# Publishing results and data of direct detection experiments

(Re) interpreting the results of new physics searches at the LHC, 20210217

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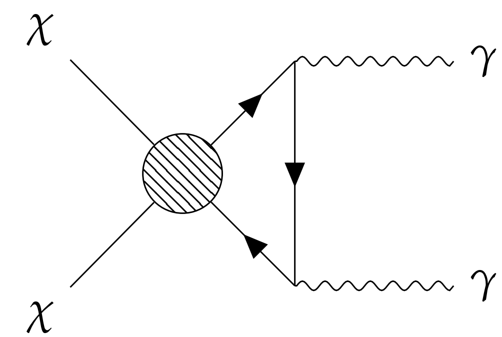
# Direct detection searches for dark matter

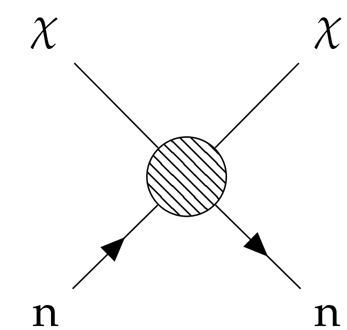
- Searches for dark matter particles interacting directly with a dark matter detector

- Detectors shielded by rock overburden and radiation shielding aim to observe the rare dark matter-matter scatters

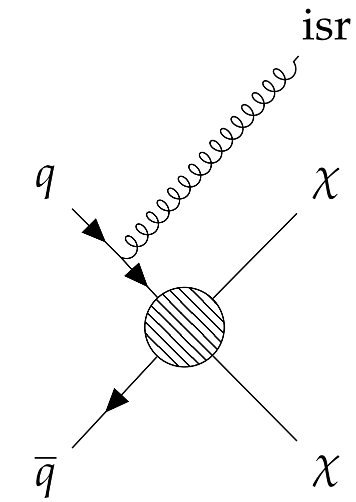
- In this talk, I will talk mainly about constraints on WIMP dark matter -matter interactions



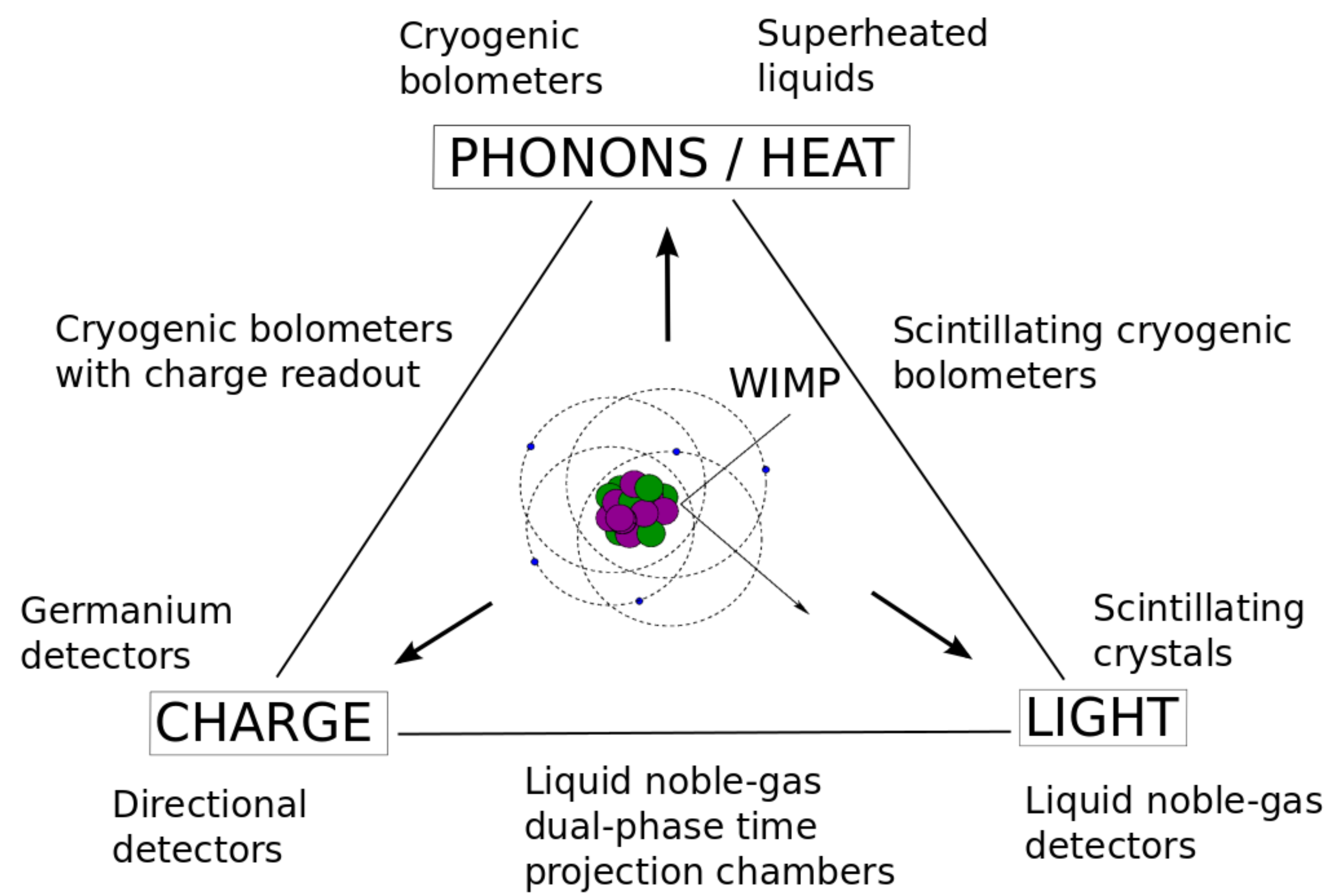

Indirect gamma-gamma signature




Direct detection




Example collider signature

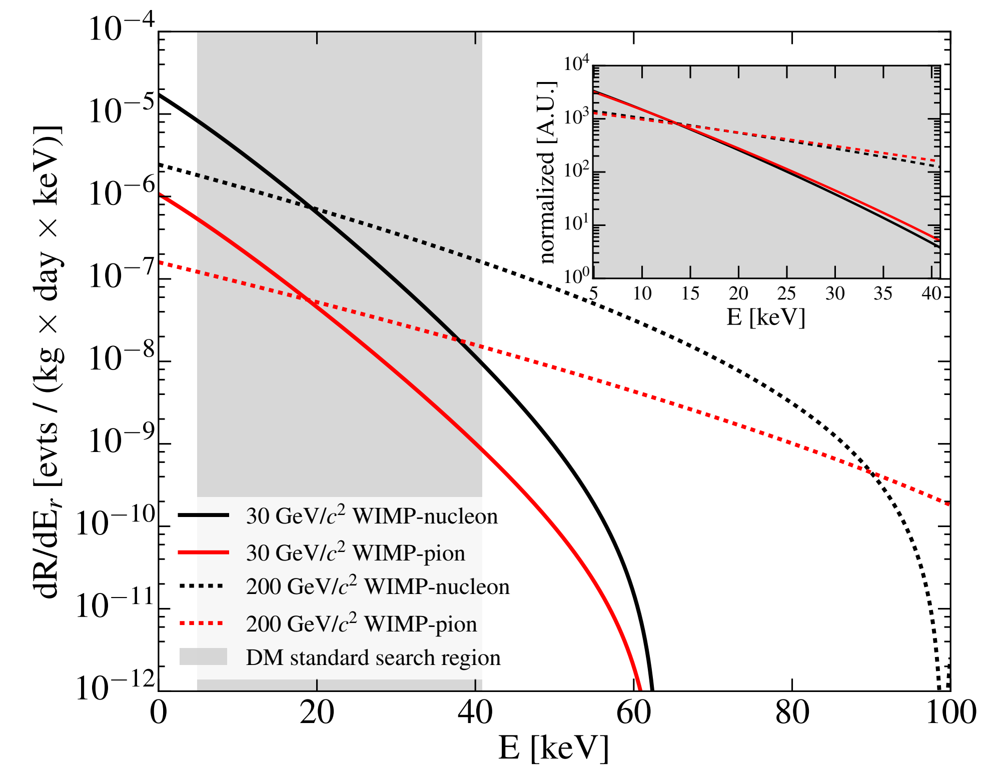


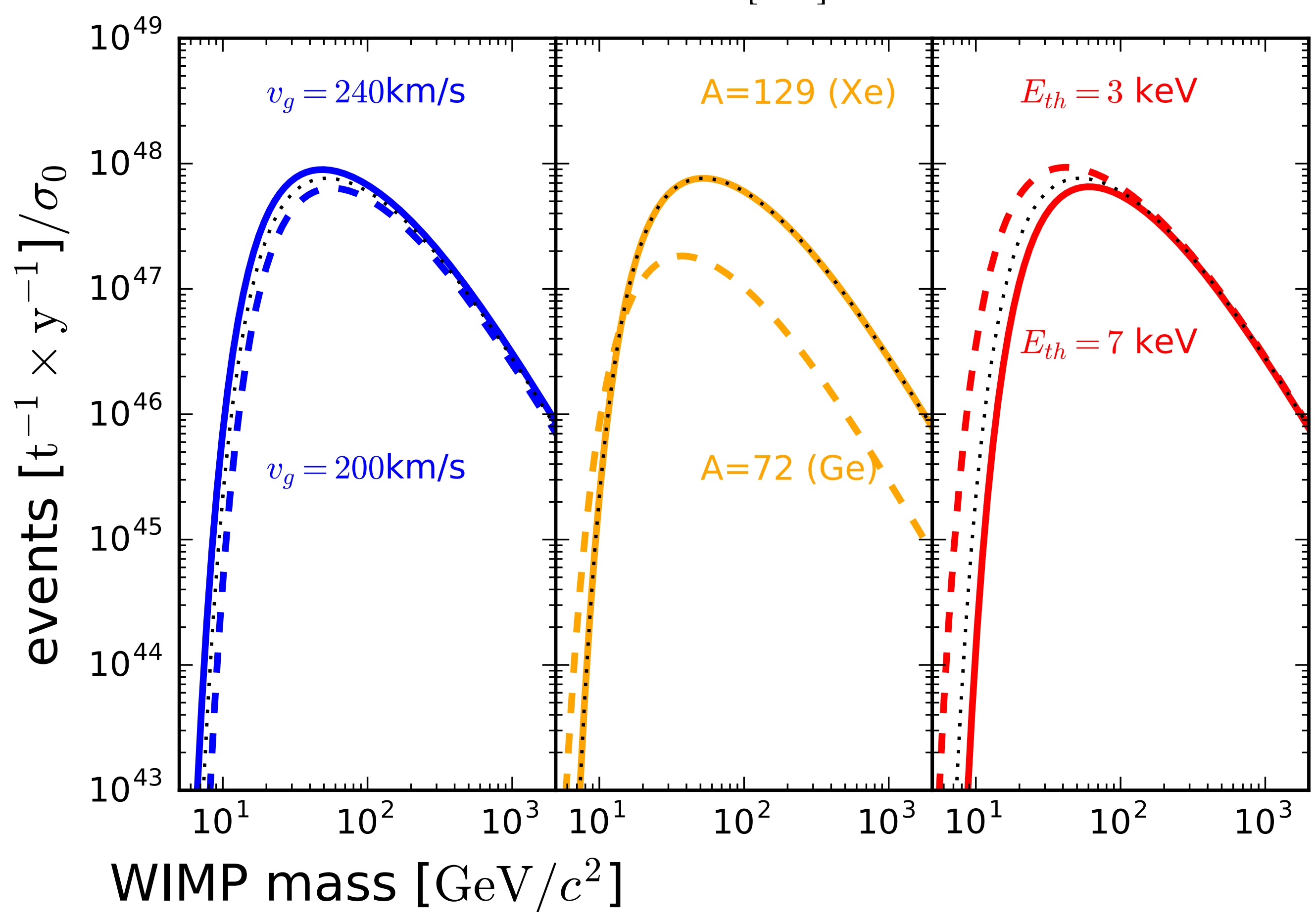

Teresa Marrodán Undagoitia and Ludwig Rauch. “Dark matter direct-detection experiments”. In: J. Phys. G43.1 (2016), p. 013001. DOI: 10.1088/0954-3899/43/1/013001.

# Dark matter-nucleus elastic scattering

- An elastic scattering between a WIMP and a nucleus can transfer up to ~50 keV to the nucleus
- The expected recoil energy spectra are featureless, falling to higher recoil energies, determined by the expected dark matter velocity distribution
- At low recoil energies, the WIMP interacts with the entire nucleus, and the cross-section is enhanced by a factor $A^2$. At higher energies, the form factor, parameterising the nuclear spatial distribution, reduces the interaction rate
- Higher-order interactions (e.g. inelastic scattering, two-body currents) or spin-dependent interactions are in general suppressed with respect to the elastic interaction

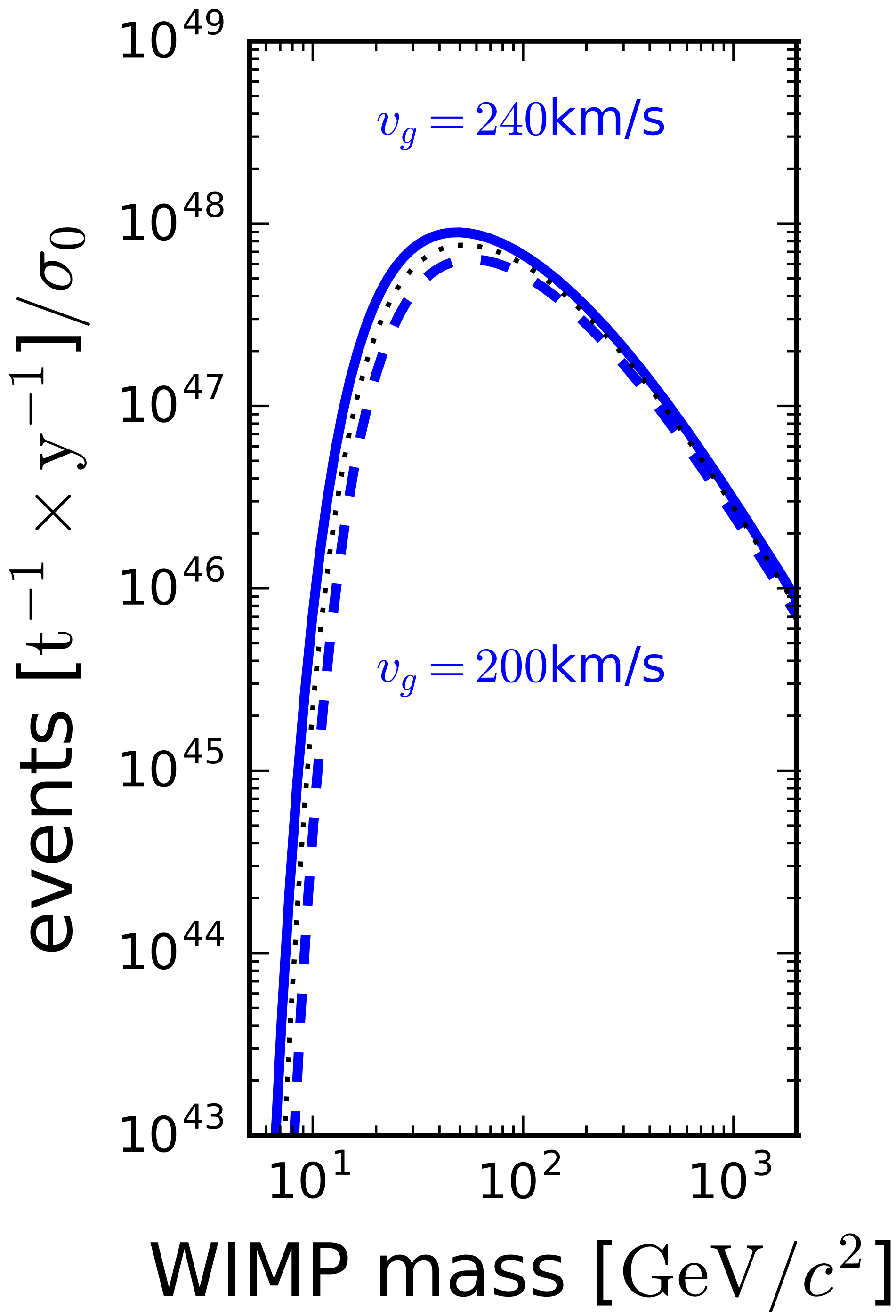
E. Aprile et al. (XENON), Phys. Rev. Le
122, 071301 (2019), 1811.12482.



# Recoil spectrum uncertainties

- Several parameters in the signal prediction have significant uncertainties:
- The dark matter velocity distribution, which largely determines the recoil energy spectrum is not known
  - Results are reported using a “Standard Halo model”— a Maxwell Boltzmann distribution truncated at a galactic escape velocity
  - The density also scales results up and down, but can easily be accounted for.
- Other assumptions include choosing to use the analytic Helm nuclear form factor
- And, perhaps most obviously— in choosing to study and constrain certain interactions— spin-independent and dependent nuclear recoils



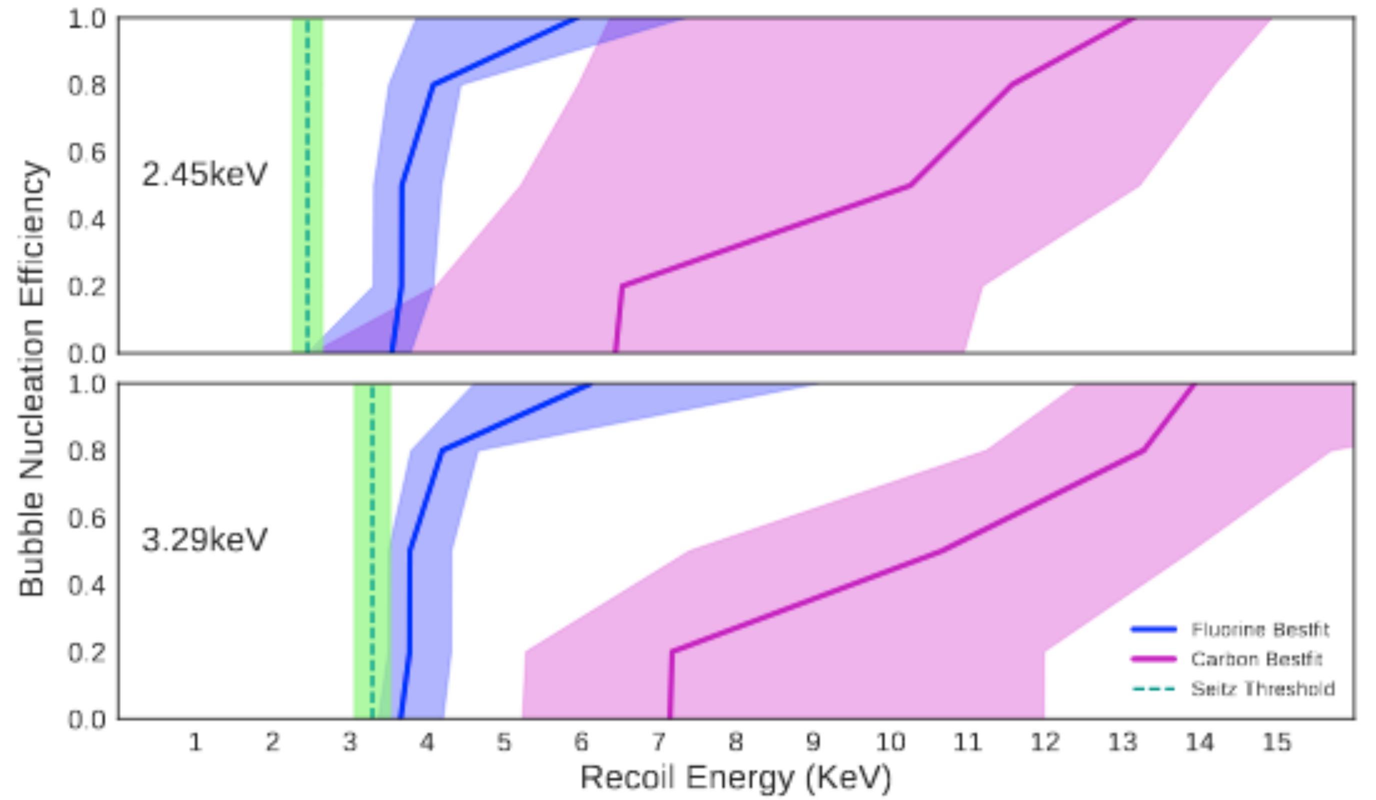

See following talk by Christopher McCabe

# General remarks

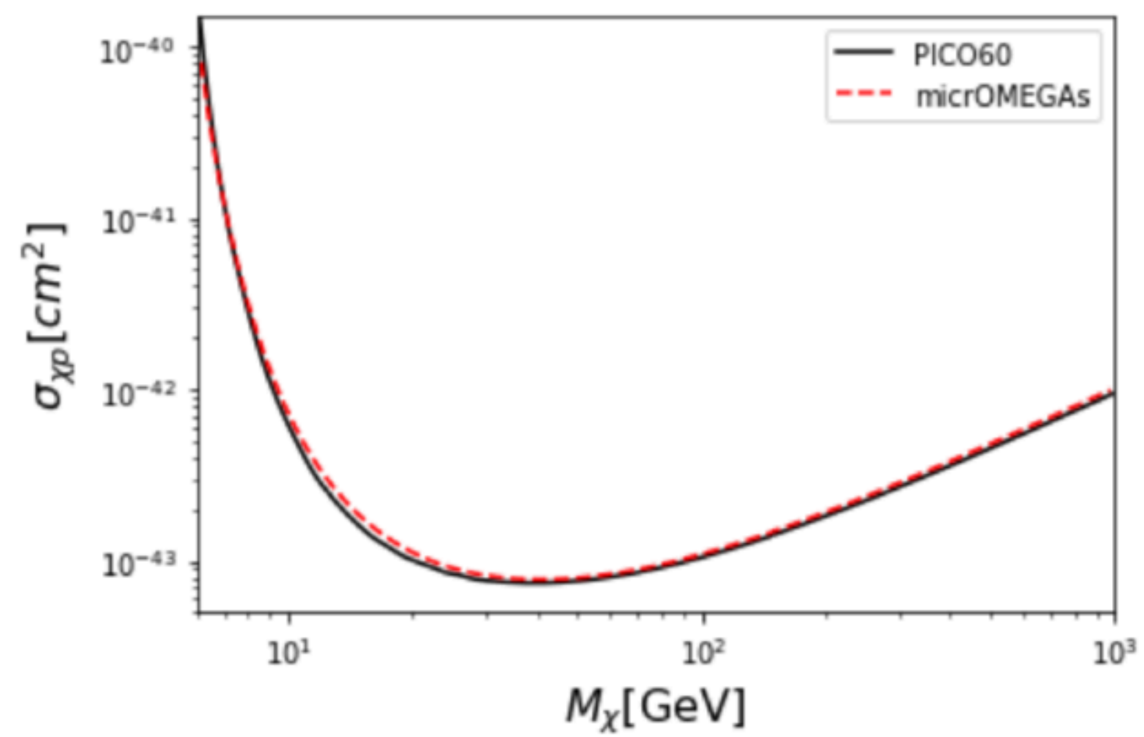
- A typical direct detection signal is determined by the recoil spectrum in the detector, and what type of recoil (on nuclei or electrons)
- Together with the low event-rates probed, finding the best-fit among spectra an experiment has constrained and scaling the rates will often perform well given typical featureless spectra.
- For more detailed recasts, the level of detail varies:
    - Some analyses, such as counting analyses, maximum gap or a 1D histogram fit are relatively simple to recast
    - Some collaborations and analyses have been performed to be easily recastable
    - Xenon TPCs, providing the most stringent limits above ~6 GeV/$c^2$ rely on multiple dimensions for powerful signal-background discrimination and are often hard to reinterpret

# PICO-60

- Bubble chamber containing $C_3F_8$ reaching 2.5 keV thermodynamic threshold with two runs of 1 and 1.5 tonne-days exposure.
- 0 and 3 events observed,
- Background rates are left unconstrained to provide a final upper-limit-only construction using the Feldman-Cousins construction
- Recast close to perfect



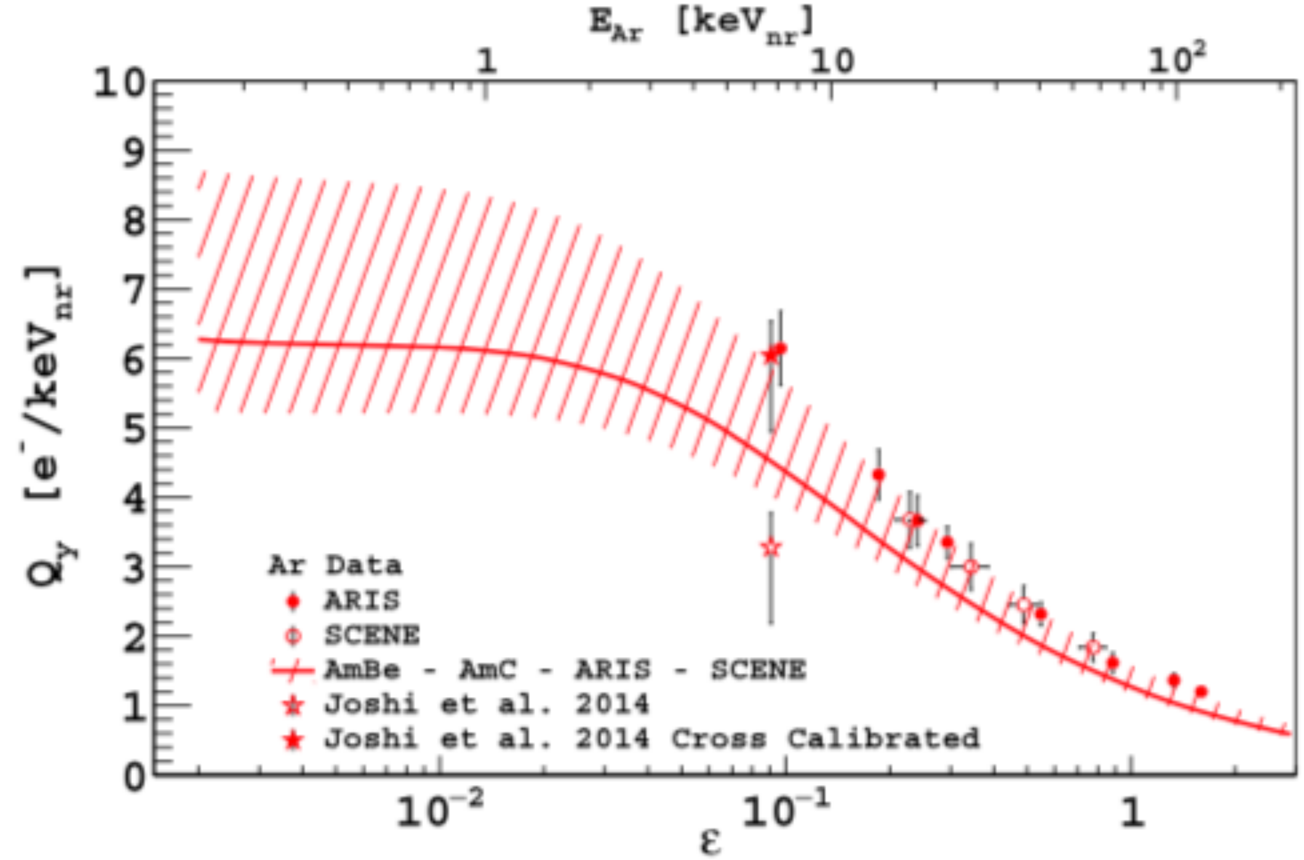

PICO Collaboration, C. Amole et al., "Dark Matter Search Resu from the Complete Exposure of the PICO-60 C3F8 Bubble Chamber," Phys. Rev. D100 no. 2, (2019) 022001

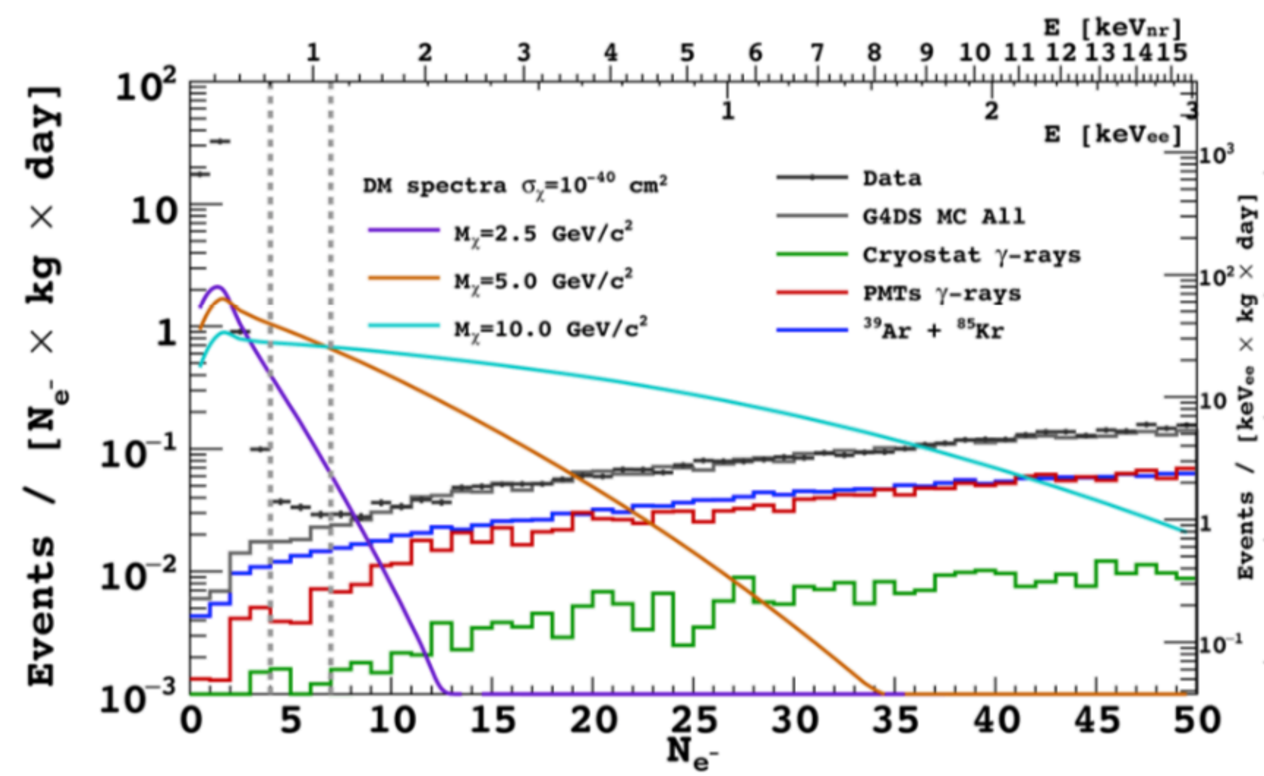



G. Belanger, A. Mjallal, and A. Pukhov (2020), 2003.08621.

# DarkSide-50 ionisation-search

- The DarkSide-50 detector is a liquid argon dual-phase TPC with a 46 kg active target
- For a low-threshold (down to 0.6 keV NR) search, using only ionisation signals and a 6786 kg-days exposure
- upper limits computed with a binned profile likelihood
- In addition to confidence intervals on spin-independent date matter, the paper includes the
  - Quenching model and efficiency needed to compute signal spectra in the $n_{e-}$ ionisation bins
  - (possibly incomplete) background expectation per $n_{e-}$ bin
  - Detection efficiency




DarkSide Collaboration, P. Agnes et al., "Low-Mass Dark Matter Search with the DarkSide-50 Experiment," Phys. Rev. Lett. 121 no. 8, (2018) 081307

[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)

Current browse context:
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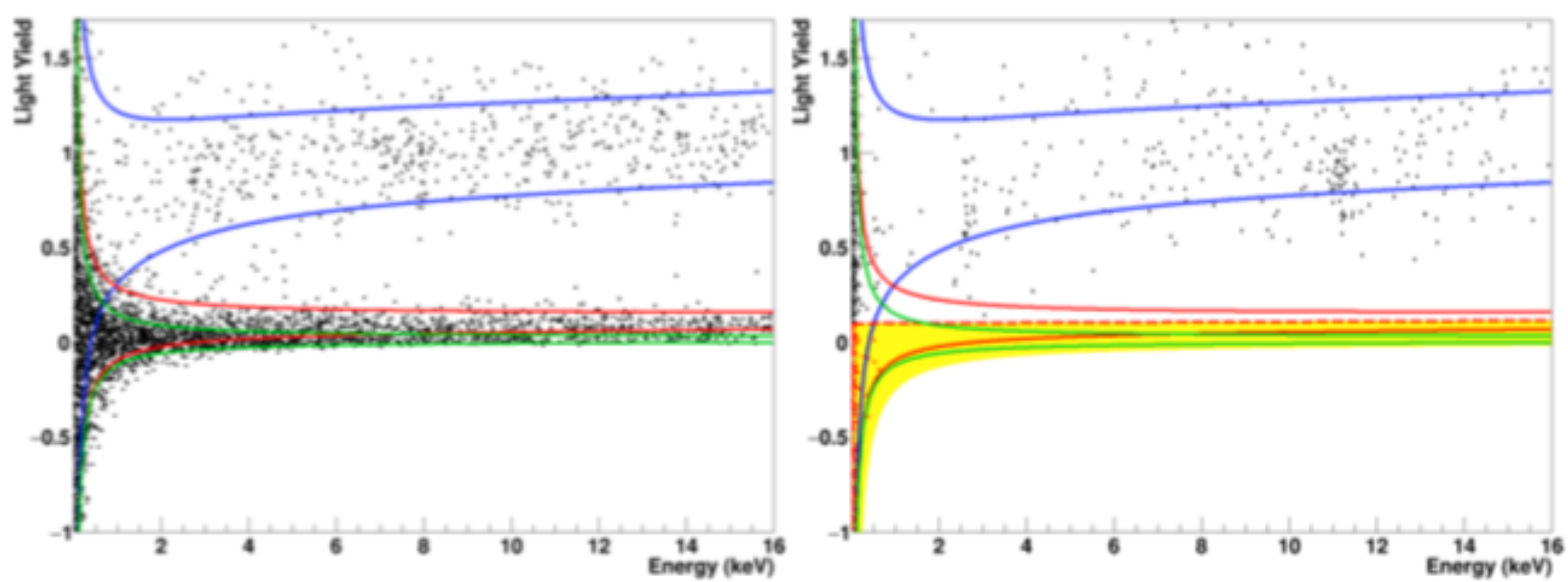
- CRESST-III releases data to reproduce their experimental results of $CaWO_4$ crystals detecting phonons and scintillation light

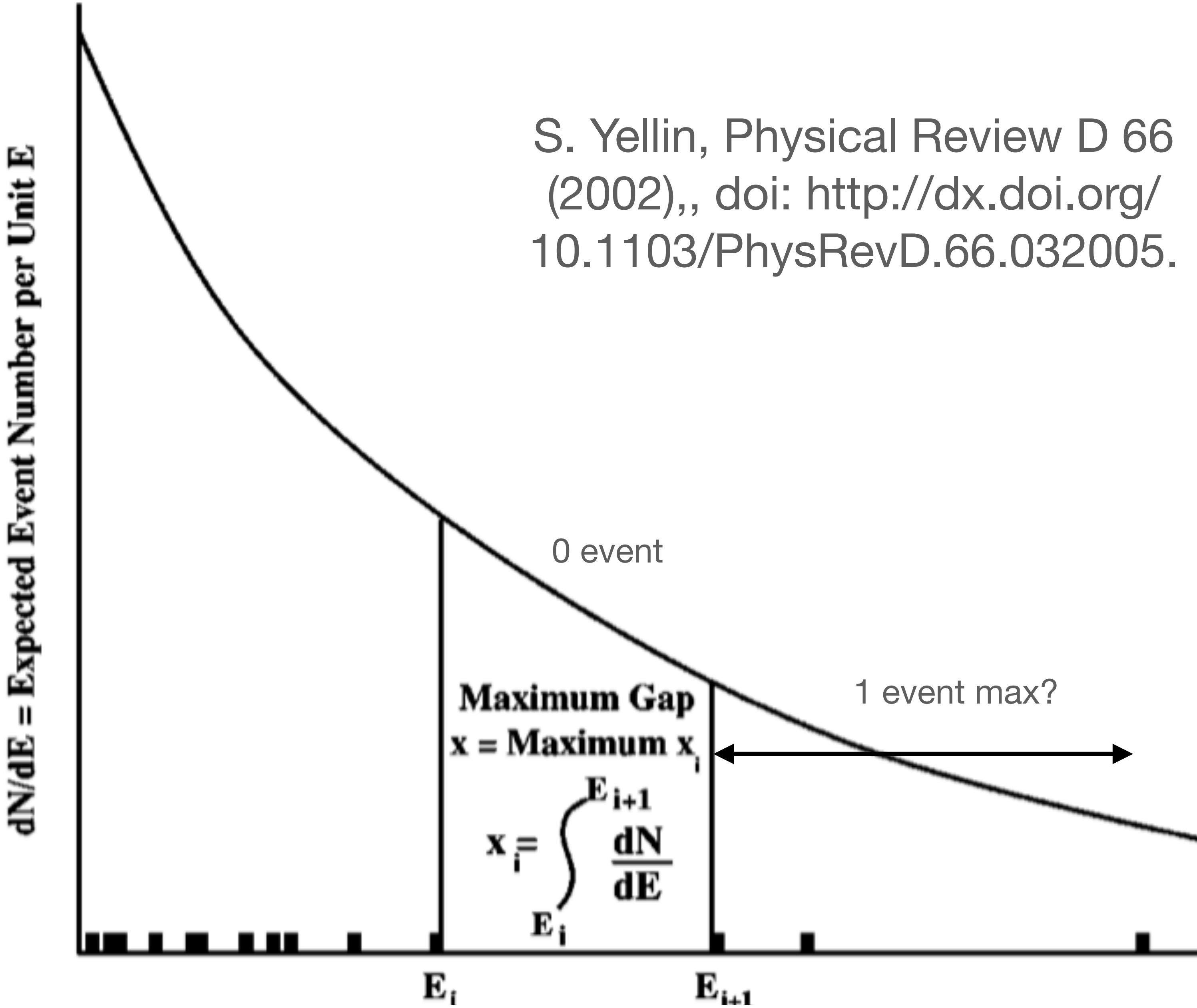


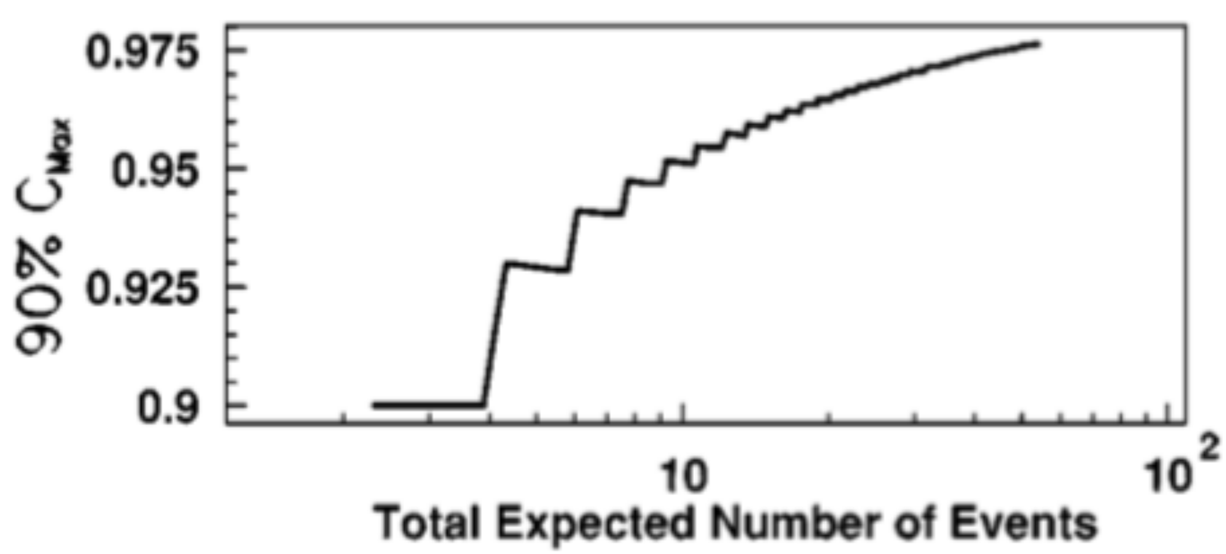

CRESST Collaboration, A. H. Abdelhameed et al., “Description of CRESST-III Data,” arXiv:1905.07335

# Maximum Gap Limits

- If the signal distribution is known along some variable, the maximum gap/optimal interval method can incorporate this
    - even in the presence of an unknown background
- Find the space between observed events containing the largest signal expectation, and find the largest signal compatible with this largest "gap".
- The method can be extended as "optimum interval" where you search for the largest interval containing 0,1,2 etc events
    - threshold for the best interval test statistic found via toyMC methods

S. Yellin, Physical Review D 66 (2002),, doi: http://dx.doi.org/10.1103/PhysRevD.66.032005.

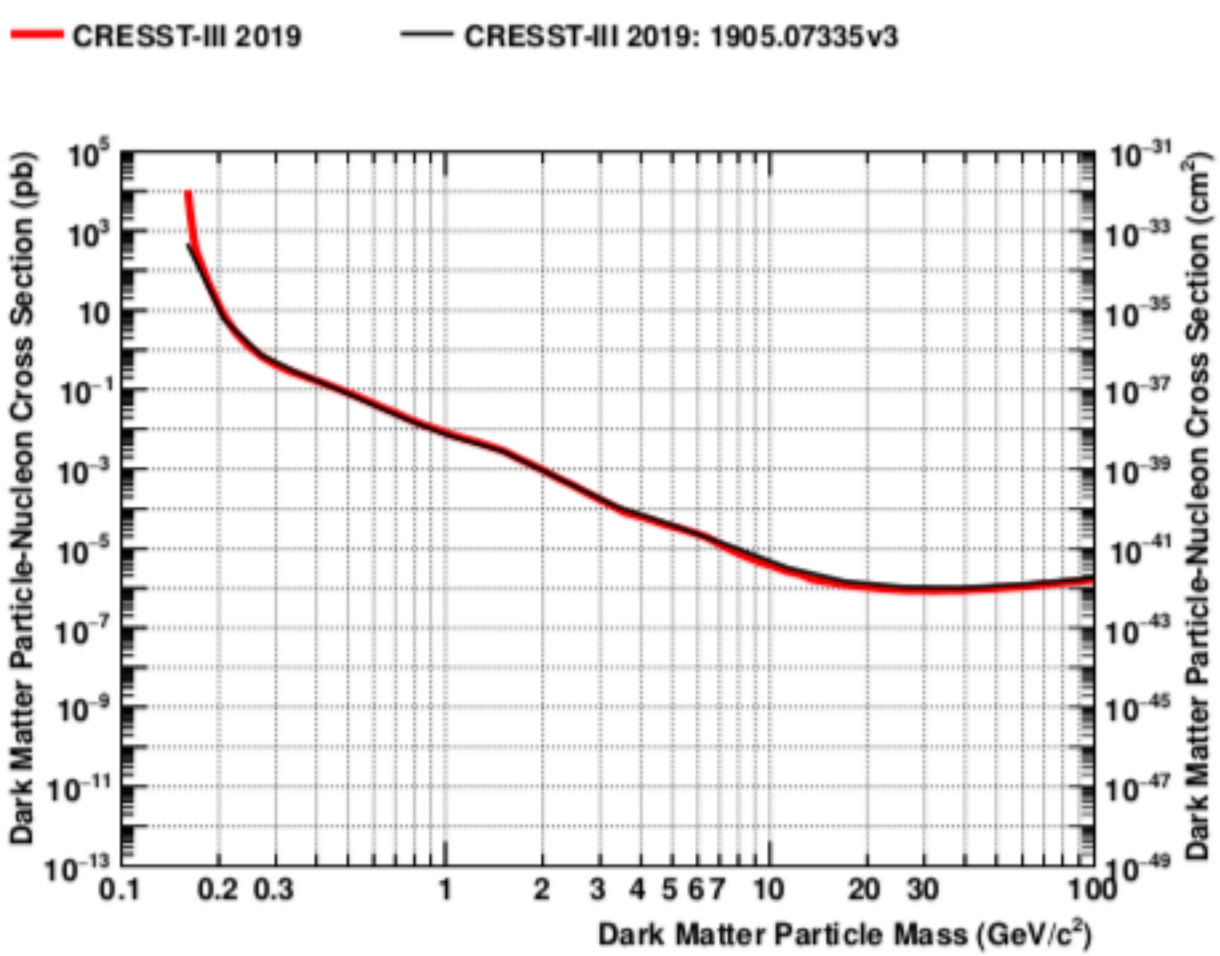


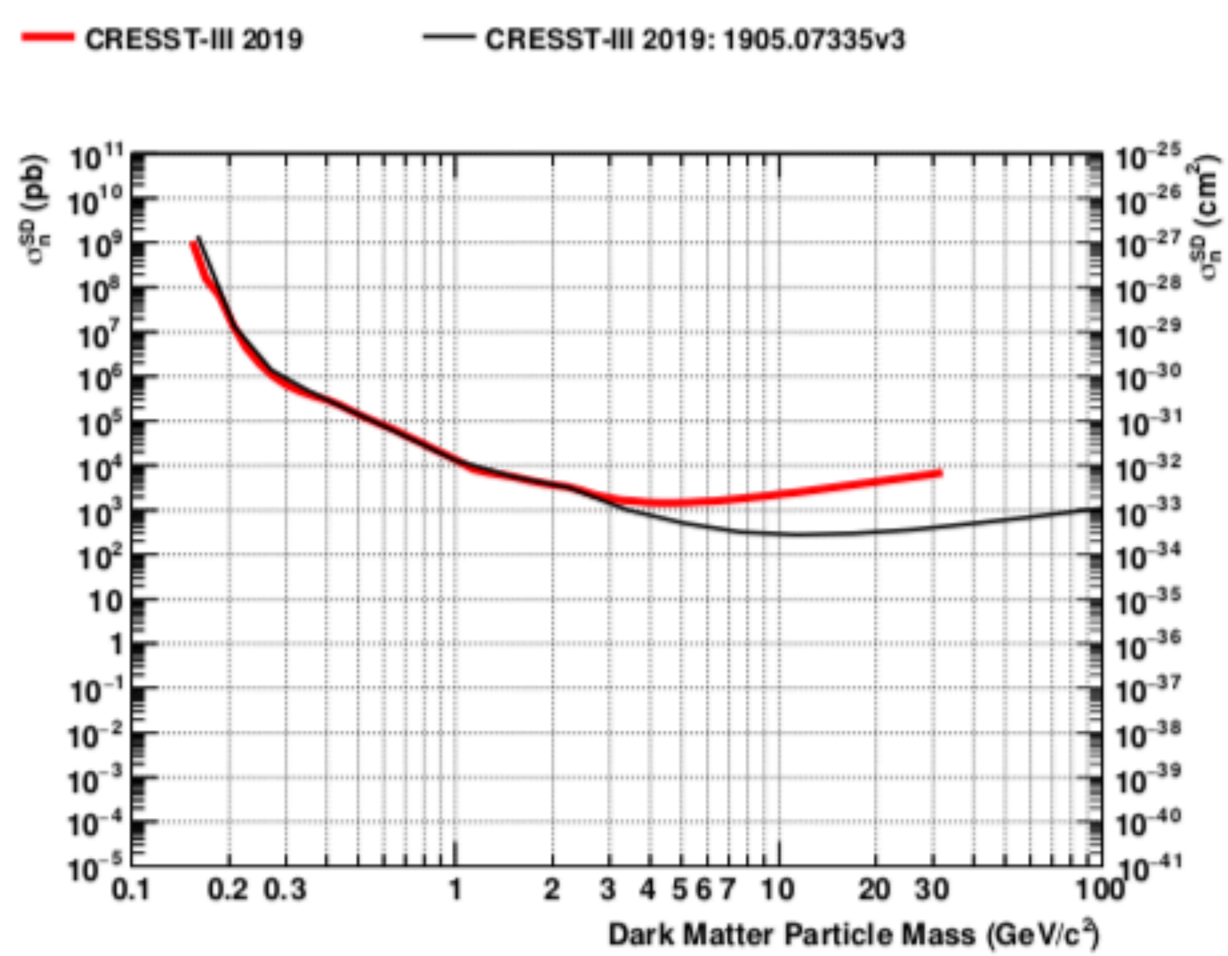



- Model for $p(E_{reco}| p_{model}(E)$ provided, with datafile for the efficiency, data-points:

$$\widetilde{p}(E_{reco}) = \Theta(E_{reco} - E_{\mathrm{thr,reco}}) \cdot \widetilde{\varepsilon} \cdot \varepsilon_{x,Acc}(E_{reco}) \cdot \int_0^{\infty} p_{\mathrm{model}}(E) \cdot \mathcal{N}(E_{reco} - E, \sigma_p^2) dE$$

- At high mass, the normal approximation to the detector resolution fails, but results are otherwise very similar to the main CRESST-III results for both spin-dependent and dependent:



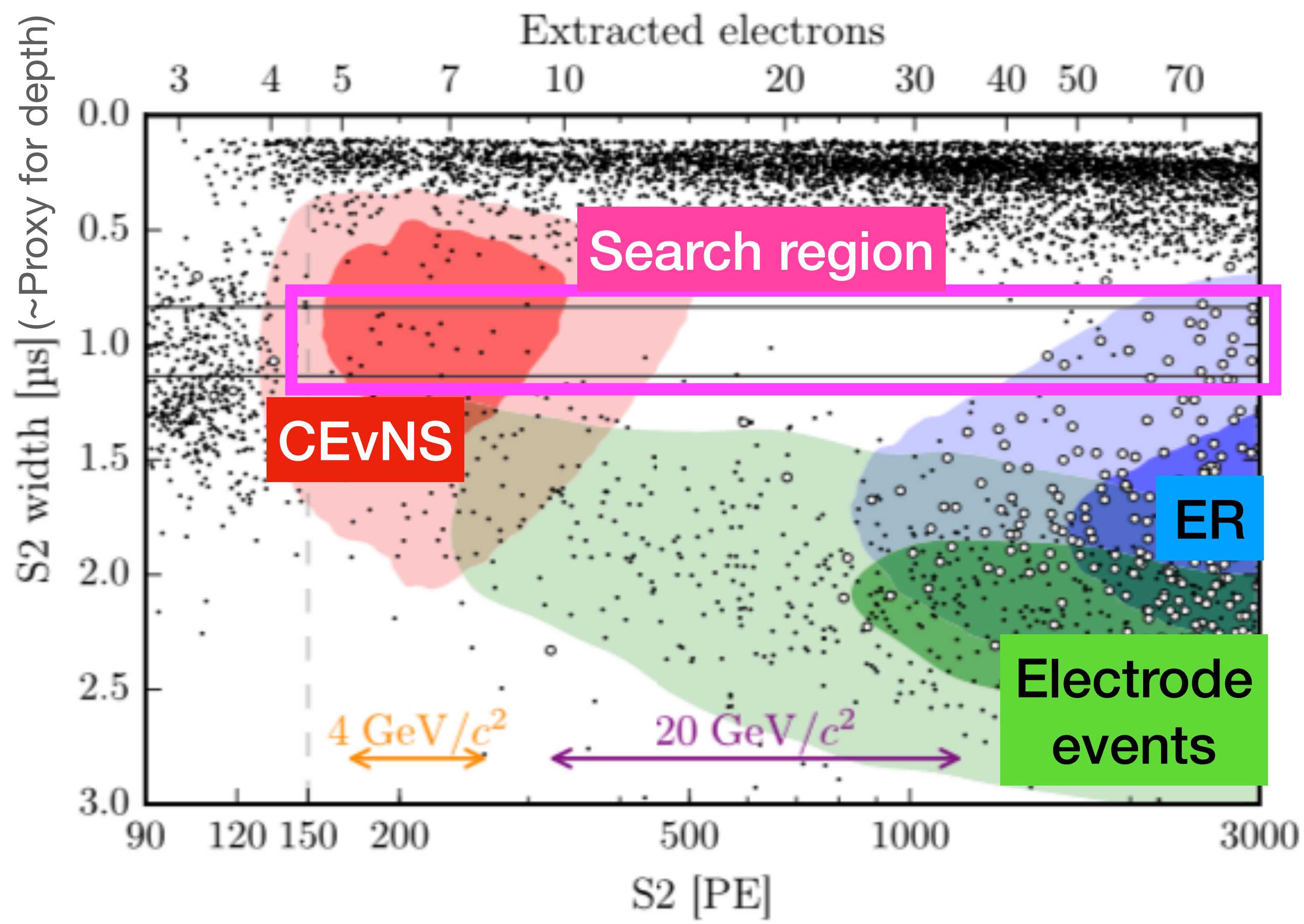



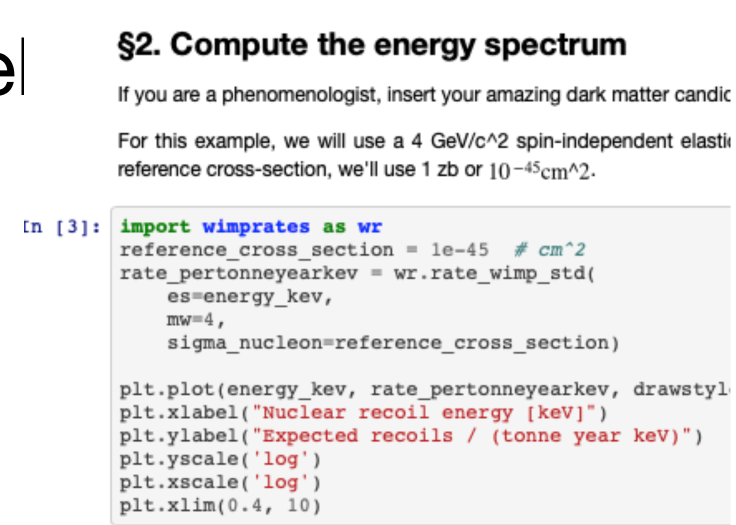

CRESST Collaboration, A. H. Abdelhameed et al., "Description of CRESST-III Data," arXiv:1905.07335

# XENON1T ionisation-only analysis

Aprile, E. et al. (XENON collaboration), Phys. Rev. Lett. 123, 251801 (2019)
https://github.com/XENON1T/s2only_data_release
http://doi.org/10.5281/zenodo.4075018

- An analysis requiring only an ionisation signal (no scintillation flash) to reach lower recoil energies
  - Event depth resolution deteriorates
  - Incomplete background model
- A 30% portion of the data is used to choose optimal ROIs for each signal model considered
- limits on elastic recoils down to 3 GeV/$c^2$



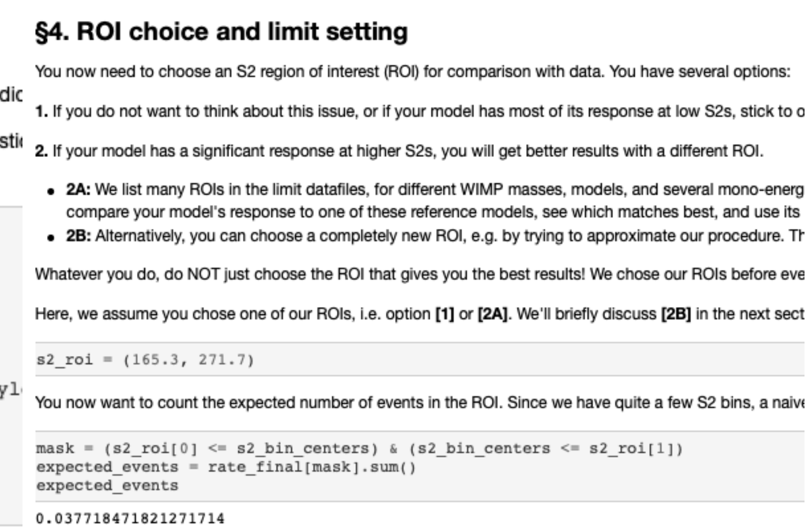
§2. Compute the energy spectrum

If you are a phenomenologist, insert your amazing dark matter candic

For this example, we will use a 4 GeV/c^2 spin-independent elasti
reference cross-section, we'll use 1 zb or $10^{-45}$cm^2.

```
In [3]: import wimprates as wr
reference_cross_section = 1e-45  # cm^2
rate_pertonneyearkev = wr.rate_wimp_std(
    es=energy_kev,
    mw=4,
    sigma_nucleon=reference_cross_section)

plt.plot(energy_kev, rate_pertonneyearkev, drawstyl
plt.xlabel("Nuclear recoil energy [keV]")
plt.ylabel("Expected recoils / (tonne year keV)")
plt.yscale('log')
plt.xscale('log')
plt.xlim(0.4, 10)
```



§4. ROI choice and limit setting

You now need to choose an S2 region of interest (ROI) for comparison with data. You have several options:

**1.** If you do not want to think about this issue, or if your model has most of its response at low S2s, stick to o

**2.** If your model has a significant response at higher S2s, you will get better results with a different ROI.

- **2A:** We list many ROIs in the limit datafiles, for different WIMP masses, models, and several mono-energ compare your model's response to one of these reference models, see which matches best, and use its
- **2B:** Alternatively, you can choose a completely new ROI, e.g. by trying to approximate our procedure. Th

Whatever you do, do NOT just choose the ROI that gives you the best results! We chose our ROIs before eve

Here, we assume you chose one of our ROIs, i.e. option **[1]** or **[2A]**. We'll briefly discuss **[2B]** in the next sect

```
s2_roi = (165.3, 271.7)
```

You now want to count the expected number of events in the ROI. Since we have quite a few S2 bins, a naive

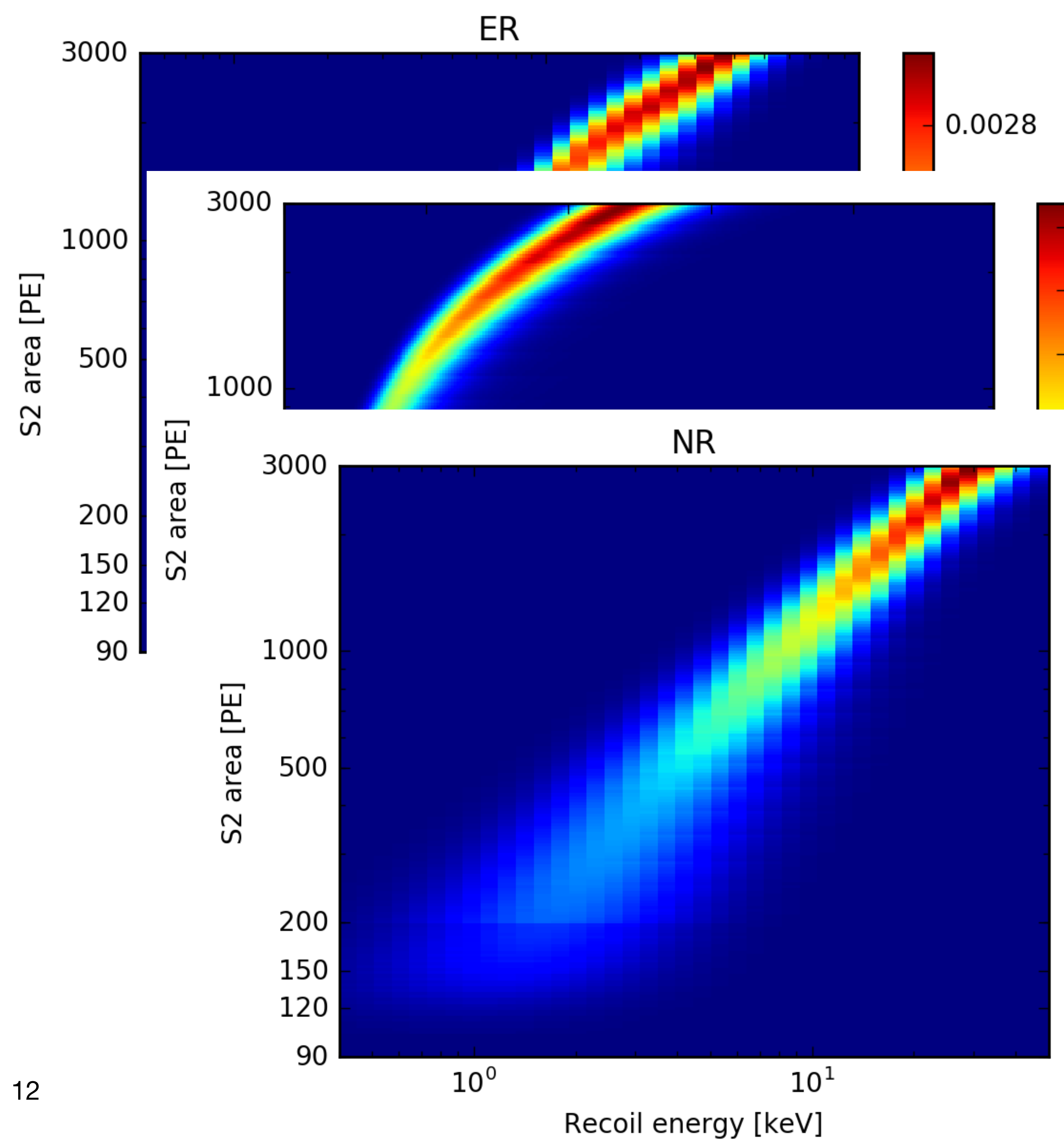
```
mask = (s2_roi[0] <= s2_bin_centers) & (s2_bin_centers <= s2_roi[1])
expected_events = rate_final[mask].sum()
expected_events
```

0.037718471821271714

# XENON1T ionisation-only analysis

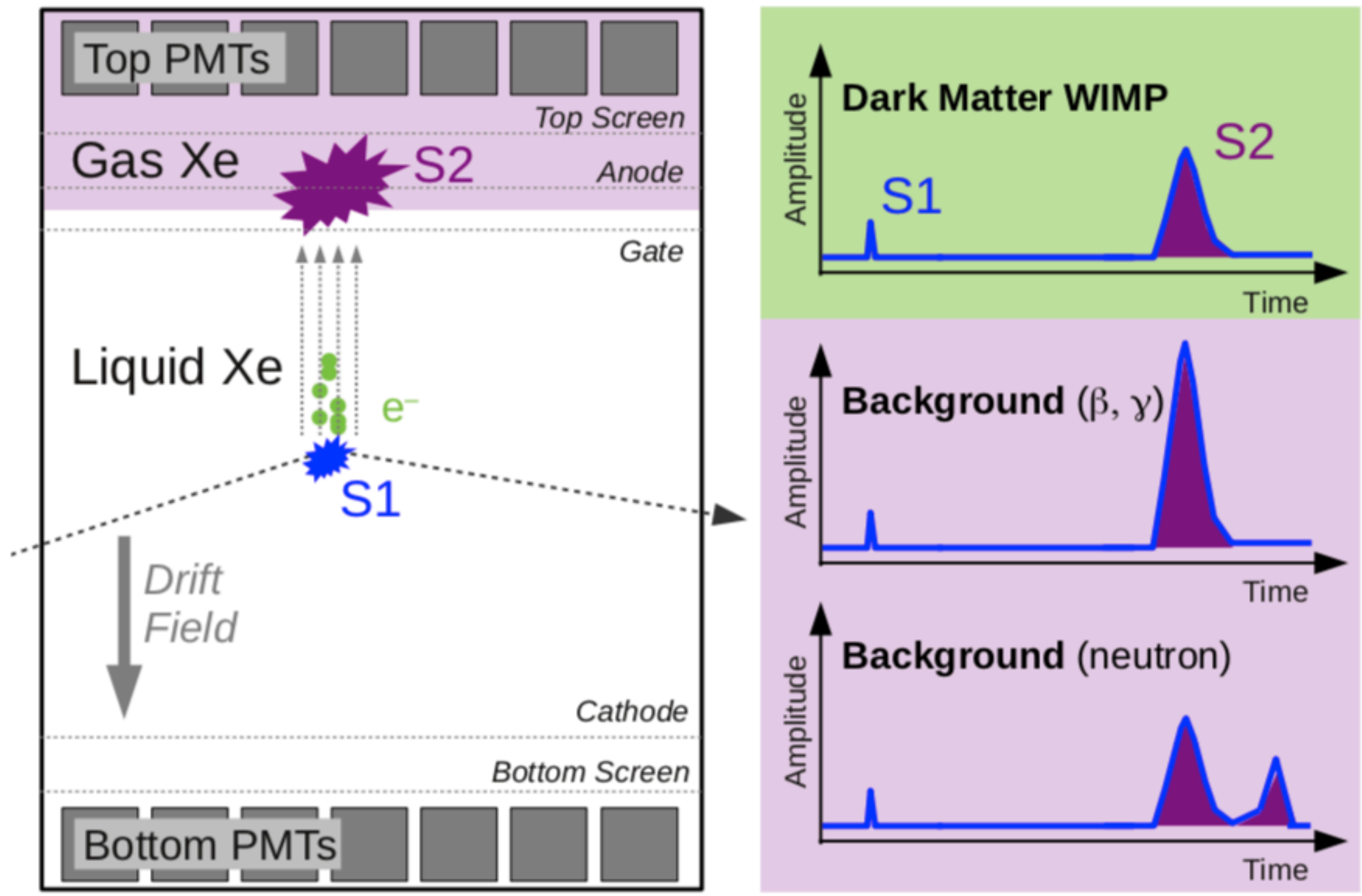
Aprile, E. et al. (XENON collaboration), Phys. Rev. Lett. 123, 251801 (2019)
https://github.com/XENON1T/s2only_data_release
http://doi.org/10.5281/zenodo.4075018

- The analysis includes a data release with
  - Data coordinates (training and science dataset)
  - detector response matrices (right) for electronic and nuclear recoils
  - the partial background model
  - Jupyter notebook to compute upper limits using the ROIs optimised for the signal models considered in the paper



# Liquid Xenon TPC NR searches

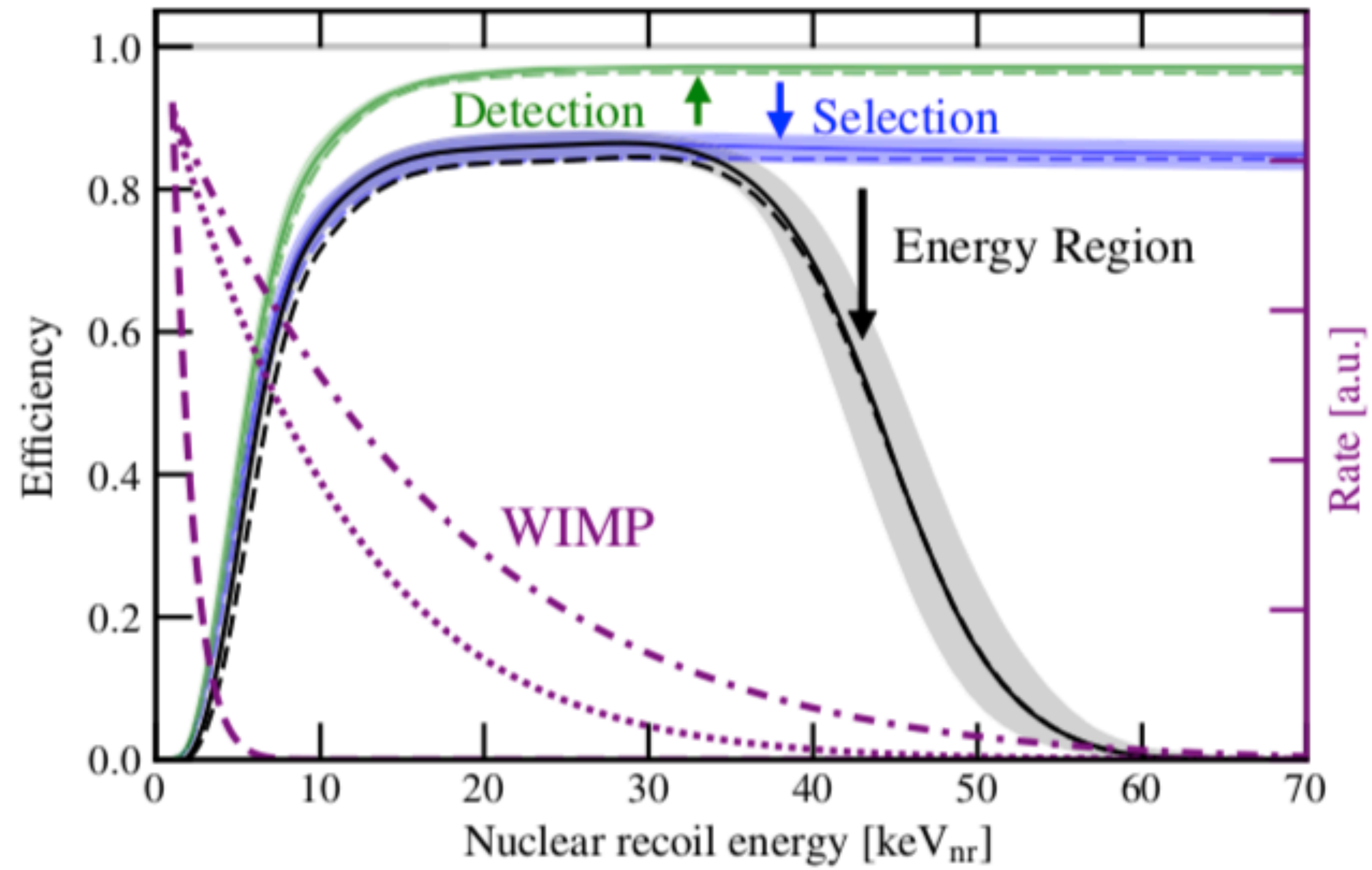
- For WIMPs above ~10 GeV/ $c^2$, xenon TPCs, reaching tonnes of active volume provide the best sensitivity
- Energy deposited in the active volume produces a scintillation flash (S1) and ionisation drifted and amplified to S2 signals
  - 3D position reconstruction
  - Energy from S1 and S2
  - Background rejection from S1/S2




From Aprile, E. et al. (XENON). “The XENON1T dark matter experi- ment”. In: Eur. Phys. J. C 77.12 (2017), p. 881. DOI: 10.1140/ epjc/ s10052-017-5326-3

# Published results

- 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
- Signal efficiencies (upper right) allows computation of the total signal expectation, but translation to the sub-regions is not generally possible without more information




| Mass (ton) | 1.3 | 1.3 | 0.9 | 0.65 |
|---|---|---|---|---|
| ($cS1$, $cS2_b$) | Full | Reference | Reference | Reference |
| ER | $627 \pm 18$ | $1.62 \pm 0.30$ | $1.12 \pm 0.21$ | $0.60 \pm 0.13$ |
| Neutron | $1.43 \pm 0.66$ | $0.77 \pm 0.35$ | $0.41 \pm 0.19$ | $0.14 \pm 0.07$ |
| CE$\nu$NS | $0.05 \pm 0.01$ | $0.03 \pm 0.01$ | 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 | $106 \pm 8$ | $4.84 \pm 0.40$ | 0.02 | 0.01 |
| Total BG | $735 \pm 20$ | $7.36 \pm 0.61$ | $1.62 \pm 0.28$ | $0.80 \pm 0.14$ |
| WIMP$_{\text{best-fit}}$ | 3.56 | 1.70 | 1.16 | 0.83 |
| Data | 739 | 14 | 2 | 2 |

E. Aprile et al. (XENON). "Dark Matter Search Results from a One Ton-Year Exposure of XENON1T". In: Phys. Rev. Lett. 121.11 (Sept. 2018), p. 111302. DOI: 10.1103/PhysRevLett. 121.111302.

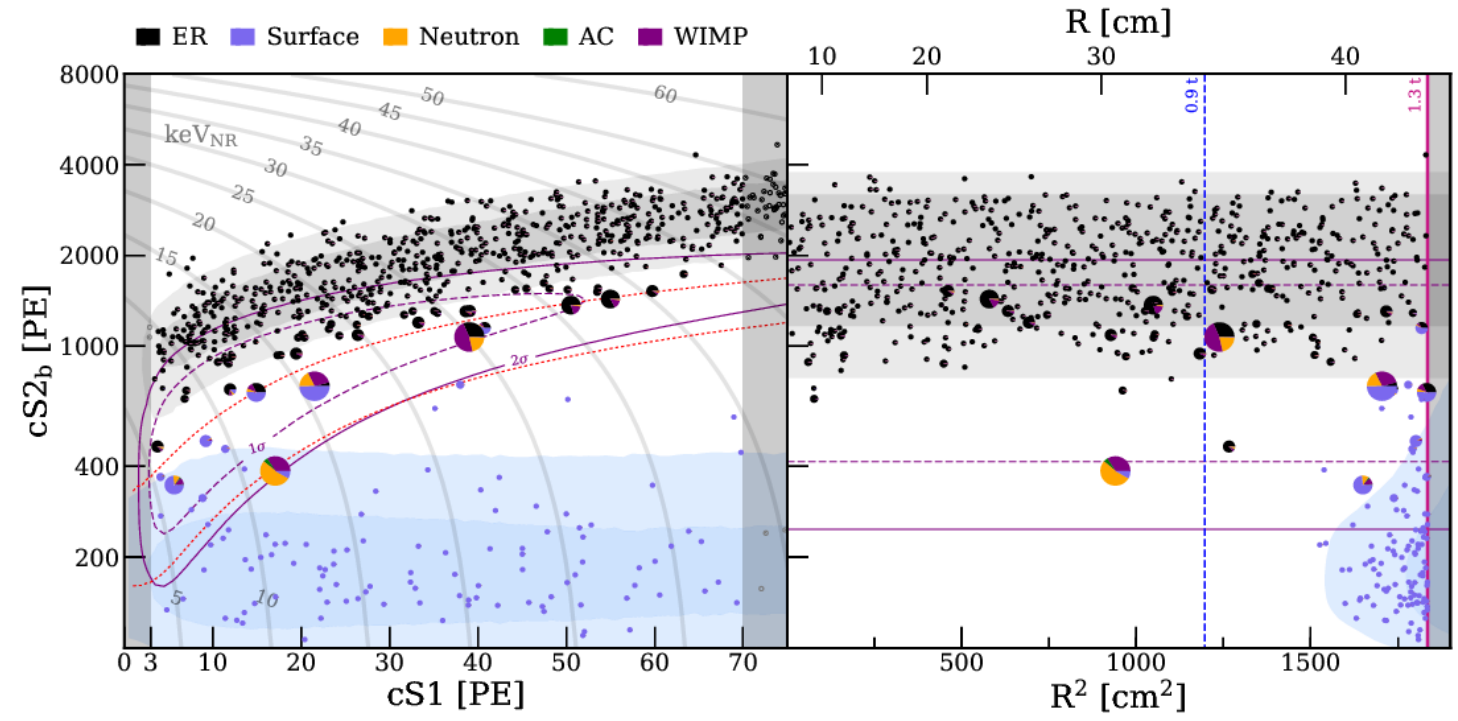
E. Aprile et al. (XENON), Phys. Rev. Lett. 121, 111302 (2018), 1805.12562.

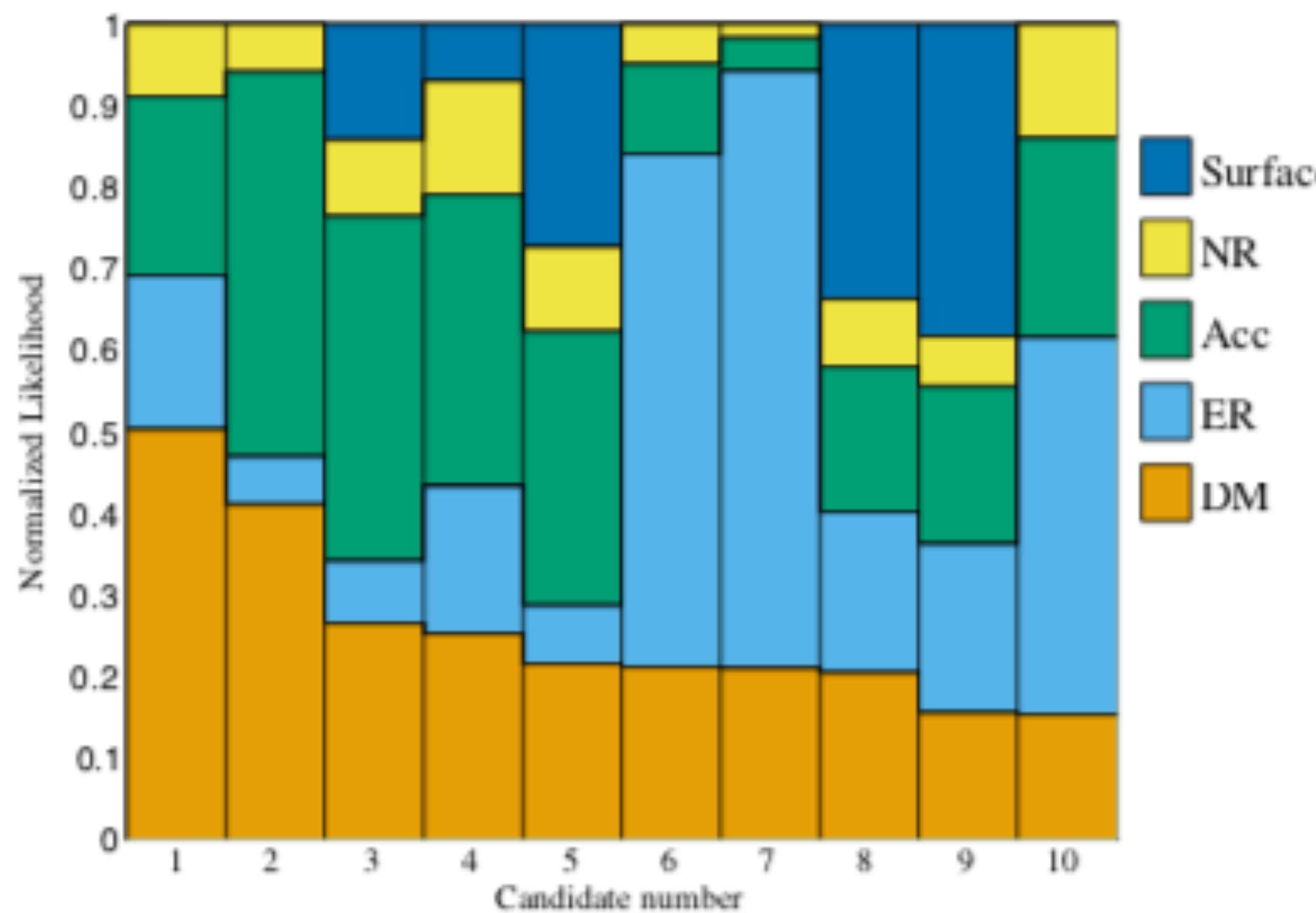
# Pie scatterplots

- In some recent liquid xenon results, collaborations published the fraction of the PDF at the most signal-like events as an indication of how signal-like they are

- These events are typically in the tail of the background distributions, where the knowledge of the background is poorest

- Currently useful primarily as an indication of which background could have produced each signal-like event




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

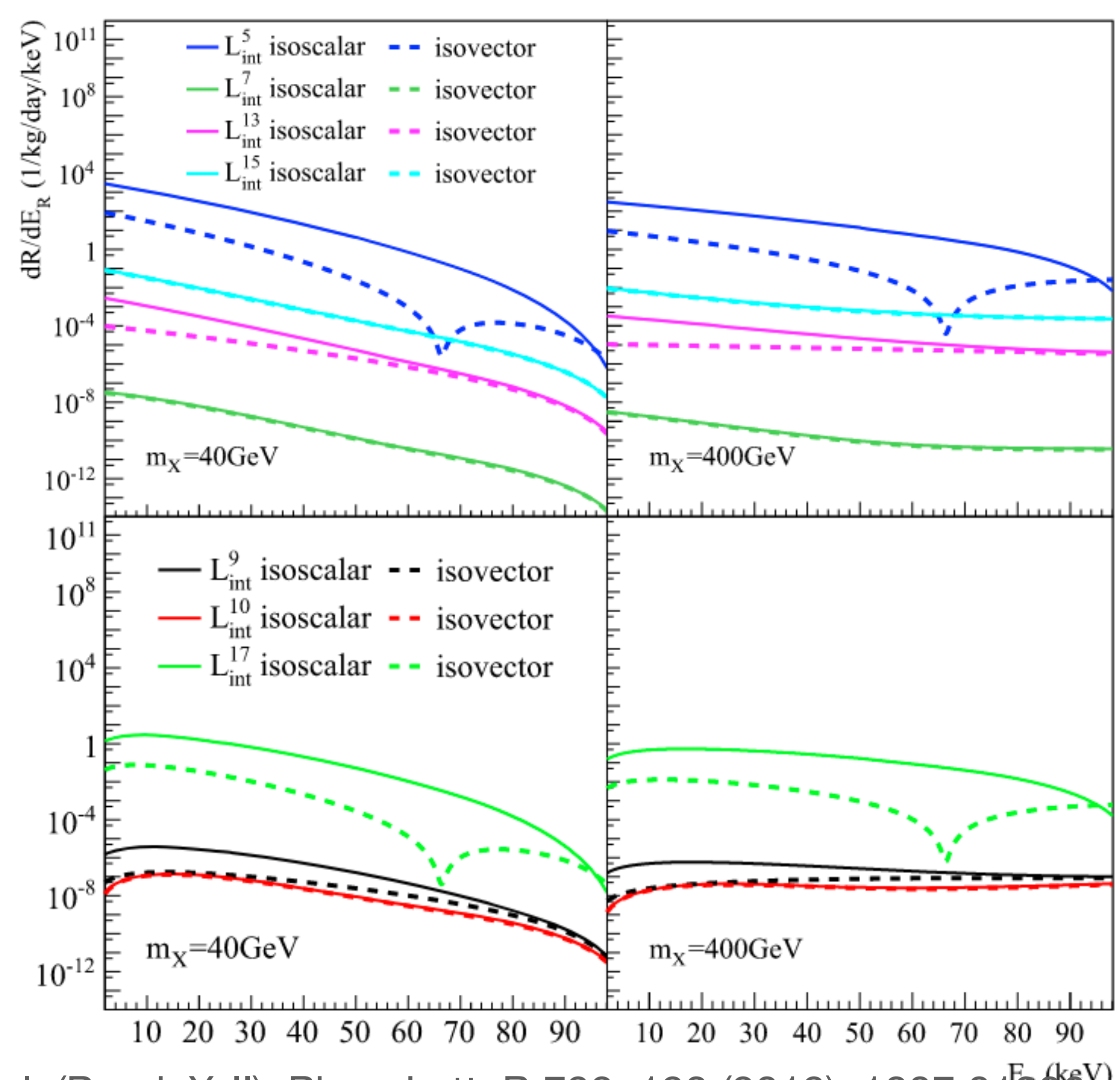
E. Aprile et al. (XENON) and B. Farmer,
Phys. Rev. D 96, 042004 (2017), 1705.02614

# Effective Field Theory

- Dark matter-matter interactions are non-relativistic so that all operators must be Galileian-invariant
- The fourteen operators depend on the dark matter and nucleon spins, the momentum exchange q and the perpendicular velocity
- Spectra may be more peaked (momentum-suppressed operators) or extend to higher energies than normal spin-independent/dependent results
- In principle, each operator may also be apply to only neutrons or protons

$$
\begin{aligned}
\mathcal{O}_1 &= 1_\chi 1_N & \mathcal{O}_9 &= i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N}) \\
\mathcal{O}_3 &= i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp) & \mathcal{O}_{10} &= i\vec{S}_N \cdot (\frac{\vec{q}}{m_N}) \\
\mathcal{O}_4 &= \vec{S}_\chi \cdot \vec{S}_N & \mathcal{O}_{11} &= i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N}) \\
\mathcal{O}_5 &= i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp) & \mathcal{O}_{12} &= \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp) \\
\mathcal{O}_6 &= (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N}) & \mathcal{O}_{13} &= i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N}) \\
\mathcal{O}_7 &= \vec{S}_N \cdot \vec{v}^\perp & & \\
\mathcal{O}_8 &= \vec{S}_\chi \cdot \vec{v}^\perp & \mathcal{O}_{14} &= i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)
\end{aligned}
$$

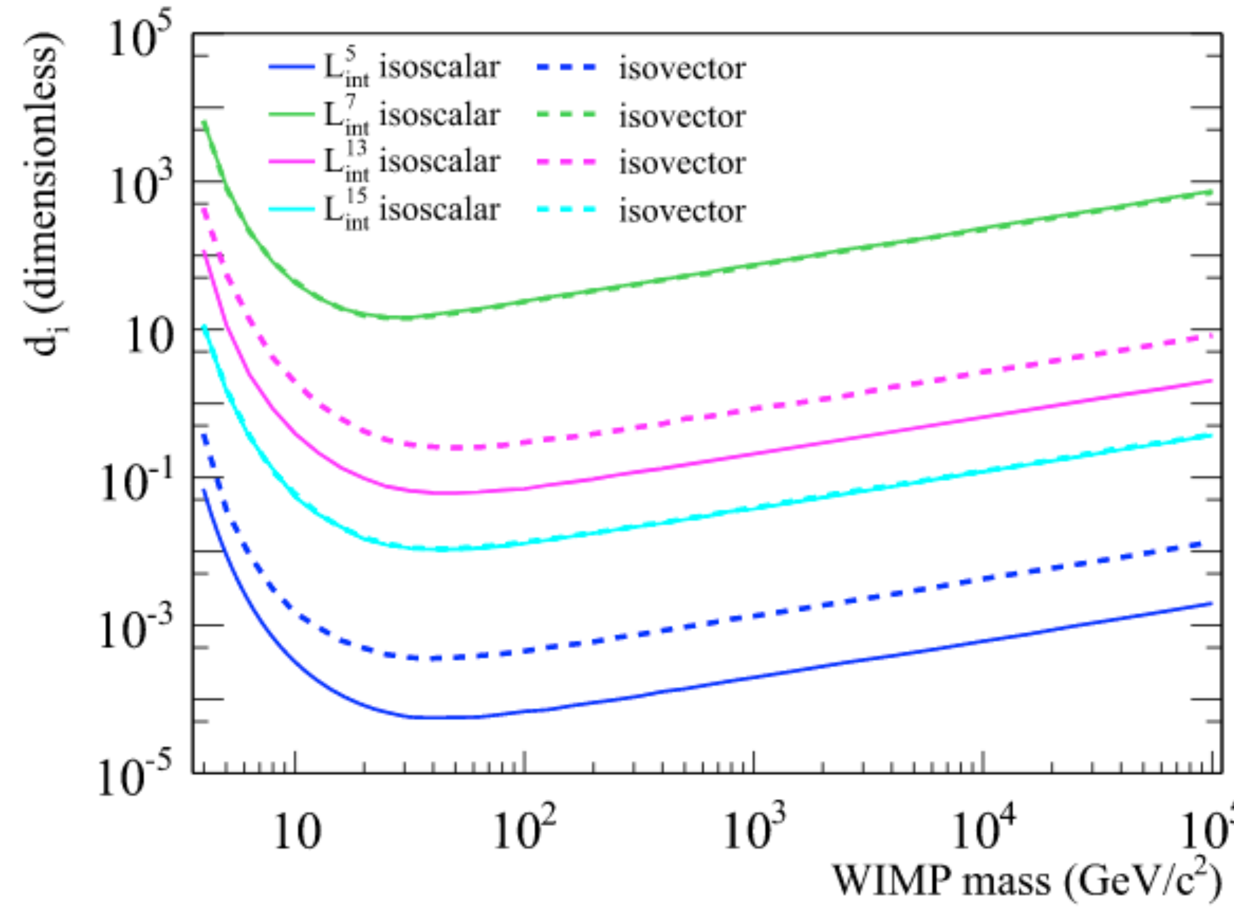
$$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left[(\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right] \qquad (1)$$

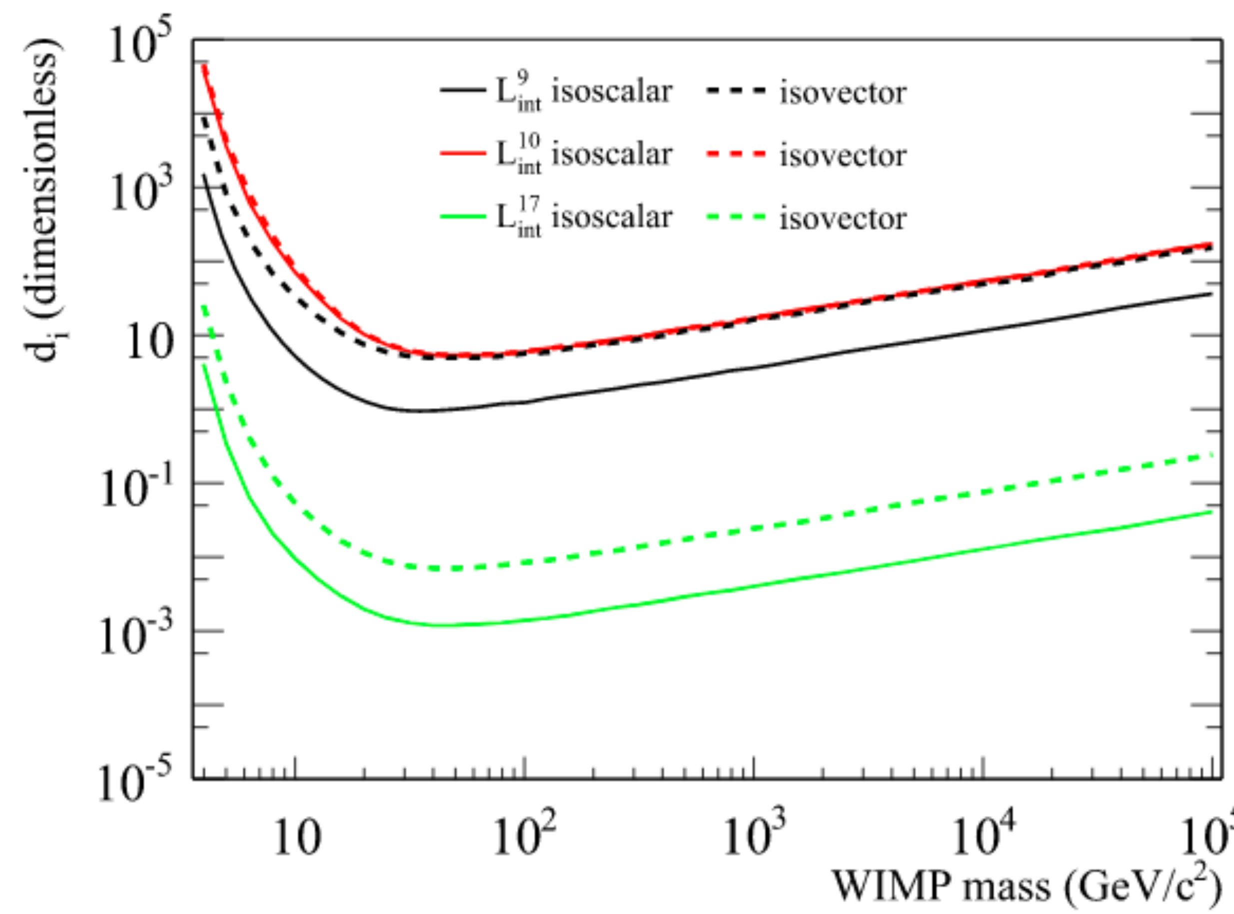



 J. Xia et al. (PandaX-II), Phys. Lett. B 792, 193 (2019), 1807.01936.

# Effective Field Theory

- Upper limits, provided per operator and WIMP mass are reported by the experiment
- Each limit is computed for a single operator turned on at the time
- Combinations of multiple operators or changes in e.g. astrophysical assumptions cannot easily be made
- Finding the best-fit spectra among those tested and re-scaling the rate will give a close answer



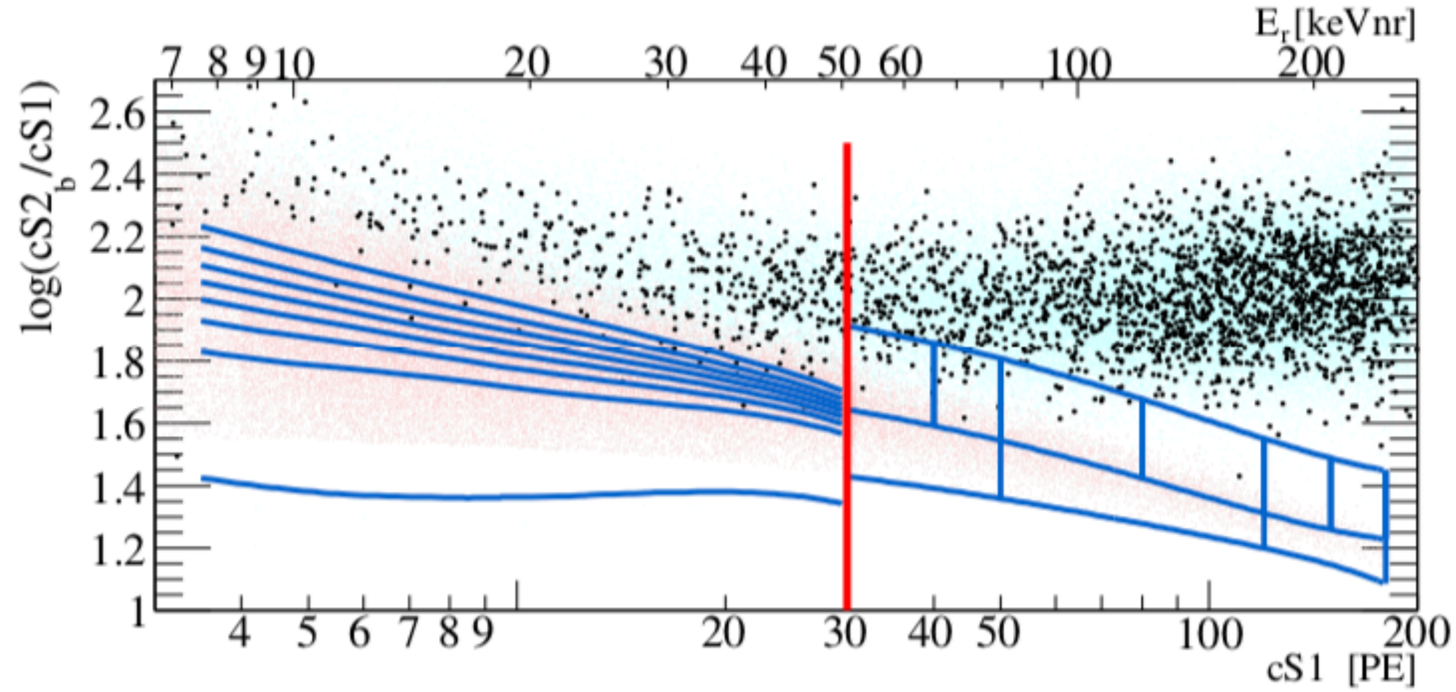





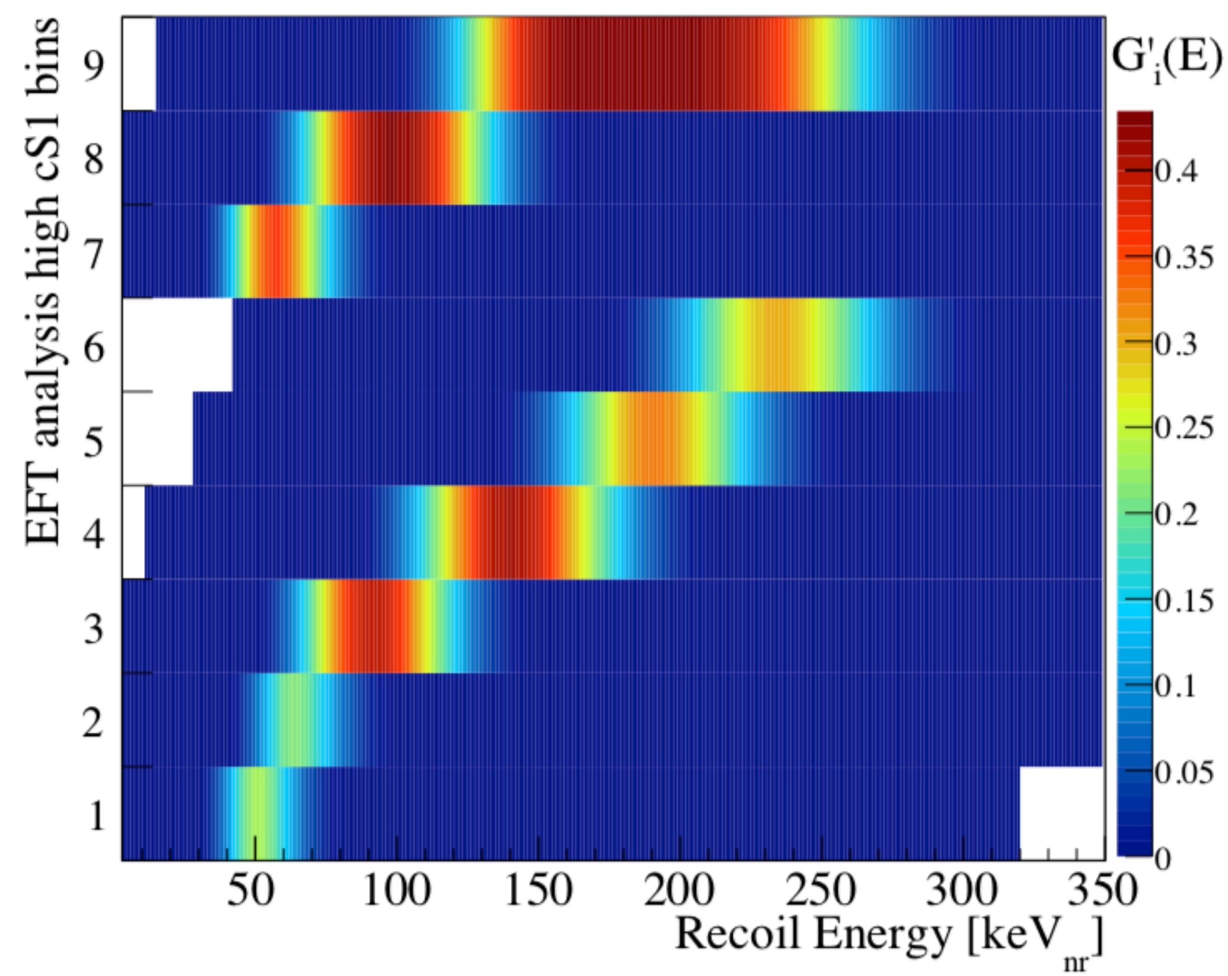

J. Xia et al. (PandaX-II), Phys. Lett. B 792, 193 (2019), 1807.01936.

# Partitioning analysis space

**XENON100 high-energy nuclear recoil search**

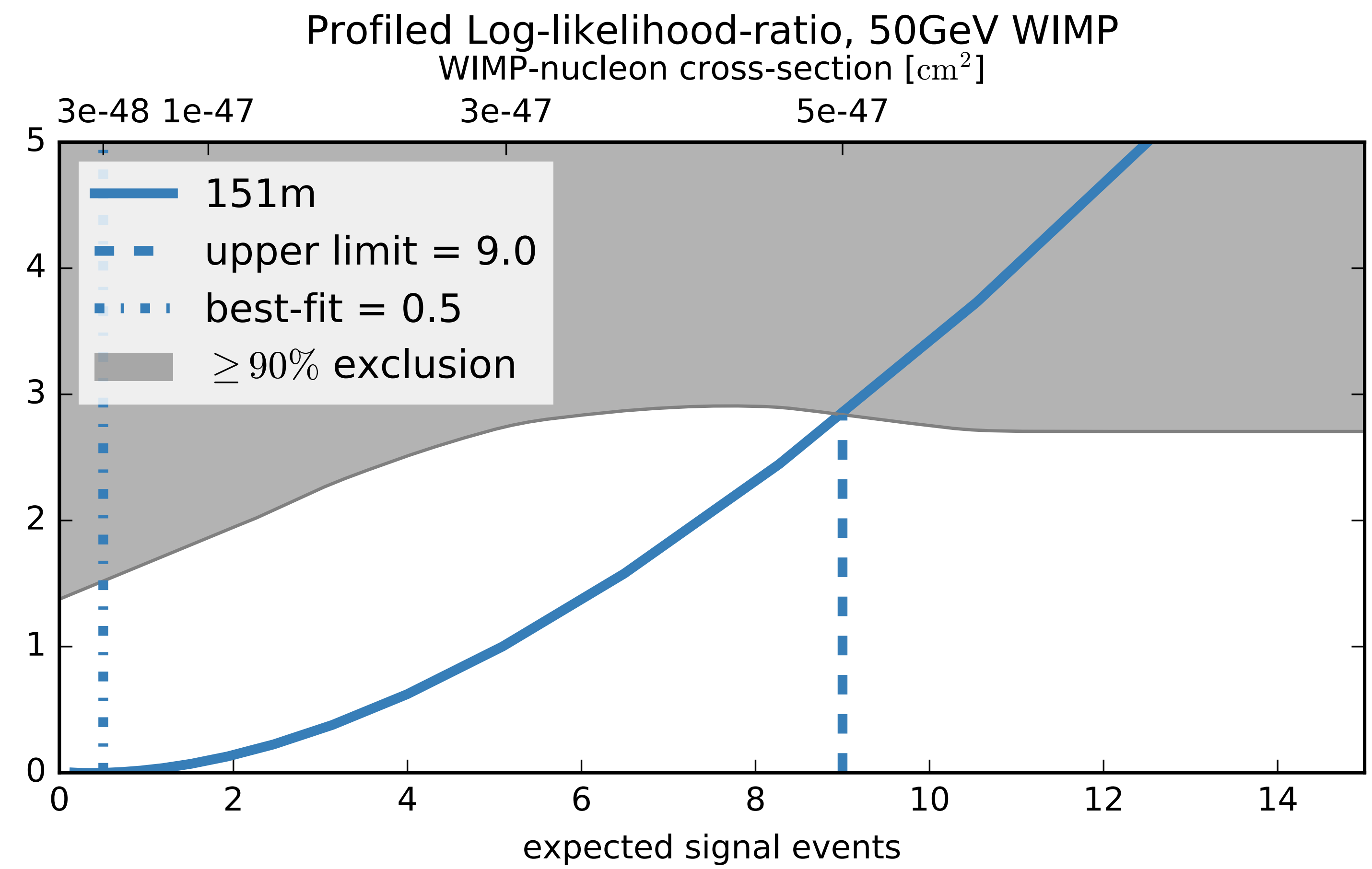



- High-energy nuclear search published alongside EFT results for low (cS1<30PE) recoil energy
- If inelastic recoils are allowed, the number of free signal parameters became intractable— 28 allowed EFT couplings, plus a WIMP mass and mass splitting
- 9 bins with event numbers, expected background, provided for a set of points in S1/S2 space
- The expected signal in each bin is given with the transfer probability matrix between true recoil energy and bin number. The transfer matrix is provided for a range of nuisance parameters




E. Aprile et al. (XENON) and B. Farmer, Phys. Rev. D 96, 042004 (2017), 1705.02614

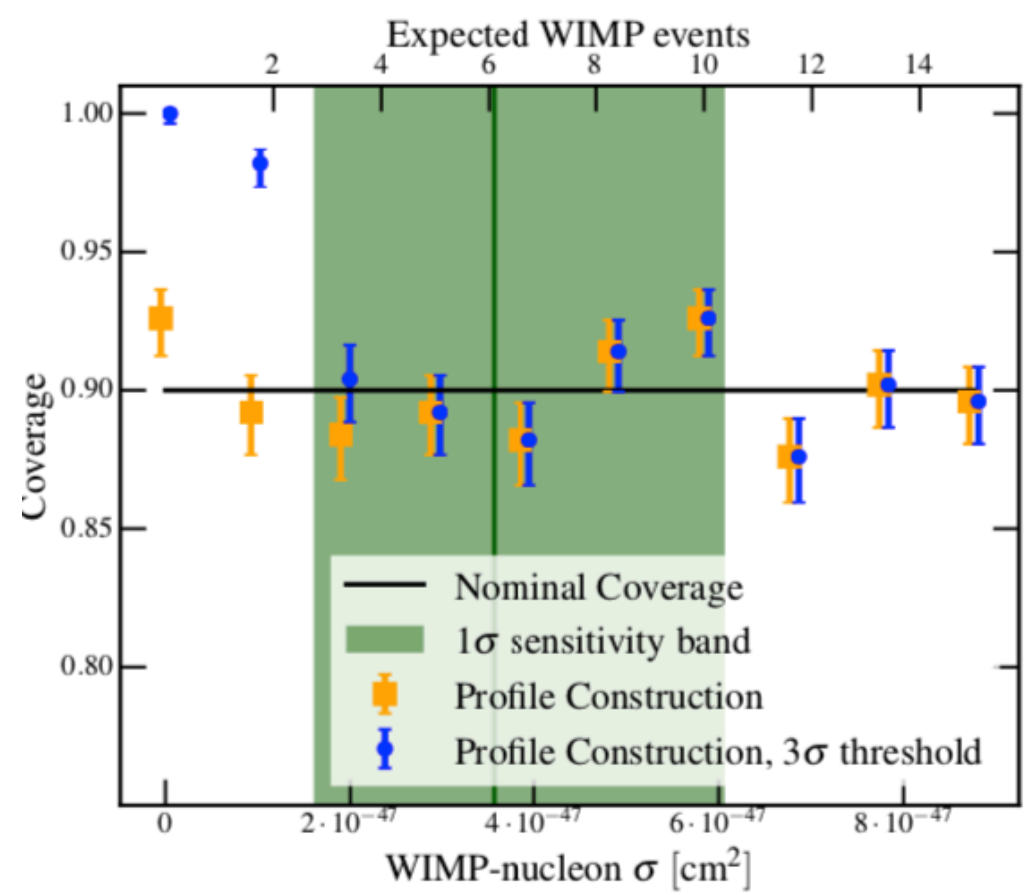
# toy-MC driven statistics:




- A Neyman construction can be built with any test statistic, including directly in the log-likelihood ratio

- The confidence interval is the region where the profiled likelihood ratio is below the 90th percentile of toyMC dataset profile likelihood ratios (upper panel)

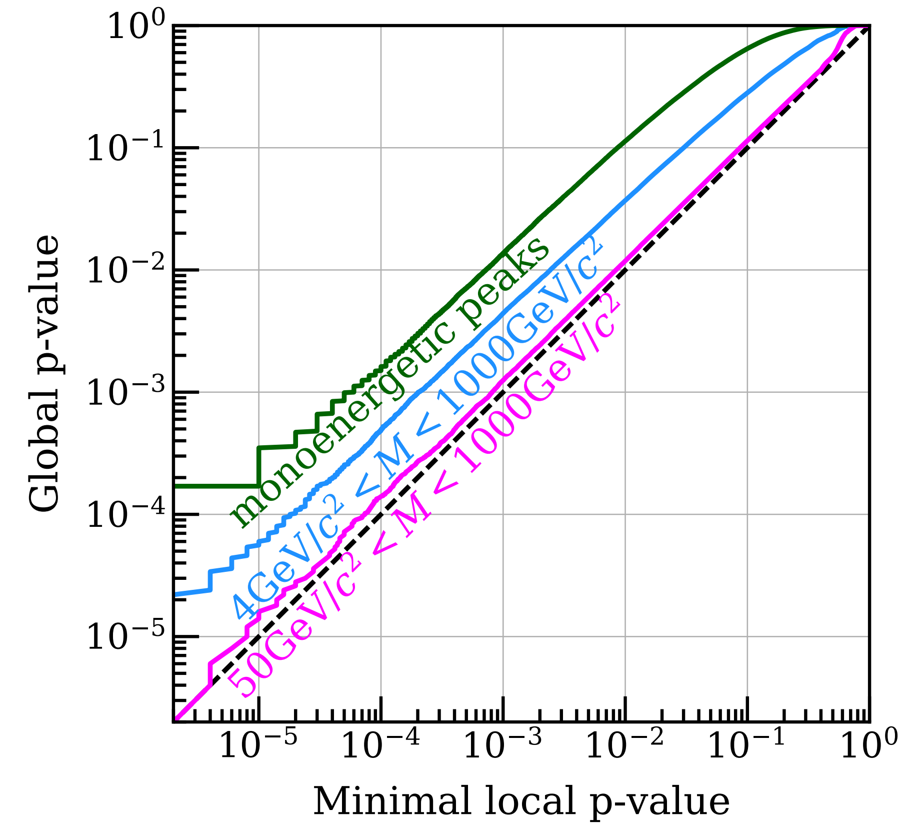
- The lower panel shows how a nuisance parameter moves along the profile— in this case the radiogenic expectation value



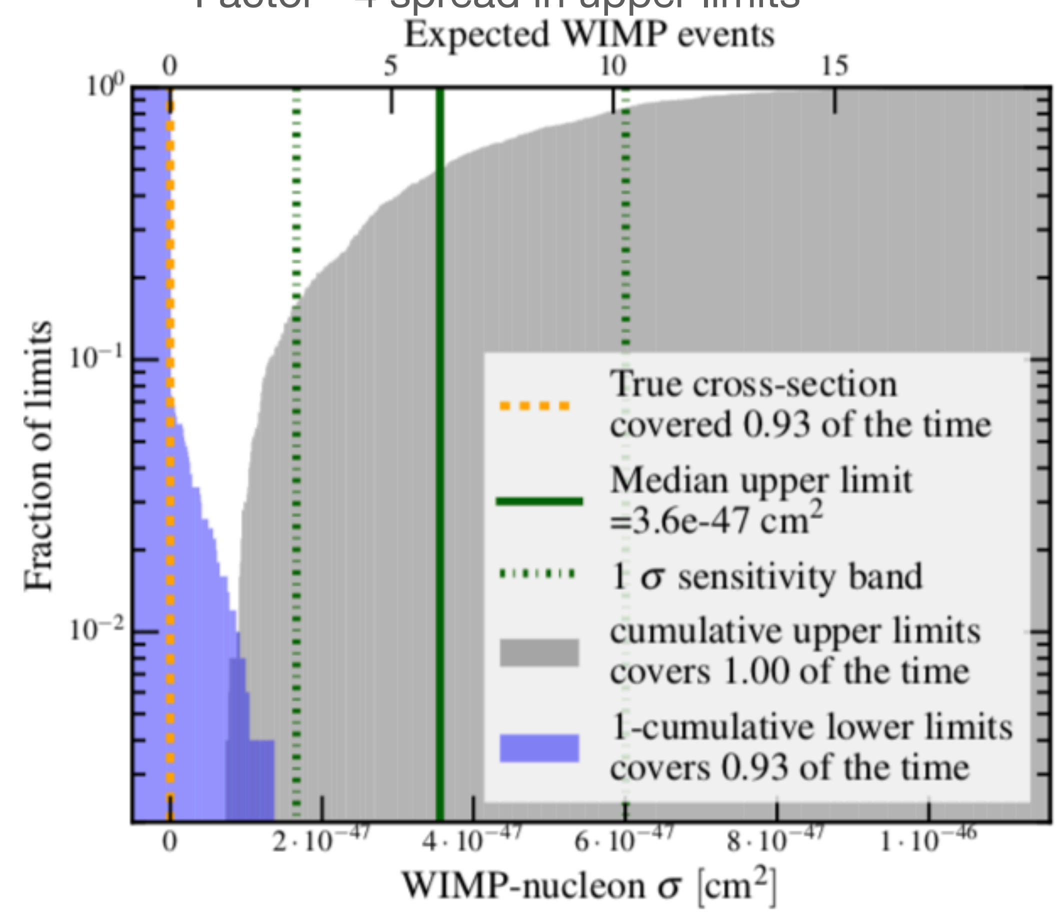

E. Aprile et al. (XENON), Phys. Rev. D 99, 112009 (2019), 1902.11297.

# Look-Elsewhere effect and related concerns

- The trial factor of the WIMP search is rather small, as the spectra vary slowly with WIMP mass
- On the other hand, the low number of signal events required for an excess (~10) and multidimensional likelihoods means both that a blind analysis is crucial, and that upper limits etc strongly depend on the search region
- When reinterpret able results are only reported in terms of "clean" sub-regions, upper limits computed therefore may not be expected to overlap.




Factor ~4 spread in upper limits




E. Aprile et al. (XENON), Phys. Rev. D 99, 112009 (2019), 1902.11297.

# Thanks!