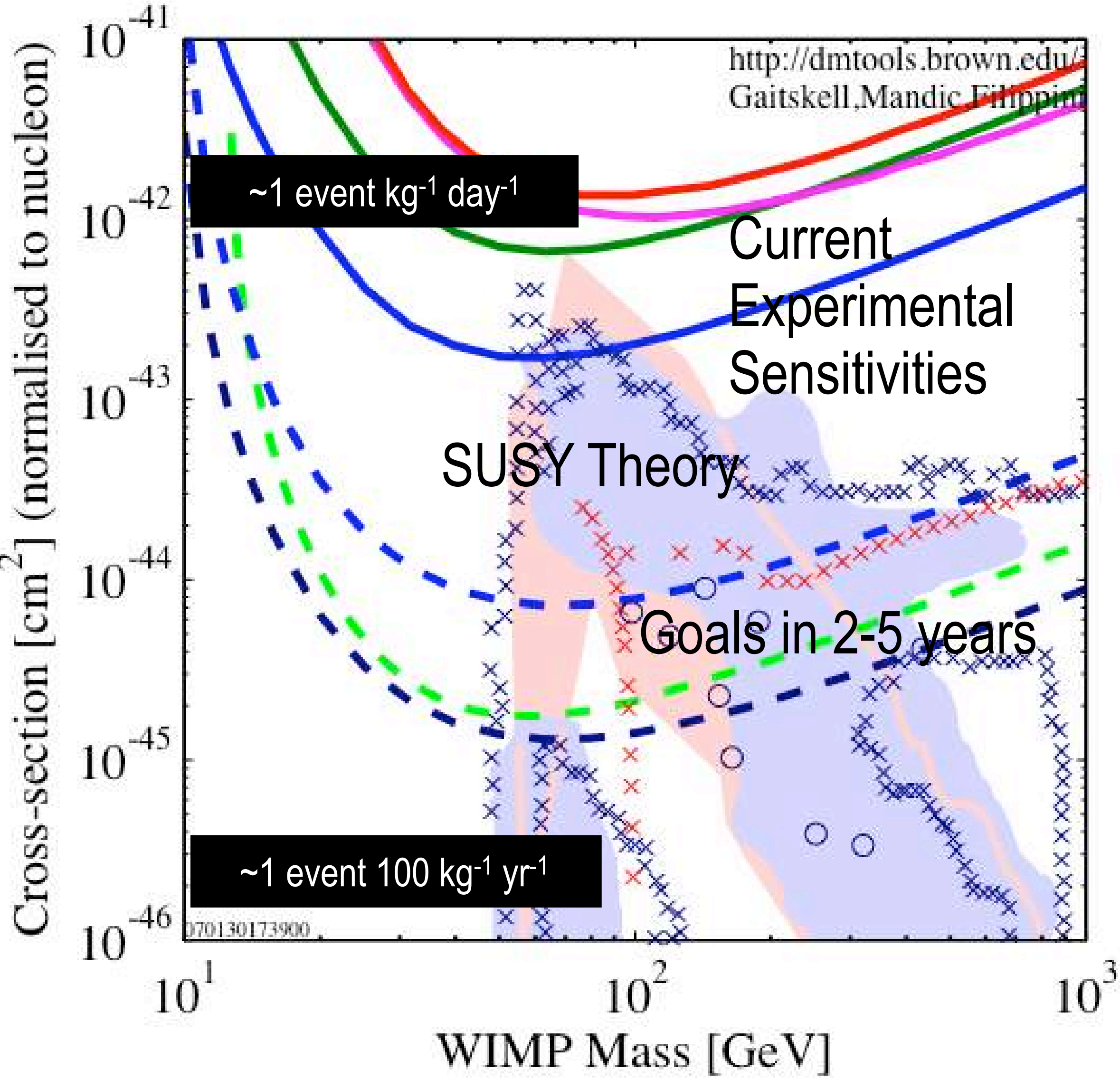
Noble Travails:
Noble Liquid Dark Matter Detectors

Rick Gaitskell
Particle Astrophysics Group, Brown University, Department of Physics
(Supported by US DOE HEP)
see information at

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

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 in unshielded detector
  - 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. High Purity Water Shield 4m gives <<1 evt/kg/day
  - But you have to focus on intrinsic U/Th contamination ppt (10^{-12} g/g) levels
- 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
    - Low energy thresholds can be achieved (although 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

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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	No long lived isotopes. 85Kr can be removed by charcoal or distillation.

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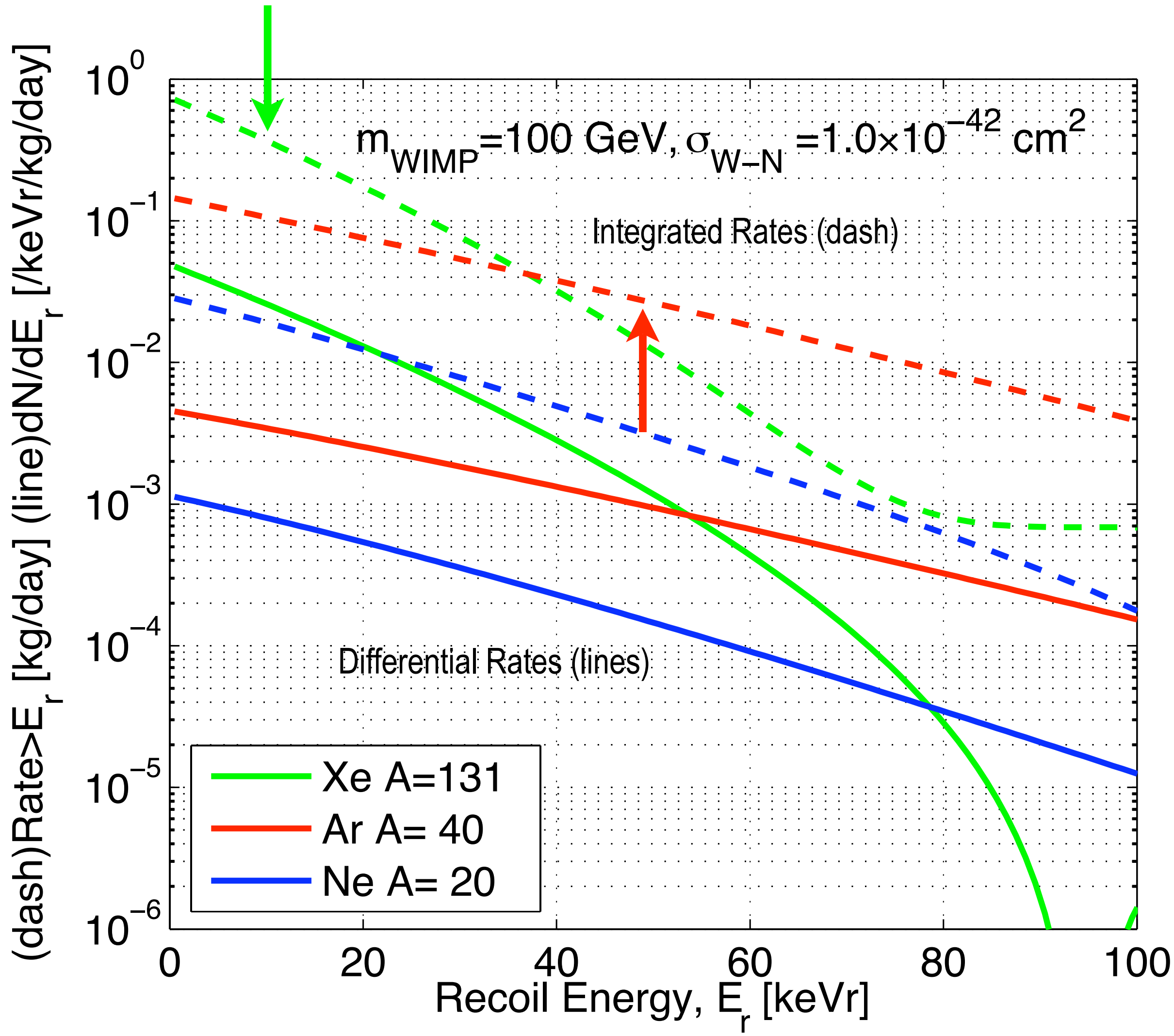


Noble Liquid Comparison (DM Detectors)

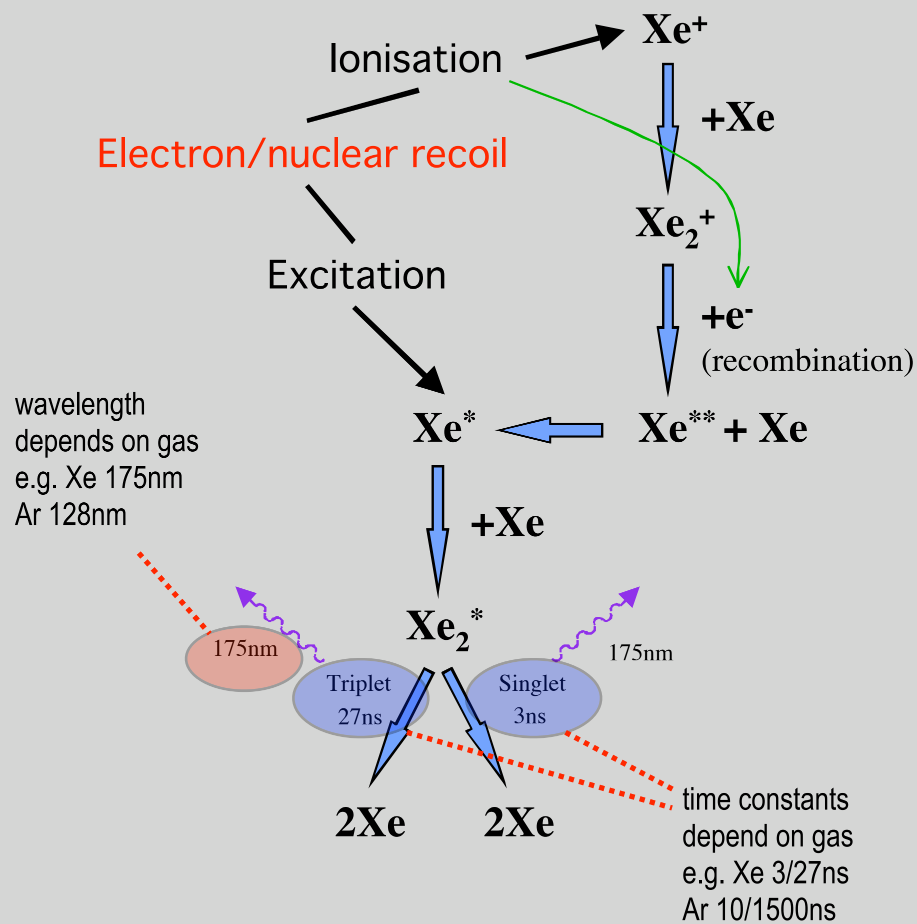
	Scintillation Light	Intrinsic Backgrounds	WIMP (100 GeV) Sensitivity vs Ge >10 keVr
Ne (A=20) $60/kg 100% even-even nucleus	85 nm Requires wavelength Shifter	Low BP (20K) - all impurities frozen out No radioactive isotopes	Scalar Coupling: Eth>50 keVr, 0.02x Axial Coupling: 0 (no odd isotope)
Ar (A=40) $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	No long lived isotopes. 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)

Energy Deposition / Partition into various excitations

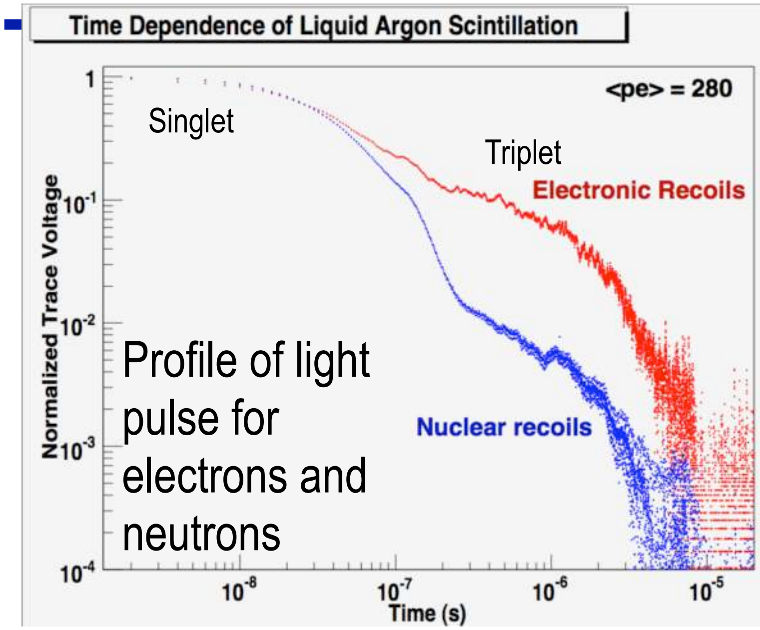


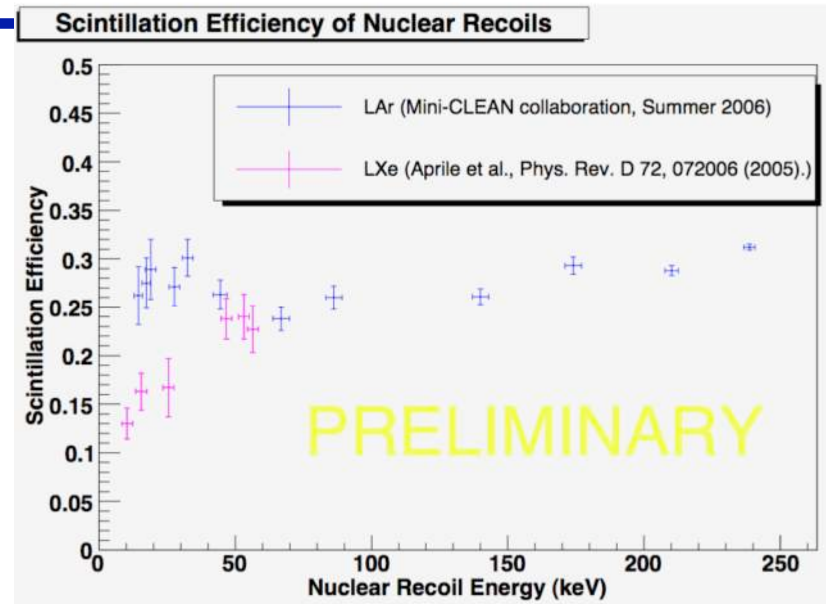
These mechanisms apply to all Nobles

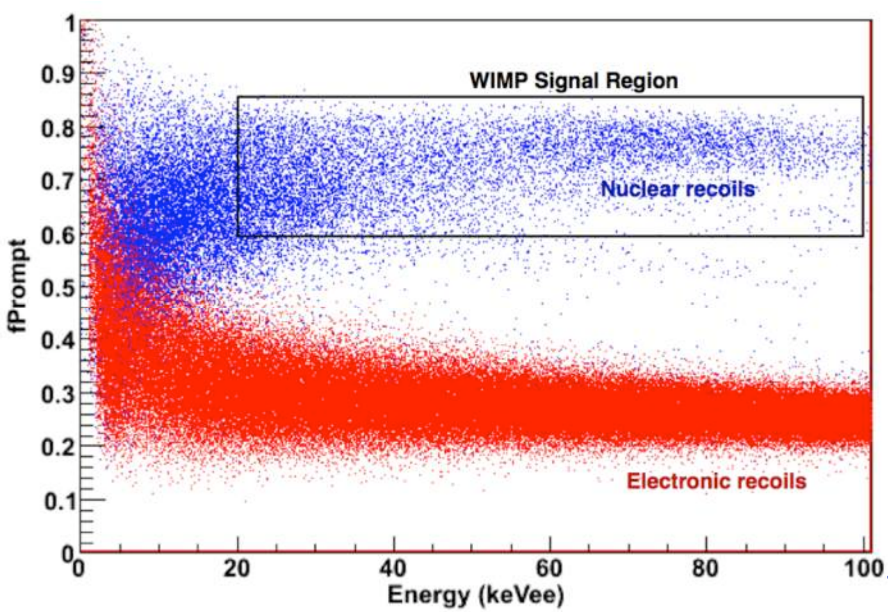
Nigel Smith, RAL

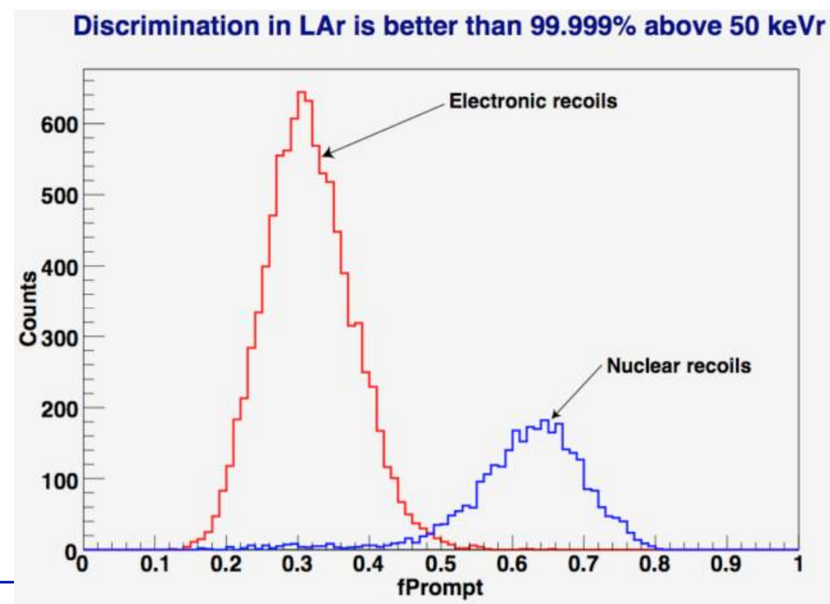
CLEAN Ar PSD

Data taken with Micro-CLEAN (McKinsey, Yale)

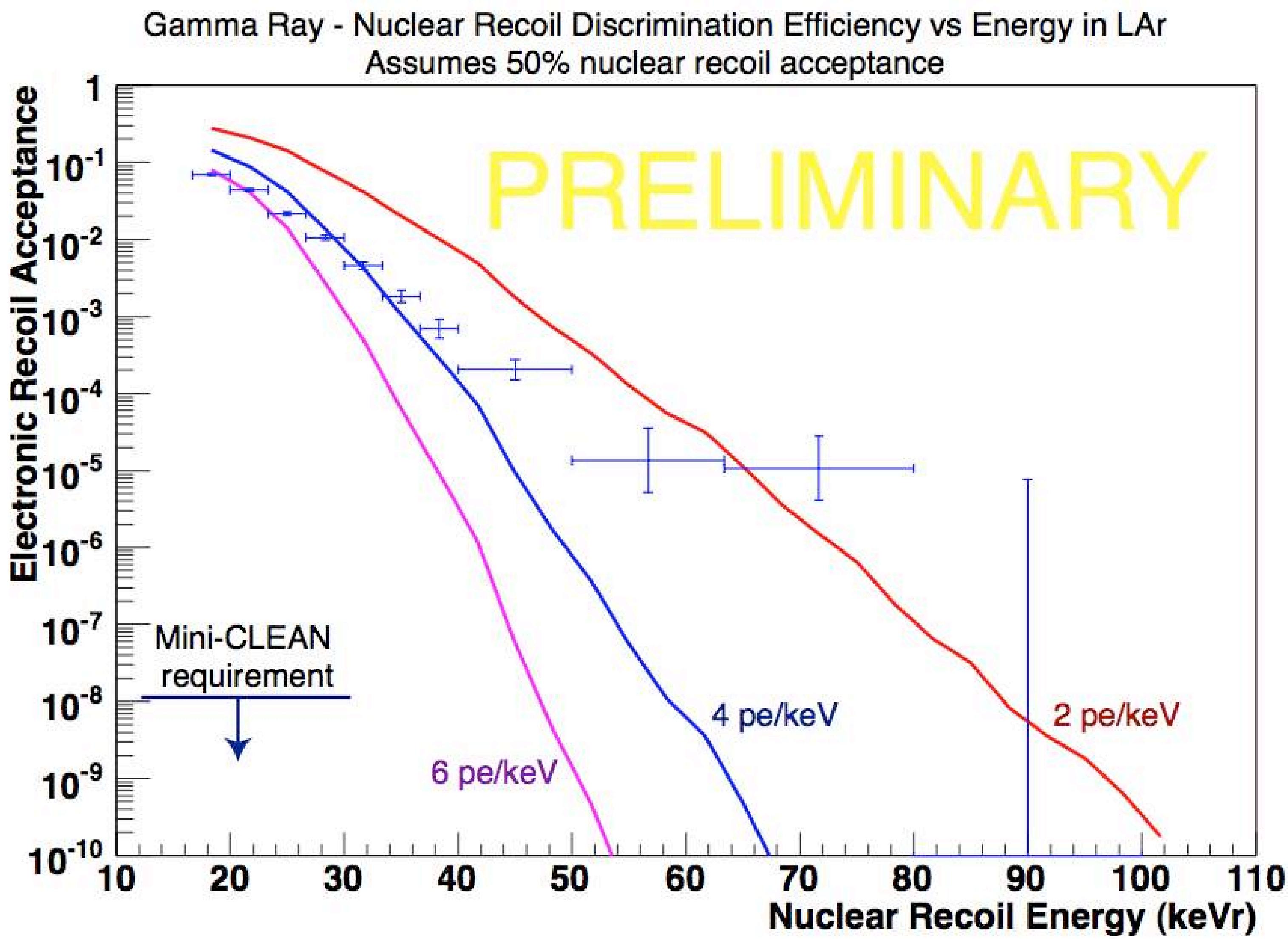








(McKinsey, Yale)

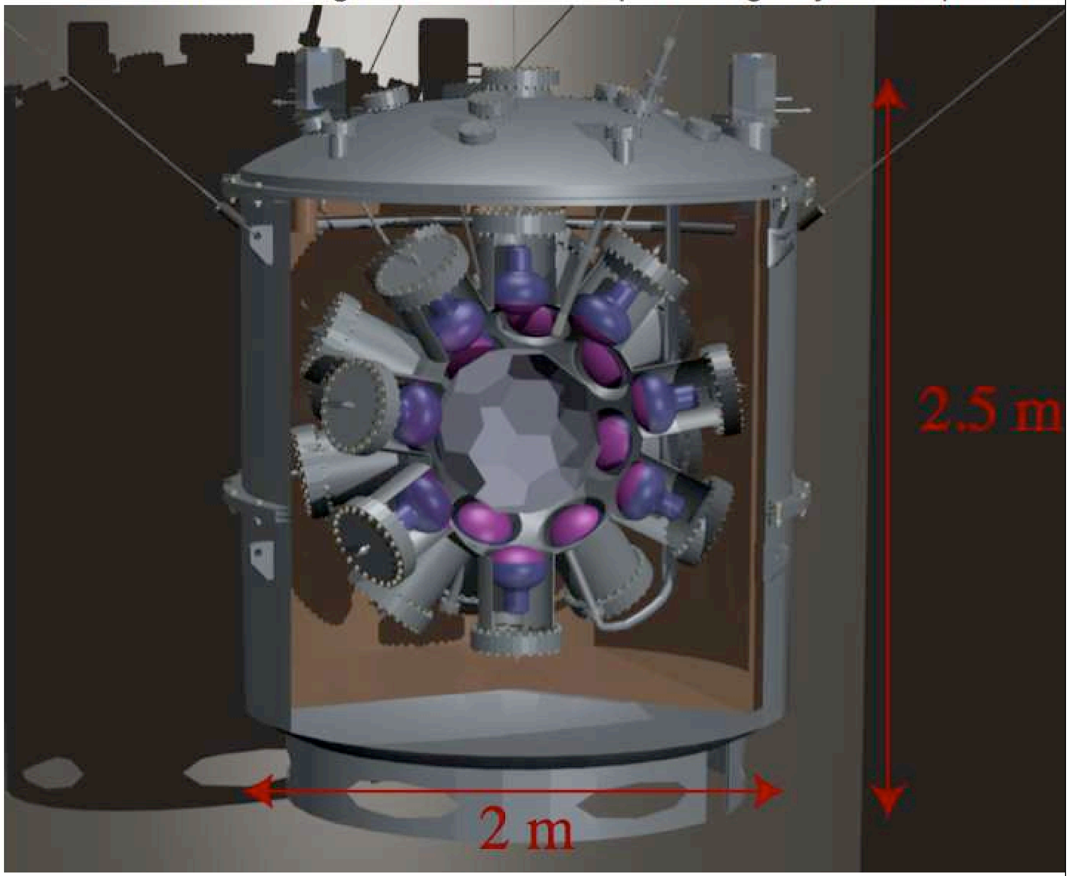


miniCLEAN (proposed)

- 100 kg miniCLEAN
  - WIMP Goal ~5 x10^{-45} cm^2
  - 10 events/year
- Backgrounds
  - PMT Gammas
    - Requires better than 10^{-8} rejection of ER at 50 keVr
    - Currently demonstrated 10^{-5} >50 keVr (limited by neutron bg in lab)
  - PMT neutrons
    - Studies on going, but these are expected to be limitation to sensitivity of smaller instrument
    - Less of problem in larger target
  - Position Reconstruction
    - How well can events leaking from outer

Mini-CLEAN

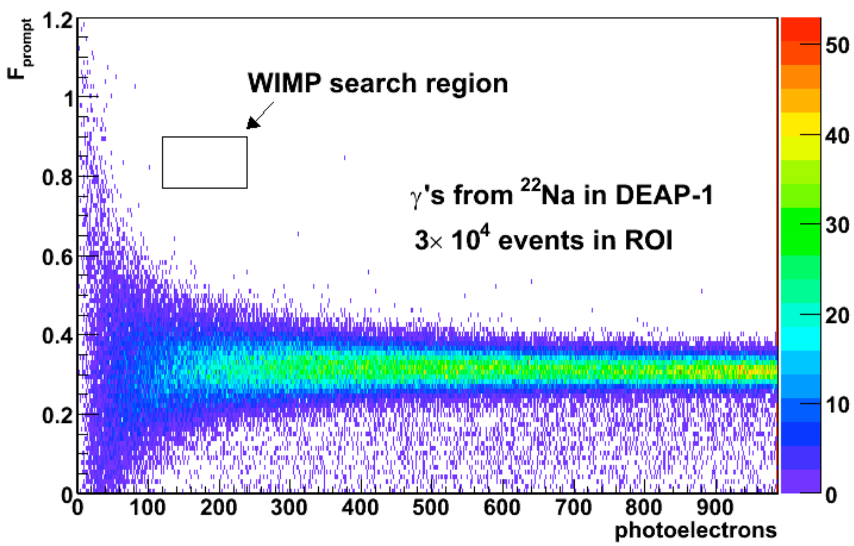
Active mass: 100 kg of LAr or LNe. Expected signal yield > 6 pe/keV

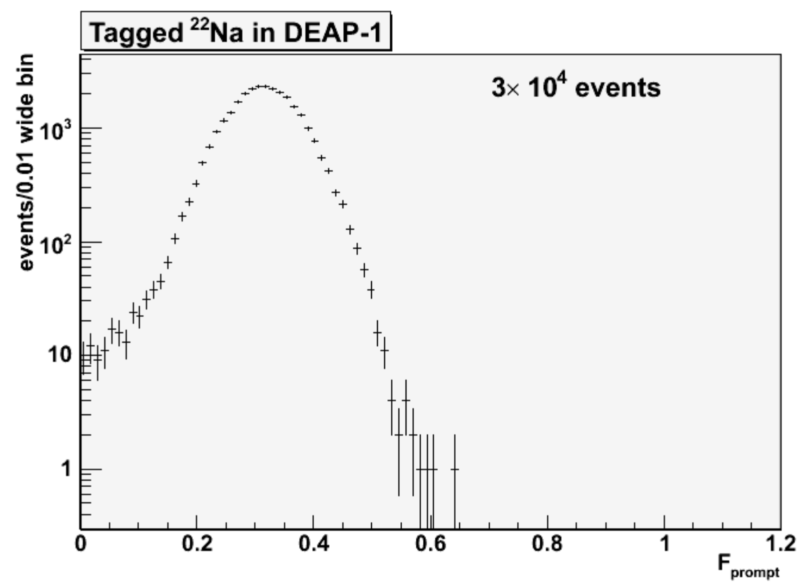


Rick Gaitskell, Brown University, DOE

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





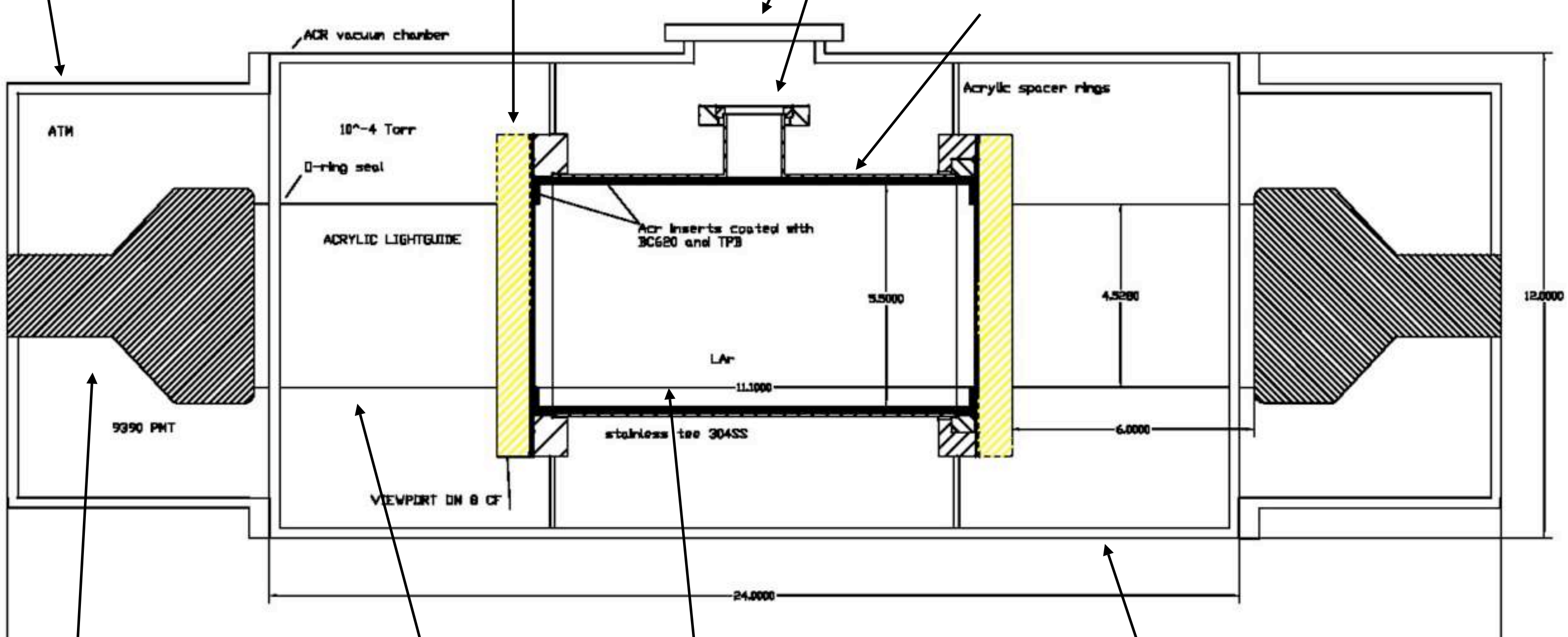
DEAP-1 design

Neck connects to vacuum and Gas/liquid lines

Quartz windows

11” x 6” (8” CF) tee

poly PMT supports



6” acrylic guide

Acrylic vacuum chamber

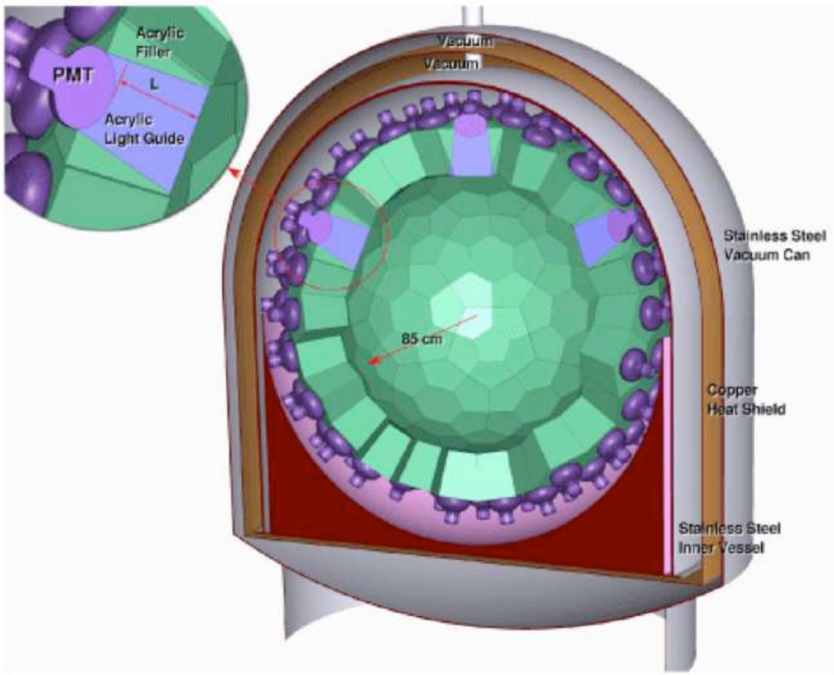
ET 9390 PMT 5”

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

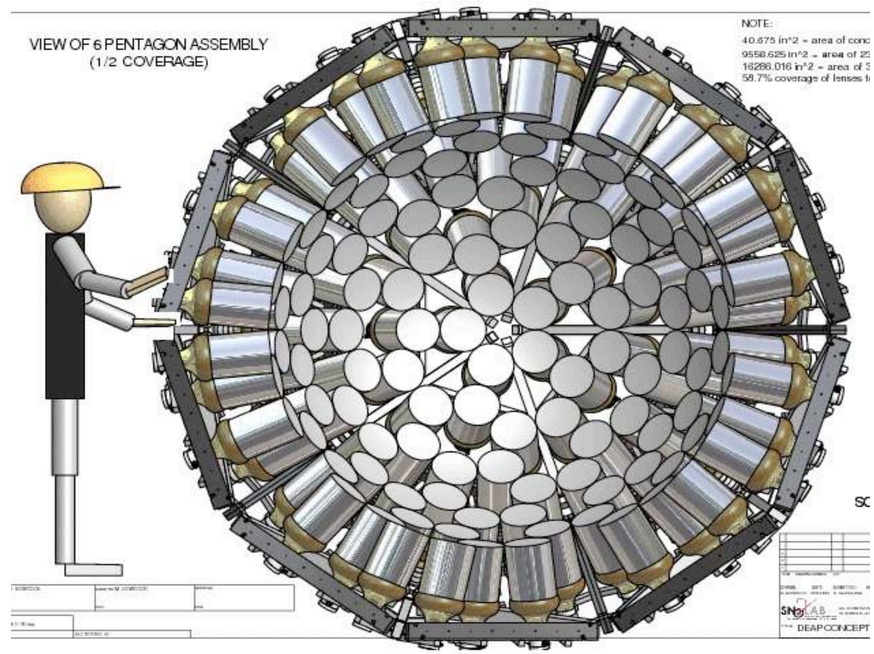
Mark Boulay

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)

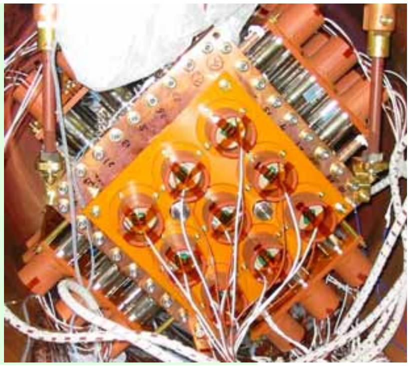
XMASS 100 kg (Xe) - Japan

- 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

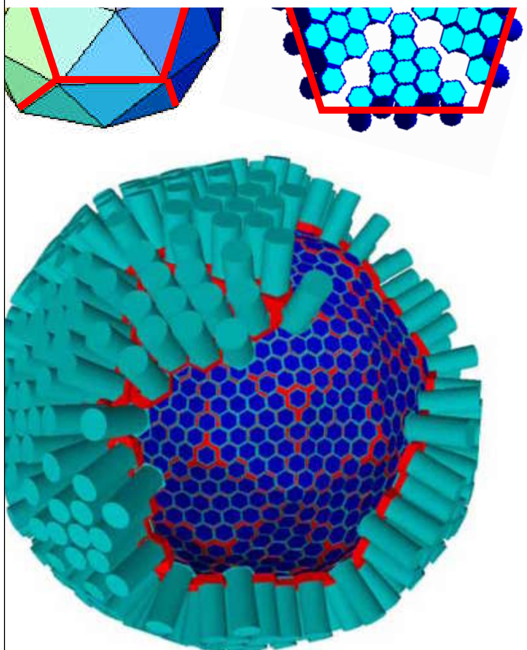


● **Detector design is going using MC**

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

● **New excavation will be done soon**

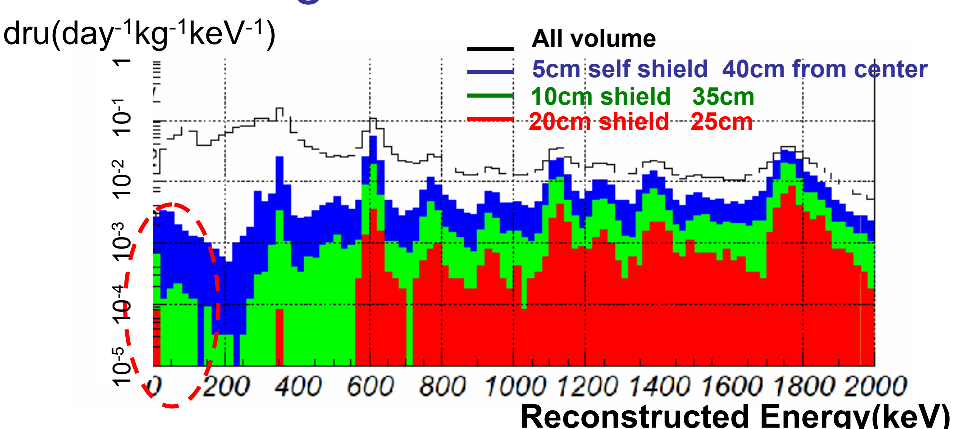
XMASS 800 kg - Japan



- 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.

Decision on funding of 800 kg phase currently be considered

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

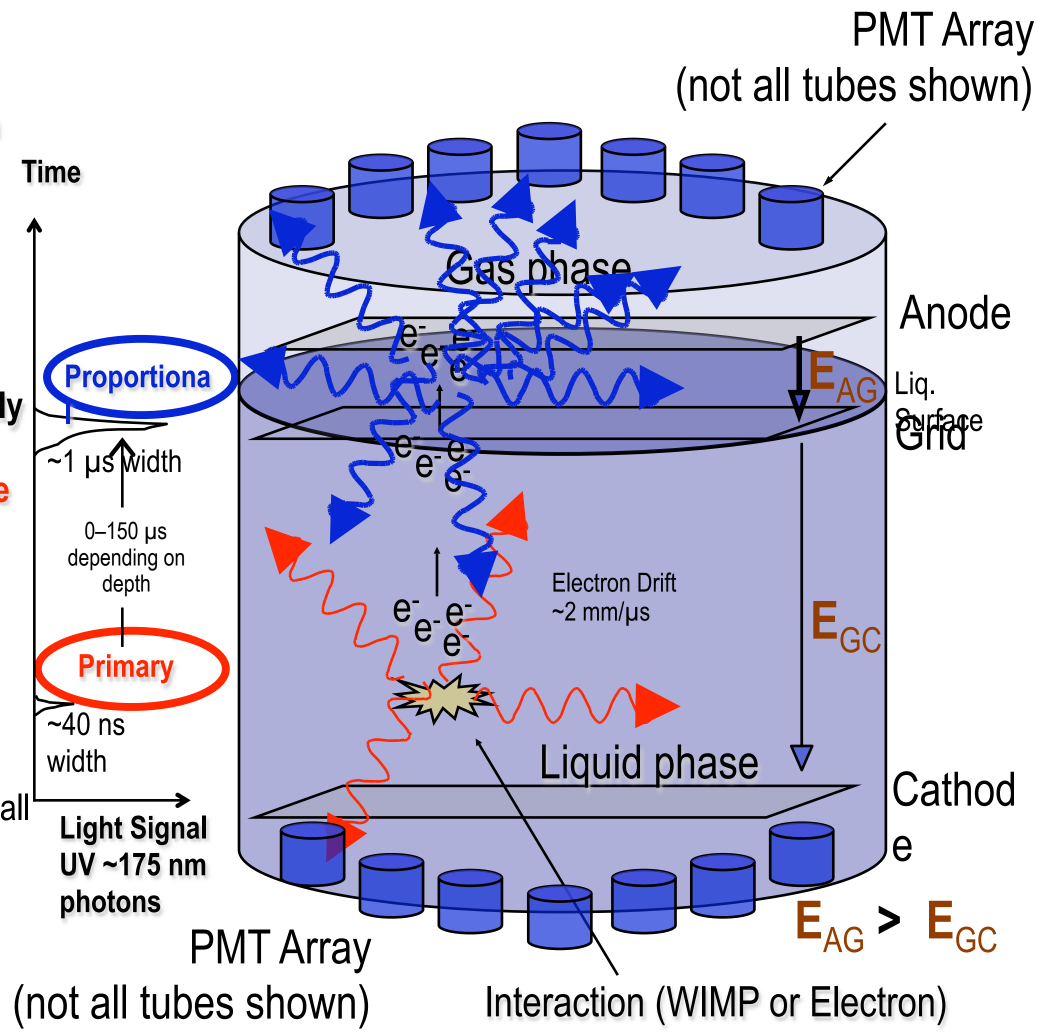
- **γ, e-, μ, (etc) => Fast electron recoils =>**

=> 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.

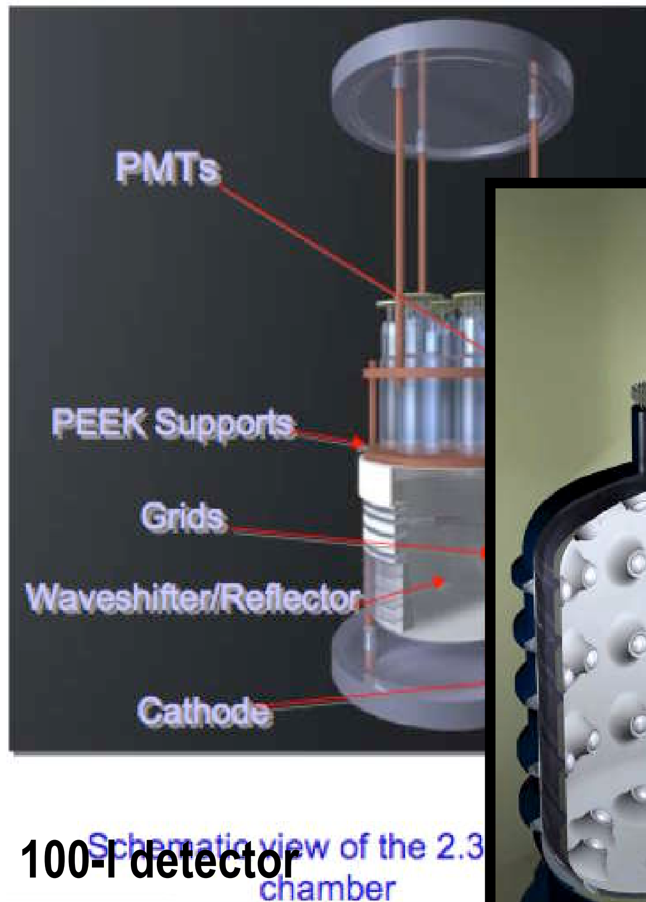
Challenge: ultra pure liquid and high drift field to preserve small electron signal **(~20 electrons)** ; efficient extraction into gas; efficient detection of small primary light signal **(~ 200 photons)** associated with **16 keVr**



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

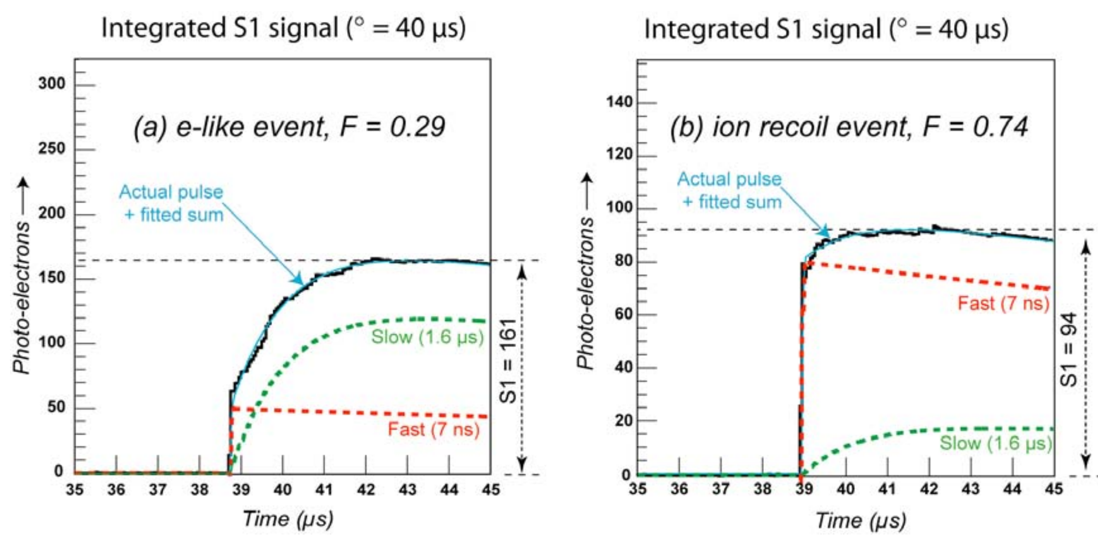


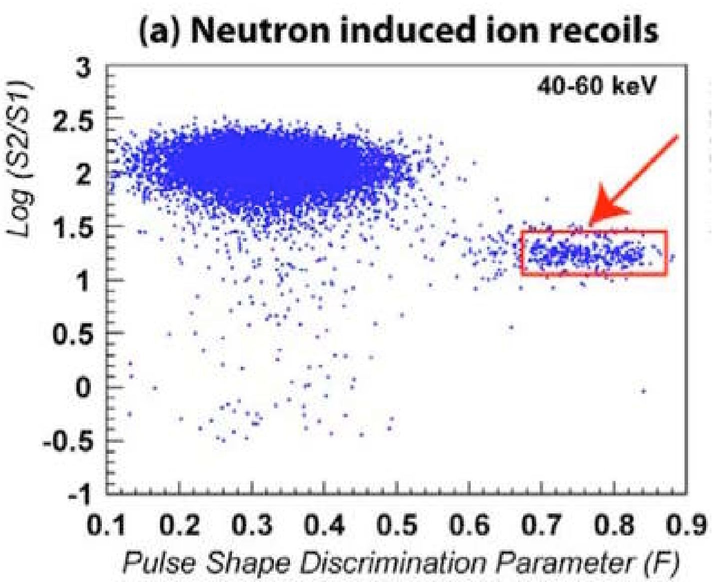
100-l detector

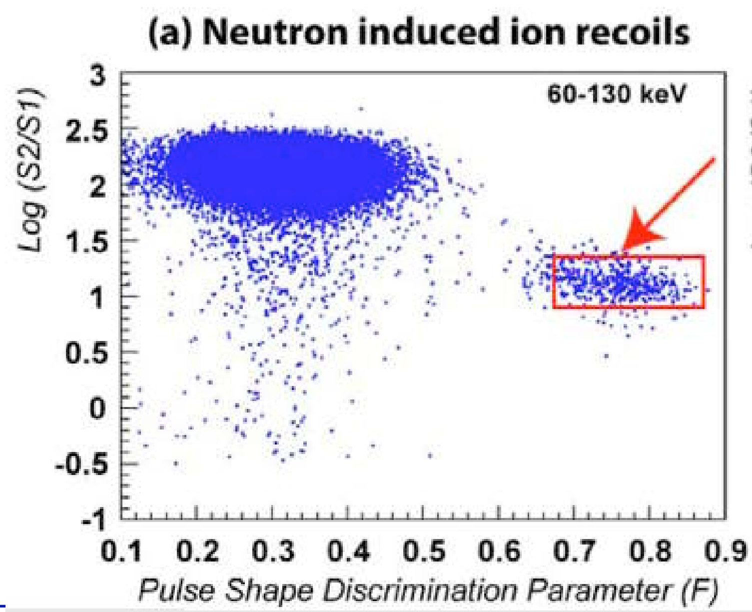
WARP

WARP - Dual Methods of Discrimination

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

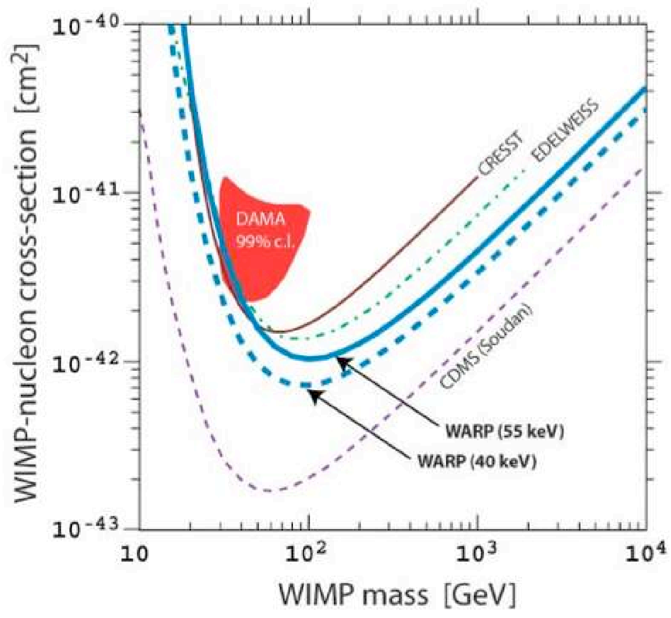


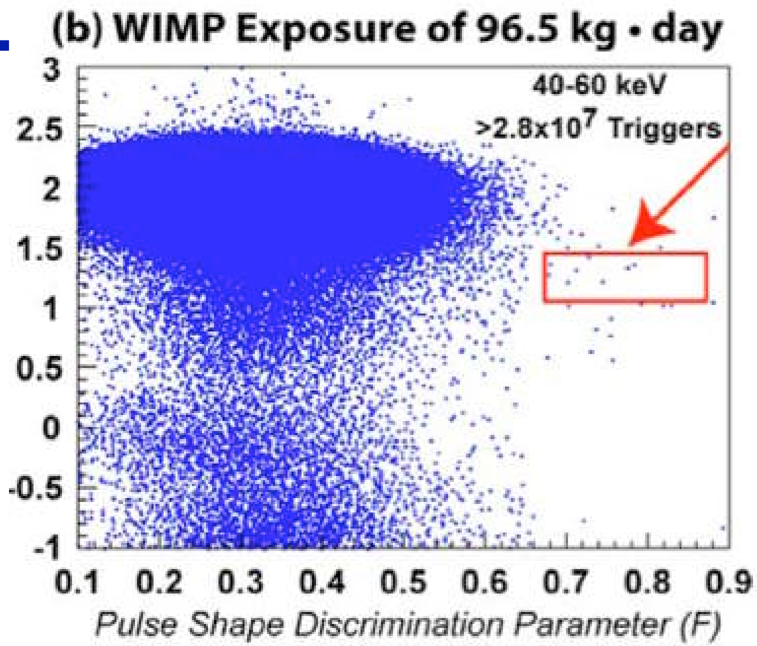


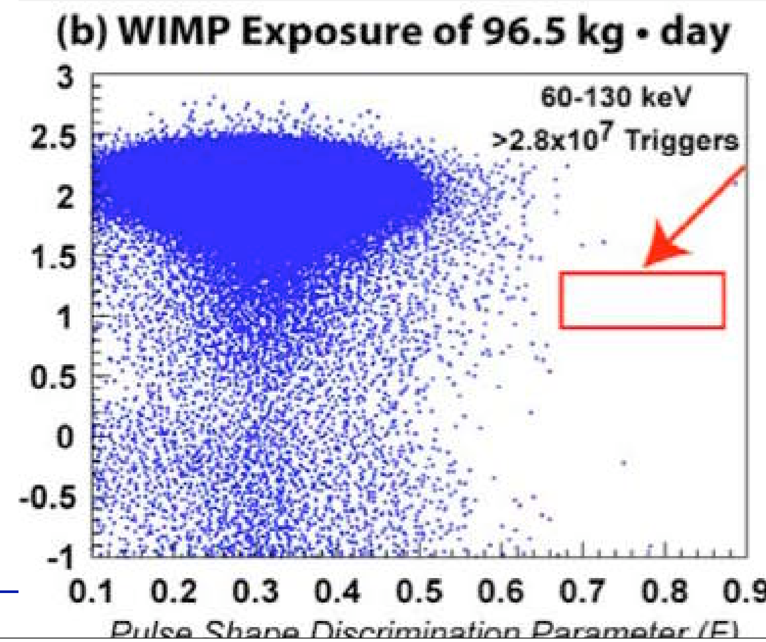


WARP Recent Results (Jan 07) astro-ph/0701286

- 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)



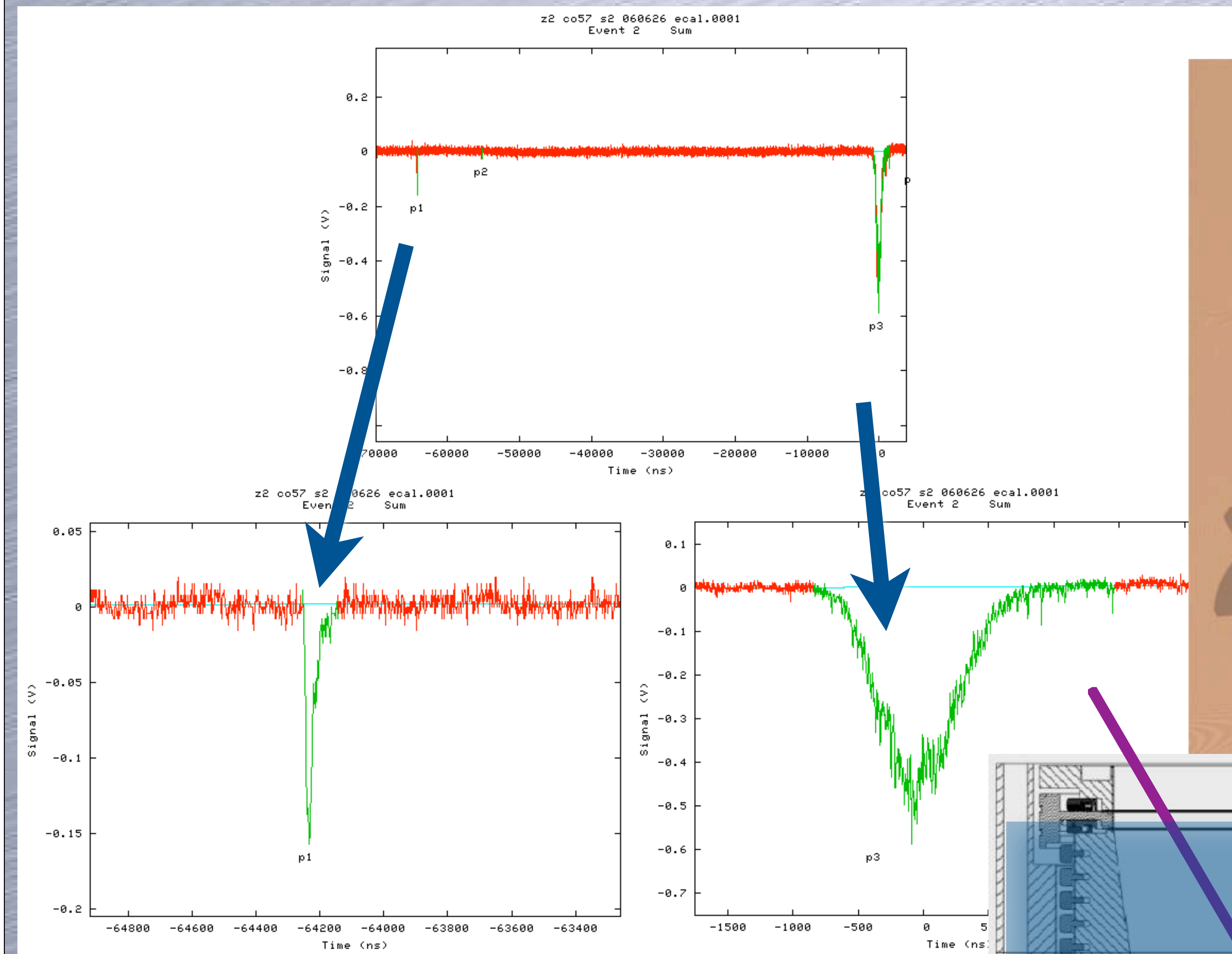


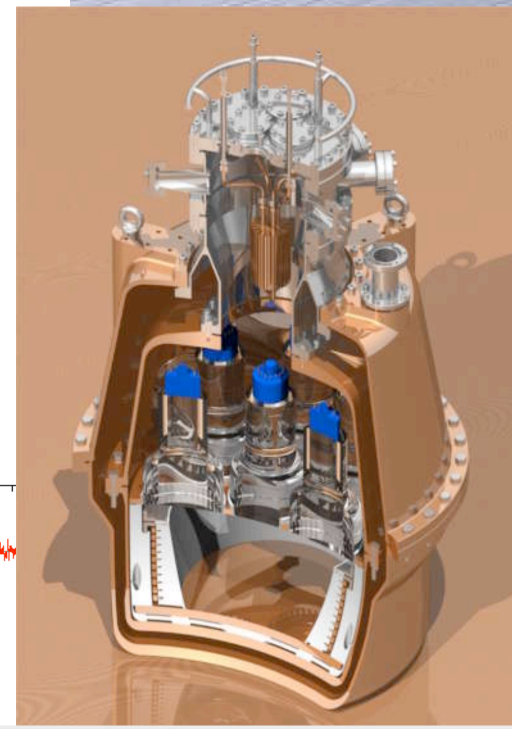


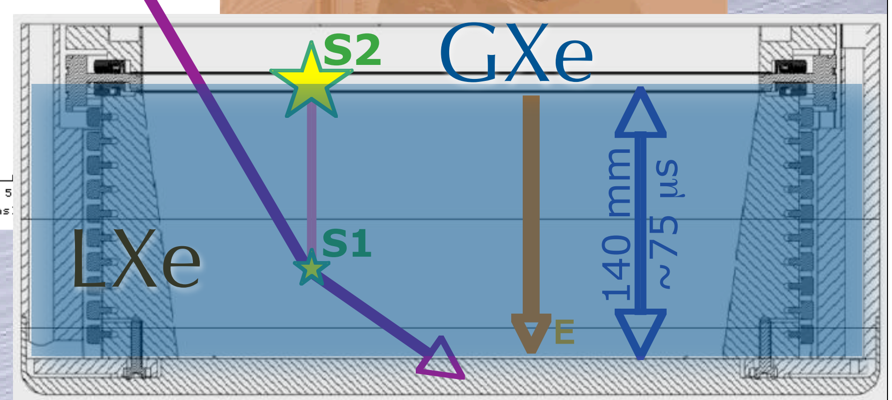
39Ar Beta Background - Event Rejection vs Removal

- 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



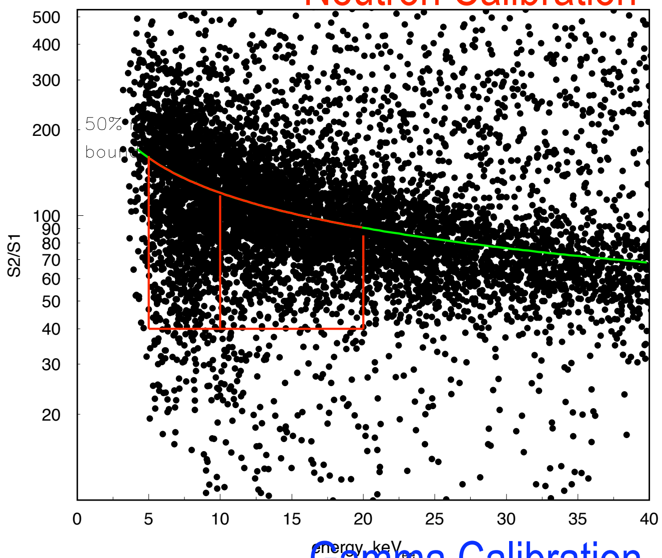




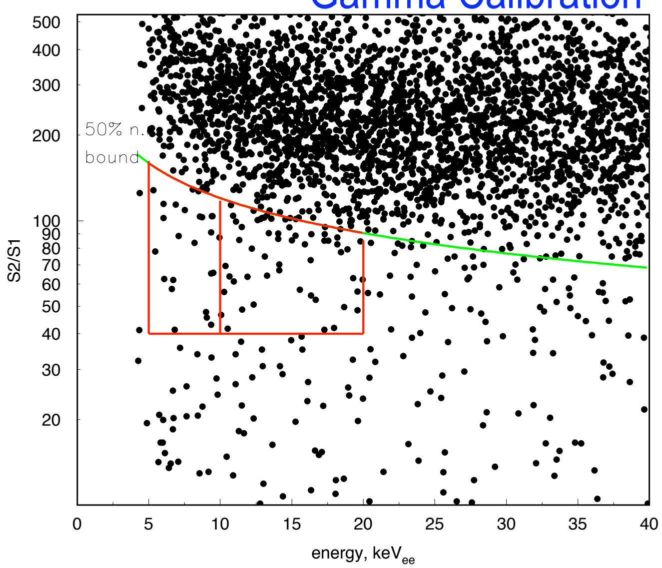
- 5 months continuous operation
- 1.0t*day of raw DM data

Discrimination Power

Neutron Calibration



Gamma Calibration

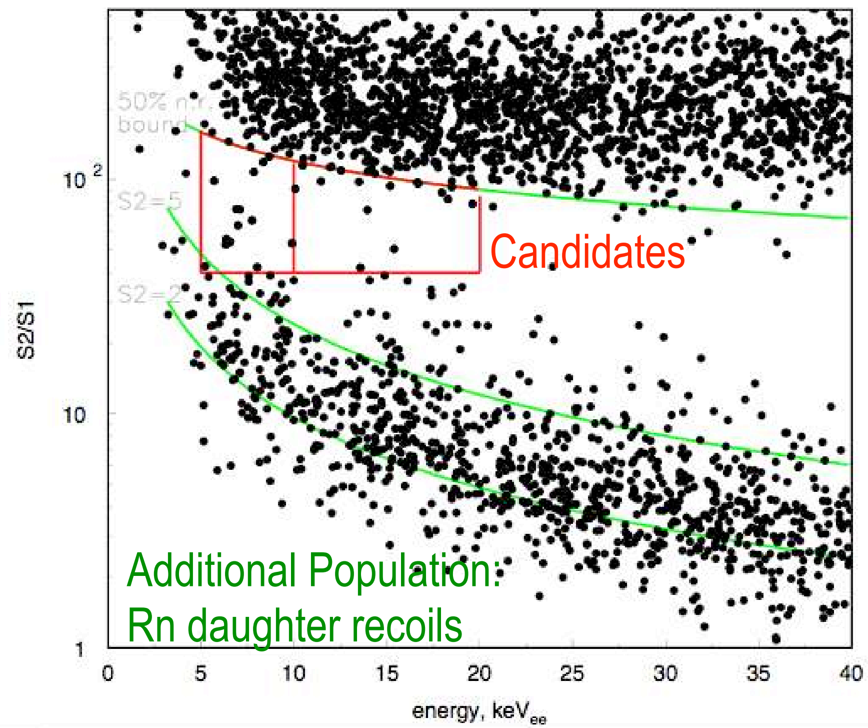


- AmBe calibration (upper)
- Co-60 Calibration (lower)
  - Used to define acceptance window
  - 50% n.r. acceptance shown
  - lower S2/S1=40 bound fixed
  - Box defined 5-20keVee
- Uniform population across plots
  - high rate calibrations (esp Co-60)
  - coincidences between events and ‘dead-region’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

ZEPLIN II

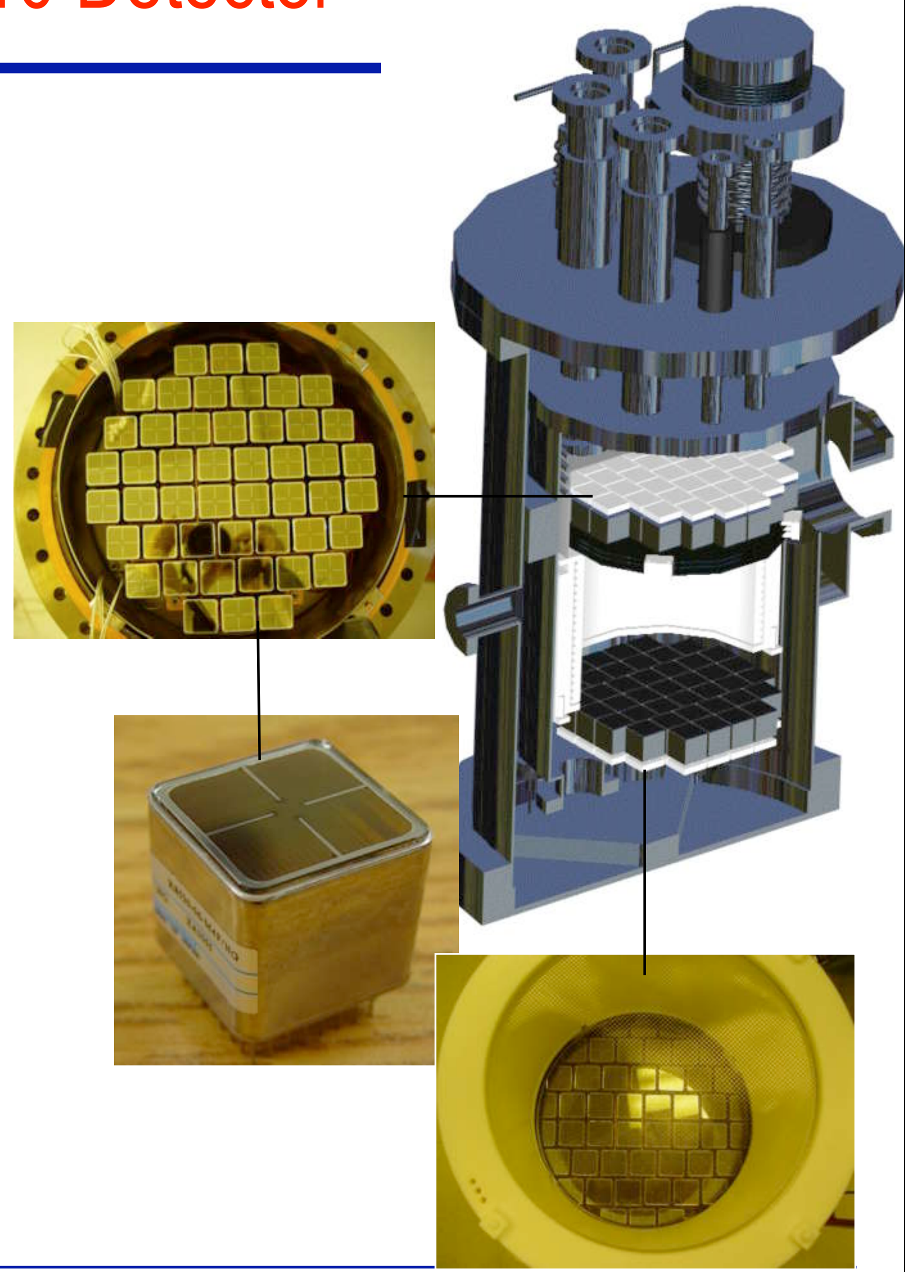
- 31 live days running, 225 kg-days exposure
  - Red Box is 5-20keVee, 50% NR acceptance based on neutron calibration
  - 29 candidate events seen
    - Estimate 50% from ER leakage from upper band
    - Other 50% from lower band which are RAdon daughters plating on PTFE side walls
  - Both populations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

WIMP Search Data



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
  - Quantum efficiency > 20% @ 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

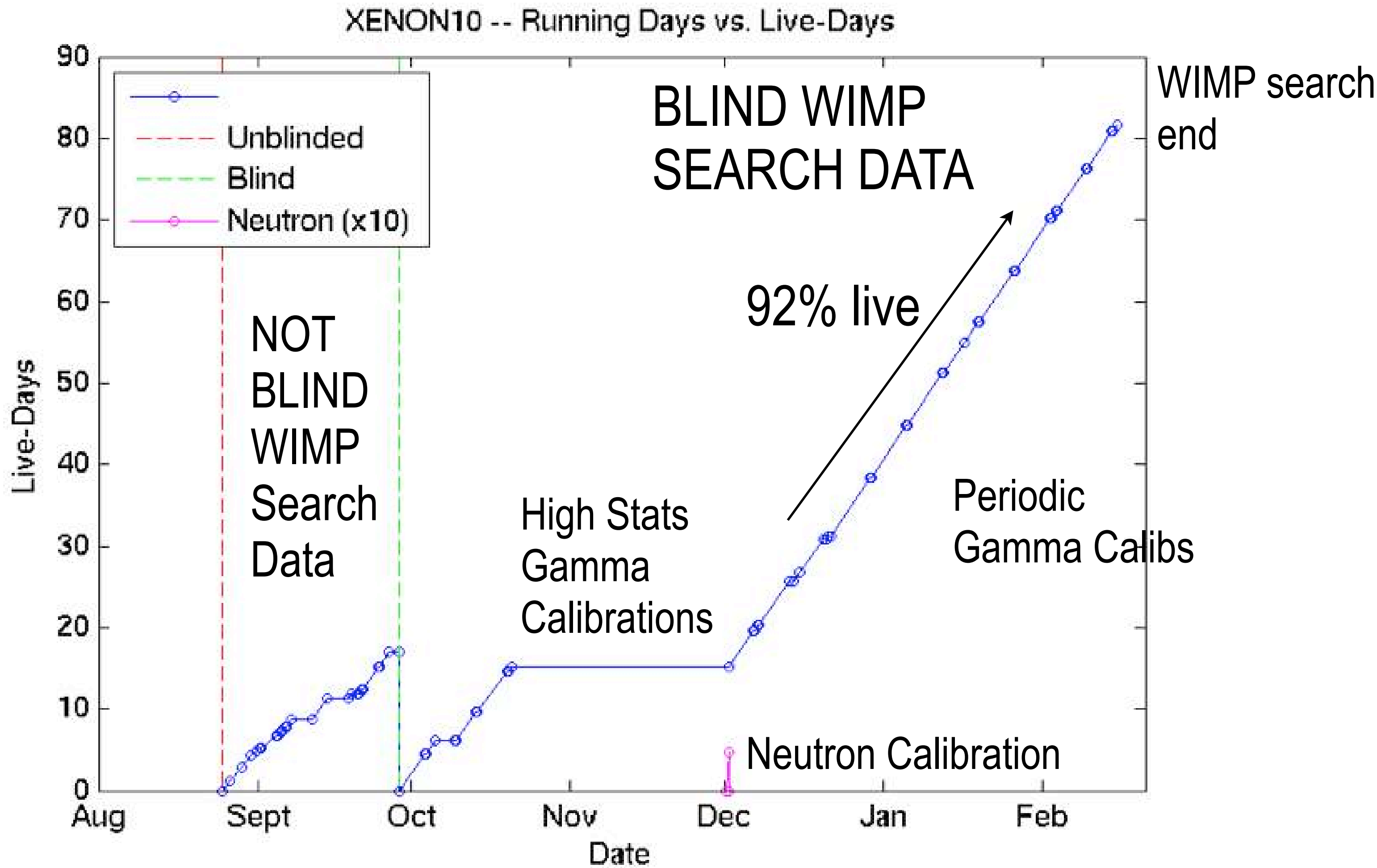
Coimbra University Jose Matias Lopes, Luis Coelho, Luis Fernandes and Joaquin Santos

XENON10: Ready for Low Background Operation

Installation of the Detector...

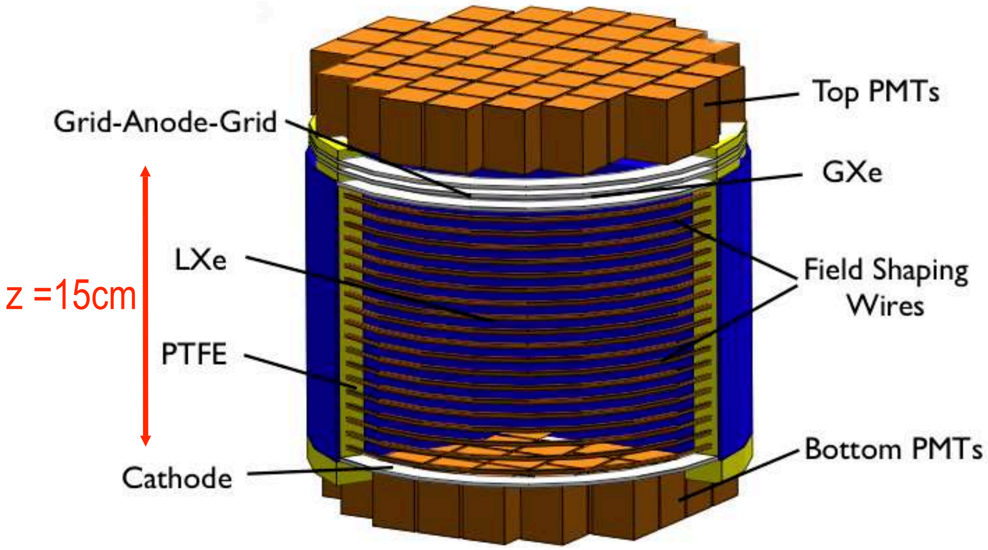
...and we are operational

XENON10 Live time at Gran Sasso

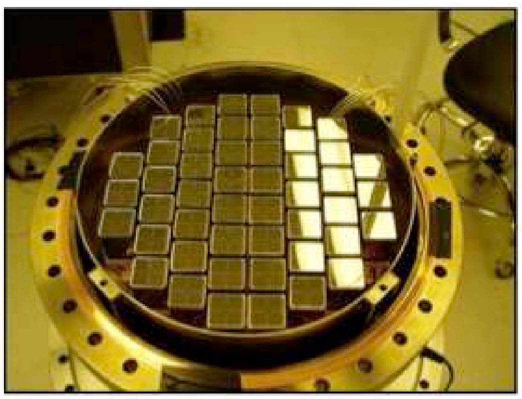


- Discuss data from High Statistics Gamma Calib, Neutron Calib and NON BLIND WIMP search data ~20 live days
- WIMP Search results (from 80 live day) will be announced at April APS Meeting

XENON10 Detector



89 PMTs: Hamamatsu R8520-AL 2.5 cm square



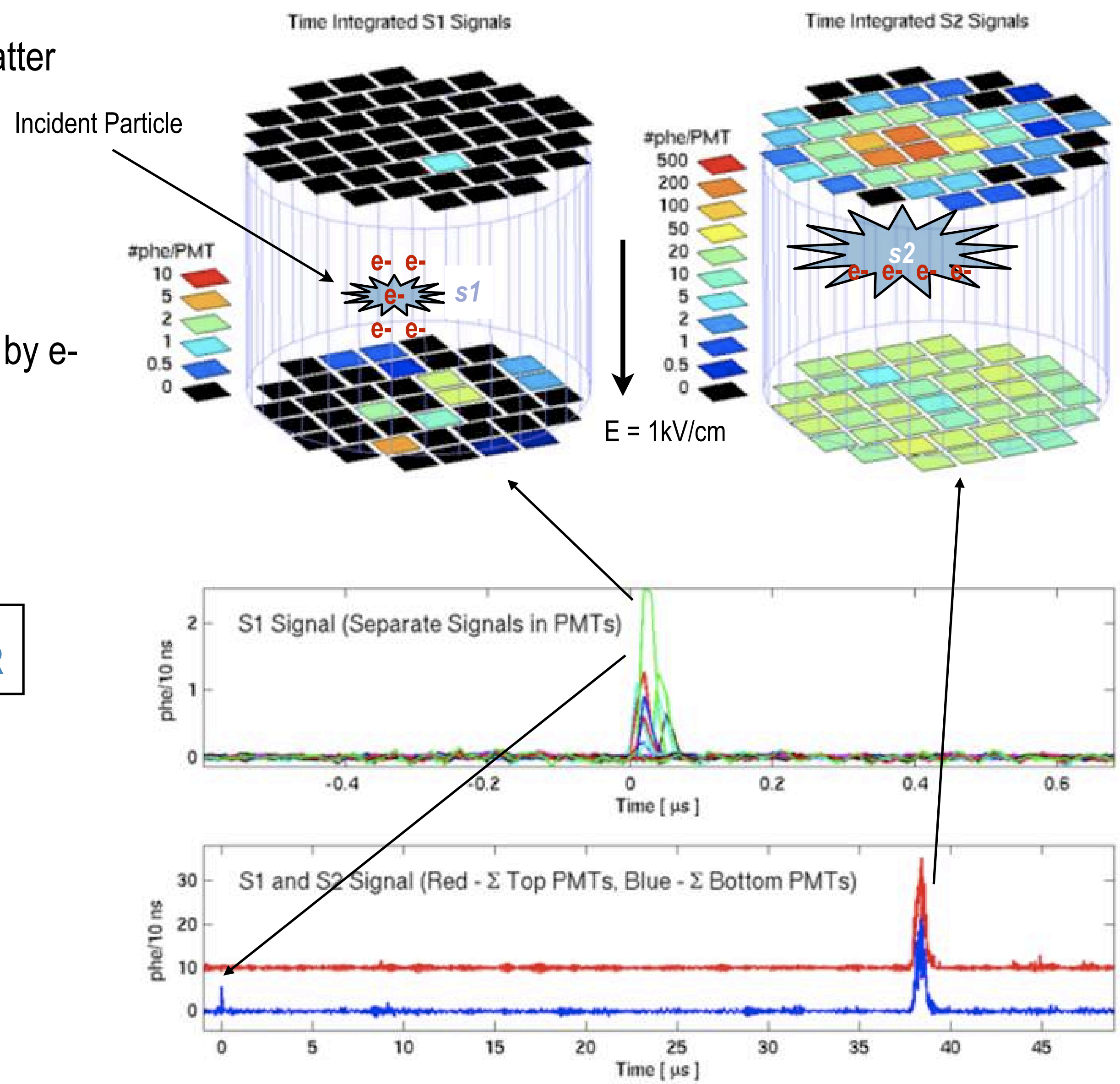
XENON10 Event Discrimination

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



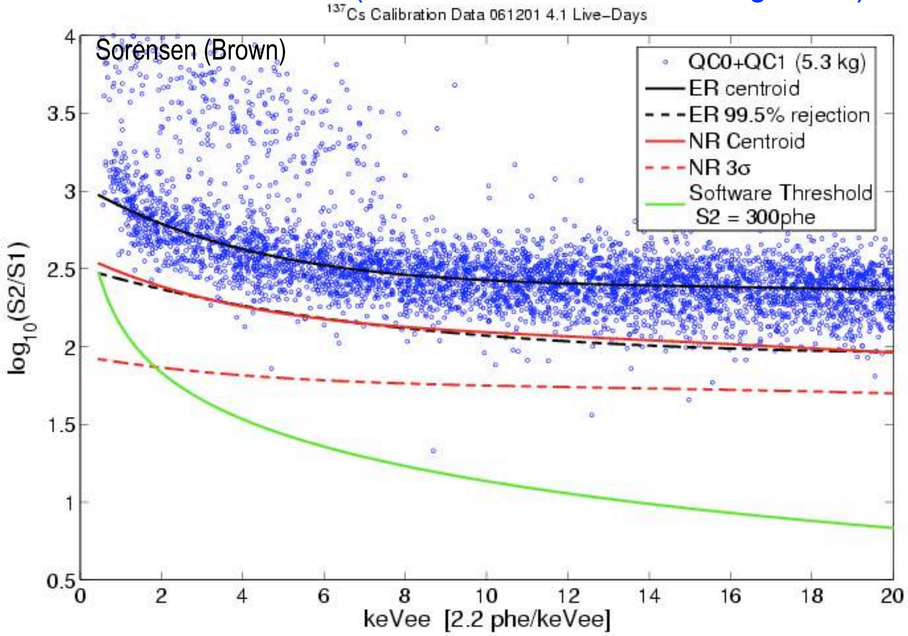
$(s2/s1)_{ER} > (s2/s1)_{NR}$

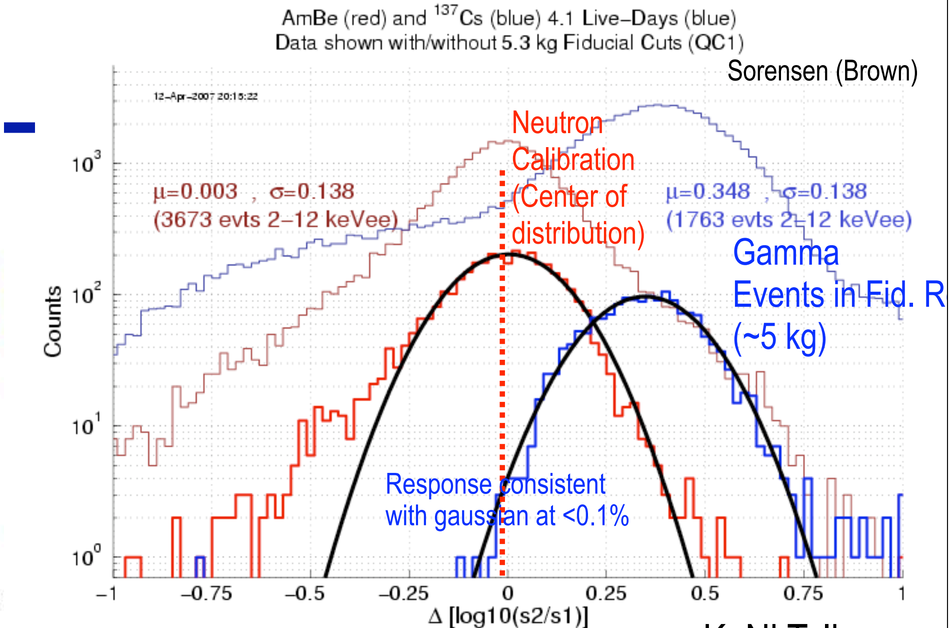
Expect > 99% rejection efficiency of γ/n Recoils…

Reduction of Backgrounds =>

Reduction of Leakage Events

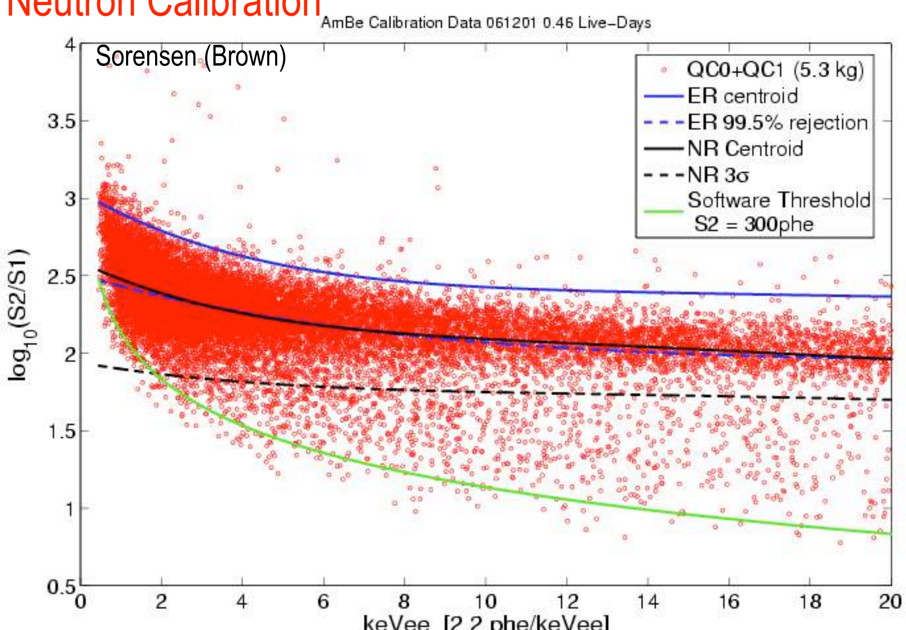
Gamma Calibration (Electron Recoils == Background)

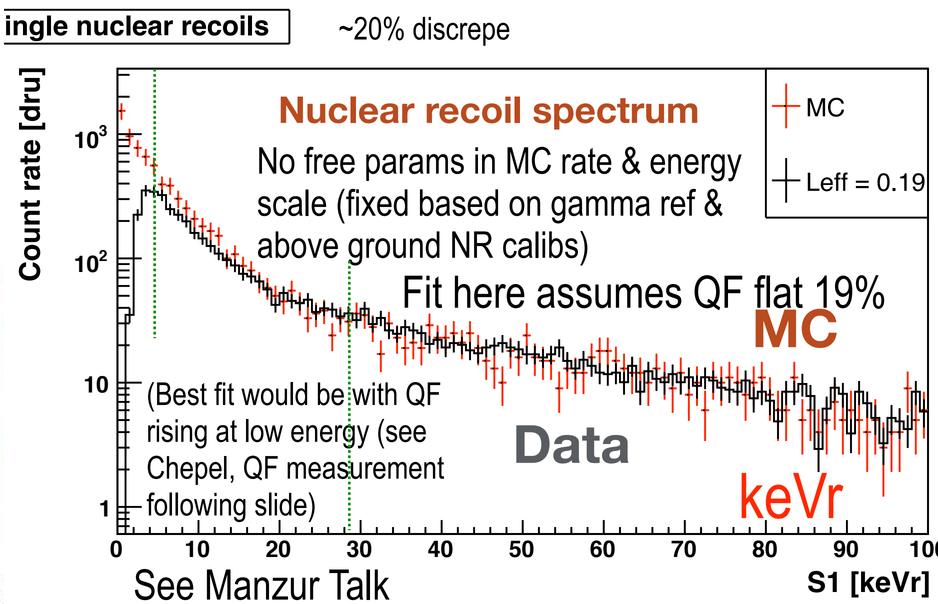




see K. Ni Talk

Neutron Calibration





See Manzur Talk

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

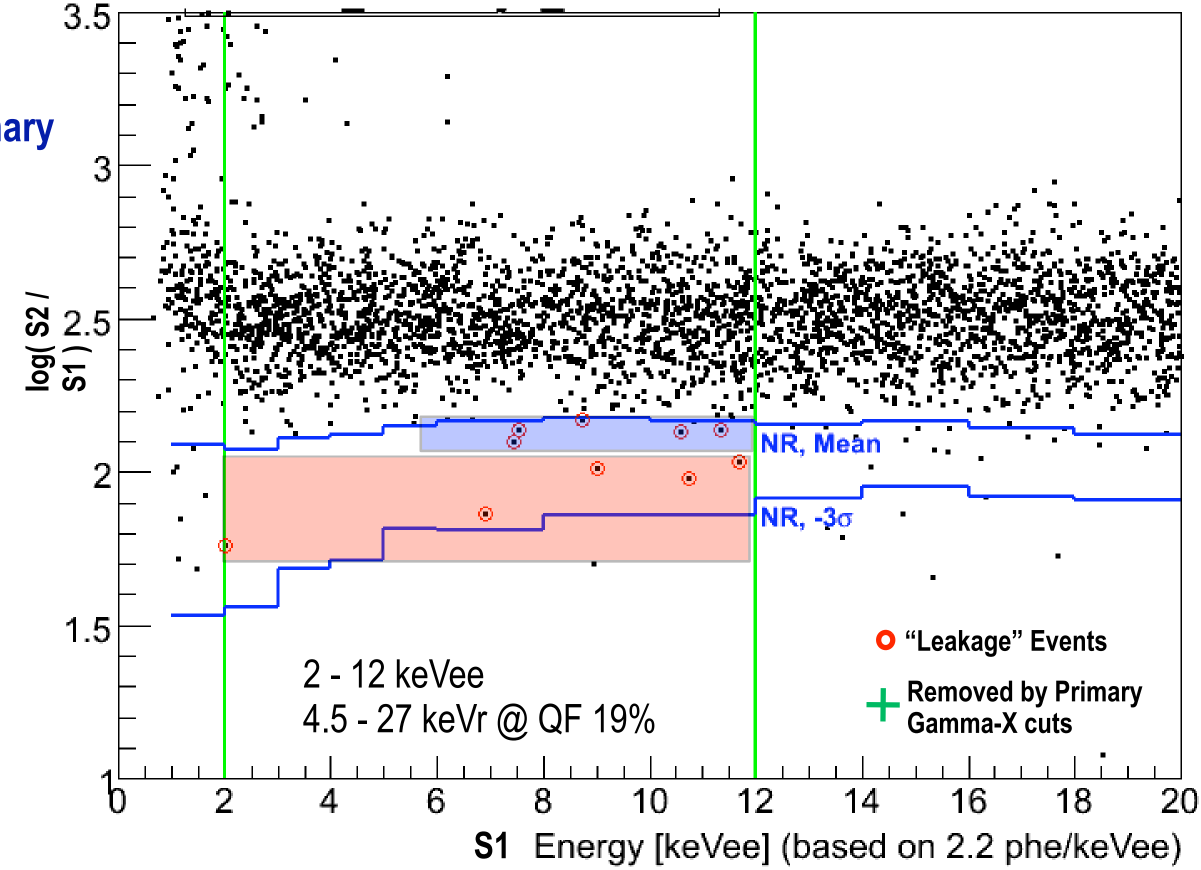
§XENON10 Blind Analysis – 58.6 days

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

See Aprile / Manalaysay Talk

log (S2 / S1) vs S1

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



Applying the Gamma-X Cuts to XENON10 Data

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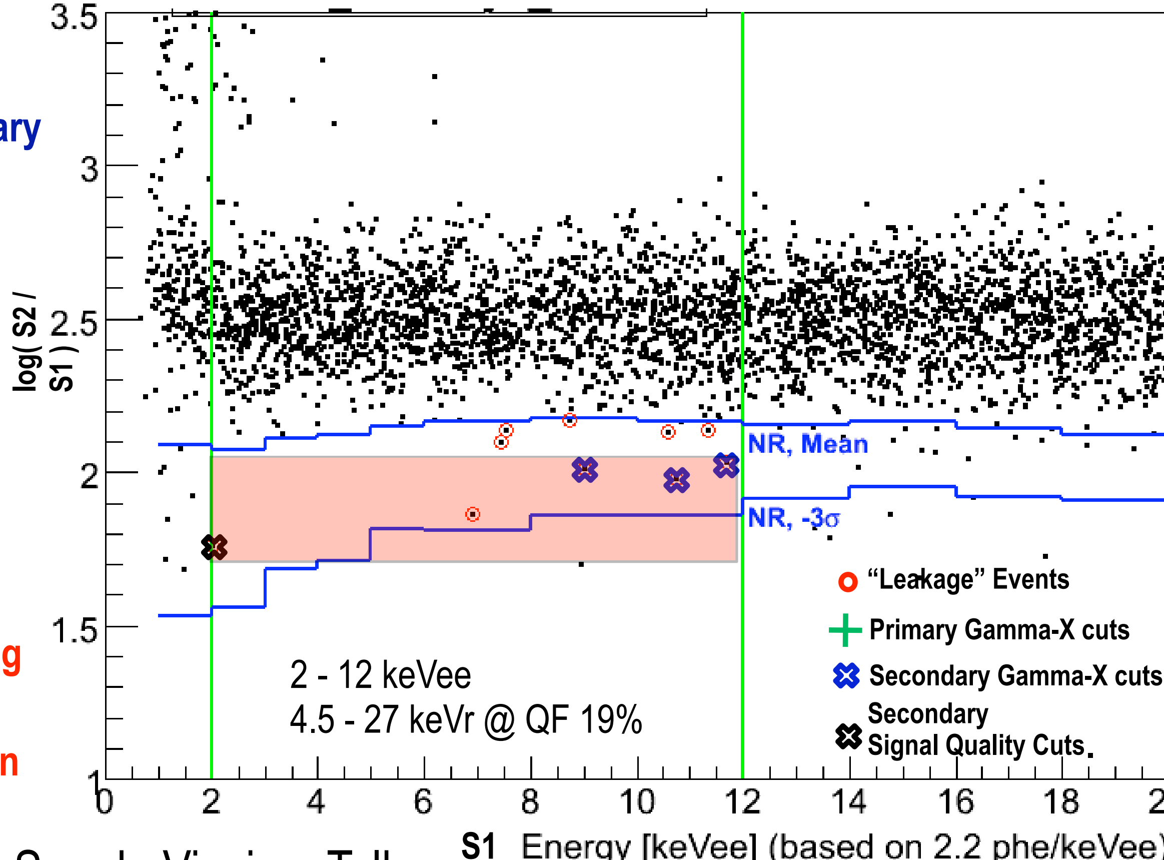
    - Fits based on ER calibrations projected 7.0 +2.1-1.0 events
  - § 5 of these are *not consistent* with Gaussian distribution of ER Background
    - 4 out of 5 events removed by Secondary Blind Analysis (looking for missing S2/Gamma-X events)
    - Remaining event would have been caught with 1% change in cut acceptance : WIMP SIGNAL UNLIKELY

log (S2 / S1) vs S1

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



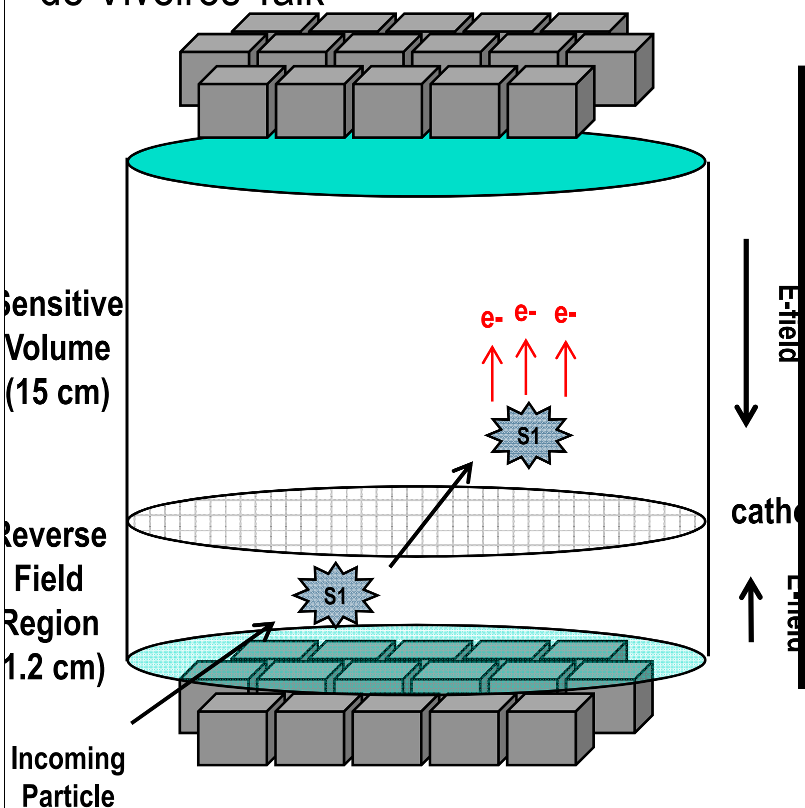
See de Viveiros Talk

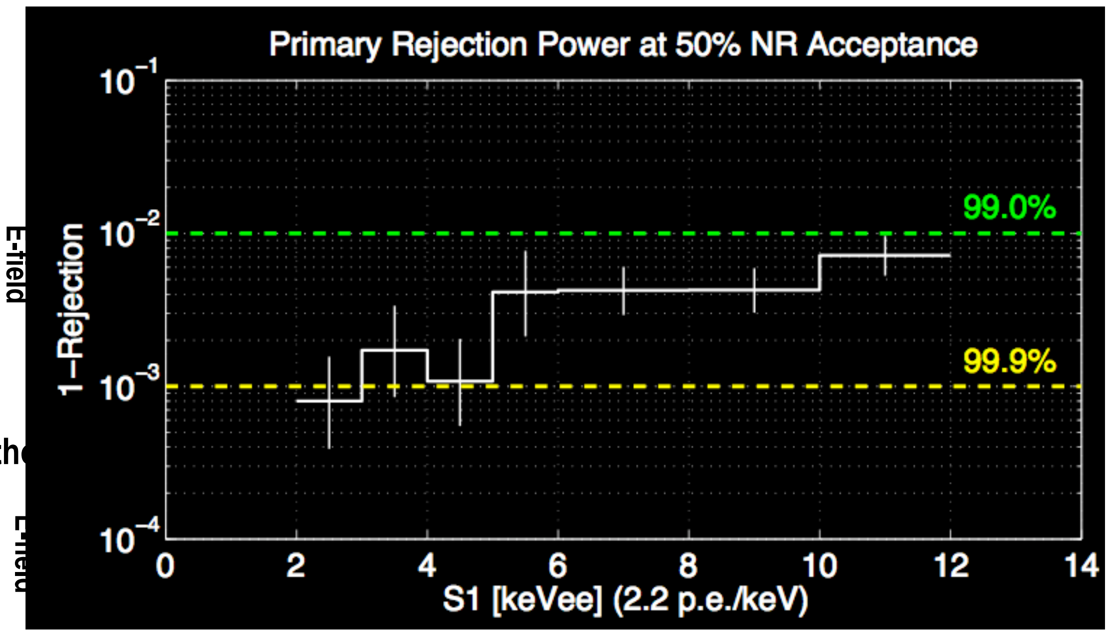
Absence of Low Energy Candidate Events (2-7 keVee)

§ 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)

de Viveiros Talk



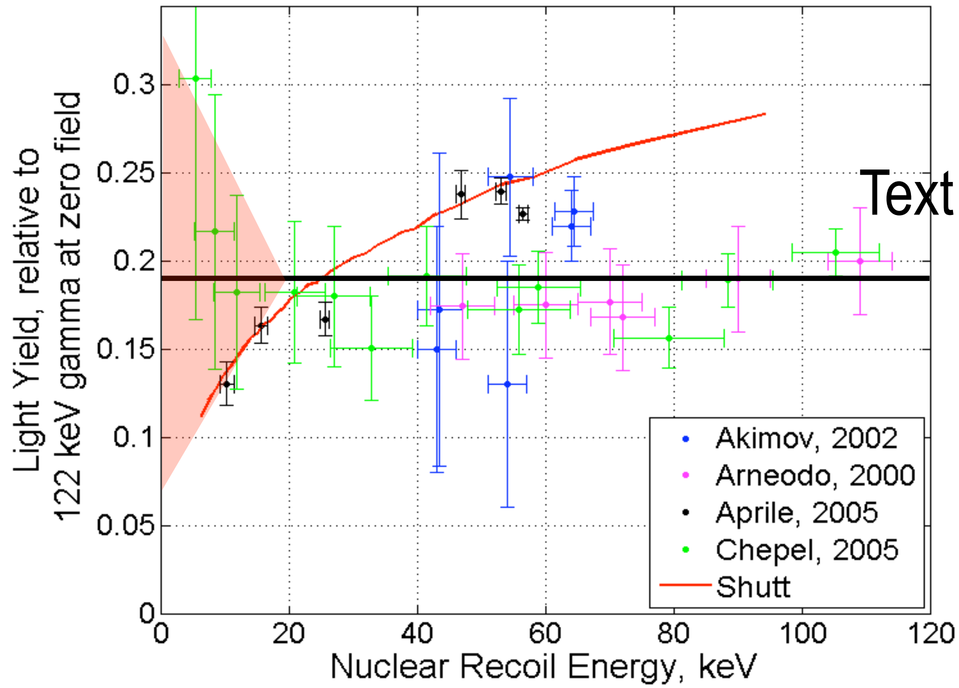


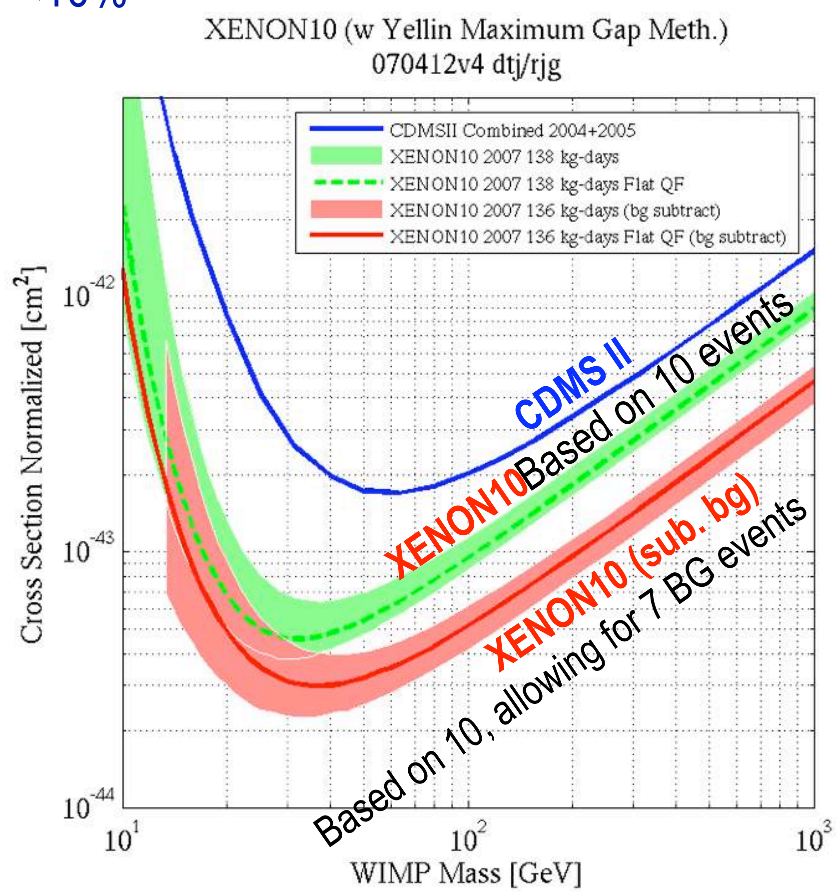
Manalaysay Talk

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 low energy asymptote >30% - <10%

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





See Dahl Talk

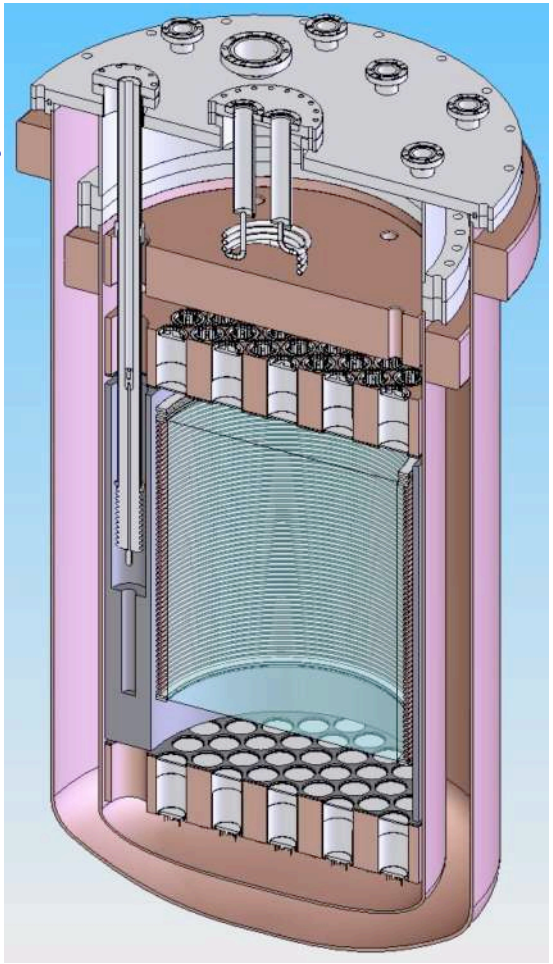
XENON10

- In situ Neutron Calibration agreed very closely with calibrations of above ground prototypes.
- High Stats Gamma Calib and Preliminary non-blind WIMP search (20 live days) shows performance very similar performance
- Discrimination (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 (but this is NON blind analysis)
    - 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

LUX Dark Matter Experiment - Summary

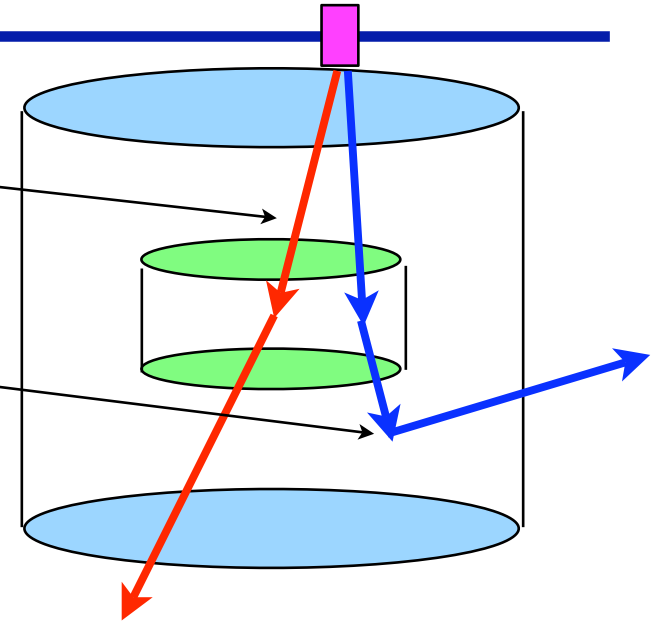
- Brown [Gaitskell], Case [Shutt], LBNL [Lesko] , LLNL [Bernstein], Rochester [Wolfs], Texas A&M [White], UC Davis [Svoboda/Tripathi], UCLA [Wang/Arisaka/Cline]
  - XENON10, ZEPLIN II (US) and CDMS; ν Detectors (Kamland/SuperK/SNO/Borexino); HEP/γ-ray astro
  - (Also ZEPLIN III Groups after their current 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 $\gamma+\beta < 7\times10^{-4}$ /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 $<5\times10^{-46}$ cm^2 reach with recent PMT activity reductions, longer running.

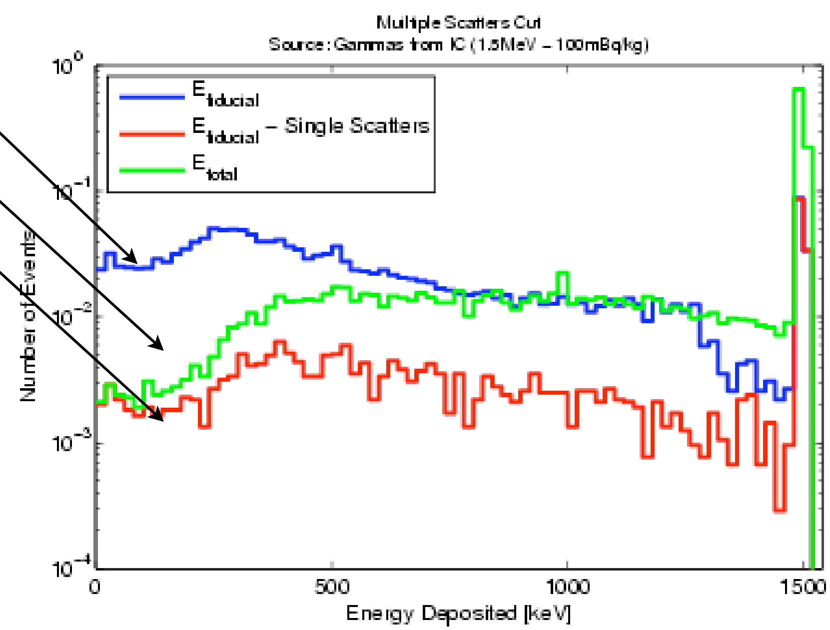


http://www.luxdarkmatter.org

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

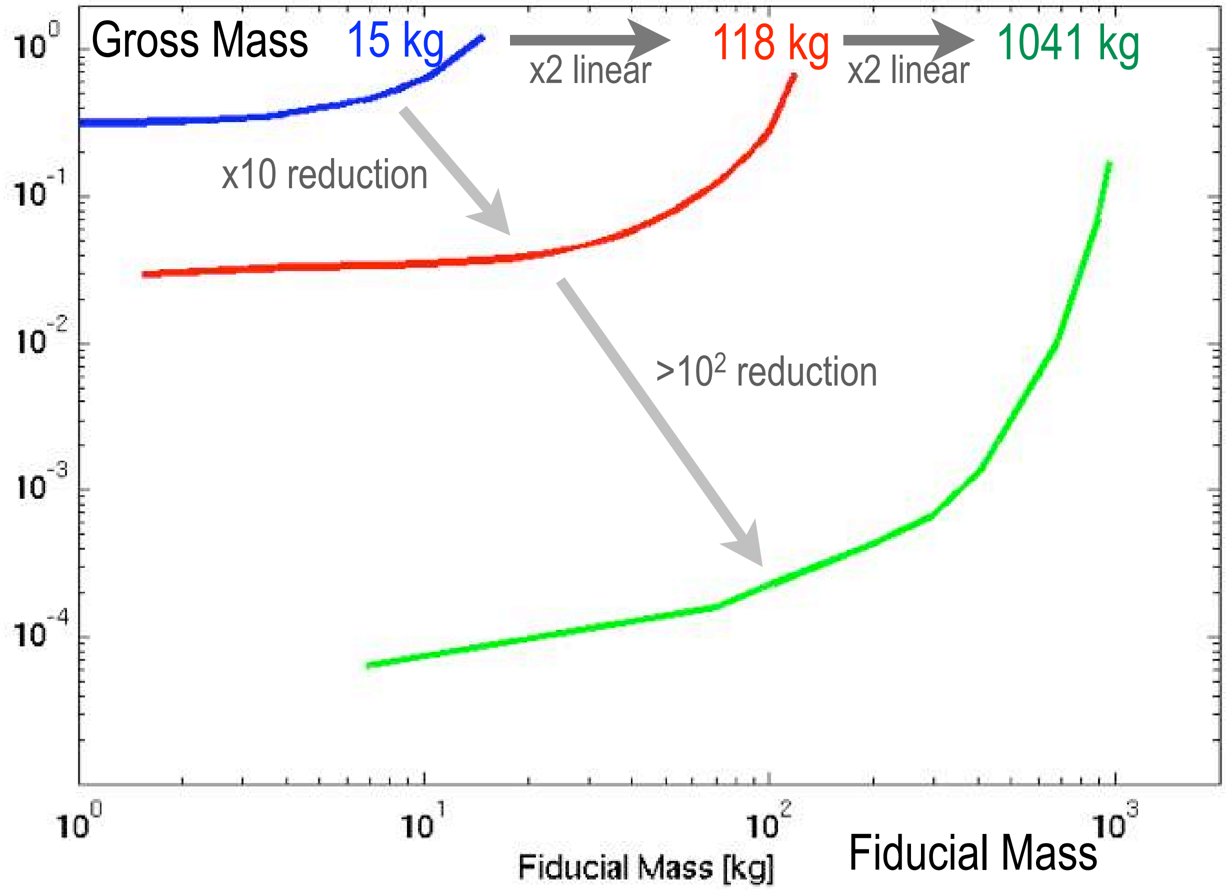


- Conclusion for Event Suppression
  - xyz resolution of detector is important simply in defining FV. Little additional reduction from locating vertices.
  - (Full xyz hit pattern does assist in bg source identification)

Scaling LXe Detector: Fiducial BG Reduction /1

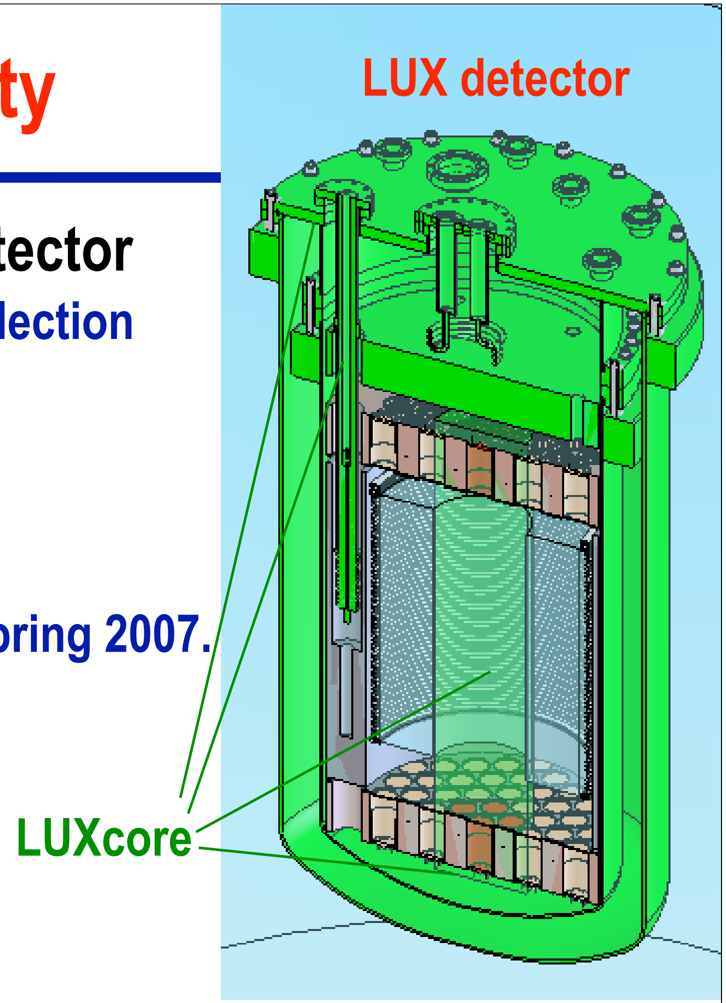
- Compare LXe Detectors (factor 2 linear scale up each time)
  15 kg (ø21 cm x 15 cm) -> 118 kg (ø42 cm x 30 cm) -> 1041 kg (ø84 cm x 60 cm)
  - Monte Carlos simply assume external activity scales with area (from PMTs and cryostat) using XENON10 values from screening

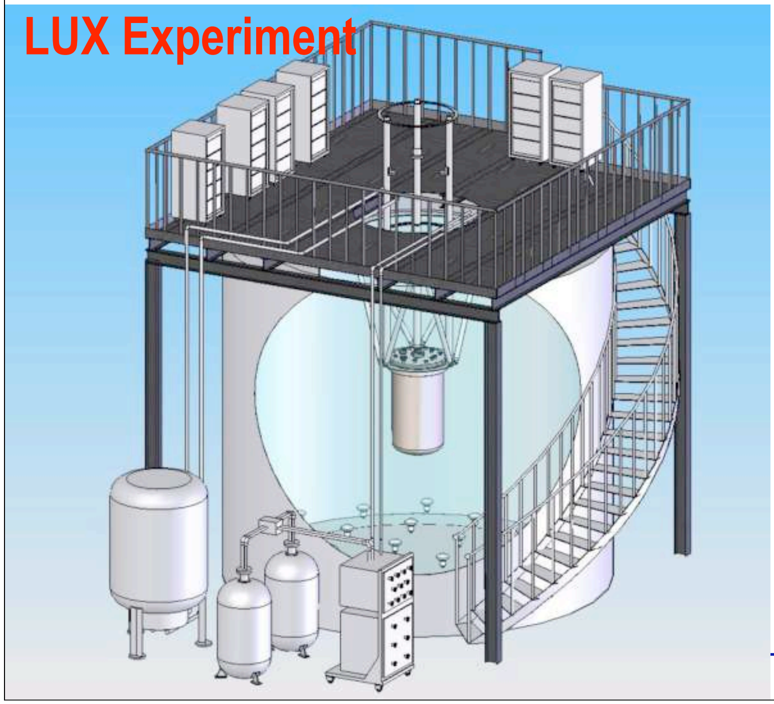
Low energy rate in FV before any ER vs NR rejection /keVee/kg/day



LUX program: exploit scalability

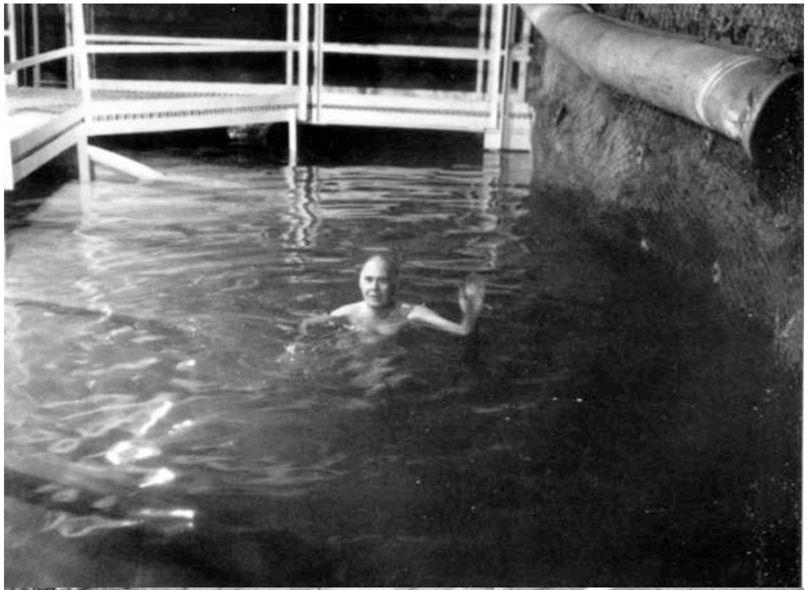
- LUXcore: Final engineering for large-scale detector
  - Cryostat, >100 kV feedthrough, charge drift, light collection over large distance
  - Full system integration, including ~1m water shield
  - 40 kg narrow “core”, 14 PMTs, 20 cm Ø x 40 cm tall.
    - Radial scale-up requires full-funding.
  -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

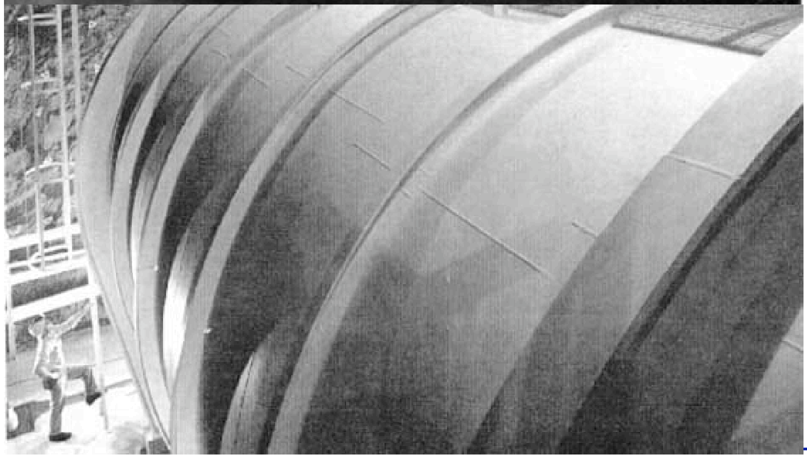


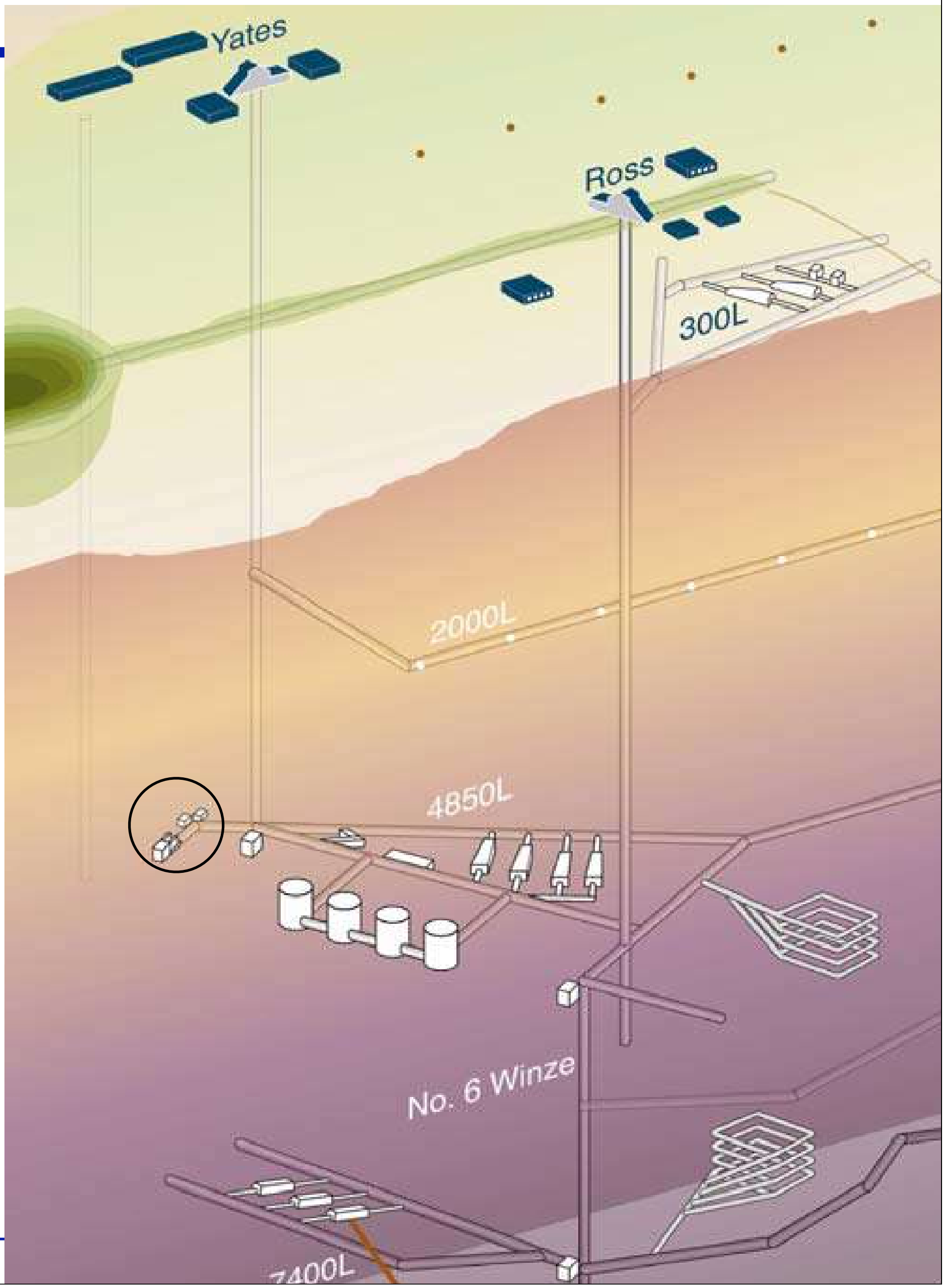


- LUX in ~ 6m Ø water shield
- Very good match to early-implementaion DUSEL (e.g., Homestake “Davis” cavern)
  - SNOLAB LOI
- System scalable to very large mass.

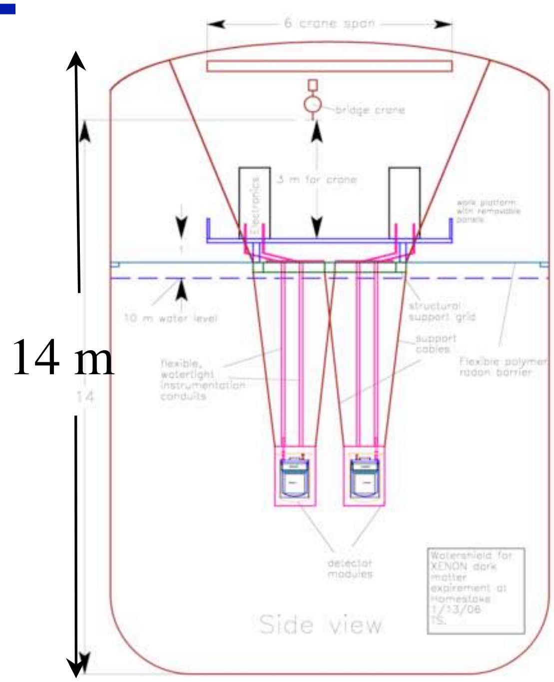
Water Shield - Homestake - Davis Cavern

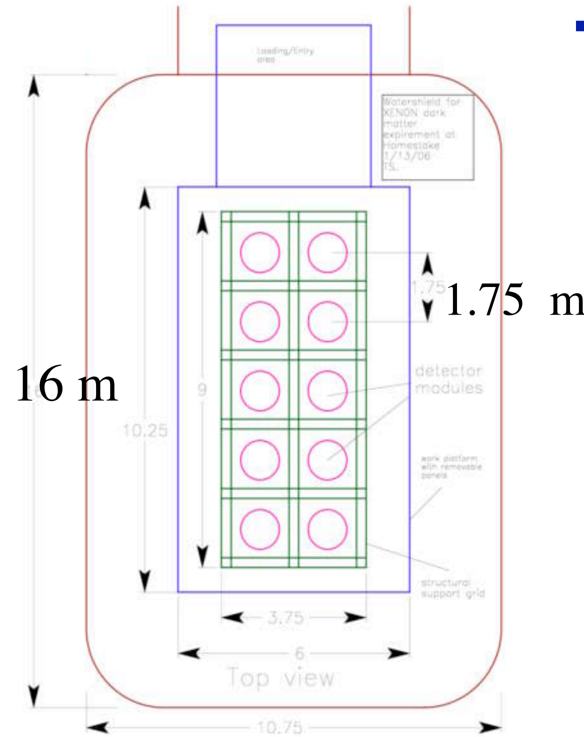






Homestake / Potential DUSEL Site (Lesko, LBL)

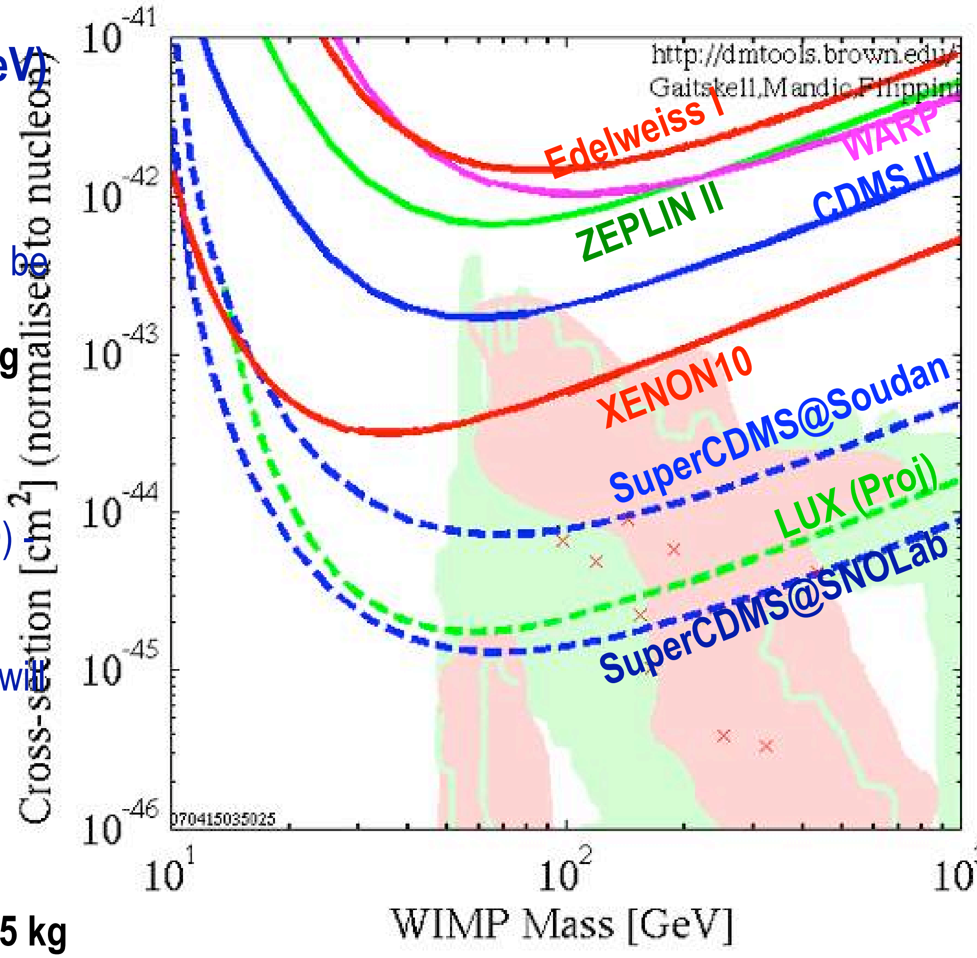




- DUSEL process for new national underground lab.
  - Site Decision mid 2007 (Full DUSEL lab 2010->)
- 4850 mwe depth at Homestake - early program.
- Water Shield: >4 m shielding / 10 module system

Dark Matter Results and (some of Goals)

- **Dark Matter Goals**
  - **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
      - ER bg assumed is dominated by guaranteed Hamamatsu PMT background (R8778 or R8520) - recent PMTs from Hamamatsu achieving lower backgrounds, but not guaranteed
      - Improvements in PMT bg (and rejection power) will extend background free running period, and DM sensitivity



  - **Comparison**
    - **SuperCDMS Goal @ SNOLab: Gross Ge Mass 25 kg (x 50% fid mass+cut acceptance)**
      Limit set for 1000 days running x 7 SuperTowers

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 $\sim10^2$: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 $\sim10^2$: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)