New Results from the XENON100 Experiment

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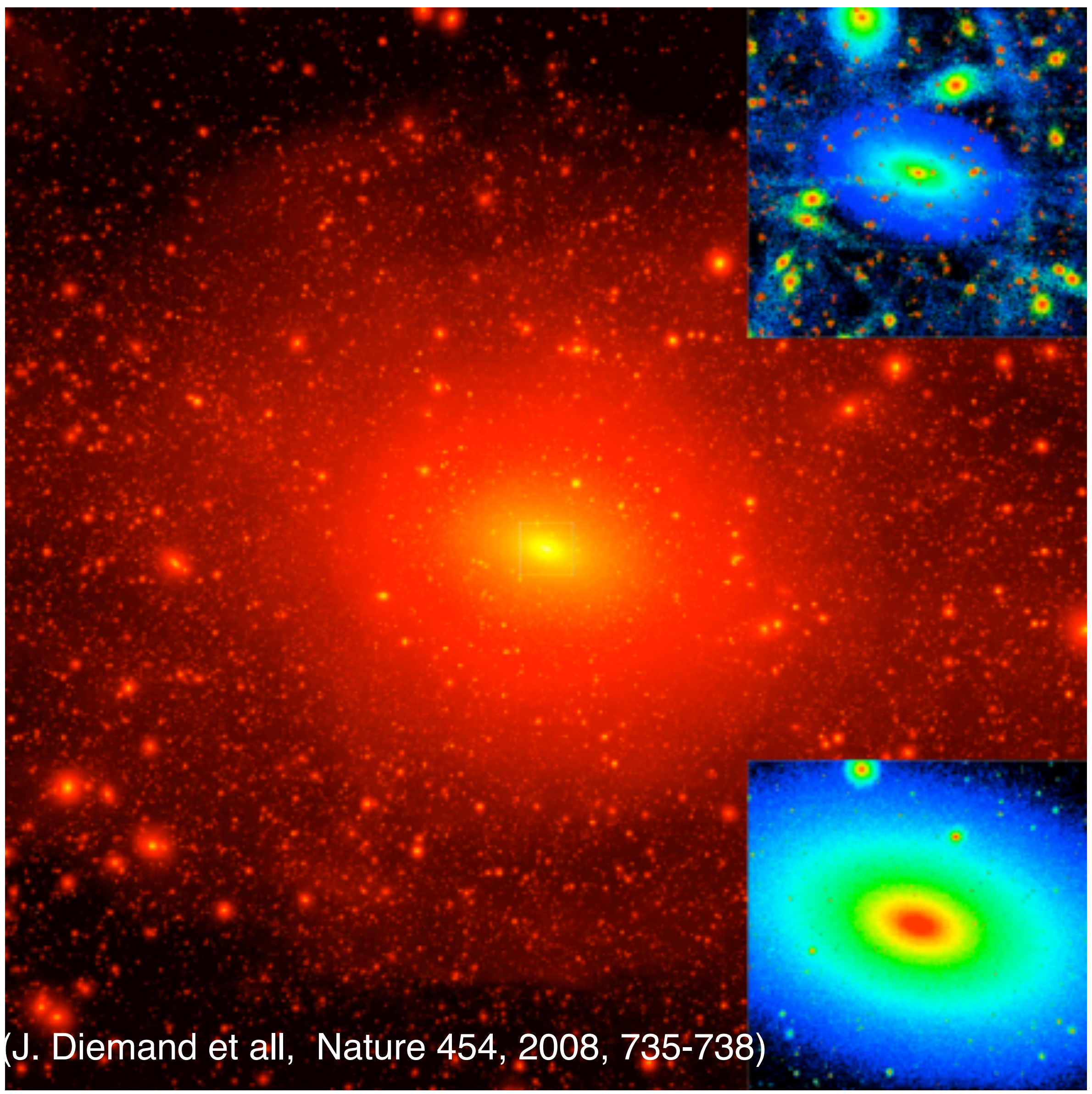
(for the XENON collaboration)

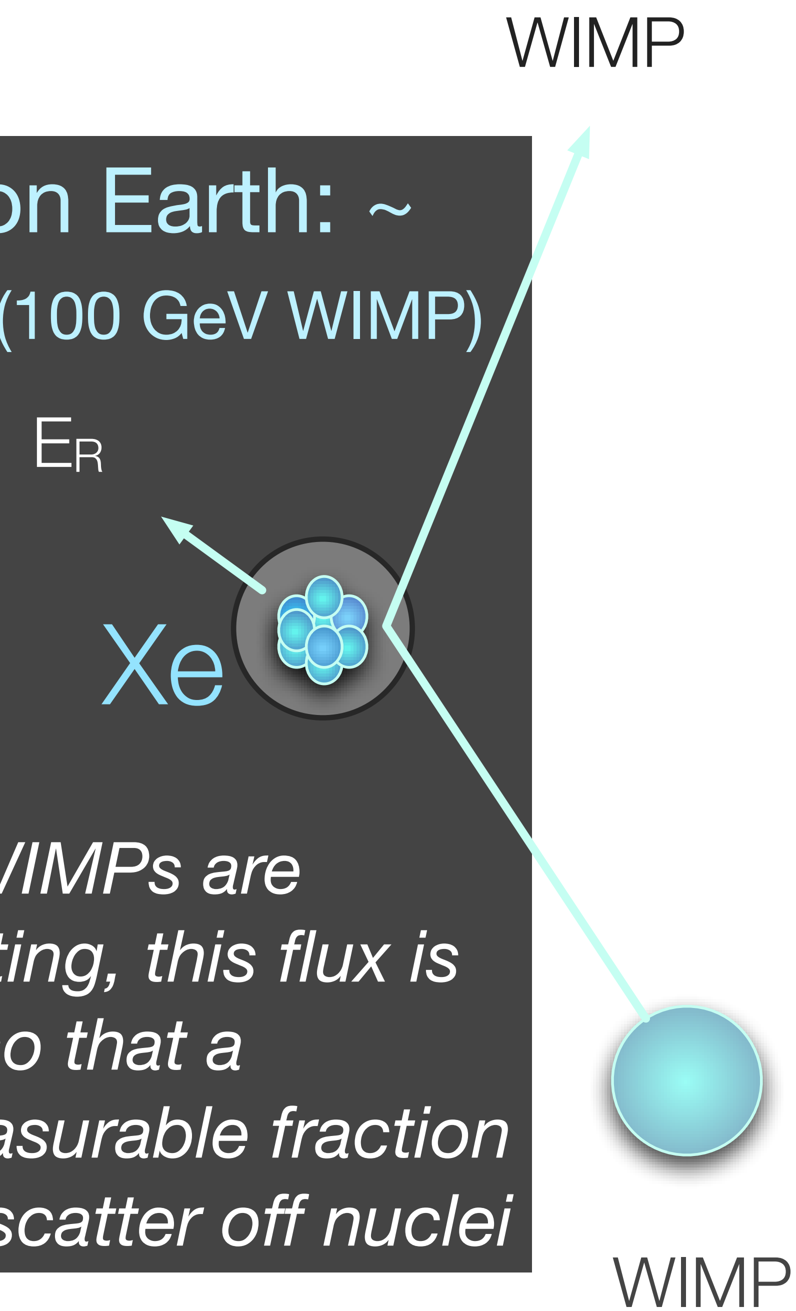
DarkAttack, Ascona, July 18, 2012

XENON100 and Cold Dark Matter

- Goal: detect Weakly Interacting Massive particles via elastic scattering off xenon nuclei in an ultra-low background time projection chamber filled with high-purity LXe


(J. Diemand et all, Nature 454, 2008, 735-738)

WIMP flux on Earth: ~ ~ 10^5 $cm^{-2}s^{-1}$ (100 GeV WIMP)

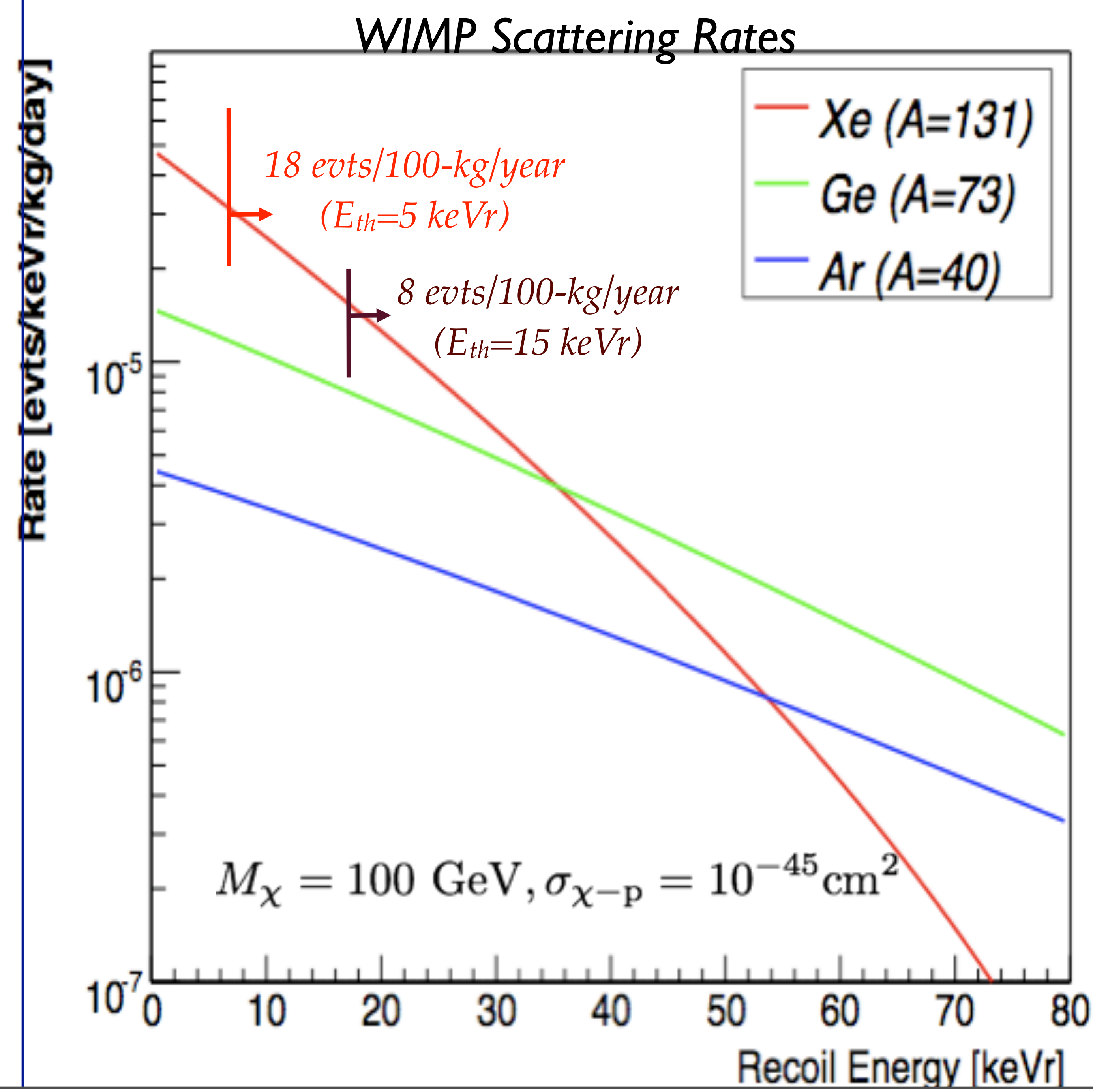


Even though WIMPs are weakly interacting, this flux is large enough so that a potentially measurable fraction will elastically scatter off nuclei

Liquid Xenon for Dark Matter Direct Detection

- **scalable:** ton scale target at modest cost (~ $1000/kg)
- **Xe nucleus (A~131):** expect high rate for SI interactions if low energy threshold for NR
- **~50% odd isotopes** (Xe-131 and Xe-129) for SD interactions
- **Intrinsically pure:** no long-lived radioactive isotopes; Kr/Xe can be reduced to ppt level
- **High Stopping Power (Z= 54):** active volume is self-shielding
- **Charge & Light:** highest yields among noble liquids. Simultaneously detected for NR discrimination

$$R \sim \frac{M_{det}}{M_{\chi}} \rho \sigma \langle v \rangle$$



The Xe Scintillation Light Mechanism

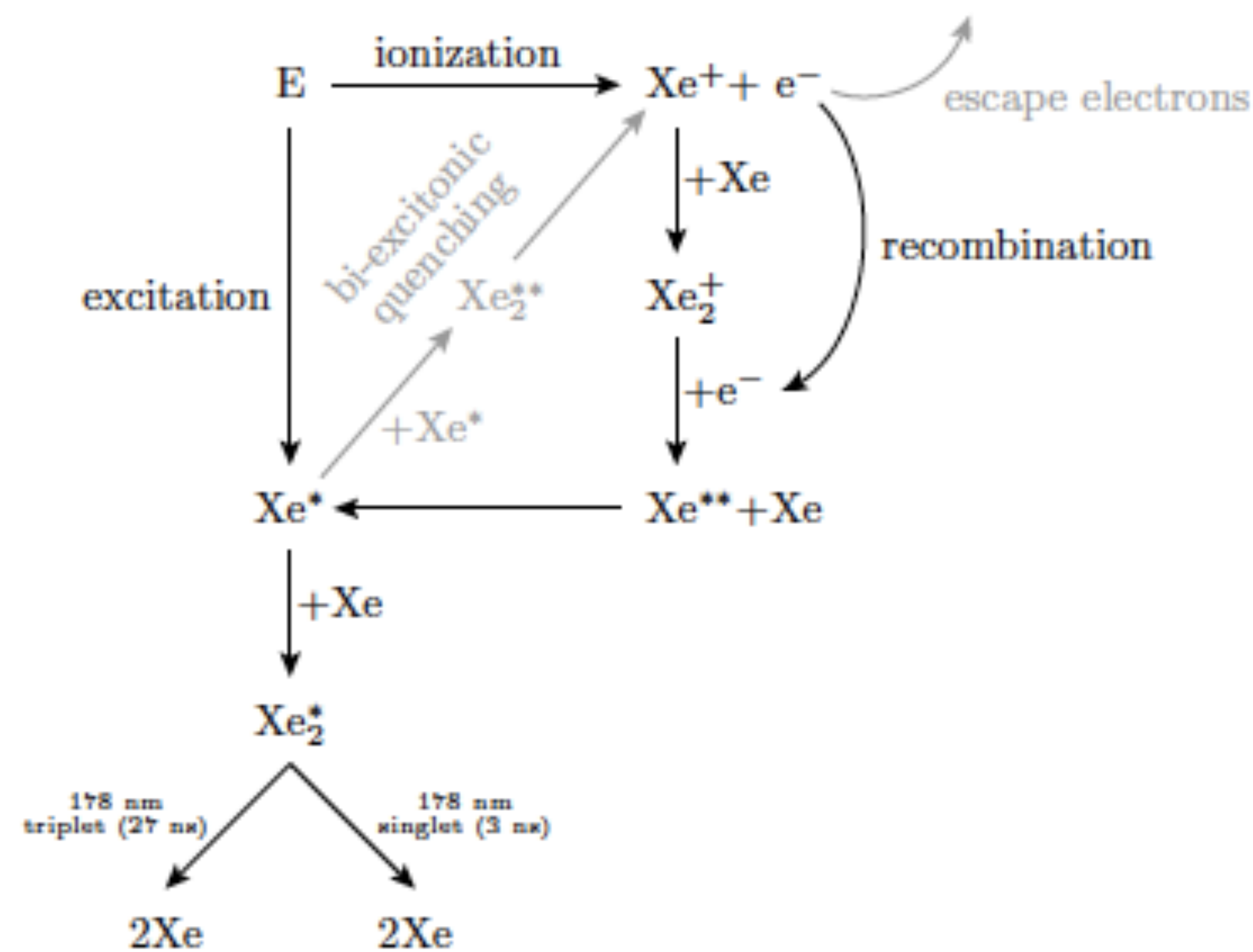
- Light originates from breakup of dimers where one partner atom is either excited or ionized by incident radiation

- This leads to two positive consequences and ..one problem

  - ➡ Near perfect transparency to its own scintillation light

  - ➡ two scintillation time constants: one from dimer breakup involving excited atoms (prompt light, few ns) and one from ionized atoms (late light, tens of ns)

  - ➡ VUV emission - windows stop working - use PMTs coupled directly with LXe



Light and Charge depend on particle dE/dx

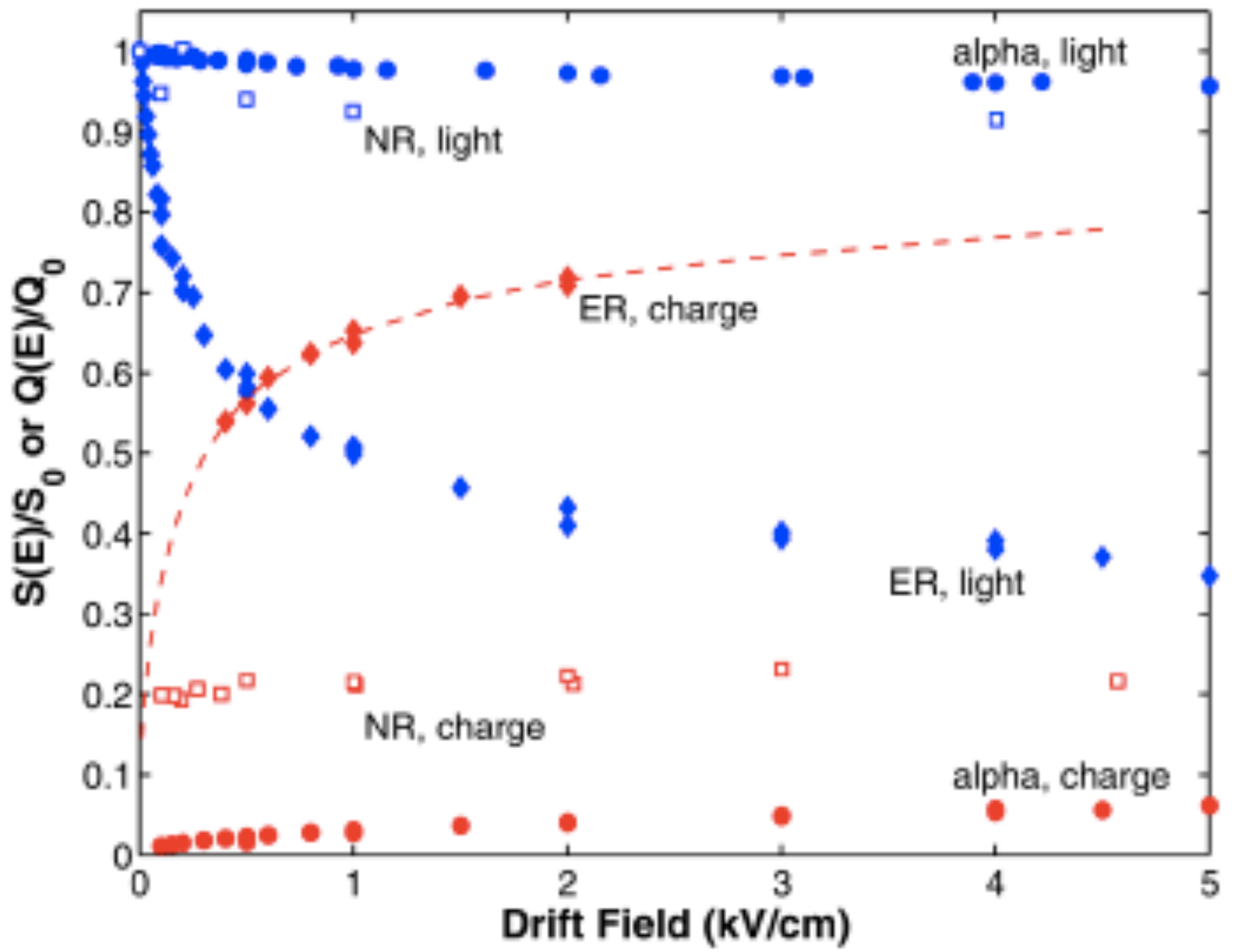


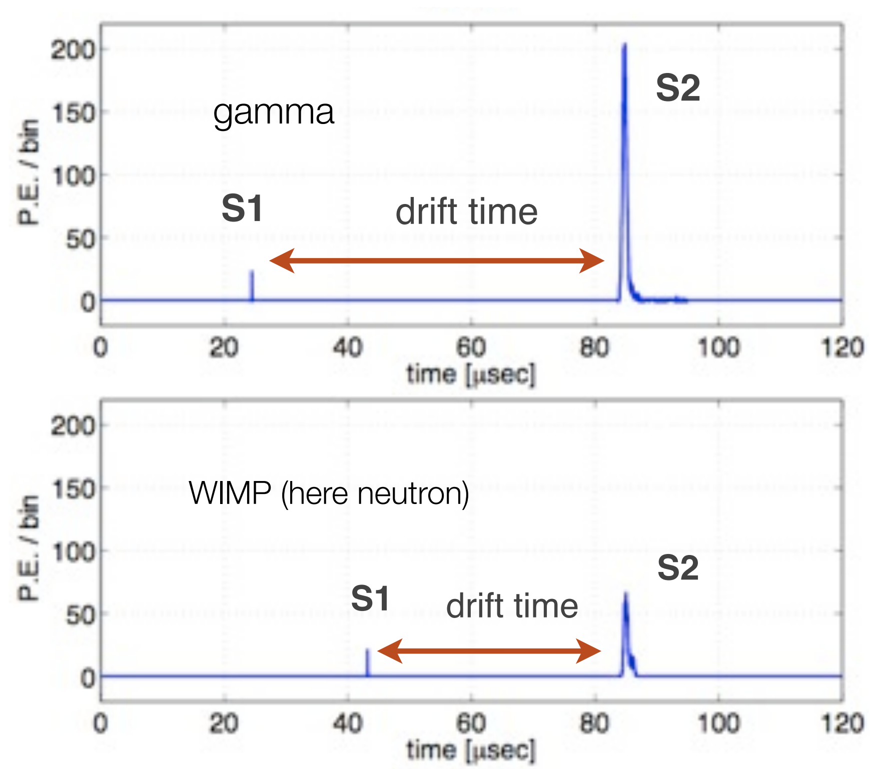
Figure 2.9: Field dependence of relative ionization and scintillation yields of α particles, electronic recoils (ER), and nuclear recoils (NR) in LXe. Figure from Aprile *et al.* (2006b).

Aprile et al., Phys. Rev. Lett., 97 (2006), 081302.

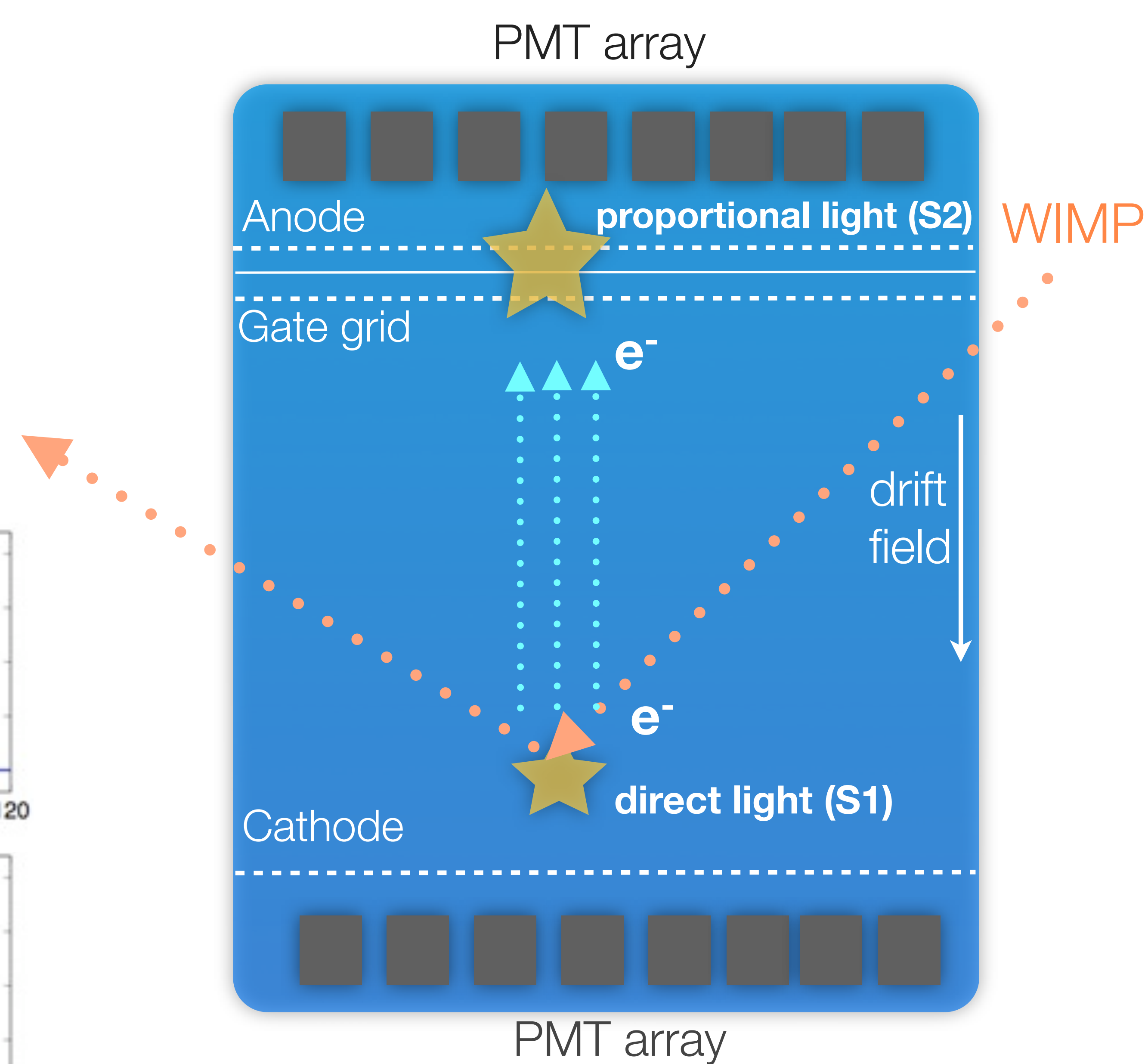
The Detection Method: a Liquid Xenon TPC

- XENON100: a large, homogeneous, scalable detector
- Particle interaction in the active volume produces prompt scintillation light (S1) and ionization electrons
- Electrons drift to interface (E= 0.5 kV/cm) where they are extracted and amplified in the gas. Detected as proportional scintillation light (S2)
- $(S2/S1)_{WIMP}$ << $S2/S1)_{Gamma}$

  ➡ 3-D position sensitive detector with particle ID



Xe (A=131); λ = 178 nm



The XENON Roadmap

XENON10

2005-2007

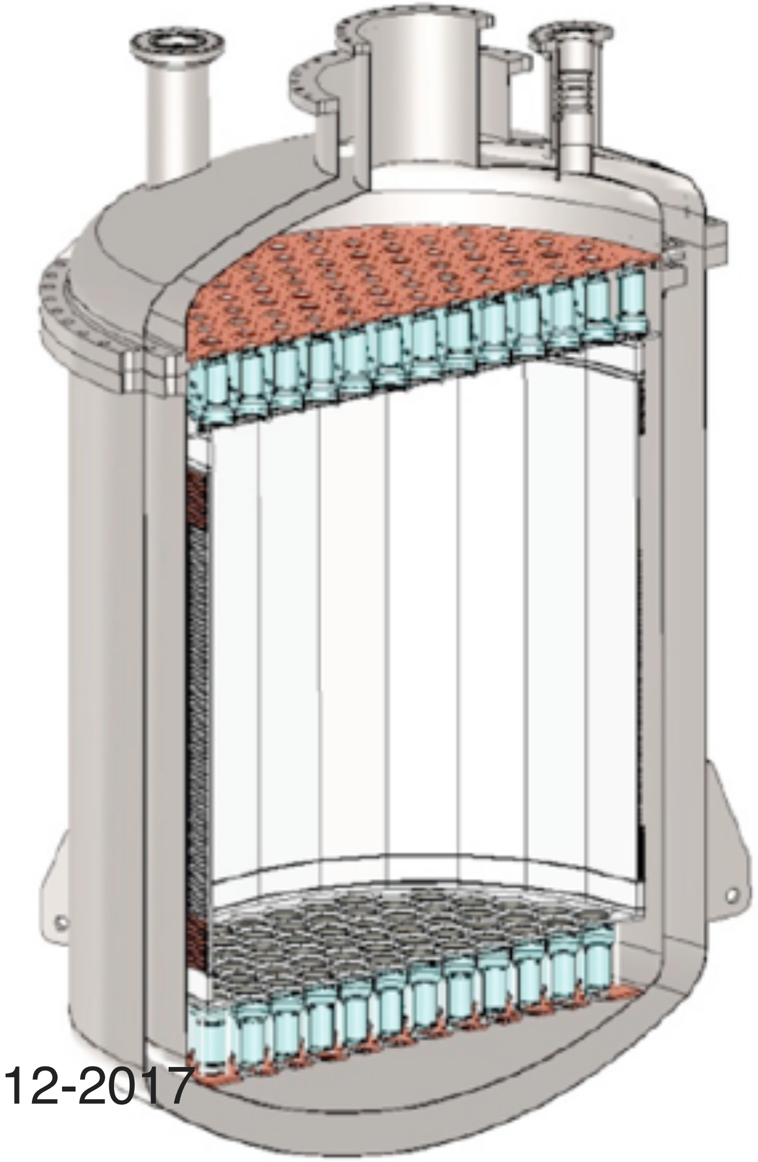
PRL100
PRL101
PRL 107
PRD 80
NIM A 601

XENON100

2007-2013

first results:
PRL105, PRL107, PRD84

XENON1T



2012-2017

approved at LNGS, Hall B
construction starts in fall 2012

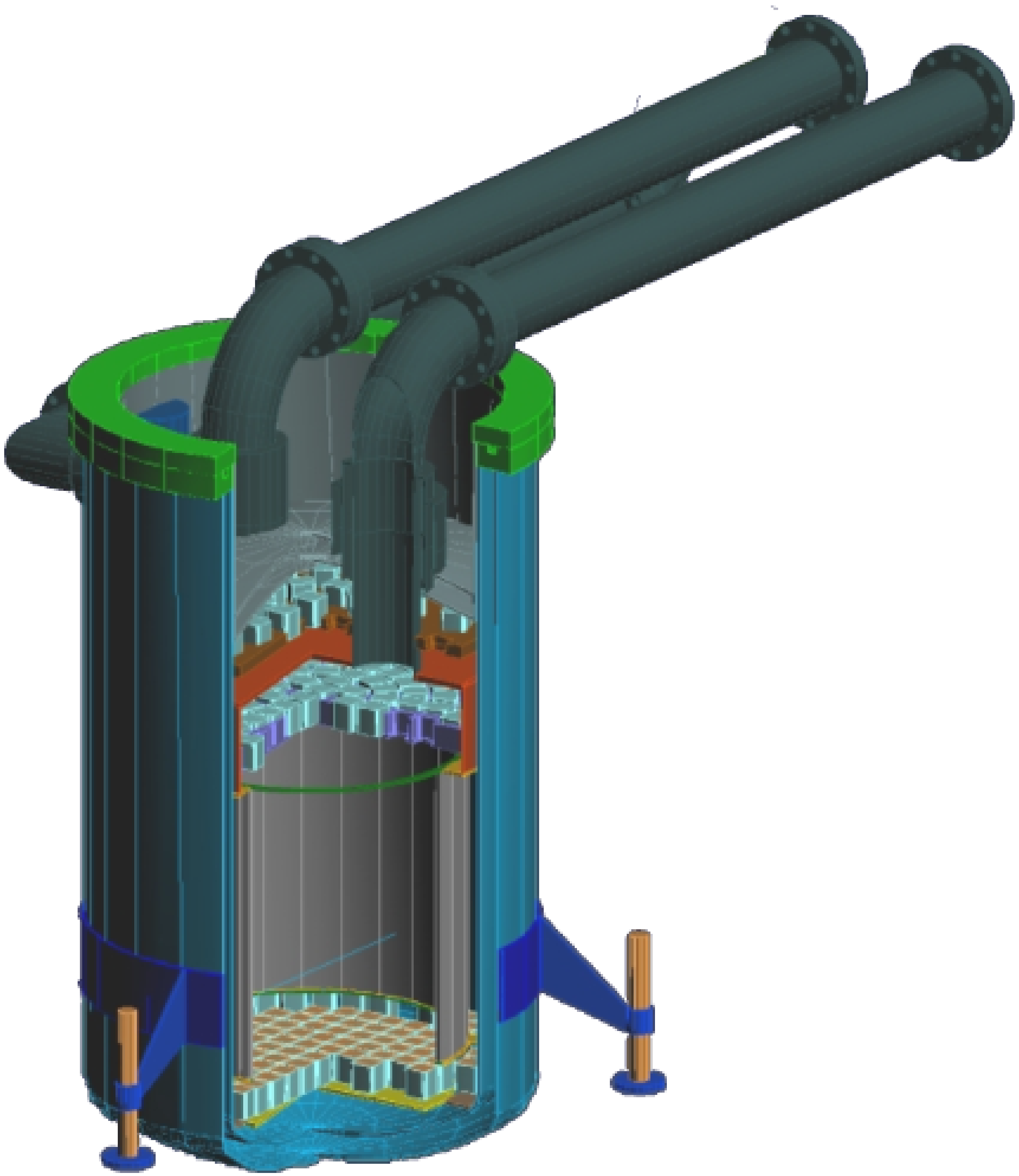
- Gradually increasing the WIMP target mass while decreasing the background level

The XENON Collaboration

Columbia Rice UCLA Zürich Coimbra LNGS SJTU

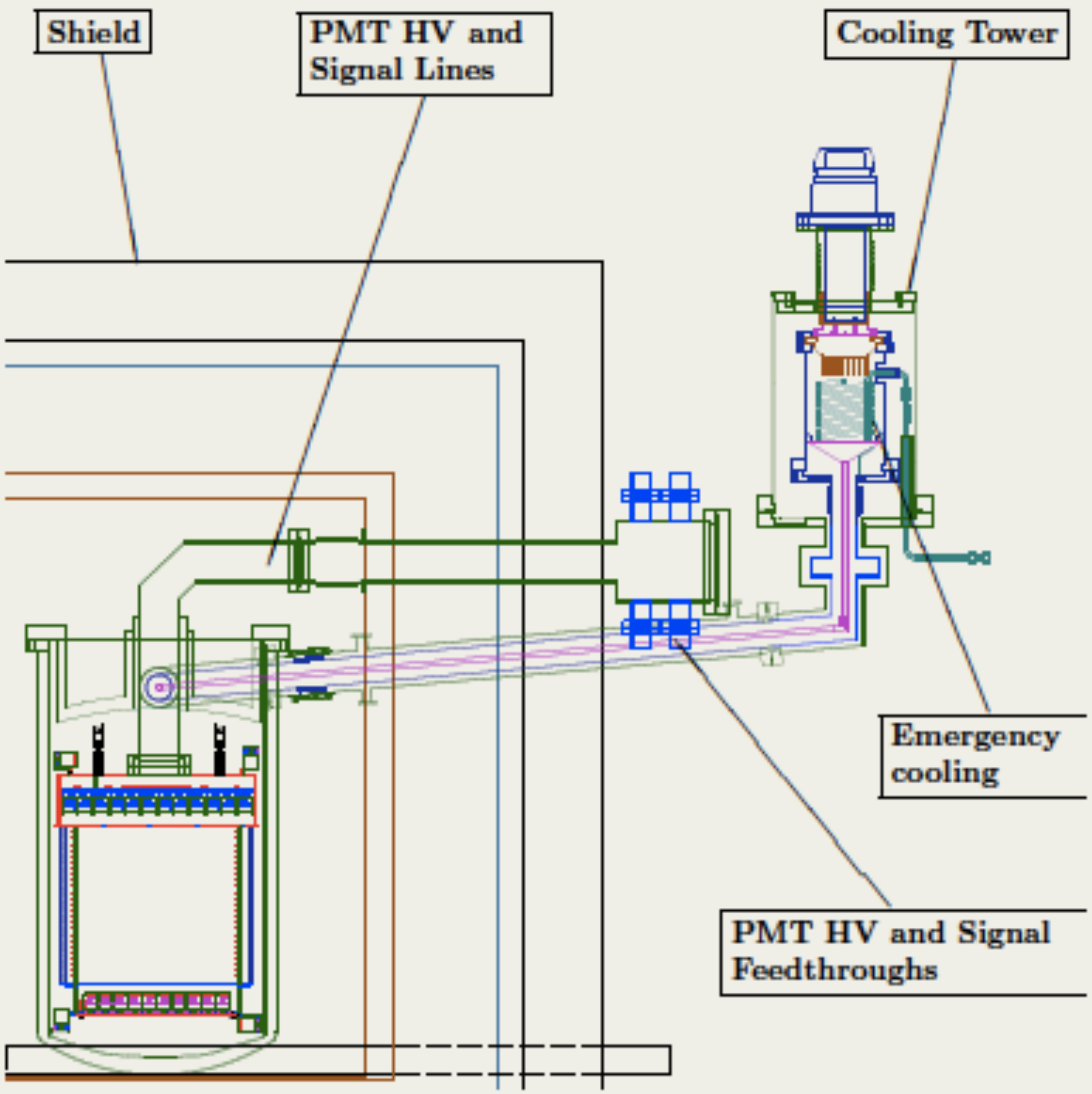
Mainz Bologna Subatech Münster Nikhef Heidelberg Weizman Purdue

The XENON100 detector overview



- 100 x less background than XENON10
- 10 x more fiducial mass than XENON10
- Cryocooler and FTs outside shield
- Materials screened for low radioactivity
- LXe scintillator active veto system
- Improved passive shield system
- Dedicated Kr distillation column
- TPC with 30 cm drift x 30 cm diameter
- 161 kg ultra pure LXe - 62 kg as target
- 1” square PMTs with ~1 mBq (U/Th)

The XENON100 Cryogenic System

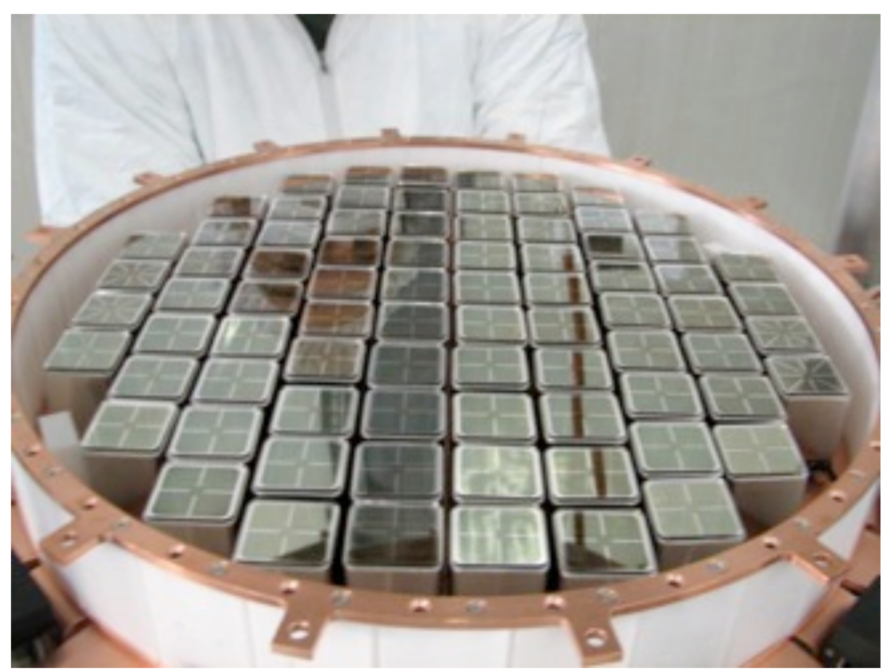


- PC150 PTR 200 W in a "cooling tower" outside passive shield.
- Copper cold finger in thermal contact with the PTR coldhead seals the top of the inner vessel. Copper "cup" with resistive heaters between the PTR coldhead and the cold finger.
- The temperature of the cold finger is regulated via a PID control loop that adjusts the heater power.
- LXe flows back from the cooling tower to the cryostat vessel through an inclined double-wall pipe.
- Recirculation takes LXe from the bottom of the vessel and pushes back GXe in the bell.
- Emergency cooling provided by LN_2 flowing through a stainless steel coil inside the cooling tower.

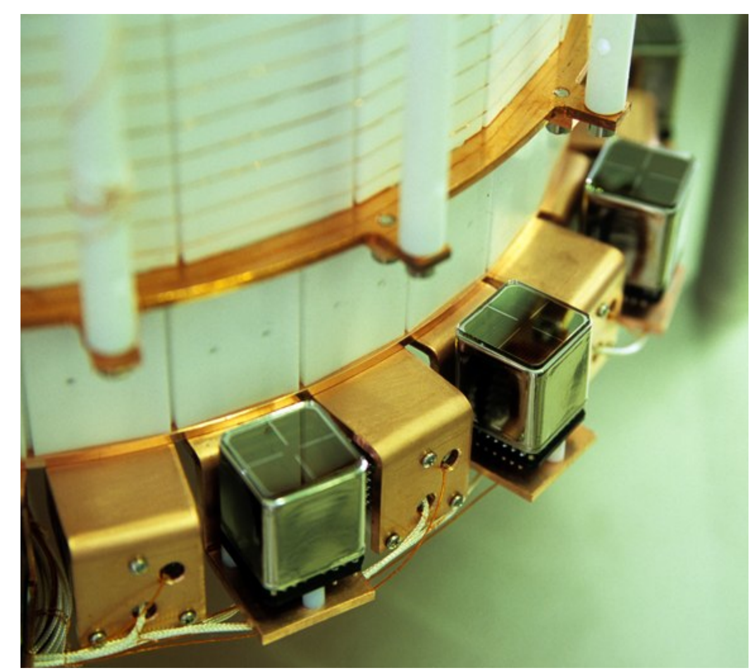
The XENON100 photosensors

- 1-inch square R8520 Hamamatsu PMTs, optimized to work at LXe T and P, and of low-radioactivity (< 1 mBq/PMT in $^{238}U/^{232}Th$)
- Top array: 98 PMTs (23% quantum efficiency) in concentric circles to improve radial event position reconstruction, teflon holder
- Bottom array: 80 PMTs, closely packed, and of higher quantum efficiency (32-34% at 178 nm), for efficient S1 light collection
- LXe veto: 64 PMTs, 23% quantum efficiency

top array

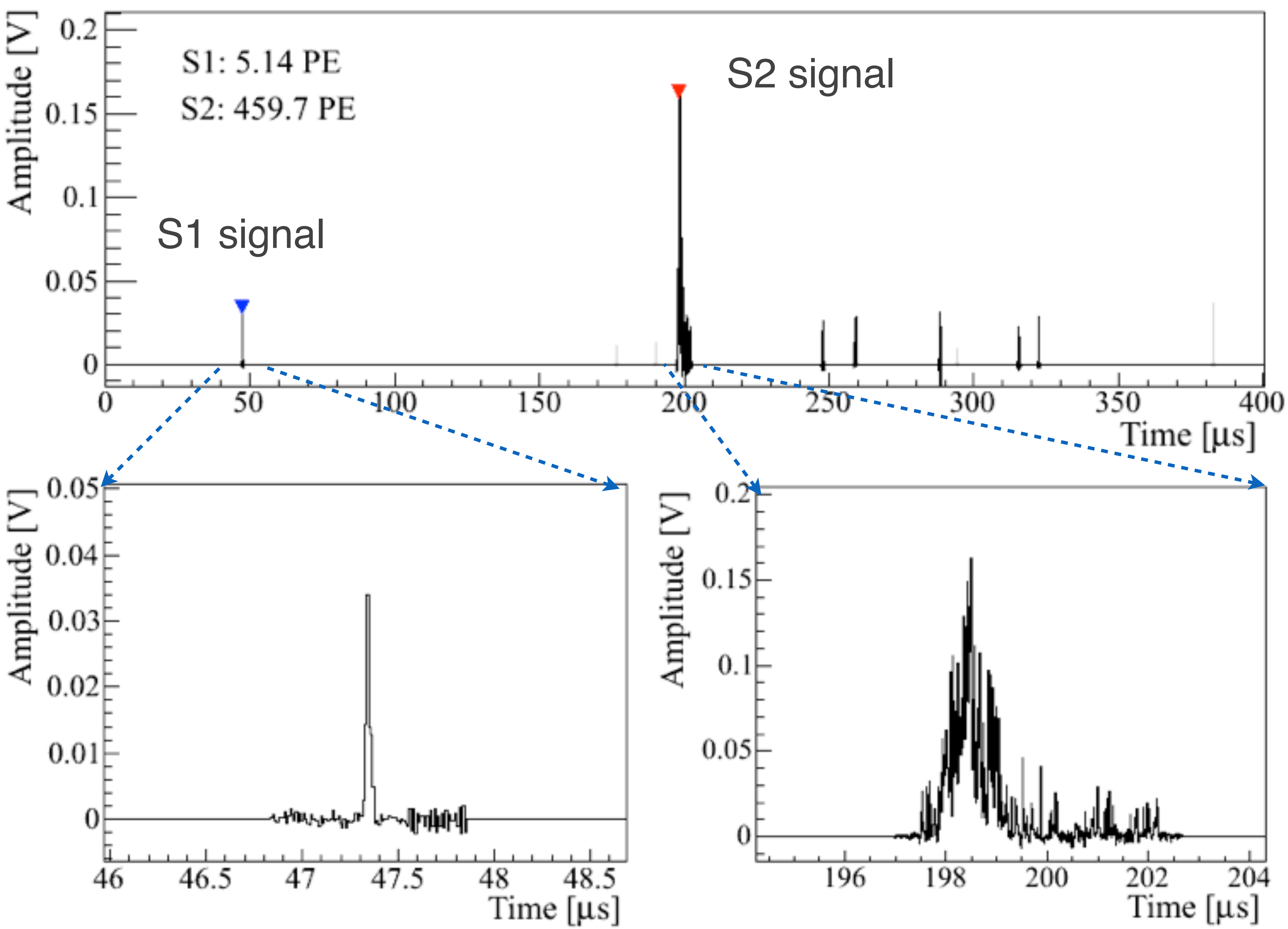


bottom array

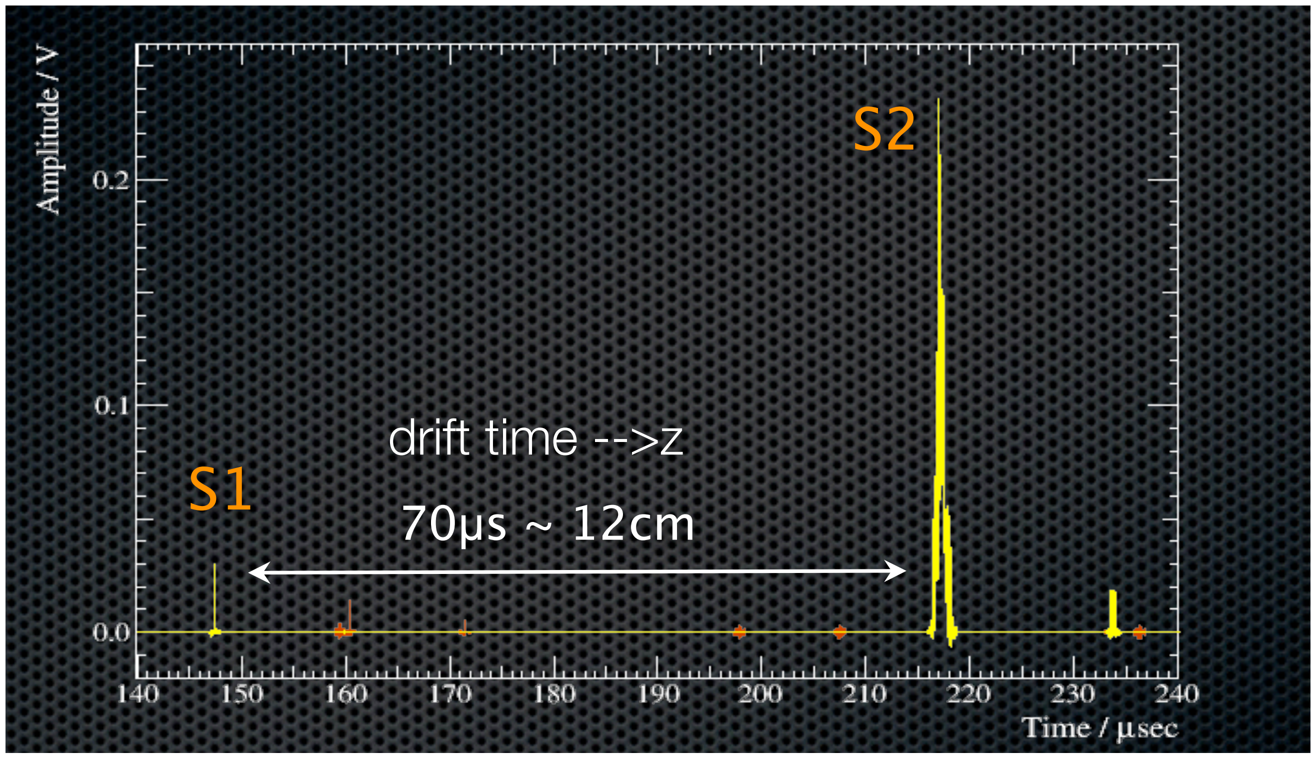


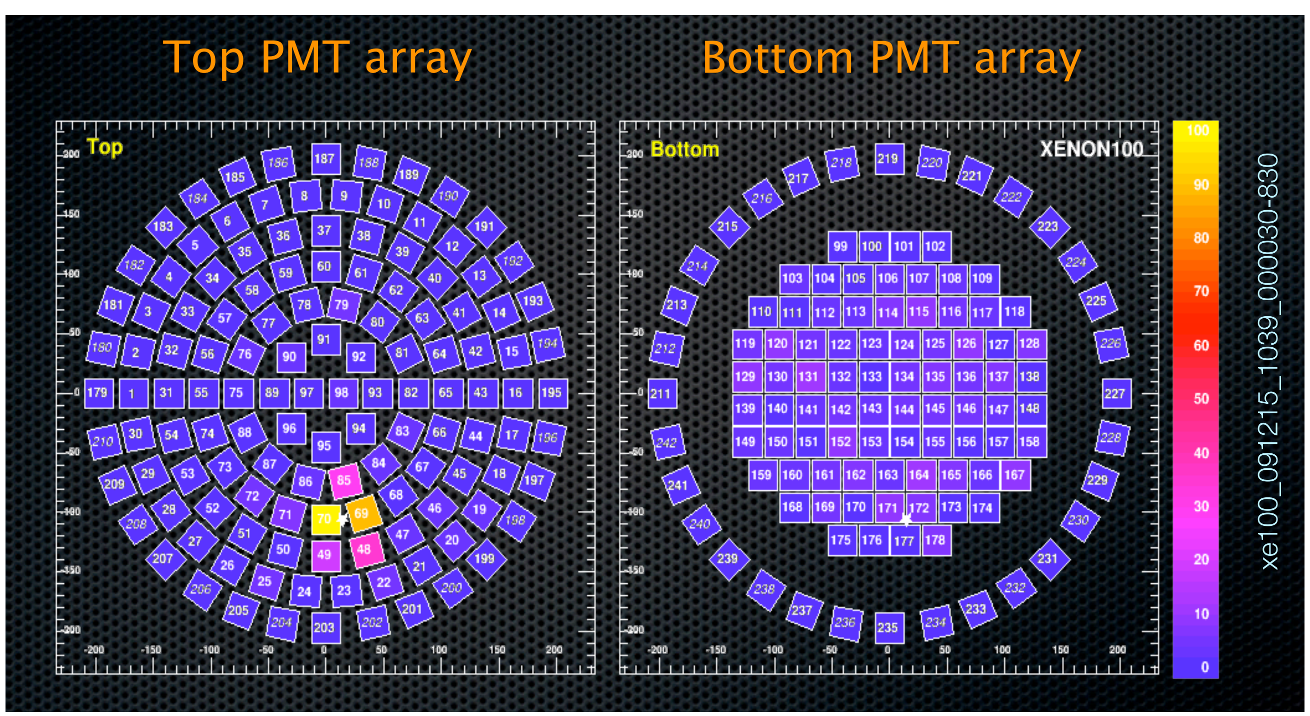
veto PMTs

Example of a low-energy event waveform



Event Position Reconstruction





Example of a low energy (9 keVnr)

4 photoelectrons detected from about 100 S1 photons

645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

Event Z-position from measured drift time t(S2) - t(S1) and known e- velocity. dZ< 0.3 mm

event X-Y position from measured S2-hit-pattern. dR < 3mm

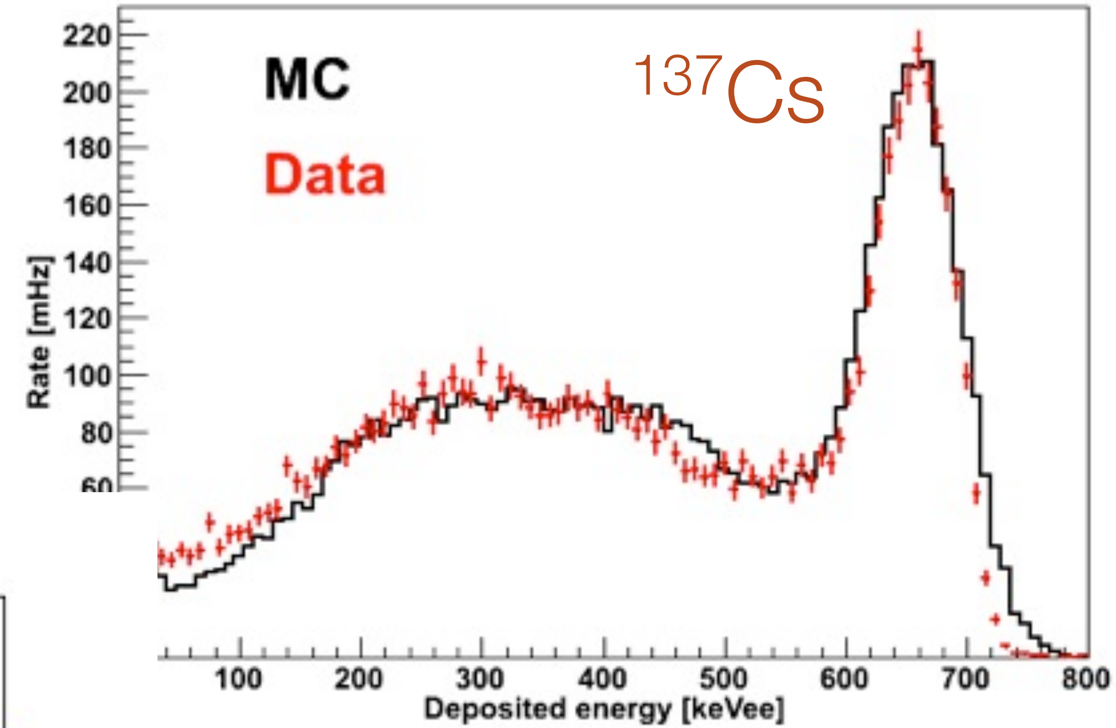
XENON100 Location and Shield

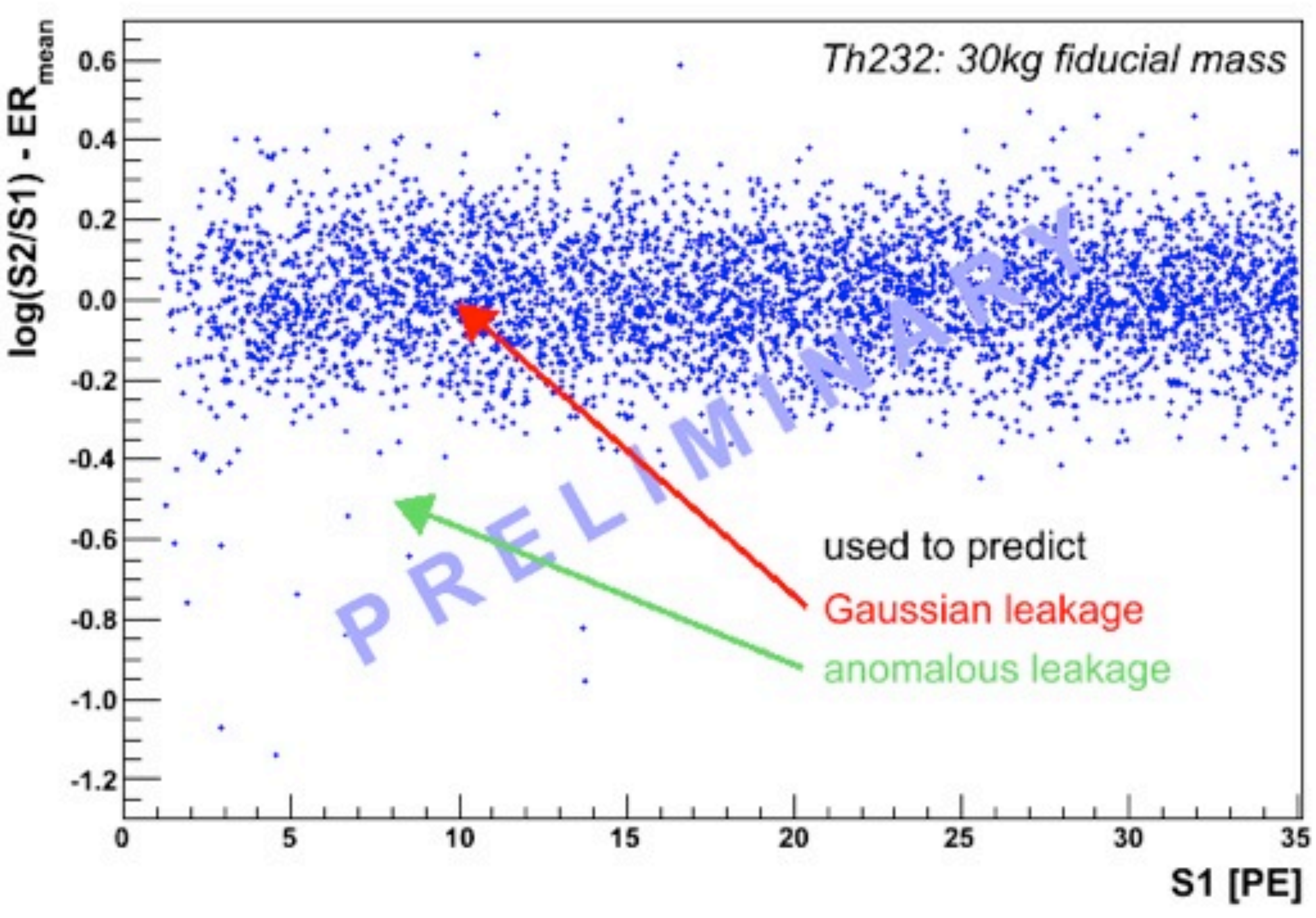
- LNGS provides the shield against cosmic rays: 1.4 km of mountain
- Passive shield:
  - ➡ 5 cm (2 tons) of Cu, 20 cm (1.6 tons) of PE, 20 cm (33 tons) of Pb, plus 20 cm water shield
- Detector housing is continuously purged with boil-off N_2, to maintain a radon level < 0.5 Bq/m^3
- All materials screened with HPGe detectors at LNGS see *Astroparticle Physics 35, 2011*

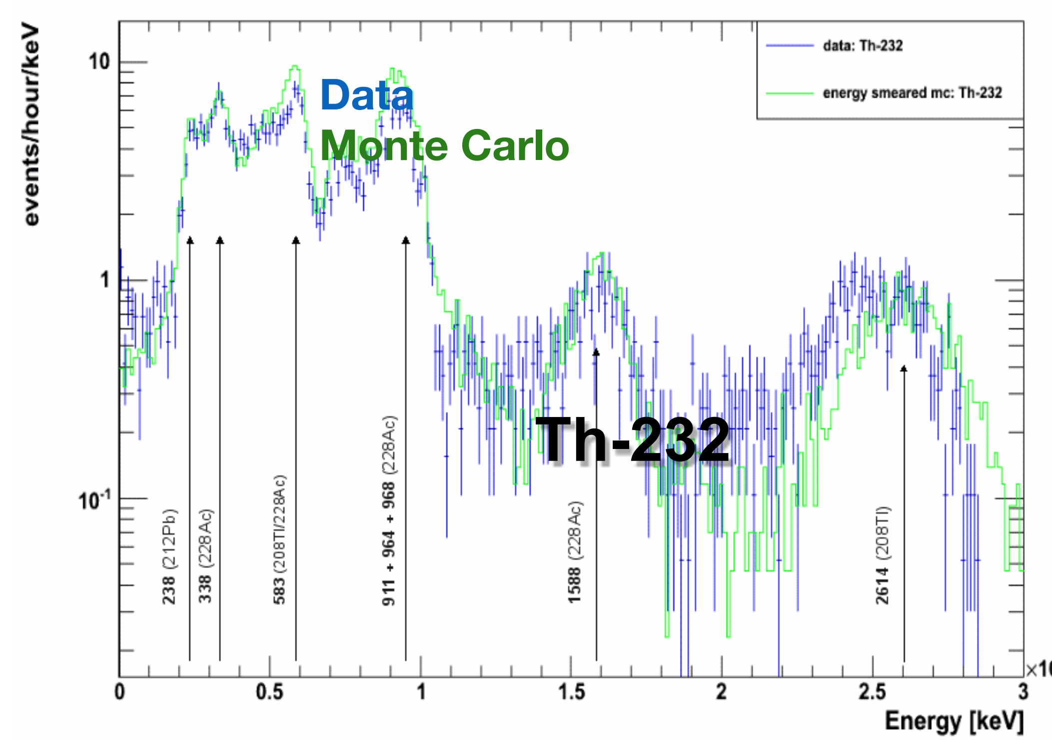
1 m

XENON100 gamma calibrations

- ^{137}Cs data to monitor the charge & light yields
- ^{60}Co and ^{232}Th data used to map the electron recoil band and predict EM background (irradiate at three points around TPC)
- ^{232}Th data also used to understand spectrum up to high energies

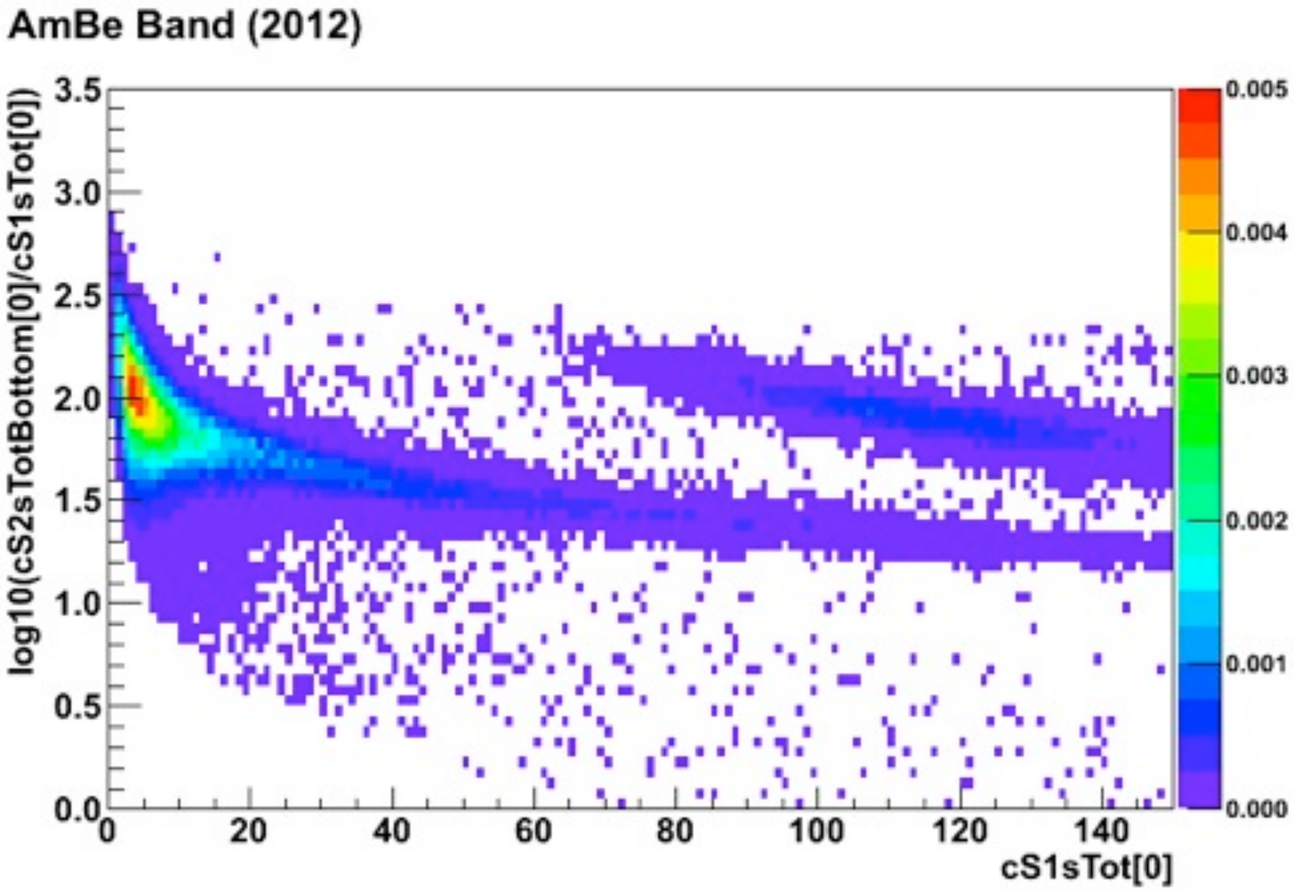


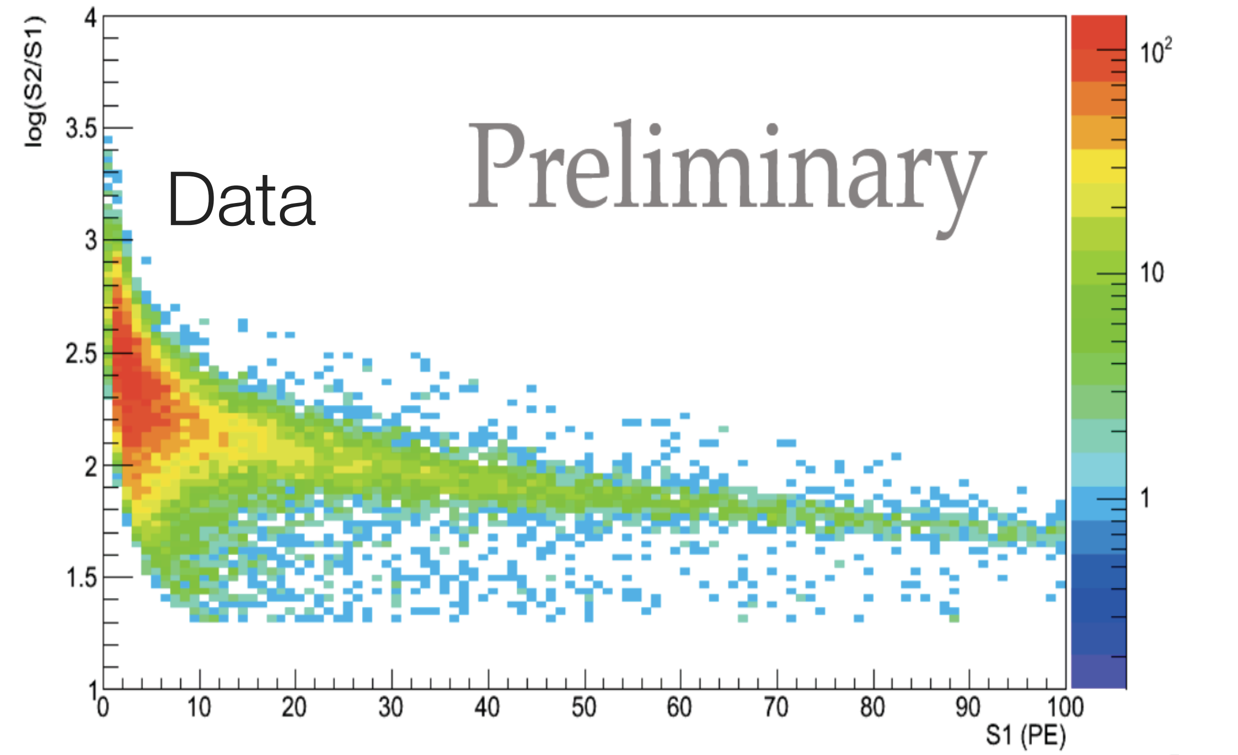


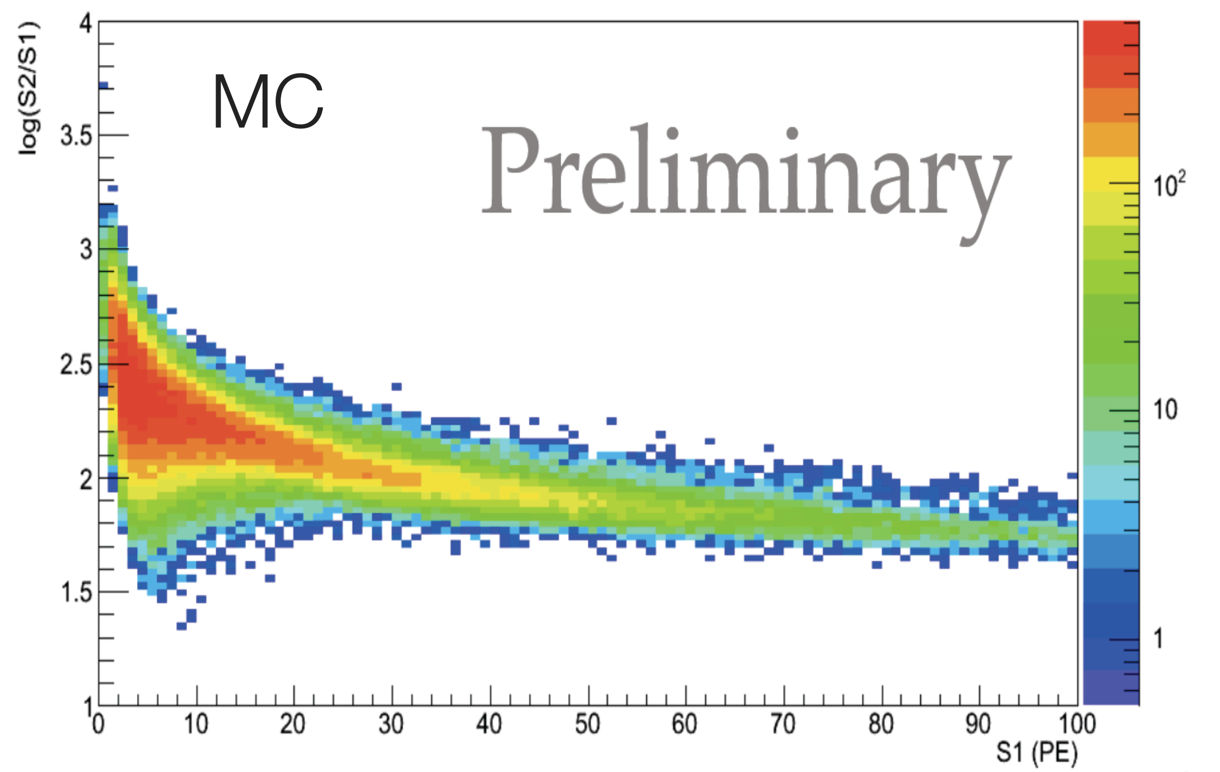


XENON100 neutron calibration

- Nuclear Recoil band calibration performed with a 220 n/s AmBe neutron source

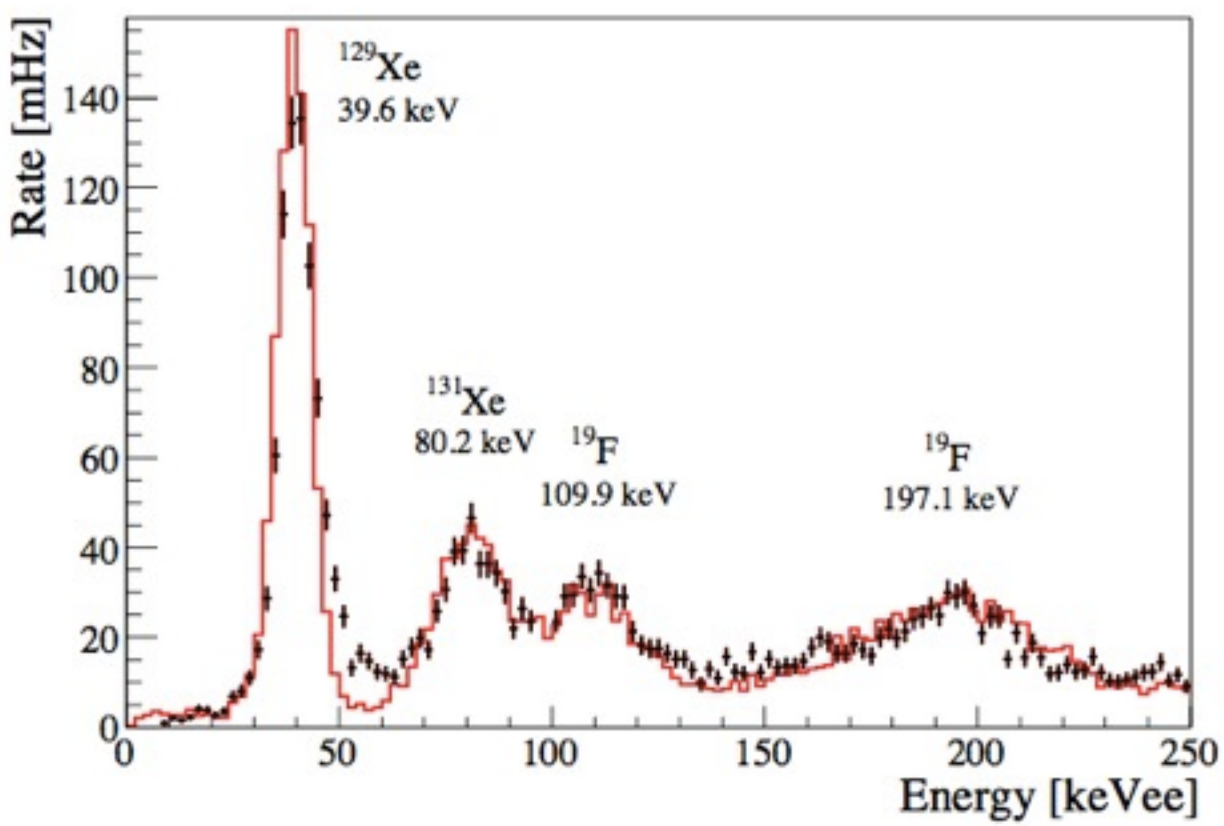


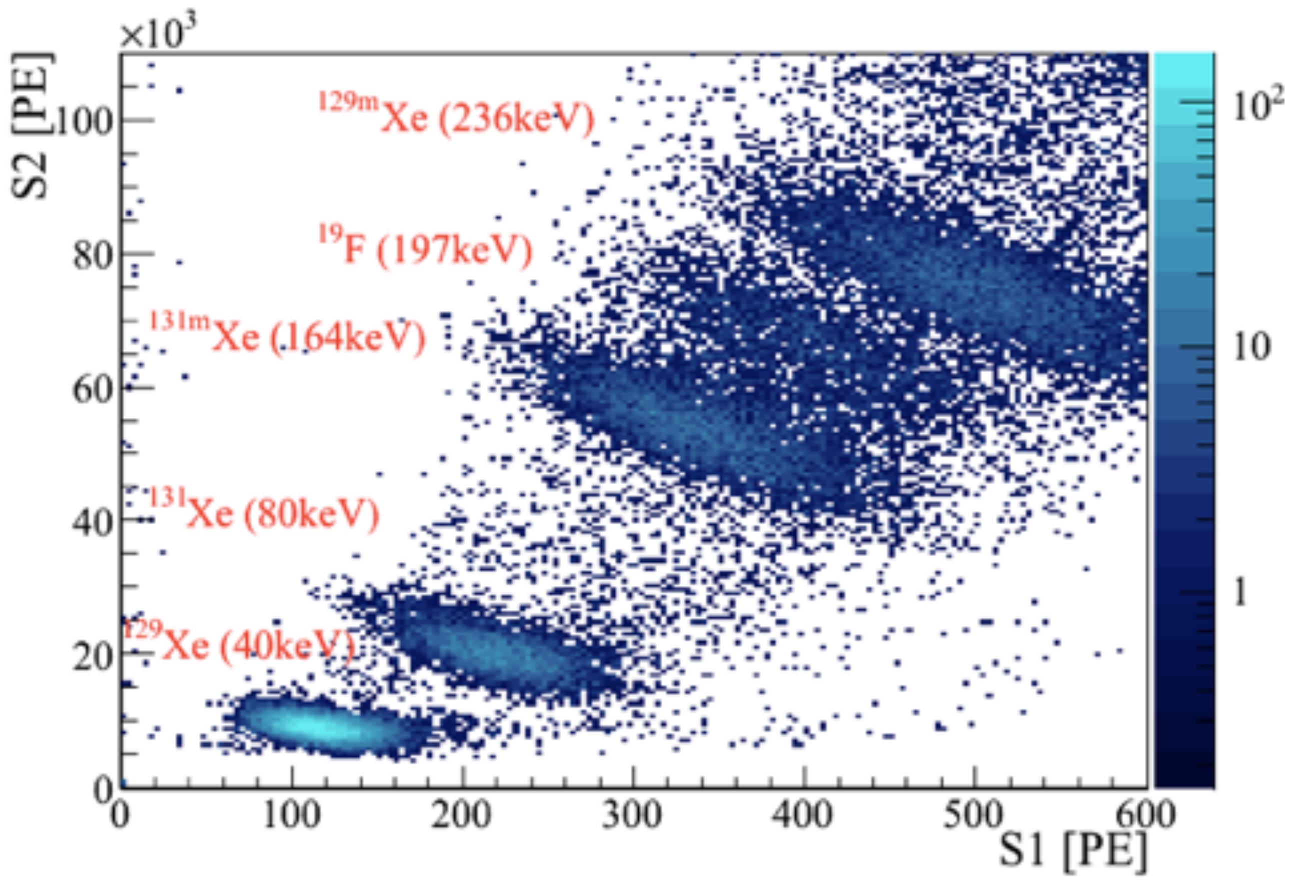




Gammas from neutron calibrations

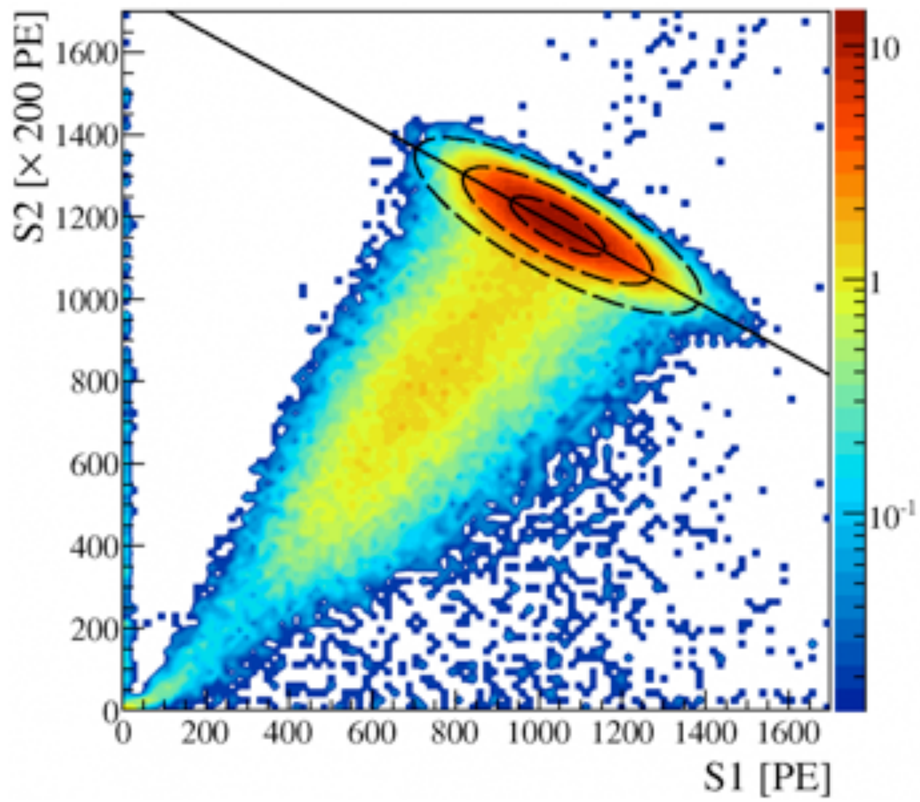
- AmBe (~ MeV neutrons) data to map the nuclear recoil band, 220 n/s
- Inelastic n-scattering on Xe: $^{129,131}Xe + n \rightarrow {}^{129,131}Xe + n + \gamma$ (40 keV, 80 keV)
- Inelastic n-scattering on F (in PTFE): $^{19}F + n \rightarrow {}^{19}F + n + \gamma$ (110 keV, 197 keV)
- Also Xe activation lines: ^{129m}Xe (236 keV) and ^{131m}Xe (164 keV)

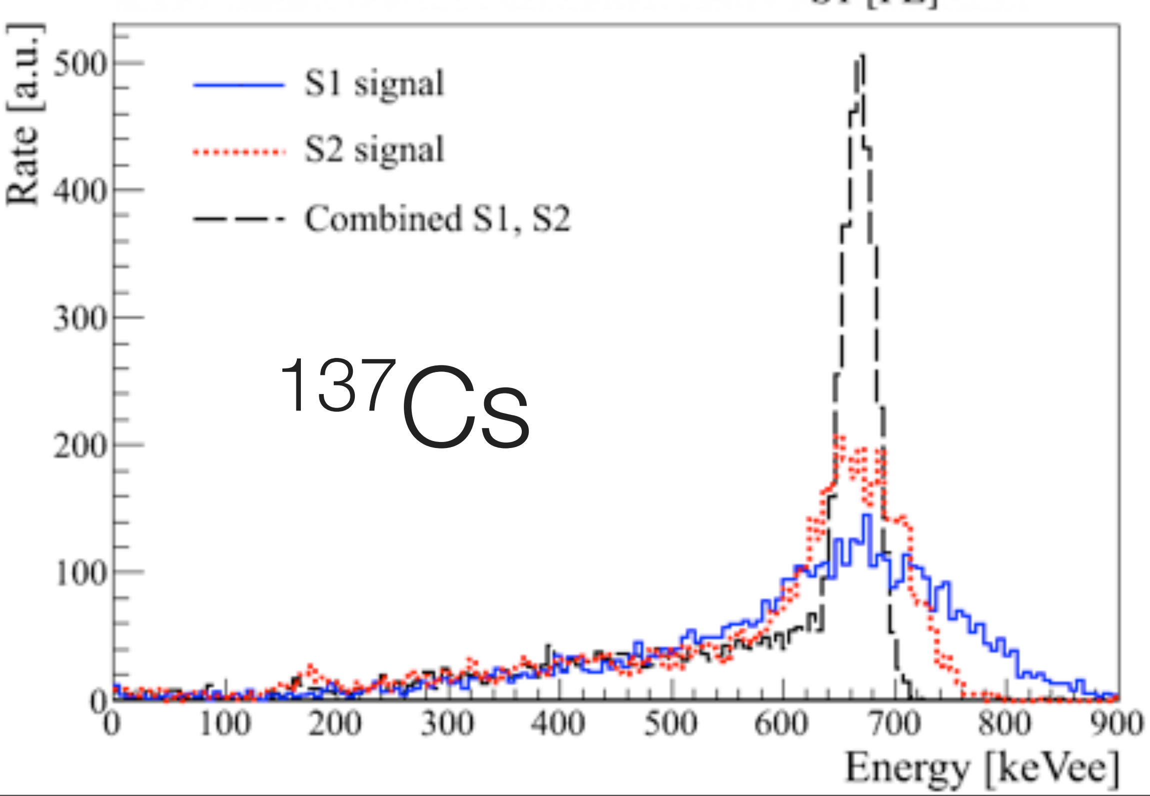


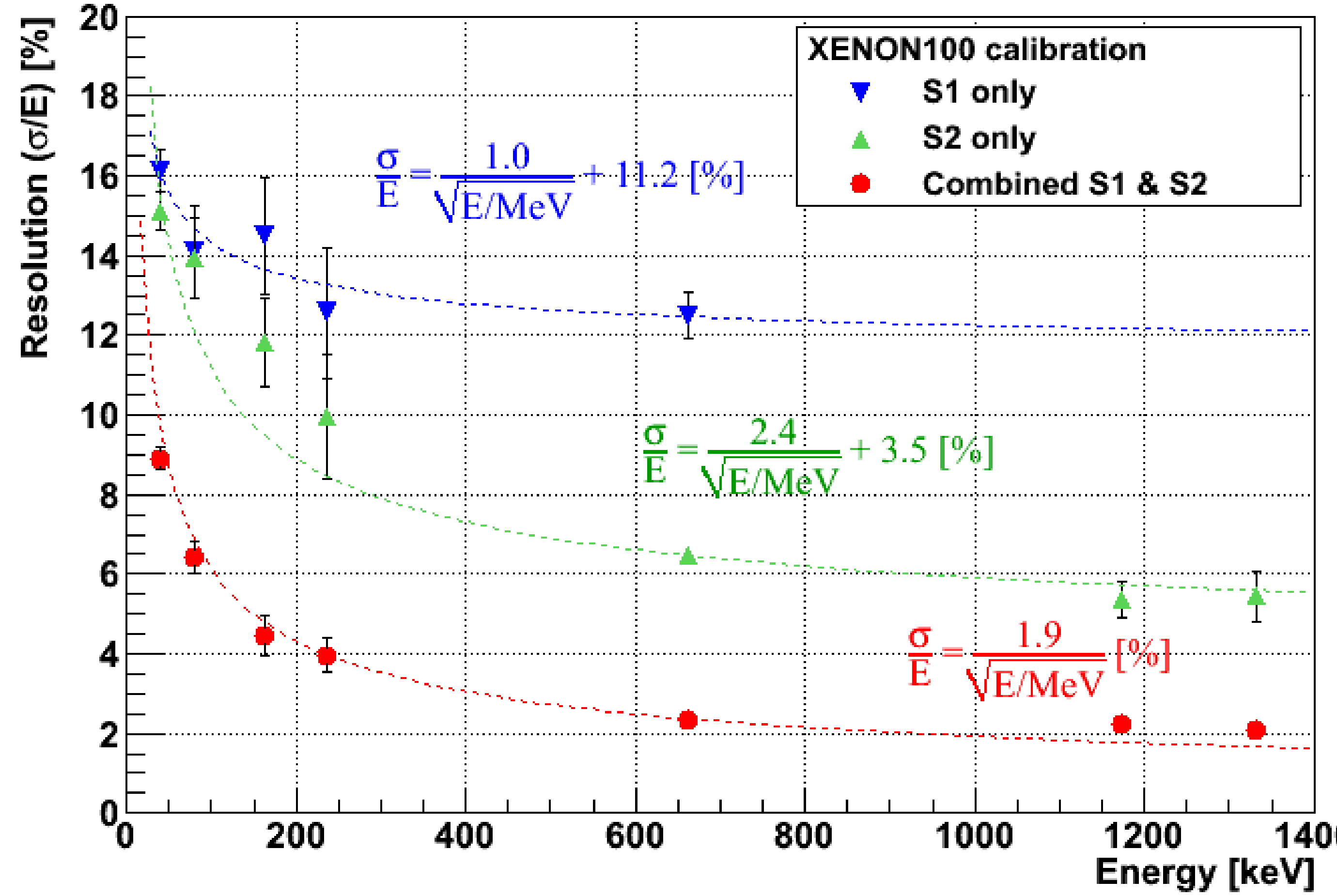


All gammas from the neutron irradiation of XENON100 are used to check/correct signal dependency with position and also to infer the LY at 122 keV

XENON100 energy resolution



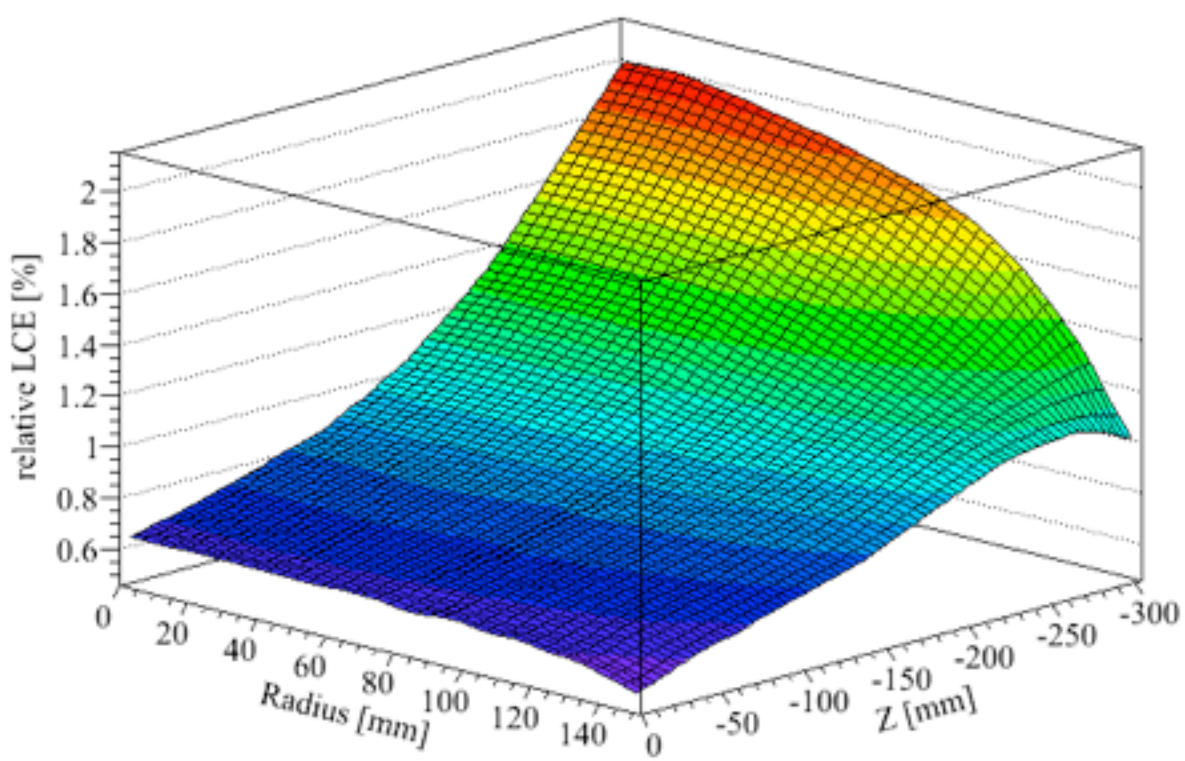




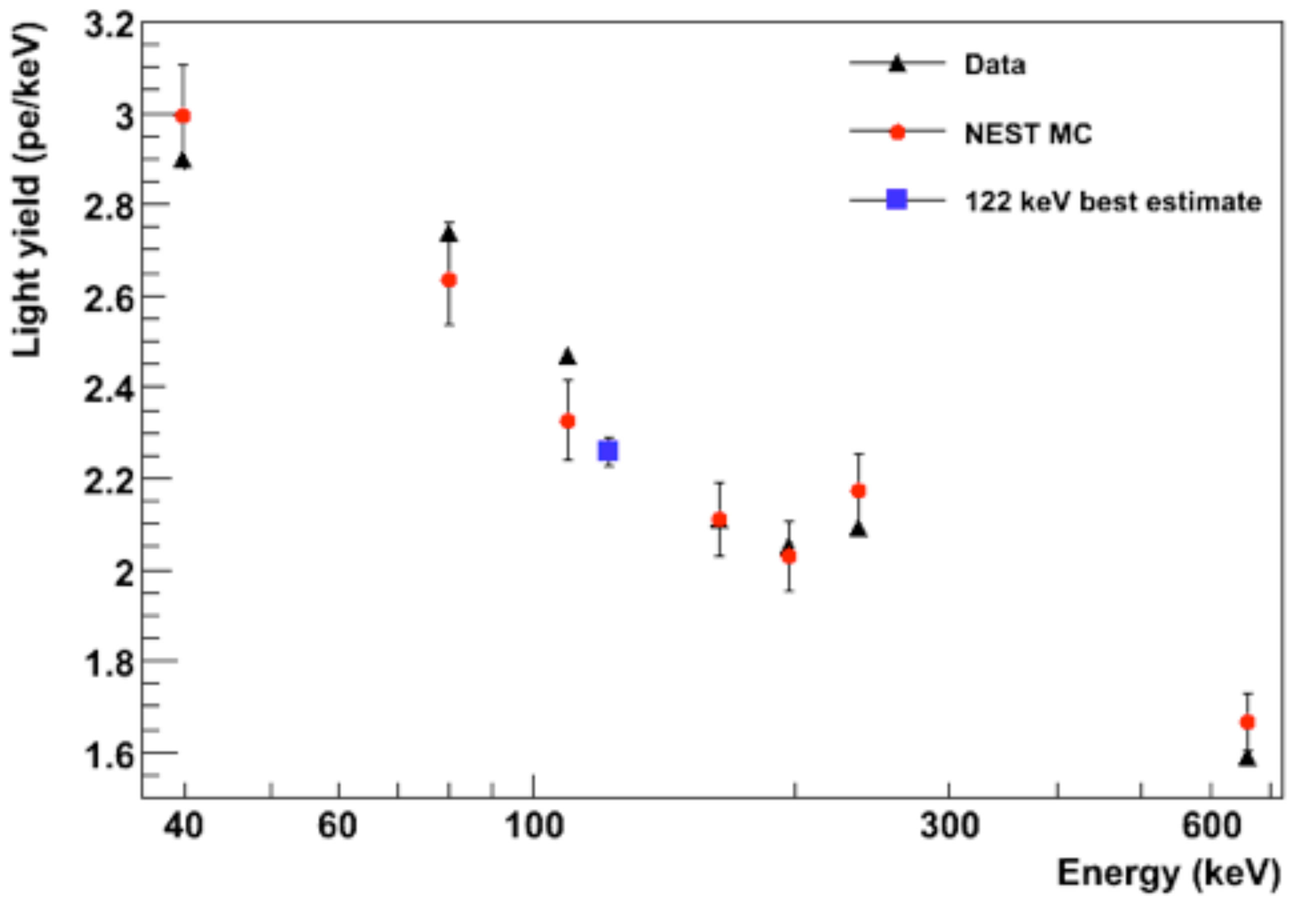
- Energy dependent energy resolution
- In S1, in S2 and in the "combined energy scale"
- Because of the anti-correlation of the S1 and S2 signals, the resolution is much improved when using both

S1 Signal Corrections

- S1 light collection depends on the event position in the TPC: a 3D map of the light collection efficiency (LCE) is inferred from irradiation with ^{137}Cs (662 keV) at different positions, from the 40 keV neutron inelastic scattering line, and the 164 keV line from n-activated ^{131m}Xe (all agree within 3%)
- Light yield at 122 keV is interpolated using NEST model and measurements at lower/higher energies with conservative 5% uncertainty. For Run10 the LY_{122keV} = (2.28 ± 0.04) PE/keV)



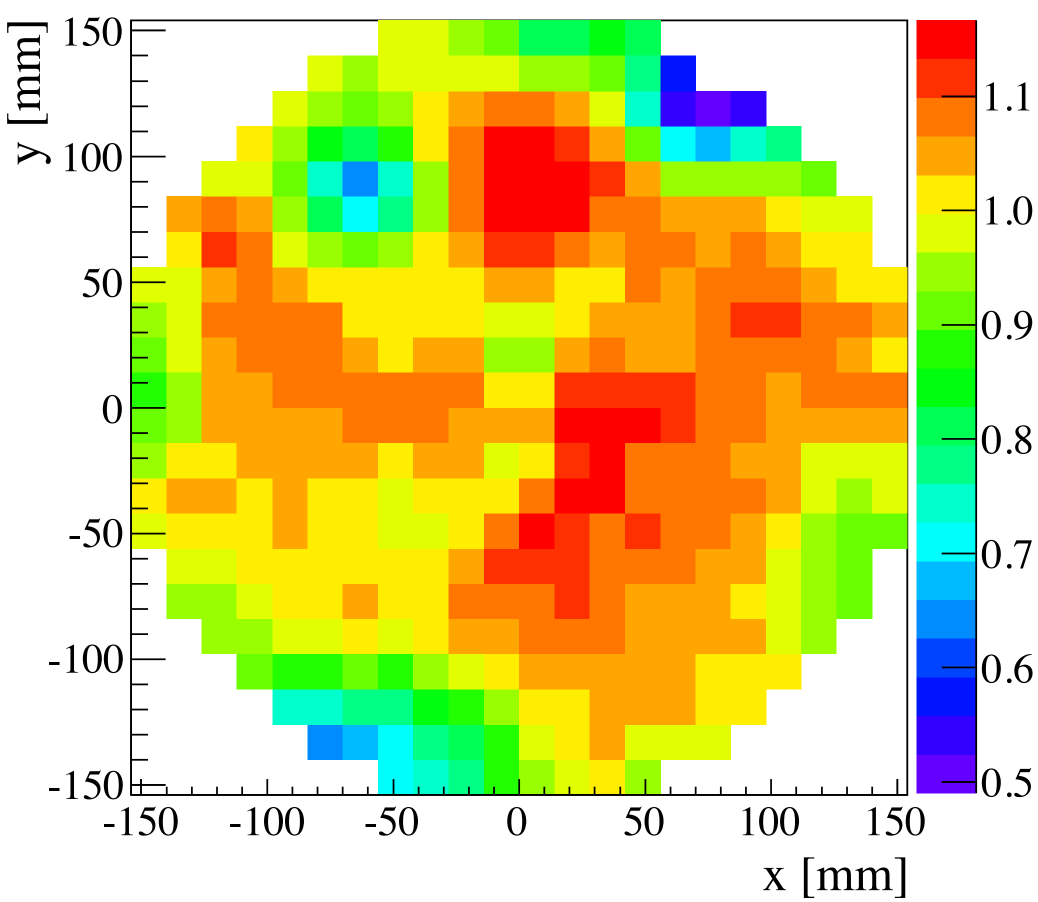
LCE correction map using the 40 keV line

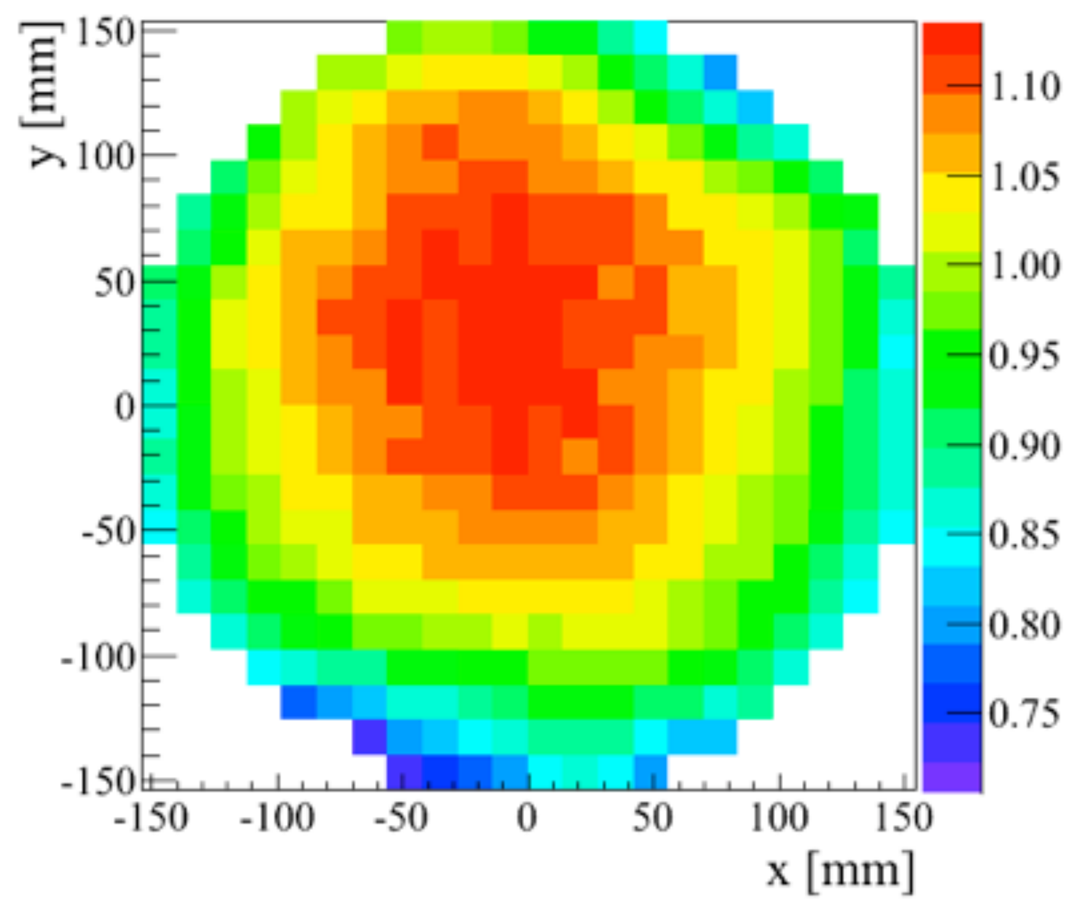


Light yield for different gamma lines

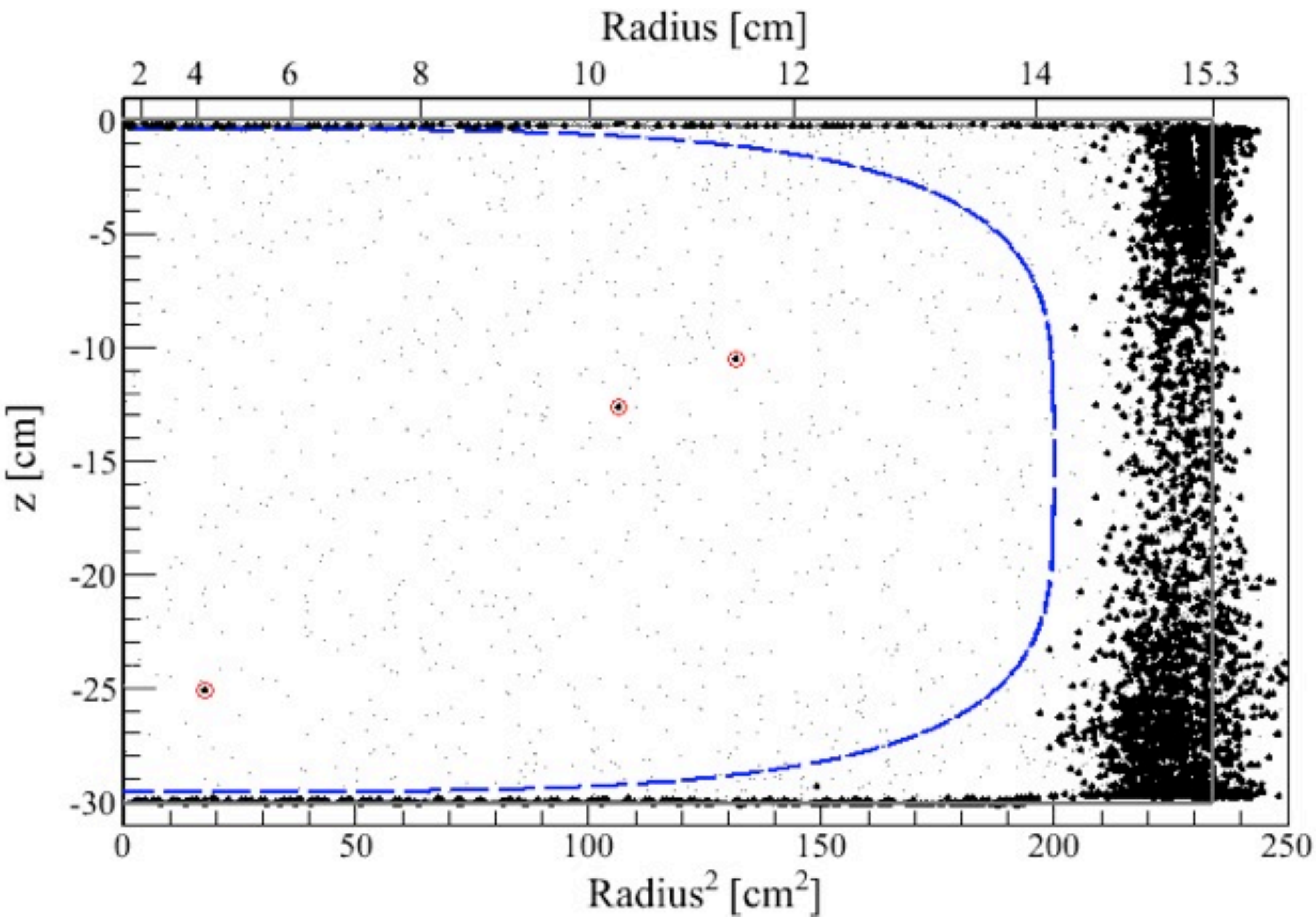
S2 Signal corrections

- S2 response on top (left) and bottom (right) measured with the 40 keV gamma line
- Shown are relative changes compared to the mean
- Decrease at large radii is due to S2 LCE
- S2 from top PMTs array shows slight warping of the anode mesh along the stretching directions
- Only S2 detected on bottom PMTs array (right map below) is used for S2/S1 discrimination parameter





Volume Fiducialization: power of a TPC



Background from published data (PRL 107)

- 3D event imaging allows to select only central volume with lowest background exploiting LXe self-shielding
- Gammas from detector components and external sources stopped at edges
- Remaining background in fiducialized volume dominated by internal sources like ^{85}Kr and ^{222}Rn in LXe

Nuclear Recoil Energy

- Nuclear recoil energy scale is set using the S1 signal

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

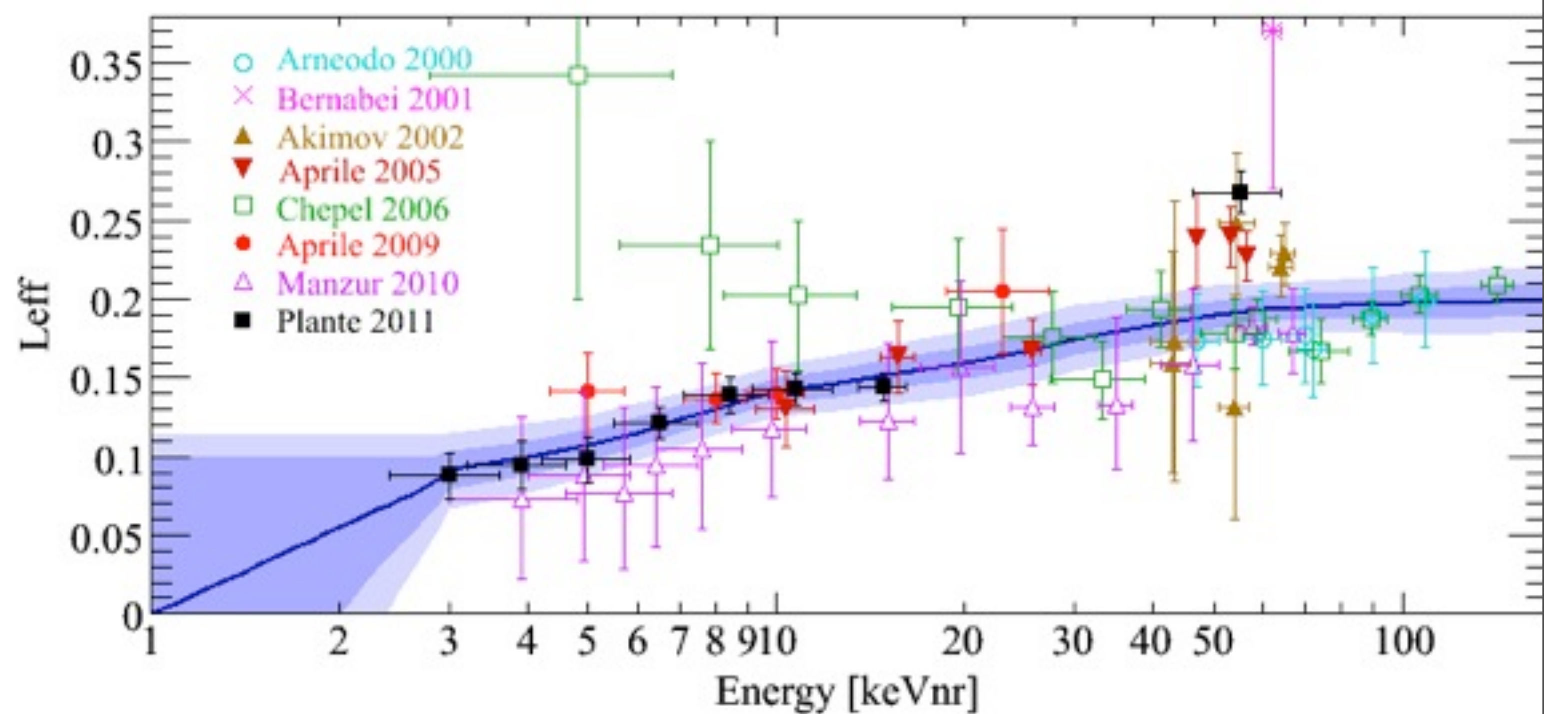
- $L_{y,er}$ is the light yield for electron recoils of 122 keVee

- S_{nr} and S_{er} represent quenching factors due to drift field

- Relative scintillation efficiency (measured in dedicated experiment) given as:

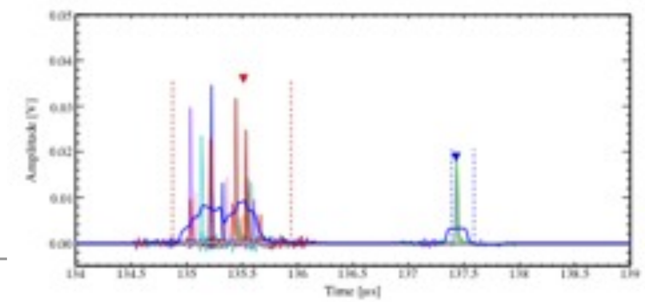
$$\mathcal{L}_{\rm eff}(E_{\rm nr}) = \frac{L_{y,\rm er}(E_{\rm nr})}{L_{y,\rm er}(E_{\rm ee} = 122\ \rm keV)}$$

Plante *et al.*, Phys. Rev. C **84**, 045805, 2011

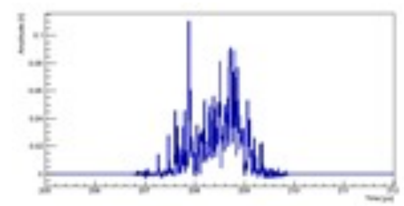


mean (solid) and 1-, 2-sigma uncertainties (blue bands)

From raw waveforms to results



Majority trigger, efficiency > 99% for S2>150 pe



Data acquisition: sample PMT traces @ 100 MS/s in windows around signals > 0.35 pe

PMT waveforms

Raw data processing, baseline and noise measurement; S1, S2 signal recognition; signal integration; position reconstruction; signal correction (gain, spatial)

root trees

Event selection, remove bad events:
- noise
- S1/S2 not matching

Select single interaction events

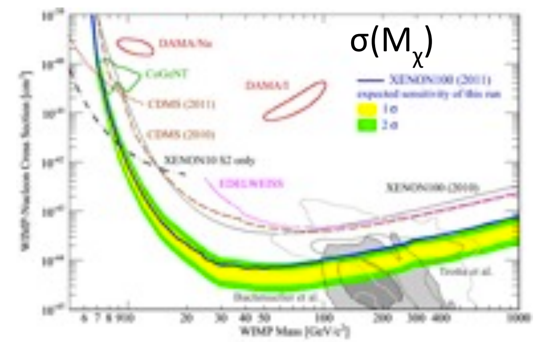
Acceptances!

reduced data

Physics analysis input: astrophysics, nuclear physics, DM data sidebands, NR and ER calibration => response, background estimate

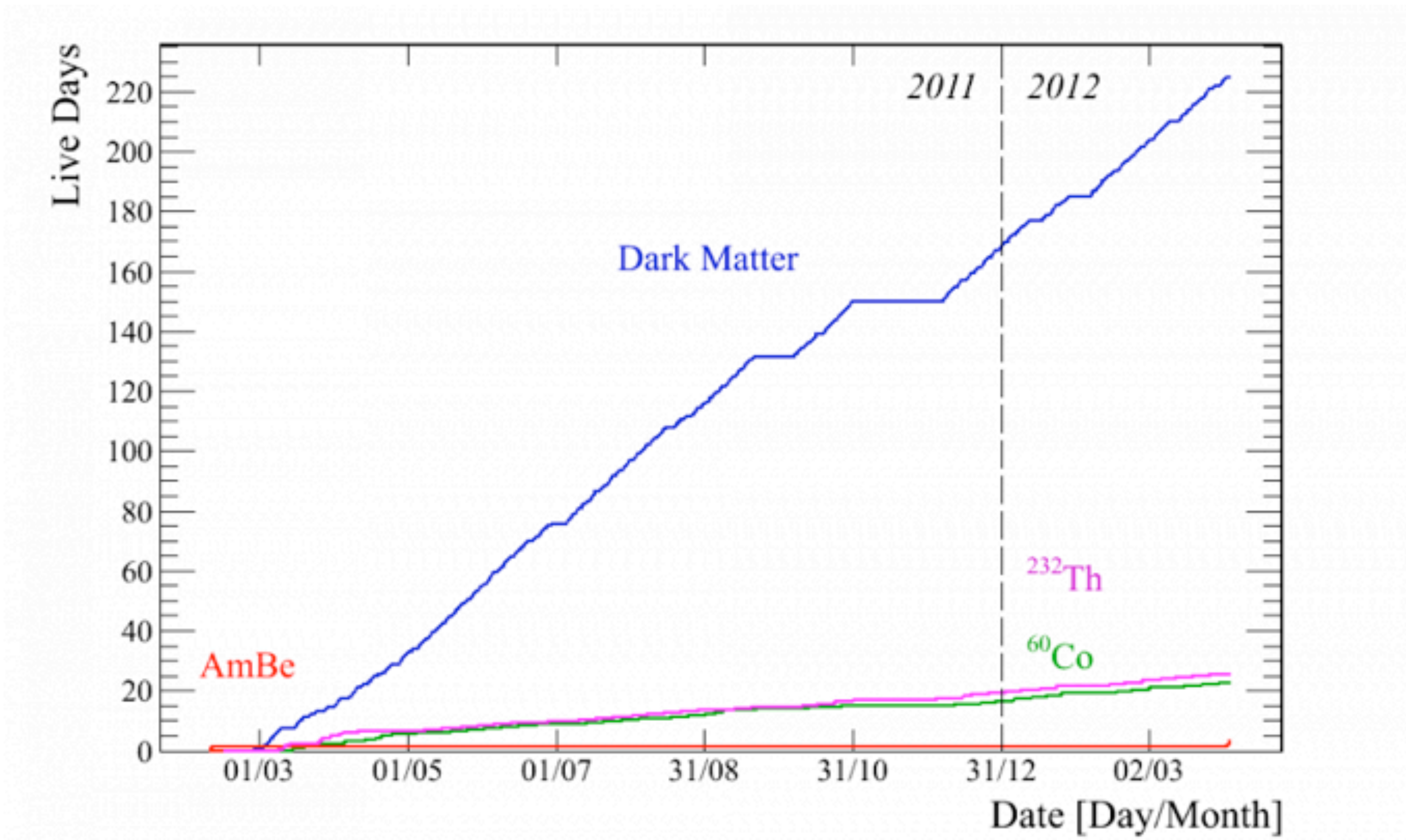
profile likelihood

results

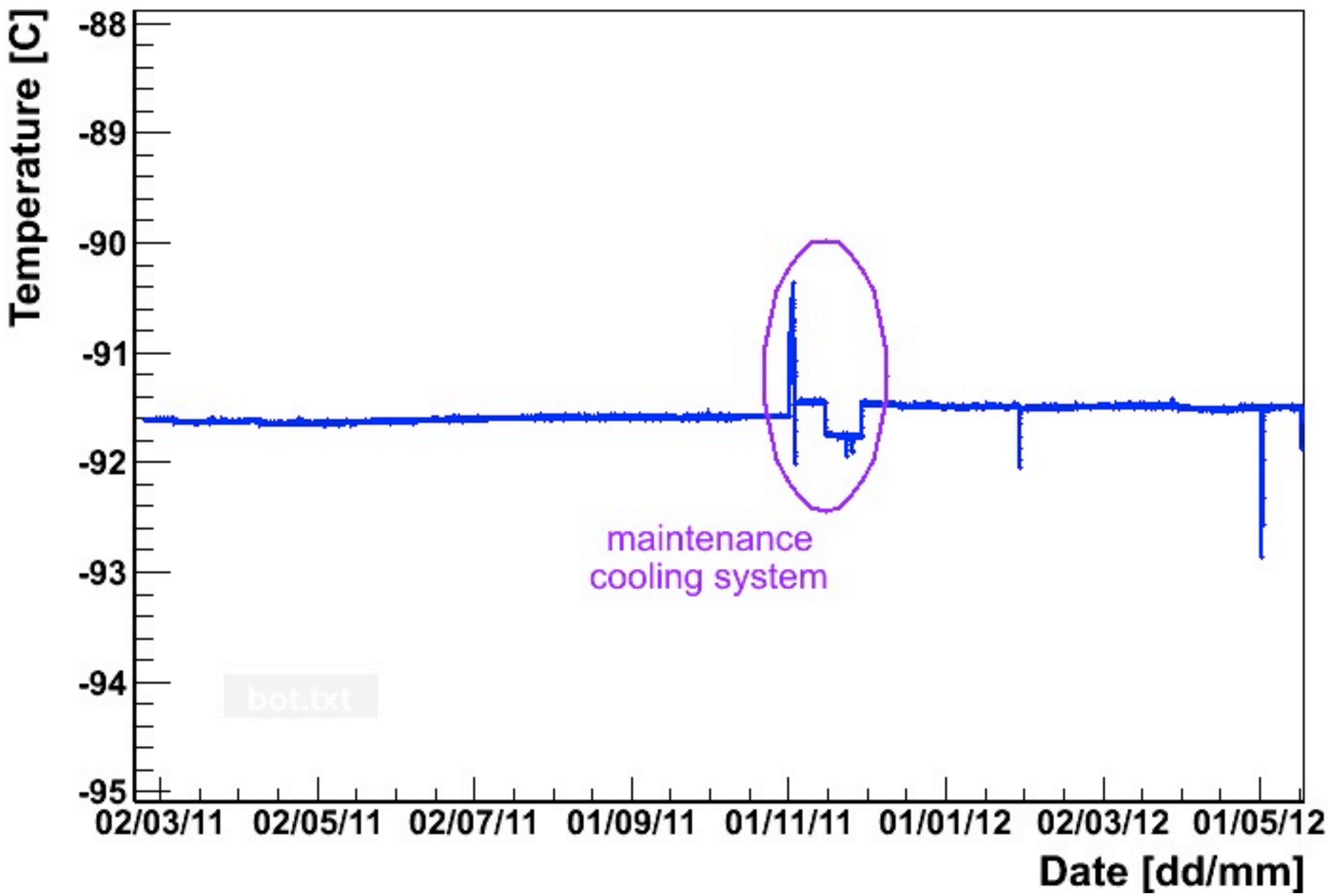


New XENON100 Dark Matter Search: Run10

- Data taking period: February 2011 - March 2012
- 224.56 live days of dark matter data
- 48 live days of ^{60}Co and ^{228}Th calibration data; 2 AmBe runs (beginning/end of science run)

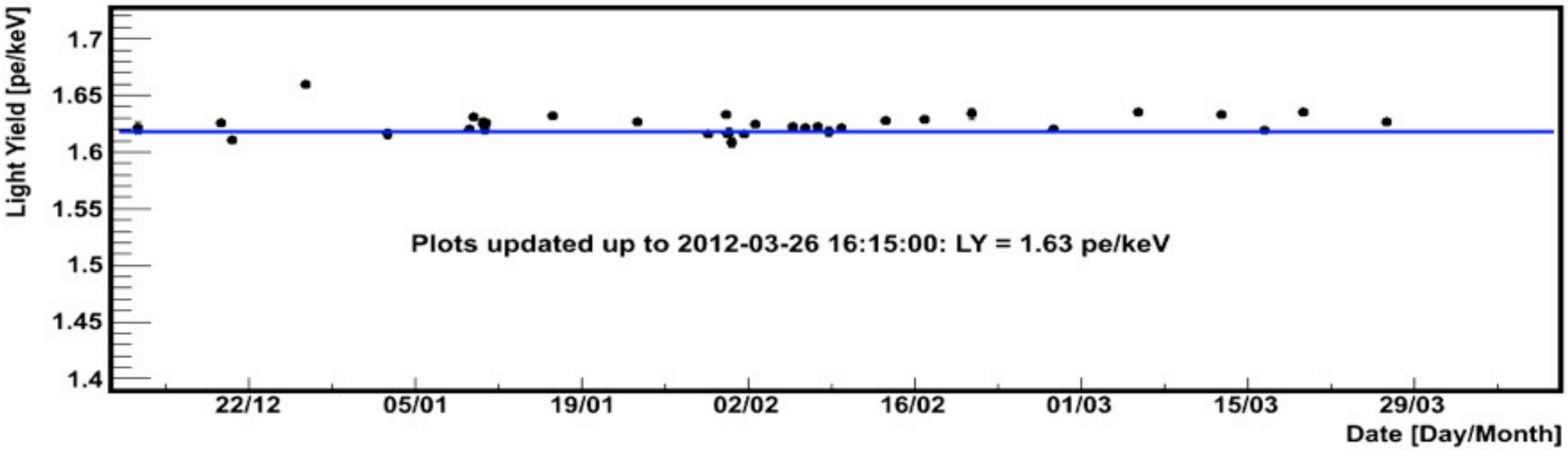


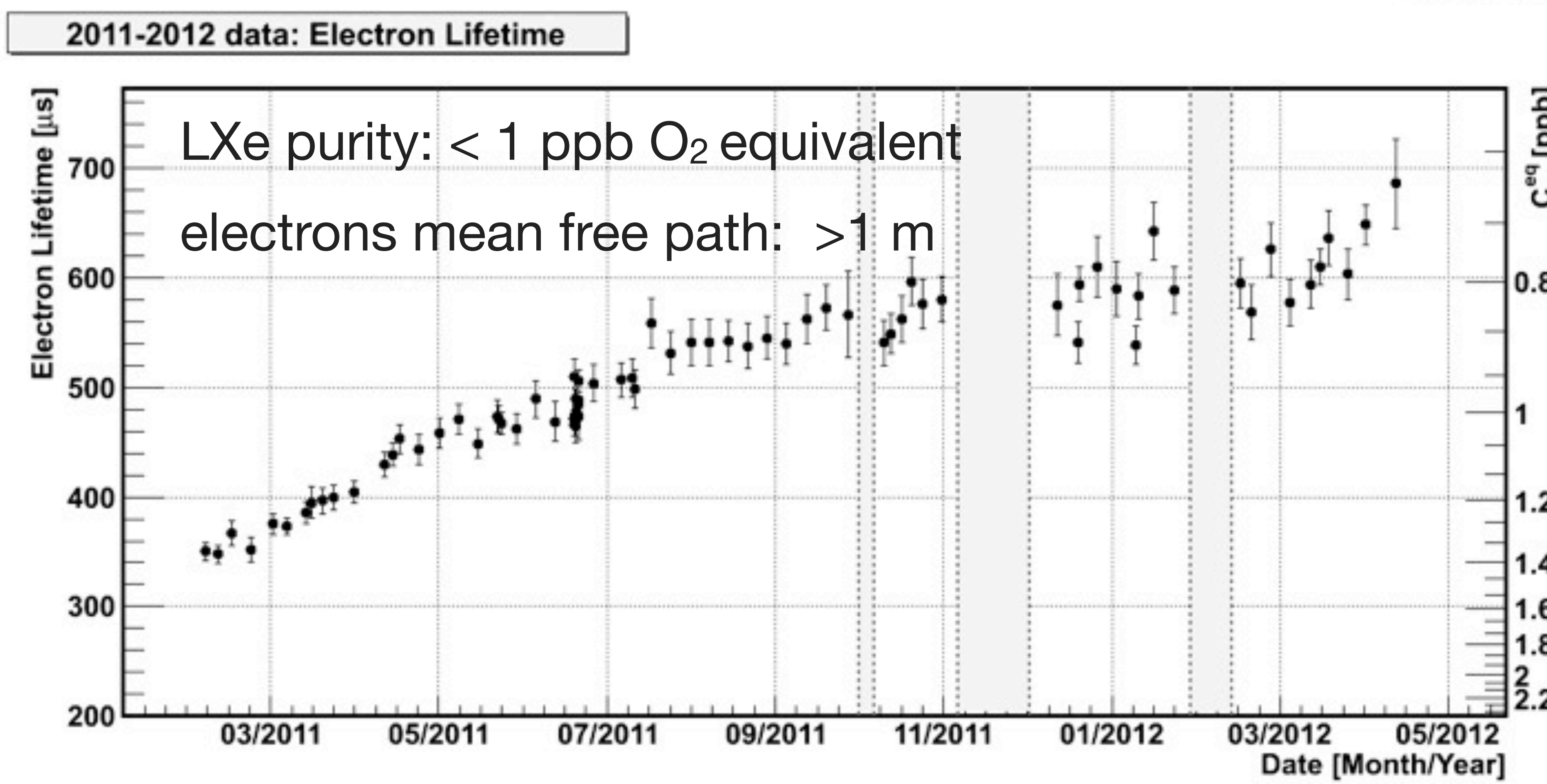
LXe Temperature Stability in Run10



XENON100 is the 1st LXe Detector operated continuously and stably for a such a long period of time

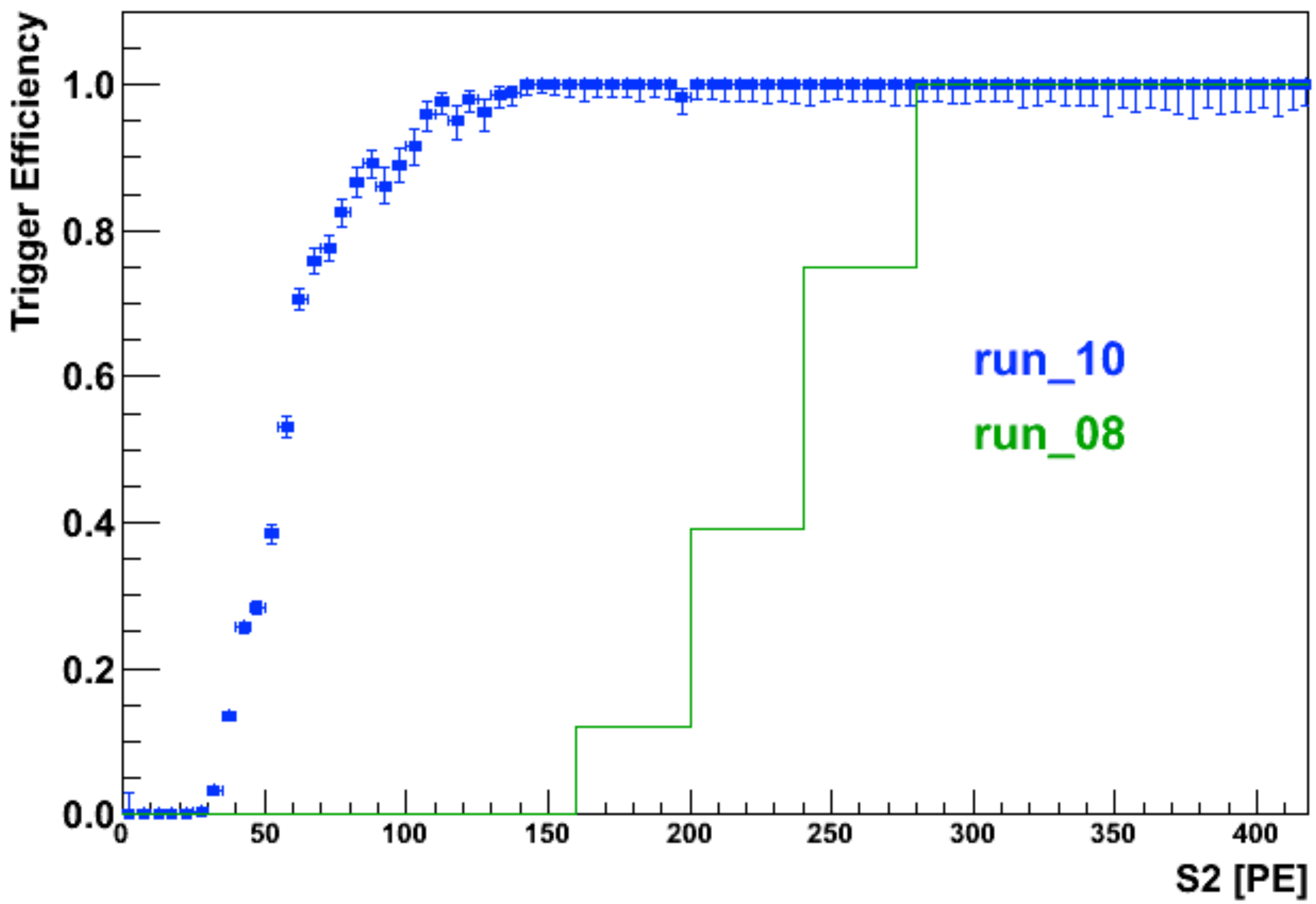
Light & Charge Evolution in Run10





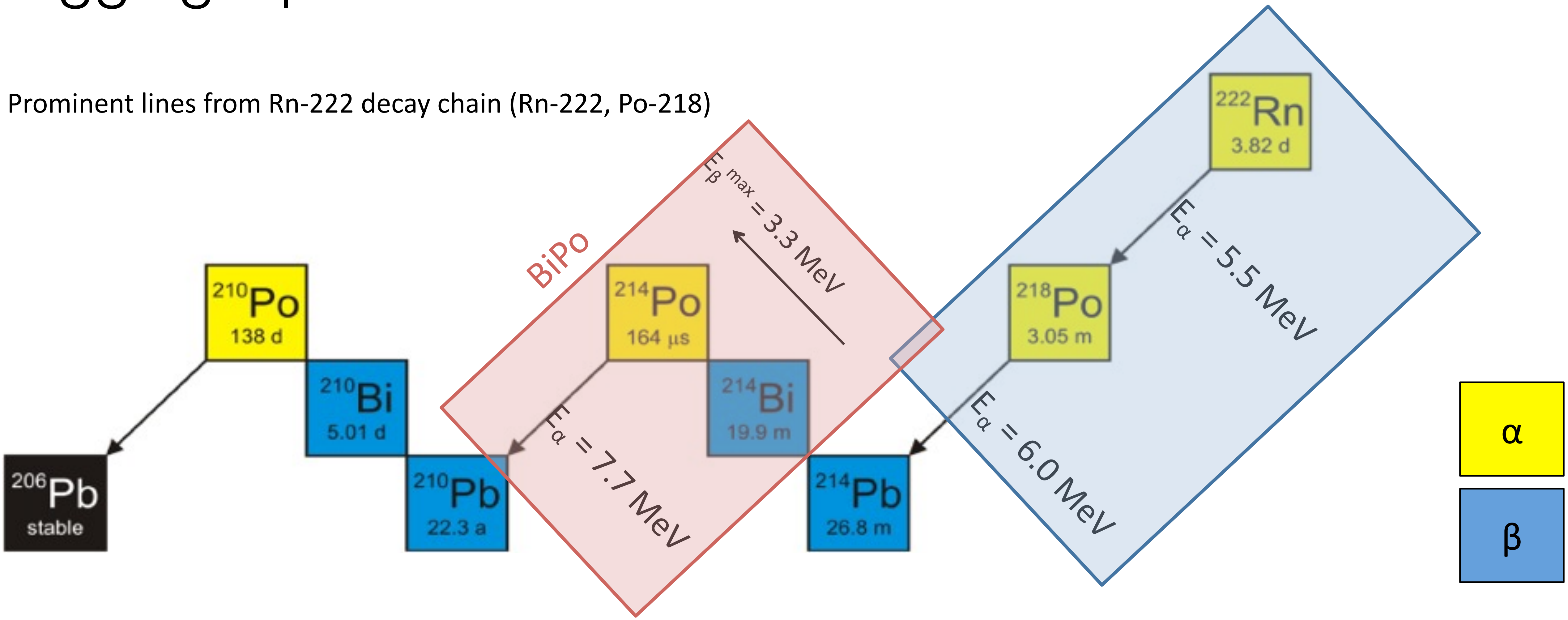
Improved S2 Trigger Efficiency

- 100% efficiency above S2= 150 photoelectrons
- ability to trigger on very low energy events (~10 electrons!)

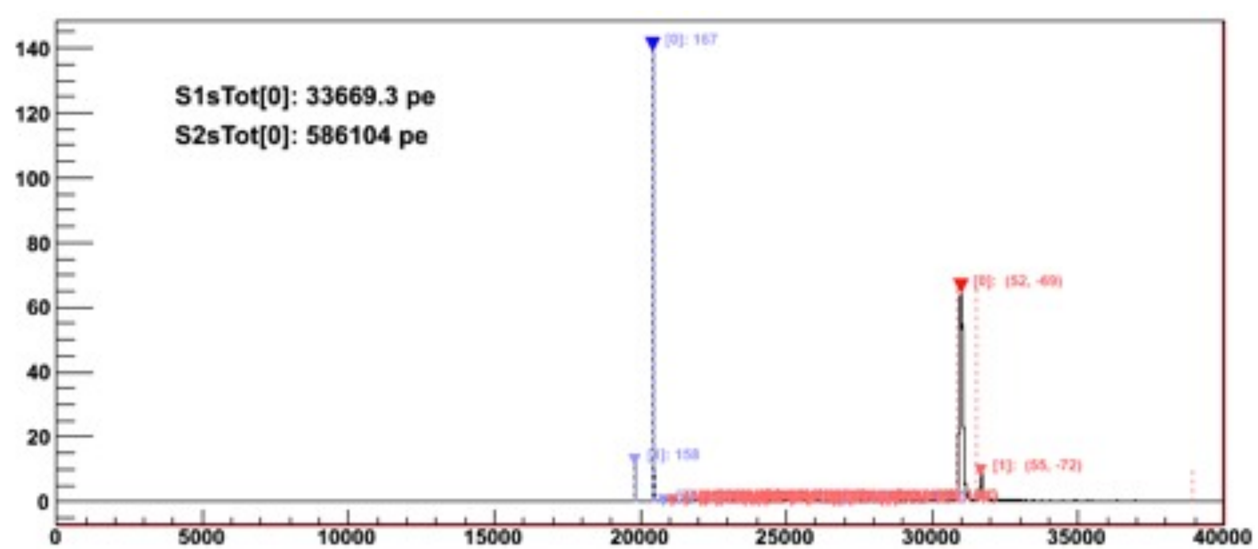


Tagging alpha events from Rn-222 in Run10

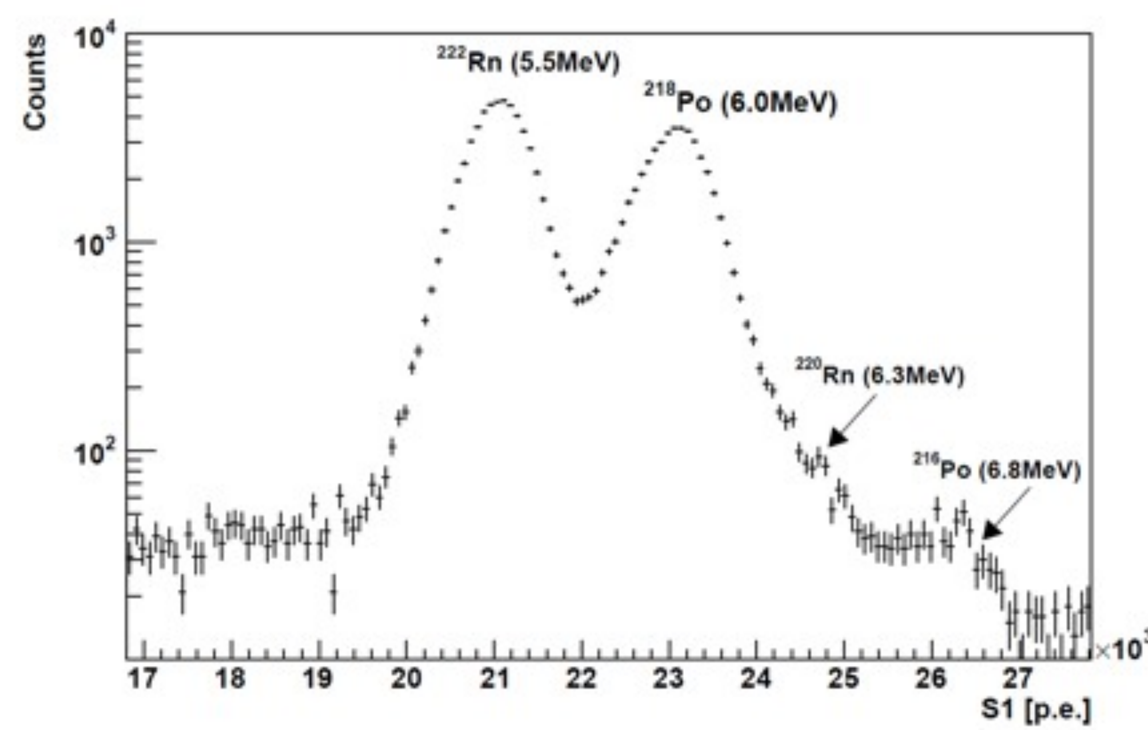
Prominent lines from Rn-222 decay chain (Rn-222, Po-218)



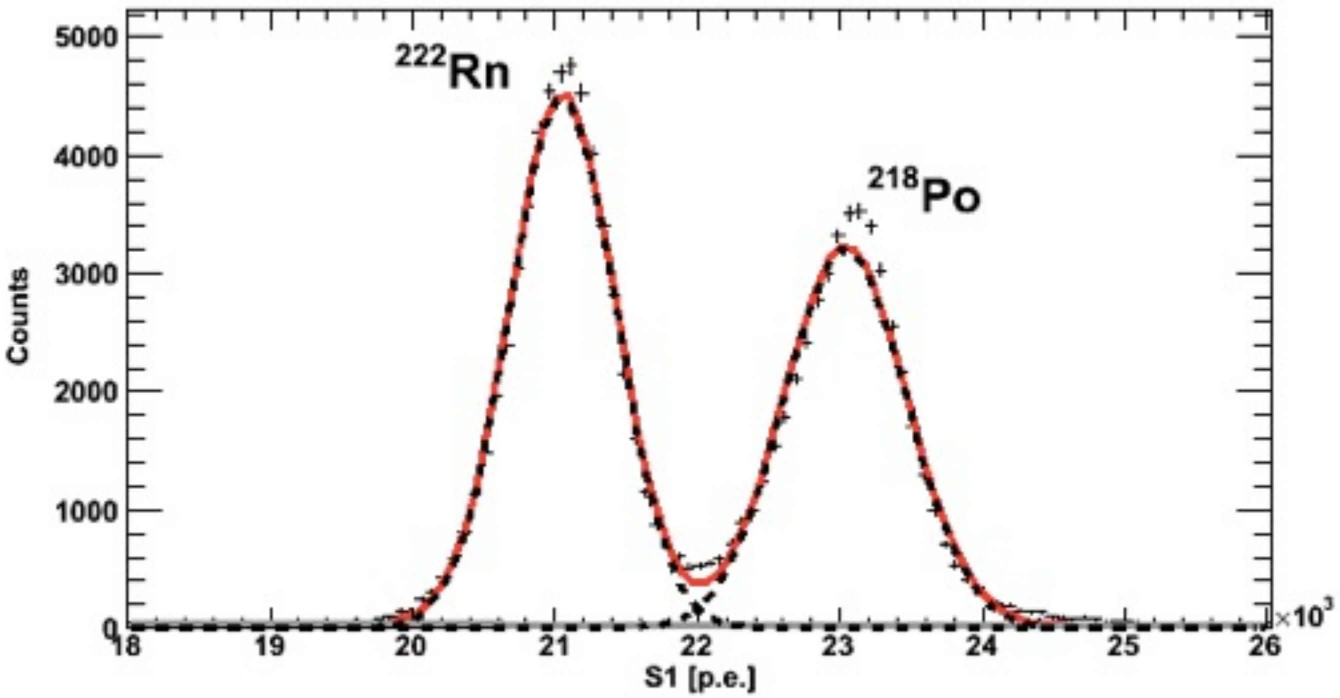
Delayed coincidence



Alpha spectroscopy



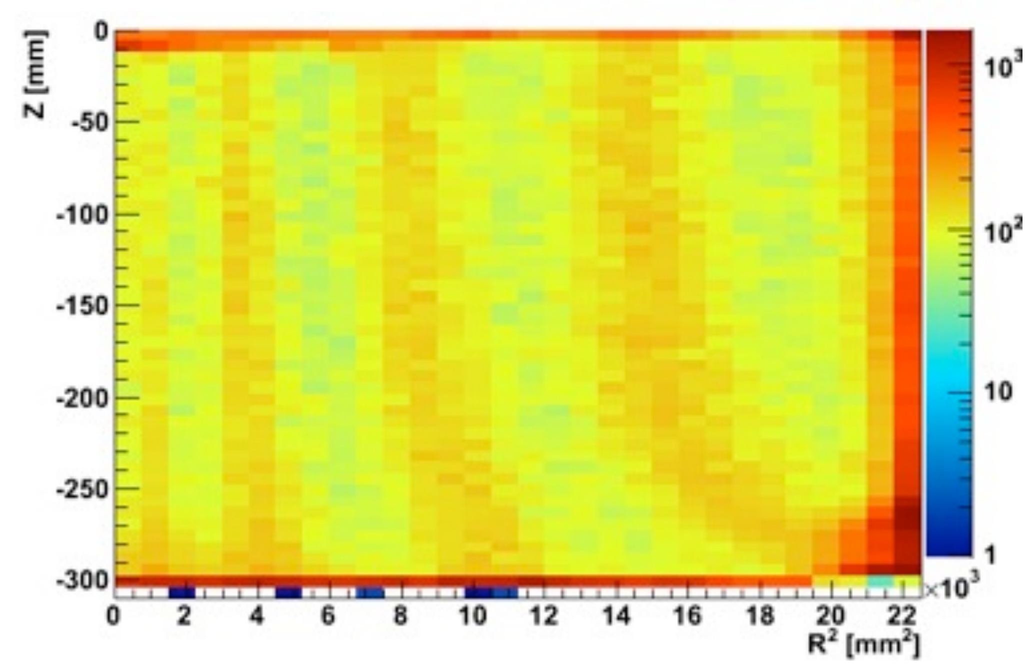
TPC allows to identify alphas via energy & position reconstruction



- High light yield from alpha decay: 3.8 p.e./keV
- *Data from 242 live days (DM Run 10)*
- *FV.: R < 145 mm, -260 < Z < -10 (47 kg Lxe)*
- *Single scatter events*
- Rn-220 chain suppressed by 2 orders of magnitude (radial cut R < 145 and short half-life of Rn-220 of only 1min)

All events without radial cut

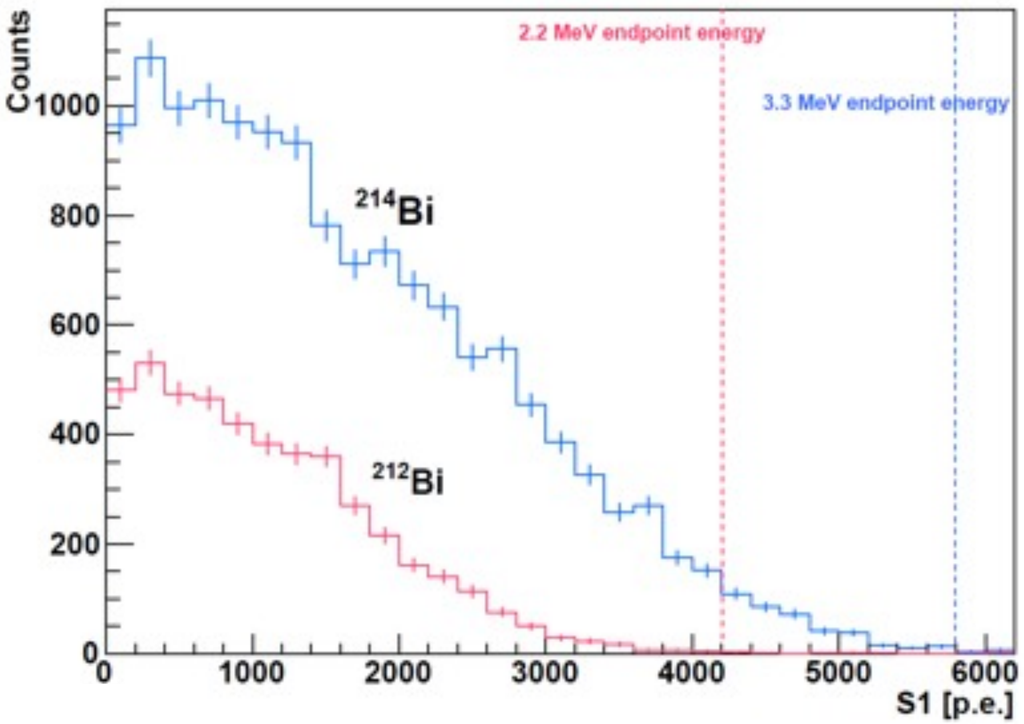
High rate at the very edges (no spectroscopic separation possible); could include short-lived Rn-220

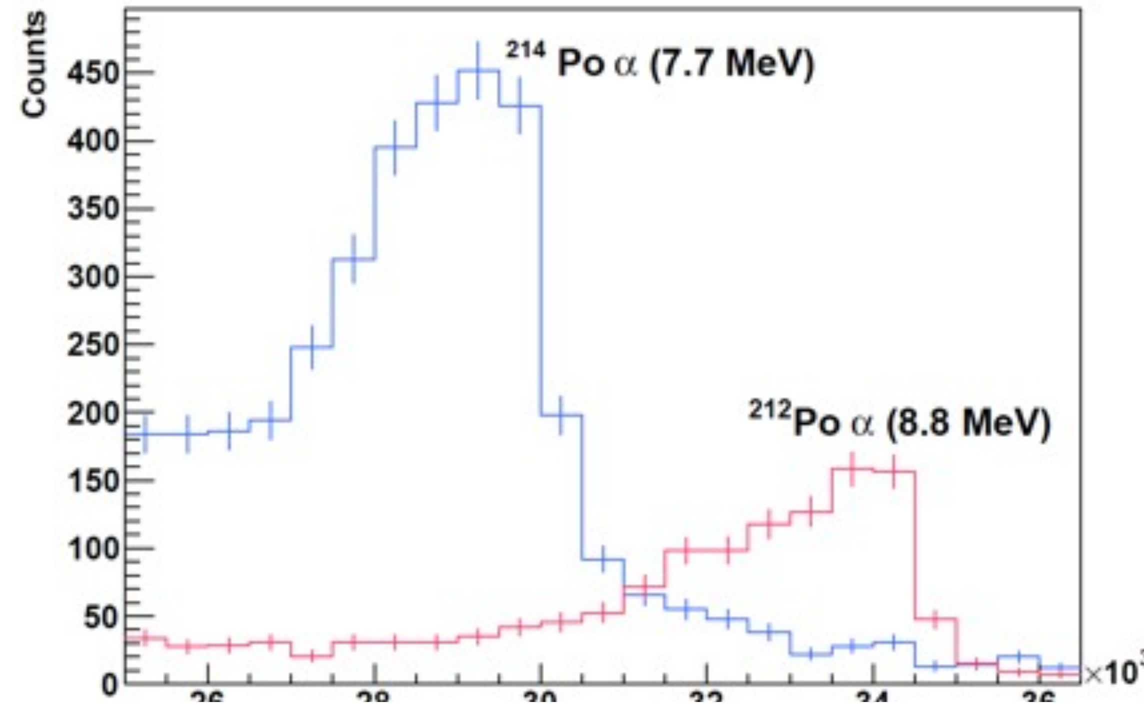


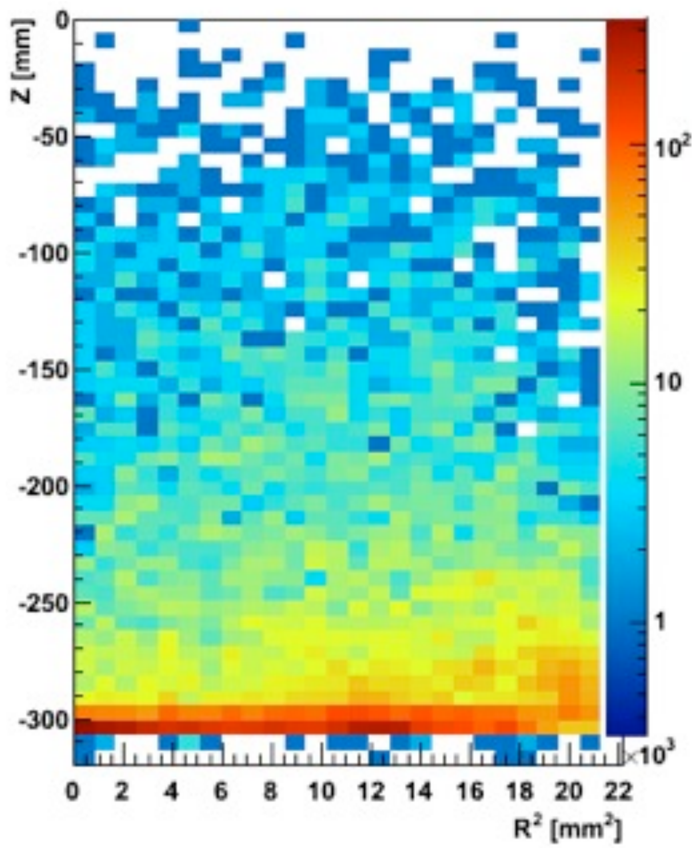
- Homogeneous distribution of Rn and Po alphas in the inner TPC
- Higher rate at the edges indicates movement and plate out of Po-218 or short-lived (low range) Rn-220 from teflon/cryostat walls

BiPo Analysis

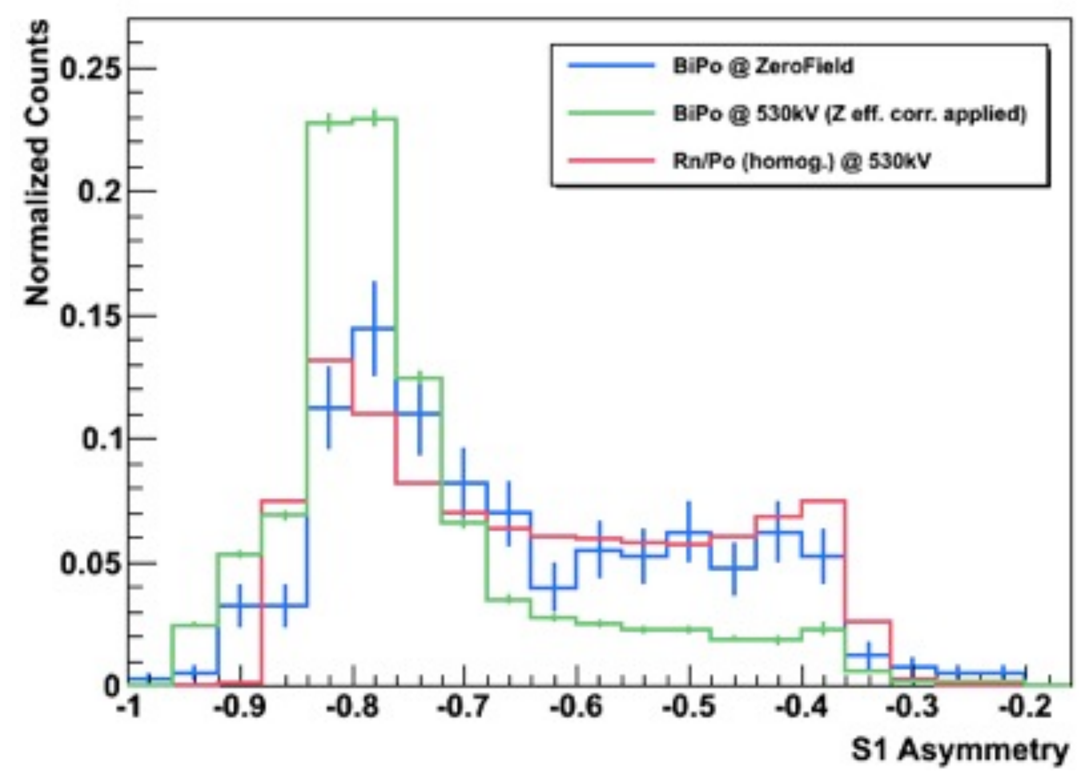
- Time coincidence method making use of short Po-214 (Po-212) half-life
- Complementary time cuts to separate 214BiPo (Rn-222 chain) from 212BiPo (Rn-220 chain)





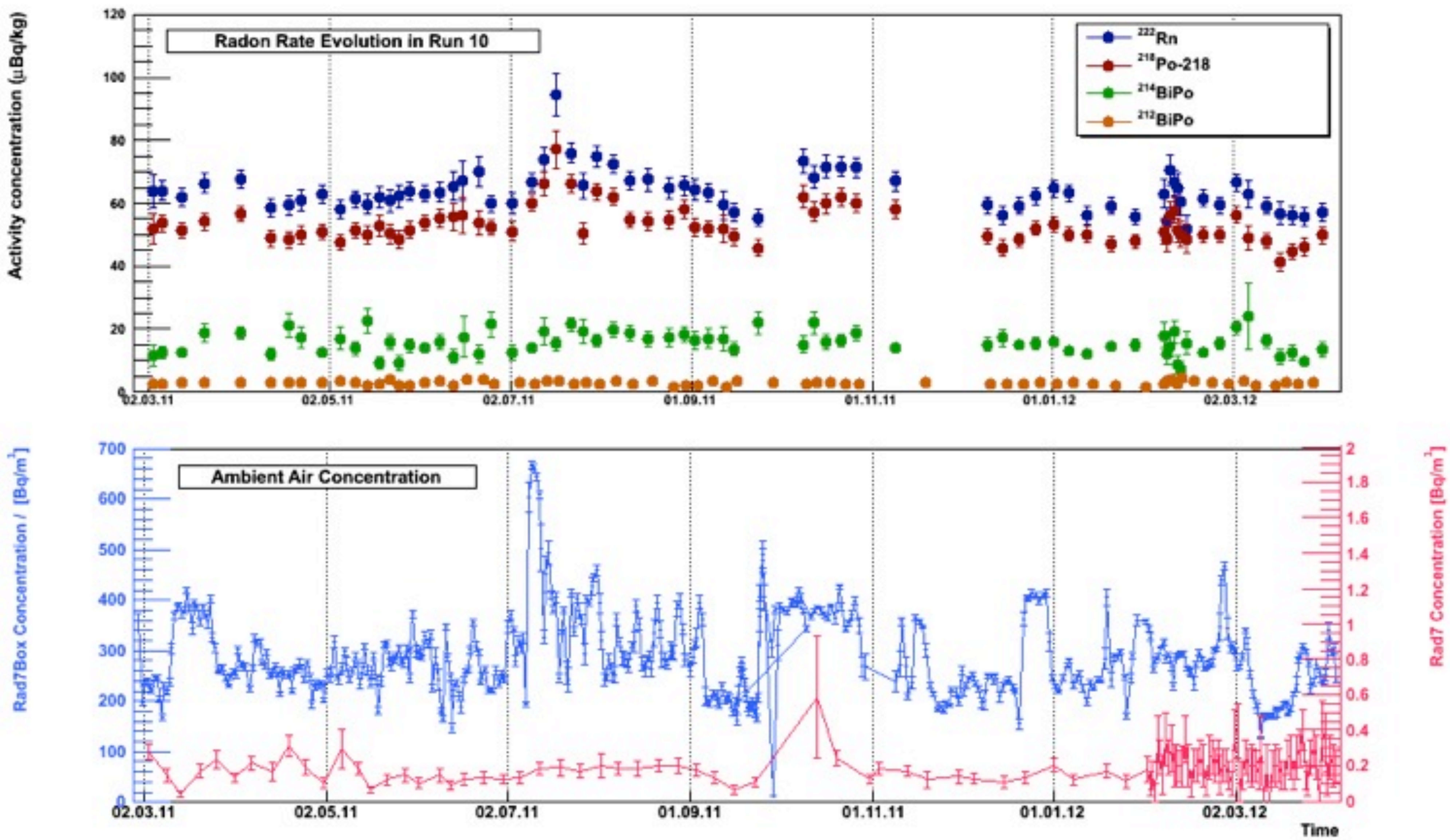


BiPo events mainly at cathode due to drift of positive ^{214}Bi ions – not the case when field switched off

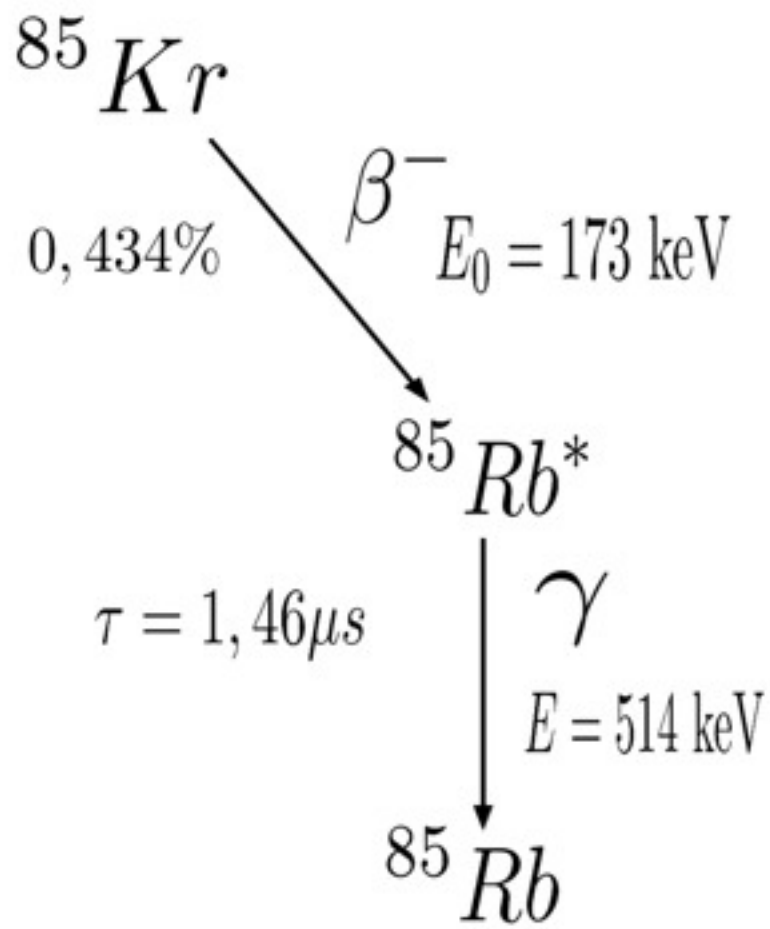


Summary on Radon level in Run10

- Almost constant over more than one year
- Variations correlated with radon level outside detector shield
- Decreasing concentration of Rn progenies along decay chain in the inner TPC
- Cannot be explained by ions drift (too short time scale) to the cathode nor diffusion to the walls (too long time scale). Convection patterns and trapping of Rn progenies at the walls as explanation
- ^{212}BiPo suppressed by a factor 10

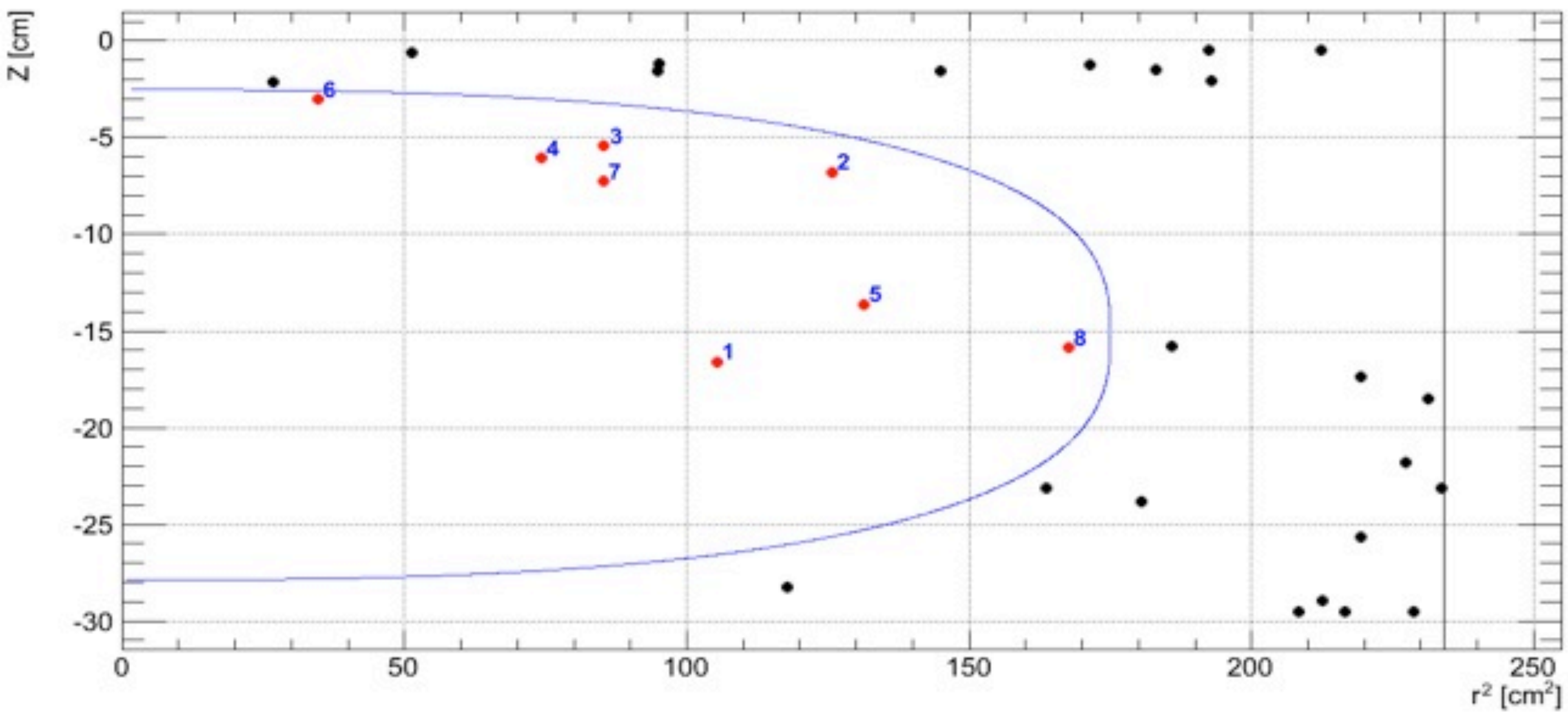


^{85}Kr from delayed β-γ coincidence analysis

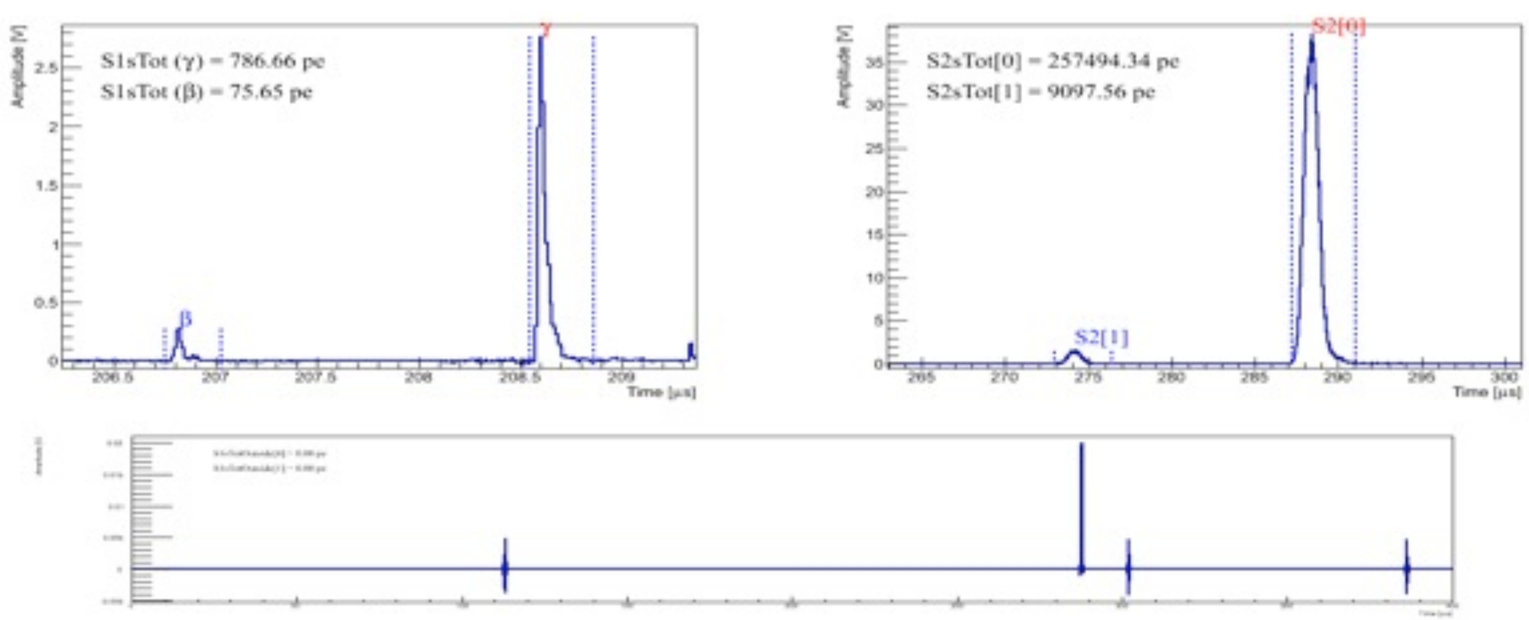


- ^{85}Kr is internal background, cannot be removed by self-shielding
- Time delay between β-γ emissions: an exponential distribution with $\tau = 1.46$ μs
- Tag and remove those events by applying event selections:
  - time difference between the first two S1 peaks
  - energy of β and γ
  - event inside the TPC (veto cut)
  - S2 signal above 150 PE
  - remove BiPo (β-α coincident) events from ^{220}Rn localized on PTFE walls (based on S2/S1-ratio)

^{85}Kr events distribution in fiducial volume (34 kg)



xe100_111030_1107_5879 (r^2 = 131.38 cm², z = -13.62 cm)



Event Number	$R^2[cm^2]$	$Z[cm]$
1	105.44	-16.62
2	125.77	-6.79
3	86.36	-5.42
4	72.22	-6.06
5	131.38	-13.62
6	34.62	-3.02
7	85.19	-7.27
8	167.61	-15.87

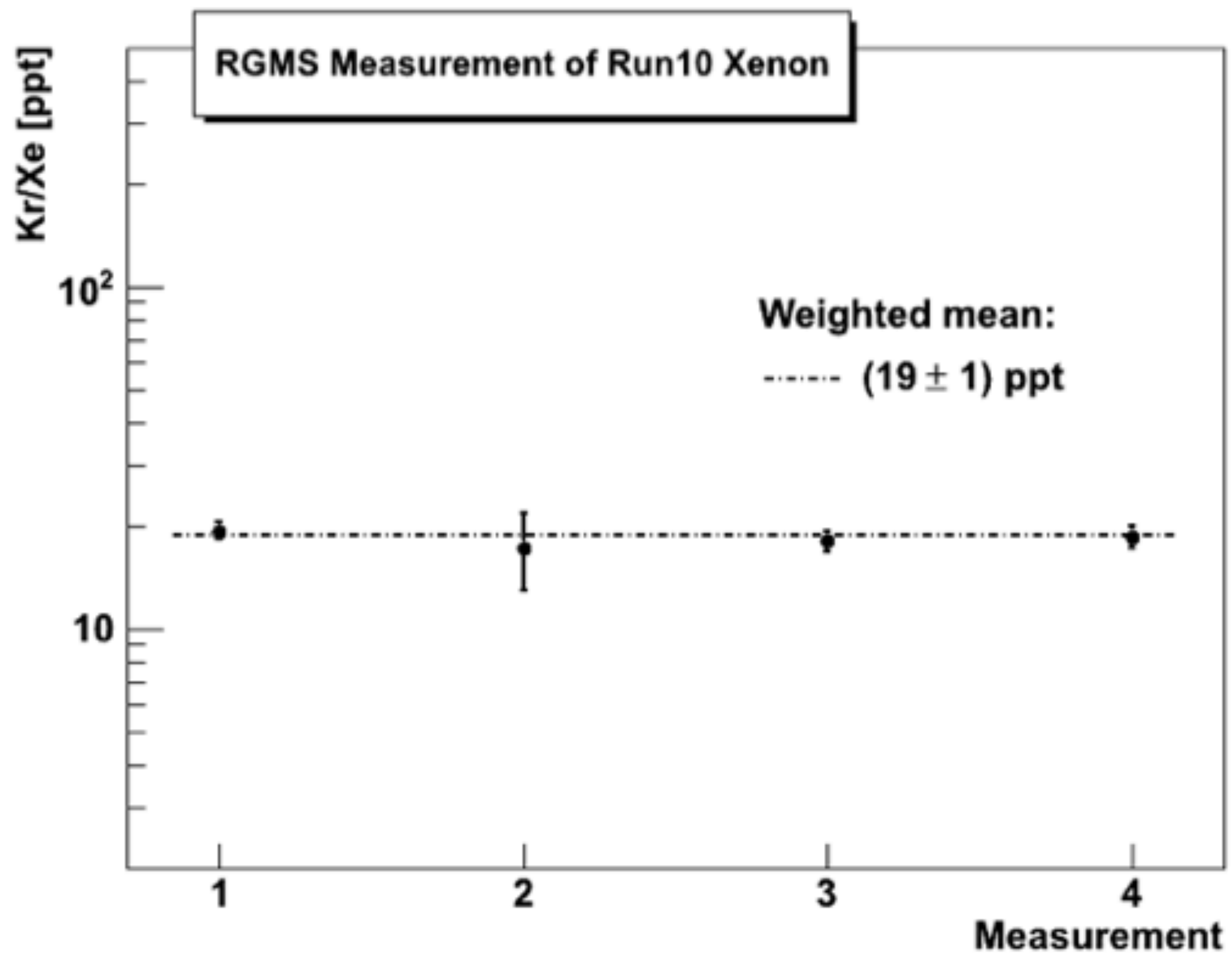
Final ^{85}Kr concentration

- The total live time is 224.56 days.
- We know the activity and the branching ratio of ^{85}Kr, and we assume that the ratio ^{85}Kr/^{nat}Kr =2.08 x 10^{-11}
- 1 ppt of ^{85}Kr inside 34 kg of Xe corresponds to 1.2 x 10^{-3} events/day
- Final ^{85}Kr concentration in 34 kg inferred by rescaling the number of events (8) found in the FV to the total live time and the total cuts efficiency (77%):

- The result from this analysis:
- 18.57 ppt
- with a confidence Interval of [9.20, 32.49] ppt at 90% C.L.
- this is consistent with a direct measurement of a Xe sample by RGMS technique

Direct Measurement of Kr/Xe in XENON100 Run10

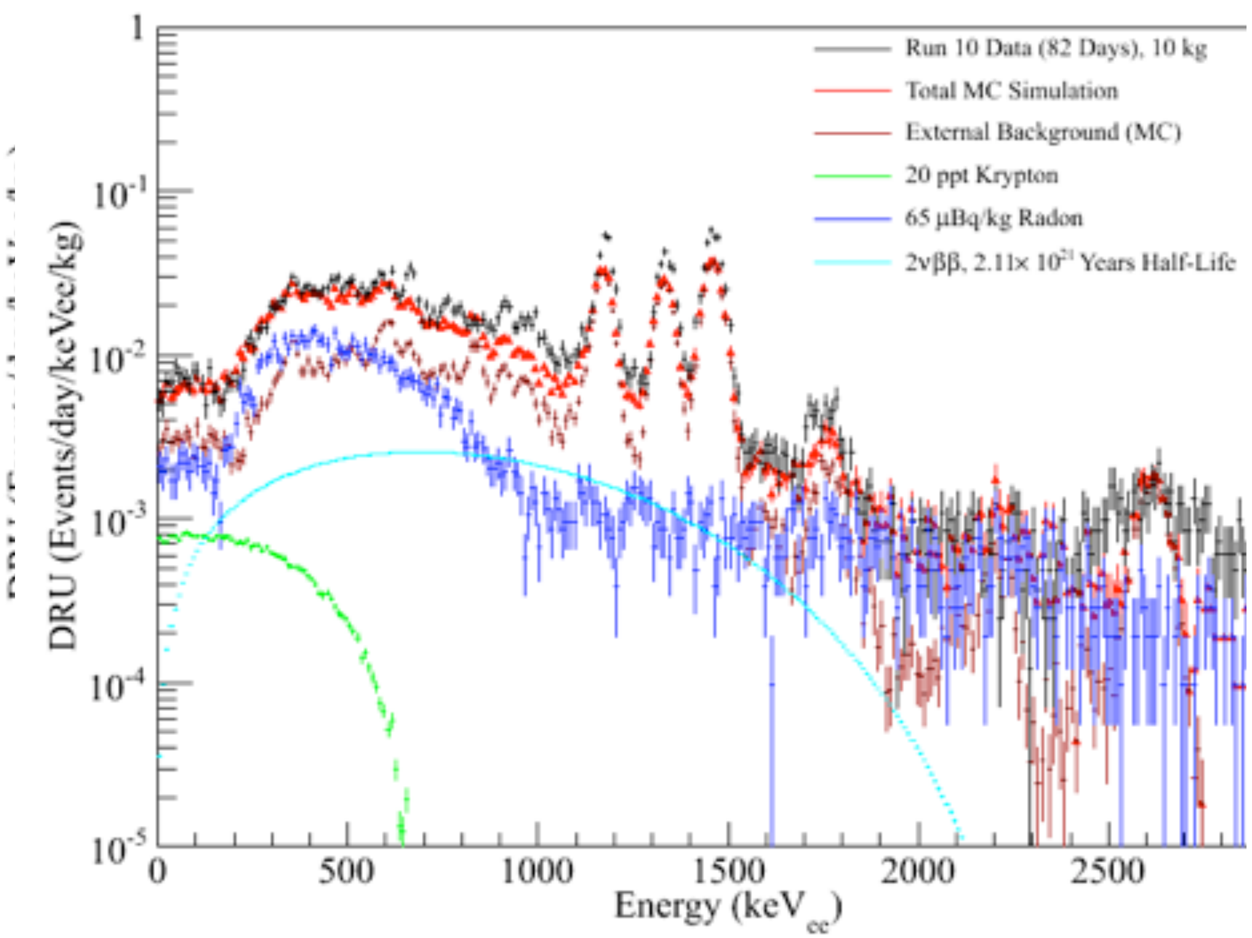
- Reduced by cryogenic distillation with dedicated 3m-column operated in Fall 2010
- Sample from detector's gas measured with a Rare Gas Mass Spectrometer at MPIK
- Kr/Xe value of (19±1) ppt validated by delayed coincidence analysis of Run10 data

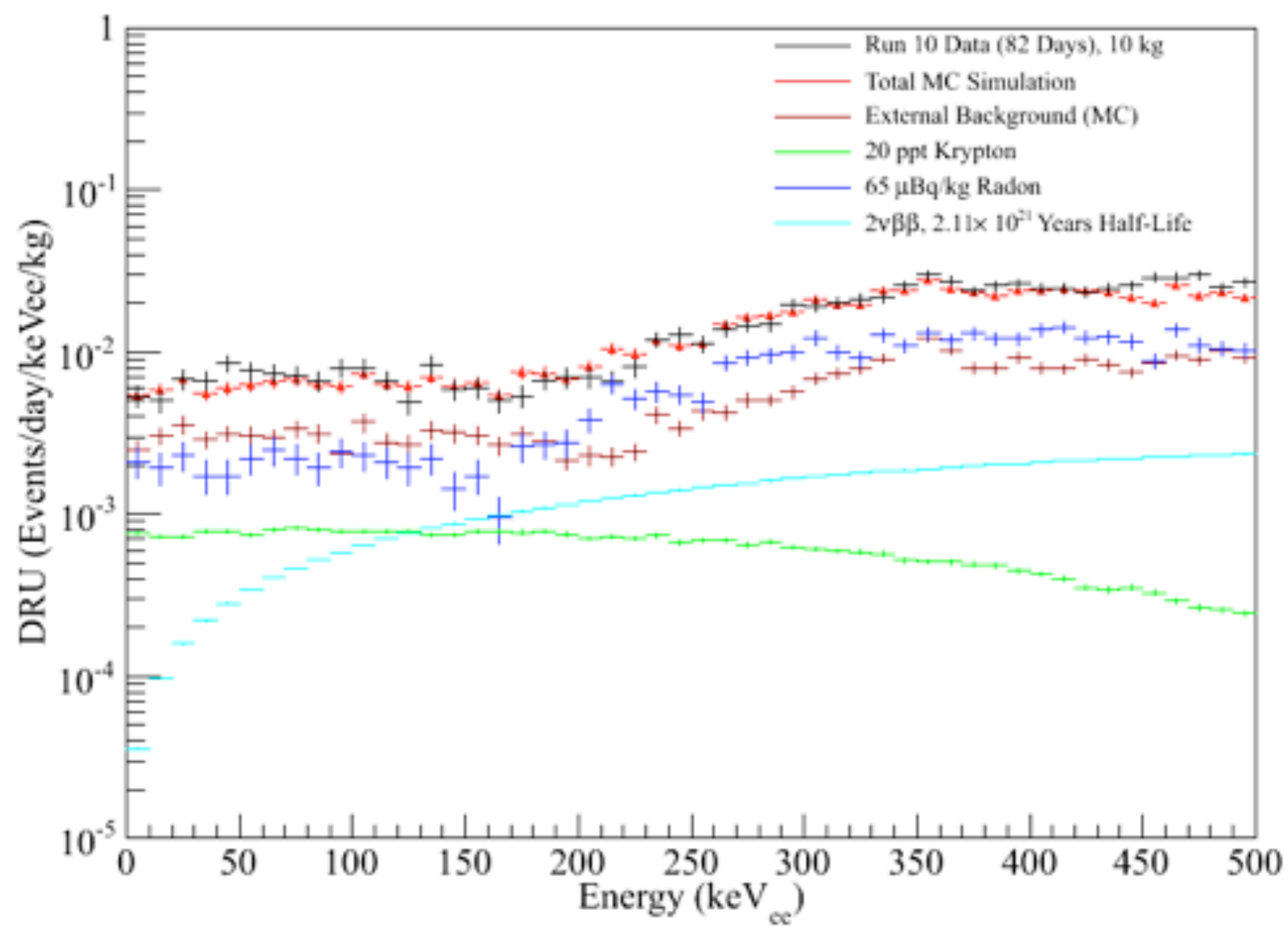


Measured Background Level in Run10

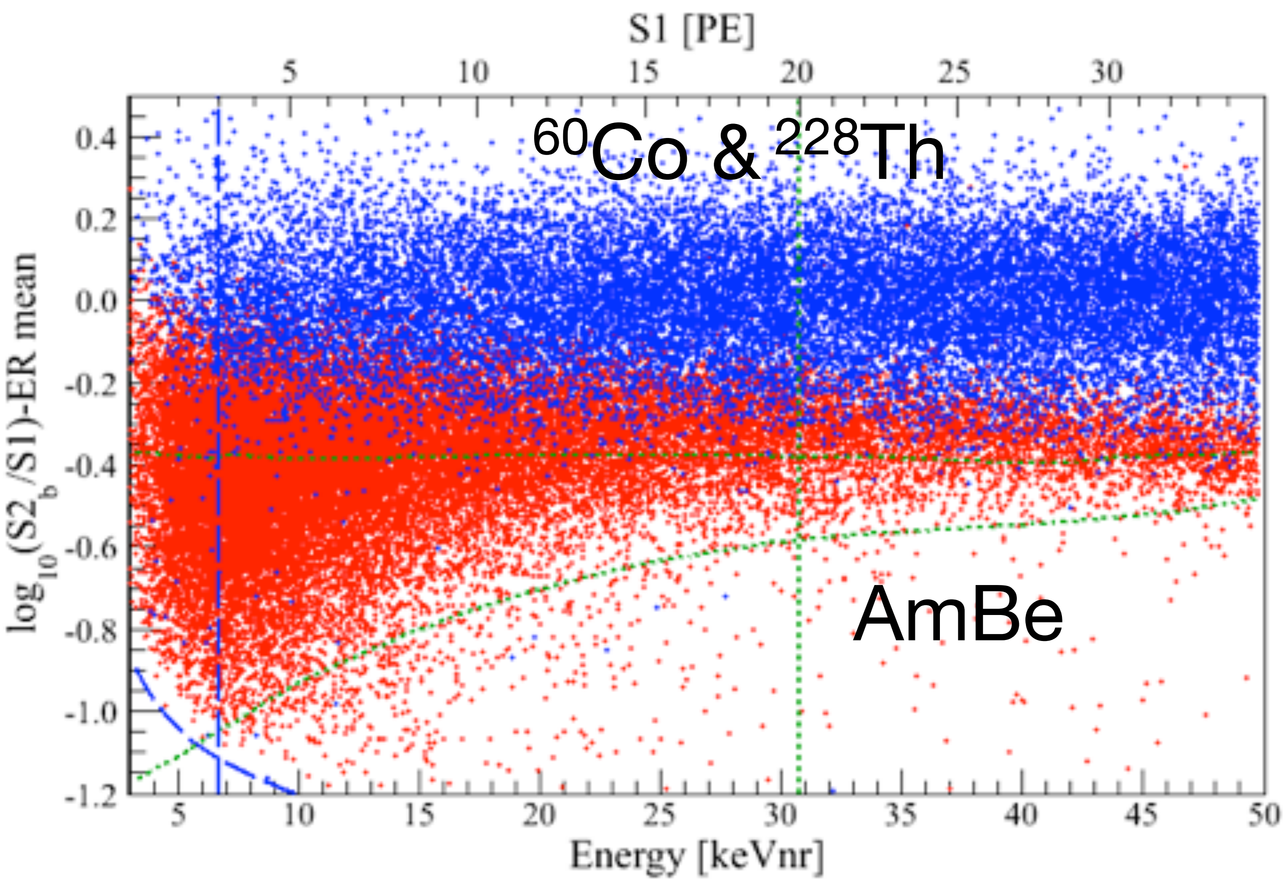
- Reached background level before S2/S1-discrimination: 5.3 x 10^{-3} events/(kg day keV)
- Same level as in 1st XENON100 results (E.Aprile *et al.*, Phys. Rev. Lett. **105,** 131302, 2010)
- see also PRD 83, 082001 (2011)

Before applying LXe veto cut

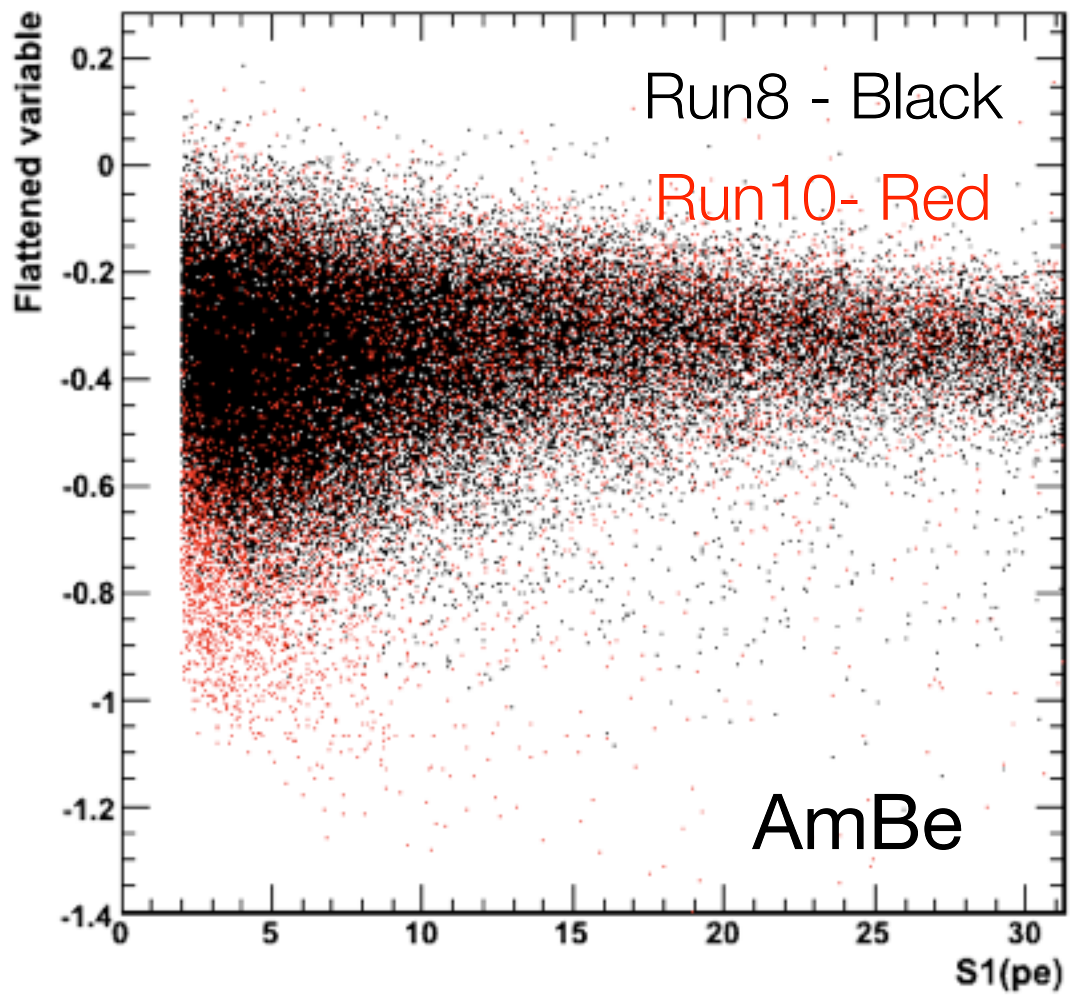




Improved Statistics of ER & NR Calibration Data

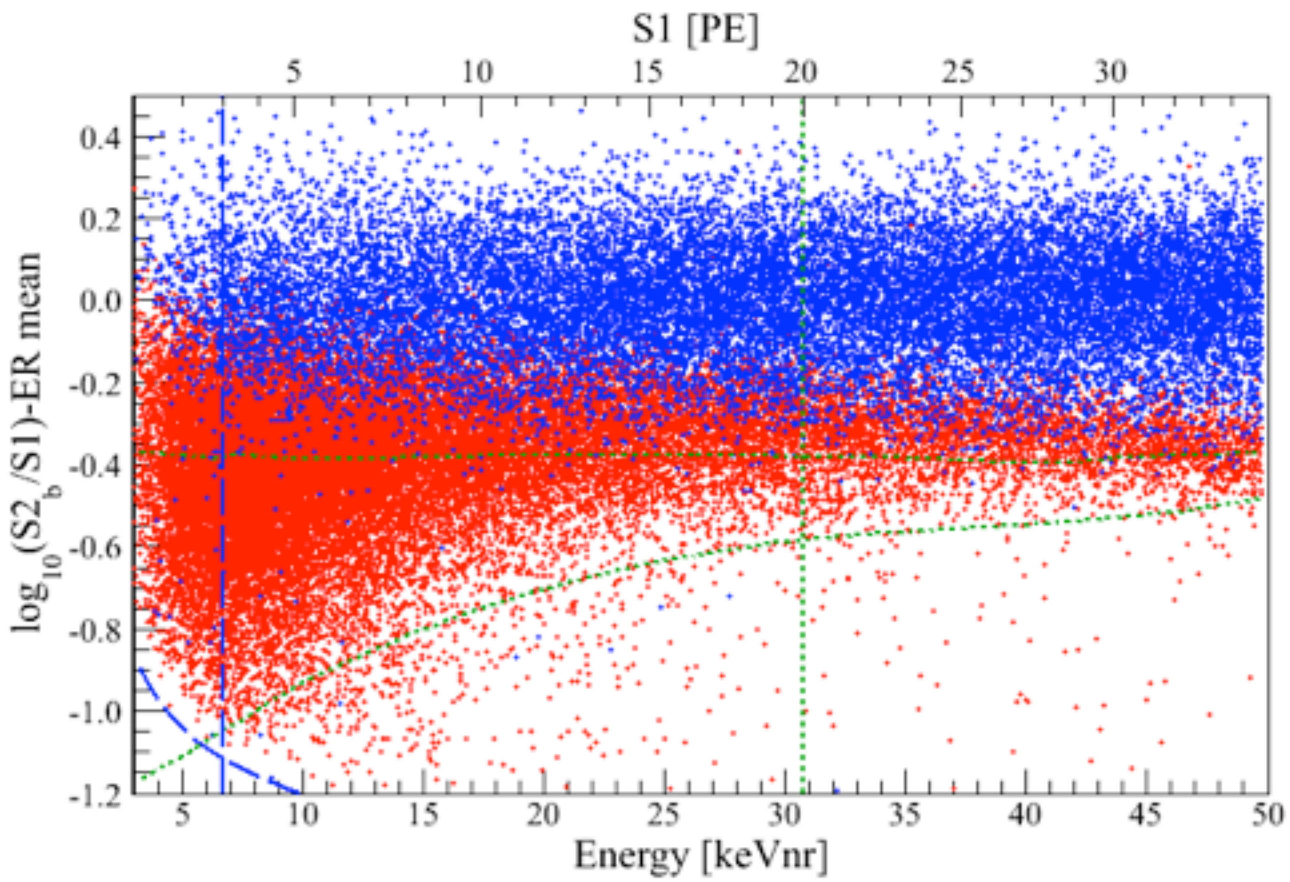


Gamma and neutron calibration data

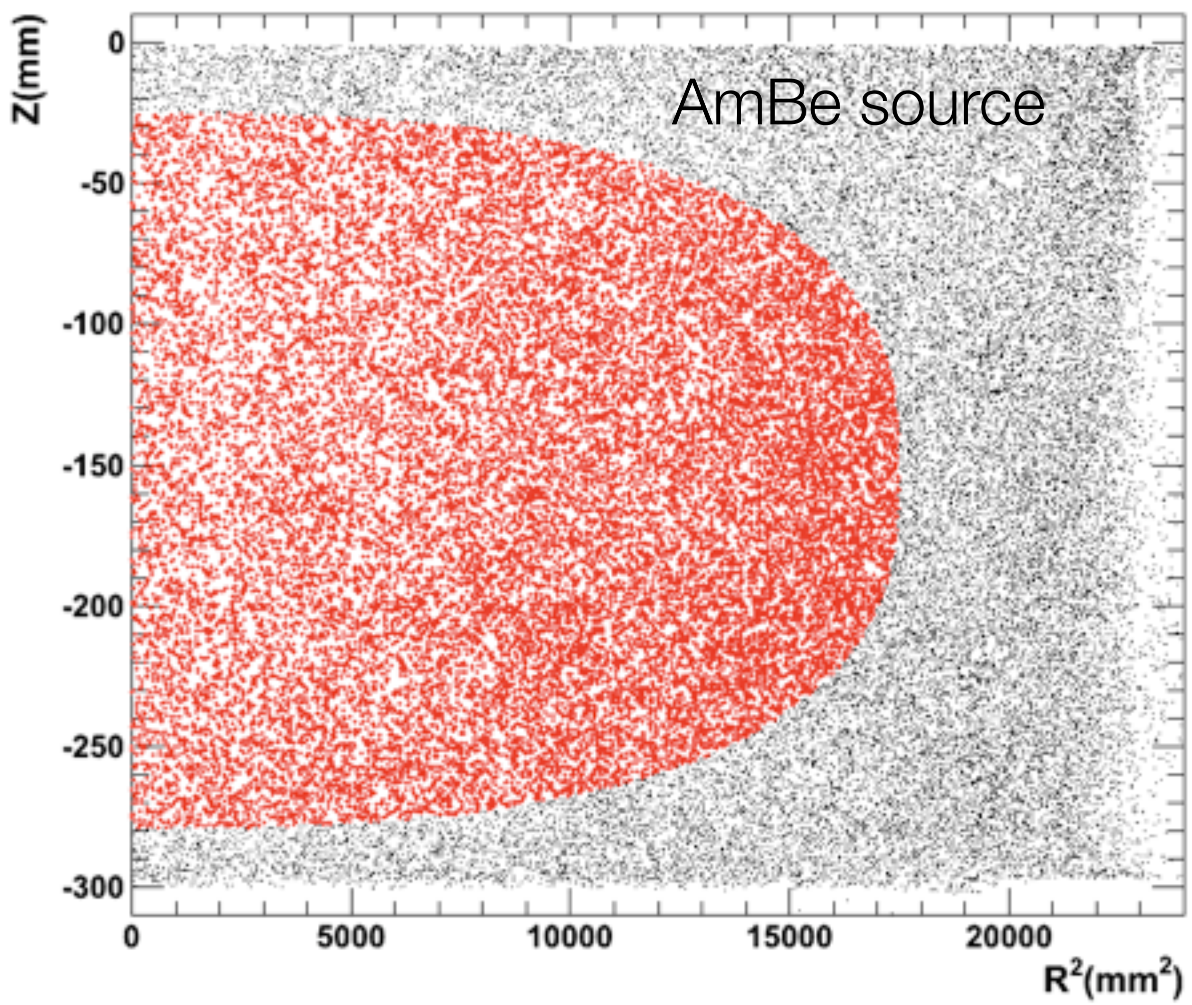


Lower Run10 S2 threshold visible

Improved Statistics of ER & NR Calibration Data



Gamma and neutron calibration data

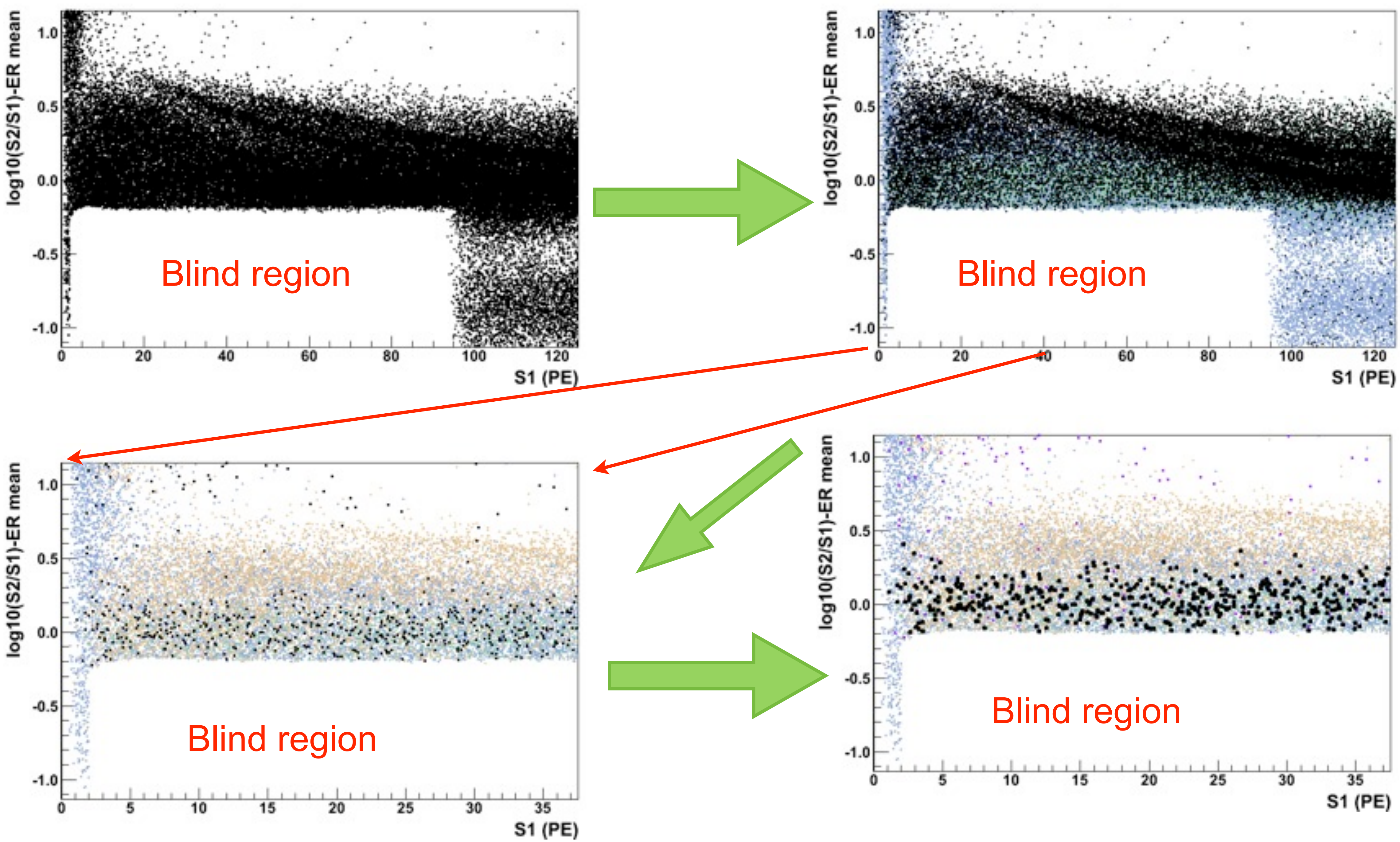


Analysis sequence for the 225 live days of data

(Different colors represent the events removed with the successive cuts)

(1) Start from all non-blind data in 48kg FV

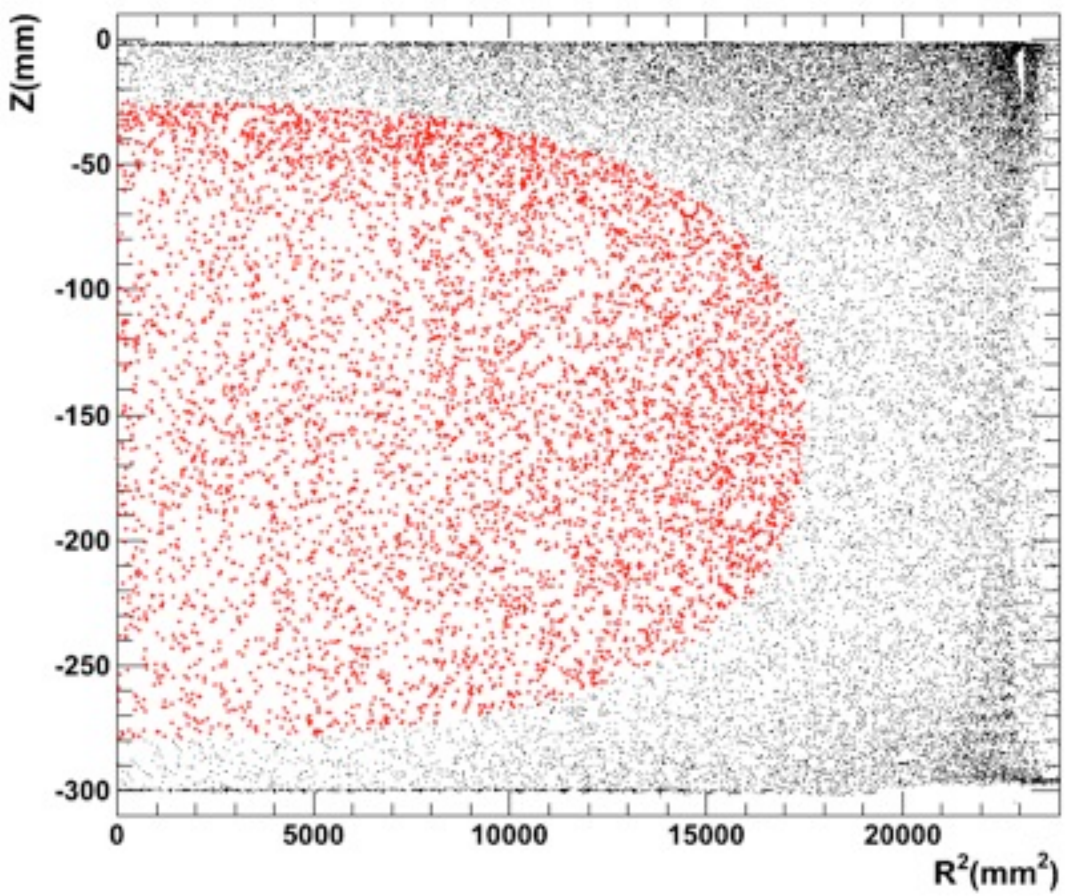
(2) Apply basic quality cuts and single scatter



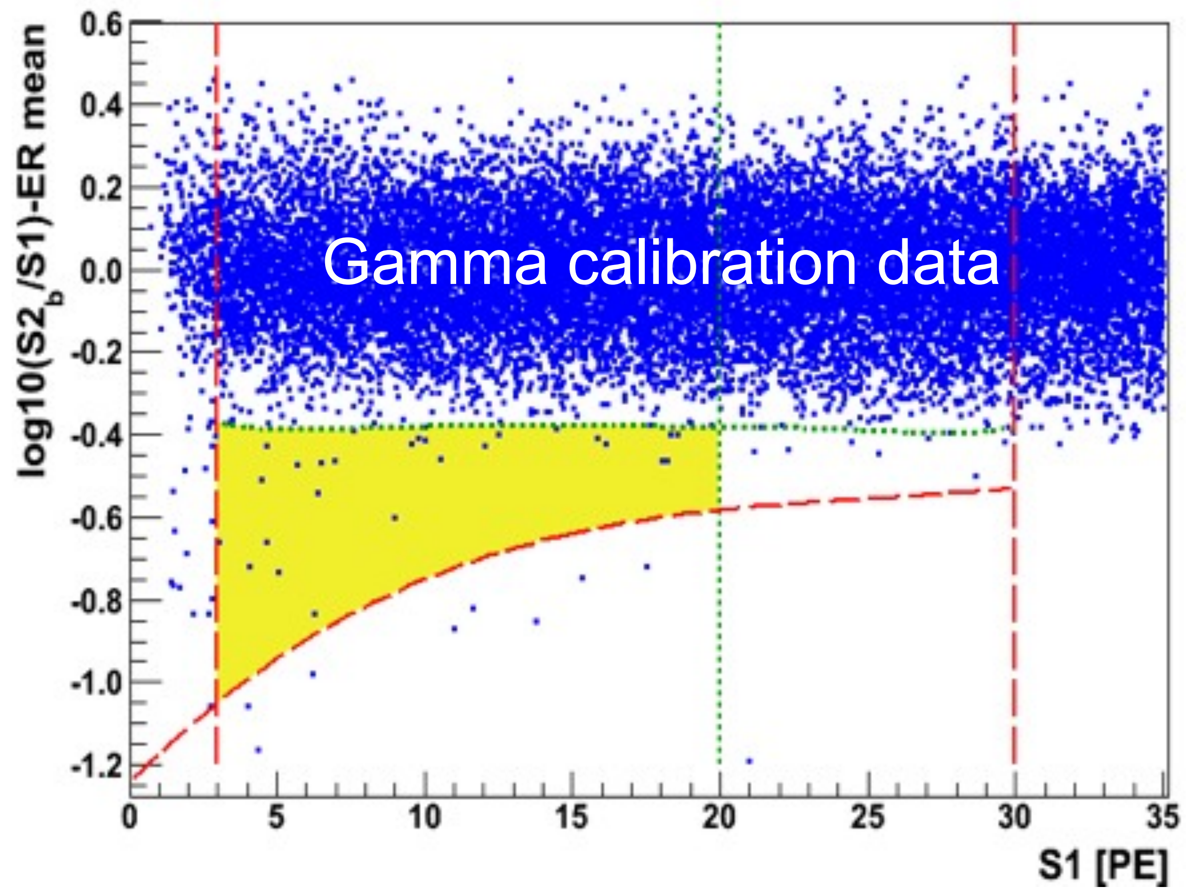
(3) Set low energy threshold, restrict to low energies and apply FV cut

(4) Add consistency cuts for the remaining events

Optimization of the fiducial volume and signal region

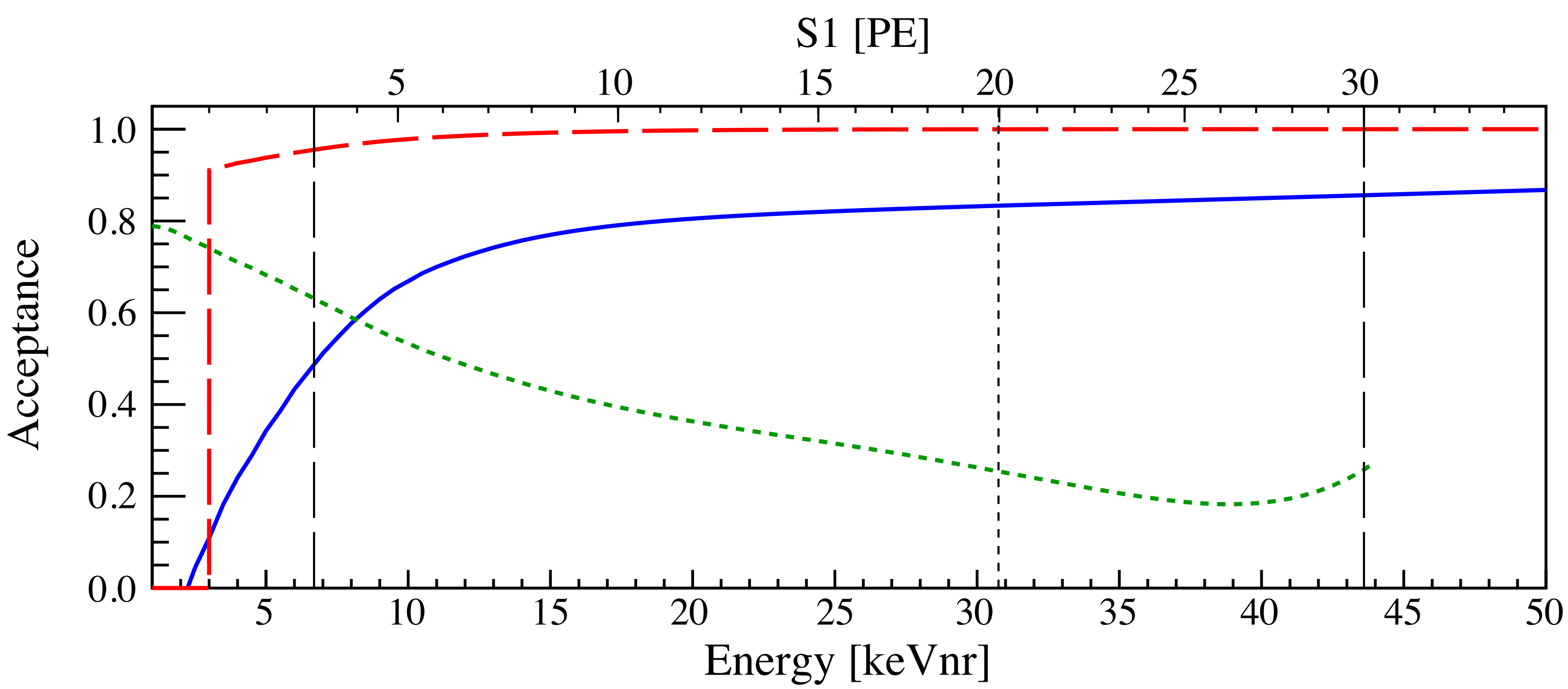


- The fiducial volume and signal region are simultaneously adjusted to maximize sensitivity
- Given the lower beta background in this run, we choose a smaller FV (34 kg) to profit from LXe self-shielding



- The signal region is chosen below the 99.75% constant rejection line for ER
- The signal region for the Maximum-Gap based analysis is set between 3 and 20 PE

Cuts acceptance and L_{eff} parameterization

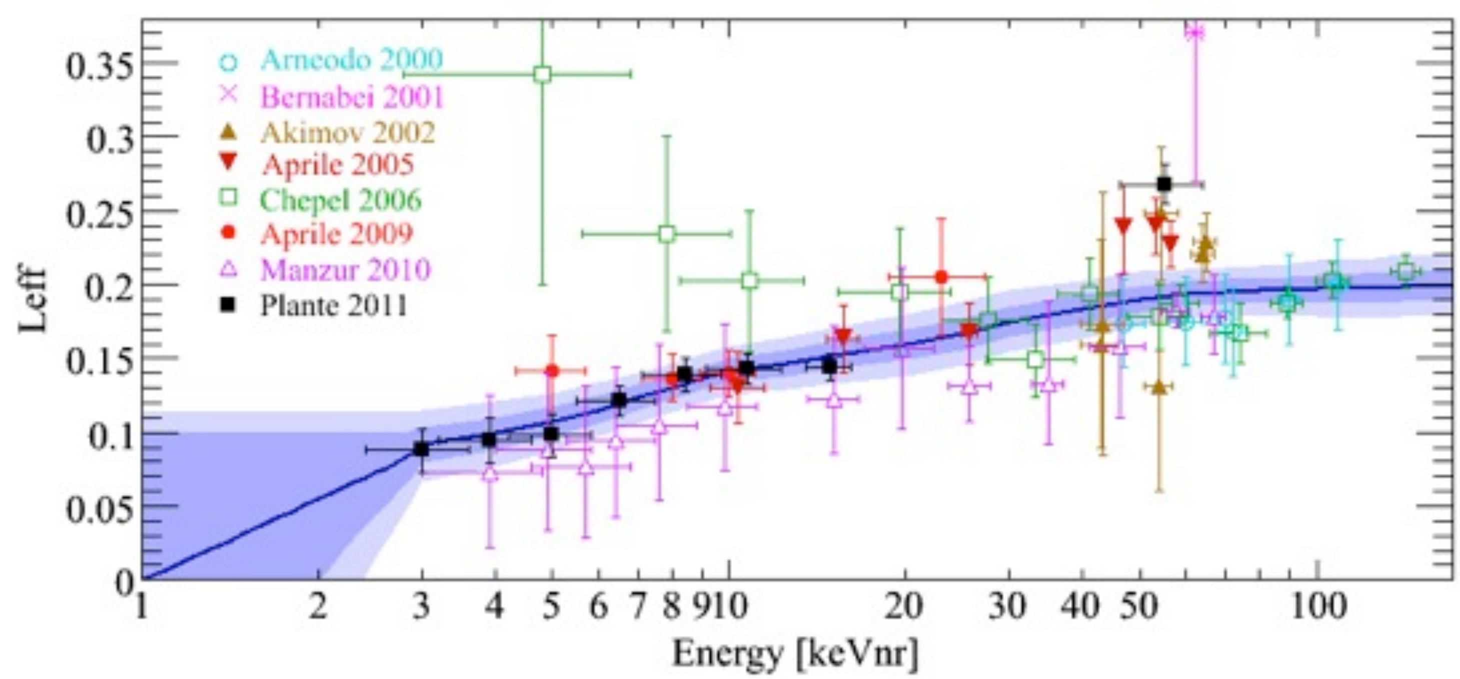


S2 threshold cut (S2 > 150 PE)

Combined acceptance

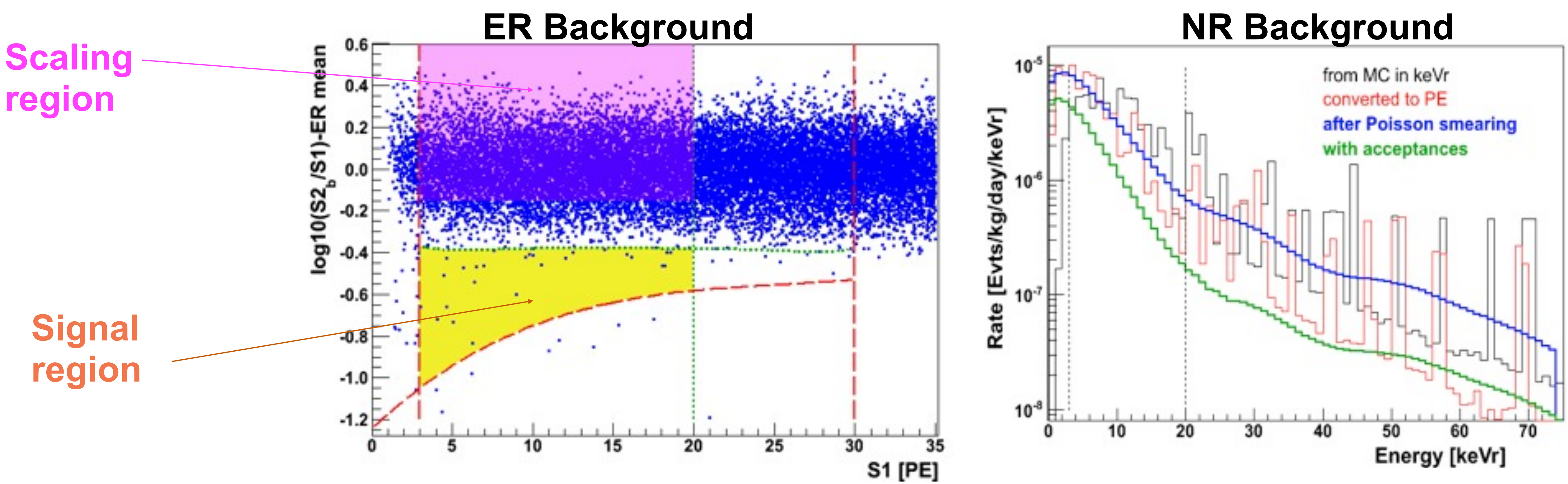
NR acceptance for a 99.75% ER rejection (Maximum Gap analysis only)

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



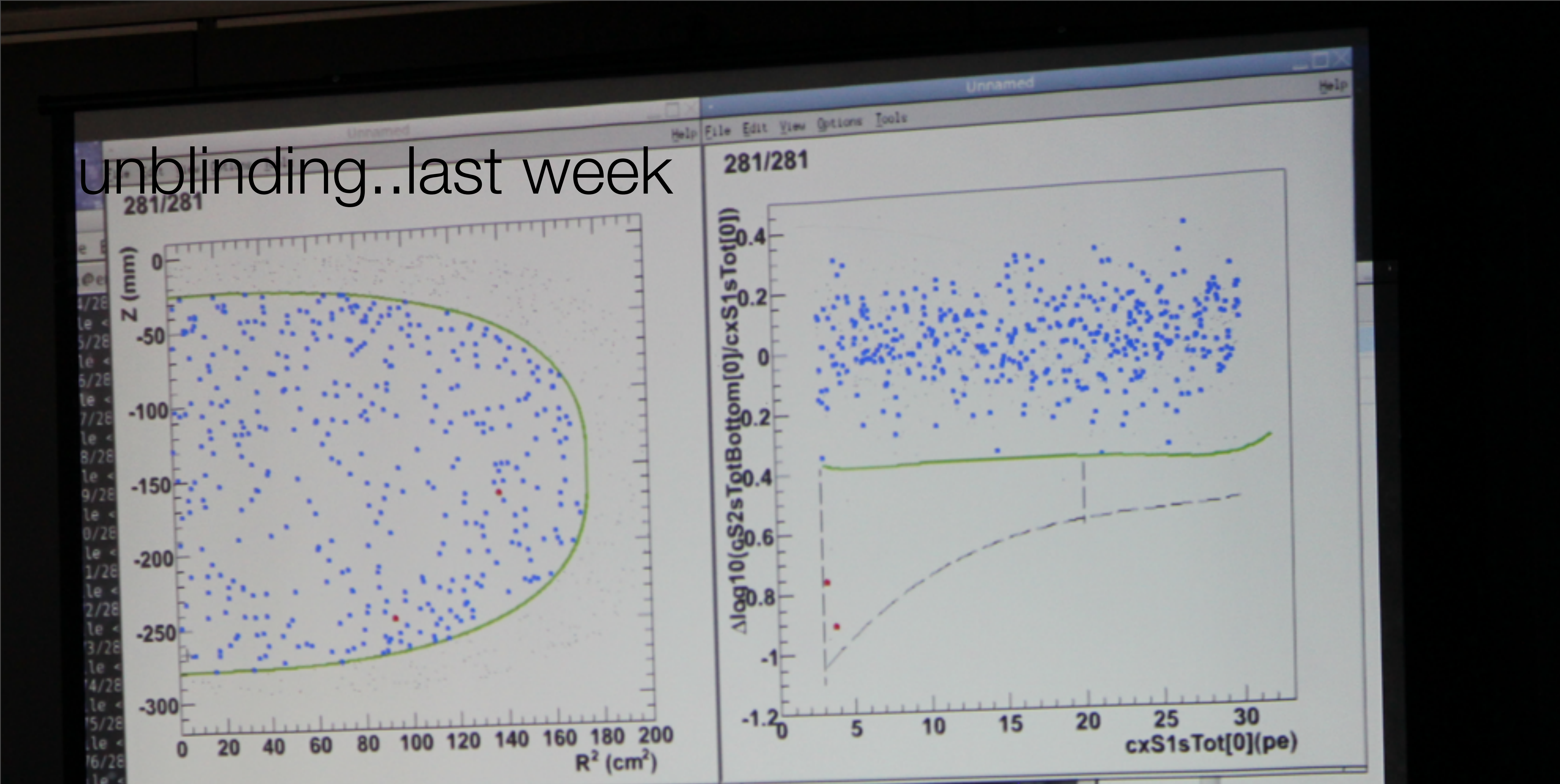
mean (solid) and 1- 2-sigma uncertainties (blue bands) of L_{eff} direct measurements

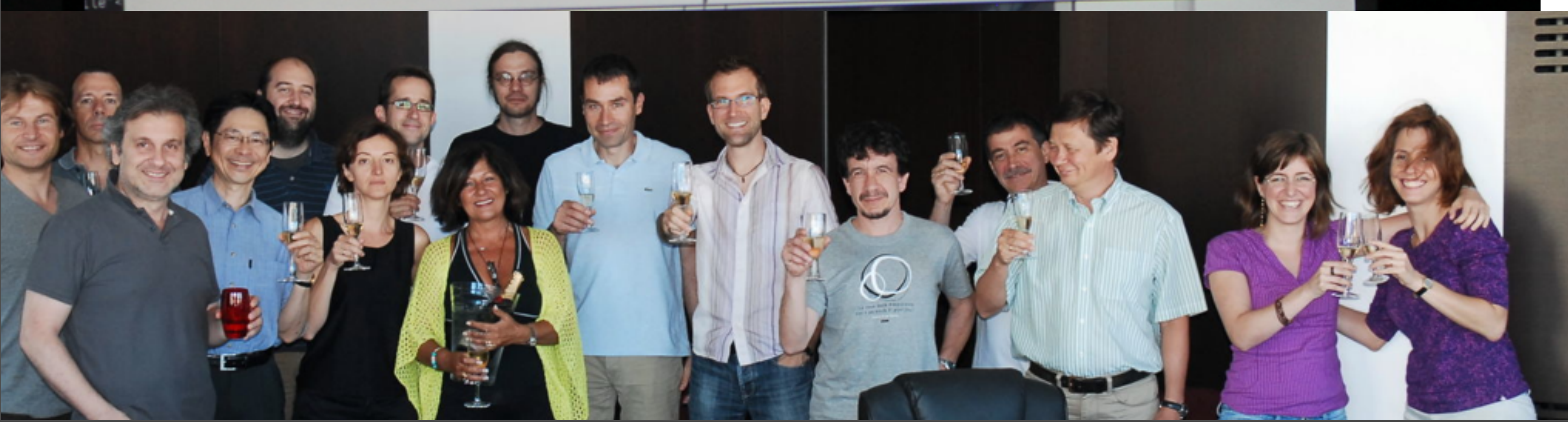
Background expectation



- 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: 1.0 ± 0.2 events (0.79± 0.16 from gammas, 0.17+0.12-0.07 from neutrons)

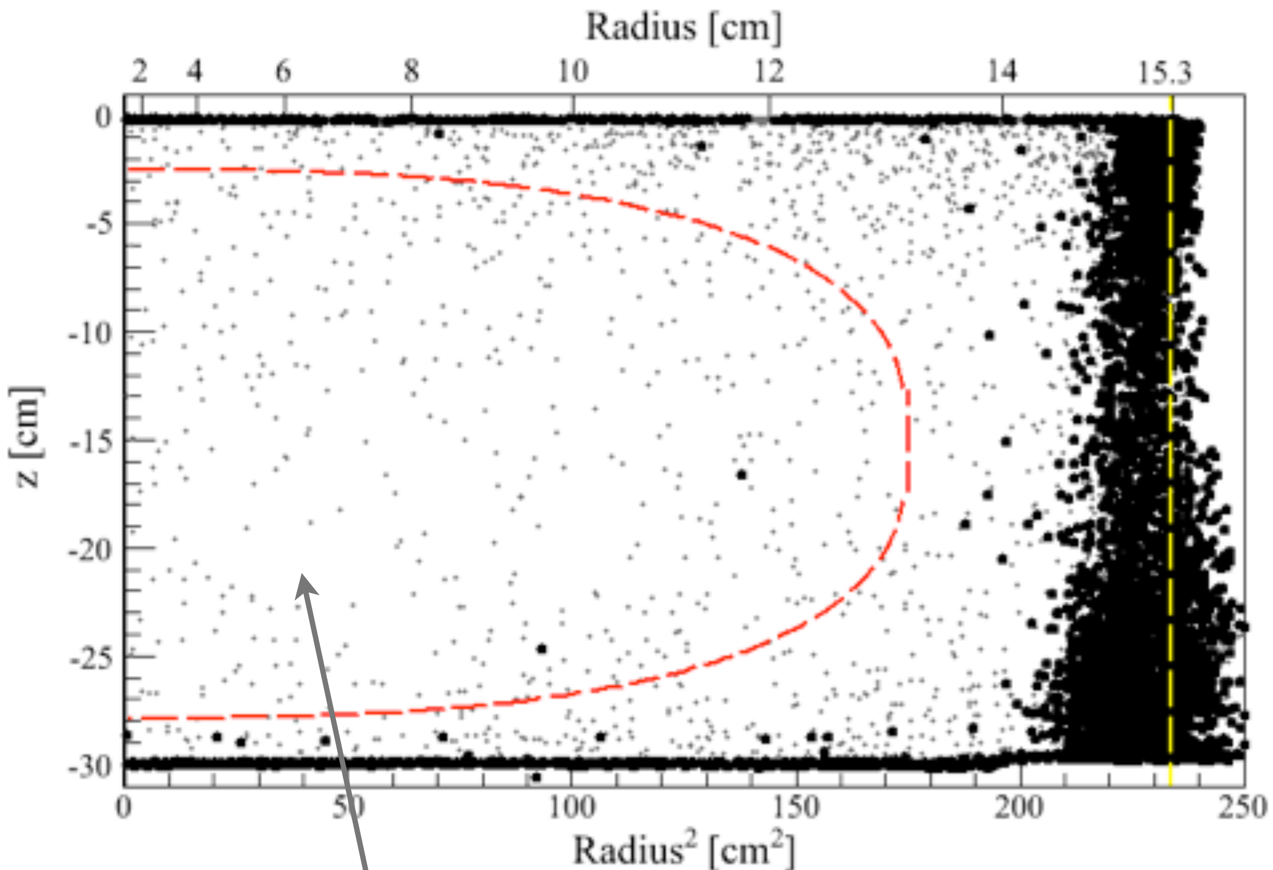
unblinding..last week

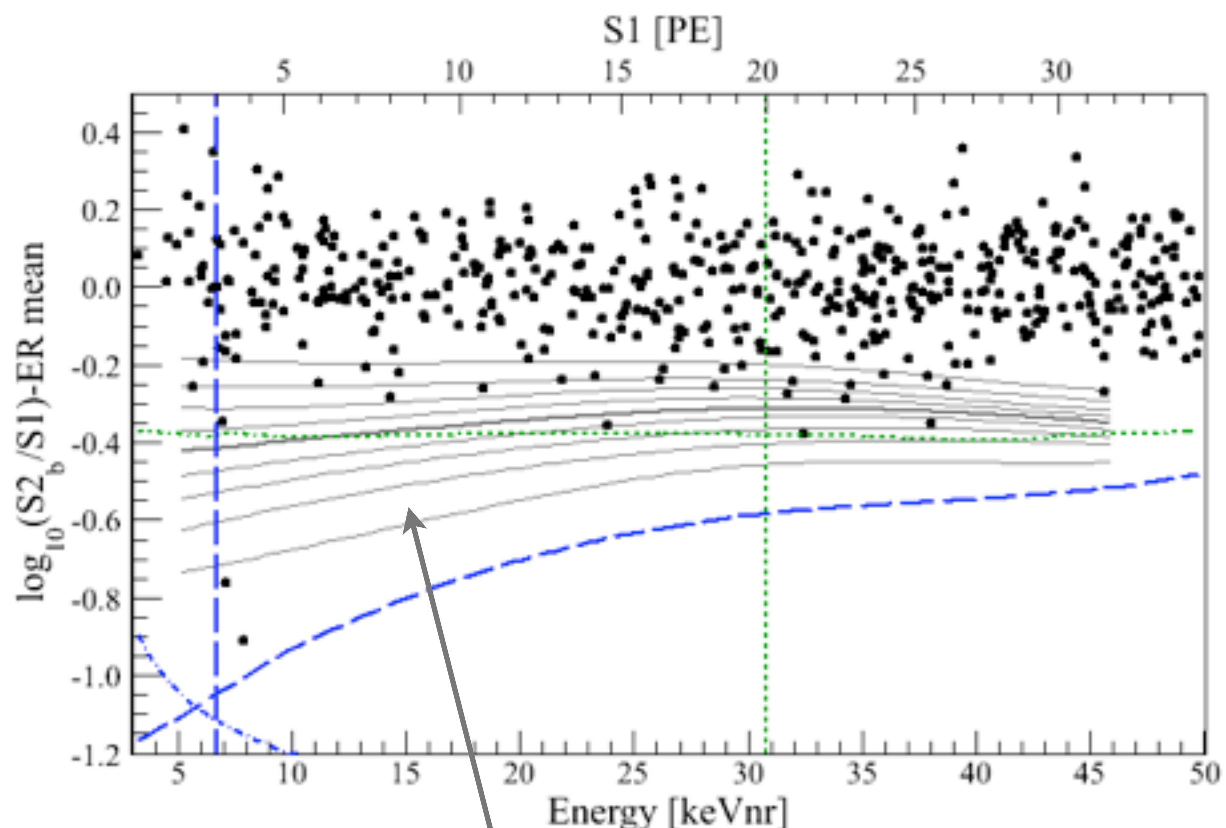




Unblinding: Distribution of events in the TPC

Exposure: 225 days x 34 kg fiducial mass

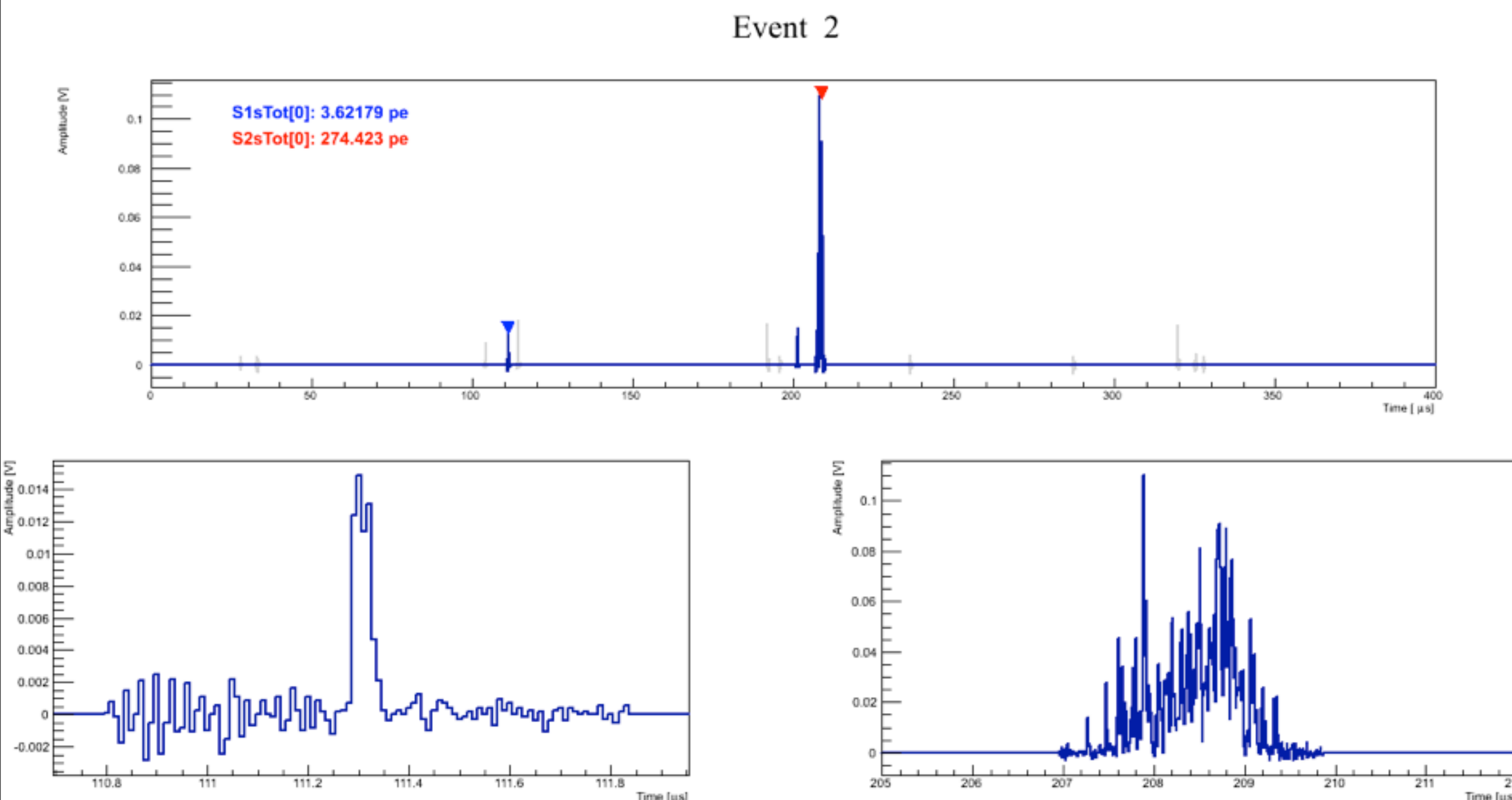




Fiducial mass region:
34 kg of liquid xenon
406 events in total

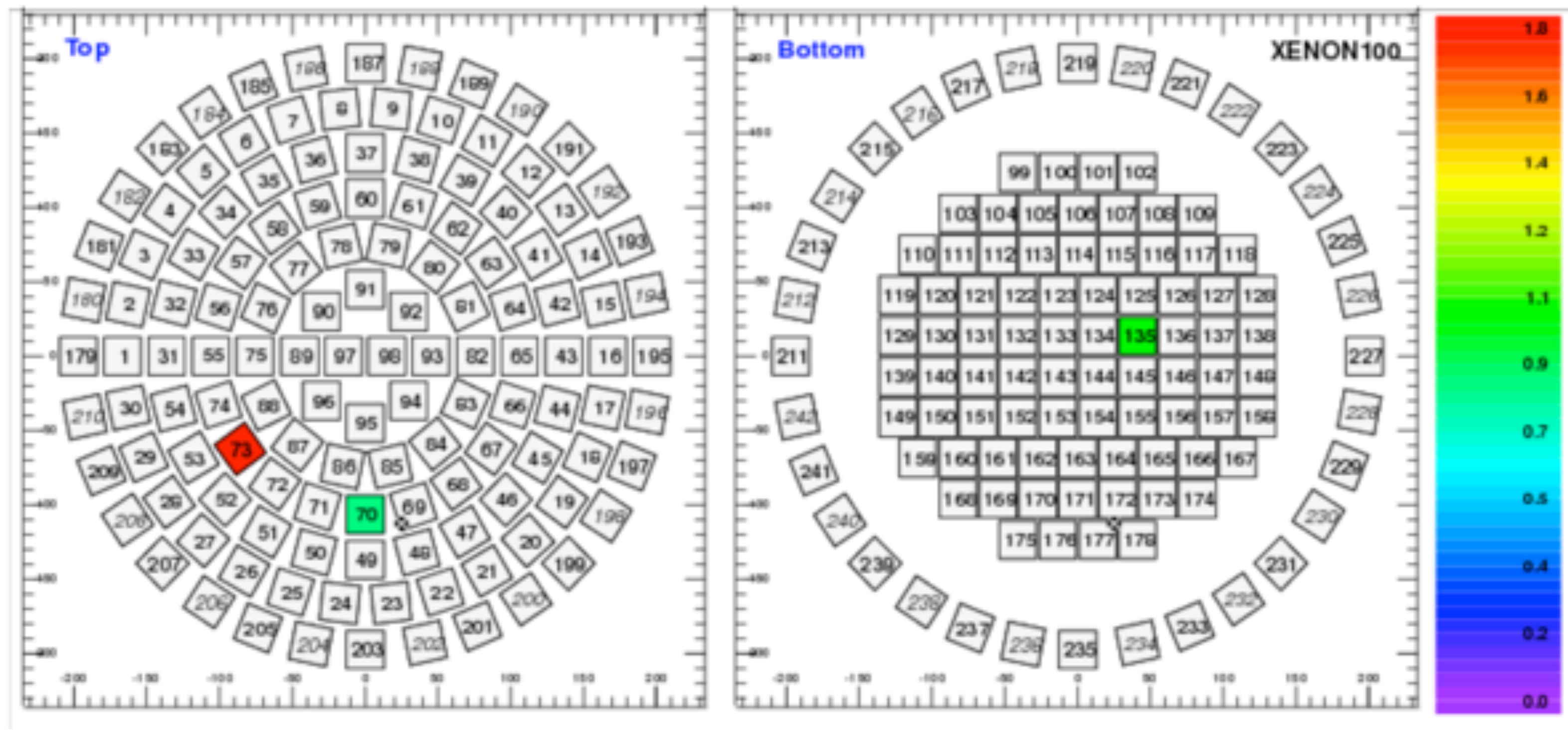
Signal region:
2 events are observed
0.79 ± 0.16 gamma leakage events expected
0.17 +0.12-0.7 neutron events expected

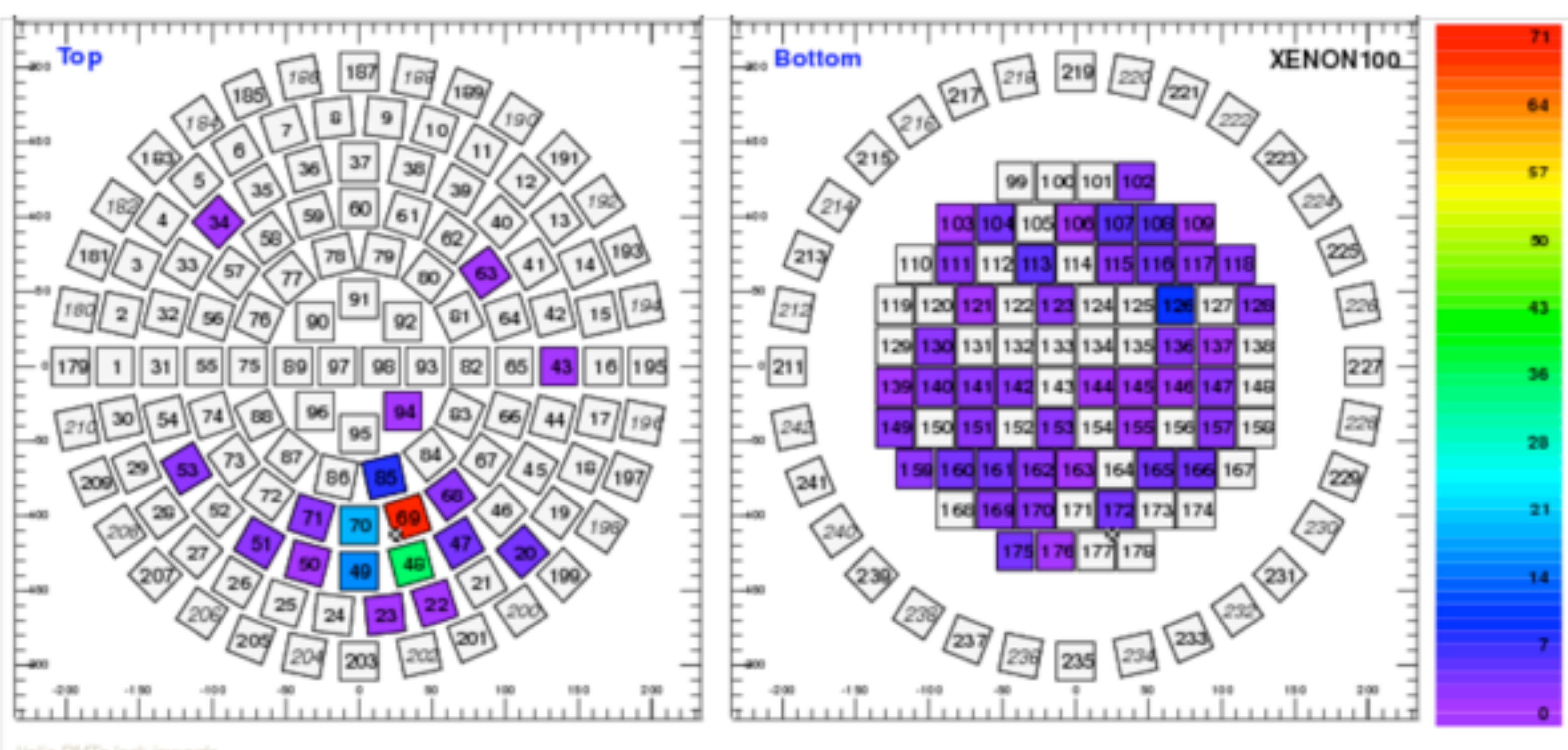
Event #1 (Xe100_120111_1920)



Event #1

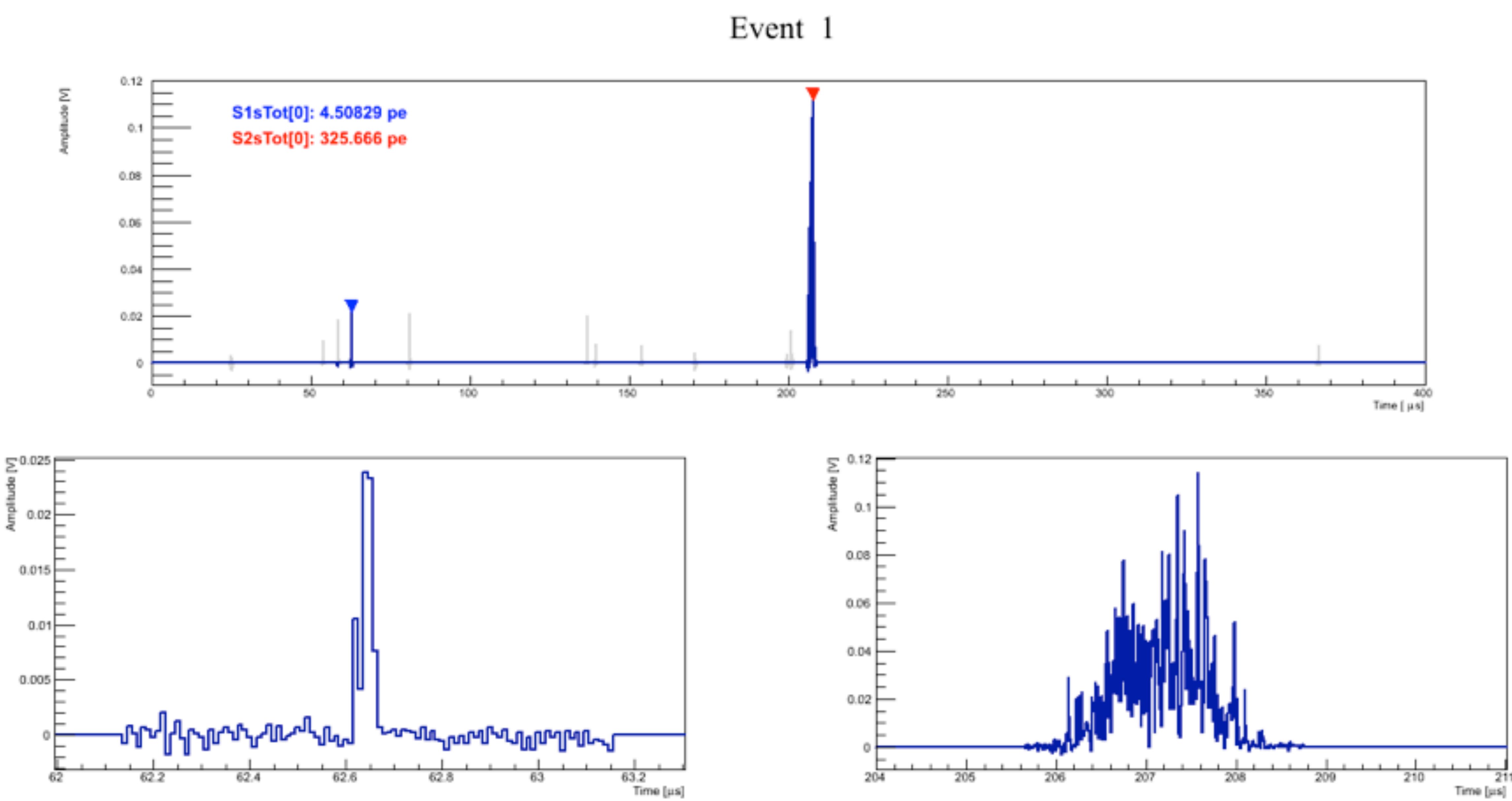
S1 Pattern



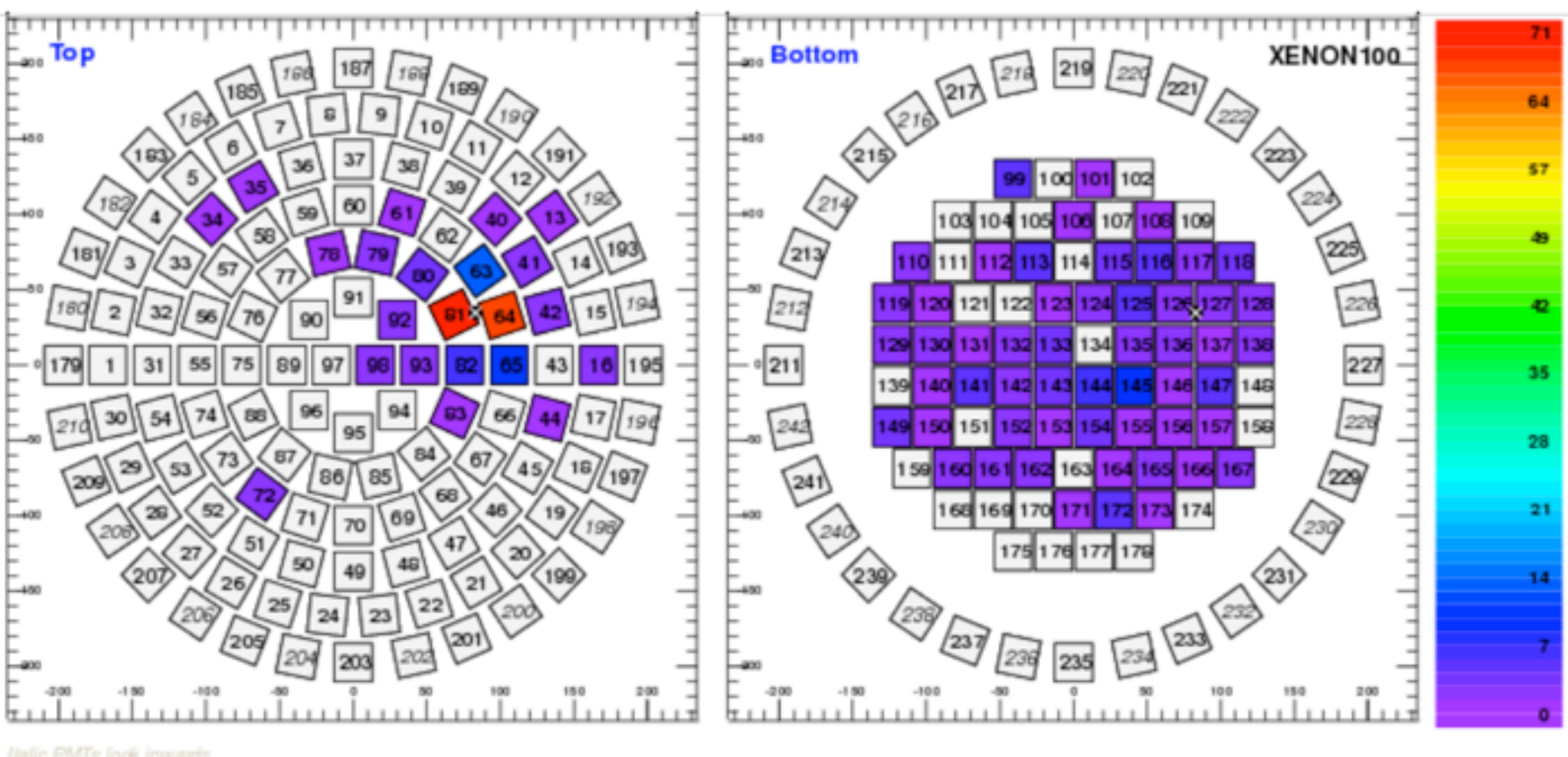


S2 Pattern

Event #2 (Xe100_111023_1101)



Event #2

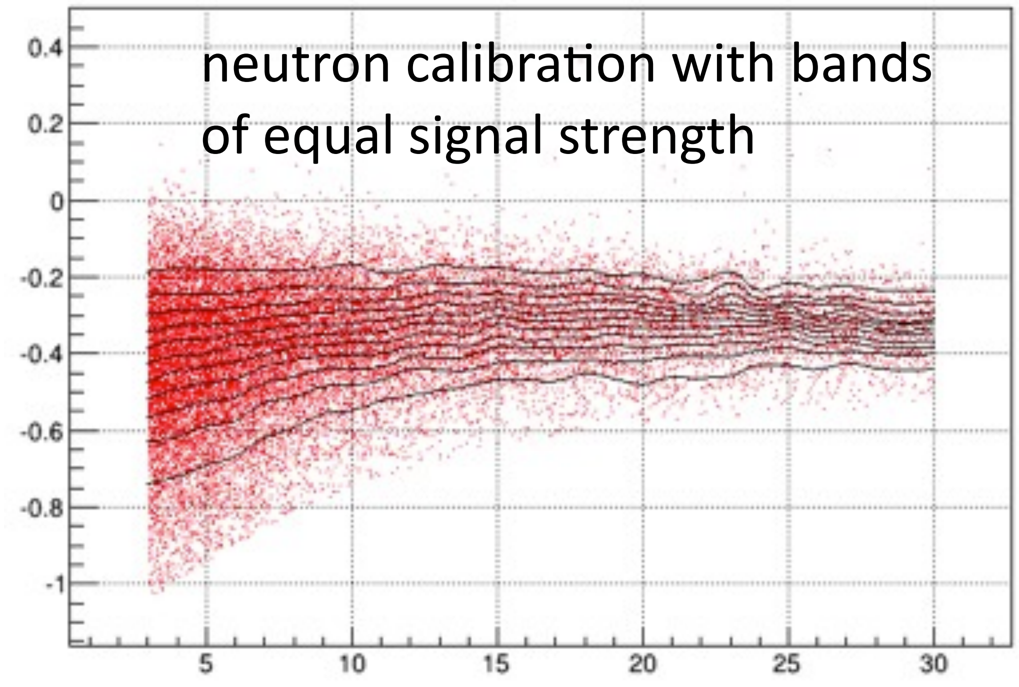


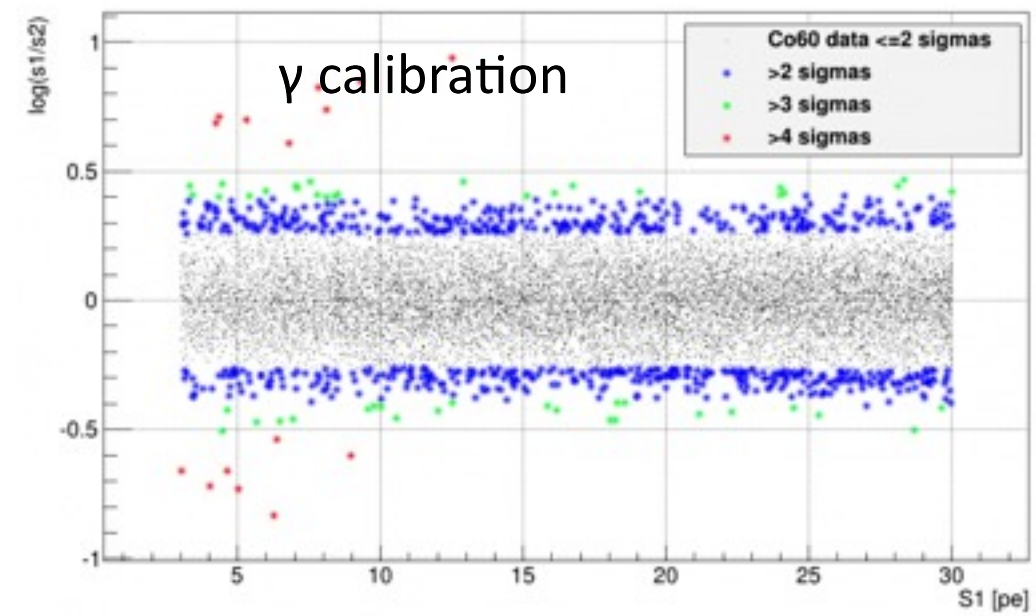
Profile Likelihood Analysis

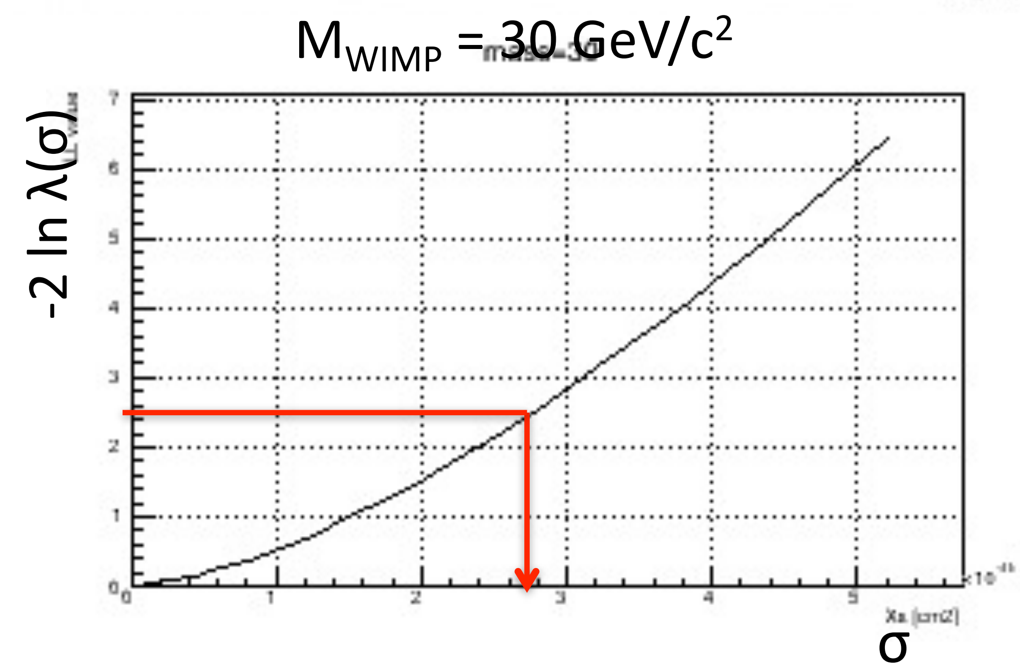
- Model WIMP response
  - Neutron calibration
  - External inputs (L_{eff}, astrophysics, form factor, …)
- Model Background
  - Gamma calibrations for ER background shape
    ➟ Gaussian + non-Gaussian tails
    Normalization to sidebands outside signal region
  - Neutron calibration for NR background
    Normalization to MC simulation based on material screening
- PL: maximum likelihood ratio with nuisance parameters

$$\lambda(\sigma) = \frac{\max\limits_{\sigma \text{ fixed}} \mathscr{L}(\sigma; \mathcal{L}_{\rm eff}, v_{\rm esc}, N_b, \epsilon_s, \epsilon_b)}{\max \mathscr{L}(\sigma, \mathcal{L}_{\rm eff}, v_{\rm esc}, N_b, \epsilon_s, \epsilon_b)}$$

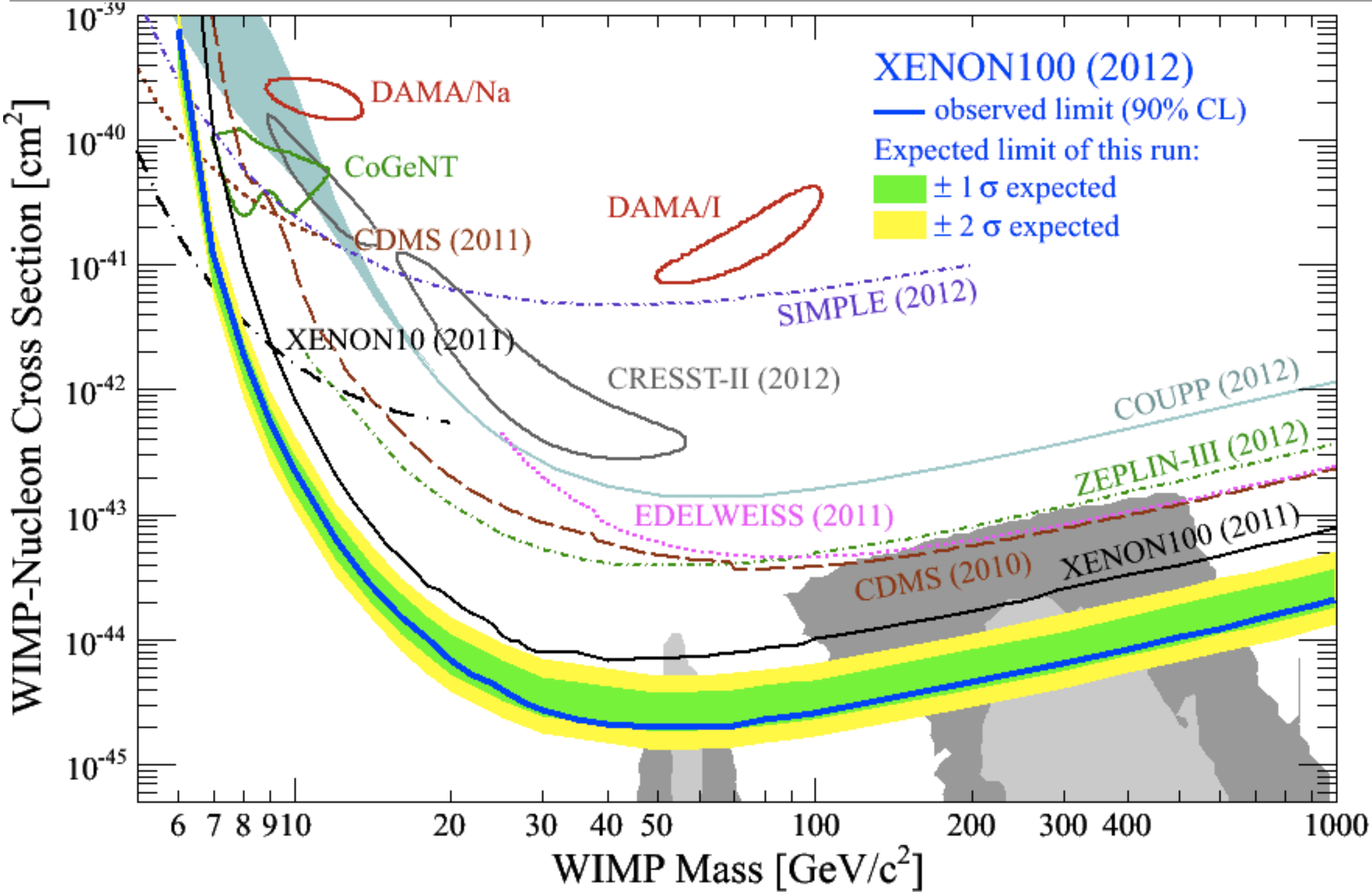
- Uncertainties in inputs accounted for (L_{eff}, …)
- Test signal and background hypotheses simultaneously. Upper limit or detection indicated by outcome of algorithm – no flip-flopping.
- Details: Phys. Rev. D 84, 052003 (2011)







XENON100: New Spin-Independent Results



Upper Limit (90% C.L.) is 2 x 10^{-45} cm^2 for 55 GeV/c^2 WIMP

What Next?

- Finish many papers based on new data:
  SD analysis, annual modulation and more..
- Continue XENON100 with lower Kr and Rn
- Continue cononstruction of XENON1T
- Strive to keep start as planned in 2015
- Aim at 100 x less background and 1ton FV
- Sensitivity Goal: 2x 10^{-47} cm ^{2} after 2yrs data