Noble Travails:
Noble Liquid Dark Matter Detectors

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see information at

http://particleastro.brown.edu/
http://gaitskell.brown.edu

Other XENON10 / LXe Talks

- Angel Manzur (Yale) - Parallel 3B
  - Calibration of Gamma and Neutron response in XENON10
- Eric Dahl (Case) - Parallel 3B
  - Liquid xenon discrimination
- Bob Svoboda (Davis/LLNL) - Parallel 1
  - LUX 300 kg Dark Matter Detector
- Previous XENON10 APS Talks available at
  - http://particleastro.brown.edu & http://xenon.brown.edu
- XENON10 Papers expected ~end May

The XENON10 Collaboration

Columbia University Elena Aprile, Karl-Ludwig Giboni, Maria Elena Monzani, Guillaume Plante, Roberto Santorelli and Masaki Yamashita

Brown University Richard Gaitskell, Simon Fiorucci, Peter Sorensen and Luiz DeViveiros

RWTH Aachen University Laura Baudis, Jesse Angle, Joerg Orboeck, Aaron Manalaysay and Stephan Schulte

Lawrence Livermore National Laboratory Adam Bernstein, Chris Hagmann, Norm Madden and Celeste Winant

Case Western Reserve University Tom Shutt, Peter Brusov, Eric Dahl, John Kwong and Alexander Bolozdynya

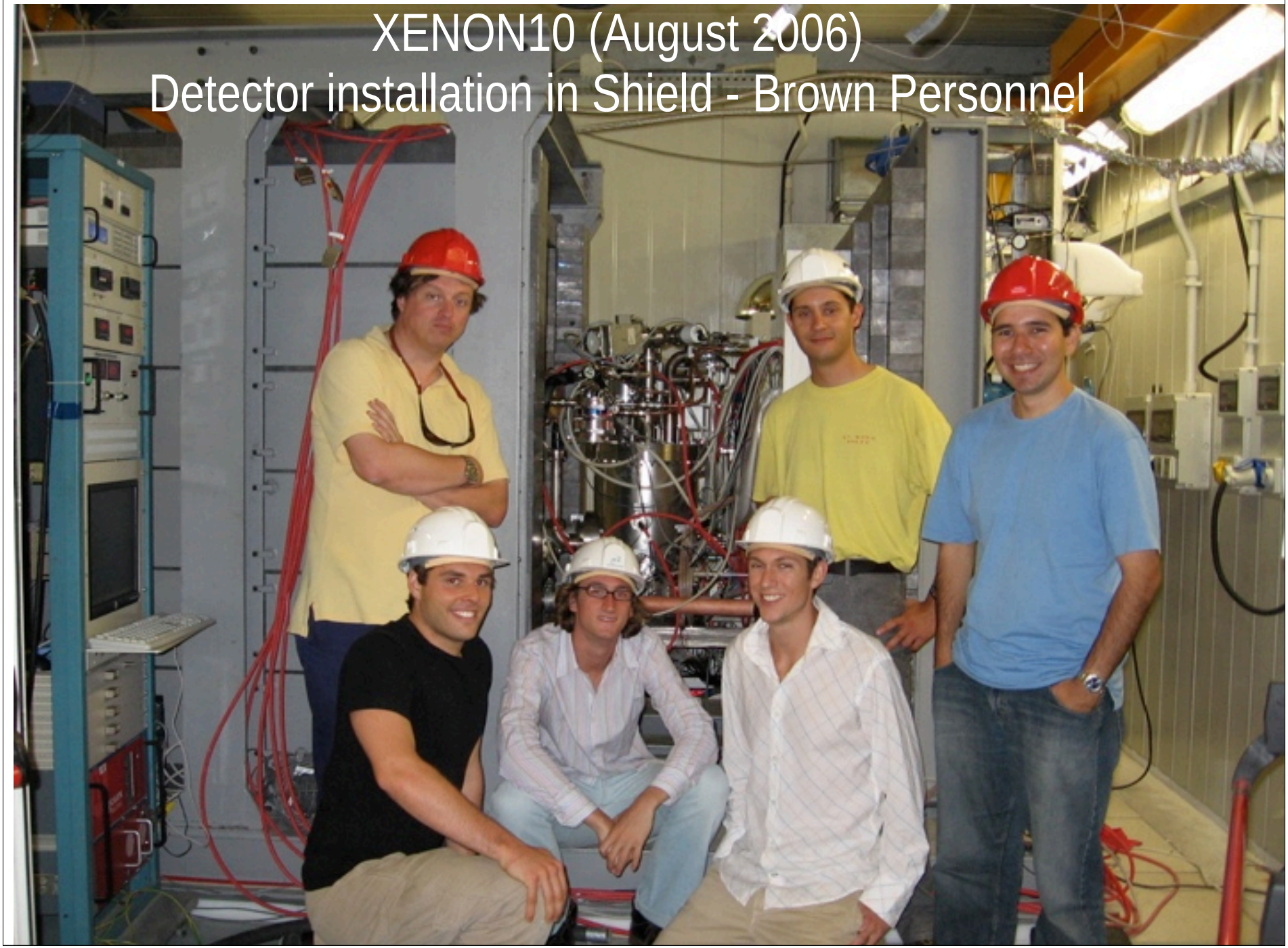
Rice University Uwe Oberlack, Roman Gomez, Christopher Olsen and Peter Shagin

Yale University Daniel McKinsey, Louis Kastens, Angel Manzur and Kaixuan Ni

LNGS Francesco Arneodo and Alfredo Ferella

Coimbra University Jose Matias Lopes, Luis Coelho, Luis Fernandes and Joaquin Santos

XENON10 (August 2006)
Detector installation in Shield - Brown Personnel



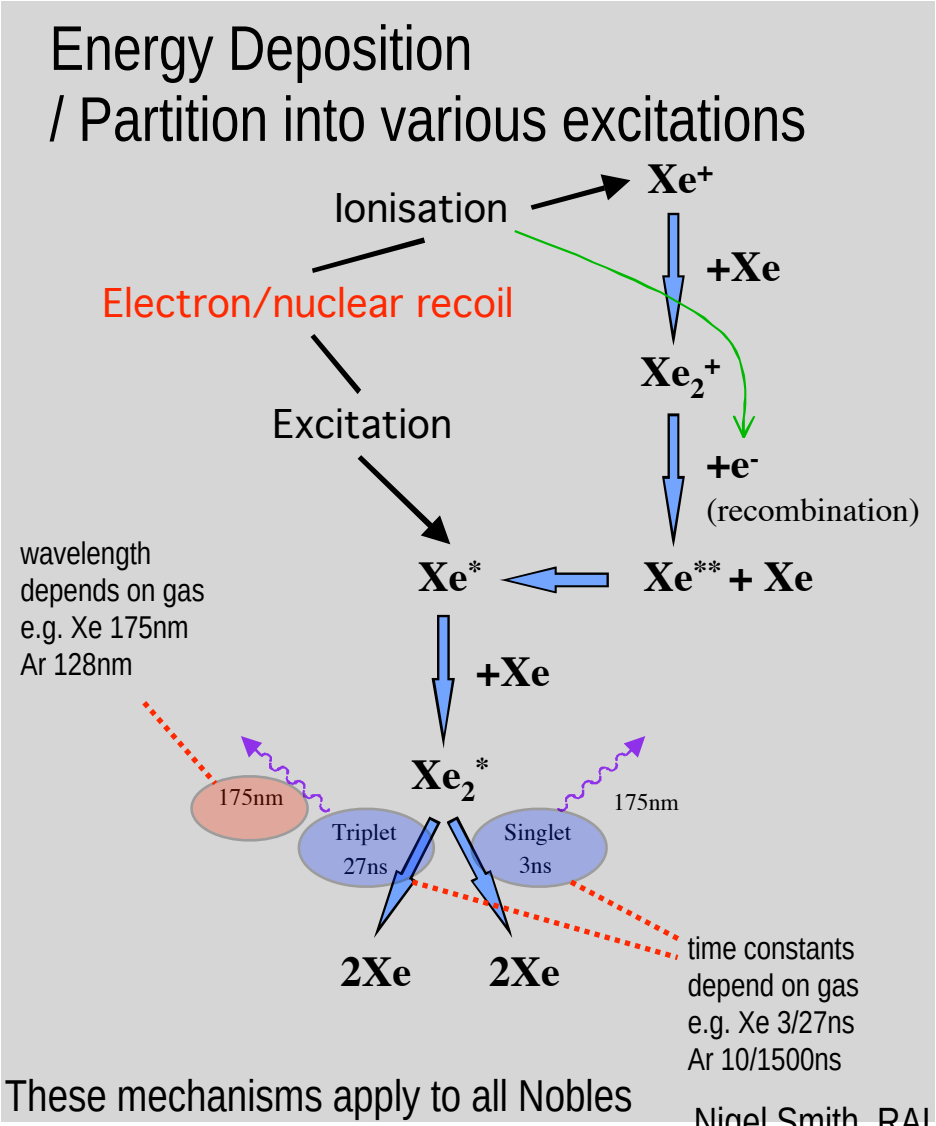
Noble Liquids

- Why Noble Liquids?
  - Nuclear vs Electron Recoil discrimination readily achieved
    - Scintillation pulse shapes
    - Ionization/Scintillation Ratio
  - High Scintillation Light Yields / Good Light Transmission (Dimer emission ≠ atomic absorption)
    - Low energy thresholds can be achieved
    - Have to pay close attention to how discrimination behaves with energy
  - Ionization Drift >>1 m, at purities achieved (<< ppm electronegative impurities)
  - Large Detector Masses are easily constructed and behave well
    - Shelf shielding means Inner Fiducial volumes have very low activity (assuming intrinsic activity of target material is low)
      - BG models get better the larger the instrument
    - Position resolution of events very good in TPC operation (ionization)
    - Dark matter cross section on nucleons goes down at least to $\sigma \sim 10^{-46}$ cm^2 == 1 event/100 kg/year (in Ge or Xe), so need a large fiducial mass to collect statistics
  - Cost & Practicality of Large Instruments
    - Very competitive / Simply Increase PMTs
- "Dark Matter Sensitivity Scales As The Mass, Problems Scale As The Surface Area"

Noble Liquid Detectors: Mechanism & Experiments

	Single phase (Liquid only) PSD	Double phase (Liquid + Gas) PSD/Ionization
Xenon	ZEPLIN I XMASS	ZEPLIN II+III, XENON, XMASS-DM, LUX
Argon	DEAP, CLEAN	WARP, ArDM
Neon	CLEAN	

- Single phase - scintillation only
  - e-ion recombination occurs
  - singlet/triplet ratio 10:1 nuclear:electron
- Double phase - ionization & scintillation
  - drift electrons in E-field (kV/cm)



Nigel Smith, RAL

XENON Event Discrimination: Electron or Nuclear Recoil?

Within the xenon target:

- Neutrons, WIMPs => Slow nuclear recoils => strong columnar recombination

=> Primary Scintillation (S1) preserved, but Ionization (S2) strongly suppressed

- γ, e-, μ, (etc) => Fast electron recoils =>

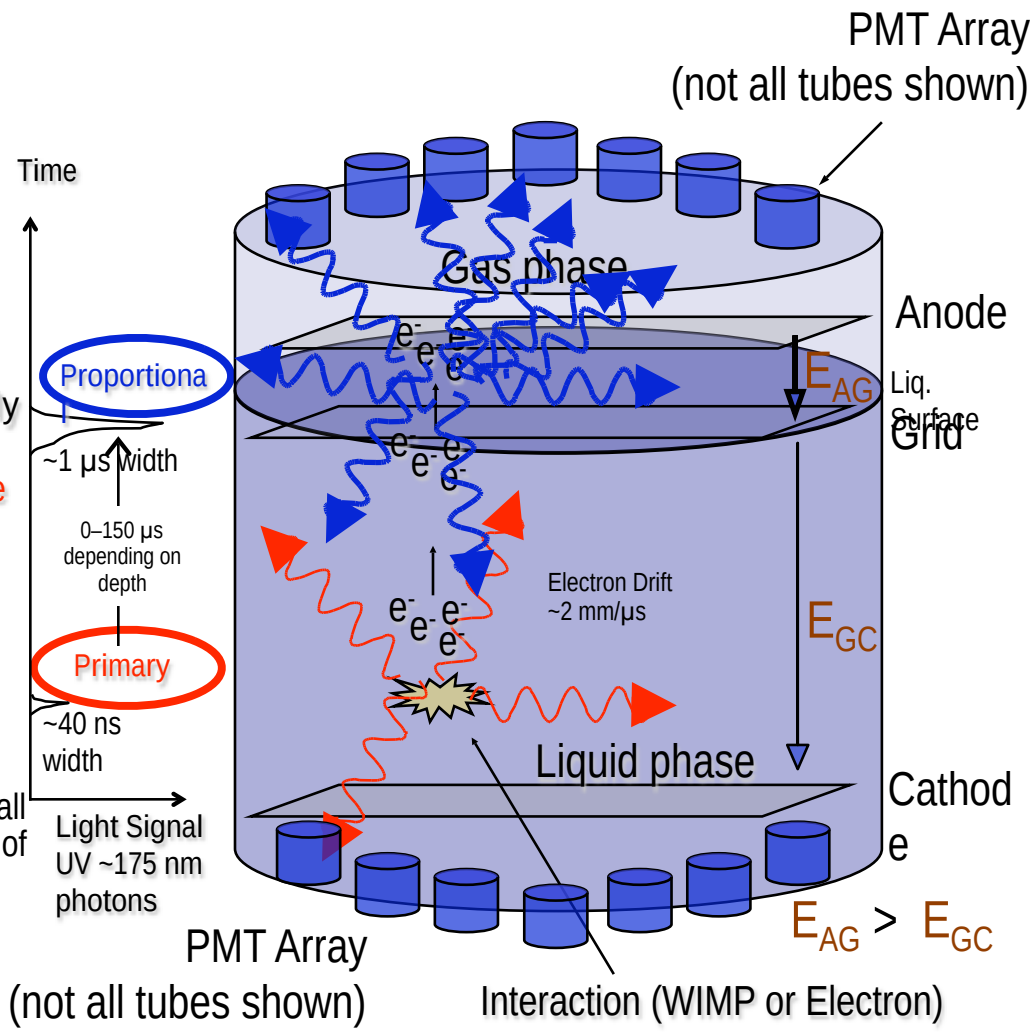
=> Weaker S1, Stronger S2

Ionization signal from nuclear recoil too small to be directly detected => extract charges from liquid to gas and detect much larger proportional scintillation signal => dual phase

Simultaneously detect (array of UV PMTs) primary (S1) and proportional (S2) light =>
Distinctly different S2 / S1 ratio for e / n recoils provide basis for event-by-event discrimination.

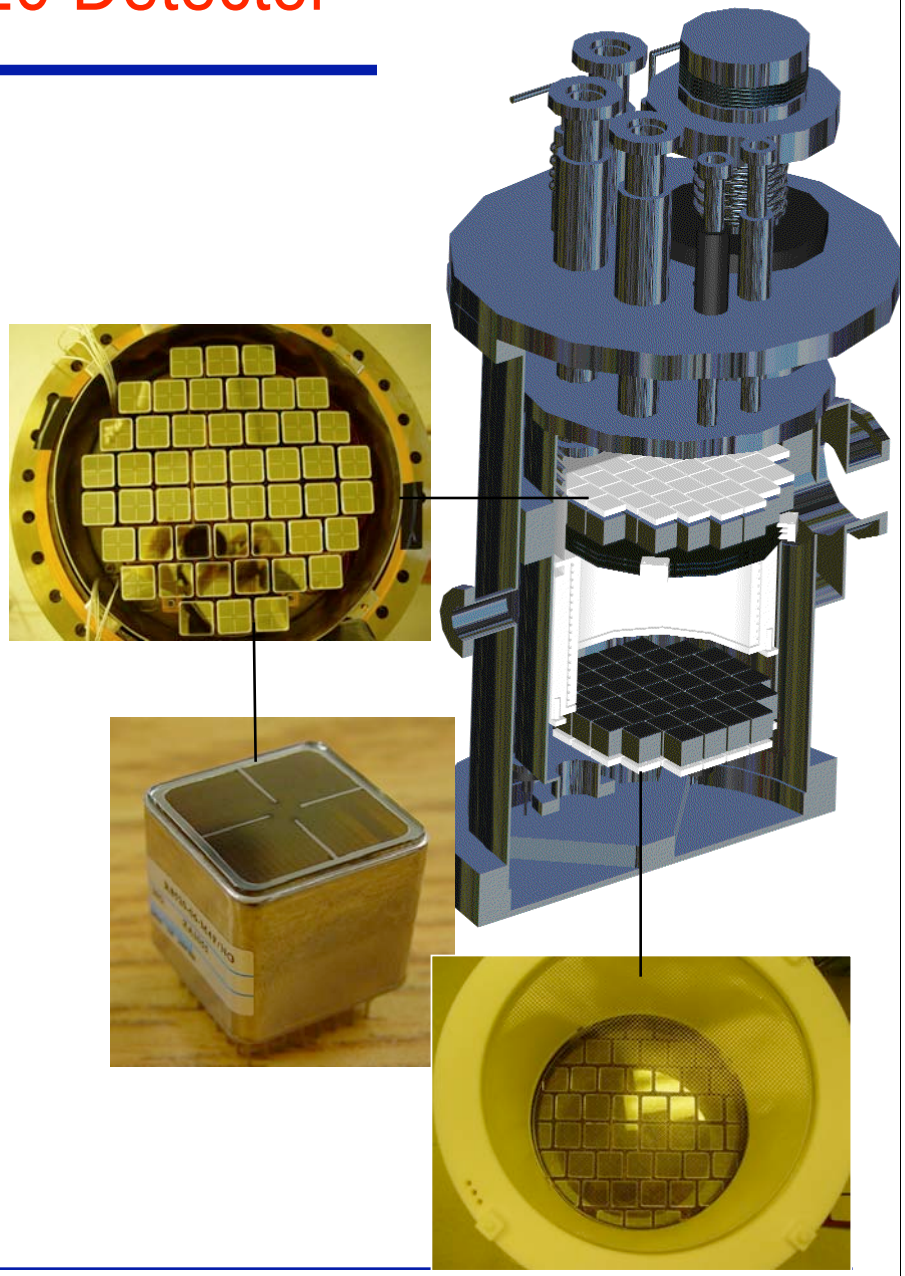
Challenge: ultra pure liquid and high drift field to preserve small electron signal ; efficient extraction into gas; efficient detection of small primary light signal

S1: ~1 phe /keVr in PMTs
S2: 5 liquid electrons / keVr, ~100 phe / keVr in PMTs
(HIGH EFFICIENCY ANALYSIS >=4 keVr)

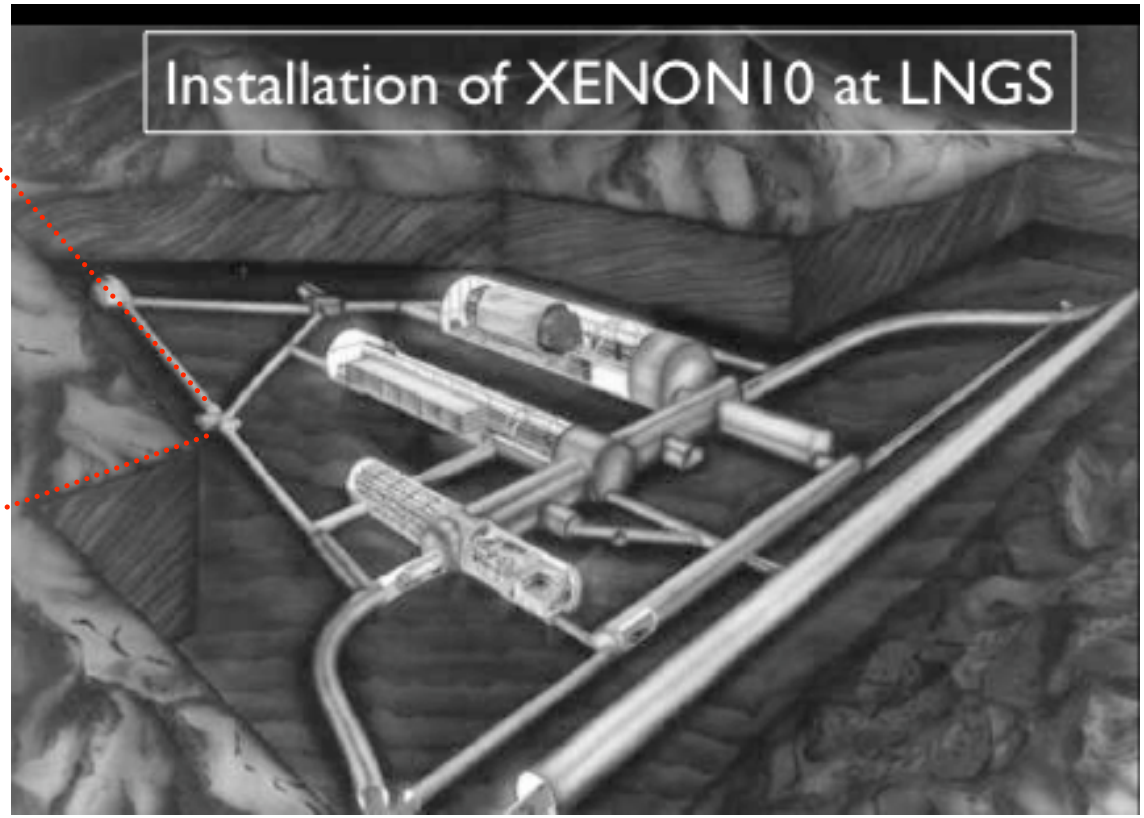


The XENON10 Detector

- 22 kg of liquid xenon
  - 15 kg active volume
  - 20 cm diameter, 15 cm drift
- Hamamatsu R8520 1”×3.5 cm PMTs
  - bialkali-photocathode Rb-Cs-Sb,
  - Quartz window; ok at -100ºC and 5 bar
  - QE + CE > 12% @ 178 nm
- 48 PMTs top, 41 PMTs bottom array
  - x-y position from PMT hit pattern; $\sigma_{x\text{-}y} \approx 1$ mm
  - z-position from Δt_{drift} ($v_{d,e^-} \approx 2$mm/μs), $\sigma_Z \approx 0.3$ mm
- Cooling: Pulse Tube Refrigerator (PTR),
- 90W, coupled via cold finger (LN2 for emergency)



XENON10 Underground Installation



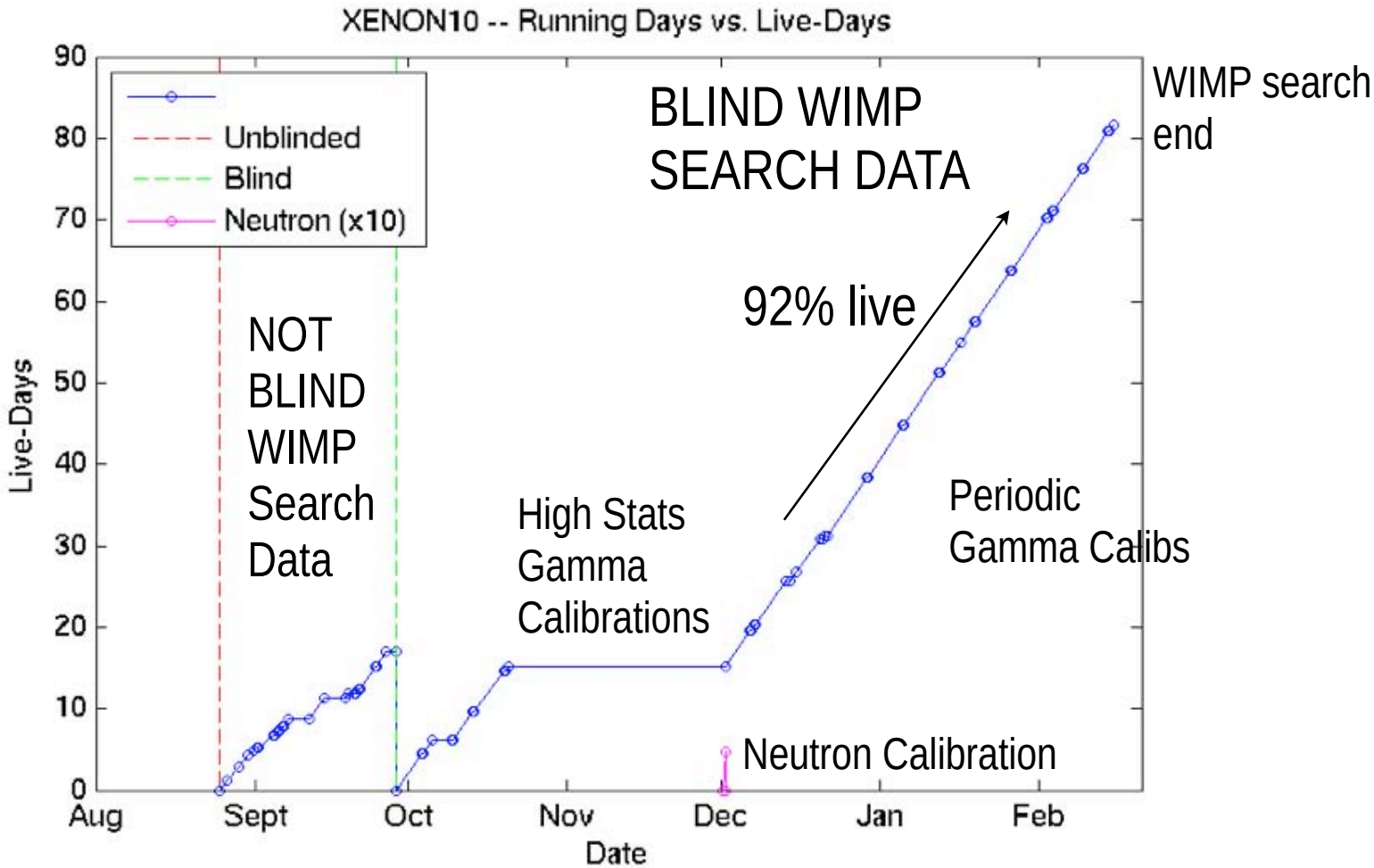
- Installed March 2006 @ LNGS (~3100 mwe)
- Muon flux ~ 24 μ/m^2/day (10^6 reduction from sea level)
- Began detector calibration end of March
- Began shield installation May 2006
- (bottom left) Installing steel frame on top of 15 cm External HDPE

XENON10: Ready for Low Background Operation

Installation of the Detector...

...and we are operational

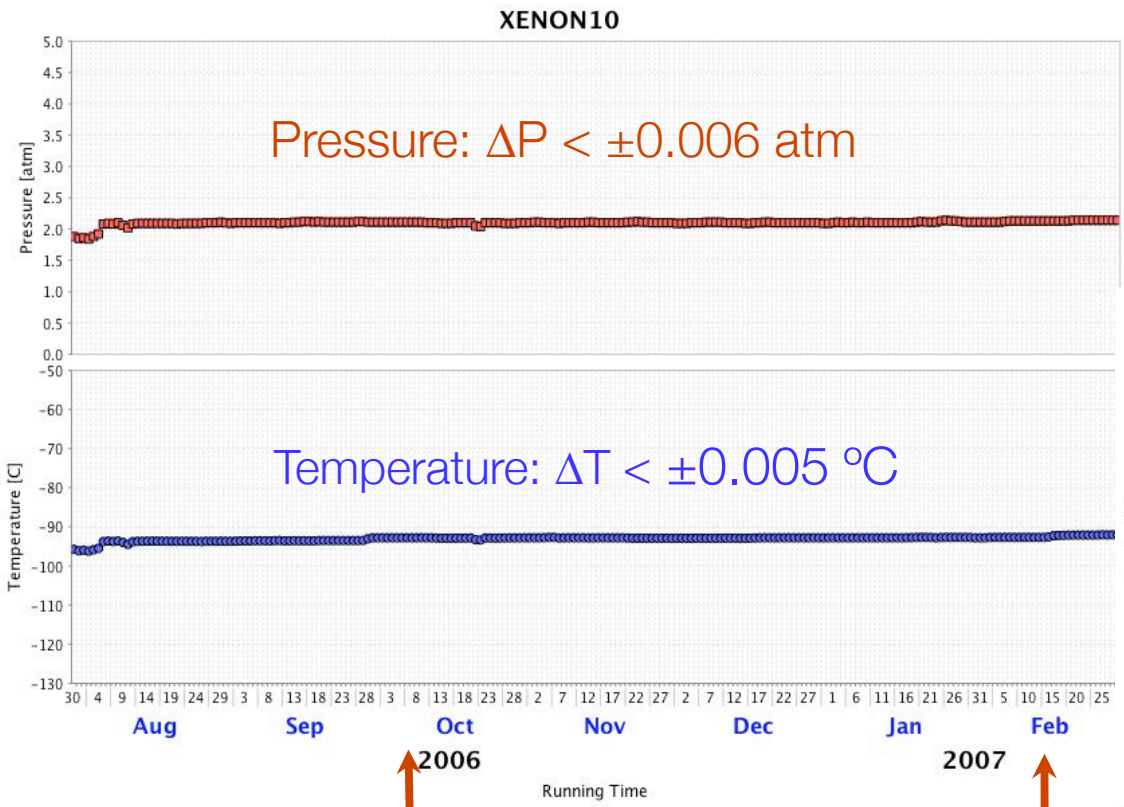
XENON10 Live time at Gran Sasso

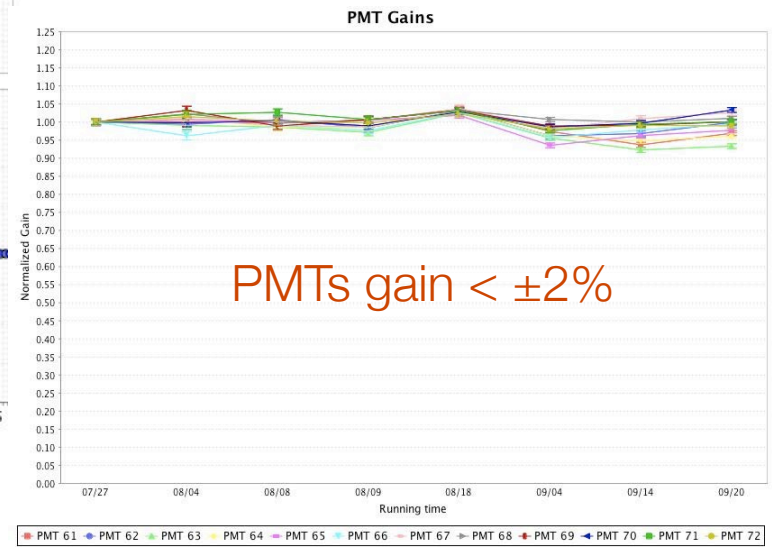


- High Statistics Gamma Calibs + 1 Neutron Calib
- NON BLIND WIMP search data ~20 live days (Sept) + 20 live days dispersed (Oct-Feb)
- BLIND WIMP Search results from 60 live day (Oct-Feb)

XENON10 Underground: Stability of Running

Detector operation and performance shows excellent stability over 9 months

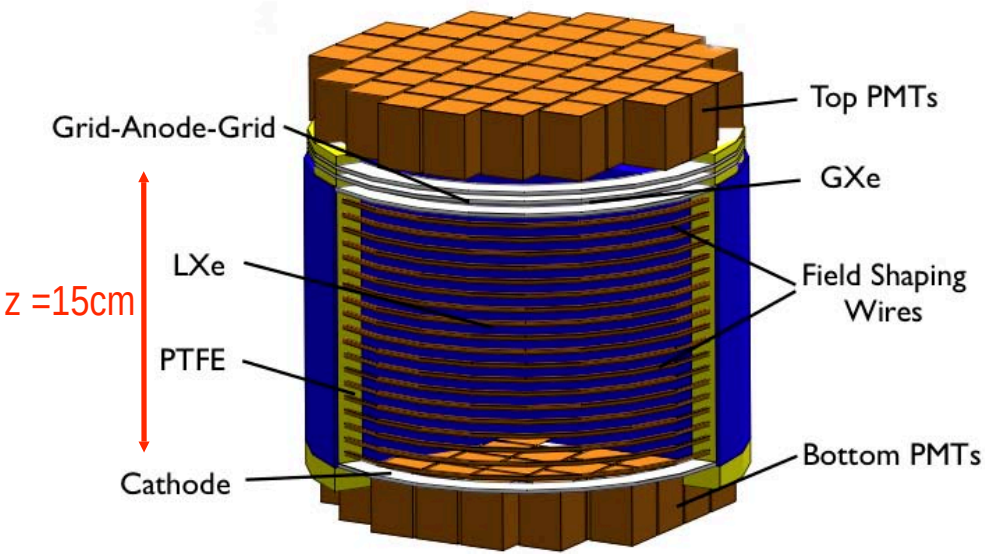




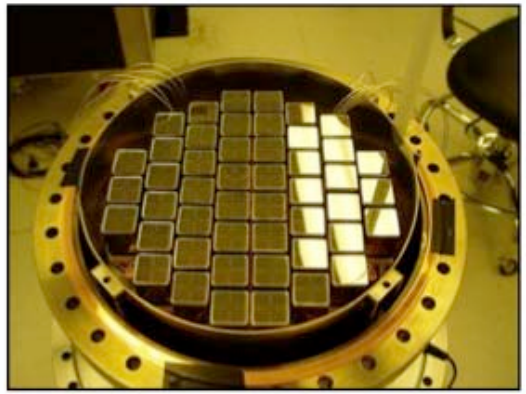
Start of Blind WIMP Search

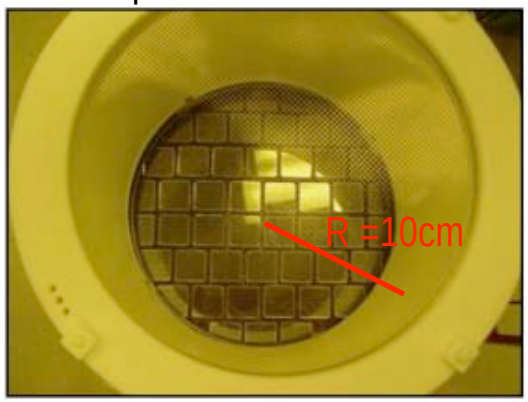
End of Blind WIMP Search

XENON10 Detector



89 PMTs: Hamamatsu R8520-AL 2.5 cm square

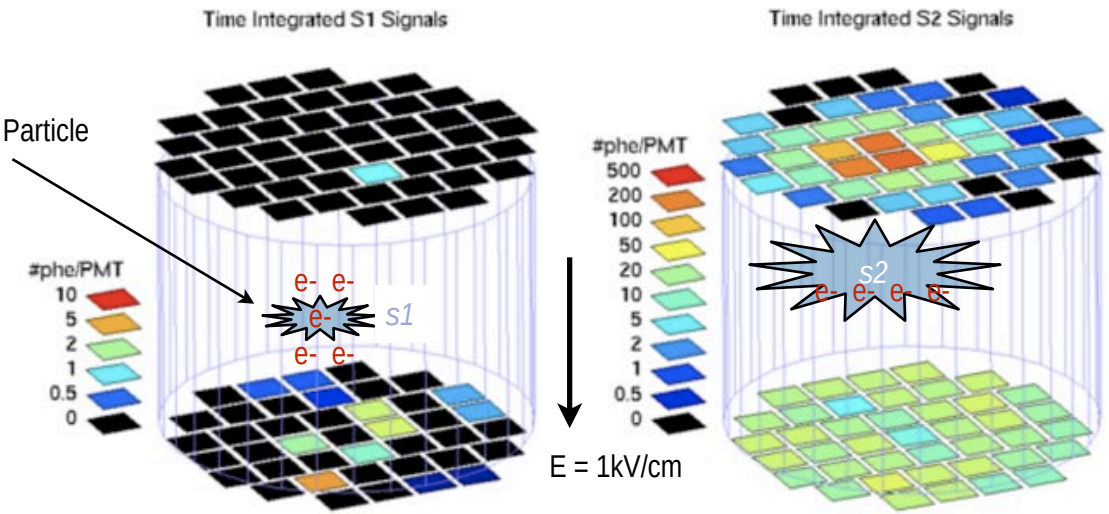




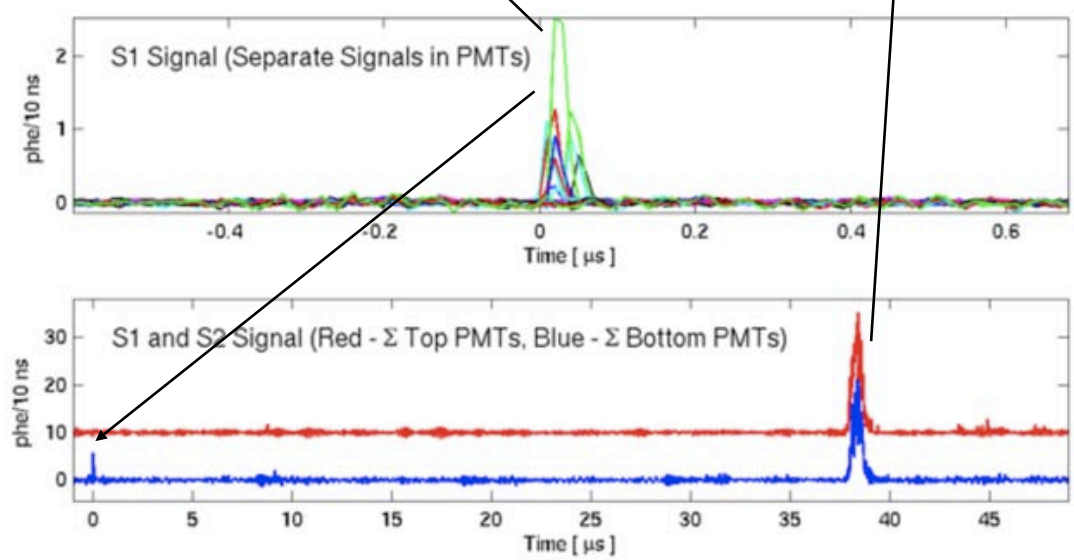
XENON10 Event Discrimination

Example: Low Energy Compton Scatter
- S1=15.4 phe ~ 6 keVee
- Drift Time ~38 μs => 76 mm

s1: Primary Scintillation Created by Interaction LXe
s2: Secondary Scintillation Created by e- extracted & accelerated in GXe

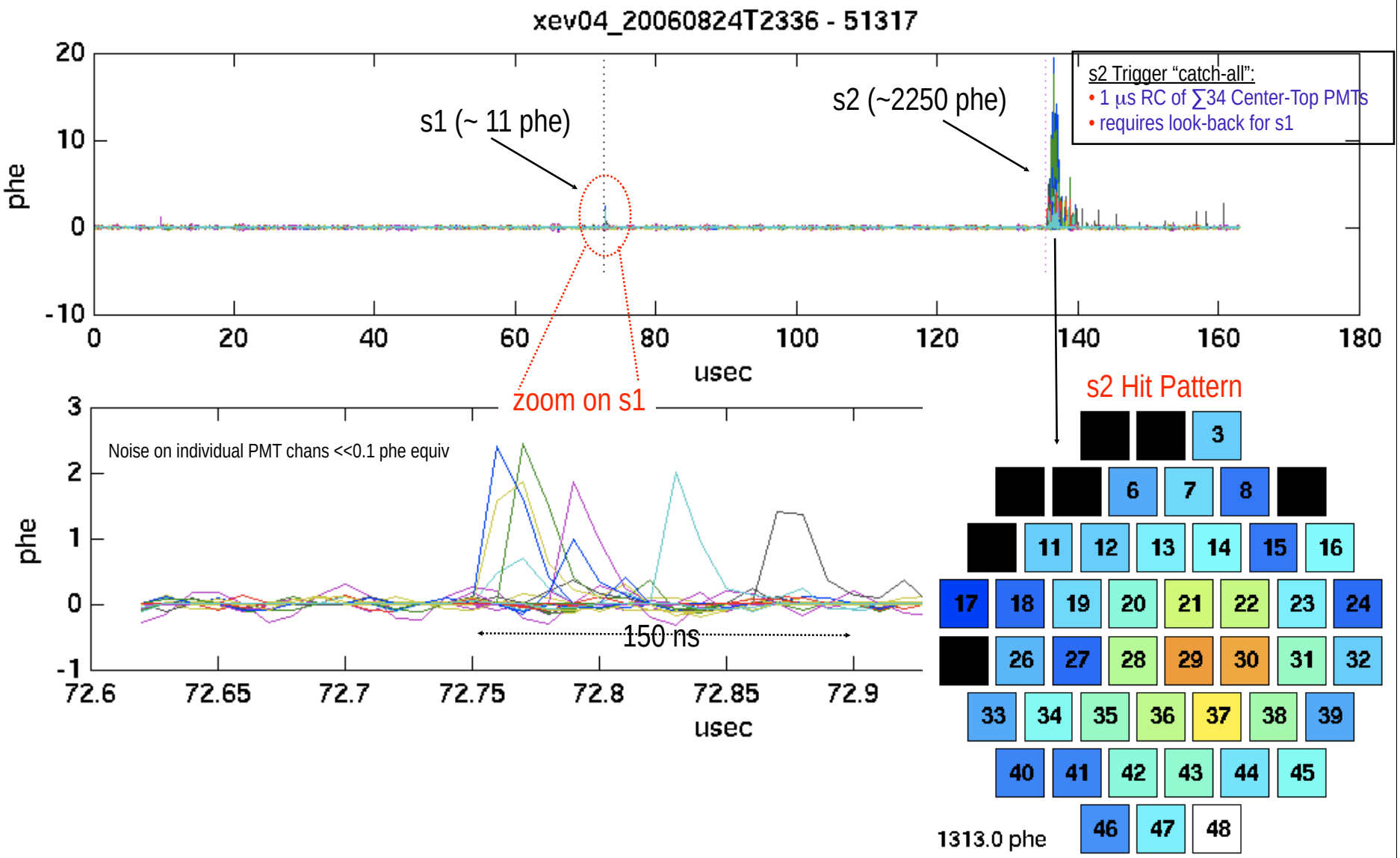


$$(s2/s1)_{ER} > (s2/s1)_{NR}$$

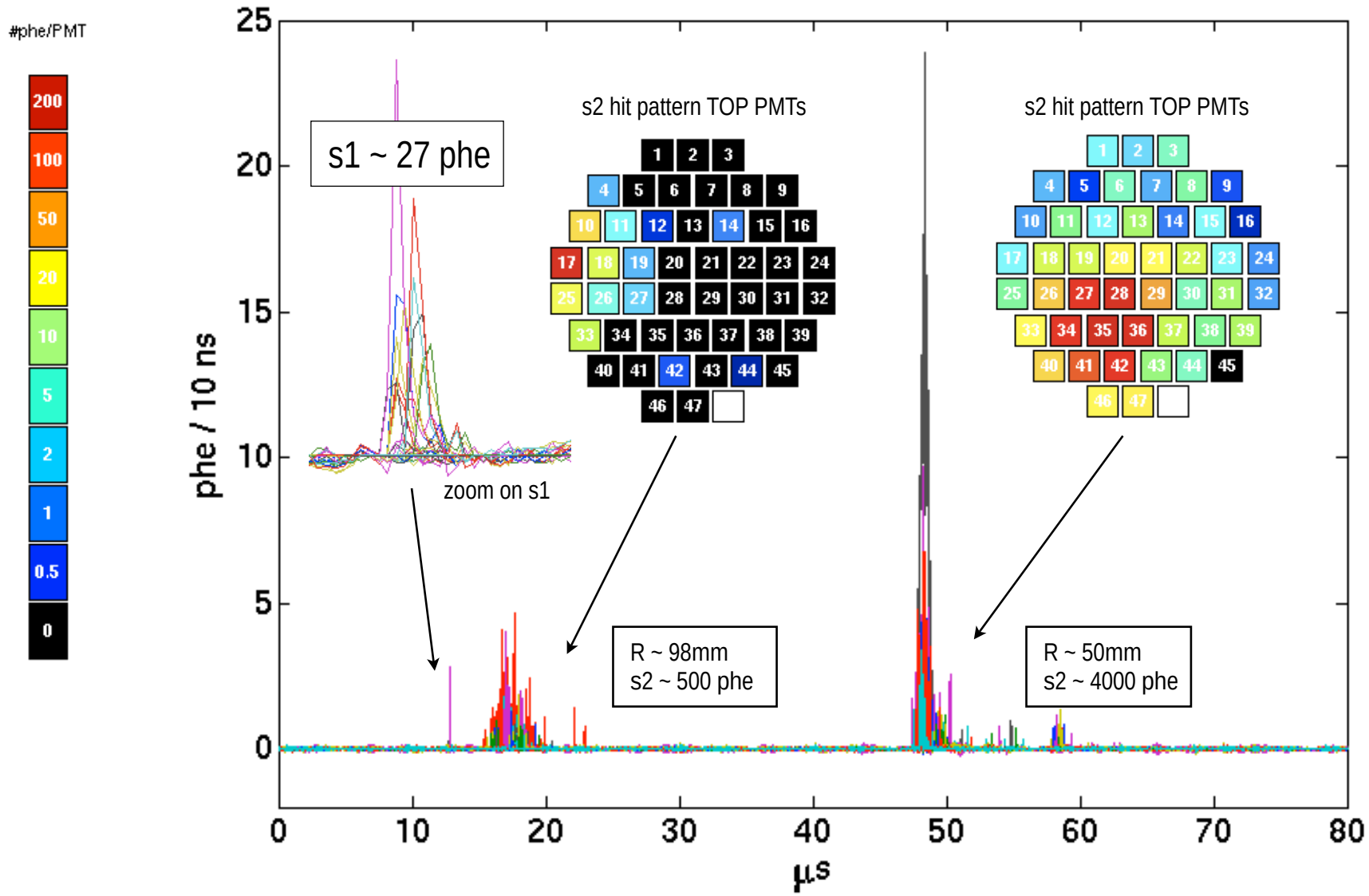


Expect > 99% rejection efficiency of γ/n Recoils…
Reduction of Backgrounds =>
Reduction of Leakage Events

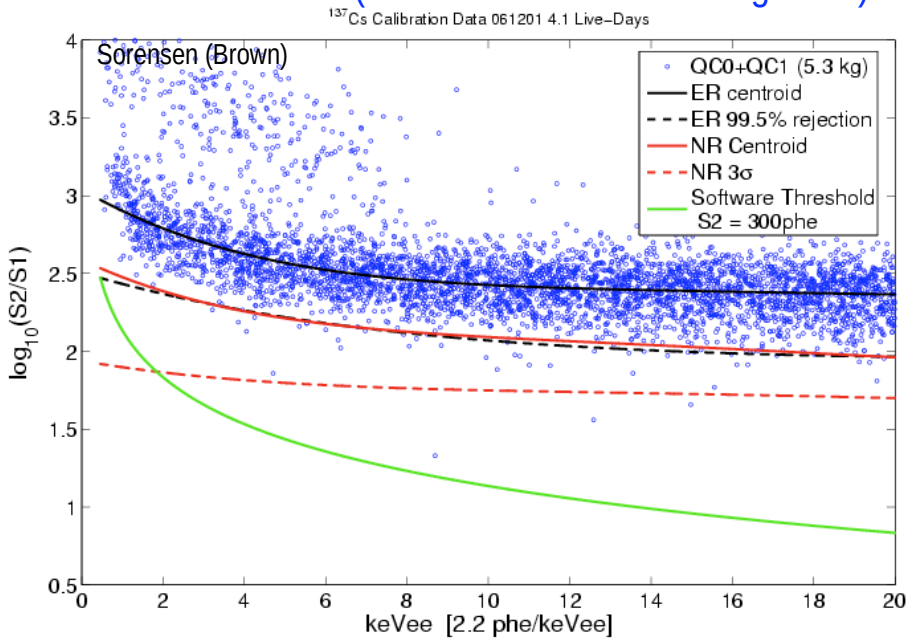
XENON10 Trigger: S2

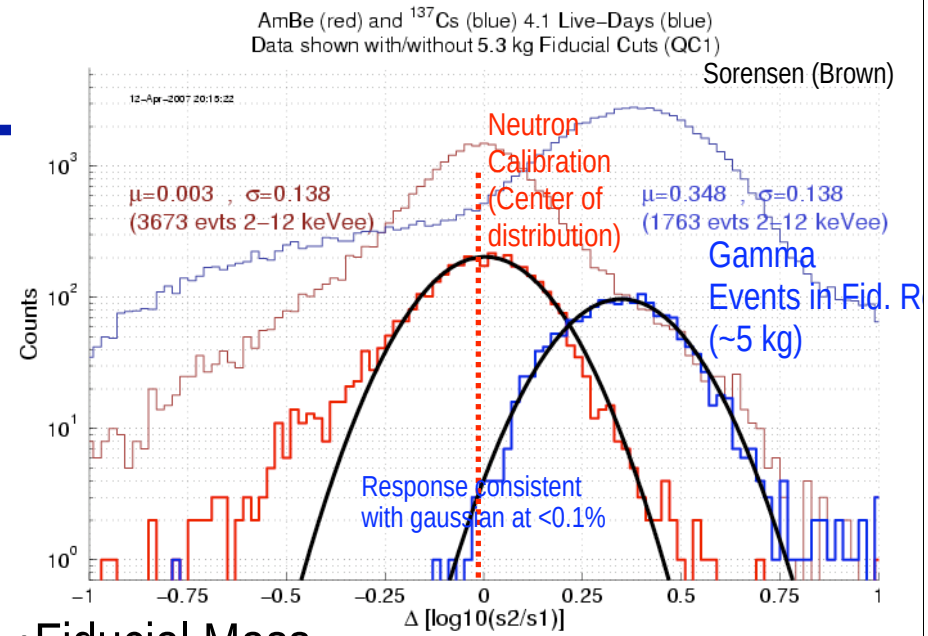


Event Localization / Double Scatter Event

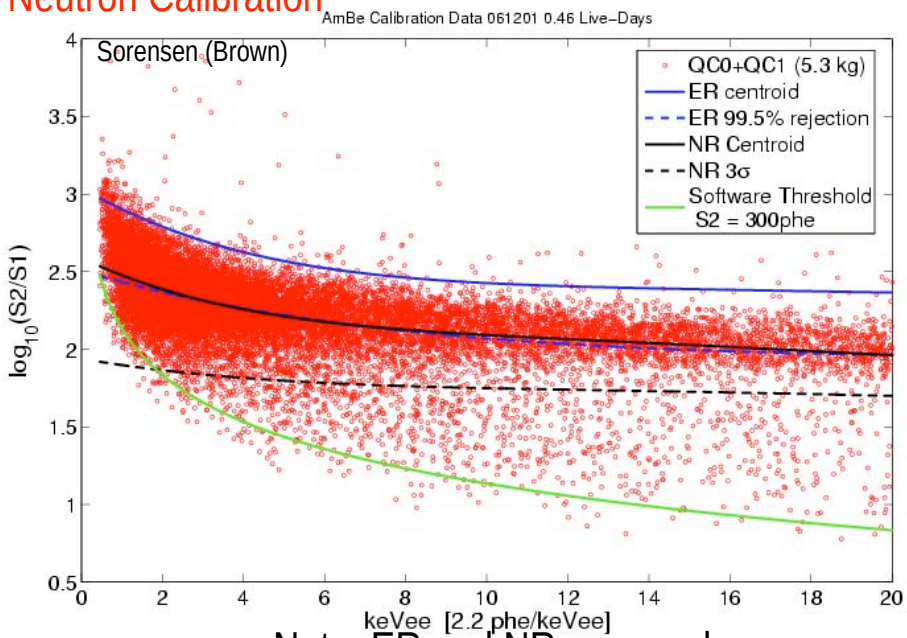


Gamma Calibration (Electron Recoils == Background)





Neutron Calibration



- Fiducial Mass
- AmBe
  - 8400 events in range 2-12 keVee
  - Characterize single scatter neutron response == WIMP nuclear recoils
- Gamma Calibs
  - ~3000 events in range 2-12 keVee
  - (15 days but only ~1.5x single scatter ER in WIMP search stats, future calibrations will have higher stats)

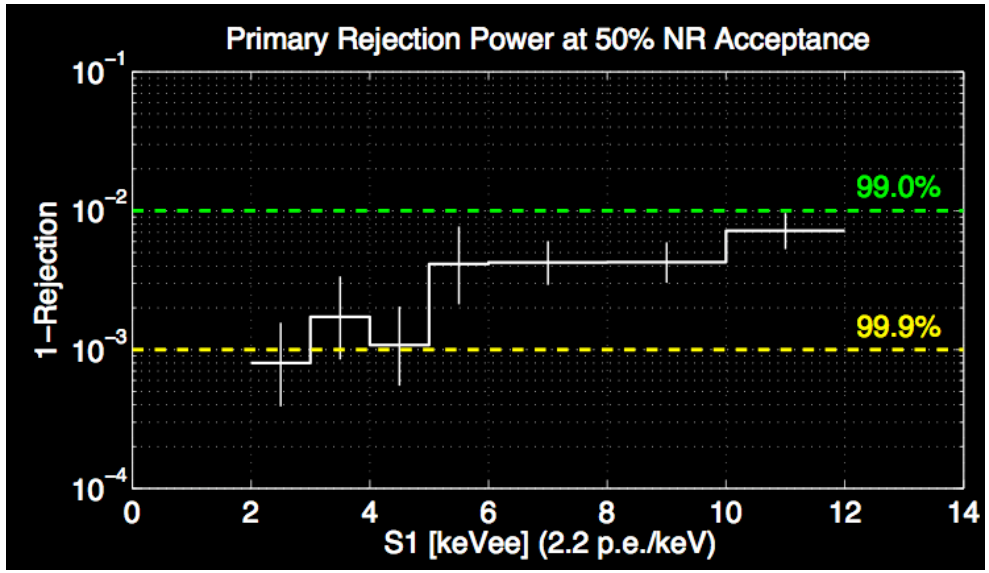
Note: ER and NR curves shown are not final versions used in 58 day WIMP Blind analysis

Nuclear Recoil (NR), Electron Recoil (ER) Discrimination

ER response appears be gaussian in Log10(S2/S1) down to better than <0.1%.

- This is an empirical observation
- We have characterized the discrimination performance using separation of means of ER and NR and sigma of gaussian
- To date we have collected <~2x number of ER calibration events as ER WIMP search events
- Any subtraction of ER leakage is therefore dominated by “statistics” of calibration
- However, gamma calibration shows improvement of leakage at lower energies. Completely consistent behavior is seen in the WIMP search data

(See Manzur Talk)
Analysis of the ER rejection was performed in energy bins 2-3, 3-4 ..-12 keVee
(See Dahl Talk)
Note that discrimination improves from 99.0% ->99.9% at lowest energies.



Errors bars shown are only those from fits of Log-Gaussian hypothesis

Cuts Explanation

QC0: Basic quality cuts

Designed to remove noisy events, events with unphysical parameters or events which are not interesting for a WIMP search

- S1 coincidence cut
- S1 single peak cut
- S2 saturation cut
- S2 single peak cut
- S2 width cut
- S2 χ^2 cut

QC1: Fiducial volume cuts

Because of the high stopping power of LXe, fiducialization is a very effective way of reducing background.

- $r < 80$ mm
- $15\,\mu\text{s} < dt < 65\,\mu\text{s}$

QC2: High level cuts

Cuts based on the distribution of the S1 signal on the top and bottom PMTs. They are designed to remove events with anomalous or unusual S1 patterns

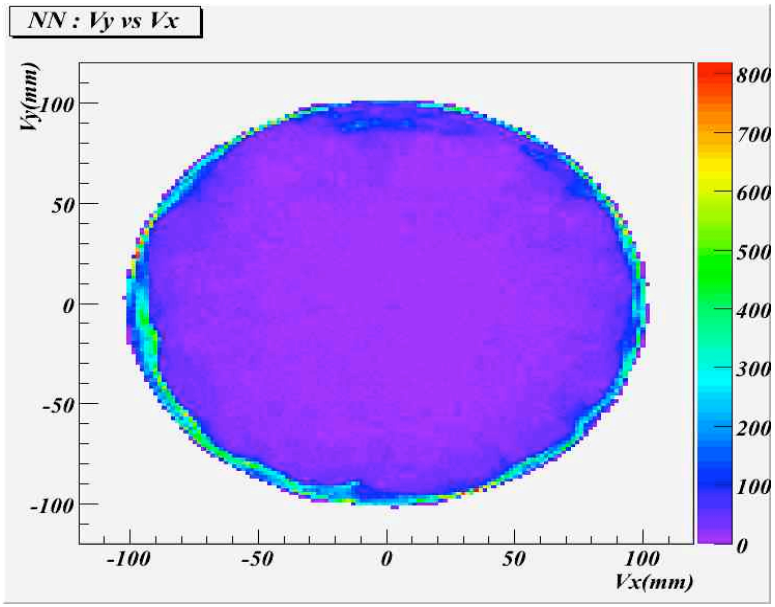
- S1 top-bottom asymetry cut
- S1 top RMS cut
- S1 bottom RMS cut

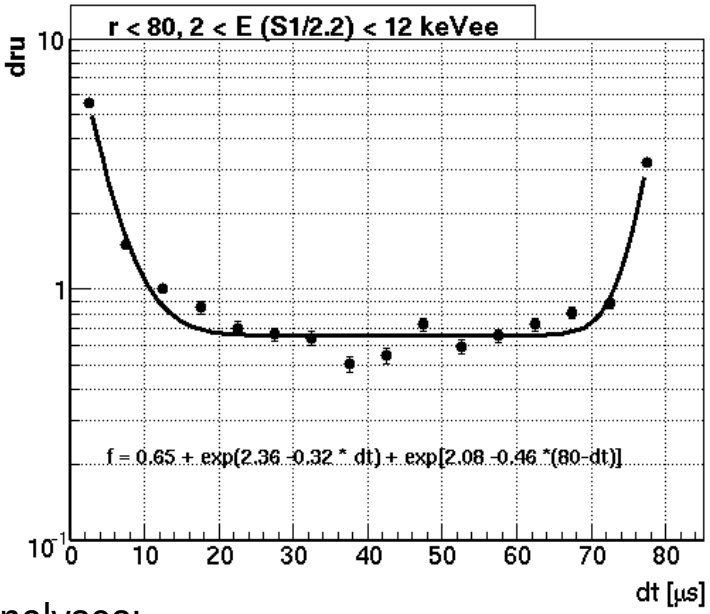
see Guillaume Plante, Columbia, APS Talk

XENON10 Blind Analysis Cuts

Energy Window: 2-12 keVee (based on 2.2 pe/keVee)

- Basic Quality Cuts (QC0): remove noisy and uninteresting events
- Fiducial Volume Cuts (QC1): capitalize on LXe self-shielding
- High Level Cuts (QC2): remove anomalous events (S1 light pattern)





Fiducial Volume chosen by both Analyses:

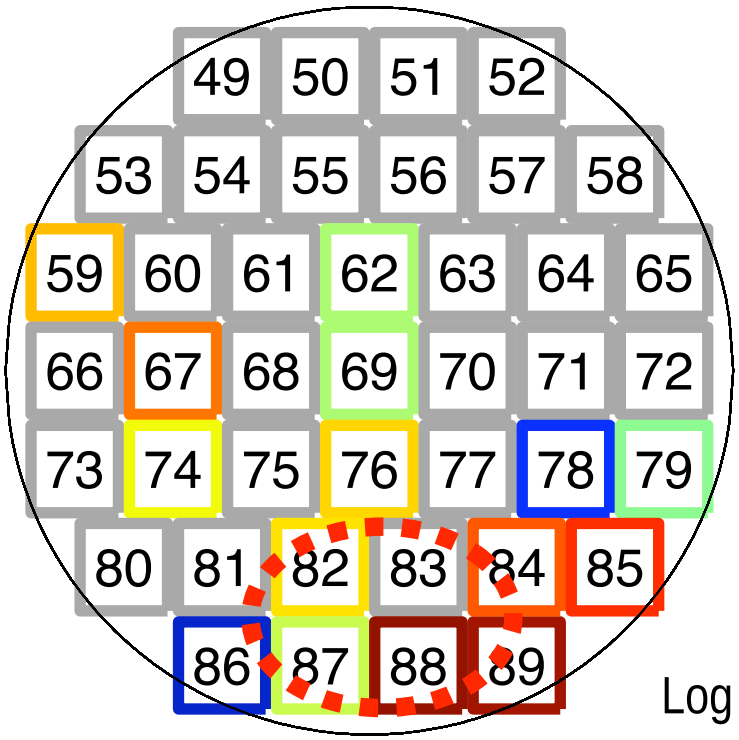
15 < dt < 65 us (max drift ~80 us), r < 80 mm

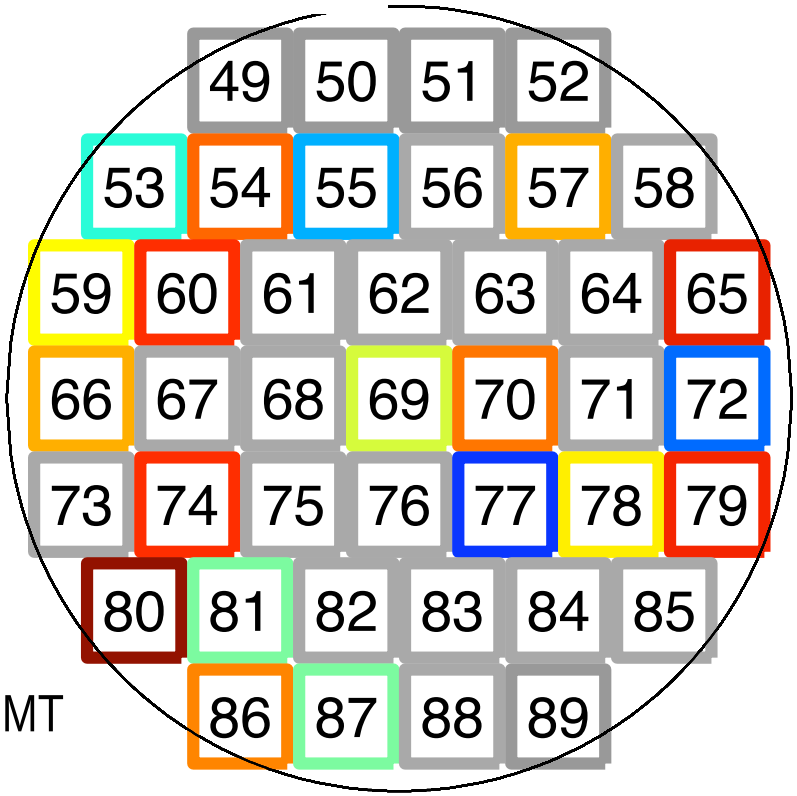
Fiducial Mass= 5.4 kg (reconstructed radius is algorithm dependent)

Overall Background in Fiducial Volume ~0.6 event/(kg d keVee)

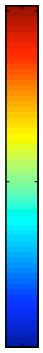
XENON10 S1 Pattern Cuts - Removing Tails in S2/S1

Primary Light (S1) Hit Pattern in BOTTOM PMTs



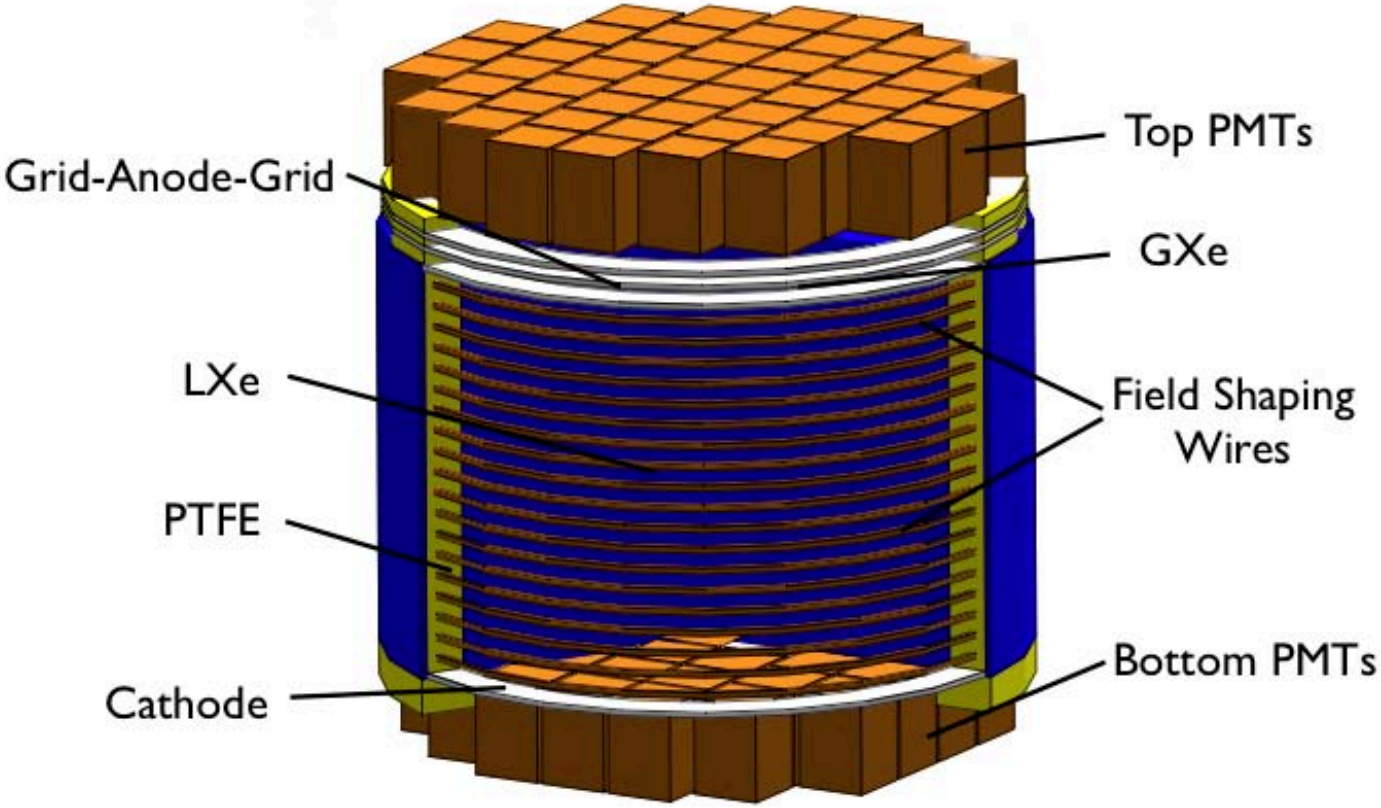


Log # phe/PMT

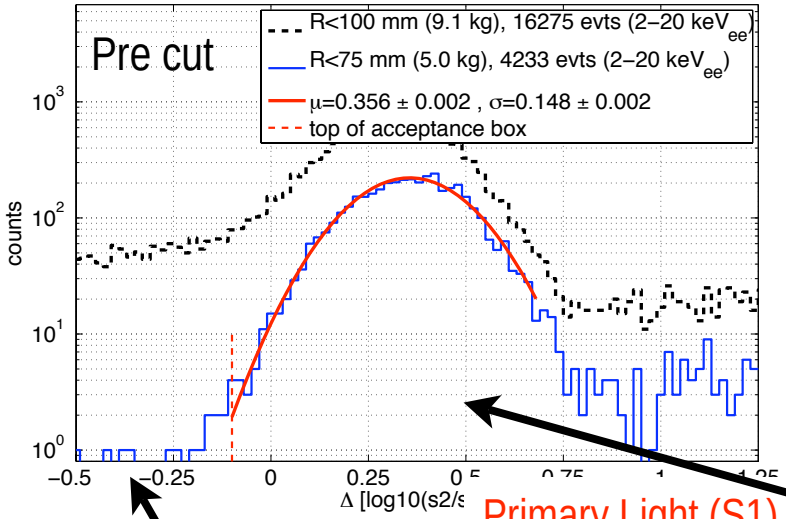


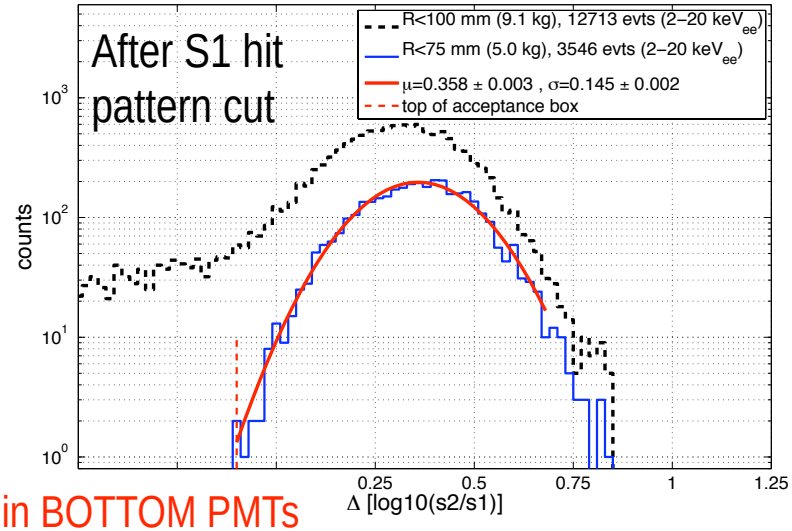
Event with light concentrated locally => multiple scatter incl hit near bottom PMTs

Regular Event for comparison

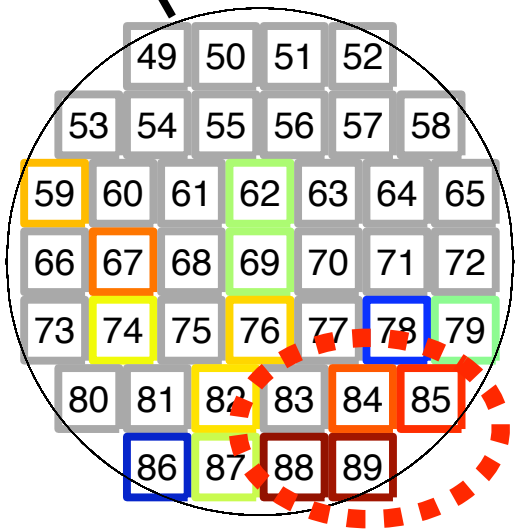

Top PMTs
Grid-Anode-Grid
GXe
LXe
Field Shaping
Wires
PTFE
Bottom PMTs
Cathode

XENON10 S1 Pattern Cuts - Removing Tails



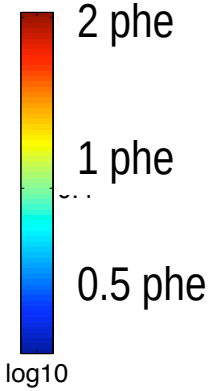


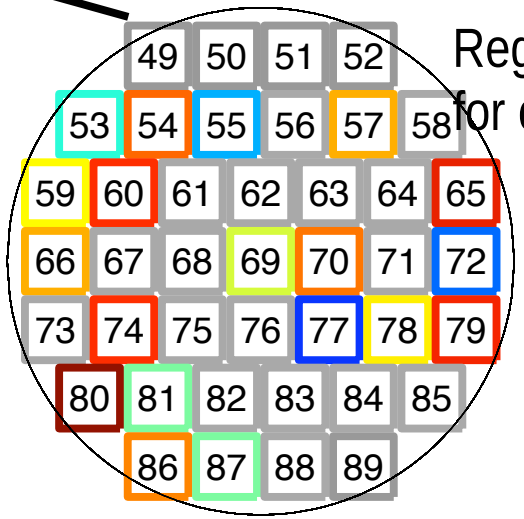
Primary Light (S1) Hit Pattern in BOTTOM PMTs



Event with light concentrated locally
=> multiple scatter incl hit near bottom PMTs

Log # phe/PMT



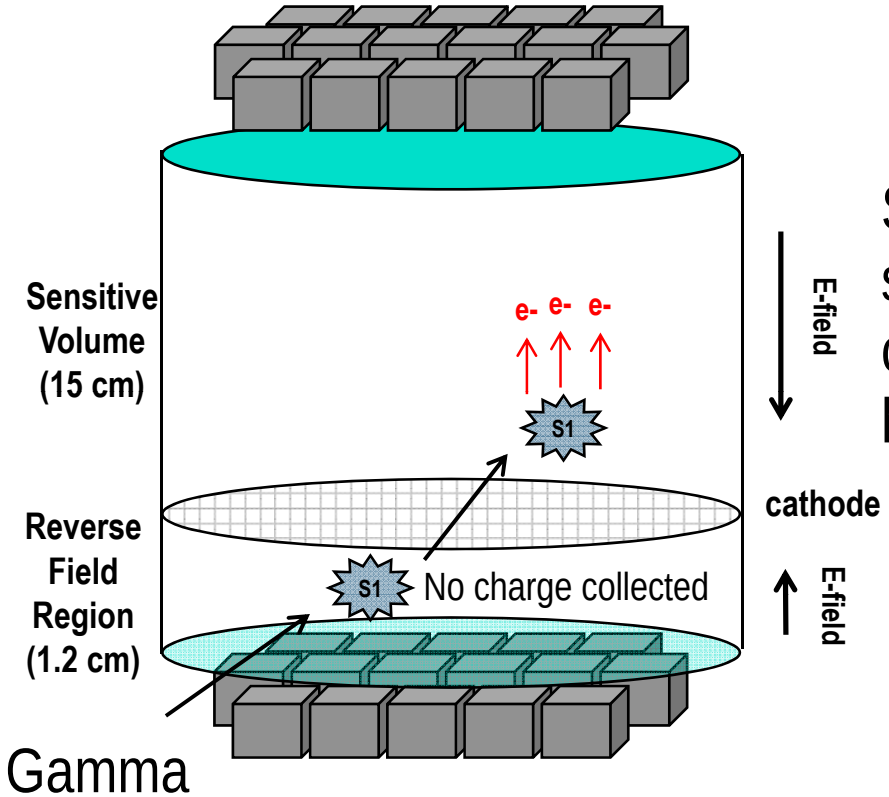


Regular Event for comparison

Anomalous S1 Hit Patters & Leakage

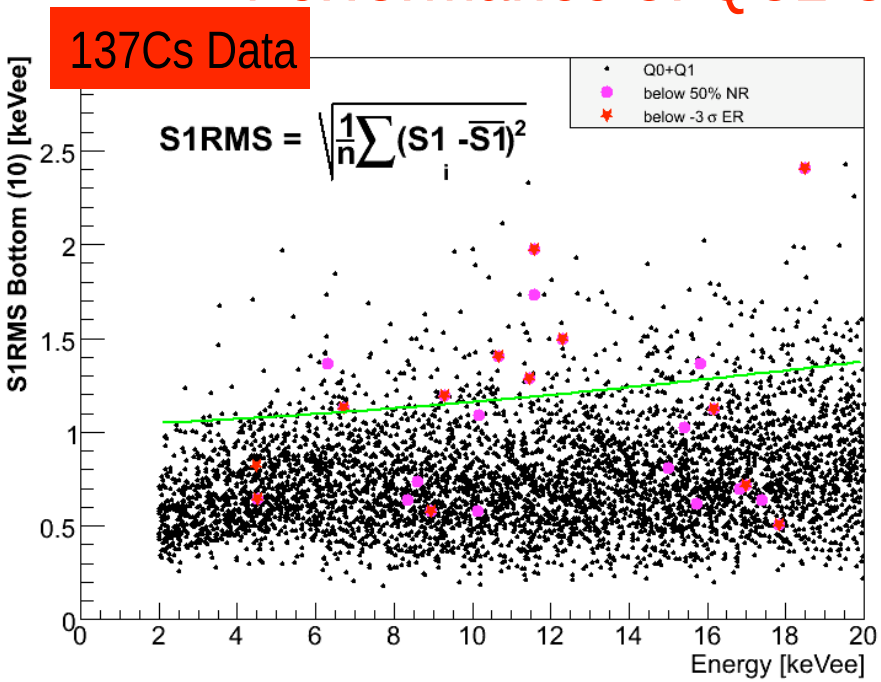
§Multiple scatter events

- But only one S2 signal ... second vertex is in LXe where we are not collecting charge e.g. Reverse Field Region below cathode



S2/S1 ratio is reduced since S1 has two contributions, but S2 has only one.

Performance of QC2 Cut (S1 RMS Cut) on Cs Data



PRIMARY ANALYSIS
QC2 cut based on RMS of S1 scintillation light signal in 10 bottom PMTs with largest signals

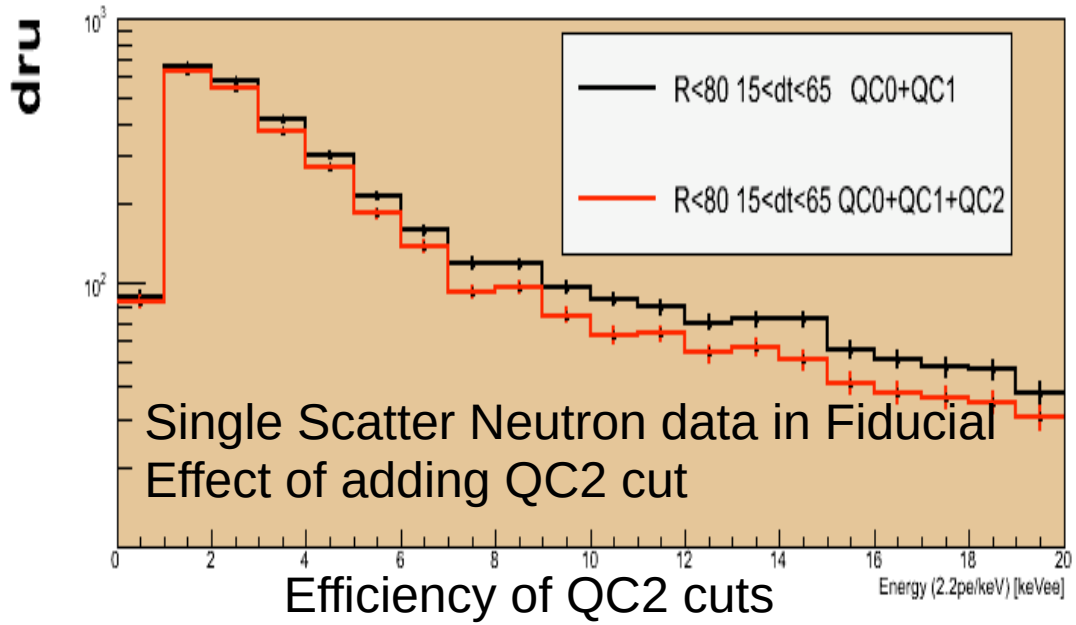
This technique was refined further in the secondary analysis designed to look for specific patterns PMTs for S1

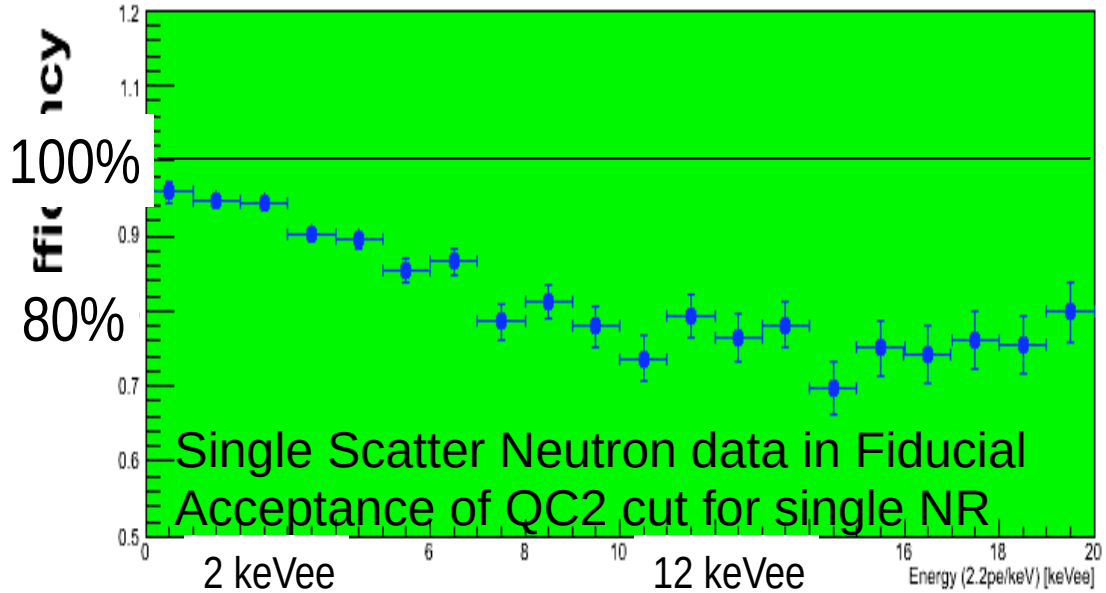
- 137Cs data (1.3 x WIMP search data) + Not Blind WIMP search data used to optimize QC2cuts.
- Define S1-RMS parameter to reject "Events with Anomalous S1 light pattern" : events with most S1 signal in a few bottom PMTs are likely to have scattered first in the LXe layer above bottom PMTs and below cathode grids, or other "dead" LXe regions.

- S1-RMS for bottom PMTs array: events with high S1-RMS parameter coincide with the non-Gaussian events from the ER-band distribution.

QC2 Primary Analysis Cuts Efficiency

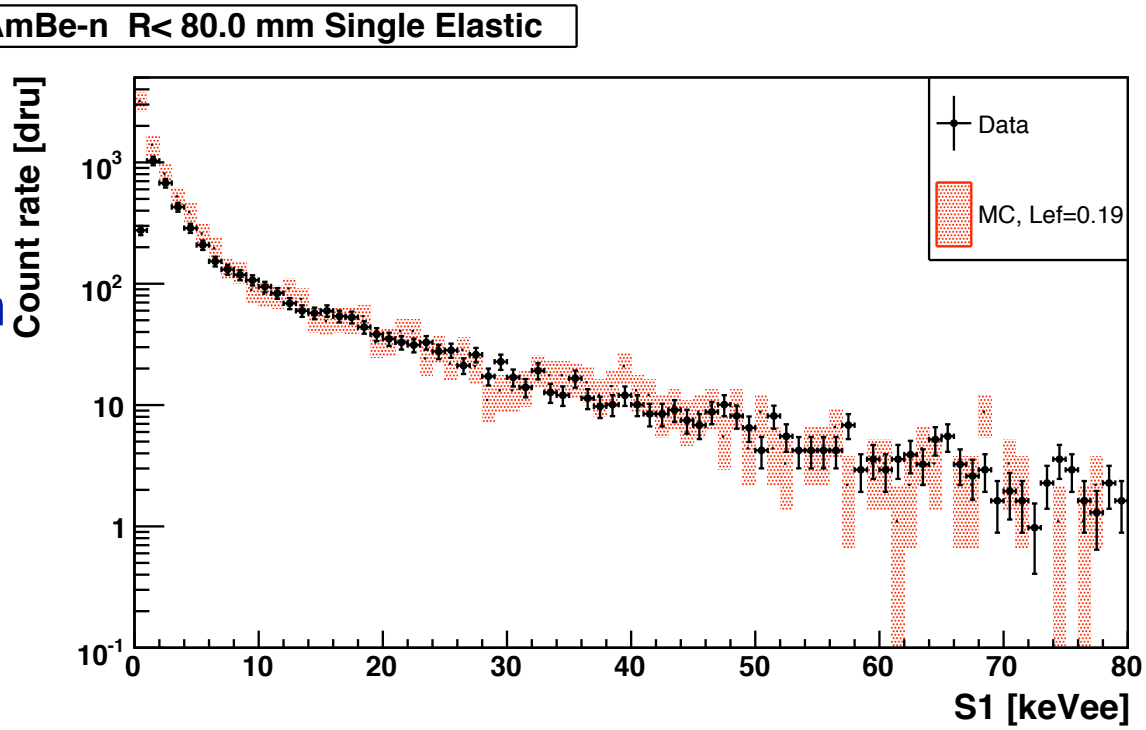
- The coincidence of 2 PMT hits is used in Primary Analysis and the S1 analysis threshold is set to 4.4 photoelectrons (=2 keVee) were efficiency is > 99% for correctly tagging S1
- The QC2 cuts efficiency varies between 95% and 78% in the 2-12 keVee energy window for single scatter nuclear recoil (NR) events in Neutron Calibration data

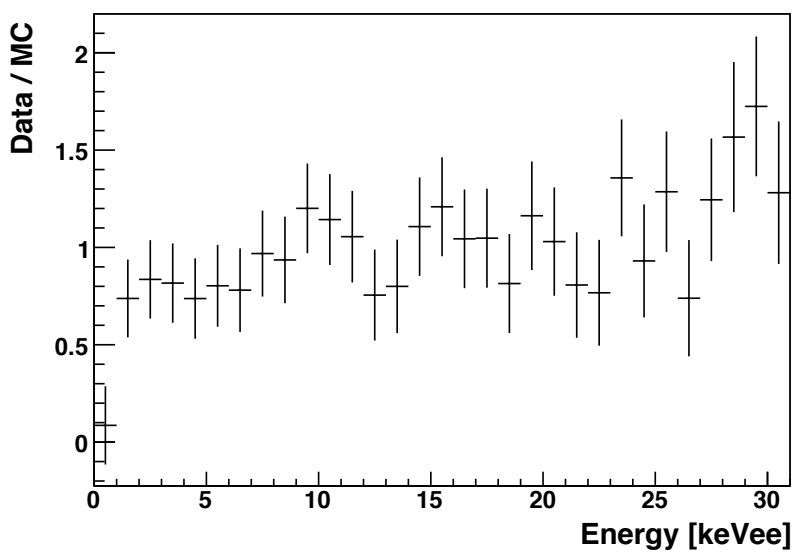




Neutron MC

- Very good agreement of observed single scatter neutron calibration events compared with Monte Carlo
- Absolute rate consistent with quoted AmBe source strength
- Using normalization on neutron event rate 30-80 keVee
- If we assume quenching factor is energy independent 19%
  - Spectrum statistically consistent 8-30 keVee
  - ~20% lower event rate in region 2-7 keVee range
- Consistent with modest drop in QF at lowest energies - see Manzur Talk

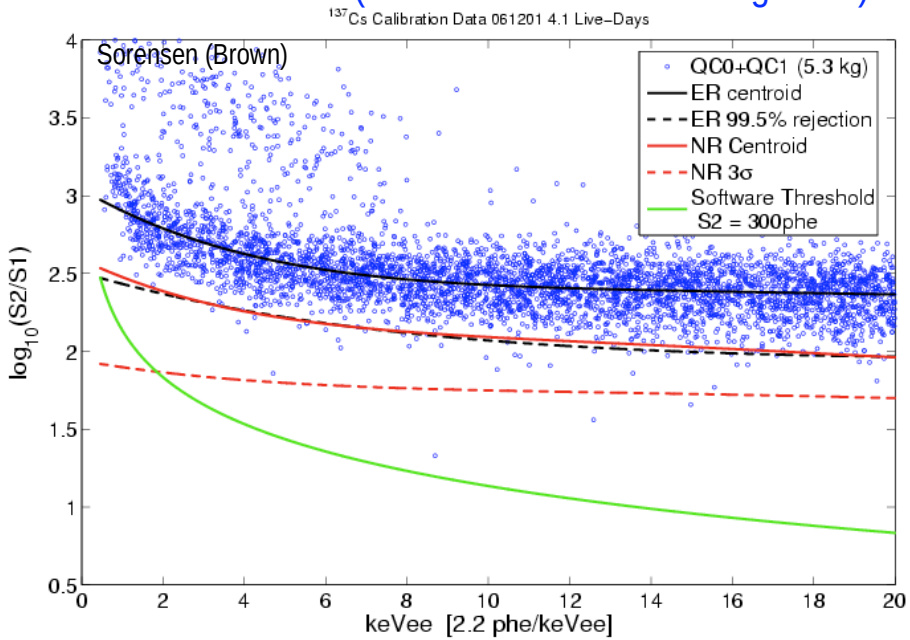




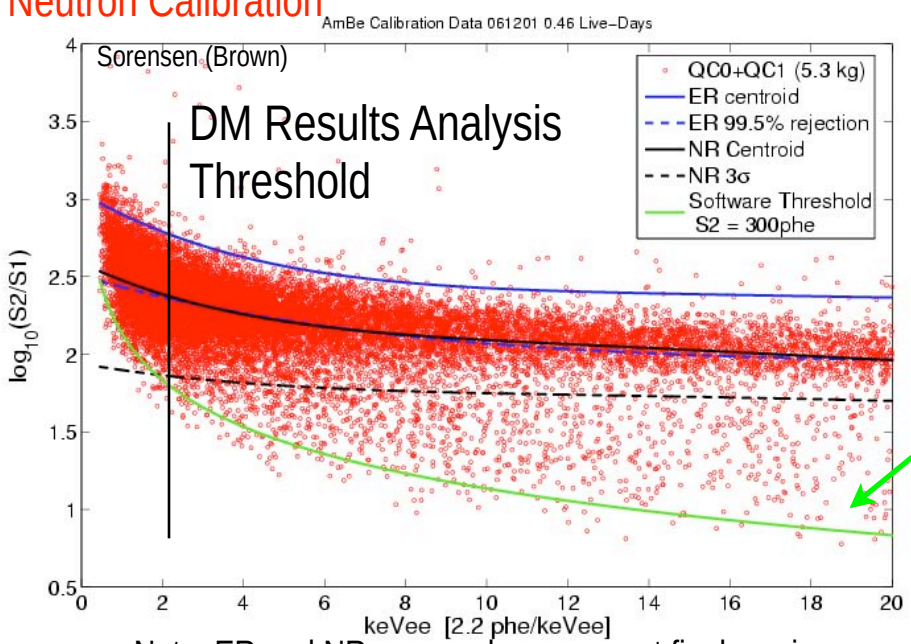
S2 Trigger / Analysis

Sorensen (Brown)

Gamma Calibration (Electron Recoils == Background)

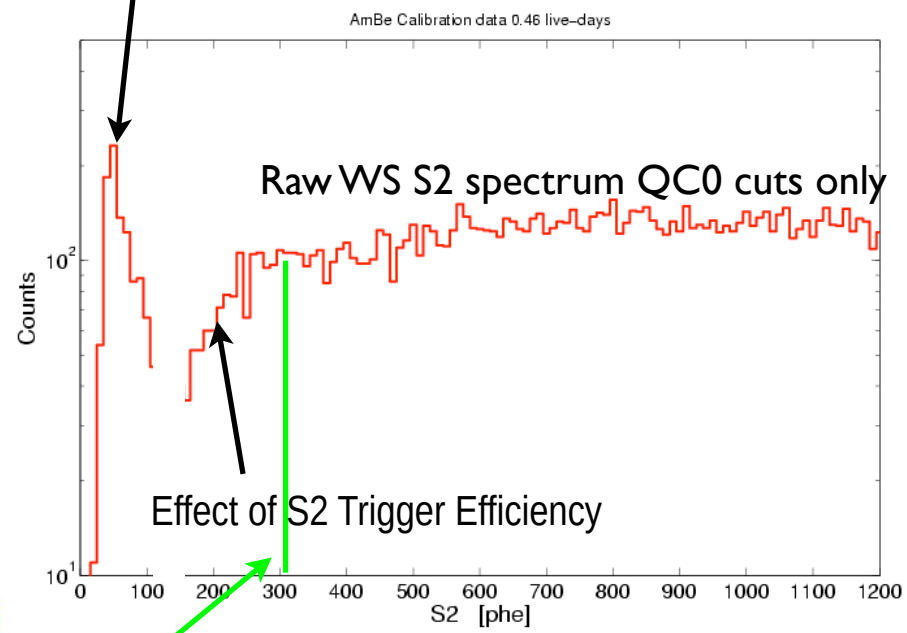


Neutron Calibration



Histogram of Random Single Electron (+multiple) Pulses observed in data

S2 25 phe ~ 1 drift electron



S2 300 phe ~ 12 drift electons

Note: ER and NR curves shown are not final versions used in 58 day WIMP Blind analysis

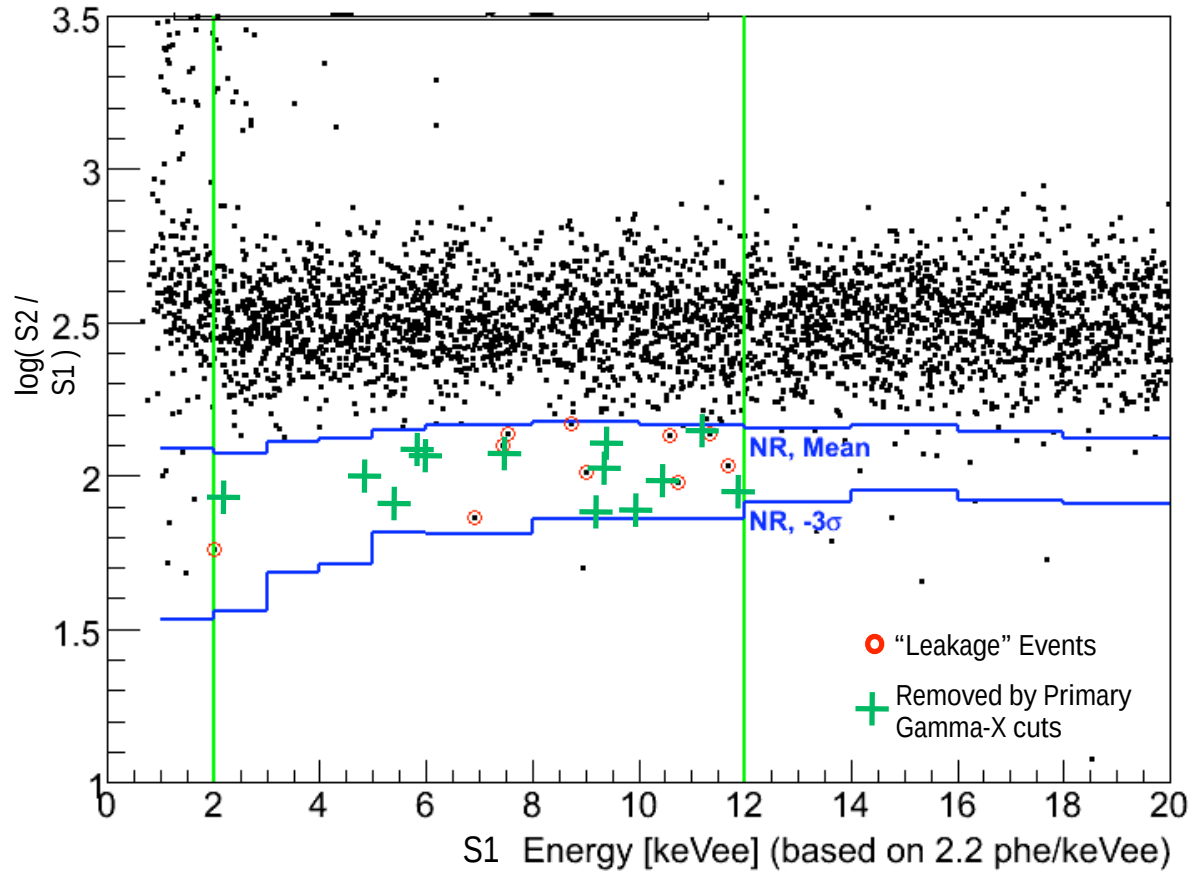
Applying the Gamma-X Cuts to XENON10 Data

§XENON10 Blind Analysis – 58.6 days

- § WIMP "Box" defined at
  - ~50% acceptance of Nuclear Recoils (blue lines): [Centroid -3**σ**]
  - 2-12keVee (2.2phe/keVee scale)
- § 23 Events in the Nuclear Recoil Acceptance Window
- § 13 events are removed from box by Primary Gamma-X Cuts (+)
- § 10 events in the "box" after all primary cuts (o)
- § 5 of these are *not consistent* with Gaussian distribution of ER Background

log (S2 / S1) vs S1

"Straightened Y Scale" – ER Band Centroid => 2.5



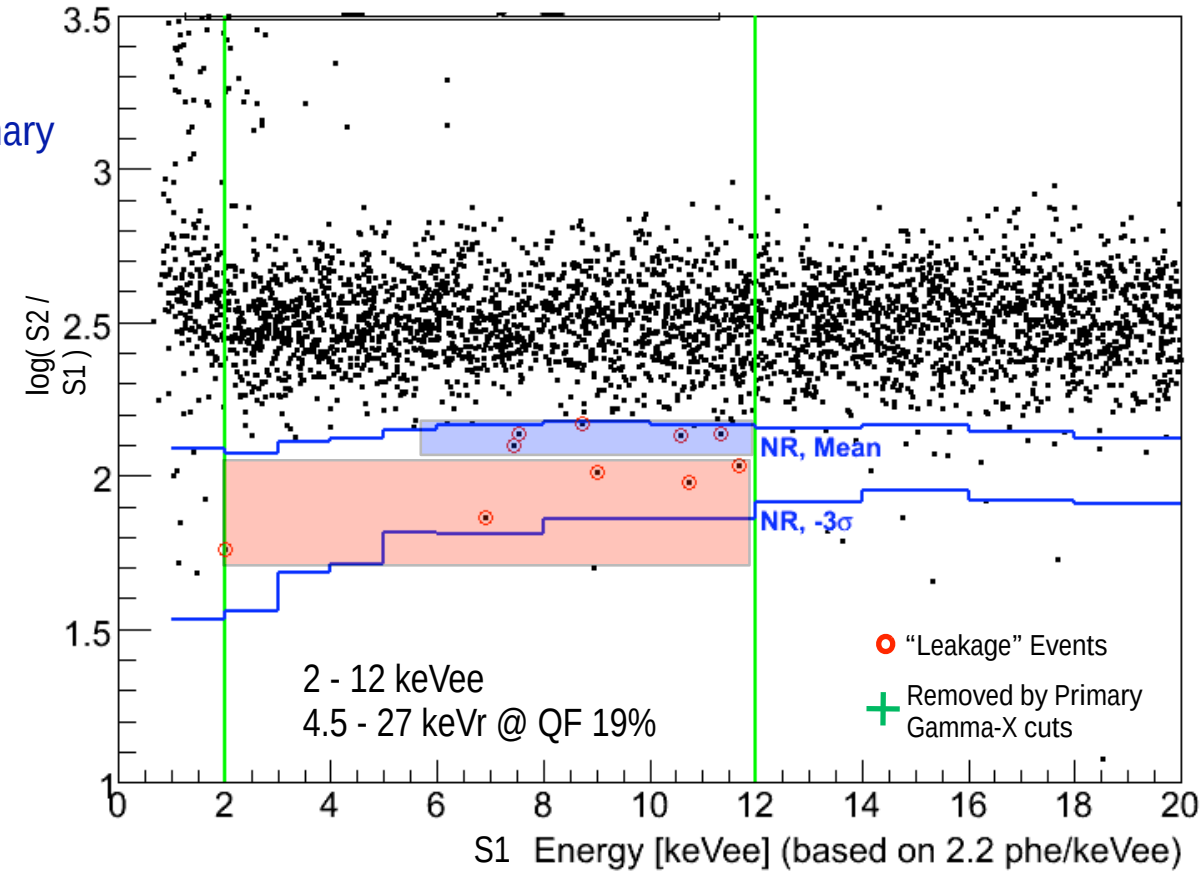
Applying the Gamma-X Cuts to XENON10 Data

§XENON10 Blind Analysis – 58.6 days

- § WIMP "Box" defined at
  - ~50% acceptance of Nuclear Recoils (blue lines): [Centroid -3**σ**]
  - 2-12keVee (2.2phe/keVee scale)
  - Assuming QF 19% 4.5-27 keVr
- § 10 events in the "box" after all primary analysis blind cuts (o)
- § 5 of events are consistent with gaussian tail from ER band
  - Fits based on ER calibrations projected 7.0 +2.1-1.0 events
- § 5 of these are *not consistent* with Gaussian distribution of ER Background

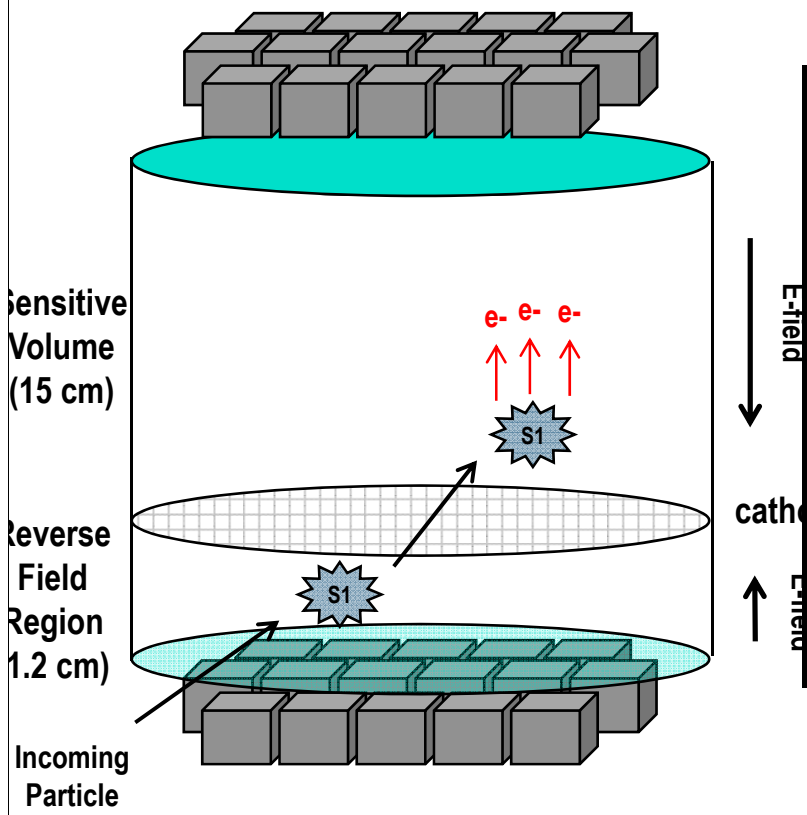
Δlog (S2 / S1) vs S1

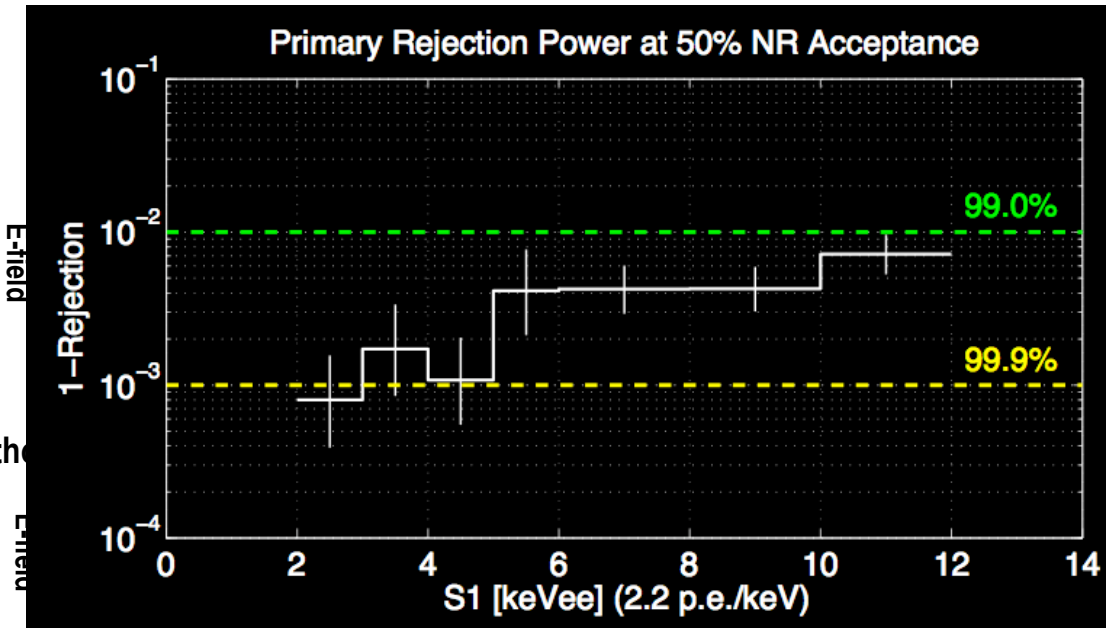
"Straightened Y Scale" – ER Band Centroid normalized => 2.5



Absence of Low Energy Candidate Events (2-7 keVee)

- Why are are there fewer events in box in low energy?
  - Discrimination improves ! at lowest energies - NR and ER bands move apart in log(S2/S1) plot
  - Missing S2 events less frequent for low energies, (multiple scatters, boost S1)

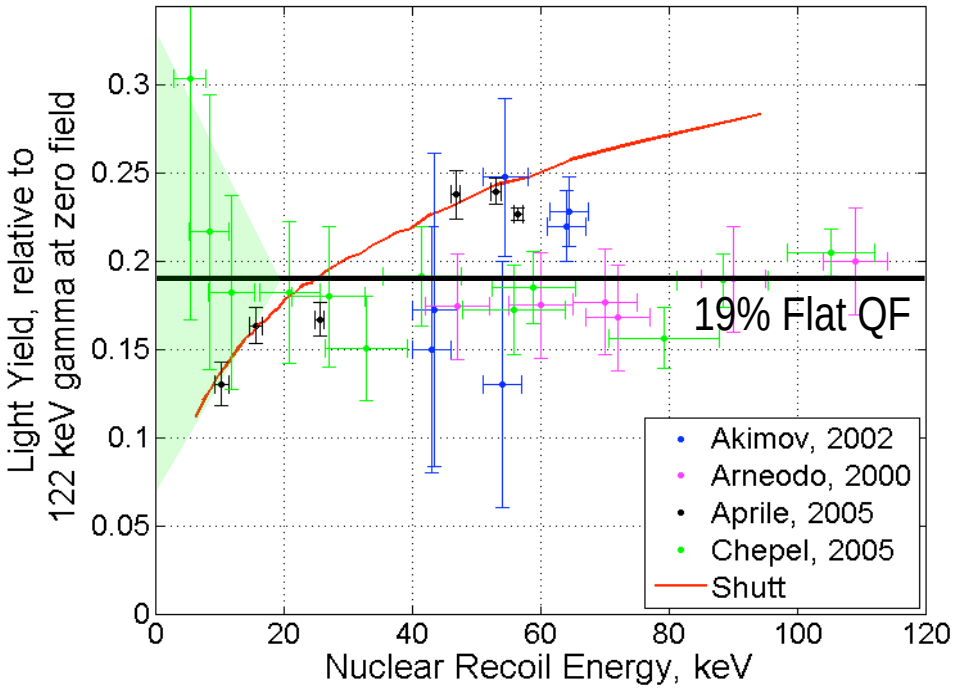


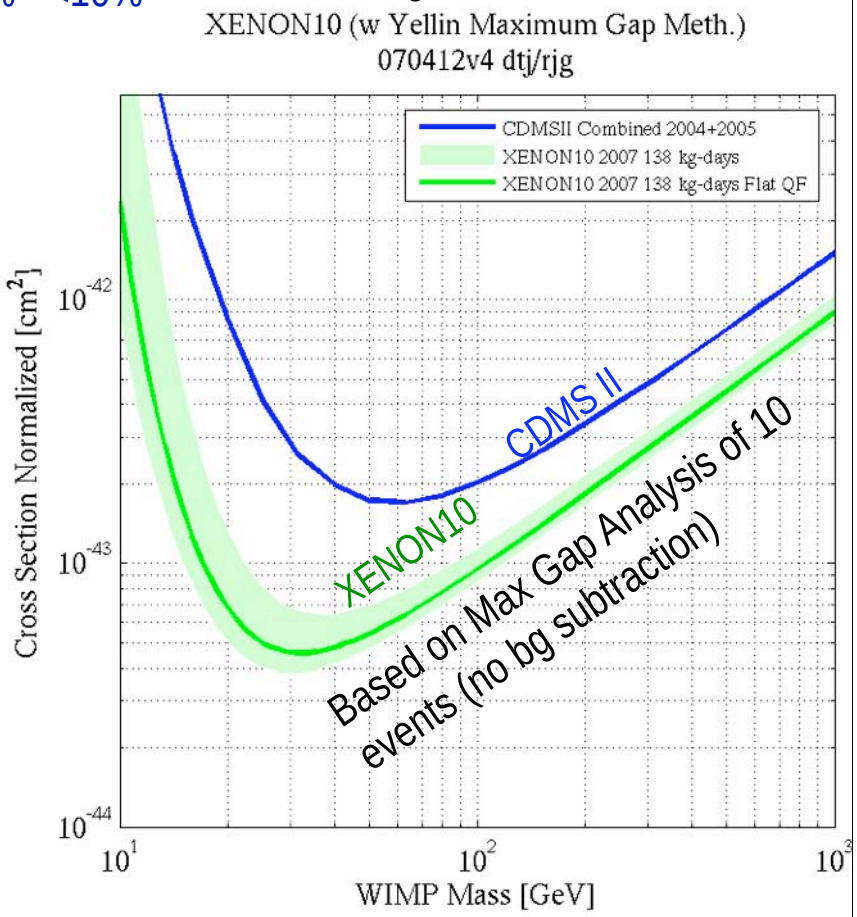


Setting Limit

- Effect on dm sensitivity associated with varying assumption of "best fit" to nuclear recoil light yield
  - Low energy QF: assume 19% constant as default
  - Also consider effect of varying low energy QFs >30% - <10%

Yellin Maximum Gap Analysis
PRD 66 (2002) 032005
Allows fit to Sig+Known BG+Unknown BG

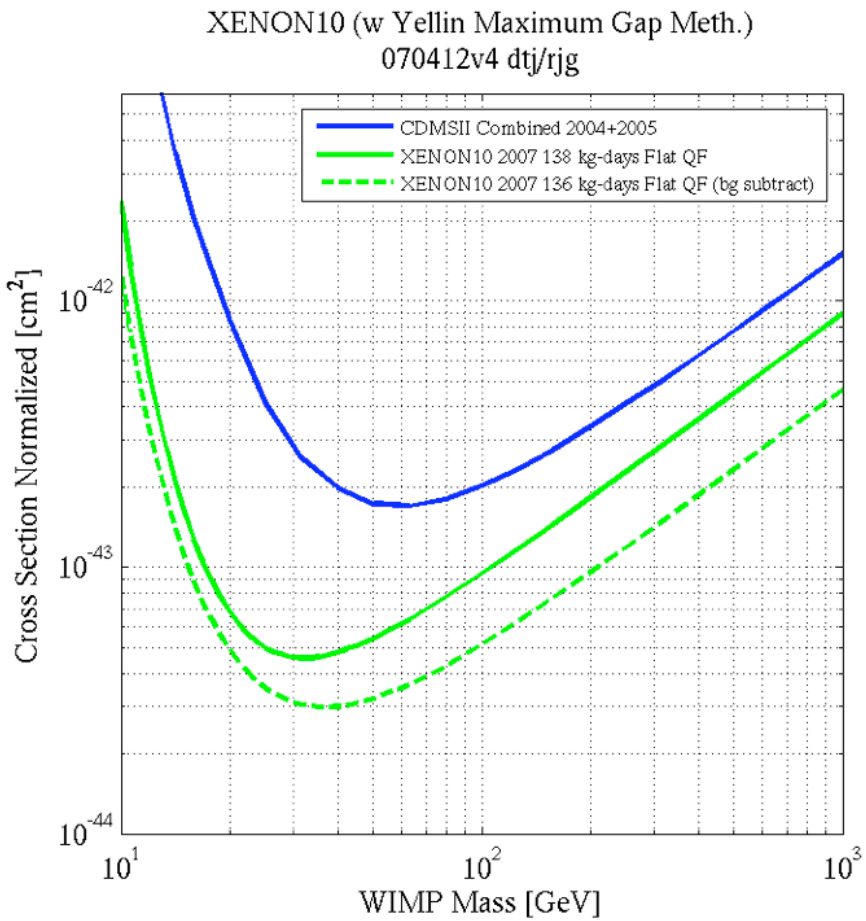




See Manzur Talk

(NOT) Subtracting Gamma Leakage Estimate

- If gamma response was perfectly known ...
- Current estimate is 2.1 leakage ER events in energy range 2-7 keVee
- We see no WIMP candidate events in the same energy range
- Taking account of this in WIMP sensitivity analysis would improve limit by factor 2
- However, since current statistical errors in gamma calibration are comparable to leakage estimate we will not use an ER leakage subtraction in current result.



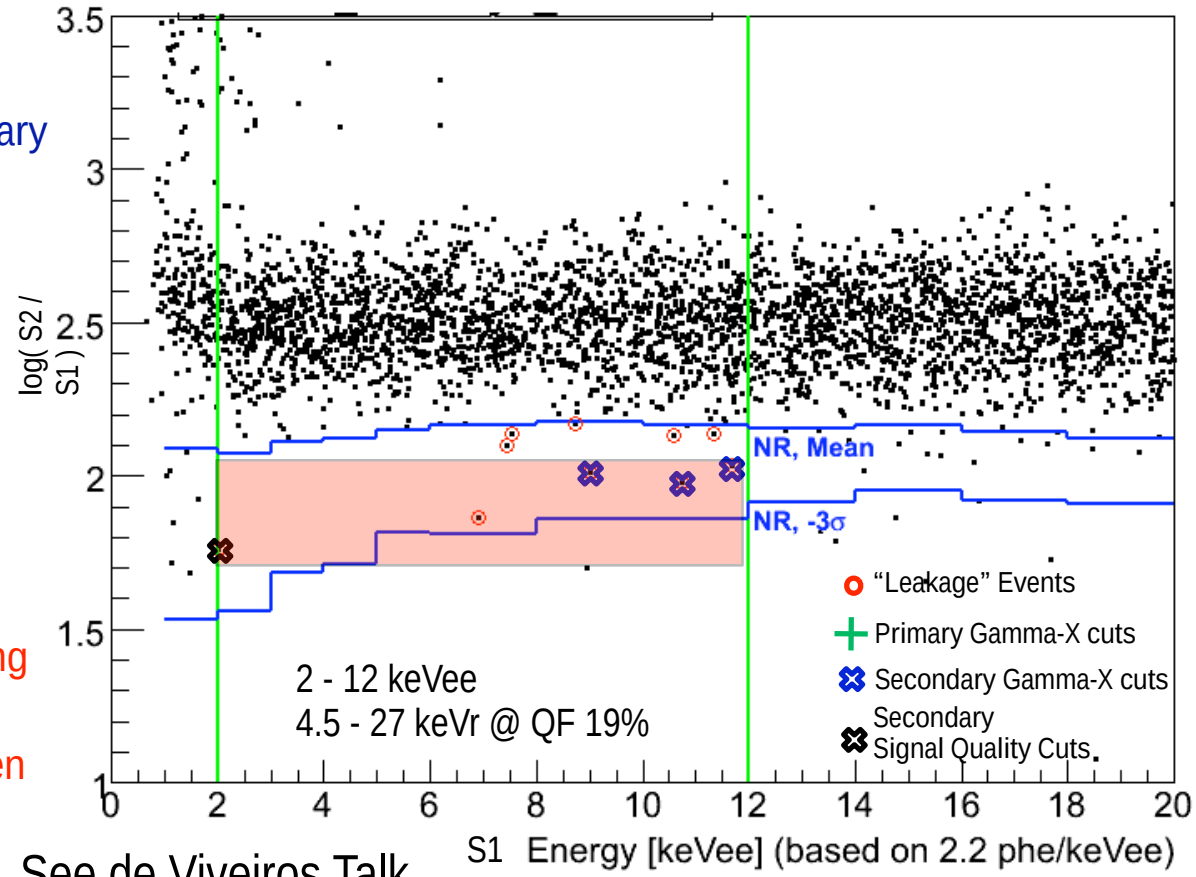
Applying the SECONDARY Gamma-X Cuts to XENON10

§XENON10 Blind Analysis – 58.6 days

- § WIMP "Box" defined at
  - ~50% acceptance of Nuclear Recoils (blue lines): [Centroid -3σ]
  - 2-12keVee (2.2phe/keVee scale)
  - Assuming QF 19% 4.5-27 keVr
- § 10 events in the "box" after all primary analysis blind cuts (o)
- § 5 of events are consistent with gaussian tail from ER band
  - Fits based on ER calibrations projected 7.0 +2.1-1.0 events
- § 5 of these are *not consistent* with Gaussian distribution of ER Background
  - 4 out of 5 events removed by Secondary Blind Analysis (looking for missing S2/Gamma-X events)
  - Remaining event would have been caught with 1% change in cut acceptance : WIMP SIGNAL UNLIKELY

log (S2 / S1) vs S1

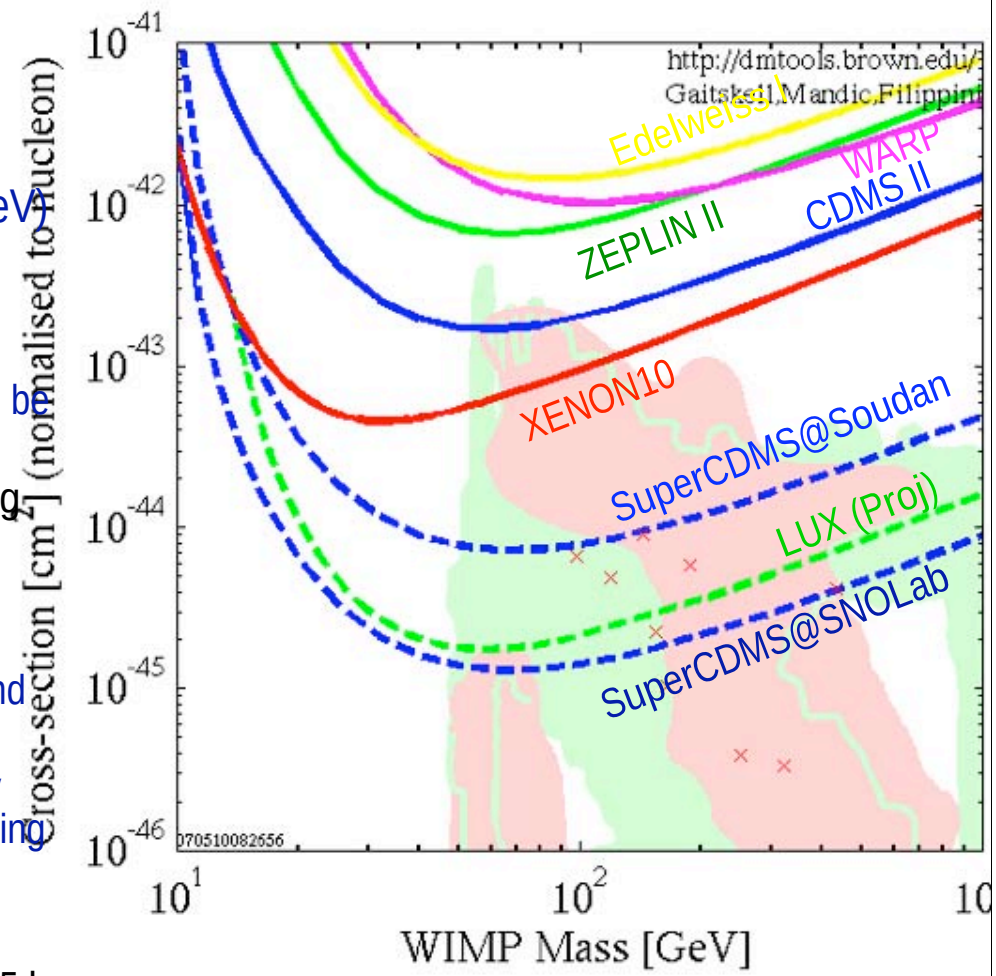
"Straightened Y Scale" – ER Band Centroid => 2.5



See de Viveiros Talk

Dark Matter Results and (some of Goals)

- Dark Matter Goals
  - XENON10
    - 136 kg-days net exposure
  - LUX - Sensitivity curve at 2×10^{-45} cm^2 (100 GeV)
    - Exposure: Gross Xe Mass 300 kg
      Limit set with 120 days running
      x 100 kg fiducial mass x 50% NR acceptance
      - If candidate dm signal is observed, run time can be extended to improve stats
    - ~1 background event during exposure assuming most conservative assumptions of
      ER 7×10^{-4} /keVee/kg/day and 99% ER rejection
      - Intrinsic BG rejection ->99.9% at low energy
      - Improvements in PMT bg will extend background free running period, and DM sensitivity
      - Curve shown is conservative - could improve by factor 10, but this would require 1200 days running to fully exploit... bigger detector
  - Comparison
    - SuperCDMS Goal @ SNOLab: Gross Ge Mass 25 kg (x 50% fid mass+cut acceptance)
      Limit set for 1000 days running x 7 SuperTowers



(XENON10 curve no background subtraction)

Factors Affecting ZEPLIN II vs XENON10

- ZEPLIN II
  - PMTs all above liquid
    - S1 0.55 phe/keVee with drift field applied
    - This limits S2/S1 discrimination due to Poisson fluctuations in S1
  - 7 x 5" PMTs - xy position reconstruction is poor (relative to diameter of target) so fiducial volume fraction is smaller (7.2 kg/35 kg) and some leakage in reconstruction of surface events
  - Room temp getter - introducing Rn into Xe (~1 Hz alphas seen in bulk)
  - Overall Gamma Background ~0.8 dru in Fiducial Volume
- XENON10
  - PMTs above and below LXe
    - S1 2.2 (3.0) phe/keVee @662 (122) keVee with drift field applied
    - 0.9 phe/keVr (assuming 19% QF for zero field)
  - 89 x 1" PMTs - xy position reconstruction very good <<5 mm. No apparent leakage due to poor position reconstruction.
  - High temp getter - not introducing significant levels of Rn (<0.04 Hz alpha seen in bulk)
  - Overall Gamma Background ~0.8 dru in Fiducial Volume

XENON10

- In situ Neutron Calibration agreed very closely with calibrations of above ground prototypes.
  - Refining QF light yield for nuclear recoil events
- High Stats Gamma Calib and WIMP search data show very similar performance in ER rejection using S2/S1 - Behavior very encouraging
  - Gaussian Component
    - Due to Recombination fluctuations, and Poisson stats at lowest energies (<5 keVee)
  - Non-gaussian (systematics) Contribution
    - Non-gaussian "LOW TAIL" component is being eliminated at better than 1000:1
      - Tail events removed using cuts tuned on gamma calib
    - Main Cuts used to
      - Fiducial Volume - eliminate events at edge Teflon where charge (S2) collection is poor
      - More than one S2 pulse indicating multiple scatter
      - S1 light hit pattern unusual - e.g. if most of signal is concentrated in few adjacent bottom PMTs, indicates additional scattering in Xe below cathode grid
- XENON10 Modifications
  - A number of components will be replaced in XENON10 to improve radioactive backgrounds
- OPTIONS FOR LARGER LIQUID XENON EXPERIMENTS are currently being explored