Noble Travails:
Noble Liquid Dark Matter Detectors

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(Supported by US DOE HEP)

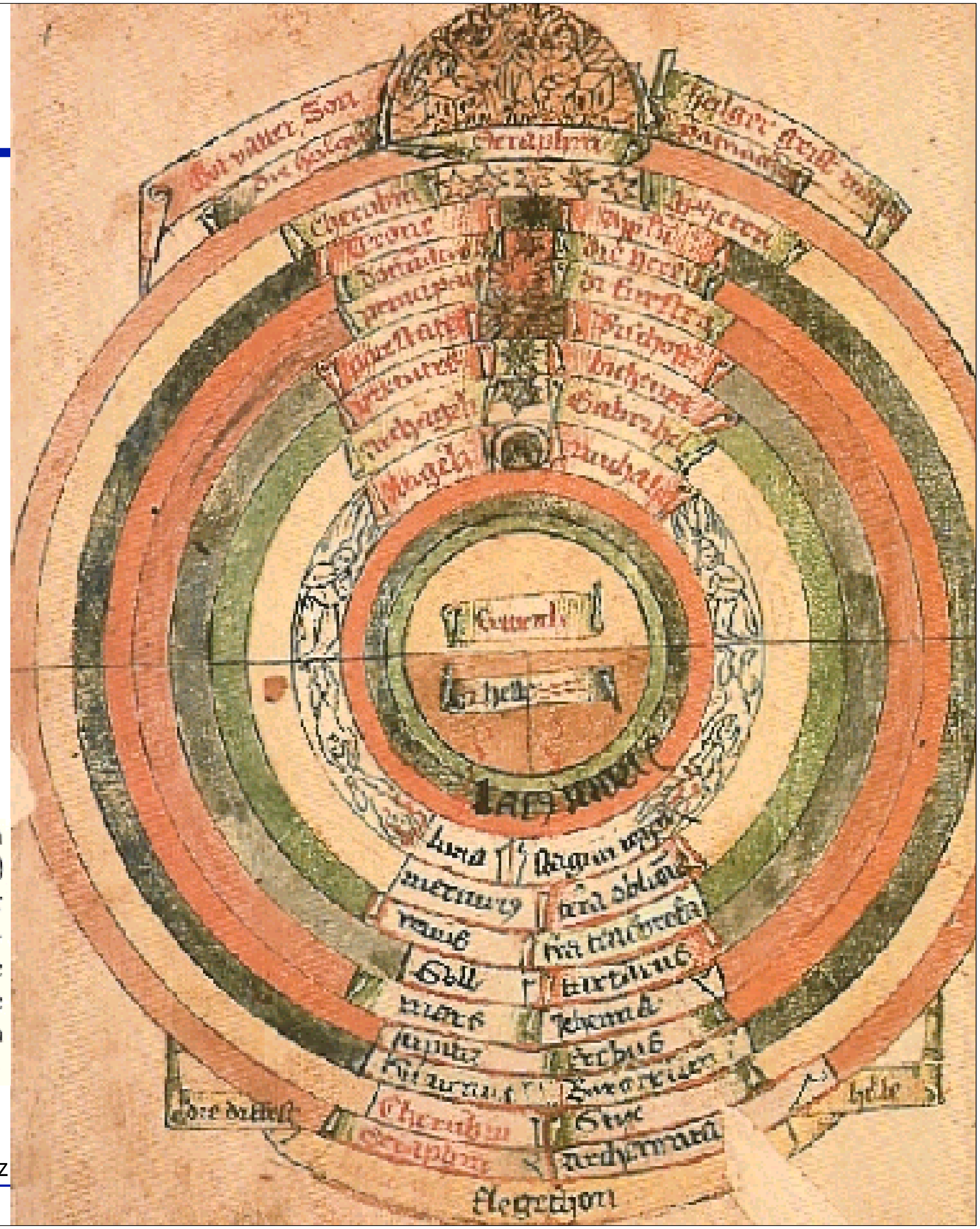
see information at

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

Medieval Universe

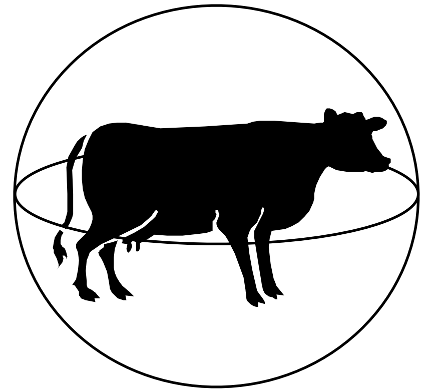
The geocentric pre-Copernican Universe in Christian Europe. At center, Earth is divided into Heaven (tan) and Hell (brown). The elements water (green), air (blue) and fire (red) surround the Earth. Moving outward, concentrically, are the spheres containing the seven planets, the Moon and the Sun, as well as the "Twelve Orders of the Blessed Spirits," the Cherubim and the Seraphim. German manuscript, c. 1450.

From Joel Primack, UC Santa Cruz



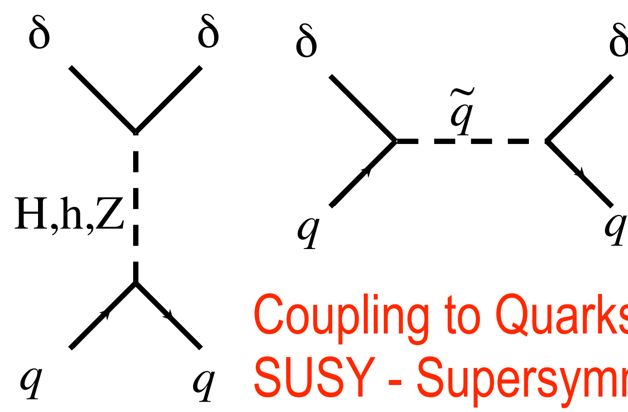
Direct Detection Astrophysics of WIMPs

- **Energy spectrum & rate depend on WIMP distribution in Dark Matter Halo**
  - **"Spherical-cow" assumptions: isothermal and spherical, Maxwell-Boltzmann velocity distribution**
  - **V_0= 230 km/s, v_{esc}= 650 km/s,**
  - **ρ = 0.3 GeV / cm^3**



- **Energy spectrum of recoils is featureless exponential with $\langle E \rangle$ ~ 50 keV**
- **Rate (based on $\sigma_{n\chi}$ and ρ) is fewer than 1 event per kg of detector per week**
- **Nucleus recoils (not electron)**

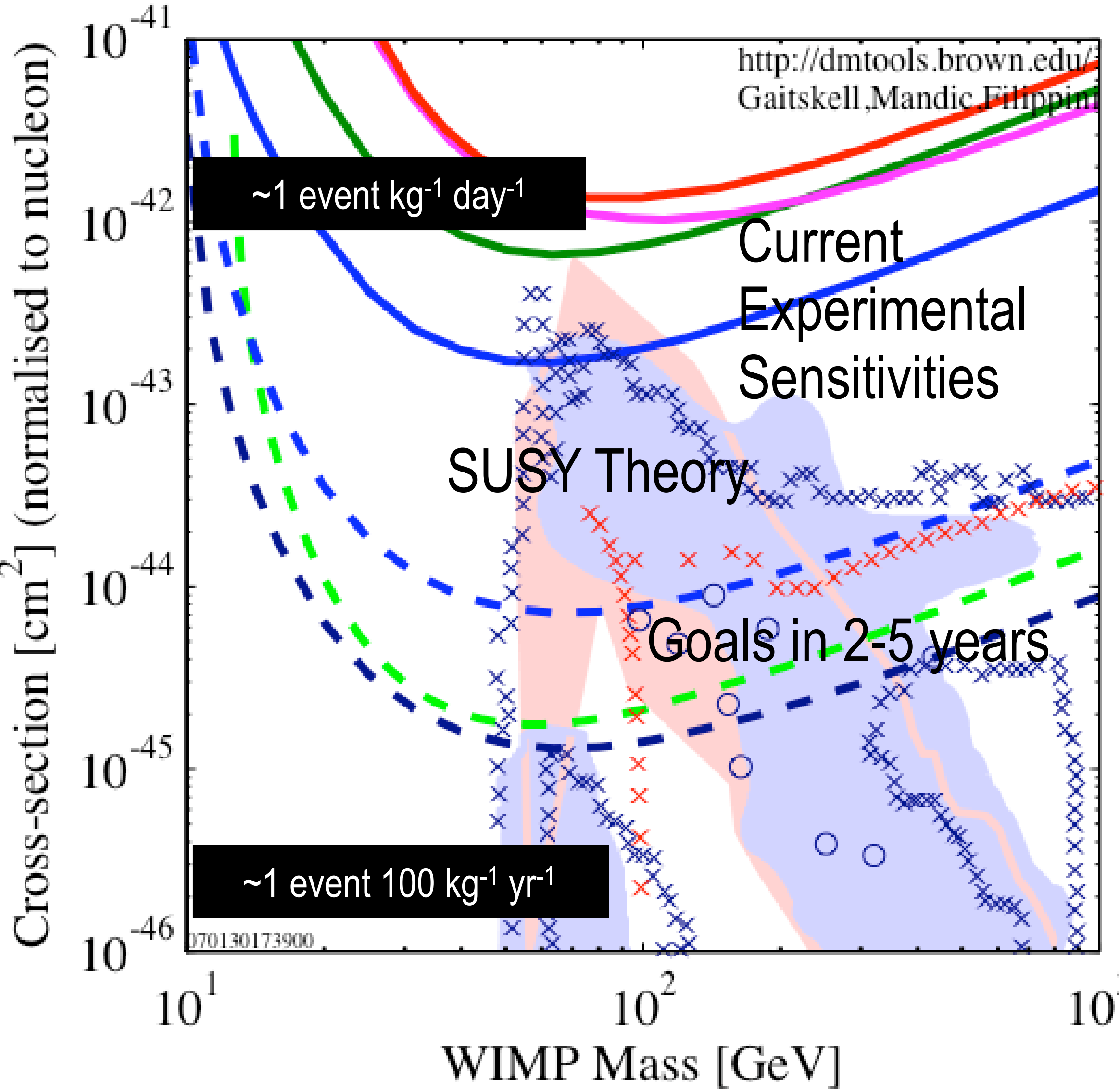
"Contains ten 60-GeV WIMPs on average. 20 billion WIMPs pass through each second."



Coupling to Quarks:
SUSY - Supersymmetry

Dark Matter Theory and Experiment

- SOME SUSY MODELS
  - [blue] T. Baltz and P. Gondolo, Markov Chain Monte Carlos. JHEP 0410 (2004) 052, (hep-ph/0407039)
  - [red] J. Ellis et al. CMSSM, Phys.Rev. D71 (2005) 095007, (hep-ph/0502001)
  - [red crosses] G.F. Guidice and A. Romanino, Nucl.Phys. B699 (2004) 65; Erratum-ibid. B706 (2005) 65, (hep-ph/0406088)
  - [blue crosses] A. Pierce, Finely Tuned MSSM, Phys.Rev. D70 (2004) 075006, (hep-ph/0406144)



Background Challenges

- Search sensitivity (low energy region <<100 keV)
  - Current Exp Limit < 1 evt/kg/20 days, ~< 10^{-1} evt/kg/day
  - Goal < 1 evt/tonne/year, ~< 10^{-5} evt/kg/day
- Activity of typical Human
  - ~10 kBq (10^{4} decays per second, 10^{9} decays per day)
- Environmental Gamma Activity
  - Unshielded 10^{7} evt/kg/day (all values integrated 0–100 keV)
  - This can be easily reduced to ~10^{2} evt/kg/day using 25 cm of Pb
- Moving beyond this
  - e.g. External Gammas: High Purity Water Shield 4m gives <<1 evt/kg/day
  - Gammas from Internal components - goal intrinsic U/Th contamination toward ppt (10^{-12} g/g) levels
  - Detector Target can exploit self shielding for inner fiducial if intrinsic radiopurity is good
- Main technique to date focuses on nuclear vs electron recoil discrimination
  - This is how CDMS II experiment went from 10^{2} -> 10^{-1} evts/kg/day
- Environmental Neutron Activity
  - (α,n) from rock 0.1 cm^{-2} day^{-1}
  - Since <8 MeV use standard moderators (e.g. polyethylene, or water, 0.1x flux per 10 cm
  - Cosmic Ray Muons generate high energy neutrons 50 MeV - 3 GeV which are tough to moderate
  - Need for depth (DUSEL) - surface muon 1/hand/sec, Homestake 4850 ft 1/hand/month

Techniques for dark matter direct detection

TYPE	DISCRIMINATION TECHNIQUE	TYPICAL EXPERIMENT	ADVANTAGE
Ionization	None (Ultra Low BG)	MAJORANA, GERDA	Searches for ββ-decay, dm additional
Solid Scintillator	pulse shape discrimination	LIBRA/DAMA, NAIAD	low threshold, large mass, but poor discrim
Cryogenic	charge/phonon light/phonon	CDMS, CRESST EDELWEISS	demonstrated bkg discrim., low threshold, but smaller mass/higher cost
Liquid noble gas	light pulse shape discrimination, and/or charge/light	ArDM, LUX, WARP, XENON, XMASS, XMASS-DM, ZEPLIN	large mass, good bkg discrimination
Bubble chamber	super-heated bubbles/ droplets	COUPP, PICASSO	large mass, good bkg discrimination
Gas detector	ionization track resolved	DRIFT	directional sensitivity, good discrimination

R.J. Gaitskell, Ann. Rev. Nucl. Par. Sci, 54 (2004) 315

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 Liquids as detector medium

	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e-/MeV]	scintillation [photon/MeV]
He	2 (4)	4.2	0.13	39,000	22,000
Ne	10 (20)	27.1	1.21	46,000	30,000
Ar	18 (40)	87.3	1.40	42,000	40,000
Kr	36 (84)	119.8	2.41	49,000	25,000
Xe	54 (131)	165.0	3.06	64,000	46,000

- Scintillation Light Yield comparable to NaI 40,000 phot/MeV
- liquid rare gas gives both scintillation and ionization signals

Noble Liquids as detector medium

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Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165.0	3.06	64	46

- liquid rare gas gives both scintillation and ionization signals
- Scintillation is decreased (~factor 2) when E-field applied for extracting ionization

In LXe ~30% of electron recoil energy appears as scintillation light (7 eV photons)

Noble Liquid Comparison (DM Detectors)

	Scintillation Light	Intrinsic Backgrounds
Ne (A=20) $60/kg 100% even-even nucleus	85 nm Requires wavelength Shifter	Low BP (20K) - all impurities frozen out No radioactive isotopes
Ar (A=40) $2/kg (isotope separation >$1000/kg) ~100% even-even	125 nm Requires wavelength shifter	Nat Ar contains ~39Ar 1 Bq/kg == ~150 evts/keVee/kg/day at low energies. Requires isotope separation, low 39Ar source, or very good discrimination (~10^6 to match CDMS II)
Xe (A=131) $800/kg 50% odd isotope	175 nm UV quartz PMT window	136Xe double beta decay is only long lived isotope - not a relevant bg for DM search >10^{46} cm^2. 85Kr can be removed by charcoal or distillation.

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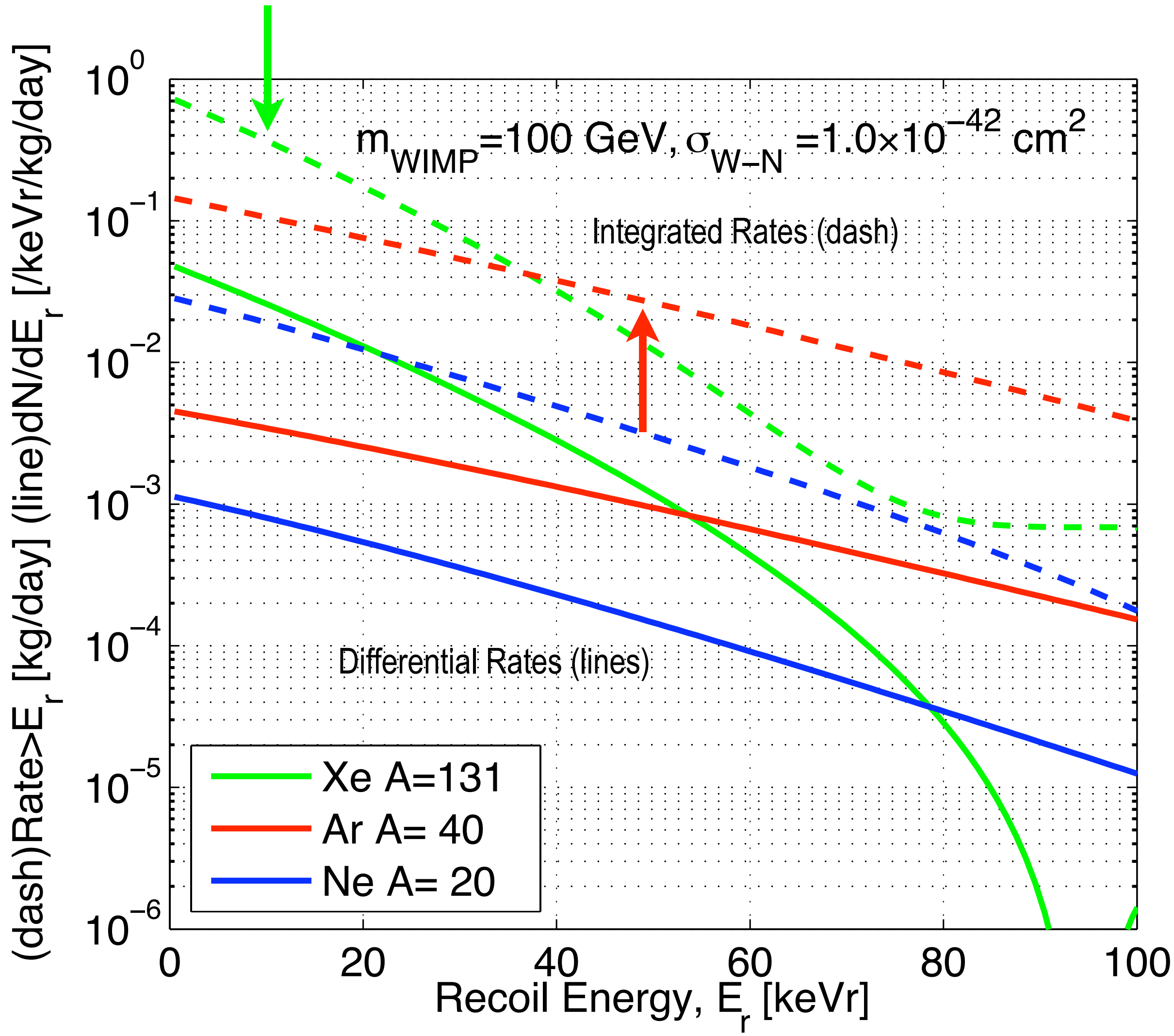


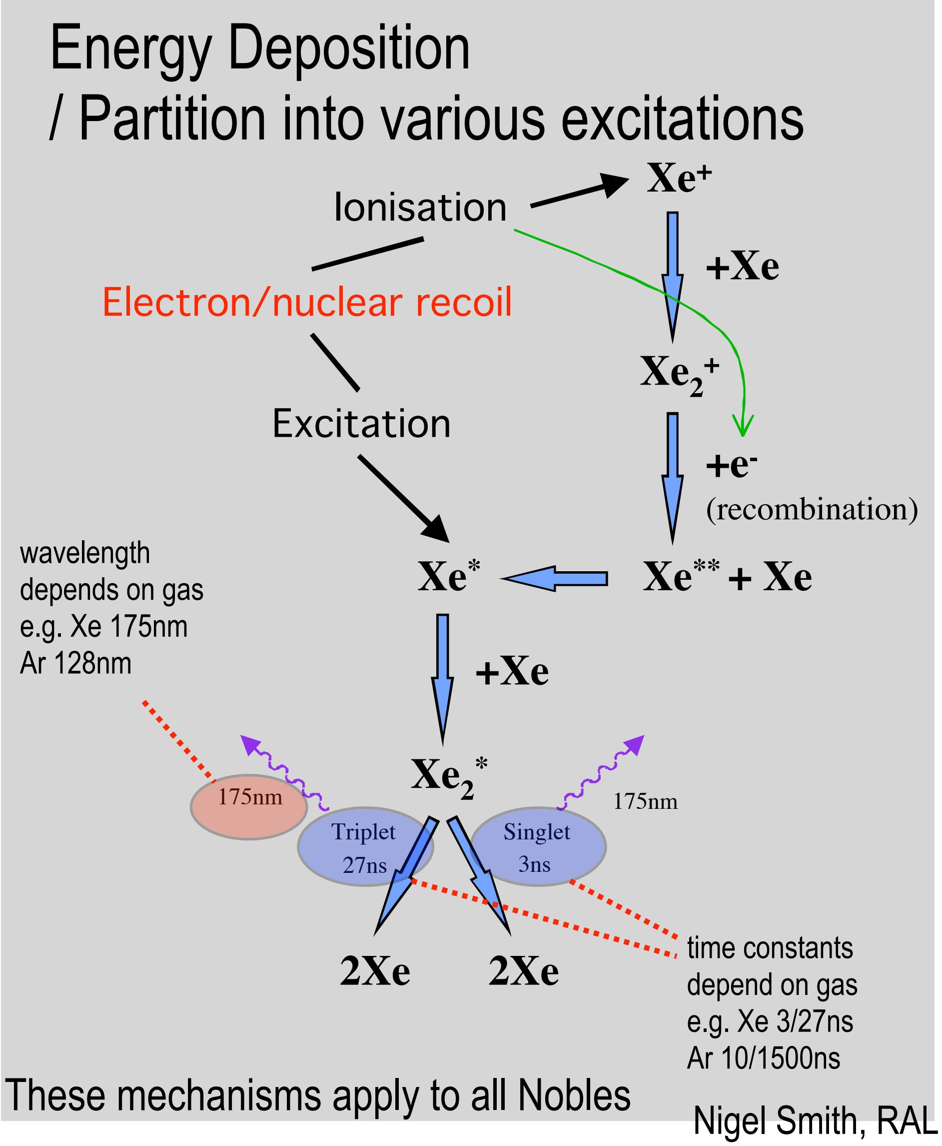
Noble Liquid Comparison (DM Detectors)

	Scintillation Light	Intrinsic Backgrounds	WIMP (100 GeV) Sensitivity vs Ge >10 keVr
Ne (A=20) $60/kg 100% even-even nucleus	85 nm Requires wavelength Shifter	Low BP (20K) - all impurities frozen out No radioactive isotopes	Scalar Coupling: Eth>50 keVr, 0.02x Axial Coupling: 0 (no odd isotope)
Ar (A=40) $2/kg (isotope separation >$1000/kg) ~100% even-even	125 nm Requires wavelength shifter	Nat Ar contains ~39Ar 1 Bq/kg == ~150 evts/keVee/kg/day at low energies. Requires isotope separation, low 39Ar source, or very good discrimination (~10^6 to match CDMS II)	Scalar Coupling: Eth>50 keVr, 0.10x Axial Coupling: 0 (no odd isotope)
Xe (A=131) $800/kg 50% odd isotope	175 nm UV quartz PMT window	136Xe double beta decay is only long lived isotope - not a relevant bg for DM search >10^{46} cm^2. 85Kr can be removed by charcoal or distillation.	Scalar Coupling: Eth>10 keVr, 1.30x Axial Coupling: ~5x (model dep) Xe is 50% odd n isotope 129Xe, 131Xe

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	

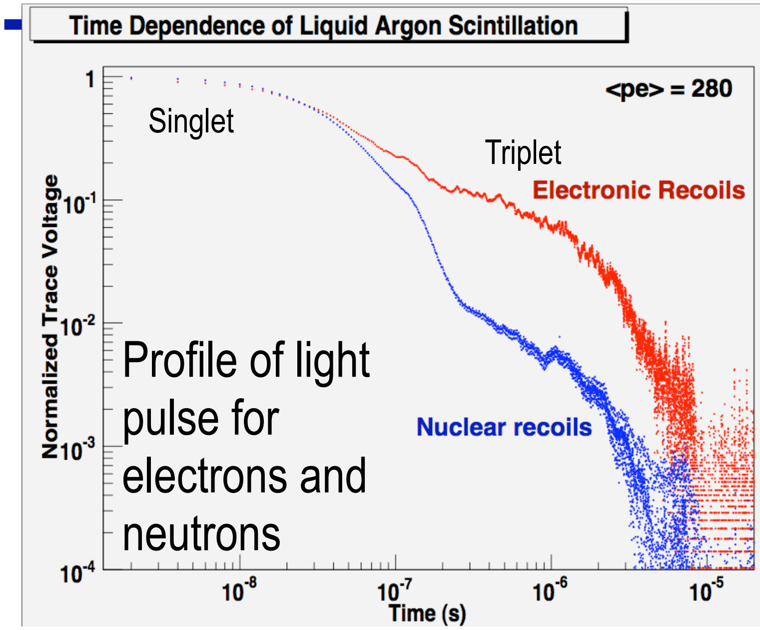
- Single phase - scintillation only
  - e-ion recombination occurs
  - singlet/triplet ratio 10:1 nuclear:electron
- Double phase - ionization & scintillation
  - drift electrons in E-field (kV/cm)

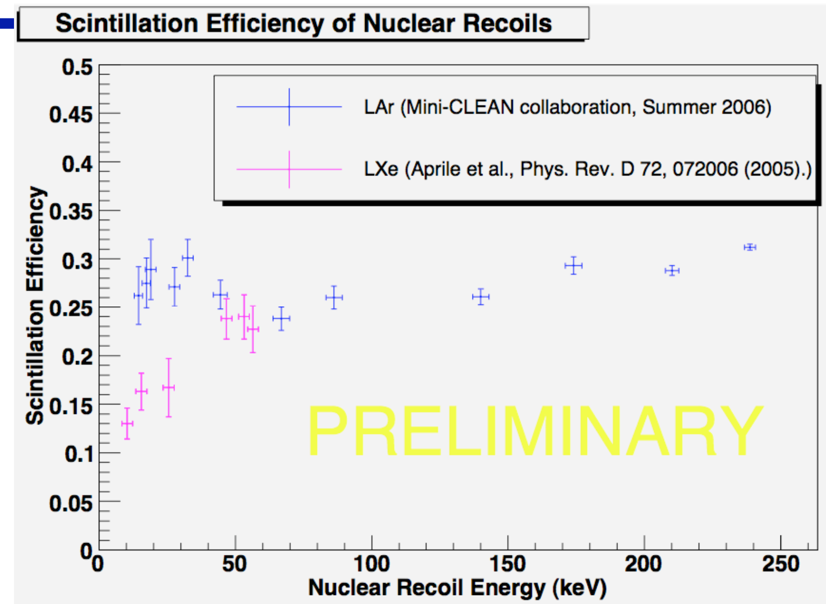


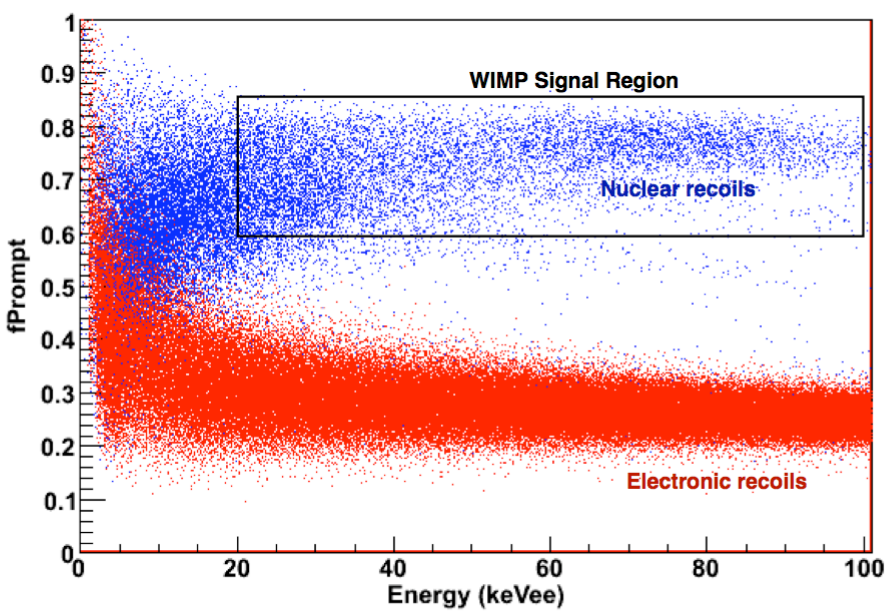
Rick Gaitskell, Brown University, DOE

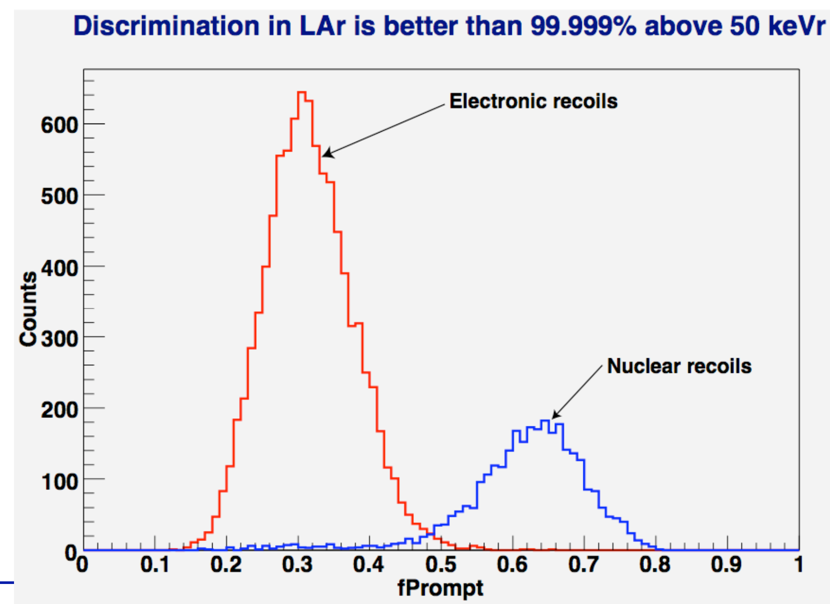
Data taken with Micro-CLEAN (McKinsey, Yale)

CLEAN Ar PSD

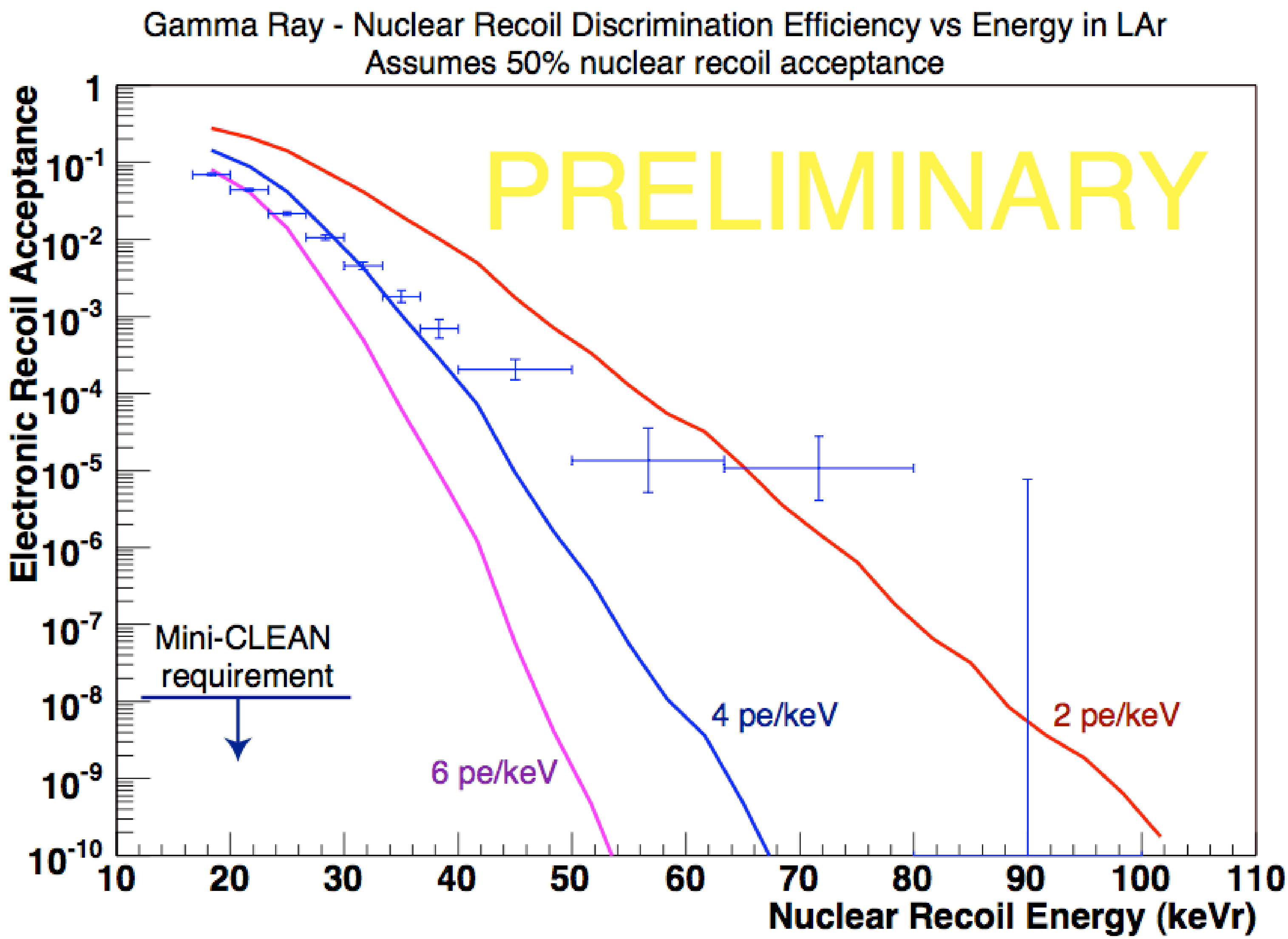






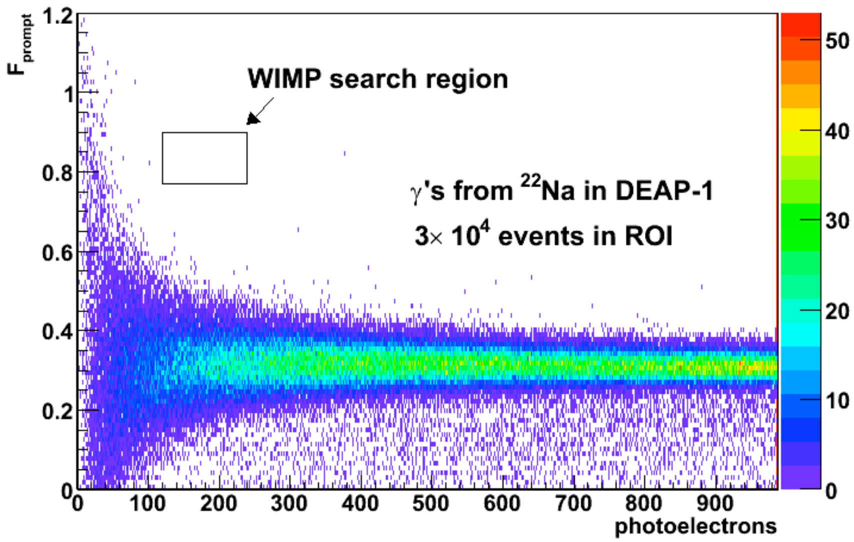


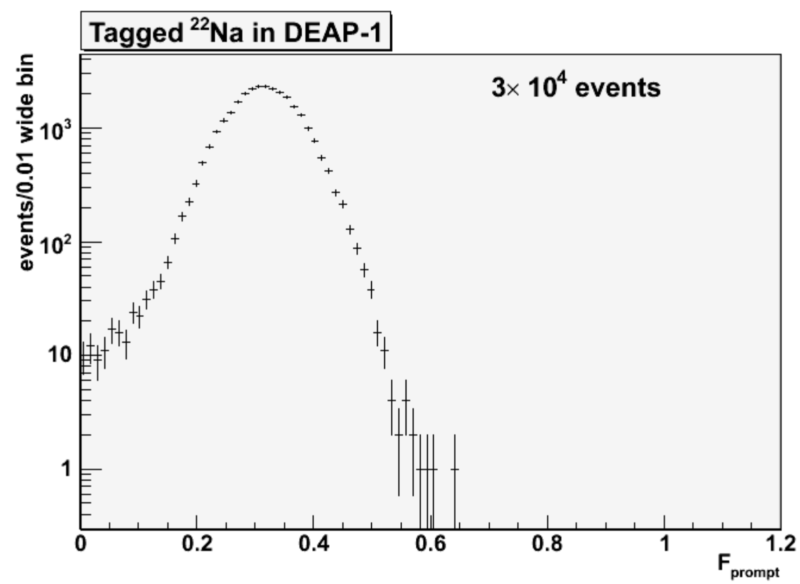
(McKinsey, Yale)



DEAP-1 (being deployed)

- DEAP-1 (Boulay / Hime)
  - Also based on scintillation PSD alone
  - Queen's (Boulay) leading effort - Canadian Groups + Yale/LANL
  - 7 kg LAr with 2x PMT
    - Have been studying PSD using tagged 22Na source to limit lab neutron contamination
    - Preliminary data showing ~10^{-4}-10^{-5} discrimination. Will continue to push stats.
  - Detector will be taken underground at SNOLab shortly
  - Poor position reconstruction and so likely to be limited by surface events





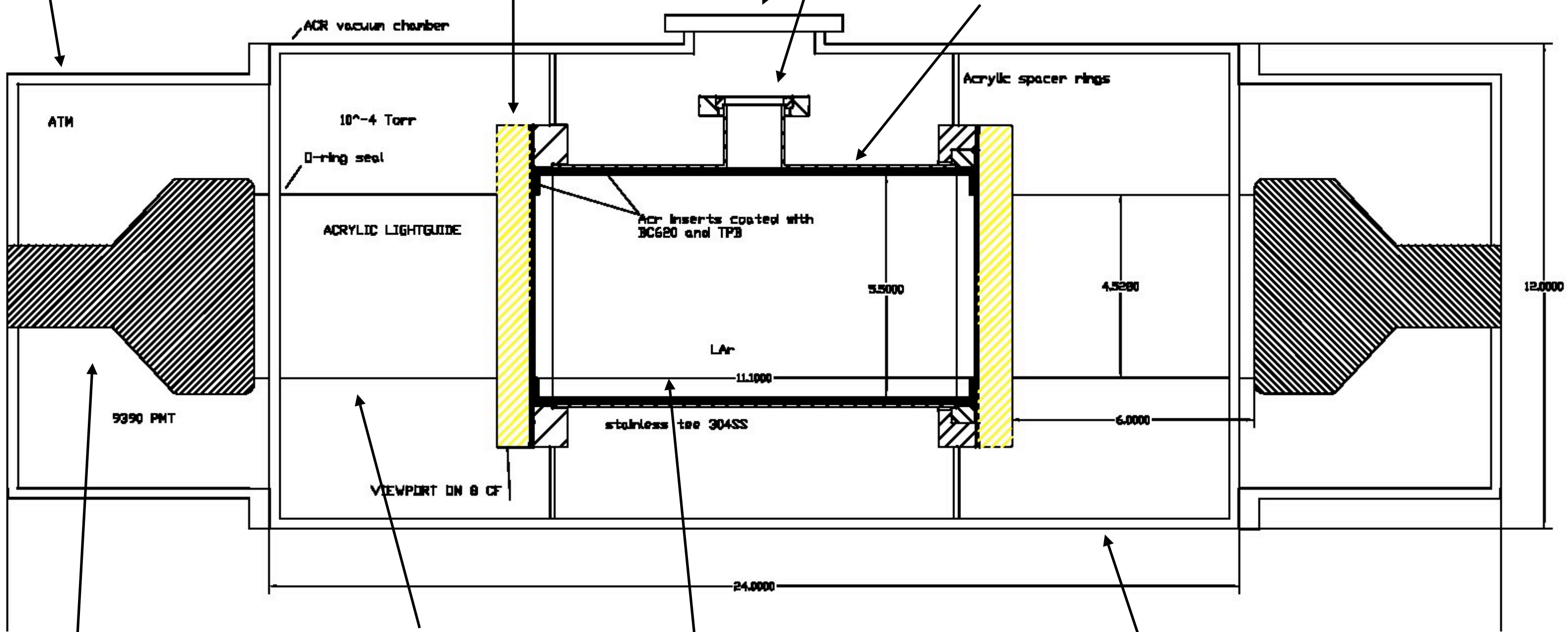
DEAP-1 design

Quartz windows

Neck connects to vacuum and Gas/liquid lines

11” x 6” (8” CF) tee

poly PMT supports



6” acrylic guide

Acrylic vacuum chamber

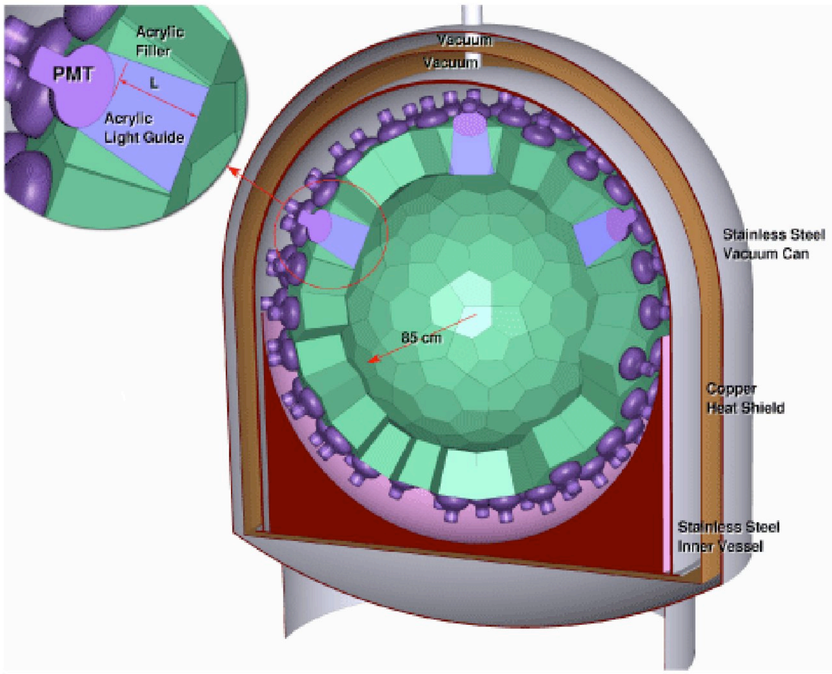
ET 9390 PMT 5”

inner surface 97% diffuse reflector,
Covered with TPB wavelength shifter

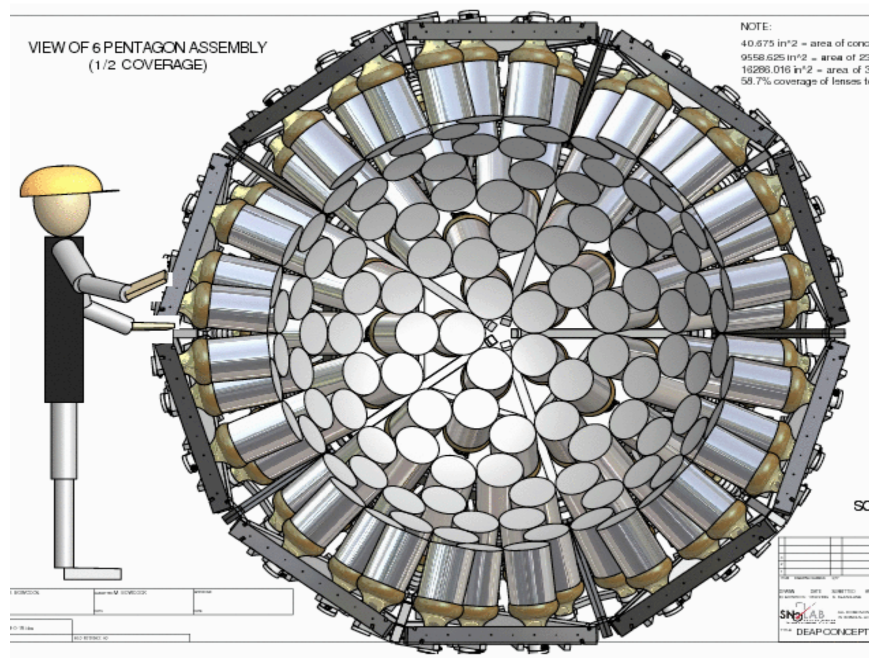
Mark Boulay

DEAP & CLEAN "ULTIMATE" designs

"miniCLEAN" 1000 kg



DEAP-3



- Design is driven by need for neutron reduction via hydrogenous material
- Vacuum thermal insulation versus ice thermal insulation
- Ice insulation not the preferred design for neon due to heat loads

- Liquid Argon 87 K (greater than LN2), Liquid Neon (27 K)

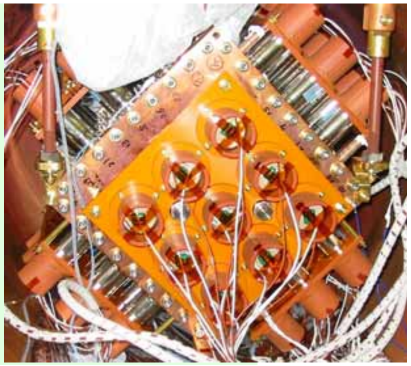
XMASS 100 kg (Xe) - Japan

- XMASS
  - 100 kg Prototype operated
    - Limited PMT coverage / Position reconstruction of events near walls at center
  - Next step is to 800 kg

➢ Status of 800 kg detector

● **Basic performances have been already confirmed using prototype detector**

✓ Method to reconstruct the vertex and energy
✓ Self shielding power
✓ BG level

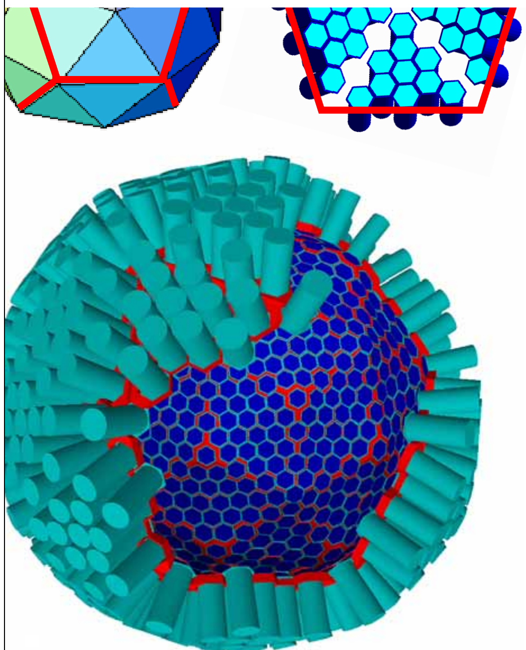


● **Detector design is going using MC**

✓ Structure and PMT arrangement (812 PMTs)
✓ Event reconstruction
✓ BG estimation

● **New excavation will be done soon**

XMASS 800 kg - Japan



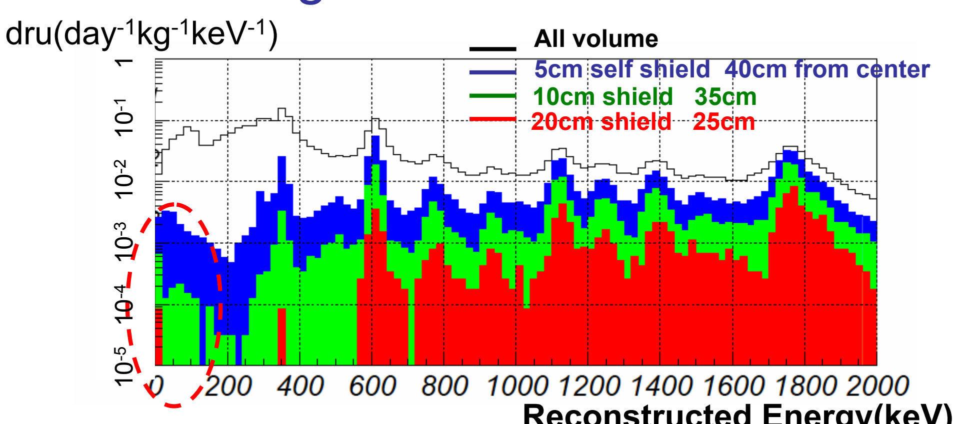
- 60 triangles
- 10 PMT/triangle x 60 = 600 PMTs
- + 212 PMTs in triangle boundary region
- Total 812 PMTs
- Photo coverage 67.0%
- Center to photocathode ~45cm
- Fiducial vloume is 25cm from center.
- PMTs are inside liquid xenon.

Funding of 800 kg phase has been recently been approved. Two year build planned 2007-2009.

Concern for DM reach relates to tails in position reconstruction for low energy events.

20 phe = 25 keVr

Background from PMT ^{238}U



- 1.8×10^{-3} Bq/PMT

Summary

- XMASS 800kg detector
  - 1 ton liquid xenon, 90cm diameter, 60 triangles, 812 PMTs
  - BG level 10^{-4} dru(day^{-1}kg^{-1}kev^{-1})
  - Dark matter search 10^{-45} cm^2
- Detector design by simulation
  - Resolution of event reconstruction
    - 10keV ~3cm 5keV ~5cm at boundary of fiducial volume
  - Background from PMT
    - ^{238}U, ^{60}Co ~10^{-5} dru inside fiducial volume
  - Water shield for ambient γ and fast neutron
    - 200cm shield is enough

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 =>**

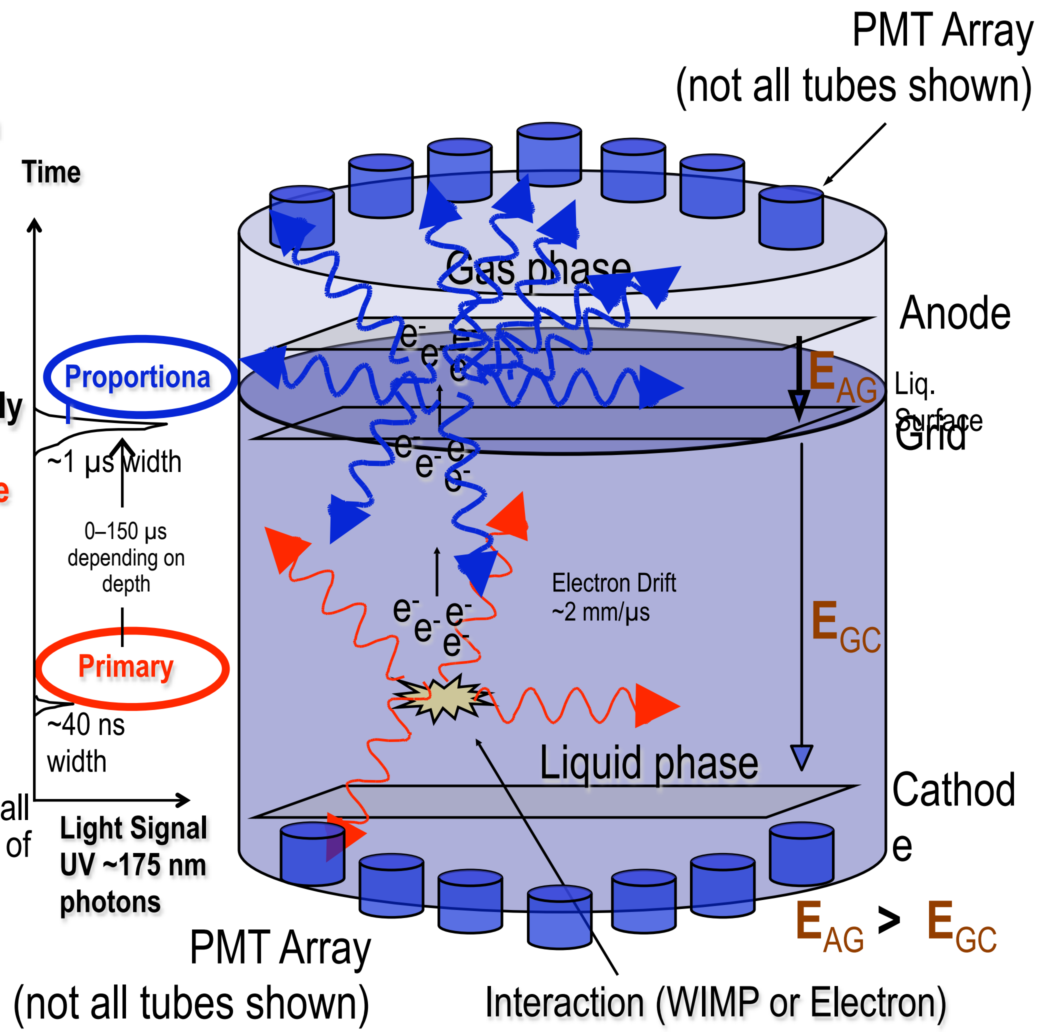
=> Weaker S1, Stronger S2

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

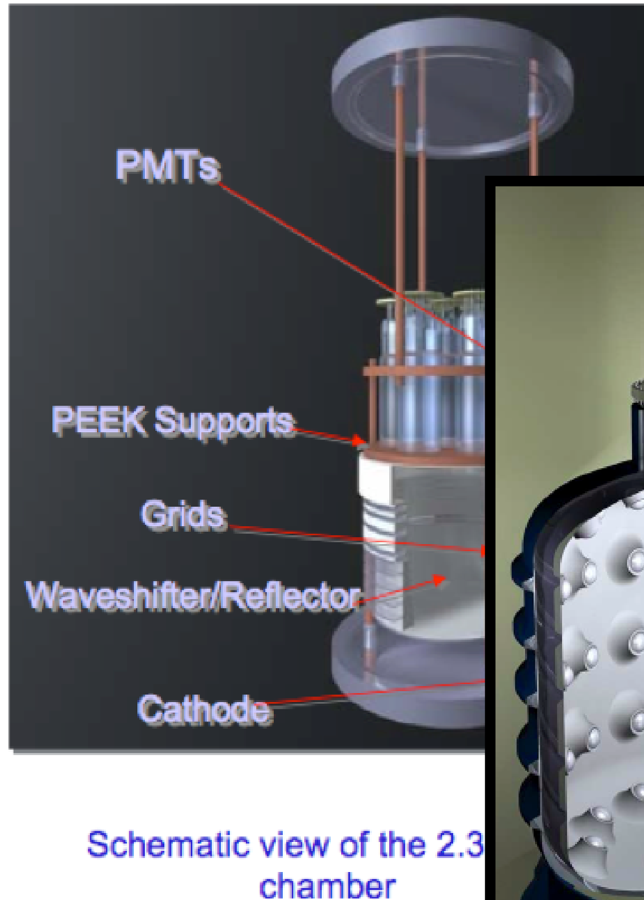
S1: ~1 phe /keVr in PMTs
S2: 5 liquid electrons / keVr, ~100 phe / keVr in PMTs
(HIGH EFFICIENCY ANALYSIS >=4 keVr)



Two-phase Argon Detectors: WARP and ArDM

- PSD and secondary scintillation from ionization drift
- WARP (Carlo Rubbia)
  - 3.2 kg prototype running at Gran Sasso
  - Preliminary results reported
  - 140-kg detector w/800-kg active veto under construction
- ArDM (Andre Rubbia)
  - LEMs for ionization readout
  - PMTs for primary scintillation
  - 1 ton prototype in construction

WARP Prototype

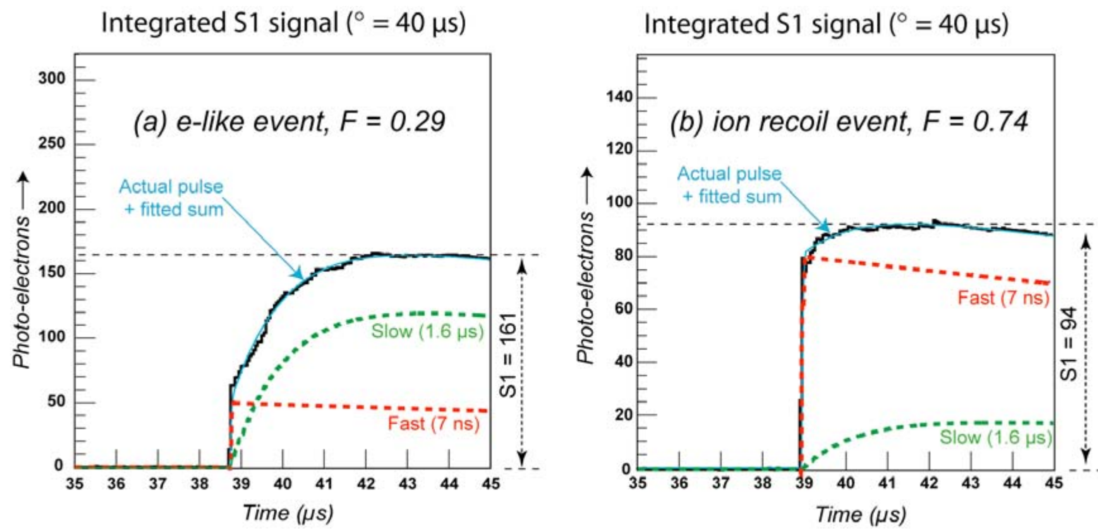


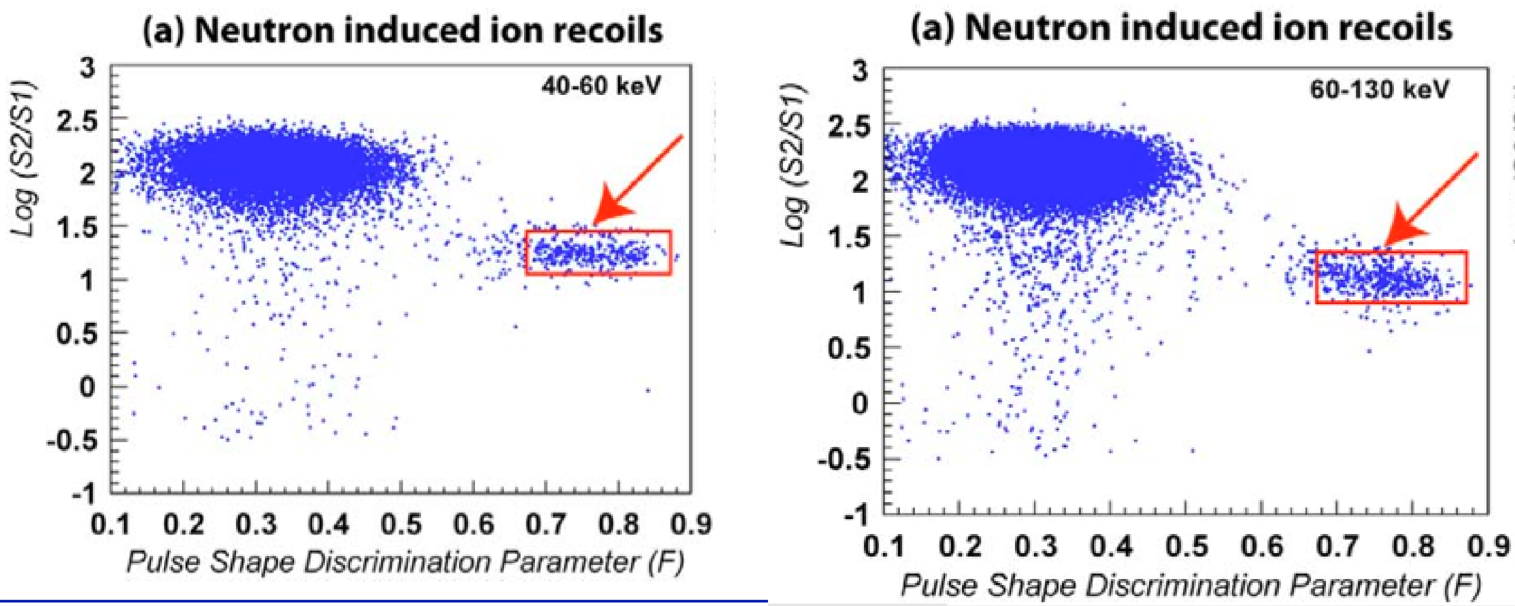
WARP

100-l detector

WARP - Dual Methods of Discrimination

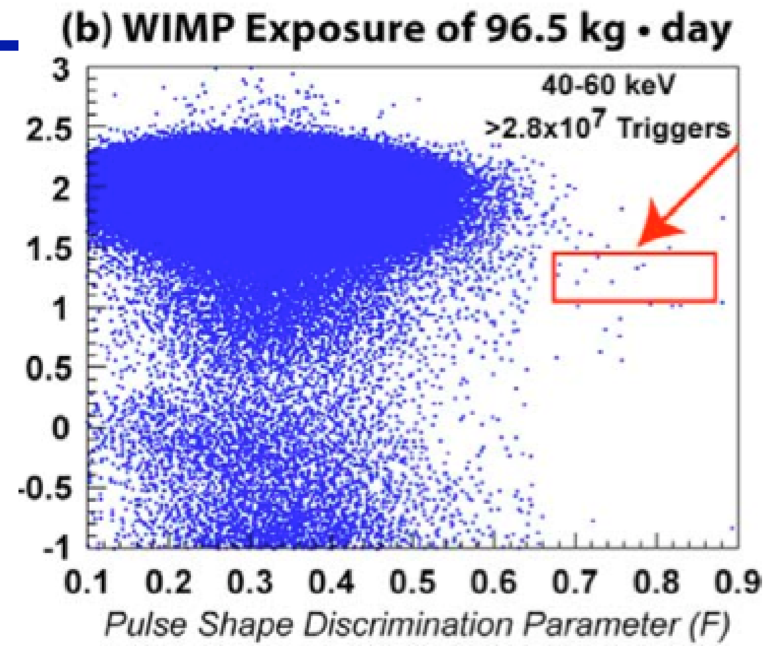
- PSD
  - Nuclear Recoil “Ion” has larger prompt component as in single phase
- S2/S1
  - Also have Ionization/ Scintillation

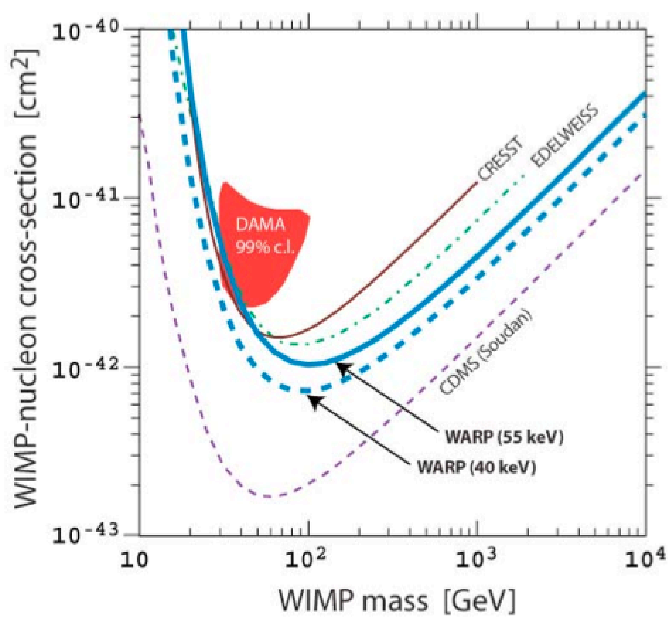


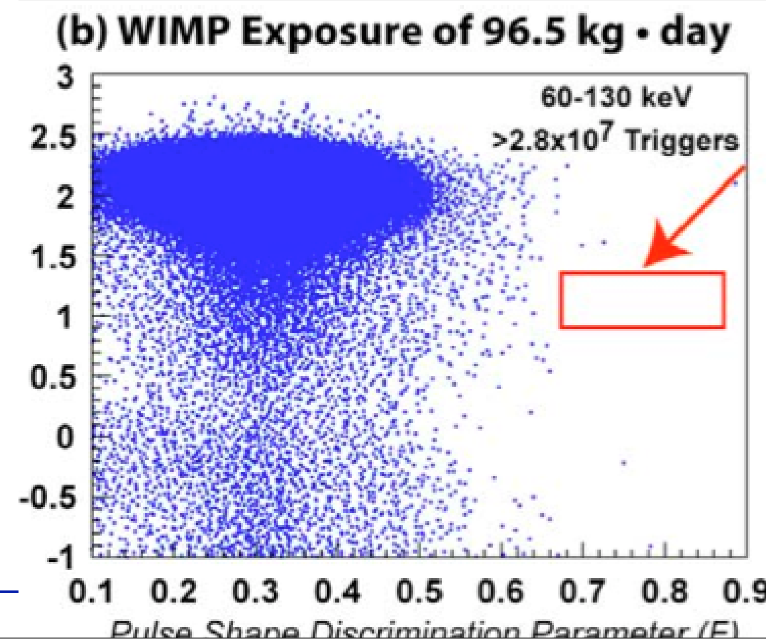


WARP Recent Results (Jan 07) astro-ph/0701286

- Analysis with no events above 55 keV (energy threshold selected a posteriori) yields limit at cyan line (5x above CDMS).
  - At this threshold energy Ar is 1/10 as sensitive to WIMPs per unit mass as Ge E>10 keV
  - The 40 keVr cyan dashed line is a simple a “what if” there were no events above 40 keVr
- Have new data run of ~50 kg-days with improved electronics - suggest that it will remove some/all of low energy events. (Announce soon)



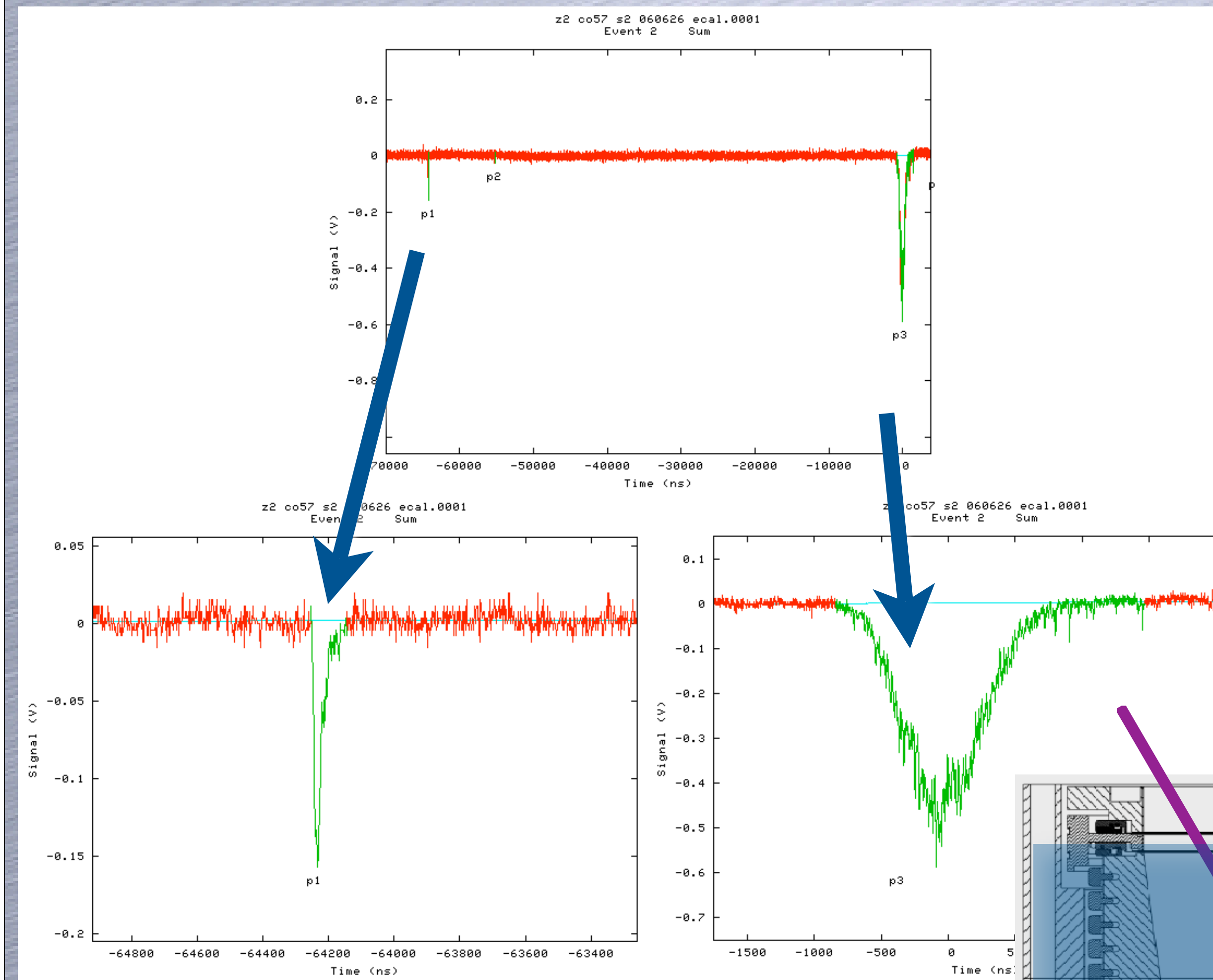


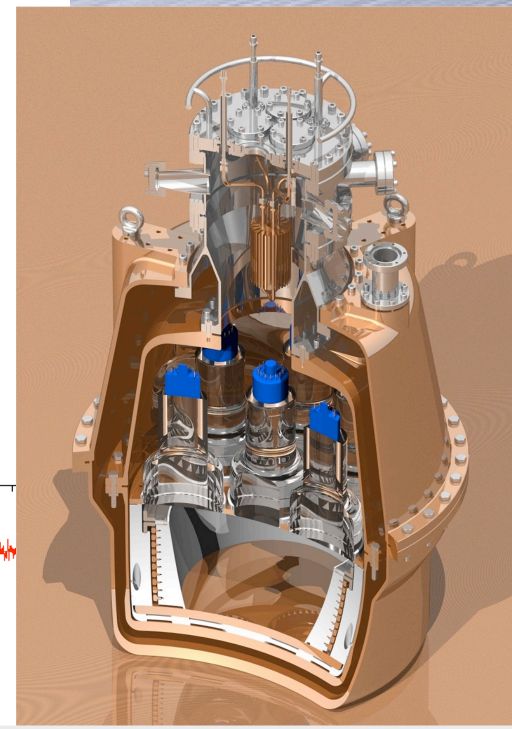


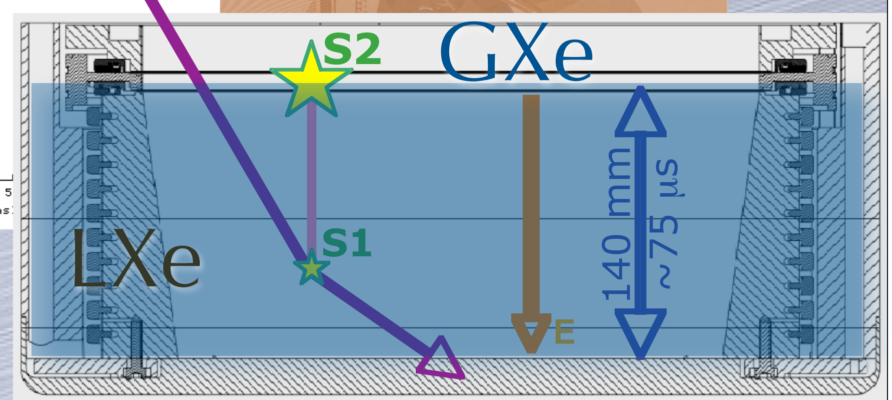
39Ar Beta Background - Event Rejection vs Removal

- Note that regular Ar contains 39Ar ~1 Bq/kg, which gives beta spectrum (end point ~500 keV) with a low energy tail of ~150 evts/keVee/kg/day
- This means that in order to match current best CDMS II sensitivity an Ar experiment must deliver at least ~10^6 rejection.
  - Fiducialization/multiple scatter cuts don't help in reducing this rate
- Possible ways of dealing with it
  - Improve discrimination so it become irrelevant (although still have to deal with the event rate 1 kHz in 1 tonne)
  - Isotopic reduction (WARP have taken delivery of 3 liters of Ar with ~1/50 activity for running in WARP prototype)
  - Extraction of Ar from underground wells
    - However, underground (n,p) process in 39K will generate 39Ar. (n > 3 MeV are generated by U/Th decays)
    - An initial sample that was tested from an underground well had 50x (larger) than usual 39Ar:Ar concentration - large survey will be required to understand factors effecting levels.

ZEPLIN-II Detector



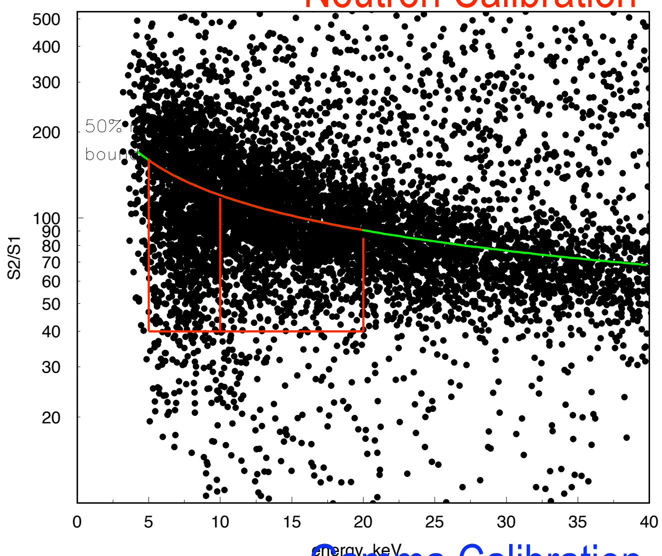




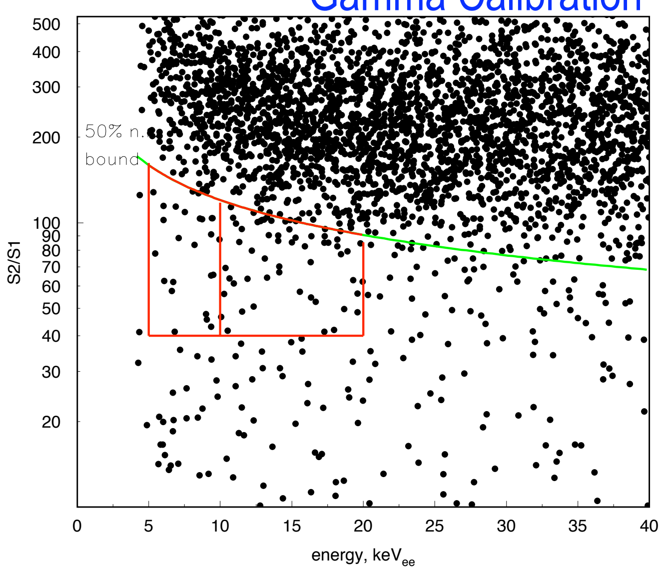
- 5 months continuous operation
- 1.0t*day of raw DM data

Discrimination Power

Neutron Calibration



Gamma Calibration



- AmBe calibration (upper)
- Co-60 Calibration (lower)
  - Used to define acceptance window
  - 50% n.r. acceptance shown
  - lower S2/S1=40 bound fixed
  - Box defined 5-20keVee
- Uniform population across plots
  - high rate calibrations (esp Co-60)
  - coincidences between events and ‘dead-region’ events
- 98.5% γ discrimination at 50% n.r. acceptance

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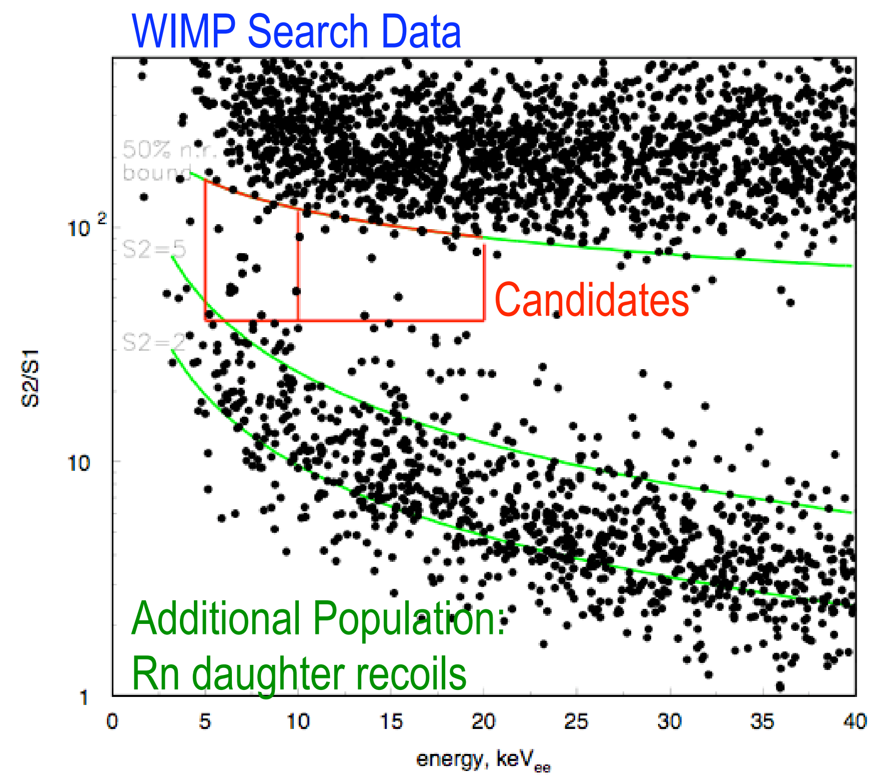
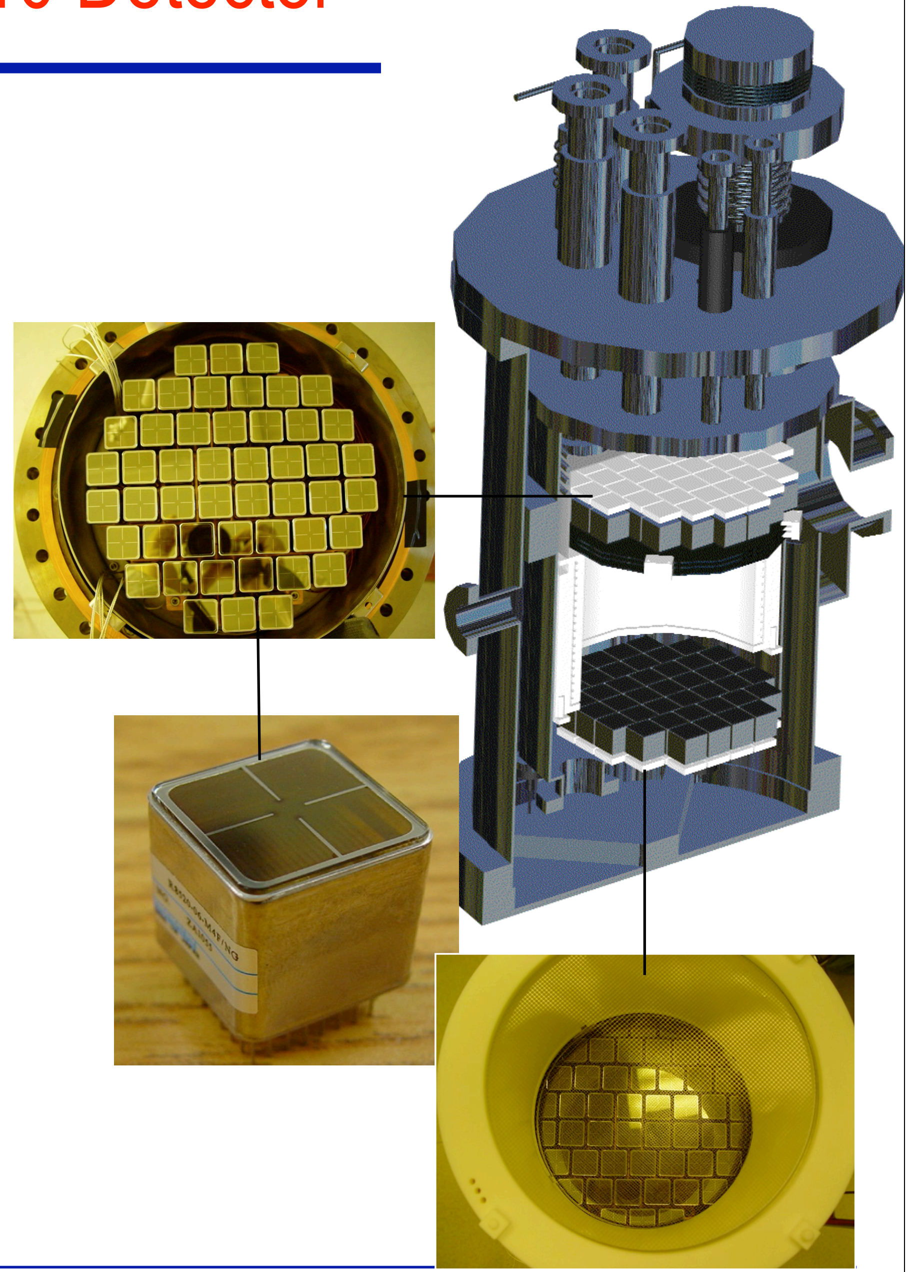
ZEPLIN II

- 31 live days running, 225 kg-days exposure
  - Red Box is 5-20keVee, 50% NR acceptance based on neutron calibration
  - 29 candidate events seen
    - Estimate 50% from ER leakage from upper band
    - Other 50% from lower band which are Radon daughters plating on PTFE side walls
  - Both populations have been modeled and subtraction performed
  - Final results is <10.4 events (90% CL) consistent with WIMP



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} ($v_{d,e-} \approx$ 2mm/µs), $\sigma_Z \approx$0.3 mm
- Cooling: Pulse Tube Refrigerator (PTR),
- 90W, coupled via cold finger (LN2 for emergency)



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

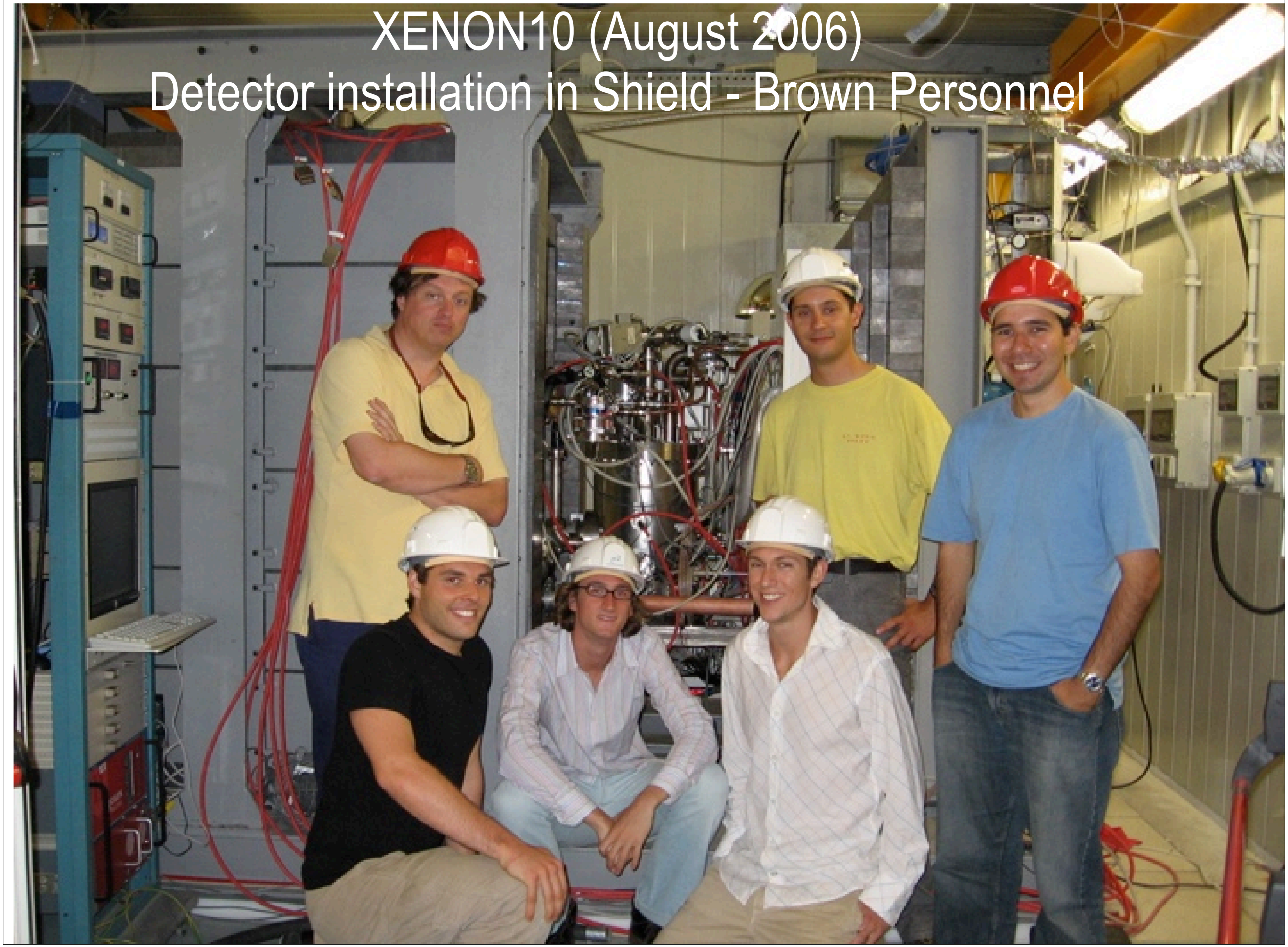
Rice University Uwe Oberlack, Roman Gomez, Christopher Olsen and Peter Shagin

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

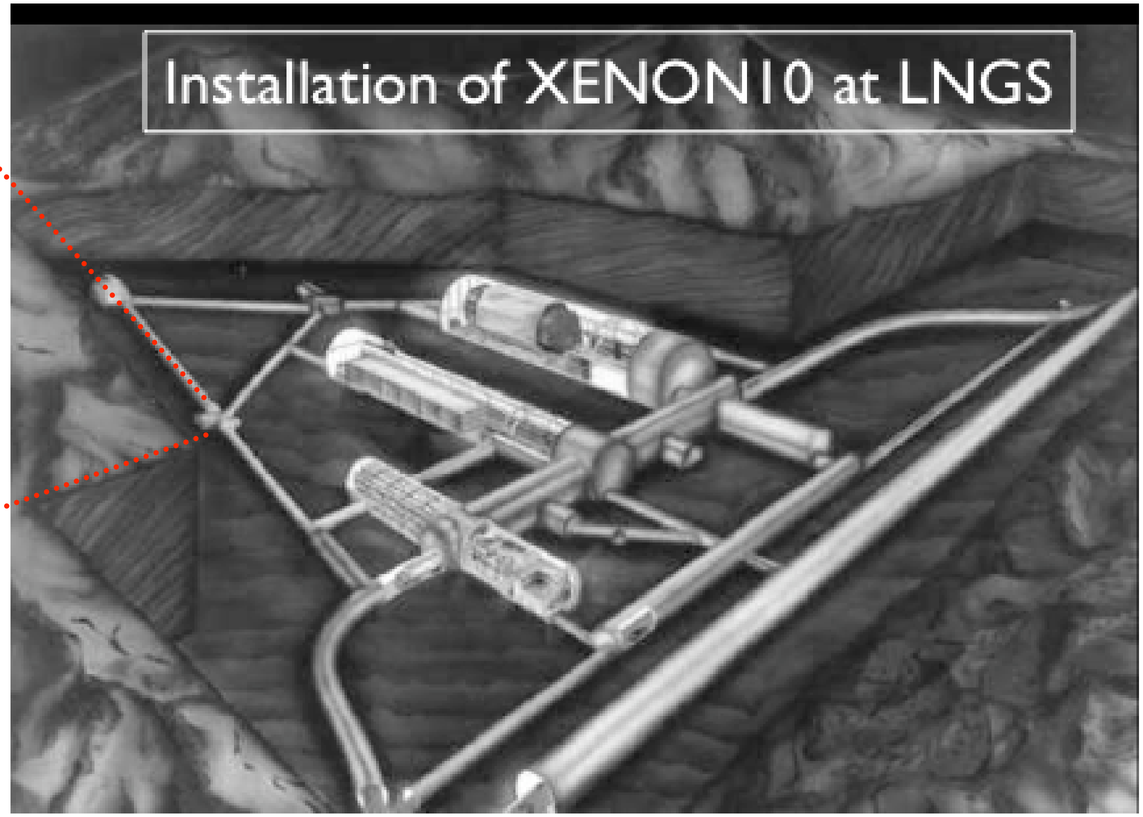
LNGS Francesco Arneodo and Alfredo Ferella

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

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



XENON10 Underground Installation



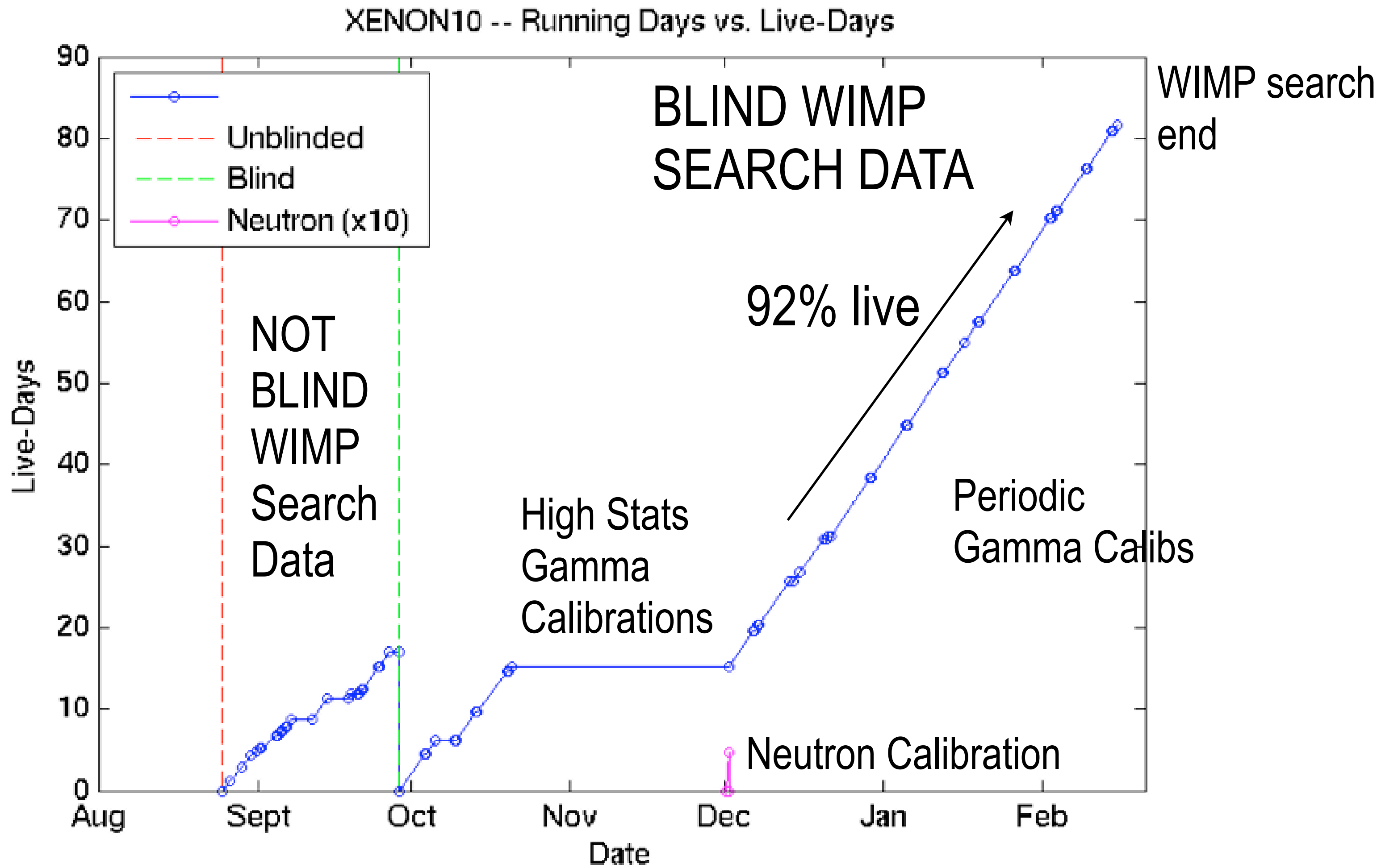
- Installed March 2006 @ LNGS (~3100 mwe)
- Muon flux ~ 24 μ/m^2/day (10^6 reduction from sea level)
- Began detector calibration end of March
- Began shield installation May 2006
- (bottom left) Installing steel frame on top of 15 cm External HDPE

XENON10: Ready for Low Background Operation

Installation of the Detector...

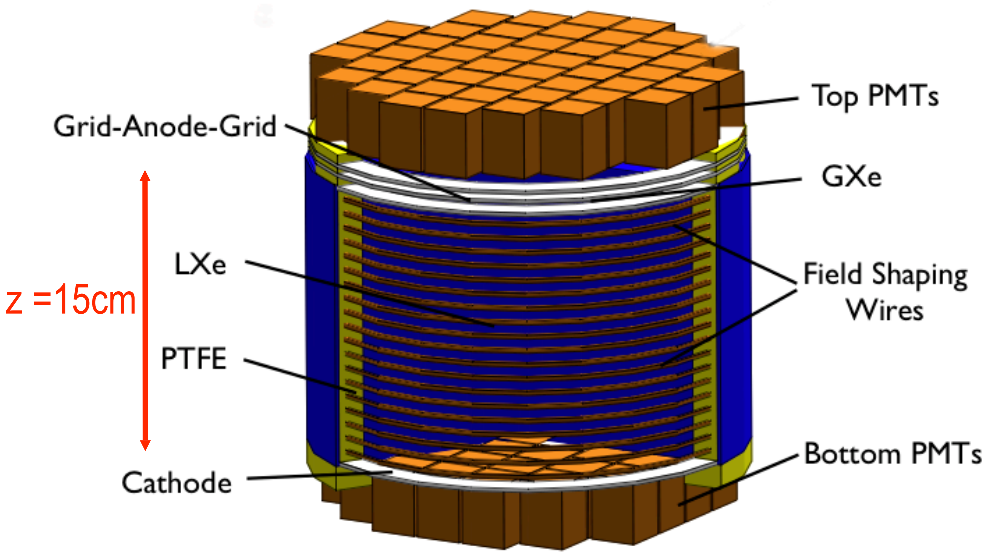
...and we are operational

XENON10 Live time at Gran Sasso

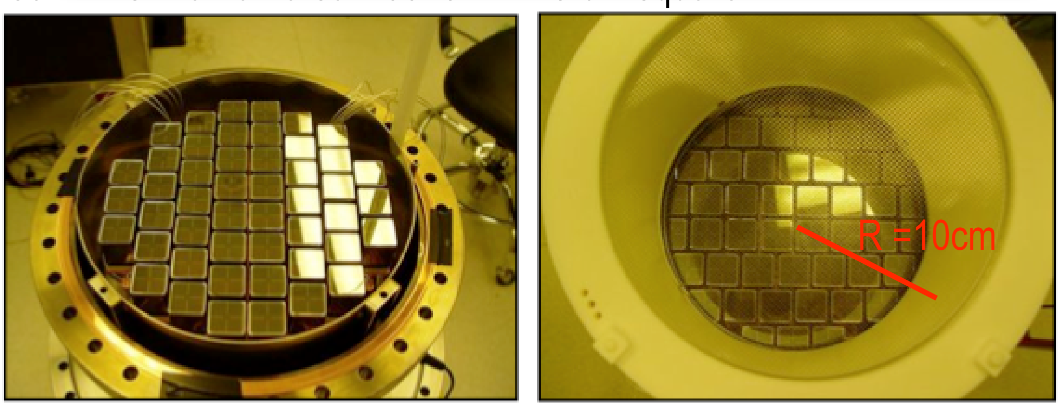


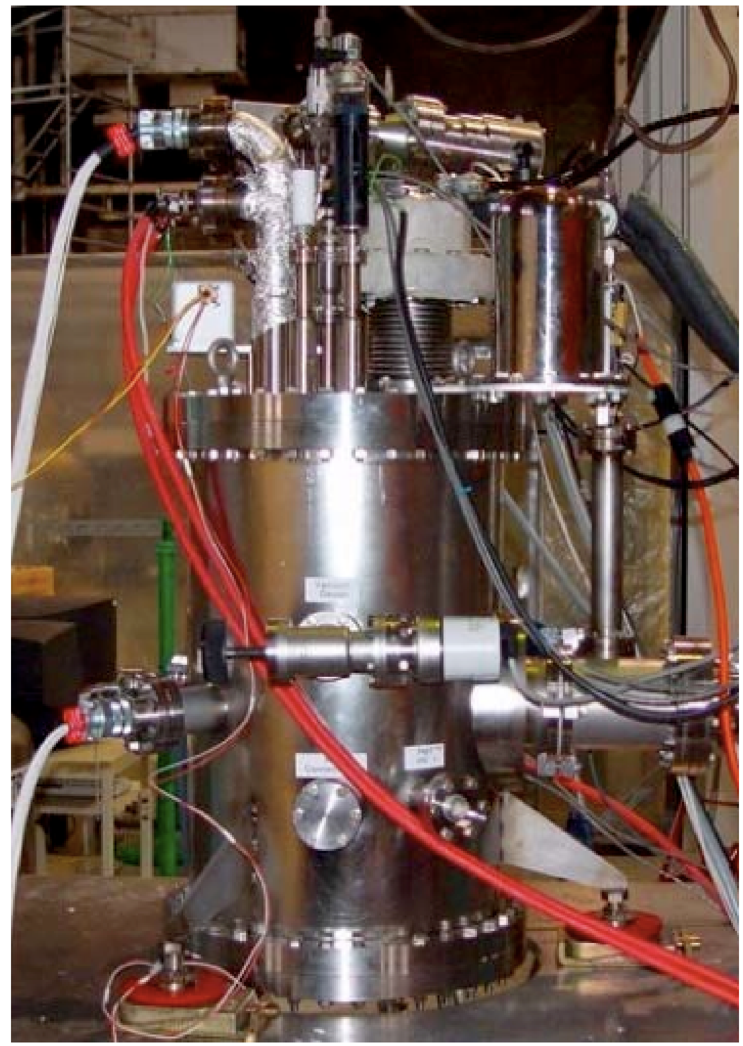
- High Statistics Gamma Calibs + 1 Neutron Calib
- NON BLIND WIMP search data ~20 live days (Sept) + 20 live days dispersed (Oct-Feb)
- BLIND WIMP Search results from 60 live day (Oct-Feb)

XENON10 Detector



89 PMTs: Hamamatsu R8520-AL 2.5 cm square

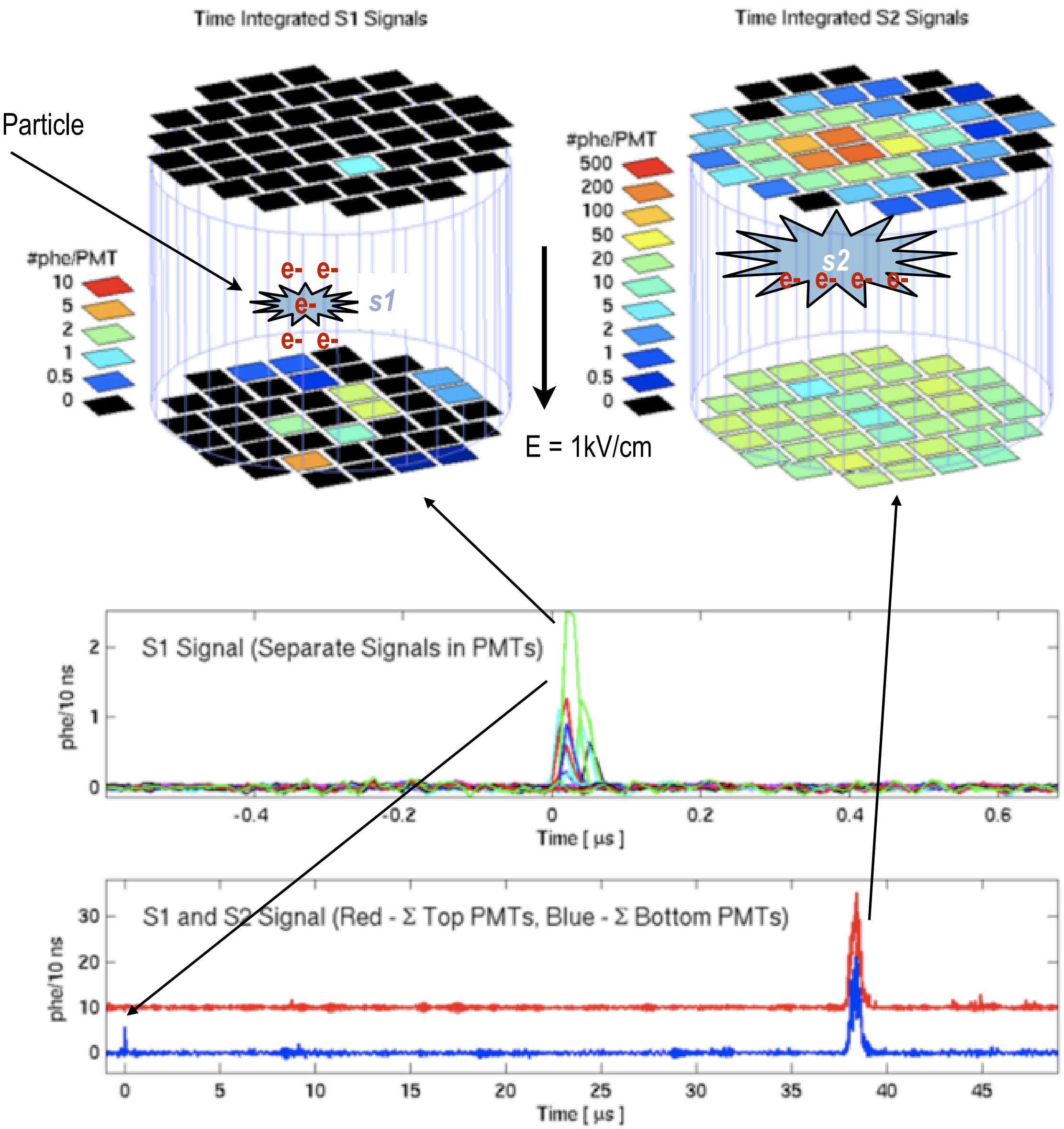




XENON10 Event Discrimination

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

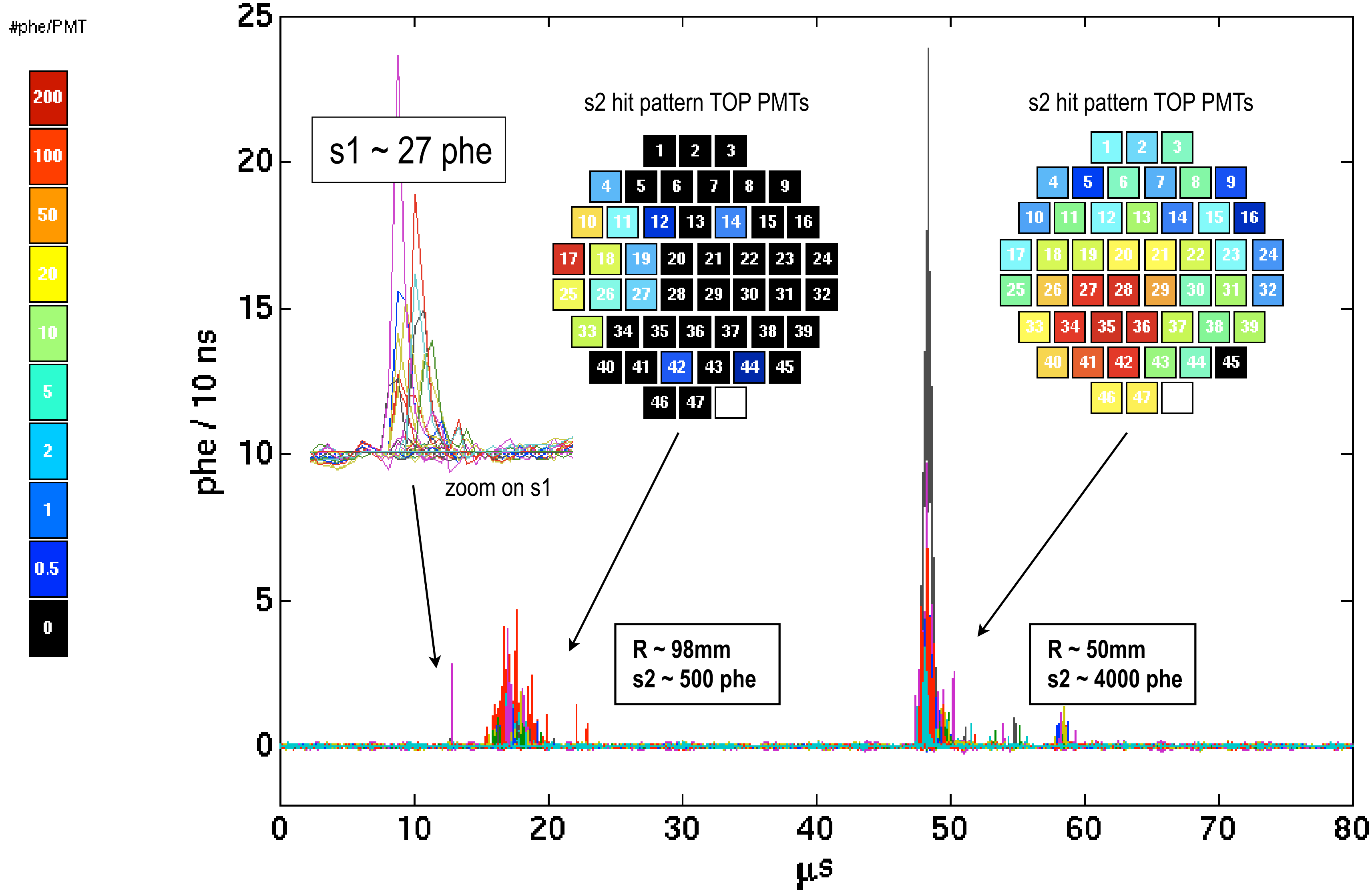
$(s2/s1)_{ER} > (s2/s1)_{NR}$

Expect > 99% rejection efficiency of γ/n Recoils…

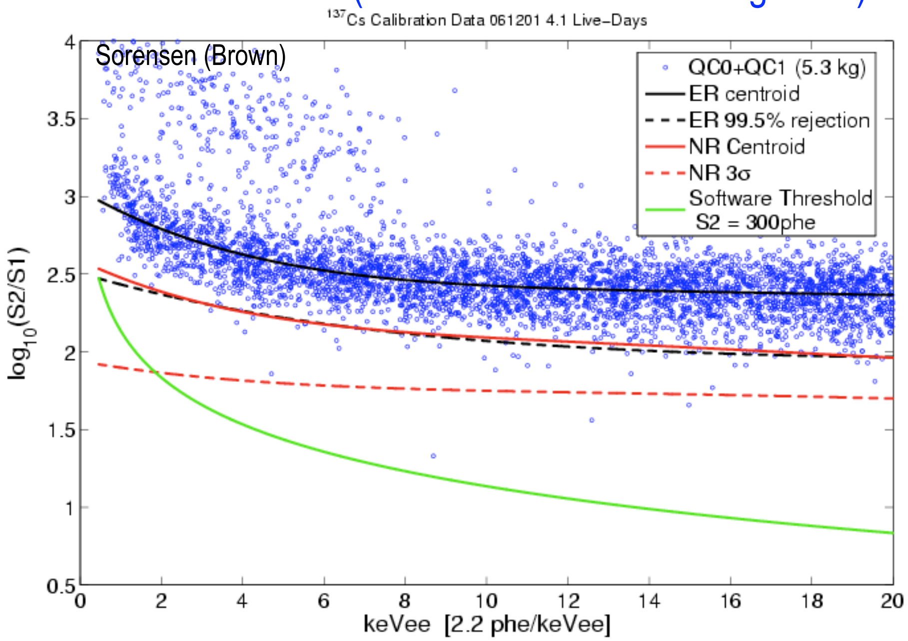
Reduction of Backgrounds =>

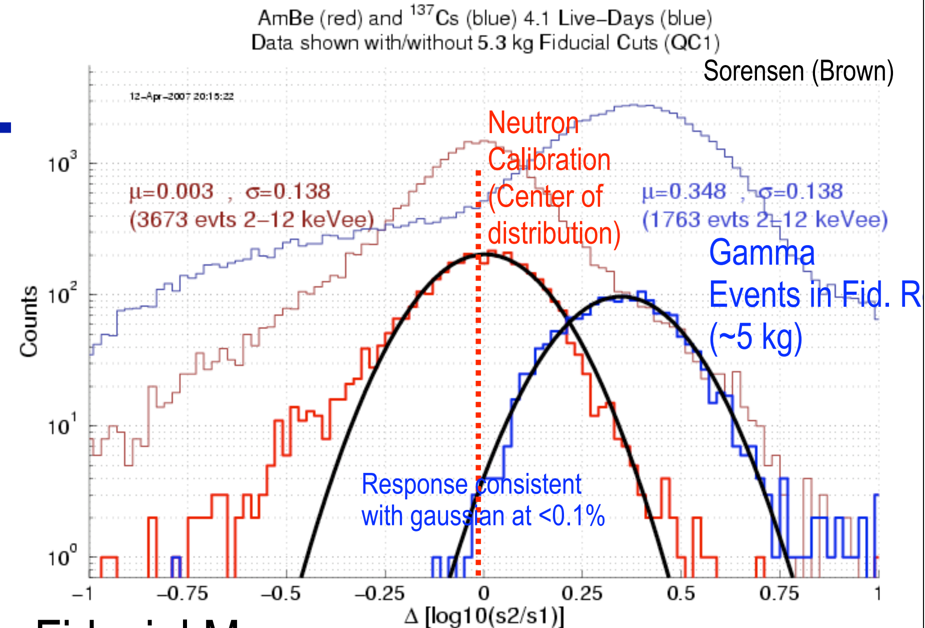
Reduction of Leakage Events

Event Localization / Double Scatter Event

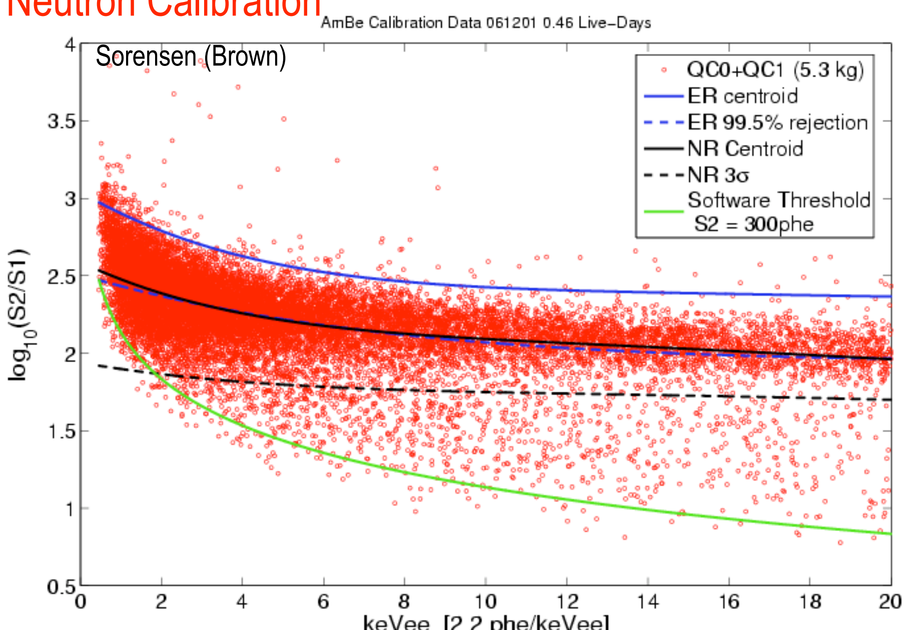


Gamma Calibration (Electron Recoils == Background)





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

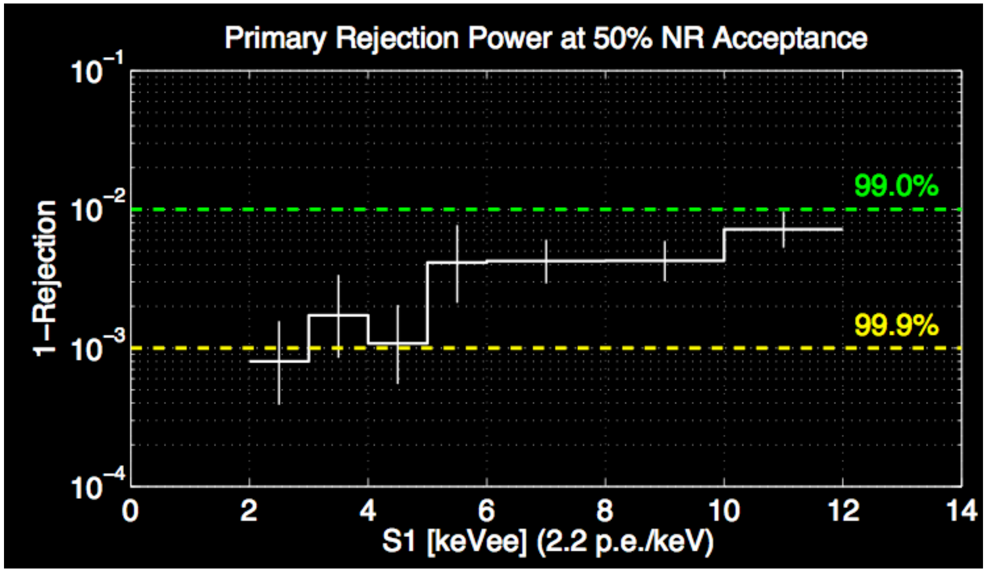
Nuclear Recoil (NR), Electron Recoil (ER) Discrimination

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

Analysis of the ER rejection was performed in energy bins 2-3, 3-4 ..-12 keVee

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.

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

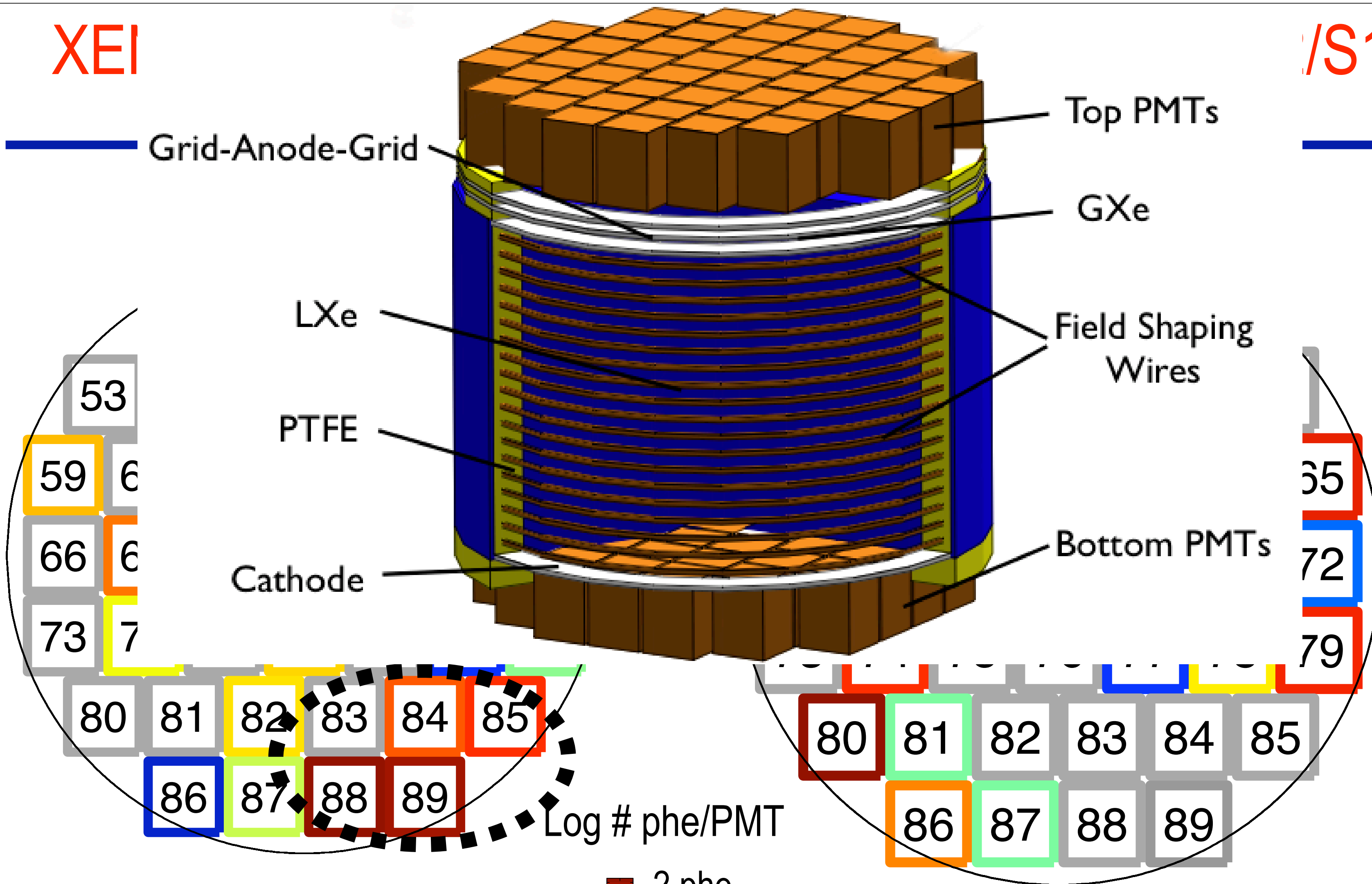
QC2: High level cuts

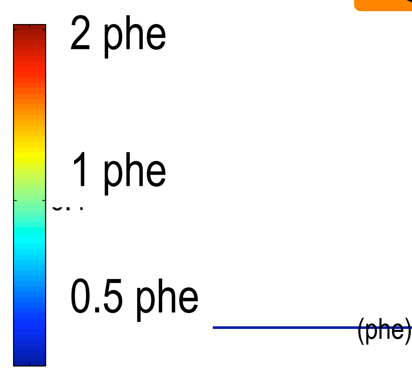
Cuts based on the distribution of the S1 signal on the top and bottom PMTs. They are designed to remove events with anomalous or unusual S1 patterns

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

see Guillaume Plante, Columbia, APS Talk

XEI /S1





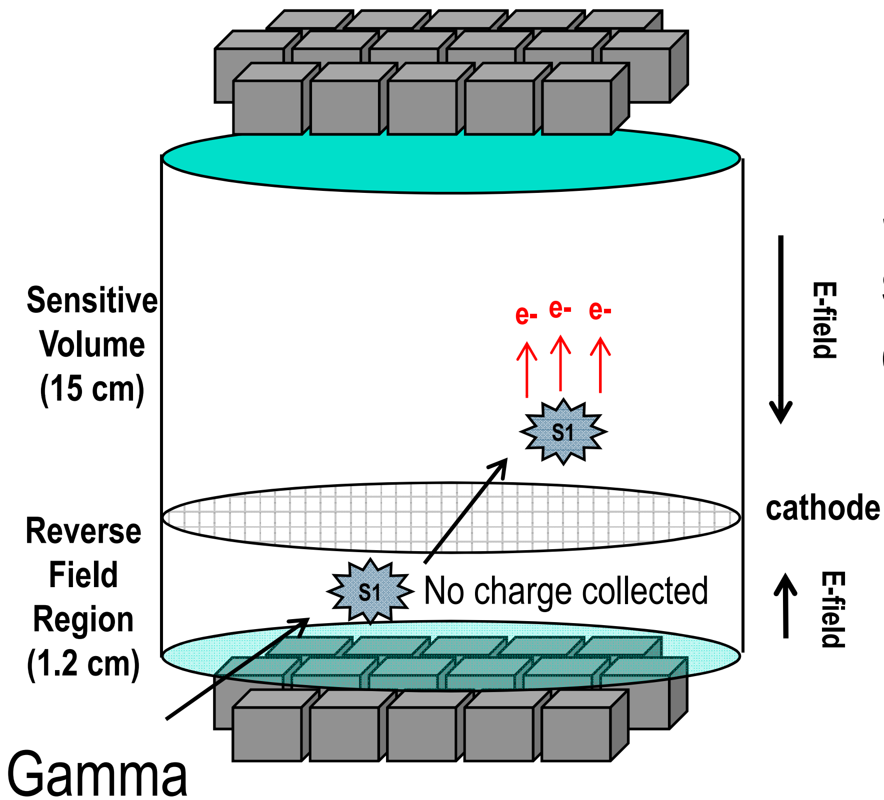
Event with light concentrated locally => multiple scatter incl hit near bottom PMTs

Regular Event for comparison

Anomalous S1 Hit Patters & Leakage

§Multiple scatter events

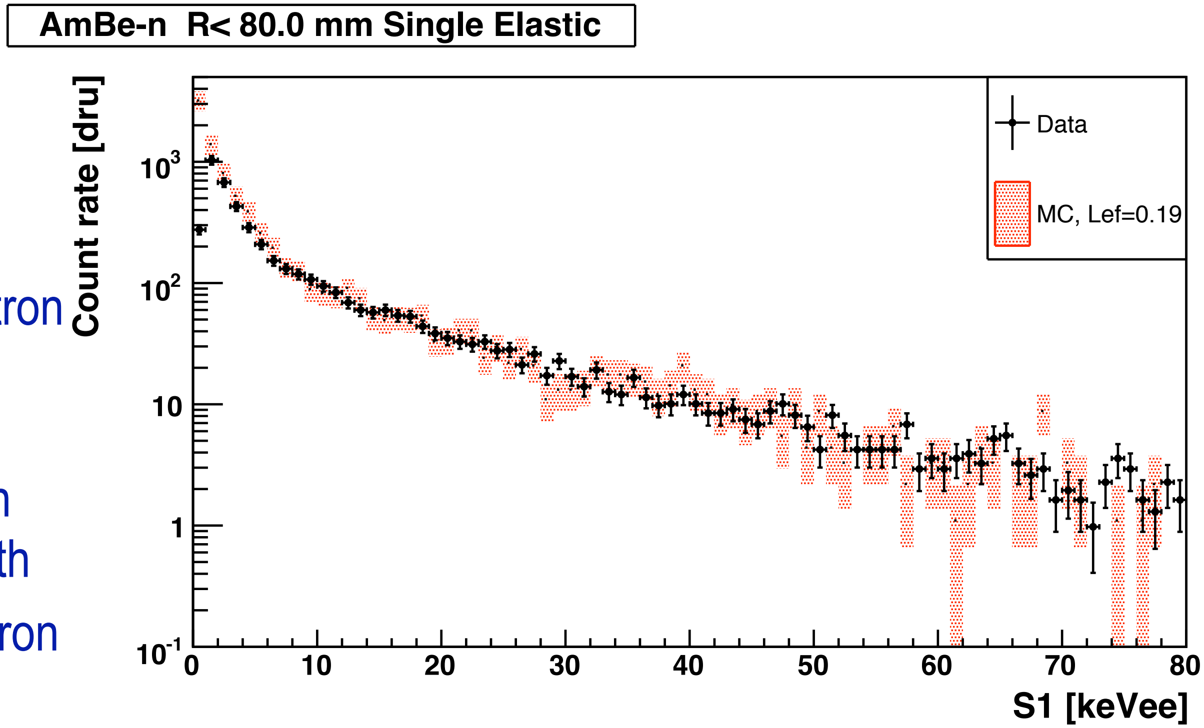
- But only one S2 signal ... second vertex is in LXe where we are not collecting charge e.g. Reverse Field Region below cathode

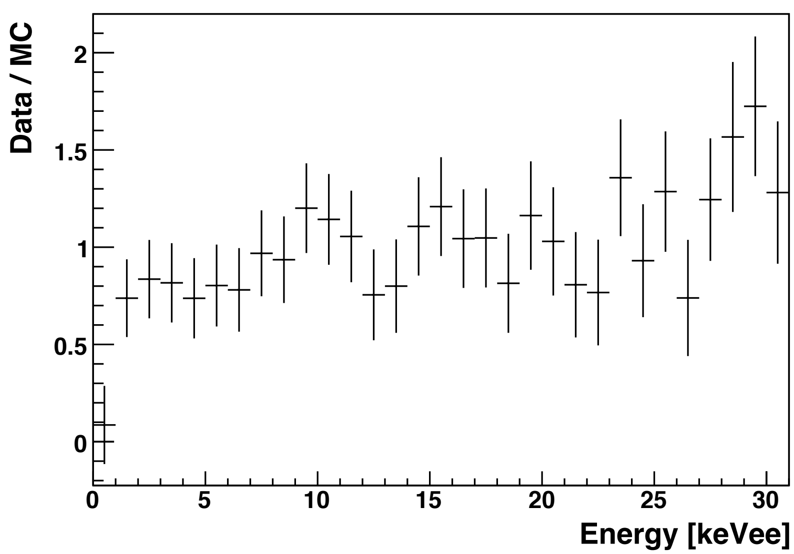


S2/S1 ratio is reduced since S1 has two contributions, but S2 has only one.

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



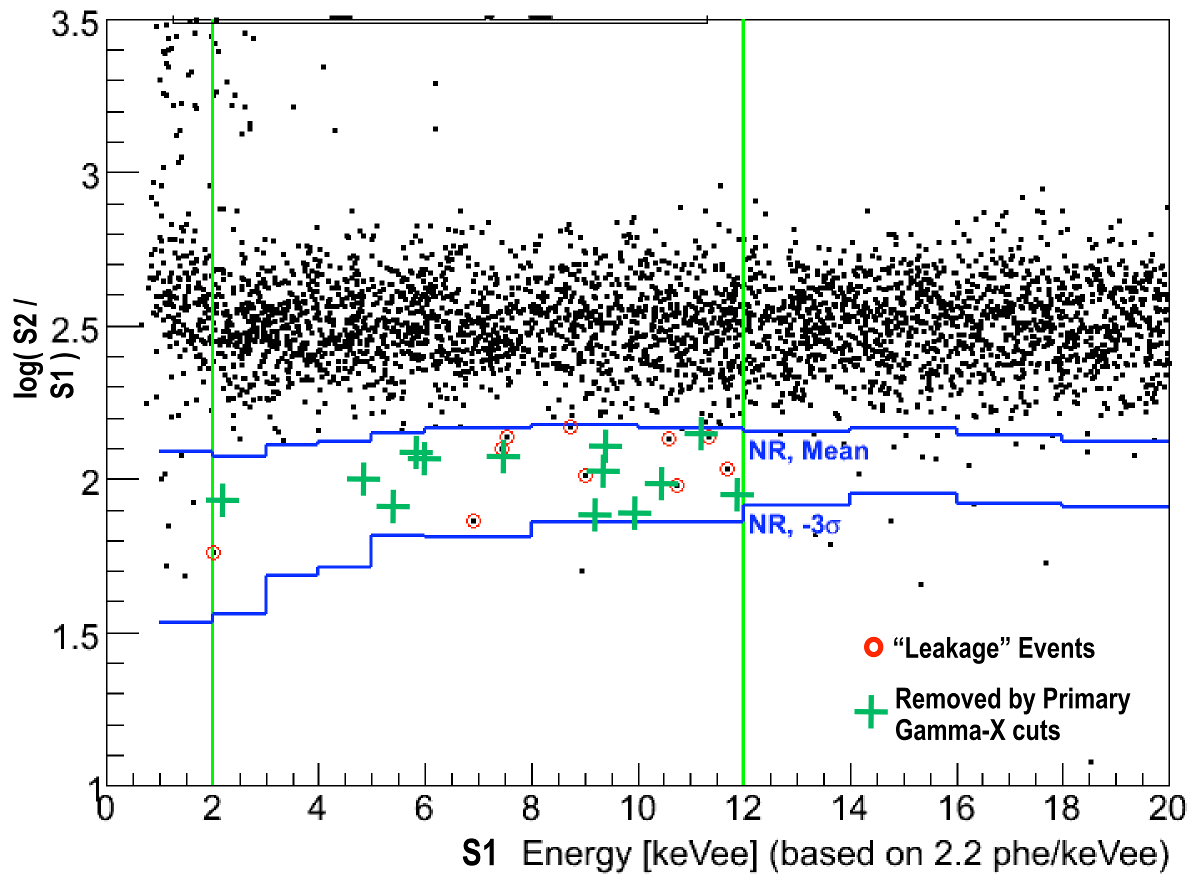


Applying the Gamma-X Cuts to XENON10 Data

- **XENON10 Blind Analysis – 58.6 days**
  - WIMP "Box" defined at
    - ~50% acceptance of Nuclear Recoils (blue lines): [Centroid -3σ]
    - 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



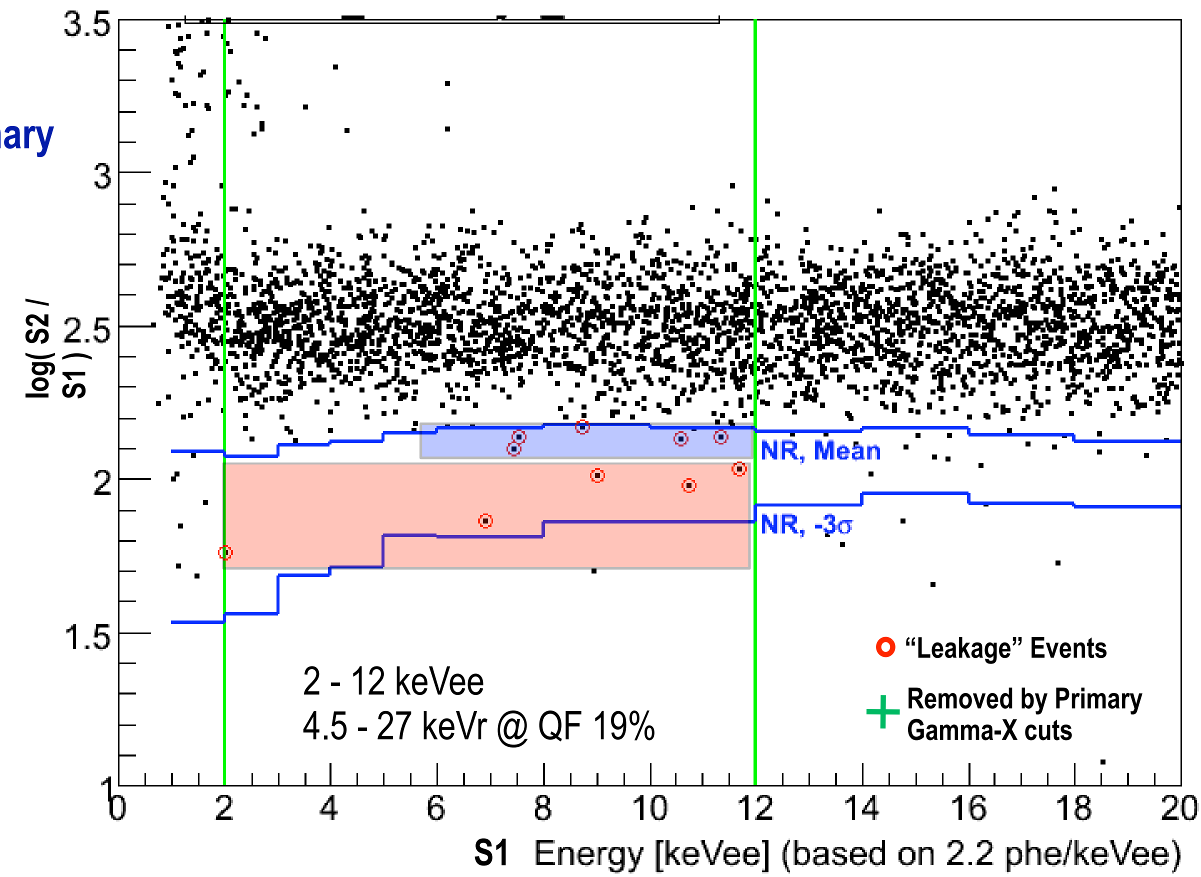
Applying the Gamma-X Cuts to XENON10 Data

§XENON10 Blind Analysis – 58.6 days

- § WIMP "Box" defined at
  - ~50% acceptance of Nuclear Recoils (blue lines): [Centroid -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

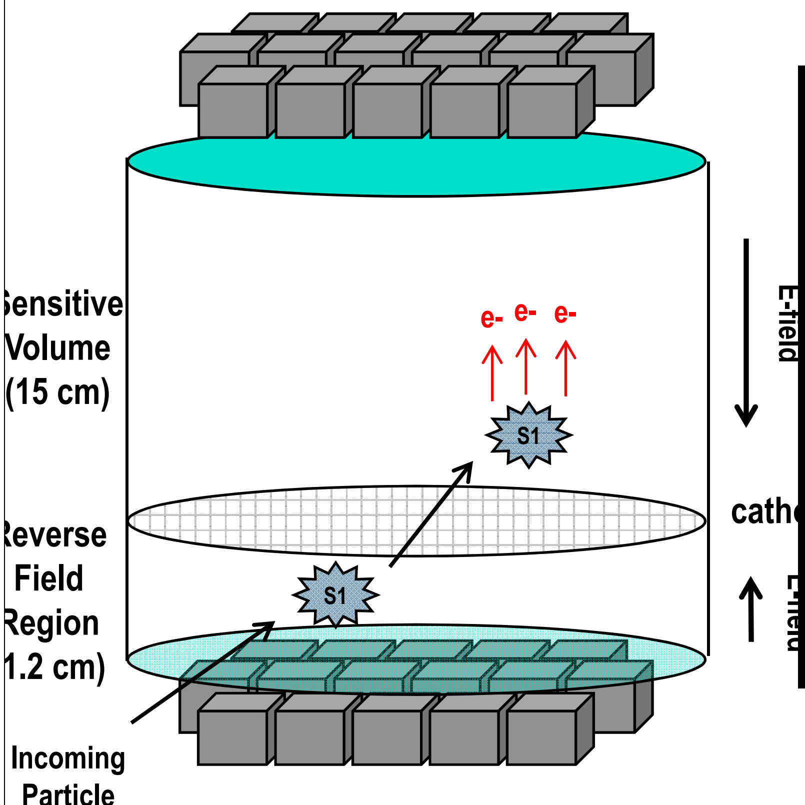
Δlog (S2 / S1) vs S1

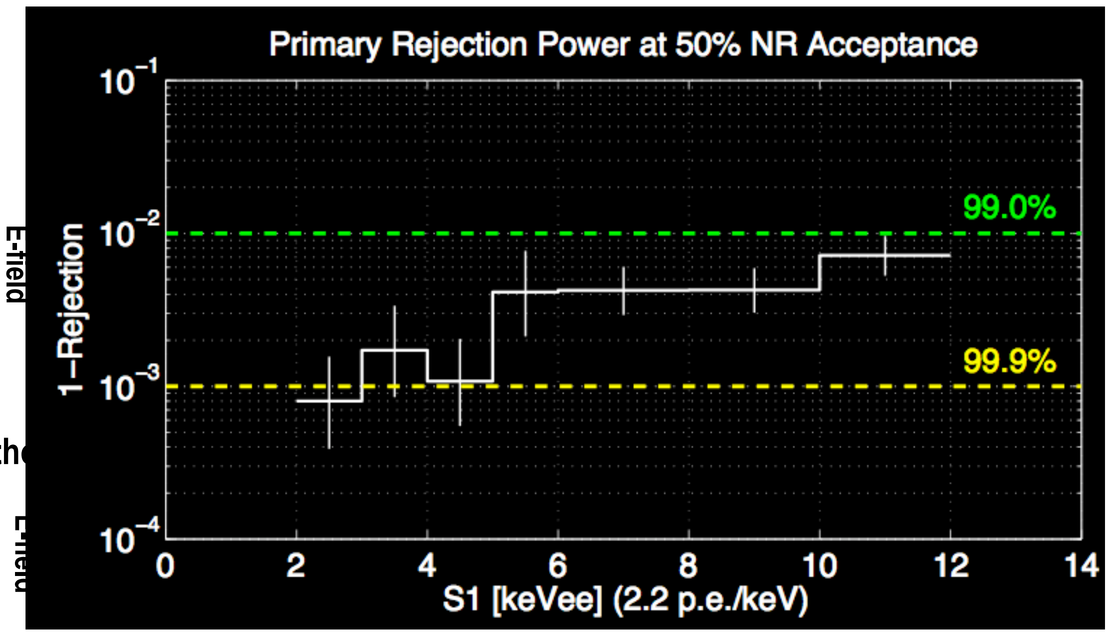
"Straightened Y Scale" – ER Band Centroid normalized => 2.5



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)



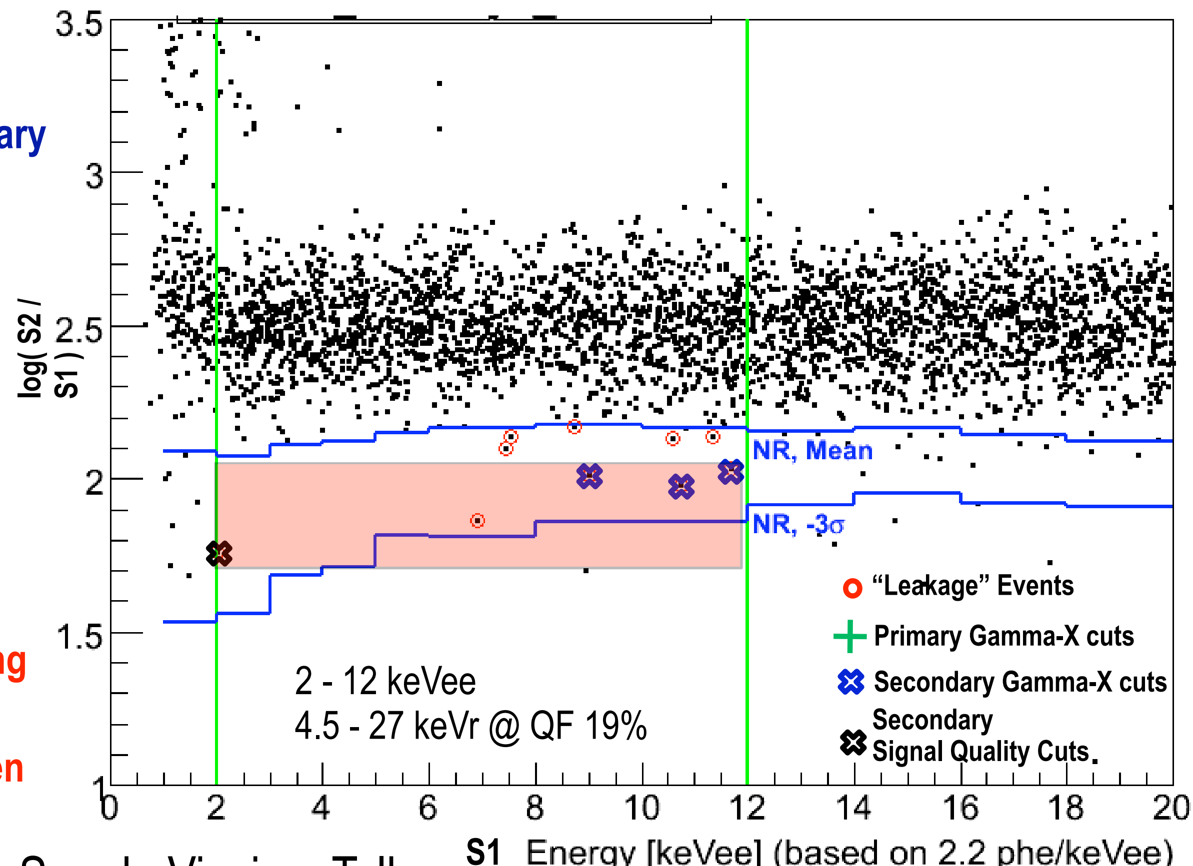


Applying the SECONDARY Gamma-X Cuts to XENON10

- 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

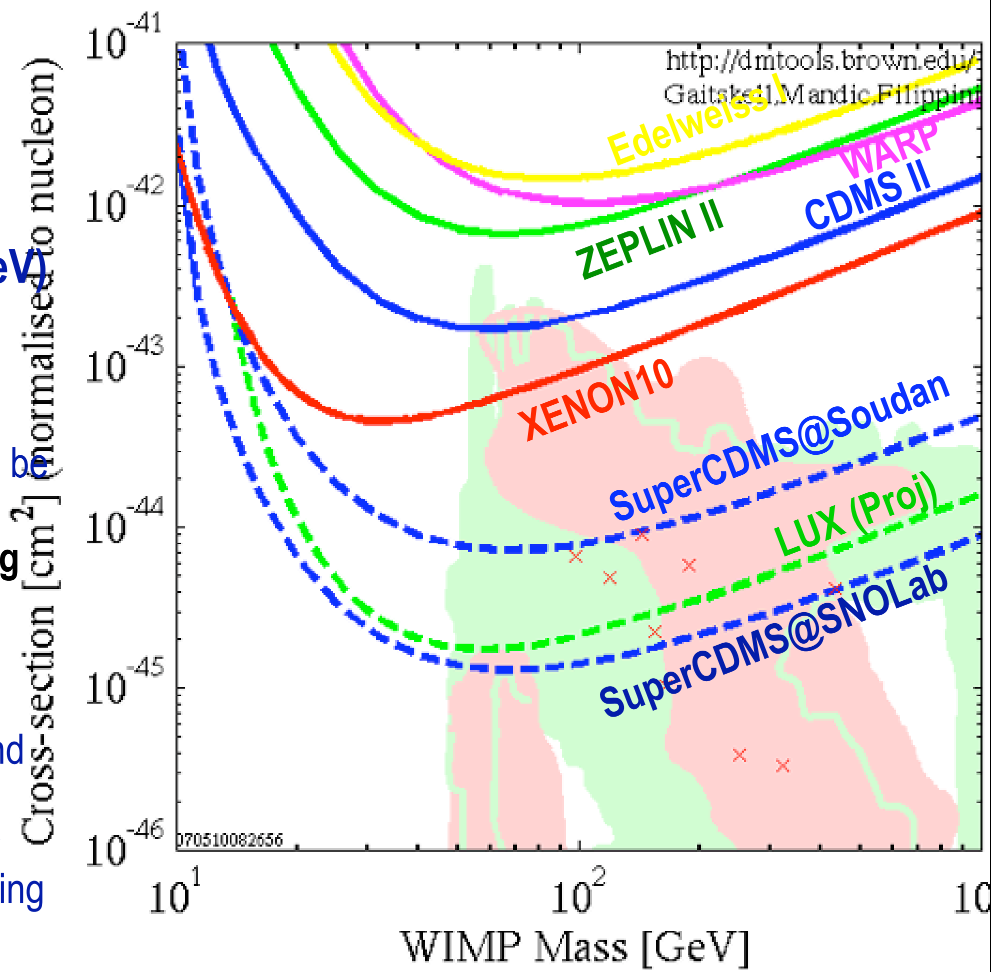
"Straightened Y Scale" – ER Band Centroid => 2.5



See de Viveiros Talk

Dark Matter Results and (some of Goals)

- Dark Matter Goals
  - XENON10
    - Two month run
    - 136 kg-days net exposure
  - LUX - Sensitivity curve at $2x10^{-45}$ 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 $7x10^{-4}$ /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

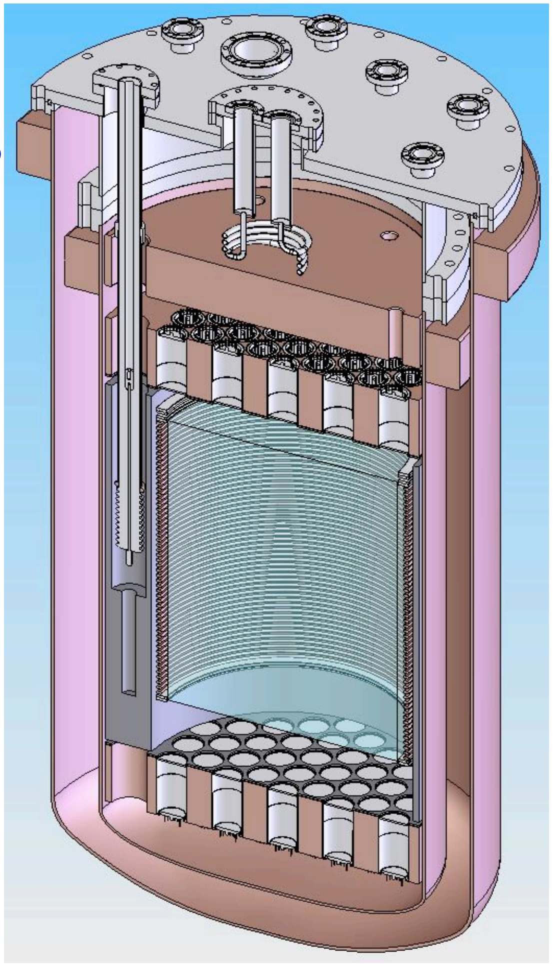


(XENON10 curve no background subtraction)

LUX Dark Matter Experiment - Summary

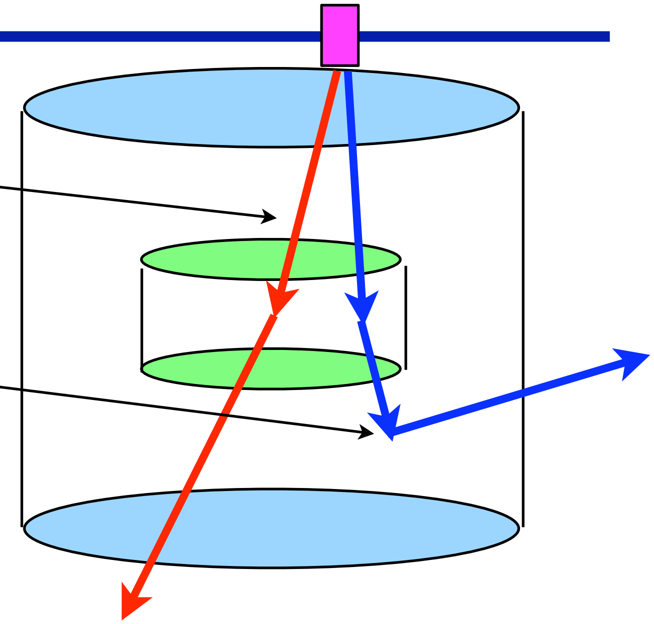
- Brown [Gaitskell], Case [Shutt], LBNL [Lesko] , LLNL [Bernstein], Rochester [Wolfs], Texas A&M [White], UC Davis [Svoboda/Tripathi], UCLA [Wang/Arisaka/Cline]
  - XENON10, ZEPLIN II (US) and CDMS; ν Detectors (Kamland/SuperK/SNO/Borexino); HEP/γ-ray astro
  - (Also ZEPLIN III Groups after their current program trajectory is established)
  - Co-spokespersons: Shutt (Case)/Gaitskell (Brown)
- 300 kg Dual Phase liquid Xe TPC with 100 kg fiducial
  - Using conservative assumptions: >99% ER background rejection for 50% NR acceptance, E>10 keVr

    (Case+Columbia/Brown Prototypes + XENON10 + ZEPLIN II)
  - 3D-imaging TPC eliminates surface activity, defines fiducial
- Backgrounds:
  - Internal: strong self-shielding of PMT activity
    - Can achieve BG $\gamma+\beta$ < 7×10^{-4} /keVee/kg/day, dominated by PMTs (Hamamatsu R8778 or R8520).
    - Neutrons (α,n) & fission subdominant
  - External: large water shield with muon veto.
    - Very effective for cavern γ+n, and HE n from muons
    - Very low gamma backgrouns with readily achievable <10^{-11} g/g purity.
- DM reach: 2×10^{-45} cm^2 in 4 months
  - Possible <5×10^{-46} cm^2 reach with recent PMT activity reductions, longer running.

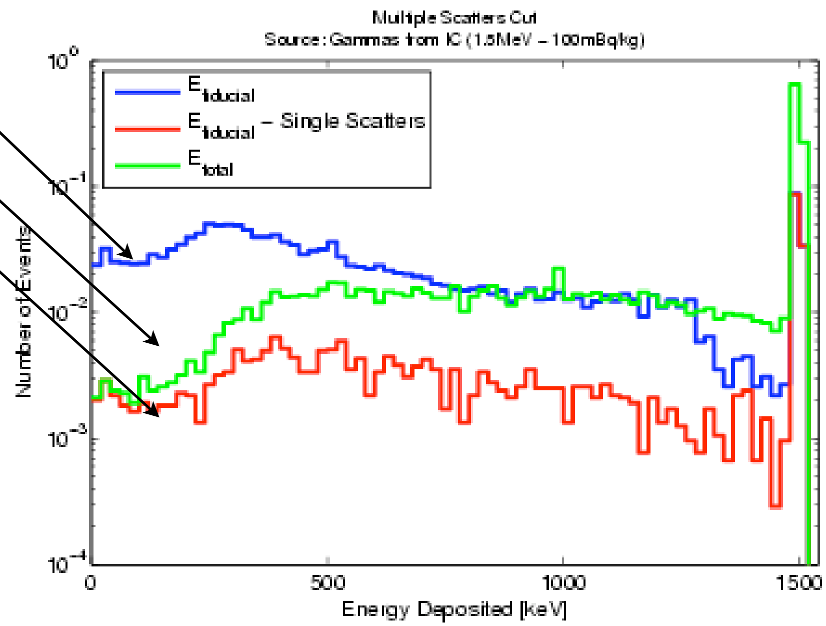


http://www.luxdarkmatter.org

Topology of Gamma Events That Deposit Energy in FV



- The rate of ER events in FV is determined by small angle scattering Compton events, that interact once in the FV
  - The rate of above events is suppressed by the tendency for the γ's to scatter a second time. Either on the way in, or way out.
  - The chance of no secondary scatter occurring is more heavily suppressed the more LXe there is
    - The important optimization is to maximize the amount of LXe that lies along a line from the greatest sources of radioactivity (PMTs?) that pass through the FV.
- Example for 1.5 MeV γ from outside LXe volume
  - Energy Spectrum for part of energy deposited in FV
  - Energy spectrum for all energy in detector
  - Additional application of multiple scatters cut has little additional effect on low energy event rate

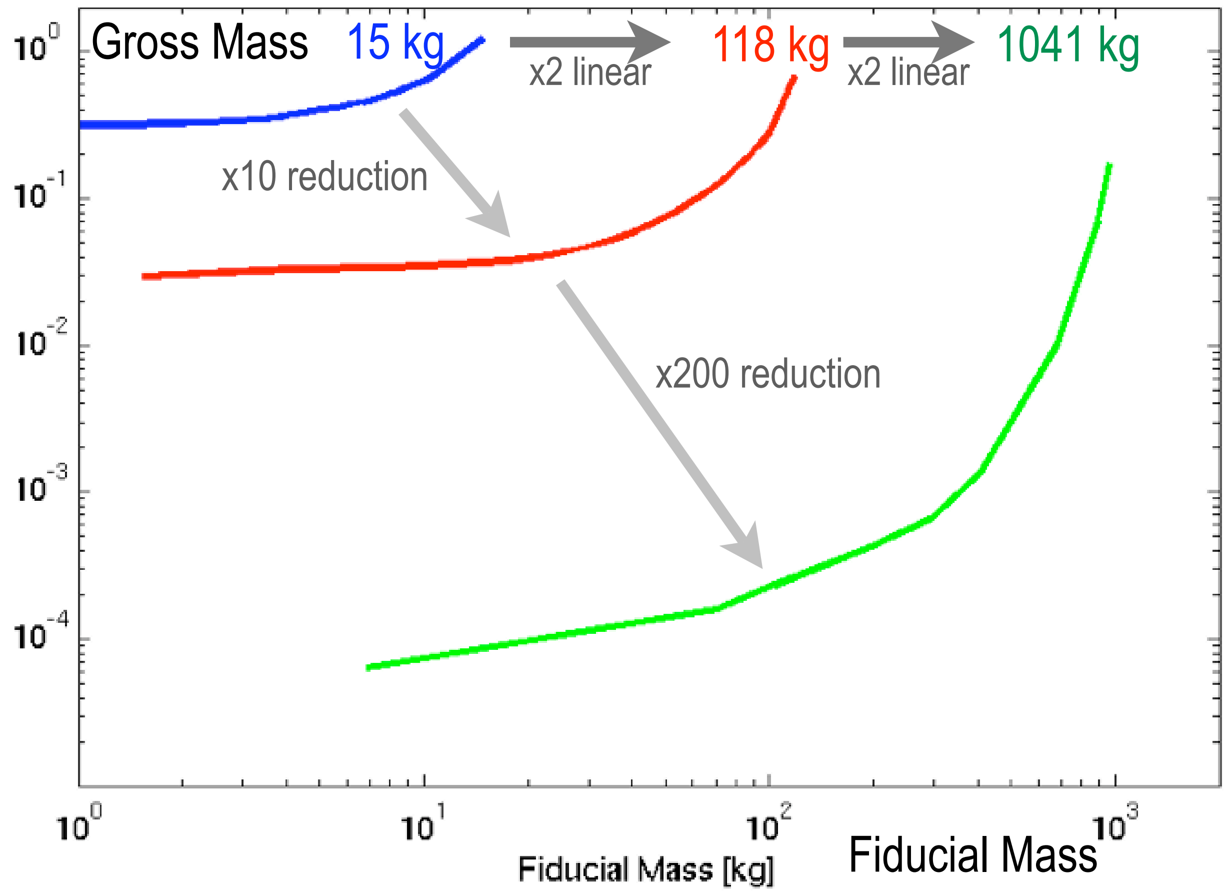


- Conclusion for Event Suppression
  - xyz resolution of detector is important simply in defining FV. Little additional reduction from locating vertices.
  - (Full xyz hit pattern does assist in bg source identification)

Scaling LXe Detector: Fiducial BG Reduction /1

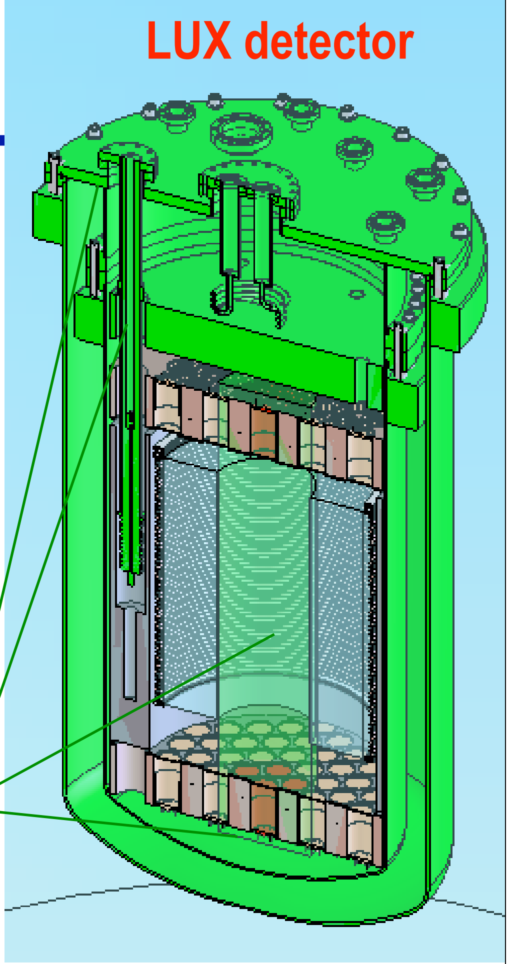
- Compare LXe Detectors (factor 2 linear scale up each time)
  15 kg (ø21 cm x 15 cm) -> 118 kg (ø42 cm x 30 cm) -> 1041 kg (ø84 cm x 60 cm)
  - Monte Carlos simply assume external activity scales with area (from PMTs and cryostat) using XENON10 values from screening

Low energy rate in FV before any ER vs NR rejection /keVee/kg/day

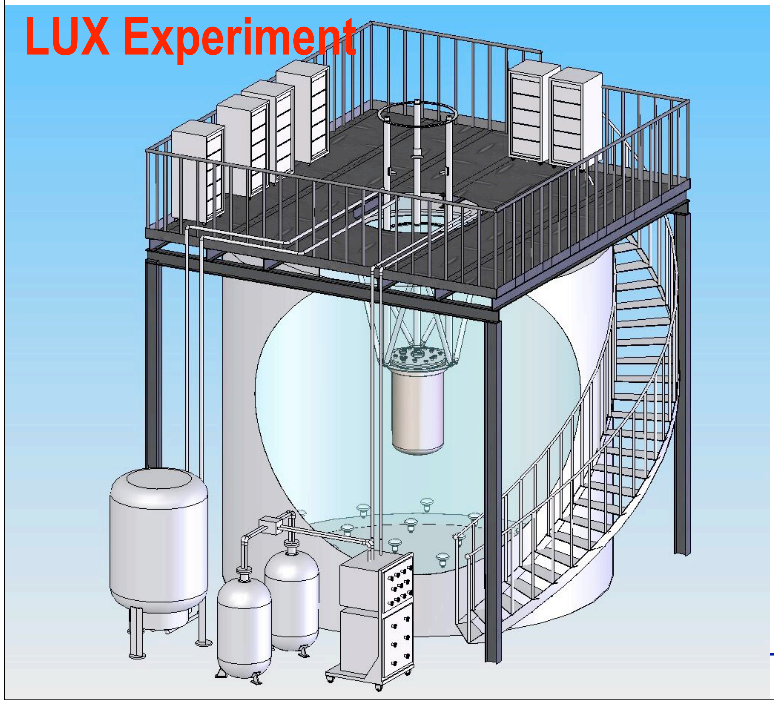


dru = cts/keVee/kg/day

LUX program: exploit scalability

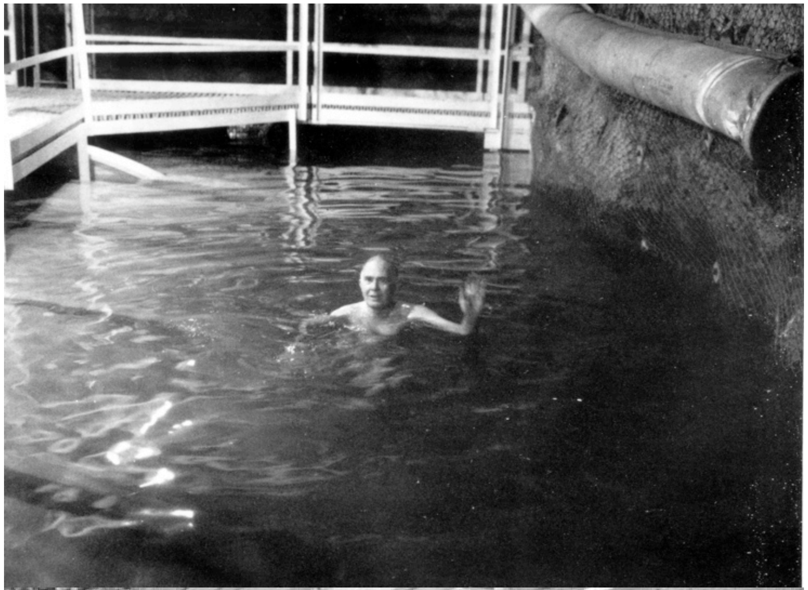


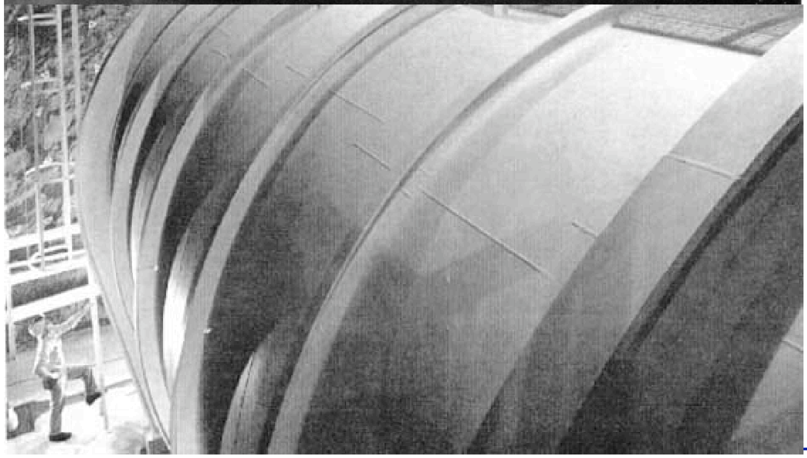
- LUXcore: Final engineering for large-scale detector
  - Cryostat, >100 kV feedthrough, charge drift, light collection over large distance
  - Full system integration, including ~1m water shield
  - 40 kg narrow "core", 14 PMTs, 20 cm Ø x 40 cm tall.
    - Radial scale-up requires full-funding.
  - Under construction, Jan 2007, operations at Case: June 2007.

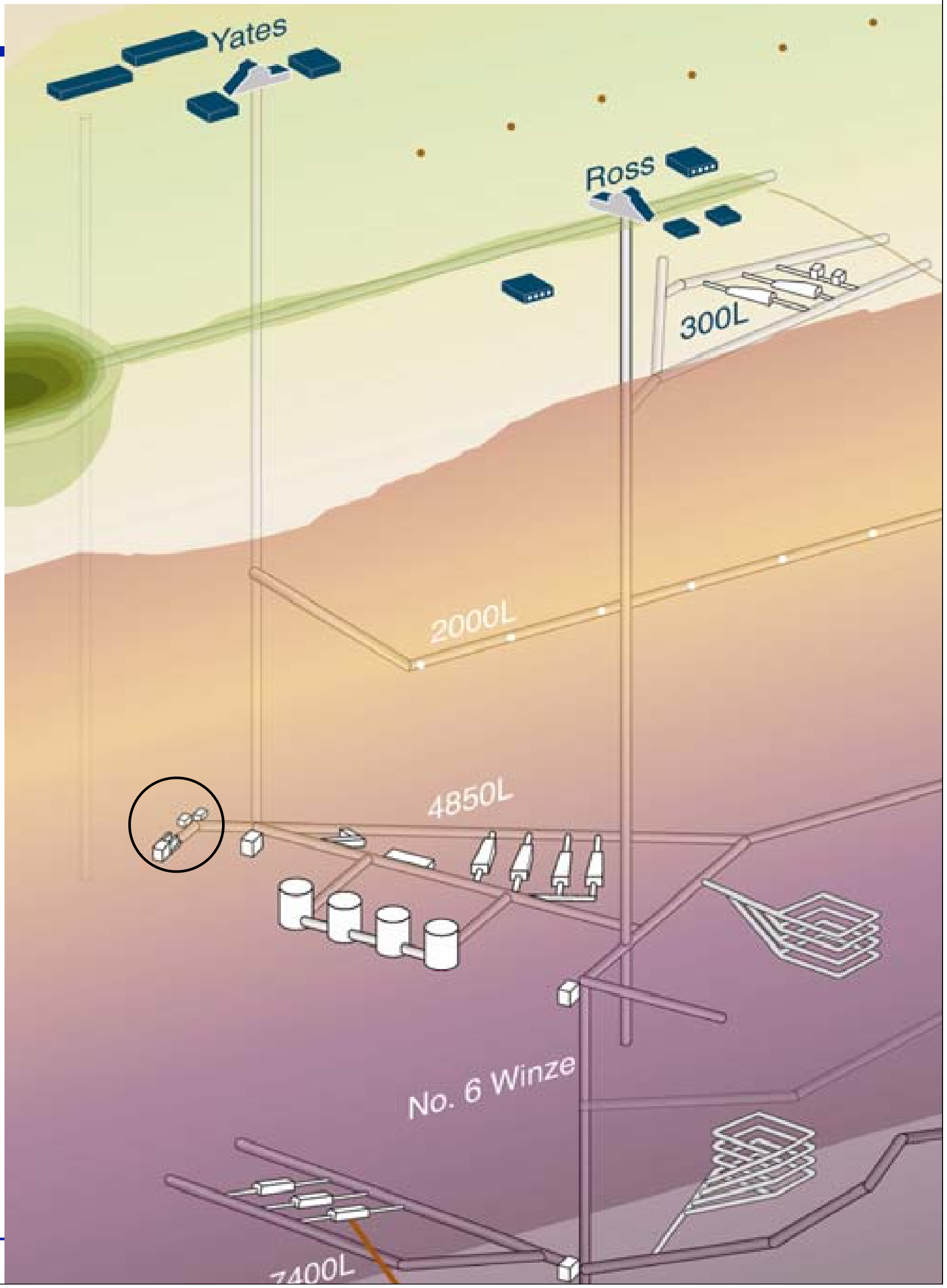


- LUX in ~ 6m Ø water shield
- Very good match to early-implementaion DUSEL (e.g., Homestake "Davis" cavern)
  - SNOLAB LOI
- System scalable to very large mass.

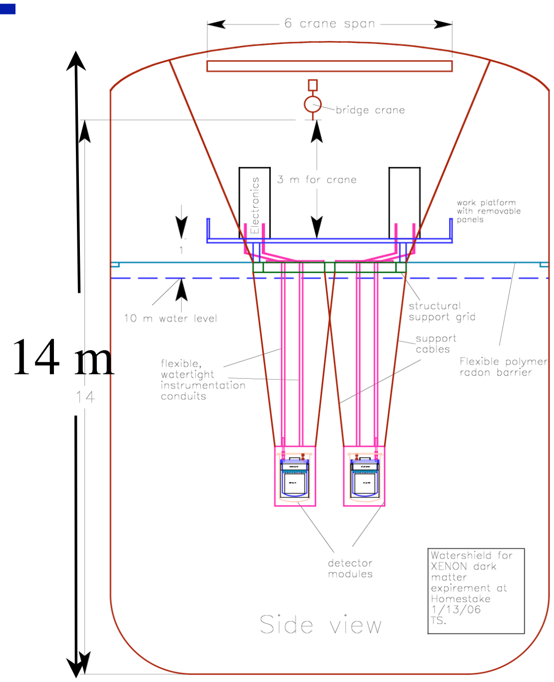
Water Shield - Homestake - Davis Cavern

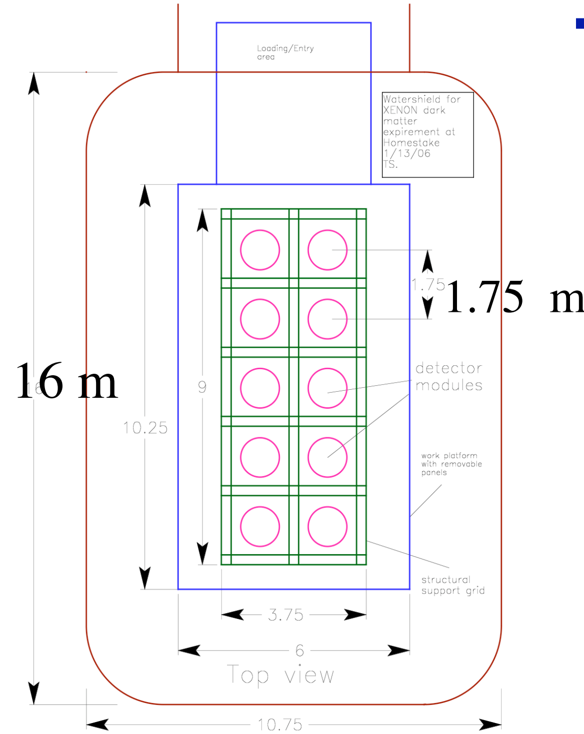






Homestake / Potential DUSEL Site (Lesko, LBL)





- DUSEL process for new national underground lab.
  - Site Decision mid 2007 (Full DUSEL lab 2010->)
- 4850 mwe depth at Homestake - early program.
- Water Shield: >4 m shielding / 10 module system

Noble Liquids for Dark Matter

- Summary
  - Past two years we have seen rapid progress in demonstrated performance (NR-ER discrimination/energy resolution/light yields) of Noble Liquid Detectors in low energy regime
  - Competitive WIMP Search Results from WARP (Ar), ZEPLIN II (Xe), XENON10 (Xe)
- Single Phase (Liquid only) - Pulse Shape Discrimination (ER)
  - Ar/Ne demonstrating >10^5:1 discrimination at 50 keVr, limitations not fundamental.
    - Will push these tests to 10^8:1 using higher light yields/shielding in test facilities (required for 10^{-45} cm^2 dm reach)
  - Position reconstruction based on photoelectron hit patterns (timing not useful in <=10 tonne scale). Mis-reconstruction
    - 39Ar (160 evts /keVee/kg/day) / Rn daughters on surfaces (major issue)
- Dual Phase (Liquid Target/Ioniz Readout in Gas) - Discrim. Ionization/Photons+PSD (Ar)
  - Xe TPC Operation: ZEPLIN II / XENON10 (20-35 kg target)
    - Discrimination established ~10^2:1 (50% NR acceptance), fiducialize to get further bg reduction
      - –Xe intrinsically very low activity (cf XMASS) , so scaling works
  - Ar TPC (WARP) - studying use of Ionization + PSD
    - Discrimination Ionization ~10^2:1 + PSD >10^4:1 (energy threshold should be improved with better elec.)
- Scaling of Technology
  - Detector WIMP sensitivity improves very significantly with size
  - Designs are very scalable - 1 event/100 kg/month (10^{-45} cm^2) in a few years seems very realizable
  - Future instruments for 10^{-46} – 10^{-47} cm2 also realistic (performance & cost)