Dark Matter
Direct Detection

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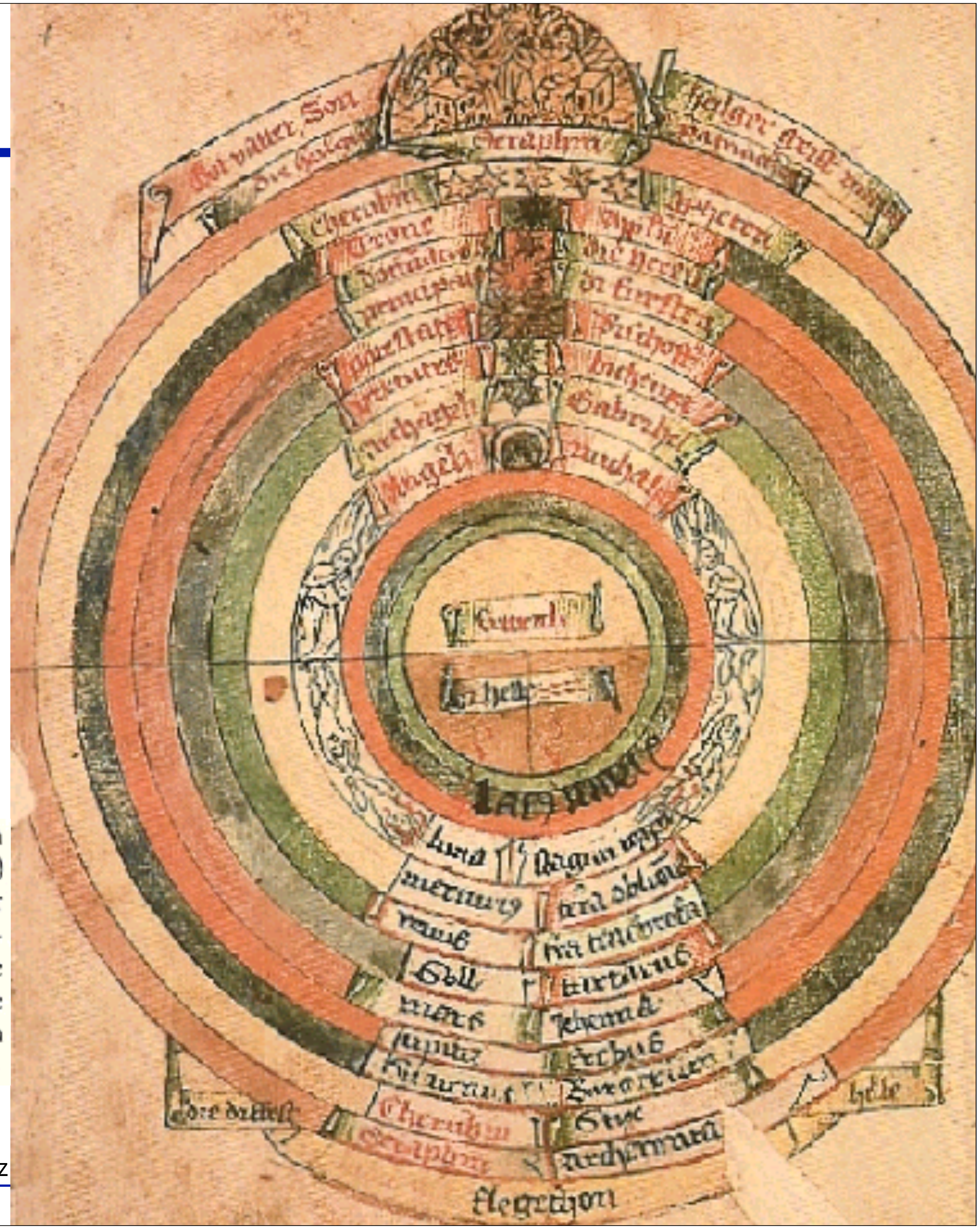
(Supported by US DOE HEP)

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

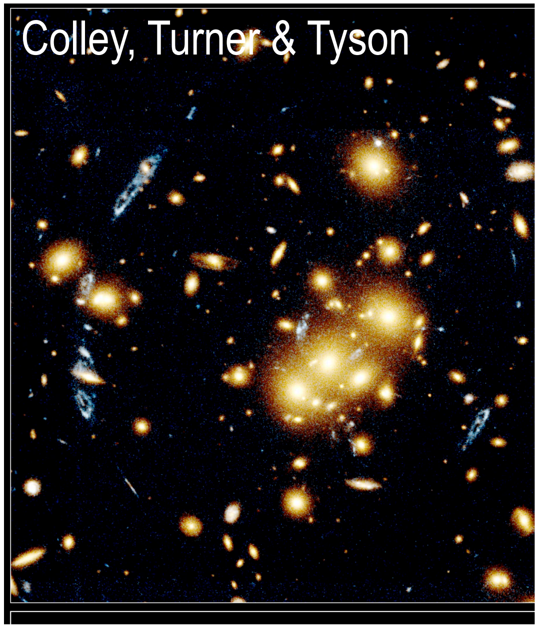
Confession

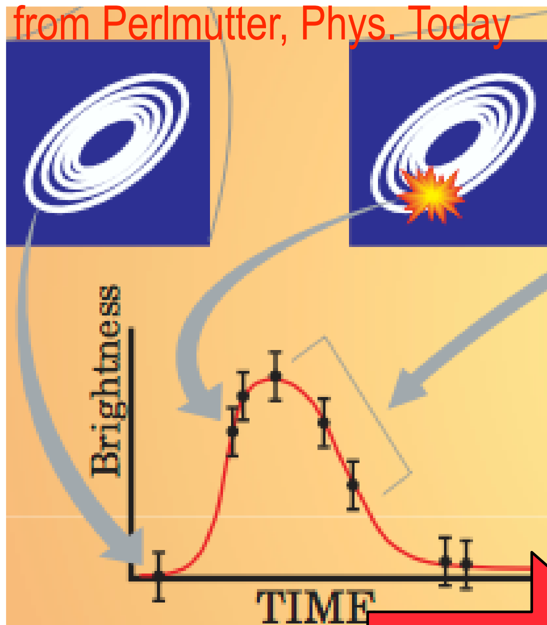
>95% of the Composition of the Universe is still unknown

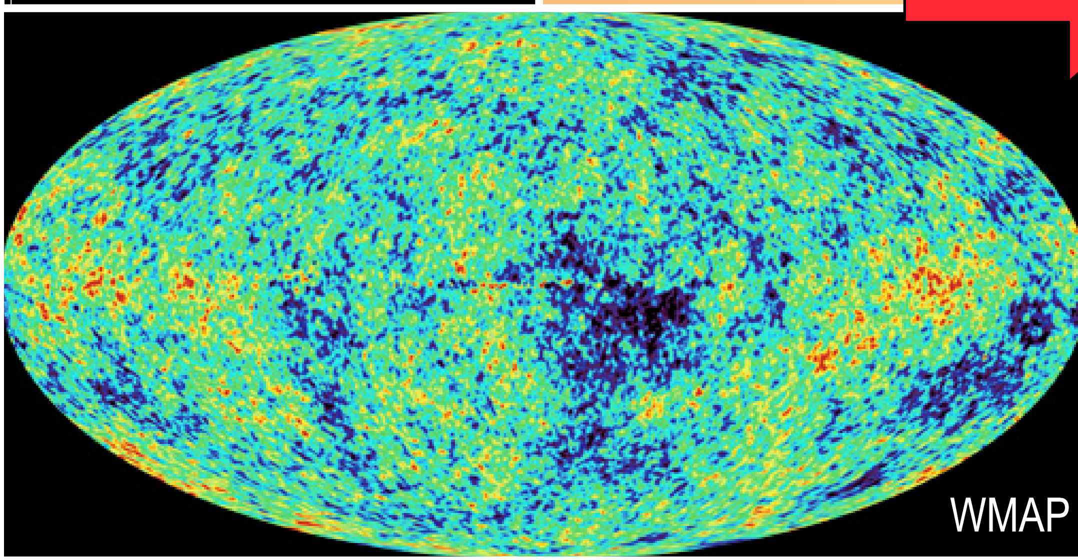
Introduction

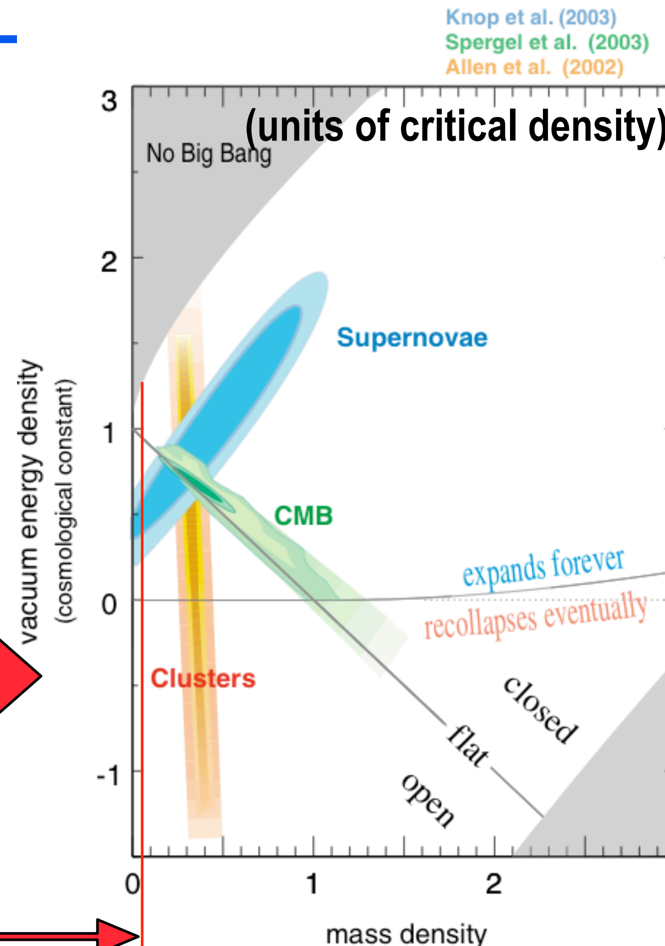
- --> 1990's For many a "known known" was that $\Omega_{Total} = 1$
  - This being matter dominated, $\Omega_m = 1$
- We have had to revise this view partially: $\Omega_{Total} = 1$, but $\Omega_m \sim 0.27$
  - Dark Matter now has to share the shadows with Dark Energy
  - Indeed it is convenient to split into 3 Dark Problems
    - Baryonic Dark Matter - Mostly known
    - Non-Baryonic Dark Matter - **Known Unknown**
    - Dark Energy - Only God knows, right now
- It has been a Problem in Cosmology that astrophysical assumptions often need to be made to interpret data/extra parameters
  - Now many independent/increasingly precise techniques are being used
  - This now enables disentanglement of "Gastrophysics"
- Ultimately new solutions will be related to Fundamental/Particle Physics
  - Non-baryonic dark matter - New Particles - SUSY, neutrinos, baryogenesis
  - Dark Energy - Gravity / Extra Dimensions

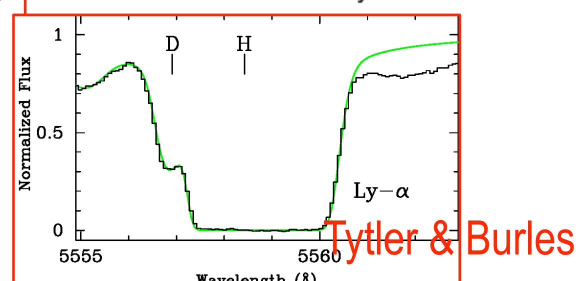
Standard Cosmology





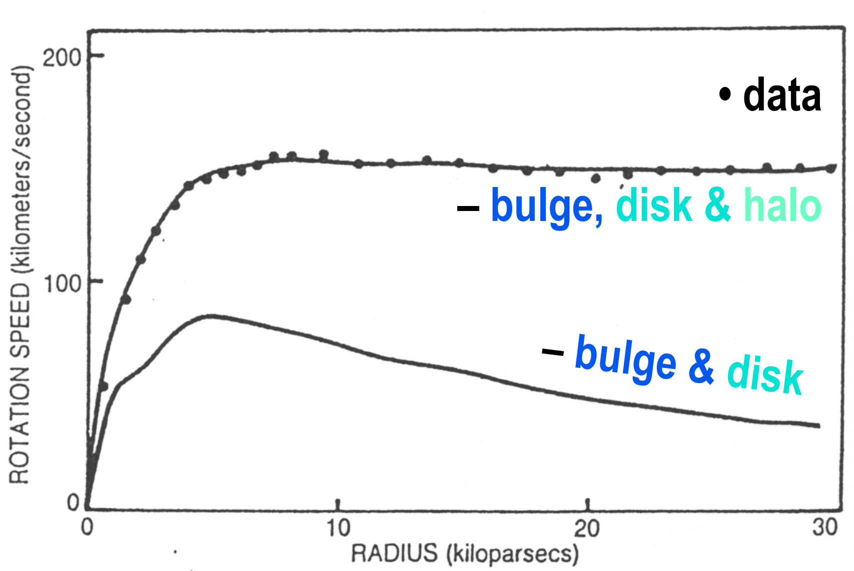


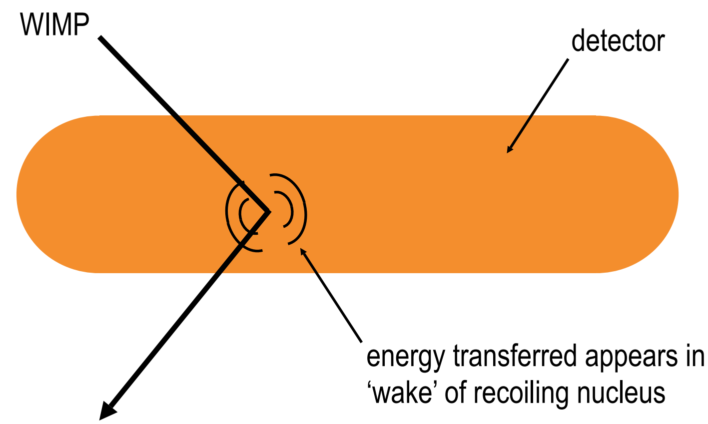




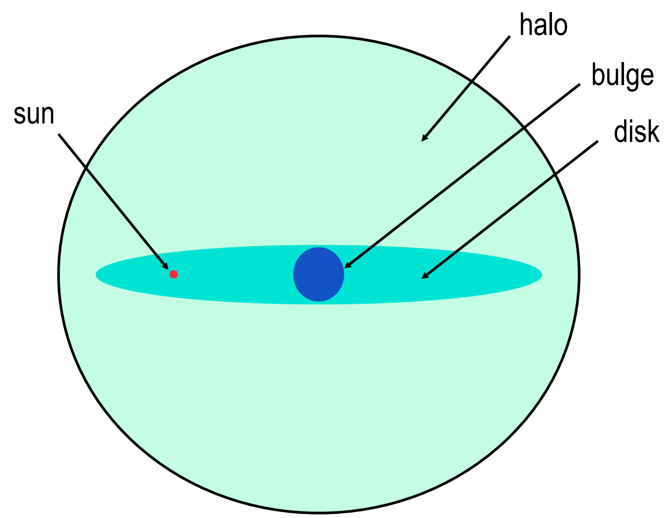
(Slide from Dan Akerib, Case)

WIMPs in the Galactic Halo



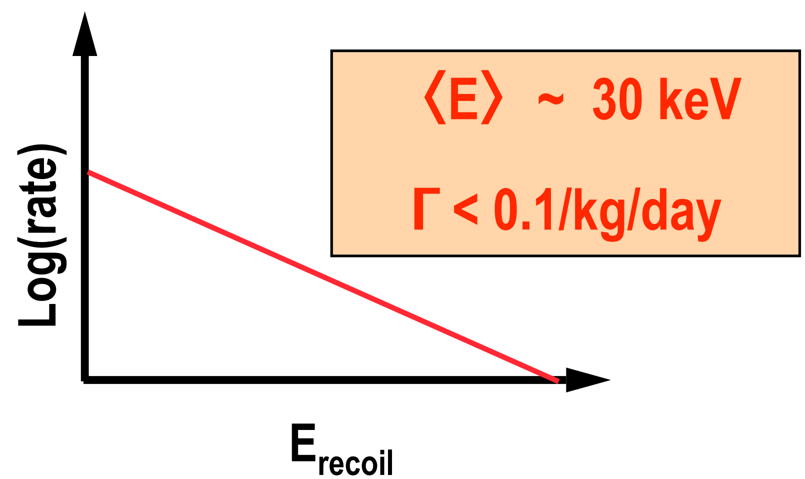


WIMP-Nucleus Scattering



The Milky Way

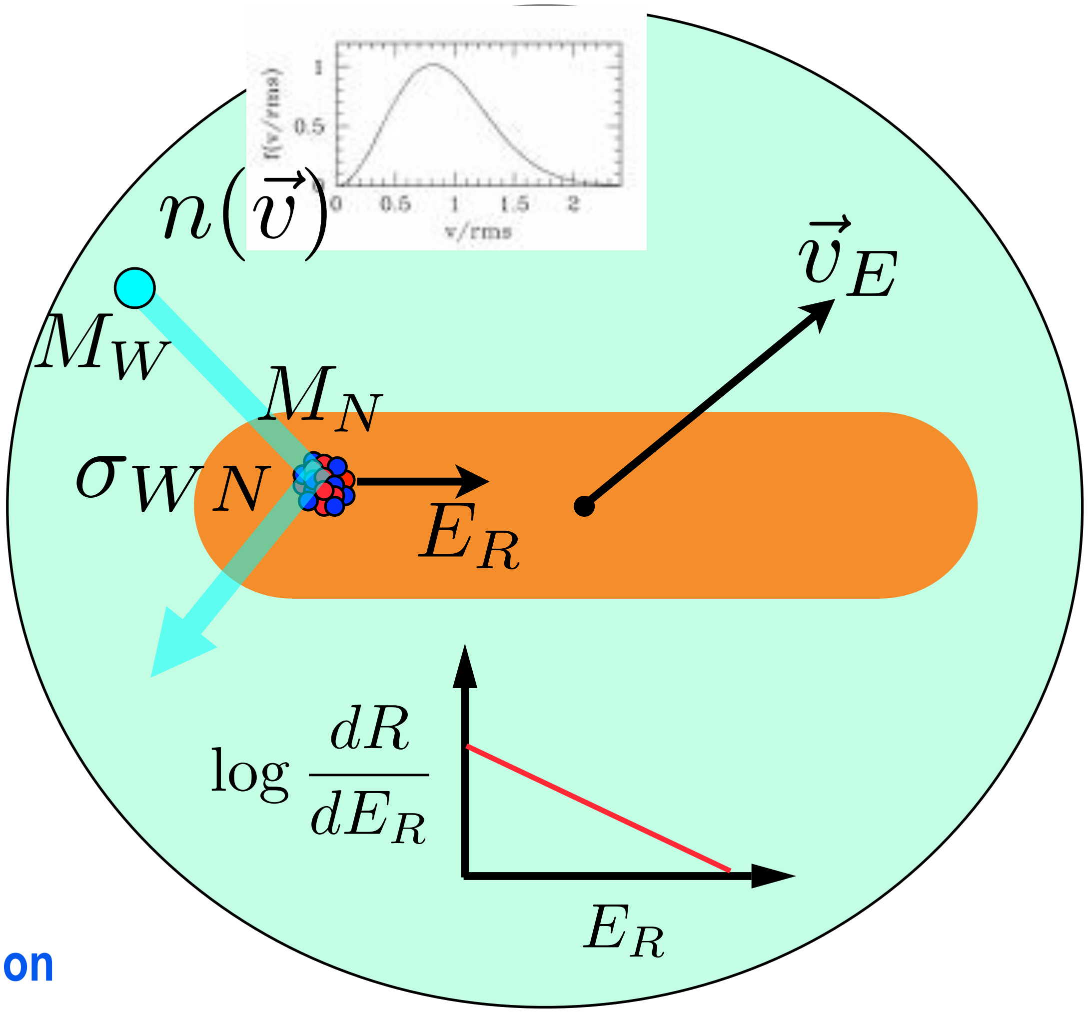
Scatter from a Nucleus in a Terrestrial Particle Detector



(Slide from Dan Akerib, Case)

Defining the Signal

- **Kinematics**
  - halo potential
  - WIMP mass
  - target mass & velocity
- **Rate**
  - halo density
  - cross section
    - SD/SI
    - coherence & form factors
- **Primary signal**
- **Secondary features**
  - annual modulation of rate
  - diurnal modulation of direction
- **Backgrounds**
- **Experimental methods & results**



(Slide from Dan Akerib, Case)

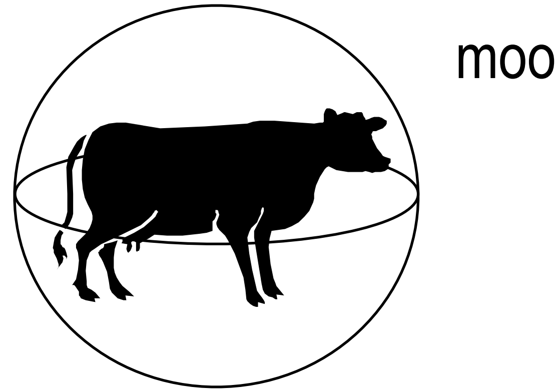
References and further reading (for students)

- References and notation - generally following the treatment of two key review articles:
  - J.D. Lewin and P.F. Smith, Astroparticle Physics 6 (1996)
  - G. Jungman, M. Kamionkowski and K. Griest, Physics Reports 267 (1996)
- See also
  - R.J. Gaitskell (experiment review) in Ann. Rev. Nucl. Part. Sci. 54 (2004) (http://particleastro.brown.edu)
  - G. Heusser (low background techniques) in Ann. Rev. Nucl. Part. Sci. 45 (1995)
  - S. Golwala, Ph.D. thesis, UC Berkeley (2000) (http://cdms.berkeley.edu)

(Slide from Dan Akerib, Case)

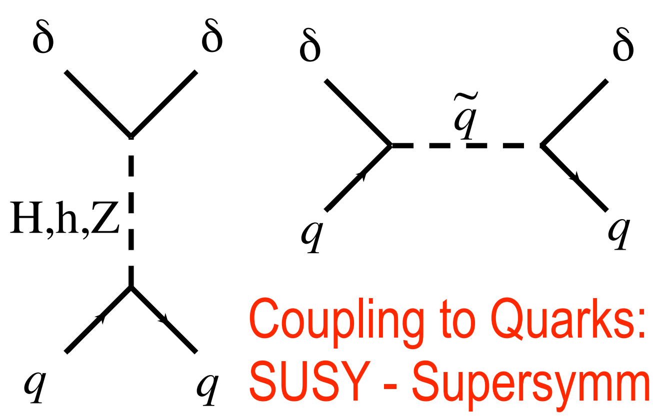
Direct Detection Astrophysics of WIMPs

- **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**



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

- **Energy spectrum of recoils is featureless exponential with 〈E〉 ~ 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)**

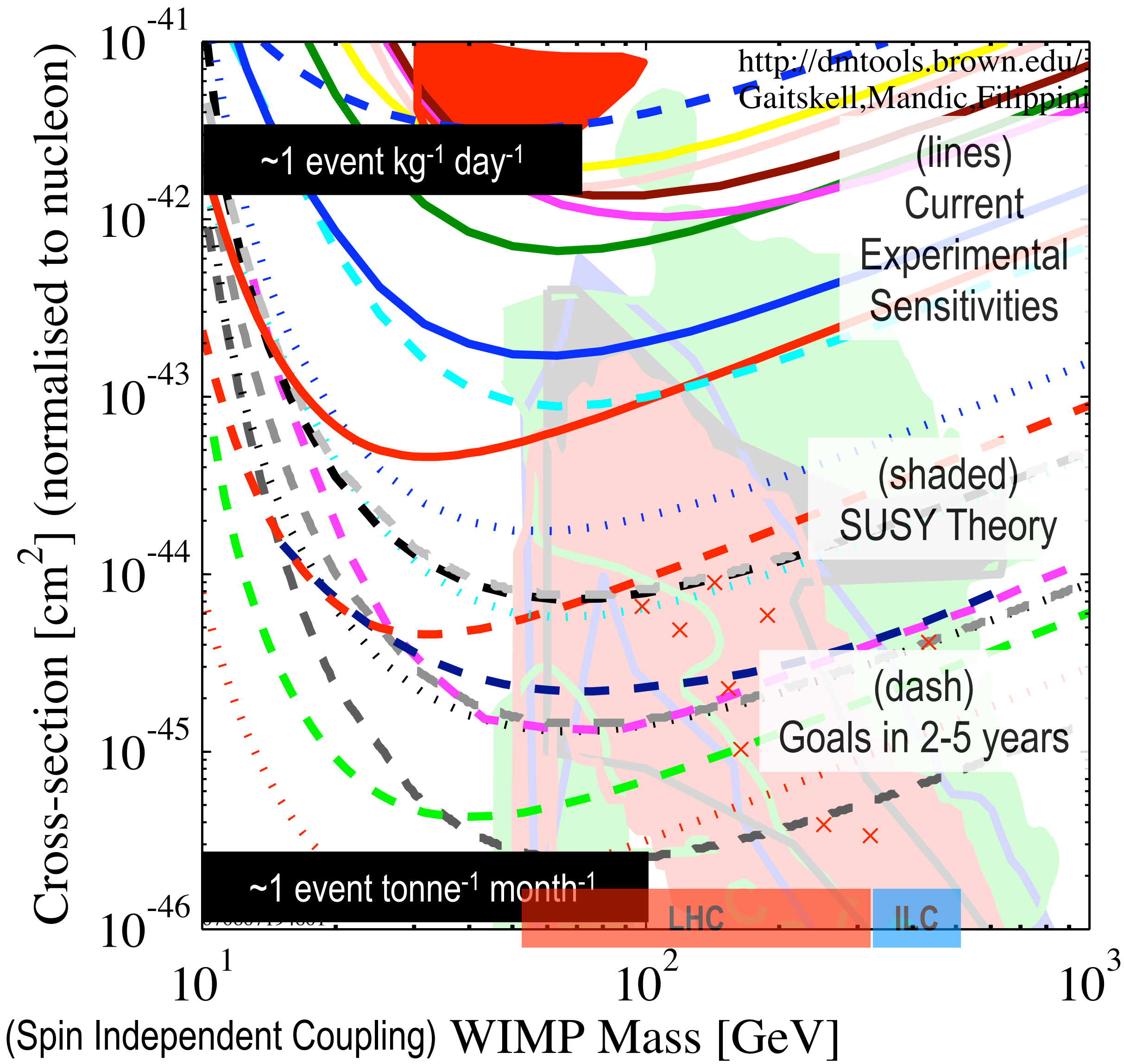


Coupling to Quarks:
SUSY - Supersymmetry

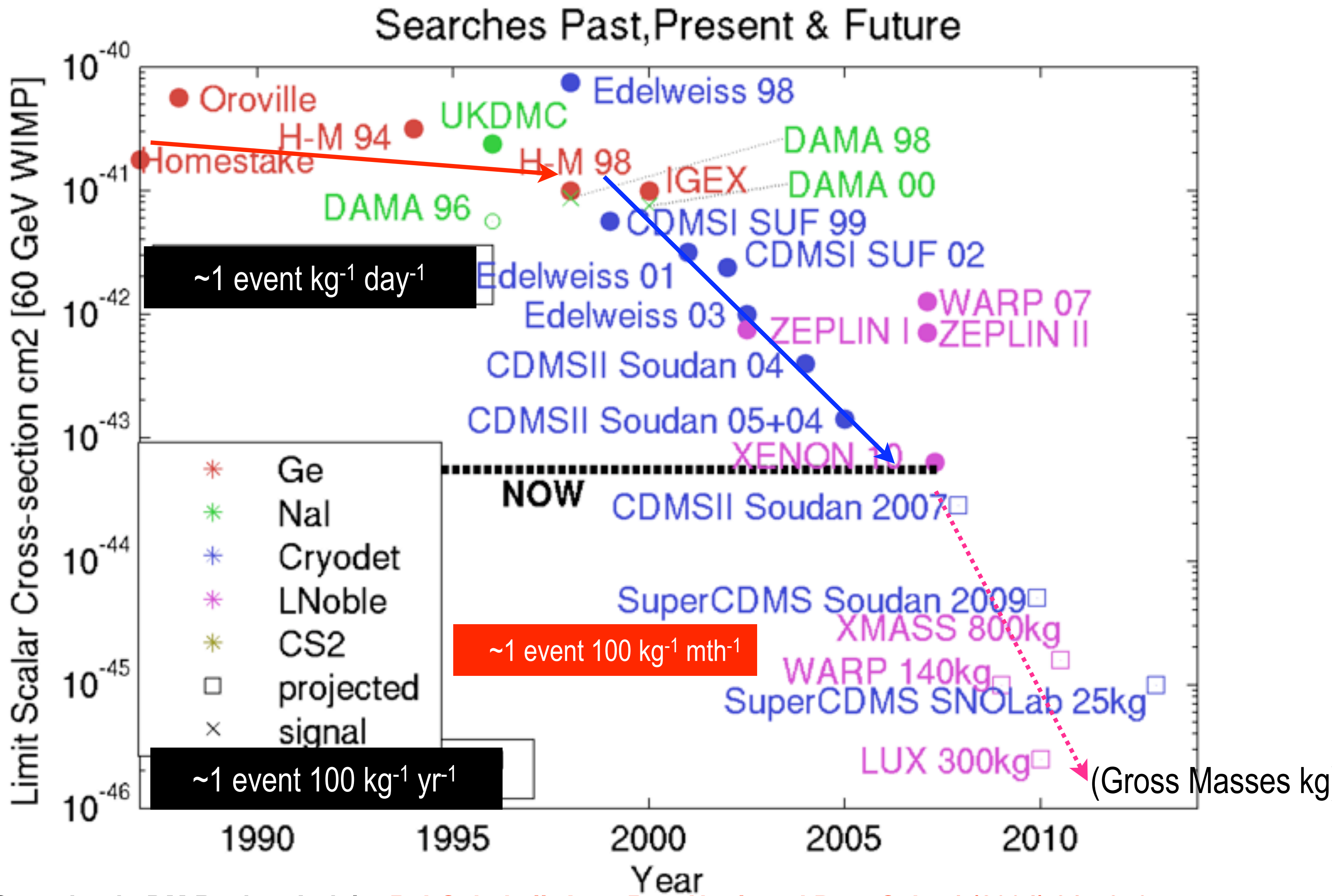
Dark Matter Theory and Experiment

SOME SUSY MODELS

- [red] T. Baltz and P. Gondolo, Markov Chain Monte Carlos. JHEP 0410 (2004) 052, (hep-ph/0407039)
- [blue] J. Ellis et al. CMSSM, Phys.Rev. D71 (2005) 095007, (hep-ph/0502001)
- [red crosses] J. Ellis et al., LHC Benchmark Points
- [green] Ruiz de Austri/Trotta/ Roszkowski (2007) CMSSM MArkov Chain Models (95% CL)
- [gray] Baer et al. (2003)



DM Direct Search Progress Over Time (2007)



Plot updated from that in DM Review Article: **R J Gaitskell, Ann. Rev. Nucl. and Part. Sci. 54 (2004) 315-359**

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, NEWAGE	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

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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 - below pp solar neutrino signal. Relevant for DM search below ~10^{-47} cm^2. 85Kr can be removed by charcoal or distillation separation.

Noble Liquid Comparison (DM Detectors)

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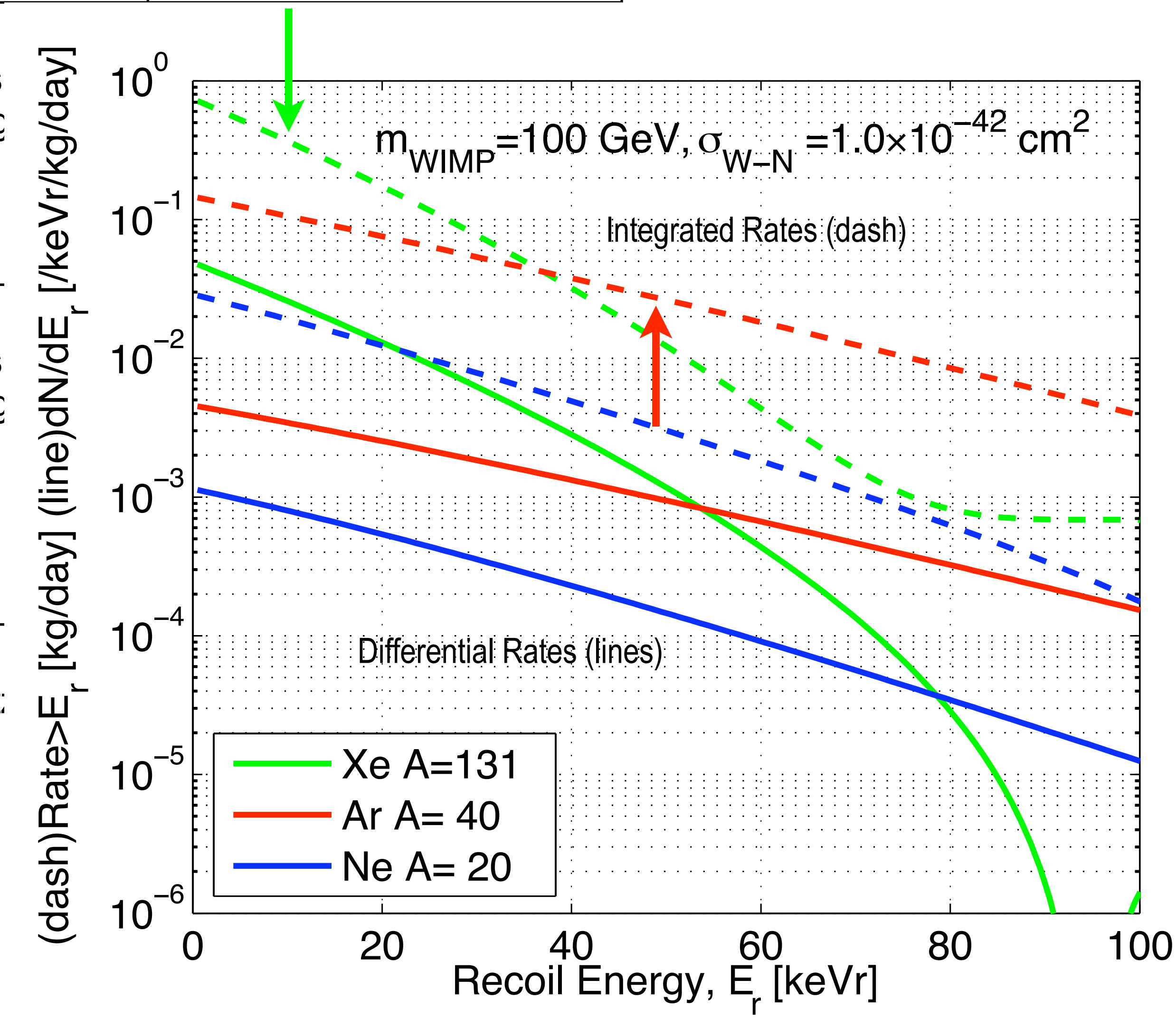
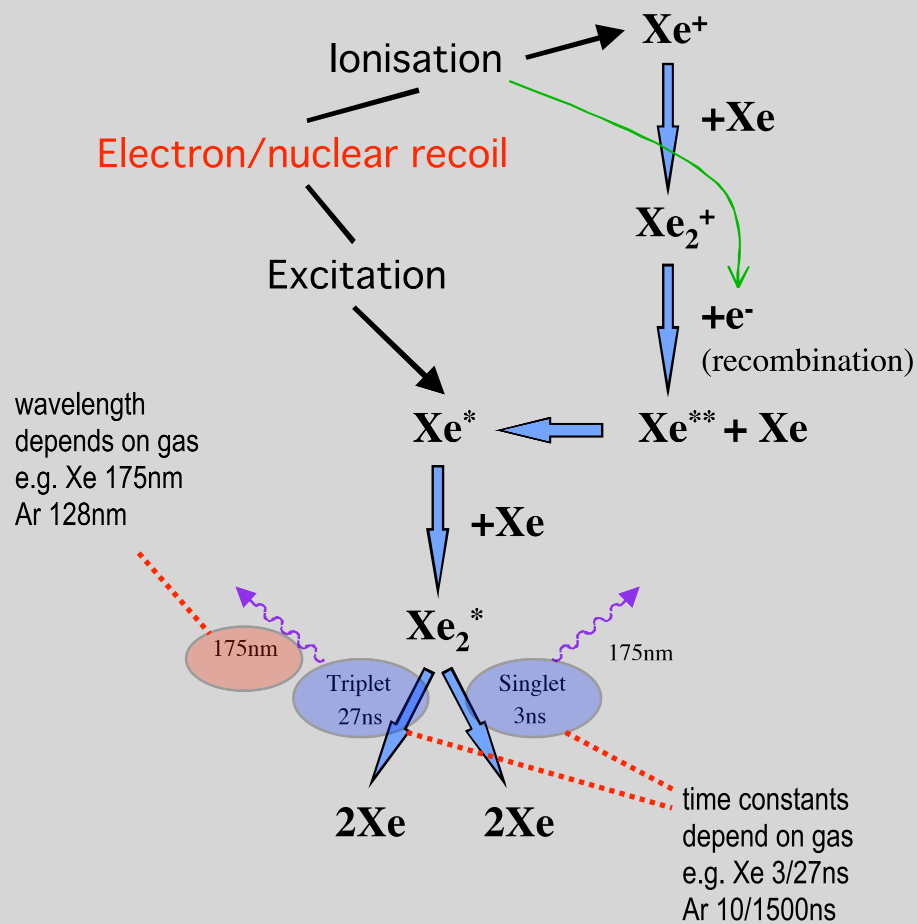


Noble Liquid Detectors: Mechanism & Experiments

	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

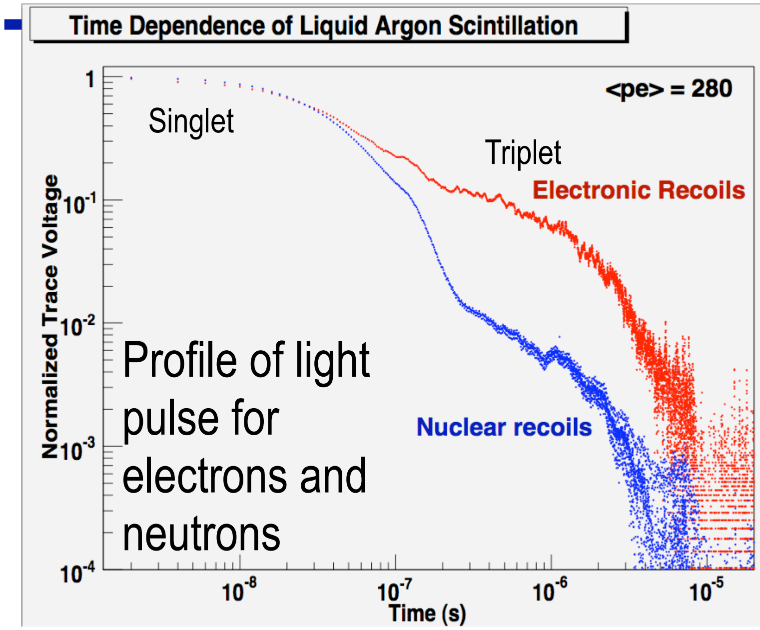


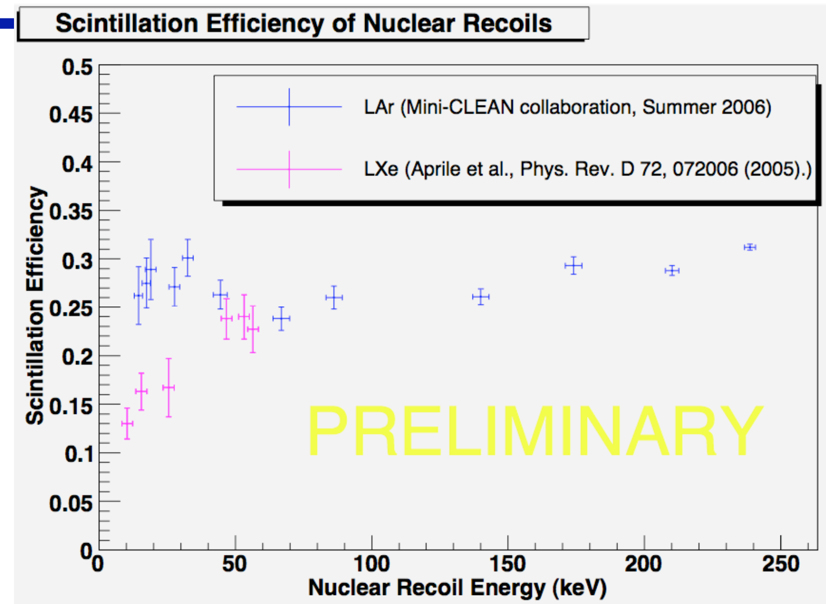
These mechanisms apply to all Nobles

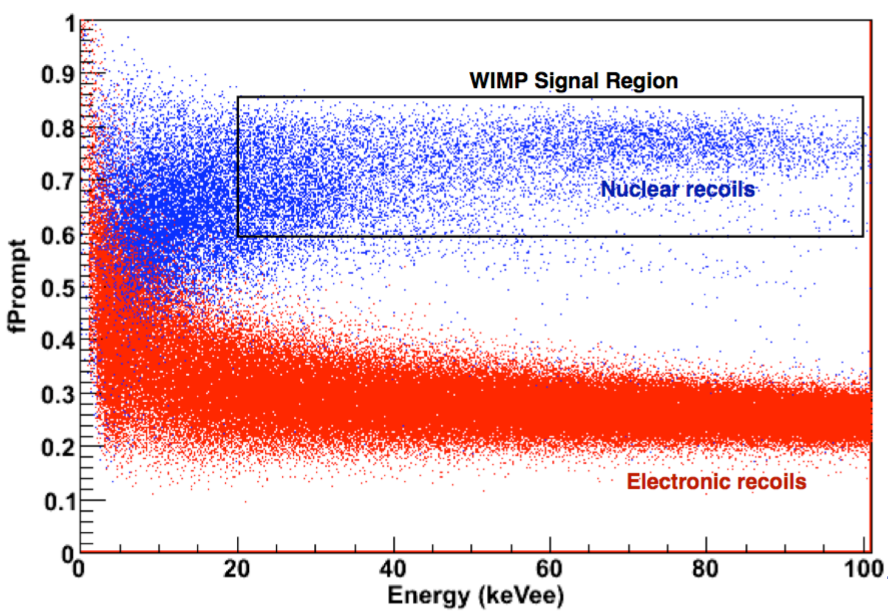
Nigel Smith, RAL

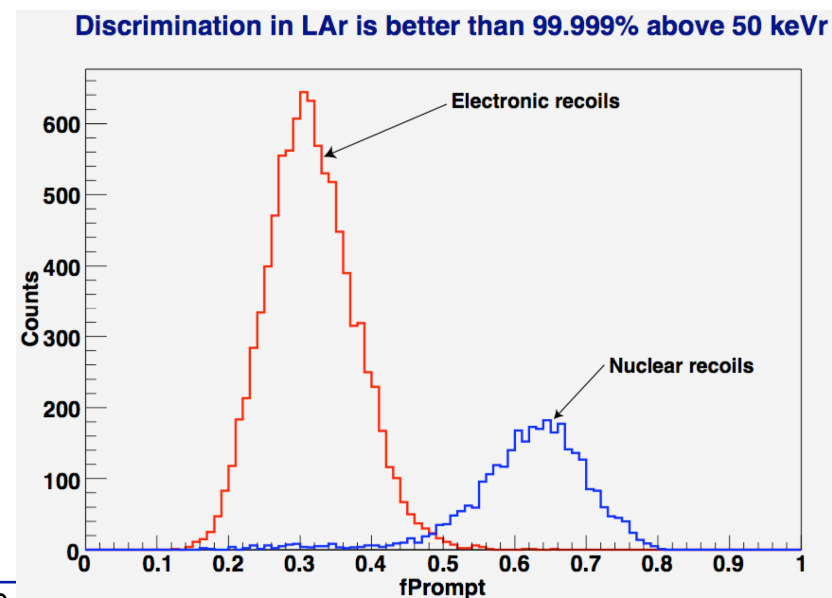
Data taken with Micro-CLEAN (McKinsey, Yale)

CLEAN Ar PSD



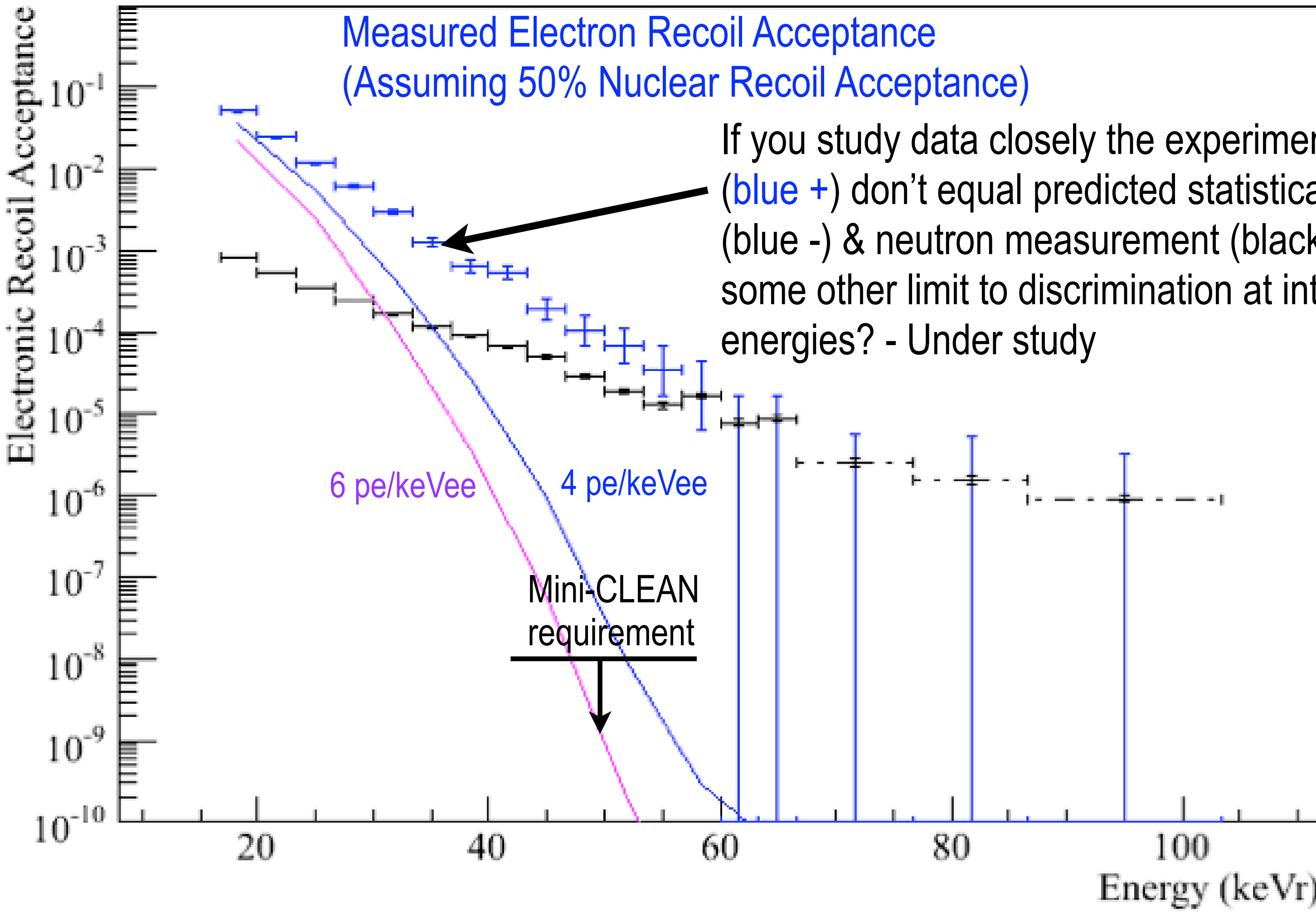






(McKinsey, Yale)

Argon Pulse Shape Discrimination



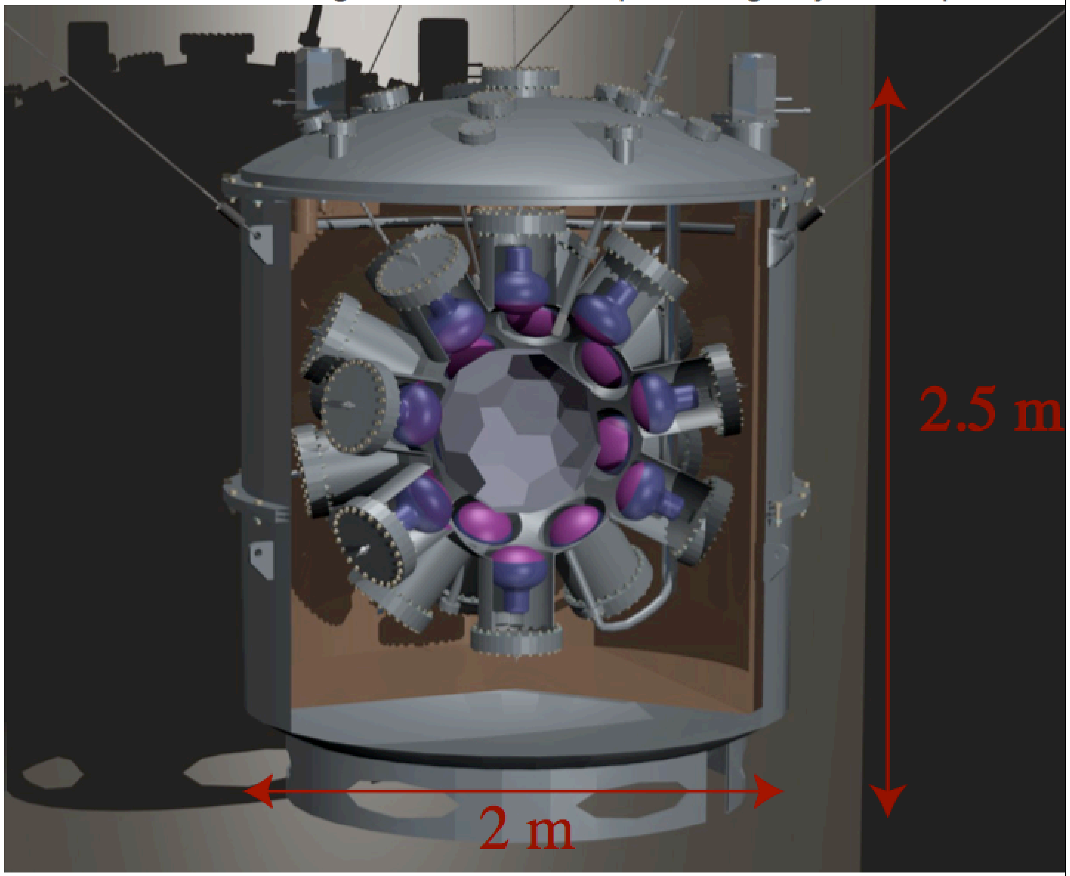
If you study data closely the experimental points (blue +) don't equal predicted statistical behavior (blue -) & neutron measurement (black +). Is there some other limit to discrimination at intermediate energies? - Under study

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 be rejected?

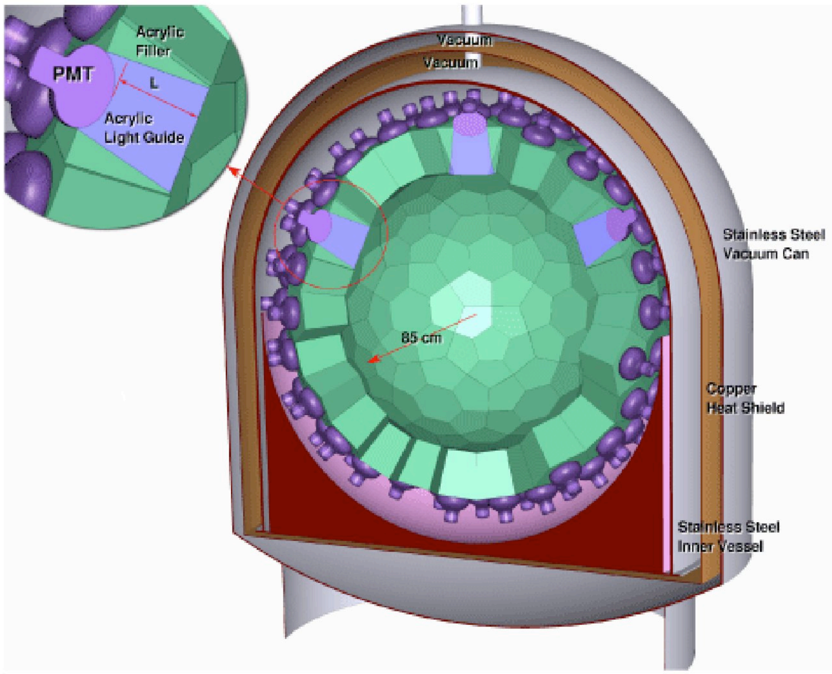
Mini-CLEAN

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

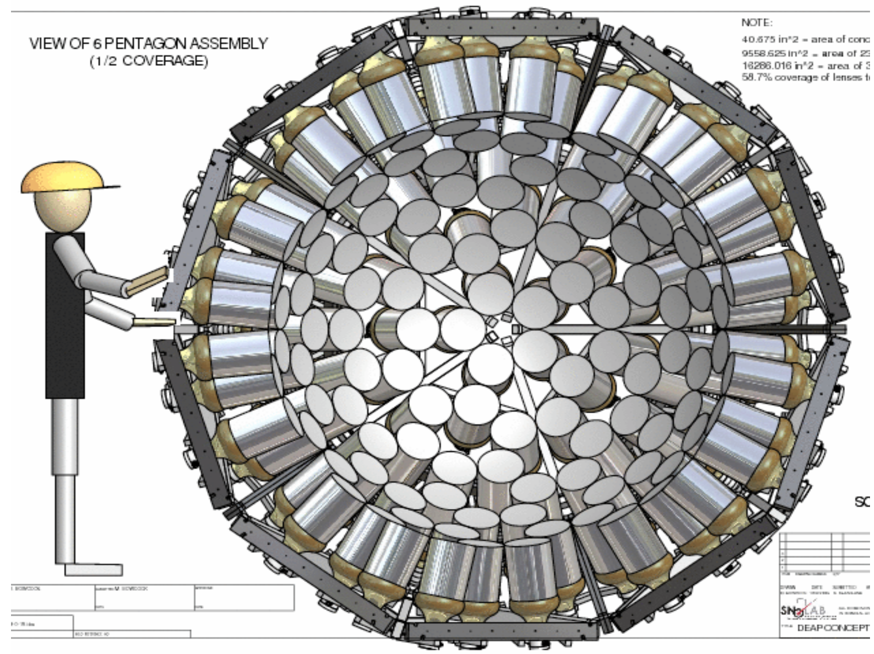


DEAP & CLEAN “ULTIMATE” designs

“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)

DEAP / CLEAN Timetable

- Hime (Los Alamos), Boulay (Queens, Canada), McKinsey (Yale), Kerns (BU), Coakley (NIST) + ...

- Starting construction of 360 kg/100 kg fid.
  - Plan to completed underground construction end 2008
  - Site not yet finalized (SNOLab / Homestake?)

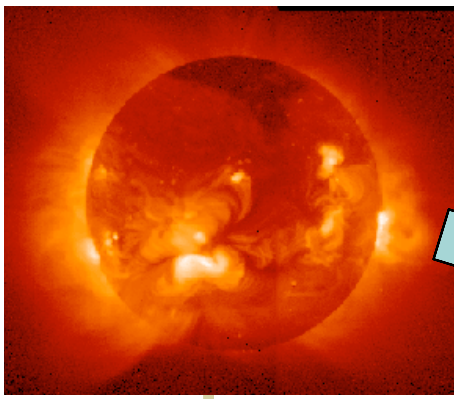
- Engineering Designs Underway for 3.6 tonne/1 tonne fiducial
  - Operation in 2010 / Site SNOLab

- Primary focus is Ar target, but also evaluating engineering to allow Ne target
  - Cryogenic insulation demands are much greater for Liq Ne (20 K) vs Liq Ar (80 K)

XMASS at Kamioka: physics targets

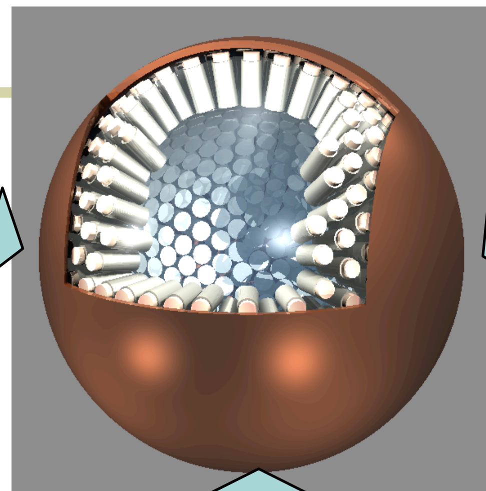
Goal: Multi purpose low-bg experiment with ~10t LXe

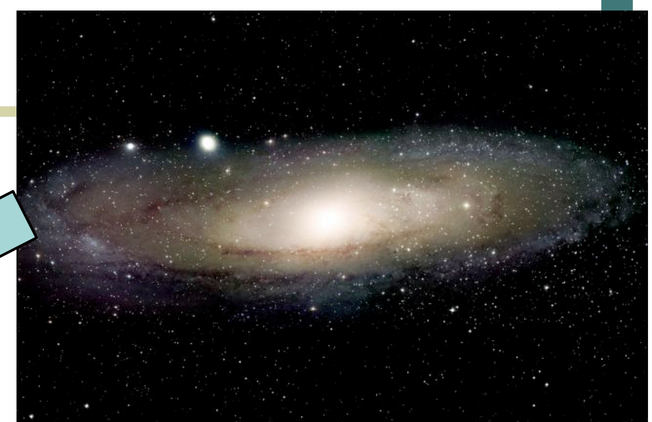
- **X**enon **MASS**ive detector for solar neutrino (**pp/^{7}Be**)
- **X**enon neutrino **MASS** detector ($\beta\beta$ **decay**)
- **X**enon detector for Weakly Interacting **MASS**ive Particles (**DM search**)



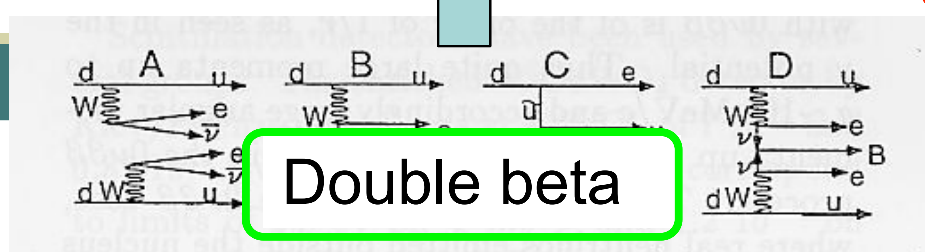
Solar neutrino

LXe scintillator





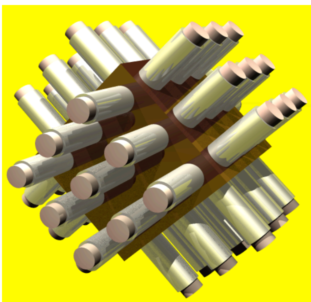
Dark matter



Double beta

XMASS: strategy for scaling up

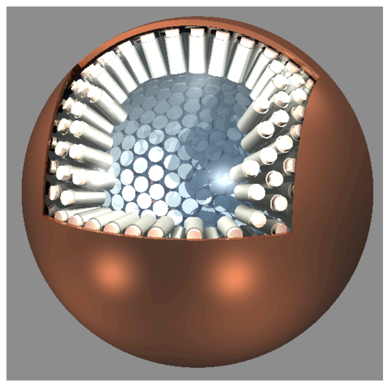
R&D phase
100kg Prototype



～30cm

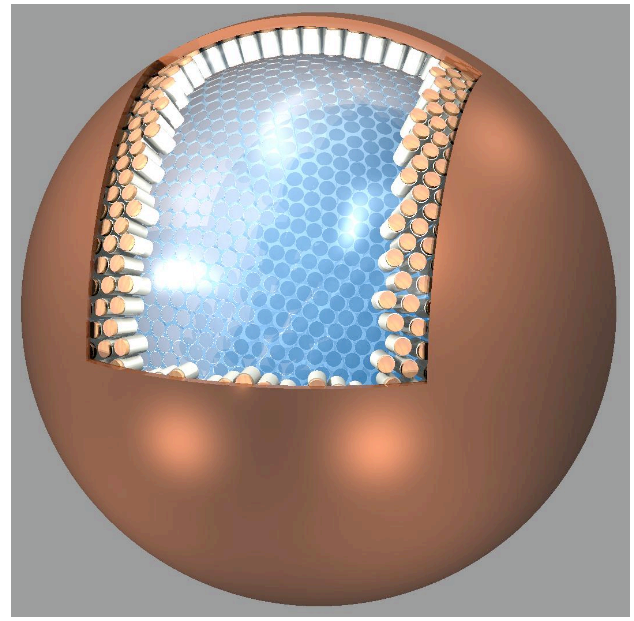
R&D

Phase 1
800kg detector



～80cm

Phase 2
~10 ton detector



～2.5m

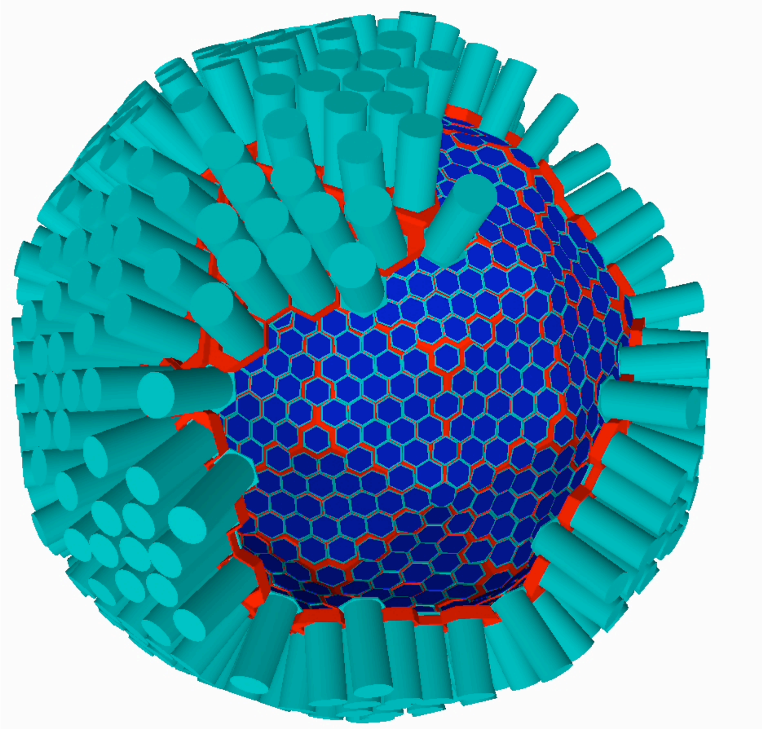
Dark matter search

Multipurpose detector
(solar neutrino, ββ …)

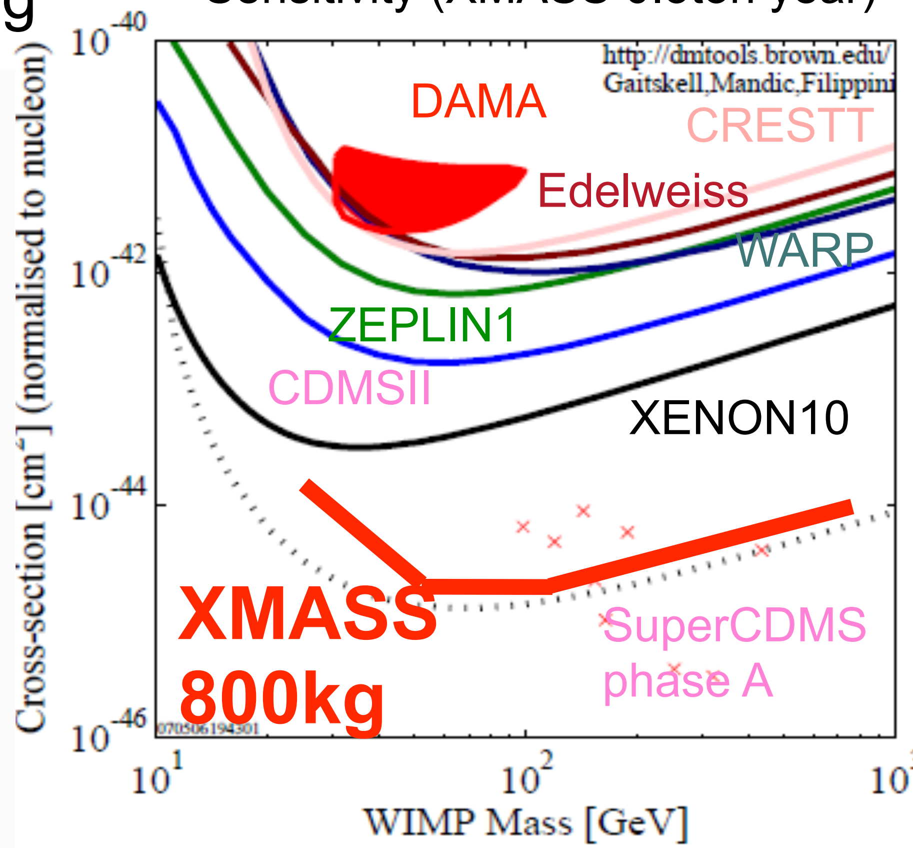
- The phase 1 is starting now.

XMASS Phase 1 (2007-2011)
DM search with 800kg LXe (100kg FV)

Detailed designing is ongoing
800 hexagonal PMTs



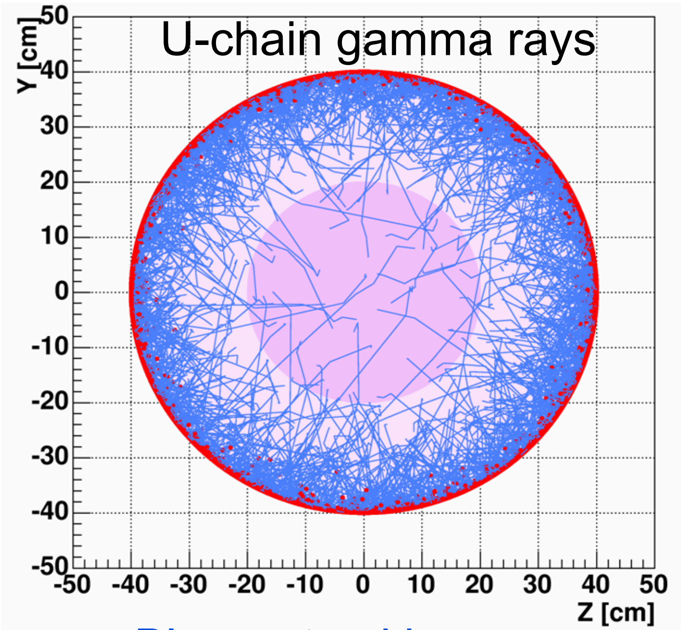
Sensitivity (XMASS 0.5ton year)



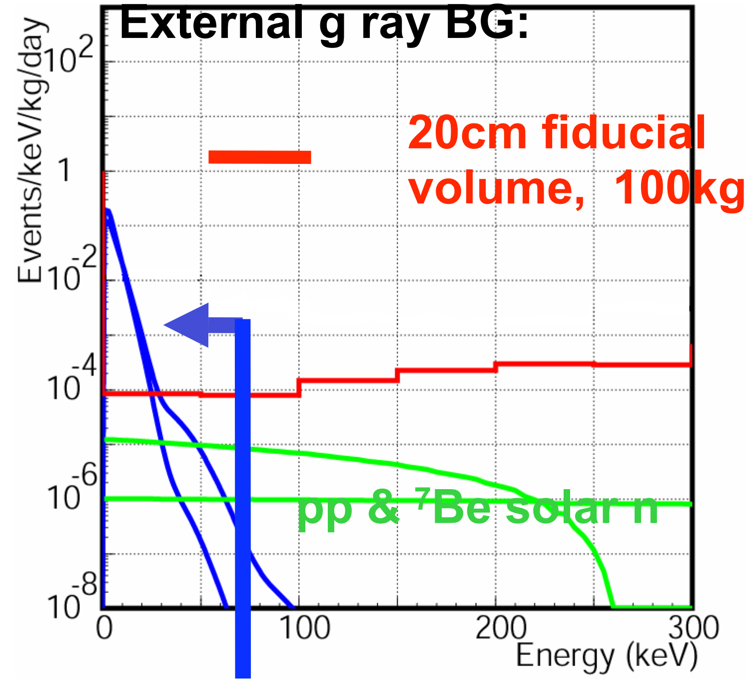
Budget approved. Construction will be started soon.

Target for 800kg : Dark Matter search

γ tracking MC from external to Xenon



Blue : γ tracking
Pink : whole liquid xenon
Deep pink : fiducial volume

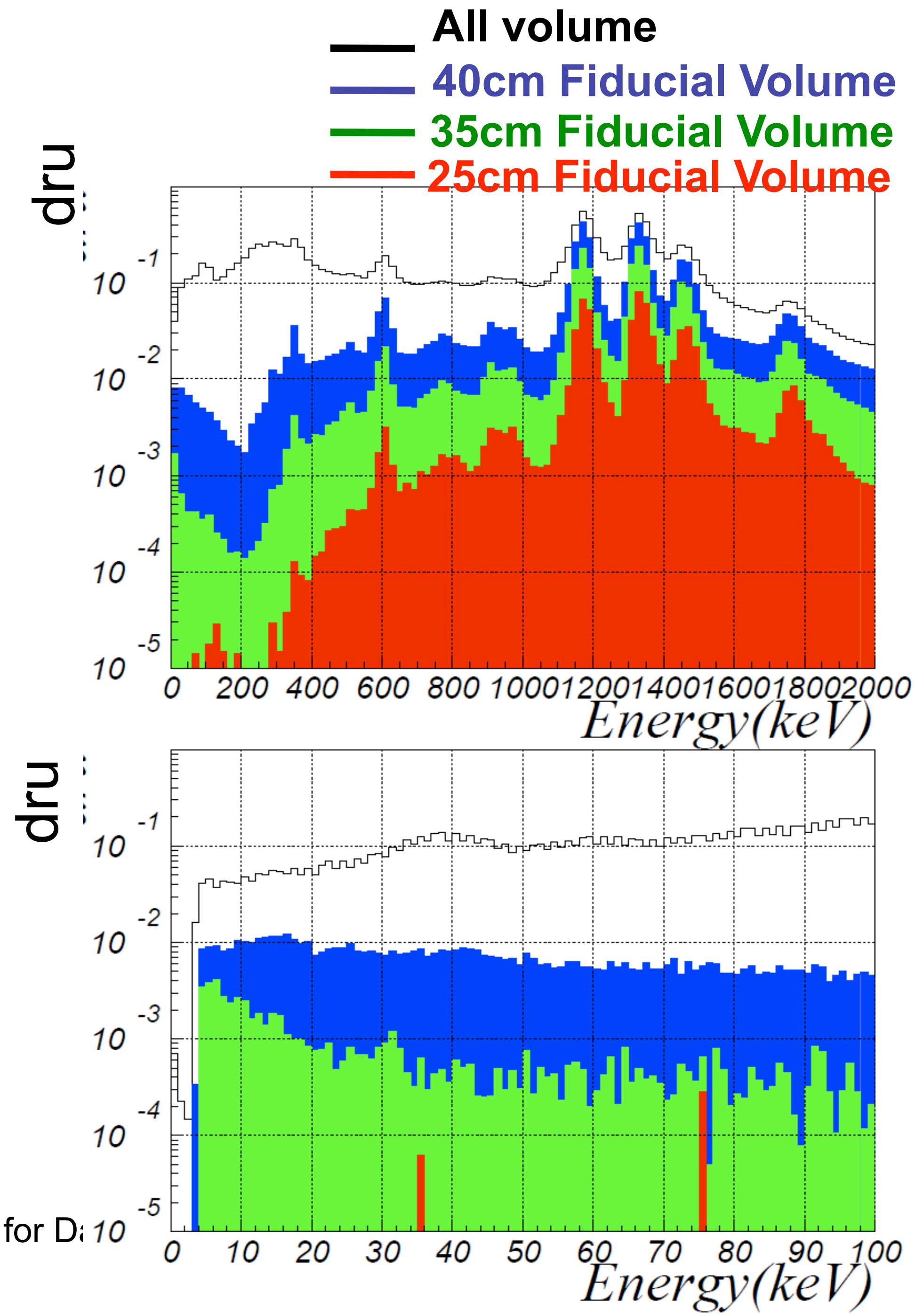


Expected dark matter signal (assuming 10^{-42} cm^2, Q.F.=0.2 50GeV / 100GeV,)

1. **Dark matter search**
    1. With liquid xenon ~1ton, reduce BG below 100 keV to 10^{-4}/day/keV/kg by self shielding.
    2. Search the signal from dark matter in low energy region.

➢ Estimated PMT BG

- Activity of PMT
  - ^{238}U chain 1.8x10^{-3} Bq/PMT
  - ^{232}Th chain 6.9x10^{-4} Bq/PMT
  - ^{60}Co 5.5x10^{-3} Bq/PMT
  - ^{40}K 1.4x10^{-2} Bq/PMT
- Below 300 keV number of events in the 25cm fiducial volume decreases rapidly.
- Below 100 keV remaining events are few.
- Below 300keV, <10^{-4} dru BG level.
- Below 100 keV, BG becomes <10^{-5} level.



Schedule of 800 kg detector

- Budget funded in this year.
- We are starting detail design of the detector.
  - Detector structure
  - Purification system
  - Cooling system
  - Electronics and etc…..
- Excavation at Kamioka will be start soon.
- Planning to finish the construction in two years.
- The measurements will be started from 2009.

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 =>**

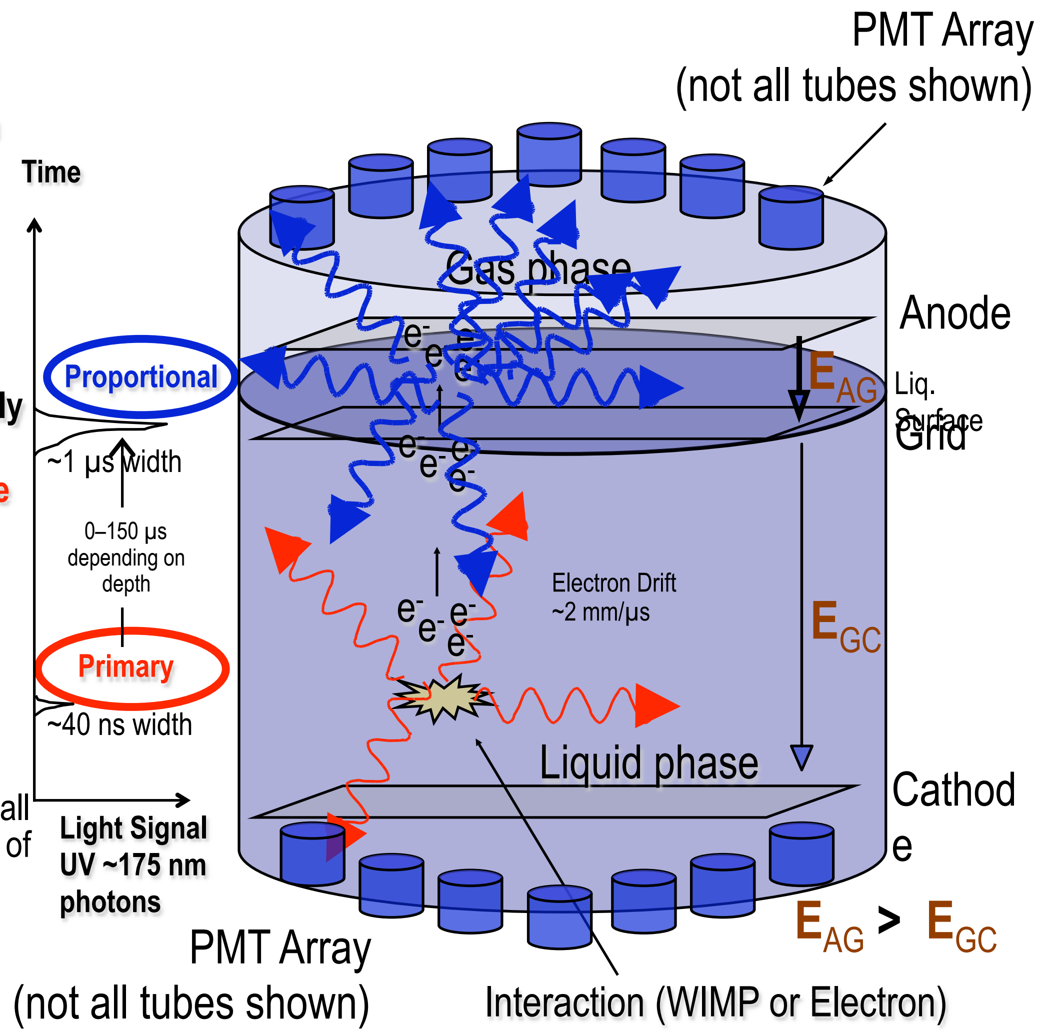
=> Weaker S1, Stronger S2

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)

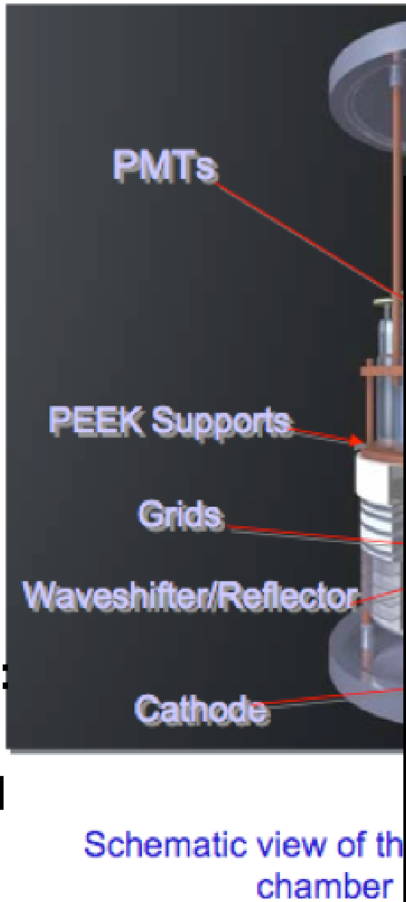


Two-phase Argon Detector: WARP

- PSD and secondary scintillation from ionization drift

- **2005-2007**
  - 3.2 kg prototype run at Gran Sasso
  - Preliminary dm results reported
    - 100 kg.d (55 keVr threshold)
    - Energy Calibration taken from slope of neutron calibration
  - Additional data taken 12/2006:
    - 43 kg.d Improved electronics
      20 MHz --> 100 Mhz
      70% NR acceptance at 50 phe (40 keVr):
      discrimination < 3e-7
    - 5kg of isotopically purified Ar delivered on March 2007 (residual 39Ar 2% of original), results pending
- **2007-** (July 2007) Carlo moved to LNGS
  - 140-kg detector + 8 tonne active veto being installed , operation in 2008

WARP Prototype

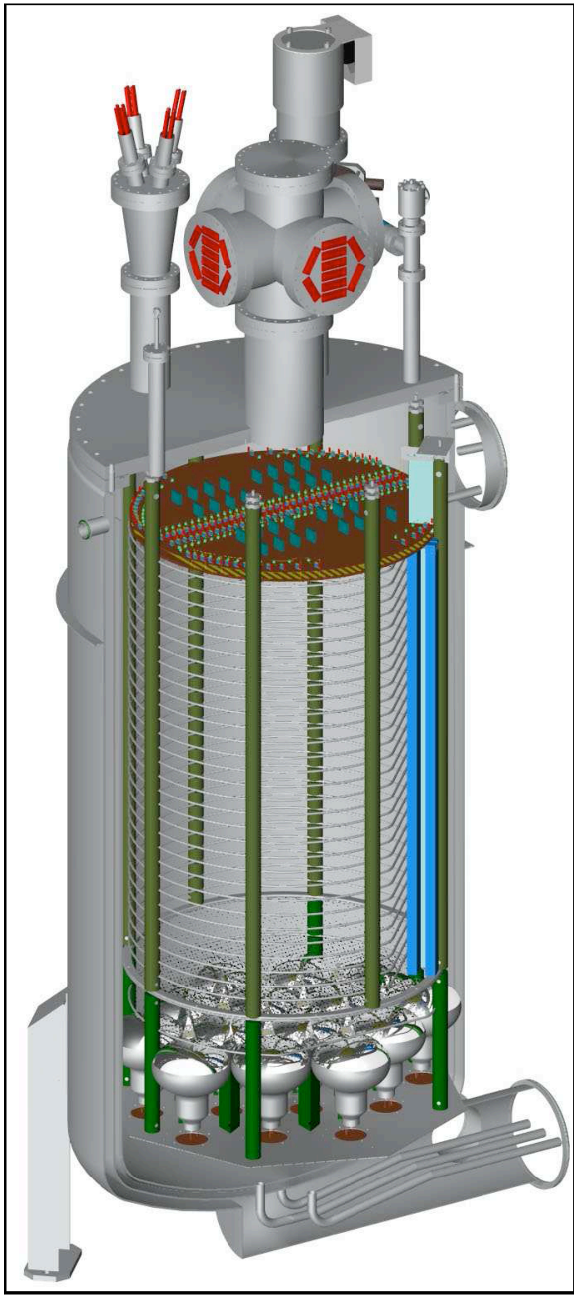


WARP

100-l detector

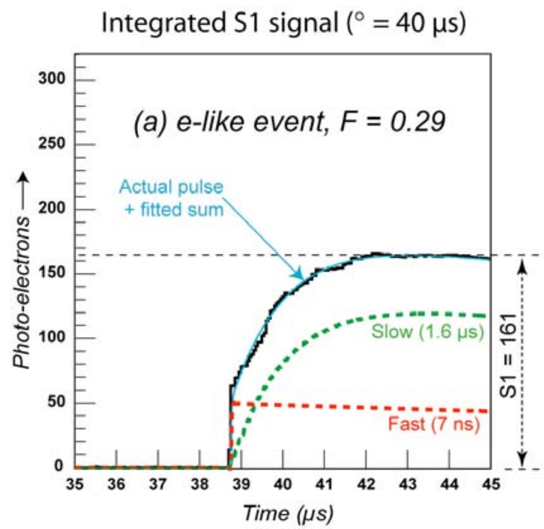
ArDM

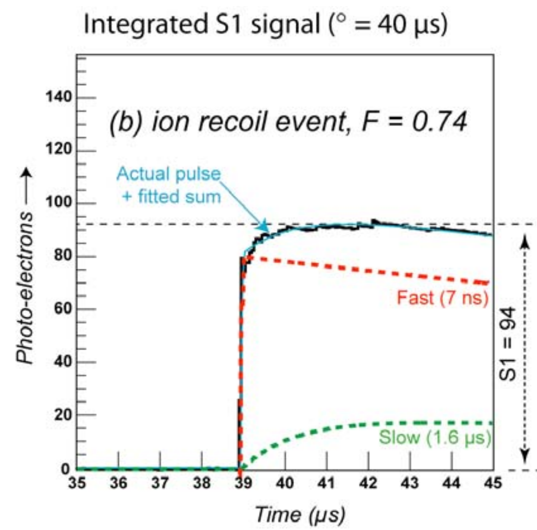
- Initiated 2004 (Andre Rubbia)
- 1st goal: 1 ton prototype currently under construction at CERN
  - LEM charge readout, PMT for primary scintillation
  - very high E field
  - efficient light readout
- 1st milestone: 2007
  - proof of principle and stability studies
  - gamma and beta rejection vs neutrons
- Future Underground Operation
  - Canfranc, Spain (no date given)
  - design of shielding / veto to be addressed
- Sensitivity goals:
  - threshold 30 keV --> reach 10^{-42} cm^2
  - further bg improvements --> reach 10e^{-44} cm^2

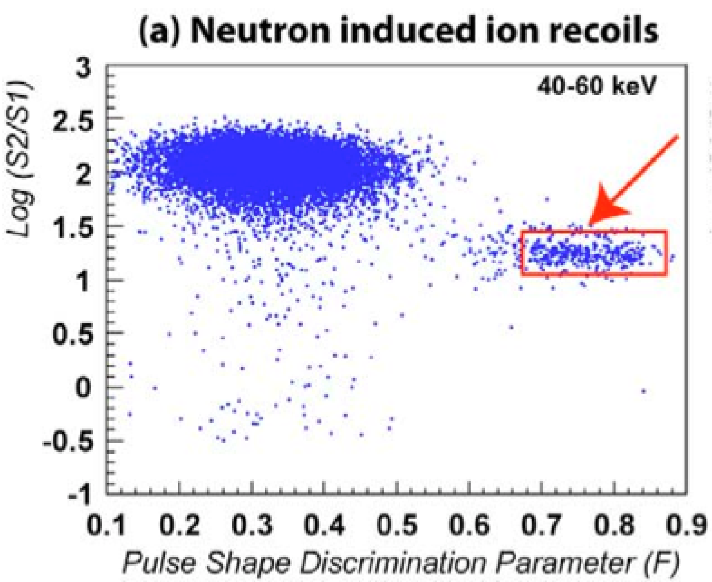


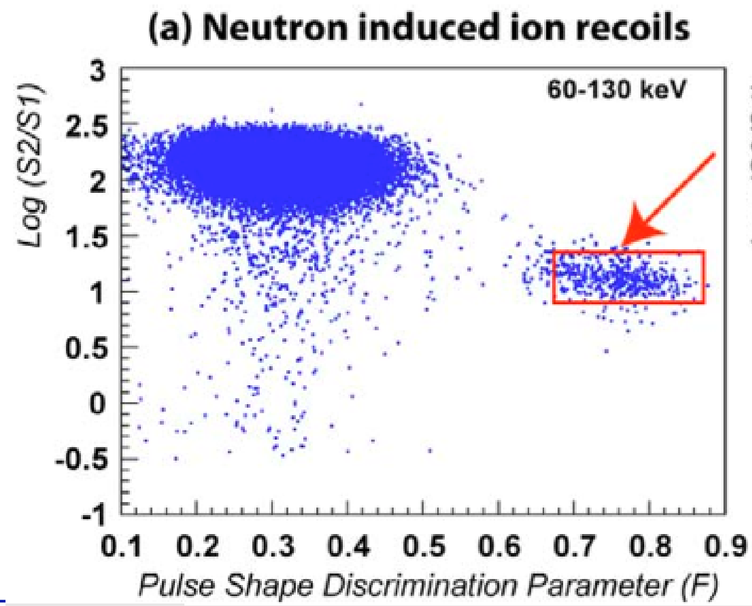
WARP - Dual Methods of Discrimination

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







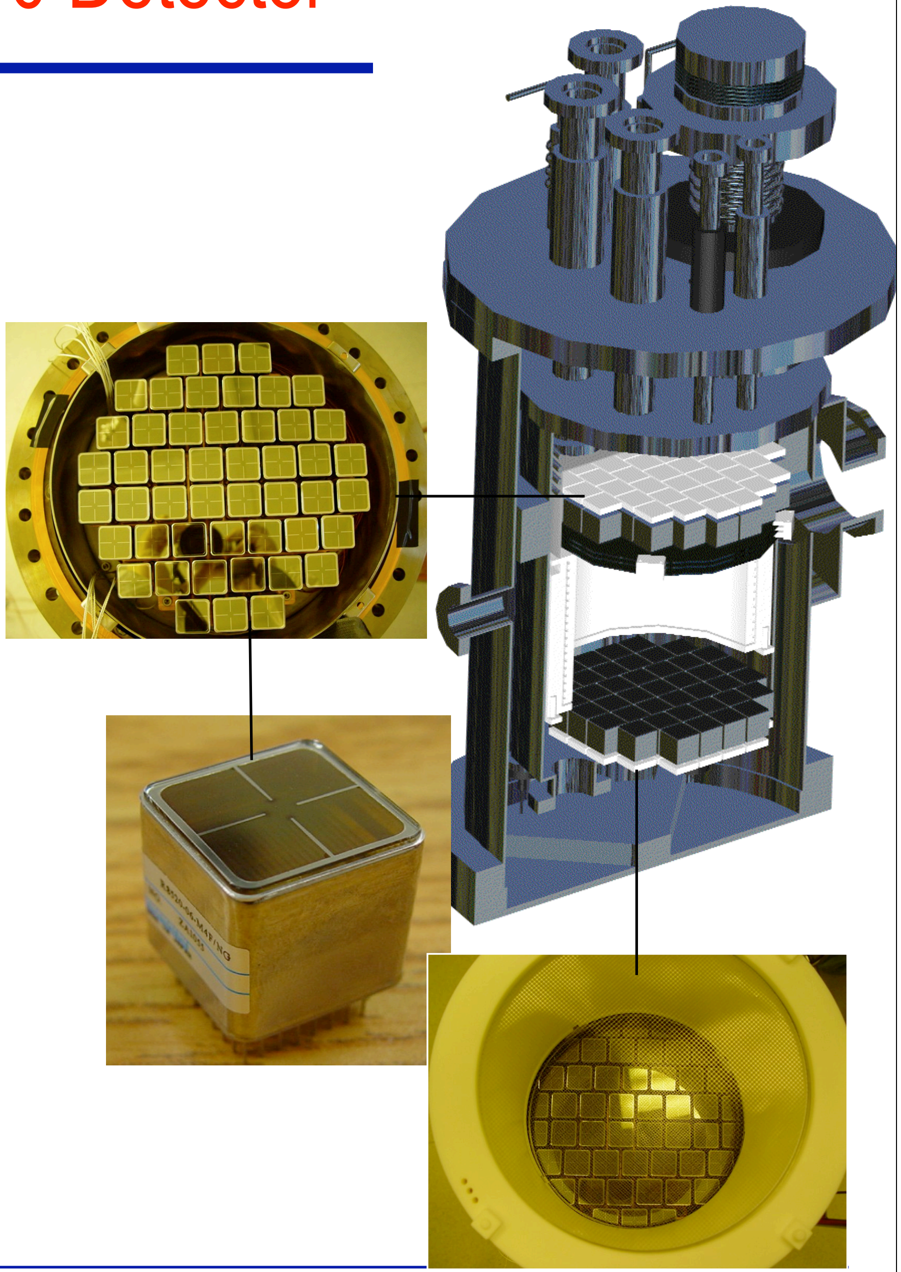


39Ar Beta Background - Event Rejection vs Removal

- 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)
    - Large survey will be required to understand factors effecting levels.

The XENON10 Detector

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



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 **(Aug 2007 Baudis -> ETF Zurich)**

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

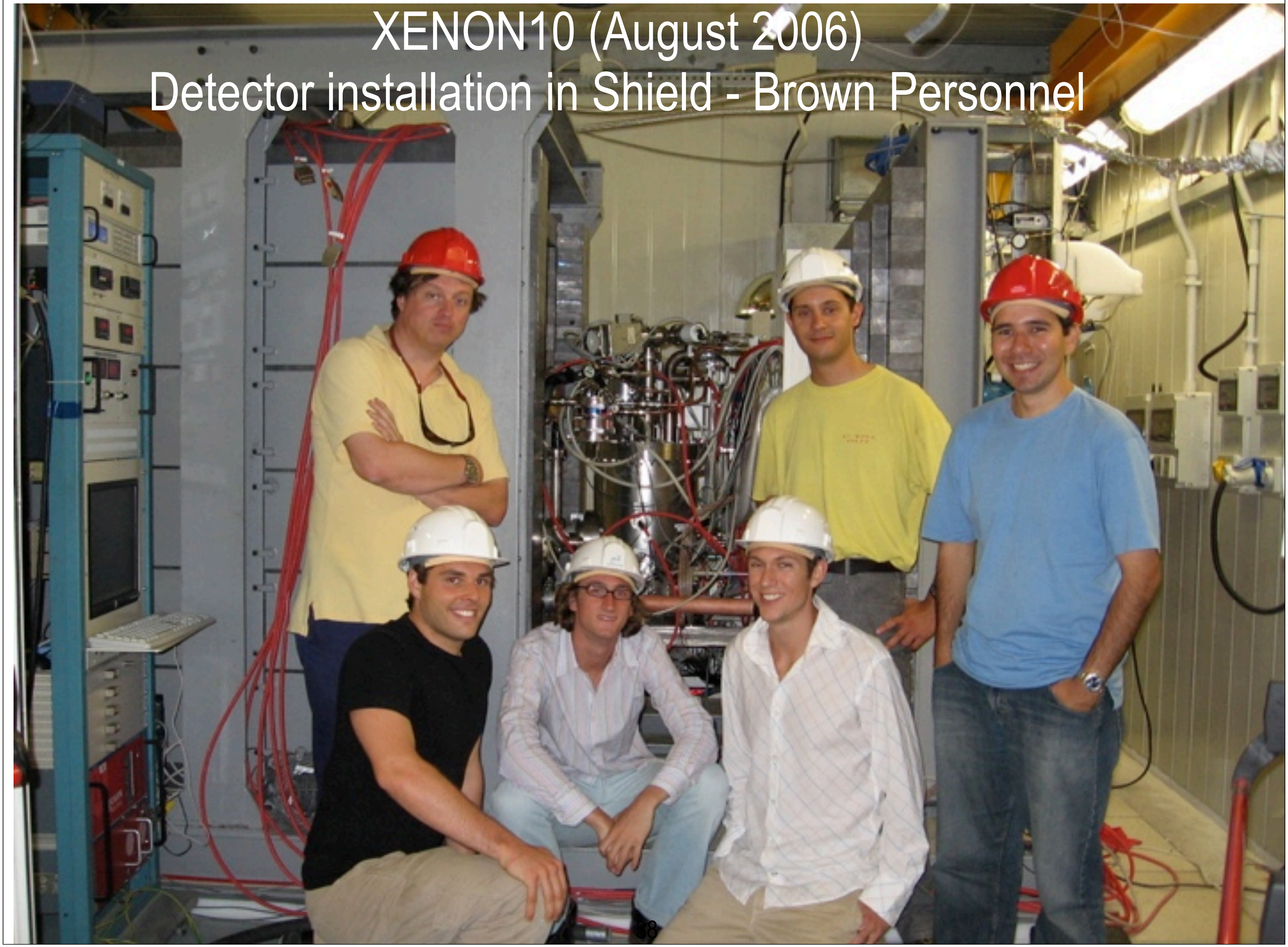
Rice University Uwe Oberlack, Roman Gomez, Christopher Olsen and Peter Shagin

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

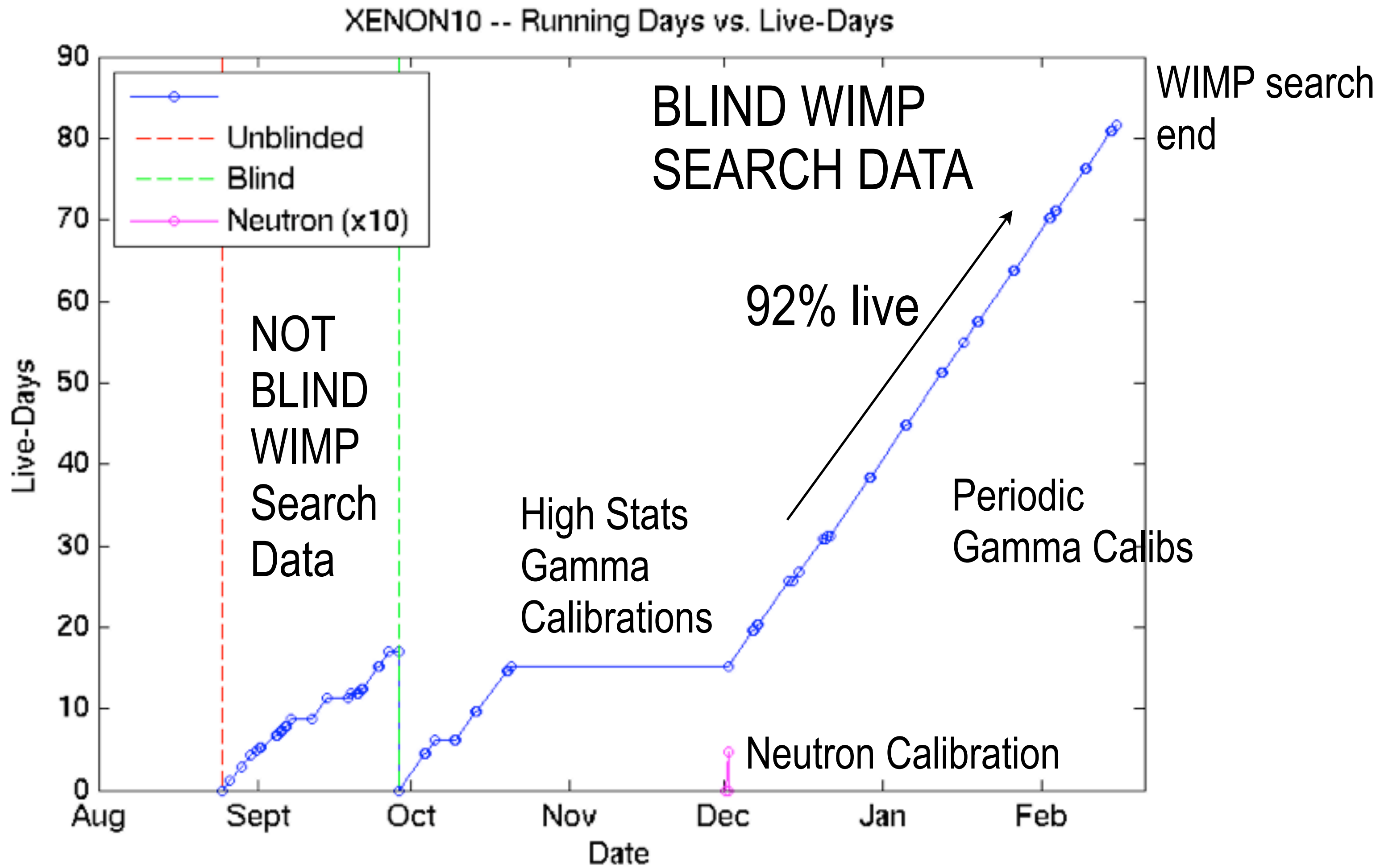
XENON10 (August 2006)
Detector installation in Shield - Brown Personnel



XENON10: Ready for Low Background Operation

Installation of the Detector... ...and we are operational

XENON10 Live time at Gran Sasso

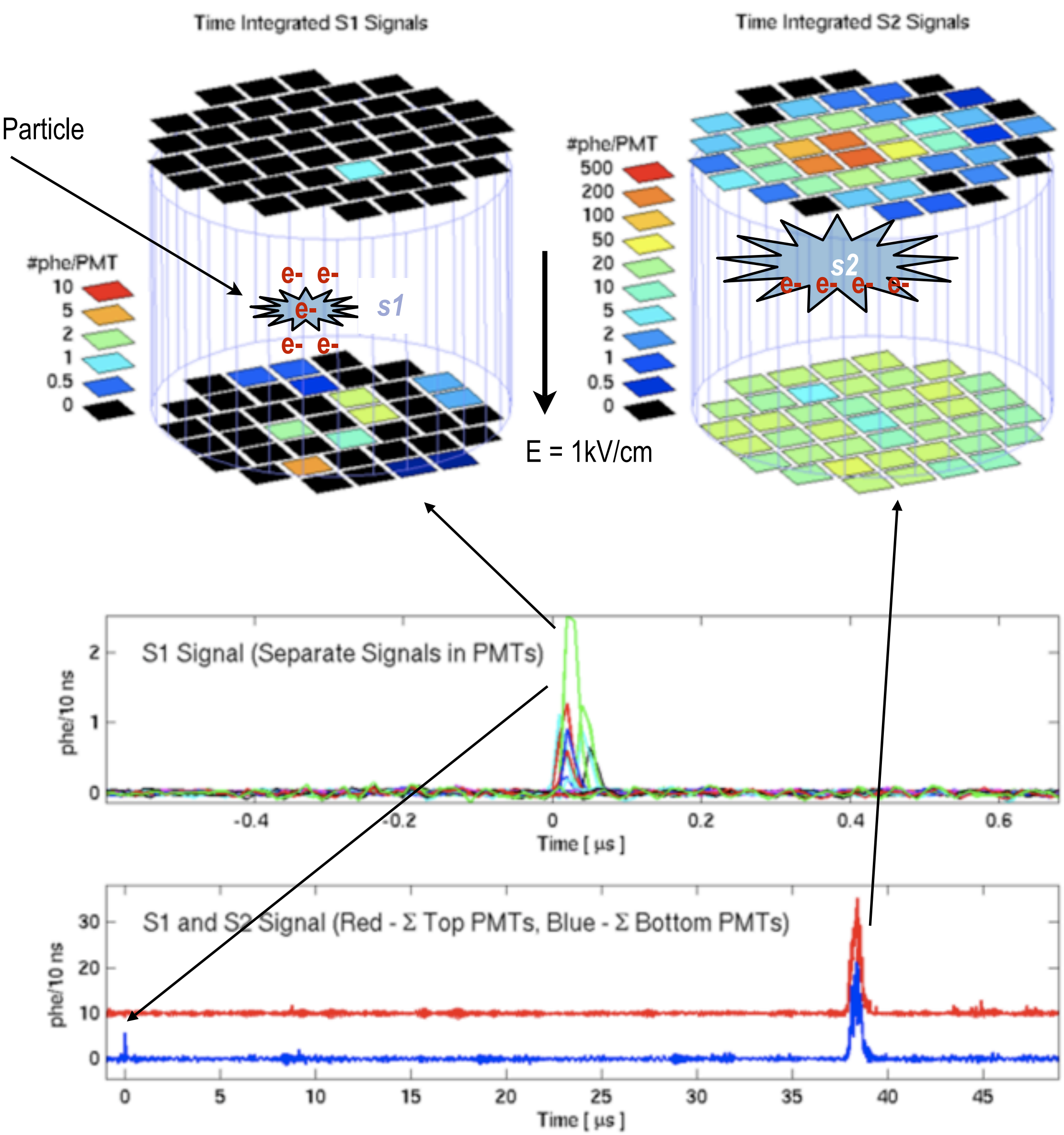


- High Statistics Gamma Calibs + 1 Neutron Calib
- NON BLIND WIMP search data ~20 live days (Sept) + 20 live days dispersed (Oct-Feb)
- BLIND WIMP Search results from 60 live day (Oct-Feb)

XENON10 Event Discrimination

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

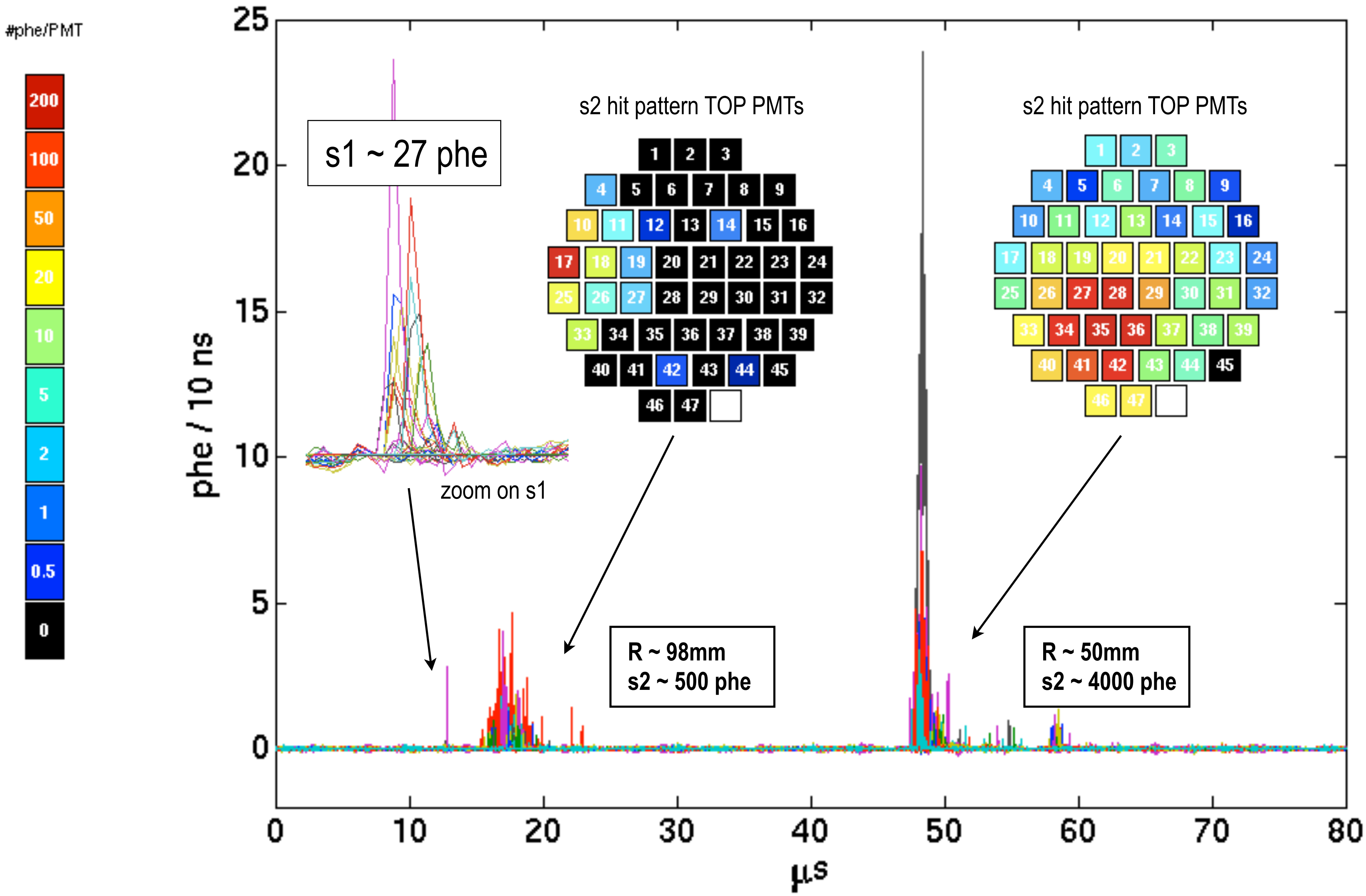
s1: Primary Scintillation Created by Interaction LXe
s2: Secondary Scintillation Created by e- extracted & accelerated in GXe



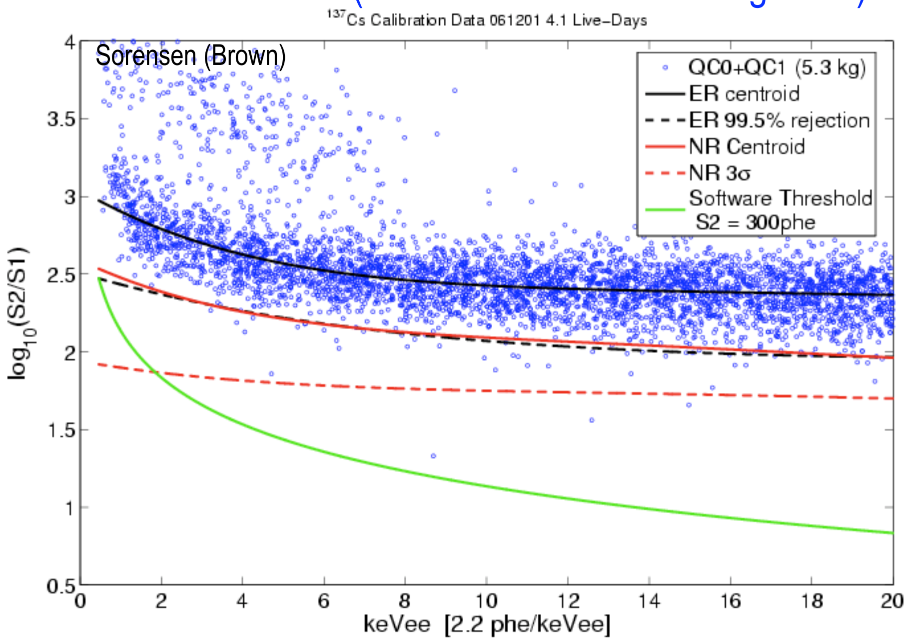
$(s2/s1)_{ER} > (s2/s1)_{NR}$

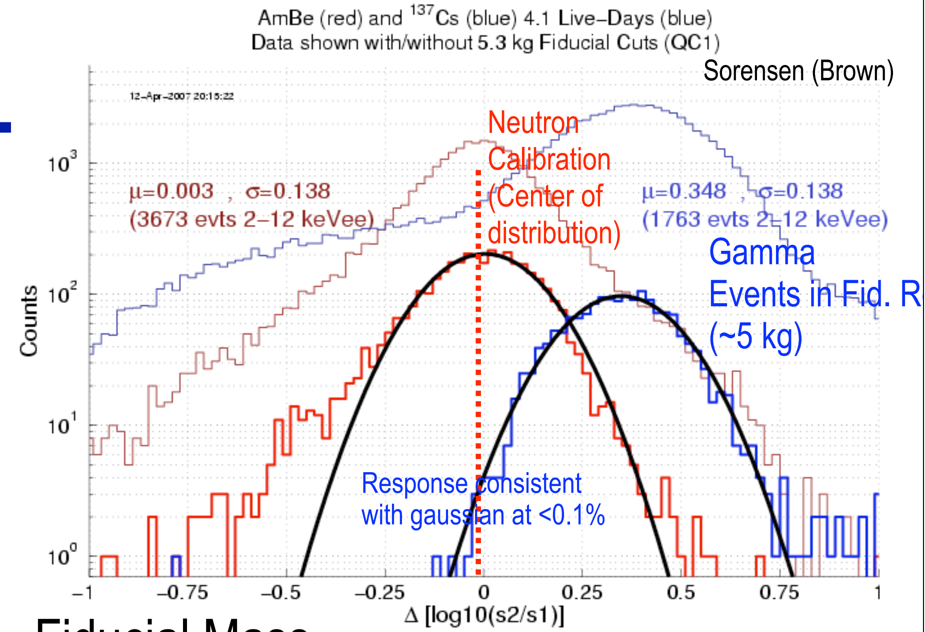
Expect > 99% rejection efficiency of γ/n Recoils…
Reduction of Backgrounds =>
Reduction of Leakage Events

Event Localization / Double Scatter Event

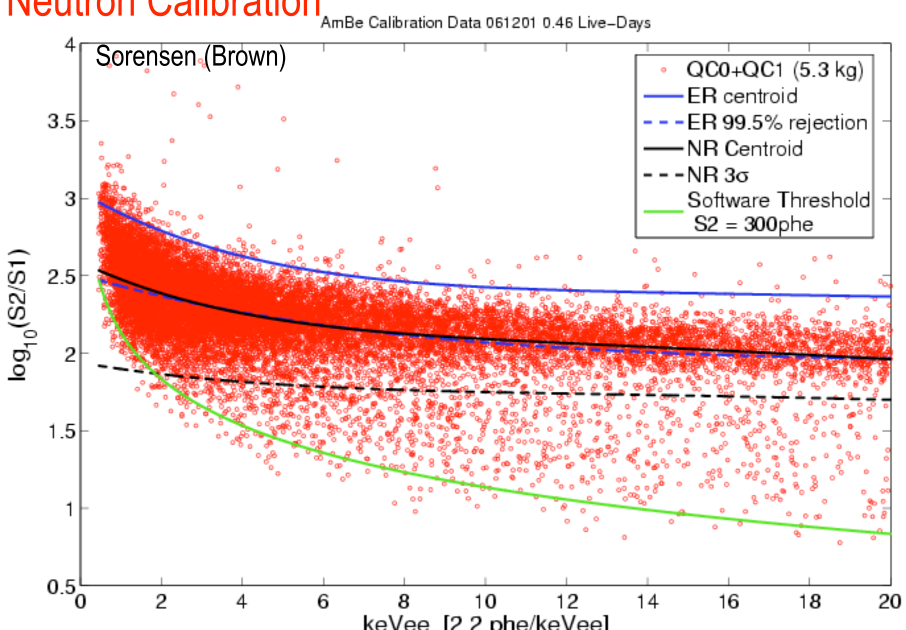


Gamma Calibration (Electron Recoils == Background)





Neutron Calibration



- Fiducial Mass
- AmBe
  - 8400 events in range 2-20 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

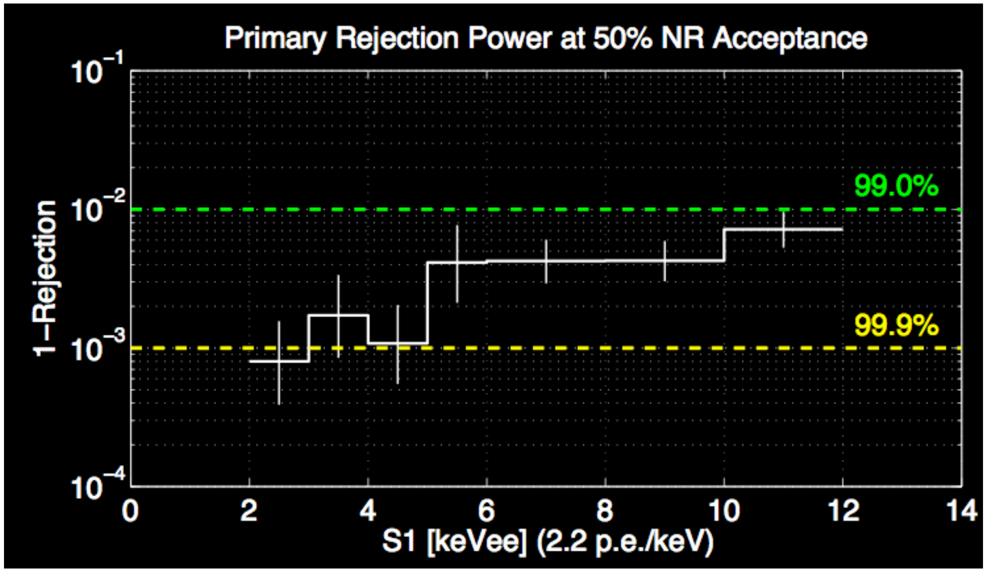
Nuclear Recoil (NR), Electron Recoil (ER) Discrimination

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.



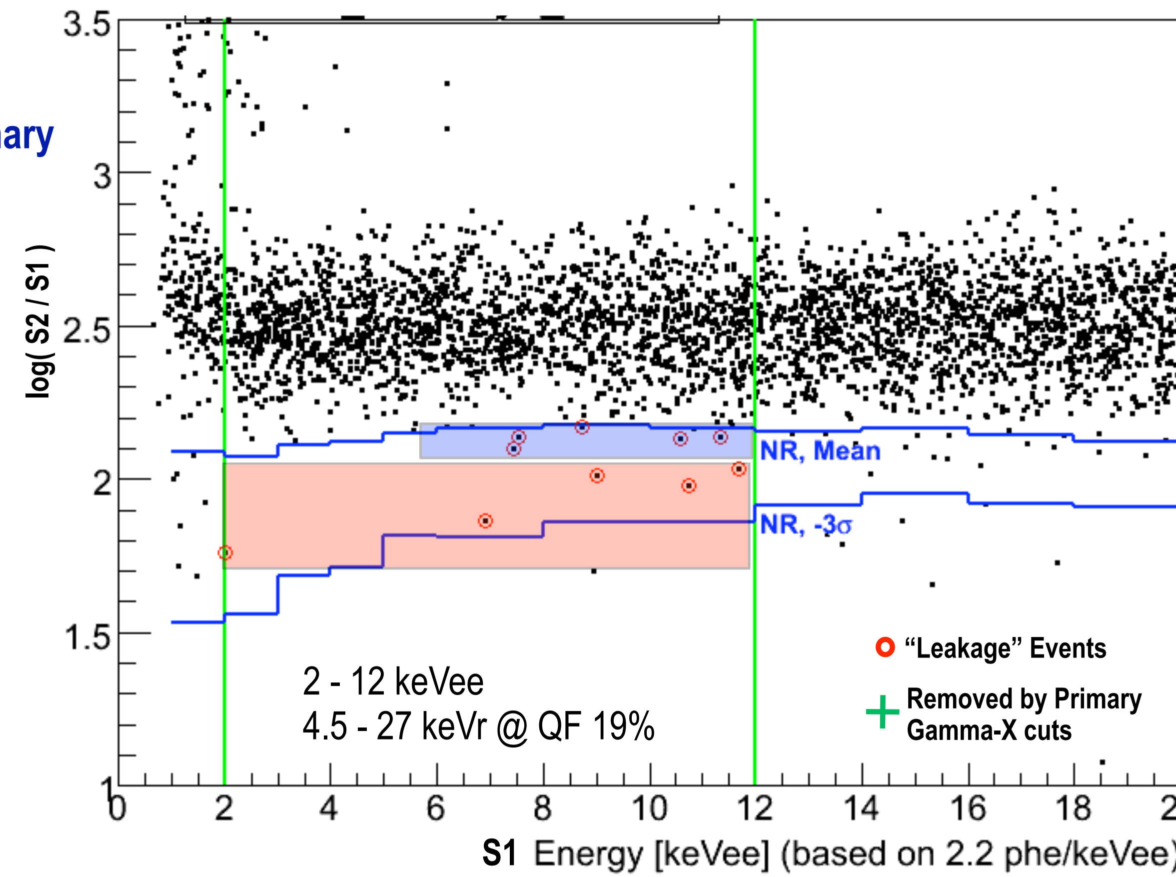
Errors bars shown are only those from fits of Log-Gaussian hypothesis

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

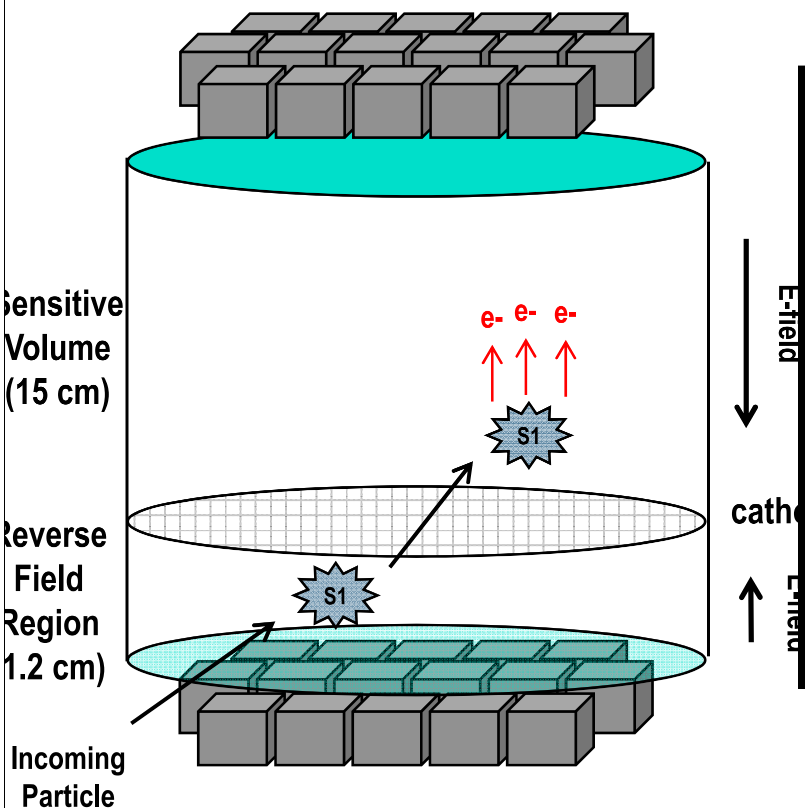
Δlog (S2 / S1) vs S1

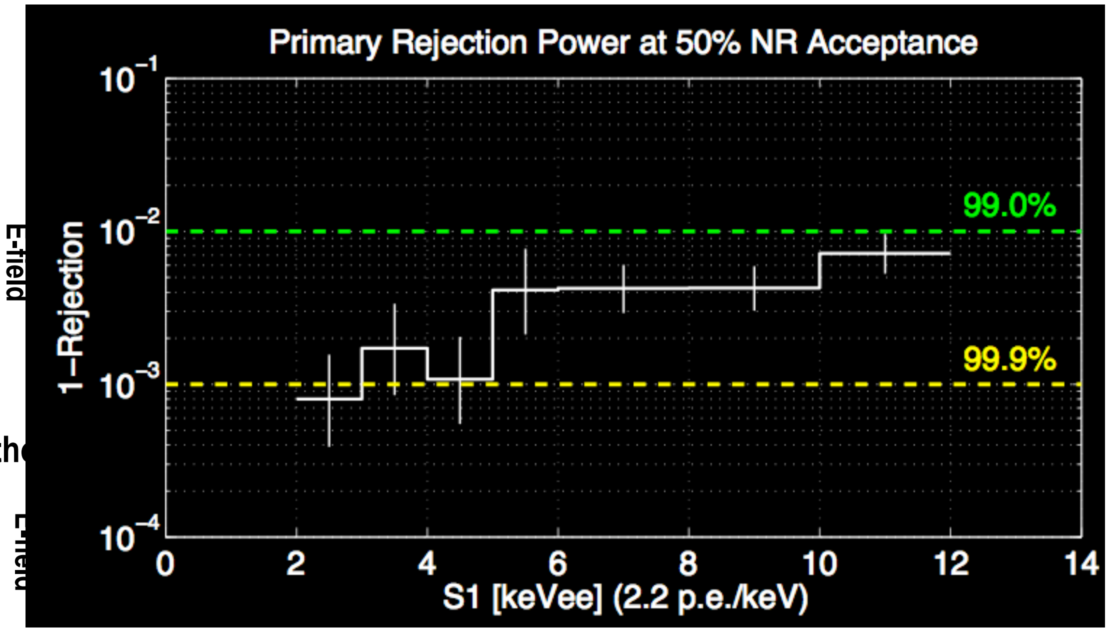
"Straightened Y Scale" – ER Band Centroid normalized => 2.5



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)





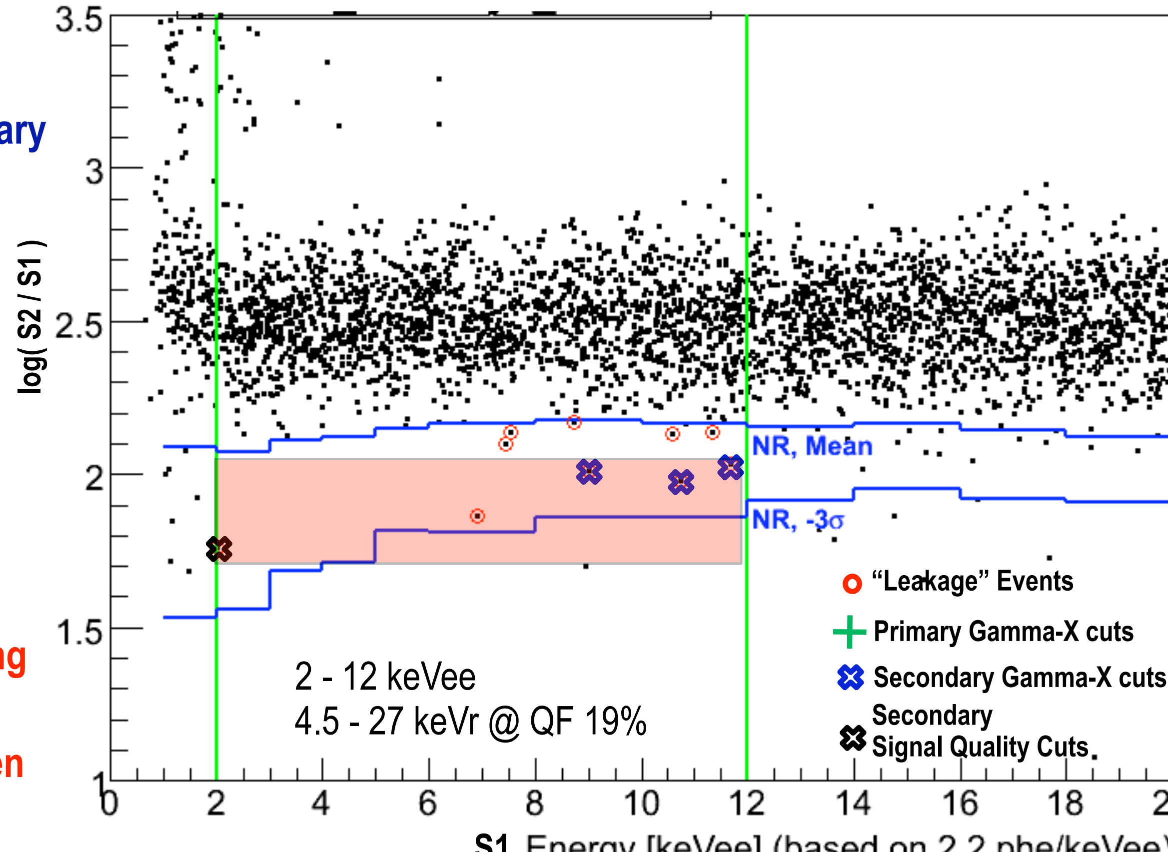
Applying the SECONDARY Gamma-X Cuts to XENON10

- **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

See Peter Sorensen Talk, this afternoon

log (S2 / S1) vs S1

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

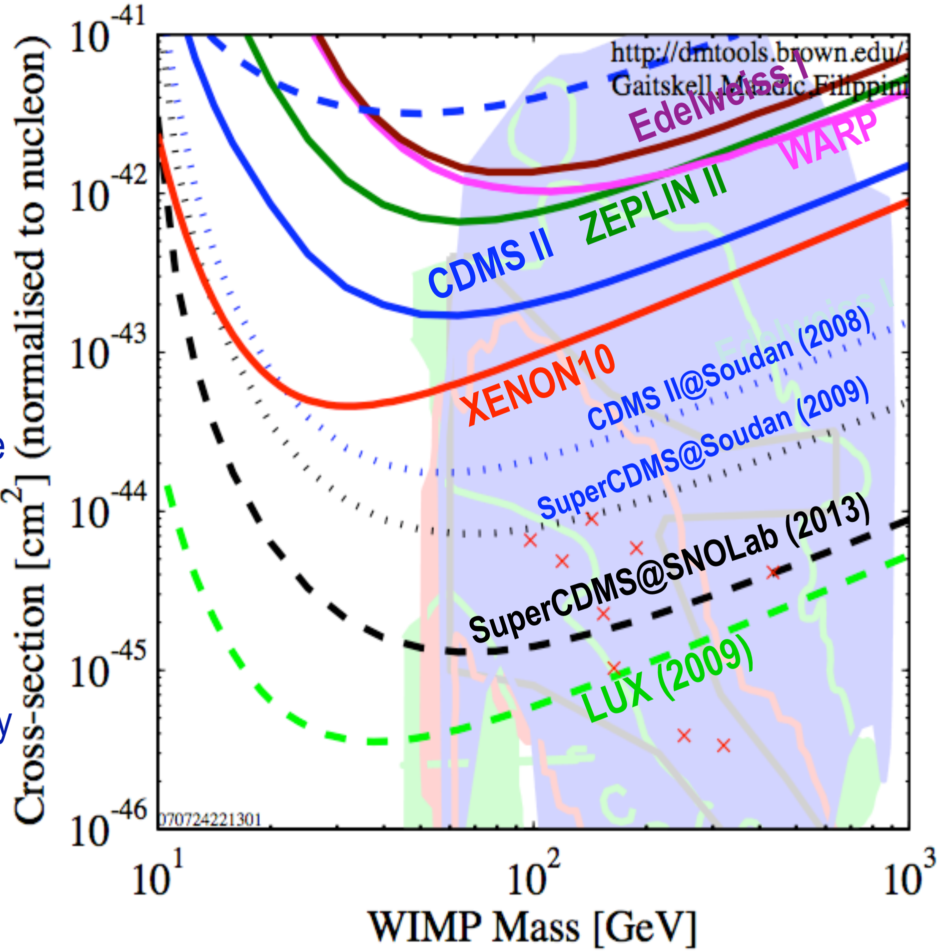


Note 1 event would be expected for $\sigma \sim 2\times10^{-44}$ cm^2

Dark Matter Result & Next Stage

Dark Matter Goals

- XENON10
  - ~60 day run (bg limited)
  - 136 kg-days net exposure
- LUX - Sensitivity curve at $7x10^{-46}$ cm^2 (100 GeV)
  - Exposure: Gross Xe Mass 300 kg
    Limit set with 300 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 XENON10 discrimination performance
    ER $8x10^{-4}$ /keVee/kg/day and >99.5% ER rejection
    - Intrinsic BG rejection ->99.9% at low energy
    - Improvements in PMT bg 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

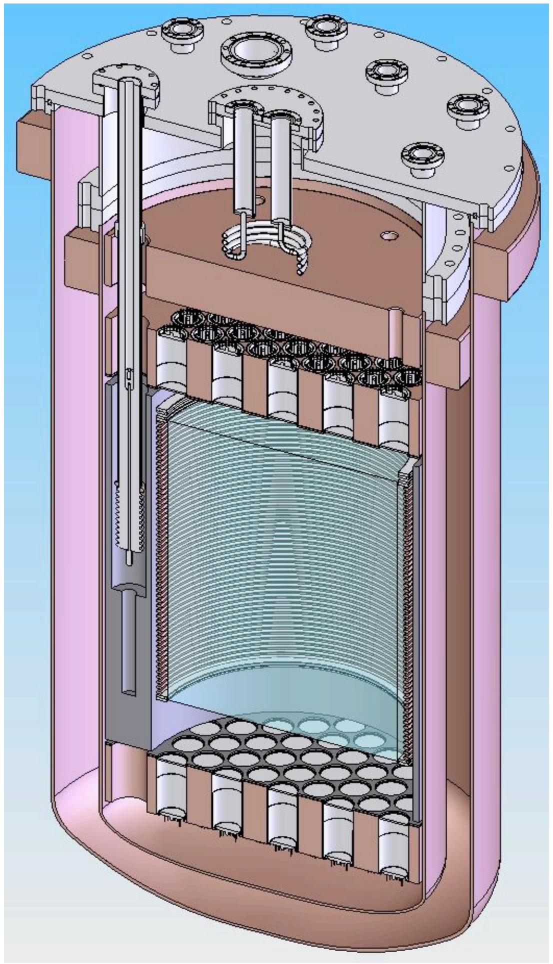


(XENON10 curve no background subtraction)

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], Yale [McKinsey]
  - 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: >99.4% ER background rejection for 50% NR acceptance, E>5 keVr (ER rejection is energy dependent)

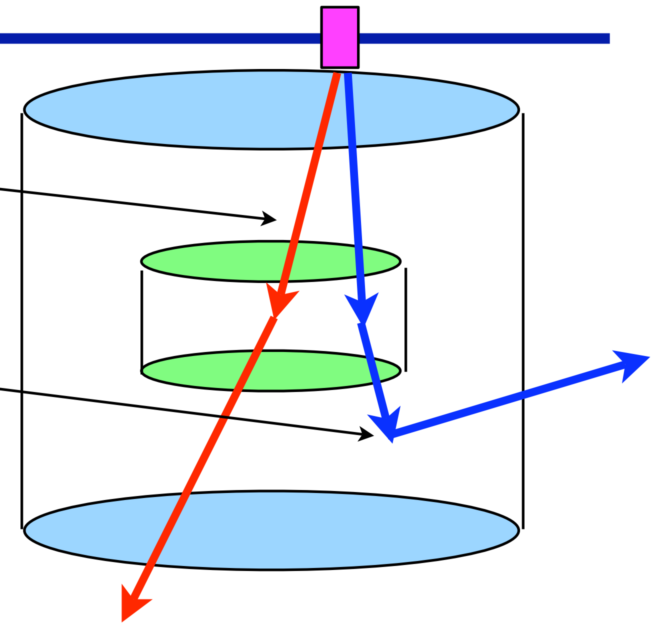
  (Case+Columbia/Brown Prototypes + XENON10 + ZEPLIN II)
  - 3D-imaging TPC eliminates surface activity, defines fiducial
- Backgrounds:
  - Internal: strong self-shielding of PMT activity
    - Can achieve BG $\gamma+\beta < 8\times10^{-4}$ /keVee/kg/day, dominated by PMTs (Hamamatsu R8778).
    - Neutrons (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 backgrounds with readily achievable $<10^{-11}$ g/g purity.
- DM reach: 7×10^{-46} cm^2 in 10 months



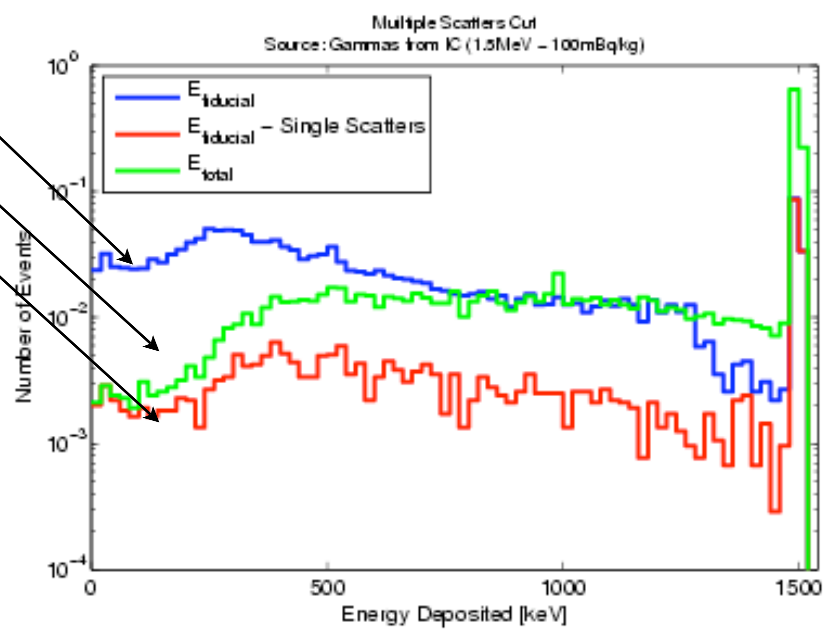
http://www.luxdarkmatter.org

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.

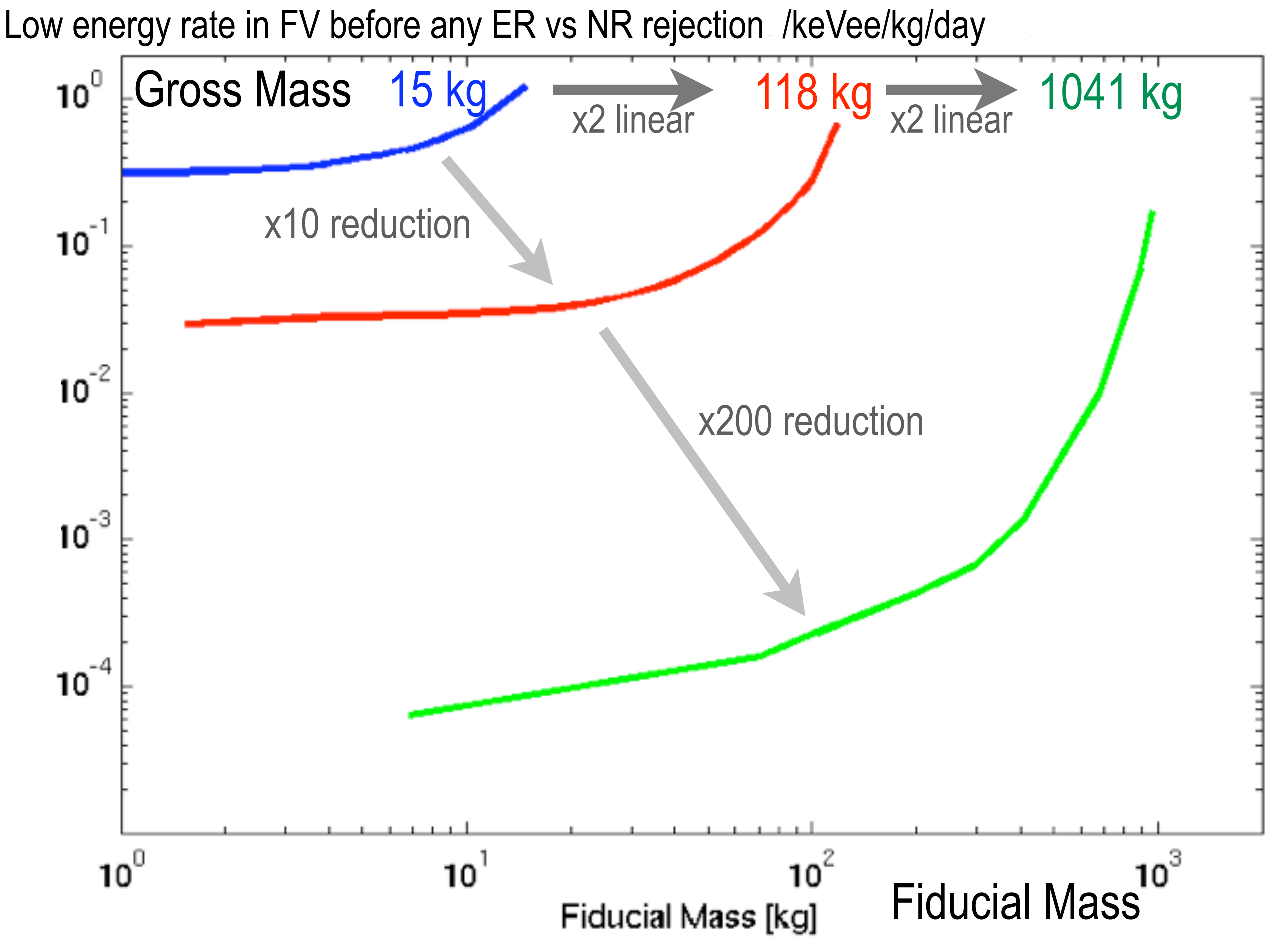


- Example for 1.5 MeV γ from outside LXe volume
  - Energy Spectrum for part of energy deposited in FV
  - Energy spectrum for all energy in detector
  - Additional application of multiple scatters cut has little additional effect on low energy event rate
- Conclusion for Event Suppression
  - xyz resolution of detector is important simply in defining FV. Little additional reduction from locating vertices.
  - (Full xyz hit pattern does assist in bg source identification)

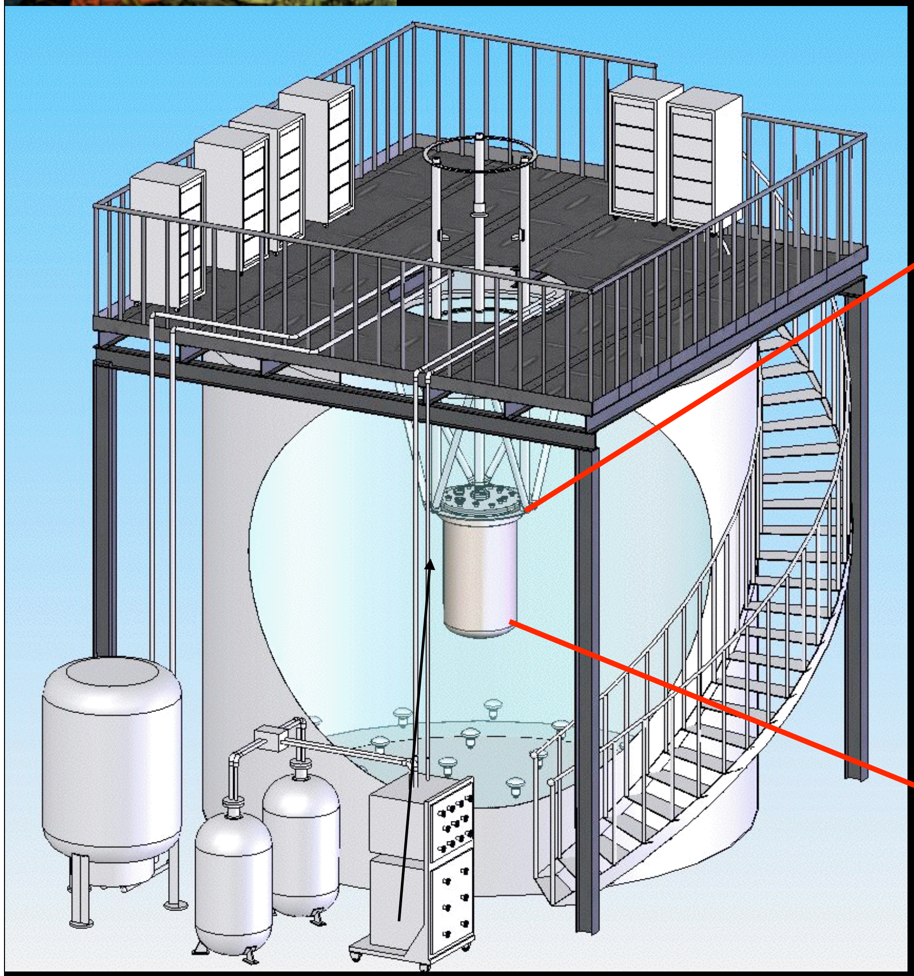


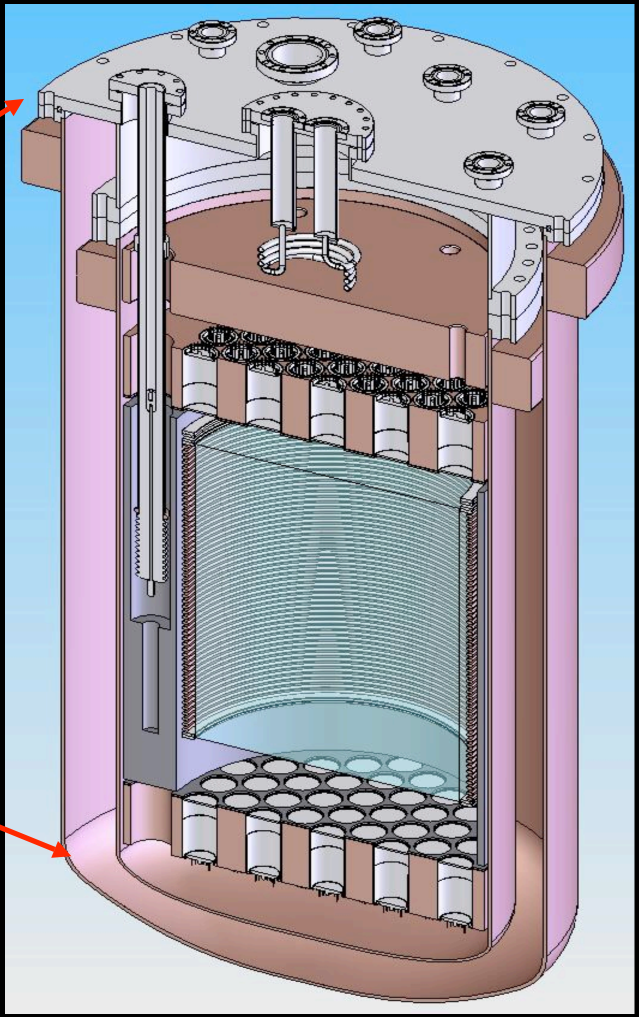
Scaling LXe Detector: Fiducial BG Reduction /1

- 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



The LUX detector





~ 6m diameter Water Cerenkov Shield.

Dual phase detector - aspect ratio ~1.2

LUX Parameters

- 350 kg Dual Phase liquid Xe TPC
- 1-2 kV/cm field in liquid (~50 cm drift), 5 kV/cm for extraction and 10 kV/cm field in gas phase
- 60 PMTs (Hamamatsu R8778) each layer - top and bottom arrays
- 3D-imaging TPC eliminates surface activity, defines fiducial
- ~100 kg achievable in the fiducial volume

Goals (Contd.)

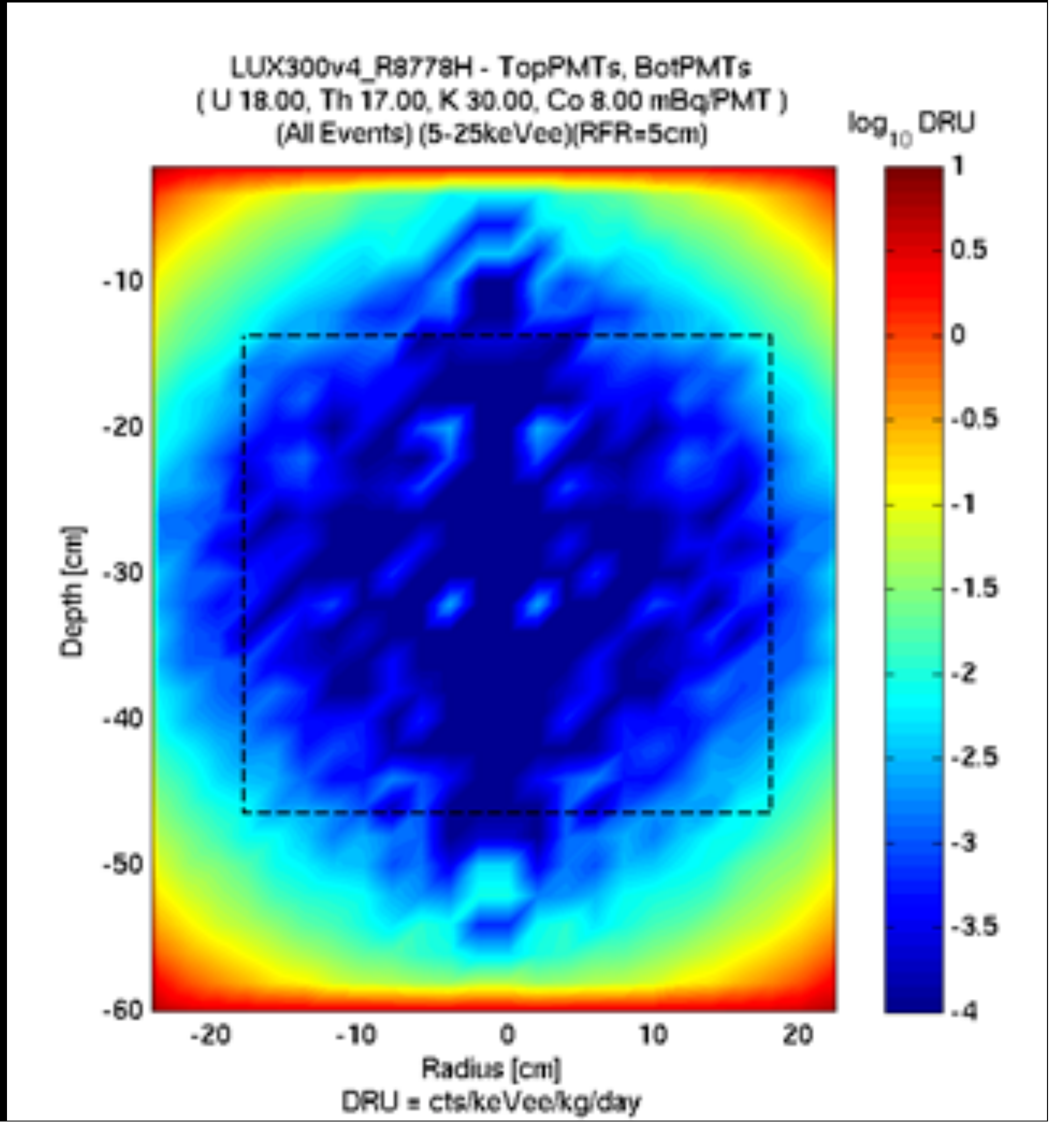
GOAL FOR WIMP SIGNAL SENSITIVTY AND REFERENCE LEVELS (UPPER LIMITS) FOR BACKGROUNDS (5–25 keVr, 1.3-8 keVee)	*NR Avg. Diff. Rate evts/keVr/kg/day*	*ER Avg. Diff. Rate evts/keVee/kg/day*	*Total Rate for a FV exposure of 30,000 kg-days (net live)*
WIMP (m = 100 GeV, $\sigma = 7\text{x}10^{-46}$ cm²)	$1.4\text{x}10^{-5}$		8.6
WIMP (after NR acceptance of 45%)	$6.5\text{x}10^{-6}$		3.9
ER Flat Spectrum (before ER rej.)		**$8.3\text{x}10^{-4}$**	180
ER Flat Spectrum (after ER rej. 99.4%)		$4.8\text{x}10^{-6}$	1.0
NR Neutron Spectrum	**$3.7\text{x}10^{-6}$**		2.2
NR Neutron Spectrum (after NR acceptance of 45%)	$1.7\text{x}10^{-6}$		1.0

Conservative

Backgrounds (Gamma)

- Internal strong self-shielding against PMT activity (main source of background events). Double Compton scatters are rejected.

- External large water shield with muon veto.
    - Very effective for cavern γ -- Very low gamma backgrounds with readily achievable $<10^{-11}$ g/g purity for water.



Status

• A revised proposal submitted to NSF/DOE.

• DUSEL site selection announced July 2007 => LUX will deploy as part of Homestake's Early Implementation Program. Mine re-entry is underway.

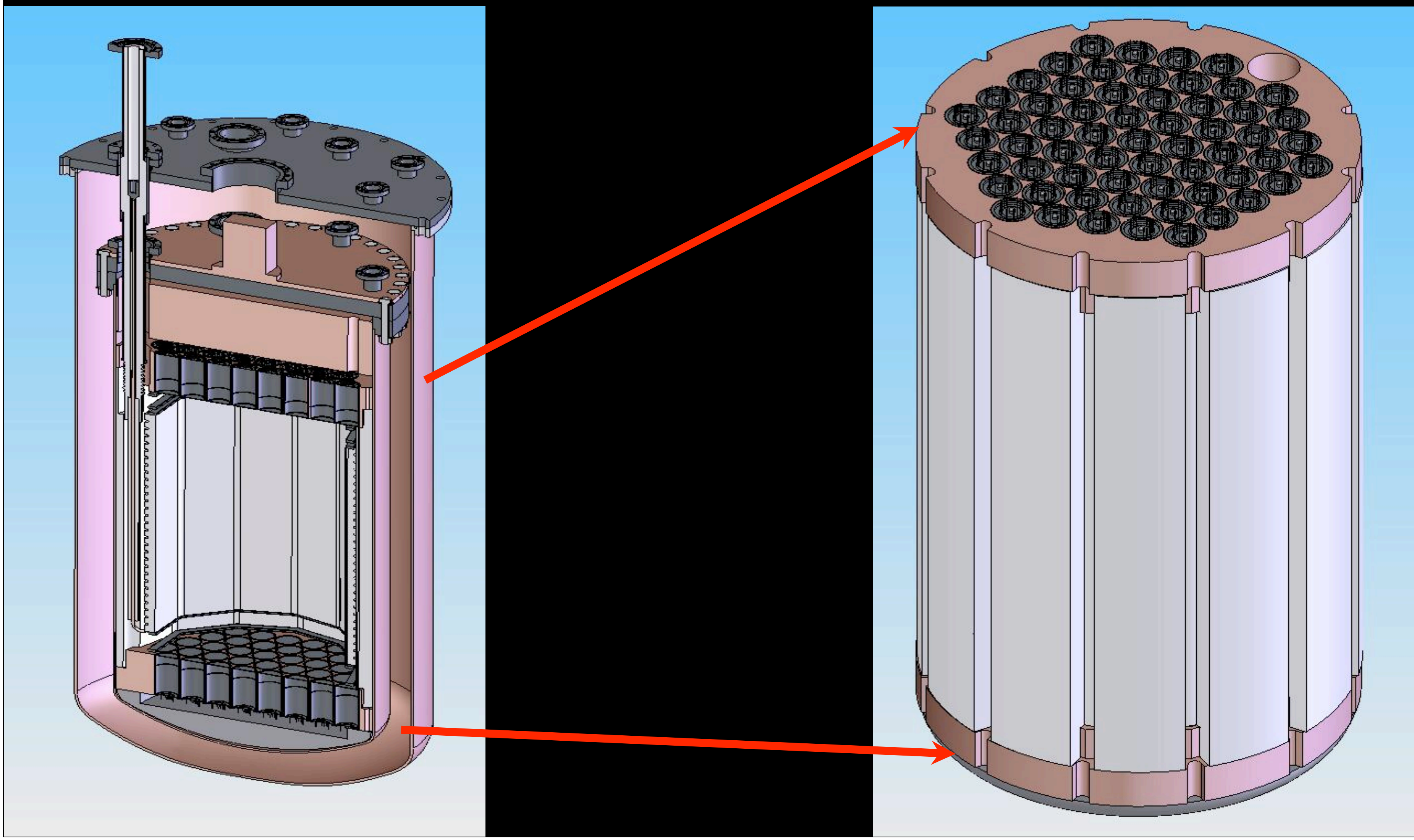
• Prototypes have been developed for several sub-systems/components.

• The cryostat has been assembled at Case and has undergone cooling cycles.

• Homestake underground access started. Cavern access in Fall of 2007. Water tank will be completed/operational July 2008.

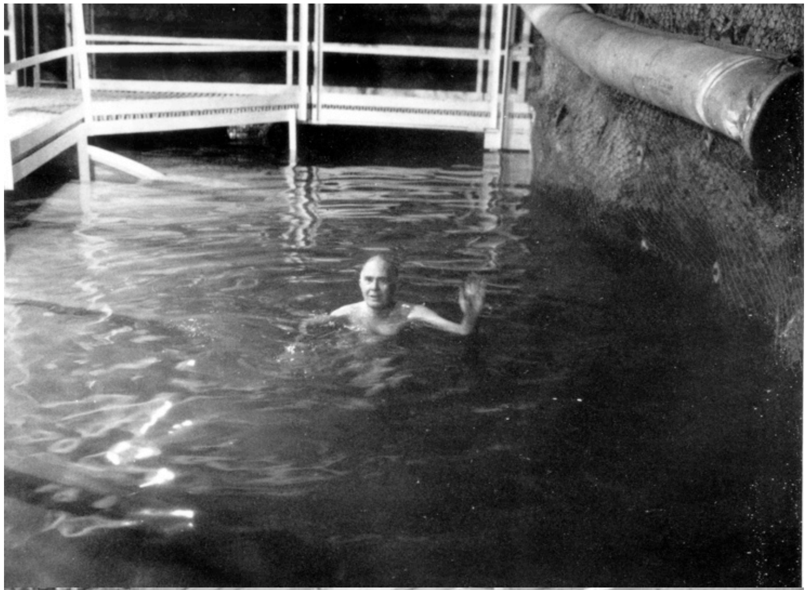
•With funds in place, physics data can start in Fall 2008.

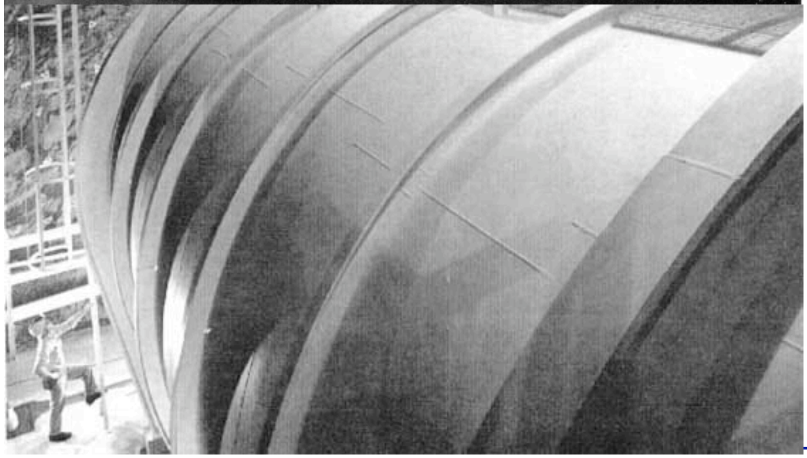
Detailed Design

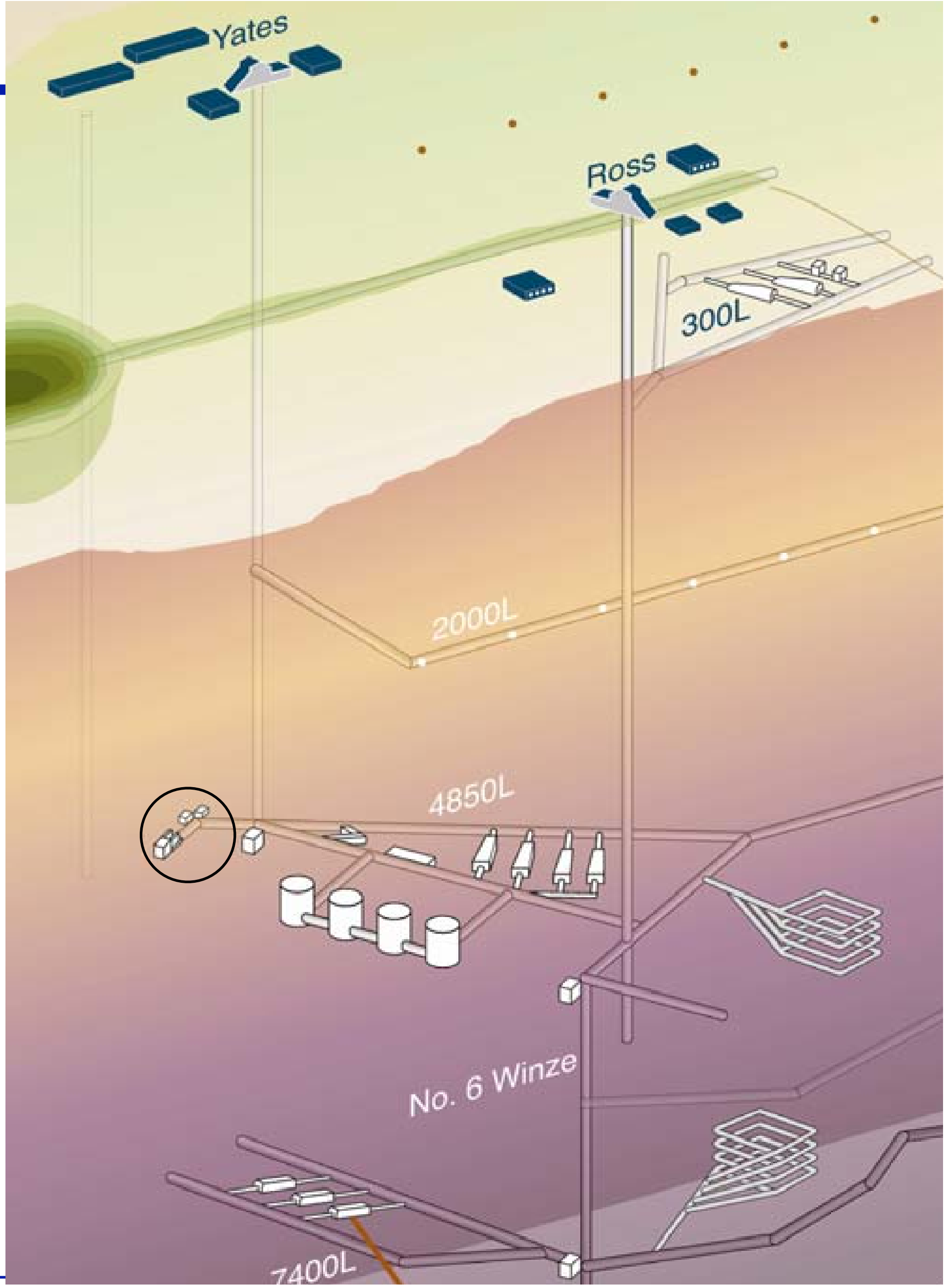


Cryostat Assembly (at Case)

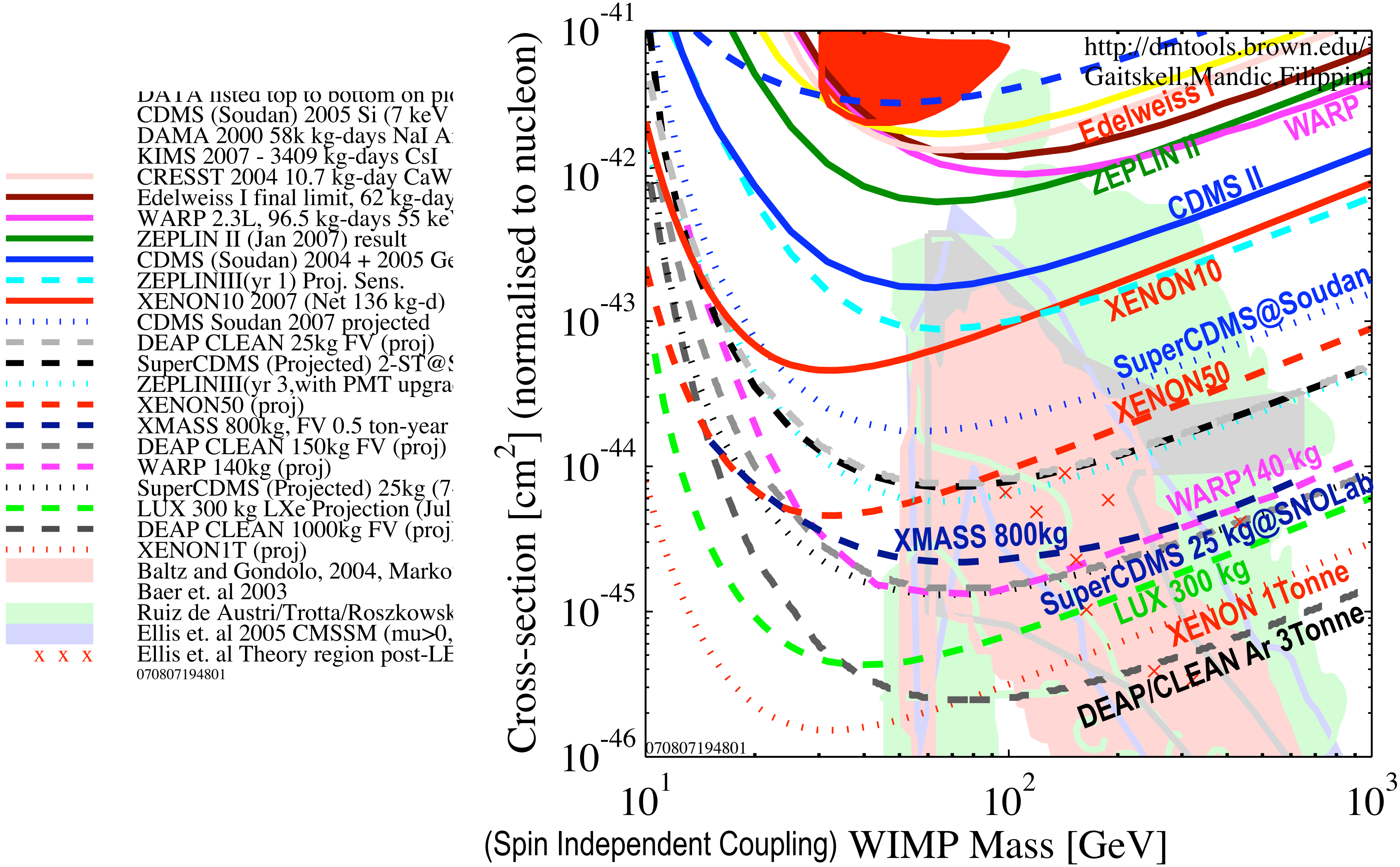
Water Shield - Homestake - Davis Cavern



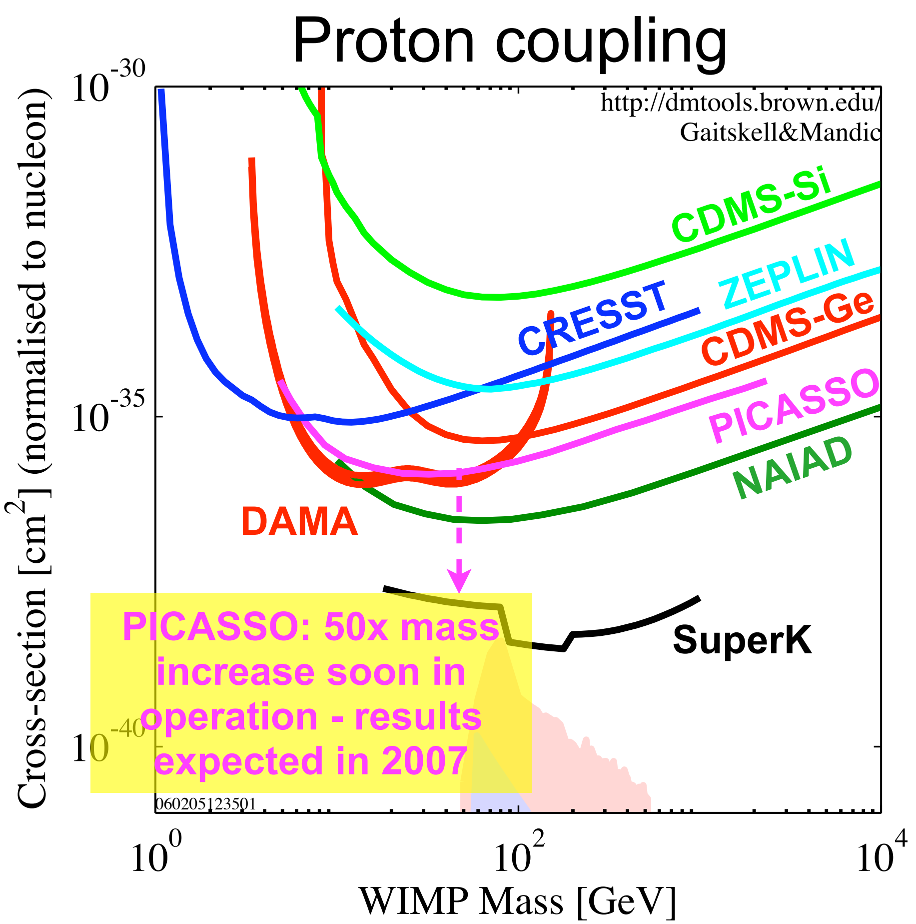


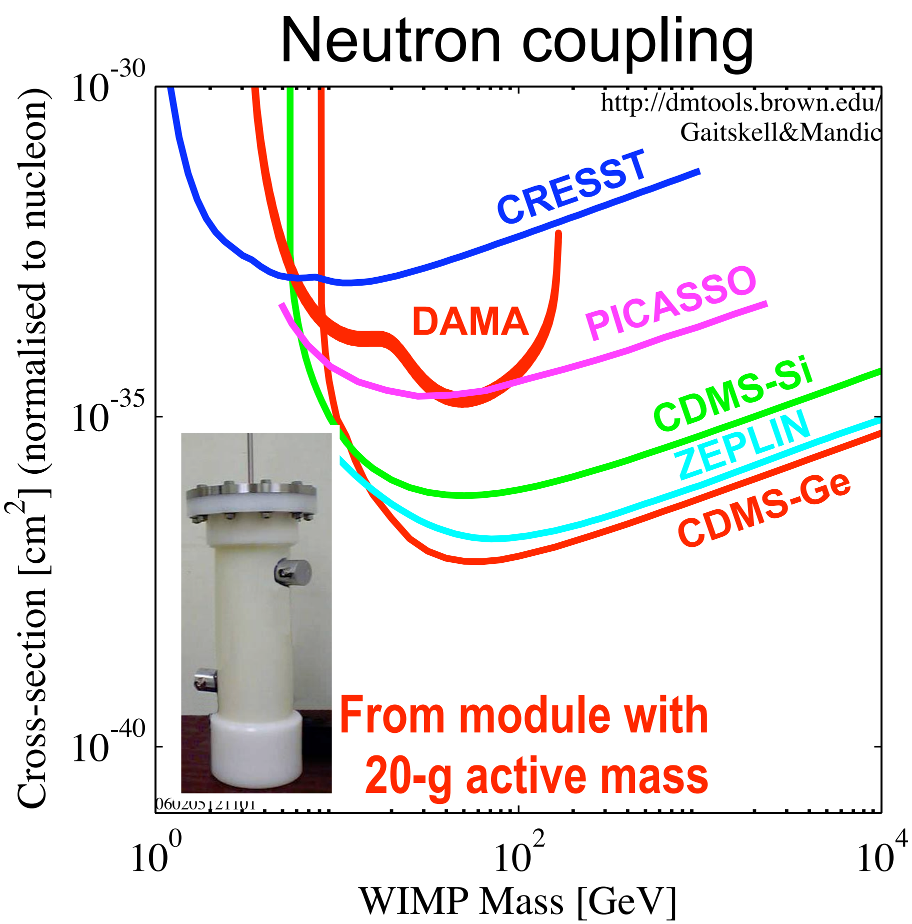


Dark Matter Projected Experiment Goals



Spin-Dependent WIMP limits





When spin independent coupling suppressed, rate dominated by axial coupling to unpaired nucleon

(DAMA regions from Savage, Gondolo and Freese)

Conclusions

- Dark Matter Direct Detection is High Priority for Funding Agencies Worldwide
  - e.g. DMSAG (US) - Dark Matter Scientific Assessment Group Report (HEPAP/AAAC)
    - http://www.science.doe.gov/hep/DMSAGReportJuly18,2007.pdf
  - Probing SUSY Particle Models (5 year program very complementary to LHC reach)

- Cryogenic Detectors
  - CDMS -> SuperCDMS (SuperTowers with detectors 0.25->1 kg)
    - 2007 Complete search using existing 30 dets = 5 Tower (5 kg) at Soudan
    - 2008 Initial operation running of 2xSuperTowers (10 kg) at Soudan
    - 2009 Review for approval of 25 kg Experiment at SNOLab
  - Edelweiss (Ge)
    - March 2007-> : 22 x 320g Ge NTD + other dets (June- Interim Result 19 kg-day no WIMP)
    - Funding for phase 30 kg requested in 2007. Goal: 10e-44 cm2
  - CRESST ($CaWO_4$)
    - Interim Result 1 kg encouraging / Now installing total 10 kg targets

Conclusion - Noble Liquids for Dark Matter

- Noble Status
  - 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)
    - 39Ar (160 evts /keVee/kg/day) / Rn daughters on surfaces (major issue)
  - Xe Self-shielding (XMASS) - Constructing 800 kg target
  - Position reconstruction based on photoelectron hit patterns (timing not useful in <=10 tonne scale). Mis-reconstruction is a concern - requires very good PMT coverage
- Dual Phase (Liquid Target/Ioniz Readout in Gas) - Discrim. Ionization/Photons+PSD (Ar)
  - Xe TPC Operation: ZEPLIN II / XENON10 (15-35 kg target)
    - Discrimination established $\sim 10^3 10^2$: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.)

Conclusions /3

- Scaling of Technology
  - Detector WIMP sensitivity improves very significantly with size
    - Self shielding can be exploited if use single target volume
  - Noble Liquid Designs are very scalable
    - Better than 1 evt/100 kg/month ($<10^{-45}$ cm^2) in a few years seems very realizable
    - These new experiments will demonstrate if >>1 tonne are reasonable
    - No obvious "show stoppers"
  - Cryogenic Detectors will continue to compete
    - But it requires long exposure periods to stay competitive with Noble targets
    - Major challenge will be cost / feasibility of >>100 kg targets
- Future Direct Detection Experiments 2010->
  - Future instruments (multi-tonne) for 10^{-46} – 10^{-47} cm^2 also realistic
    - "Attempt to guarantee WIMP discovery if SUSY models are reasonable"
    - Need multiple targets / technologies to confirm observation & study signals
  - Solar Neutrinos will become background (require ER/NR discrimination to beat it down)
  - Expect to form smaller number of large international collaborations
- Many Other Possibilities for Detection
  - Cosmic Rays / Neutrinos / LHC