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DIRECT DETECTION OF DARK MATTER

RECENT RESULTS

PHENO2021 PRESENTATION MAY 25 2021

INTRODUCTION TO DARK MATTER AND DIRECT DETECTION

EXTENDING DIRECT DETECTION TO DARK MATTER-ELECTRON SCATTERING

LOWERING ENERGY THRESHOLDS FOR TWO-PHASE LIQUID XENON TPCS

ELECTRONIC RECOIL SEARCHES

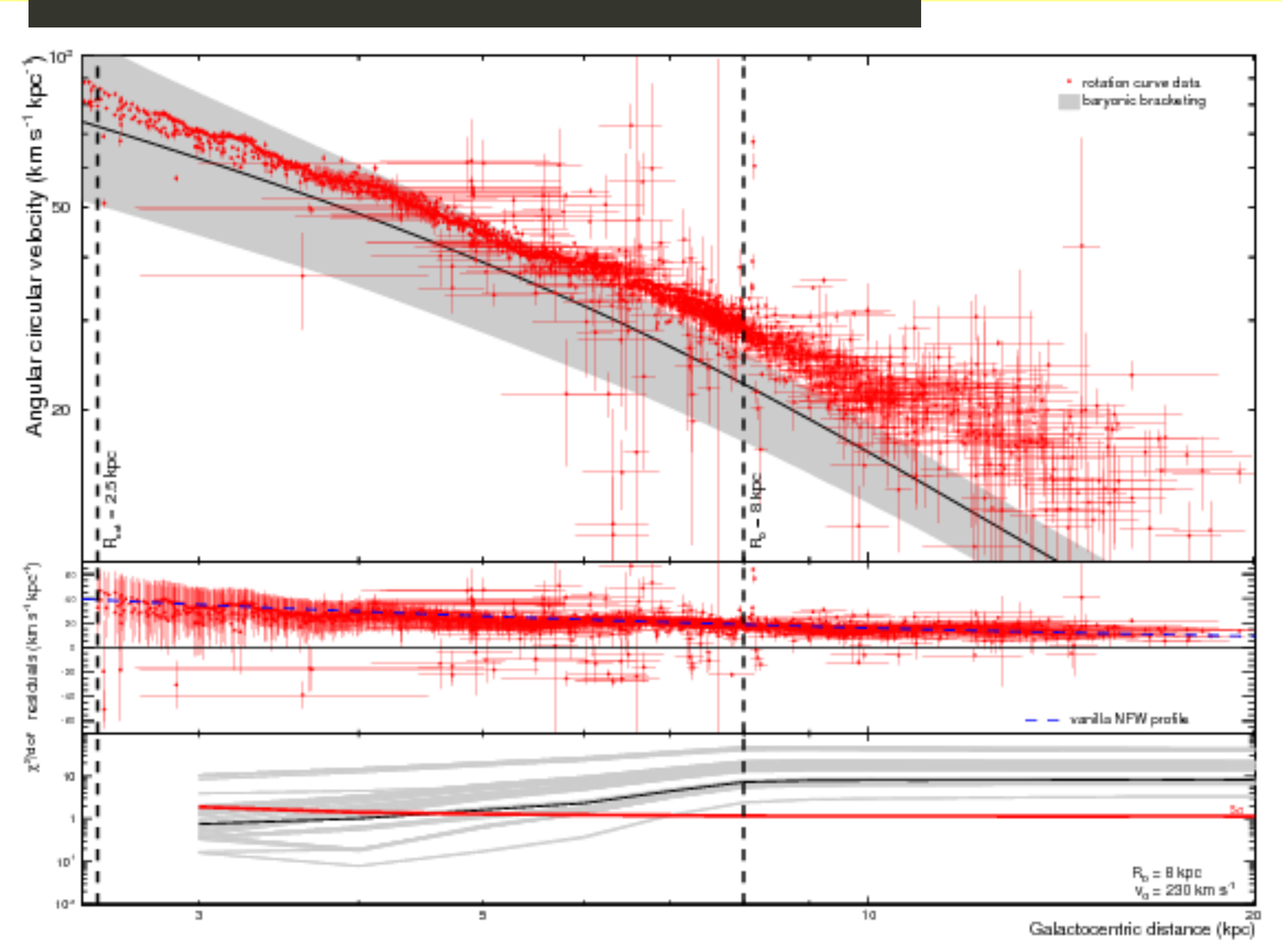
INTRODUCTION TO DARK MATTER DIRECT DETECTION

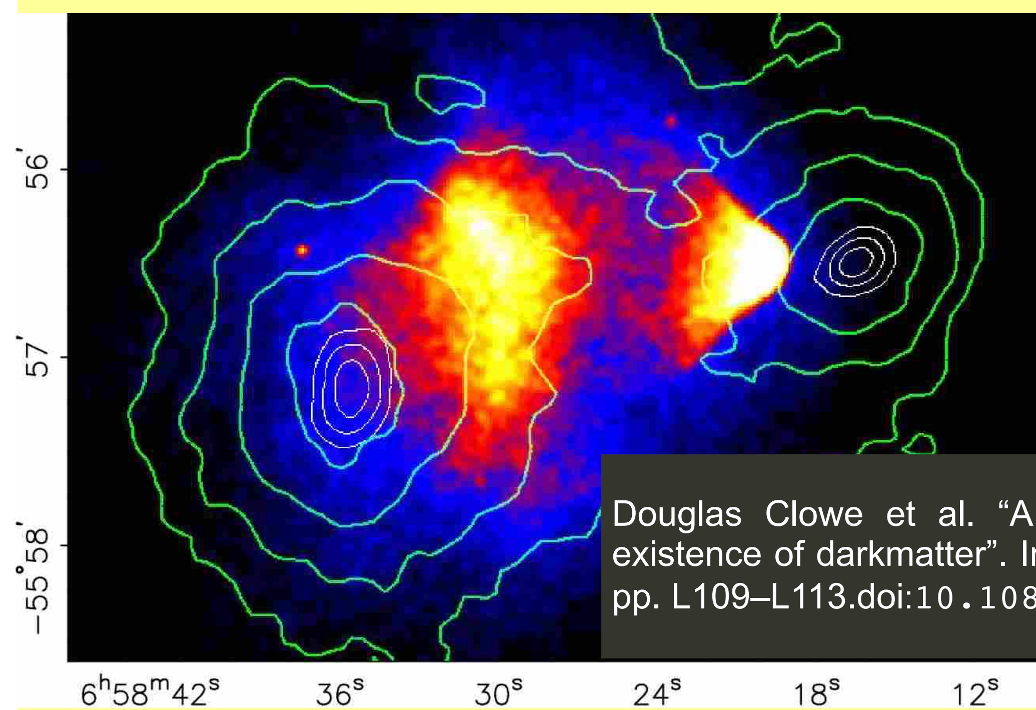
- Quick introduction to:
  - The evidence for dark matter
  - WIMP dark matter
- Direct detection signatures of dark matter
- (re) interpreting dark matter limits

DARK MATTER

- Cosmological and dynamical evidence are all consistent with ordinary matter being only a small part (15% or so) of matter in the universe
- Cluster mergers/collisions point towards a particle nature
- The dark matter density at the Sun’s distance from the Galactic Centre is estimated around $0.3\ \mathrm{GeV/c^2/cm^3}$

Fabio Iocco, Miguel Pato, and Gianfranco Bertone. “Evidence for darkmatter in the inner Milky Way”. In:Nature Phys.11 (2015), pp. 245–248.doi:10.1038/ nphys3237.

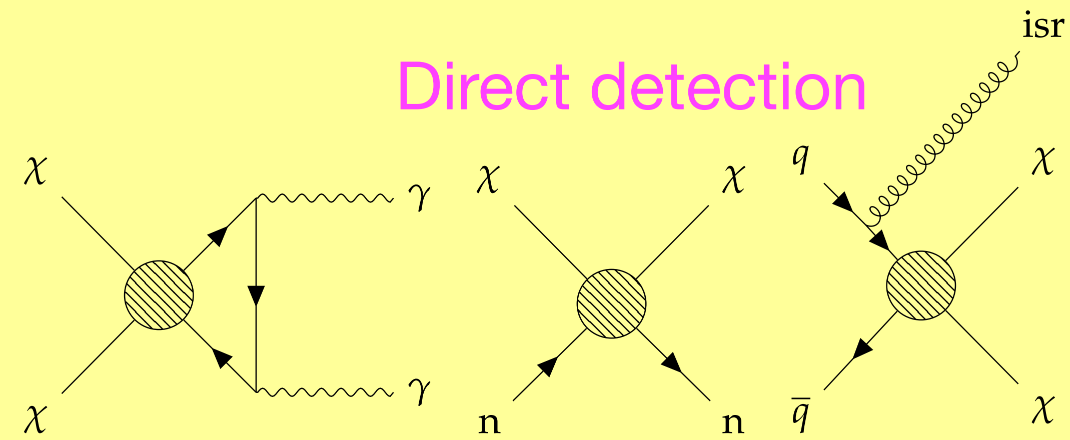


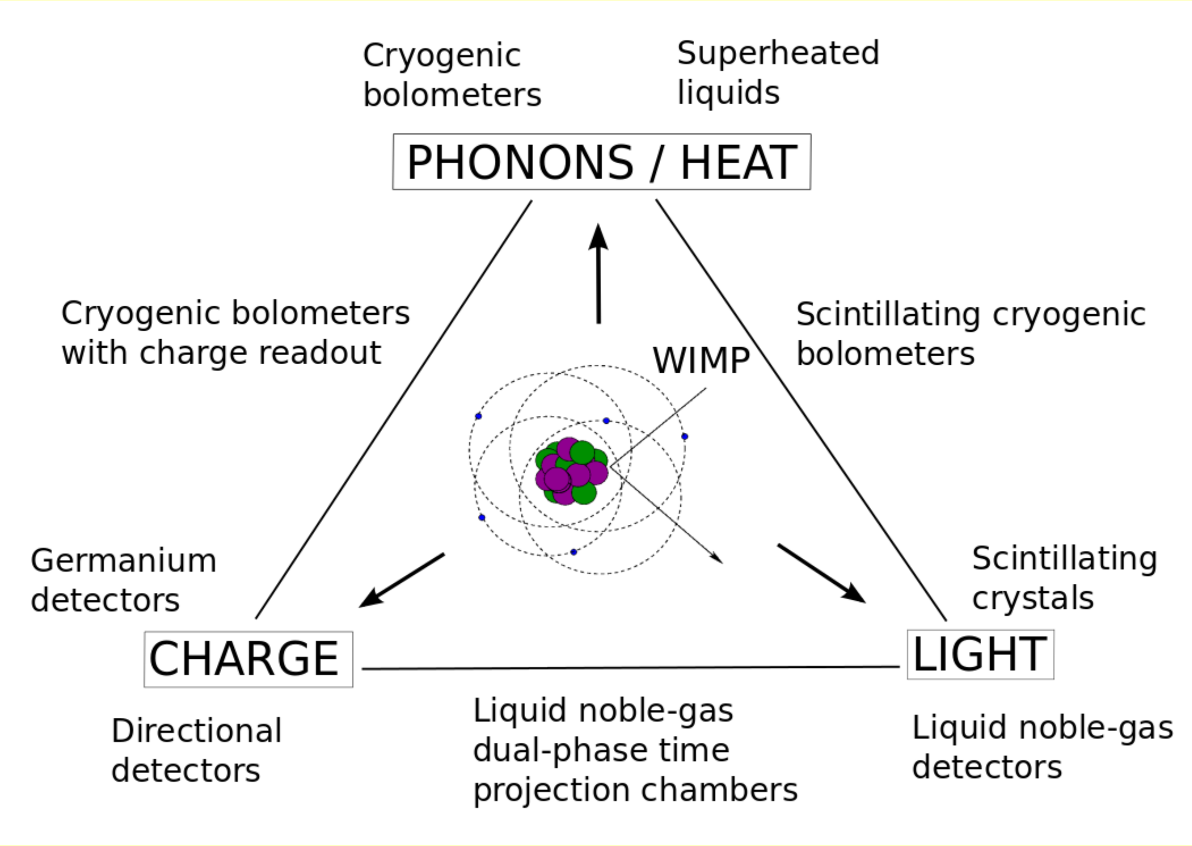


Douglas Clowe et al. “A direct empirical proof of the existence of darkmatter”. In:Astrophys. J. Lett.648 (2006), pp. L109–L113.doi:10.1086/508162.

DIRECT DETECTION

- Searches for dark matter particles interacting directly with a dark matter detector
- Energy deposited in the detector target is deposited into:
  - Phonons (in crystals) or heat
  - Ionisation / charge
  - Scintillation light
- Using more than one observable can allow some degree of discrimination between different recoil types



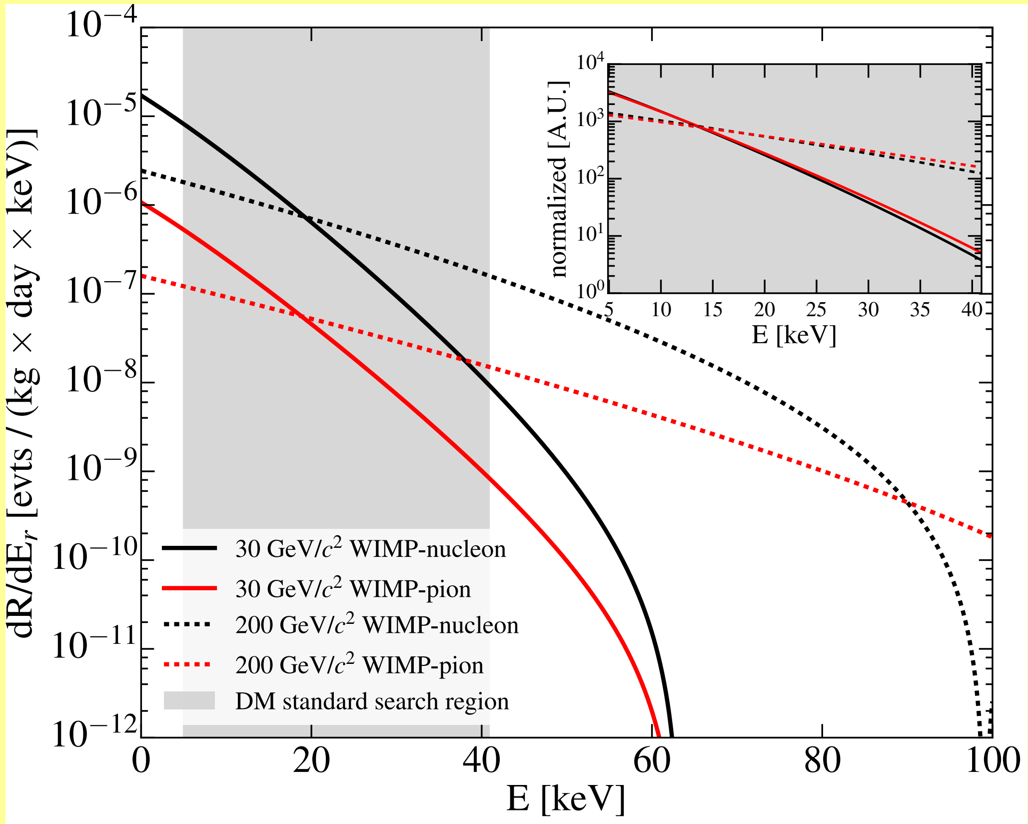


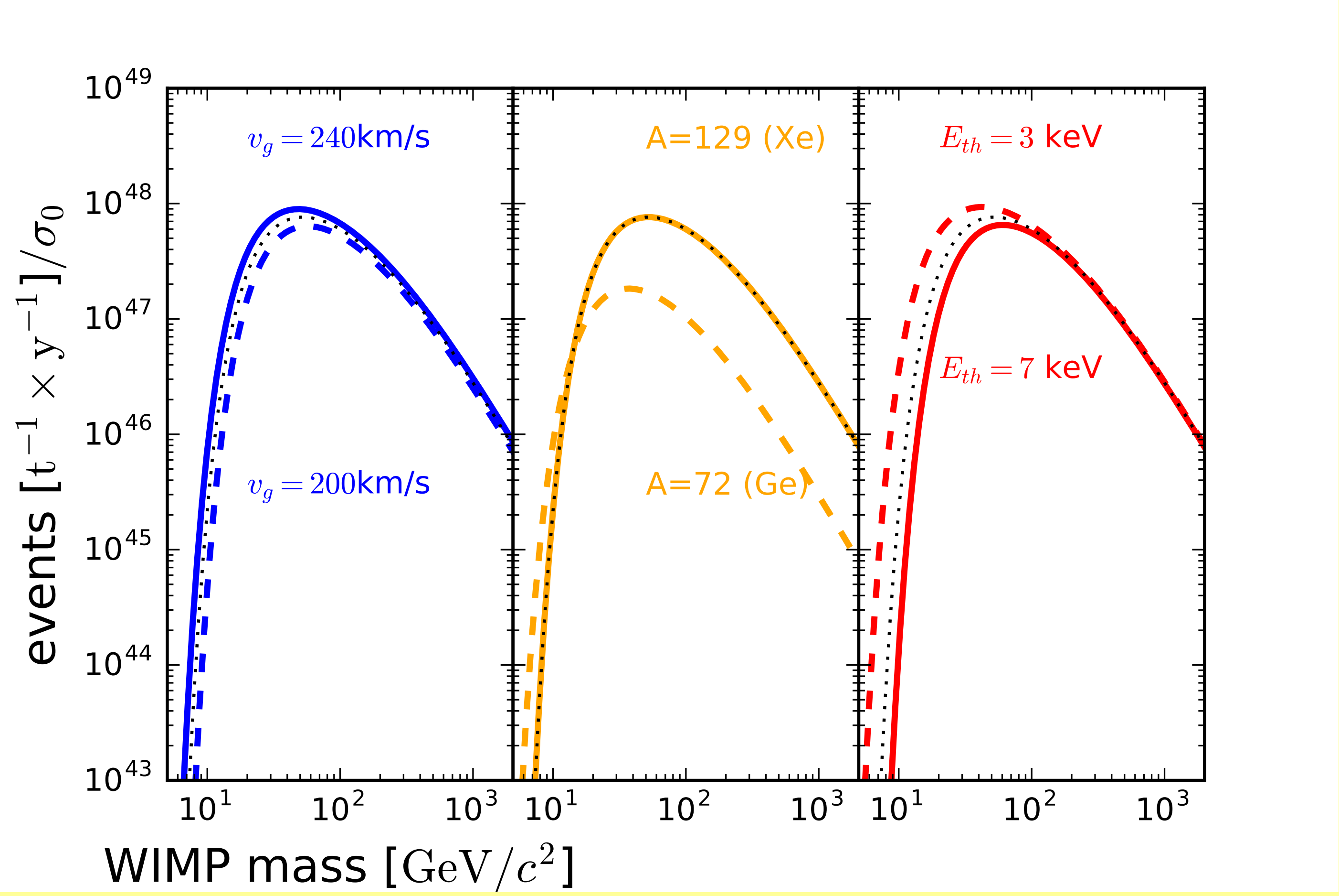
Teresa Marrodán Undagoitia and Ludwig Rauch. "Dark matter direct-detection experiments". In: J. Phys. G43.1 (2016), p. 013001. DOI: 10.1088/0954-3899/43/1/013001.

DETECTING WIMP DARK MATTER

- At galactic velocities, a WIMP with typical weak-scale (GeV-TeV) would deposit some to tens of keV of nuclear recoil energy
- For low recoil energies, the WIMP scatters on the entire nucleus— coherent scattering boosts the rate by a factor A^2
- Transferred energy is maximised when the target nucleus and the WIMP have the same mass

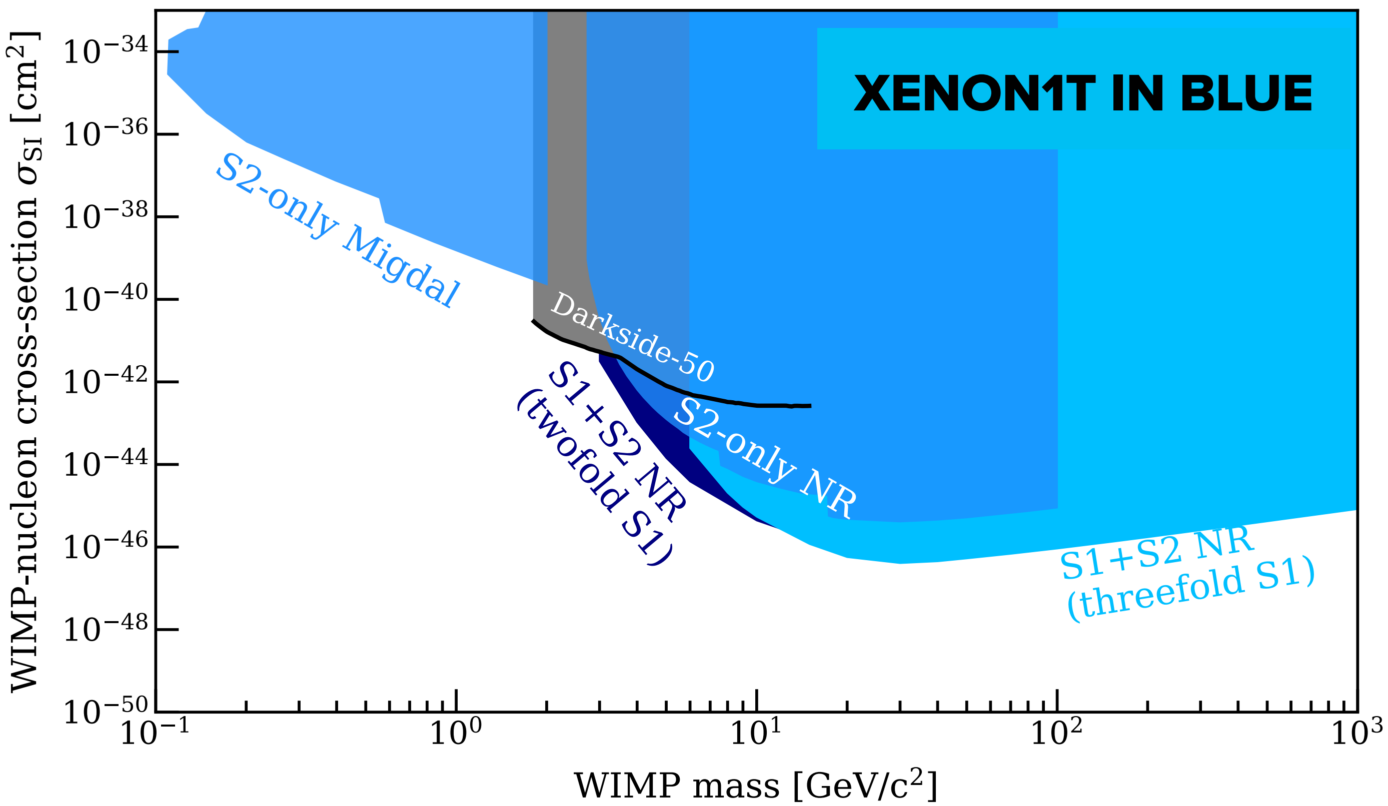
XENON collaboration. "First results on the scalar WIMP-pion coupling, using the XENON1T experiment." Physical review letters 122.7 (2019): 071301.



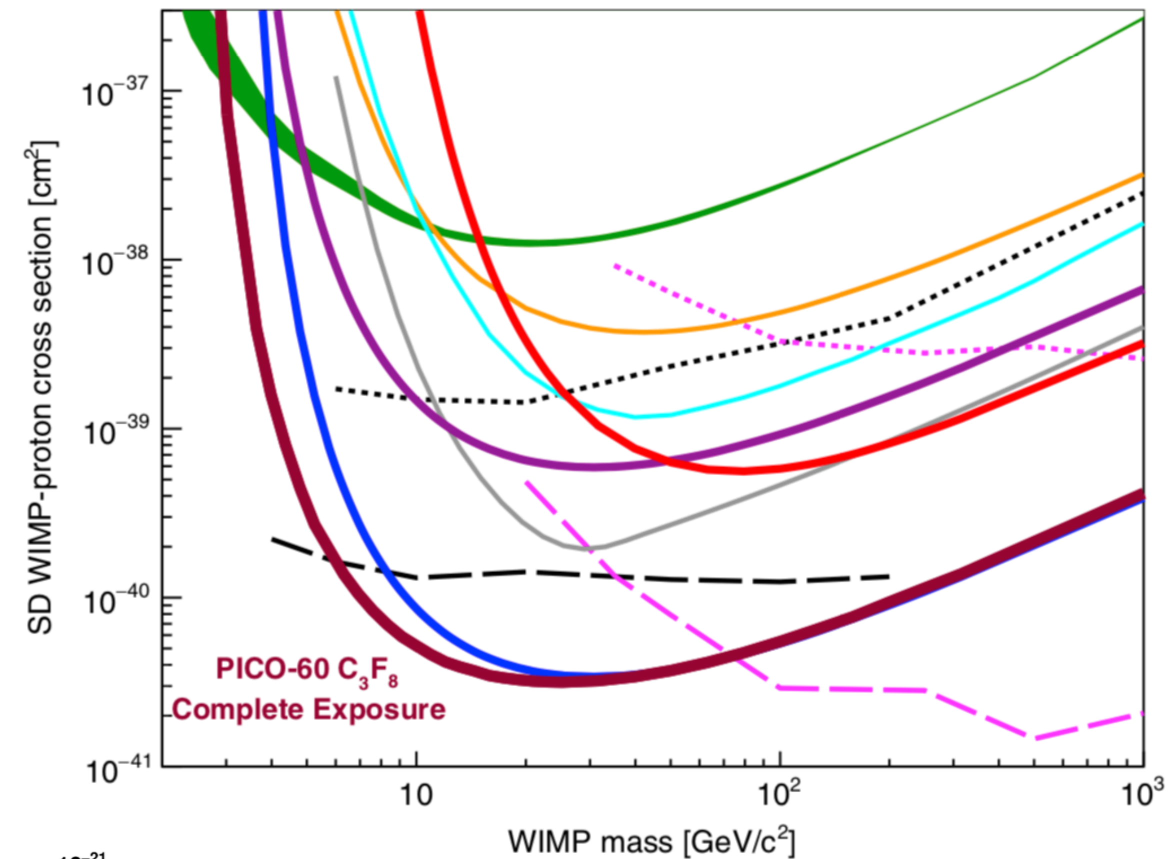


CLASSICAL WIMP RESULTS

SPIN-INDEPENDENT WIMP-NUCLEON

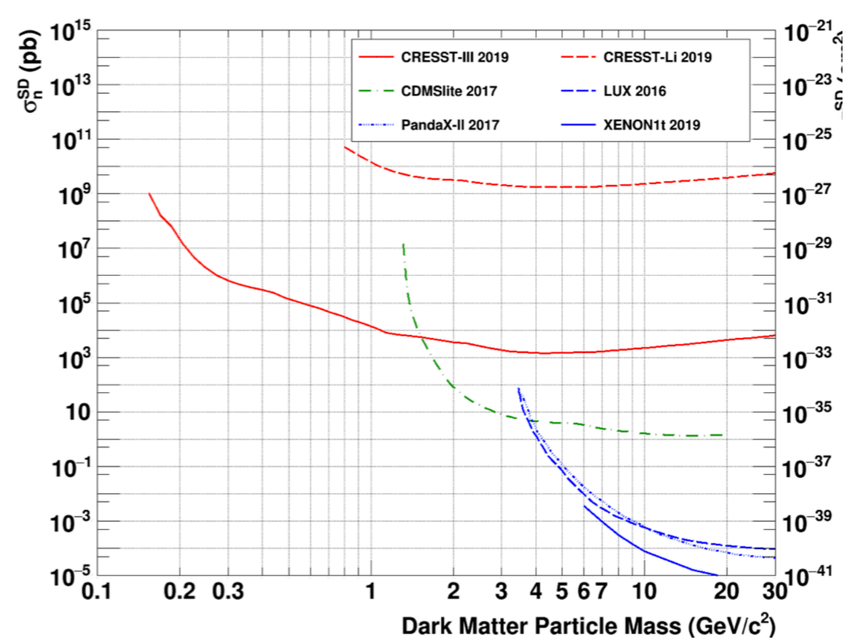


SPIN-DEPENDENT WIMP-PROTON



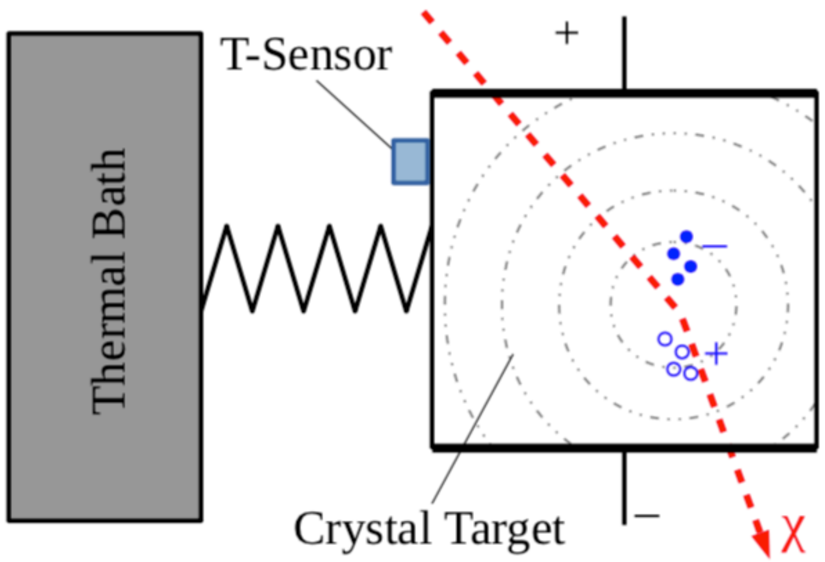
C. Amole et al. (PICO Collaboration). “Dark Matter Search Results from the Complete Exposure of the PICO-60 C3F8 Bubble Chamber”. In: Phys. Rev. D 100.2 (2019), p. 022001. doi: 10.1103/PhysRevD.100.022001.

SPIN-DEPENDENT WIMP-NEUTRON

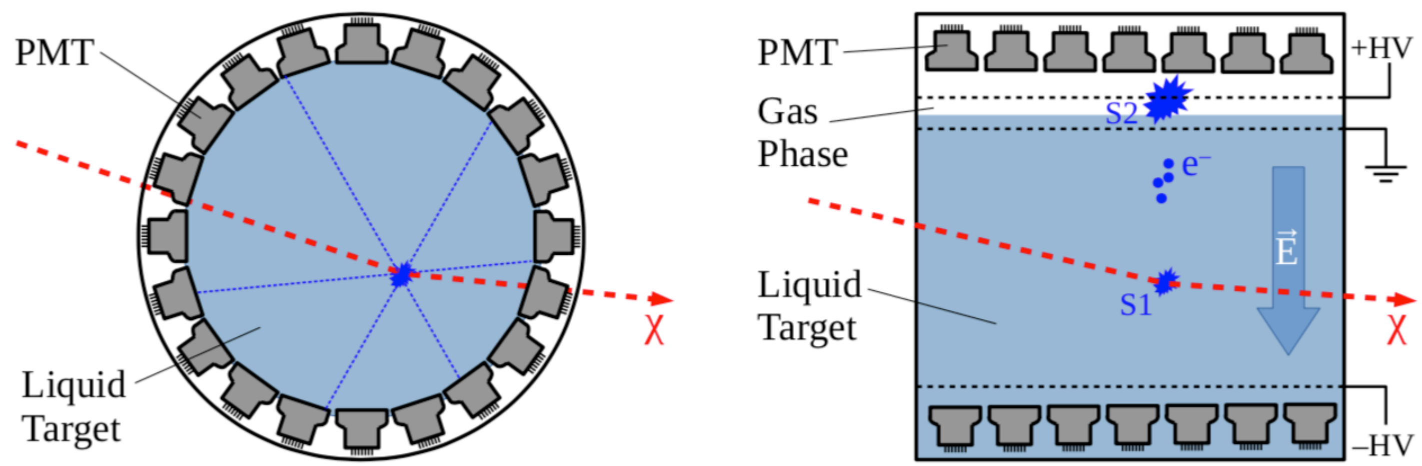


A. H. Abdelhameed et al. (CRESST Collaboration). “First results from the CRESST-III low-mass dark matter program”. In: Phys. Rev. D 100.10 (2019), p. 102002. doi: 10.1103/PhysRevD.100.102002

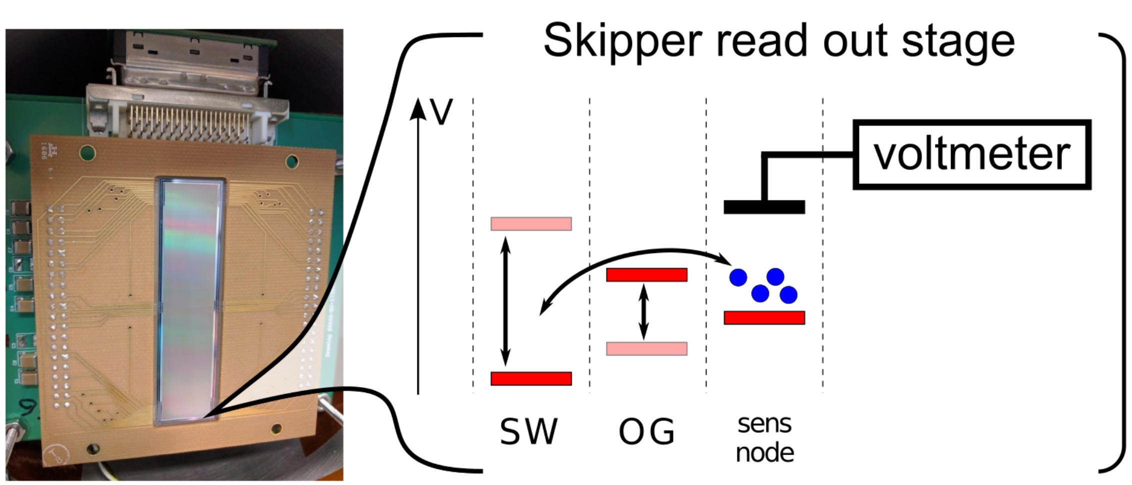
DETECTOR TECHNOLOGY EXAMPLES



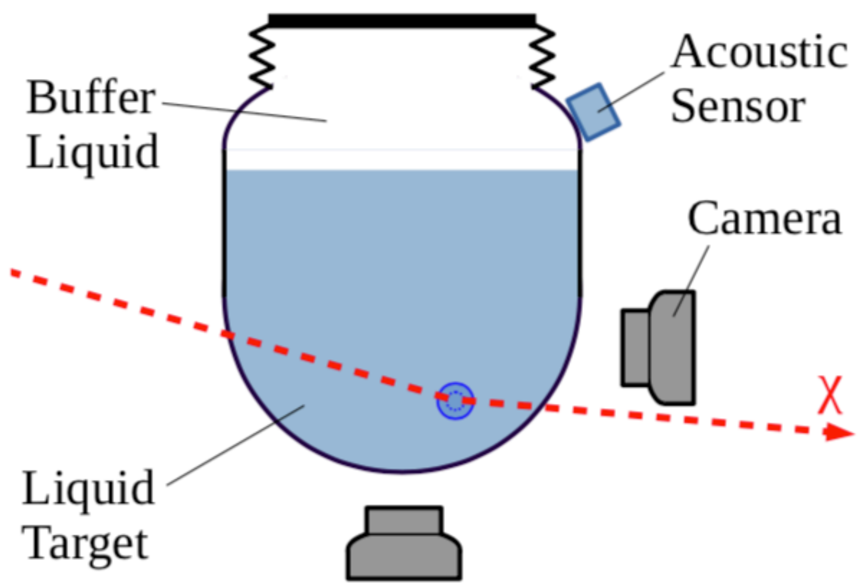
CRYOGENIC DETECTOR: HEAT & IONISATION



LIQUID NOBLE GAS 1- AND 2-PHASE TPCS



CCD READ OUT REPEATEDLY PER-PIXEL



BUBBLE CHAMBER

Figures except SENSEI from: Marc Schumann. “Direct Detection of WIMP Dark Matter: Concepts and Status”. In: J. Phys. G 46.10 (2019), p. 103003. doi: 10.1088/1361- 6471/ab2ea5.
SENSEI illustration from https://sensei-skipper.github.io/#SkipperCCD

MAKING DIRECT DETECTION LIMITS REINTERPRET ABLE

A. H. Abdelhameed et al. (CRESST Collaboration). “Description of CRESST- III Data”. (May 2019). arXiv: 1905.07335

[Submitted on 17 May 2019 (v1), last revised 6 Apr 2020 (this version, v3)]

Description of CRESST-III Data

CRESST Collaboration: A. H. Abdelhameed, G. Angloher, P. Bauer, A. Bento, E. Bertoldo, C. Bucci, L. Canonica, A. D'Addabbo, X. Defay, S. Di Lorenzo, A. Erb, F. v. Feilitzsch, S. Fichtinger, N. Ferreiro Iachellini, A. Fuss, P. Gorla, D. Hauff, J. Jochum, A. Kinast, H. Kluck, H. Kraus, A. Langenkämper, M. Mancuso, V. Mokina, E. Mondragon, A. Münster, M. Olmi, T. Ortmann, C. Pagliarone, L. Pattavina, F. Petricca, W. Potzel, F. Pröbst, F. Reindl, J. Rothe, K. Schäffner, J. Schieck, V. Schipperges, D. Schmiedmayer, S. Schönert, C. Schwertner, M. Stahlberg, L. Stodolsky, C. Strandhagen, R. Strauss, C. Türkoglu, I. Usherov, M. Willers, V. Zema

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Ancillary files (details):
- C3P1_DetA_AR.dat
- C3P1_DetA_DataRelease_SD.xy
- C3P1_DetA_DataRelease_SI.xy
- C3P1_DetA_cuteff.dat
- C3P1_DetA_eff_AR_Ca.dat

(3 additional files not shown)

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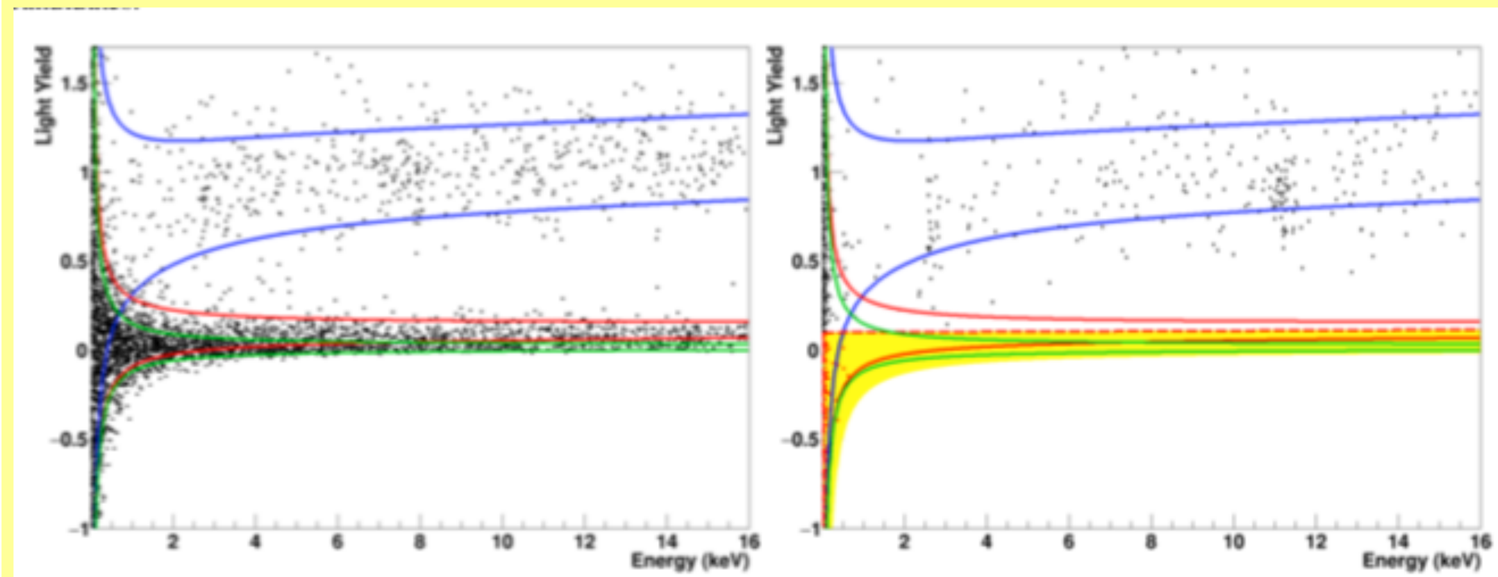
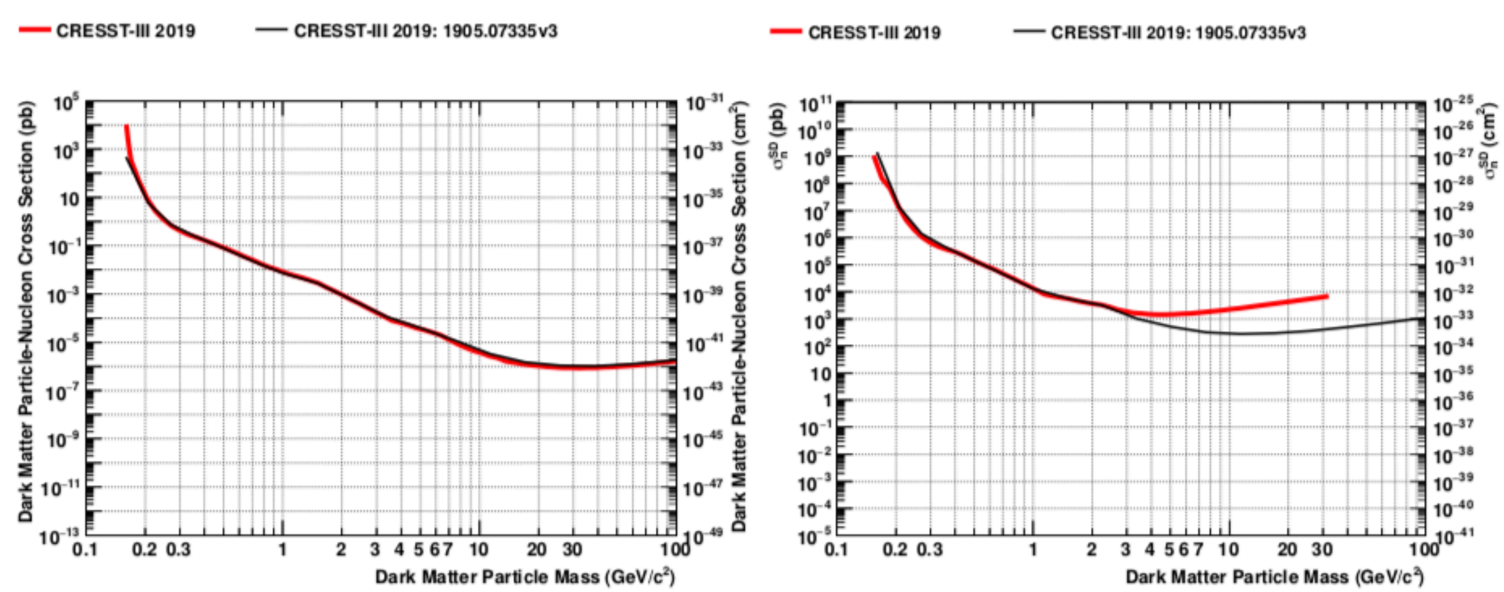
- Depending on the complexity of the analyses and data, recasting experimental results may be more or less challenging
- Counting analyses and spectral searches using maximum gap or a 1D histogram fit are relatively simple to recast using the efficiency and resolution is provided
- Some collaborations and analyses have been performed to be easily recast-able, such as CRESST-III



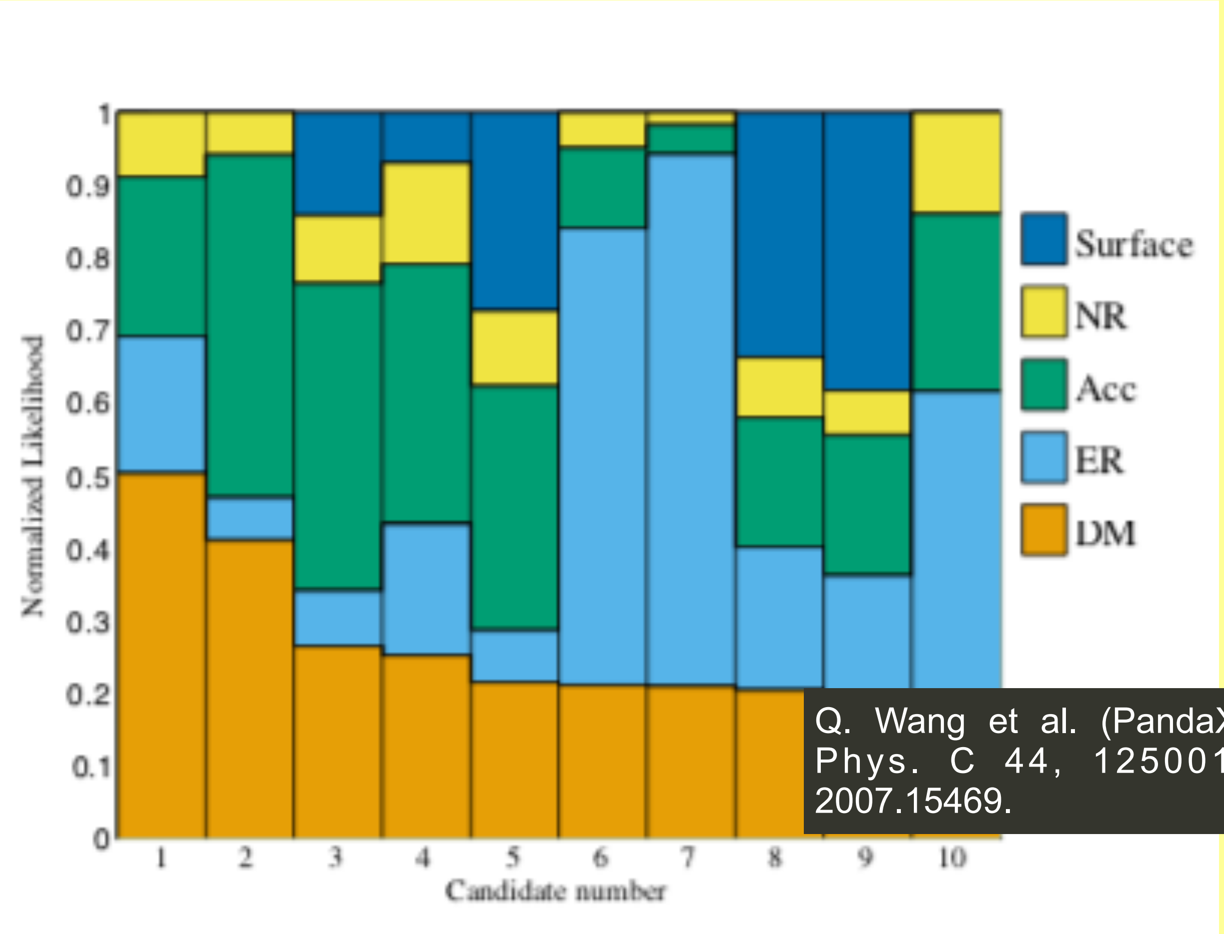


Example recast of several limits in:

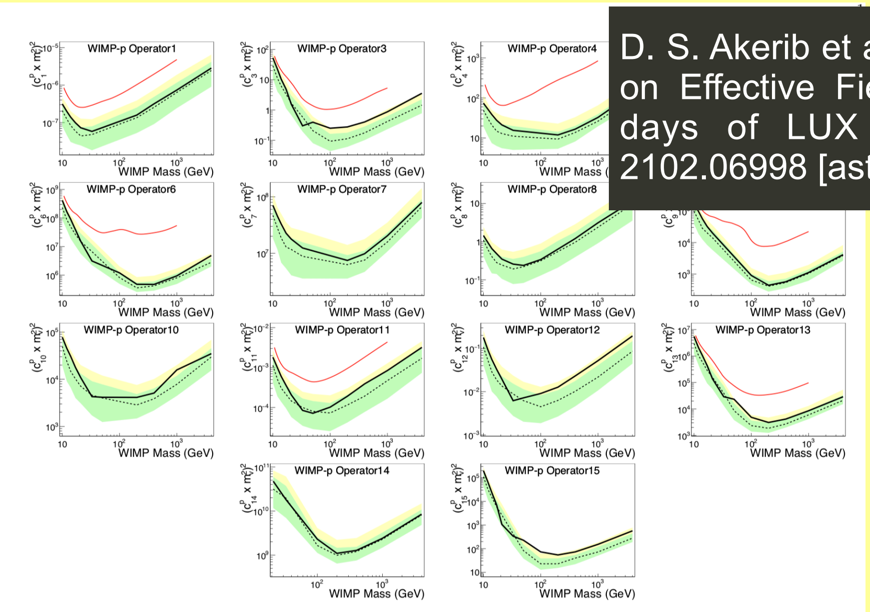
G. Belanger, A. Mjallal, and A. Pukhov. “Recasting direct detection lim- its within micrOMEGAs and implication for non-standard Dark Matter scenarios”. In: Eur. Phys. J. C 81.3 (2021), p. 239. doi: 10.1140/epjc/ s10052-021-09012-z

MAKING DIRECT DETECTION LIMITS REINTERPRET ABLE

- Spin-independent WIMP-nucleon results from the three big lXe TPCs (LUX, PandaX and XENON1T) were computed using unbinned likelihoods in S1, S2 and spatial dimensions
- Best-fit background and signal events commonly provided—often in a signal-like subregion. Sometimes, the PDF evaluated at each event is included as an indication.
- Since experimental sensitivities reach $\sim 5 - 10$ signal events, smaller changes in signal spectra will typically not have large effects, and limits on similar spectra may simply be scaled up/down
    - Effective field theory results will have a complete set of operators to match with



Q. Wang et al. (PandaX-II), Chin. Phys. C 44, 125001 (2020), 2007.15469.



D. S. Akerib et al. (LUX Collaboration). "Constraints on Effective Field Theory Couplings Using 311.2 days of LUX Data". In: (Feb. 2021). arXiv: 2102.06998 [astro-ph.CO]

PROPOSED COMMON REPORTING CONVENTIONS:

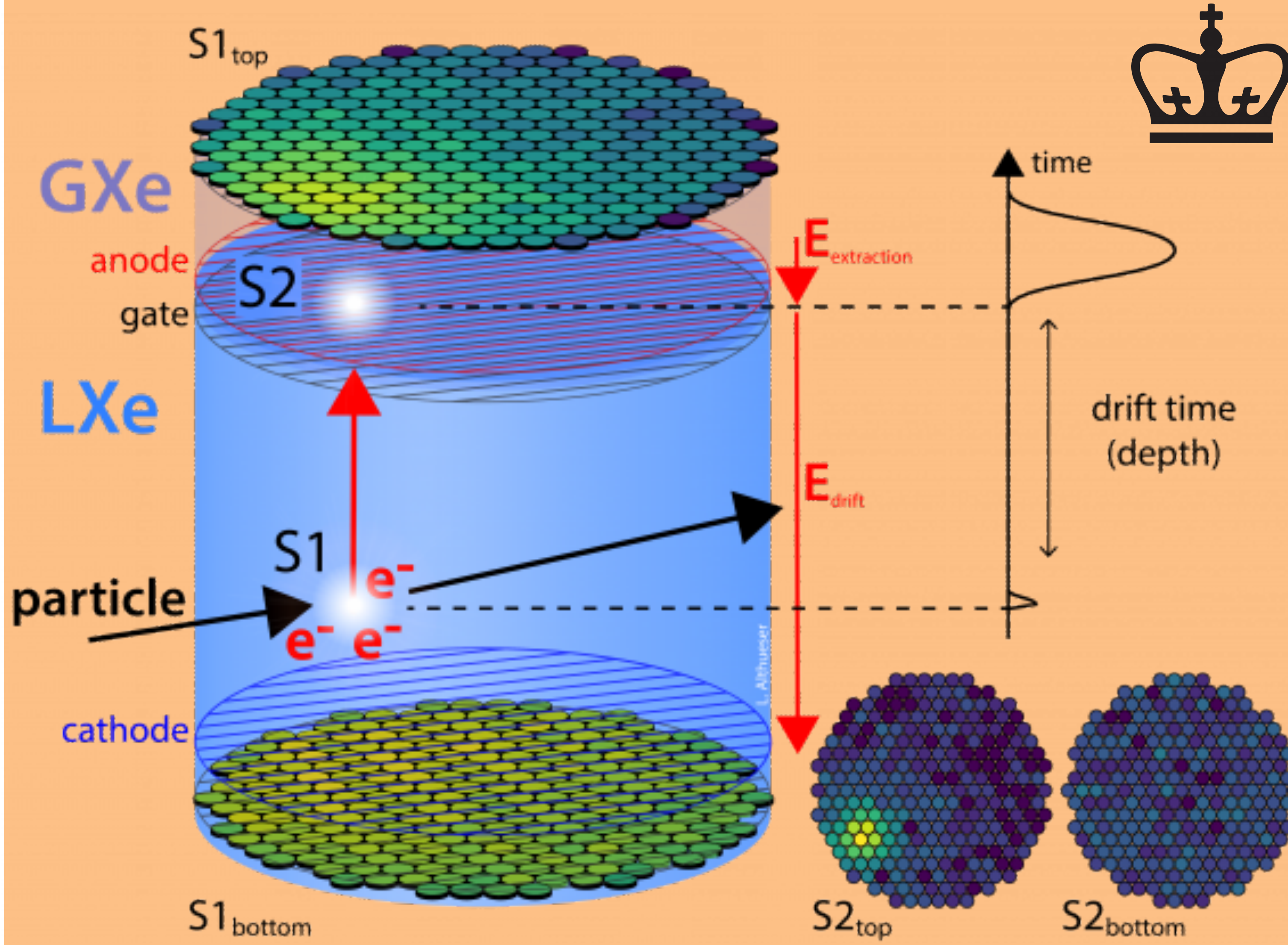
D. Baxter et al. "Recommended conventions fo reporting results from direct dark matte searches". In: (May 2021). arXiv: 2105.0059 [hep-ex].

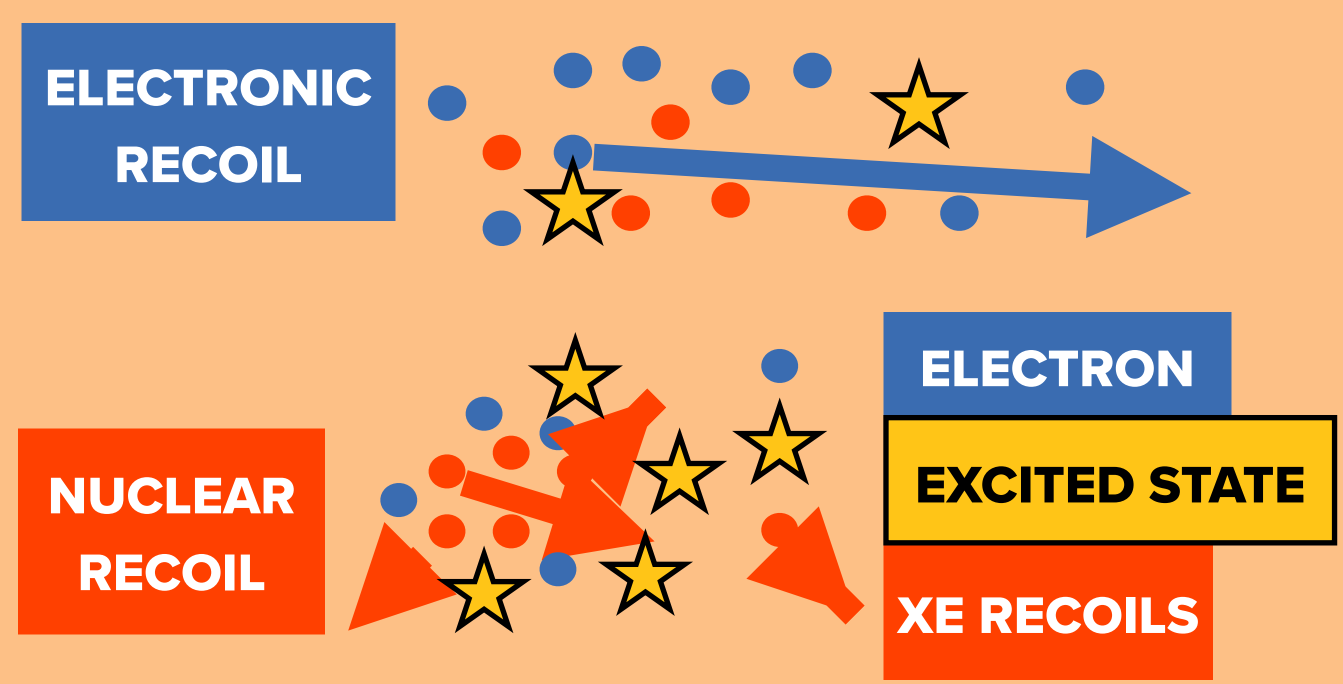
LOWERING ENERGY THRESHOLDS FOR TWO-PHASE LIQUID XENON TPCS

- **Analyses aim to make further use of the data taken by the previous generation of detectors while all three collaborations work to upgrade to multi-ton fiducial masses.**
- **Lowering detector thresholds raise background levels and challenges in reconstructing signals, but may yield significant increases in the expected signal**

2-PHASE LIQUID XENON TPCS

- Currently provide the strongest limits on spin-independent WIMP-nucleon cross-sections above 6 GeV/c^2
- Scintillation photons are detected by top and bottom photomultiplier arrays
- Electrons drift upwards in an electric field to the surface of the liquid xenon
- A stronger field extracts them from the liquid and causes a proportional scintillation signal
- Position and energy information from the S1 and S2 signals



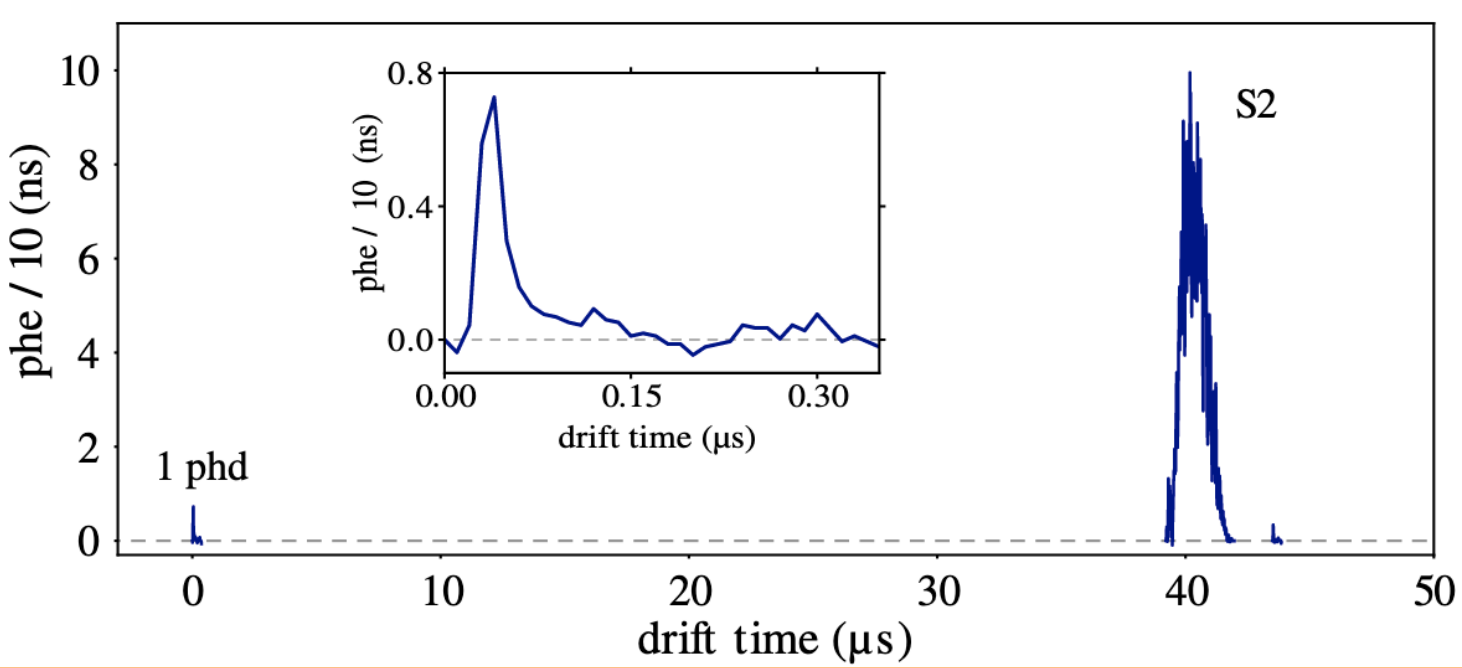


LUX SEARCH WITH SINGLE-PHOTON SCINTILLATION SIGNAL

- At the lower edge of acceptance, two-phase lXe TPCs are typically limited by the prompt scintillation signal, which may be just 1-3 photons hitting a photomultiplier (PMT)
- Previous LUX analyses required at least two PMTs to be hit:
  - avoiding spurious events where PMT dark-count signals mimicked a one-photon scintillation signal,
  - 3.3 keV threshold
- New analysis uses double photoelectron emission: a genuine scintillation photon has a probability of $\sim 17\,\%$ to liberate two photoelectrons hitting a PMT

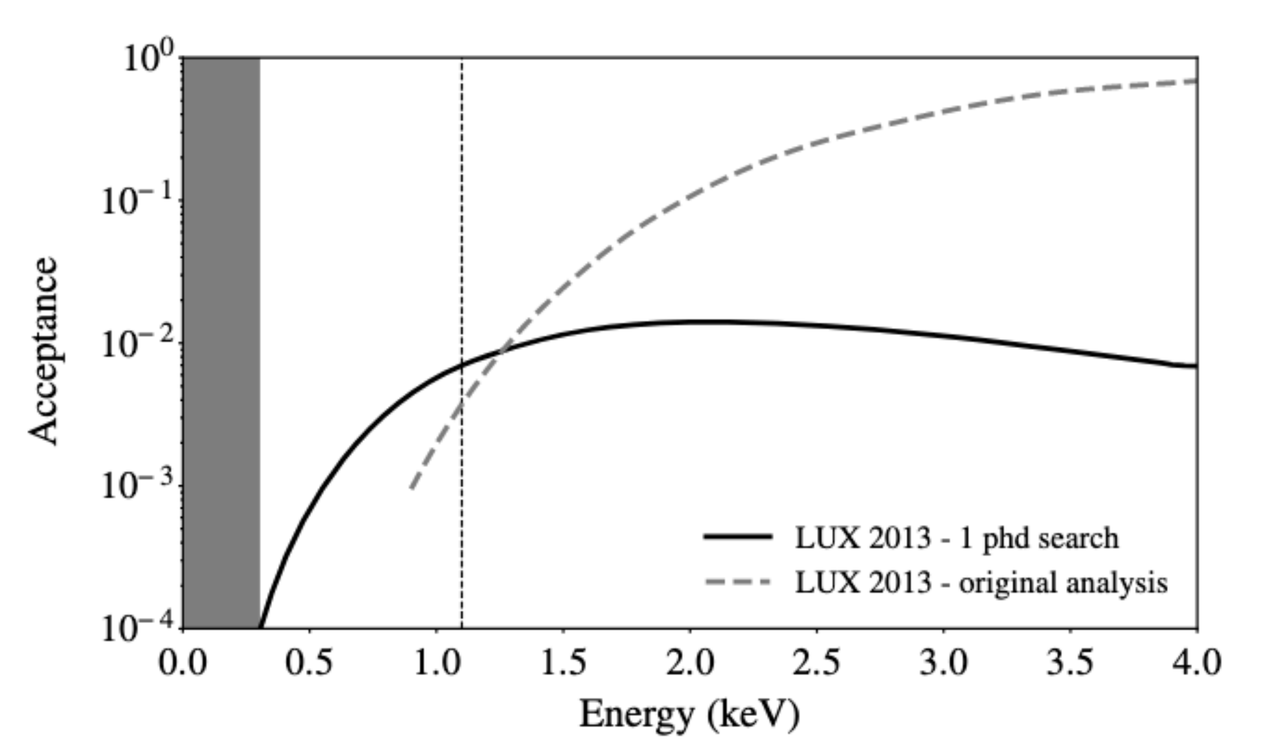
D. S. Akerib et al. (LUX Collaboration). “Extending light WIMP searches to single scintillation photons in LUX”. In: Phys. Rev. D 101.4 (2020), p. 042001. doi: 10.1103/PhysRevD.101.042001.

EXAMPLE SIGNAL:



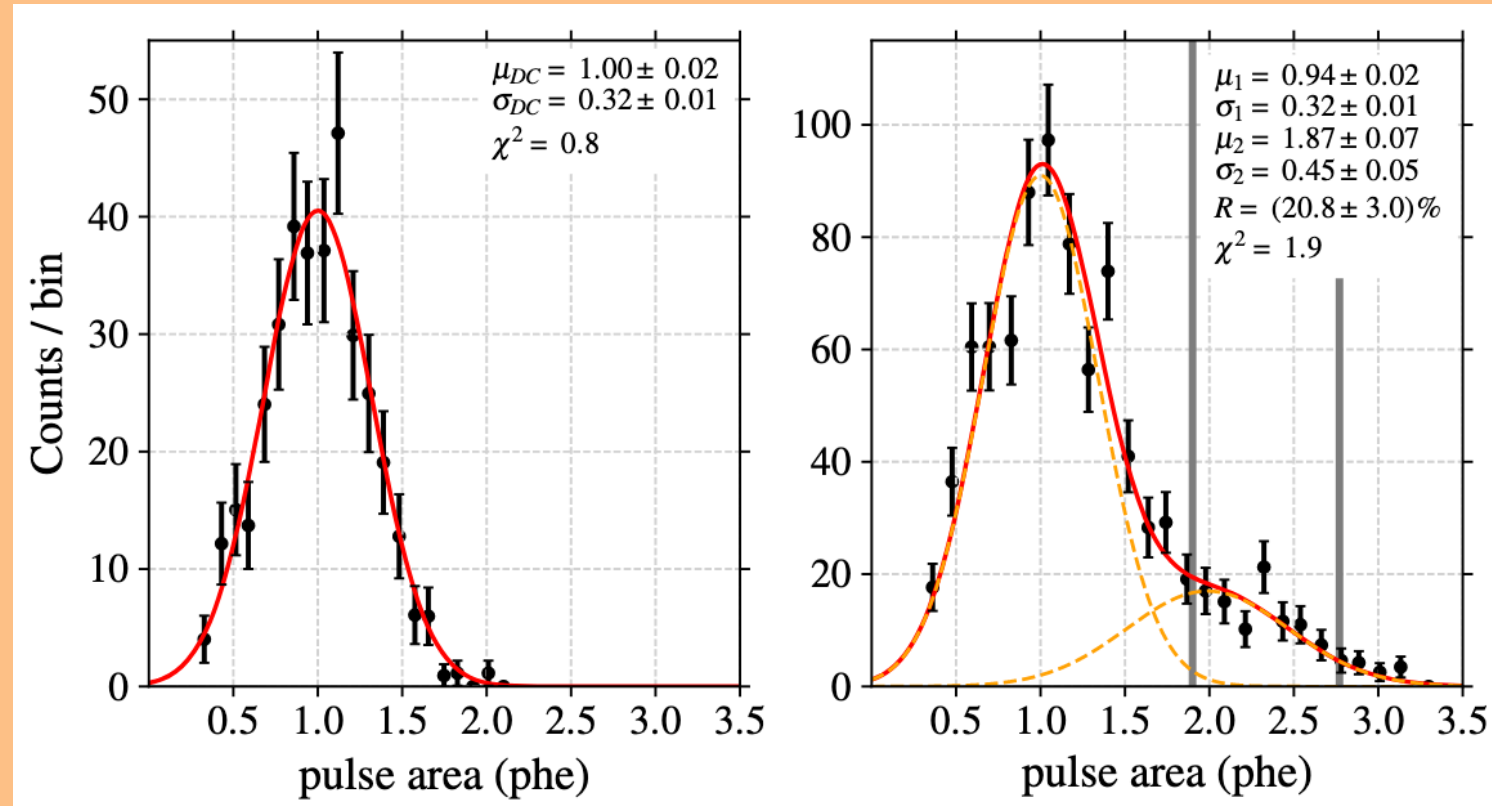
S1 COMPATIBLE WITH DOUBLE-PHOTOELECTRON

S2 SIGNAL MUCH LARGER, PREVIOUSLY A LONE-S2 CANDIDATE



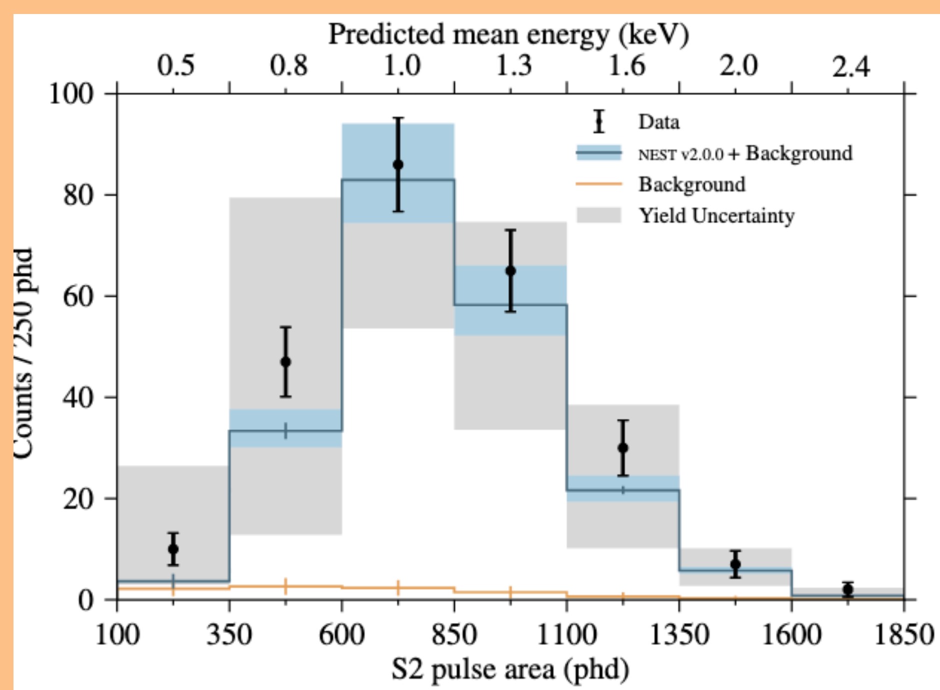
LUX SEARCH WITH SINGLE-PHOTON SCINTILLATION SIGNAL

- Properties of dark-counts and double-photoelectron signals were studied with low-energy ER events from tritiated methane
- “Dark count” may be a misnomer: Asymmetric single-electron rates for top and bottom PMT arrays indicate at least some of the dark-count originates in the TPC, possibly fluorescence of TPC walls
- No double-emission signal was observed when studying single-photon signals not associated with events
- Studying PMT pulses from small events gave a sample of real scintillation photons, and the mean fraction of double-emission events was measured as 0.169 ± 0.016. Individual channels were fit separately in the data analysis



SINGLE-PHOTOELECTRON SIGNAL

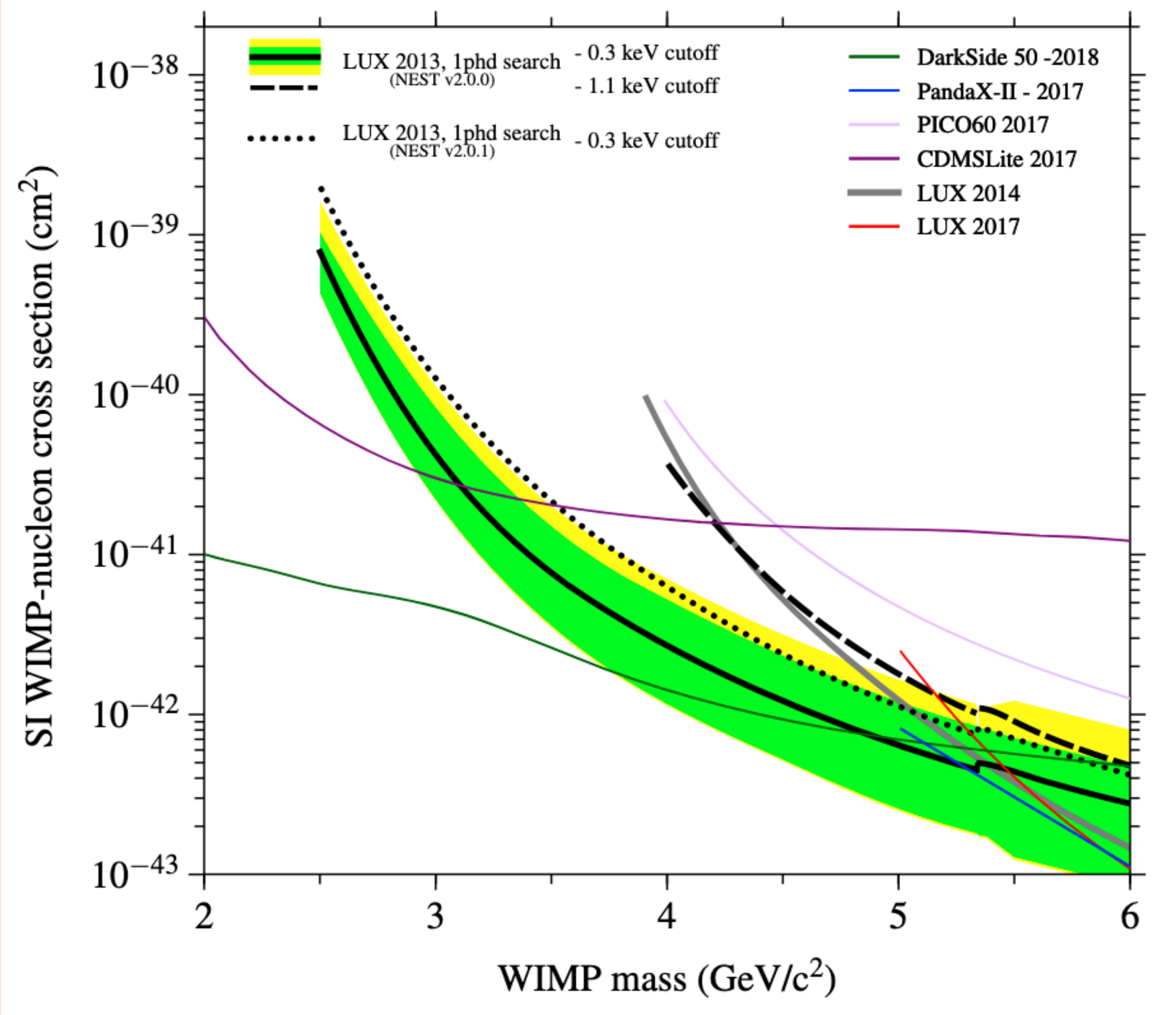
SCINTILLATION PHOTONS



TRITIUM S2 SPECTRUM FOR EVENTS WITH DOUBLE-EMISSION S1

LUX SEARCH WITH SINGLE-PHOTON SCINTILLATION SIGNAL

- Six events observed with 5 expected, and analysed counting within regions optimised per WIMP mass.
- With improved low-energy acceptance, the new limits reach 2.5 keV
- The probability of a double electron emission depends on photomultiplier technology—LZ and XENONnT will both use PMTs with a somewhat higher ($\sim 23\,\%$) double photoelectron probability

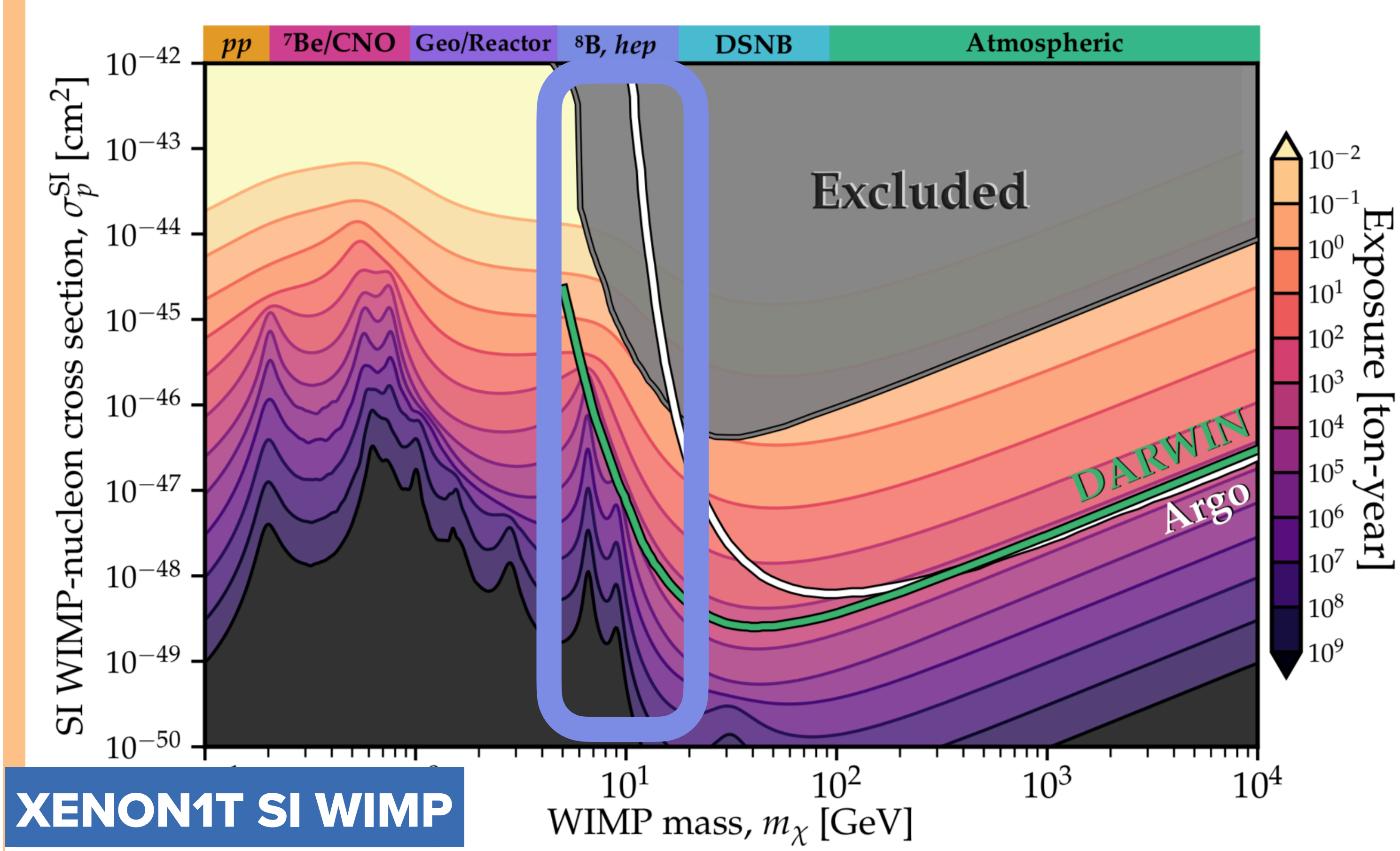


SPIN-INDEPENDENT UPPER LIMITS

D. S. Akerib et al. (LUX Collaboration). “Extending light WIMP searches to single scintillation photons in LUX”. In: Phys. Rev. D 101.4 (2020), p. 042001. doi: 10.1103/PhysRevD.101.042001.

XENON1T CEνNS SEARCH

- Neutrinos tick all the boxes of the WIMP acronym, and astrophysical neutrinos will yield recoils indistinguishable from dark matter scattering
- The first spectrum expected to be observed is coherent elastic scattering of solar ^{8}B neutrinos, which have a recoil spectrum nearly indistinguishable from a $6\ \mathrm{GeV}/c^2$ WIMP with cross-section $\sim 2 \times 10^{-45} \mathrm{cm}^2$
- Right at the lower threshold of the signals the standard WIMP search reached



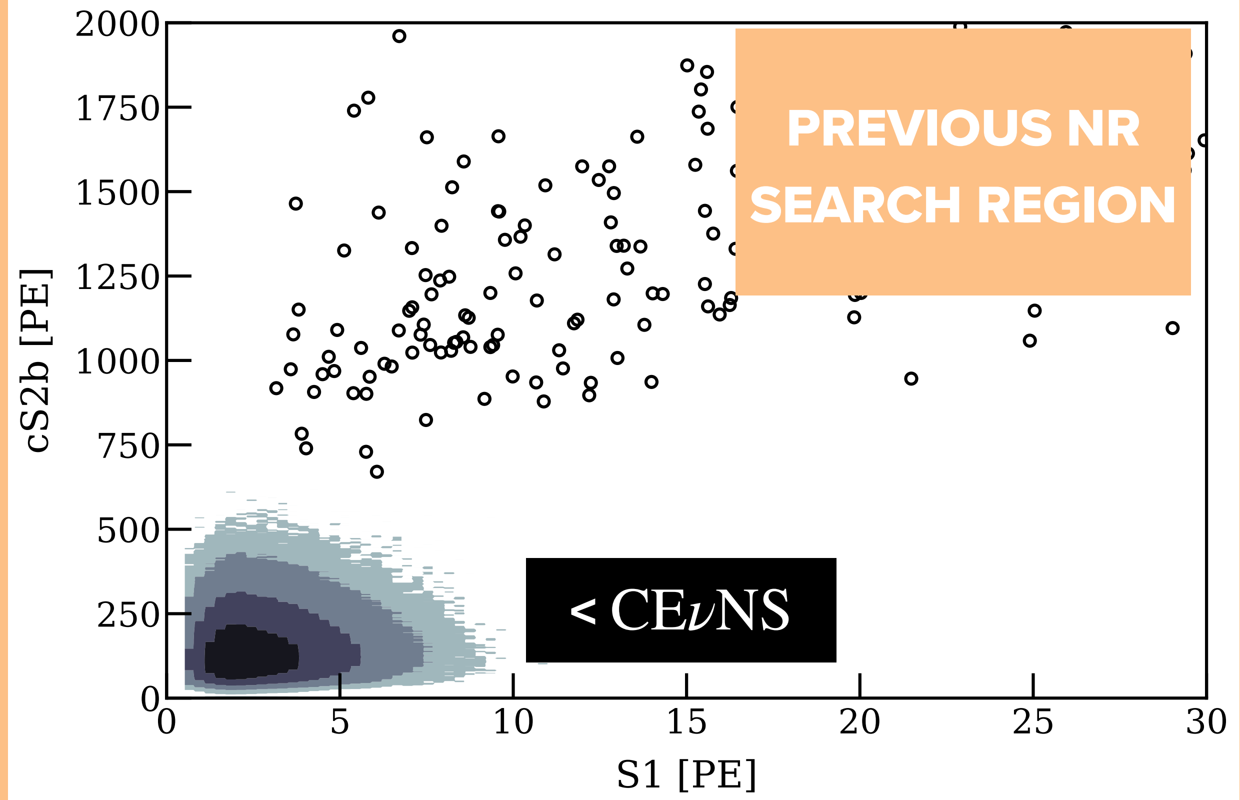
O'Hare C. A. J. "Can we overcome the neutrino floor at high masses?" Phys.Rev.D 102 (2020) 6, 063024, DOI: 10.1103/PhysRevD.102.063024

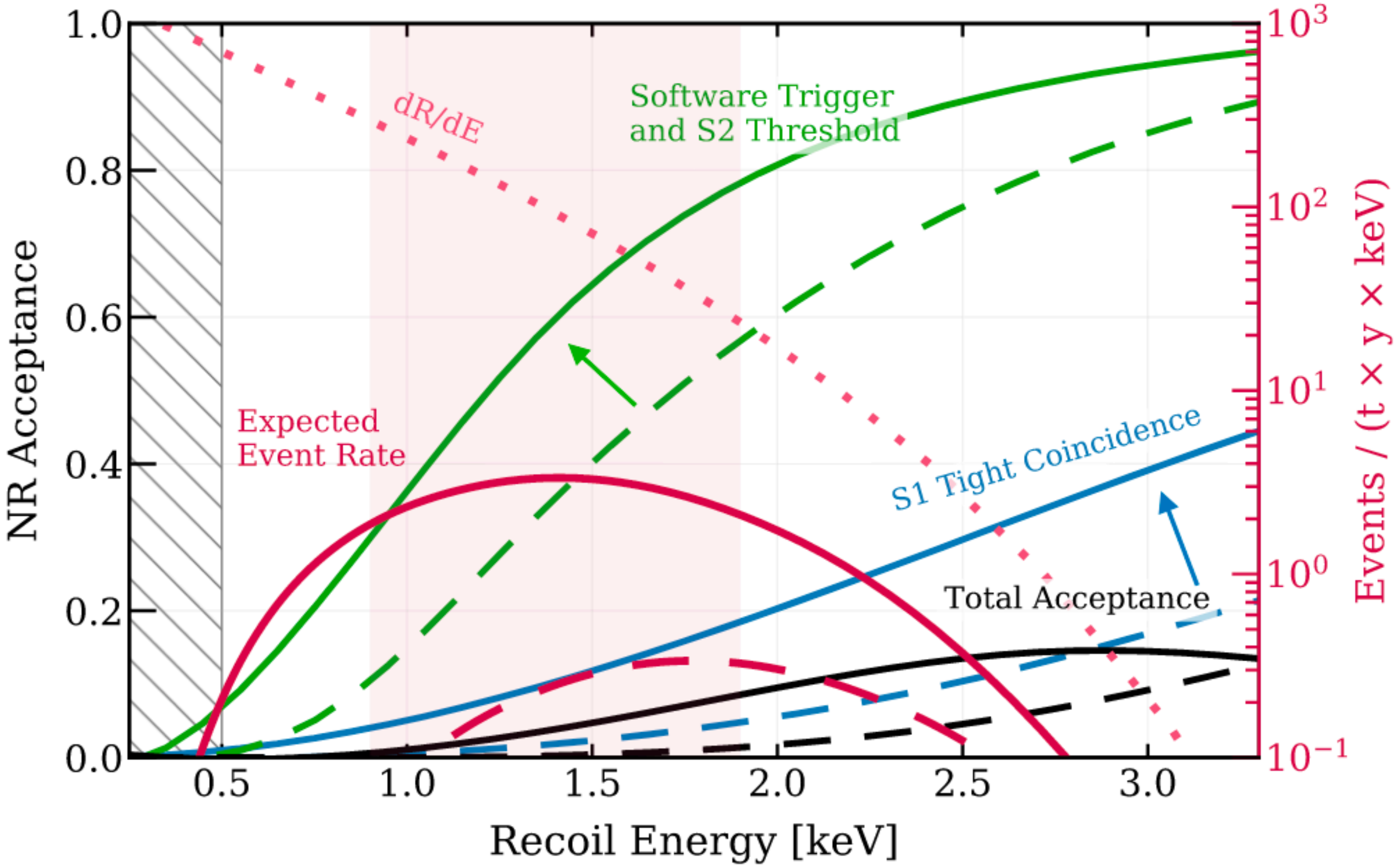
XENON1T SI WIMP

Mass (ton)	1.3
($cS1$, $cS2_b$)	Full
ER	627 ± 18
Neutron	1.43 ± 0.66
CEνNS	0.05 ± 0.01
AC	$0.47_{-0.00}$
Surface	106 ± 8
Total BG	735 ± 20
WIMP$_{\text{best-fit}}$	3.56
Data	739

LOWERING THE XENON1T ENERGY THRESHOLD

- demanding two PMTs hit within 50ns (the standard analysis requires 3)
- lower the S2 threshold from 200 to 120 PE
- 5% acceptance edge reduced from 2.6 to 1.6 keV, and 50-fold increase in signal rate— expect to observe 2.25 ^{8}B neutrino interactions
- New discrimination variables reduced the accidental coincidence background to 5 expected events
- Low discovery power: $\sim 20\,\%$ for a 3σ excess

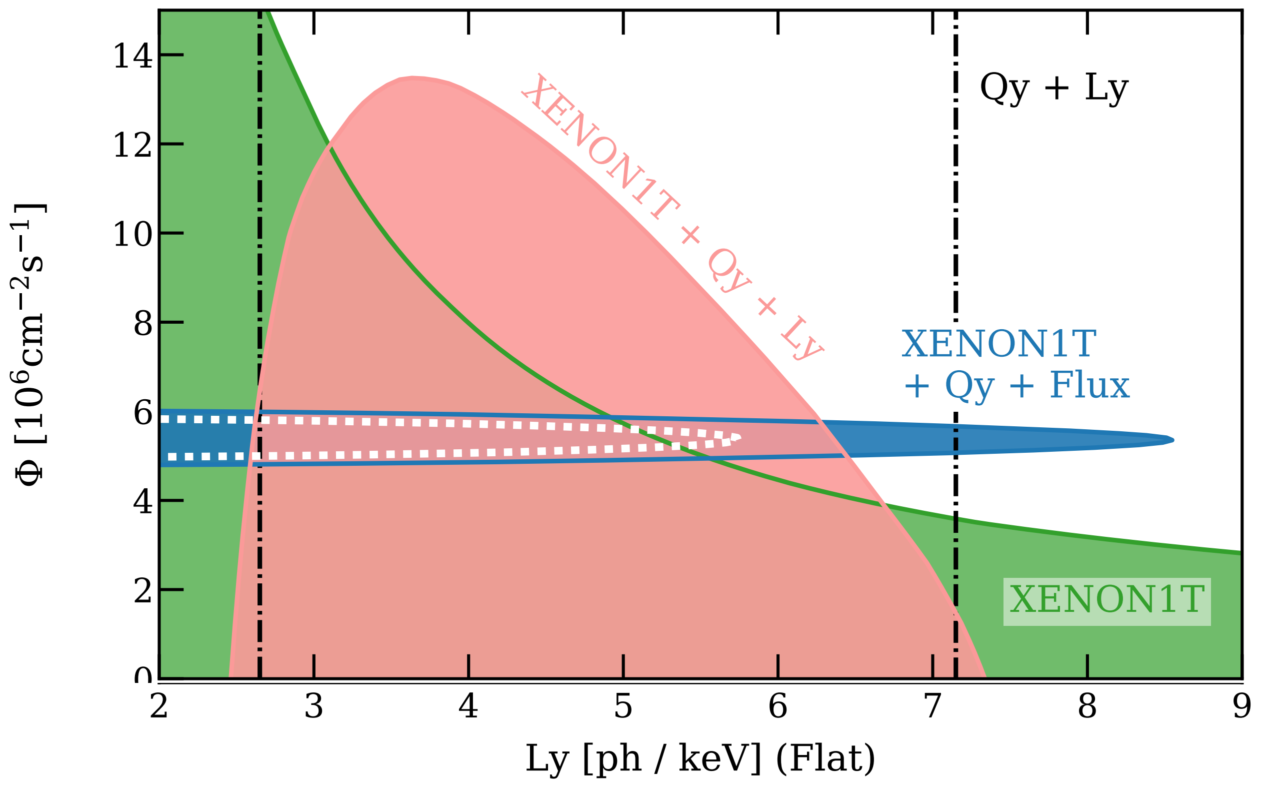


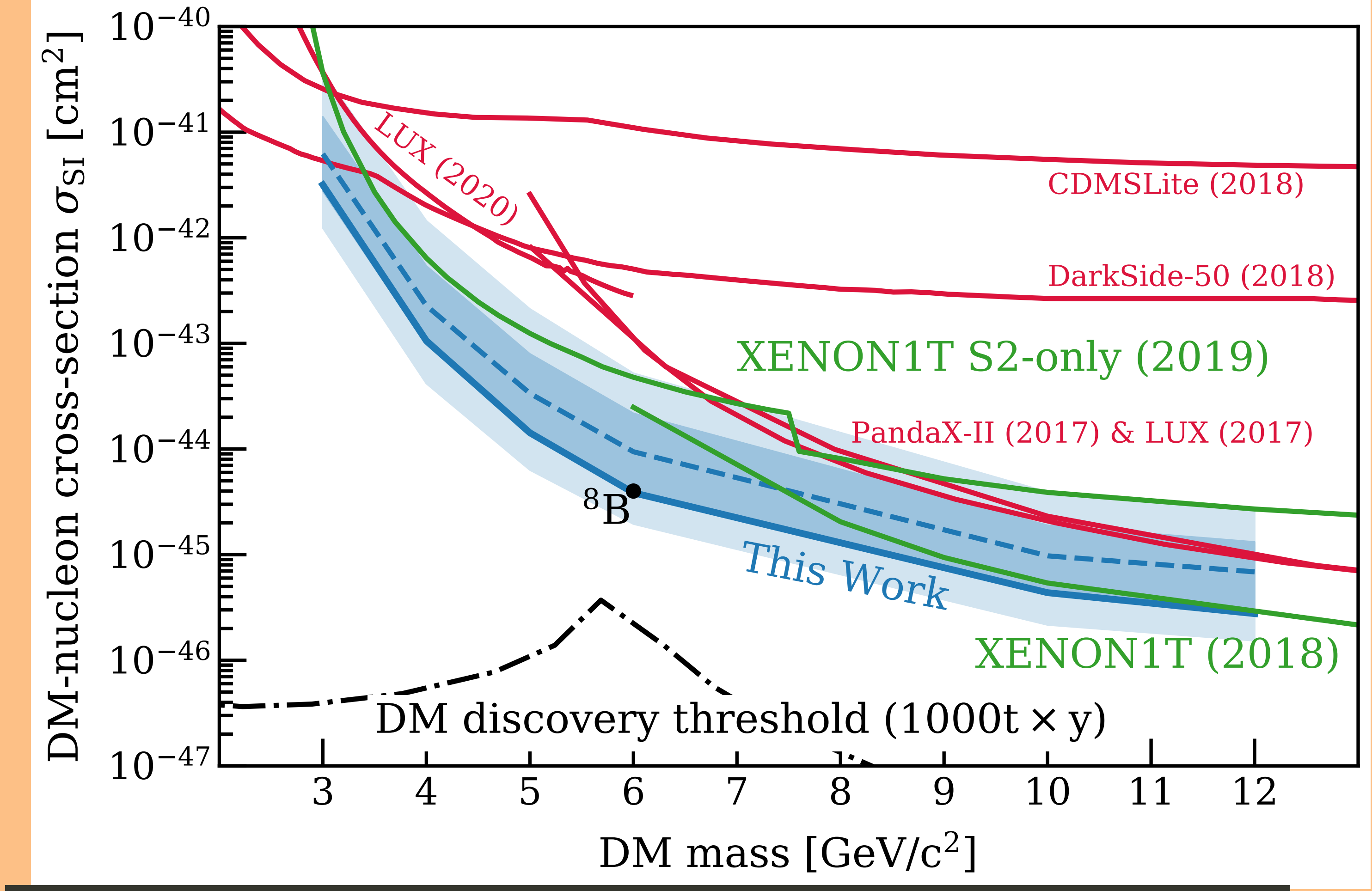


E. Aprile et al. (XENON Collaboration). "Search for Coherent Elastic Scattering of Solar 8B Neutrinos in the XENON1T Dark Matter Experiment". In: Phys. Rev. Lett. 126 (2021), p. 091301. doi: 10.1103/ PhysRevLett.126.091301.

XENON1T CEνNS SEARCH RESULT

- Best fit: 0 ^{8}B solar neutrino events, and good agreement with the background model.
- Xenon response parameters are almost degenerate with the solar neutrino flux, and including external constraints on one or more allows for confidence intervals on the others
  - Limits on the neutrino flux were also presented in terms of non-standard neutrino-quark interactions
- Alternately, the result can be used to place limits on a WIMP signal above the expected neutrino flux— XENON1T sets new limits between 6 and 12 GeV/c²





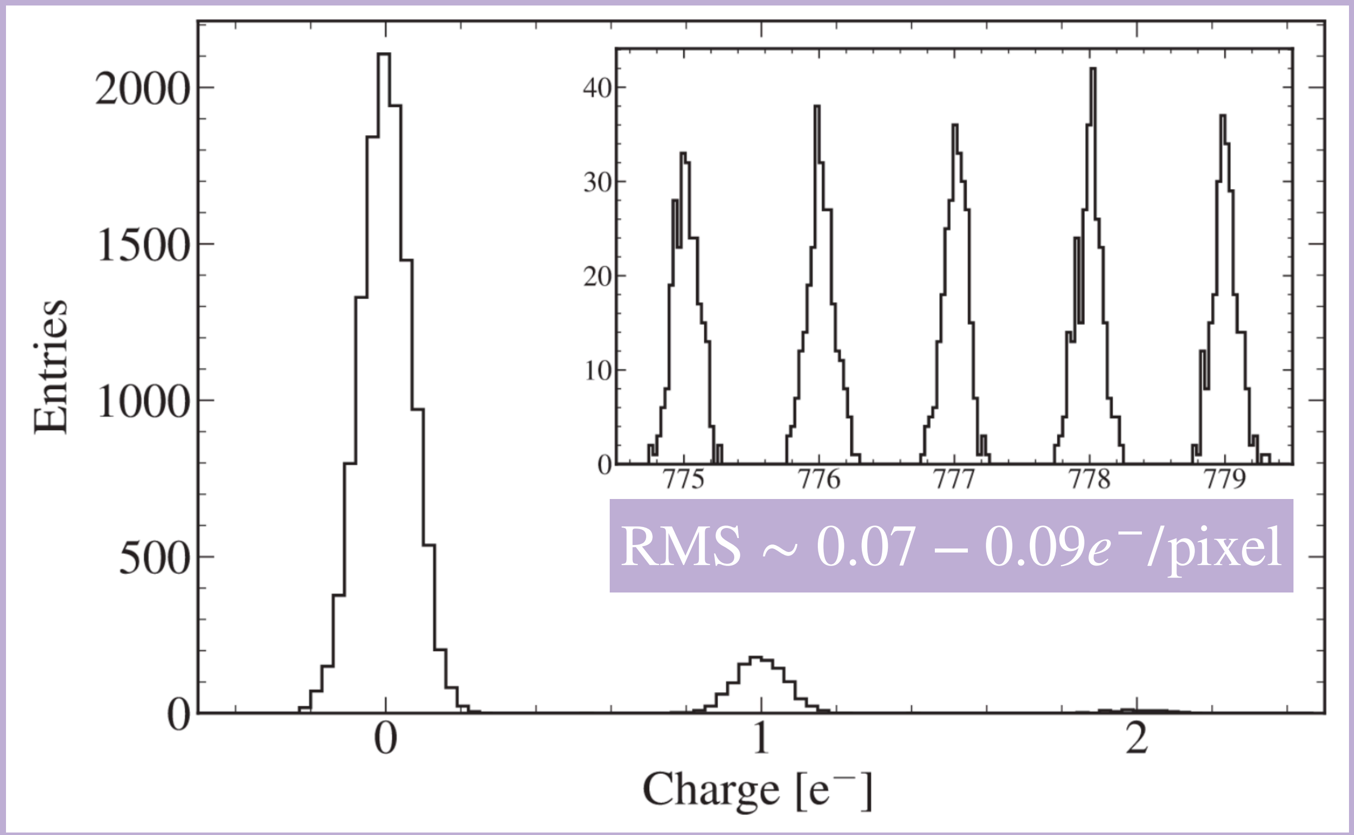
E. Aprile et al. (XENON Collaboration). “Search for Coherent Elastic Scattering of Solar 8B Neutrinos in the XENON1T Dark Matter Experiment”. In: Phys. Rev. Lett. 126 (2021), p. 091301. doi: 10.1103/ PhysRevLett.126.091301.

DARK MATTER-ELECTRON SCATTERING

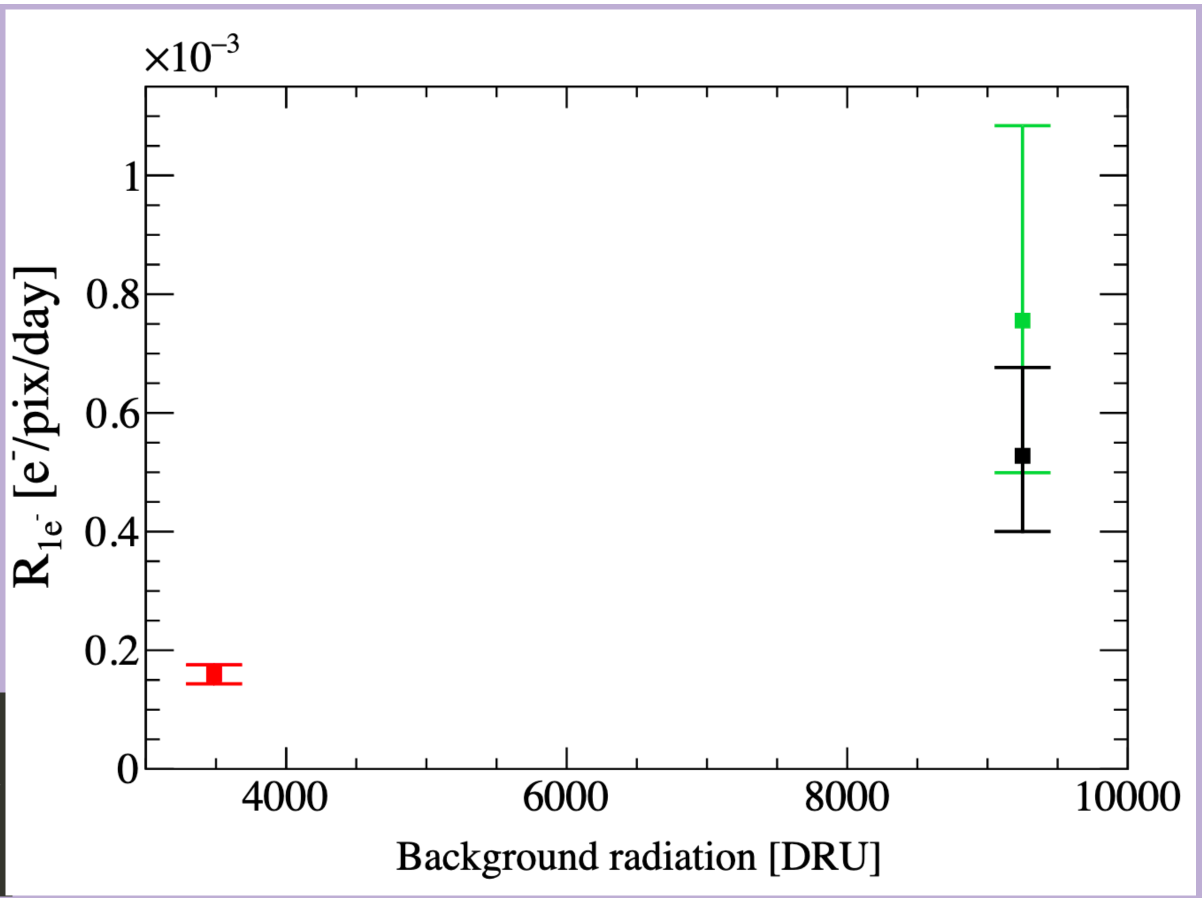
- **Single-charge sensitive detectors for electron scatter have improved limits on dark matter-electron interactions (as well as other interactions)**
- **At very low masses, electrons provide a better kinematically matched target than nuclei, with limits reaching $\sim$ MeV**
- **For e.g. TPCs, large background populations must typically be dealt with, but analyses provide new constraints above ~ 10 MeV**

SENSEI

Javier Tiffenberg et al. (SENSEI Collaboration). “Single-electron and single-photon sensitivity with a silicon Skipper CCD”. In:Phys. Rev. Lett.119.13(2017), p. 131802.doi:10.1103/PhysRevLett.119.131802.



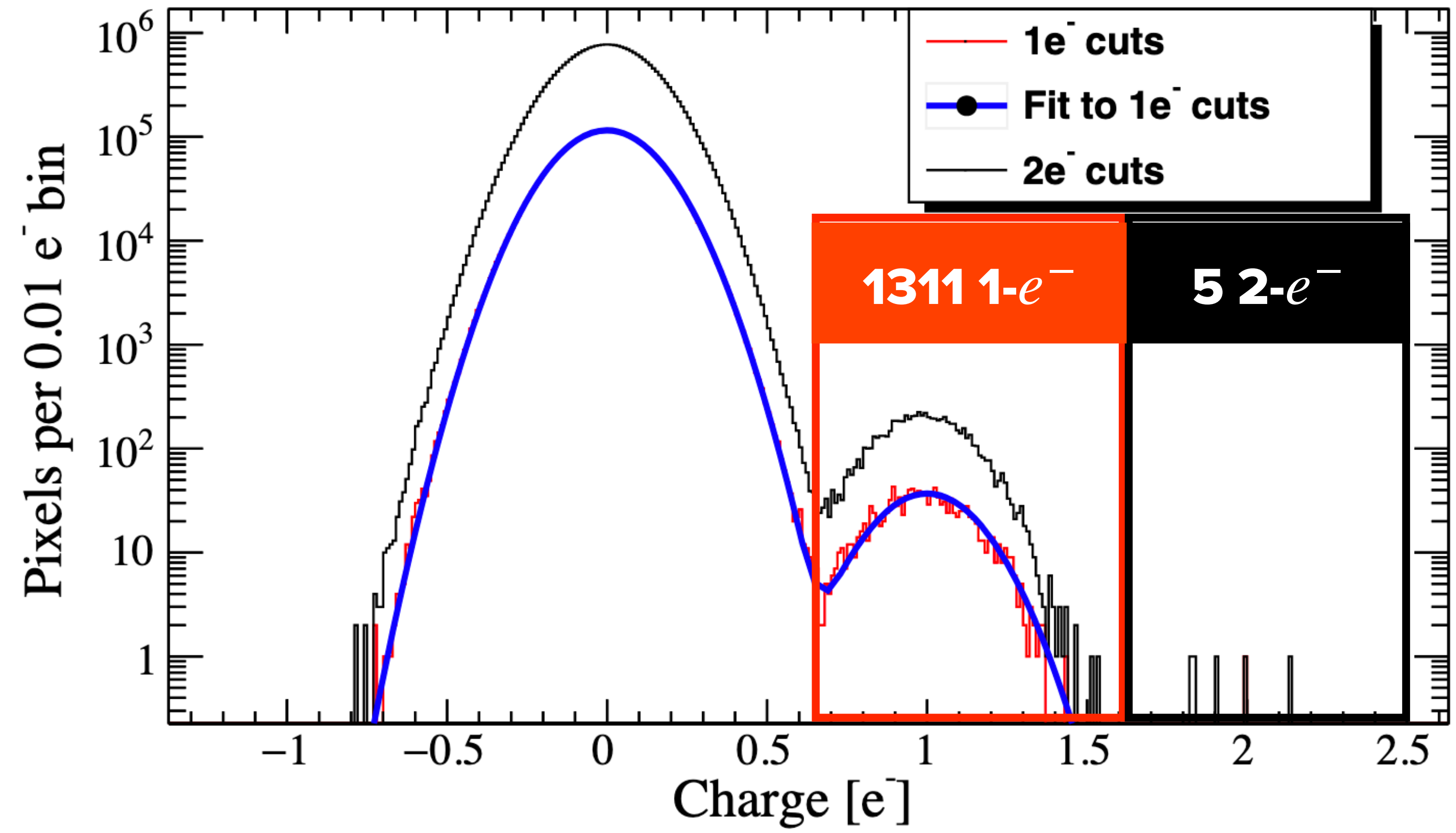
- Sensei uses Skipper silicone CCD readout technology to repeatedly sample the charge from each pixel
- WIth enough samples, it reaches charge resolutions far below one electron.
- A clear correlation between detector shielding and the rate of single-electron events indicates that the “dark count” measured in these CCDs before included an appreciable environmental component
  - Other known backgrounds include noise when shifting charge between pixels
- Record-low rate of single-e^- with semiconductors: $(450 \pm 50)/\text{gramme} - \text{day}$



Liron Barak et al. (SENSEI Collaboration). “SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD”. In: Phys. Rev. Lett. 125.17 (2020), p. 171802. doi: 10.1103/PhysRevLett.125. 171802

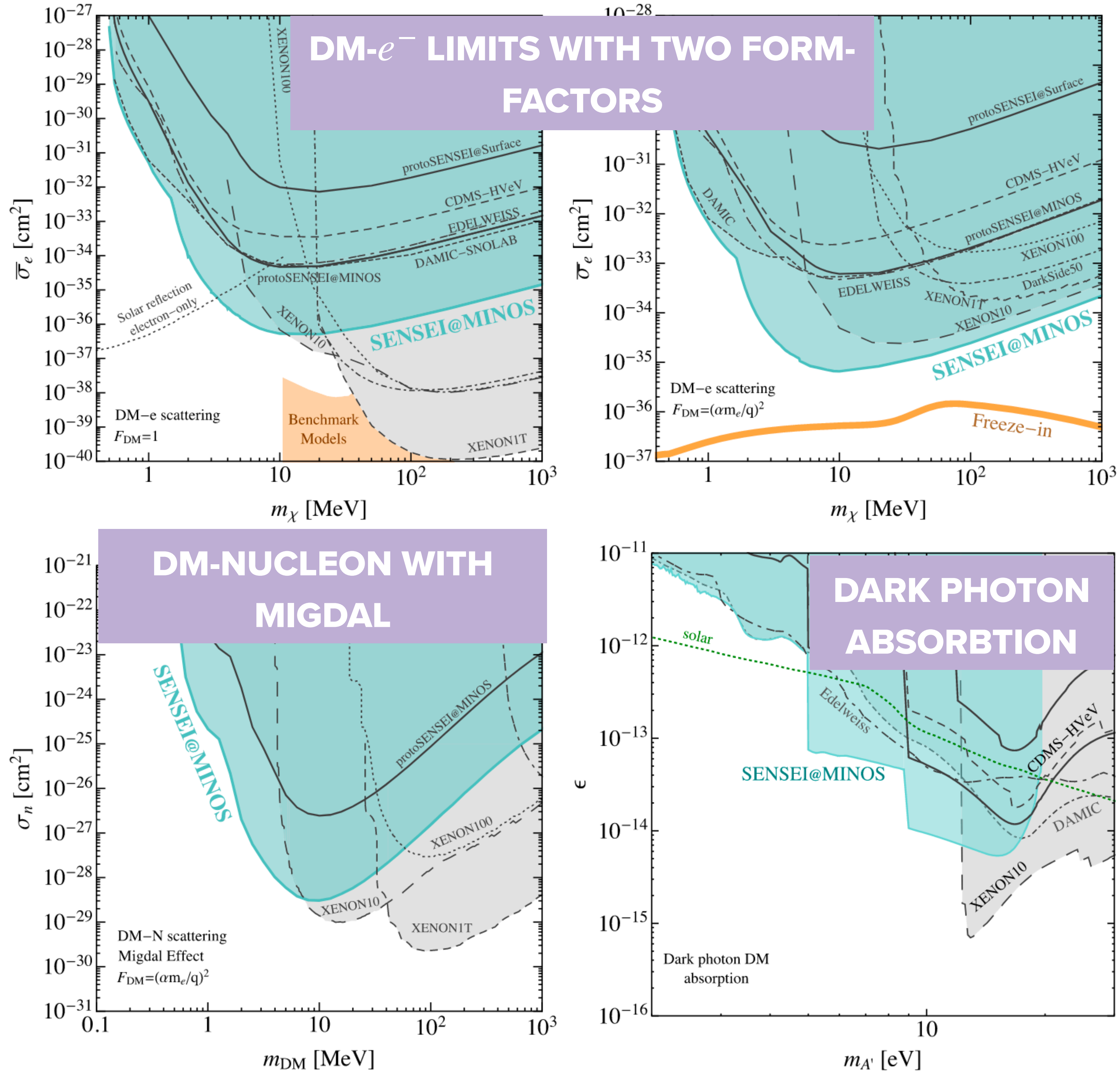
SENSEI SUB-GeV DARK MATTER SEARCH

- $2\ \mathrm{g} \times 24\ \mathrm{days}$ **exposure with purpose-made CCDs** ~ 104 **m underground**
- **Energy thresholds;** $\sim 500\ \mathrm{keV}$ **for DM-**e^- **scatterings, and** $\sim\ 1.2\mathrm{eV}$ **if the DM is absorbed — the band gap of silicon**
- **Analysis performed on events in exposure with 1-4 electrons**
  - **No 3 or 4-electron events observed**
  - **Effective exposures of** 1.38 **g-day** $(1\ e^-)$ **to** 9.10 **g-day** $(4\ e^-$ **cuts**$)$



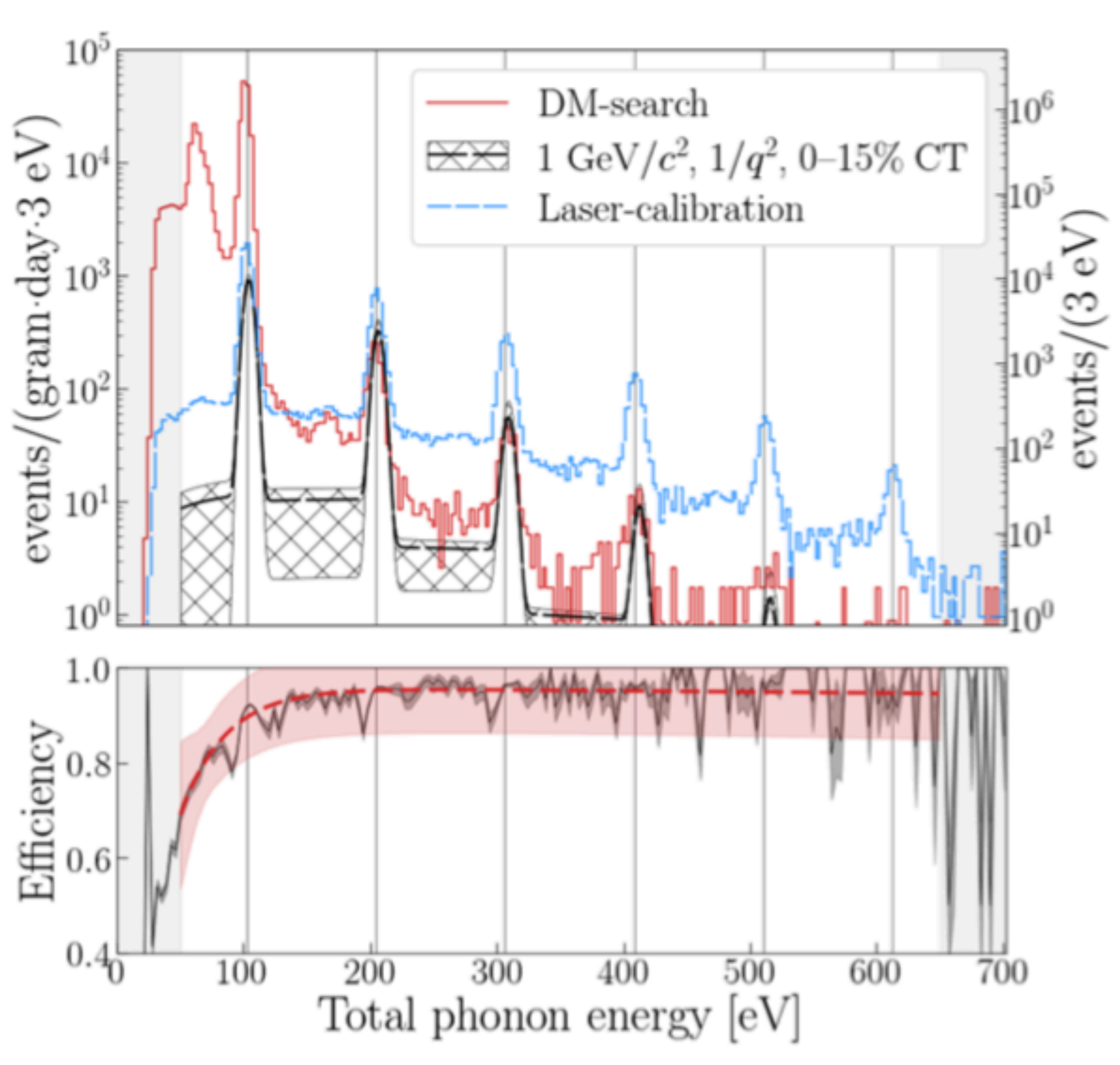
EVENTS OBSERVED WITH 1- AND 2-ELECTRON QUALITY CUTS

SENSEI SUB-GeV DARK MATTER SEARCH



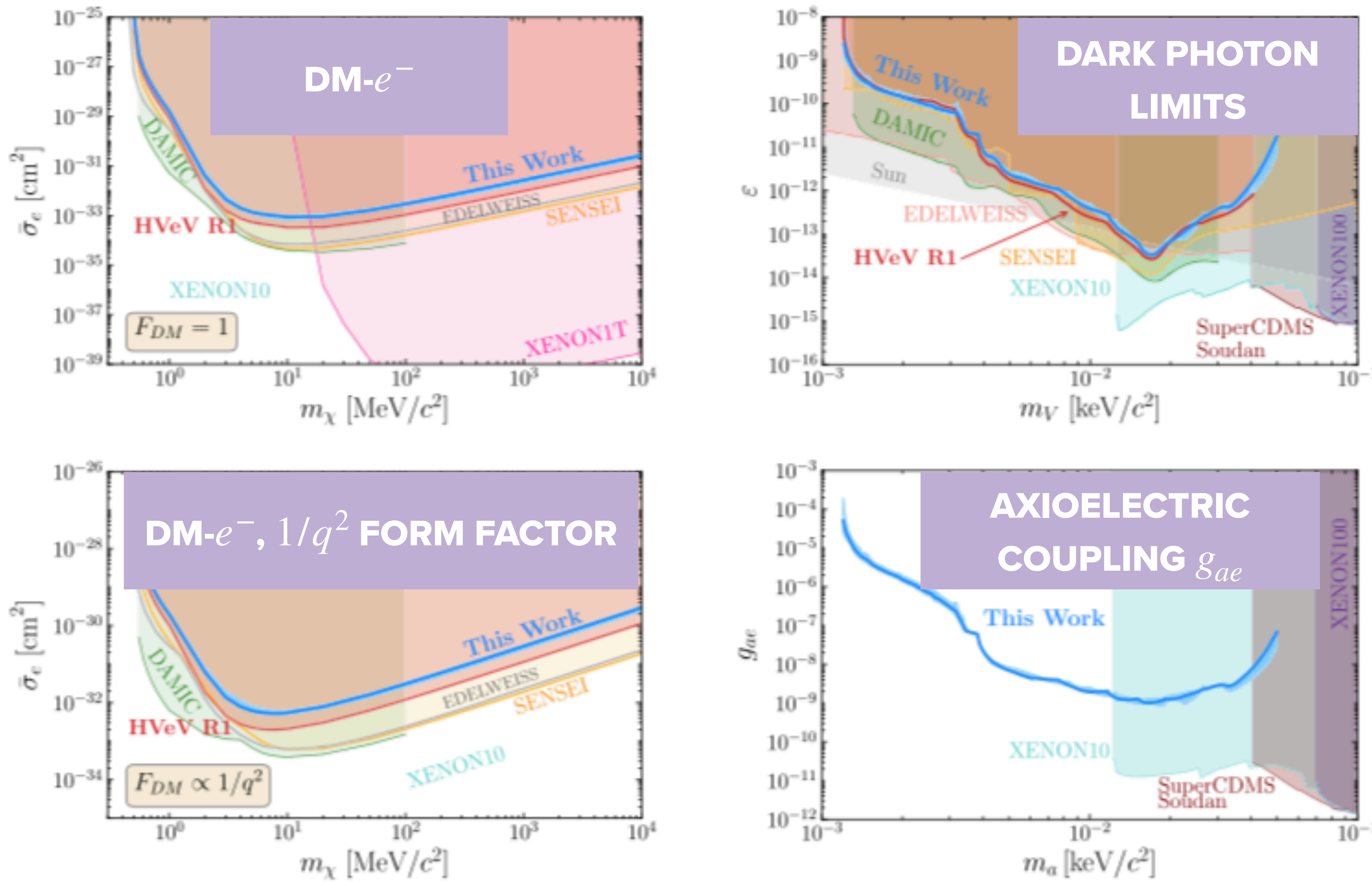
SUPERCDMS SINGLE-CHARGE SENSITIVE RUN

- R&D run at surface: 1.2 g-days using a silicon detector crystal coupled to two transition edge sensor phonon detectors
- Detector operated with a high (100V) bias voltage
  - Amplify small signals—drifting charges in the high field generates additional phonons
- charge resolution $\sim 3\,\%$ of an electron-hole pair
- Focused on 1-6 e^- signal region



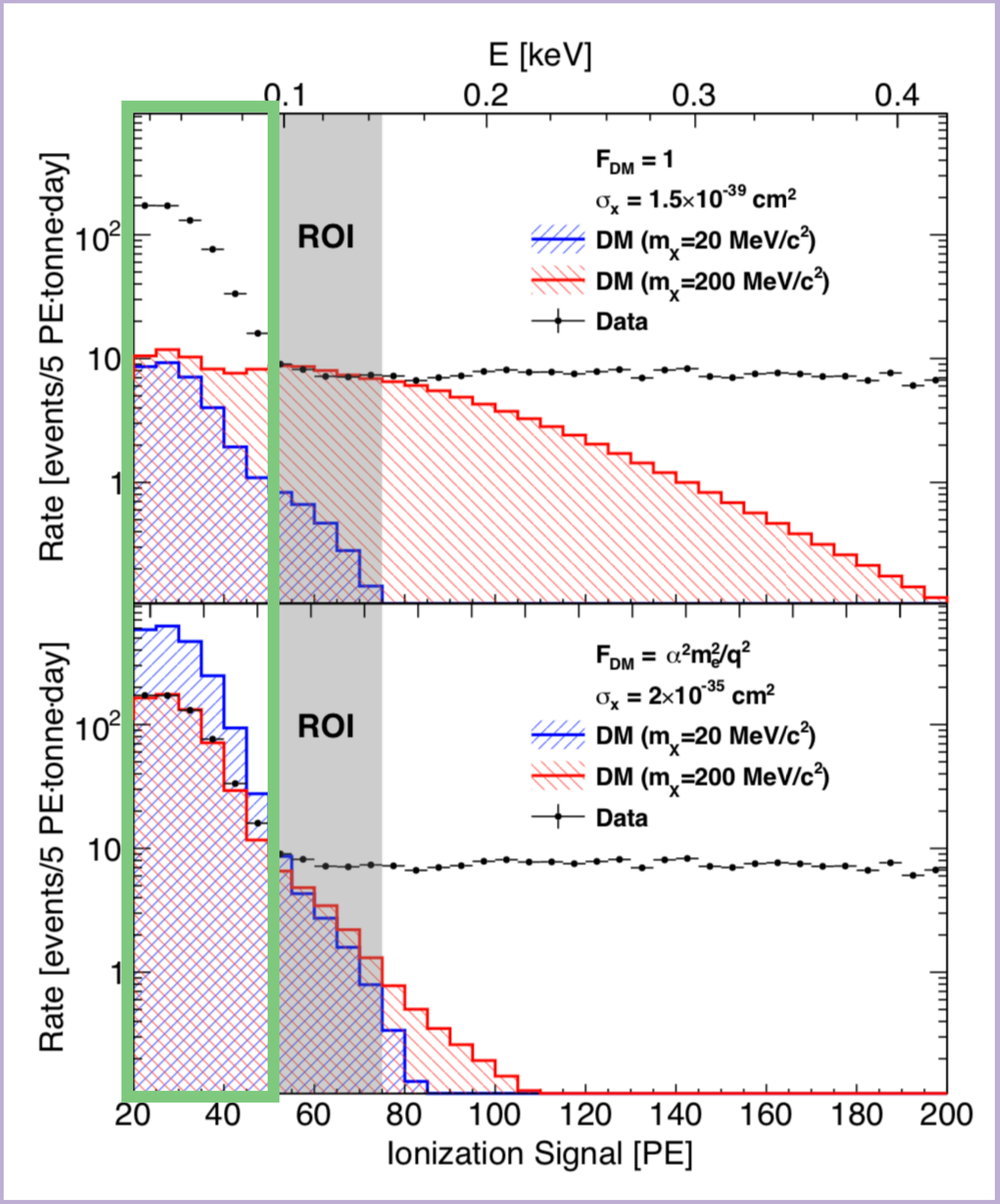
D. W. Amaral et al. (SuperCDMS Collaboration). "Constraints on low-mass, relic dark matter candidates from a surface-operated SuperCDMS single-charge sensitive detector". In: Phys. Rev. D 102.9 (2020), p. 091101. doi: 10.1103/PhysRevD.102.091101.

SUPERCDMS SINGLE-CHARGE SENSITIVE RUN



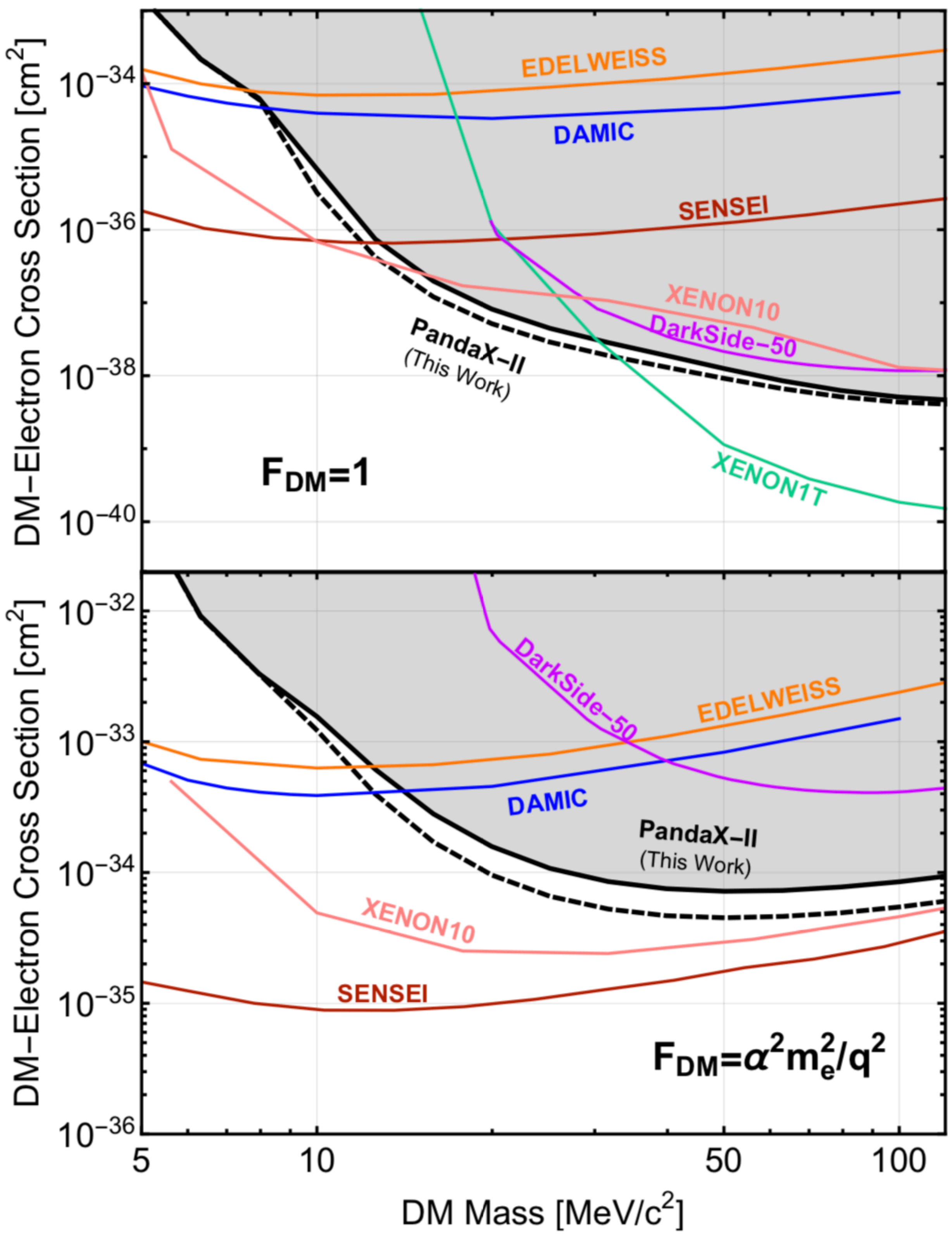
DARK MATTER-ELECTRON SCATTERING WITH PANDAX-II

- PandaX-II performed an S2-only search in a region corresponding to 0.08 keV – 0.15 keV recoil energies
- Without the scintillation flash, information about the depth of the interaction must be inferred from other parameters such as S2 signal width or shape
- The lowest-energy region below the region of interest (green box) is dominated by single-electron events.



Xiaopeng Zhou et al. (PandaX-II Collaboration). "A search for solar ax- ions and anomalous neutrino magnetic moment with the complete PandaX- II data". In: (Aug. 2020). doi: 10.1088/0256-307X/38/1/011301.

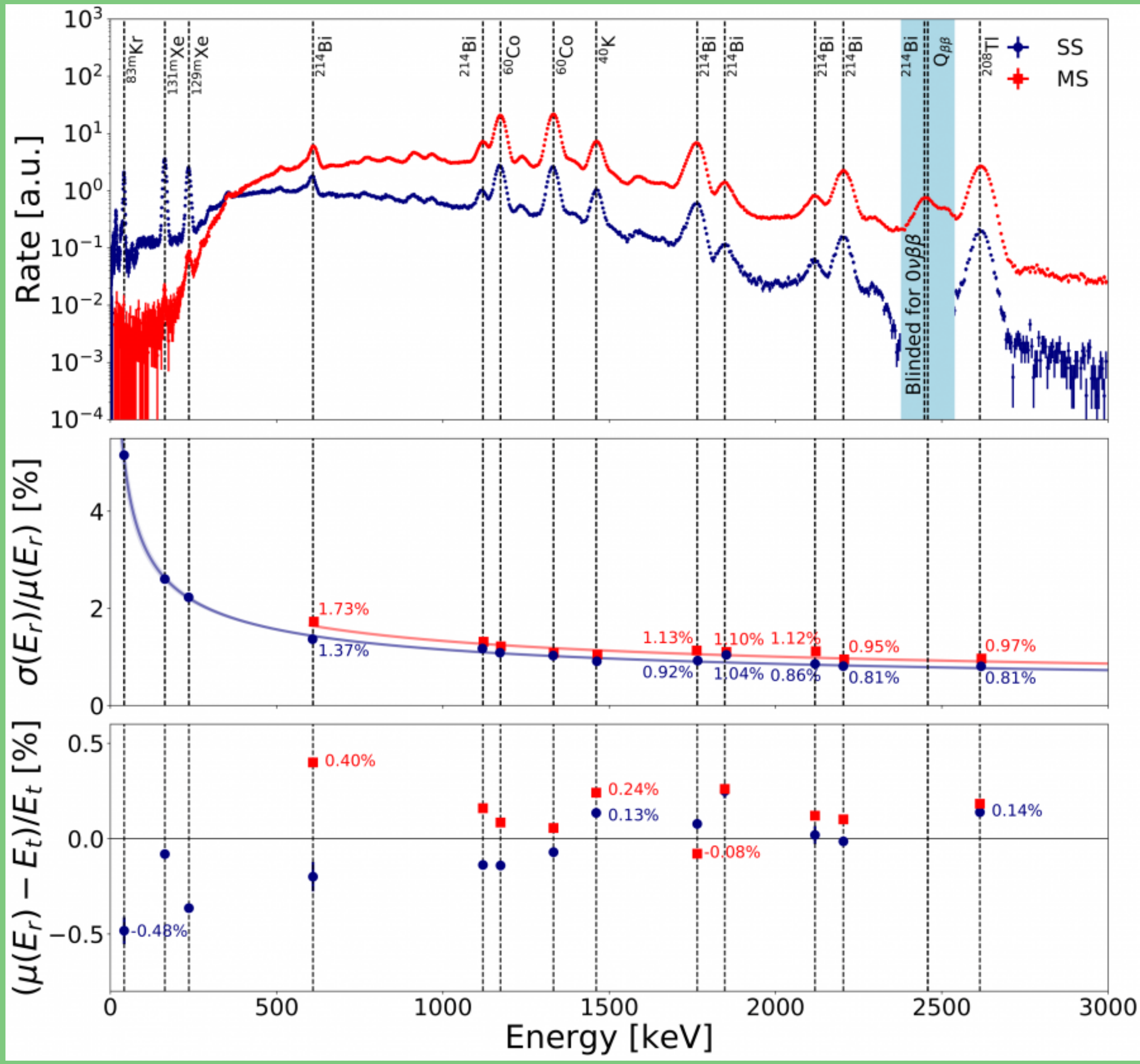
DARK MATTER-ELECTRON SCATTERING WITH PANDAX-II



Xiaopeng Zhou et al. (PandaX-II Collaboration). “A search for solar ax- ions and anomalous neutrino magnetic moment with the complete PandaX- II

ELECTRONIC RECOIL SEARCHES

- lXe TPCs feature good energy resolutions and low background rates to electronic recoil signals such as from:
  - Light dark matter scattering on e^-
  - Several other new physics models, such as axions or dark photons



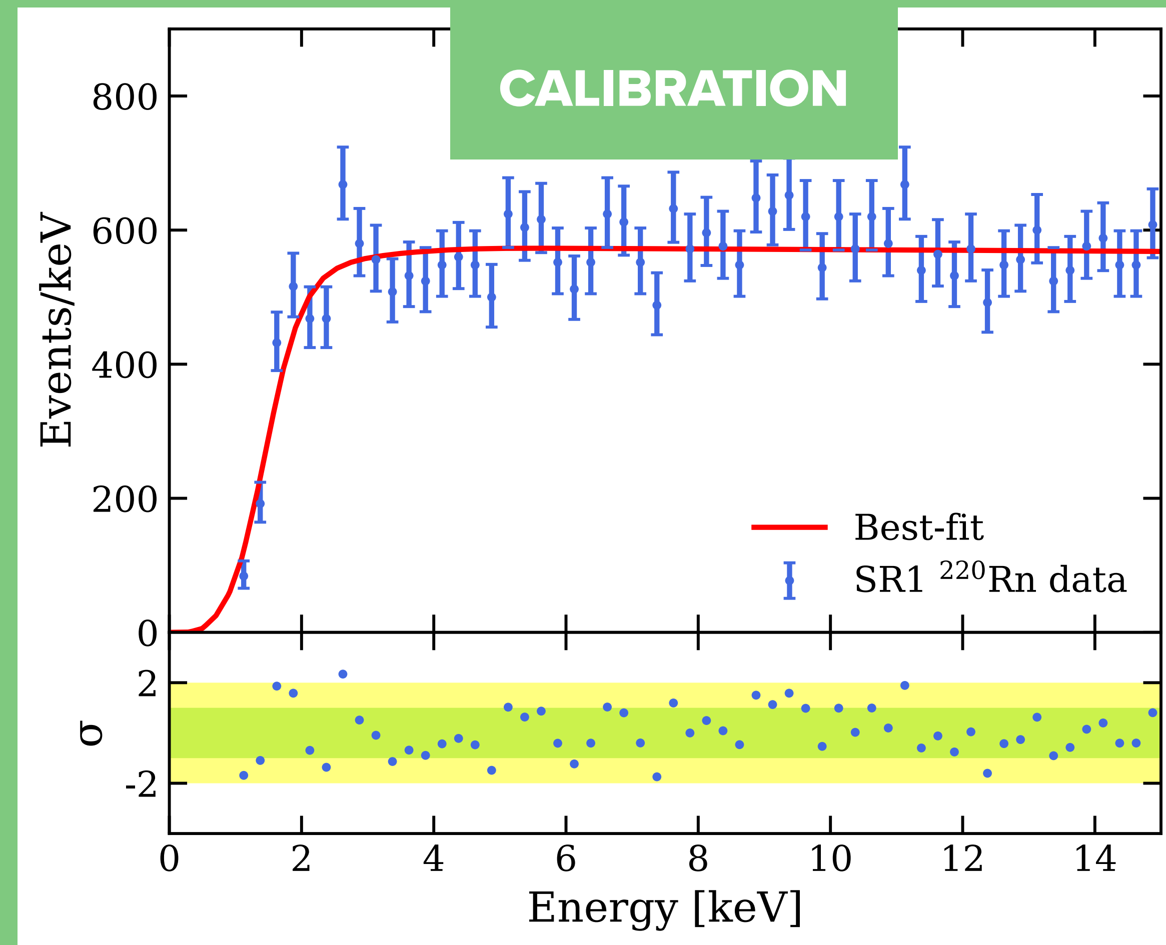
XENON collaboration: “Energy resolution and linearity of XENON1T in the MeV energy range” Eur.Phys.J.C 80 (2020) 8, 785, DOI: 10.1140/epjc/s10052-020-8284-0

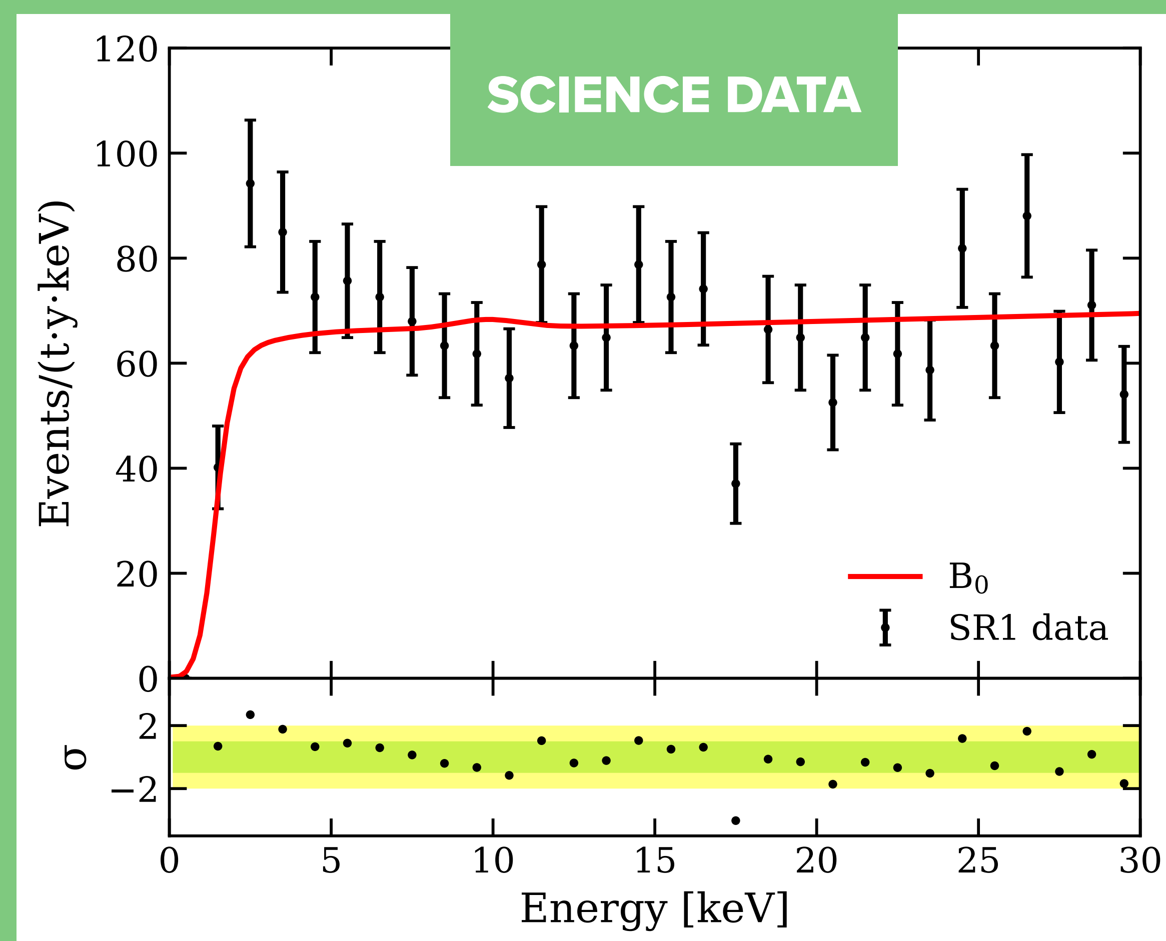
$$E_{\text{er rec}} = W(\cdot cS1/g_1 + cS2_b/g_2)$$

EXCESS ELECTRONIC RECOIL EVENTS IN XENON1T

- 0.65 tonne-year exposure, between 1 and 210 keV reconstructed energy
- Background model and efficiency at low energies validated with ^{220}Rn calibration data
- Best-fit background rate in science data fit: 63 events / tonne year keV
- Below 7keV, the science data shows an excess of around 50 events
  - Uniformly distributed inside the detector
  - No detectable time-variation
  - Corresponding to a $\sim 3\sigma$ statistical fluctuation

E. Aprile et al. (XENON Collaboration). "Excess electronic recoil events in XENON1T". In: Phys. Rev. D 102.7 (2020), p. 072004. doi: 10.1103/ PhysRevD.102.072004.

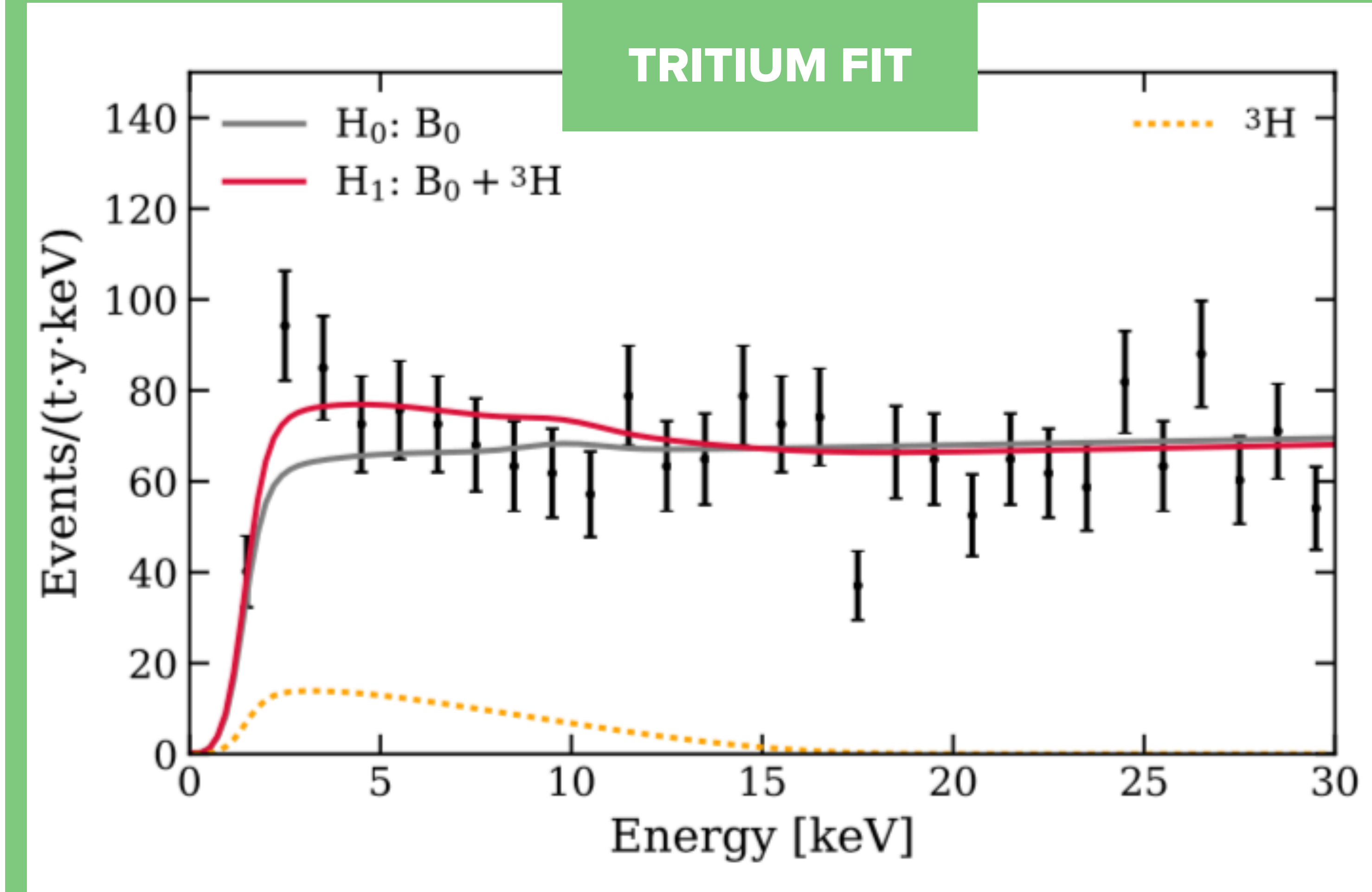




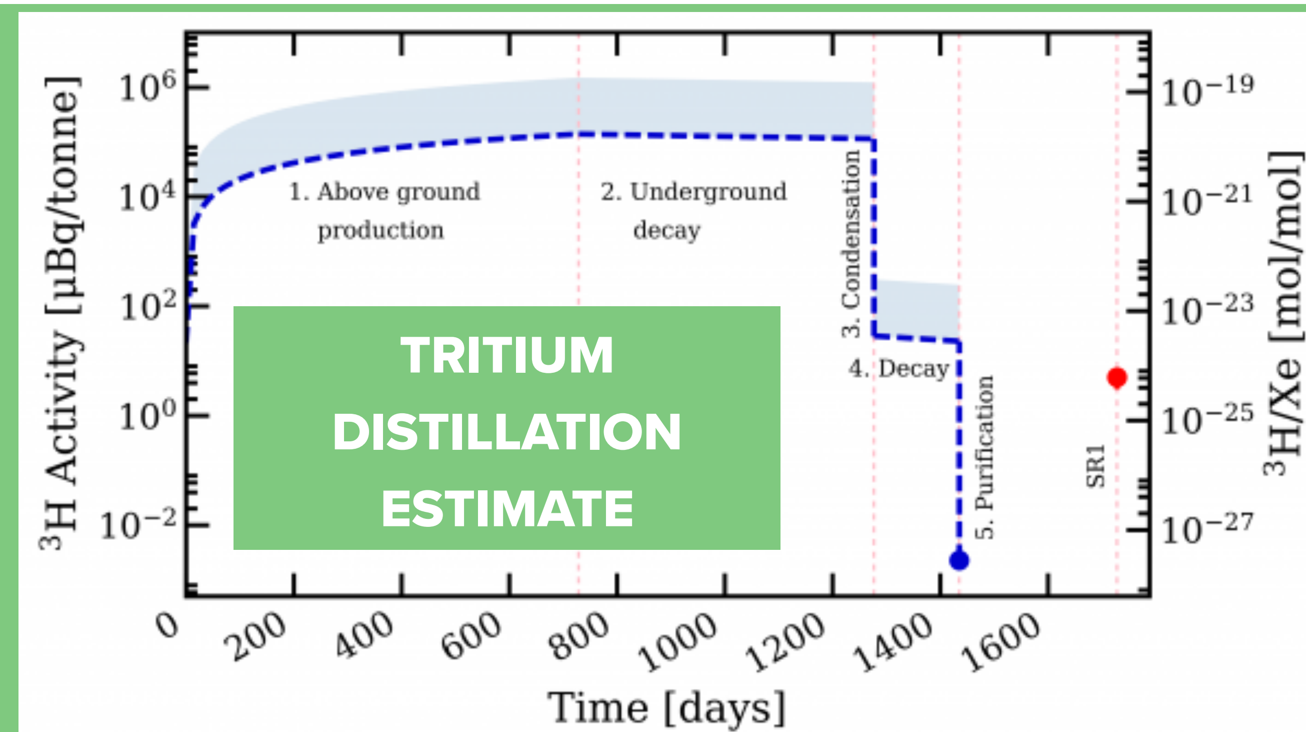
POSSIBLE SOURCES OF THE EXCESS

- A ^3H “signal” is favoured over the background-only fit at 3.2σ.
- The best-fit ^3H concentration of $(6.2\pm2)\times10^{-25}$ $^3H/Xe$, if in the form of tritiated water, is expected to have been purified as part of the filling process
- the XENON1T light yield suggests a too-low water concentration to explain the rate.
- Emanating and dissolved H_2, if it is to explain the rate, must be present at ~100 times the electronegative impurity rate, but is not ruled out.
- ^{37}Ar produces a 2.8 keV peak, but with a half-life (discounting purification) of 35 days, it would have to be replenished by a leak
- The upper limit on air leaks using Kr is 0.9 l/y, while the required leak to explain the excess is >13 l/y

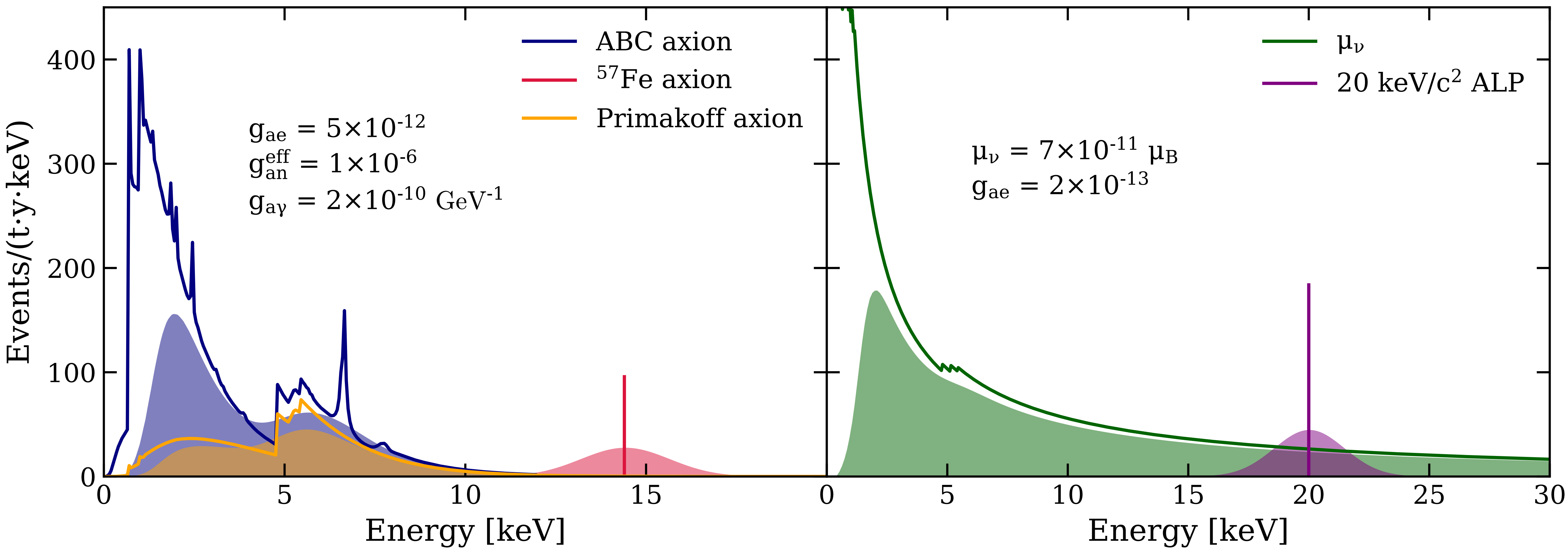
TRITIUM FIT



TRITIUM DISTILLATION ESTIMATE



ELECTRONIC RECOIL SIGNALS



SOLAR AXIONS:
Solar axions, boosted to keV energies may be detected by XENON1T
Axions may be produced in three channels, each scaling differently with three couplings
All three would create ERs in XENON1T

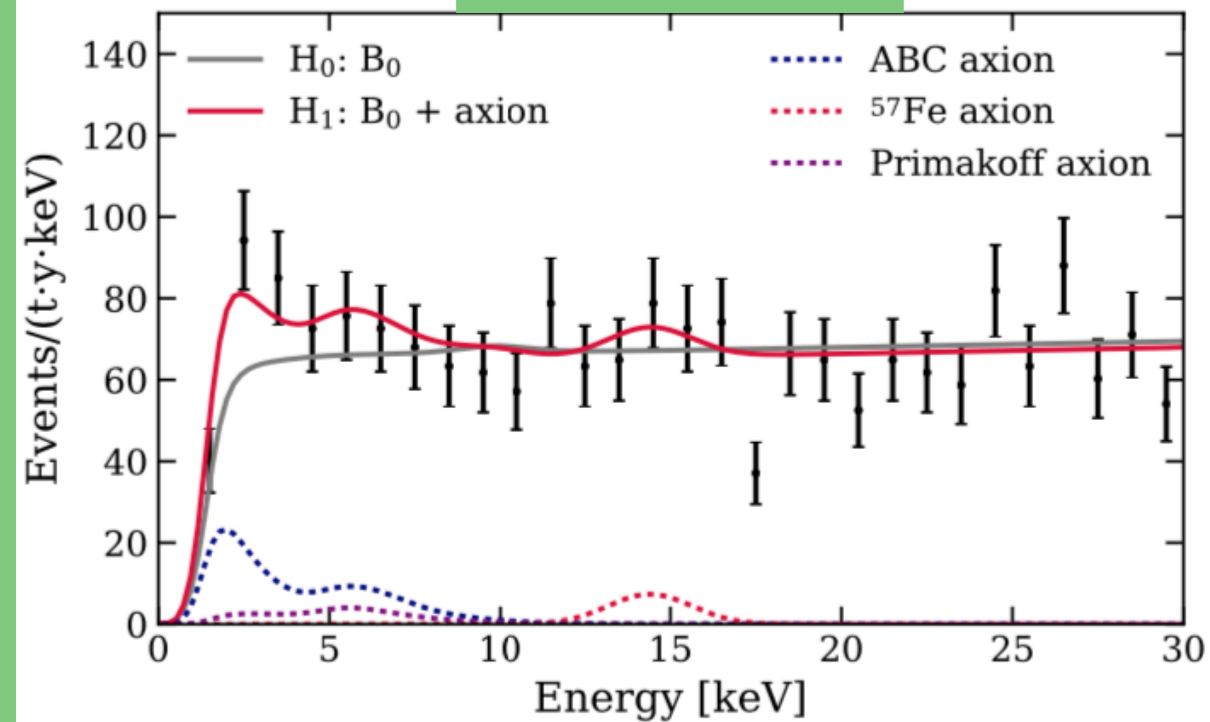
(SOLAR) NEUTRINO MAGNETIC MOMENT:
A magnetic moment is implied by neutrinos being massive— if new physics raises this magnetic moment, it may cause an enhanced neutrino scattering rate

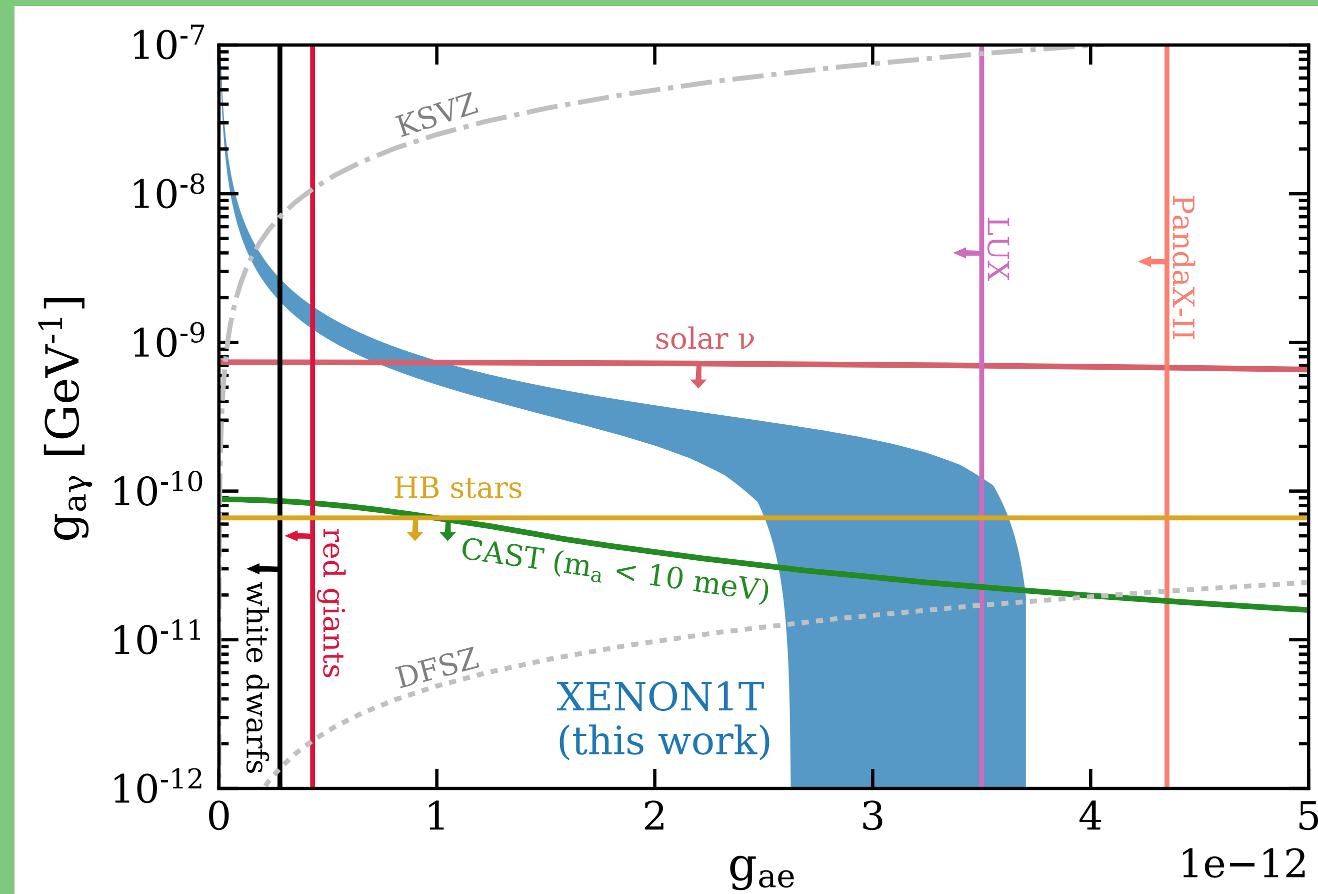
BOSONIC DM:
Axion-like particles or dark photons may be absorbed in the lXe target, giving a monoenergetic ER signal

INTERPRETING THE EXCESS AS A SOLAR AXION

- A solar axion is preferred over the background-only fit with a significance of 3.4σ
- An unconstrained tritium fit reduces the excess significance to 2σ
- The solar axion model depends on couplings to electrons, photons and nucleons, and the confidence interval is computed in the 3D volume of $g_{ae}, g_{a\gamma}, g_{an}$
- Stellar cooling constraints are in tension with almost the entire parameter space favoured in this fit.

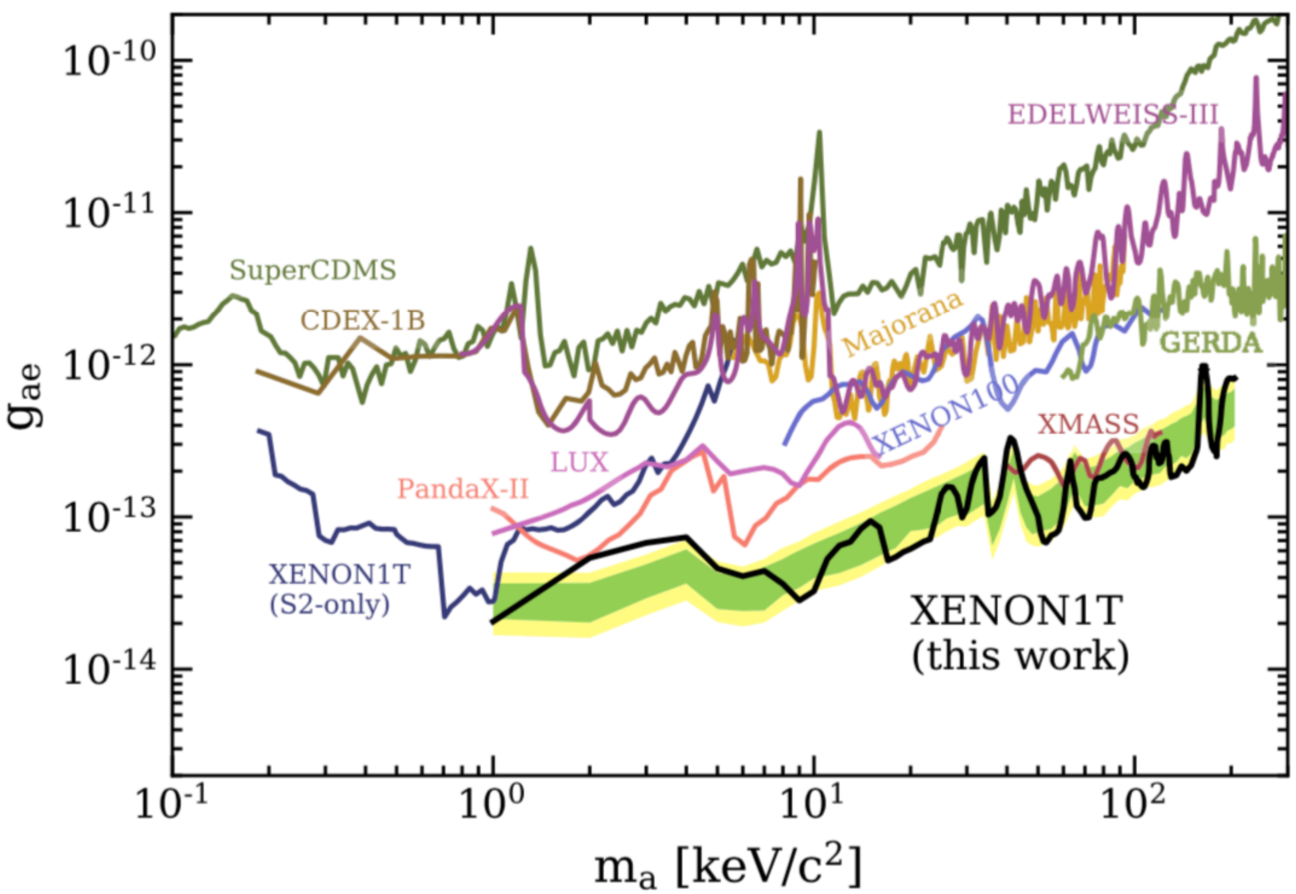
AXION FIT



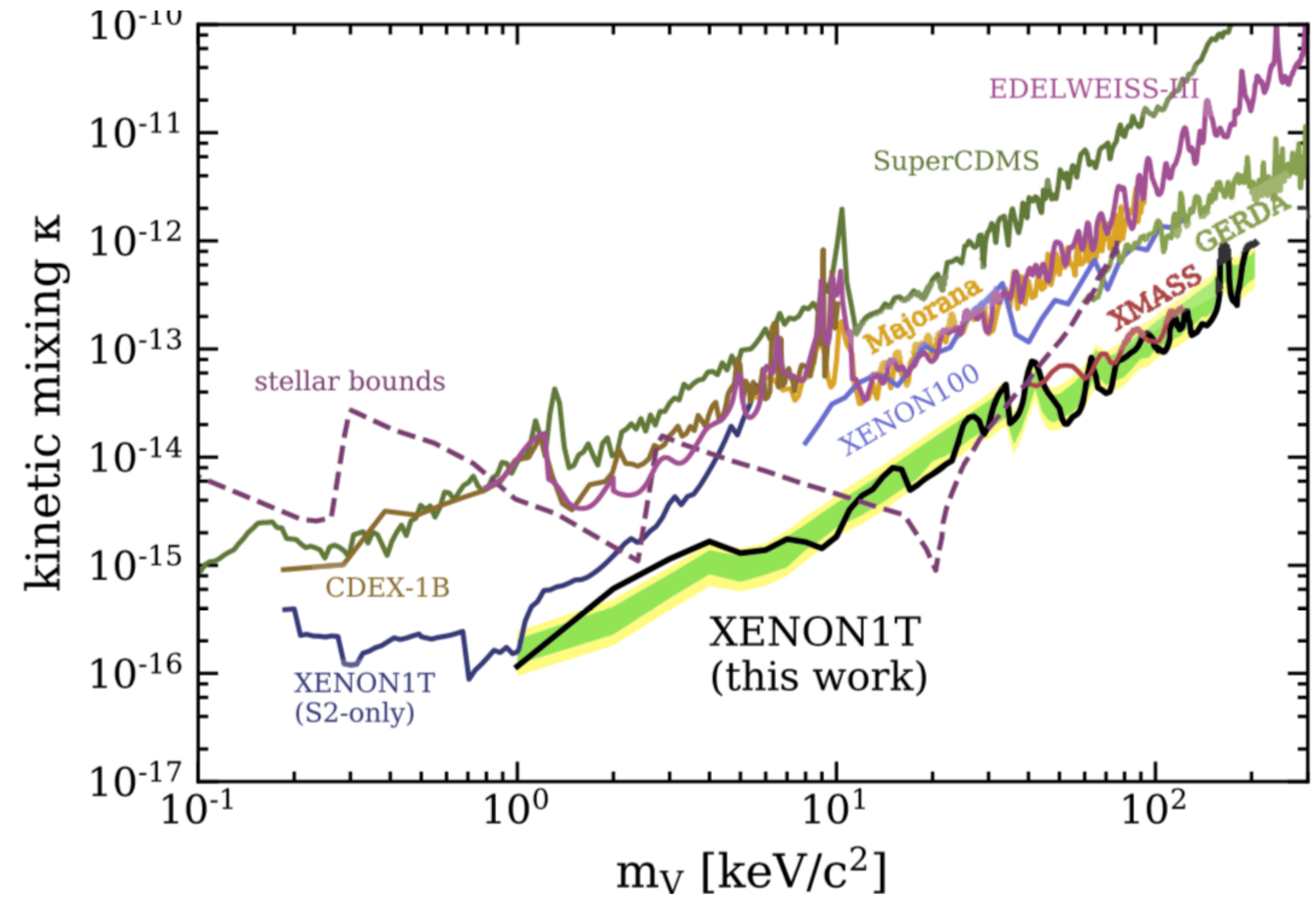


FURTHER LIMITS

ALP DARK MATTER LIMITS



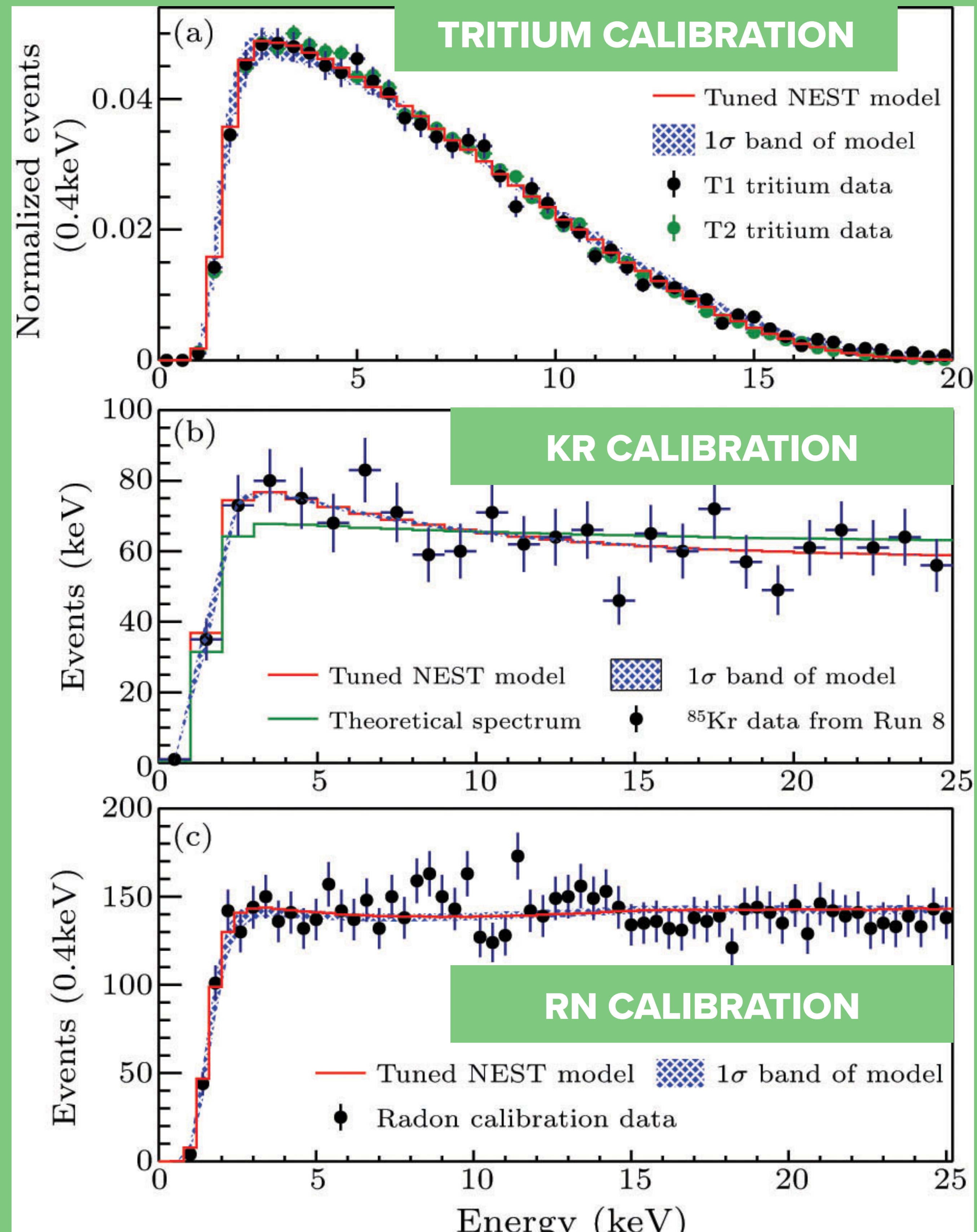
VECTOR BOSON DARK MATTER LIMITS



PANDAX-II ELECTRONIC RECOIL SEARCH

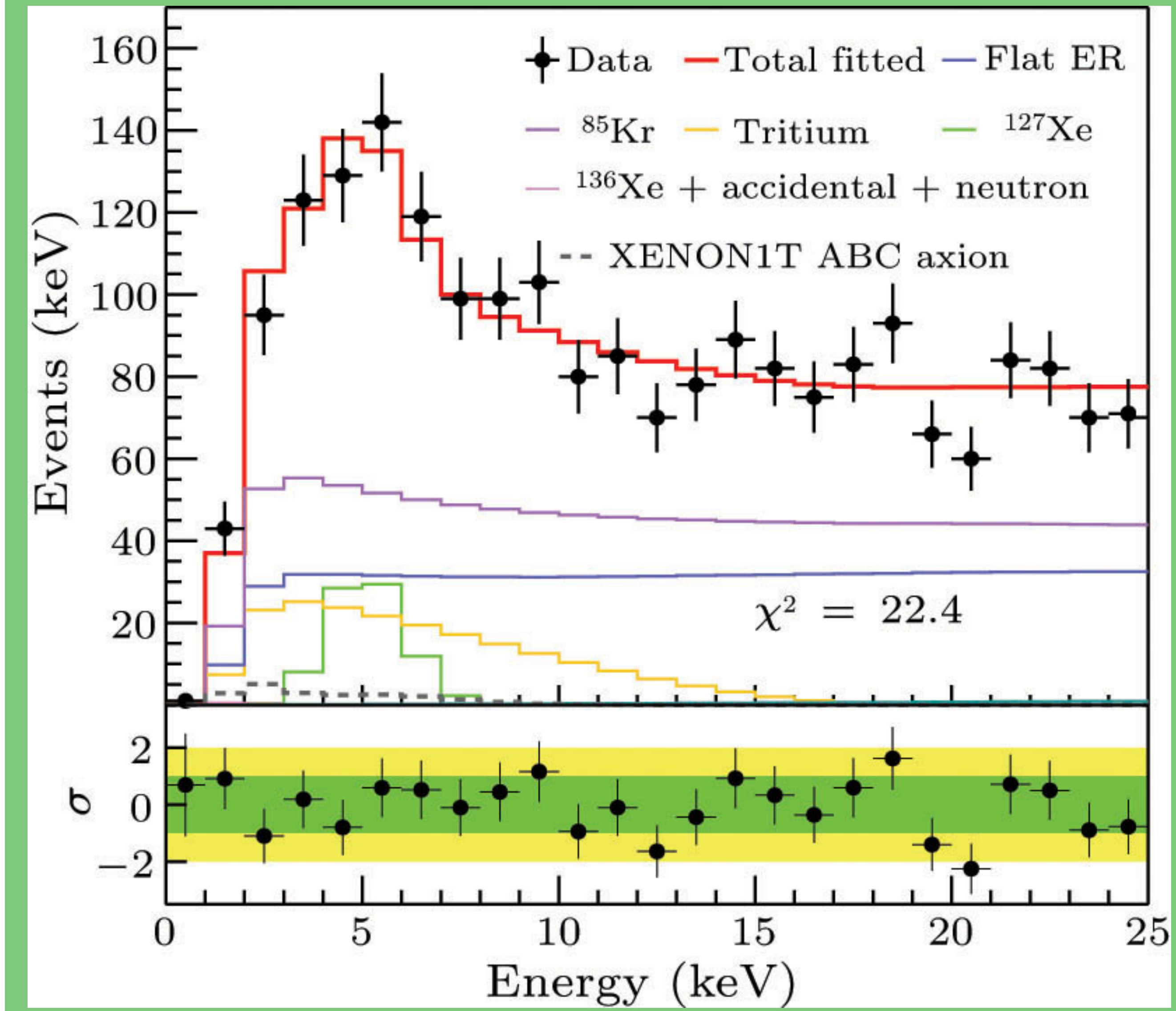
- Searching for axion and neutrino magnetic moment signatures with 0.28 tonne-year of data up to 25 keV
- PandaX-II performed a tritium calibration that gives them a high-statistics sample of low-energy ER calibration events
  - However, some of this tritiated methane remained as a background in the science search

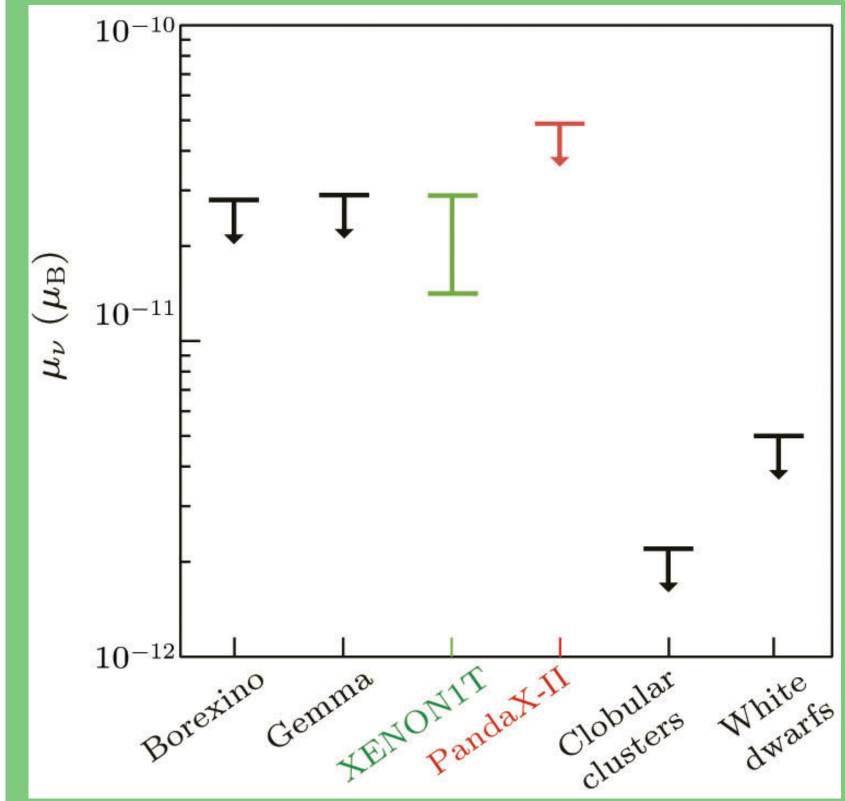
Xiaopeng Zhou et al. (PandaX-II Collaboration). "A search for solar axions and anomalous neutrino magnetic moment with the complete PandaX- II data". In: Chinese Phys. Lett. 38 011301(Aug. 2020). doi: 10.1088/0256-307X/38/1/011301.



PANDAX-II ELECTRONIC RECOIL SEARCH

- At the lowest energies, the PandaX-II electronic recoil background is dominated by ^{85}Kr events,
- Best-fit flat background rate in science data fit: ~ 100 events / tonne year keV
- Best-fit signal of 15.8 events within 1σ of both 0-signal and the XENON1T best-fit,
- Limits set on both the neutrino anomalous magnetic moment and $g_{\rm ae}$ also compatible with XENON1T
- In the plot to the right, the ^{127}Xe activation line is prominent, is only present in one of four science runs



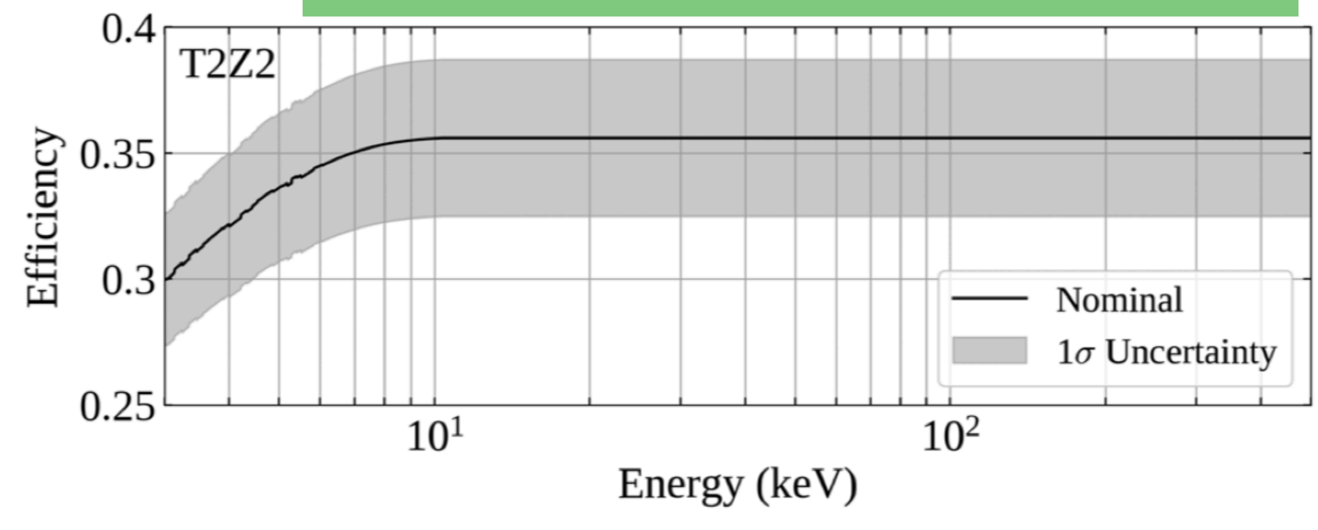


ν ANOMALOUS MAGNETIC MOMENT

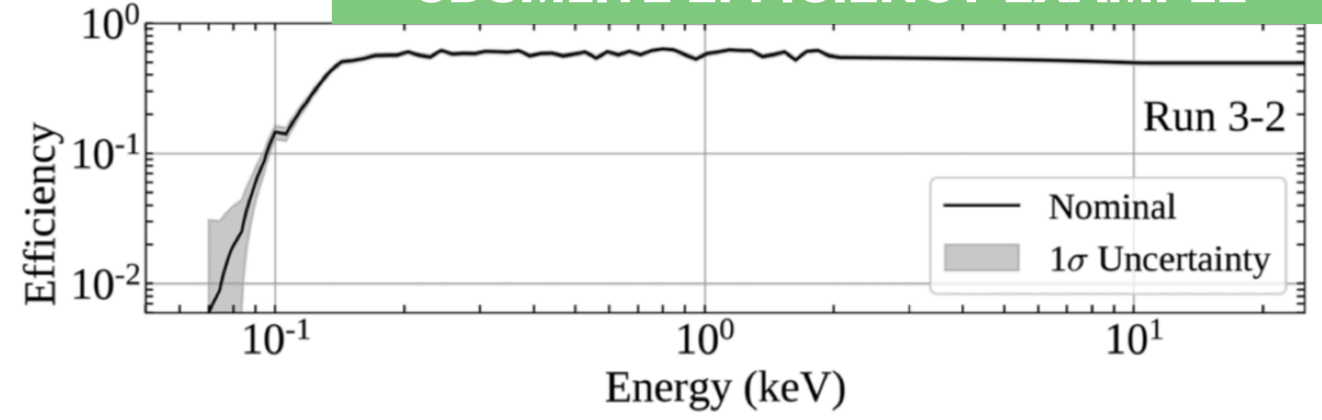
SUPERCDMS ALP AND DARK PHOTON CONSTRAINTS

- Germanium crystals with interleaved charge and phonon sensors (iZIP) allow ER/NR discrimination, surface rejection and a higher energy range
- Data also taken using higher bias voltages (CDMSlite) to lower the threshold of modules
- Combined, the analysis covers 40 eV – 500 keV
- New cut definition and efficiency measurements:
  - Extending CDMSlite efficiency to 30 keV
  - Selecting ER (rather than NR) events for the iZIPs, and altering the fiducial volume cut to use charge only

IZIP EFFICIENCY EXAMPLE



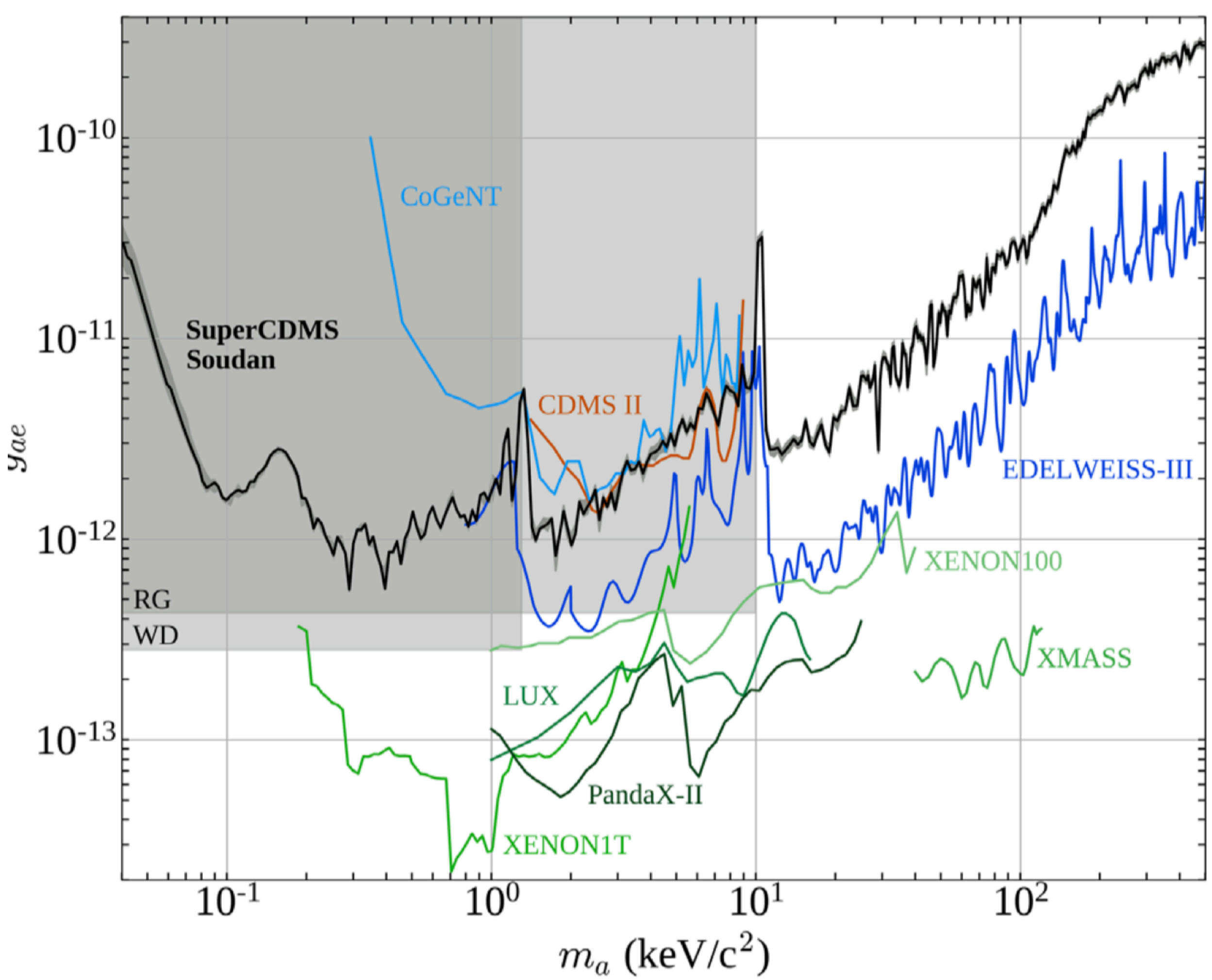
CDSMLITE EFFICIENCY EXAMPLE



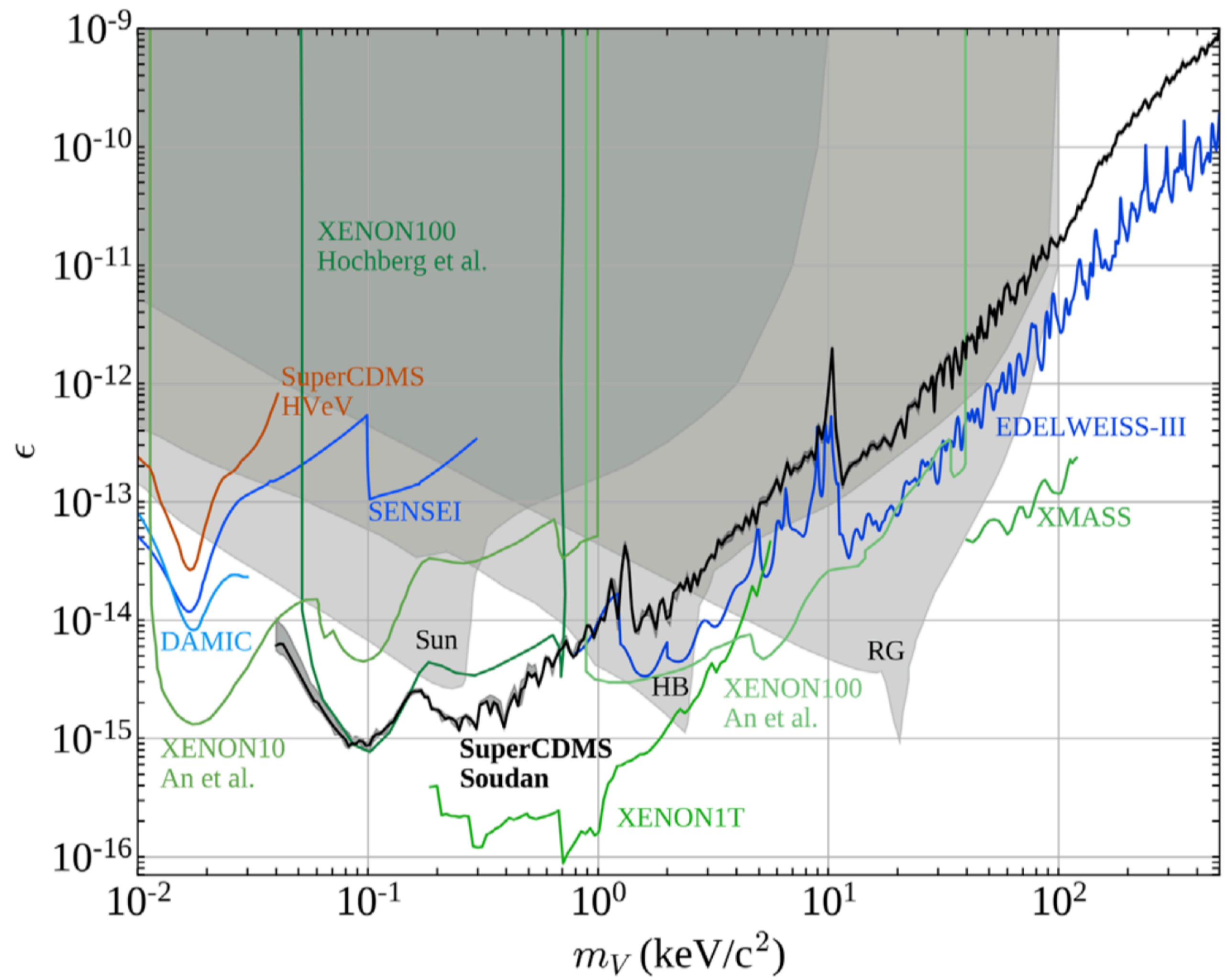
T. Aralis et al. (SuperCDMS Collaboration). "Constraints on dark pho- tons and axionlike particles from the SuperCDMS Soudan experiment". In: Phys. Rev. D 101.5 (2020). [Erratum: Phys.Rev.D 103, 039901 (2021)], p. 052008. doi: 10.1103/PhysRevD.101.052008.

SUPERCDMS ALP AND DARK PHOTON CONSTRAINTS

ALP DARK MATTER LIMITS



DARK PHOTON LIMITS



SUMMARY

- two-phase TPC results are improving analysis as the next generation is being constructed and commissioned
- CDMS and Sensei both published single-electron-counting results from a low exposure ahead of larger science runs
- The ER excess will be tested by new detectors with high power in the coming years