

Noble Travails: Noble Liquid Dark Matter Detectors

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(Supported by US DOE HEP)

see information at

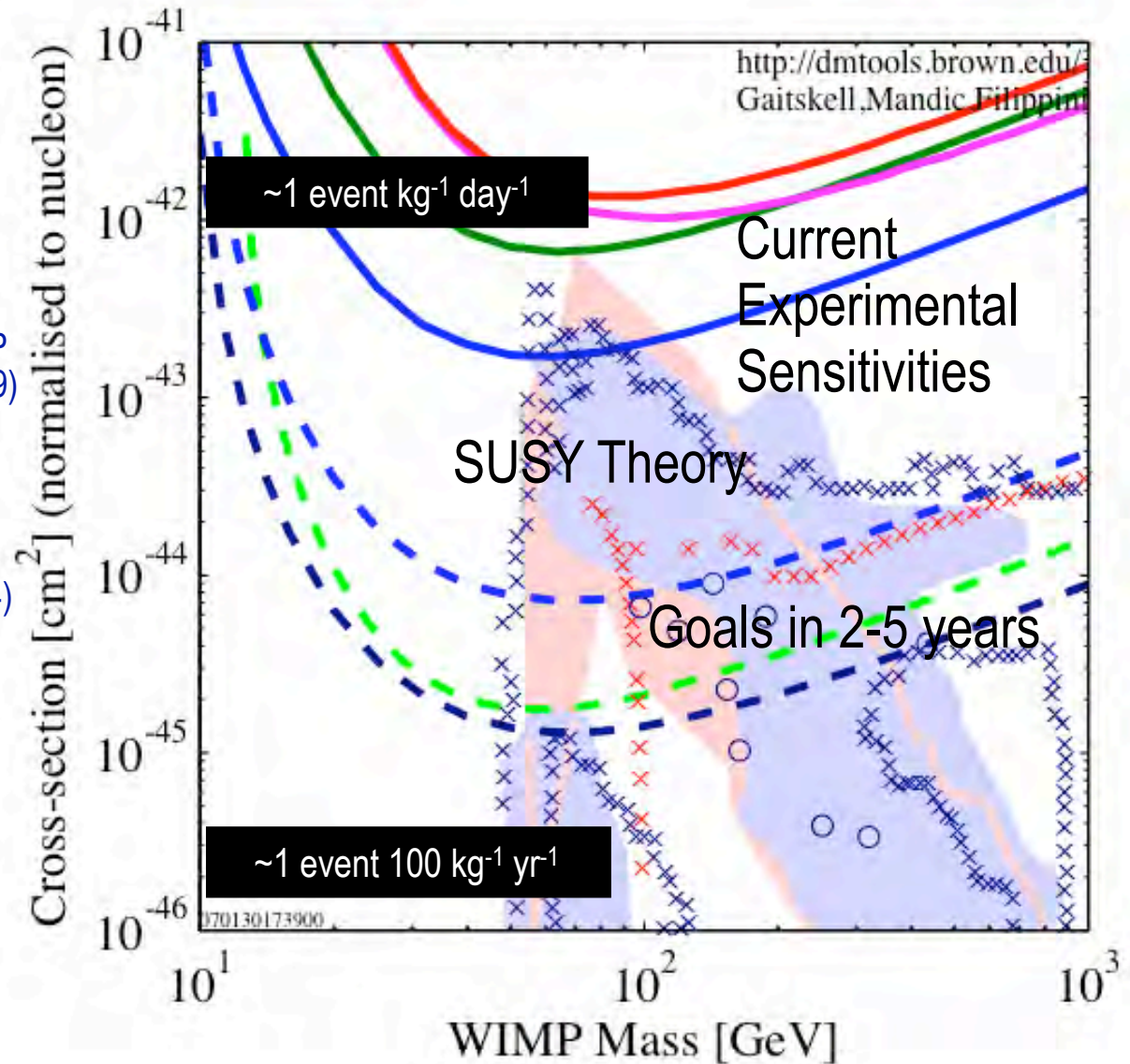
<http://particleastro.brown.edu/>

<http://gaitskell.brown.edu>

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. Giudice 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 $\ll 100$ keV)
 - Current Exp Limit < 1 evt/kg/20 days, $\sim < 10^{-1}$ evt/kg/day
 - Goal < 1 evt/tonne/year, $\sim < 10^{-5}$ 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 $\sim 10^2$ evt/kg/day using 25 cm of Pb
- Moving beyond this
 - e.g. High Purity Water Shield 4m gives $\ll 1$ 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 $10^2 \rightarrow 10^{-1}$ evts/kg/day
- Environmental Neutron Activity
 - (α, n) from rock $0.1 \text{ cm}^{-2} \text{ day}^{-1}$
 - Since < 8 MeV use standard moderators (e.g. polyethylene, or water, $0.1 \times$ 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 $\beta\beta$ -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

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 $\gg 1$ m, at purities achieved (\ll 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 $\sigma \sim 10^{-46} \text{ cm}^2 \Rightarrow 1 \text{ event}/100 \text{ kg}/\text{year}$ (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

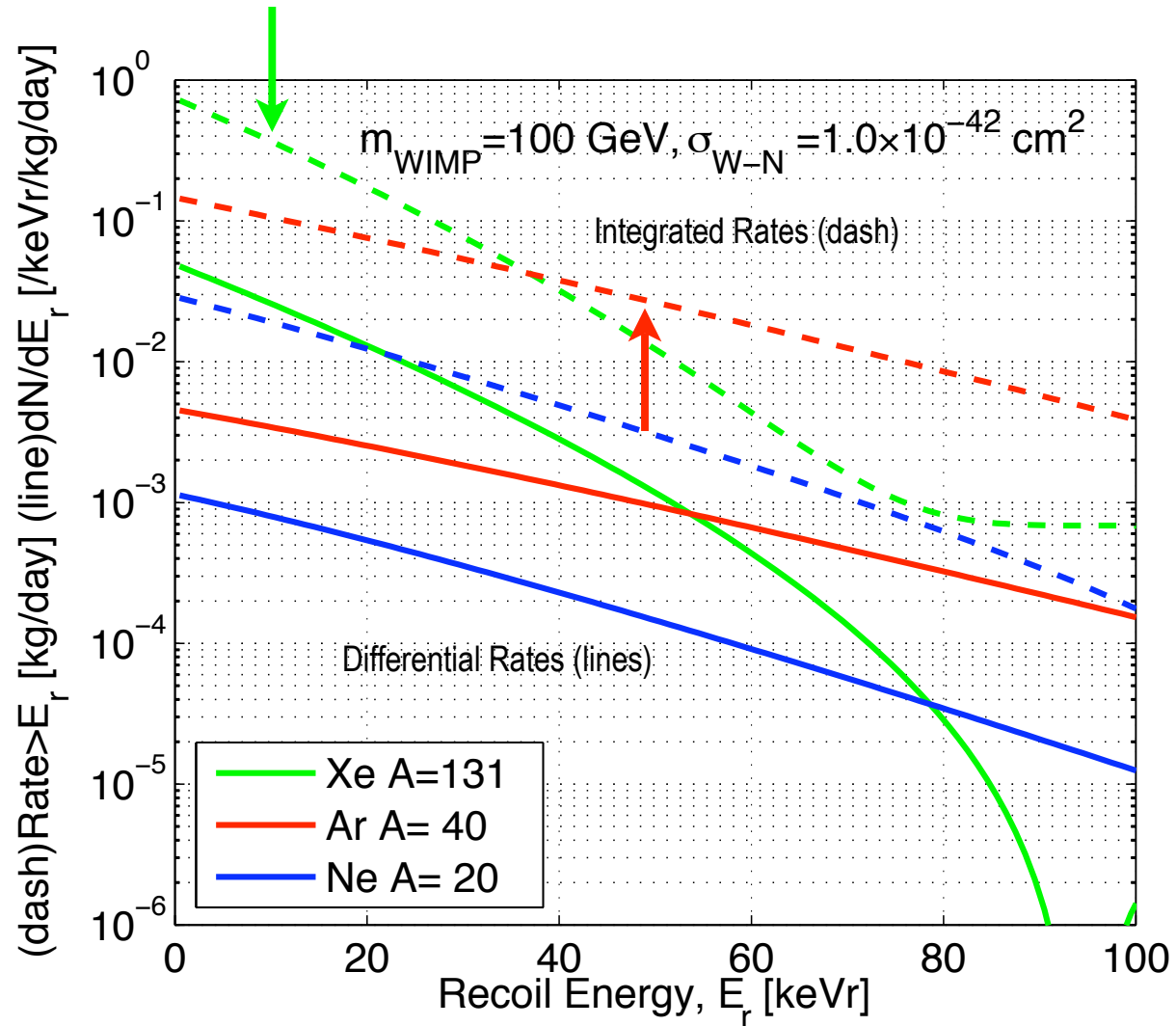
In LXe ~30% of electron recoil energy appears as scintillation light (7 eV photons)

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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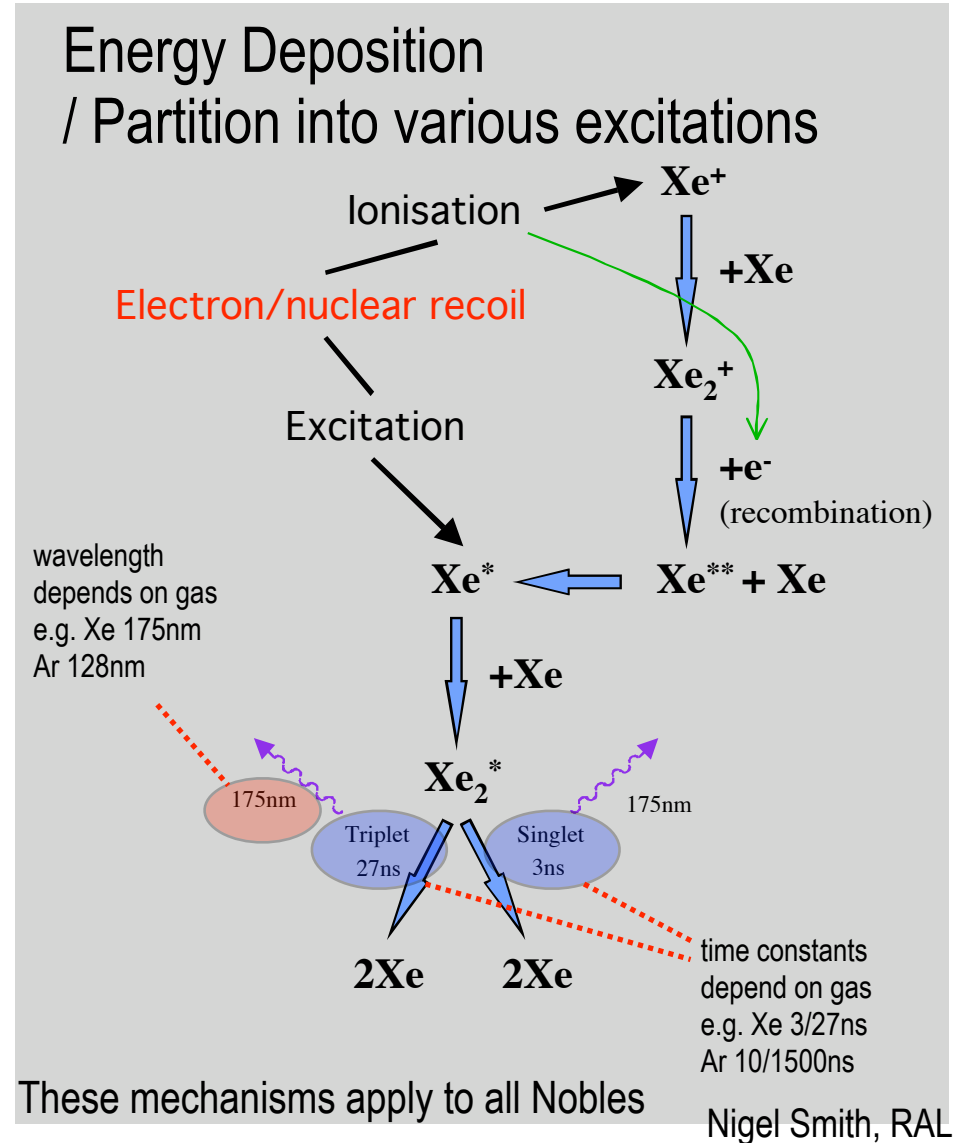
Noble Liquid Comparison (DM Detectors)

	Scintillation Light	Intrinsic Backgrounds	WIMP (100 GeV) Sensitivity vs Ge >10 keVr
<p>Ne (A=20) \$60/kg</p> <p>100% even-even nucleus</p>	<p>85 nm Requires wavelength Shifter</p>	<p>Low BP (20K) - all impurities frozen out</p> <p>No radioactive isotopes</p>	<p>Scalar Coupling: Eth>50 keVr, 0.02x</p> <p>Axial Coupling: 0 (no odd isotope)</p>
<p>Ar (A=40) \$2/kg (isotope separation >\$1000/kg) ~100% even-even</p>	<p>125 nm Requires wavelength shifter</p>	<p>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 (~10⁶ to match CDMS II)</p>	<p>Scalar Coupling: Eth>50 keVr, 0.10x</p> <p>Axial Coupling: 0 (no odd isotope)</p>
<p>Xe (A=131) \$800/kg</p> <p>50% odd isotope</p>	<p>175 nm UV quartz PMT window</p>	<p>No long lived isotopes. 85Kr can be removed by charcoal or distillation.</p>	<p>Scalar Coupling: Eth>10 keVr, 1.30x</p> <p>Axial Coupling: ~5x (model dep) Xe is 50% odd n isotope 129Xe, 131Xe</p>

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	

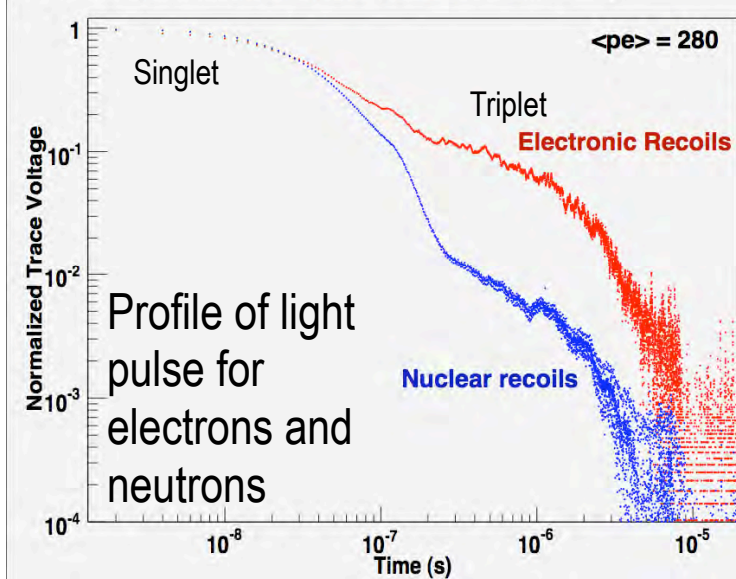
- Single phase - scintillation only
 - e-ion recombination occurs
 - singlet/triplet ratio 10:1 nuclear:electron
- Double phase - ionization & scintillation
 - drift electrons in E-field (kV/cm)



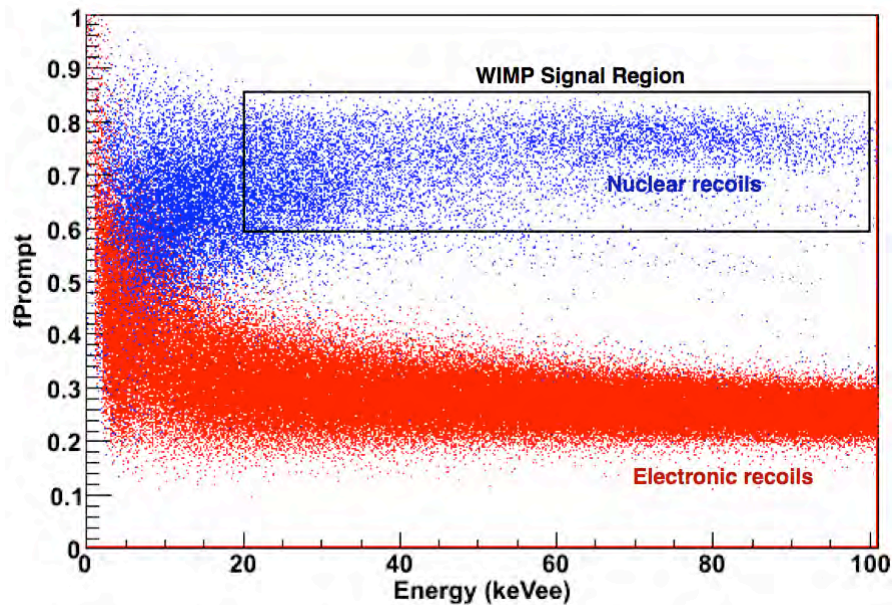
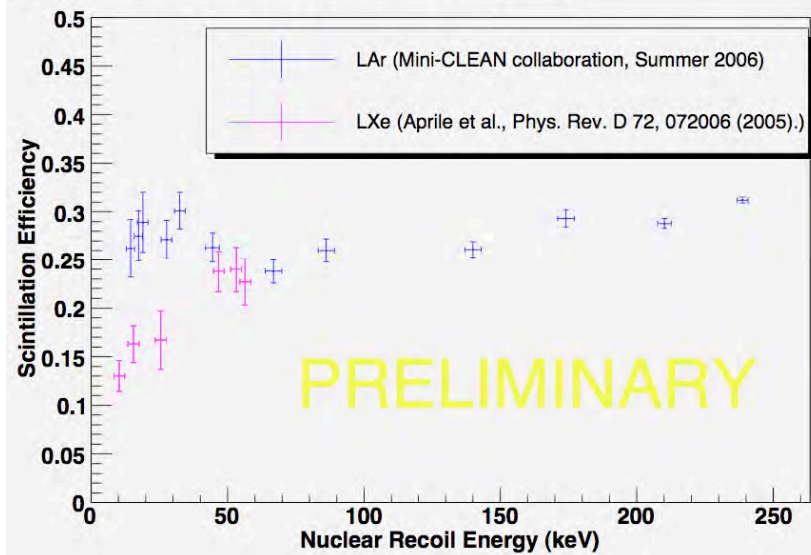
Data taken with Micro-CLEAN (McKinsey, Yale)

CLEAN Ar PSD

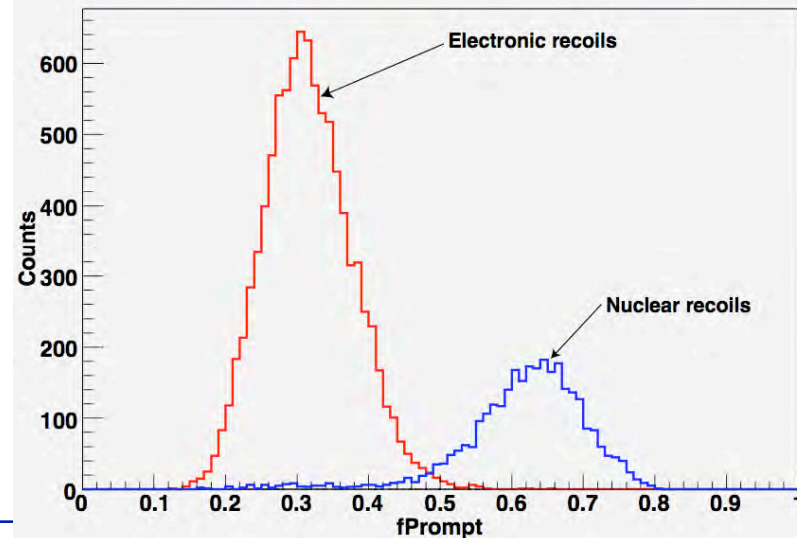
Time Dependence of Liquid Argon Scintillation



Scintillation Efficiency of Nuclear Recoils

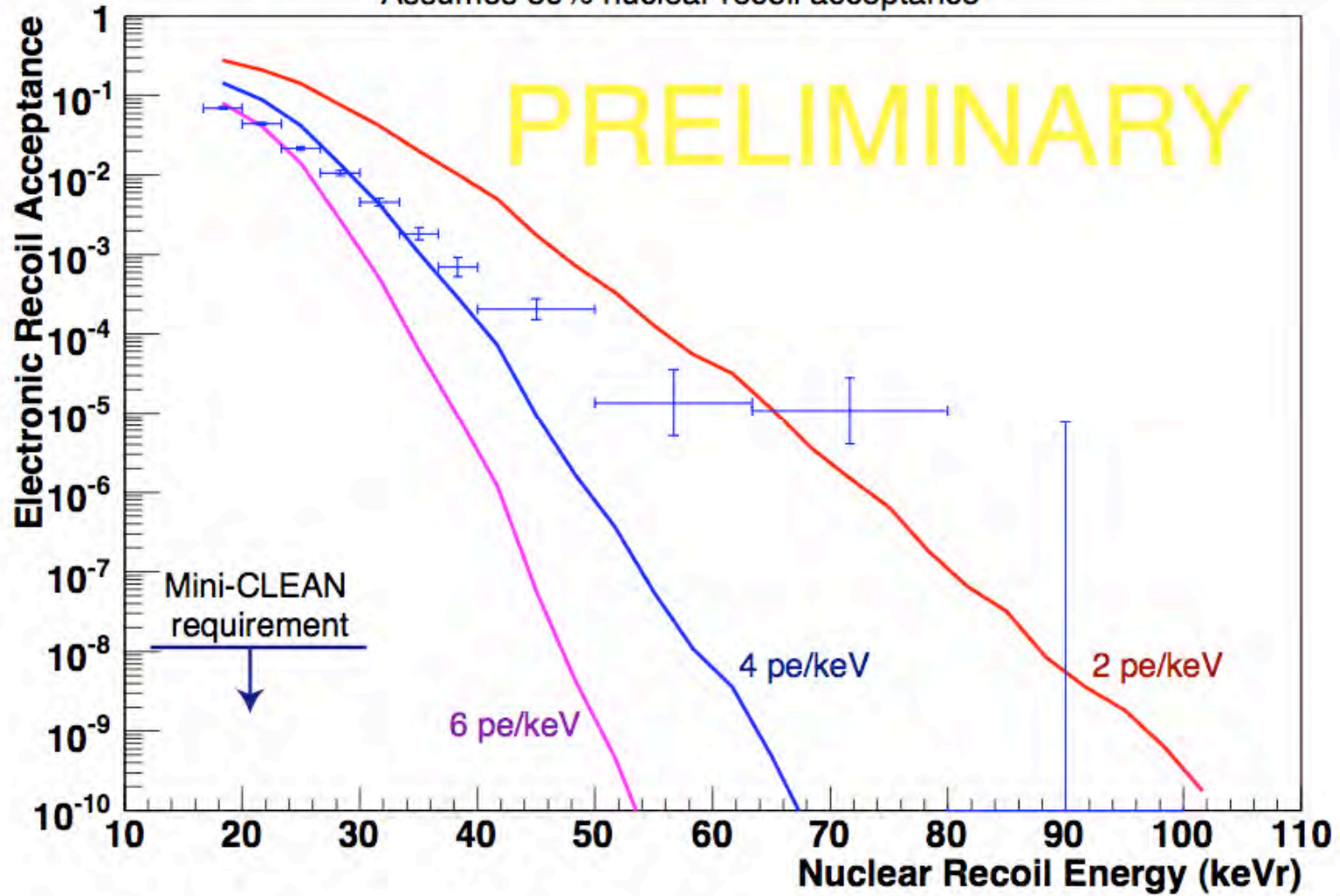


Discrimination in LAr is better than 99.999% above 50 keVr



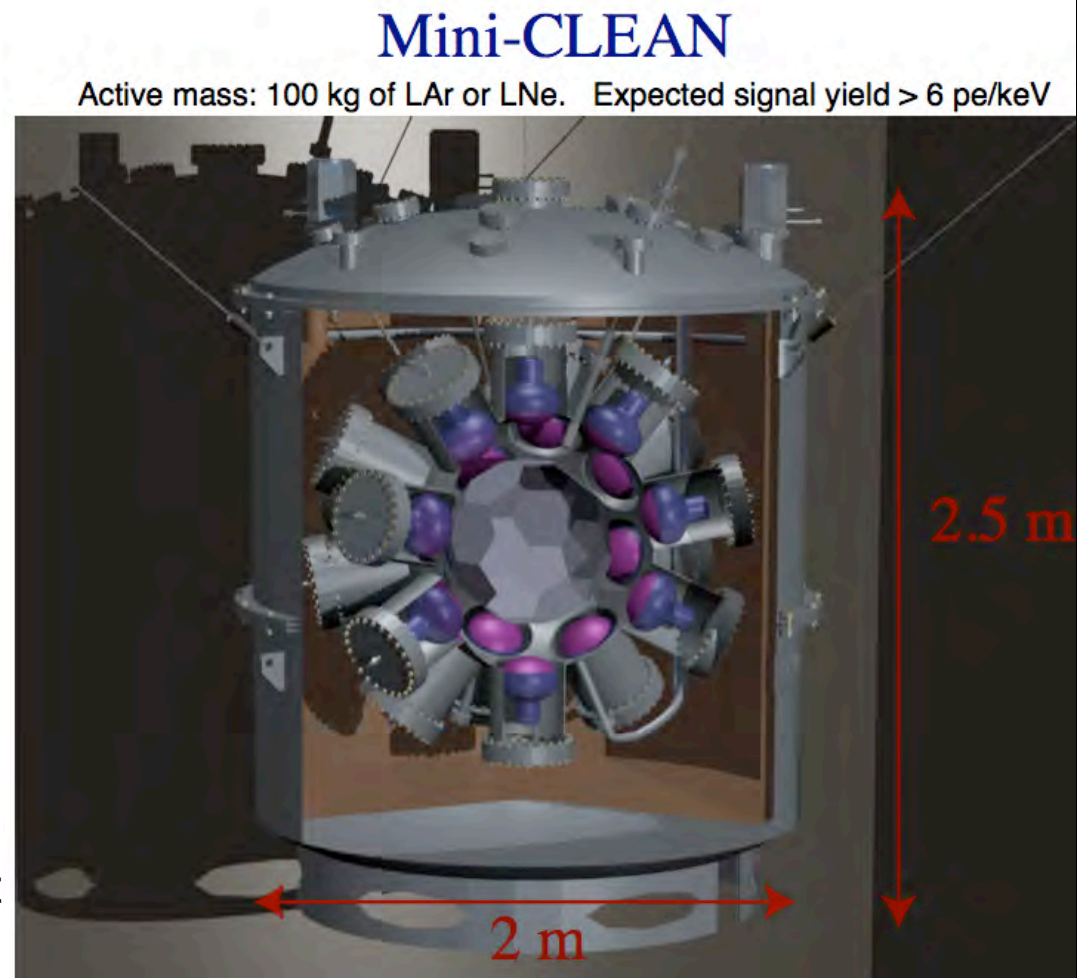
(McKinsey, Yale)

Gamma Ray - Nuclear Recoil Discrimination Efficiency vs Energy in LAr
Assumes 50% nuclear recoil acceptance



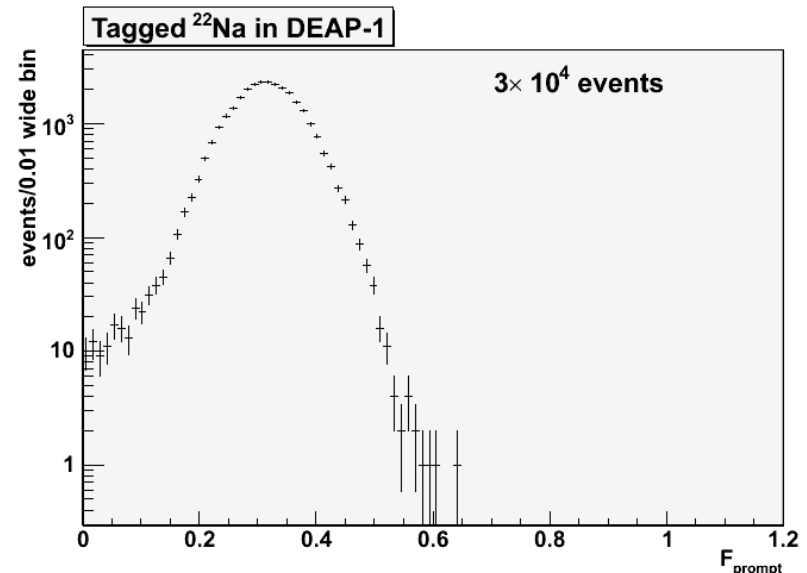
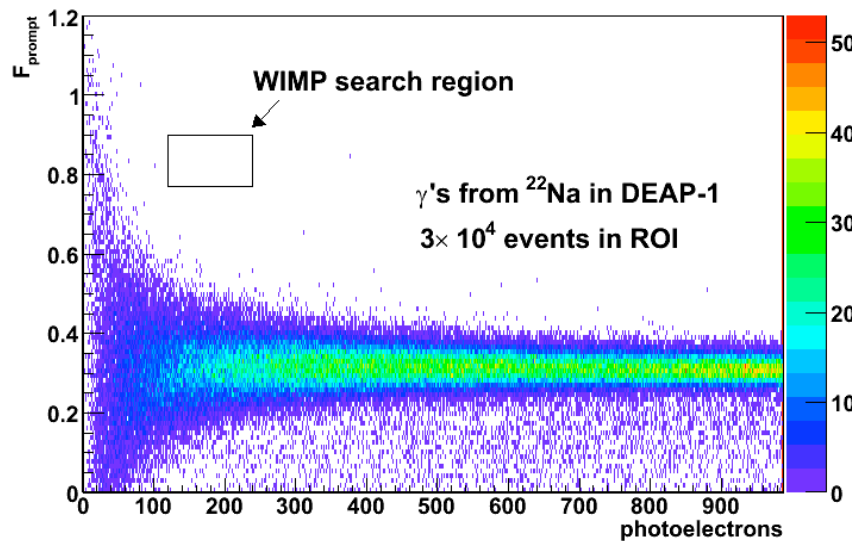
miniCLEAN (proposed)

- 100 kg miniCLEAN
 - WIMP Goal $\sim 5 \times 10^{-45} \text{ cm}^2$
 - 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

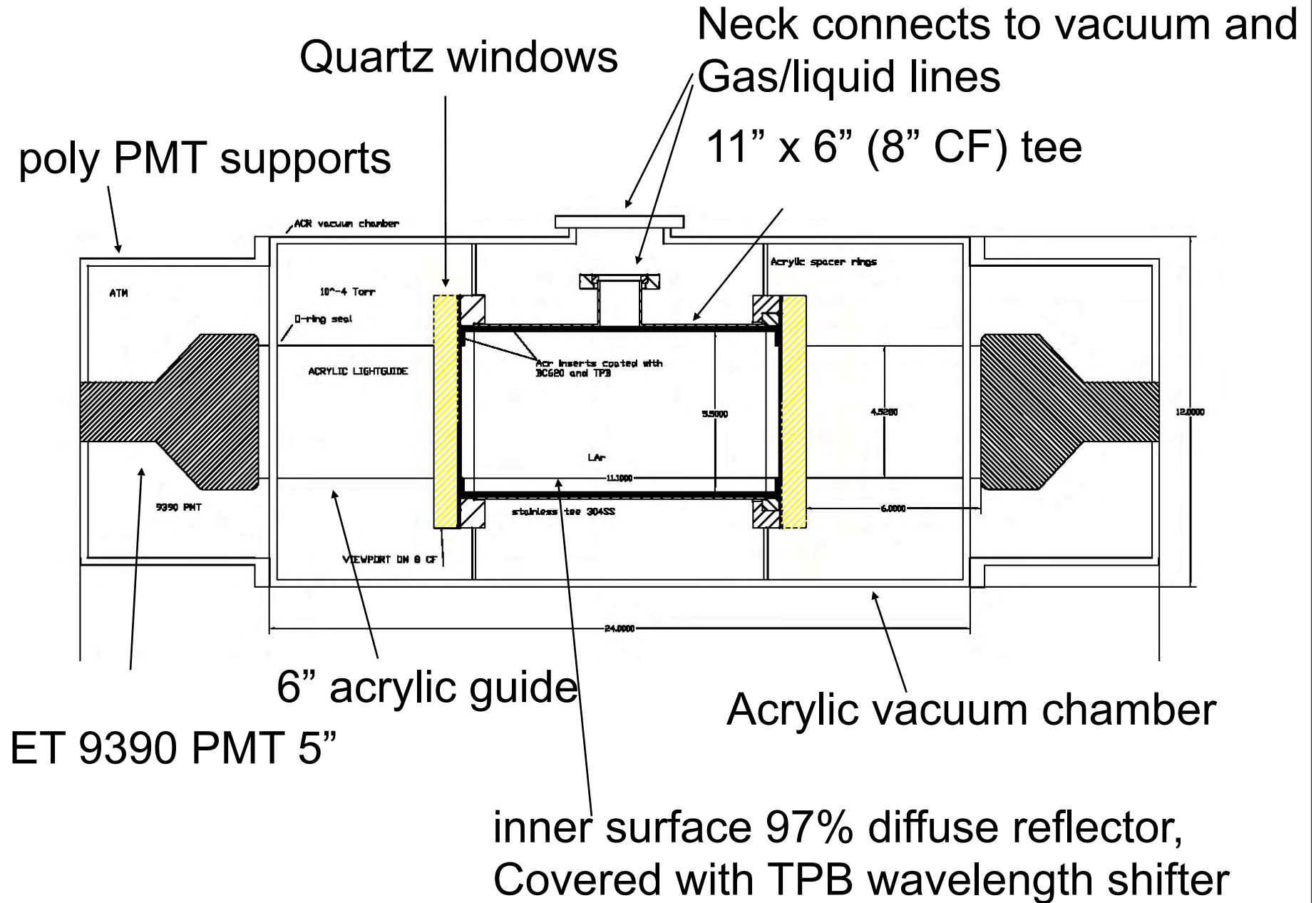


DEAP-1 (being deployed)

- 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 ^{22}Na source to limit lab neutron contamination
 - Preliminary data showing $\sim 10^{-4}$ - 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

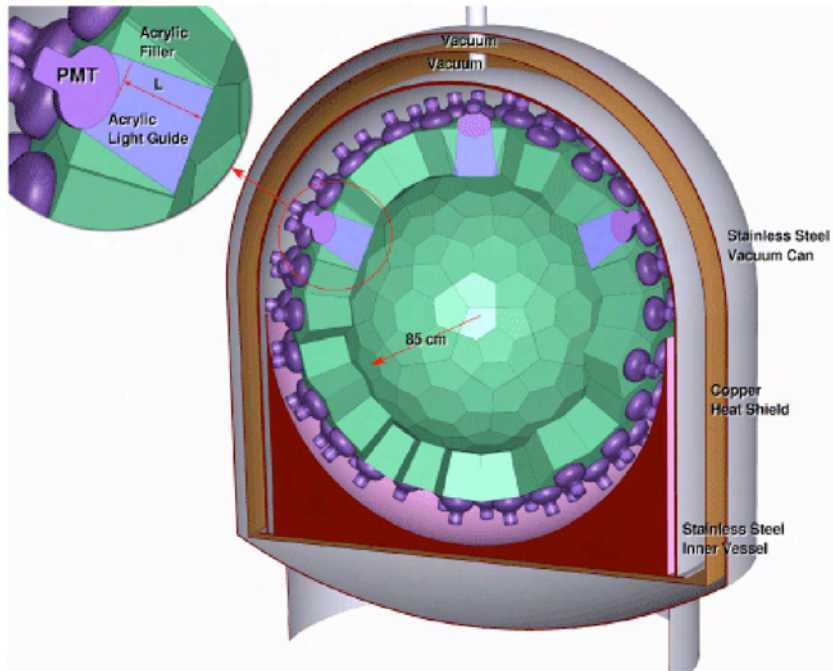


DEAP-1 design

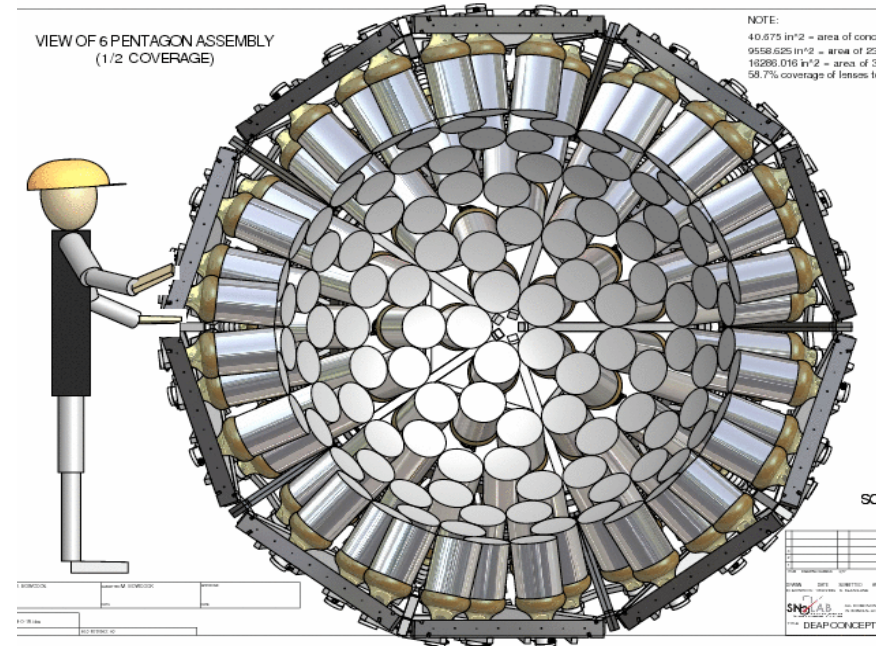


DEAP & CLEAN “ULTIMATE” designs

“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

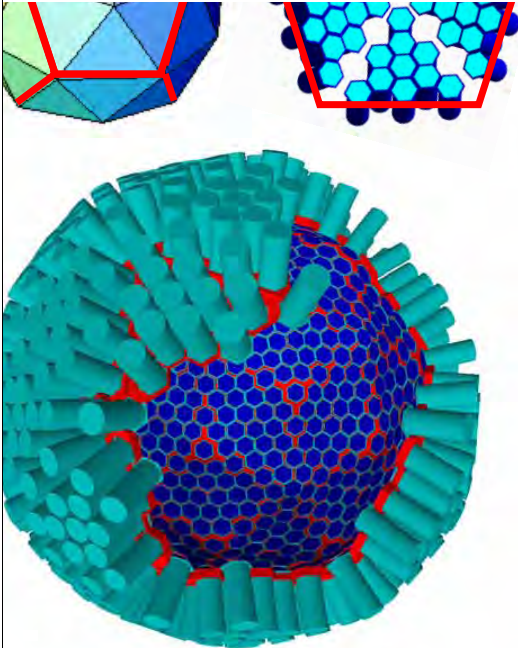


- Detector design is going using MC

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

- New excavation will be done soon

XMASS 800 kg - Japan



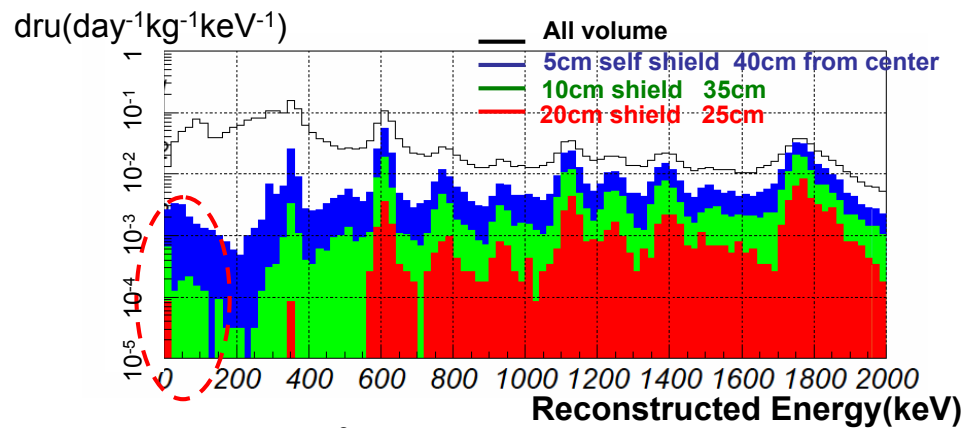
- 60 triangles
- 10 PMT/triangle x 60 = 600 PMTs
- + 212 PMTs in triangle boundary region
- **Total 812 PMTs**
- **Photo coverage 67.0%**
- Center to photocathode ~45cm
- Fiducial volume is 25cm from center.
- PMTs are inside liquid xenon.

Decision on funding of 800 kg phase currently be considered

Summary

- XMASS 800kg detector
 - 1 ton liquid xenon, 90cm diameter, 60 triangles, 812 PMTs
 - BG level 10^{-4} $\text{dru}(\text{day}^{-1}\text{kg}^{-1}\text{keV}^{-1})$
 - 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 $\sim 10^{-5}$ dru inside fiducial volume
 - Water shield for ambient γ and fast neutron
 - 200cm shield is enough

Background from PMT ^{238}U



- $1.8 \times 10^{-3} \text{ Bq/PMT}$

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**

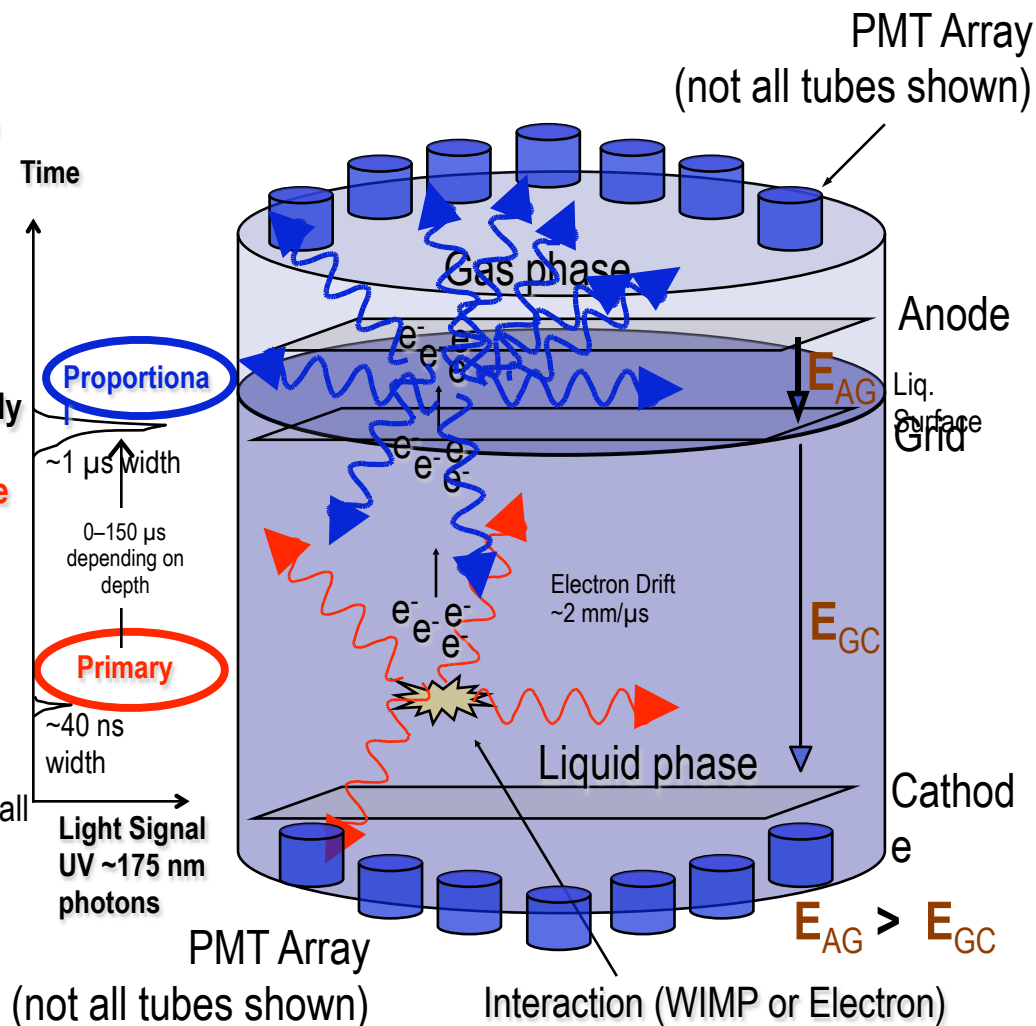
Ionization signal from nuclear recoil too small to be directly detected => **extract charges from liquid to gas** and detect much larger proportional scintillation signal => **dual phase**

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

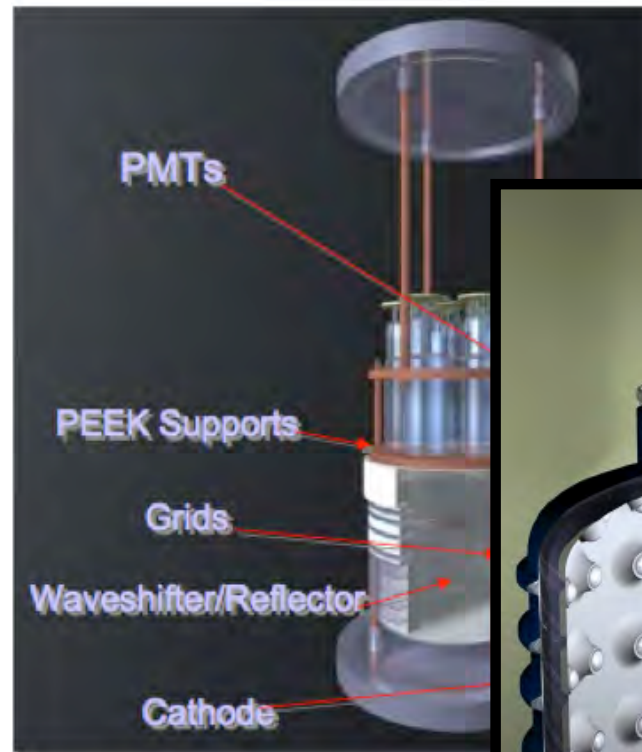
(**~ 200 photons**) associated with **16 keVr**



Two-phase Argon Detectors: WARP and ArDM

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

WARP Prototype



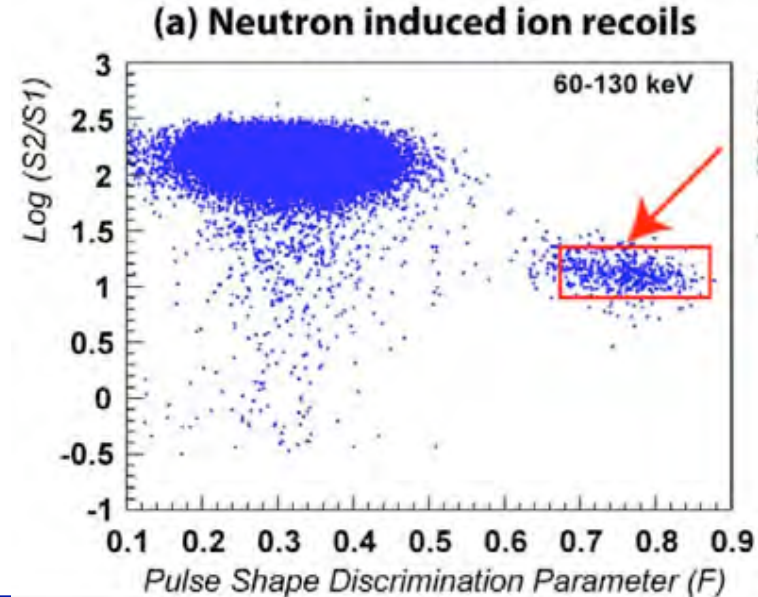
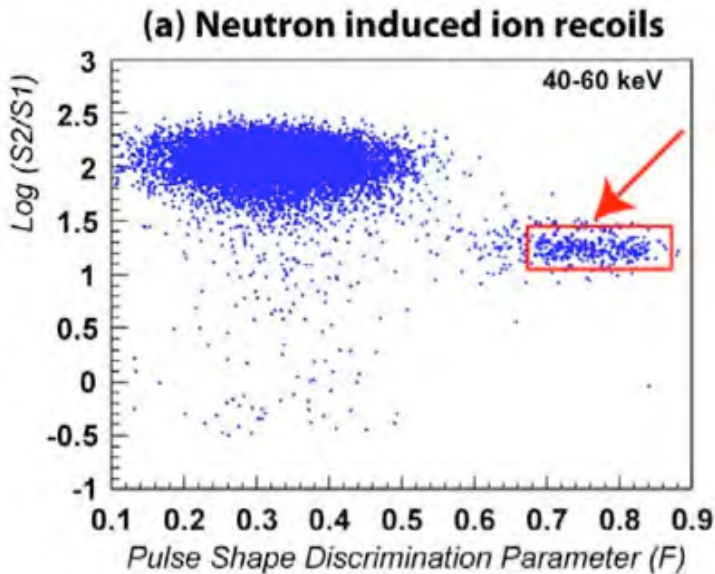
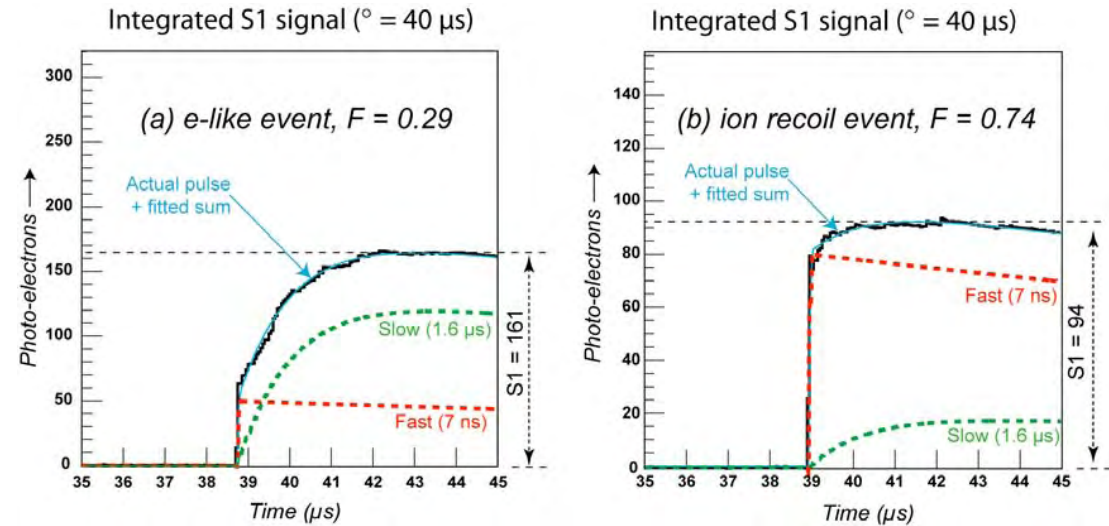
WARP



Schematic view of the 2.3 chamber
100-I detector

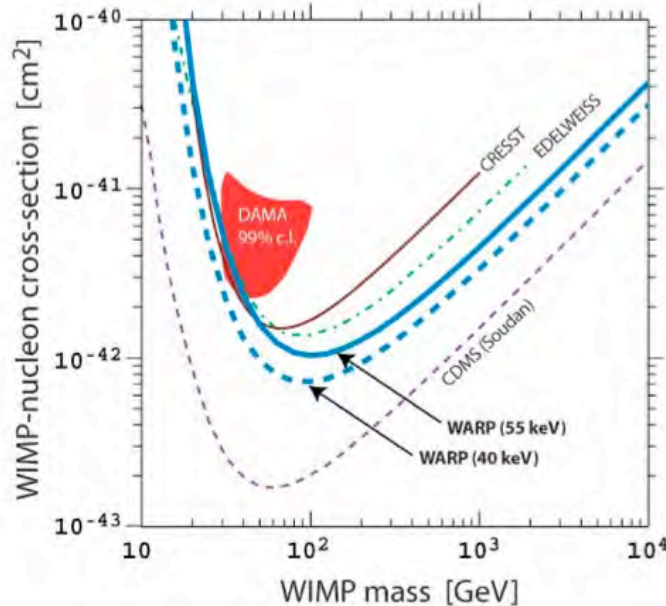
WARP - Dual Methods of Discrimination

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

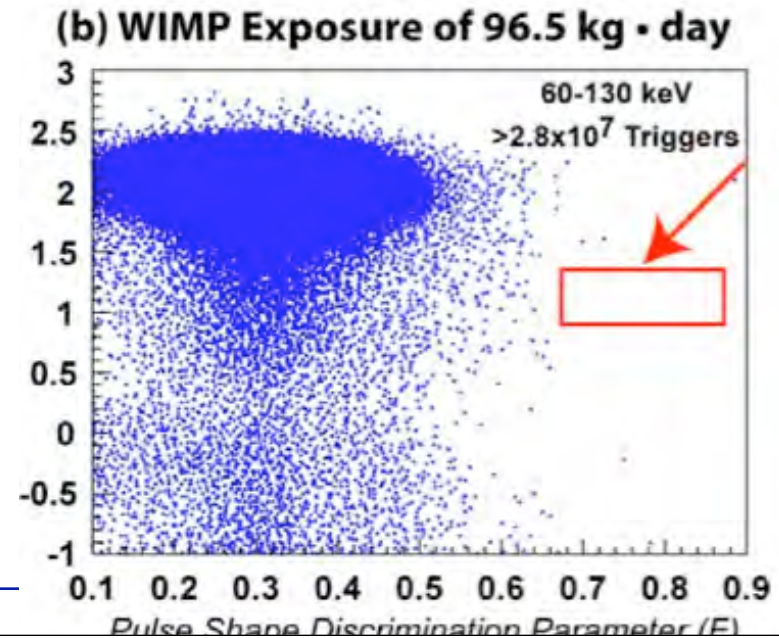
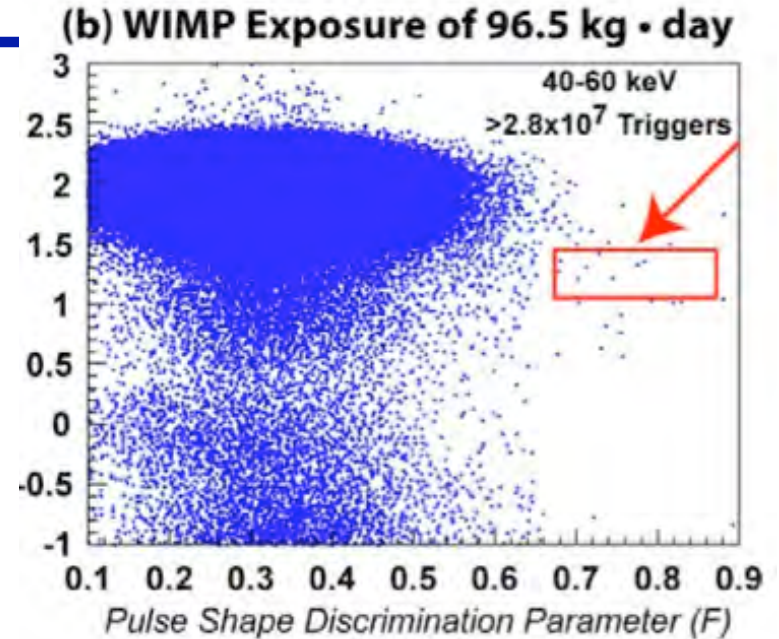


WARP Recent Results (Jan 07) astro-ph/0701286

- 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 “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)



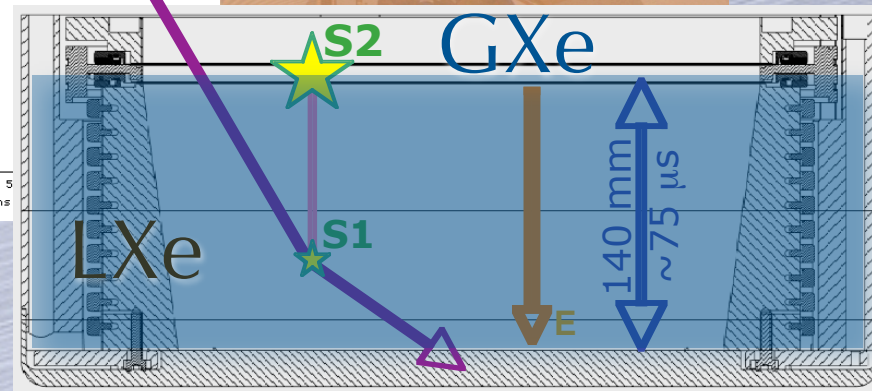
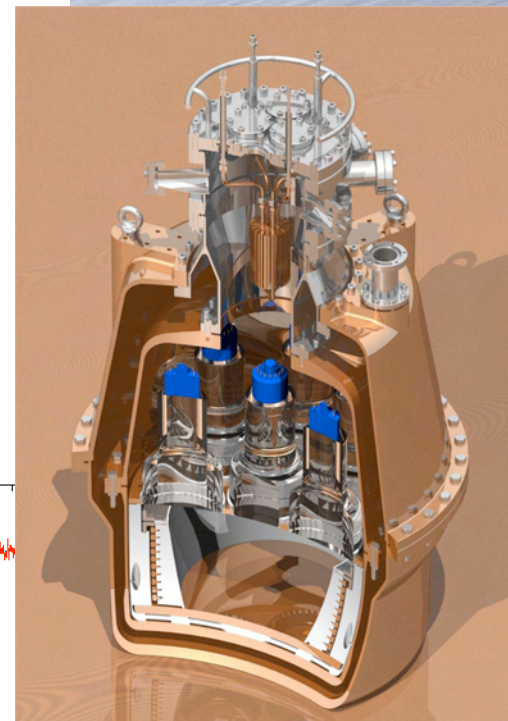
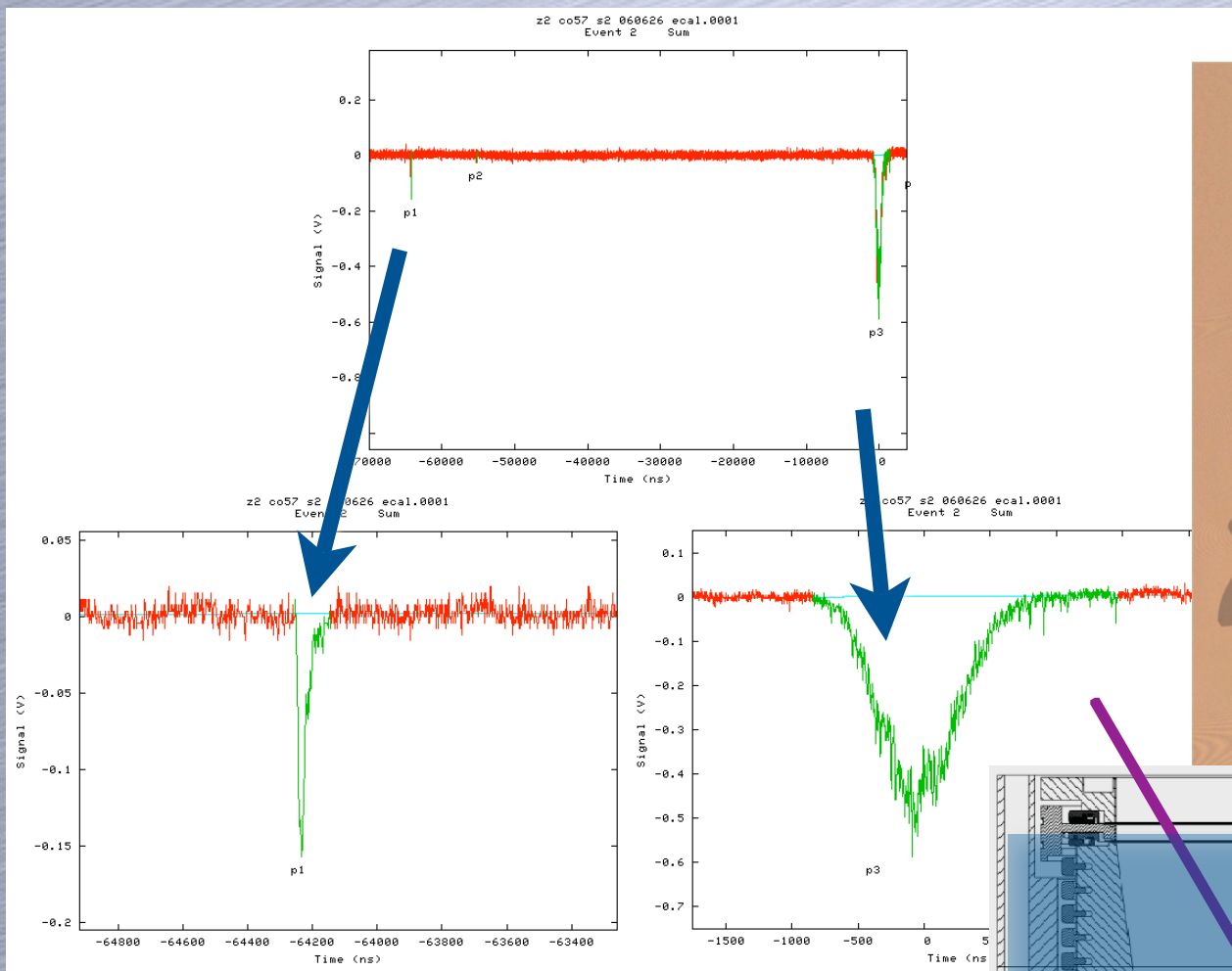
Noble Liquids



39Ar Beta Background - Event Rejection vs Removal

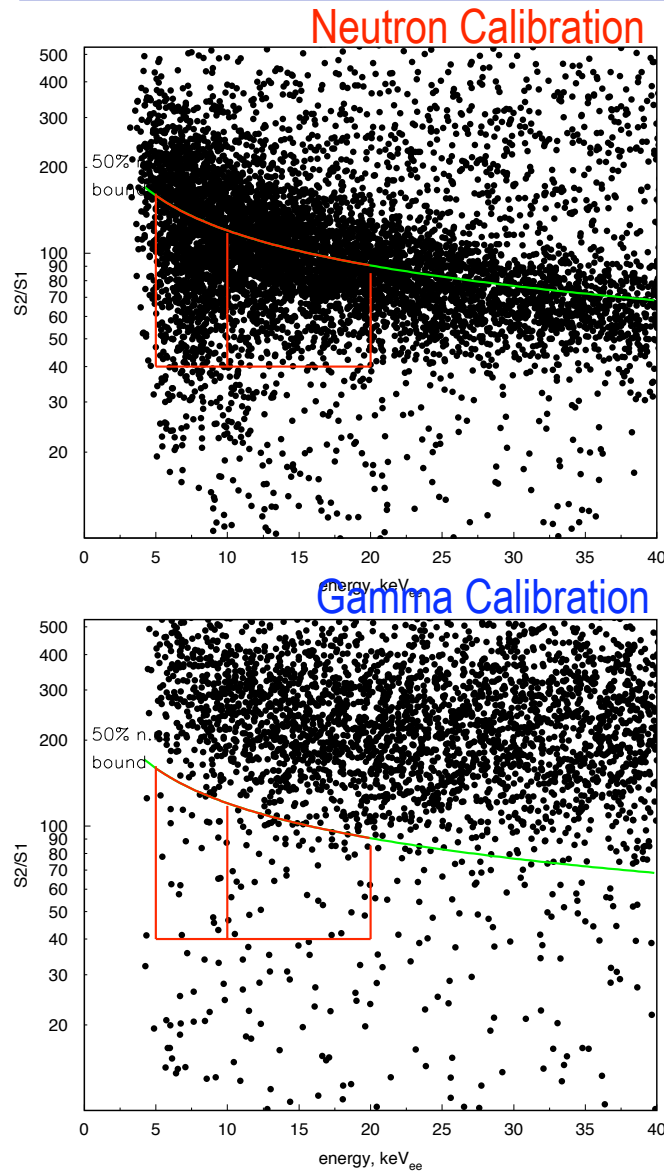
- Note that regular Ar contains 39Ar ~ 1 Bq/kg, which gives beta spectrum (end point ~ 500 keV) with a low energy tail of ~ 150 evts/keVee/kg/day
- This means that in order to match current best CDMS II sensitivity an Ar experiment must deliver at least $\sim 10^6$ rejection.
 - Fiducialization/multiple 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 $\sim 1/50$ 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

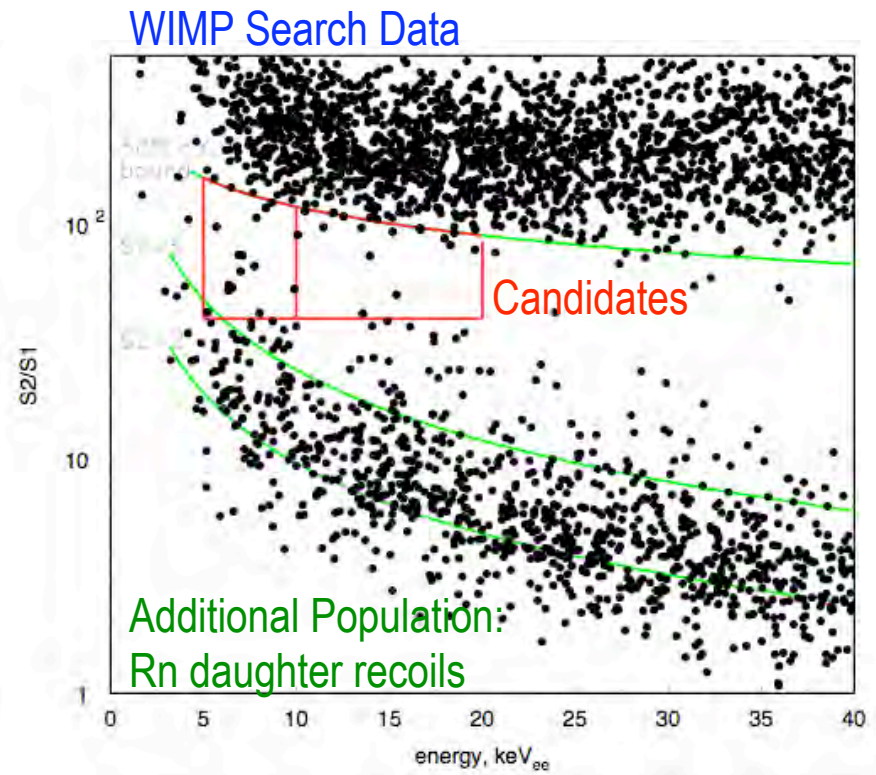
Discrimination Power



- 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

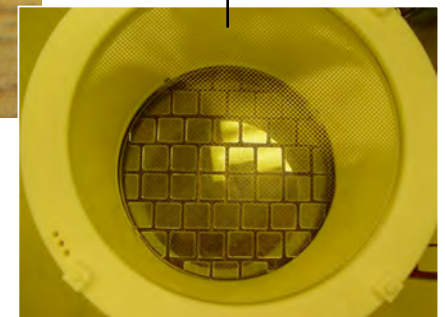
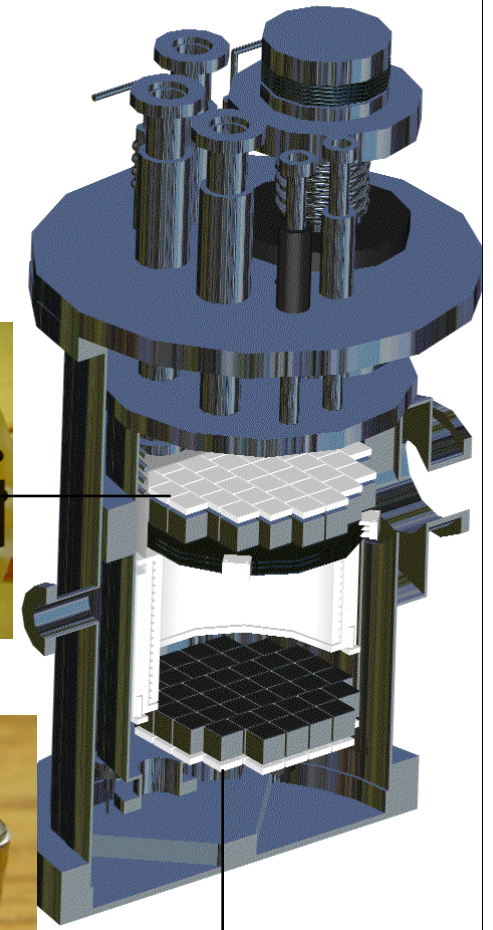
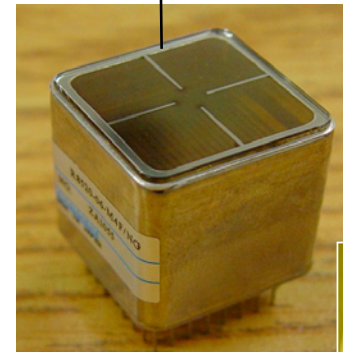
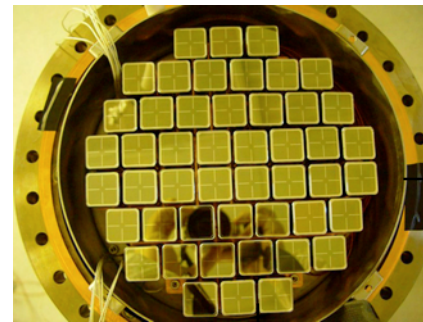
ZEPLIN II

- 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



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 -100°C and 5 bar
 - Quantum efficiency > 20% @ 178 nm
- 48 PMTs top, 41 PMTs bottom array
 - x-y position from PMT hit pattern; $\sigma_{x-y} \approx 1$ mm
 - z-position from Δt_{drift} ($v_{d,e} \approx 2$ mm/ μ s), $\sigma_Z \approx 0.3$ 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



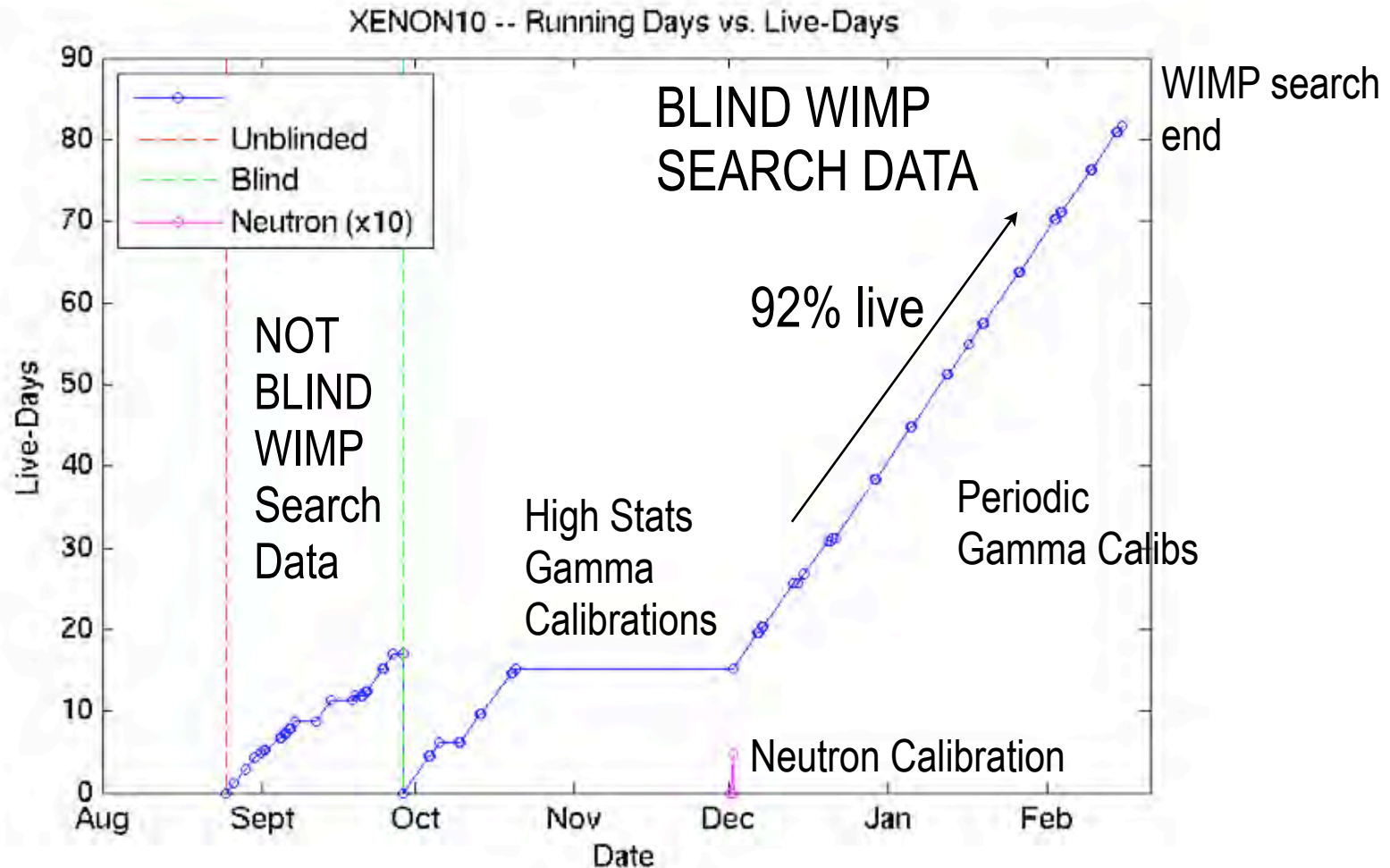
XENON10: Ready for Low Background Operation

Installation of the Detector...

...and we are operational

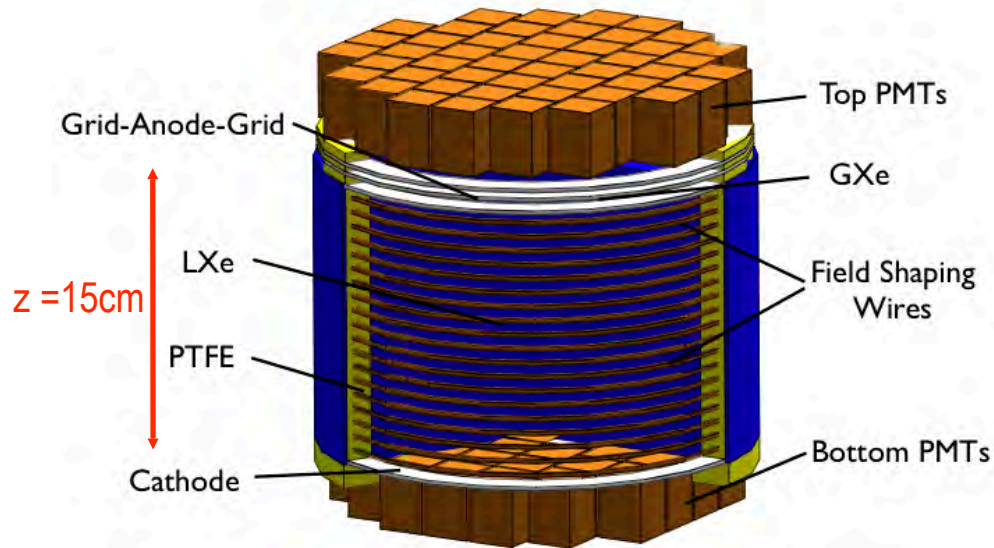


XENON10 Live time at Gran Sasso

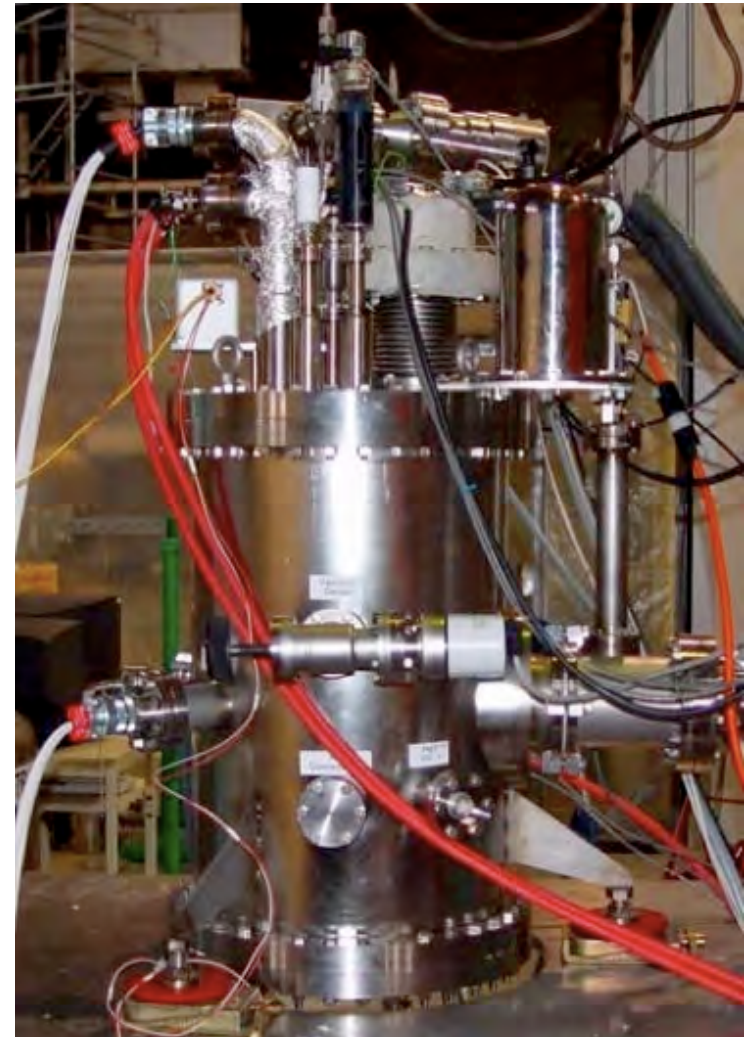
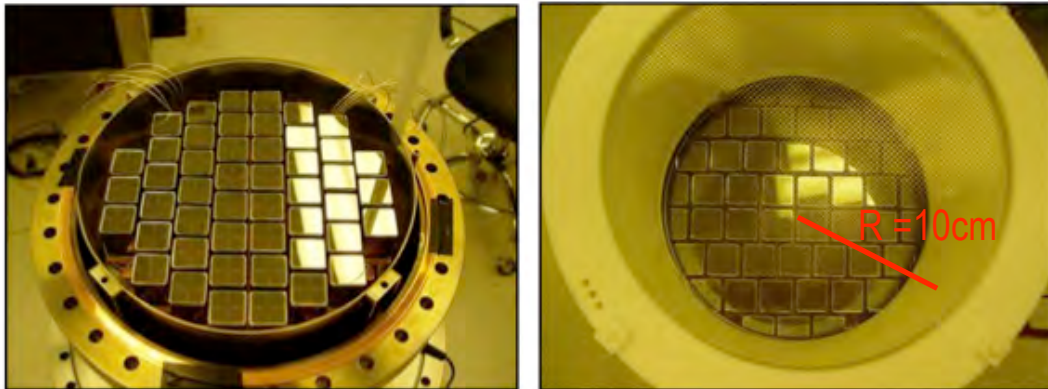


- Discuss data from High Statistics Gamma Calib, Neutron Calib and NON BLIND WIMP search data ~20 live days
- WIMP Search results (from 80 live day) will be announced at April APS Meeting

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 μ s => 76 mm

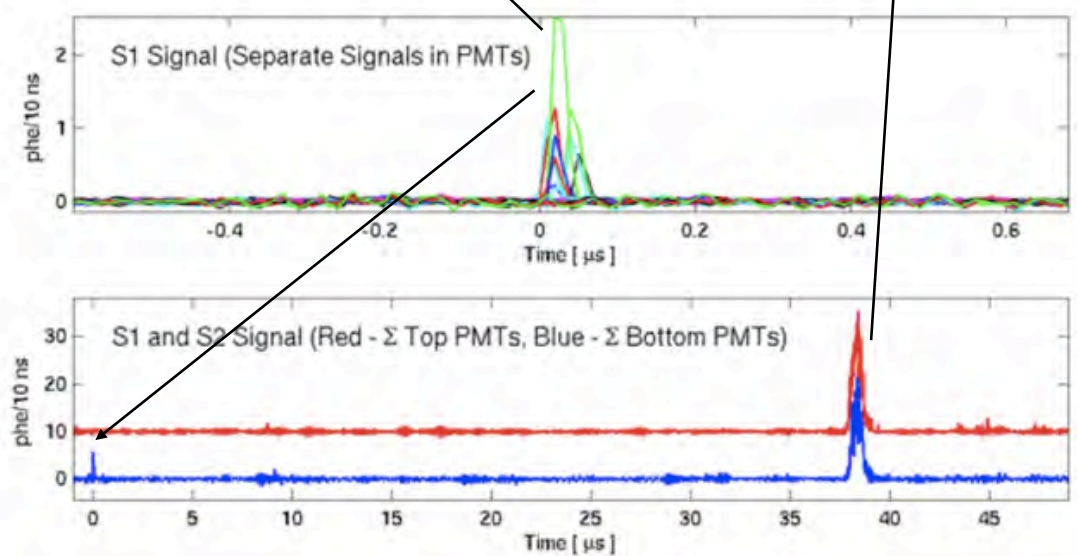
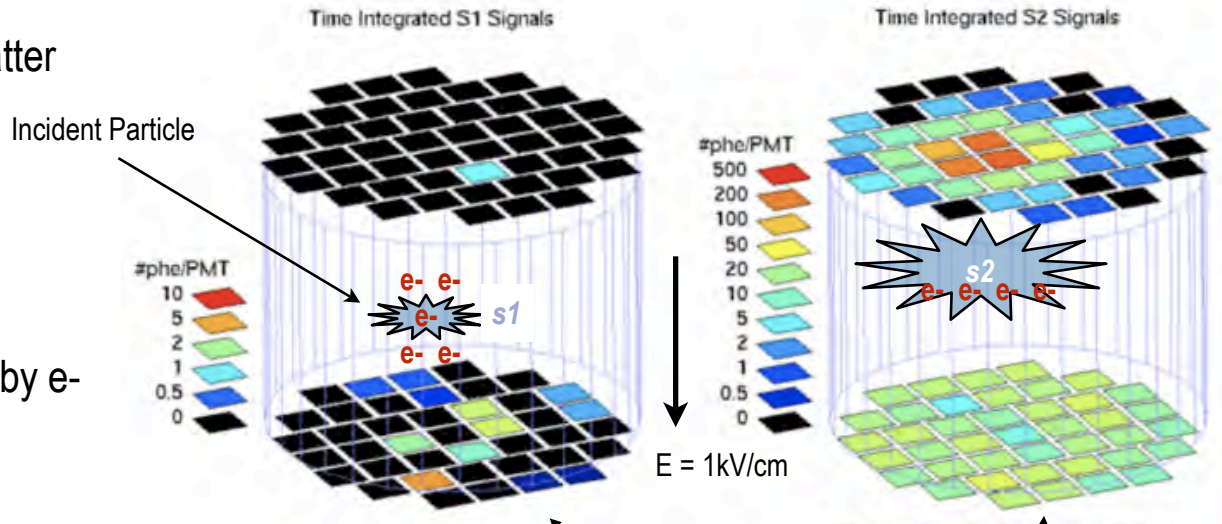
s1: Primary Scintillation Created by Interaction LXe

s2: Secondary Scintillation Created by e- extracted & accelerated in GXe

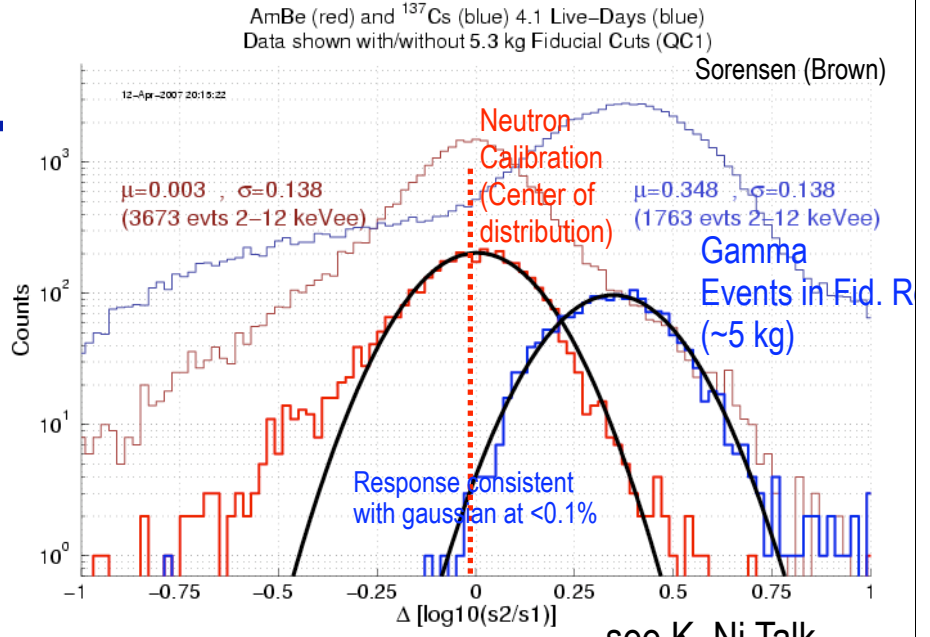
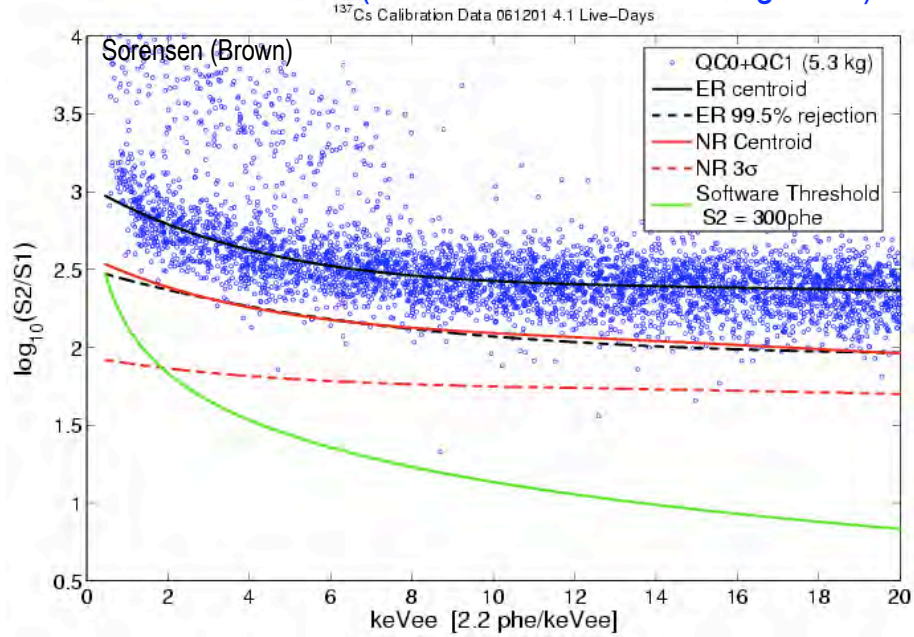
$$(s2/s1)_{ER} > (s2/s1)_{NR}$$

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

Reduction of Backgrounds =>
Reduction of Leakage Events

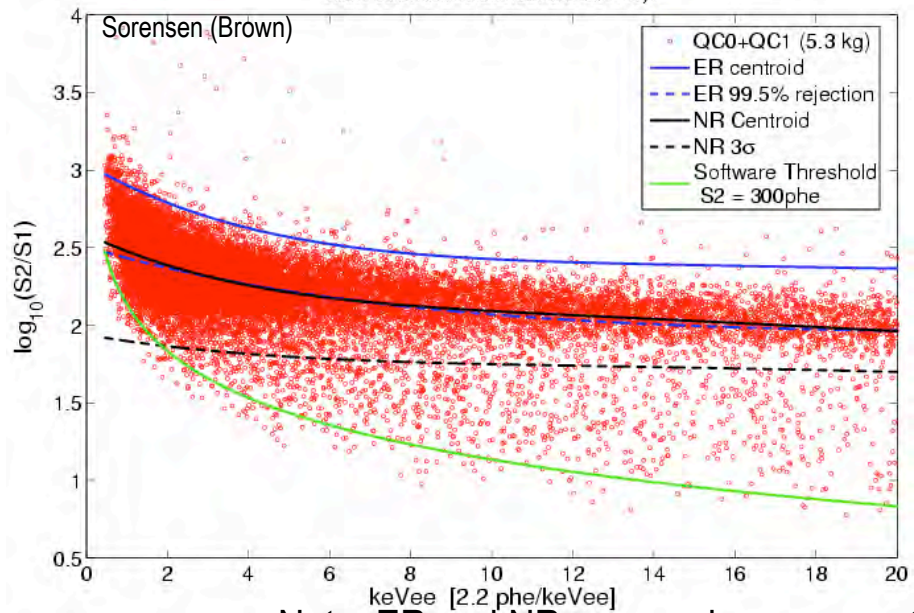


Gamma Calibration (Electron Recoils == Background)

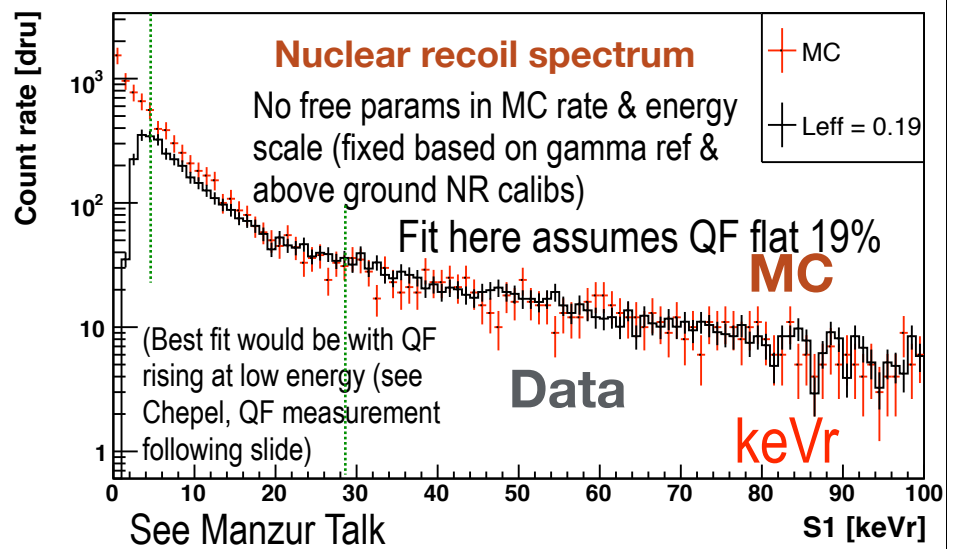


see K. Ni Talk

Neutron Calibration



single nuclear recoils ~20% discrep



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

See Aprile / Manalaysay

Talk

§ 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

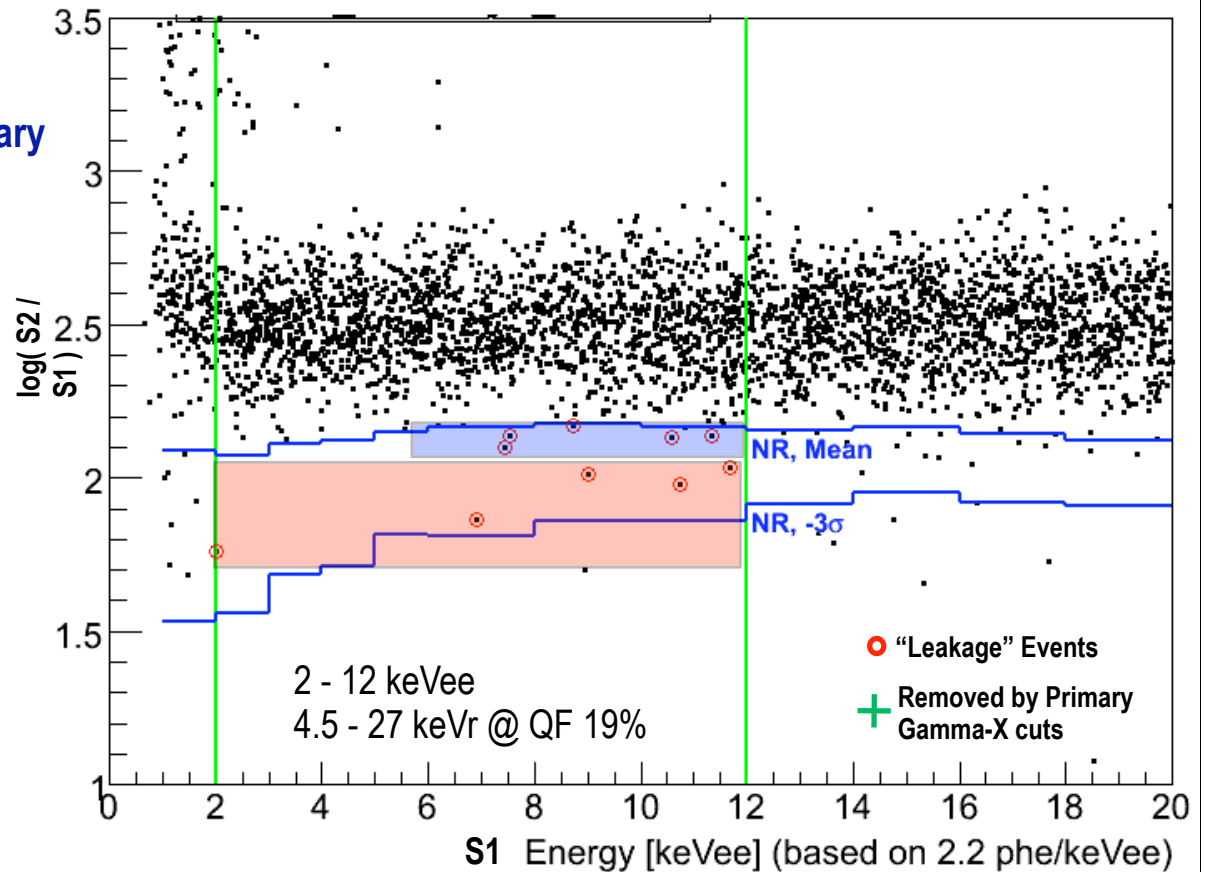
§ 10 events in the “box” after all primary analysis blind cuts (o)

§ 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

$\log (S2 / S1)$ vs S1
“Straightened Y Scale” – ER Band Centroid $\Rightarrow 2.5$



Applying the Gamma-X Cuts to XENON10 Data

§ XENON10 Blind Analysis – 58.6 days

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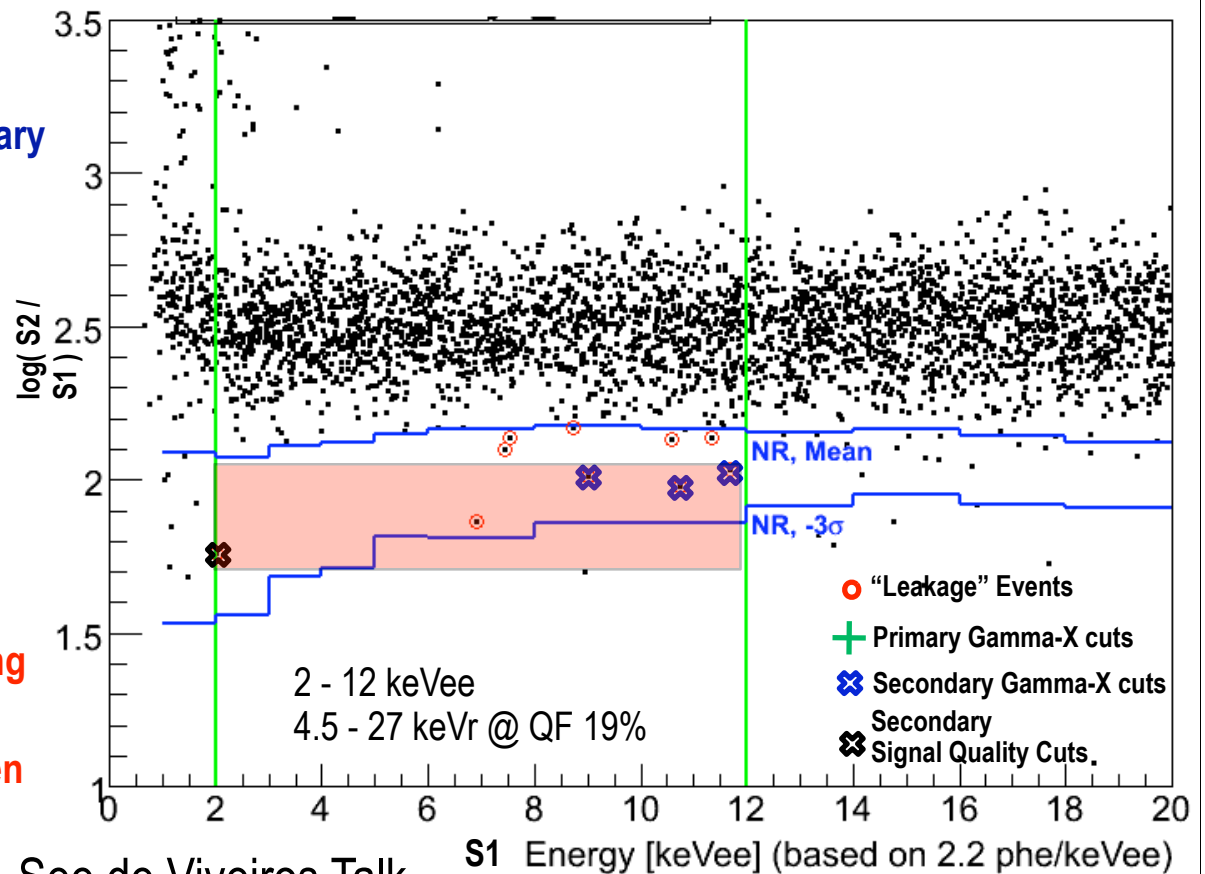
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§ 5 of these are *not consistent* with Gaussian distribution of ER Background

- 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

S1 Energy [keVee] (based on 2.2 phe/keVee)

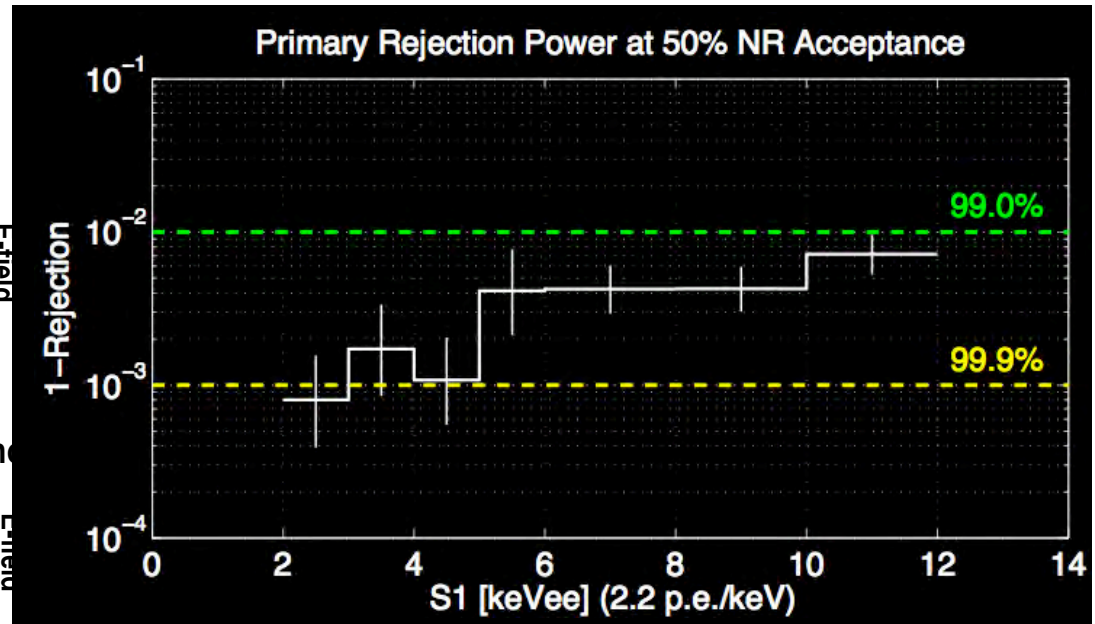
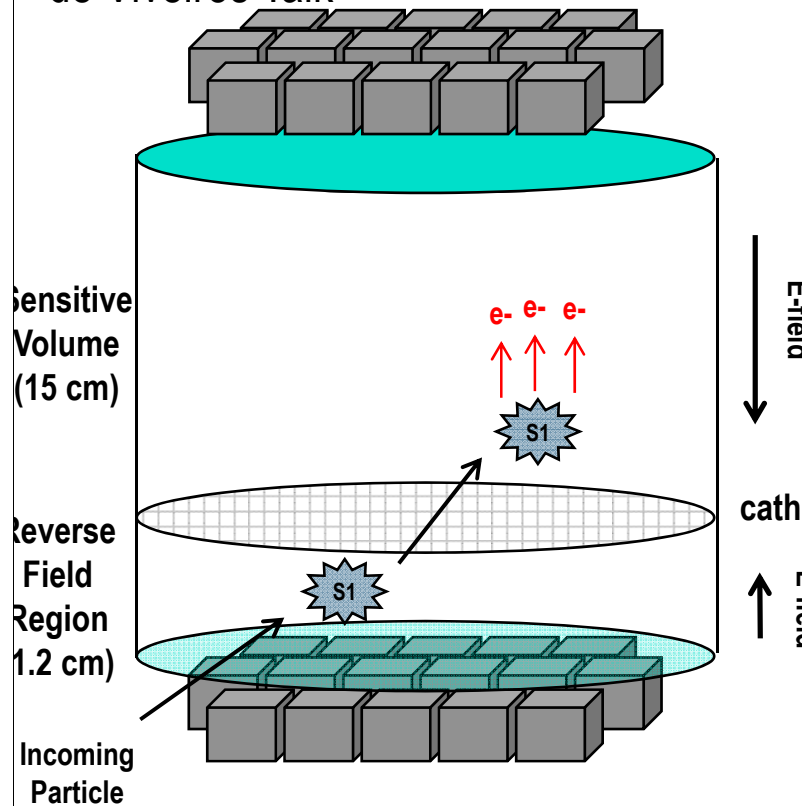
Absence of Low Energy Candidate Events (2-7 keVee)

§ Why 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 $>30\%$ - $<10\%$

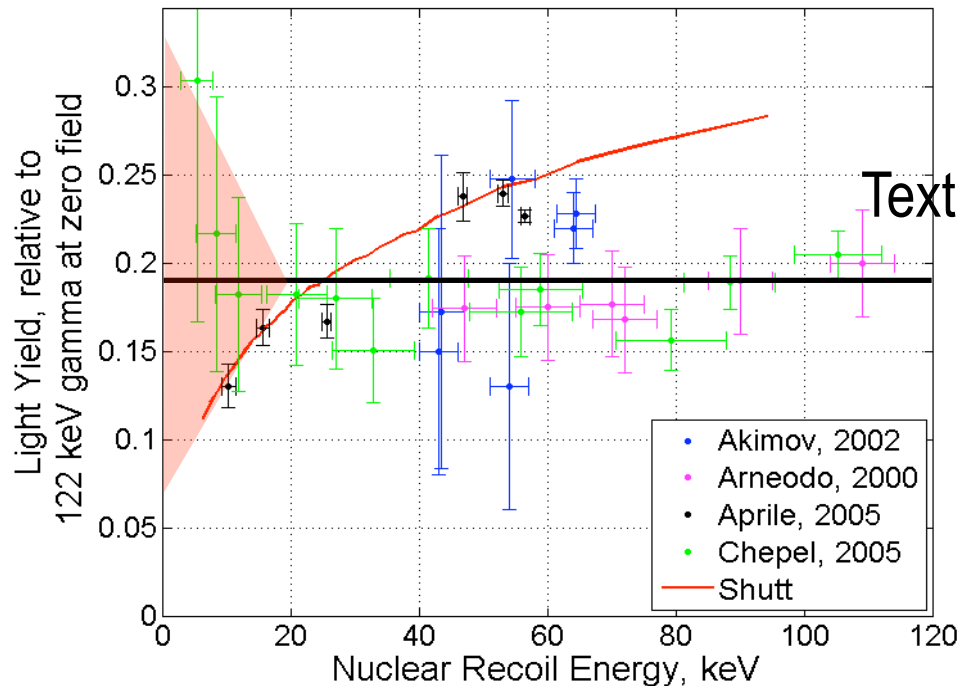
Yellin Maximum Gap Analysis

PRD 66 (2002) 032005

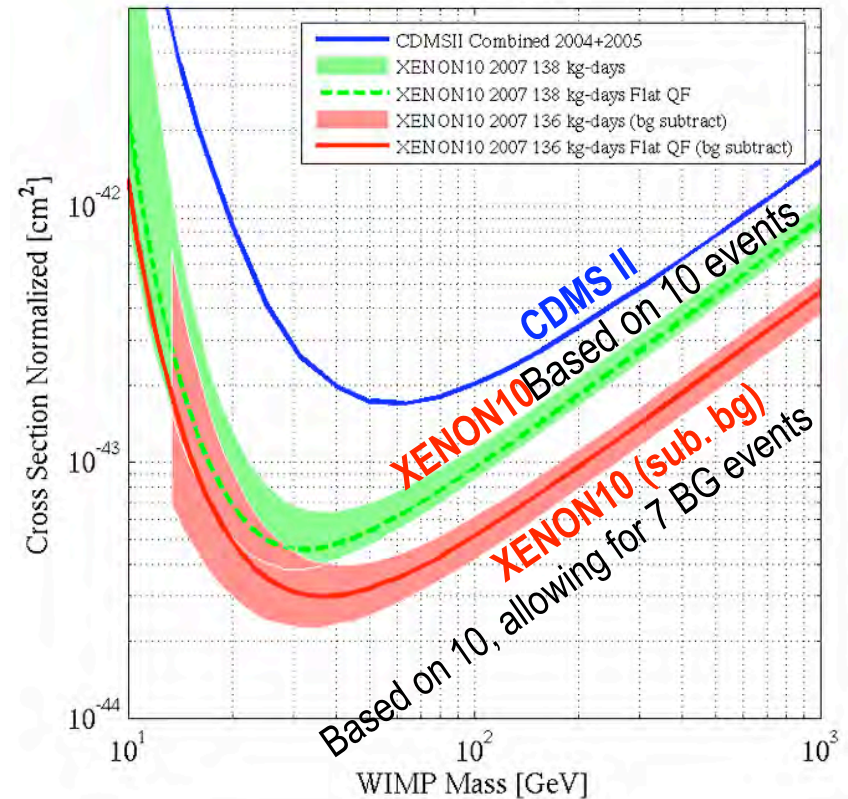
Allows fit to Sig+Known BG+Unknown BG

XENON10 (w Yellin Maximum Gap Meth.)

070412v4 dtj/rjg



See Dahl Talk

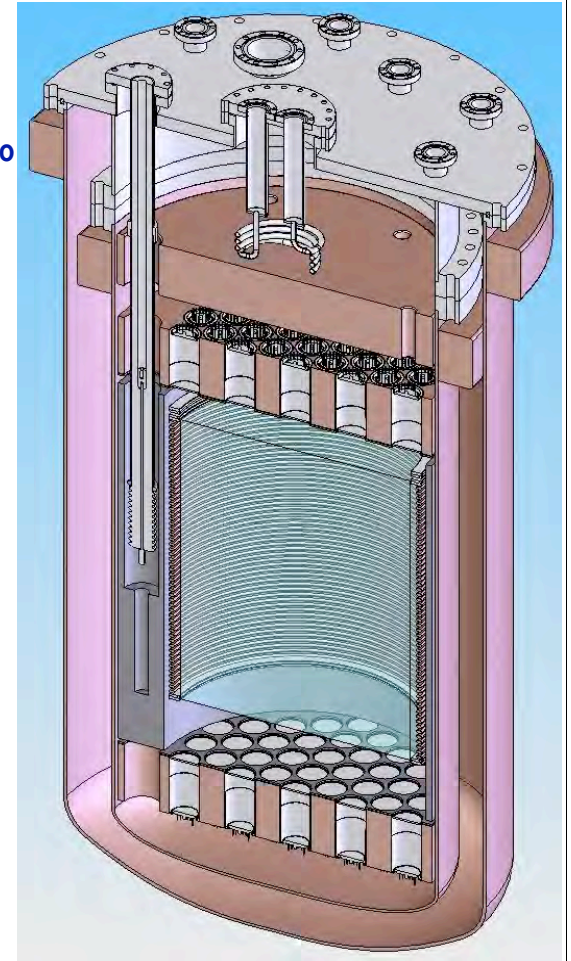


XENON10

- 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

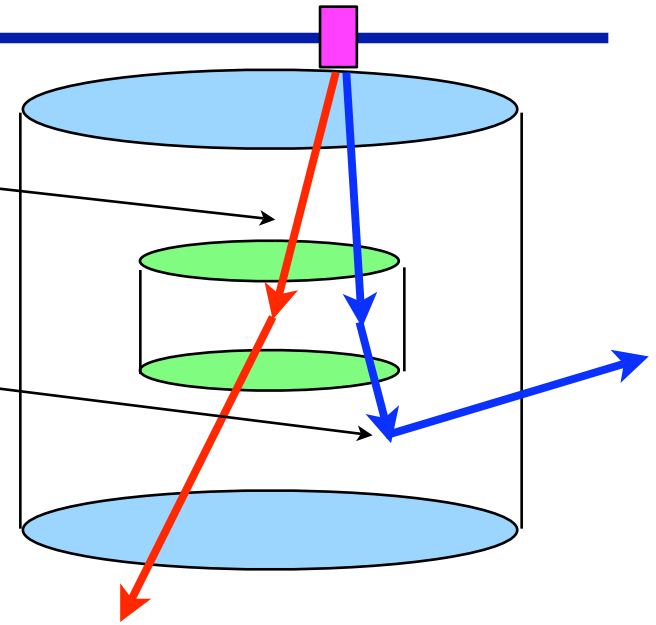
- Brown [Gaitskell], Case [Shutt], LBNL [Lesko], LLNL [Bernstein], Rochester [Wolfs], Texas A&M [White], UC Davis [Svoboda/Tripathi], UCLA [Wang/Arisaka/Cline]
 - XENON10, ZEPLIN II (US) and CDMS; ν Detectors (Kamland/SuperK/SNO/Borexino); HEP/ γ -ray astro
 - (Also ZEPLIN III Groups after their current 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 $\gamma + \beta < 7 \times 10^{-4}$ /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 $\gamma + n$, and HE n from muons
 - Very low gamma backgrounds with readily achievable $< 10^{-11}$ g/g purity.
- DM reach: 2×10^{-45} cm² in 4 months
 - Possible $< 5 \times 10^{-46}$ cm² reach with recent PMT activity reductions, longer running.



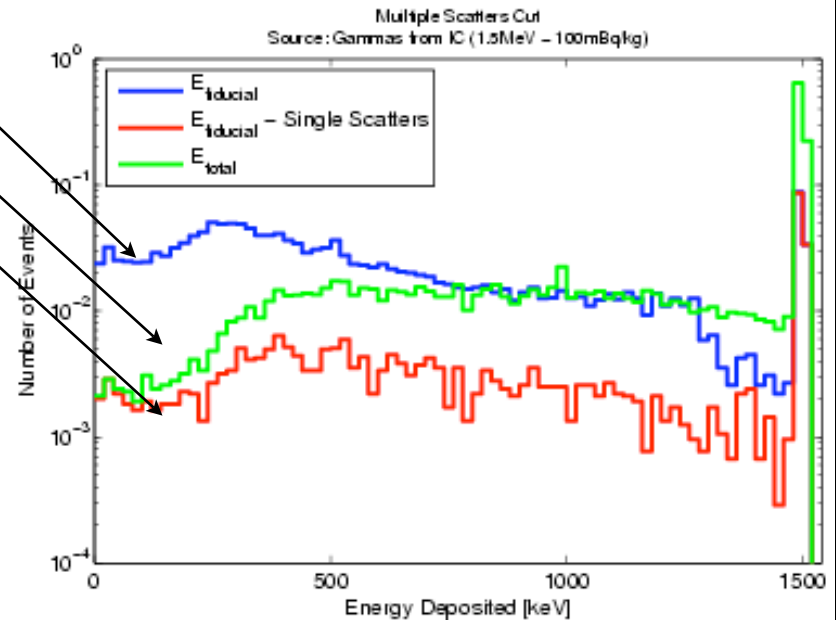
[http://
www.luxdarkmatter.org](http://www.luxdarkmatter.org)

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.



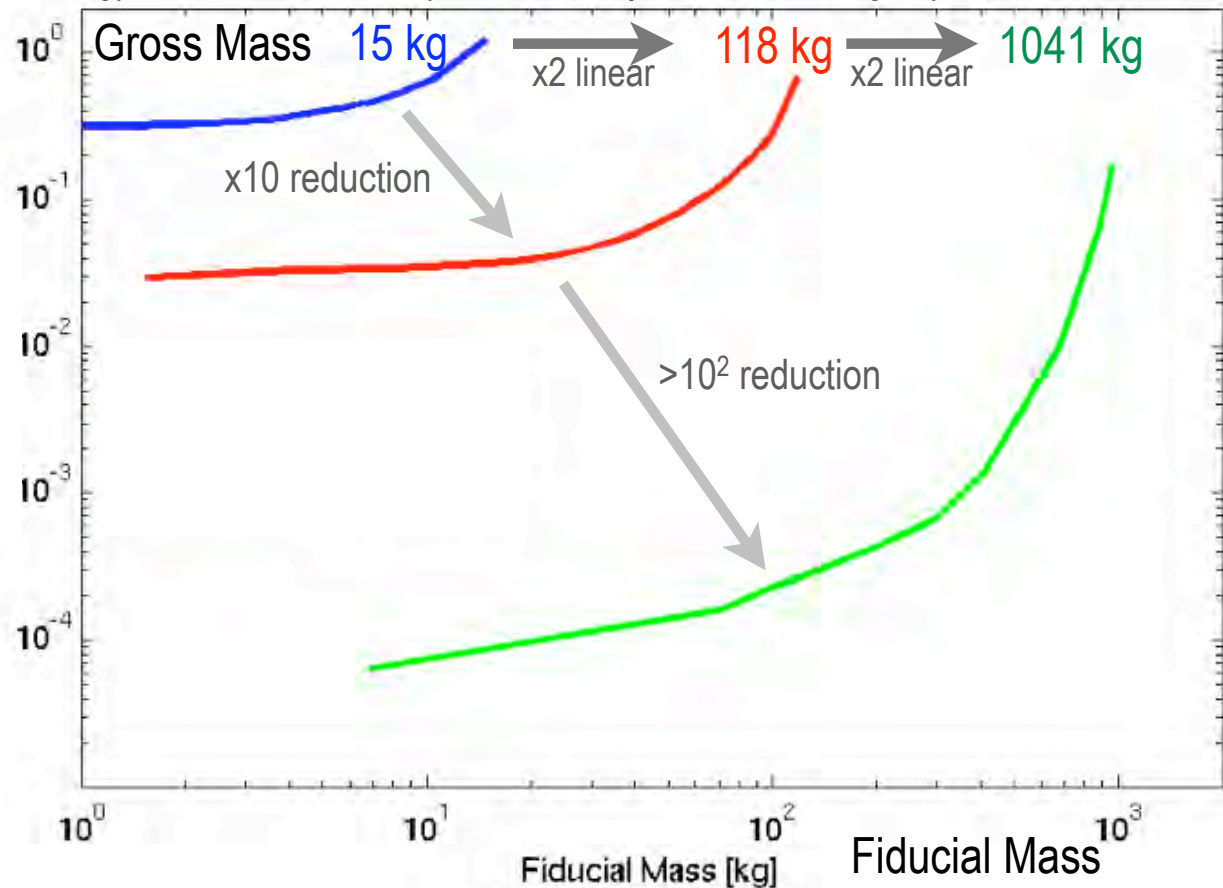
- Example for 1.5 MeV γ from outside LXe volume
 - Energy Spectrum for part of energy deposited in FV
 - Energy spectrum for all energy in detector
 - Additional application of multiple scatters cut has little additional effect on low energy event rate
- Conclusion for Event Suppression
 - xyz resolution 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 (\varnothing 21 cm x 15 cm) \rightarrow 118 kg (\varnothing 42 cm x 30 cm) \rightarrow 1041 kg (\varnothing 84 cm x 60 cm)
 - Monte Carlos simply assume external activity scales with area (from PMTs and cryostat) using XENON10 values from screening

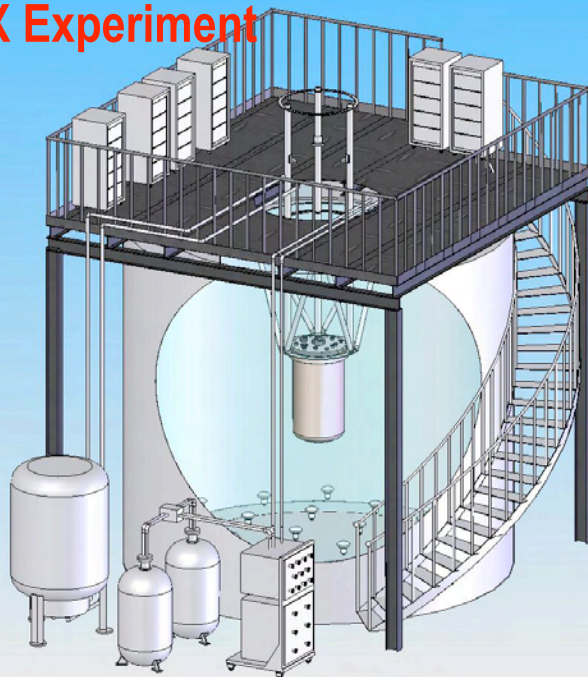
Low energy rate in FV before any ER vs NR rejection /keVee/kg/day



LUX program: exploit scalability

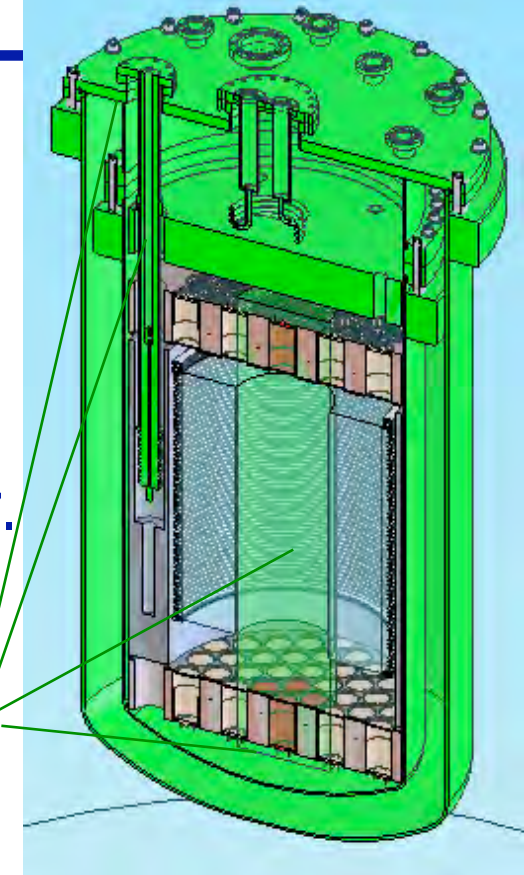
- **LUXcore: Final engineering for large-scale detector**
 - Cryostat, >100 kV feedthrough, charge drift, light collection over large distance
 - Full system integration, including ~1m water shield
 - 40 kg narrow “core”, 14 PMTs, 20 cm Ø x 40 cm tall.
 - Radial scale-up requires full-funding.
 - Under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

LUX Experiment



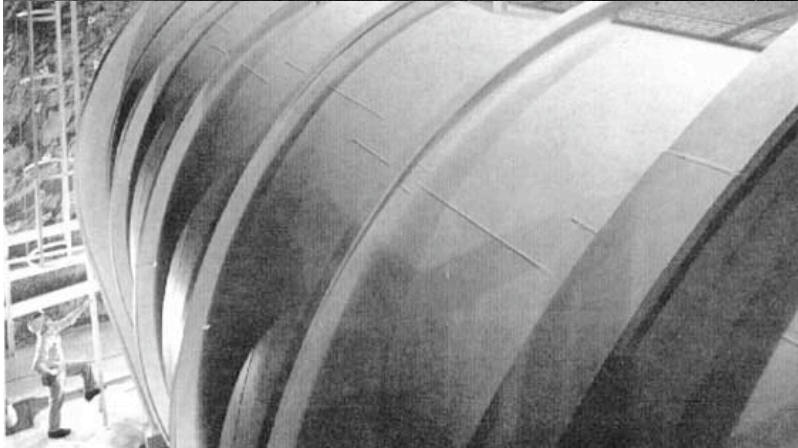
LUX detector

LUXcore

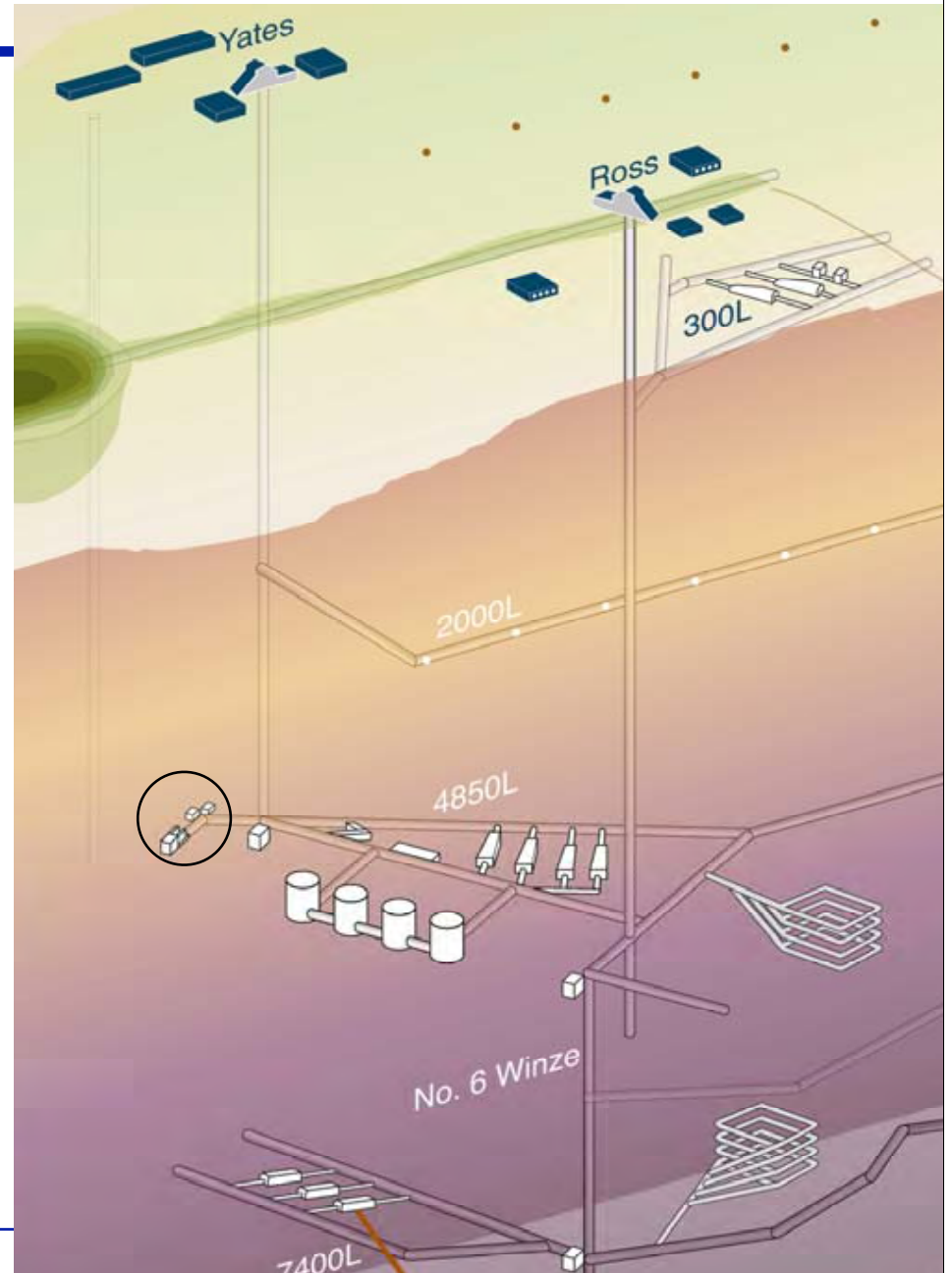


- LUX in ~ 6m Ø water shield
- Very good match to early-implementation DUSEL (e.g., Homestake “Davis” cavern)
 - SNOLAB LOI
- System scalable to very large mass.

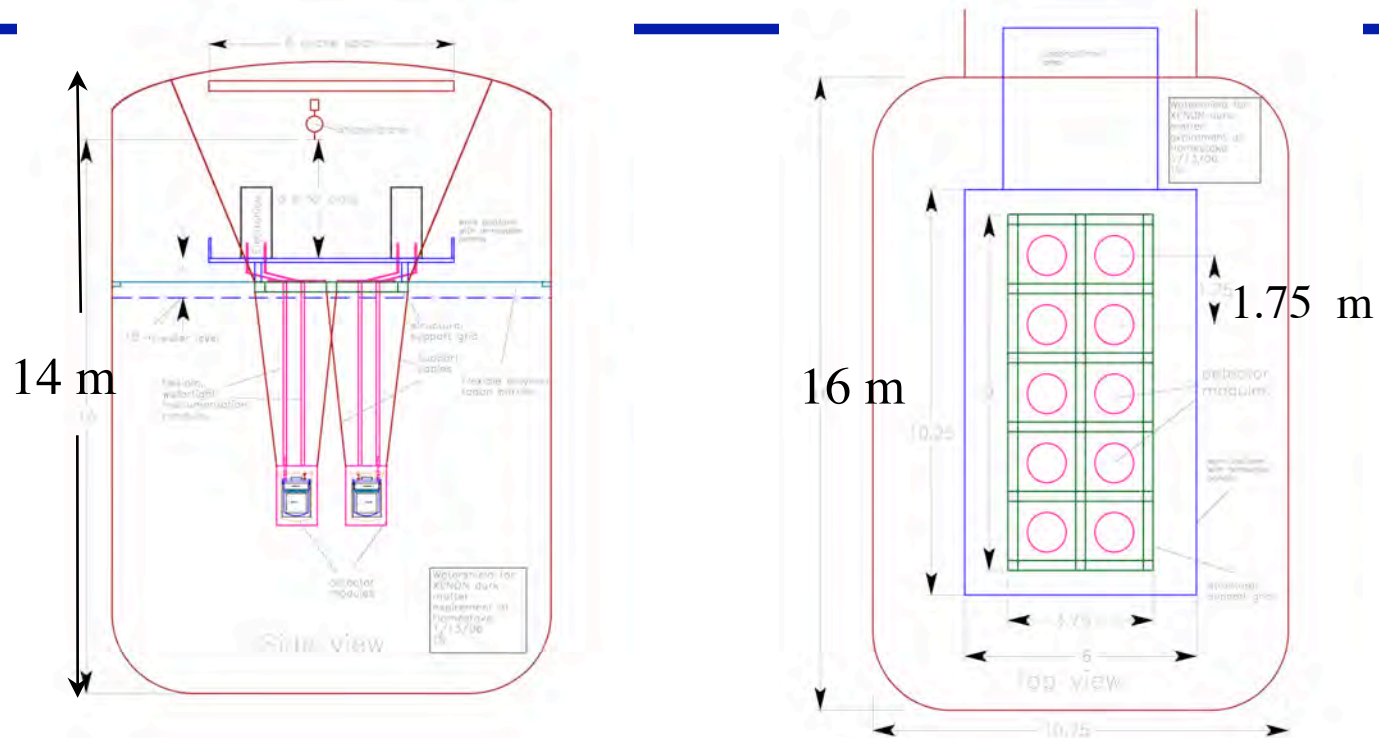
Water Shield - Homestake - Davis Cavern



LUX Dark Matter Collaboration



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)

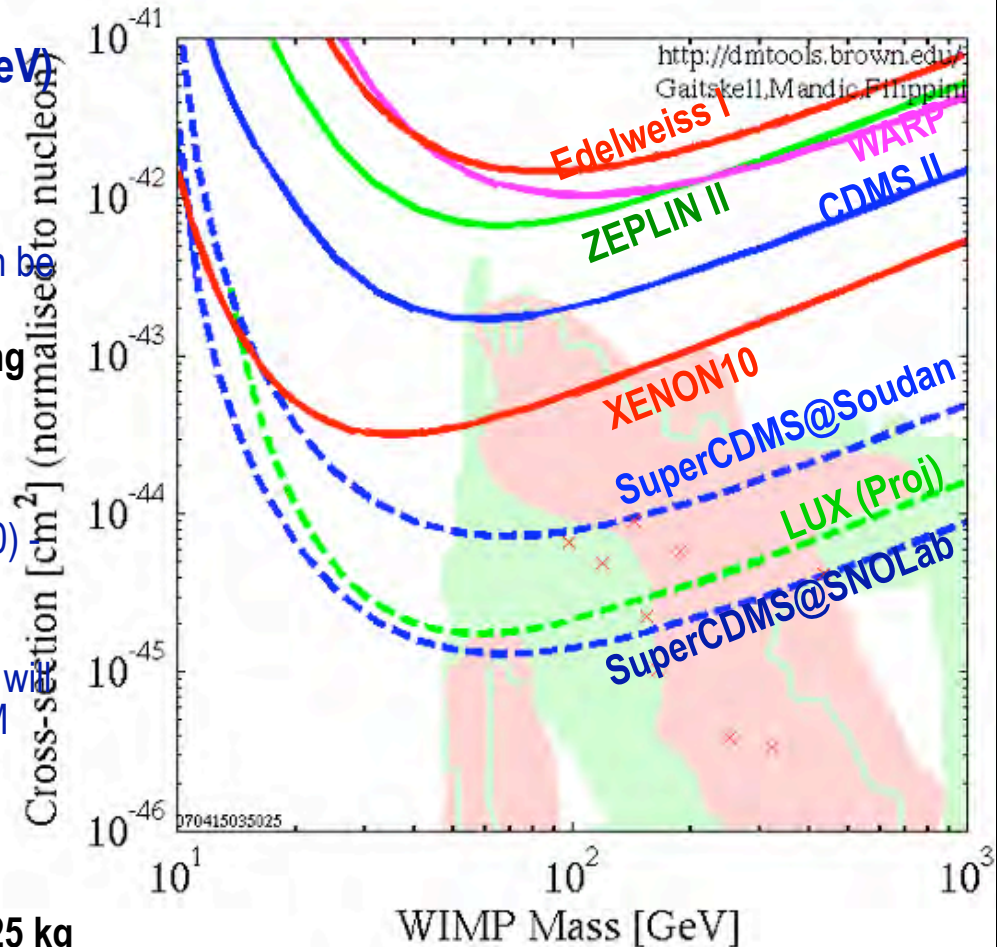
• Dark Matter Goals

◦ LUX - Sensitivity curve at $2 \times 10^{-45} \text{ cm}^2$ (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} cm² dm reach)
- Position reconstruction based on photoelectron hit patterns (timing not useful in ≤ 10 tonne scale). Misreconstruction
 - 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 $\sim 10^2:1$ (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 $\sim 10^2:1$ + 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} cm²) in a few years seems very realizable
- Future instruments for 10^{-46} – 10^{-47} cm² also realistic (performance & cost)