# Search for Dark Matter with the XENON100 detector

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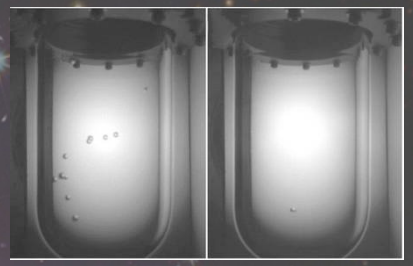
**on behalf of the XENON100 collaboration**
**Columbia University**
**June 8th 2011**

# The XENON100 collaboration

# Dark Matter Direct Detection

PICASSO
SIMPLE
COUPP



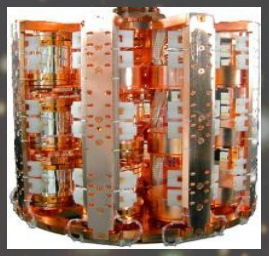
CDMS I-II
superCDMS
EDELWEISS I-II

HEAT

WIMP

Detector

CRESST -II
ROSEBUD



+time measurement

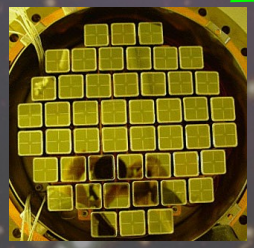
ZEPLIN I
CLEAN
DEAP
XMASS

WIMP

IONIZATION

SCINTILLATION

HPGe exp.
IGEX → GEDEON
GERDA
GENIUS
CoGeNT

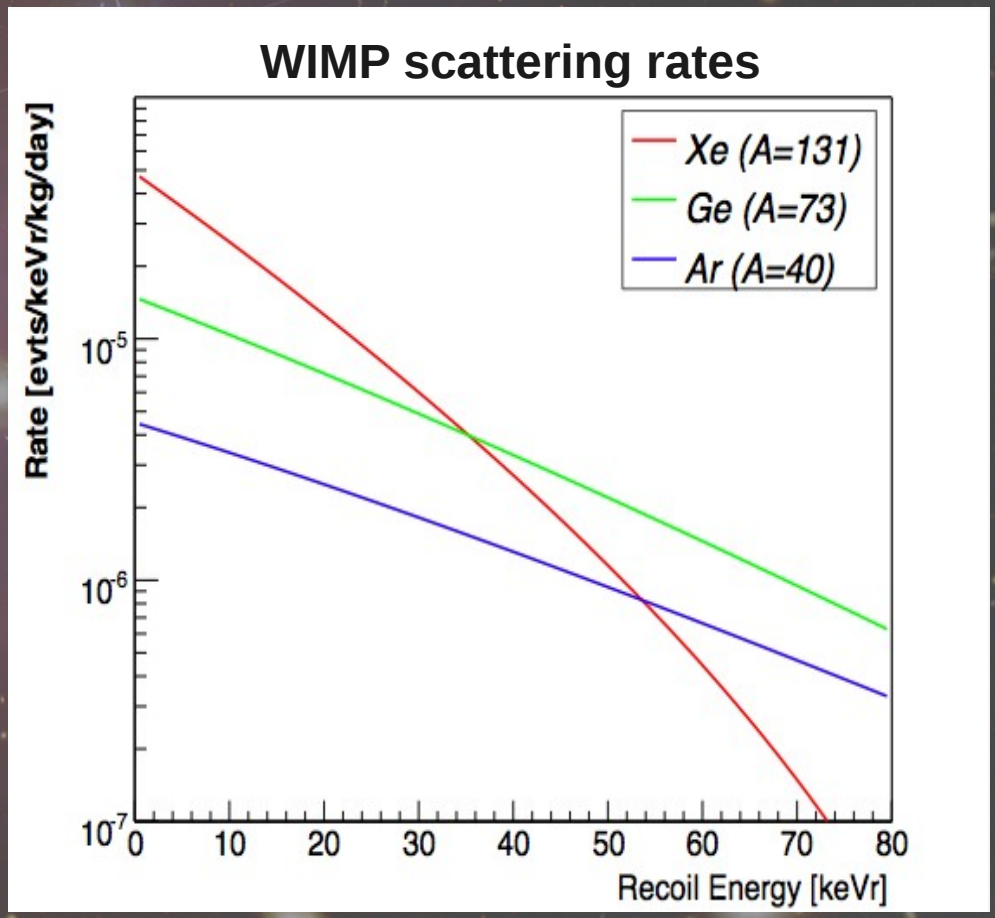


ZEPLIN II-III
XMASS II
XENON
WARP,
ArDM
DarkSide

DAMA / LIBRA
KIMS

# 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



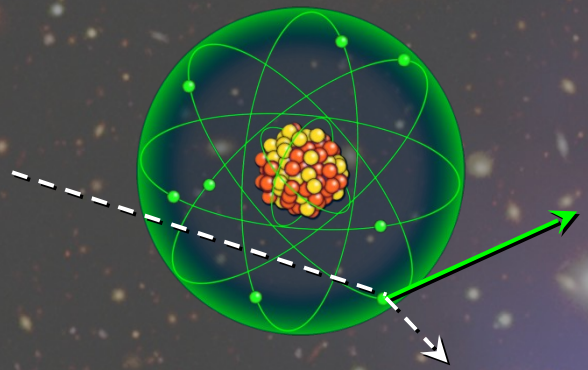
# The XENON100 detector

- 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

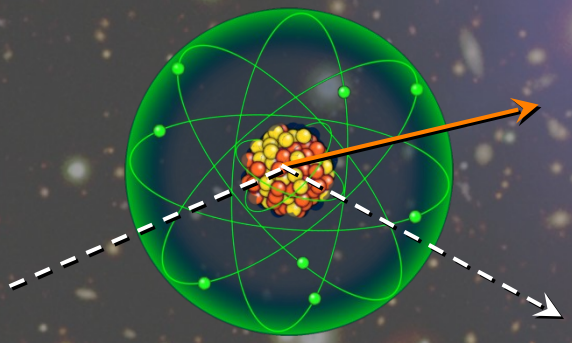
- 1 mBq (U/Th) and ~30% QE 1-inch square PMTs
- LXe veto around target on all sides
- Multilayer passive shield (Cu,Poly, Pb+Water)

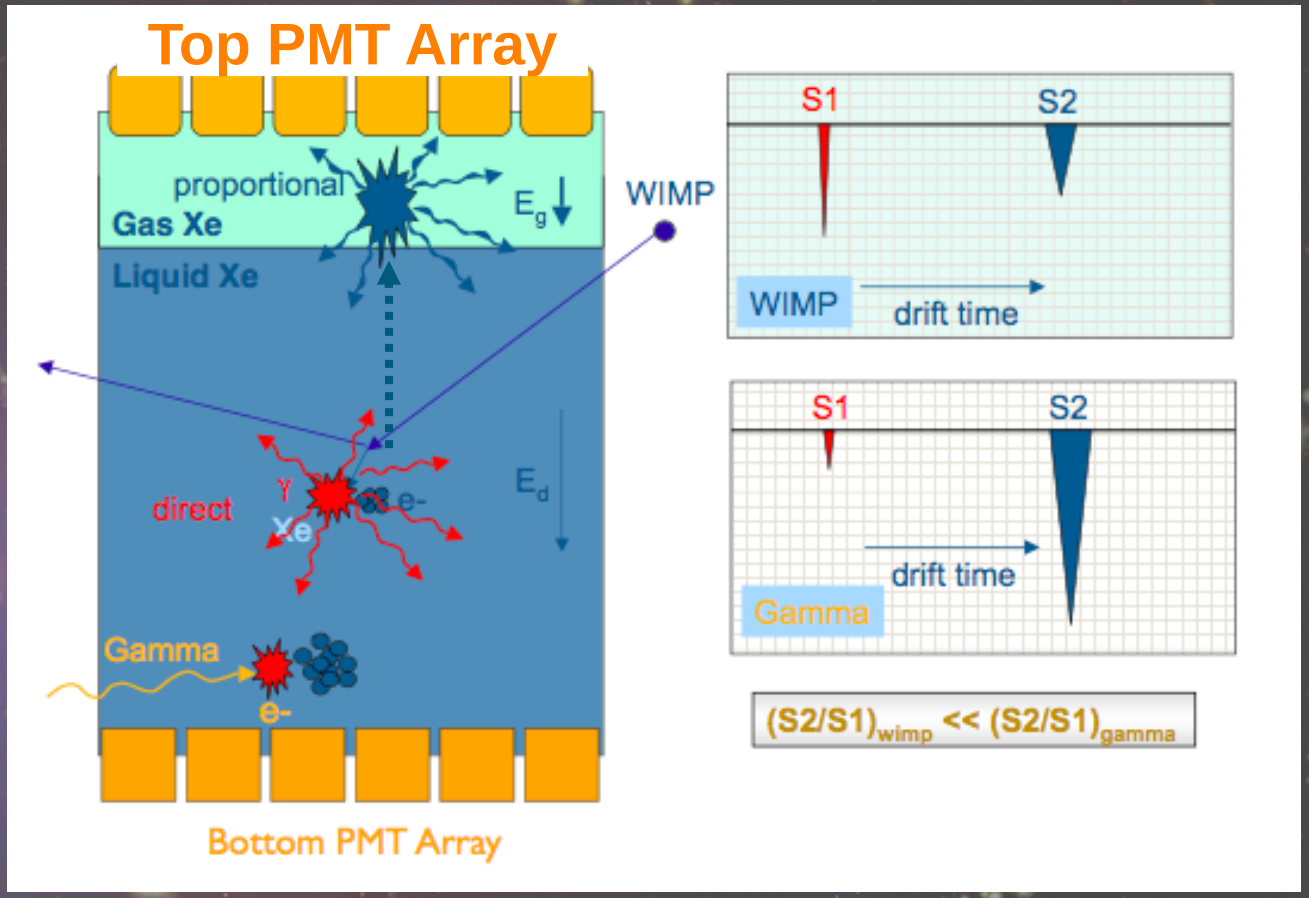
# The XENON two phase TPC

**$e^-/\gamma$: electron recoil**



**n/WIMPs: nuclear recoil**



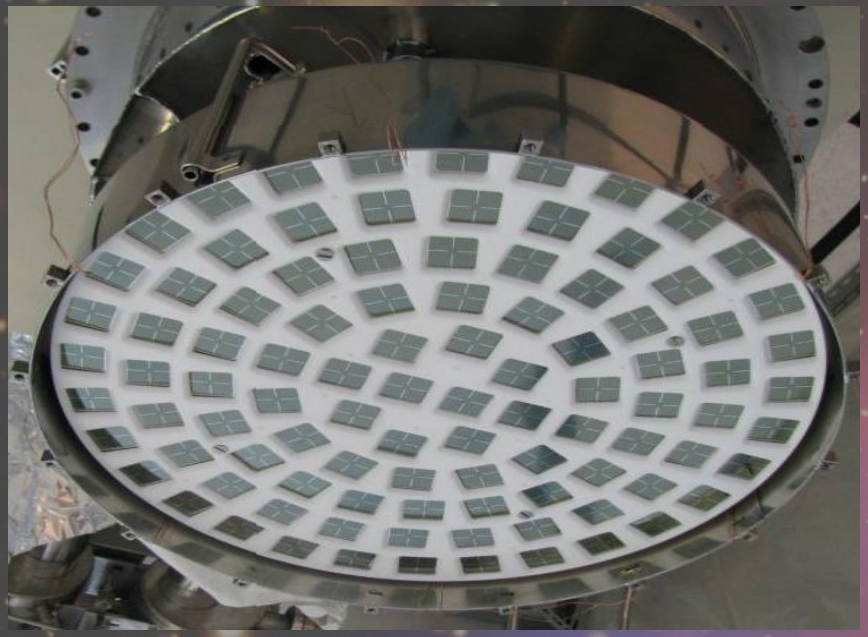



- **Single electron and single photon measurement sensitivity**
- **> 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1)**
- **3D event-by-event imaging with millimeter spatial resolution**

# XENON100 TPC

- The XENON100 TPC is made of 24 PTFE interlocking pannels. The high reflectivity of PTFE for xenon wavelength increases the light collection. It contains 62kg of LXe
- A cathode placed near the bottom of the detector is supplied with high voltage to generate an electric field in the TPC
- Field shaping rings equally spaced in the TPC at different voltages make the field homogeneous across the whole drift length
- The anode mesh stack in the top of the TPC close the electric field and provide a higher electric field region in the liquid-gas interphase to extract the electrons and produce proportional scintillation light

# PMT Arrays



- The top PMT array is composed of 98 PMTs
- Using a bell system, the PMTs are kept constantly in xenon gas
- The S2 PMT pattern distribution is related to the interaction position. The radial distribution of the PMTs is optimized to reconstruct the position of the interactions

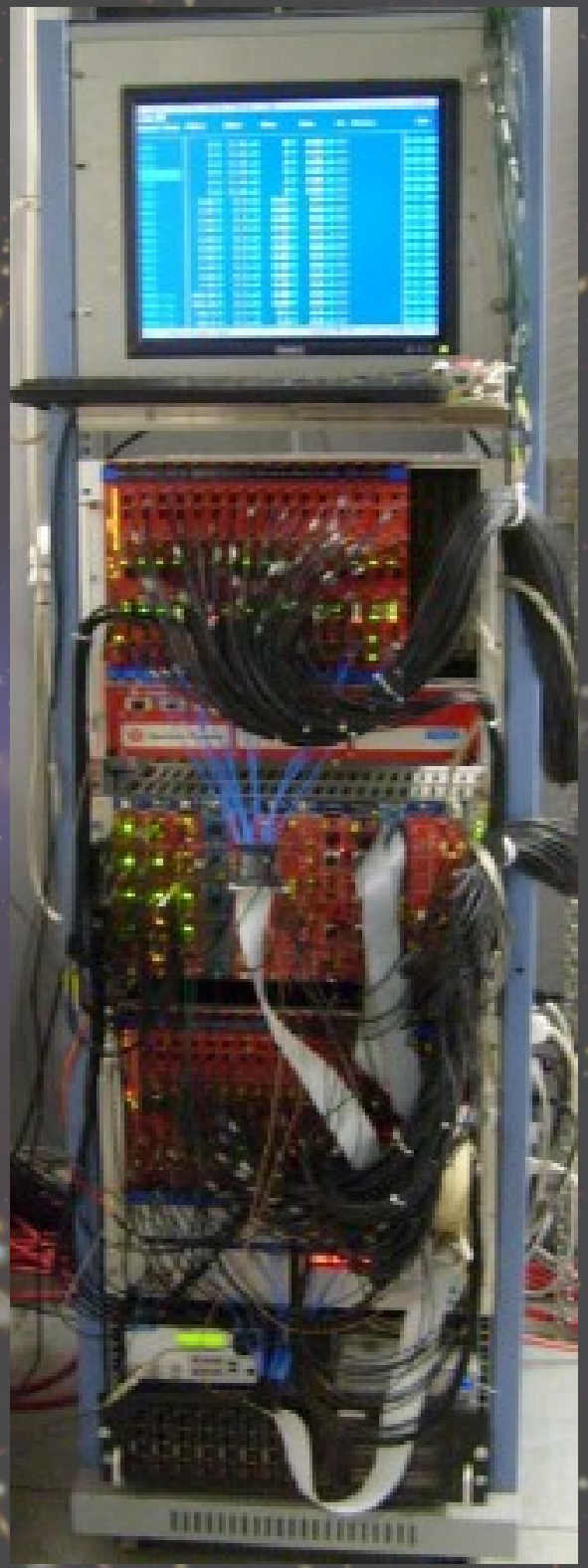
- The bottom PMT array is made of 78 PMTs
- The PMTs are placed in the liquid to improve the light collection
- PMTs in the bottom array are specially selected for high QE
- The PMTs are very packed to maximize the amount of light detected

# XENON100 Veto

- The volume surrounding the TPC is filled with ~100 kg of liquid xenon
- This liquid xenon acts as a radiation shield thanks to the high Z and density
- The volume is instrumented with 64 PMTs facing the top, bottom and sides of the TPC to reject interactions with one deposition inside the TPC and one in outside (active veto)

# Electronics

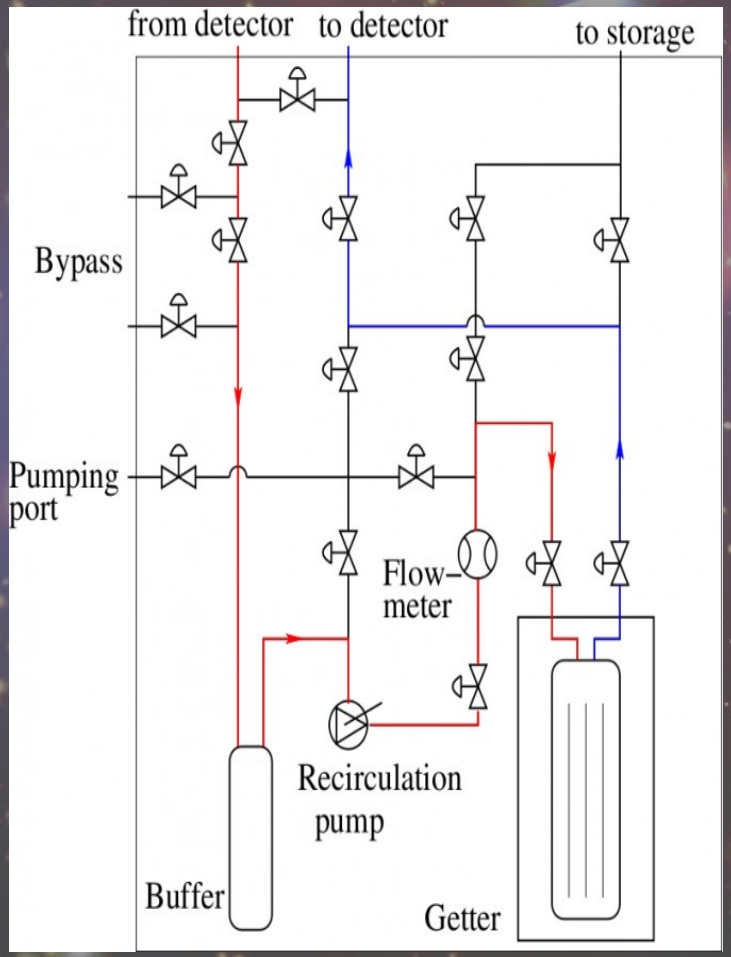
- Requirements:
  - Digitize full waveform (400μs) of 242 PMTs
  - No dead time
  - High rate capability for calibration
- Solution: CAEN V1724 Flash ADC, 14 bit, 100MHz
  - circular buffer, very short dead time
  - on board FPGA: Zero Length Encoding



# Purification system

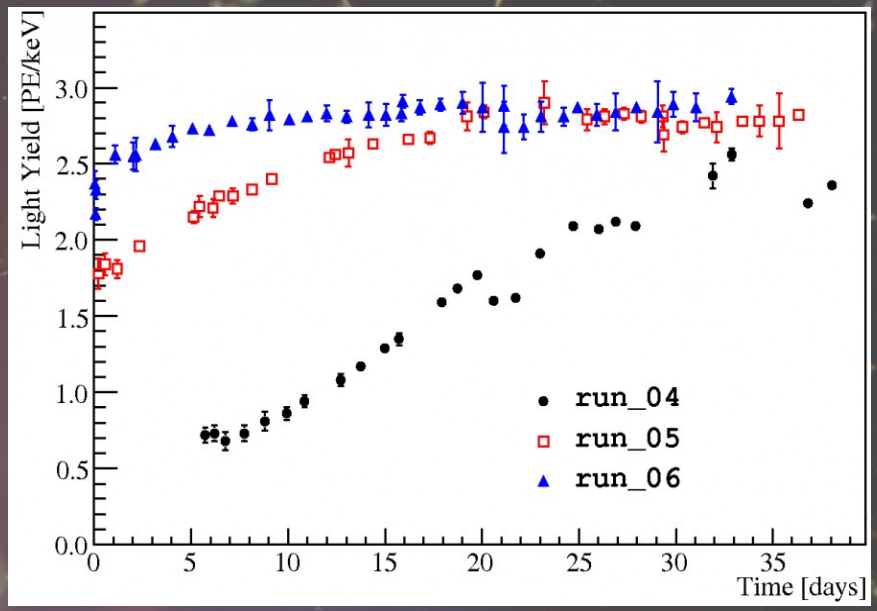
- Impurities in liquid xenon can reduce the amount of light and charge collected in the detector

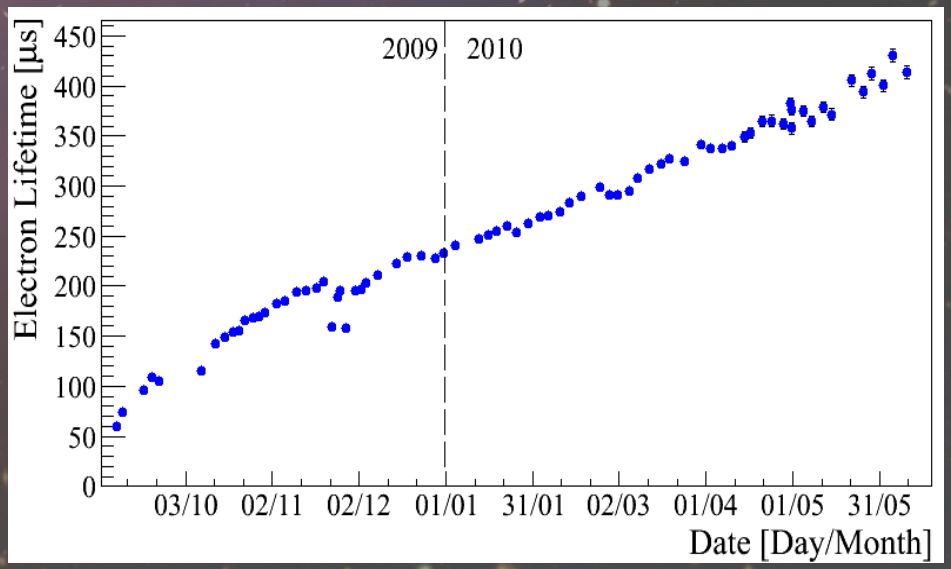
- The xenon is continously recirculated with a double diaphragm pump through a hot getter at 10slpm




# Purification system

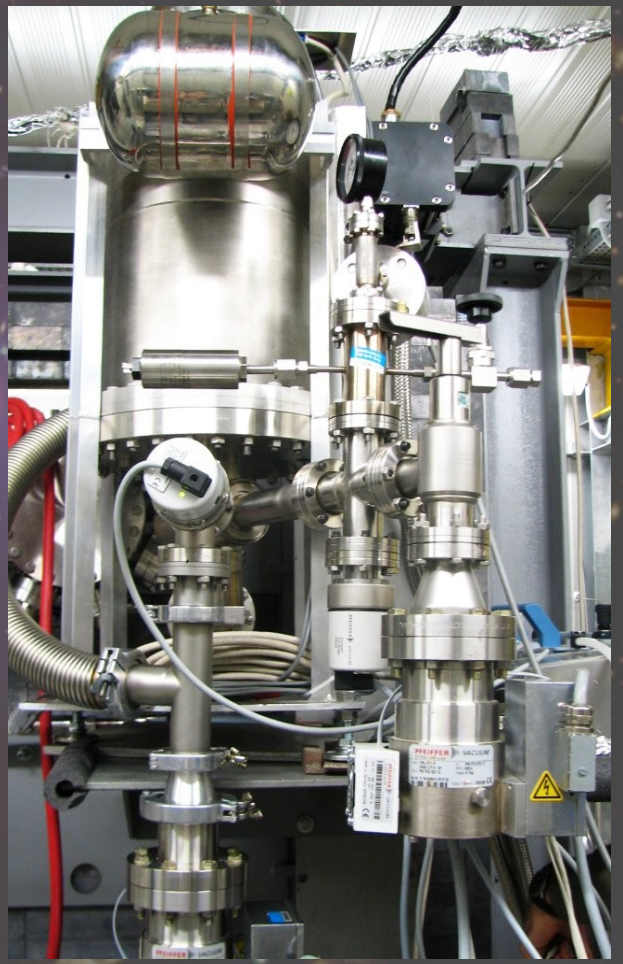
- Sources of impurities:
  - Leaks: minimized during construction
  - Xe gas contamination
  - Materials outgassing: No bake out before construction and hard to bake-out in situ at high temperatures due to the presence of PMTs. Largest contribution and time dependent
- Continuous monitoring of detector behaviour

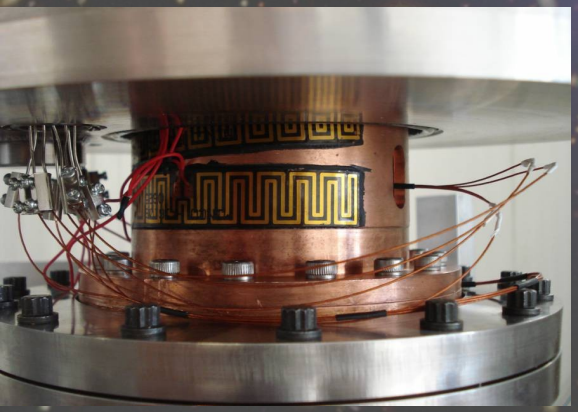


# Cooling system

Xenon is cooled down by a Helium pulse tube refrigerator.
A system of heaters with variable voltage input is used to keep the coldhead temperature at a constant level
Liquid Xenon drops are collected with a funnel and go into the detector trough a pipe with a small inclination





# XENON100 Krypton removal system

- Xe has no long lived isotopes but has traces of radioactive Kr85 (Emax = 687 keV, t~11 yr) present in natural Kr at ~$10^{-11}$
- The Kr level in XENON100 fill gas is ~1ppb, measured with delayed coincidence events
- A dedicated cryogenic distillation tower has been commissioned and installed next to XENON100
- An initial distillation reduced the Kr concentration to ~140ppt. However, due to a leak in the gas system it increased to ~700ppt

# Shield

- 4 layers of material
  - Water: Stop neutrons from the outside
  - Lead: Stop gammas from the outside
  - Polyethylene: Stop neutrons from outside and from lead
  - Copper: Stop gammas from polyethylene

# XENON100 at LNGS

## taking data since the first decade of the millenium



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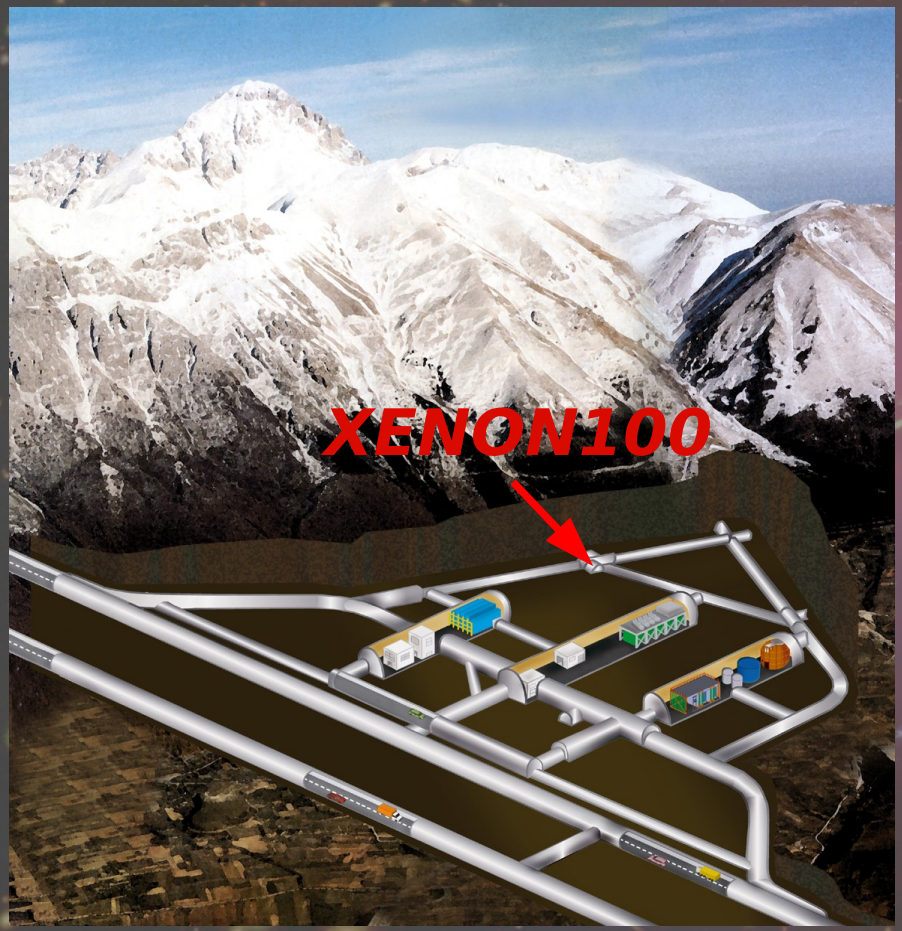
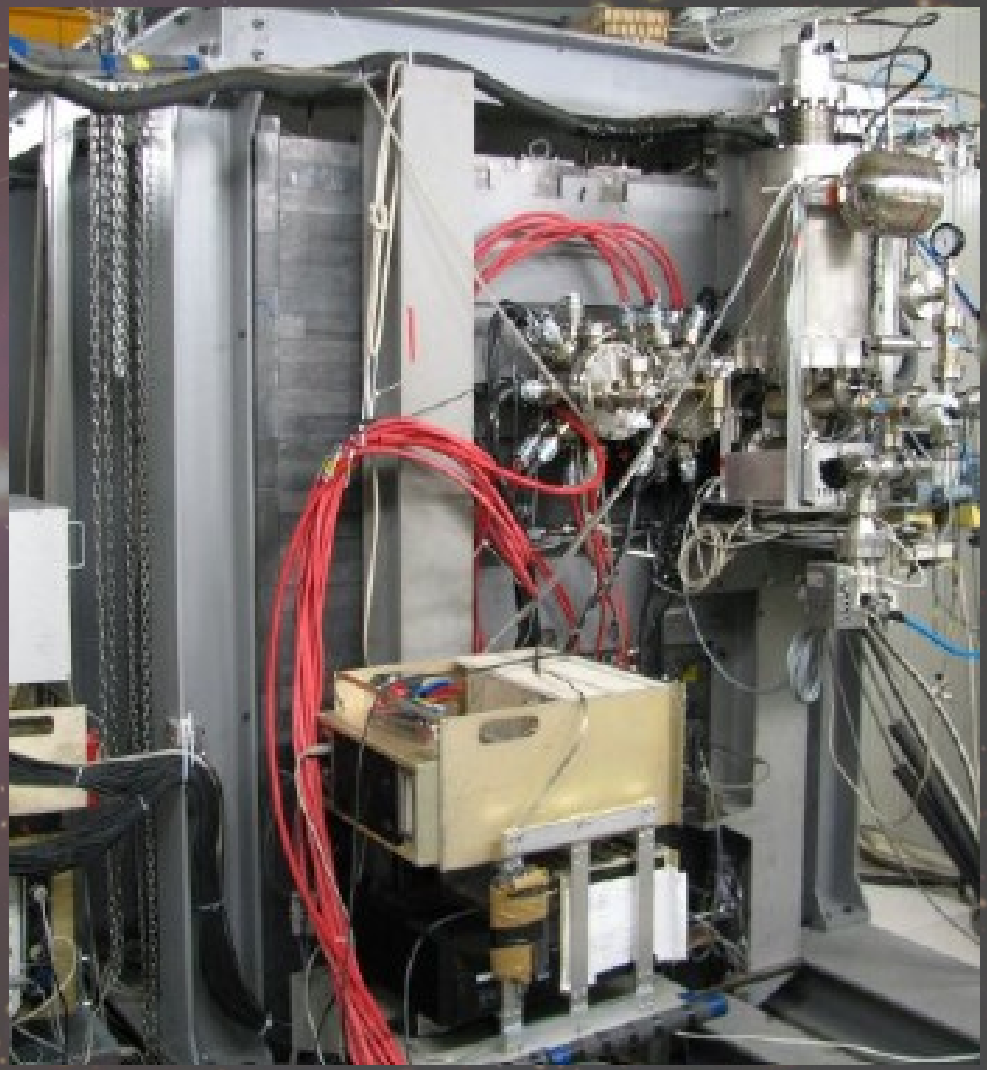
# XENON100 at LNGS

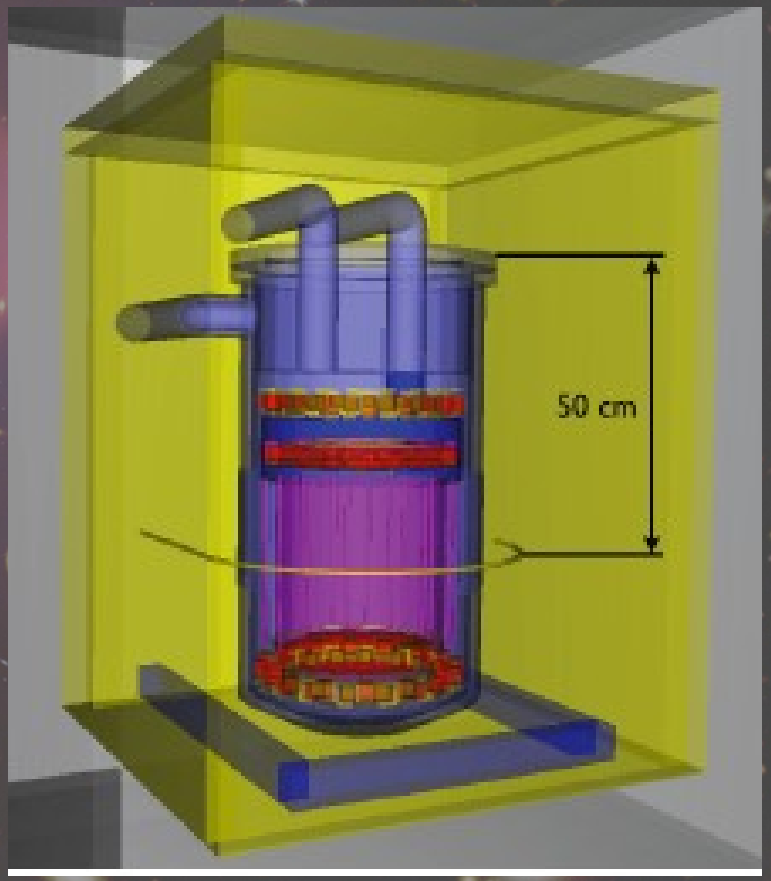
taking data since the first decade of the millenium



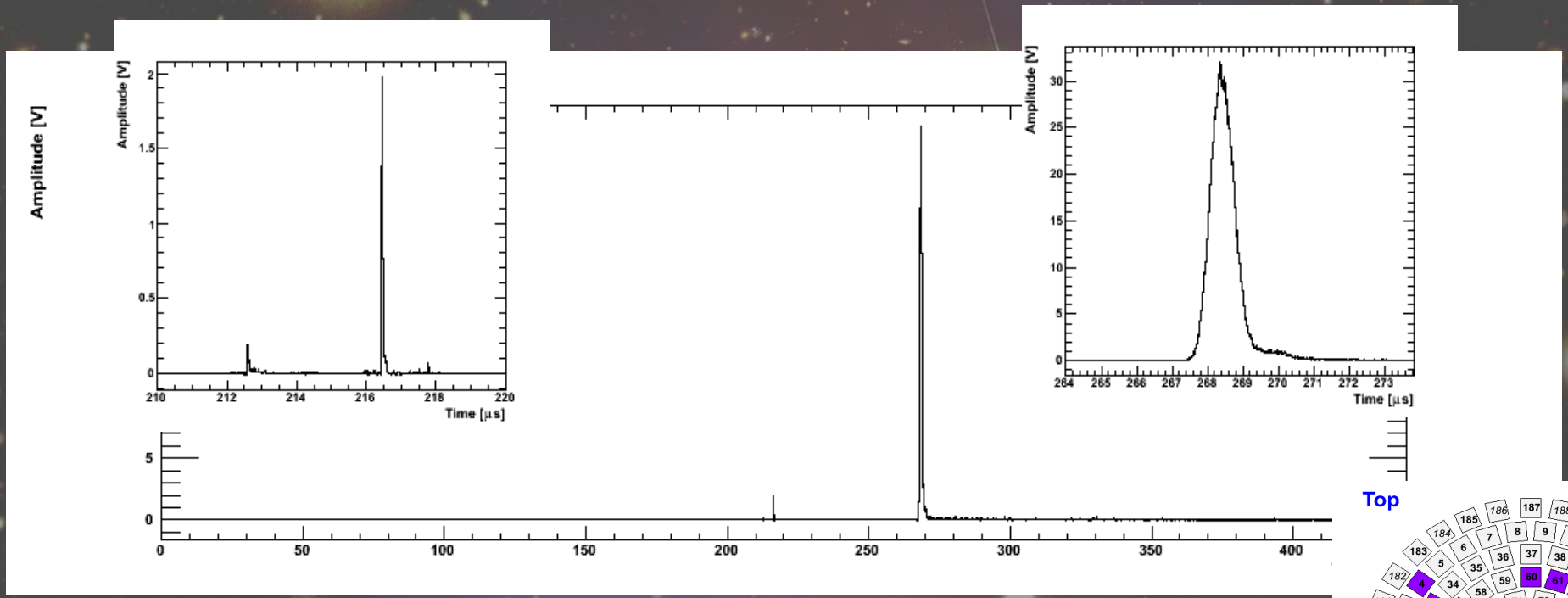



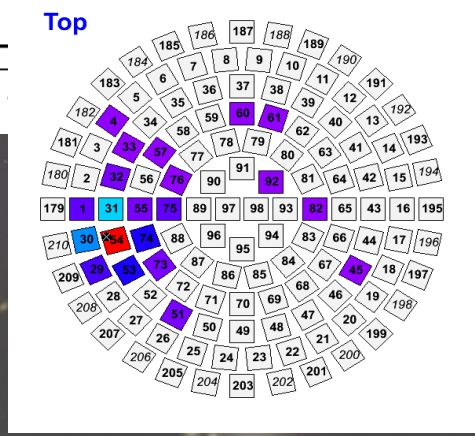
# Understanding the detector

- In order to characterize the response of the detector, we constantly irradiate it with different sources. The informations we want to get are:
  - Accuracy of position reconstruction
  - Homogeneity in light and charge collection and light yield
  - Electron life time evolution
  - Discrimination power between electron-like and neutron-like interactions



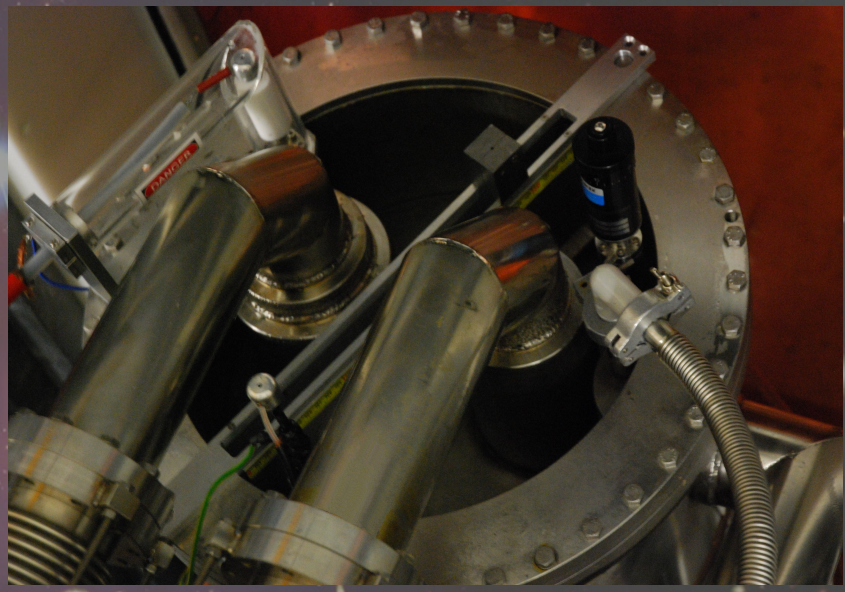
# A typical XENON100 event

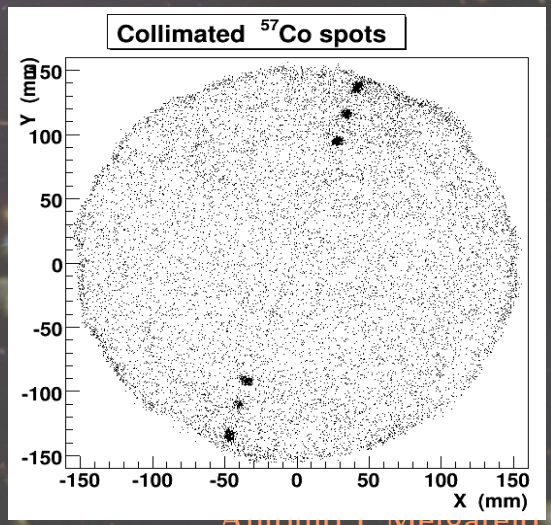


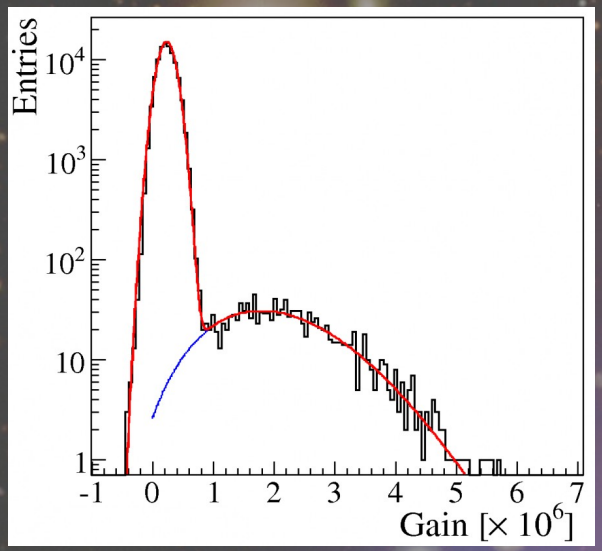
# Calibration of XENON100: positioning

- 3 different position reconstruction algorithms have been developed
- A dedicated setup has been used to test them: a $^{57}$Co source is placed in a lead collimator and data are taken at different radii
- Agreement between the results and the MC yield a resolution ≤ 3 mm

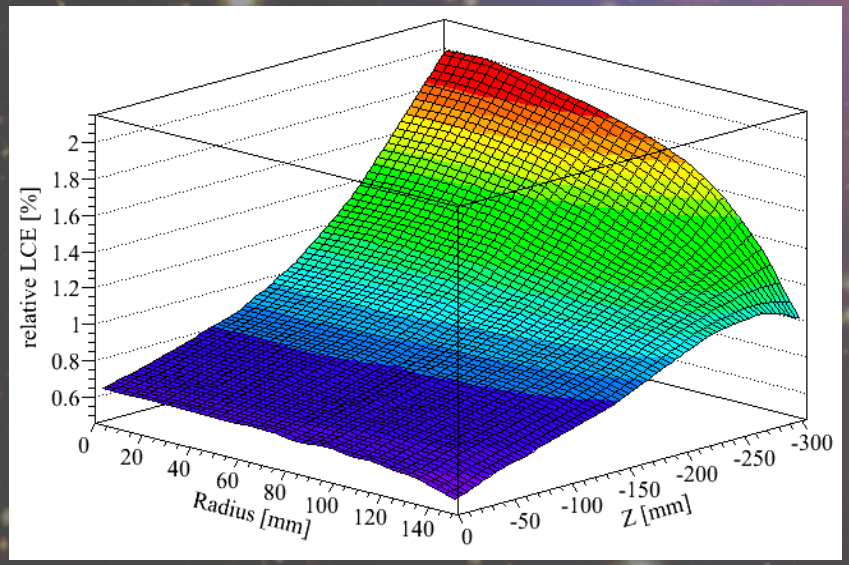


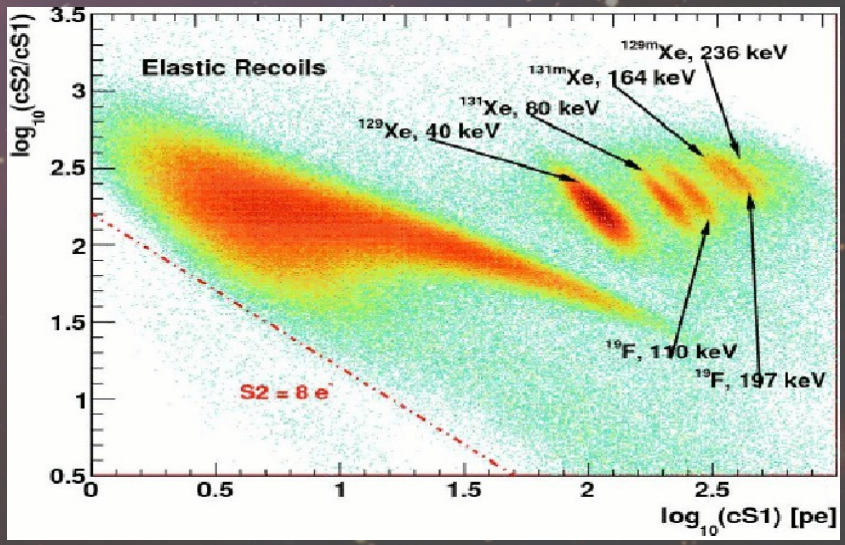


# Calibration of XENON100: Light



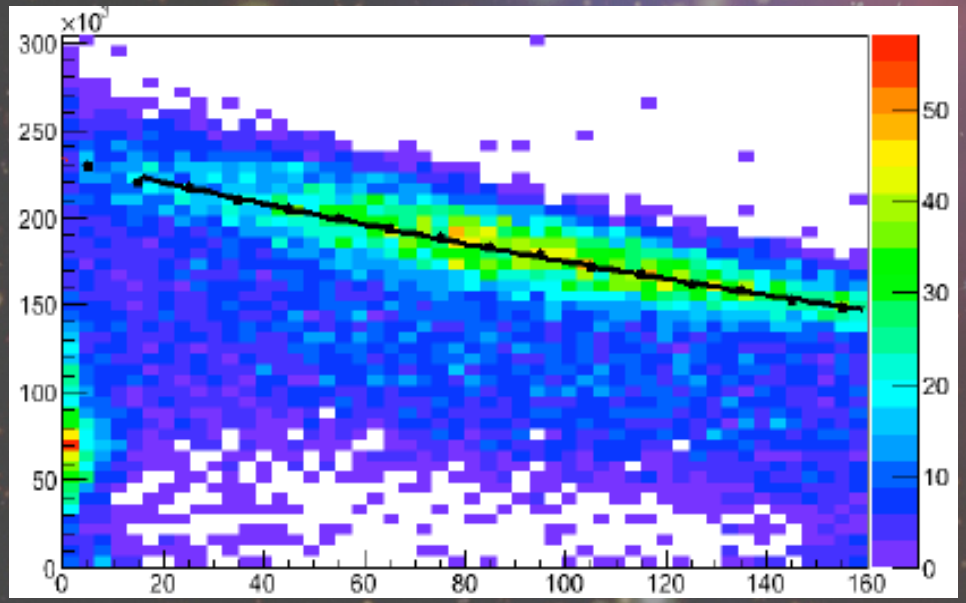

- The light response of each PMT is periodically calibrated with LED light
- A map of the light collection efficiency for the detector has been measured. We can correct our results to have a homogeneous response
- Measurements from different sources with different energies give the same result

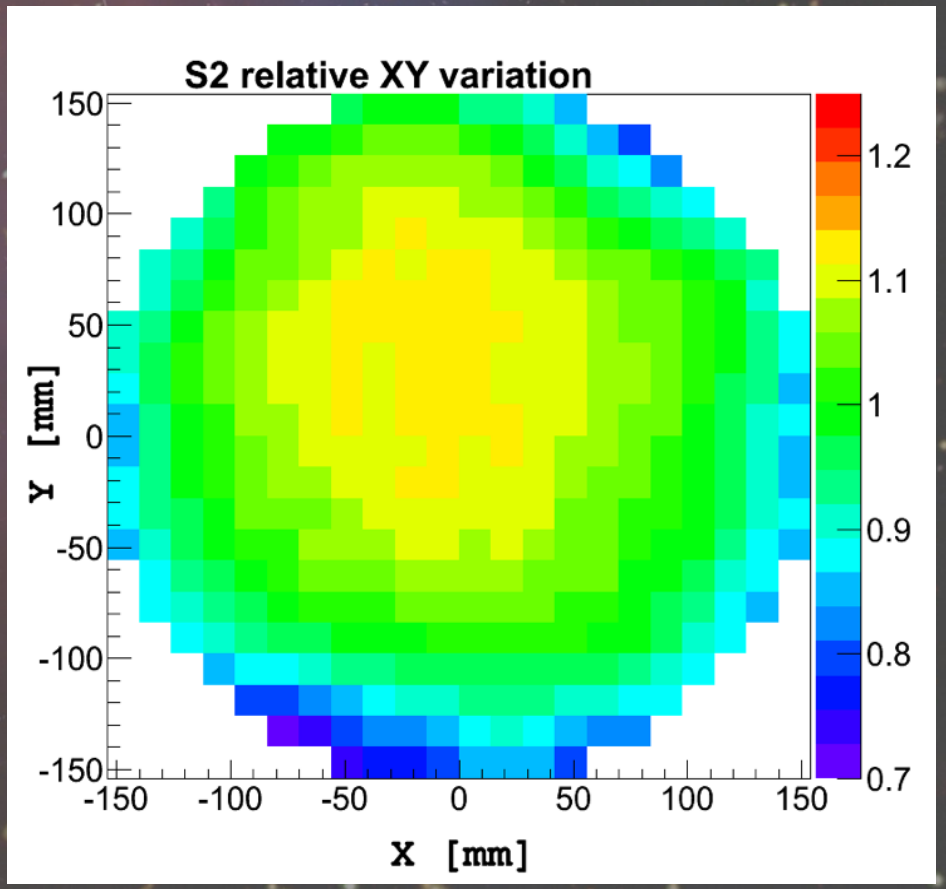


# Calibration of XENON100: Charge

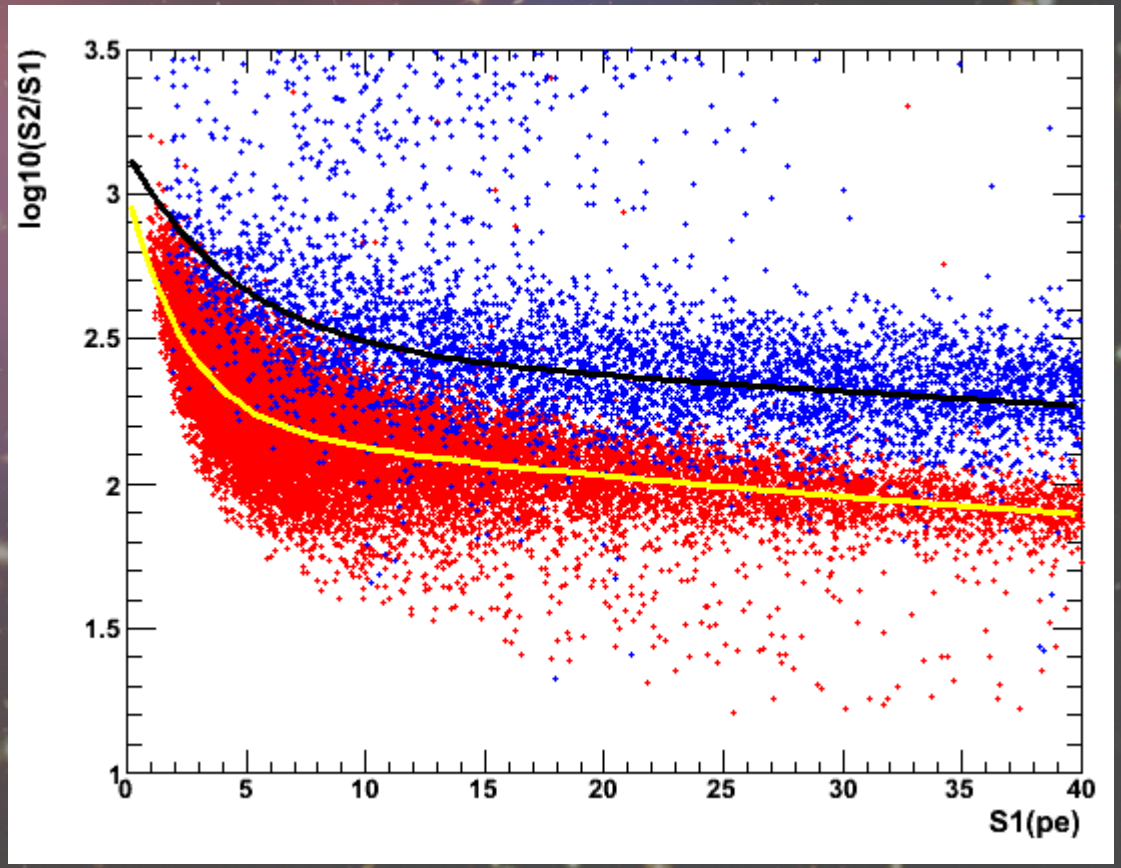
- x-y position dependent S2 correction map defined with $^{137}Cs$ data taken at low gas anode to minimize PMT saturation
- Charge attenuation due to impurities is measured in time to account for purification



# Neutron/gamma discrimination

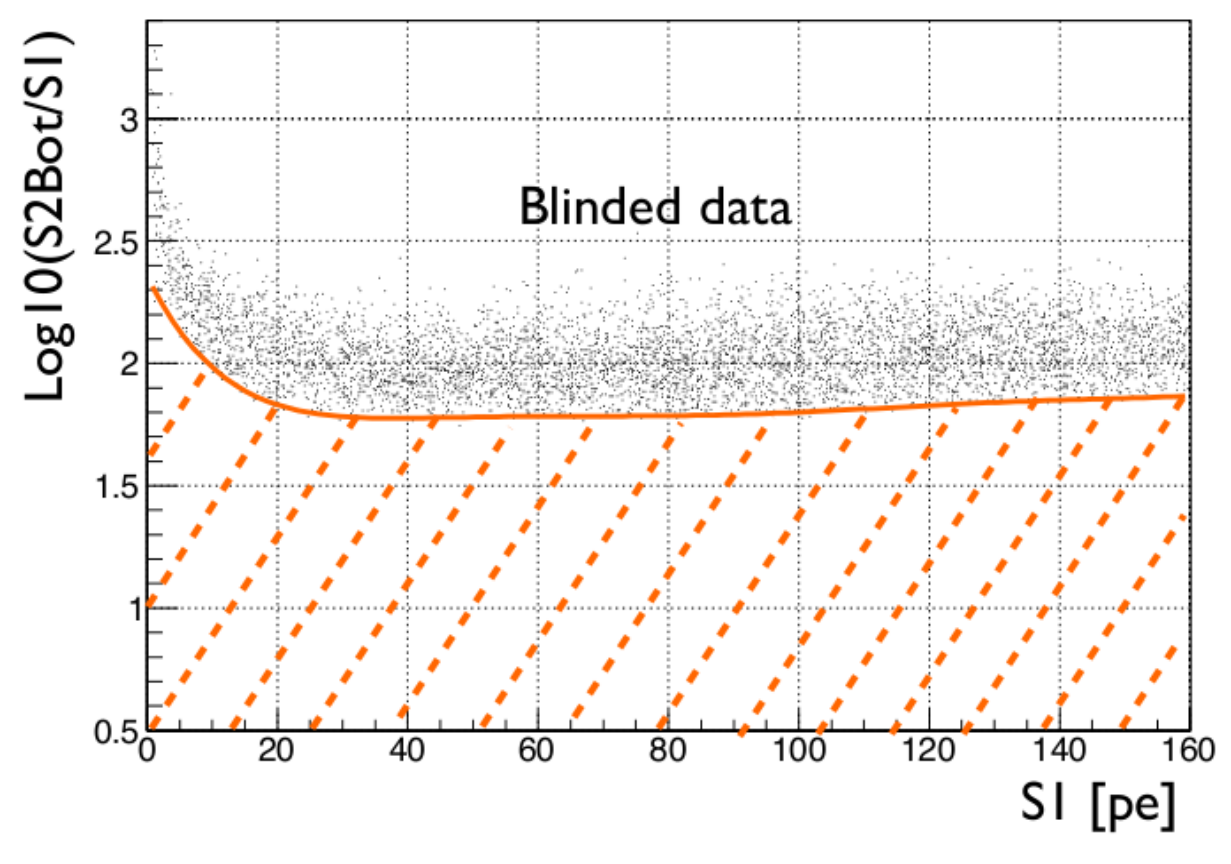
- We use an Am/Be neutron source to irradiate the detector. For each interaction the charge and light are collected
- Measurements with gamma sources are performed routinarely
- The comparison of the chrage/light ratio allows to define a region where we will have most of the neutron and few gammas The discrimination power is ~99.5% at low energies for a 50% neutron acceptance



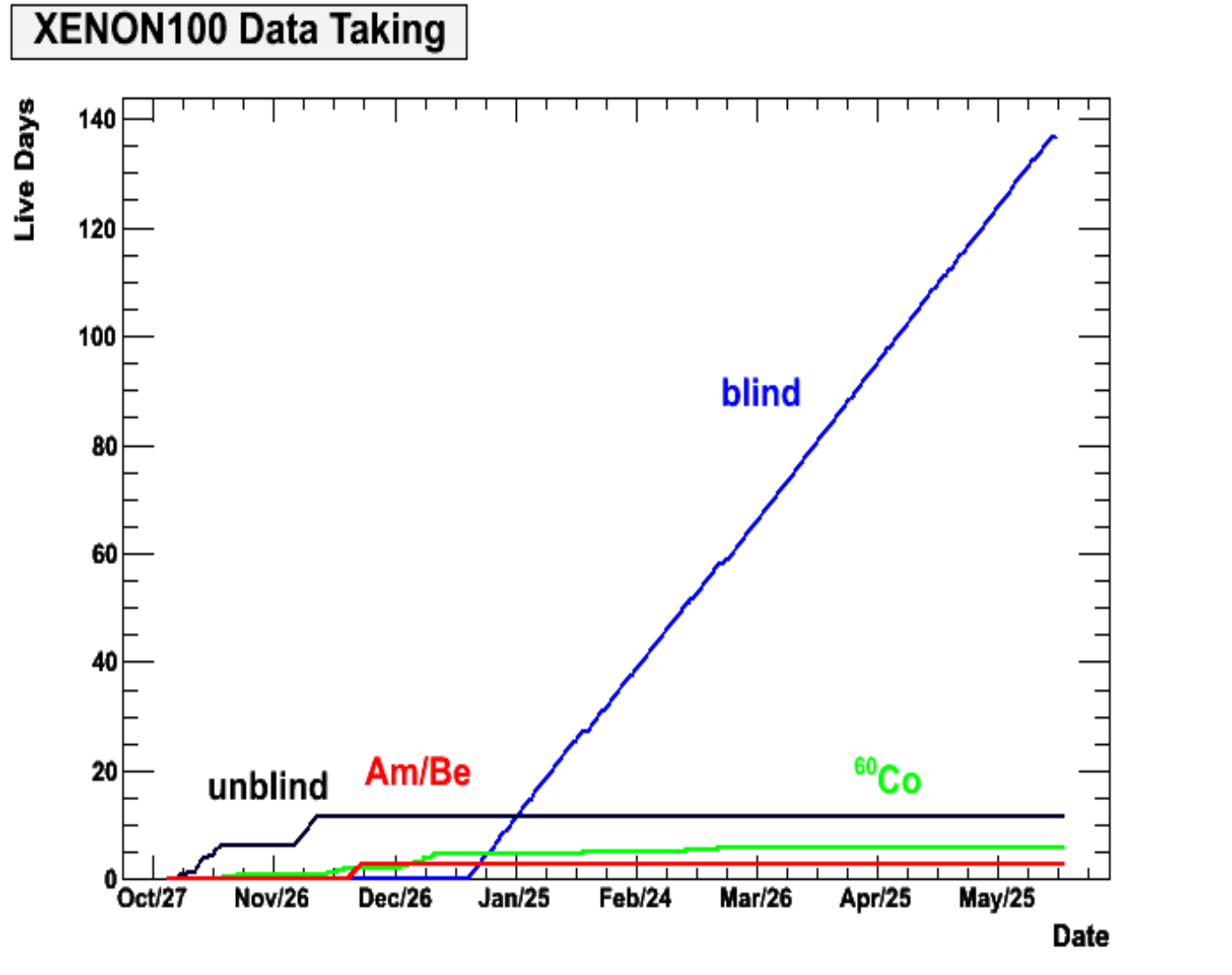
# Analysis of 100 days of data: Data blinding

- Before starting the cut development we blind the data below the lower 10% quantile of the electron recoil distribution

These data are not available to anybody in the collaboration until the end of the analysis



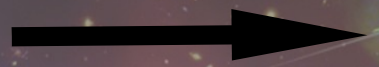
# Data taken during Run08



# Analysis cuts

DEVELOPED WITH CALIBRATION DATA

A trigger is generated if the integrated sum of the PMT signals passes a predefined threshold



S2 Trigger
Efficiency > 99% for S2 >300

All the recorded events have to be analyzed to see if they correspond to physical interactions inside the TPC

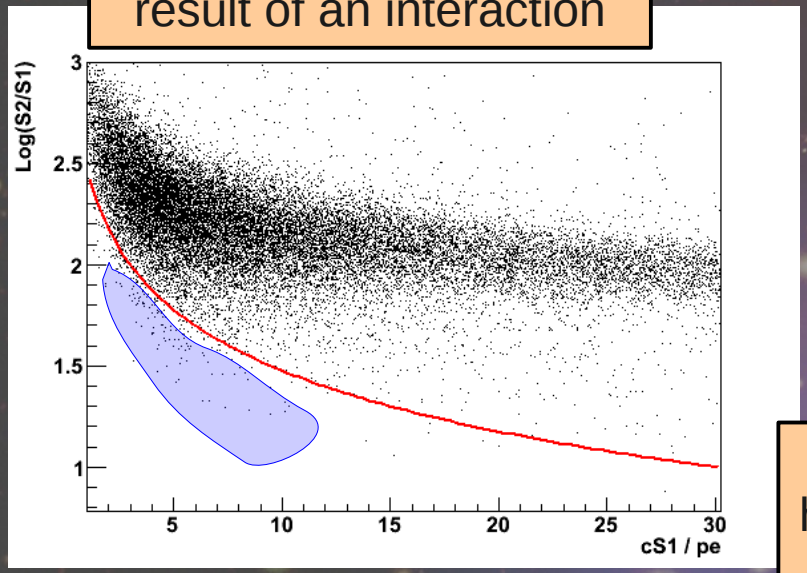
Remove noise events

Remove multiple scatters

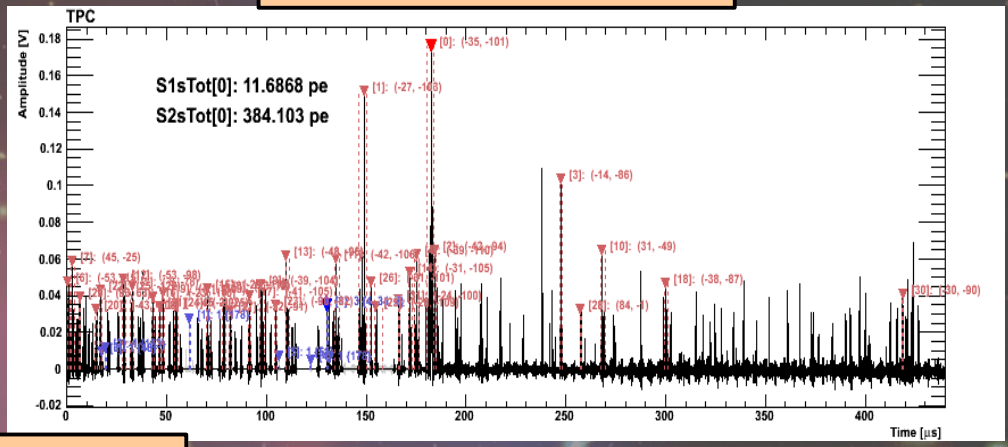
Remove events in which the S2 and S1 don't match the reconstructed position

# Cuts to remove noise events

The biggest S2 must be large enough to be the result of an interaction

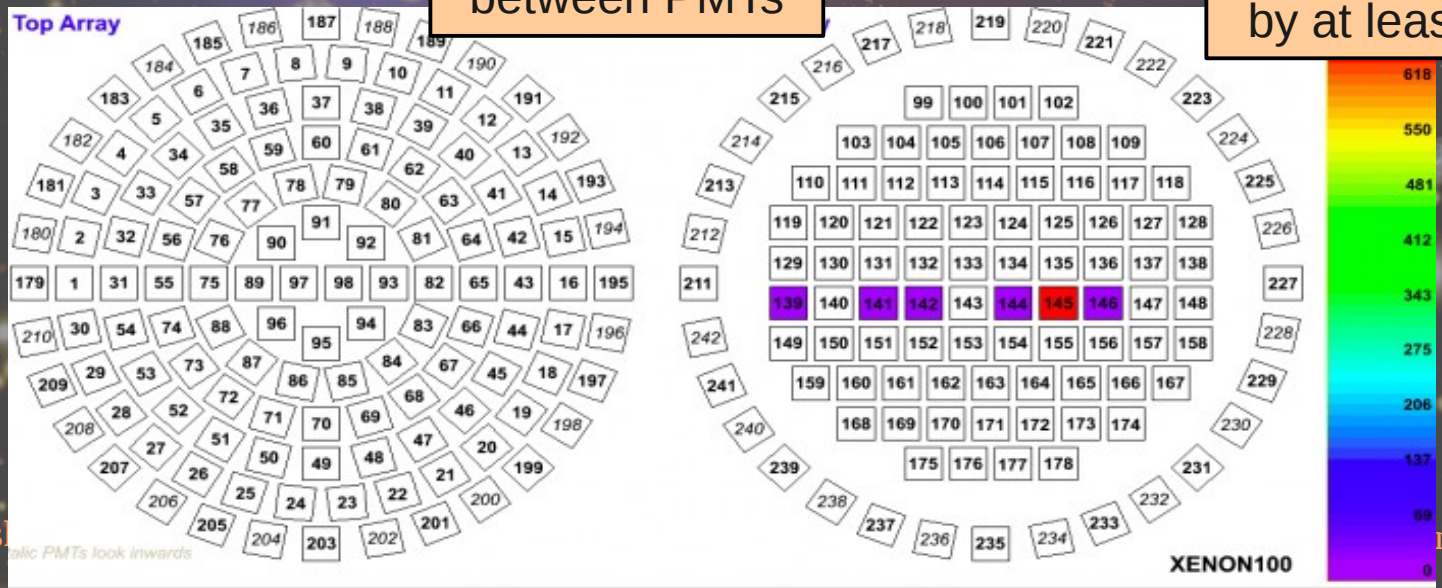



Most of the signal in the S1 and the S2




Light distributed homogeneously between PMTs

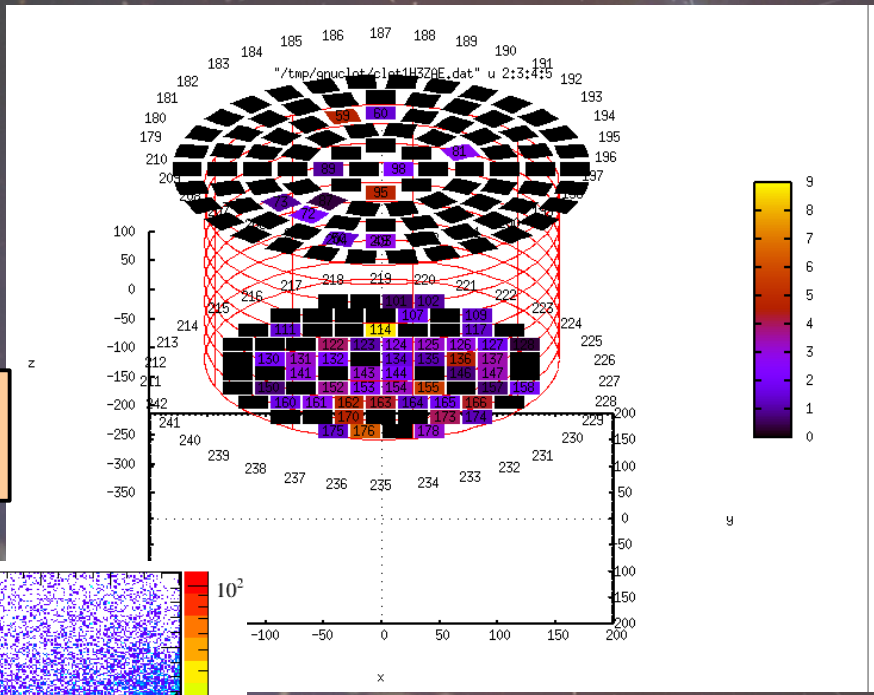
S1 signal must be simultaneously seen by at least 2 PMTs

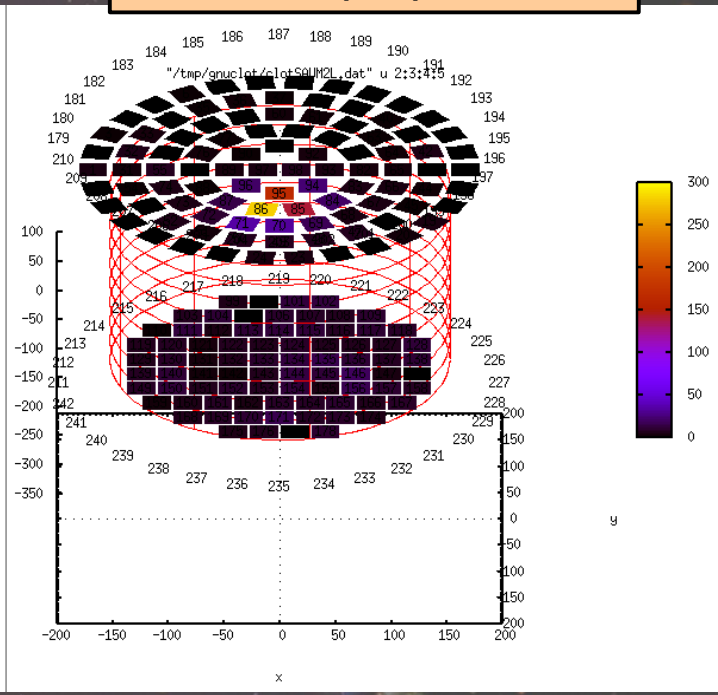


# Remove events where S2 and/or S1 don't match the position

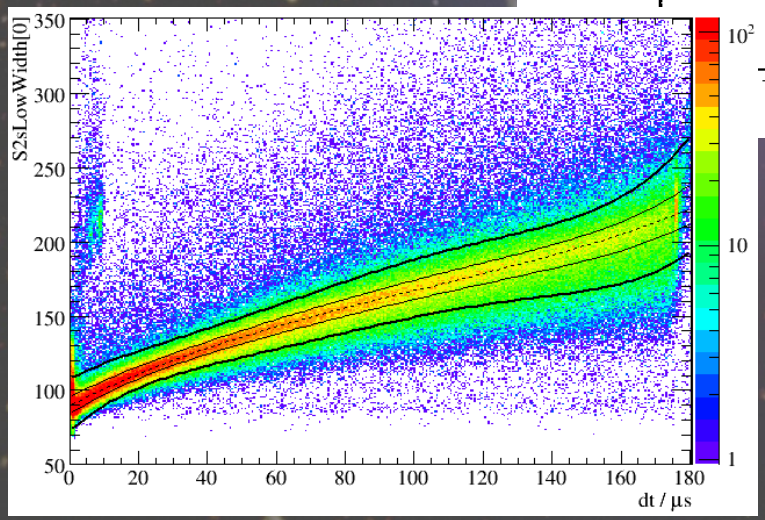
S1 light pattern compatible with the event position

S2 distributed between the top and the bottom with the proper ratio




S2 Width compatible with the event depth

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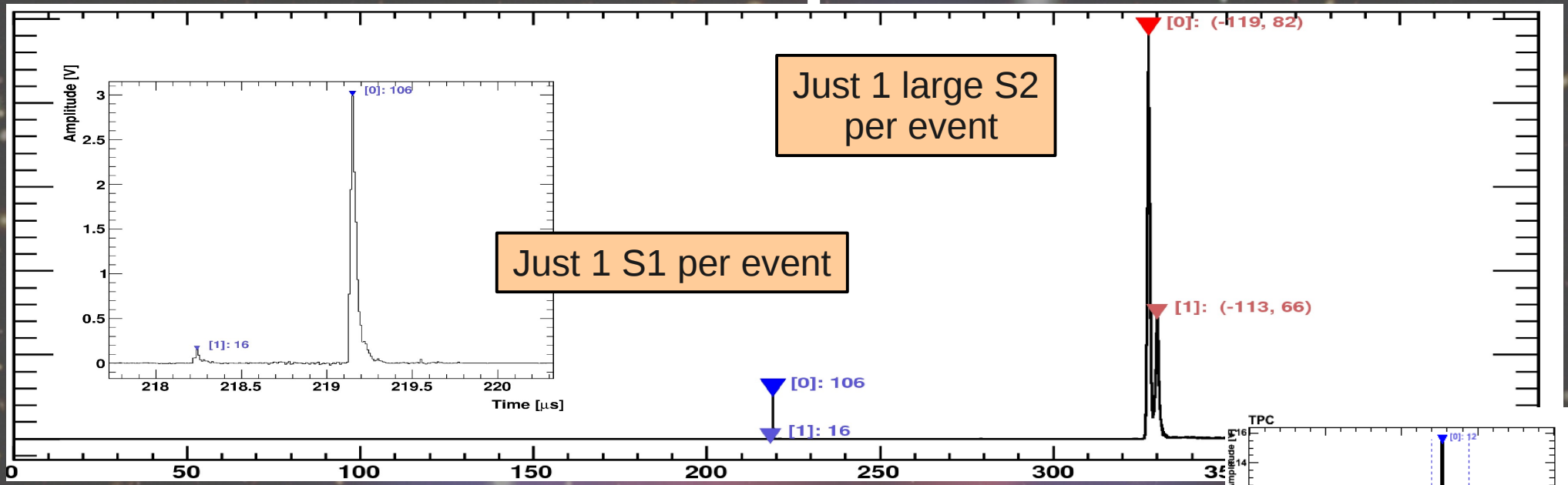
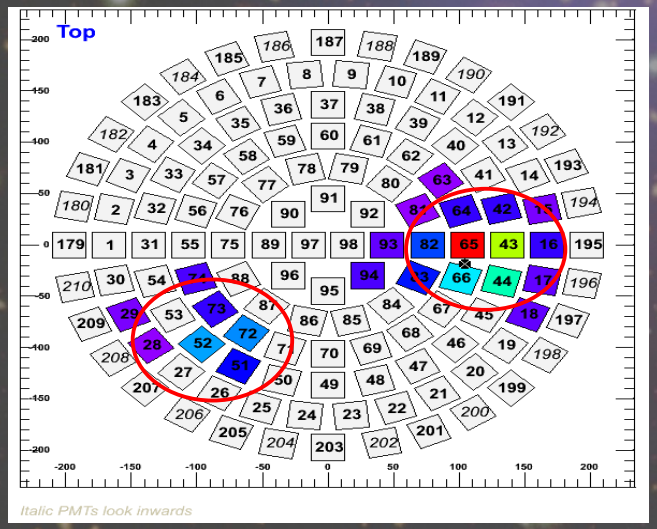
# Remove multiple scatters



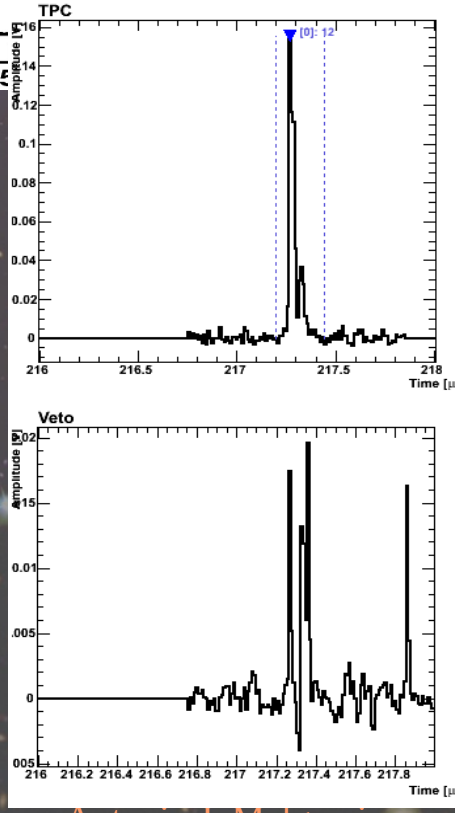

Just 1 large S2 per event

Just 1 S1 per event

S2 PMT pattern compatible with one single interaction

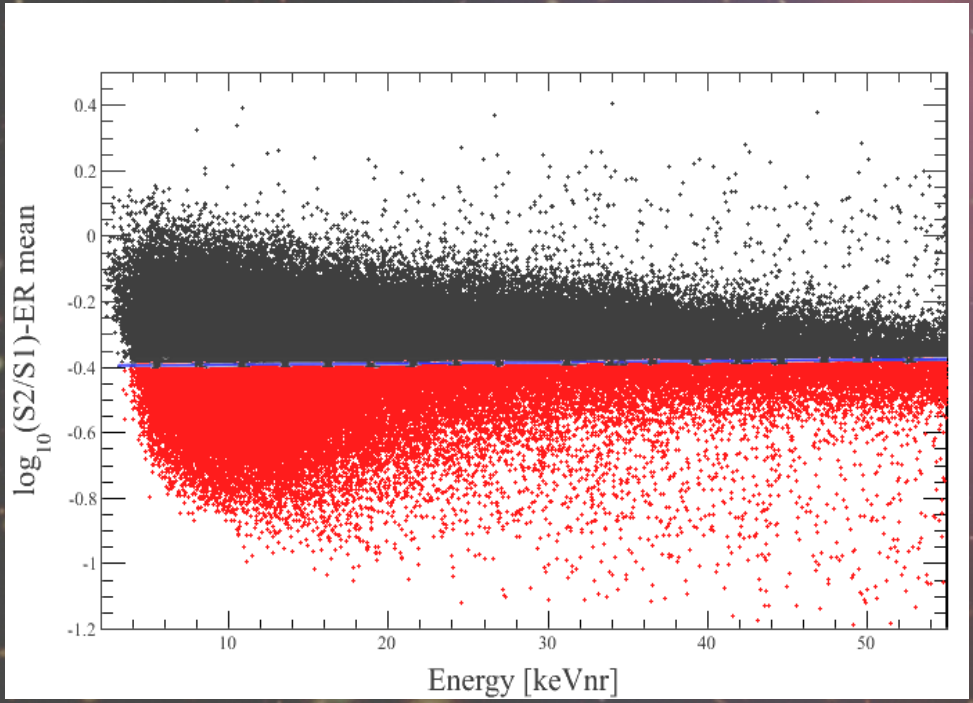


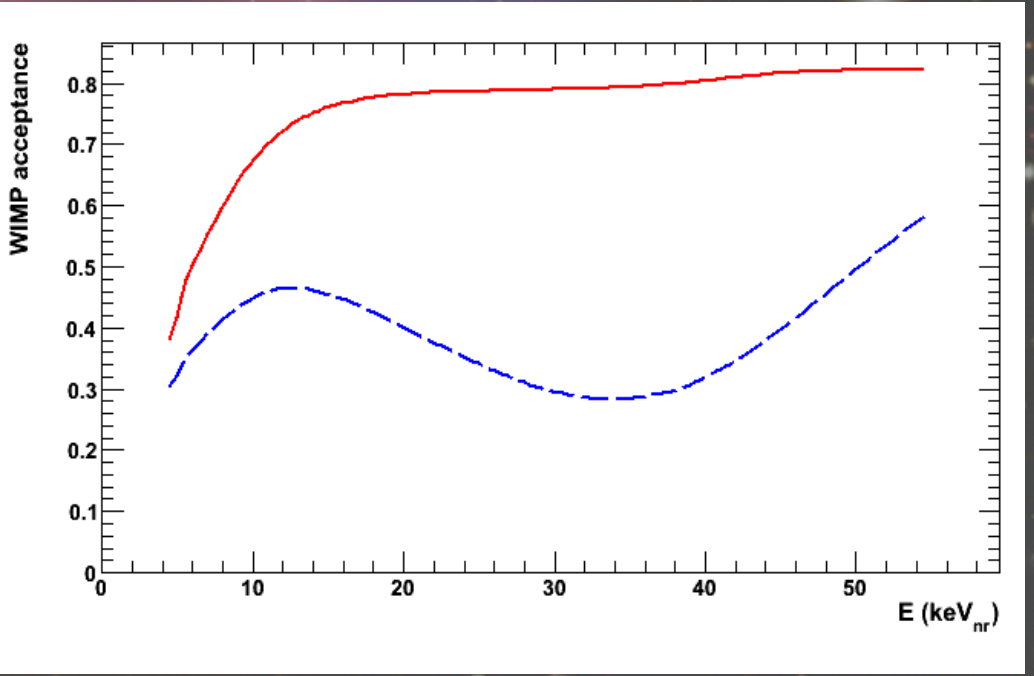

No energy deposit in the veto



# WIMP acceptance

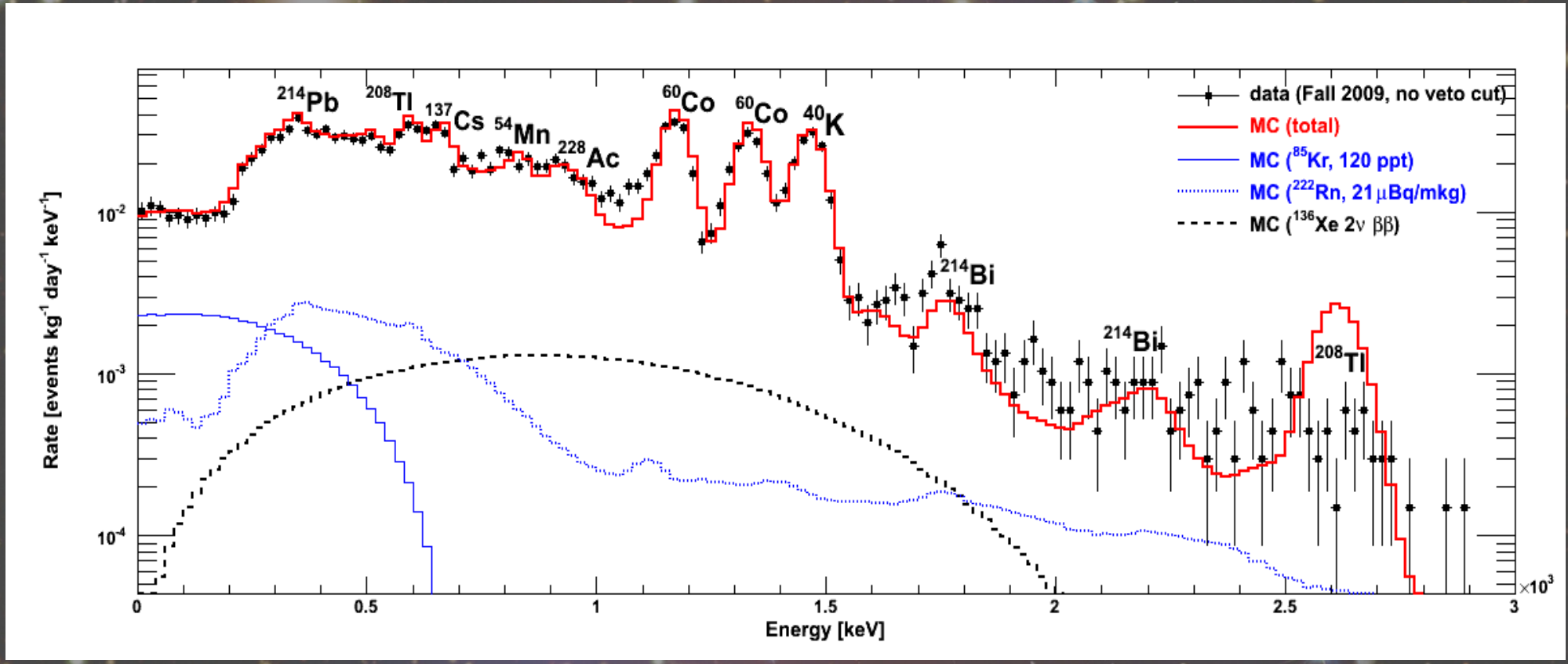
- AmBe data are used to compute the probability for WIMPs passing the analysis cuts
- The acceptance for the signal cut is computed independently



# Background spectrum

## Physical Review D 83, 082001, 2011



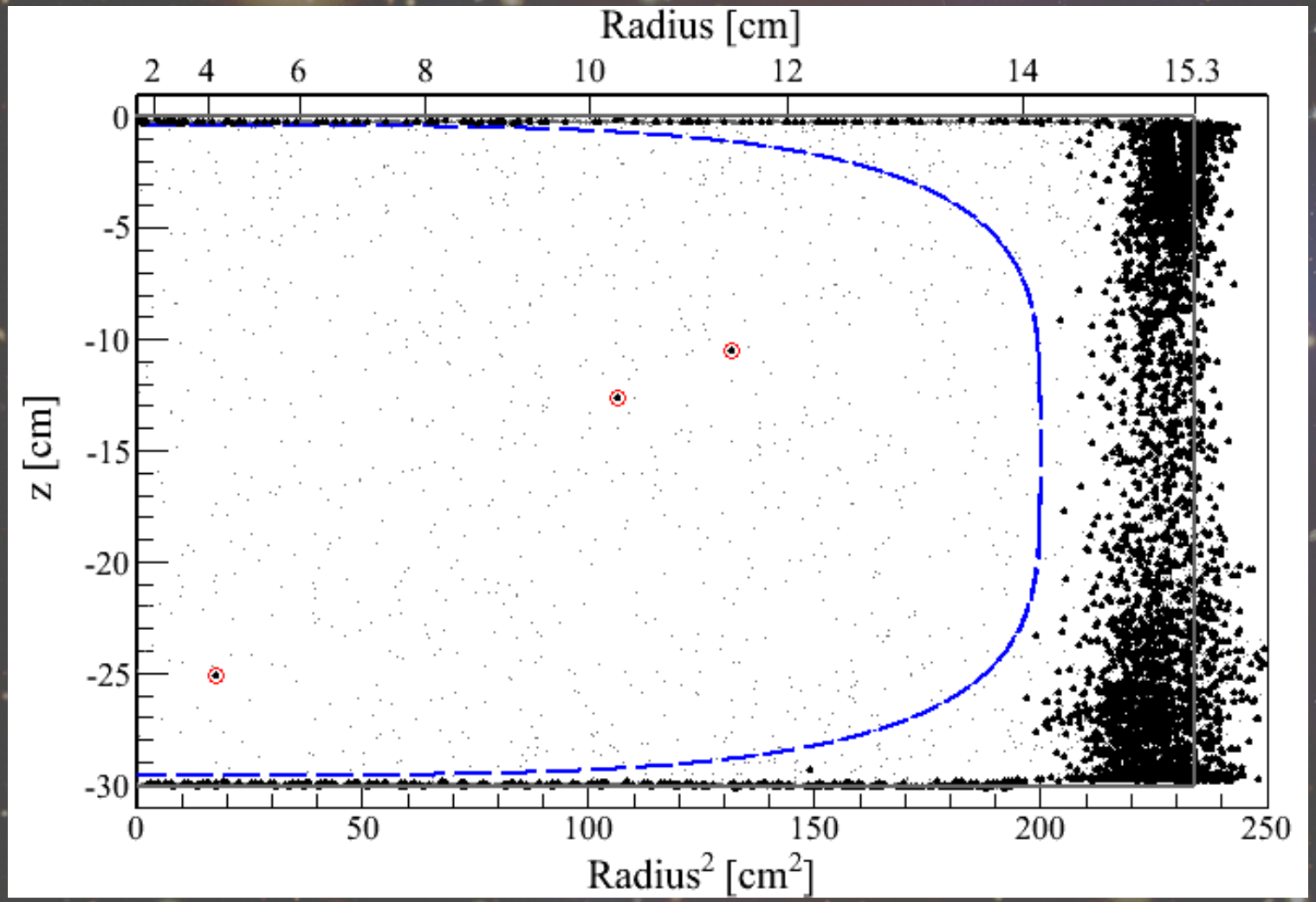

- Note that all the isotopes also contribute to the low energy background through Compton scattering
- Very good agreement between data and MonteCarlo. NO TUNING IN THE MONTECARLO, only measured activities!!

# Data unblinding

- 6 events were observed during the unblinding of the data
- However, inspection of the waveforms of these events show that only 3 of them were real, while all the other were produced by electronic noise in some PMTs
- A full population of these events was identified below 4 pe
- Two cuts were developed to remove this population:
  - look at the signal in empty channels
  - look at the width of the S1 signal

# Data Unblinding

**Selection of a 48kg superellyptical fiducial volume + S1 range 4-30 pe**




**Background rate higher than in previous run due to a leak in the gas system**

# Some words about energy measurement

Measured signal

Light quenching due to electric field for gammas @122keV

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

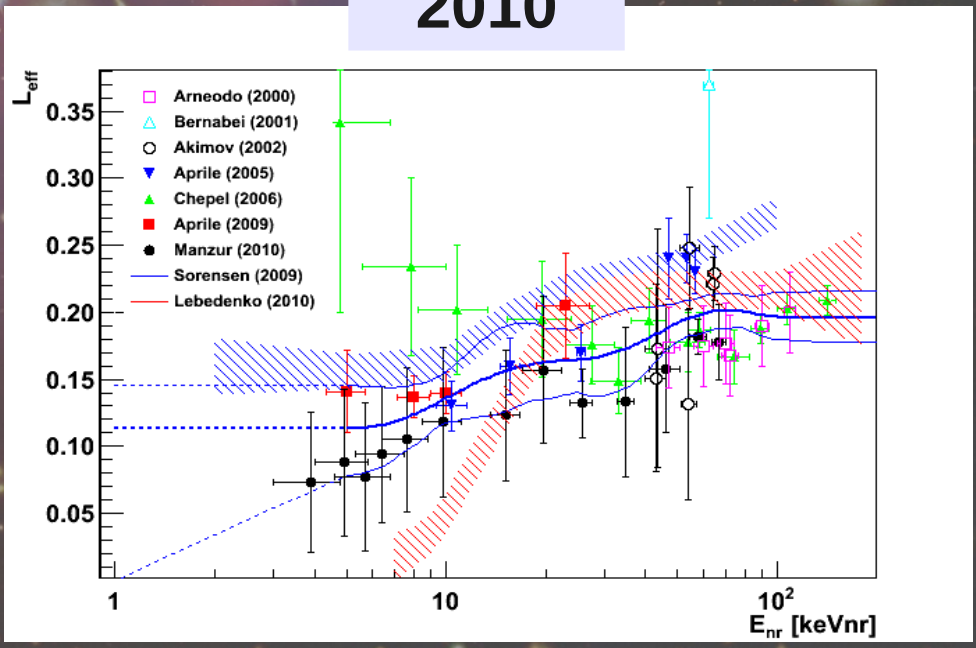
Light quenching due to electric field For nuclear recoils

Light yield for gamma @122 keV

Scintillation eff. for nr at 0 field

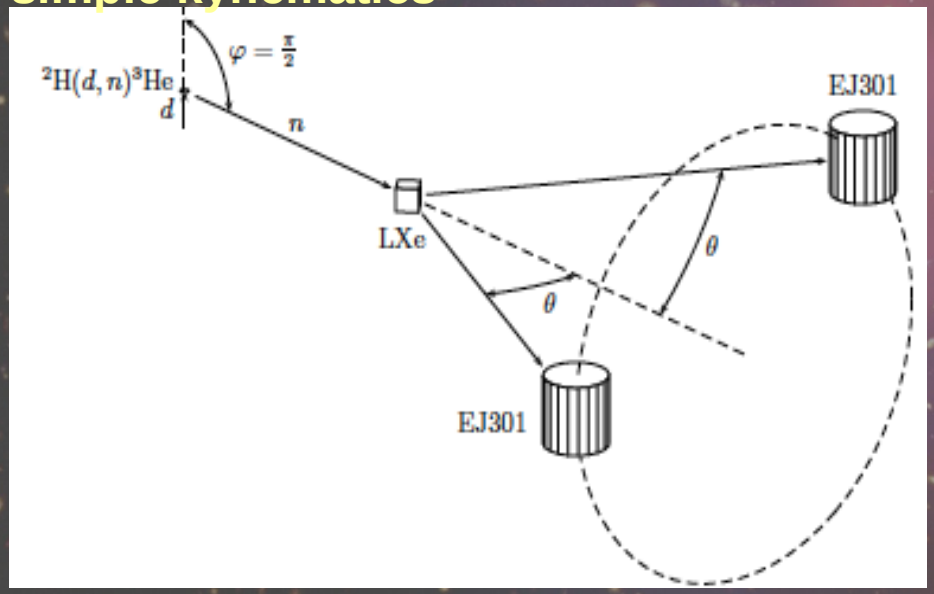
- Some controversy:
  - arXiv:1005.0380
  - arXiv:1005.0838
  - arXiv:1005.2615
  - arXiv:1005.3723

2010

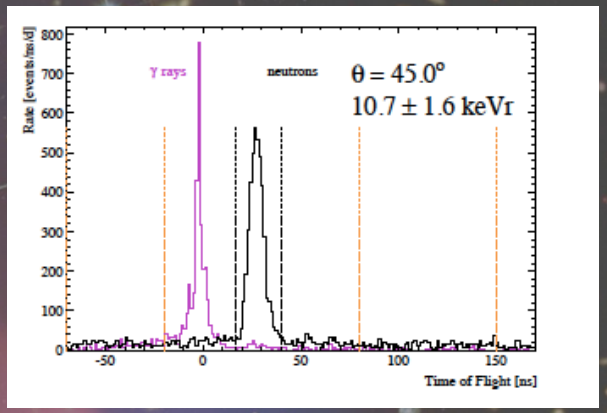


# New Leff Measurement

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

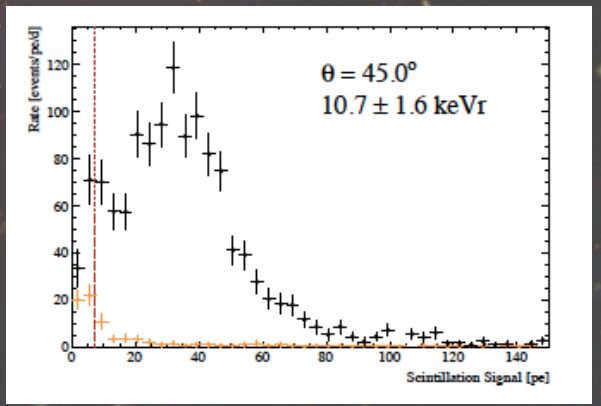



$$E_r \approx 2E_n \frac{m_n M_{Xe}}{(m_n + M_{Xe})^2}(1 - \cos\theta)$$

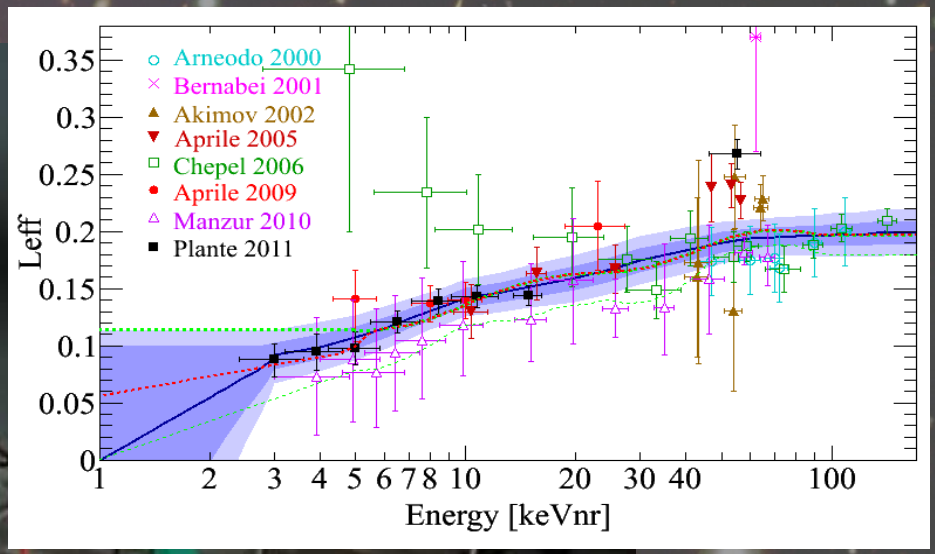



An interaction is accepted if an energy deposition is also registered in one of the scintillators
A TOF cut allows to select only those neutrons that don't interact in the detector materials

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



# New Leff Measurement



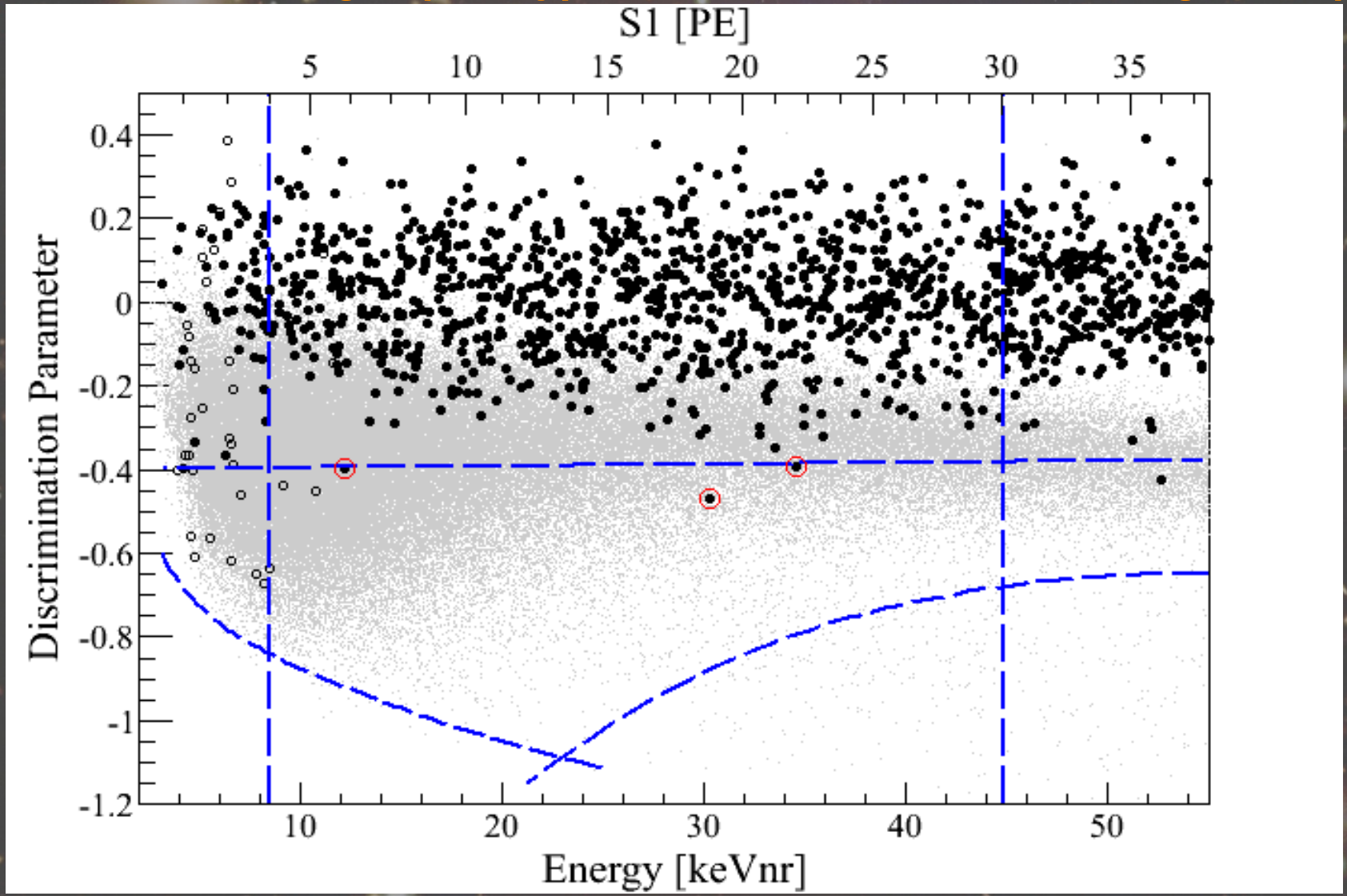





arXiv:1104.2587

# Data Unblinding

**Selection of a 48kg superellyptical fiducial volume + S1 range 4-30 pe**

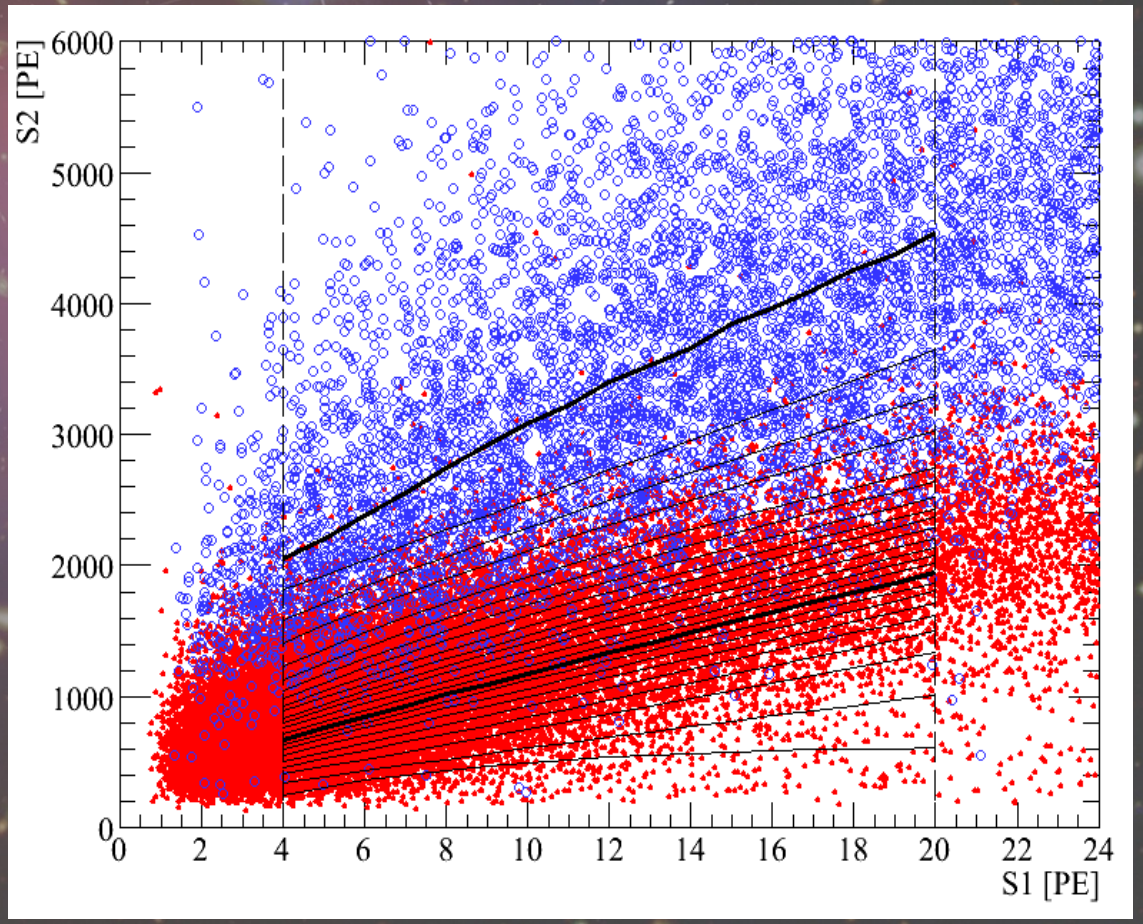


# An alternative statistical approach

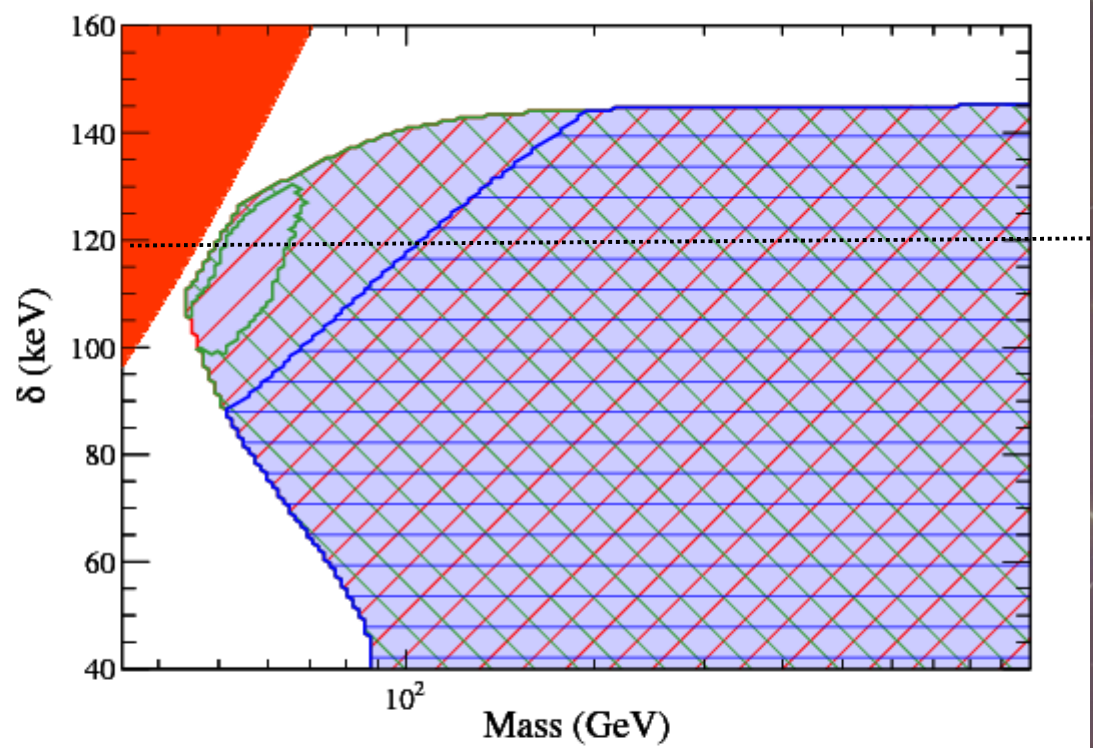
$$\begin{aligned}\mathscr{L} &= \mathscr{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, \mathcal{L}_{\rm eff}, v_{\rm esc}; m_\chi) \\ &\times \mathscr{L}_2(\epsilon_s) \times \mathscr{L}_3(\epsilon_b) \\ &\times \mathscr{L}_4(\mathcal{L}_{\rm eff}) \times \mathscr{L}_5(v_{\rm esc}).\end{aligned}$$

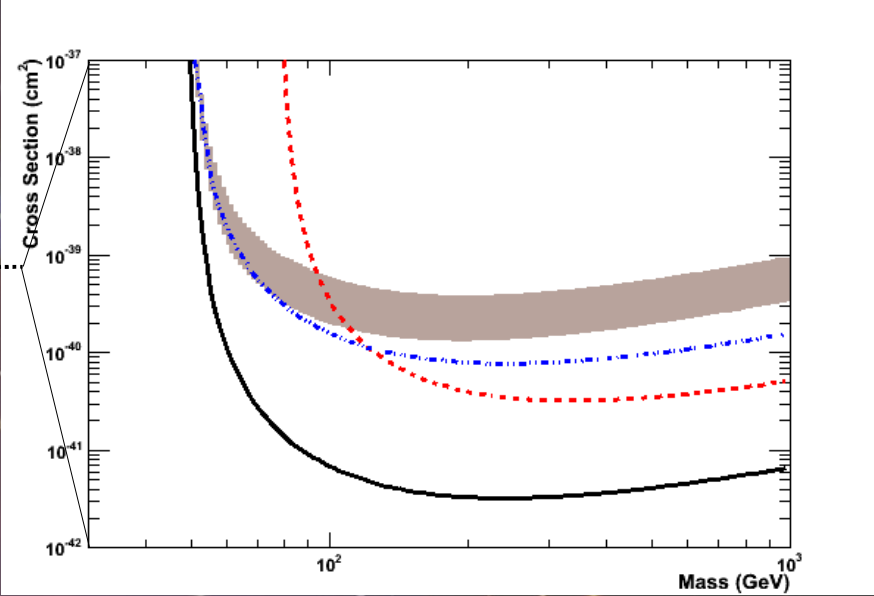
- We construct a likelihood distribution with our calibration data, including all the uncertainties as nuissance parameters
- We divide our signal space in different regions and count the number of events on each region
- For the actual measurement we compute the probability that the result is signal+background (limit) and take the σ that gives a 10%

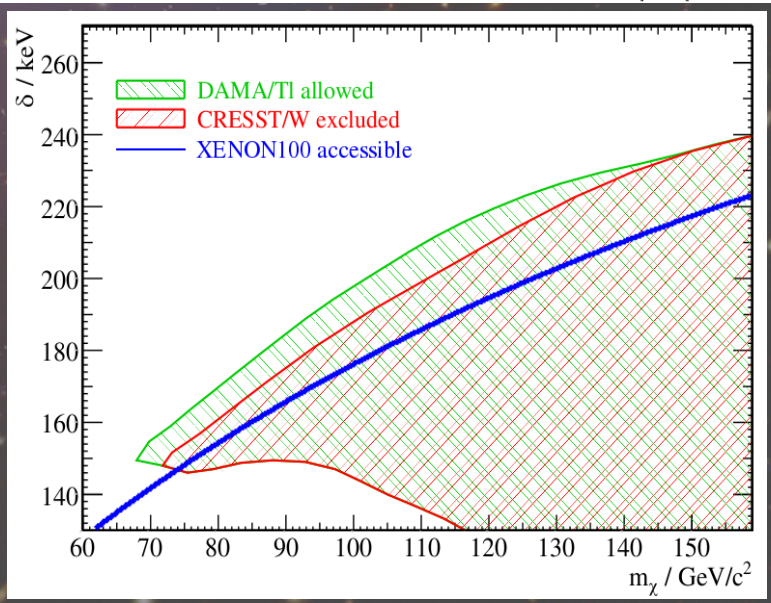
arxiv:1103.0303



# Inelastic Dark Matter



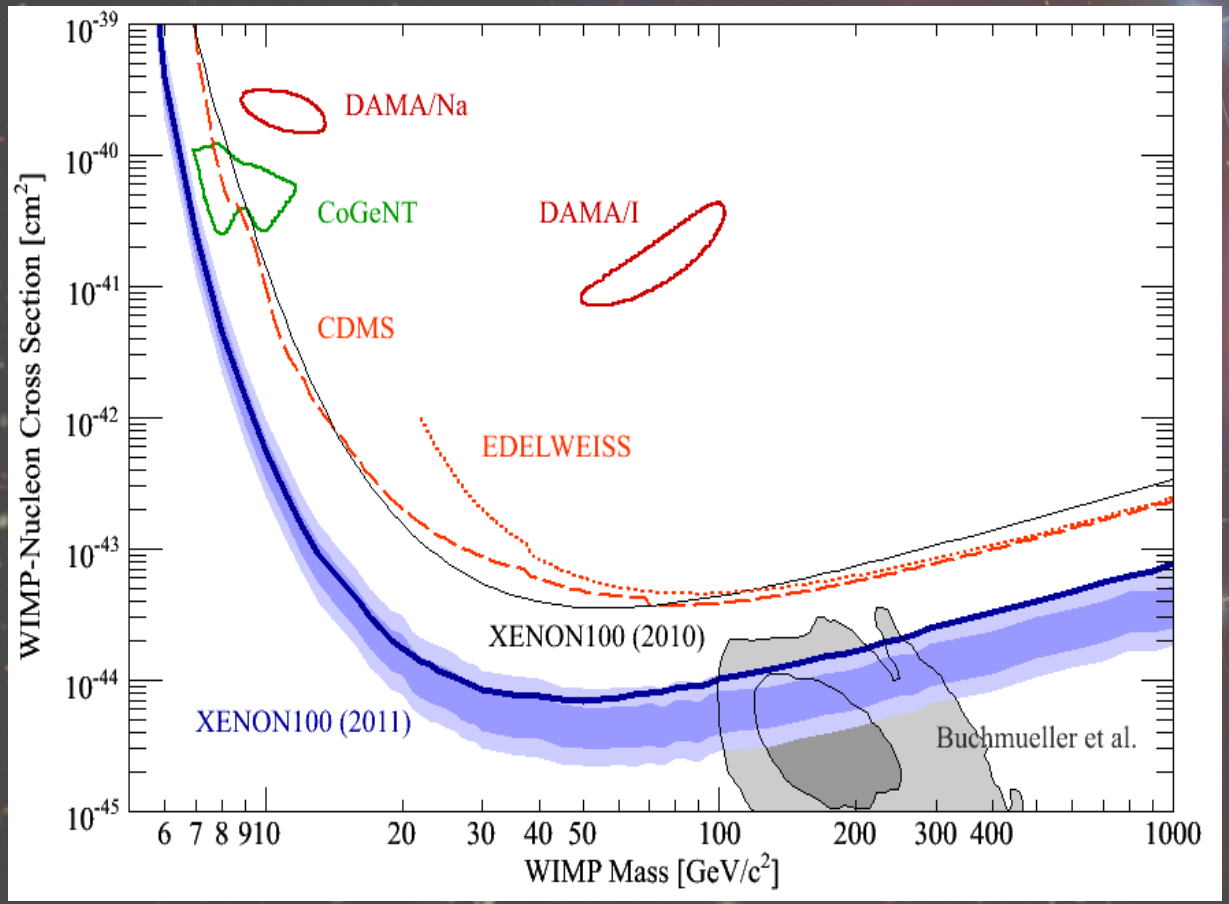




- Inelastic WIMP scattering of I nuclei is excluded as an explantion for the DAMA modullation signal at 90% CL arXiv:1104.3121
- However, nothing can be said about WIMP scattering off Tl

# Spin Independent Elastic Dark Matter

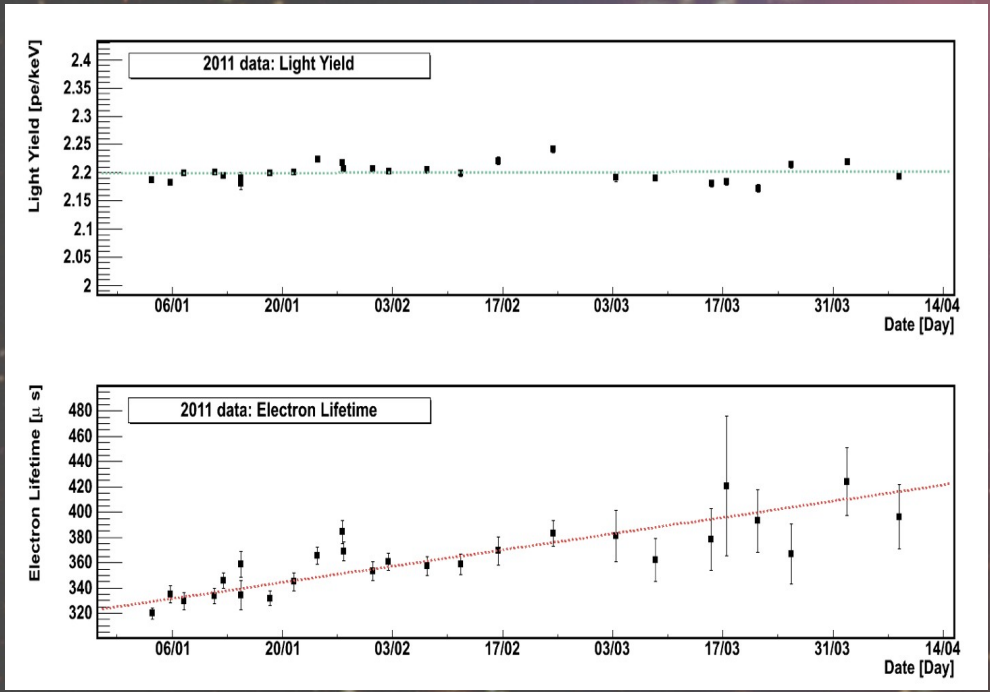
**arXiv:1104.2549, submitted to PRL**

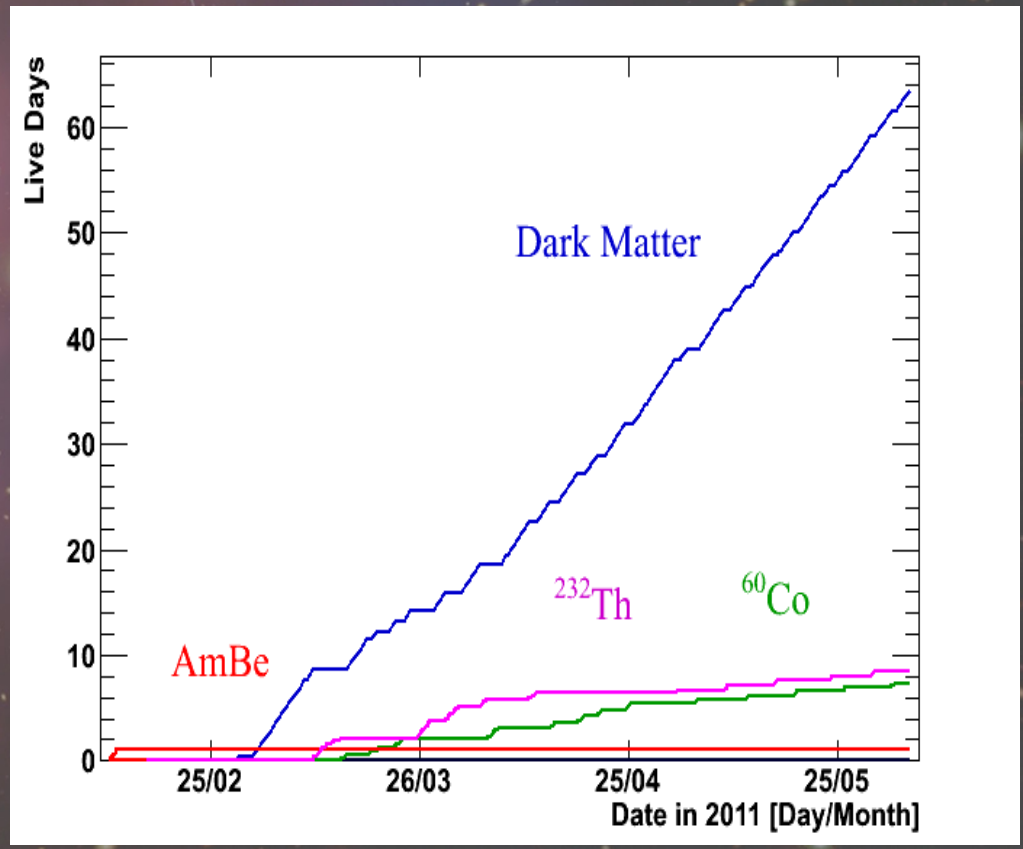



- CoGeNT and DAMA/Na regions severely constrained at 90%CL. This result does not strongly depend on the extrapolation of Leff below 3keVr
- The best limit on spin independent dark matter to date: $7 \cdot 10^{-45} cm^2$
- For the first time we explore the predicted region for SUSY candidates

# The future: Run10

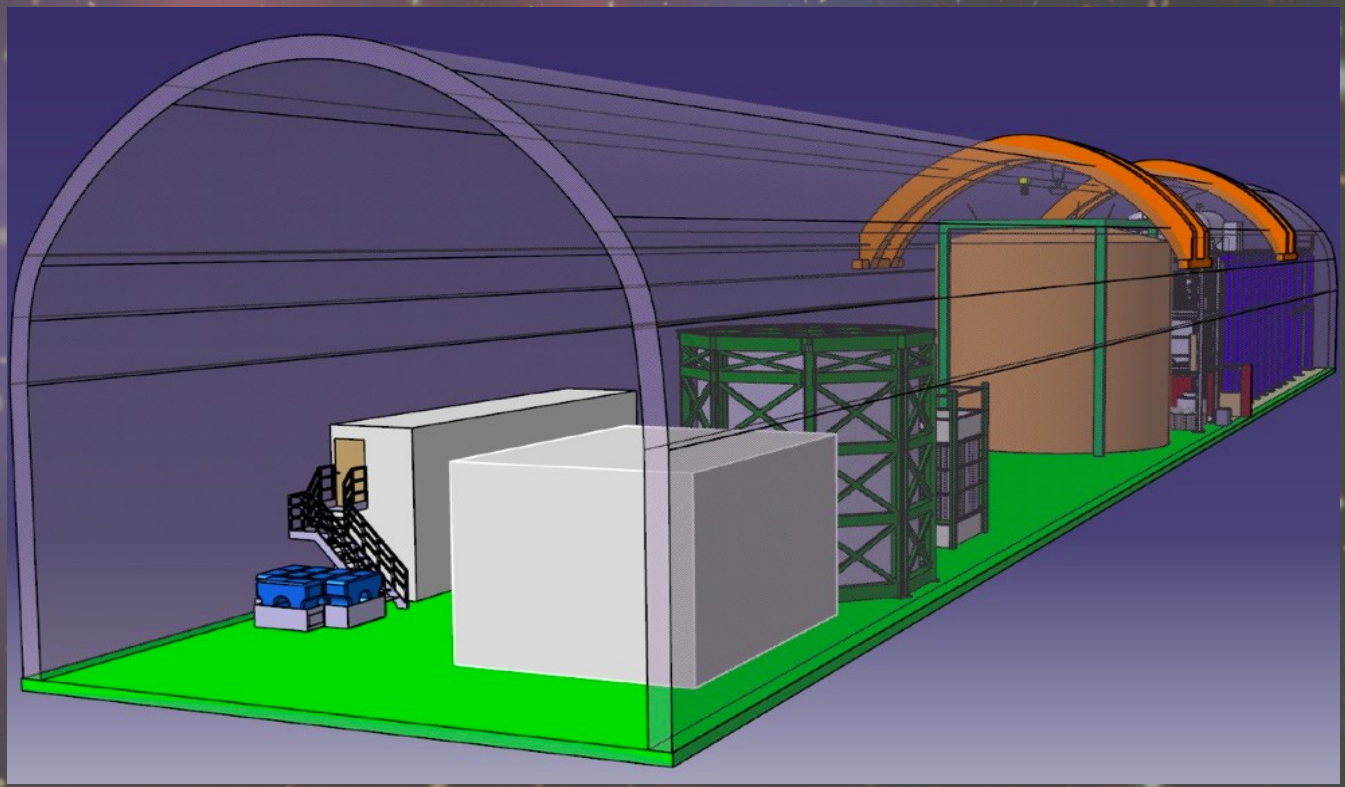
- A new krypton column distillation has reduced the krypton level to that in 2009
- Data taking has resumed in great conditions



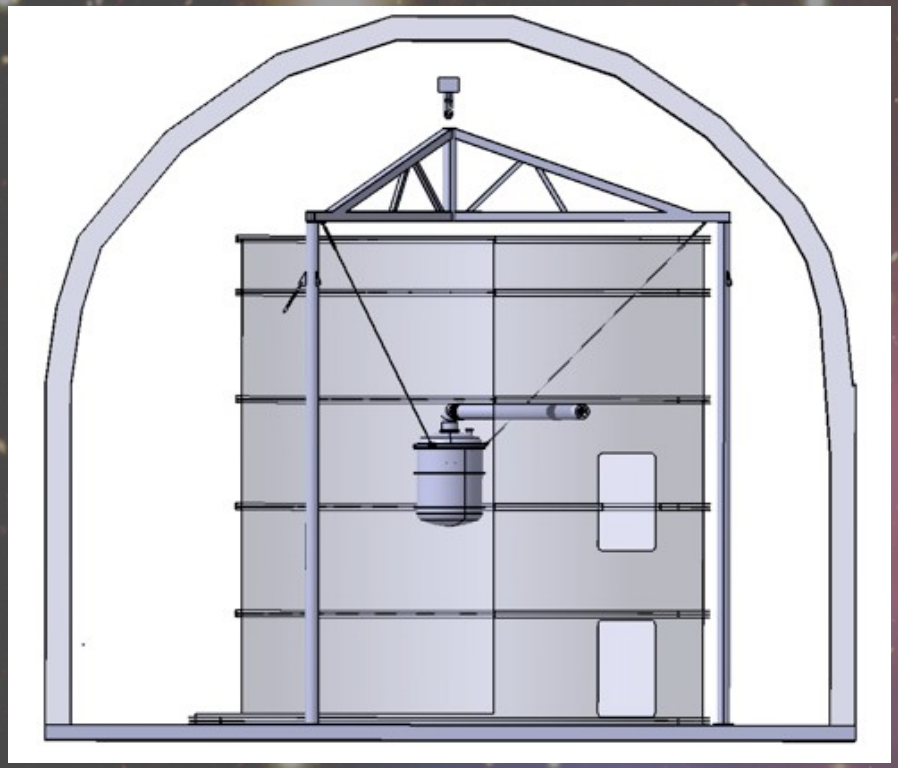



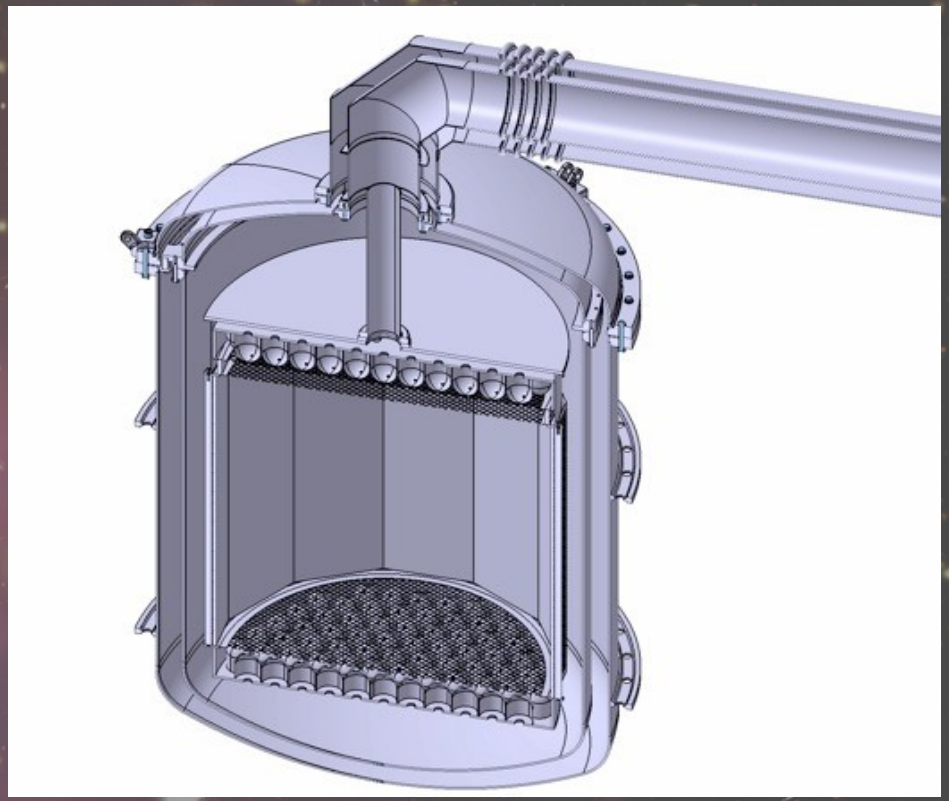
# The future: XENON1T

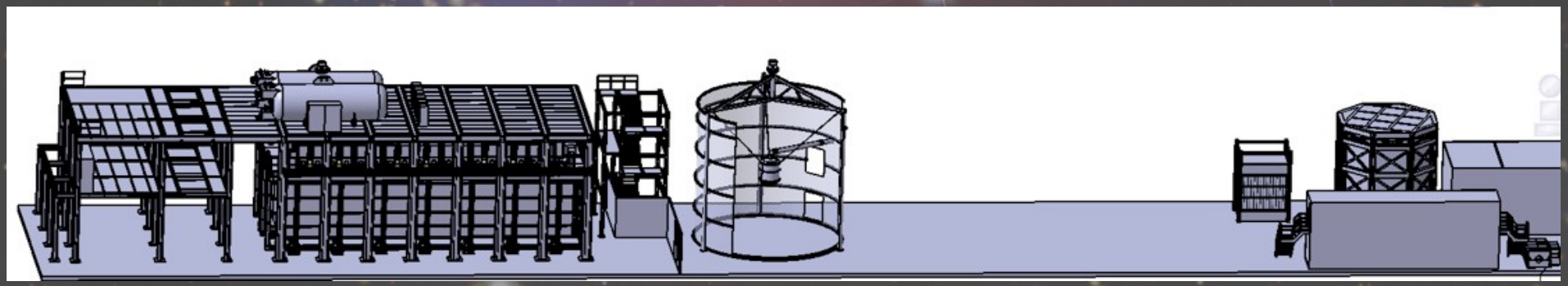
- 2.4 tons of liquid Xenon with a 1 ton fiducial volume
- 5 meter radius water shield instrumented with PMTs
- Approved to be built in Hall B in LNGS



# The future: XENON1T



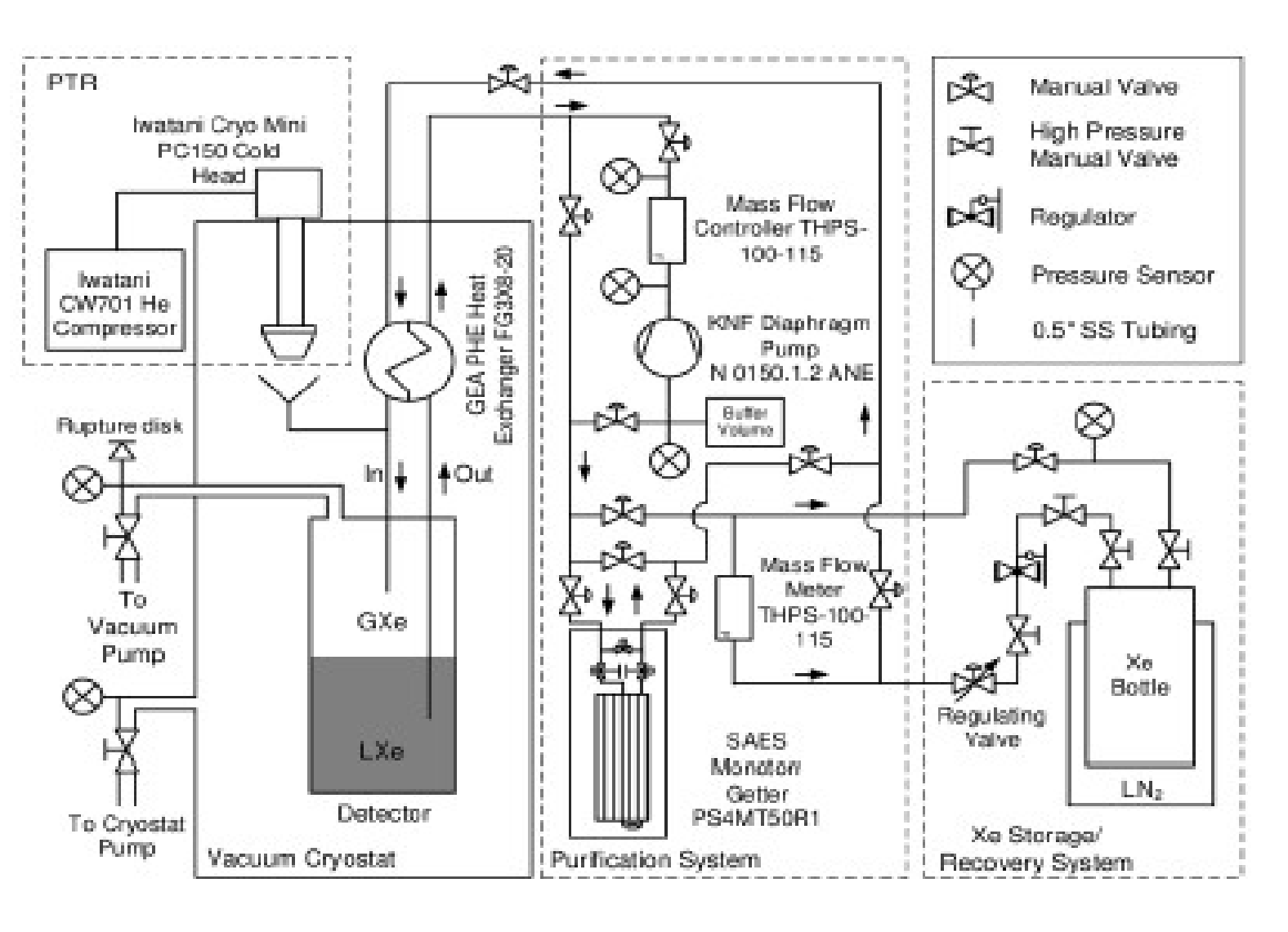




# Highlights of technologies and concepts for XENON1T

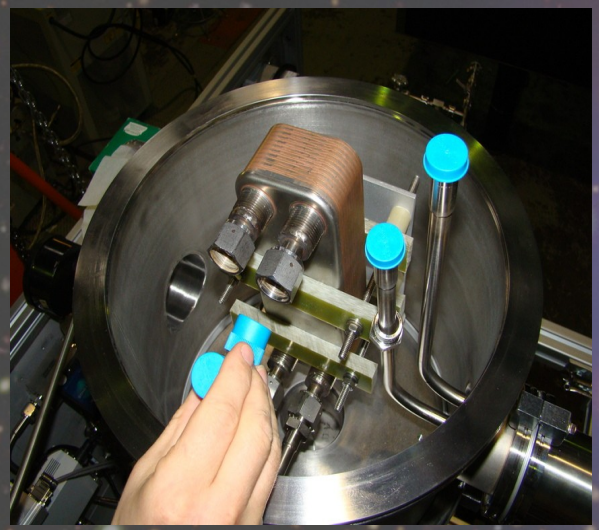
- XENON1T Demonstrator for long drift and HV tests (Columbia and Rice)
- Cryogenics system with heat exchanger high flow rate purification (Columbia)
- Measured  QE at low temperature of 3” Hamamatsu R1140 and R8520 with LT Bialkali PC (Columbia & Munster)
- Measured response of 3” QUPIDs in LXe (UCLA)
- Measured radioactivity of all above PMTs for XENON (Zurich)
- Measured low activity SS and Ti for XENON1T cryostat (Zurich)
- Designed a new system for storage of 3 ton Xe in gas and liquid phase (Subatech)
- Designing new Kr distillation column (Munster)
- Developed Atom Trap (Columbia) and Mass Spectrometry system (MPKI) for < 1ppt measurement of Kr/Xe

# Improved cooling-recirculation system



# Improved cooling-recirculation system

**Efficient heat exchange between outgoing cold liquid and incoming hot gas**



**Optimized gas system for faster recirculation speed**

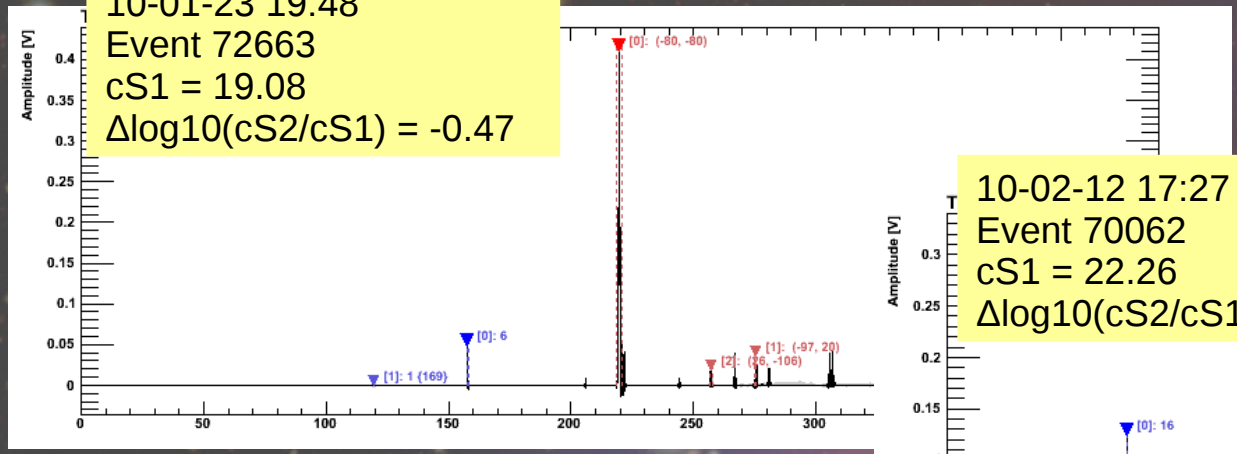
# Summary

- XENON100 is the first direct detection experiment exploring the region of theoretical predictions for WIMPs
- A 100 days exposure has been collected in 2010. 3 events in the signal region have been observed for a background expectation of 1.8±0.6 events
- With these data the iDM scattering of I for DAMA has been ruled out at 90% CL. These data constrain the CoGeNT and DAMA explanation of a low mass WIMP
- We have found the most restrictive limit for dark matter up to date with a cross section of $7 \cdot 10^{-45}$ $cm^2$
- New data are already being acquired. XENON1T has been aproved for installation in LNGS starting 2011. Tests for many of the needed new technologies have already started

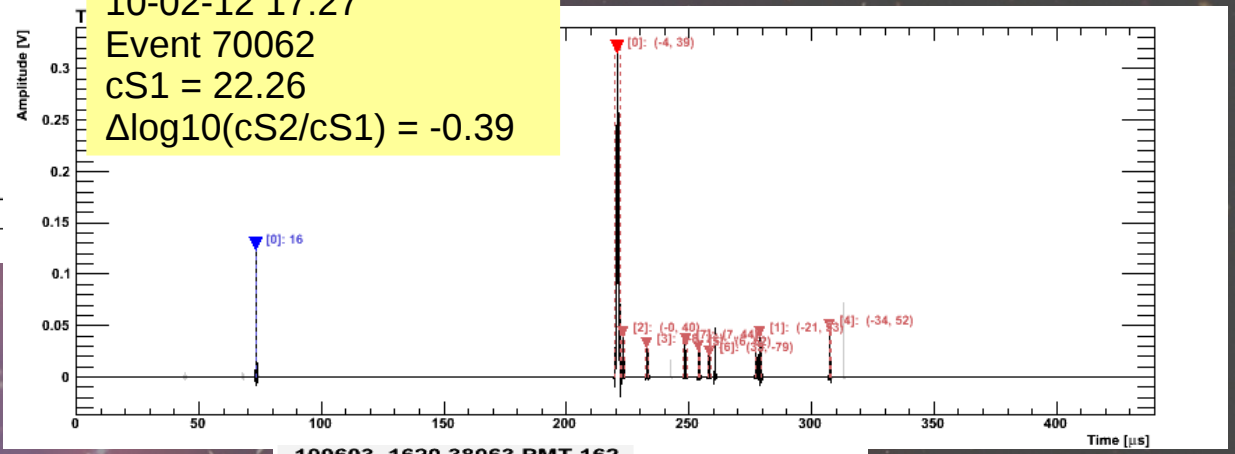

End

# Valid Events

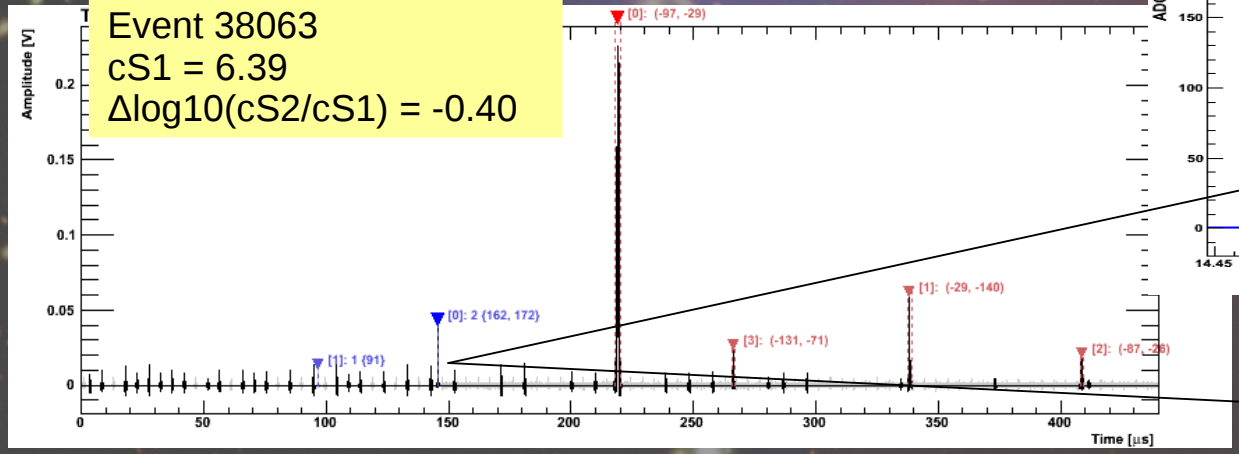
10-01-23 19:48
Event 72663
cS1 = 19.08
Δlog10(cS2/cS1) = -0.47

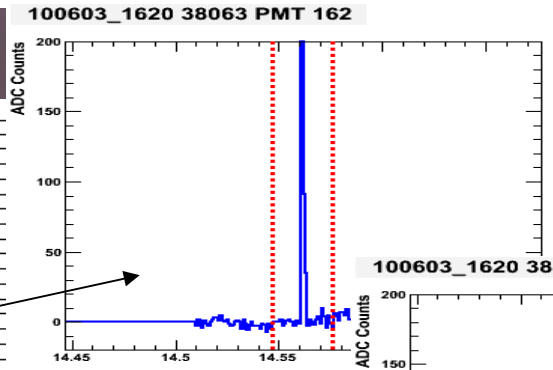


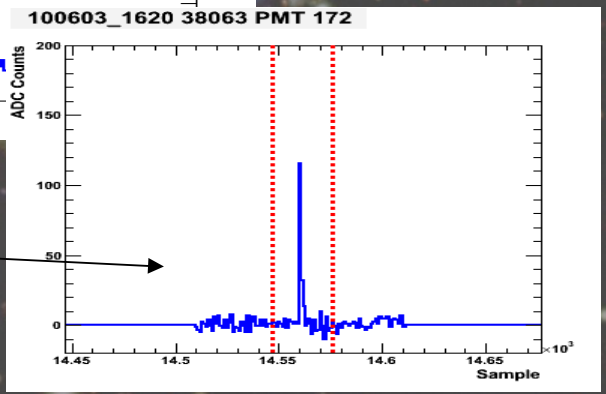

10-02-12 17:27
Event 70062
cS1 = 22.26
Δlog10(cS2/cS1) = -0.39



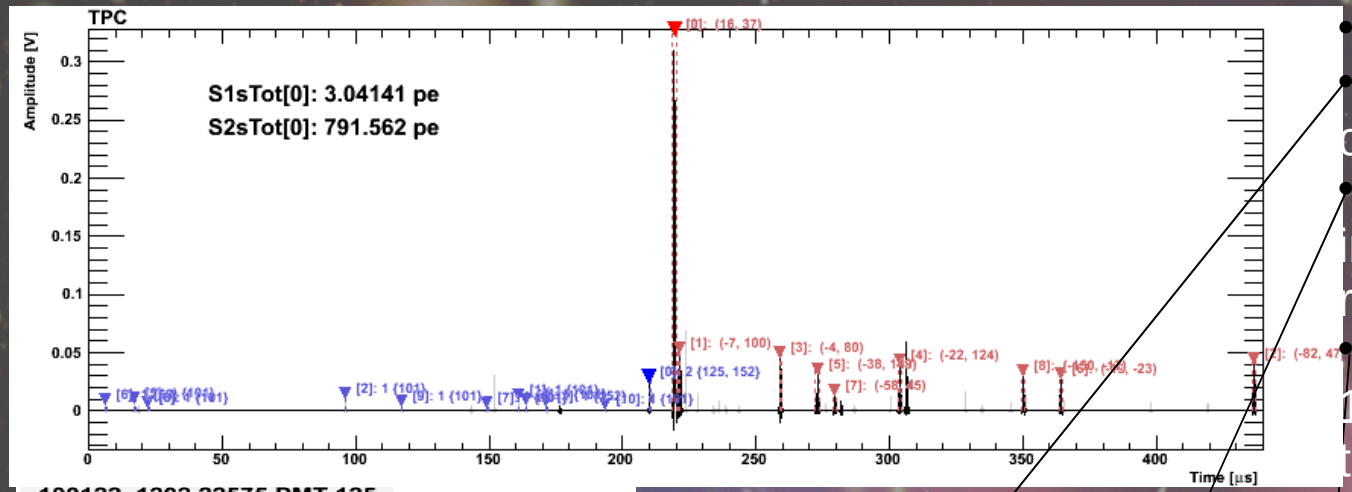

10-06-03 16:20
Event 38063
cS1 = 6.39
Δlog10(cS2/cS1) = -0.40

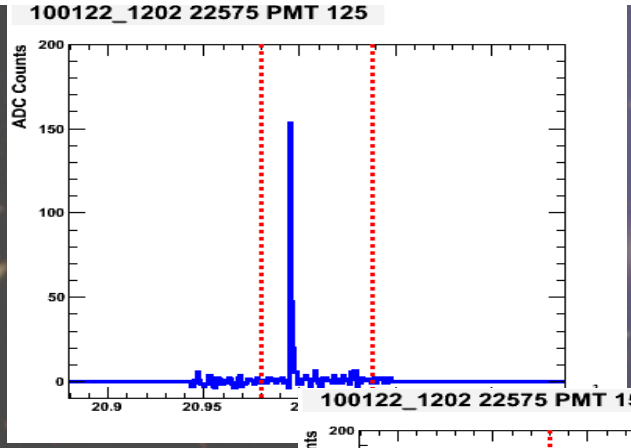


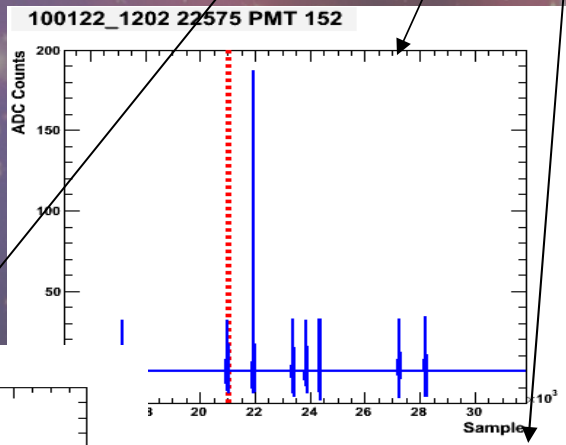



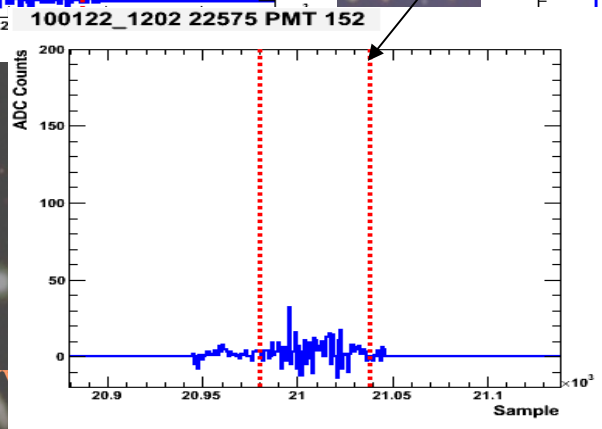



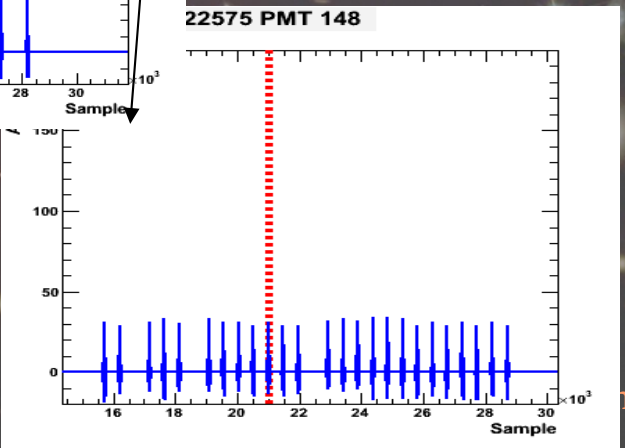
# 10-01-22 12:02 Event 22575



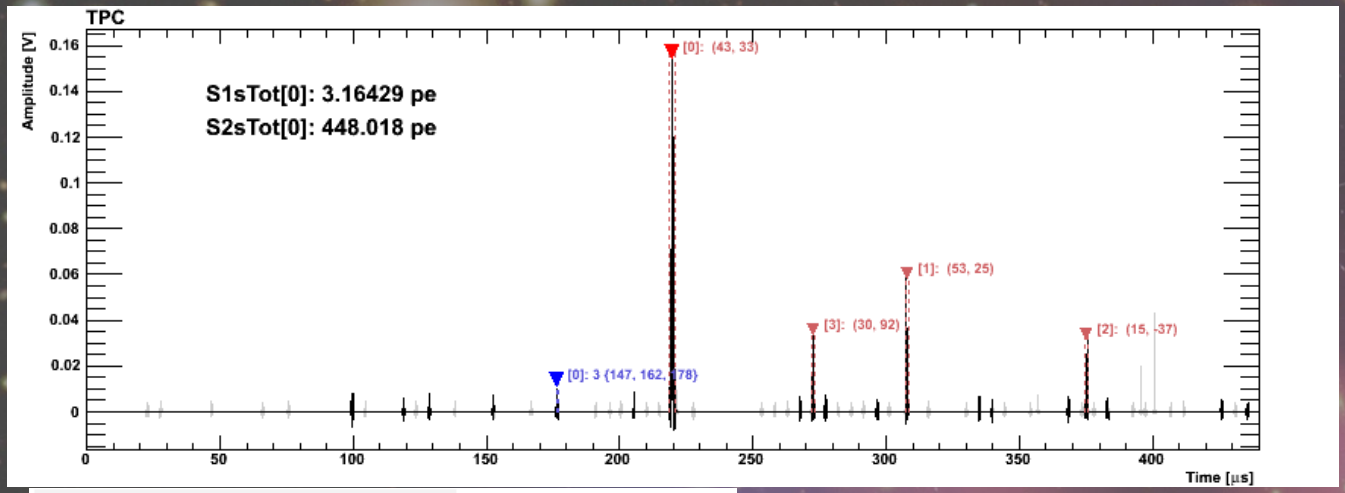



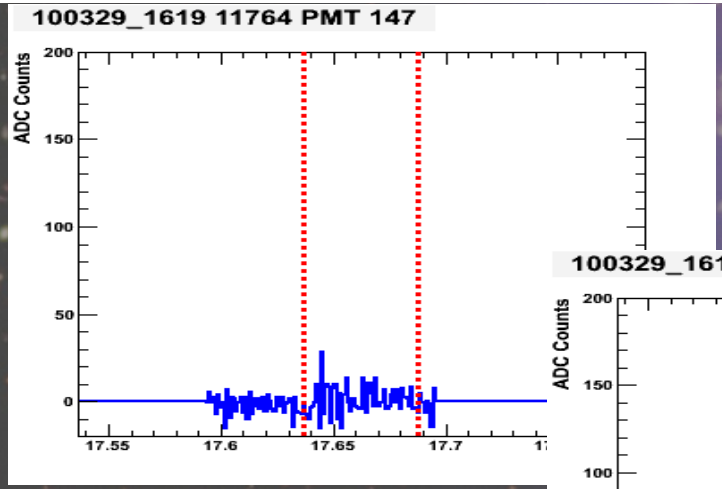



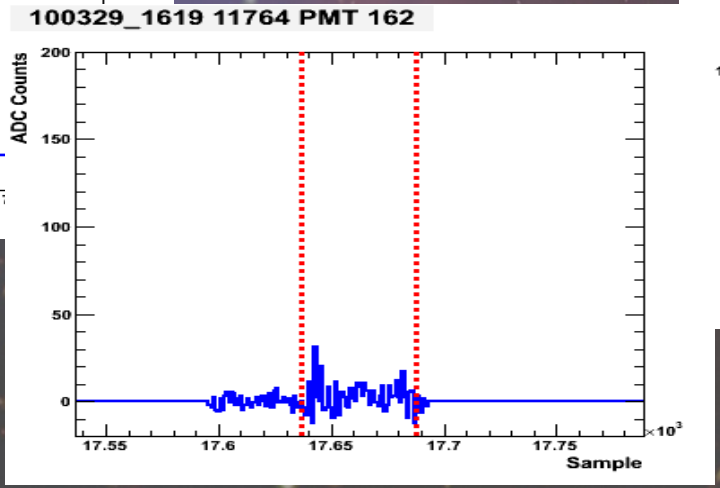

- This event is seen by two PMTs
- However, the signal in PMT152 can be identified as noise
- There are multiple noise peaks in PMT 152 outside the signal region
- The presence of noise in channel 148, which is off, is another proof that this is a noise event
- This event does not fulfill the double coincidence requirement

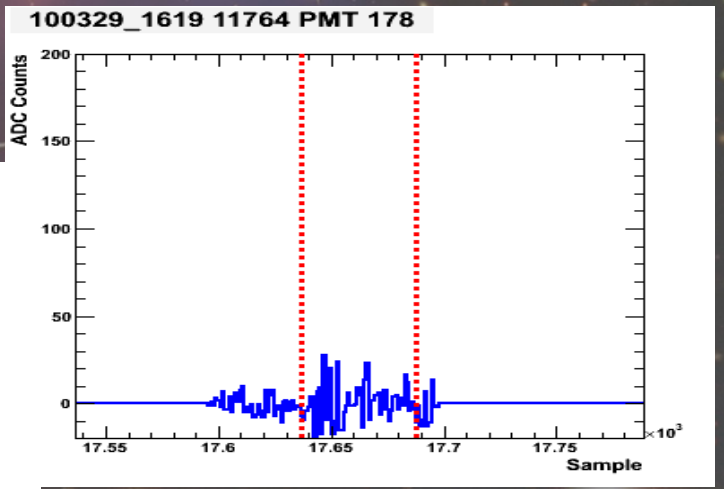
# 10-03-29 16:19 Event 11764



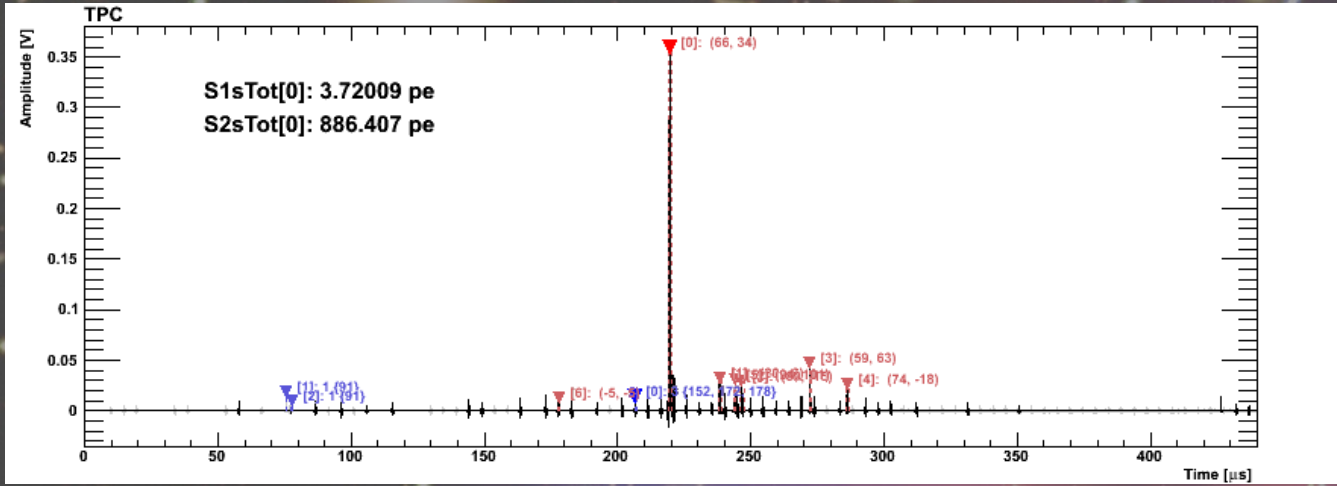

- This event is seen by three PMTs
- The signal in all three PMTs can be identified as noise
- This event does not have a valid S1
- The event does not pass the new cut on the S1 width



# 10-05-18 12:23 Event 10207




- This event is seen by three PMTs
- The signal in all three PMTs can be identified as noise
- This event does not have a valid S1
- The event does not pass the new cut on the S1 width