XENON1T and Beyond: the Search for ***Heavy*** and ***Light*** Dark Matter Particles

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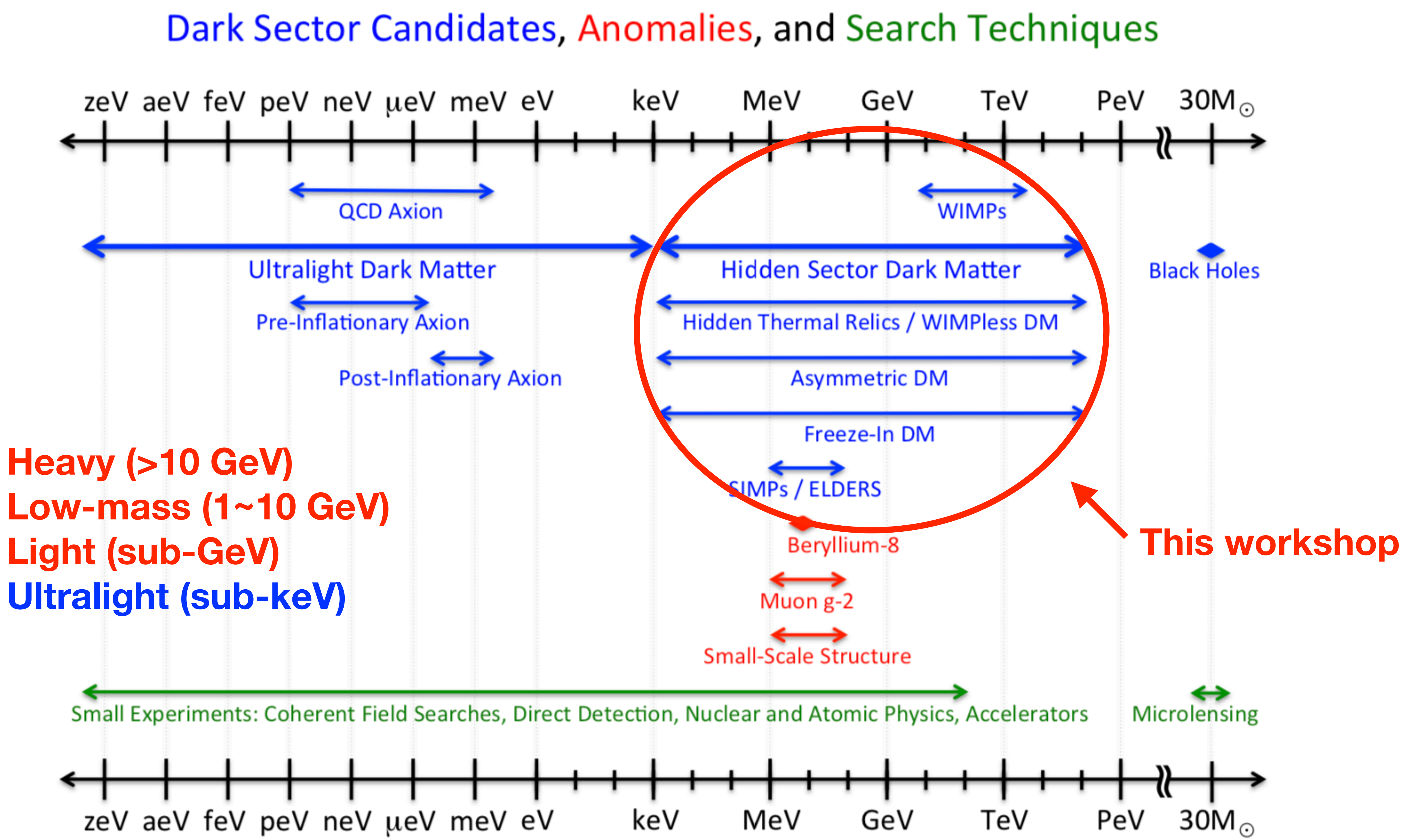
(on behalf of the XENON Collaboration)

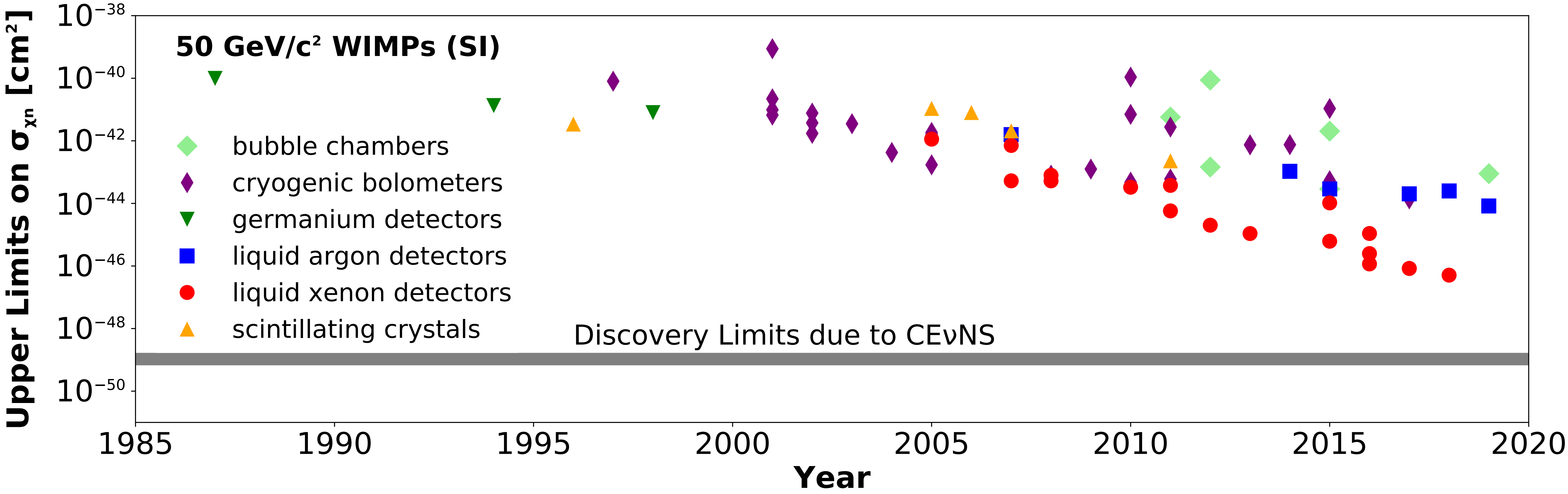
PKU DM Workshop, Beijing, 10/16/2019

Heavy, Low-mass and Light Dark Matter

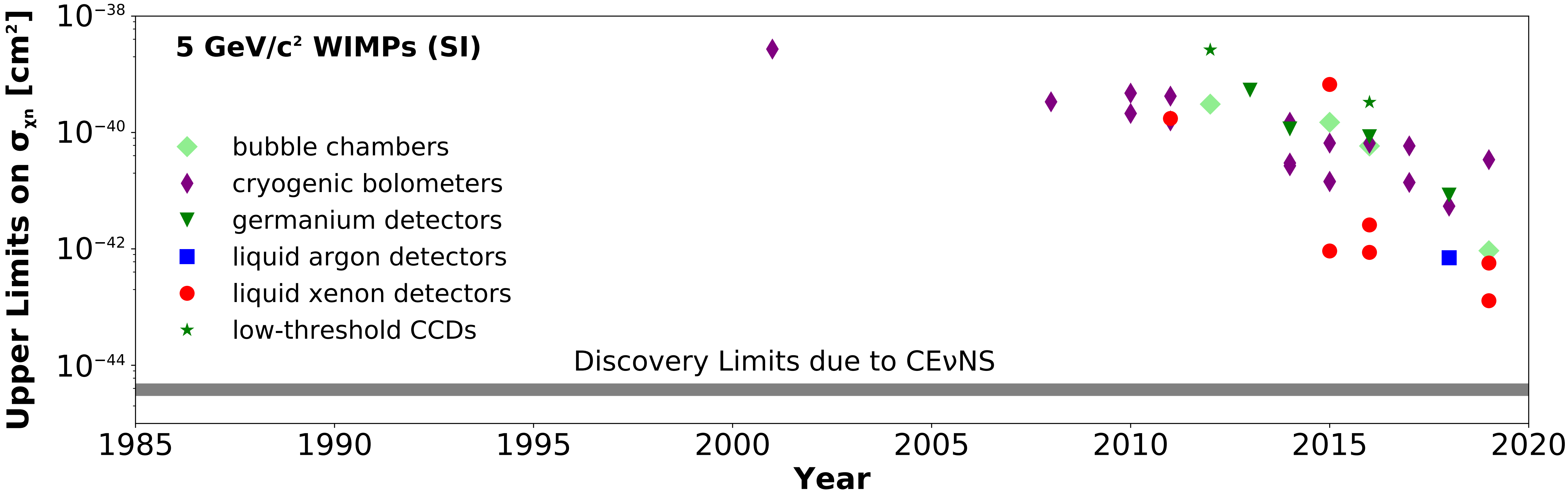


US Cosmic Visions: New Ideas in Dark Matter 2017, 1707.04591

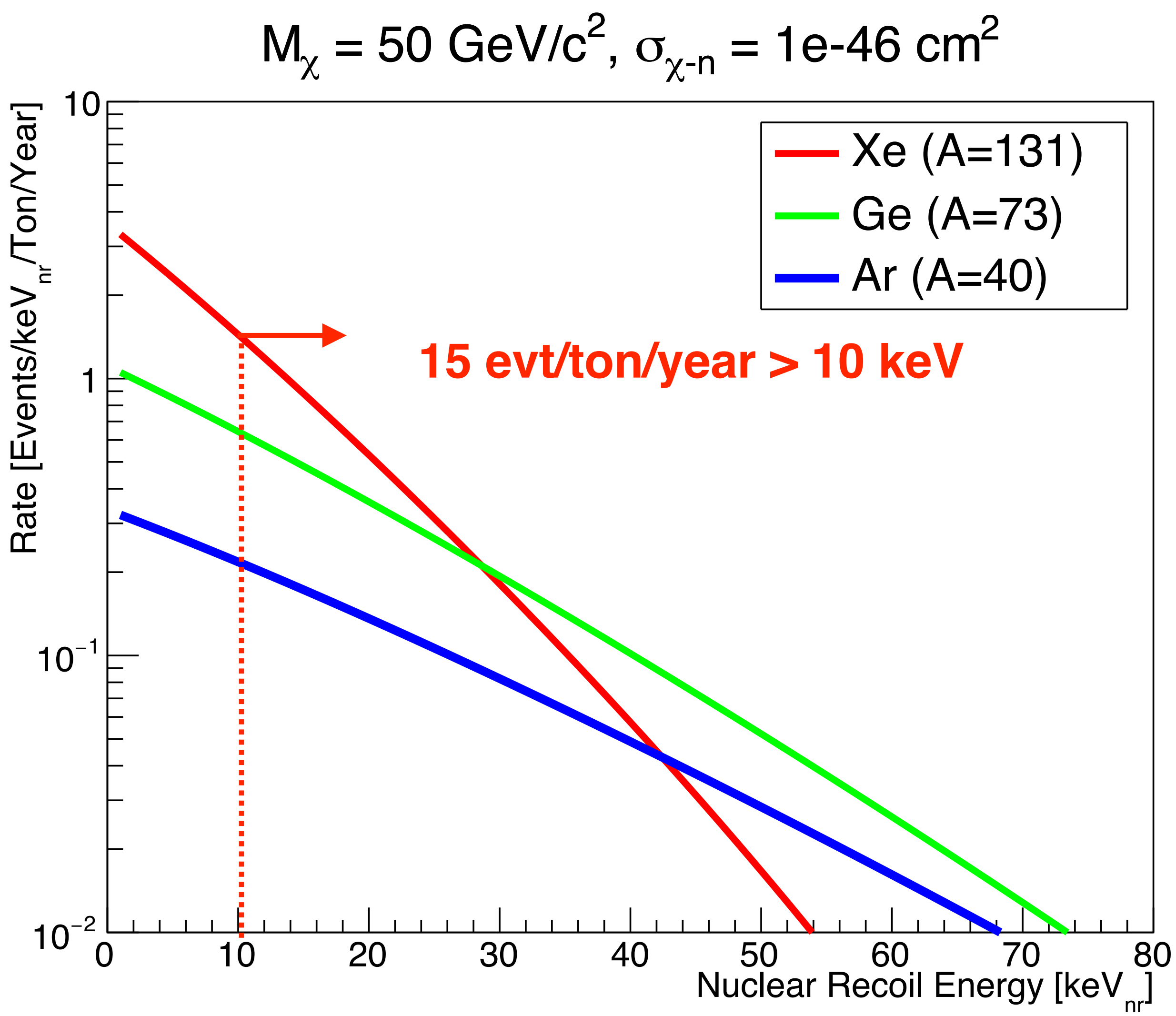
Heavy DM: limits improved by 5 orders of magnitude in the last 20 years



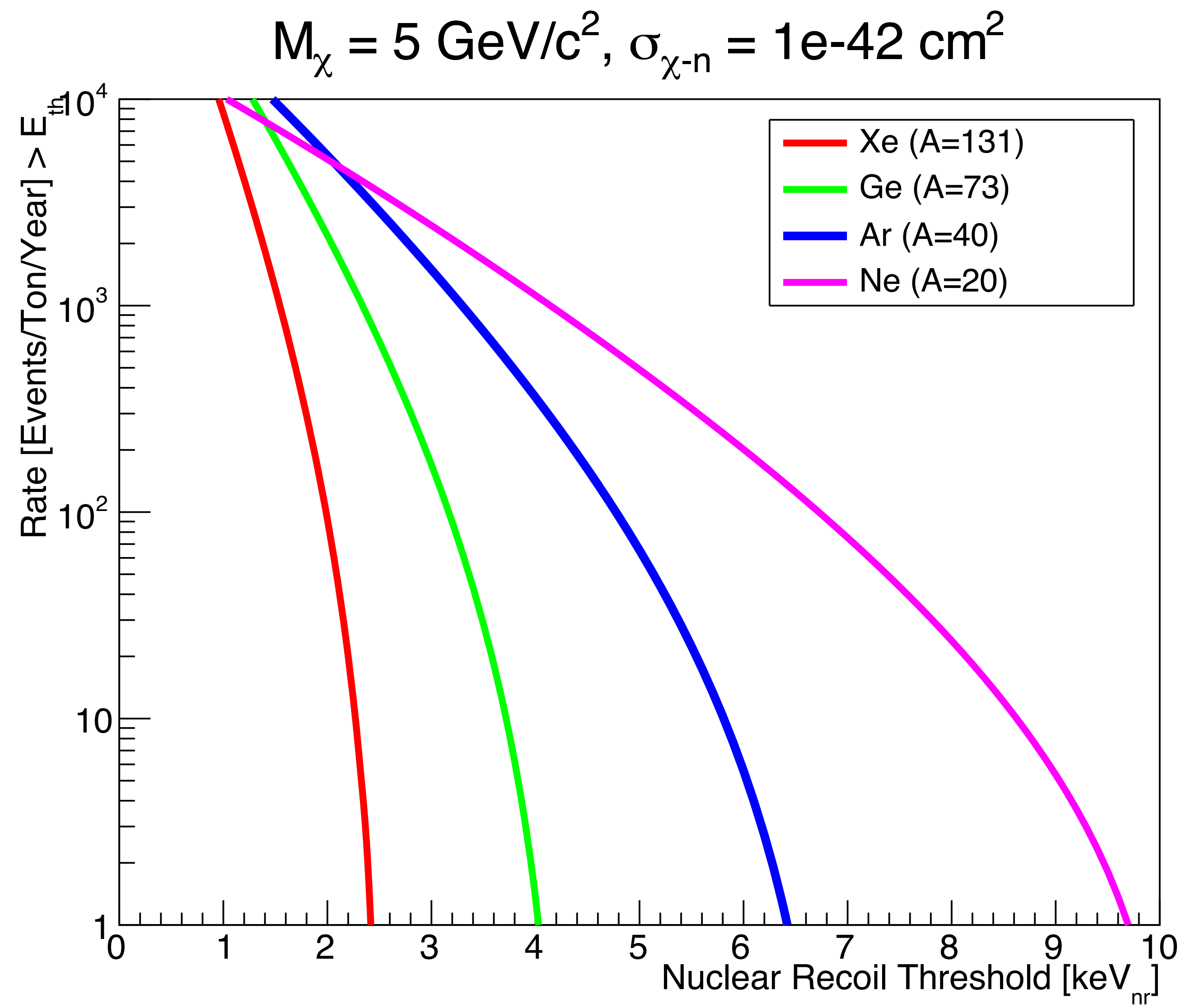
Low-mass DM: limits improved by 4 orders of magnitude in the last 10 years



Expected nuclear recoil event rates from WIMPs

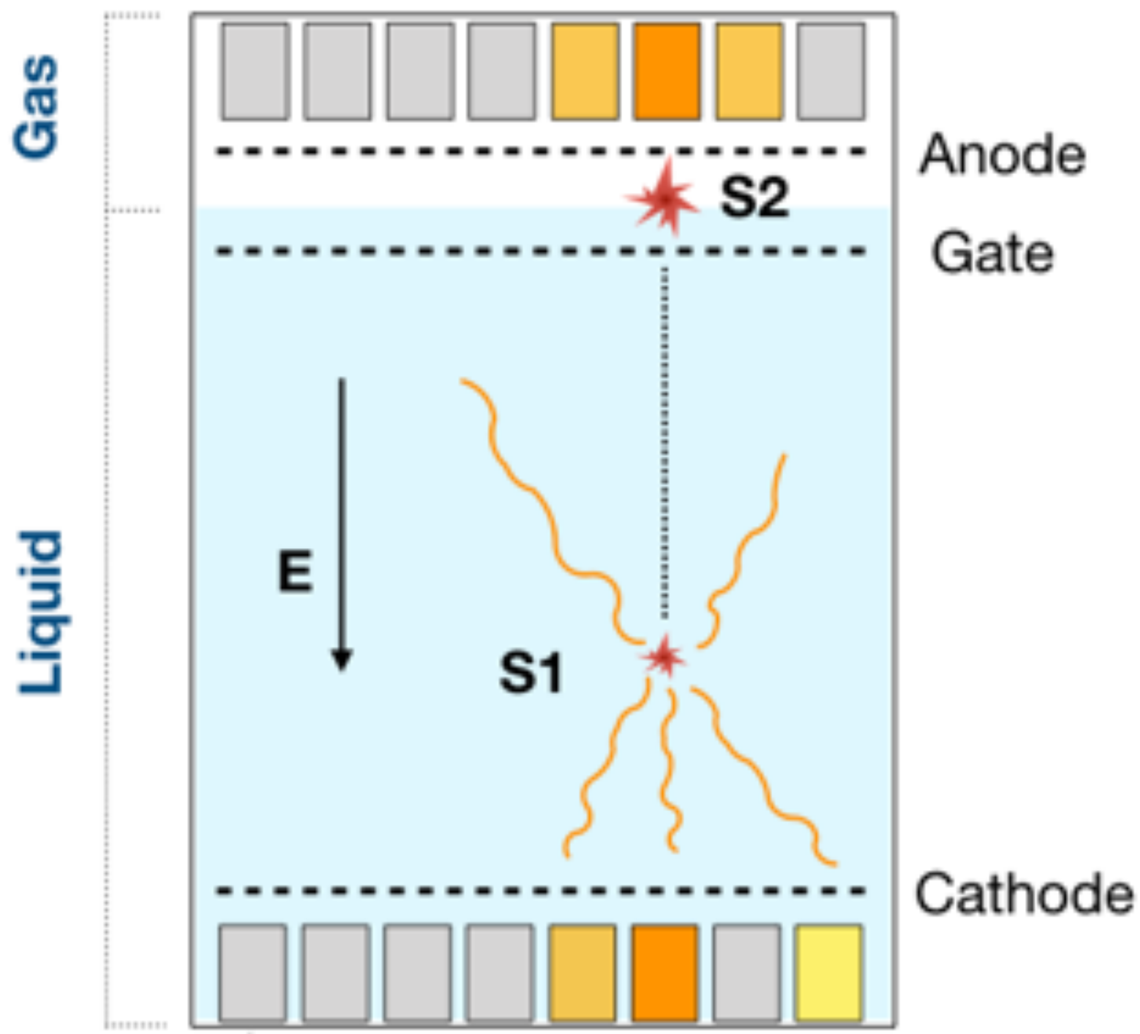


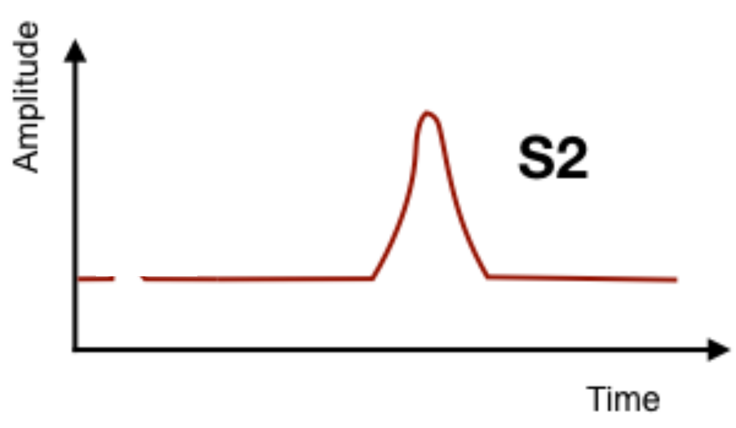
Heavy WIMPs



Low-mass WIMPs

Two-phase Xenon detectors for both Heavy and Light Dark Matter





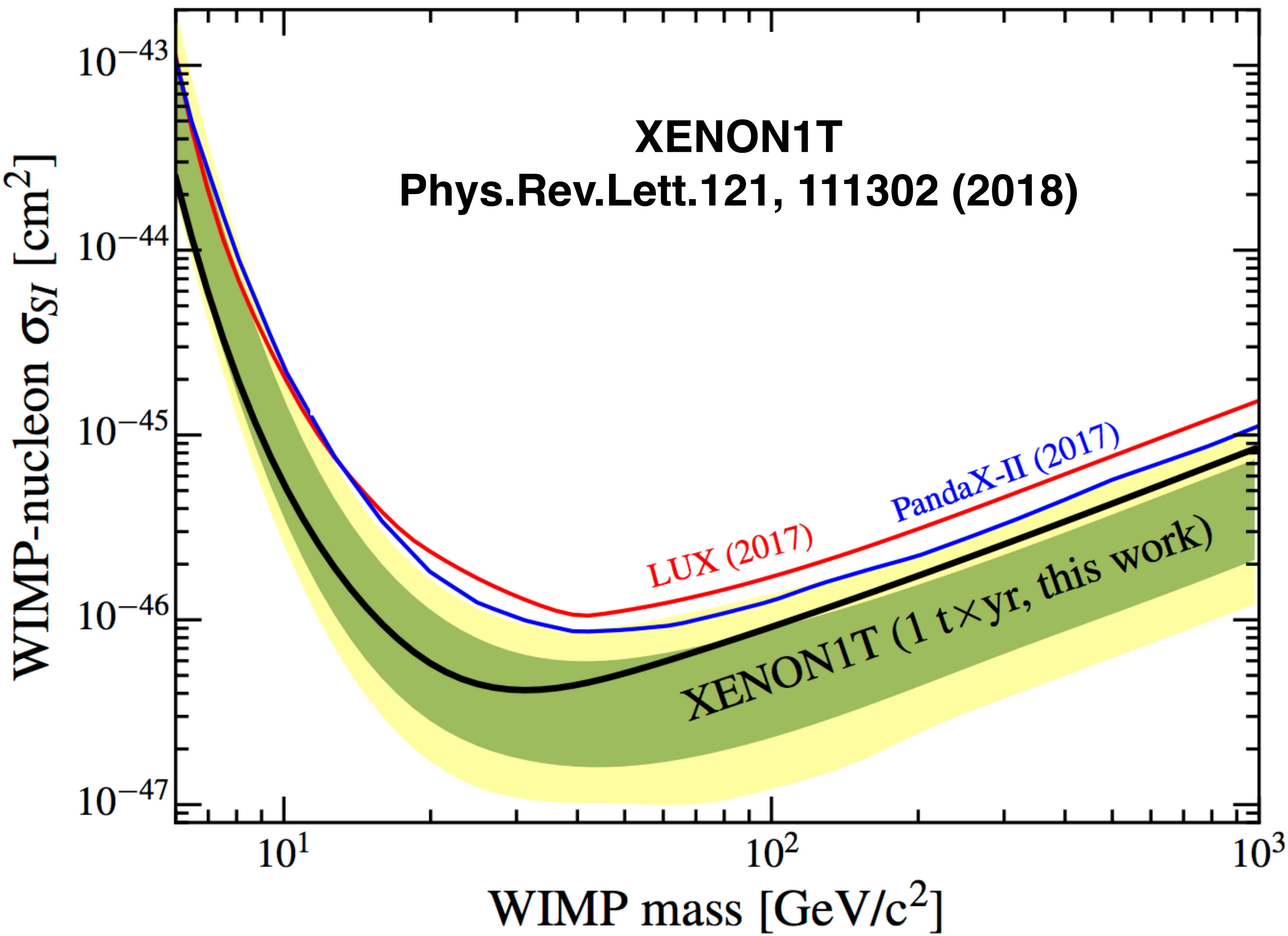
With both S1 and S2 signals (TPC mode):

- **Low threshold: keV (set by S1: 2-3 PE)**
  - **Corresponding S2: > 200 PE**
- **Ultra-low background**
  - **3D fiducialization**
  - **ER/NR discrimination with S2/S1**

With S2-only signal (EC - Electron Counting mode):

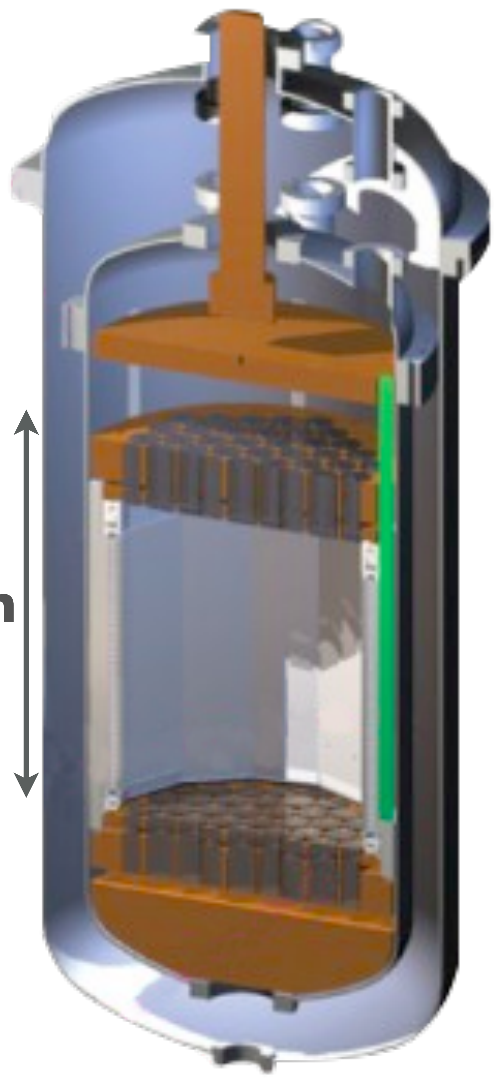
- **Ultra-low threshold: 10-100 eV (set by S2)**
  - **single e- signal: 10~100 PE**
- **Background control a challenge:**
  - **No ER/NR discrimination**
  - **Only XY position determined, no Z**
  - **Known/unknown source of single/few electrons**

The **three most constraining limits** for **heavy** dark matter interaction are **all from liquid xenon based experiments.**



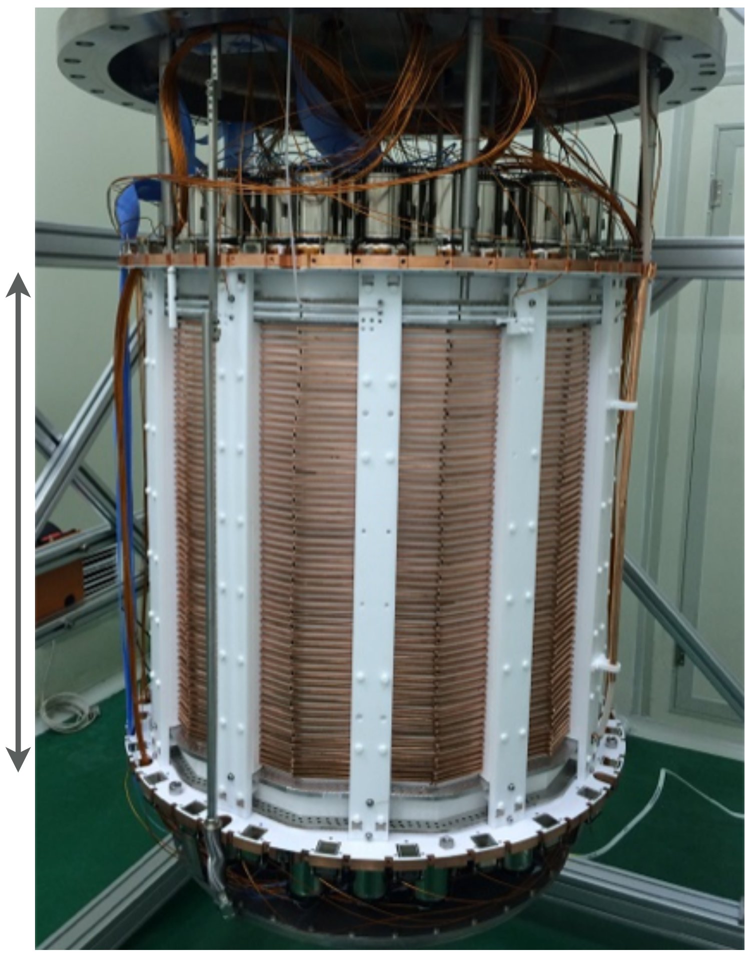
The Era of Liquid Xenon Time Projection Chambers

48 cm



LUX
Active Target: ~250 kg
Location: US
decommissioned

60 cm

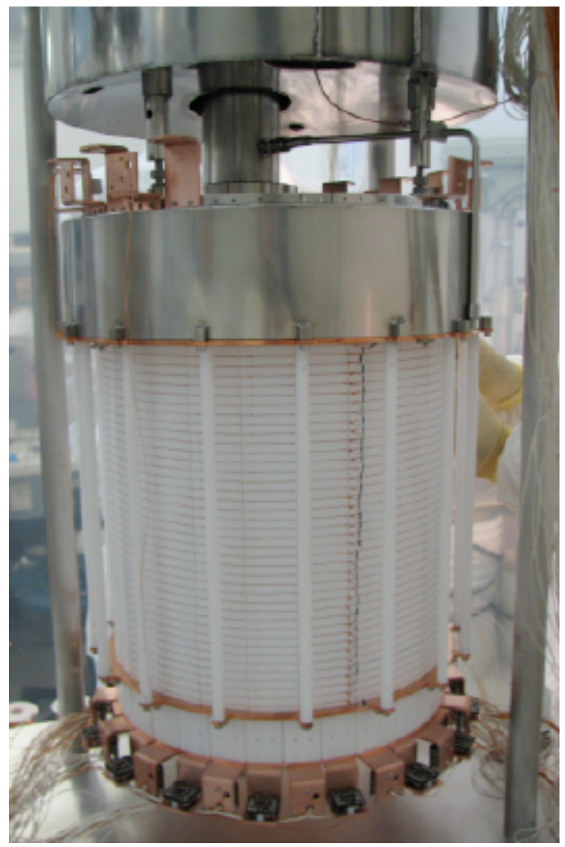


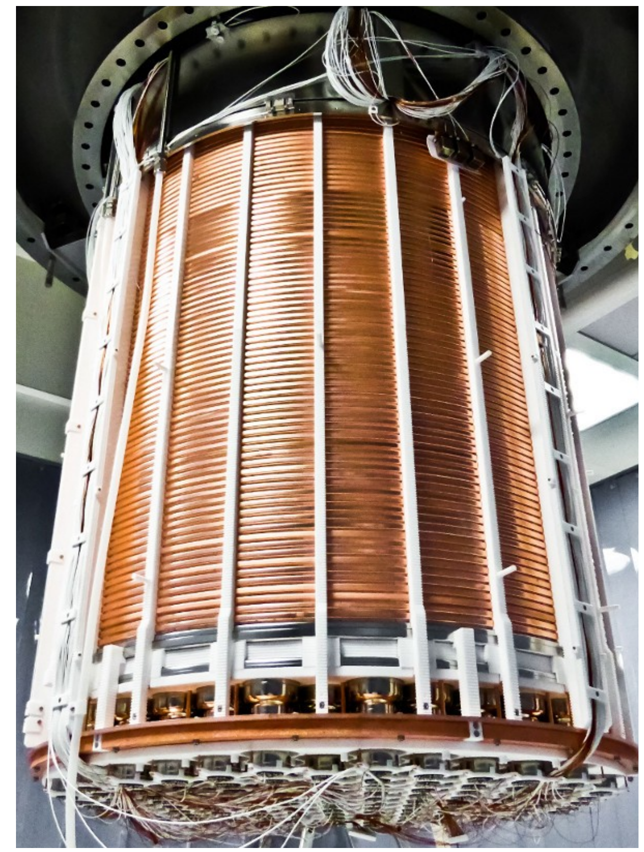
PandaX-II
Active Target: ~580 kg
Location: China
Data-taking: 2016-2019
finished data taking

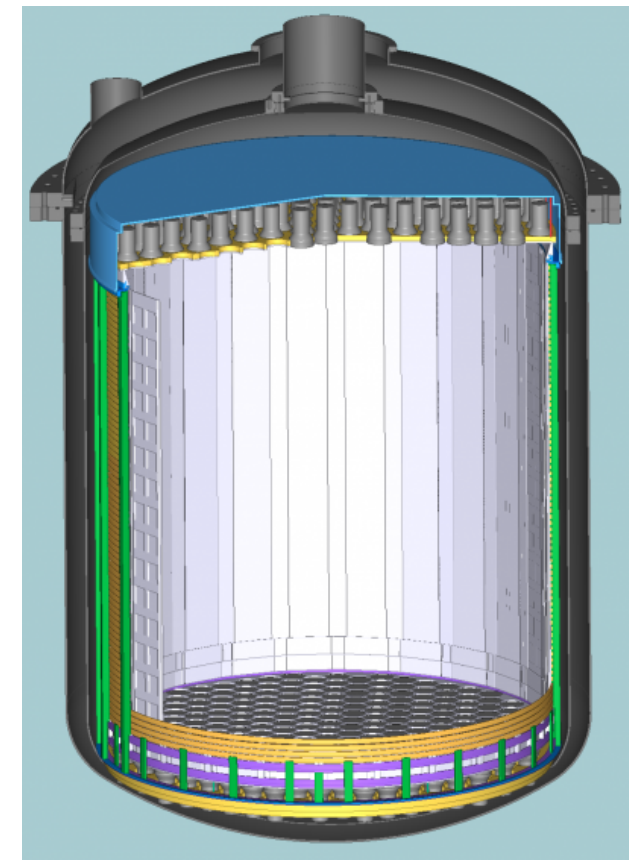
100 cm

XENON1T
Active Target: 2000 kg
Location: Italy
Data-taking: 2016-2018
decommissioned

The XENON Dark Matter Search Program







XENON10	XENON100	**XENON1T**	XENONnT
2005-2007	2008-2016	2012-2018	2019-2025
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2

The XENON International Collaboration

Columbia, RPI, Nikhef, Muenster, KIT, Stockholm, Mainz, MPIK, Heidelberg, Freiburg

Chicago

UCSD

Rice

Purdue

Zurich

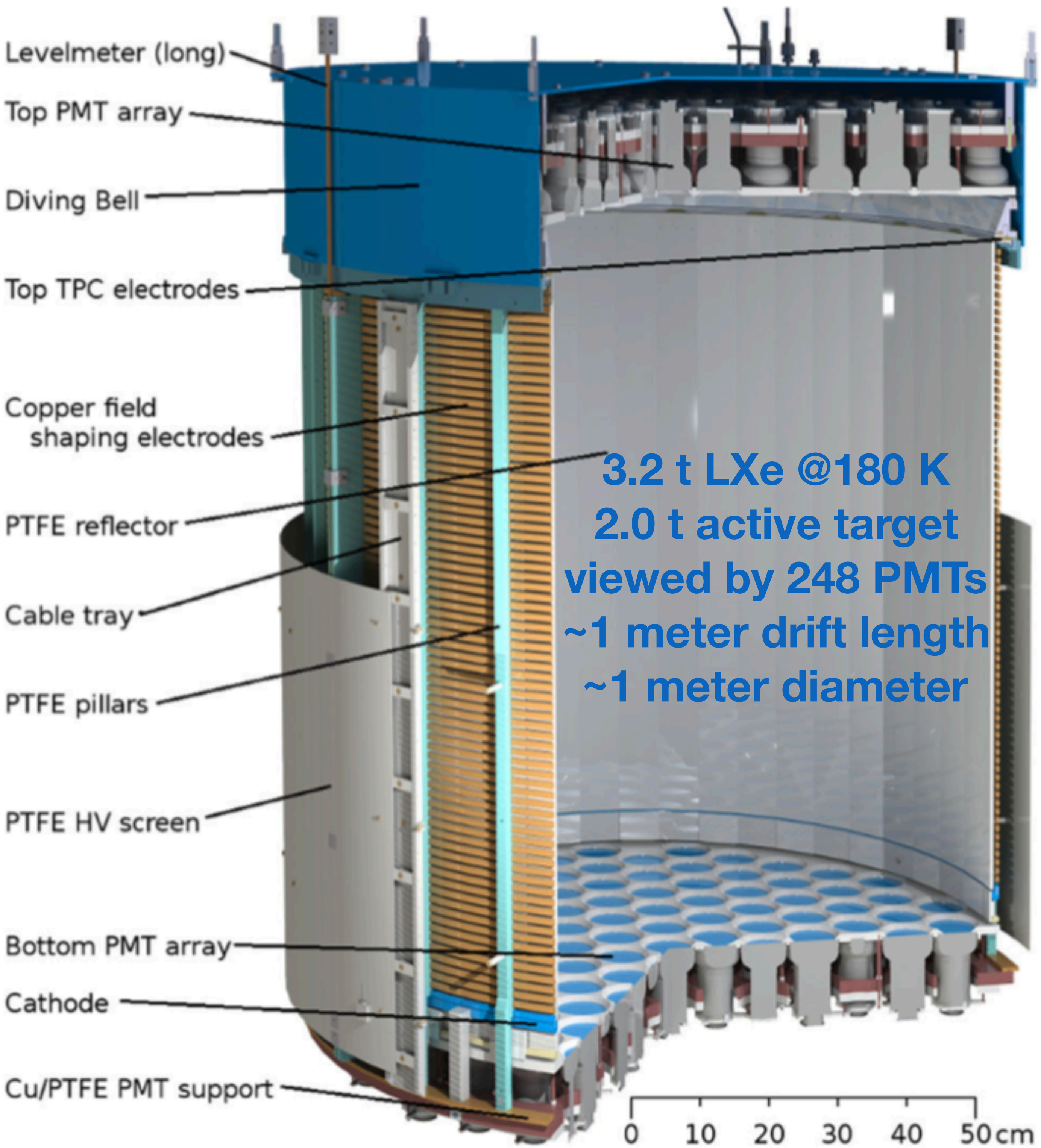
Tokyo

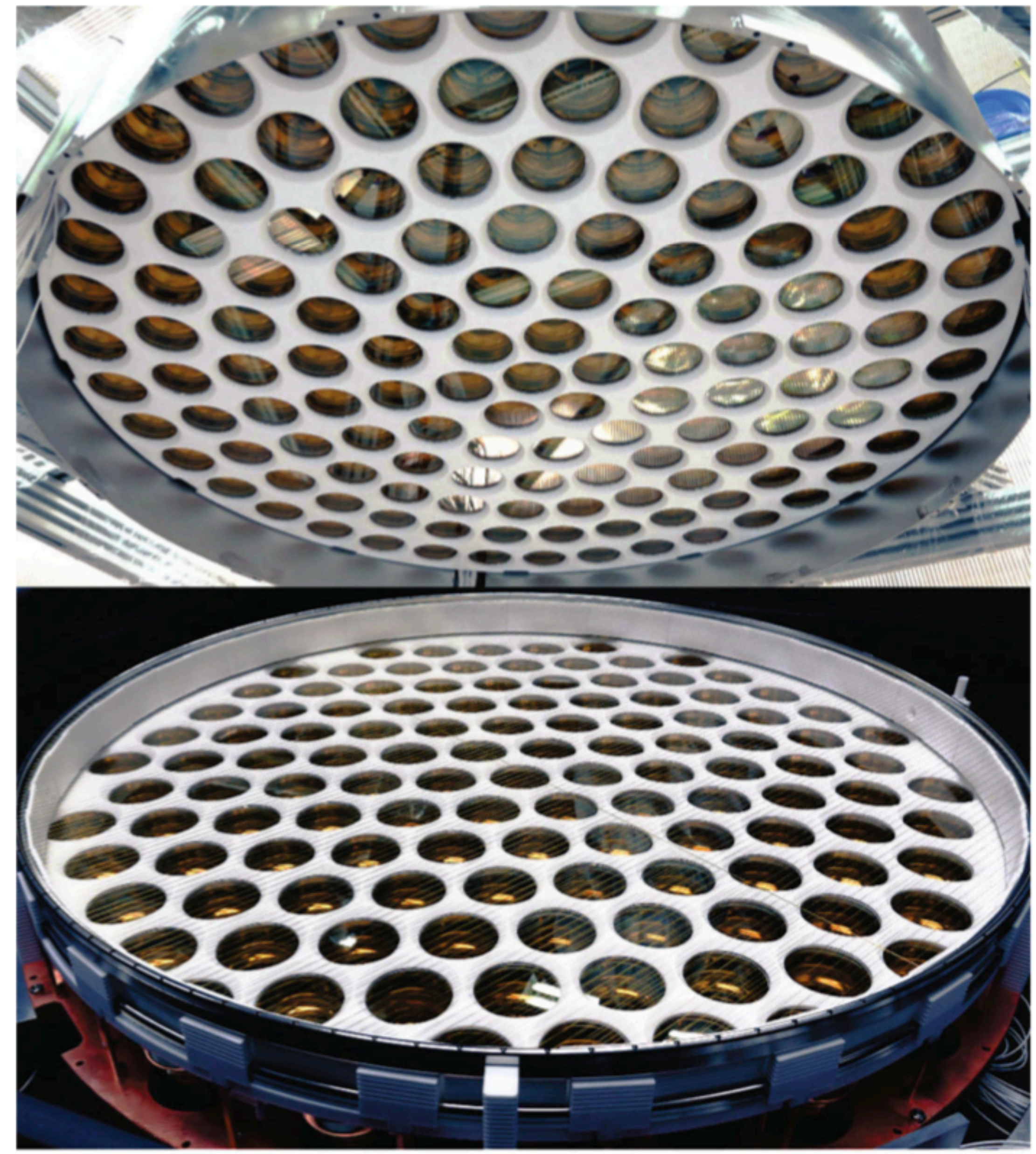
Nagoya

Coimbra, Subatech, LPNHE, LAL, Bologna, LNGS, Torino, Napoli, Weizmann, NYUAD, Kobe

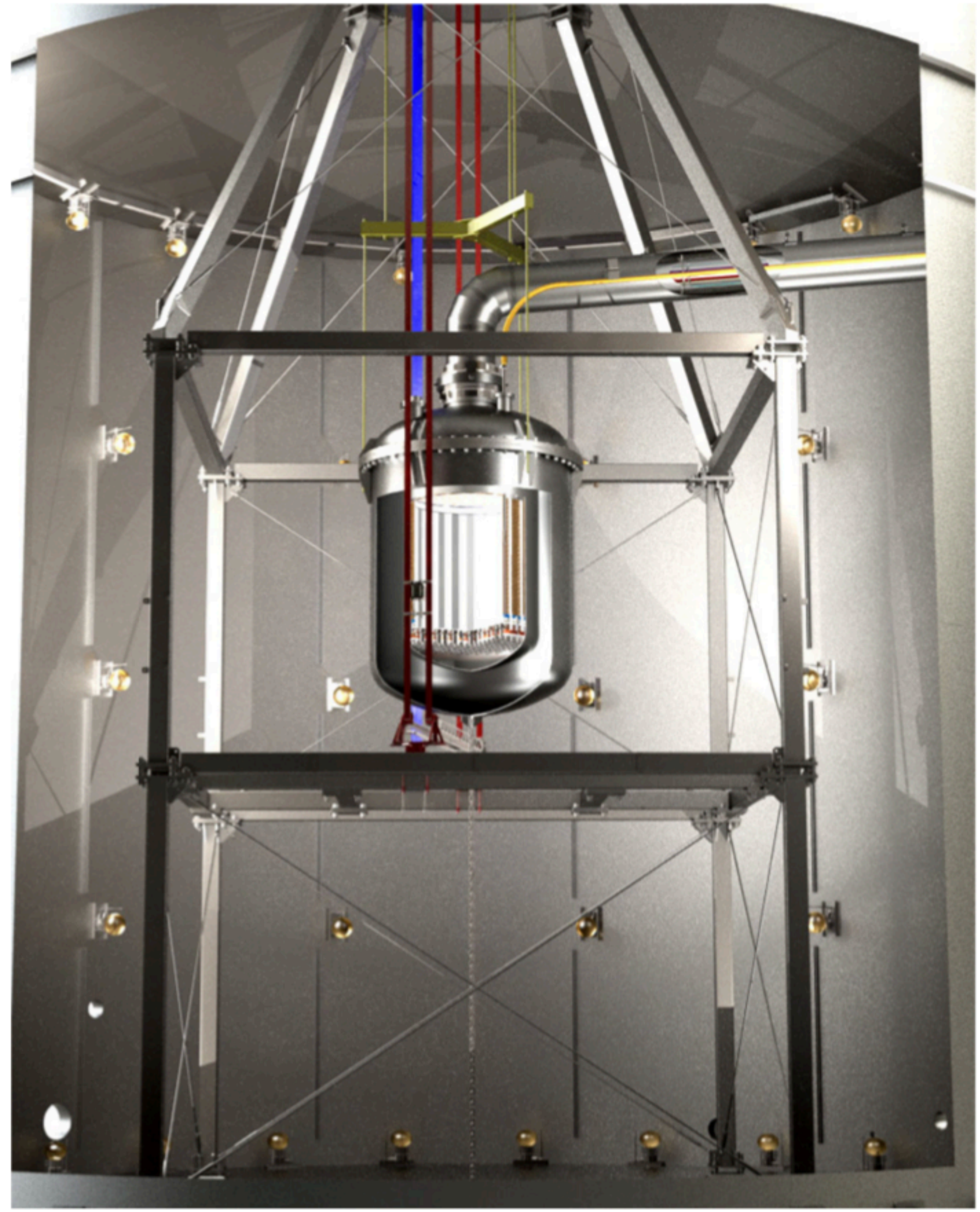
3 continents, 26 institutions, 165 members

Central Detector Components





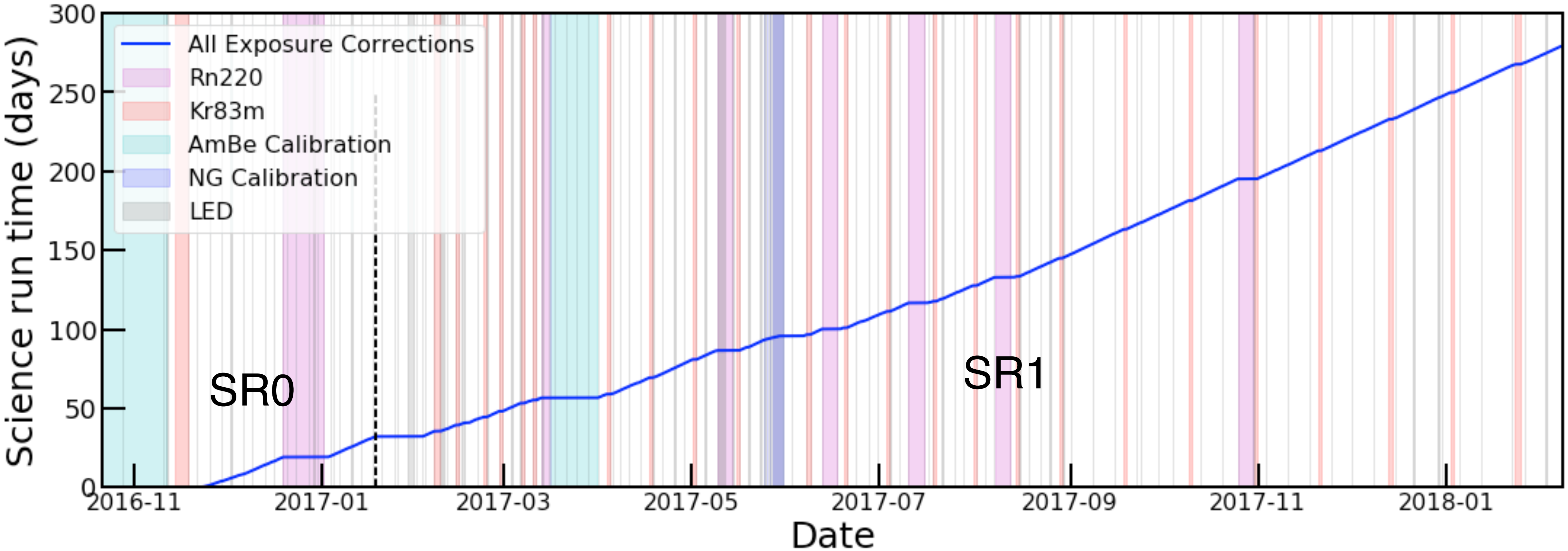
The XENON1T Detector and Water Shield/Veto



The XENON1T Dark Matter Experiment
EPJ (2017), arXiv:1708.07051

XENON1T Data taking

279 live-days low background physics data collected between Nov. 2016 and Feb. 2018. More data (SR2) collected until end of 2018.



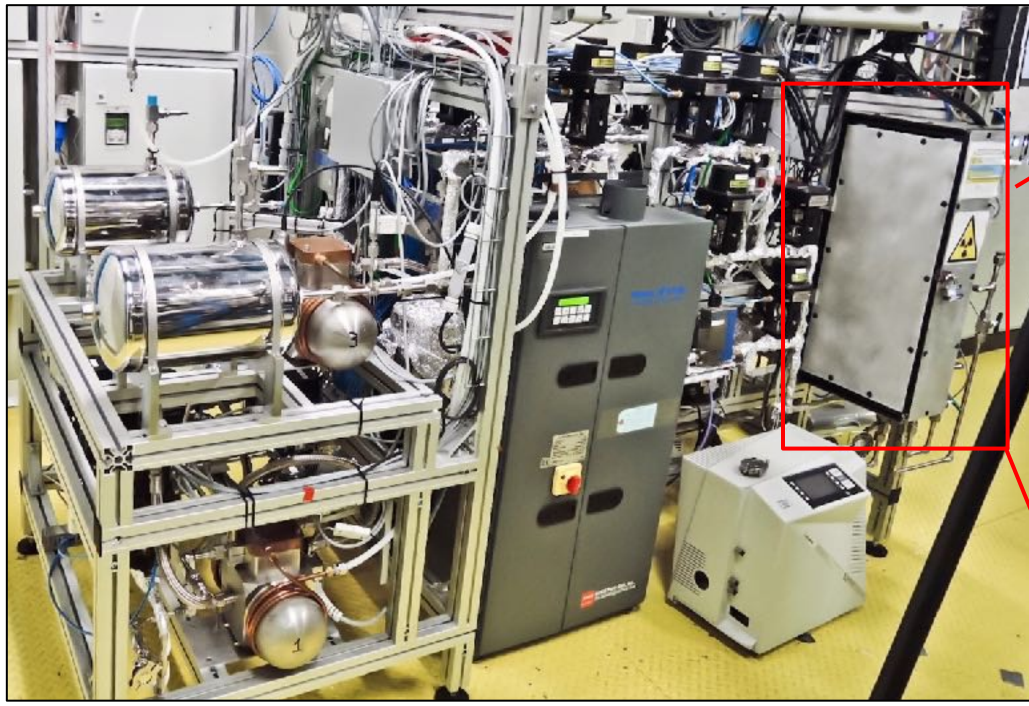
SR2

Instrument & Projection
JCAP 04, 027 (2016), 1512.07501
EPJ C 77, 881 (2017), 1708.07051

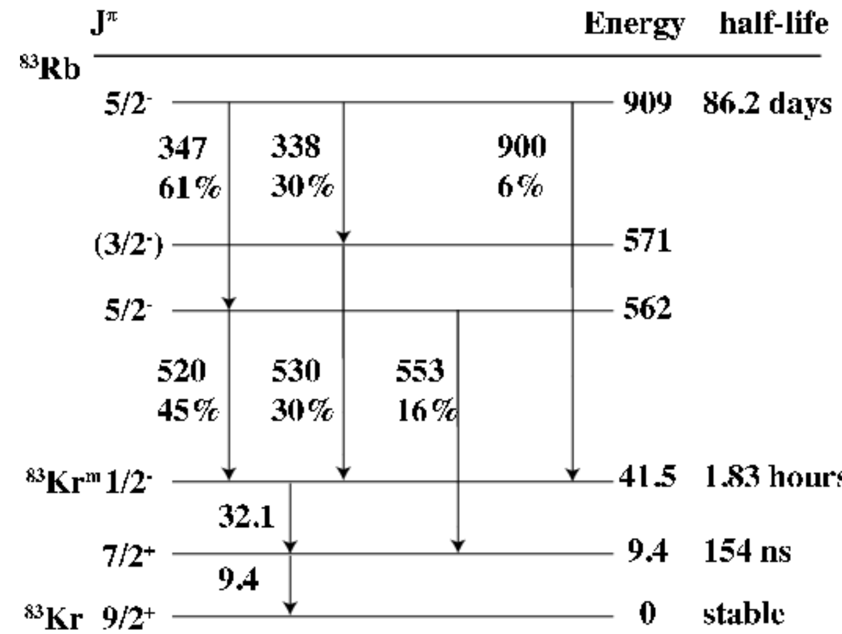
Analysis papers:
PRD 99, 112009 (2019), 1902.11297
PRD 100, 052014 (2019), 1906.04717

Physics results:
PRL 119,181301 (2017): first result
PRL121, 111302 (2018): SI
PRL 122, 071301 (2019): WIMP-pion
PRL 122, 141301 (2019): SD
Nature, 568, 532 (2019): Xe124 DEC
arXiv:1907.11485 (PRL): light DM
arXiv:1907.12771 (PRL): Migdal effect

Detector Calibrations



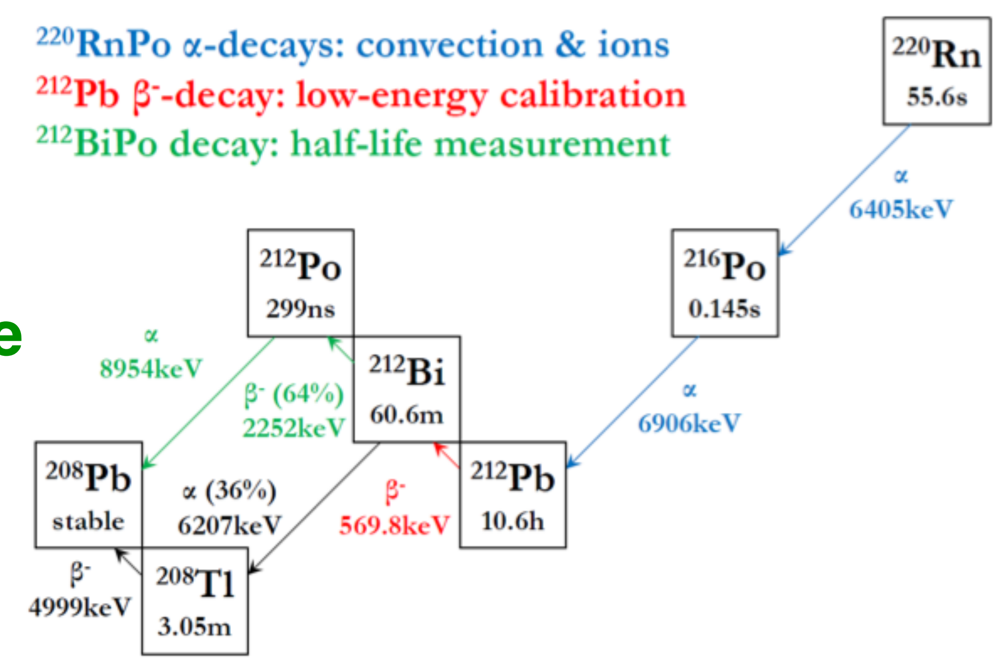
^{83m}Kr: to calibrate the energy response



AmBe neutrons

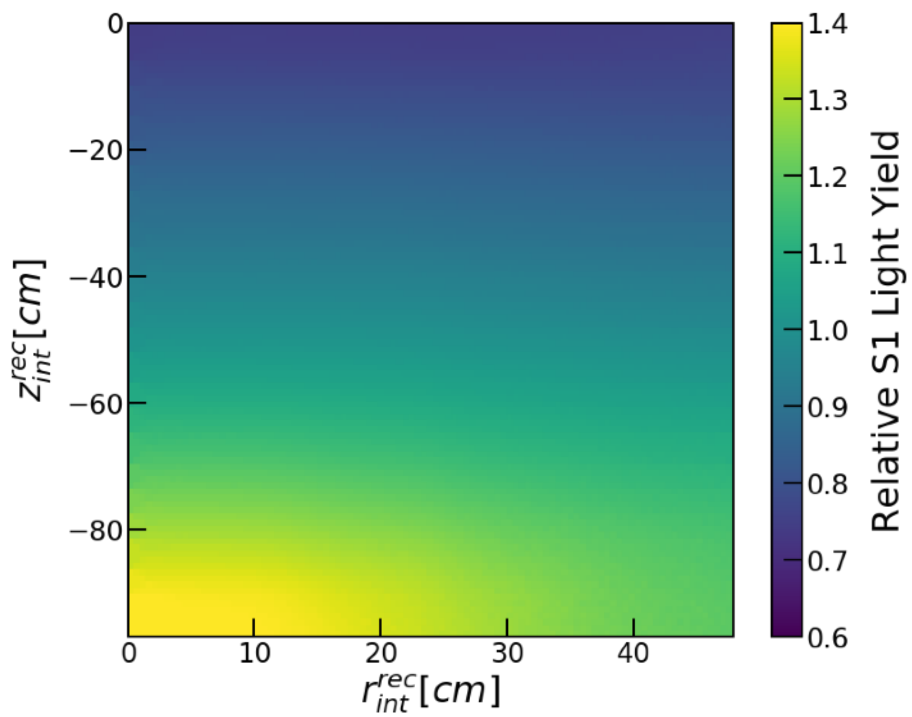
use neutrons to calibrate the Nuclear Recoil (NR) signals

^{220}Rn: to calibrate the Electronic Recoil (ER) background from ^{222}Rn

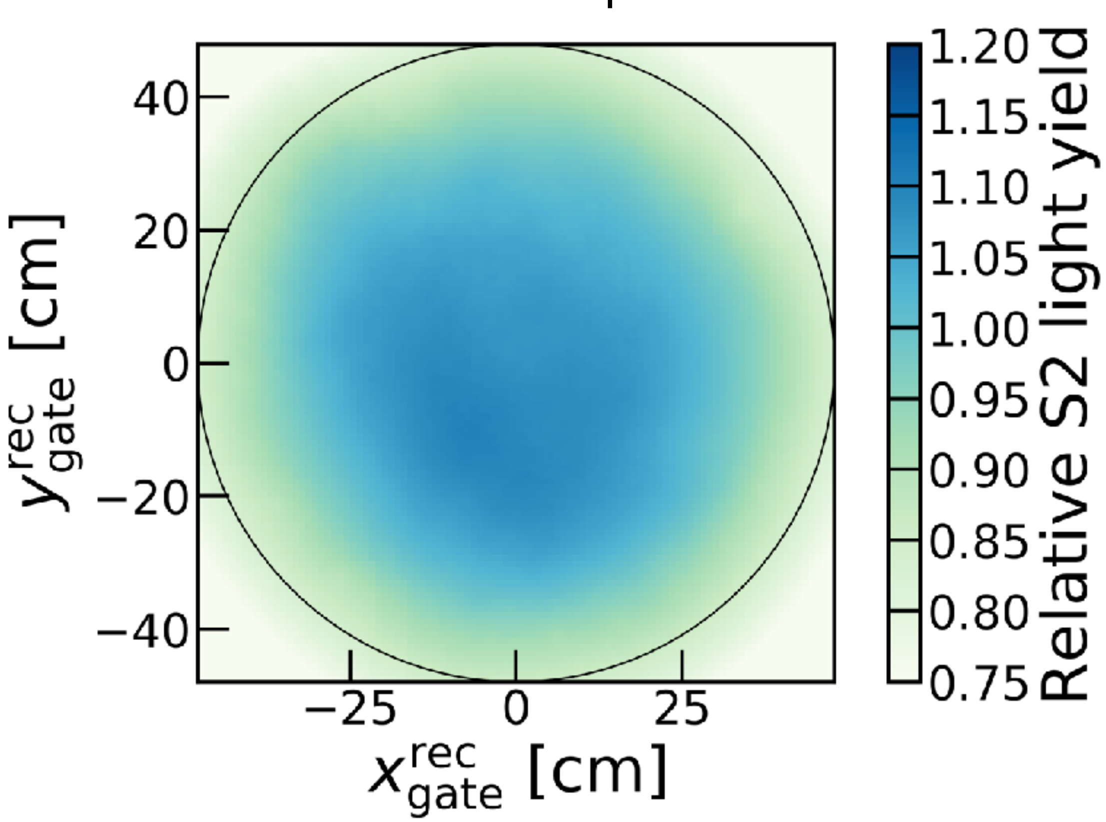


Energy response with fixed energy gammas

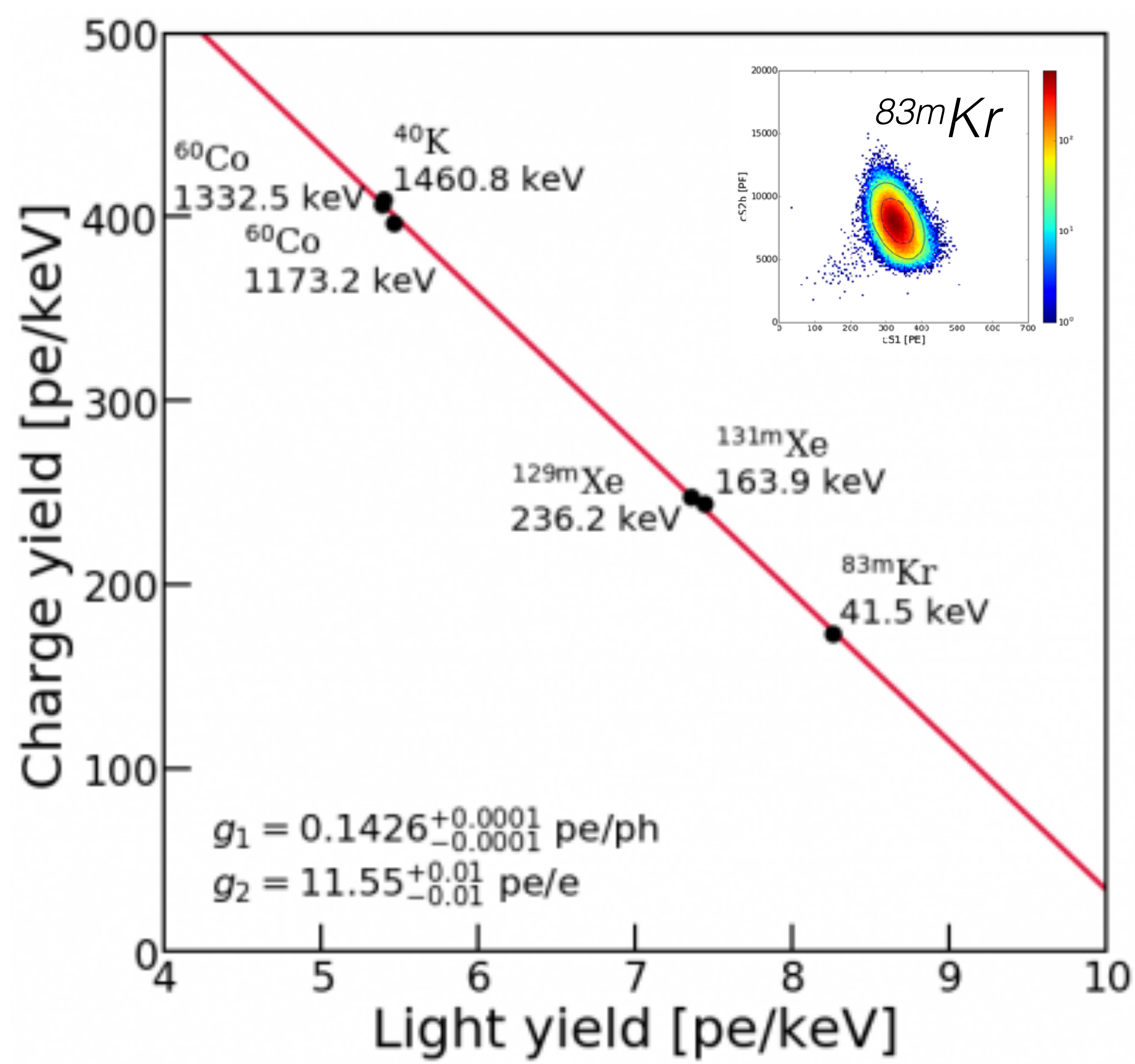
S1 Position Dependence



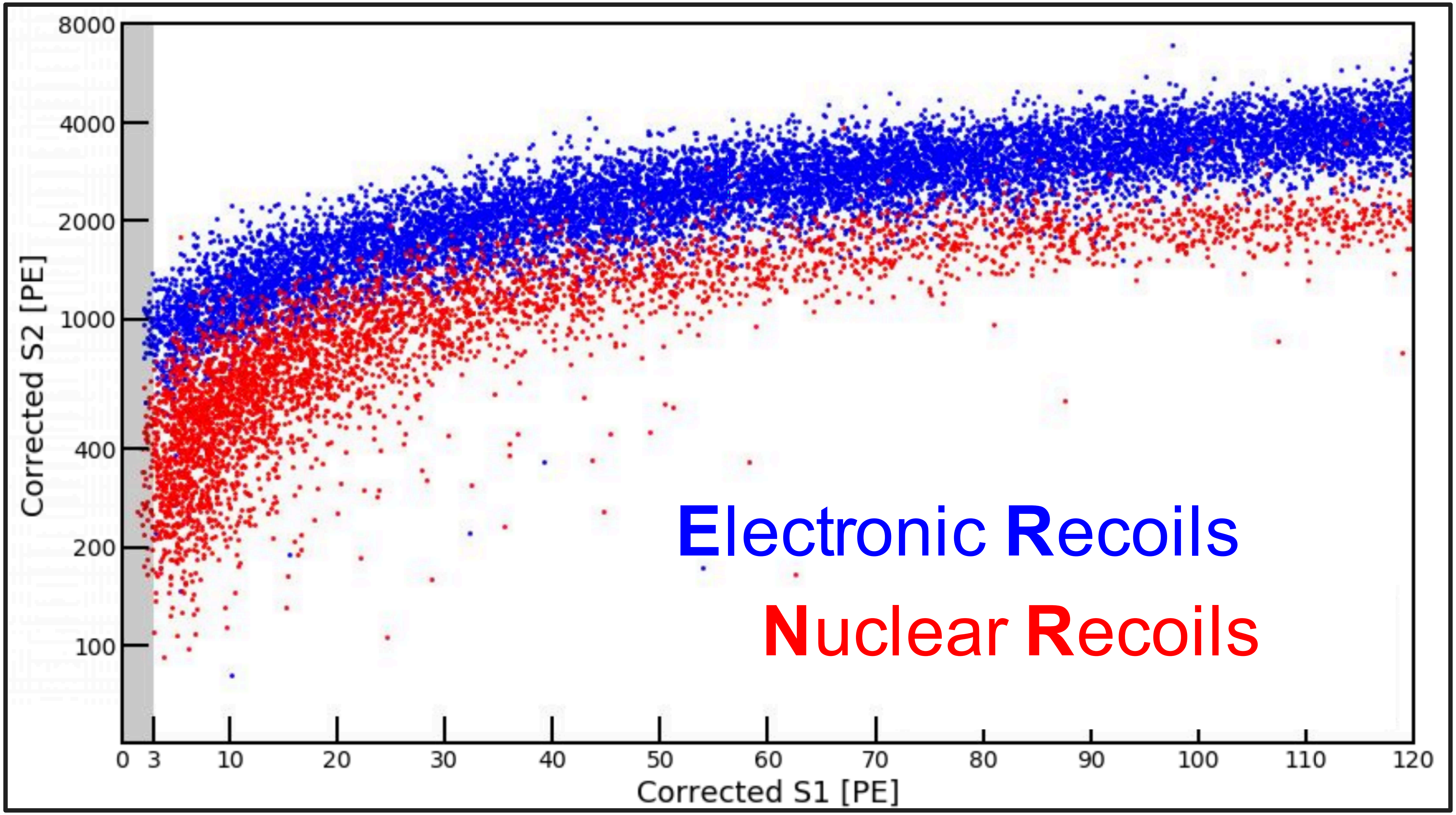
S2 Position Dependence



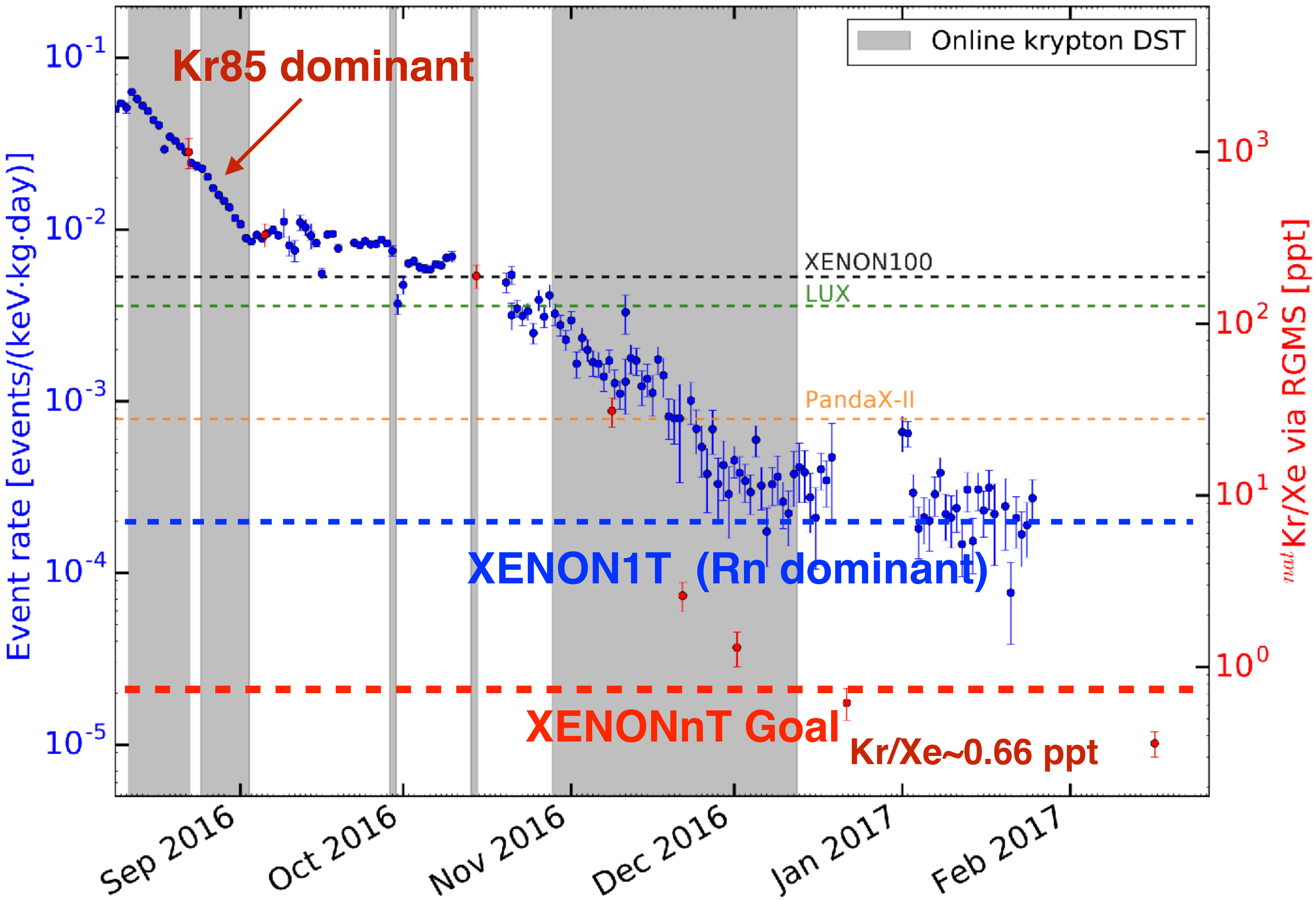
$$E = (n_{ph} + n_e) \cdot W = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$



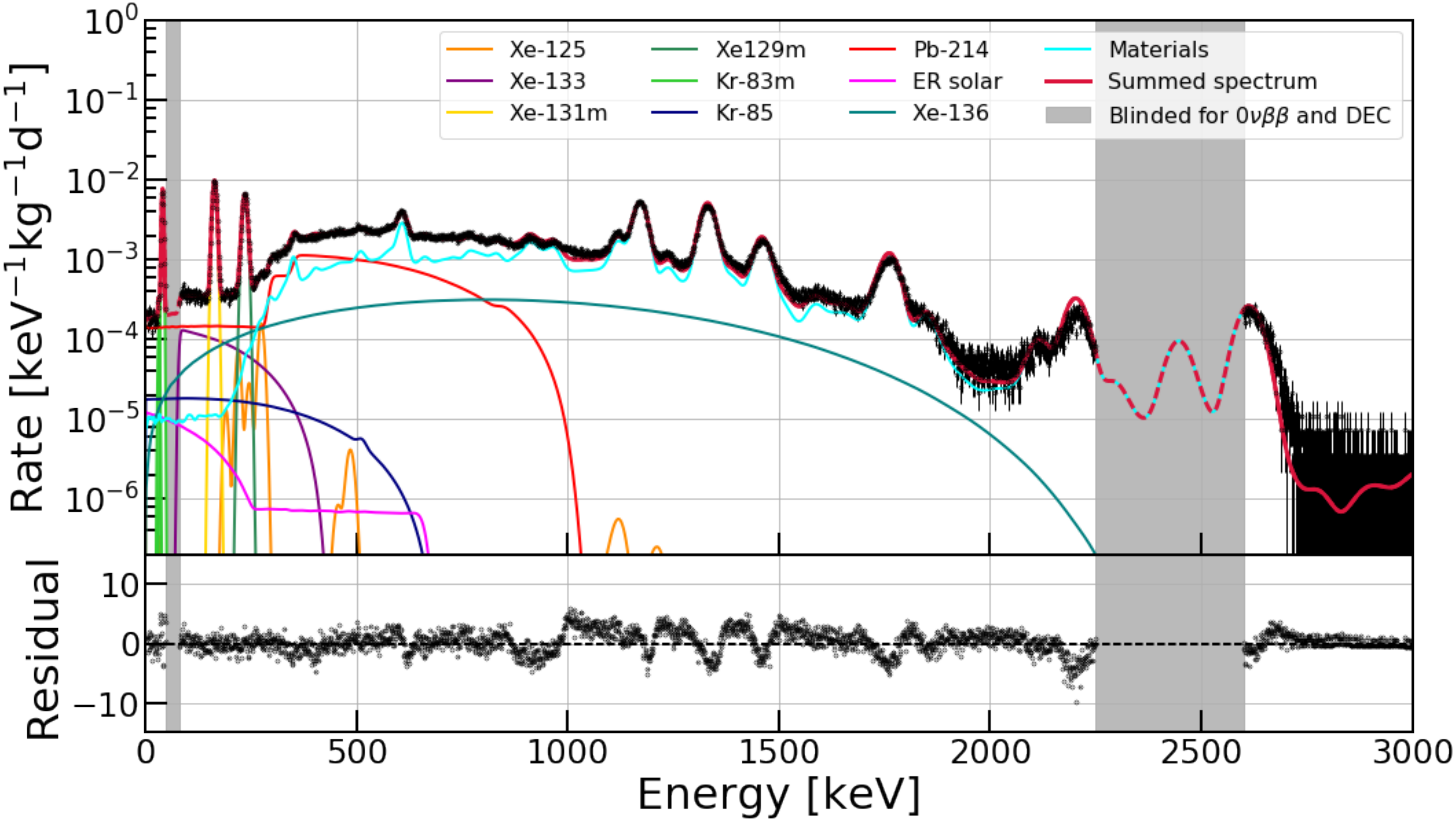
Calibrating Electronic and Nuclear Recoils



XENON1T achieved the lowest electronic recoil background, with major contribution from remaining Radon-222 (~10 μBq/kg)



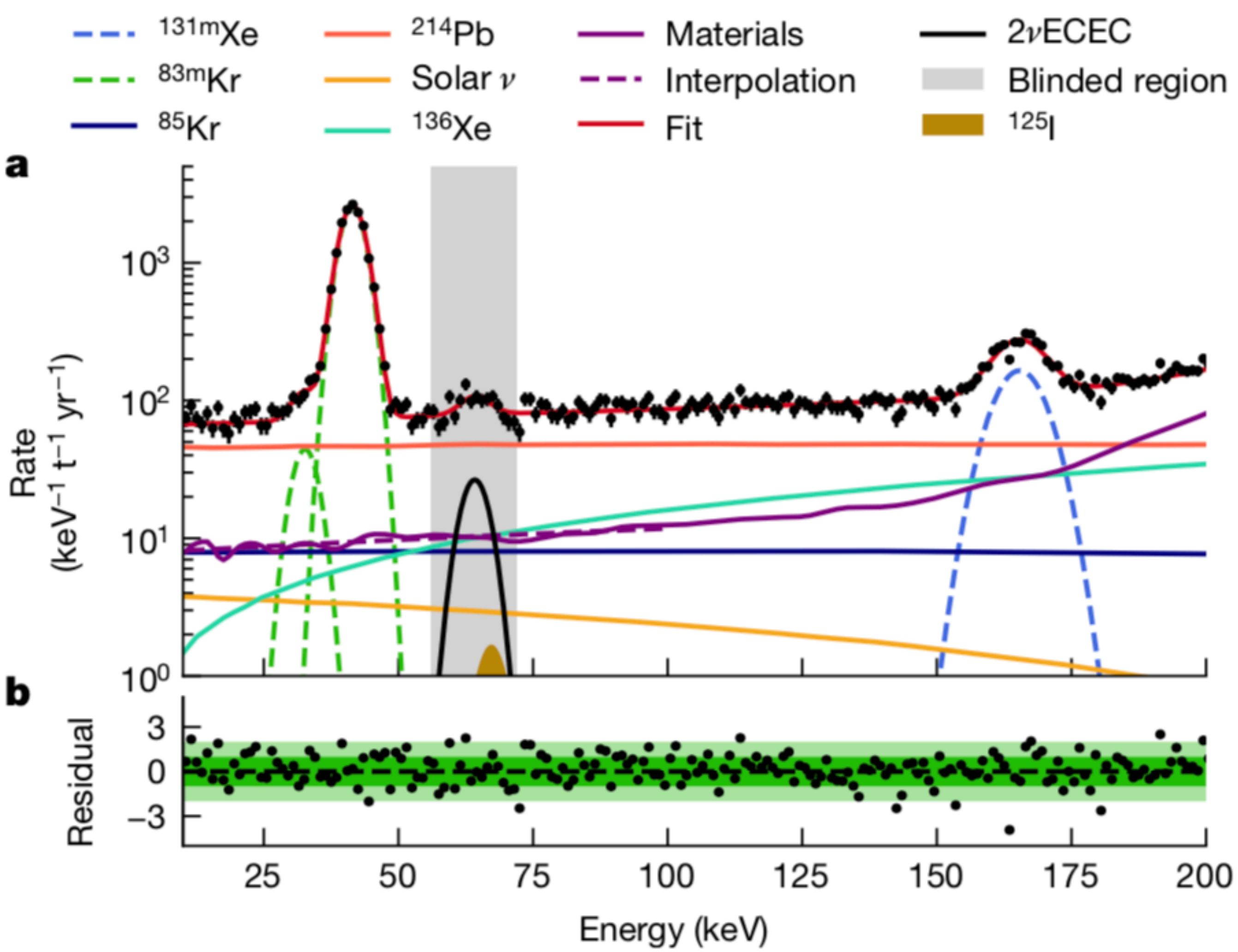
The ultra-low Electronic recoils (ER) background allows the search for other rare processes in nature.

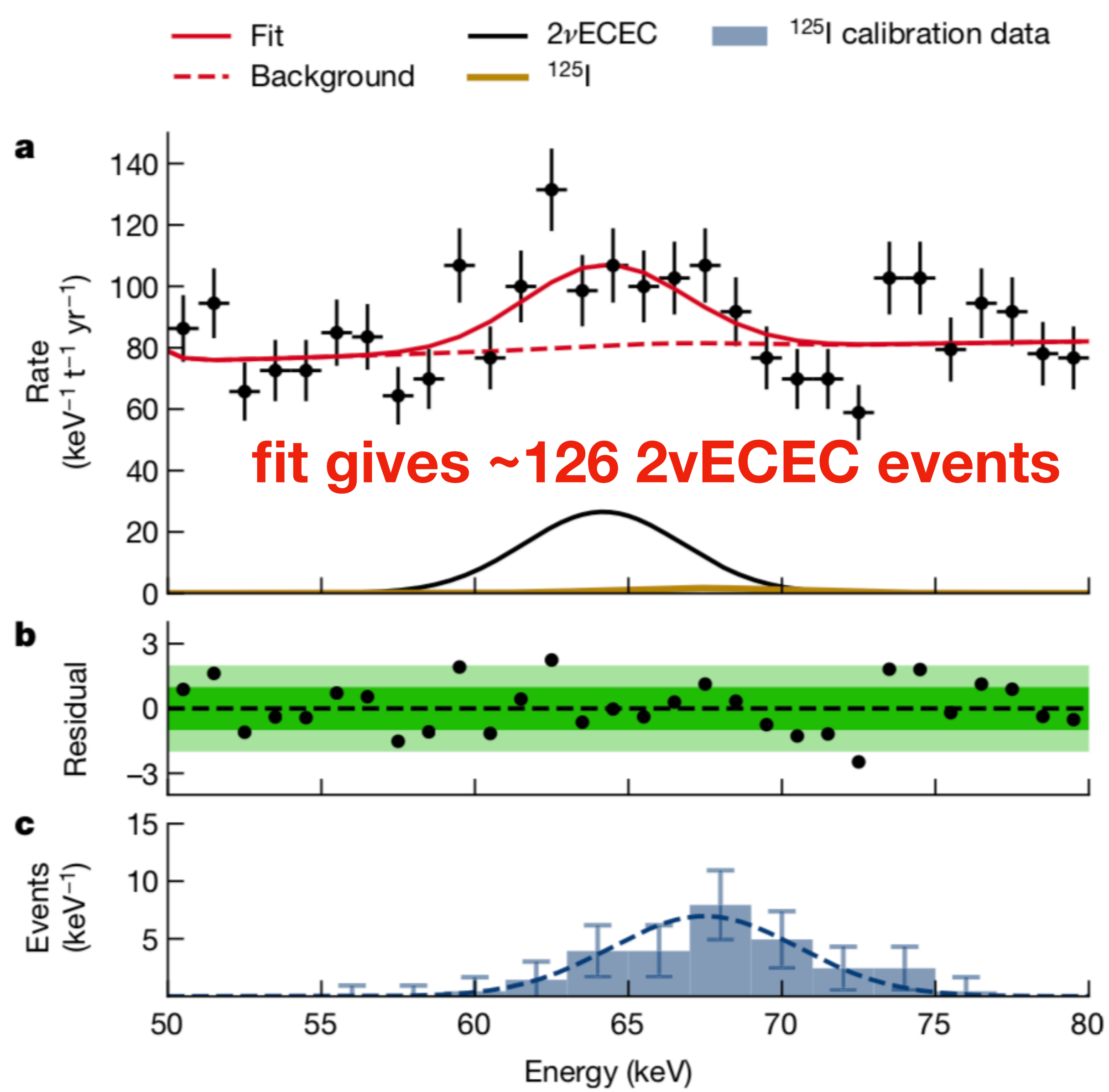


Other three main types of background: Surface, Accidental Coincidence, Radiogenic neutrons

Observation of two-neutrino double electron capture in Xe-124 with XENON1T

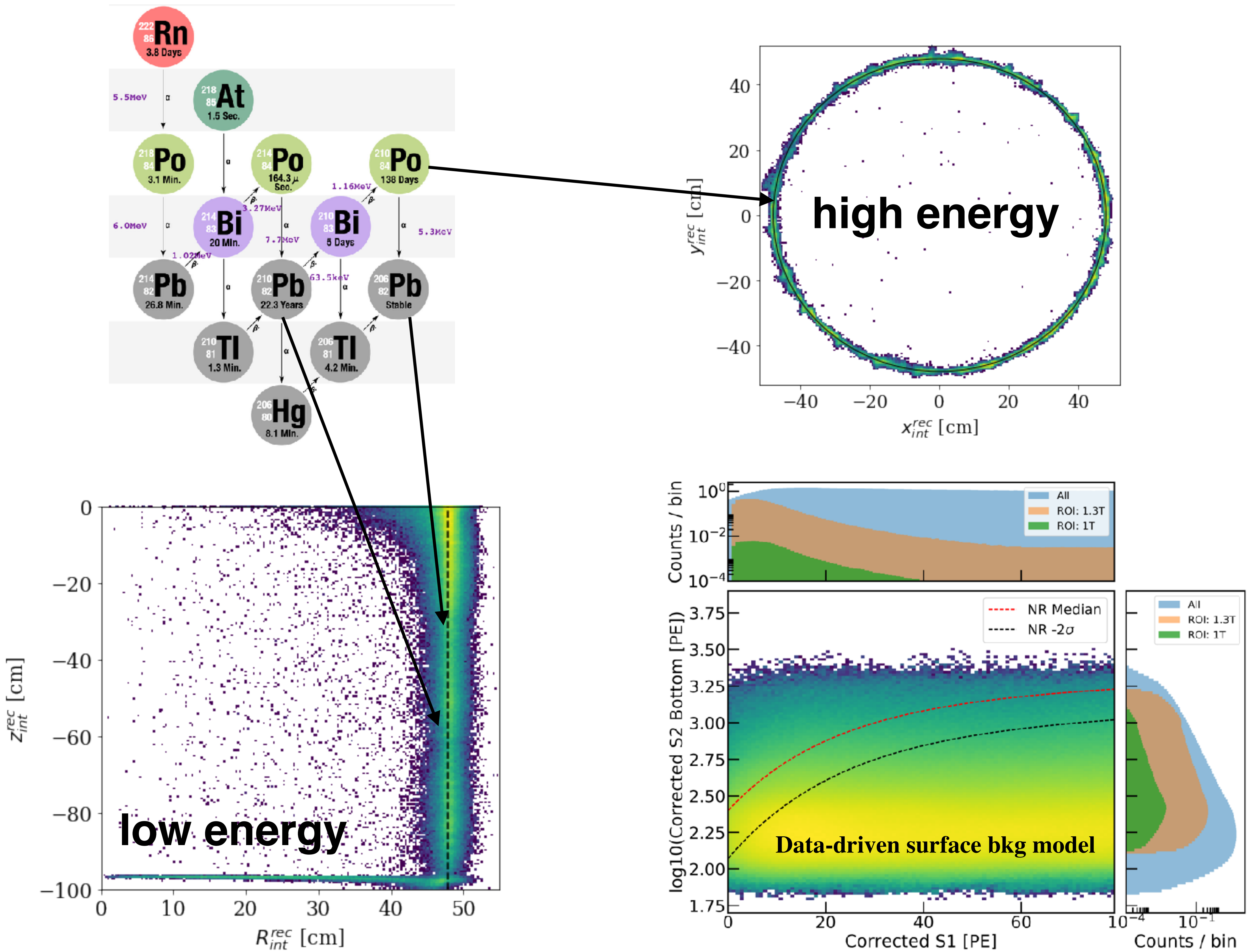
Nature, 568 (2019)



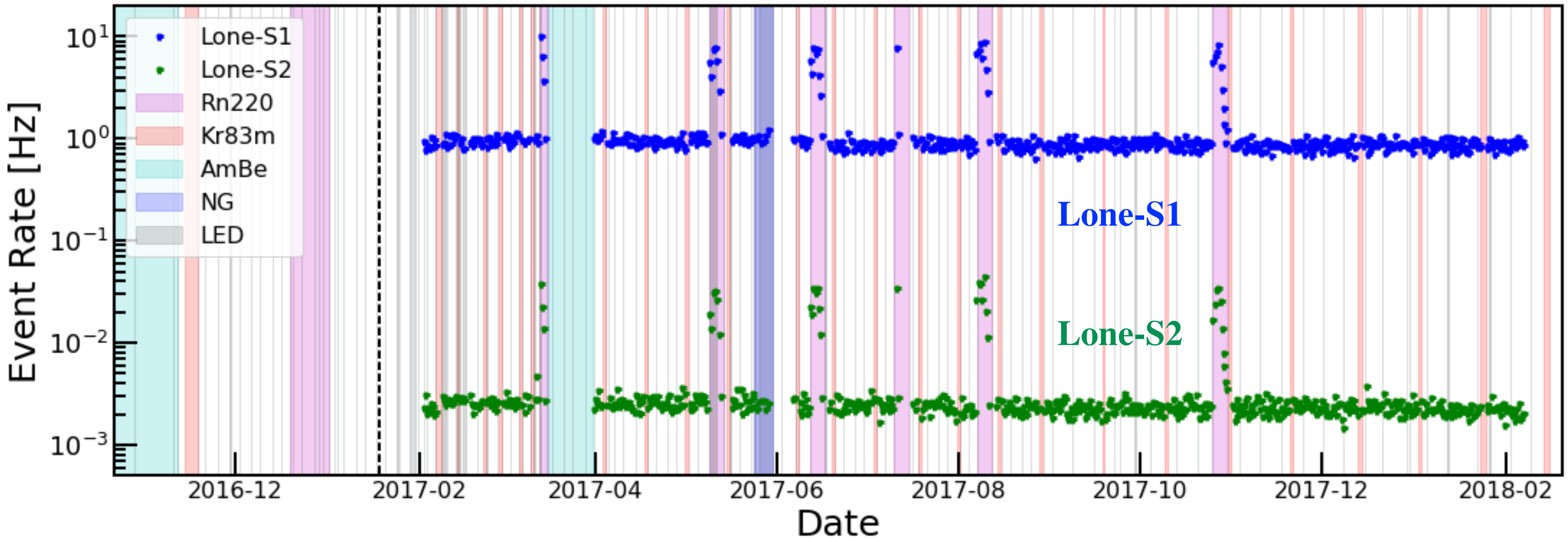


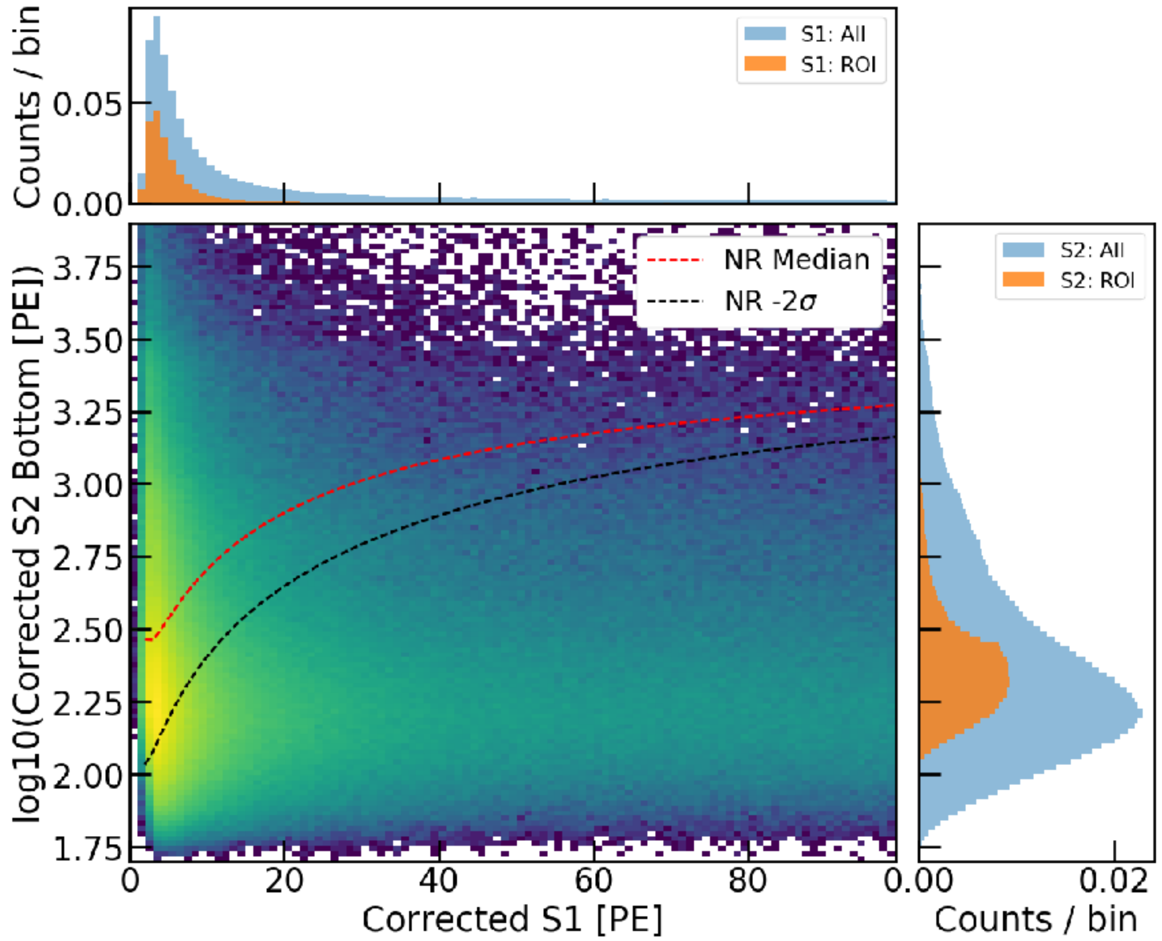
Xe-124 2νECEC half-life measured: $[1.8 \pm 0.5(\mathrm{sys}) \pm 0.1(\mathrm{stat})] \mathrm{x} 10^{22}$ **years**

Surface Background, from reduced-S2 events from Rn-daughters on the PTFE surface



Accidental Coincidence (AC)





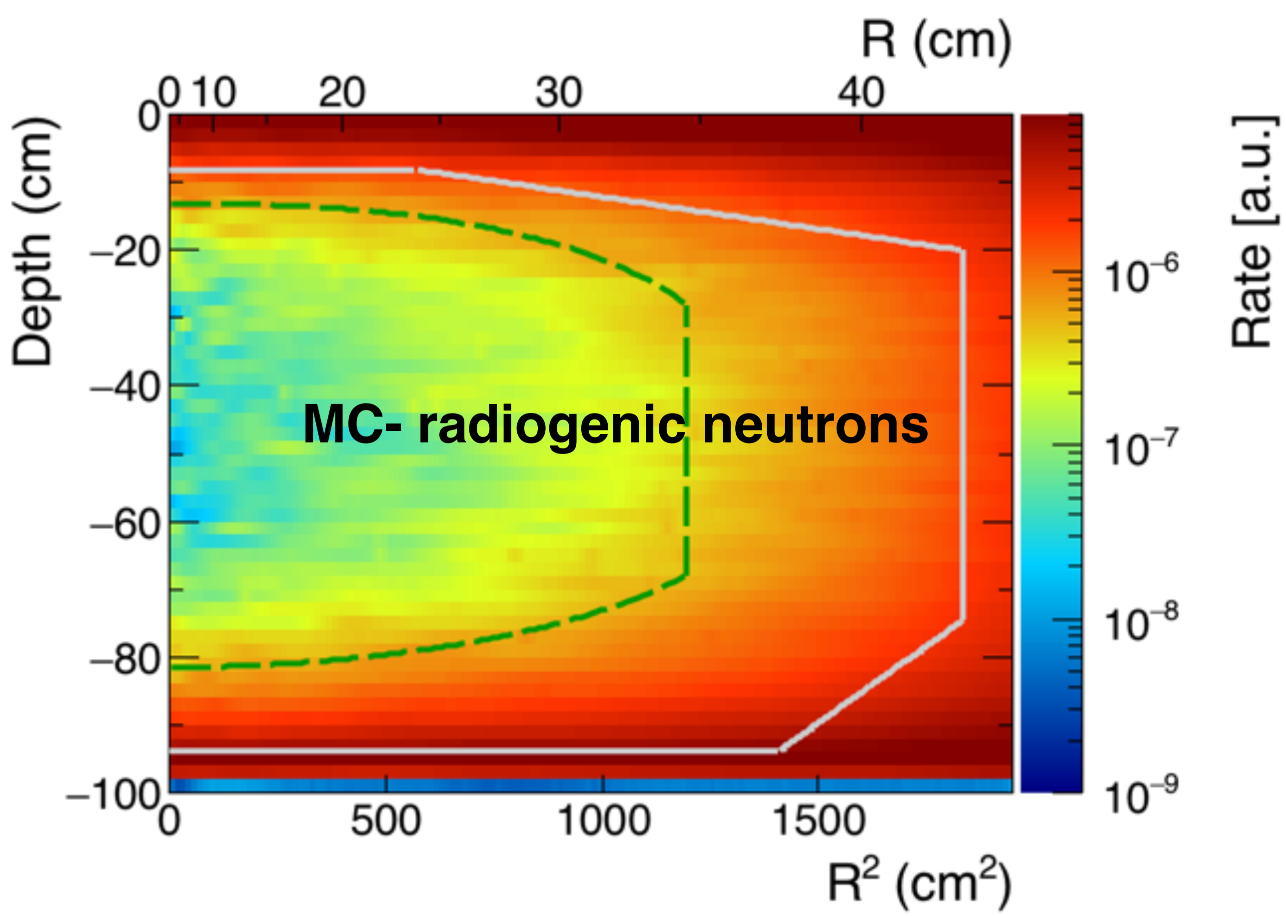
Radiogenic neutrons

Simulated NR single-scatter rate

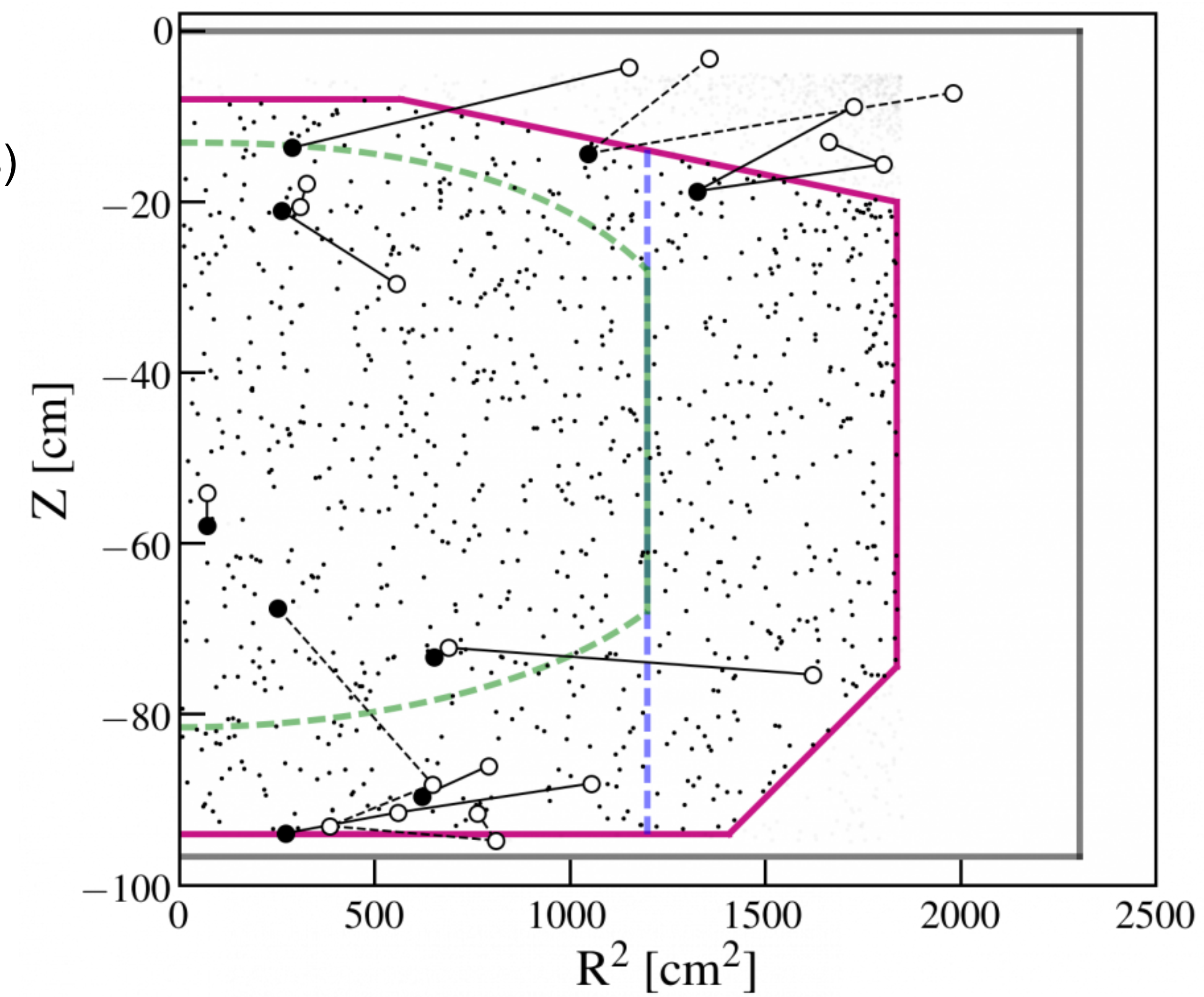
Source	Rate [t^{-1} y^{-1}]	Fraction [%]
Radiogenic n	0.6 ± 0.1	96.5
CEνNS	0.012	2.0
Cosmogenic n	< 0.01	< 2.0

(Expectations in 4-50 keV search window, 1t FV, single scatters)

JCAP04 (2016) 027

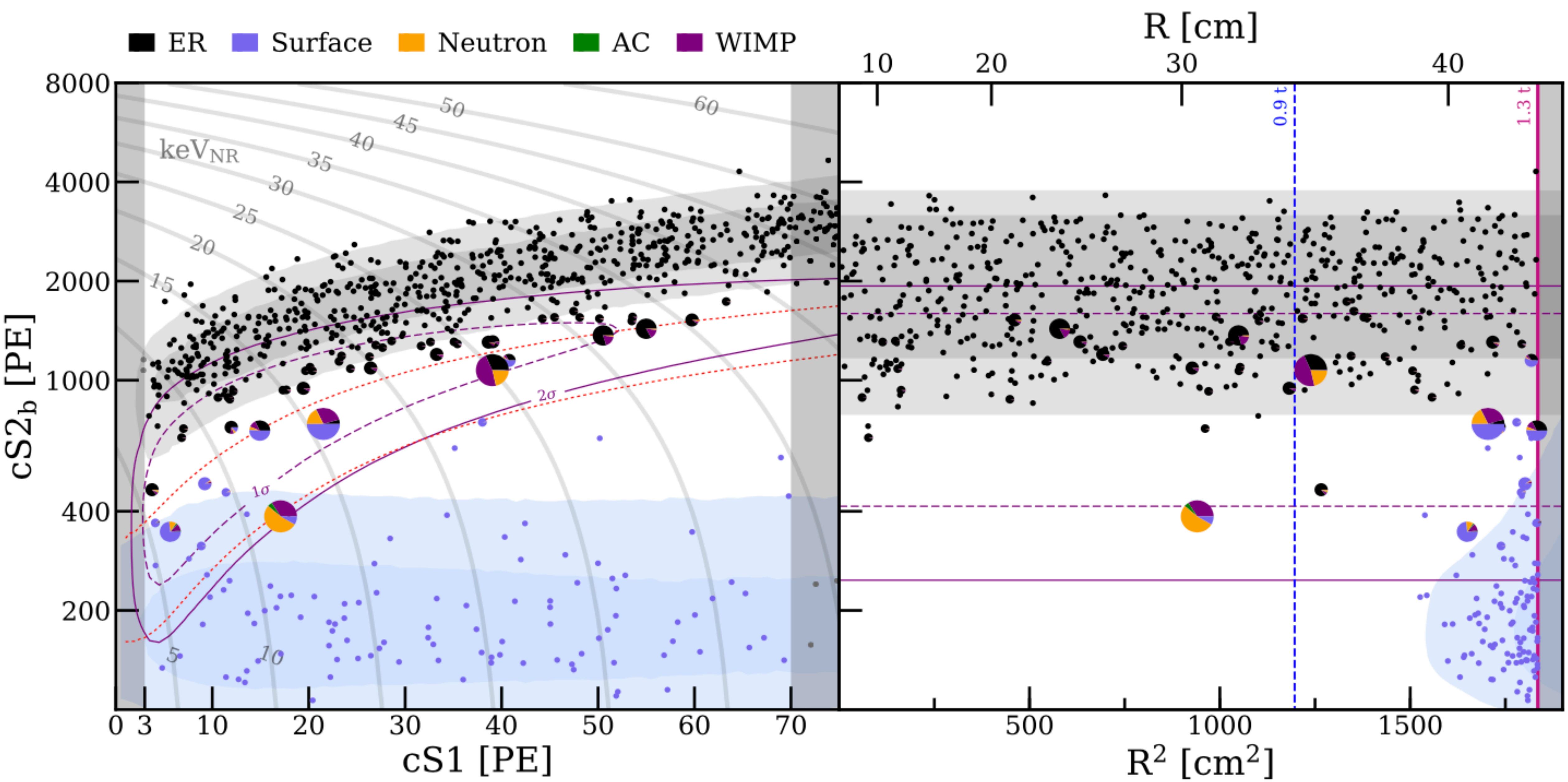


verify the neutron rate with multiple scattered NR events in data



One ton-year of data, after unblinding

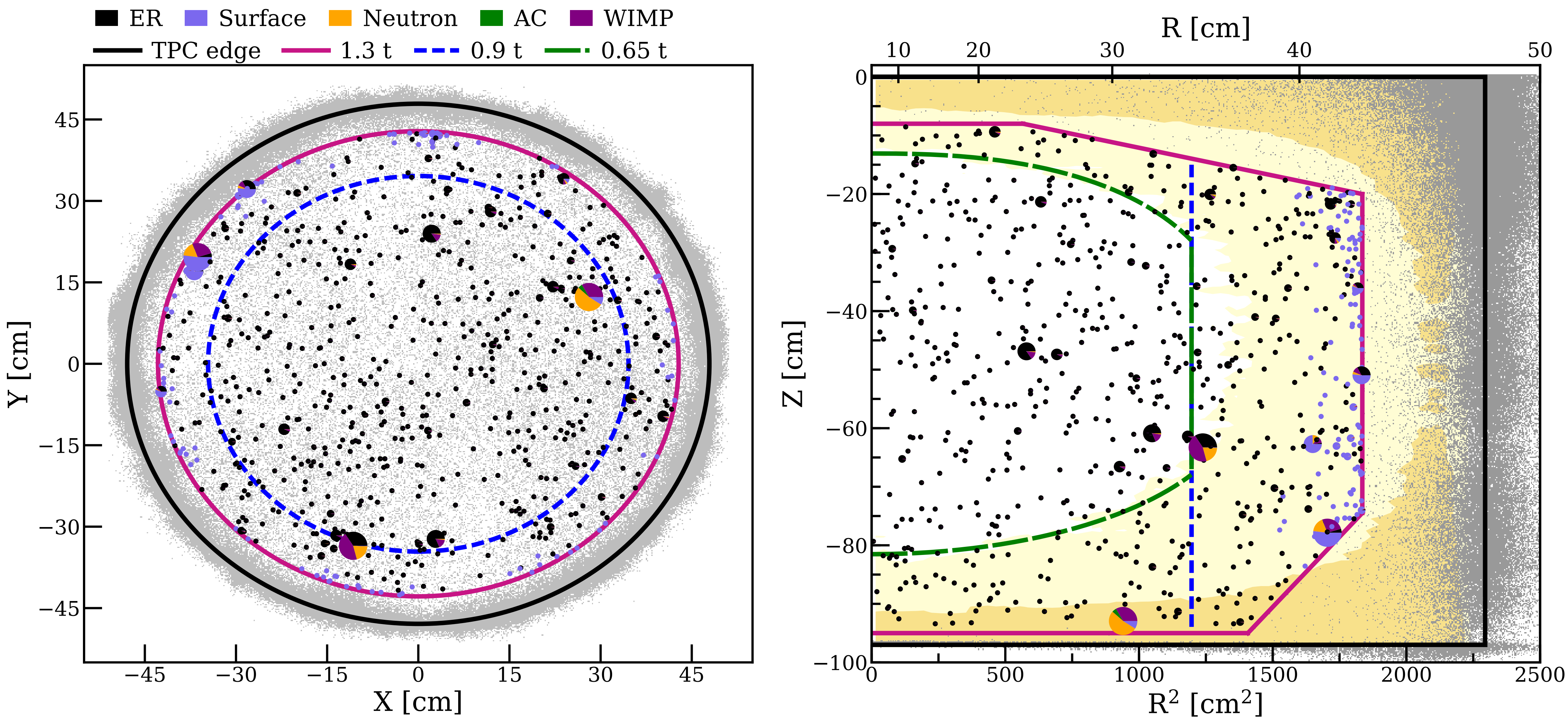
Phys.Rev.Lett.121, 111302 (2018)
(arXiv:1805.12562)



Piecharts indicate the relative PDF of background and the best-fit of 200 GeV/c^2 WIMPs at cross-section of 4.7x10^{-47} cm^2

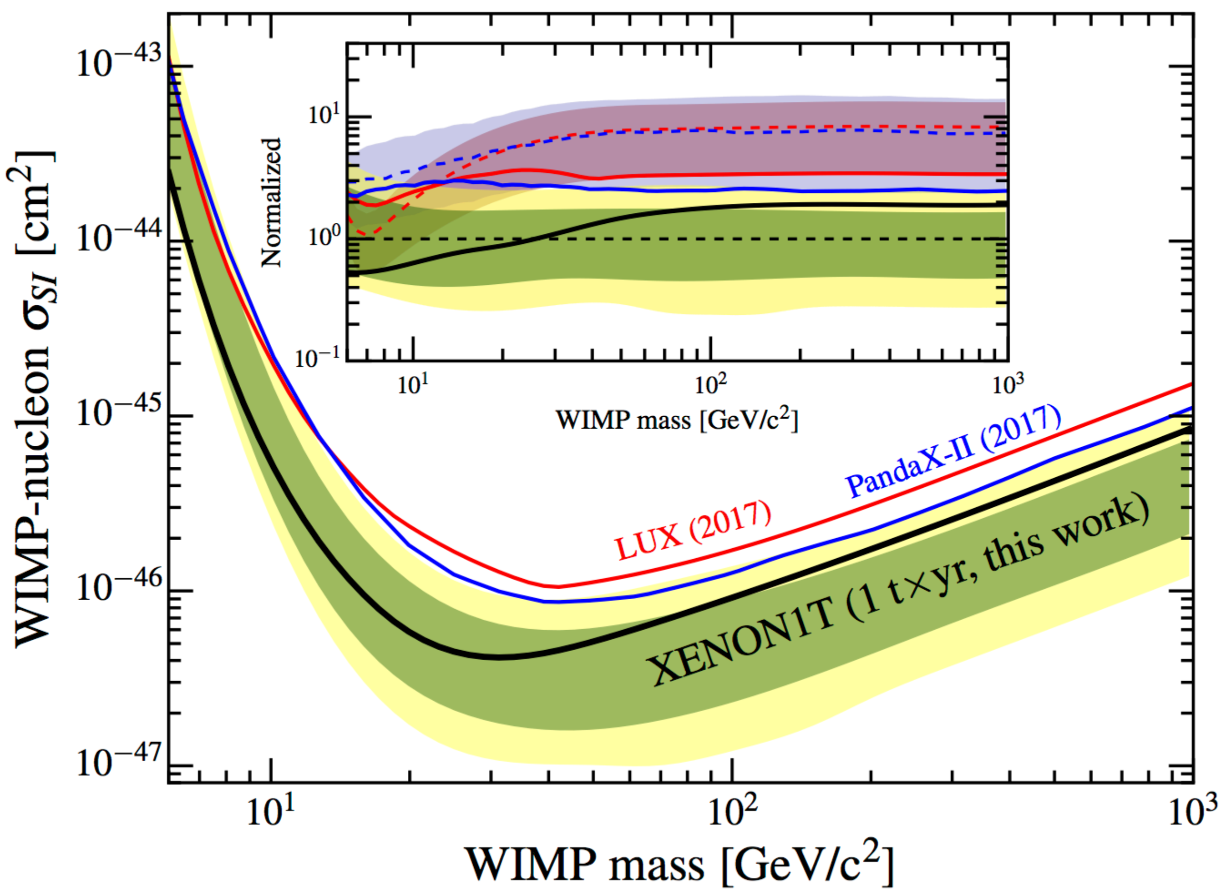
One ton-year of data, after unblinding

Phys.Rev.Lett.121, 111302 (2018)
(arXiv:1805.12562)



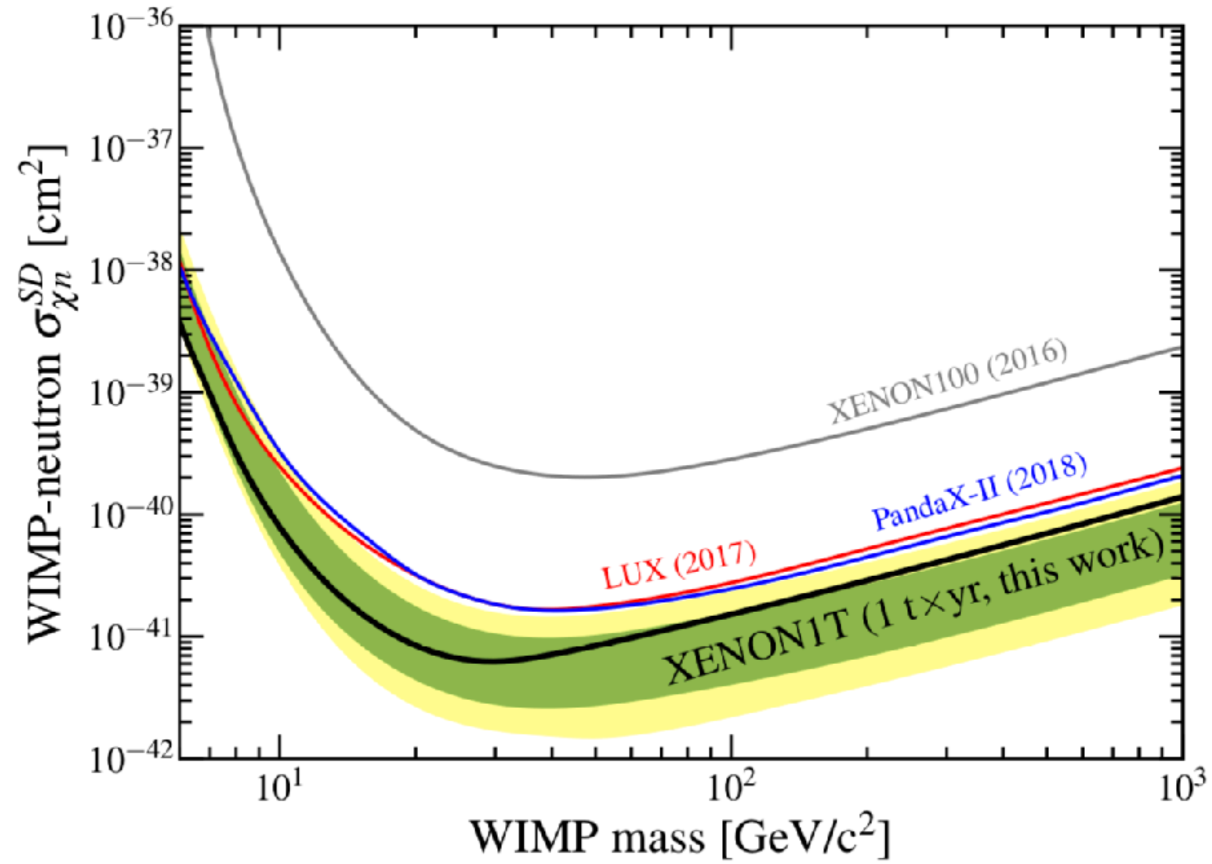
XENON1T
placed the most stringent constraints for heavy WIMPs above 6 GeV/c²

Spin-independent
PRL 121, 111302 (2018)



- 279 days data in 1.3 ton (1.0 ton yr)
- Energy region: 5-41 keVnr (1.4-10.6 keVee)
- ER background: 82 evts/ton/yr/keVee
- Best SI limit: 4.1 x10^{-47} cm^2 at 30 GeV/c^2

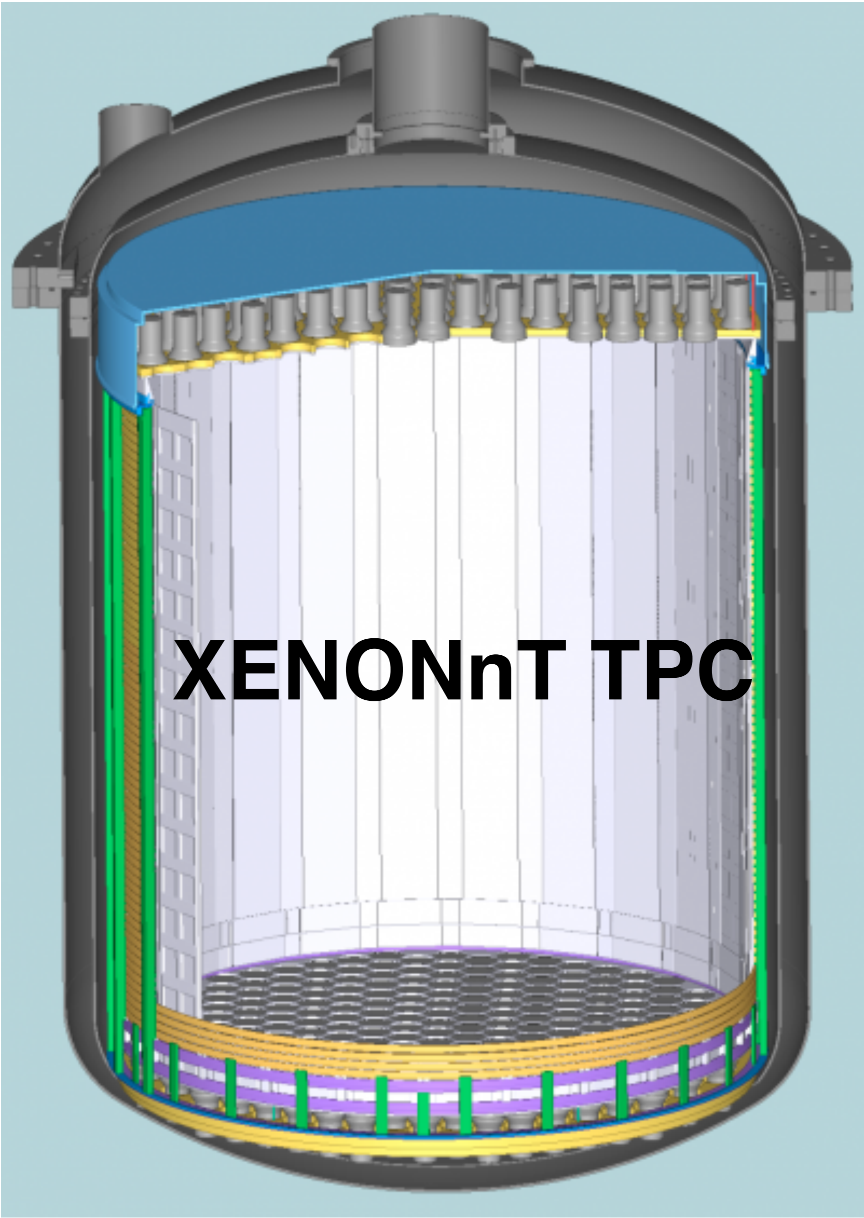
Spin-dependent
PRL 122, 141301 (2019)



- same data as for the SI search
- Xe129 (29.5%), Xe131 (23.7%)
- best SD-neutron limit: 6.3x10^{-42} cm^2 at 30 GeV/c^2

From XENON1T to XENONnT

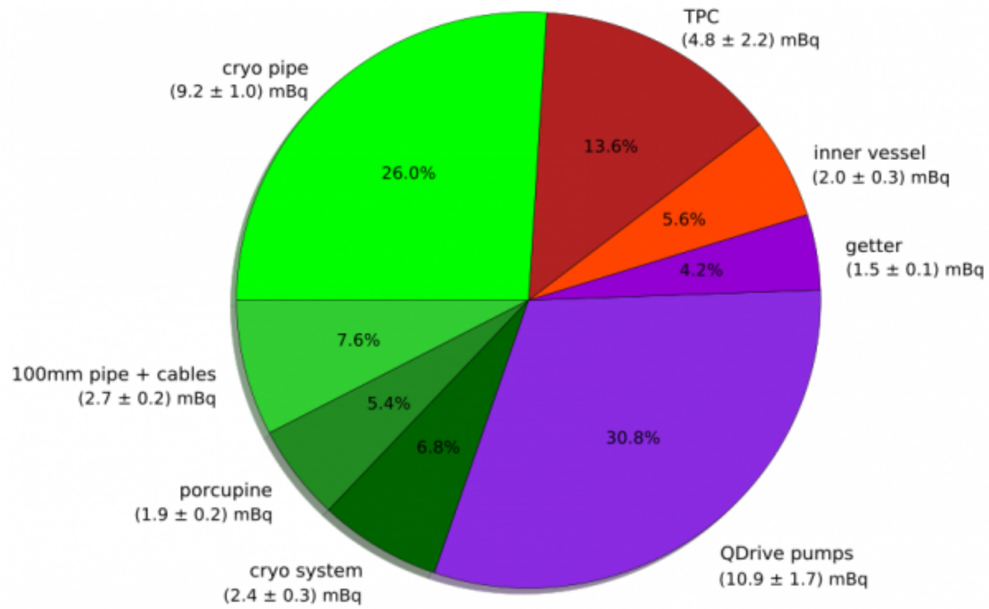
Upgrade from XENON1T to XENONnT



Basic characteristics of XENON1T & nT TPCs

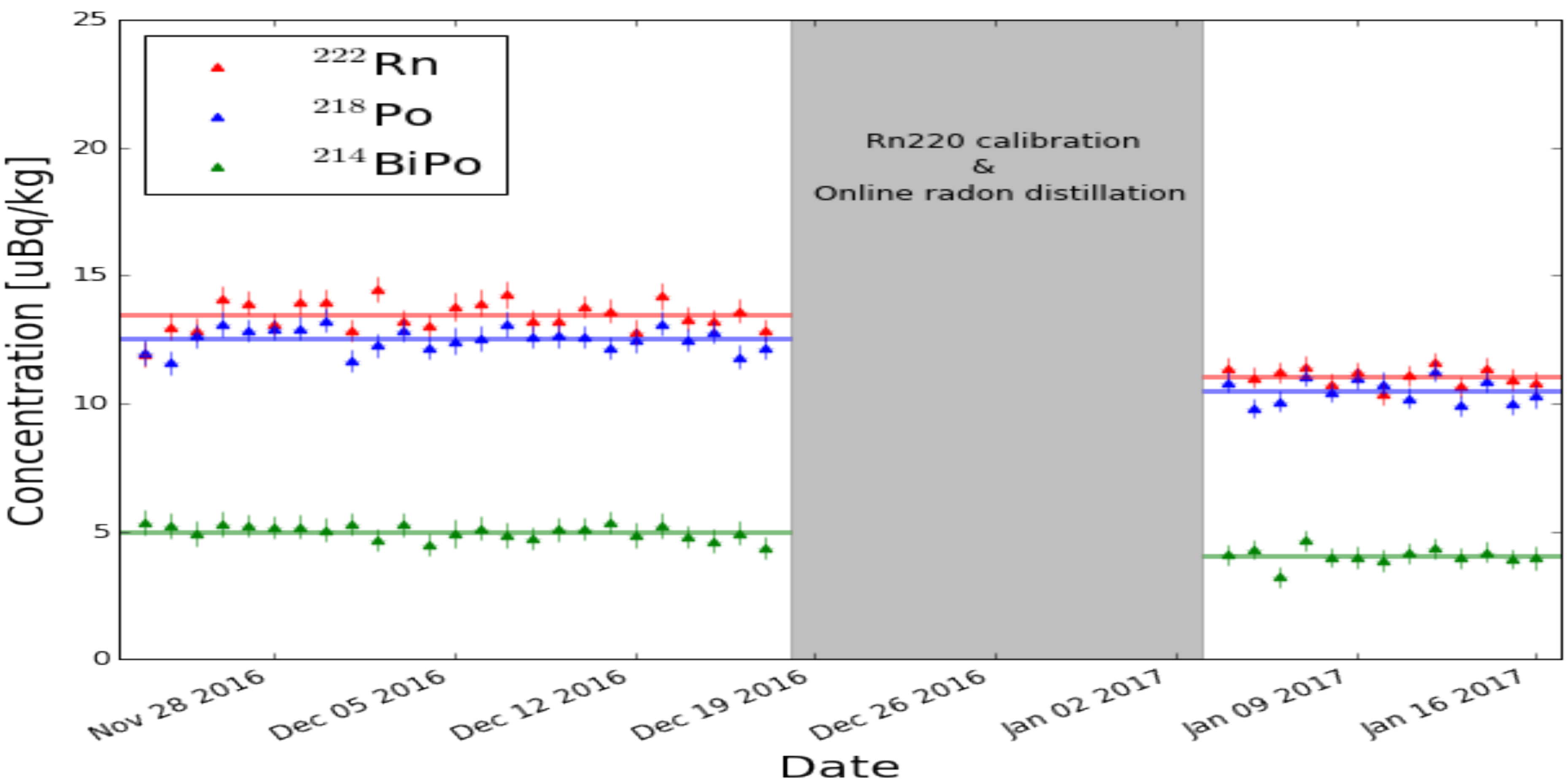
	XENON1T	XENONnT
Drift (cm)	97	148
Diameter (cm)	96	133
# of PMTs (R11410)	248	494
Active Mass (tonne)	2.0	5.9
Total Mass (tonne)	3.2	8.4

XENON1T to XENONnT: Reduce Rn background by 1/10



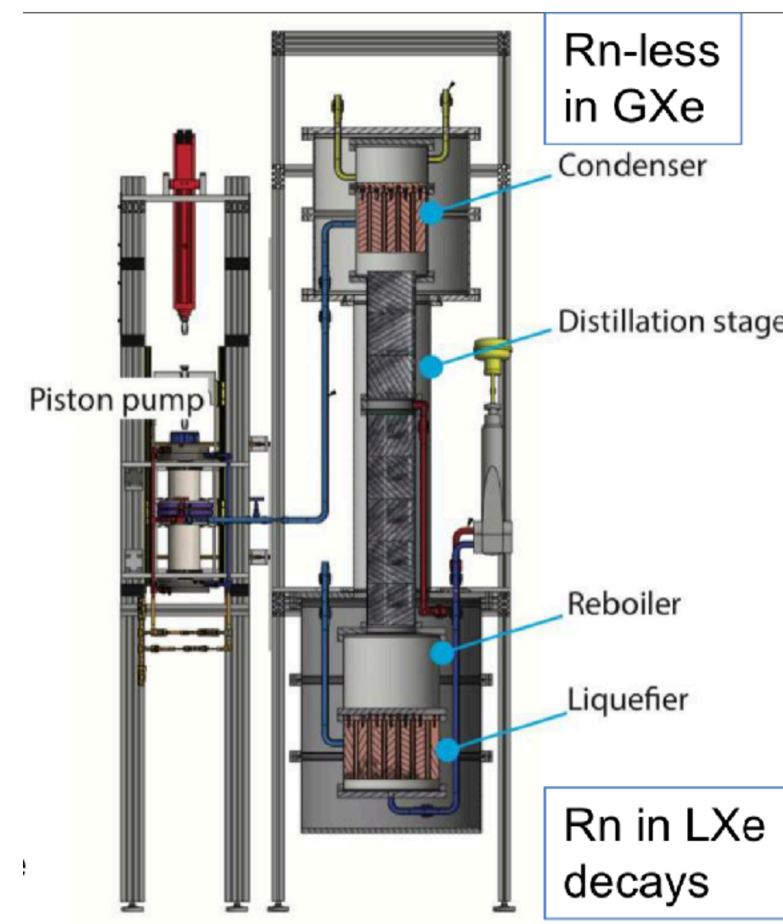
Radon source identified in XENON1T

- Material selection with ^{222}Rn screening
  - screening facilities with few atoms/probe sensitivit
- Replace parts with large Rn contribution
- Post-manufacturing surface treatment
- Reduction with high through-put online distillation
- Goal: 1 μBq/kg



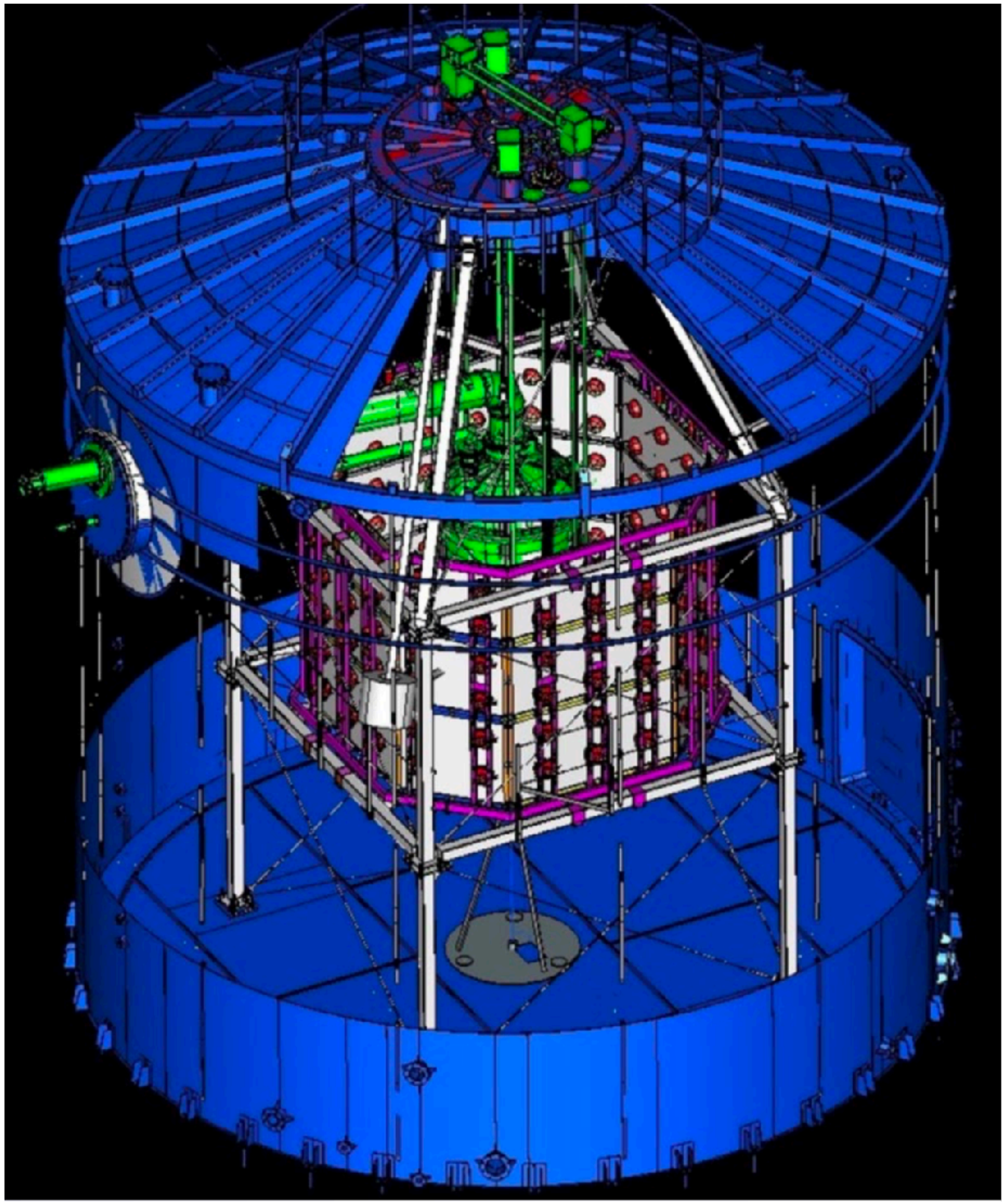
Online Rn removal with distillation tested in XENON100 and XENON1T

(Eur. Phys. J. C, 77:358, 2017)



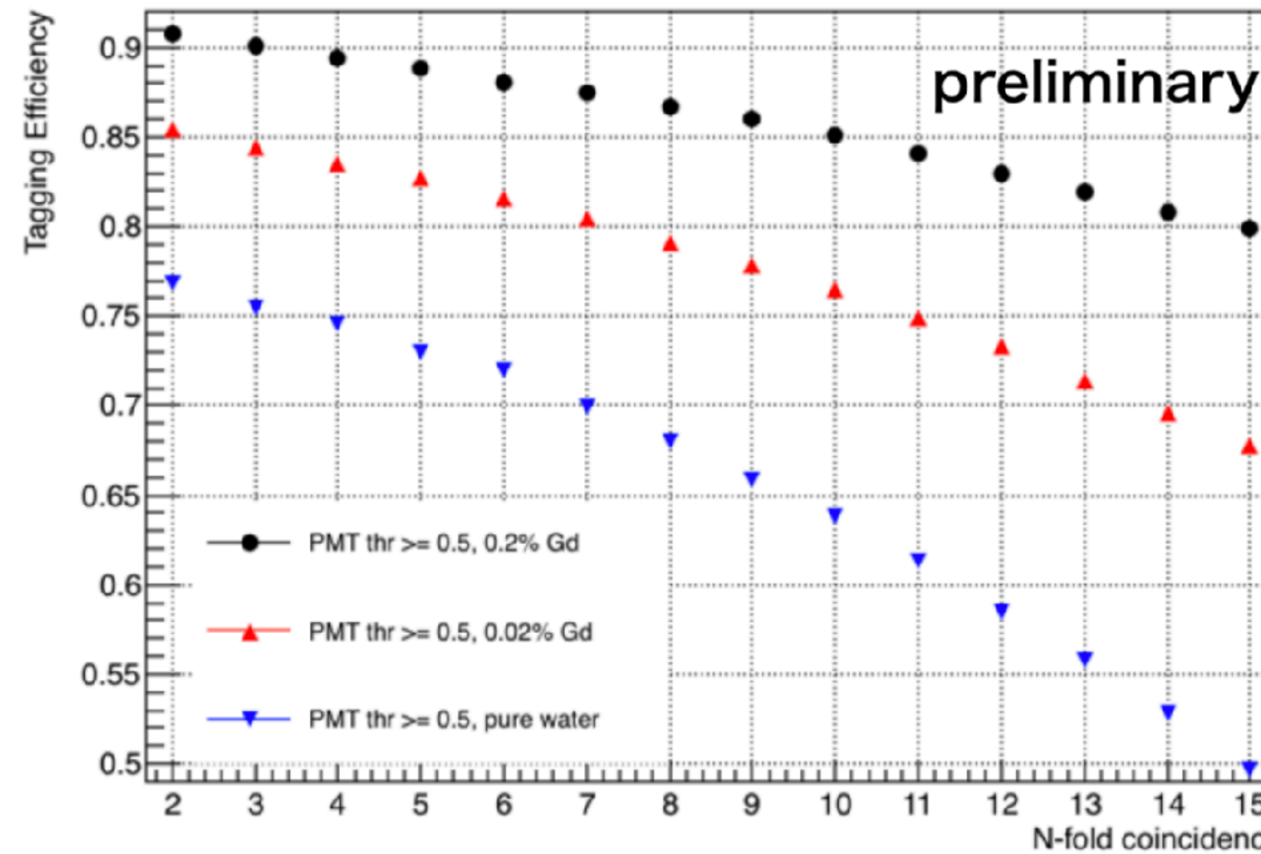
Dedicated Rn distillation column

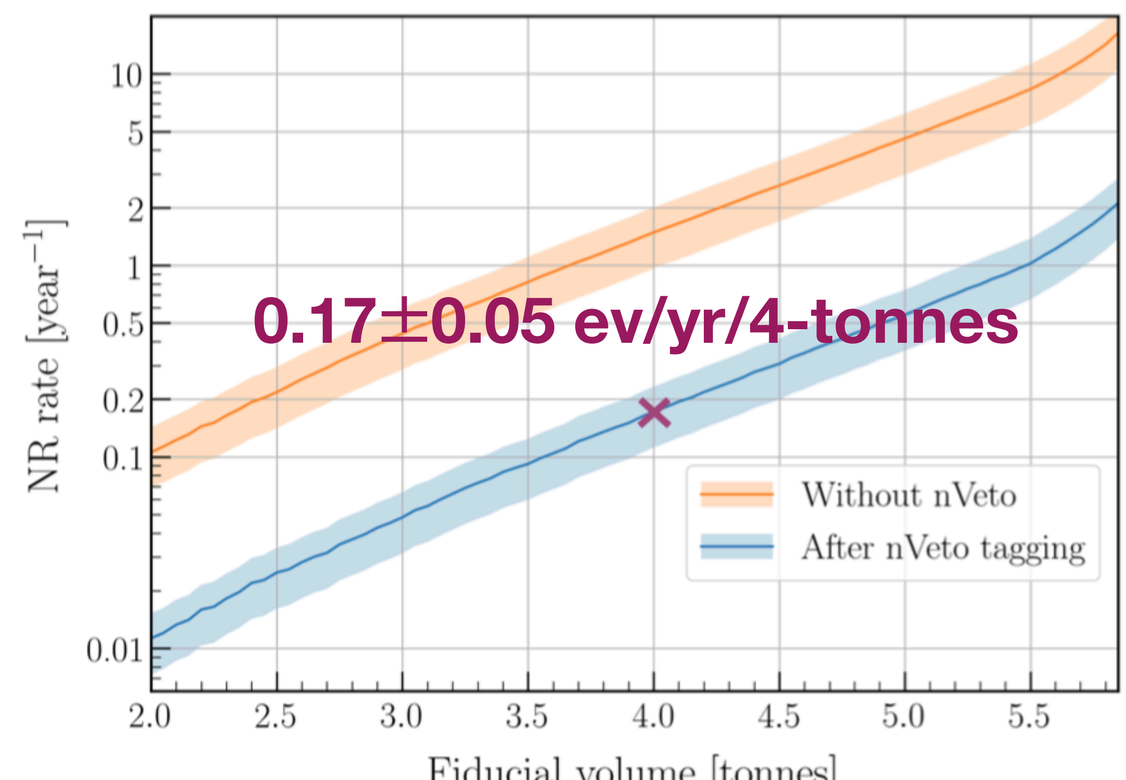
XENON1T to XENONnT: reduce nuclear recoil background



0.2% Gd-loaded water neutron-veto

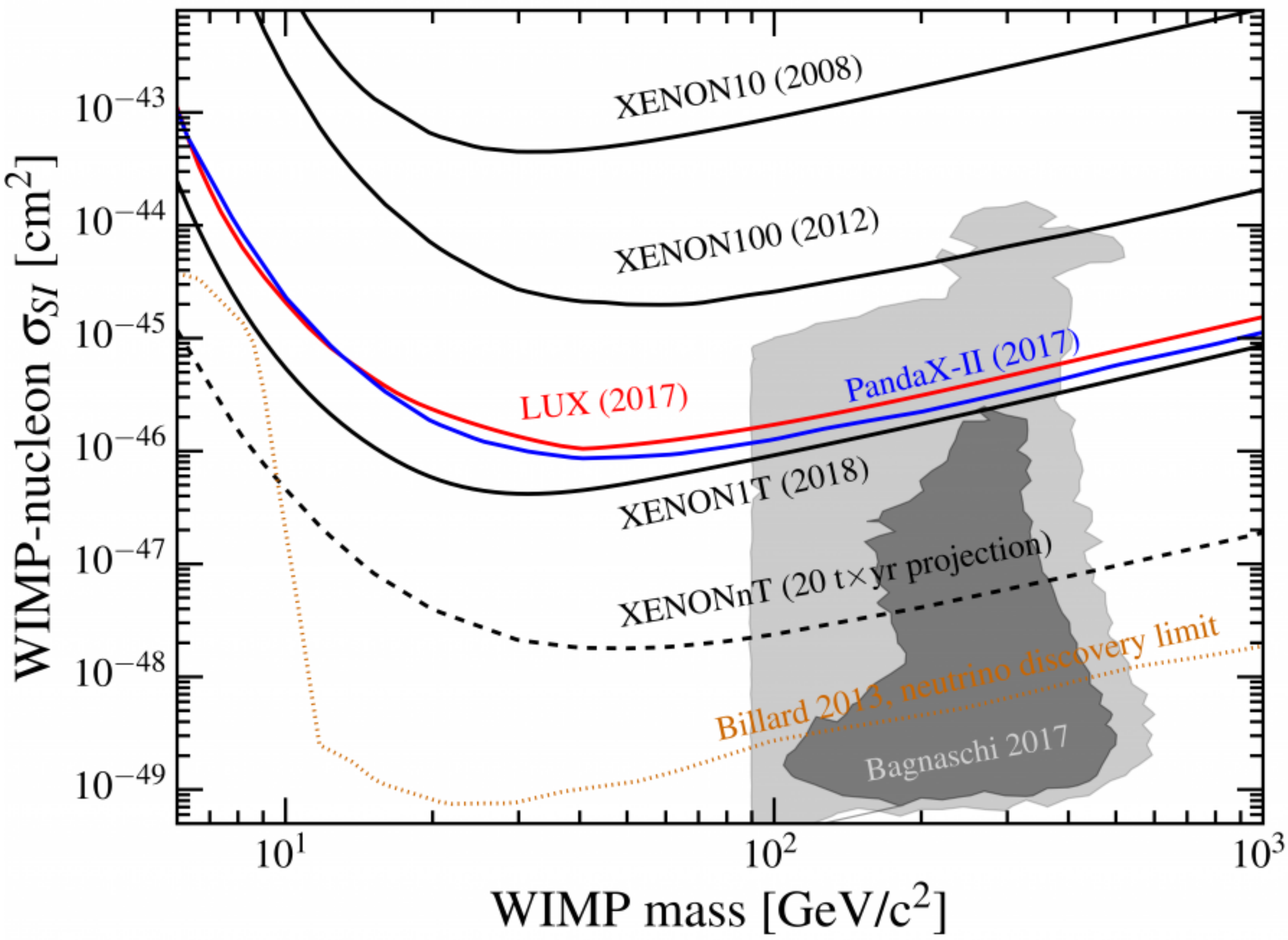
Neutron-veto efficiency



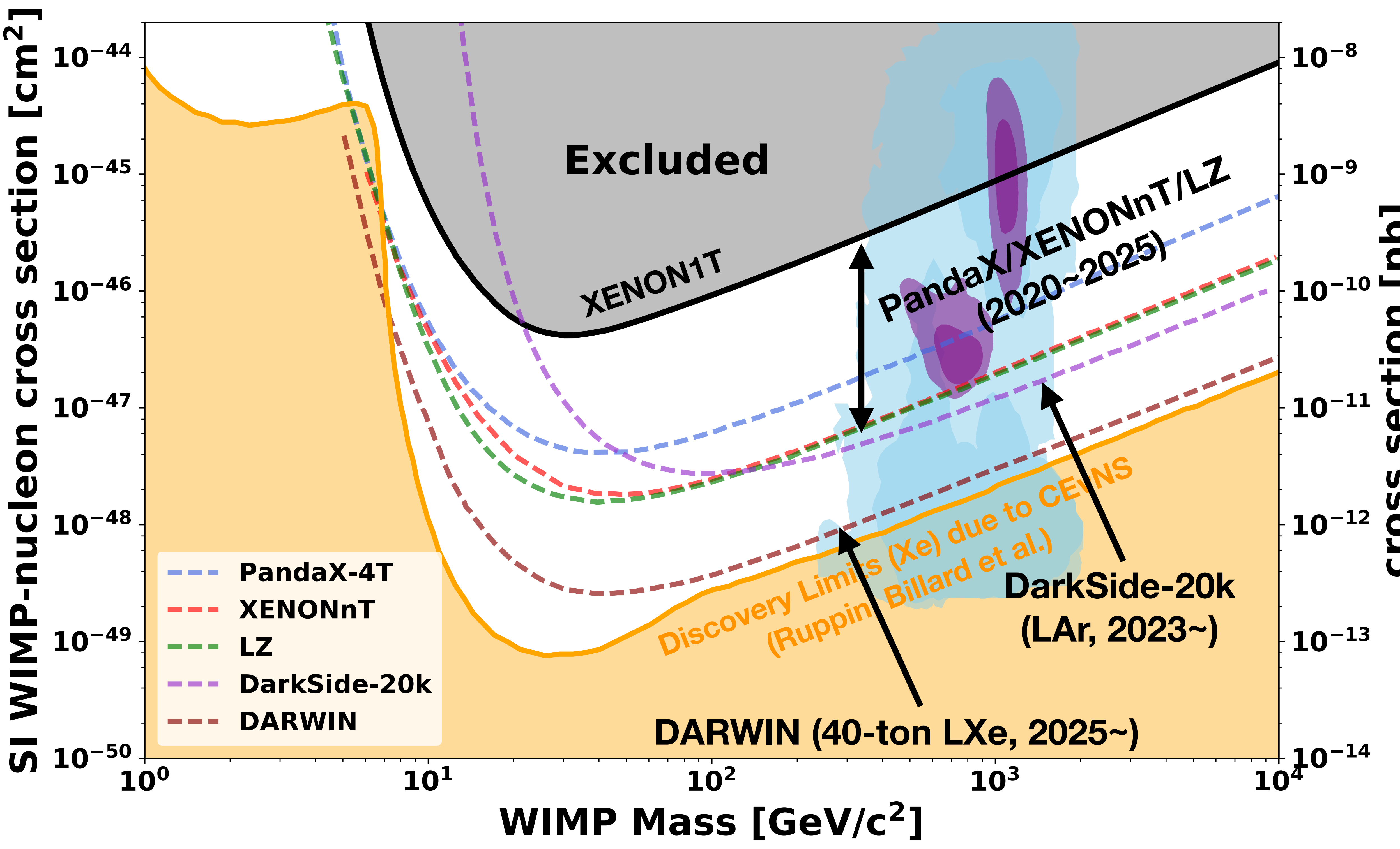


Upgrade in the making

Great discovery potential

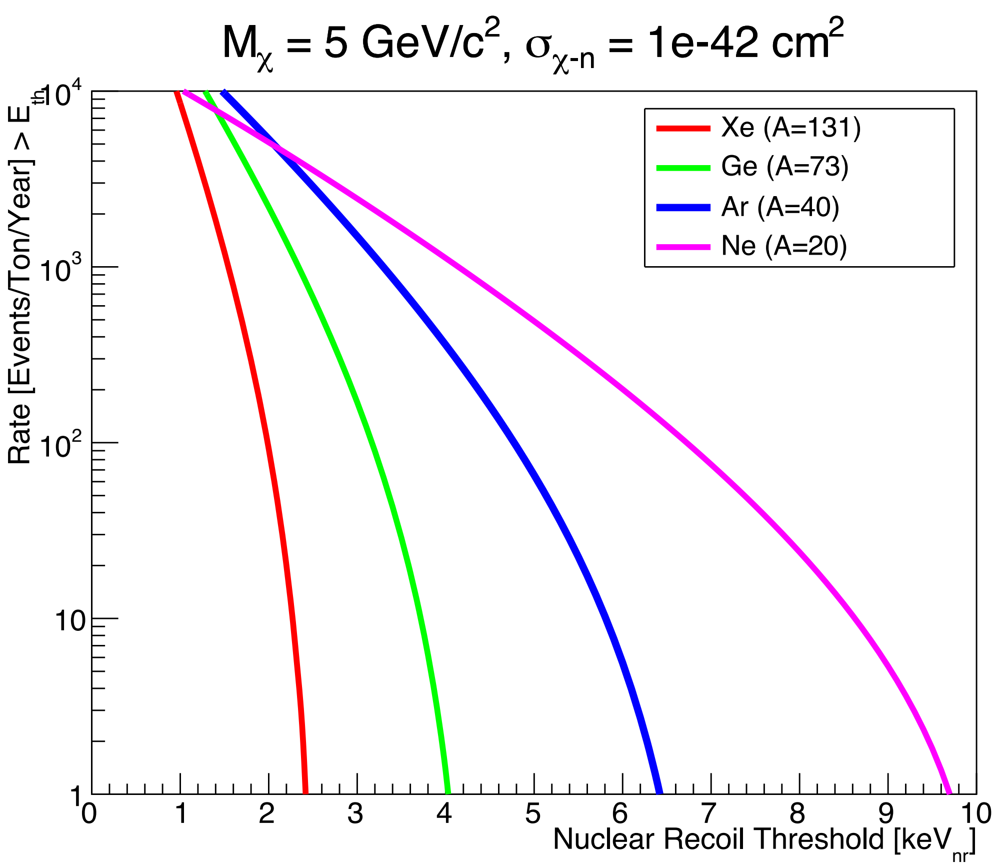


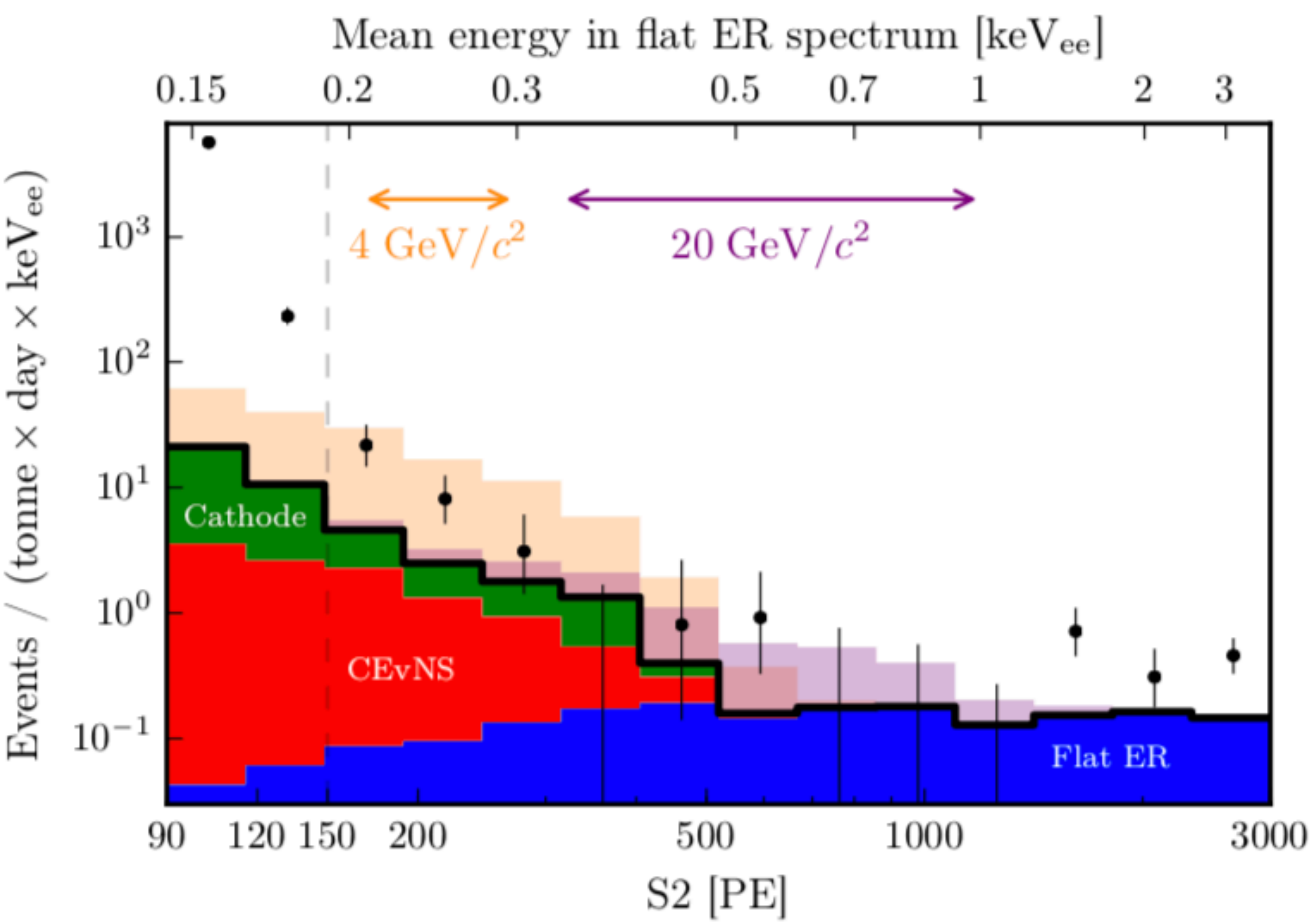
Prospect of the global heavy dark matter search



XENON1T's S2-only results for Low-Mass Dark Matter Nuclear Recoil Scattering

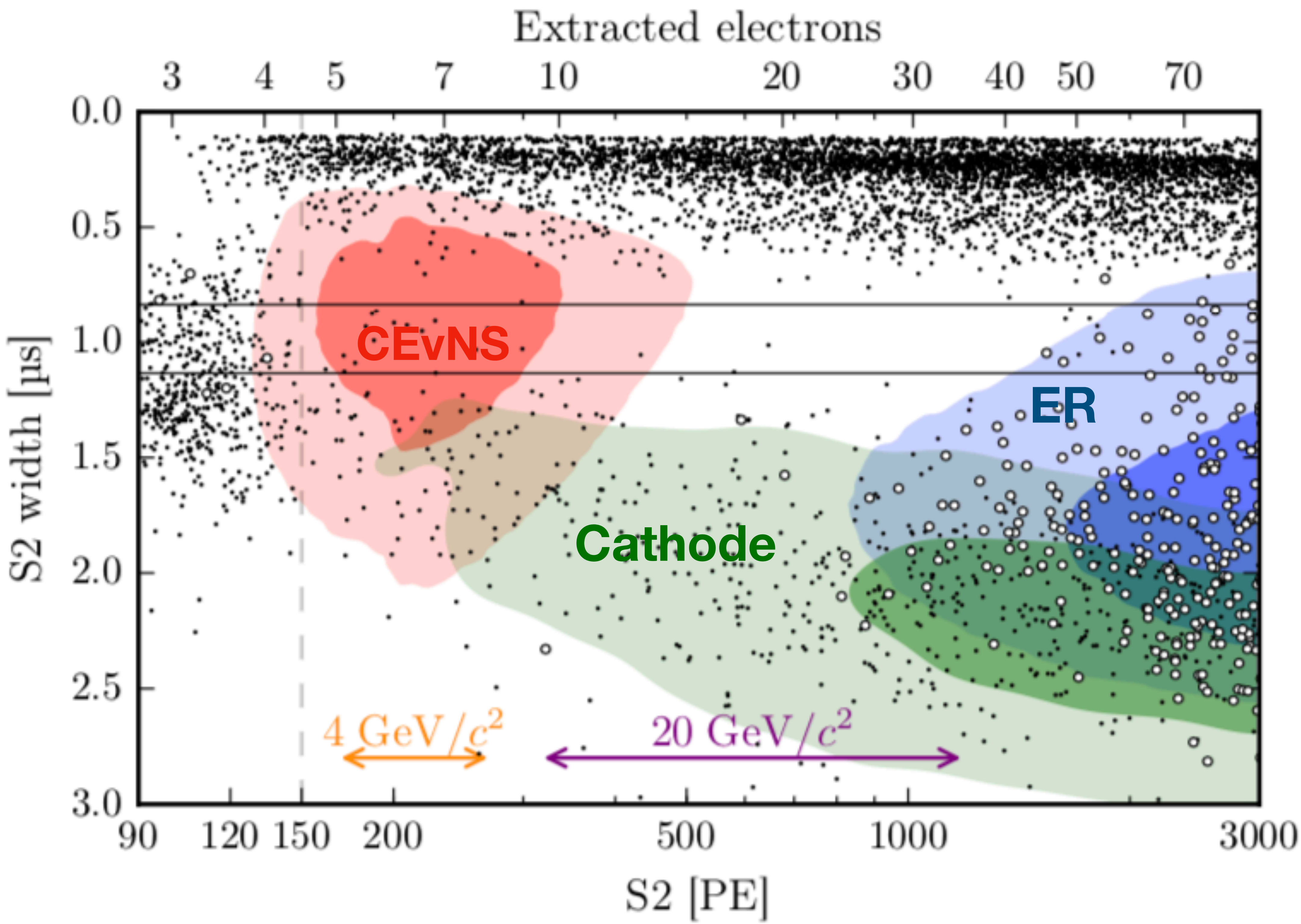
arXiv:1907.11485



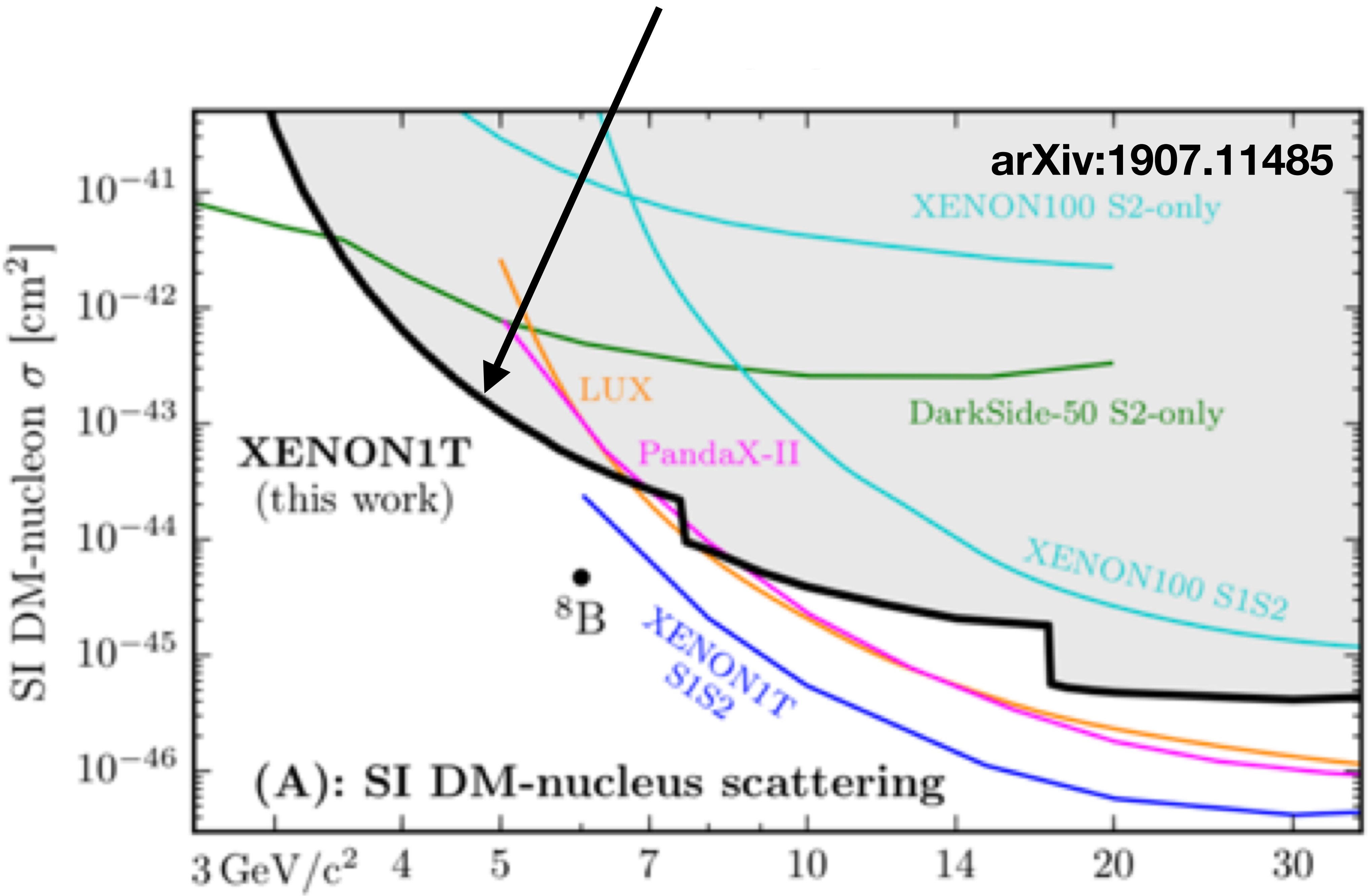


- **Threshold: ~200 eVee (4~5 e-)**
- **Exposure: 22 tonne-days (60 kg-year)**
- **Background: ~1 event/keVee/tonne/day (>400 eVee)**

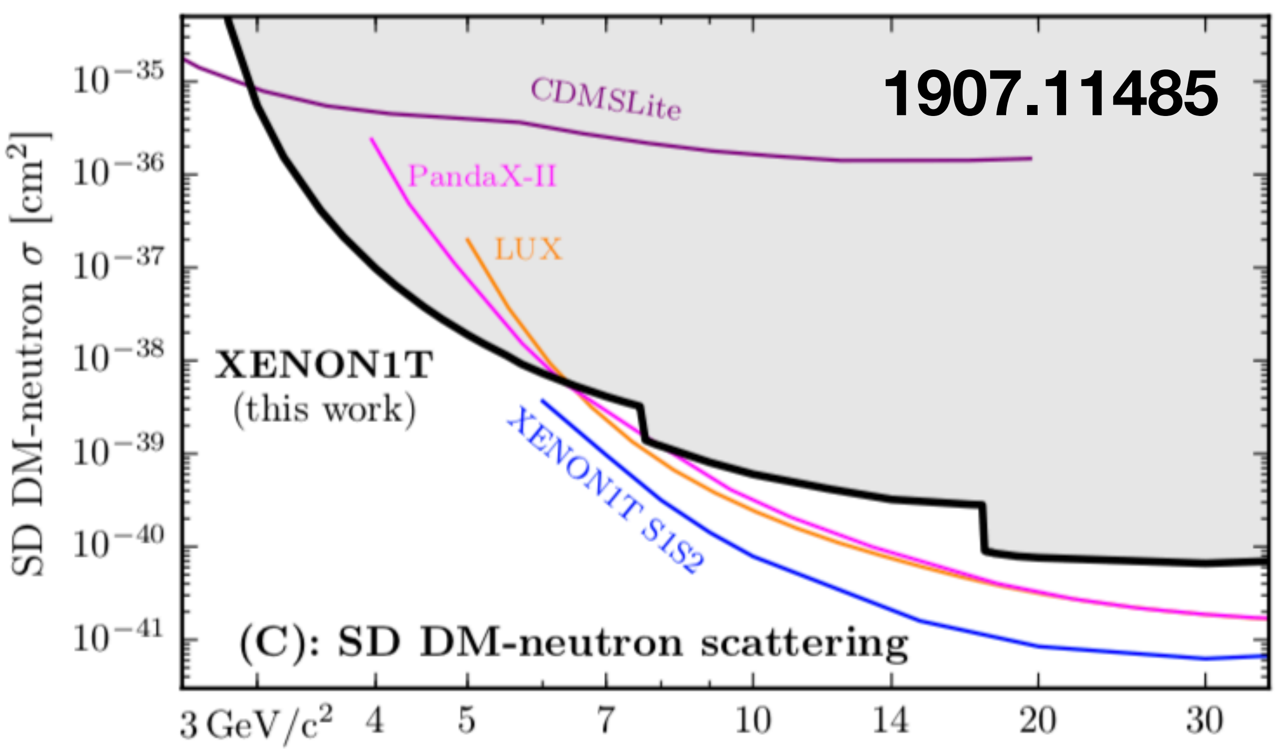
Background for S2-only Events



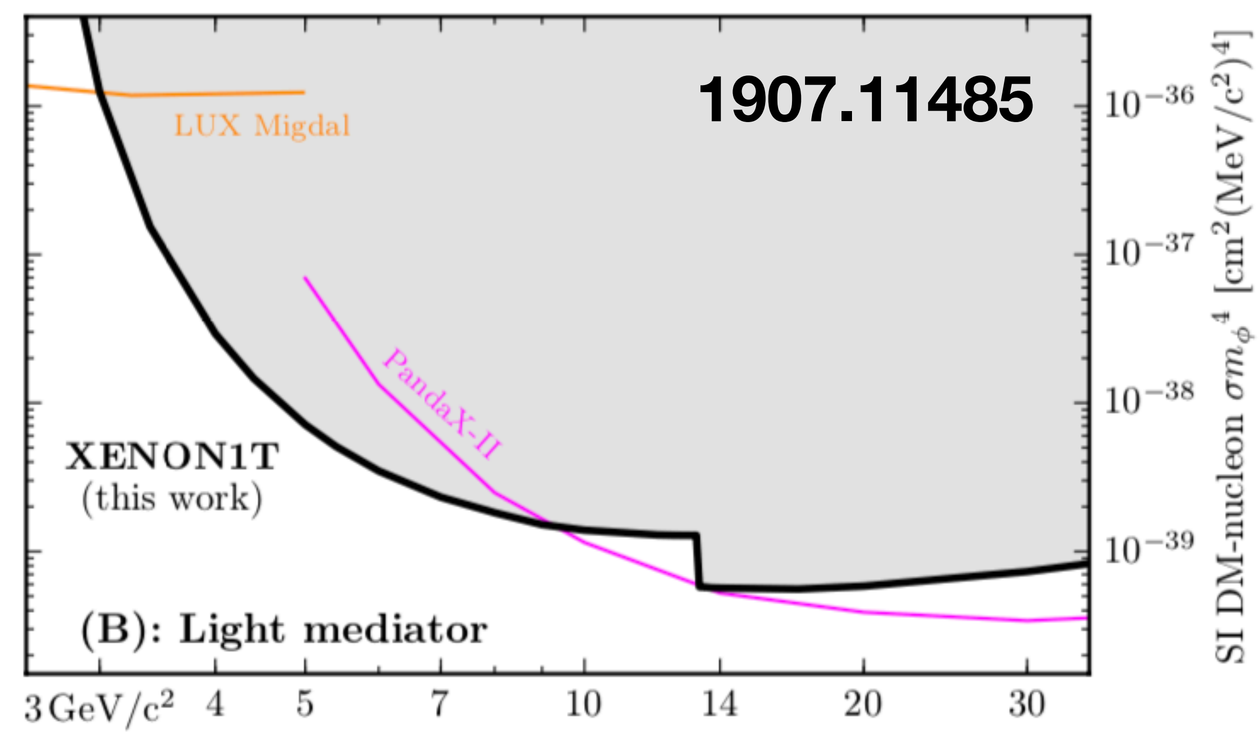
The lowered S2 threshold further constrained WIMP mass below 6 GeV



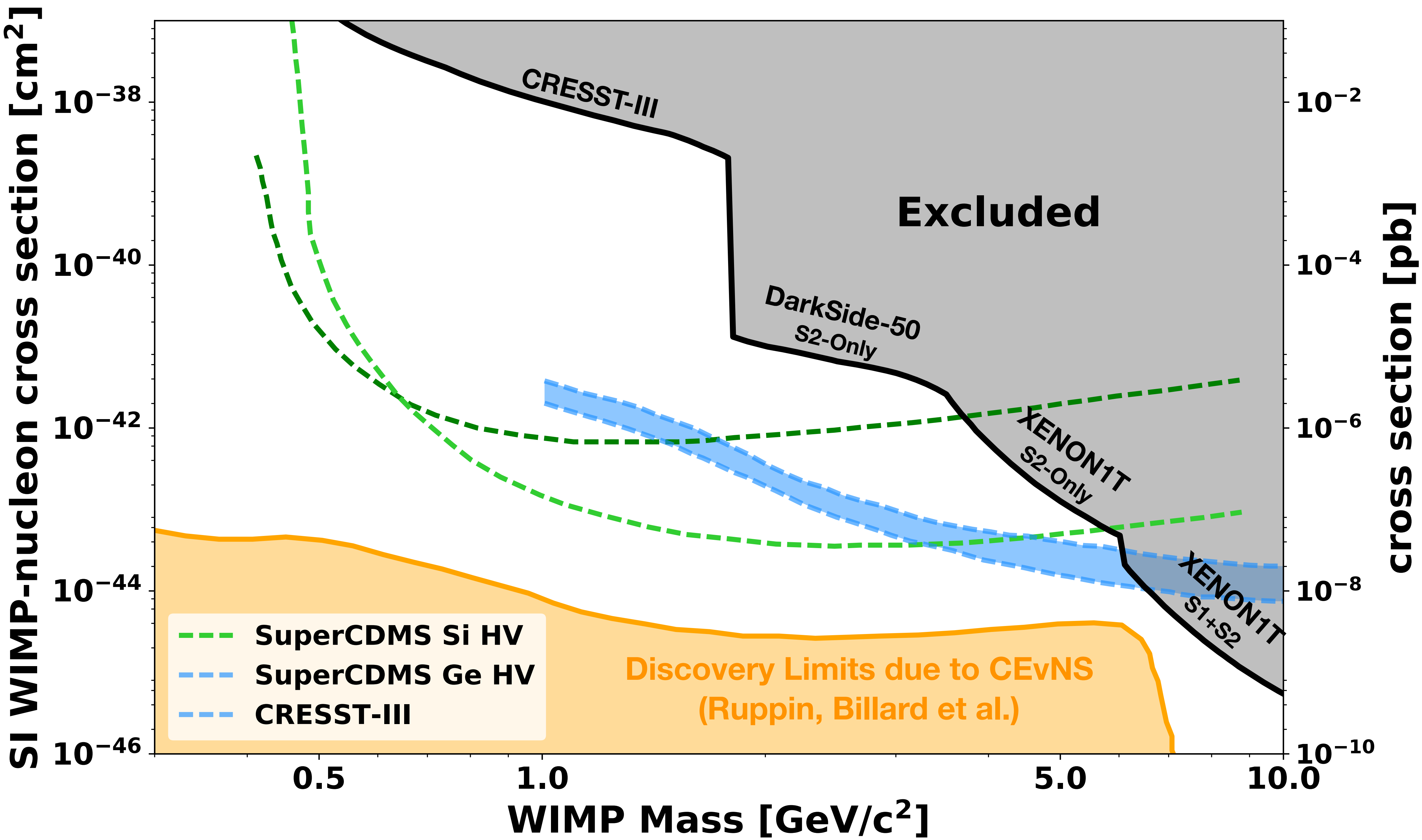
SD-neutron scattering



SI with light mediator



Status of the Low-mass (GeV-scale) Dark Matter Searches



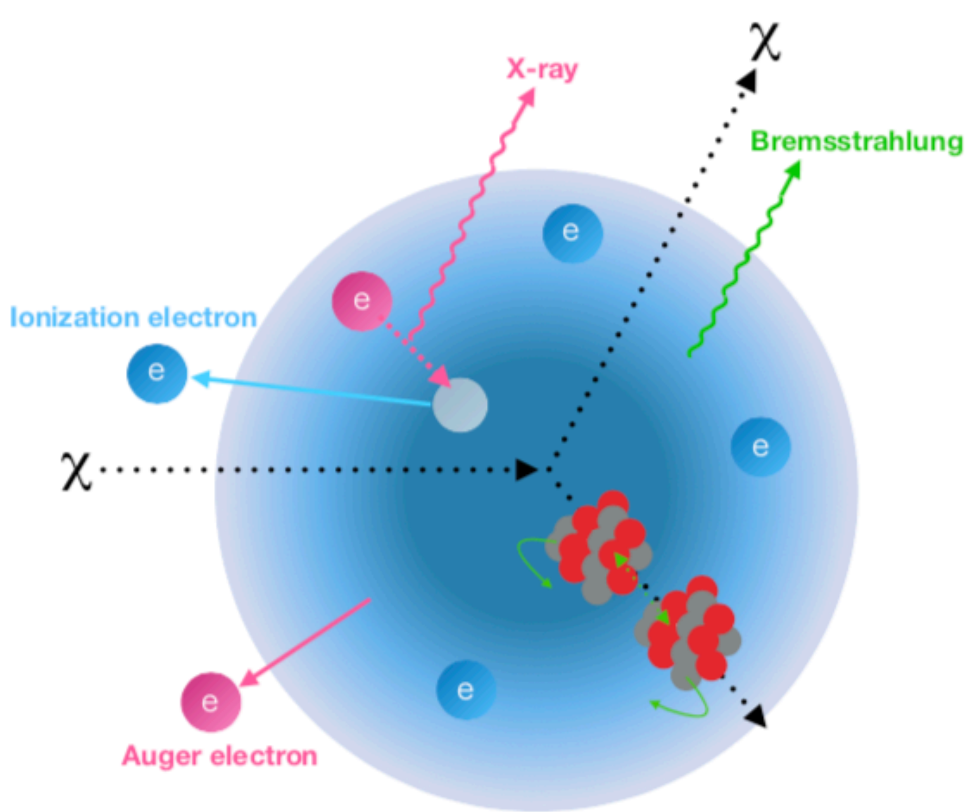
For future:

Need improvement to suppress the background.

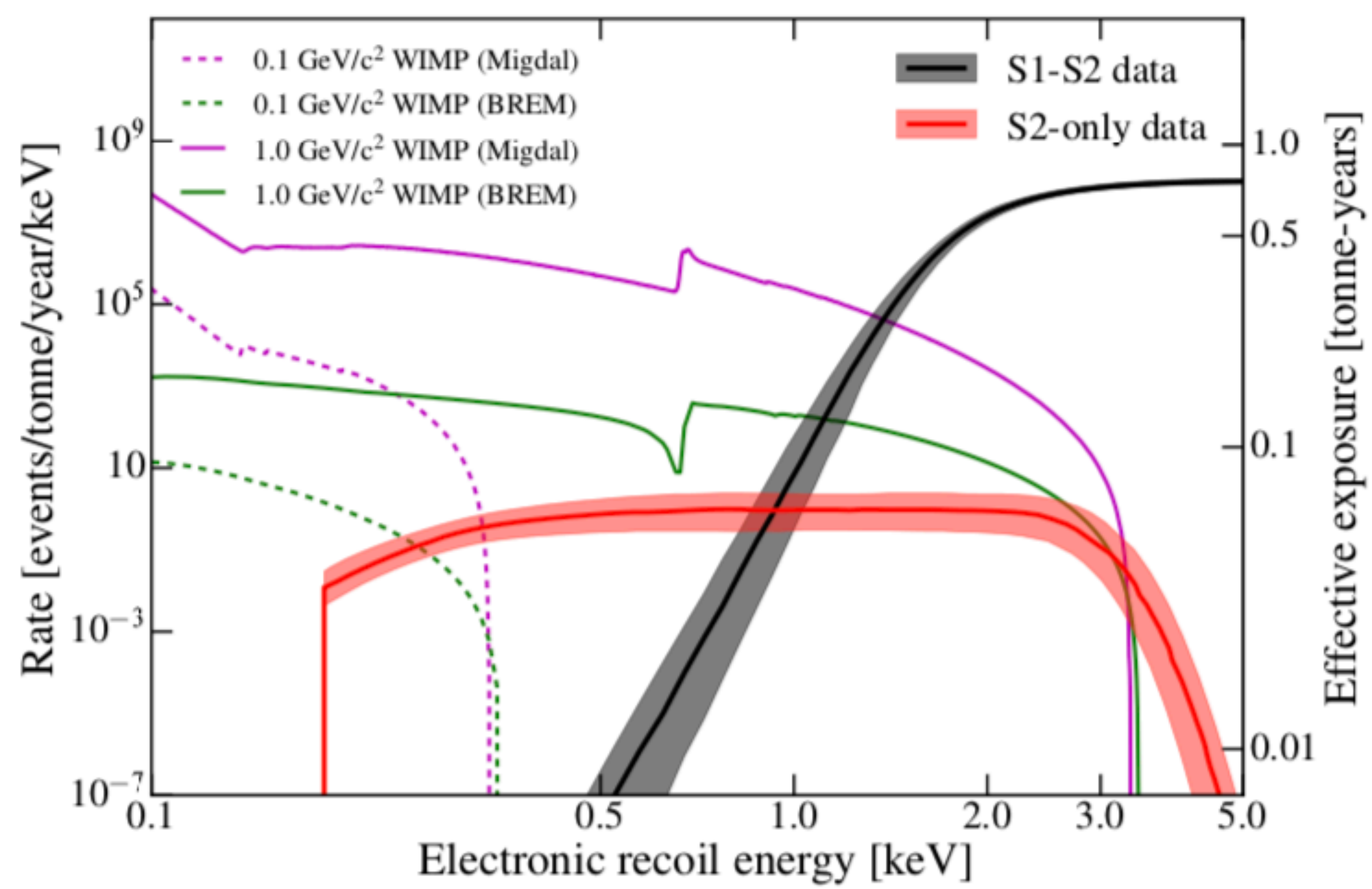
Need a reasonable large target mass (~100 kg).

Light DM Search with the Migdal effect

- **Migdal effect in dark matter detection**
  - Masahiro Ibe et al, arXiv:1707.07258, Dolan et al., 1711.09906
  - **atomic electrons** lags behind **recoil nucleus** resulting in ionization/excitation of atoms



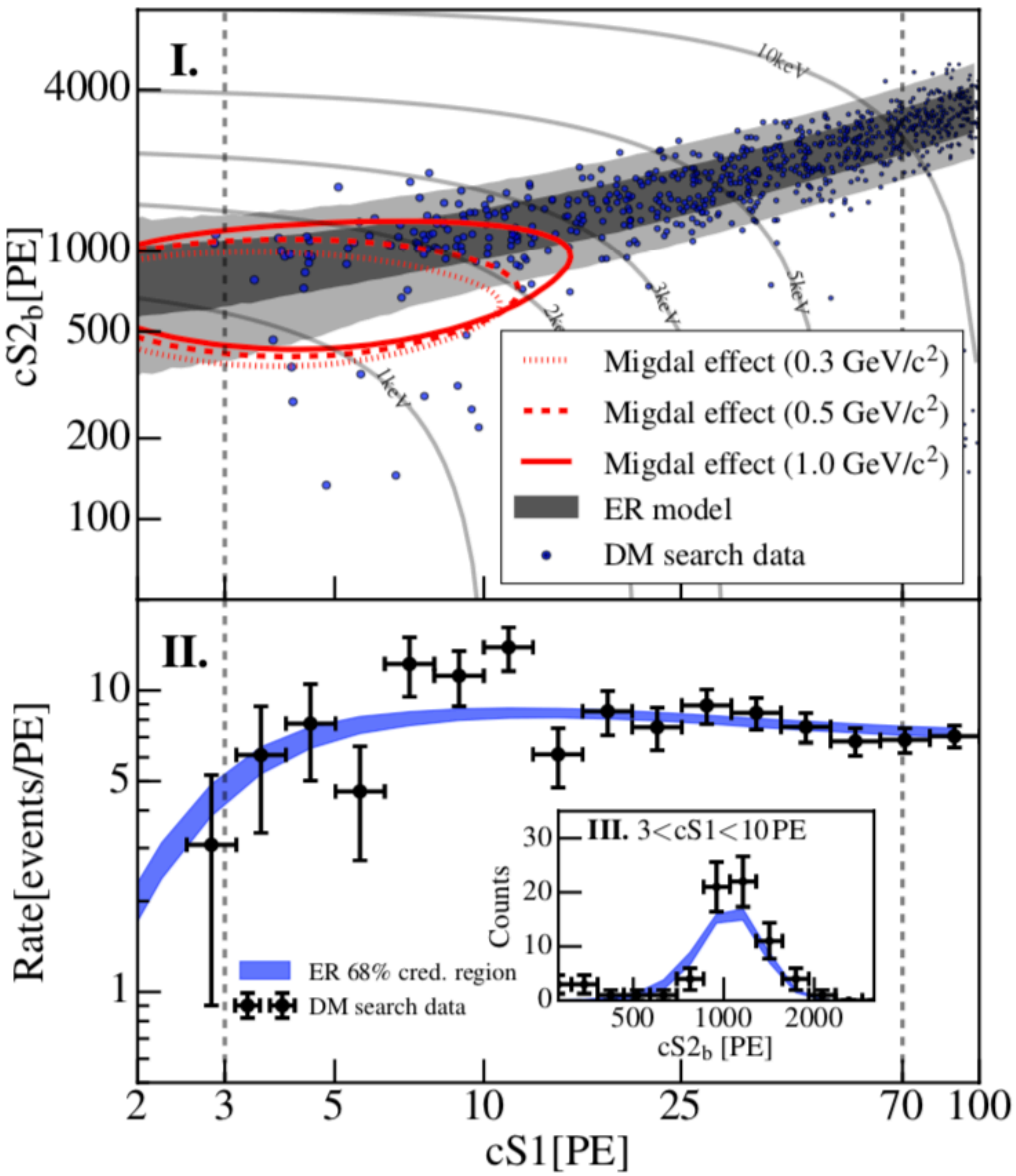
XENON1T, arXiv:1907.12771

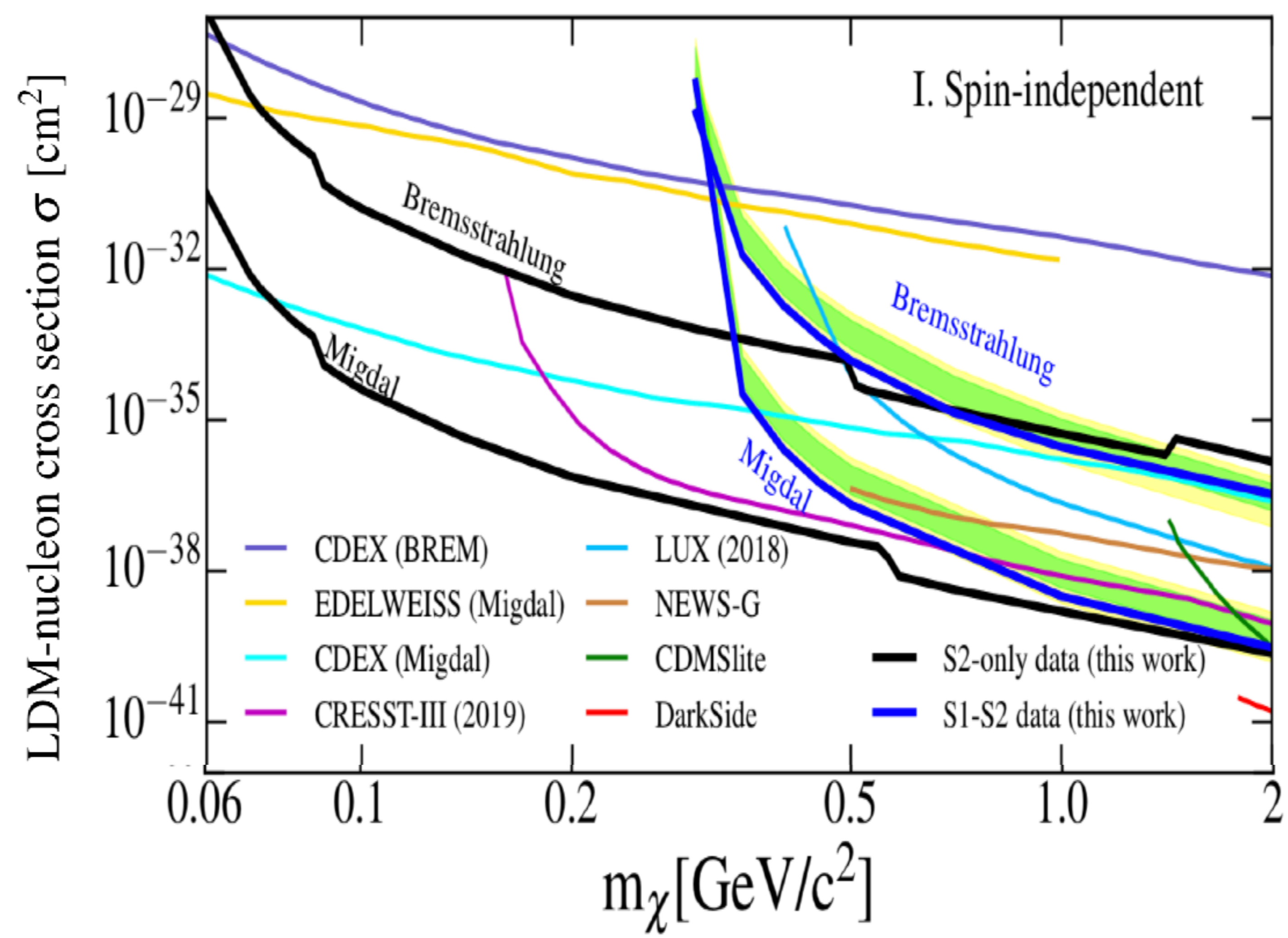


Expected rate for SI cross section of 10^{-35} cm^2

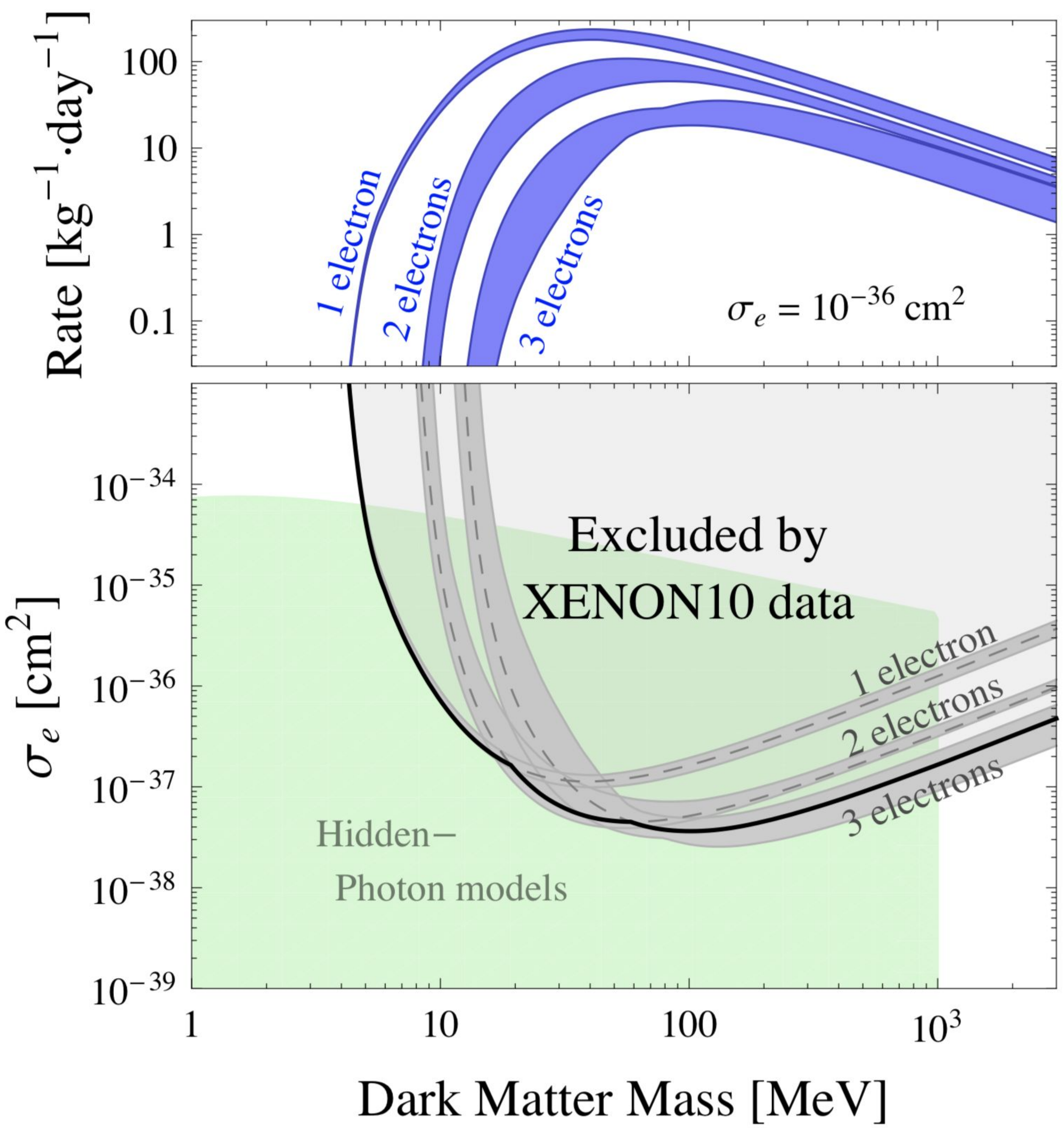
Looking for "Migdal" electron recoil signals from sub-GeV DM produced nuclear recoils

XENON1T, arXiv:1907.12771

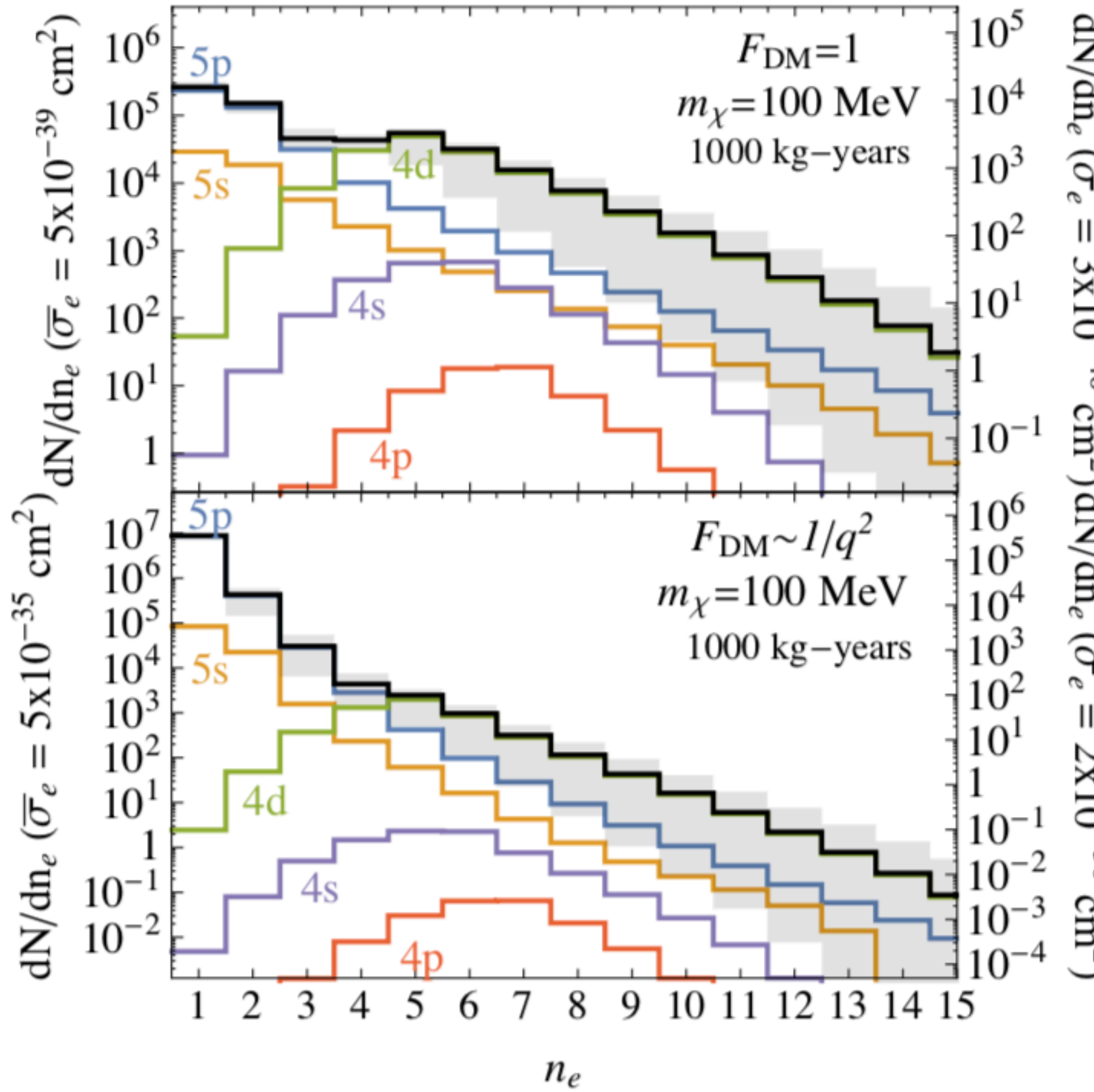




Searching for light dark matter interaction with electrons



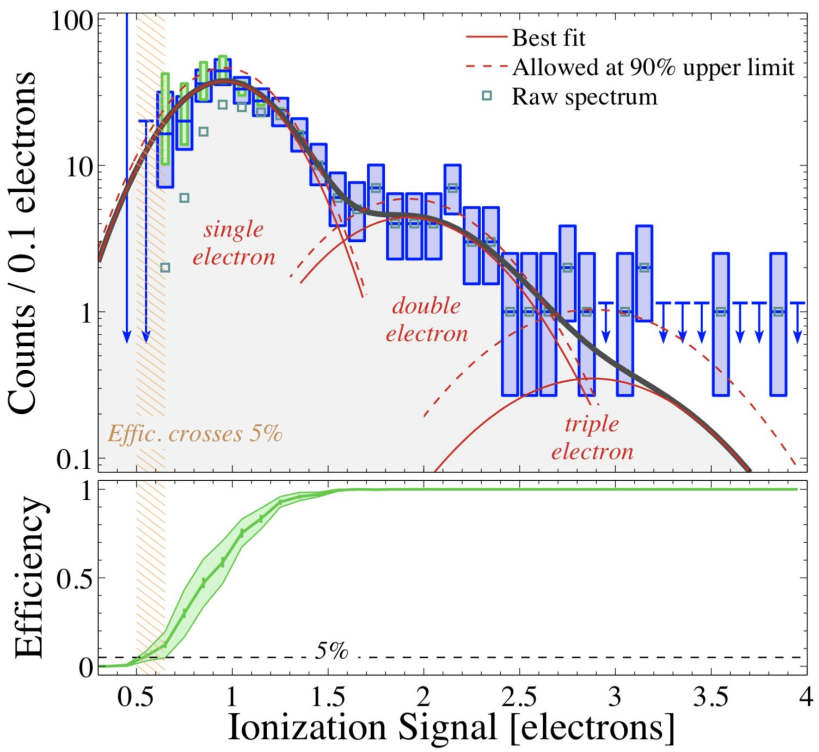
Essig et al., arXiv:1206.2644



Essig et al., 1703.00910

Single and a few electron rate in the LXe bulk

XENON10, arXiv:1206.2644

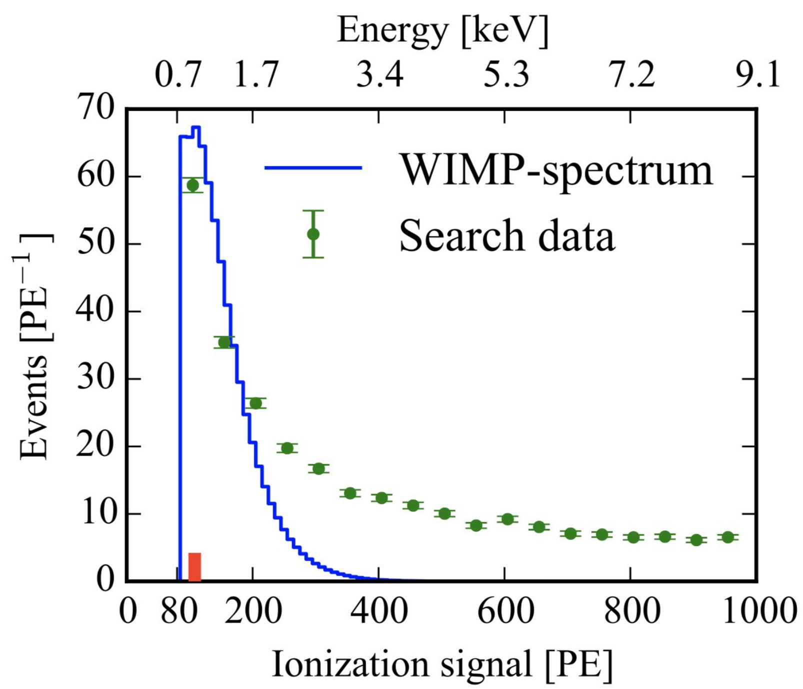


15 kg-day

Rate: 0.1~10/kg/day at 2~3 e-

10~100/kg/day at single e-

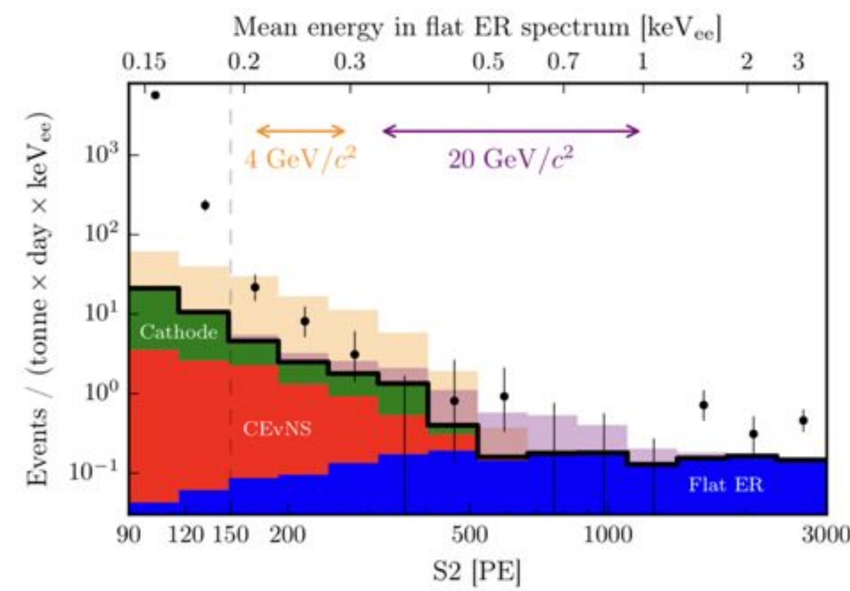
XENON100, arXiv:1605.06262



11,000 kg-day

Rate: 0.1/kg/day at ~4 e-

XENON1T, arXiv:1907.11485



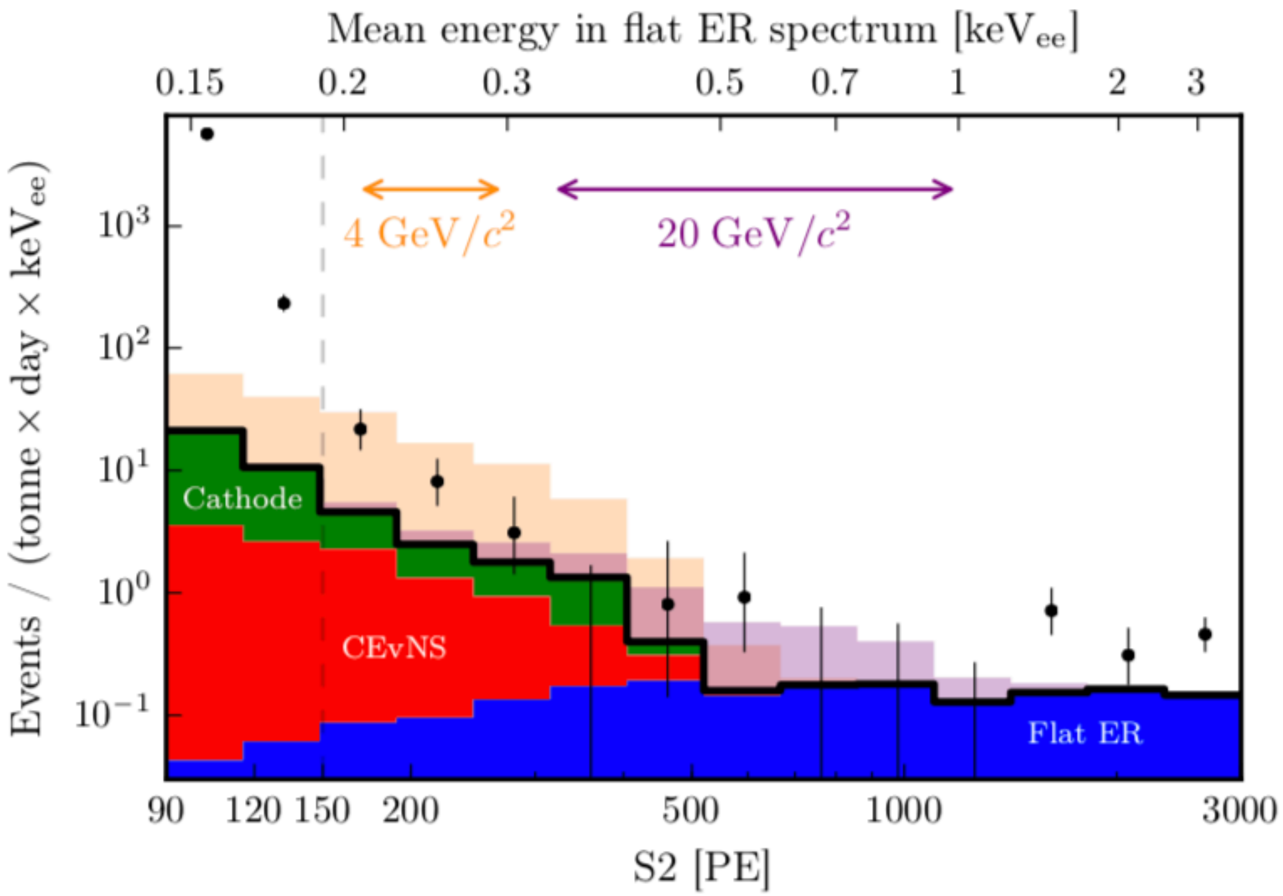
22,000 kg-day

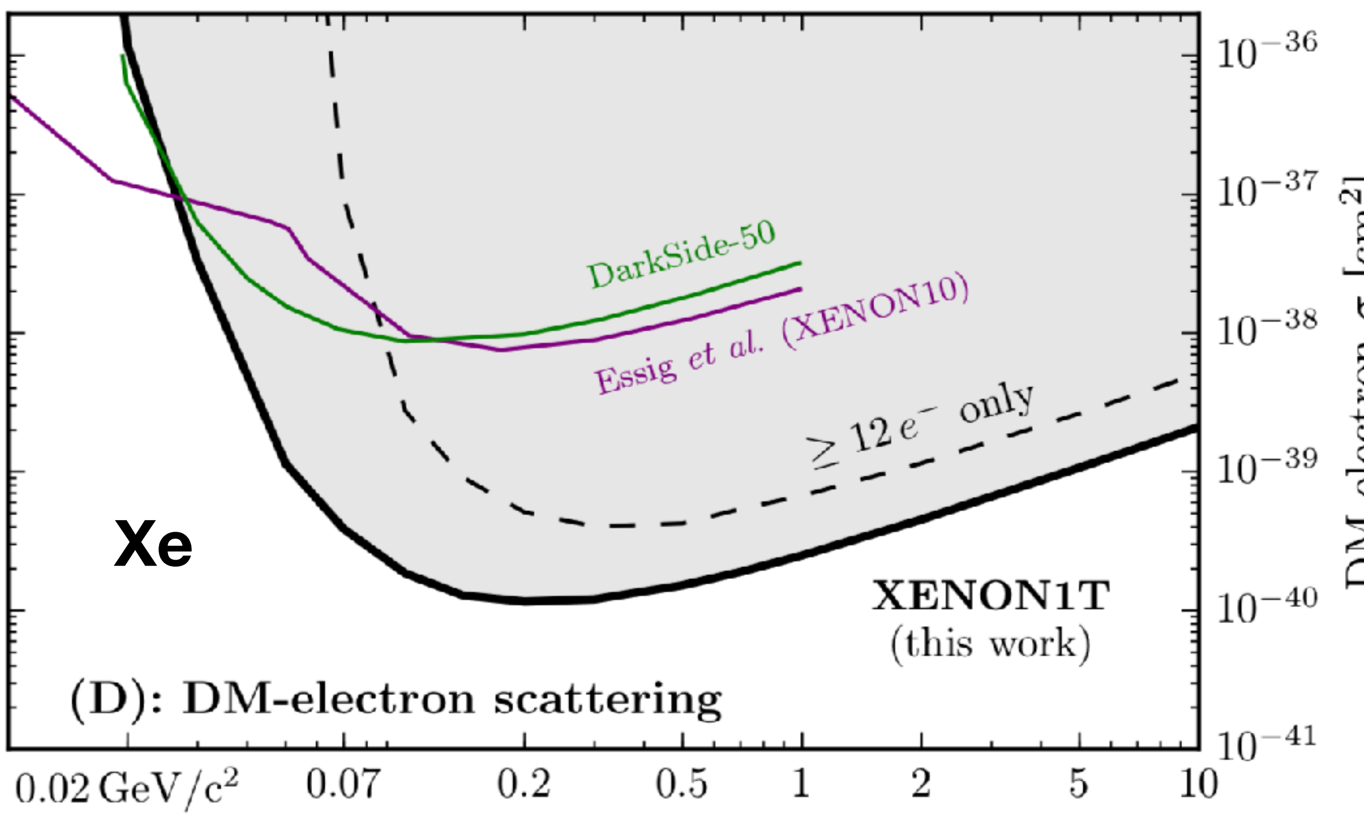
0.01~1/kg/day at 3~4 e-

- **Background at a few electron level is not always going down with increasing target mass.**
- **We now understood much better the sources of these background electrons.**

XENON1T S2-only search for dark matter electron scattering

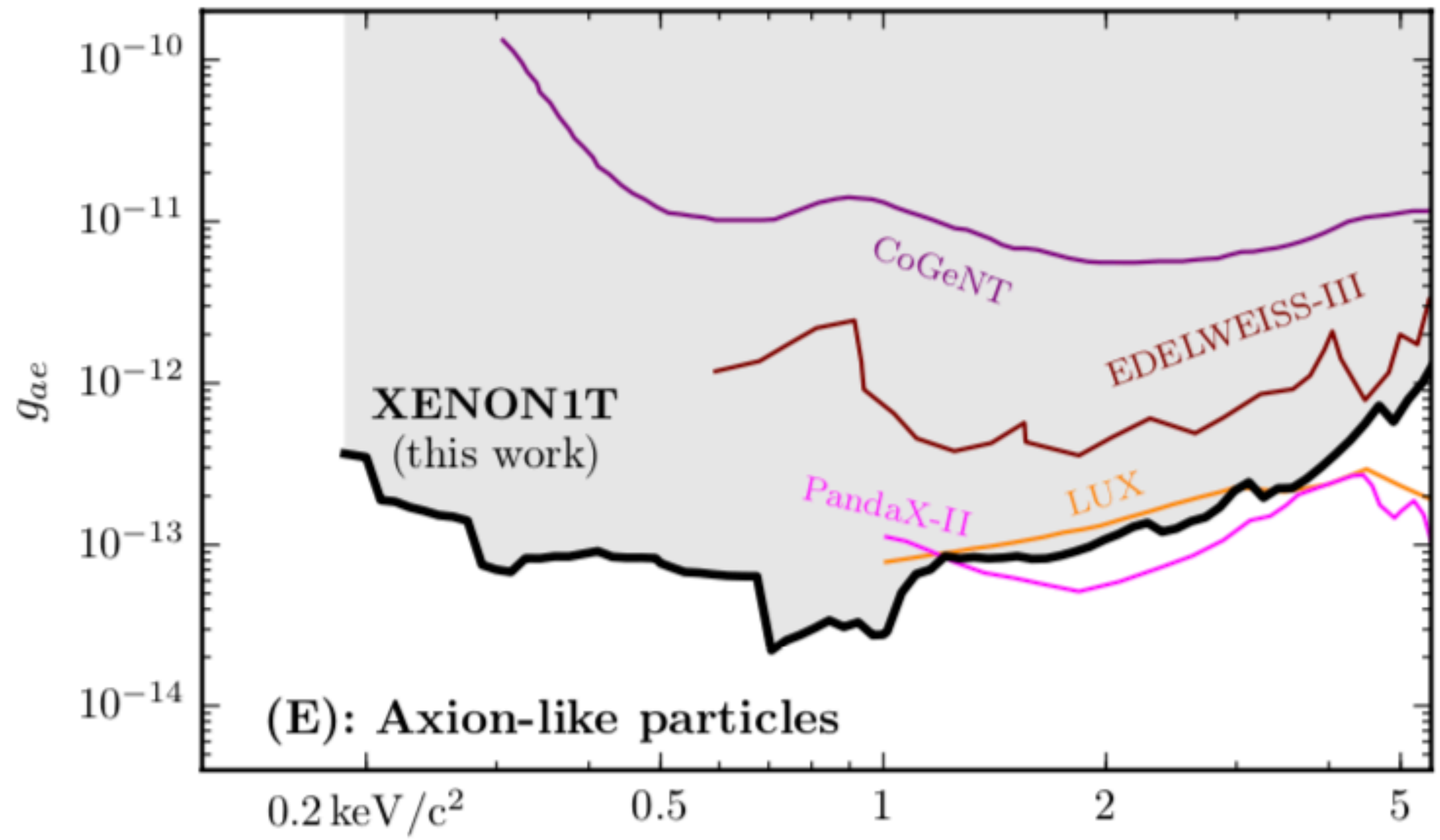
arXiv:1907.11485



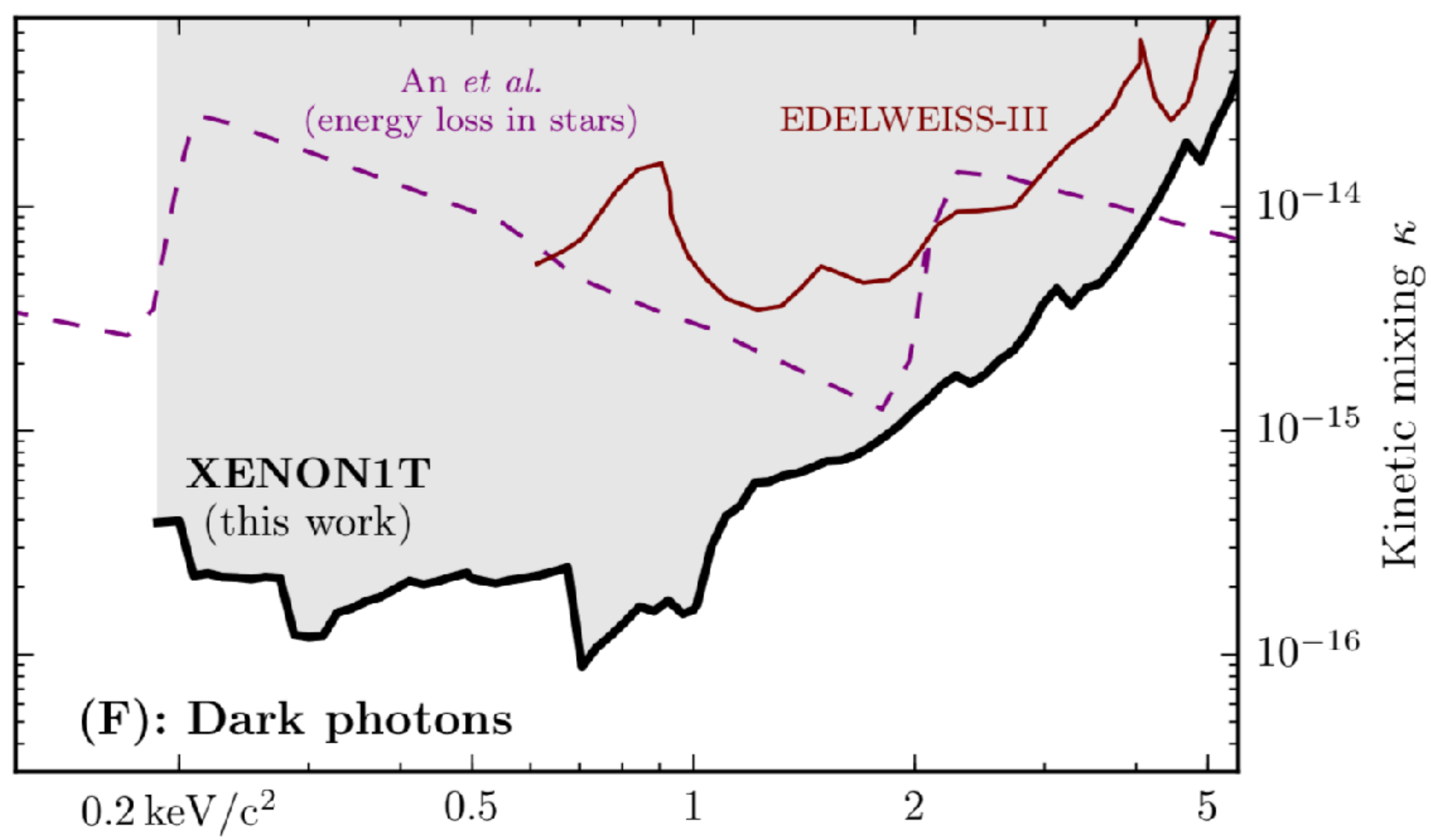


The search is limited by background (not target mass or threshold).
For future: background understanding and suppression needed

Dark photon dark matter absorption & Axion-like particles



XENON1T S2-only
arXiv:1907.11485



Summary

- **XENON1T achieved the lowest background among any DM search experiments with more than one-tonne of target**
- **XENON1T has set the most constraining limits across a large mass range for heavy DM, low-mass DM, light DM, dark photon and axion-like particles.**
- **With the upcoming XENONnT, together with PandaX-4T, LZ and DarkSide-20k, the next few years of dark matter hunting will be VERY exciting!**