Dark Matter Searches with Ionization Signals in XENON1T

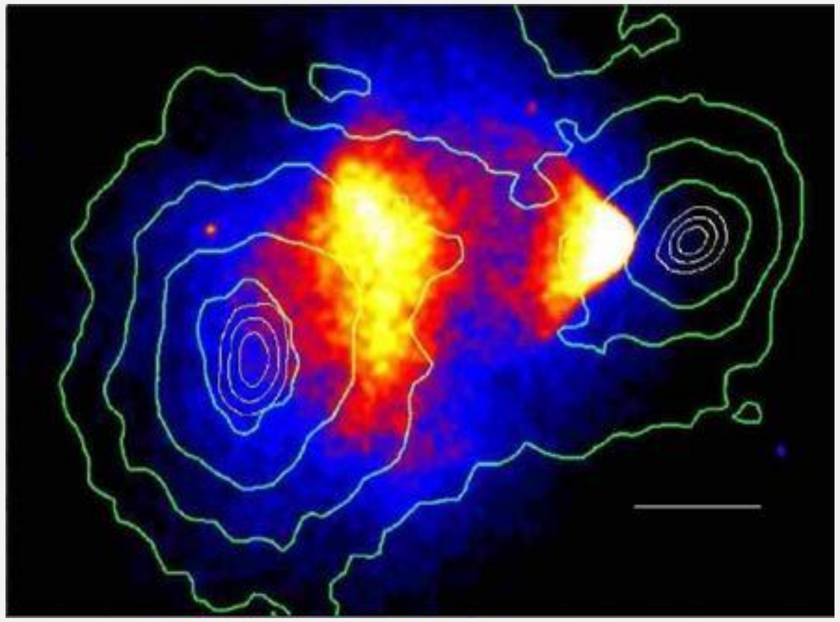
Jacques Pienaar
University of Chicago
Kavli Institute of Cosmological Physics

LPNHE
January 14, 2020

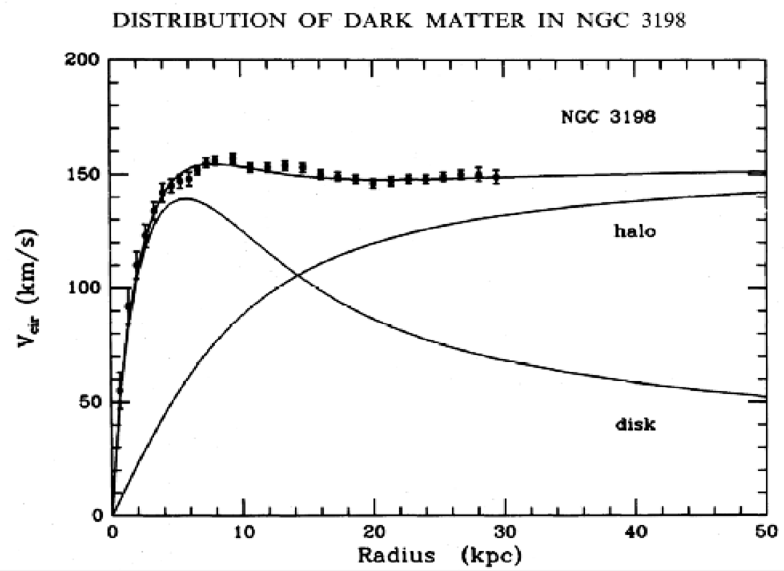
Dark Matter

Evidence at Various Length/Time Scales

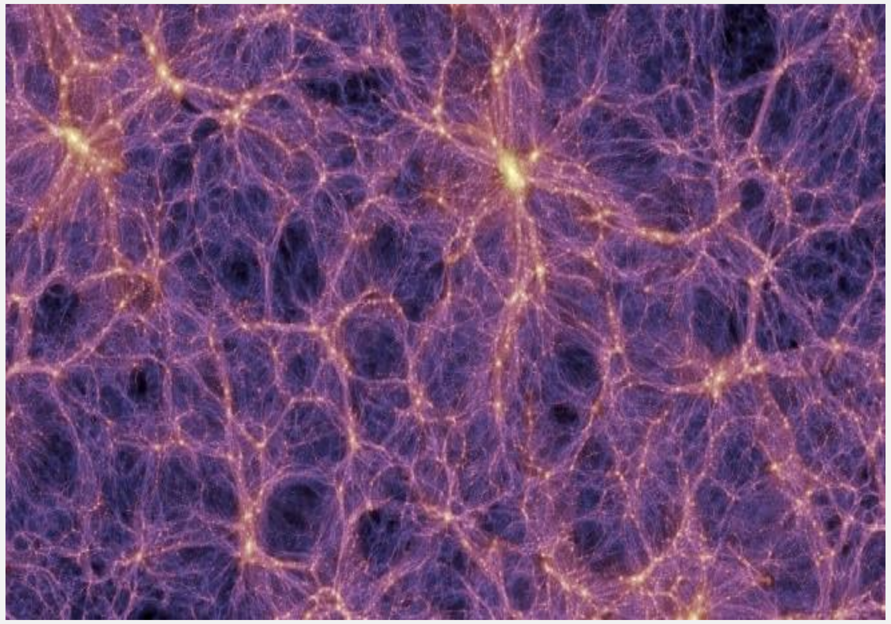
GALAXY CLUSTERS



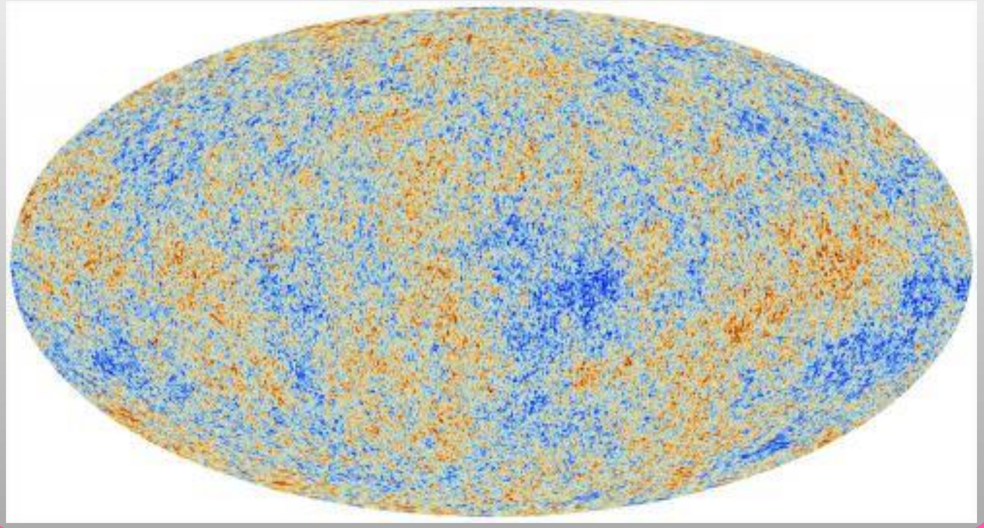
ROTATION CURVES



LARGE SCALE STRUCTURE



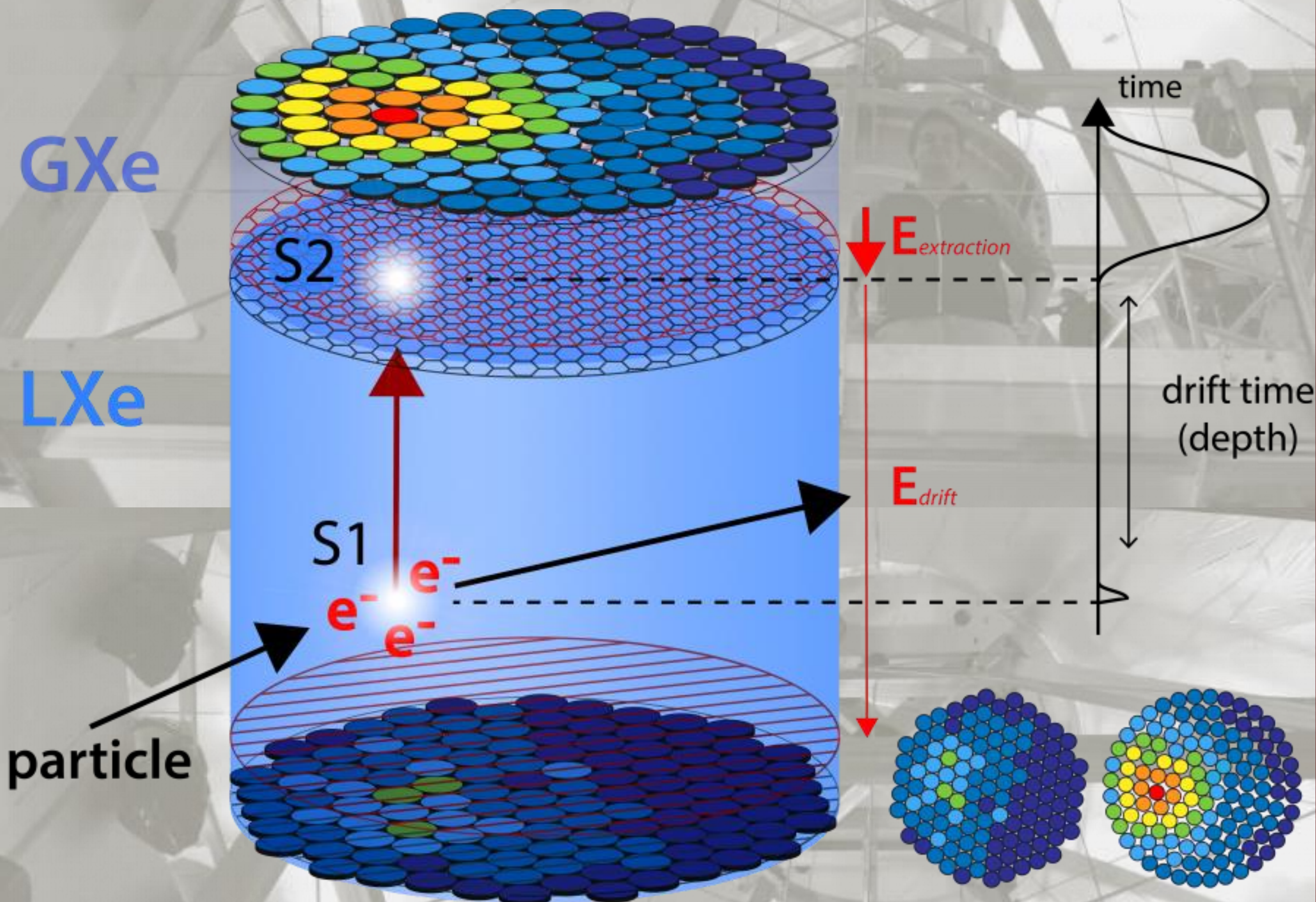
COSMIC MICROWAVE BACKGROUND



arXiv:1502.0158

RESULTS FROM PLANCK 2015	
Ω_Λ	0.691 ± 0.006
Ω_{CDM}	0.256 ± 0.006
$\Omega_{baryons}$	0.0482 ± 0.0005

Jacques Pienaar, jpienaar@uchicago.edu



Dual Phase Time Projection Chambers

Full 3D reconstruction of interaction

Discrimination between ER/NR events

Sub-keV energy threshold

Scalable to multi-tonne low background detectors

Ideal for WIMP (and rare process) Searches

Dual Phase Time Projection Chambers

Fiducialization and Surface Bkg Suppression

Suppression of γ/β backgrounds

Low energy threshold $\longrightarrow$ Sensitivity $\uparrow$

Larger Exposures $\longrightarrow$ Sensitivity $\uparrow$

Full 3D reconstruction of interaction

Discrimination between ER/NR events

Sub-keV energy threshold

Scalable to multi-tonne low background detectors

XENON1T Instrument Paper
Eur. Phys. J. C (2017) ***77:*** *881*

Jacques Pienaar, jpienaar@uchicago.edu

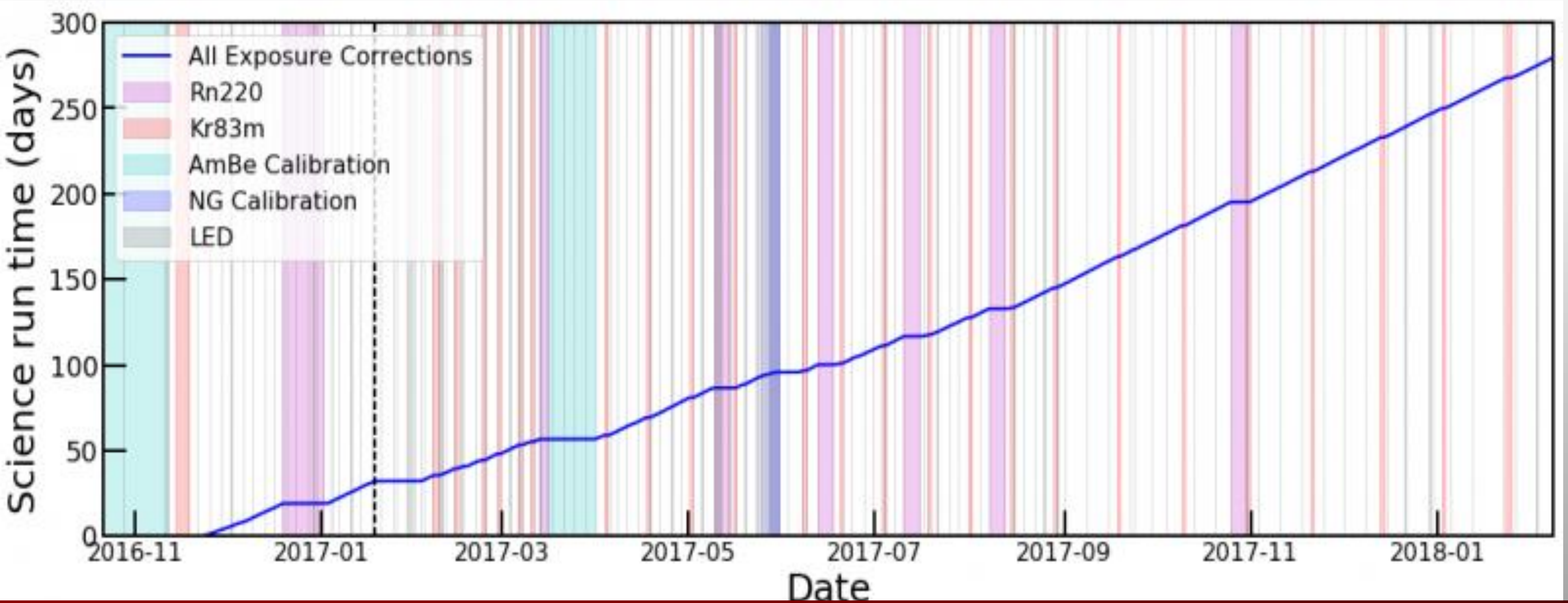
XENON1T Data Runs

Position Dependent Signal Corrections - Energy

Dark Matter Data collected:

- **Science Run 0: 32.1 Days (Up to Jan 2017 Earthquake)**
- **Science Run 1: 278.9 Days**

Additional post SR1 data taken to explore new calibration sources (^{37}Ar), upgraded purification systems, and dedicated data sets for double electron capture search in ^{124}Xe



Jacques Pienaar, jpienaar@uchicago.edu

THE UNIVERSITY OF CHICAGO

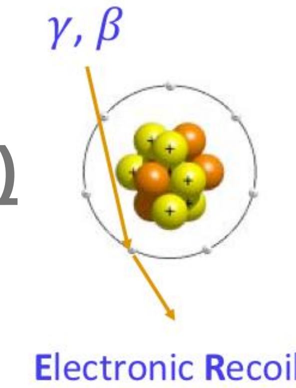
Backgrounds

	Surface	Homogeneous
NR	Neutrons	CEvNS
Other	Surface (^{210}Pb)	Accidental Coincidence
ER	Materials (γ, β)	^{85}Kr, ^{222}Rn

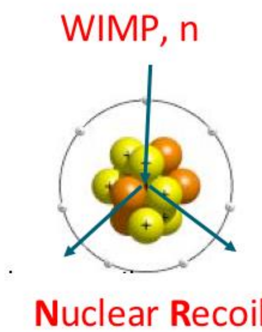
Reduce by fiducializition

Reduce through S2/S1 discrimination

Electronic Recoil (ER)
γ,β Backgrounds

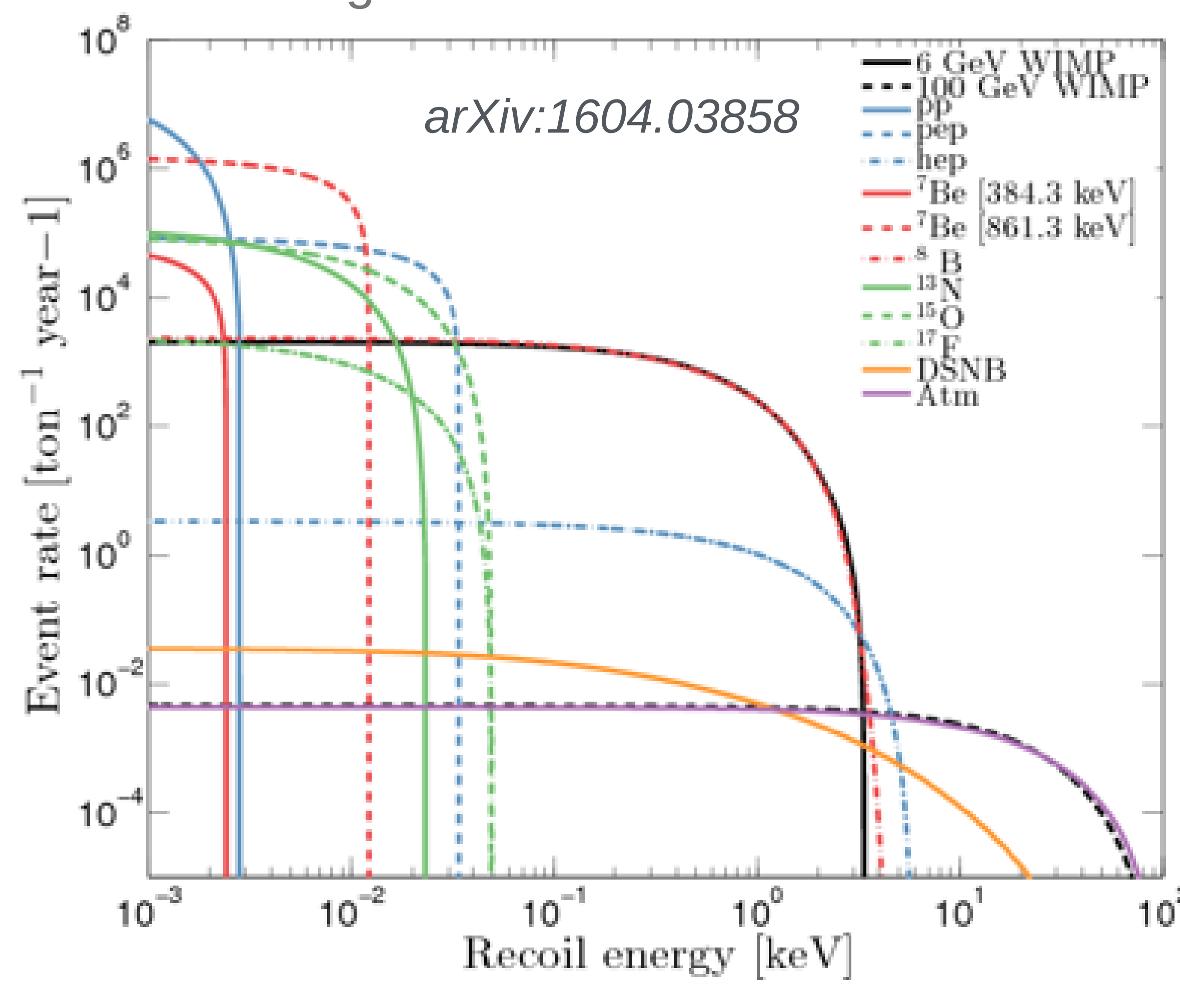


Nuclear Recoil (NR)
WIMP signal, neutrons, CEvNS



!! WIMP-Like Background !!

^{8}B Solar neutrino signal looks like a 6 GeV WIMP



Backgrounds

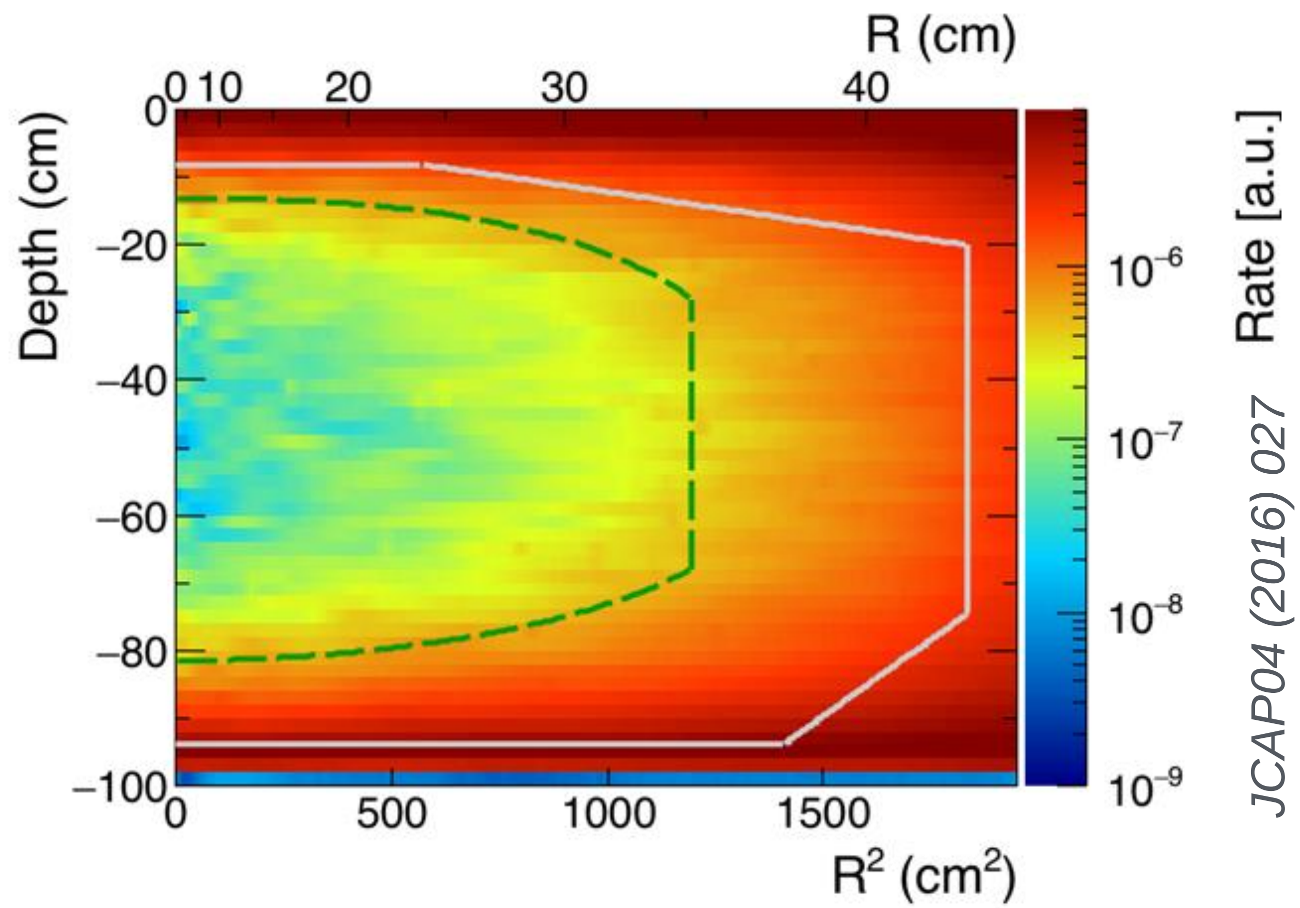
	Surface	Homogeneous
NR	***Neutrons***	CEvNS
Other	Surface (^{210}Pb)	Accidental Coincidence
ER	Materials (γ, β)	^{85}Kr, ^{222}Rn

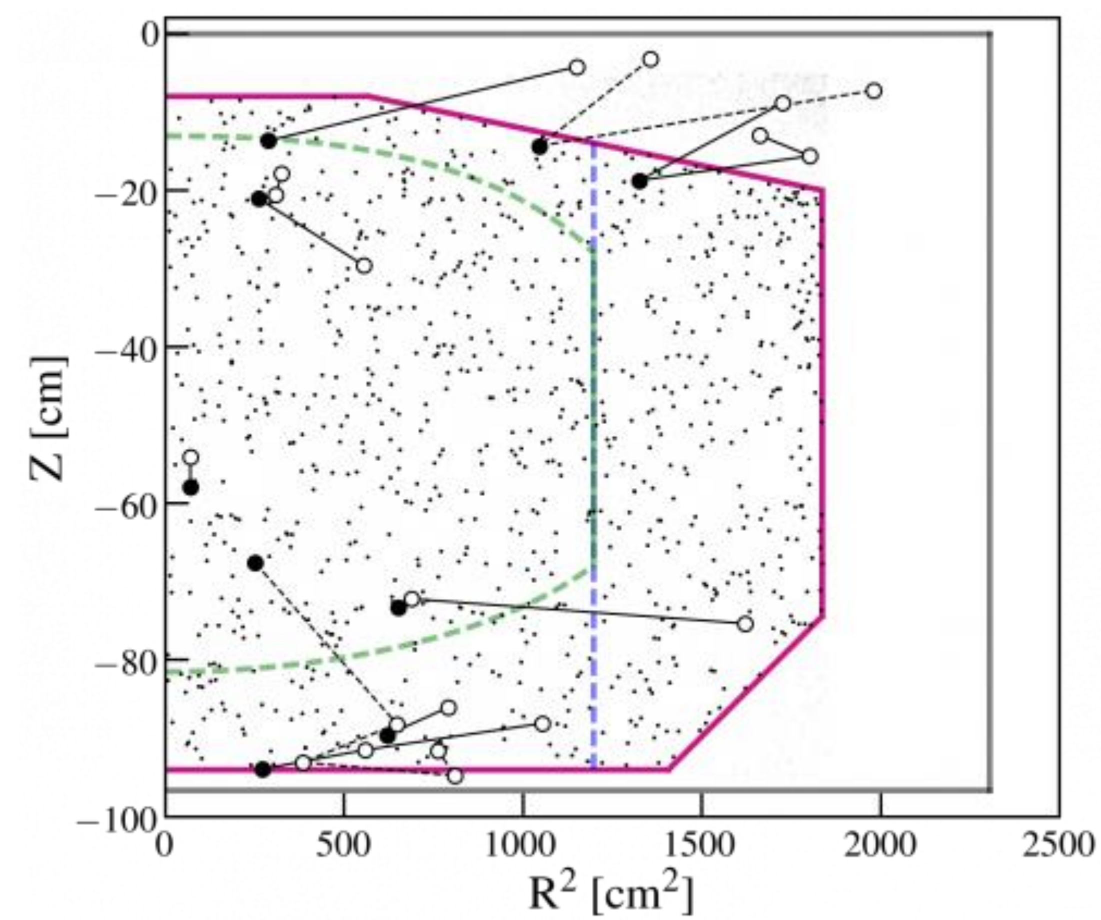
Induce NR

Origin
- **Materials**
- **Environment**
- **Cosmic rays**

Mitigation
- **Reject multiple scatter events**
- **Cosmogenic events tagged using muon veto**
- **Passive water shielding**
- **Fiducialization**
- **Use detected multiple scatter NR events and MC to constrain bkg.**

THE UNIVERSITY OF CHICAGO





Backgrounds

	Surface	Homogeneous
NR	Neutrons	CEvNS
Other	***Surface (^{210}Pb)***	Accidental Coincidence
ER	Materials (γ, β)	^{85}Kr, ^{222}Rn

Degraded Reconstruction

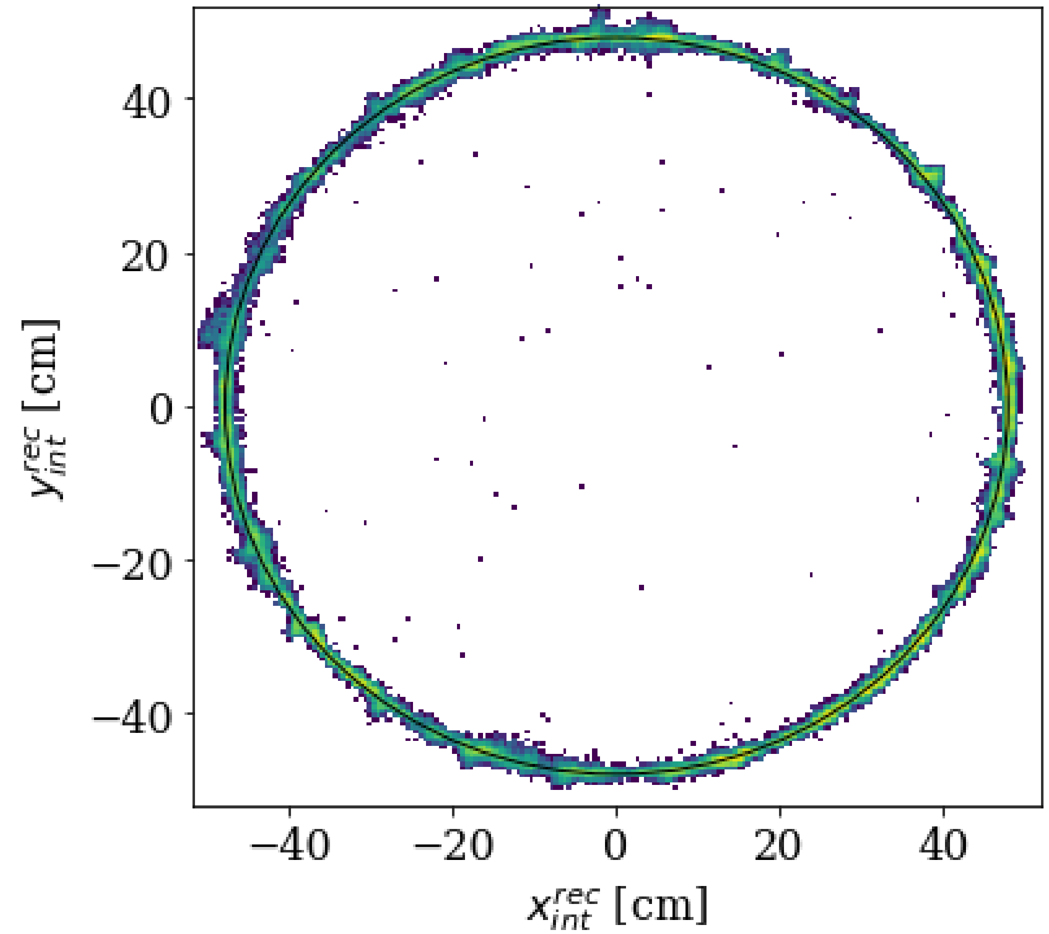
Origin

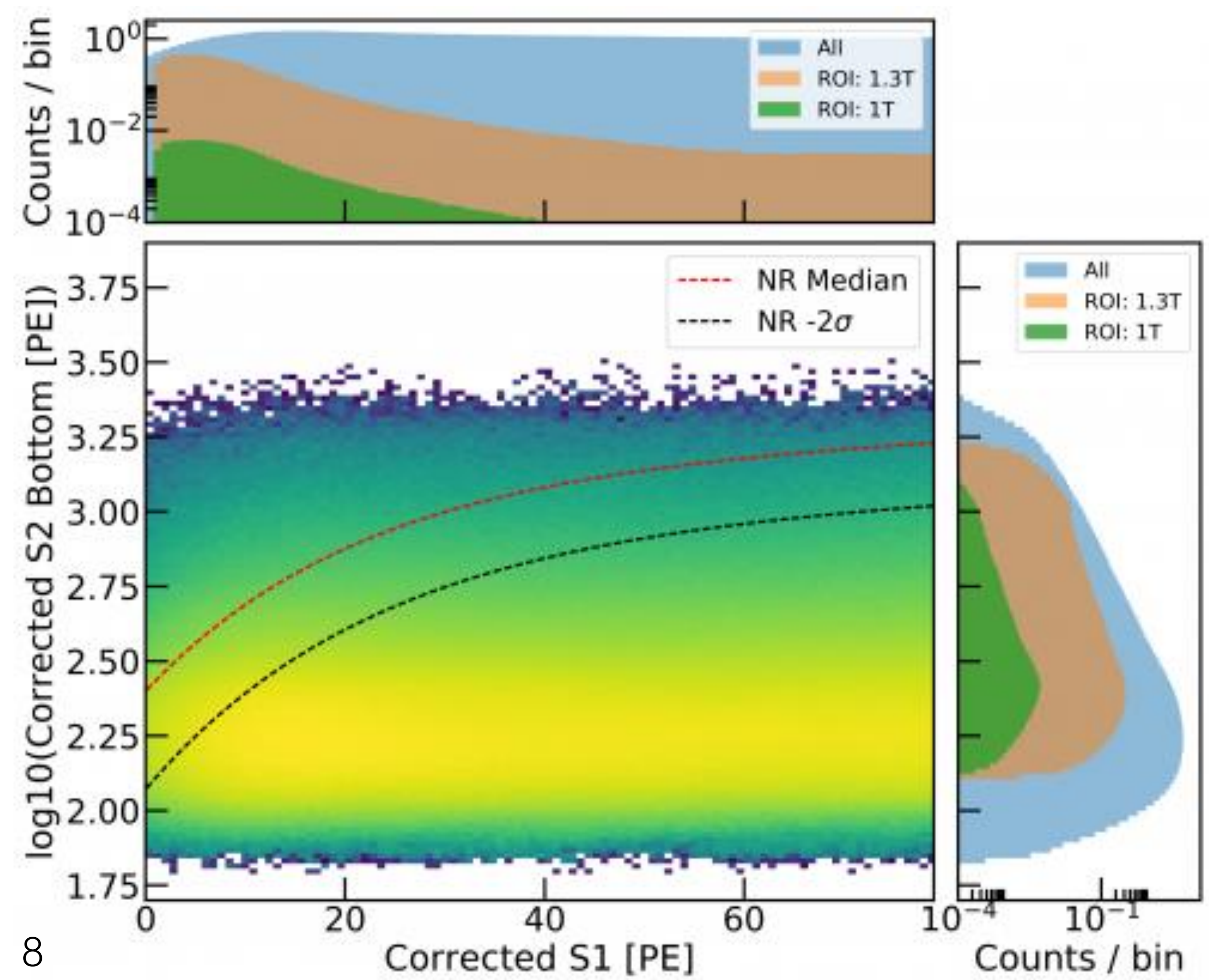
- **From plate out of ^{210}Pb on PTFE walls of TPC**
- **Some of charge quanta are lost, reducing S2 size**
- **Results in event being shifted into NR band.**

Mitigation

- **Data driven background model used to develop PDF for likelihood**

THE UNIVERSITY OF CHICAGO





Backgrounds

	Surface	Homogeneous
NR	Neutrons	CEvNS
Other	Surface (^{210}Pb)	***Accidental Coincidence***
ER	Materials (γ, β)	^{85}Kr, ^{222}Rn

Degraded Reconstruction

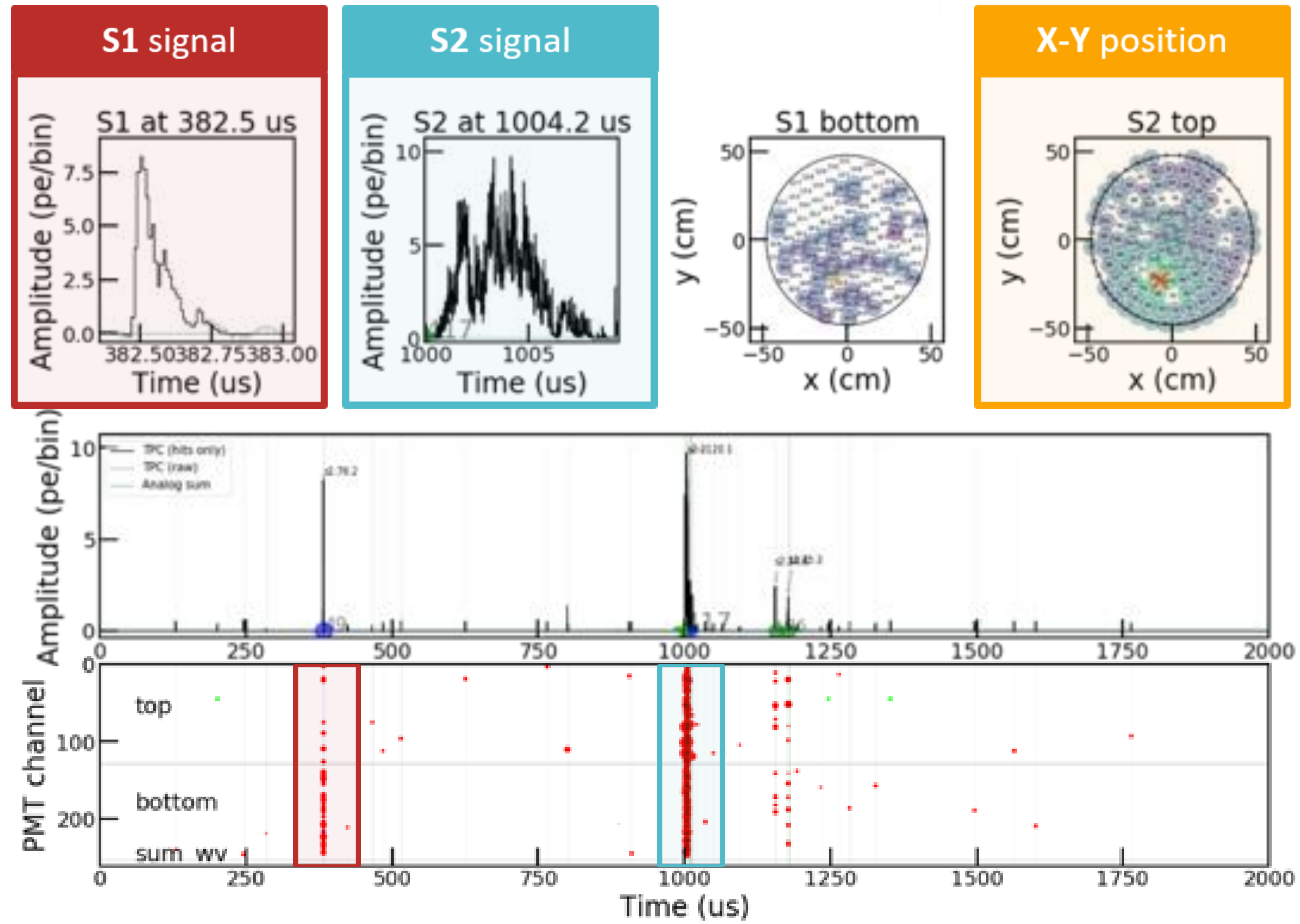
Origin

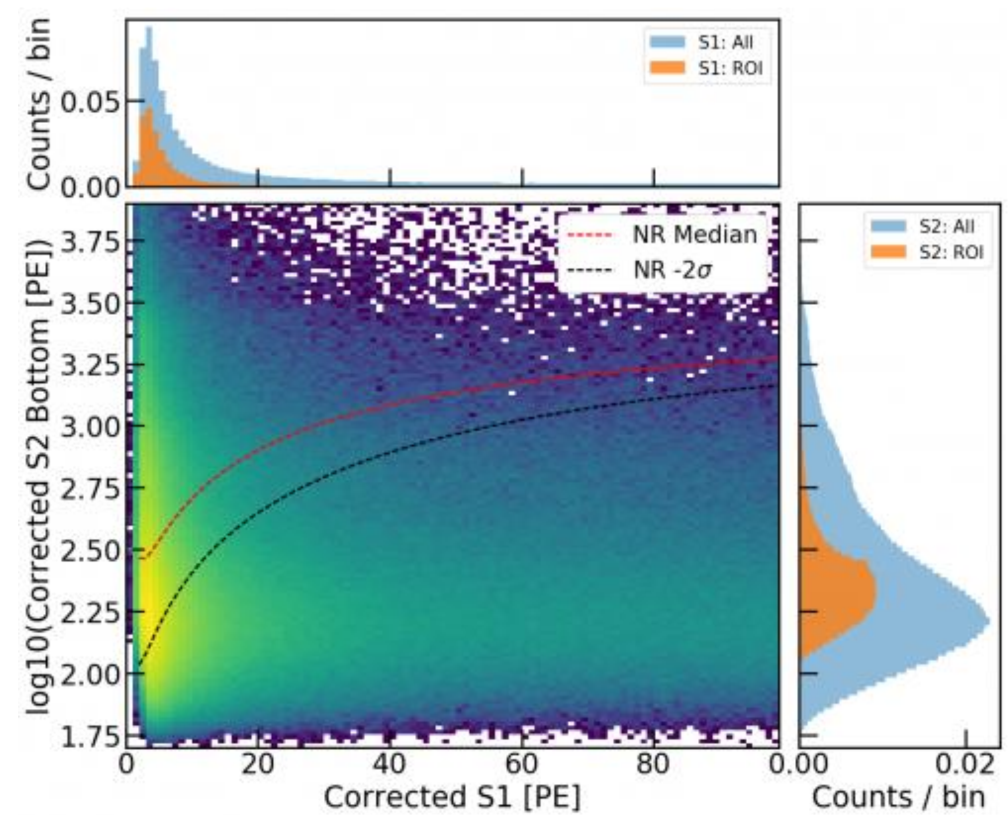
- **Random pairing of lone S1 and S2 signals**
- **Accidental pairing of small S1 and S2 signals produce events reconstructed within the search region**

Mitigation

- **PDF derived from data and used in likelihood estimation**

https://github.com/XENON1T/pax





Backgrounds

	Surface	Homogeneous
NR	Neutrons	CEvNS
Other	Surface (^{210}Pb)	Accidental Coincidence
ER	***Materials (γ, β)***	^{85}Kr, ^{222}Rn

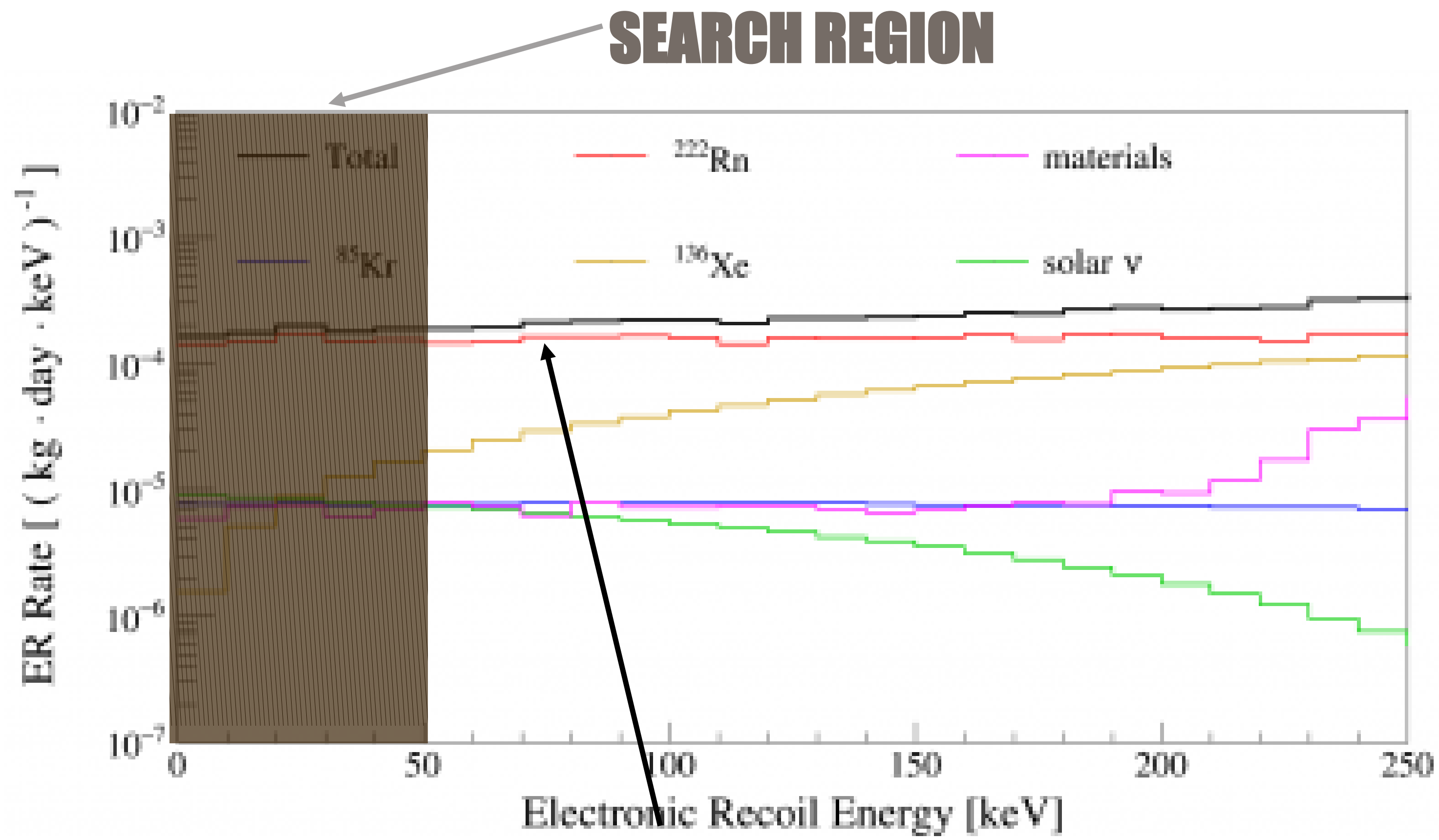
Induce ER

Origin

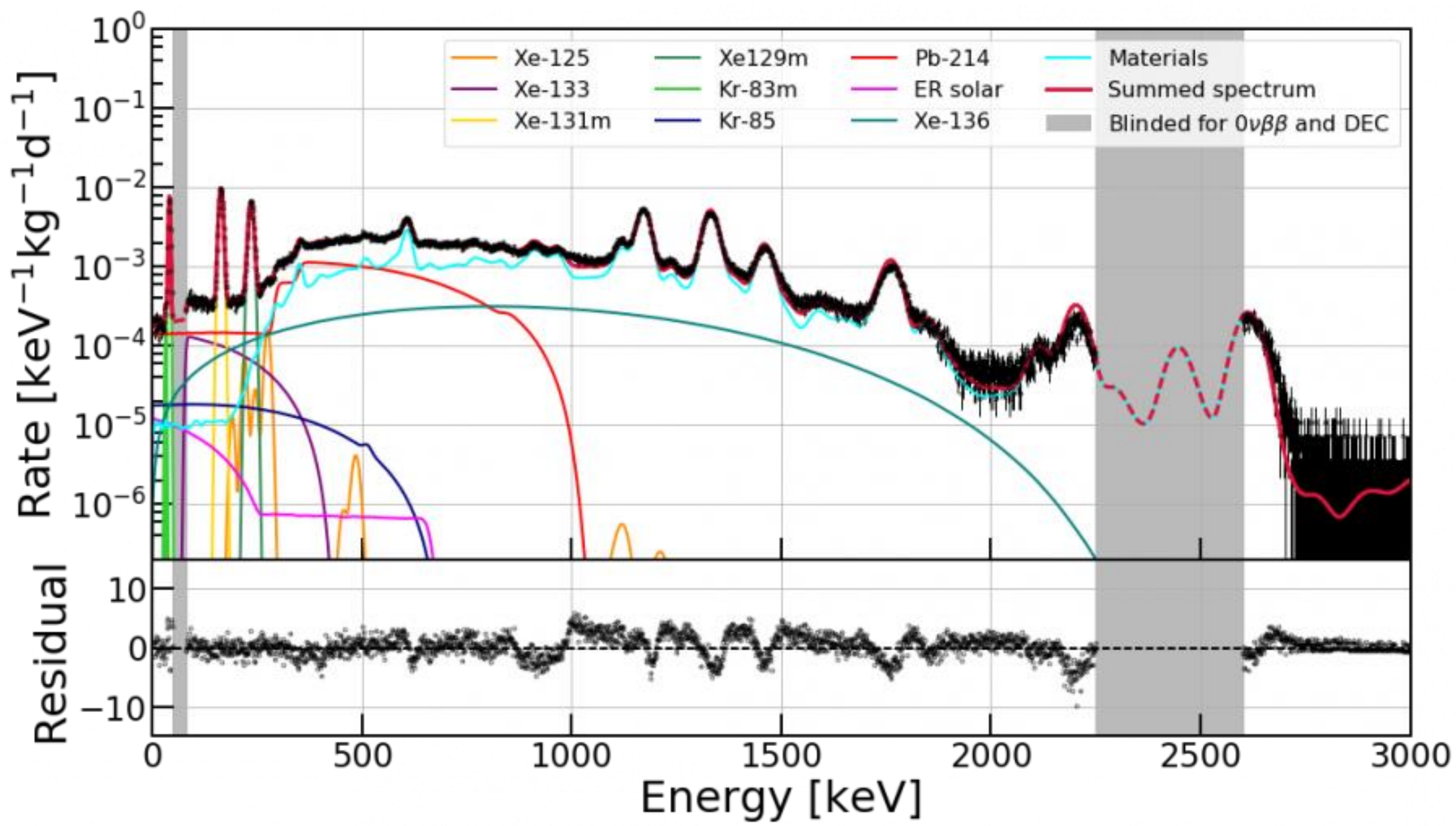
- **Environment**
- **Detector Materials**

Mitigation

- **Use ultra-pure materials as well as passive water shielding**
- **Reject multi-hit events (for γ)**
- **Fiducialization**
- **Reject through S2/S1 (50% NR acceptance for >99.75% ER rejection)**



Radon is our dominant background



THE UNIVERSITY OF CHICAGO

Backgrounds

	Surface	Homogeneous
NR	Neutrons	CEvNS
Other	Surface (^{210}Pb)	Accidental Coincidence
ER	Materials (γ, β)	***^{85}Kr, ^{222}Rn***

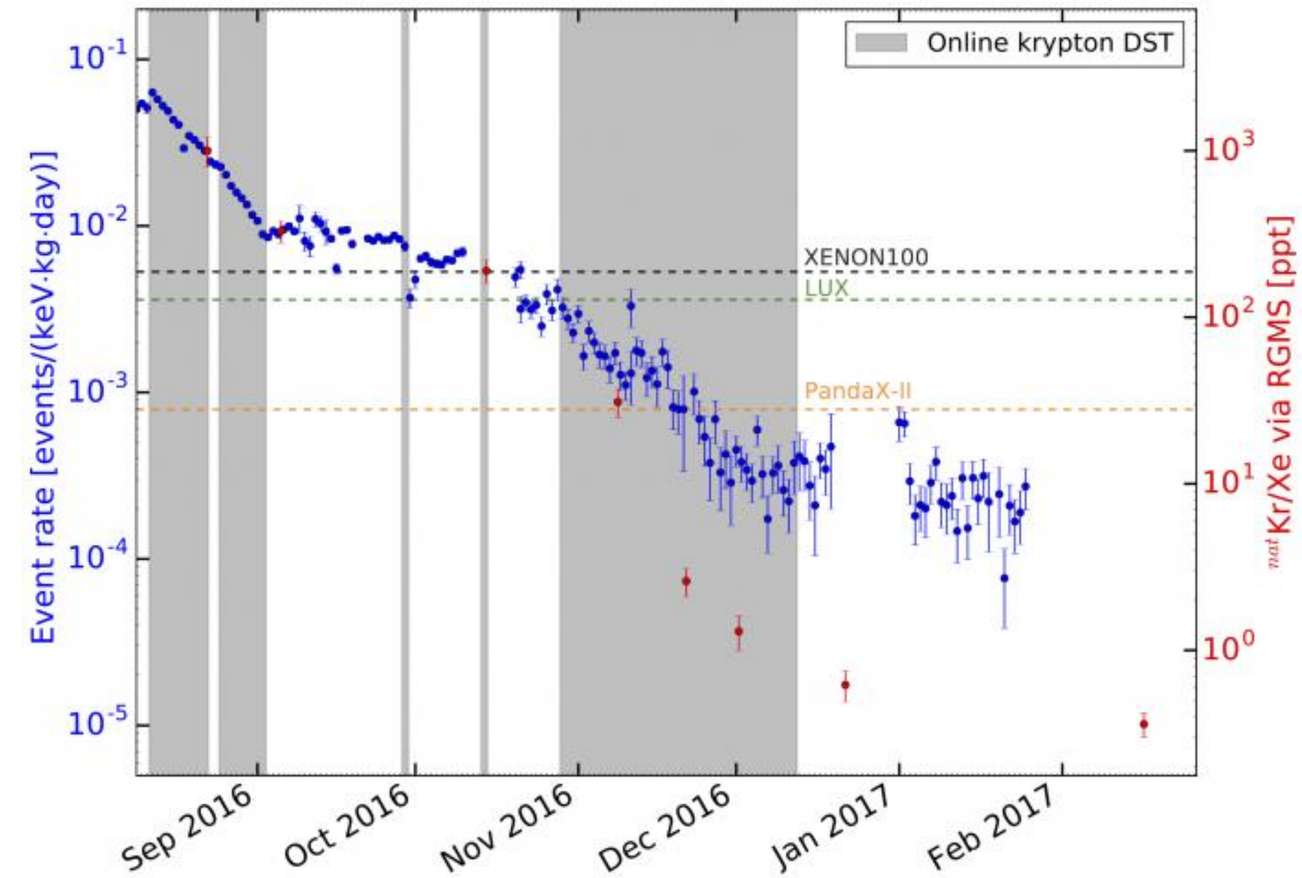
Induce ER

Origin

- **From contaminants in the liquid Xe target**

Mitigation

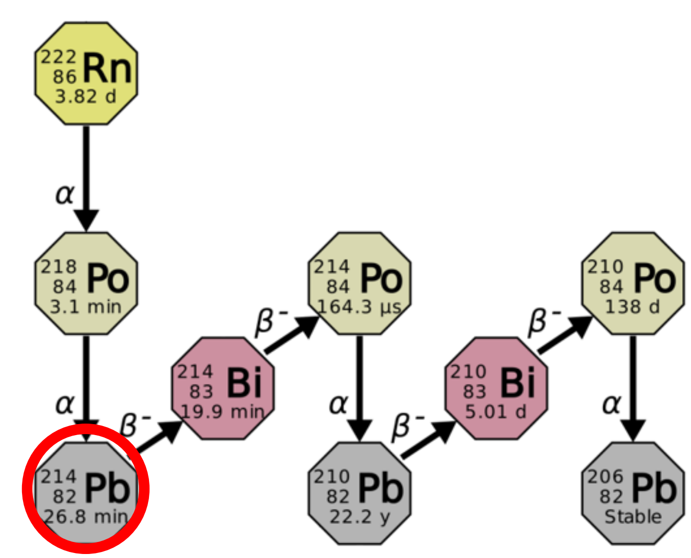
- **^{85}Kr : remove by distilling the xenon down to sub-ppt concentrations of ^{nat}Kr/Xe**
- **^{222}Rn: Selecting radiopure material and with as low Rn emanation as possible**
- **S2/S1 discrimination**

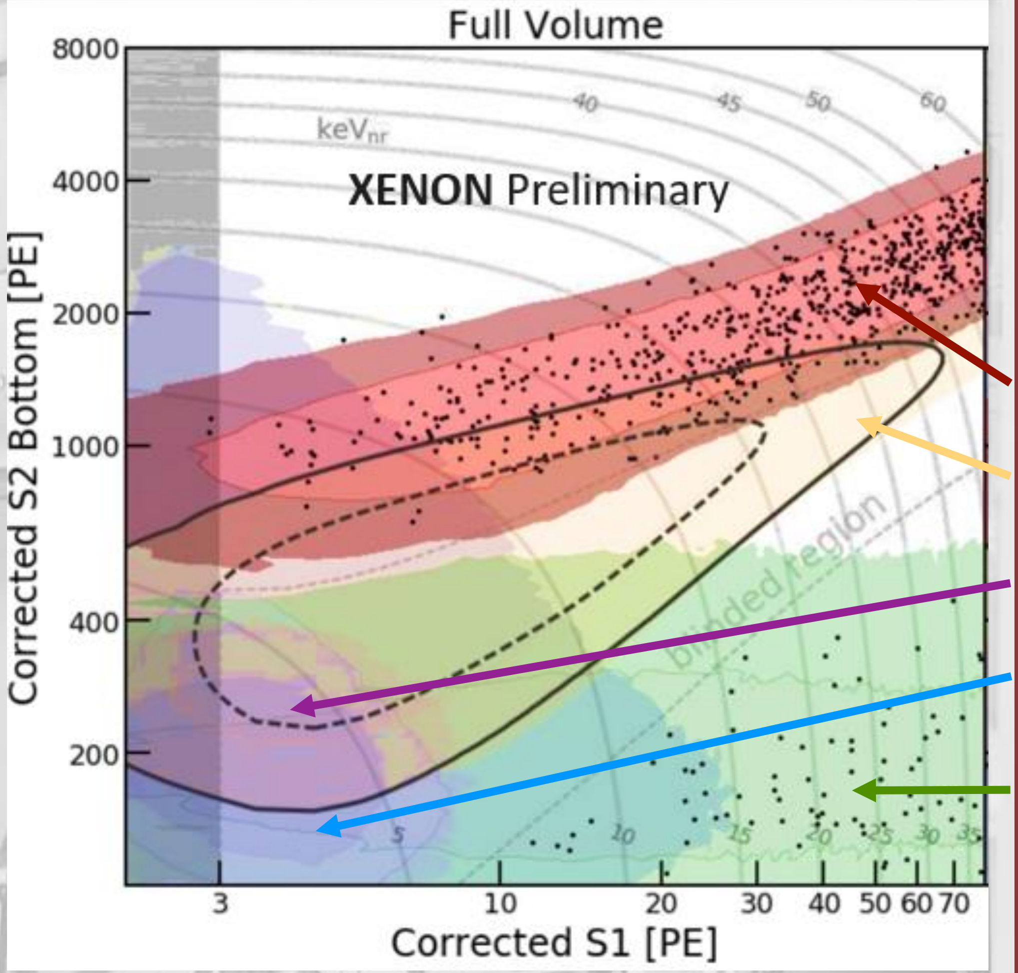


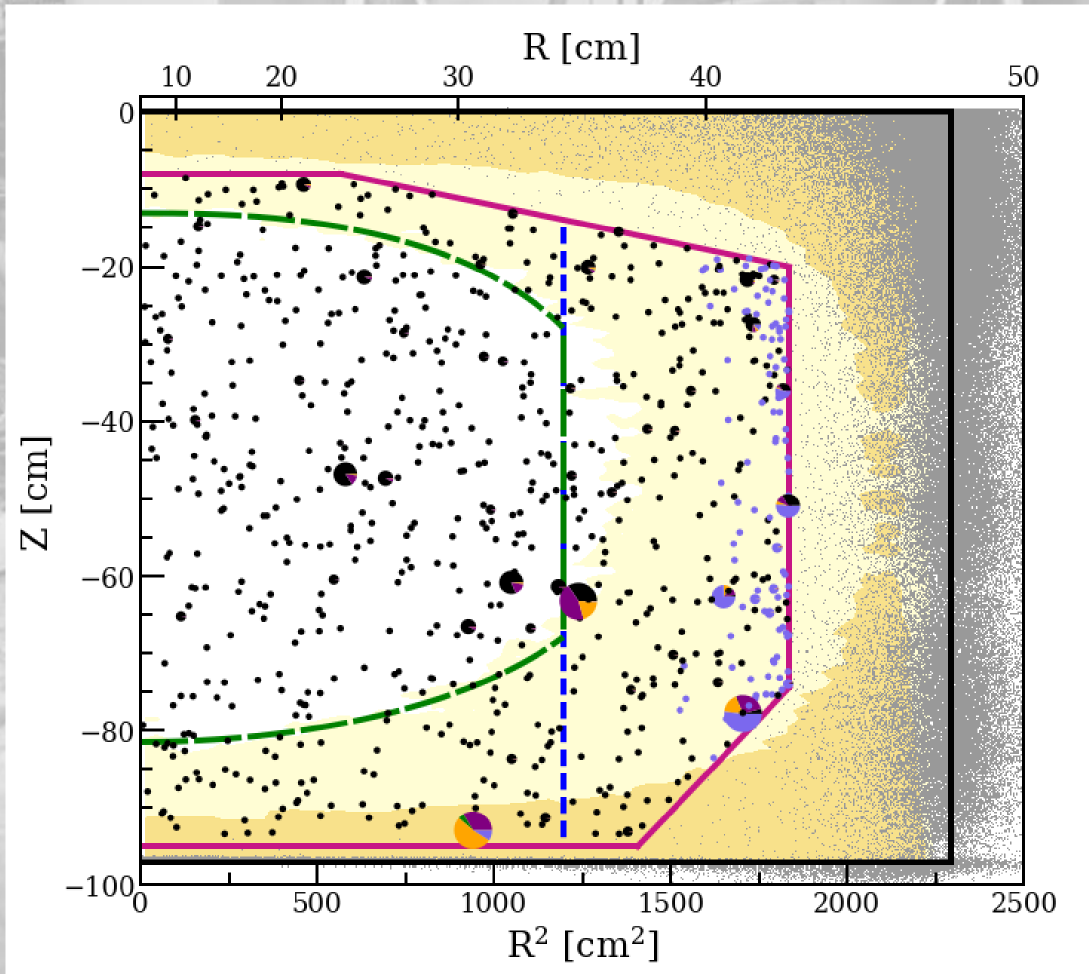
(0.17 ± 0.01) events / (tonne·day·keV$_{ee}$) in 1300 kg FV

WIMP search region: (82_{-6}^{+8}) events / (tonne·yr·keV$_{ee}$)

Of which:
~8 events / (tonne·yr·keV$_{ee}$) from **^{85}Kr**
~56 events / (tonne·yr·keV$_{ee}$) from **^{214}Pb** (inferred from Bi-Po time coincidences)







Background Prediction

Mass	1.3t	1.3t	0.9t
(S2, S1)	Full	Reference	Reference
ER	627 ± 18	1.62 ± 0.3	1.12 ± 0.21
Neutron	1.43 ± 0.66	0.77 ± 0.35	0.41 ± 0.19
CEvNS	0.05 ± 0.01	0.03 ± 0.01	0.02
AC	$0.47^{+0.27}$	$0.10^{+0.06}$	$0.06^{+0.03}$
Surface	106 ± 8	4.84 ± 0.4	0.02

BG TOTAL	735 ± 20	7.36 ± 0.61	1.62 ± 0.28
WIMPs best-fit (200GeV)	3.56	1.70	1.16

Data	739	14	2

Background models in 4 dimensions: S1, S2, r, z

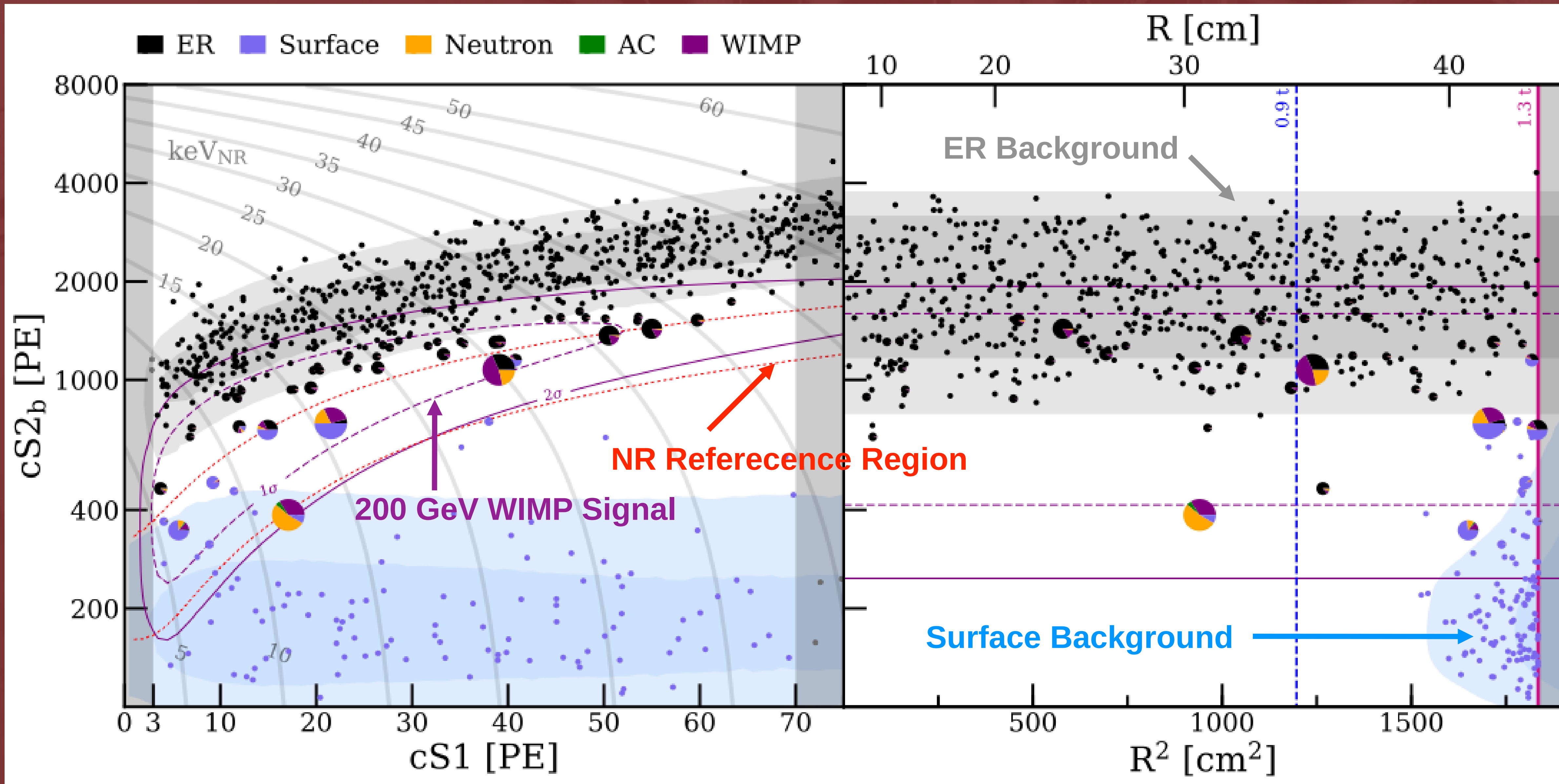
Numbers in table for illustration

Statistical inference done with PLR analysis in 1.3t fiducial volume and full (S1,S2) space

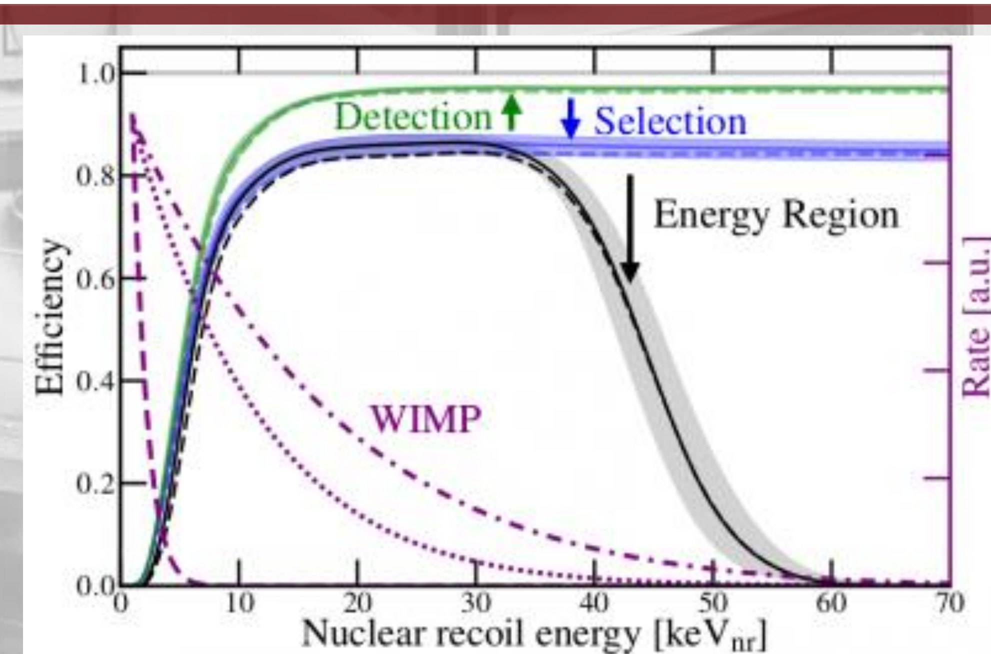
Jacques Pienaar, jpienaar@uchicago.edu

SR0+SR1 Combined Results

Energy Space

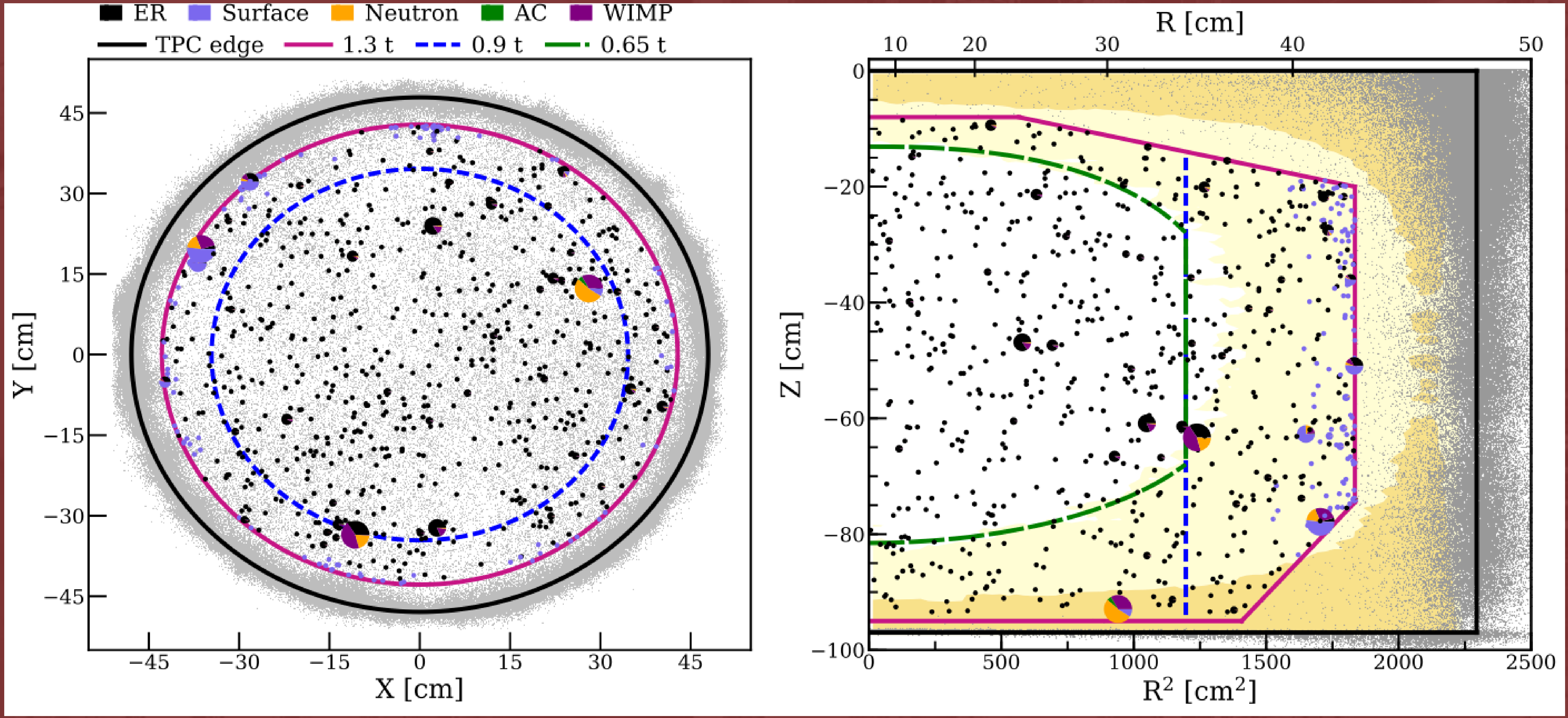


- Events that pass all cuts are shown.Small (single coloured) charts correspond to unambiguously bkg events. Larger Pie Charts represent larger WIMP probability
- Events are shown as pie charts showing relative PDF from each component for the best fit model of a 200 GeV WIMP (σ=4.4·10^{-47} cm^2)

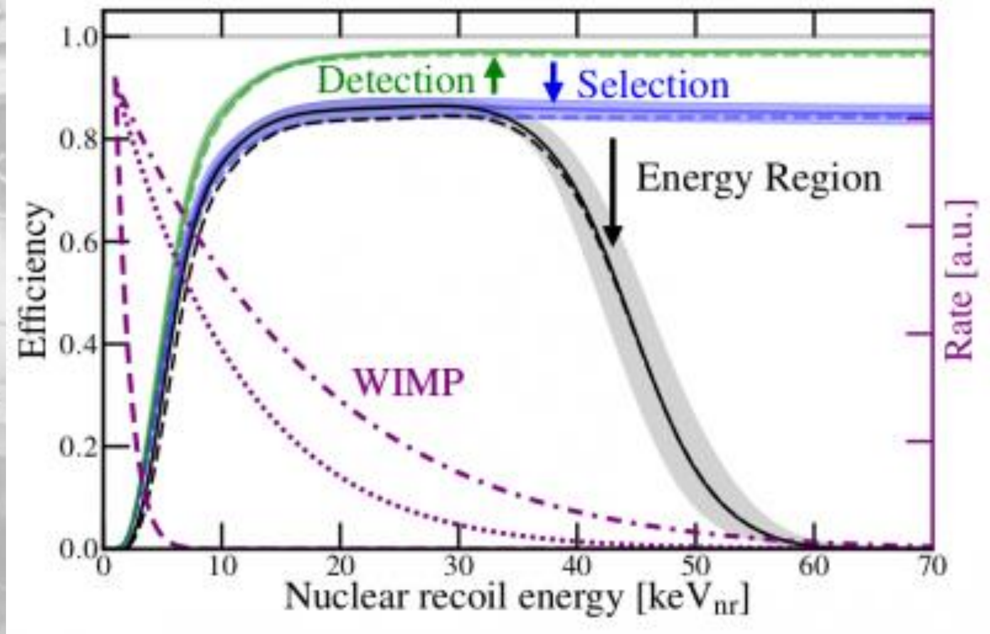


SR0+SR1 Combined Results

Spatial Distribution

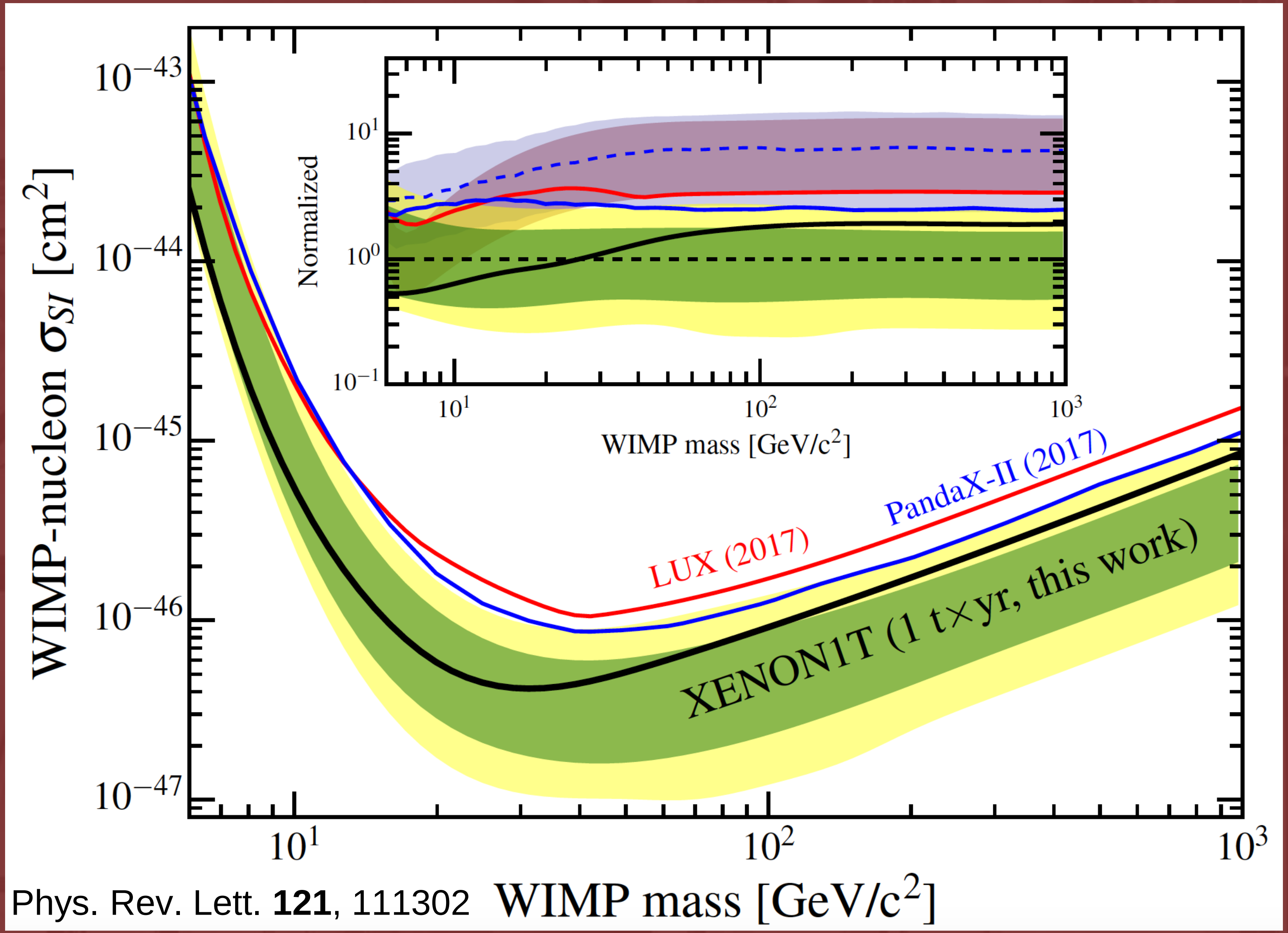


- **Performed unbinned profile likelihood. Model uncertainties included as nuisance parameters.**
- **Maximum radius of FVs set by surface event contributions**
- **Corners due to constraining radio-impurity contribution to ER to be sub-dominant to uniform ^{222}Rn bkg**

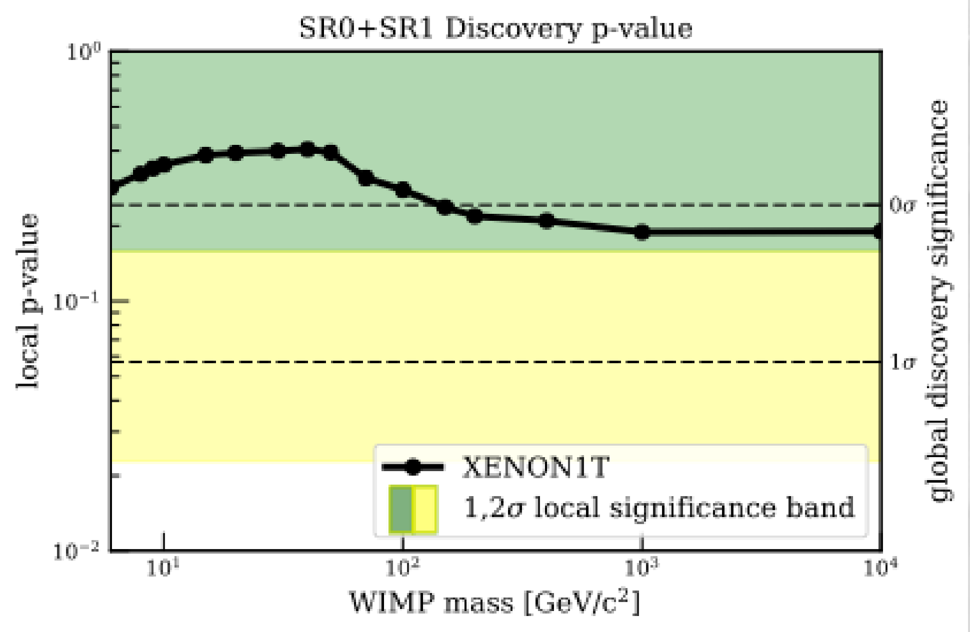


SR0+SR1 Combined Results

Spin Independent Limits

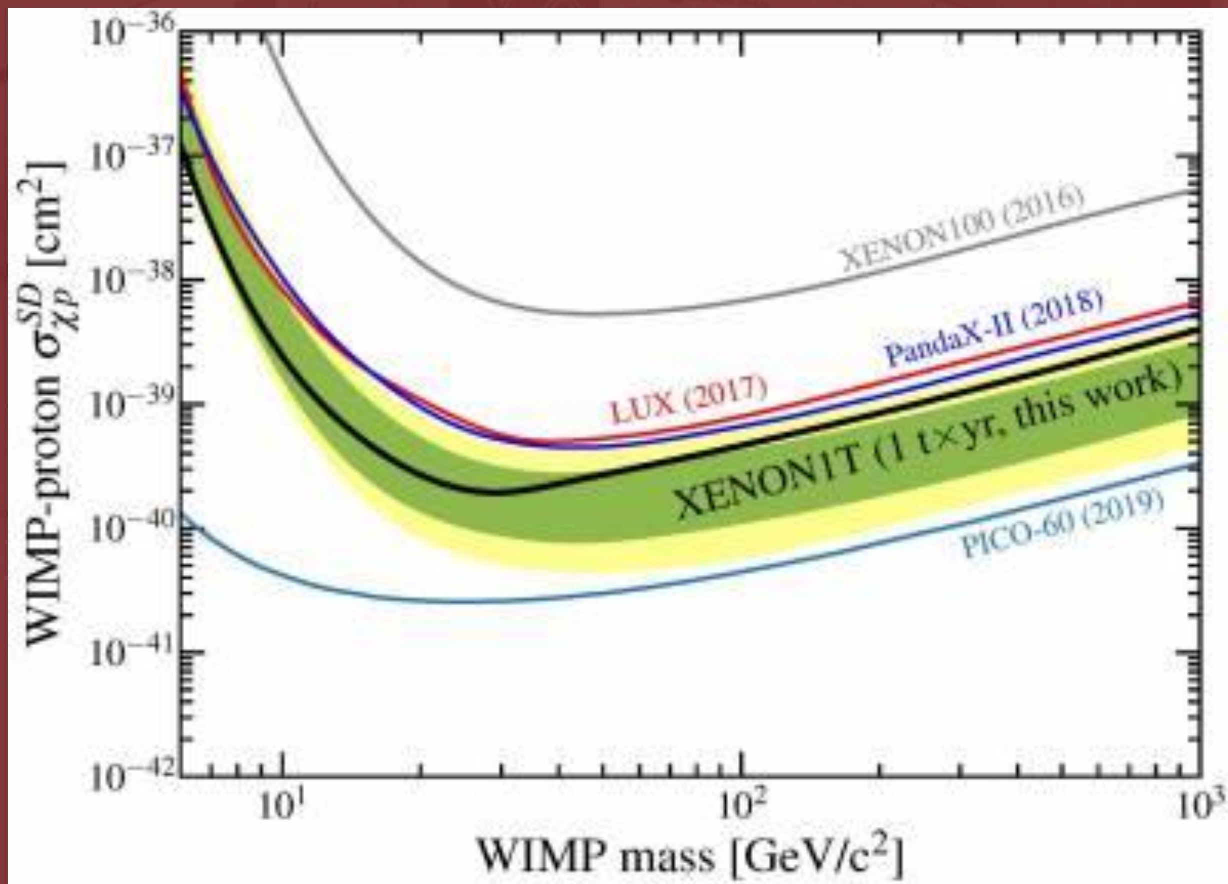


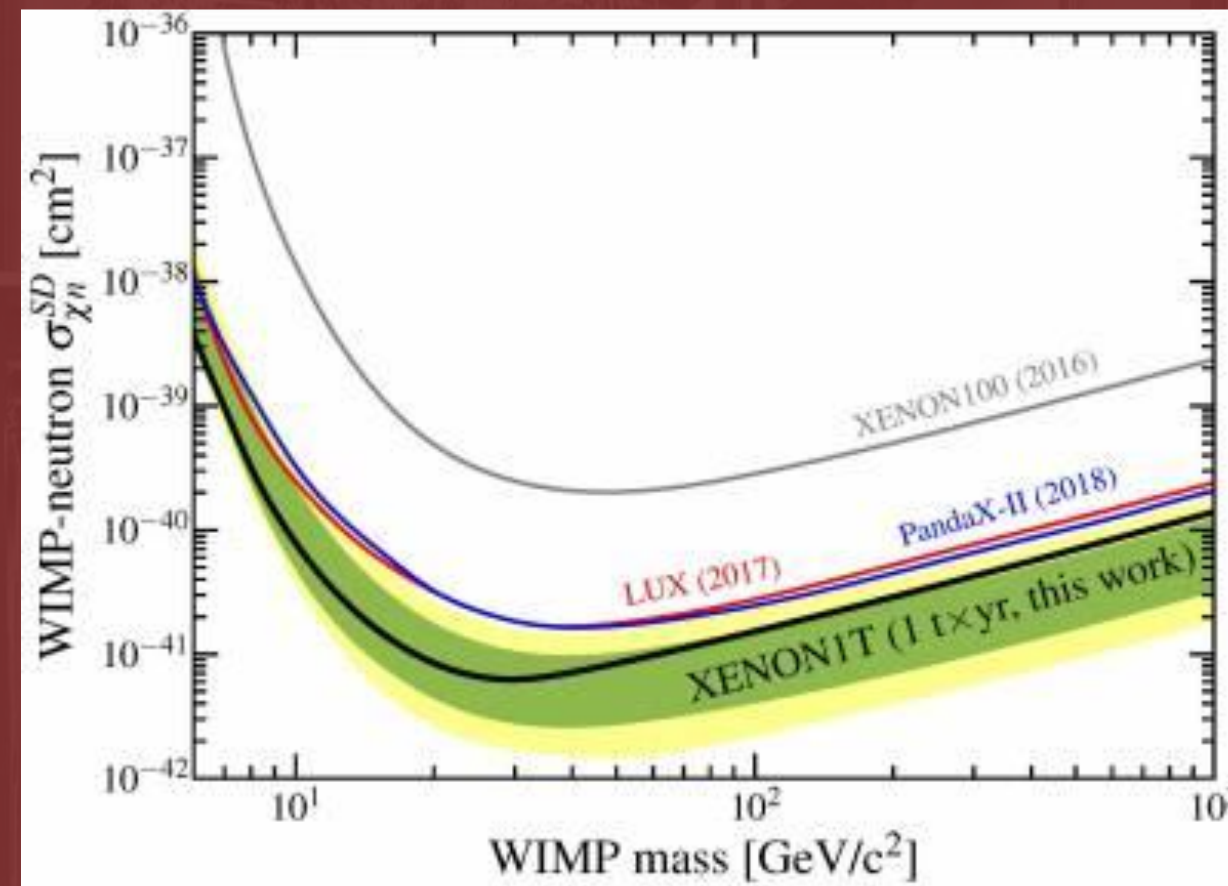
Phys. Rev. Lett. **121**, 111302



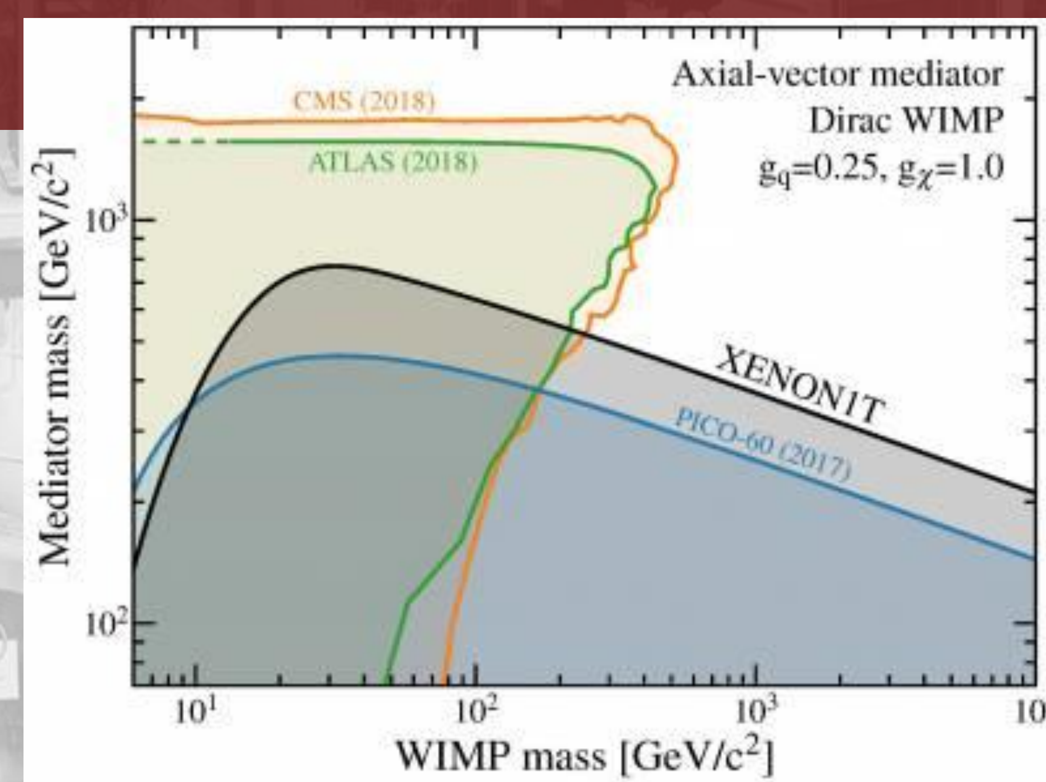
SR0+SR1 Combined Results

Spin Dependent Limits

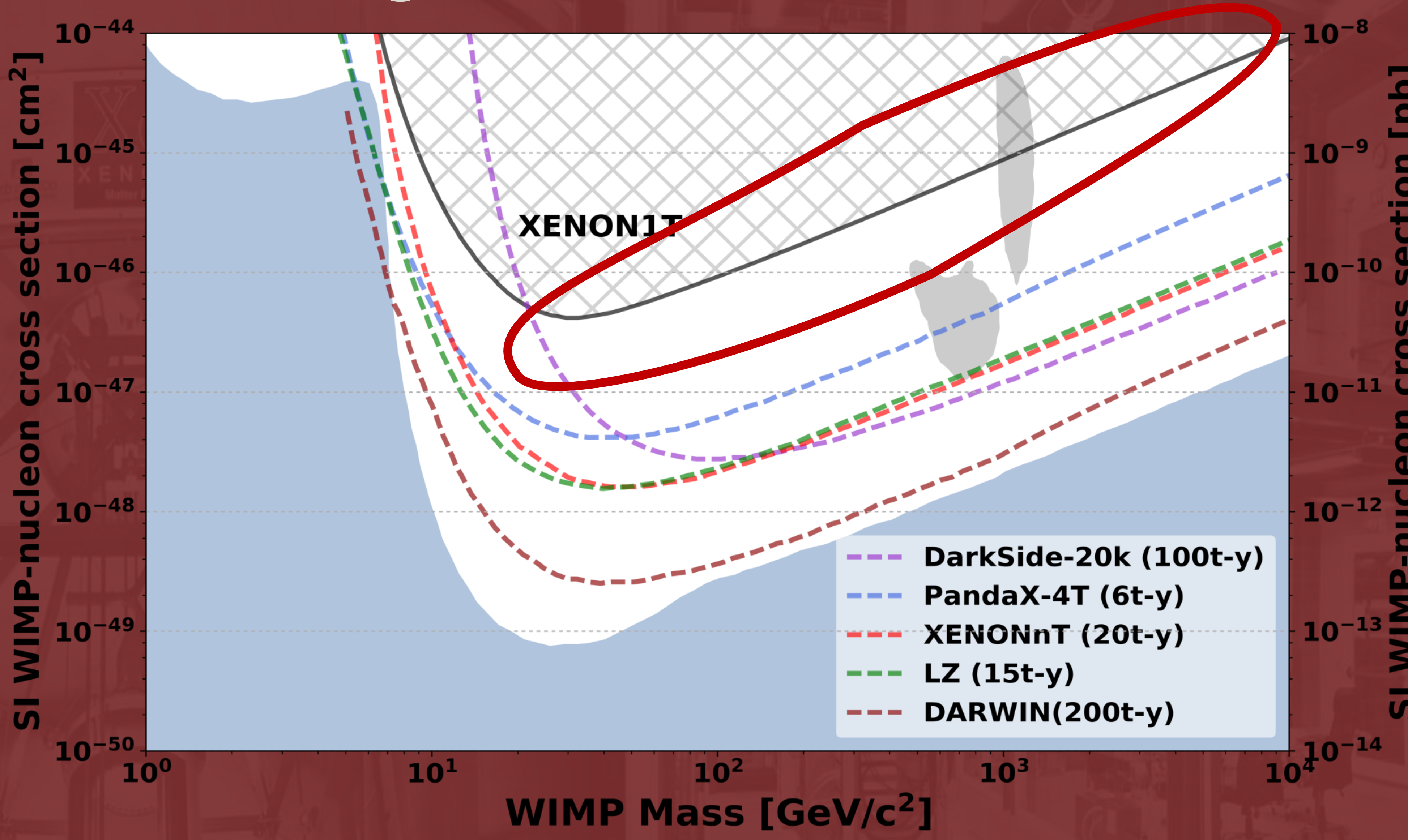




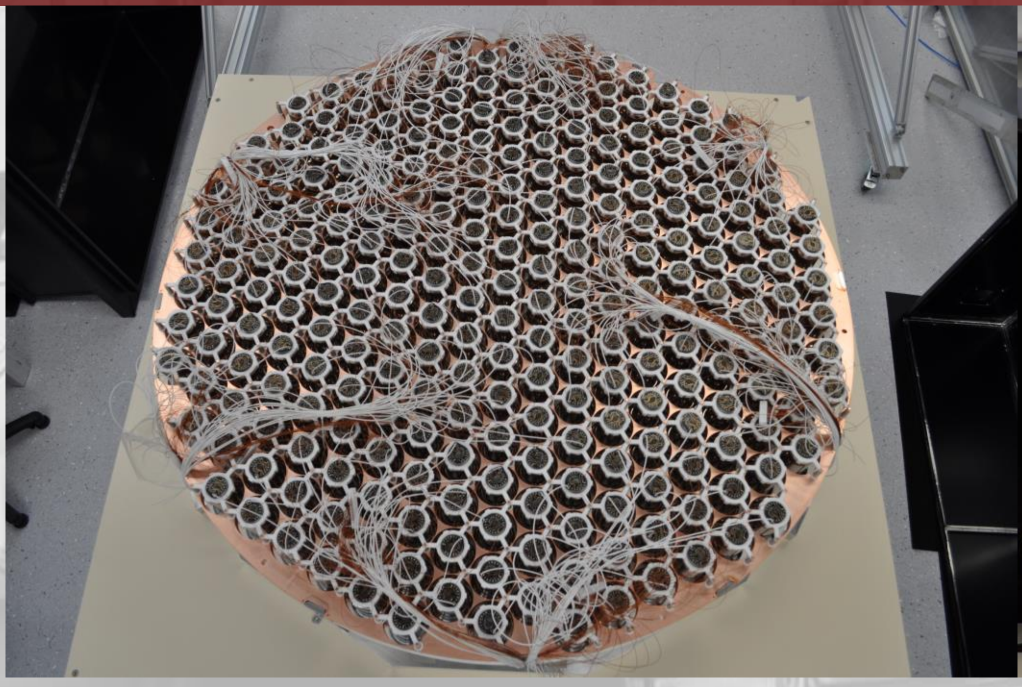
- **Same event selection criteria and event corrections as applied to SI search**
- **Most stringent limit on WIMP-Neutron scattering cross section**
- **Exclude new parameter space in isoscalar theory with axial-vector mediator**



Extending the Reach of LXe Detectors



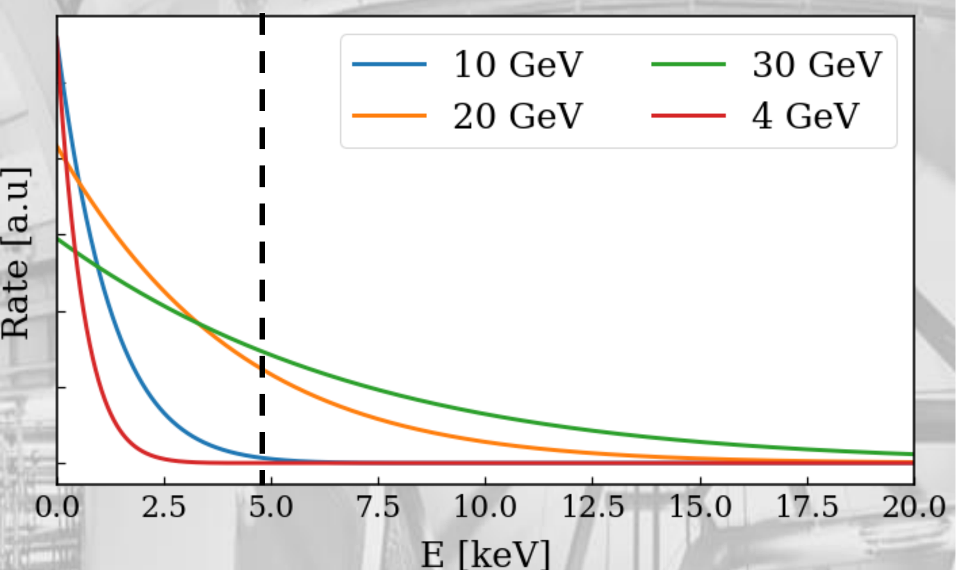
- For WIMP masses above ~10 GeV, larger exposure and better control of intrinsic backgrounds.
- XENONnt: 4x Fiducial Volume, 1/10 ER background
- Operational in 2020



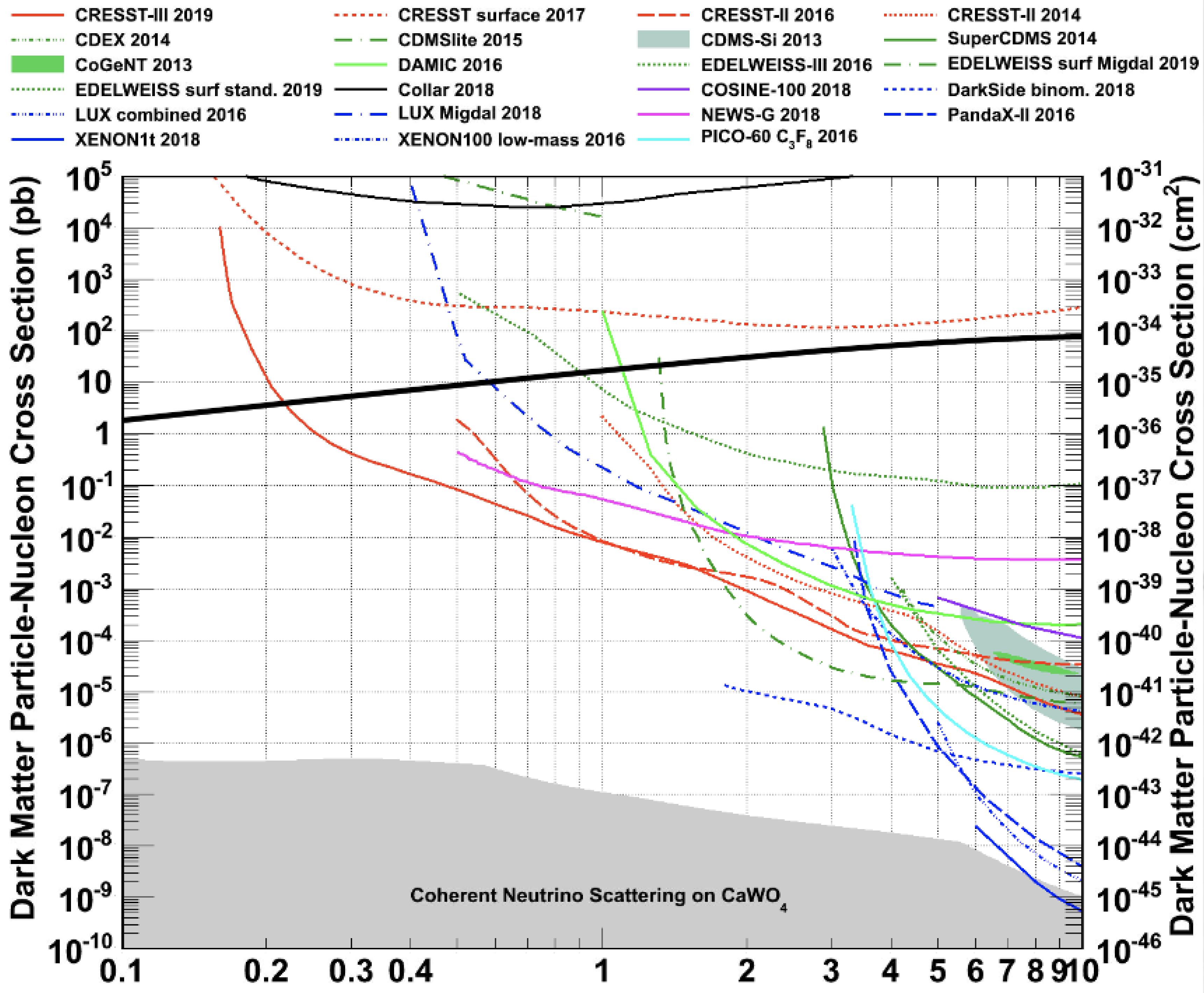
Jacques Pienaar, jpienaar@uchicago.edu

Extending the Reach of LXE Detectors

WIMP Recoil Rates in LXe



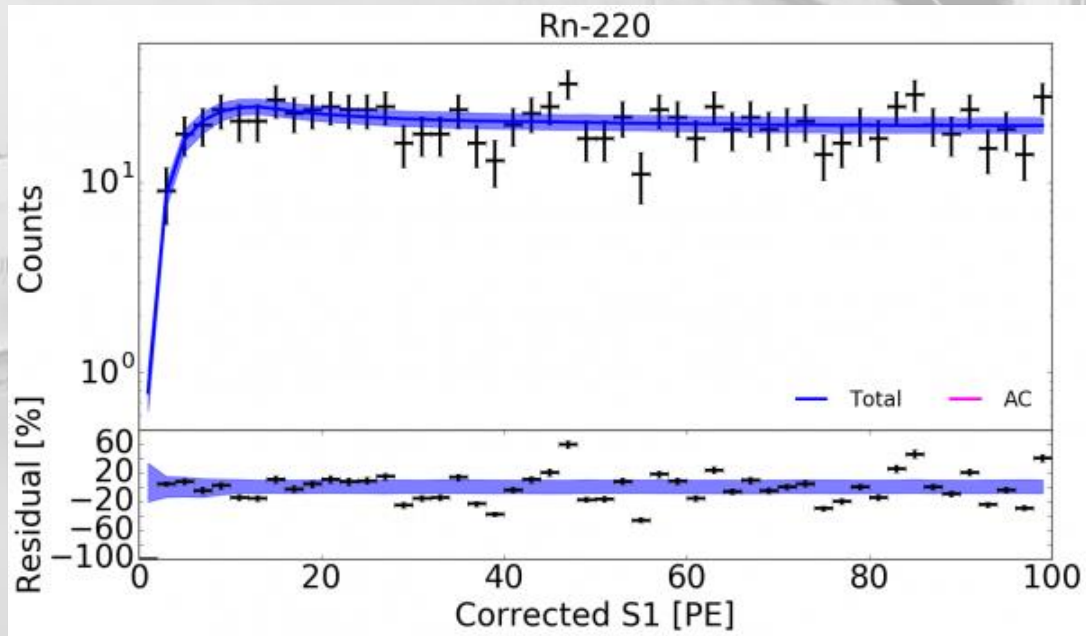
- At low energies still huge opportunities to improve reach of LXe detectors
- Current limits driven by threshold effects

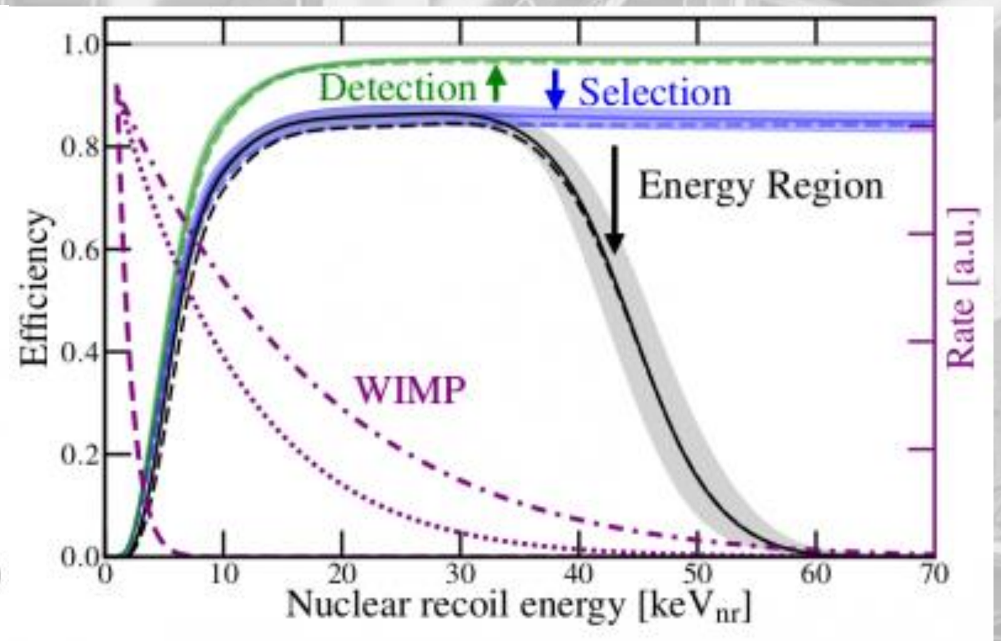


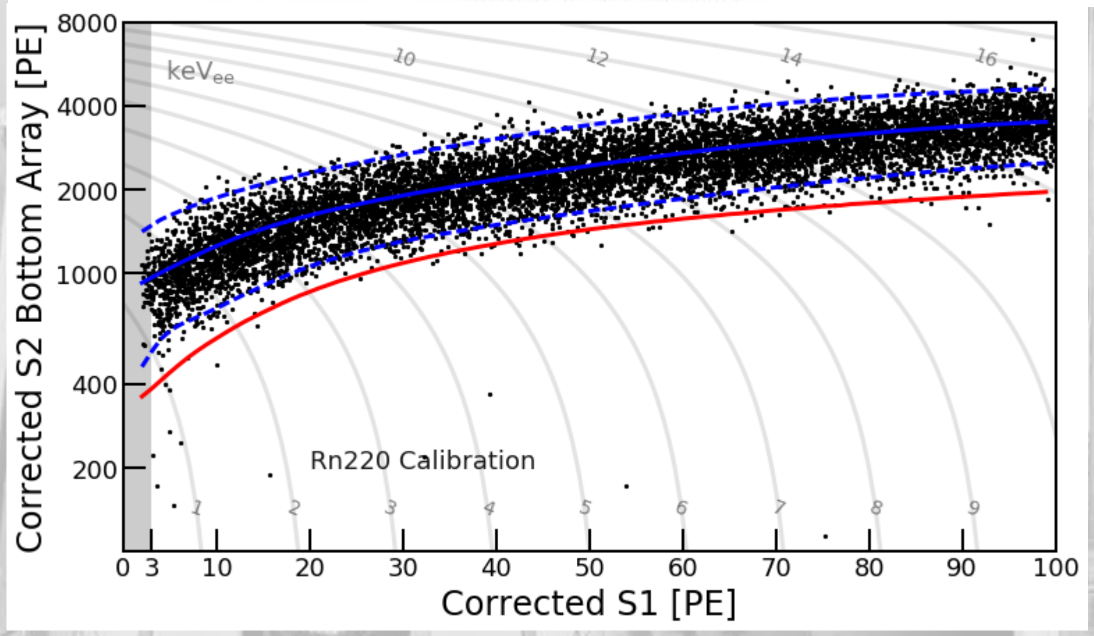
Phys.Rev. D101 (2020) 023005

Jacques Pienaar, jpienaar@uchicago.edu

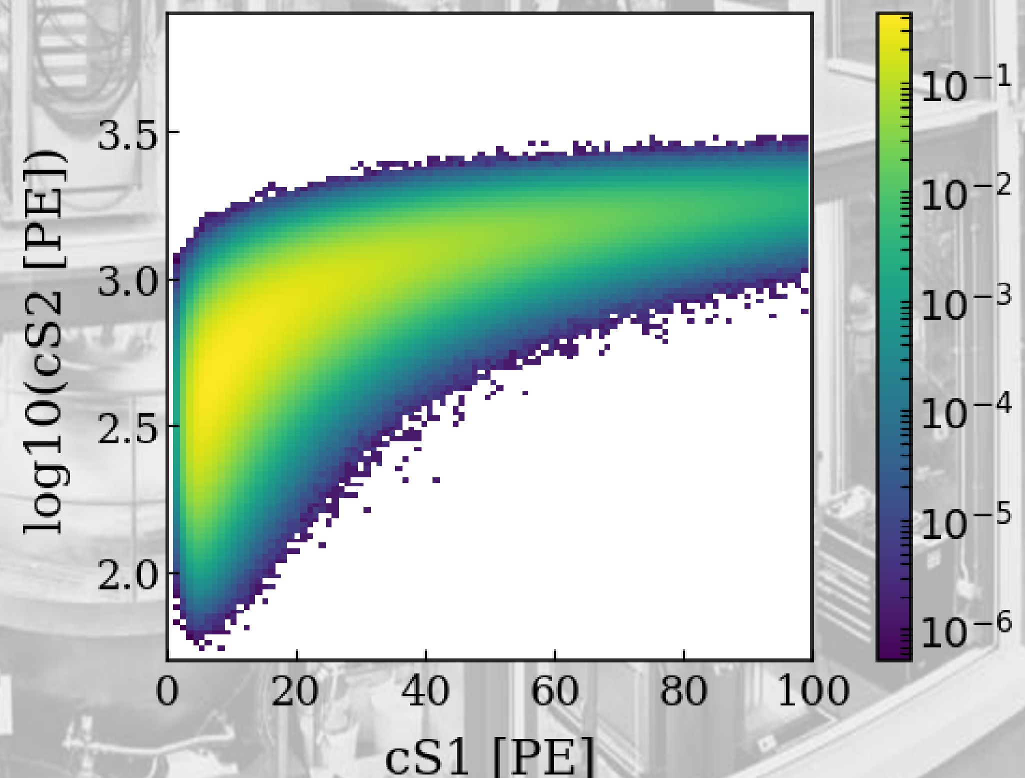
Threshold Dominated by S1 Detection







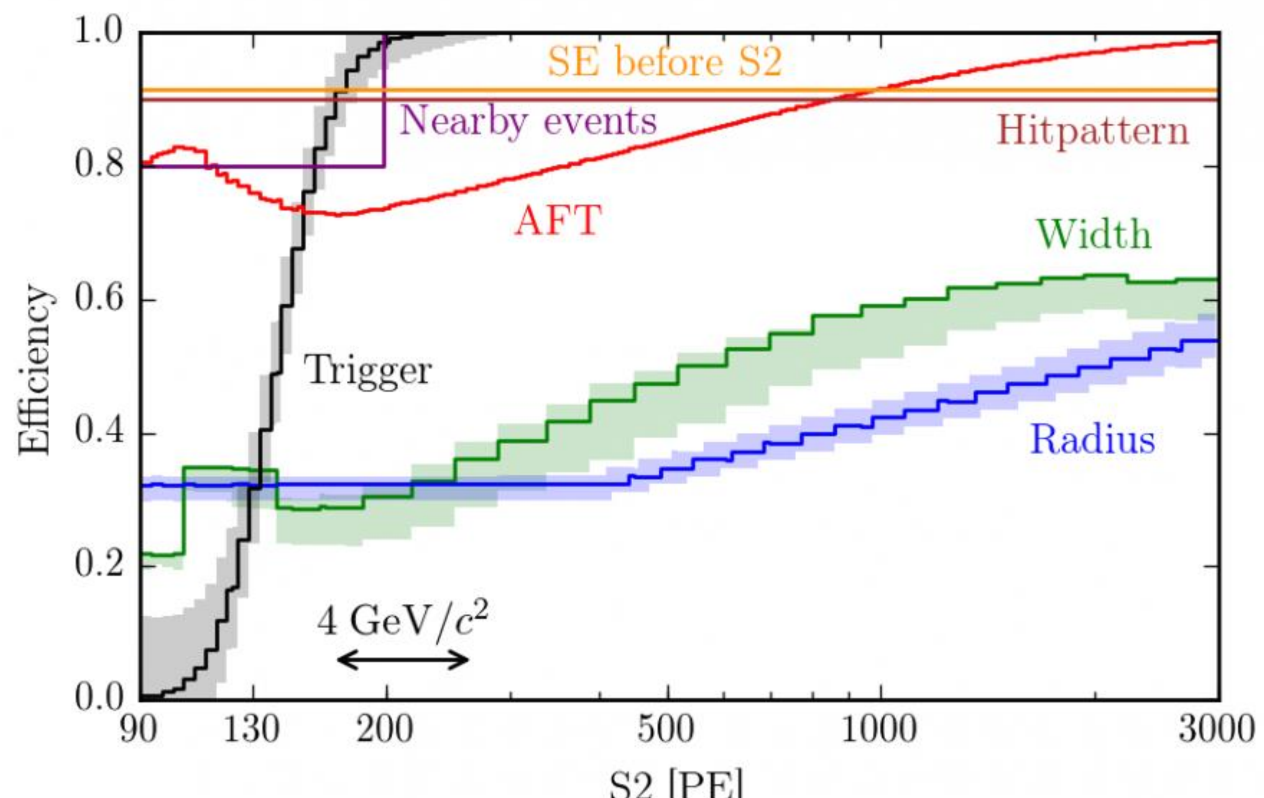
50 GeV WIMP signal in cS1-cS2 space



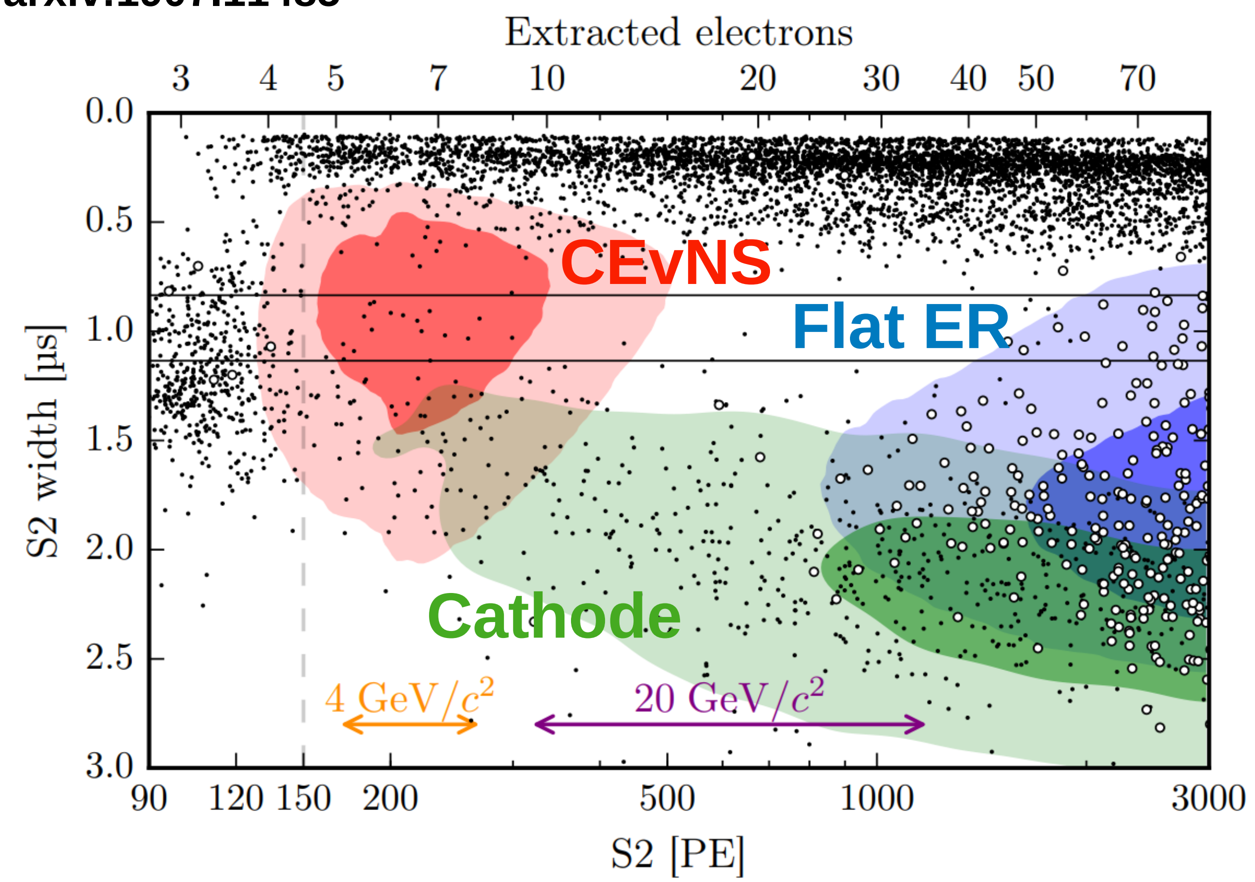
- **Normally require 3-fold coincidence to detect S1s**
- **Applies an effective ~3 PE threshold on WIMP searches**
- **For smaller WIMPs, majority of signal is below S1 threshold.**
- **S2 Signals are much larger and not affected by this threshold effect**

Jacques Pienaar, jpienaar@uchicago.edu

S2-Only Searches



arxiv:1907.11485



Possible to extend searches to lower WIMP masses by simply removing the requirement to have detected an S1

Comes at the cost of:

1. ER/NR discrimination
2. Drift-time information (Partially recovered with information about the width of the detected S2)

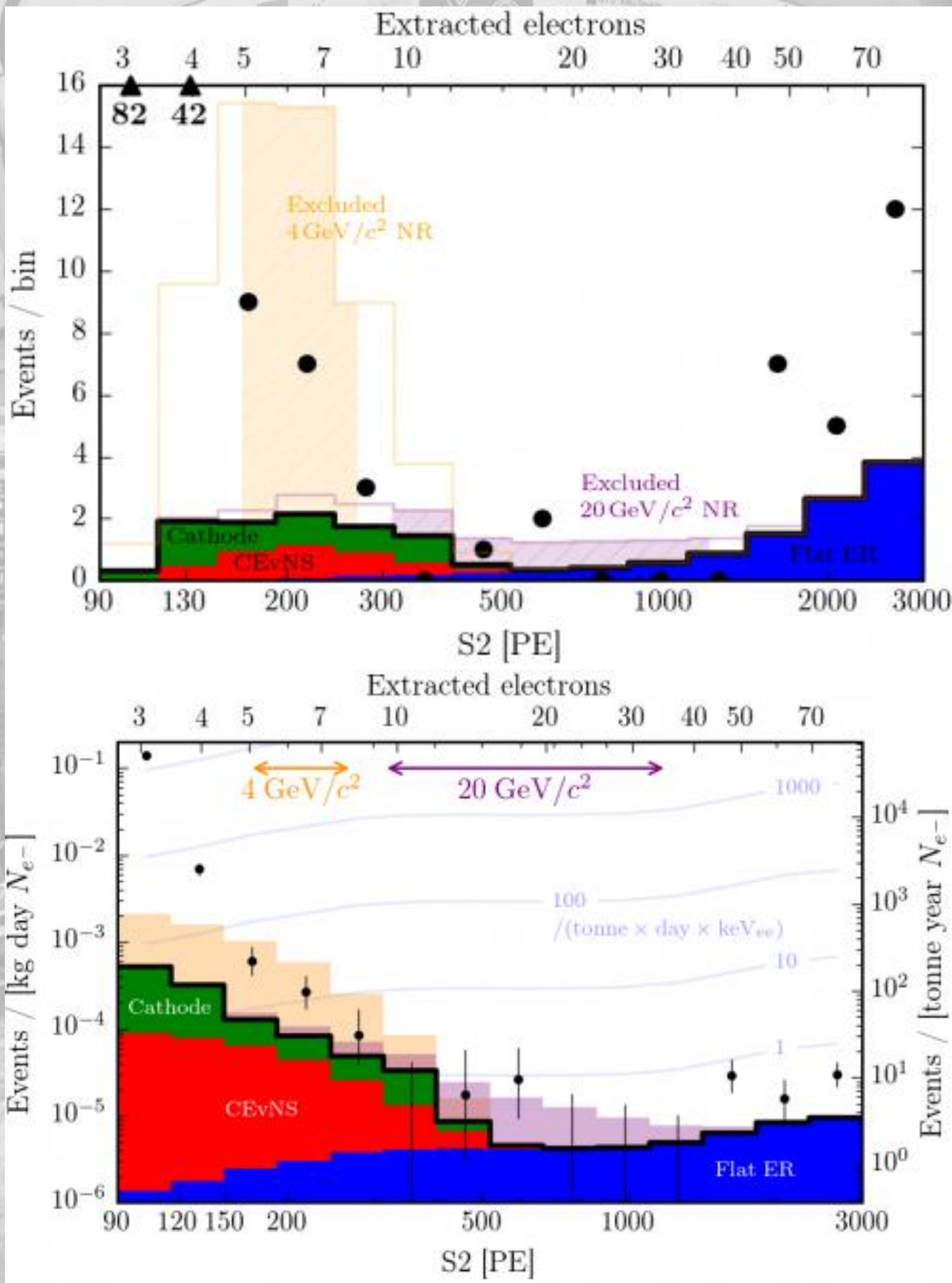
Currently not possible to completely describe the background in this region. Account for three backgrounds:

1. CEvNS
2. Flat ER Component (from Pb214)
3. Cathode Events

Since background models are incomplete, currently limited to limit-only searches using S2-only methods

Jacques Pienaar, jpienaar@uchicago.edu

S2-Only Searches



Used 30% of the full science data avilable to train the cuts.

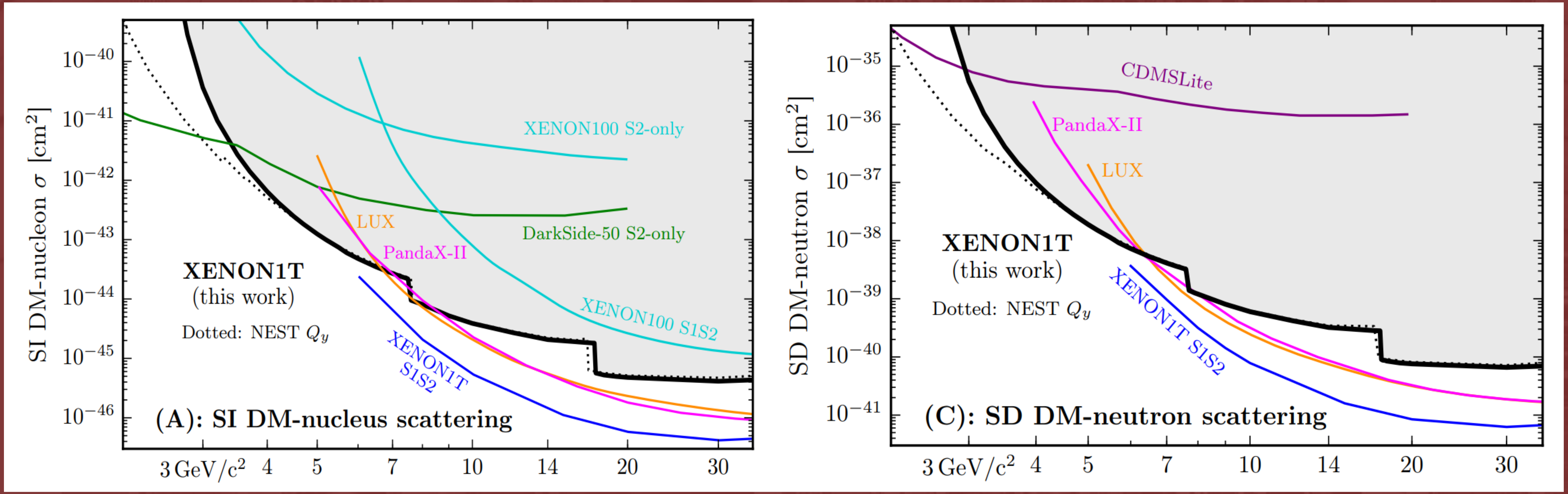
Training data also used to constrain Regions of Interest (S2) for each WIMP mass. (With a minimum of 150 PE)

Resultant rates above 300 PE are below 1 event/(tonne.day.keV)

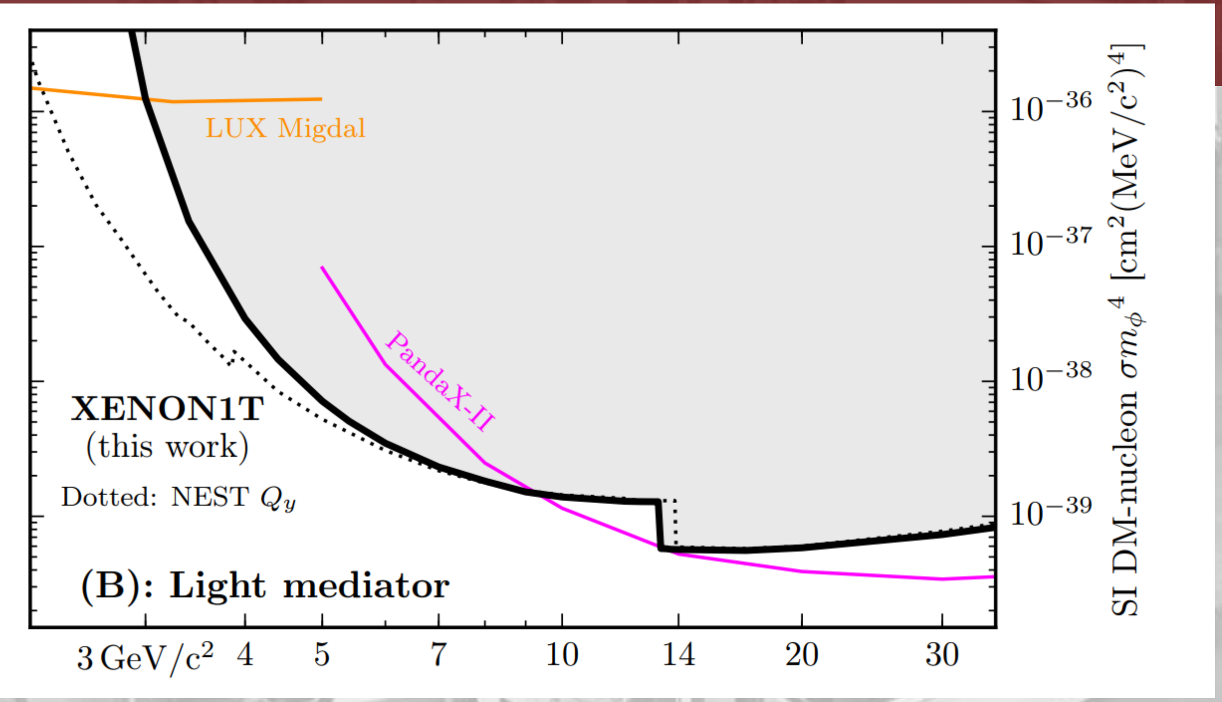
Rate below 150 PE rises rapidly due to unmodeled backgrounds. Mostly driven by single electron emisison

Jacques Pienaar, jpienaar@uchicago.edu

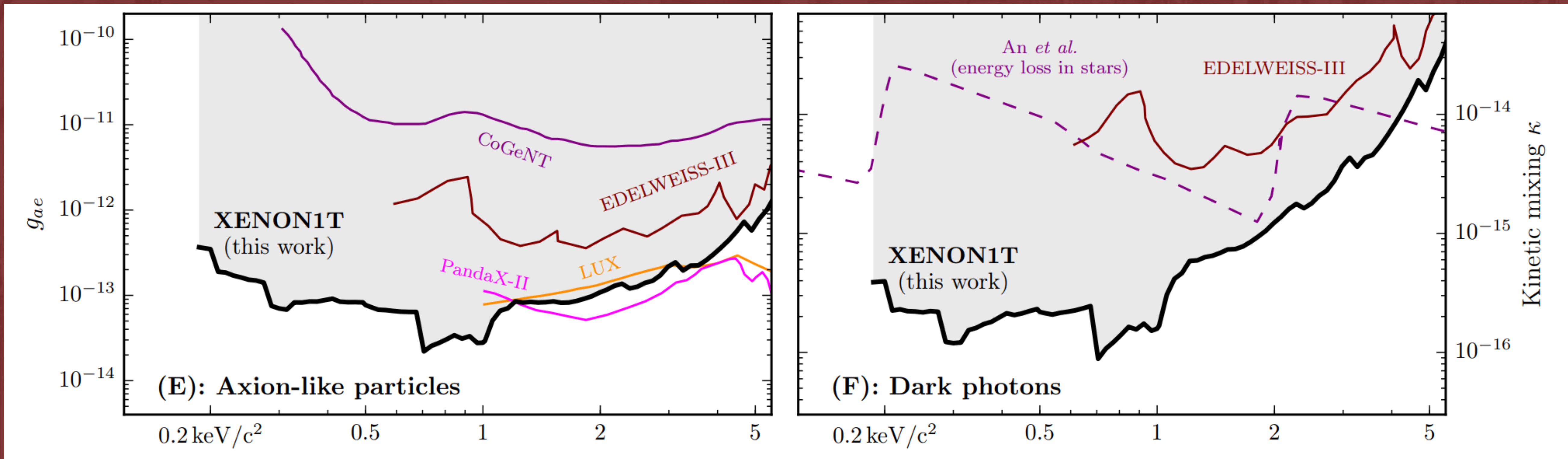
WIMP-Nucleon Couplings

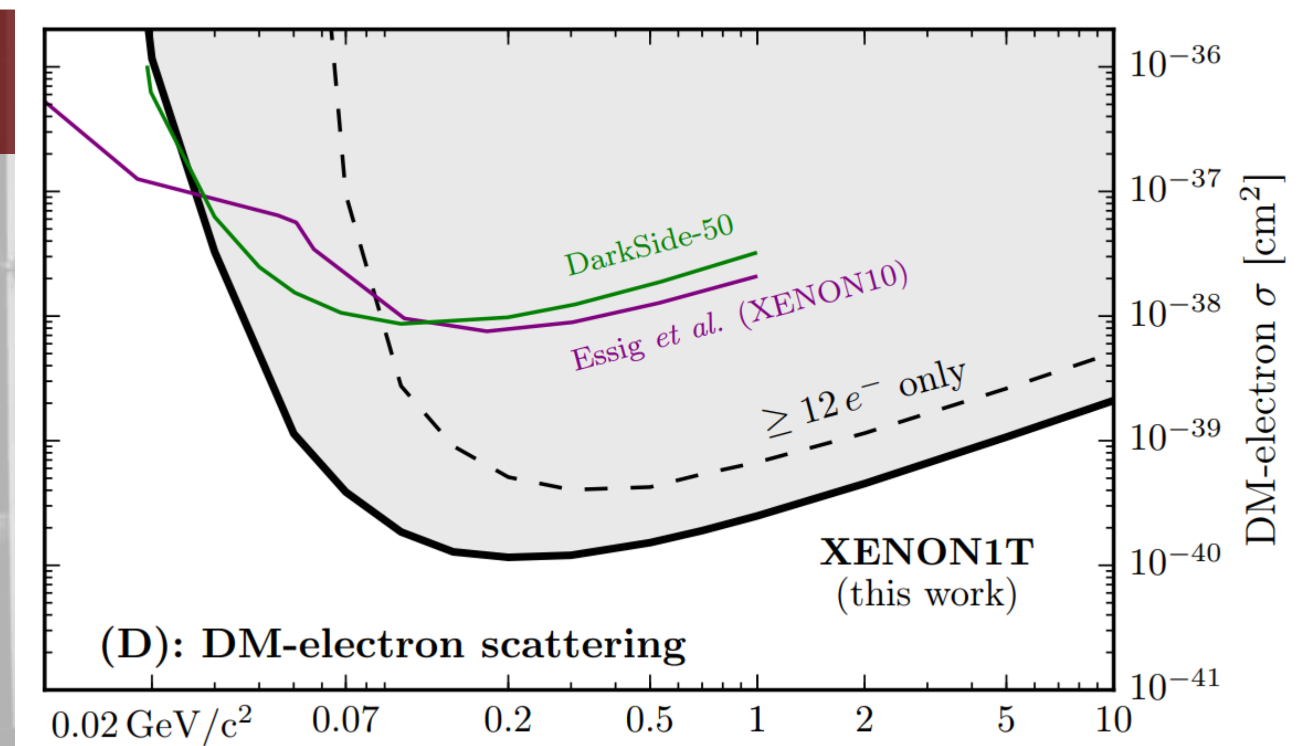


- Same astrophysical and particle physics models as used in the standard S1-S2 analysis used fo SI and SD results
- Step features in limits are due to discrete nature of ROIs used for different WIMP masses
- Investigate light mediator which scales differential scattering rate by m_ϕ^4 (m_ϕ is the mediator mass)



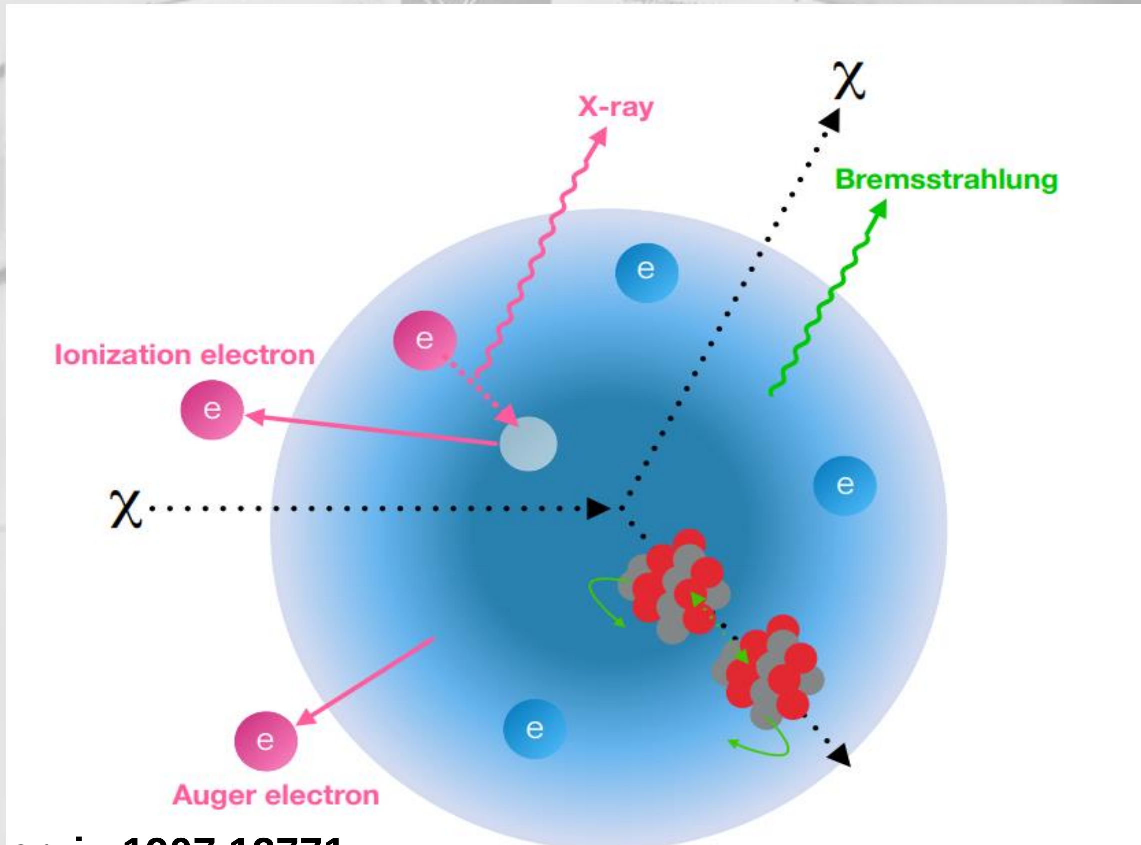
Dark Matter Models



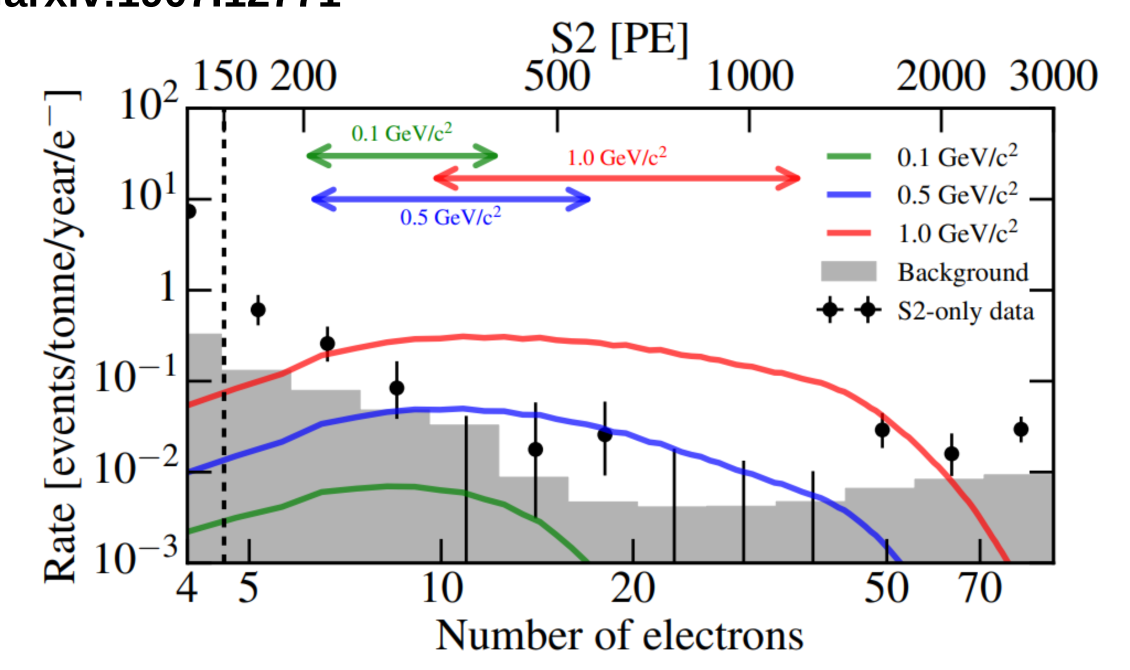


- **Search for DM electron scattering using non-relativistic approach. Conservative compared to relativistic predictions**
- **Bosonic DM candidates, e.g. dark photons and axion-like particles, can be absorbed by Xenon atoms.**

Migdal Process



arxiv:1907.12771



After DM scatter off of Xe nuclei, atom is polarized and results in sudden kinetic boost of atomic electrons

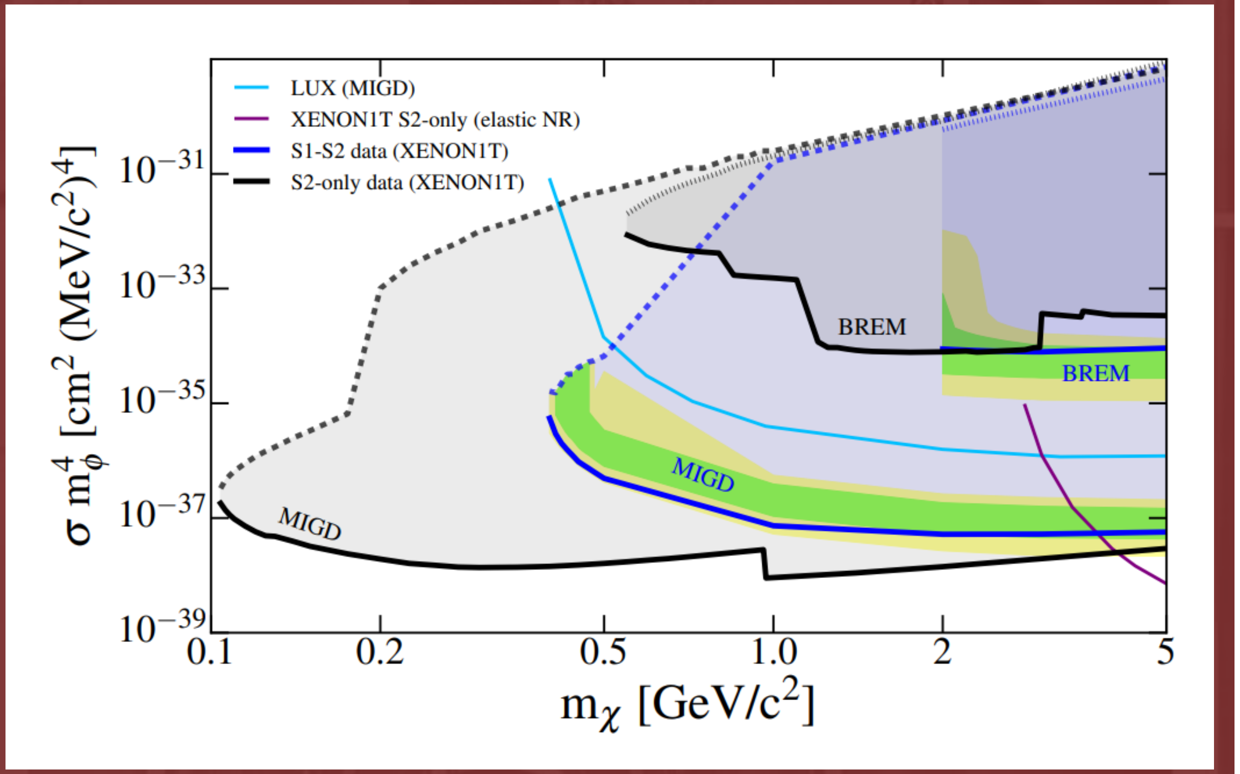
De-polarization can lead to Bremsstrahlung

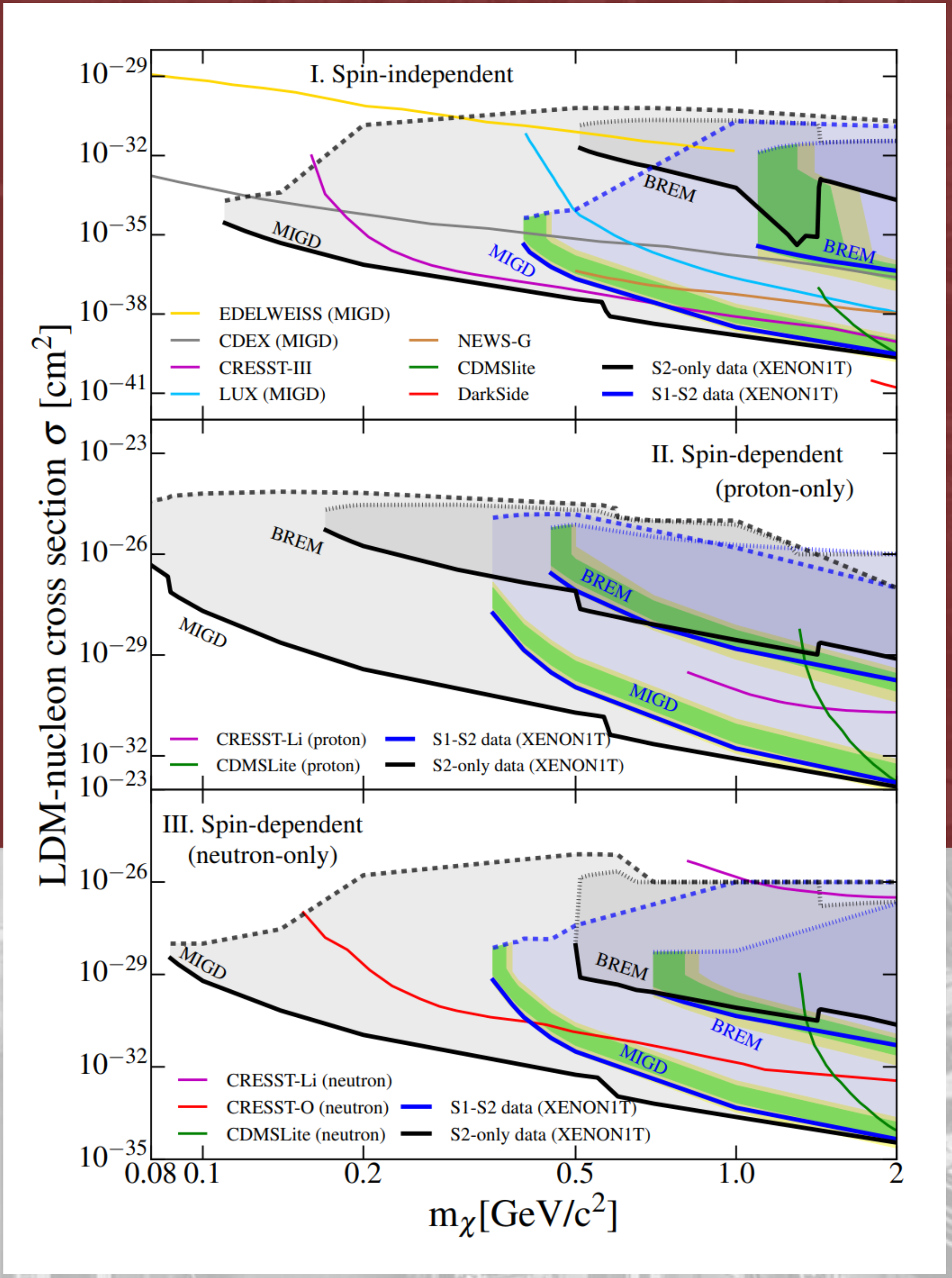
Kinematic boost can produce ionization or excitation, causing secondary radioation known as the Migdal effect

Search conducted in S1-S2 space, but since much of the signal lies below the S1 threshold, can pursue an S2-only search using the same techniques decsribed here.

Jacques Pienaar, jpienaar@uchicago.edu

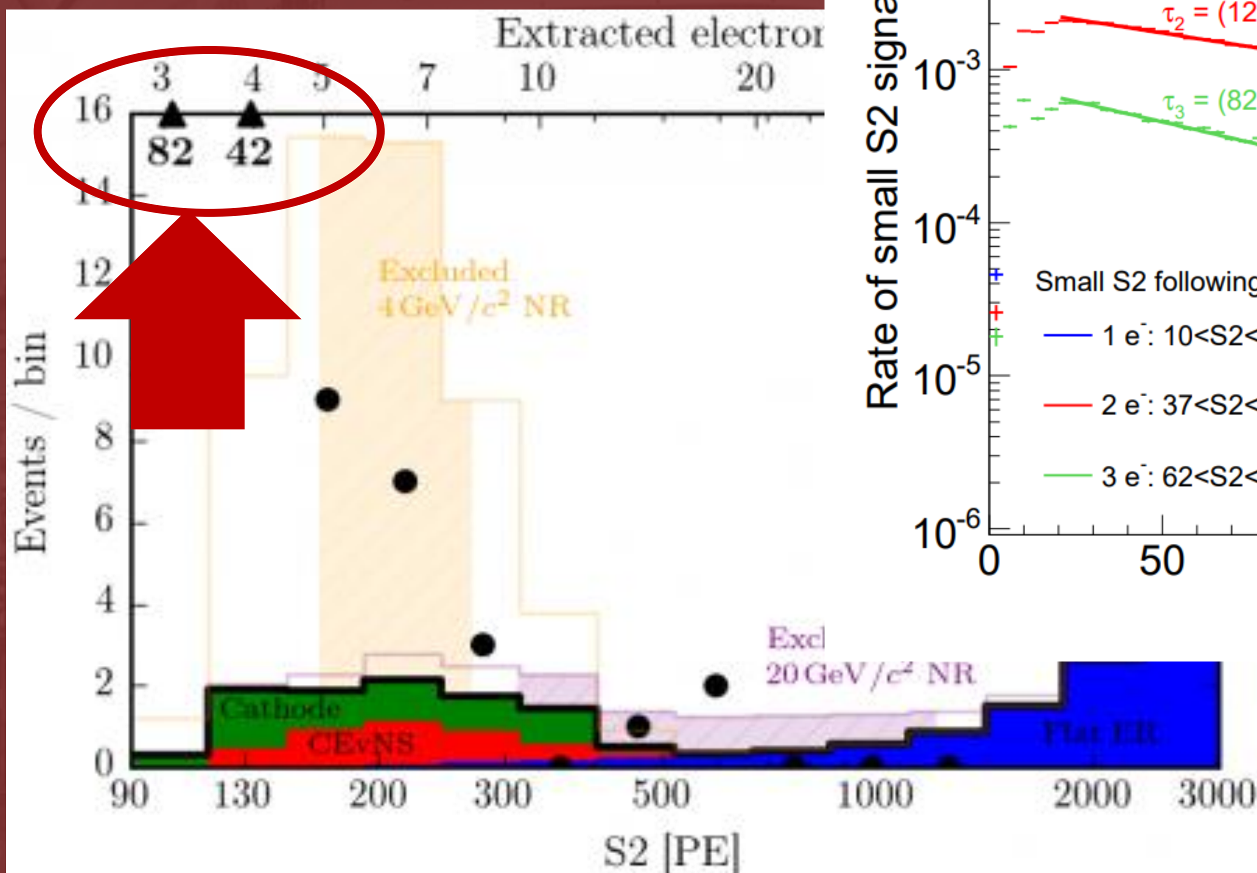
Migdal Process

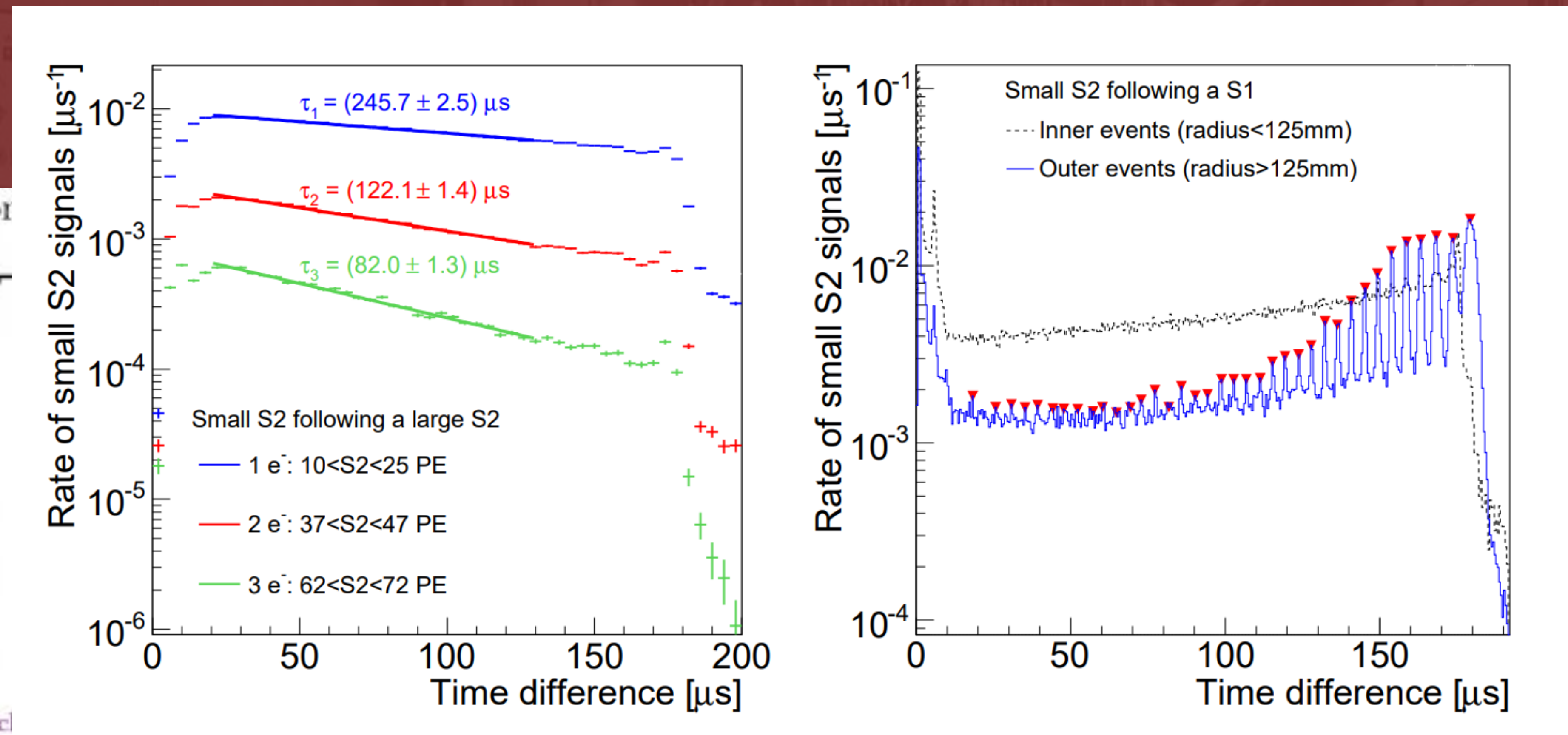


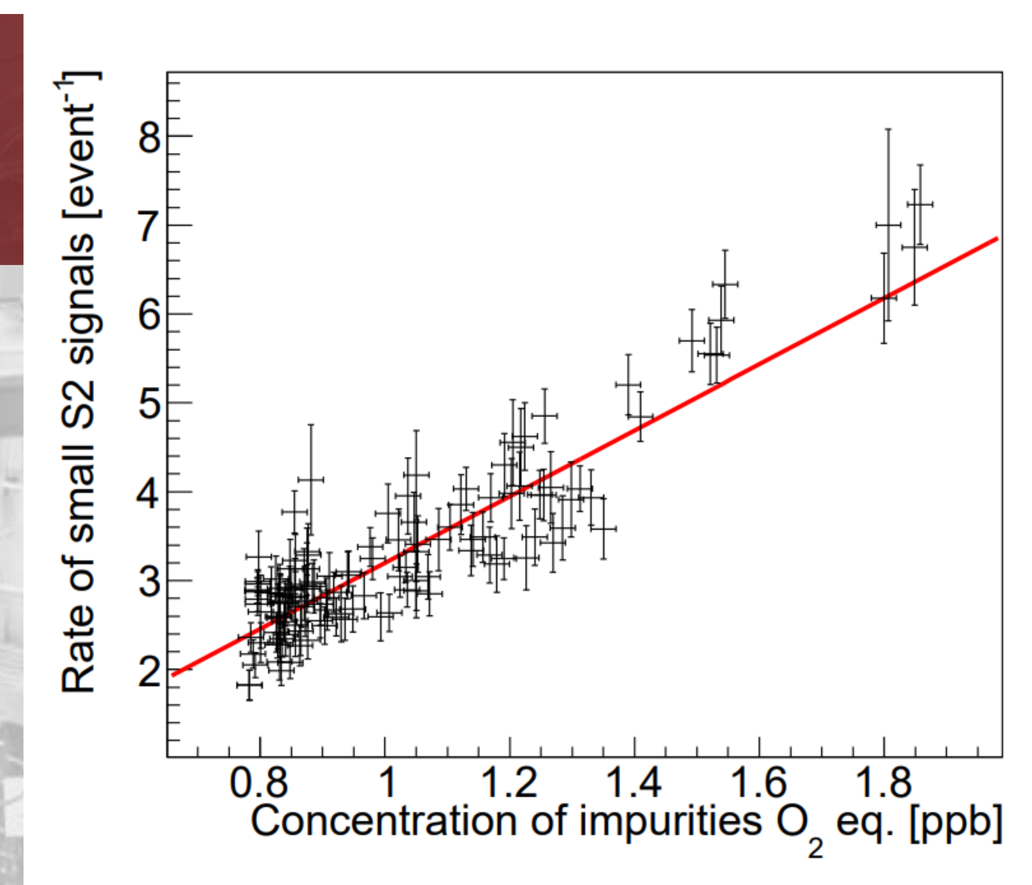


- **Able to set limits using both S1-S2 searches, and S2-only limits.**
- **Limits set using unbinned profile likelihood method and Poisson statistics.**

Extending to Single Electron Regime

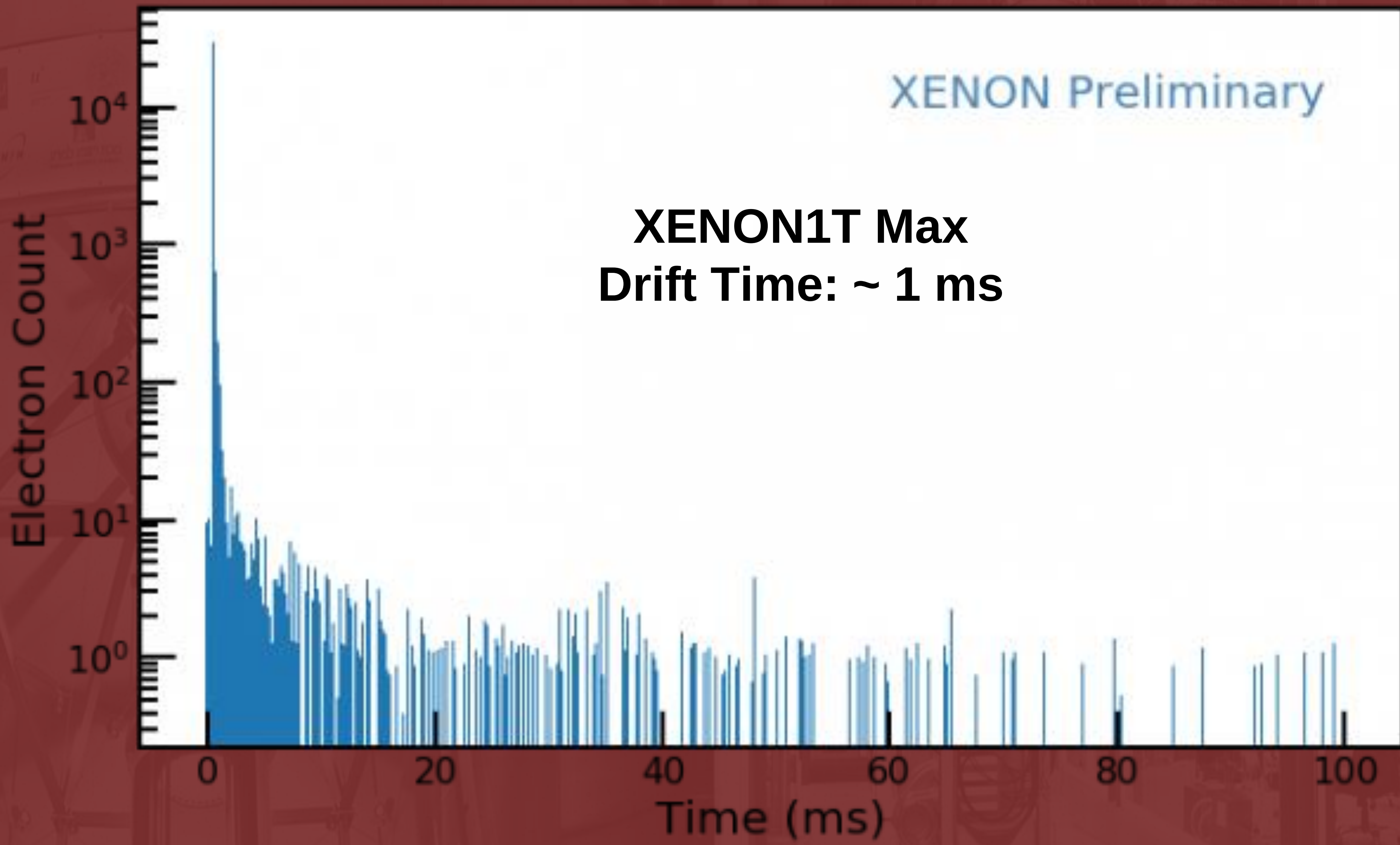






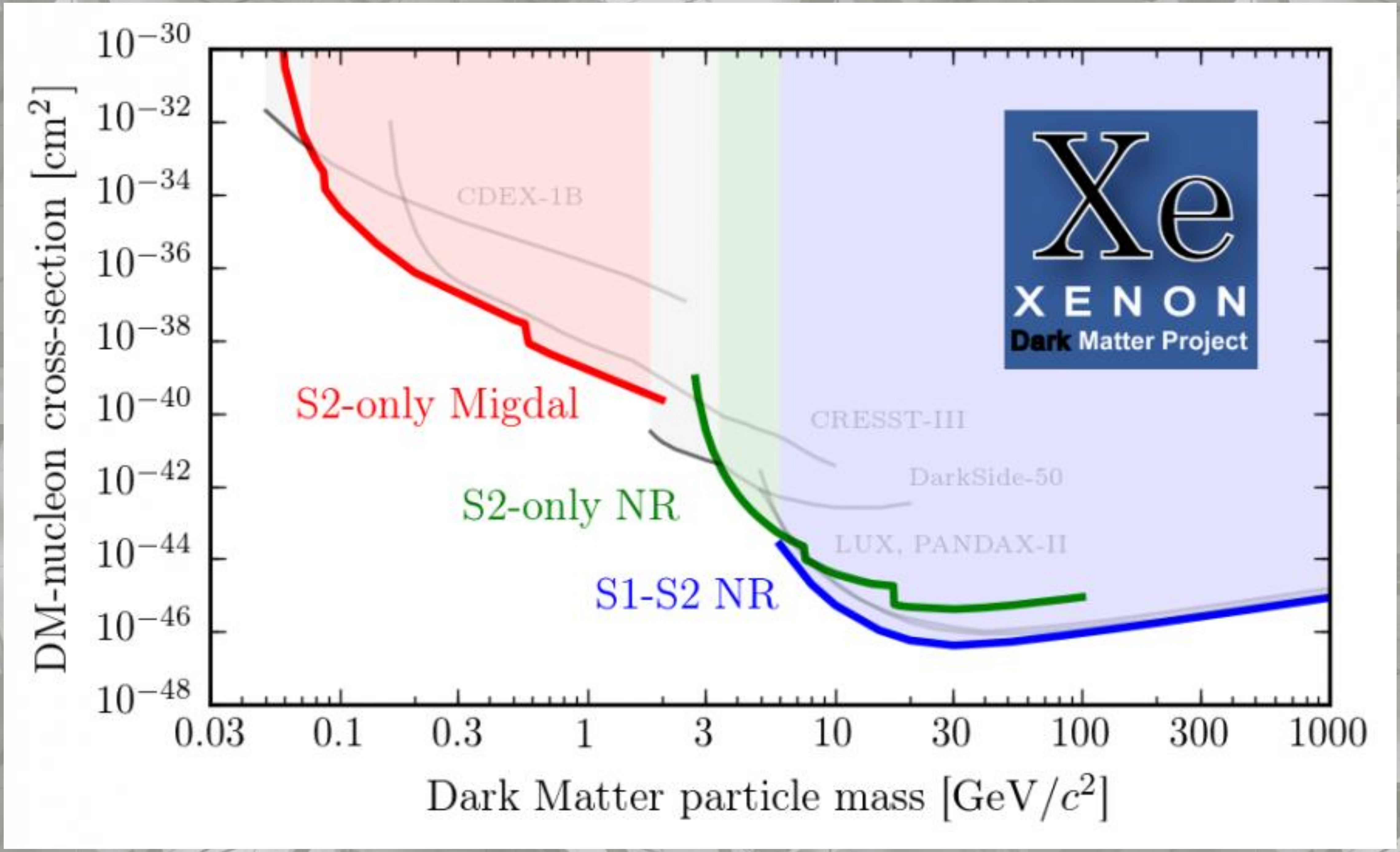
- **At few electron regime (<~150 PE/5 Electrons) rate of bakcground increases dramatically**
- **Vast majority of Ses observed originate from photo-ionization of metal surfaces and impurities in the detector.**
- **Can simply be vetoed away**

Next frontier: Long Lived SEs



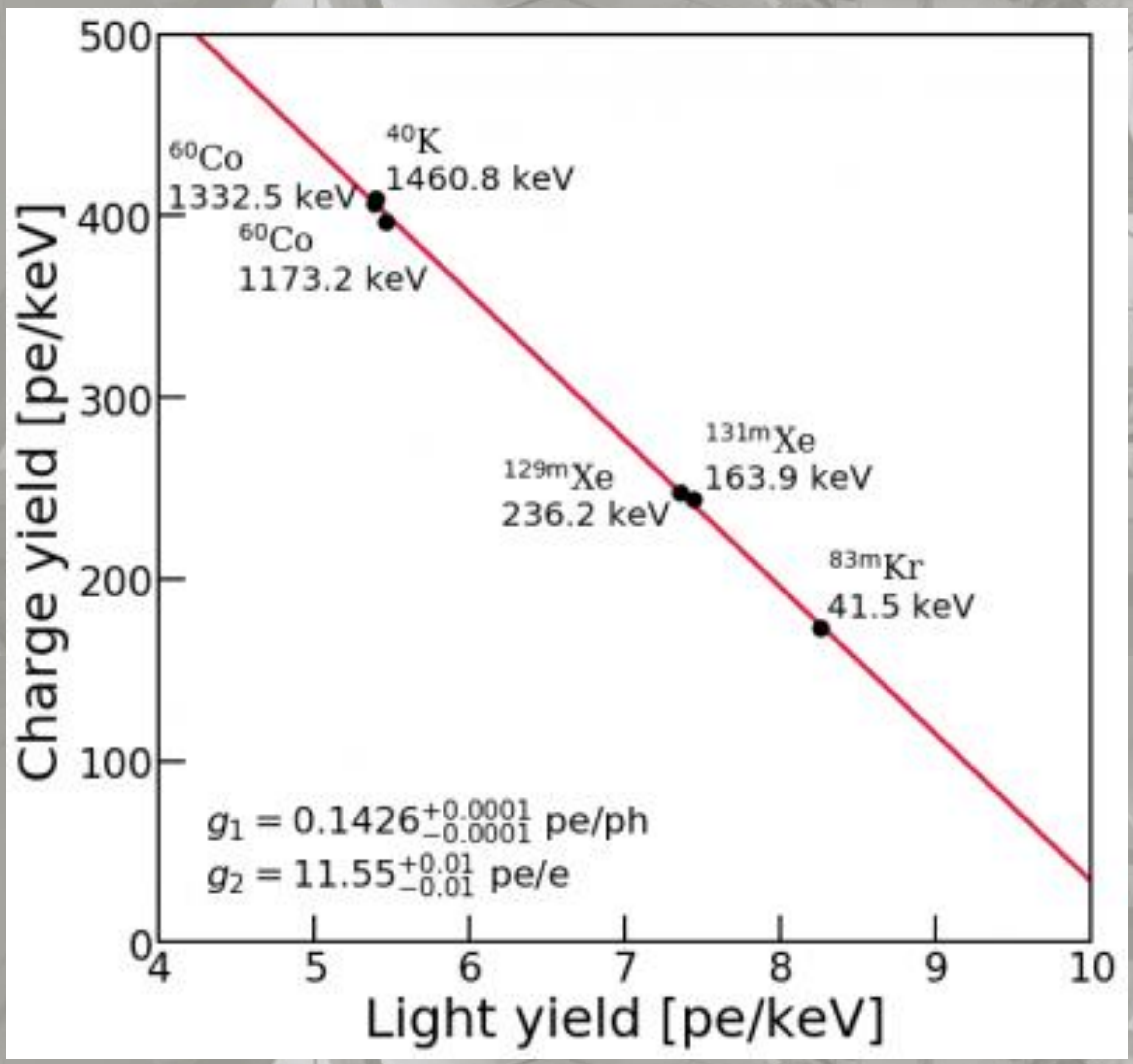
- **Observe SE emission emitted well after 1 drift length in XENON1T**
- **Emission of these long-lived SEs is correlated to large energy deposition in the Lxe**
- **Decays away over timescale of 10s of ms.**

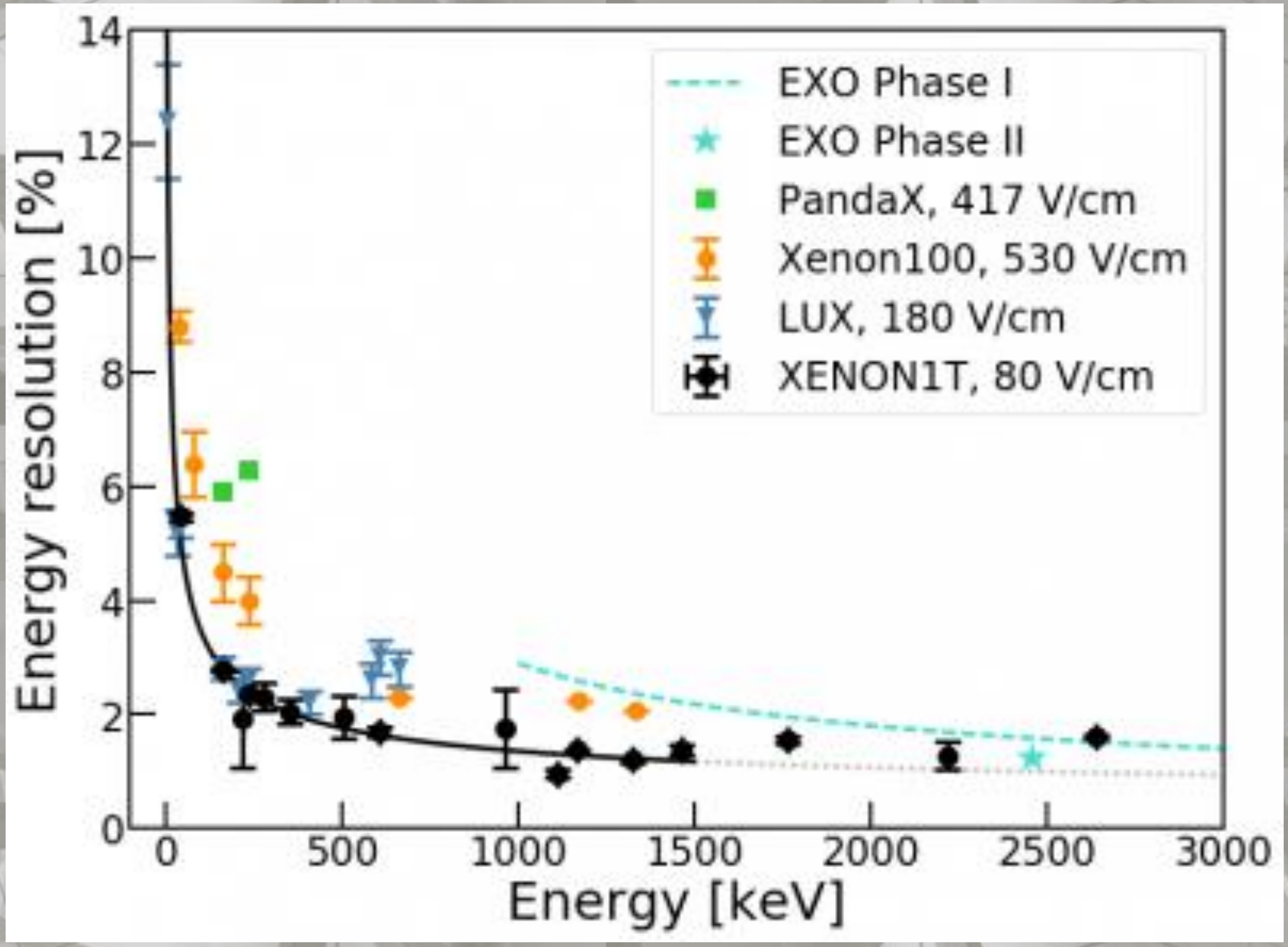
Jacques Pienaar, jpienaar@uchicago.edu



Jacques Pienaar, jpienaar@uchicago.edu

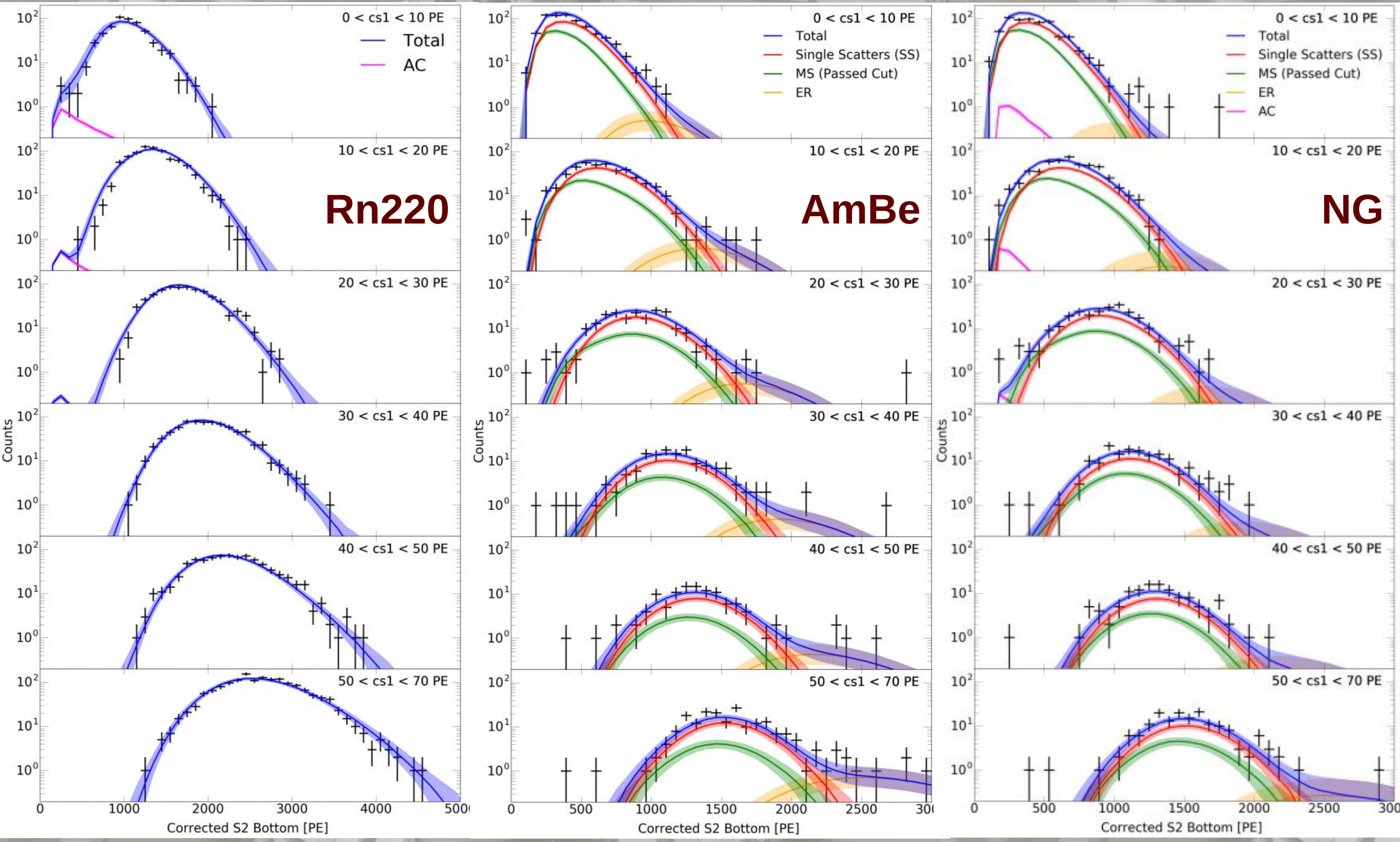
Energy Resolution





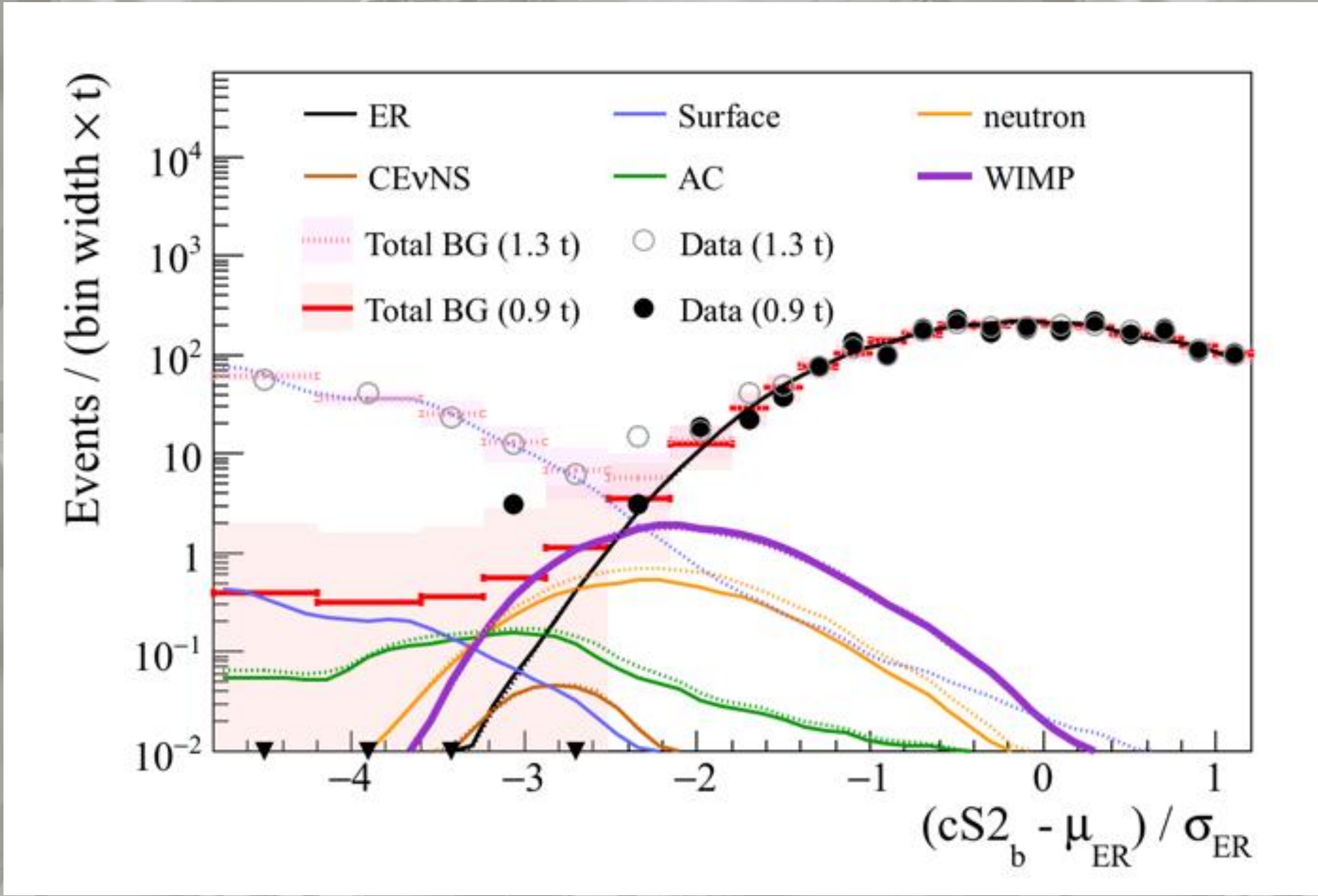
Jacques Pienaar, jpienaar@uchicago.edu

Calibration Fits



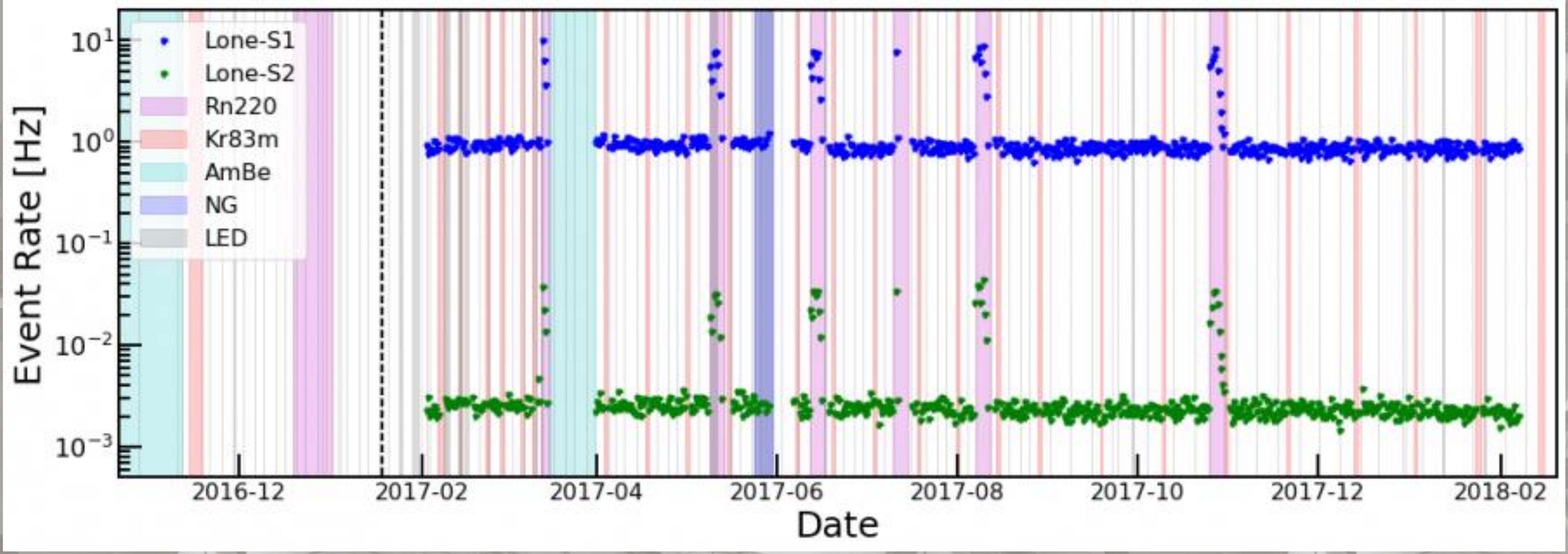
Jacques Pienaar, jpienaar@uchicago.edu

Model/Data Comparison



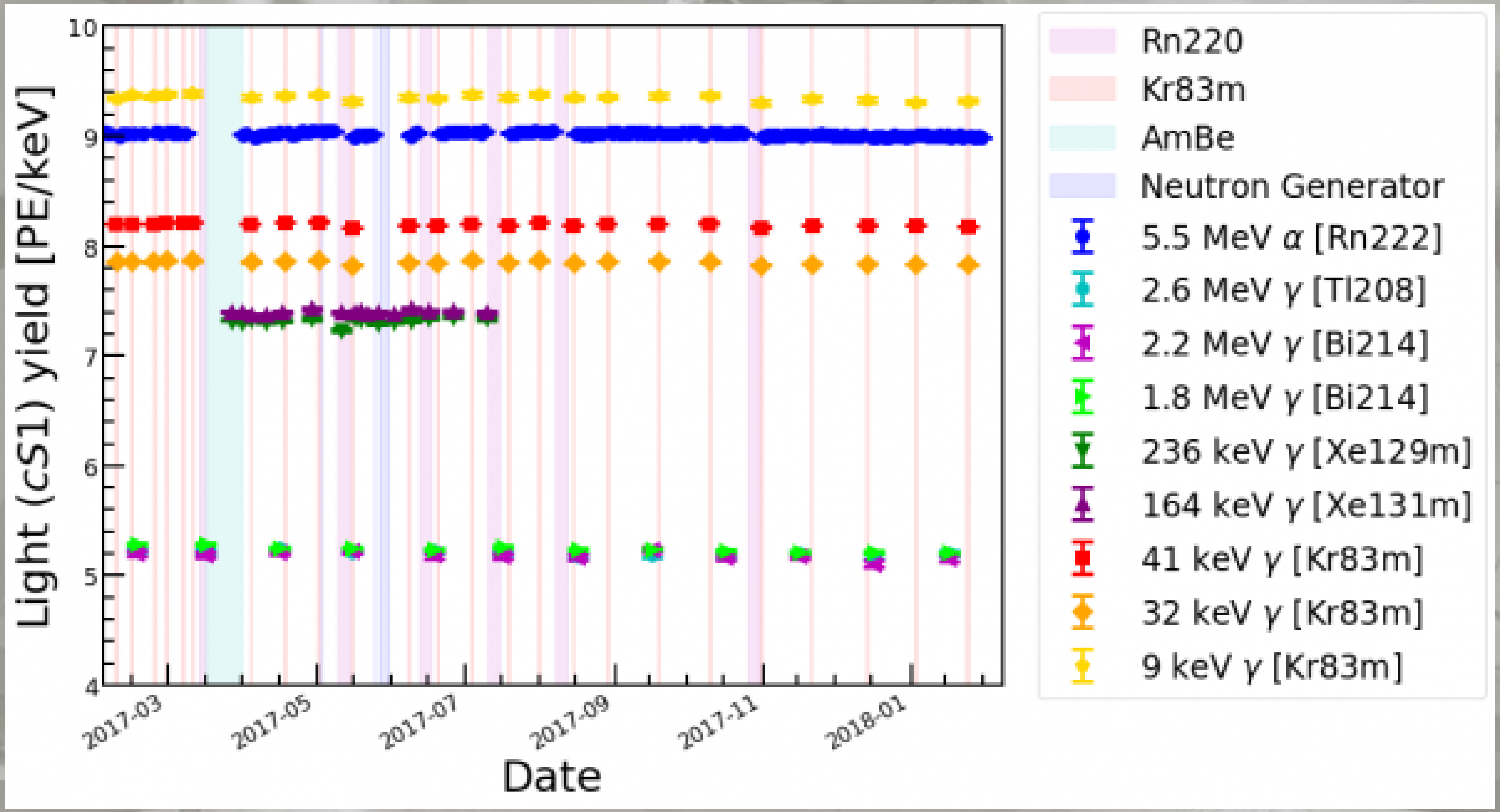
Jacques Pienaar, jpienaar@uchicago.edu

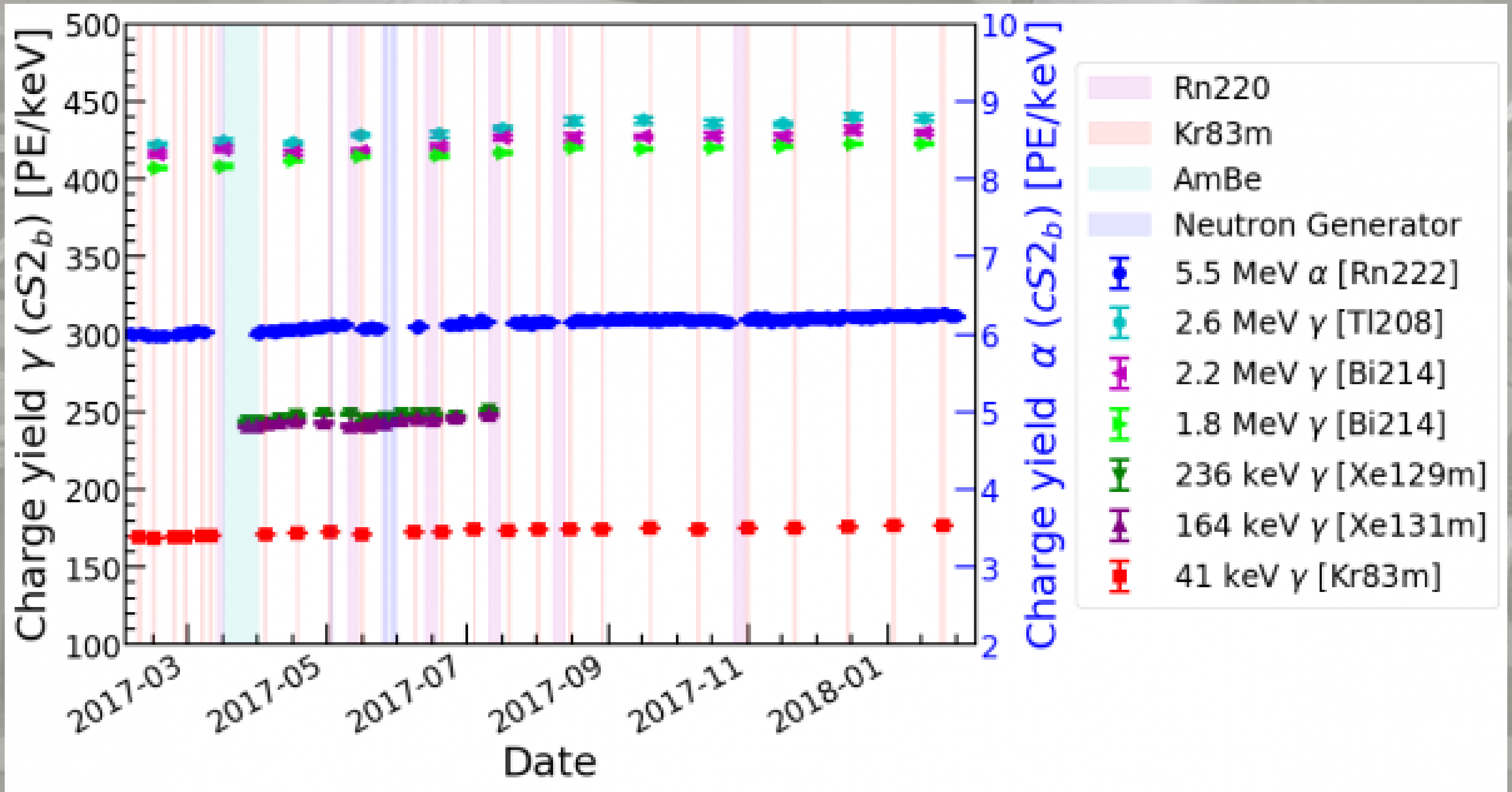
Lone S1/S2 Rate



Jacques Pienaar, jpienaar@uchicago.edu

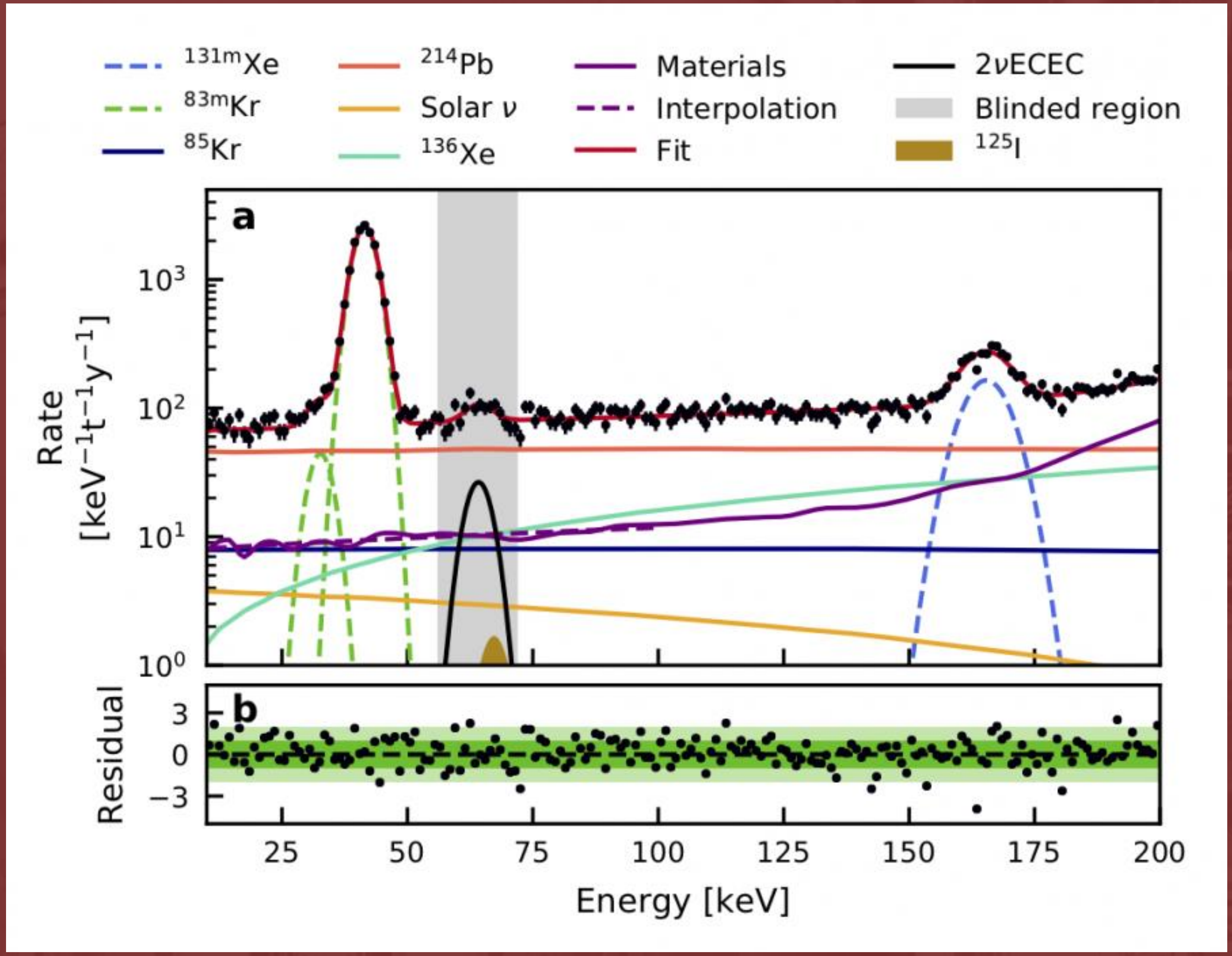
Light/Charge Yield Stability

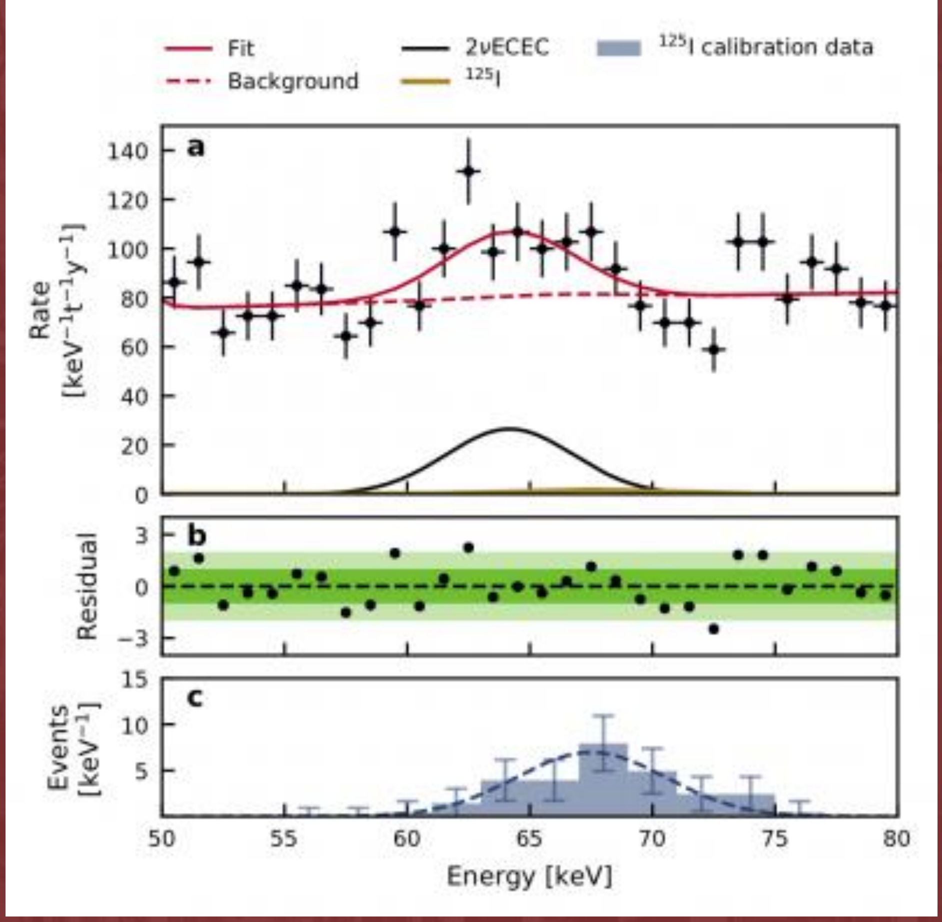




Jacques Pienaar, jpienaar@uchicago.edu

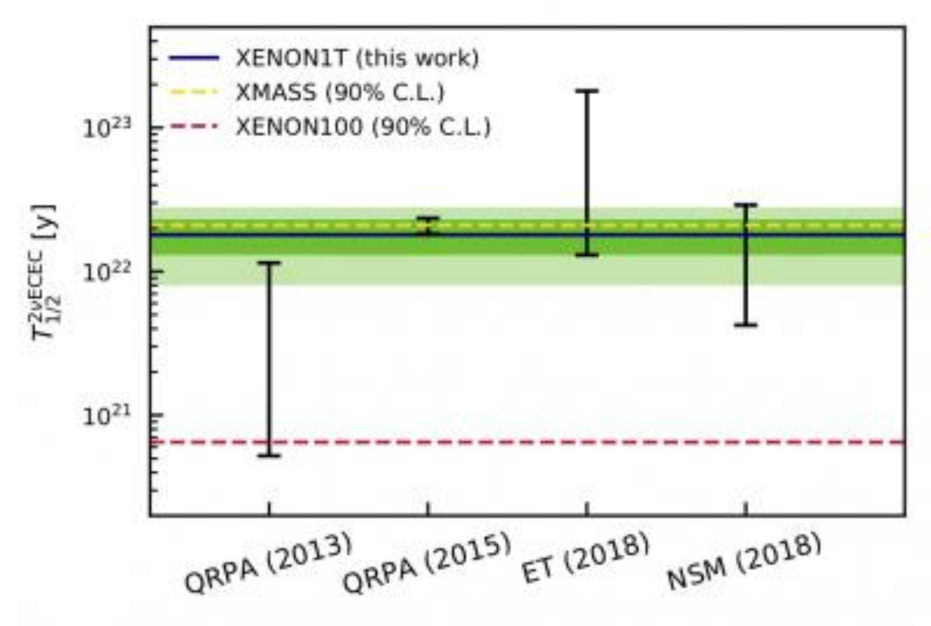
Double Electron Capture





Nature 568, 532–535 (2019)

- **Constrained ^{125}I background using dedicated activation measurements with neutron generator**
- **Measured double ecetron capture deacy half-life of ^{124}Xe**
- **Longest lived process ever measured (1.8 +- 0.5$_{stat}$ +- 0.1$_{sys}$) x10^{22} years**



XENON Infrastructure

Jacques Pienaar, jpienaar@uchicago.edu