THE XENON DARK MATTER PROJECT

Roberto Santorelli
Physik-Institut der Universität Zürich

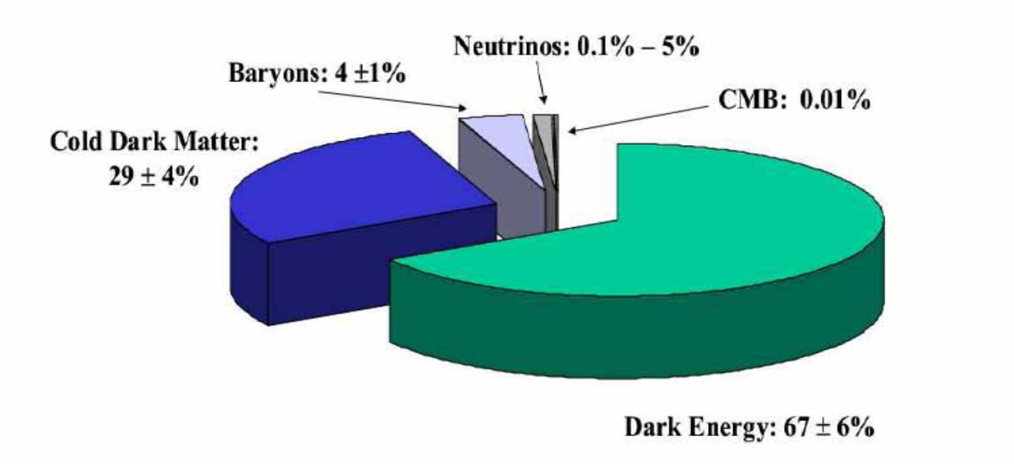
Moriond EW – March 05, 2008

OUTLINE

- LXe for dark matter research
- The XENON project
- XENON10 detector
- XENON10 results
- XENON100 detector
- Conclusions

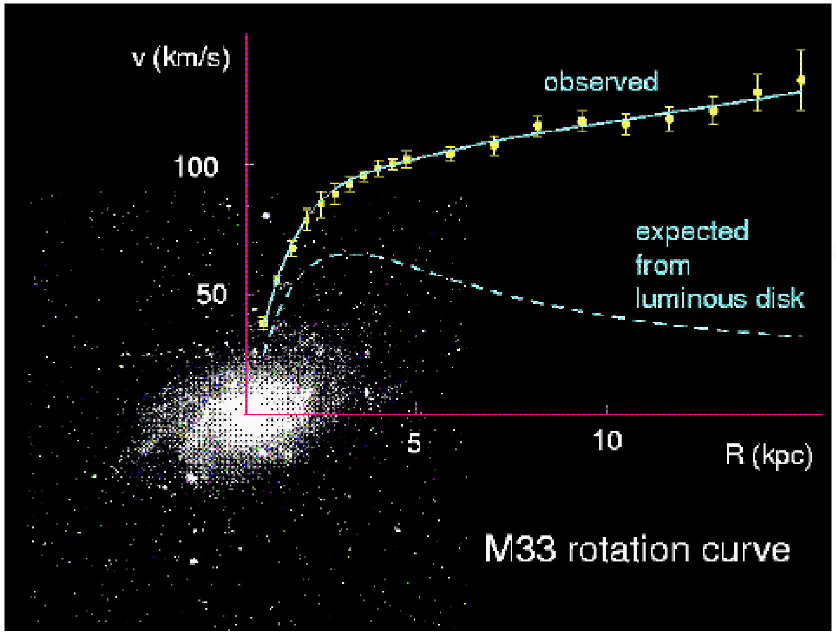
DARK MATTER DETECTION

- most DM is non-baryonic
- cold
- dark

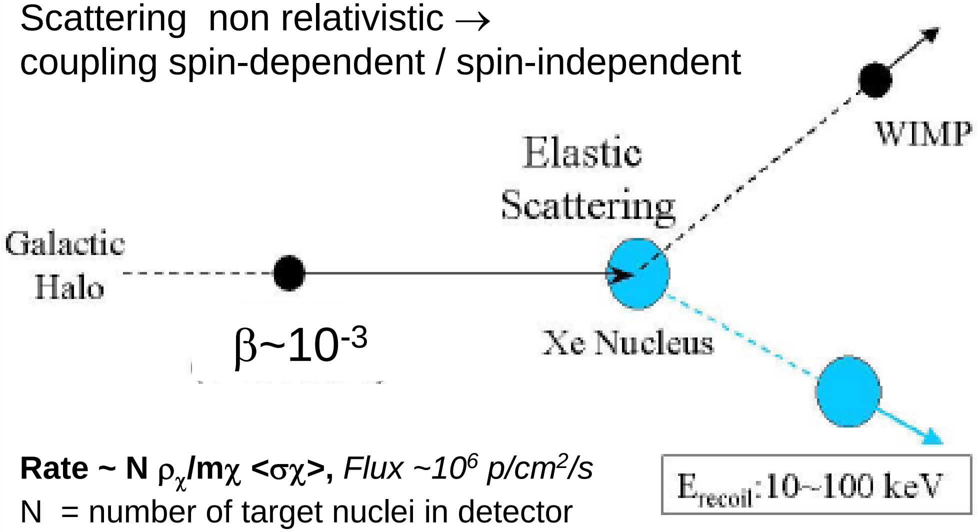


Weakly **I**nteractive **M**assive **P**article

- stable
- slow
- relic from the Bing Bang
- part of a motivated theory → Candidates exits in many extension of the SM : Neutralino, Axion ….etc



Scattering non relativistic →
coupling spin-dependent / spin-independent



Rate ~ N ρ_χ/mχ <$\sigma\chi$>, *Flux ~10^6 p/cm^2/s*

N = number of target nuclei in detector

ρ_χ = local WIMP density

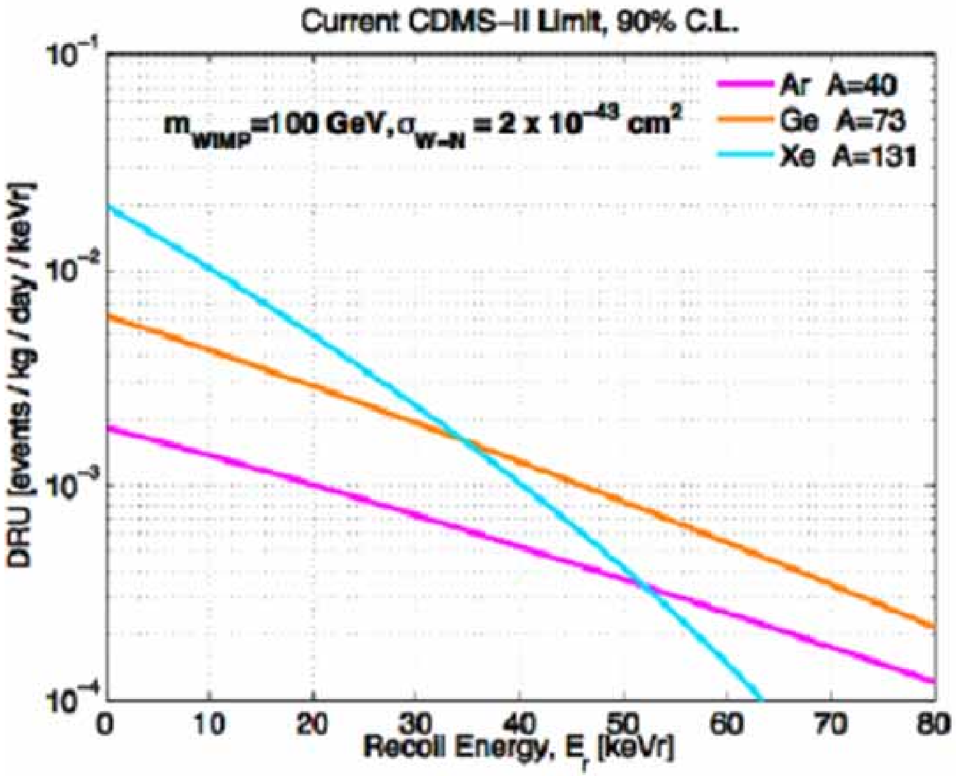
$<\sigma_\chi>$ = scattering cross section

NOBLE LIQUIDS AS DETECTOR MEDIUM

Liquid rare gas give both scintillation and ionization signals

Element	***Z(A)***	***Boiling point (Tb) @1bar [k]***	***Liquid density @Tb [g/cm^3]***	***Energy loss dE/dx (MeV/cm)***	***Radiation length X_0(cm)***	***Collision length λ(cm)***	***Ionization [e^-/keV]***	***Scintillation [γ/keV]***	***Cost***
Ne	10(20)	27.1	1.21	1.4	24	80	46	7	
Ar	18(40)	87.3	1.40	2.1	14	80	42	40	
Kr	36(84)	119.8	2.41	3.0	4.9	29	49	25	
Xe	54(131)	165.0	3.06	3.8	2.8	34	64	46	

LIQUID XENON FOR DARK MATTER DETECTION



λ_{LXe}~*175 nm* λ_{LAr}~*128 nm* λ_{LNe}~77.5nm

Quartz windows: NO SHIFTING WITH LXe

- **High atomic number Xe nucleus(Z=54,A~131) and density (r=3g/cm^3) good for compact and flexible detector geometry. Good stopping power (i.e. self shielding active volume)**
- **~50% odd isotopes (^{129}Xe, ^{131}Xe) for spin dependent interactions**
- **"Easy" cryogenics at –180K**
- **No long-lived radioactive isotopes. ^{85}Kr contamination reducible to ppb level (high electron drift)**
- **High scintillation (W~13 eV) yield with fast response (yield ~80% of NaI)**
- **High ionization (W=15.6eV) yield and small Fano factor for good $\Delta E/E$**
- **low diffusion for excellent spatial resolution. Calorimetry and 3D event localization powerful for background rejection based on fiducial volume cuts and event multiplicity**
- **Distinct charge/light ratio for electron/nuclear energy deposits for high background discrimination**
- **Available in large quantity and "easy" to purify with a variety of methods (~2k$/kg).**

THE XENON DARK MATTER PROGRAM

- Detect WIMPS through their elastic scattering with Xe nuclei
- **XENON10** first implementation of the concept. Data taken in 2006/2007.
  (Reached sensitivity ~10^{-43}cm^2 for 100GeV WIMP)
- LXe double-phase TPC, 3D position sensitive detector
- Event by event discrimination (>99.5%) by simultaneous charge and light detection
- Low energy threshold ~5keVr with 89 PMTs readout (>3pe/keV)
- **XENON100** currently under commissioning at Gran Sasso laboratory

  Goal: gamma background reduction by ~100 and fiducial mass increase by a~10

  (sensitivity up to ~2x10^{-45}cm^2 by the end of 2008)
- Ultimate goal **XENON1T** -> σ_{SI}~10^{-46}cm^2 (to be proposed for 2009-2011)

XENON10 collaboration

Brown University

Rick Gaitskell, Peter Sorensen, Luiz de Viveiros, Simon Fiorucci

Case Western Reserve University

Tom Shutt, Alexander Bolozdyna, Paul Brusov, Eric Dahl, John Kwong

Universidade de Coimbra

Jose Matias, Luis Coelho, Luis Fernandes, Joaquim Santos, Luis Coelho

Columbia University

Elena Aprile (P.I.), Karl Giboni, Maria Elena Monzani, Guillaume Plante, Roberto Santorelli, Masaki Yamashita

Laboratori Nazionali del Gran Sasso

Francesco Arneodo, Serena Fattori

Lawrence Livermore National Laboratory

Adam Bernstein, Norm Madden, Celeste Winant, Chris Hagmann

Rice University

Uwe Oberlack, Roman Gomez, Peter Shagin

Yale University

Dan McKinsey, Kaixuan Ni , Louis Kastens, Angel Manzur

Universität Zürich

Laura Baudis, Alfredo Ferella, Eirini Tziaferi, Jesse Angle, Ali Askin, Marijke Haffke, Alexander Kish, Aaron Manalaysay, Martin Bissok, Stephan Shulte

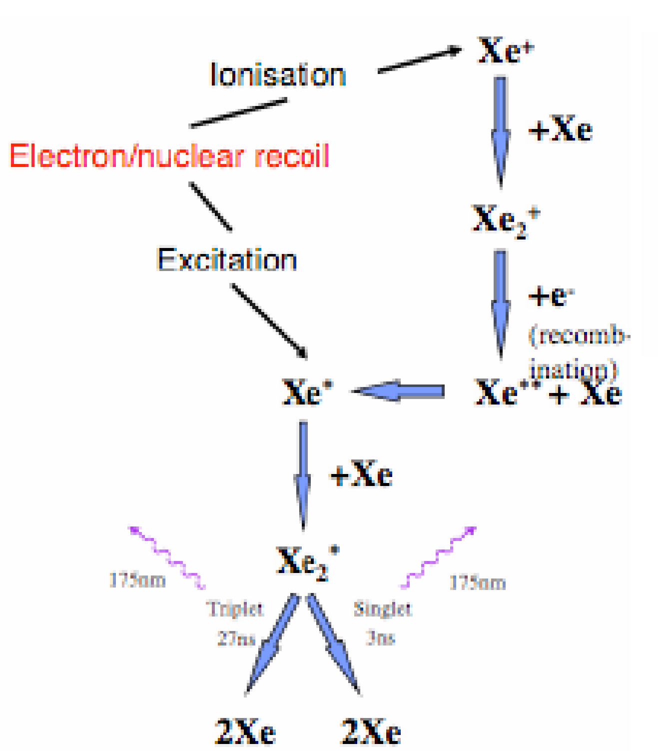
THE DOUBLE PHASE XeTPC:

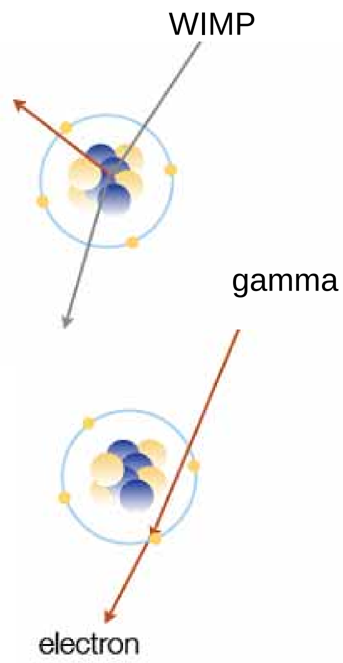
Wimps (or neutrons) → Slow nuclear recoils

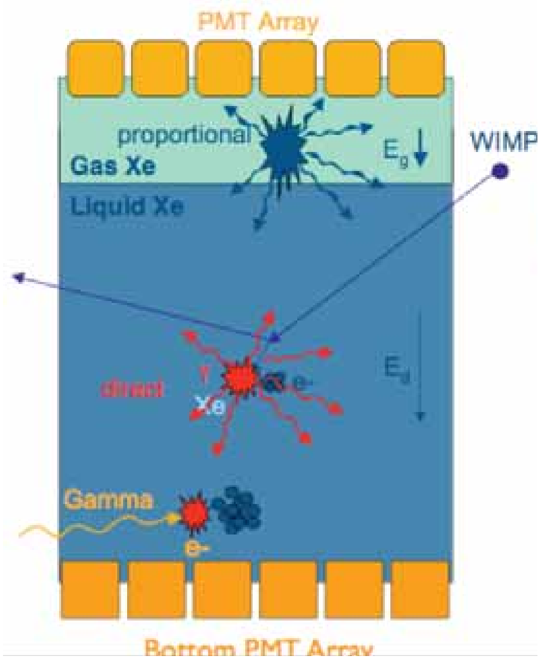
γ,e⁻ etc → Fast electron recoils

Applying a drift field fewer and fewer electrons recombine with the parent ions (recombination light suppressed).
Due to different track structures of recoiling electron and nuclei we have two different amount of quenching

Different ionization/scintillation ratio for electron and nuclear recoil providing basis for
Event by Event discrimination







Ionization signal from nuclear recoil too small to be directly detected : electron extracted from liquid to gas

→ larger proportional scintillation signal *S2*

⇒ **DUAL PHASE DETECTOR**

(s2/s1)electron >> (s2/s1)nuclear

Ultra pure liquid necessary to preserve small electron signal (~10 el)

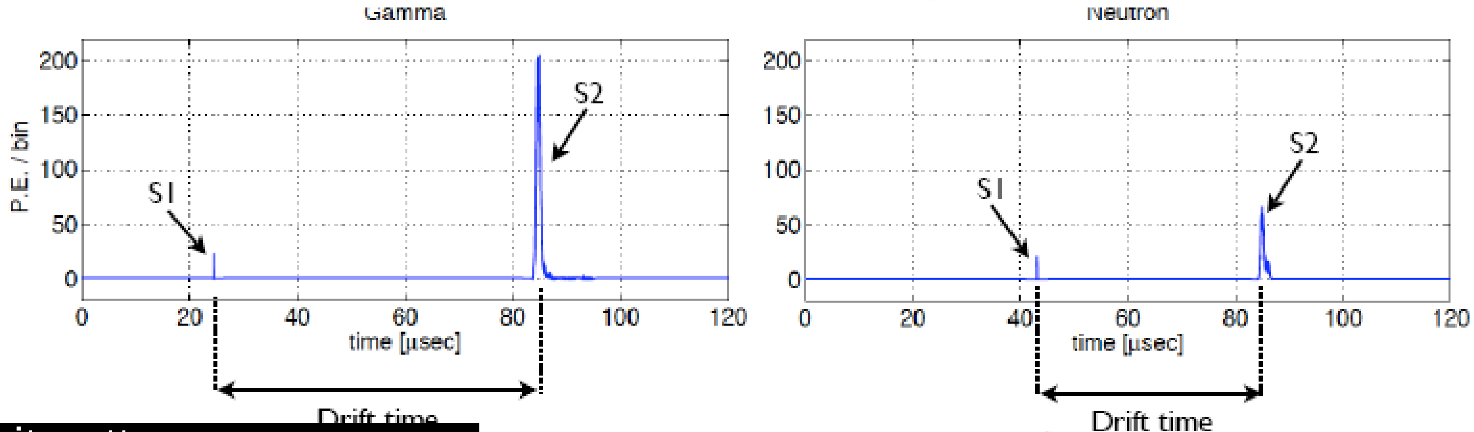
TYPICAL SIGNAL IN XENON10

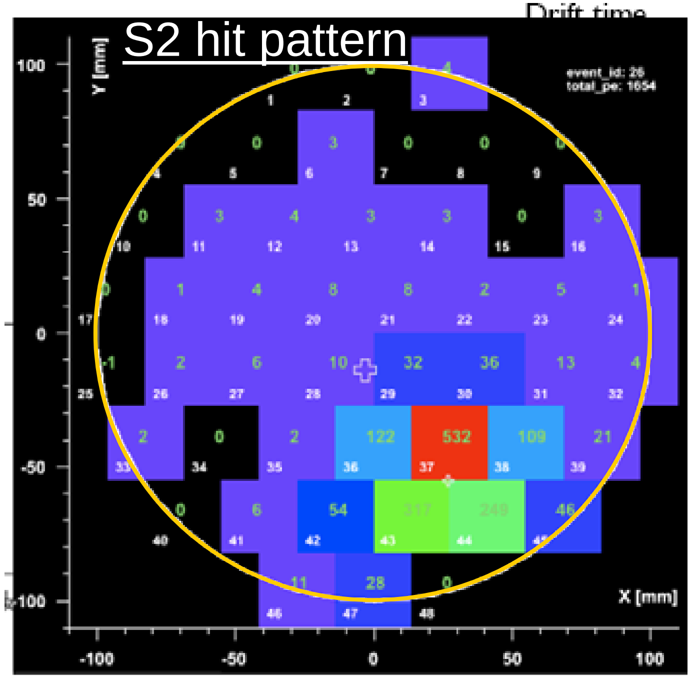
Primary scintillation S1 (created by interaction in LXe) : spread signal mostly on the bottom (20/80 top/bottom)

Secondary scintillation S2 (proportional signal in gas Xe) : mostly on the top array

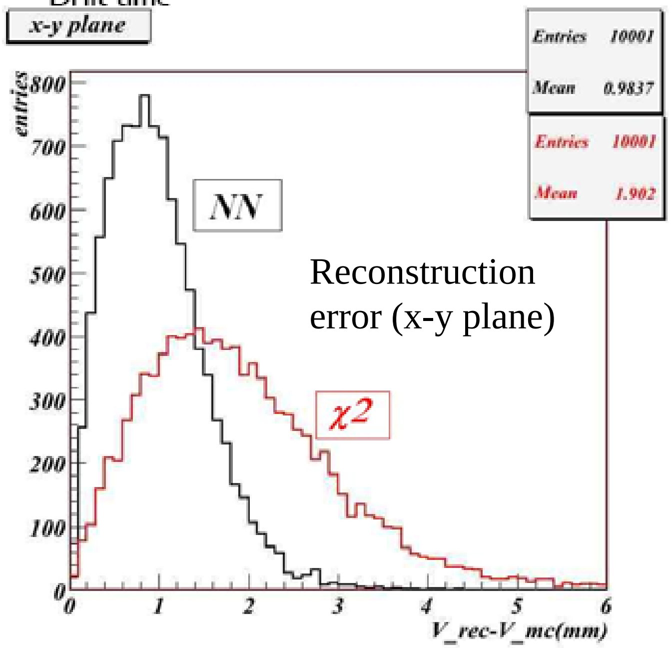
⇒ **xy position** reconstructed through the S2 light pattern (σ_{xy}~ 1 *mm*) on the top array

Drift time (maximum drift 15 cm / 80μs) → **Z position** (σ_z~ 0.3 *mm*)





← *Neural Network* technique →



XENON10 DETECTOR

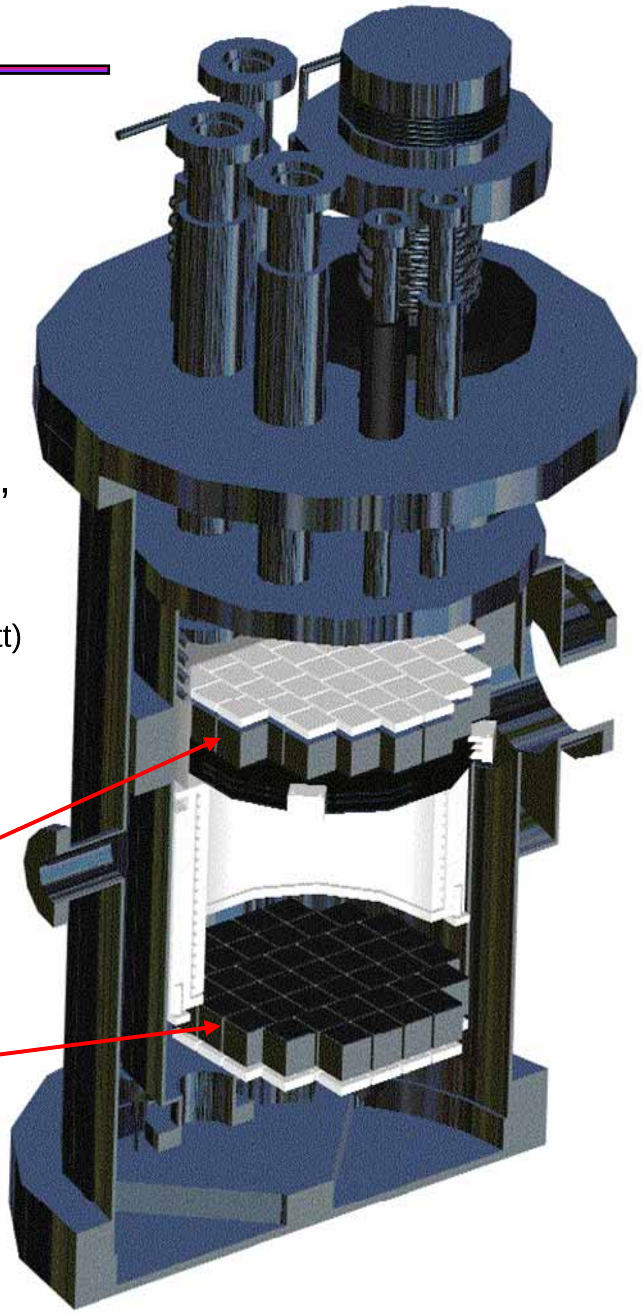
- Physical active region : cylinder r=10cm z=15cm
  22 kg LXe, 15 kg active, 5.4 fiducial

- Cryogenics : 90W Pulse Tube Refrigerator (PTR)

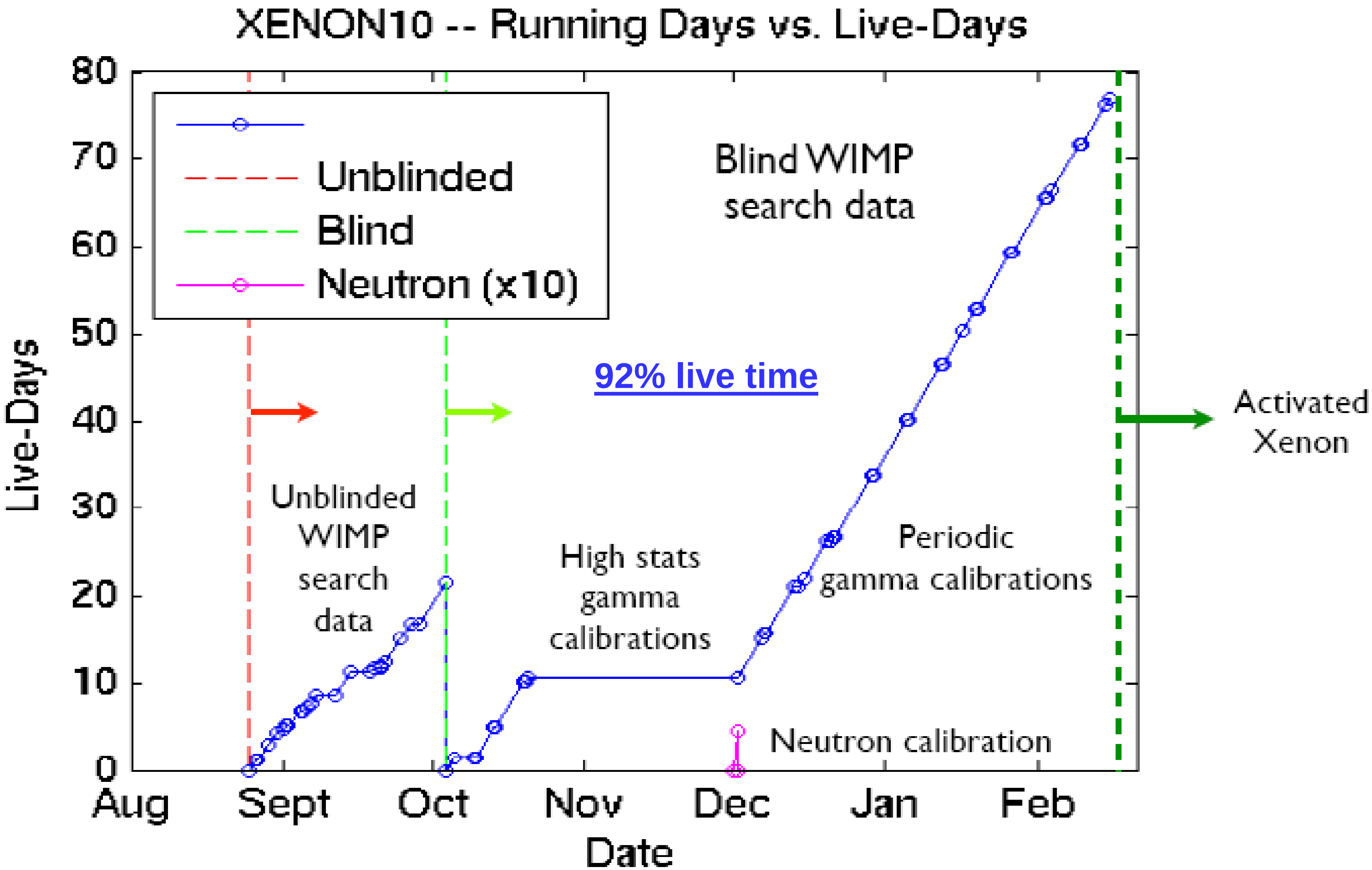
- Shielding 20 cm poly + 20 cm lead

- Running condition: T=180K, P=2.2 bar, Drift Field=0.73kV/cm, Extraction Field= 9kV/cm

- Readout : 89 PMTs Hamamatsu R8520 (48 PMTs top, 41 PMTs bott)
  Hamamatsu R8520 (1",Al)
  Bialkali photocathode Rb-Cs-Sb
  Quantum efficiency > 20% @178 nm




XENON10 @ LNGS



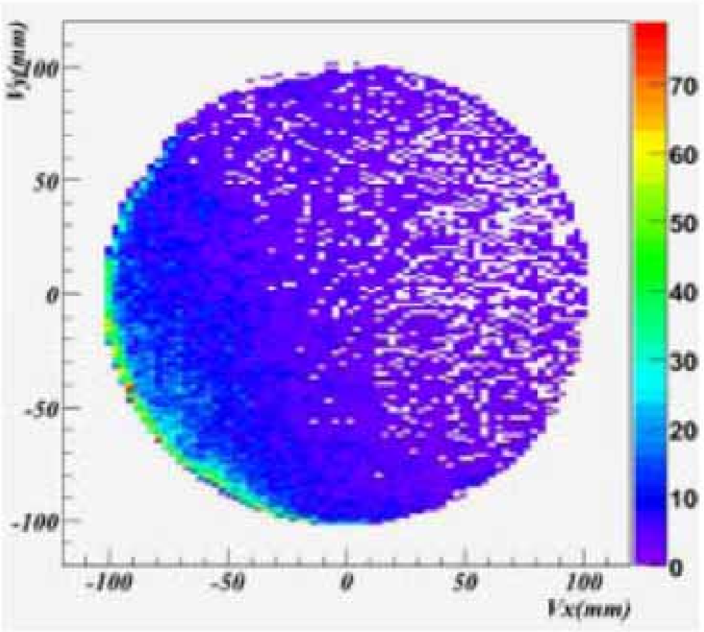
GAMMA CALIBRATION – ^{57}Co ^{137}Cs (introduced in the shield)

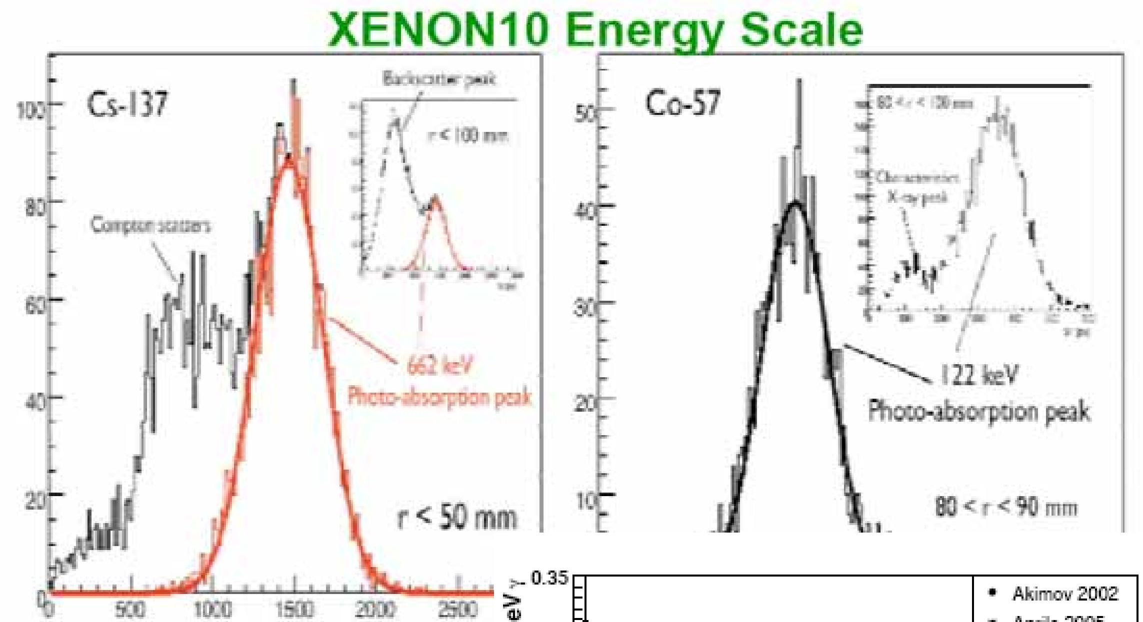
Determine electron lifetime : (1.8±0.4)ms ⇒ 1ppb (O_2 equiv) purity

Determine energy scale from primary light : 2.25 pe/keV @ 662keV and 3.0 pe/keV @ 122keV

Test XY position reconstruction algorithm and vertex resolution

Determine (μ,σ) of electron recoil band → background rejection

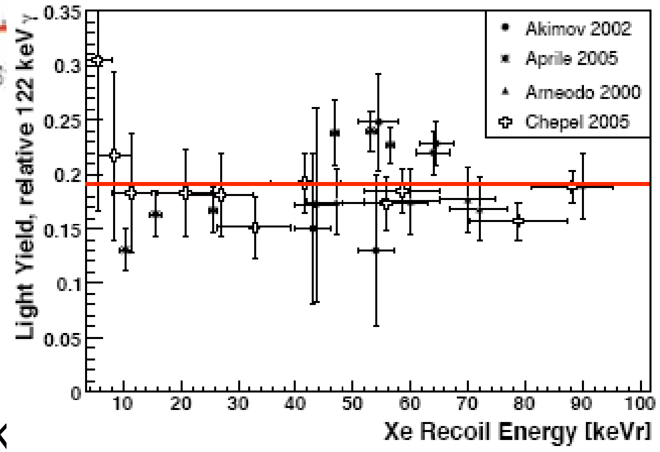




Nuclear recoil energy : $E_{nr} = S1 / L_y / \mathcal{L}_{eff} \cdot S_{er}/S_{nr}$

Measured signal in # of pe

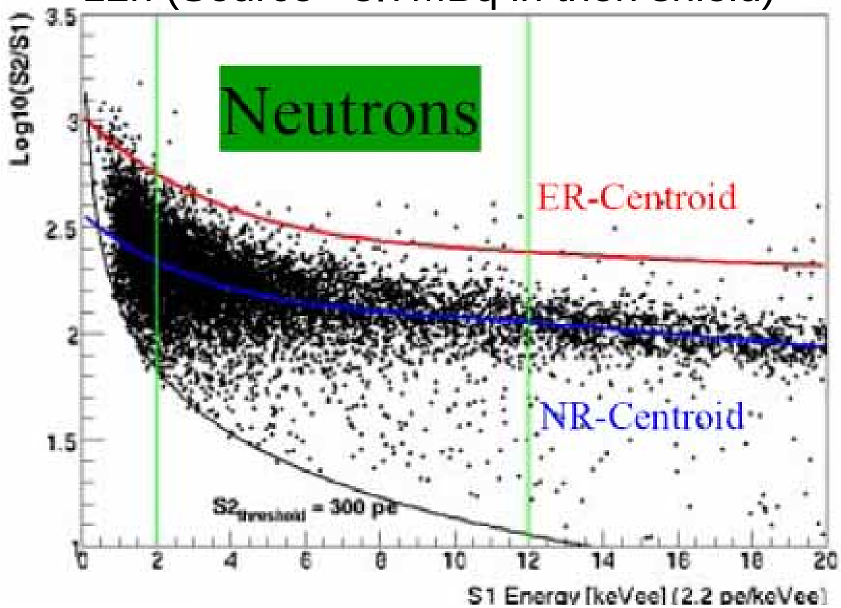
Light yield for 122keV γ in pe/keVee (3.0 pe/k

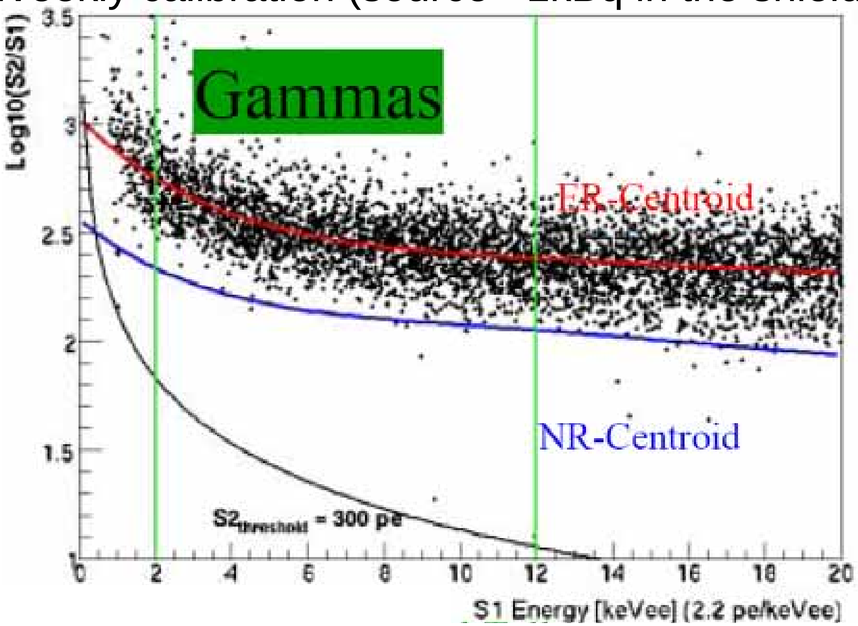


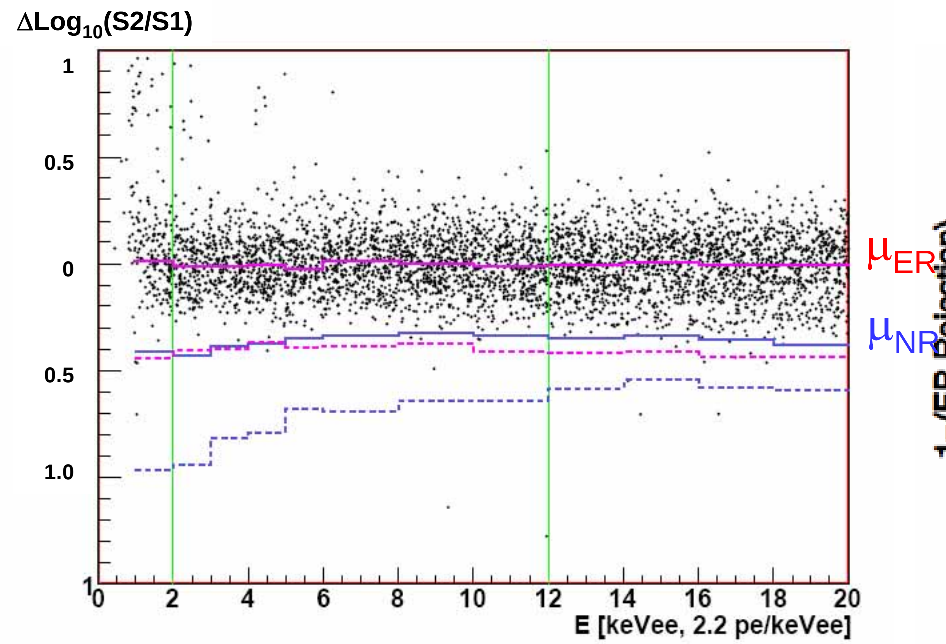
XENON10 background rejection power

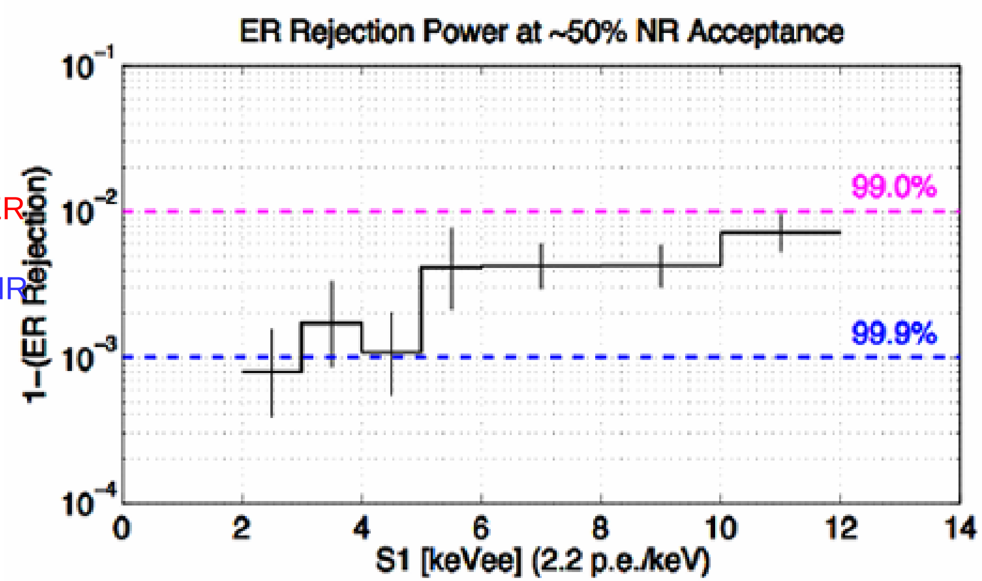
AmBe neutron calibration (NR-band)
12h (Source ~3.7MBq in then shield)

Cs-137 Gamma Calibration (ER-band)
Weekly calibration (source ~1kBq in the shield)



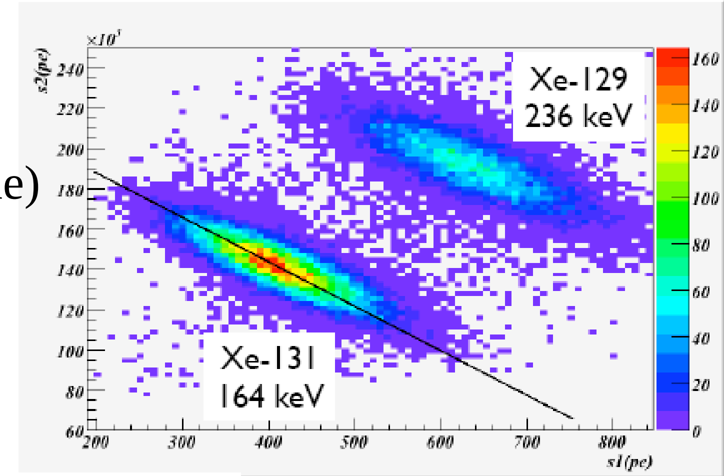


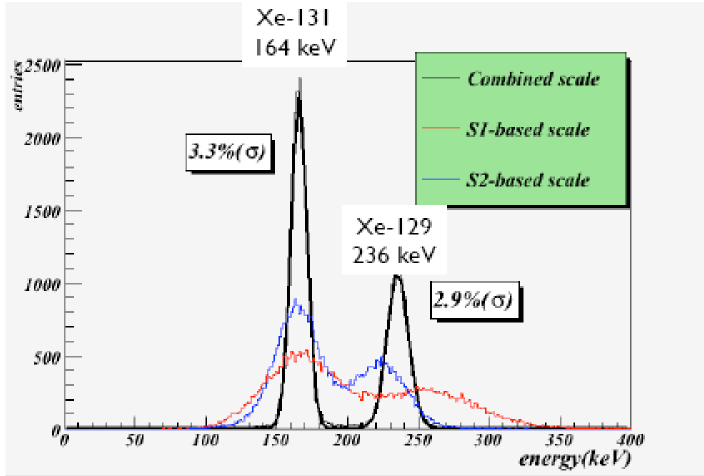


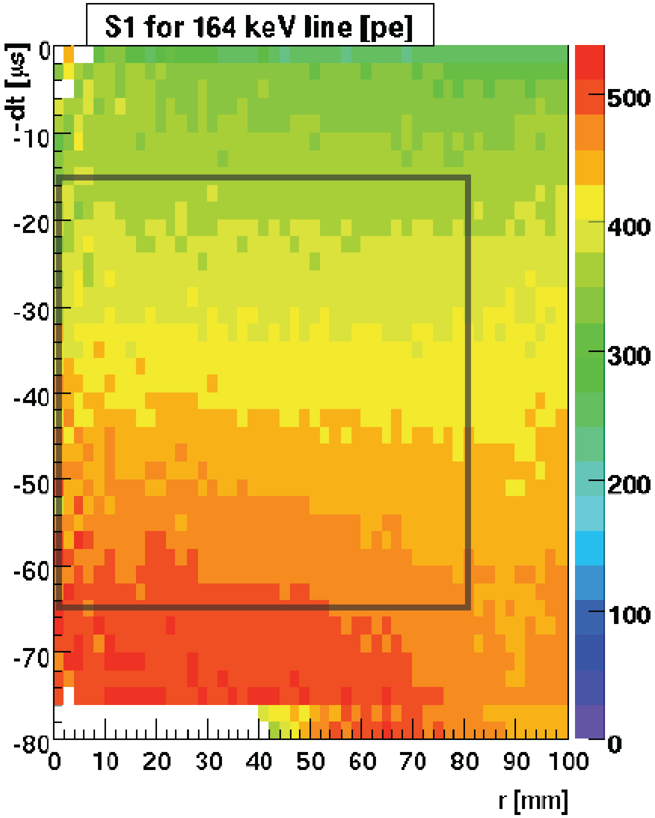


CORRECTIONS TO IMPROVE SIGMA – Activated Xe

Gamma ray peaks
164 keV – 236 keV
(from ^{129m}Xe and ^{131m}Xe)

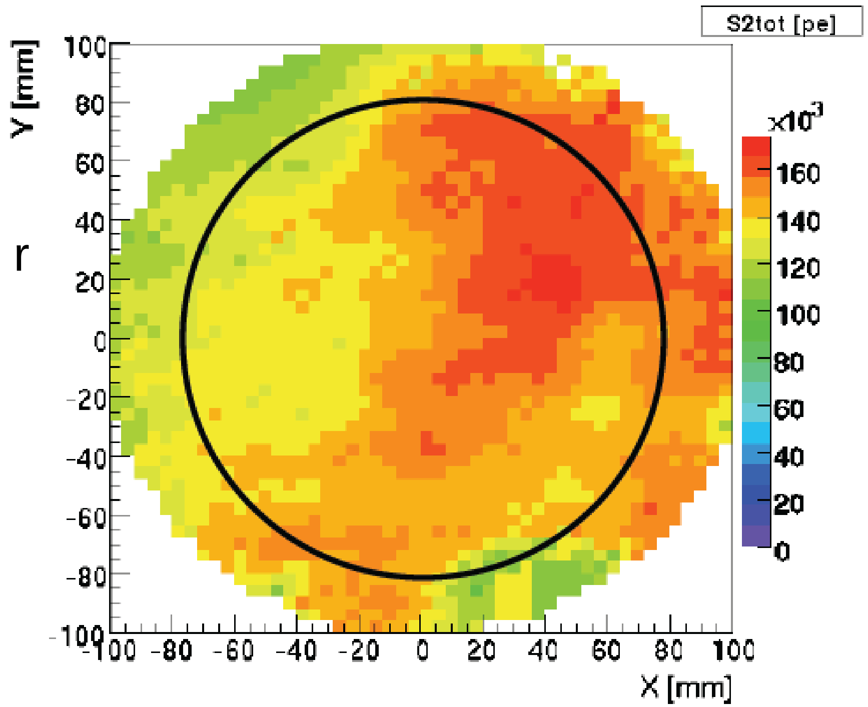






S1:
20% variation across z
~constant with r

S2:
20% variation on xy

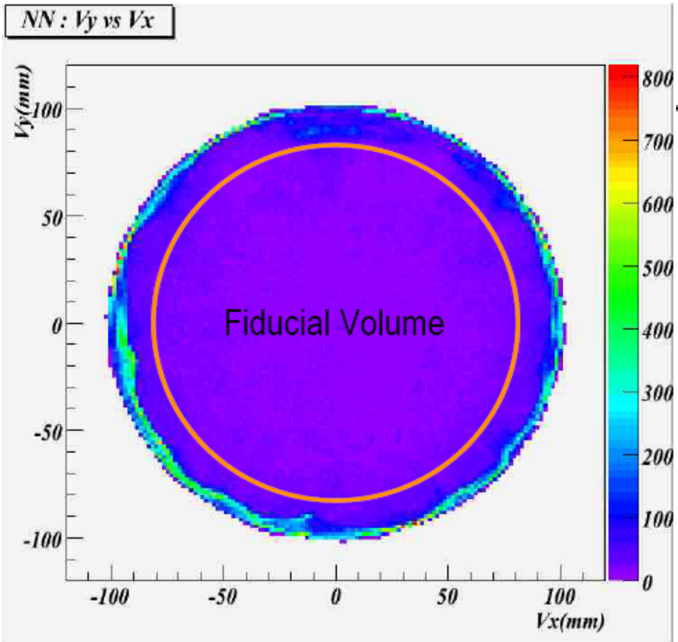


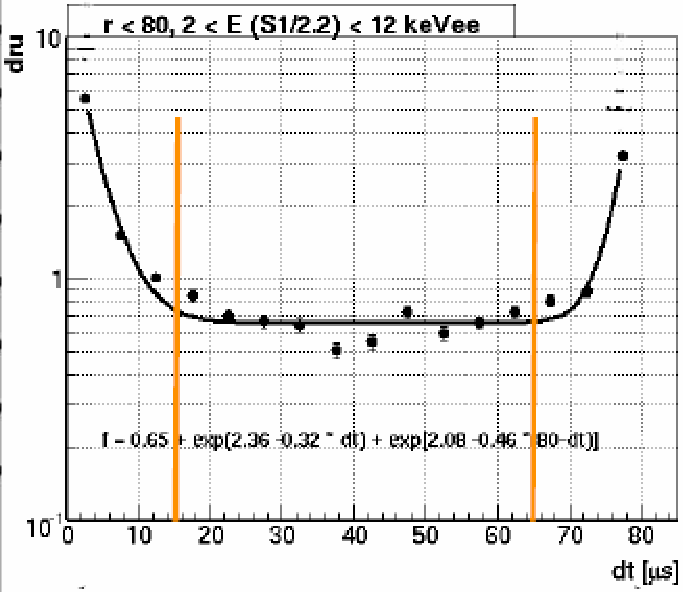
XENON10 WIMP SEARCH RUN

- WIMP search from data accumulated between October,06 and February,07
- ***Blind analysis*** : data from WIMP search run in the box until cut definitions completed. Cuts defined on data from gamma and neutron calibration
- Two independent analyses (choose the one with NN technique and better analysis of the digitized signal waveform, different selection and cuts)
- Box open on April,07

Three levels of cuts to select good events

- Basic quality cuts (QC0) : reject saturation, no S1 or multiple S2 peaks, S2 χ^2
- Fiducial volume cuts (QC1) : r<80mm && 15μs<dt<65μs
- High level cuts (QC2) : to remove events with anomalous and unusual S1

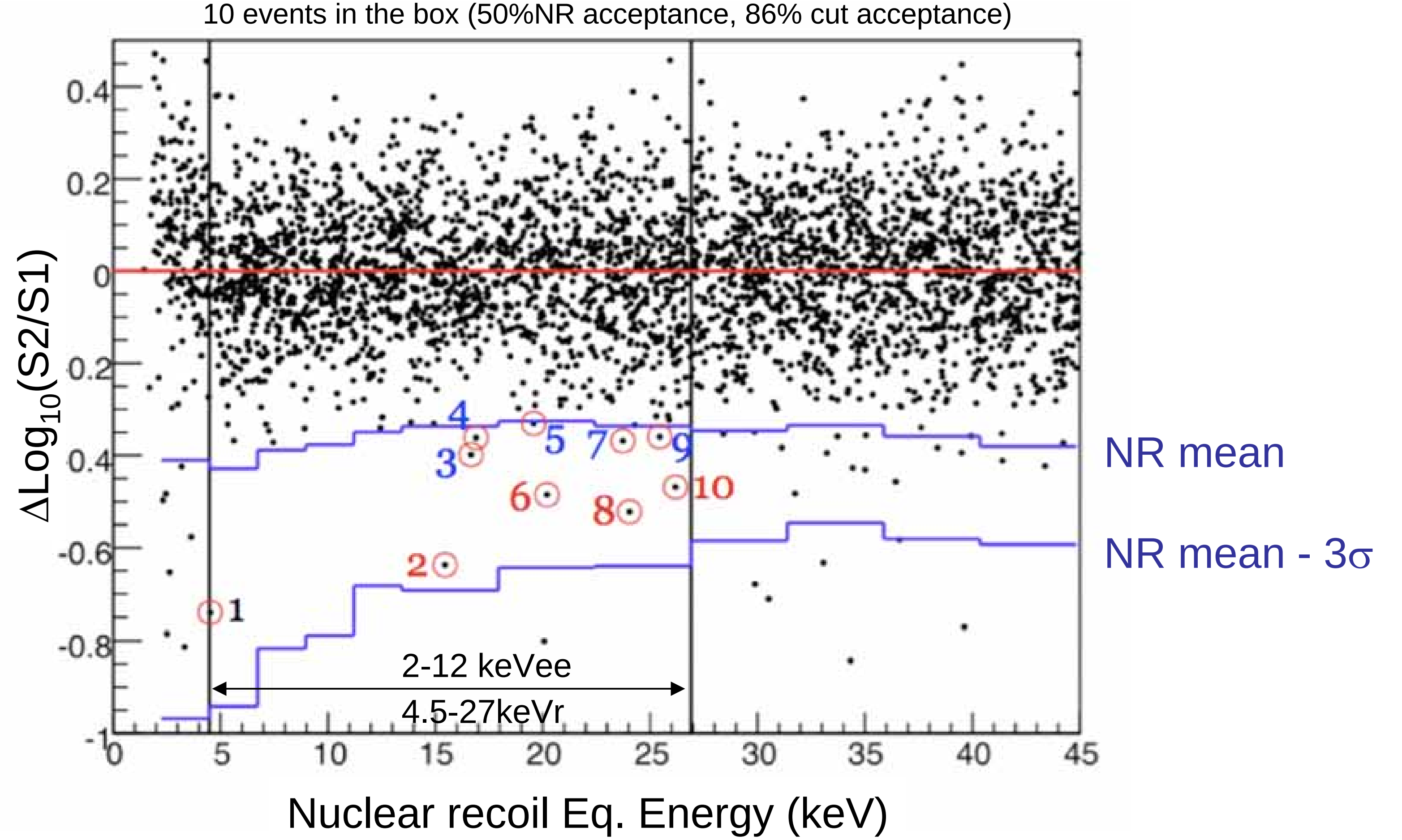




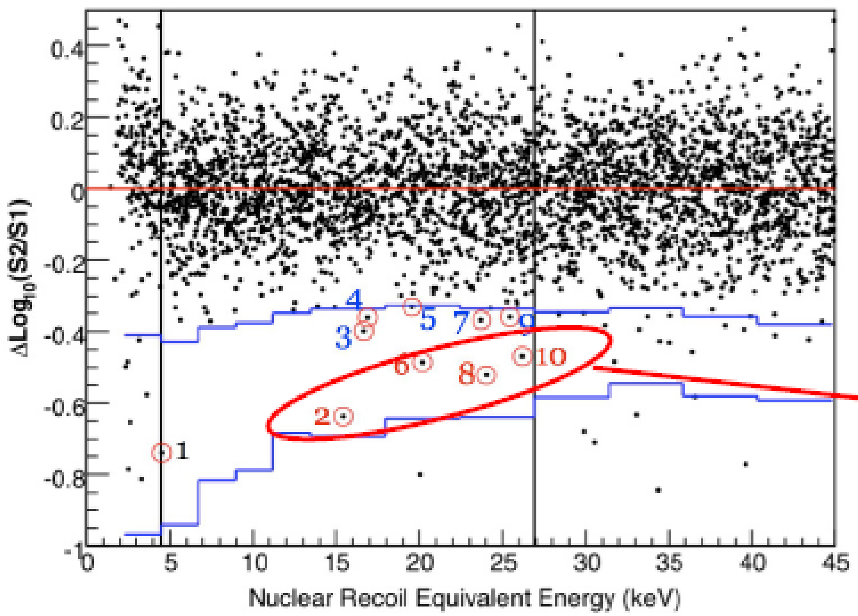
Overall background in the fiducial volume ~0.6 event/(kg·day·keVee)

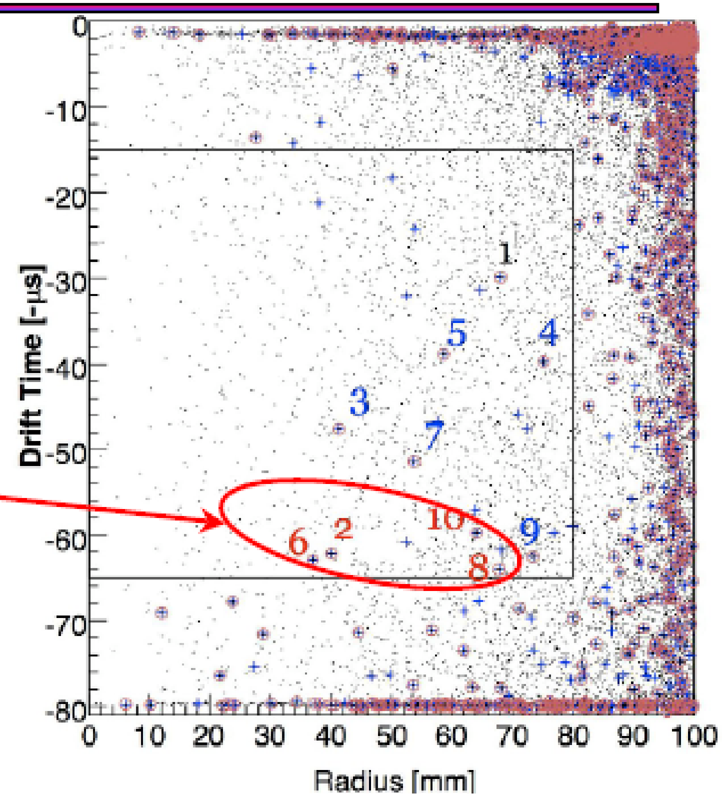
WIMP SEARCH DATA

- WIMP acceptance window defined as ~50% acceptance of NR [mean,-3σ] from gaussian fits
- ~1800 events in the energy box
- 10 events in the acceptance window after the primary analysis (QC0,QC1,QC2 cuts)
- 6.9 events expected from the γ calibration
- 5 events not consistent with the γ calibration



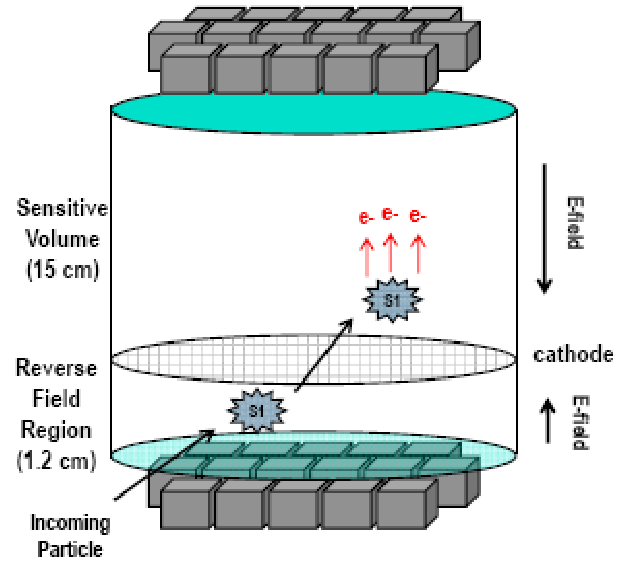
ANOMALOUS EVENTS





Secondary analysis:

- ❑ 5 events are consistent with statistical leakage from electron recoil band (6.9 events expected)
- ❑ 4 of the 5 non-Gaussian events are removed by a more sophisticated gamma-x cut (~3 events expected from simulations)
- ❑ 1 event removed by signal quality cut (noise event)

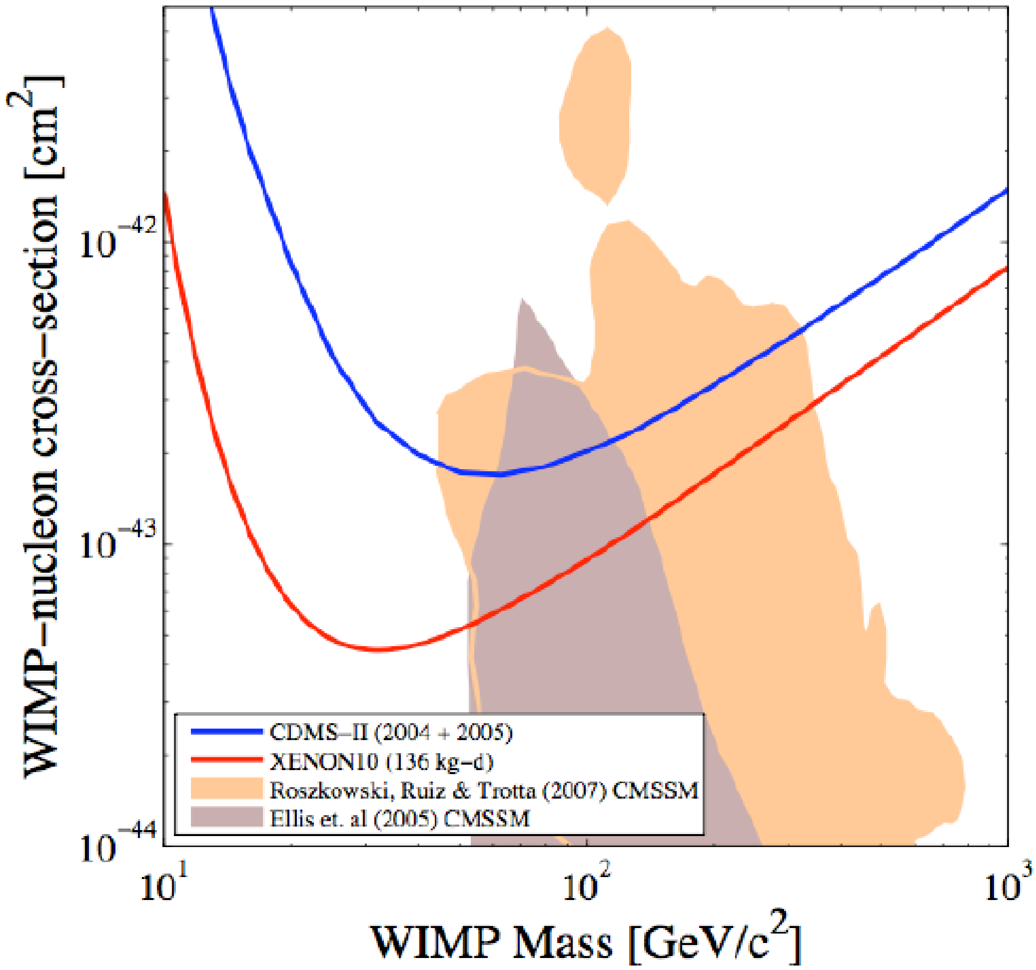


WIMP SIGNAL UNLIKELY

Detector upgraded in May 2007: Teflon blinders placed around bottom PMTs to reduce the rate of gamma-x events (~50 live days)

XENON10 EXCLUSION LIMIT FOR SPIN-INDEPENDENT WIMP INTERACTION (90% CL)

$\sigma < 8.8\ 10^{-44}$ cm for m=100 GeV
(factor 2.3 below the best previous limit at 100 GeV)
(CDMS-II 2004+2005)

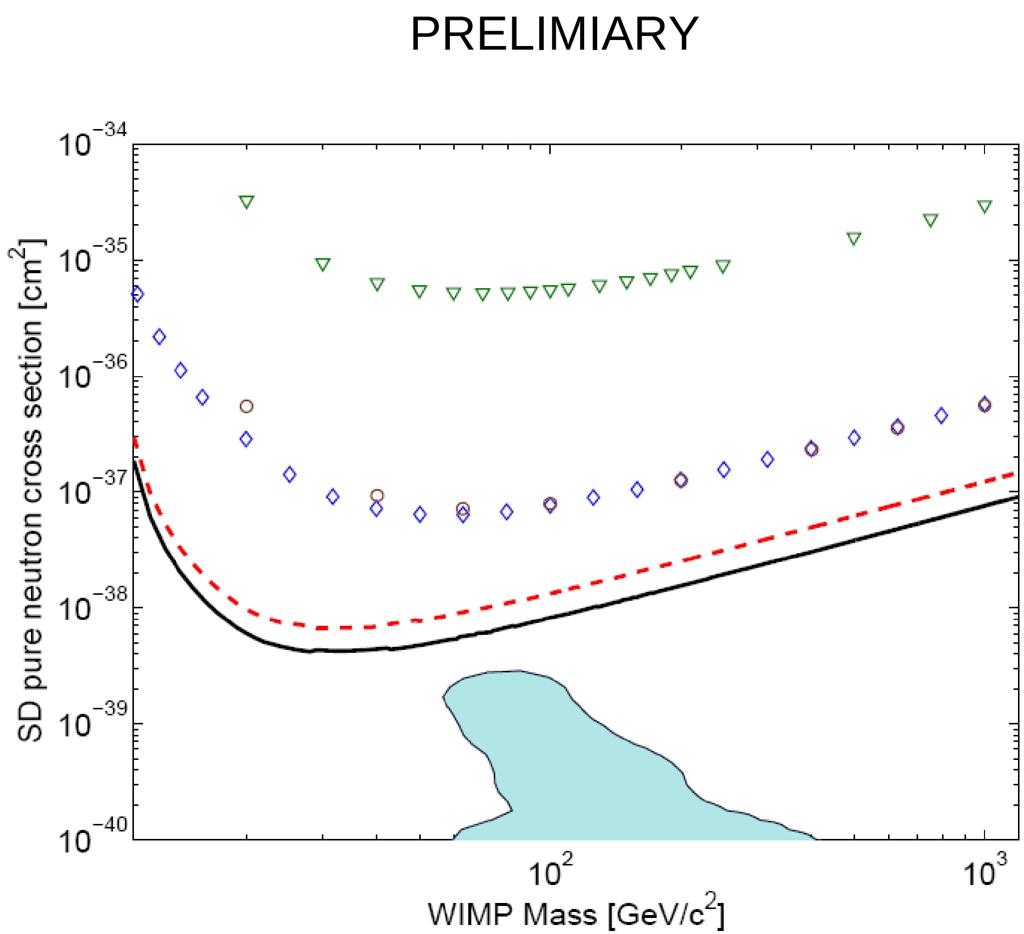


Results based on Yellin maximal gap method
NO BKG SUBTRACTION

XENON10 is probing a significant part of the theoretically predicted cross section for WIMPs

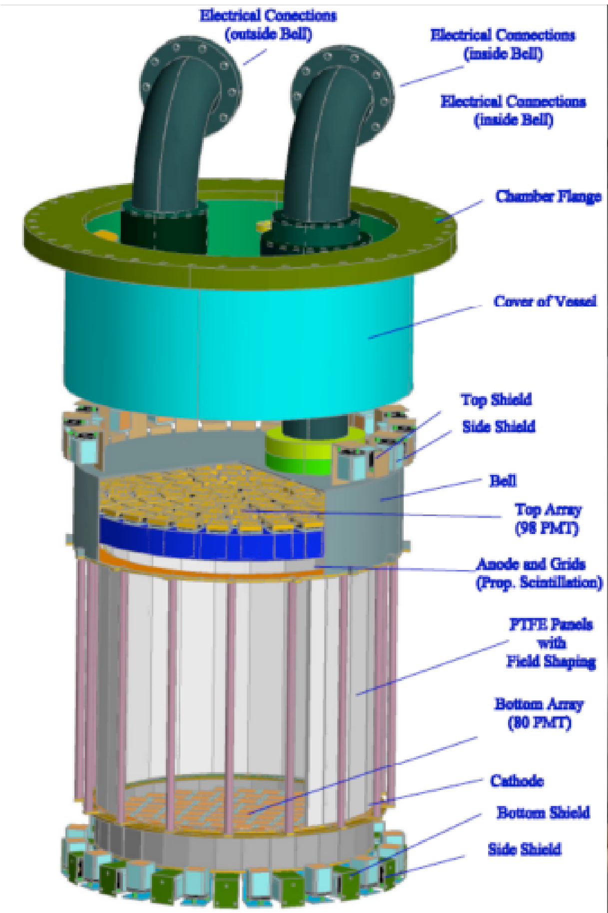
PRL 100,021303 (2008)

Spin Dependent analysis



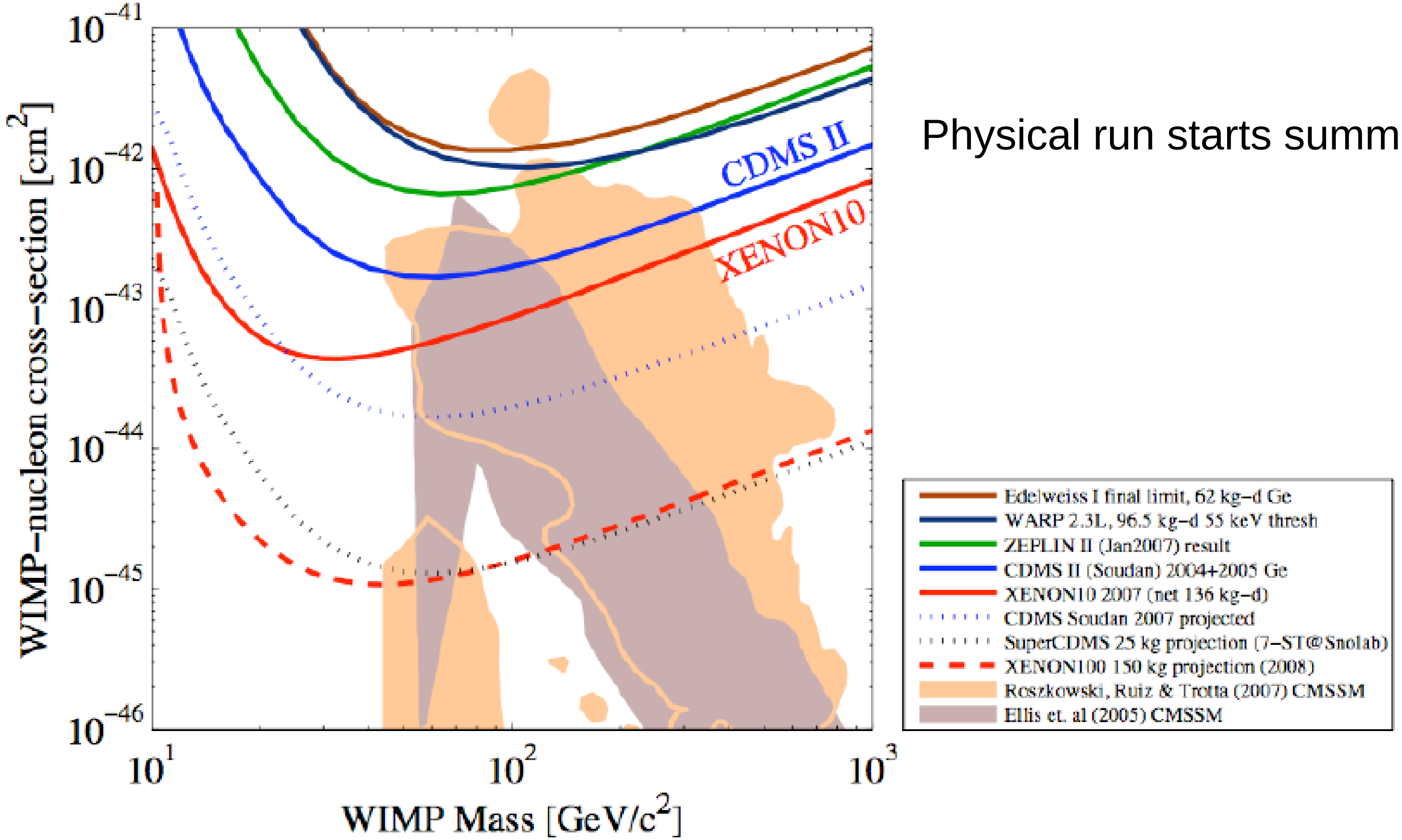
XENON100 DETECTOR

- New detector in the same shield at LNGS
- 170kg total - 70 kg target LXe (15 cm radius , 30 cm drift)
- Active veto
- New high QE (>30%@175nm) low activity 1” R8520 PMTs (total 242 PMTs)
- Cryocooler (170 W) and feed-through outside the shield
- Material screening facility at LNGS (gamma background reduction ~100)



EXPECTED SENSITIVITY

~2 x 10^{-45} cm^2 for m=100 GeV



Physical run starts summer 2008

SUMMARY

- XENON10 demonstration of the concept

- XENON10 has placed the most stringent DM limits (SI - SD)

- XENON10 upgraded: new data (~50 live-days) under analysis

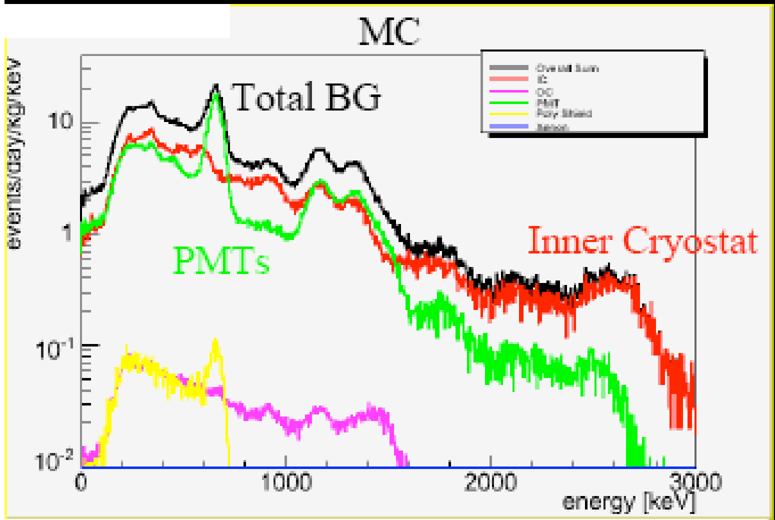
- XENON100 $\rightarrow$ increased mass, reduced background
  Moved underground Feb 2008

- MC studies on XENON1T started

Thank you!

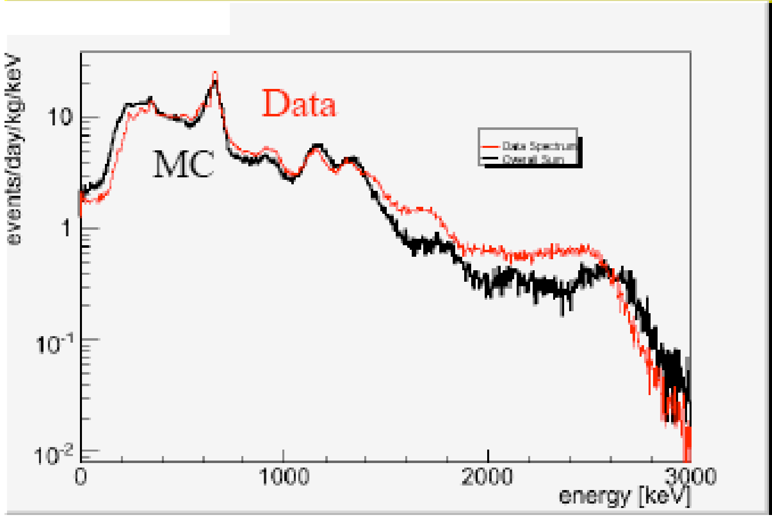
EXTRA SLIDES

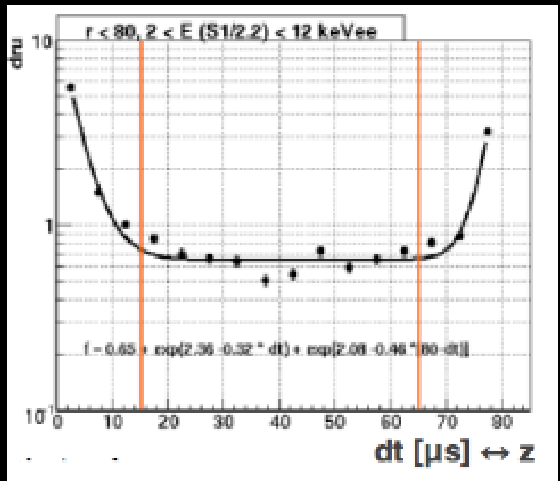
Backgrounds

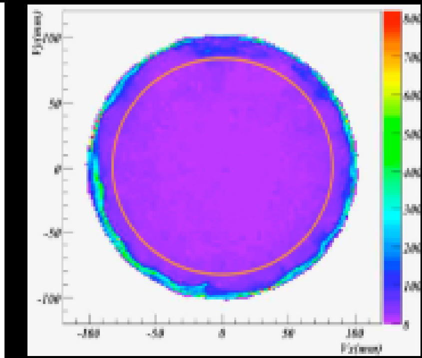


The gamma backgrounds have been simulated using *GEANT4*, at left. The main contributions come from the PMTs and the steel of the inner vacuum can (IC).

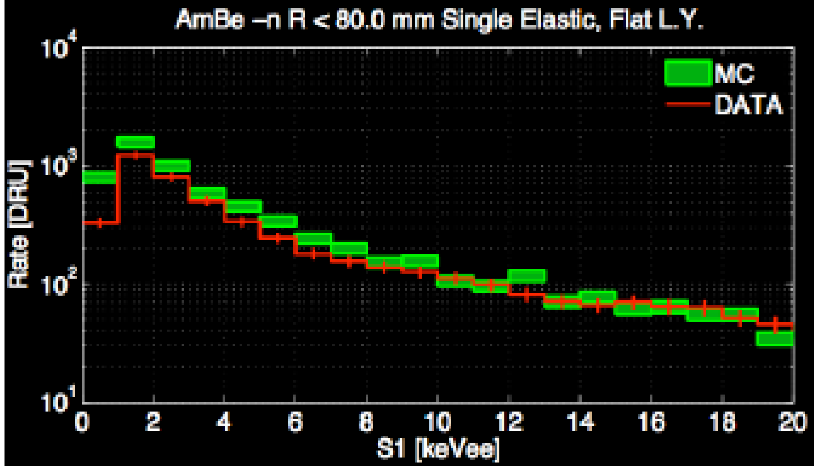
Below, the radial dependence on the background rate clearly indicates the effect of LXe self-shielding the inner regions.



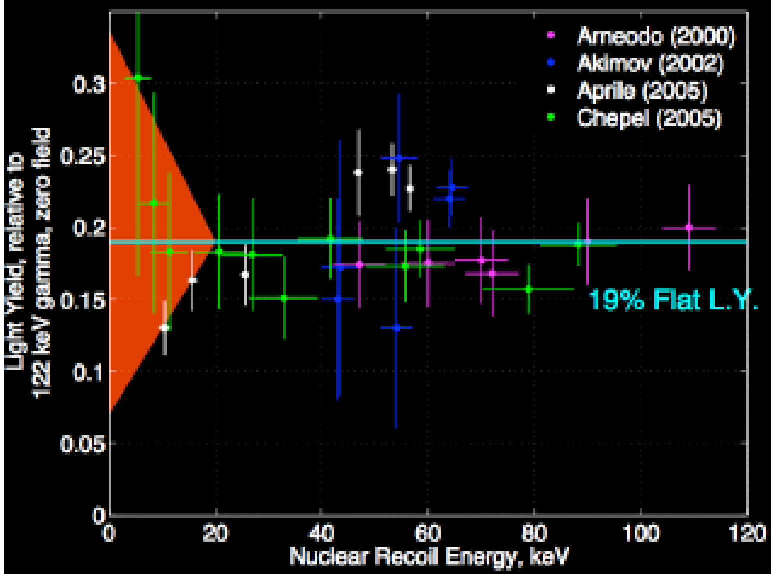


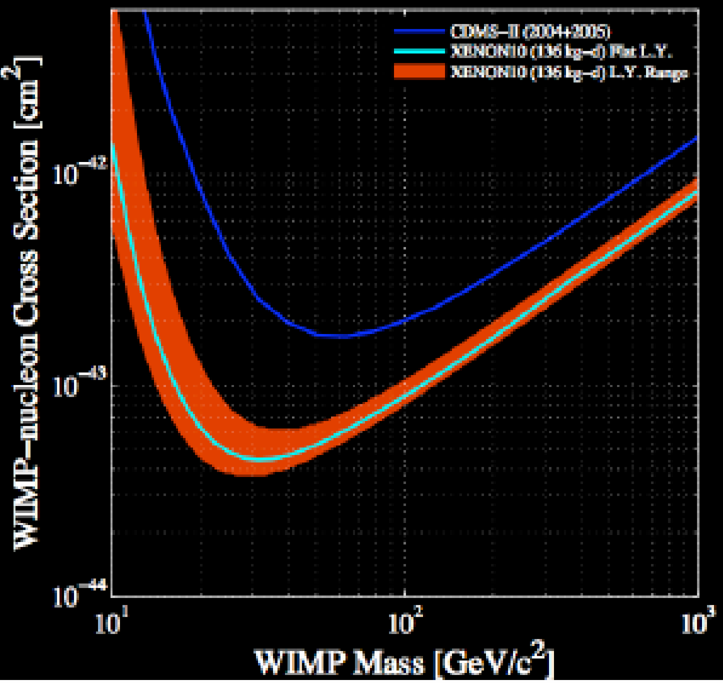


L_{eff} uncertainty



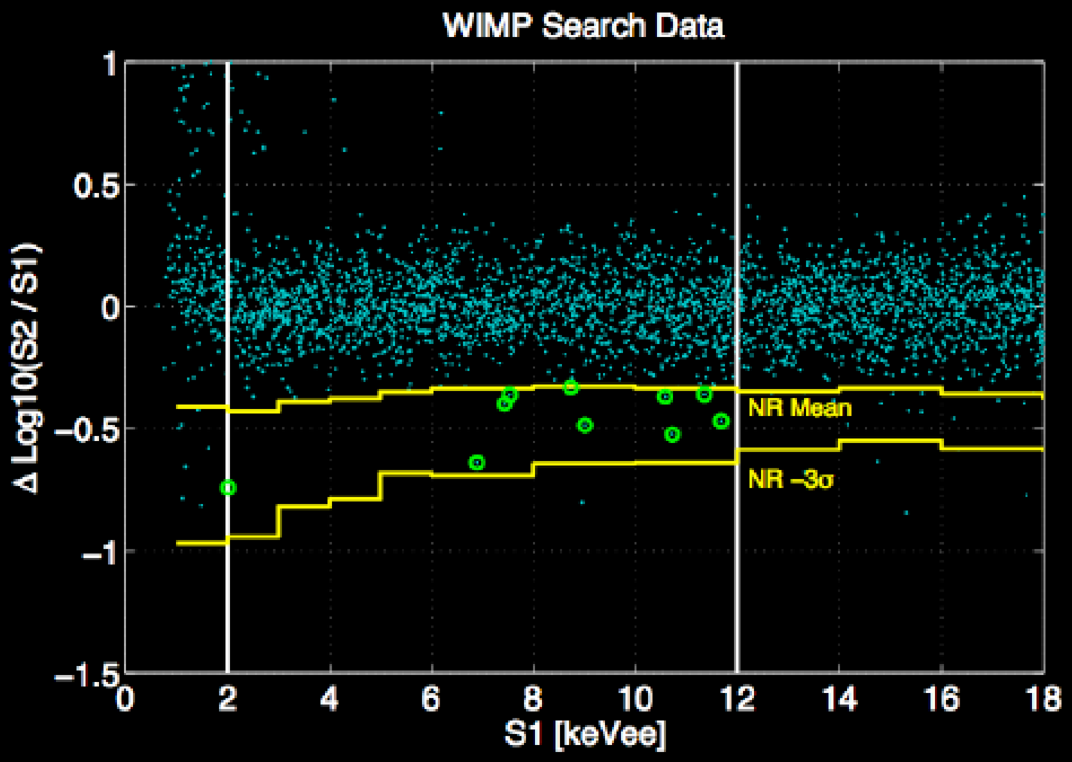
Due to the wide range of results from beam measurements on L_{eff}, we chose to use a flat 19% value. This value shows very good agreement when comparing neutron calibration data to MC, and indeed the best-fit for L_{eff} is not far from the flat value that we chose.





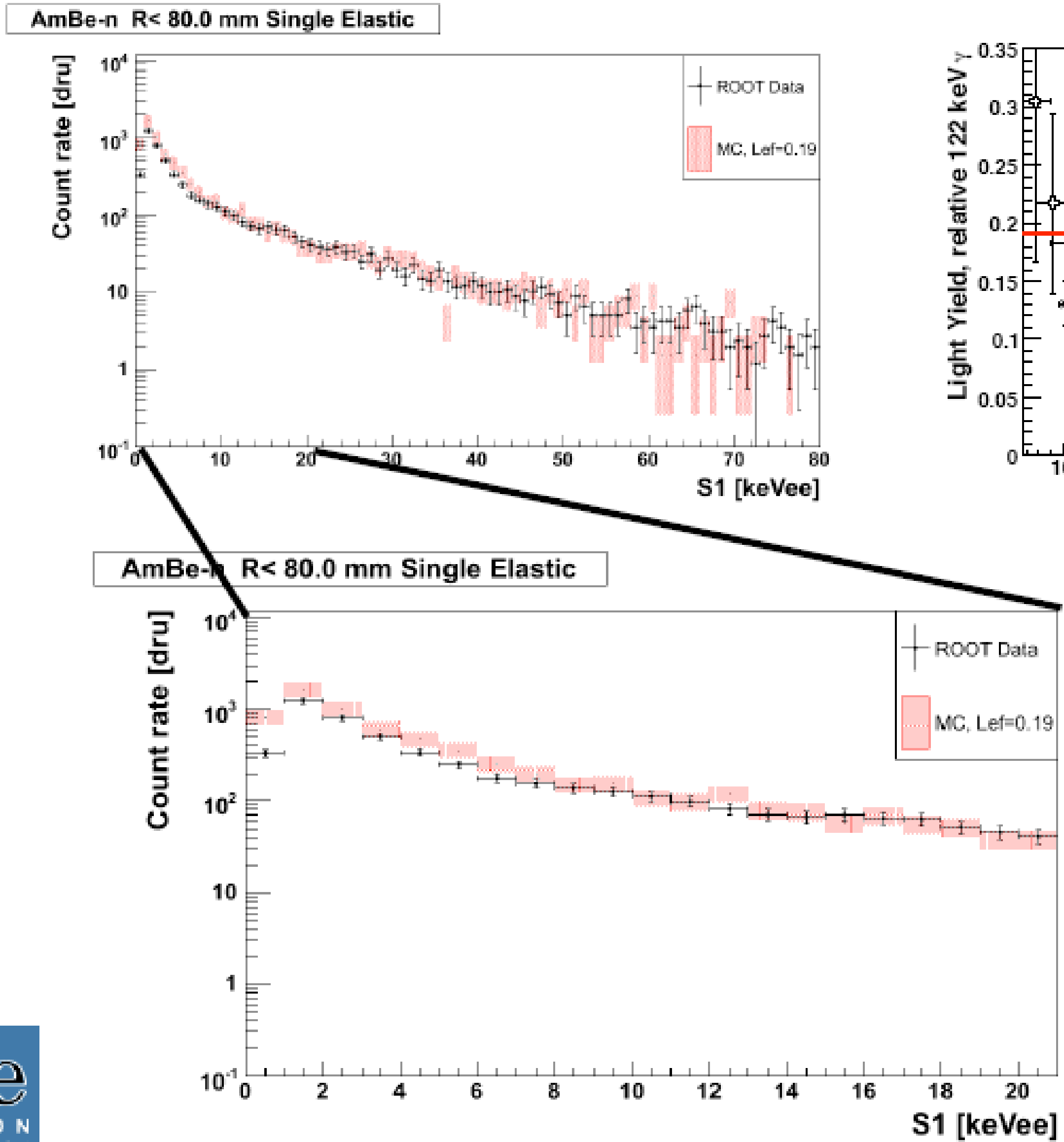
XENON10 Blind Data

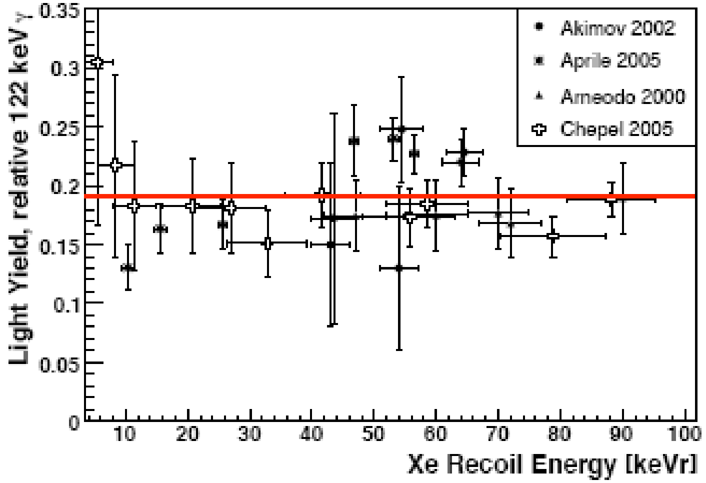
136 kg-d exposure = 58.6 live-days x 5.4 kg x 0.86 (ε) x 0.50 (NR acceptance)



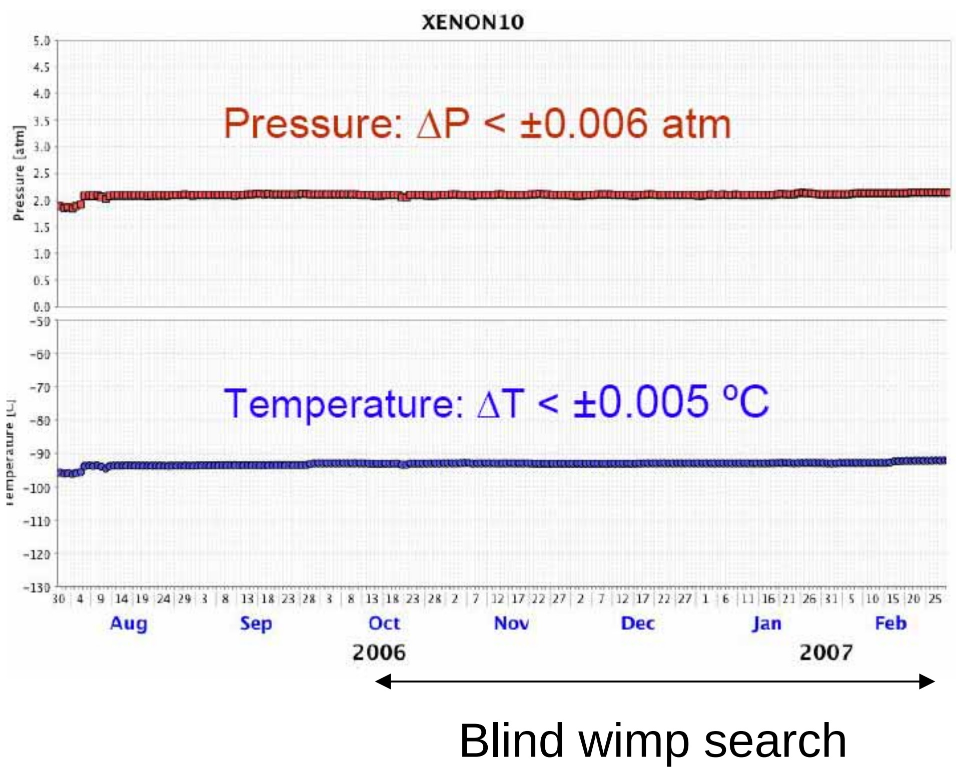
- WIMP acceptance window defined as ~50% acceptance of nuclear recoils [mean, -3σ] from gauss fit (yellow lines).
- 10 events in the acceptance window after all cuts
- 7.0 events expected from γ calibration, although not used for background subtraction.

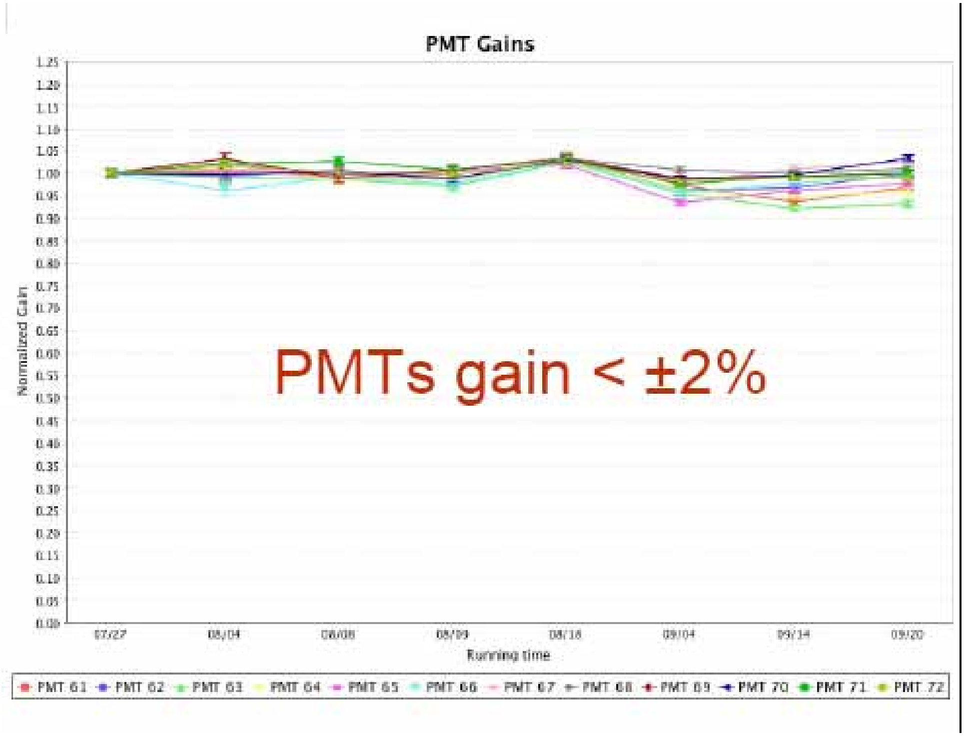
Neutron MC Simulations





XENON10 UNDERGOUND @ lngs
EXCELLENT STABILITY OVER 10 MONTHS





- WIMP search data collected between October 2006 and February
- 58.6 live days total used for WIMP limit