Dark Matter search with the XENON100 Experiment

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On behalf of the XENON100 collaboration

April 16th, Light Dark Matter: Asymmetric, thermal and non-thermal dark matter and its detection

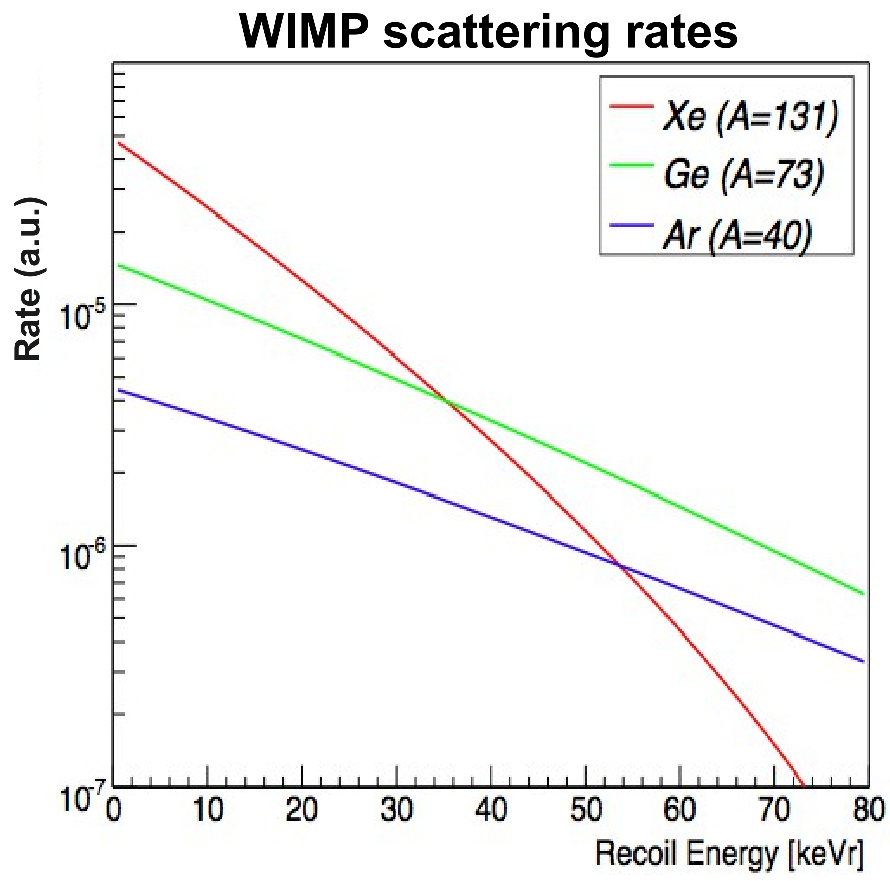
XENON100 Collaboration

Columbia Rice UCLA Zürich Coimbra LNGS INFN SJTU Purdue

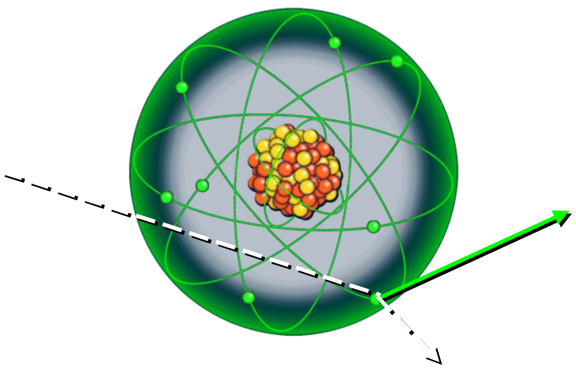
Bologna Subatech Münster Heidelberg Nikhef Weizmann Mainz Bern

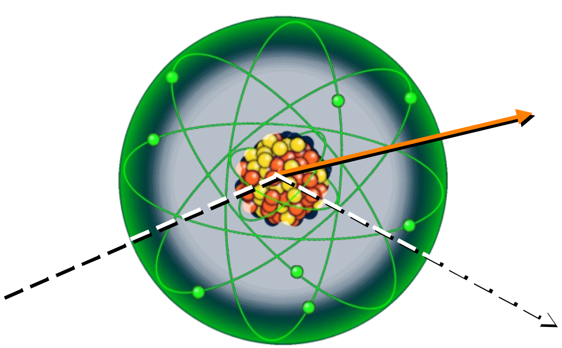
Liquid Xenon for Dark Matter Searches

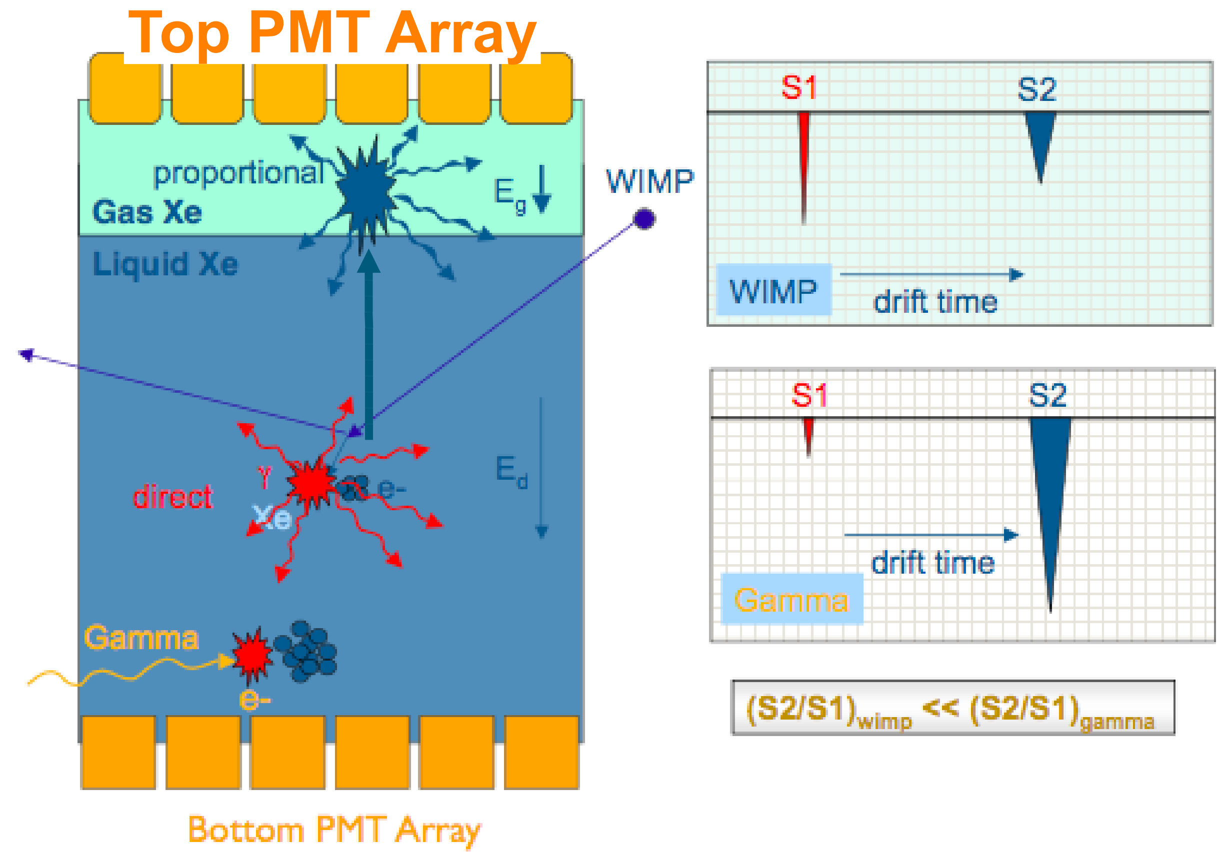
- **Scalability:** relatively inexpensive for very large detector (today ~$1000/kg)
- **Xe nucleus (A~131):** good for SI plus SD sensitivity (~50% odd isotopes)
- **Self shielding:** High atomic number Z=54 and density 2.8kg/l
- **Charge & Light:** highest yield among noble liquids and best self-shielding
- **Low energy threshold:** photosensors within liquid for efficient light detection
- **background reduction:** by charge-to-light ratio and 3D-event localization
- **Intrinsically pure:** no long-lived radioactive isotopes; Kr/Xe reduction to ppt level with established methods



The XENON Two Phase TPC



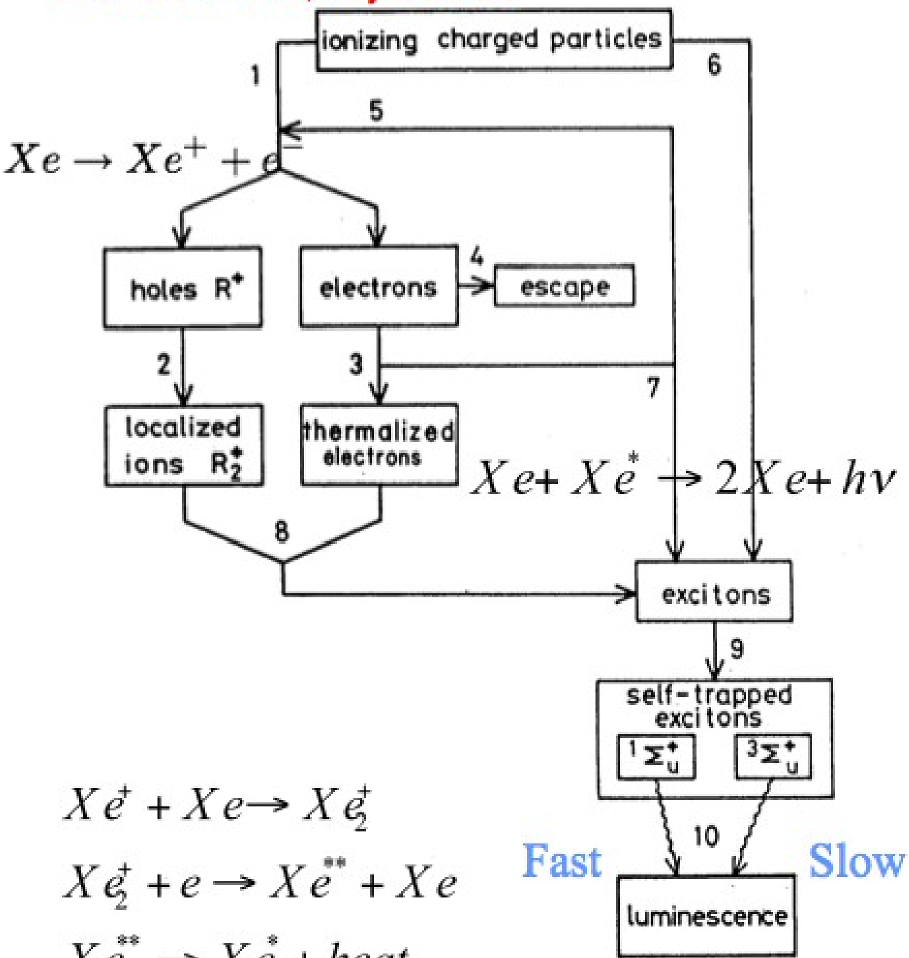


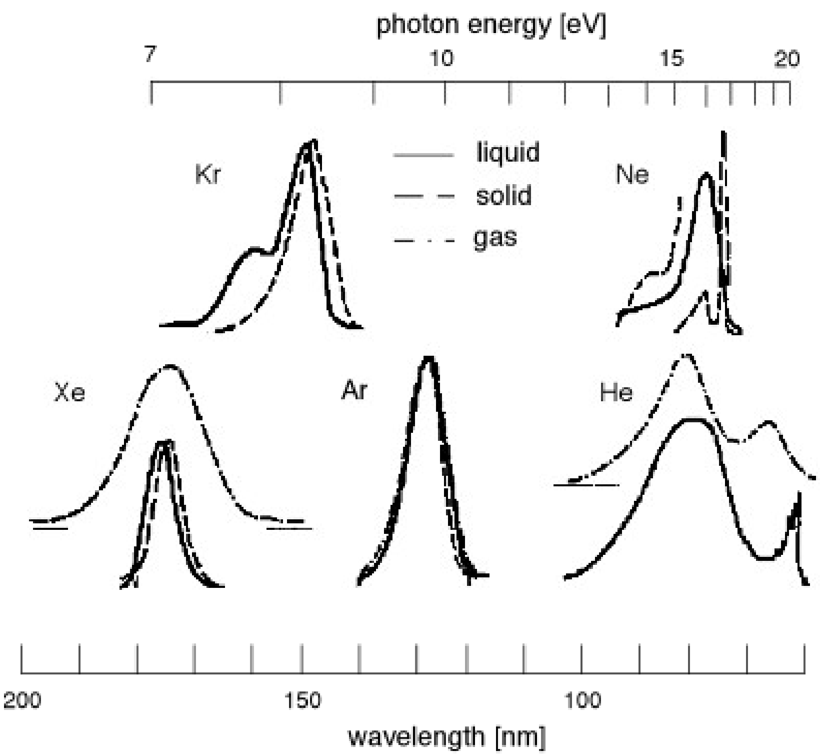


- **Single electron and single photon measurement sensitivity**
- **> 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1) for 50% NR acceptance**
- **3D event-by-event imaging with millimeter spatial resolution**

Signal production in Liquid Xenon

Kubota et al. 1979, Phys. Rev.B





$$Xe^{+} + Xe \rightarrow Xe_2^{+}$$

$$Xe_2^{+} + e \rightarrow Xe^{**} + Xe$$

$$Xe^{**} \rightarrow Xe^{*} + heat$$

$$Xe + Xe^{*} \rightarrow Xe_2^{*} \rightarrow 2Xe + h\nu$$

$$\lambda \sim 128_{LAr}$$

$$\lambda \sim 175_{LXe}$$

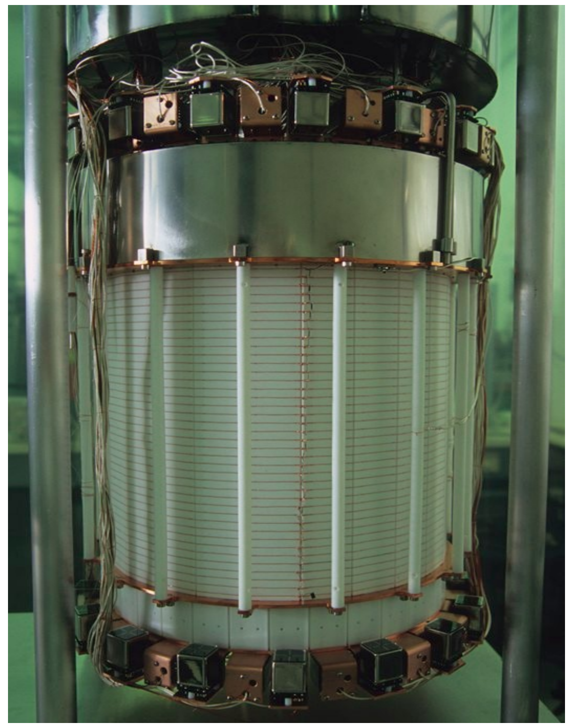
$$\lambda \sim 77.5_{LNe}$$

The XENON Roadmap

XENON10

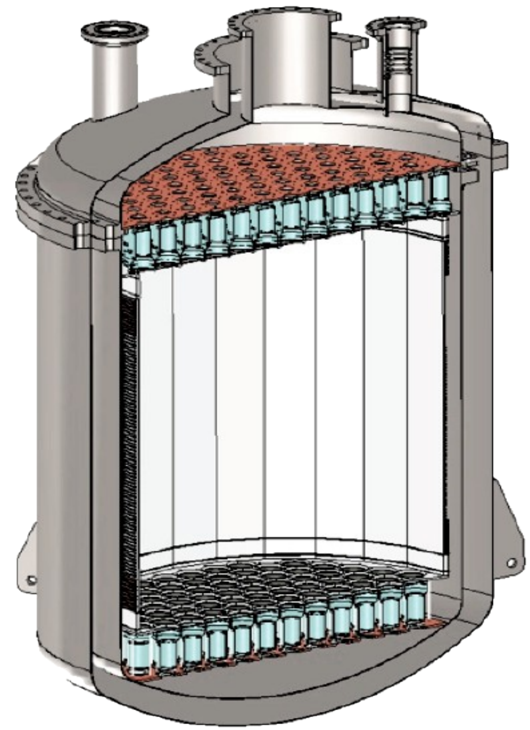
2005-2007
PRL100
PRL101
PRL 107
PRD 80
NIM A 601

XENON100



2008-2013
first results:
PRL105, PRL107, PRD84
PRL109
Reached projected sensitivity
More to come soon

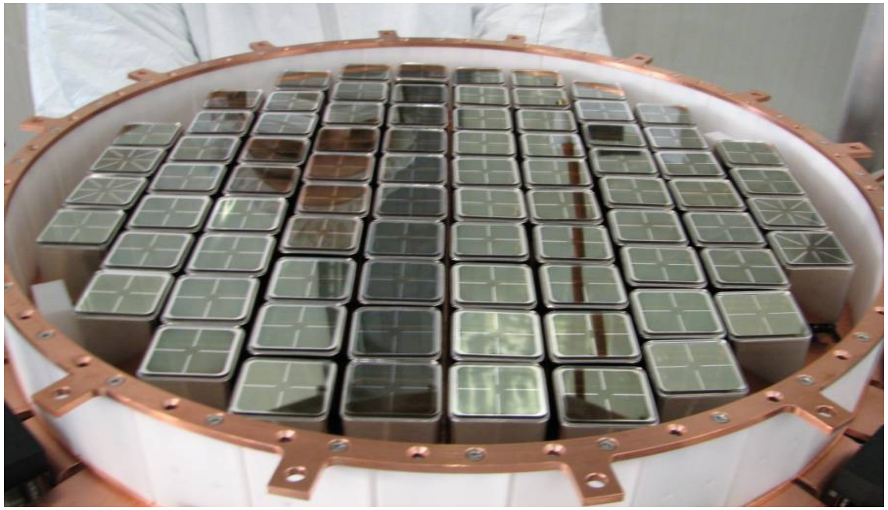
XENON1T



2013-2017
Projected sensitivity
$2x10^{-47}cm^2$

The XENON100 Detector

- XENON100 was designed to be ~100 times more sensitive than XENON10
- Target: 30 cm drift x 30 cm diameter TPC
- 162 kg ultra pure LXe (target + veto)
- Cryocooler and FTs outside shield
- Selection of materials for low radioactivity



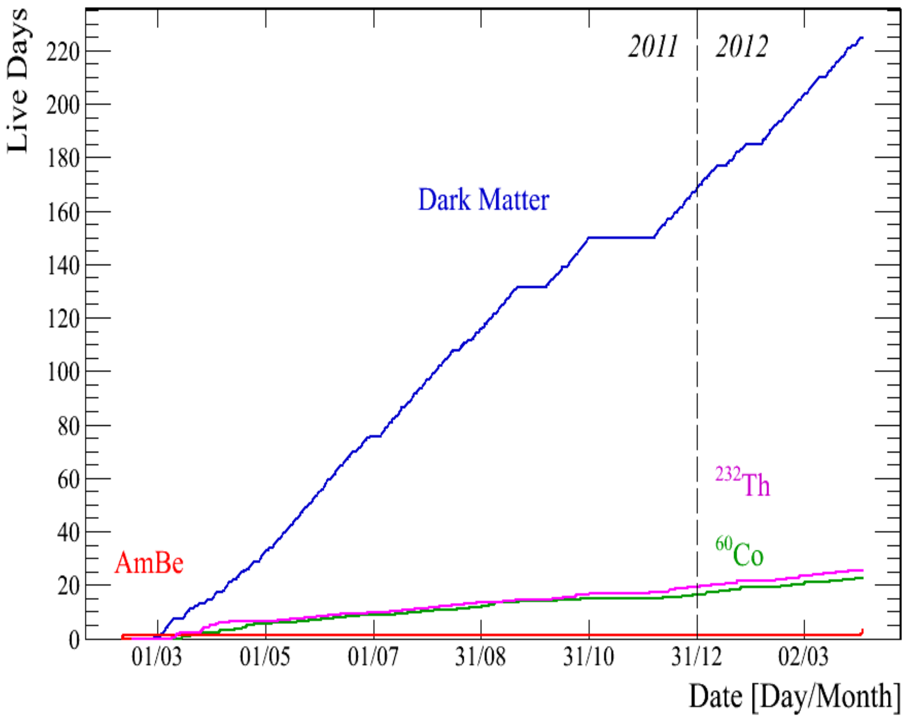
- 242 1-inch square PMTs: 1 mBq (U/Th) and ~30% QE
- LXe veto around target on all sides
- Multilayer passive shield (Cu,Poly, Pb+Water)

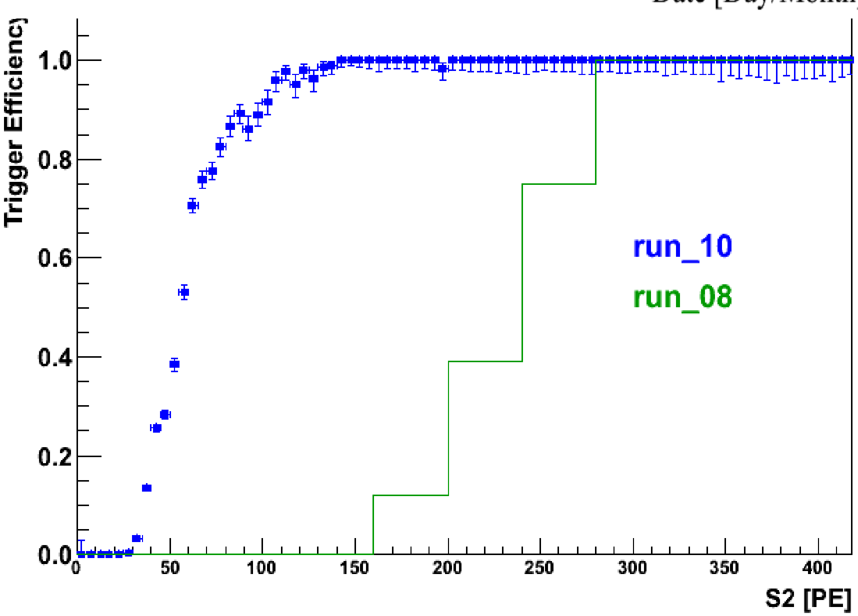
XENON100 at LNGS

taking data since the first decade of the millenium

See Astropart. Phys. 35 (2012), 573-590 for a full description of the detector

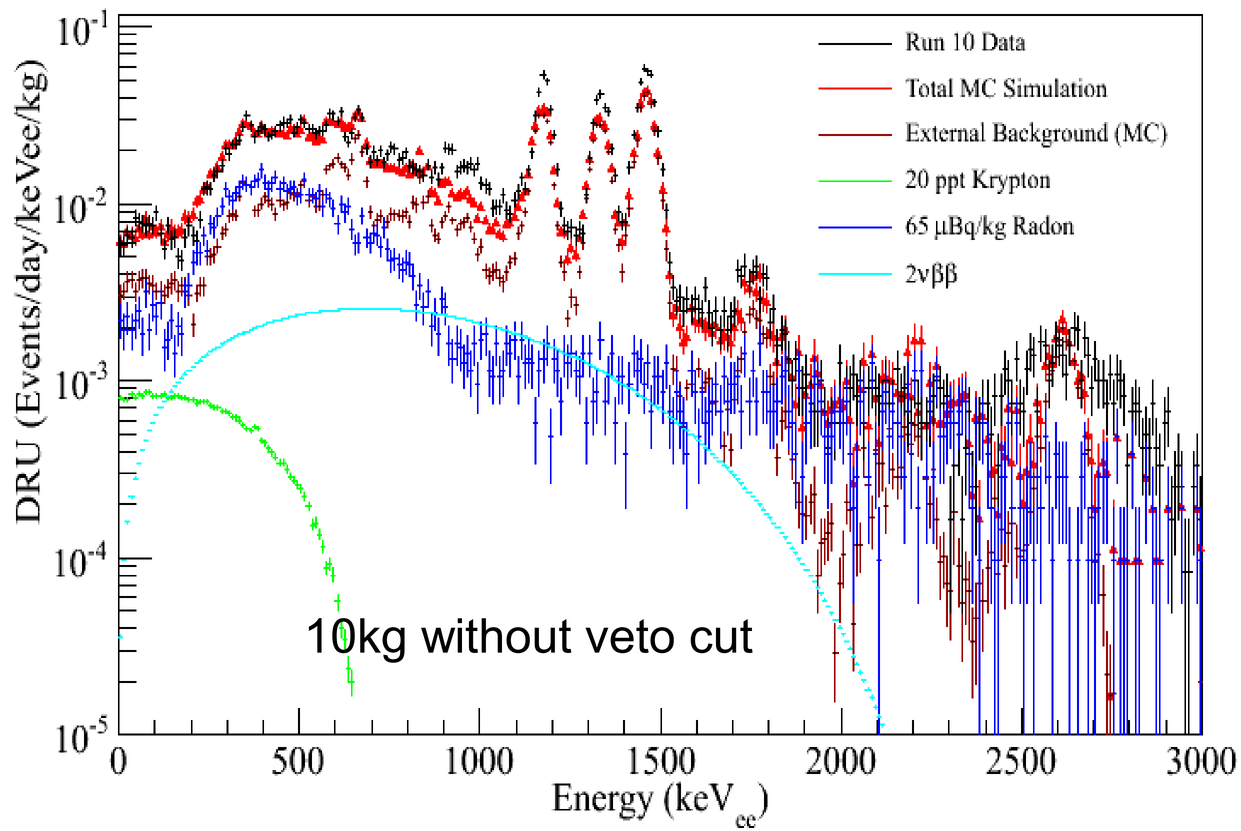
2011-12 Run Data





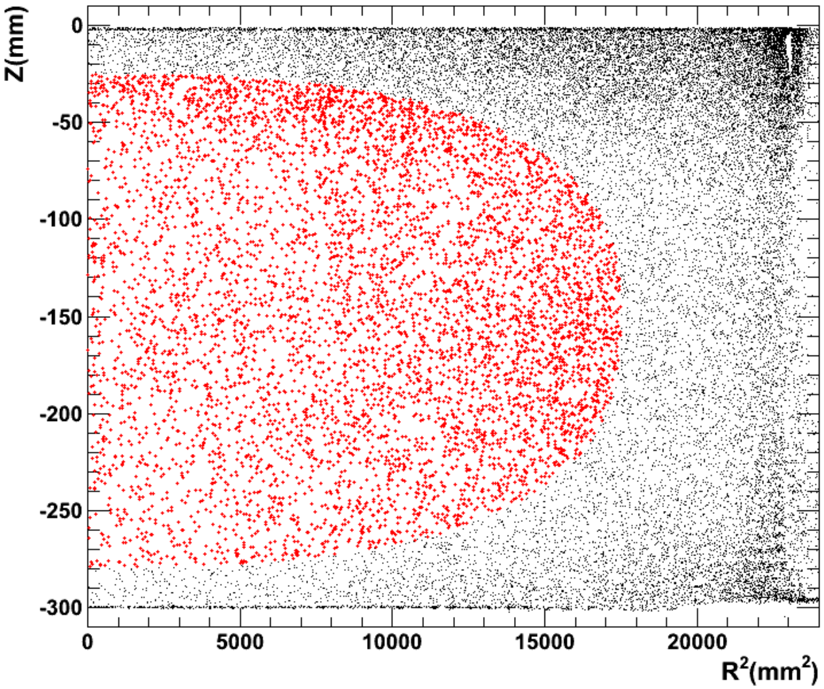
- Data taken between February 2011 and March 2012
- Data following maintenance periods removed from analysis
- Trigger threshold lowered to about 10 electrons in S2. ~100% efficiency for events with S2>150pe
- S1 Energy threshold decreased to 3 pe (~6.6 keV_{nr})
- Reduced noise and improved cuts to identify/reject "noisy" events

Background of 2011-12 Run

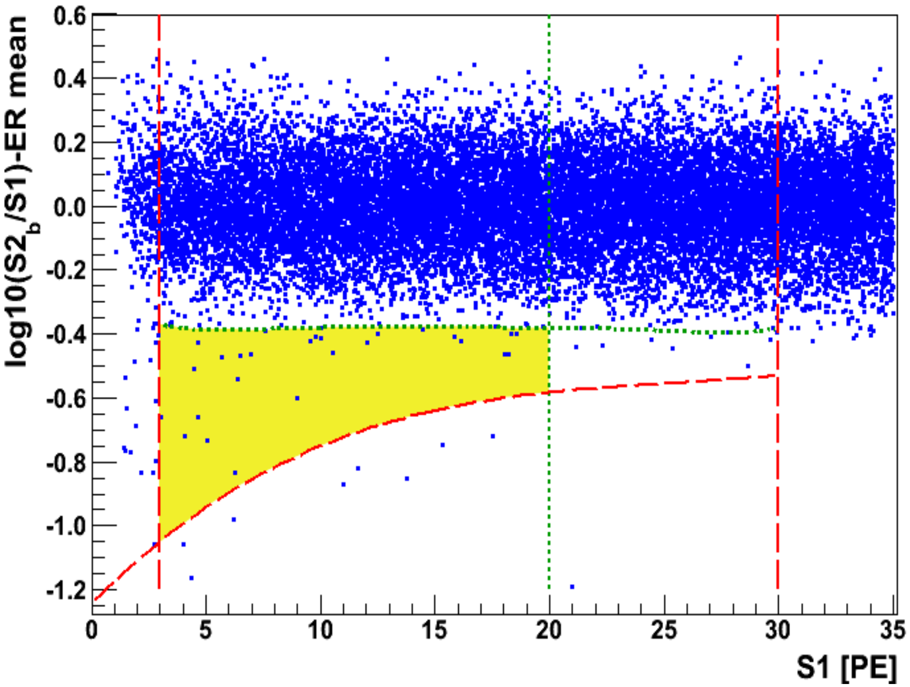


- Gamma emission from detector's materials radioactivities is the main source of EM Background
- Radioactivities intrinsic to LXe (Kr and Rn) add to this background
- Kr contamination measured by RGMS to be 19±1 ppt. Delayed coincidence result agrees. Reduction of more than a factor 10 with respect to previous run
- Rn contamination studied via alpha spectroscopy and delayed coincidence analysis (BiPo)
- Excellent agreement between our measurements and a MonteCarlo simulation
- Measured background is 5.3±0.6 mdru before discrimination

Optimization of the Fiducial Volume and Signal Region

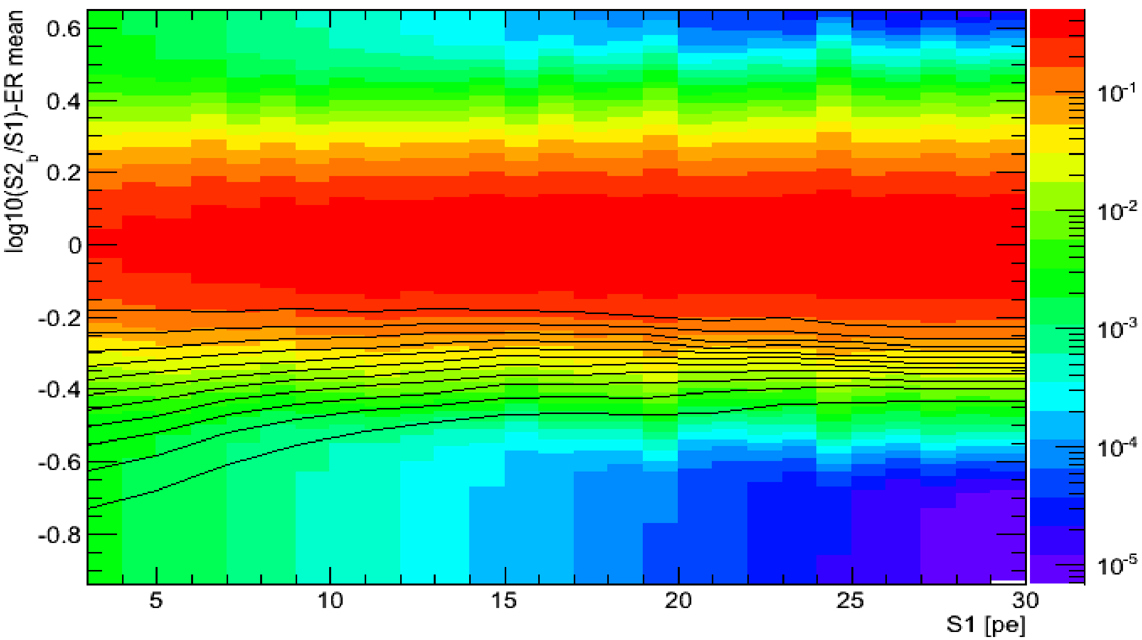


- The fiducial volume and signal region are simultaneously adjusted to maximize sensitivity
- Given the lower beta background in this run, we choose a smaller FV (34kg) to benefit from LXe self-shielding



- The signal region is chosen below the 99.75% constant rejection line for ER from calibration with Co and Th
- The signal region for the cuts based analysis is set between 3 and 20 pe
- For a detailed explanation of the analysis check arXiv:1207.3458

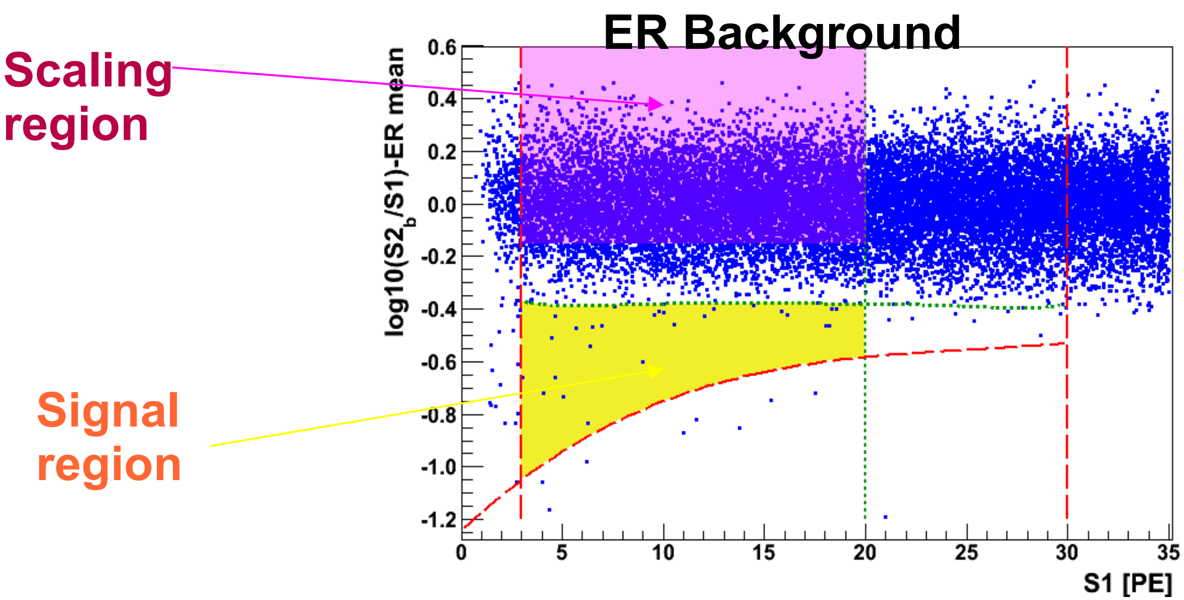
Background Expectation (Profile Likelihood Analysis)

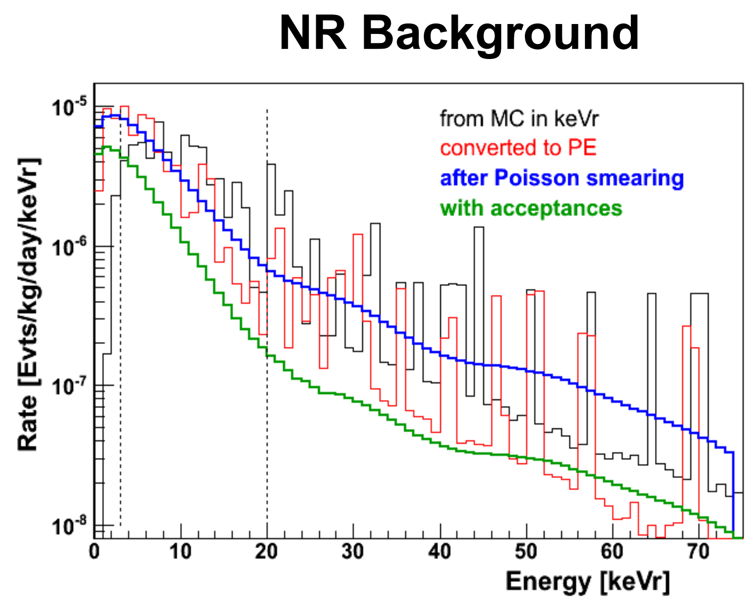


$$\begin{aligned}\mathscr{L} &= \mathscr{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, \mathcal{L}_{\text{eff}}, v_{\text{esc}}; m_\chi) \\ &\quad \times \mathscr{L}_2(\epsilon_s) \times \mathscr{L}_3(\epsilon_b) \\ &\quad \times \mathscr{L}_4(\mathcal{L}_{\text{eff}}) \times \mathscr{L}_5(v_{\text{esc}}).\end{aligned}$$

- The ER calibration data are modelled in a two dimensional distribution
- This model has been tested with a likelihood analysis to properly represent the data
- The background contamination in every band used for to compute the likelihood is calculated from the model
- An additional contribution from neutrons is added to the final background
- Both expectations (Cuts and PL) use the same data as input
- See for details Phys. Rev. D 84, 052003 (2011)

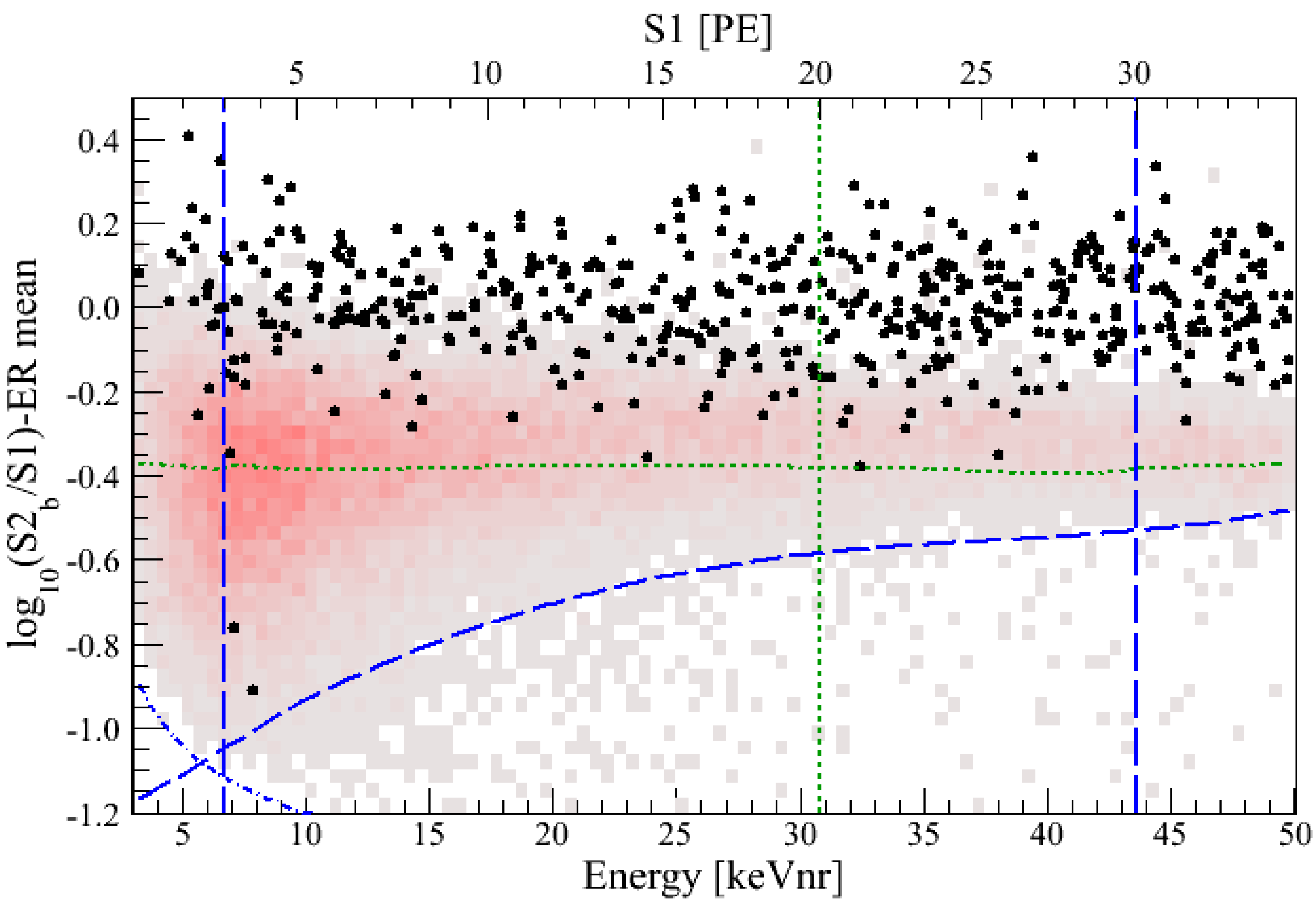
Background Expectation (Signal Region Analysis)





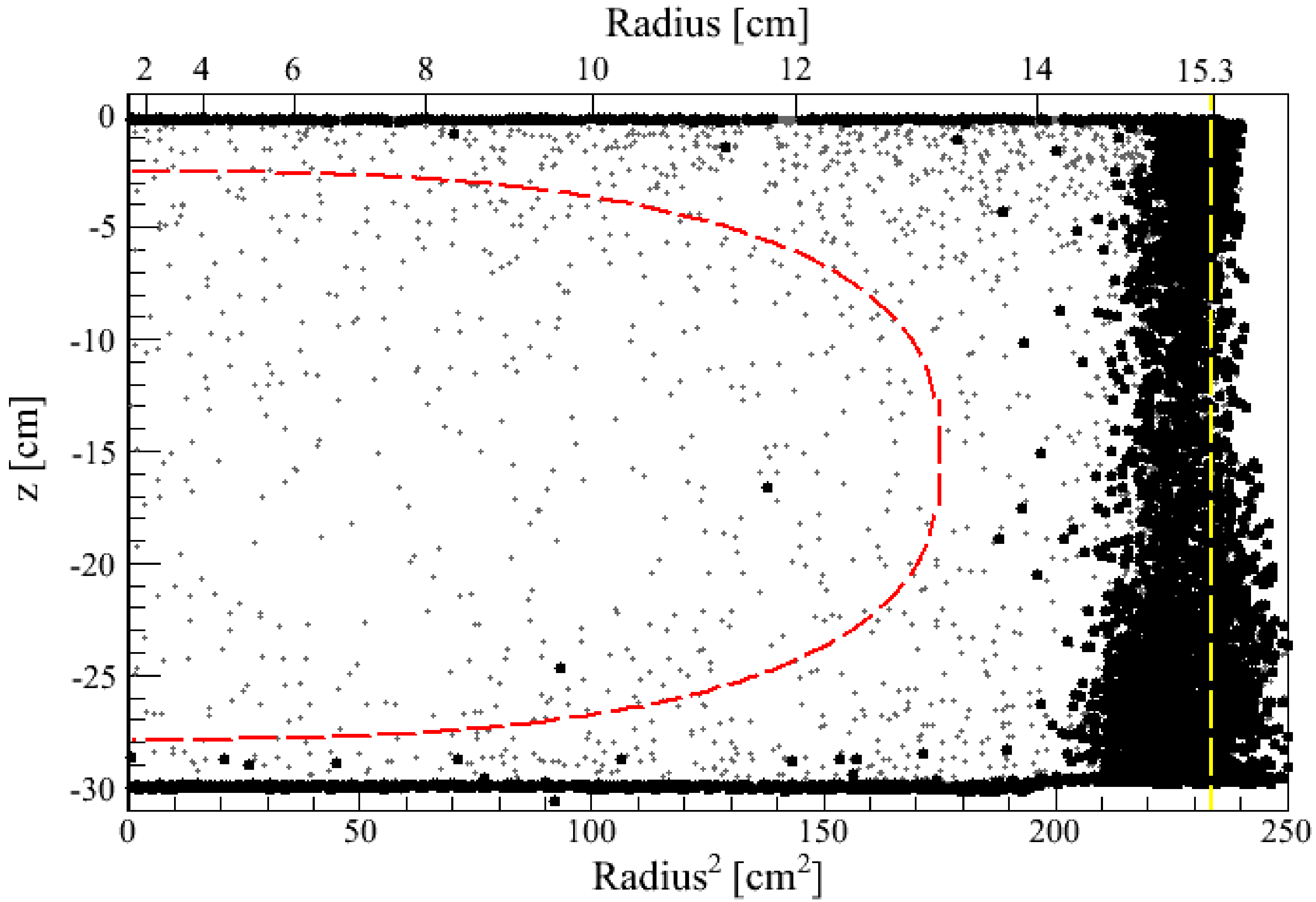
- The background expectation is computed from the calibration data
- The number of events in the signal region from ER calibration data is counted
- That number is scaled to the number of events in the non-blinded region
- An additional contribution from neutrons from the materials is added to the final number and scaled to the total exposure
- Background expectation: ER:(0.79 ± 0.16); NR: (0.17 + 0.12 -0.07); Total background: **(1.0 ± 0.2) events**

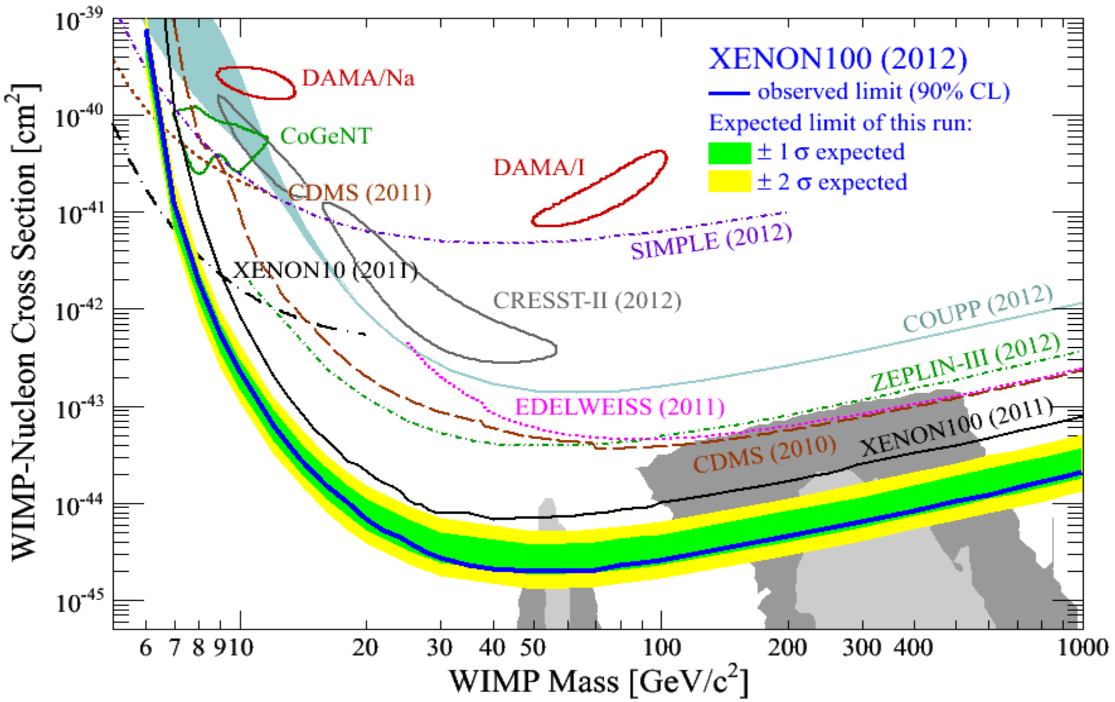
Unblinding results



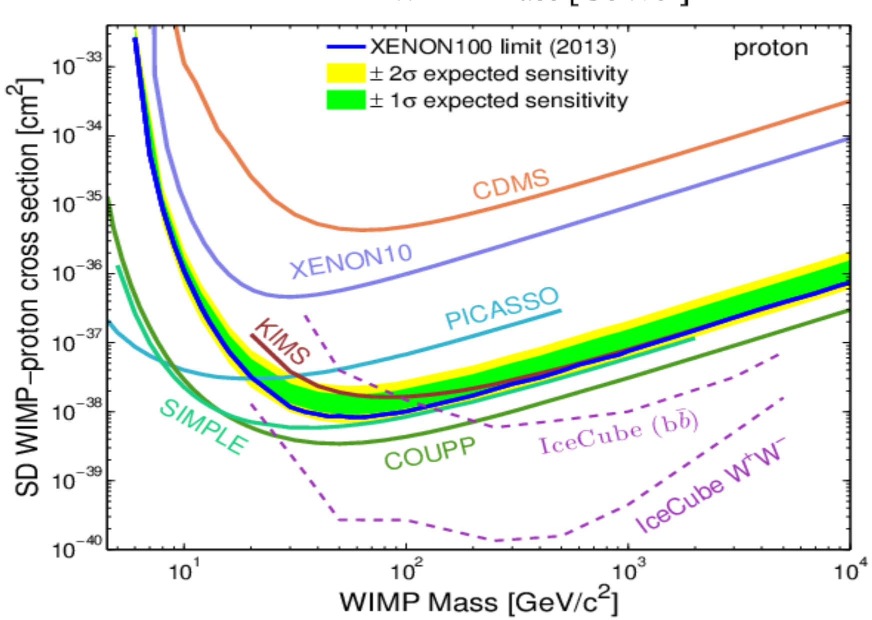
- 2 events observed in the signal region with (1.0±0.2) expected
- No events below the software threshold

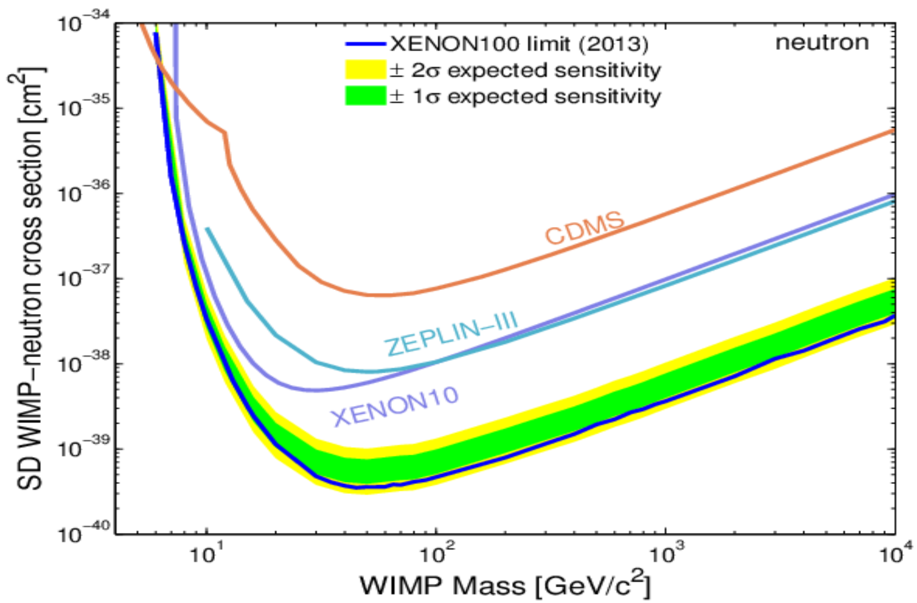
Unblinding results





SI, Phys. Rev. Lett. 109, 181301 (2012)

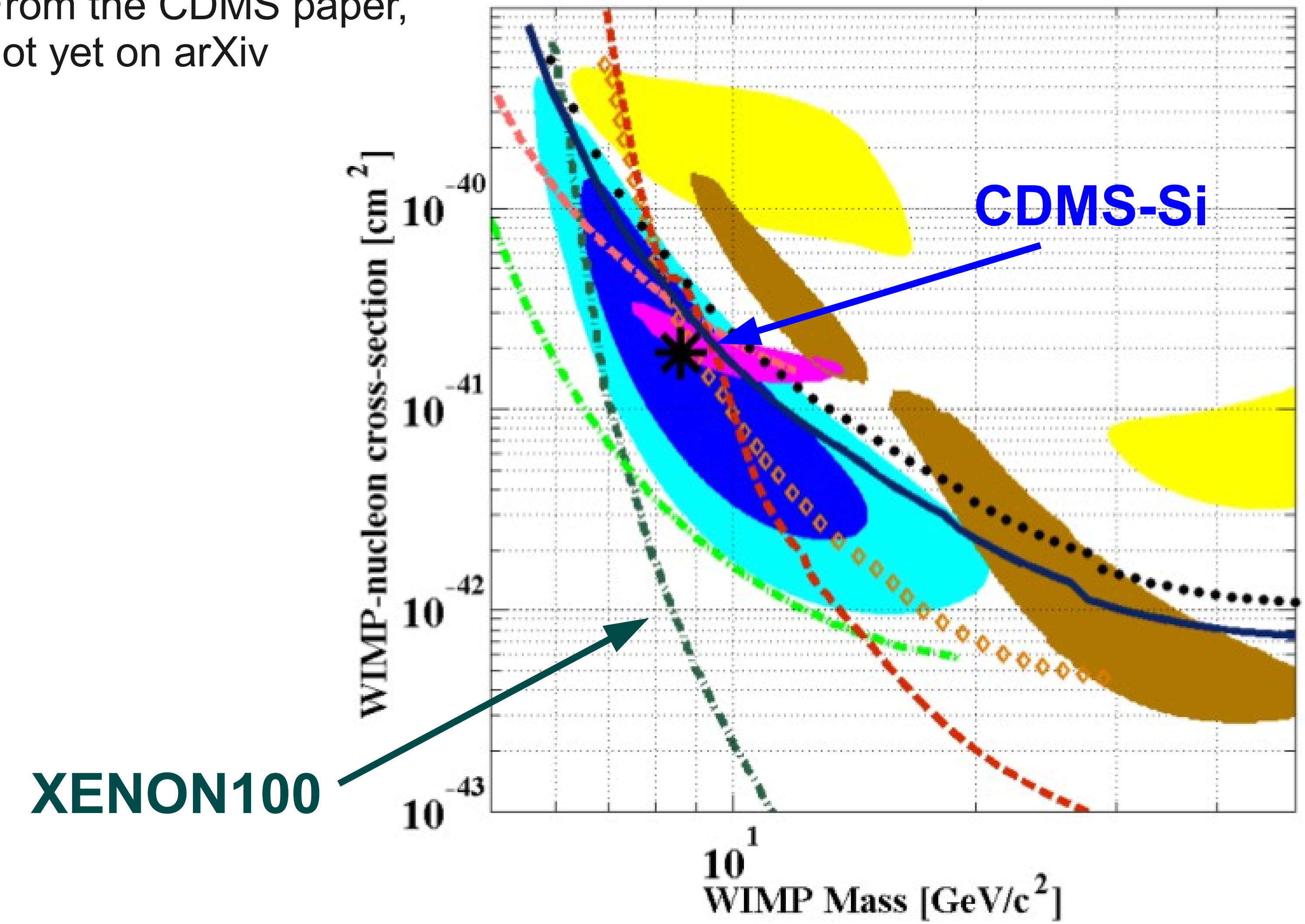




SD, arXiv:1301.6620

And then yesterday...

From the CDMS paper,
not yet on arXiv



Energy Scale and the meaning of Leff

- The energy deposit of a nuclear recoil is computed through the expression:

$$E_{nr} = \frac{S1}{L_y \cdot L_{eff}} \cdot \frac{S_e}{S_r}$$

- From that expression we can understand the meaning of Leff:

Light yield of the NR interaction

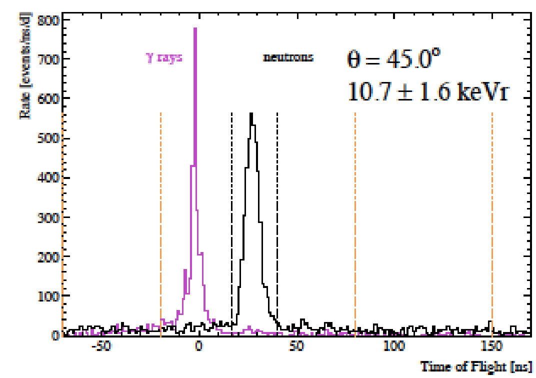
=1 at 0 field

$$L_{eff} = \frac{S1}{E_{nr}} \frac{1}{L_y} \cdot \frac{S_e}{S_r}$$

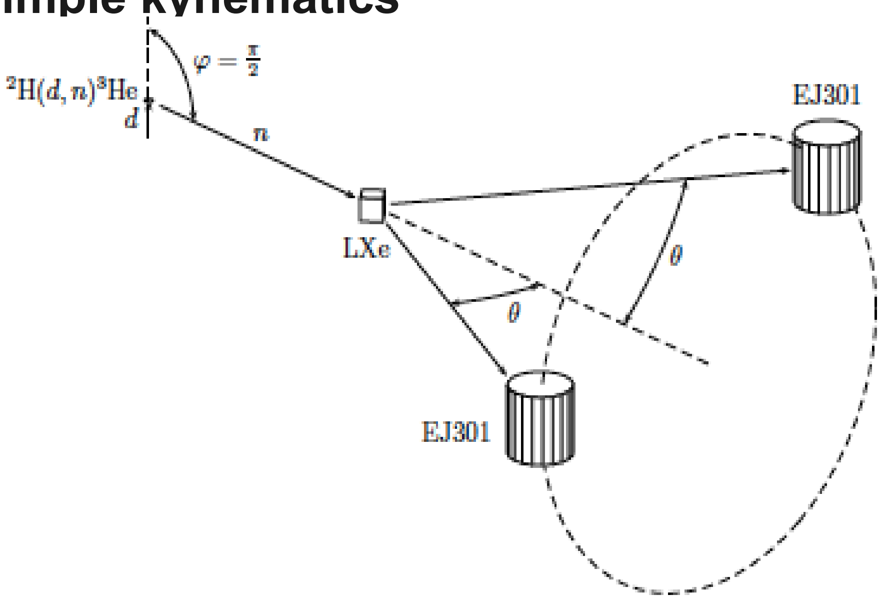
Light yield for gamma @122 keV

- Leff is the ratio of the scintillation yield for a nuclear recoil of given energy and the scintillation yield of an electronic recoil of 122 keV at 0 field
- It is a property of liquid xenon, it does NOT depend on the detector

Leff Measurement



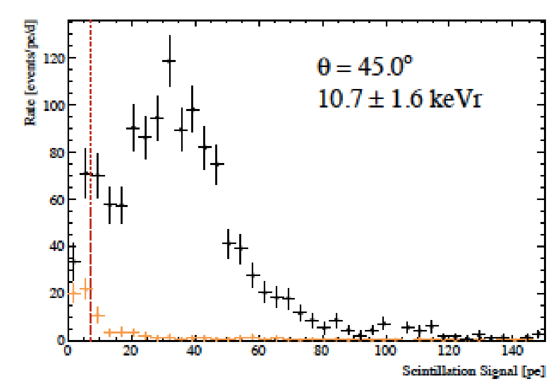
A dd neutron generator is used to produce an almost monoenergetic neutron beam. Following an interaction in our detector the energy of the Xe recoil atom can be computed from simple kynematics



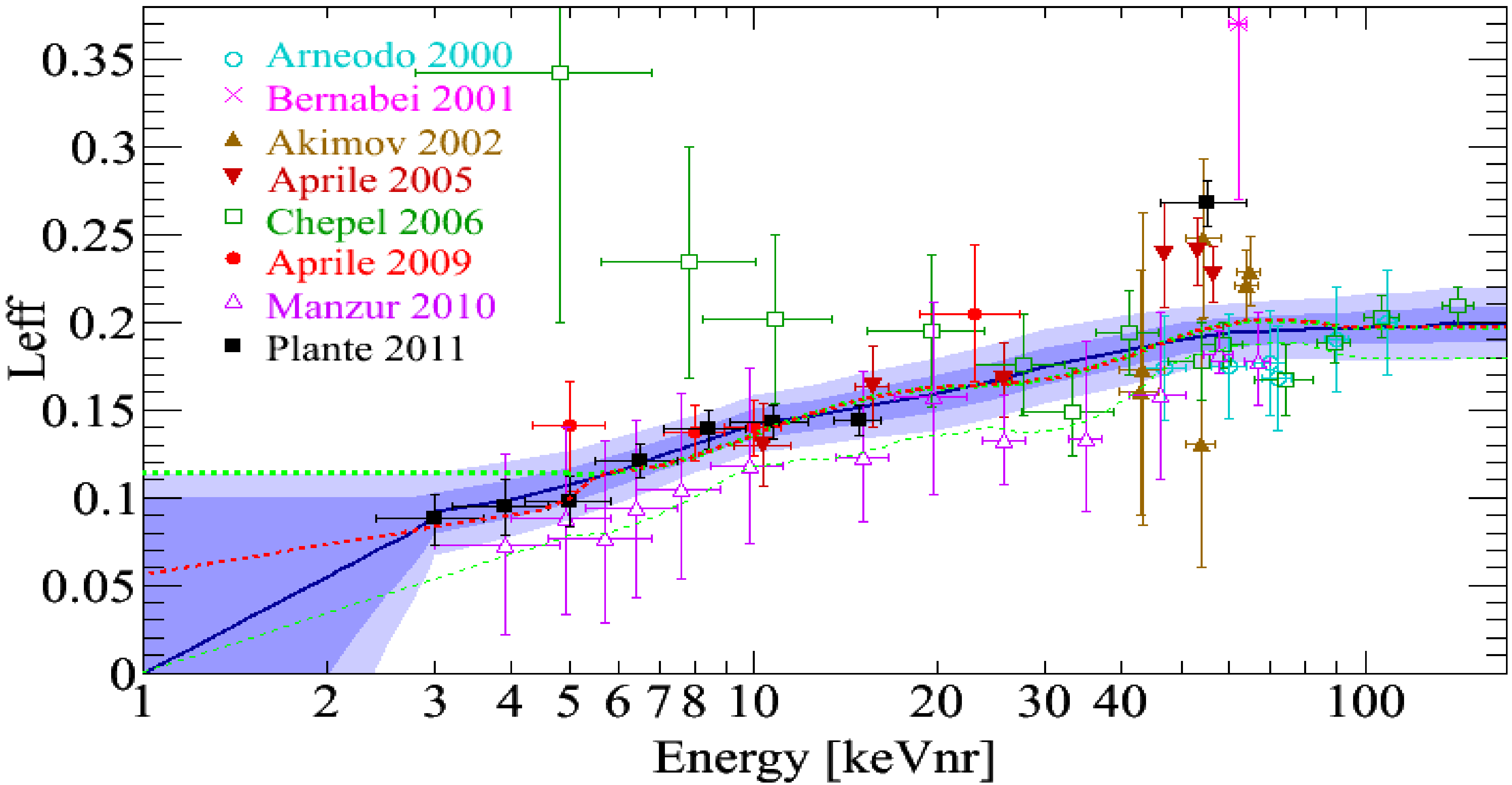
$$E_r \approx 2E_n \frac{m_n M_{Xe}}{(m_n + M_{Xe})^2}(1 - \cos\theta)$$

An interaction is accepted if an energy deposition is also registered in one of the scintillators
A TOF cut allows to select only those neutrons that don't interact in the detector materials

The average light is computed comparing the result of a detailed MC with the actual measurement



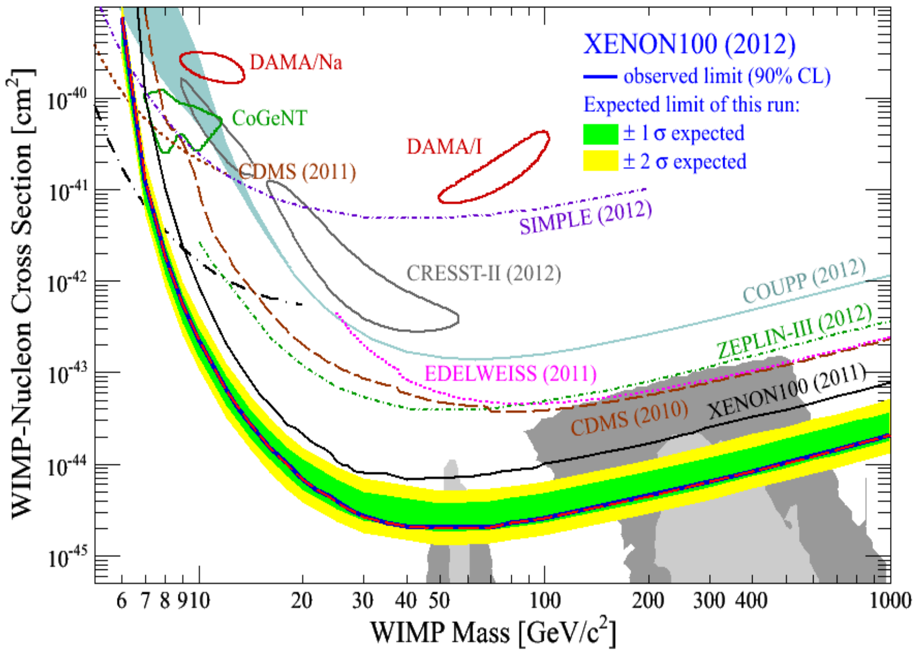
Leff Result

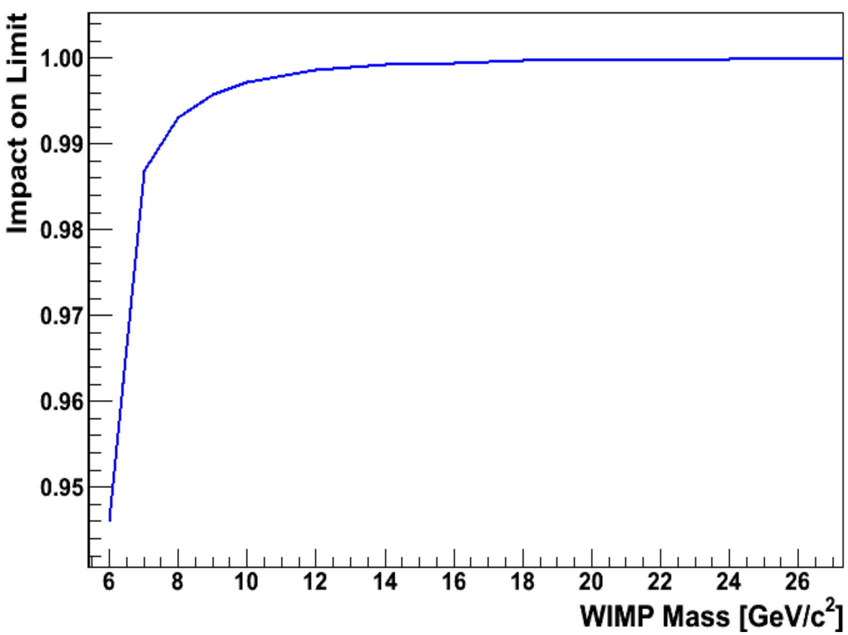


Phys.Rev. C84 (2011) 045805

Impact of Leff

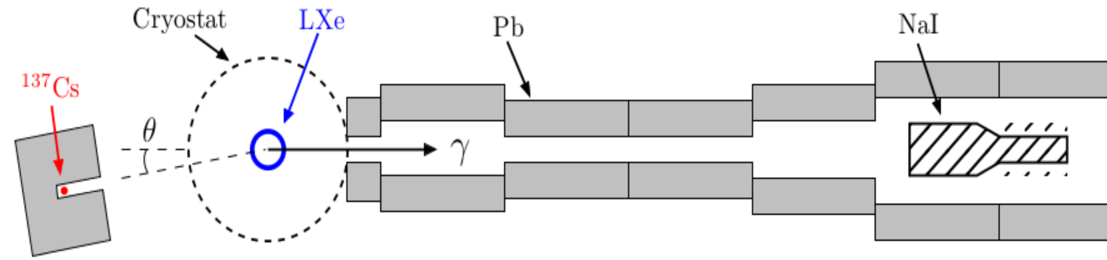
- As an excersise, we have computed the same limit with the approximation that Leff is 0 below 3 keVnr (red line in the figure)
- The impact on the limit is below 5% for all the relevant mass range

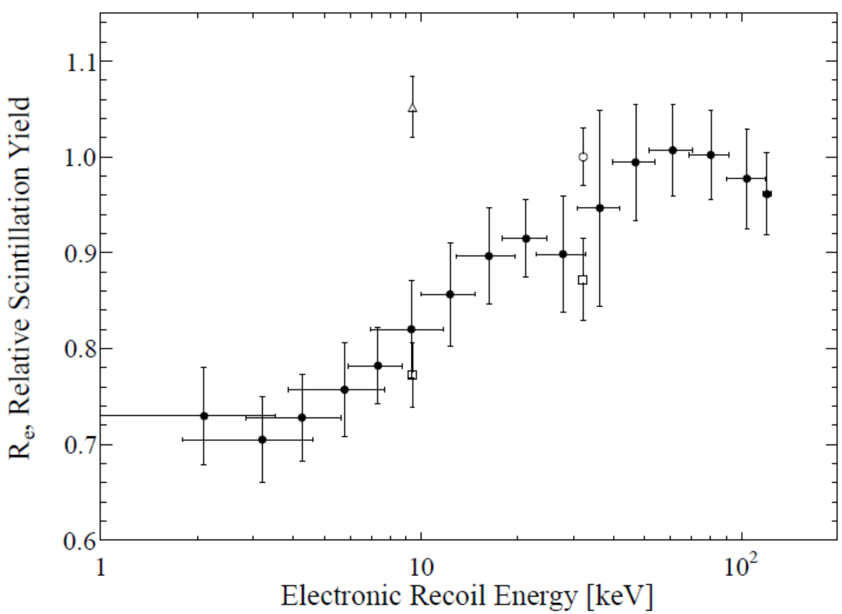


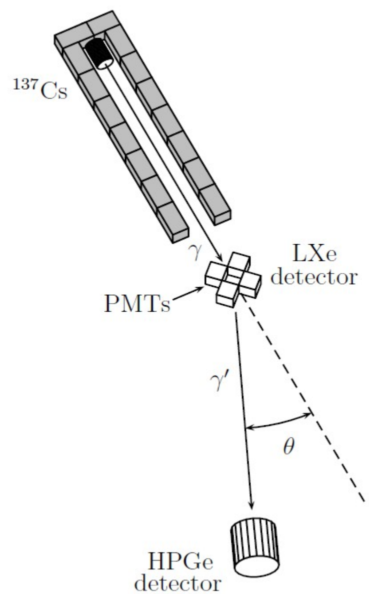


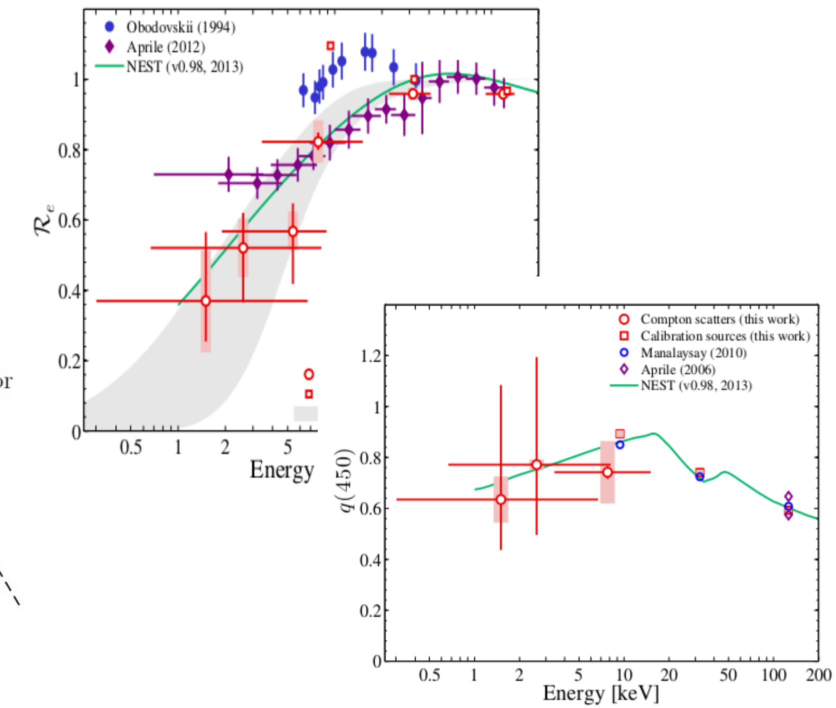
ER Energy scale

$$E_r = E_\gamma - \frac{E_\gamma}{1 + \frac{E_\gamma}{mc^2}(1 - cos\Theta)}$$









Columbia, Phys.Rev. D86 (2012) 112004

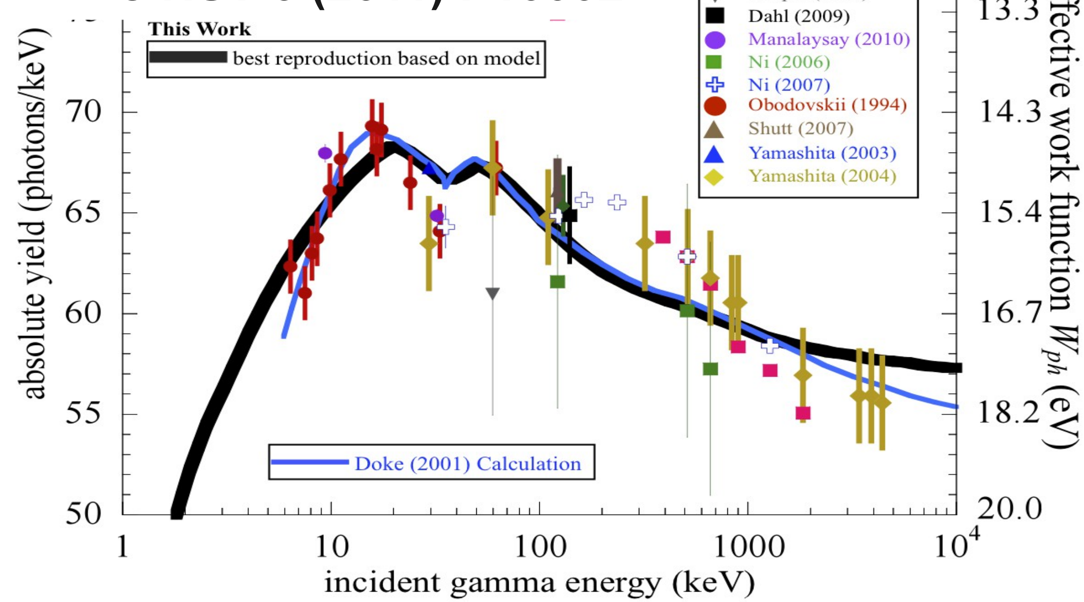
Zurich, arXiv:1303.6891

- **Needed for annual modulation studies**
- **Next: Measurements with different electric fields**

The meaning of below threshold fluctuations

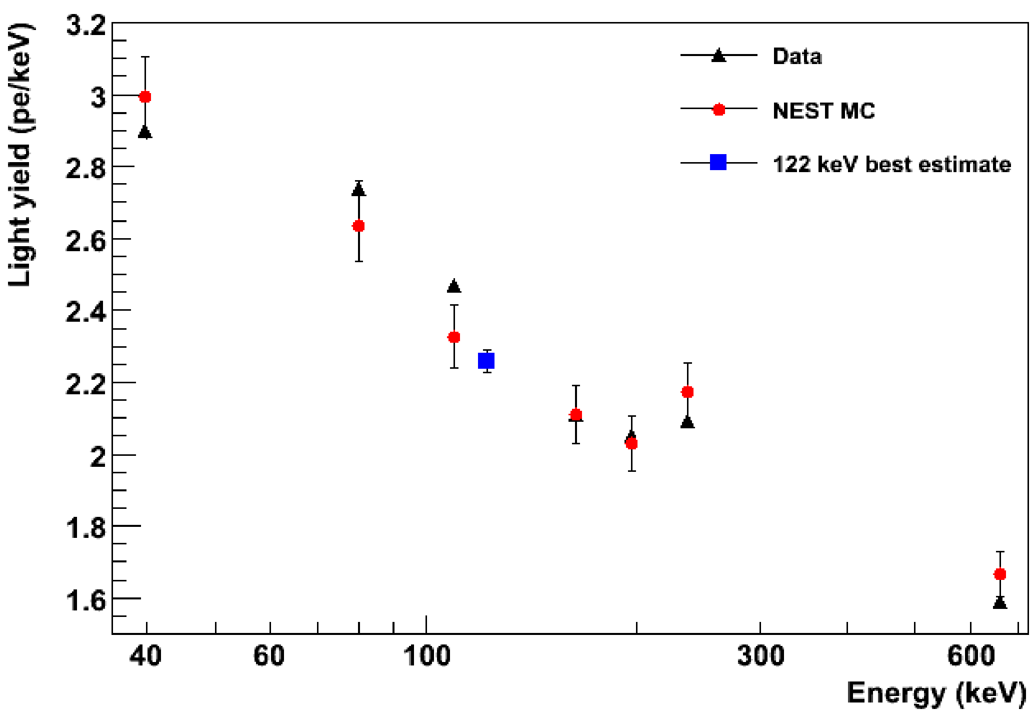
- For LXe the effective work function to create a photon in the absence of electric field is approximately 15.4 eV for a 122 keV electronic recoil
- This means that for 122 keV 7900 photons are created
- In the presence of a 0.53 kV/cm electric field the light quenching is 0.58
- Hence, in such an electric field only 4600 photons are produced

From Szydagis et al., JINST 6 (2011) P10002



The meaning of below threshold fluctuations

- In XENON100 we have a light yield of 2.28 pe/keV for 122 keV which means 278 pe detected on average
- With the ratio between these two numbers, we can see that the probability for detecting a photon in XENON100 is only ~6%

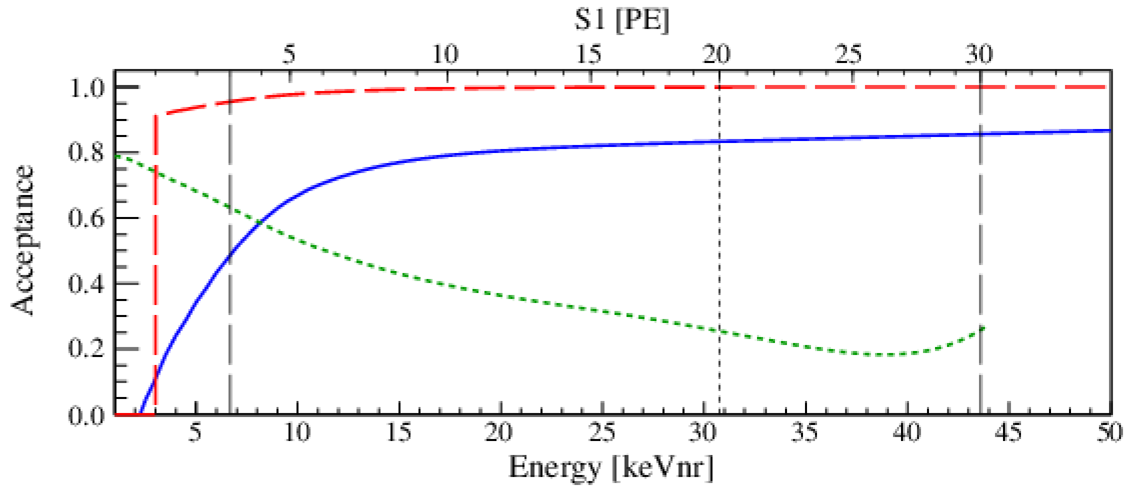


The meaning of below threshold fluctuations

- The measured value of Leff at 3keVnr is 0.092 (from XENON100 best fit)
- This means that for a 3 keV nuclear recoil we detect, on average, 1.03 pe (Note that the quenching factor for NR is 0.95)
- However, the number of photons generated is much larger (~17), and each of those has a probability of ~6% of being detected
- Hence, while on average we will detect 1.03 pe, we will have events in which the detected number of pe will be larger
- For simplicity, and since the probability for detecting a photon is low, we represent this process with a Poisson function
- Note that other effects as the Fano factor are not considered here

The meaning of below threshold fluctuations

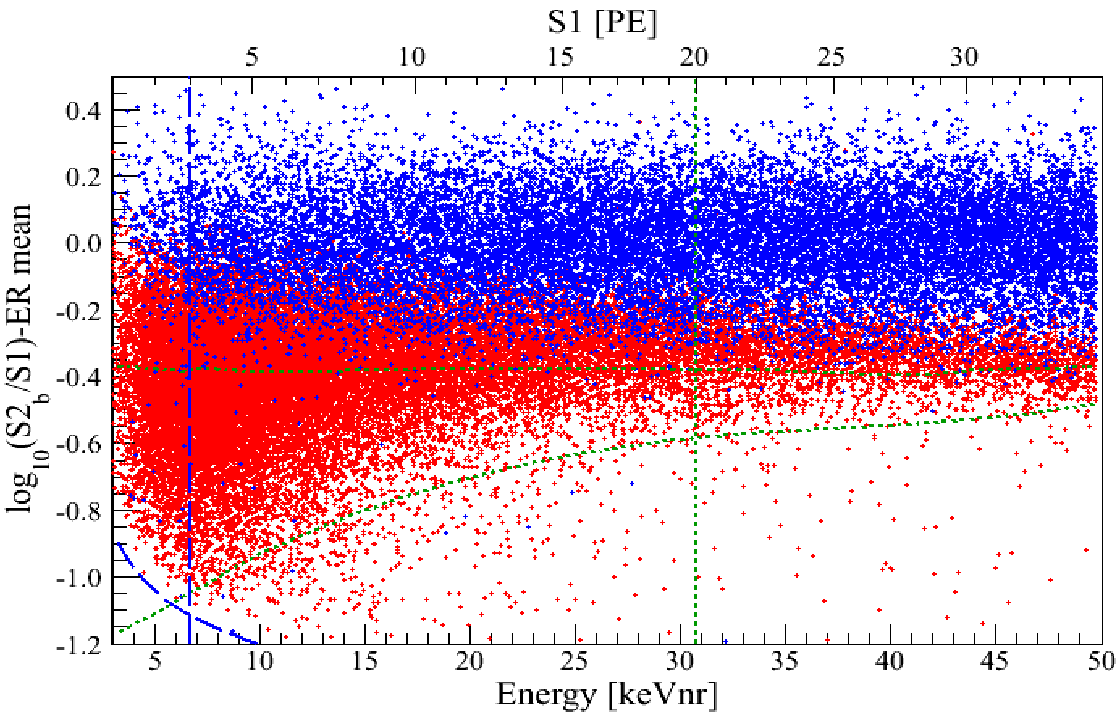
- All our cut efficiencies are also applied for these events, further reducing the detection probability
- S2 fluctuates independently from S1, i.e., if S1 happens to be over threshold this does not mean that S2 is larger too



- Hence, the value of the discrimination parameter, log(S2/S1), will be lower that for a more energetic recoil for which the same amount of light was detected
- The acceptance of the S2 signal is hence computed before S1 fluctuations. However, given the much better threshold for this run, the effect is much less important than in the previous one

AmBe Calibration

- "**Response of the XENON100 Dark Matter Detector to Nuclear Recoils**" (arXiv:1304.1427)
- The detector was calibrated with an AmBe source at the beginning of the 2011-12 run
- Neutron interactions should produce nuclear recoils indistinguishable from those of WIMPs
- By absolute data/MC matching, we were able to demonstrate that we understand the response of XENON100 to NRs down to 3 keVr

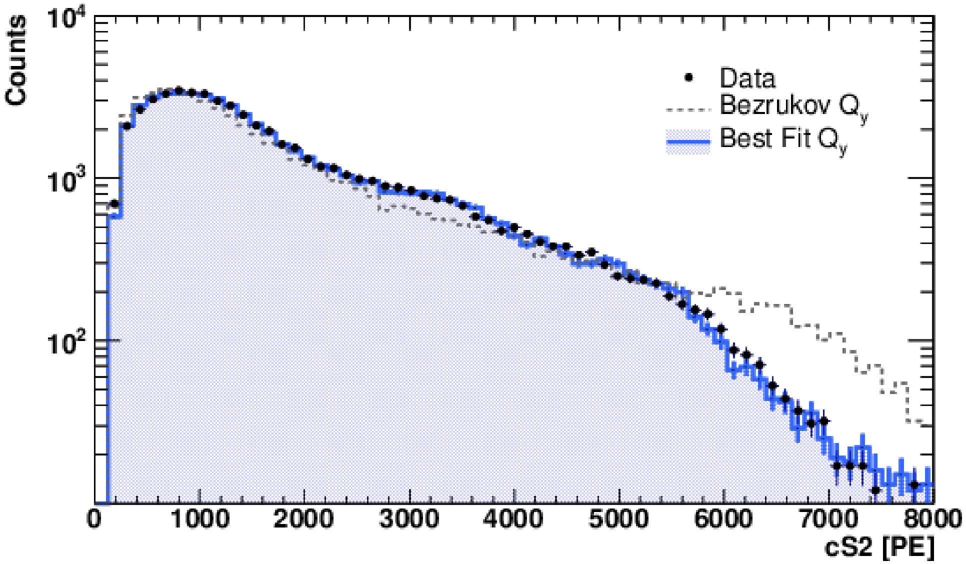


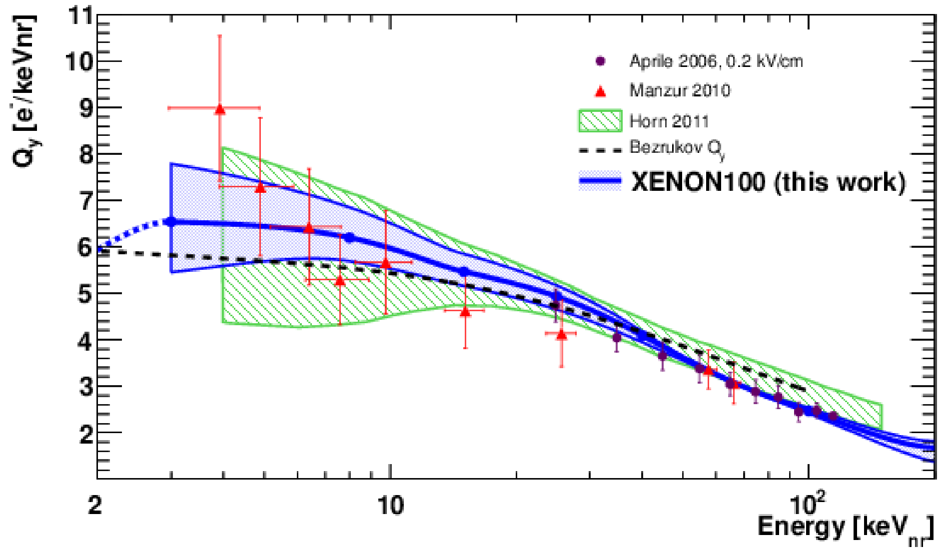
AmBe Analysis

- Steps in the analysis:
  - Using the Leff from the XENON100 analysis, try reproduce our S2 spectrum by getting the optimal Qy
  - Using the obtained Qy, reproduce our S1 spectrum and obtain a new Leff
  - Using the obtained Leff and Qy, make a simultaneous comparison of the band as a whole in S2 vs S1 space
- The analysis is performed adding into the MC the same efficiencies that we have in the data
- The activity of the used AmBe source has been measured at the Physikalisch-Technische Bundesanstalt (PTB), the German National Metrology Institute, in August 2012. The measured strength is (160±4) n/s

S2 spectrum matching

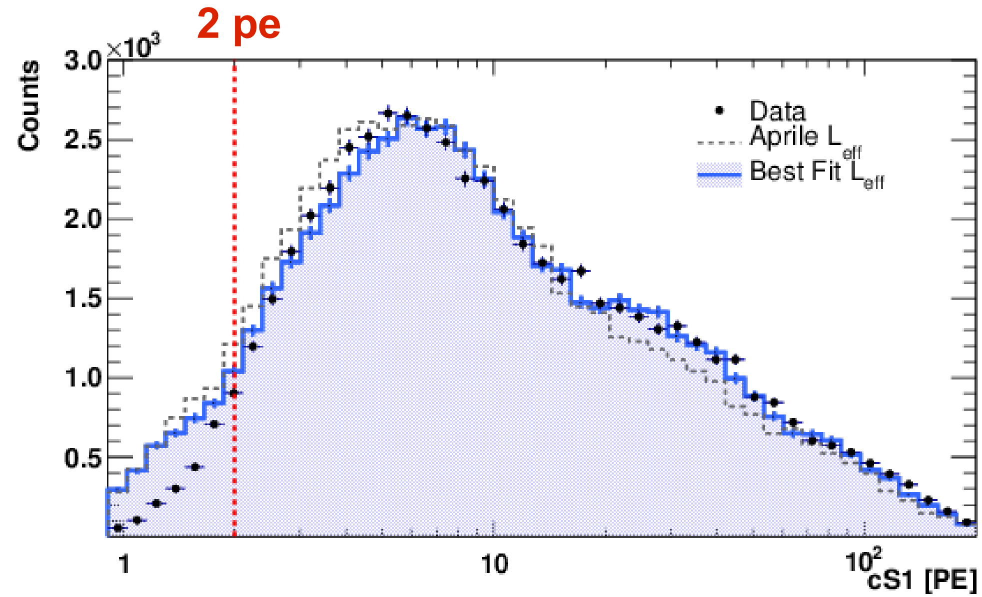
- The energy spectrum of the interactions in the detector is obtained from a GEANT4 simulation
- For each event the number of generated electrons is computed from Qy
- Poisson fluctuations on this number are then applied. Then the electron attenuation due to impurities and PMT response are applied
- Qy is changed until the best fit is obtained

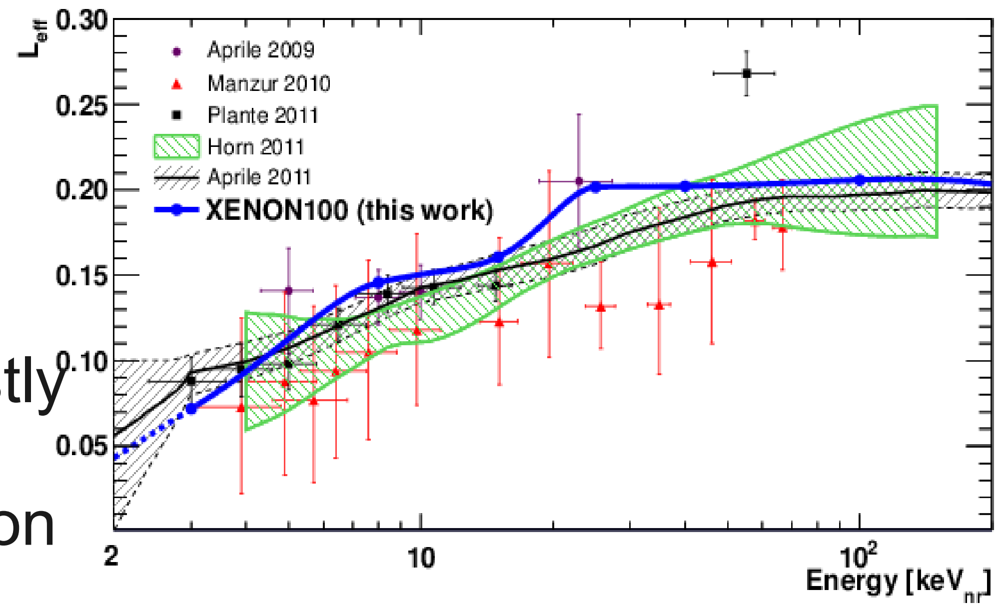




S1 spectrum matching

- For every event the energy is converted into an observed number of pe using Leff
- The number of detected pe is poisson smeared and then “uncorrected” for position dependence. PMT resolution is finally applied
- Good overall agreement. Best fit Leff matches very well previous measurements
- Poor agreement below 2 pe, mostly due to bad knowledge of the efficiencies and detector calibration near hardware threshold

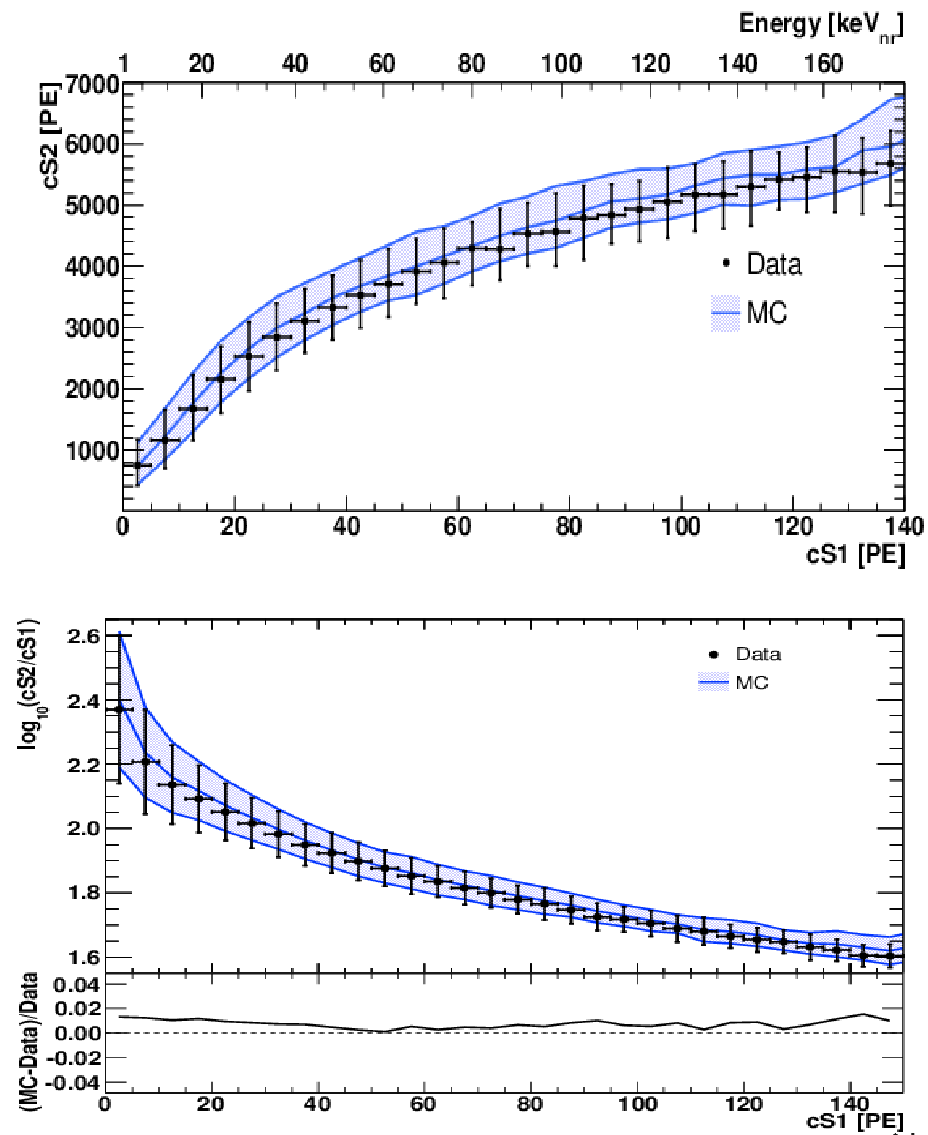




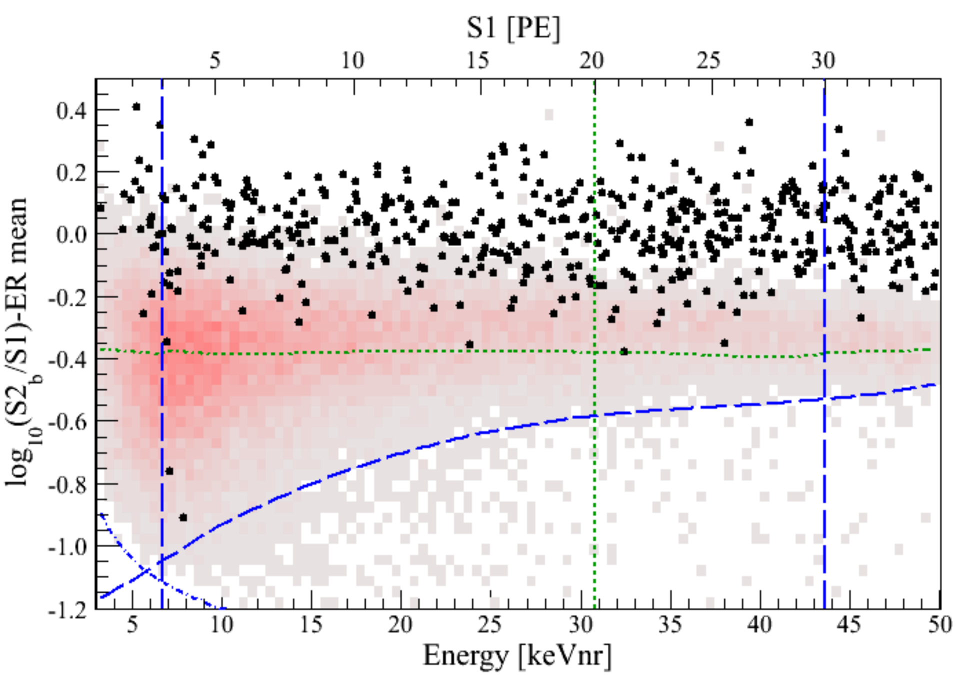
Errors from Manzur are over-quoted

S2-S1 simultaneous matching

- Provides a robust consistency test
- Simultaneously sensitive to Leff and Qy
- Very good consitency between the results: disagreements at the 2% level
- Impact of neutron-X events needs to be studied
- Overall, our MonteCarlo model of neutron interactions can explain the observed distributions in S2 and S1
- Best matching is achieved for 159 n/s (measured (160±4) n/s)

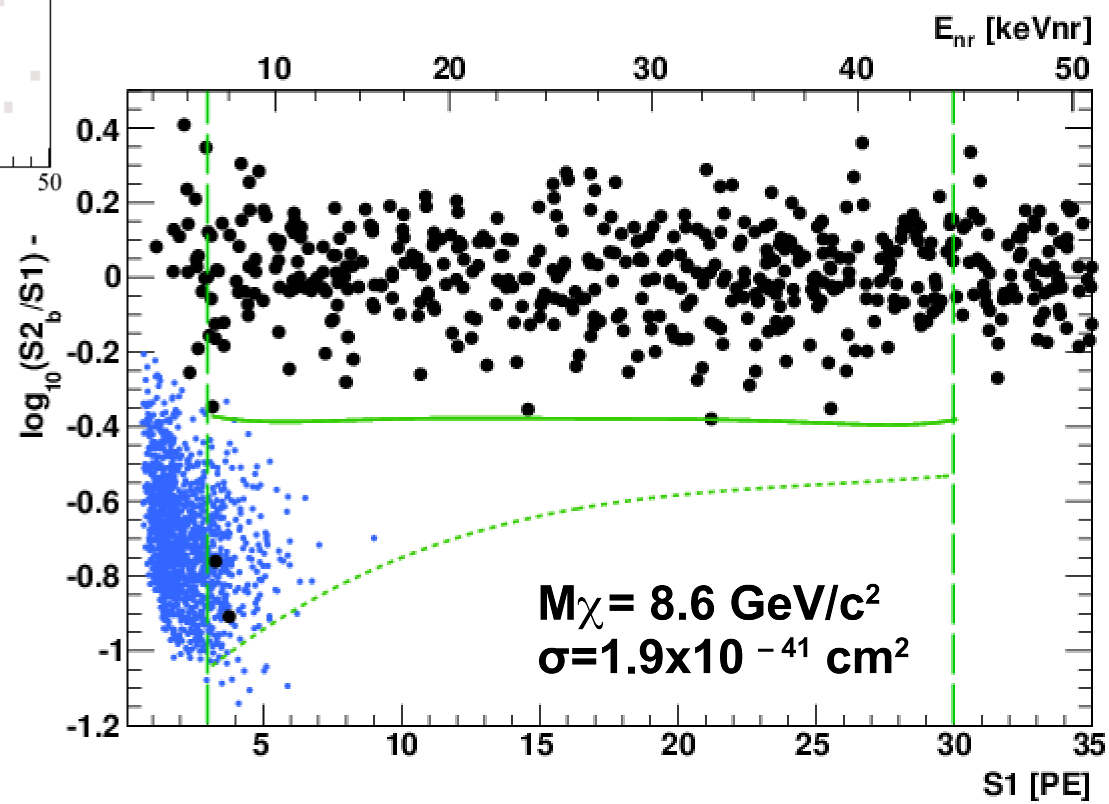


How does a low mass WIMP looks like in XENON100?



What we see

What we would expect



Future work

- We are still analyzing the XENON100 data from 2012. This is a list of ongoing analyses:
  - Response of the detector to single electrons
  - Annual modulation
  - Low mass dark matter
  - Sub-GeV dark matter
- At the same time, XENON100 will resume science data taking in the next few days. Internal backgrounds have been further reduced
- Plan to calibrate the detector with new sources: Kr83m, YBe, DD Neutron generator
- Construction of XENON1T about to begin

Conclusions

- XENON100 has been taking data since 2009
- Up to now, 2 runs completed with exposure over 100 days in each of them
- No evidence for the presence of dark matter
- Best limit for a WIMP mass of 55 GeV and a cross section of $2x10^{-45}cm^2$
- Some sensitivity at low masses. The results in that region are in tension with some other experiments
- Very good matching of the AmBe data and MC achieved