Status of the XENON100 Dark Matter Search

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on behalf of the XENON Collaboration

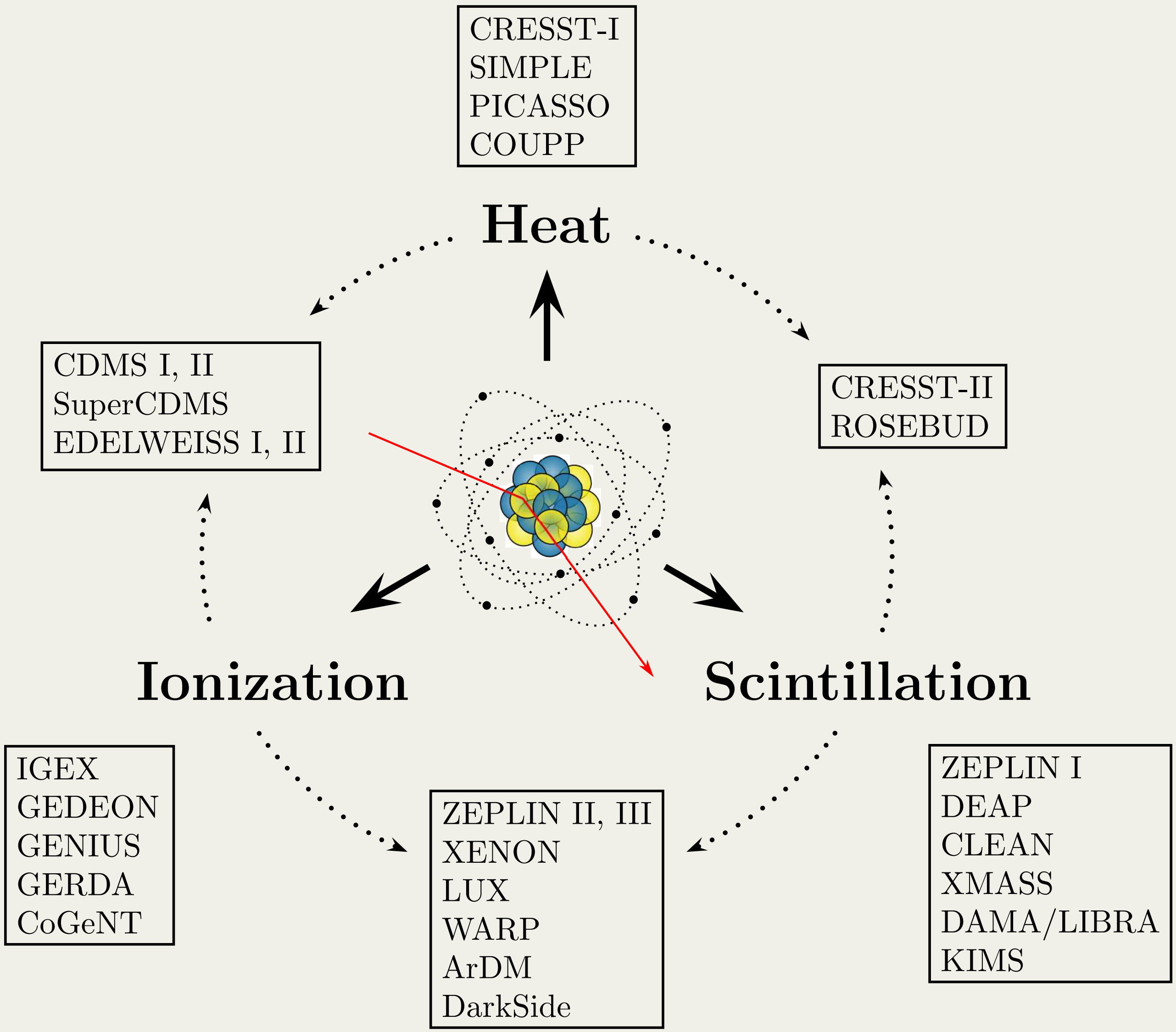
Exploring Low-Mass Dark Matter Candidates - PITT PACC - November 14-16, 2011

XENON100 Collaboration

Columbia · Rice · UCLA · Zurich · Coimbra · LNGS · SJTU

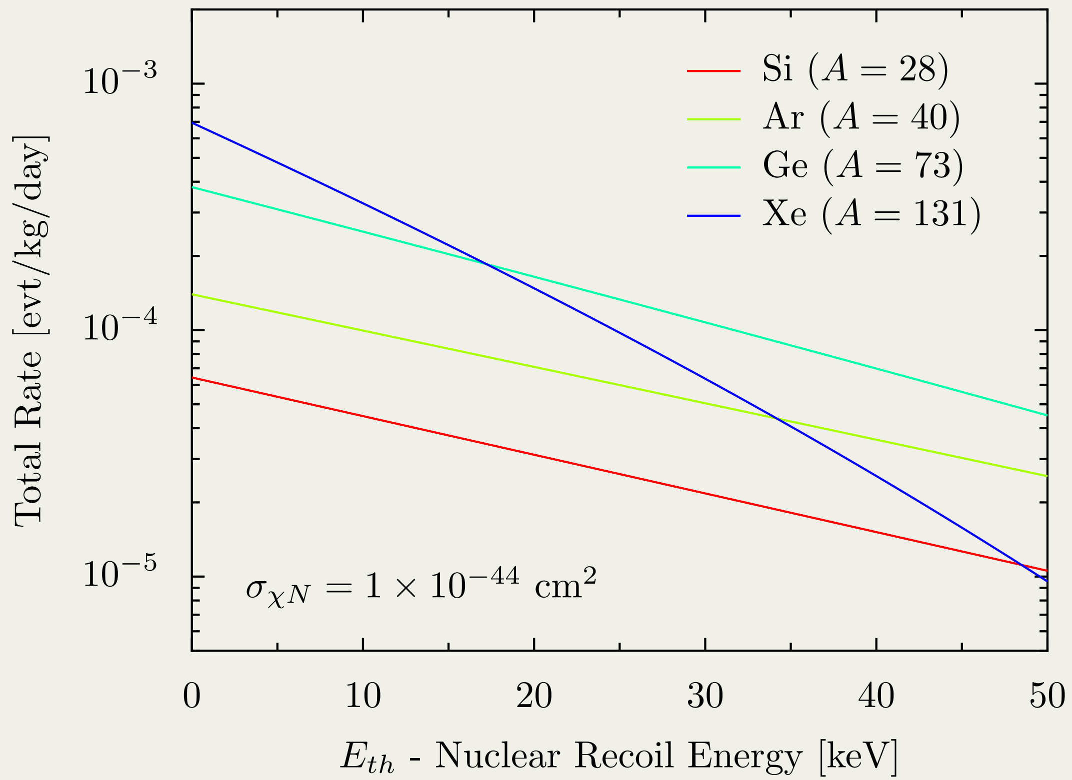
Mainz · Bologna · MPIK · NIKHEF · Subatech · Münster · WIS

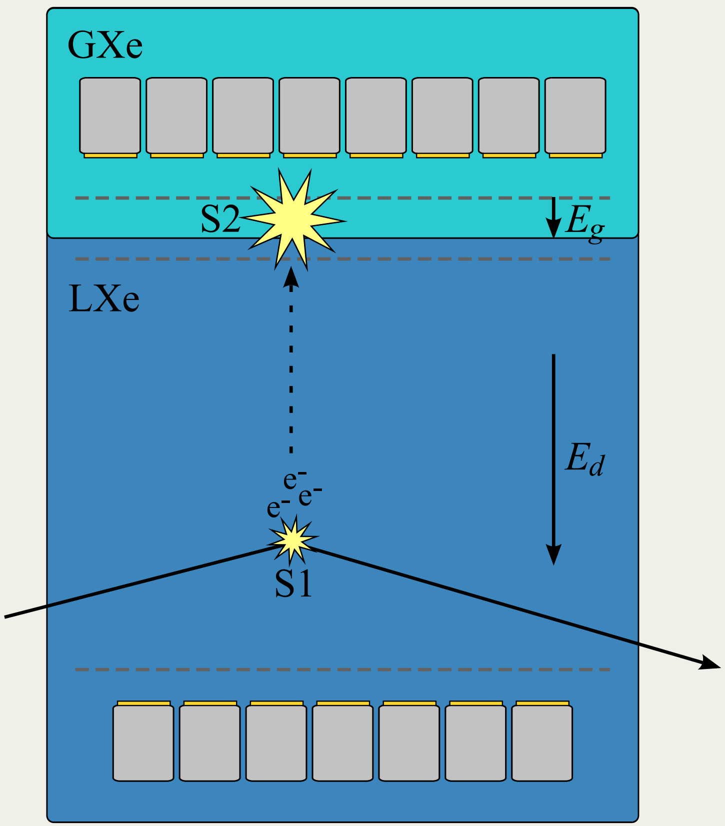
Direct Detection

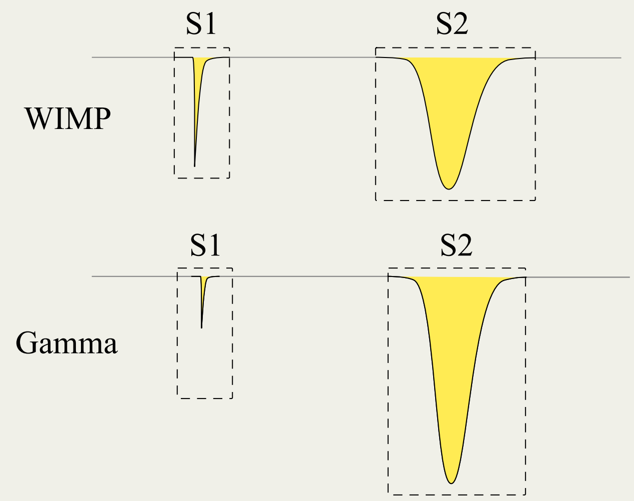


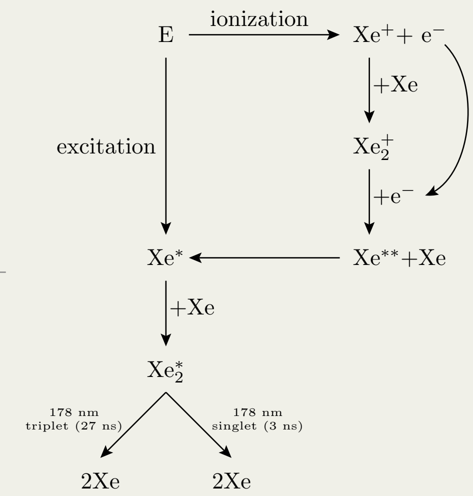
Why Xenon?

- Large mass number A (∼131), expect high rate for SI interactions ($\sigma \sim A^2$) if energy threshold for nuclear recoils is low
- ∼50% odd isotopes ($^{129}\mathrm{Xe}$, $^{131}\mathrm{Xe}$) for SD interactions
- No long-lived radioisotopes, Kr can be reduced to ppt levels
- High stopping power ($Z = 54$, $\rho = 3\,\mathrm{g\,cm^{-3}}$), active volume is self shielding
- Efficient scintillator (∼80% light yield of NaI), fast response
- Scalable to large target masses
- Nuclear recoil discrimination with simultaneous measurement of scintillation and ionization



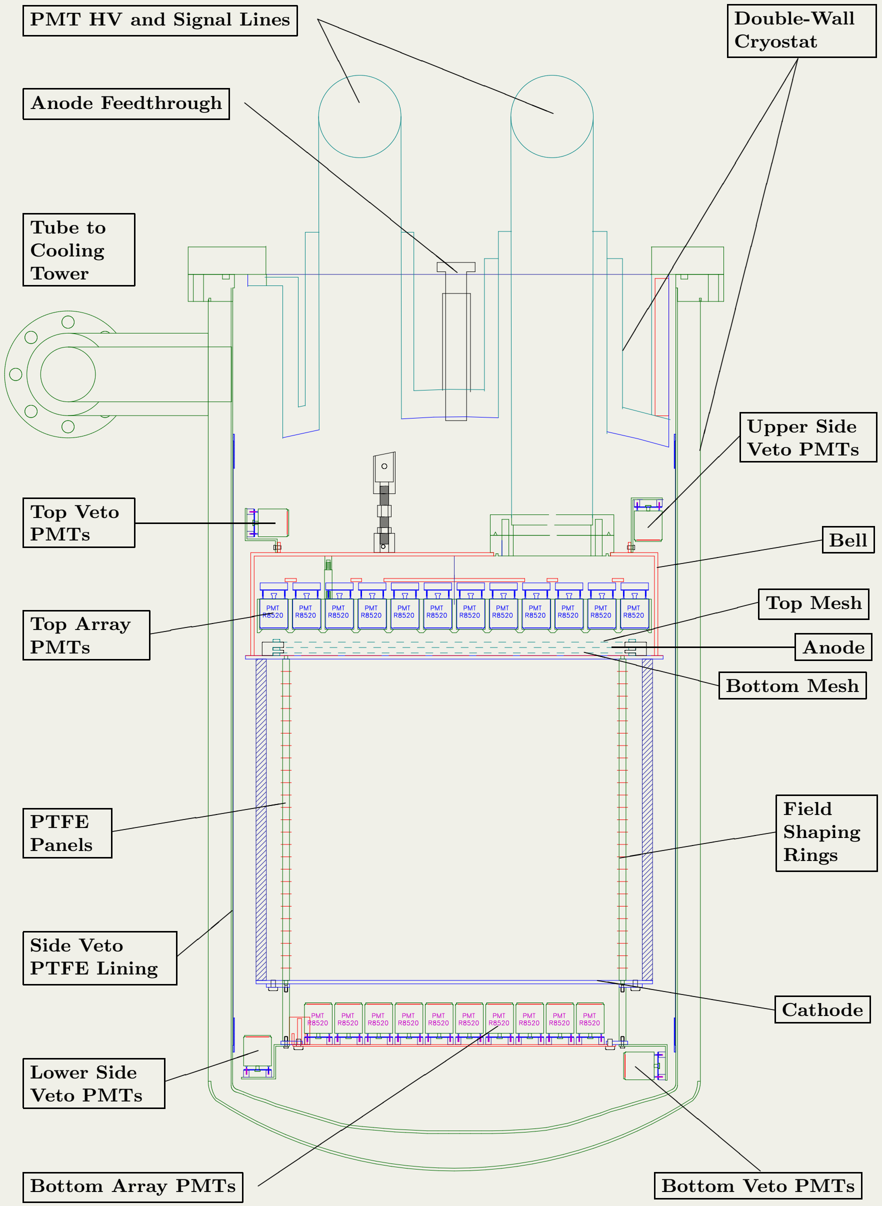






- Bottom PMT array below cathode, fully immersed in LXe to efficiently detect scintillation signal (S1).
- Top PMTs in GXe to detect the proportional signal (S2).
- Distribution of the S2 signal on top PMTs gives xy coordinates ($\Delta r < 3\,\mathrm{mm}$) while drift time measurement provides z coordinate ($\Delta z < 300\,\mu\mathrm{m}$) of the event.
- Ratio of ionization and scintillation (S2/S1) allows discrimination between electron and nuclear recoils.

XENON100: Design



- Goal was to build a detector with a $\times 10$ increase in fiducial mass and a $\times 100$ reduction in background compared to XENON10.
- All detector materials and components were screened in a dedicated low-background counting facility
- 161 kg LXe total mass consisting of a 62 kg target surrounded by a 99 kg active veto. 15 cm radius, 30 cm drift length active volume.
- TPC inner volume defined by 24 interlocking PTFE panels. Drift field uniformity ensured by 40 double field shaping wires, inside and outside the panels.
- Cathode at -16 kV, drift field of 0.533 kV/cm. Anode at 4.5 kV, proportional scintillation region with field $\sim$12 kV/cm. Custom-made low radioactivity HV feedthroughs.
- Aprile *et al.*, `arXiv:1107.2155`

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Xe
XENON
Dark Matter Project

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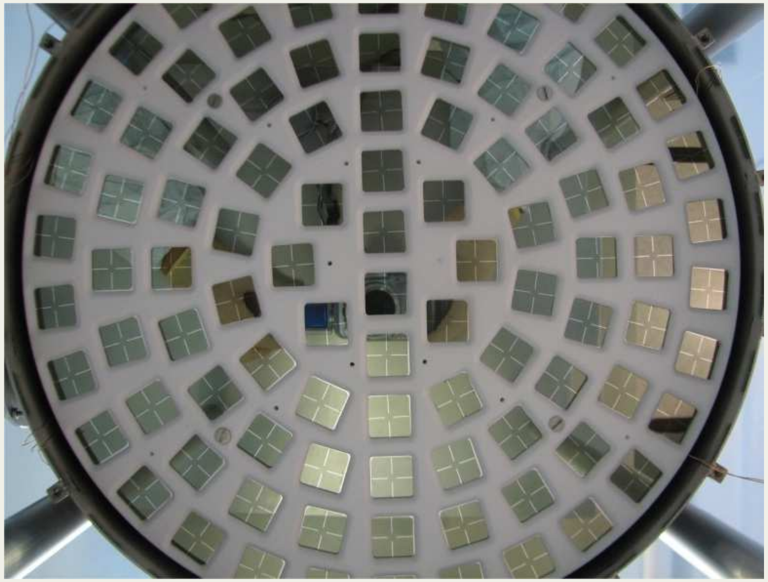
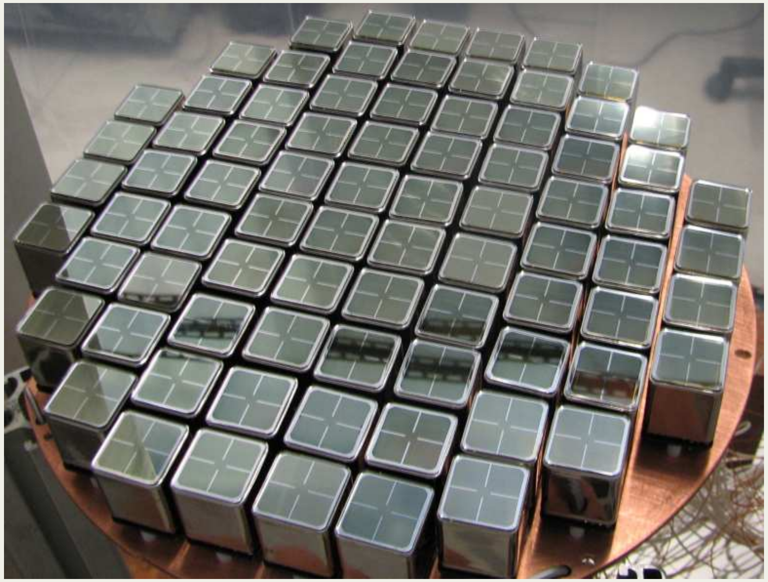
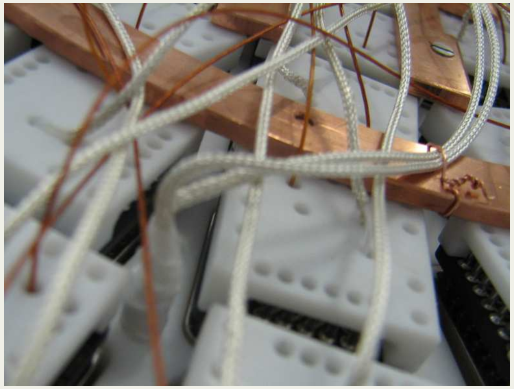
XENON100: PMT Arrays

- 242 low activity Hamamatsu R8520-06-Al 1" square PMTs,
- 98 tubes on top (QE ~23%), in concentric circles and enclosed in a PTFE structure,
- 80 high QE (~33%) tubes on bottom, on a rectangular grid to maximize photocathode coverage,
- 64 tubes in the LXe veto, in two rings, alternating inward and down (up) to allow them to view the top, bottom and sides of the veto volume.



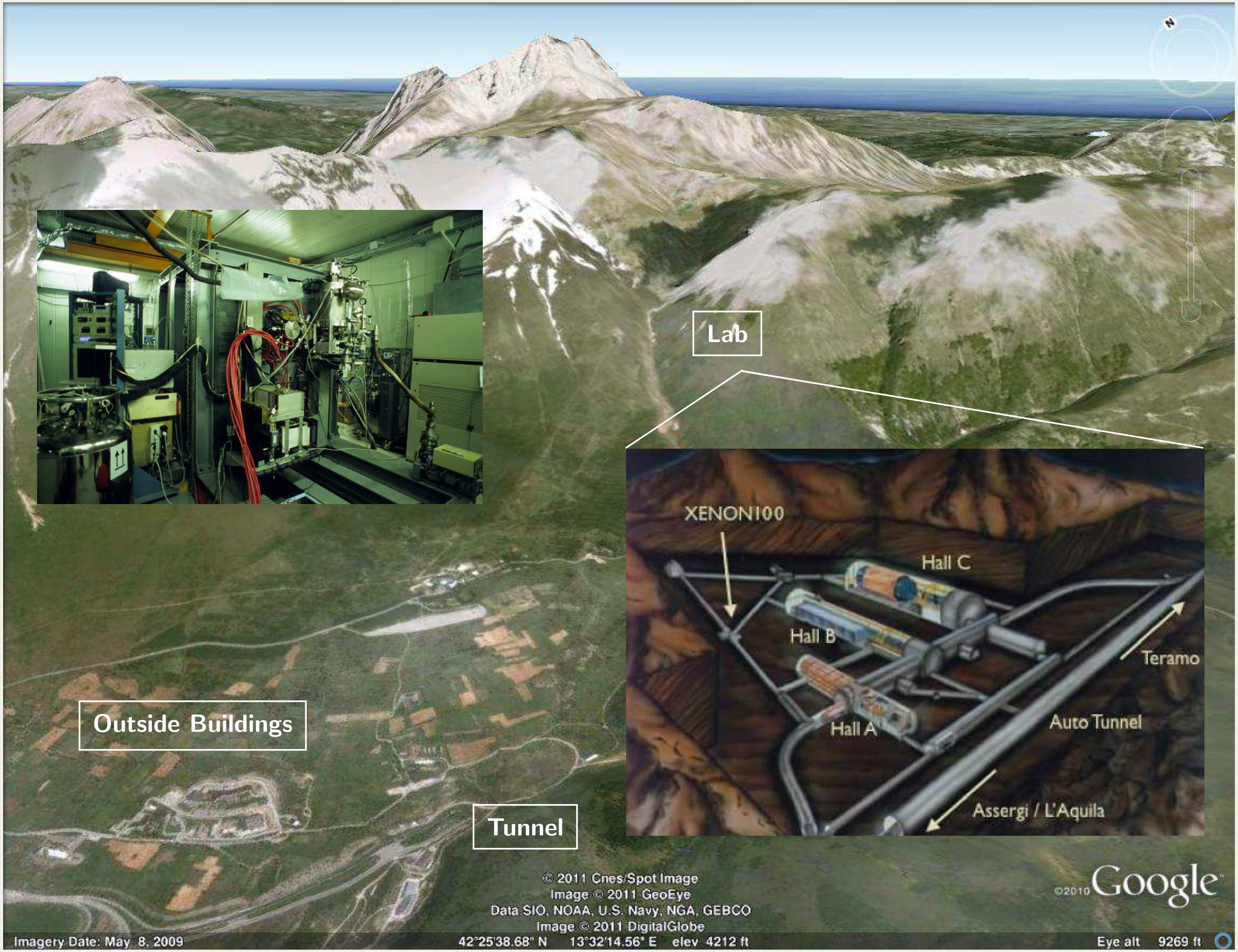




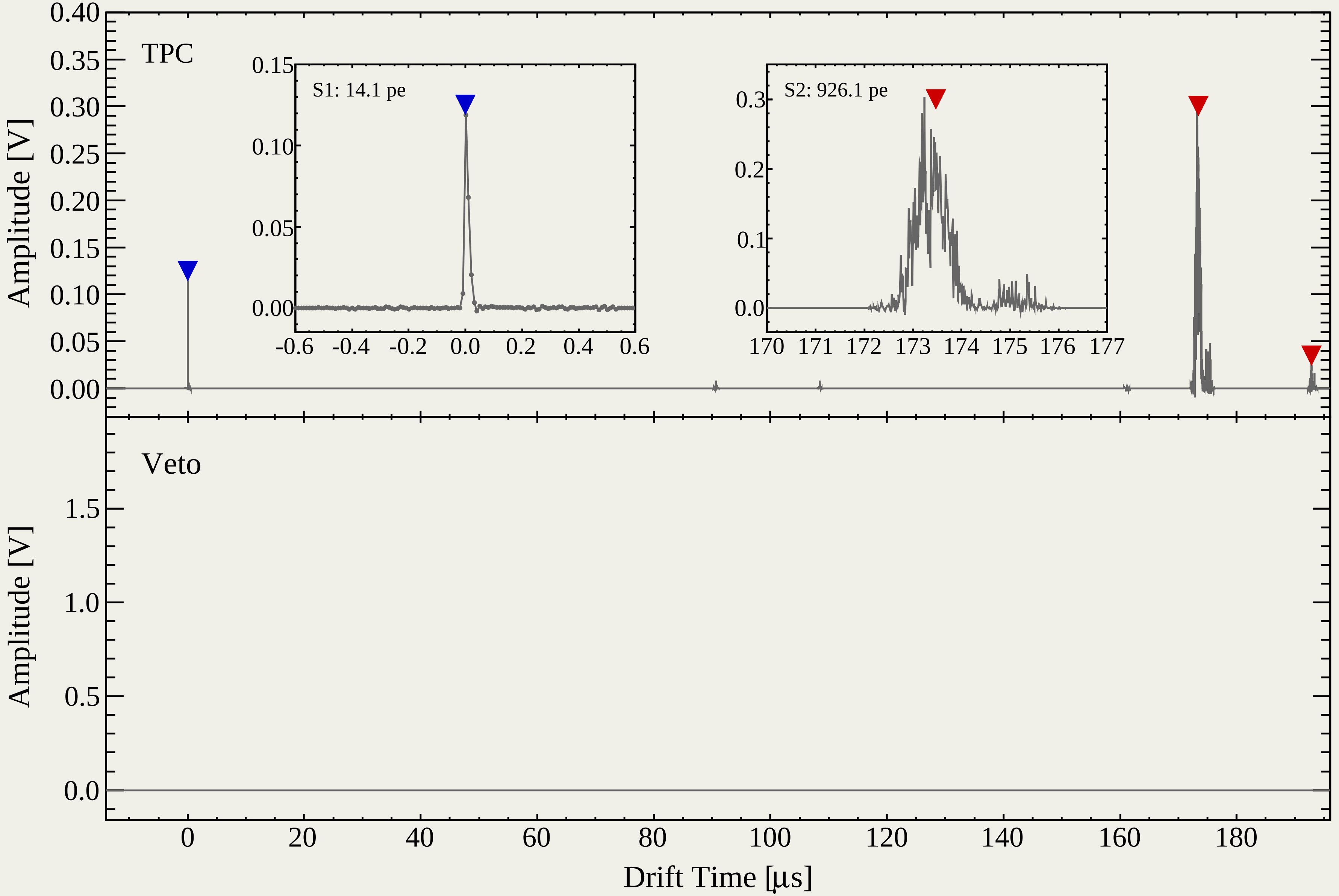
XENON100: Shield

- XENON100 installed in a passive shield to suppress external backgrounds:
  - 20 cm of H_2O to moderate neutrons produced in the cavern rock
  - 20 cm Pb (inner 5 cm with low radioactivity Pb) to stop gamma rays
  - 20 cm polyethylene to moderate neutrons produced in the Pb
  - 5 cm Cu to stop gamma rays from the polyethylene
  - Shield cavity continuously purged with N_2 to keep $^{222}\mathrm{Rn}$ level $< 1\,\mathrm{Bq/m^3}$.

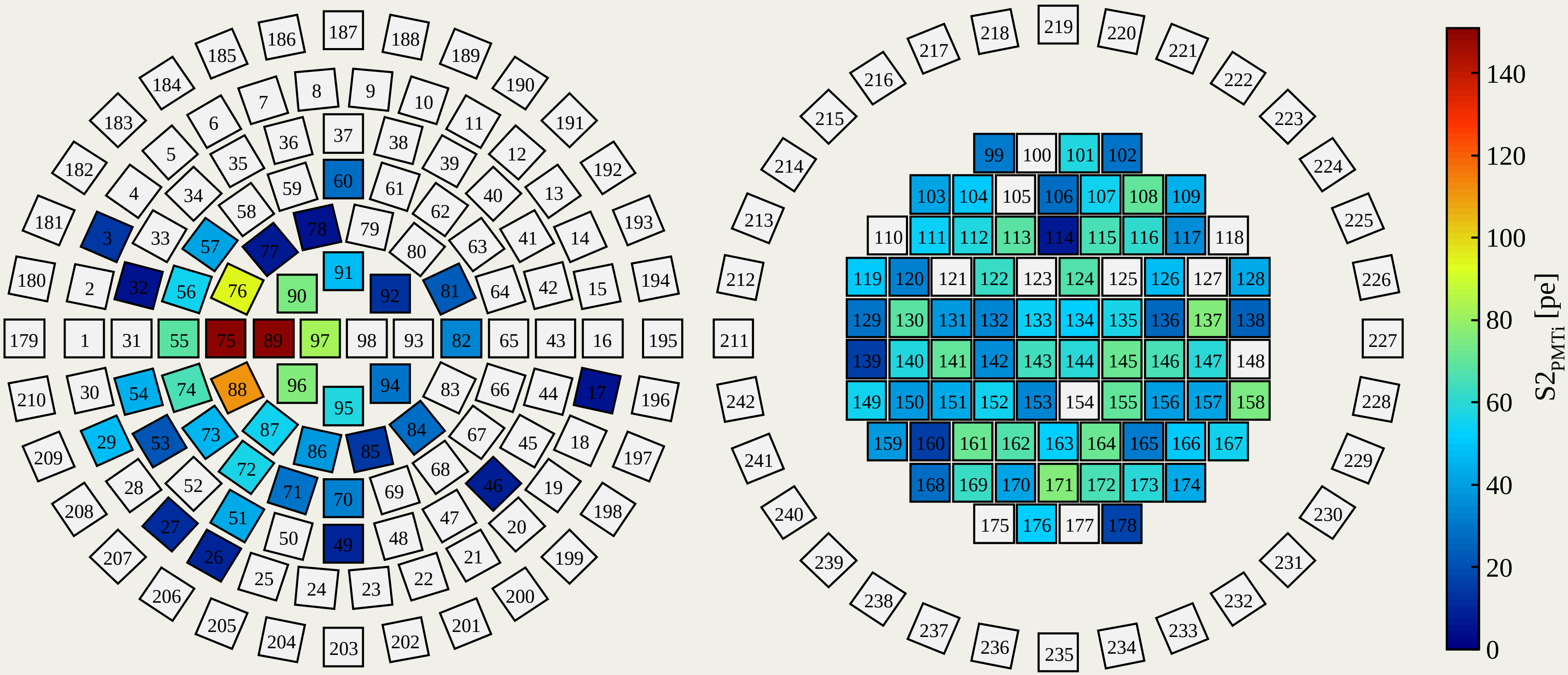
XENON100: Gran Sasso



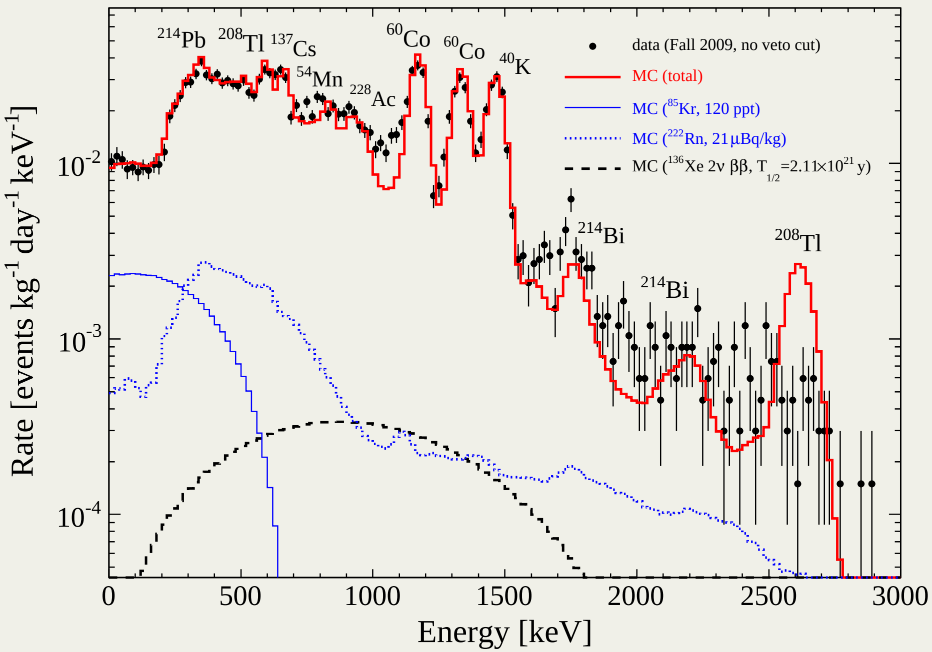
XENON100: Typical Low Energy Event

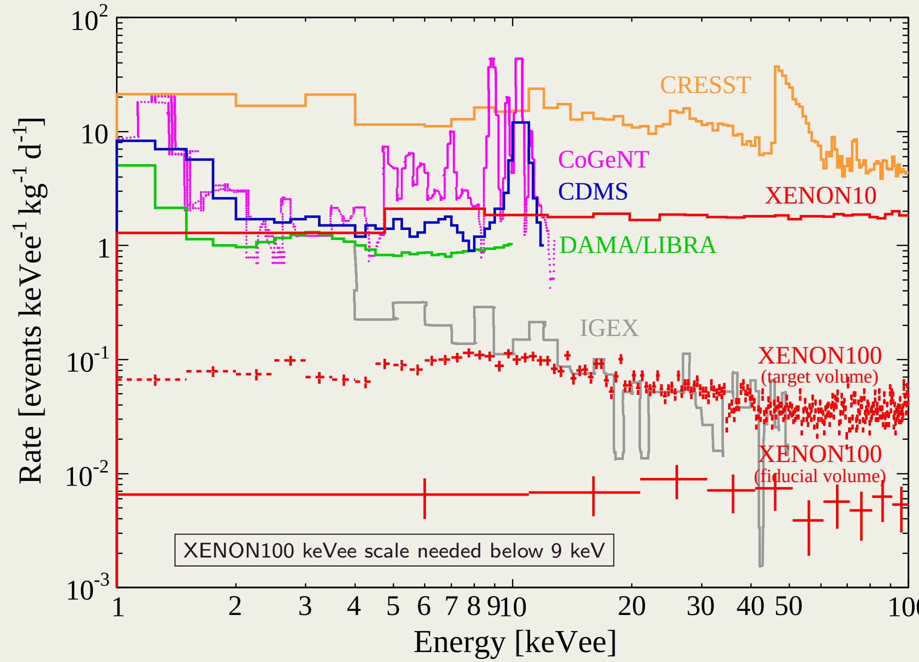


XENON100: Typical Low Energy Event



XENON100: ER Background

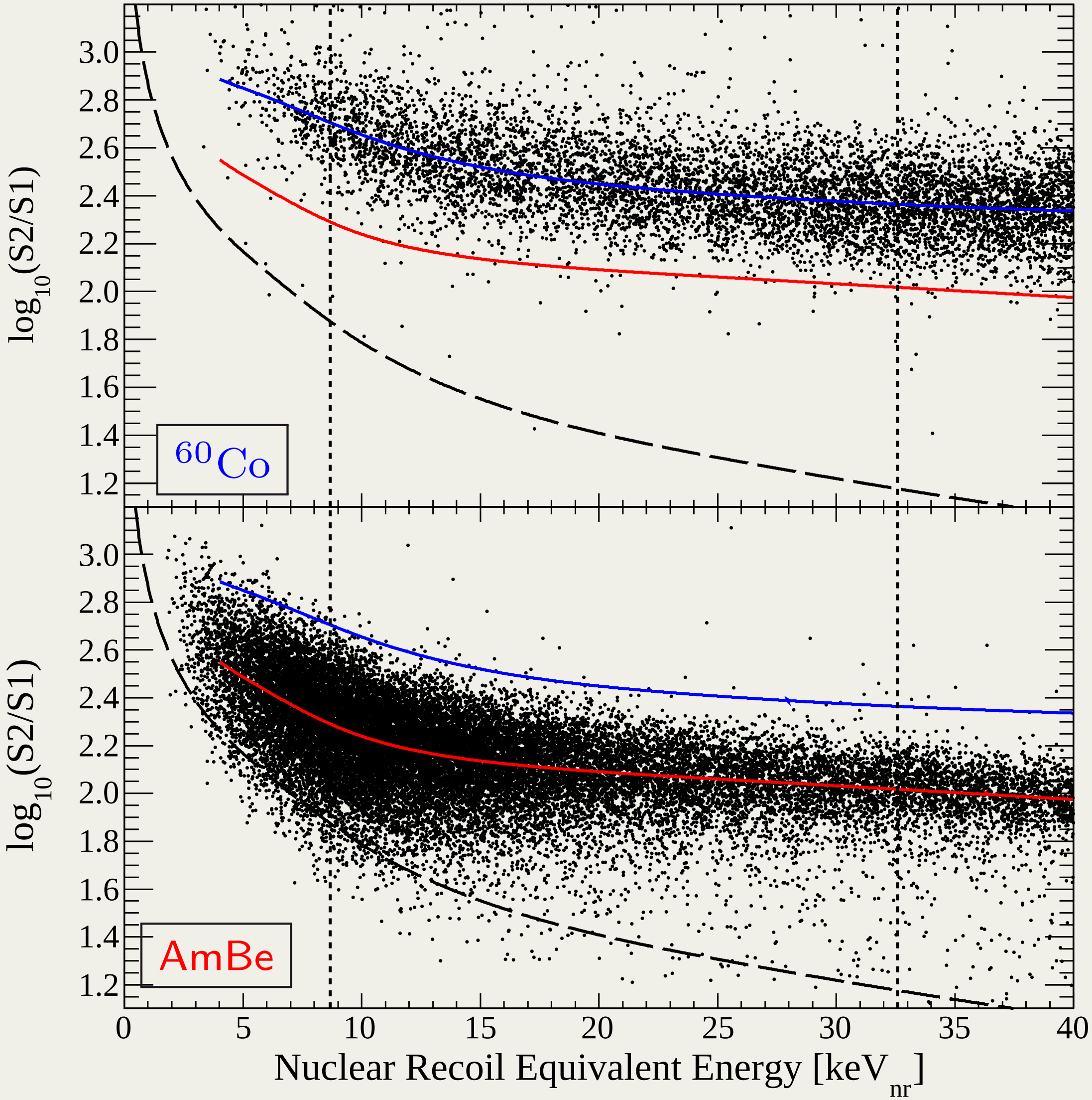




- Measured and predicted ER background without veto cut and for a 30 kg fiducial volume.
- Measured ER background (9.6×10^{-3} events keV^{-1} kg^{-1}d^{-1}) is in good agreement with Monte Carlo predictions (no tuning). Background from materials is dominated by PMTs.
- ER background level in fiducial volume ($< 6 \times 10^{-3}$ events keV^{-1} kg^{-1}d^{-1}, with veto coincidence cut) is $\times 100$ lower than XENON10 (0.6 events keV^{-1} kg^{-1}d^{-1}).
- Details in Aprile *et al.*, Phys. Rev. D **83**, 082001, 2011

XENON100: Calibration

- Electronic recoil band calibration performed with high energy gammas from ^{60}Co (1.17 Mev, 1.33 MeV).
- Background in the energy region of interest is due to low energy Compton scatters from high energy gamma rays or β decays.
- Nuclear recoil band calibration performed with 3.7 MBq (220 n/s) AmBe neutron source.
- Since WIMPs are expected to elastically scatter off of nuclei understanding the behavior of single elastic nuclear recoils in Xe is essential.



Nuclear Recoil Equivalent Energy

Xe
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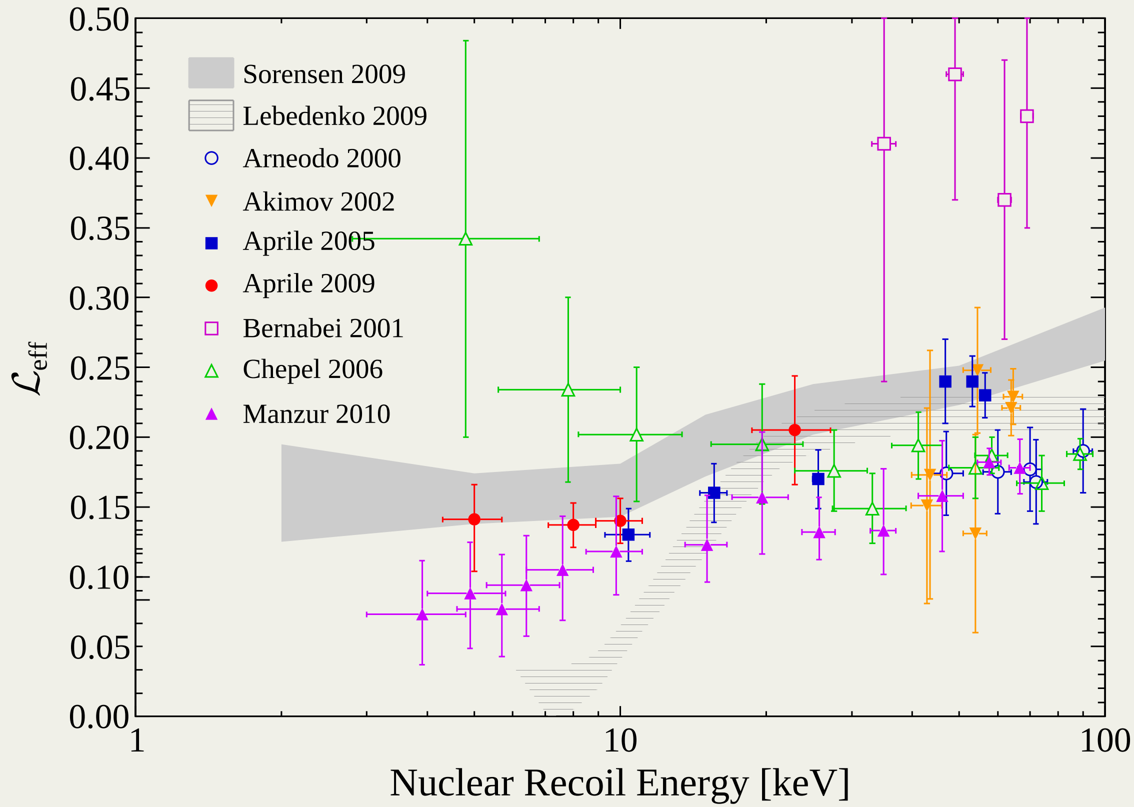
- Nuclear recoil equivalent energy E_{nr} is obtained from the S1 signal

$$E_{\mathrm{nr}} = \frac{S1}{L_{y,\mathrm{er}}} \frac{1}{\mathcal{L}_{\mathrm{eff}}(E_{\mathrm{nr}})} \frac{S_{\mathrm{er}}}{S_{\mathrm{nr}}}$$

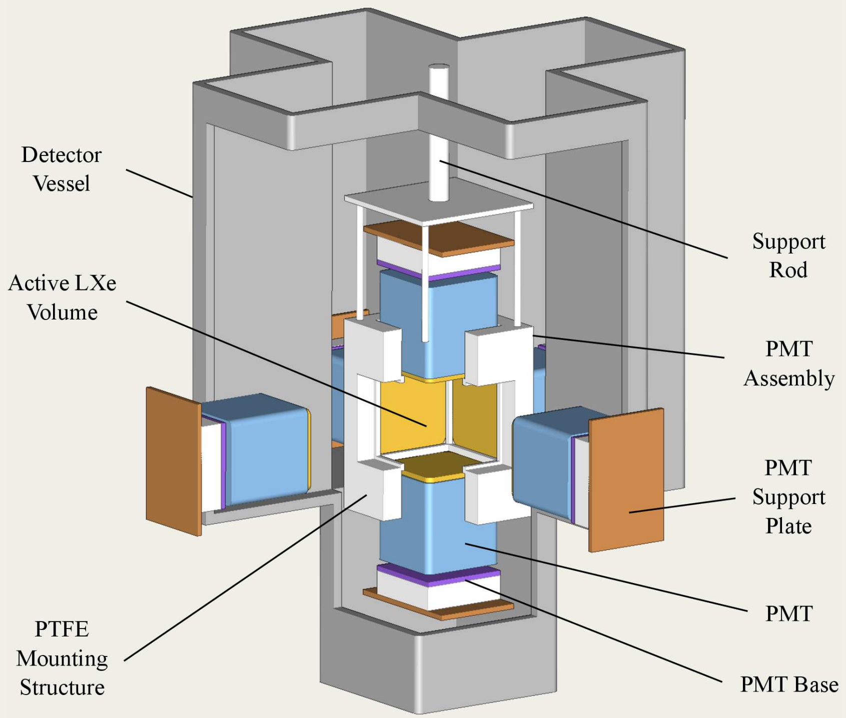
- $L_{y,\mathrm{er}}$, light yield of electron recoils from 122 keV γ rays
- S_{er}, S_{nr}, scintillation light quenching due to drift field
- Relative scintillation efficiency $\mathcal{L}_{\mathrm{eff}}$

$$\mathcal{L}_{\mathrm{eff}}(E_{\mathrm{nr}}) = \frac{L_{y,\mathrm{nr}}(E_{\mathrm{nr}})}{L_{y,\mathrm{er}}(E_{\mathrm{ee}} = 122\,\mathrm{keV})}$$



- The uncertainty in $\mathcal{L}_{\mathrm{eff}}$ at low energies is the largest systematic uncertainty in the reported results from LXe WIMP searches at low WIMP masses.
- Recent measurement performed at Columbia University, lowest energy measured 3 keV.

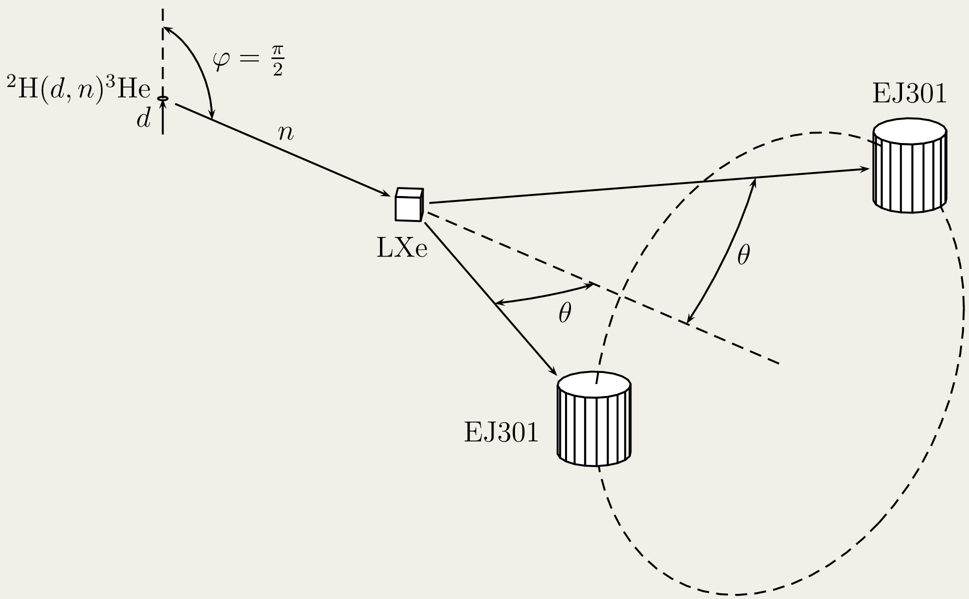
New Measurement of $\mathcal{L}_{\text{eff}}$: Detector

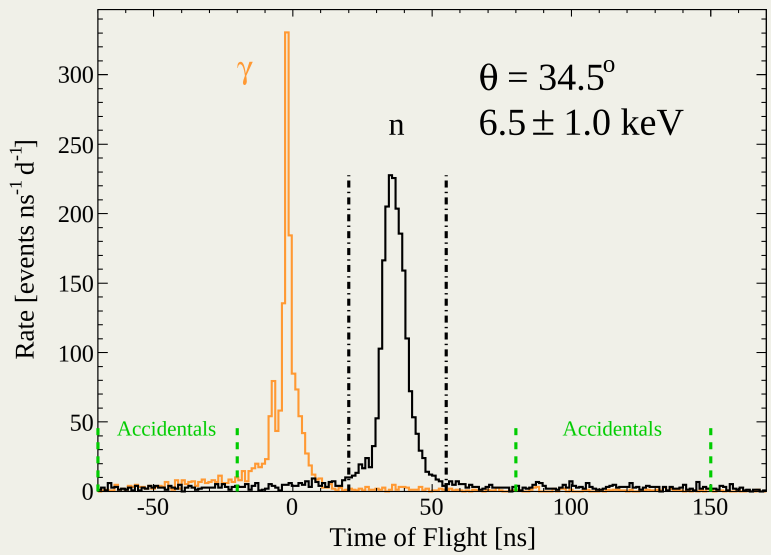


- Built a new special purpose LXe detector with maximized scintillation light detection efficiency

- Cubic sensitive volume with six 2.5 x 2.5 cm Hamamatsu R8520-406 SEL High QE PMTs
- Calibration with 122 keV γ rays from a $^{57}\mathrm{Co}$ source gives a light yield of $L_y = 24.14 \pm 0.09(\mathrm{stat}) \pm 0.44(\mathrm{sys})\ \mathrm{pe/keVee}$ with a resolution (σ/E) of 5%
- Very high light yield, enables a measurement with a low energy threshold

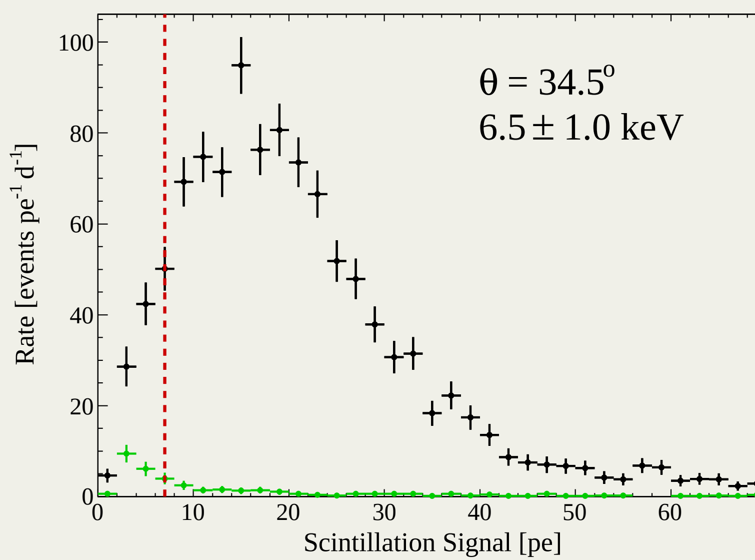
New Measurement of $\mathcal{L}_{\mathrm{eff}}$: Setup



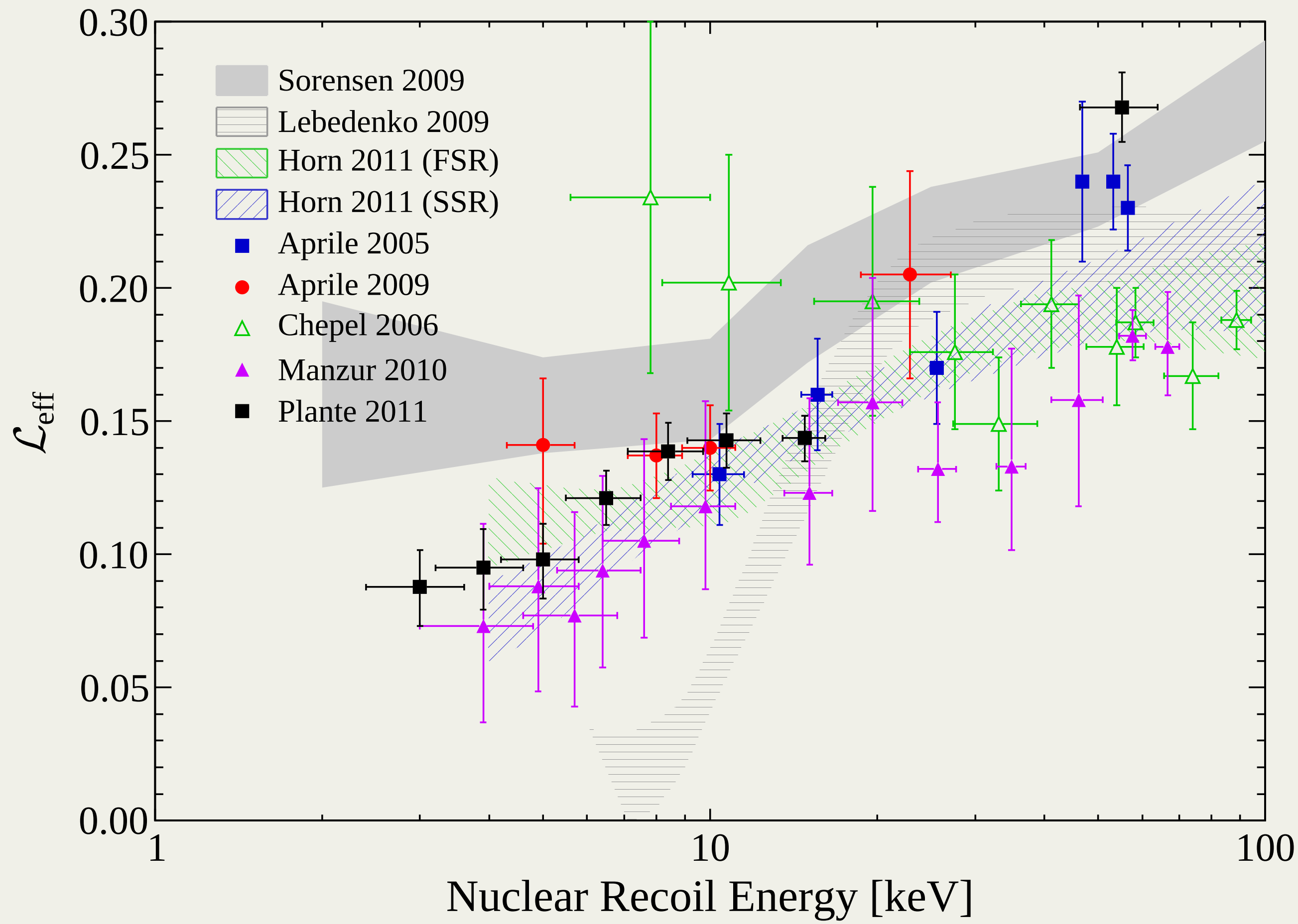


- Record fixed-angle elastic scatters of monoenergetic neutrons tagged by organic liquid scintillators with n/γ discrimination
- Use $^2\mathrm{H}(d,n)^3\mathrm{He}$ 2.5 MeV neutrons from a compact sealed-tube neutron generator
- Recoil energy is fixed by kinematics

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

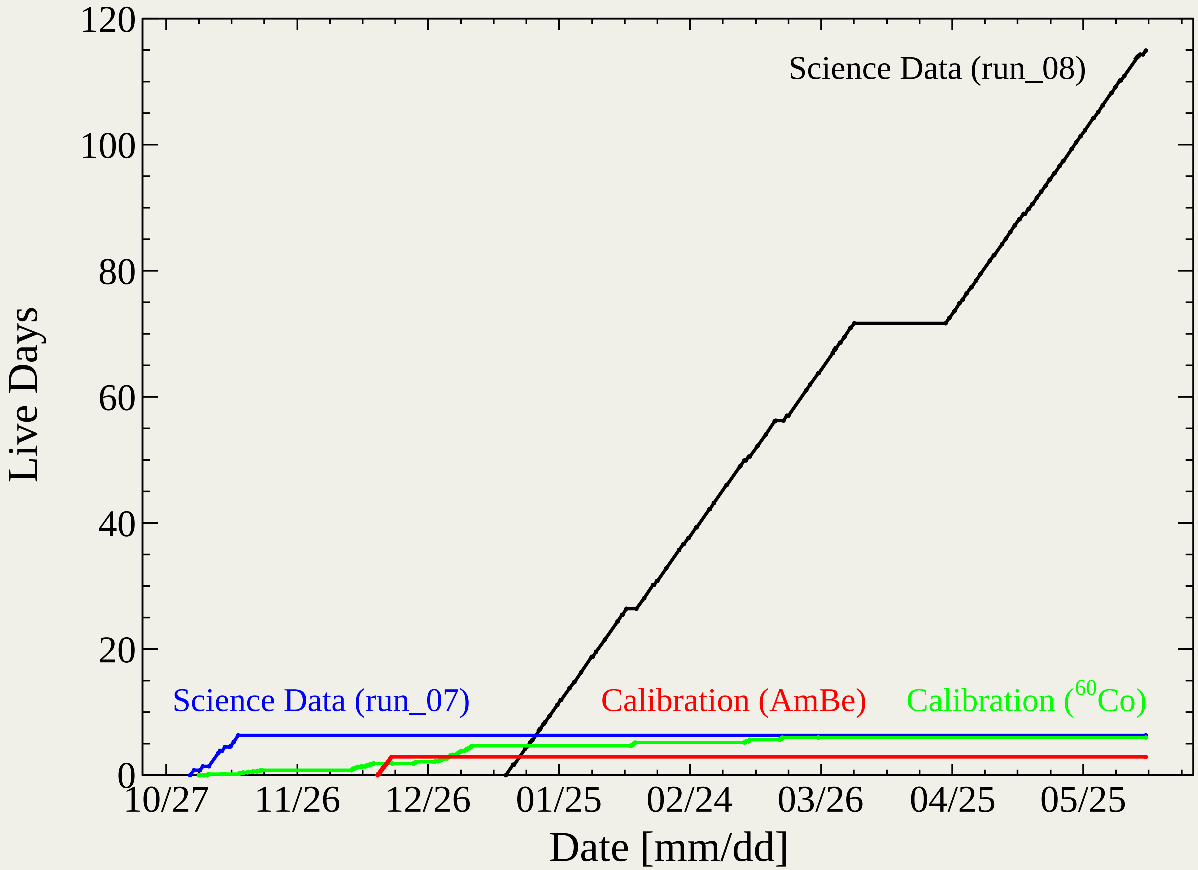


New Measurement of $\mathcal{L}_{\mathrm{eff}}$: Result



- Lowest energy (3 keV) and most precise $\mathcal{L}_{\mathrm{eff}}$ direct measurement achieved to date.
- For details see Plante *et al.*, Phys. Rev. C **84**, 045805, 2011

XENON100: Data Taking 2009/2010



- Results from 11.2 days unblinded data in Aprile *et al.*, Phys. Rev. Lett. **105**, 131302, (2010).
- Data taken in the first half of 2010, blinded region of interest, 100.9 live days
- Results from the blind 100.9 days in Aprile *et al.*, Phys. Rev. Lett. **107**, 131302, 2011

XENON100: Data Selection

Basic quality cuts

Designed to remove noisy events, events with unphysical parameters. Very high acceptance.

- S1 coincidence cut
- S2 threshold cut
- S2 saturation cut
- Signal/Noise cut

Scatter cuts

Designed to remove events with multiple interactions (multiple S2s), with delayed coincidences (multiple S1s) or misidentified S1s.

- S1 single peak cut
- S2 single peak cut
- Veto cut

Fiducial volume cut

Because of the high stopping power of LXe, fiducialization is an extremely effective way of reducing background. Fiducial volume chosen:

- 48 kg super-ellipsoid

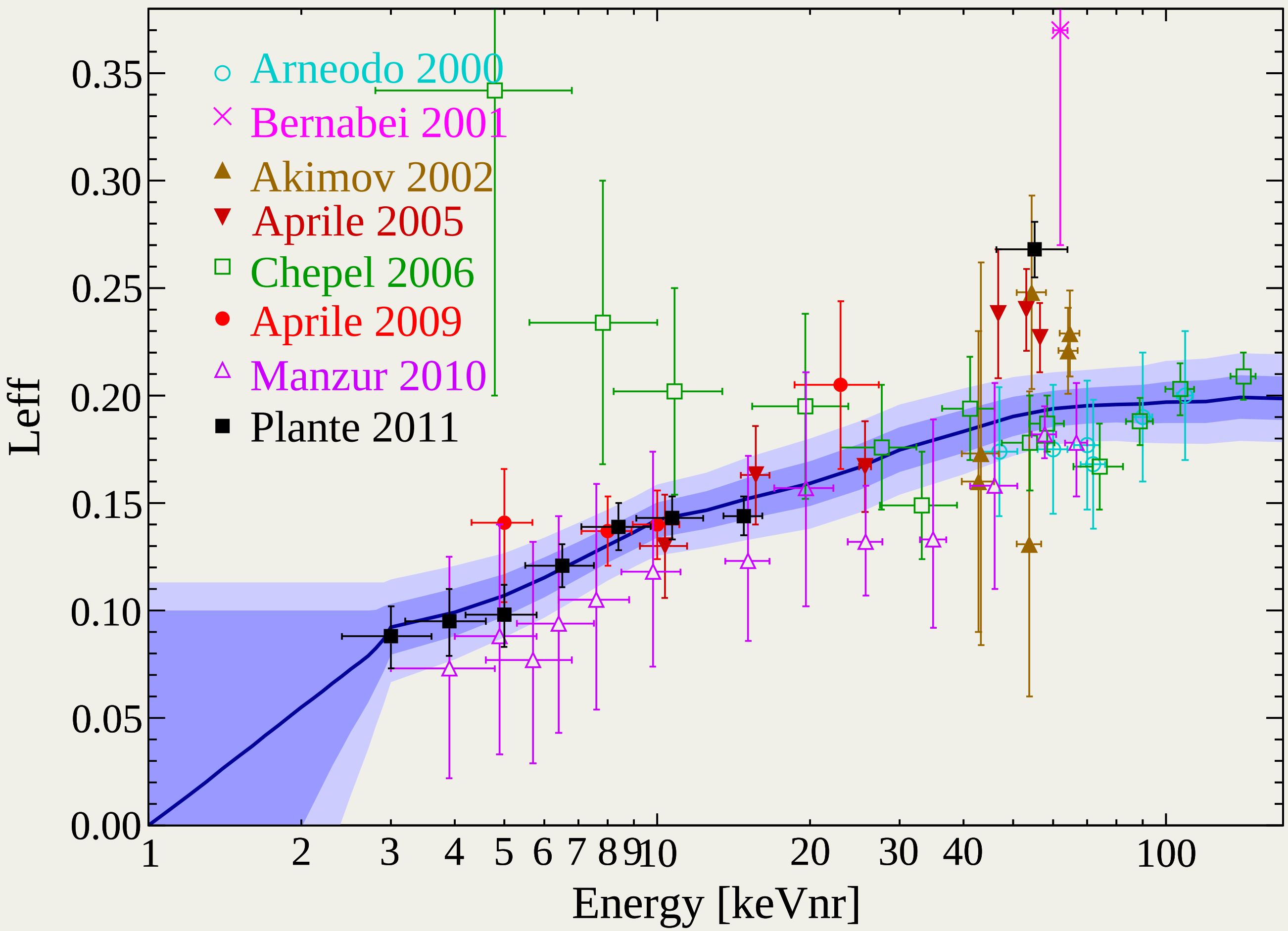
Advanced cuts

Designed to remove events which fail consistency checks, e.g. mismatch in positions from different algorithms, or with S1 PMT patterns not consistent with their position in the TPC

- S1 PMT pattern cut
- S2 width consistency cut
- Position reconstruction cut

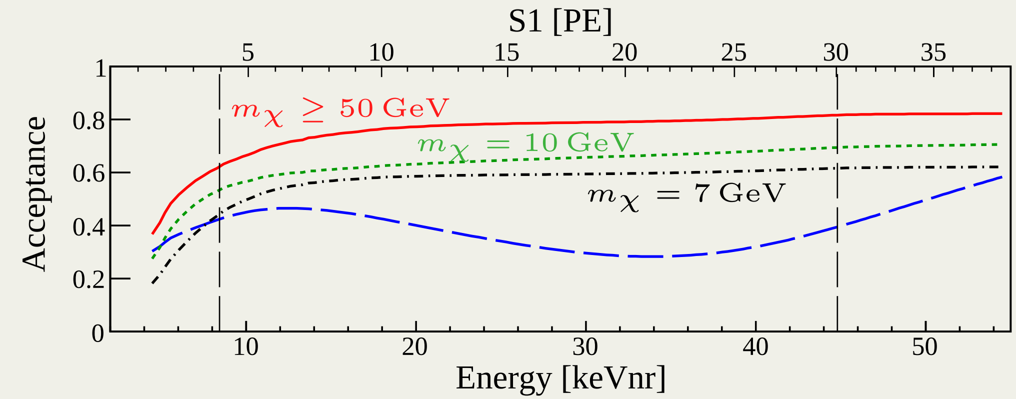
XENON100: $\mathcal{L}_{\mathrm{eff}}$ Parametrization

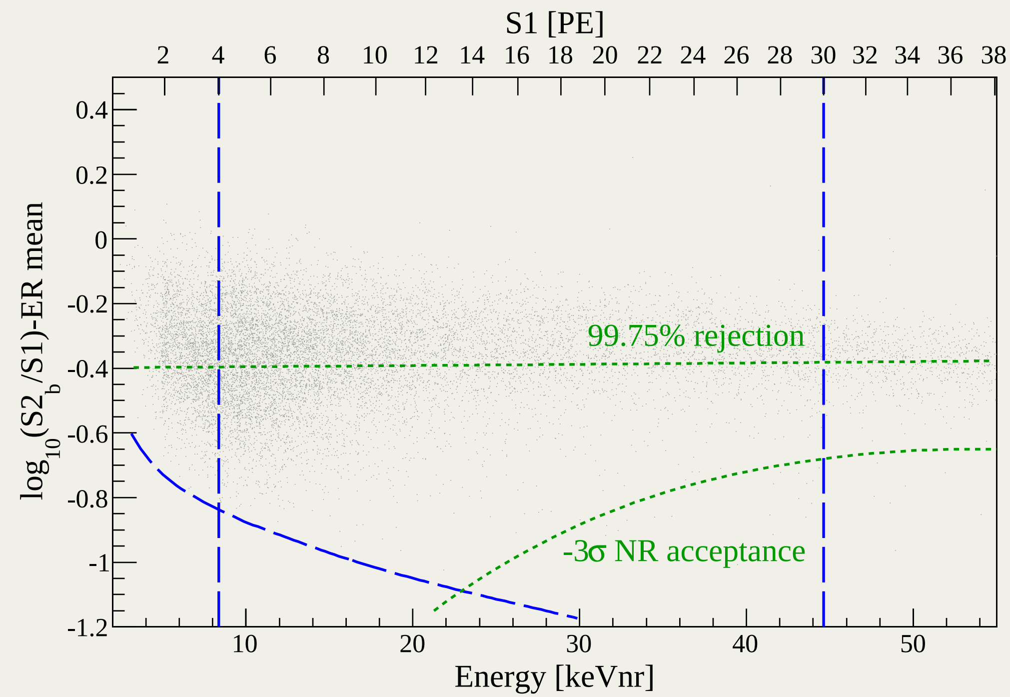
Xe XENON Dark Matter Project



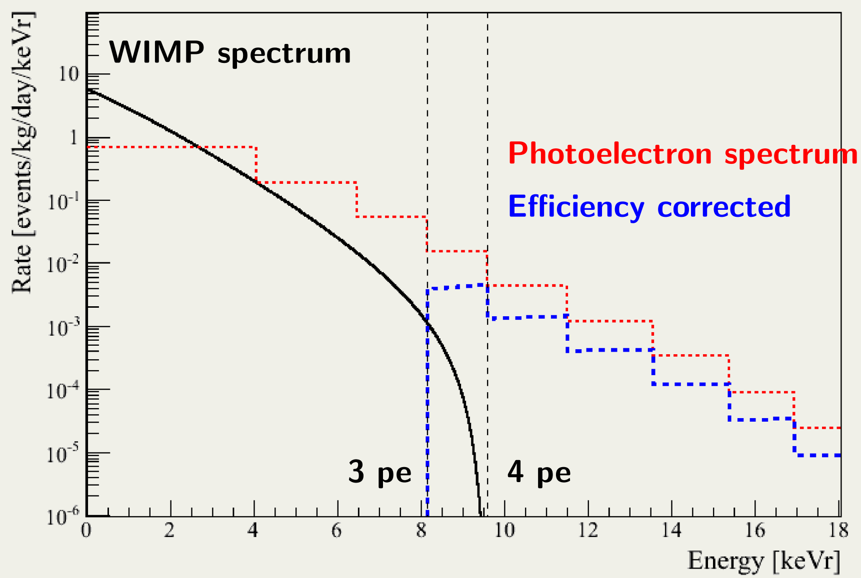
- $\mathcal{L}_{\mathrm{eff}}$ parametrization is an average of the direct fixed angle neutron scattering $\mathcal{L}_{\mathrm{eff}}$ measurements
- New measurement of $\mathcal{L}_{\mathrm{eff}}$ at low energies added to the data used to obtain the parametrization

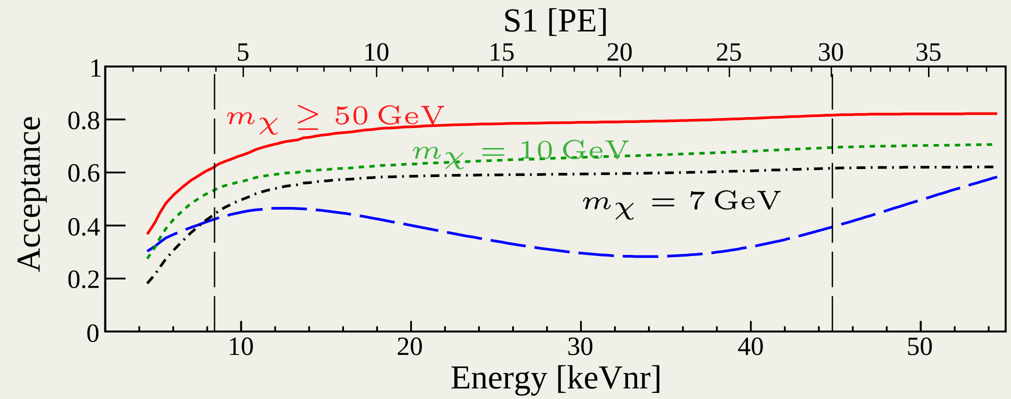
- Keep acceptance high (think discovery)
- Data quality cuts acceptance estimated from AmBe and ^{60}Co calibration data, MC simulations, and ERs outside the WIMP search energy range
- Decided a priori to use Profile Likelihood approach and test both background only and signal+background hypotheses
- No S2/S1 rejection cut in the Profile Likelihood approach
- Define a benchmark WIMP region for a parallel cuts-based analysis
  - 99.75% ER rejection line
  - S2 threshold
  - NR band lower 3-σ

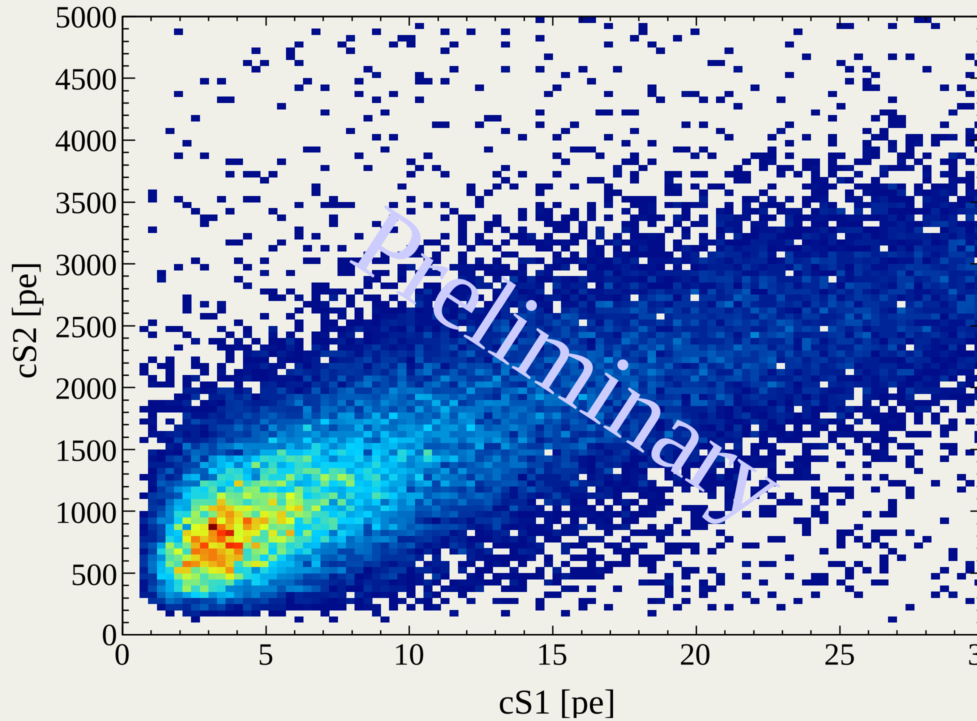




XENON100: Nuclear Recoil Acceptance



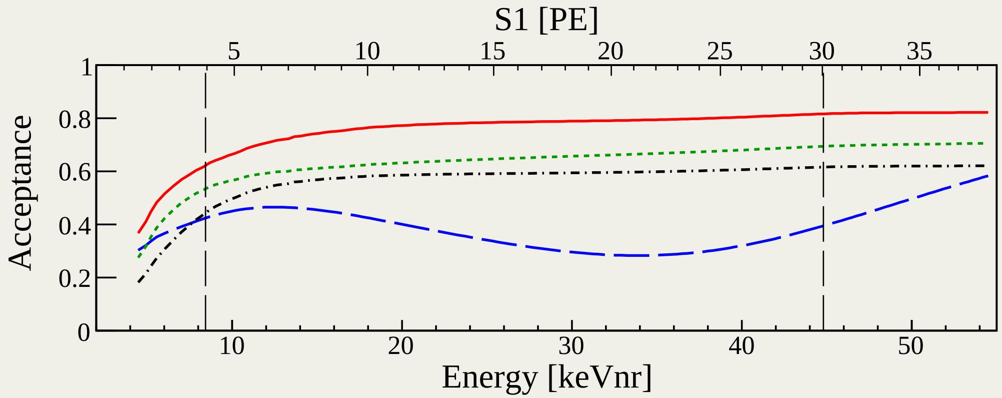


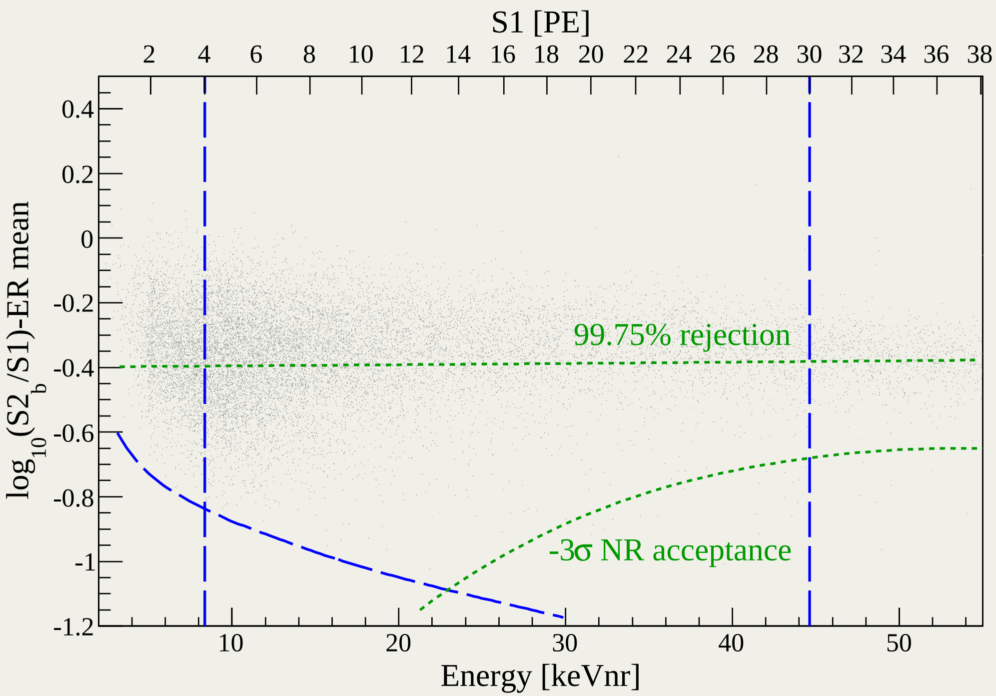


- Resolution near threshold is dominated by statistics in photon detection efficiency.
- For each WIMP mass, convert the energy spectrum to a S1 spectrum in photoelectrons, apply the S2 acceptance function, convolve the spectrum with a Poisson distribution.

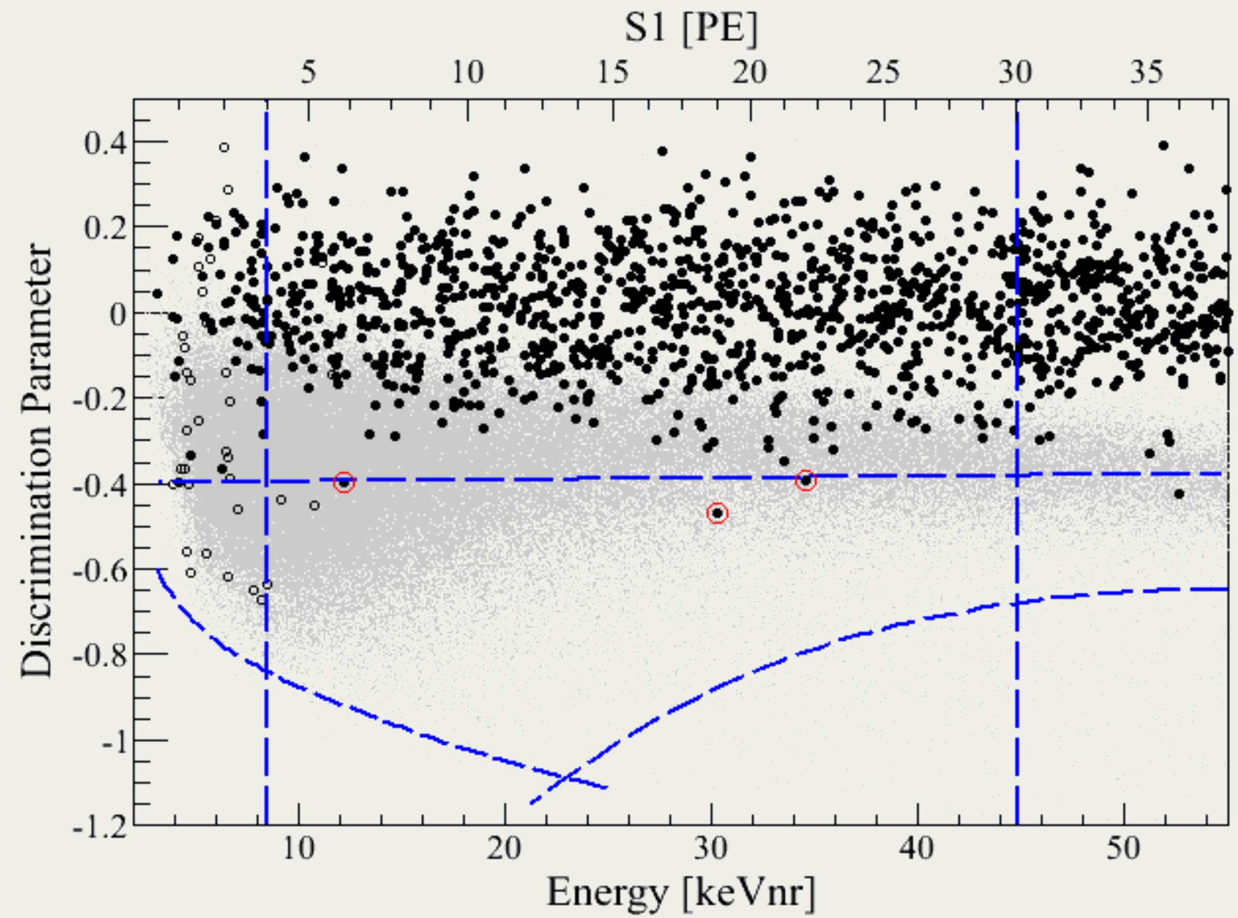
XENON100: Background Prediction

- Expected background: 48 kg fiducial mass, 99.75% electronic recoil rejection, 100.9 live days
- Statistical leakage (from electronic recoil events)
  - 1.14 ± 0.48 events, estimated from the non-blinded electronic recoil band from background
  - Dominated by $^{85}\mathrm{Kr}$ (Kr concentration $\sim$700 ppt) due to a previous leak
- Anomalous leakage
  - 0.56 ± 0.25 events, estimated using data and MC from $^{60}\mathrm{Co}$ and background
- Neutron prediction from MC
  - 0.11 ± 0.08 events, muon-induced fast neutrons and neutrons from (α, n) reactions and spontaneous fission
- Total 1.8 ± 0.6 events in 100.9 days





XENON100: Unblinding



- 6 events in the signal region after unblinding, inspection reveals 3 are due to electronic noise
- Population of noise events near threshold, leaks into signal region

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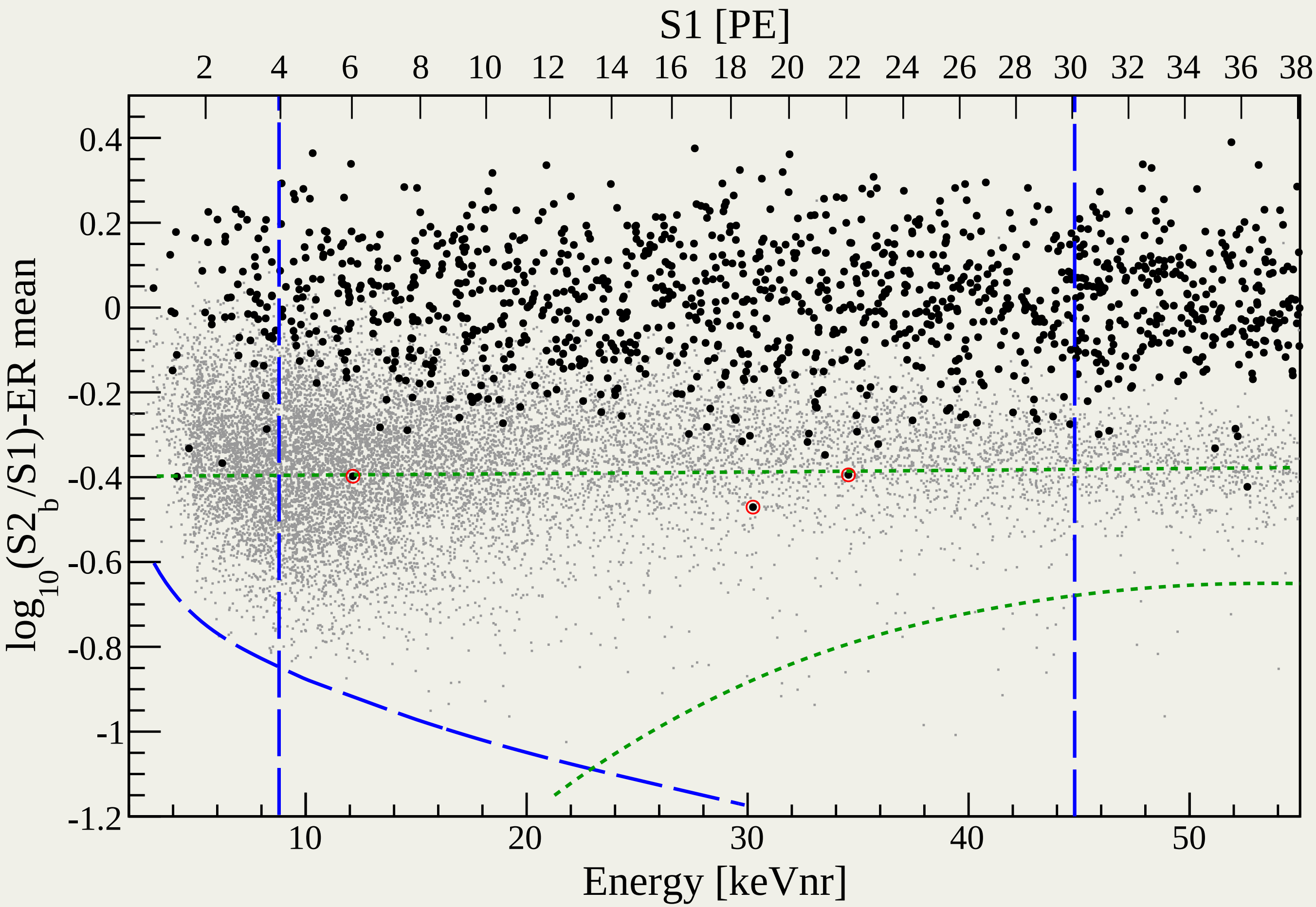
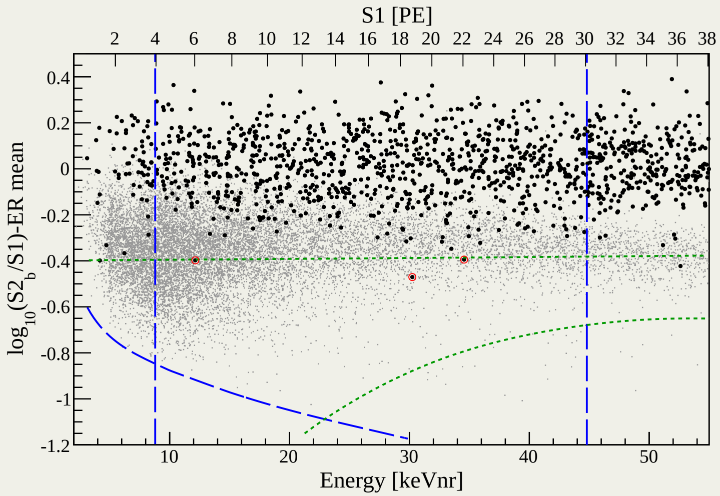
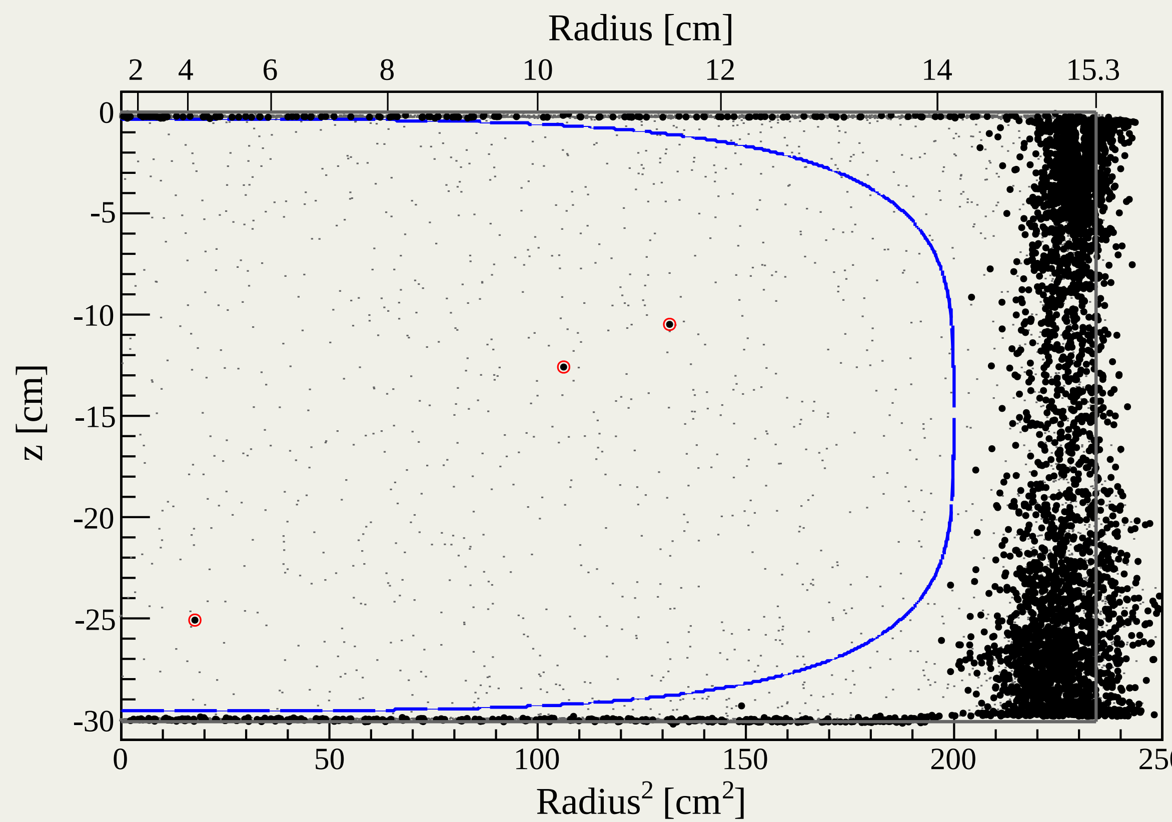


- 6 events in the signal region after unblinding, inspection reveals 3 are due to electronic noise
- Population of noise events near threshold, leaks into signal region
- Remove population with noise post-unblinding cut, 3 candidate WIMP events remain

XENON100: Event Distribution





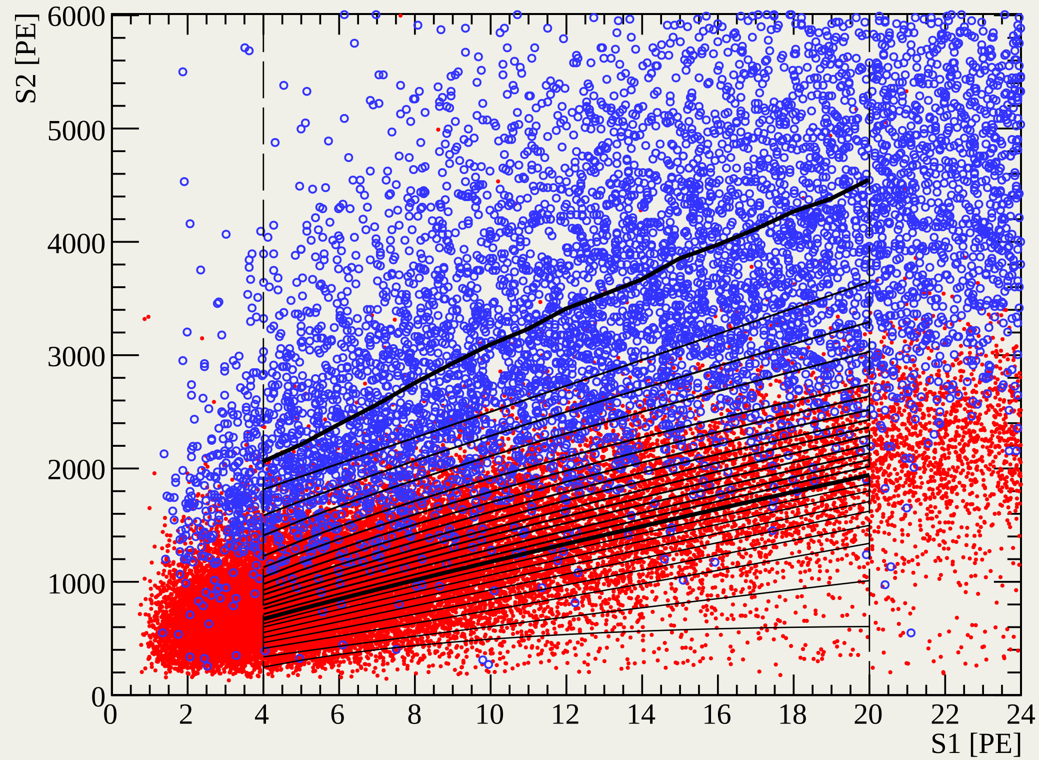
- 3 candidate events clearly inside the 48 kg fiducial volume
- Probability (Poisson) to observe 3 or more events when expecting 1.8 ± 0.6 is 28%
- Profile Likelihood analysis does not yield a significant signal excess either, background-only hypothesis has a p-value of 31%

XENON100: Profile Likelihood Approach

- Construct the Likelihood function

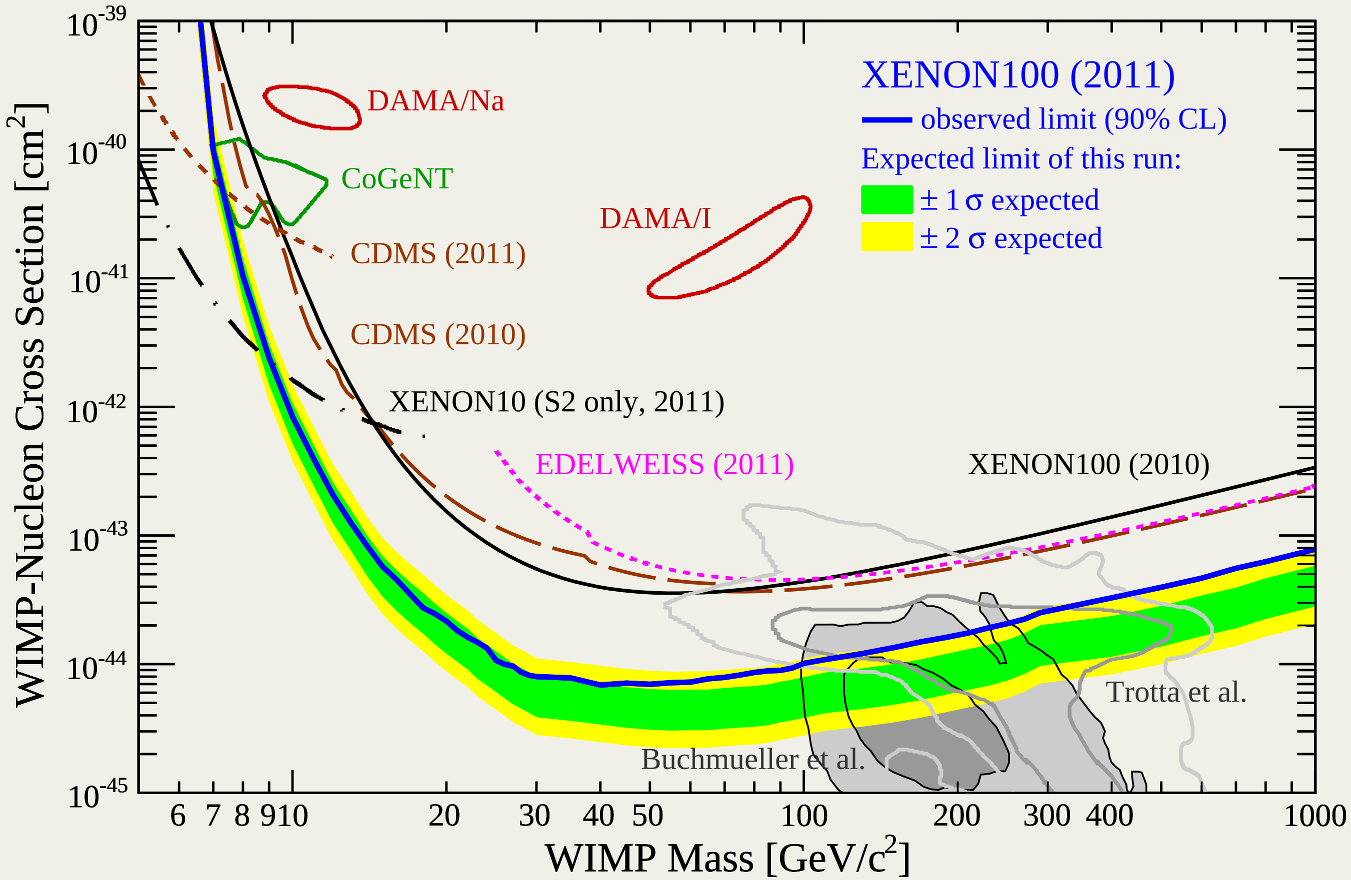
$$\mathscr{L} = \mathscr{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, \mathcal{L}_{\text{eff}}, v_{\text{esc}}; m_\chi) \times \mathscr{L}_2(\epsilon_s) \times \mathscr{L}_3(\epsilon_b) \times \mathscr{L}_4(\mathcal{L}_{\text{eff}}) \times \mathscr{L}_5(v_{\text{esc}})$$

- Main term contains only one parameter of interest, the signal cross-section σ, other parameters are nuisance parameters and profiled out
- Additional terms constrain the nuisance parameters in the main term
- Makes use all observed events in the WIMP search data, no sharp S2/S1 discrimination cut, energy distribution
- Allows systematic uncertainties to be incorporated in a consistent manner



- More details in

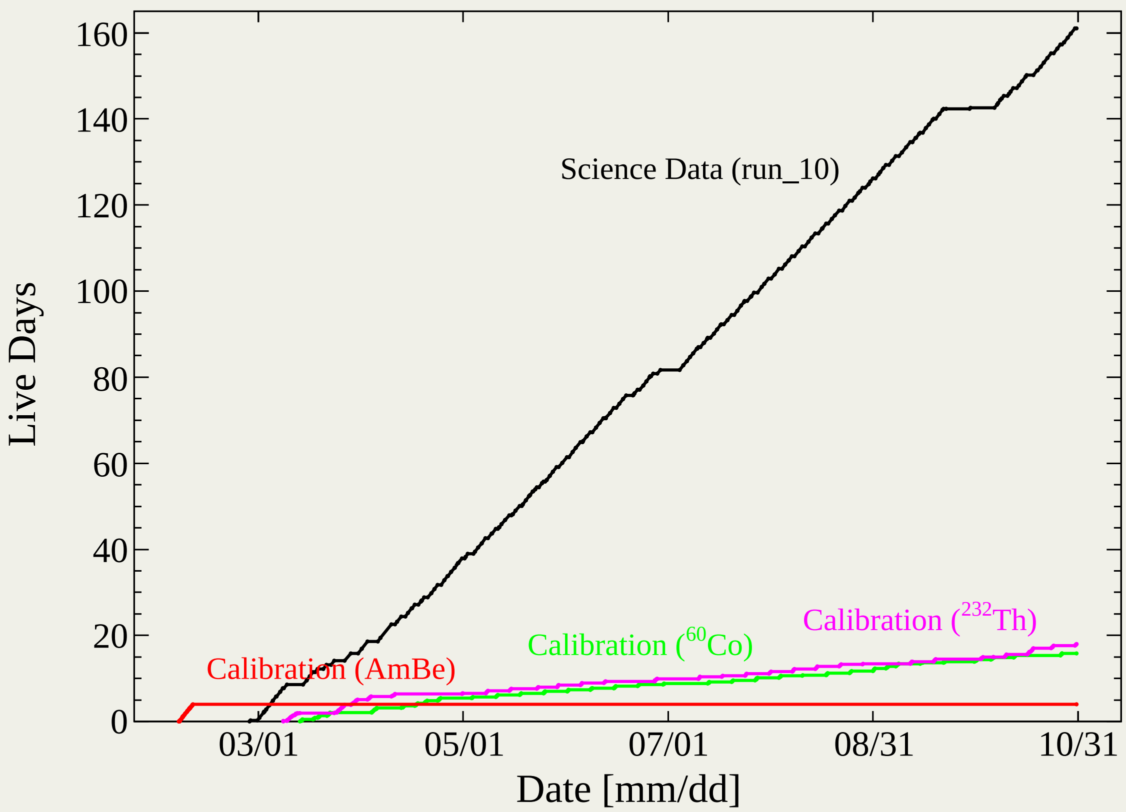
Aprile *et al.*, Phys. Rev. D **84**, 052003, 2011

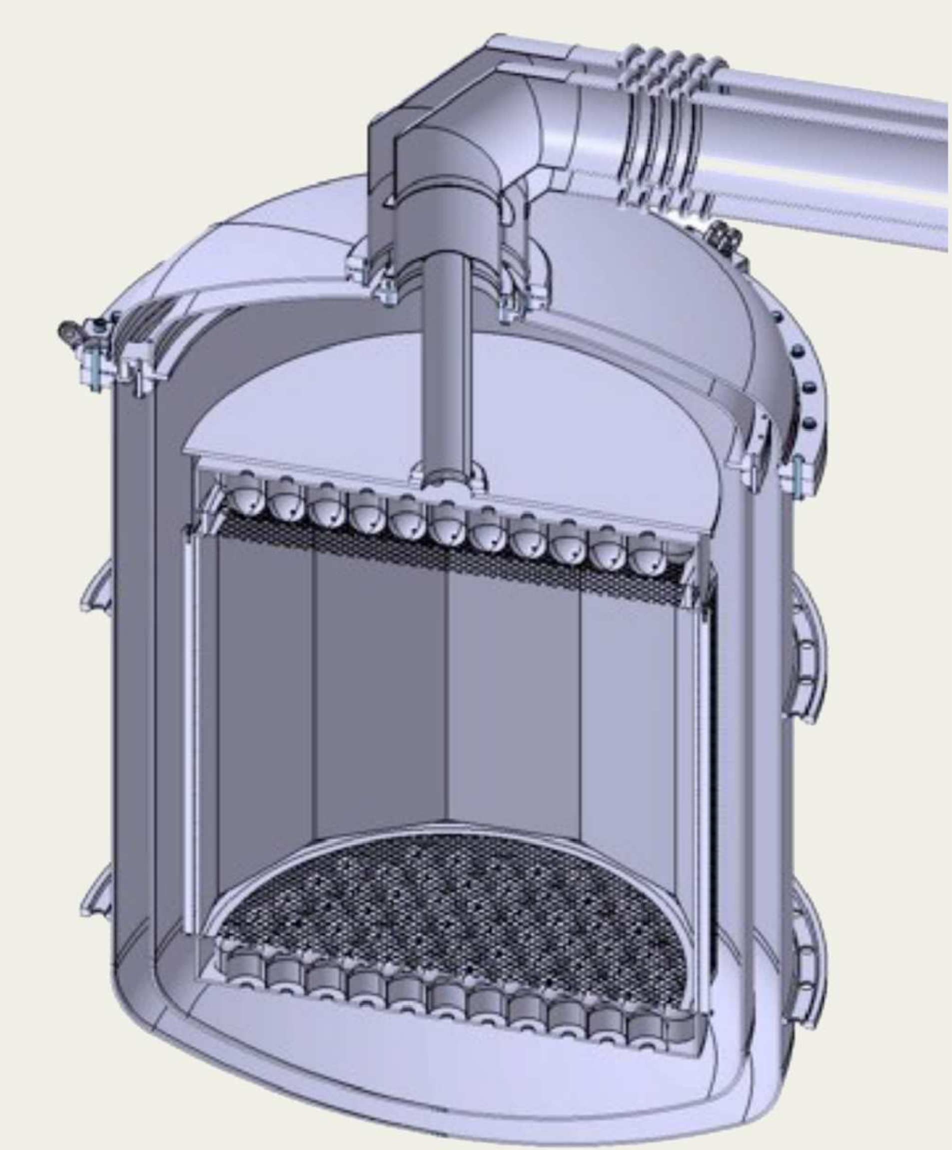


- Strongest limit to date over a large WIMP mass range, challenges the interpretation of CoGeNT and DAMA signals as being due to low mass WIMPs
- Results recently published | Aprile *et al.*, Phys. Rev. Lett. **107**, 131302, 2011 |

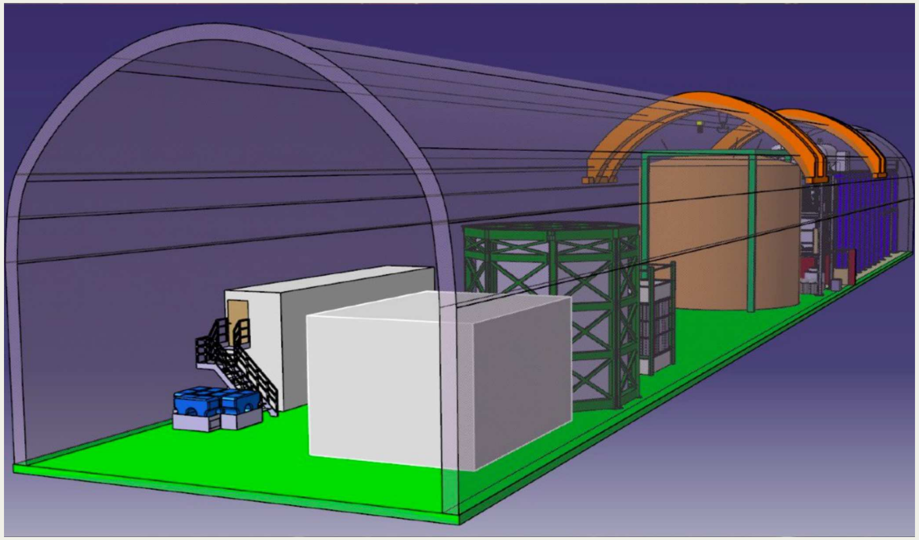
XENON100: Current Data Taking Status

- Kr concentration reduced by more than $\times 5$ (~50% background reduction)
- Improved S2 trigger with lower trigger threshold
- New dark matter run started early 2011, ~160 live days accumulated
- Much more ER calibration data, already ~16 live days $^{60}\mathrm{Co}$ and ~18 live days $^{232}\mathrm{Th}$

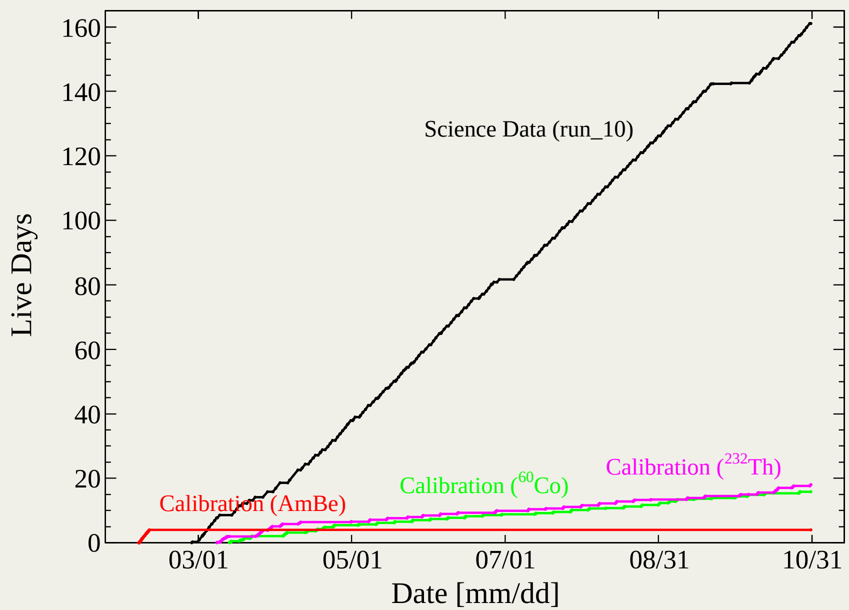


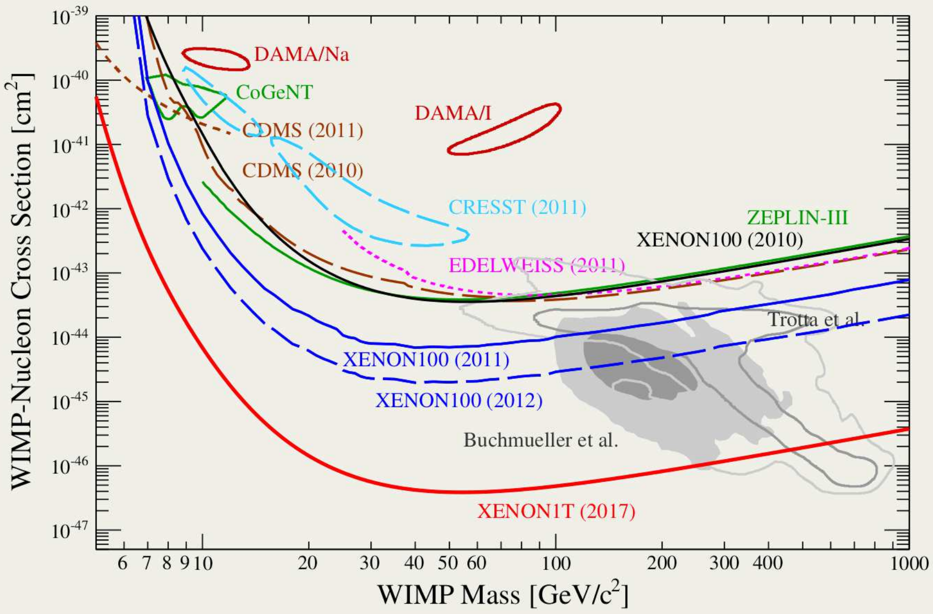


- $1\,\mathrm{m}^3$ TPC, 2.4t LXe, 1t fiducial mass
- $\times 100$ background reduction compared to XENON100
- Low radioactivity photosensors
- 10 m water shield
- Currently in design phase, construction 2012
- Approved for construction in Hall B at LNGS



Summary

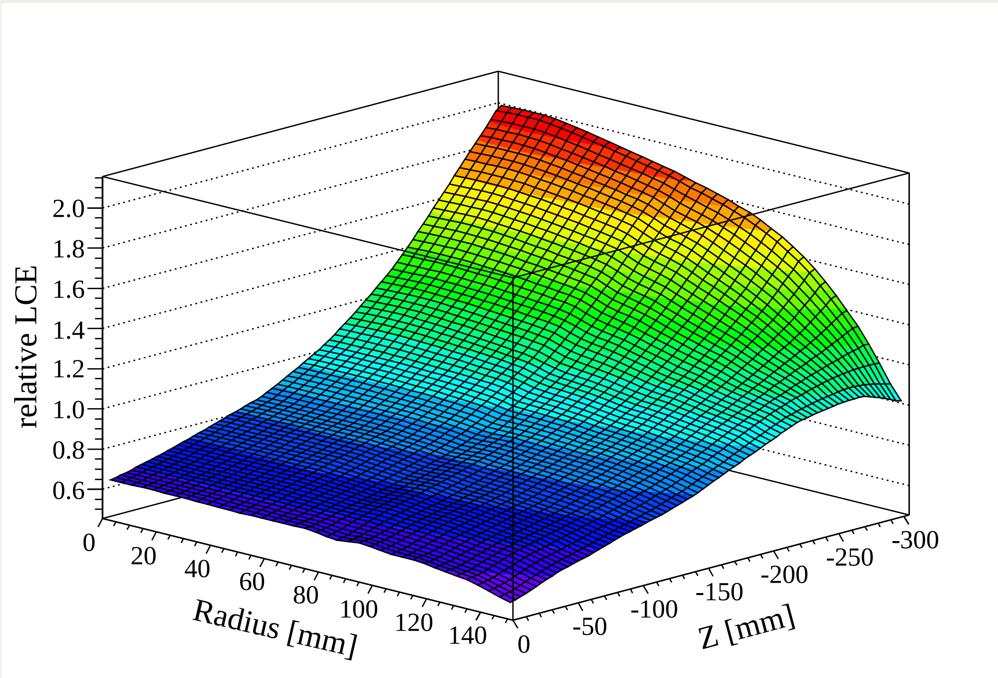


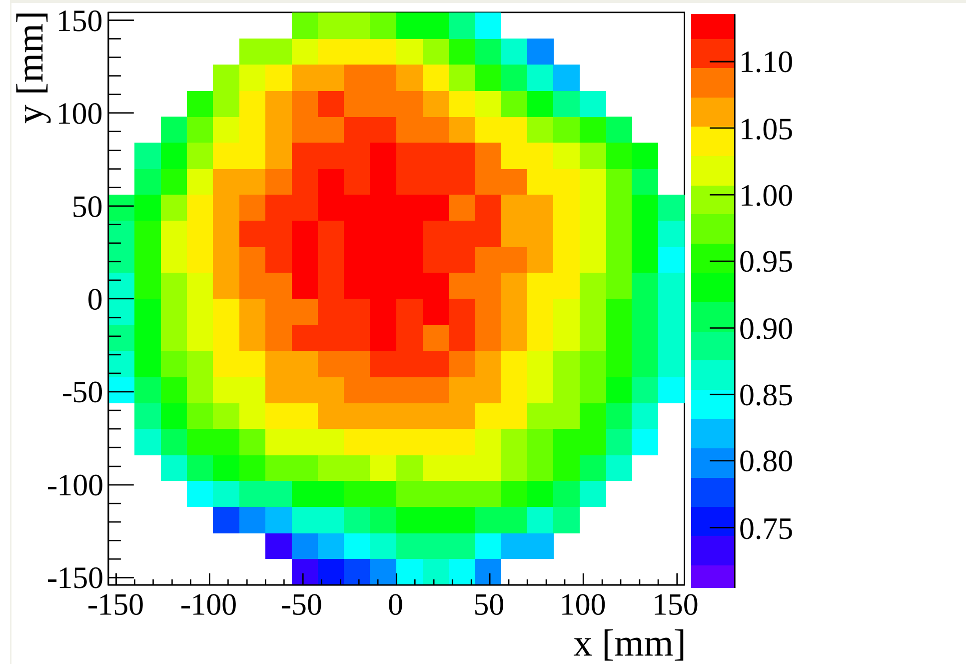


- XENON100 background goal achieved, detector is taking dark matter data
- Accumulated 100 days exposure in 2010, 3 events observed with an expectation of 1.8 ± 0.6
- Set the most stringent limit to date on the WIMP-nucleon spin-independent cross section
- Already $\sim$160 days exposure accumulated with lower background level and improved trigger threshold, stay tuned for new results

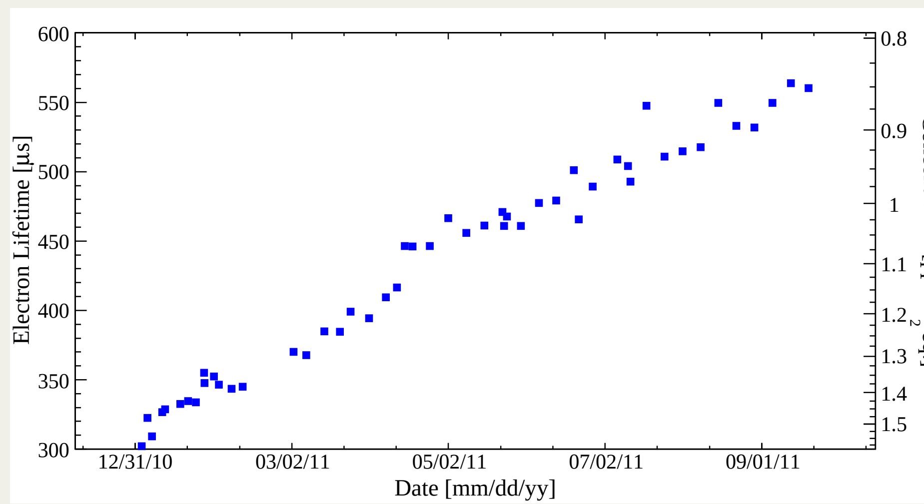
Extras

XENON100: Position Dependent Corrections

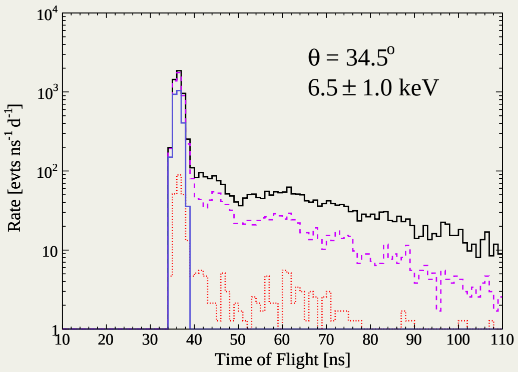


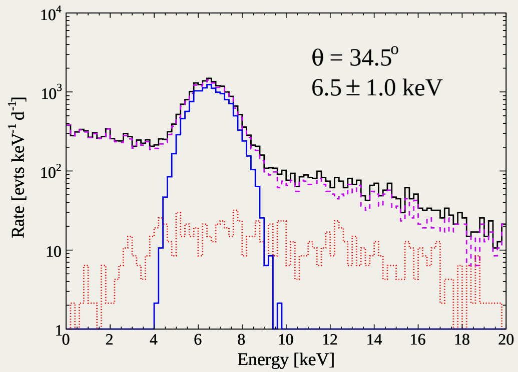


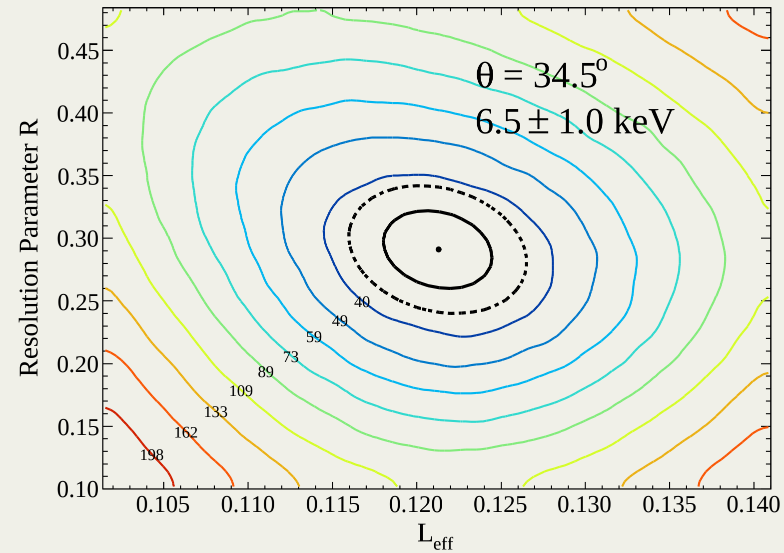
- Corrections from measurements with $^{137}\mathrm{Cs}$, AmBe (40 keV inelastic), $^{131m}\mathrm{Xe}$ (164 keV), with agreement better than 3%.
- S1 rz and S2 xy correction due to spatial dependence of the light collection.
- S2 z correction due to finite electron lifetime.

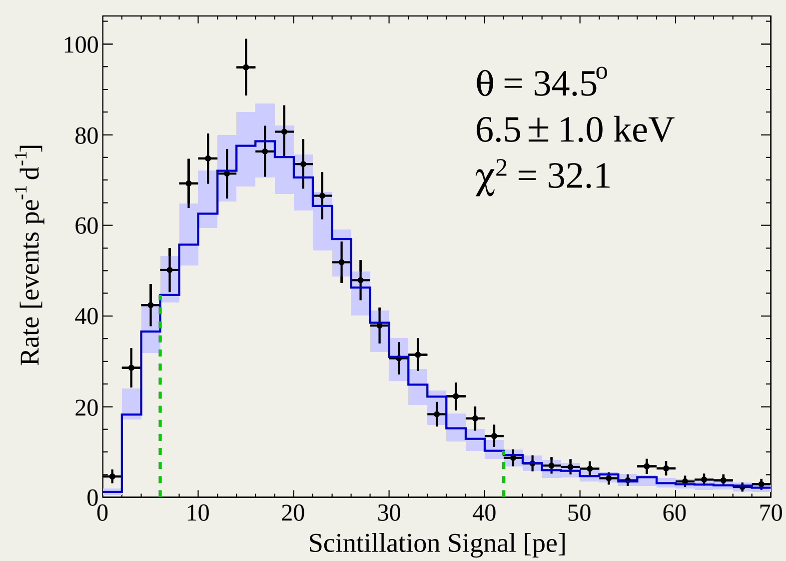


New Measurement of $\mathcal{L}_{\mathrm{eff}}$: Extracting $\mathcal{L}_{\mathrm{eff}}$









- Transform the MC recoil energy spectrum into a simulated scintillation spectrum g using $S1 = L_y \cdot \mathcal{L}_{\mathrm{eff},j} \cdot E_r$, with gaussian energy resolution $\sigma = R\sqrt{E_r}$, PMT gain fluctuations, and applying trigger efficiency
- Extract the energy dependence of $\mathcal{L}_{\mathrm{eff}}$ by minimizing the χ^2 between the measured and simulated spectra, h and g

$$\chi^2\left(\mathcal{L}_{\mathrm{eff},j}, R_j\right) = \sum_{i=0}^{N} \frac{\left[h_i - g_i\left(\mathcal{L}_{\mathrm{eff},j}, R_j\right)\right]^2}{\sigma_{h,i}^2 + \sigma_{g,i}^2\left(\mathcal{L}_{\mathrm{eff},j}, R_j\right)}$$

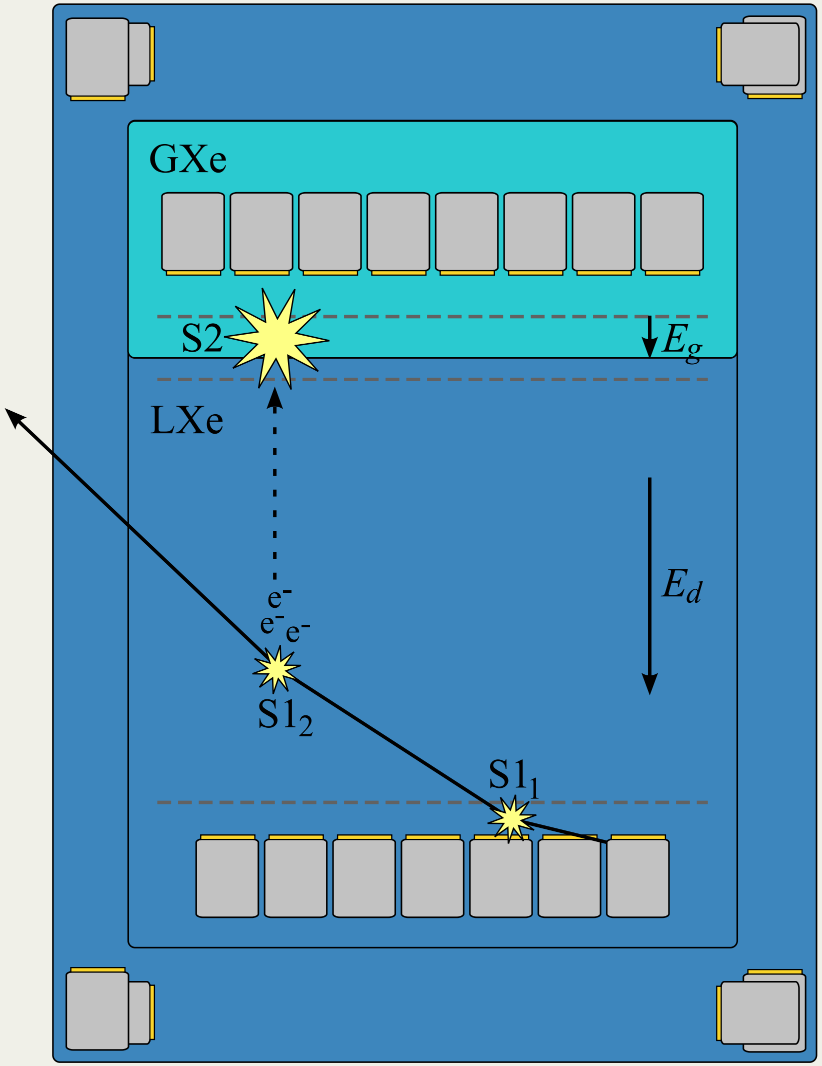
Uncertainty in $\mathcal{L}_{\text{eff}}$

$$\sigma^2_{\mathcal{L}_{\text{eff}}} = \sigma^2_{\mathcal{L}_{\text{eff}},\text{fit}} + \left(\frac{\partial \mathcal{L}_{\text{eff}}}{\partial L_y}\right)^2 \sigma^2_{L_y} + \left(\frac{\partial \mathcal{L}_{\text{eff}}}{\partial E_{\text{nr}}}\right)^2 \sigma^2_{E_{\text{nr}}} + \left(\frac{\Delta \mathcal{L}_{\text{eff}}}{\Delta \epsilon}\right)^2 \sigma^2_{\epsilon} + \left(\frac{\Delta \mathcal{L}_{\text{eff}}}{\Delta r_g}\right)^2 \sigma^2_{r_g} + \left(\frac{\Delta \mathcal{L}_{\text{eff}}}{\Delta r_s}\right)^2 \sigma^2_{r_s}$$

- The total uncertainty on $\mathcal{L}_{\text{eff}}$ is computed from
  - $\sigma_{\mathcal{L}_{\text{eff}},\text{fit}}$, uncertainty from the fit
  - σ_{L_y}, uncertainty ^{57}Co light yield
  - $\sigma_{E_{\text{nr}}}$, spread in nuclear recoil energies
  - σ_{ϵ}, liquid scintillator cut efficiency uncertainty
  - σ_{g}, neutron generator position uncertainty
  - σ_{s}, liquid scintillator position uncertainty
- $\partial \mathcal{L}_{\text{eff}}/\partial E_{\text{nr}}$ is computed from a logarithmic fit to the measured values
- $\Delta \mathcal{L}_{\text{eff}}/\Delta \epsilon$, $\Delta \mathcal{L}_{\text{eff}}/\Delta r_g$, and $\Delta \mathcal{L}_{\text{eff}}/\Delta r_s$ are calculated from MC simulations
- At all energies, the dominant contribution is from $\sigma_{E_{\text{nr}}}$ Below 6.5 keV, the second largest contribution is from σ_{ϵ}. At 6.5 keV and above, the second largest contribution is from $\sigma_{\mathcal{L}_{\text{eff}},\text{fit}}$

XENON100: Anomalous Leakage

- Two types of leakage from the ER band, statistical leakage and anomalous leakage
- We assume the ER band is Gaussian in $\log(S2/S1)$, fixed discrimination at 99.75% gives the expected statistical leakage
- Events with low non-Gaussian S2/S1 also in gamma calibration data, e.g. $^{60}\mathrm{Co}$
- One source for those "anomalously leaking" events is multiple scatter events where one or more scatter occurs in a charge insensitive region of the detector
- Use the S1 Pattern likelihood cut to remove events likely due to two energy deposits
- Compute the expected anomalous leakage in background using $^{60}\mathrm{Co}$ as reference



Example Noise Event