Monte Carlo in Xenon1T analysis

knut.mora@fysik.su.se for the XENON1T collaboration

Stockholms universitet

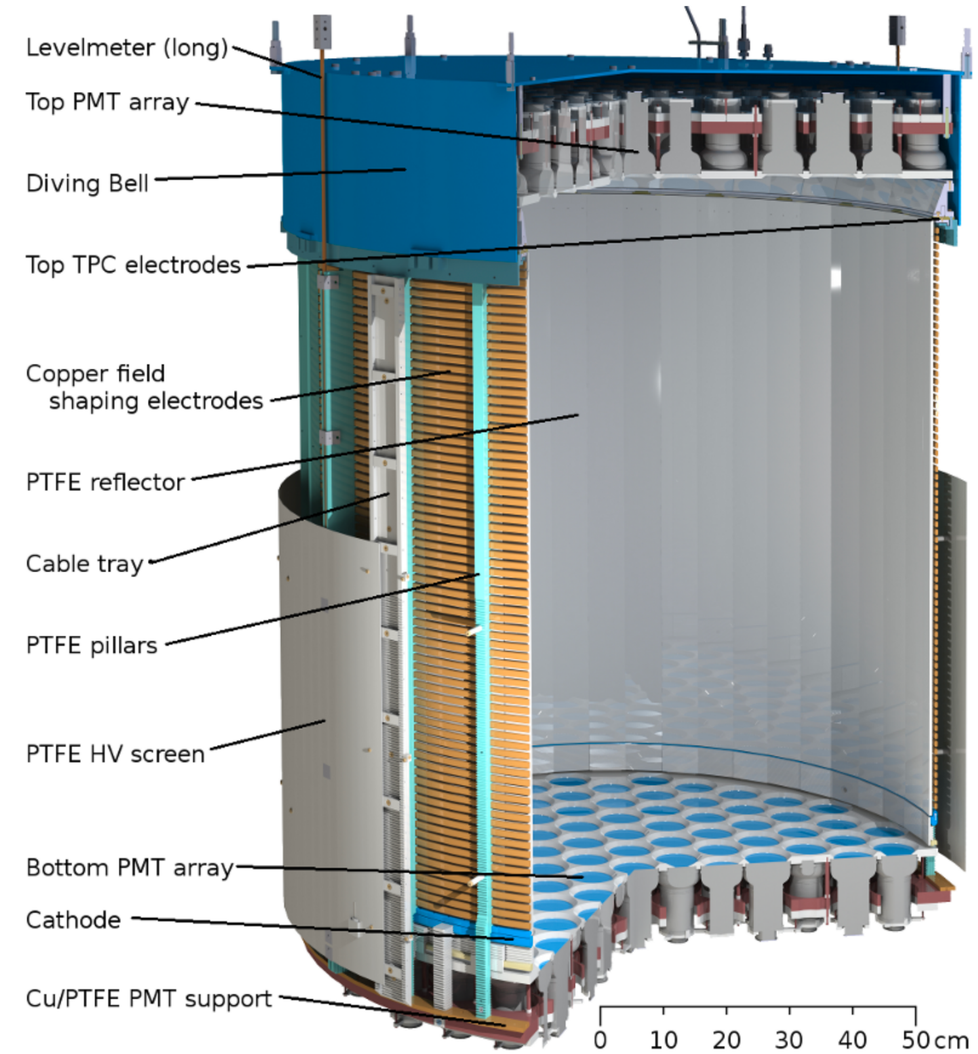
XENON Dark Matter Project

Oskar Klein centre

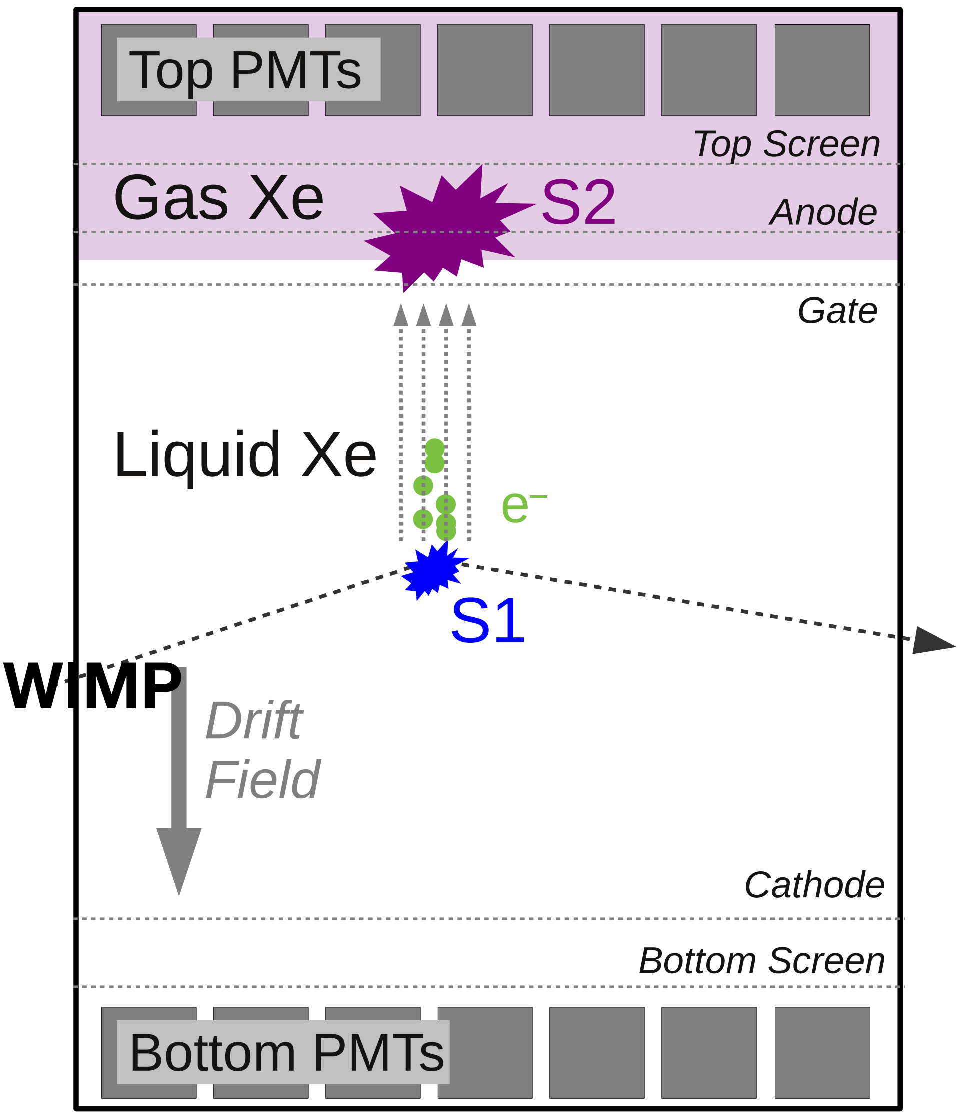
XENON1T Overview

The XENON1T detector

- XENON1T searches for dark matter in the form of Weakly Interacting Massive Particles using a target of 2 tonnes of liquid Xenon.
- Placed underground, shielded by rock amounting to 3.6 km water at the LNGS in Italy, as well as an instrumented water tank and non-active liquid Xenon
- Circulation and purification of the liquid Xenon removes impurities, allowing electrons to drift the length of the TPC
    - Destillation of Krypton reduces the intrinsic event rate in the analysis region to roughly 2 events/day

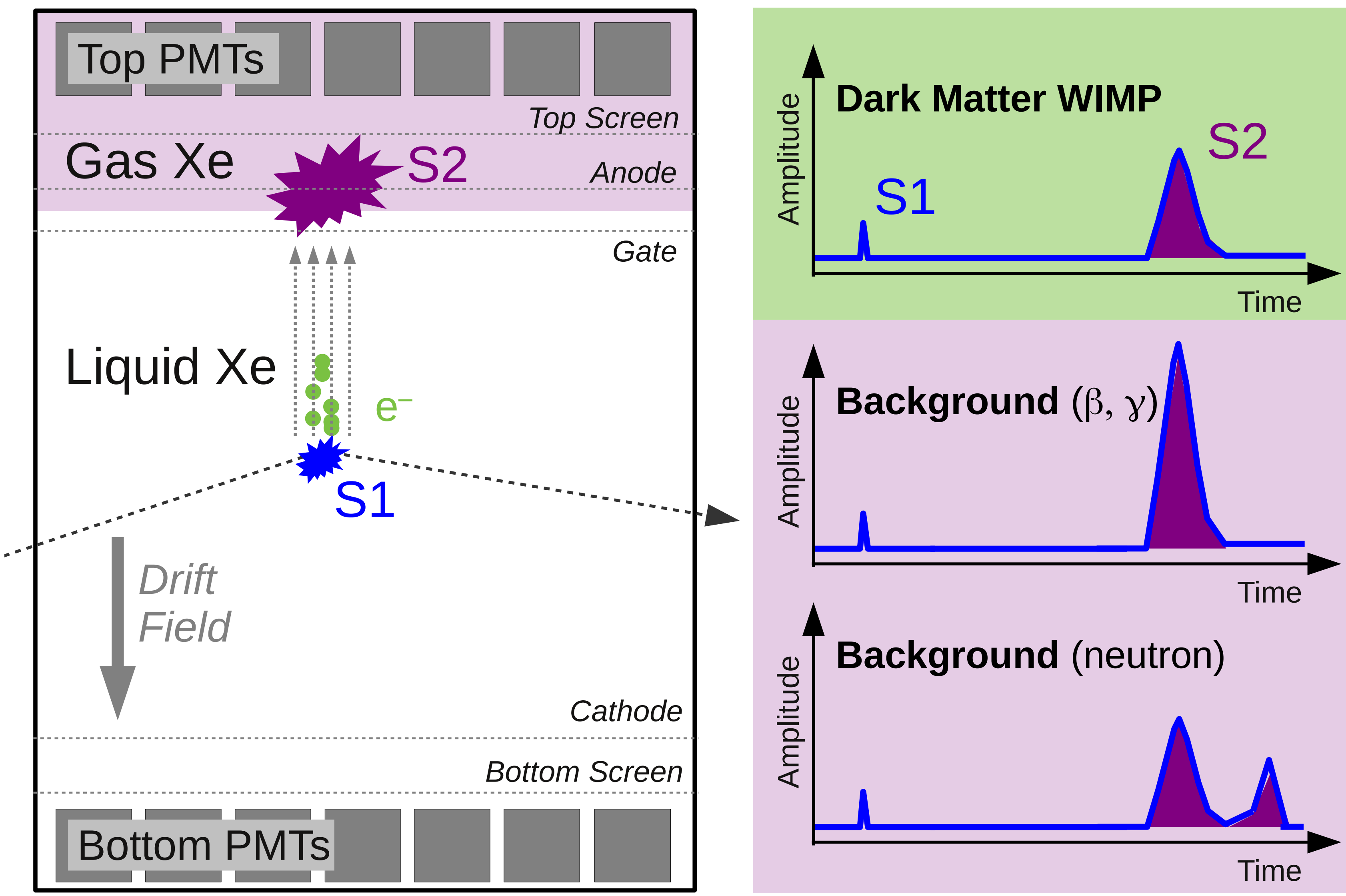


XENON1T detection principle: Two-phase time-projection chamber



- Xenon atoms hit by radiation will emit scintillation light, as well as free electrons.
- Electrons drift at a known speed in an electric field, until they are accelerated at the top of the detector in the gas phase, producing an amplified scintillation flash.
- Photomultipliers at the top and bottom of the time projection chamber (TPC) detect both the first (S1) and second (S2) flashes.

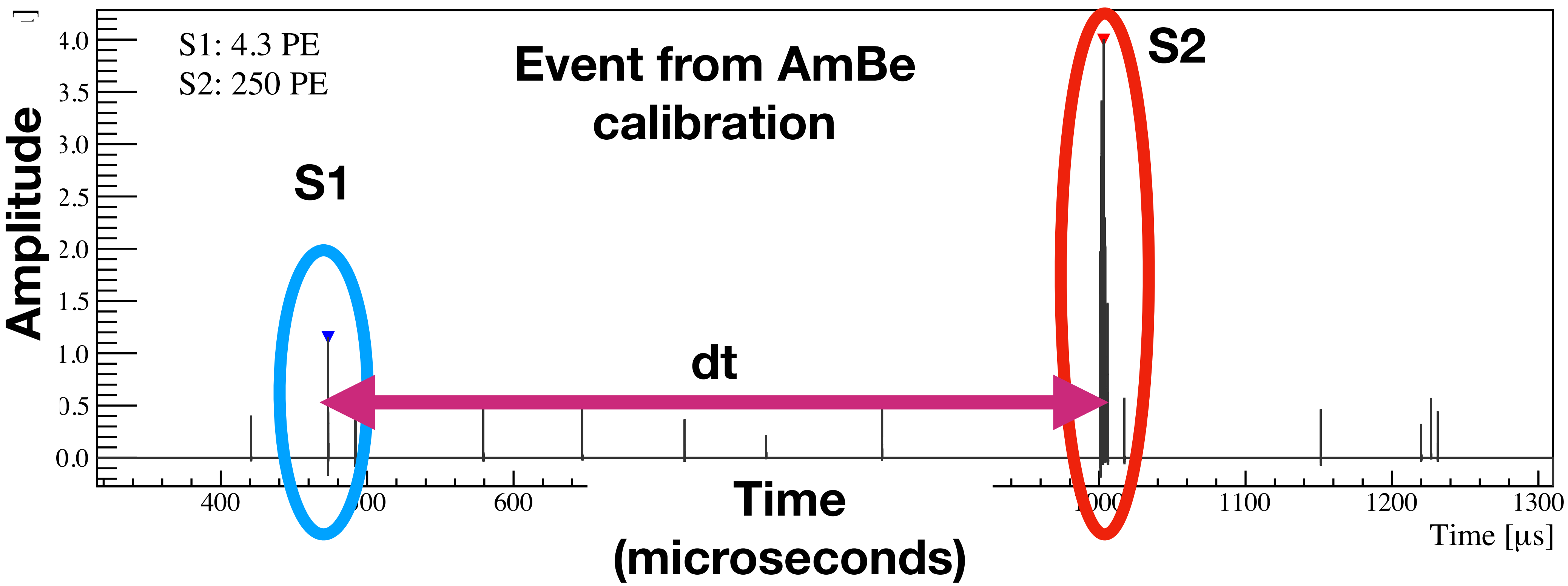
S2/S1 discriminates between nuclear and electronic recoils



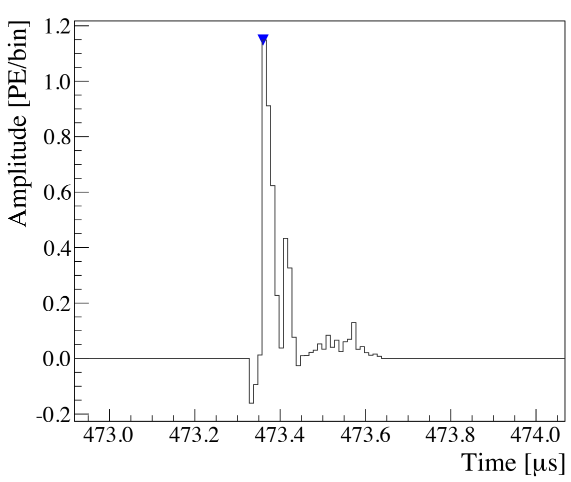
- Recoils with the Xenon atom electron cloud, electronic recoils (ER) produce more ionisation than
- recoils with the nucleus, NR

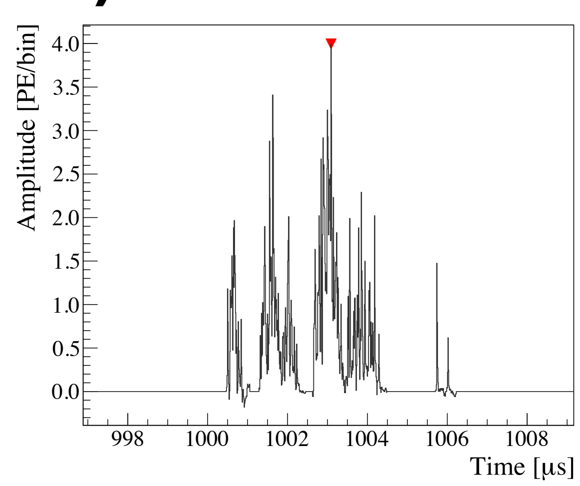
E. Aprile et al. The XENON1T Dark Matter Experiment. *Eur. Phys. J.*, C77(12):881, 2017.

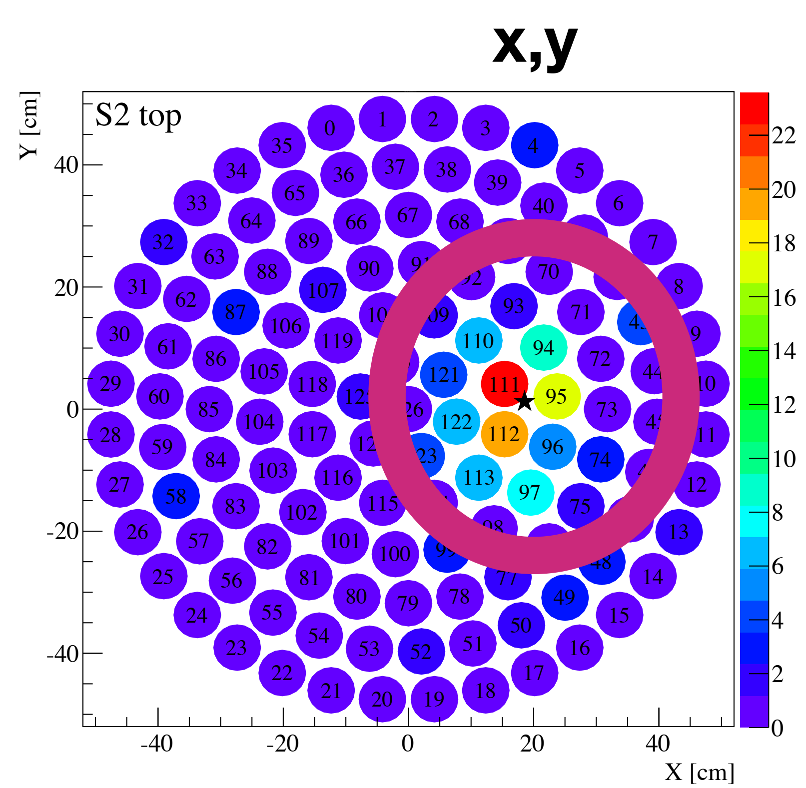
Example Event from NR, and reconstructed parameters:



- S1 = 4.3pe
- S2 = 250pe
- Z = -75.9cm
- X,y

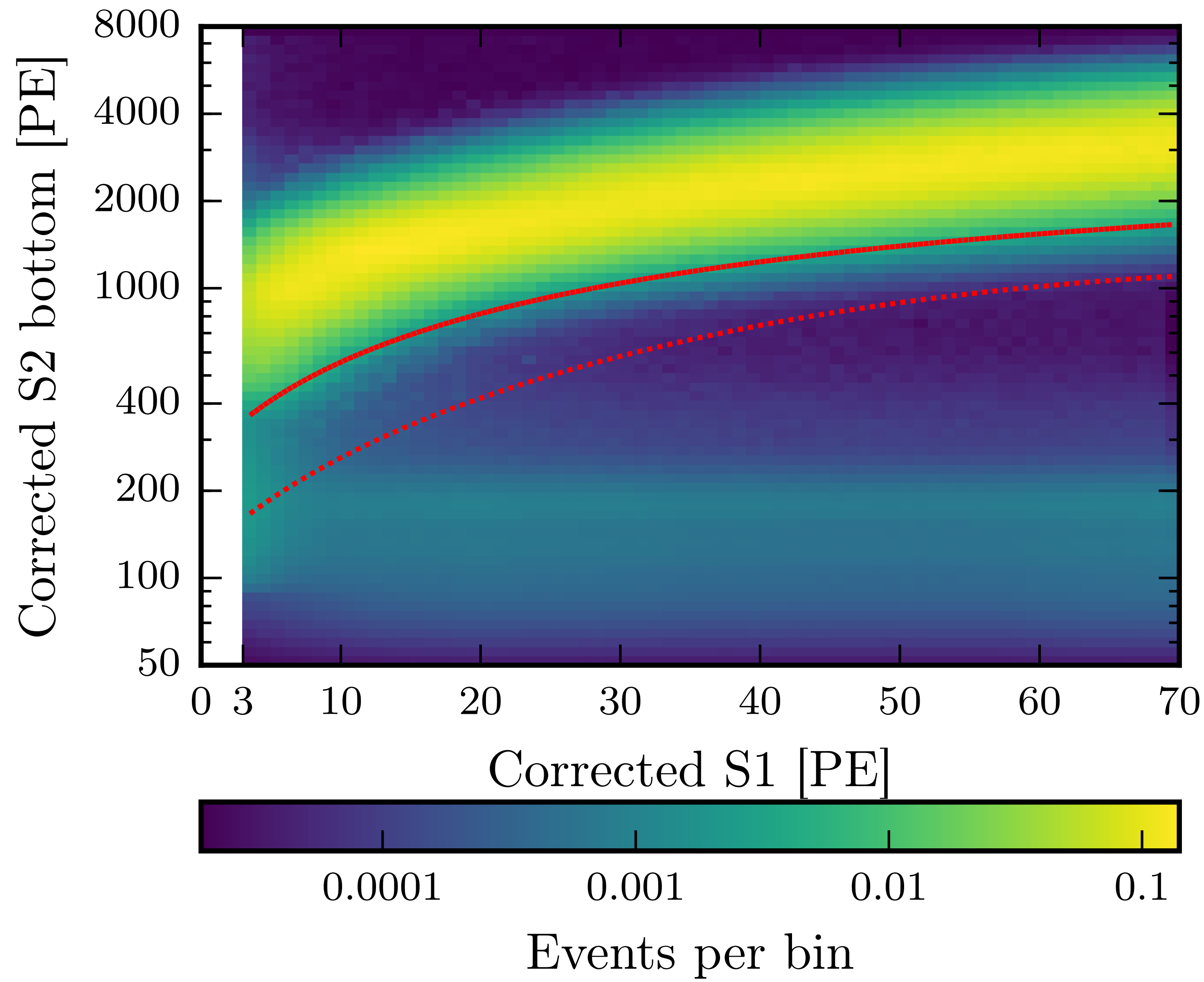






Analysis Overview

- The main analysis space is corrected s1 versus s2, in addition to radius.
    - Each event s1,s2 is normalised to an average detector response based on position.
- In order to match results to data, multiple simulations at different levels are used— both full GEANT4 simulations, as well as fast Monte Carlos, which are fitted to calibration data
- Red lines show the median and -1 sigma line of the nuclear recoil band

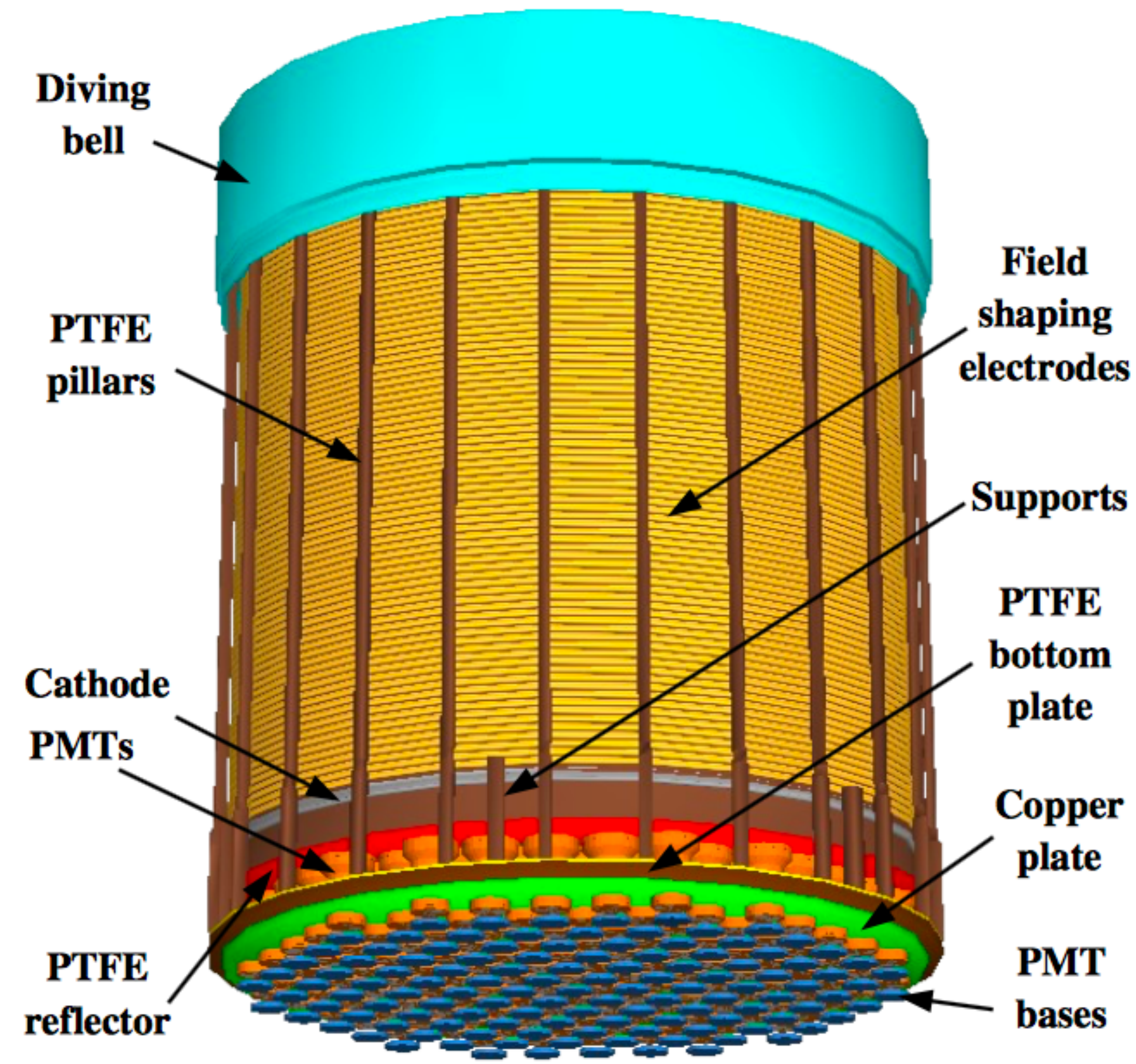


Sum of best-fit background model and median,-2sigma lines of NR

E. Aprile et al. First Dark Matter Search Results from the XENON1T Experiment. *Phys. Rev. Lett*
119(18):181301, 2017.

Detector Simulation

- Particle propagation and interaction simulated in GEANT4, with detector model from drawings, and radioactive contaminations measured in screening campaign



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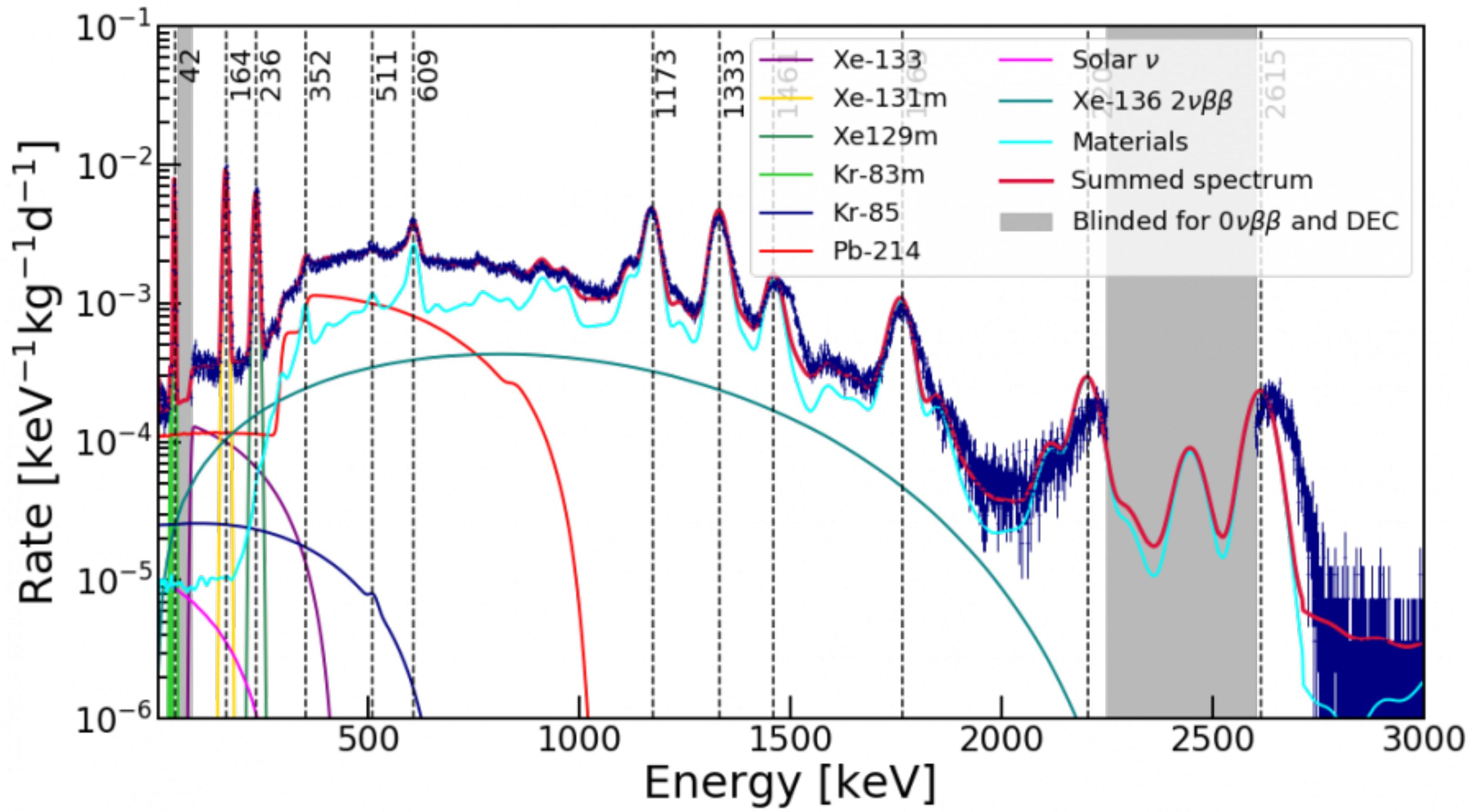
Background Estimation

- The total background estimate, from measurement of material radioactivity, and detector simulation shows good agreement over a large energy range

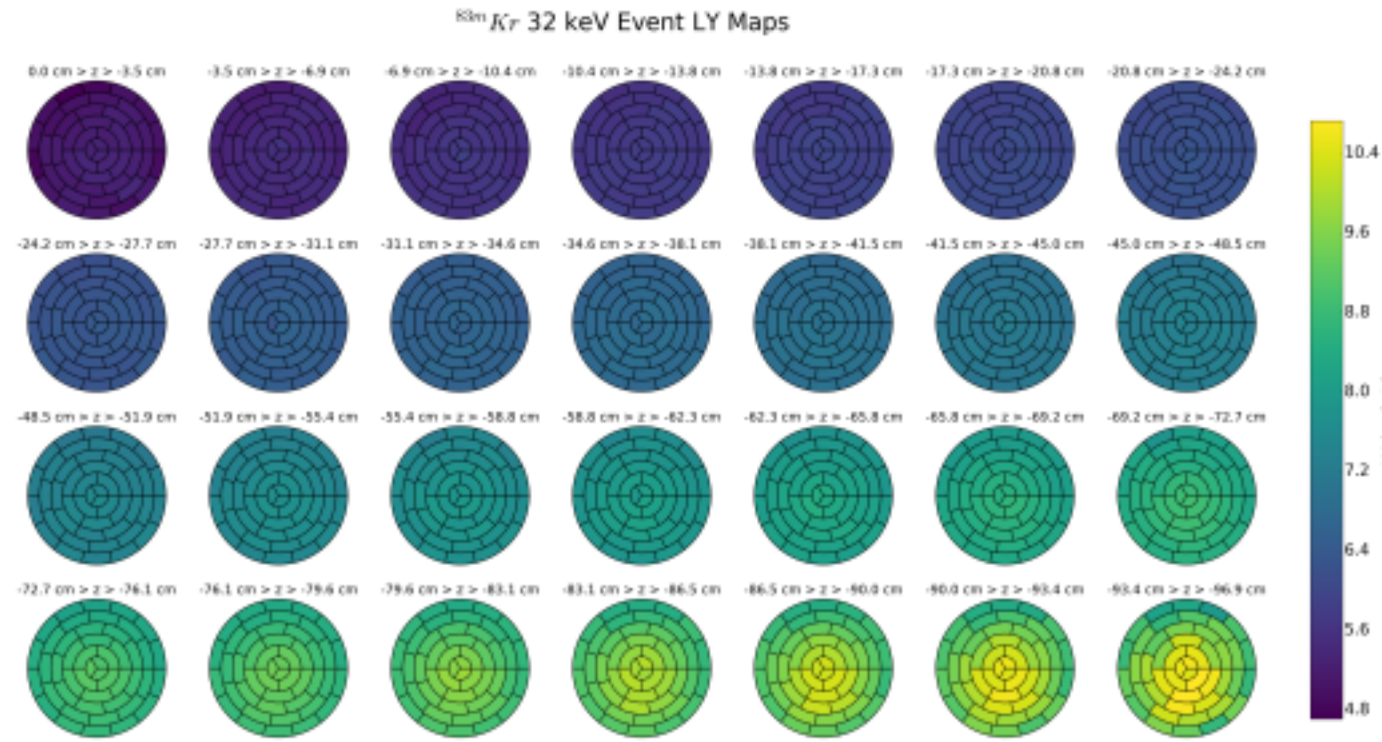
- GEANT4 simulation of decay, data from Evaluated Nuclear Structure Data Files

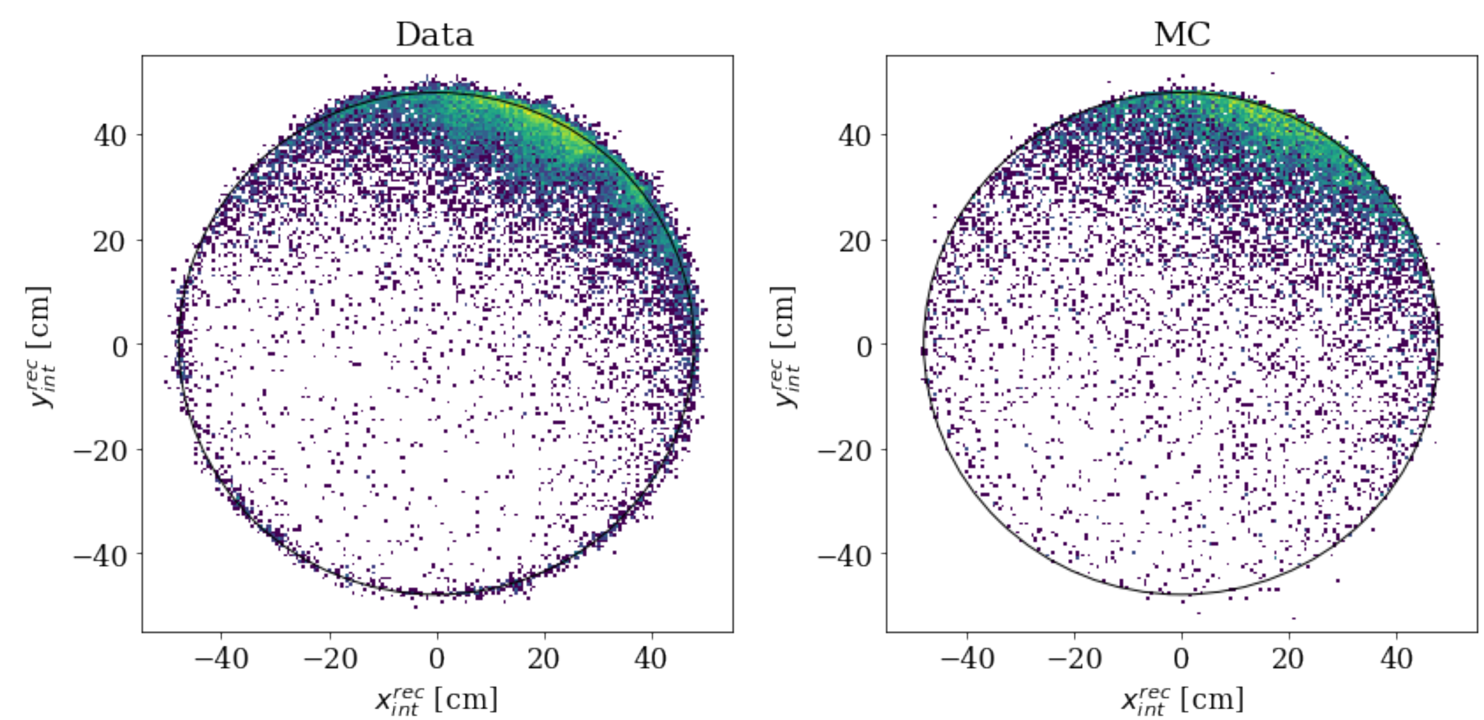
- Gray band shows regions blinded for other analyses.



Optical MC

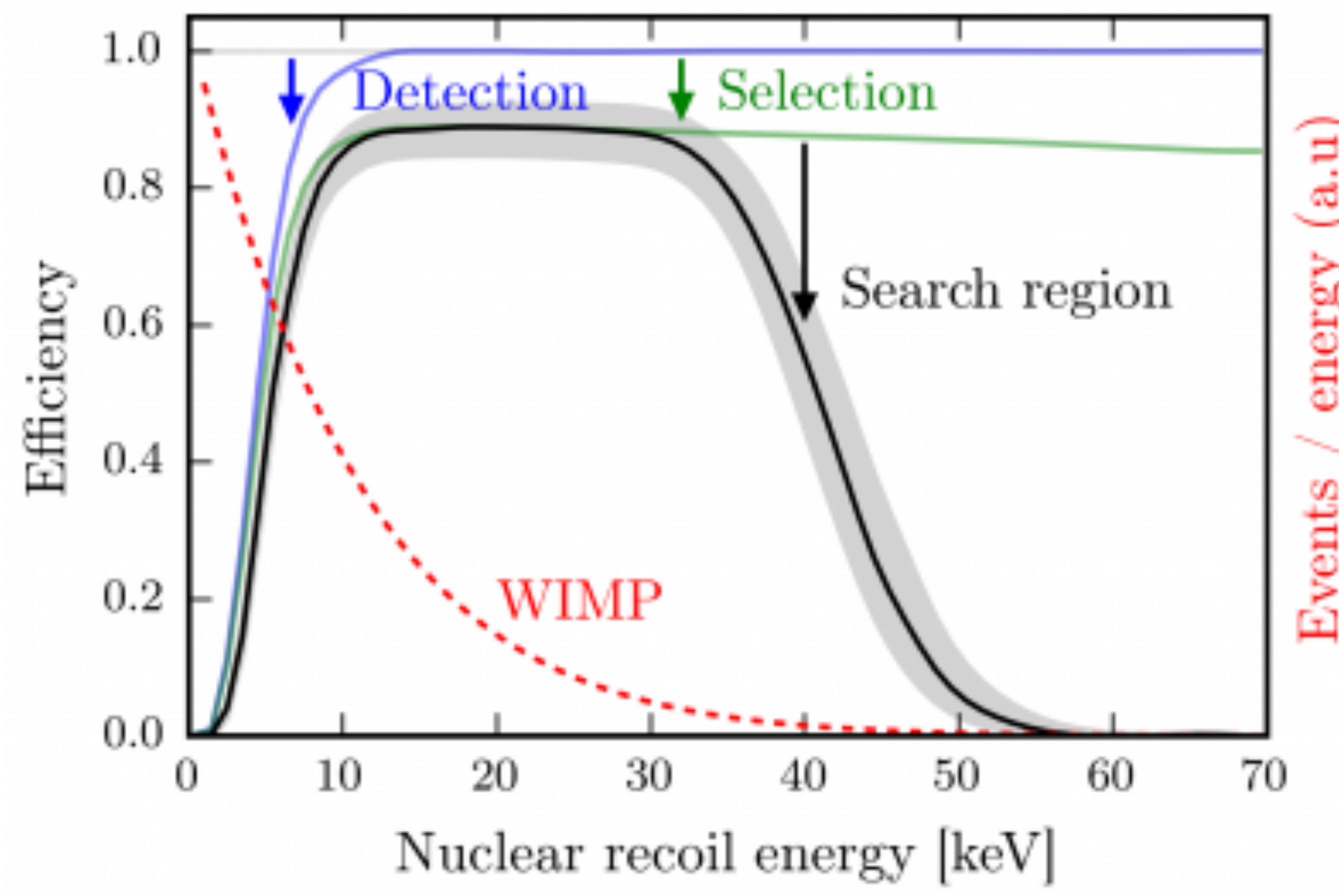
- The reconstruction of the x-y position of the event is driven by an optical Monte-Carlo (calibrated with Krypton) which is used to:
  - Train a Neural Net (used for 278 day analysis)
  - Construct a per-PMT likelihood
    - Both with similar performance





Acceptance estimation by

- The XENON1T low-energy threshold is set by the ability to identify the primary scintillation signal from low-energy events, with at least three photo-electrons.
- The detector electronic response, noise as well as peak-finding and digitisation is simulated
- Simulated “waveforms”— events are passed to trigger and processing software to compute detection efficiency (right for 34.2-day analysis)
- The Xenon signal processing software — PAX is available as open-source software



Data Processor:
GitHub.com/XENON1T/pax

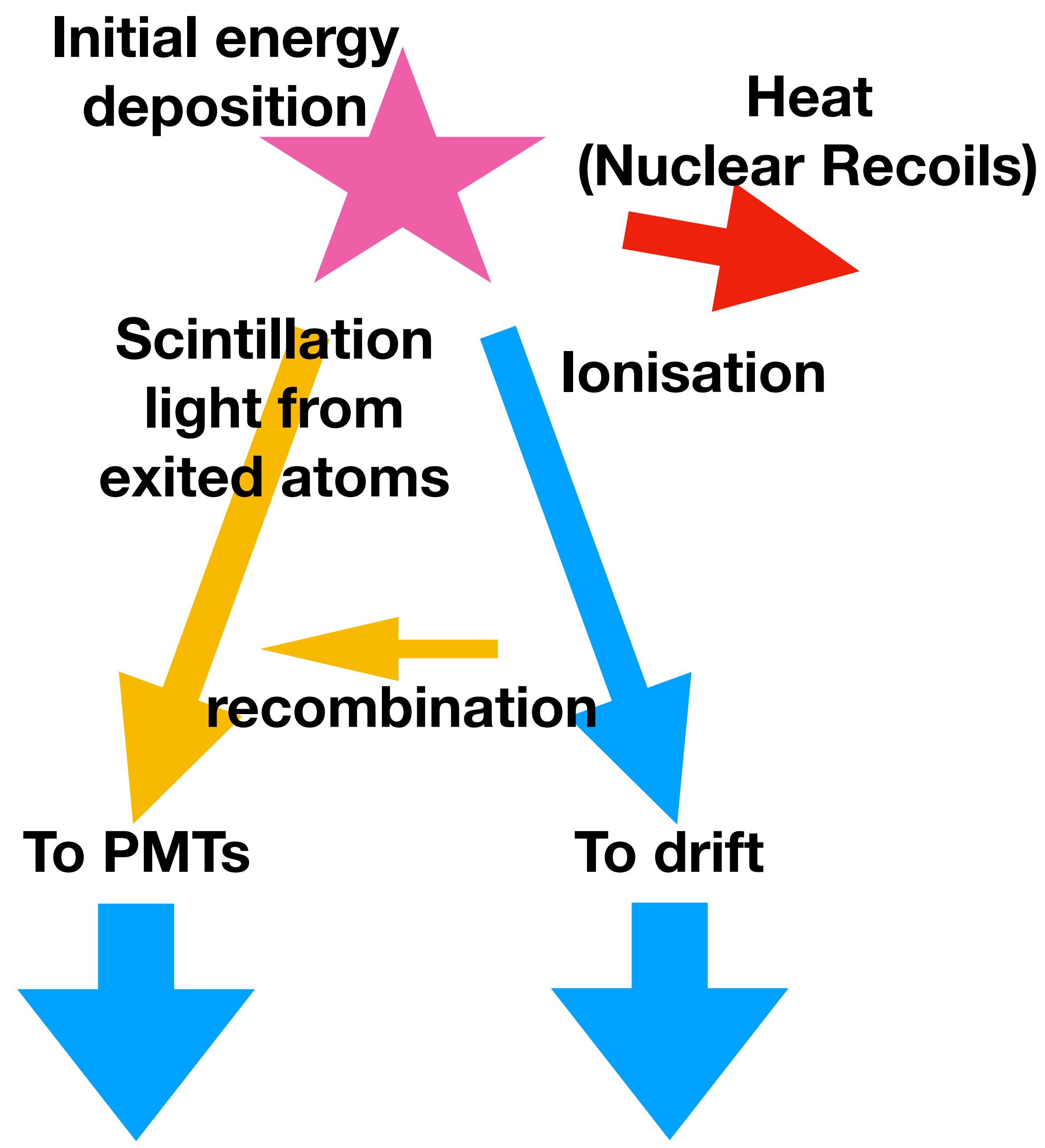
E. Aprile et al. First Dark Matter Search Results from the XENON1T Experiment. *Phys. Rev. Lett.*, 119(18):181301, 2017.

Component	Fraction of signal-like background*	Estimation
Signal	-	Fast Monte-Carlo fitted Americium-Beryllium (n-source) and neutron-generator calibration
Electronic Recoil	72 %	Fast Monte-Carlo fitted to Rn220 calibration data
Radiogenic Neutrons	6 %	Fast Monte-Carlo fitted Americium-Beryllium (n-source) and neutron-generator calibration
CNNS	3 %	Fast Monte-Carlo fitted Americium-Beryllium (n-source) and neutron-generator calibration
Accidental Coincidence	23 %	Data-driven
Surface background	3 %	Model from sidebands, fit to data

*** In published 34.2-day analysis**

NEST

- The conversion of recoil energy into photons, ionisation and heat in liquid Xenon is included in Monte Carlo simulations by the NEST plugin to GEANT4
- NEST simulates the partition of energy to exited atoms and ion-electron pairs
    - Nuclear recoils also loose a portion of energy to heat
- Parametrisation fit to data, including electric field dependence
- In XENON simulations,

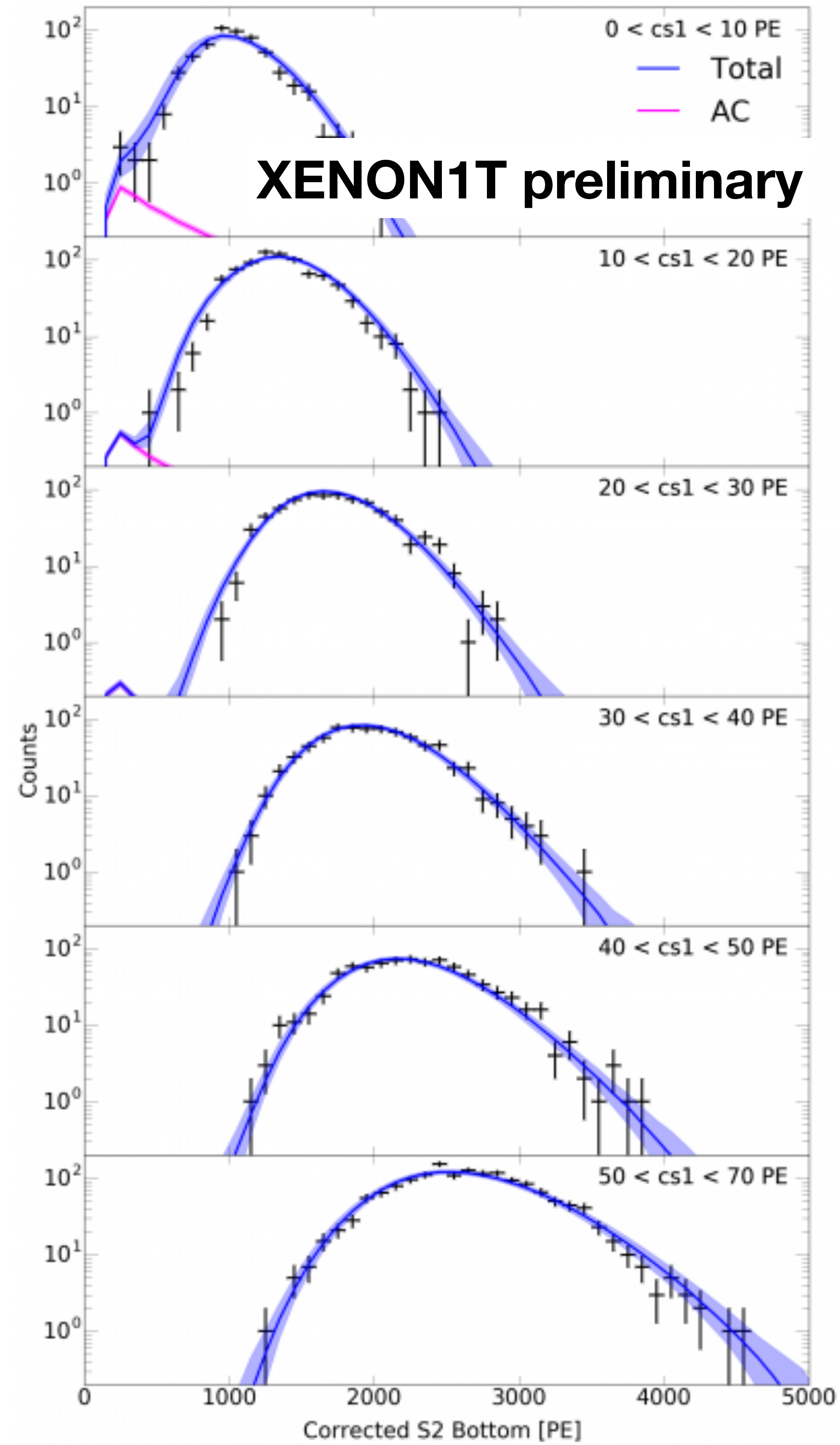


B. Lenardo *et al.*, IEEE Transactions on Nuclear Science **62**, no. 06, 3387 (2015) [arXiv:1412.4417].

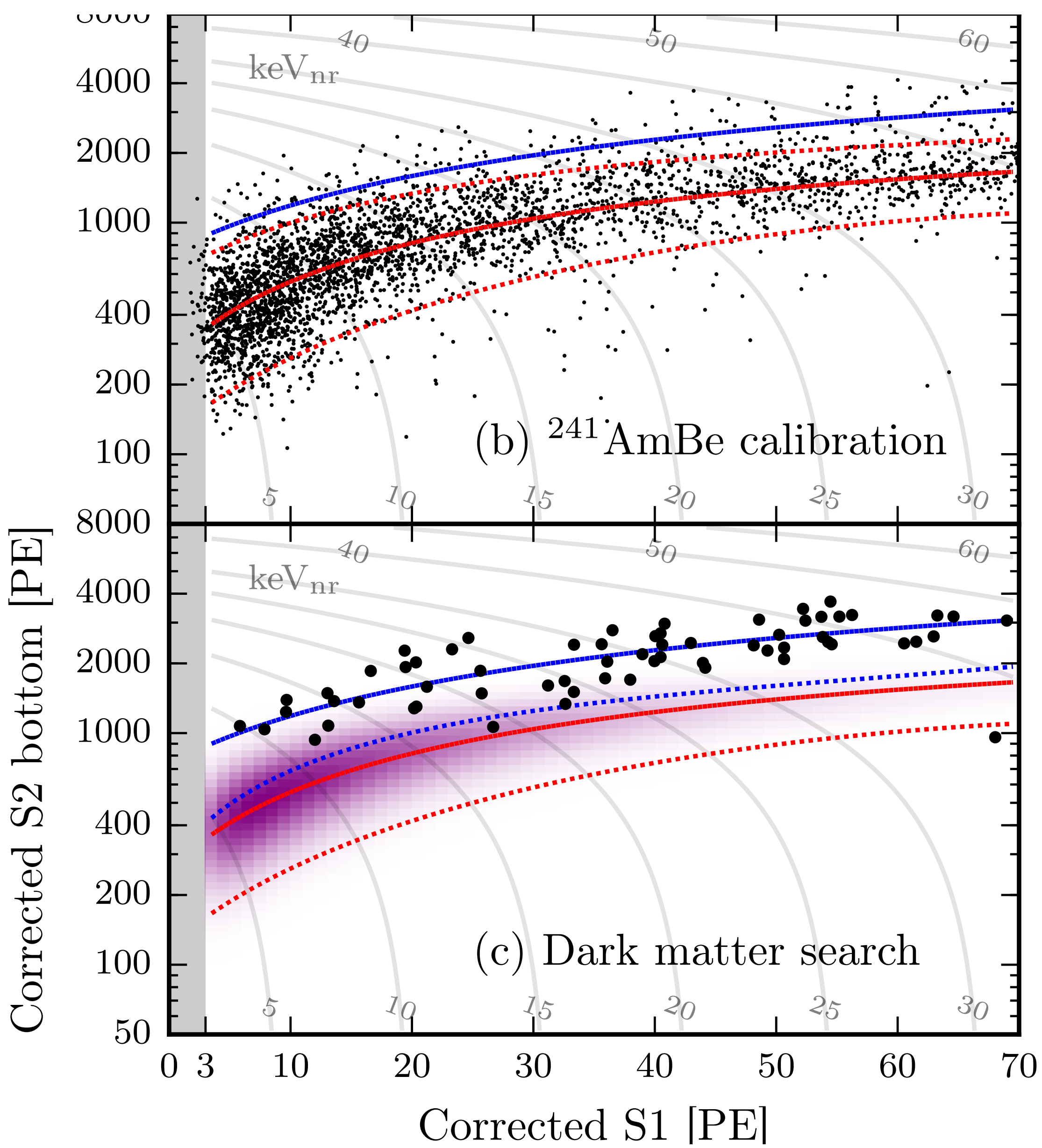
Calibration Fitting with MCMC

- In the science analysis, a fast Monte Carlo, similar to NEST, is used rather than a full detector simulation.
  - In addition, the measured detector response; efficiencies and reconstruction uncertainties, are applied to the produced quanta
  - Important scintillation parameters include the photon yield, and the size of recombination fluctuations
  - Priors from other experiments or NEST, refit to data.
- Simultaneous fit to multiple calibration sources and data-taking periods
- Uses GPU processing to handle large amount of nuisance parameters

Electronic Recoil Fit



Calibration Fitting with MCMC



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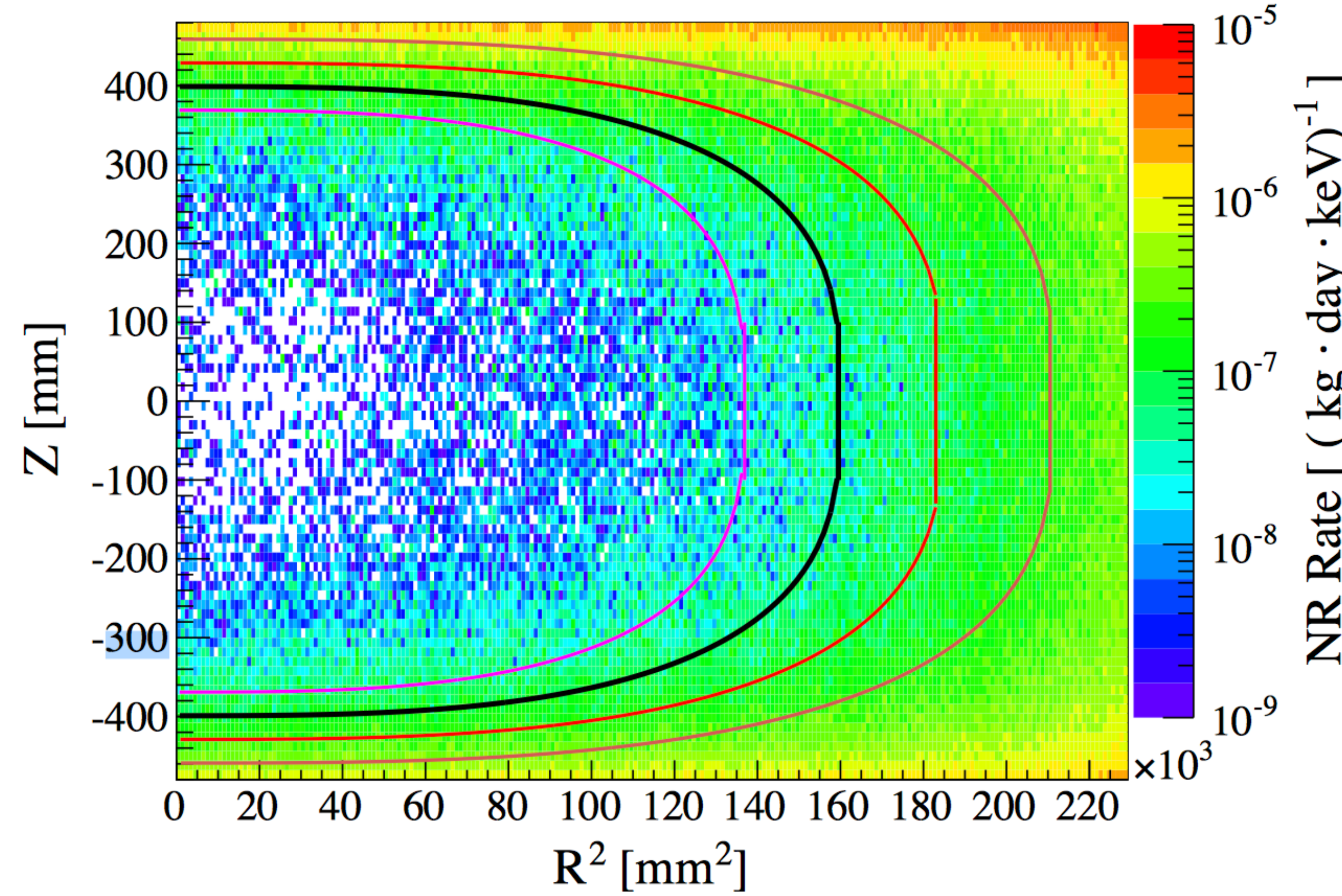
- Calibration sources of both ER and NR are used to characterise the detector response
- The neutron calibration was performed with an AmBe source, and fitted with a physics-motivated model
- The Bayesian fit incorporates a large number of detector and physics uncertainties, and fits the calibration well.
- WIMP and other NR source distributions are obtained by using the best-fit model above.
- In addition, two parameters were identified as important uncertainties; the efficiency and the exiton-to-ion ratio

Radiogenic Neutrons, CNNS/CEvNS

- Neutrons from radioactive decay or muons produce nuclear recoils similar to a WIMP
  - A cut on multiple scattering targets neutrons— GEANT4 simulation to incorporate both self-shielding and double-scatter efficiency.
- Neutrino scattering constitute an irreducible background, concentrated at very low cs1

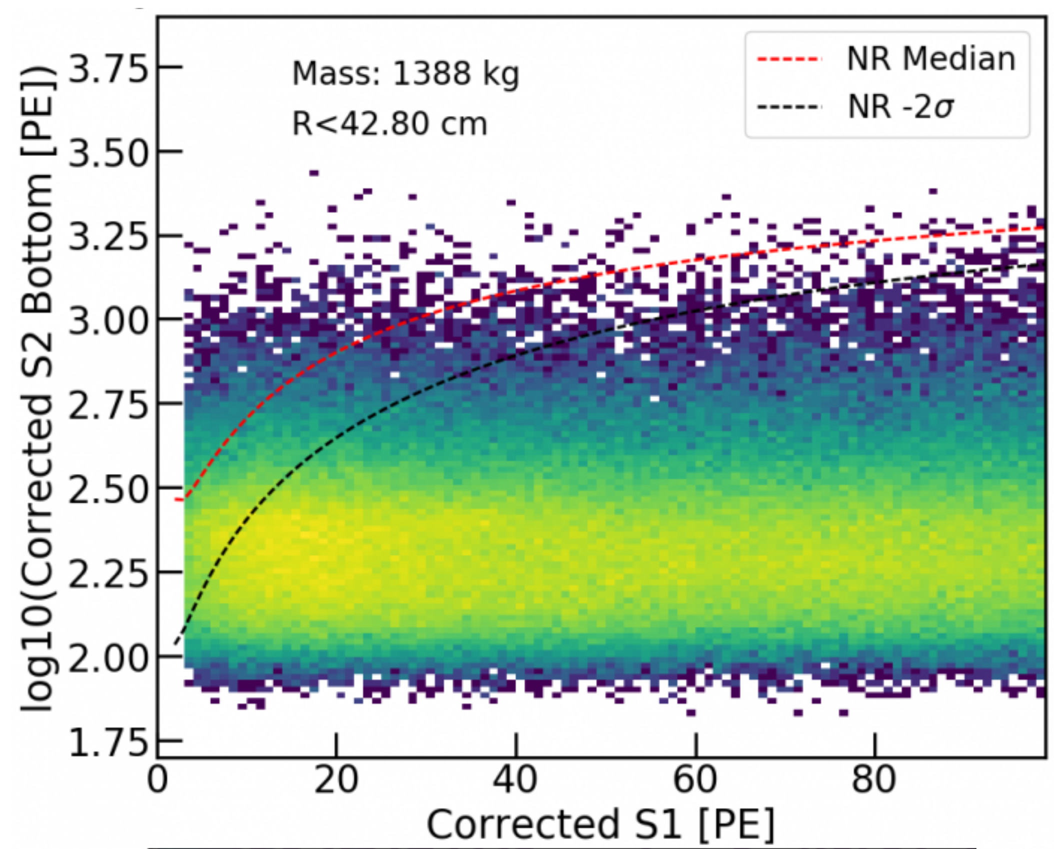


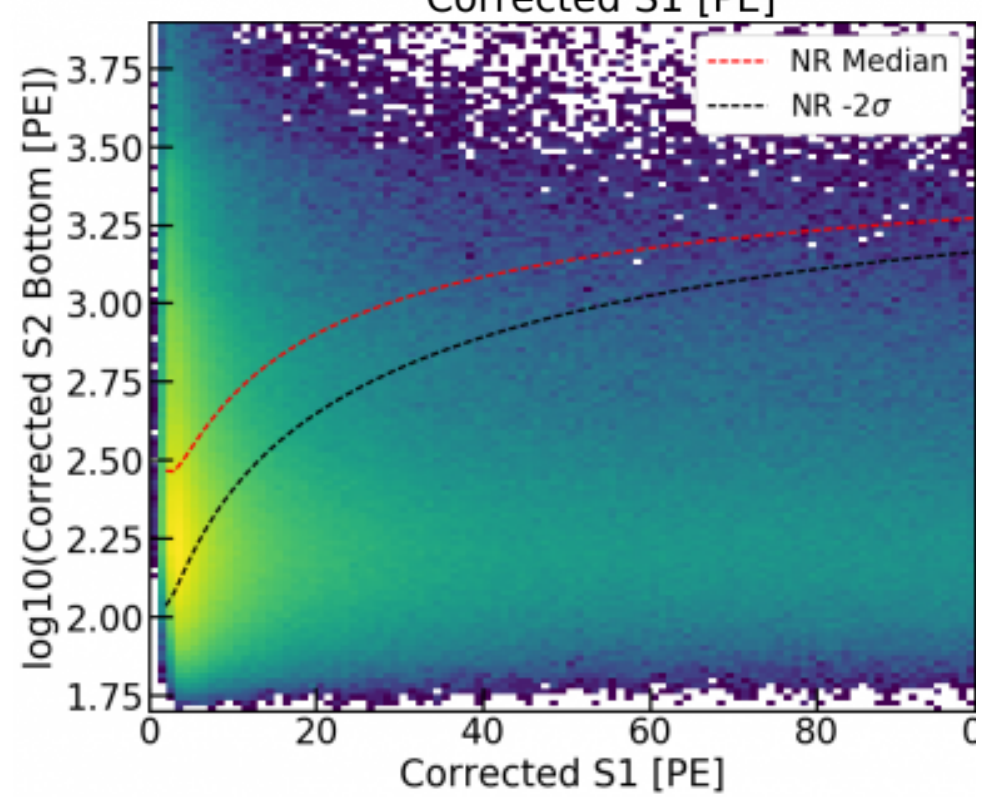
Expected Radiogenic distribution versus r and z

E. Aprile et al. Physics reach of the XENON1T dark matter experiment. *JCAP*, 1604(04):027, 2016.

Data-driven backgrounds

- "Surface events" occur at the outer edge of the detector, where the position reconstruction and drift field homogeneity is the poorest.
  - cs1/cs2 shape estimated from events reconstructed at high r, with radial PDF estimated from sidebands
- Accidental coincidence events, random pairings of s1 and s2 signals, are simulated by randomly pairing lone signals





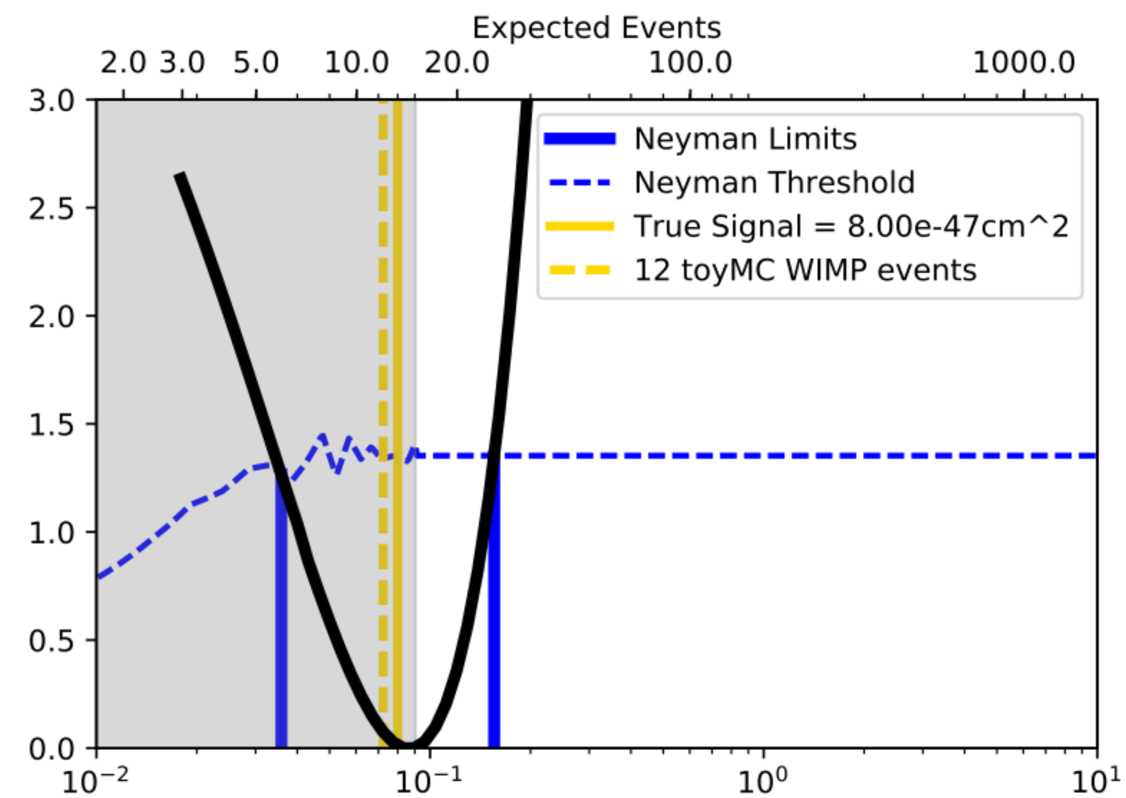
Statistical toyMC treatment

- The low background allows XENON1T to exclude signal expectations of only a few events. Asymptotic results from likelihood ratios can be inaccurate, so large toyMC production and fitting runs are necessary.

- Large increases in computing power needed, in particular when two science runs are combined with separate nuisance parameters

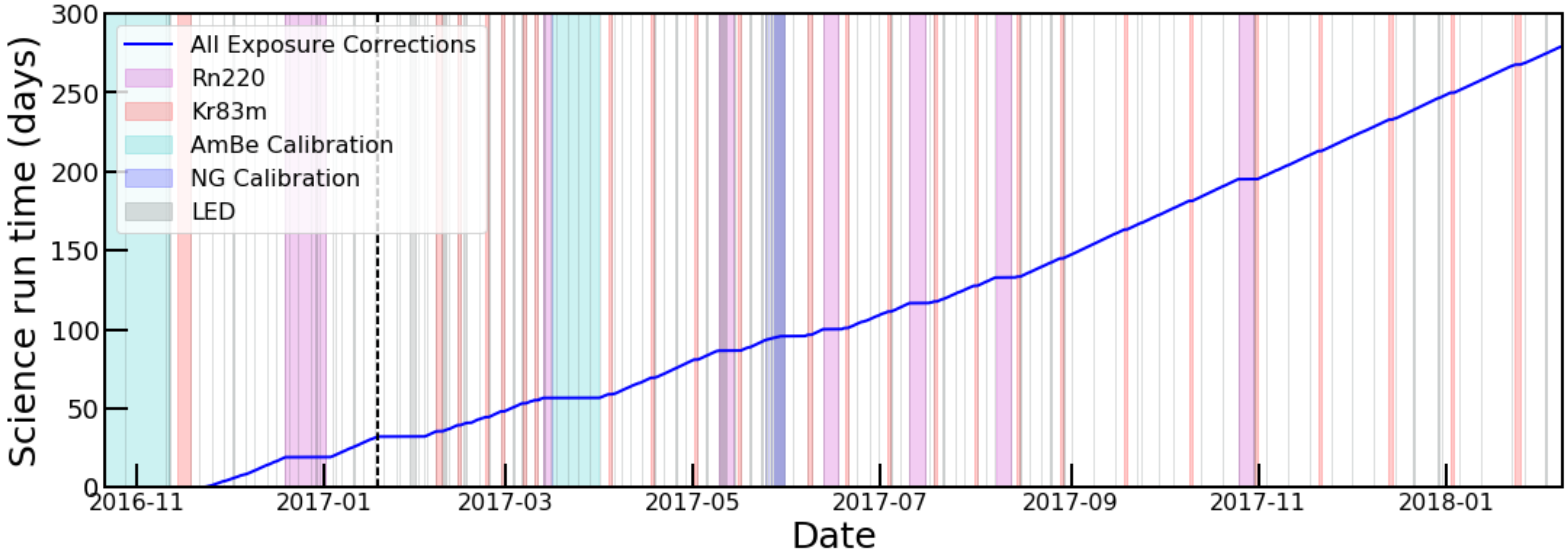
- Plus large amounts of optimisation studies

ToyMC example:



WIMP cross-section/1e45cm^2

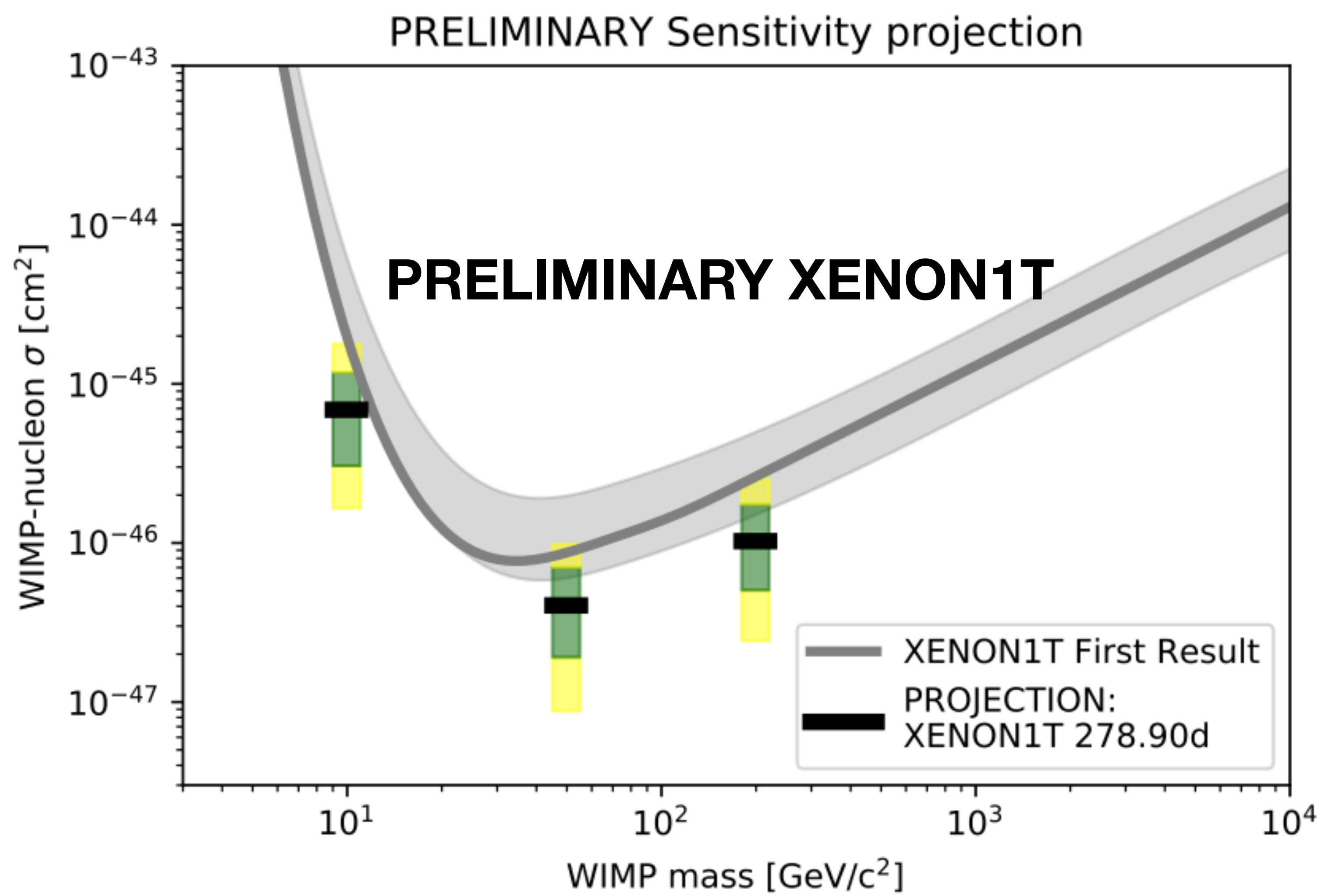
Upcoming Results



- The XENON collaboration is currently analysing a total (including the previous 34.2 days) of 279 live-time days.

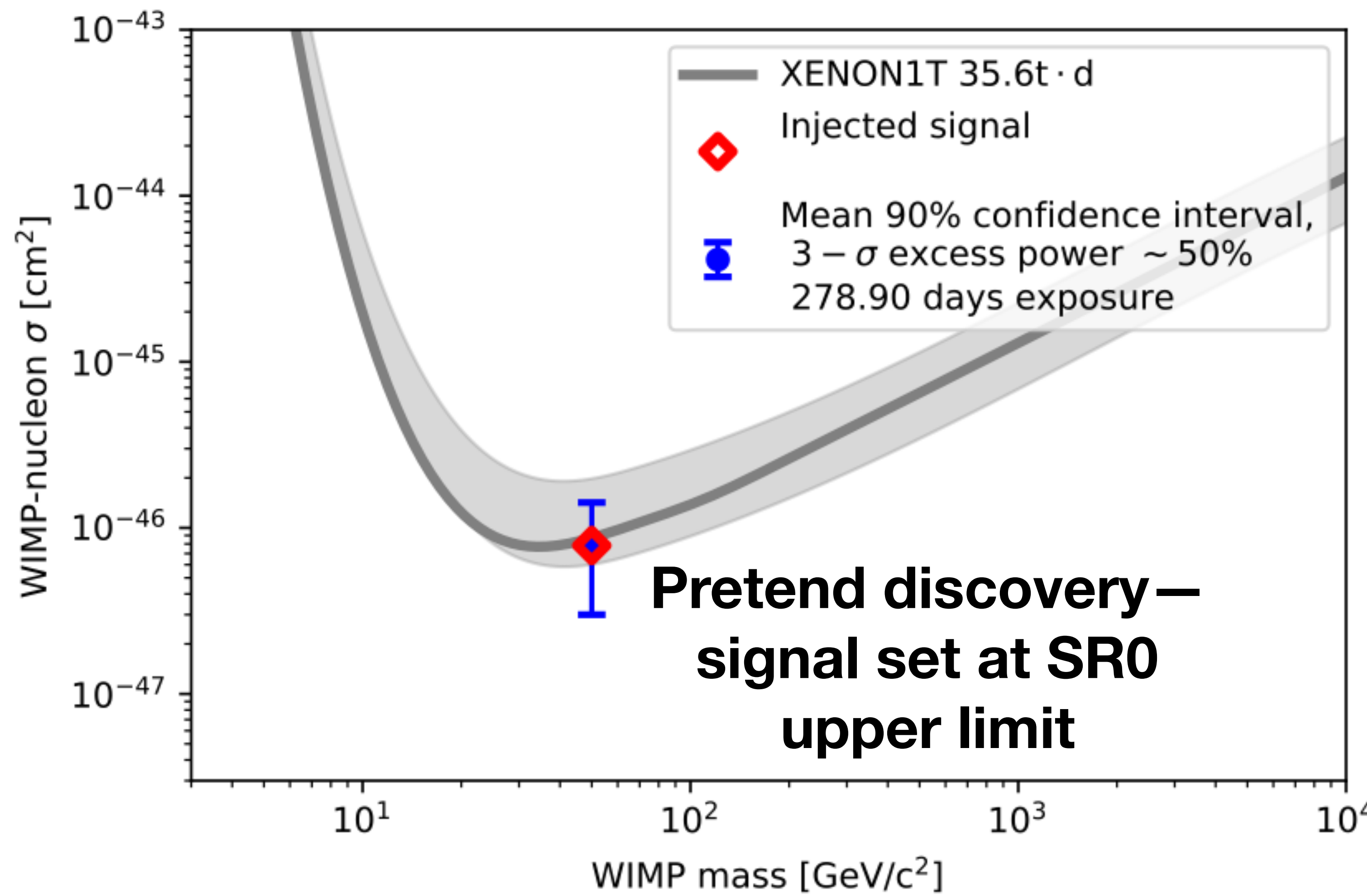
Upcoming Results

- A combined 279-day analysis
- Interaction-dependent correction of position for inhomogeneous electric field increases the analysis volume to 1.3 tonne.
- Significant improvement in sensitivity, moving the range of expected upper limits down.



Summary

- XENON1T is finalising a 278.9-day exposure analysis
- As that analysis winds down, more specialised search groups are convening;
    - Annual Modulation
    - Spin dependent/ other operators
    - inelastic scattering
- Readying foran upgrade from 1T to XENONnT
    - Water tank is sized to accept larger TPC
    - Cooling



References, backup slides

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E. Aprile et al. First Dark Matter Search Results from the XENON1T Experiment. *Phys. Rev. Lett.*, 119(18):181301, 2017.

E. Aprile et al. The XENON1T Dark Matter Experiment. *Eur. Phys. J.*, C77(12):881, 2017.

B. Lenardo, K. Kazkaz, A. Manalaysay, J. Mock, M. Szydagis, and M. Tripathi. A Global Analysis of Light and Charge Yields in Liquid Xenon. *IEEE Trans. Nucl. Sci.*, 62(6):3387–3396, 2015.

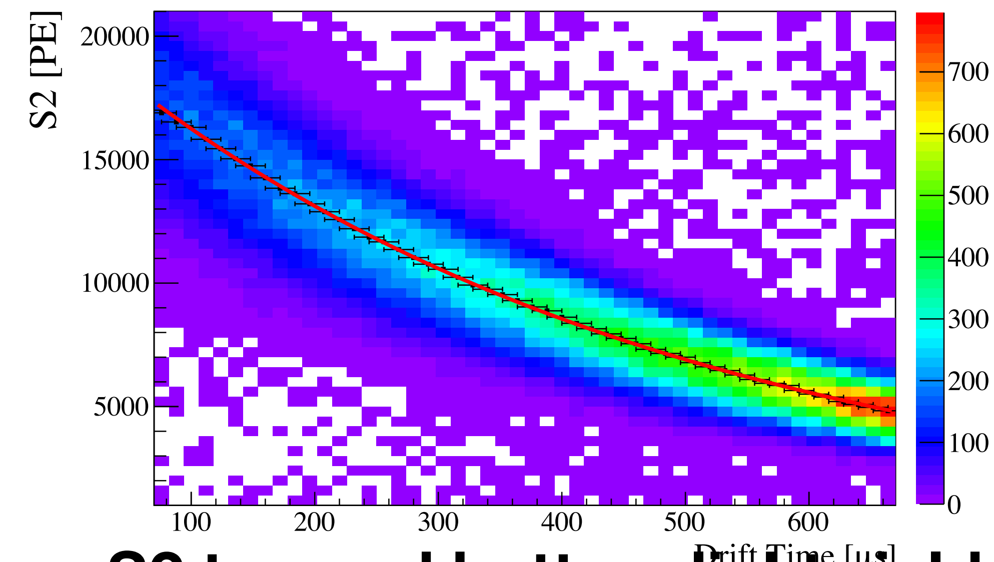
Normalisation of the detector response

- Both S1 and S2 signals are normalised by the spatially varying detector response:

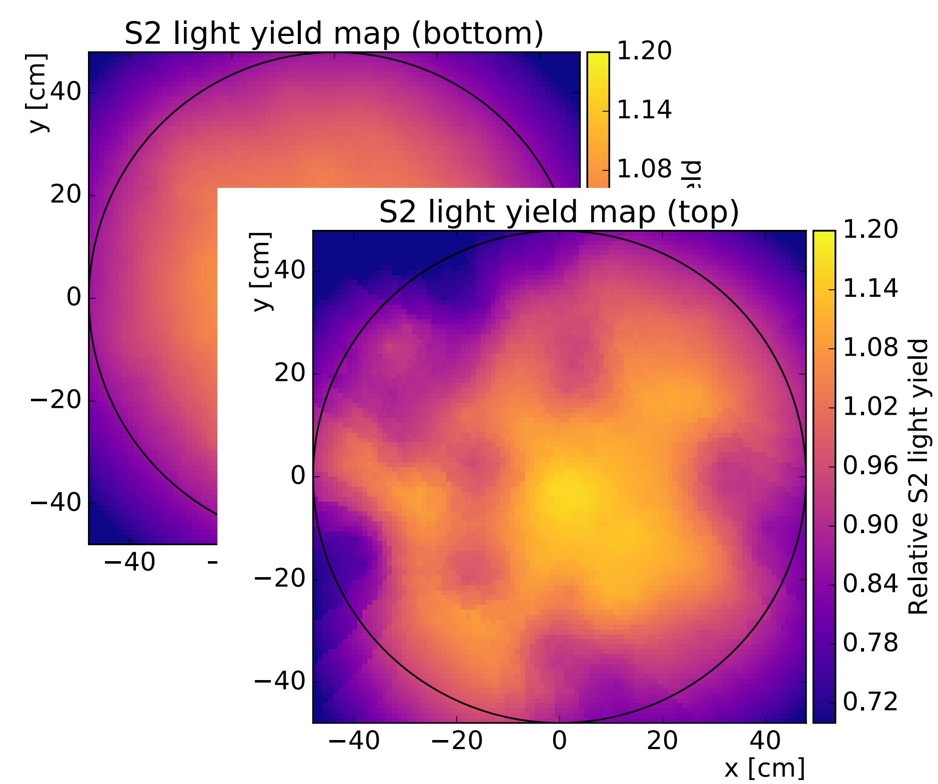
  - S1 signals are corrected by the light-collection efficiency

  - S2 signals are corrected the loss of electrons as they drift farther (top right), and the PMT array efficiencies (lower right)

S2 vs drift time for ^{83m}Kr)

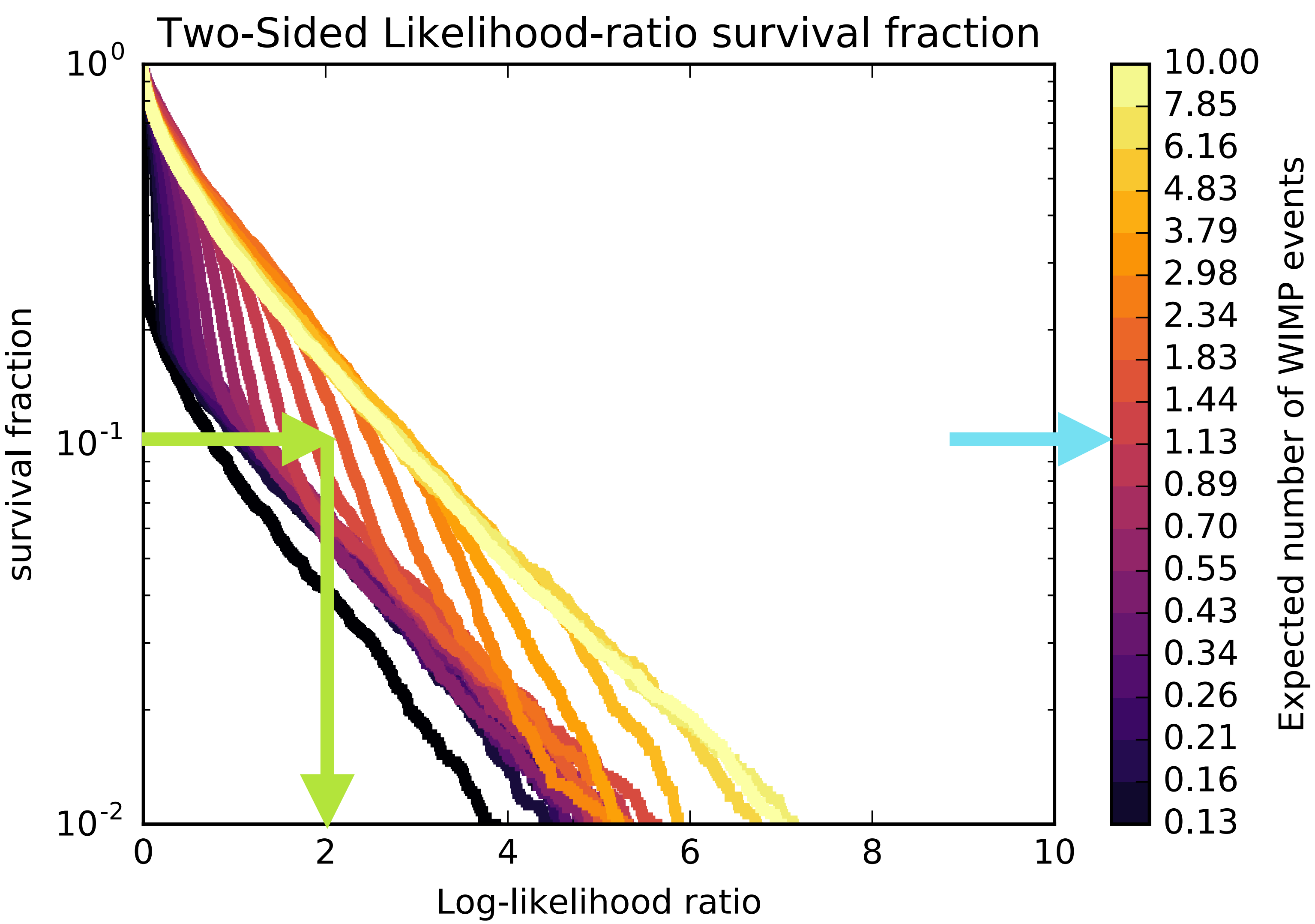


S2 top and bottom light yields

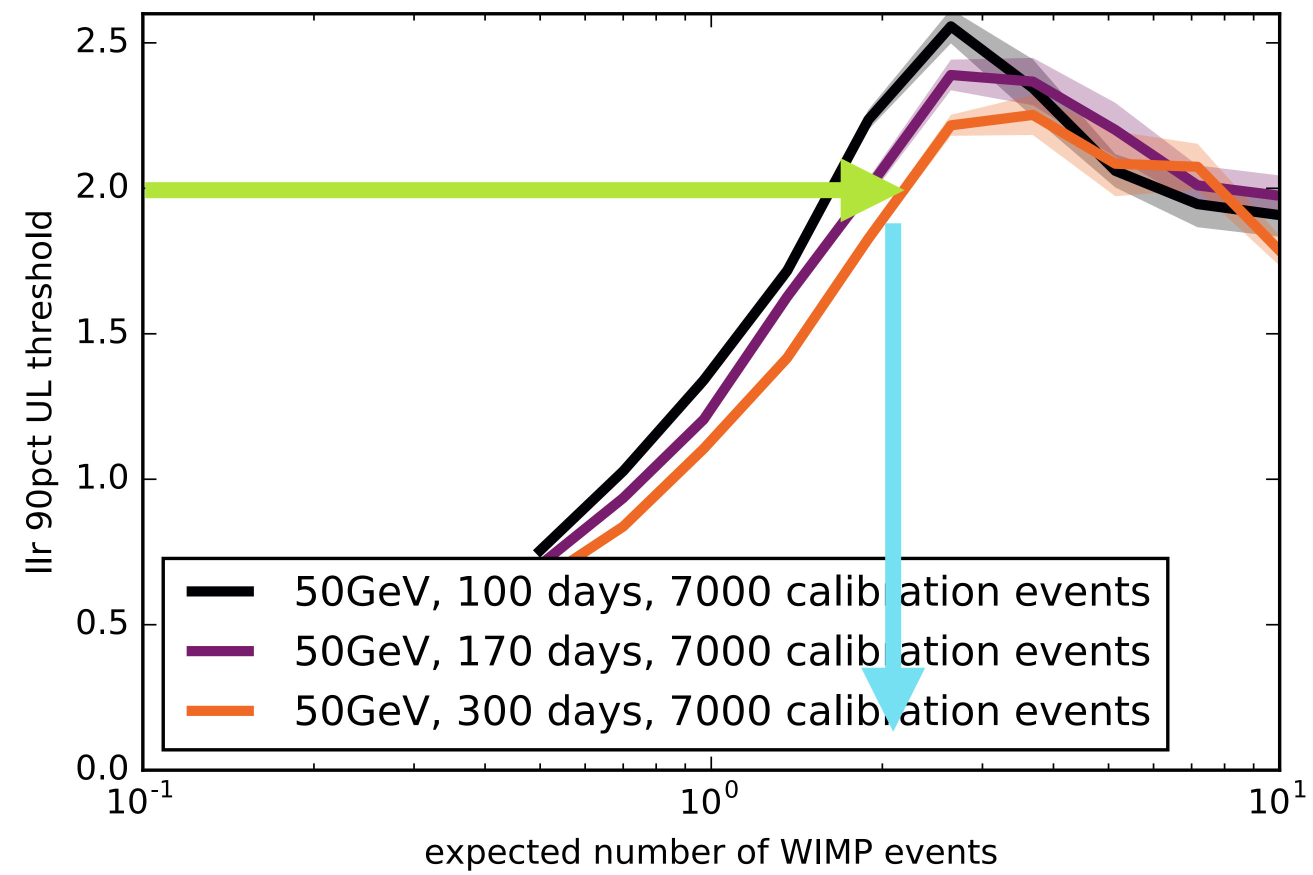


How thresholds are computed

- For steps in (true) expected signal, toyMC datasets are generated.
- to the right, the survival distribution for different signal expectation are shown as function of log-likelihood ratio
- The threshold we use is what likelihood ratio above which 10% of the toyMC fall



- The thresholds found this way, plotted versus signal expectation is the line above which we exclude a signal size at 90% confidence level



Intervals

- To the right, one can see the median upper and lower edge of this Feldman-Cousins interval as function of true signal

- This is the typical size of the uncertainty on the signal size if we have an excess