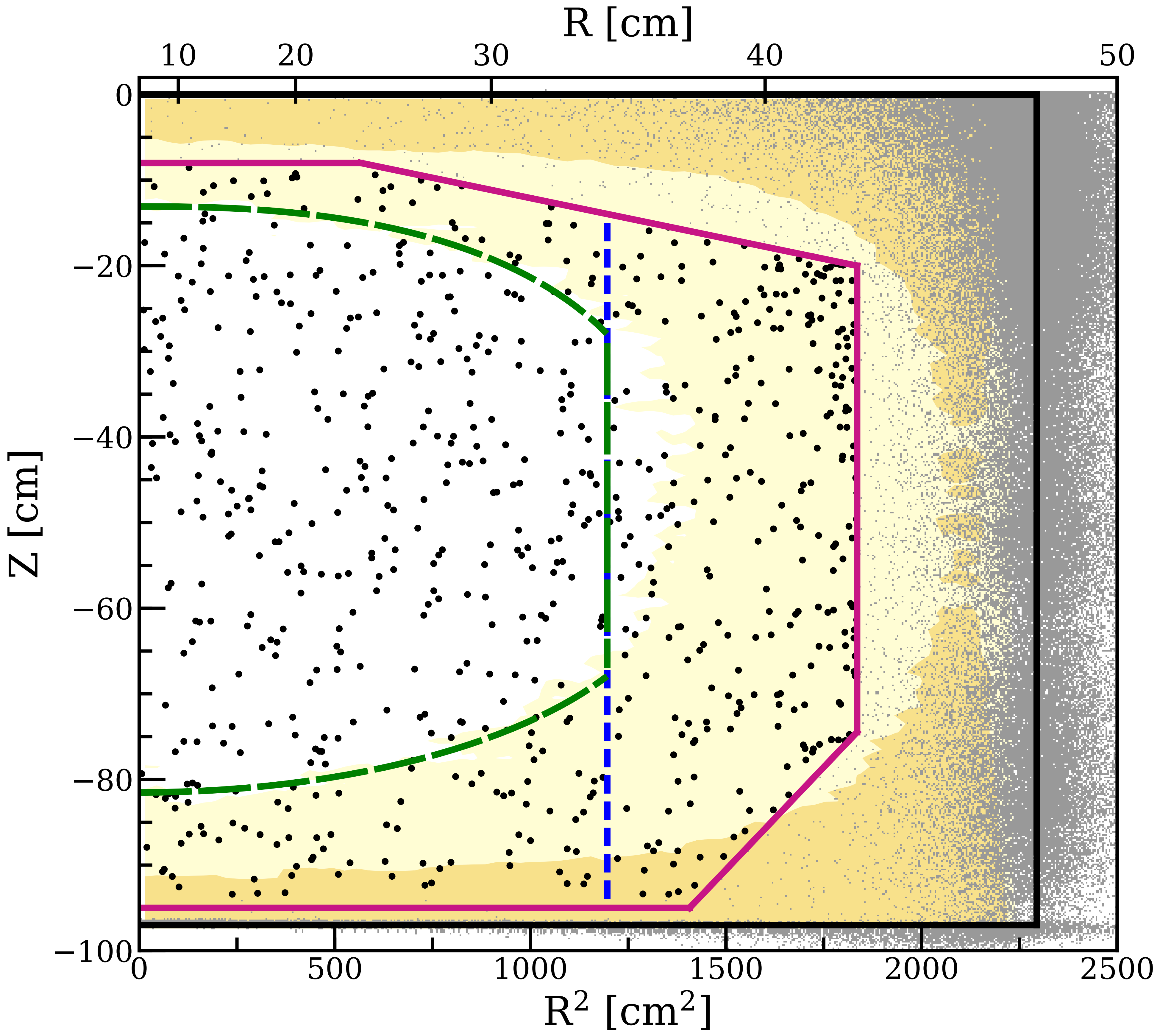
equiv: ER: 1.4 - 10.6 keV$_{ee}$

NR: 4.9 - 40.9 keV$_{nr}$

Analysis was: Blinded & "Salted"

Fiducial mass Selection

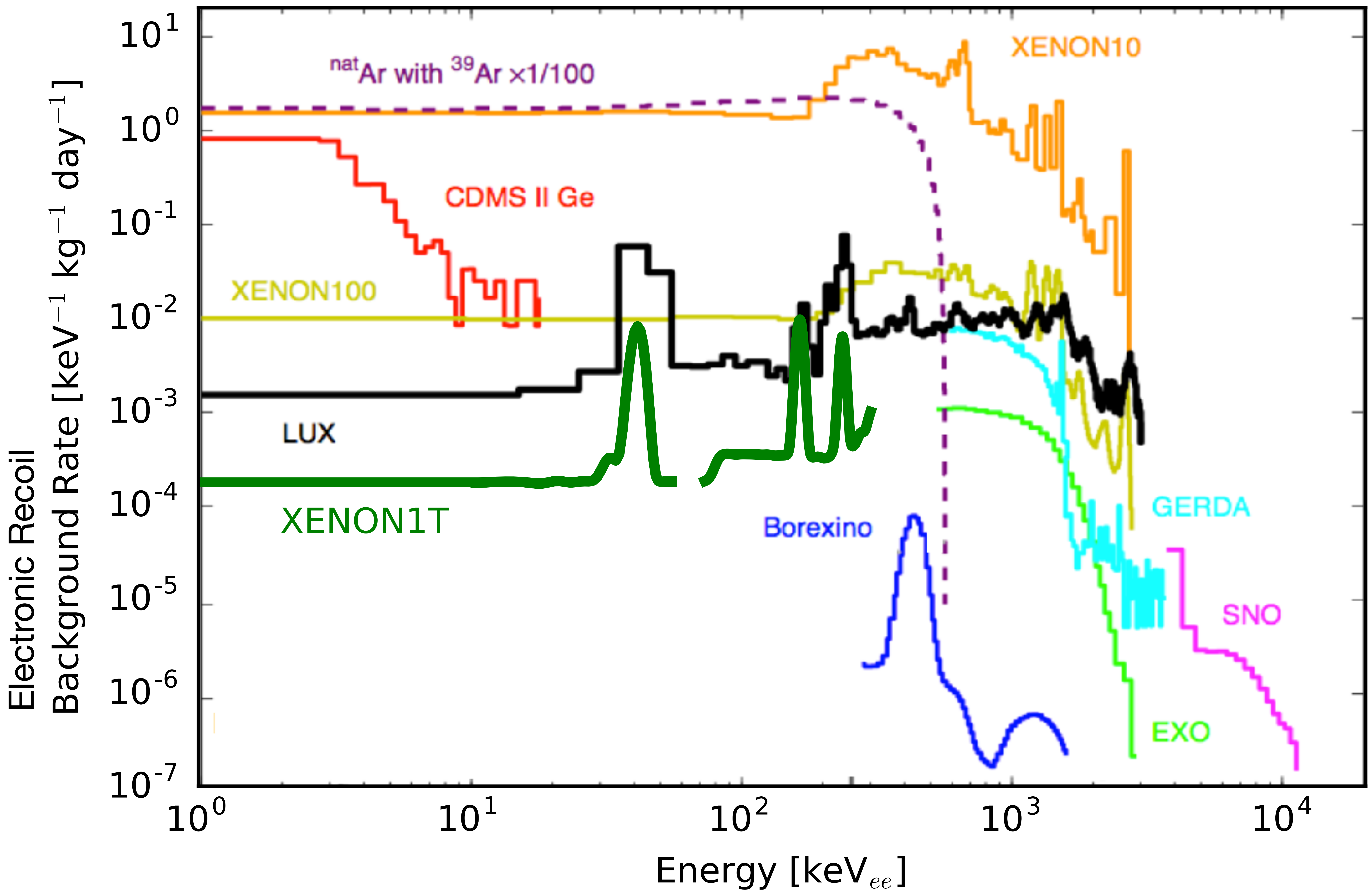




- Signal and background are modeled in (cS1, cS2, R, "z") space
- Fiducial mass increased from 1 ton → 1.3 tons
- Total exposure of SR0+SR1: 1 ton x year

Low, low Background

Thesis
Sander Breur

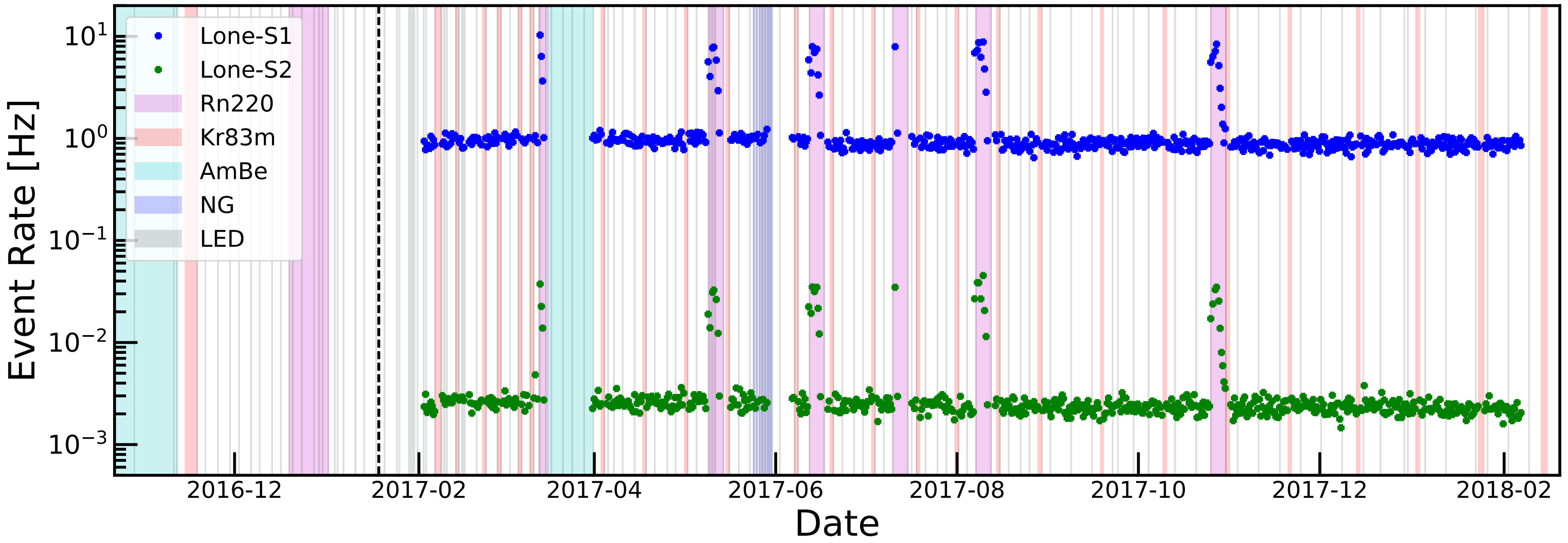


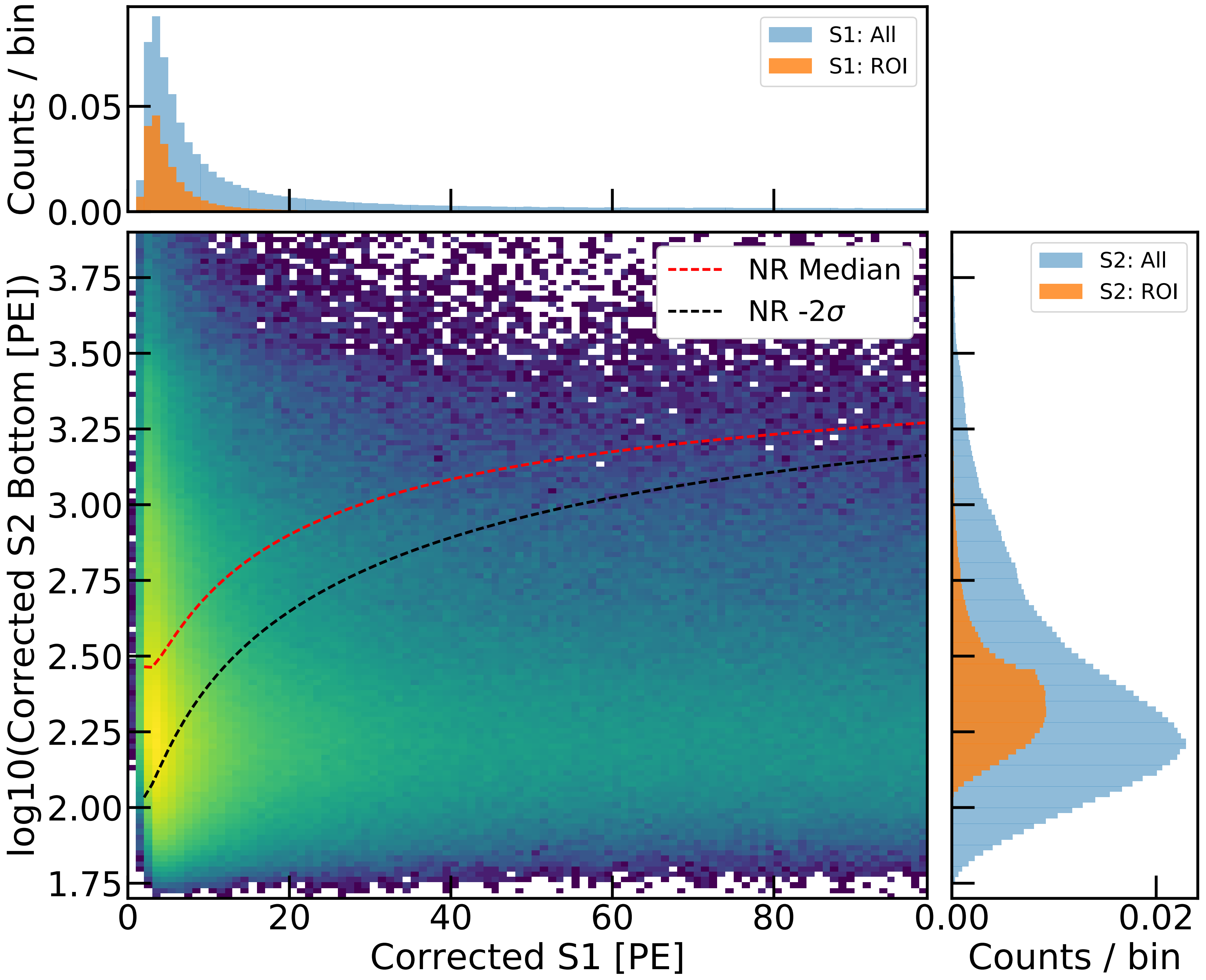
- **Lowest BG ever achieved in a dark matter detector!**

Accidental + Surface Backgrounds

Thesis Sander Breur

Accidental Background





Surface Background

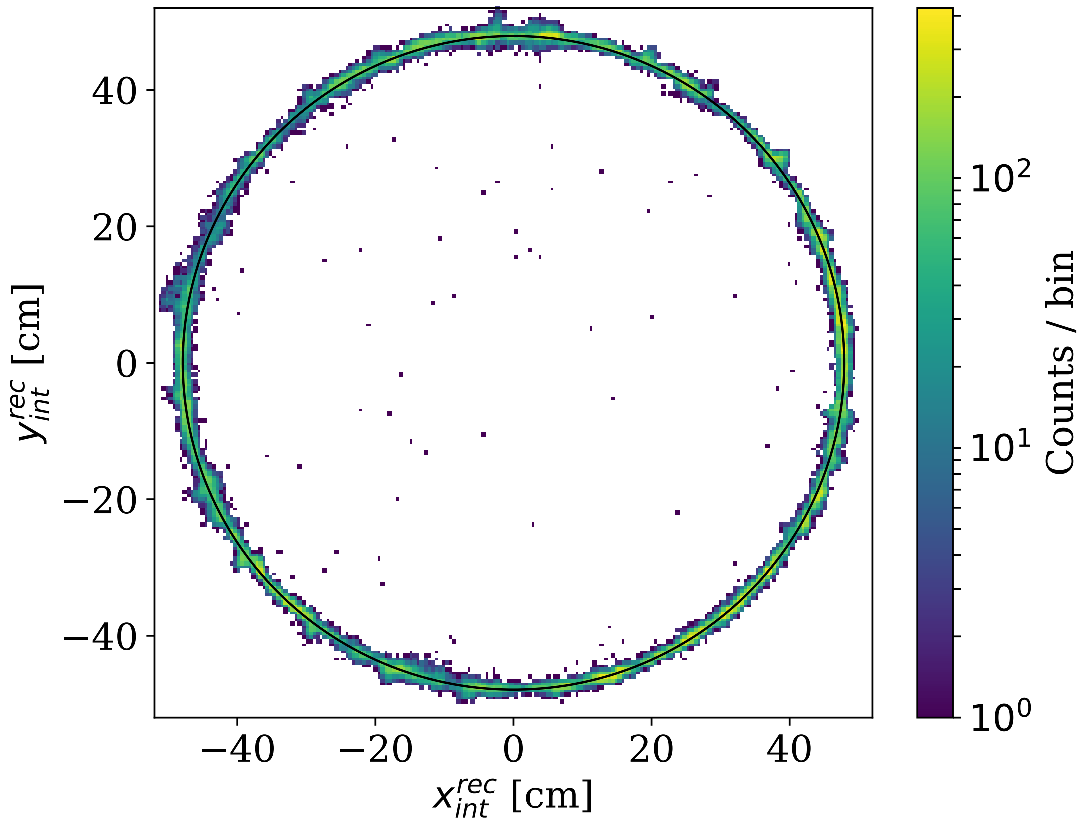
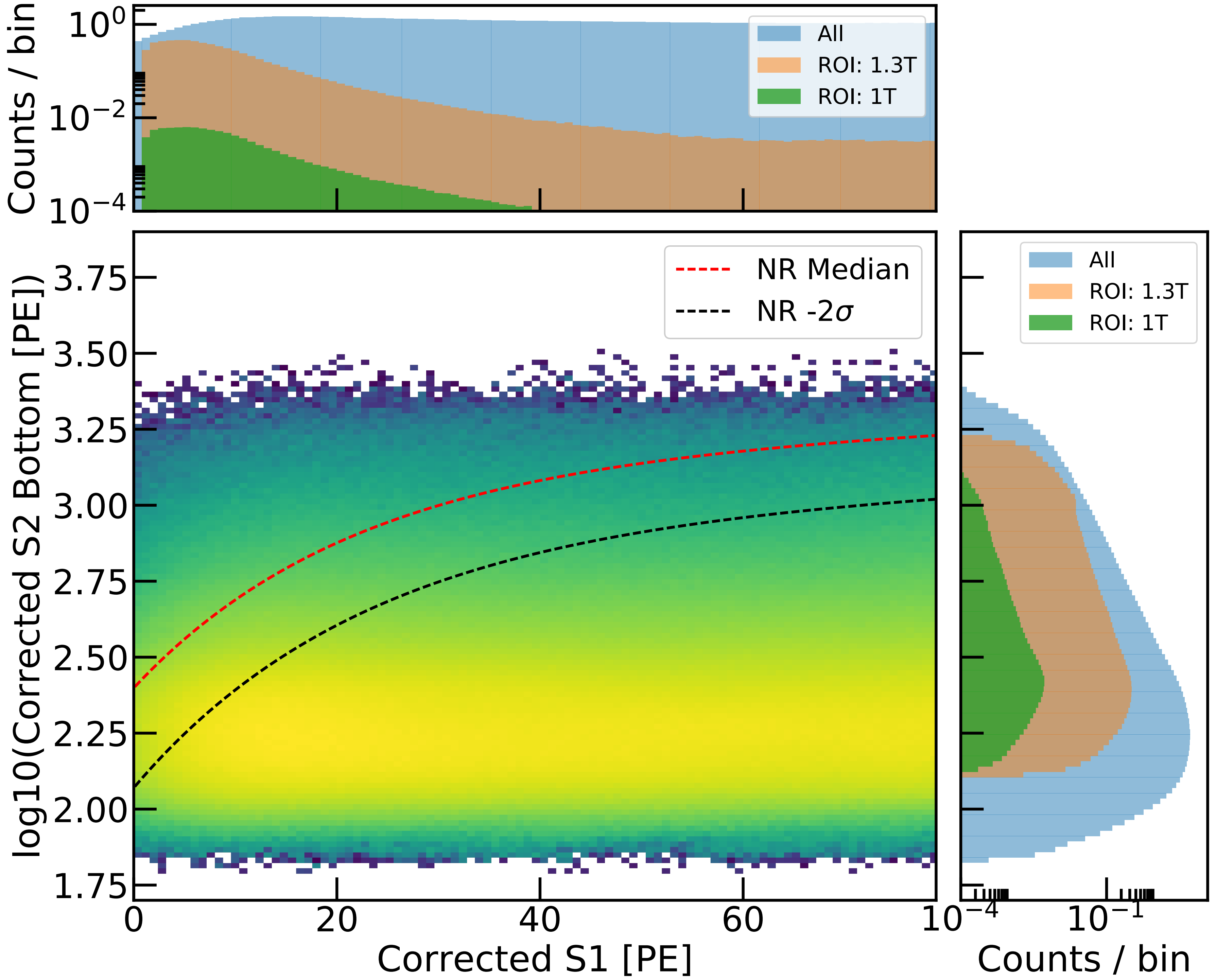


Plate out of ^{210}Po and incomplete charge (S2) collection



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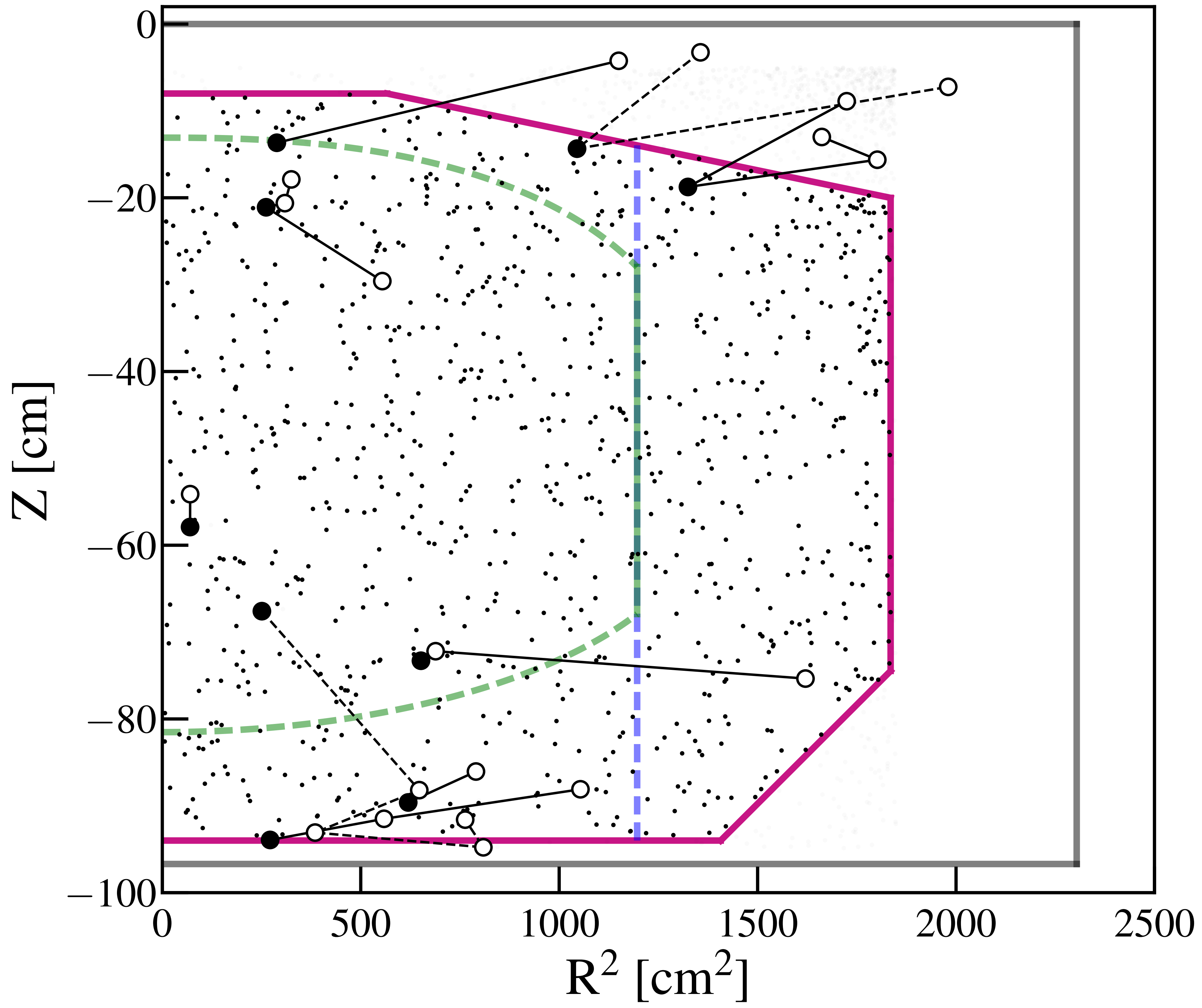
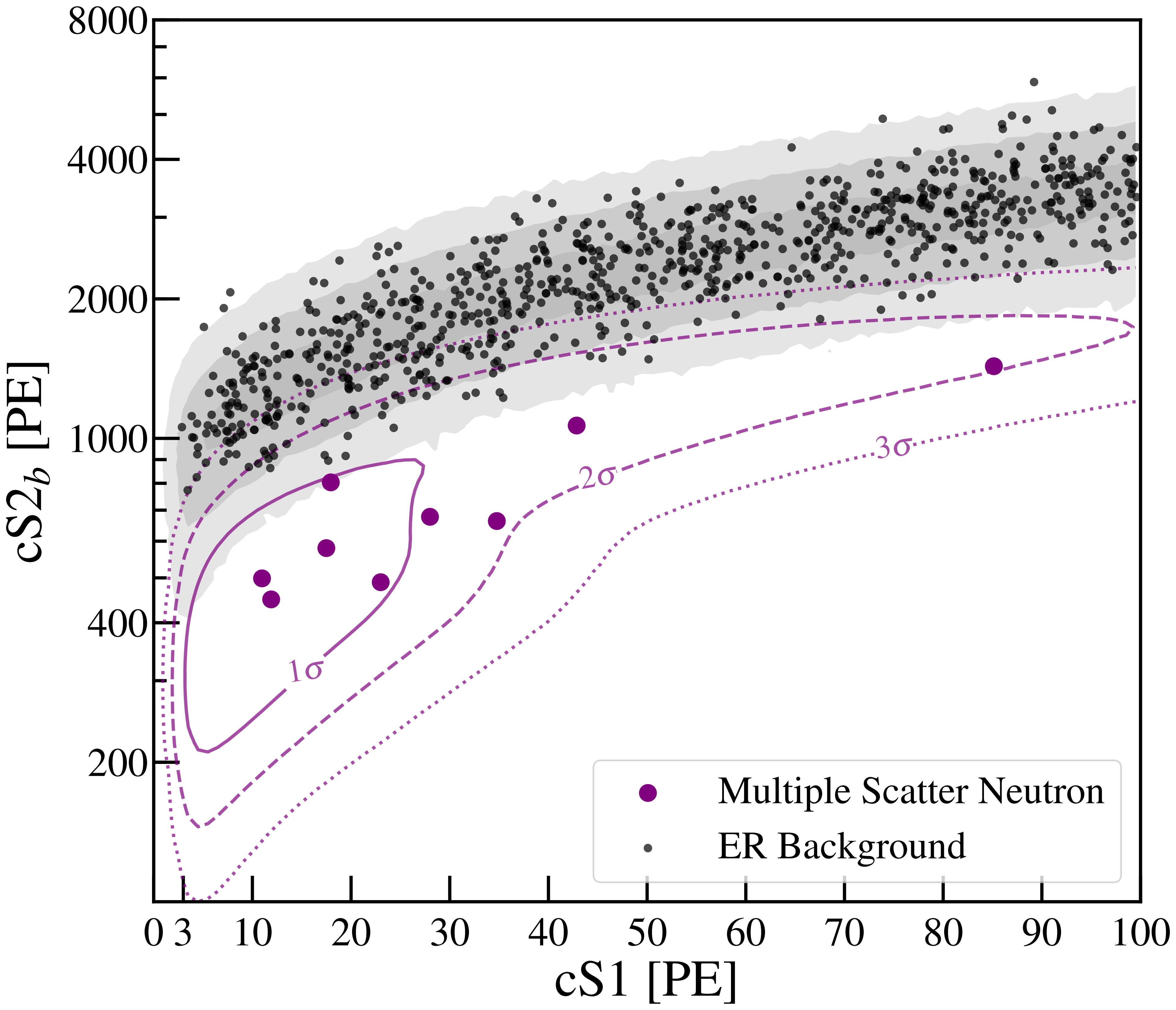
NR Background

Neutrons will multiple scatter in LXe - WIMPs will not



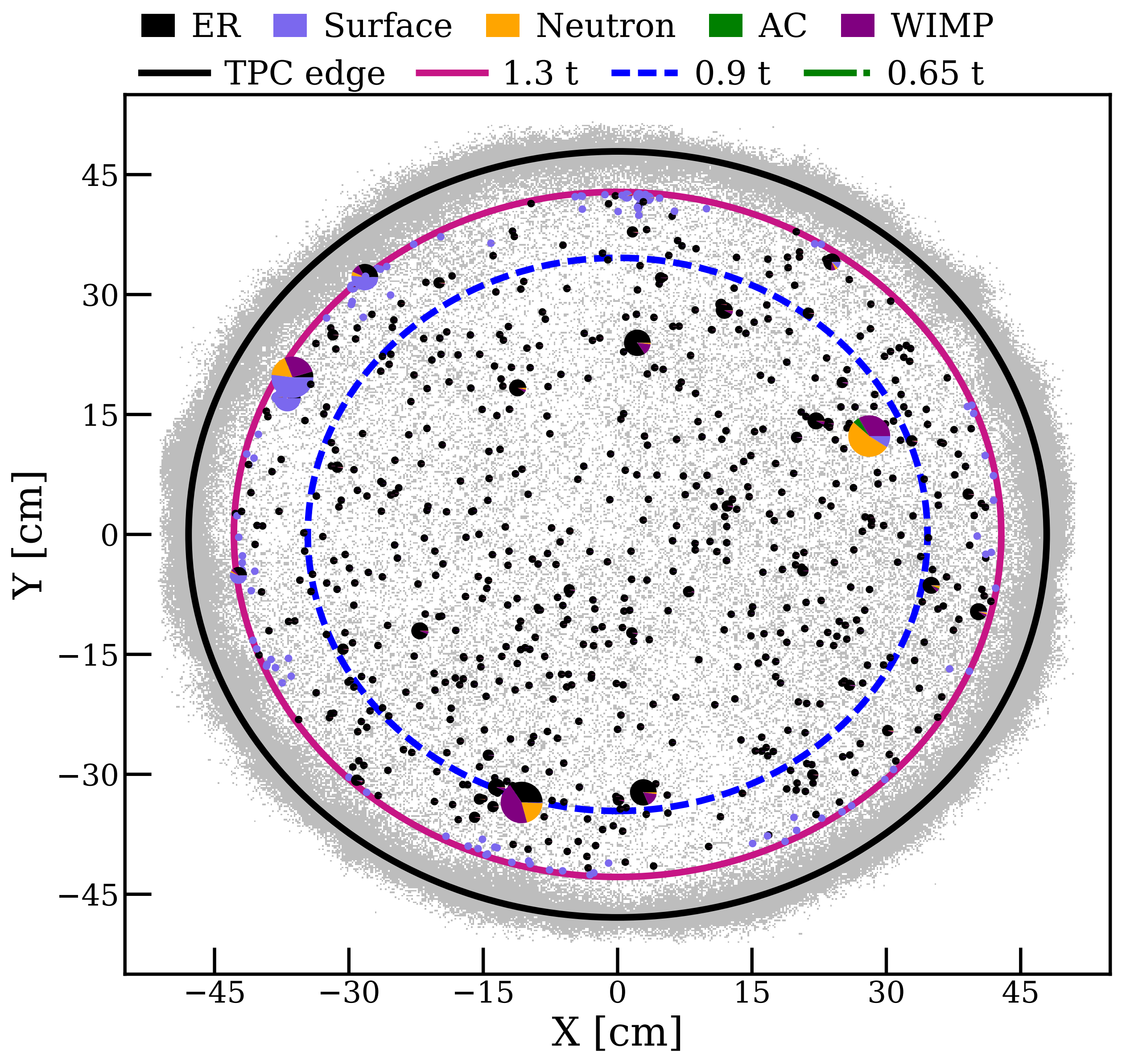


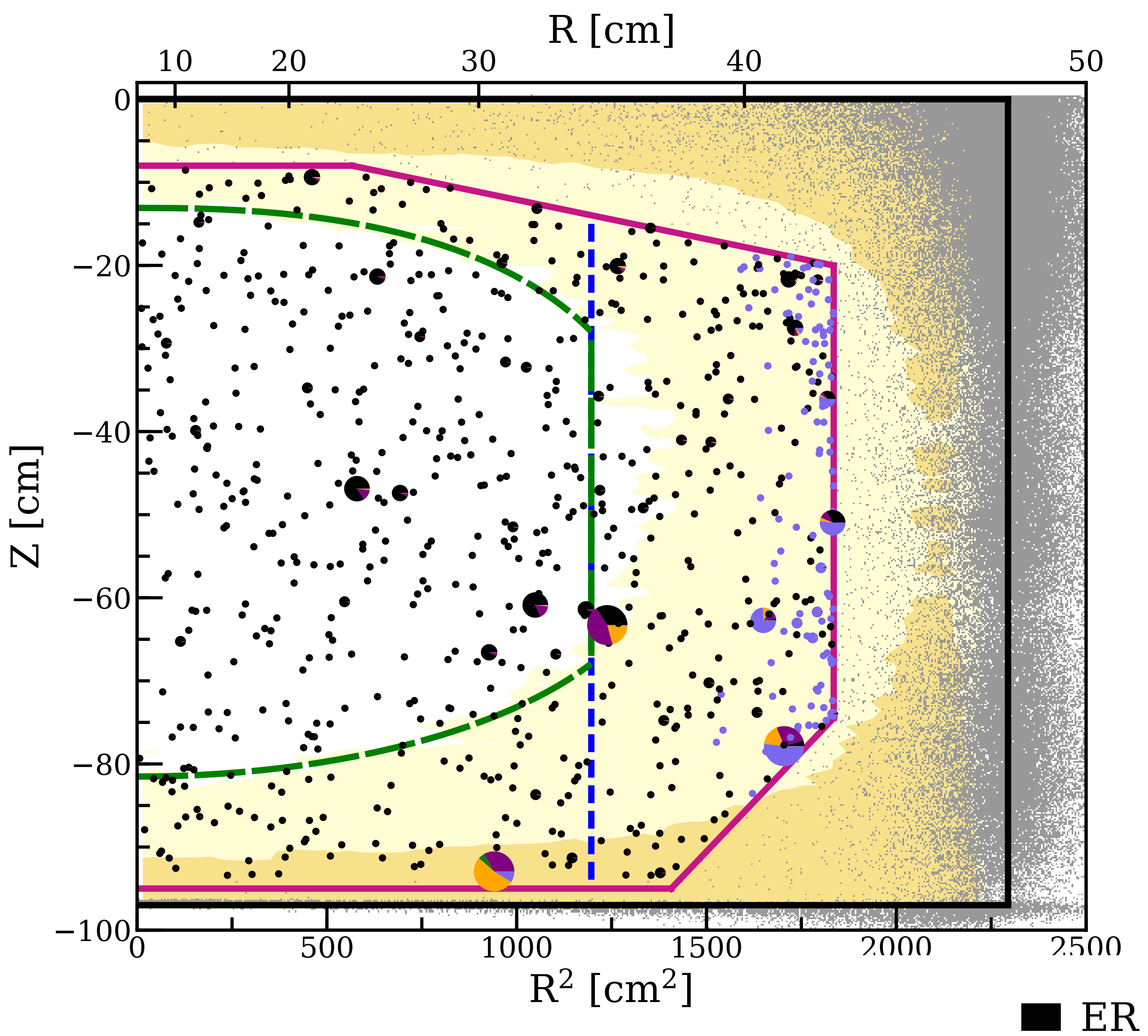
Validation of NR model

Component	NR rate [ev/(t · yr))]
Radiogenic n	0.6 ± 0.1
CNNS	0.012
Cosmogenic	<0.01

1 ton FV

Results after unblinding + unsalting

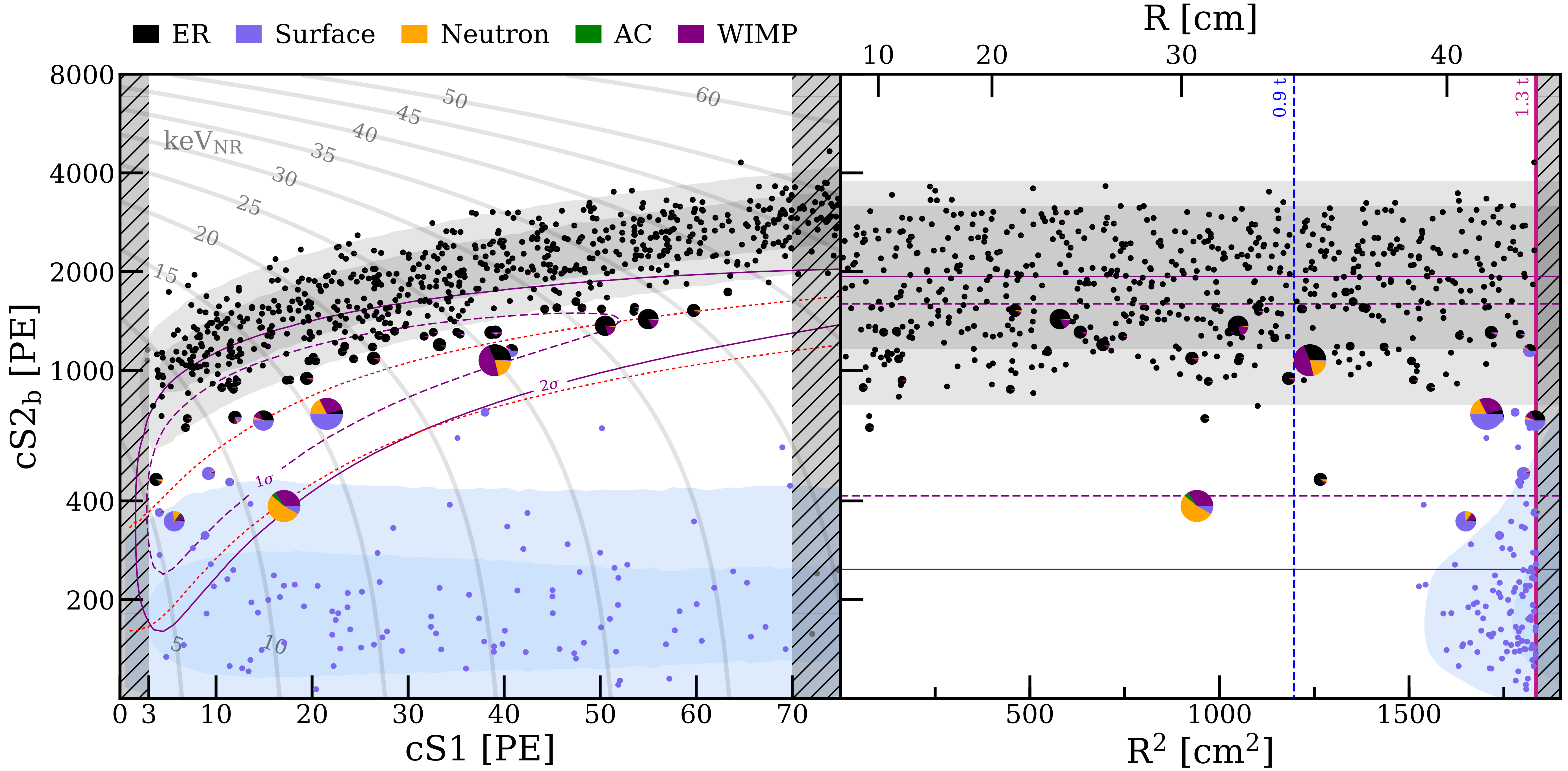




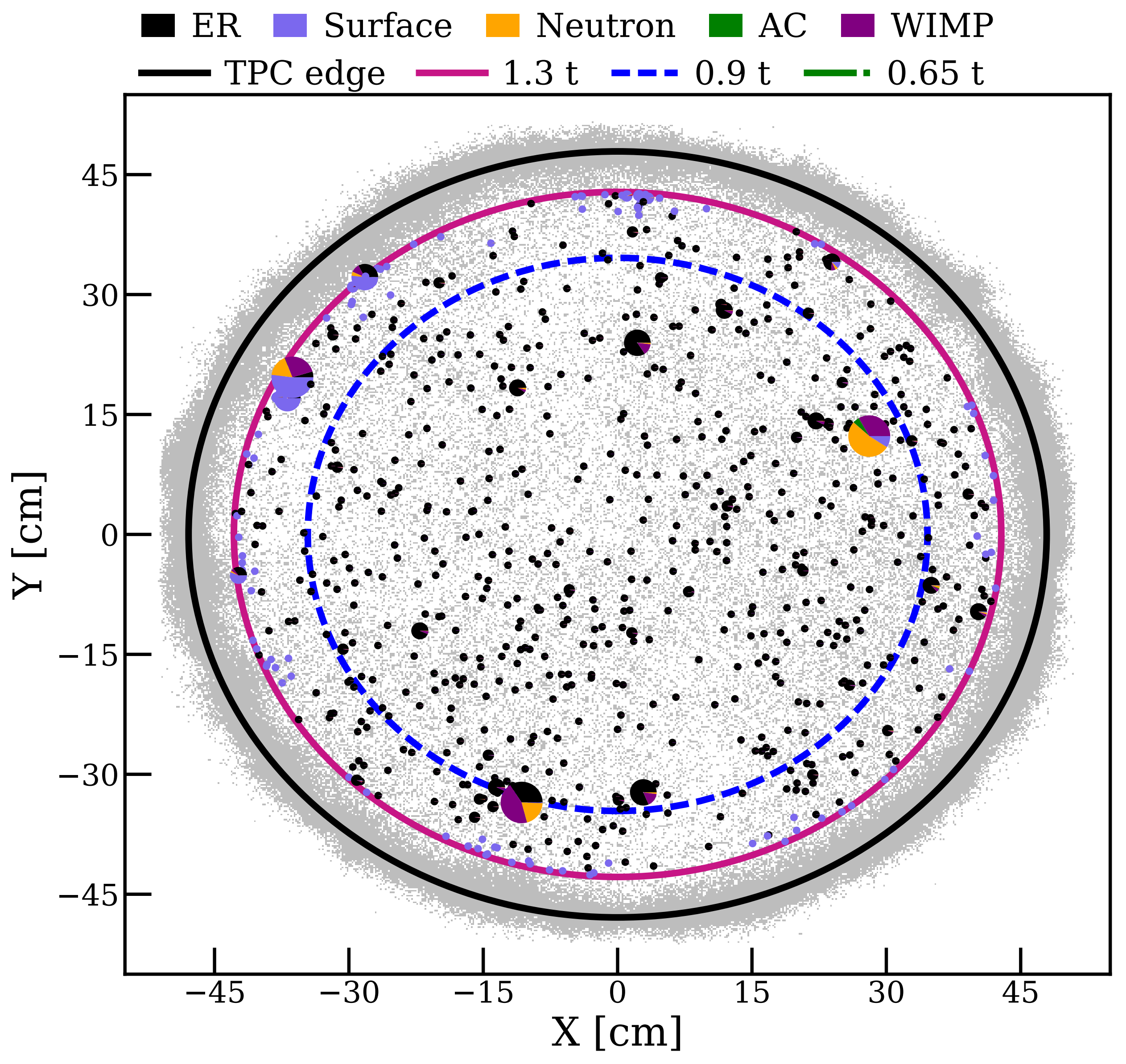
Pie charts:
events passing all cuts,
rel. prob. of BG and signal,
assuming 200 GeV WIMP

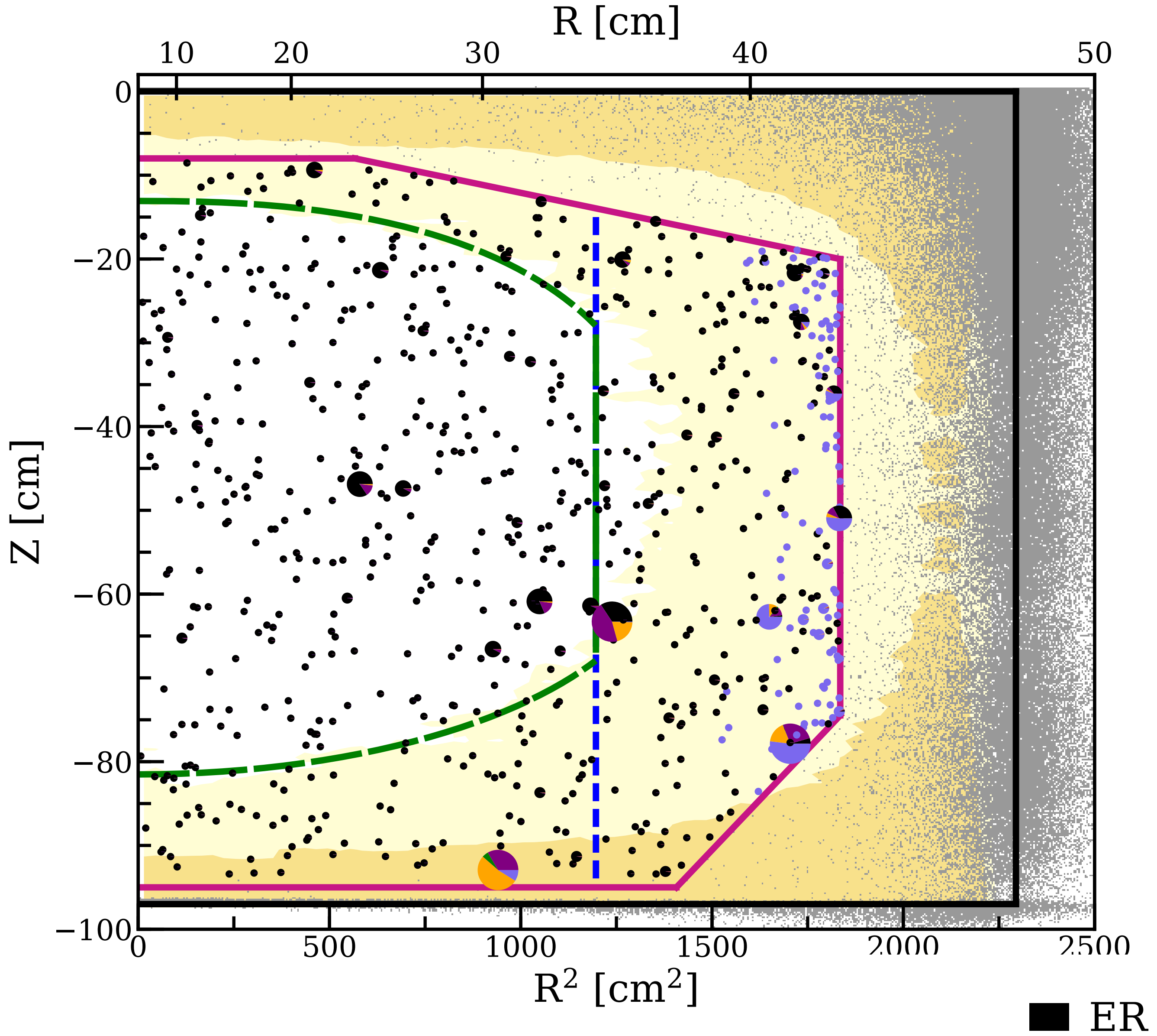
Ref NR region

200 GeV WIMP
(for illustration)



Results after unblinding + unsalting



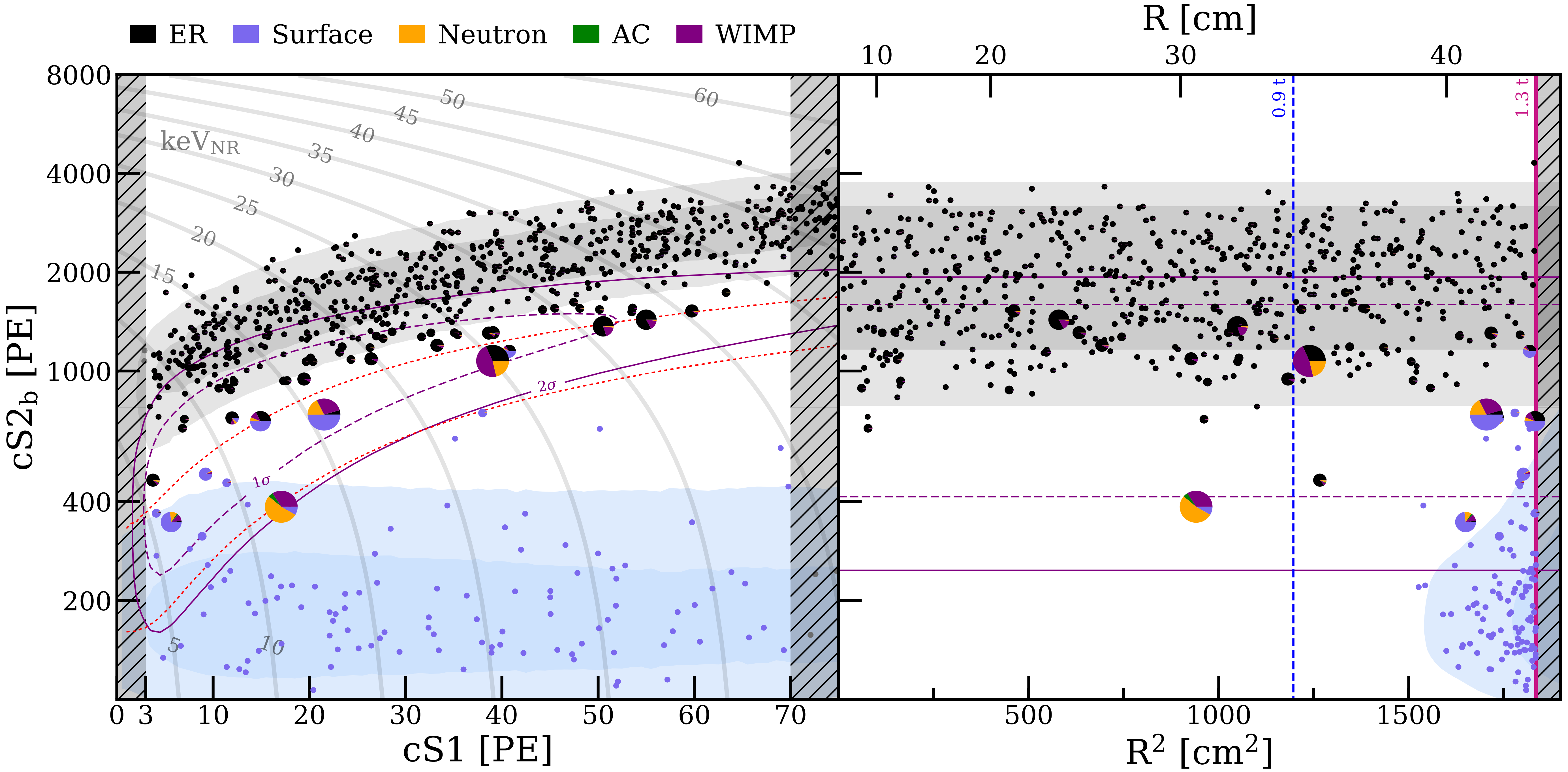


Pie charts:
events passing all cuts,
rel. prob. of BG and signal,
assuming 200 GeV WIMP

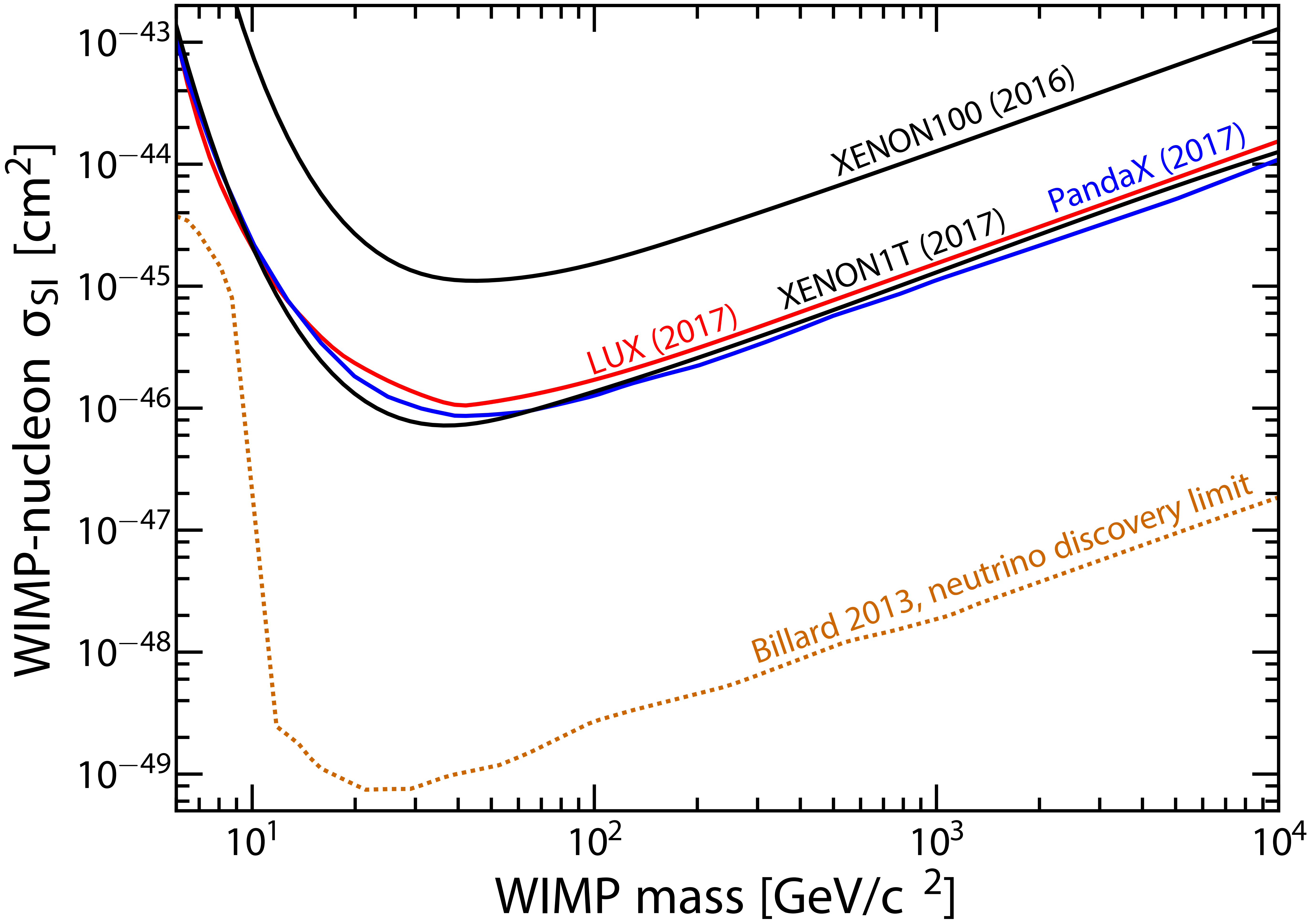
Had to make post-unblinding changes to BG model and Fiducial Mass segmentation:
2% (4%) increase in final limit (med. sens.)

Ref NR region

200 GeV WIMP
(for illustration)

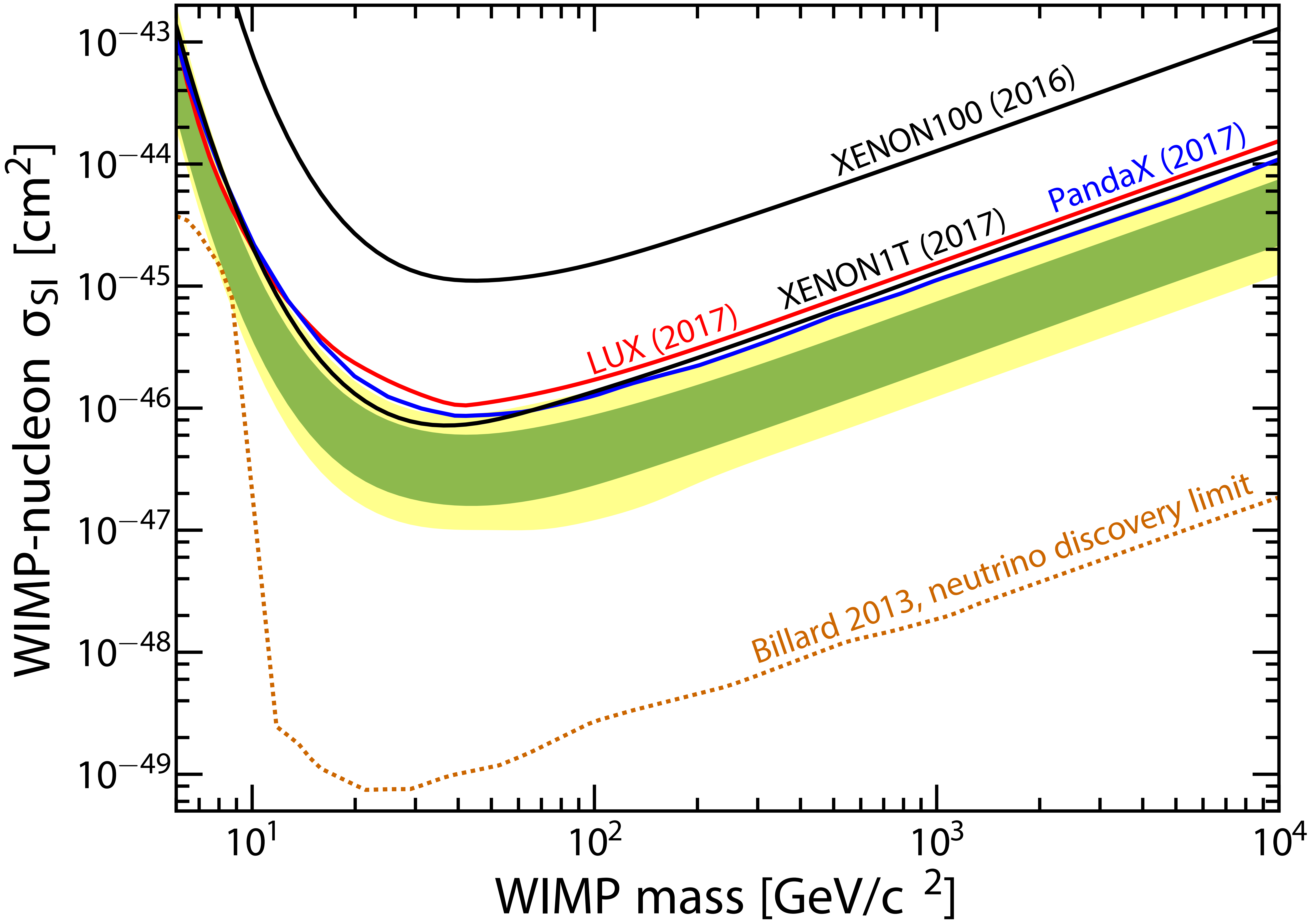


XENON1T: 1 ton x year Exposure



PRL 121, 111302, arXiv:1805.12562

XENON1T: 1 ton x year Exposure



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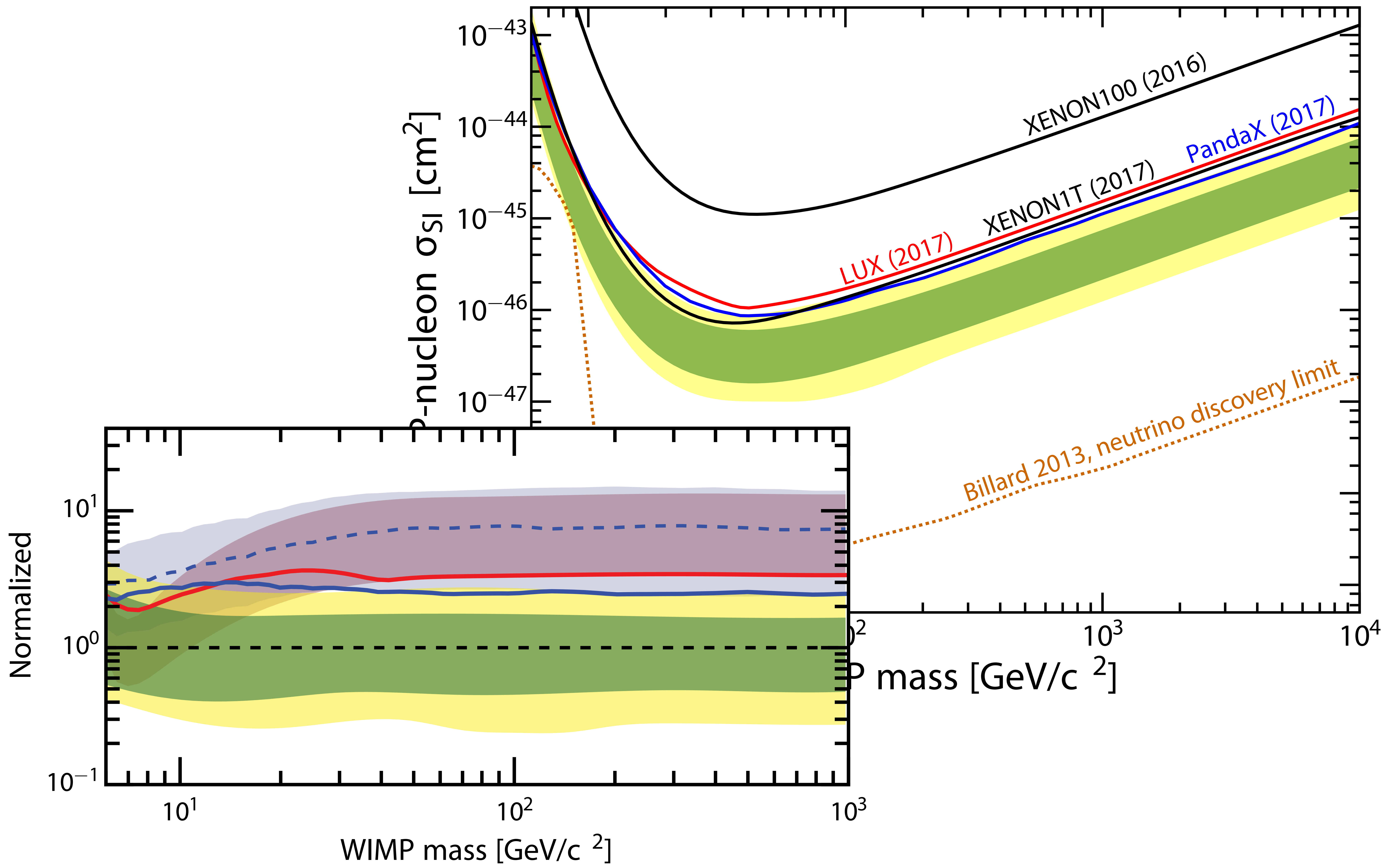

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PRL 121, 111302, arXiv:1805.12562

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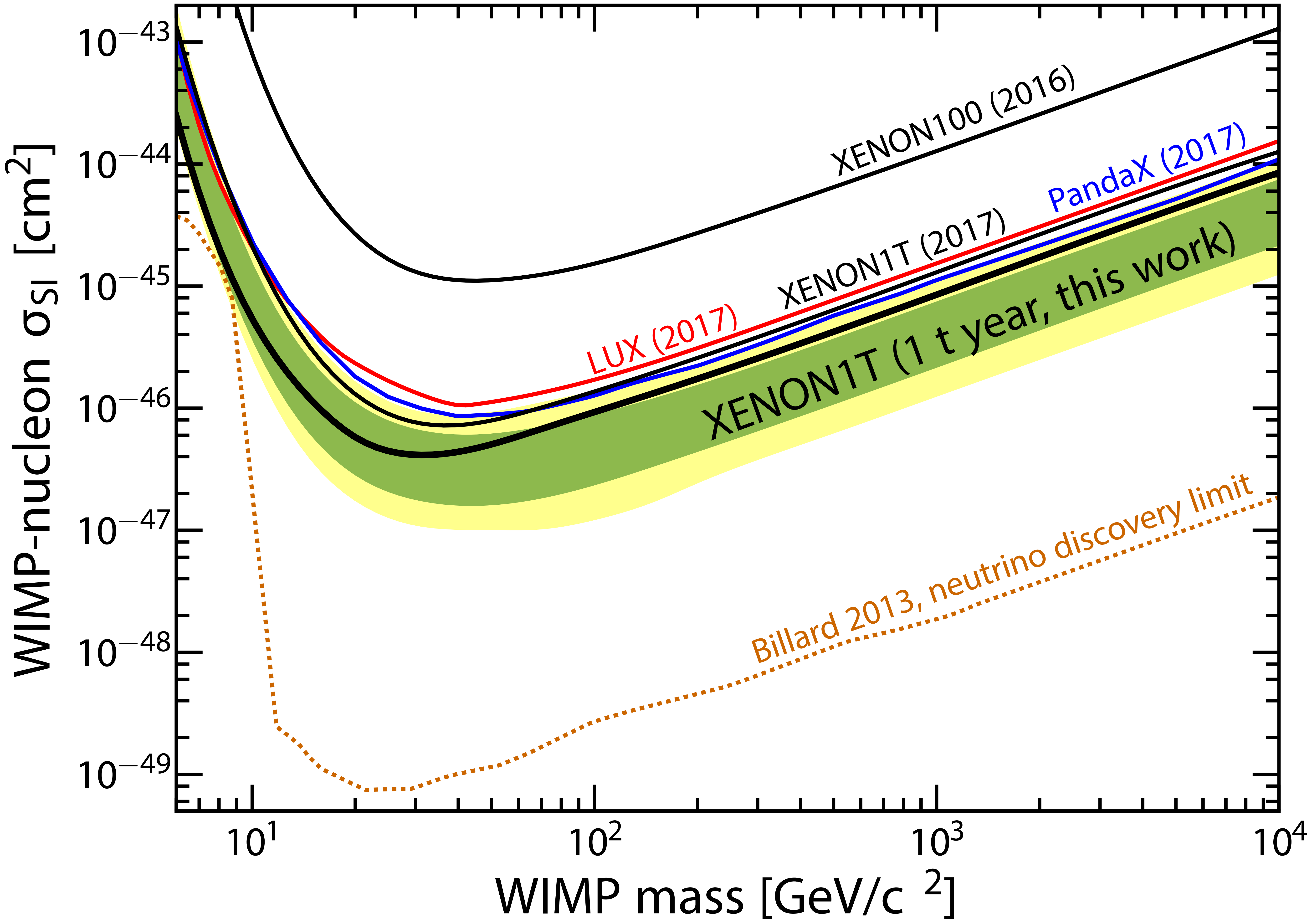

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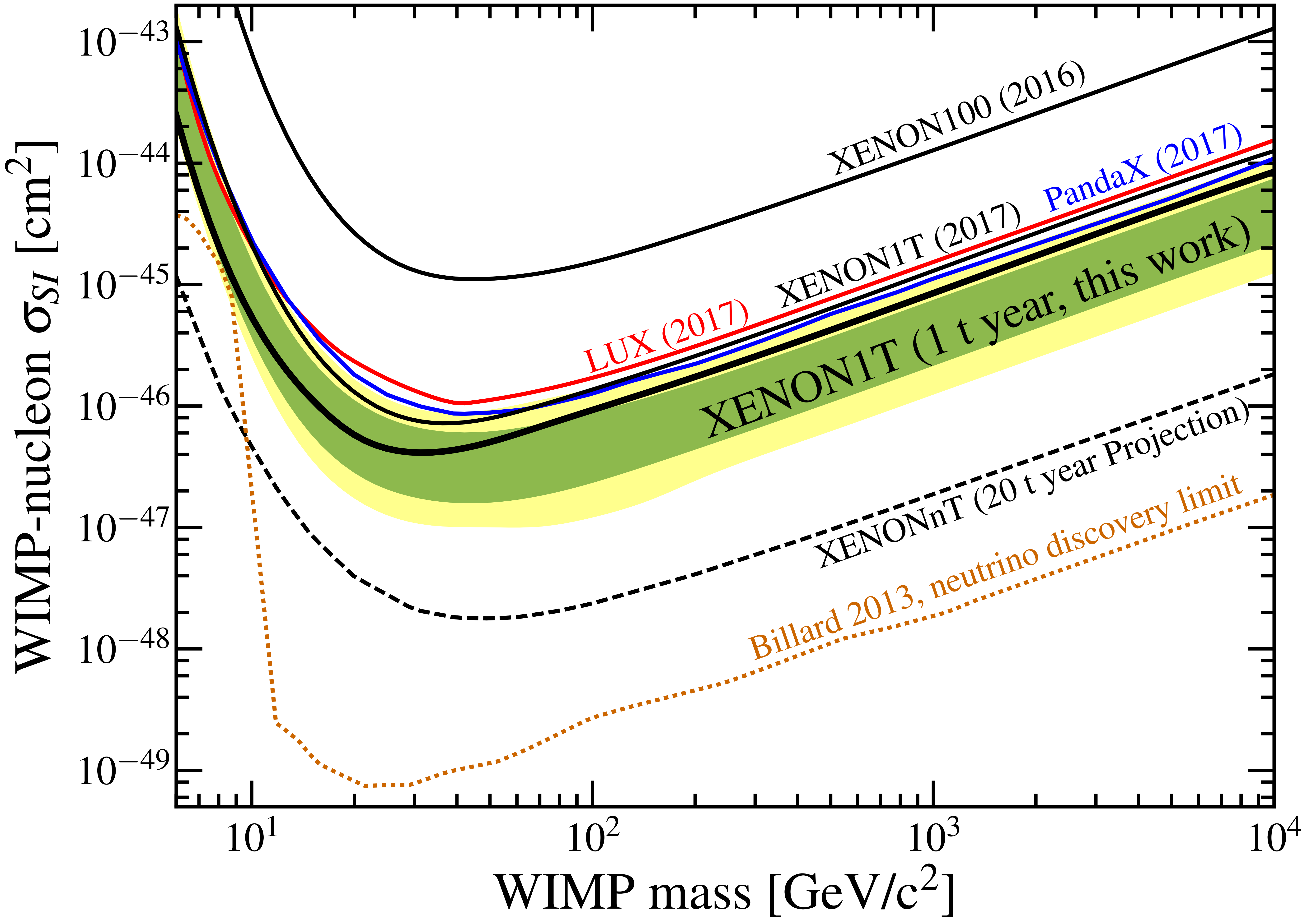

PRL 121, 111302, arXiv:1805.12562

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1. **Planck 2018 results. VI. Cosmological parameters**
(350) Planck Collaboration (N. Aghanim (Orsay, IAS) *et al.*). Jul 17, 2018. 71 pp.
e-Print: **arXiv:1807.06209 [astro-ph.CO]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
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2. **Dark Matter Search Results from a One Ton-Year Exposure of XENON1T**
(192) XENON Collaboration (E. Aprile (Columbia U.) *et al.*). May 31, 2018. 8 pp.
Published in **Phys.Rev.Lett. 121 (2018) no.11, 111302**
DOI: 10.1103/PhysRevLett.121.111302
e-Print: **arXiv:1805.12562 [astro-ph.CO]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 192 records 100+

3. **Planck 2018 results. X. Constraints on inflation**
(159) Planck Collaboration (Y. Akrami (Leiden U. & Inst. Theor. Astrophys., Oslo) *et al.*). Jul 17, 2018. 66 pp.
e-Print: **arXiv:1807.06211 [astro-ph.CO]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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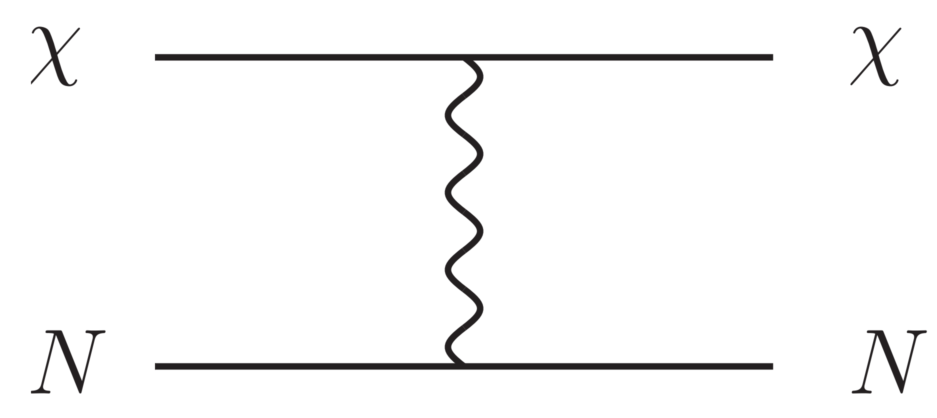
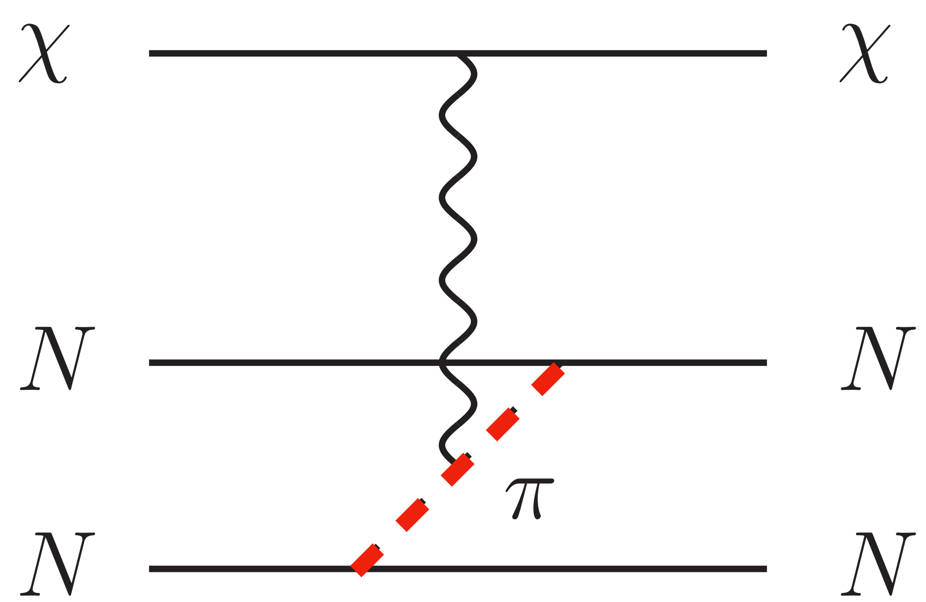
Patr

4. **An absorption profile centred at 78 megahertz in the sky-averaged spectrum**

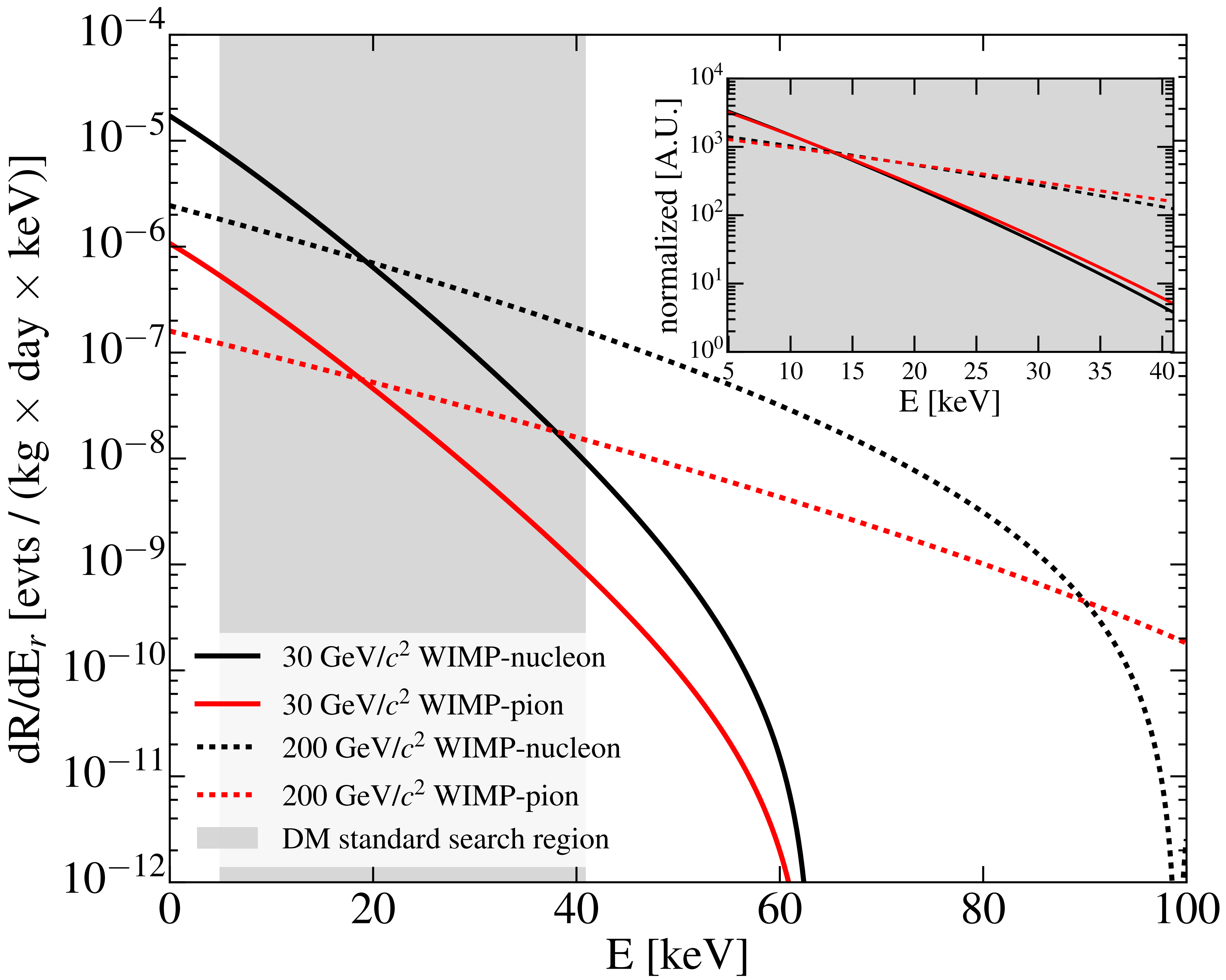
WIMP-pion coupling

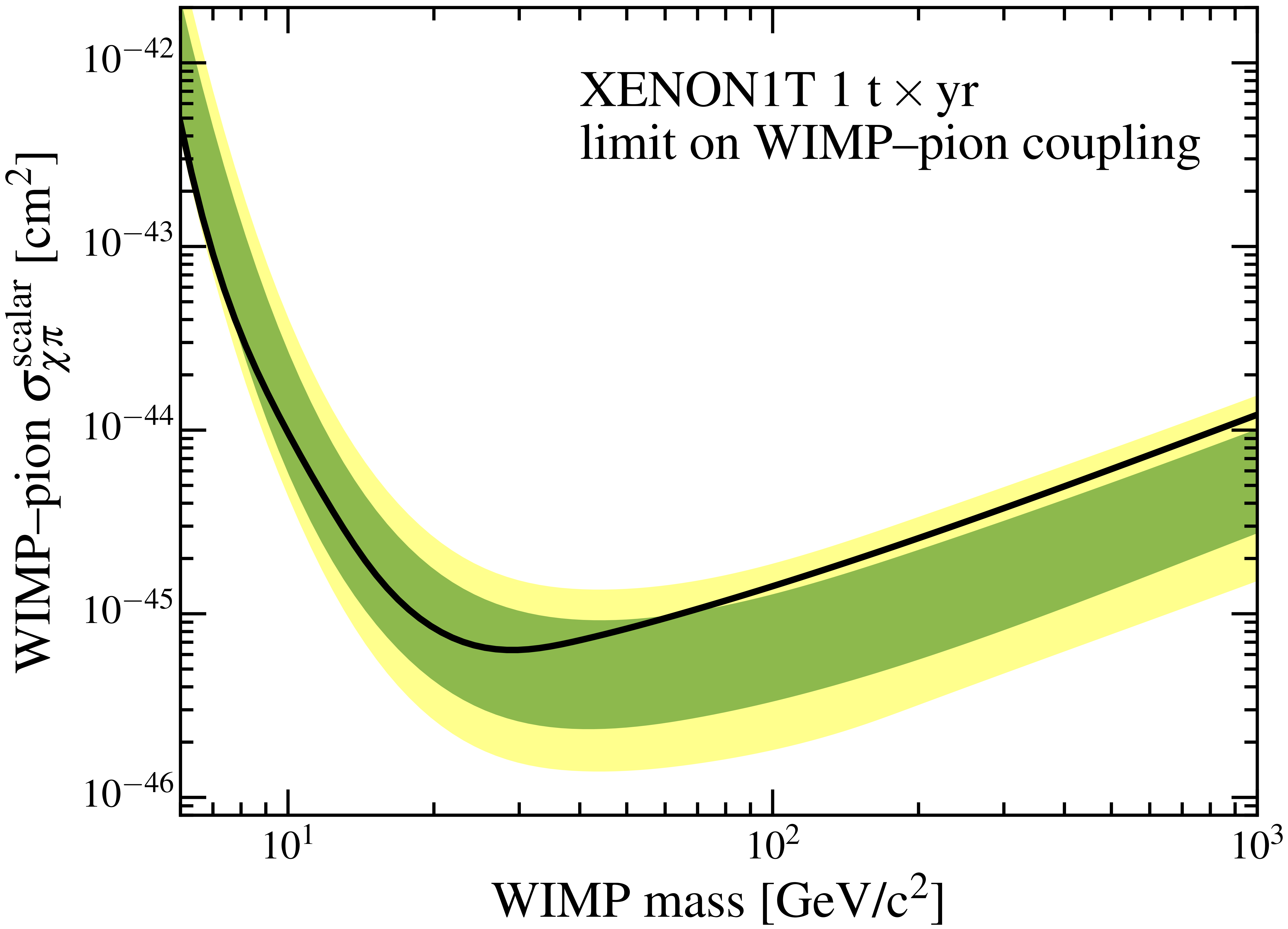


Leading: WIMP-single nucleon



Coupling to pion-exchange

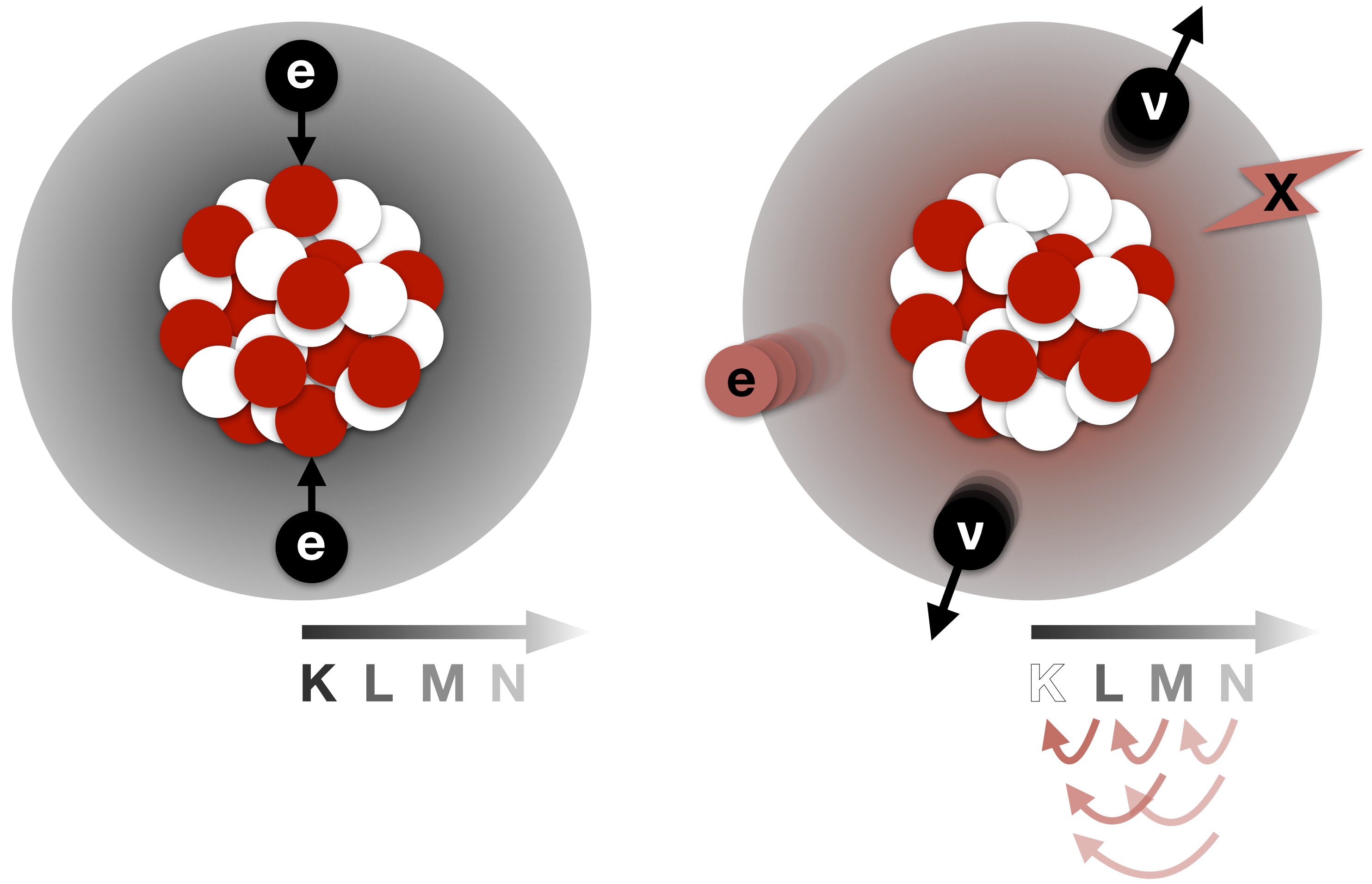




XENON Coll, arXiv:1811.12482

Double Electron Capture

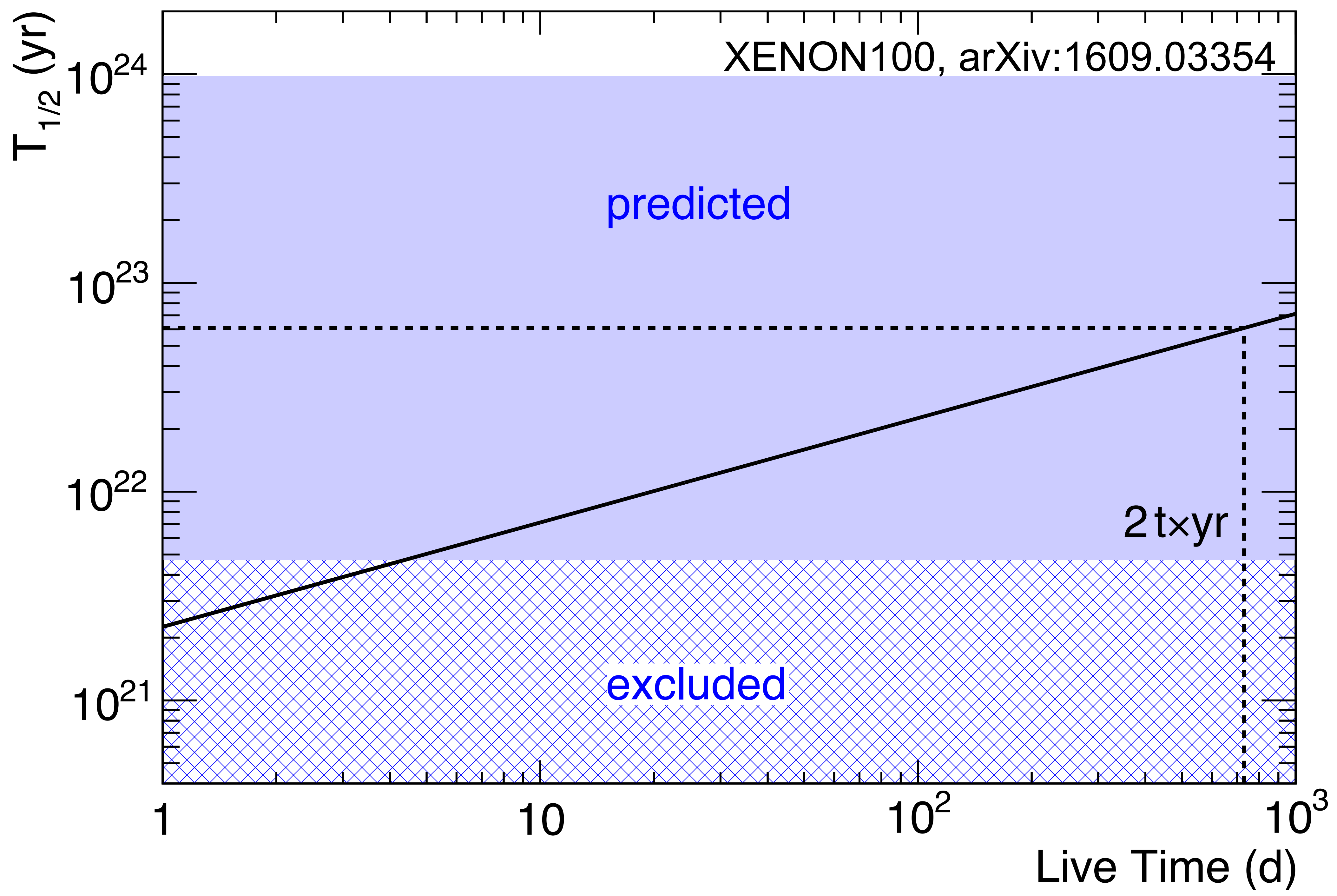
- Second order process like double β-decay, but longer lived - so far only measured in ^{130}Ba and ^{78}Kr
- ^{124}Xe is a candidate isotope
  - 0.095% Nat. abundance
  - Peak at 64.3 keV from K-shell captures



$$T_{1/2}^{2\nu 2EC} \propto G_{2\nu} |M_{2\nu}|^2$$

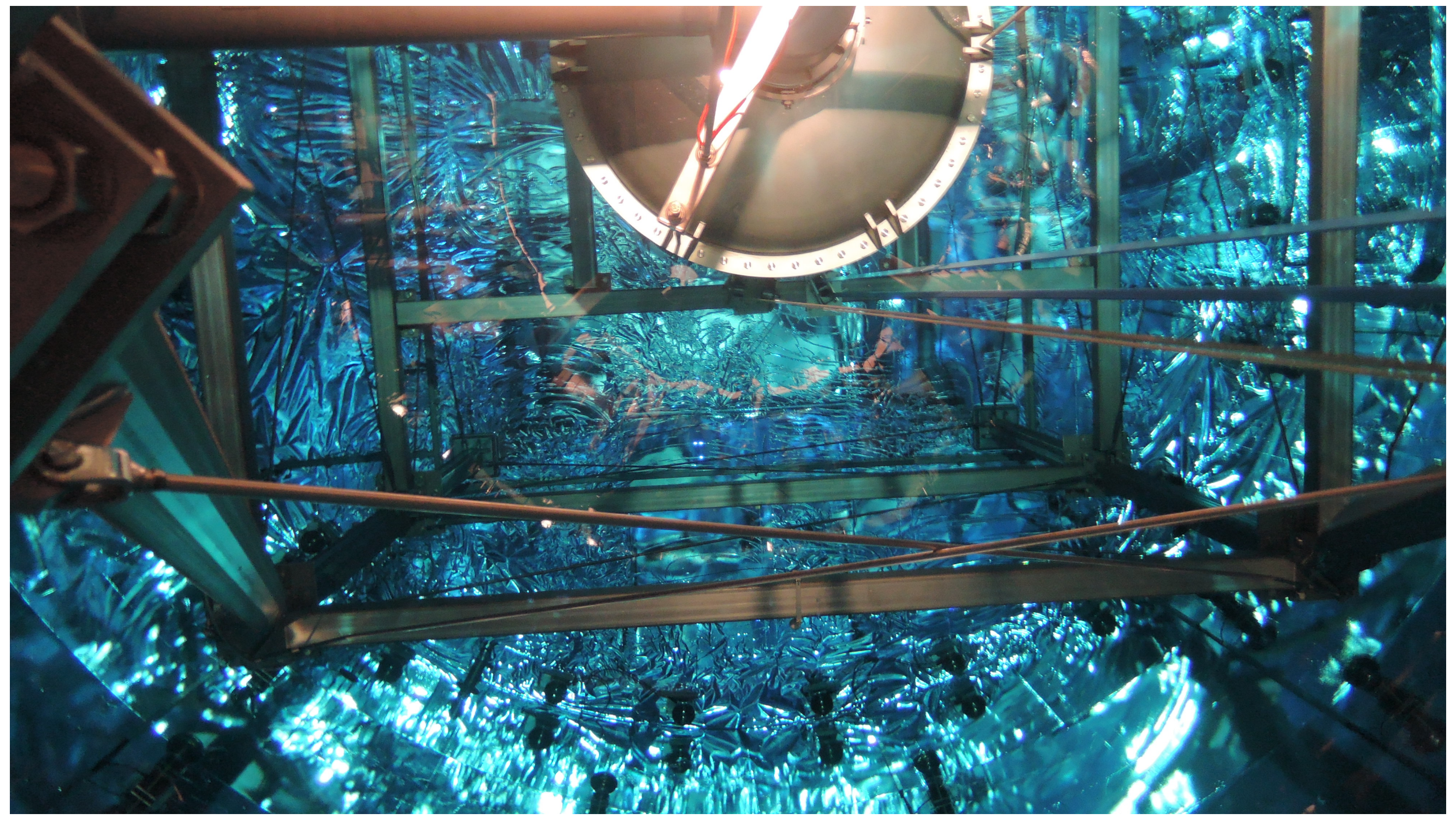
Phase Space Factor

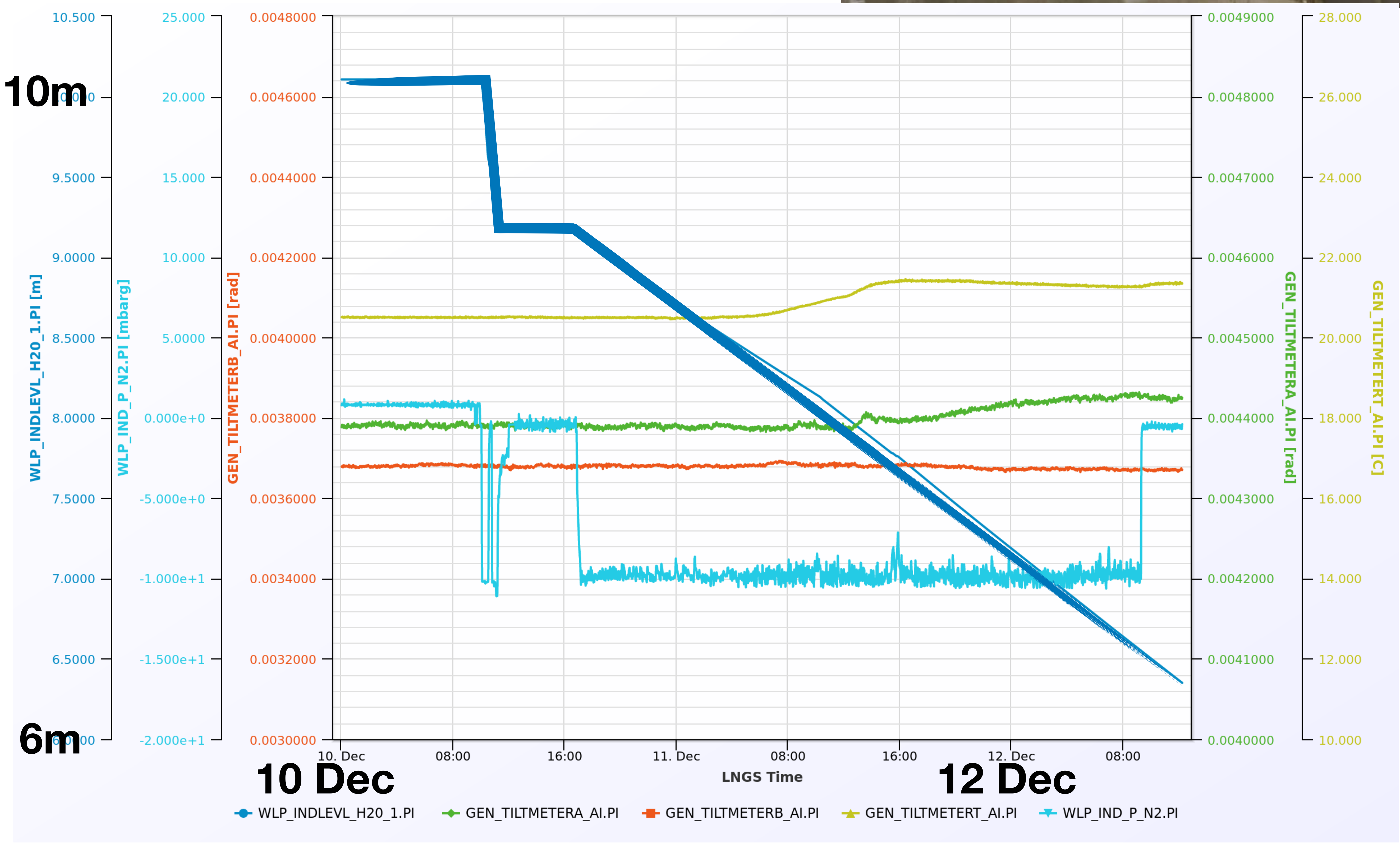
Nuclear Matrix Element



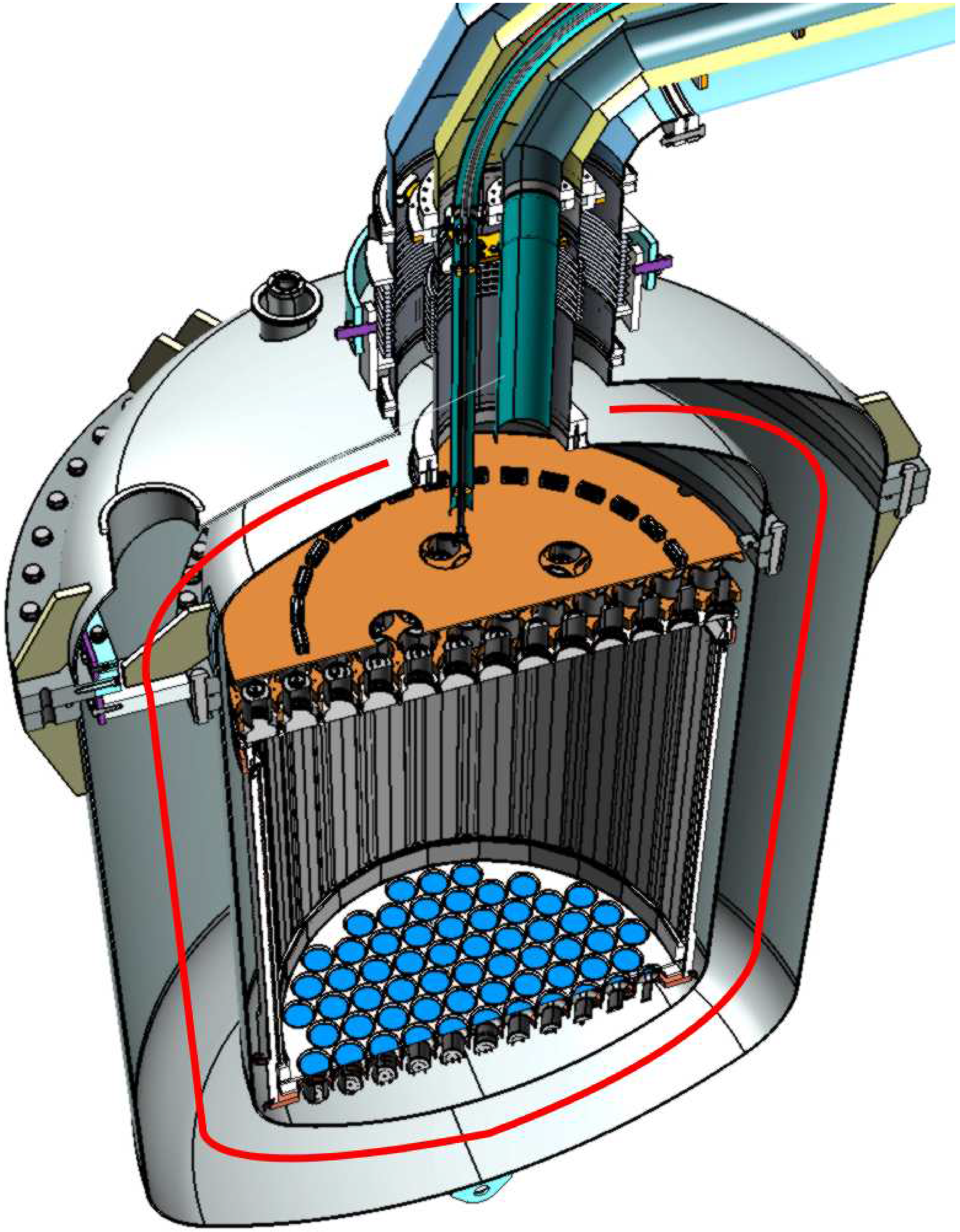
Ending XENON1T Ops

- XENON1T as XENONnT R&D setup since May 2018:
  - XENONnT DAQ test
  - ^{37}Ar calibration: 2.82 and 0.27 keV lines
  - Continuous Rn distillation
  - Changing drift and extraction fields
  - …
- **XENON1T officially ended December 10**
  - Water from the water tank discharged
- LXe recuperation ongoing…





From XENON1T to XENONnT

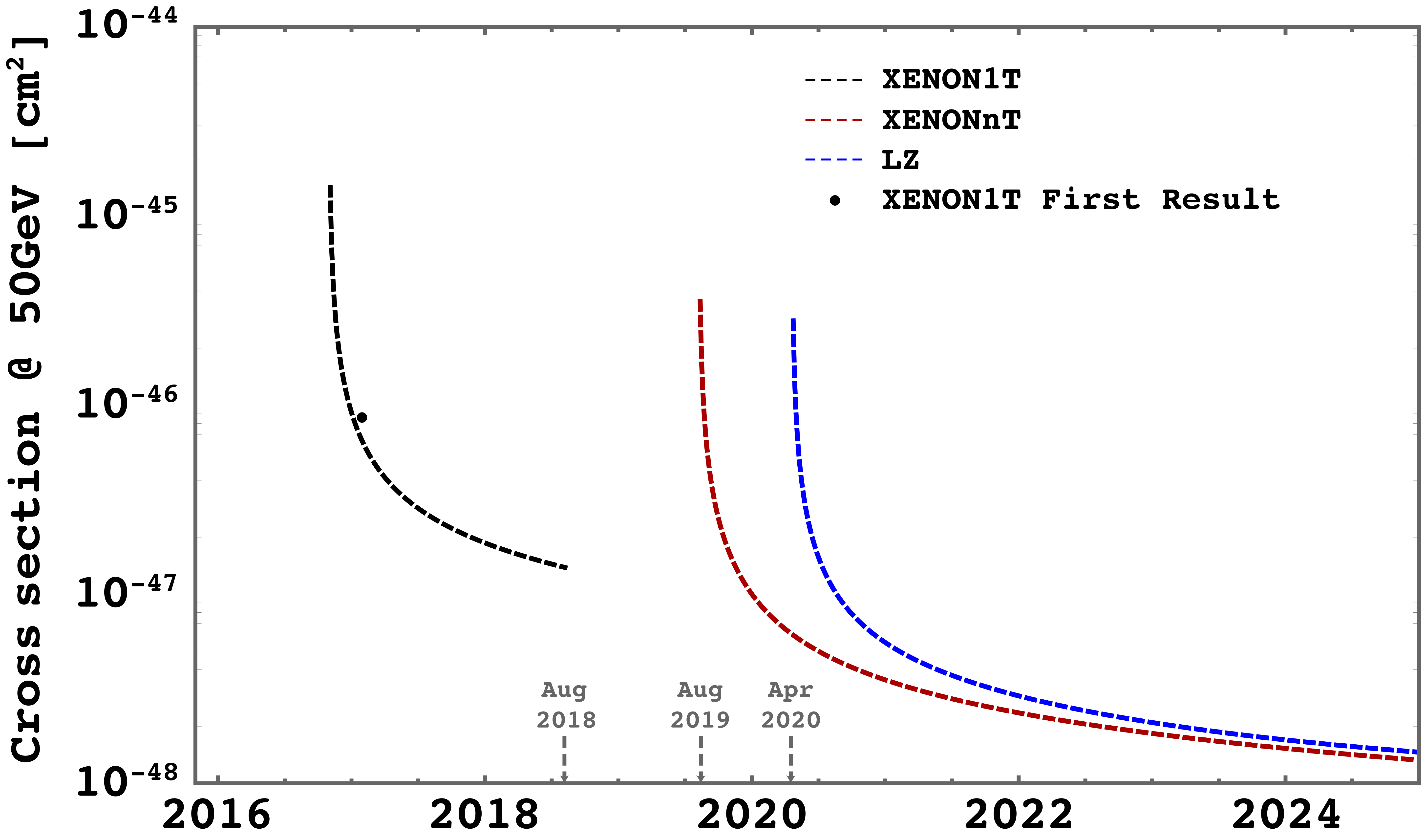


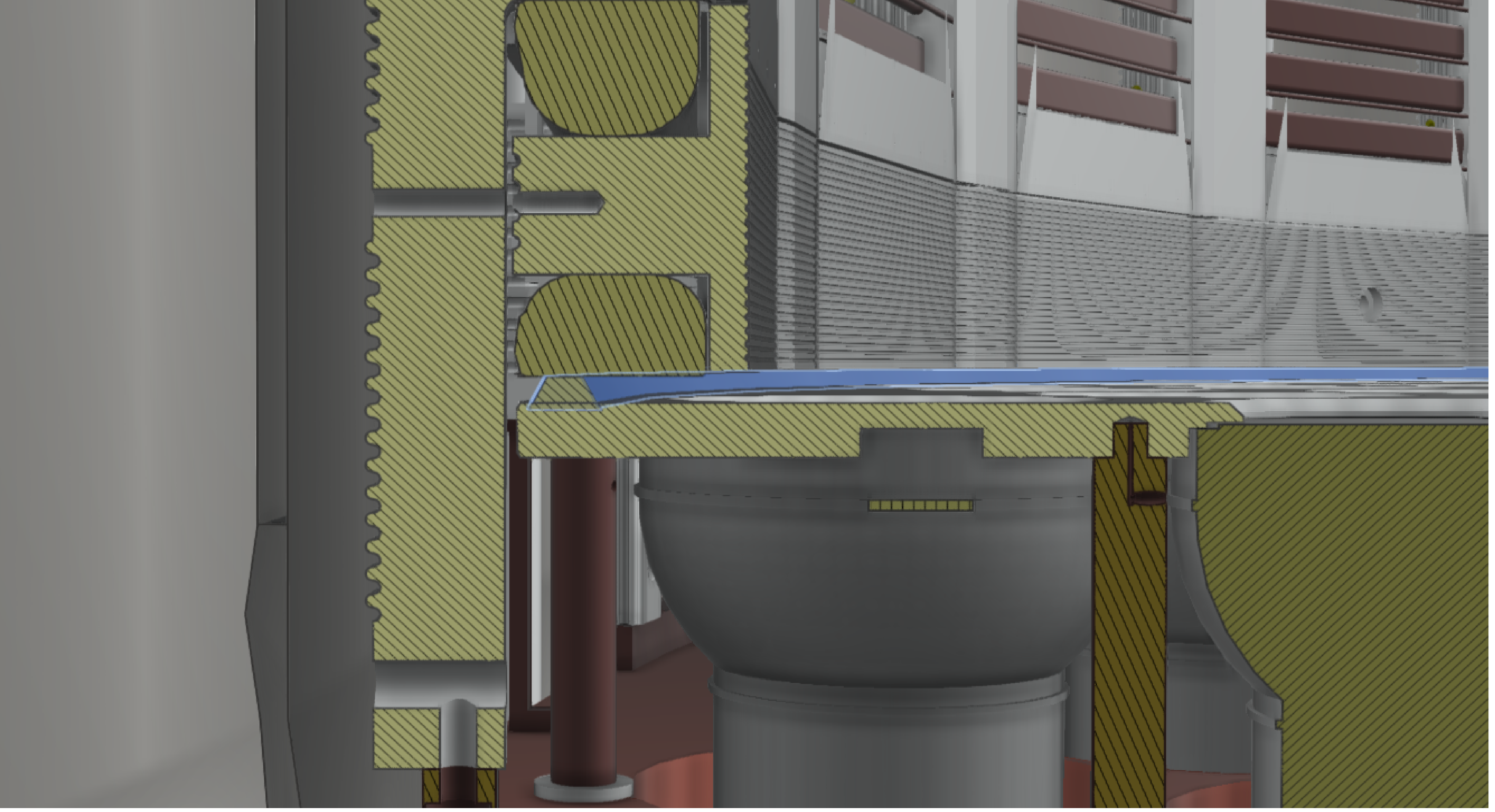
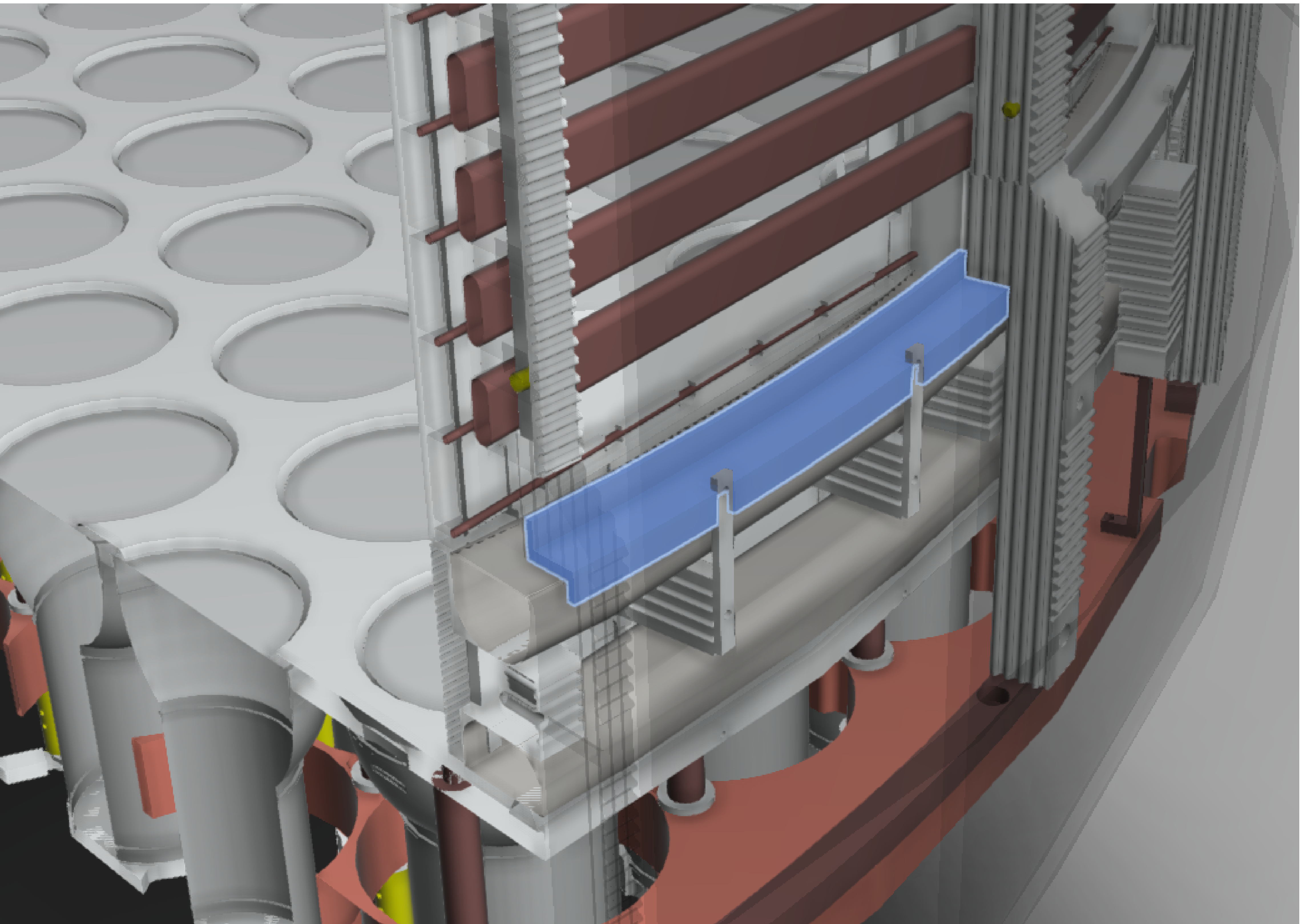
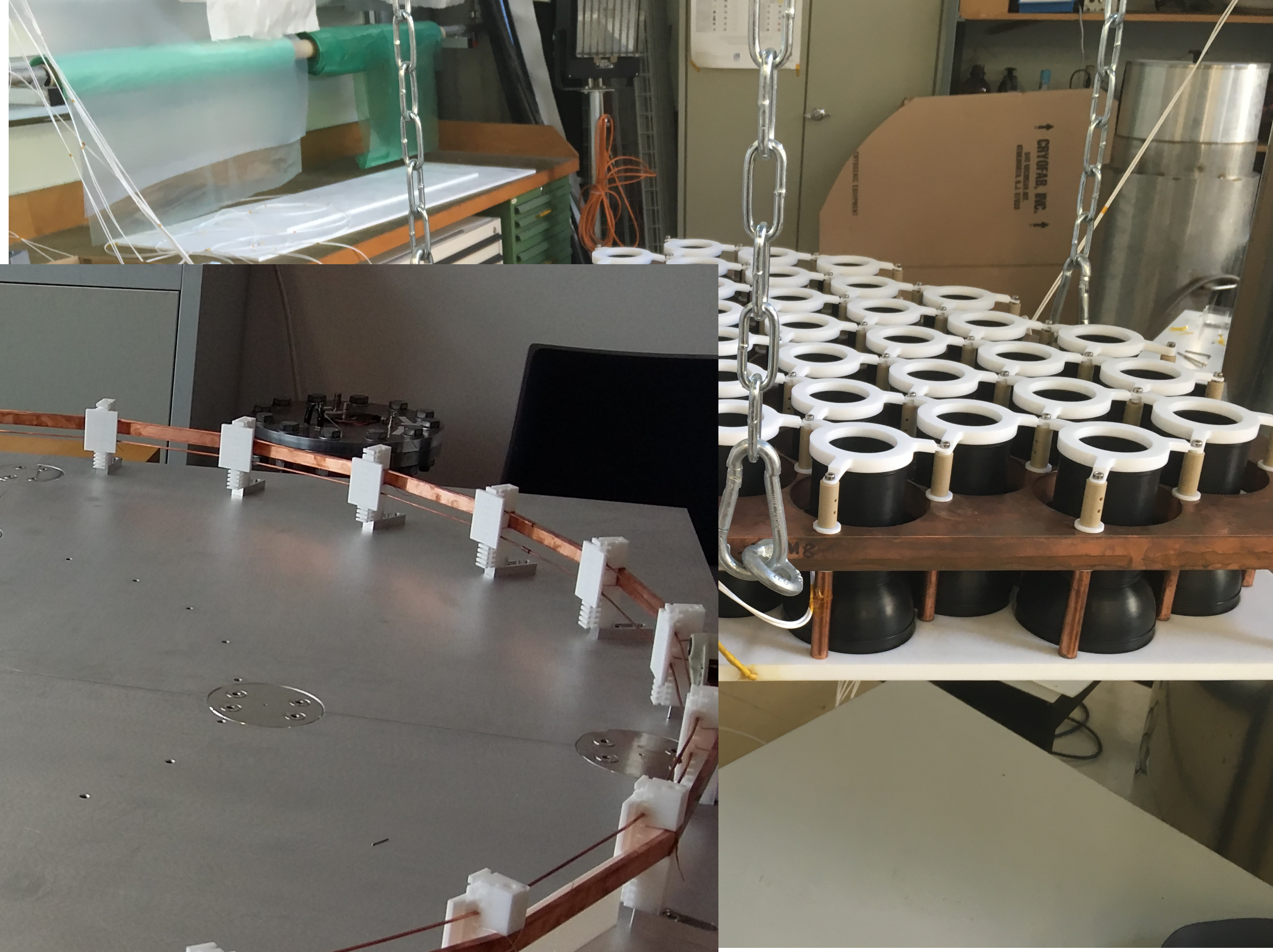
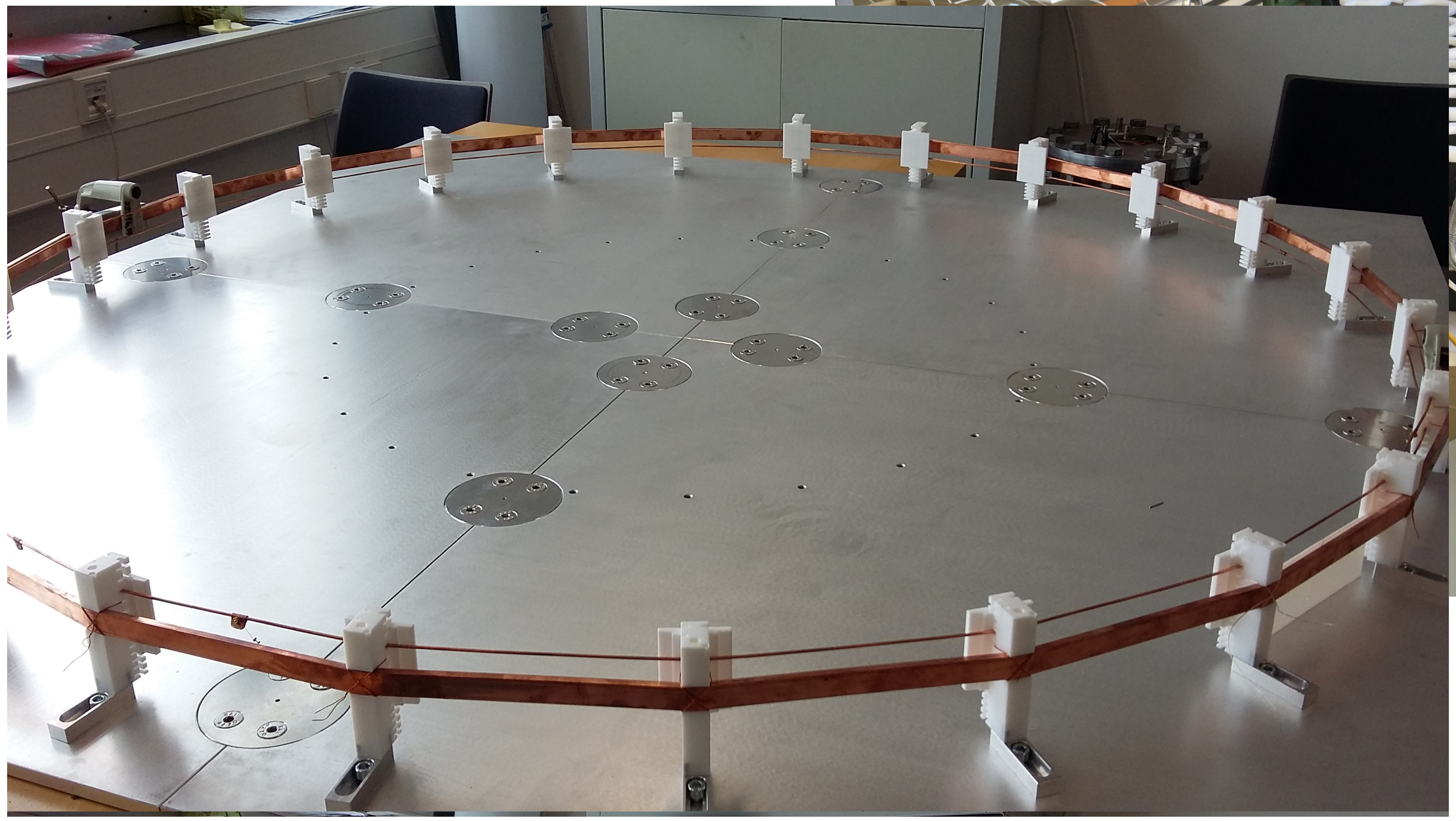
- Reuse most of XENON1T
- Larger inner cryostat vessel
- New TPC
- Additional ~250 PMTs (~500 total)
- Total of ~8 tons of LXe
- 10x lower ^{222}Rn
- Funding complete
- Detector being built / designed
- Start in 2019

Similar efforts: LZ (USA), PandaX-xT (China)

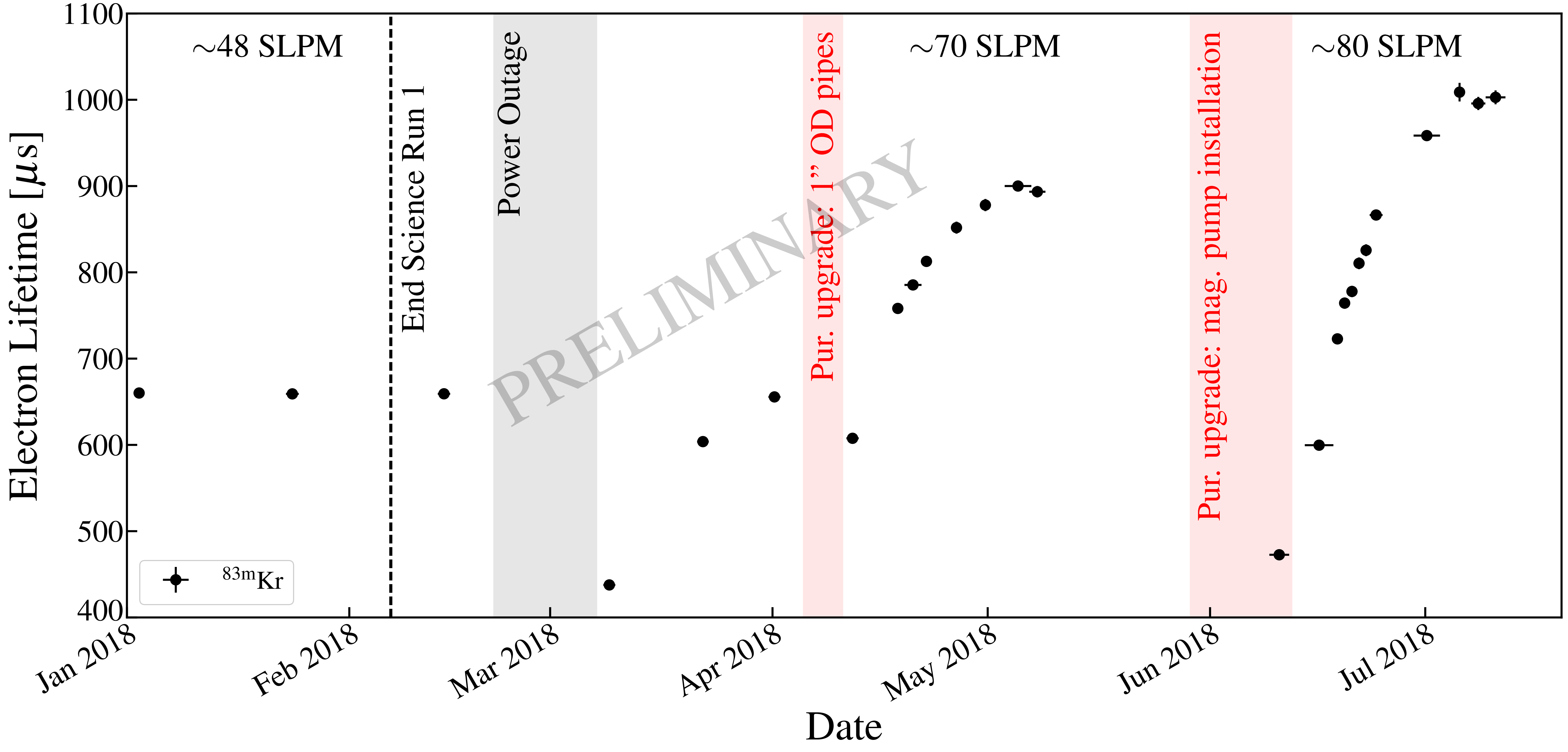
Our XENONnT Goal

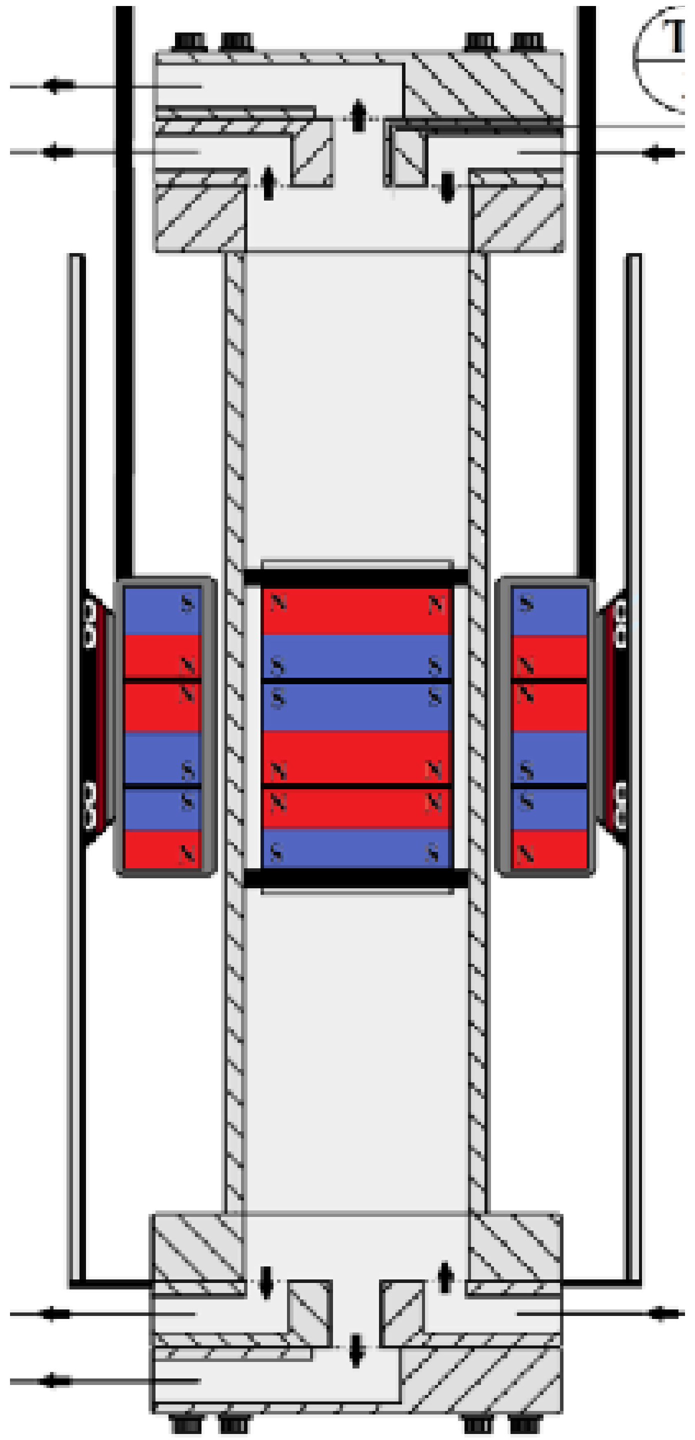
- Increase Xe mass by 3x
- Reduce ^{222}Rn background by 10x
- Veto the ultimate neutron background
- Complement continuous gas purification by liquid purification




New Magnetic Pump

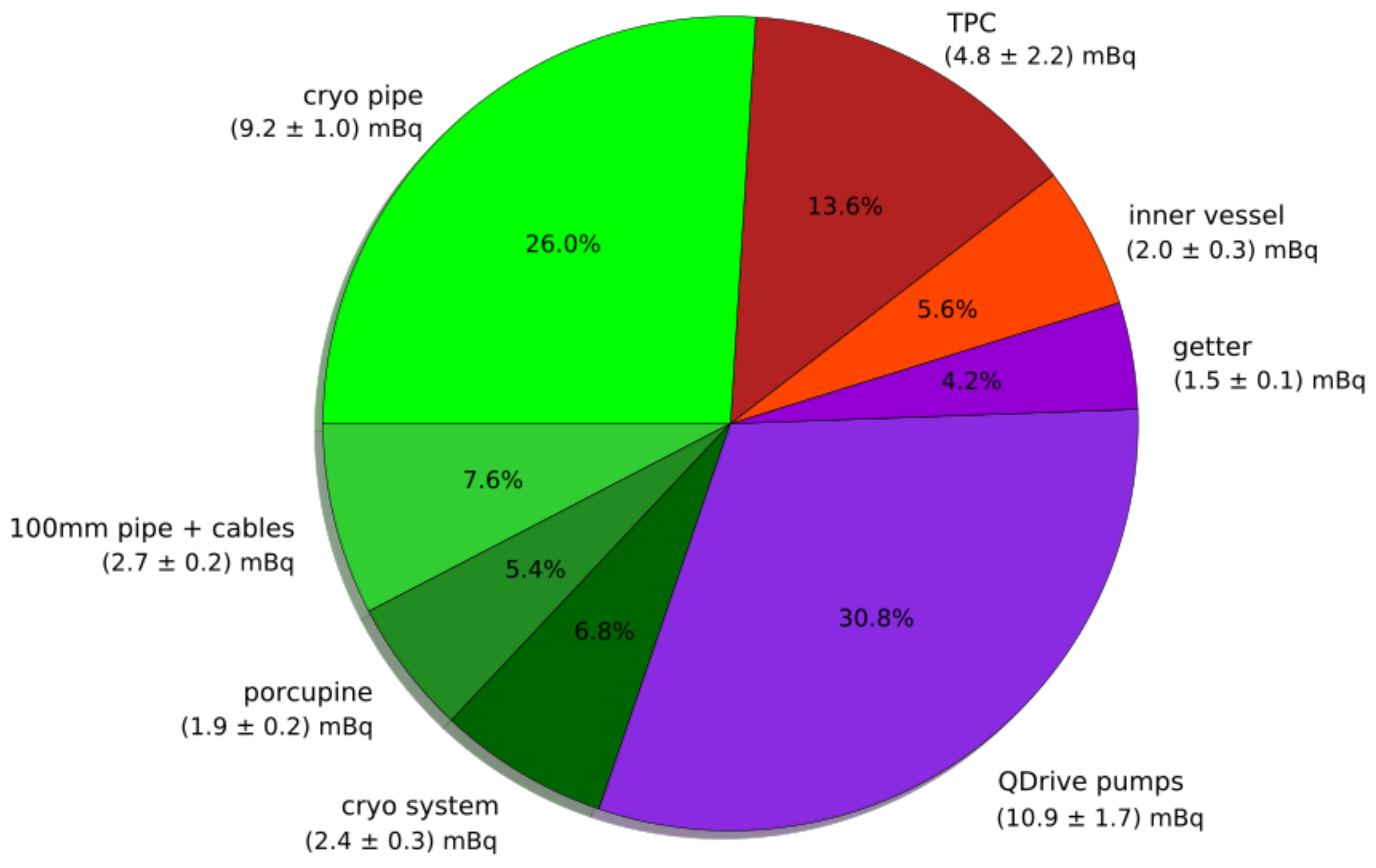


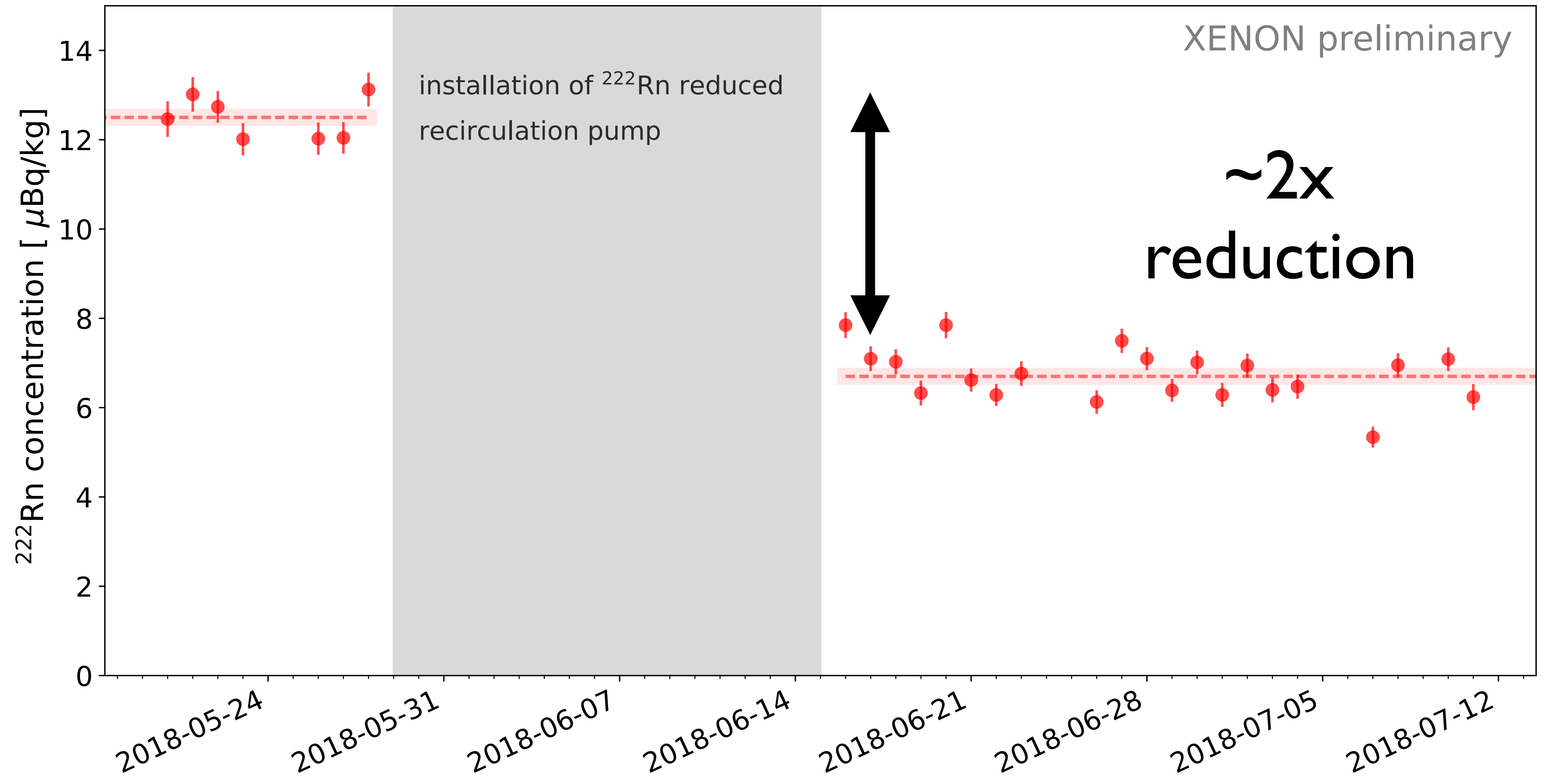


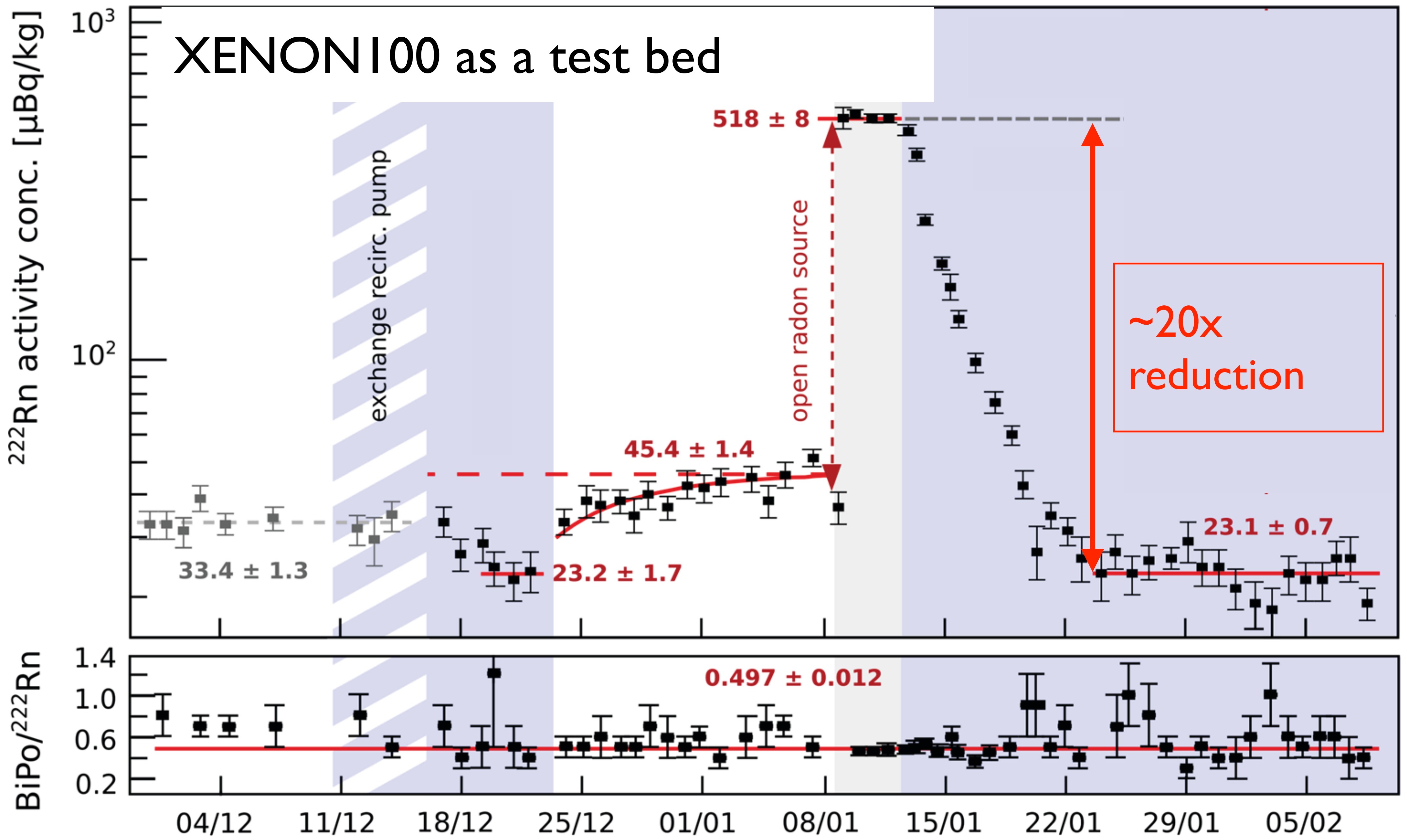
- XENONnT R&D on XENON1T
- New Magnetic Pump
  - Increase LXe purity - longer drift
  - Reduce ^{222}Rn contamination (from emanation of pump materials)

^{222}Rn Background

^{222}Rn contributions in XENON1T

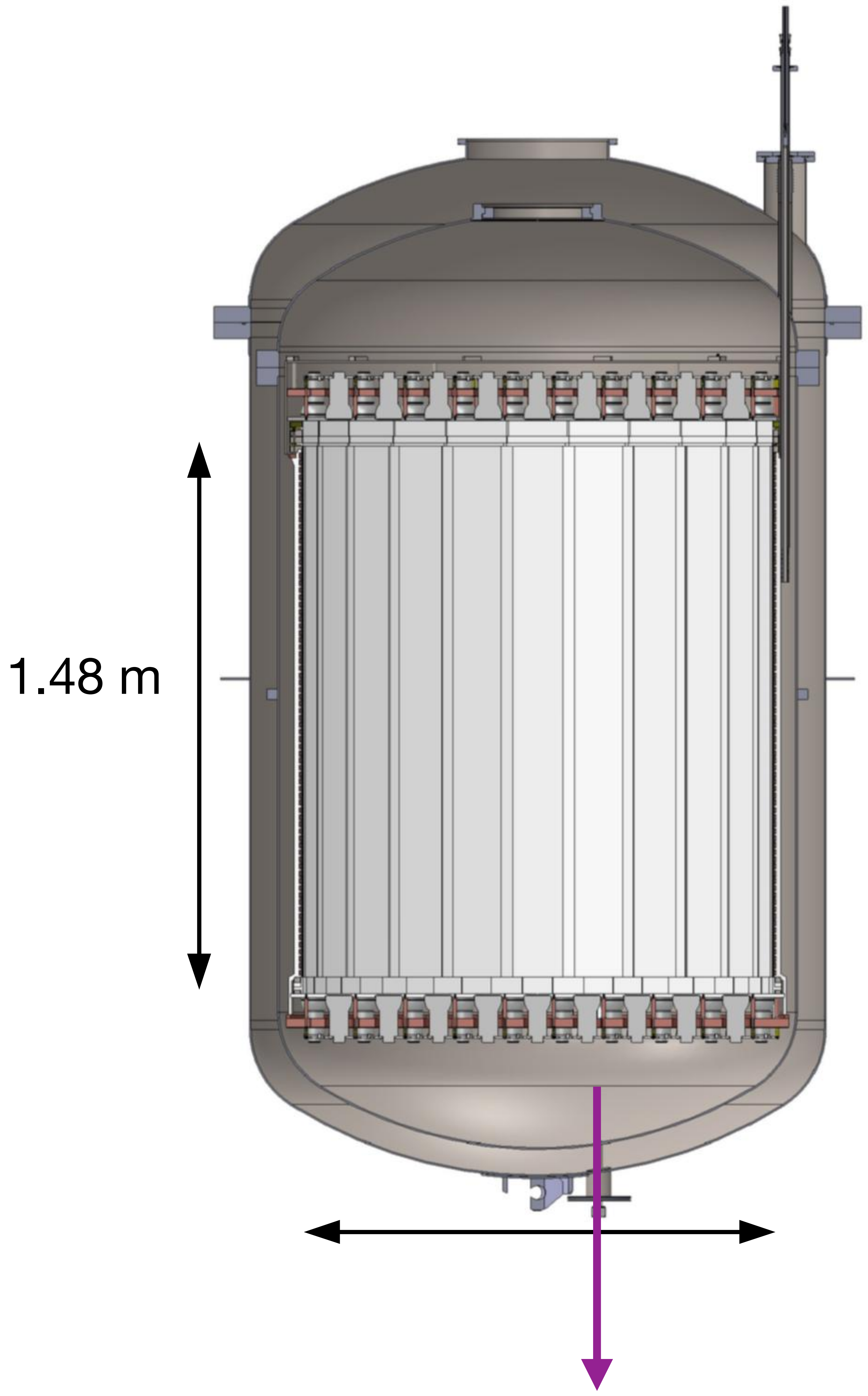






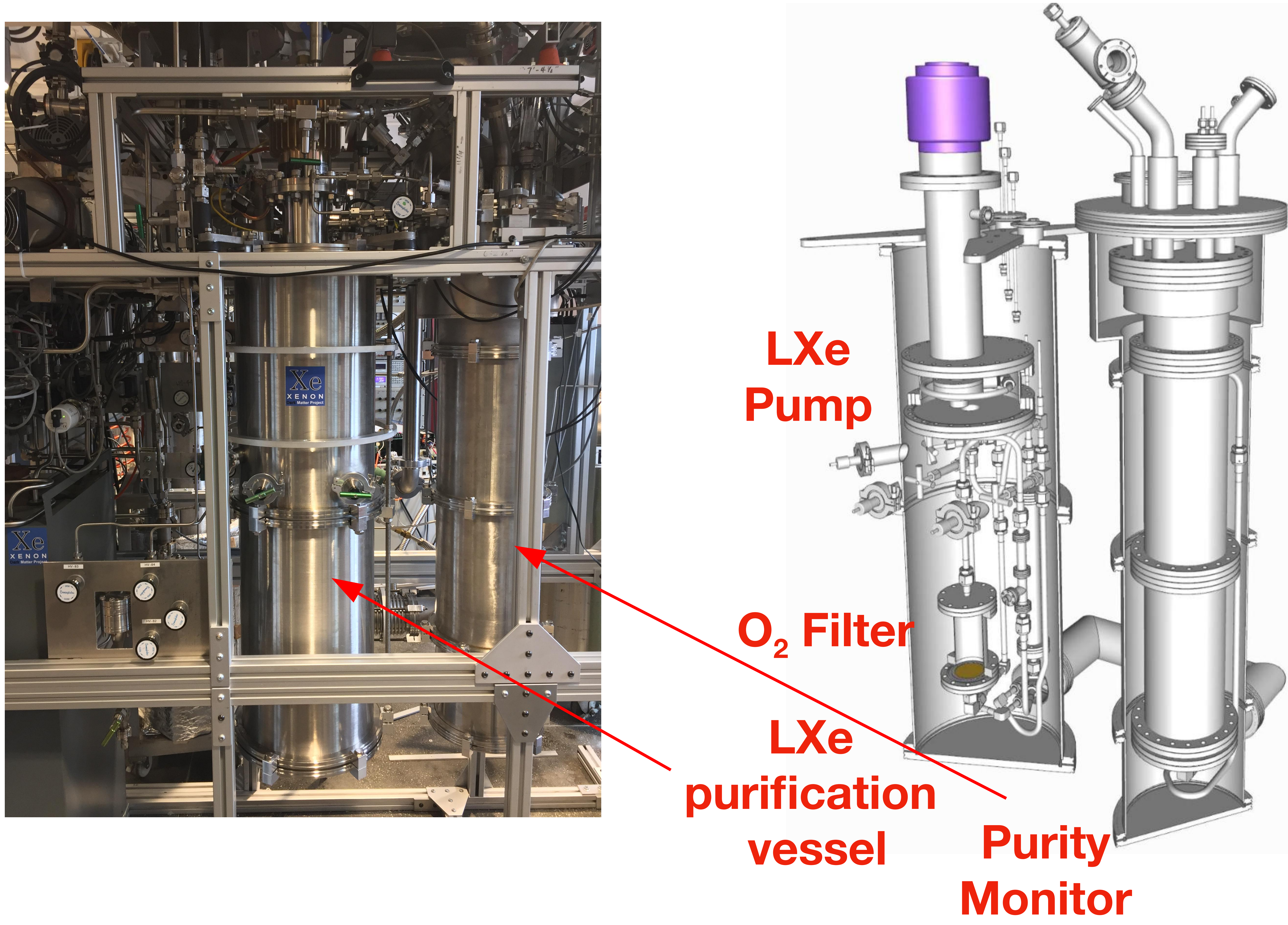
- Ten-fold radon reduction:
  - New pumps:
    - Novel magnetic piston pump R&D
  - Continuous radon distillation
    - Already shown to work

LXe purification

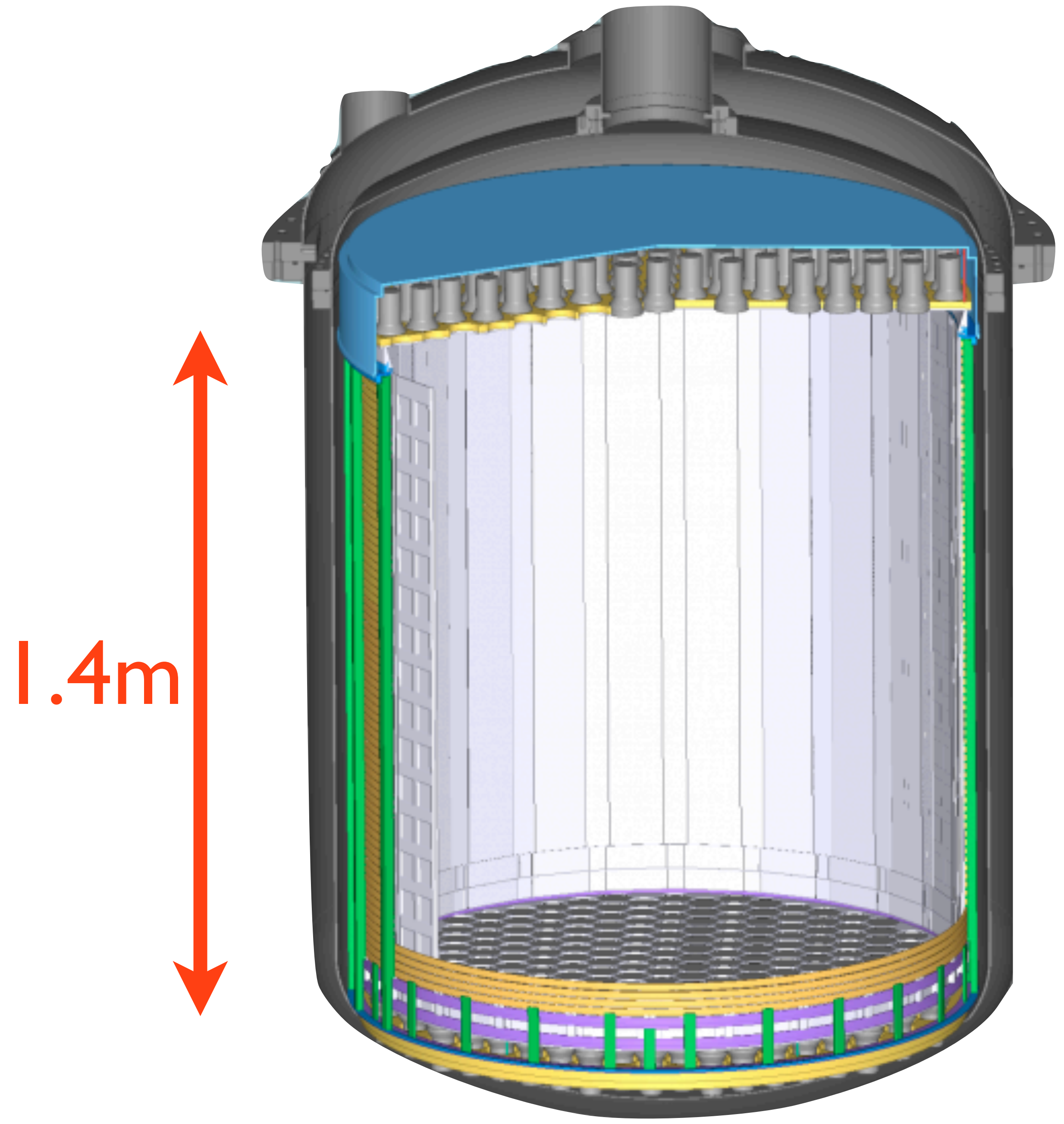


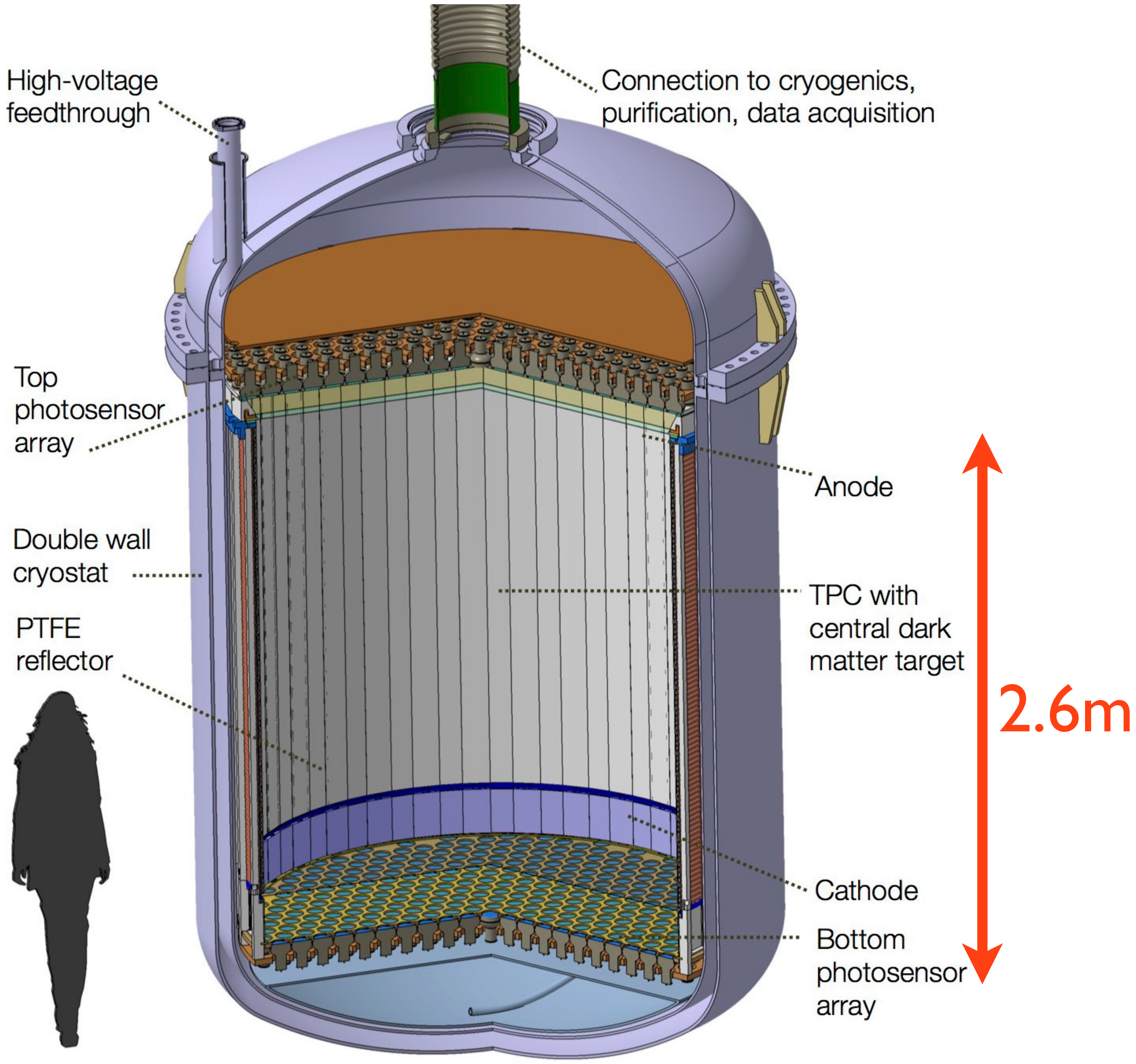
To LXe purification

Demonstrator at Columbia



Even larger Xe detectors





<u>XENONnT</u>

8t of LXe total
Reuse a lot of XENON1T infrastructure
Funding fully secured
Start in 2019

<u>DARWIN</u>

50t of LXe total
Global effort
Funded through 2 ERC grants
Start in 2025

Physics Channels

As detector size increases physics channels open up

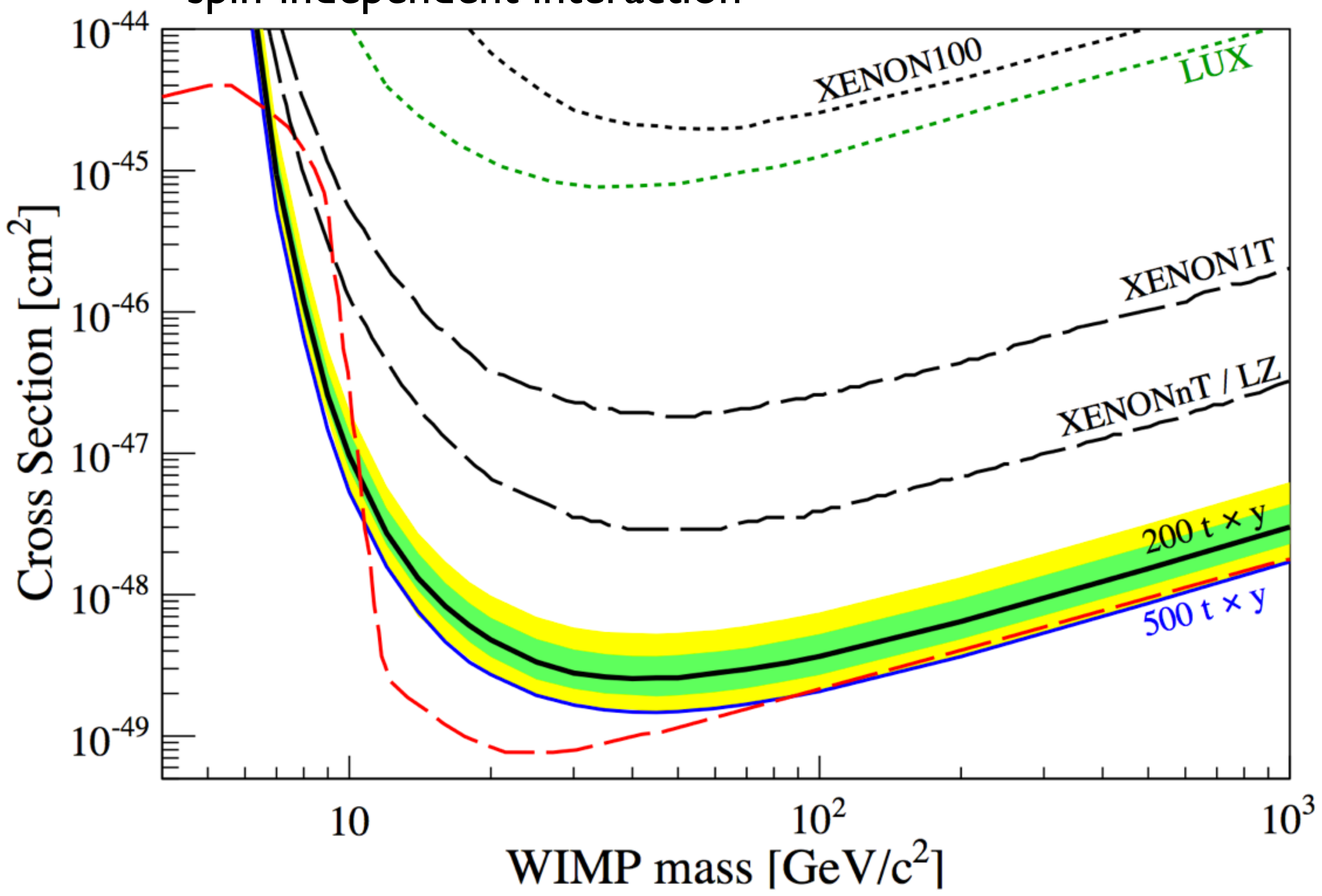
- **WIMP searches** NR
  - Spin-independent
  - Spin-dependent and inelastic interactions
- **Solar axions and galactic axion-like particles (ALPs)** ER
  - Alternative dark matter candidates
  - Coupling to electrons via axio-electric effect
- **Supernova neutrinos** NR
  - Sensitivity to all neutrino flavors (via CNNS)
  - Complementarity to large-scale neutrino detectors
- **Coherent neutrino-nucleus scattering (CNNS)** NR
  - Predicted by SM, *only very recently observed!*
- **Low-energy solar neutrinos: pp, ^{7}Be** ER
  - Test/improve solar model, test neutrino models
- **Neutrinoless double beta decay** ER
  - Lepton number violating process, effective Majorana mass
  - No enrichment in ^{136}Xe required

DARWIN WIMP Sensitivity

JCAP 10, 016 (2015)

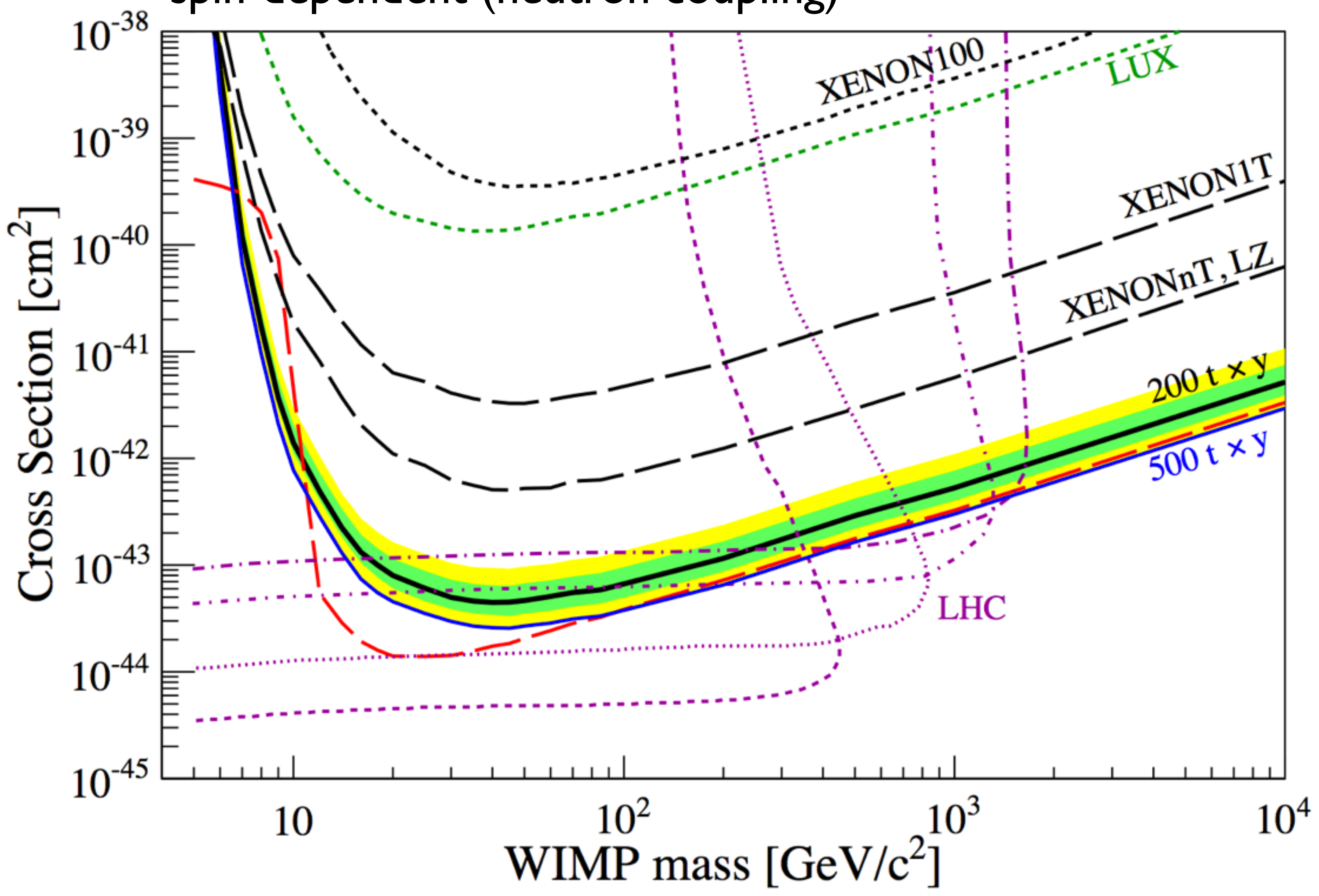
- Assumed exposure 200 ton×yr,   all backgrounds included
- Likelihood analysis: 99.98% ER rejection, 30% NR acceptance
- Combined (S1+S2) energy scale
- Energy window 5-35 keV_{nr}
- Light yield 8 PE/keV

spin-independent interaction



→ minimum sensitivity: 2.5×10^{-49} cm^2 @ 40 GeV/c^2

spin-dependent (neutron coupling)

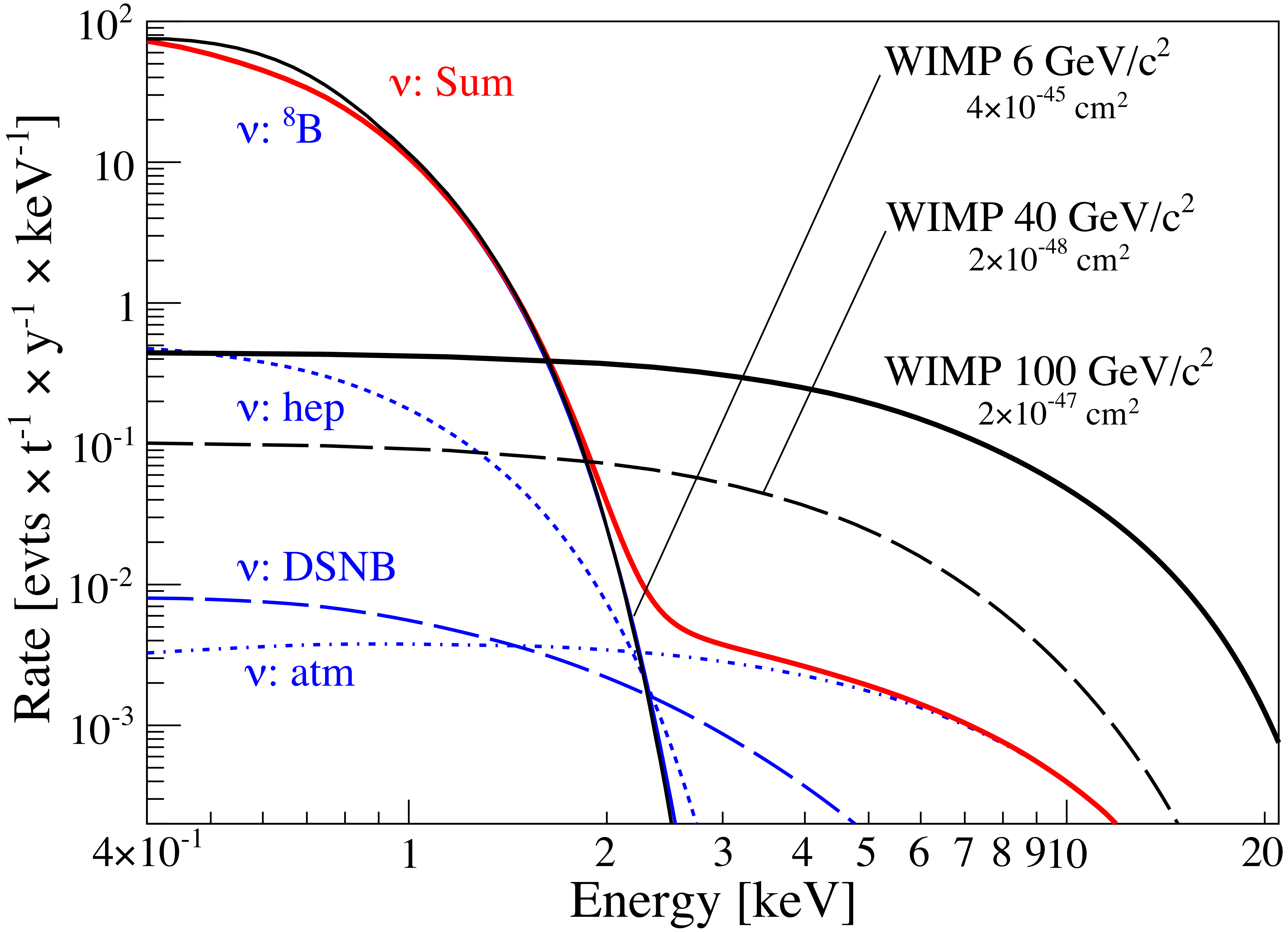


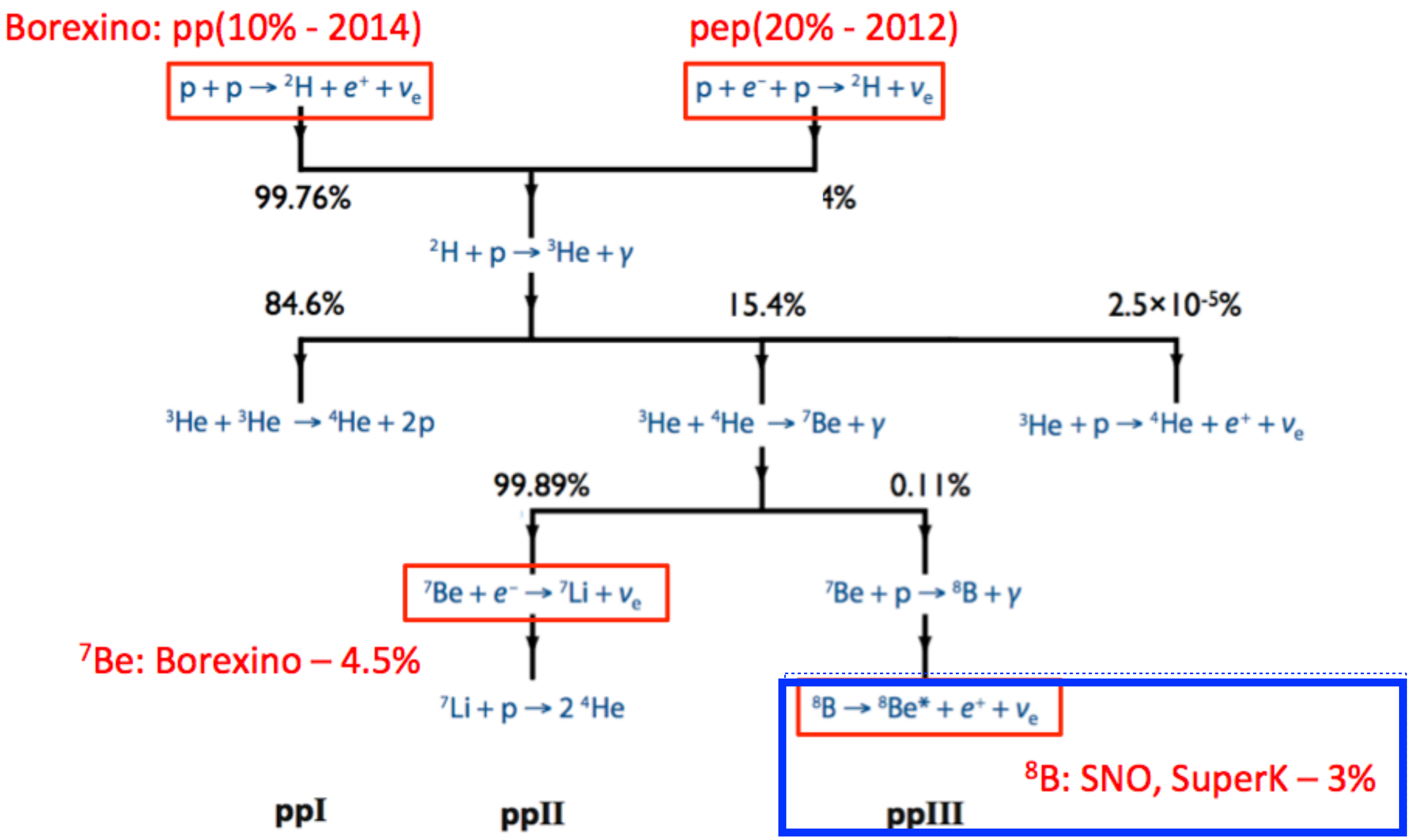
→ complementarity to LHC searches

Coherent Neutrino-Nucleus Scattering

JCAP 01, 044 (2014)

- $\nu + N_{Xe} \rightarrow \nu + N_{Xe}$
- Predicted by SM, recently observed
- CNNS is background for WIMPs,
- Steeply falling spectrum





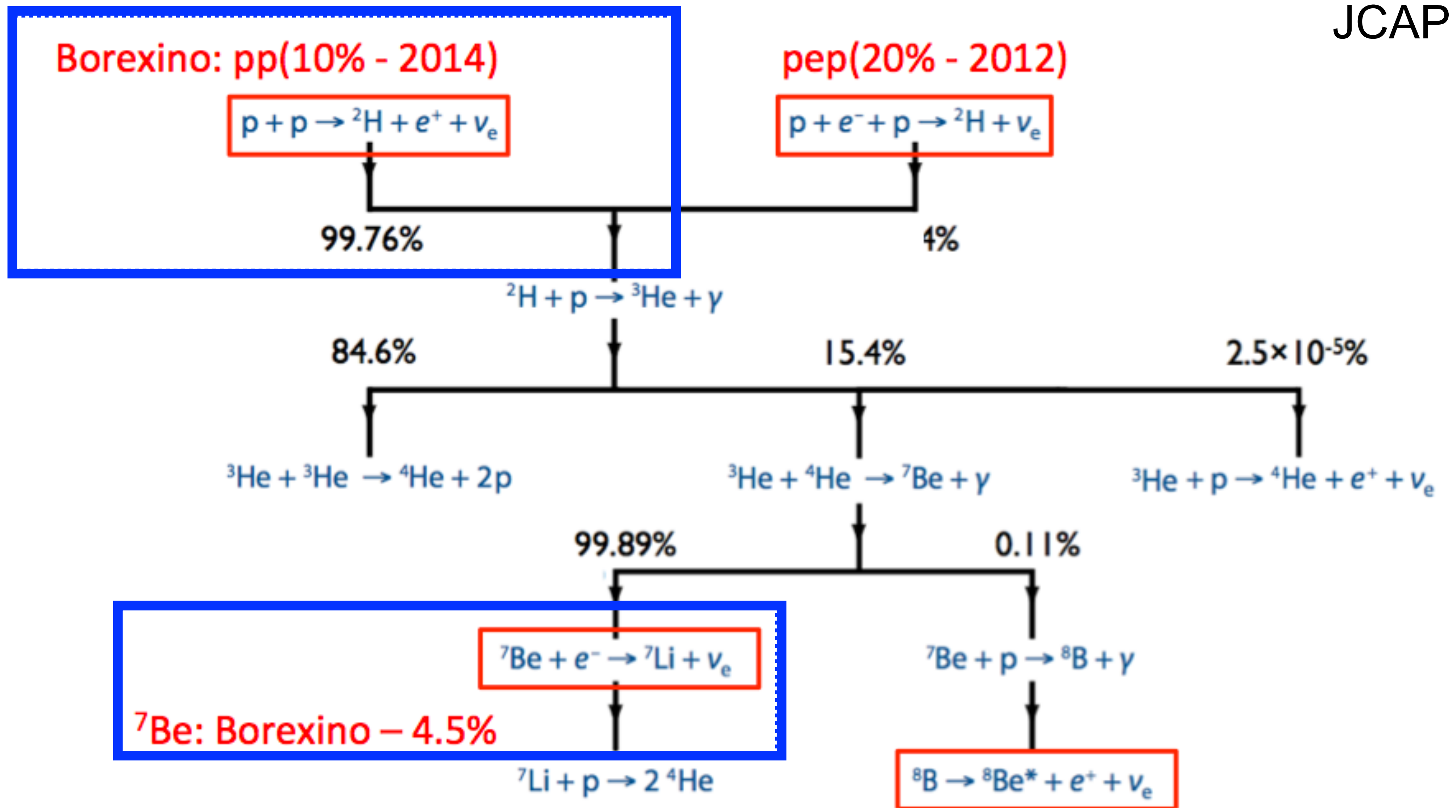
Solar Neutrinos

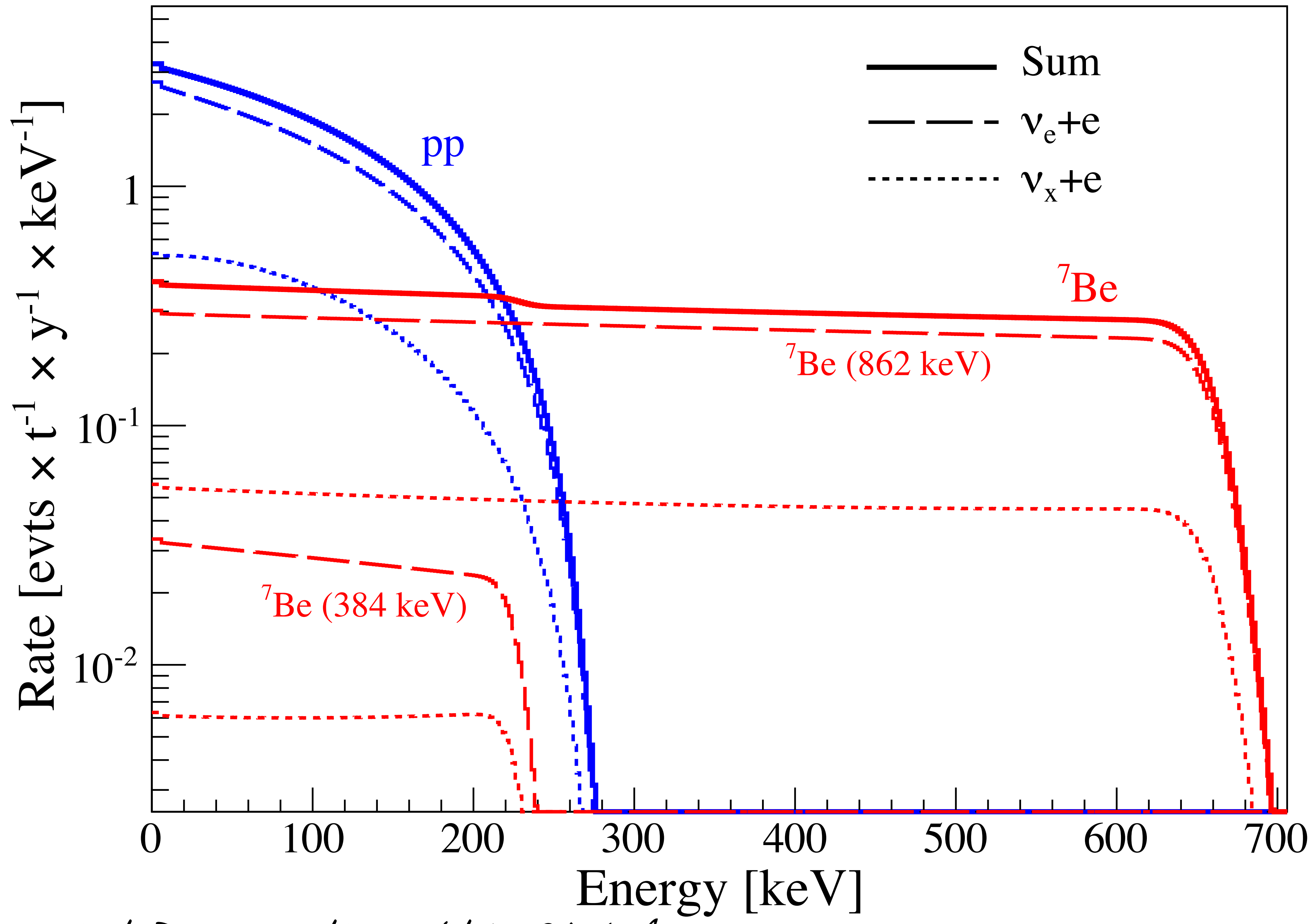
- Neutrino-electron elastic scattering
- Real-time measurement of neutrino flux
  → 7.2 events/day from pp
  → 0.9 events/day from ^{7}Be

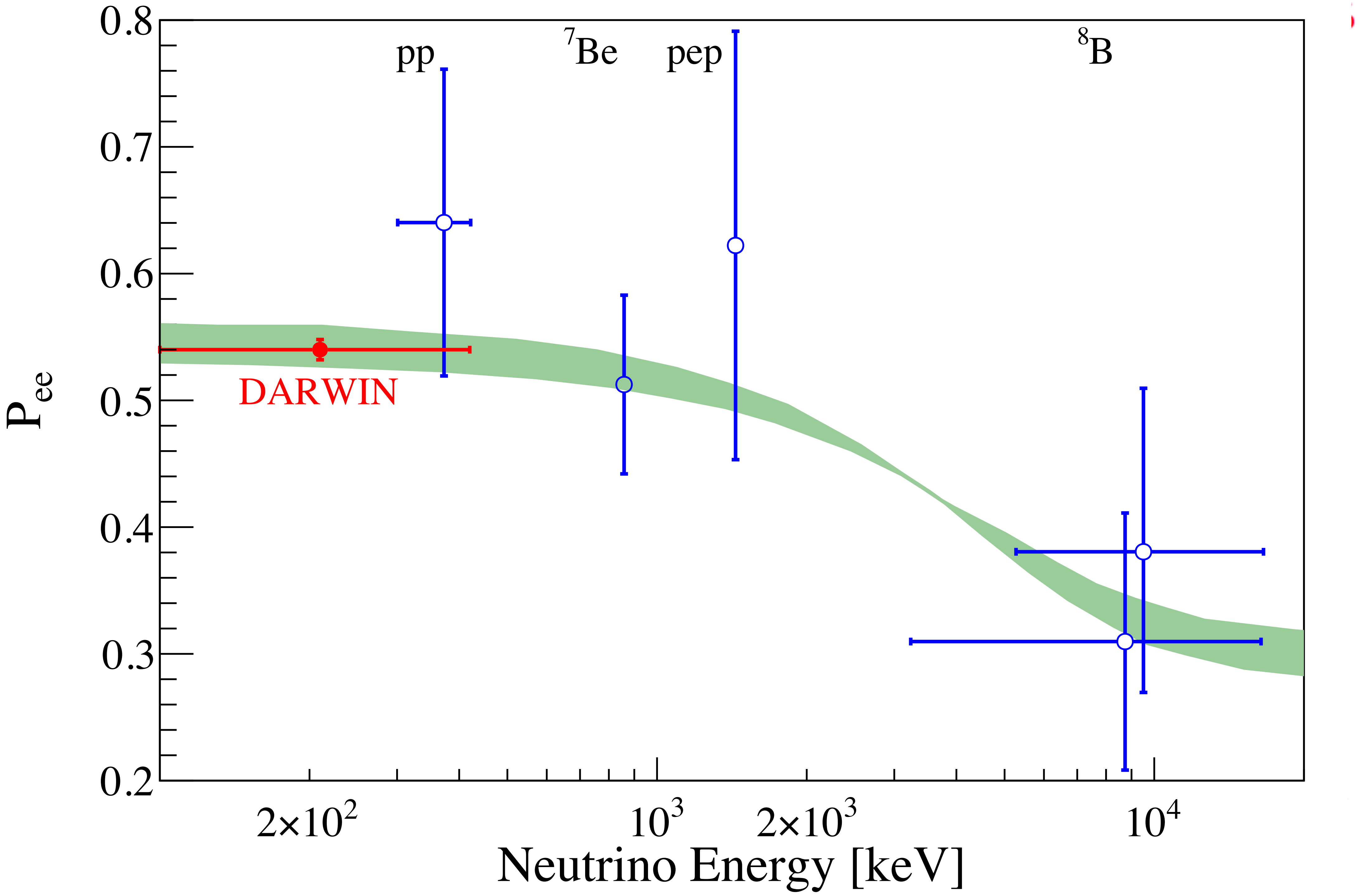
(40 ton LXe detector)

- 2% (1%) *statistical* precision after 1 year (5 years)
  → constrain solar models
- Neutrino survival probability measurement
  → deviation from prediction indicates new physics
- Atomic binding effects have to be taken into account!

JCAP 01, 044 (2014)







Patrick Decowski - Nikhef/UvA

Supernova Neutrinos

R. Lang et al., arXiv:1606.09243

- Low threshold (due to S2-only)
- Negligible background due to short burst (~sec)
- >5σ sensitivity to a supernova burst in Milky Way
- Detection of all 6 neutrino species via neutral current reactions

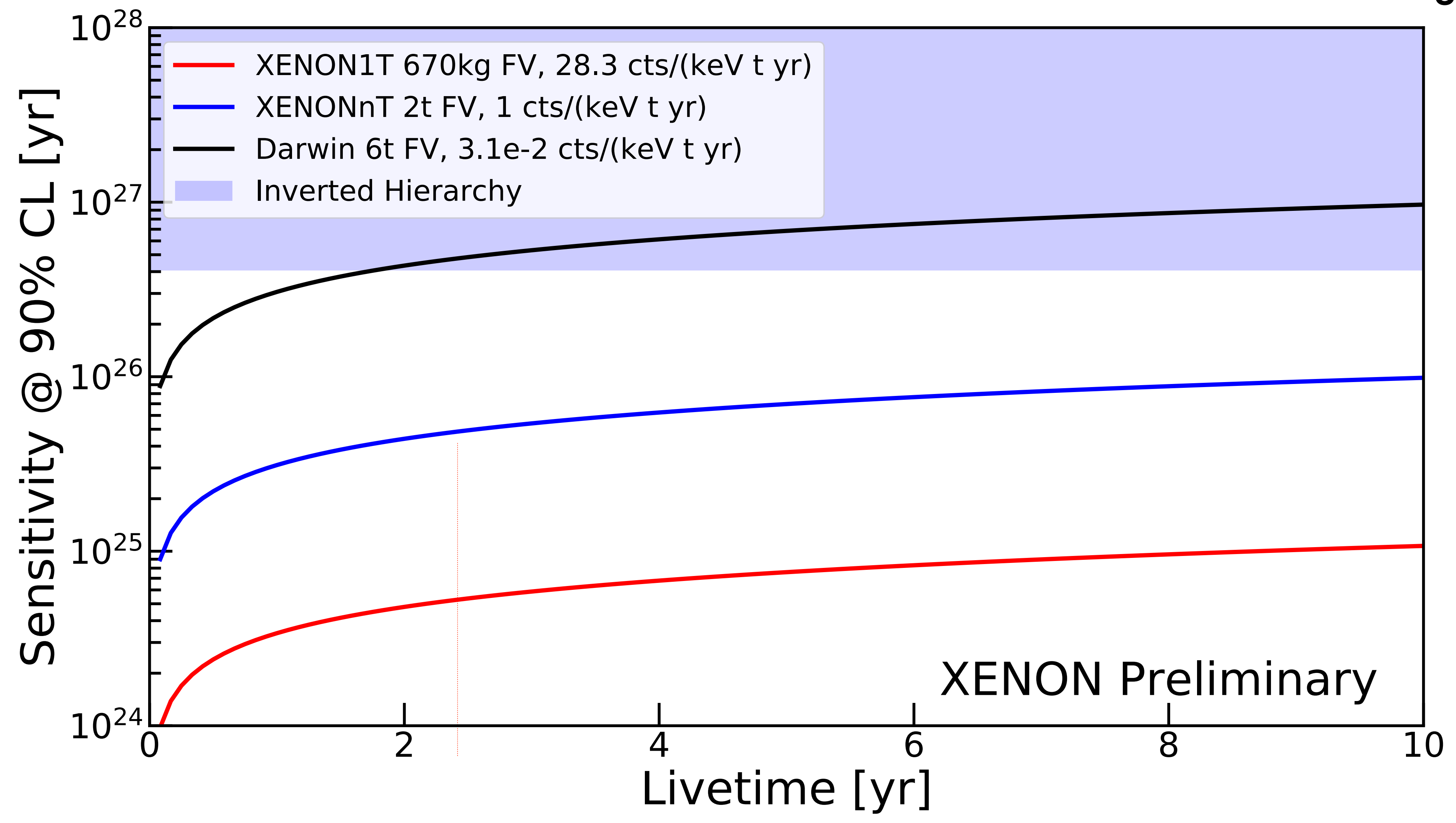
- **Hundreds** of events for a 27M$_\odot$ SN progenitor at 10 kpc
- Flavor-insensitive neutrino energy measurement
  → constrain total explosion energy and reconstruct the SN light curve

Neutrinoless Double Beta Decay

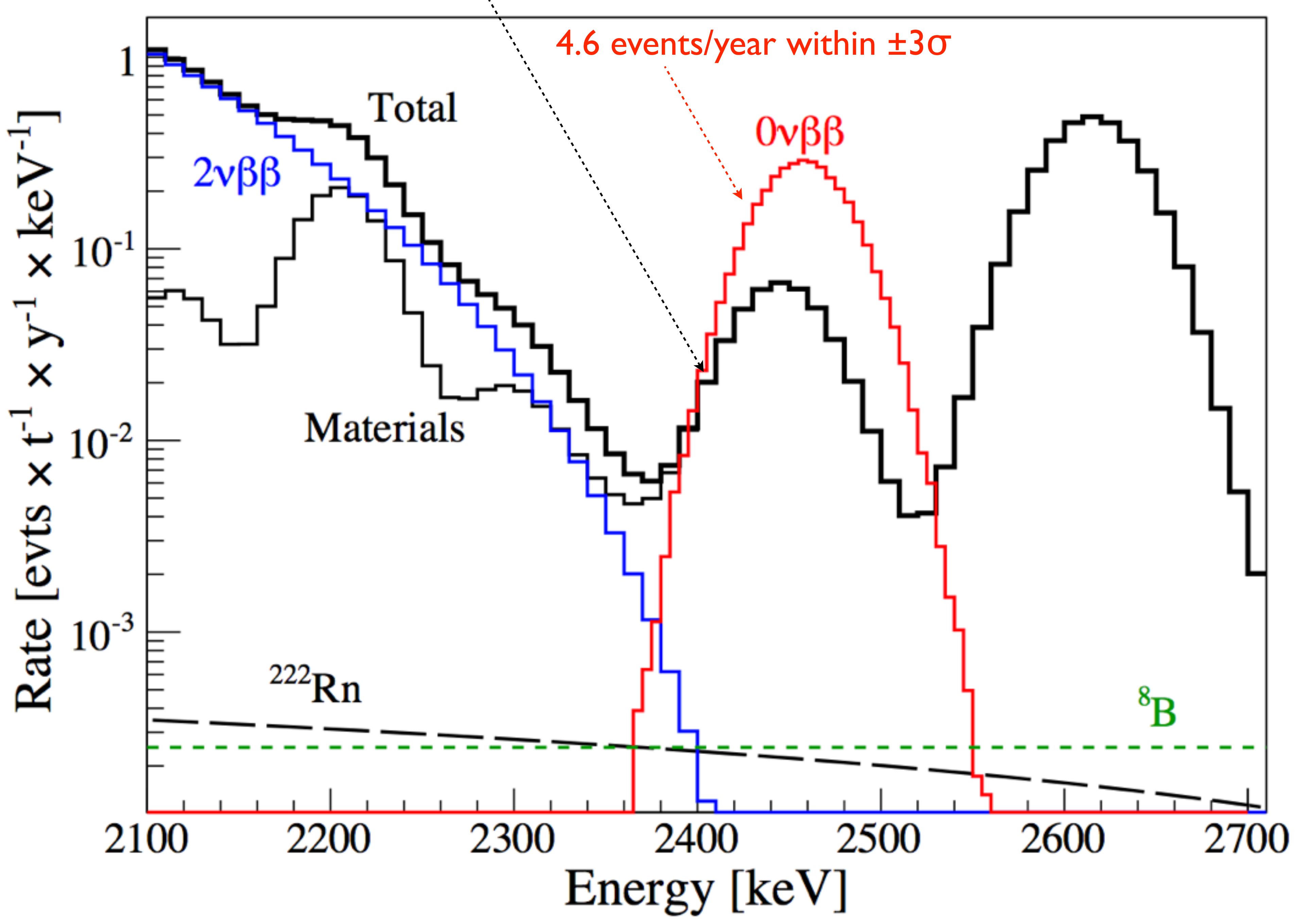
JCAP 01, 044 (2014)

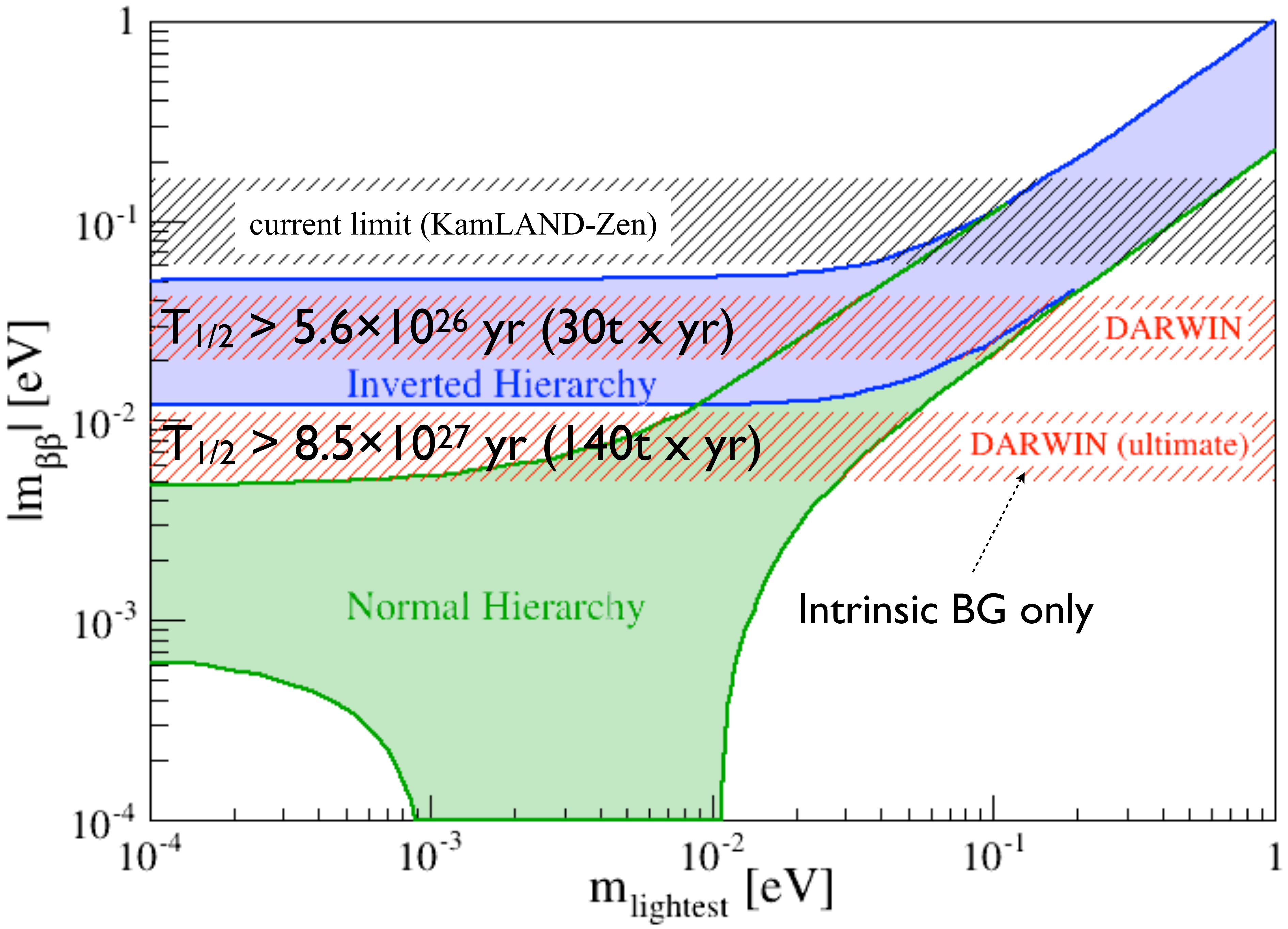
Is the neutrino a Majorana particle?

- ^{136}Xe abundance in natural xenon 8.9%
  - 40t of Xe has 3.6t of ^{136}Xe
- Q-value (2458.7±0.6) keV
- Energy resolution (σ/μ) at $Q_{\beta\beta}$ 1%



^{214}Bi → ^{214}Po + e⁻ + γ (2448 keV)





Summary

- XENON1T has achieved extraordinary sensitivity and is the leading direct detection DM exp
  - Still many analysis ongoing: many papers in the pipe-line
- WIMP dark matter still very much alive and a large parameter space has not yet been probed
  - Future experiments (~2025) will improve sensitivity by 100x!
- At the same time - diversify
  - Look for broader DM candidates: low-mass WIMPs, Axions, ALPs, sterile nus, …
  - New physics channels: extraordinarily pure volume - new surprises?
- XENONnT, DARWIN are addressing all of these!
- Finally: big thank you to the MT, ET and CT/PDP groups for all their help!

Cut & Count

Mass	1.3 t	1.3 t	0.9 t	0.65 t
($cS1$, $cS2_b$)	Full	Reference	Reference	Reference
ER	627±18	1.62±0.30	1.12±0.21	0.60±0.13
neutron	1.43±0.66	0.77±0.35	0.41±0.19	0.14±0.07
CEνNS	0.05±0.01	0.03±0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
Surface	106±8	4.84±0.40	0.02	0.01
Total BG	735±20	7.36±0.61	1.62±0.28	0.80±0.14
$\mathrm{WIMP}_{\text{best-fit}}$	3.56	1.70	1.16	0.83
Data	739	14	2	2

Using full S+BG model
(S1, S2, R, "Z") space

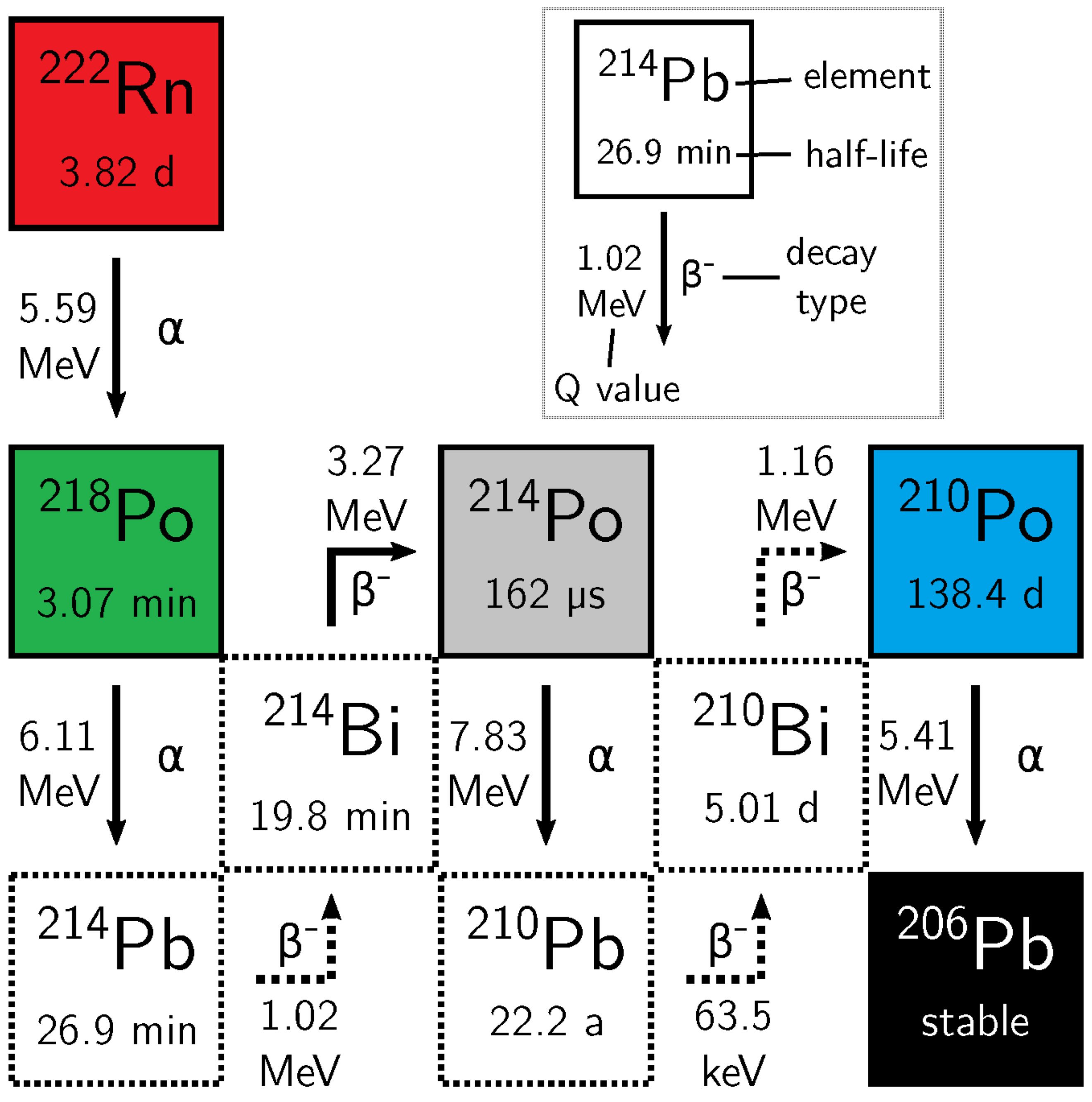
"Safe" reference regions

Plate out in PTFE

Thesis
Sander Breur

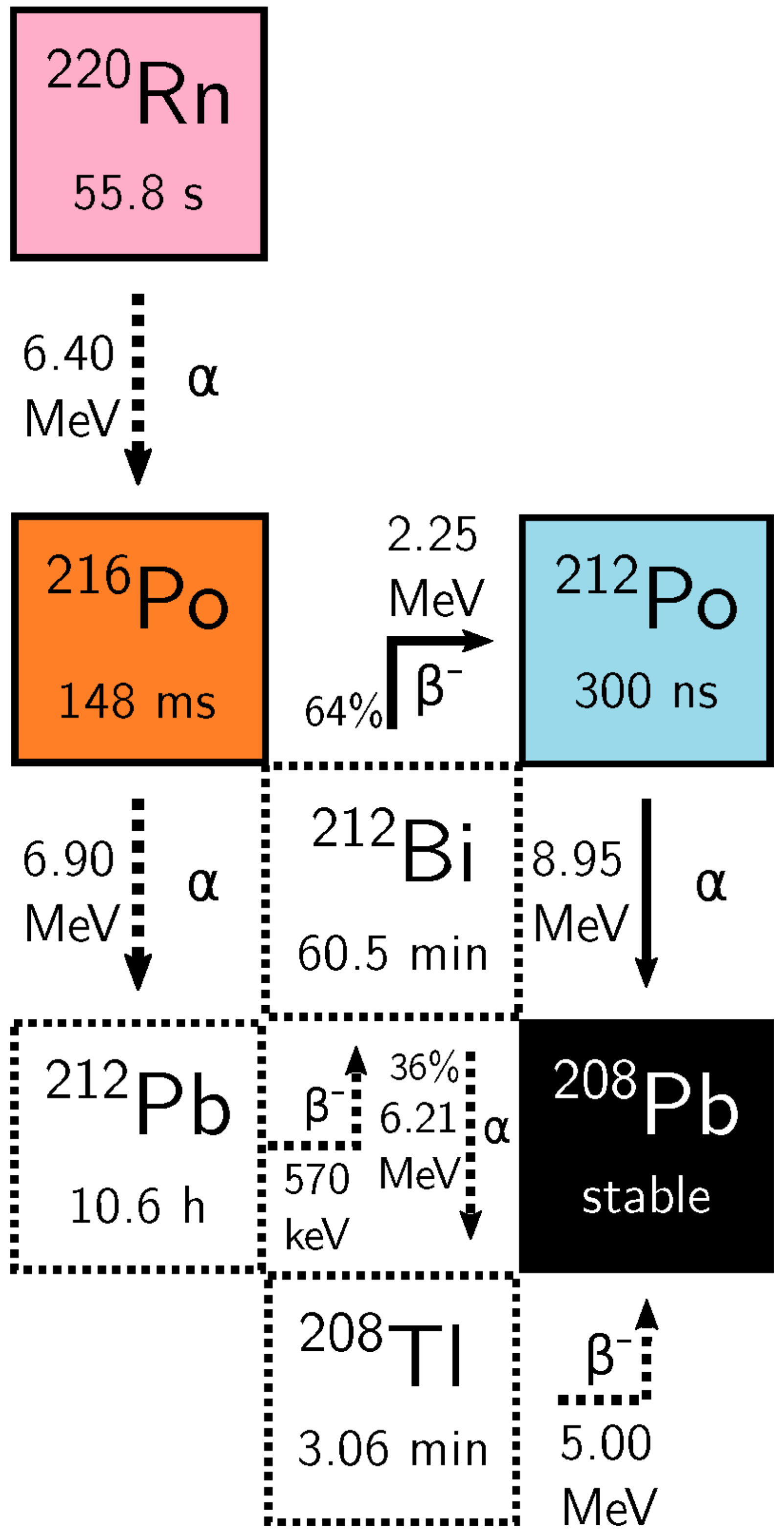
Radon decay chains

“Bad” Radon



Background

“Good” Radon



Calibration